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Next Generation Long Baseline Experiments

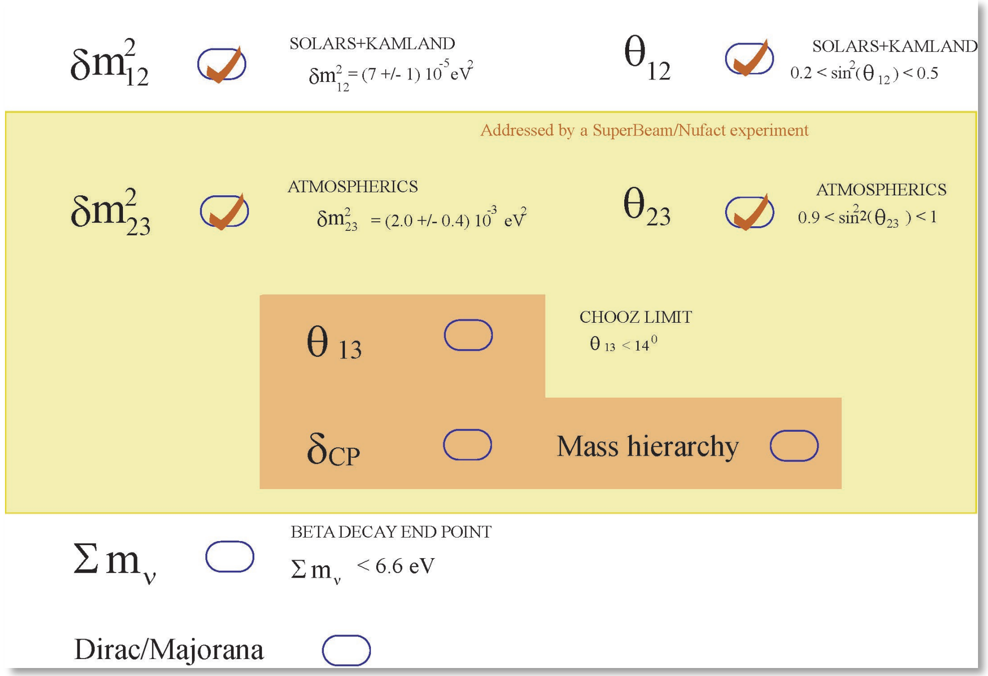
With a focus on Hyper-Kamiokande

Thanks to G. Collazuol, G. DeRosa, M. Grassi, A. Longhin, L. Ludovici, C. Touramanis for the material and useful discussions

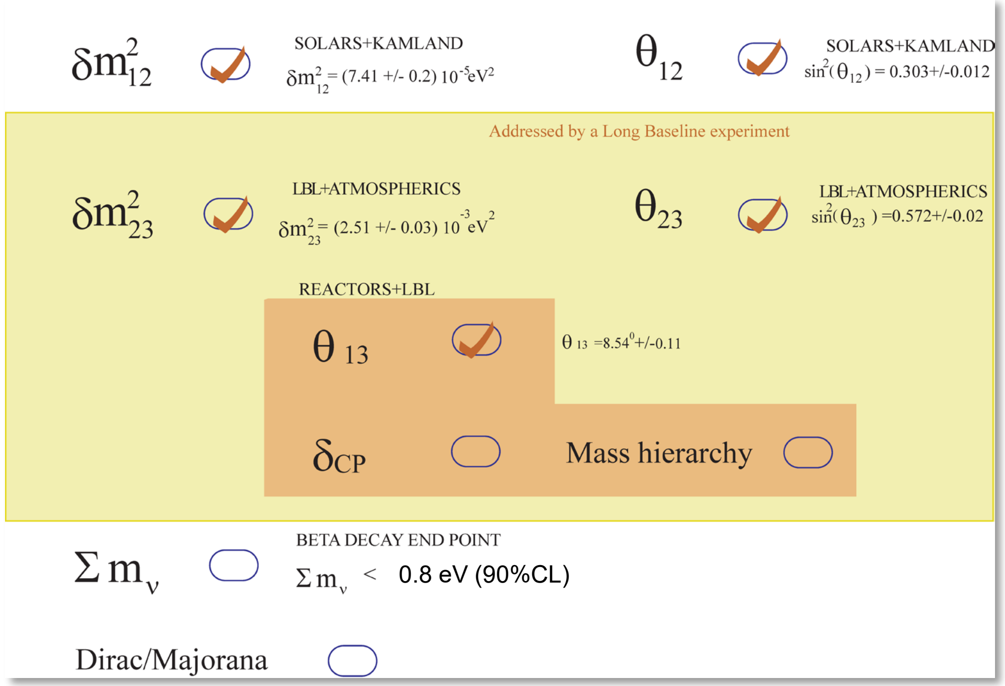
Padova, March 20 , 2024

Neutrino Physics in the past 20 years

2004



2024



Apparently not a great record (but have a look to the greatly increased precision).
So why several thousands of physicists are joining next generation long baseline experiments, and they are among the first priorities in hep in most of the world countries (not in Europe)?
Let's have a closer look to the achievements of neutrino oscillations physics

Major achievements in neutrino oscillations

See also wikipedia page: Oscillazione dei neutrini

Before 90's: detection of Solar Neutrinos (**Homestake**) and detection of SuperNova neutrinos (**Kamiokande**), awarded with the **2002 Nobel Prize** to Ray Davis and Masatoshi Koshiba "*for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos* "

Low energy neutrino astronomy remains a pillar of the physics case of the far detectors of Long Baseline neutrino experiments

At the same conference, **Chooz** reported no evidence of reactor $\bar{\nu}_e$disappearance while **MACRO** reported a ~2.5σ signal of atmospheric neutrino oscillation

1998: **Super-Kamiokande** discoveries neutrino oscillations by studying atmospheric neutrinos. Awarded with the **2015 Nobel Prize** to Takaaki Kajita "*for the discovery of neutrino oscillations, which shows that neutrinos have mass*"

2002: **SNO** provides a model independent signature of solar neutrinos oscillations. Art McDonald shares the 2015 Nobel prize.

Gallex/GNO at LNGS had provided a model dependent evidence of solar neutrino disappearance

T2K and then **Double Chooz** reported early indications of non-zero θ_{13} values

2012: the reactor experiments **Daya Bay** and **RENO** provide the first observation of a non-zero value of θ_{13}. Awarded with the EPS-HEP prize in 2023. For a longer discussion of the θ_{13} saga you can read the long citation of the prize. SK, SNO, Kamland, Daya Bay and T2K awarded with the Breakthrough prize 2016

M. Koshiba at Neutrino Telescopes 1988

Ray Davis at Neutrino Telescopes 1990

Art McDonald at Neutrino Telescopes 2011

Laurea Honoris Causa to T. Kajita, Unipd 2016

EPS-HEP Prizes 2023

Daya Bay

RENO

Cecilia Jarlskog

Why neutrino oscillations matter

Neutrino oscillations only possible if neutrinos are massive ($\Delta m^2 \neq 0$)

In two ν generations (α,β flavor, i,j mass eigenstates):

$$P(\nu_\alpha \to \nu_\beta, \alpha \neq \beta) = \sin^2(2\theta_{ij}) \sin^2(1.27 \frac{\Delta m_{ij}^2 (eV^2) L(km)}{E(GeV)})$$

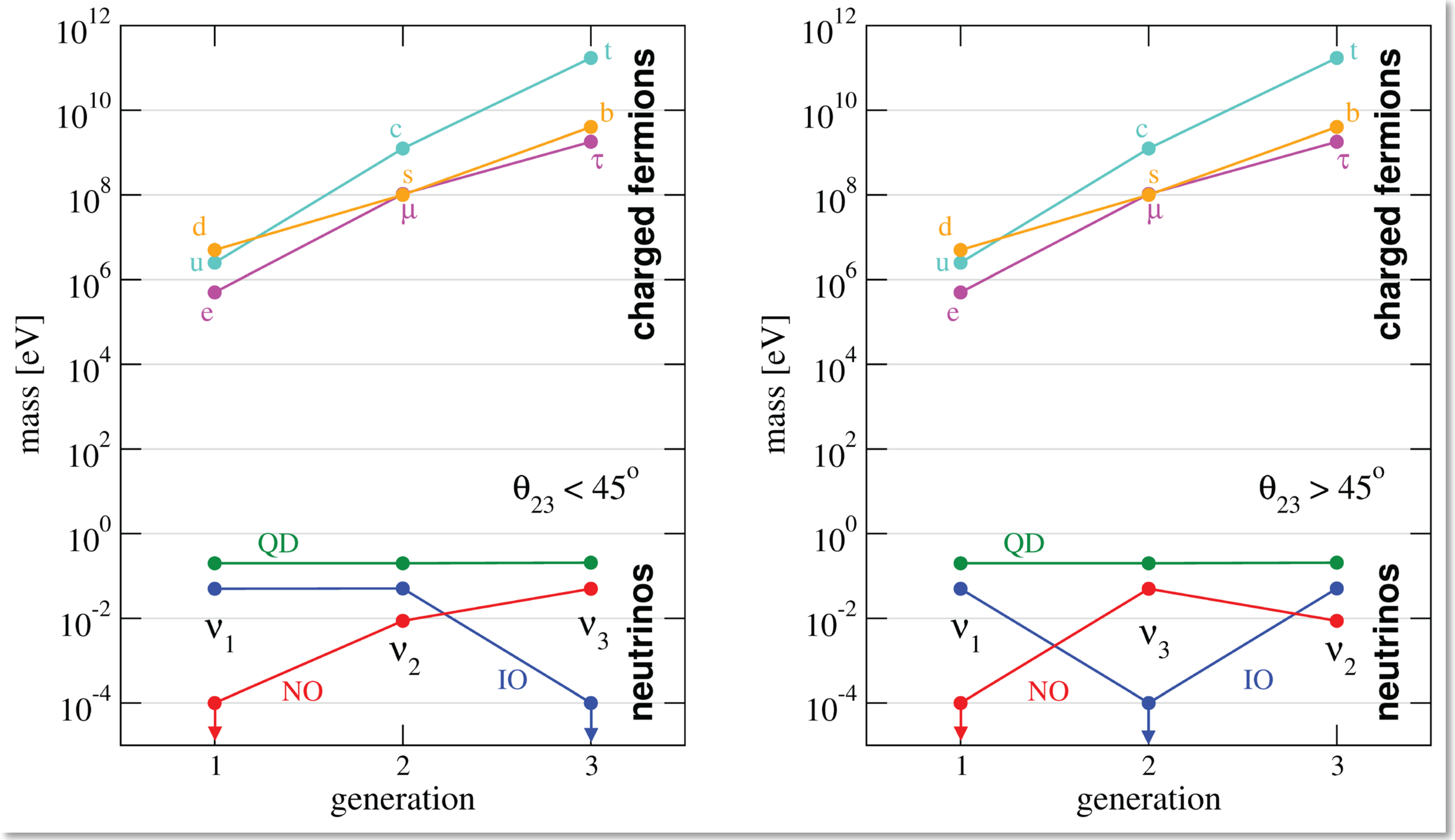
In the Standard Model neutrinos are **massless**

- Absence of right-handed neutrinos → **no Dirac mass for neutrinos**
- Lepton number is an accidental symmetry at the renormalizable level → given SM fields and gauge symmetry, lepton number cannot be violated at dimension 4 → **no Majorana mass can be generated**

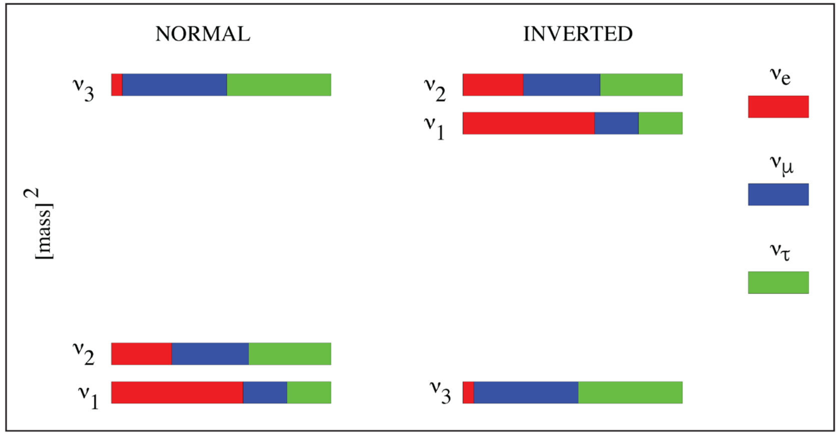
→ Neutrino masses require physics beyond the SM

What ν oscillations still have to say about ν masses

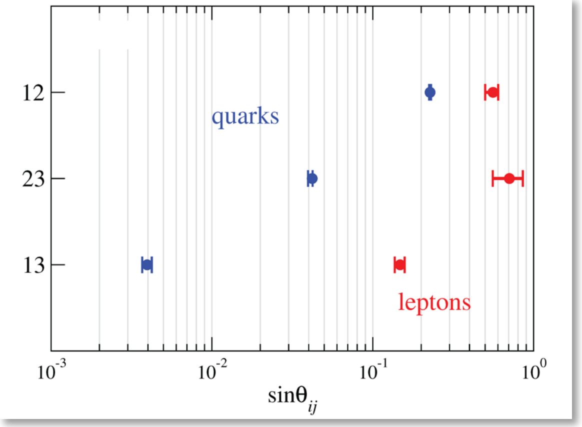
Neutrino oscillations cannot measure absolute neutrino masses, but can determine their pattern by measuring neutrino mass ordering (MO) and the octant of θ_{23} (which decides if ν_3 is mostly ν_μ or ν_τ)



From T. Schwetz talk at EPS-HEP 2021



Neutrino mass ordering: normal (NO) or inverted (IO), measurable by Long Baseline experiments (the 1-2 ordering already decided by solar oscillations)



Even neutrino mixing is very different from quarks

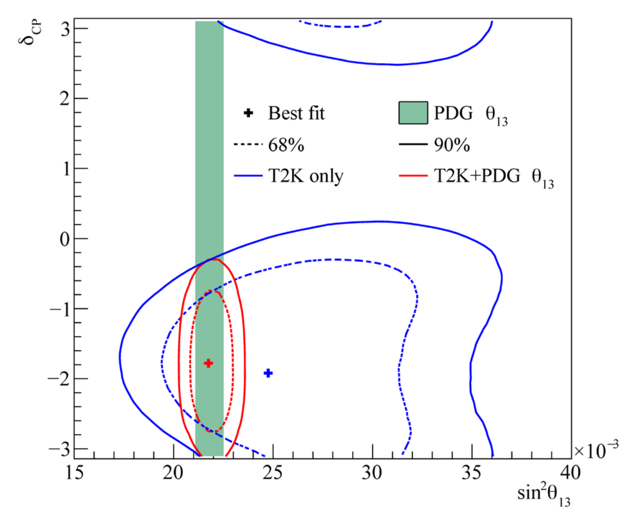
Why θ_{13} matters

Its value decided the strategy for δ_{CP} searches:

"large" θ_{13} values provide large ν_e ($\bar{\nu}_e$) appearance rates, with small asymmetries. Ultimately dominated by systematic errors (this is the case: $\theta_{13} \sim 8^0$ is "large").

"small" values provide small appearance rates (with large asymmetries). Experiments dominated by backgrounds, and conventional neutrino beams inadequate to sensitive CP searches. Need for new accelerator concepts like neutrino factories or beta beams.

As measured via $\bar{\nu}_e$ disappearance by reactor experiments it breaks any θ_{13}- δ_{CP} degeneracy in LBL experiments and greatly improves their sensitivity



T2K: *Eur.Phys.J.C* 83 (2023) 9, 782

The Jarlskog invariant in neutrino oscillations:

$$J_\nu = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta_{CP}$$

has a maximum value about three orders of magnitude bigger than the invariant in the quark sector

$$J_\nu(\max) = 3.2 \cdot 10^{-2}$$

$$J_{quark} = 3.8 \cdot 10^{-5}$$

opening the possibility of a role of neutrino oscillations in explaining the matter-antimatter asymmetry in the Universe through Leptogenesis.

This enhances a lot the interest in measuring the CP phase δ_{CP}

Three generations of Long Baseline Experiments

Long baseline experiments produce intense $\nu_\mu(\bar{\nu}_\mu)$ beams and detect them at the maximum of atmospheric oscillations.

Leading process are $\nu_\mu \to \nu_\tau$ oscillations, and so ν_μ disappearance, allowing to measure the atmospheric parameters θ_{23} and Δm^2_{23}

Subleading process are $\nu_\mu \to \nu_e$ oscillations, sensitive to θ_{13} and δ_{CP}

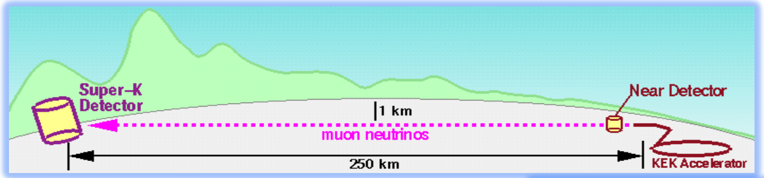
Disappearance formula

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2(\theta_{13})\sin^2(\theta_{23})[1 - \cos^2(\theta_{13})\sin^2(\theta_{23})]\sin^2(\frac{\Delta m^2{}_{23} L}{4E})$$

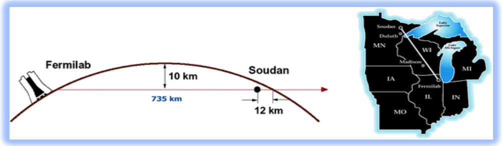
Subleading ν_e appearance formula

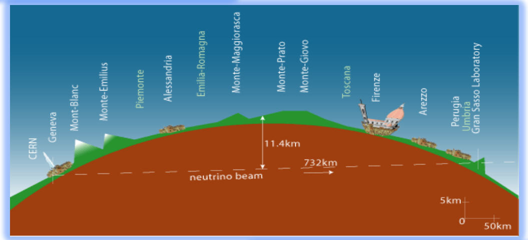
$$\begin{aligned}
p(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\frac{\Delta m_{13}^2 L}{4E} \times \left[1 \pm \frac{2a}{\Delta m_{13}^2}(1-2s_{13}^2)\right] && \theta_{13} \text{ driven} \\
& + 8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\sin\frac{\Delta m_{12}^2 L}{4E} && \text{CPeven} \\
& \mp 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\sin\frac{\Delta m_{12}^2 L}{4E} && \text{CPodd} \\
& + 4s_{12}^2 c_{13}^2\{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\}\sin\frac{\Delta m_{12}^2 L}{4E} && \text{solar driven} \\
& \mp 8c_{12}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\frac{aL}{4E}(1-2s_{13}^2) && \text{matter effect (CP odd)}
\end{aligned}$$

First Generation: **K2K** in Japan, aimed to confirm the Super-Kamiokande results with accelerator neutrinos by detecting ν_μ disappearance.

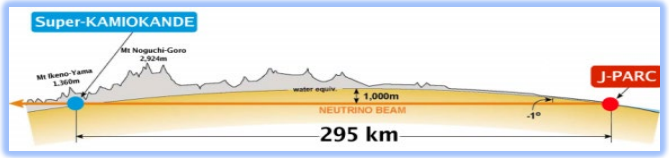


Second Generation: **Minos** in the States (ν_μ disappearance) and **Opera** at CNGS (ν_τ appearance), aimed to improve the Super-Kamiokande results.





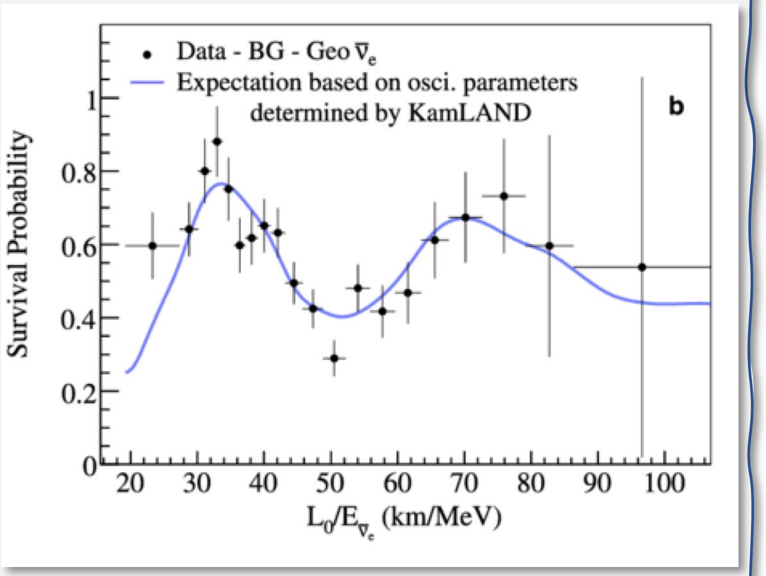
Third Generation: **T2K** in Japan and **NOvA** in the States. Aimed to measure θ_{13} and sensitive to CP violation in the leptonic sector.



Furthermore (other major achievements)...

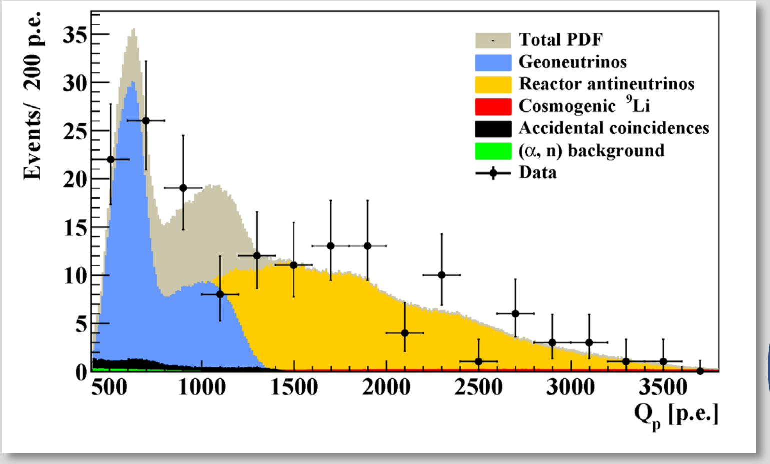
Solar results

Independently confirmed by the **Kamland** reactor experiment



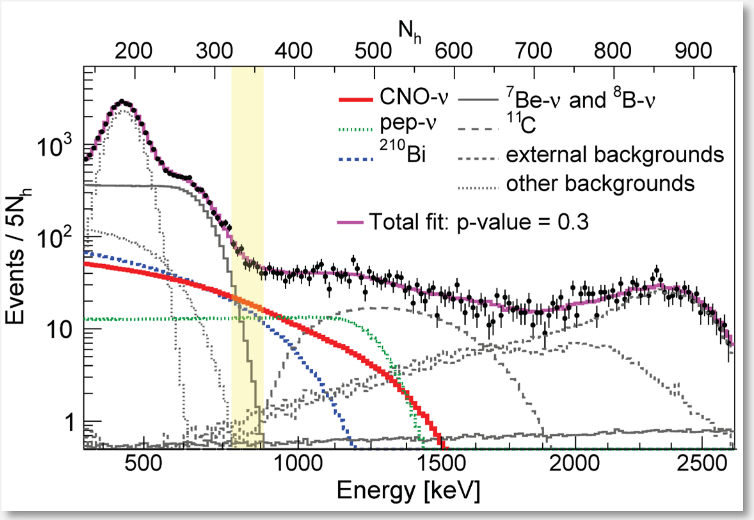
Geoneutrinos

Discovered by **Kamland** and **Borexino**



Solar fusion processes

Neutrino emissions of all the fusion processes measured by **Borexino**



Accelerators: ν_e events > 0
Reactors: $\bar{\nu}_e$ (meas/expected) <1

Timeline of θ_{13} (dates from arXiv, citations from iNSPIRE at 11/3/23)

14/06/11 — **T2K**, "Indication of ...", **2.5 σ**, 1737 citations

29/07/11 — **MINOS**, "Improved search ...", **89%CL**, 898 citations

29/11/11 — **Double Chooz**, "Indication for...", **1.3 σ**, 1567 citations, Phys.Rev.Lett. 108 (2012) 131801

08/03/12 — **Daya Bay**, "Observation of ...", **5.2 σ**, 2759 citations, Phys. Rev. Lett. 108 (2012) 171803

03/04/12 — **Reno**, "Observation of ...", **4.9 σ**, 2398 citations, Phys. Rev. Lett. 108 (2012) 191802

27/07/12 — **Double Chooz**, "Reactor electron antineutrino disappearance ...", **2.8 σ**, 575 citations.

