Istituto Nazionale di Fisica Nucleare
Piano Triennale 2025 | 2027
LECCE

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Next Generation Neutrino Oscillation Experiments

INFN

Outline of the talk

Introduction
- The physics case of Neutrino Oscillations
- What happened in the recent past

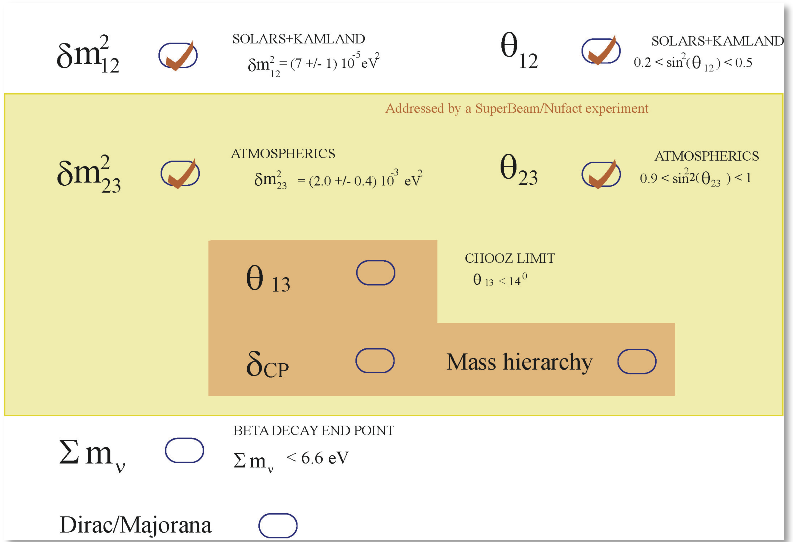
Next generation experiments (with a focus on INFN activities)
- JUNO
- KM3NeT
- Hyper-Kamiokande
- DUNE

Sterile Neutrinos
- ICARUS

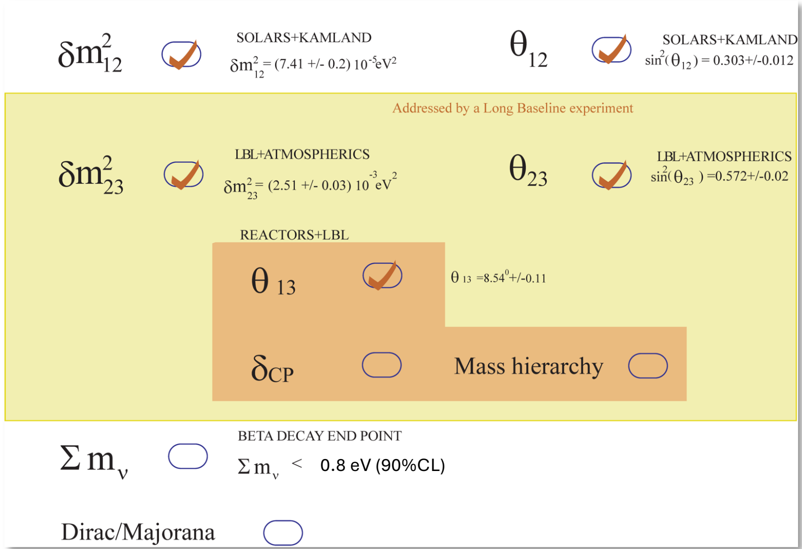
I'm in debt with G. Collazuol, R. Coniglione, G. Cuttone, G. DeRosa, M. Grassi, A. Guglielmi, E. Lisi, A. Longhin, L. Ludovici, L. Patrizii, G. Ranucci, M. Spurio, L. Stanco, C. Touramanis for the material and useful discussions.

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, which are among the priorities in hep in many countries (Italy included)?
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

... from the photo album.

M. Koshiba at Neutrino Telescopes 1988

Ray Davis with Milla Baldo Ceolin at
Neutrino Telescopes 1990

Why neutrino oscillations matter

Neutrino oscillations → 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**

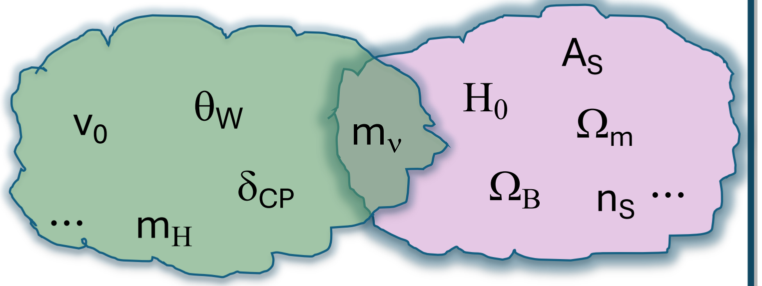
- Absence of right-handed neutrinos → **no Dirac mass for neutrinos**
- Lepton number is an accidental symmetry at the renormalizable level → given SM fields and gauge symmetry, lepton number cannot be violated at dimension 4 → **no Majorana mass can be generated**

New physics is required to give mass to neutrinos

- The only parameter measurable both by hep and cosmology
- **A crucial test of consistency**

Standard model of particle physics

Standard model of cosmology



But ...

Cosmology measures $\sum_i m_i$

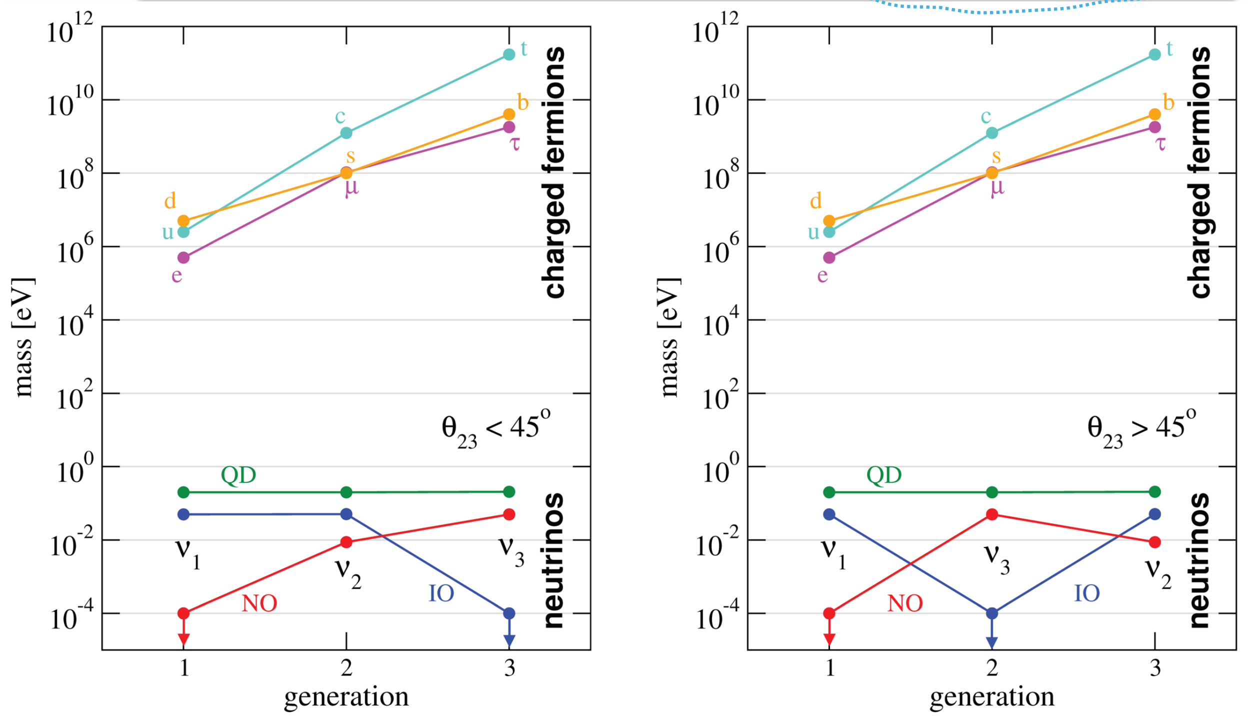
Double beta decay measures $\left|\sum_i U_{ei}^2 m_i\right|$

Direct searches measure $\left(\sum_i |U_{ei}^2| m_i^2\right)^{\frac{1}{2}}$

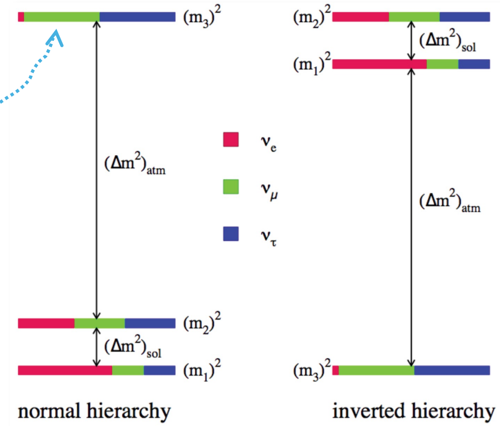
To **single out** individual neutrino masses you need to measure neutrino mass ordering.

What ν oscillations still have to say about ν masses

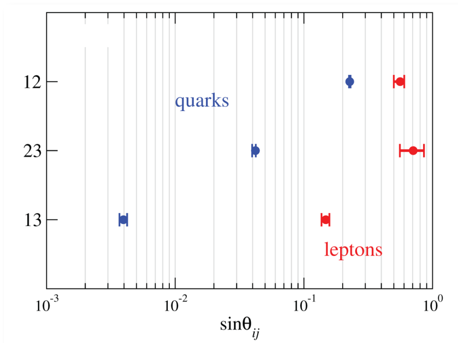
Neutrino oscillations cannot measure absolute neutrino masses, but can determine their pattern by measuring neutrino mass ordering (NMO) and the octant of θ_{23} (which decides if ν_3 is mostly ν_μ or ν_τ)



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)

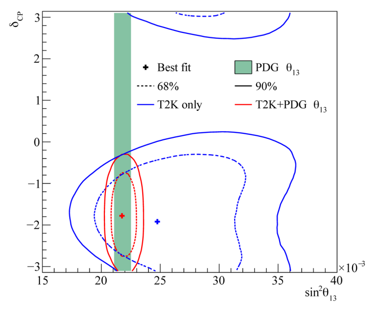


The **neutrino mixing** is also very different from quarks

Why θ_{13} matters

No way to decide the next generation LBL strategy without knowing the θ_{13} **value:**
A "small" θ_{13} value (÷2) would have made conventional neutrino superbeams (the same neutrino beams of the '70s + brute force) useless: need for new concepts as neutrino factories or beta beams. Neutrino mass ordering searches would have been almost impossible.

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 ν_μ ($\bar{\nu}_\mu$) 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}

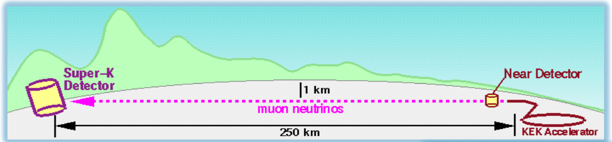
Disappearance formula

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

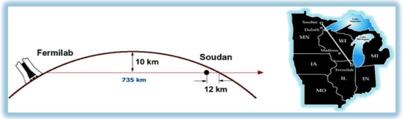
Subleading ν_e appearance formula

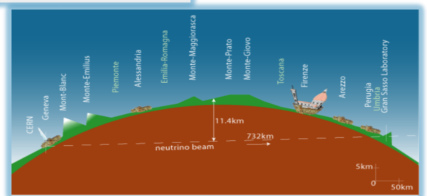
$$\begin{aligned}
p(\bar{\nu}_\mu \to \bar{\nu}_e) = {} & 4c^2_{13}s^2_{13}s^2_{23}\sin^2\frac{\Delta m^2_{13}L}{4E} \times \left[1 \pm \frac{2a}{\Delta m^2_{13}}(1-2s^2_{13})\right] && \theta_{13}\text{ driven} \\
& + 8c^2_{13}s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\frac{\Delta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

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

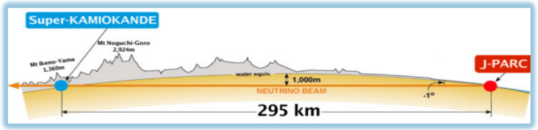


Second Generation: **Minos** in the States (ν_μ disappearance) and **Opera** at CNGS (ν_τ appearance), aimed to **improve** the Super-Kamiokande results.



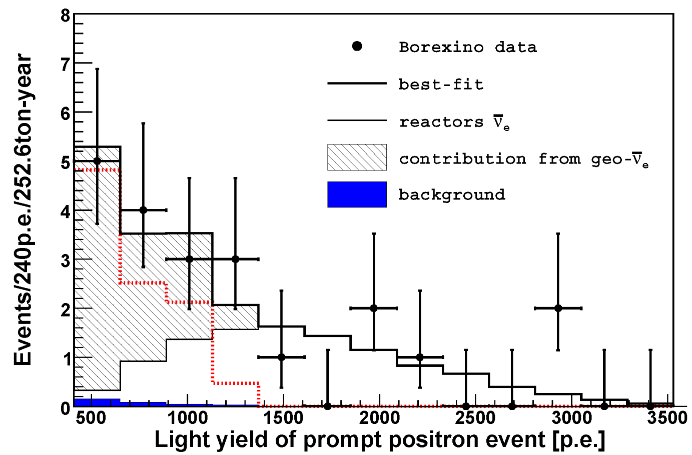


Third Generation: **T2K** in Japan and **NOvA** in the States. Sensitive to subleading processes, aimed to **measure θ_{13}** and **constrain CP violation** in the leptonic sector.



Furthermore wonderful results by Borexino

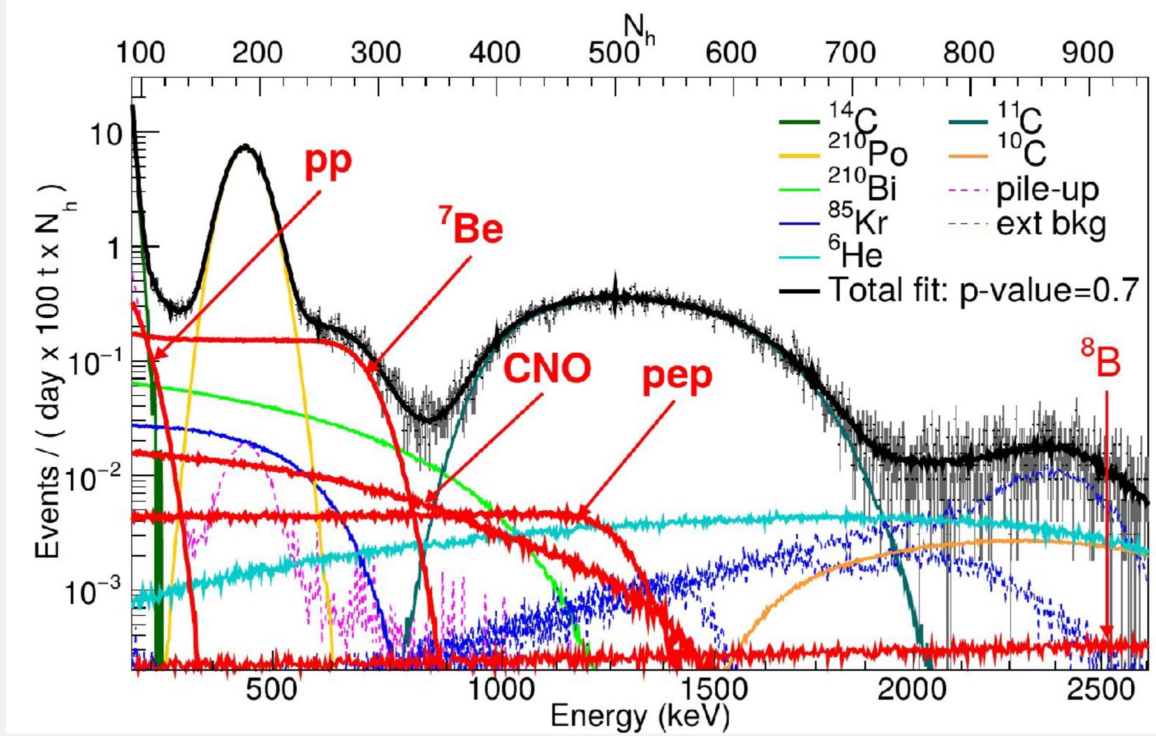
Observation of Geo Neutrinos



Solar fusion processes

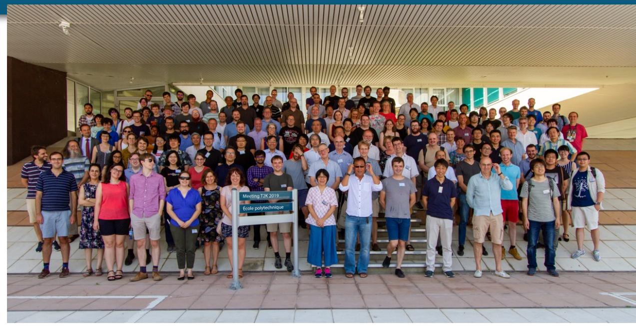
Neutrino emissions of all the solar fusion processes.

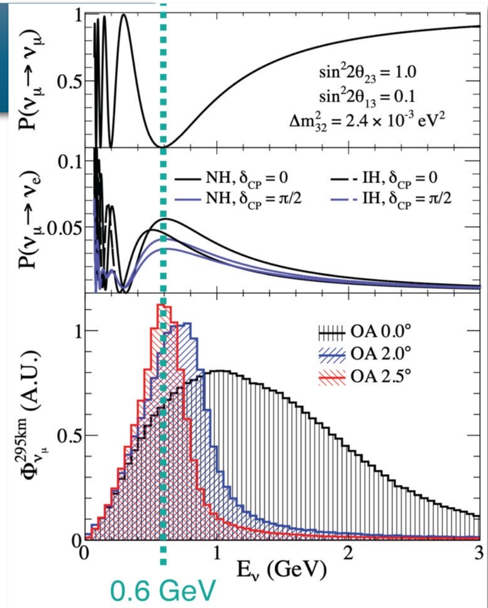
Awarded with the EPS-HEP Cocconi price, 2021

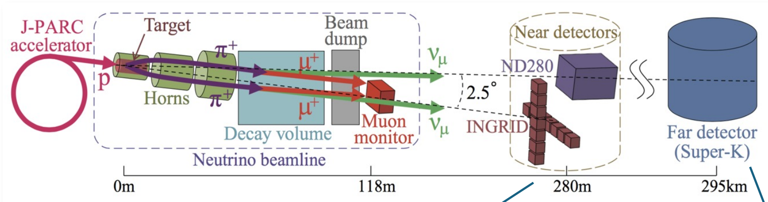


The T2K experiment

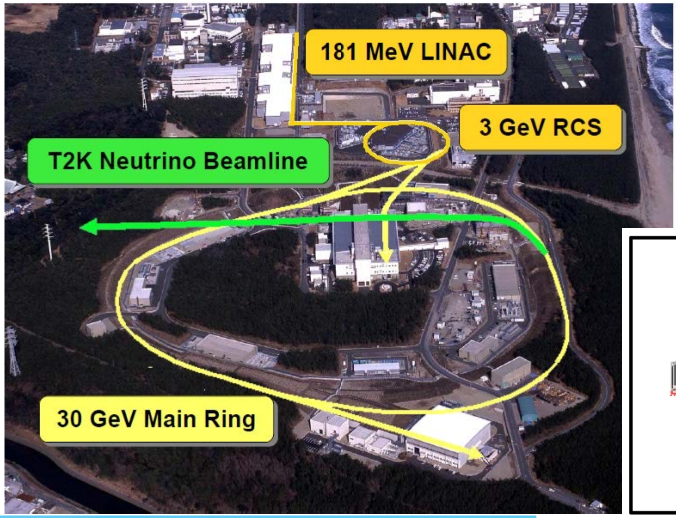
- T2K: Tokai to Kamioka (295 km baseline)
- Running since 2010
- ~575 members, 75 Institutes, 14 countries
- First indication of $\theta_{13} \neq 0$
- Precise measurements of the atmoshperic parameters θ_{23} and Δm^2_{23}
- Constrain the CP violation phase δ_{CP}
- Neutrino cross-section measurements

