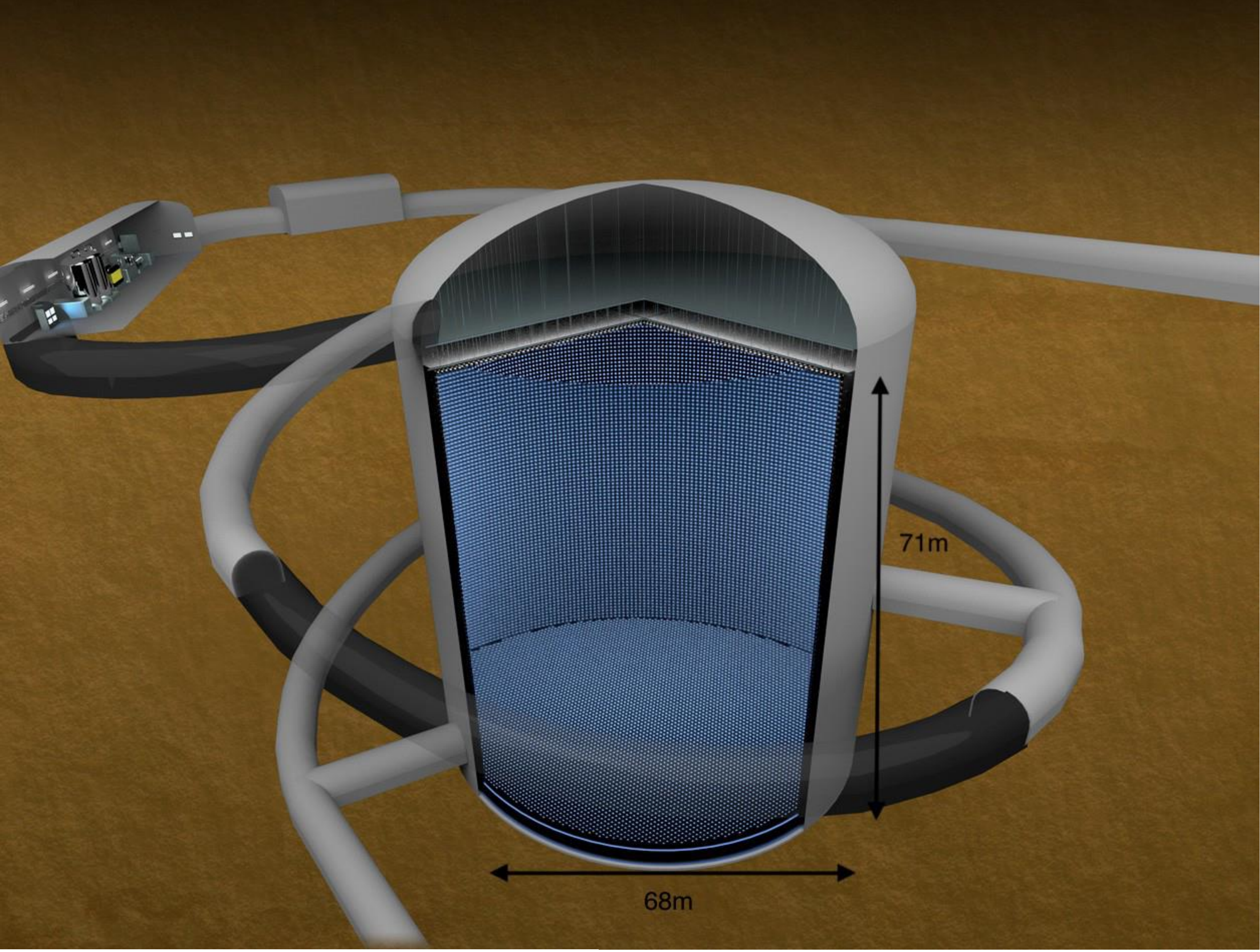
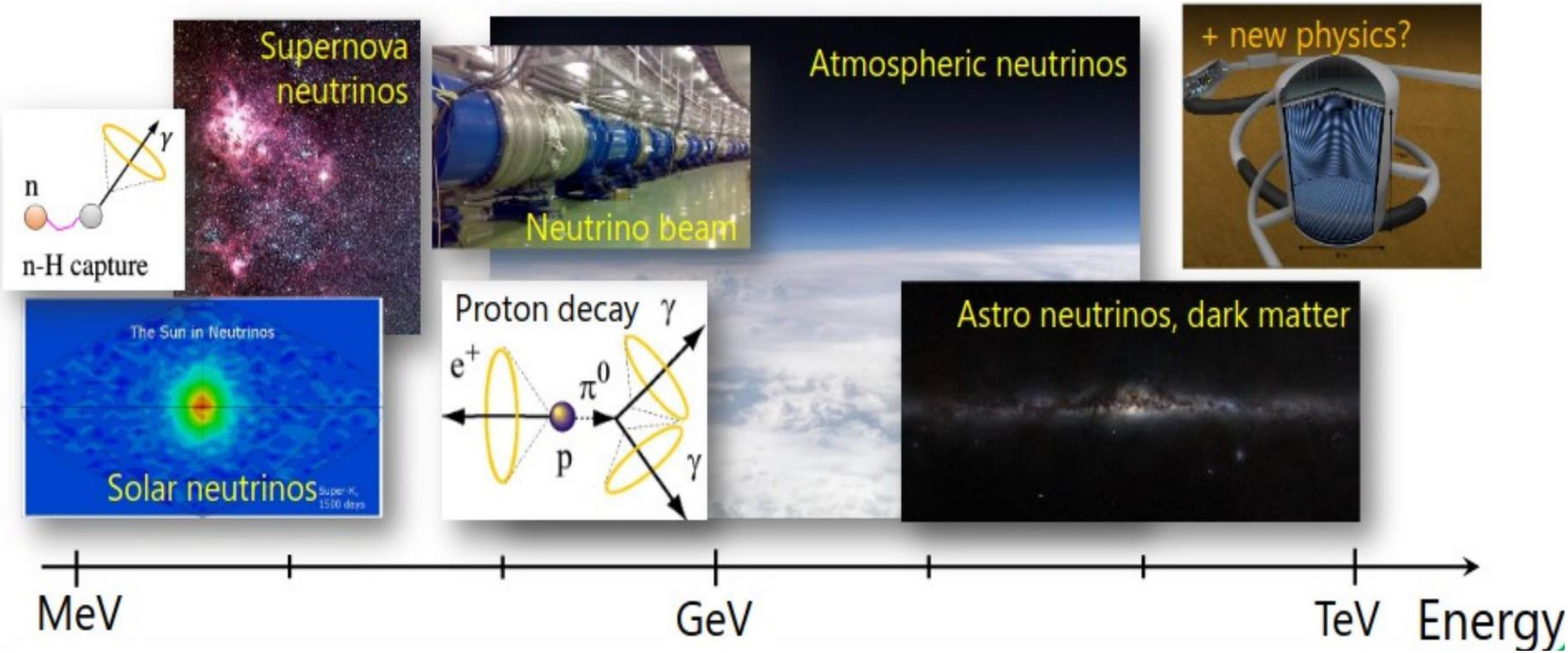
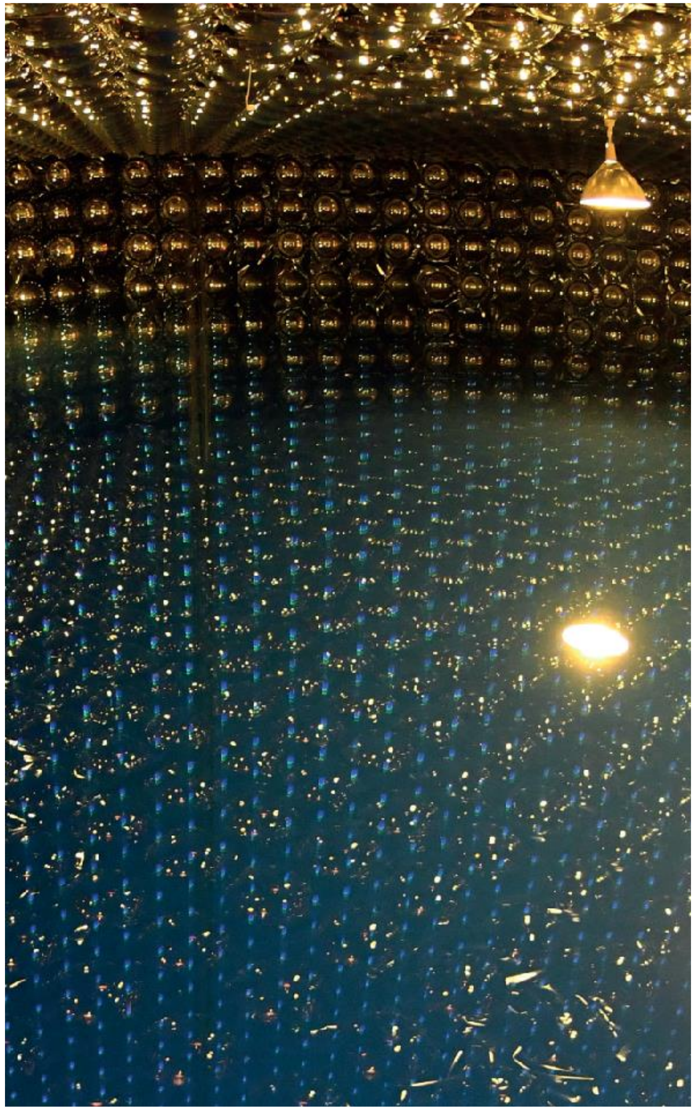


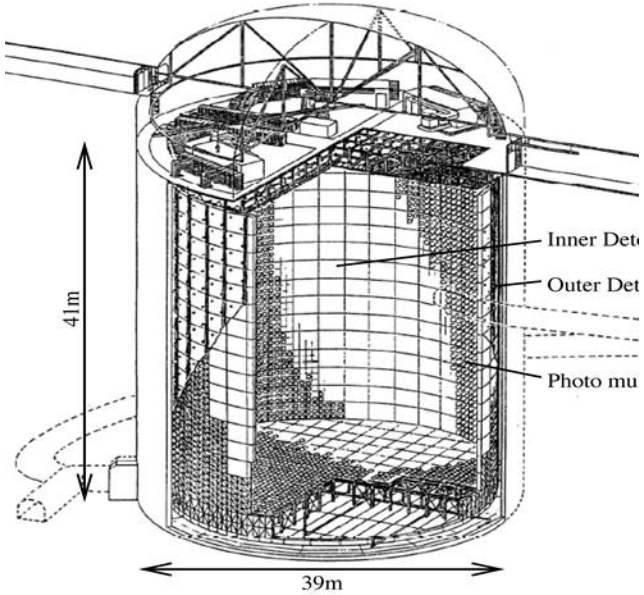
Hyper-K
T2K
Super-K

Gianfranca De Rosa
Per il gruppo Hyper-K di Napoli

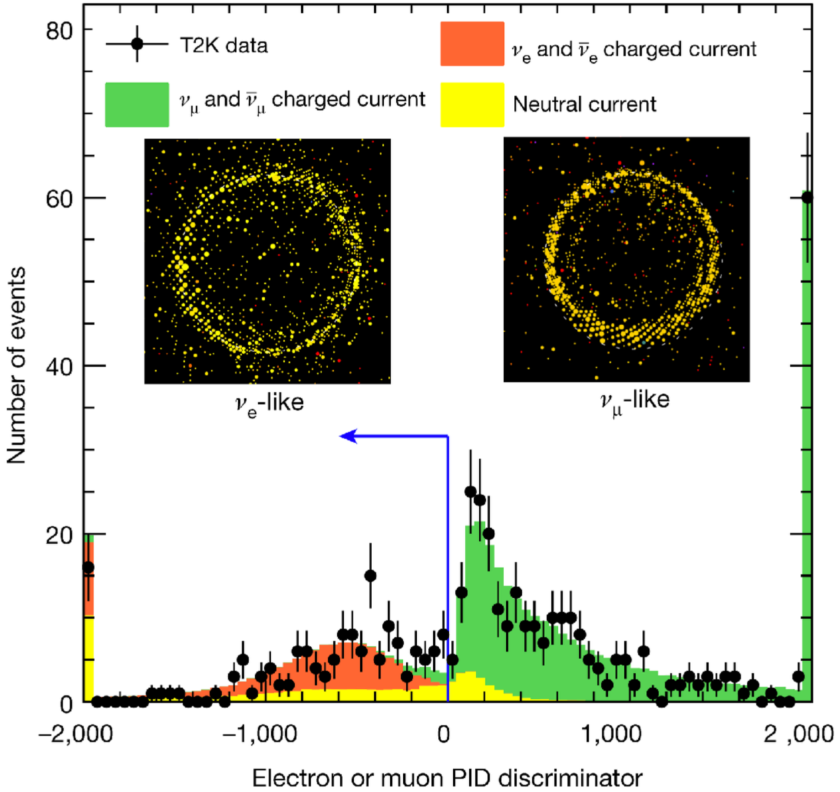

n
γ
n-H capture
Supernova neutrinos
Neutrino beam
Atmospheric neutrinos
+ new physics?
The Sun in Neutrinos
Solar neutrinos
Super-K, 1500 days
Proton decay γ
e+
π0
p
γ
Astro neutrinos, dark matter
MeV
GeV
TeV
Energy

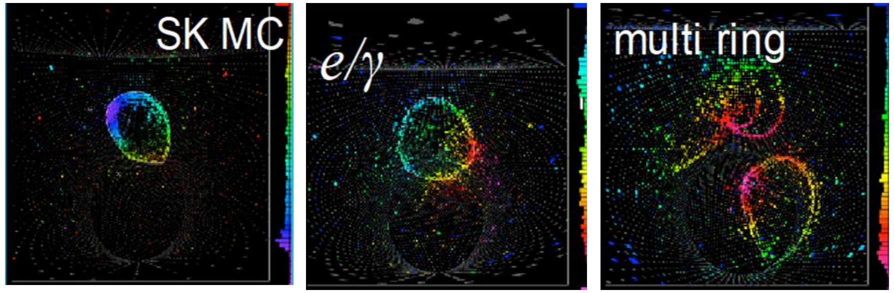
Super-Kamiokande





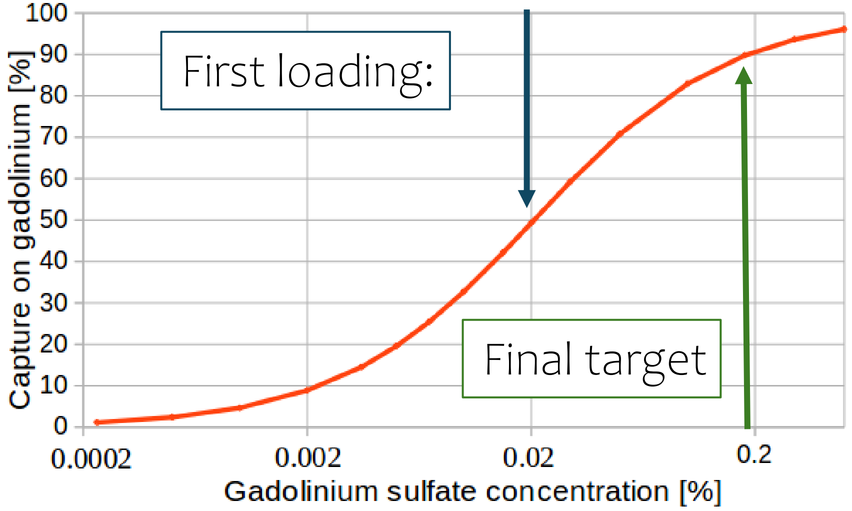
- Particle identification
- Interaction vertex reconstruction
- Particle range
- Electromagnetic energy reconstruction
- Track Multiplicity
- Hadronic interactions

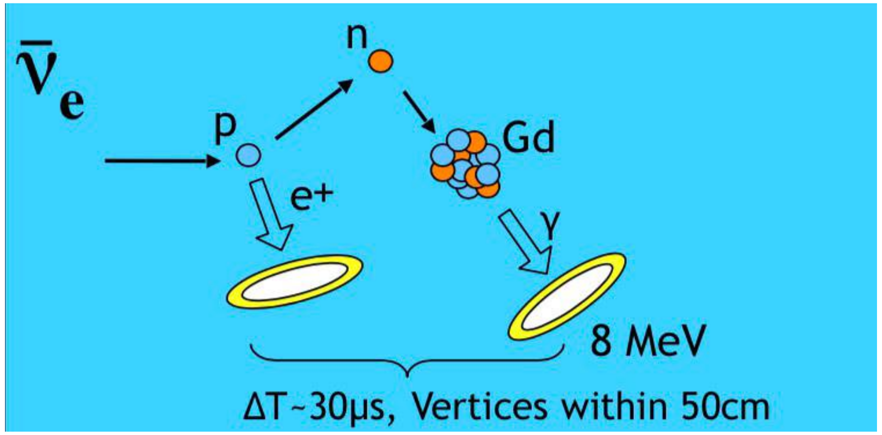


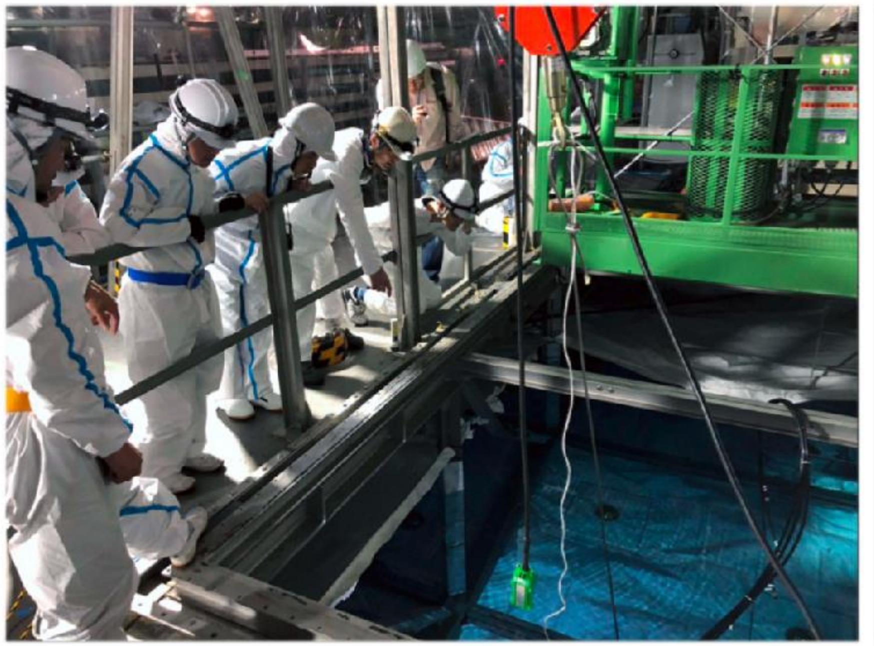


SK Gadolinium

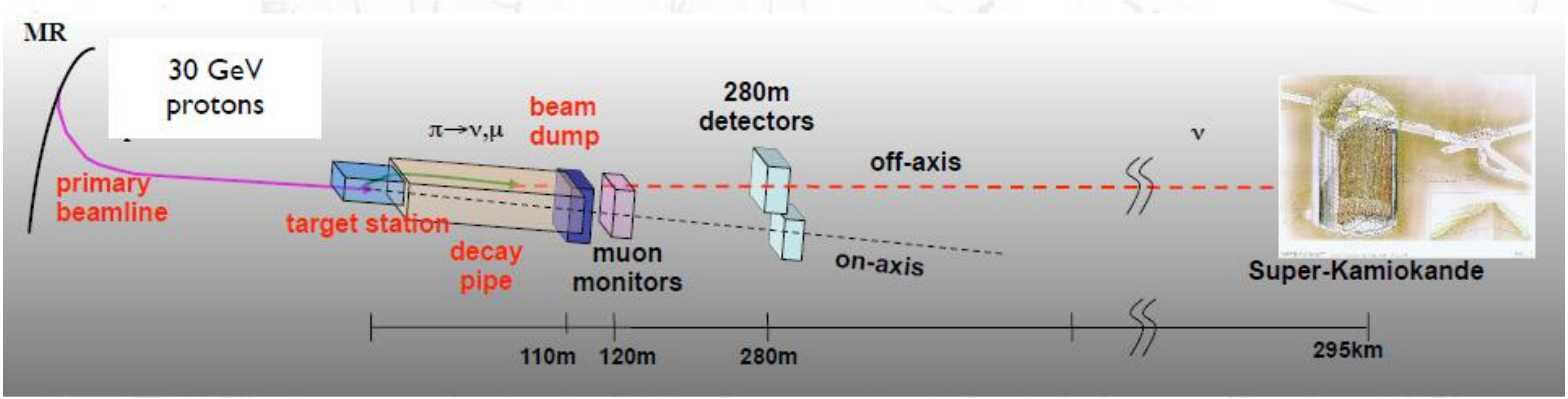
- enhance neutron detection
- improve low-energy νe detection
- may provide wrong-sign background constraint in νe
- more data samples
- Leak repairs to SK tank finished in 2019
- Load $Gd_2(SO_4)_3$ in stages up to 0.2%.







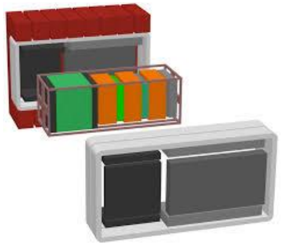
T2K experiment



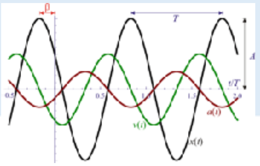
Neutrinos produced in a particle accelerators or nuclear reactors.

