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

Aurora Langella

Riunione Gruppo 1 Napoli

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Astrophysical neutrino sources

Several astrophysical objects are suggested as sources of neutrinos, mainly those which are considered or confirmed to be cosmic rays acceleration sites (hadronic processes). Some of these are:

Core collapse supernovae (CC-SNe). First confirmed transient source of neutrinos (SN1987A)

Supernova remnants (SNRs) with shocks accelerating cosmic rays.

Binary systems involving compact objects producing jets and accreting matter (e.g. BNS mergergers, Microquasar).

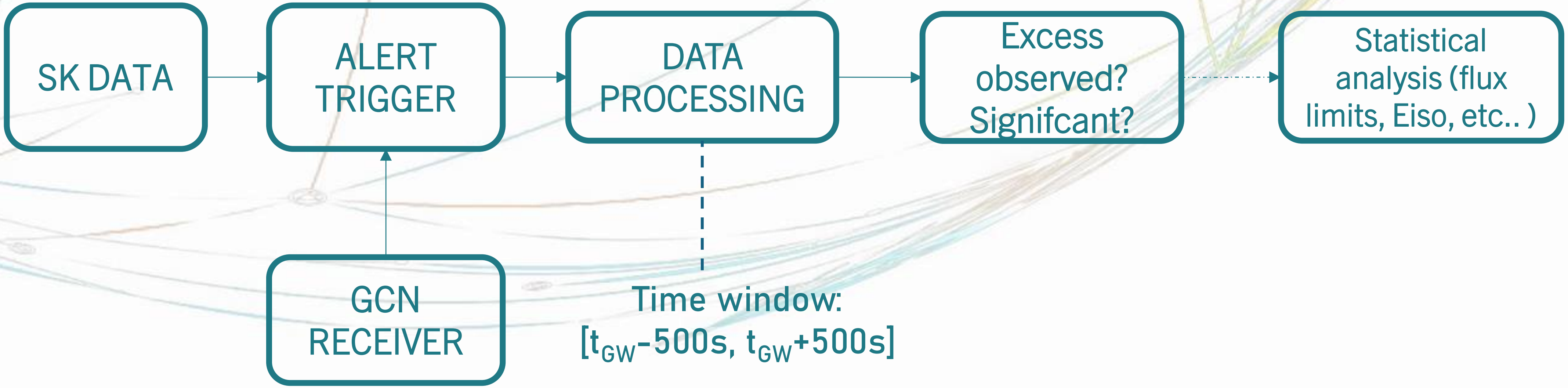
Pulsar wind nebulae (PWNe) powered by rapidly spinning neutron stars.

Most of these sources are particularly interesting for multi-messengers astrophysics.

Follow-up Analysis on GW-O4a catalog in Super-K

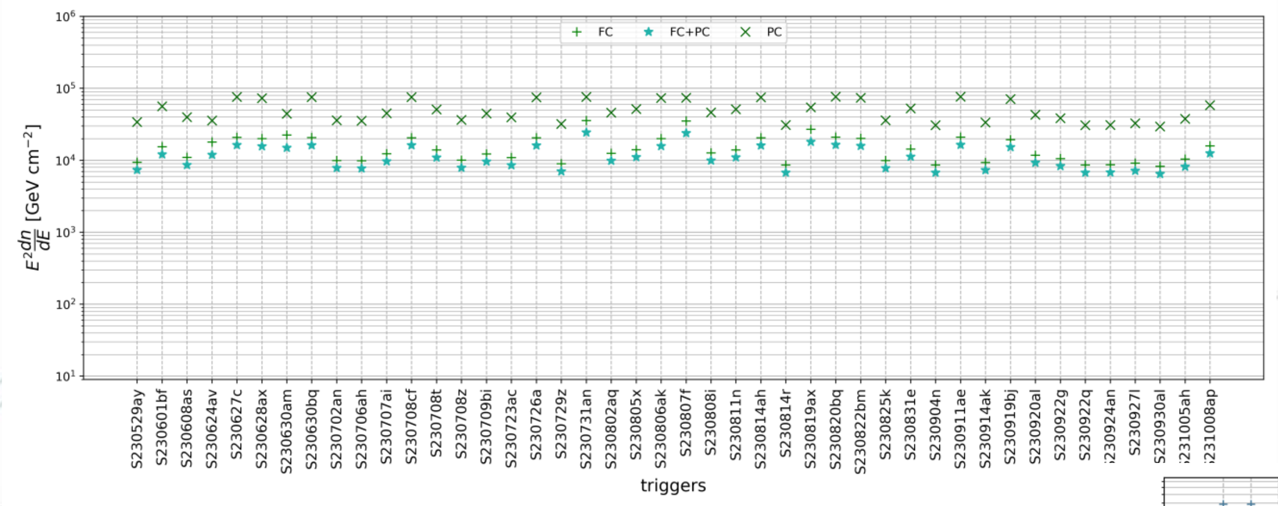
A follow-up coincident analysis for neutrino counterpart with GW events detected during O4a run (May ‘23 – Oct ‘23) has been performed.