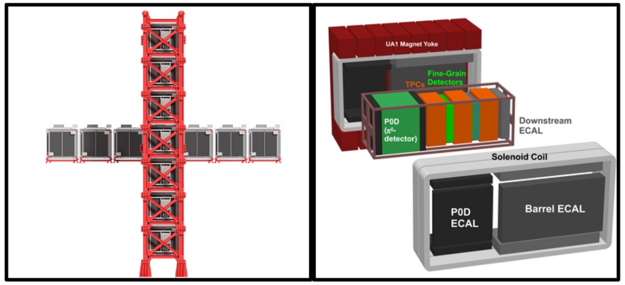


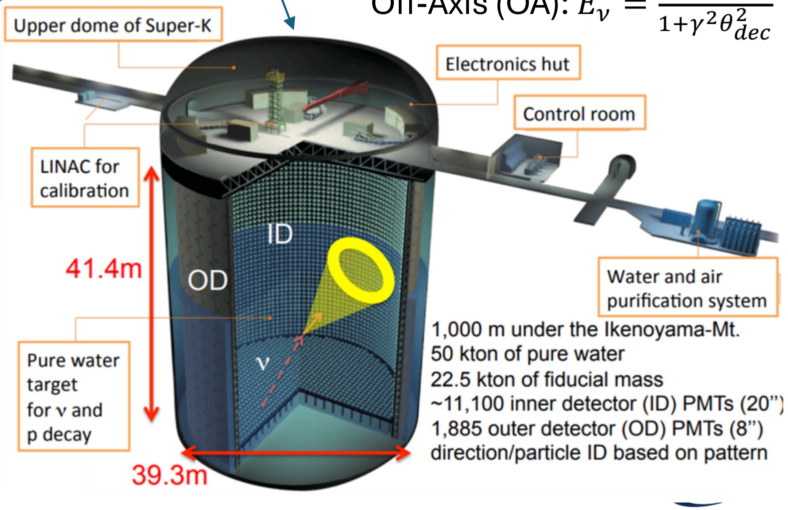


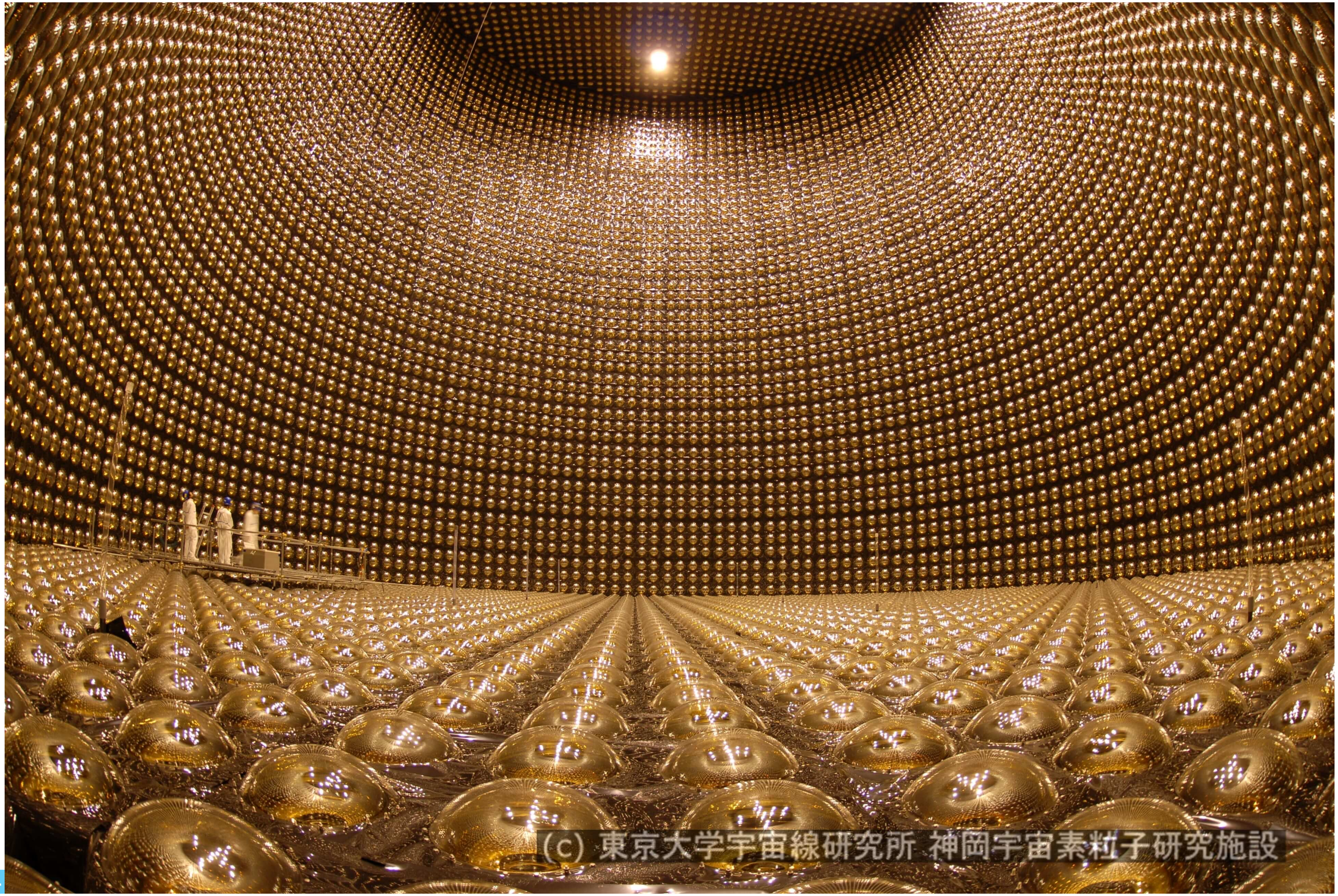


Off-Axis (OA): $E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2_{dec}}$



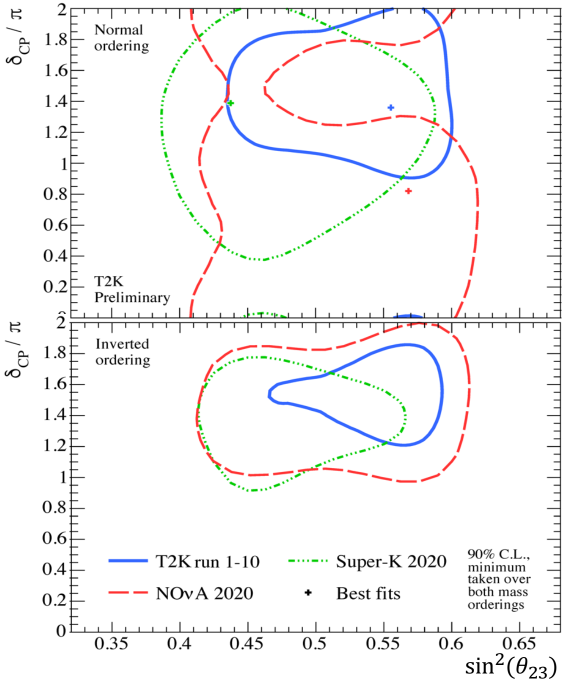





(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設

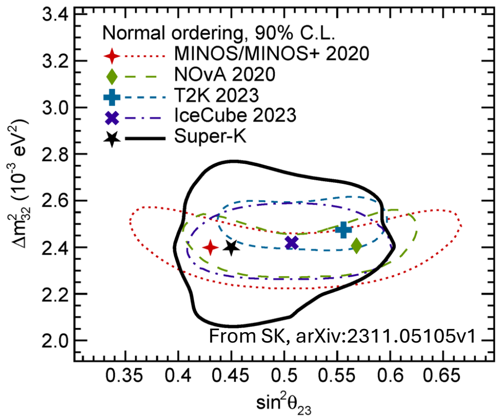
Present status of neutrino oscillations

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



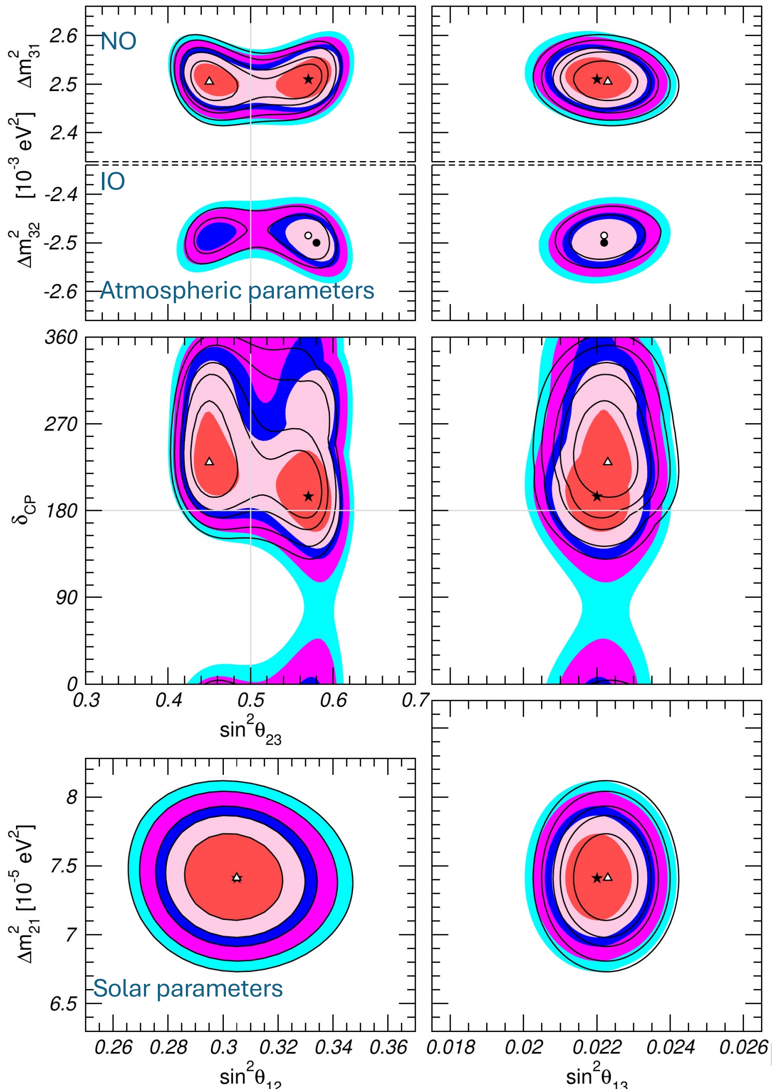
- CP conservation disfavored at slightly less than 2σ (NO) or almost 3σ (IO)
- Normal Ordering slightly preferred
- The θ_{23} octant unstable in the global fits
- Joint T2K-SK and T2K-NOvA fits just presented

Signal plots of the atmospheric parameters by different experiments.



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

NuFIT 5.2 (2022)



$\sin^2\theta_{12} = 0.307 \pm 0.013$

$\Delta m^2_{12} = (7.53 \pm 0.18)\times 10^{-5}$

$\sin^2\theta_{23} = 0.534^{+0.021}_{-0.024}$ (IO)

$\sin^2\theta_{23} = 0.547^{+0.018}_{-0.024}$ (NO)

$\Delta m^2_{23} = (-2.519 \pm 0.033)\times 10^{-3}\ \mathrm{eV}^2$ (IO)

$\Delta m^2_{23} = (2.437 \pm 0.033)\times 10^{-3}\ \mathrm{eV}^2$ (NO)

$\sin^2\theta_{13} = (2.20 \pm 0.07)\times 10^{-2}$

$\delta_{CP} = 1.23 \pm 0.21\ \pi$ rad

PDG 2023

Main goals of next gen experiments

CP violation: 5σ sensitivity for the widest possible range ($\geq 50\%$) of δ_{CP} values

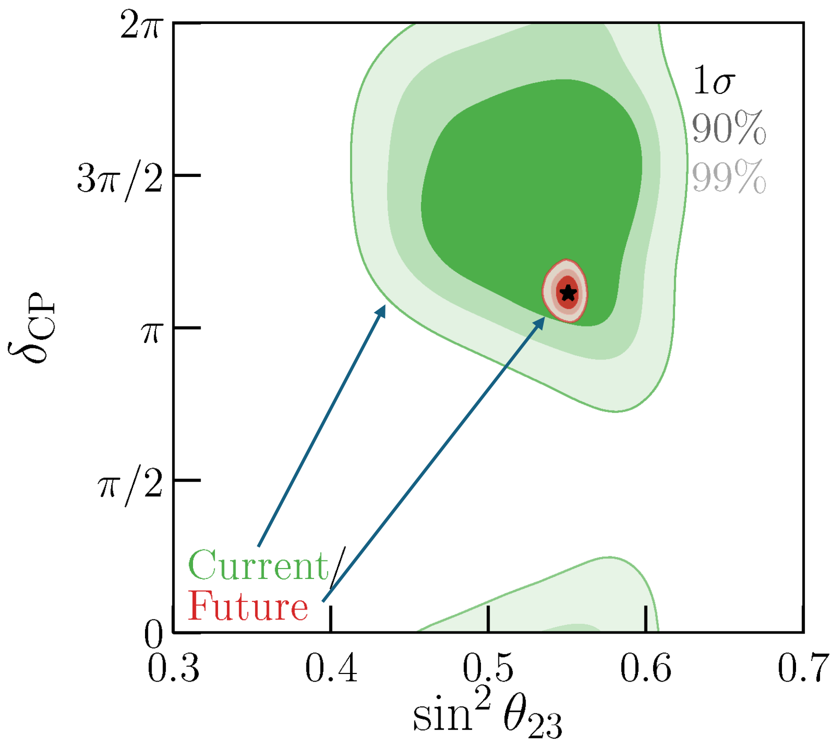
Mass Ordering: decide between Normal and Inverted Ordering at 5σ

Precision physics/Exotics (next slide)

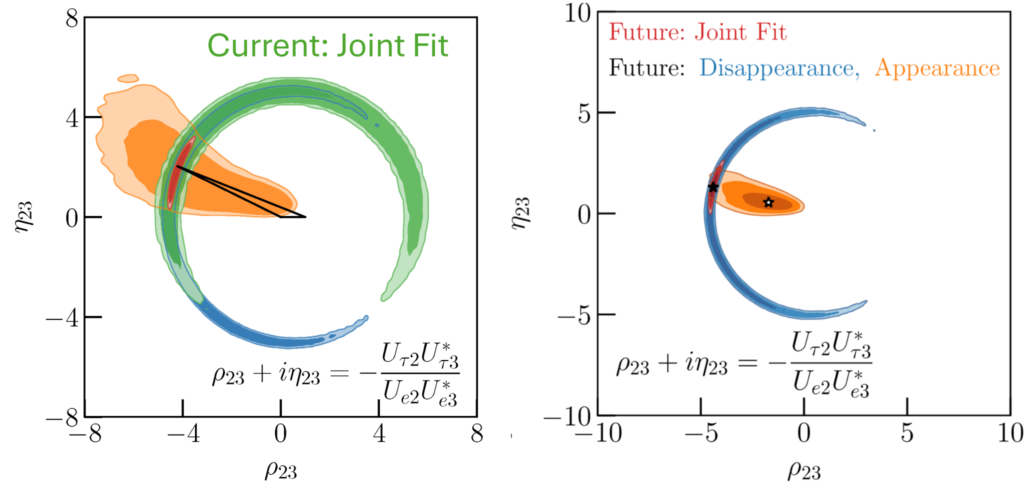
Astrophysics: the gigantic far detectors are excellent observatories for rare decays and astrophysical measurements

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 as true value 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, China, $\bar{\nu}_e$ disappearance at reactors, 53 km baseline.

Liquid Scintillator Detectors

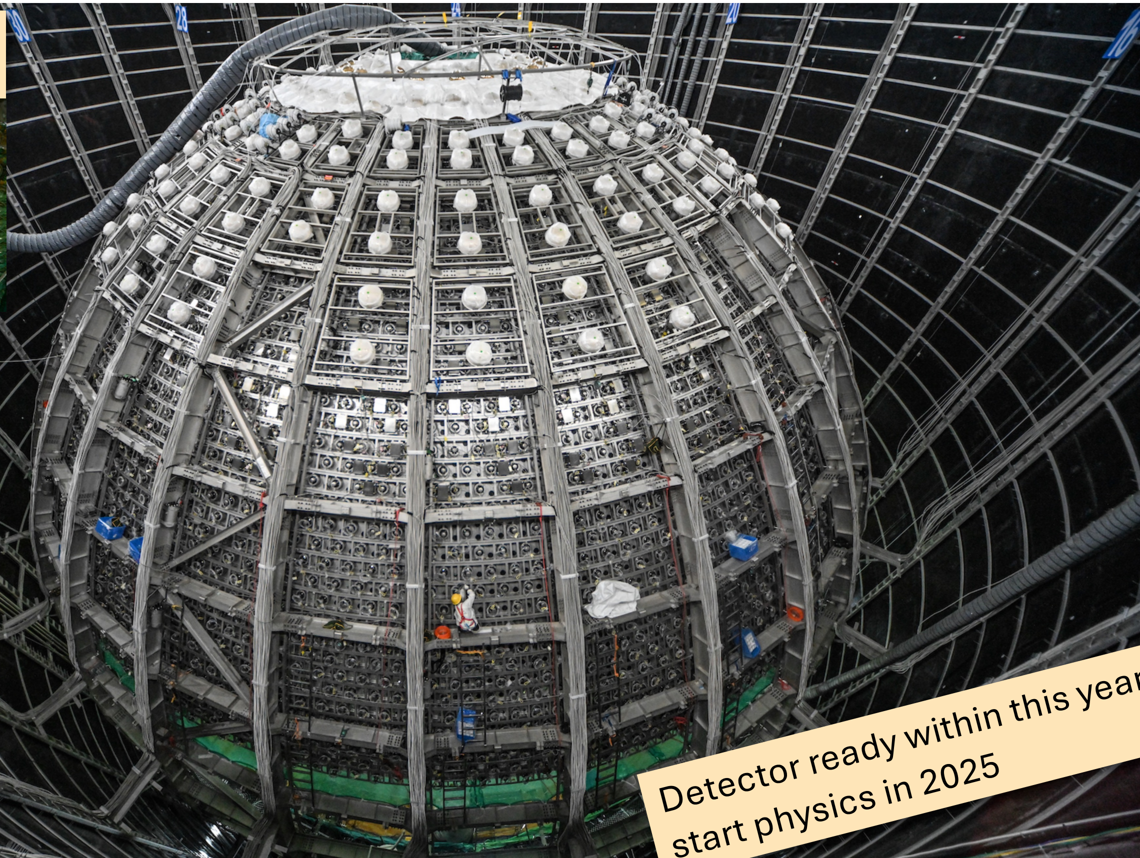
	Target mass	Energy resolution (σ)
Daya Bay	20 ton	8%/√E
Borexino	300 ton	5%/√E
KamLAND	1000 ton	6%/√E
JUNO	20 000 ton	3%/√E

Photo coverage: 78%
1600 p.e./MeV

74 institutes (8 INFN)
17 countries/regions
~700 collaborators

Signal rates

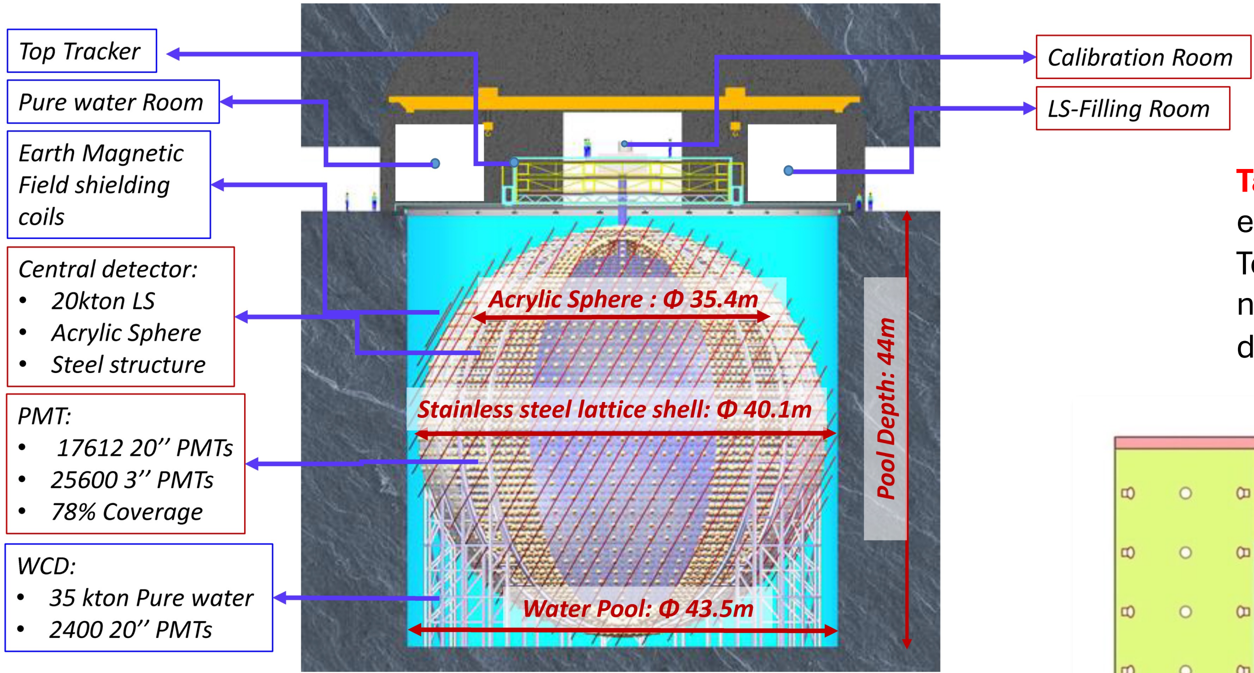
Neutrino source	Expected signal
Reactor	45 evts / day
Supernova burst	10^4 evts at 10 kpc
Diffuse supernova background	2-4 evts/ year
Sun ^{8}B (^{7}Be)	16 (490) / day
Cosmic rays	100+ / year
Earth crust & mantle	400 / year