14/06/13 — **T2K**, "Observation of ...", **7.2 σ**, 696 citations

First paper with more than 3 σ

29/01/19 — **Double Chooz**, *Nature Phys.* 16 (2020) 5, **7.5 σ**, 138 citations,

"**The establishment of θ_{13}** awaited the Daya Bay experiment's observation in 2012 [10]; confirmed soon after by the RENO experiment [11]."

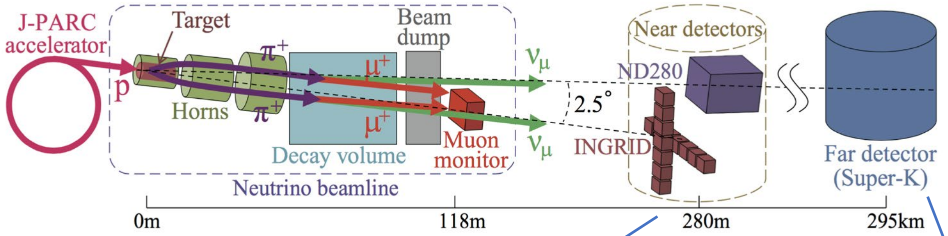
Breakthrough prize 2016: Daya Bay (China); KamLAND (Japan); K2K / T2K (Japan); Sudbury Neutrino Observatory (Canada); and Super-Kamiokande (Japan)
Panofsky prize 2014: "...For their leadership of the Daya Bay experiment, which produced the first definitive measurement of θ_{13} angle of the neutrino mixing matrix."
Pontecorvo prize 2016: Daya Bay, Reno, T2K

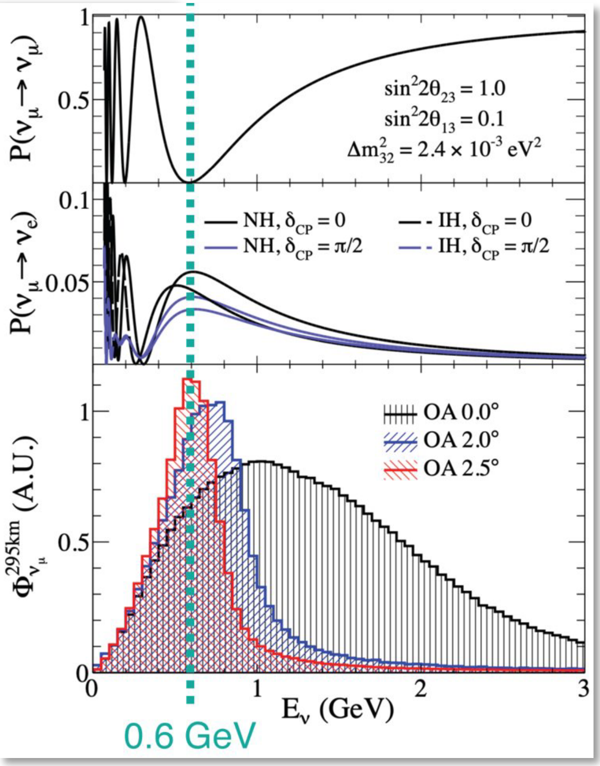
From the long citation of the EPS-HEP prize

… Indications of non-zero values of θ_{13} were provided in the year 2011 by global fits to atmospheric and solar neutrino oscillations, initial results on electron neutrino appearance by the accelerator long-baseline T2K experiment, and by the reactor neutrino experiment Double Chooz. T2K could not improve its results due to the catastrophic earthquake of 2011 in Japan, which caused a one year shutdown, while Double Chooz, a pioneer of the new generation of short baseline experiments at reactors, was unable to improve its sensitivity due to logistical problems with the construction of its near detector.
The first observations of non-zero values of θ_{13} were reported in 2012 by the reactor neutrino experiments Daya Bay and RENO, detecting short baseline electron antineutrino disappearance with a significance of 5.2 and 4.9 standard deviations, respectively. The Daya Bay experiment, based in China, consisted of eight identical antineutrino detectors, each containing 20 tons of gadolinium-doped liquid scintillator. Four of them acted as close detectors at about 360 m from the Daya Bay and Ling Ao nuclear power plants, which have a total nuclear power of 17.4 GW, while 4 detectors were located at 1.8 km from the reactor cores. Daya Bay had been designed to achieve the smallest possible systematic errors (down to 0.2%) and for precision measurements of θ_{13}. The RENO experiment was based in South Korea and consisted of two identical detectors, containing 16.5 tons of gadolinium-doped liquid scintillator, placed at 294 m and 1383 m from the Yoinggwang (now Hanbit) nuclear power plant, which delivers 16.4 GW nuclear power.
At present the best determination of θ_{13} is $\sin^2(\theta_{13})$ = 0.0220 +/- 0.0007, setting a large enough amplitude of the processes leading to CP violation to allow sensitive searches by long-baseline neutrino experiments with conventional accelerator neutrino beams …

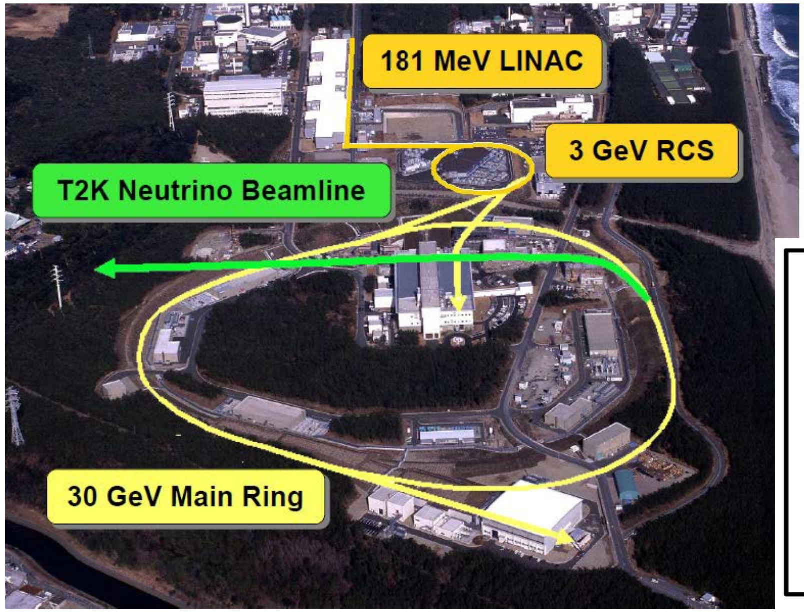
The T2K experiment

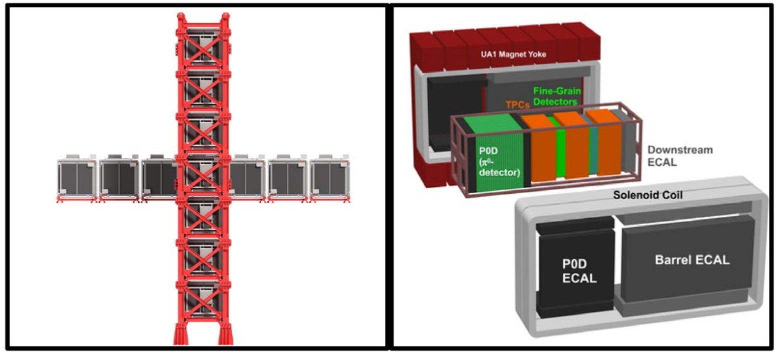
- T2K: Tokai to Kamioka (295 km baseline)
- Running since 2010
- ~575 members, 75 Institutes, 14 countries
- Precise measurements of the atmoshperic parameters θ_{23} and Δm^2_{23}
- Constrain the CP violation phase δ_{CP}
- Neutrino cross-section measurements

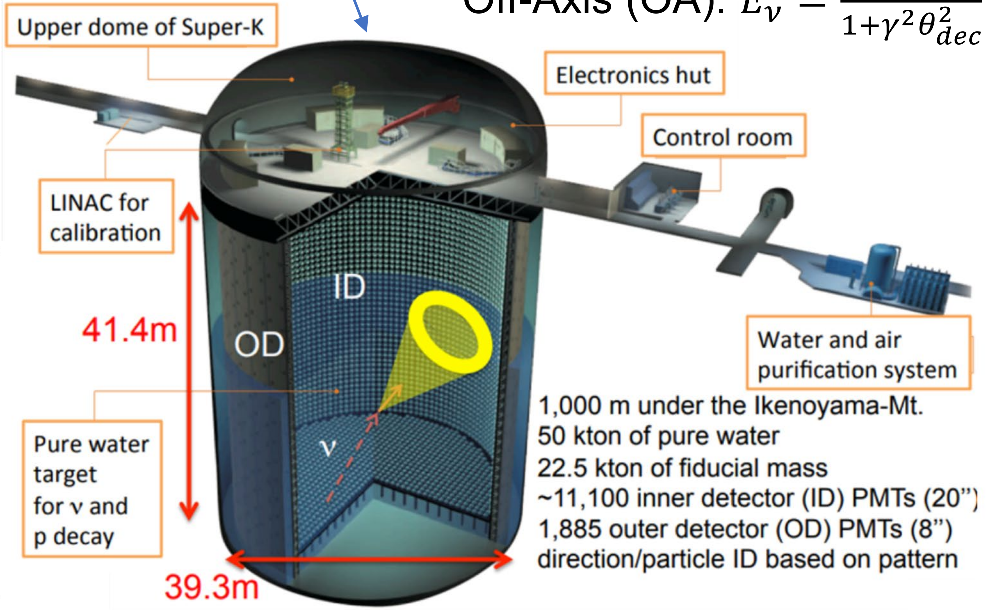




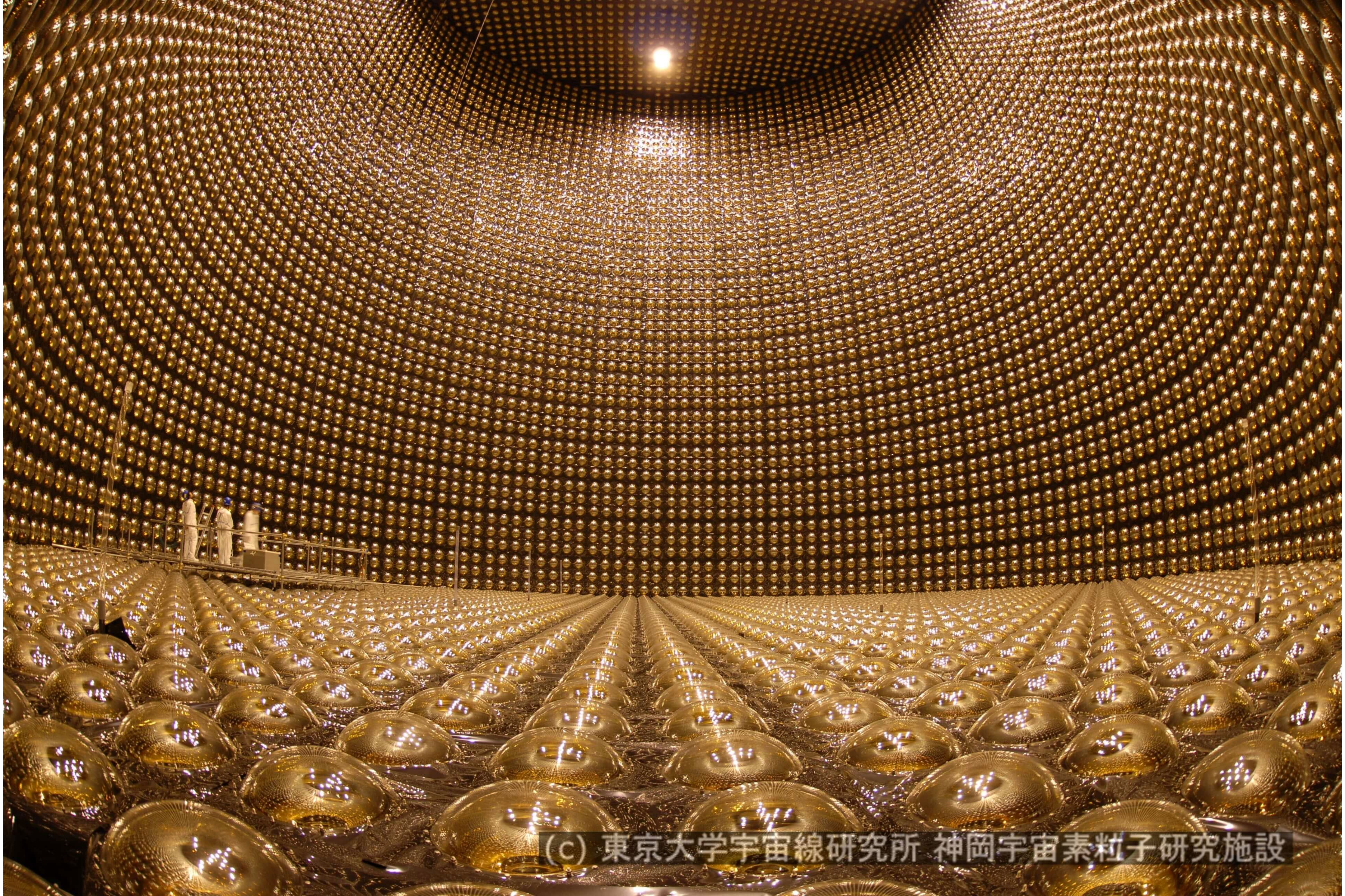
Off-Axis (OA): $E_\nu = \frac{0.43\ E_\pi}{1+\gamma^2\theta^2_{dec}}$





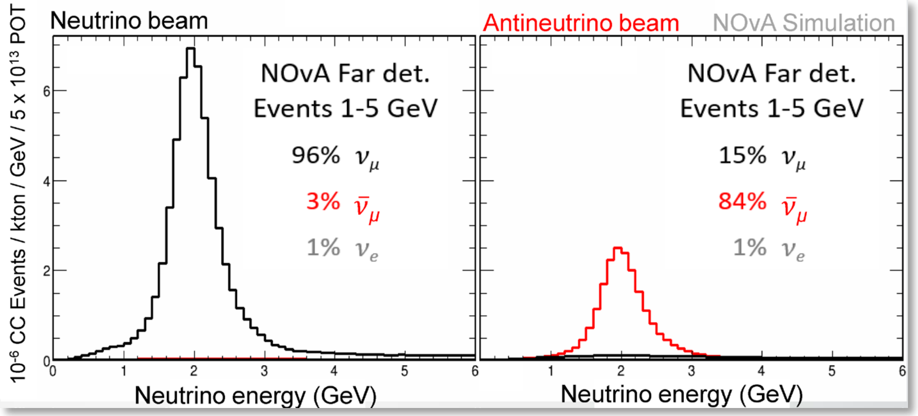


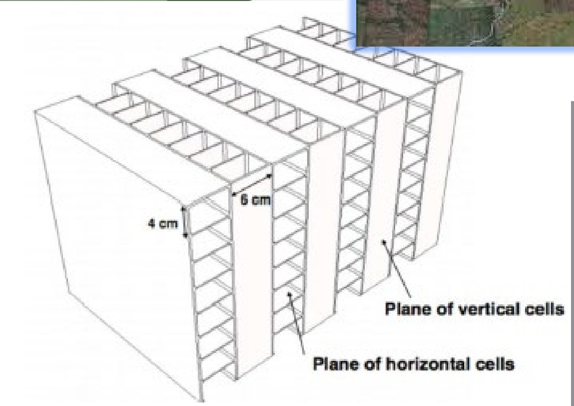
1,000 m under the Ikenoyama-Mt.
50 kton of pure water
22.5 kton of fiducial mass
~11,100 inner detector (ID) PMTs (20")
1,885 outer detector (OD) PMTs (8")
direction/particle ID based on pattern

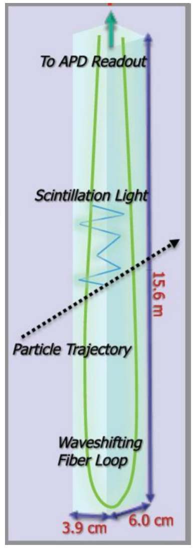

(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設

The NOvA experiment

- NuMI π decay-in flight beam from Fermilab
- 14.6 mrad off-axis beam for narrow peak @ 2 GeV
- High-purity neutrino or antineutrino mode polarities
- Two detectors: 14 kton far detector (FD) 810 km from beam source, 300 ton near detector (ND) @ 1 km
- ND has high number (>1M ν_μ CC) of interactions







On Surface

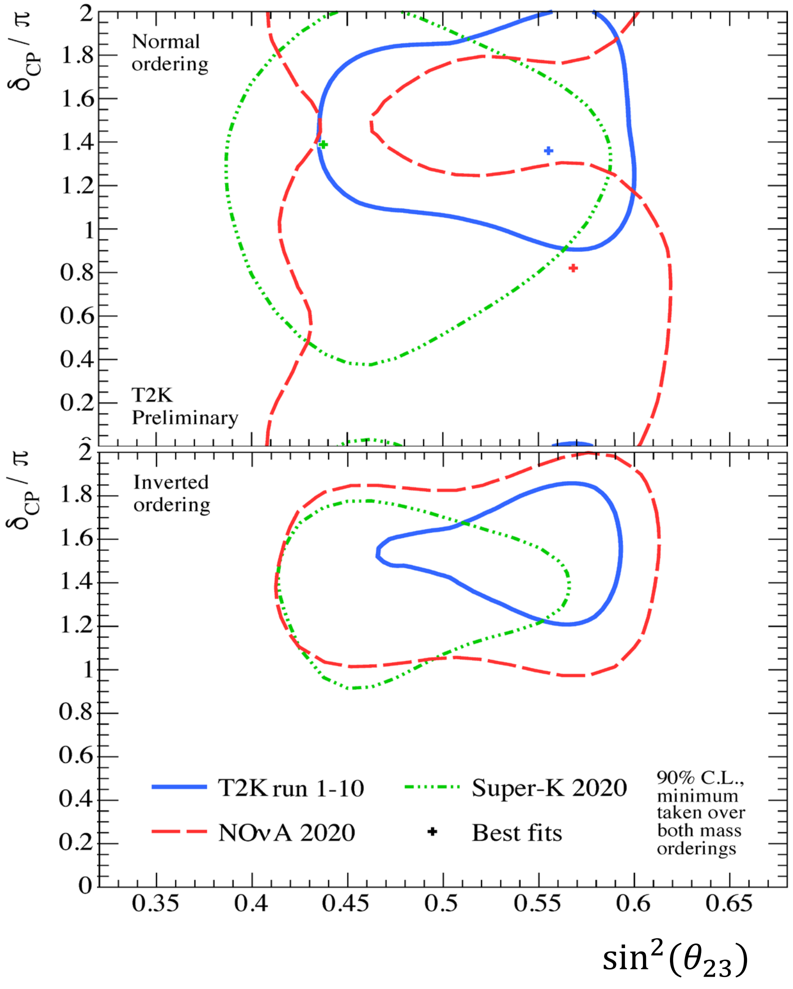
Detectors are tracking calorimeters

- 4 cm x 6 cm x 16 m (FD) ‘cells’ are extruded plastic filled with liquid scintillator
- Wavelength-shifting fibers connected to APDs collect light
- Cells are alternately oriented horizontally or vertically for full 3D picture

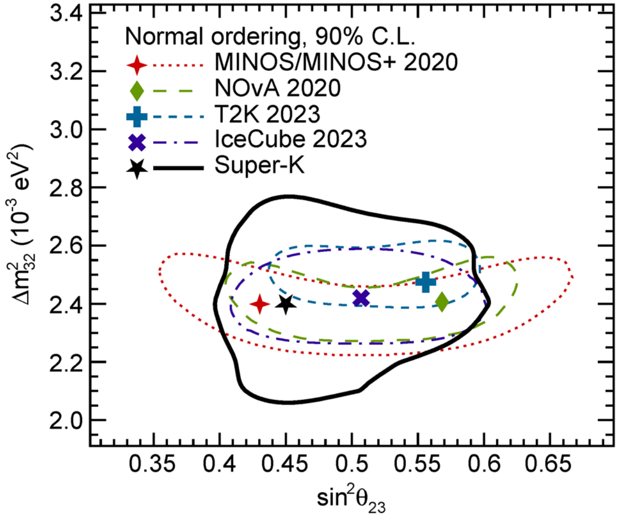
Present status of neutrino oscillations

- NO preferred (at 2.5σ according to NuFIT, latest results are less sharp)
- Null CP violation disfavored at slightly less than 2σ (NO)
- The θ_{23} octant unstable in the global fits

T2K, Nova and Super-K results about δ_{CP}. Tension in case of NO



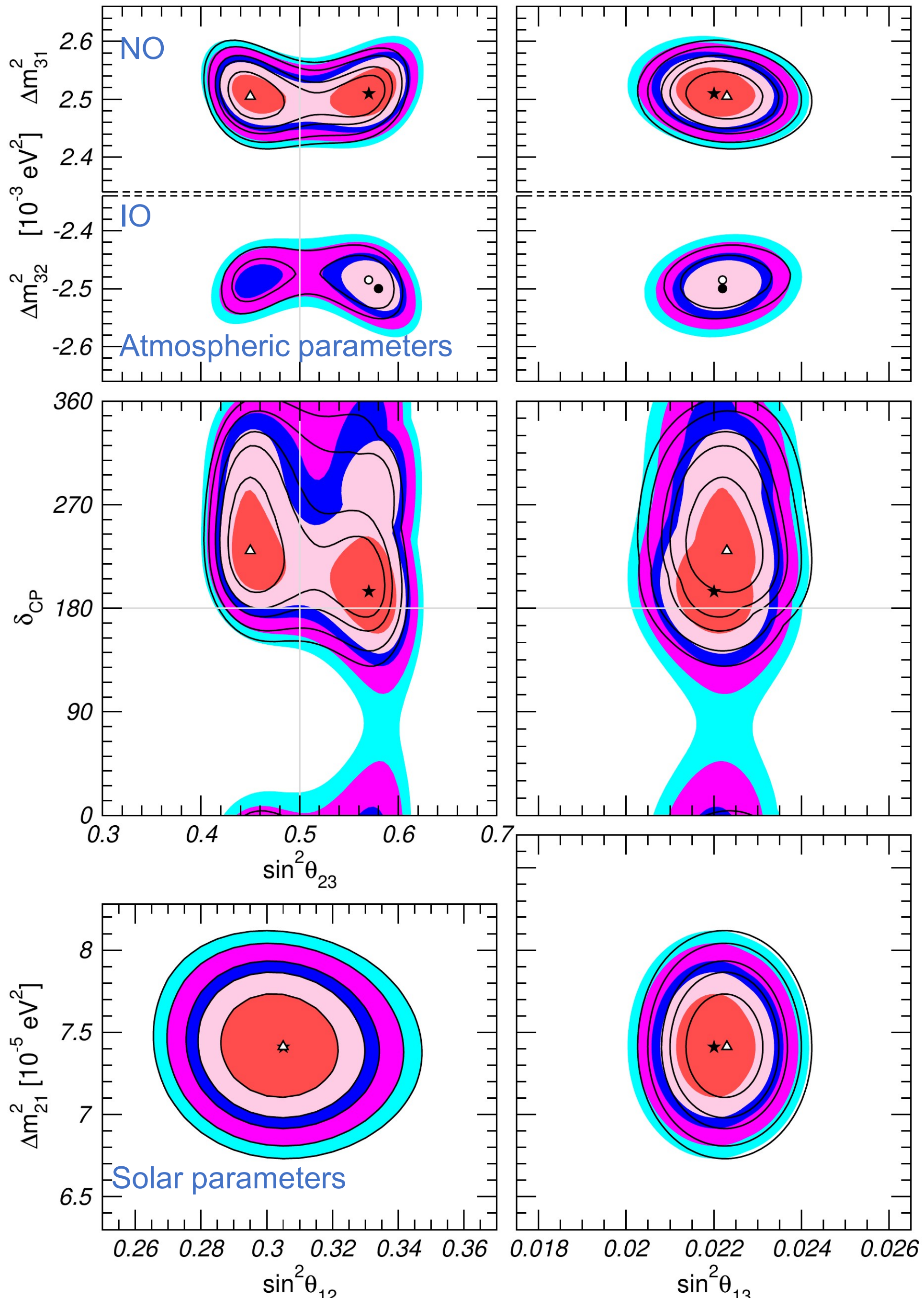
Signal plots of the atmospheric parameters by different experiments.