All SK data samples have been considered (E> 6 MeV) with different approaches based on the samples.



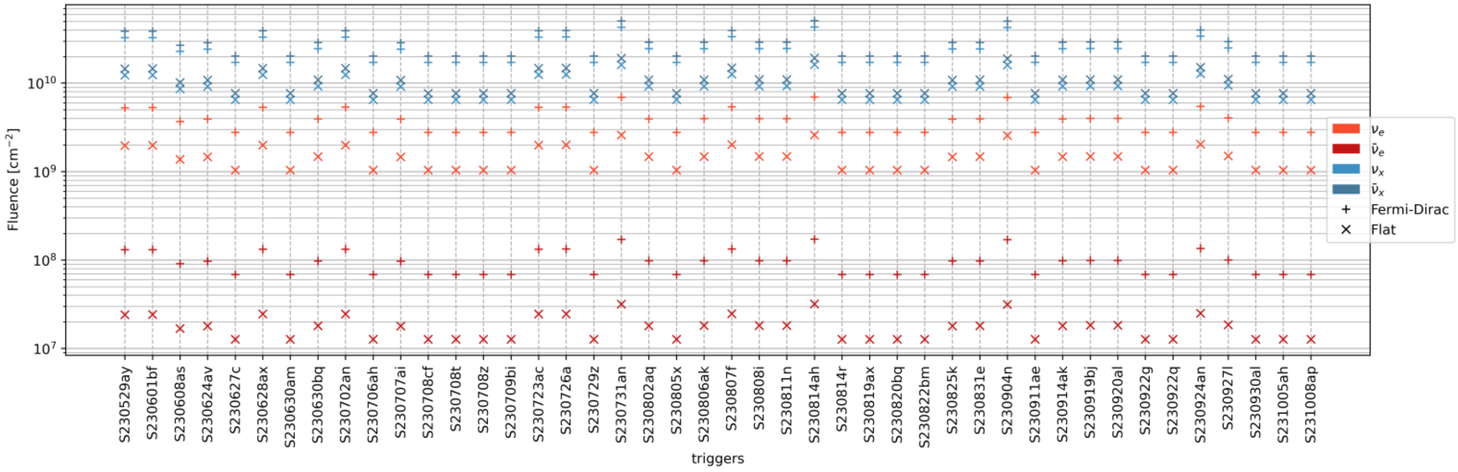
Follow-up Analysis on GW-O4a catalog in Super-K

No excess of events has been observed. Based on the sample flux/fluence have been computed considered different spectra scenario.



Flux limits for high energy samples (E > 100 MeV) assuming a E^{-2} spectrum

Fluence limits for low energy samples assuming flat/Dirac spectrum



Next: GW online follow-up system

The aim of the second project was to realize a real-time follow-up system for gravitational waves in Super-Kamiokande.
Models of low-energy neutrino emission from BNS events suggest that the emission should persist for approximately hundreds of seconds following the GW signal.