$\nu_\mu / \bar{\nu}_\mu$

Neutrino flux properties



ν oscillations

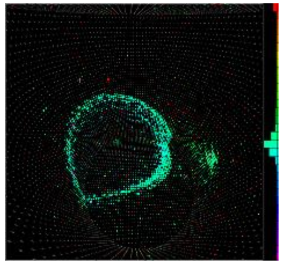


$\nu_\mu / \bar{\nu}_\mu$

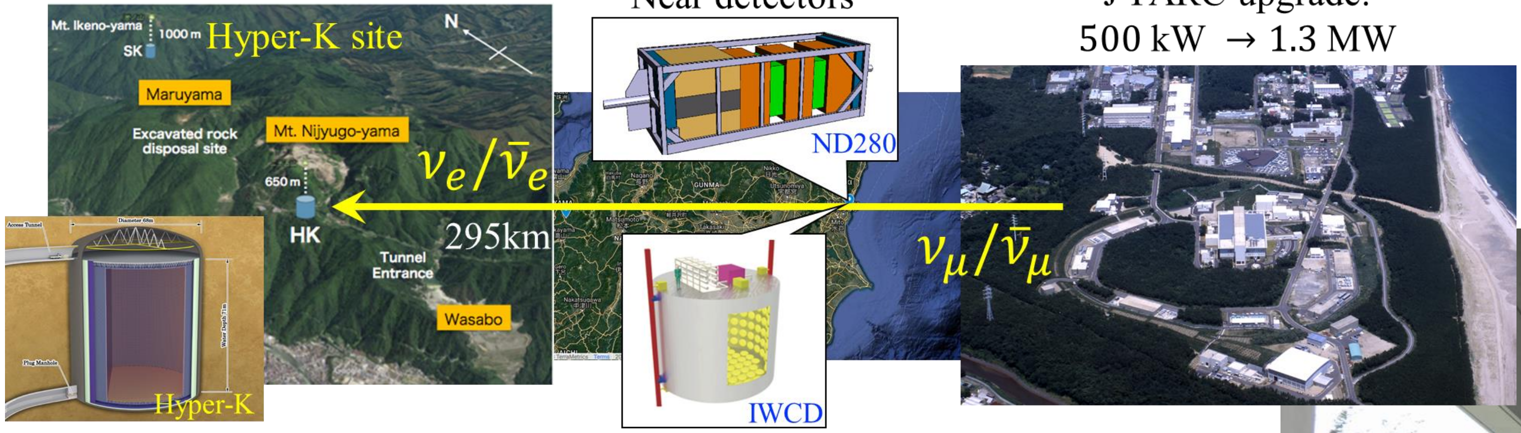
»

$\nu_e / \bar{\nu}_e$

Neutrino flux & flavour



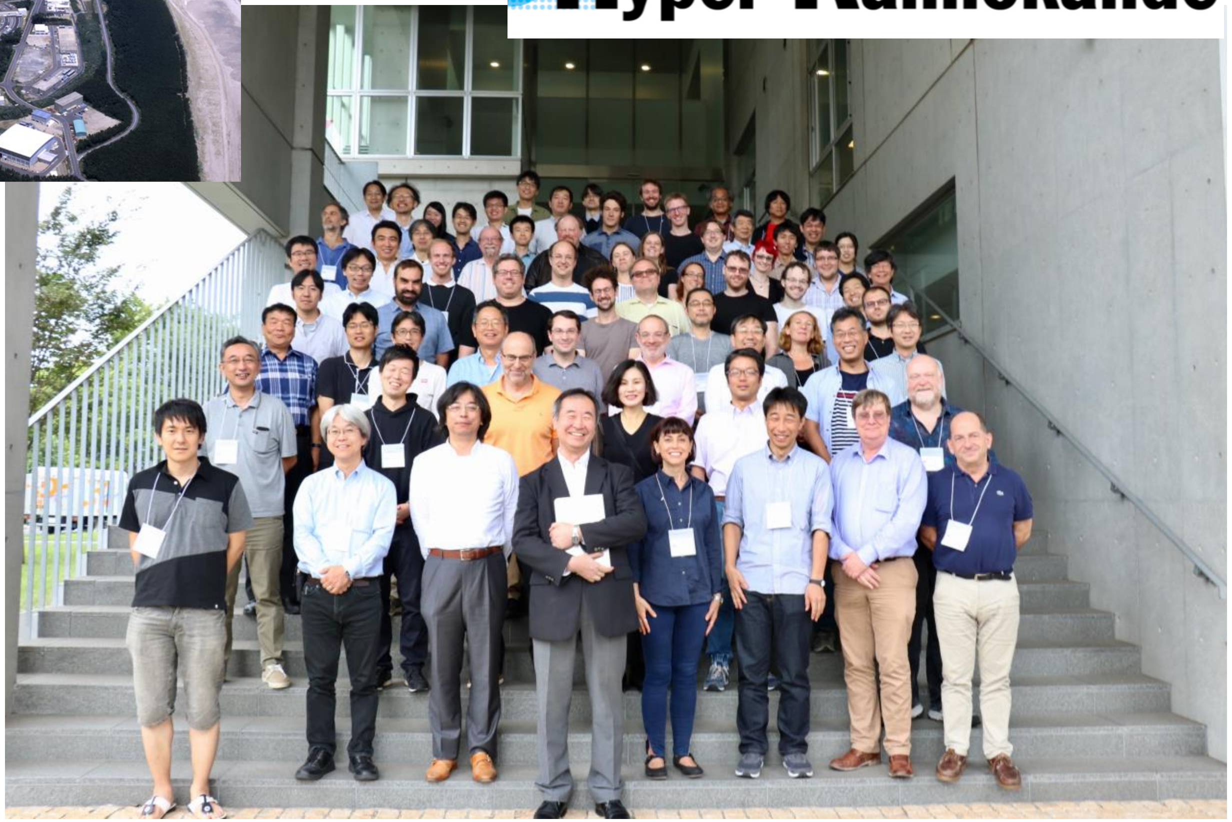
Hyper-Kamiokande



Near detectors

J-PARC upgrade:
500 kW → 1.3 MW

Hyper-Kamiokande



- Hyper-K detector will be built with 8.4 times larger fiducial mass (190 kiloton) than Super-K and will be instrumented with double-sensitivity PMTs.
- J-PARC neutrino beam will be upgraded from 0.5 to 1.3 MW
- x8 Natural Neutrino Rate and x20 Accelerator Neutrino Rate
- New and upgraded near detectors to control systematic errors

Neutrino Oscillation

$$(\nu_e,\nu_\mu,\nu_\tau)^T = U_{\alpha i}^{MNS}(\nu_1,\nu_2,\nu_3)^T \quad \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\cos\vartheta_{12} & \sin\vartheta_{12} & 0\\ -\sin\vartheta_{12} & \cos\vartheta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\cos\vartheta_{13} & 0 & \sin\vartheta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\vartheta_{13}e^{i\delta} & 0 & \cos\vartheta_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\vartheta_{23} & \sin\vartheta_{23}\\ 0 & -\sin\vartheta_{23} & \cos\vartheta_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

U^{PMNS}: Pontecorvo-Maki-Nakagawa-Sakata matrix

$$P(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\frac{(m_i^2-m_j^2)L}{4E_\nu}$$

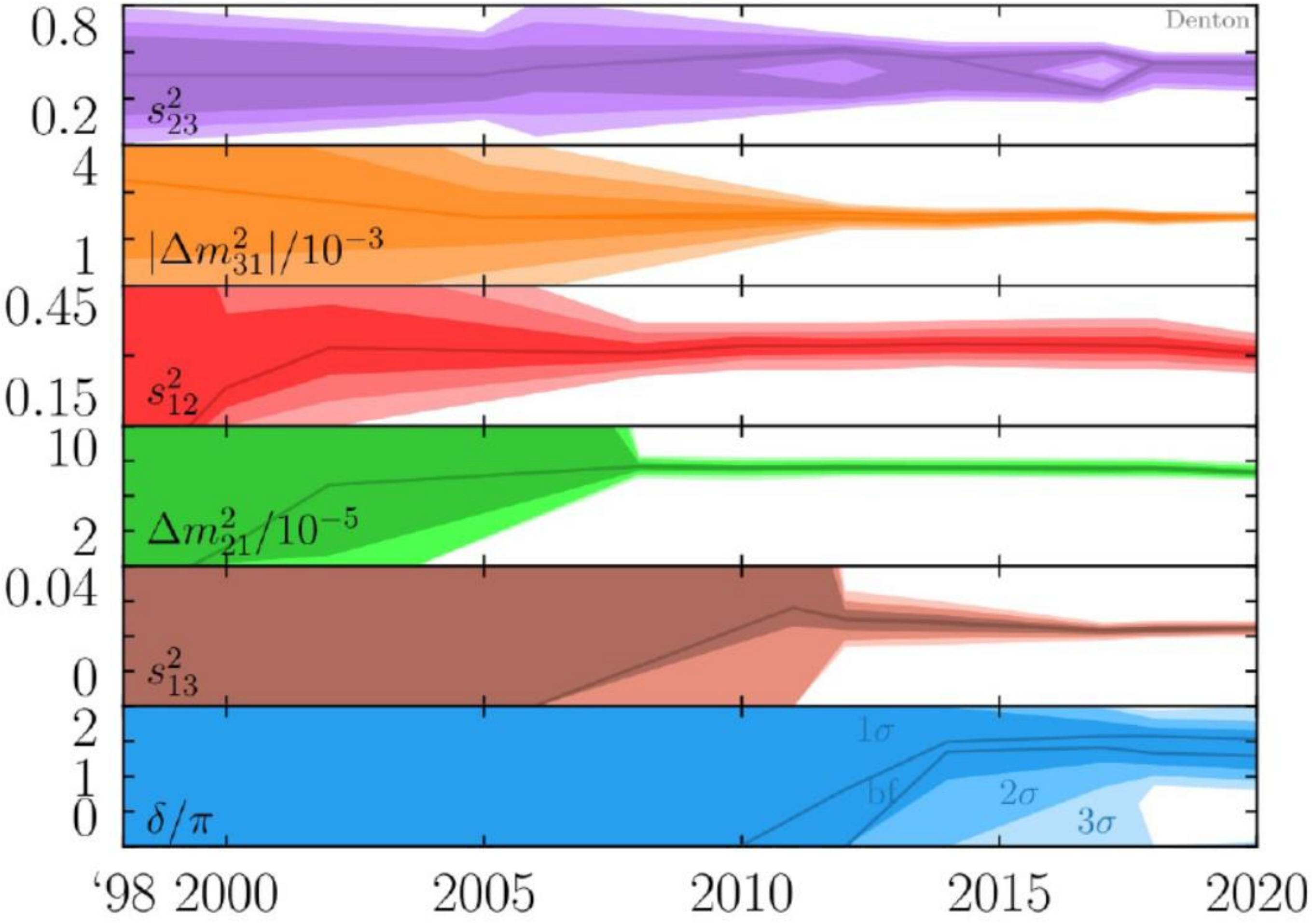
$$(\pm)2\sum_{i>j}\mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\frac{(m_i^2-m_j^2)L}{2E_\nu}$$

Matter-effects neglected

Neutrino Oscillation Parameters: 6 = 3 angles, one phase and 2 mass-squared differences

θ_{23}~45±5° **$\Delta m^2_{23}=2.4\times10^{-3}$eV^2** Atmospheric, Accelerator Neutrinos	**θ_{12}~34±3°** **$\Delta m^2_{21}=7.6\times10^{-5}$eV^2** Solar, Reactor Neutrinos	**θ_{13}~9°** Accelerator, Reactor Neutrinos	**δ=unknown** Accelerator, Atmospheric Neutrinos

Entering discovery and precision era



θ_{23}~45°

$|\Delta m^2_{32}|$~24 10^{-4} eV^2

θ_{12}~33°

Δm^2_{21}~ 0.75 10^{-4} eV^2

θ_{13}~9°

Δ_{CP} = ?

from P.Denton

Hyper-Kamiokande, T2K, Super-K

Run/Analysis

- **T2K/SK running experiments**
  - Analysis: OA, new samples, xsects
  - SK-GD: 0.03% Gd

Data taking
Analysis
Run until 2027

Commissioning

- **T2K-II assembly and installation**
  - Beam upgrade
  - ND280 upgrade
  - Nuove HATPC

Installed last May

R&D/Prototyping

- **Hyper-K design and construction**
  - mPMTs
  - FEB 20“, timing
  - computing

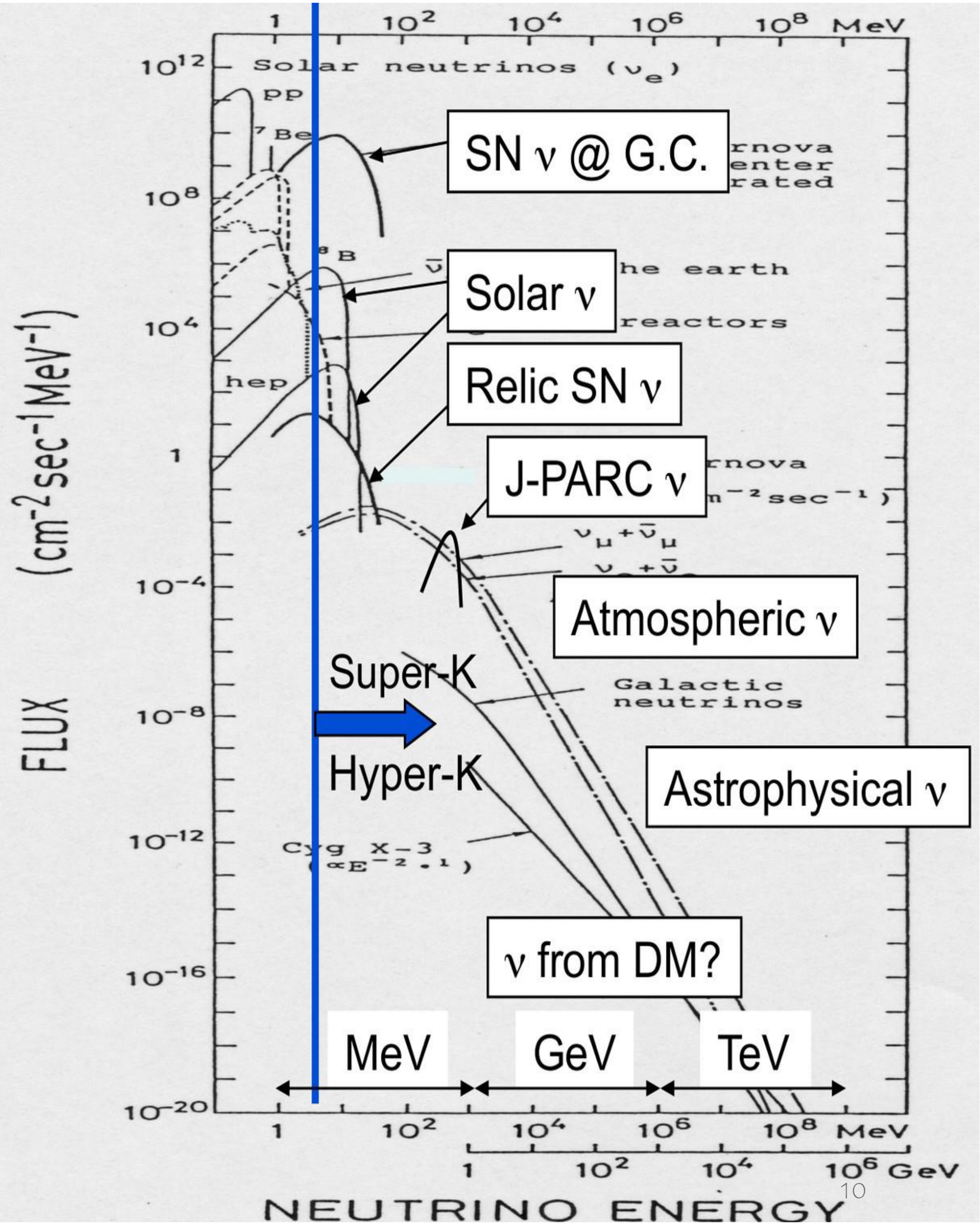
Final Design Review
Excavation
Procurement
Run 2027-

Hyper-Kamiokande Physics

Neutrino Physics
Accelerator & atmospheric oscillation:
CPV & mass ordering

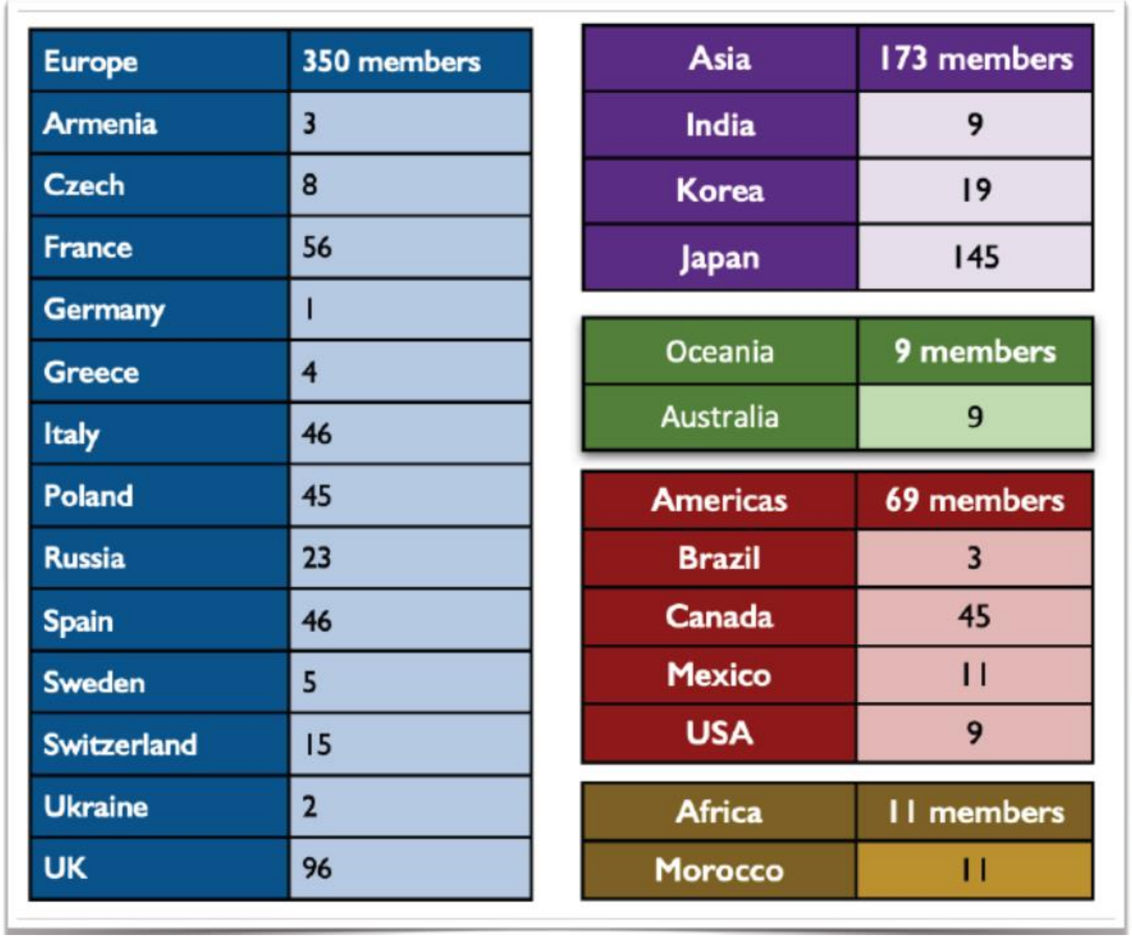
Astrophysics
Supernovae
Sun
astrophysics sources

Physics BSM
Nucleon decay
 dark matter
non-standard interactions



Hyper-Kamiokande Collaboration

- 22 countries, 106 institutes, ~650 people as of December 2024, and growing
- ~24% Japanese/~76% non-Japanese.