From SK, arXiv:2311.05105v1

The different contours correspond to the two-dimensional allowed regions at 1σ, 90%, 2σ, 99%, 3σ CL

NuFIT 5.2 (2022)



Main goals of next gen experiments

CP violation: 5σ sensitivity for the widest possible range $\ngtrsim 60\%)$ of δ_{CP} values

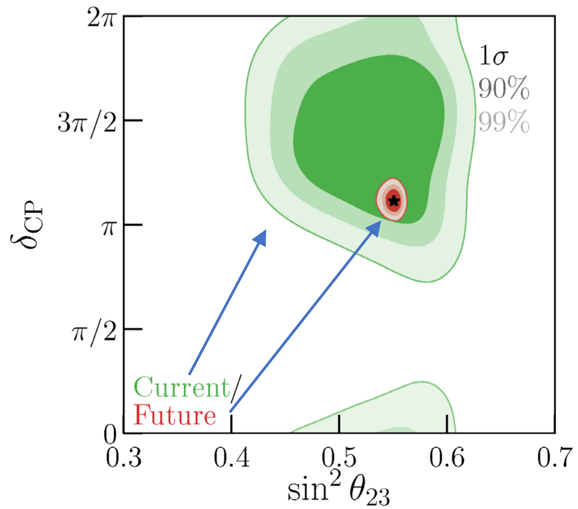
Mass Ordering: decide between Normal and Inverted Ordering at 5σ or better

Precision physics/Exotics (next slide)

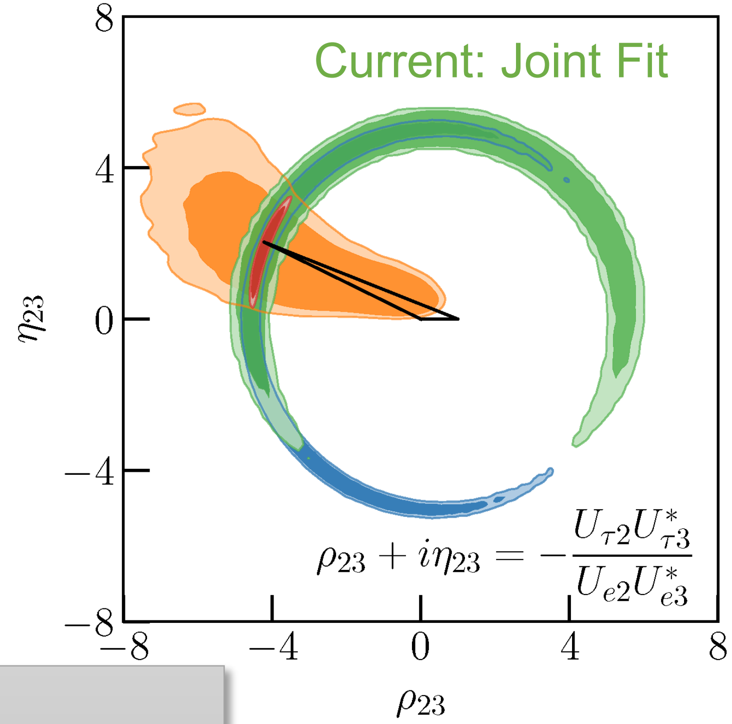
Astrophysics: the gigantic far detectors are excellent observatories for rare decays and astrophysical measurements

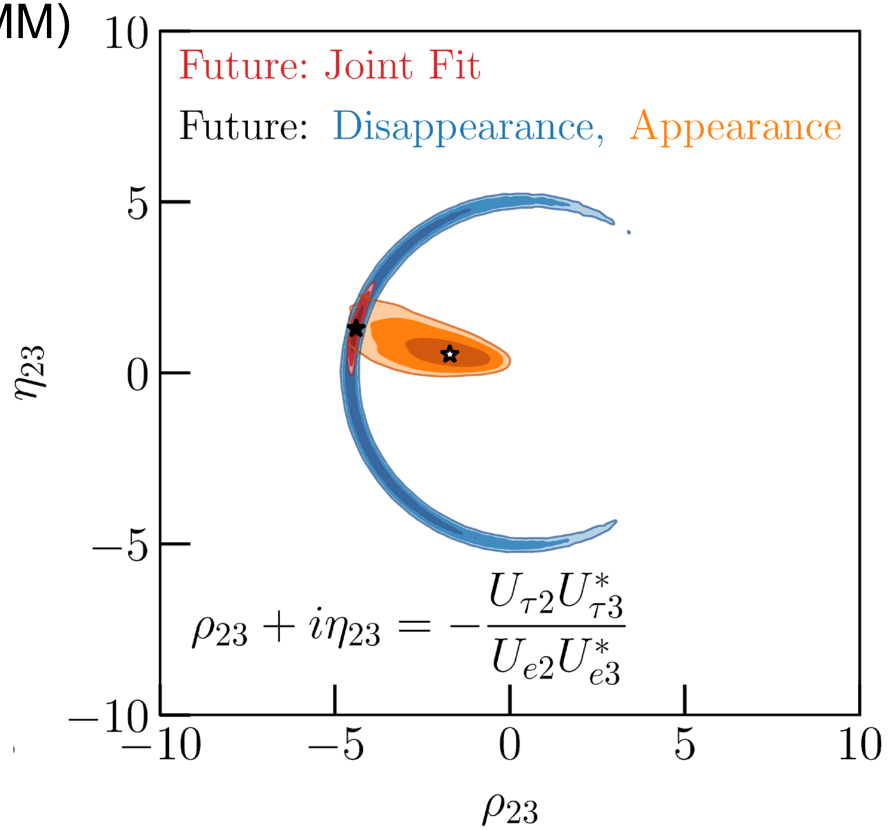
Precision physics → new physics

For instance by studying non-unitary leptonic mixing matrixes (LMM)



Current and future fit to atmospheric and CP oscillation variables, assuming for future the best fit of present data.
From *Phys.Rev.D* 102 (2020) 11, 115027.





From *Phys.Rev.D* 102 (2020) 11, 115027.
Data are simulated with a non-unitary LMM, but analyzed assuming it is.

Other exotic searches

- Non Standard neutrino Interactions
- Neutrino decays
- Heavy neutrino decays
- Lorentz and CPT violations
- Sterile neutrinos
- ….

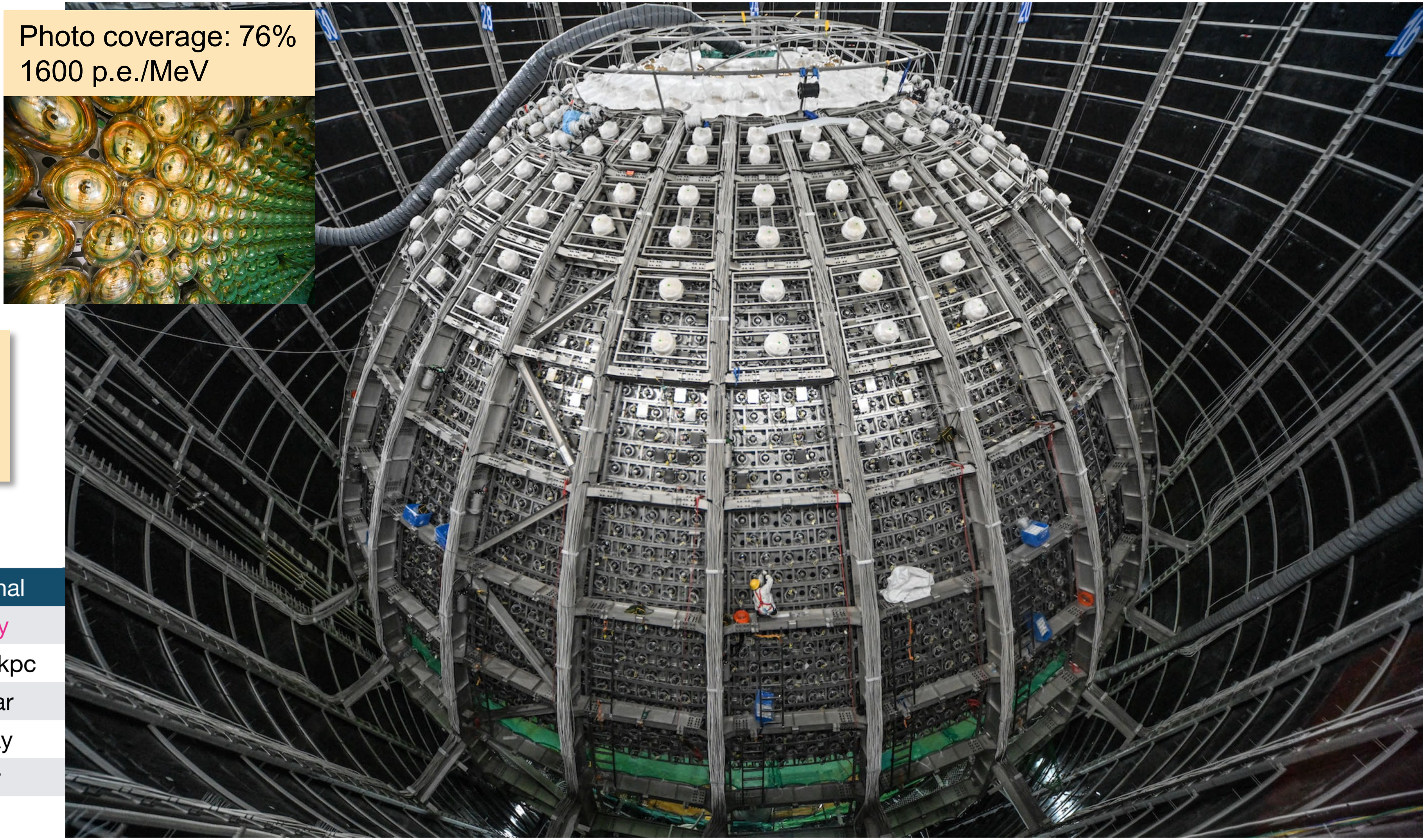
The JUNO experiment

Jiangmen Underground Neutrino Observatory, detecting $\bar{\nu}_e$ disappearance at reactors.

Liquid Scintillator Detectors

	Target mass	Energy resolution (σ)
Daya Bay	20 ton	8%/√E
Borexino	300 ton	5%/√E
KamLAND	1000 ton	6%/√E
JUNO	20 000 ton	3%/√E

Photo coverage: 76%
1600 p.e./MeV



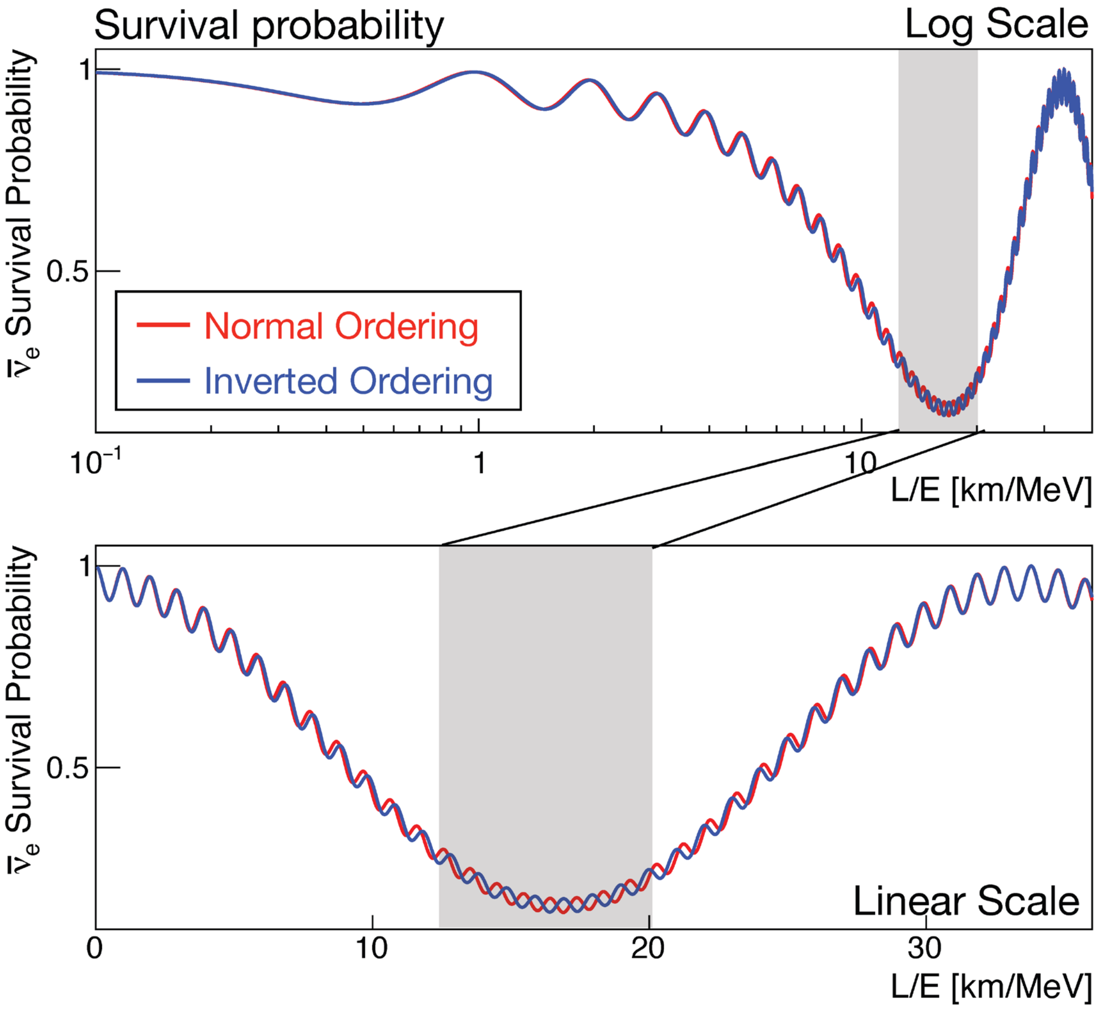
74 institutes
17 countries/regions
~700 collaborators

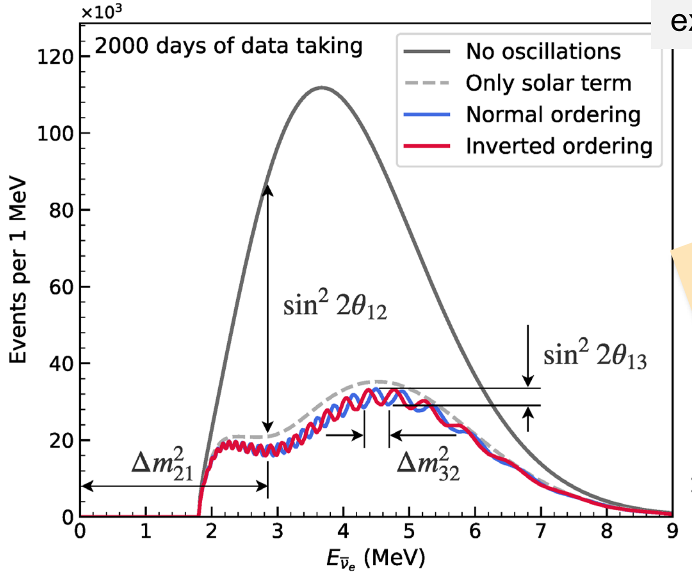
Signal rates

Neutrino source	Expected signal
Reactor	45 evts / day
Supernova burst	10^4 evts at 10 kpc
Diffuse supernova background	2-4 evts/ year
Sun ^{8}B (^{7}Be)	16 (490) / day
Cosmic rays	100+ / year
Earth crust & mantle	400 / year

Detect for the first time solar and atmospheric oscillation modes simultaneously

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{12}\, c_{13}^4 \sin^2 \Delta_{21} - \sin^2 2\theta_{13} \left(c_{12}^2 \sin^2 \Delta_{31} + s_{12}^2 \sin^2 \Delta_{32} \right)$$



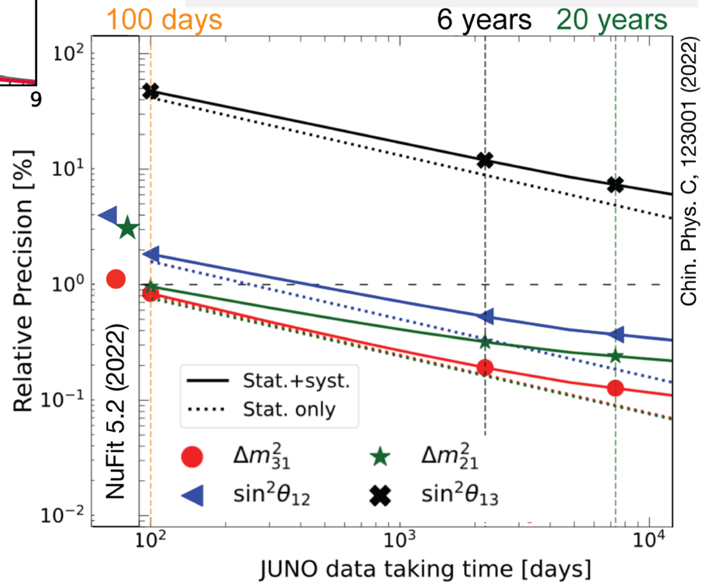


To measure MO: decide if the oscillation pattern corresponds to the blue or to the red curve. Requires high statistics and extreme control of the energy scale.

From the detected spectrum is possible to extract several oscillation parameters…

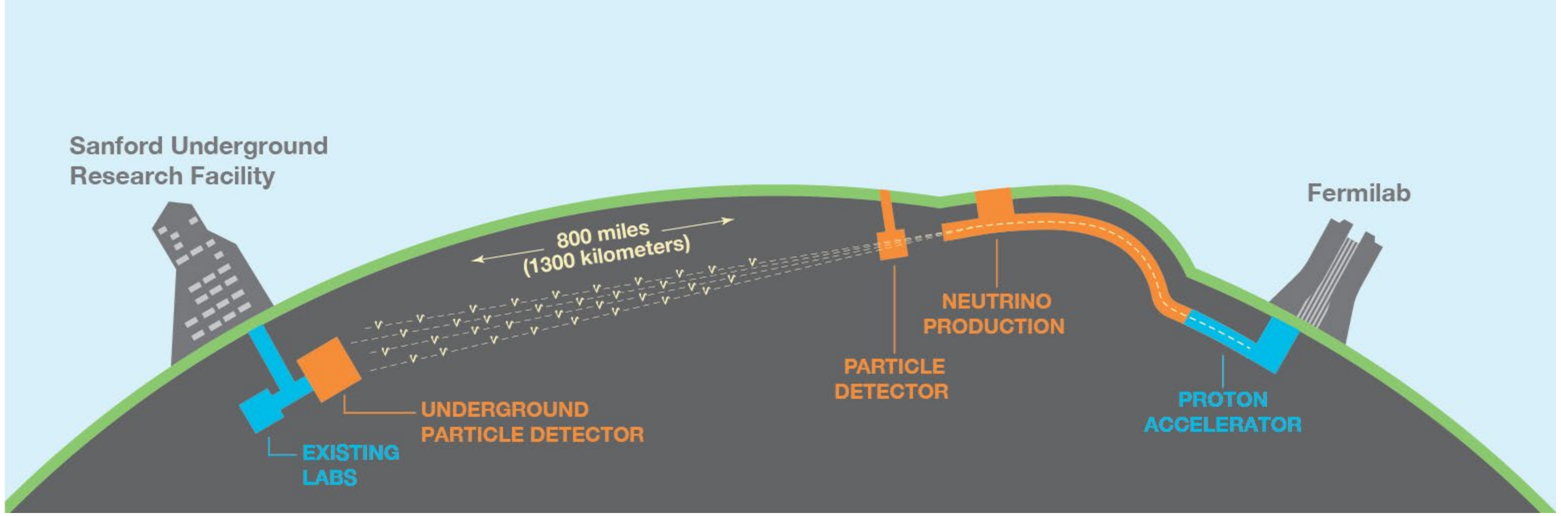
Detector ready within this year, start physics in 2025

… whose accuracy will exceed present values



DEEP UNDERGROUND NEUTRINO EXPERIMENT

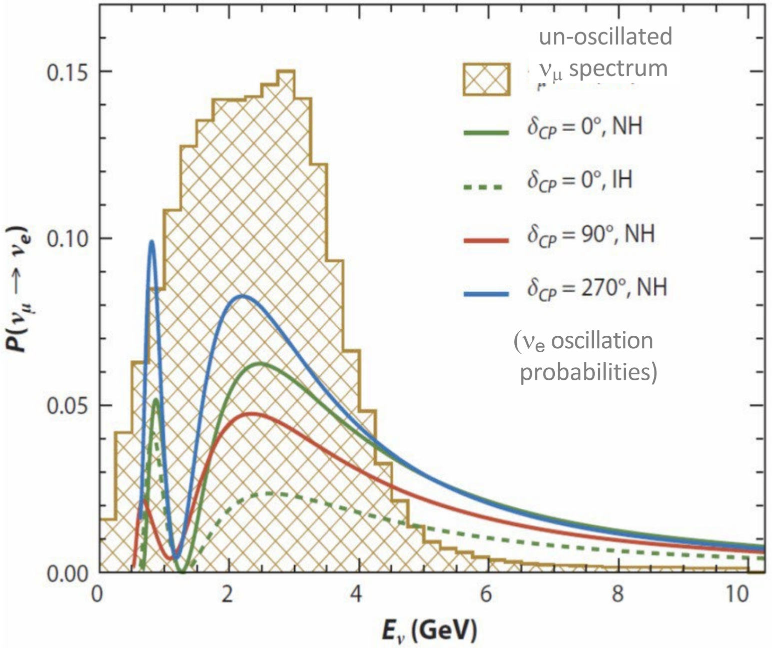
Slides borrowed from Christos Touramanis talk at Neutrino Telescopes on 23/10/23



- 1450 collaborators
- 215 Institutes
- 35 Countries

- On-axis
- Sensitive to first and second oscillation maxima
- Part of the spectrum above the tau creation threshold (~3.5 GeV)

- *High precision measurements of neutrino mixing in a single experiment.*
- Determination of the neutrino mass ordering in the first few years.
- Observation and measurement of CP Violation in the neutrino sector.
- Test of the 3-neutrino paradigm (PMNS unitarity).
- Observatory for astrophysical neutrino sources (solar, atmospheric, supernova).
- Search for BSM physics.



Current status and future plans in a nutshell

- LBNF is being delivered in its entirety.
- DUNE Phase I:
  - FD (approved): 2 x 17 kt (total) LAr TPCs: one Horizontal Drift, one Vertical Drift.
  - ND (baseline TBC and approved by 2025): NDLAr with TMS; DUNE-PRISM; SAND on-axis.
- PIP II: ongoing construction, first beam in 2031, reaching 1.2 MW by end 2032.

- Phase 2, as submitted to P5 (report due in early December):
  - DUNE ND plan: More Capable Near Detector (HPGAr TPC, magnet, calorimeter).
  - DUNE FD plan: FD3, FD4.
  - Fermilab plan: ACE: MIRT, Booster Replacement. Can provide up to 2.1 MW at DUNE start.

P5 recommendations

“**DUNE** will comprehensively explore the quantum realm of neutrinos, potentially unearthing new physics beyond current theoretical frameworks. Early implementation of the accelerator upgrade ACE-MIRT advances the **DUNE** program significantly, hastening the definite discovery of the neutrino mass ordering. This upgrade in conjunction with the deployment of the third far detector and a more capable near detector are indispensable components of the re-envisioned next phase of **DUNE**.”

