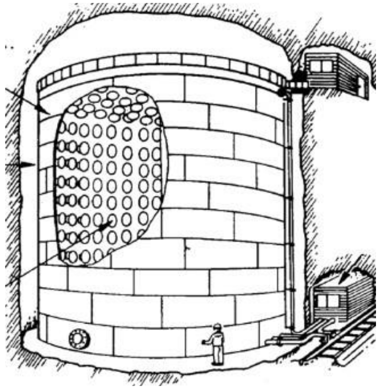
Hyper-Kamiokande
Experiment status and its supernova neutrino physics potential

Gianfranca De Rosa on behalf of Hyper-Kamiokande Collaboration

SNvD 2023@LNGS: International Conference on Supernova Neutrino Detection

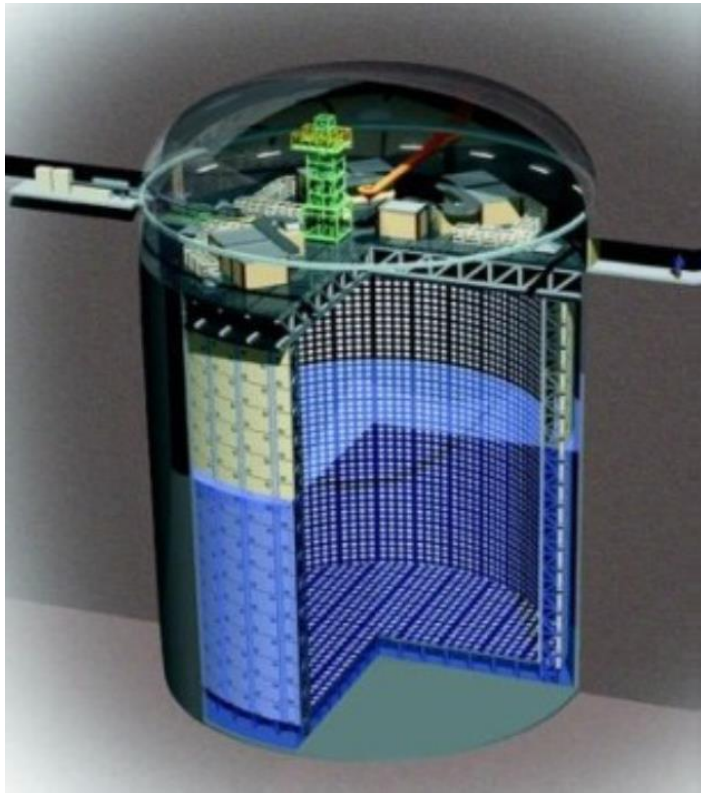
Neutrino Water Cherenkov Detectors in Japan



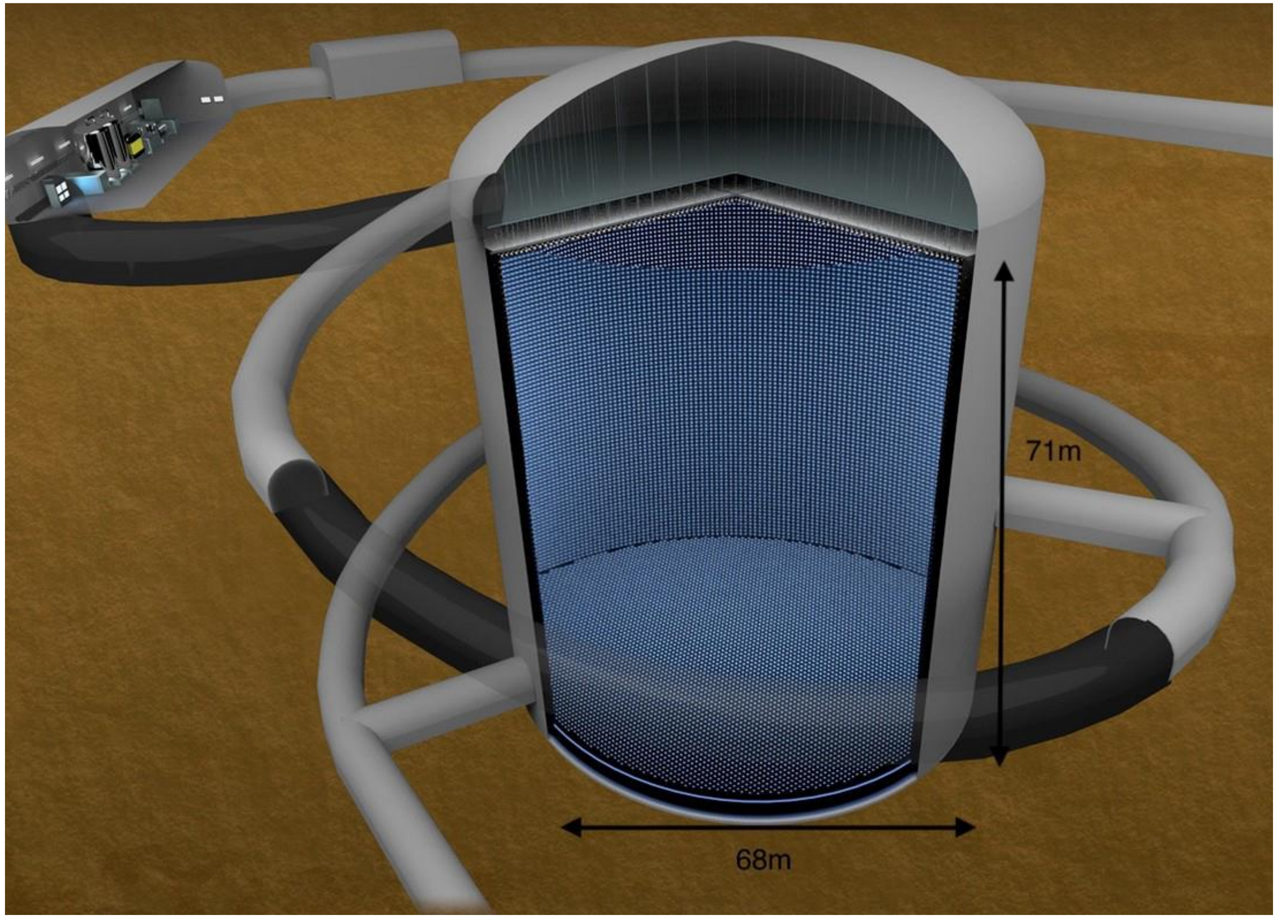
Kamiokande
- 1983 – 1996
- 3 kton total
- 680 ton fiducial

Observation of SN987A

Neutrino astronomy era



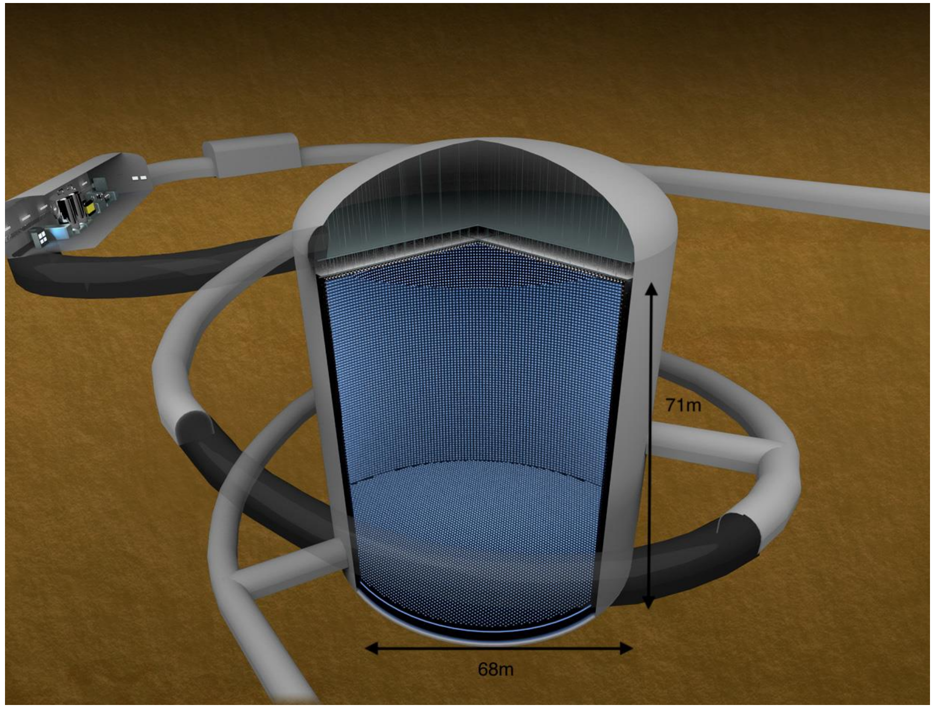
Super-Kamiokande
- 1996 – 2020 (w/o Gd)
  2020 – present (w/ Gd)
- 50 kton total
- 22.5 kton fiducial



Hyper-Kamiokande
- 2027 –
- 258 kton total
- 188 kton fiducial

8.4 times larger fiducial volume than Super-Kamiokande

Hyper-Kamiokande: overview

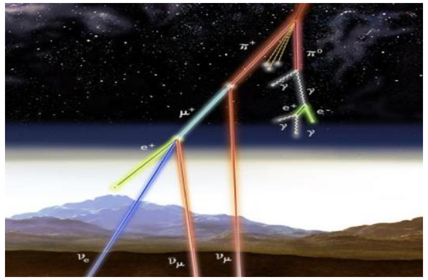


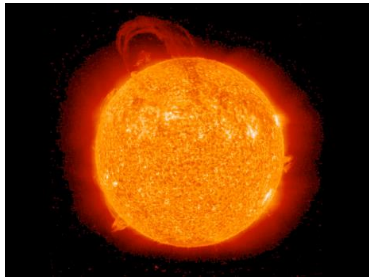
Hyper-Kamiokande (Hyper-K) is a multi-purpose **Water-Cherenkov detector** with a variety of scientific goals:

✧ Neutrino oscillations (atmospheric, accelerator and solar);
✧ Neutrino astrophysics;
✧ Proton decay;
✧ Non-standard physics.

Low energy threshold combined with a very large fiducial volume

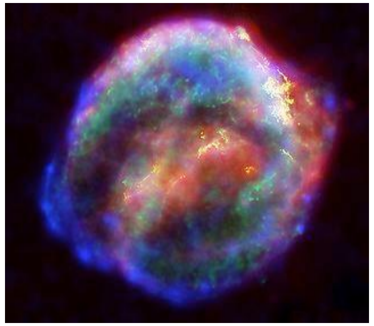
Atmospheric ν



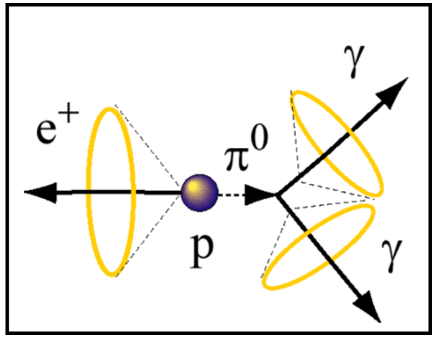


Solar ν

Supernova ν

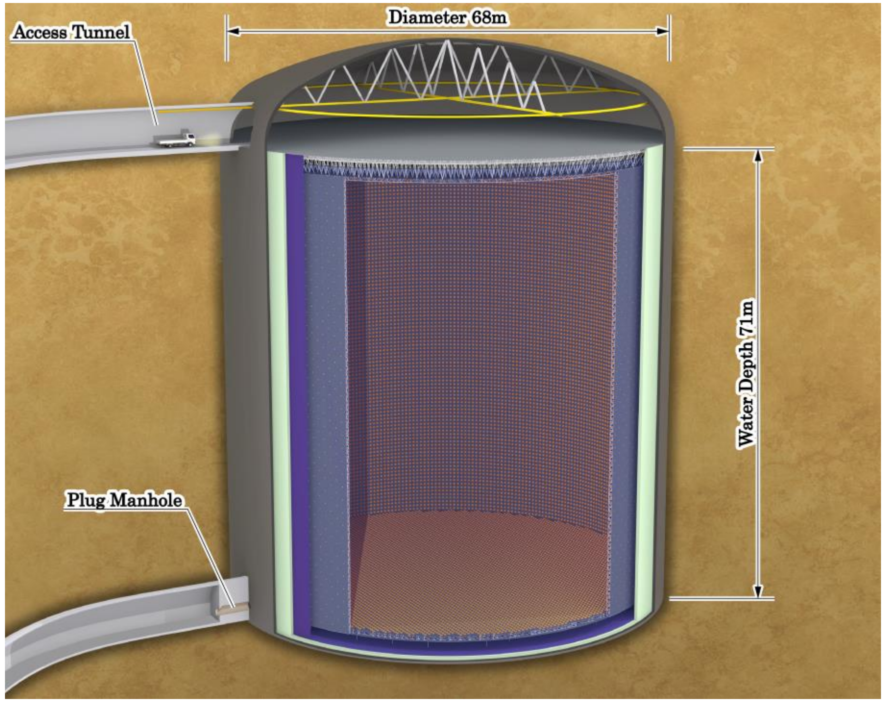


Accelerator ν



Proton decay

Hyper-Kamiokande design



Hyper-K builds on the successful strategies used to study neutrino oscillations in Super-Kamiokande, K2K and T2K with:

- ➢ Larger detector for increased statistics
- ➢ Improved photo-sensors for better efficiency
- ➢ Higher intensity beam and updated/new near detector for accelerator neutrino part

Hyper-K is under construction

Operation is expected to begin in 2027

Hyper-K Far Detector (HK-FD)

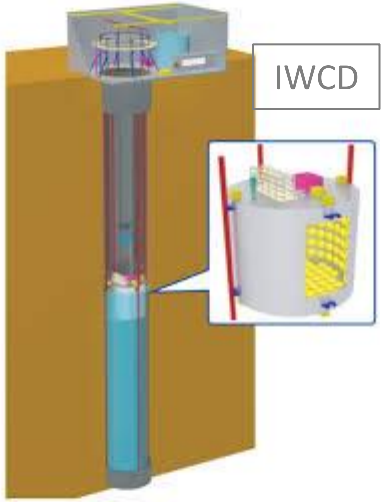
- ➢ Cylindrical tank: Φ 68 m and H 71 m
- ➢ Fiducial volume: 0.19Mtons;

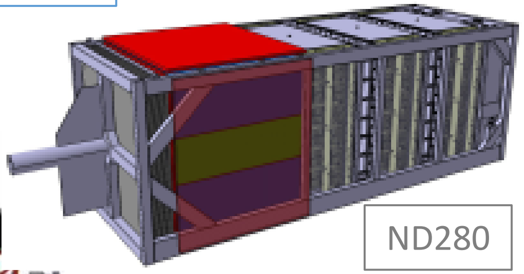
  ~ × 8 SK → HK-FD

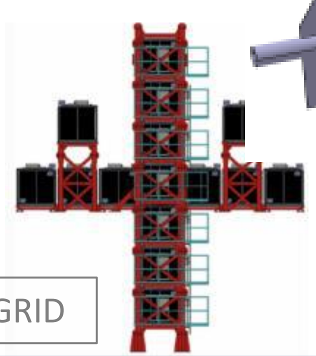
Intermediate Water Cherenkov Detector (IWCD)

- ➢ 1 kilo-ton scale water Cherenkov detector located ~1 km from the neutrino beam source

HyperK near detectors







Photodetectors

Requirements

Wide dynamic range

High time&charge resolutions, high detection efficiency, ..

~nsec time resolution

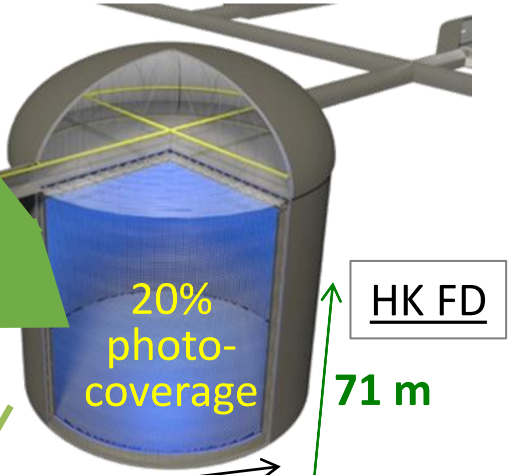
low background

Clear photon counting,

High rate tolerance

multi-PMT

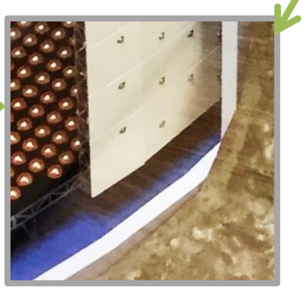
Box&Line PMT



HK FD

for 1 tank

Outer Veto Detector
3’’ waterproof PMT



Fiducial volume:
188 kt

New high-QE 20’’ Box&Line PMT

× 2 high pressure bearing

× 2 high detection efficiency
and half time&charge resolutions

compared to Super-K PMT

Multi-PMT

Firstly proposed by KM3Net Collaboration

Photodetectors and electronics arranged inside a pressure resistent vessel

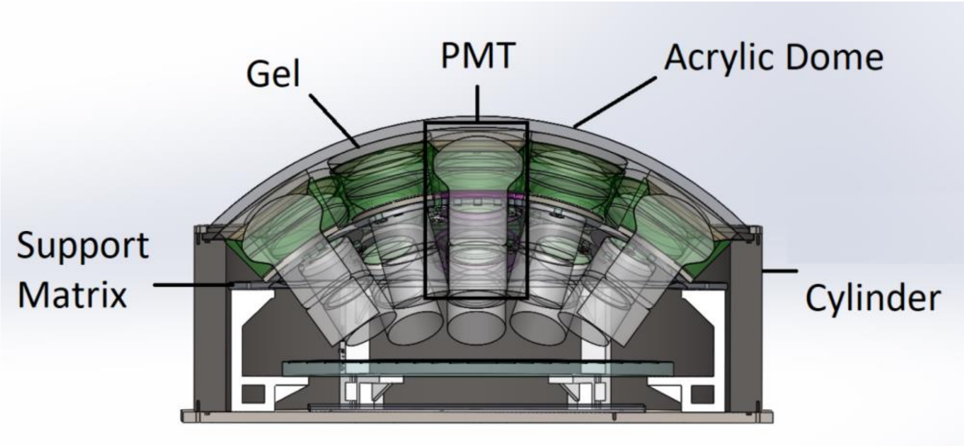
Increased granularity

Enhanced event reconstruction, in particular for multi-ring events

HK FD
ID Hybrid Design:
20’’ PMTs and mPMTs

IWCD
mPMTs

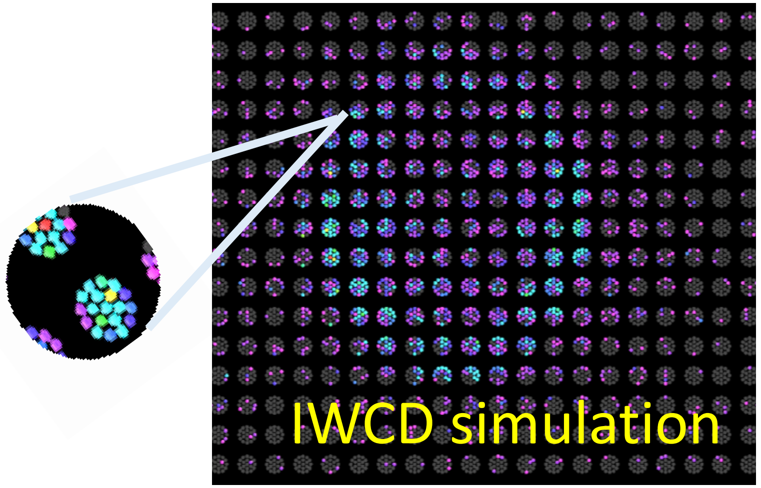
The mPMT Option



ID-mPMT (19 PMTs)

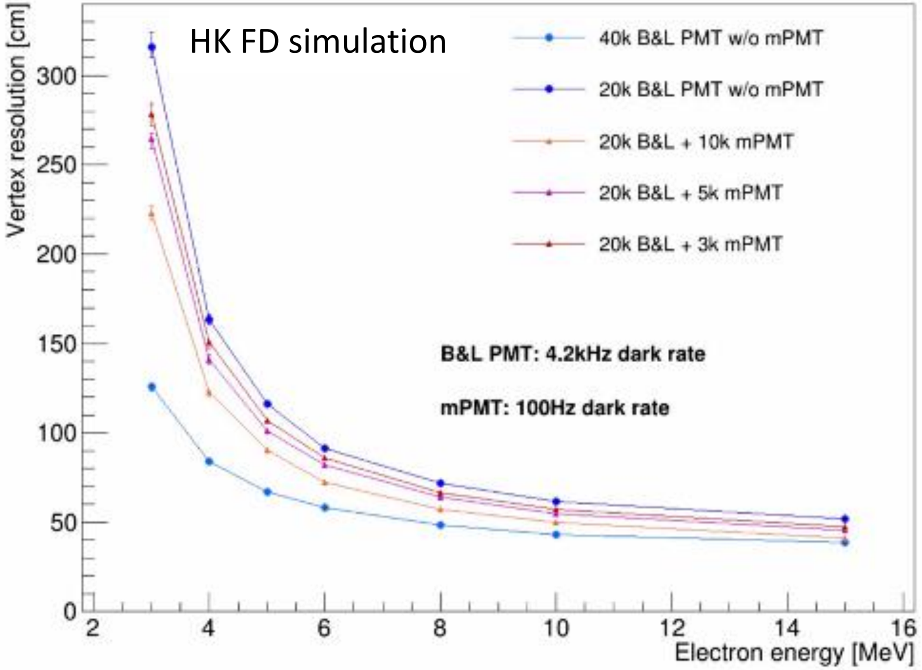
Advantages:

- Superior photon counting
- Improved angular acceptance
- Extension of dynamic range
- Intrinsic directional sensitivity
- Local coincidences

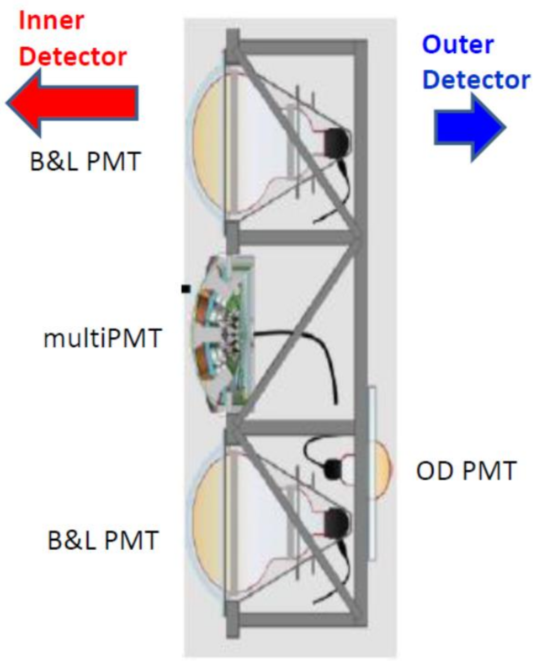


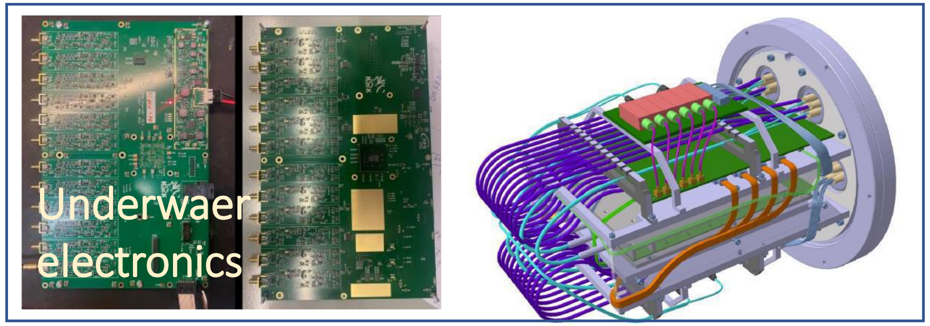
HK FD Simulation studies
Preliminary results:

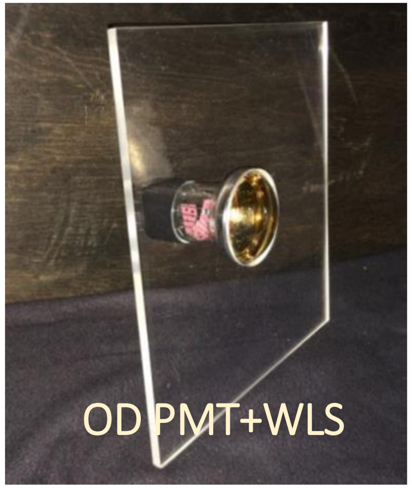
- Vertex and angular resolution better for low energy
- At high energy: muon/electron separation improved near the wall; vertex resolution improved
- Improvements strongest near edges of FV

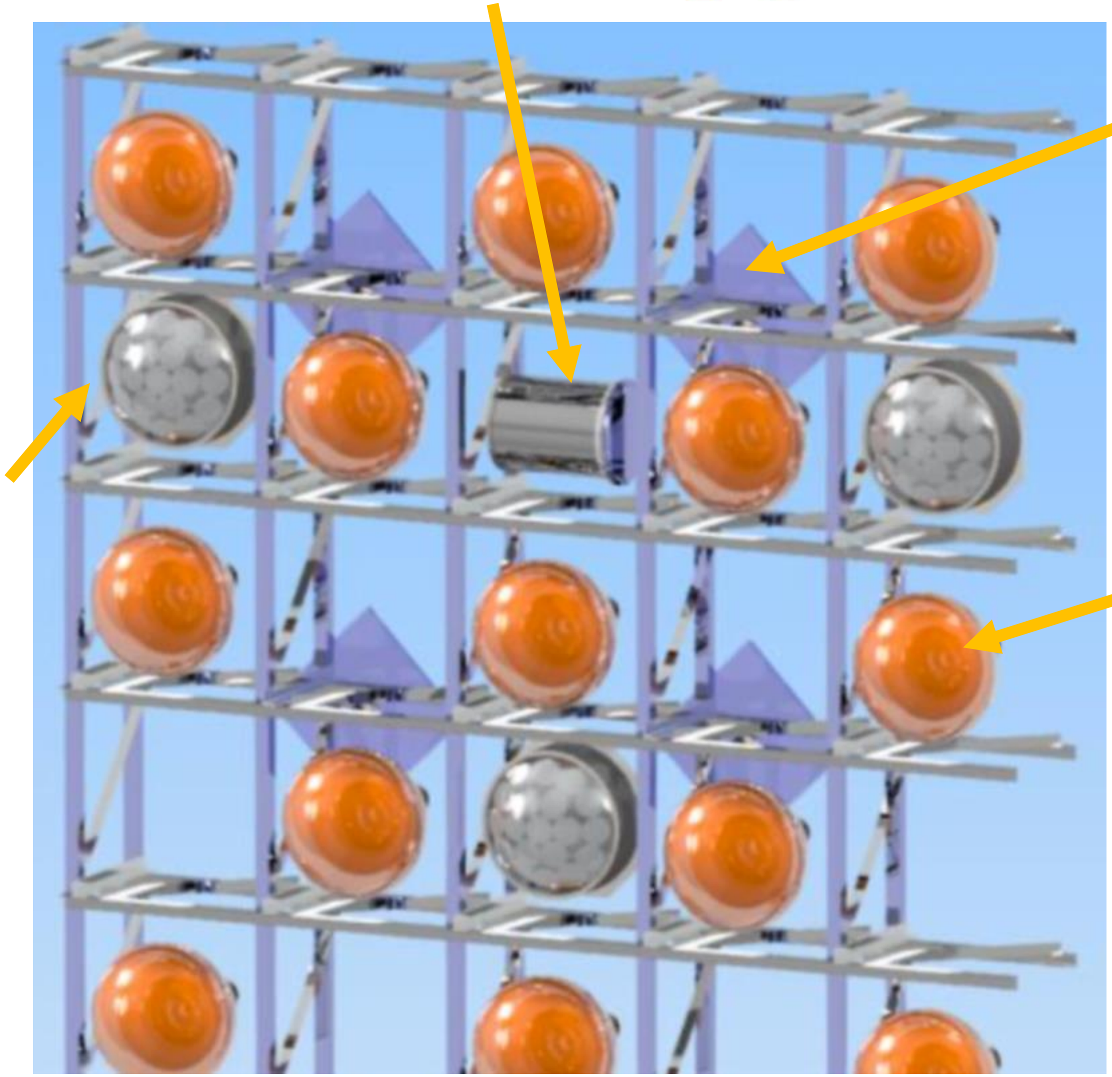


Improvements for Cherenkov ring reconstruction and reference for detector calibration