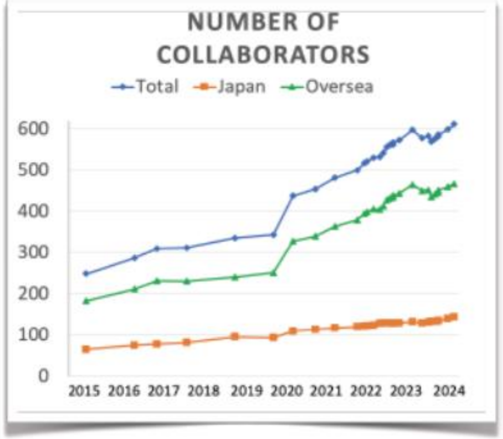
Europe	350 members
Armenia	3
Czech	8
France	56
Germany	1
Greece	4
Italy	46
Poland	45
Russia	23
Spain	46
Sweden	5
Switzerland	15
Ukraine	2
UK	96

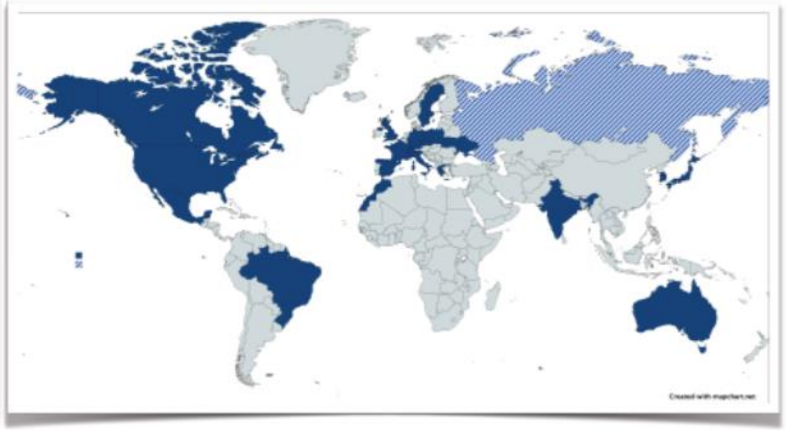
Asia	173 members
India	9
Korea	19
Japan	145

Oceania	9 members
Australia	9

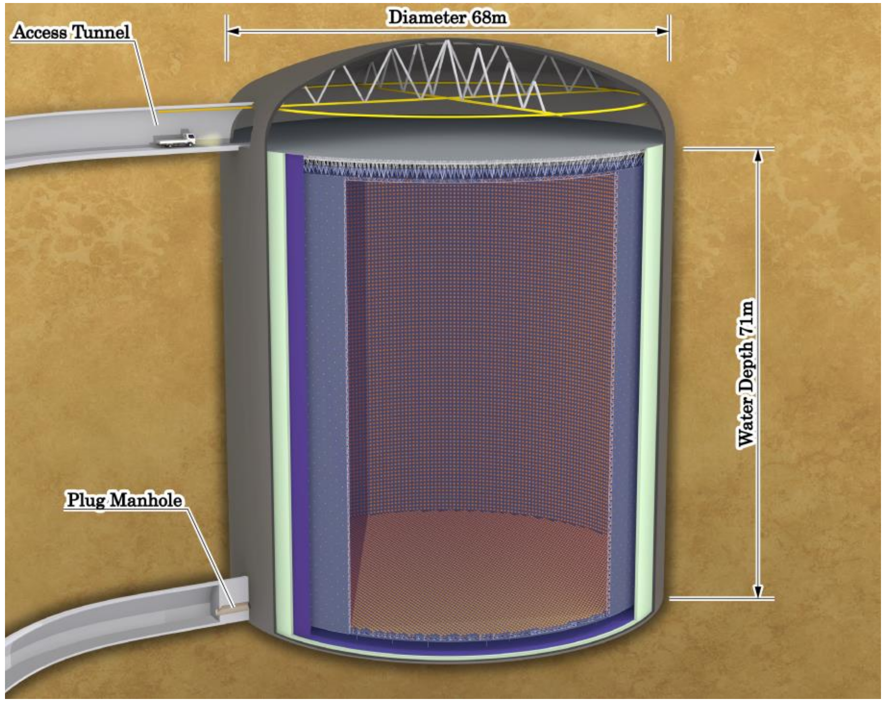
Americas	69 members
Brazil	3
Canada	45
Mexico	11
USA	9

Africa	11 members
Morocco	11





Hyper-Kamiokande design



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)

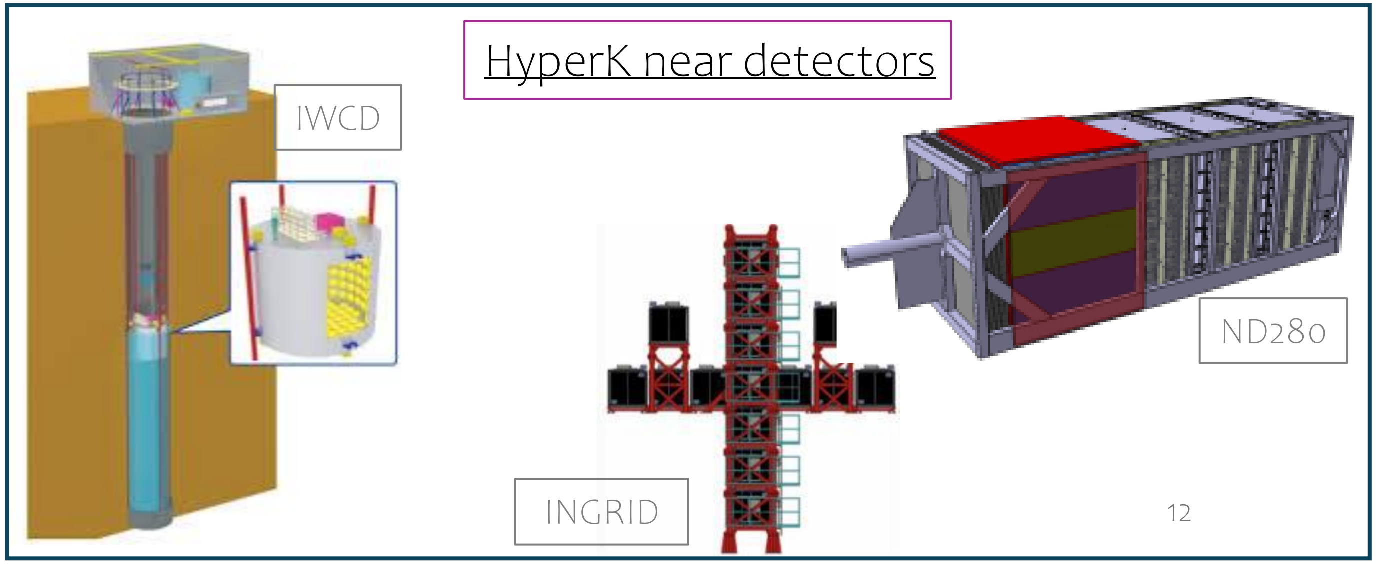
- ➢ 1 kilo-ton scale water Cherenkov detector located ~1 km from the neutrino beam source

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

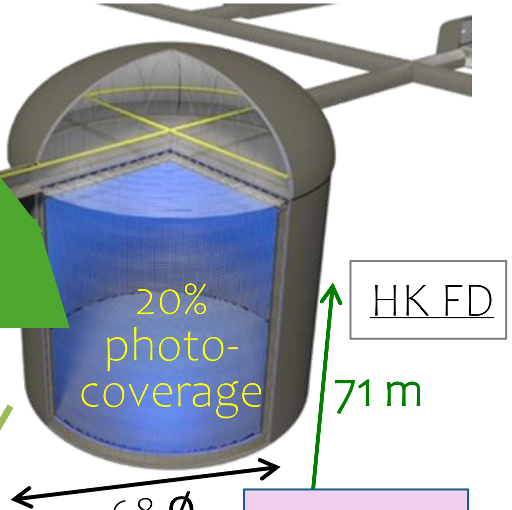
Operation is expected to begin in 2027


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



HK FD

for 1 tank

Box&Line PMT

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.

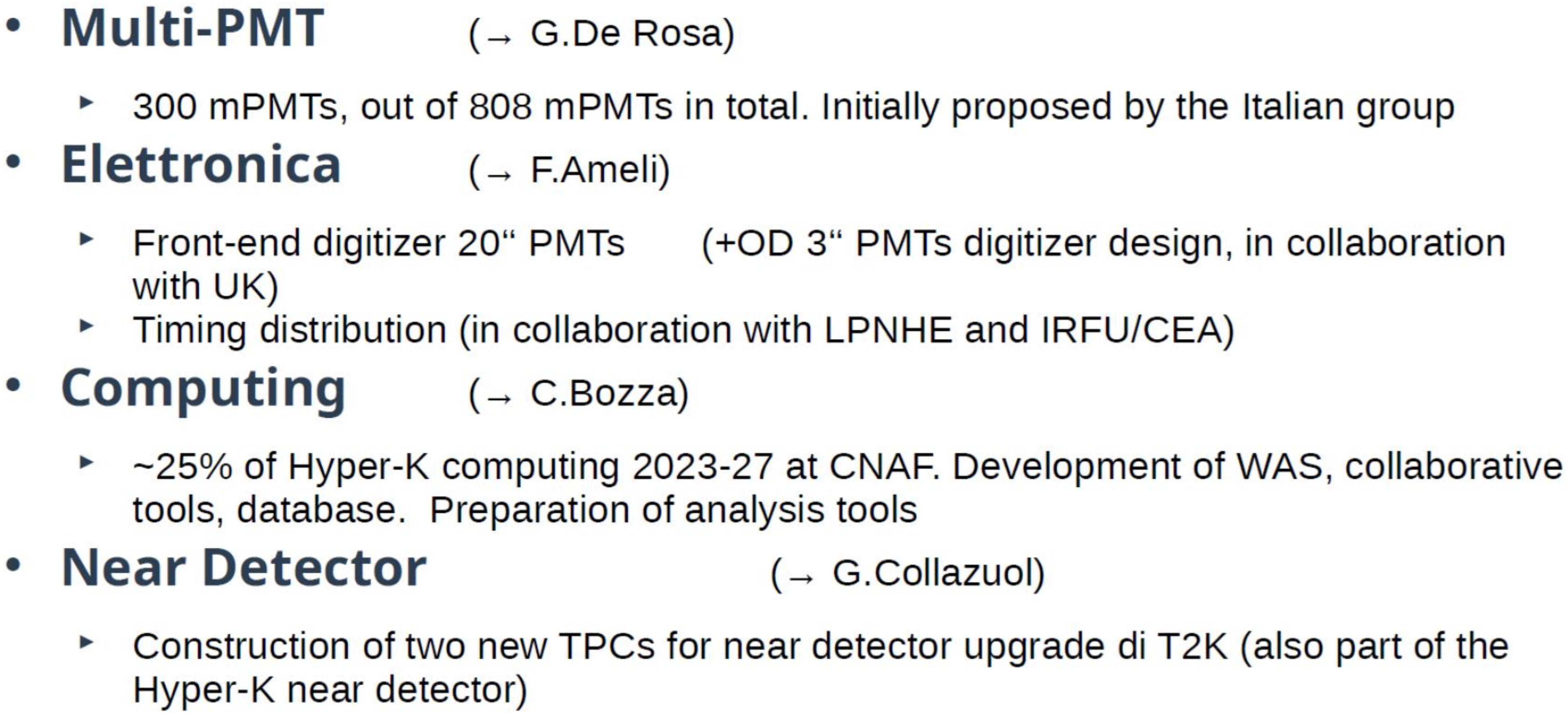
Photodetectors and electronics arranged inside a pressure resistent vessel

Increased granularity

Enhanced event reconstruction, in particular for multi-ring events

HK FD
ID Hybrid Design:
20" PMTs and mPMTs
IWCD
mPMTs

INFN contribution in Hyper-K



- **Multi-PMT** (→ G.De Rosa)
  - 300 mPMTs, out of 808 mPMTs in total. Initially proposed by the Italian group
- **Elettronica** (→ F.Ameli)
  - Front-end digitizer 20“ PMTs (+OD 3“ PMTs digitizer design, in collaboration with UK)
  - Timing distribution (in collaboration with LPNHE and IRFU/CEA)
- **Computing** (→ C.Bozza)
  - ~25% of Hyper-K computing 2023-27 at CNAF. Development of WAS, collaborative tools, database. Preparation of analysis tools
- **Near Detector** (→ G.Collazuol)
  - Construction of two new TPCs for near detector upgrade di T2K (also part of the Hyper-K near detector)

Gruppo INFN Napoli

Antonio Di Nitto Reponsabile locale
Gianfranca De Rosa
Massimo Della Valle (INAF)
Alessandro Di Nola (Dottorando)
Aurora Langella (Dottoranda)
Luigi Lavitola (Dottorando/Tecnologo INFN)
Pasquale Migliozzi
Carlos Maximiliano Mollo
Giulia Ricciardi
Daniele Vivolo
Davide Bianco (CIRA)

INFN-Napoli contribution in Hyper-K/T2K/Super-K

mPMT

- Proposta del gruppo di Napoli
- Sviluppo e test dell’elettronica → **SER, Calcolo,** L. Lavitola, A. Di Nola
- Sviluppo e test della meccanica → **OM, PM**, D. Bianco
- Sviluppo e test cavi subacquei → **SER,** L. Lavitola, A. Di Nola
- Sviluppo procedura di assemblaggio e assemblaggio prototipi

20’’ Electronics

- Proposta del gruppo di Napoli
- Sviluppo e test in collaborazione con RM1 → **SER,** L. Lavitola, A. Di Nola
- Partecipazione ai test finali e all’assembly al CERN → L. Lavitola, A. Di Nola

OD Electronics

- Sviluppo prototipo → **SER,** L. Lavitola, A. Di Nola

Computing

- Sviluppo del DB dell’esperimento (SA) → C. Bozza

Near detector

- Partecipazione alle attività al CERN per le HATPC → A. Langella, L. Lavitola, A. Di Nola

Grandi risultati ottenuti
Fondamentale il
contributo di TUTTI i
servizi INFN

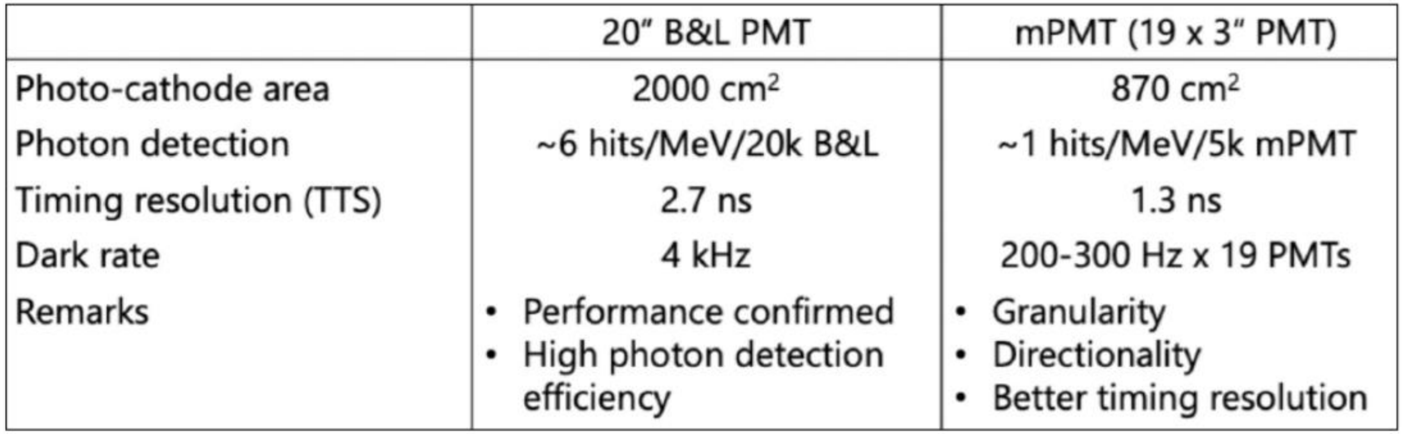
INFN-Napoli contribution in Hyper-K/T2K/Super-K

Analysis

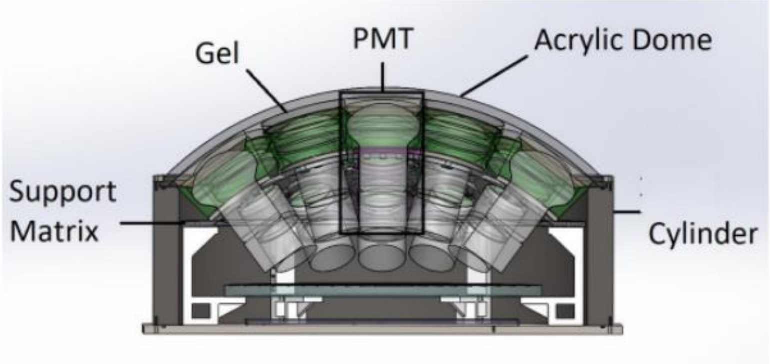
- Supernova Model Discrimination with Hyper-Kamiokande → A. Langella, L. N. Machado (now at Glasgow)
- Sensitivity Study for Astrophysical Neutrinos at Super-K and Hyper-Kamiokande → A. Langella, L. N. Machado
- Long-baseline neutrino oscillation sensitivities with Hyper-Kamiokande → C. Riccio (now at Stony Brook)
- Combined Pre-supernova Alert System with KamLAND and Super-Kamiokande → L. N. Machado
- Neutrino Fluxes from Different Classes of Galactic Sources → A. Langella, M. Della Valle
- Low- and High-energy Neutrinos from Supernovae → A. Langella , M. Della Valle
- Dark rate reduction with machine learning techniques for the Hyper-Kamiokande experiment → A. Langella, B. Spisso, L. N. Machado
- More precise calculation of $\bar{\nu}_e + p \rightarrow e^+ + n$ cross section → G. Ricciardi

multi-PMTs in Hyper-K

- Idea originale sviluppata in KM3NeT.
- Proposti in HK dall'INFN che ne è leader (Poland, Canada, Czech Rep., Greece, Mexico)
- HK INFN R&D dal 2015 (~300k€ 2015-22)
- Flagship della proposta italiana per il FD
- Informazioni uniche e complementari ai 20'' PMTs
- Riduzione delle sistematiche sui parametri dell'acqua e sulla scala di energia
- Usato con specifiche differenti, come unico fotorivelatore in IWCD

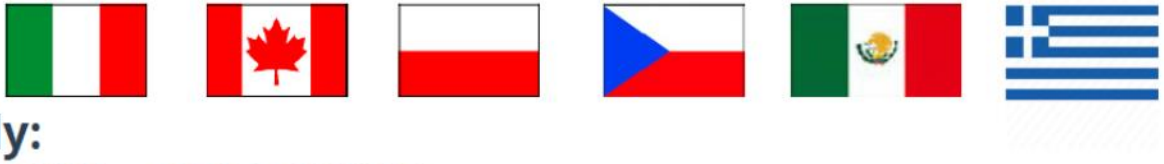


	20" B&L PMT	mPMT (19 x 3" PMT)
Photo-cathode area	2000 cm^2	870 cm^2
Photon detection	~6 hits/MeV/20k B&L	~1 hits/MeV/5k mPMT
Timing resolution (TTS)	2.7 ns	1.3 ns
Dark rate	4 kHz	200-300 Hz x 19 PMTs
Remarks	• Performance confirmed • High photon detection efficiency	• Granularity • Directionality • Better timing resolution

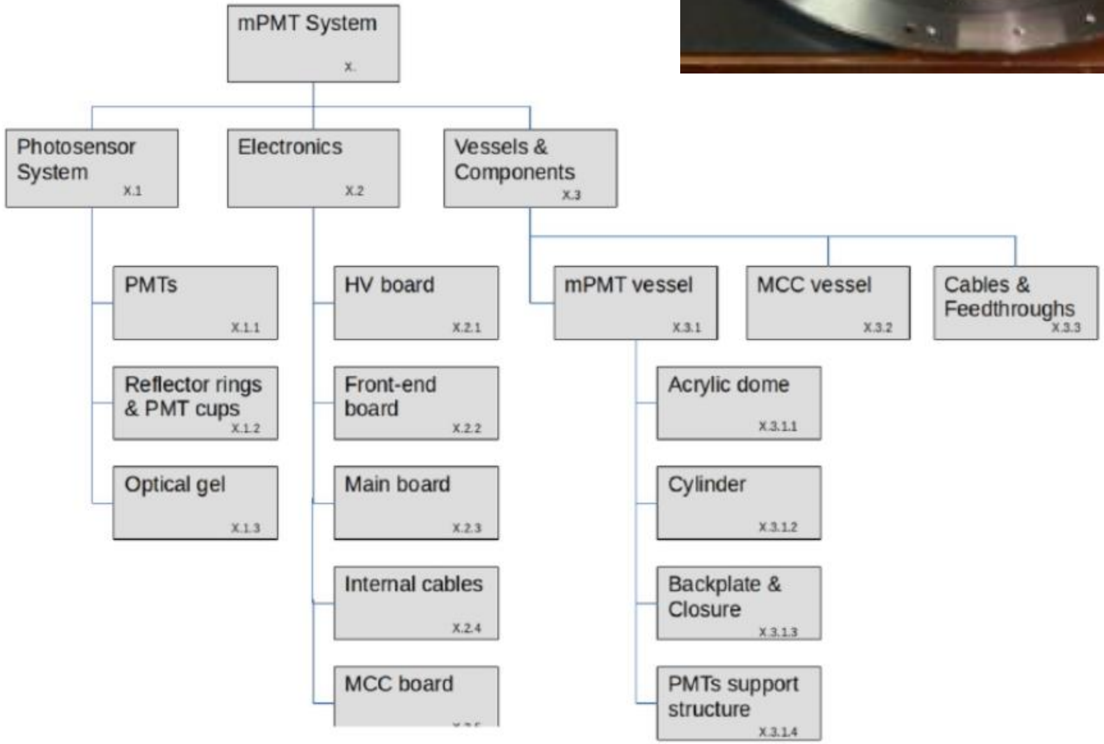


Schedule for the FD mPMT
- Contracts in 2023-2025
- Assembly: Oct 2025-Oct 2026

multi-PMTs in Hyper-K



- **2018 simulation study:**
  20K 20"PMT + 5000 mPMT ~ 40K 20"PMT
- **Complex objects (see PBS →)**
- **Production (5-10/week/site) limited by resources (funds, assembly sites,...)**
- **808 mPMTs are now planned to be installed in the Far Detector**
- **Assembly lines in Italy (Naples), Poland and Canada**
- **>500 mPMTs play an important role on systematics: energy scale and water parameters**
- **Photo-sensors R&D for future upgrades**



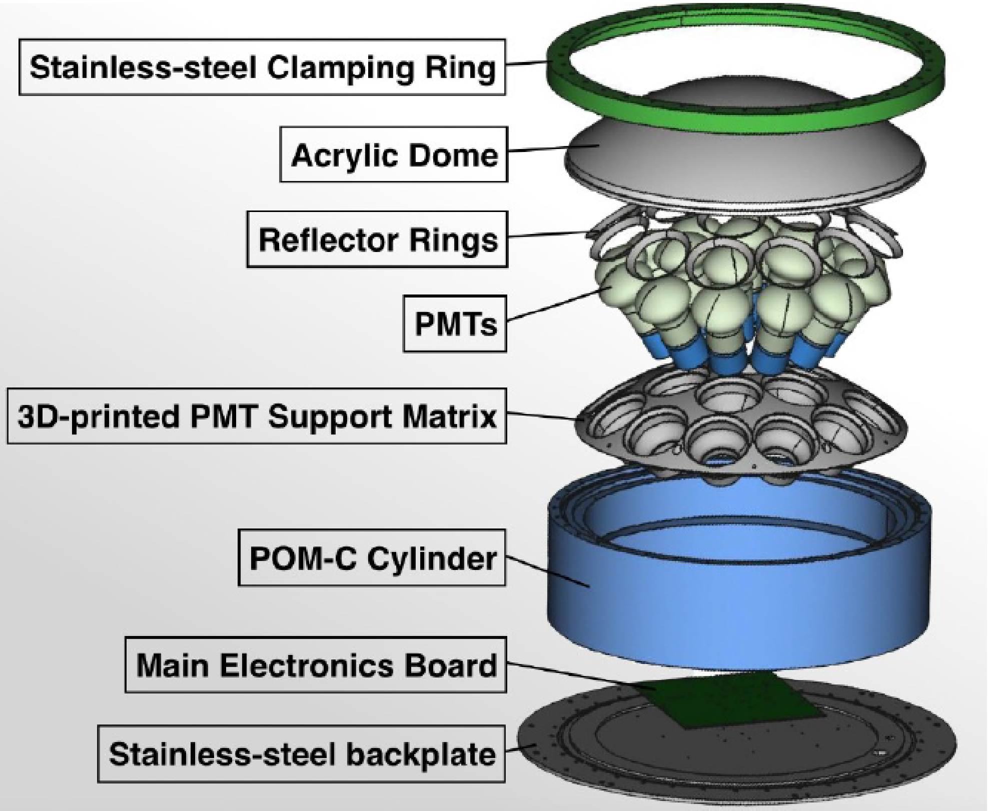
- mPMT System X.
  - Photosensor System X.1
    - PMTs X.1.1
    - Reflector rings & PMT cups X.1.2
    - Optical gel X.1.3
  - Electronics X.2
    - HV board X.2.1
    - Front-end board X.2.2
    - Main board X.2.3
    - Internal cables X.2.4
    - MCC board
  - Vessels & Components X.3
    - mPMT vessel X.3.1
      - Acrylic dome X.3.1.1
      - Cylinder X.3.1.2
      - Backplate & Closure X.3.1.3
      - PMTs support structure X.3.1.4
    - MCC vessel X.3.2
    - Cables & Feedthroughs X.3.3