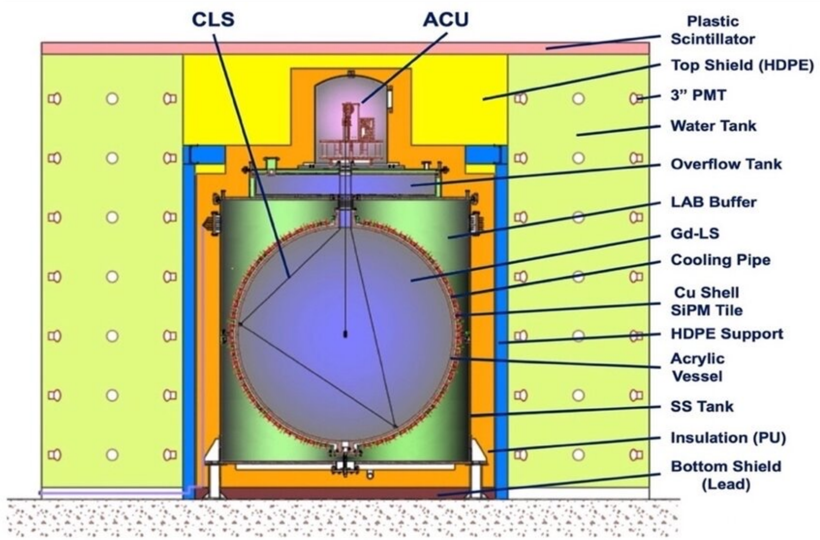
Detector ready within this year, start physics in 2025

JUNO far and close detectors

Far Detector

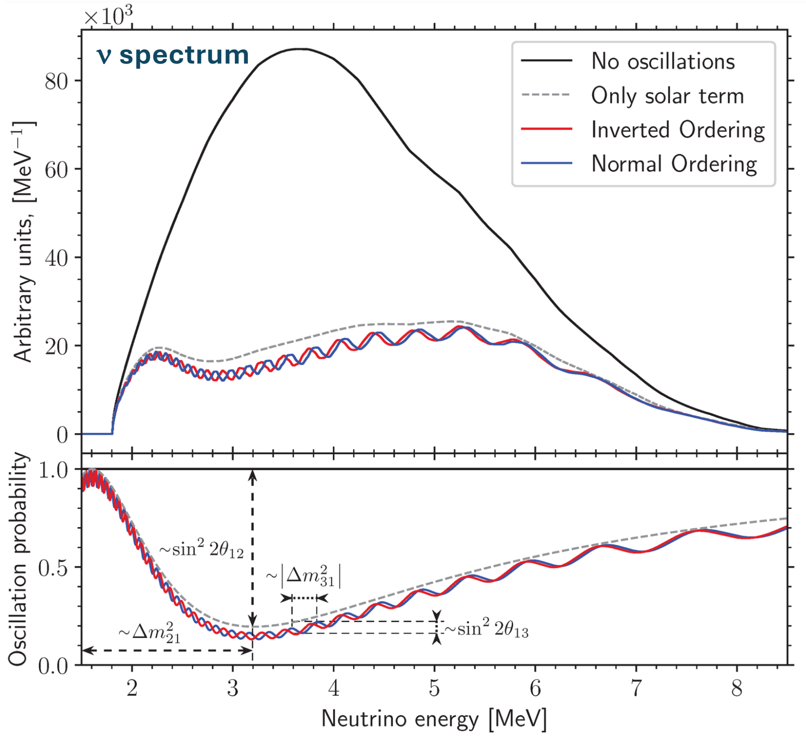


Taishan Antineutrino Observatory (TAO): a high energy resolution LS detector at **30m** from the core. To measure the fine structure of the reactor neutrino spectrum, and eliminate the model dependence of JUNO NMO determination.

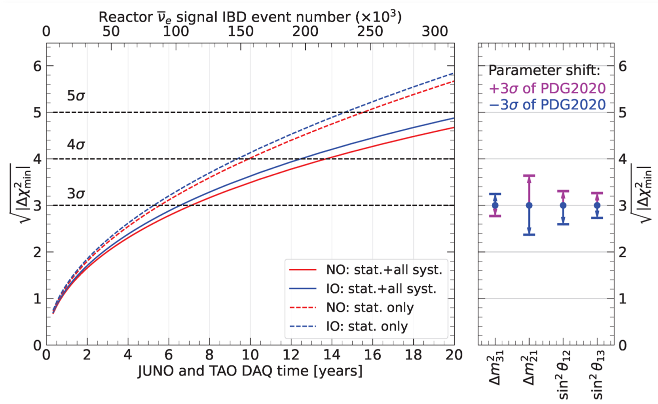


Detect for the first time solar and atmospheric oscillation modes simultaneously

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



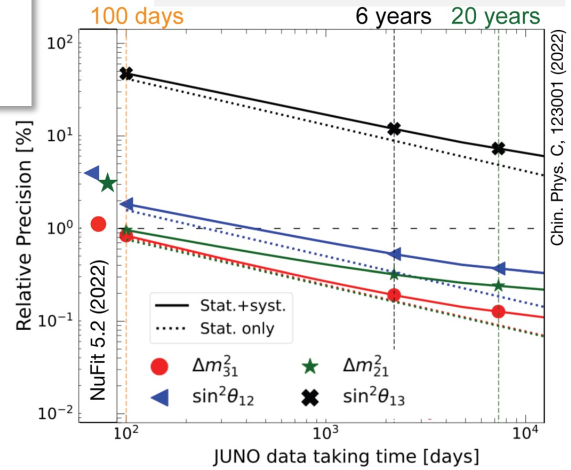
Sensitivity to NMO vs DAQ time



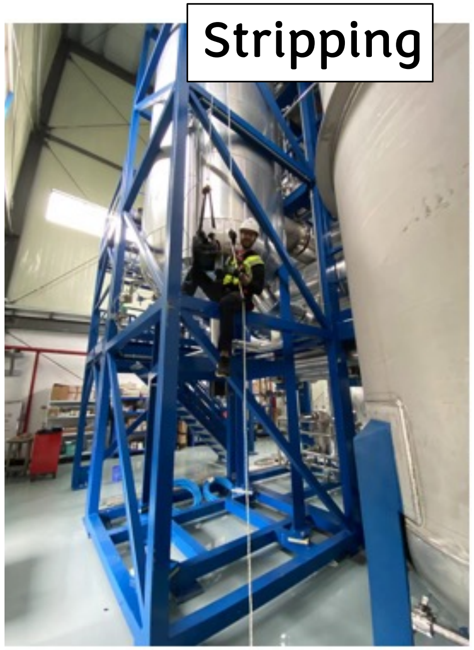
To measure NMO: decide if the oscillation pattern corresponds to the blue or to the red curve. Requires high statistics and extreme control of the energy scale.
Expected **3σ sensitivity in 7.1 years**.

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

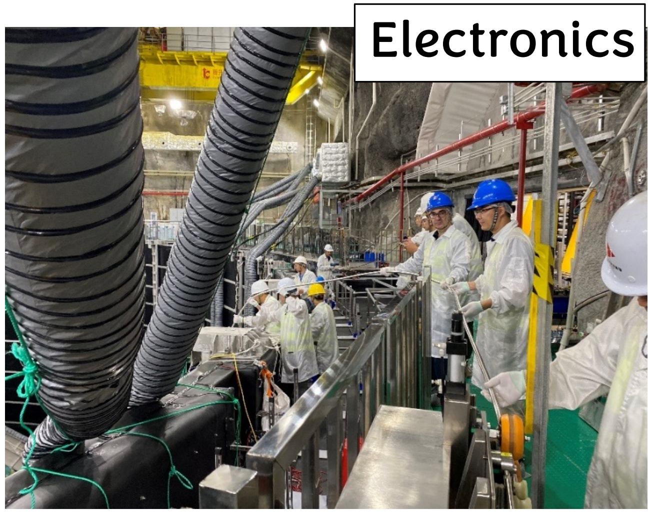
… whose accuracy will exceed present values



INFN contributions to JUNO I



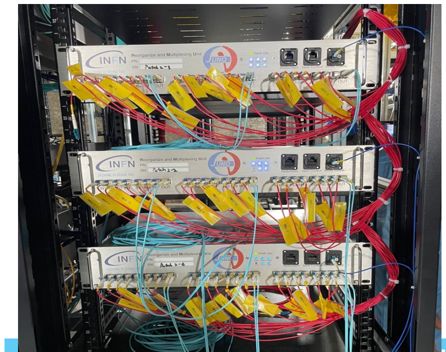
Distillation (for heavy impurities) and **stripping** (for gaseous impurities) plants for liquid scintillator purification - designed on the basis of the **Borexino** experience – built in Italy and now installed commissioned and ready for operation at the JUNO site



Global control units GCU for read-out electronics
All 7000 boards already produced, tested and assembled in the Under Water Boxes (submarine electronics) – 35% of them already mounted in the detector

INFN contributions to JUNO II

1000 read-out boards for the TOP Tracker (retrieved from **OPERA**) electronics already produced tested and delivered to the JUNO site – installation foreseen in the Fall – last item to be installed
-In addition, **80 concentrator boards** to collect their signals



Trigger units for the global trigger generation – produced, tested delivered and already assembled in the JUNO electronic room

Other JUNO involvements
-**Radioactivity control and screening** of materials - Nuclear Activation Analysis of the liquid scintillator
-**Computing** (also **CNAF**) and realization of the **DCI** Distributed Computing Interface
- **Geological modeling** for geoneutrino signal
-**Laboratory measurements** for liquid scintillator properties characterization
-Study of reactor antineutrino spectra
-Increasing effort for MC and analysis in view of data taking

Moreover for the **JUNO_TAO** near detector
-Selection and contribution to purchase and testing of the read-out **SiPM - 4000 units in total**

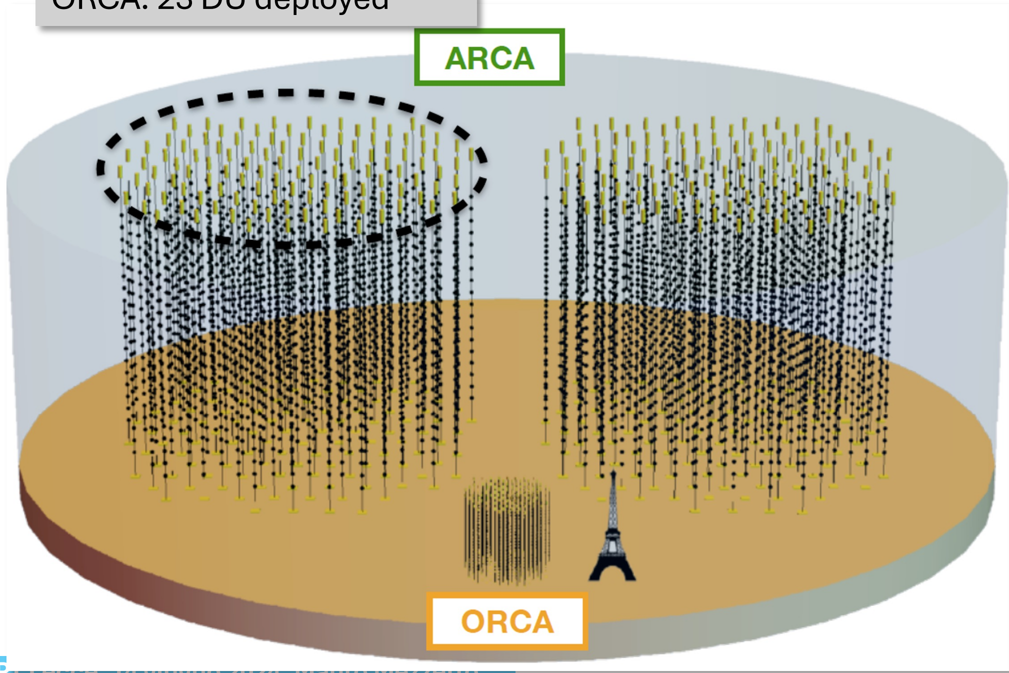
-Design of the **Front-end boards** and **ADC boards** of the related read-out electronics
-**Prototyping done** and ready for mass production

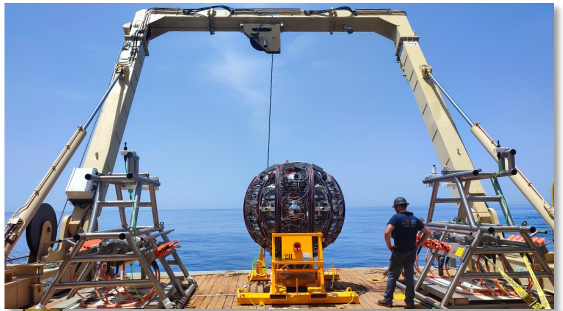
Sezioni INFN in the Collaboration :
Catania, Ferrara, Frascati, Milano, Milano Bicocca, Padova, Perugia, Roma Tre

KM3NeT

2016 and 2020 ESFRI Roadmap
KM3NeT4RR: KM3NeT for Next Generation EU (PNRR)
14 countries, 47 institutions (8 INFN), ~ 300 collaborators

Status:
ARCA: 28 DU deployed
ORCA: 23 DU deployed

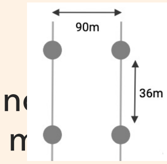




Detector Unit (DU): 18 DOMs

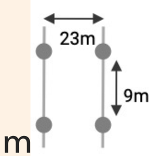
Optical Sensor (DOM): 31 PMTs (3")

ARCA (Astroparticle Research with Cosmics in the Abyss)



- Depth ~3500 m
- Two blocks of 115 DU each (130 fun
- Average distance between DU~90 m
- Vertical distance between DOMs ~36 m
- **Volume (0.5 × 2) km3**

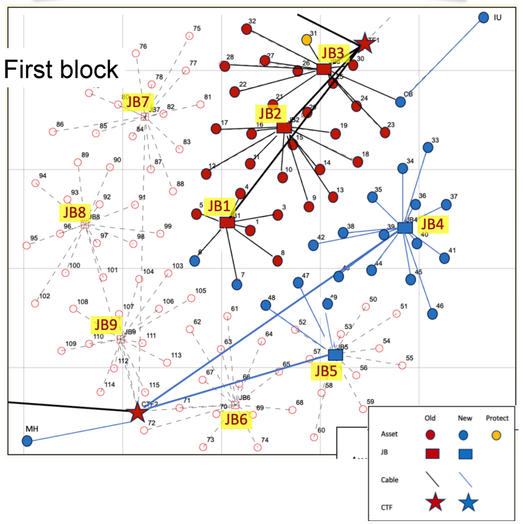
ORCA (Oscillation Research with Cosmics in the Abyss)



- Depth ~2500 m
- One block of 115 DU (50 funded)
- Average distance between DU ~20 m
- Average vertical distance btw DOMs ~9 m
- **≈8 Mton**

ARCA - status and future plans

Current status 28 DUs deployed
27 DUs taking data



Next sea campaign

September sea campaign 👉 Recover the not working DU and add ~19 DUs 👉 ~46 DUs

Funds

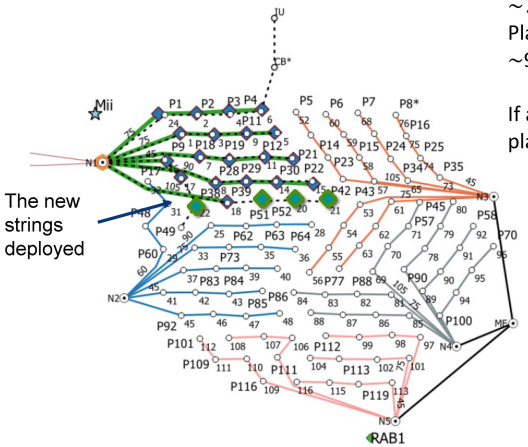
Funded already 125DUs (1 full building block + 10DUs of the second block)
New request for funds on going 👉 in total 150 DUs + sea floor infrastructure

If all the funds are available completion (230DUs) is planned for 2028

ORCA - status and future plans

Since the 4th of June 👉 23DUs deployed (added 4DUs)

Almost completed node 1 (24DUs)



Funds

Funds already available for ~50DUs
Extra internal French funds promised 👉 in total ~70DUs
Plan for a request of external funds 👉 in total ~90DUs

If all funds are available completion (115DUs) is planned for 2028

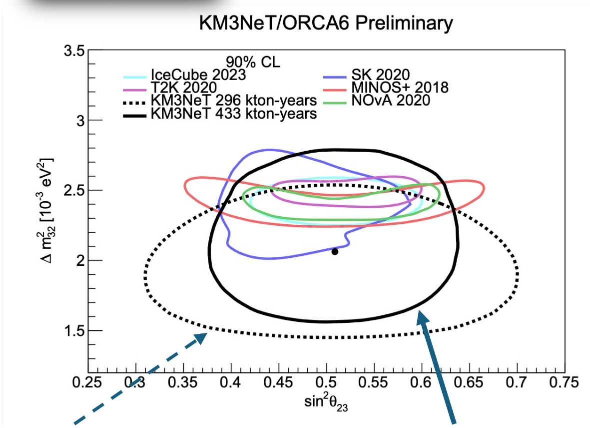
Orca sensitivity to oscillation parameters

Full Statistics

Δm^2_{32} vs $\sin^2\theta_{23}$

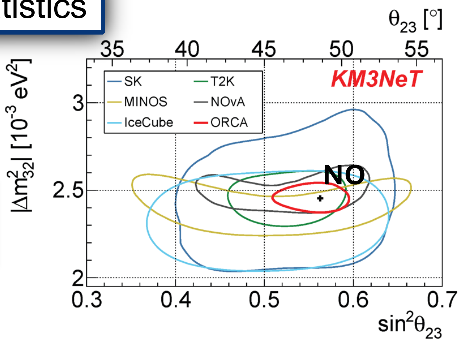
ICRC 2023
Neutel 2023

Will be updated next week @Neutrino 2024

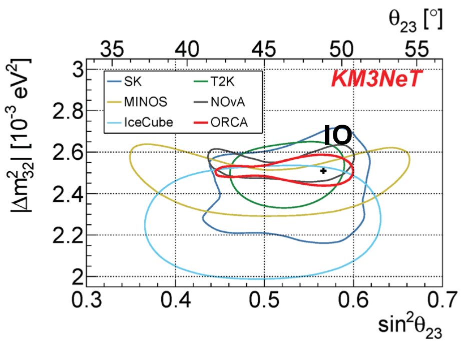


ORCA6 DUs 354days

ORCA 6 DUs 510days

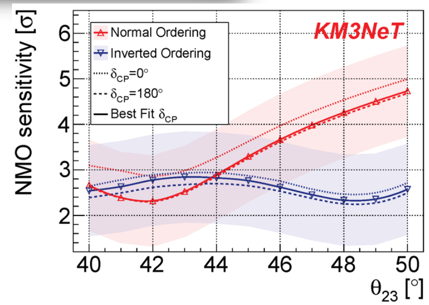


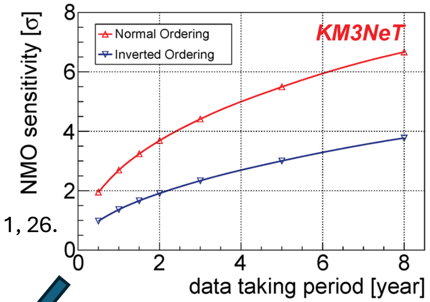
(a)



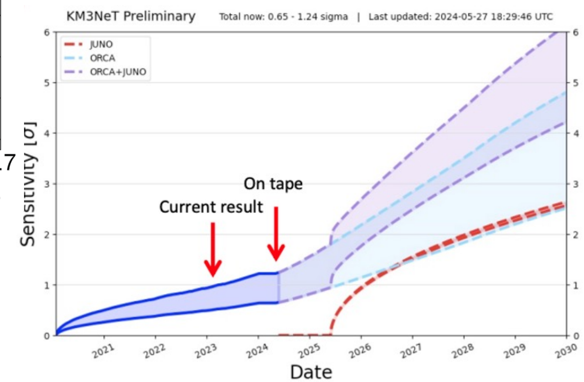
Three years of data taking. 115 DOMs. Educated guess about systematics