Inner Detector
Outer Detector
B&L PMT
multiPMT
OD PMT
B&L PMT


Underwaer electronics

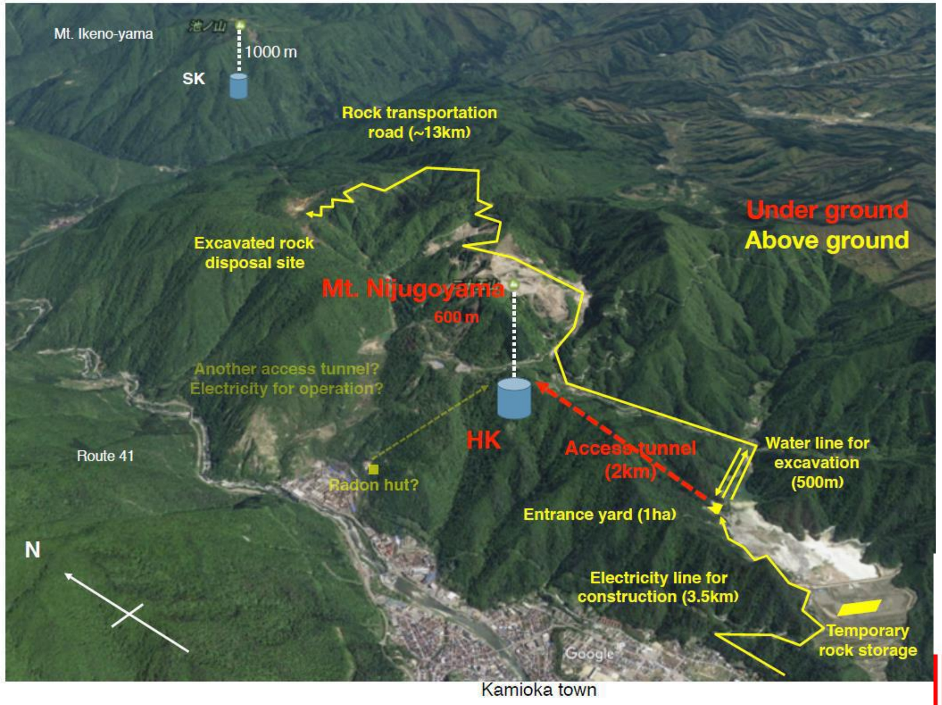

OD PMT+WLS



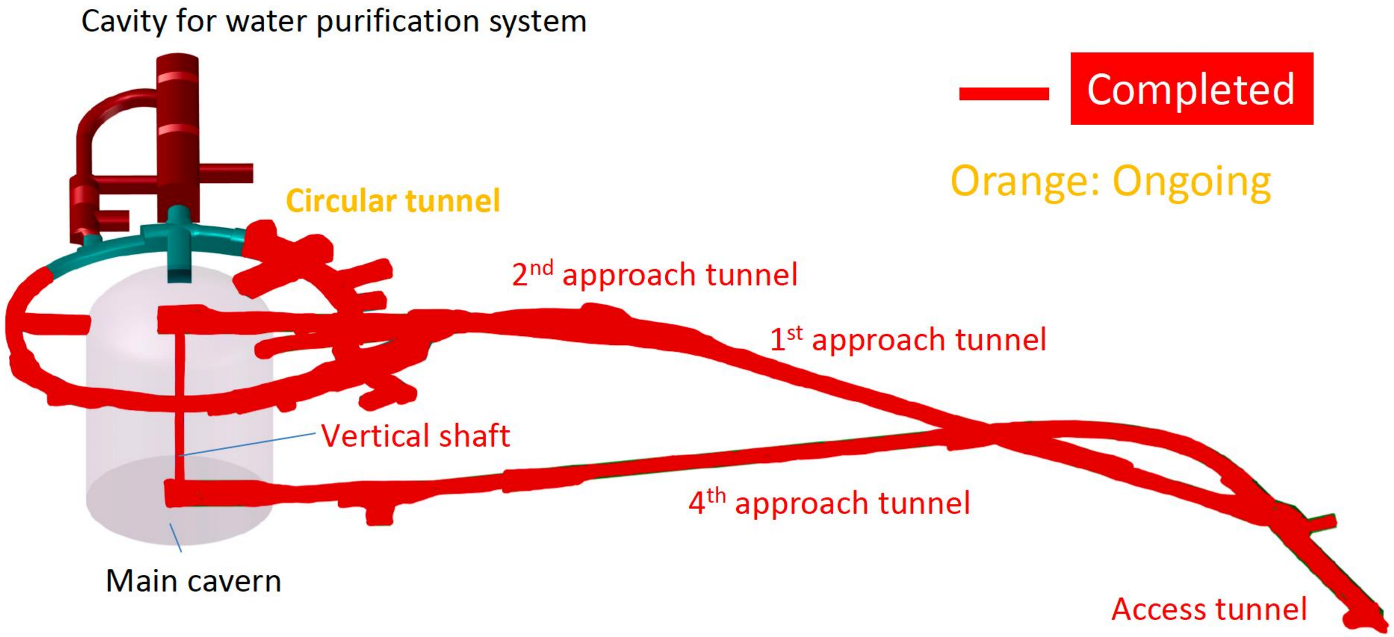

mPMT

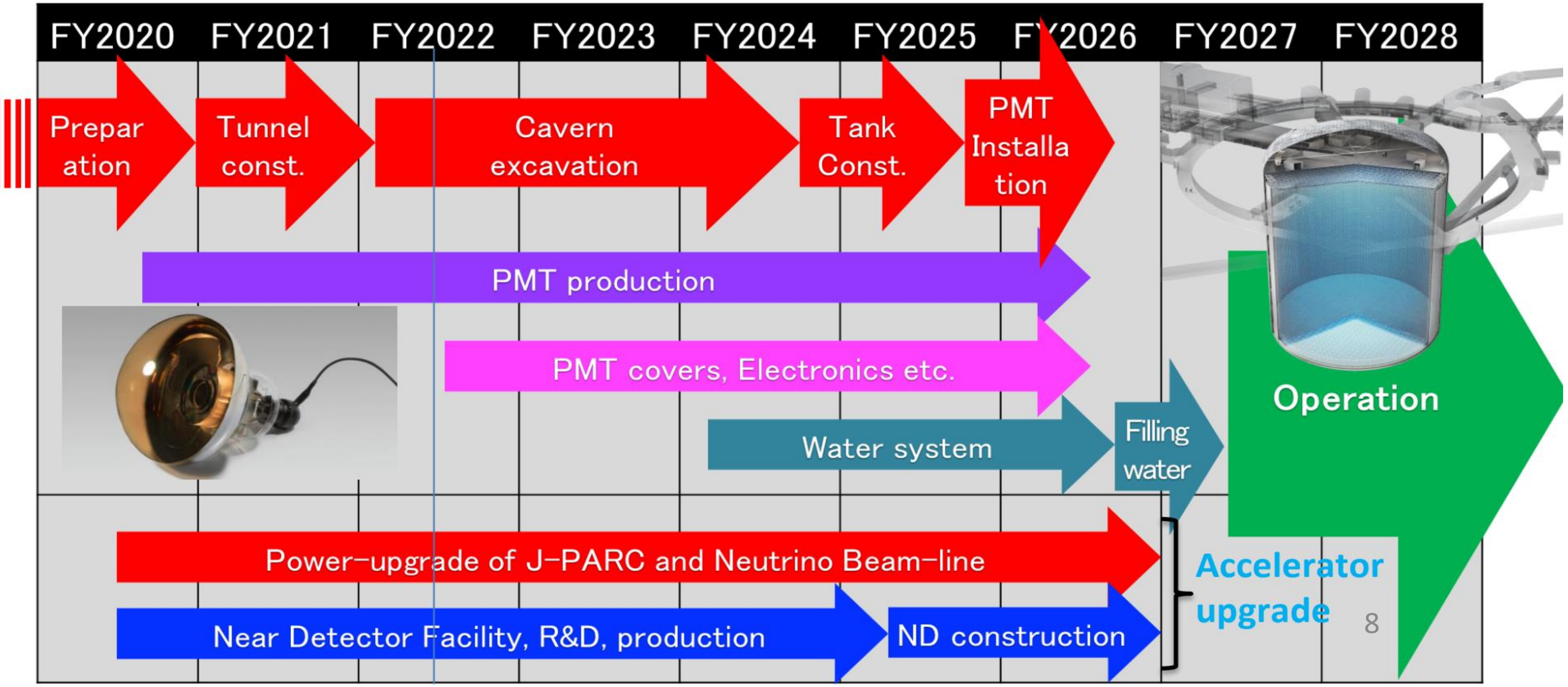

20” Box&Line PMT

Hyper-K construction



- Excavation of the access tunnel (2 km) completed
- Approach & circular tunnel excavation are over.
- Main cavern excavation has started
- **Everything on track!**





Hyper-K construction

Entrance yard finished (Aug. 2020)

2021/05 : ground-breaking ceremony

©Institute for Cosmic Ray Research, The University of Tokyo

Tunnel entrance (June 2021)

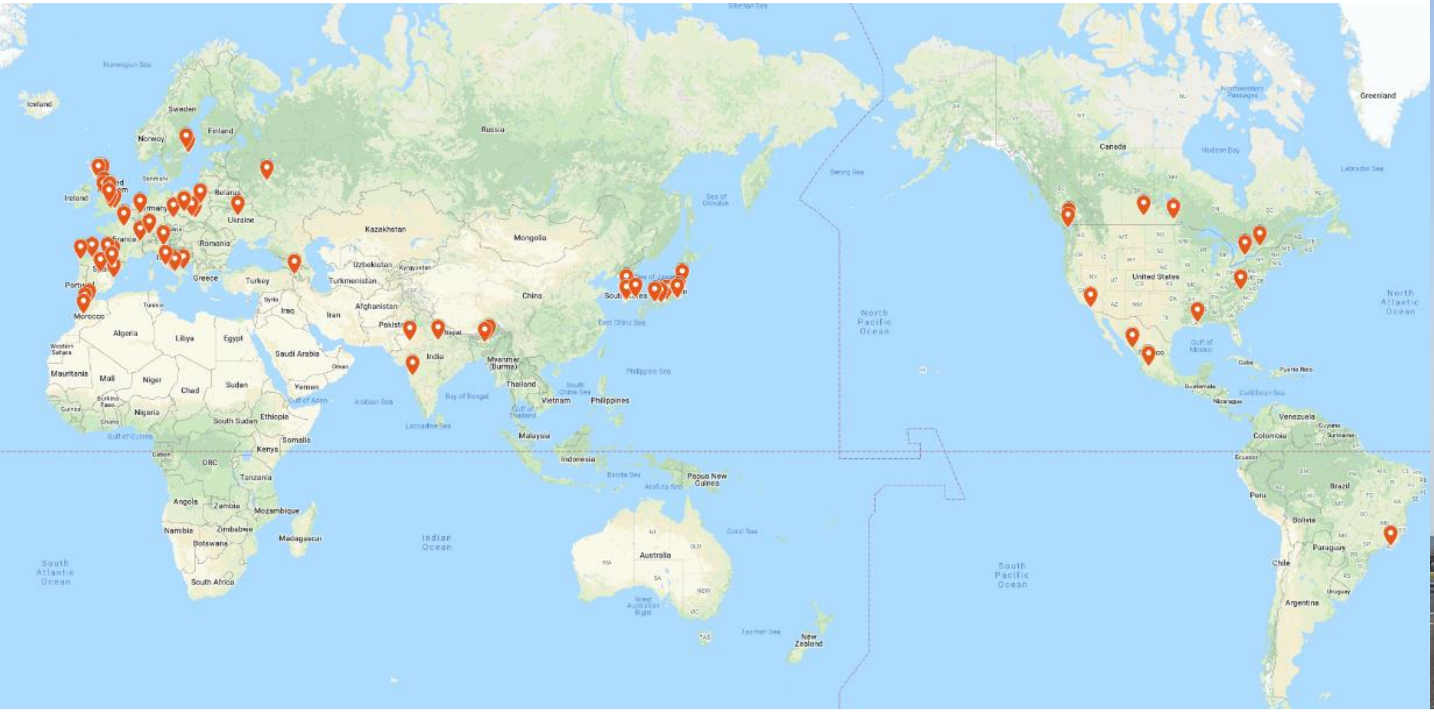
New building finalized
Summer 2022

Center of the future Hyper-K Main Cavern's Dome reached on June 2022

Excavation of the future Hyper-K Main Cavern's Dome ongoing

PMT production started

The Hyper-Kamiokande collaboration




March 2023 : our very 1st collaboration meeting in person after Covid !

~ 500 collaborators from all around the world working together, sharing expertise and building a milestone in particle physics

~ 100 institutes from ~ 20 countries

UTokyo and KEK host the project

Neutrino astronomy in Hyper-Kamiokande

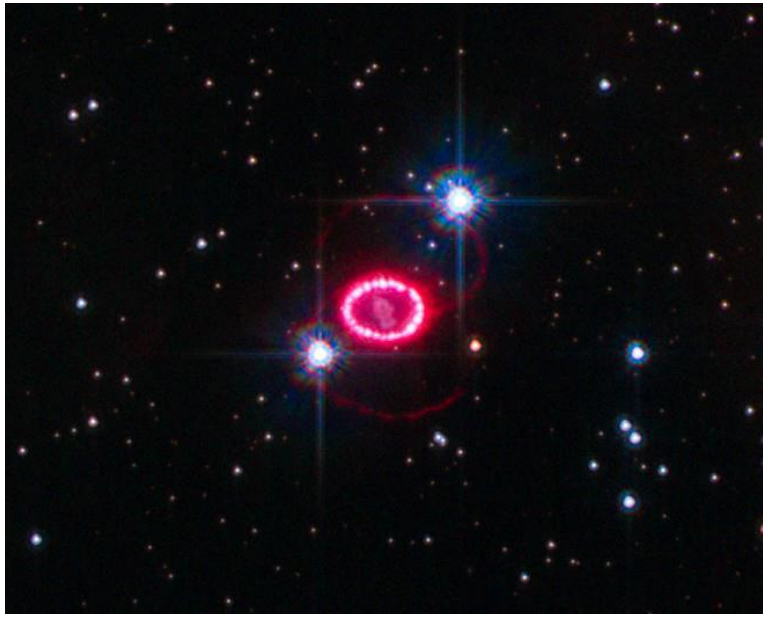
Astrophysical neutrinos are a unique probe to assess various physical phenomena in the universe

By searching for neutrinos in conjunction with other astronomical phenomena, Hyper-K will take a unique role as multi-messenger observatory

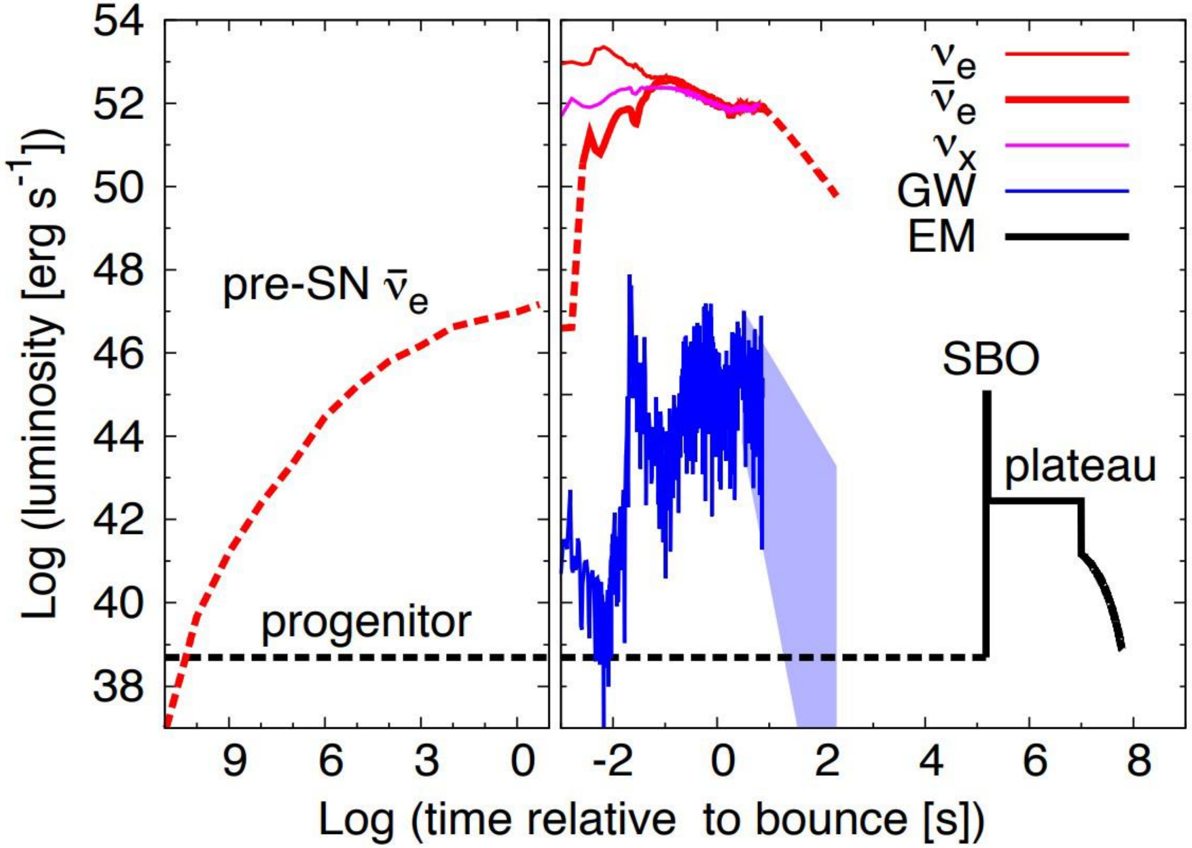
Hyper-K will expand on the successful multi-messenger science program of Super-Kamiokande

In particular, it has the potential to detect neutrinos in coincidence with gravitational waves

Core-Collapse Supernova Neutrinos



Since 1987A supernova (SN), we know that in case of supernova a burst of neutrino is expected to be produced few minutes to several hours before the stellar explosion.
If the SN is close enough, we can detect this burst on Earth and give an early warning to astronomers looking for the light from the stellar explosion.