Figure 97: Preliminary PBS for the mPMTs

mPMTs for Hyper-Kamiokande

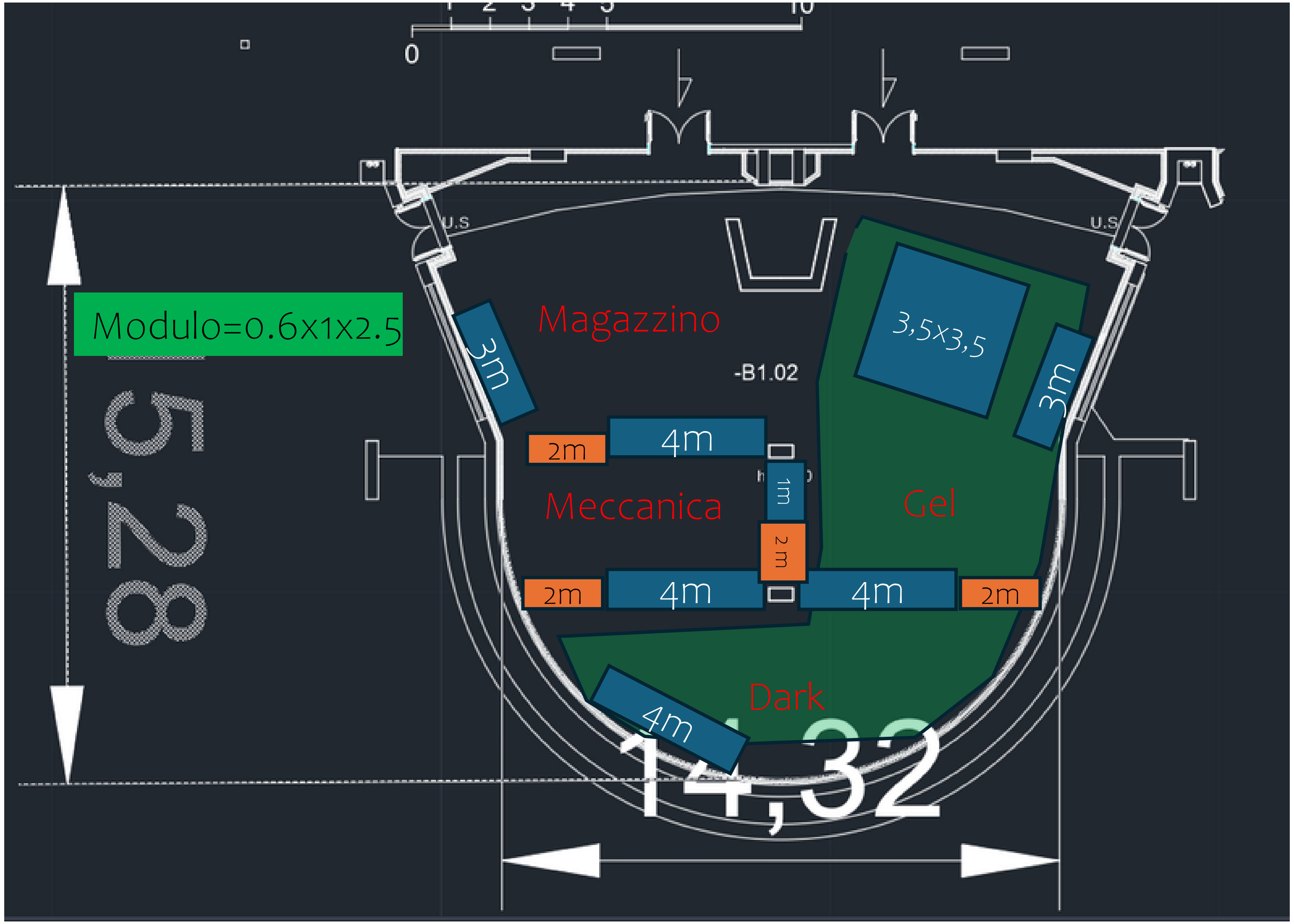
- 808 mPMTs for the Hyper-K Far Detector (FD)
- 400 mPMTs for IWCD
- Common R&D but FD mPMT different from IWCD mPMT:
  - Withstand pressure → robust backplate, thick POM-C cylinder
  - Low radioactive contamination
  - Gelling has to cope with acrylic dome deformation
  - Different (slower, low power) electronics

- 4 INFN FD mPMTs 2023 prototypes are installed together with ~100 IWCD mPMTs in the Water Cherenkov Test Experiment (WCTE) at CERN (taking data at T9 TB, October 2024)

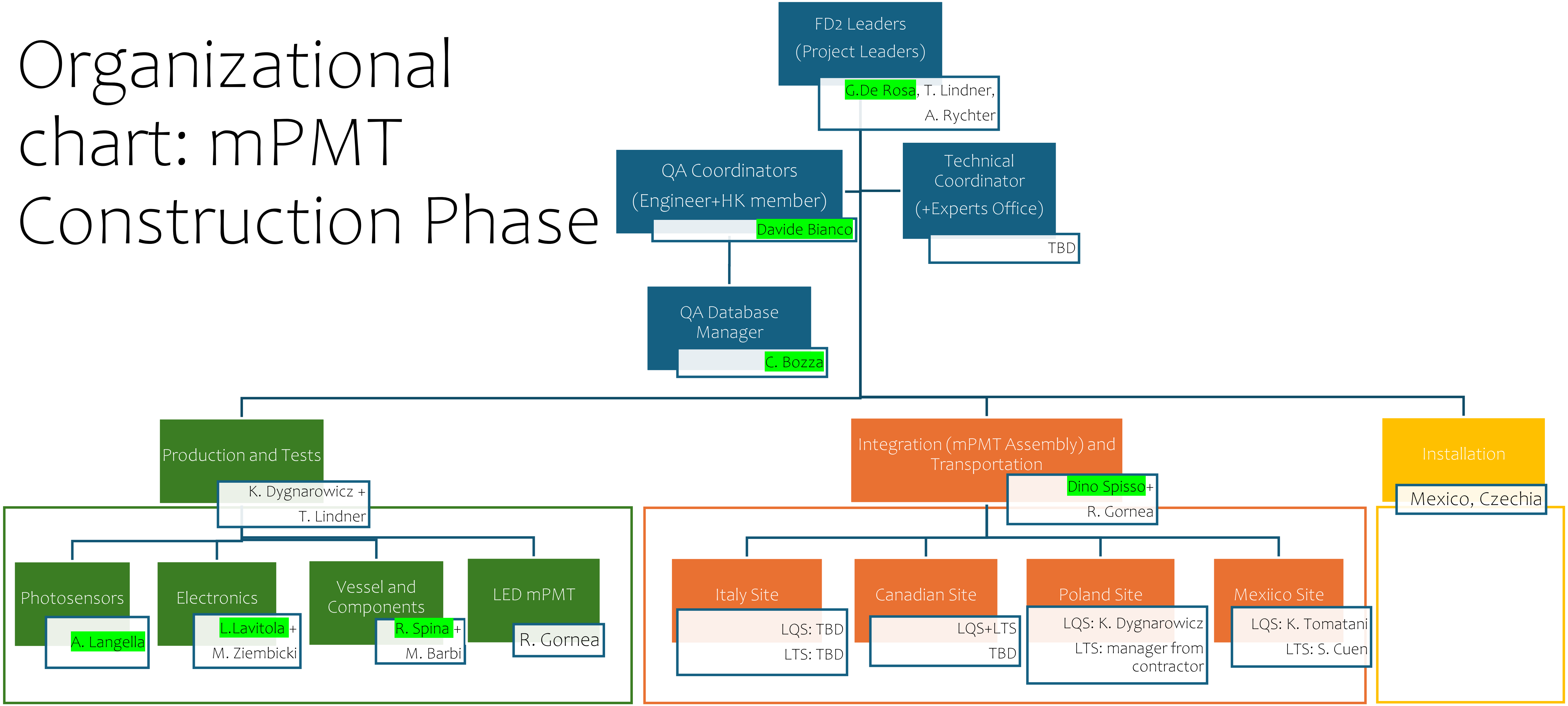


HK Lab

Lavori di adattamento in corso (parete per zona oscura, sistema illuminazione, preparazione sistemi per assemblaggio mPMT e test PMT/mPMT ….)



Organizational chart: mPMT Construction Phase



FD2 Leaders
(Project Leaders)
G.De Rosa, T. Lindner,
A. Rychter

QA Coordinators
(Engineer+HK member)
Davide Bianco

Technical Coordinator
(+Experts Office)
TBD

QA Database Manager
C. Bozza

Production and Tests
K. Dygnarowicz +
T. Lindner

Photosensors
A. Langella

Electronics
L.Lavitola +
M. Ziembicki

Vessel and Components
R. Spina +
M. Barbi

LED mPMT
R. Gornea

Integration (mPMT Assembly) and Transportation
Dino Spisso+
R. Gornea

Italy Site
LQS: TBD
LTS: TBD

Canadian Site
LQS+LTS
TBD

Poland Site
LQS: K. Dygnarowicz
LTS: manager from contractor

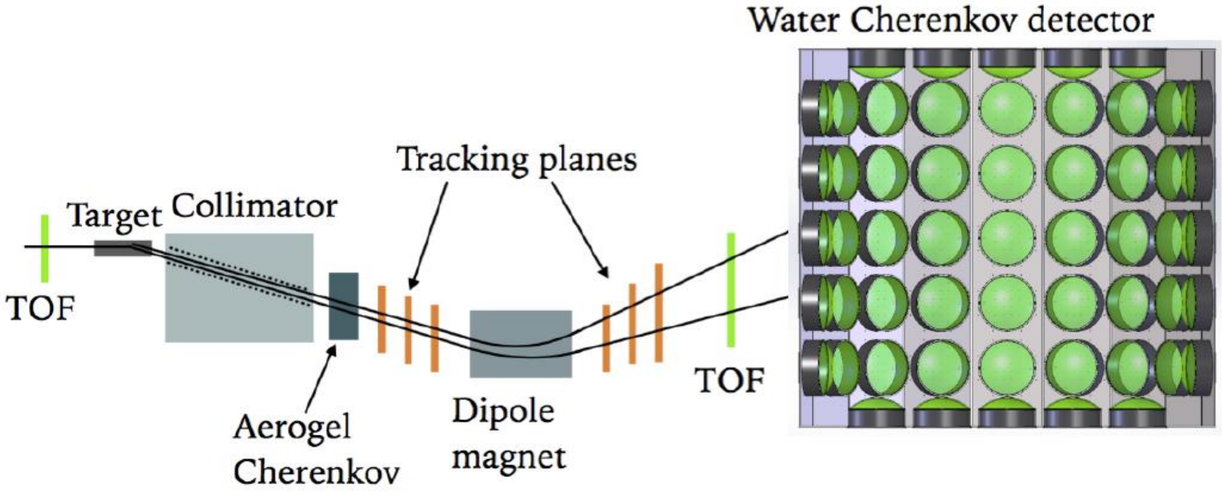
Mexiico Site
LQS: K. Tomatani
LTS: S. Cuen

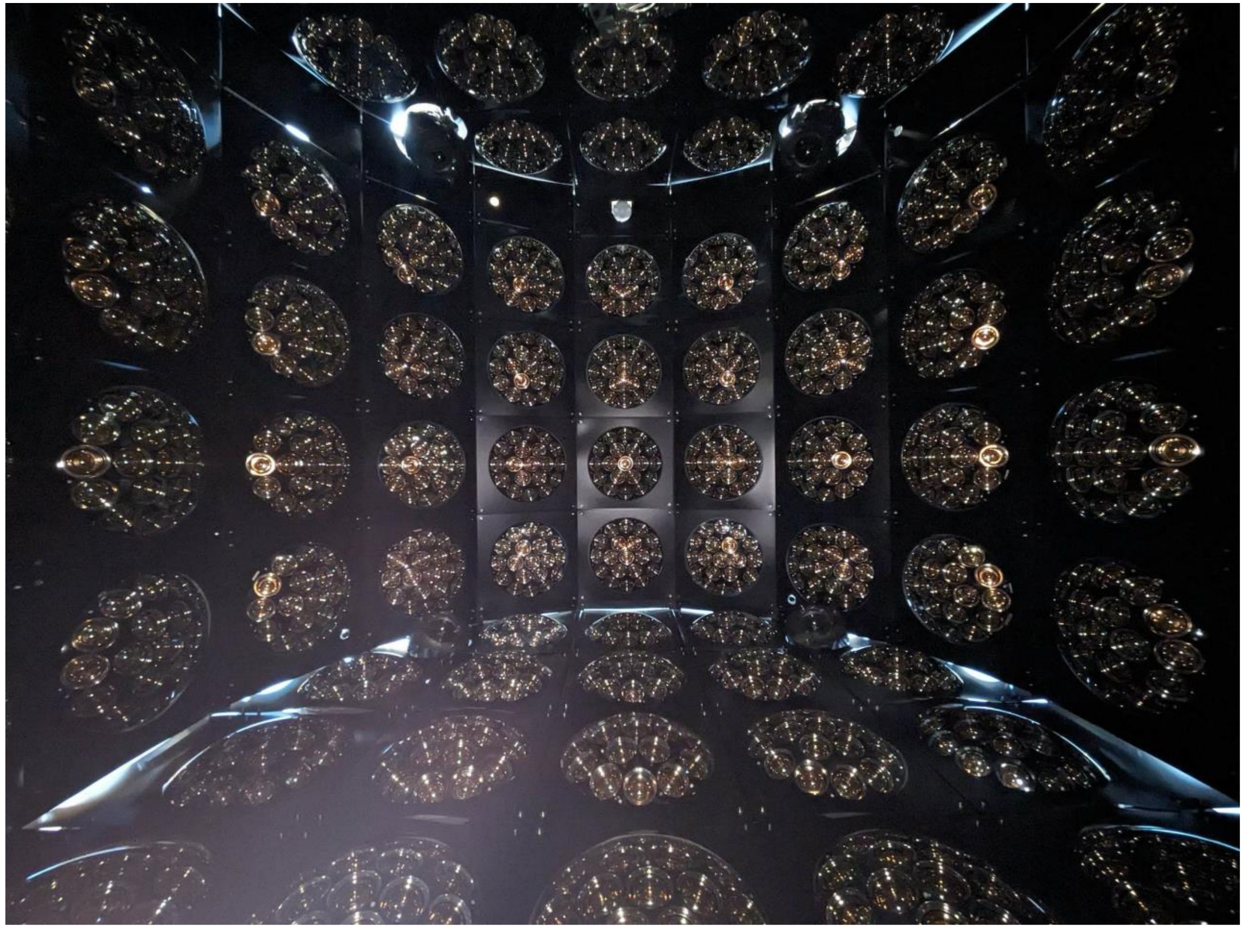
Installation
Mexico, Czechia

LQS = Local Quality Supervisor
LTS = Local Technical Supervisor

The Water Cherenkov test experiment @ CERN

multi-collaboration group
(Hyper-K, ESSnuSB, THEIA)





Finished making 100 mPMTs for WCTE.
Many problems found and solved along the way, but overall successful
WCTE operation will start in October

A. Di Nola responsible for FD mPMTs

HK Electronics

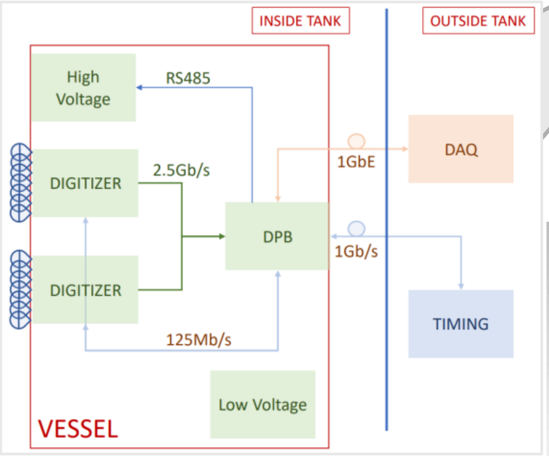
INFN groups developed the front end electronics for the experiment

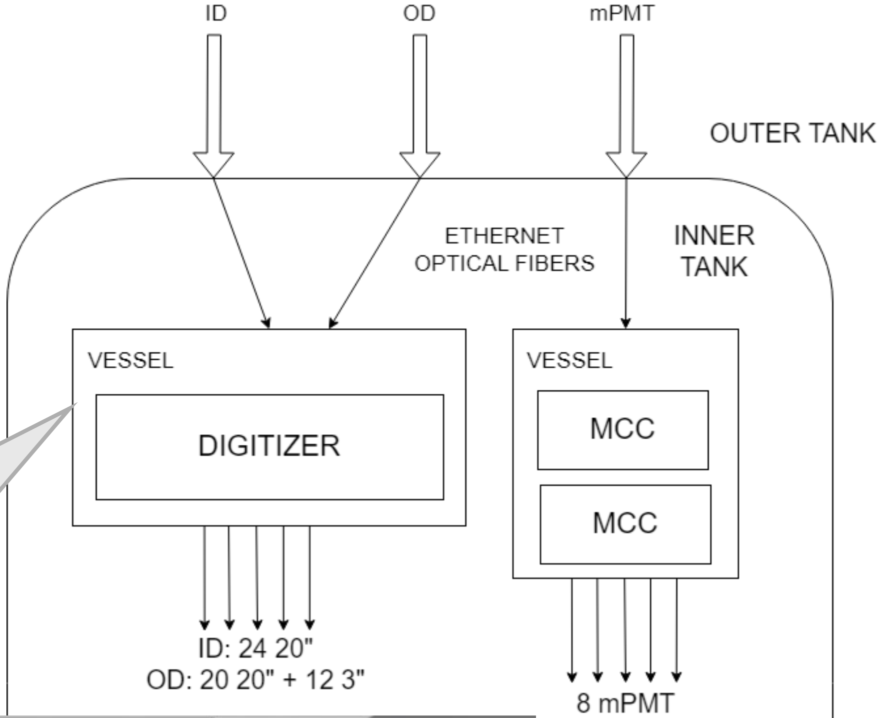
6 pairs of optical fibers + power supply:

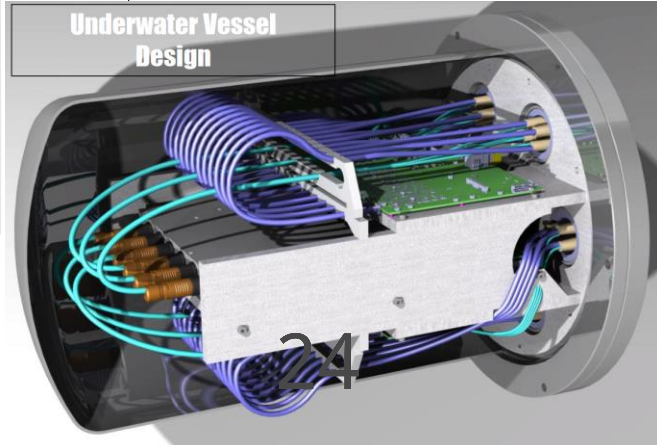
- 2 couples for data
- 2 couples for clock
- 2 couples spare

Underwater electronics inside pressure resistant vessels

Vessels will be assembled at CERN and shipped to Kamioka



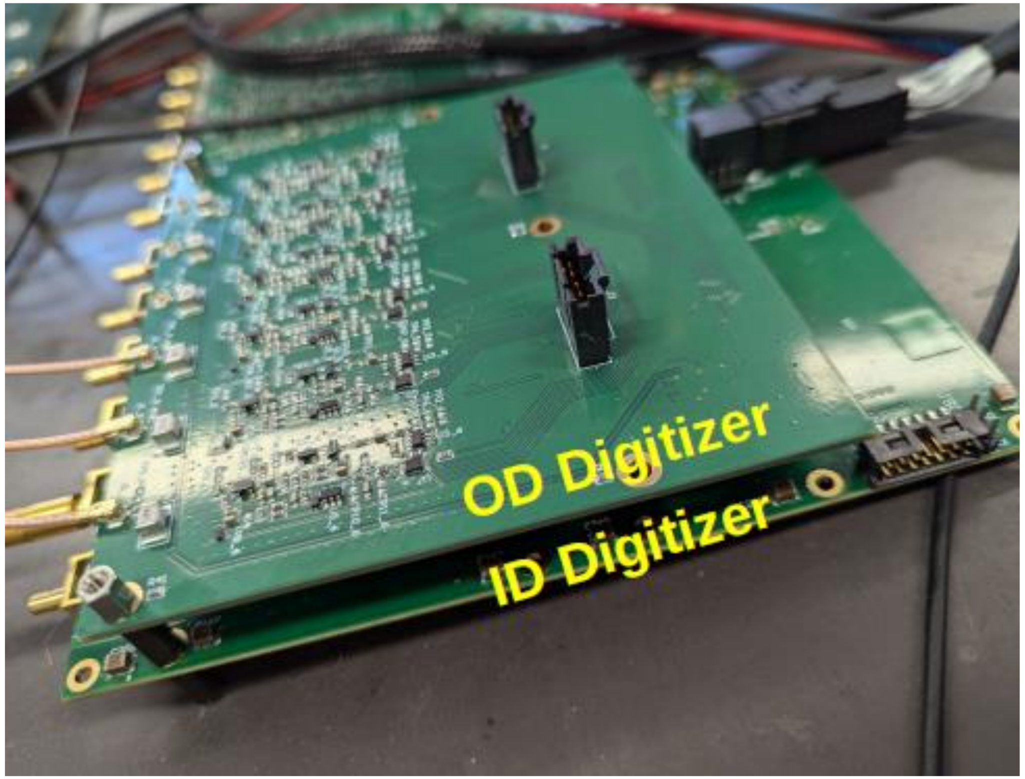




OD digitizer

Hybrid ID/OD design
INFN responsibility on the OD electronics was **limited** to the OD digitizer single channel schematics, layout and prototype (Oct.2022)