1) As the highest priority independent of the budget scenario (7 recommendations, 2 of which are about neutrinos, the other are running experiments NOvA, SBN and T2K)

"The first phase of DUNE and PIP-II to determine the mass ordering among neutrinos, a fundamental property and a crucial input to cosmology and nuclear science"

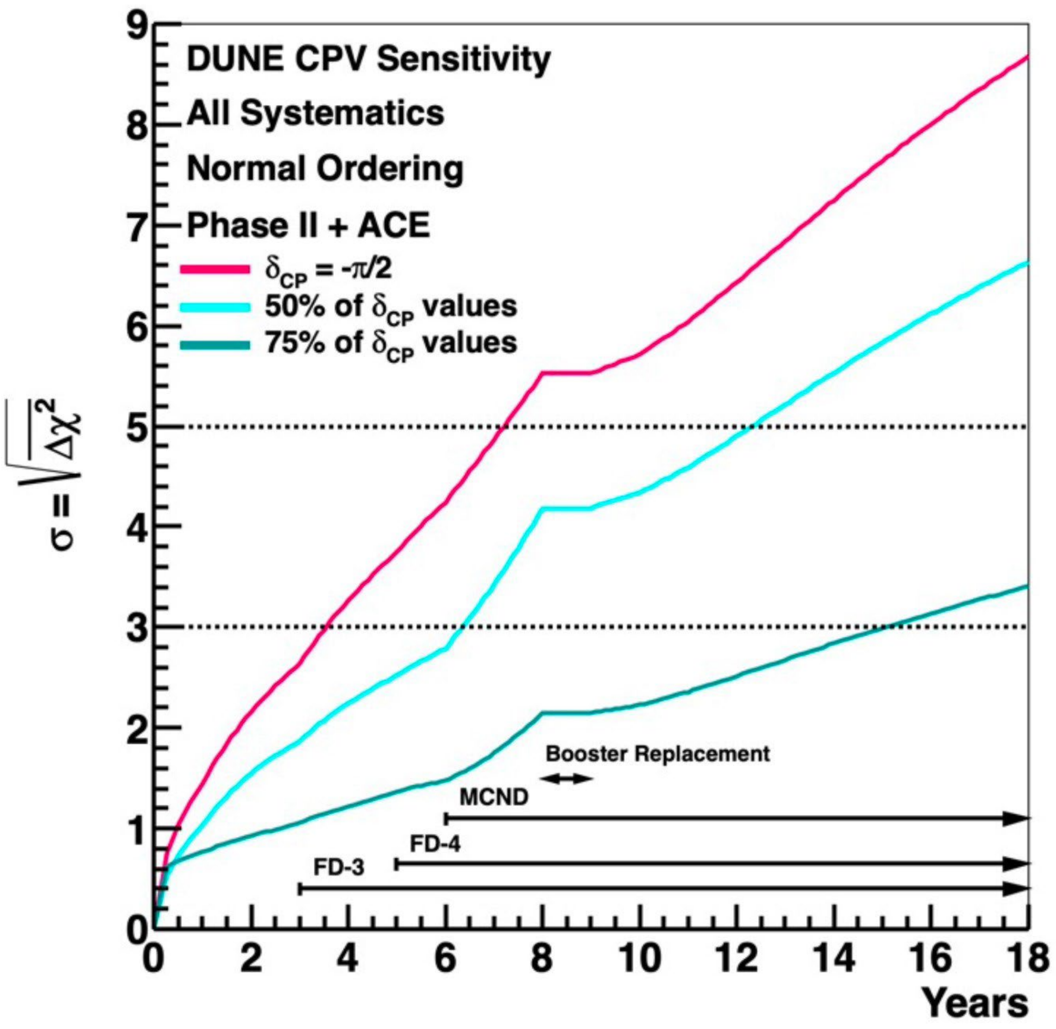
2) Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe (5 projects, 2 of which are about neutrinos, the other one is Ice Cube Gen2)

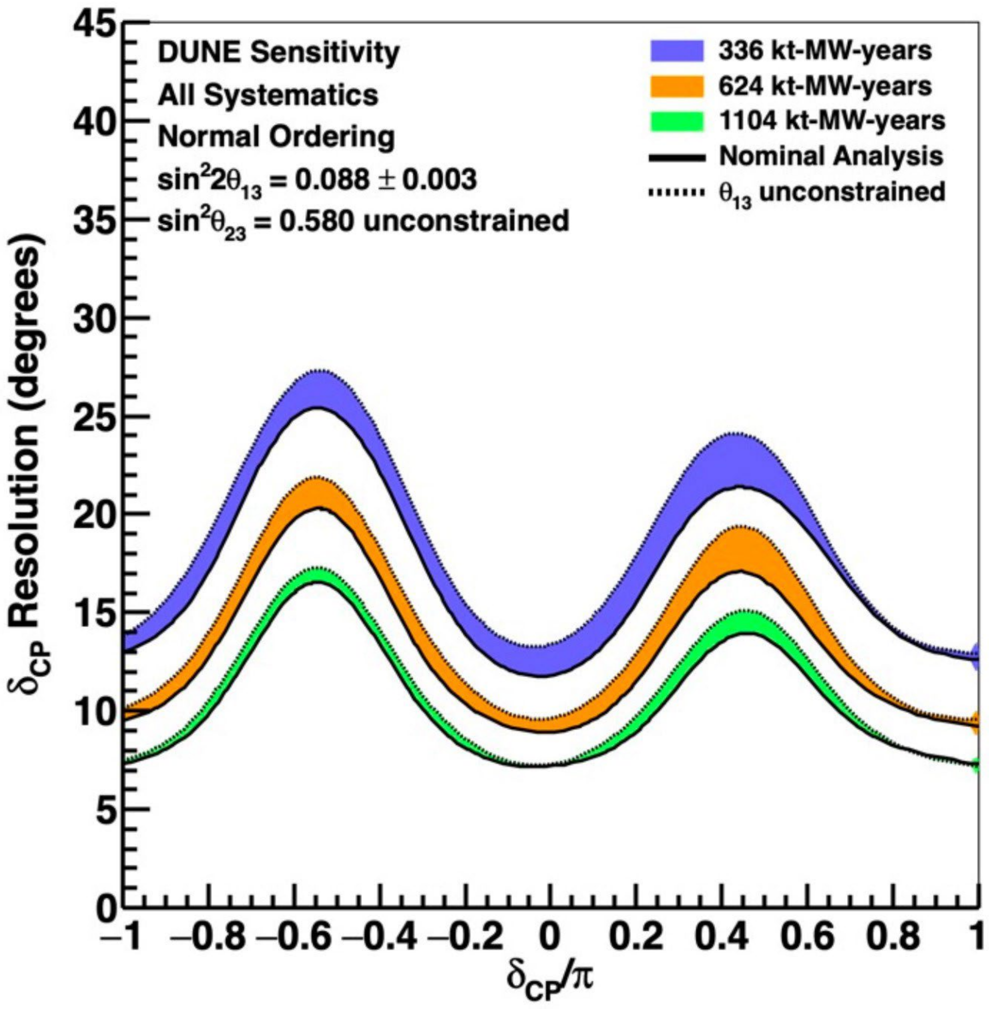
"Re-envisioned second phase of DUNE with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind"

Less Favorable Budget Scenario

"DUNE Third Far Detector (FD3), but defer ACE-MIRT and the More Capable Near Detector (MCND)."

Observation of CP Violation, measurement of Σ_{CP}





Determining Mass Ordering with DUNE Phase I using ν_e and anti-ν_e spectra.

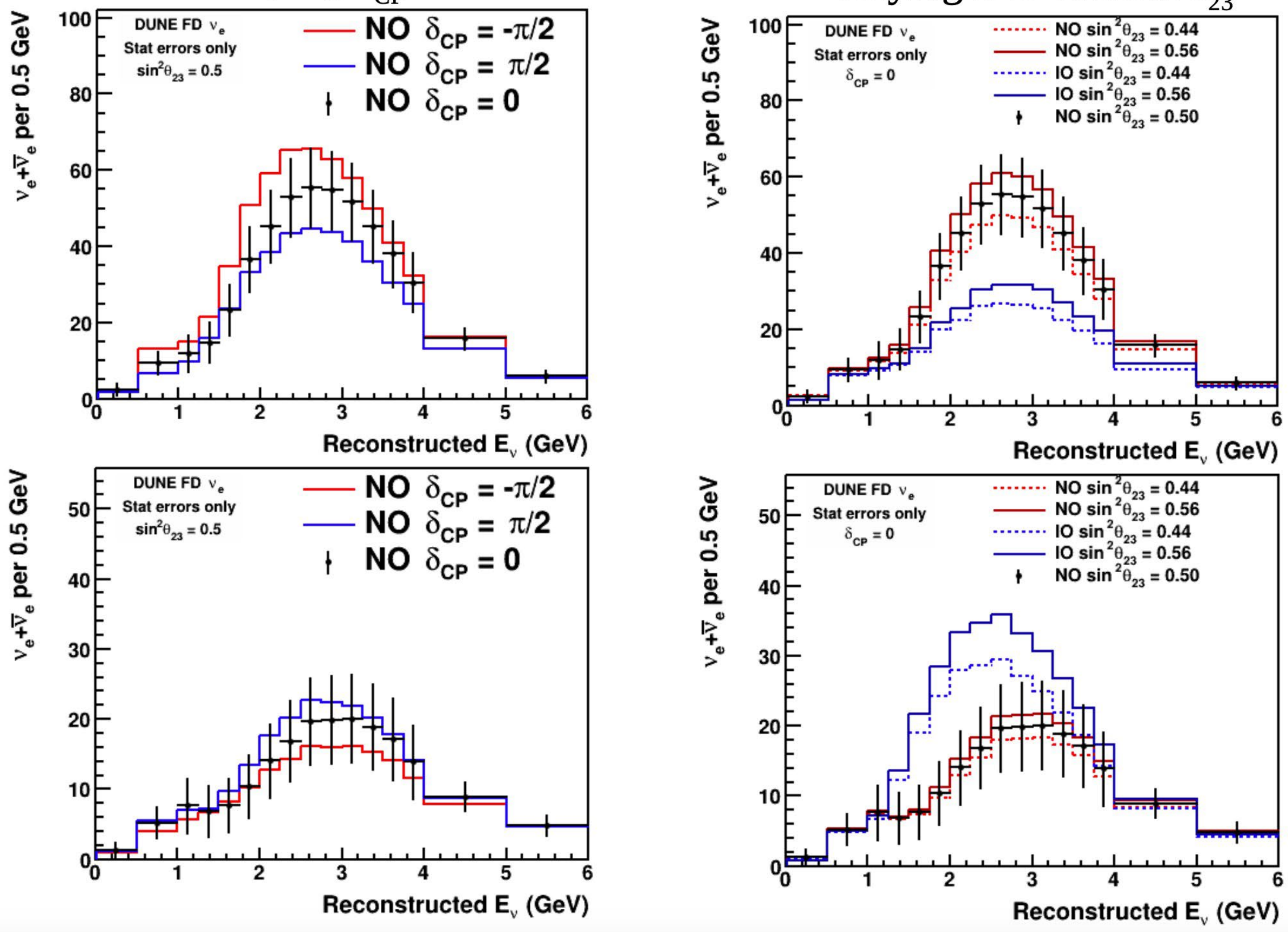
Data points show NO, δ_{CP} = 0, $\sin^2\theta_{23}$ = 0.5

Neutrino mode

Phase I

Antineutrino mode

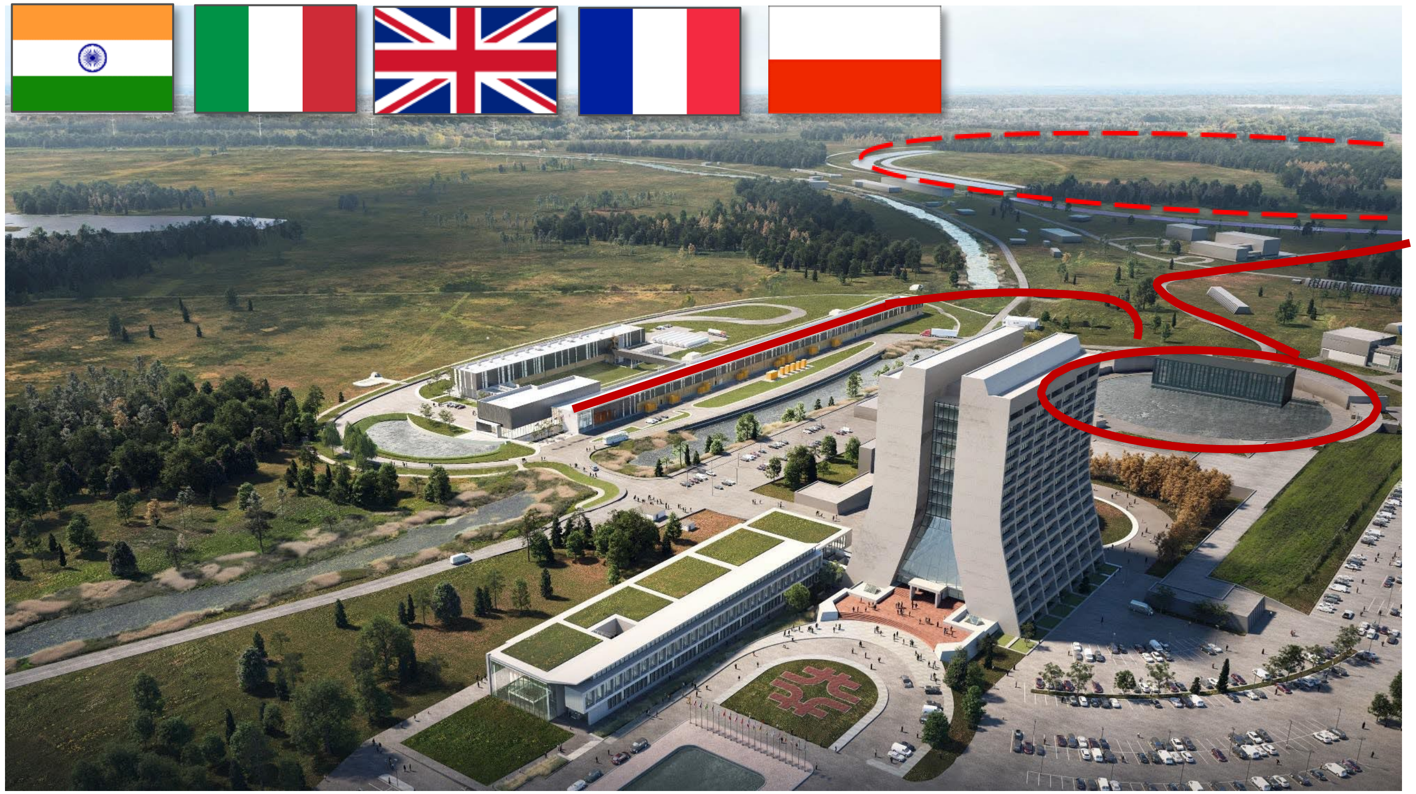
Varying δ_{CP} | Varying MO and $\sin^2\theta_{23}$

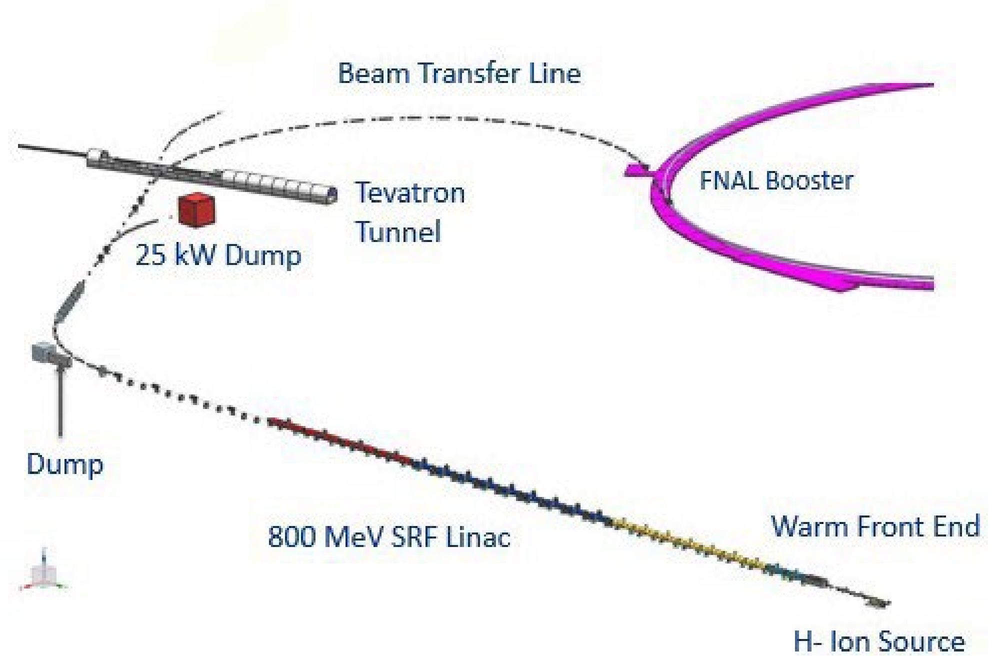


UNIVERSITY OF LIVERPOOL

PIP-II

- New proton source for Fermilab : 800 MeV H⁻ SRF linac.
- 1.2 MW protons, upgradable to multi-MW, CW-compatible.
- Linac to Booster transfer line.
- Accelerator Complex upgrades.





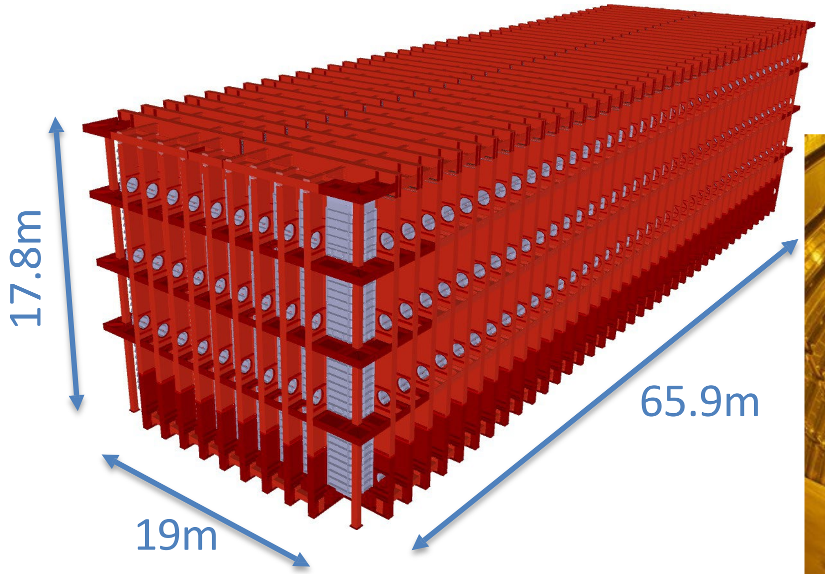
Beam Schedule:
Fermilab beams stop end 2026
Beam commissioning: 2029-30
Beam to DUNE: Fall 2031, ~ 1 MW
1.2 MW by end 2032

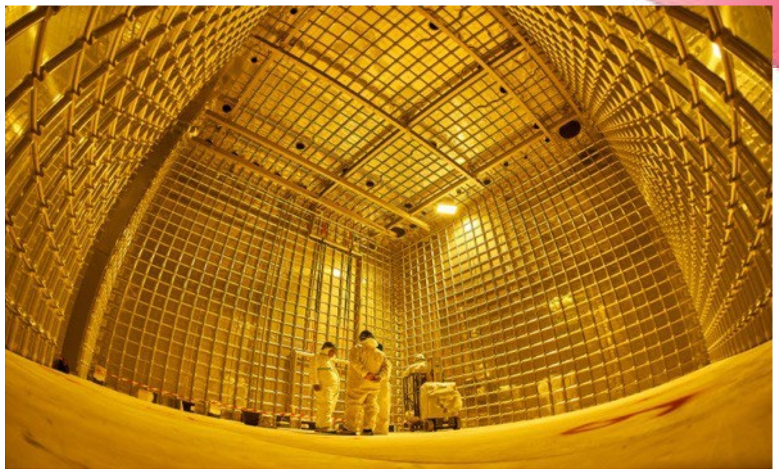
Far Detectors

- 2 (max 4) LAr TPCs, 17 kt Argon total (10 kt fiducial) each one:
  - Horizontal (charge) Drift
  - Vertical (charge) Drift

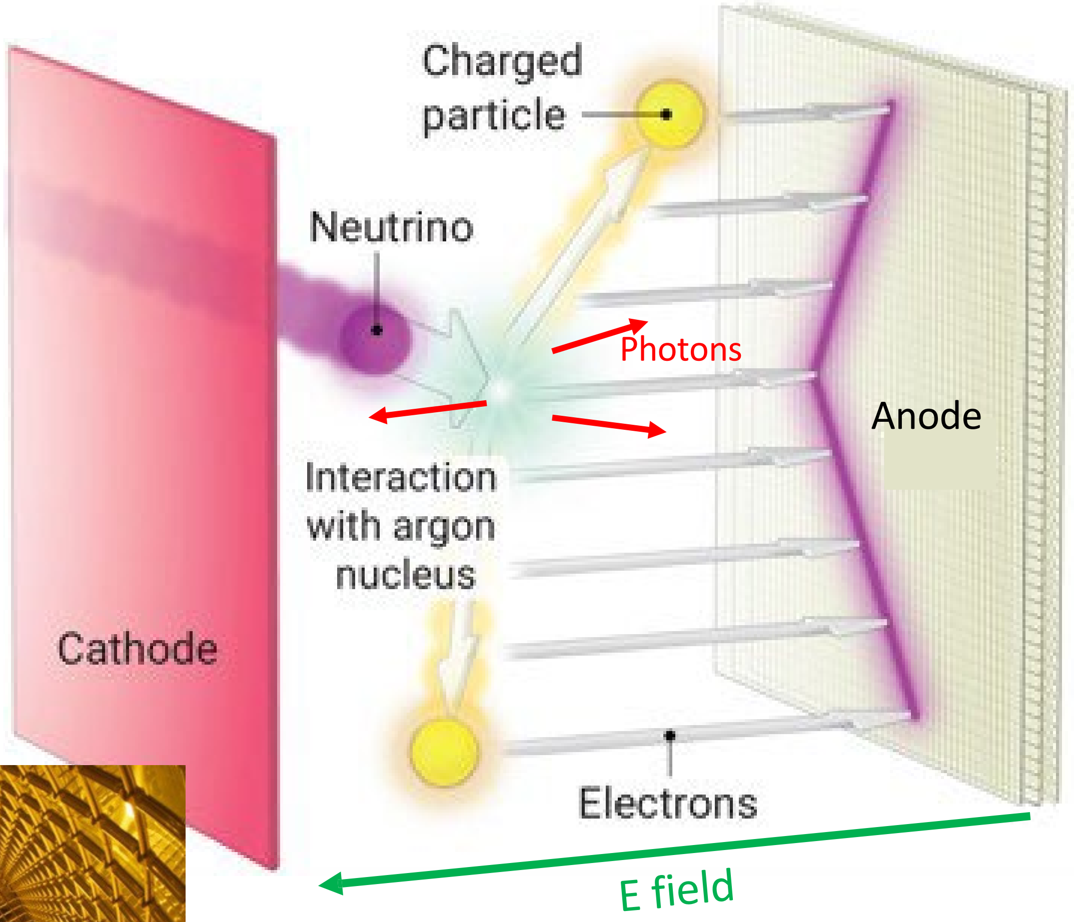
Each membrane cryostat has internal volume :

