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Neutrino astronomy for multi-messenger studies in Super-Kamiokande and prospects for Hyper-Kamiokande

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Abstract

Neutrinos, as neutral and weakly interacting particles, play a crucial role in the field of multi-messenger astronomy. This thesis presents a comprehensive study of neutrino emission from various multi-messenger sources, from supernovae to the galactic disk.

Two works will be discussed about the expected neutrino flux on Earth from a selected catalog of galactic sources and from a recent supernova, SN2023ixf, exploded in the nearby galaxy M101.

In the second part of this thesis, a focus is given to the connection between neutrinos and gravitational waves, two complementary messengers that can provide insights into high-energy astrophysical processes. Preliminary results from a follow-up search of neutrinos in coincidence with the gravitational waves detected during the first period of O4 run using Super-Kamiokande data will be presented. Although no excess of events in coincidence with any gravitational wave has been observed, this has been used to constraint the expected flux of neutrino from these sources.

One of the key contributions of this work is the development of an on-line pipeline for the Super-Kamiokande experiment designed to search for neutrino counterparts to gravitational wave detections. By leveraging real-time data from gravitational wave observatories, the pipeline enables rapid identification and correlation of potential neutrino signals, facilitating timely follow-up observations and enhancing the potential for multi-messenger discoveries.

Prospects of neutrino astronomy with the future Hyper-Kamiokande will be also presented.

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Introduction

Neutrino astronomy has garnered significant interest in recent years as a powerful tool to probe the Universe. From a cosmological perspective, neutrinos are produced in vast quantities in the early universe and during astrophysical events such as supernovae, neutron star mergers, and active galactic nuclei activity. They can travel long distances across the universe without being deflected or absorbed, making them ideal cosmic messengers. By studying neutrinos, one can gain valuable information about the most energetic and distant astrophysical sources, and even about processes that occurred shortly after the Big Bang.

A primary aspect of this research involves investigating the theoretical models that describe the production of neutrinos in these astrophysical environments. An extended investigation on the role of neutrinos in the multi-messenger astronomy, from production processes to source models, is performed. In particular, concerning the emission models, two research projects in which I actively collaborated are presented in Chapter 3.

One of the most recent and nearby supernova explosion observed is SN2023ixf, a supernova that occurred in May 2023 in the M101 galaxy at a distance of 6.4 Mpc, and classified as a type II SN. Given its nature and proximity, in [1]

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we considered this supernova to test several models regarding the emission of both low-energy and high-energy neutrinos.

For the low-energy emission, several models have been considered which take into account different progenitor masses, neutrino luminosity, oscillations parameters as well as varying the simulation treatments (either 1D, 2D or 3D simulations). To estimate the expected number of neutrinos detected on Earth, both Super-Kamiokande and its successor, Hyper-Kamiokande, have been considered, since Super-Kamiokande is currently the most sensitive detector for supernovae and Hyper-Kamiokande will potentially have an even greater sensitivity.. Even so, due to the supernova distance, all models resulted in an expected number of neutrinos under-threshold for both detectors.

For the high-energy emission, the so-called "choked jet" model has been tested. This model contemplates the possibility that, after the core collapses, jets may be produced and, if the star still retains its H/He core (i.e. a type II supernova), these jets are trapped due to the massive envelopes, thus the appellation "choked jets". Inside the shock regions generated by the propagation of the jet, accelerated protons may interact with photons and produce neutrinos. A simulation of this model has been performed, varying several model parameters. Another model considered was the production of high-energy neutrinos via the interaction of the SN ejecta with a dense CSM. In both cases, the lack of detection of neutrinos by IceCube has been used to impose constraints on the models.

In the second work [2], we estimated the total high-energy ($E > TeV$) neutrino flux from a selected catalog of galactic sources (both steady and

transient) based on their observed TeV gamma-ray fluxes. This estimation provides constraints on the origin of the recent galactic diffuse neutrino flux observed by the IceCube Telescope. By computing the flux of each single source, we also evaluated the expected number of neutrinos in both IceCube and KM3NeT telescopes and found which may be the most promising significant sources to be detected in the future.

The second part of this thesis focuses on the potential to detect neutrinos in coincidence with gravitational waves, since it offers an unprecedented opportunity to study catastrophic events such as neutron star or black hole mergers and could potentially act as a more robust trigger alert for other experiments, compared to the single gravitational waves detection.

In particular, for neutrino detection, I refer to the Super-Kamiokande experiment, a 50 kton water Cherenkov detector located in Japan and primarily focused on the detection and study of neutrinos and proton decay.

In Chapter 5, preliminary results of a follow-up analysis to search neutrino counterparts in Super-Kamiokande to the gravitational waves detected during the first period of the Gravitational Waves O4 run (GW-O4a) are presented. No significant excess was observed in coincidence with any GW event so far, either considering low-energy or high-energy samples. As a consequence limits on the expected flux on Earth have been determined.

In Chapter 6, the techniques for the development of an online pipeline for Super-Kamiokande, designed to perform rapid searches for neutrino counterparts in response to gravitational wave detections, are presented. The pipeline is aimed at automating the entire process, from receiving gravitational wave alerts and filtering data, to selecting candidate events and per-

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forming searches within the Super-Kamiokande data set.

This infrastructure significantly improves the response time for detecting potential neutrino counterparts and can be extended to future neutrino observatories. The framework is designed with an eye toward the increasing sensitivity of both neutrino detectors and gravitational wave facilities. Once finalized, the goal is to adapt and install this online pipeline also in the future Hyper-Kamiokande detector, which, thanks to the higher statistics and improved detectors, will be characterized by a higher sensitivity to astrophysical neutrinos.

Thus, in the last chapter, the prospects for astrophysical searches in Hyper-Kamiokande are presented. In particular, I focus on the improvements that will be obtained thanks to the deployment of the mPMT module, a photo-sensor developed by the INFN/Hyper-K group in Naples and to which I highly contributed during the R&D phase. This module, thanks to its design, which consists of 19 PMTs installed in a pressure vessel, each with a unique orientation, provides a better reconstruction of the direction of the incoming neutrinos as well as a notable improvement for calibration studies which are crucial for low energy detection.

Chapter 1

Neutrino physics

Neutrinos are among the most fascinating particles in both elementary physics and cosmology, playing a crucial role in understanding the fundamental forces and structure of the universe.

Proposed by Wolfgang Pauli in 1930 to explain the apparent loss of energy in beta decay [3], neutrinos have revolutionized our understanding of weak interactions and the nature of particle mass. Neutrinos interact only through the weak force, making them extremely elusive, but their study has led to key discoveries, such as neutrino oscillations [4], which revealed that neutrinos possess mass, something initially unaccounted for in the Standard Model of particle physics.

Neutrinos remain a prominent focus in the field as scientists aim to resolve open questions such as the neutrino mass hierarchy (the ordering of the neutrino mass states), the exact values of their masses, and the potential for

lepton CP violation. CP violation, if confirmed in neutrinos, could provide insight into why the universe is dominated by matter rather than antimatter.

In this chapter, the main features of neutrinos - properties, sources, and interactions - will be discussed.

1.1 Neutrino Oscillations

The first idea of neutrino oscillations was introduced by Pontecorvo in 1957. At that time only one neutrino family was assumed (ν_e) and he proposed the possibility of having neutrino/antineutrino oscillations of the type $\nu \longrightarrow \bar{\nu}$ in analogy with K_0 oscillations [5, 6]. The limitations of the first proposal were overcome with the discovery of a second neutrino family (ν_μ).

In 1962 Maki, Nakagawa, Sakata considered the possibility of having oscillations of neutrinos among different families [7].

In 1978 Wolfenstein pointed out a new effect that concerns neutrinos propagating in ordinary matter [8, 9]; its physical meaning and relevance was clarified by Mikheyev and Smirnov in 1986 [10] and will be discussed in the following.

The evidence of oscillations accumulated from the observation of solar and atmospheric neutrinos over many years (e.g. [11, 12]). The decisive role of the results of SNO (Sudbury Neutrino Observatory)[13] and Super-Kamiokande (Super-K) [14] as a proof of oscillations was recognized with the Nobel prize in 2015. In the following, a basic description of neutrino oscillations mechanism will be given.

1.1.1 Two flavors oscillations

The main features of neutrino oscillations can be readily understood by considering only two flavors. Let's consider the weak eigenstates ν_e and ν_μ and the mass eigenstates ν_1 and ν_2 . In quantum mechanics, neutrino oscillations are a consequence of the fact that the mass eigenstates don't correspond to the weak eigenstates. This means that the basis of weak eigenstates can be related to the basis of mass eigenstates by a unitary matrix U :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} \\ U_{\mu 1} & U_{\mu 2} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \quad (1.1)$$

When considering a unitary 2×2 matrix, this can be parametrized in terms of a single mixing angle θ :

$$U = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \quad (1.2)$$

As an example, let's suppose a neutrino beam is generated along the x-axis, containing a flavor state $|\nu_\alpha(0)\rangle$ which describes a neutrino generated with a definite flavor $\alpha(= e, \mu)$ at the space-time point $(x, t) = (0, 0)$. Suppose the neutrino beam is free to propagate in vacuum. By using Eq. 1.1, at any space-time point $(\vec{x}, t)$ the flavor state can be written in terms of the mass eigenstates as:

$$|\nu_\alpha(\vec{x}, t)\rangle = \sum_{k=1,2} U_{\alpha k} |\nu_k(\vec{x}, t)\rangle = \sum_{k=1,2} U_{\alpha k} e^{-i\phi_k} |\nu_k(0, 0)\rangle \quad (1.3)$$

where we assumed that the state evolves in time according to the Schrodinger

equation. At the same time, by inverting Eq. 1.1 and using the unitary matrices' property $U^{-1} = U^\dagger \equiv (U^*)^T$, we can write a certain mass eigenstate $|\nu_i\rangle$ in terms of the weak eigenstates as:

$$|\nu_i\rangle = \sum_{\gamma=e,\mu} U_{i\gamma}^* |\nu_\gamma\rangle \quad (1.4)$$

Substituting Eq. 1.4 in Eq. 1.3, we get the relation between the flavor state at any space-time $(\vec{x}, t)$ in terms of the flavor states at the generation point:

$$|\nu_\alpha(\vec{x}, t)\rangle = \sum_{k=1,2} U_{\alpha k} e^{-i\phi_k} \sum_{\gamma=e,\mu} U_{k\gamma}^* |\nu_\gamma(0, 0)\rangle = \sum_{k=1,2} \sum_{\gamma=e,\mu} U_{k\gamma}^* e^{-i\phi_k} U_{\alpha k} |\nu_\gamma(0, 0)\rangle \quad (1.5)$$

Now suppose a detector is placed at distance L from the beam generator. The transition amplitude for detecting a neutrino of flavor β will be:

$$\begin{aligned} A(\nu_\alpha(0, 0) \rightarrow \nu_\beta(\vec{x}, t)) &= \langle \nu_\beta(\vec{x}, t) | \nu_\alpha(0, 0) \rangle \\ &= \sum_{k=1,2} \sum_{\gamma=e,\mu} U_{\gamma k} e^{-i\phi_k} U_{k\beta}^* \langle \nu_\gamma(0, 0) | \nu_\alpha(0, 0) \rangle \\ &= \sum_{k=1,2} U_{\alpha k} e^{-i\phi_k} U_{k\beta}^* \end{aligned} \quad (1.6)$$

where the last step comes from the orthogonality of the flavor states

$$\langle \nu_\gamma(0, 0) | \nu_\alpha(0, 0) \rangle = \delta_{\gamma\alpha} \quad (1.7)$$

The oscillation probability is then the coherent sum of the transition

amplitude:

$$\begin{aligned}
 P(\nu_\alpha \rightarrow \nu_\beta) &= |A(\nu_\alpha(0,0) \rightarrow \nu_\beta(\vec{x},t))|^2 = \left| \sum_{k=1,2} U_{\alpha k} e^{-i\phi_k} U_{k\beta}^* \right|^2 \\
 &= \sum_{k=1,2} \sum_{j=1,2} U_{\alpha k} U_{k\beta}^* U_{j\alpha}^* U_{\beta j} e^{-i(\phi_k - \phi_j)}
 \end{aligned} \tag{1.8}$$

By expressing the unitary matrix as in Eq. 1.2 and by performing all the calculations we find out that:

$$P(\nu_\alpha \rightarrow \nu_\beta) = 2 \sin^2(2\theta) \sin^2\left(\frac{\Delta\phi_{21}}{2}\right) \tag{1.9}$$

Since $\phi_i = E_i t - \vec{p}_i \cdot \vec{x}$, the phase difference is then:

$$\Delta\phi_{21} = (E_2 - E_1)t - (\vec{p}_2 - \vec{p}_1) \cdot \vec{x} \tag{1.10}$$

Considering neutrinos as relativistic particles we can write that $t = |\vec{x}| = L$ (where L is the distance between the source and the detector expressed in natural units). Moreover, supposing an equal momentum $\vec{p}$ for both mass eigenstates (the result isn't altered by this assumption), in the relativistic approximation the phase difference can be written as follows:

$$\Delta\phi_{21} = \frac{\Delta m^2 L}{2E} \tag{1.11}$$

Substituting this back into Eq. 1.9 we get:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right) \tag{1.12}$$

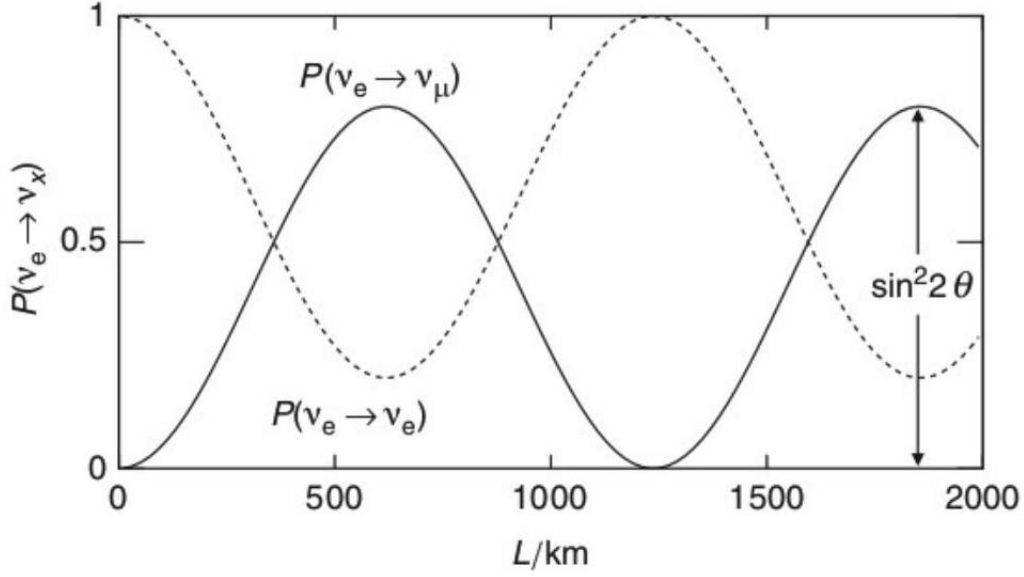


Figure 1.1: The two-flavor oscillation probability $P(\nu_e \rightarrow \nu_\mu)$ and the survival probability $P(\nu_e \rightarrow \nu_e)$ plotted as function of L for $E_\nu = 1\text{GeV}$, $\Delta m^2 = 0.002\text{eV}^2$ and $\sin^2(2\theta) = 0.8$.

This is the probability that one generates a ν_α but detects a ν_β and is called the *oscillation probability*.

The oscillatory behavior comes from the difference in energy of the two mass eigenstates, which is interpreted as coming from different masses of the eigenvalues. A plot of the oscillation probability as a function of the distance between the source and the detector is shown in Figure 1.1 for a particular set of parameters.

1.1.2 Three flavor oscillations

The derivation of the neutrino oscillation probability for two flavors contains nearly all of the essential physics, namely the relationship between the weak and mass eigenstates and that the oscillations originate from the phase dif-

ference between the mass eigenstates in the time-dependent wave function. The full three-flavors derivation of the neutrino oscillation probabilities follows closely the steps above. In this case the relation between the weak eigenstates and mass eigenstates will be:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad (1.13)$$

The matrix U is known as the **Pontecorvo-Maki-Nakagawa-Sakata (PMNS)** matrix. The elements of the PMNS matrix are fundamental parameters of the lepton flavor sector.

The standard parametrization of the PMNS matrix employs 3 rotation matrices and 3 complex phases:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\beta} & 0 \\ 0 & 0 & e^{i\gamma} \end{pmatrix} \quad (1.14)$$

where $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$.

$(\theta_{12}, \theta_{13}, \theta_{23})$ are the three mixing angles while δ_{CP} is the possible CP-violating phase. The final sub-matrix in this expression includes the so-called Majorana phases, $e^{i\beta}$ and $e^{i\gamma}$, i.e. the terms that define whether neutrino are Majorana particles (the particle is its own anti-particle). This matrix plays no part in the description of neutrino flavor oscillations but it does play a part in neutrino-less double beta decay, a theoretical nuclear process where two

CHAPTER 1. NEUTRINO PHYSICS

neutrons in a nucleus decay into two protons and two electrons without emitting neutrinos. This decay can only occur if neutrinos are Majorana particles.

Following a similar procedure as the previous section and using the unitary matrices' property:

$$\sum_{i=1,2,3} \sum_{\alpha=e,\mu,\tau} \sum_{\beta=e,\mu,\tau} U_{\alpha i} U_{\beta i}^* = \delta_{\alpha\beta} \quad (1.15)$$

we get the following oscillation probability:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left(U_{\alpha 1} U_{\beta 1}^* e^{-i\phi_1} + U_{\alpha 2} U_{\beta 2}^* e^{-i\phi_2} + U_{\alpha 3} U_{\beta 3}^* e^{-i\phi_3} \right)^2 \quad (1.16)$$

By using Eq. 1.11 and the complex relationship:

$$|z_1 + z_2 + z_3|^2 = |z_1|^2 + |z_2|^2 + |z_3|^2 + 2\Re(z_1 z_2^* + z_1 z_3^* + z_2 z_3^*) \quad (1.17)$$

We can write Eq. 1.16 as follows:

$$\begin{aligned} P(\nu_\alpha \rightarrow \nu_\beta) = & \delta_{\alpha\beta} - 4 \sum_{i>j} \Re \left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \sin^2 \left(\Delta m_{ij}^2 \frac{L}{4E} \right) \right) \\ & + 2 \sum_{i>j} \Im \left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \sin^2 \left(\Delta m_{ij}^2 \frac{L}{4E} \right) \right). \end{aligned} \quad (1.18)$$

If we suppose that there is no CP-violation (i.e. $\delta_{CP} = 0$) the probability can be written as follows:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re \left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \sin^2 \left(\Delta m_{ij}^2 \frac{L}{4E} \right) \right) \quad (1.19)$$

Although Eq. 1.18 provides a detailed description of neutrino oscillations, certain terms and CP-violation effects have often been negligible in many experimental contexts. As a result, the two-flavor oscillation framework was sufficient and widely used for decades, especially before experiments achieved the sensitivity needed to observe subdominant effects. However, with the aim of determining the CP-violation phase in future long-baseline experiments, the three-flavor oscillation framework has now become essential.

1.1.3 Neutrino mass hierarchy

Since the neutrino oscillation probabilities depend on differences of the squared neutrino masses, the experimental measurements of neutrino oscillations do not constrain the overall neutrino mass scale. To date, there are no direct measurements of neutrino masses, only upper limits [15, 16, 17].

The results of recent neutrino oscillation experiments provide determinations of differences of the squares of the neutrino masses [18]:

$$\begin{aligned} |\Delta m_{21}^2| &= |m_2^2 - m_1^2| \approx 7.5_{0.17}^{+0.19} \times 10^{-5} \text{eV}^2 \\ |\Delta m_{31}|^2 &= |m_3^2 - m_1^2| \approx 2.457_{-0.047}^{+0.047} \times 10^{-3} \text{eV}^2 \end{aligned} \tag{1.20}$$

Regardless of the absolute mass scale of the lightest neutrino, there are two possible hierarchies for the neutrino masses, shown in Figure 1.2. In the normal hierarchy, or normal ordering (NO), $m_3 > m_2$ and in the inverted hierarchy, or inverted ordering (IO), $m_2 > m_3$. Regardless of the hierarchy, because $|\Delta m_{21}^2| \ll |\Delta m_{32}^2|$ in most circumstances it is reasonable to make the approximation [19]:

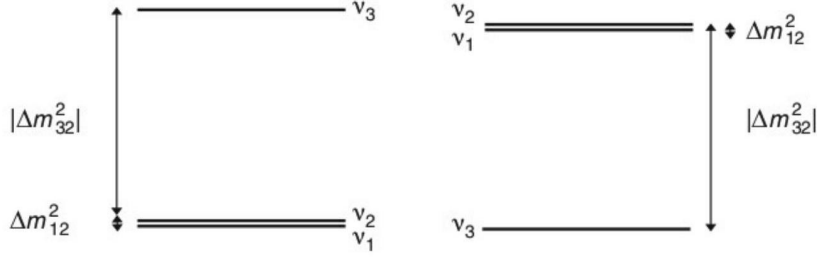


Figure 1.2: The two possible neutrino mass hierarchies, normal where $m_3 > m_2$ and inverted where $m_2 > m_3$.

$$|\Delta m^2_{32}| \approx |\Delta m^2_{31}| \quad (1.21)$$

In this context, astrophysical neutrinos offer a unique pathway to probe the neutrino mass hierarchy, as their oscillations over astronomical distances are sensitive to the mass ordering, providing a complementary approach to terrestrial experiments and offering insights into fundamental properties of neutrinos that influence particle physics and cosmology.

1.1.4 CP violation in neutrino oscillations

As we have previously seen, neutrino oscillations depend on the phase δ_{CP} of the PMNS matrix (Eq. 1.14), making it possible to observe the violation of the CP symmetry in neutrino oscillations.

The magnitude of the CP violation in neutrino oscillation can be characterized by the difference of the probabilities between neutrino and antineutrino appearance channels: $\Delta P_{\alpha\beta} \equiv P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$ which is twice the

imaginary term in the three-flavor oscillation probability (Eq. 1.18)[19]:

$$\Delta P_{\alpha\beta} = -16J_{\alpha\beta} \sin\left(\frac{\Delta m_{12}^2}{4E}\right) \sin\left(\frac{\Delta m_{31}^2}{4E}\right) \sin\left(\frac{\Delta m_{32}^2}{4E}\right) \quad (1.22)$$

where

$$J_{\alpha\beta} \equiv \Im(U_{\alpha 1}U_{\beta 1}^*U_{\alpha 2}^*U_{\beta 2}) = \pm J \quad (1.23)$$

with positive (negative) sign for (anti-)cyclic permutation of the flavor indices e, μ and τ . The quantity J is a measure of CP violation of the PMNS matrix and is known as the **Jarlskog invariant**. Using the standard parametrization of the PMNS matrix it's possible to write:

$$J = \frac{1}{8} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin \delta_{CP} \quad (1.24)$$

Therefore, a necessary condition for observing CP violation in neutrino oscillations is that all three mixing angles θ_{ij} are non-zero and that the phase δ_{CP} is different from 0 and π . Furthermore, one can see from Eq. 1.22 that $\Delta m_{21}^2, \Delta m_{31}^2$ and Δm_{32}^2 must be non vanishing, i.e. all neutrinos masses should be different. Currently, the T2K experiment [20] have determined a 3σ confidence interval for δ_{CP} value. In case of normal mass ordering it is $[-3.41, -0.03]$ while in case of inverted mass ordering it is $[-2.54, -0.32]$ [21]. This exciting result has pushed to upgrade the neutrino oscillation program in Japan, thus the project to realize a bigger experiment, Hyper-Kamiokande [22], that, with an improved detection system, an upgraded beam and more statistics, can hopefully lead to a 5σ confidence interval for δ_{CP} .

1.1.5 Neutrino Oscillations in Matter

Neutrino oscillations occur because of a difference in phase between the wave packets of each mass eigenstates. This phase difference can occur from wave packets which propagate with different velocities due to mass differences. This is what happens in the vacuum. In matter, however, the phase difference is determined by the total energy of the mass eigenstate. If the neutrino is propagating in a potential V , then the total energy of a state is $E + V$, and if the potential is different for different neutrino flavors (i.e. different flavors interact differently) then a phase difference can be introduced through the interaction potential and the neutrinos will oscillate through matter effects. This is what happens with electron neutrinos (and antineutrinos), that have different interactions with matter compared to other neutrinos flavors. When travelling through matter, ν_e can have both charged current and neutral current elastic scattering with electrons, while ν_μ or ν_τ have only neutral current interactions with electrons. This fact gives rise to an extra potential $V_e = \pm 2G_F N_e$, where N_e is the electron density in matter, G_F is the Fermi constant, and the positive (negative) sign applies to electron neutrinos (antineutrinos).

The modification of the oscillation probability is known as the **Mikheyev-Smirnov-Wolfenstein (MSW)** effect [8, 9, 10].

Let's see what happens in the two flavor mixing case. In the case of vacuum oscillation, we know that the time evolution of the mass eigenstates is governed by Schrodinger equation. If we approximate the energy as $E = \frac{m^2}{2p} + p$ and write the mass eigenstates in terms of the flavor eigenstates, it's easy to

show that the time evolution of flavor eigenstates satisfies the Schrodinger equation:

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = H \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \quad (1.25)$$

where, neglecting constant terms that will eventually appear as a constant phase, the Hamiltonian is:

$$H = \frac{\Delta m^2}{4E} \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} \quad (1.26)$$

By considering the extra $\nu_e - \nu_e$ element and by performing some elementary calculations, the effective Hamiltonian H_M , which governs the propagation of neutrinos in matter, can be written as:

$$H_M = \frac{\Delta m^2}{4E} \begin{pmatrix} -\cos 2\theta + A & \sin 2\theta \\ \sin 2\theta & \cos 2\theta - A \end{pmatrix} \quad (1.27)$$

where

$$A = \pm \frac{2\sqrt{2}G_F N_e E}{\Delta m^2} \quad (1.28)$$

The solution of the corresponding Schrodinger equation is simple in the case where the matter density is constant. In this case, we can simply diagonalize H_M obtaining a matrix similar to that for vacuum, which leads to the usual functional dependence of the oscillation probability:

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta_m \sin^2 \left(\frac{\Delta m_m^2 L}{4E} \right) \quad (1.29)$$

The relation between the effective mixing parameters in matter and in

vacuum is:

$$\begin{aligned}\Delta m_m^2 &= C \Delta m^2 \\ \sin 2\theta_m &= \frac{\sin 2\theta}{C}\end{aligned}\tag{1.30}$$

where

$$C = \sqrt{(\cos 2\theta - A)^2 + \sin^2 2\theta}\tag{1.31}$$

These formula are useful to understand the following important consequences of the MSW effect:

1. If $\sin 2\theta = 0$ then $\sin 2\theta_m = 0$, regardless of the potential. Thus, to observe oscillation in matter, there must be the possibility of vacuum mixing.
2. If the matter is very dense then $\sin 2\theta_m \rightarrow 0$. In very dense matter, oscillation cannot occur via matter effects.
3. Oscillation probabilities for neutrino and antineutrinos can be different due to matter effects (because of the $\pm$ sign in front of A), even if neutrino interactions with matter do not violate CP;

1.2 Neutrino Interactions

Understanding how neutrinos interact and the relative cross sections is essential for their detection. Cross sections are energy dependent; thus, based on the energy sensitivity of the detector, different processes will be dominant. Neutrino interacts only via weak interaction, which can be divided in two main classes: (i) charged current processes (CC) with the exchange of a $W^\pm$

boson; (ii) neutral current processes (NC) with the exchange of a Z^0 boson.

At very high energies ($E > 100\text{GeV}$), the dominant process is the deep inelastic scattering with nucleons.

In a deep inelastic scattering, the neutrino interacts with a quark inside a nucleon, resulting in the breakup of the nucleon into multiple hadrons:

$$\nu_l + p \rightarrow l^- + X \quad (CC) \tag{1.32}$$

$$\nu_l + p \rightarrow \nu_l + X \quad (NC) \tag{1.33}$$

Cross sections are very well known for this process, see for example [\[23\]](#).

In the $[0.1, 100]$ GeV, other processes become dominant like quasi-elastic scattering and pion production.

In a quasi-elastic scattering, a neutrino interacts with a nucleon, causing a simple nucleon transition without breaking it apart:

$$\nu_l + n \rightarrow l^- + p \quad (CC) \tag{1.34}$$

$$\nu_l + n \rightarrow \nu_l + n \quad (NC) \tag{1.35}$$

Cross sections for this process on various target can be found in [\[24\]](#).

In a single pion production, a neutrino interaction produces a pion along

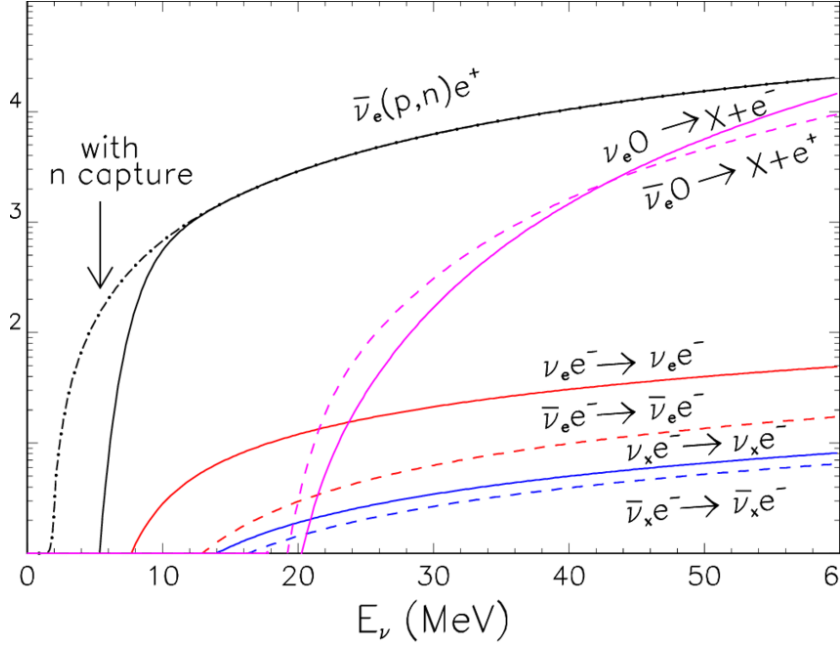


Figure 1.3: Cross sections for low energy neutrino interactions. Credits to [26].

with a nucleon:

$$\nu_l + p \rightarrow l^- + p + \pi^+ \quad (CC) \quad (1.36)$$

$$\nu_l + n \rightarrow \nu_l + n + \pi^0 \quad (NC) \quad (1.37)$$

The cross section for pion production can be found in [25].

At lower energies, in the [1,100] MeV energy range, the most dominant process is Inverse Beta Decay (IBD):

$$\bar{\nu}_e + p \rightarrow n + e^+ \quad (1.38)$$

The energy threshold for IBD is 1.806 MeV. This channel is particularly important for experiments like Super-Kamiokande that looks for astrophys-

ical neutrino sources like the next galactic supernova. In particular for supernovae, about 90% of events detected in Super-K are expected to be IBD [27].

Other relevant channels are the quasi-elastic scattering already mentioned and the elastic scattering:

$$\nu_e + e^- \rightarrow \nu_e + e^- \quad (1.39)$$

This channel is particularly useful for studying solar neutrinos, since most of the solar neutrino emission consists of ν_e with MeV energies. Fig. 1.3 reports the cross sections of main neutrino interactions in the low energy regime.

1.3 Neutrino Sources

1.3.1 Atmospheric Neutrinos

Atmospheric neutrinos are produced by the decay of pions and kaons in the atmosphere produced by primary cosmic rays in the upper layers of the atmosphere.

Neutrinos' energy range goes from about 100 MeV to 100 TeV. More energetic neutrino can be produced through the decay of charmed D mesons. Atmospheric neutrinos are valuable for studying neutrino oscillations, as they travel long distances through Earth, allowing scientists to observe changes in their flavor composition. The observation of atmospheric neutrinos was one of the first indication of neutrino oscillations. The source-detector dis-

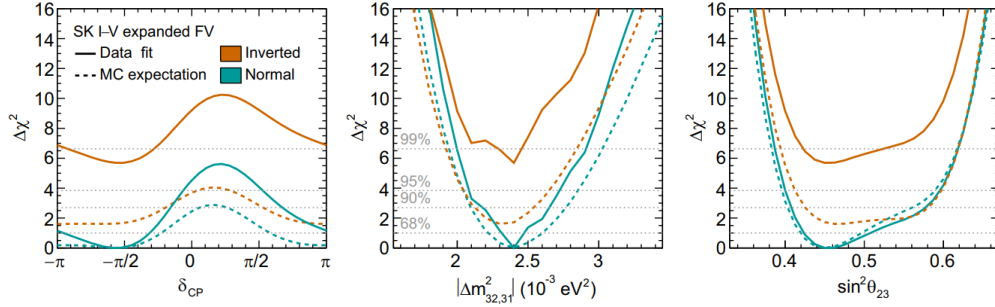


Figure 1.4: Latest result on oscillation parameters using atmospheric neutrinos by Super-Kamiokande Collaboration. Taken from [12].

tance ranges from about 10 km for neutrinos going downwards, to about 1.3×10^4 km for neutrinos going upwards.

These neutrinos also serve as a background for high-energy astrophysical neutrino searches, making their study essential for understanding both fundamental particle physics and astrophysical phenomena.

Atmospheric neutrinos are studied by experiments like Super-Kamiokande [14], MINOS [28], SNO [13] and IceCube [29]. Figure 1.4 shows the latest fit results for oscillation parameters in Super-Kamiokande.

1.3.2 Solar Neutrinos

Fusion reactions in the core of the Sun produce a huge flux of neutrinos [30]. Different spectra of neutrinos are emitted depending which "cycle" of reaction is burning hydrogen (pp-chain, CNO-cycle).

Neutrinos interact weakly with matter, they can travel from the Sun's core to Earth without any appreciable absorption by the Sun's outer layers. Since they are produced through different cycles and chains, it implies different neutrino energy distributions. The energy spectrum of neutrinos expected

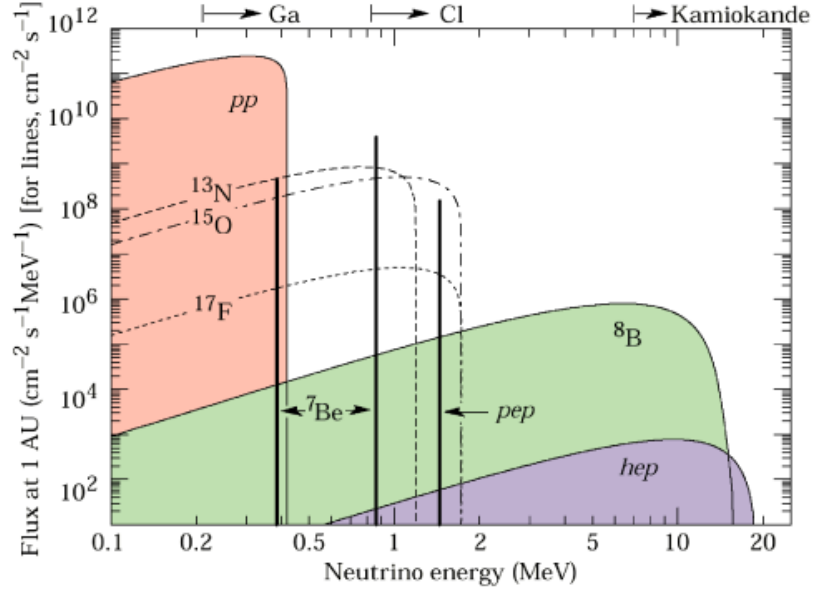


Figure 1.5: The Standard Solar Model prediction of the solar neutrino flux. Thresholds for each of the solar experiments is shown at the top. Super-K and SNO are only sensitive to ^8B and high energy neutrinos. The Gallium experiments have the lowest threshold and can observe pp neutrinos.

from the different cycles is shown in Figure 1.5 along with the thresholds of the main solar neutrino experiments.