Test being carried out at CERN and at Kamioka



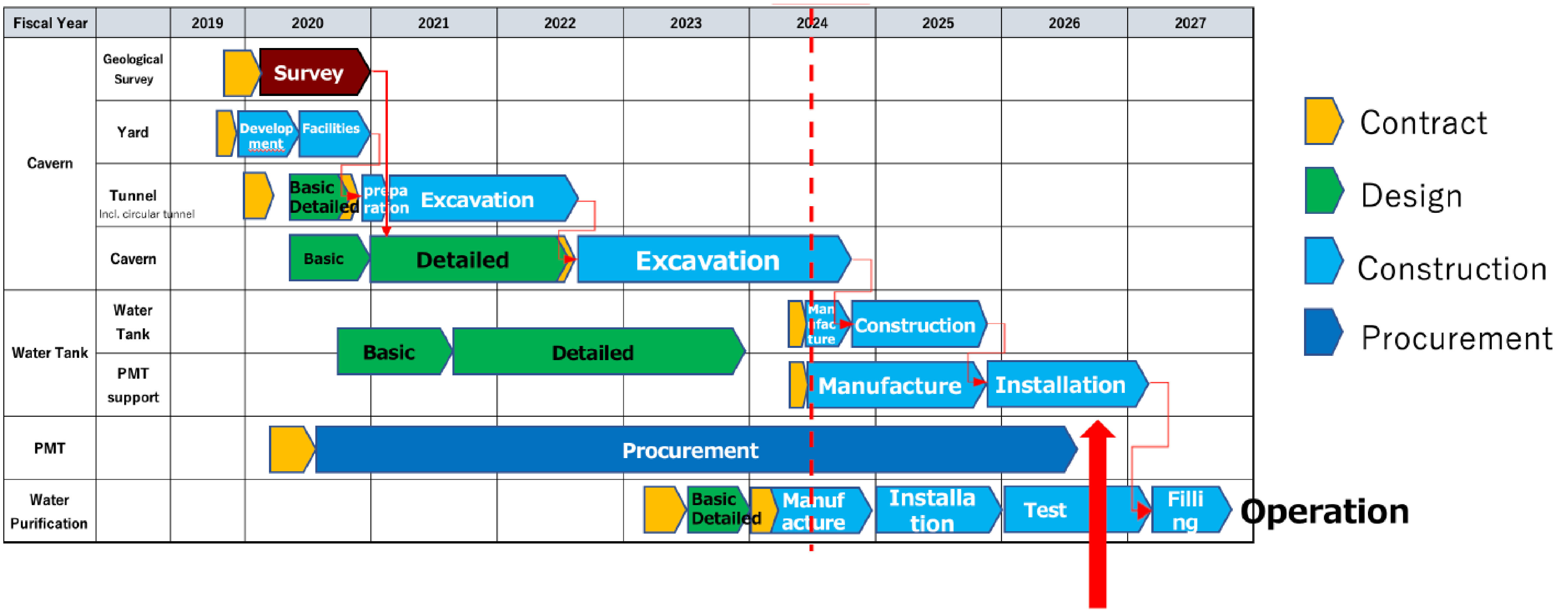
Impegni INFN

SuperK: Presa dati

T2K: Produzione 2 nuove HATPC, installazione e integrazione con le TPC esistenti

HyperK:
- Produzione di 300 (su 808 in totale) mPMT (proposta INFN 2015, approvata nel 2022)
- Front end digitizerper i PMT da 20”
- Timing distribution
- 25% del computing

HyperKamiokande Schedule

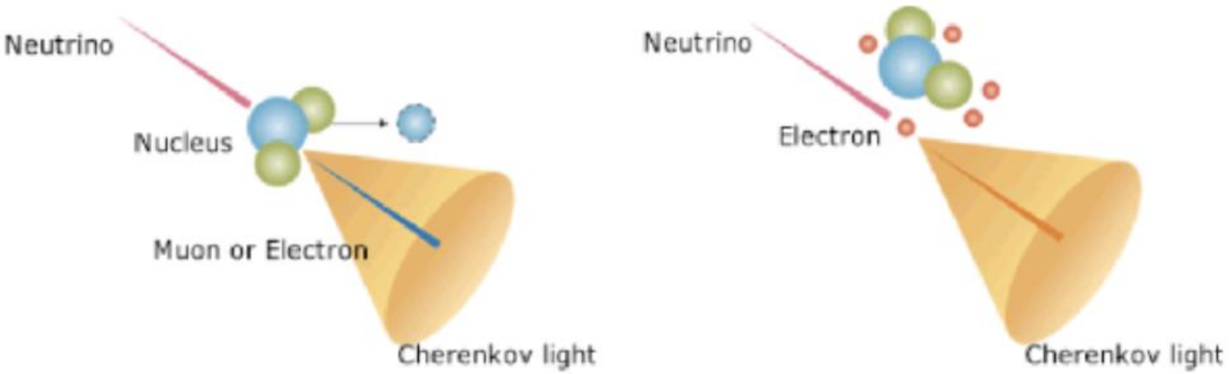


Construction completion is delayed by 5 months

Start full detector data taking in 2027

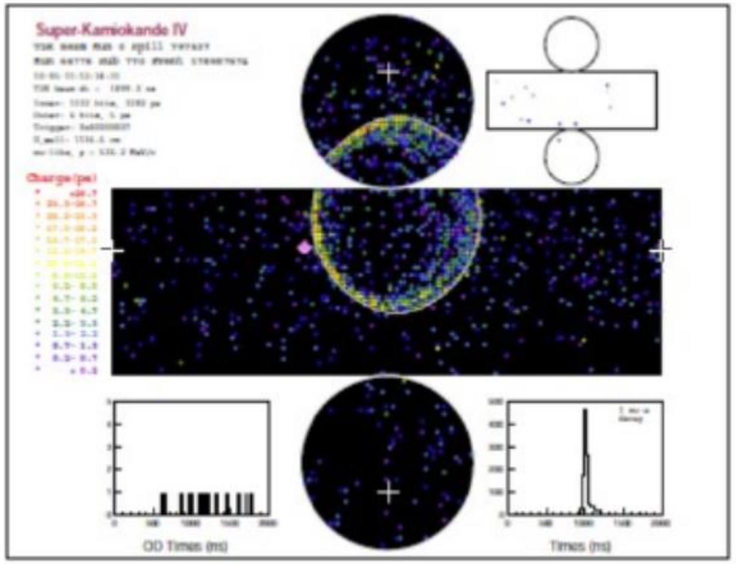
Thank you!

Water Cherenkov detection

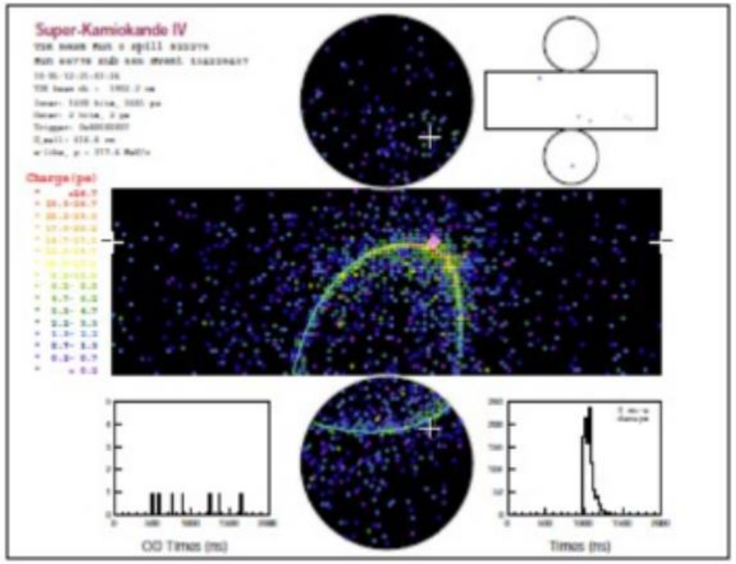


The generated charged particle emits the Cherenkov light.

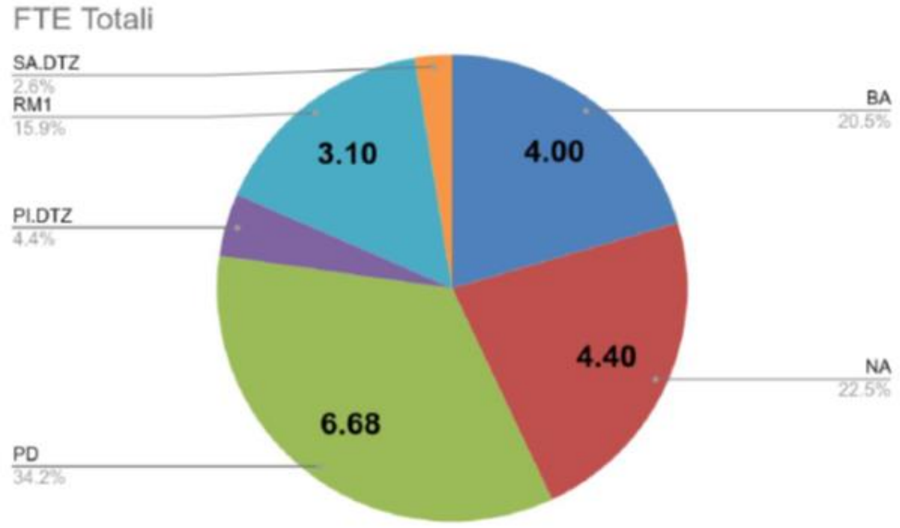
Muon: sharp ring

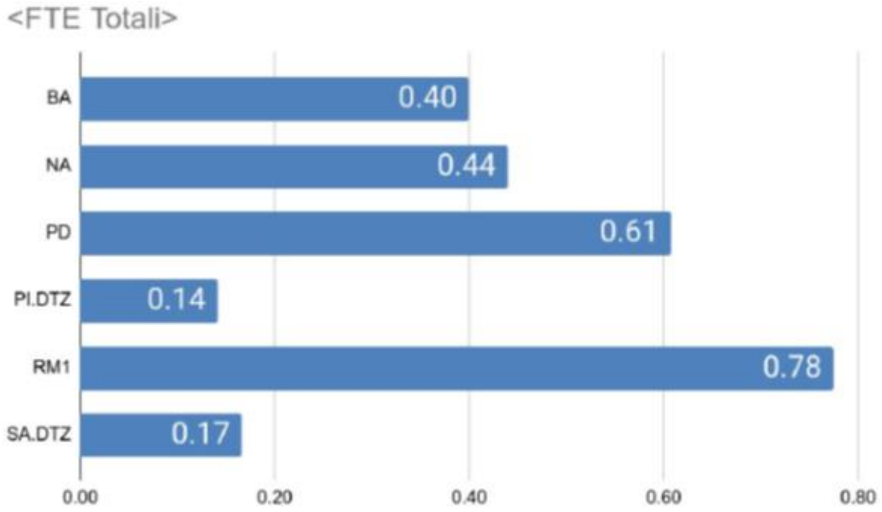


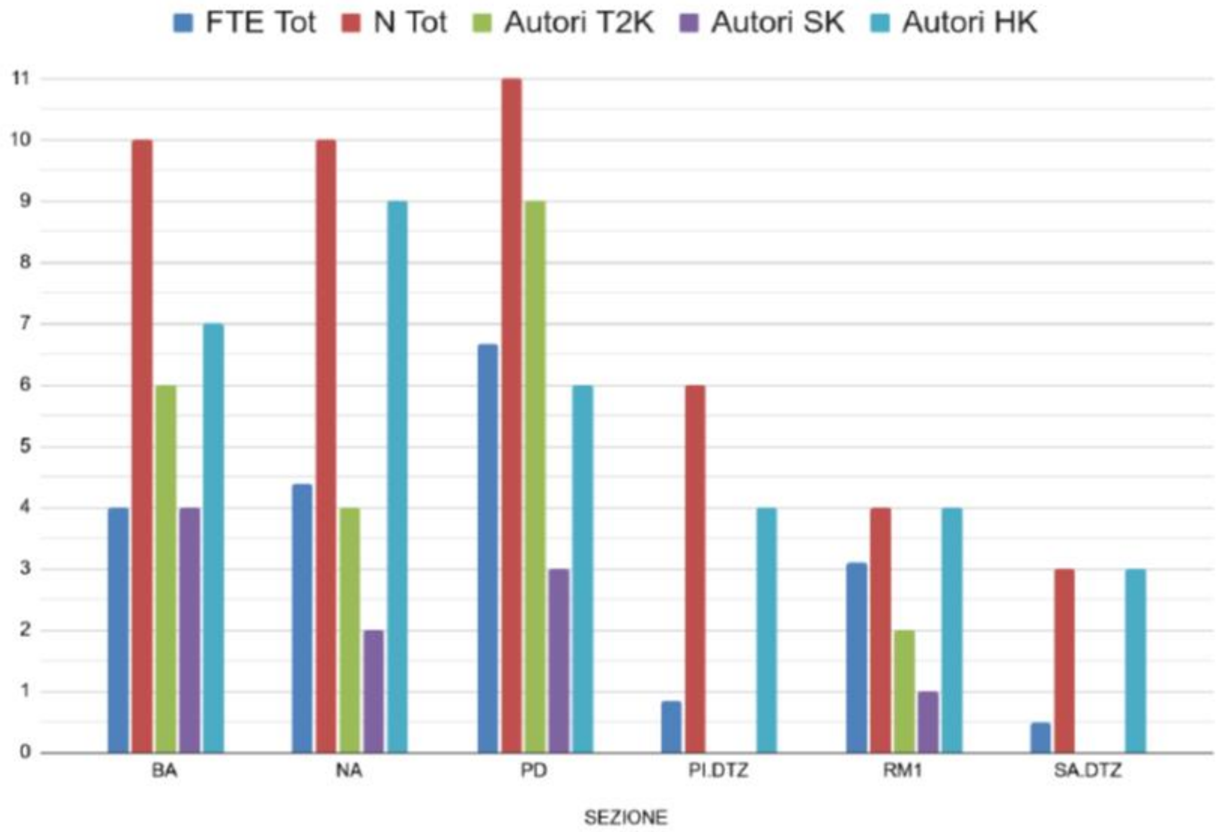
Electron: fuzzy ring



Anagrafica INFN

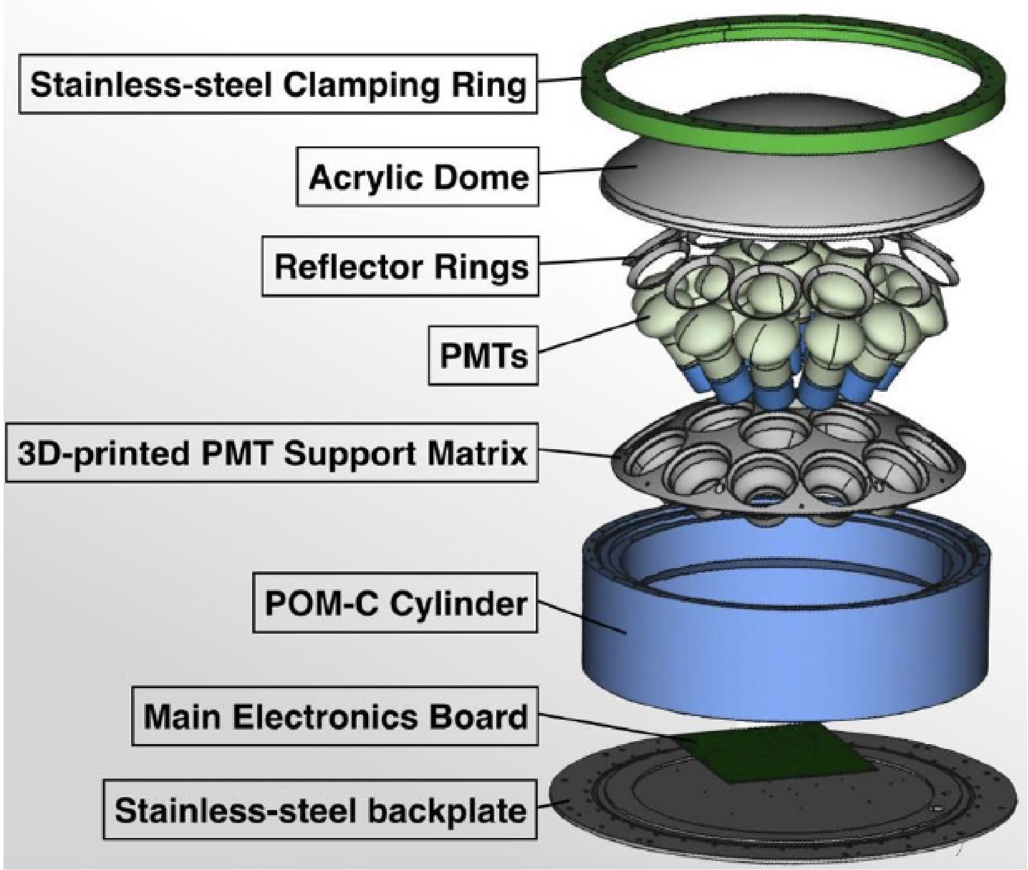




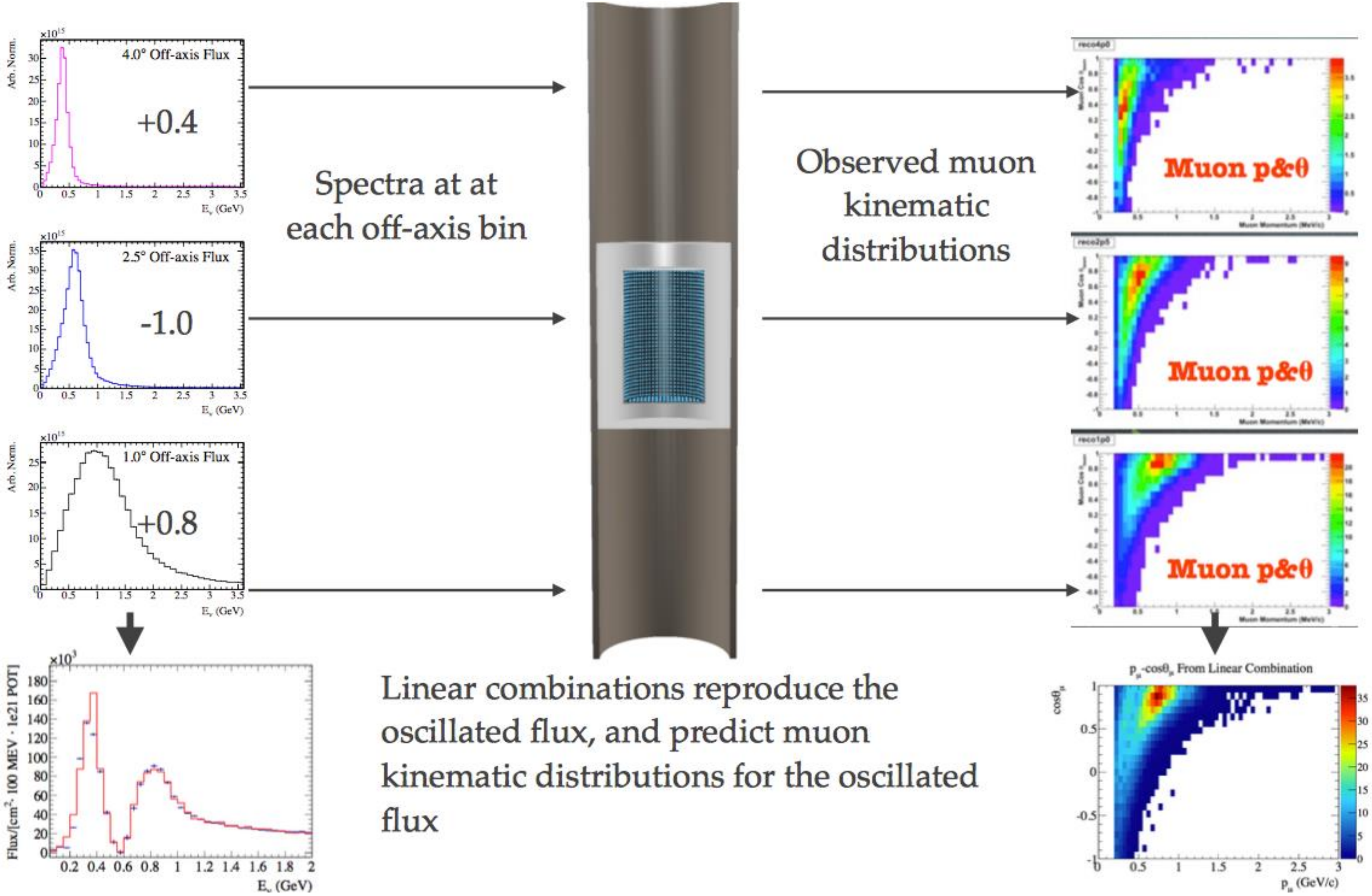


Impegni INFN

- SuperK
  - ✓ Presa dati
- T2K
  - ✓ Produzione 2 nuove HATPC, installazione e integrazione con le TPC esistenti
- HyperK
  - ✓ Produzione di 300 (su 808 in totale) mPMT (proposta INFN 2015 da KM3NeT, approvata nel 2022)
  - ✓ Front end digitizer per i PMT da 20''
  - ✓ Timing distribution
  - ✓ 25% del computing