AUTOMATED OFFLINE ANALYSIS FRAMEWORK → ONLINE FOLLOW-UP SYSTEM

REDUCE TIME FOR ANALYSIS

- Apply a pre-selection before reconstruction

REDUCE TIME WINDOW FOR LE ν

- Speed up analysis & reduce background
- Expected limit on ΔToF between GW and ν: $\Delta ToF < 5s$

Online GW follow-up system in Super-K

- A python-based prototype of the pipeline has been realized and tested for low energy analysis:
  - ✓ A focused study has been performed to define a proper pre-selection on data.
  - ✓ Different time windows have been considered and are currently being tested to determine the optimal one.

- First results of testing proved the feasibility of performing real-time analysis:

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

Considering a time window of +-6 s around the GW arrival time

Other projects: Estimating neutrino fluxes from various astrophysical sources

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Neutrino Fluxes from Different Classes of Galactic Sources

Silvia Gagliardini[1,2,3], Aurora Langella[4], Dafne Guetta[1], and Antonio Capone[1,3]
[1] Department of Physics, Ariel University, Ariel, Israel
[2] Dipartimento di Fisica, Università Sapienza, P. le Aldo Moro 2, Rome, Italy
[3] Istituto Nazionale di Fisica Nucleare, Sezione di Roma, P. le Aldo Moro 2, I-00185 Rome, Italy
[4] University of Naples Federico II, Napoli, Italy and INFN Naples, Italy
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Abstract

We estimate the neutrino flux from different kinds of galactic sources and compare it with the recent diffuse neutrino flux detected by IceCube. We find that the flux from these sources may contribute to ∼20% of the IceCube neutrino flux. Most of the sources selected in this work populate the southern hemisphere, therefore a detector like KM3NeT could help in resolving the sources out of the observed diffused galactic neutrino flux.

Unified Astronomy Thesaurus concepts: High energy astrophysics (739)

DOI: 10.3847/1538-4357/ad4960

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Low- and High-energy Neutrinos from SN 2023ixf in M101

Dafne Guetta[1], Aurora Langella[2,3], Silvia Gagliardini[1,4], and Massimo Della Valle[2,3,5,6]
[1] Physics Department, Ariel University, Ariel, Israel; dafneguetta@gmail.com
[2] University of Naples Federico II, Napoli, Italy; alangella@na.infn.it
[3] Infn Naples, Italy
[4] Istituto Nazionale di Fisica Nucleare, Sezione di Roma, P. le Aldo Moro 2, I-00185 Rome, Italy; silvia.gagliardini@roma1.infn.it
[5] ICRANet, Piazza della Repubblica 10, I-65122 Pescara, Italy
[6] Capodimonte Observatory, INAF-Naples , Salita Moiariello 16, I-80131-Naples, Italy; massimo.dellavalle@inaf.it
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Abstract

Supernova (SN) 2023ixf in M101 is the closest SN explosion observed in the last decade. Therefore, it is a suitable test bed to study the role of jets in powering the SN ejecta. With this aim, we explored the idea that high-energy neutrinos could be produced during the interaction between the jets and the intense radiation field produced in the SN explosion and eventually be observed by the IceCube neutrino telescope. The lack of detection of such neutrinos has significantly constrained both the fraction of stellar collapses that produce jets and/or the theoretical models for neutrino production. Finally, we investigated the possibility of detecting low-energy neutrinos from SN 2023ixf with the Super- and Hyper-Kamiokande experiments, obtaining, in both cases, subthreshold estimates.