The combined observations from Super-Kamiokande and SNO in 2001 gave evidence for the neutrino oscillations. Super-Kamiokande used neutrino-electron elastic scattering to measure the recoil of electrons and zenith angle dependence of solar neutrinos, while SNO measured neutrino-deuteron charged-current reaction rate and exploit its unique capability to observe neutral current interactions, evaluating the flux of all neutrino types. These combined measurements provided evidence of electron neutrino oscillation into other flavors of neutrinos [13][31].

1.3.3 Reactors Neutrinos

Reactors are one of the two artificial sources detected by current experiments. Nuclear reactors gain their power via the fission of isotopes like ^{235}U , ^{238}U , ^{239}Pu , ^{241}Pu which produces lighter elements that consequently decays via beta decay and produce electron antineutrinos.

Several experiments have been designed to search for reactor neutrinos, in particular for oscillation studies, such as Daya-Bay[32], Double Chooz [33] and Reno [34]; the future Juno experiment [35] will improve even further the detection capabilities to use reactor neutrinos to determine neutrino mass ordering and more precise measurements of oscillation parameters, especially θ_{13} [36].

1.3.4 Accelerators Neutrinos

Accelerators are the second artificial source of neutrinos. Neutrino beams are created to travel a fixed distance. For that, protons are accelerated and hit a target, producing new particles which then decay into neutrinos. The experiments have the tuning power to create both neutrinos and antineutrinos, using magnets to select positive or negative pions created by the interaction of protons with the target. Accelerator neutrino experiments can be classified in terms of the distance source-detector: short-baseline (SBL) accelerator neutrino experiments with $L \sim 10\text{ m} - 1\text{ km}$ and long-baseline (LBL) accelerator neutrino experiments with $L \sim 10^2 - 10^3\text{ km}$.

While traveling long distances implies a large oscillation probability, when traveling a short distance, the oscillation probability is small, so they are

used to study anomalous neutrinos appearance or disappearance. Short-baseline experiments can also serve as near detectors for Long-baseline experiments. Experiments like Minerva [37] or MicroBoone [38] are examples of Short-baseline experiments while T2K [20] and Nova [39] are examples of Long-baseline experiments.

1.3.5 Astrophysical Neutrinos

Neutrinos can also be probes to explore the Universe. Since they're chargeless and interact weakly, they can travel cosmic distances without being deflected or absorbed, thus giving information about the extreme processes that produce them.

In 1987, for the first time, the observation of 24 neutrinos coming from the supernova SN 1987A was carried out by Super-Kamiokande, IMB and Baksan [40, 41, 42].

Future experiments like Hyper-Kamiokande, JUNO, and DUNE will offer significant upgrades that will enhance the exploration of neutrino astronomy in the low-energy range. Nowadays, with neutrino telescopes like IceCube [29] and the future KM3NeT [43], very energetic neutrinos are observed with energies that reach the PeV scale[44]. These experiments allow to understand powerful cosmic events capable of accelerating particles to incredibly high energies. In particular, they allowed to identify several astrophysical objects as neutrino sources. An extended description of these sources will be given in the next chapter.

Chapter 2

Neutrinos in the Multi-messenger era

2.1 Introduction

The field of astronomy has experienced a paradigm shift with the advent of multi-messenger (MM) astronomy, a revolutionary approach that combines information from different cosmic messengers: electromagnetic radiation, cosmic rays, neutrinos, and gravitational waves. This interdisciplinary synergy enables a more comprehensive understanding of the universe, uncovering phenomena that would remain hidden if observed through a single type of messenger.

Neutrinos played a pivotal role in this field with the observation of the supernova SN1987A [45], marking the first time that both neutrinos and photons (and, in general, two different types of cosmic messengers) were detected from the same astronomical event, other than the sun. Discovered

in February 1987, this supernova in the Large Magellanic Cloud provided an unprecedented opportunity to study the core-collapse of a massive star. This event not only validated the role of neutrinos in stellar evolution but also demonstrated the potential of multi-messenger observations to provide a more complete understanding of cosmic phenomena. SN1987A paved the way for the development of modern neutrino detectors and highlighted the importance of combining different observational channels to gain deeper insights into the universe.

A new exciting phase in multi-messenger astronomy started in 2015 when the LIGO/Virgo Collaborations detected the first gravitational wave event [46]. Gravitational waves (GW), ripples in spacetime predicted by Einstein's theory of General Relativity, originate from cataclysmic events such as the merging of black holes and neutron stars, providing unprecedented information about the properties and dynamics of these objects.

Since then, several multi-messenger sources have been discovered (which will be discussed in the following sections), widening each time our understanding of the Universe.

Currently, many efforts are done to create networks that involve extensive collaboration between ground-based detectors and satellites, such as IceCube Telescope and Super-Kamiokande for neutrinos, Fermi-LAT [47] and Swift [48] satellites for gamma rays, MAGIC [49] and VERITAS [50] telescopes for high-energy photons, along with gravitational wave observatories like Advanced LIGO [51], Advanced Virgo [52], and KAGRA [53]. These facilities

coordinate in real-time to share alerts, allowing telescopes across the globe to quickly follow up on potential multi-messenger events. Additionally, upcoming projects like the Einstein Telescope [54] and LISA [55] promise to further enhance sensitivity to gravitational waves, expanding the range of detectable sources and improving the temporal and spatial resolution of observations.

In Section 2.2 the main mechanisms that allow astrophysical neutrinos production will be discussed. In Section 2.3 a list of the most probable astrophysical neutrino sources, and mainly relevant to this work, will be given, focusing on which processes lead to the emission of neutrinos, as well as the latest observational results. In Section 2.4, a description of the main platforms that allows multi-messenger networking will be given.

2.2 Astrophysical Neutrino Production

When considering the production of astrophysical neutrinos, the energy is a key factor in understanding which processes may produce them.

In astrophysical environments, several thermal processes produce low-energy neutrinos ($E_\nu < 100\text{MeV}$) [56]. One of the key processes is *thermal pair production*, where an electron and a positron annihilate to form a neutrino-antineutrino pair:

$$e^- + e^+ \rightarrow \nu + \bar{\nu} \tag{2.1}$$

Another important process is the *photo-neutrino process*, where a photon interacts with an electron to produce a neutrino-antineutrino pair:

$$\gamma + e^- \rightarrow e^- + \nu + \bar{\nu} \quad (2.2)$$

The *plasma process* occurs in dense plasma, where plasma oscillations produce neutrinos:

$$\gamma_{\text{plasma}} \rightarrow \nu + \bar{\nu} \quad (2.3)$$

Additionally, the *bremsstrahlung process*, where electrons scatter off charged particles and emit neutrinos, can be described by:

$$e^- + Z \rightarrow e^- + Z + \nu + \bar{\nu} \quad (2.4)$$

Another key mechanism is the *URCA process*, where alternating beta decay and electron capture in dense environments generate neutrinos. In the direct URCA process, we have:

$$n \rightarrow p + e^- + \bar{\nu}_e \quad (2.5)$$

$$p + e^- \rightarrow n + \nu_e \quad (2.6)$$

These processes significantly influence the cooling mechanisms in stars and compact objects like neutron stars.

High-energy neutrinos ($E_\nu > 100 \text{ MeV}$) are instead expected to be produced due to the interaction of high-energy protons either with other protons (pp

collisions) or with high-energy photons (*pγ collisions*):

$$p + p \rightarrow \pi + X \quad (2.7)$$

$$p + \gamma \rightarrow pi + \pi^0 \quad (2.8)$$

$$p + \gamma \rightarrow n + \pi^+ \quad (2.9)$$

$$(2.10)$$

The pions subsequently decay and produce neutrinos or gammas:

$$\pi_0 \longrightarrow \gamma + \gamma$$

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \longrightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu \quad (2.11)$$

$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu \longrightarrow e^- + \bar{\nu}_e + \bar{\nu}_\mu + \nu_\mu + \bar{\nu}_\mu$$

Typically, a neutrino from the charged pions production channel receives about 5% of the energy from the initial cosmic ray nucleon while each gamma-ray in a neutral pion decay has, on average, 10% of the energy of the parent proton. From this kind of interaction we expect almost the same number of π_0 , π_- and π^+ particles, due to isospin symmetry [57].

High energy neutrinos are therefore tightly connected to other cosmic messengers and their sources need to be understood in the context of multi-messenger observations.

2.3 Sources of astrophysical neutrinos

Neutrino sources are usually classified as either galactic or extragalactic sources. In this section, a description of both will be given. Although the list is not exhaustive, it includes the sources most relevant to the topics of this thesis.

2.3.1 Galactic sources

The Galactic Plane is the most dense region of the Milky Way, where most of the stars, dusts and other matter is concentrated. Due to the high concentration of material and energetic processes occurring within it—such as supernovae explosions, pulsars, and intense star formation—it serves as an ideal laboratory to study cosmic ray acceleration sites. These cosmic rays, which are highly energetic charged particles, are thought to be accelerated by shock waves from supernova remnants or magnetic fields around pulsars (see [58] for a review). When these cosmic rays interact with the dense gas and dust in the Galactic Plane, they produce secondary particles such as pions, which can decay into neutrinos and gamma rays (see Eqs. 2.11).

Recent observations by the IceCube Neutrino Observatory have led to the first-ever detection of high-energy neutrinos originating from the Milky Way [59]. They reported the observation of a diffuse neutrino emission from the Galactic plane at a 4.5σ level of significance, by comparing diffuse emission models to a background-only hypothesis. Moreover, the Galactic diffuse neutrino flux agrees with multi-messenger expectations of the Galactic diffuse γ -ray flux above 400 TeV recently found by Tibet AS γ [60] and LHAASO [61].

This is a significant breakthrough in neutrino astronomy, finally proving that our galaxy can be a source of these elusive particles. Moreover, based on [62], extra unresolved sources are needed to explain the LHAASO measurements in the γ -ray spectrum and a hadronic component responsible for the high-energy emission cannot be excluded.

2.3.2 Supernovae

Supernovae are among the most powerful explosions in the universe and the most significant sources of astrophysical neutrinos. These cataclysmic events, which mark the violent death of massive stars, release an immense amount of energy in the form of light, neutrinos, and other particles.

Supernovae are classified into two main types based on their underlying mechanisms:

- **Type I supernovae:** they lack hydrogen lines in their spectra and are further divided into several subcategories: Type Ia supernovae occur in binary systems where a white dwarf accretes material from a companion star, eventually reaching a critical mass and undergoing a runaway thermonuclear explosion. Type Ib and Ic supernovae result from the core collapse of massive stars that have lost their outer hydrogen layers (in Type Ib) or both hydrogen and helium layers (in Type Ic).
- **Type II supernovae:** also known as Core-Collapse Supernovae (CC-SNe), these supernovae exhibit hydrogen lines in their spectra and arise from the gravitational collapse of the core of a massive star (i.e. with

a mass greater than 8 solar masses) once nuclear fusion can no longer support it. The collapse triggers a catastrophic explosion, expelling the star’s outer layers and leaving behind a dense core that often forms a neutron star or, in extreme cases, a black hole.

The observation of 24 neutrinos few hours before the visible explosion of the type II supernova SN1987A [41, 40, 42], proved that explosions could occur from the collapse of the core of a massive star, confirming the basic core-collapse supernova engine and providing insights into the physics of dense matter, nucleosynthesis, and the mechanisms driving the explosion (see [63] for a general review of CC-SNe).

Nowadays it is widely accepted that neutrinos play a fundamental role in the star explosion: the most favored model for the CC explosion mechanism is the ”delayed neutrino-heating mechanism” [64]. At the beginning of the stellar collapse, a few milliseconds after the core bounce, a prompt burst of electron neutrinos is emitted, which, alongside iron photo-disintegration, drains energy from the post-shock material and reduces the pressure behind the shock. Thus, the expanding shock is replaced by an accretion shock characterized by matter in-falling. While the core density increases (until hundreds of milliseconds after the bounce), neutrinos get trapped in the core, transferring energy to the surrounding material. Neutrino-energy deposition behind the stalled bounce shock can revive the shock and thus initiate the SN explosion. Moreover, due to their weak interactions with matter, neutrinos can escape the core of the supernova almost immediately, reaching detectors on Earth before the light from the explosion, thus offering a unique and early probe of the event (neutrinos from SN1987A were detected 3 hours before the optical

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observation of the SN explosion, although the connection was done afterwards). Almost 99% of the supernova energy is expected to be transported by neutrinos with thermal energies ($\sim$ tens of MeV).

Although SN1987A gave the opportunity to understand many aspects of a supernova explosion, the limited statistics prevented a full understanding of the mechanism that drives it. For this reason, many models and numerical simulations have been proposed over the past decades, employing a variety of approximations and simplifying assumptions. Therefore, each new supernova discovery serves as a critical test-bed for these models, allowing for their validation or, in the absence of observed neutrinos, placing constraints on them.

While thermal neutrinos are responsible for the explosion mechanism and provide insight into the core of the star, some model predict that also high-energy neutrinos ($E > GeV$) may be produced during a supernova explosion. Some of these model propose that the relativistic jets that drive GRBs may also be produced during core-collapse supernovae [65, 66, 67]. The idea is that, in case of a type II-P SN (i.e. a SN that displays a plateau in its light curve followed by a normal decay), after the core collapses, jets may be produced and, if the star still retain its H/He core, these jest are trapped due to the massive envelops, thus the appellative "choked jets". Consequently, by interacting with the stellar material, they create a cocoon where they transfer their energy (up to $E^{51} - E^{52} \text{ erg}$, i.e. similar to supernova energies). A forward shock and a reverse shock are produced when the jet is propagating in the hydrogen envelope. In the region of the reverse shock, electrons can be accelerated and emit photons that are free to move inside the jet [68]; how-

ever, they cannot leave the source as the envelopes of circumstellar medium outside are largely optically thick to Thomson scattering. Inhomogeneities inside the jets may lead the protons of the jets to interact with these photons, thus producing charged pions and consequently high-energy neutrinos.

Moreover, in core-collapse supernovae, gravitational waves are also expected to be emitted during the rapid and turbulent collapse of a massive star's core, see e.g. [69, 70, 71]. As the core contracts, it produces asymmetrical motions and anisotropic mass flows that emit GWs, offering a unique window into the dynamics of the collapse. Combining information from GW and neutrinos can significantly enhance the probability of detection of one of the two messengers. In [72], for example, they proved that by combining the clusters of low-energy neutrinos observed by LVD and KamLAND detectors in combination with the gravitational wave triggers from LIGO-Virgo detector network, an increase of the probability to detect the gravitational wave signal from a core-collapse supernova at 60 kpc, from zero to $\sim 33\%$, can be obtained for some specific gravitational wave emission model.

Diffuse Supernova Neutrino Background

Neutrinos from all historical core-collapse supernovae (CCSNe) are expected to contribute to a background flux across the Universe, known as the "Diffuse Supernova Neutrino Background" (DSNB) or "Supernova Relic Neutrinos" (SRNs). Detecting this flux could yield valuable insights into both the explosion mechanisms of CCSNe and the star formation history of our universe. The isotropic and time-independent signal of the DSNB flux consists of neu-

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trinos and antineutrinos of all flavors with expected energies up to 40 MeV [73].

The general formalism of the DSNB flux (Φ_{DSNB}) is expressed as the convolution of three key components:

$$\Phi_{DSNB} \propto \frac{dN_\nu}{dE_\nu} \times R_{CCSN}(z) \times P_{osc} \quad (2.12)$$

where $\frac{dN_\nu}{dE_\nu}$ is the average CCSN energy spectrum, $R_{CCSN}(z)$ is the CCSN rate per comoving volume at redshift z and P_{osc} encompasses effects from neutrino oscillations in matter. The energy spectrum is estimated using a pinched Fermi-Dirac distribution, while the $R_{CCSN}(z)$ is determined by the cosmic star formation rate density $\rho^*(z)$, representing the star formation rate per unit time and comoving volume, and the initial mass function (IMF) $\psi_{IMF}(M)$, which characterizes the distribution of stellar masses at birth. In high-density environments, such as the core of a supernova, the MSW effect can cause a resonant enhancement or suppression of the flavor composition in the DSNB flux observed on Earth. Consequently, in DSNB flux predictions, the expression for the differential neutrino yield is adjusted to incorporate this effect.

Several models have been proposed and used to make DSNB flux predictions [74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84]. In particular, since for the DSNB energy range, in current neutrino detectors, such as Super-Kamiokande, the highest sensitivity is to IBD events, predictions are usually made for $\bar{\nu}_e$. Fig. 2.1 shows the expected $\bar{\nu}_e$ flux assuming several theoretical models for DSNB. Despite several experimental efforts, the DSNB flux has not yet

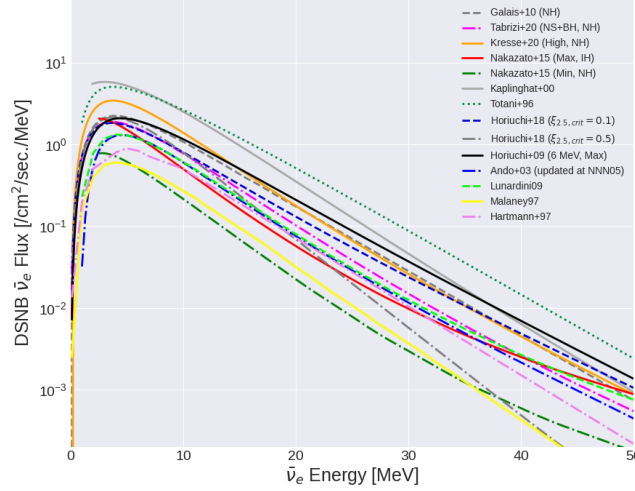


Figure 2.1: DSNB $\bar{\nu}_e$ flux predictions from several theoretical models. [74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84]

been observed. The Super-Kamiokande detector and the KamLAND liquid scintillation detector have placed the most stringent upper limits on the DSNB flux [85, 86]. Exciting new results are expected in the SK-Gd era, as the DSNB search relies solely on the IBD channel, which significantly benefits from the addition of gadolinium (Gd).

2.3.3 Binary neutron star mergers

Binary neutron star (BNS) mergers are a key focus of modern astrophysics because they involve extreme physical conditions that cannot be recreated in terrestrial laboratories. These mergers, which occur when two neutron stars spiral toward each other and collide, offer unique insights into the behavior of matter under extreme densities and temperatures.

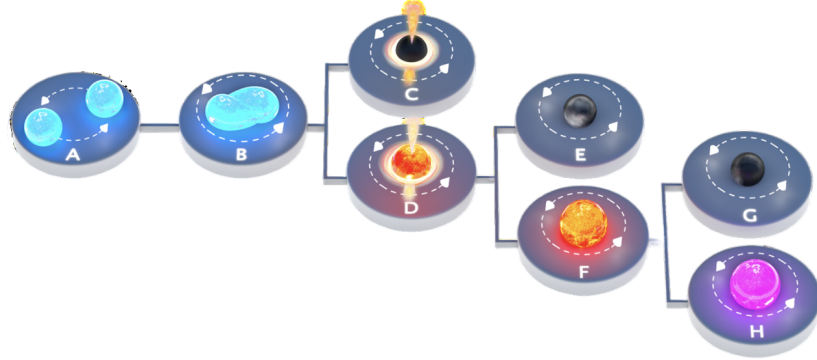


Figure 2.2: The fate of binary neutron star merger remnants. Two neutron stars coalesce, losing orbital angular momentum through the emission of gravitational waves until they eventually merge (panels A $\rightarrow$ B). Depending on the mass of the remnant, it will either promptly collapse to form a black hole with an accretion torus and jet (panels B $\rightarrow$ C), or form a rapidly differentially-rotating neutron star (panels B $\rightarrow$ D). Depending on the mass of this neutron star, it will either be hypermassive, in which case it will collapse to form a black hole in $O(1 \text{ s})$ (panels D $\rightarrow$ E), it will be supramassive, collapsing to form a black hole in 10^{-5} s (panels F $\rightarrow$ G), or it will form an infinitely stable neutron star (panels F $\rightarrow$ H). Credits to [87]

At the moment of the merger, the intense gravitational and nuclear forces can create either a stable neutron star, a short-lived, hyper-massive neutron star or can collapse directly into a black hole, depending on the mass of the system [87] (see Fig. 2.2). The collision produces an enormous release of energy, including a burst of gravitational waves, gamma rays (resulting in a short gamma-ray burst), and other forms of radiation.

Additionally, during the merger, neutron-rich material is ejected into space, where it undergoes rapid neutron capture, known as the r-process, producing heavy elements like gold and platinum. This ejected material is responsible for the electromagnetic counterpart known as a kilonova, which can be observed in optical and infrared wavelengths.

This mechanism was confirmed thanks to the gravitational wave event GW170817

[88], a landmark for multi-messenger astrophysics, detected by the LIGO-Virgo collaborations. This event marked the first time gravitational waves were observed from a binary neutron star merger, and it was accompanied by a broad spectrum of electromagnetic signals, including gamma rays, X-rays, optical light, and radio waves [89, 90]. The simultaneous detection of the gravitational wave, GRBs and its afterglow as well as a kilonova provided a comprehensive view of the cosmic event, offering insights into the formation of heavy elements, the behavior of matter in extreme conditions, and the expansion of the universe.

In this exciting context, neutrinos play a fundamental role. The emission of neutrinos is critical for the cooling of the newly formed hypermassive neutron star (or black hole), as well as in driving the dynamics of the merger, including the production of heavy elements through the r-process [91].

During a BNS merger, intense gravitational forces compress and heat nuclear matter to temperatures of several tens of MeV, resulting in significant neutrino emission. Electron neutrinos are emitted during neutronization with energies of 5-30 MeV, while electron antineutrinos are dominantly produced during the cooling phase with similar energies. Muon and tau neutrinos, along with their antineutrinos, are produced in smaller quantities with energies ranging from several MeV to a few tens of MeV. The peak neutrino luminosity can reach about 10^{53} erg/s and the total energy emitted is around 10^{52} erg, with the intense emission lasting from 1 to several seconds. Neutrinos are also expected to be produced by the β -decay of heavy elements produced during r-process, although the flux could not be high enough to observe a consistent signal [92]. Several models and simulation have stud-

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ied the impact of neutrinos during a BNS merger and the expected neutrino emission, see e.g. [91, 93, 94, 95, 96]. A similar mechanism is expected also in case of black hole - neutron star mergers, see e.g. [97, 98]. Fig. 2.3 shows an example of simulation of neutrino luminosity and energies for different flavors of neutrino during a BNS merger [93]. Although these plots indicate a strong emission of thermal neutrinos during BNS mergers, it has not yet been possible to link any detected neutrino emission to these events. This limitation arises from the fact that most BNS mergers occur at very large distances, resulting in an extremely faint flux on Earth. Any potential signal is therefore masked by the overwhelming background. In this context, multi-messenger studies of BNS mergers provide a crucial approach to enhancing detection significance, in particular considering the expected simultaneity (within hundreds of milliseconds) of the GW and neutrino emissions.

High energy neutrinos (HEN, $E_\nu > \text{GeV}$ s) are also expected to be produced during a BNS merger (e.g. [99], [100]). In particular, the event GW170817 confirmed the already supposed link between gravitational waves and Gamma-Ray Bursts (GRB), among the most energetic explosions in the universe, characterized by intense gamma-ray emissions lasting from milliseconds to several minutes ([101]). These catastrophic events are expected to generate also high-energy neutrinos through the formation of relativistic jets, where particles are accelerated to near the speed of light and interact with surrounding material (e.g. [99], [102]).

Binary neutron star systems may also produce a detectable MeV neutrino signal before the merger starts. In [103], they explore the possibility of de-

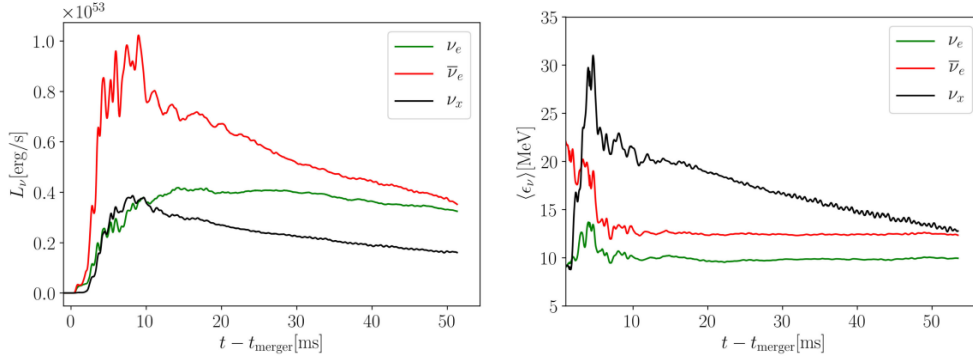


Figure 2.3: Simulation of the neutrino luminosity and average energy as a function of time for the three different species ($\nu_e, \bar{\nu}_e, \nu_x = \nu_\mu + \nu_\tau$) expected from a BNS merger. Results taken from [93].

tecting MeV neutrinos emitted during the rare but intense interactions between neutron stars and their stellar companions, known as common-envelope (CE) phases. In these events, a neutron star enters the envelope of a companion star, causing rapid inspiral and dramatic heating as the envelope material is ejected. This violent process generates large quantities of thermal MeV neutrinos, similar in energy to those produced in core-collapse supernovae. The authors examine the potential for detecting these neutrinos with current or future detectors, proposing that they could serve as a unique signal of CE interactions involving neutron stars. Detecting such neutrinos would offer a new probe of CE evolution, neutron star mergers, and the formation of compact object binaries, which are essential for understanding gravitational wave sources and astrophysical processes.

2.3.4 Black hole mergers

Stellar-mass binary black hole (BBH) mergers are currently the primary source of gravitational wave detections. These mergers can originate from

two main channels: binary stellar evolution, where two stars collapse into black holes and eventually merge, or dynamical formation, where black holes form and merge through close encounters in dense environments such as globular clusters or galactic nuclei. The properties of these binaries, such as their mass, mass ratio, and spin, differ depending on their formation channel.

BBH mergers are generally not expected to produce significant emissions beyond gravitational waves, as they involve the collision of two black holes with little to no surrounding matter. However, in certain dense environments, such as accretion disks of active galactic nuclei (see next section) or regions with residual gas from stellar evolution, these mergers may produce electromagnetic or even neutrino emissions [104, 105].

2.3.5 Active Galactic Nuclei

Active Galactic Nuclei (AGN) are some of the most energetic and luminous objects in the universe, powered by supermassive black holes (SMBHs) at the centers of galaxies. These black holes accrete matter from their surroundings, forming an accretion disk. As matter spirals into the black hole, immense gravitational and frictional forces heat the material, causing it to radiate across a broad spectrum, from radio waves to gamma rays and results in the formation of jets and outflows.

AGN are classified based on their observational characteristics, which can vary due to orientation, the structure of the surrounding material, and the physical conditions near the black hole. The main categories include:

- **Seyfert galaxies:** These are spiral galaxies with bright, compact nu-

clei. They are divided into Seyfert 1, which show broad and narrow emission lines, and Seyfert 2, which show only narrow lines, depending on the orientation of the dusty torus around the black hole.

- **Quasars:** The most luminous type of AGN, quasars can outshine their host galaxies. They are typically found in the distant universe and are often associated with massive galaxies.
- **Blazars:** A subclass of AGN characterized by relativistic jets that are pointed almost directly toward Earth, making them appear highly variable and bright across all wavelengths.

AGN jets, winds, and the innermost region near the SMBH—including the accretion disk and a surrounding corona of hot electrons—have been suggested as potential sites for neutrino production [106]. In these environments, particles may be accelerated through mechanisms such as diffusive shock acceleration, magnetic reconnection, and stochastic acceleration driven by plasma turbulence [107, 108]. The intense radiation fields and the presence of target matter in these regions provide the necessary conditions for generating high-energy neutrinos [109].

In September 2017 a groundbreaking evidence of the correlation between neutrinos and AGN was obtained through the spatial and temporal coincidence of a very-high-energy muon event ($E_\nu \sim 290 \text{ TeV}$), detected by the IceCube Telescope [110] and the blazar TXS 0506+056 detected by the Fermi-LAT [111] satellite and MAGIC telescope [112]. Motivated by this correlation, the IceCube Collaboration investigated archival data for evidence of past neutrino emission from TXS 0506+056. This analysis revealed a neutrino flare

(with higher significance) between 2014 and 2015.

A second piece of evidence was reported by the IceCube Neutrino Observatory in 2022, when they observed an excess of neutrinos coming from the Seyfert galaxy NGC 1068 with a significance of 4.2σ [113]. The best-fit neutrino flux measured by IceCube exceeded the observed gamma-ray emission in the HE and VHE band, which implied a neutrino production site opaque to GeV-TeV gamma-rays.

2.4 Multi-messenger global networks

Coordinating platforms and networks are essential for ensuring rapid and efficient multi-messenger observations by connecting various observatories and instruments worldwide. They represent the backbone of multi-messenger astrophysics, as they facilitate real-time data sharing and alert systems, enabling astronomers to quickly respond to detected cosmic events across different messengers (gravitational waves, neutrinos, electromagnetic radiation, and cosmic rays). In the following, a description of the key platforms and networks involved in multi-messenger astrophysics is reported.

2.4.1 SNEWS (Supernova Early Warning System)

SNEWS [114] is a global alert network designed to detect and quickly distribute notifications of nearby supernova explosions. It specifically monitors neutrino bursts from supernovae, as neutrinos are released in vast quantities when a massive star collapses into a neutron star or black hole. Neutrinos are typically detected by underground observatories like Super-Kamiokande

and KamLAND, which can identify the faint neutrino signals well before the electromagnetic radiation from the explosion reaches Earth.

Neutrinos escape the supernova core minutes to hours before light does, making SNEWS an important tool for early warning. Once multiple neutrino detectors observe a burst and confirm a supernova candidate, SNEWS sends out an alert to the scientific community. This early warning enables telescopes to focus on the source’s location to observe the supernova in real time as it becomes visible in the electromagnetic spectrum.

2.4.2 Astrophysical Multi-messenger Observatory Network (AMON)

AMON [115] is a global system designed to integrate and correlate data from different types of observatories, such as gravitational wave detectors (LIGO, Virgo), neutrino detectors (IceCube), and gamma-ray observatories (Fermi-LAT). AMON’s primary goal is to detect coincident signals from multiple messengers, enhancing the chances of identifying astrophysical sources. It operates as a real-time alert network, issuing notifications when a significant multi-messenger event is detected. AMON helps reduce false positives and improves the accuracy of identifying astrophysical phenomena like neutron star mergers or gamma-ray bursts.

2.4.3 General Coordinates Network (GCN)

The GCN [116] is a NASA-operated platform that distributes real-time alerts primarily on gamma-ray bursts (GRBs) and other high-energy transients de-

tected by instruments such as Fermi-GBM and Swift, as well as high-energy neutrinos, gravitational waves and supernova and pre-supernova neutrinos. GCN delivers automated alerts and positional data, allowing astronomers to rapidly observe the source of a transient event, facilitating multi-wavelength and multi-messenger follow-up.

2.4.4 Transients and Alert Systems (ZTF and LSST)

Projects like the Zwicky Transient Facility [117] and the upcoming Legacy Survey of Space and Time [118] provide wide-field optical sky surveys that can quickly identify transient phenomena such as supernovae, kilonovae, and GRBs. These facilities send out real-time alerts when they detect transient objects or signals that could correspond to multi-messenger events, such as gravitational wave detections from Ligo-Virgo-Kagra (LVK) or neutrino events from IceCube. ZTF and LSST play a crucial role in the optical follow-up of transient events by scanning large portions of the sky rapidly.

2.4.5 SCiMMA (Scalable Cyberinfrastructure for Multimessenger Astrophysics)

SCiMMA [119] is a relatively new initiative aimed at developing a robust cyberinfrastructure for handling the large volumes of data generated by multimessenger observations. SCiMMA integrates data from gravitational wave detectors, neutrino observatories, and electromagnetic telescopes, enabling rapid data sharing and collaboration between researchers. By providing scalable tools for real-time data processing and analysis, SCiMMA helps stream-

line the identification of astrophysical events across different messengers.

Chapter 3

Estimating neutrino fluxes from various astrophysical sources

In the previous chapter, a detailed overview of the current multi-messenger panorama in prospect of neutrino astronomy was provided. An important conclusion from this discussion is that numerous astrophysical sources are expected to emit neutrinos. For most of these sources, a multi-messenger approach is essential to understand the mechanisms driving neutrino emission. This can involve linking the emission of other messengers, such as electromagnetic radiation, to neutrino production by examining processes capable of generating both signals and thus understanding what is the expected neutrino flux from the given source. Alternatively, it may involve performing coincident searches (either temporally or spatially) to identify potential signal excesses within specific time windows in current neutrino detector data. In this chapter, two projects I worked on, focused on the study of neutrino emission from different astrophysical sources, will be presented.

3.1 Neutrino fluxes from different classes of galactic sources

3.1.1 Introduction

In Section 2.3.1 we have seen that the recent observation of a neutrino diffuse emission from the Galactic Plane is in partial agreement with the observed γ -ray diffuse spectrum observed by several telescopes. This finding supports the long-standing hypothesis of hadronic production of neutrinos in our galaxy and paves the way for identifying specific Galactic sources contributing to the observed neutrino flux.

Motivated by these observations, in [2] we performed a study on the expected neutrino flux from a selected catalog of known galactic γ -ray sources.

We evaluated the expected flux by considering two main neutrino telescopes, IceCube and KM3NeT (ARCA). Among the many observed γ -ray sources there are several that are expected to be potential cosmic ray accelerators and therefore candidate neutrino sources. This is particularly true for sources characterized by very high-energy (VHE) γ -ray emissions in the range between TeV and PeV. Some examples of very high-energy galactic sources include:

- **Supernova remnants (SNRs)** represent the rest of supernovae explosions and can either derive from the emission of the shocked material that has a shell-type (Shell) structure or from binary star system where there is a combination of a white dwarf and a massive companion star, in which cases are known as Composite SNRs. Some SNRs originate

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from core-collapse supernova explosions of massive stars in molecular clouds (MC), in which cases are associated with the relative MC.