The Hyper-Kamiokande Intermediate Water Cherenkov Detector



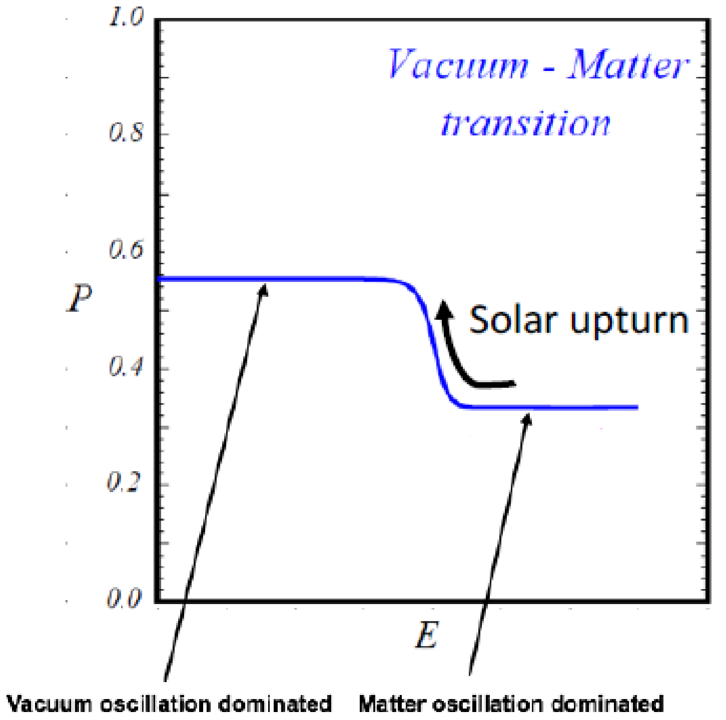
Spectra at at each off-axis bin

Observed muon kinematic distributions

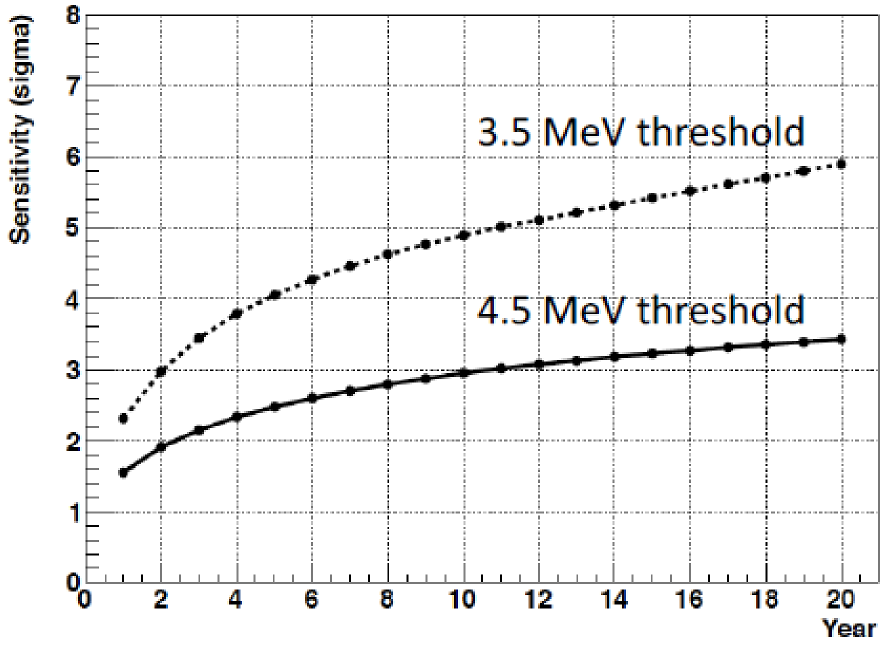
Linear combinations reproduce the oscillated flux, and predict muon kinematic distributions for the oscillated flux

Solar neutrinos

Measuring the transition region



Solar upturn sensitivity

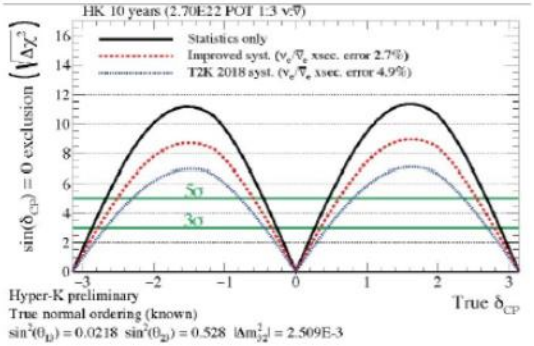


Hyper-K can measure the solar upturn to ~5σ (3σ) after 10 years with
3.5 MeV (4.5 MeV) threshold

Potenziale di Hyper-K

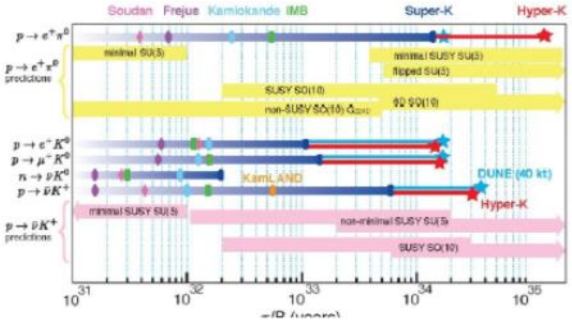
CP Violation

- 5σ discovery per >60% dei valori di δ_{CP}
- Per CP massimale, $\delta_{CP} = -\pi/2$, CPV a 5σ in 2-3 anni
- Simile a Dune (4 moduli) con un vantaggio di 3-5 anni, a circa un quarto del costo
- Sensibilità, efficienze, fondi, sistematici da dati, le misure in T2K, più che da MonteCarlo



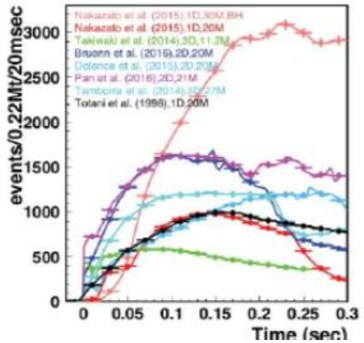
Proton decay

- Migliora di un ordine di grandezza il limite di SK nel canale principale p → e π°
- Competitivo con Dune (4 moduli) negli altri canali
- Oscillazione neutrone-antineutrone a 10^9s



SN neutrinos

- 70k eventi per una SN a 10 kpc (SN1987A, ~50 kpc, osservata con 25 eventi)
- Time profile permette di discriminare modelli di esplosione di SN (arXiv:2101.05269)
- Sensibilità fino ad Andromeda M31 (~780kpc) con ~10 eventi



Potenziale di Hyper-K

Supernova relic neutrinos (DSNB)

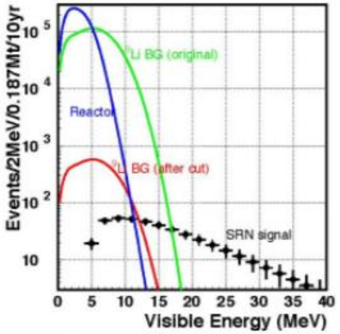
- ~4 eventi/anno. Discovery potential >3σ in 10 anni
- Misura dei neutrini emessi dalle esplosioni di SN dall'inizio dell'Universo
- Forniscono informazioni sul collasso stellare, la nucleosintesi e la rate di formazione di stelle nell'Universo

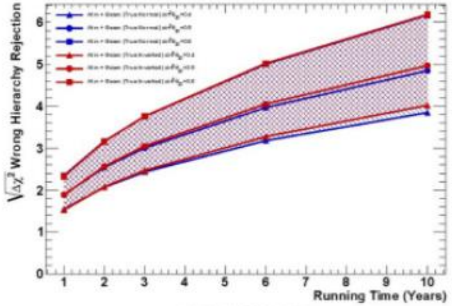
Neutrini atmosferici e solari

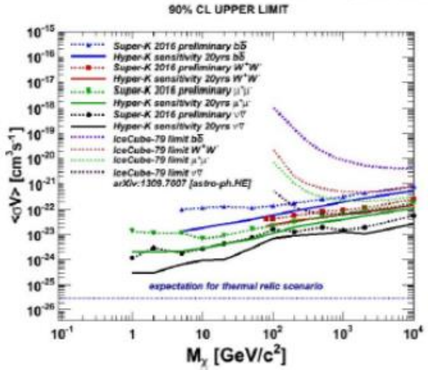
- Gerarchia di massa a 3.8-6.2σ, secondo $\sin^2\theta_{23}$. Early discovery combinando SK, Juno, IceCube, Orca.
- Sensitività all'ottante di θ_{23}
- Solari: Day/night a 5σ, upturn dello spettro a 3σ, hep neutrinos a 2-3σ

Altri canali astrofisici

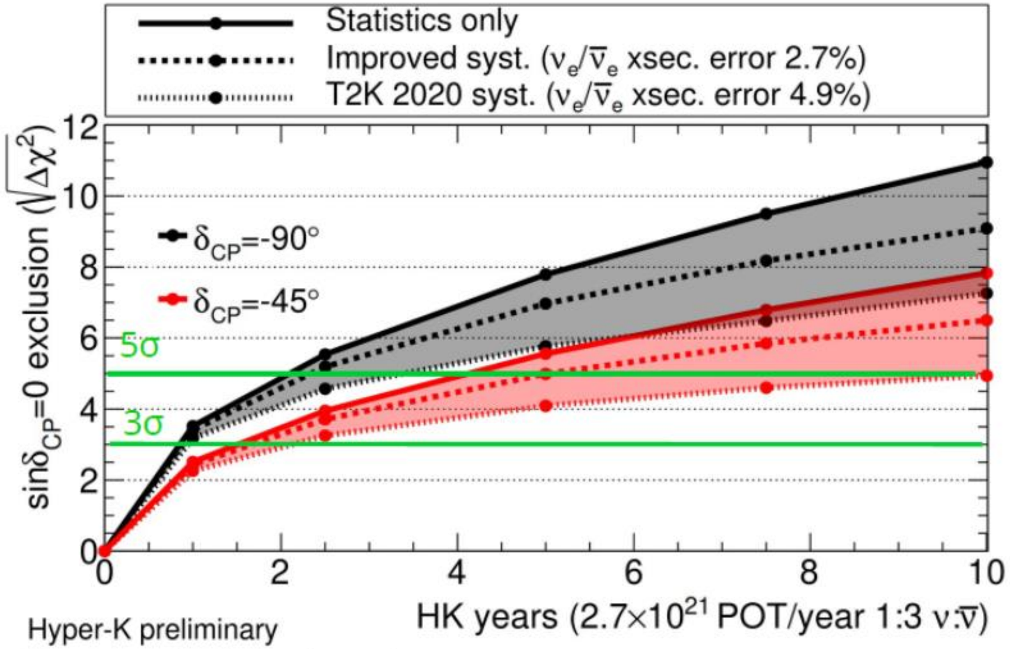
- Indirect DM detection
- Rivelazione di neutrini di bassa energia (~10 MeV) da merging di stelle di neutroni nella nostra galassia
- Geoneutrini (gadolinio)
- NB: SK ha pubblicato circa 400 lavori finora su oscillazioni (T2K escluso) e canali astrofisici e vinto un premio Nobel



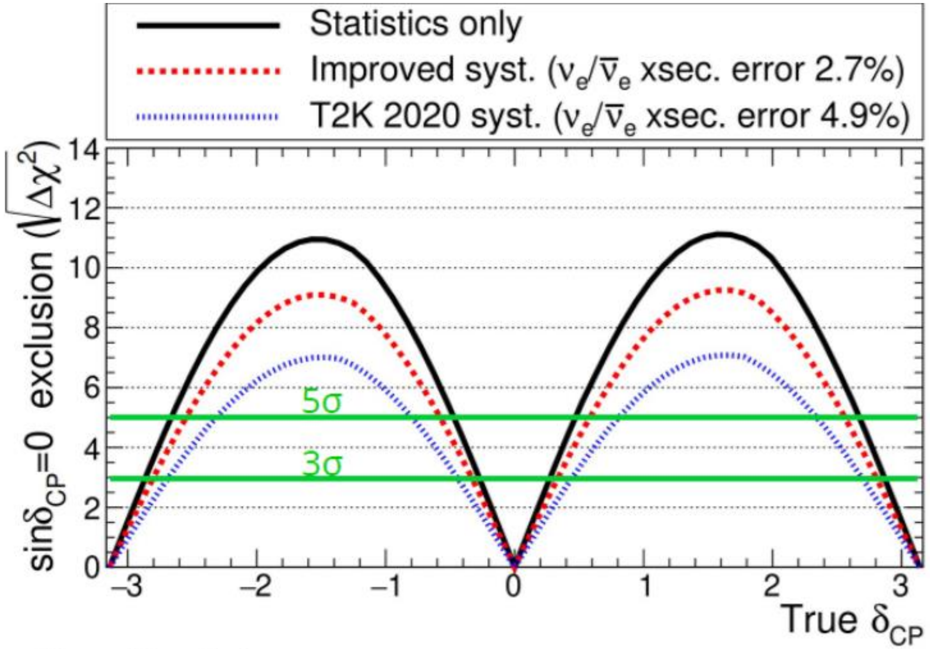




Sensitivity to CP violation



Hyper-K preliminary
True normal ordering (known)
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\mathrm{eV}^2/c^4$



Hyper-K preliminary
True normal ordering (known), 10 years (2.7×10^{22} POT 1:3 $\nu:\overline{\nu}$)
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\mathrm{eV}^2/c^4$

For maximal CP violation ($\delta_{CP}=-\pi/2$), sensitivity to rule out CP conservation at 5σ within 2-3 years

After 10 years, CP conservation excluded at >5σ(3σ) for 62.8%(78.5%) of δ_{CP} values

Assumption: mass ordering known

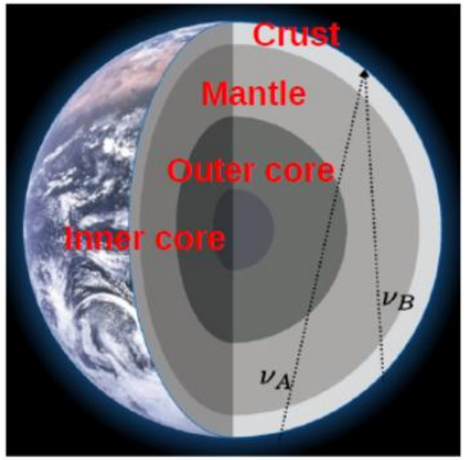
Atmospheric neutrinos and mass ordering

Mass Ordering can be measured through matter effects

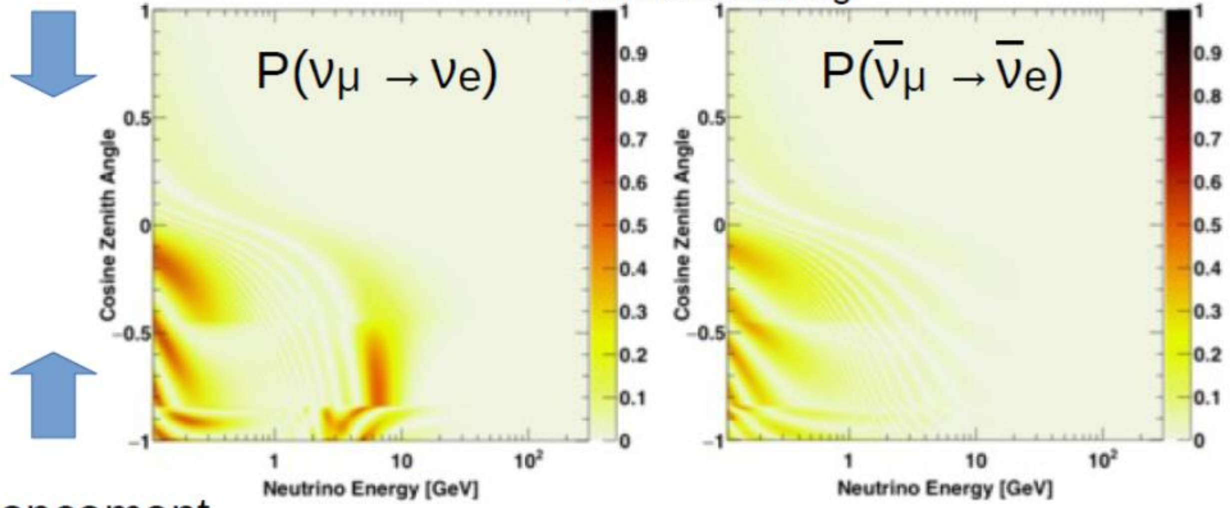
Baseline 295km, L/E tuned at 1st maximum, in order to maximize CPV effects with small matter effects

Atmospheric neutrinos have a broad range of L,E

Complementarity → atmospheric and beam combination to disentangle parameter degeneracy



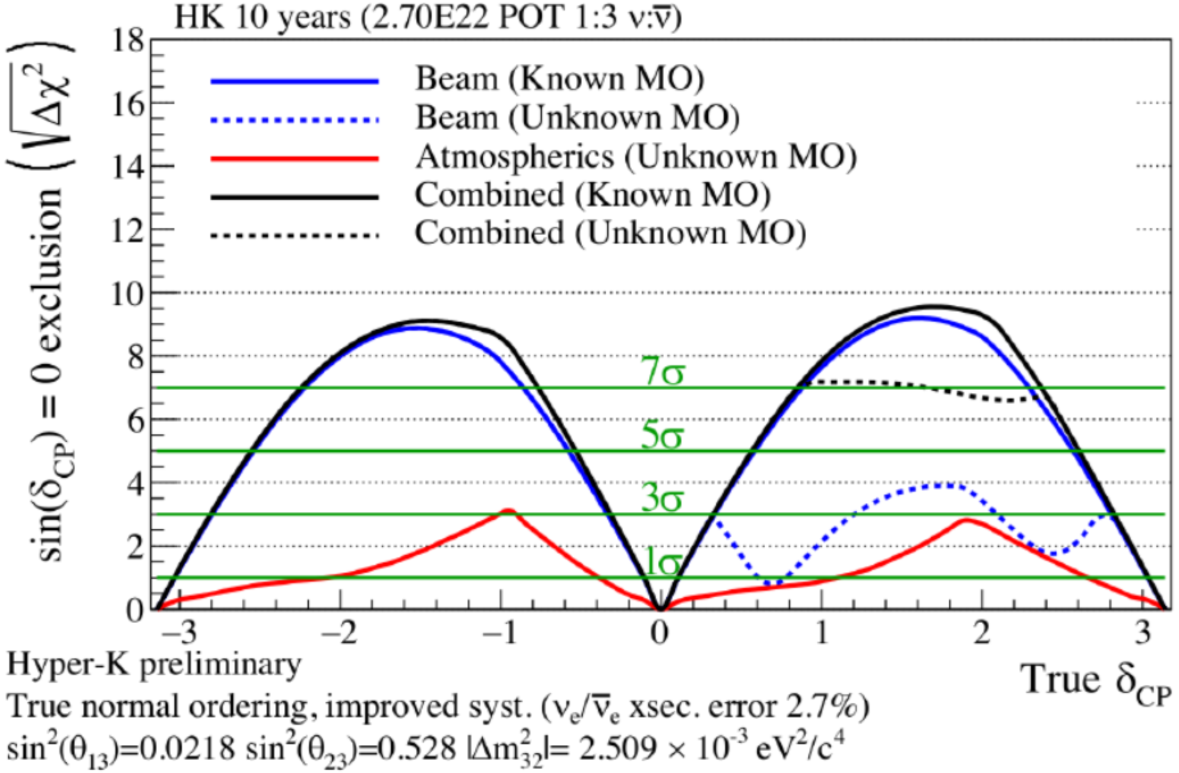
Normal Ordering



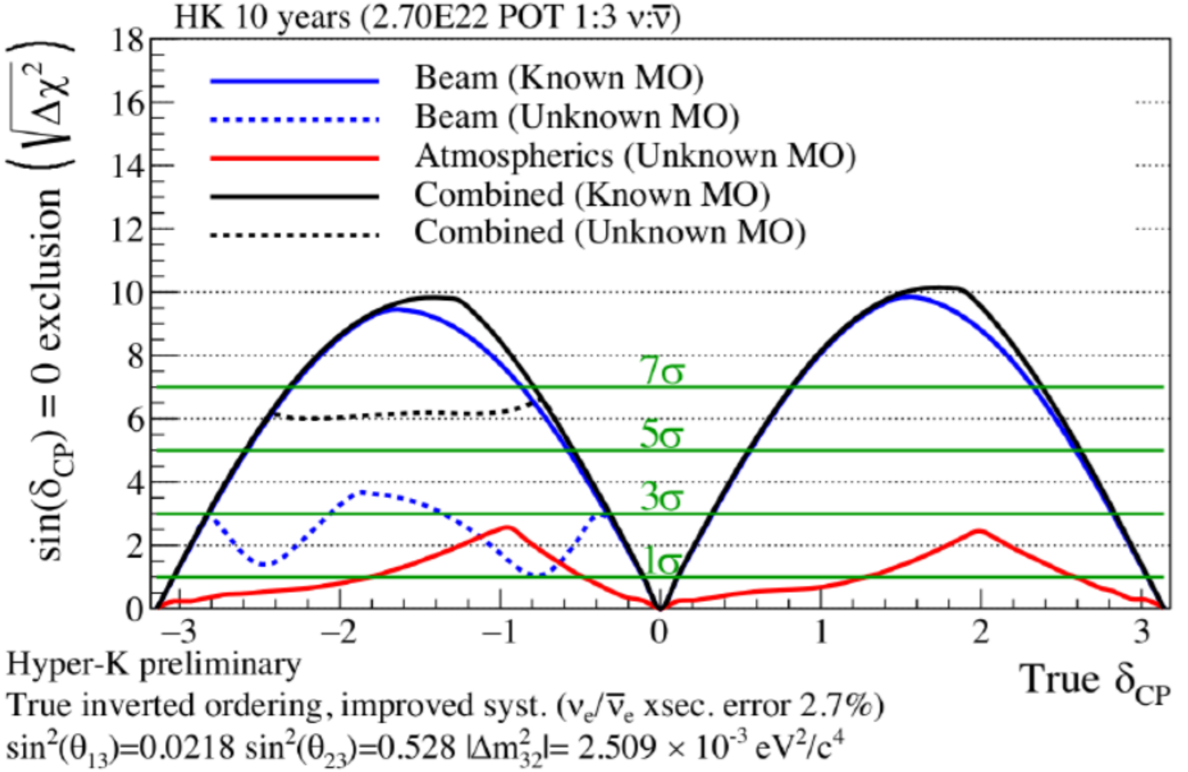
Normal Ordering: $\nu_\mu \to \nu_e$ enhancement
Inverted Ordering: $\bar{\nu}_\mu \to \bar{\nu}_e$ enhancement

Many samples: rings-ID (e-like, μ-like), number of rings, energy (sub-GeV, multi-GeV),...
Mass Ordering determined mainly by the (upward-going) multi-GeV electron-like events