~28’500 m^3, ~17’500 tons of LAr

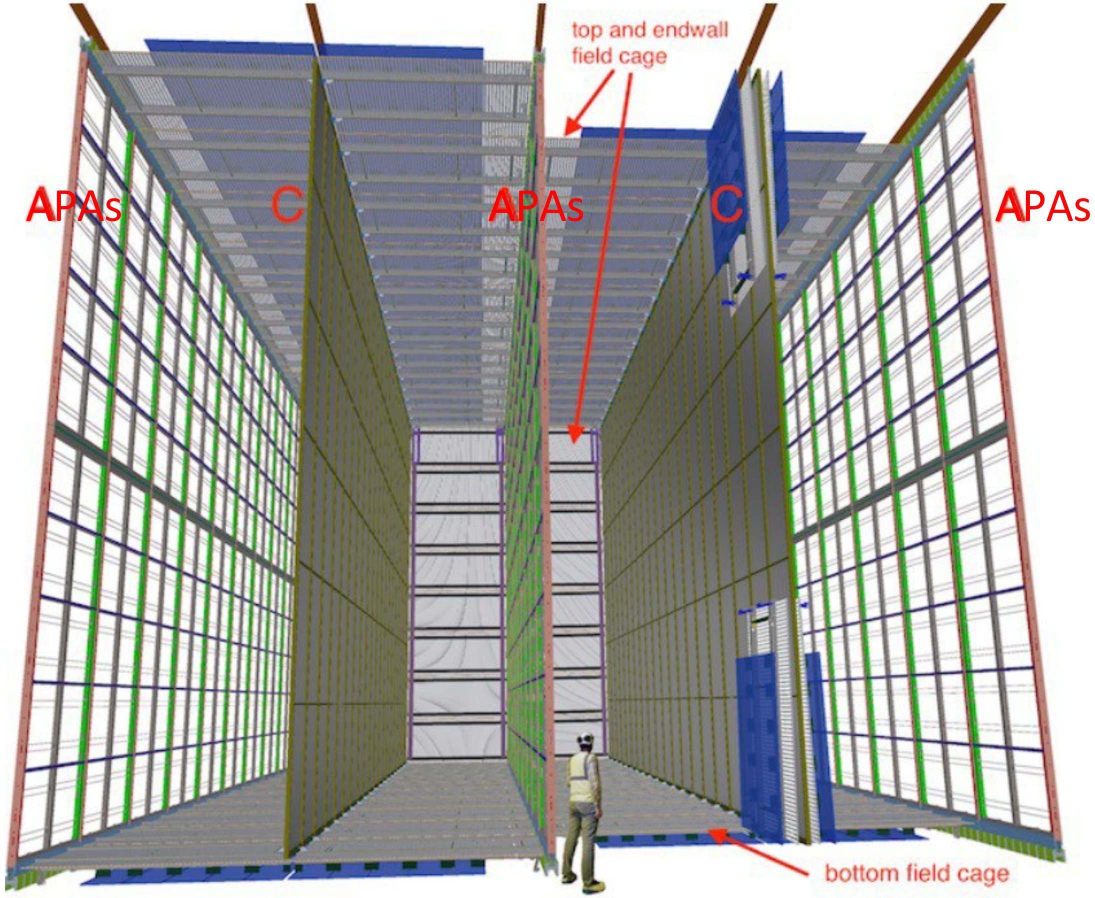




ProtoDUNE cryostat
Same technology
1/25 of FD module

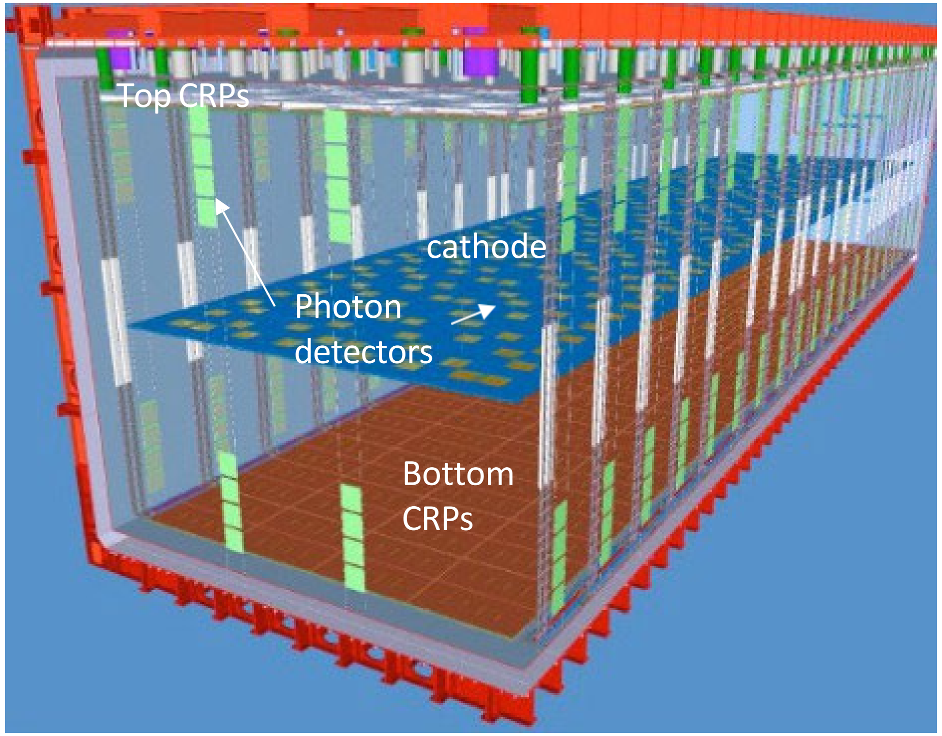


Horizontal Drift



- APA : based on a wire chamber technology
- Drift length ~ 350 cm -> ~ 180 KV on cathode
- ~ 9800 m^3 = ~ 13'661 tons of active LAr

Vertical Drift

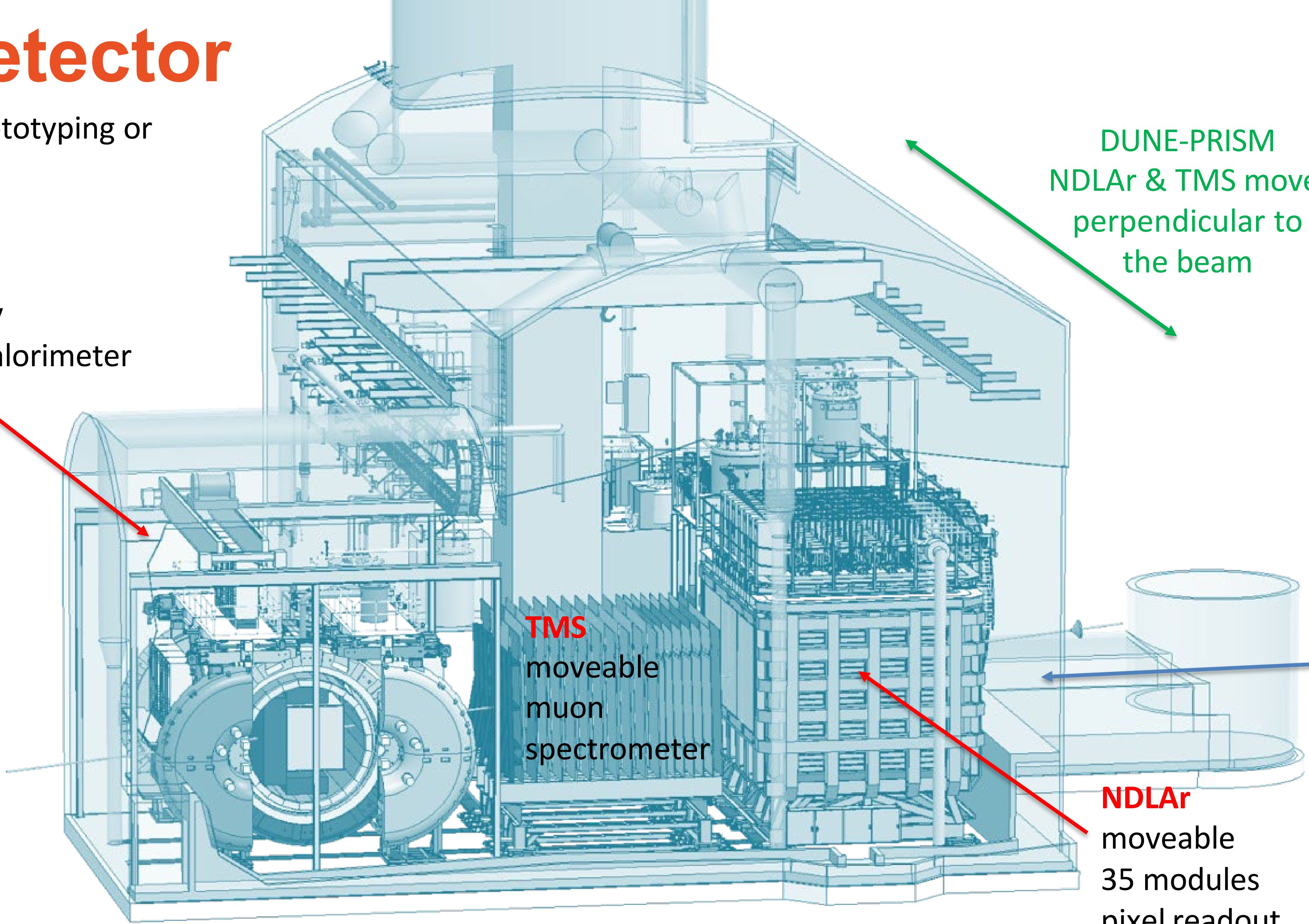


- CRP : based on perforated PCB technology
- Drift length ~ 640 cm -> ~ 300 KV on cathode
- Photon detectors on the cathode at 300 KV
- ~ 10180 m^3 = ~ 14'190 tons of active LAr

Near Detector

All systems in prototyping or preparation

SAND
on-axis, stationary
KLOE magnet & calorimeter
Straw Tubes
GRAIN: 1 ton LAr



TMS
moveable
muon
spectrometer

DUNE-PRISM
NDLAr & TMS move perpendicular to the beam

neutrino beam

NDLAr
moveable
35 modules
pixel readout

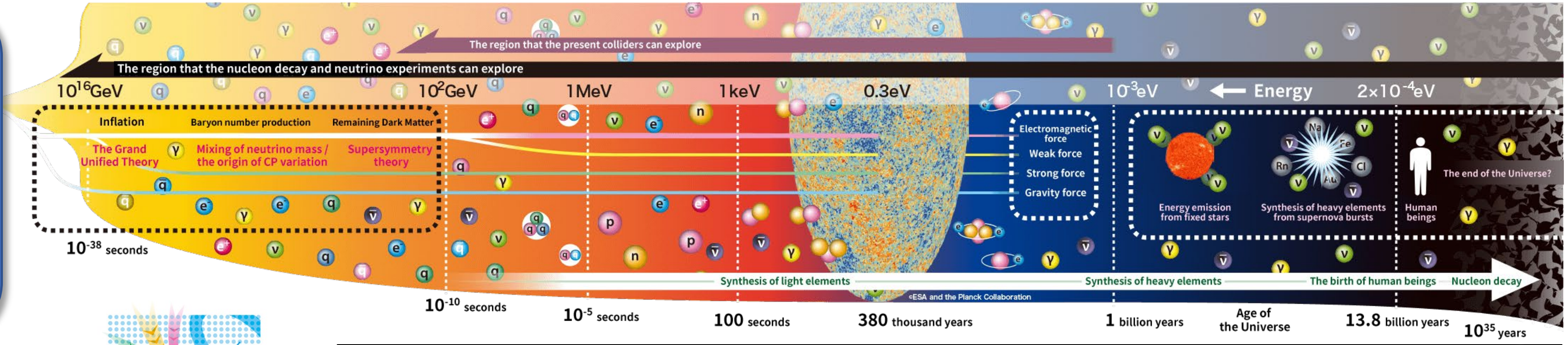
The future

- First Far Detector ready taking data: 2029: Start of non- beam physics.
- Second Far Detector taking Data: 2030

- Near Detector taking data: 2031
- Beam on: 2031: Main physics program starts: Oscillations, MO, CPV

- Phase II: MCND, FD3, FD4, >2 MW proton beam, to come online in the next decade

Hyper-Kamiokande



~600 collaborators
103 Institutes
22 Countries
(Italy: ~ 10% of the collaboration)

Hyper-Kamiokande

- ~2027 onwards
- 260 kton (188 kton FV)

X 8.4

Super-Kamiokande

- 1996 onwards
- 50 kton (22.5 kton FV)
- 2015 Nobel Prize - Kajita

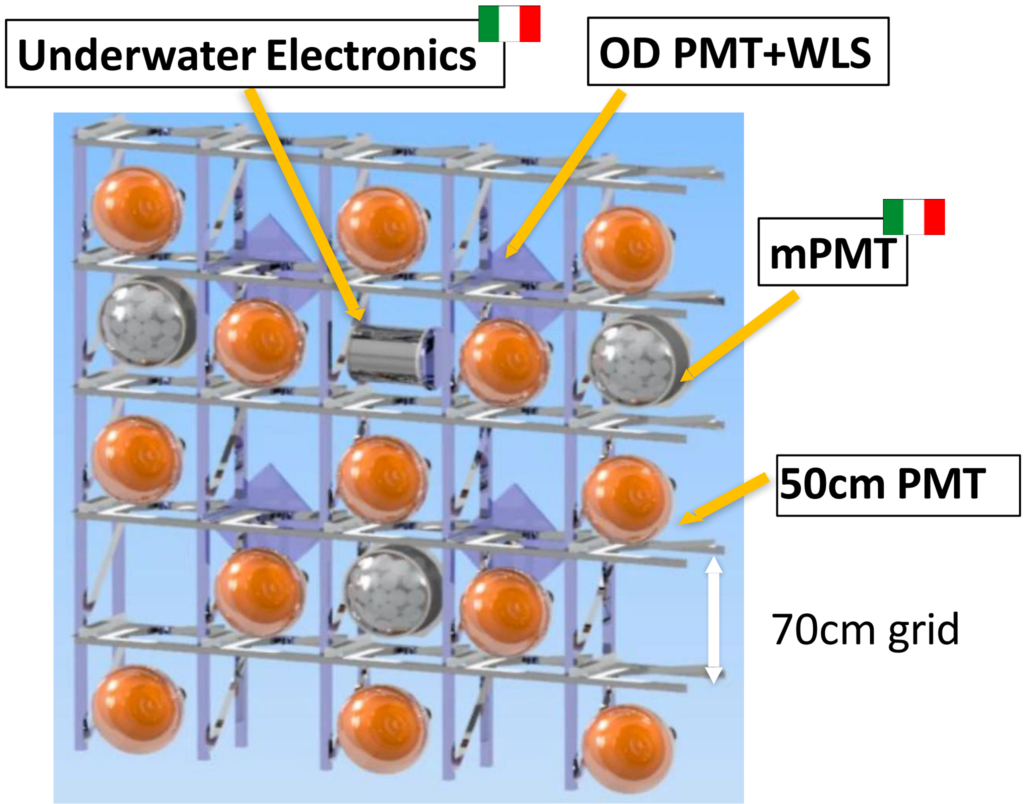
Kamiokande

- 1983 – 1996
- 3 kton
- 2002 Nobel Prize - Koshiba

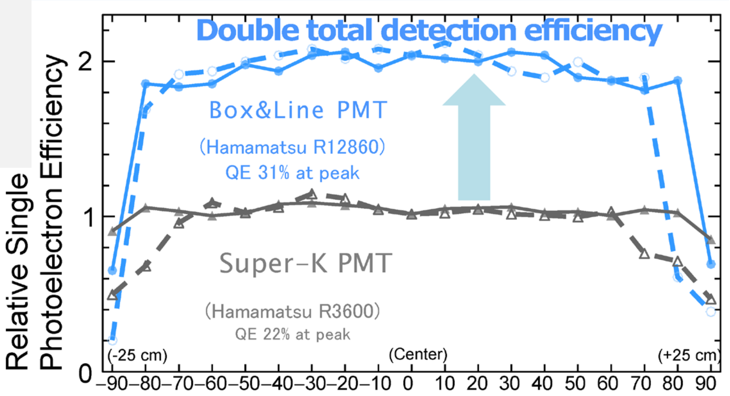
X 20

Hyper-K detector configuration

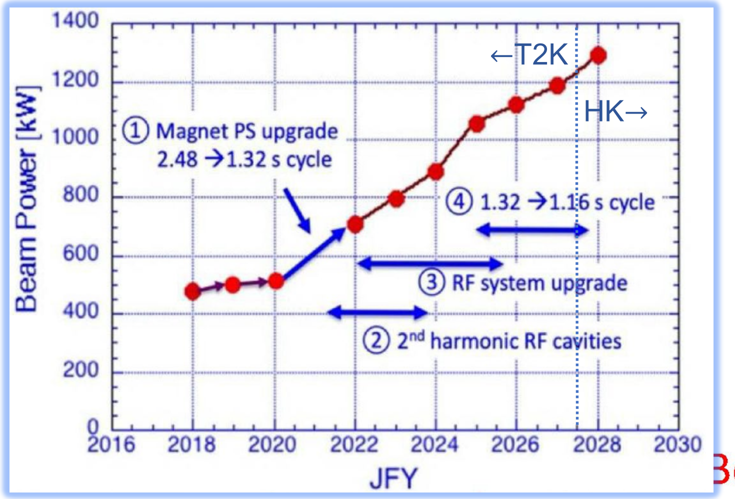
- **Inner Detector (ID)**
  - 64.8m diameter, 65.8m height
  - 40k PMTs, 50 cm, will be installed
  - 800 Multi-PMT modules will be integrated as hybrid configuration
- **Outer Detector (OD)**
  - 1m (barrel) or 2m (top/bottom) thick
  - 3-inch PMT + WLS plate
  - Walls are covered with high reflectivity Tyvek sheets



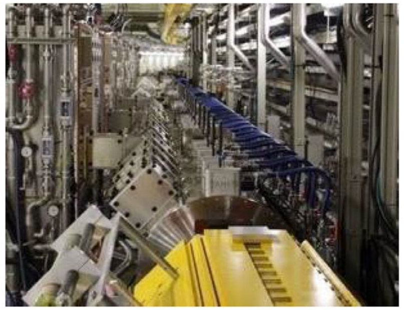
Half coverage (20%) versus Super-K but twice efficiency

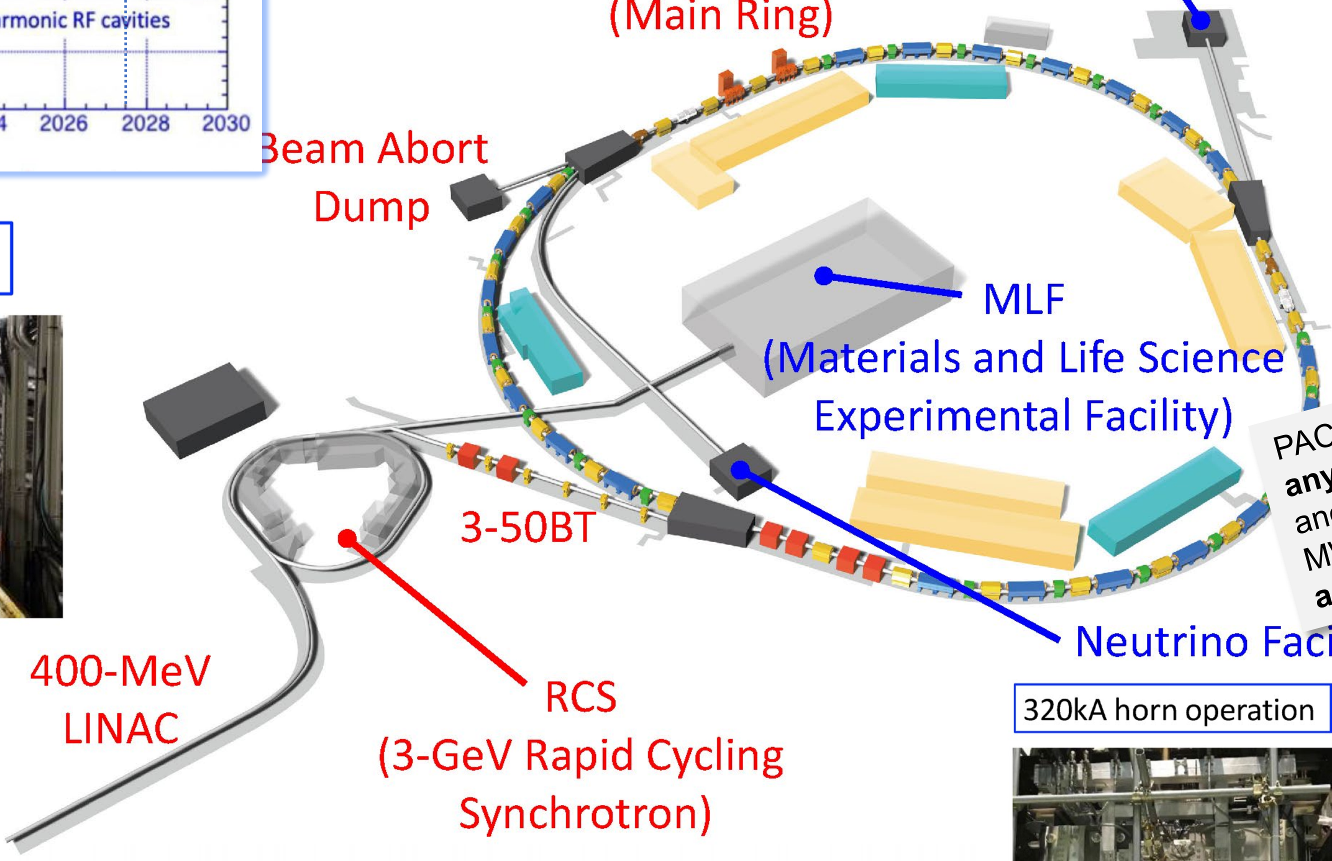


J-PARC Upgrade



MR-RF cavities

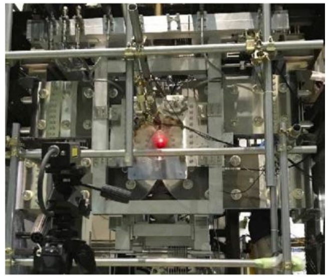




New main magnet PS for high rep. rate

PAC review panel: "**The committee did not identify any major show-stoppers** for the neutrino beamline and its infrastructure to be ready for operation at 1.3 MW after 2025, **assuming that the mentioned budget and needed workforce are made available**"

320kA horn operation

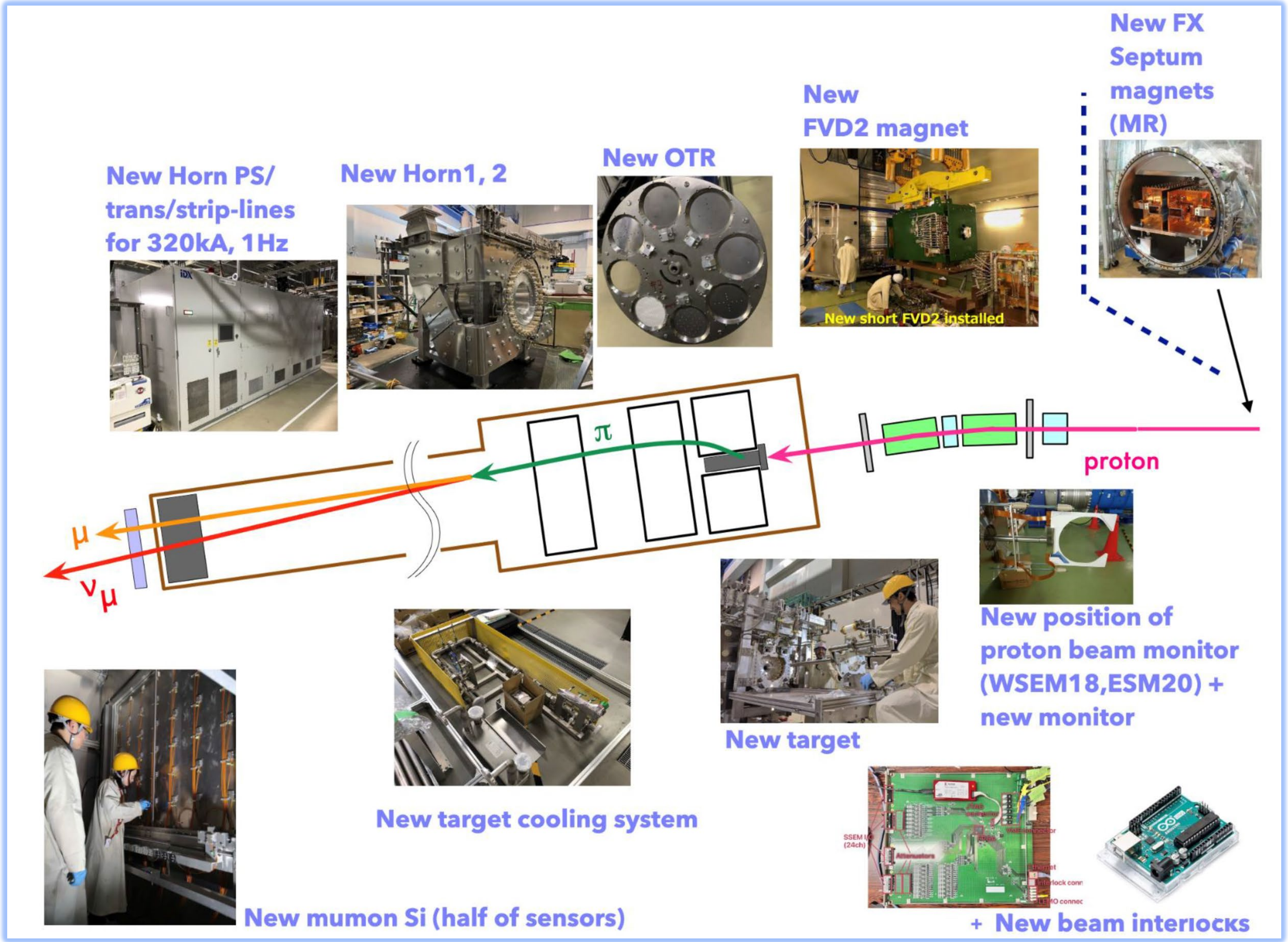


	RCS	MR
Circumference	348.333 m	1567.5 m
Super-periodicity	3	3
Injection	Multi-turn, charge-exchange	bunch to bucket
Injection energy	400 MeV	3 GeV
Injection period	0.5 ms (307 turns)	120 ms
Harmonic number	2	9
Number of bunches	2	8
Transition γ	10.8	$31.6i$
Extraction energy	3 GeV	30 GeV
Repetition rate	25 Hz	0.4-0.86 Hz
Particles per pulse	8.33×10^{13}	3.3×10^{14}
Beam power	1 MW	0.75-1.3 MW