- **Pulsar wind nebulae (PWNe)** are the result of the explosion of a supernova characterized by a diffuse nebulae powered by the wind of a fast-spinning, highly magnetised neutron star.
- **Microquasars (MQ)** are X-ray binaries characterized by non-thermal jets. These systems are believed to consist of a compact object, a neutron star or a black hole, and a companion star. The name Microquasar derived from the similarity in terms of the physical processes with extragalactic Quasars, even though the scale where these processes happen is smaller.
- **TeV Halos (TH)** are a relatively new class of sources, seen as an extended TeV γ -ray emission surrounding pulsars. TeV Halos are found to be coincident in position with pulsars or PWNe. However, since these sources appear morphologically and dynamically distinct from PWNe detected in X-ray and radio observations, they have been classified as a new γ -ray source class.
- **Novae** are powerful eruptions following a thermonuclear runaway (TNR) that occurs below the surface of a White Dwarf (WD). During its cycle (accretion, eruption and decline) a Nova producing system could possibly be observed in the infrared (IR), ultraviolet (UV), soft and hard X-rays and even γ -rays.

If part of the diffuse γ -ray emission observed in our galaxy is due to

CHAPTER 3. ESTIMATING NEUTRINO FLUXES FROM VARIOUS ASTROPHYSICAL SOURCES

hadronic processes, a correlation with a diffuse neutrino flux emission is expected. The energy budget of high-energy cosmic rays (HECRs), PeV neutrinos, and isotropic sub-TeV γ -rays are comparable [120], supporting a strong correlation between these high-energy cosmic particles.

Thus, with these assumptions, we created our catalog of γ -ray sources, selecting from the TeVCat catalog [121] all galactic sources whose spectrum has been observed until TeV energies and that can be describe by a power law:

$$\frac{dN_\gamma}{dE_\gamma} = N_0 \left(\frac{E}{E_0} \right)^{-\alpha} \quad (3.1)$$

The final catalog includes different kinds of sources: PWNe, SNRs, Molecular Clouds (MCs), TeV Halos (THs), Binary Systems, MQs, Novae, Superbubbles and Massive Stellar Clusters (MSCs), as well as some unidentified source. In particular, two Novae are included in the catalogue: one is RS Ophiuchi, since recent observations of TeV emission from this recurrent nova suggested the involvement of hadronic processes in producing the high-energy emission [122]; the second one is T CrB, which has not yet been observed at TeV energies. However, assuming its TeV γ -ray spectrum resembles that of RS Oph, we estimate its neutrino flux. Given that T CrB is three times closer than RS Oph, its neutrino flux is anticipated to be approximately nine times stronger and is also expected to soon erupt. Positioned in the northern sky at a declination of $+25^\circ$, T CrB is an excellent candidate for observation with the IceCube telescope while also being accessible to KM3NeT. The complete list of sources selected, alongside their spectral properties and distance can be seen in Tab. 3.1.

3.1. NEUTRINO FLUXES FROM DIFFERENT CLASSES OF GALACTIC SOURCES

We then used the spectral information of each source in order to:

1. Evaluate the total neutrino flux expected from all the sources and compare it to the diffuse flux observed by IceCube;
2. For each source, evaluate the expected number of event detected by the IceCube and KM3NeT/ARCA [43] experiments in one year and the relative detection significance.

Table 3.1: Spectral properties of the selected catalogue. A Power Law spectrum (Eq. 3.1) is used for each source according to the parameters listed in the catalogue. Sources included are PWN/TeVHalo (PWN/TH), Shell-like SNR(Shell), SNR/MolecularCloud (SNR/MC), Composite SNR (comp.SNR), Superbubble (SB), Massive Star Cluster (MSC) as well as some unidentified sources (unid).

Begin of Table 3.1							
<i>Source</i> <i>Name</i>	<i>Type</i>	δ [degree]	N_0 [$TeV^{-1}cm^{-2}s^{-1}$]	α	E_0 [TeV]	<i>Distance</i> [kpc]	<i>Ref.</i>
Geminga	PWN/TH	17.76	$3.77 \cdot 10^{-16}$	2.6	35	0.3	[123]
Vela X	PWN/TH	-45.66	$1.83 \cdot 10^{-12}$	1.89	3.02	0.3	[124]
Boomerang	PWN	61.24	$7.09 \cdot 10^{-16}$	2.6	35	0.8	[123]
SNR G106.3+02.7	Shell	60.88	$1.15 \cdot 10^{-13}$	2.29	3	0.8	[125]
T-CrB	Nova	25.92	$4.75 \cdot 10^{-11}$	3.33	0.35	0.9	*
ARGO J2031+4157	SB	42.5	$2.5 \cdot 10^{-11}$	2.6	1	1.4	[126]
CTA 1	PWN	72.98	$9.1 \cdot 10^{-11}$	2.2	3	1.4	[127]
HESS J0632+057	Binary	5.79	$4.56 \cdot 10^{-12}$	2.67	0.5	1.4	[128]
IC 443	Shell	22.53	$1.00 \cdot 10^{-11}$	3.1	0.4	1.5	[129]
TeV J2032+4130	PWN	41.58	$2.1 \cdot 10^{-14}$	3.22	10	1.8	[130]
PSR J2032+4127	Binary	41.46	$1.45 \cdot 10^{-12}$	2.73	1	1.8	[131]
LS I +61 303	MQ	61.27	$4.4 \cdot 10^{-13}$	2.4	1	2.0	[132]
Crab	PWN	22.01	$2.83 \cdot 10^{-11}$	2.62	1	2.0	[133]
3C 58	PWN	64.85	$2 \cdot 10^{-13}$	2.4	1	2.0	[134]
HESS J1800-240A	SNR/MC	-24.02	$4.8 \cdot 10^{-12}$	2.47	0.95	2.0	[124]
W28	SNR/MC	-23.34	$7.5 \cdot 10^{-13}$	2.66	1.00	2.0	[124]
SN 1006 NE	Shell	-41.8	$4.65 \cdot 10^{-13}$	2.35	1	2.2	[135]

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Continuation of Table 1							
<i>Source</i> <i>Name</i>	Type	declination [degree]	N_0 [$TeV^{-1}cm^{-2}s^{-1}$]	α	E_0 [TeV]	<i>Distance</i> [kpc]	<i>Ref.</i>
Cygnus X-1	MQ	35.20	$2.3 \cdot 10^{-12}$	3.2	1	2.2	[136]
HESS J1026-582	PWN	-58.23	$3.64 \cdot 10^{-13}$	1.81	4.43	2.3	[124]
HESS J1708-443	PWN	-44.29	$1.23 \cdot 10^{-12}$	2.17	1.70	2.3	[124]
HESS J1356-645	PWN	-64.51	$5.73 \cdot 10^{-13}$	2.2	2.74	2.4	[124]
LS 5039	MQ	-14.85	$9.82 \cdot 10^{-13}$	2.32	1.05	2.5	[124]
PSR B1259-63	Binary	-63.85	$2.62 \cdot 10^{-13}$	2.59	1.40	2.7	[124]
HESS J1729-345	unid	-34.53	$8.25 \cdot 10^{-13}$	2.43	1.16	3.2	[124]
Westerlund 1	MSC	-46.26	$7.87 \cdot 10^{-12}$	2.54	1.05	3.2	[124]
HESS J1731-347	Shell	-34.76	$4.67 \cdot 10^{-12}$	2.32	0.78	3.2	[124]
SNR G318.2+00.1	SNR/MC	-59.46	$2.2 \cdot 10^{-12}$	2.52	1.54	3.5	[124]
Tycho	Shell	64.14	$2.2 \cdot 10^{-13}$	2.92	1	3.5	[137]
HESS J1809-193	unid	-19.33	$6.62 \cdot 10^{-12}$	2.38	1.05	3.7	[124]
HESS J1825-137	PWN/TH	-13.97	$1.72 \cdot 10^{-11}$	2.38	1.16	3.9	[124]
HESS J1826-130	unid	-13.02	$2.73 \cdot 10^{-13}$	2.04	2.06	4.0	[124]
HESS J1834-087	unid	-8.75	$5.79 \cdot 10^{-12}$	2.61	0.87	4.0	[124]
HESS J1718-385	PWN	-38.51	$4.01 \cdot 10^{-14}$	1.78	4.02	4.2	[124]
RS Ophiuchi	Nova	-6.7	$2.38 \cdot 10^{-12}$	3.33	0.35	4.2	[138]
HESS J1813-178	PWN	-17.83	$1.01 \cdot 10^{-12}$	2.07	1.40	4.7	[124]
SNR G015.4+00.1	Comp.SNR	-15.47	$1.07 \cdot 10^{-13}$	2.21	1.54	4.8	[124]
HESS J1833-105	PWN	-10.57	$4.22 \cdot 10^{-13}$	2.42	0.95	4.8	[124]
SNR G292.2-00.5	PWN	-61.45	$7.96 \cdot 10^{-13}$	2.64	1.27	5.0	[124]
MSH 15-52	PWN	-59.16	$2.58 \cdot 10^{-12}$	2.26	1.54	5.2	[124]
HESS J1848-018	MSC	-1.89	$2.51 \cdot 10^{-12}$	2.57	0.87	5.3	[124]
W 51	SNR/MC	14.14	$4.52 \cdot 10^{-13}$	2.55	1.40	5.4	[124]
SS 433 w1	MQ	5.04	$8.6 \cdot 10^{-14}$	2.54	3	5.5	[139]
SS 433 e1	MQ	4.93	$4.5 \cdot 10^{-17}$	3.3	50	5.5	[139]
Kookaburra (PWN)	PWN	-60.75	$8.41 \cdot 10^{-13}$	2.20	1.87	5.9	[124]
HESS J1804-216	unid	-21.74	$2.13 \cdot 10^{-11}$	2.69	0.72	6.2	[124]
SNR G054.1+00.3	PWN	18.84	$1.28 \cdot 10^{-13}$	2.59	1.70	6.2	[124]
HESS J1846-029	PWN	-2.97	$5.96 \cdot 10^{-13}$	2.41	1.05	6.3	[124]
HESS J1616-508	PWN	-50.86	$7.55 \cdot 10^{-12}$	2.32	1.16	6.5	[124]
HESS J1303-631	PWN	-63.19	$1.53 \cdot 10^{-12}$	2.33	1.87	6.6	[124]
HESS J1837-069	PWN	-6.96	$2.00 \cdot 10^{-11}$	2.54	0.95	6.6	[124]
IGR J18490-0000	PWN	-0.04	$7.66 \cdot 10^{-14}$	1.97	2.74	7.0	[124]

3.1. NEUTRINO FLUXES FROM DIFFERENT CLASSES OF GALACTIC SOURCES

Continuation of Table 1							
<i>Source Name</i>	Type	declination [degree]	N_0 [$TeV^{-1}cm^{-2}s^{-1}$]	α	E_0 [TeV]	Distance [kpc]	Ref.
CTB 37A	SNR/MC	-38.52	$2.76 \cdot 10^{-13}$	2.52	1.05	7.9	[124]
Westerlund 2	MSC	-57.78	$7.50 \cdot 10^{-13}$	2.36	1.87	8.0	[124]
SNR G000.9+00.1	PWN	-28.15	$8.38 \cdot 10^{-13}$	2.40	1.00	8.5	[124]
HESS J1640-465	Comp.SNR	-46.57	$4.59 \cdot 10^{-12}$	2.57	0.95	8.6	[124]
HESS J1634-472	unid	-47.23	$1.73 \cdot 10^{-12}$	2.31	1.40	8.6	[124]
SNR G327.1-01.1	PWN	-55.09	$5.79 \cdot 10^{-14}$	2.19	2.26	9.0	[124]
W 49B	SNR/MC	9.09	$3.15 \cdot 10^{-13}$	3.14	1.00	11.3	[124]
SNR G349.7+00.2	SNR/MC	-37.44	$2.25 \cdot 10^{-13}$	2.80	1.00	11.5	[124]
CTB 37B	Shell	-38.22	$1.74 \cdot 10^{-12}$	2.74	0.79	13.2	[124]
End of Table 3.1							

3.1.2 Galactic diffuse neutrino flux estimate

By assuming that the entire high-energy photon emission detected from these sources at $\sim$ TeV energies is due only to hadronic processes, one can convert the gamma flux to a neutrino flux, averaged over all flavors, using the following relation:

$$\frac{dN_{\nu+\bar{\nu}}}{dE_{\nu+\bar{\nu}}} \approx \frac{dN_{\gamma}}{dE_{\gamma}} \quad (3.2)$$

For a derivation of the formula see [140, 141, 142].

As a consequence, one can write:

$$\int_{E_{\nu+\bar{\nu}}^{\min}}^{E_{\nu+\bar{\nu}}^{\max}} E_{\nu+\bar{\nu}} \frac{dN_{\nu+\bar{\nu}}}{dE_{\nu+\bar{\nu}}} dE_{\nu+\bar{\nu}} = \int_{E_{\gamma}^{\min}}^{E_{\gamma}^{\max}} E_{\gamma} \frac{dN_{\gamma}}{dE_{\gamma}} dE_{\gamma} \quad (3.3)$$

where $E_{\gamma}^{\min}=E_{\nu+\bar{\nu}}^{\min}$ and $E_{\gamma}^{\max}=E_{\nu+\bar{\nu}}^{\max}$ are the minimum and maximum pho-

CHAPTER 3. ESTIMATING NEUTRINO FLUXES FROM VARIOUS ASTROPHYSICAL SOURCES

ton/neutrino energies respectively. In the following, " ν " will refer to the sum of neutrinos and antineutrinos.

As already stated before, for the considered sources, the high energy photon emission is represented by a single Power Law (Eq. 3.1), thus we can assume the same shape also for the neutrino flux.

For each neutrino energy E_k we evaluated the flux from a single source i in the following way:

$$(d\Phi_k)_i = N_{0,i} \left(\frac{E_k}{E_{0,i}} \right)^{-\alpha_i} \quad (3.4)$$

Then, for $E_\nu = E_k$, we summed the neutrino fluxes over all the sources considered in the sample defined in Table 3.1 and we compare the result with the galactic neutrino flux observed by IceCube in [59]:

$$d\Phi_k = \sum_{i=1}^M N_{0,i} \left(\frac{E_k}{1 \text{ TeV}} \right)^{-\alpha_i} \quad (3.5)$$

where M is the total number of sources, $N_{0,i}$ the normalization coefficient of the i source in $\text{TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ and α_i the spectral coefficient for each source.

Fig. 3.1 shows the comparison between the total neutrino spectral energy distribution (SED) due to the galactic sources selected and the IceCube galactic diffuse neutrino flux. This plot tell us that if the entire TeV emission is due to a hadronic component, the galactic sources can contribute to the diffuse neutrino flux detected by IceCube at the level of $\sim 20\%$ up to ~ 10 TeV and at $> 50\%$ at higher energies. Considering the fact that part of the TeV photon emission could also be caused by a leptonic mechanism inside

3.1. NEUTRINO FLUXES FROM DIFFERENT CLASSES OF GALACTIC SOURCES

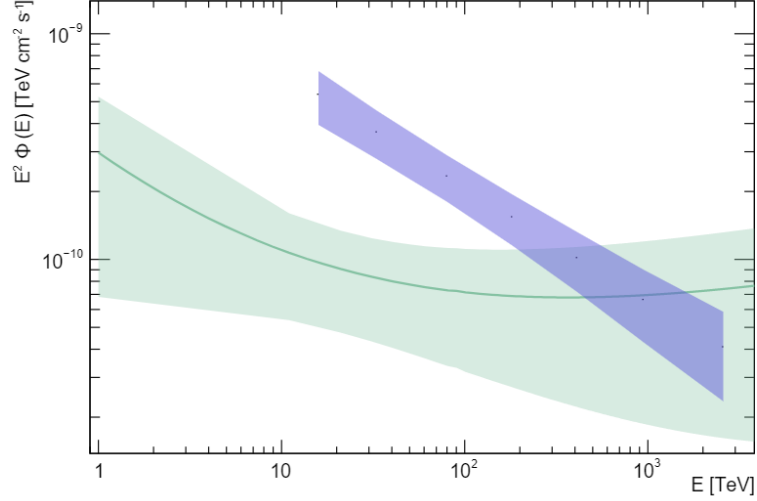


Figure 3.1: Total neutrino spectral energy distribution (SED) due to galactic point sources in green, compared with the IceCube Galactic diffuse neutrino flux [59] in blue.

the sources, our result may be considered as an upper limit on the hadronic contribution to the high-energy photon emission.

3.1.3 Neutrino fluxes from point like galactic sources

Once we calculated the flux from each sources, we used the effective areas of IceCube and KM3NeT telescopes to evaluate the expected number of neutrinos with energies in the [1,1000] TeV energy range in both detectors in a year of data-taking:

$$n_{events} = \int_{E_1}^{E_2} T \frac{dN_\nu}{dE_\nu} A(E_\nu) dE_\nu \quad (3.6)$$

where T is the exposure time and $A(E_\nu)$ the effective area of the consid-

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ered telescope. The number of neutrino interactions expected in IceCube, for which the effective area is known as a function of the energy and of the source declination $A(E_\nu, \delta)$ [143], is estimated as:

$$n_{events}^{IC} = \int_{E_1}^{E_2} T \frac{dN_\nu}{dE_\nu} A(E_\nu, \delta) dE_\nu \quad (3.7)$$

The number of neutrino interactions expected in KM3NeT/ARCA full detector, made by two building blocks, is obtained knowing the total effective area [144] and taking into account the source visibility $V(\delta)$ characterized by its declination δ as given by [145]:

$$n_{events}^{ARCA} = \int_{E_1}^{E_2} T \frac{dN_\nu}{dE_\nu} A(E_\nu) V(\delta) dE_\nu \quad (3.8)$$

To evaluate the significance of each possible detection we compared the resulting number of events with the number of background events expected during the chosen time exposure (1 year).

The primary background component arises from the flux of atmospheric neutrinos, produced when cosmic rays interact with the Earth's atmosphere. These interactions generate charged mesons, such as pions and kaons, which subsequently decay into neutrinos and muons.

The atmospheric neutrino flux above 1 TeV is expressed as a power law:

$$\frac{d\Phi_{\nu_{atm}}}{dE_{\nu_{atm}} d\Omega} = C_{\nu_{atm}} E_{\nu_{atm}}^{-\beta} \quad (3.9)$$

We obtained the parameter $C_{\nu_{atm}}$ and β by fitting the Zenith-averaged, unfolded atmospheric muon neutrino energy spectrum from 100 GeV to 400

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TeV [146]:

$$\Phi_{\nu_{\mu},atm}(E_{\nu}) = 2.64 \cdot 10^{-8} E_{\nu}^{-3.4} cm^{-2} s^{-1} sr^{-1} TeV^{-1} \quad (3.10)$$

The background arising from atmospheric neutrino interactions cannot be distinguished on an event-by-event basis. Instead, its contribution to the dataset is estimated and statistically subtracted. For each detector, we calculated the expected number of background events within the same search cone defined around the source of interest:

$$n_{BG}^{IC} = \int_{\Delta\Omega} \int_{E_1}^{E_2} 2T \frac{d\Phi_{\nu}}{dE_{\nu}d\Omega} A(E_{\nu}, \delta) dE_{\nu} d\Omega \quad (3.11)$$

$$n_{BG}^{ARCA} = \int_{\Delta\Omega} \int_{E_1}^{E_2} 2T \frac{d\Phi_{\nu}}{dE_{\nu}d\Omega} A(E_{\nu}) V(\delta) dE_{\nu} d\Omega \quad (3.12)$$

where $\Delta\Omega$ is the aperture of the search cone around the source position, due to the detector Point Spread Function, dictated by the detector angular resolution. In this computation we consider an opening angle $\alpha = \pm 5^\circ$ around the source. This conservative choice ensures broad coverage but could potentially be refined by experiments as the detectors' capabilities become better understood.

For each source i the statistical significance for neutrino detection is then defined as:

$$\sigma_i = \frac{n_{events,i}}{\sqrt{n_{BG,i}}} \quad (3.13)$$

The resulting number of expected events, background and significance for

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each source can be seen in Table 3.2.

Table 3.2: Number of events expected to be collected in T=1 year of data taking by IceCube and KM3NeT/ARCA neutrino telescopes. We report the significance σ that can be obtained with the number of signal n_{events} and background n_{bg} events collected in 1 year of data taking.

Begin of Table 3.2							
Source Name	δ [degree]	n_{events}^{IC} [$1 - 10^3$ TeV]	n_{BG}^{IC} [$1 - 10^3$ TeV]	σ^{IC} [$1 - 10^3$ TeV]	n_{events}^{ARCA} [$1 - 10^3$ TeV]	n_{BG}^{ARCA} [$1 - 10^3$ TeV]	σ^{ARCA} [$1 - 10^3$ TeV]
VelaX-1	-45.66	1.7	$1.5 \cdot 10^{-2}$	14.3	45.4	40.7	7.1
HESSJ1026-582	-58.23	1.0	$1.5 \cdot 10^{-2}$	8.4	26.1	46.9	3.8
Crab	22.01	9.07	34.0	1.6	6.2	22.7	1.3
ARGOJ2031+4157	42.5	8.0	35.6	1.34	4.5	18	1.1
HESSJ1825-137	-13.97	2.7	4.8	1.3	11.9	29.9	2.2
HESSJ1718-385	-38.51	0.1	$1.5 \cdot 10^{-2}$	0.9	2.2	39.6	0.4
HESSJ1616-508	-50.86	0.1	$1.5 \cdot 10^{-2}$	0.9	9.5	46.9	1.4
MSH15-52	-59.16	0.1	$1.5 \cdot 10^{-2}$	0.8	7.2	46.9	1.1
TeVJ2032+4130	41.58	4.7	35.6	0.8	2.5	18.4	0.6
HESSJ1356-645	-64.51	0.1	$1.8 \cdot 10^{-2}$	0.8	6.6	46.9	0.9
HESSJ1708-443	-44.29	0.1	$1.5 \cdot 10^{-2}$	0.7	5.1	44.9	0.8
HESSJ1809-193	-19.33	1.4	4.8	0.7	6.3	31.1	1.1
HESSJ1837-069	-6.96	1.2	4.8	0.6	5.7	28.6	1.1
Kookaburra(PWN)	-60.75	$6.5 \cdot 10^{-2}$	$1.8 \cdot 10^{-2}$	0.5	4.2	46.9	0.6
HESSJ1303-631	-63.19	0.1	$1.8 \cdot 10^{-2}$	0.5	5.7	46.9	0.8
SS433e1	4.93	2.2	34.0	0.4	1.7	26.3	0.3
Boomerang	61.24	2.0	31.6	0.3	0.5	6.6	0.2
HESSJ1634-472	-47.23	$3.9 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	0.3	3.5	46.9	0.5
HESSJ1813-178	-17.83	0.7	4.8	0.3	2.5	30.7	0.4
Geminga	17.76	1.3	34.0	0.2	0.9	23.8	0.2
Westerlund1	-46.26	$2.6 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	0.2	4.7	46.9	0.7
Westerlund2	-57.78	$2.6 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	0.2	2.6	46.9	0.4
HESSJ1731-347	-34.76	$2.6 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	0.2	1.9	37.0	0.3
HESSJ1826-130	-13.02	0.5	4.8	0.2	1.5	29.7	0.3
HESSJ1804-216	-21.74	0.4	4.8	0.2	2.4	31.7	0.4
SNRG318.2+00.1	-59.46	$2.2 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	0.2	3.6	46.9	0.5
HESSJ1800-240A	-24.02	0.4	4.8	0.2	1.8	32.4	0.3
IGRJ18490-0000	-0.04	0.3	4.8	0.1	0.9	27.3	0.2
SNRG106.3+02.7	60.88	0.7	31.6	0.1	0.2	6.8	0.1
CTA1	72.98	0.6	31.6	0.1	0	0	-
HESSJ1834-087	-8.75	0.2	4.8	0.1	1.1	28.9	0.2
SS433w1	5.04	0.5	34.0	0.1	0.4	26.3	0.1
HESSJ1640-465	-46.57	$1.0 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	0.1	2	46.9	0.3
LS5039	-14.85	0.1	4.8	0.1	0.6	30.1	0.1
W51	14.14	0.4	34.0	0.1	0.3	24.4	0.1
PSRJ2032+4127	41.46	0.4	35.6	0.1	0.2	18.4	$4.9 \cdot 10^{-2}$
SNRG327.1-01.1	-55.09	$7.1 \cdot 10^{-3}$	$1.5 \cdot 10^{-2}$	0.1	0.4	46.9	$6.4 \cdot 10^{-2}$
HESSJ1729-345	-34.53	$6.4 \cdot 10^{-3}$	$1.5 \cdot 10^{-2}$	0.1	0.6	36.9	0.1
CygnusX-1	35.20	0.3	35.6	0.1	0.18	19.9	$4.0 \cdot 10^{-2}$
HESSJ1848-018	-1.89	0.1	4.8	0.1	0.5	27.6	0.1

3.1. NEUTRINO FLUXES FROM DIFFERENT CLASSES OF GALACTIC SOURCES

Continuation of Table 3.2							
<i>Source</i> <i>Name</i>	δ [degree]	n_{events}^{IC} [$1 - 10^3$ TeV]	n_{BG}^{IC} [$1 - 10^3$ TeV]	σ^{IC} [$1 - 10^3$ TeV]	n_{events}^{ARCA} [$1 - 10^3$ TeV]	n_{BG}^{ARCA} [$1 - 10^3$ TeV]	σ^{ARCA} [$1 - 10^3$ TeV]
SNRG000.9+00.1	-28.15	0.1	4.8	$4.0 \cdot 10^{-2}$	0.4	33.8	0.1
LSI+61303	61.27	0.2	34.0	$3.9 \cdot 10^{-2}$	0.2	27.1	$3.5 \cdot 10^{-2}$
HESSJ0632+057	5.79	0.2	34.0	$3.5 \cdot 10^{-2}$	0.2	26.3	$3.2 \cdot 10^{-2}$
SN1006NE	-41.8	$3.9 \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$	$3.2 \cdot 10^{-2}$	0.3	41.6	0.1
HESSJ1846-029	-2.97	$6.8 \cdot 10^{-2}$	4.8	$3.1 \cdot 10^{-2}$	0.3	27.8	0.1
SNRG054.1+00.3	18.84	0.2	34.0	$2.9 \cdot 10^{-2}$	0.1	23.4	$2.5 \cdot 10^{-2}$
TCrB	25.92	0.2	34.0	$2.9 \cdot 10^{-2}$	0.1	22.1	$2.3 \cdot 10^{-2}$
SNRG292.2-00.5	-61.45	$2.8 \cdot 10^{-3}$	$1.8 \cdot 10^{-2}$	$2.1 \cdot 10^{-2}$	0.6	46.9	0.1
SNRG015.4+00.1	-15.47	$4.1 \cdot 10^{-2}$	4.8	$1.8 \cdot 10^{-2}$	0.2	30.2	$3.1 \cdot 10^{-2}$
W28	-23.34	$3.9 \cdot 10^{-2}$	4.8	$1.8 \cdot 10^{-2}$	0.2	32.2	$3.8 \cdot 10^{-2}$
HESSJ1833-105	-10.57	$3.6 \cdot 10^{-2}$	4.8	$1.6 \cdot 10^{-2}$	0.2	29.2	$2.9 \cdot 10^{-2}$
IC443	22.53	$8.7 \cdot 10^{-2}$	34	$1.5 \cdot 10^{-2}$	$5.9 \cdot 10^{-2}$	22.6	$1.2 \cdot 10^{-2}$
3C58	64.85	$7.7 \cdot 10^{-2}$	31.6	$1.4 \cdot 10^{-2}$	$6.5 \cdot 10^{-3}$	2.1	$4.5 \cdot 10^{-3}$
PSRB1259-63	-63.85	$1.5 \cdot 10^{-3}$	$1.8 \cdot 10^{-2}$	$1.1 \cdot 10^{-2}$	0.3	46.9	$4.4 \cdot 10^{-2}$
CTB37A	-38.52	$1.0 \cdot 10^{-3}$	$1.5 \cdot 10^{-2}$	$8.6 \cdot 10^{-3}$	0.1	39.6	$2.3 \cdot 10^{-2}$
CTB37B	-38.22	$9.5 \cdot 10^{-4}$	$1.5 \cdot 10^{-2}$	$7.9 \cdot 10^{-3}$	0.3	39.3	$4.4 \cdot 10^{-2}$
W49B	9.09	$4.5 \cdot 10^{-2}$	34.0	$7.7 \cdot 10^{-3}$	$3.5 \cdot 10^{-2}$	26.4	$6.8 \cdot 10^{-3}$
Tycho	64.14	$3.7 \cdot 10^{-2}$	31.6	$6.5 \cdot 10^{-3}$	$2.3 \cdot 10^{-3}$	1.84	$1.7 \cdot 10^{-3}$
SNRG349.7+00.2	-37.44	$1.7 \cdot 10^{-4}$	$1.5 \cdot 10^{-2}$	$1.4 \cdot 10^{-3}$	$6.1 \cdot 10^{-2}$	38.8	$9.7 \cdot 10^{-3}$
RSOphiuchi	-7	$1.2 \cdot 10^{-3}$	4.8	$5.4 \cdot 10^{-4}$	$7.0 \cdot 10^{-3}$	28.5	$1.3 \cdot 10^{-3}$

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Although a single source detection is quite challenging across all considered classes, by calculating the expected number of event from each source in KM3NeT , we saw that PWN and PWN/THs are the most probable sources to be detected (i.e. the ones with the highest significance). By applying a stacking procedure (i.e. overlapping the signal expected from multiple sources of the same class in the same position) to these most promising galactic neutrino sources, KM3NeT should be able to detect in 1 year a neutrino flux from the stacking of at least three PWNs and PWN/THs, with a $\sim 7.5\sigma$ statistical significance, whereas this significance is defined as:

$$\sigma_{tot}(m) = \frac{\sum_{i=1}^m n_{events,i}}{\sqrt{\sum_{i=1}^m n_{BG,i}}} \quad (3.14)$$

where $m = (2, 3, 4, 5, \dots M)$ is the number of overlapped galactic sources.

Finally, we estimated the maximum distance ($d_{horizon}$) can be detected in 1 year by KM3NeT/ARCA. We indirectly define the horizon distance such as:

$$\sigma = \frac{n_{events}}{\sqrt{n_{BG,Ref}}} = \frac{T}{\sqrt{n_{BG,Ref}}} \frac{d_{Ref}^2}{d_{horizon}^2} \int \frac{dN_{Ref}}{dEdS} A(E_\nu) dE_\nu \quad (3.15)$$

where with REF we indicated the neutrino flux properties of the most luminous source for each class. For the most luminous source in our catalog (SNR G318.2+00.1) we found $d_{horizon} < 3 \text{ kpc}$, remembering that the relation between the detection significance and the distance is only based on the source luminosity.

It is important to note that the estimate of the number of expected neutri-

nos from the galactic sources has been performed without considering any specific physical model for the source to produce the TeV fluxes, thus our analysis can be used also to put strong constraints on some specific models for high-energy neutrino emission.

3.2 Low- and High-energy neutrinos from SN2023ixf in M101

3.2.1 Introduction

One of the most recent and nearby supernova explosion observed is SN2023ixf, a supernova that occurred in May 2023 in the M101 galaxy at a distance of 6.4 Mpc [147]), classified as a type II SN by Perley et al. [148].

A preliminary analysis of this supernova (SN) has been reported by [149], highlighting spectra taken during the very early stages (t 2 days). These spectra exhibit narrow line features, such as H_α , HeII, NIV, and CIV, which are indicative of interactions between the SN ejecta and a dense circumstellar medium (CSM) [150, 151, 152]. However, these narrow components rapidly disappeared—likely within two weeks of maximum light, as shown in Fig. 4 of [149] and noted by [153]. This observation suggests that the CSM was located very close to the progenitor star, and the interaction with the ejecta occurred almost immediately after the explosion. Consequently, the window for detecting "delayed neutrinos" is significantly constrained.

Given its nature and proximity, in [1] we considered this supernova to test several models regarding the emission of both low-energy and high-energy

neutrinos.

3.2.2 Low-energy neutrino emission

To estimate the expected number of low-energy neutrinos on Earth, both Super-Kamiokande and its successor, Hyper-Kamiokande, have been considered, since Super-Kamiokande is currently the most sensitive detector for supernovae and Hyper-Kamiokande will be characterized by a higher sensitivity. Given that the dominant reaction (about 90% of all events) of supernova neutrinos in Super-Kamiokande is IBD, we considered only the events produced by IBD for both detectors.

Several supernova neutrino emission have been considered taking into account different progenitor masses, neutrino luminosity, oscillations parameters as well varying the simulation treatments (either 1D, 2D or 3D simulations):

- The Livermore model (or Totani model) [74] uses a $20 M_{\odot}$ progenitor, which was modeled to reproduce the light curve of SN1987A, and a simulation code developed by Wilson and Mayle [154, 155]. The simulation is one-dimensional, assumes an amount of energy radiated in electron antineutrinos equal to $L_{\bar{\nu}_e} = 2.9 \cdot 10^{53} \text{erg}$ and is performed from the start of the collapse to 18 s after the core bounce. Although outdated, it represents a baseline supernova model as it is the first simulation based on SN1987A data and it is one of the few SN models that provide predictions of neutrino emission until supernova late stages.
- The Nakazato model [156] is a family of models that includes different

progenitor masses ($13\text{-}50 M_{\odot}$) and metallicities ($Z = 0.02, 0.004$). It has been widely used in many supernova studies, e.g. [157, 158, 159, 160]. Similar to the Livermore model, it performs a 1-D simulation and can describe neutrino emission until 20 s after the bounce but it implements a more advanced description of neutrino transport and can take into account neutrino oscillation during the propagation.

Based on [161], the progenitor of SN2023ixf is consistent with RSG models of initial mass $11 M_{\odot}$, therefore we considered in the simulation a progenitor mass of $13M_{\odot}$, with a metallicity of $Z = 0.02$ and a shock revival time of 300 ms. The total energy emitted by electron anti-neutrinos is $L_{\bar{\nu}_e} = 7 \cdot 10^{52} \text{erg}$. Given the distance of SN2023ixf, neutrino oscillation doesn't impact significantly the expected number of anti-electron neutrinos at Earth, thus we didn't consider this effect in our scenario.

- The Fornax (2021) model [162] is a 2-D simulation that considers progenitors with solar metallicity ($Z=0.02$) and masses in the range $[12,26]M_{\odot}$. It simulates neutrino emission until 4.5 s post-bounce using the FORNAX code [163]. With respect to 1-D models, 2-D simulations allow to describe the turbulent convection in the core while requiring less computational time than 3-D simulations. We adopted the same initial mass as in the Nakazato model, i.e. $13 M_{\odot}$ while the total energy emitted by electron anti-neutrinos in this model is around $8 \cdot 10^{52} \text{ erg}$. As before, neutrino oscillation was omitted.

We refer to [164] to evaluate the number of neutrinos expected from

CHAPTER 3. ESTIMATING NEUTRINO FLUXES FROM VARIOUS ASTROPHYSICAL SOURCES

SN2023ixf based on the Livermore model given its distance ($D = 6.4$ Mpc) and a threshold of 5 MeV.