CP Violation and Mass Ordering



Normal Ordering

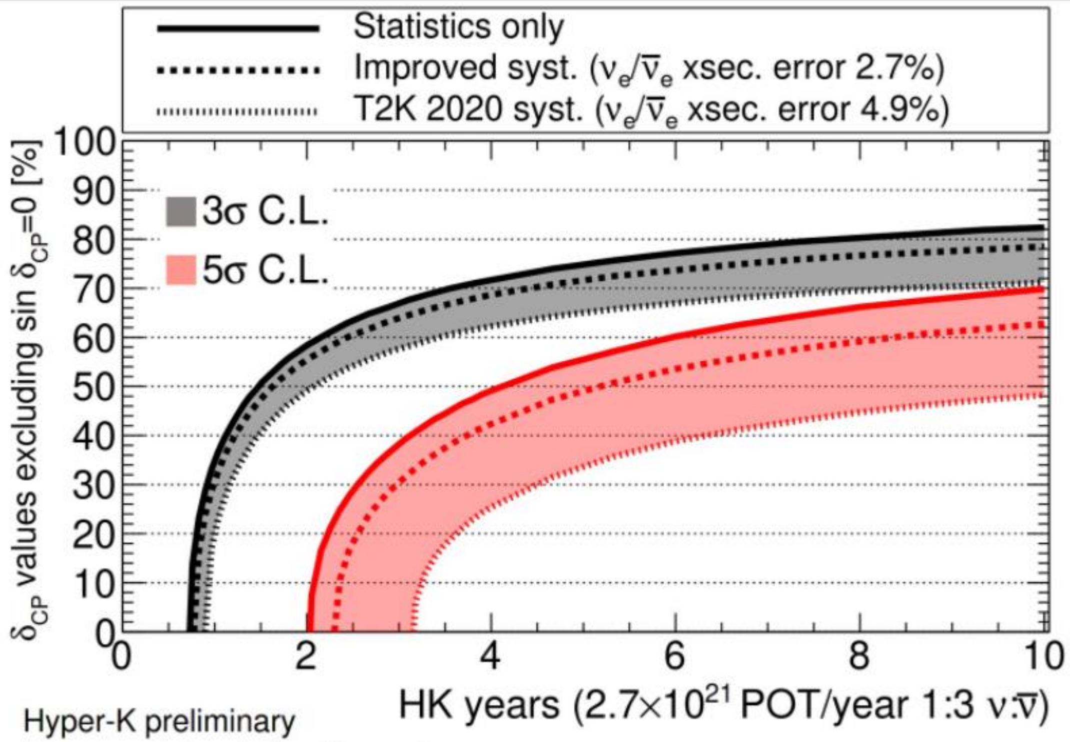


Inverted Ordering

Even if mass ordering unknown, with beam+atmospheric → small effect on CPV sensitivity

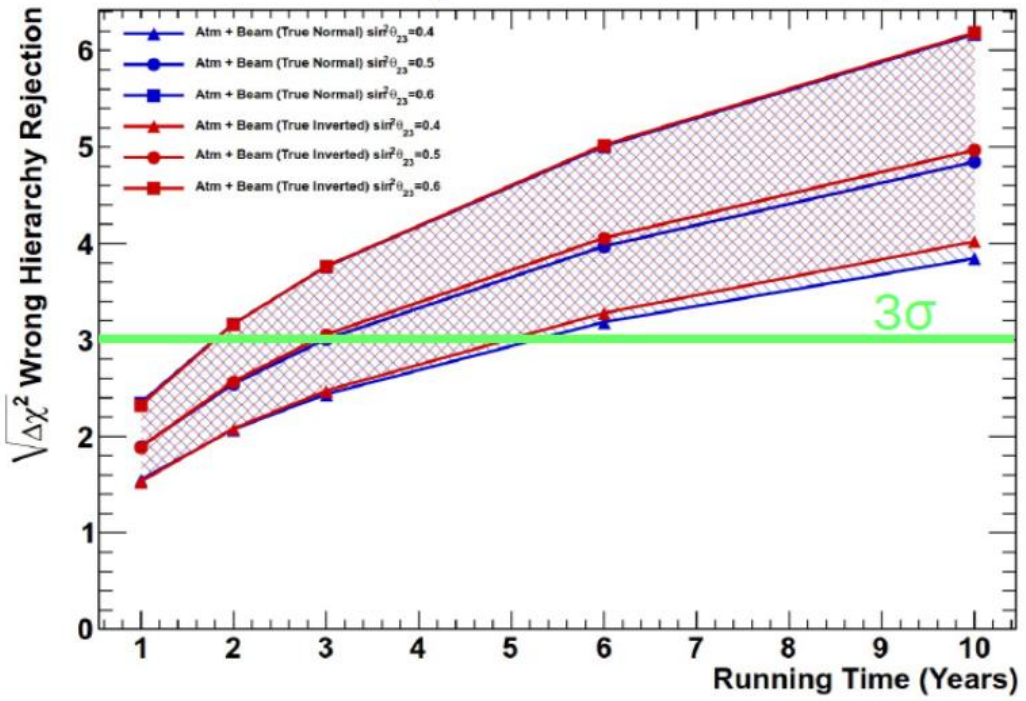
Combination of beam + atmospheric

Fraction of δCP values excluding CP conservation



Hyper-K preliminary
True normal ordering (known)
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\text{eV}^2/c^4$

Sensitivity to Mass Ordering



Even if mass ordering unknown, with beam+atmospheric → small effect on CPV sensitivity
CPV sensitivity 5σ in 10 years for 63% of δCP values, 3σ in 2-3years for 50-60% of δCP values
Mass Ordering determination at 3σ within 2-5 years and at 4-6σ after 10 years

Near Detector importance

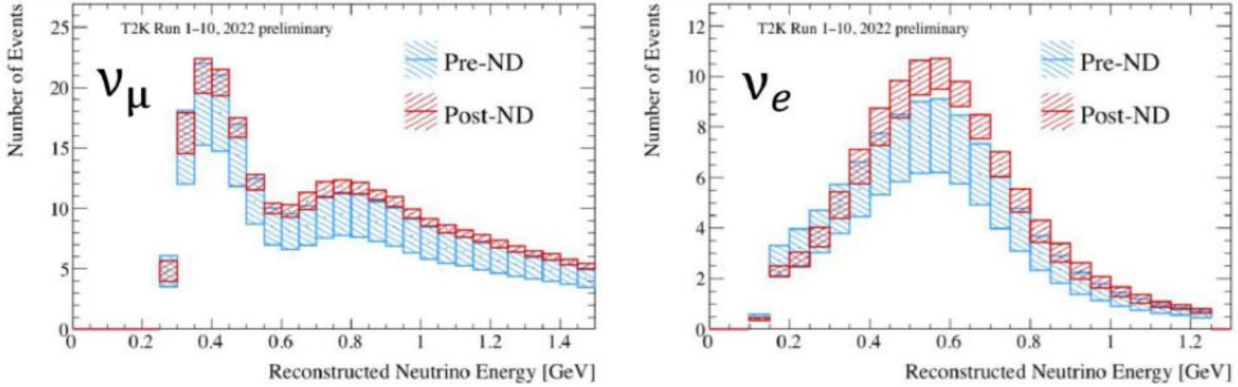
Significant reduction of flux and cross-section systematics in the oscillation analisys

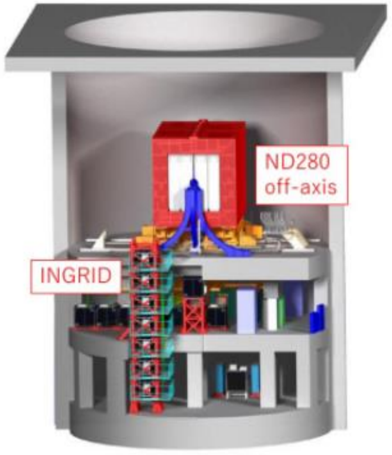
ND280 upgrade important now to extend the T2K run to 2027 and then for HK

No further upgrade, only M&O, before HK starts. MoU between T2K and HK for the ND280 legacy (detector, know-how, software, data)

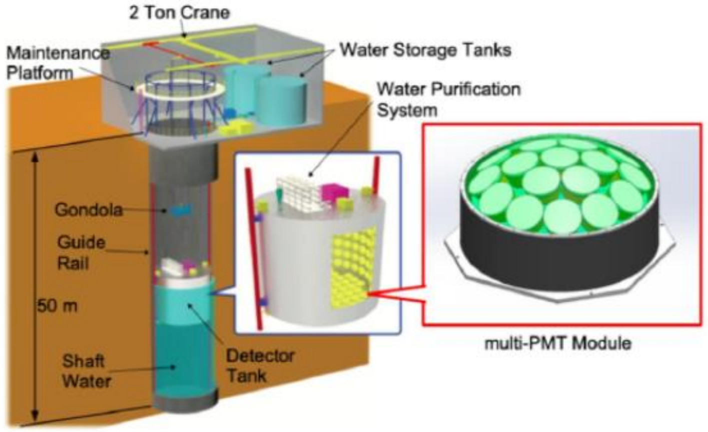
New IWCD (Intermediate Water Cherenkov Detector) under construction. Water target, changeable off-axis angle → different neutrino energies

Far detector energy spectra uncertainty with and w/o ND280 (T2K)





ND280 (at 280m)



IWCD (at 850m)

T2K-NOvA joint analysis

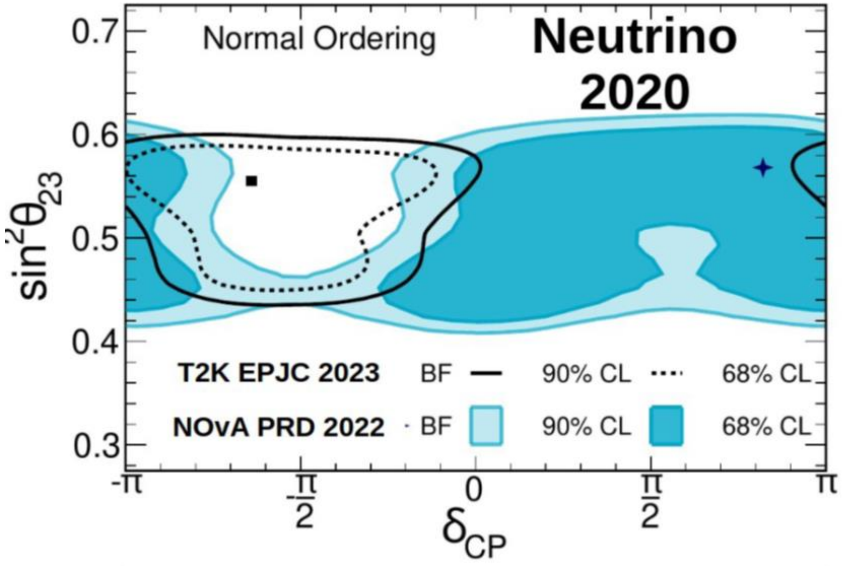
Different baselines and energies lift parameter degeneracies

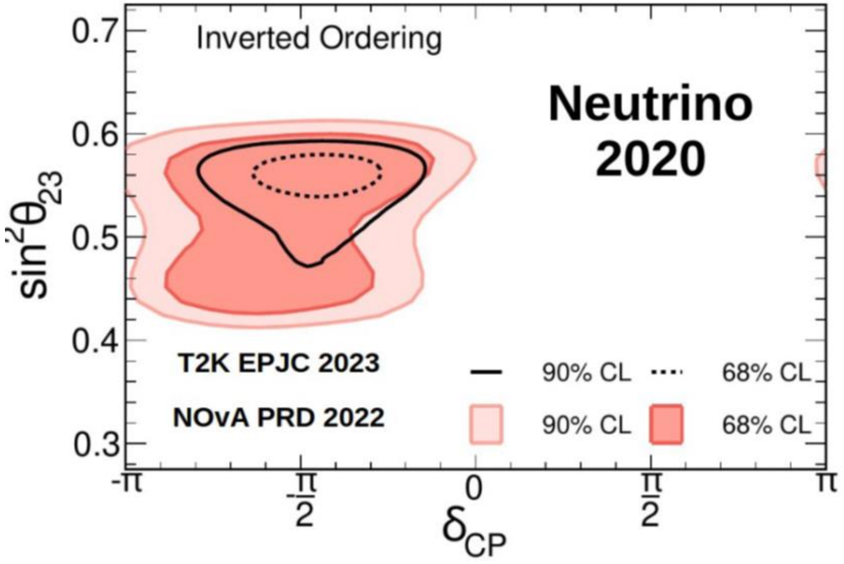
Proper combination of fulll detailed likelihood with a coherent statistical inference across full phase space

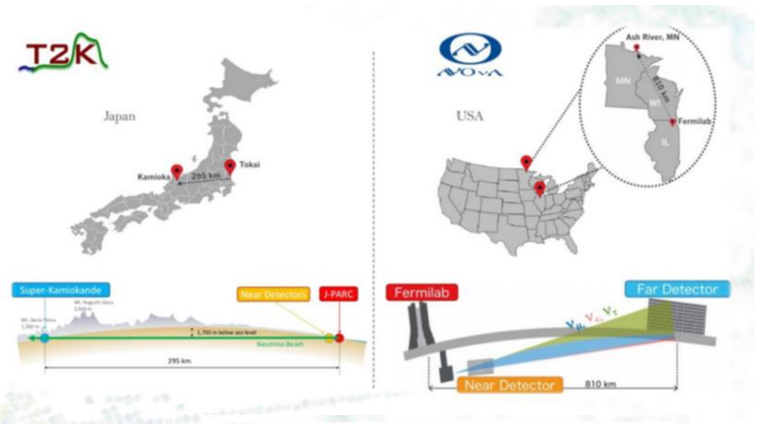
Review and implementation of detectors effects, models and systematic uncertainties

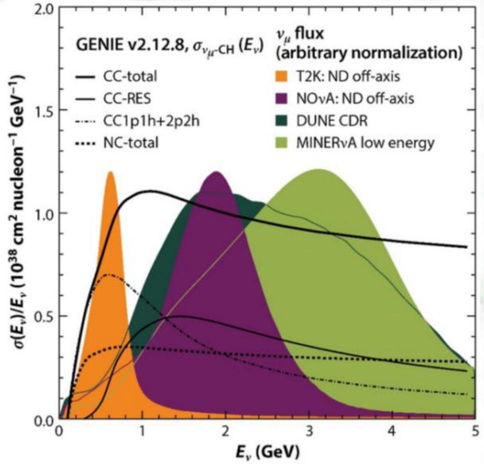
Exploitation of different approaches to the OA in a consistent framework

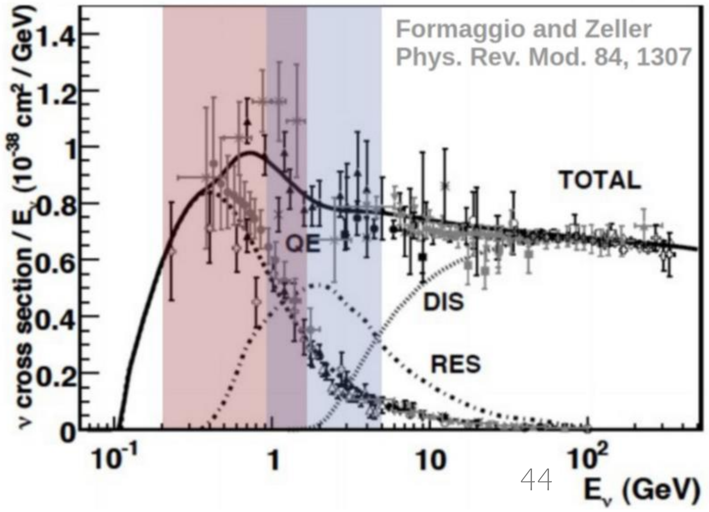
→ The result of several years work of a T2K/NOvA joint analysis group



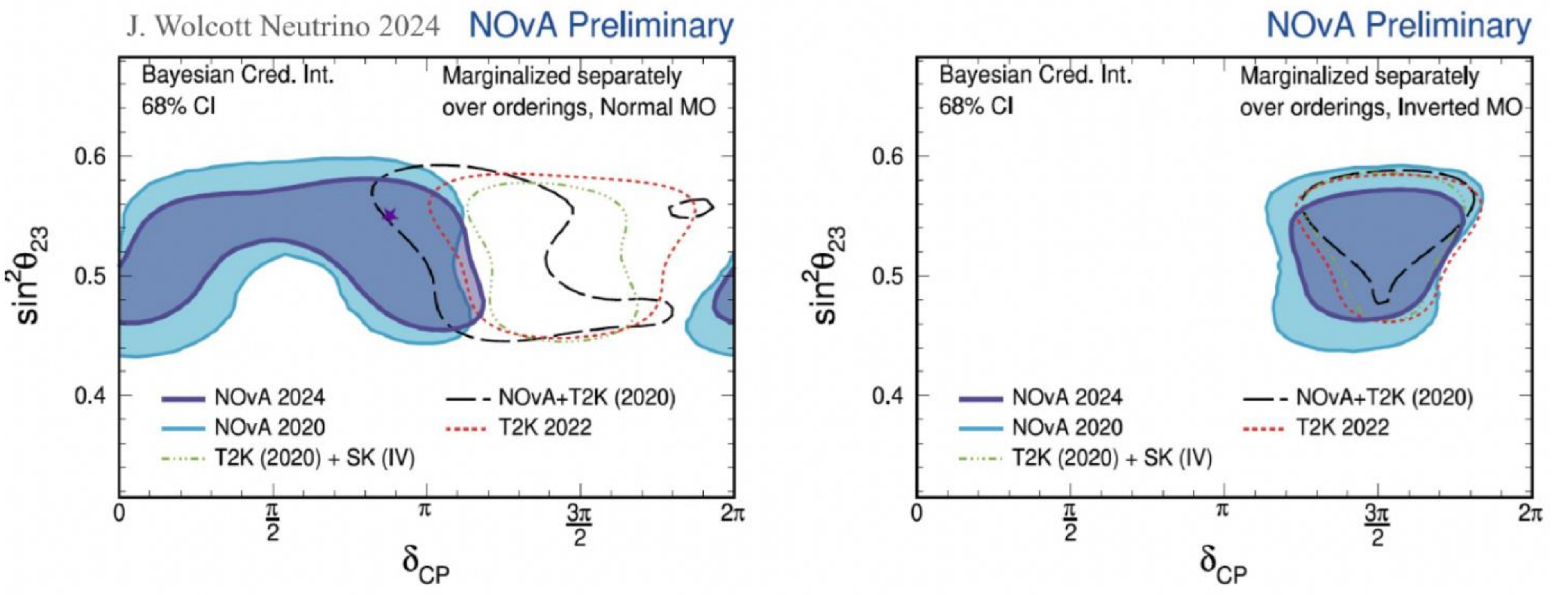








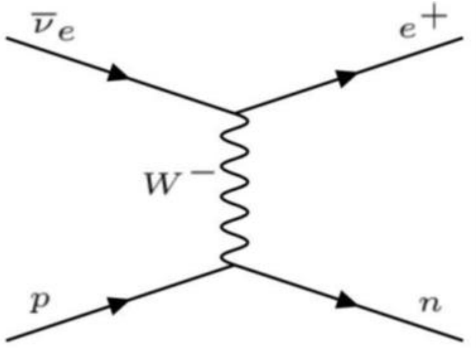
Tensions between T2K (and T2K+SK) vs NOvA



- NOvA update at Neutrino 2024 confirms 2020 result
- T2K and NOvA favors different oscillation parameters and the joint fit find a compromise
- More data will tell if the difference vanishes or becomes more statistically significative

Supernova Neutrino Interactions in Hyper-Kamiokande

Dominant cross-section is inverse beta decay (IBD)



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

~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

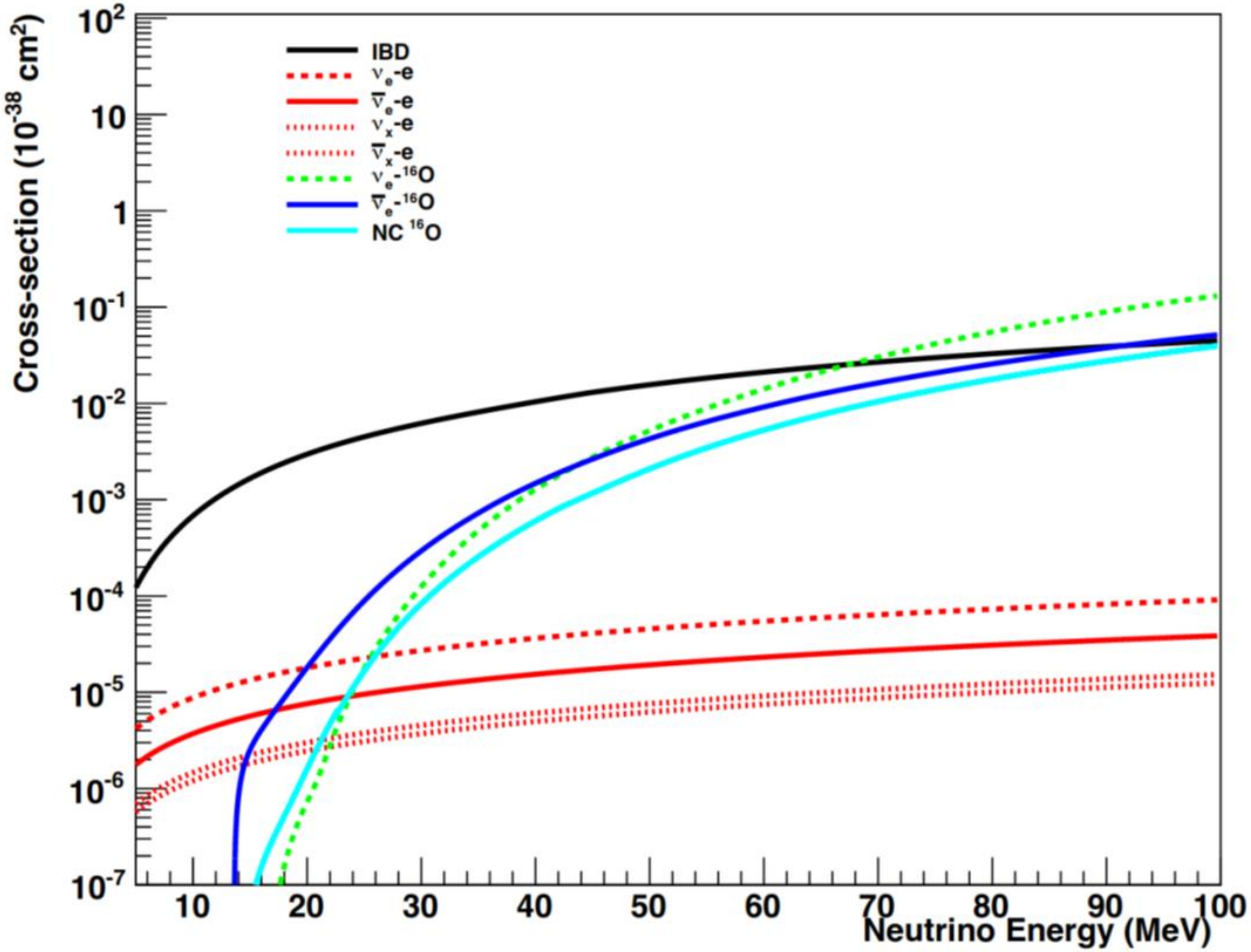
Preserves direction information

Other modes

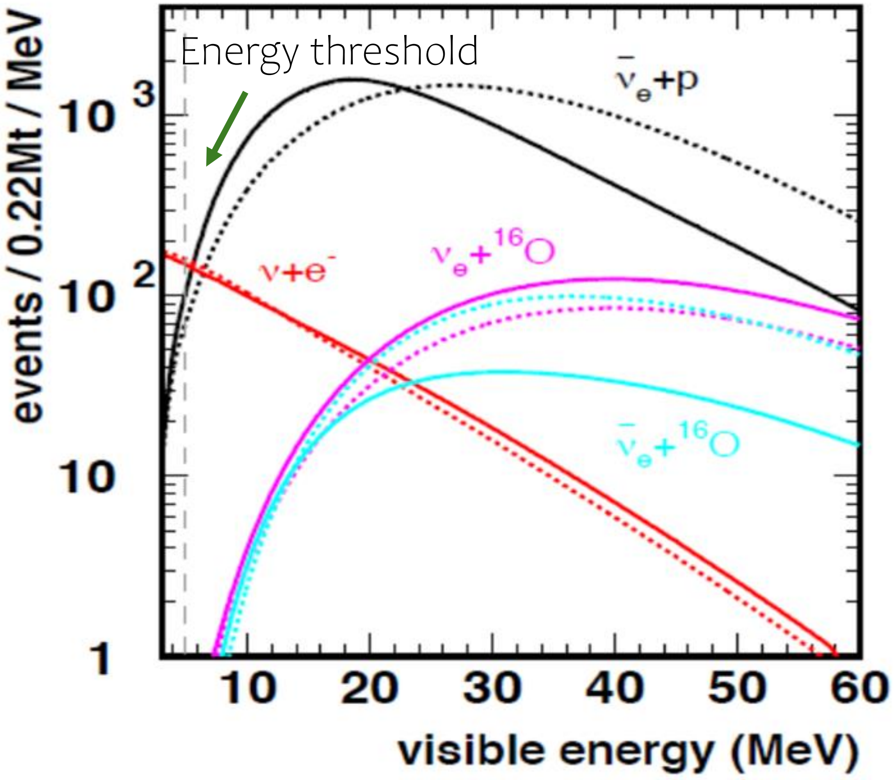
Highly model dependent, due to threshold effects