Neutrino mass ordering



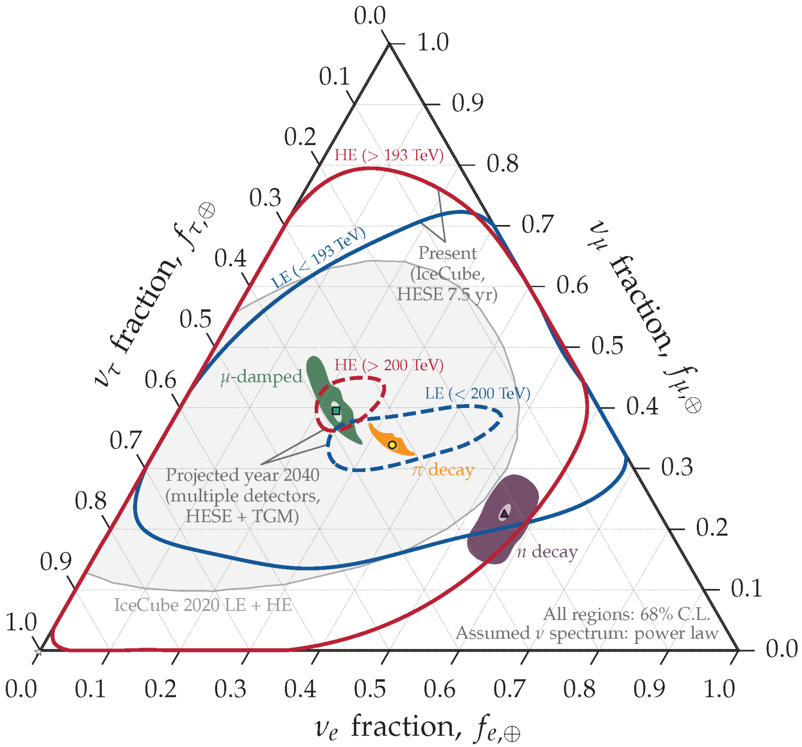


Eur.Phys.J.C 82 (2022) 1, 26.
θ_{23}=48.6° and δ_{CP}=221°



Most updated prediction following the deployment master plan, the error band considers both NO and IO and the range of the θ_{23} allowed values

An example about the many different ways to look for new physics with oscillations at Neutrino Telescopes



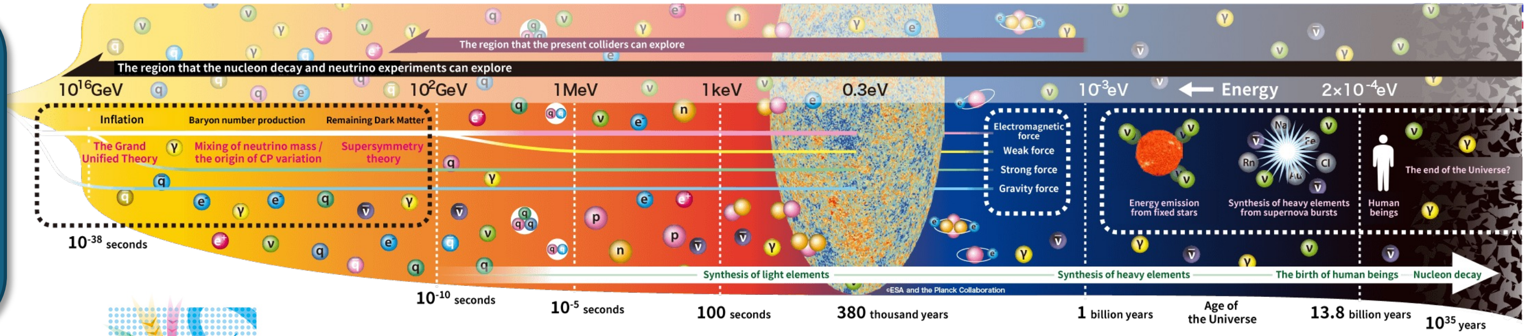
Q.Liu et al., arXiv:2312.07649

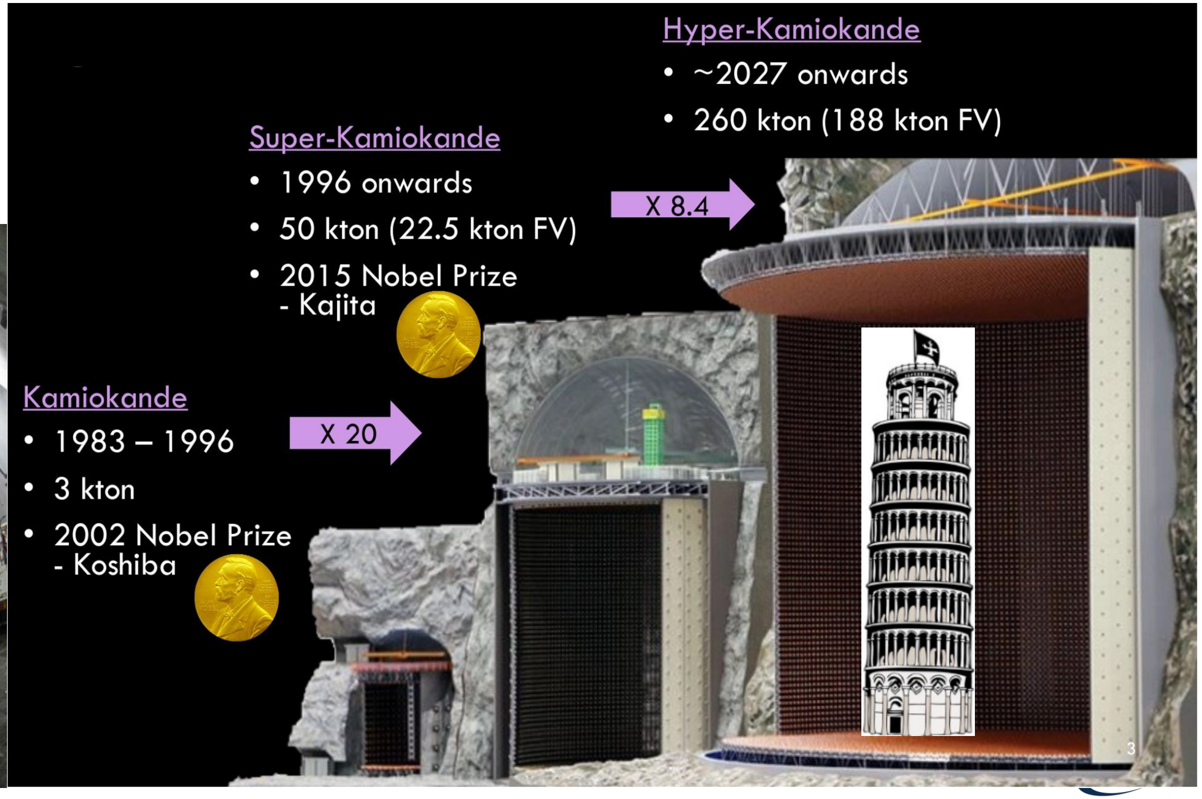
This representation was first introduced by Fogli, Lisi et al., Phys.Rev.D 52 (1995) 5334

- Cosmic sources produce neutrinos with a well defined flavor composition
- Oscillations randomize the flavor composition in their travel, but not completely.
- If something happens different from oscillations, it will modify the composition at earth:signature for new physics
- Present precision is far from enough for these studies, but in the future, also combining several experiments, it will be possible to look for new physics signatures in this plane.
- The role of KM3NeT/ARCA could be crucial

Hyper-Kamiokande

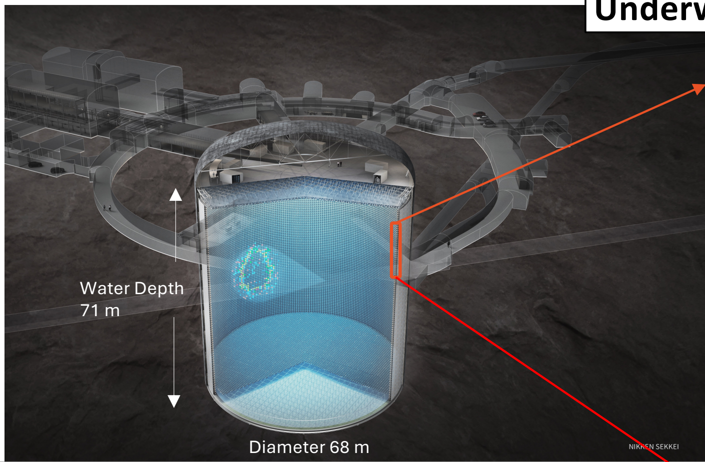
~600 collaborators
106 Institutes
22 Countries
(INFN: 6 sezioni ~ 10% of the collaboration)





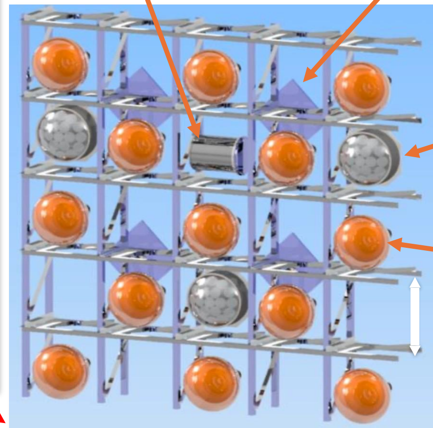
Hyper-K detector configuration

- **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



Underwater Electronics

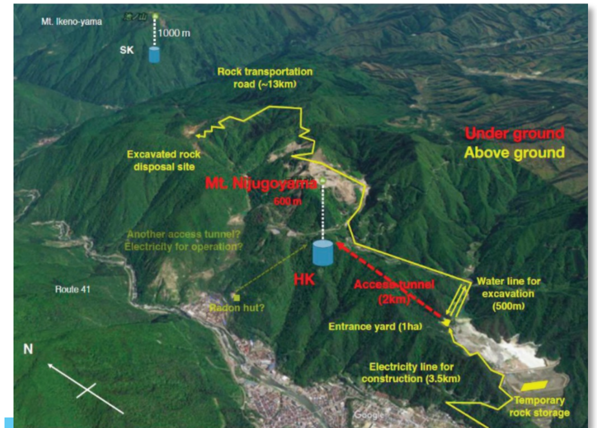
OD PMT+WLS



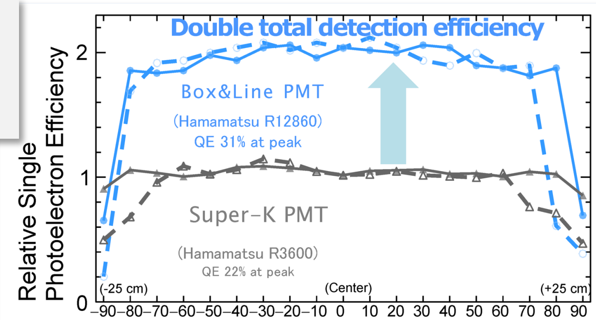
mPMT

50cm PMT

70cm grid



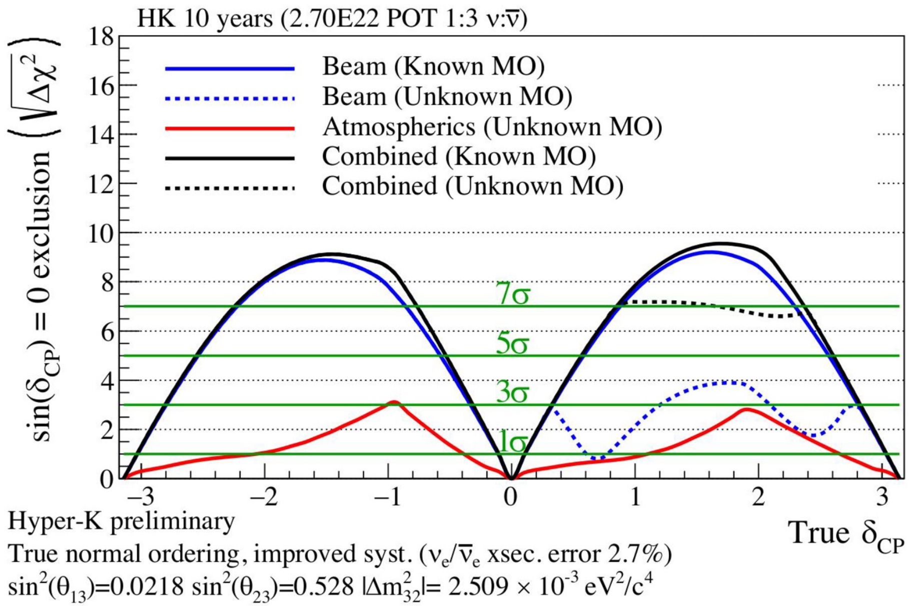
Half coverage (20%) versus Super-K but twice efficiency



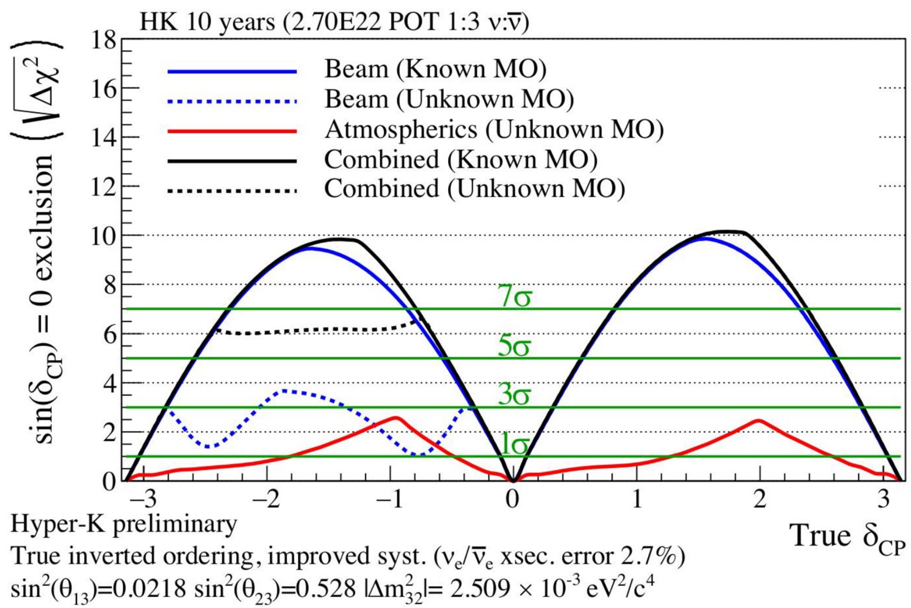
CP violation sensitivity

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

Normal Ordering



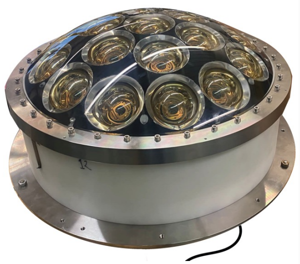
Inverted Ordering

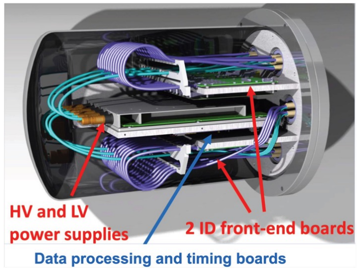


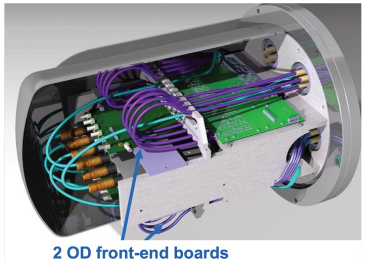
By combining beam neutrinos and atmospherics

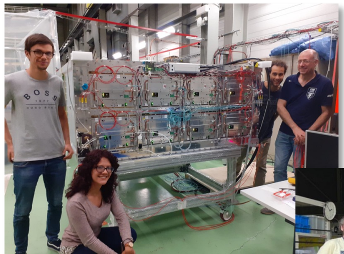
- For maximal CP violation (δ_{CP}=-π/2) 5σ sensitivity is reached in 3 years.
- In 10 years, CP conservation excluded at 5σ for 60% of δ_{CP} values.

INFN contributions in Hyper-K









Multi-PMT

300 mPMTs by INFN (**project leader**), 808 mPMTs total. Derived from KM3NeT DOMs.

Electronics

20' PMTs Front-end digitizer, **project leader**, INFN design chosen vs Japan and France.

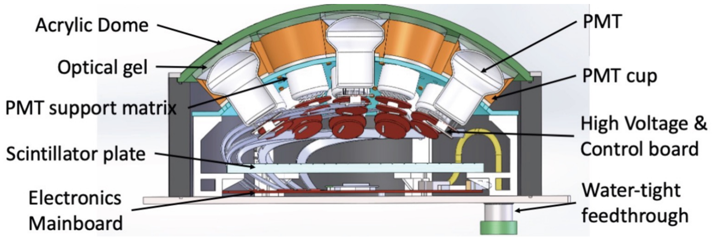
Timing distribution

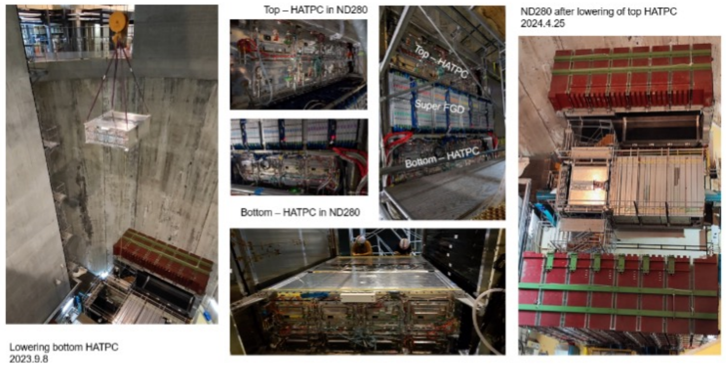
Computing

~25% computing power of Hyper-K 2022-26 at CNAF, collaborative tools, analysis tools

High Angle TPCs

Just installed: two new TPCs for the near detector upgrade of T2K (**will be part of the near detector of Hyper-K**)





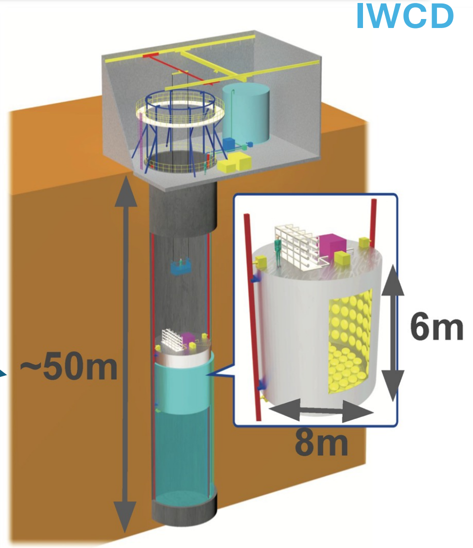
Systematic Errors

T2K overall systematic errors for the ν_e appearance channel are 4.7% (initial goal was 5%).

Without the close detectors they are about 13%.