Unified Astronomy Thesaurus concepts: Supernova neutrinos (1666); Jets (870)

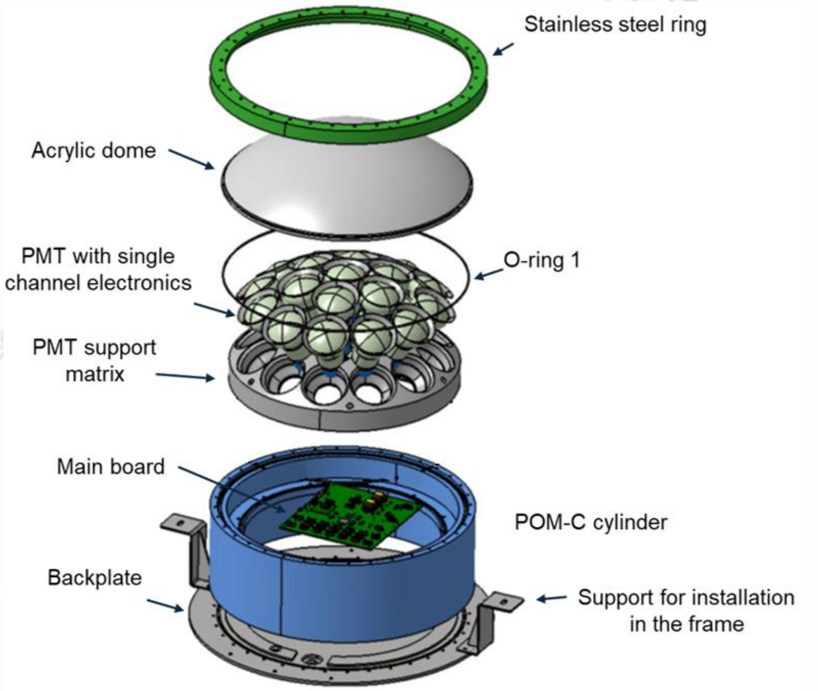
DOI: 10.3847/2041-8213/acf573

The multi-PMT (mPMT)

The mPMT has several advantages as a photosensor module:

- Increased granularity;
- Superior photon counting;
- Improved angular acceptance;
- Extension of dynamic range;
- Intrinsic directional sensitivity;

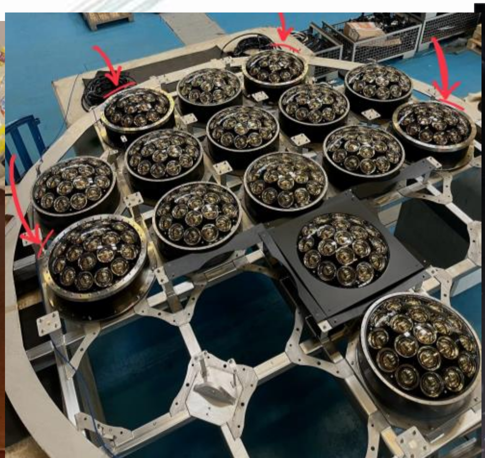
} BETTER VERTEX RESOLUTION

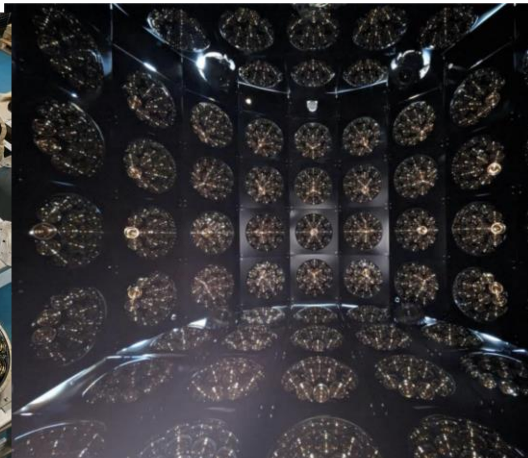


The Hyper-K group in Naples is the group leader of the mPMT project.
Since 2022 I've been the convener of the photosensors sub-working group for the mPMT, managing the testing and reqwuirements for the 3" PMTs across the international laboratories.