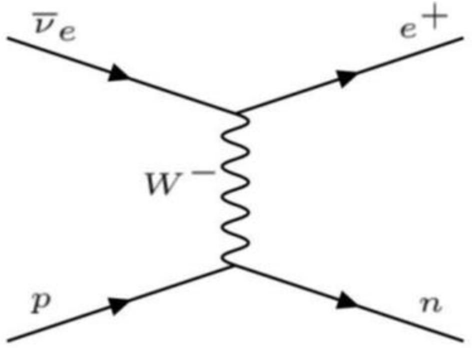


MNRAS, 461, 3296 (2016) arXiv:1602.03028

The observation of neutrinos from SN1987A was consistent with basic features predicted by the delayed neutrino-driven explosion mechanism with the presence of an accretion phase in the first 500 ms

Supernova Neutrino Interactions in Hyper-Kamiokande

Dominant cross-section is inverse beta decay (IBD)



$\overline{\nu}_e + p \rightarrow e^+ + n$

~90% of the expected interactions

Positron emission is (roughly) nondirectional

Sub-dominant interaction

Elastic scattering $\nu + e \rightarrow \nu + e$

~5% of the expected interactions

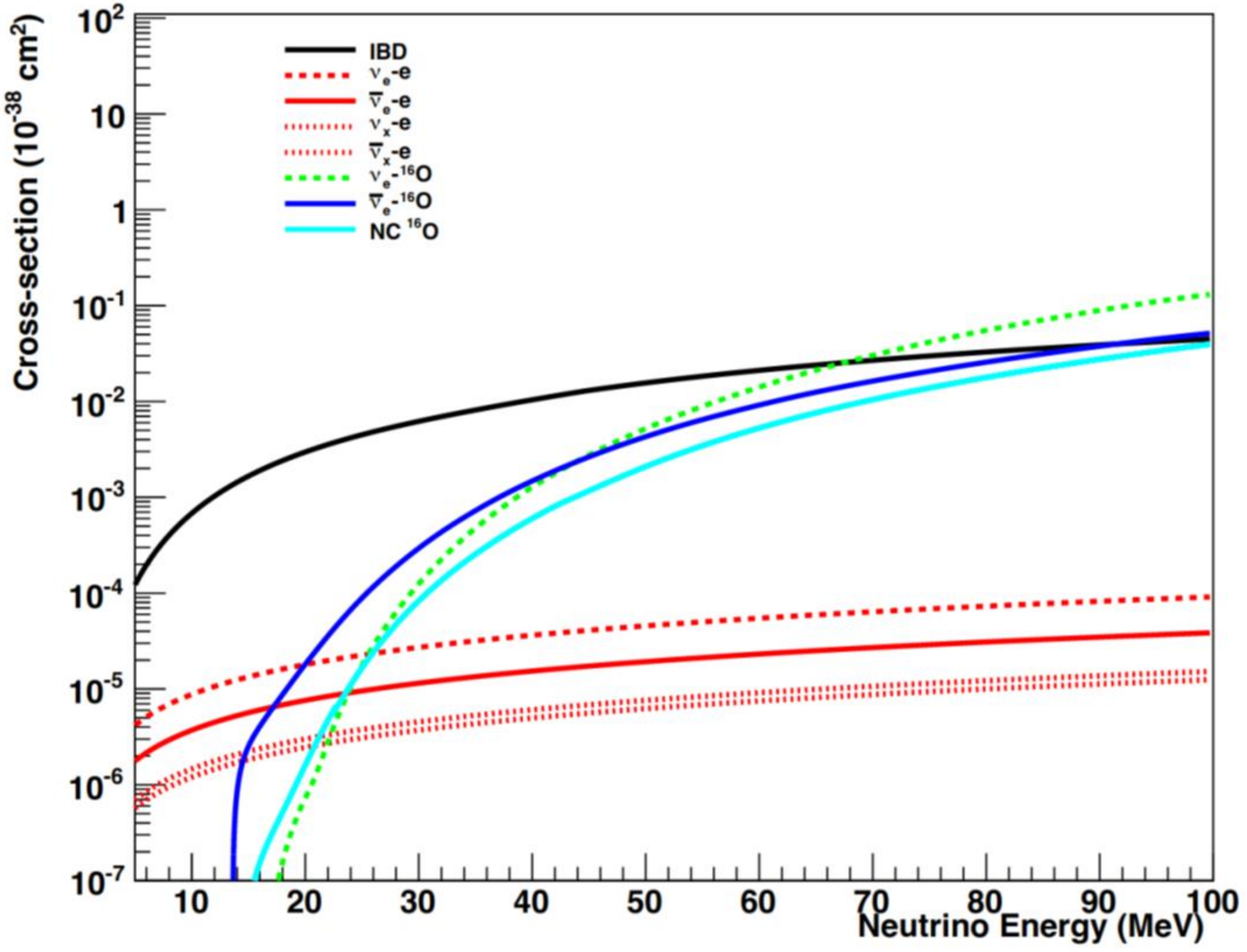
Preserves direction information

Other modes

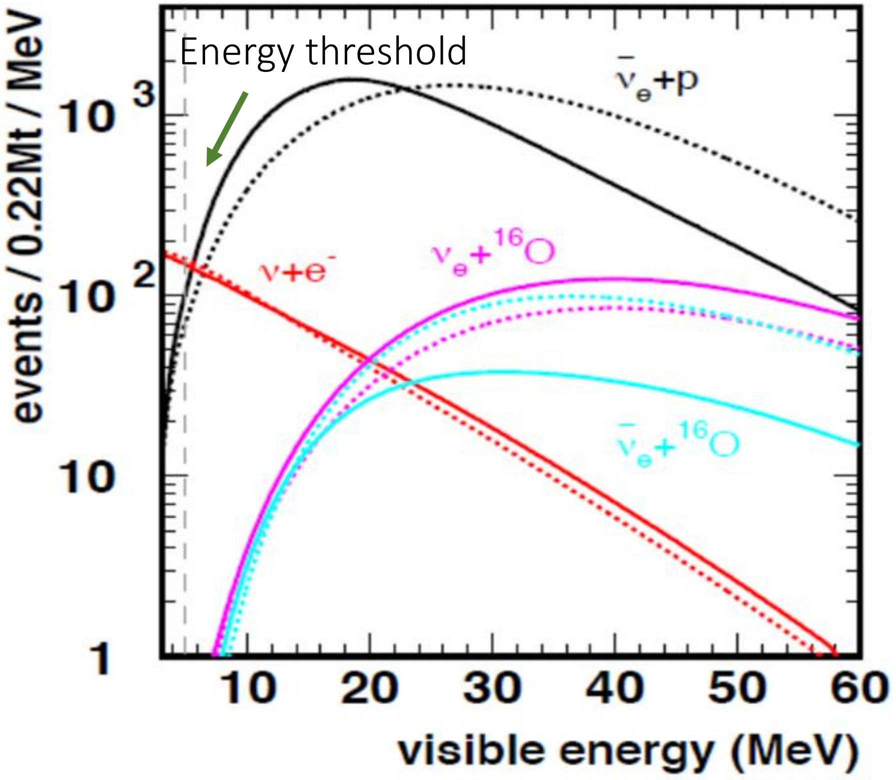
Highly model dependent, due to threshold effects

e.g. $\nu_e + {}^{16}O \rightarrow e + {}^{16}F$ ($E_{thresh} = 15$ MeV)

~5% of the expected interactions



Supernova Neutrinos in Hyper-Kamiokande



True energy spectra of prompt events in the ID for a supernova at 10 kpc. Solid (dashed) lines correspond to normal (inverted) mass ordering

K. Abe *et al* 2021 *ApJ* **916** 15

IBD is responsible for about 90% of events

→ Hyper-Kamiokande most sensitive to $\bar{\nu}_e$

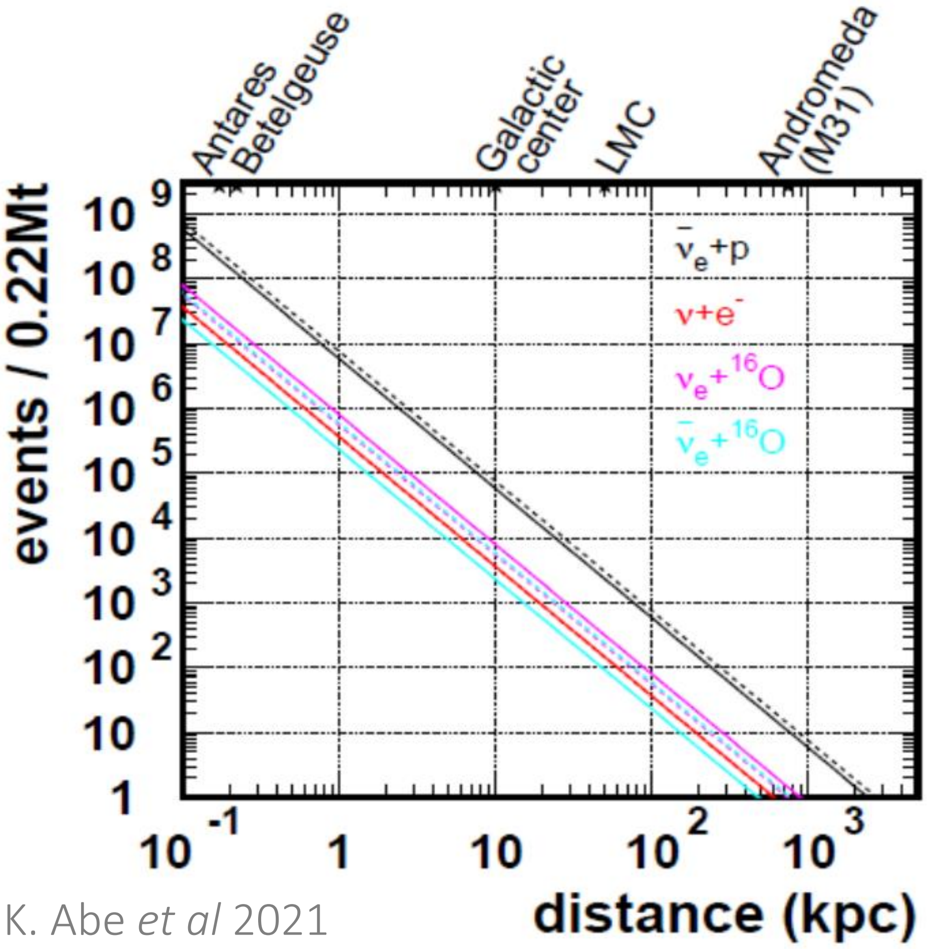
Elastic neutrino-electron scattering subdominant interaction channel to which all neutrino flavours contribute
Angular distribution ES electrons strongly peaked into a forward direction

→ can be used to determine the direction of a supernova at the fiducial distance of 10 kpc with an accuracy of about 1°

→ essential for distributing early alerts and multi-messenger observations.

Charged-current interactions on O nuclei are subdominant channels: sensitive probe of the high-energy tail of the supernova neutrino flux

Supernova Neutrinos in Hyper-Kamiokande



K. Abe *et al* 2021
ApJ **916** 15

In case of Galactic supernova at a distance of 10 kpc, Hyper-Kamiokande is expected to observe 54 000 to 90 000 events in a burst with a duration of a few tens of seconds.
For a nearby supernova (e. g. Betelgeuse at 0.2 kpc), the peak event rate could reach 10^8 Hz.
This rate was taken into account during the design of the DAQ system.

The large volume also gives Hyper-Kamiokande an unprecedented ability to detect neutrinos from supernovae beyond the Milky Way:
For a supernova in the Large Magellanic Cloud at 50 kpc distance, it would still detect about 3000 events, while for a supernova in the Andromeda galaxy (M31) at 780 kpc distance, O(10) events are expected.