Aim to reduce them to around 2% (full simulation undergoing):

- **ND280 redesigned and optimized** to better constrain systematic errors (already fully in place)
- A new Intermediate (0.75 km) Water Cherenkov Close Detector (**IWCD**) to further constrain systematic errors (ready for Hyper-K)
- 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:

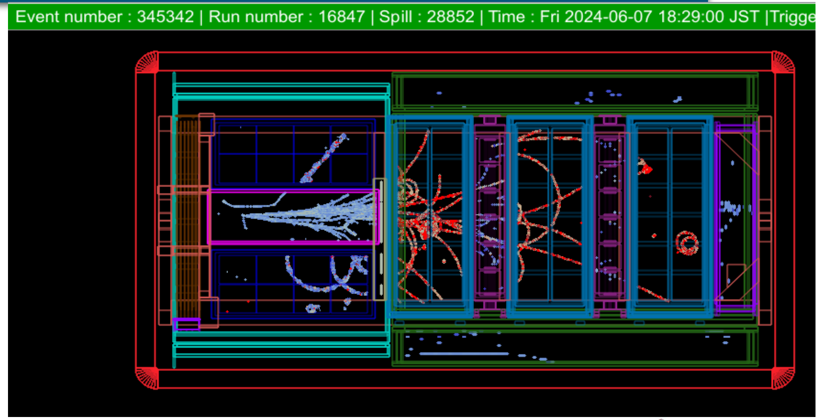
Error model	μ-like ν-mode	μ-like $\bar{\nu}$-mode	e-like ν-mode 0 d.e.	e-like $\bar{\nu}$-mode 0 d.e.	e-like ν-mode 1 d.e.	e-like $\nu/\bar{\nu}$ modes 0 d.e.
T2K 2020	3.0%	4.0%	4.7%	5.9%	14.1%	4.6%
Improved	1.2%	1.1%	2.1%	2.2%	5.2%	2.0%

HK Expected event rate @10 years vs T2K today

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

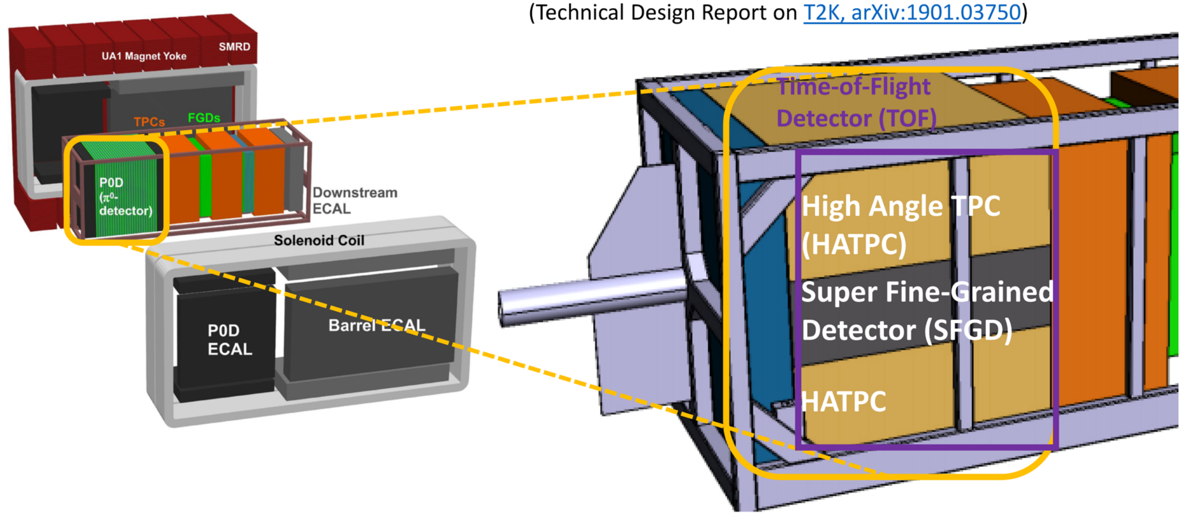
	HK	T2K
ν-mode, 1 ring μ-like	~8800	318
$\bar{\nu}$-mode, 1 ring μ-like	~12000	137
ν-mode, 1 ring e-like	~2100	94
$\bar{\nu}$-mode, 1 ring e-like	~1800	16
ν-mode, 1 ring e-like, 1 decay e-	~300	14

Near detector (ND280) upgrade

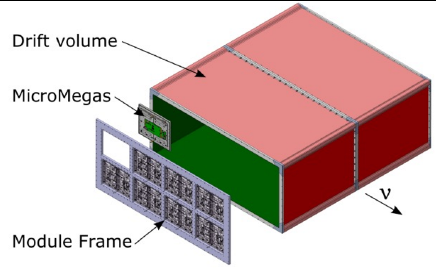


Almost in place now for T2K, will be re-used by Hyper-K
More (and more granular) mass for the neutrino interactions: **SFGD**
More angular acceptance: **High Angle TPCs → INFN responsibility**
Better veto for external tracks: **Time-of-flight**
Significant lower energy threshold for protons and much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

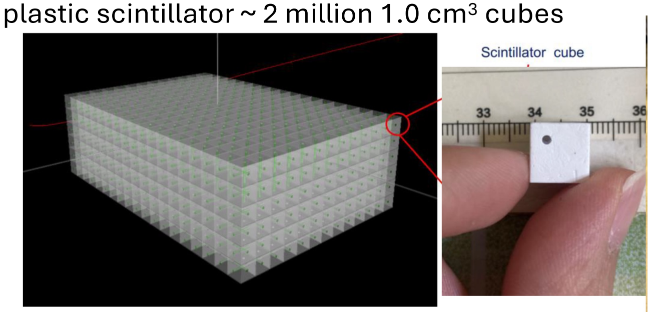
(Technical Design Report on T2K, arXiv:1901.03750)



HATPC



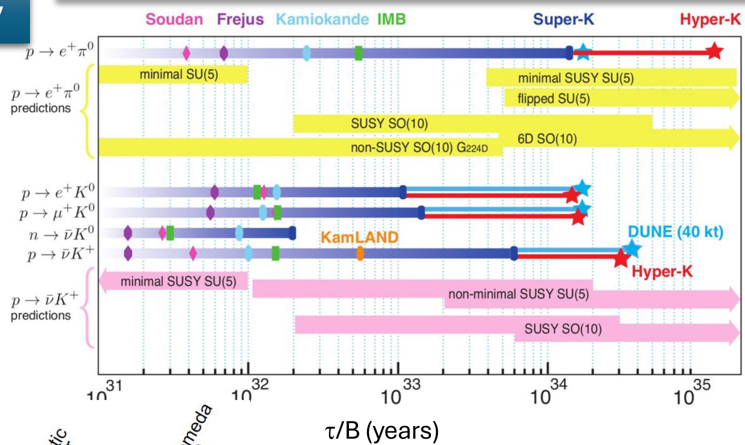
SFGD:
3D plastic scintillator ~ 2 million 1.0 cm^3 cubes



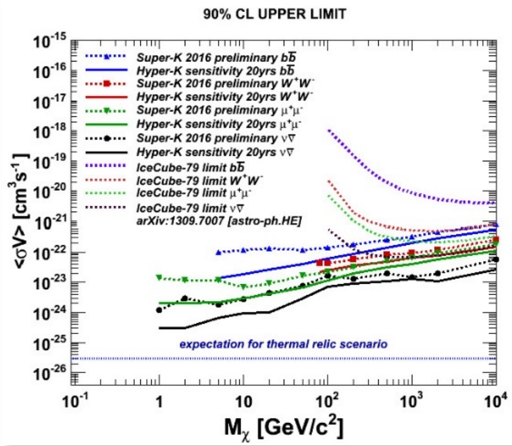
Rare decays and astrophysics in HK

Great complementarity with DUNE and JUNO in most of these searches

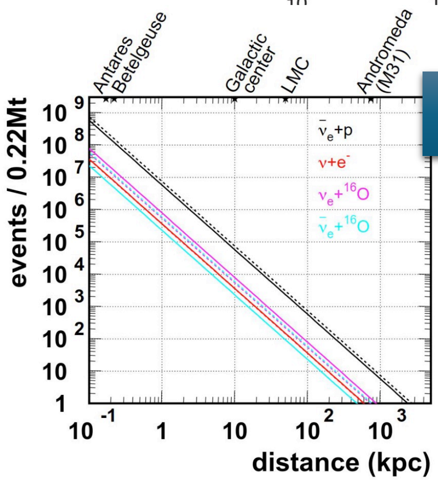
Proton Decay



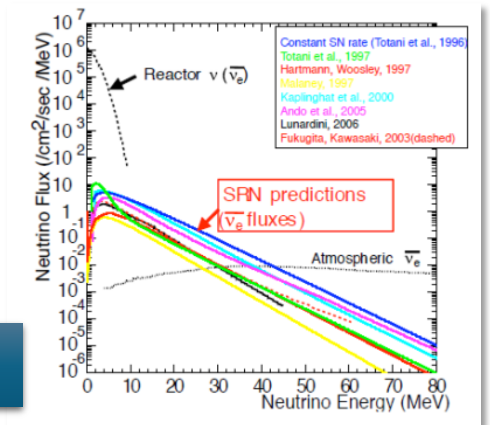
Indirect Dark Matter searches



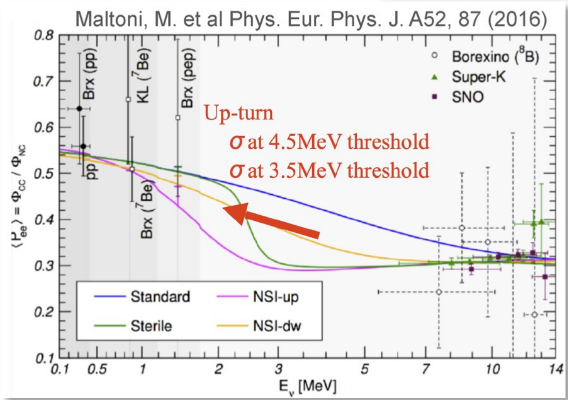
SuperNova burst ν



SuperNova relic ν

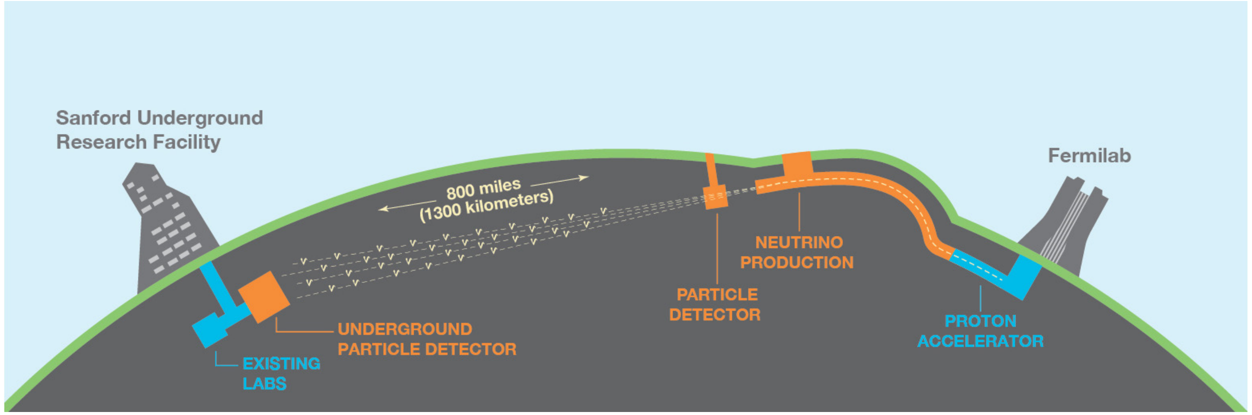


Solar ν



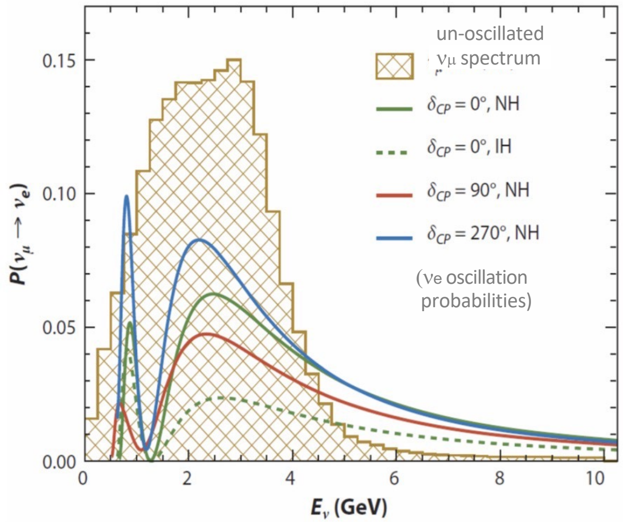
Low energy ν bursts

DEEP UNDERGROUND NEUTRINO EXPERIMENT



- 1450 collaborators
- 215 Institutes (11 INFN)
- 35 Countries

- On-axis, with a baseline of 1300 km
- 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 (ready in 2029), one Vertical Drift (ready in 2030).
  - 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"

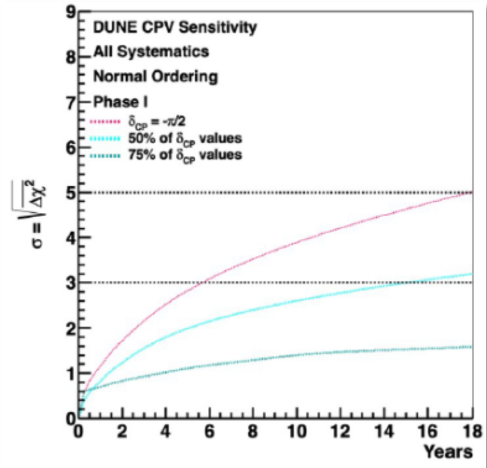
2) Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe (5 projects, 2 of which are about neutrinos, the other one is Ice Cube Gen2)

"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

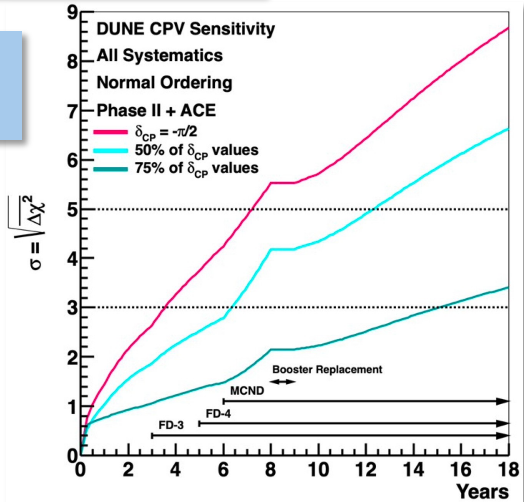
"DUNE Third Far Detector (FD3), but defer ACE-MIRT and the More Capable Near Detector (MCND)."

CP Violation and neutrino mass ordering

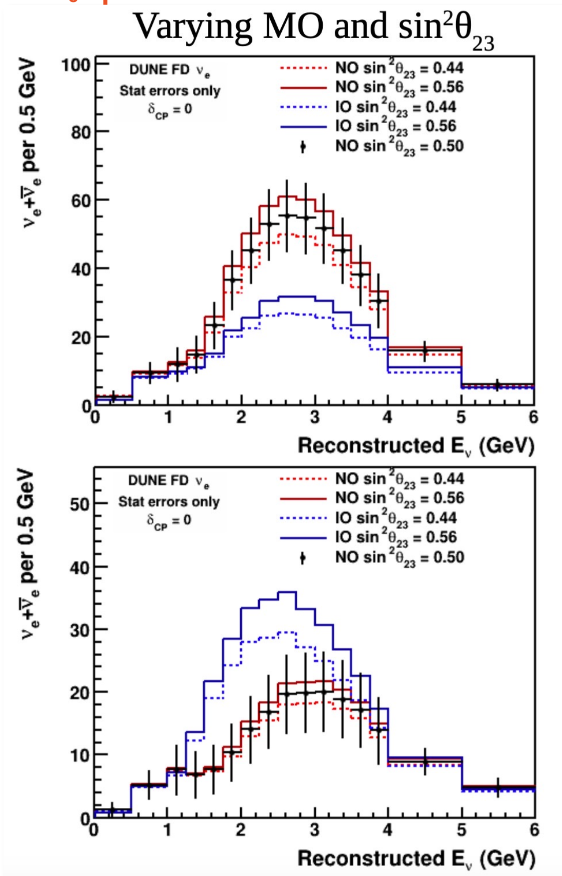


CPV sensitivity, Phase I

CPV sensitivity, Full Phase II



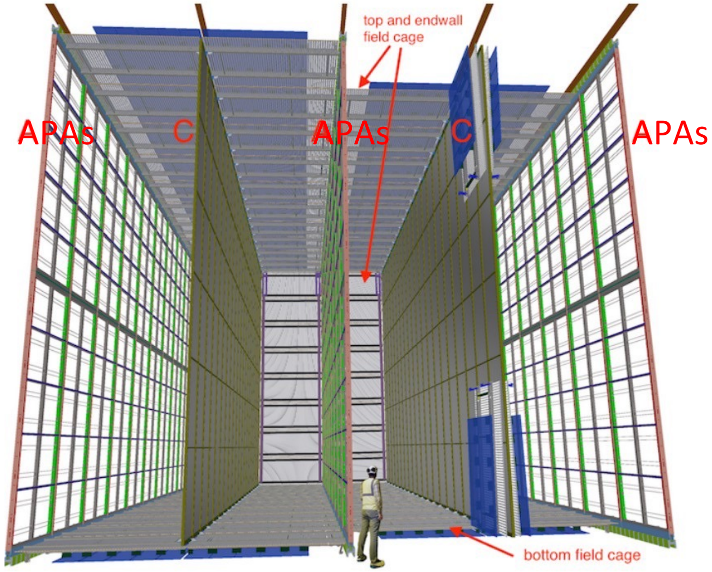
Determining Mass Ordering with DUNE Phase I, 4 yrs, using ν_e and anti-ν_e spectra.



Far Detectors

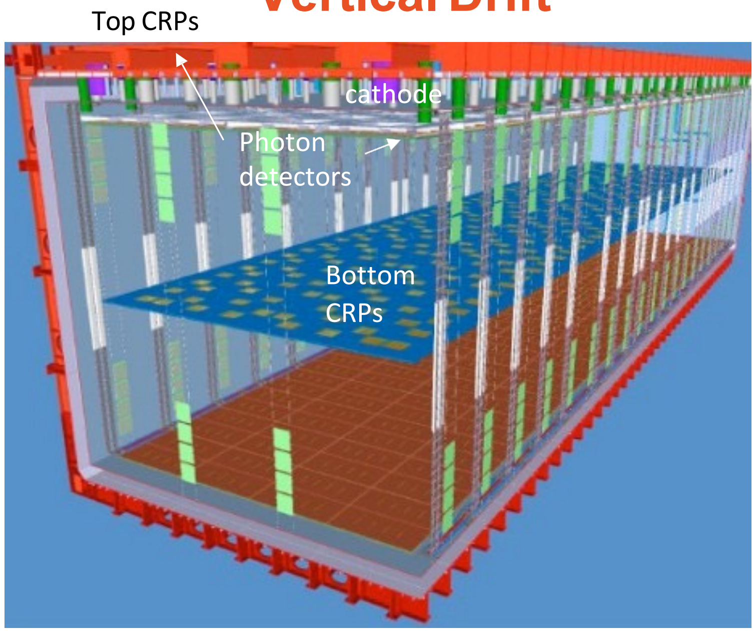
2 (max 4) LAr TPCs, 17 kt Argon total (10 kt fiducial) each one:

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 = 14190 tons of active LAr

ND System and SAND overview

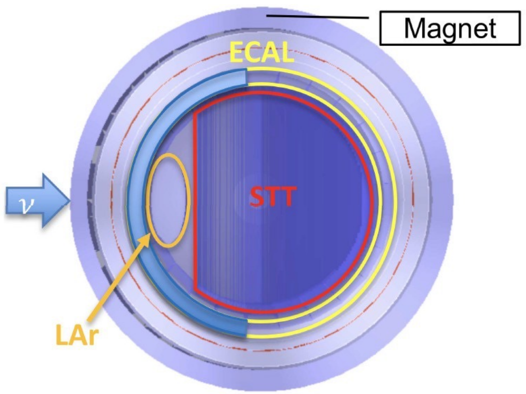
ND measurements shall be of sufficient precision to ensure that when extrapolated to FD to **predict the FD event spectra,** the associated systematic error must not dominate the measurement precision.