Assembly @ HK-NA

WCTE@CERN





Future plans

Super-Kamiokande:

- Completion of the full GW-O4 follow-up analysis
- Finalization the online follow-up system for Super-K
- Optimization of the SK pre-SN alarm

Hyper-Kamiokande:

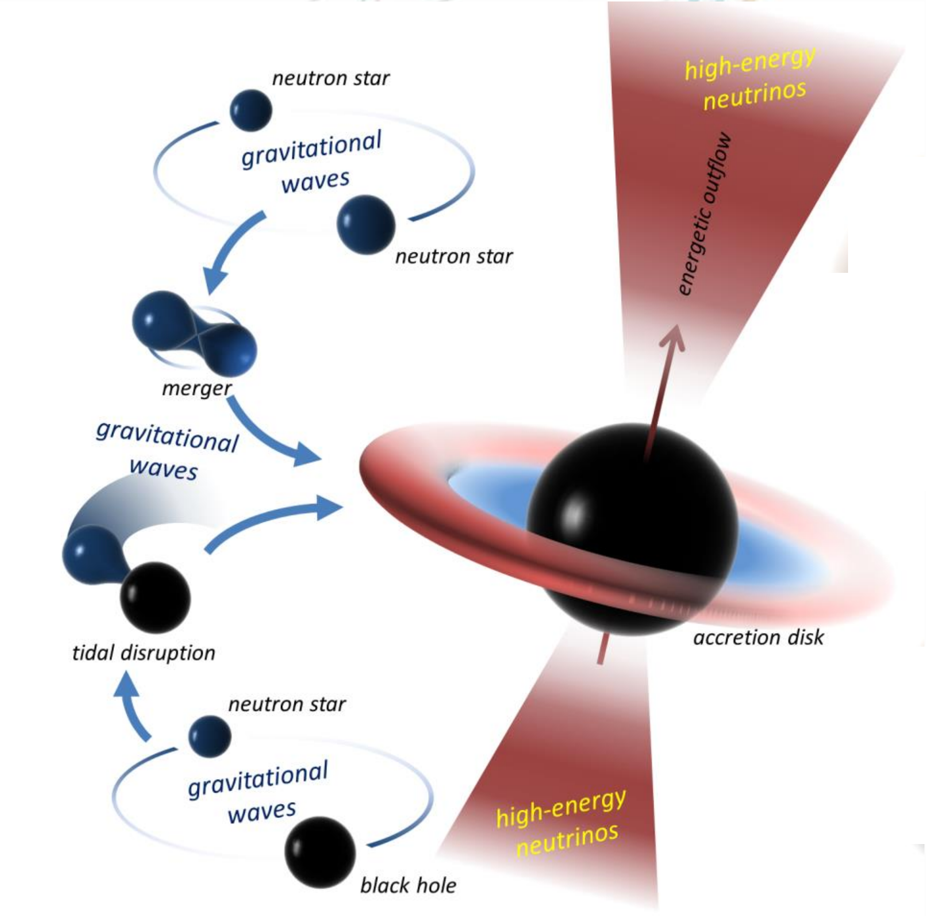
- Development of a similar online follow-up system for Hyper-K for multi-transients analysis
- Development of the SN monitor for Hyper-K
- Development of pre-SN alarm for Hyper-K