SN1987A at 50 kpc, only 11 events in Kamiokande

Supernova Neutrinos search in Hyper-Kamiokande

A likelihood-based model discrimination analysis has been developed
Full time and energy information are used to identify which supernova model best matches a set of observed events
”Supernova Model Discrimination with Hyper-Kamiokande”, K. Abe *et al* 2021 *ApJ* **916** 15

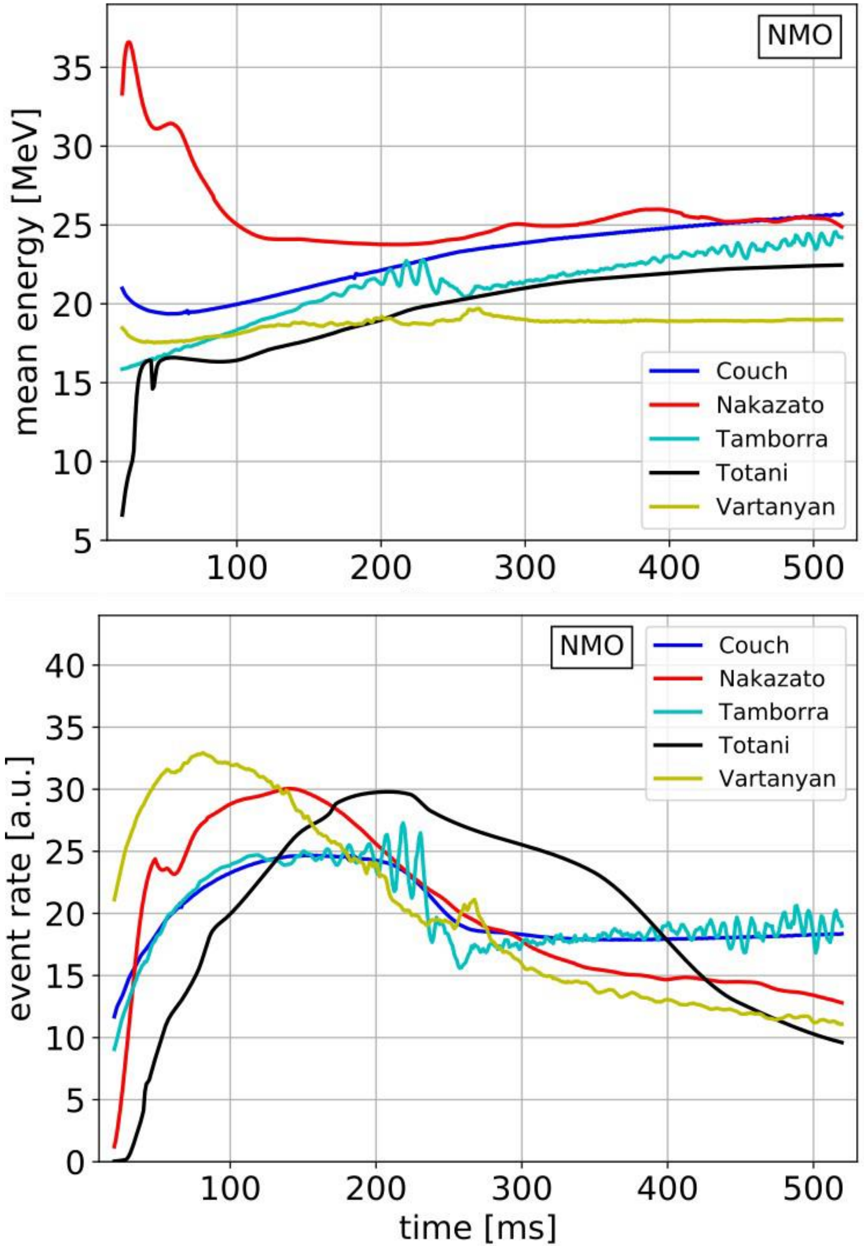
Newly-developed, high-precision supernova event generator and realistic detector simulation and event reconstruction

Investigate Hyper-Kamiokande's response to five supernova models simulated focusing on the prompt signal from the charged lepton in all interaction channels

Just 100 (300) events within the first 500 ms of the supernova burst to distinguish between different supernova models with good accuracy

Supernova Neutrinos in Hyper-Kamiokande: Model Discrimination

Model	Mass		events at 10 kpc*	N=100	N=300
Totani arXiv:astro-ph/9710203	20 $M_\odot$	1D	19716	140 kpc	81 kpc
Nakazato arXiv:1210.6841	20 $M_\odot$	1D	17978	134 kpc	77 kpc
Couch arXiv:1902.01340	20 $M_\odot$	1D	27539	166 kpc	96 kpc
Vartanyan similar to arXiv:1804.00689	9 $M_\odot$	2D	10372	102 kpc	59 kpc
Tamborra arXiv:1406.0006	27 $M_\odot$	3D	25021	158 kpc	91 kpc



Assuming the distance to the supernova unknown; event rate normalized to produce the same total number of events for each model

Only time and energy structure to distinguish between models

100 (300) events corresponding to a supernova distance of at least 102 kpc (59 kpc) required to separate the models

The lower data set size was chosen in order to determine the lowest number of events needed to separate the models

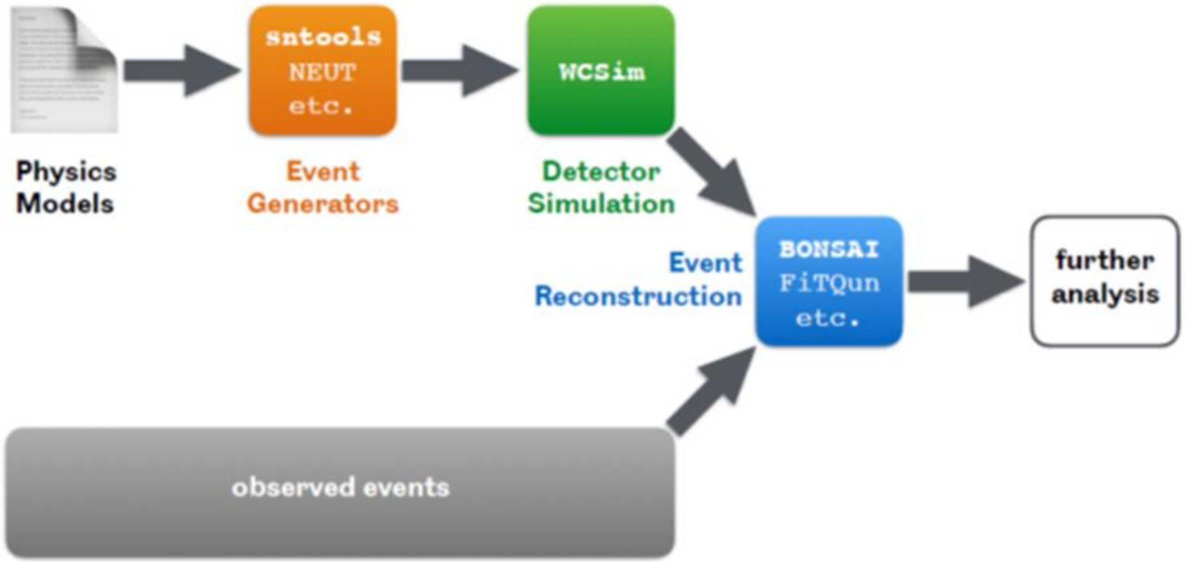
* during 20 – 520 ms after core bounce, assuming Normal Mass Ordering

Supernova Neutrinos in Hyper-Kamiokande: Event Generator

Sntools:

Event generator for supernova burst neutrinos

- Uses most modern & precise cross sections for main interaction channels
- Modular and easily extensible
- Written in Python
- Originally designed for Hyper-Kamiokande using water target
- Extended to include liquid scintillator and water-based liquid scintillator
- Adopted by other experiments / proposed experiments, incl. SNO+, WATCHMAN, THEIA

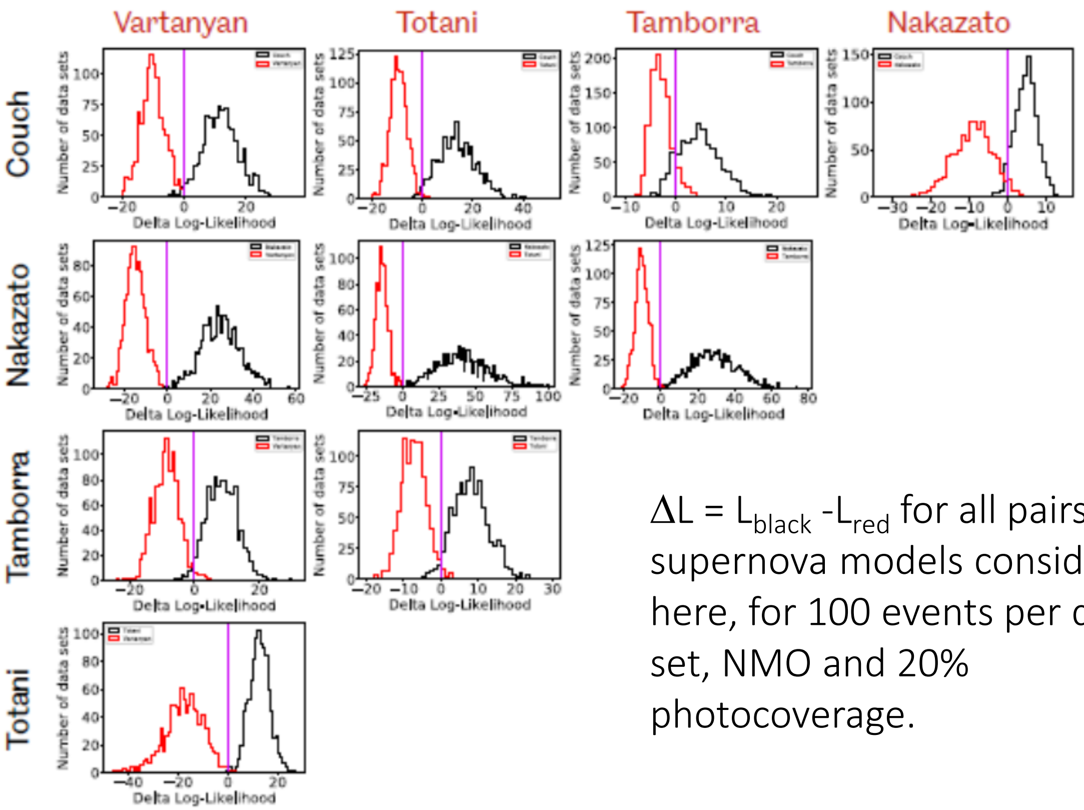


Open source:
https://github.com/JostMigenda/sntools
Migenda *et al.*, *JOSS* 02877 (2021)

sntools available as a library & use it from other code

Supernova Neutrinos in Hyper-Kamiokande: Likelihood Analysis

- **Generation:** *Sntools* was used to generate 1000 data sets for each model
  - Normal & inverted mass ordering both considered
  - N = 100 and 300 events per data set
- **Simulation:** Full detector simulation was run for all data sets
- **Reconstruction & reduction:**
  - Full event reconstruction was applied to the simulated data
  - 5 MeV threshold cut on reconstructed energy to eliminate low-E backgrounds
  - Vertex required to be inside HK fiducial volume
  - 80 – 85% of events remain after applying trigger simulator and cuts



$\Delta L = L_{black} - L_{red}$ for all pairs of supernova models considered here, for 100 events per data set, NMO and 20% photocoverage.