For Nakazato and Fornax (2021) models, we adopted the public tool SNEWPY [165]. It consists of a Python-based code that allows to study the detection prospects of supernova neutrinos in many neutrino detectors, based on different supernova models. In this pipeline, the detectors' response is simulated using the SNOwGLOBES tool [166].

Last model adopted (indicated in the following as Vissani model) is based on [167]. In this paper, rather than numerically simulate the explosion of a supernova, they propose a parameterized expression for the electron anti-neutrino flux expected at Earth, based on SN1987A data.

By following the methodology described in Section 2 of [167] while considering the updated IBD cross section included in [168], we assumed $L_{\bar{\nu}_e} = 10^{53}$ and $D = 6.4$ Mpc and calculated the expected IBD positron spectrum in Super-K derived from anti-electron neutrinos produced by SN2023ixf. Then, by varying the distance of the supernova and integrating the spectrum in the range [5, 100] MeV, the number of expected events as a function of distance for Super-K has been evaluated.

Hyper-K's response to SN event based on the Livermore model has been extracted from [169] (where a 0.56 Mton fiducial volume is assumed) and re-scaled it considering the current expected fiducial volume in Hyper-K (0.22 Mton) reported in [170].

For the Nakazato, Fornax (2021), and Vissani models we used the same tools and methodology as for Super-K but scaled the results considering Hyper-K's

volume (0.22 Mton).

We also adopted a fifth model for Hyper-K, based on [171]. In this model, it is considered a non-rotating solar-metallicity progenitor with a mass of $17M_{\odot}$, which retains its hydrogen envelope (thus a type II supernova is expected). In this case, the simulation produces neutrino emission for the first 7 s after the core bounce. Neutrino MSW mixing is considered during propagation in the star's envelopes. Only IBD events in the range 18-30 MeV are considered for Hyper-K.

Hyper-K's response to CCSNs in nearby galaxies (few Mpc) is approximated as follows¹:

$$N_{\bar{\nu}_e} \simeq 8.5 \left(\frac{D}{1Mpc} \right)^{-2} \left(\frac{M_{det}}{0.56Mton} \right) \quad (3.16)$$

Fig 3.2 shows the expected number of neutrinos as a function of the distance for both detectors.

In both cases, the expected number of neutrinos from SN2023ixf falls below the detection threshold. This result was confirmed by the Super-Kamiokande Collaboration, which performed a search for a neutrino signal correlated to SN2023ixf in a time window of 2 days prior to the SN and no excess signal was found [172].

This demonstrates that while both experiments are highly effective for observing supernovae at galactic distances or in very nearby galaxies, detecting supernovae that occur within the Local Group remains quite challenging.

¹The formula is a corrected version of Eq.5 in [171], obtained after a private communication with Ko Nakamura.

CHAPTER 3. ESTIMATING NEUTRINO FLUXES FROM VARIOUS ASTROPHYSICAL SOURCES

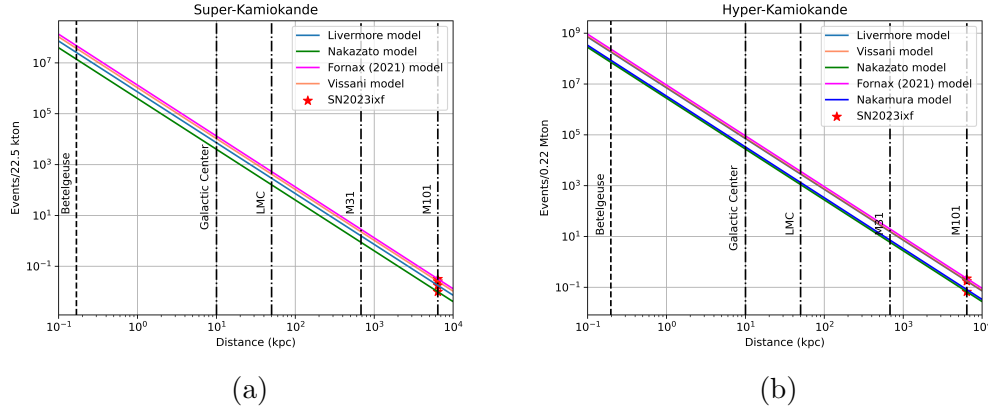


Figure 3.2: Expected number of supernova neutrinos as a function of distance in Super-Kamiokande (a) and Hyper-Kamiokande (b). The black dashed lines correspond to “typical” distances within the Milky Way and in the Local Group up to M101, the host galaxy of SN2023ixf. Taken from [1].

3.2.3 High-energy emission

For the high energy neutrino emission, the “choked jet” model, previously discussed, has been tested. A numerical simulation has been performed based on the models proposed in [68, 173, 174]. We generated a flux of accelerated protons, in the IS region, with energies from 100 GeV up to 10^9 GeV. The simulation considers different set of parameters varying the baryon loading f_p (i.e. the amount of baryons present in the jet), the relativistic nature of the jet (in terms of the bulk Lorentz factor Γ), the duration of the jet and its kinetic energy. Once we obtained the neutrino flux, we calculated the expected number of events detected by the IceCube telescope [29]. Figure 3.3 shows the expected number of neutrinos in IceCube as a function of the baryon loading for different sets of parameters. These results tell us that the lack of detection by IceCube [175] can be explained in different ways: either just a small fraction of kinetic energy ($f_p < 10\%$) is converted in accelerated

3.2. LOW- AND HIGH-ENERGY NEUTRINOS FROM SN2023IXF IN M101

photons; or the jet is ultra-relativistic ($\Gamma \sim 100$) and has a very long duration ($t_{jet} = 10^4 s$) so that protons will lose all their energy due to synchrotron emission and won't interact with photons; or finally that jets do not drive supernovae explosions.

Another model for high-energy neutrinos considered is described in [176] and proposes a scenario in which the SN ejecta crashes into the dense circumstellar shells of the external medium. A significant fraction of the ejecta kinetic energy is converted to the internal energy of the shocked shells. Protons can be accelerated at the shocks and interact with the protons present in the external medium. Accelerated protons are mostly confined and produce mesons via inelastic pp scattering, which leads to the production of neutrinos. With this model, assuming that all the energy goes into accelerating the protons, ~ 50 neutrinos with $E > 1 \text{ TeV}$ are expected at the distance of SN2023ixf. Similarly to one of the previous results, the lack of detection can be explained in this model by assuming that only a small fraction of energy is transferred to accelerated protons ($f_p < 10\%$).

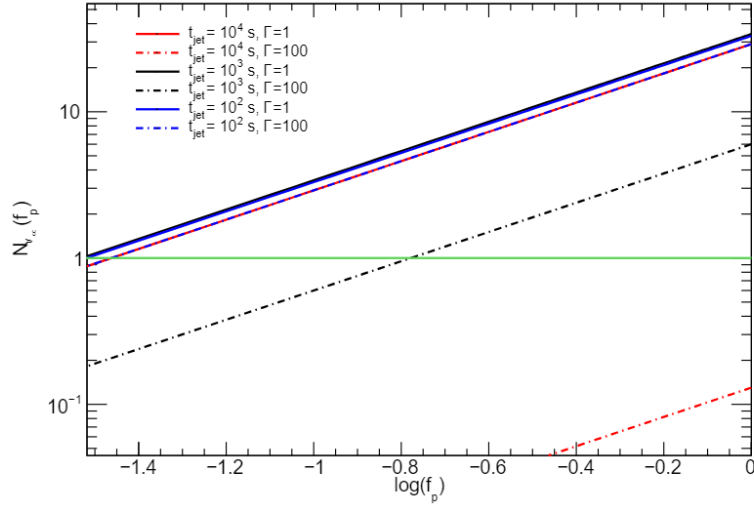


Figure 3.3: Expected number of ν_μ and $\bar{\nu}_\mu$ in IceCube, as a function of the baryon loading f_p for different sets of the parameters $t_{jet} = 10^2, 10^3, 10^4 s$ and $\Gamma = 1, 100$. The kinetic energy of the jet is $E = 10^{51} erg$.

Chapter 4

The Super-Kamiokande Experiment

Super-Kamiokande (Super-K, SK) is a 50-kton water Cherenkov detector currently operating in Japan, primarily aimed at the study and detection of neutrinos. In this chapter a full description of the experiment will be given.

4.1 Detection principle: Cherenkov radiation

Given that neutrinos cannot be detected directly, they are observed via the products of their interactions. Super-Kamiokande in particular detect neutrinos via the Cherenkov radiation emitted by the charged particles, such as electrons or positrons, produced when neutrinos interact in the water.

The Cherenkov radiation is a type of radiation that is emitted when a charged particle travels through a dielectric medium at a speed greater than the speed of light in that medium [177]. The angle θ_C of the emitted Cherenkov radi-

ation relative to the particle's trajectory is given by:

$$\cos \theta_C = \frac{c}{nv} \quad (4.1)$$

where c is the speed of light in a vacuum, n is the refractive index of the medium, and v is the velocity of the particle. The threshold energy at which particles start to produce Cherenkov light is given by:

$$E_{th} = \frac{m}{\sqrt{1 - \left(\frac{1}{n(\lambda)}\right)^2}} \quad (4.2)$$

In pure water it correspond to 0.257 MeV.

The number of photons emitted per unit length per unit wavelength is:

$$\frac{d^2 N}{dx d\lambda} = \frac{2\pi z^2 \alpha}{\lambda^2} \left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) = \frac{2\pi z^2 \alpha}{\lambda^2} \sin^2 \theta_C \quad (4.3)$$

In Super-Kamiokande, by taking into account the detector characteristics and given that most of the neutrino products are relativistic particles, we expect that around 342 Cherenkov photons are produced per centimeter.

4.2 Detector overview

The detector consists of a cylindrical tank with a diameter of 39.3 meters and a height of 41.4 meters, holding 50 kilotons initially of ultra-pure water (the current Gd-doped phase will be discussed in the following), which acts as the target material and dielectric medium for Cherenkov radiation. To reduce the cosmic-ray background, it is located 1,000 meters underground

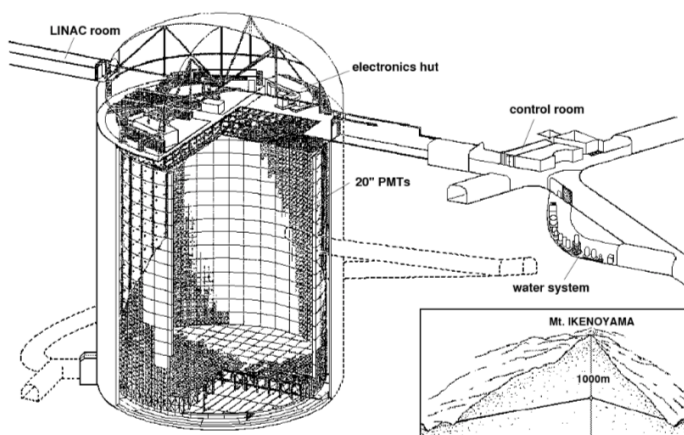


Figure 4.1: A schematic overview of Super-Kamiokande.

beneath Mt. Ikenoyama in Gifu Prefecture, Japan.

The water tank is divided into an inner tank (ID) and an outer tank (OD), separated by a 60 cm stainless steel structure. The ID contains about 32.5 kilotons of water and is equipped with 11,129 20-inch photomultiplier tubes (PMTs) covering 40% of its surface. The gaps between PMTs are covered by a black sheet to minimize light reflection and maintain optical isolation.

The OD is about 2 meters thick, holding approximately 17.5 kilotons of water, and is equipped with 1,885 8-inch PMTs facing outwards. The OD's inner surface is covered with a high-reflectivity white Tyvek sheet on the OD side and a black sheet on the opposite side, enhancing photon collection efficiency.

Inside the ID, a Fiducial Volume (FV) is defined, to reduce low energy background. A typical selection criterion used in the analysis involves considering only interactions occurring within a volume that is at least 2 meters from the walls. A schematic of the detector can be seen in Fig. 4.1.

4.3 Super-Kamiokande Phases

Operating since 1996, Super-Kamiokande's history can be divided in different phases:

SK-I: The first phase of the experiment began in April 1996 and continued until July 2001, when it was shut down for maintenance. During this period, it operated with a photon coverage of 40%, using 11,146 ID PMTs and 1,885 OD PMTs.

SK-II: During the tank refilling in November 2001, an implosion of a PMT caused the destruction of more than half of the PMTs inside the tank. Data collection resumed in October 2002 with only 5,182 ID PMTs, resulting in a reduced photon coverage of 19%. To prevent similar accidents, each PMT was encased in fiber-reinforced plastic (FRP). The experiment continued until October 2005, when it was halted for a complete rebuild.

SK-III: A photon coverage of 40% was reached again during the third phase which lasted from July 2006 until September 2008.

SK-IV: While keeping the same photo-coverage, the fourth phase of SK was characterized by an upgraded Front-End electronics and lasted from September 2008 until May 2018.

SK-V: Started on January 2019, this phase was characterized by the preparation for the loading of gadolinium sulfate to enhance neutron capture. In addition, some new PMTs that will be used for Hyper-Kamiokande have been installed for testing.

SK-VI: This was the first phase with gadolinium dissolved, with a concentration of 0.01%. The efficiency for neutron capture reached a 50% level.

SK-VII: A second gadolinium loading was carried out for the seventh phase of SK, reaching a total concentration by mass of 0.03%. This phase started in June 2022 and was characterized by a neutron capture efficiency of 75%. In October 2023, there was a failure in the geomagnetic compensation coil system (see slide 37 from [178]), affecting the detector's performance. Repair work was conducted in July/August 2024.

SK-VIII: This current phase started in September 2024, after the reparation of the coil system. Gadolinium concentration is still 0.03%.

4.4 Photo-multiplier Tubes in Super-Kamiokande

In order to collect the Cherenkov light produced inside SK, PMTs are adopted. These devices are highly sensitive detectors that convert faint light signals into an amplified electrical signal via photo-electric effect. They consist of a photocathode, which emits electrons when struck by photons, followed by a series of dynodes that multiply these electrons through secondary emission, resulting in a significantly amplified signal that can be easily measured. Different solutions are adopted for the ID and OD.

4.4.1 ID PMT

For the ID, Hamamatsu R3600 produced by Hamamatsu Photonics K.K. are used. This PMT has a diameter of 20" (~ 50 cm) and has a bialkali (Sb-

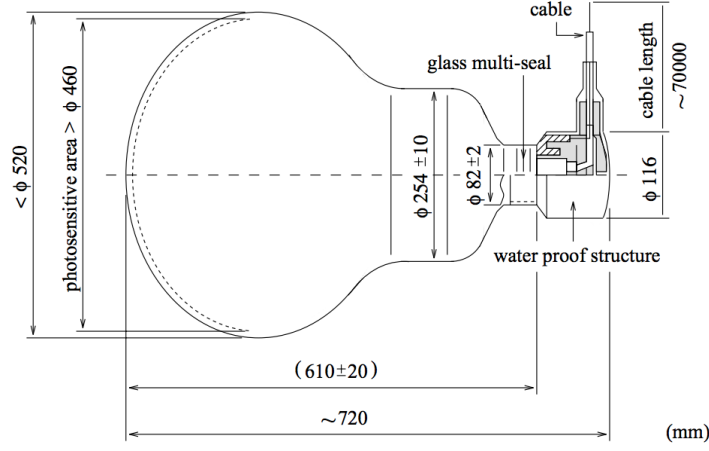


Figure 4.2: General scheme of the 20-inch Photo-Multiplier.

K-Cs) photocathode which offers excellent quantum efficiency (QE) for the Cherenkov light wavelength. Fig. 4.2 shows a scheme of the PMT.

Its sensitivity range spans from 280 to 660 nm, with a QE peaking at around 22% at approximately 390 nm. The average collection efficiency at the first dynode is about 70%, and the PMT gain is around 10^7 at approximately 2 kV of high voltage (HV). The transit time is roughly 10 ns, with a relative spread of about 2.2 ns at 1 sigma [14].

4.4.2 OD PMT

The PMTs installed on the OD surface have a diameter of 8" (~ 22 cm). During SK-I, the PMT used for the IMB experiment [179] were adopted. After the 2001 accident, most of the OD PMTs were replaced with new Hamamatsu R5912 models. These new PMTs are similar in size and have a photon sensitivity comparable to that of the IMB PMTs. Given the small photo-coverage of these PMTs, each one is attached to a wavelength shifter

(WS) plate measuring 60 cm x 60 cm x 1.3 cm. The WS is an acrylic plate infused with 50 mg/L of bis-MSB ($C_{24}H_{22}$), which absorbs light in the ultraviolet range and re-emits it in the blue to green range, matching the peak quantum efficiency of the OD PMTs. The WS increases the collection efficiency of the OD to 60%, though the timing resolution has decreased from 13 ns to 15 ns. Currently, 1,275 OD PMTs are evenly distributed on the OD walls, with 308 on the bottom and 302 on the top.

4.5 DAQ Electronics and Triggers System

During SK-IV, a significant upgrade in the data acquisition system was made with the introduction of a QTC-Based Electronics with Ethernet (QBEE). This system replaced the previous analog time module (ATM) based system, providing enhanced event detection and data recording capabilities for both ID and OD PMTs. The QBEE system was designed to reduce dead time, address signal reflection issues, and improve the overall efficiency of data acquisition. In particular, the QBEE system enabled the detection of low-energy events that were previously unobservable, significantly enhancing the capabilities of Super-K.

Each QBEE module consists of 24 analog input channels for PMT signals, distributed across 8 charge time converters (QTCs), with each QTC handling 3 channels. These channels operate with three gain ranges - small, medium, and large - with gain ratios of 1, 1/7, and 1/49, respectively. This setup covers a wide charge dynamic range (0.2-2500 pC) while maintaining high resolution. The QTC integrates the charge from the PMT signals and

generates an output signal proportional to the charge, which is then digitized by a time-to-digital converter (TDC).

The digitized signals are transferred to front-end PCs and then sent to merger PCs, where they are combined and processed through a software trigger. A scheme of the QBEE system is shown in Figure 4.3.

The software trigger scans the signals and applies specific conditions, such as the number of PMT hits within a 200 ns window, which corresponds to the time it takes for a Cherenkov photon to traverse the SK tank. Various trigger types are employed based on energy: Super Low Energy (SLE), Low Energy (LE), High Energy (HE), and Super High Energy (SHE), each with adjustable thresholds based on the event rate (the event rate is higher at lower energy due to environmental radiation and random coincidence of PMT dark noise). The OD trigger is activated when 22 or more OD PMT hits occur within the same time frame. When a trigger is applied, all hits from $-5 \mu s$ to $35 \mu s$ are recorded. However, in the case of SLE, all hits from $-0.5 \mu s$ to $1.0 \mu s$ are recorded due to the high trigger rate. Detailed information about standard triggers in Super-K are reported in Table 4.1. In addition to these, a special trigger, AFT, was implemented from SK-IV onward to save delayed neutron capture signals, which are crucial particularly for the Supernova Relic Neutrino (SRN) search.

4.5.1 Wideband Intelligent Trigger

To improve the performance of Super-Kamiokande at very low energies, a threshold-less trigger system, known as Wideband Intelligent Trigger (WIT)

4.5. DAQ ELECTRONICS AND TRIGGERS SYSTEM

Trigger type	N_{200} threshold [μs]	Event window [μs]	Trigger rate [kHz]
SLE	34/31	1.5 [-0.5,+1.0]	3.0-4.0
LE	47	40 [-5,+35]	80
HE	50	40 [-5,+35]	30
SHE	70/58	40 [-5,+35]	3
OD	22 (Only OD)	40 [-5,+35]	2

Table 4.1: Threshold for each type of trigger in Super-Kamioande.

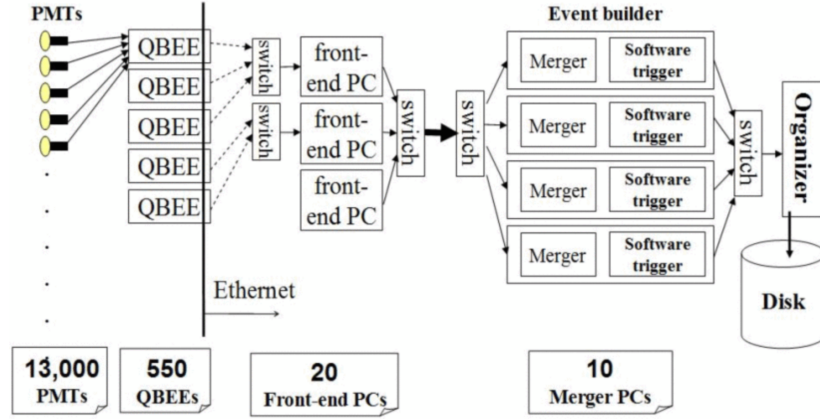


Figure 4.3: Schematic of the DAQ system with QBEE. Taken from [180].

[181], has been implemented during SK-IV and it is still in operation. This system allows to completely process in real time all of the data in the un-triggered, raw stream and extract super low energy electrons with efficiency close to 100% down to a recoil electron kinetic energy of about 2.5 MeV.

Data arrives to the WIT system from a "buffer" machine, which watches for a supernova neutrino burst and then saves all data associated with it, see Fig. 4.4 for a scheme. This 'SN Data Recorder' buffer machine continuously transmits data-blocks of 23 ms, consisting of 1344 consecutive data reads of 17 μs each.

Nineteen WIT computers take care of receiving, triggering, and reconstructing the raw data-blocks. These reconstruction algorithms run in real time,

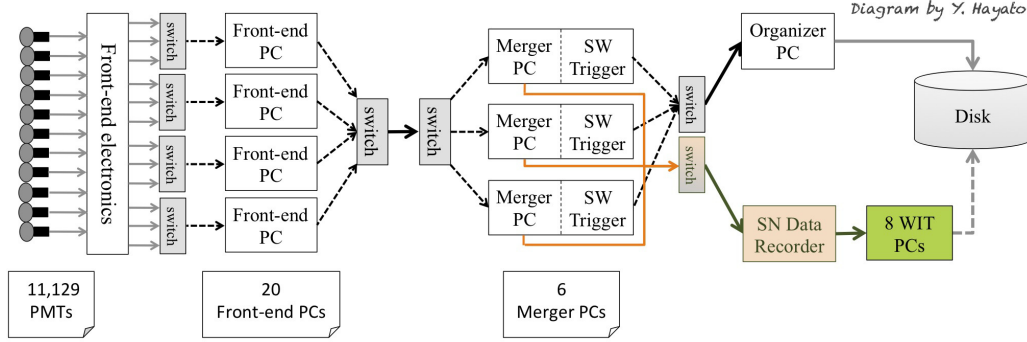


Figure 4.4: WIT scheme. Taken from [181]. Since [182], WIT has been updated and contains now 19 PCs.

simultaneously to the trigger, independently evaluating each data-block in a massive parallel fashion. Then the reconstructed events within the fiducial volume are sent to the organizer WIT computer, which sorts the reconstructed events based on the arrival time and then sends the online data to the offline machine where they will undergo a further reduction and offline reconstruction.

WIT is used for low energy analysis, given its very low threshold, like supernova neutrinos, DSNB, reactor neutrinos and solar neutrinos analyses. Moreover, a pre-SN trigger is installed in WIT, which looks for neutrino emission from preliminary stages of SN explosion, i.e. during the silicon burning phase [182]. In Chapter 6 the development of a real-time GW follow-up system in WIT will be discussed.

4.6 Water and Air Purification System

The quality of the water in Super-K detector is essential for accurate neutrino observations, as it ensures minimal attenuation of Cherenkov light and re-

duces background noise from radioactive contaminants. The water, sourced from the Kamioka mine, undergoes continuous purification to remove particulates, metal ions, bacteria, and radioactive materials like radon, which is a significant background source for MeV-scale neutrino analyses. Typical radon concentrations in water coming into the purification system from the Super-Kamiokande tank are $9.1mBq/m^3$ and in water output by the system, $1.7mBq/m^3$ [183]. This clearly affects the background level in low energy analysis, but it is reduced by applying a FV cut.

The purification system involves filtering water through various stages, including UV sterilizers and degasifiers, which effectively remove particles larger than $0.2\ \mu m$, bacteria, dissolved oxygen, and radon. A scheme of the water purification system is shown in Figure 4.5. The purified water is introduced at the bottom of the tank and collected from the top, creating a vertical asymmetry in water quality, with clearer water at the bottom. Although convection could be a solution to prevent this asymmetry, at the same time, it would lead to the mixing of radon-contaminated water from the tank walls with the water from the central region, worsening the overall water purity. Thus, the water's temperature is carefully controlled around $13.5^\circ C$ to $14^\circ C$ to avoid convection. This temperature regulation also allows for suppression of bacterial growth and stabilizes the PMT dark noise.

Additionally, the experimental hall's environment is managed to minimize radon contamination. The mine's rocks naturally leak radon, so the walls are coated with polyurethane, and low-radon air is continuously pumped into the area to maintain a radon concentration of $30 - 50\ Bq/m^3$. This air, processed through dehumidifiers and carbon filters, ensures that the degasifiers in the

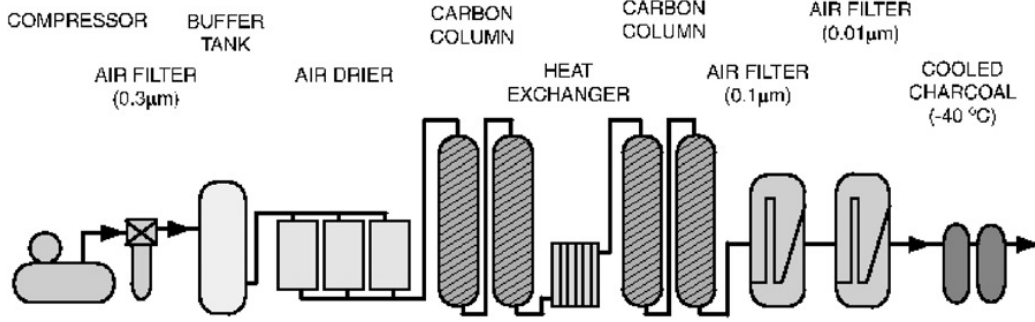


Figure 4.5: A scheme of the water purification system. Image taken from [14].

water purification system operate effectively.

4.7 Super-Kamiokande with Gadolinium

In 2020, the new phase SK-VI was characterized by the addition of gadolinium sulphate octahydrate to the water. Since then, the experiment is also known as Super-Kamiokande with Gadolinium or SK-Gd. The main reason behind this relies in the outstanding efficiency of this salt in capturing neutrons. This aspect is particularly crucial for DSNB search, i.e. the overall neutrino flux of all core collapse supernovae that happened in the history of our universe.

DSNB is detected via Inverse Beta Decay (Eq. 1.38) in Super-Kamiokande. The products of IBD are a positron and a neutron. If the neutron is captured by hydrogen through Thermal Neutron Capture (TNC), a 2.2 MeV γ -ray is emitted, which is very hard to detect being near the cherenkov threshold. If gadolinium is added, even in small quantities, neutrons will be captured by it, given the highest cross section [184], and will produce more energetic γ -ray

cascades (around 8 MeV) that can be easily detected in Super-Kamiokande. Other analyses such as galactic supernova neutrinos, atmospheric neutrinos, proton decay and reactor neutrinos can benefit from the Gd loading. During SK-VI, 13 tons of gadolinium sulphate octahydrate were added bringing the Gd concentration to 0.01% [185]. In 2022, SK-VII phase started and it was marked by the addition of 26.1 more tons of gadolinium sulphate octahydrate, which brought the final concentration of dissolved gadolinium to 0.033%. The new Gd loading in particular brought the neutron capture efficiency from 50% during SK-VI to around 75% [186].

4.8 Calibration

The response of each PMT is fine-tuned using controlled calibration sources to ensure accurate and uniform detection of physics events. Additionally, the propagation of light within the SK water is thoroughly characterized. In the following, only ID PMTs calibration will be described, since OD PMTs are only used as veto for the analysis described in the following chapters.

4.8.1 High-voltage calibration

To interpret the digitized detector output in terms of physical quantities, precise calibration of the ID PMTs and electronics is essential. The calibration focuses on key parameters such as photon counts and the arrival time of digitized PMT hits. The process follows a systematic approach, starting with PMT charge calibration, followed by the fine-tuning of timing response, which depends on the charge calibration.

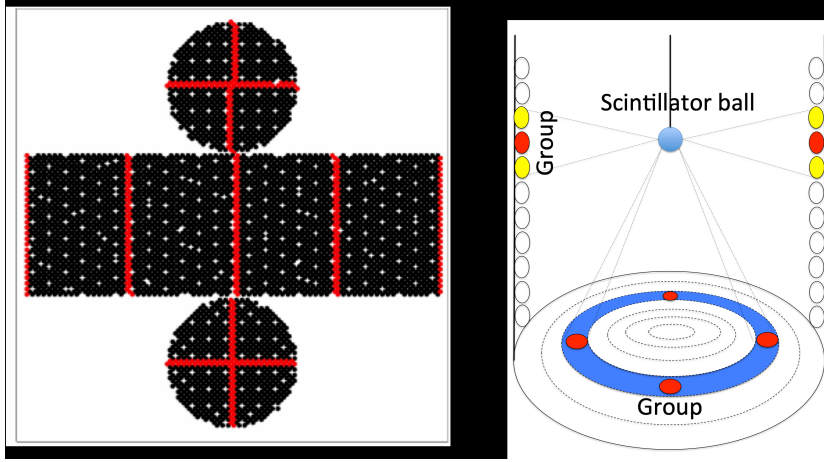


Figure 4.6: The positions of the reference PMTs (left) and a schematic illustrating the grouping of individual PMTs with reference PMTs based on their symmetrical geometrical relationship with the calibration source (right).

Before installation, 420 "reference PMTs" were calibrated in a μ -metal shield using a xenon (Xe) lamp and a scintillator ball to ensure uniform charge output. The variability of their output, under identical light conditions, was maintained below 1.3% RMS. These reference PMTs were then installed symmetrically along the detector walls (Figure 4.6). After the full installation of the ID PMTs, the pre-calibrated scintillator ball was positioned at the tank center. This setup allowed for the adjustment of high voltage for each PMT to match the charge response of reference PMTs located symmetrically around the tank. This tuning achieved consistent output variability below 1.3%, aligning with pre-calibration results.

This high-voltage adjustment was conducted once in 2006 after an incident damaged half of the PMTs. The scintillator ball remains in place for ongoing real-time and long-term monitoring of detector performance.

4.8.2 Gain calibration

PMT "gain" refers to the amplification factor of its dynode chain. Measuring the gain involves two steps:

- **Relative Gain:** Using a variable-intensity light source, the relative gain for each PMT is determined by comparing its charge output at high intensity with its single-photoelectron hit rate. This procedure yields a relative gain distribution with an RMS spread of 5.9%.
- **Absolute Gain:** A Nickel "ball," containing NiO and polyethylene with a Cf source, emits neutrons that induce isotropic 9 MeV photons through Ni capture. Since most hits from these photons correspond to single photoelectrons, the absolute gain is determined by analyzing the corrected single-photoelectron charge distribution, averaged across all ID PMTs .

4.8.3 Quantum Efficiency (QE) Measurement

The relative QE, defined as the product of photon-to-photoelectron conversion efficiency and electron collection efficiency, quantifies a PMT's likelihood of detecting a photon. Before measurement, the water temperature was stabilized to ensure uniform transparency. Using the same Nickel ball setup, relative QE differences were measured based on recorded hits, with corrections for photon attenuation and angular acceptance from Monte Carlo (MC) simulations (Figure 4.7). The results are tabulated for integration into the detector's MC model.

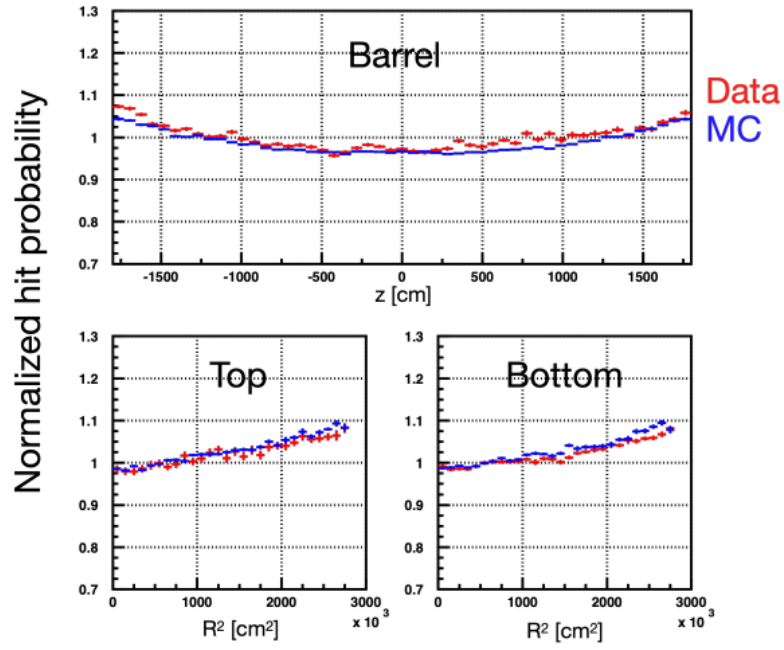


Figure 4.7: The normalized hit probabilities of PMTs, derived from single-photon level light emitted by the Nickel source, in both expected (blue) and observed (red) distributions. These distributions are shown in relation to the vertical positions of PMTs on the tank barrel (top figure) and the radial positions of PMTs on the tank top and bottom walls (bottom two figures). Taken from [187].

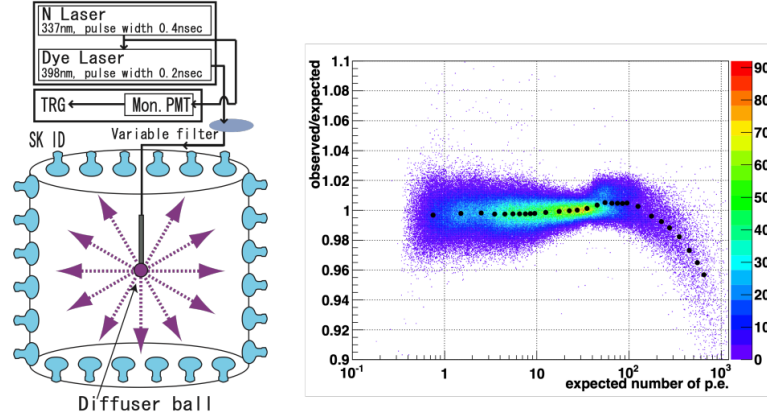


Figure 4.8: Setup featuring the N-dye laser diffuser ball for PMT charge linearity and timing response calibration (left), along with the observed charge linearity plotted against the expected charge output (right).

4.8.4 Charge Linearity Calibration

PMTs exhibit $\sim 5\%$ non-linearity for signals exceeding 250 photoelectrons. To measure this, a nitrogen-laser-driven dye laser, paired with a magnesium oxide diffuser ball, was placed at various positions and intensities within the detector. The ratio of observed to expected charge outputs was recorded and incorporated into the MC simulation to account for the non-linearity. Figure 4.8 shows the calibration configuration as well as the ratio between the observed and expected charge outputs as a function of the expected values.