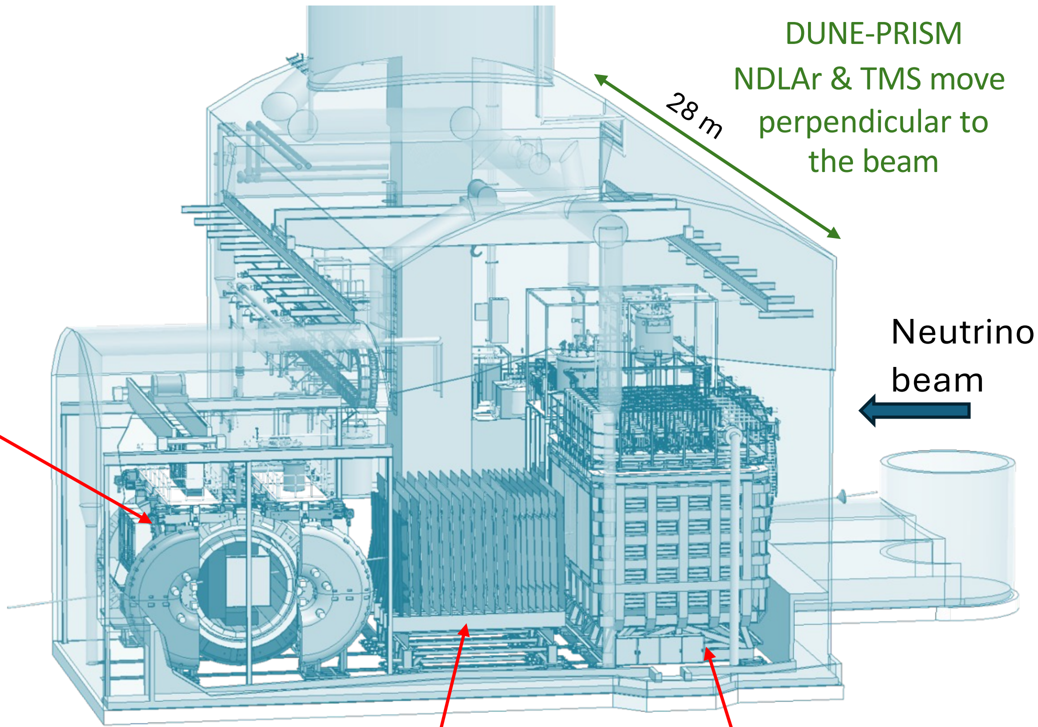
SAND: on-axis magnetized neutrino detector, multipurpose detector with a high-performant ECAL, light-targeted tracker, a thin LAR “lens”, all of them in a magnetic field, mostly recovered by **KLOE** (LNF), in-kind contribution to DUNE from INFN, with new TRACKER and the thin LAr “lens

STT FV mass: 4.7 t CH_2 557 kg C

GRAIN mass: 1 t LAr

Front ECAL mass: 22.8 t Pb





DUNE-PRISM
NDLAr & TMS move perpendicular to the beam

Neutrino beam

TMS
moveable
muon spectrometer

NDLAr
moveable 35 modules
pixel readout

KLOE-TO SAND activity at Frascati

going on smoothly

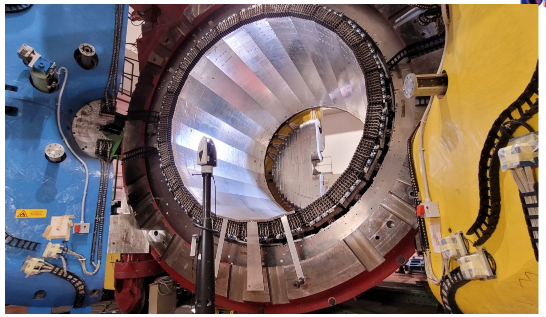
<u>Plan of operations:</u>

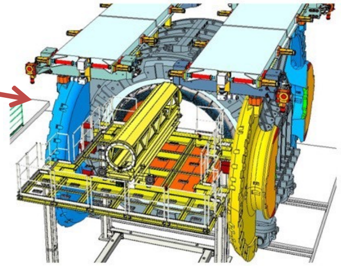
✓ Removal of all cables and the FEE+HV racks

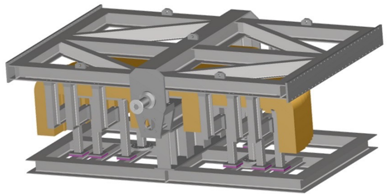
✓ Extraction of the Drift Chamber

Calorimeter

- Laser tracker survey before ECAL dismounting
- Extraction of Barrel (24 modules)
  - original insertion/extraction machine completely refurbished and operational
  - platform construction is amost completed
- Dismounting of EndCaps
  - original insertion/extraction/rotation machine is being refurbished and modified
- Operational test of ECAL modules
- Studies for the ECAL working point & FEE







Magnet and Yoke

- Installation of new Power Supply
  - new Power supply is being purchased (CAENels)
  - Power Electronics is being revamped (OCEM)
  - Control system and full support for magnet test/ dismount/remount by ANSALDO ASG
- Cooling of coil
- Operational test of magnet
  - in preparation
- Extraction of coil
- Dismounting of Iron Yoke

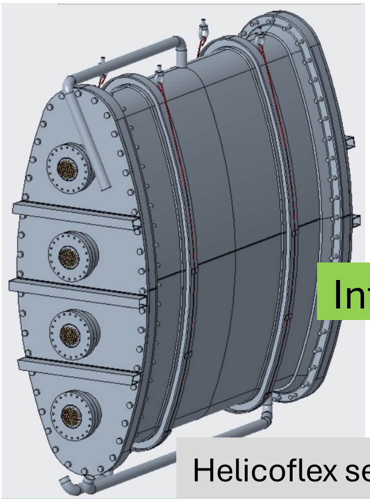
EndCap

Packaging & Shipping at Fermilab for beginning 2026

Recent news on GRAIN

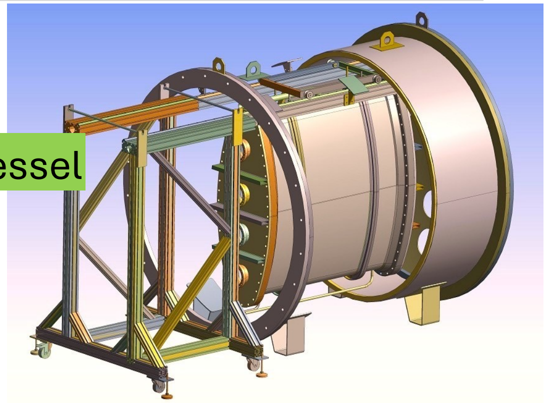
Granular Argon for Interaction of Neutrinos, 1t liquid argon cryostat inside SAND magnetic volume with imaging devices on the inner walls to take pictures of neutrino interactions

Vacuum tank for Inner Vessel test at INFN-Legnaro almost ready for tender

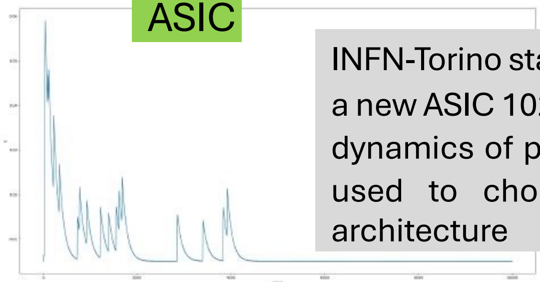


Helicoflex sealing under simulation

Internal Vessel

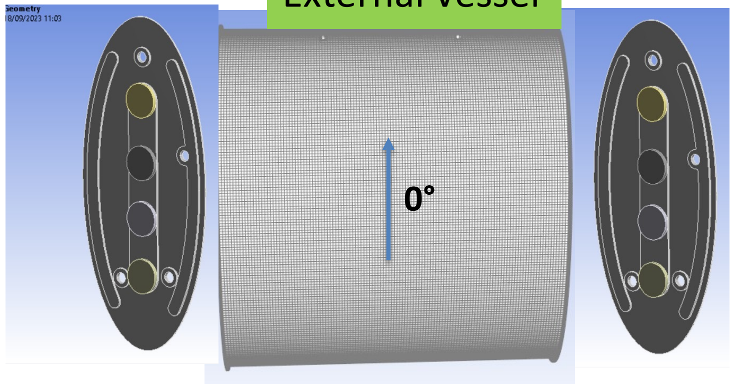


ASIC



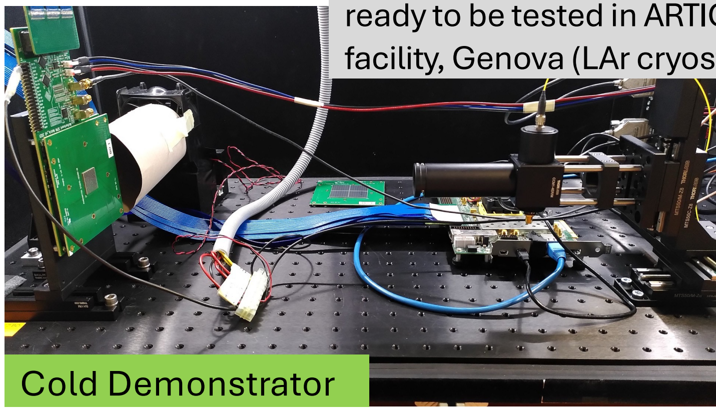
INFN-Torino started the design of a new ASIC 1024 channels. Expected dynamics of photon arrival on SiPMs Is used to choose optimized frontend architecture

External Vessel



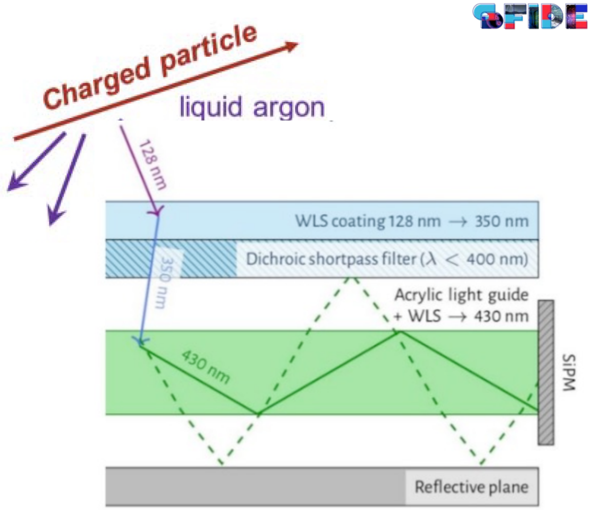
Test degassing and permeability of different samples of Carbon Fiber composites in INFN-FrascaA (next weeks)

Camera with 256 channels ready to be tested in ARTIC facility, Genova (LAr cryostat)



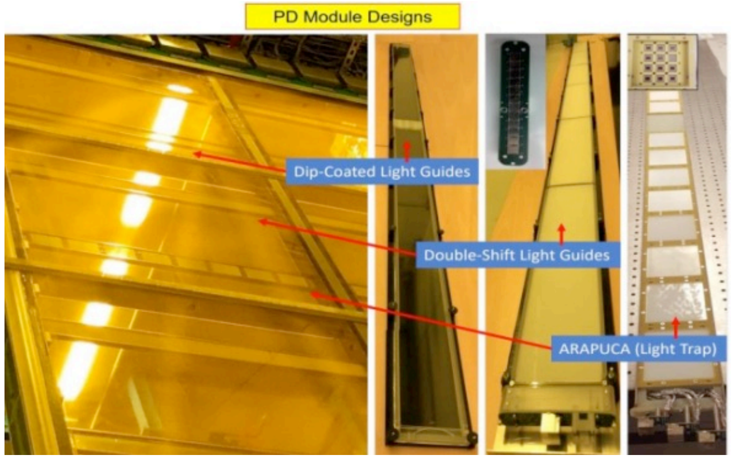
Cold Demonstrator

The Photon Detection System of DUNE (X-ARAPUCA)



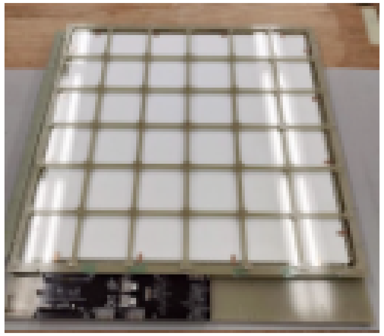
The t_0 for the LAr TPCs is provided by scintillation light.
The wavelength of scintillation light in LAr doesn't match the sensitivity range of photodetectors.
The 'X-ARAPUCA' technique, developed by INFN, is available in two types for the first (FD1-HD) and the second module (FD2-VD).

INFN plays a leading role in the Consortium, which has been further strengthened with the signing of the MoU for Vertical Drift



Horizontal Drift: 1500 rectangular 'modules' (2m x 20 cm^2),each with four channels, containing 48 SiPM (288000 SiPM in total)

Vertical Drift: 672 square tiles (60 x 60 cm2), each with two channels containing 80 SiPMs (107000 SiPM in total)



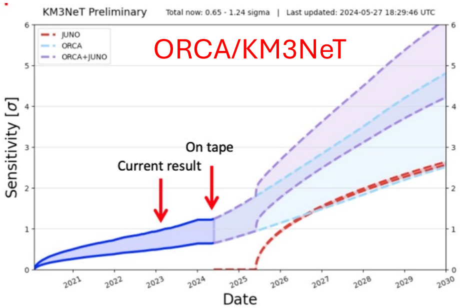
Half of SiPMs by FBK and half by Hamamatsu.

The race for neutrino mass ordering (aka hierarchy)

NMO can only be +/-1, so sensitivity means wrong ordering rejection

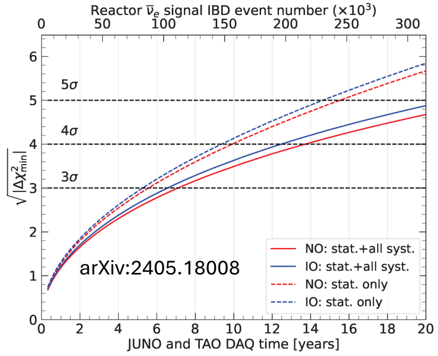
The experimental quantity is sign(Δm^2_{23})

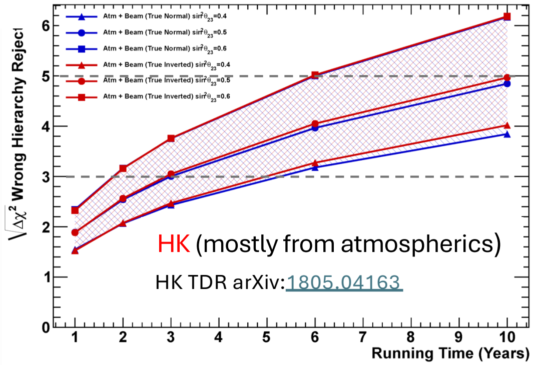
Plug your preferred starting years and guess



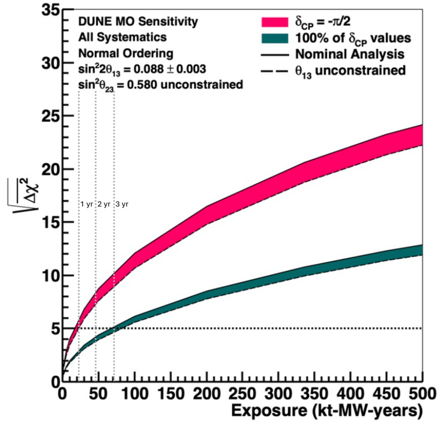
Most recent update of Eur.Phys.J.C 82 (2022) 1, 26.

JUNO





DUNE Phase 1: 1yr=24 kt-MW

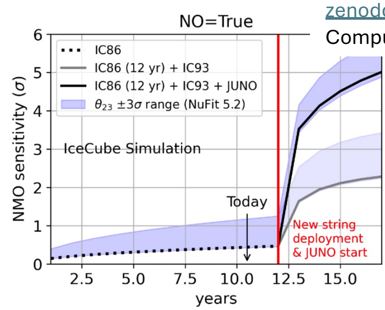


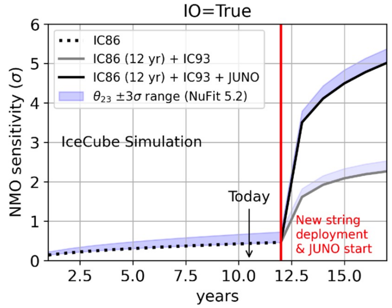
Vertical Drift TDR: arXiv:2312.03130

IceCube (+Upgrade)

Neutel 2023: https://doi.org/10.5281/zenodo.10567782

Computed for θ_{23}=40°





Depend on:

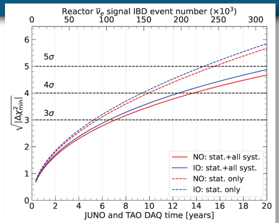
- Assumptions on θ_{23} (atmospherics have terms ∝ $\sin^4\theta_{23}$)
- Assumptions on δ_{CP} (DUNE)
- True Ordering
- Degree of optimism in the calculation of systematic errors
- Performance of the detector (JUNO)
- Fiducial mass (ORCA)

No way to display these curves in a single plot keeping the same assumptions

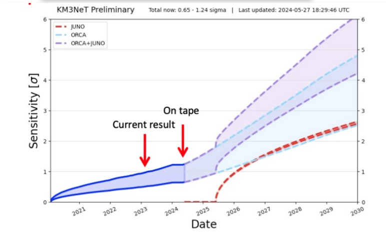
Anyway ....

... The race for neutrino mass ordering (aka hierarchy)

NMO can only be +/-1, so sensitivity means wrong ordering rejection

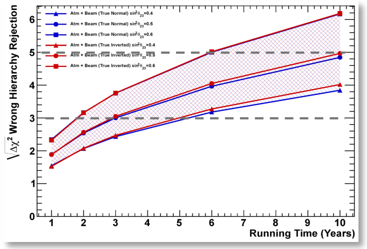


JUNO
arXiv:2405.18008



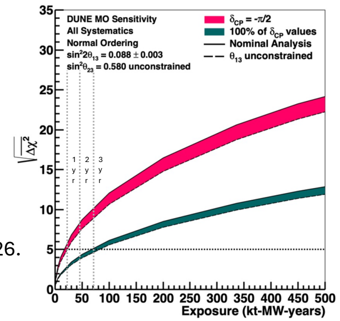
ORCA/KM3NeT

Most recent update of Eur.Phys.J.C 82 (2022) 1, 26.



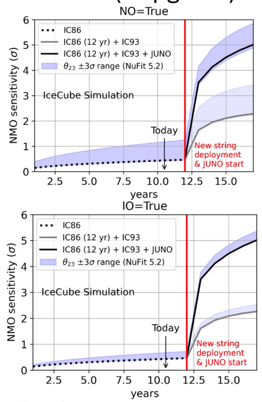
HK (mostly from atmospherics)
HK TDR arXiv:1805.04163

DUNE Phase 1: 1yr=24 kt-MW

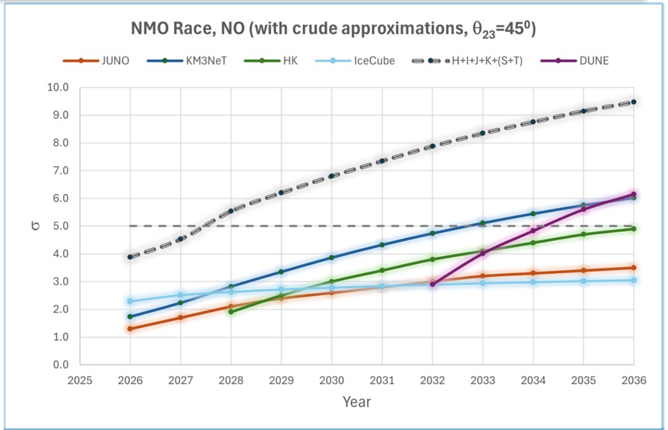


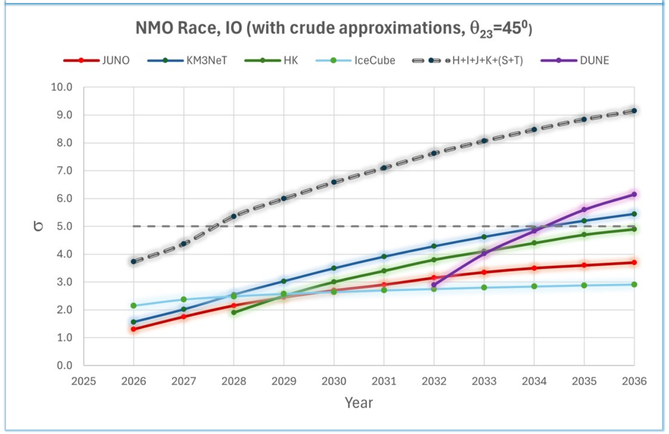
Vertical Drift TDR: arXiv:2312.03130

IceCube (+Upgrade)



Neutel 2023: https://doi.org/10.5281/zenodo.10567782
Computed for θ_{23}=40°





H+I+J+K+(S+T): combination of HK, IceCube, JUNO, KM3NeT and joint analysis of SK and T2K at full statistics

Nominal Starting Dates
2025: JUNO and IceCube Upgrade
2027: Hyper-K
2028: Full ORCA
2031: DUNE Phase I
(T2K joint SK @ full statistics :$\Delta\chi^2$=8)

Depend on:

- Assumptions on θ_{23} (atmospherics have terms ∝ $\sin^4\theta_{23}$)
- Assumptions on δ_{CP} (DUNE)
- True Ordering
- Degree of optimism in the calculation of systematic errors
- Performance of the detector (JUNO)
- Fiducial mass (ORCA)

No way to display these curves in a single plot keeping the same assumptions

... anyway

INFN

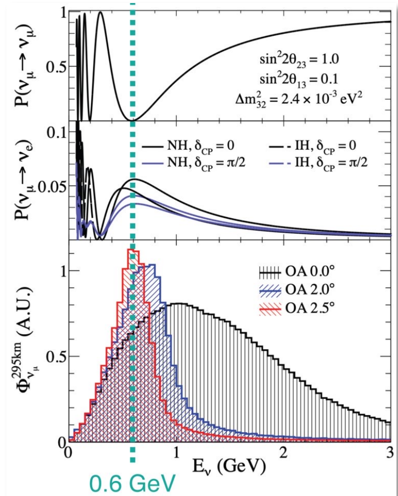
About the complementarity of Hyper-K and DUNE

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

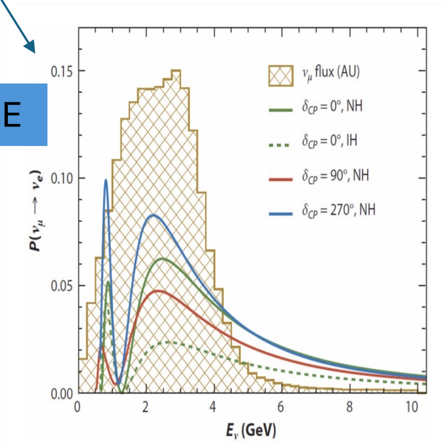
To make the most of complementarity, it would be necessary to form and support a joint working group. After the very positive experience of the T2K-NOvA combined analysis.

- 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).