SPARES

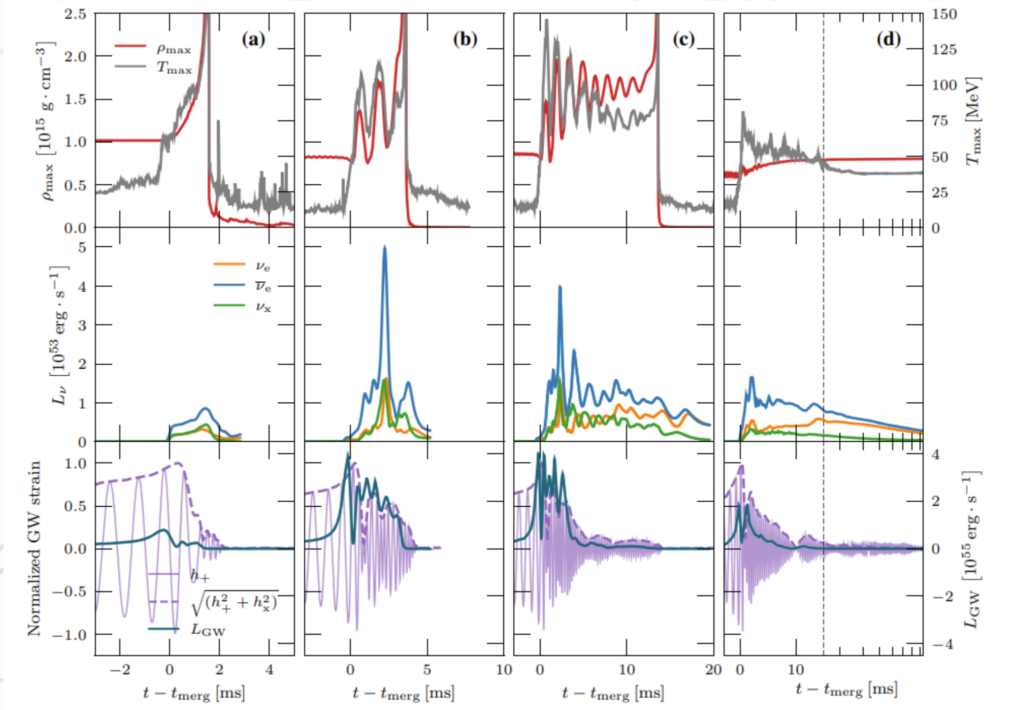
Binary Neutron Star (BNS) merger

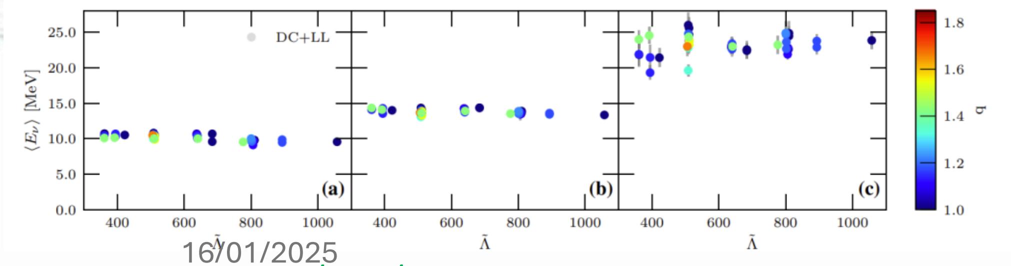
A Binary Neutron Star (BNS) merger occurs when two neutron stars in a close orbit eventually collide due to the emission of gravitational waves.

- BNS mergers are a promising source for multi-messenger astronomy. They are among the primary sources of gravitational waves.
- GW170817 was the first event where gravitational waves, gamma rays, and electromagnetic counterparts were simultaneously observed, marking a breakthrough in the study of neutron star mergers.
- Several models suggest the emission of both high-energy and low-energy neutrinos.



Low-energy neutrino emission from BNS merger





Low-energy neutrinos (MeVs) are also expected to be emitted during BNS mergers, mostly from three sites:

1) From matter expanding from the contact interface between the two stars at merger and soon after it;
2) From the merger remnant, before collapse;
3) From the innermost, hot part of the post-merger accretion disc.

Several models have been proposed which implement different parameters: progenitor masses, EoS, life of remnants…

…But most of them seem to agree on some points:

- All flavors of neutrinos are expected although $\bar{\nu}_e$ are characterized by higher luminosity;
- Most of the emission is expected within hundreds of milliseconds from the GW emission;
- Luminosity reaches a peak $> 10^{53}$ erg/s;
- Energy ranges from ~5 MeV to 30 MeV;