4.8.5 Timing calibration

The timing response is calibrated using the same setup shown in Fig. 4.8, considering factors such as signal transit times, cable lengths, and the time-walk effect (where larger signals arrive earlier). Laser pulses with sub-nanosecond

precision were used to map the relationship between signal charge and timing offsets. This relationship is modeled using a segmented polynomial function, referred to as the TQ-map, which provides charge-dependent timing corrections for each PMT.

Daily laser-based timing checks ensure calibration stability within 0.1 ns, with a statistical accuracy of 0.05 ns per readout channel. Corrected PMT timing distributions are fitted with asymmetric Gaussian functions to evaluate timing resolution, demonstrating reliable detector performance.

4.8.6 Photon tracking calibration

During their propagation through water, photons are subject to scattering and absorption, both of which depend on the wavelength. To study these effects, a monochromatic laser beam with varying wavelengths is injected from the top to the bottom of the SK tank, as shown in Figure 4.9.

The SK detector employs an empirical model to describe photon propagation, assuming an exponential light attenuation in the form of $e^{-l/L(\lambda)}$ where l is the photon track length, and L is the characteristic attenuation length, also called water transparency. $L(\lambda)$ is parameterized as:

$$L(\lambda) = \frac{1}{\alpha_{abs}(\lambda) + \alpha_{sym}(\lambda) + \alpha_{asy}(\lambda)} \quad (4.4)$$

where $\alpha_{abs}(\lambda)$, $\alpha_{sym}(\lambda)$, $\alpha_{asy}(\lambda)$ represent amplitudes (in m^{-1}) of absorption, symmetric scattering, and asymmetric scattering, respectively.

These coefficients are fitted using simulation comparisons to laser calibration data for different wavelengths. They are also parametrized to account

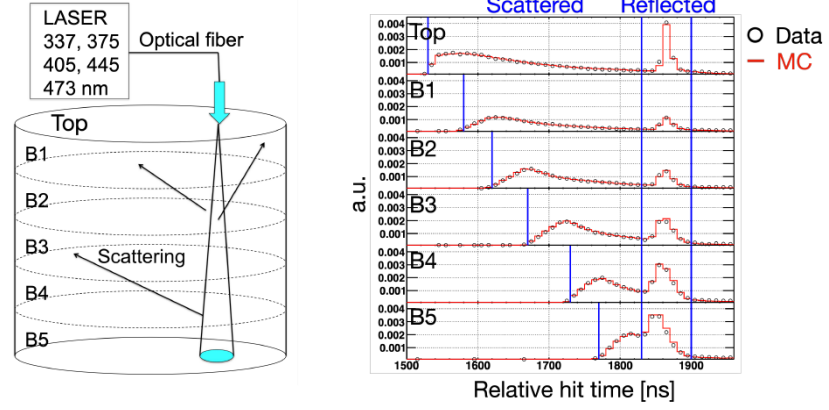


Figure 4.9: A schematic illustrating the photon tracking calibration through monochromatic laser injection (left) and the observed PMT hit time distributions divided into various tank regions (right). In the right figure, the milder peak on the left is attributed to scattered photons, while the sharper peak on the right is a result of photons reflected at the tank bottom. Taken from [187].

for wavelength dependence, as detailed in [187]. The resulting parameters, collectively termed "water parameters," provide insights into scattering and absorption rates. Fig. 4.10 shows the dependence of α and L^{-1} on λ , demonstrating a transparency over 120 m for $\lambda = 440\text{nm}$, i.e. in the Cherenkov regime.

Additionally, photons may be reflected when transitioning between materials with differing refractive indices. In the SK simulation, the following four materials are modeled:

- **Water**
- **Glass** (PMT cover)
- **Bialkali** (PMT photocathode)
- **Vacuum** (air)

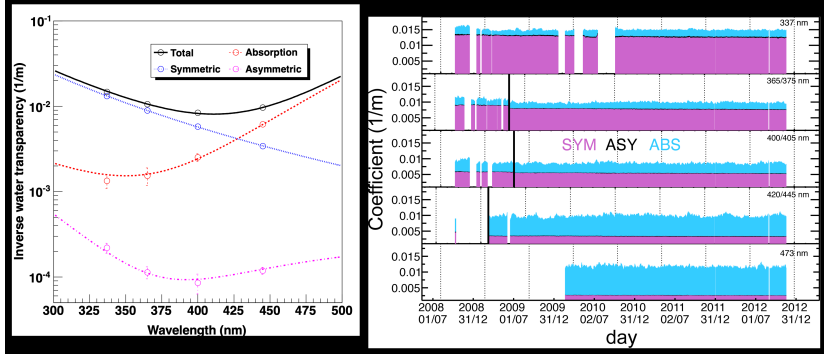


Figure 4.10: Illustration of fitted absorption, symmetric scattering, and asymmetric scattering amplitudes parametrized by photon wavelength (left), along with the temporal variation of these amplitudes (right). Taken from [187].

Reflection occurs on the surfaces of PMTs or the black sheets lining the tank walls. The refractive index of bialkali, parameterized as $n_{\text{real}} + i \cdot n_{\text{imag}}$, is tuned for different laser wavelengths. This tuning ensures consistency with the sharper reflection peaks observed in the laser calibration data.

To measure the reflectivity of the black sheets covering the tank walls a laser injector and a black sheet sample were submerged in the tank. Light reflected from the black sheet sample was measured by the ID PMTs. Reflectivity was calculated by comparing the charge output ratios with and without the black sheet sample. This procedure ensures accurate modeling of photon reflections from the tank walls in the SK simulation.

4.8.7 Absolute QE tuning

Following the calibration of water parameters for each SK phase, the absolute QE scale, referred to as COREPMT, is determined. COREPMT normalizes the overall charge output response of the PMTs and is established by com-

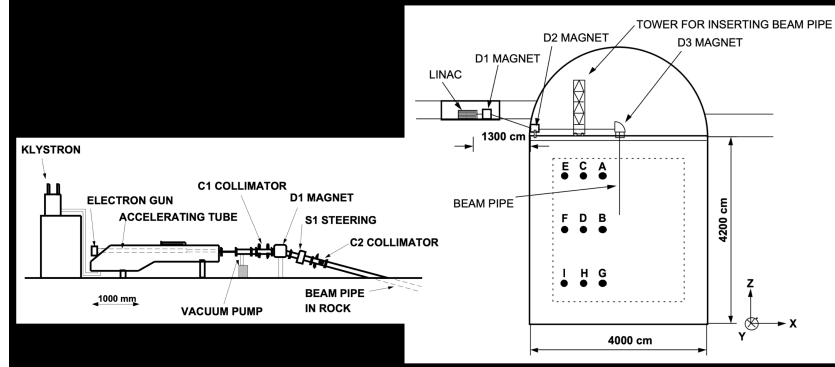


Figure 4.11: LINAC setup (right) and the calibration arrangement (right). Taken from [188].

paring simulation results with calibration data. Two distinct calibration data sets are employed by the two analysis groups within SK.

For low-energy neutrino detection, a linear accelerator (LINAC) is used for calibration. The LINAC produces an electron beam with energies spanning from 5 to 18 MeV. This electron beam is delivered directly into the detector through a beamline system, which includes three bending magnets and a beam pipe positioned at the top of the tank. The LINAC setup is illustrated in Figure 4.11. The calibration with LINAC is used to set absolute energy scale for low energy analyses and also for determining energy, vertex, and angular resolutions.

For high-energy neutrino detection, through-going cosmic ray muons are employed for calibration. These muons traverse both the top and bottom of the detector with relatively consistent path lengths. The absolute QE value is determined by selecting the value that best fits the observed charge distribution of through-going muons.

The values obtained from two distinct calibration datasets (LINAC data and cosmic ray muons) show an agreement within 1%, owing to the high dynamic range and charge linearity of the ID PMTs.

More information regarding calibrations in Super-Kamiokande can be found in [187].

4.9 Data reconstruction

The SK detector registers around one million triggers per day, mostly due to low-energy radioactive backgrounds at a rate of about 11 Hz, and cosmic muons at around 3 Hz. The procedure for isolating potential neutrino interactions from these background triggers is referred to as *reduction*. The deduction of the characteristics of particles detected within the time window around the trigger based on the patterns of hit PMTs is called instead *reconstruction*.

Both reduction and reconstruction are energy-dependent and *ad-hoc* software have been realized to reconstruct low- and high-energy events.

4.9.1 High Energy Events

High-energy neutrino candidates ($E_\nu > 100 \text{ MeV}$) are classified in three broad sub-categories: fully-contained (FC), partially-contained (PC), and upward-going muon (UPMU). The distinguishing characteristics between these classifications are:

- FC events have an interaction vertex reconstructed within the ID, and no OD activity. Hence, all final state particles are fully contained.

- PC events have an interaction vertex reconstructed within the ID, and no entry point in the OD, but do have an exit point in the OD. The exiting particle is typically a muon produced by a CC- ν_μ interaction.
- UPMU events are induced by neutrinos interacting in the rock around SK or in the OD water. These events look like cosmic muons, but pointed upward, i.e., coming from below the horizon. UPMU neutrino events well-below the horizon have a low contamination from cosmic muons, since the Earth acts as a shield against cosmic muons coming from below. These events are classified as either through-going (with a track length requirement of more than 7 m) or stopping in the detector (with a reconstructed muon momentum requirement of more than 1.6 GeV)

The SK reduction procedure identifies the interactions corresponding to each class by applying a series of successive cuts. Earlier cuts remove obvious background events using simple calibrated detector information and are applied on online data. More complex cuts identify each sub-category and are applied after reconstruction is performed. These cuts suppress any remaining low-energy events, entering cosmic muon backgrounds, and events with poor reconstructed fit information. The three samples are also characterized by different energy ranges: FC events have energies between 0.1 and 10 GeV, PC between 0.1 and 100 GeV and UPMU between 1.6 GeV and 1 TeV. A detailed description of high-energy samples reduction process can be found in [\[189\]](#).

To reconstruct high energy events, SK uses a set of algorithms to identify,

count, and categorize Cherenkov rings, collectively called *APFit* [190]. A separate algorithm, FITQUN, has also been used to reconstruct SK events [191].

The timing information of hits establishes an event vertex. For FC and PC events, a preliminary vertex fit in the ID is performed, based on the residual hit times after subtracting the time-of-flight to the vertex. APFit refines this time-of-flight vertex later using additional information. The residual times from a trial vertex, $\vec{x}$, are computed as:

$$t_i^{Resid.}(\vec{x}) = t_i - \frac{n}{c} |\vec{x} - \vec{x}_i^{PMT}| \quad (4.5)$$

where n is the index of refraction in water, t_i represents the calibrated hit time relative to the trigger, and $\vec{x}_i^{PMT}$ is the position of the i -th PMT. The best vertex is taken as the point which minimizes the width of the distribution of $t_i^{Resid.}$.

In a second stage, a fit considering the spatial distribution and observed charges of hit PMTs determines the particle's direction, momentum, and particle type. APFit separates rings into e -like and μ -like: electrons and photons tend to scatter and produce electromagnetic showers, resulting in many overlapping rings which appear as a single ring with blurred edges. Figure 4.12 shows an example of the Cherenkov light patterns observed in SK following a neutrino candidate interaction, and their fitted properties.

Heavier particles such as muons and charged pions do not create showers and therefore have sharp ring edges. Higher-momentum particles produce more light, so the charge contained within the ring provides an estimate of the

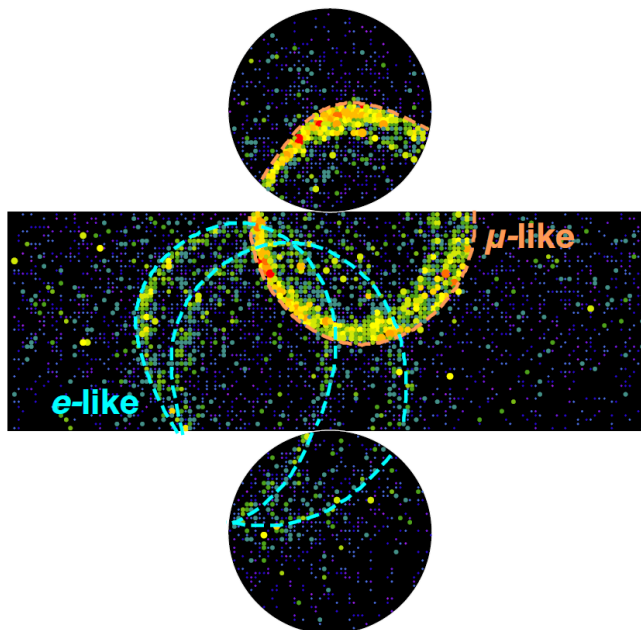


Figure 4.12: Event display of a multi-ring atmospheric neutrino candidate event in SK V data. Hit ID PMTs are displayed on an unrolled view of the cylindrical detector, with the color and radius of each hit PMT corresponding to the detected charge. The reconstruction algorithm APFit identifies three Cherenkov rings, indicated by dashed outlines: one bright μ -like ring, and two fainter e -like rings. Taken from [12].

particle's momentum.

In addition to detecting Cherenkov rings, SK also identifies electrons produced from muon decays. Decay electrons are detected by scanning for clusters of time-correlated hits that exceed the background level following a primary neutrino interaction trigger. A hit-time-based fitter is used to estimate the decay electron's vertex for each candidate hit cluster, and candidates are accepted if 50 or more hits are registered within a 50 ns time window. Additional reductions and filters can also be applied based on the specific physics focus of the analysis, e.g. atmospheric or accelerator-based studies.

4.9.2 Low Energy Events

For low energy events, the first filter applied to pre-triggered events is the *Software Trigger Online Reconstruction of Events (STORE)*. This filter identifies PMT hits that may originate from a single vertex, as low-energy electrons can only travel a few centimeters in water, causing their Cherenkov light to resemble a point source [181]. STORE calculates the temporal and spatial separations between hits. The *ClusFit* vertex fit is then applied to the selected hits, removing isolated hits to reduce the effects of reflected and scattered light, as well as dark noise. If the vertex reconstructed by *ClusFit* lies within the fiducial volume, the *Branch Optimization Navigating Successive Annealing Iterations (BONSAI)* fitter is applied.

BONSAI performs a maximum likelihood fit to the timing residuals of the PMT hits, testing different vertex hypotheses. The timing residual is defined as:

$$T_{\text{residual}} = T_{\text{hit}} - T_{\text{flight}} - T_{\text{vertex}}, \quad (4.6)$$

where T_{hit} is the PMT hit time, T_{flight} is the time taken for light to travel from the testing vertex to the PMT, and T_{vertex} is the time of the testing vertex. The hypothesis with the highest likelihood is chosen as the reconstructed vertex. A goodness value also is also calculated to evaluate the fit quality.

While BONSAI is a more accurate fitter, it is slower. Thus, using fast filters like STORE and ClusFit prior to BONSAI is important for CPU time efficiency [192].

For direction reconstruction, an energy-dependent likelihood is employed to compare Cherenkov ring patterns between data and simulations. These patterns and their energy dependencies are simulated over various energy ranges [193].

For energy reconstruction, the energy is estimated using a variable that counts the number of PMT hits within a 50 ns window, known as N_{50} . Before converting these hits to an energy value, several corrections are applied to account for scattering, reflection, water transparency, and dark noise, yielding an effective number of hits, denoted N_{eff} . The total energy is then calculated as a function of N_{eff} , with precise calibration. The accuracy of the absolute energy scale is better than 1% [194].

Other important variables calculated during event reconstruction include $n18$ (the number of hits in the interval $-6 \text{ ns} < T_{\text{residual}} < 12 \text{ ns}$ at the reconstructed vertex), $dwall$ (the shortest distance from the reconstructed vertex to the detector wall), and $effwall$ (the distance from the reconstructed vertex to the wall along the direction of the reconstructed trajectory).

In the low energy range, the largest cross section is the inverse beta decay (IBD) of electron antineutrinos ($\bar{\nu}_e + p \rightarrow e + n$), and the second most dominant is neutrino elastic scattering (ES) ($\nu + e^- \rightarrow \nu + e^-$), which is sensitive not only to electron neutrinos but also to other flavors. Since positron from IBD are emitted almost isotropically (especially in the low energy range), IBD events don't preserve a directional information of the incoming neutrinos. Since for ES events, the cinematic is fixed, it is possible to reconstruct the incoming neutrino direction.

The ES channel is used mainly to study solar neutrinos, since electron neutrinos are the primary type of neutrinos produced in the Sun's core. Solar neutrinos in Super-K have energies between 3.5 MeV and 20 MeV. In this energy range the main background comes from muon spallation and radioactive isotopes in the surrounding rocks, in the PMT enclosures, the PMT glass, and the detector wall structure.

The event selection in solar analysis can be summarized in the following steps:

1. *Run selection*: Short runs (less than 5 minutes), runs with hardware and/or software problems, and calibration runs are not used for analysis.
2. *Ambient background reduction*: Several cuts remove low-energy radioactive backgrounds. These backgrounds originate mostly from the PMT enclosures, the PMT glass, and the detector wall structure. The cuts are mainly related to variables that evaluate the goodness of the arrival times as well as of the hit pattern and Cherenkov cone. Small hit cluster cuts remove radioactive background coming from the PMT enclosure or glass. Spurious events from calibration sources are also removed in this phase.
3. *External events cut*: To remove radioactive background coming from the PMTs or the detector wall structure, the distance to the PMT-bearing surface from the reconstructed vertex looking back along the reconstructed event direction is calculated. It can be interpreted as the

minimal distance needed for a radioactive particle produced near the wall to travel to the event vertex. The relative cuts are both position- and energy-dependent [195].

4. *Fiducial volume cut*: Events occurring near the detector's walls are rejected. The standard reduction consists of removing events whose reconstructed vertex is within 2 m from the ID edge. For solar analysis, tighter cuts are considered based on the energy [195].
5. *Spallation cut*: Some cosmic-ray muons generate radioactive elements by fragmenting an oxygen nucleus [196]. When these radioactive nuclei eventually decay, they release beta particles and/or gamma rays in what is known as a spallation event. A spallation likelihood function is constructed based on the closest distance between the preceding muon track(s) and a solar neutrino candidate, their time difference, and the charge deposited by the prior muon(s). This likelihood function is used to filter out events that resemble spallation.
6. *Cosmic muons*: Cosmic muons are removed by applying a cut on the number of hits, consequently constraining the energy of the incoming particle. In the most recent analysis, a cut corresponding to about 60 MeV for electron type events was chosen [195].

As an example, Fig. 4.13 shows the final solar spectrum obtained using SK-IV data [195].

The IBD channel is mainly used to detect supernova neutrinos and DSNB, since electron antineutrinos are produced abundantly during the cooling

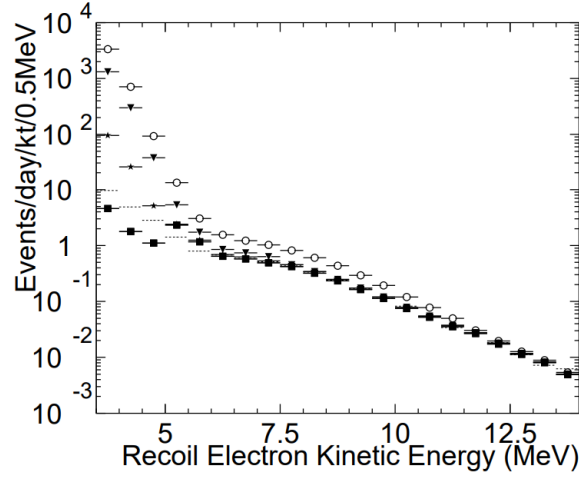


Figure 4.13: Energy spectrum after each reduction step in the solar analysis during SK-IV [195]. The open circles (filled inverted triangles) correspond to the reduction step after the spallation (ambient) cut. The stars give the spectrum after the external event cut, and the final SK-IV sample after the tight fiducial volume cut is given by the filled squares. The dashed line shows the final sample of SK-III [193].

phase of the collapsed core. For DSNB, the spectrum is expected to extend from 8 MeV to approximately 80 MeV. As stated before, the identification of an IBD events is through the detection of the final products, i.e. a positron and a neutron. Super-Kamiokande cannot distinguish the detection of positrons from electrons, so the distinction between Inverse Beta Decay and Beta Decay relies on the detection of the neutron in coincidence with the positron. Thanks to the gadolinium loading, the efficiency of neutron detection has increased to 75%.

Most of background for DSNB search comes from atmospheric neutrinos, cosmic ray muon spallation, radioactivity, reactor and solar neutrinos. Thus a proper event selection is applied to reduce these contamination.

The initial steps of DSNB event selection are similar to those used for solar analysis, i.e. ambient background reduction, fiducial volume cut, cosmic rays and spallation cuts. Of course, cut values and methods may change between the two selections. For a detailed discussion on DSNB cuts, see [85]. Once standard background is removed, IBD events are classified via the identification of both the prompt positron signal and the delayed neutron signal.

The positron is identified via the following steps:

1. *Incoming event cut*: This cut is defined similarly to the external event cut and is used to reduce the signals produced by radioactivity near the detector wall and by muon spallation in the rock surrounding the detector.
2. *Pre- and post-activity cuts*: Atmospheric neutrino interactions can produce both prompt signals from photons, electrons, or energetic heavy particles, and delayed signals from decay of muons and pions to electrons. Depending on which particle deposits most light, unusually high activity can be noticed either before or after the main peak. Thus, ad-hoc cuts are applied to avoid this source of background.
3. *Cherenkov angle*: The opening angle of the Cherenkov light cone (θ_C) emitted by highly relativistic particles, electrons and positrons in the current context, in pure water is around 42° . Since heavier particles are characterized by smaller angles and NCQE interactions usually present wider angles due to the formation of multiple Cherenkov cones, a tight cut on the Cherenkov angle is applied. In [85] for example the chosen

interval for θ_C was $[48^\circ, 50^\circ]$. Thus this cut is a very powerful variable to identify the positron.

4. *Ring clearness*: Since electrons and positrons do not follow a straight trajectory in SK due to scattering and bremsstrahlung, the resulting Cherenkov rings look fuzzy. This information is used to remove pions-induced events, whose Cherenkov rings are more delineated.
5. *Average charge deposit*: Since energetic muons scatter less than electrons and hence often deposit more charge in individual PMTs than electrons and positrons, a cut is applied which takes into account the charge deposited in a given time.

To enable neutron tagging, all positron-like events must be followed by an AFT trigger within $500 \mu s$. Given the challenge of detecting the low 2.2 MeV signal in SK, a machine learning (ML) based algorithm was developed to maximize the efficiency of neutron. In [85] the Boosted Decision Tree (BDT) discriminator with 22 characteristic variables was applied, which provided a $\sim 20\%$ efficiency with approximately 12.5% relative uncertainty identification. Fig. 4.14 shows the final spectra using SK-IV data alongside the predicted spectrum and they agree within uncertainties.

With the advent of SK-Gd a new algorithm has been developed to account for the great impact of Gd on neutron tagging. A detailed description of the new algorithm can be found in [197].

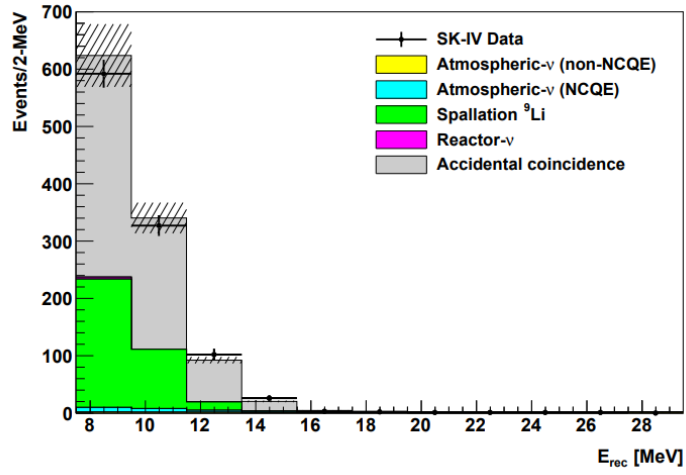


Figure 4.14: Predicted and observed spectra for events passing DSNB selection. Here is applied a uniform neutron tagging cut with a 20% signal efficiency for all energies. The systematic uncertainties are shown by the hatched lines. Taken from [85].

Chapter 5

Search for neutrino counterparts to the Gravitational Waves 04a run catalog

5.1 Introduction

Since the beginning of LIGO and Virgo observing runs, several follow-up analyses have been conducted in Super-Kamiokande, e.g. [198], [199], [200], although no excess of neutrinos was observed in coincidence with any gravitational waves (GW) so far.

In May 2023, LIGO started its fourth observing run, referred as O4. The first part of this run, O4a, lasted until January 2024. Virgo joined O4 run during O4b in April 2024 while KAGRA is expected to join before the end of O4

run¹. During O4a, 81 candidate events have been detected with high confidence [201]. In this chapter, the results of a follow-up analysis of neutrinos in coincidence with GW events from O4a run will be presented.

5.2 The GW O4a catalog

The current GW O4 run marks a significant step forward in the field of gravitational wave astronomy. Launched in May 2023, the first part of O4 observing run (O4a) involved only the upgraded LIGO detectors, with Virgo joining the run at a later stage due to ongoing upgrades. KAGRA, the Japanese gravitational wave observatory, has not yet joined the run but is expected to participate later as it completes its own enhancements. Despite the staggered participation, LIGO’s improved sensitivity has already led to the detections of 81 significant sources between May 2023 and January 2024. In order to perform this follow-up analysis, information about the GW events were obtained through the GraceDB database [202]. GraceDB serves as a communications hub and as a database for storing and displaying information about candidate gravitational-wave events and related electromagnetic events. For coincidence searches the main information needed are the arrival time of the GW event and the possible localization of the source. For GW, this is not provided as a simple parameter but as a probability-density map of the event location on the sky. This map is obtained by calculating the probability distribution of the GW source’s position over the celestial sphere, using a Bayesian approach. For each possible direction, a likelihood is calcu-

¹<https://observing.docs.ligo.org/plan/>

lated based on how well the observed data in all detectors match the expected signal from a source in that direction. The output is a map that shows the probability of the GW source's location in terms of angular coordinates on the sky. An example of probability sky map is reported in Fig. 5.1. Other relevant information distributed through alert notices are the distance of the source and the nature of the event, although for the unofficial catalog (such as the one considered for this analysis), the latter are expressed in terms of probability of belonging to each class: Binary Black Hole (BBH), Neutron Star - Black Hole (NSBH) and Binary Neutron Star (BNS). Due to instabilities in Super-K, caused by a geo-magnetic compensation coil failure, we opted to consider a reduced GW catalog, containing the O4a candidates detected from the start of O4 until October 2024. A total of 56 GW candidates events are included in this reduced catalog, among which two of them are likely associated with NSBH mergers, while all the other with BBH mergers, except for one source which is most probable of terrestrial origin and one unmodeled, i.e. not associated with a particular source.

Table 5.1 shows all the events considered in this analysis. For each event the name of the event, the date and time of the event, the most probable class of merger and the estimated distance are reported.

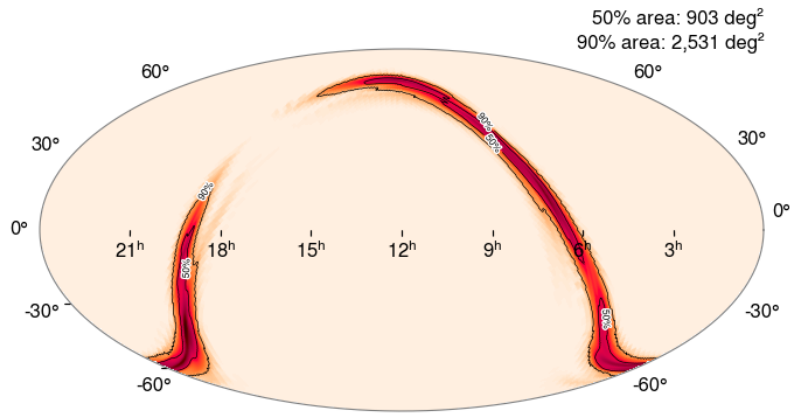


Figure 5.1: An example of probability map for the localization of the GW event S230601bf.

5.2. THE GW O4A CATALOG

Table 5.1: The reduced catalog of GW detected during O4a run considered in this analysis. The GW class represents the most probable nature of the event: binary black hole merger (BBH), neutron star - black hole merger (NSBH), binary neutron star merger (BNS), terrestrial (Terr.). The unmodeled source indicates an event that has been detected but not associated to any class.

GW Name	Event Time	GW Class	Distance
S230529ay	2023-05-29 18:15:00	NSBH (62.4%)	197.2 +/- 62.1 Mpc
S230601bf	2023-06-01 22:41:34	BBH (100.0%)	3578.5 +/- 998.1 Mpc
S230605o	2023-06-05 06:53:43	BBH (98.8%)	1096.4 +/- 332.8 Mpc
S230606d	2023-06-06 00:43:05	BBH (99.9%)	1817.8 +/- 557.5 Mpc
S230608as	2023-06-08 20:50:47	BBH (100.0%)	3193.1 +/- 955.7 Mpc
S230609u	2023-06-09 06:49:58	BBH (96.1%)	3389.6 +/- 1124.9 Mpc
S230624av	2023-06-24 11:31:03	BBH (95.3%)	2556.4 +/- 787.0 Mpc
S230627c	2023-06-27 01:53:37	NSBH (49.2%)	291.0 +/- 64.1 Mpc
S230628ax	2023-06-28 23:12:00	BBH (100.0%)	2047.0 +/- 585.1 Mpc
S230630am	2023-06-30 12:58:06	BBH (98.3%)	8709.7 +/- 2734.9 Mpc
S230630bq	2023-06-30 23:45:32	BBH (96.8%)	998.8 +/- 285.7 Mpc
S230702an	2023-07-02 18:54:53	BBH (100.0%)	2427.9 +/- 848.9 Mpc
S230704f	2023-07-04 02:12:11	BBH (99.7%)	2965.0 +/- 978.1 Mpc
S230706ah	2023-07-06 10:43:33	BBH (97.3%)	2143.4 +/- 684.3 Mpc
S230707ai	2023-07-07 12:40:47	BBH (95.1%)	4073.7 +/- 1484.6 Mpc
S230708cf	2023-07-08 23:09:35	BBH (98.9%)	2055.5 +/- 607.8 Mpc
S230708t	2023-07-08 05:37:05	BBH (97.3%)	3010.0 +/- 987.8 Mpc
S230708z	2023-07-08 07:18:59	BBH (95.4%)	5795.8 +/- 1853.9 Mpc
S230709bi	2023-07-09 12:27:27	BBH (99.7%)	5008.6 +/- 1547.1 Mpc

GW Name	Event Time	GW Class	Distance
S230723ac	2023-07-23 10:18:34	BBH (86.7%)	1685.9 +/- 515.0 Mpc
S230726a	2023-07-26 00:29:40	BBH (100.0%)	2077.0 +/- 698.7 Mpc
S230729z	2023-07-29 08:23:17	BBH (99.7%)	1494.7 +/- 444.5 Mpc
S230731an	2023-07-31 21:53:07	BBH (81.4%)	1056.2 +/- 278.8 Mpc
S230802aq	2023-08-02 11:33:59	BBH (90.3%)	444.1 +/- 156.4 Mpc
S230805x	2023-08-05 03:42:49	BBH (100.0%)	3852.2 +/- 1193.3 Mpc
S230806ak	2023-08-06 20:40:41	BBH (99.7%)	4578.1 +/- 1472.8 Mpc
S230807f	2023-08-07 20:50:45	BBH (95.3%)	6817.7 +/- 2379.4 Mpc
S230808i	2023-08-08 04:03:46	Unmodeled	-
S230811n	2023-08-11 03:21:16	BBH (90.6%)	1904.8 +/- 672.5 Mpc
S230814ah	2023-08-14 23:09:01	BBH (100.0%)	329.6 +/- 104.8 Mpc
S230814r	2023-08-14 06:19:20	BBH (93.2%)	5634.3 +/- 2023.2 Mpc
S230819ax	2023-08-19 17:19:10	Terr. (77.5%)	4216.3 +/- 1645.0 Mpc
S230820bq	2023-08-20 21:25:15	BBH (95.8%)	4784.6 +/- 1467.7 Mpc
S230822bm	2023-08-22 23:03:37	BBH (98.1%)	6854.1 +/- 2325.3 Mpc
S230824r	2023-08-24 03:30:47	BBH (100.0%)	4713.7 +/- 1348.4 Mpc
S230825k	2023-08-25 04:13:34	BBH (99.8%)	7075.1 +/- 2287.2 Mpc
S230831e	2023-08-31 01:54:14	BBH (98.5%)	4899.9 +/- 2126.1 Mpc
S230904n	2023-09-04 05:10:13	BBH (99.1%)	1205.0 +/- 375.0 Mpc
S230911ae	2023-09-11 19:53:24	BBH (100.0%)	1757.8 +/- 588.2 Mpc
S230914ak	2023-09-14 11:14:01	BBH (99.2%)	2826.0 +/- 745.3 Mpc
S230919bj	2023-09-19 21:57:12	BBH (100.0%)	1703.0 +/- 471.4 Mpc
S230920al	2023-09-20 07:11:24	BBH (100.0%)	3163.6 +/- 923.4 Mpc

GW Name	Event Time	GW Class	Distance
S230922g	2023-09-22 02:03:44	BBH (100.0%)	1863.9 +/- 472.9 Mpc
S230922q	2023-09-22 04:06:58	BBH (100.0%)	6653.3 +/- 2347.8 Mpc
S230924an	2023-09-24 12:44:53	BBH (98.6%)	2557.9 +/- 703.0 Mpc
S230927be	2023-09-27 15:38:32	BBH (100.0%)	1055.8 +/- 308.3 Mpc
S230927l	2023-09-27 04:37:29	BBH (97.6%)	3358.6 +/- 951.0 Mpc
S230928cb	2023-09-28 21:58:27	BBH (100.0%)	5603.9 +/- 1691.9 Mpc
S230930al	2023-09-30 11:07:30	BBH (99.4%)	5123.1 +/- 1615.4 Mpc
S231001aq	2023-10-01 14:02:20	BBH (99.6%)	1569.4 +/- 465.3 Mpc
S231005ah	2023-10-05 09:15:49	BBH (99.8%)	4122.8 +/- 1302.1 Mpc
S231005j	2023-10-05 02:10:30	BBH (99.0%)	10543.4 +/- 3318.0 Mpc
S231008ap	2023-10-08 14:25:21	BBH (99.9%)	3356.4 +/- 1119.1 Mpc
S231014r	2023-10-14 04:05:32	BBH (98.6%)	2863.6 +/- 905.8 Mpc
S231020ba	2023-10-20 14:29:47	BBH (100.0%)	1056.4 +/- 341.3 Mpc
S231020bw	2023-10-20 18:05:09	BBH (100.0%)	2620.2 +/- 693.7 Mpc

5.3 Analysis procedure

The follow-up analysis has been performed using a similar strategy as [200]. The analysis framework used for previous studies was improved to perform a more comprehensive search of neutrinos signals in coincidence with gravitational waves, such as considering new detector status (after the start of SK-Gd), inclusion of analysis tools for low energy samples and statistical evaluation methods and an improvement of the GW alert receiver.