Achieved 760 kW (continuous) in JFY2023
Aiming 1.3 MW by JFY2028

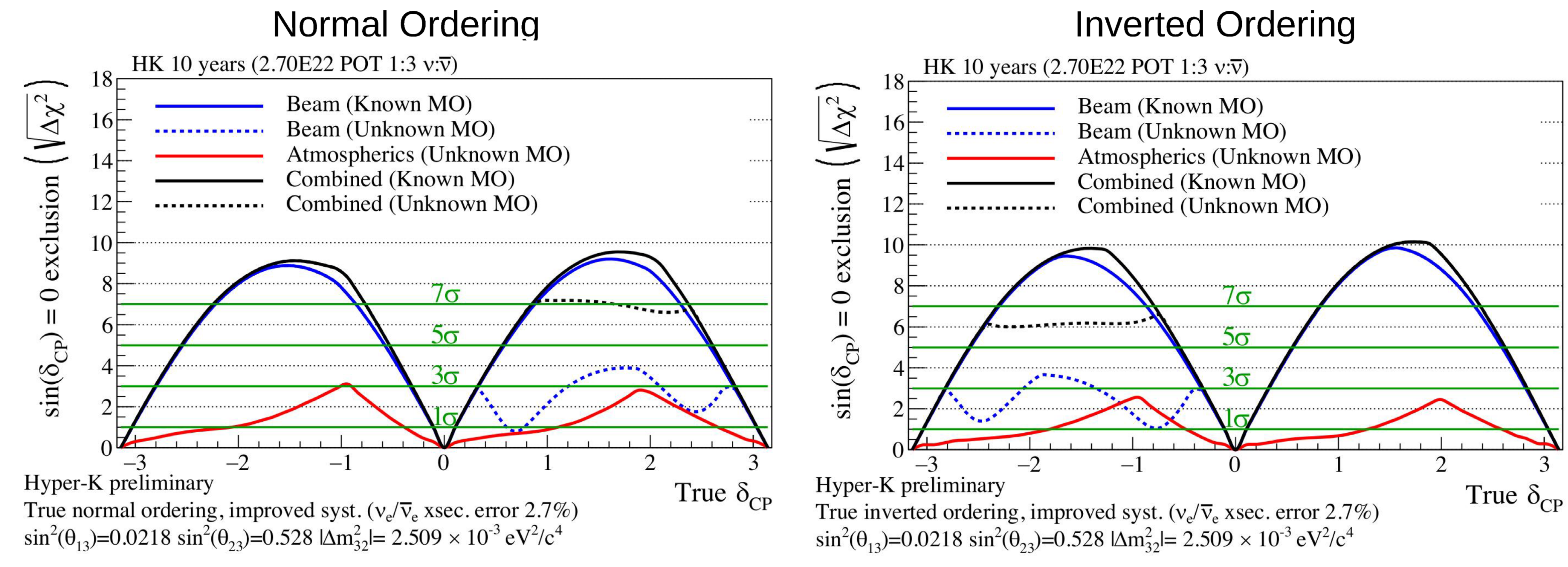
Most of the neutrino beam line upgrades already in place

T2K will run until 2027 and profit of the J-PARC power upgrades



CP violation sensitivity

It's important to stress that efficiencies, backgrounds, systematic errors come from more than 10 years of T2K analysis efforts

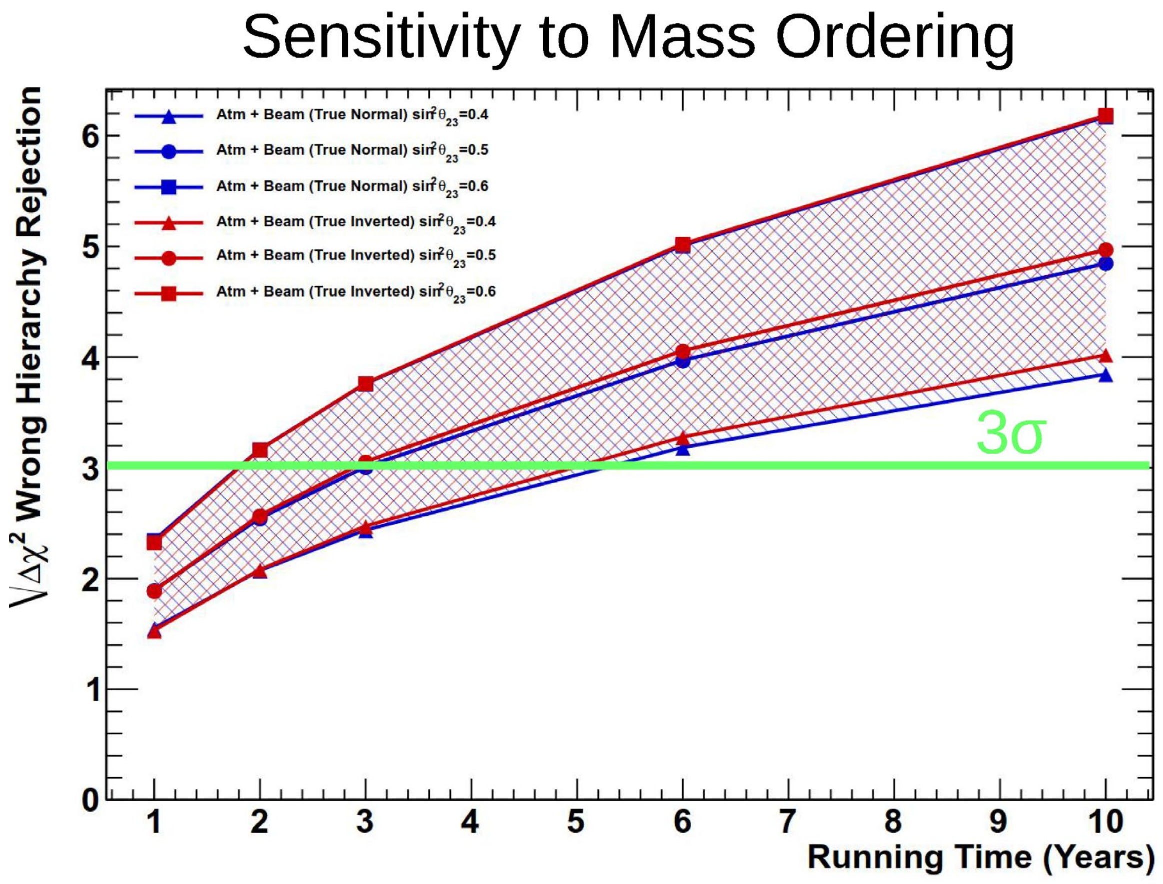


By combining beam neutrinos and atmospherics

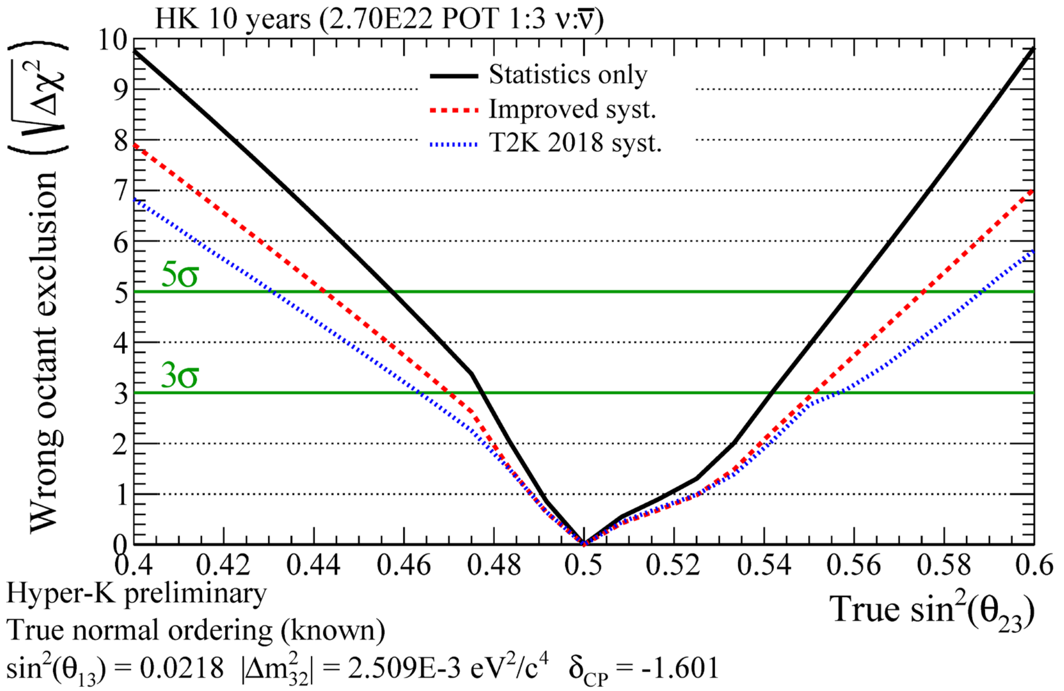
- For maximal CP violation ($\delta_{CP}=-\pi/2$) 5σ sensitivity is reached in 3 years.
- In 10 years, CP conservation excluded at 5σ for 60% of δ_{CP} values.

Mass Ordering and θ_{23} octant sensitivity

Sensitivity to mass ordering comes from matter effects: the "short" baseline of Hyper-K prevents good sensitivity, that is partially compensated by atmospheric events (a combined T2K + Super-K analysis has just been released).



Wrong octant 3σ exclusion as a function of true $\sin^2\theta_{23}$ for different systematics model for 10 HK-years (beam+atmospherics).

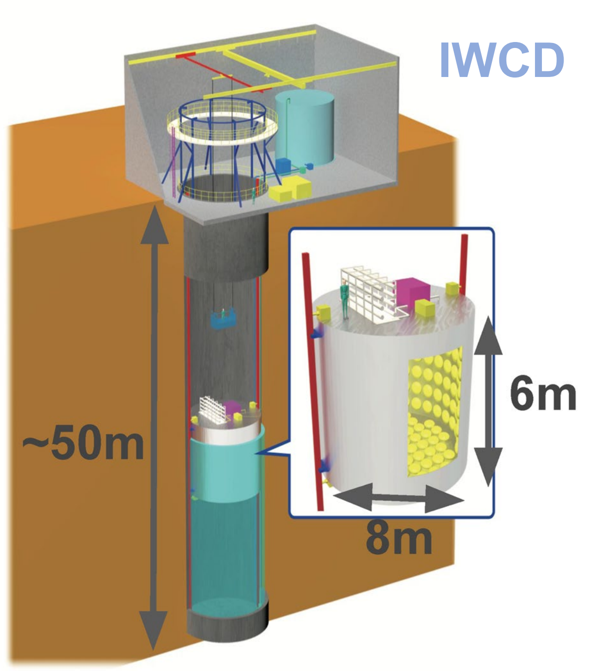


Systematic Errors

T2K overall systematic errors for the ν_e appearance channel are 4.7%.

Aim to reduce them to 2.1% (full simulation undergoing):

- ND280 redesigned and optimized to better constrain systematic errors (will be fully in place within this summer)
- A new Intermediate (0.75 km) Water Cherenkov Close Detector (**IWCD**) to further constrain systematic errors
- More statistics (20x T2K) will allow close detectors to constrain ν-nucleus interaction models better (no assumptions on better models)
- Gadolinium doping can enhance efficiency and purity of antineutrinos' detection (will not be added on day one)
- Dedicated experiments like **Enubet** could reduce (anti-)ν_e cross section uncertainty further.



Total percentage error on sample event rates:

Error model	μ-like ν-mode	μ-like $\bar{\nu}$-mode	e-like ν-mode 0 d.e.	e-like $\bar{\nu}$-mode 0 d.e.	e-like ν-mode 1 d.e.	e-like $\nu/\bar{\nu}$ modes 0 d.e.
T2K 2020	3.0%	4.0%	4.7%	5.9%	14.1%	4.6%
Improved	1.2%	1.1%	2.1%	2.2%	5.2%	2.0%

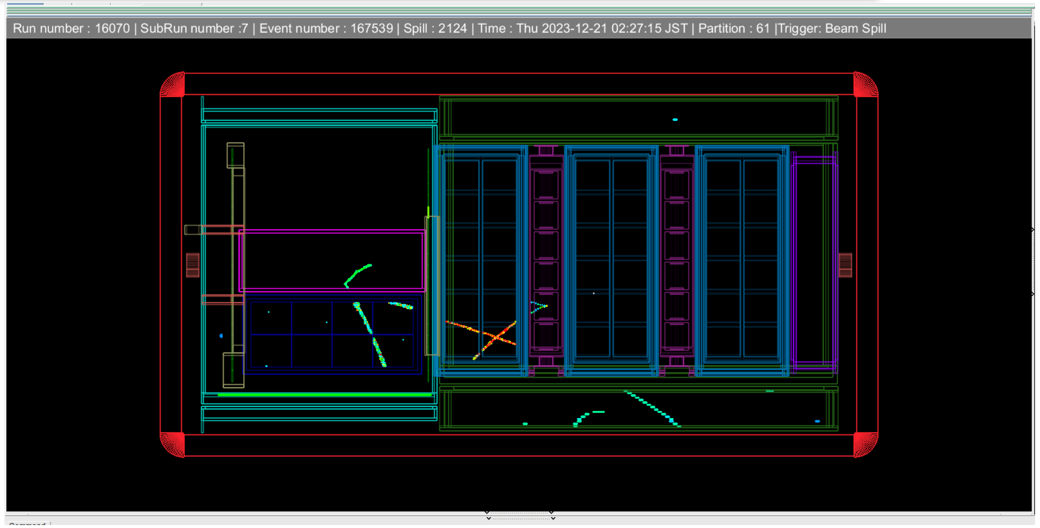
HK Expected event rate @ 10 years vs T2K today

$\nu:\bar{\nu}$ = 1:3 (T2K is 1:0.7), @ $\delta_{CP} = 0$

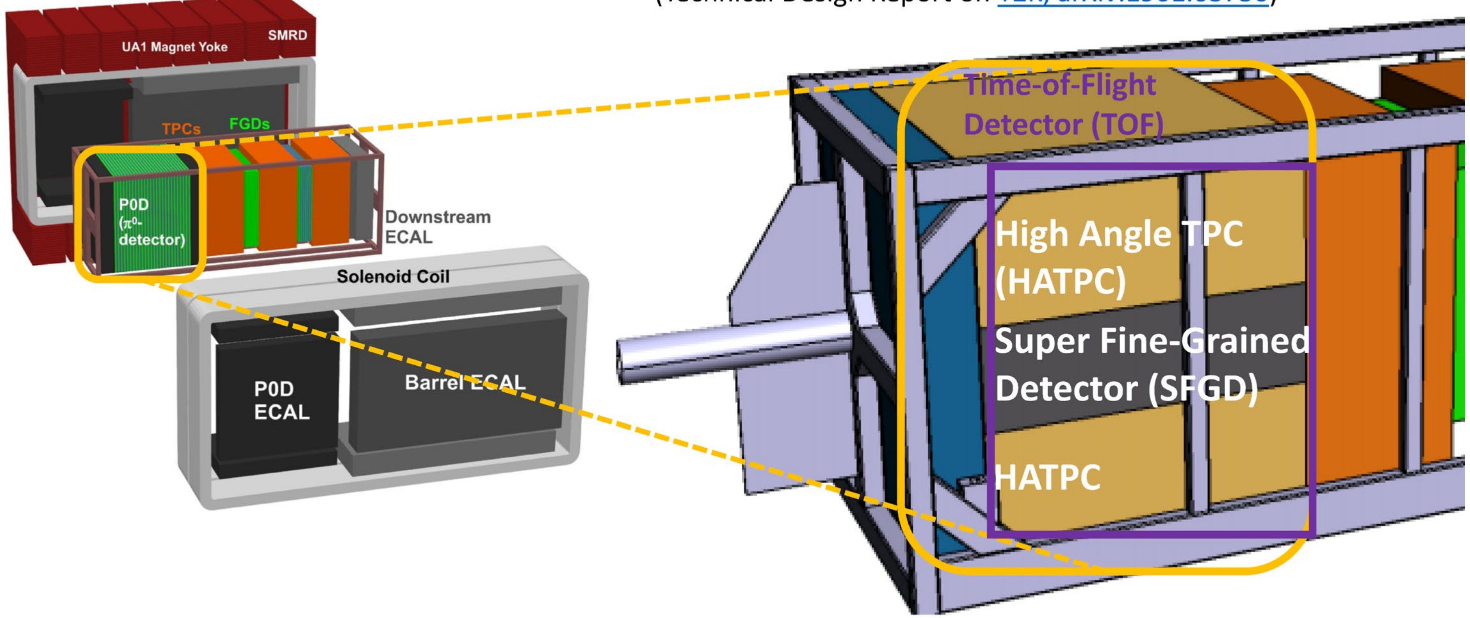
	HK	T2K
ν-mode, 1 ring μ-like	~8800	318
$\bar{\nu}$-mode, 1 ring μ-like	~12000	137
ν-mode, 1 ring e-like	~2100	94
$\bar{\nu}$-mode, 1 ring e-like	~1800	16
ν-mode, 1 ring e-like, 1 decay e-	~300	14

Near detector (ND280) upgrade

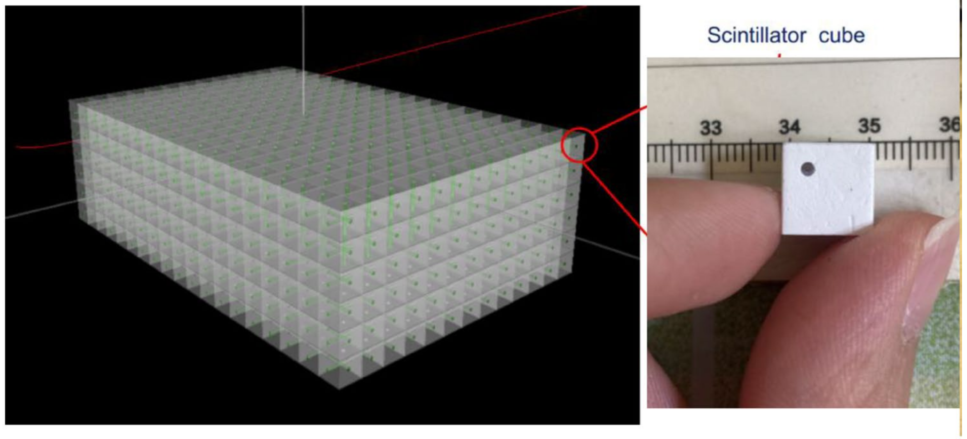
Almost in place now for T2K, will be re-used by Hyper-K
More (and more granular) mass for the neutrino interactions: **SFGD**
More angular acceptance: **High Angle TPCs → INFN responsibility**
Better veto for external tracks: **Time-of-flight**
Significant lower energy threshold for protons and much better neutron detection efficiency.
Inside the former UA1 and Nomad magnet: original contribution of INFN at the beginning of T2K



(Technical Design Report on T2K, arXiv:1901.03750)

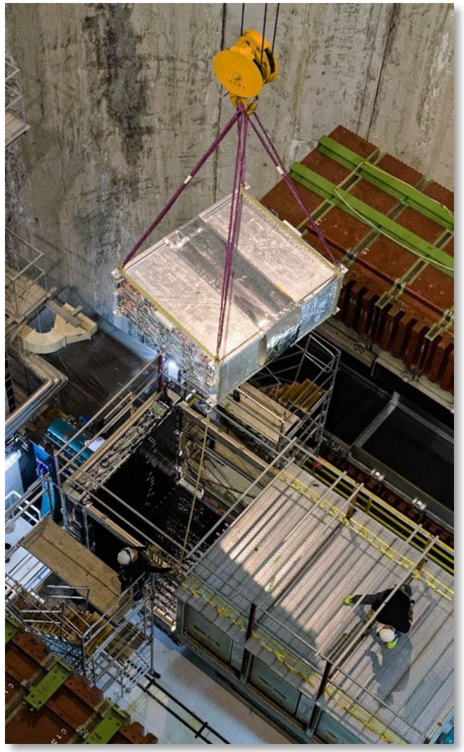


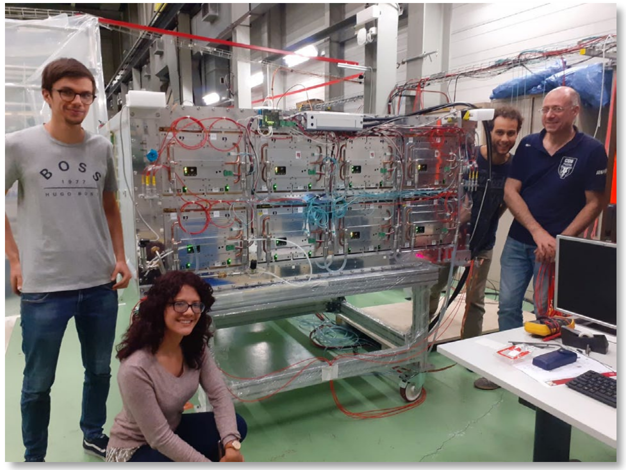
SFGD:
3D plastic scintillator ~ 2 million 1.0 cm^3 cubes



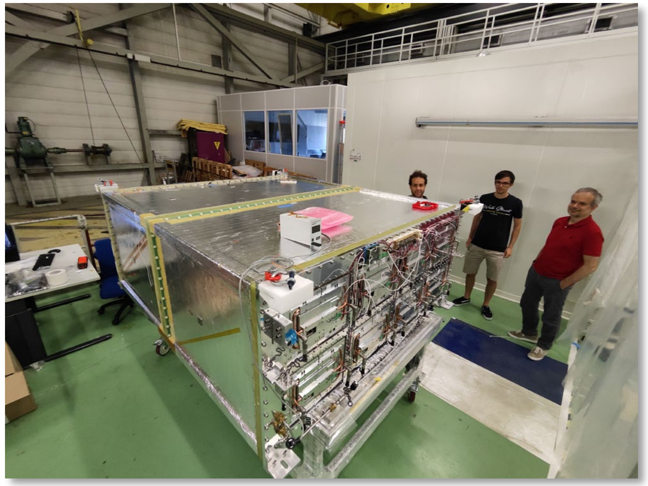
High Angle TPCs

- In addition to the 3 longitudinal TPCs already underway
- Optimized field cage with a design that minimizes the dead   space and maximizes the tracking volume (INFN).
- Use of resistive micromegas (ERAM) instead of the standard bulk micromegas
- Prototype mounted and tested at LNL
- Cameras mounted at CERN and tested at CERN and DESY
- First (bottom) TPC already running at ND280
- Second TPC expected for April this year





Nucl.Instrum.Meth.A 957 (2020) 163286
Nucl.Instrum.Meth.A 1025 (2022) 166109
Nucl.Instrum.Meth.A 1052 (2023) 168248