- **Analysis:** For each data set, calculate the unbinned log-likelihood *L* for each SN model

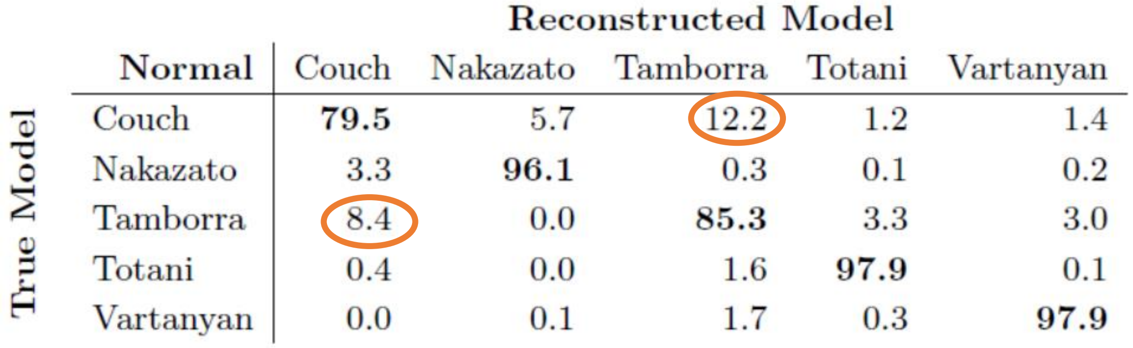
$$L = \ln \mathscr{L} = \sum_{\text{evt } i} \ln\left(\frac{d^2N(t_i, E_i)}{dt\, dE}\right) - N_{\text{exp}}$$

Based on: Loredo & Lamb, *Annals N.Y. Acad. Sci.* **571**:601 (1989)

Supernova Neutrinos in Hyper-Kamiokande: Model Discrimination Accuracy

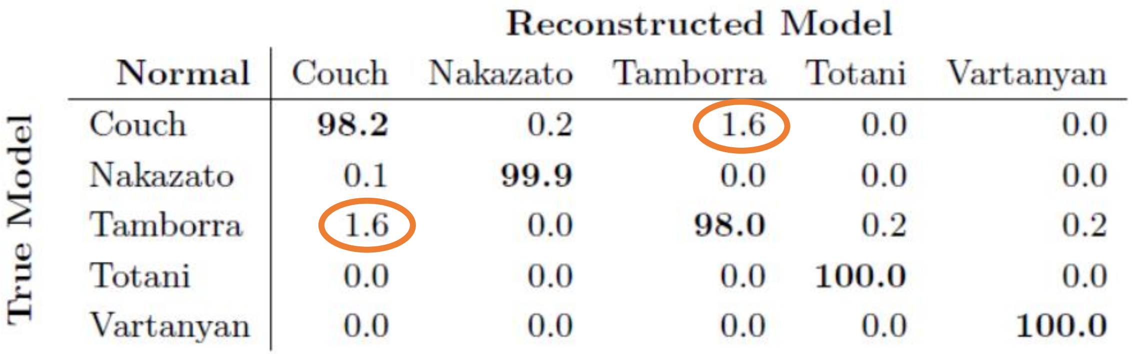
Fraction of the 1000 data sets generated for a given model identified as each of the five models

100 events per data set

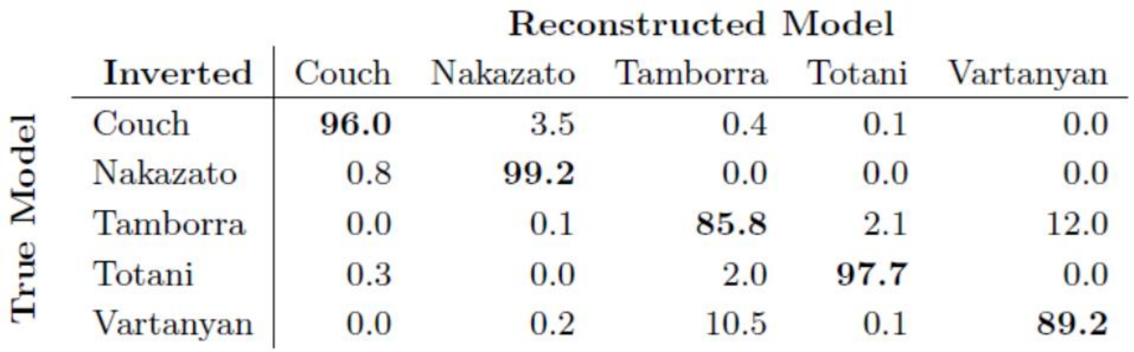


		Reconstructed Model				
	Normal	Couch	Nakazato	Tamborra	Totani	Vartanyan
True Model	Couch	**79.5**	5.7	12.2	1.2	1.4
	Nakazato	3.3	**96.1**	0.3	0.1	0.2
	Tamborra	8.4	0.0	**85.3**	3.3	3.0
	Totani	0.4	0.0	1.6	**97.9**	0.1
	Vartanyan	0.0	0.1	1.7	0.3	**97.9**

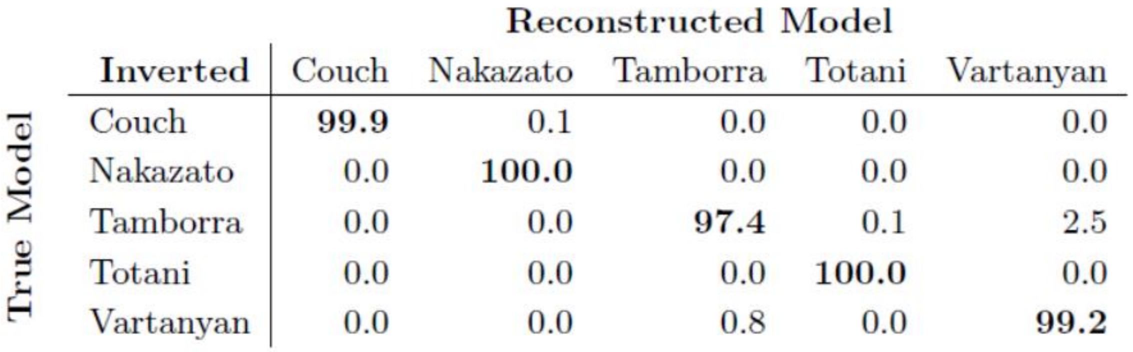
300 events per data set



		Reconstructed Model				
	Normal	Couch	Nakazato	Tamborra	Totani	Vartanyan
True Model	Couch	**98.2**	0.2	1.6	0.0	0.0
	Nakazato	0.1	**99.9**	0.0	0.0	0.0
	Tamborra	1.6	0.0	**98.0**	0.2	0.2
	Totani	0.0	0.0	0.0	**100.0**	0.0
	Vartanyan	0.0	0.0	0.0	0.0	**100.0**



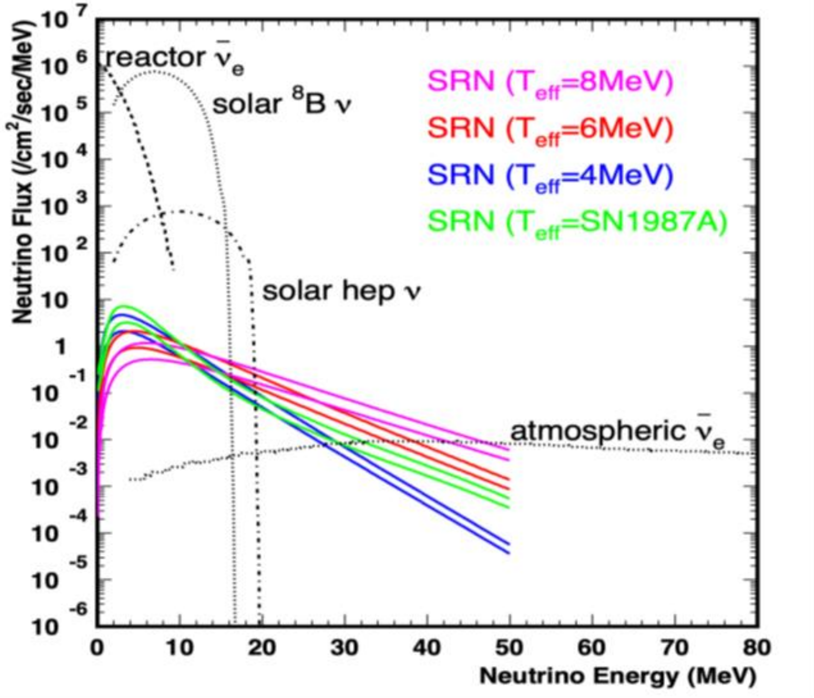
		Reconstructed Model				
	Inverted	Couch	Nakazato	Tamborra	Totani	Vartanyan
True Model	Couch	**96.0**	3.5	0.4	0.1	0.0
	Nakazato	0.8	**99.2**	0.0	0.0	0.0
	Tamborra	0.0	0.1	**85.8**	2.1	12.0
	Totani	0.3	0.0	2.0	**97.7**	0.0
	Vartanyan	0.0	0.2	10.5	0.1	**89.2**



		Reconstructed Model				
	Inverted	Couch	Nakazato	Tamborra	Totani	Vartanyan
True Model	Couch	**99.9**	0.1	0.0	0.0	0.0
	Nakazato	0.0	**100.0**	0.0	0.0	0.0
	Tamborra	0.0	0.0	**97.4**	0.1	2.5
	Totani	0.0	0.0	0.0	**100.0**	0.0
	Vartanyan	0.0	0.0	0.8	0.0	**99.2**

When considering larger data sets, the effect of random fluctuations between individual data sets will decrease and the accuracy of model identification increase

SRN with Hyper-Kamiokande

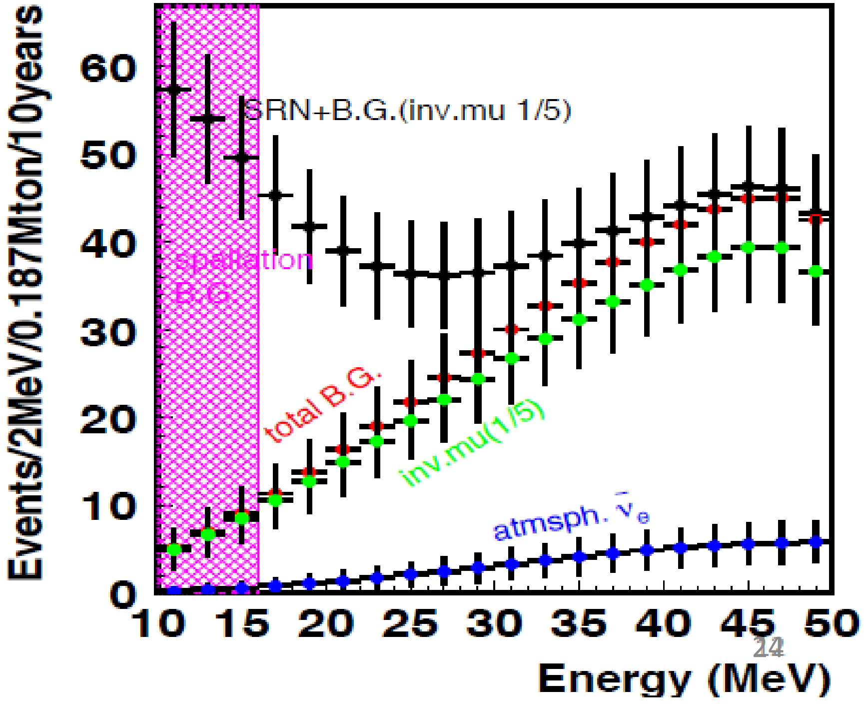


Supernova Relic Neutrino (SRN)

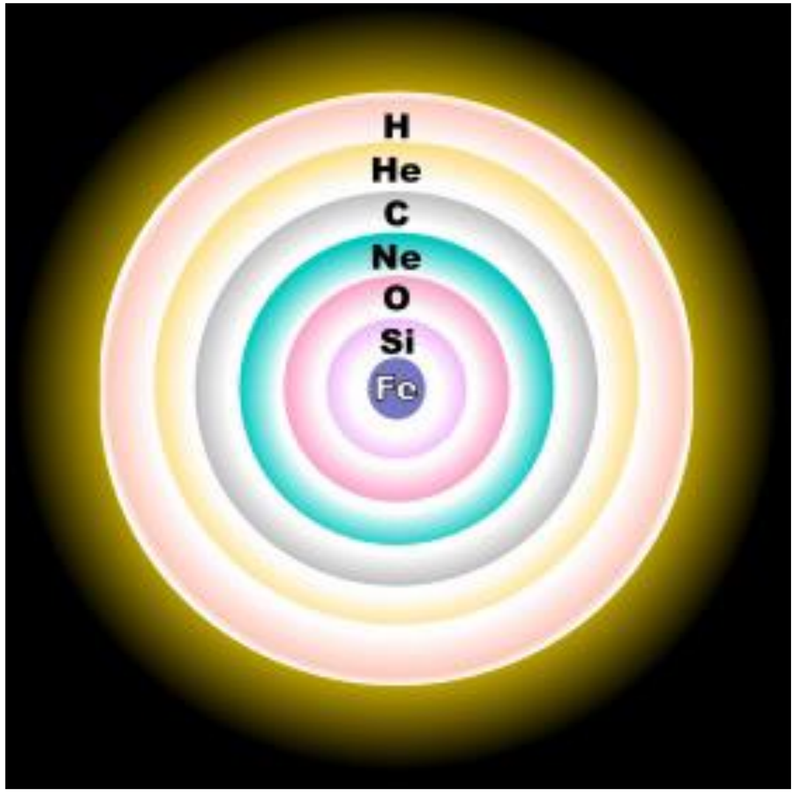
- Diffused neutrinos coming from all past supernovae
- Not discovered but promising extra-galactic ν

SRN with Hyper-K

- SRN can be observed by Hyper-K in 10y with ~40 event at 16-30 MeV with the detector photo-coverage of 20%
- It is > 3σ for SRN signal.