For each GW trigger event, both the high-energy (HE) and the low-energy (LE) samples were analyzed, looking for neutrinos in time coincidence with the external trigger t_0 . In this analysis, we use a ± 500 s time window centered on t_0 , which is a conservative assumption based on the correlation between high-energy neutrinos, gravitational waves and GRBs [203].

In the case of the high energy samples, the directional information are strongly relevant and therefore can be used to estimate the significance of the observation, given the angular overlap between the detected neutrinos and the GW localization. This gives rise to a full statistical analysis, whose output is a p-value as well as flux limits.

In the following sections, the results for both HE and LE samples will be presented, alongside the statistical analysis performed. These results are to be considered *preliminary*, until the official GW catalog will be released.

5.4 Observational significance

The significance of an observation is quantified using a p-value, which consists of two components: temporal (p_{time}) and spatial (p_{space}).

The total p-value is the product of these two components ($p = p_{time} \times p_{space}$).

This method separates the discrete time component from the continuous spatial component, allowing for better discrimination.

For LE- ν samples, the reconstructed neutrino direction is not reliably correlated with the original source position. Therefore, only the temporal component, p_{time} , is considered.

The temporal component evaluates the probability of observing at least one

SK event in the selected time window, calculated using a Poisson distribution:

$$p_{time} = 1 - e^{-n_B} \quad (5.1)$$

where n_B is the expected number of events in the chosen time window.

To determine p_{space} , the method used in [204] has been adapted to Super-Kamiokande. The spatial component is derived using a maximum likelihood method, where the GW localization acts as a spatial prior. The best-fit sky position of the potential joint source is determined by maximizing the log-likelihood ratio, and the resulting test statistic is compared to its expected distribution from background events. This allows p_{space} to be interpreted as the probability that the observation is consistent with the background-only hypothesis, given that at least one SK event in time coincidence has been observed.

The point-source likelihood for each sample k (FC, PC, UPMU) is defined as:

$$\mathcal{L}_\nu^{(k)}(n_S^{(k)}, \gamma; \vec{\Omega}_S) = \frac{e^{-(n_S^{(k)} + n_B^{(k)})} (n_S^{(k)} + n_B^{(k)})^{N^{(k)}}}{N^{(k)}!} \prod_{i=1}^{N^{(k)}} \frac{n_S^{(k)} \mathcal{S}^{(k)}(\vec{x}_i, E_i; \vec{\Omega}_S, \gamma) + n_B^{(k)} \mathcal{B}^{(k)}(\vec{x}_i, E_i)}{n_S^{(k)} + n_B^{(k)}} \quad (5.2)$$

where $n_S^{(k)}$ is the number of signal events in the sample (to be fitted), γ is the spectral index of the signal neutrino spectrum ($dn/dE_\nu \propto E^{-\gamma}$, to be fitted as well), Ω_S is the probed source direction, $n_B^{(k)}$ is the expected number of background events in the time window, and $N^{(k)}$ is the observed number of events. $S^{(k)}(\vec{x}_i; E_i; \Omega_S; \gamma)$ is the signal probability density function (pdf), which depends on reconstructed event direction $\vec{x}_i$, reconstructed event energy E_i , source spectral index γ , and source direction Ω_S . $B^{(k)}(\vec{x}_i; E_i)$ is

the background pdf, which depends solely on the event information.

Both $S^{(k)}$ and $B^{(k)}$ have been obtained through Monte Carlo simulations for each separate samples. These can be computed as the product of a term that take into account the angular resolution of the detector at a given energy and an energy term obtained as the convolution of the neutrino energy spectrum and SK energy response function::

$$S^{(k)}(\vec{x}_i; E_i; \Omega_S; \gamma) = A_S(\vec{x}_i; E_i; \Omega_S) \epsilon_S(E_i; \gamma) \quad (5.3)$$

$$B^{(k)}(\vec{x}_i; E_i) = A_B(\vec{x}_i) \epsilon_B(E_i) \quad (5.4)$$

The log-likelihood ratio is defined as:

$$\Lambda(\vec{\Omega}_S) = 2 \sum_k \ln \left[\frac{\mathcal{L}_\nu(\widehat{n}_S, \widehat{\gamma}; \vec{\Omega}_S)}{\mathcal{L}_\nu(n_S = 0; \vec{x}_S)} \right] + 2 \ln P_{GW}(\vec{\Omega}_S) \quad (5.5)$$

where $\widehat{n}_S$ and $\widehat{\gamma}$ are the values that maximize the likelihood function and $P_{GW}(\vec{\Omega}_S)$ in the spatial prior given by the GW probability sky map.

Consequently, the test statistic (TS) is defined as the direction that maximizes the log-likelihood ratio:

$$TS = \max_{\vec{\Omega}_S} \left[\Lambda(\vec{\Omega}_S) \right] \quad (5.6)$$

Finally, to extract p_{space} , 10^5 background toys were generated with neutrino events distributed according to the background distribution and for each toy, TS was computed and the probability distribution function $P_{bkg}(TS)$ was

obtained and compared to the data value:

$$p_{space} = \int_{TS_{data}}^{\infty} P_{bkg}(TS) dTS \quad (5.7)$$

5.5 High energy events

All high-energy samples (FC, PC, and UPMU) were included in this analysis. Given the low and stable rate, characteristic of these samples, a fixed background rate was used to evaluate the expected number of events in each time window. This value was calculated by averaging the event rate of each sample during the SK-VII data taking phase. Out of the 56 triggers, only 7 cases showed at least 1 event (FC type) coincident with the GW trigger. However, when assessing their significance, these events were found to be consistent with the background-only hypothesis. Results for events with an observed number of events higher than the expected ($N_{OBS} > N_{EXP}$) are reported in Table 5.2.

GW EVENT	GW TYPE	FC EXP	FC OBS	PC EXP	PC OBS	UPMU EXP	UPMU OBS	p_{time}	p
S230624av	BBH (95.3%)	1.10E-01	1	7.09E-03	0	1.39E-02	0	0.12	0.41
S230630am	BBH (98.3%)	1.08E-01	1	7.08E-03	0	1.39E-02	0	0.12	0.53
S230731an	BBH (81.4%)	1.08E-01	1	7.09E-02	0	1.39E-02	0	0.12	0.50
S230807f	BBH (95.3%)	1.08E-01	1	7.09E-03	0	1.39E-02	0	0.12	0.68
S230819ax	BBH (99.3%)	1.08E-01	1	7.09E-03	0	1.39E-02	0	0.12	0.20
S230927be	BBH (100.0%)	1.08E-01	1	7.10E-02	0	1.40E-02	0	0.12	0.54
S231001aq	BBH (99.6%)	1.08E-01	1	7.10E-03	0	1.40E-01	0	0.12	0.99

Table 5.2: Number of expected and observed events of FC, PC and UPMU samples in coincident with GW from the O4a reduced catalog. Only GW events with $N_{OBS} > N_{EXP}$ are shown. In the last two columns the temporal component of p-value p_{time} and the overall p-value are reported. No significant excess is observed.

5.6 Low energy events

Two samples were considered in the low energy range. The first sample is obtained via the solar neutrino selection (hereafter referred to as the solar sample) with energies ranging from 6 to 8 MeV.

The second sample is obtained via DSNB selection (hereafter referred to as the DSNB sample), with energies ranging from 8 to 16 MeV. The results presented here refer to a sample without neutron tagging applied. The reason behind this was to explore a broader range of events, although the results obtained are valid even if n-tagging is applied.

Both selection methods have been extensively described in Section 4.9.2.

In the low energy range, there are more sources of background compared to the high energy range, causing greater fluctuation in the background rate. Therefore, we evaluated the expected number of events in each time window by averaging the event rate over the week surrounding the trigger time t_0 , excluding the specific time window in question. Results using the solar sample are reported in Table 5.3, listing only those events where $N_{OBS} > N_{EXP}$. Although some excesses were observed, none were significant.

Results using the DSNB sample are shown in Table 5.4, also restricted to cases where $N_{OBS} > N_{EXP}$. In this case, we observed an event, S230924an, which showed an interesting p-value. To further analyze this event, we calculated the false positive rate expected given the background and the observed event. The false positive rate was calculated using a toy Monte Carlo in which we accounted how many times fluctuations of backgrounds expected for that event would give a detection significance greater than 3 sigma in a

century. After correcting the p-value to account for this false positive rate, the event was determined not significant ($p_{post} = 0.23$).

GW event	GW TYPE	BKG EXP	N OBS	p_{time}
S230814ah	BBH (100.0%)	9.34E-01	3	0.07
S230731an	BBH (81.4%)	9.73E-01	3	0.08
S230904n	BBH (91.1%)	1.02E+00	3	0.08
S230924an	BBH (100.0%)	8.71E-01	2	0.22
S230807f	BBH (86.4%)	9.50E-01	2	0.25
S230726a	BBH (100.0%)	9.80E-01	2	0.26
S230702an	BBH (100.0%)	1.01E+00	2	0.27
S230723ac	BBH (86.7%)	1.01E+00	2	0.27
S230628ax	BBH (100.0%)	1.01E+00	2	0.27
S230601bf	BBH (100.0%)	1.07E+00	2	0.29
S230529ay	NSBH (62.4%)	1.09E+00	2	0.30

Table 5.3: Number of expected and observed events of solar samples ($6MeV < E < 8MeV$) in coincident with GW from the O4a reduced catalog. Only GW events with $N_{OBS} > N_{EXP}$ are shown. In the last column, the significance of temporal correlation, p_{time} , between the GW and the neutrinos is reported. No significant excess is observed.

GW event	GW TYPE	BKG EXP	N OBS	P_{time}
S230924an	BBH (98.6%)	1.27E-01	2	0.007
S230729z	BBH (99.7%)	1.25E-01	1	0.118
S230822bm	BBH (98.1%)	1.47E-01	1	0.137

Table 5.4: Number of expected and observed events of DSNB samples ($E > 8MeV$) in coincident with GW from the O4a reduced catalog. In the last column, the significance of temporal correlation, p_{time} , between the GW and the neutrinos is reported. No significant excess is observed.

5.7 Flux limits

Given the absence of a statistically significant excess of events within each chosen time window, this result can be used to establish an upper limit on the incoming neutrino flux. Preliminary results for FC, PC and solar samples are discussed in the following, while the results for UPMU and DSNB samples are yet to be released.

For the HE samples, the calculation has been performed separately for FC, PC and a combination of both (FC+PC), assuming a power law spectrum for the neutrino flux:

$$\frac{dN}{dE} = \phi_0 \times E^{-\gamma} \quad (5.8)$$

with $\gamma = 2$, a typical value assumed for astrophysical neutrino sources.

Limits have been calculated for $\nu_{tot} = \Sigma_f \nu_f + \bar{\nu}_f$, where the sum is intended on all neutrino flavors.

For a given sample k , flavor f and source position Ω_S , the expected number of neutrinos to be detected is related to the incoming neutrino flux dN/dE via:

$$N_{sig} = \phi_0^{(k,f)} \times \int A_{eff}^{(k,f)}(E_\nu, \Omega) \times E_\nu^{-2} dE_\nu \quad (5.9)$$

$$= \phi_0^{(k,f)} \times c^{(k,f)}(\Omega) \quad (5.10)$$

where $c^{(k,f)}(\Omega)$ is the detector acceptance, which takes into account the detector effective area for the selected sample at a given direction and the neutrino energy spectrum. The convolution of two terms was integrated in the energy $[0.1 - 10^5] \text{ GeV}$. The effective area was taken from [200] and

was estimated using Monte Carlo simulations. For Super-Kamiokande, the biggest available sample is the standard atmospheric MC, corresponding to 500-years-equivalent. In the analysis, the SK-IV Monte-Carlo sample is used. Given that the location of the GW is expressed in terms of a probability sky map, instead of computing flux limits for each direction of the sky, the direction is marginalized by defining the following flux likelihood:

$$\mathcal{L}^{(k,f)}(\phi_0; n_B^{(k)}, N^{(k)}) = \int \frac{c^{(k,f)}(\Omega) \times \phi_0 + n_B^{(k)} N^{(k)}}{N^{(k)}!} e^{-(c^{(k,f)}(\Omega) \times \phi_0 + n_B^{(k)} N^{(k)})} P_{GW}(\Omega) d\Omega \quad (5.11)$$

The 90% confidence level (C.L.) upper limits are derived by computing the likelihood as a function of ϕ_0 and finding the 90% percentile, for each sample and flavor:

$$\frac{\int_0^{\phi_0^{90\%}} \mathcal{L}^{(k,f)}(\phi_0; n_B^{(k)}, N^{(k)}) d\phi_0}{\int_0^{\text{inf}} \mathcal{L}^{(k,f)}(\phi_0; n_B^{(k)}, N^{(k)}) d\phi_0} = 0.90 \quad (5.12)$$

In order to combine different samples (which are characterized by different sensitivities), a different approach has been adopted which implements the test statistic previously defined (Eq. 5.6) [205].

A pdf $P_{n_s}(TS)$ was computed based on signal simulations that assume the same energy spectrum and that at most two signal neutrinos are detected in SK; the source direction has been chosen randomly based on GW sky map P_{GW} and the distribution of signal toy events between the samples is done according to the relative effective areas. The likelihood has been accordingly

changed as follows:

$$\mathcal{L}(\phi_0; TS_{\text{data}}, P_{GW}) = \int \sum_{k=0}^2 \left[\frac{(c(\Omega)\phi_0)^k}{k} \exp(-c(\Omega)\phi_0) P_k(TS_{\text{data}}) \right] \times P_{GW}(\Omega) d\Omega \quad (5.13)$$

The 90% C.L. flux upper limits are then obtained as previously described. The resulting flux upper limits for HE-samples are shown in Fig. 5.2. The obtained values are in the range $[10^3, 10^4] \text{ GeV cm}^{-2}$ and are consistent with the limits obtained in [200]. Limits on combined samples agree mainly with the most stringent samples between the two. The detected flux limits obtained are of course strictly related to the detector performances, in particular the effective area. However, the true physical quantity is rather the total energy emitted in neutrinos from the source. To evaluate this quantity, it's fundamental to know the flux limit, since it can be evaluated as (assuming a perfect known distance r and an isotropic emission):

$$\begin{aligned} \frac{E_{\text{iso}}}{4\pi r^2} &= \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{dn_{\text{tot}}}{dE} E dE \\ &= \phi_{0,\text{tot}} \int_{E_{\text{min}}}^{E_{\text{max}}} E^{-2} E dE \end{aligned} \quad (5.14)$$

Results about the limit on the isotropic energy emitted at the source are yet to be officialised, thus are not included in this thesis.

Given that no spatial information can be inferred from the low-energy samples, only fluence limit were calculated. This has been performed separately for each neutrino flavor and using only the solar sample. The upper

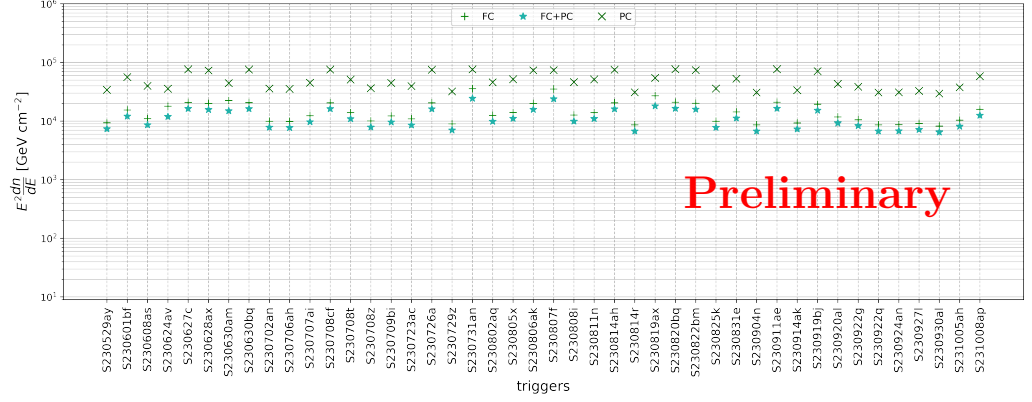


Figure 5.2: 90% C.L. upper limits on $E2dn/dE$ for all neutrino flavors and for the different GW triggers. Only FC, PC and FC+PC samples are considered. A E^{-2} flux is assumed.

limit on the total fluence ($\Phi = \int dn/dEdE$) is computed as:

$$\Phi_{90} = \frac{N_{90}}{N_T \int \lambda(E_\nu) \sigma(E_\nu R(E_e, E_{vis})) \epsilon(E_{vis}) dE_\nu} \quad (5.15)$$

where N_{90} is the 90% C.L. upper limit on the number of signal events (calculated from a Poisson distribution), N_T is the number of target nuclei in SK fiducial volume, σ is the combined cross section for all interactions, ϵ is the detection efficiency, λ is the energy density assuming a given spectrum ($dn/dE_\nu = \phi \times \lambda(E)$) and R is the response function to convert electron or positron energy (E_e) to visible energy in SK (E_{vis}).

Two spectra shapes have been considered: a flat spectrum and a Fermi-Dirac spectrum peaked at 20 MeV. Results are shown in Fig. 5.3. The fluence limits are in the range $[10^7, 10^{11}] cm^{-2}$, similar to the previous results in [200], and are most stringent for $\bar{\nu}_e$, since that the main interaction channel in this energy range is IBD.

Although these limits don't constrain directly physical quantities, they can be a basis to constrain parameters like the intrinsic energy emitted by neutrinos and to perform population constraints [200].

The complete analysis, incorporating a more comprehensive statistical treatment to impose meaningful physical constraints, will be conducted once the official GW-O4 catalog (which will provide a full characterization of the GW events, including details such as the masses of the two objects) will be released.

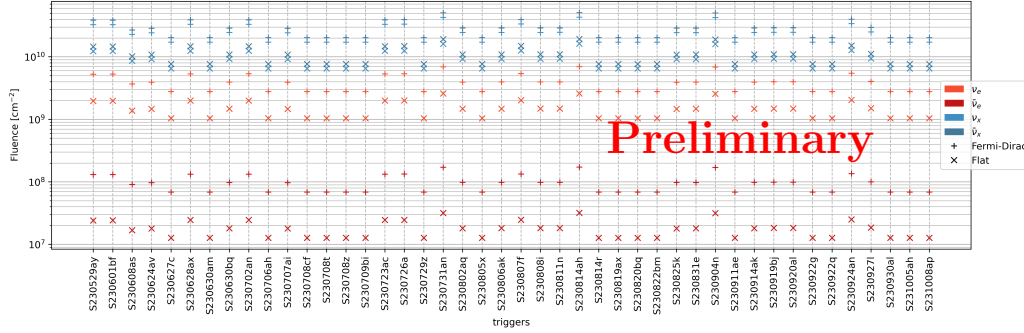


Figure 5.3: 90% C.L. upper limits on the total neutrino fluence [in cm^{-2}] using the solar sample for $\nu_e, \bar{\nu}_e, \nu_x = \nu_\mu + \nu_\tau, \bar{\nu}_x = \bar{\nu}_\mu + \bar{\nu}_\tau$ assuming a Fermi-Dirac spectrum and a flat spectrum.

Chapter 6

An online follow-up system for gravitational waves in Super-Kamiokande

6.1 Introduction

Real-time alert systems are nowadays a fundamental key in the multi-messenger context (see Section [2.4](#)).

Super-Kamiokande currently has two alert systems installed aimed at supernova detection, given the high sensitivity of the detector in the supernova neutrinos energy range.

The first one is the Real-Time Supernova Neutrino Burst Monitor [\[27\]](#), which is a monitor that looks for neutrino bursts from supernovae and is able to provide a fast warning to the world within one hour, via external alert system like SNEWS and GCN.

The second one is the Pre-Supernova Neutrino Alert System [182], which can give early alerts of incipient core-collapse supernovae through the detection of electron anti-neutrinos from thermal and nuclear processes responsible for the cooling of massive stars before the gravitational collapse of their cores (i.e. during the silicon burning phase). Recently, this alert system has been extended, combining both Super-Kamiokande and KamLAND detectors [206]. When it comes to BNS mergers, similar mechanisms are expected to produce a high flux of MeV neutrinos. But, as we have seen in Section 2.3.3, given the average distances at which these catastrophic events are detected, the expected flux of neutrinos at Earth is very small, making almost impossible to observe an excess of neutrinos and linked it to a neutron star merger. This difficulty can be overcome by the combination with other messengers, primary gravitational waves.

In fact, since gravitational waves are expected to be the first messenger to be detected, they can serve as alerts for other messengers. Observing an excess of neutrinos in coincidence with a gravitational wave event, both temporally and spatially, can significantly enhance the detection's significance.

In the previous chapter, we discussed about the results of an offline follow-up analysis of neutrinos in coincidence with gravitational waves. Although combining observations of neutrinos and gravitational waves, either offline or online, can lead to more detailed models of astrophysical phenomena, considerable efforts are now focused on developing a system for real-time coincidence analysis in Super-Kamiokande. The main reason behind this is that a real-time follow-up system would help pinpoint the location of the event and potentially serve as a trigger for other experiments (Super-Kamiokande

can reach an angular resolution as low as $\sim 3^\circ$ for UPMU tracks).

This chapter will provide a description of this real-time GW follow-up system under development.

6.2 State of art

An automatic follow-up system already exists in Super-Kamiokande. It runs following the methodology outlined in Chapter 5.

The system is located in the same machine where SK keeps data for the usual analyses (indicated as "Disk" in Fig. 4.3). This means that, in order to start the follow-up analysis, data must have been first fully transferred, reduced, and reconstructed. This induces a certain latency (up to many hours) which doesn't allow for a rapid follow-up.

The system's fundamental structure can be outlined as follows:

- A receiver of GCN Notice is implemented by using the python library `GCN[207]` and is always listening for new alerts. A GW notice message is received as the VOEvent format written in XML, and we can extract several information from the message such as event ID, trigger time, classification of the event, the type of the alert, and links to the web page and Fits file (containing the GW probability sky map) of the event in GraceDB.
- The extracted information of the event are filled out into a data base written with a CSV format, and the original VOEvent message is also

saved into a single file.

- The newly added item to the database initiates the search for relevant data in Super-Kamiokande. It triggers a parallel analysis of both the low- and high-energy samples, enabling simultaneous investigations of neutrino events across different energy ranges. When a new alert is received, the first step is to check whether SK was running in normal mode in the chosen time window ($LIVETIME > 0$) and if so, a comparison is made between the expected background and the number of events detected. The time window used so far is the same considered in the previous chapter, i.e. ± 500 s around the GW arrival time. If an excess is observed, the significance of the observation is calculated, otherwise only flux limits are computed.

The analysis steps carried out are illustrated in Figure 6.1. This system has been used until the end of O3 run and the full results of the follow-up analysis have been presented in [200].

When O4 run started, Super-Kamiokande was in a new phase (SK-VII). As a consequence, in order to restart the automatic pipeline, the initial steps focused on adapting the alert receiver and data handling processes to align with the requirements of this new SK phase. Additionally, to enable the use of fully reconstructed data while allowing for a real-time analysis, improvements are being tested to expedite the process, particularly for high-energy neutrino analysis.

For the low-energy range, a new, faster system has been proposed in this work, which will be described in the following section.

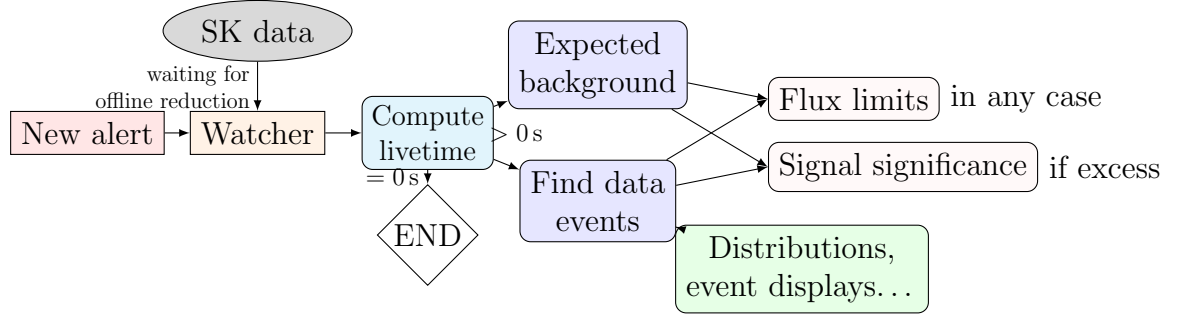


Figure 6.1: Overview of the follow-up analysis system in Super-Kamiokande.

6.3 Real-time follow-up system in WIT

To improve the pipeline’s performance, the initial step is to identify methods for reducing the analysis computation time.

For the low-energy analysis, a project to implement the online system on a WIT machine (Section 4.5.1) is under development and will be described in the following.

First of all, installing the pipeline on WIT means having the system running in one of the WIT’s online machines, right after the data acquisition and fast online reconstruction is performed, thus reducing the delay time needed to access data after a GW alert is received.

Moreover, to reduce the analysis time and to increase the significance, models concerning the emission of low-energy neutrinos from BNS mergers have been considered (see Section 2.3.3). All models considered expect that a strong emission of thermal neutrinos is produced during the merger and during the short lifetime of the remnant, before it turns into a black hole [91]. Several simulation studies performed, like the one shown in Fig. 6.2 demonstrate that the expected MeV neutrino emission and the emission of gravitational

waves are almost simultaneous, within a time range between hundreds of milliseconds and few seconds. Although the neutrino emission could last longer, based on the livetime of the remnant, the luminosity still reaches its peak during the merger itself. Moreover, one can evaluate the upper limit of the time-of-flight difference between GW and neutrinos as [208]:

$$\Delta T_{flight} < D_{max} \left(\frac{1}{v_\nu} - \frac{1}{c} \right) = \frac{D_{max}}{c} \left(\sqrt{1 + \frac{m_\nu^2 c^4}{p_\nu^2 c^2}} - 1 \right) \approx \frac{1}{2} \frac{D_{max}}{c} \frac{m_\nu^2 c^4}{E_\nu^2} \quad (6.1)$$

where D_{max} is the distance of the farthest GW source detected and v_ν, m_ν, p_ν and E_ν are respectively the velocity, mass, momentum and energy of the neutrino. If we consider the most distant source detected during O4 and the most recent constraint on neutrino mass [17], this give us:

$$\Delta T_{flight} < 5 \text{ s} \quad (6.2)$$

This led us to consider a time window for coincidence searches in the low-energy range that is shorter than the one previously considered (in Chapter 5 we considered $\pm 500s$ around the GW arrival time t_0). This adjustment significantly impacts data processing, given the higher background in low-energy samples.

Moreover, improvements are also expected in terms of angular resolution in the low-energy range thanks to the presence of gadolinium in the detector (which was not included in the original alert system). The latter can enhance the angular resolution for low-energy neutrinos by tagging neutrinos from IBD interactions, which do not provide directional information, allow-

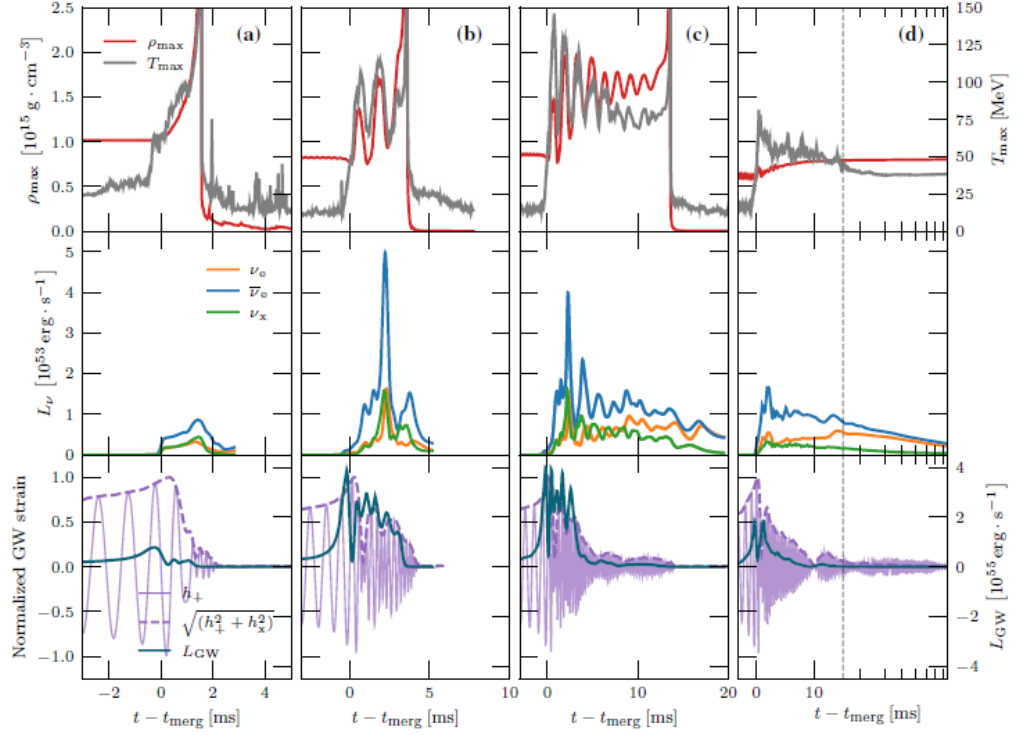


Figure 6.2: Evolution of the maximum density and temperature (top panels), and neutrino luminosity for the three neutrino species (middle panels) and normalised GW strain and GW luminosity (bottom panels), for four models simulated in [91]. (a) prompt collapse of the remnant into a black hole; (b) very short lived remnant; (c) delayed collapse of the remnant; (d) long lived remnant, i.e. the simulation never reached the black hole formation. Image taken from [91].

ing for better use of directional information from neutrinos produced via ES interactions (whose angular resolution depends on the number of detected events as $\Delta\theta \approx 25^\circ/\sqrt{N}$).

6.3.1 System architecture

The scheme of the online follow-up system for WIT is shown in Fig. 6.3 and can be summarized as follows:

- When the general GCN receiver finds a new alert, it sends the information to the WIT machine allowing to start the follow-up analysis;
- First, given the GW arrival time t_0 we apply a time cut, selecting WIT data that falls into $[t_0 - a, t_0 + b]$. So far, only symmetrical window have been tested ($a = b$). Several time windows have been tested, where the most stringent assumed $a = b = 6$ s;
- A pre-selection is applied to further reduce the dimension of the data to be analyzed;
- Data are then reconstructed.
- Two parallel processes apply different reduction on data;
 - The first selection aim to detect ν_e using the standard solar selection;
 - The second one aim to detect $\bar{\nu}_e$ via DSNB selection with Gd;
- Finally, a check for any excess is performed by comparing the number of events that pass all stages of reduction with the expected background in that time window. A smart and efficient system has been developed for storing only necessary information and using less memory as possible.

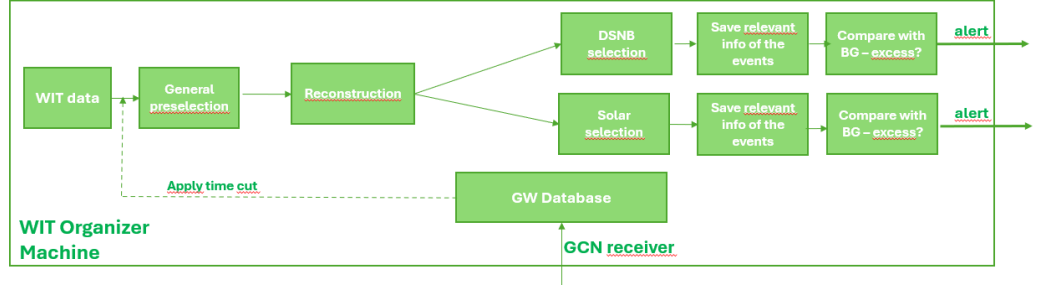


Figure 6.3: Scheme of the online follow-up system using WIT data developed for this PhD project.

The system is currently under development. The pipeline has been automated and testing is ongoing using fake GW alerts to evaluate the performance of the system with real WIT data. All the initial tests have shown that the system is behaving as expected, selecting the data inside the correct time interval in respect to the GW event and performing dedicated reduction and reconstruction in real-time. The analysis methods similar to what was performed on LE samples in Chapter 5 are being implemented.

Adding both selections can potentially lead to significant improvements in direction reconstruction. Specifically, neutron tagging using gadolinium allows for the precise identification of electron anti-neutrinos via IBD. As previously discussed, it's not possible to directly reconstruct the incoming neutrino direction from IBD events. However, if an excess of events is observed and IBD events are identified, the remaining non-IBD events can be used to reconstruct the neutrino direction, thereby improving the angular resolution for low-energy neutrinos.

As an example, Table 6.1 shows the estimated latency time of each step after initial tests of the online follow-up system in the case where only solar selection is applied on data.

Table 6.1: Estimated latency time of each step after initial tests of the online follow-up system in WIT. A 12 s time cut centered on the GW arrival time is applied. Total latency time is the sum of the latency of each step.

Process	Estimated Time
GW Alert Latency	up to 10 mins
Time Window Cut + Pre-selection (on a 90 s subrun file)	1 min
Reconstruction	40 s
Solar selection	0.13 s

6.3.2 Pre-selection

To further reduce the reconstruction time, a potential pre-selection on data has been investigated.

When applying solar and DSNB selections, several cuts are commonly used for both. These are preliminary cuts mainly related to the quality of data or to reduce common background (in particular the fiducial volume cut). As already discussed in Section 4.9.2, for low energy events, the event vertex is reconstructed using the BONSAI fitter which performs a likelihood fit on the residual times of the hits. In WIT, a first fast BONSAI reconstruction is performed in the online machine yielding variables like the interaction vertex, the direction, the arrival time, and the quality of data (in terms of goodness of the fit).

Typically, quality and fiducial volume cuts are applied to the fully reconstructed variables (in the offline machine), which may slightly differ from those obtained in the fast reconstruction. Therefore, the first step was to examine the correlation between these two sets of variables.

In the following, we will refer to the output of the fast reconstruction as "online variables," while the fully reconstructed variables will be referred to

as "offline variables".

Fig. 6.4 shows the correlation between the online and offline variables. We also introduced a new online variable, indicated as FROMWALL which represents the vertex's distance from the detector wall and is calculated using the online vertex coordinate BSX, BSY, BSZ. The correlation plot shows a strong correlation between FROMWALL and BSWALL, as expected since BSWALL has the same definition of FROMWALL but uses the offline vertex coordinates BS_REC_X, BS_REC_Y, BS_REC_Z. Thus we opted to use the same cut but using FROMWALL variable ($\text{FROMWALL} > 200$ cm), i.e. using only events whose online reconstructed vertex is at least at 2 m from the detector's walls.

Similarly, there's a correlation between the online variable BGOODNESS and the offline variables BS_GOOD and BS_OVAQ. Both these variables are commonly used for data quality (DQ) check in solar and DSNB analysis.