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

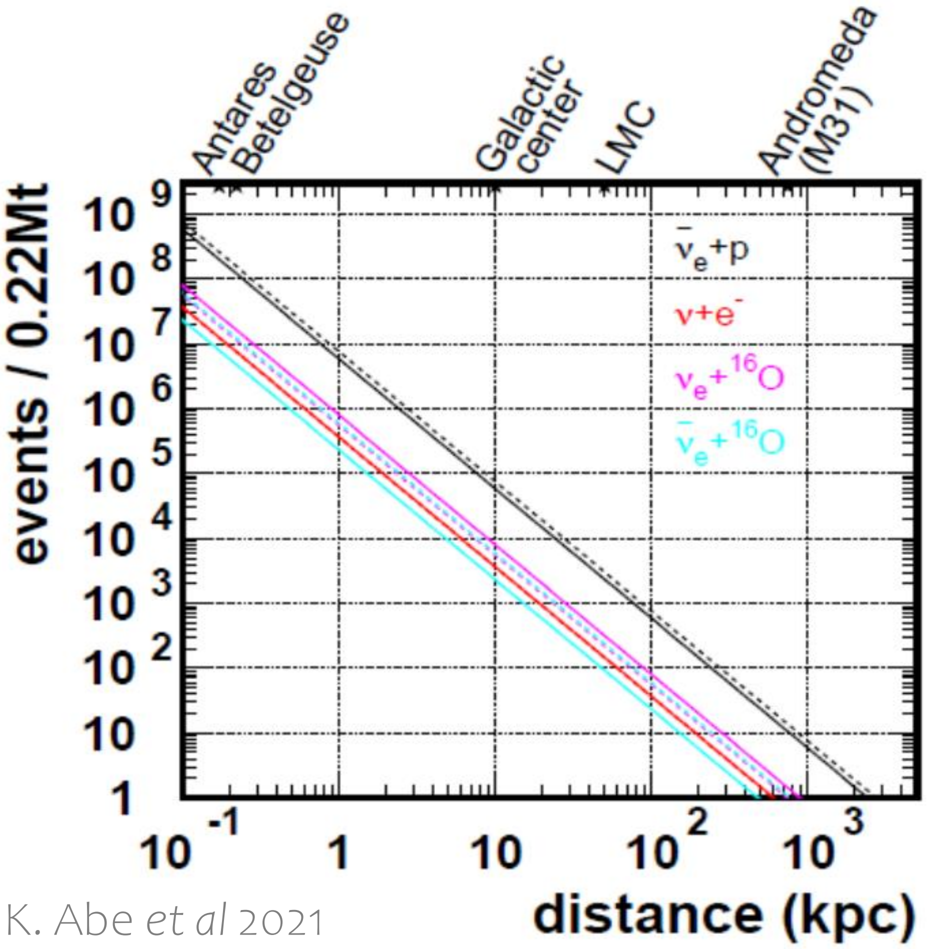
Angular distribution ES electrons strongly peaked into a forward direction

→ 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



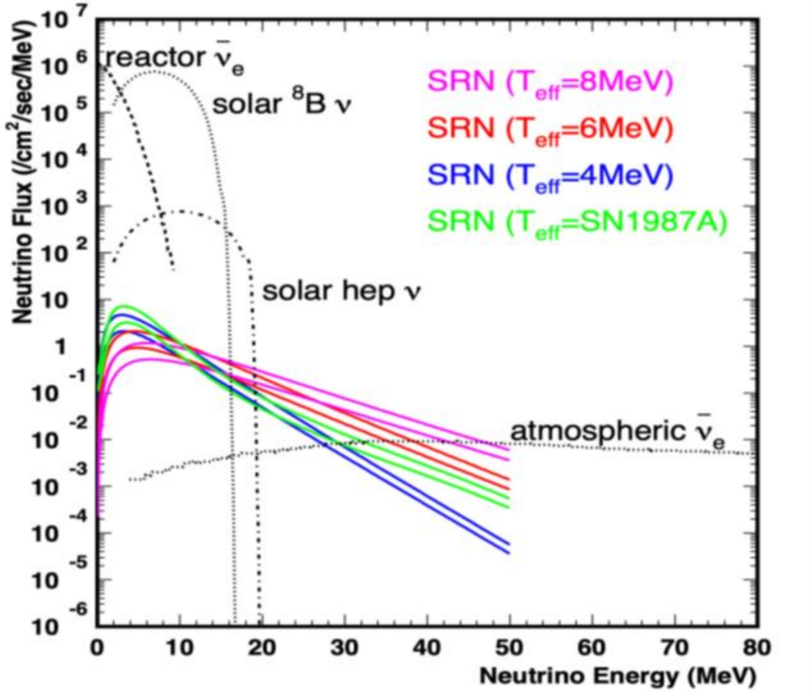
K. Abe *et al* 2021
ApJ 916 15

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

SRN with Hyper-Kamiokande

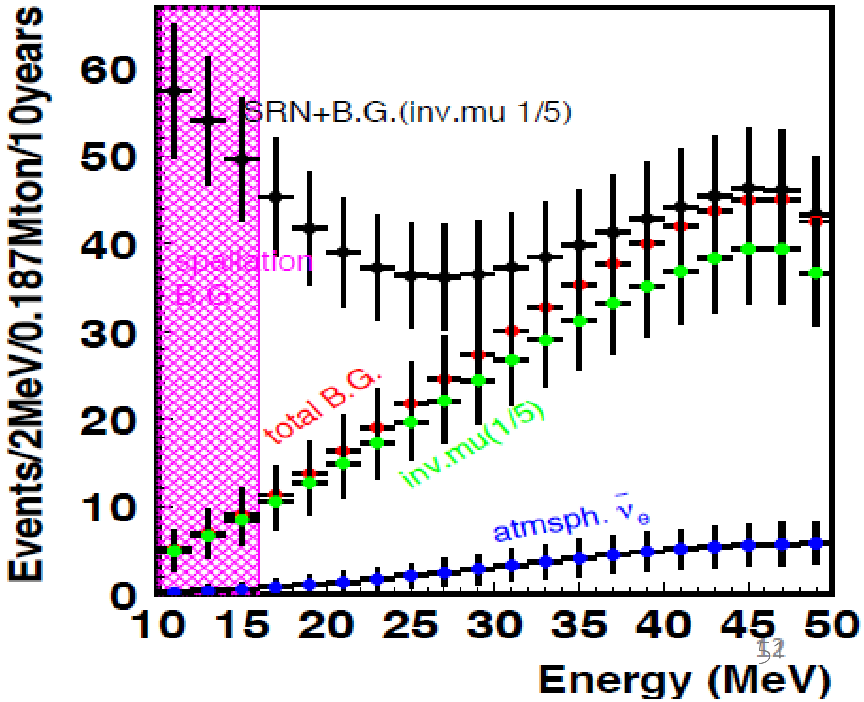


Supernova Relic Neutrino (SRN)

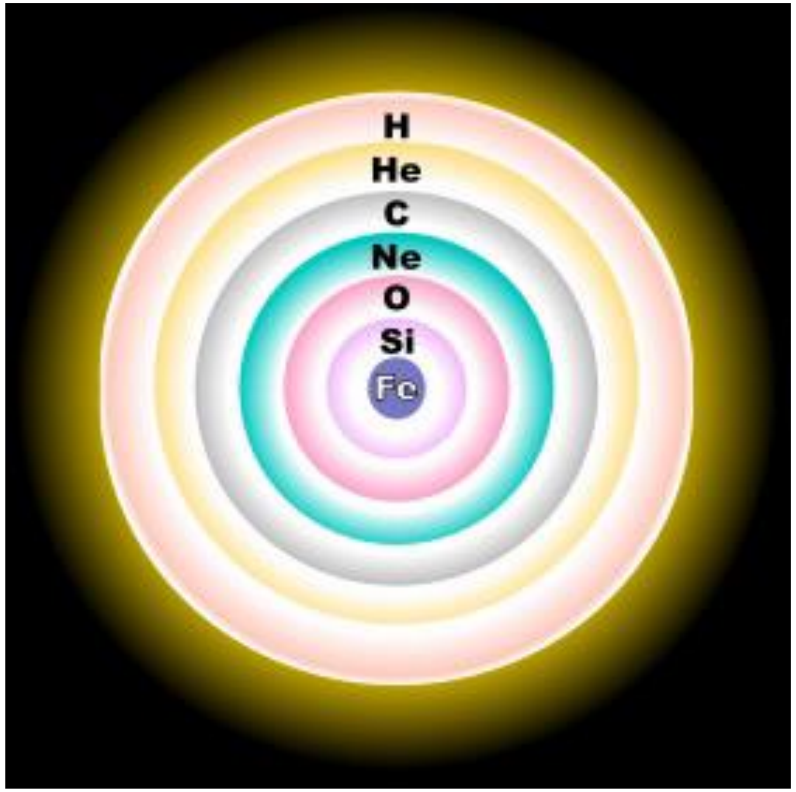
- Diffused neutrinos coming from all past supernovae
- Not discovered but promising extra-galactic ν

SRN with Hyper-K

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

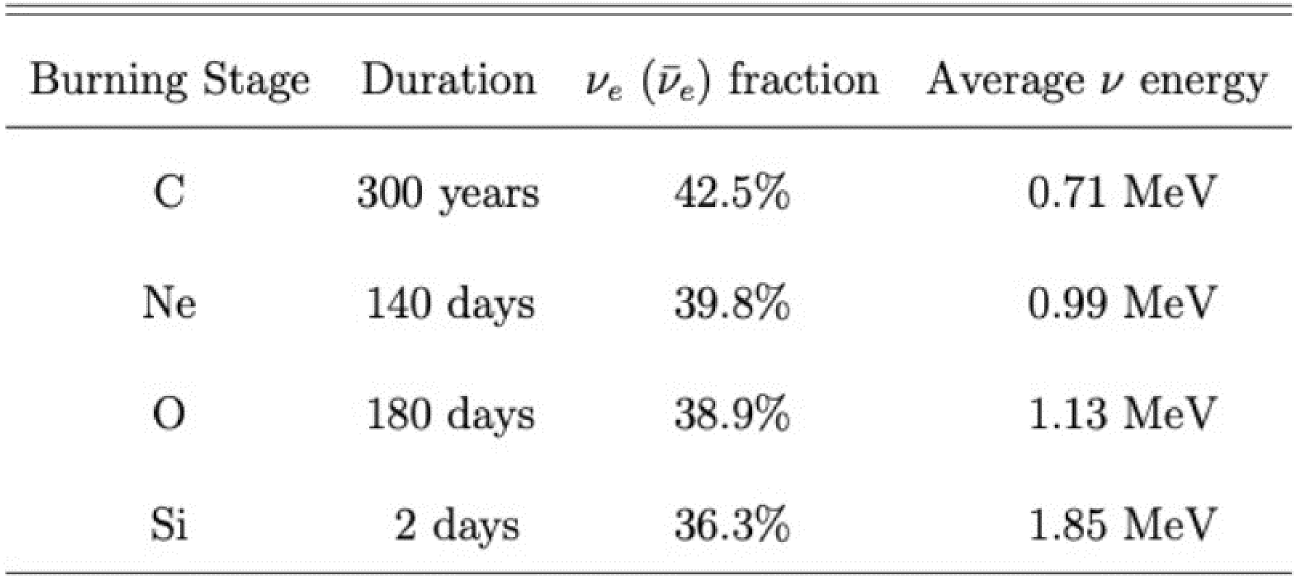


Pre-Supernova Neutrinos



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

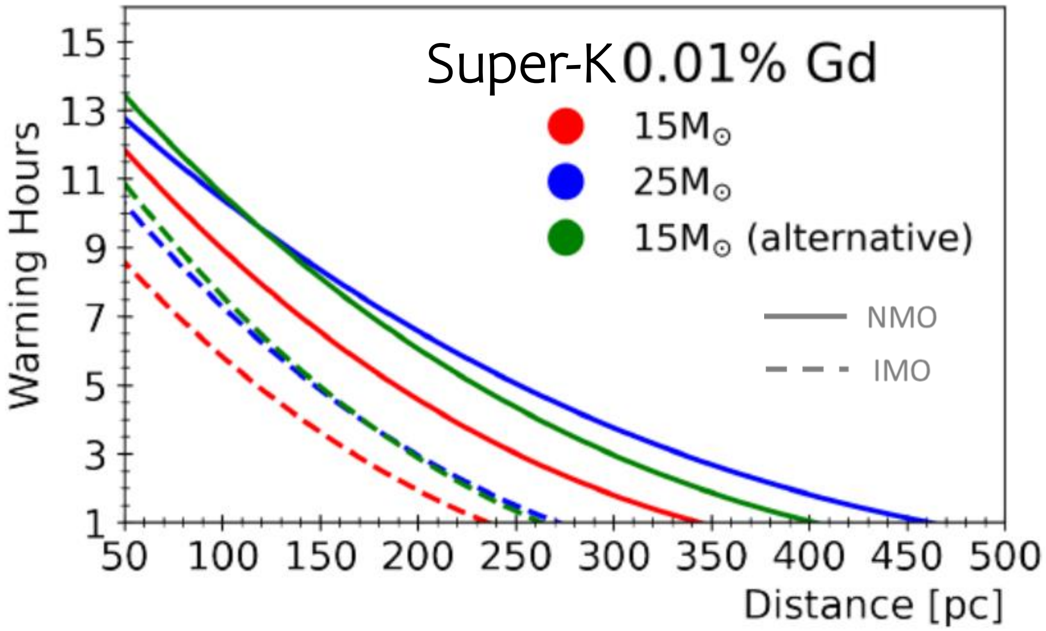
Energy released by each pre-Supernova phase

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

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)

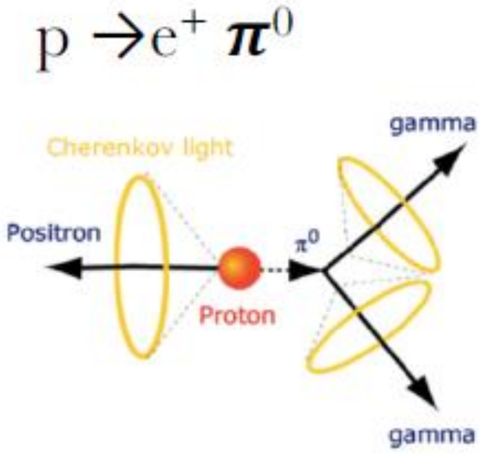
Warning time for a 3σ detection by the pre-supernova alert system for Super-Kamiokande

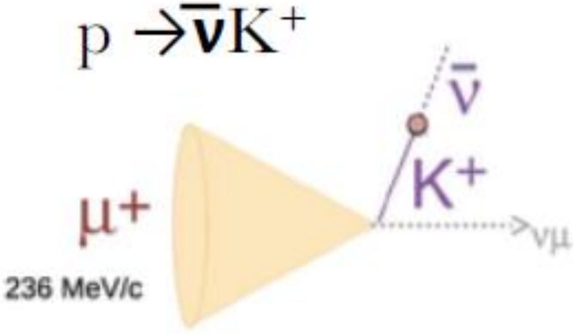


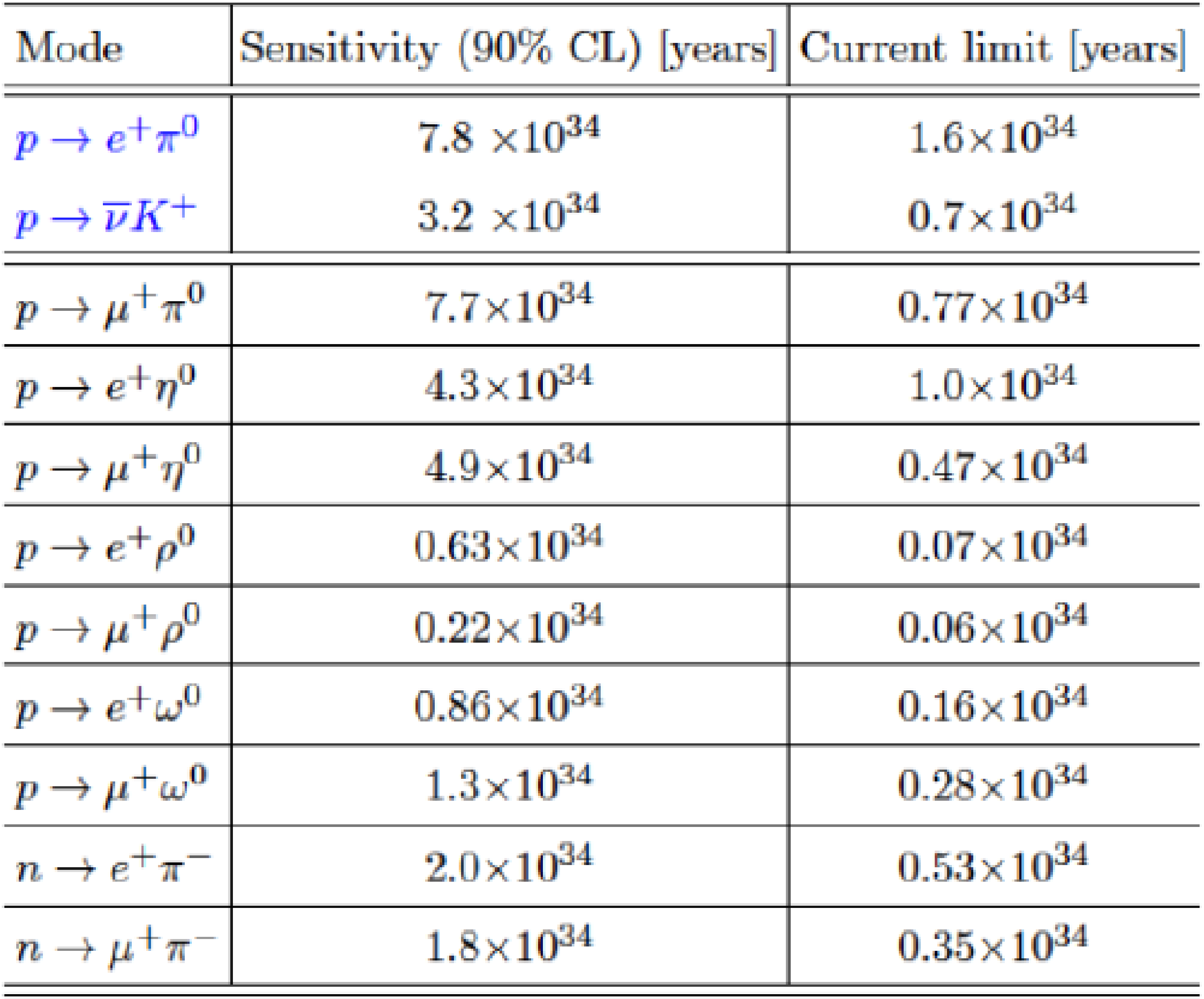
If Hyper-K will be gadolinium-doped, it will be able to detect pre-Supernova neutrinos, with great sensitivity due to a much bigger FV.
A powerful pre-Supernova alarm could be developed, as many more events are expected, increasing early warnings and ranges of detection compared to SK-Gd.

Nucleon decay

Flagship nucleon decay modes:







Mode	Sensitivity (90% CL) [years]	Current limit [years]
$p \to e^+\pi^0$	7.8×10^{34}	1.6×10^{34}
$p \to \overline{\nu} K^+$	3.2×10^{34}	0.7×10^{34}
$p \to \mu^+\pi^0$	7.7×10^{34}	0.77×10^{34}
$p \to e^+\eta^0$	4.3×10^{34}	1.0×10^{34}
$p \to \mu^+\eta^0$	4.9×10^{34}	0.47×10^{34}
$p \to e^+\rho^0$	0.63×10^{34}	0.07×10^{34}
$p \to \mu^+\rho^0$	0.22×10^{34}	0.06×10^{34}
$p \to e^+\omega^0$	0.86×10^{34}	0.16×10^{34}
$p \to \mu^+\omega^0$	1.3×10^{34}	0.28×10^{34}
$n \to e^+\pi^-$	2.0×10^{34}	0.53×10^{34}
$n \to \mu^+\pi^-$	1.8×10^{34}	0.35×10^{34}