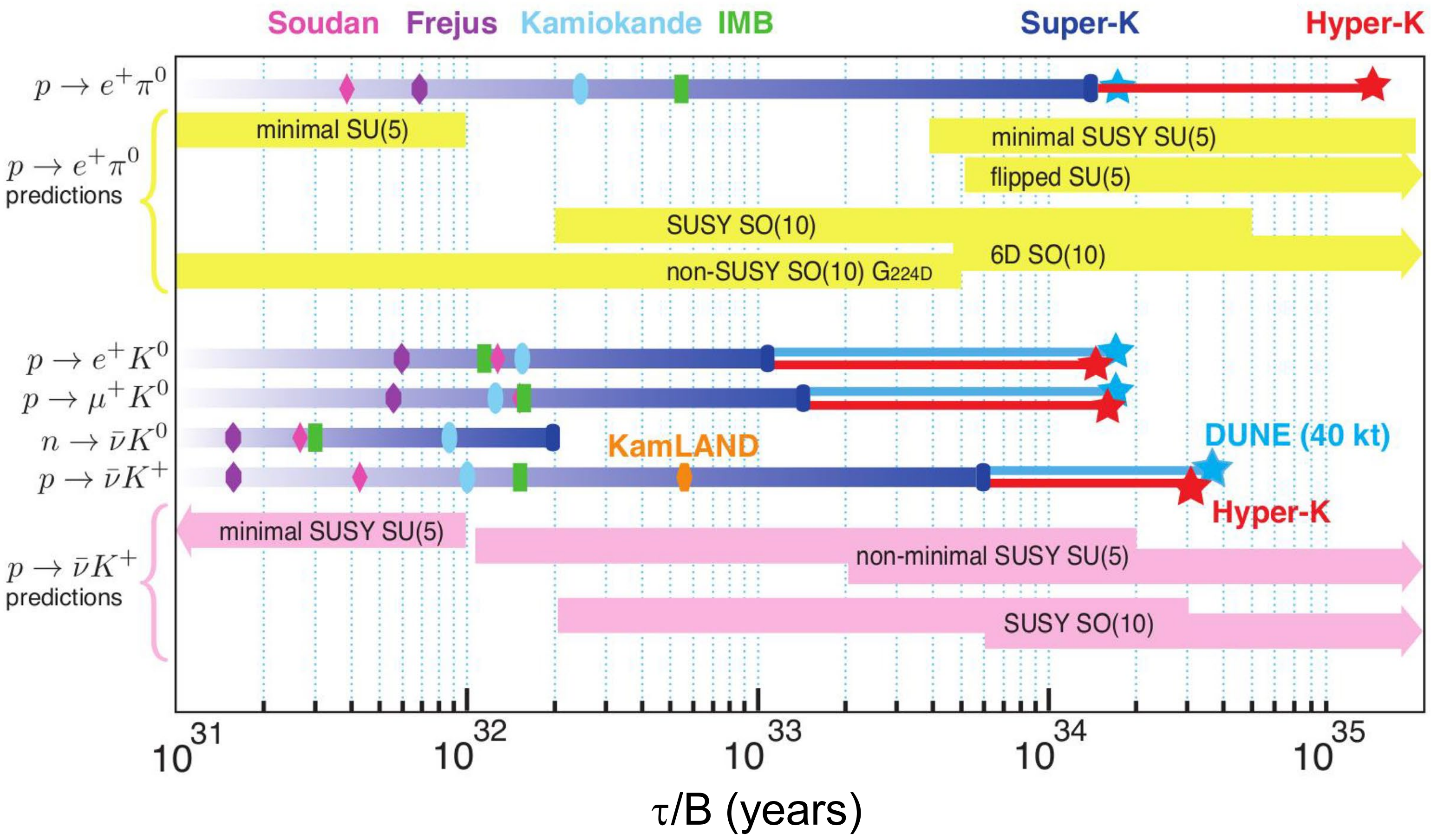


Hyper-K: Rare decays and astrophysics

Proton Decay

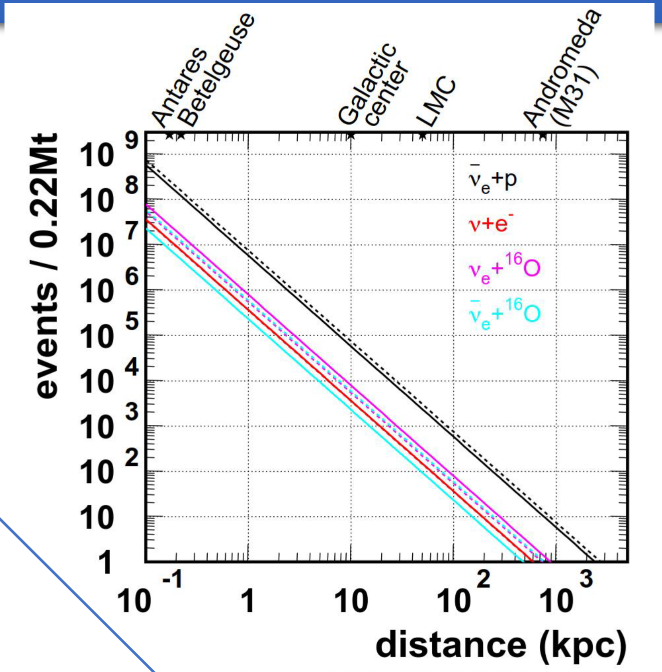
The golden channel for Barion Number Violation

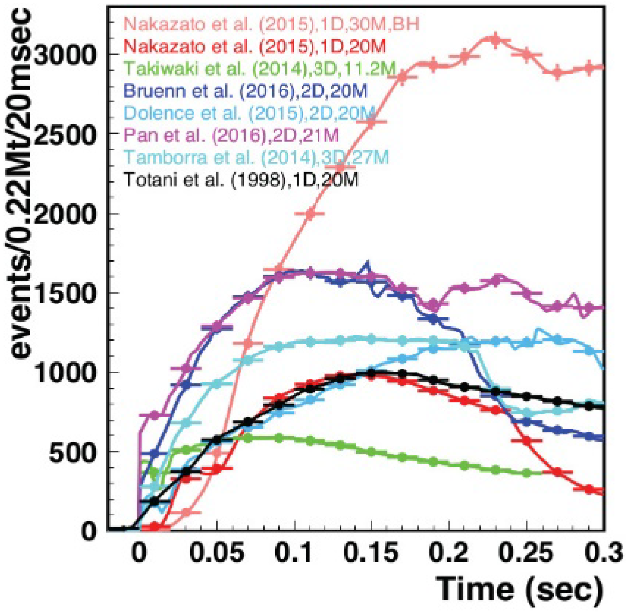
- Improve the SK limits by about one order of magnitude
- Neutron-antineutron oscillation sensitivity at 10^9s



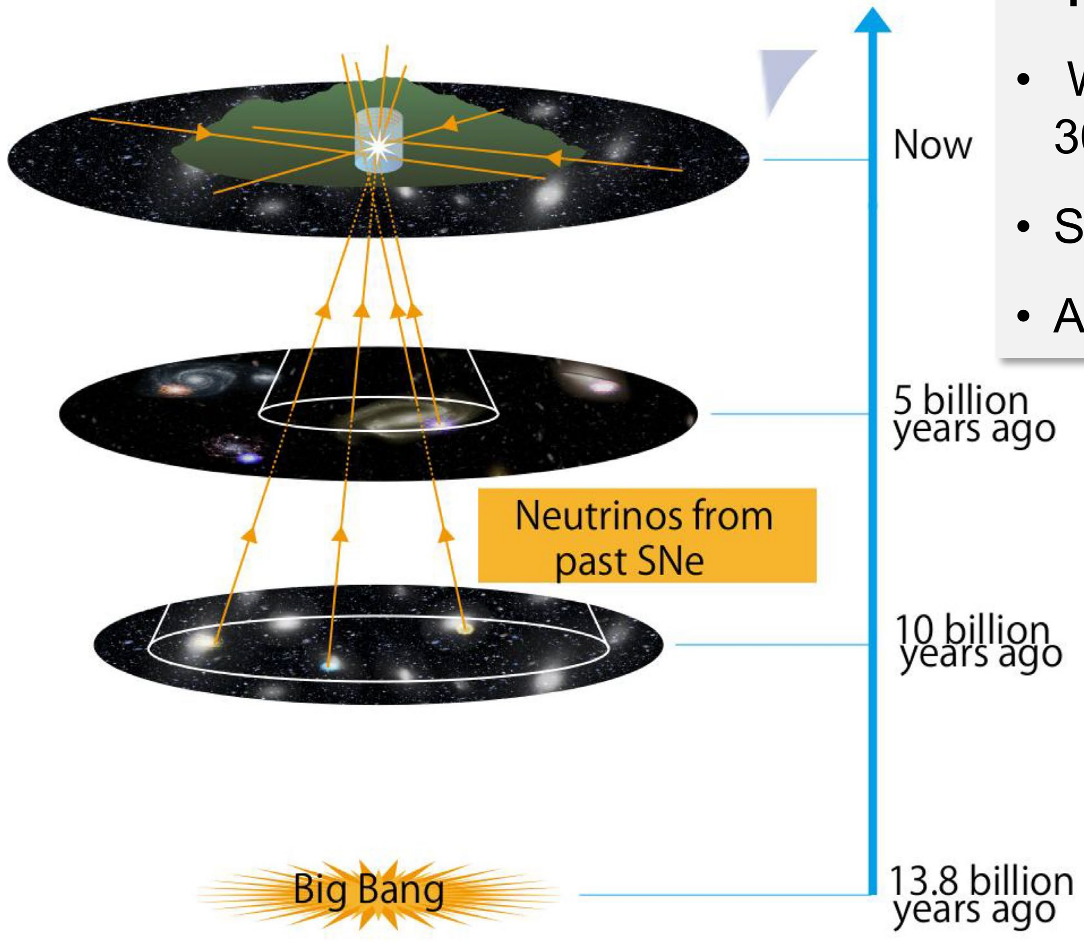
SuperNova Burst Neutrinos

- SN1987a (at 51.4 kpc) discovered with 24 neutrinos (11 in Kamiokande)
- At 10 kpc (Galactic SN) 54k-90k neutrinos → can discriminate among SN explosion models (*Astrophys.J.* 916 (2021) 1, 15) with just the time arrival information
- At 0.2 kpc (Betelgeuse) rate as high as 10^8 events → DAQ design (buffering)
- At 50 kpc (LMC) ~ 3000 events
- Sensitivity up to 780 kpc (Andromeda M31) with ~ 10 events
- DUNE, JUNO and Hyper-K detect different ν flavors and different processes → great complementarity for SN burst neutrinos



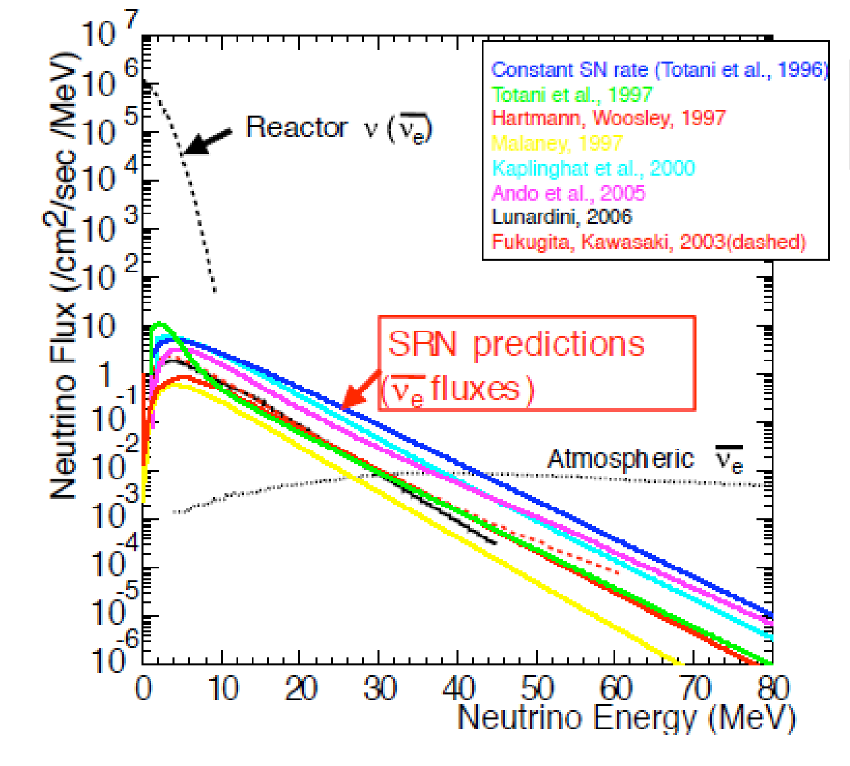


SuperNova Relic Neutrinos



Current Super-K SRN limits close to prediction (→ SK-Gd)

- **Neutron tag** to control background/lower threshold
- Window between solar, reactors and atmospheric neutrinos: 16-30 MeV
- Stellar collapse, nucleosynthesis and history of the Universe
- About 70 events expected in 10 years, for a significance of ~4.2σ



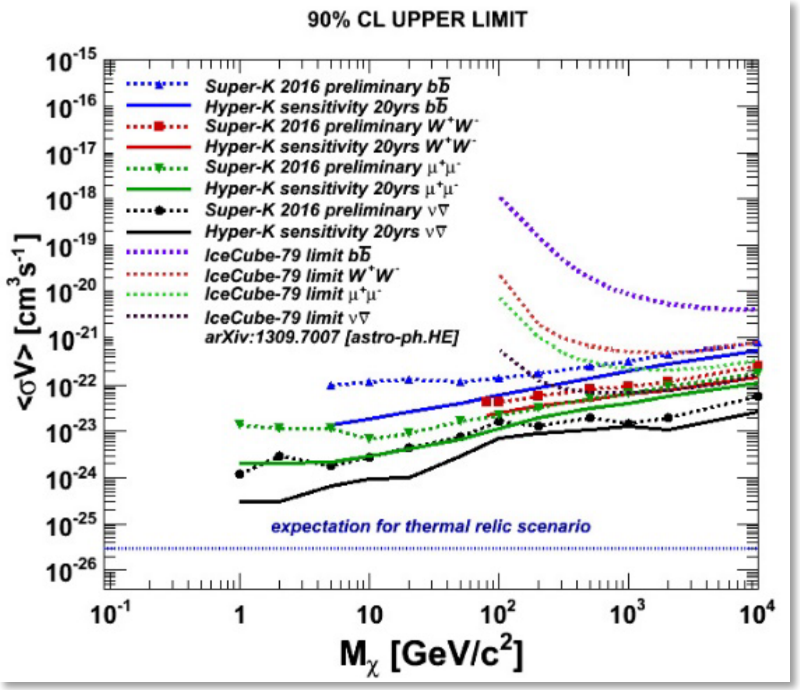
Assuming gadolinium doping

Other Astrophysical Goals

Indirect Dark Matter Detection

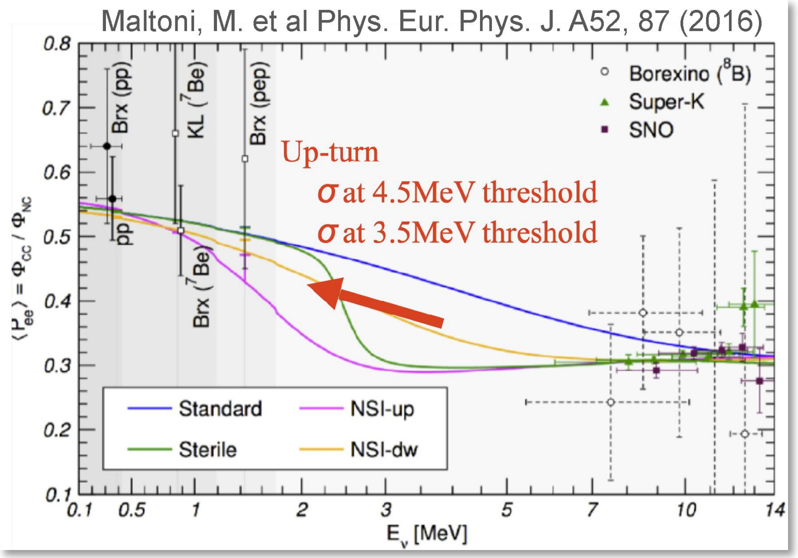
The scattering of DM on the nuclei present in the Sun/Earth leads to their gravitational capture. The equilibrium is then expected to be set between their capture and annihilation rate. Neutrinos, as one of the annihilation products, can escape the dense matter region of the core and could be detected using neutrino telescopes.

Sensitive to DM masses from ~1 GeV to ~10 TeV



Solar neutrinos

By detecting ~130 ν/day can study with great statistics the B^8 spectrum and measure day/night effects.
Potential to detect neutrinos from the hep reaction for the first time.



Low energy ν bursts

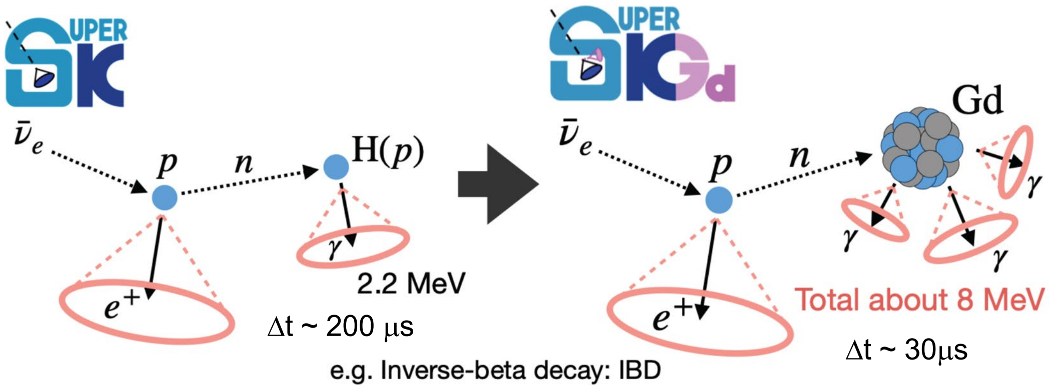
Produced f.i. by neutron star mergings in our Galaxy, solar flares, magnetars, pulsar wind nebulae, active galactic nuclei, gamma ray bursts ...

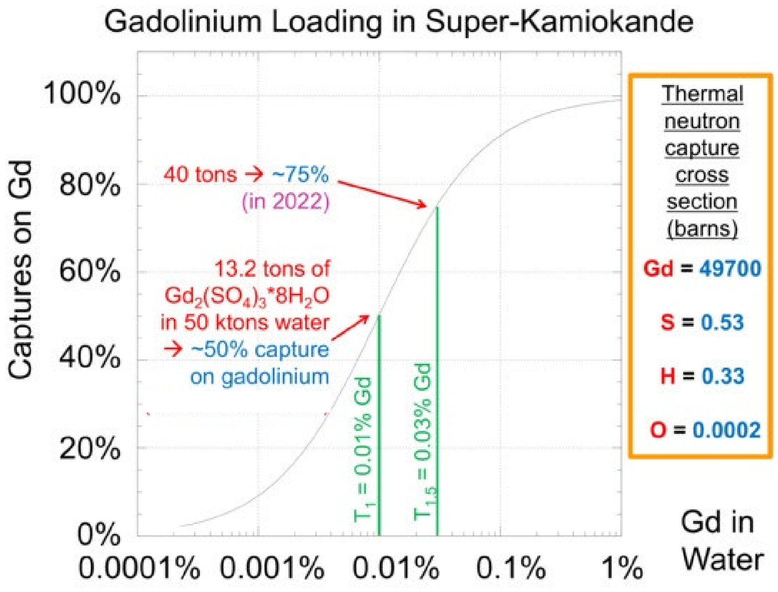
Gadolinium loading

Super-K so far has loaded the water with a 0.03% fraction of Gadolinium (in a sulphate salt)

While HK will not contain gadolinium on Day 1, it is assumed that gadolinium will very likely be added to the new detector eventually, such that all proposed HK detector components and materials must be certified to be compatible with extended immersion in Gd-loaded water.

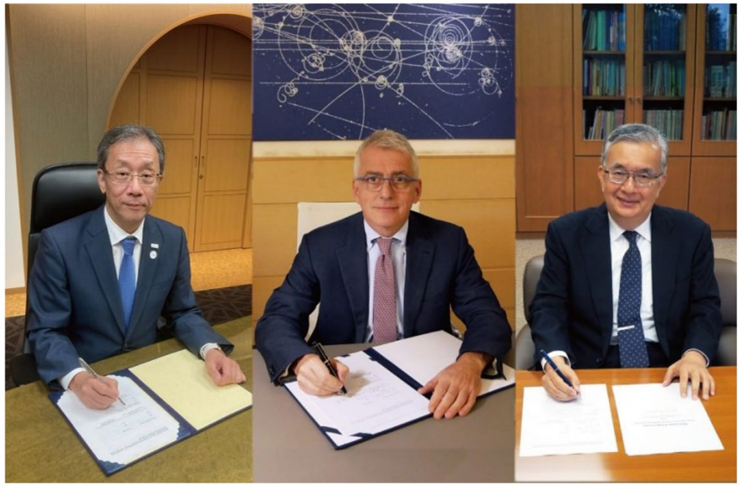
- Detect for the first time Diffuse Supernova Neutrino Background (DSNB)
- Improvement of supernova direction pointing accuracy and allowing pre-supernova neutrino detection (early warning for SN).
- Enhance ν and $\bar{\nu}$ identification in atmospheric and beam oscillation analyses
- Reduce background in nucleon decay searches



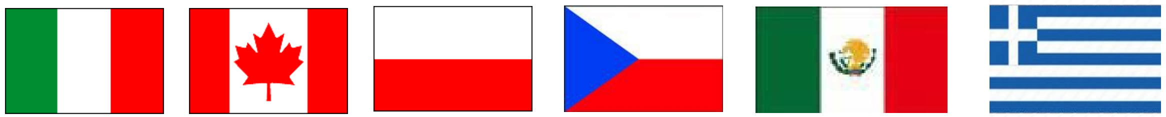
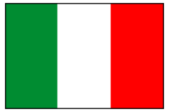
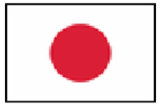


Italian contributions in Hyper-K

The Italian National Institute for Nuclear Physics (INFN) , KEK and UTokyo Sign MoU to Promote Hyper-Kamiokande Project



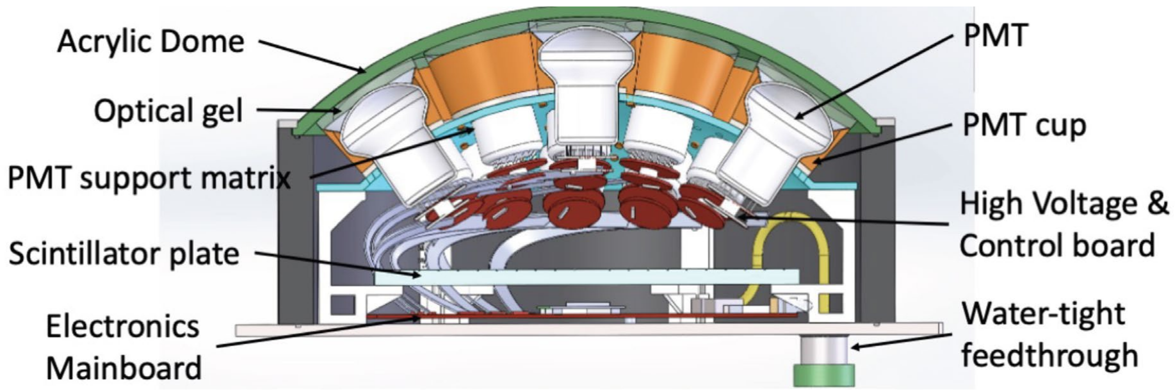
UTokyo President Fujii (left), INFN President Zoccoli (center) and KEK Director General Yamauchi (right) signing the MoU respectively

- Multi-PMT 
  - 300 mPMTs, Italy (project leader), 874 mPMTs total
- Electronics
  - 20' PMTs Front-end digitizer  + ()
  - Timing distribution (in collaboration with LPNHE and IRFU/CEA)
- Computing
  - ~25% computing power of Hyper-K 2022-26 at CNAF, collaborative tools, analysis tools
- Near Detector
  - In construction: two new TPCs for the near detector upgrade of T2K (will be part of the near detector of Hyper-K)

Multi PMTs (mPMTs)

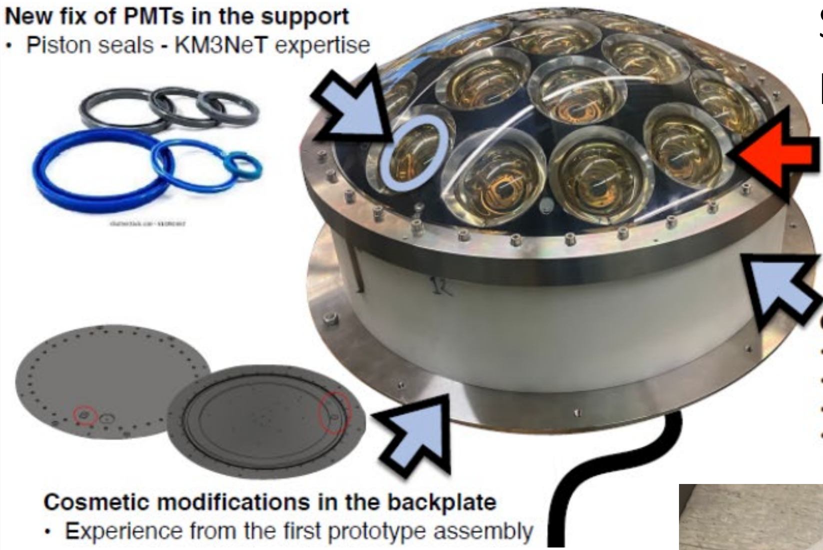
- Original design, derived from KM3NeT
- Proposed by INFN, which leads the project (with Poland, Canada, Mexico, Czech rep.)
- HK INFN R&D since 2015 (~200k€)
- Flagship of the Italian participation to the far detector, together with the front-end electronics
- 19 3" PMTs per mPMT
- 800 mPMT in the Inner Detector
- They will also equip the IWCD (400 units)
- Provide complementary information to the 20” PMTs.
- Reduce calibration and energy scale systematics
- Electronics also designed by INFN