By considering the standard DQ cuts employed in low-energy analyses on BS_GOOD and BS_OVAQ, we tested several cut values on BGOODNESS aiming to find a good balance between data reduction and maintaining data quality. This resulted in an optimal cut of $\text{BGOODNESS} > 0.4$.

The combination of fiducial volume and DQ cuts reduced the data size by at least 45%, resulting in a reconstruction time that is only a quarter of the time required for processing the entire dataset.

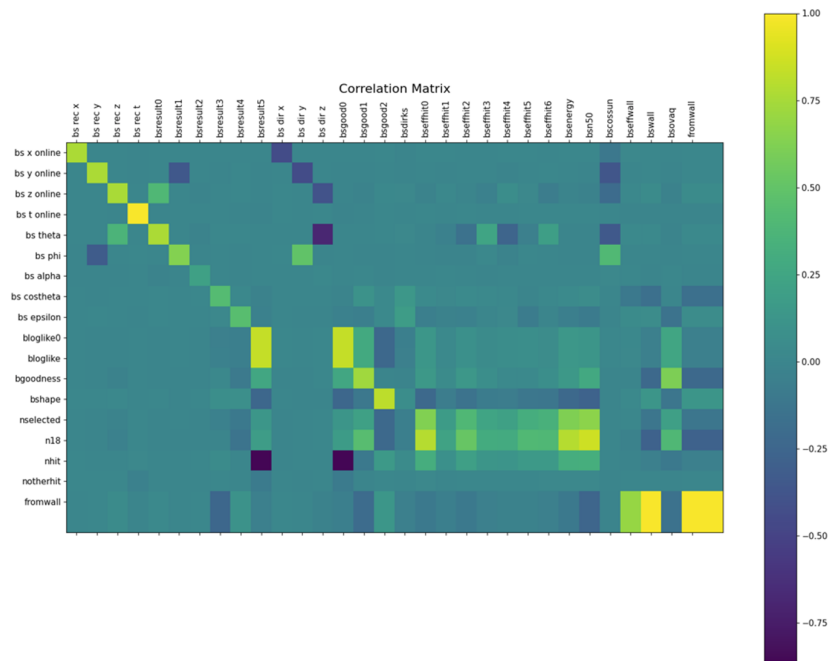


Figure 6.4: Correlation matrix between fast reconstructed variables in the online WIT machine and fully reconstructed variables.

6.4 Prospects

By the time of writing, the full online pipeline for GW follow-up analysis is under development. The final system will operate across multiple machines, enabling the initiation of simultaneous searches on SK data across the entire energy range.

The main goal of this work was to enable a fast search of low energy events in Super-Kamiokande, given a certain GW alert. This was achieved through several key improvements. First, a new low-energy trigger, WIT, was integrated. Though not part of the previous alert system, WIT is a promising trigger for neutrino astronomy and is already utilized in the pre-SN alert system. This integration supports fast data reconstruction, significantly reducing computation time. As stated before, the framework for the real-time system in WIT has been developed and is currently under test. Analysis methods already adopted in Chapter 5 will be used. Other important improvements are the adoption of a time window optimized for the expected emission of MeV neutrinos during BNS mergers rather than focusing solely on high-energy emission, and the application of efficient data filtering to reduce the analysis time.

For high-energy neutrino analysis, improvements are underway to expedite the process, while maintaining the same time window (± 500 seconds around t_{GW}) based on GRB, GW and HEN emission models [203].

One important feature of the proposed system is its versatility. Since the only constraint arising from model assumptions is the chosen time window, it can be easily adapted to other multi-messenger transient sources, such as

GRBs and novae, thereby expanding the potential for multi-messenger discoveries.

Chapter 7

Prospects for neutrino astronomy in Hyper-Kamiokande

Hyper-Kamiokande (Hyper-K, HK)[\[22\]](#) is the next generation of large water Cherenkov neutrino detector with a wide range of scientific goals, such as the observation of atmospheric, solar and accelerator neutrino oscillations, neutrino astrophysics, proton decay and physics beyond the Standard Model. Its primary objective will be the measurement of CP violation in the leptonic sector. To do so, the Hyper-Kamiokande project will comprehend both the neutrino beam system at J-PARC, which represents an upgrade of the T2K experiment with a higher intensity neutrino beam and updated near detectors, and the water Cherenkov detector located in Kamioka which will act as Far Detector (FD). Moreover, a new detector, known as Intermediate Water Cherenkov Detector (IWCD), will be constructed between the near detectors

and the far detector.

In the following, due to the primary focus on neutrino astrophysics of this thesis, we will refer to Hyper-K exclusively in relation to its FD structure.

Hyper-K will be characterized by a fiducial volume which will be approximately 8 times larger than its precursor Super-Kamiokande, an increased statistics and an improved photo-sensors for better efficiency.

With its large fiducial volume, capacity to gather high-statistics data over extended periods, and a planned operational duration of at least 20 years, Hyper-Kamiokande has strong potential for making substantial discoveries in neutrino astronomy.

In this chapter, a description of the experiment will be provided, along with an overview of the prospects for implementing a similar real-time system for follow-up searches.

7.1 Upgrade to the Beam-line and the Near Detector

The Hyper-K experiment will make use of the J-PARC accelerator complex, which will provide a 1.3 MW power proton beam with a beam energy of 30 GeV from the J-PARC Main Ring synchrotron. The J-PARC accelerators are a facility maintained by the host laboratories, J-PARC and KEK. The proton beam is extracted to the neutrino beam line, which will be upgraded by Hyper-K from the current beam line used by T2K to allow operation up to 1.3 MW beam power [209]. The neutrino beam line is broken into the

7.1. UPGRADE TO THE BEAM-LINE AND THE NEAR DETECTOR

primary beam line, which transports the proton beam from the main ring to the target hall, and focuses the proton beam spot on the target, and the secondary beam line, which includes the production target, magnetic horns decay volume and beam dump. Both the primary and secondary beam lines include beam monitors, INGRID [210] and MUMON [211]. To achieve operation at 1.3 MW beam power, upgrades to both the primary and secondary beam lines have been pursued. These include new high intensity beam monitors, remote maintenance systems in the final focus section of the primary beam line, upgrades to the target station beam window, upgrades to the target and horn cooling, and upgrades to the radioactive cooling water disposal system. So far, a 800 kW beam power has already been obtained thanks to the upgrades completed in the horn currents (going from 250 kA to 320 kA) and RF system.

An improvement in data analysis is also expected. T2K demonstrated in its publications about ν_e appearance that aspects of the data analysis such π_0 rejection can be improved [212]. Other improvements to the data analysis technique are under development, including ν_e detection efficiency, precision of the vertex determination (which could allow for an increased fiducial volume), and an improvement in π/μ separation.

Hyper-K plans a suite of near and intermediate detectors measuring the neutrino beam at 280 m and 1000 m after production to address all systematic effects that are critical for the Hyper-K physics program and to measure the neutrino fluxes and interaction cross sections.

Hyper-K will use the INGRID on-axis detector to monitor the neutrino beam direction with better than 0.3 mrad precision and to monitor the neutrino

interaction rate. It is expected that minimal upgrades to INGRID is needed to keep it operational during Hyper-K.

ND280 detector [213] is used to study exclusive final states, including reconstruction of the hadronic recoil system. ND280 also measures the charge of final state lepton, providing a measurement of the wrong-sign component of the beam. Upgrades of ND280 to improve the angular acceptance and the reconstruction of the hadronic recoil system are being carried out by T2K [214]. It is expected that Hyper-K may need to make additional upgrades of ND280, both for improved longevity and for improved physics output. The extent of upgrades needed for Hyper-K will depend on the scope and performance of the upgrades carried out by T2K.

7.2 The Intermediate Water Cherenkov Detector (IWCD)

An Intermediate Water Cherenkov Detector with off-axis spanning and Gd loading capabilities, placed at 1 km from the J-PARC beam line, will be installed to measure the intrinsic ν_e and $\bar{\nu}_e$ backgrounds, the $\sigma_{\nu_e}/\sigma_{\nu_\mu}$ and $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$ cross section ratios, the neutrino energy vs. final state and neutron multiplicities. In particular, for the $\sigma_{\nu_e}/\sigma_{\nu_\mu}$ and $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$ cross section ratios, the goal is to reach a 2.7% with same detection principal (CC-QE) as in the Hyper-K Far detector. These measurements will be used to predict the expected event rates in Hyper-K as a function of the oscillation parameters and to measure the properties of neutrino interactions to reduce systematic

7.2. THE INTERMEDIATE WATER CHERENKOV DETECTOR (IWCD)

errors related to neutrino cross section uncertainty. The detector provides an identical nuclear target to Hyper-K with no need for subtraction analyses. It also naturally provides 4π angular coverage, although the momentum coverage is limited by the detector size.

The detector size is large enough to contain neutrons, and with Gd loading, the detector can be used to study the neutron multiplicities in neutrino and antineutrino interactions with different observed final states.

The design of the IWCD includes the capability to make measurements at different off-axis angles by moving the instrumented detector vertically. This capability will allow the detector to probe the relationship between neutrino energy and final state particle multiplicities and kinematics. Ideally, mono-energetic neutrino beams would allow the final state charged lepton kinematic distributions to be measured for each energy, including all of the nuclear effects contributing to the event distributions. Narrow energy beams can be with the off-axis spanning detector by using measurements at different off-axis angles to subtract the contributions from low-energy and high-energy tails in the neutrino spectra. The conceptual design foresees that the vertical shaft will be filled with water to a few meters above the position of the instrumented detector region allowing for shielding. The instrumented detector is placed in a water-tight stainless steel tank to allow for primary containment when the detector is loaded with Gd. The detector diameter is 10 m. An outer detector region of 1 m gives an inner detector diameter of 8 m. With a such inner detector diameter the detector has high efficiency to contain muons up to 1 GeV/c. The 8 m diameter also allows for the containment of most neutrons produced in neutrino interactions at the center of the

tank. The energy range of interest for the near detector physics measurements spans from ~ 8 MeV for the neutron capture events on Gadolinium, up to ~ 2 GeV for the higher energy contained muons from beam interactions, which peak at ~ 0.6 GeV, requiring calibration over a large dynamic range. The IWCD baseline design is equipped with multi-PMT module (mPMT) as photo-detection system, which will be described in the following.

7.3 The Hyper-K Far Detector

Hyper-K FD site will be located about 1 km south of the Super-K site and at the same off-axis angle. The construction started in May 2021 while the data taking will start in 2027.

A schematic view of Hyper-K is shown in Fig. 7.1. It will consist of a tank with a cylindrical shape characterized by a total mass of 258 kton and a fiducial mass of 187 kton [22]. The detector mass is one of the key detector parameters that determines the event statistics in neutrino observations and nucleon decay searches. We need a detector mass of at least $O(10^2)$ kton in order to accumulate $O(10^3)$ electron neutrino signal events from the J-PARC neutrino beam, necessary to measure the CP violation effect with a few % accuracy. This mass of water contains $O(10^{35})$ nucleons which would give an unprecedented sensitivity to nucleon lifetime at the level of 10^{35} years.

The detector will be filled with highly transparent purified water. A light attenuation length above 100 m can be achieved which would allow to detect a large fraction of the emitted Cherenkov light around the periphery of the water volume. Radon concentration in the supplied water will be kept

below 1 mBq/m^3 to control the radioactive background event rate in solar neutrino and other low energy observation. An option being investigated is the Gd-doping of the water.

The detector will be instrumented with an array of sensors with single-photon sensitivity in order to enable reconstruction of the spatial and timing distributions of the Cherenkov photons. Similarly to its predecessor, its structure will be divided in an Inner Detector (ID) and Outer Detector (OD). The ID will be observed by 20000 20" Hamamatsu Photonics R12860-HQE PMT and about 800 multi-PMTs. The OD will acts mainly as veto for entering particles and will be monitored by thousands of 3" PMTs photosensors. The final decision on the OD PMTs is yet to be made. The dimension of the photo-sensors and their density have been subject to an optimization taking into account the required signal identification efficiencies, background rejection power, and cost.

With the current design, the OD has a thickness of 1 m (barrel) and 2 m (end cap), and there is a dead region of 60 cm between the OD and ID photosensors, determined by the size of the ID covers. The inner and outer walls of the OD are covered with reflecting materials to increase the photon collection efficiency.

7.4 20" PMTs

Hyper-K will be equipped with 20,000 Hamamatsu 20" R12860-HQE PMTs (also referred as B&L PMTs, see Fig. 7.2), developed specifically for Hyper-K requirements.

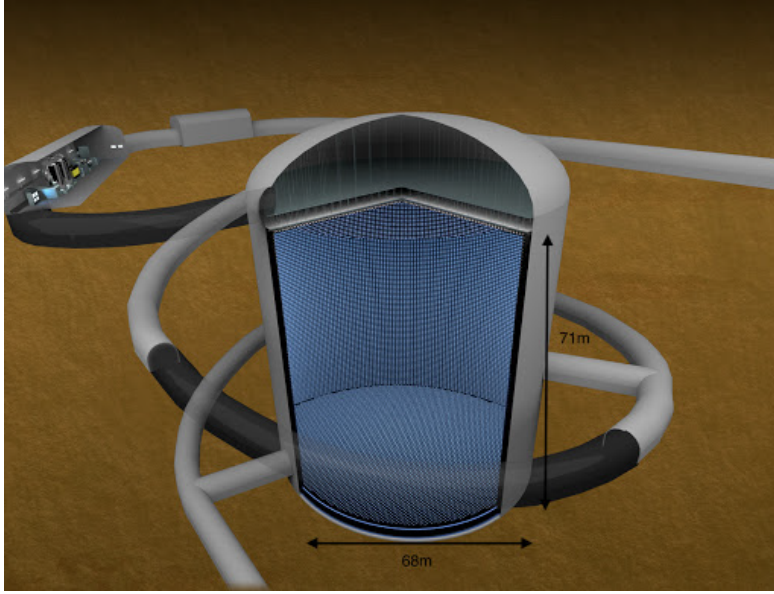


Figure 7.1: A schematic view of Hyper-Kamiokande.

This represents a significant advance over the Hamamatsu R3600 PMTs used in Super-K, offering faster time response, improved charge resolution, and greater detection efficiency with a more consistent response across the detection area.

Two major upgrades include the shift in dynode configuration from Venetian blind to box-and-line (B&L), and an increase in quantum efficiency, which peaks at 30%, compared to 22% in the previous SK PMTs. The box-and-line dynode offers a more uniform drift path for electrons, enhancing timing resolution and lowering the chances of electrons missing the first dynode. For single photo-electron events, the TTS has been reduced from 6.73 ns to 2.59 ns (see Fig. 7.4), while charge resolution has improved from 60.1% to 30.8% (see Fig. 7.3).

In the summer of 2018, Super-K underwent refurbishment to prepare for the SK-Gd project. During this process, malfunctioning ID PMTs were replaced



Figure 7.2: Hamamatsu 20" R12860-HQE PMTs.

with B&L PMTs. A total of 136 B&L PMTs were installed in Super-K. Their performance was assessed during the initial calibration campaign when data collection resumed, and the results confirmed the enhanced performance compared to the R3600 PMTs used in Super-K.

PMT cases will envelope each photo-sensors to avoid a potential chain reaction accident due to the implosion of a glass bulb in the water. Development of these covers is ongoing in Hyper-Kamiokande.

7.4.1 20" PMT Electronics

In Super-K, all electronics were located outside of the water, with five main electronics huts positioned on top of the tank. In contrast, in Hyper-K, the main front-end electronics will be housed underwater in watertight vessels, with only the DAQ and the initial portion of the timing system located on top of the tank.

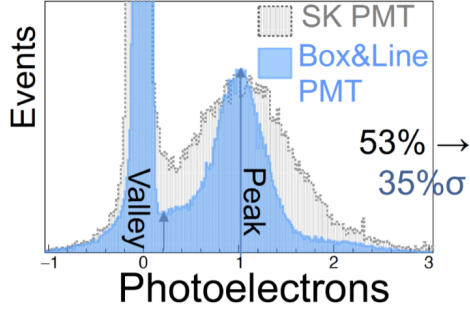


Figure 7.3: Comparison of the single photon distribution for the B&L PMT and the SK R3600 PMT.

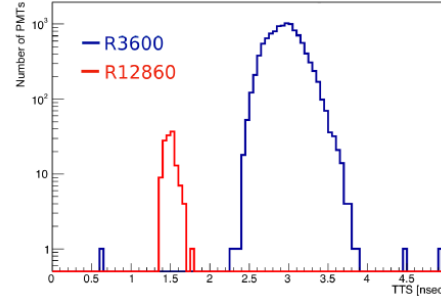


Figure 7.4: Comparison of the TTS between the B&L PMT and the SK R3600 PMT.

The electronics system in Hyper-K is designed to collect the charge and arrival time of signals from each PMT, with all channels synchronized to enable event detection. To manage and power 20,000 20" PMTs, approximately 900 electronics vessels will be installed within the detector, divided into two types: a pure-ID type and a hybrid ID+OD type.

In the pure-ID configuration, 24 individual 20" PMTs connect to an electronics unit through ~ 20 m cables, with each unit located underwater. These units provide high voltage to the PMTs, digitize signals independently, and send the data to the surface DAQ system via optical cables up to 150 m long. This setup shortens the distance between PMTs and front-end electronics, reducing signal attenuation, lowering thresholds, and enabling a lighter, more cost-effective detector structure. However, long-term reliability is essential since the electronics will be inaccessible during operations, with the goal being no more than 10% dead acquisition channels after ten years. Approximately 560 pure-ID units will manage the ID PMT. The hybrid ID+OD unit will instead operate twenty 20" PMTs and also 12 3" PMTs for the OD. In

total about 320 hybrid units will operate a fraction of the ID 20" PMTs and all the OD 3" PMTs.

7.5 The multi-PMT module

The multi-PMT (mPMT) module is a photo-detector system proposed firstly for the KM3NeT experiment [215] and proposed by INFN to the Hyper-Kamiokande Collaboration. The hardware functionality and physics capability of the mPMT concept have been demonstrated in-situ with the deployment and operation of KM3NeT prototypes in the Mediterranean sea. A newly design, optimized for Hyper-K's requirements, has been realized (see Fig. 7.5 for the final design). It consists of a cylindrical pressure-resistant vessel with 19 3" PMTs, full readout electronics and power supply inside.

The outer structure is composed of a POM-C cylinder closed on a side by a AISI-304 stainless steel back-plate while on top of it there's a transparent acrylic dome fixed through a clamping ring, still made of AISI-304 stainless steel.

The acrylic has been chosen based on optical and mechanical properties, water absorption and radioactivity contamination (which is the main background for low energy neutrino events). The final decision on acrylic was Plexigas GS UVT by Rohem Company.

Inside the vessel, the 19 PMTs are placed on a support structure that allows each photosensor to have a specific orientation inside the detector. Whilst the final solution for the support structure is still under decision, the best so far resulted to be a 3D printed structure, custom-made for the mPMT

requirements.

To avoid water penetration through the holes that host the PMTs, each PMT is equipped with a gasket.

The space between the PMT photo-cathodes and the acrylic dome is filled with an optical silicon gel (Silgel 612 by Wacker Company), which ensures optical and mechanical coupling.

To ensure a total effective area similar to that of the 20" PMT, the effective area of the 3" PMTs is enhanced through a reflector ring installed around each respective photocathode.

The electronics is fully contained inside the vessel with only one Ethernet cable which provides the power for the whole system, the clock and a transmission link to send data outside the detector.

The mPMT module is designed to occupy the same $70 \times 70 \text{ cm}^2$ footprint as the 20" PMT to aid integration within the Hyper-K photosensors support structure.

Fig. 7.6 shows a schematic of all mPMT components.

7.5.1 3-inch PMTs

An extensive measurements campaign has been performed within the Hyper-K Collaboration in order to identify the best candidate for the 3" PMT inside the mPMT. Several manufacturers like Hamamatsu Photonics K.K., ET Enterprises Ltd., MELZ FEU Ltd. and HZC Photonics Ltd. have been considered but most efforts have focused on the Hamamatsu R14374 and the HZC XP82B20. Measurements of the time resolution and charge resolution of



Figure 7.5: The final design of the mPMT prototype for Hyper-Kamiokande.

both PMTs and are showed in Figs. 7.7 and 7.8. While the charge resolution is similar to both PMTs, the time resolution of the Hamamatsu PMT is significantly better than the HZC PMT's one. Since the timing resolution should be significantly better than the 20" PMT's one (i.e. $< 2\text{ ns}$ for 1 p.e. at HV_{op}), the final decision was to adopt the Hamamatsu R14374.

An important parameter of these PMTs, particularly for low energy analysis, is the dark rate count, i.e. the amount of current that the PMT sees when there's no light source.

Dark rate must be as low as possible, in particular since, as we will discuss later, the PMT operates with a negative high voltage. This increases the likelihood of discharges on the PMT's bulb due to the potential difference between the photocathode and the surrounding environment and consequently an increase of the dark rate.

To mitigate the effects of this HV configuration, a coating has been applied to the PMT bulb, serving as insulation and preventing the formation of dis-

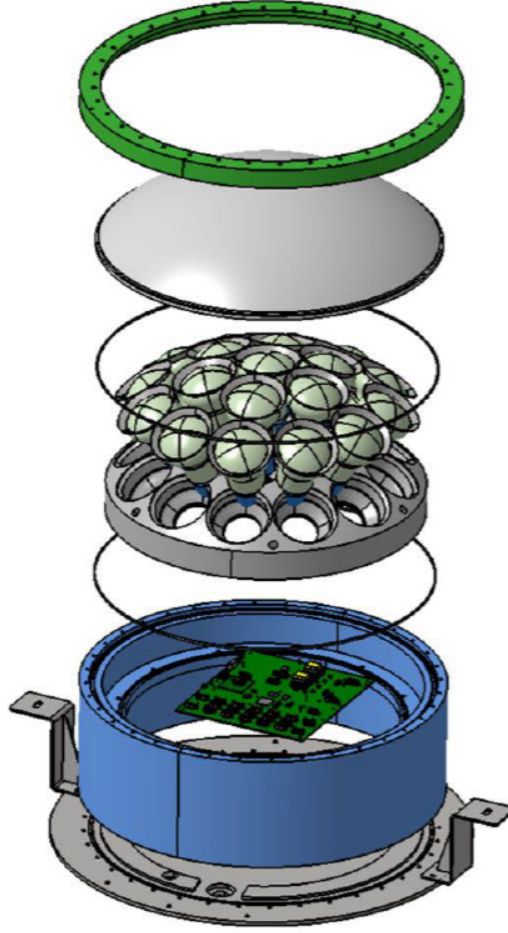


Figure 7.6: A schematic of the mPMT components.

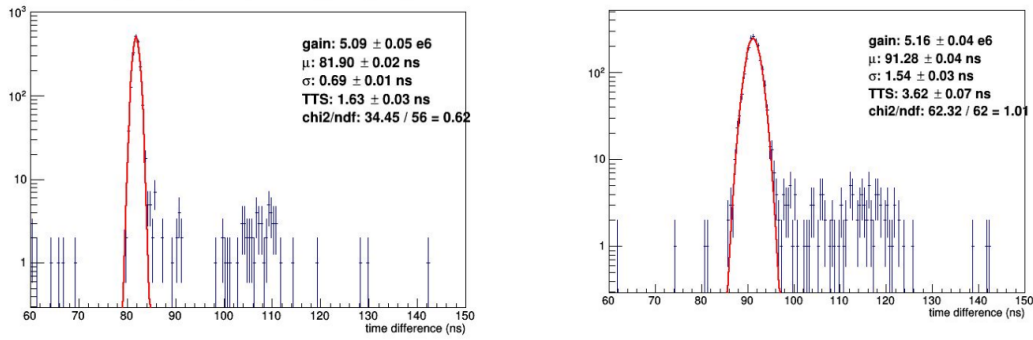


Figure 7.7: TTS of the Hamamatsu R14374 (left) and the HZC XP82B20 (right) with a gain of 5×10^6 .

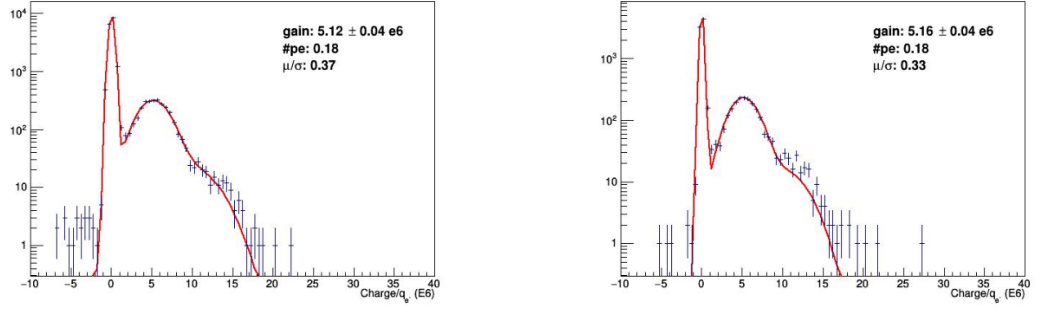


Figure 7.8: Charge resolution of the Hamamatsu R14374 (left) and the HZC XP82B20 (right) with a gain of 5×10^6 . for

charges. We have tested different coating solutions and the final decision was between two coatings: the first one is the HA-coating, i.e. the coating applied by Hamamatsu consisting of a conductive paint at the same potential of the photo-cathode and an insulant cover; the second one is the DCB, a specialist black opaque modified alkyd conformal coating specifically designed for the protection of electronic circuitry. Both coating solutions are showed in Figs. 7.9 and 7.10. By comparing the dark rate of three PMTs, one with DCB and two with HA-coating, operating under the same conditions, we observed that similar performances in terms of dark rate are achieved. Fig. 7.11 in particular show the dark rate as a function of the threshold for all PMTs tested. Since the DCB offers advantages in terms of assembly, as it allows simultaneous coating of both the PMT and the HV board at a lower cost, the final decision was to use the DCB.

7.5.2 mPMT Electronics

The Hyper-K mPMT electronics to be used for the FD shall conform to the following performance requirements:



Figure 7.9: HA-coating solution.



Figure 7.10: DCB coating solution.

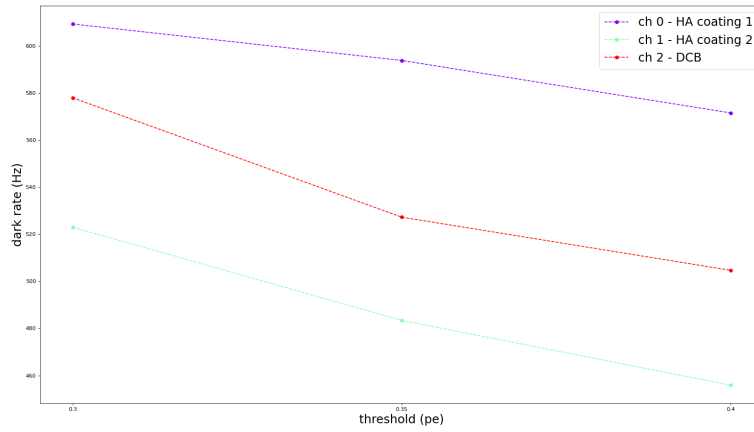


Figure 7.11: Comparison of dark rate as a function of threshold of three PMTs: two coated with HA-coating (purple and green lines) and one with DCB (red line).

- Timing resolution: it should be better than 3" PMT TTS, namely less than 1.5 ns for 1 p.e. This requirement implies that the timing resolution from electronics for 1 p.e. should be about 500 ps; a better timing resolution of about 200 ps is required for large p.e. pulses.
- Charge resolution: 0.1% at Full Width Half Maximum (FWHM) in the range ~ 0.05 p.e. up to 25 p.e..
- Power consumption: Driven by water circulation requirements and its temperature stability, it should be less than 4 W per mPMT module.

To match these requirements, a Q/T digitization based on discrete components has been designed and fully tested at INFN. On the electronic point of view, the circuit can be divided in three blocks: directly connected to the PMT there is the High Voltage (HV) Board, then, connected to it, there is the Front End Board (FEB) while the last is the Main Board to which are connected the FEBs of all the 19 PMTs (Figures 7.12 and 7.13).

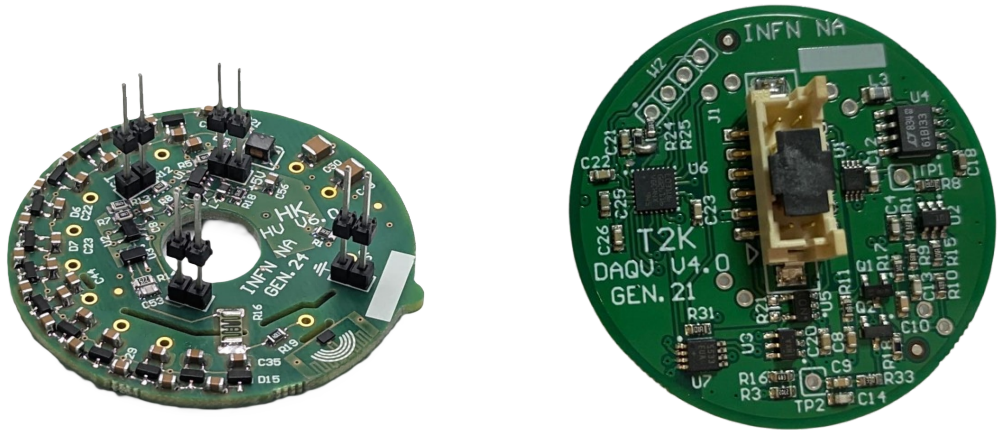


Figure 7.12: The FEB Board (left) and the HV Board (right) of a single PMT .

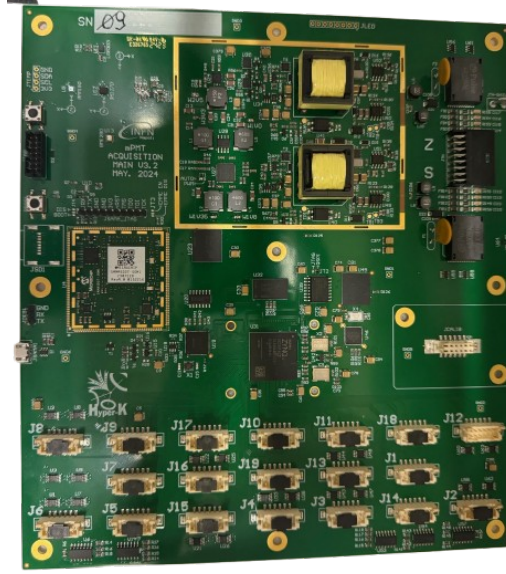


Figure 7.13: The Main Board of the mPMT module.

HV board

To produce a signal, the anode of the PMT has to be at a higher voltage with respect to the cathode, so there are two possible choices: if the cathode is grounded, the anode must be set to a positive high voltage, otherwise the anode is set to ground potential and the cathode to a negative high voltage. For Hyper-K, the anode-grounding scheme was chosen since, with the alternative solution, a decoupling capacitance would be required, and potential HV noise could be detected on the signal. The main issue of adopting an anode grounding scheme is an increase of the noise rate due to possible discharges, but we proved that it could be solved with the right coating.

The voltage multiplier is based on a Cockcroft-Walton multiplier. Since the gain of a PMT is related to the power supply value, it's very useful to monitor the voltage. Moreover, to detect the state of a PMT, it's also very useful

to monitor the absorbed current. For these reasons, an embedded current and voltage monitor has been added on the HV Board. The HV board has a single 5 V supply and can produce negative voltages up to 1500 V. It needs only one analogue input and one digital input. The analog input is the reference voltage, in the range 0-2.4 V to set the voltage. The digital input is the on/off bit. With the on/off bit is possible to enable and disable the high voltage part of the circuit. The output of the board are the 11 high voltages for the dynodes of the PMT and two analogue values in the range 0-3.3 V related to the voltage and the absorbed current monitoring.

Front-End Board

The FEB is the interface between the PMTs and the acquisition system. To minimize the effect of the electronic noise on the charge and time measurements, the FEB has been designed to be very closed to the PMT. A Micro Controller Unite (MCU) controls the parameters of both the HV and the FEB. A "two floor board" with only one connector has been designed to reduce the circuit area. The FEB has a smaller diameter with respect to the HV board. The FEB has two supplies (5V and 3.3V) and it is controlled with a 3.3 V TTL UART while the outputs are a logic differential signal to generate the time stamp and the trigger and a SPI for the charge information. In Figure 7.14 the block diagram of the FEB is shown. It can be basically divided in two parts: the time measurement circuit and the charge measurement circuit. Both circuits are based on discrete components to fulfill the restrictive requirement on the power consumption. The time measurement circuit generates a logic transition when the PMT gives a signal. A very

fast circuit is needed to generate the logic transition with a very low jitter, in order to have a good time resolution. The same signal will also be used to generate the hold signal for the ADC. This part of the FEB is composed by two blocks. The first stage is a fast amplifier with a very high gain, the second part of the circuit is the discriminator. The input signal is amplified and compared with a settable threshold. If there is a signal, the output of the amplifier gets over the threshold and the discriminator generates a logical differential signal used by the FPGA of the Main Board to produce the time stamp and the hold signal for the ADC.

The charge measurement circuit measures the charge of the PMT signals. Following the requirements, the charge data must be acquired with a resolution of 0.1% FWHM in the range 0.05-25 p.e. The purpose of this circuit is the conversion of the charge generated from the PMT. Due to the large impedance of the fast amplifier in the time measurement circuit, most of the PMT signal is transferred to the charge measurement circuit. The input signal is shaped with a three-stage integrator. The first step is a passive low-pass filter. With this solution a less performing operational amplifier can be used to reduce the power consumption because of the reduced input signal slope. The second stage is an active integrator, based on an operational amplifier. The output of this stage is integrated again with a passive filter to respect the ADC input impedance requirement and to generate a very smooth signal. A 1 MHz maximum rate is expected so the time available to charge and completely discharge the integrator is at most $1\ \mu s$. The time constant of the low-pass filter circuit is designed to produce a flat shape signal as ADC

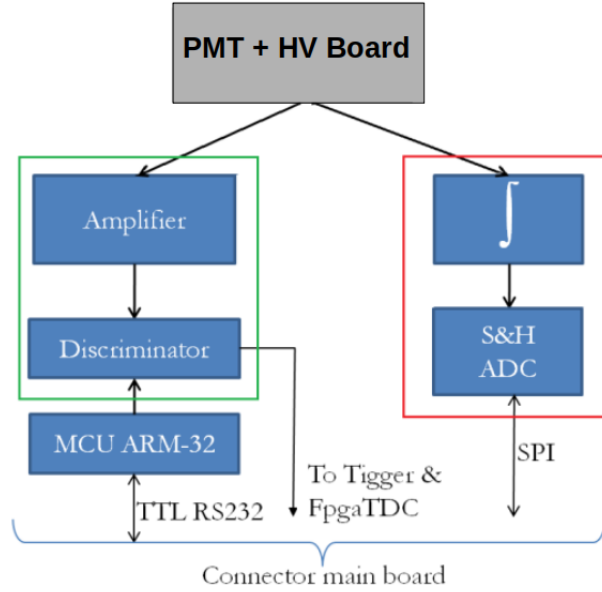


Figure 7.14: Block diagram of the Front-End Board. In the red box the energy measurement circuit and in the green box the time measurement circuit.

input, in order to have a good energy measurement even if the hold signal of the ADC is produced within a defined range whose size is defined taking into account the jitter of the hold signal generated by the FPGA. The last step in the energy measurement chain is a Sample and Hold ADC. The hold signal is generated by the FPGA starting from the time measurement with a programmable delay.