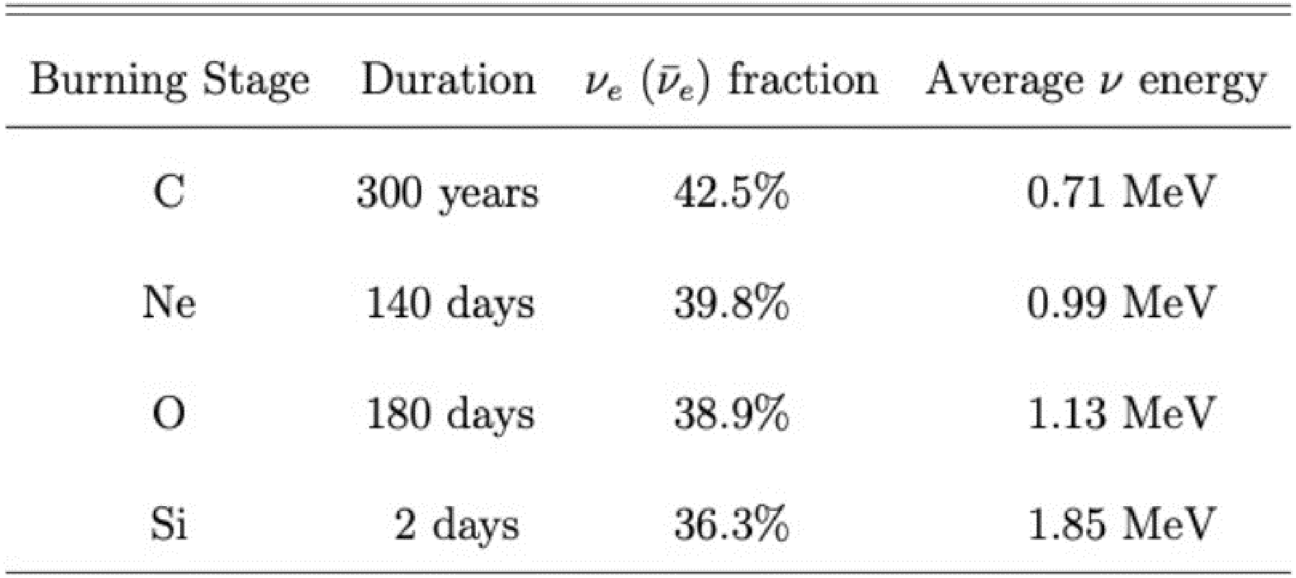


Pre-Supernova Neutrinos



In advance of a SN burst, neutrinos of all types are emitted by the progenitor star.
If detected, they can serve as an early warning
for the burst

A significant fraction of the signal is above threshold for IBD.



Burning Stage	Duration	ν_e ($\bar{\nu}_e$) fraction	Average ν energy
C	300 years	42.5%	0.71 MeV
Ne	140 days	39.8%	0.99 MeV
O	180 days	38.9%	1.13 MeV
Si	2 days	36.3%	1.85 MeV

Energy released by each pre-Supernova phase

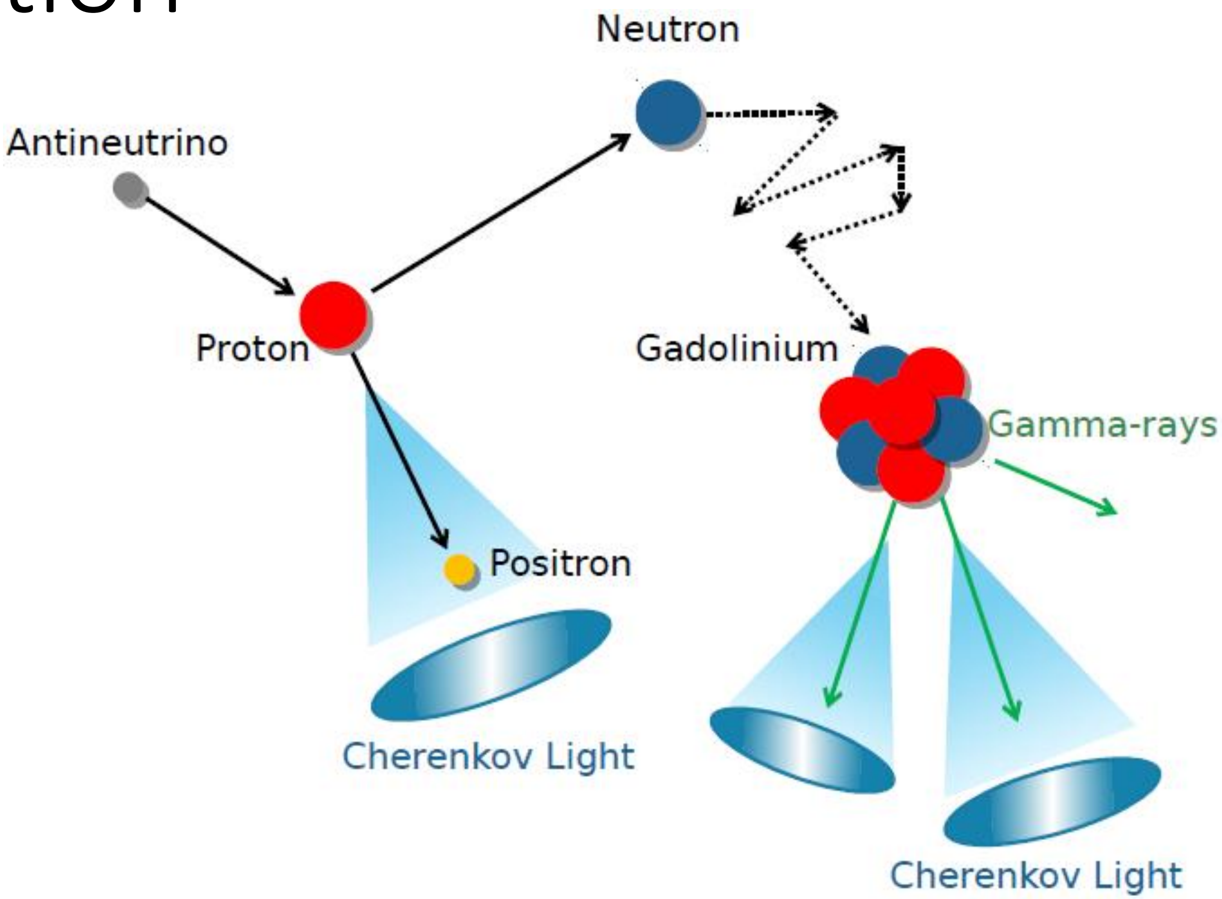
The last stage of these stars before the core-collapse is the **Si-burning**
Neutrinos emitted at the Si-burning stage have an average energy of 1.85 MeV

Hyper-Kamiokande Gd Option

Capture of neutron on Gd allows tagging to identify events such as IBD interactions.

The thermal neutron capture cross section of Gd is about 10^5 times larger than that of H → a **0.1%** Gd concentration results in **~90%** of neutrons capturing on Gd!

	H_2O	H_2O + 0.1% Gd
Thermal capture cross section (s)	~ 0.3 barns	~49,000 barns
Capture time (t)	~220 μsec	~30 μsec
Energy released	2.2 MeV (single γ)	~8 MeV (γ cascade)



This enhances SN pointing resolution and enables searches from pre-SN neutrinos (*e.g.*, from Si burning)

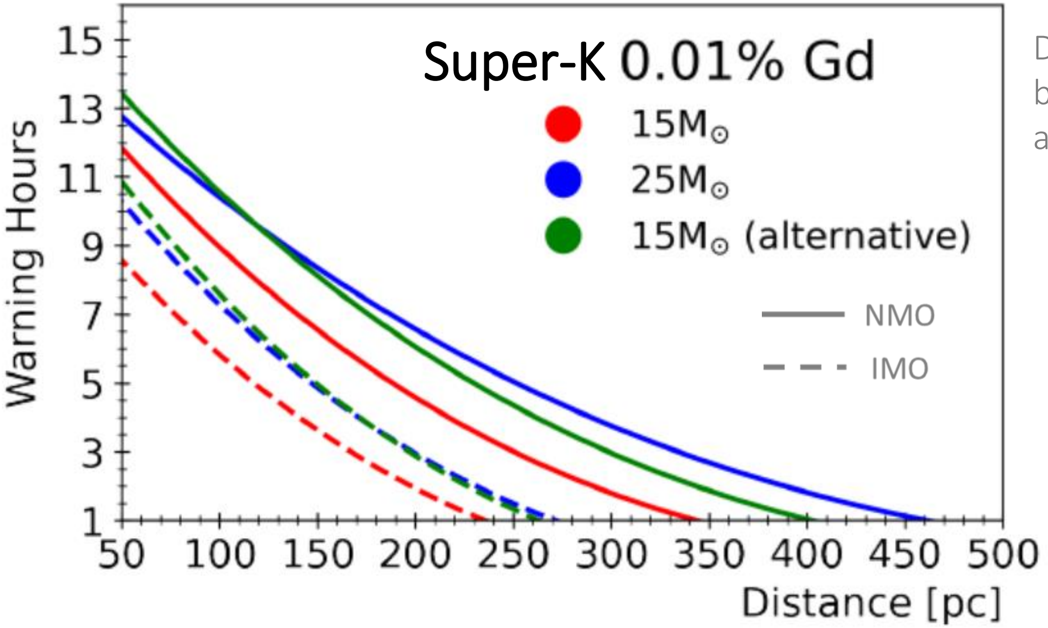
Also boosts sensitivity to SRN / DSNB

Pre-Supernova Neutrinos in Hyper-Kamiokande

Super-Kamiokande developed an alarm system to probe these pre-SN neutrinos for close progenitors

(L. Machado et al., The Astrophysical Journal, 935:40 (14pp), 2022 August 10)

Warning time for a 3σ detection by the pre-supernova alert system for Super-Kamiokande



Details: talks by A. Takeda and M. Eizuka

If Hyper-K will be gadolinium-doped, it will be able to detect pre-Supernova neutrinos, with great sensitivity due to a much bigger FV.

A powerful pre-Supernova alarm could be developed, as many more events are expected, increasing early warnings and ranges of detection compared to SK-Gd.

Summary

HyperK is under construction
Operation is expected to begin in 2027

For a galactic supernova at a fiducial distance of 10 kpc, Hyper-Kamiokande will detect O(10^5) neutrinos within about 10 s:

- time variations can be revealed
- information on properties of the progenitor (like its rotation) or on details of the supernova explosion mechanism

Newly-developed, high-precision supernova event generator to simulate Hyper-Kamiokande's response to five different supernova models

Hyper-Kamiokande will be able to distinguish between these models with high accuracy for a supernova at a distance of up to 100 kpc.

….and Outlook

Hyper-Kamiokande will provide the largest sample of SN neutrino events, including elastic scatter events with direction of the supernova and enable the astronomical community to engage in multi-messenger discoveries.

Better understand the core-collapse in SN, the explosion mechanism, the proto neutron-star formation, the black hole formation

SN alert with directional information could be followed up on multi-messenger analyses, combining observations with gravitational wave, gamma-ray, X-ray emissions

Pre-Supernova alarm could be developed
→ early warnings for Supernova detection!

Thank you!