	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



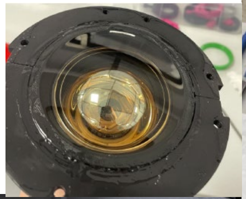
Tendering process started in Italy and Poland
Production chain: tested at INFN-Na
Tests of mPMTs in water at CERN: April this year
Mass production: 2024-25
Installation in Hyper-K: 2026

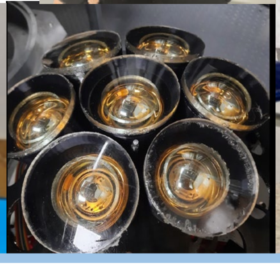
Prototypes construction in Canada, Italy, Poland



Several mPMT prototypes assembled

QC tools and procedures in preparation

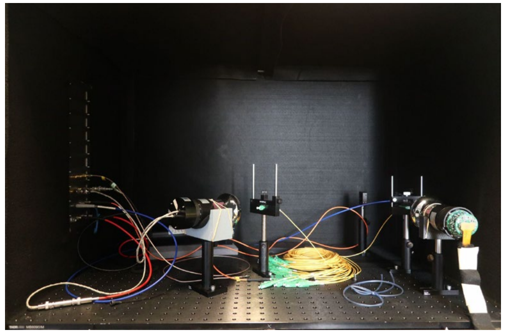


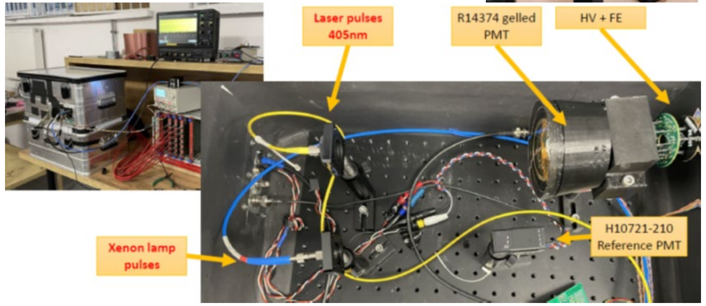


Photomultiplier test station in Poland, Canada and Czech

Preparation for testing station and procedures for testing during mass production ongoing

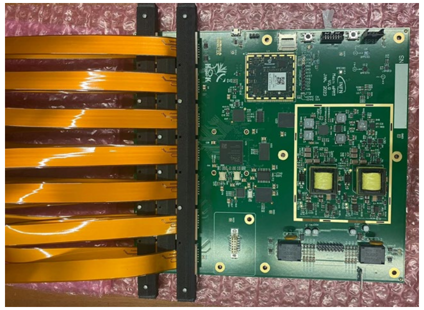
Test station during construction planned in Czech





Electronics test station in Italy

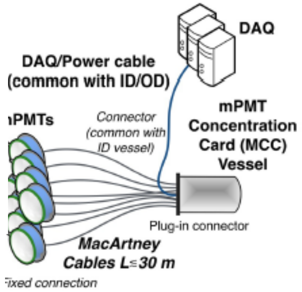
Preparation for testing station and procedures for testing during mass production ongoing

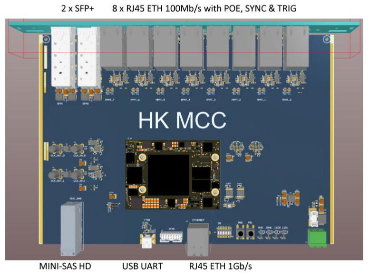


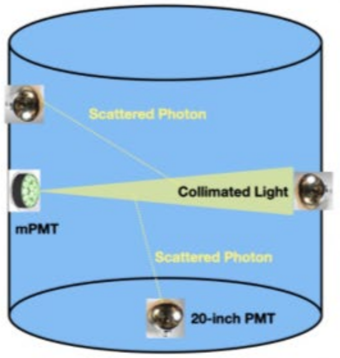
Test station during construction planned in Italy

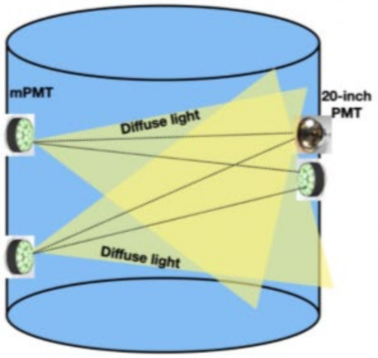
HV Automatic test bench

MCC Electronics in Poland and MCC Vessel in Czech



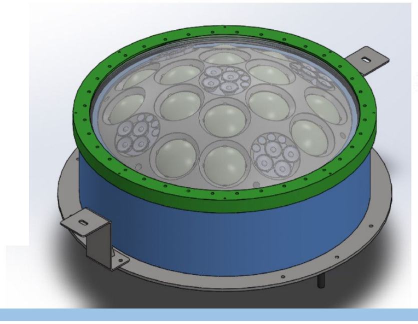






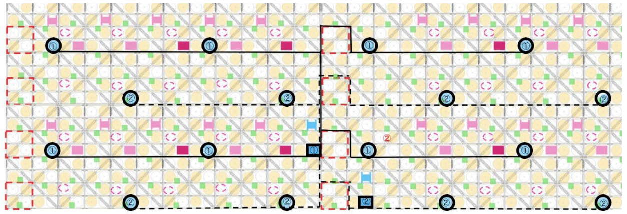
- 200 LED mPMTs
  - grid of 10m spacing
- Collimated light
  - water scattering/ absorption
    - Time of flight to identify the scattering position
  - Reflection measurement
- Wide-angle light
  - PMT angular response
  - timing select direct light

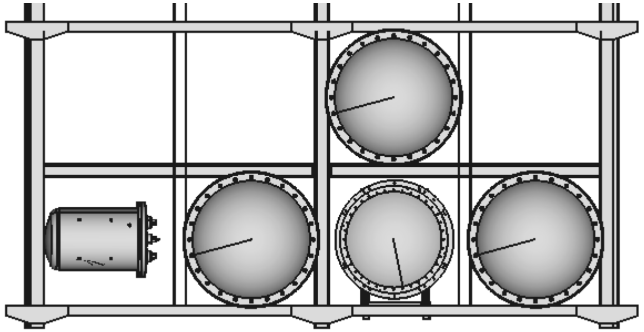
LED-focused mPMTs in Canada

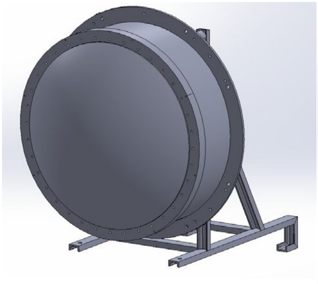


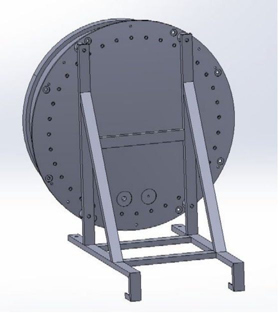
mPMT installation studies in Czech, Italy, Mexico

Mechanics for installation in the frame and cabling
Studies fot Installation Check
Quality and Signal Check









mPMT Packaging and Transportation Tests in Mexico

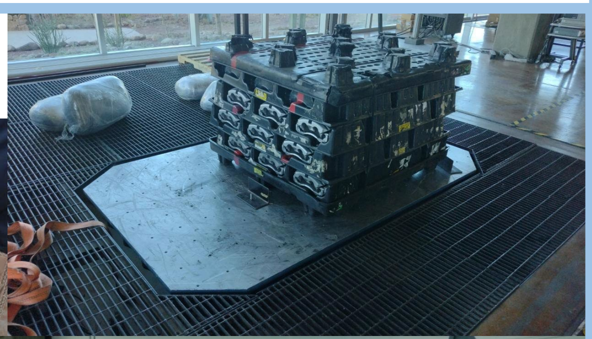
Studies on packaging

- Design consider mPMT cable and opening for in-box testing of the mPMT
- Optimization studies ongoing for cost reduction

Studies for transportation

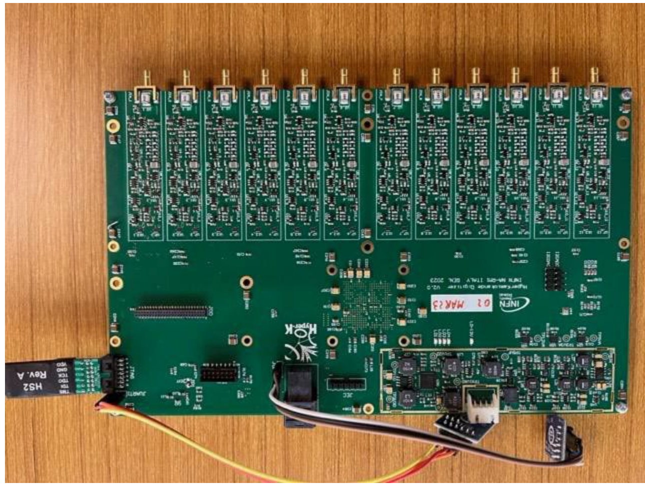
- Compression test to evaluate that the box is capable of withstanding the stowage
- Shock (drops) test
- Vibration tests: frequency based on transport frequencies
- Inclined impact test

First packing prototype built!

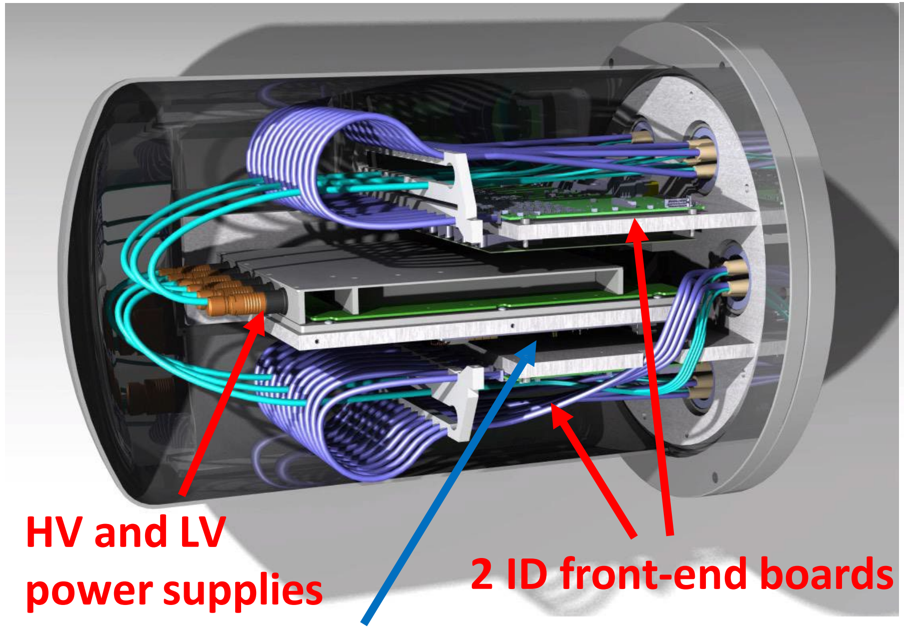


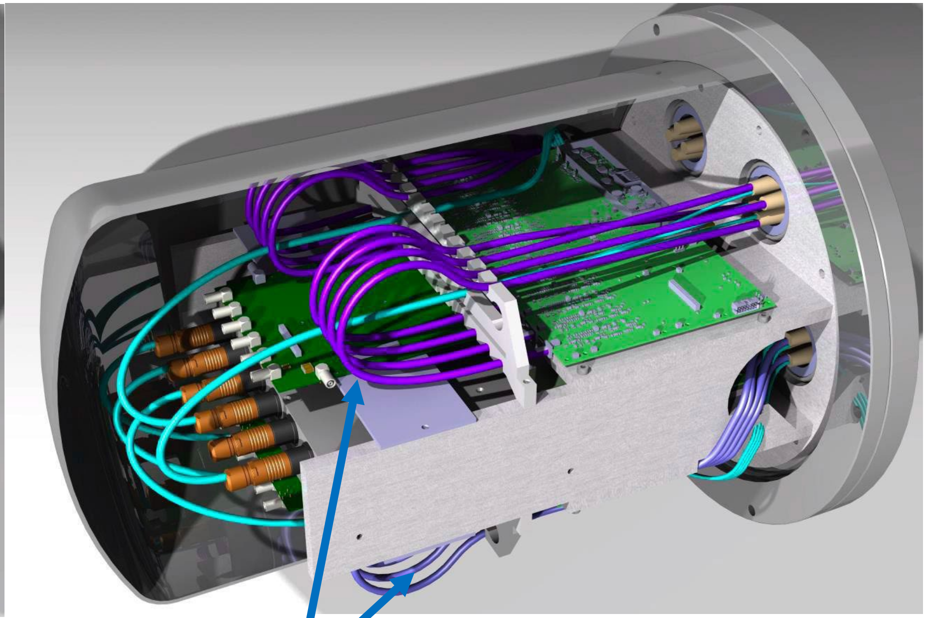
Hyper-K Electronics

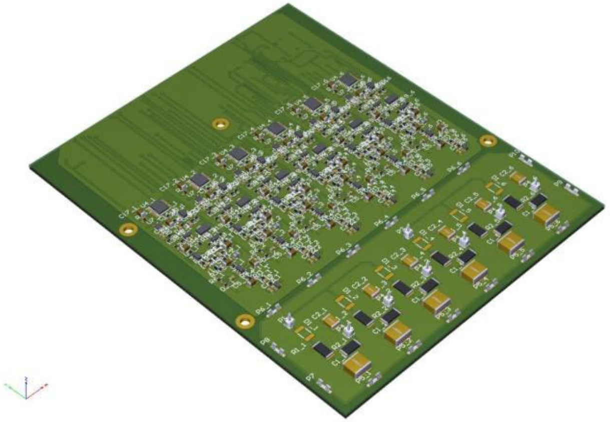
- Front-end electronics placed in underwater vessels
- Two types of underwater electronics vessels
  - Inner detector vessels: 24 ID channels read out by two PCBs
  - Hybrid outer + inner detector vessels: 20 ID + 12 OD channels



ID 12-channel front-end board



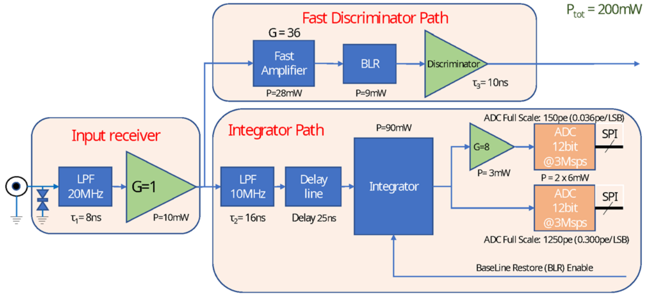




OD 6-channel FE board

20" PMTs Frontend Electronics

- 3 competing designs originally proposed by INFN, Japan and France
- INFN discrete components design selected: performance, flexibility & fast prototyping cycle
- Measuring Charge, Timing and ToT (Time over Threshold), allowing detection of the pre or late pulses of the PMT.
- Self triggering at max 2MHz (charge) at 1/6 pe
- Dynamic range up to 1250 pe
- Power consumption is 4.7W/12ch, 390mW/ch
- Collaboration with Japan on the onboard calibration card

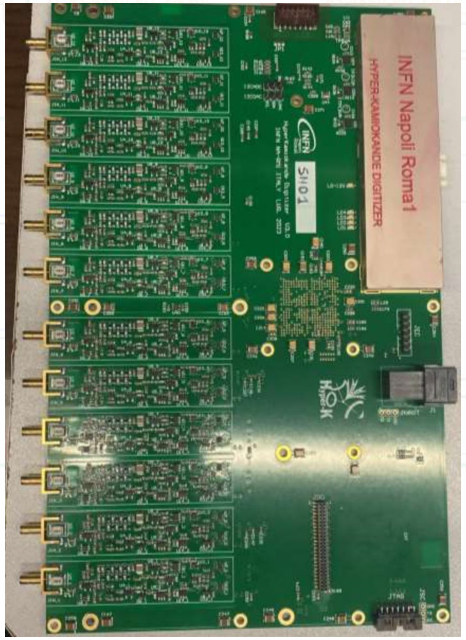


Critical components reviewed and procurement and tendering started in 2023

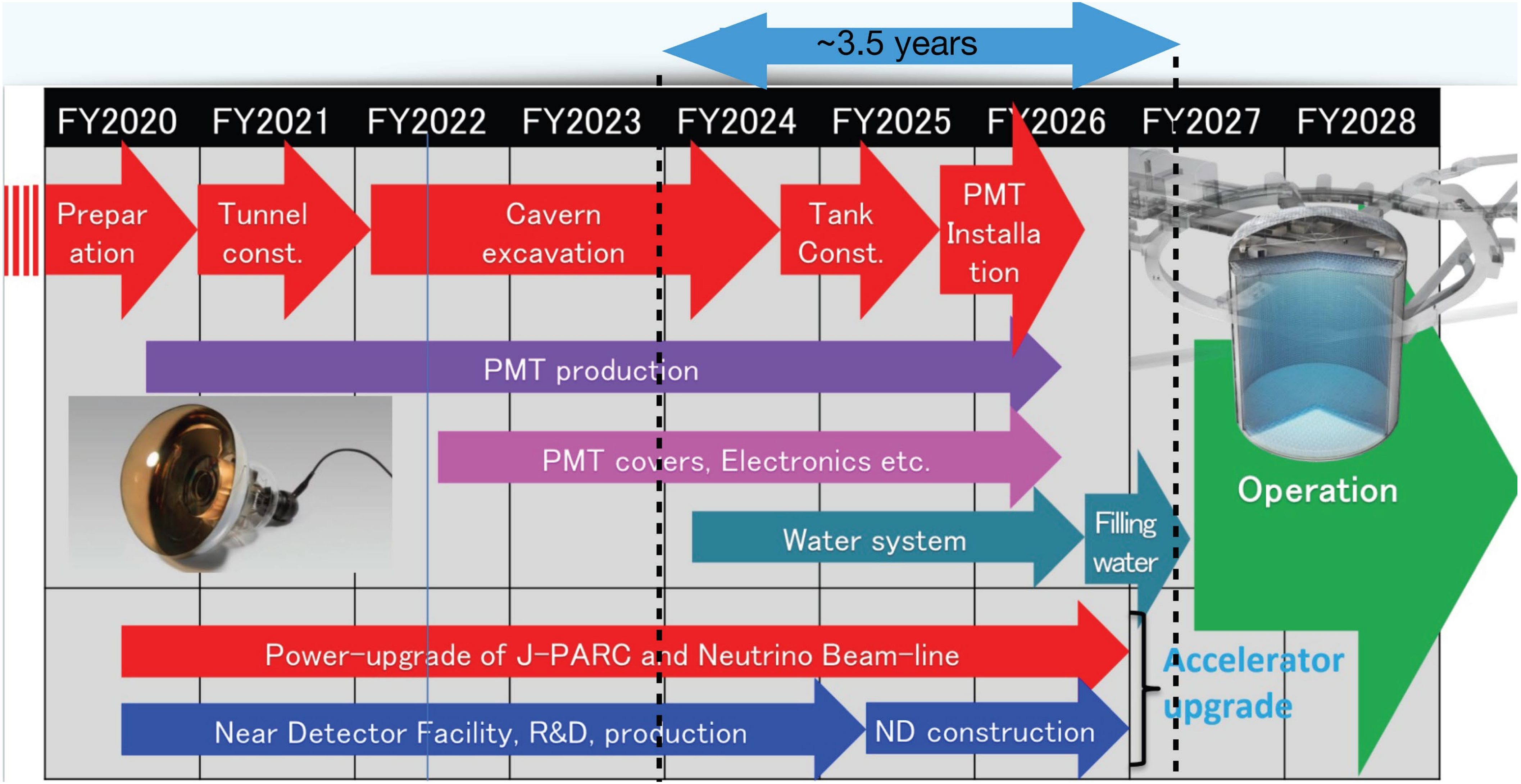
Final prototype early 2024

The tender for the board production will start early 2024

Start mass production by the end of 2024



Hyper-K timetable

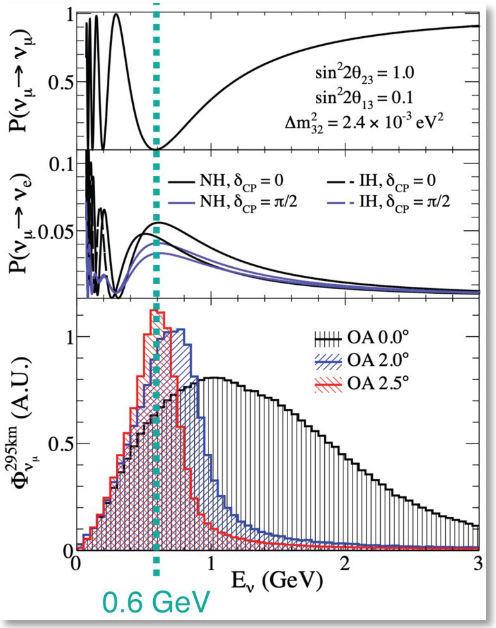


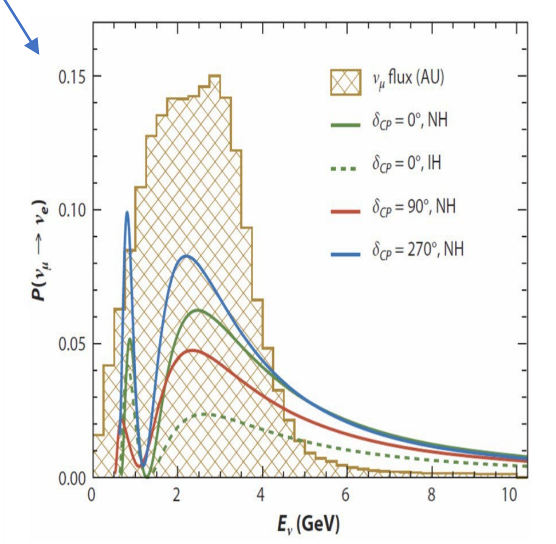
About the complementarity of Hyper-K and DUNE

Discussed the first time by the ICFA Neutrino Panel: arXiv:1501.03918

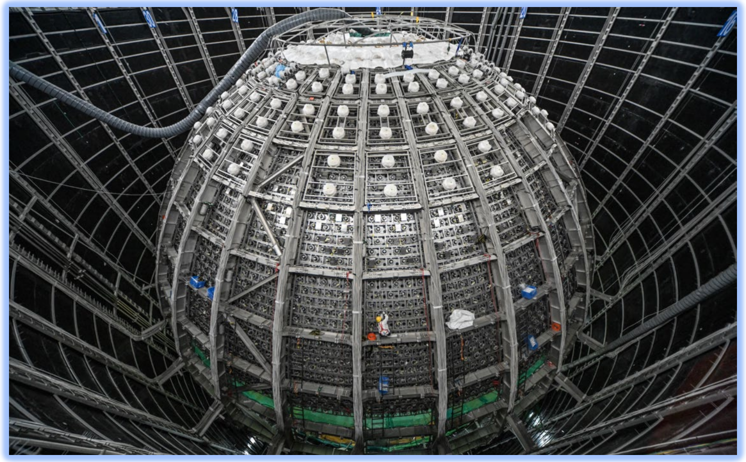
To make the most of complementarity, it would be necessary to form and support a joint working group. After the very positive experience of the T2K-NOvA combined analysis.

- Same L/E but the baselines, L, and energies, E, differ by almost a factor of 5.
- Hyper-K is off-axis, with a narrow neutrino spectrum optimized to the first oscillation maximum
- DUNE is on-axis with a wide spectrum that can cover the second oscillation maximum and with a tail above the tau production threshold
- The differing degree to which the matter effect modifies the oscillation probabilities at Hyper-K and DUNE may be exploited to break parameter degeneracies
- To fully understand the mechanisms of supernova explosion requires accurate measurements of the ν_e and $\bar{\nu}_e$ fluxes, along with some neutral current data (which is sensitive to the flux of $\nu_{\mu,\tau}$). These measurements can not be made with Hyper-K or DUNE alone (and also JUNO contribution is important).





Conclusions



JUNO

DUNE

Hyper-K

The outstanding achievements of neutrino physics in the past 25 years will allow exciting new neutrino physics for the next 25 (at minimum)

Both guaranteed signals and new physics searches will be performed

With a great complementarity between JUNO, DUNE and Hyper-K

Not discussed in this talk: atmospheric and astrophysical neutrinos from IceCube (Gen2) and KM3NeT will play an interesting role.

The gigantic 3-liquids far detectors are the ultimate observatories for low-energy neutrino astronomy