Main Board

The Main Board is the interface between the single channel electronics and the outside of the mPMT. It provides the power supply to each PMT channel and collects, processes and transfers the data acquired by the FEB. The power supply is composed by three different parts: the Power on Ethernet

module, the DC-DC converters and the single channel switch. The data processing is composed by two stages. The FPGA acquires and processes the data and generates an output of 10 Byte/event that are transferred to the Single Board Computer (SBC) Linux where a C++ program collects the data and transmits them on the Ethernet cable. On the Main Board is also placed a sensor to allow online monitoring of temperature, humidity and pressure. The sensor chosen is a BME280. Because of the power consumption of the FEB and HV board, about 3 W are used for the Main Board to satisfy the requirement of 4 W total power consumption.

7.5.3 Physics performances with mPMT

The mPMT features several attractive advantages compared to the 20" B&L PMT, while keeping the same production costs:

- *Improved segmentation:* Single-photon hits can be distinguished from multi-photon hits analyzing the signal in neighboring PMTs.
- *Superior photon counting:* The total number of deposited photoelectrons can be derived from the number of hits of each PMT.
- *Extension of dynamic range:* Multiple photons arriving at the same time are more likely to hit different PMTs.
- *Intrinsic directional sensitivity:* The direction of the incoming particle can be better reconstructed by analyzing the charge deposited on each PMT, as they all have different orientations.
- *Local coincidences:* Uncorrelated single-hit noise, such as dark rate, can be suppressed using coincidences between individual PMT in one

module.

- *Lower dark rate:* 3" PMTs are characterized by lower dark rate compared to 20" PMTs. This feature allows to better reconstruct the vertex of interaction for low energy events.
- *Lower sensitivity to the Earth's magnetic field:* in this way magnetic shielding become unnecessary.
- *Lower failure rate:* since each 3" PMT is equipped with full electronics, the loss of one PMT doesn't imply the loss of the whole mPMT, minimizing the loss in photo-coverage by single modules in case of failure.

Detailed simulation studies are ongoing to investigate the impact of the mPMT system in Hyper-K physics in both the high- and low-energy sectors. Simulation are performed using WCSim software [216] while high energy event are reconstructed using the fiTQun software [191] and low energy events using BONSAI software [192].

The main consequences of the addition of mPMTs are the improvement of both particle identification (PID) as well as the vertex resolution. Figure 7.15 shows the performance of particle identification by fiTQun for 500 MeV electrons and muons as a function of distance to wall. The purities of electrons (muons) are evaluated using a sample that contains an equal number of electrons and muons . A 95% efficiency for electrons (muons) is required when electron (muon) purity is evaluated.

Figure 7.16 show the vertex resolutions for 500 MeV electrons and muons as a function of distance from the inner detector wall. The plots tell that the vertex resolution can be improved with additional multi-PMTs and the

performance can be better than 40k B&L PMTs if 10k multi-PMT modules are installed.

Figure 7.17 shows the comparison of the vertex resolution for 5 MeV electrons with different assumptions of the dark rate of 3" PMT as a function of the number of mPMT modules in addition to 20k B&L PMTs. A 4.2 kHz dark rate is assumed for B&L PMT. This plot tells the improvement with mPMT is clear and the impact is more significant with more mPMTs in addition to 20" PMTs.

Since approximately 800 mPMTs are currently planned for installation in the tank, enhancements in physics performance are expected to be limited. However, in a second phase (potentially around ten years after data acquisition begins), additional mPMTs may be installed, creating the opportunity to achieve these upgrades. Furthermore, it has been demonstrated that calibration also benefits significantly from the addition of mPMTs, even when only hundreds are added, as will be discussed in the next section. Calibration will be especially crucial for low-energy neutrino detection in Hyper-Kamiokande. It plays a pivotal role in ensuring the accuracy of measured energy and precise event positioning, which are essential for identifying subtle Cherenkov light signals from low-energy neutrinos, such as those from solar or diffuse supernova backgrounds. Through calibration, the detector response can be optimized to account for PMT sensitivity variations, water transparency, and detector geometry. This optimization improves background rejection and particle identification efficiency, critical for distinguishing low-energy neutrino events from noise or other non-neutrino signals. The addition of mPMTs, even in small numbers, can thus have a significant impact on en-

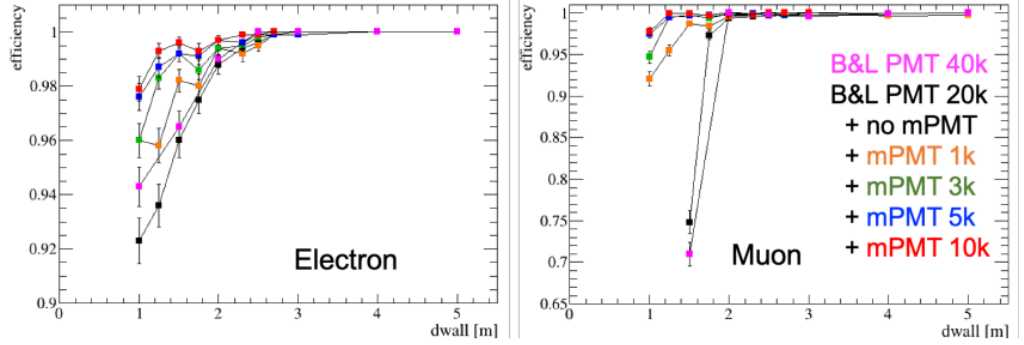


Figure 7.15: Left: purity of electrons for half and half 500 MeV electron and muon sample in case 95% efficiency for both is required. Right: same plot for muons.

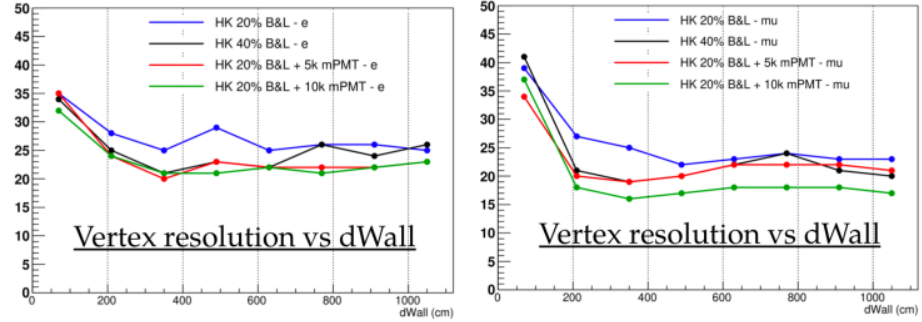


Figure 7.16: Vertex resolutions of 500 MeV electrons (left) and muons (right) as a function of distance from wall.

hancing neutrino astronomy studies in Hyper-Kamiokande.

7.5.4 Calibration performances with the mPMT

The mPMTs have a great impact on Hyper-K calibration, since they can provide valuable information for refining the detector response model.

A simulation study using dozens of light injectors and hundreds of mPMTs showed substantial improvements in measuring both the PMT angular re-

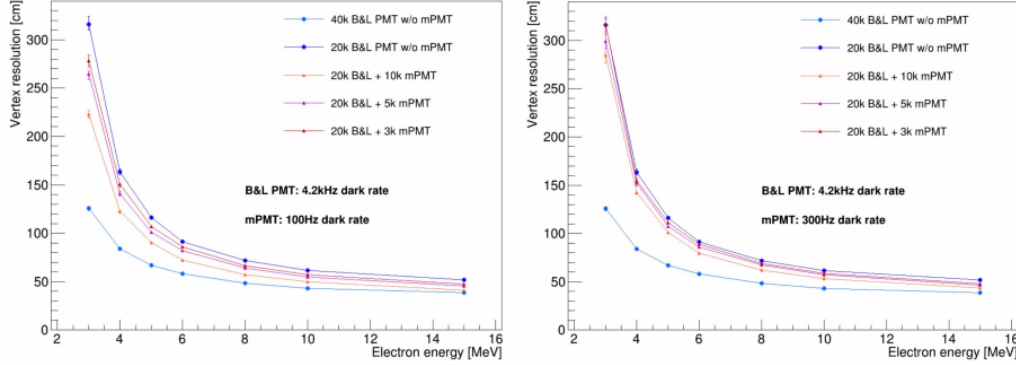


Figure 7.17: Vertex resolution for low energy events with 20k B&L PMT, 40k B&L PMT and 20k B&L PMT mPMT with 100 Hz (left) and 300 Hz (right) dark rates. 4 kHz dark rate is assumed for B&L PMT in both plots.

sponse and water attenuation. Adding more mPMTs and/or light sources could further enhance this capability by detecting the position dependence of water quality and variations in PMT angular response. The number of systematic parameters that can be constrained depends on the number of light-source and mPMT combinations. With the dozens of light injectors, up to dozens of mPMTs can receive the narrow beam for the water transmission measurement with improved separation of scattered and transmitted light. To further improve calibration studies, a newly version of mPMT has been proposed which incorporates the LED inside the vessel. This so-called LED mPMT is shown in Figure 7.18, although the final design is still under development. The basic idea is to substitute 5 PMTs with a LED-module consisting of 8 fast LEDs. This would dramatically increase the number of light-source - mPMT combinations, making for more robust calibrations and improved sensitivity to systematic effects. In essence, their purpose is to refine the Hyper-K detector response model, thereby reducing bias and variance.

One of the benefits of the LED-mPMTs is to enable Raman scattering (i.e. inelastic scattering by water molecules) to be studied, which is not currently taken into account in existing analyses. Due to Raman scattering, 300 nm light is shifted to 350 nm: this has a significant impact on the Cherenkov light detection, since the photon detection efficiency of 300 nm light is almost zero for the PMT whereas after Raman scattering, the light is close to the peak sensitivity of the PMT and detected. This effect is further enhanced because the Cherenkov light yield increases at shorter wavelengths ($\sim \lambda^{-2}$), and the Raman scattering probability also rises at shorter wavelengths ($\sim \lambda^{-2}$), as shown in the left plot of Figure 7.19. The right plot instead illustrates the detected Cherenkov light distribution for a 60 m light path in water, plotted against light wavelength. The Raman scattering component is substantial and should be incorporated into the Cherenkov light ring pattern reconstruction, especially for backward-scattered light, which plays a key role in accurate vertex reconstruction.

Another crucial benefit is for the detector response model. Hyper-K functions as an imaging detector to estimate the properties of charged particles. The spatial bias goals for the detector are much smaller than the PMT diameter (typical for imaging detectors). The PMTs most sensitive to particle properties are those near the edges of the Cherenkov rings, where Cherenkov light produces non-uniform illumination. To avoid introducing bias, a well-defined response model for PMTs with non-uniform illumination is essential. 20" PMTs and mPMTs can measure calibration light sources with large

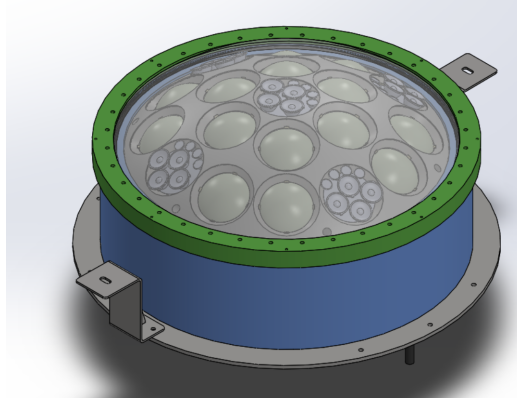


Figure 7.18: A schematic of LED systems embedded in a LED-mPMT. Five 3-inch PMTs are replaced by a LED-module which consists of 8 LEDs, 4 wavelengths ((295, 365, 405, 475 nm) and two emission angles (wide, narrow).

intensity gradients and compare these with their response models. A high number of sources and mPMTs distributed throughout the detector is needed to capture a broad range of incident angles.

7.6 Data Acquisition

Hyper-Kamiokande will operate as a trigger-less experiment, i.e. each channel will continuously collect and transmit all potential hits to the DAQ system, without preliminary filtering. Although the experiment's large scale, this approach is feasible given the manageable rate of interesting events.

The DAQ system will be crucial, as its failure could lead to permanent data loss. Each underwater detector module will connect to the surface through a 1 Gbps Ethernet link, making Ethernet communication and standard servers essential for data handling, initial calibration, event building, and triggering.

To manage this, Hyper-K will use ToolDAQ, a modular DAQ framework built for scalability and adaptability across various experiments. ToolDAQ

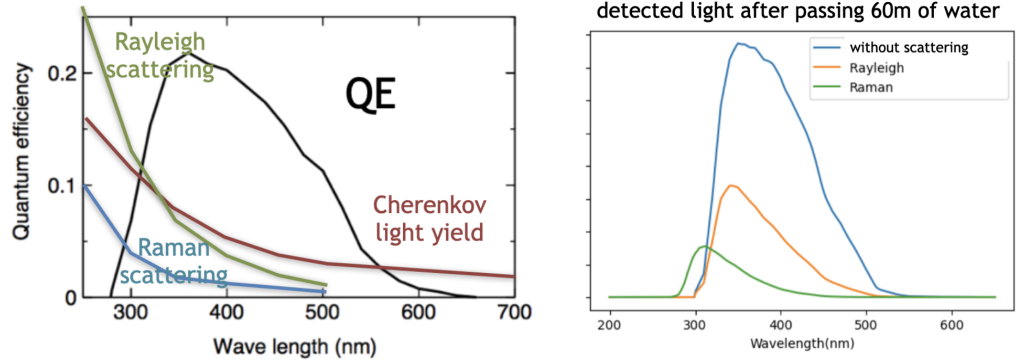


Figure 7.19: Wavelength dependence of light scatterings with respect to the quantum efficiency of PMTs and the Cherenkov light (Left). Convolution of the detected light in PMT after traveling 60 m of water as a function of initial wavelength is shown on the right (arbitrary units on y-axis). Since Raman scattering shifts the wavelength by ~ 50 nm, Cherenkov light below 300 nm is detected.

employs a ToolChain execution model, where each step, or "Tool," is modular, facilitating fault tolerance, error correction, and data routing—key features for long-term, large-scale experiments like Hyper-K. Data is transferred between tools using the reliable ZeroMQ (ZMQ) protocol.

The DAQ system collects data from underwater Data Processing Boards (DPB) boards via Gigabit switches at the surface, then routes it to the Read-out Buffer Unit (RBU), where raw data is organized and calibrated. Data is then processed in 10 ms chunks by the Trigger Processing Unit (TPU) to identify potential events. The RBU is designed to buffer data for extended periods during high data rates, allowing the TPU sufficient time for event detection. Only triggered events are stored long-term and backed up. The data format remains under discussion, with a custom binary format anticipated to optimize bandwidth and storage efficiency. An overview of the DAQ network structure can be seen in Figure 7.20.

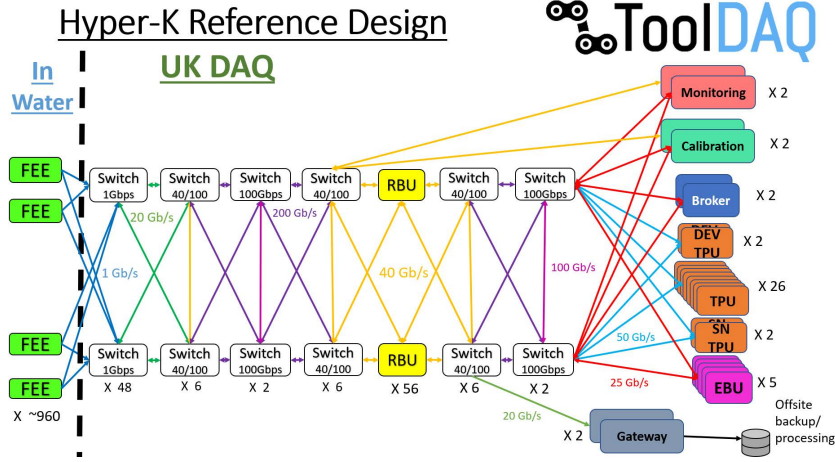


Figure 7.20: An overview of the network structure representing the DAQ hardware for HyperK.

Hyper-K physics program spans a vast energy range, from a few MeV to many GeV, necessitating a highly accurate and efficient detection system. To address this, a variety of specialized trigger algorithms will operate in parallel, determining which time slices in the data are stored for analysis. Before triggering, raw data undergo pre-processing, where hits are sorted by timestamp, calibrated, and adjusted for inactive PMTs.

A basic trigger, the NHits trigger, counts hits in a time slice and triggers if they exceed a threshold. Parameters like threshold and time slice length are optimized for high performance.

To enhance sensitivity to very low-energy events ($< 8 \text{ MeV}$), a more advanced trigger tests around 2000 candidate points as potential vertices, looking for hit clusters that align in space and time. This method can detect events down to 3 MeV and provides preliminary vertex information, useful for reconstructing particle motion. The efficiency of both triggers as a function of the energy is shown in Fig. 7.21.

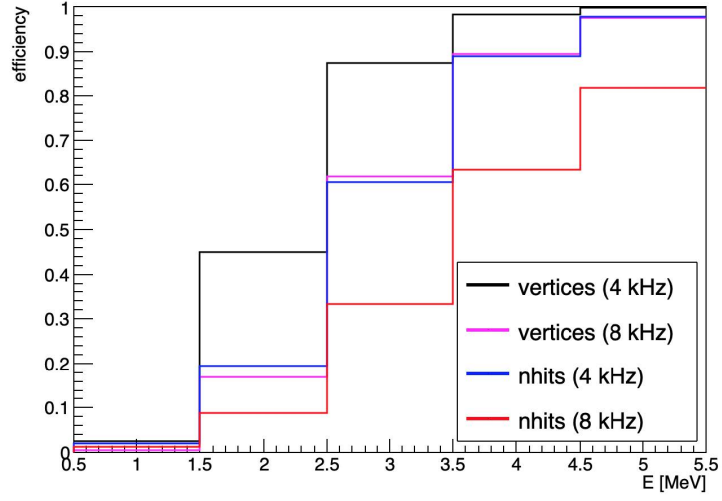


Figure 7.21: Trigger efficiency as a function of electron kinetic energy, for both the NHits trigger and the test vertices trigger, and for two levels of dark noise (4.2 or 8.4 kHz per PMT). Only 20" PMTs are considered.

Additionally, a cluster trigger identifies small, dense hit clusters in space and time, distinguishing signal from noise more effectively than the NHits trigger, achieving high efficiency at even lower energies (2–3 MeV).

Ultimately, the optimal combination of these triggers, potentially incorporating neural networks, will be selected once the actual hardware is available.

Discussions are also underway regarding the potential installation of advanced trigger systems specifically designed for neutrino astronomy. These could include such as a trigger for pre-SN neutrinos as well as the follow-up system for gravitational waves and other transient astronomical events. Such systems would expand Hyper-Kamiokande's capabilities in multi-messenger astronomy, enabling more precise and timely data collection from a variety of astrophysical sources.

7.7 Prospects for neutrino astronomy

One of Hyper-Kamiokande advantages will be an improved potential for astrophysical neutrino detection, thanks in particular to its bigger volume. Hyper-K will also have improved resolution and reduced background noise, allowing for more precise reconstruction of neutrino energies and directions. This means that Hyper-K could better identify the origins of astrophysical neutrinos and contribute significantly to multi-messenger astronomy, especially when combined with gravitational wave and gamma-ray observation.

Hyper-K will have exceptionally high sensitivity to supernovae, especially those occurring within our galaxy. It will detect neutrinos with energies as low as 3 MeV. Precise, event-by-event measurements will be crucial for an in-depth study of supernova neutrinos, particularly in capturing the detailed, time-dependent energy spectrum. These capabilities will enable Hyper-K to carry out unique measurements that can uncover the mechanisms behind supernova explosions.

Thanks to its increased directional sensitivity, the direction of a supernova at 10 kpc (i.e. a distance that contains half of the stars in our galaxy) can be reconstructed with an accuracy of about 1 to 1.3 degrees with Hyper-K, assuming the performance of event direction reconstruction similar to Super-K [27]. Figure 7.22 shows time profiles of the main interactions in the low-energy range expected at Hyper-K for a supernova at a distance of 10 kpc. The assumed model for the supernova explosion is the Livermore model [74]. The three plots assume different hypotheses on neutrino oscillations:

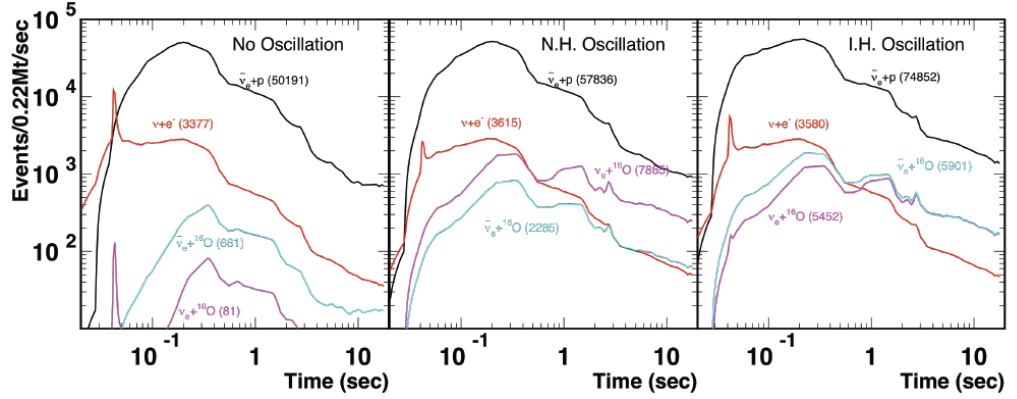


Figure 7.22: Expected time profile of a supernova at 10 kpc in Hyper-K. Left, center, and right figures show profiles for no oscillation, normal hierarchy, and inverted hierarchy, respectively. Black, red, purple, and light blue curves show event rates for interactions of IBD, νe -scattering, $\nu e^{16}\text{O} CC$ and $\bar{\nu} e^{16}\text{O} CC$ respectively. The numbers in parentheses are integrated number of events over the burst. The fluxes and energy spectra are from the Livermore simulation [74]. Taken from [22].

no oscillations, normal hierarchy, and inverted hierarchy, respectively. The burst time period is about 10 s and the peak event rate of inverse beta decay events reaches about 50 kHz at 10 kpc. The DAQ and its buffering system of Hyper-K will be designed to accept the broad range of rates, for a galactic SN closer than 10 kpc. A sharp peak is expected for νe -scattering events at the time of neutronization, which would allow to a precised direction measurement.

Fig 7.23 shows the expected number of events in Hyper-K from different interactions as a function of the SN distance. It clearly demonstrates the feasibility of Hyper-K to detect SN also in nearby galaxies, particularly from the Local Group (for a supernova from the Andromeda Galaxy - M31 - about 10 to 16 events are expected). Moreover, a detailed study demonstrated that with Hyper-K it will be possible to discern between several SN models, by

observing the first 500 ms of the neutrino burst, corresponding to the accretion phase [217].

Other significant contributions to supernova theory will be the possible observation of black hole formation after the collapse of the star, detectable as a sharp drop in neutrino flux, a possible measurement of the absolute neutrino mass by analyzing neutrino arrival times, further studies on neutrino oscillation as well as insights into mechanisms that modulate the supernova neutrino flux, such as the Standing Accretion Shock Instability (SASI) [218] and supernova rotation effects [219].

Hyper-K is also expected to provide evidences of the interaction of supernovae with the surrounding circumstellar medium (CSM) by detecting the anticipated GeV emission associated with this phenomenon, see e.g. [220]. These high-energy neutrinos are detectable hours to months after the core-collapse, and detecting the signals will give new insights into how collision-less shocks are formed and CR acceleration starts, as well as the connection to supernova remnants as the origin of Galactic CRs. The best scenario would be to see the time evolution of multi-energy neutrino emission from the core-collapse to shock breakout and following interactions with the circumstellar material. Physics beyond the standard model also can be tested, e.g. sterile neutrinos, the neutrino magnetic moment, the neutrino non-standard interaction and the axion.

Similarly, Hyper-K holds substantial promise for the study of DSNB. Hyper-K's capabilities will allow for a clearer signal extraction from background noise, especially through advanced background suppression tech-

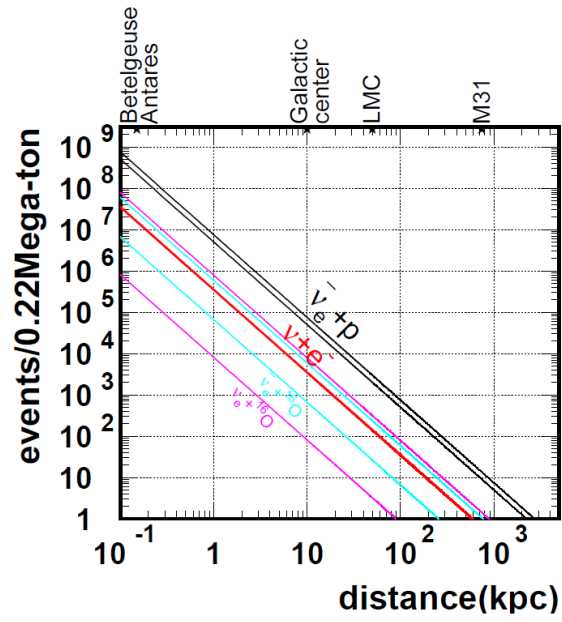


Figure 7.23: Expected number of supernova burst events for each interaction as a function of the distance to a supernova in Hyper-K. The band of each line shows the possible variation due to the assumption of neutrino oscillations. Taken from [22].

niques and precise energy threshold control, which are essential for DSNB detection. By measuring the DSNB flux and energy spectrum, Hyper-K could open a new window into cosmology and the history of stellar explosions in the universe.

Hyper-K has significant potential also for dark matter searches, particularly for Weakly Interacting Massive Particles (WIMPs). Its large water volume and high sensitivity allow for the detection of rare interactions between WIMPs and nucleons, producing detectable Cherenkov radiation. Additionally, Hyper-K could observe neutrinos from dark matter annihilation events in high-density regions like the Earth or the Sun, providing valuable constraints on dark matter properties. The detector's capability to measure solar and atmospheric neutrinos can help distinguish dark matter signals from background noise, while its setup is also suitable for exploring alternative dark matter models, such as axions or sterile neutrinos.

The increased statistics, enhanced photo-coverage, and greater sensitivity of Hyper-Kamiokande will also improve the detection potential of other astrophysical sources, such as gamma-ray bursts (GRBs) and gravitational wave (GW) sources. These upgrades will allow Hyper-K to better capture high-energy neutrino signals from such transient events, providing valuable multi-messenger insights into extreme cosmic phenomena. Observation of GeV-TeV neutrinos will be feasible for GRBs occurring at distances ≤ 100 Mpc and successful detection of such neutrinos would allow for distinguishing between different prompt emission mechanisms and probing the composition

of GRB jets. This could be particularly fruitful to verify models like supernovae driven by relativistic outflows and choked-GRB models (e.g. [173, 221, 68]). For a supernova at a distance of 10 Mpc it is expected that Hyper-K will be able to detect ~ 5 signal events from such a jet-driven supernova [22].

Another intriguing scenario arises if a supernova explosion leaves behind a fast-spinning neutron star. In this case, neutrons are loaded into the proto-neutron star wind through neutrino heating. Near the outflow base, particle density is high enough that neutrons and ions are strongly coupled via elastic collisions. As the Poynting-dominated pulsar wind accelerates, neutrons and ions are also accelerated. When the outflow becomes relativistic enough to cross the pion-production threshold, inelastic collisions become the primary dissipation mechanism for the relativistic neutrons. These neutrons then interact with shock-decelerated material and possibly with remaining stellar material, producing 0.1–1 GeV neutrinos [222]. Detecting such signals would offer insight into the obscured processes of jet acceleration and the physics underlying the birth of rotating, magnetized proto-neutron stars during core collapse. Hyper-K could potentially observe around 20–30 events (for $E_\nu^{iso} \approx 10^{48} \text{ erg}$) from a core-collapse supernova at a distance of 10 kpc.

Finally, Hyper-Kamiokande has the potential to detect thermal neutrinos from nearby neutron star merger events, within about 10 Mpc. Simulations studies of thermal neutrino emission from BNS mergers proved also that, in the Gd-dope scenario, by choosing a very narrow time window after the GW signal, even at distances of 200 Mpc it could be possible to

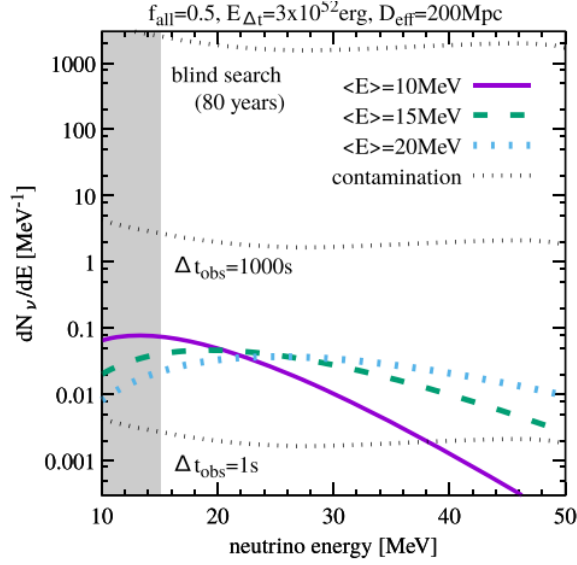


Figure 7.24: Spectrum of thermal neutrinos from BNS expected in Hyper-K, assuming Gd-doping. Different averages have been considered, as well as different time window searches after the GW signal.

have a significant neutrino detection [96]. Fig. 7.24 shows the spectrum of detected thermal neutrinos normalized to a single event between 10 and 50 MeV obtained through the simulation performed in [96]. Purple-solid, green-dashed, and blue-dotted curves show the expected spectra at the detector for $E_i = 10, 15, 20$ MeV respectively, assuming only the IBD channel. Black dotted curves show the expected spectrum of contamination during a blind search of 80 years expected to be required for a single detection (top), the commonly adopted $\Delta t_{obs} = 1000$ s for all the mergers during this period (middle), and $\Delta t_{obs} = 1$ s proposed in this work (bottom). The shaded area on the left approximately represents the energy range unavailable due to the spallation background. This figure clearly shows that the chance of detecting thermal neutrinos arises only when a short time interval of $\Delta t_{obs} = 1$ s after the merger is considered. Concurrent observations of neutrinos and

gravitational waves will provide crucial insights into the central regions of these violent cosmic explosions during the Hyper-Kamiokande era. Specifically, when Hyper-K begins operations, the GW O5 run is expected to start, increasing sensitivity in the GW sector and leading to exciting new observations. Consequently, the plan is to implement the described real-time GW follow-up system in Hyper-Kamiokande. Discussions are already underway within the collaboration, and initial foundations for the pipeline have been established. The goal is to enable a real-time follow-up system for various transient searches, thereby expanding Hyper-K's astrophysical potential to encompass multiple phenomena.

Conclusions

Neutrino astronomy has proven invaluable for probing cosmic phenomena, offering insights into events and processes spanning from supernovae to the early Universe. This thesis has presented a detailed investigation of the production models for neutrinos from astrophysical sources. It has also shown the preliminary results of a follow-up search for neutrinos (detected by Super-Kamiokande) in coincidence with gravitational waves, as well as the development of a real-time for follow-up analysis in Super-Kamiokande and future prospects for Hyper-Kamiokande.

A first investigation presented is related to the recent supernova SN2023ixf, a type II SN exploded in the M101 galaxy at a distance of 6.4 Mpc, which has been used to test several models regarding the emission of neutrinos both in different energy ranges. In the low-energy range, several models have been considered and the response of both the Super-Kamiokande and the future Hyper-Kamiokande have been considered. Given the sub-threshold number of event obtained, no constraints were imposed on the considered models. This result was also confirmed by the Super-Kamiokande experiment, which didn't observe any neutrino emission from SN2023ixf. For the high-energy

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emission, two models have been considered. One is the so-called "choked jet" model which hypothesizes a jet and the interaction of the supernova eject with a dense CSM. In both cases, the non-observation of neutrinos by IceCube has been used to constrain these models, particularly regarding the fraction of accelerated particles that produce neutrinos through their interactions (in both cases, it resulted that this fraction should be $f_p < 10\%$). In the case of the choked jet model, another possible interpretation based on our results is that the jet is ultra-relativistic and characterized by a long duration ($t_{jet} > 10^4 s$).

A second study was presented, focused on the galactic origin of neutrinos. In particular, a selected catalog of TeV γ -ray sources has been considered and, based on the observe γ spectrum, the neutrino spectrum has been computed and used to evaluate the expected number of neutrinos in both the IceCube and KM3NeT telescopes. By evaluating the overall neutrino spectrum expected by all the sources contemplated, constraints on the origin of the IceCube-detected galactic neutrino flux have been imposed. The results of stacking analysis on the catalog also highlighted the most promising neutrino sources for potential observation by the KM3NeT experiment, given its superior sensitivity to galactic neutrino sources, which resulted to be Pulsar Wind Nebula and TeV Halo. Based on this analysis, KM3NeT should be able to detect in 1 year a neutrino flux from the stacking of at least three PWNs and PWN/THs, with a $\sim 7.5\sigma$ statistical significance.

The second part of the thesis focused on the potential for joint neu-

trino and gravitational wave detections, emphasizing the enhanced insights gained from combined signals in catastrophic events like neutron star mergers. Preliminary results of a follow-up analysis with the Super-Kamiokande detector in combination with the GW events detected during the current O4 run have been presented. Although no excess was observed in coincidence with any GW event, this non-detection has been used to place constraints on the expected neutrino flux from each source, which resulted in the order of $10^3 - 10^4 \text{ GeV cm}^{-2}$, assuming a power law spectrum E^{-2} for high-energy neutrinos.

The interest in conducting these follow-up searches promptly has driven the development of an online follow-up system for GW coincidence searches in Super-Kamiokande. Thus, this thesis has presented a description of how the proposed system works along with its current status and the results of the first tests. In particular, the results of these tests have demonstrated the possibility to run the system in real-time. The implementation of this system opens up exciting possibilities for discovery in multi-messenger astronomy, thanks also to its versatility for extension to other multi-messenger sources beyond gravitational waves.

Lastly, this thesis presented the future prospects in neutrino astronomy for the Hyper-Kamiokande detector, specifically the advancements expected from the integration of mPMT modules for which I actively participated in the R&D, characterization as well as in the assembly of the first prototypes. These modules improve directional reconstruction and calibration, setting

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the stage for enhanced sensitivity to astrophysical neutrinos and offering an expanded reach in multi-messenger astronomy with Hyper-Kamiokande.

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