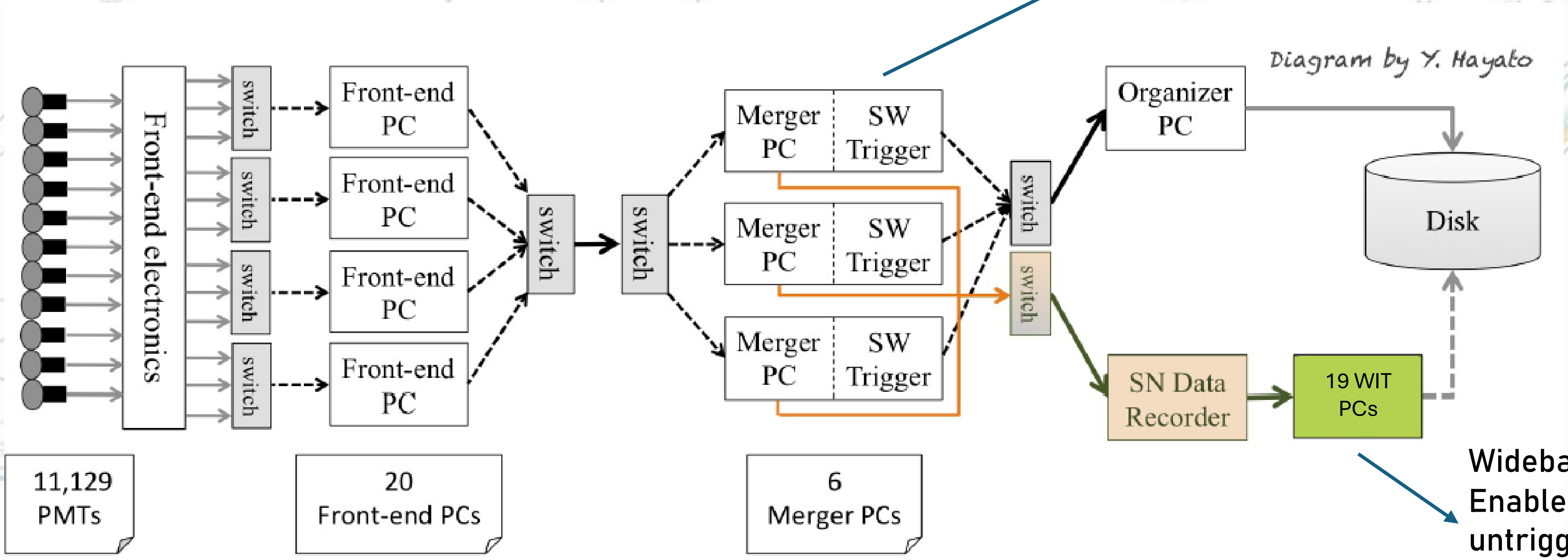
10.1140/epja/s10050-022-00743-5

Super-Kamiokande triggers

Super-Kamiokande employs multiple software triggers, each designed to target the detection of neutrinos within specific energy ranges.

Standard SLE trigger has a 4.5 MeV threshold.

Trigger type	N_{200} threshold $[/\mu s]$	Event window $[\mu s]$	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



Wideband Intelligent Trigger (WIT): Enables real-time processing of the untriggered raw data stream
→Efficiency ~100% down to E_{kin}~2.5 MeV.

Classification of events in Super-Kamiokande

LOW-ENERGY EVENTS (LE)
$E_\nu \sim 3.5 - 100$ MeV

FULLY CONTAINED EVENTS (FC)
$E_\nu \sim 0.1 - 10$ GeV
$\Delta\theta \sim 10°\text{-}100°$