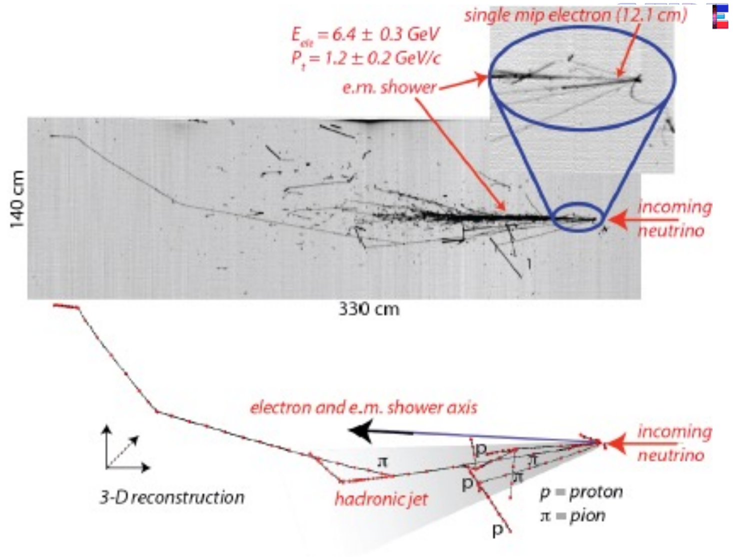
HK

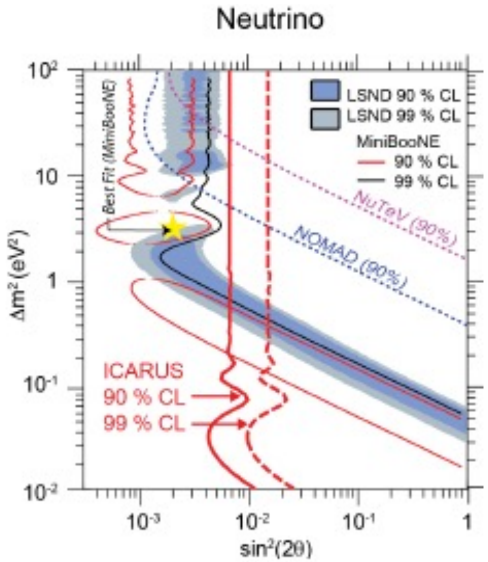


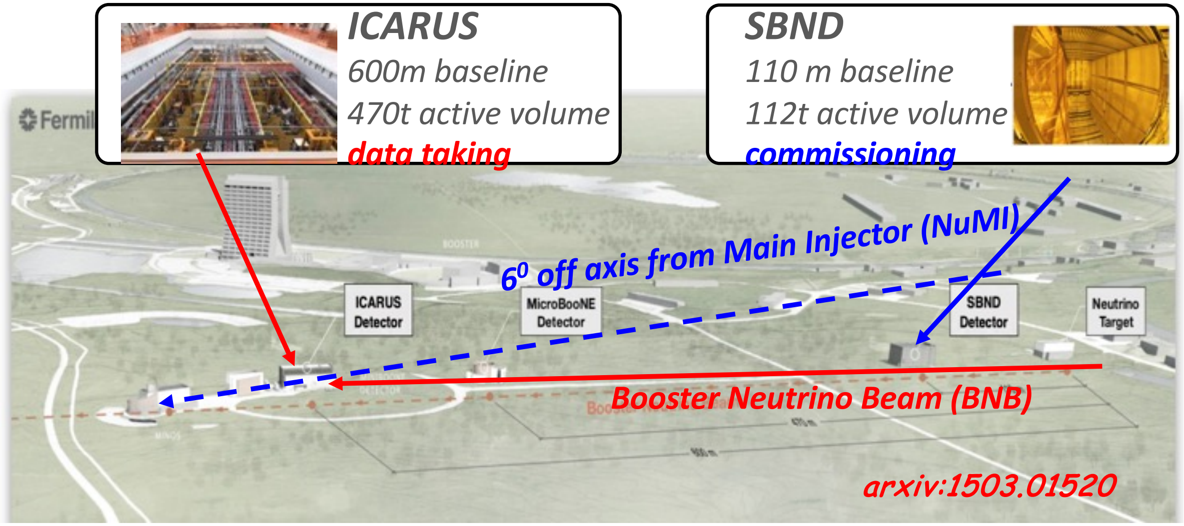
DUNE

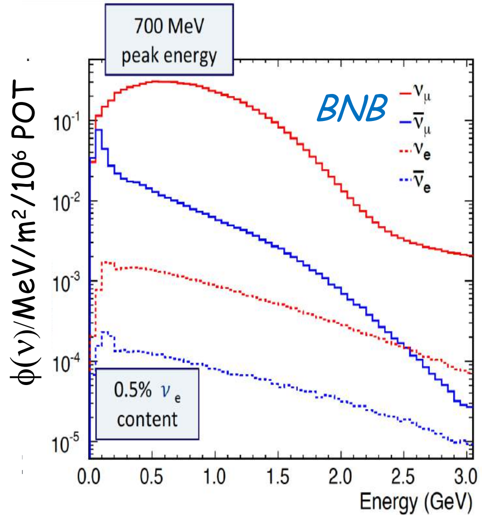


ICARUS at LNGS: Sterile Neutrinos









- SBN program should clarify the question of sterile neutrinos exploiting the BNB beam and comparing the ν_e and ν_μ interactions at different distances from target by ICARUS and SBND LAr-TPCs installed at 600 and 110 m from target.
- In addition: Beyond Standard Model/Dark Matter searches, high-stat. ν-Ar cross-section measurement and event identification/reconstruction tools in the region of interest of DUNE:
  - ~10^6 events/y in SBND < 1 GeV from Booster
  - ~10^5 events/y in ICARUS > 1 GeV from off-axis NuMI beam.

ICARUS: 12 INFN groups, 12 US institutions, CERN, 1 Mexican institution, 1 Indian Institution
Spokesperson: C. Rubbia

SBN Program: sterile neutrino sensitivity, 3 years (6.6×10^{20} pot)

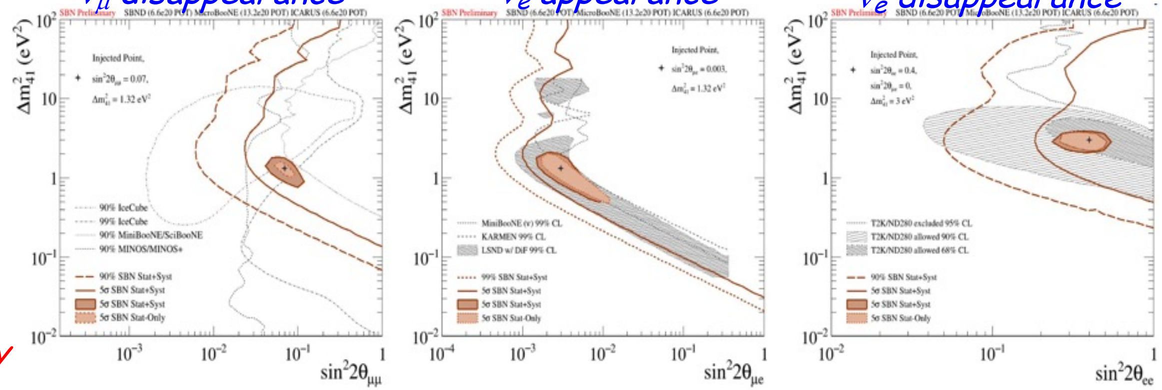
- Combined analysis of events collected far by ICARUS at far site and by SBND at near using the same LAr-TPC event imaging technology greatly reduces the expected systematics:

✓ *5σ coverage of the parameter area relevant to LSND anomaly*

✓ *Probing the parameter area relevant to gallium and reactor anomalies.*

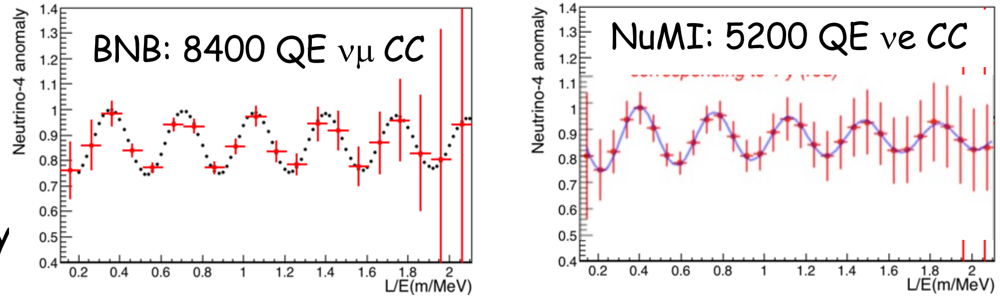
Unique capability to study ν app./disapp. simultaneously

ν_μ disappearance *ν_e appearance* *ν_e disappearance*



- Exciting new result from Neutrino-4 experiment at nuclear reactor, which could change all the sterile neutrino story, investigated by ICARUS before the joint operation with SBND:

➢ Oscillations should produce disapp. pattern of $\nu\mu$ in BNB and of νe in NuMI in the same L/E ~1-3 m/MeV but events collected at ~100 times energy

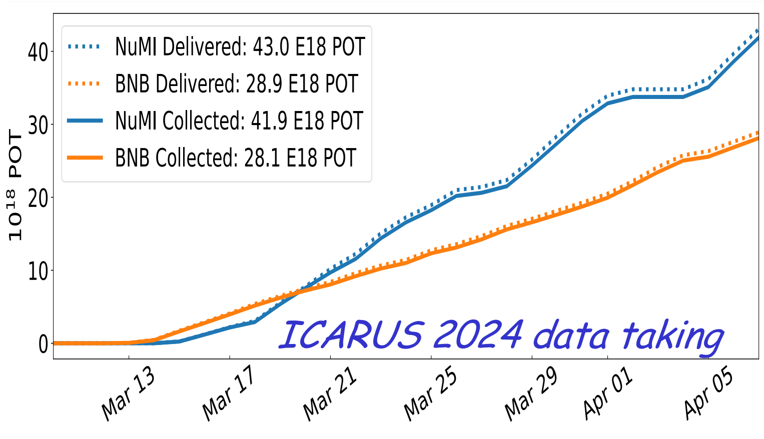


Expected measured ν oscillation pattern (red) for Neutrino-4 best fit: $\Delta m^2_{14}=7.25\ eV^2$, $\sin^2 2\theta_{14}=0.26$

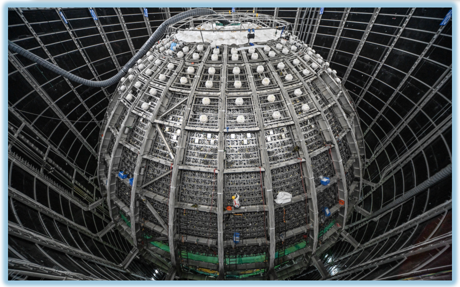
ICARUS detector status and data taking

- ICARUS is successfully taking data since June 2021 exposed to Booster and NuMI ν beams with remarkable stability/performance of all detector components, collecting high quality neutrino events in RUN1, 2: BNB (2.5 10^{20} PoT) and NuMI (3.5 10^{20} PoT).
- Significant investments by the ICARUS Collaboration devoted to achieve better performance following the initial detector operation. Several detector improvements took place during 2022, '23 beam summer shutdowns and before the delayed restart of FNAL accelerator complex on mid March 2024:
  - Higher liquid argon purity - increases ionization e- signal detected on TPC wires;
  - Reduction of the electronic noise of the TPC – increases track reconstruction efficiency;
  - New PMT external cabling - increases/better defines scintillation light signals;
  - Improved trigger system - increases event detection efficiency at low energy;
  - Improved Cosmic Ray Tagger exploitation.

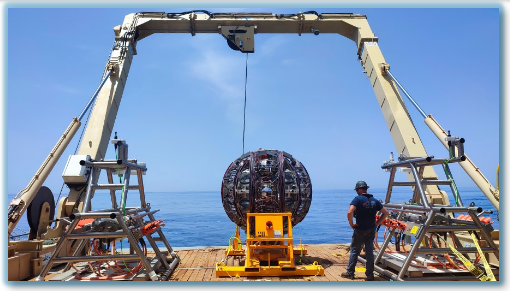
- RUN3 officially started on March 15th taking data with BNB & NuMI extending to July 12th;
- Expected ICARUS RUN3 beam exposure: 1.5 10^{20} (BNB), and 1.9 10^{20} (NuMI) PoT;
- Data taking is supposed to restart in the fall, still depending on FNAL, extending to 31/12/2027.



Conclusions



JUNO



KM3NeT

Hyper-K

DUNE

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, ORCA, DUNE and Hyper-K

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

INFN always played a leading role in neutrino oscillations, and significantly invested in new experiments. In 2024, 246 FTE are involved in these experiments, in 2014 we were 136!

If you like to hear about neutrinos at Lecce don't miss NOW 2024, September 2-8, Otranto

Backup slides

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]."

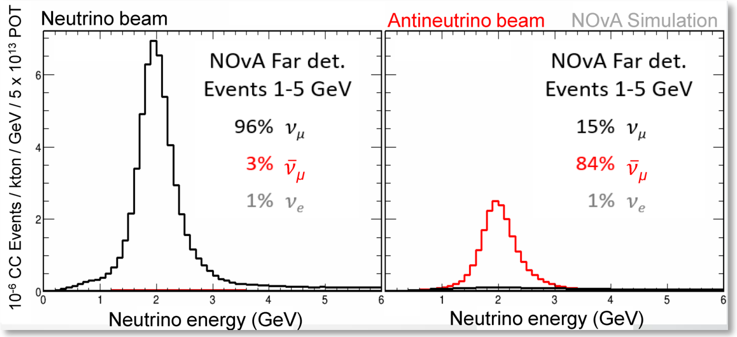
Breakthrough prize 2016: Daya Bay (China); KamLAND (Japan); K2K / T2K (Japan); Sudbury Neutrino Observatory (Canada); and Super-Kamiokande (Japan)
Panofsky prize 2014: "…For their leadership of the Daya Bay experiment, which produced the first definitive measurement of θ_{13} angle of the neutrino mixing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

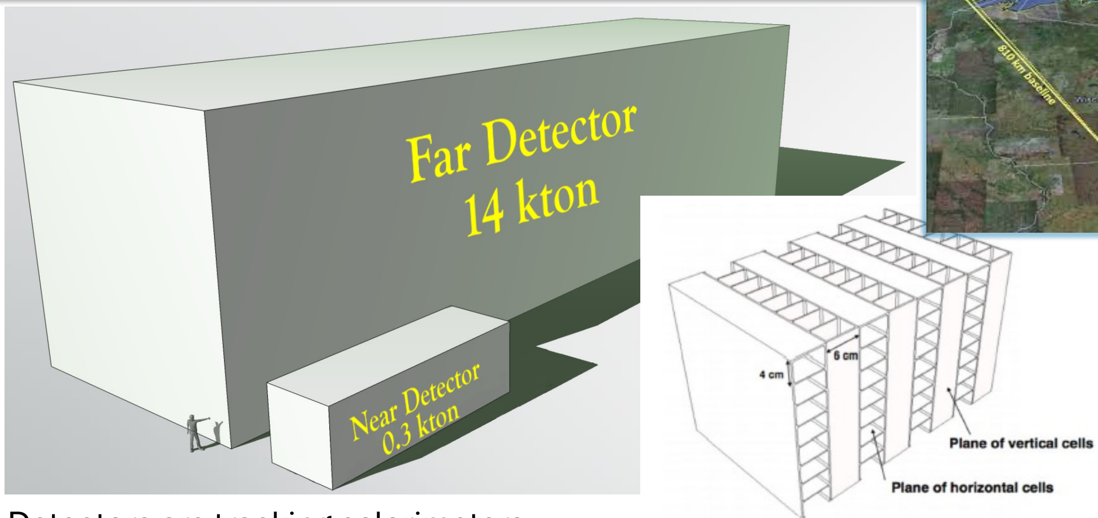
From the long citation of the EPS-HEP prize

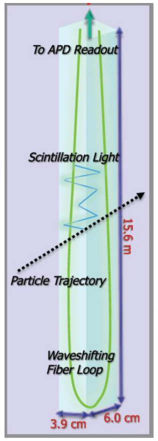
… Indications of non-zero values of θ_{13} were provided in the year 2011 by global fits to atmospheric and solar neutrino oscillations, initial results on electron neutrino appearance by the accelerator long-baseline T2K experiment, and by the reactor neutrino experiment Double Chooz. T2K could not 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 …