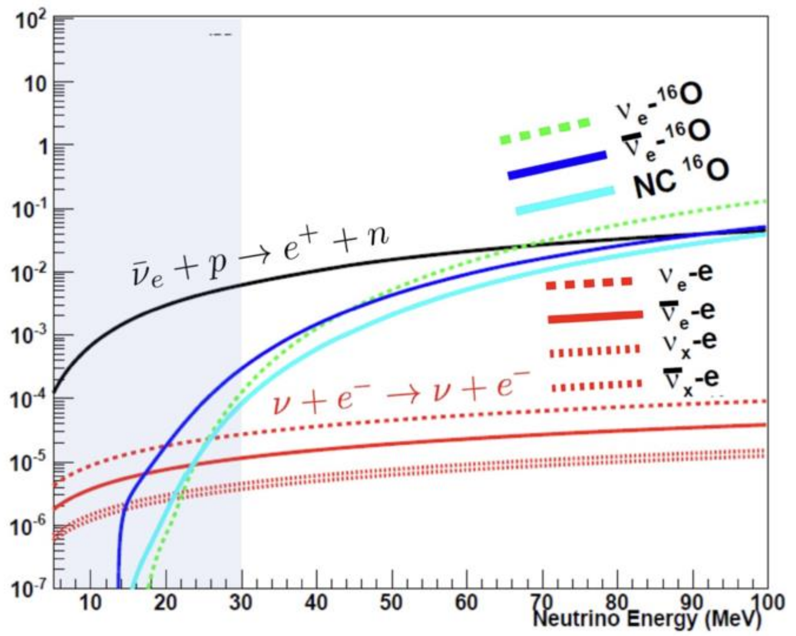
PARTIALLY CONTAINED EVENTS (PC)
$E_\nu \sim 0.1 - 100$ GeV
$\Delta\theta \sim 10°$

UPGOING MUONS (UPMU)
$E_\nu \sim 1.6 - 10^3$ GeV
$\Delta\theta \sim 3°\text{-}10°$

INCREASING ENERGY

Low-energy events

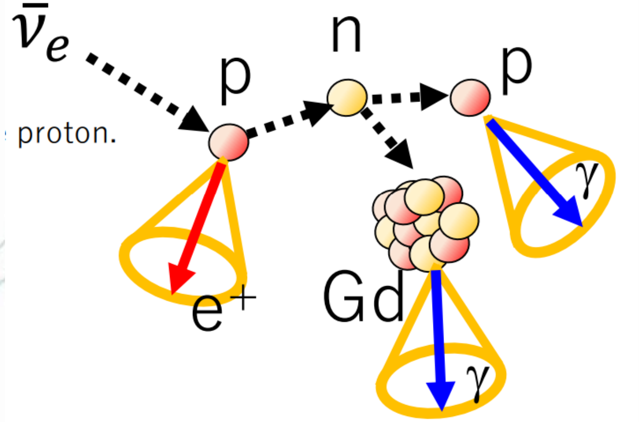
In the MeV energy range, the two main neutrino interactions in water Cherenkov detectors are:



LE neutrino interactions cross section

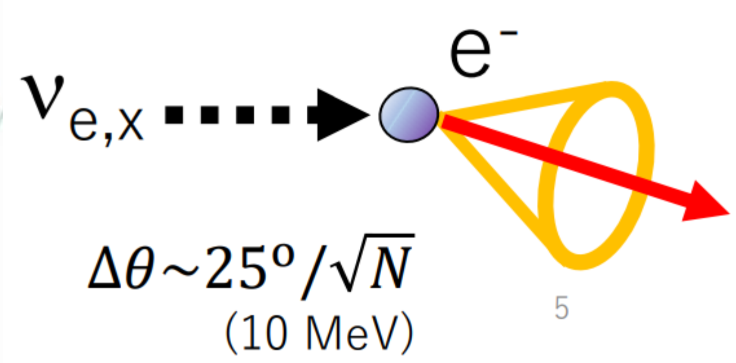
Inverse beta decay (IBD)

DSNB Selection → Looking for $\bar{\nu}_e$



Electron scattering (IBD)

Solar Neutrino Selection → Looking for ν_e



With low energy events produced via IBD, we can't extract the information about neutrino direction, while via electron scattering it is possible.

▷ Separating ES from IBD allows to improve the direction pointing accuracy of the detector;
▷ In SK-Gd phase we can enhances the tagging of IBD events thanks to the characteristic delayed coincidence between the IBD's positron emission and delayed neutron capture