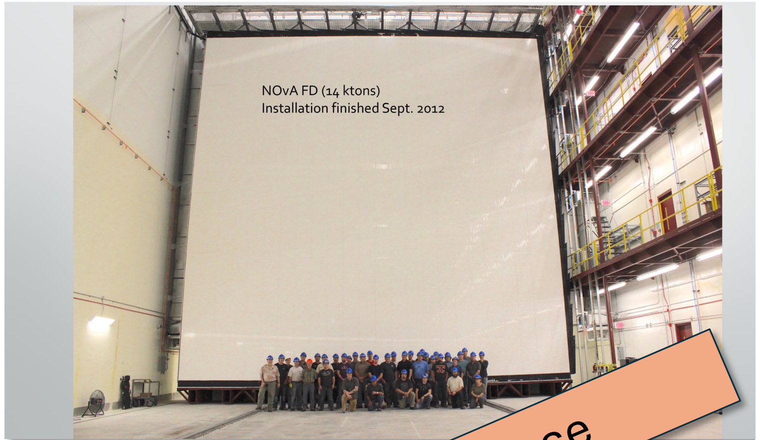
The NOvA experiment

- 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







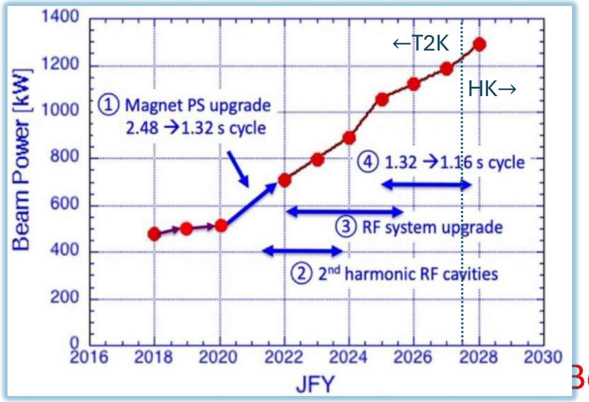


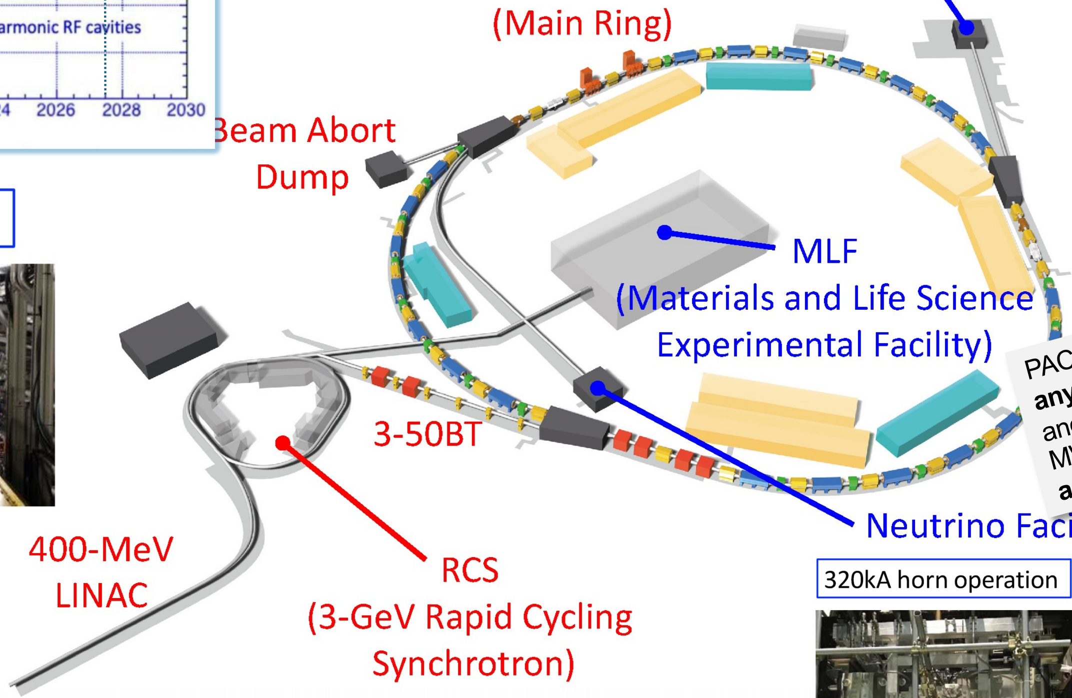
On Surface

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

J-PARC Upgrade



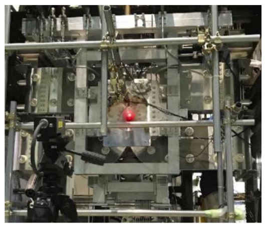


MR-RF cavities

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

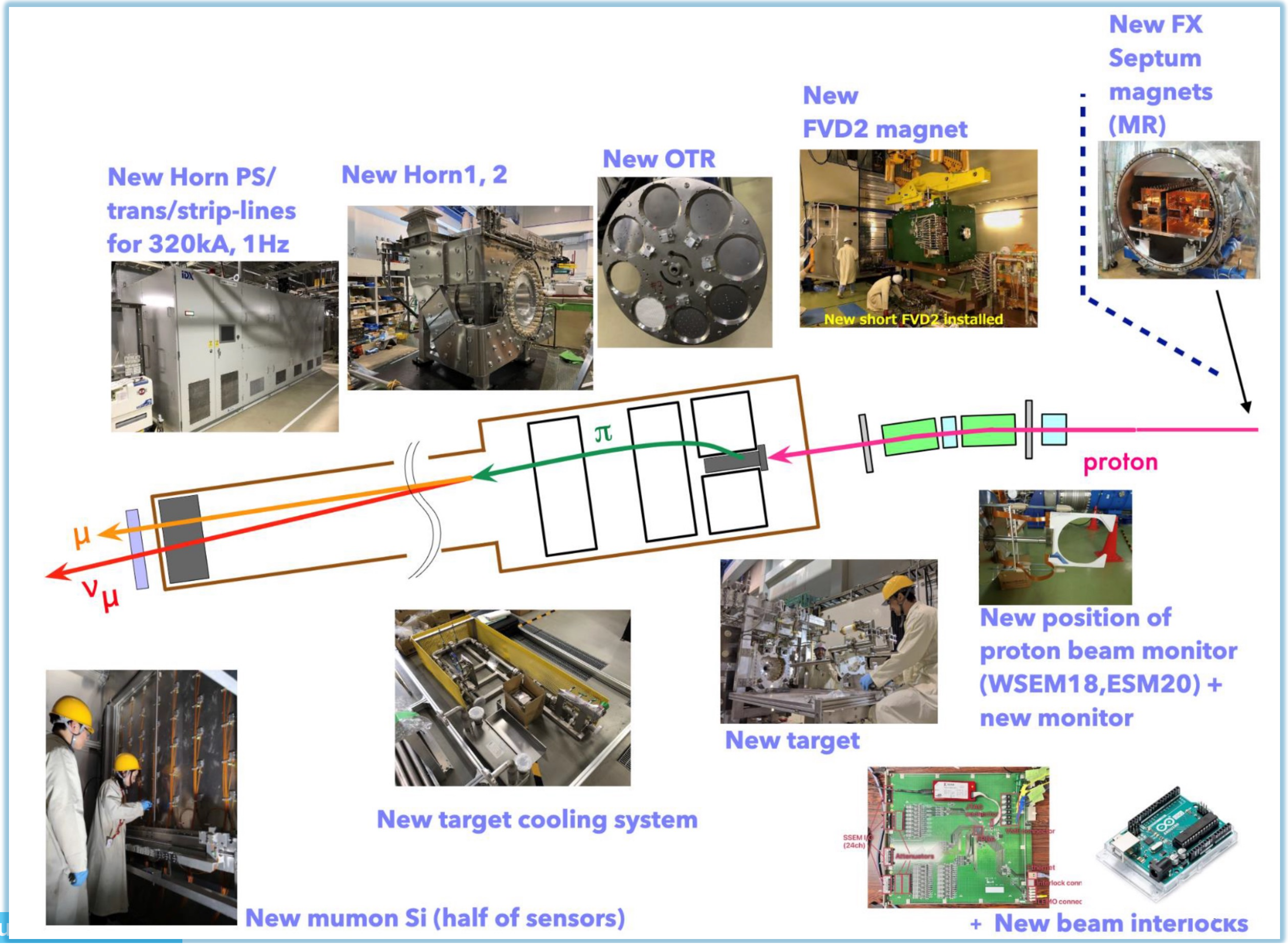


	RCS	MR
Circumference	348.333 m	1567.5 m
Super-periodicity	3	3
Injection	Multi-turn, charge-exchange	bunch to bucket
Injection energy	400 MeV	3 GeV
Injection period	0.5 ms (307 turns)	120 ms
Harmonic number	2	9
Number of bunches	2	8
Transition γ	10.8	$31.6i$
Extraction energy	3 GeV	30 GeV
Repetition rate	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

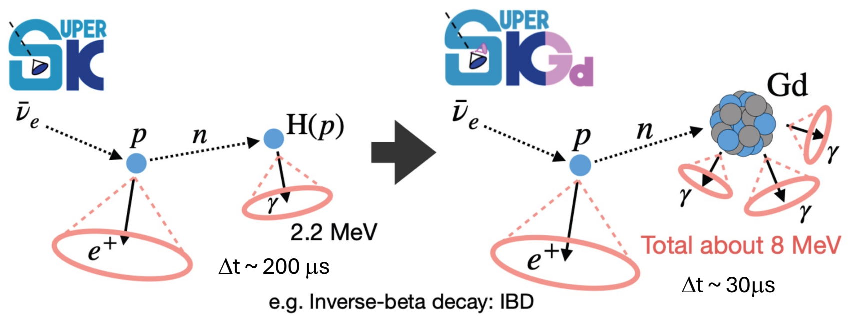
T2K will run until 2027 and profit of the J-PARC power upgrades



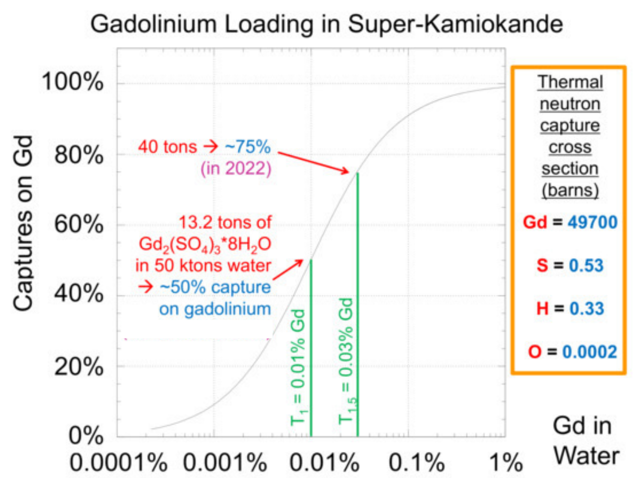
Gadolinium loading

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.

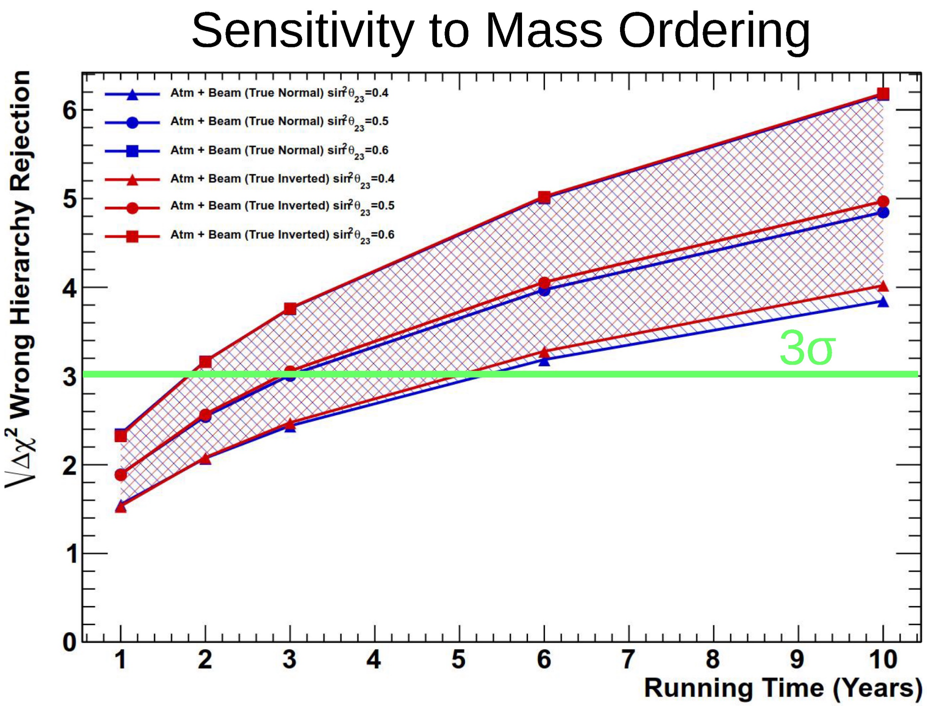


- Detect for the first time Diffuse Supernova Neutrino Background (DSNB)
- Improvement of supernova direction pointing accuracy and allowing pre-supernova neutrino detection (early warning for SN).
- Enhance ν and $\bar{\nu}$ identification in atmospheric and beam oscillation analyses
- Reduce background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

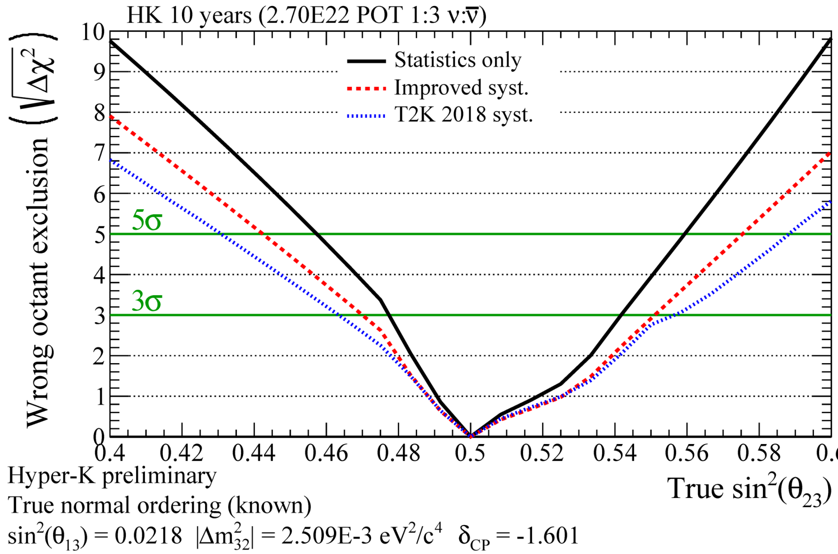


Mass Ordering and θ_{23} octant sensitivity

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).

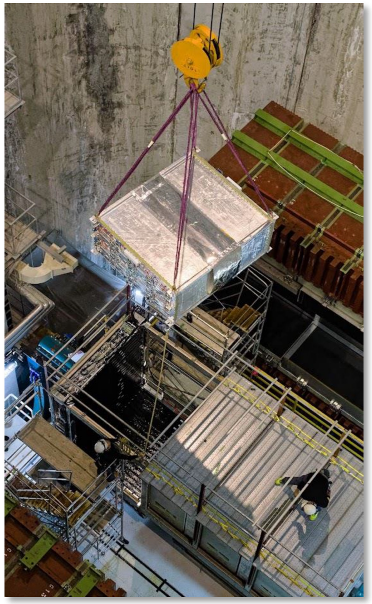


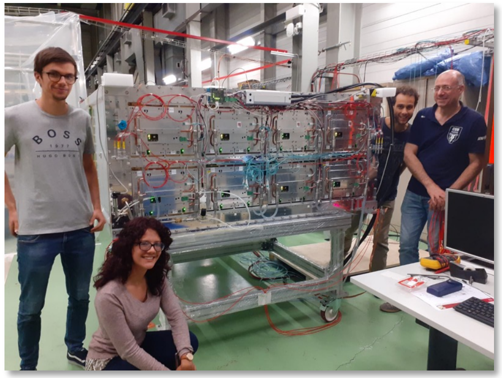
Wrong octant 3σ exclusion as a function of true $\sin^2\theta_{23}$ for different systematics model for 10 HK-years (beam+atmospherics).

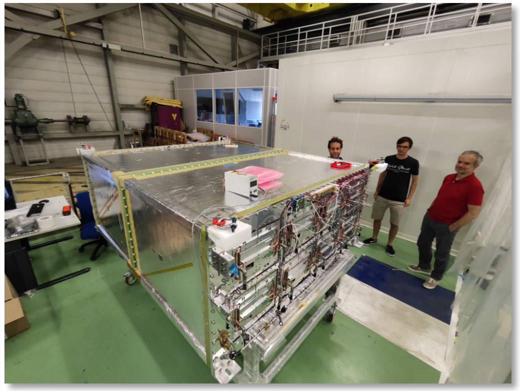


High Angle TPCs

- 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
- Both TPCs now ready at ND280



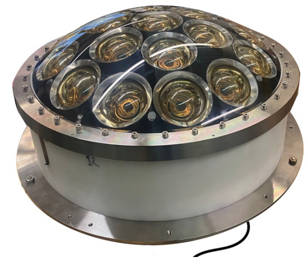




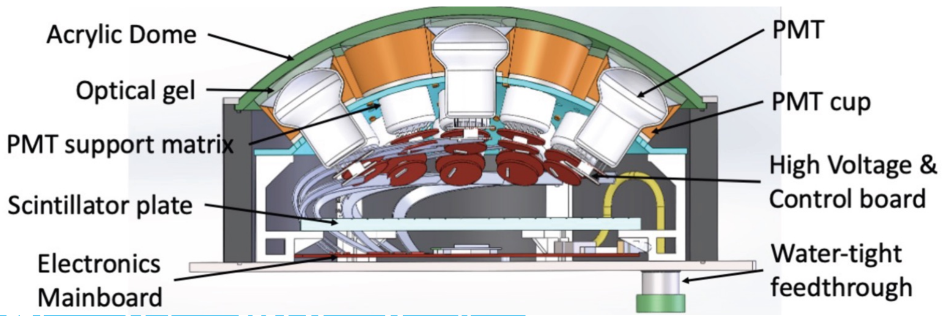
Nucl.Instrum.Meth.A 957 (2020) 163286
Nucl.Instrum.Meth.A 1025 (2022) 166109
Nucl.Instrum.Meth.A 1052 (2023) 168248

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



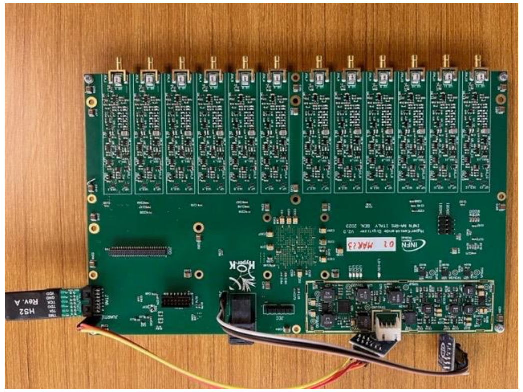
Tendering process started in Italy and Poland
Production chain: tested at INFN-Na
Tests of mPMTs in water at CERN: April this year
Mass production: 2024-25
Installation in Hyper-K: 2026

Hyper-K Electronics

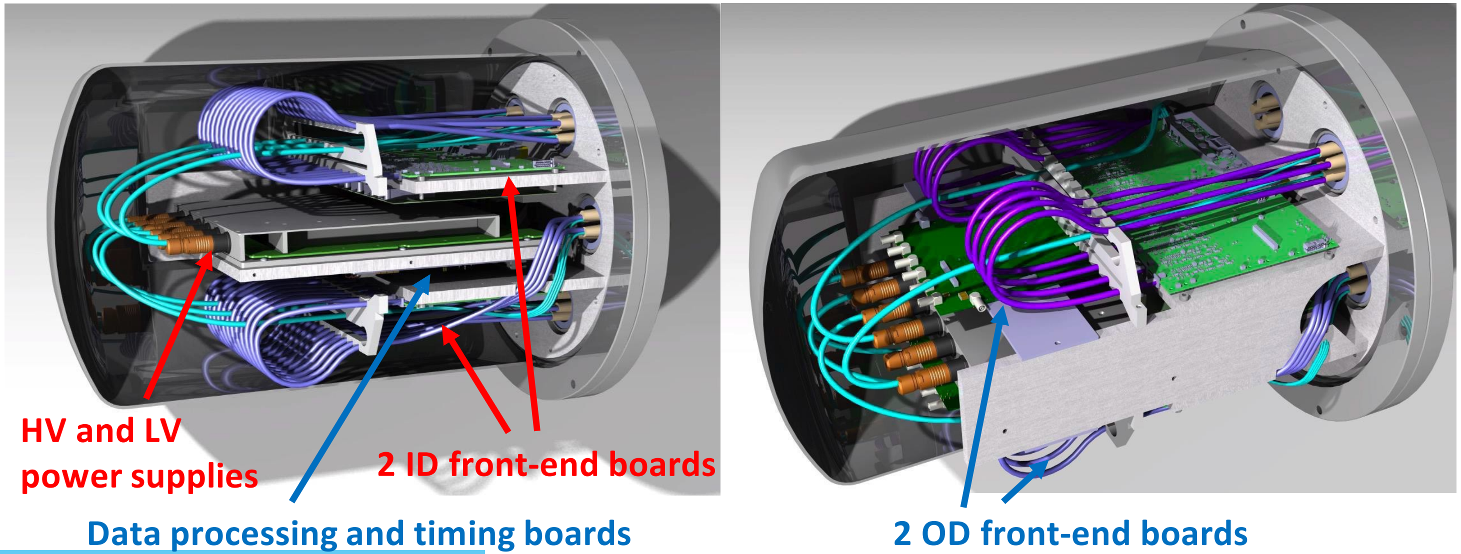
- 3 competing designs originally proposed by INFN, Japan and France
- INFN discrete components design selected: performance, flexibility & fast prototyping cycle
- Measuring Charge, Timing and ToT (Time over Threshold), allowing detection of the pre or late pulses of the PMT.

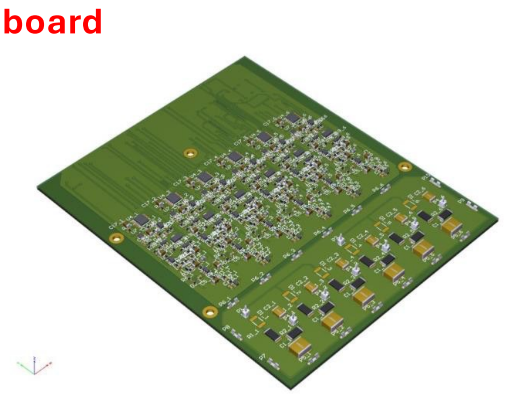
Front-end electronics placed in underwater vessels
Two types of underwater electronics vessels

- 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

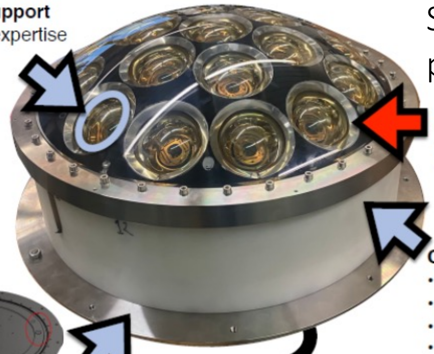




OD 6-channel FE board

Prototypes construction in Canada, Italy, Poland

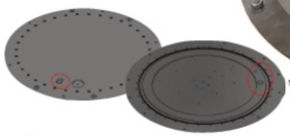
New fix of PMTs in the support
- Piston seals - KM3NeT expertise



Several mPMT prototypes assembled

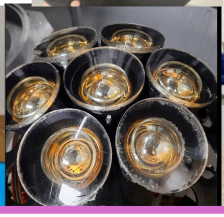
Reflector ring needs optimization
- Need to select best material
- Clipping in the support

Cylinder from POM-C
- More rigid than **HDPE**
- Lighter than stainless steel
- Issue with long lead time resolved
- Reasonable price for mass production

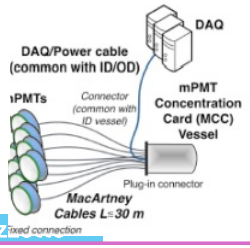


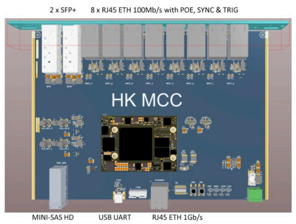
Cosmetic modifications in the backplate
- Experience from the first prototype assembly

QC tools and procedures in preparation



MCC Electronics in Poland and MCC Vessel in Czech

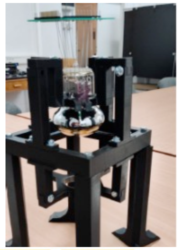


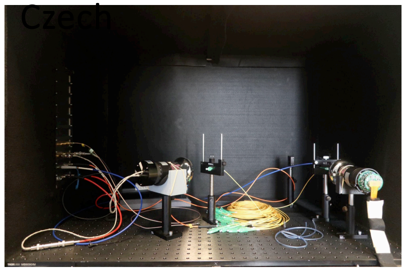


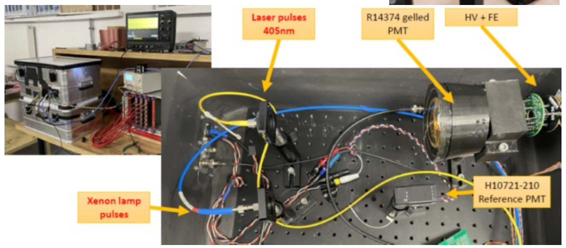
Photomultiplier test station in Poland, Canada and Czech

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

Test station during construction planned in Czech

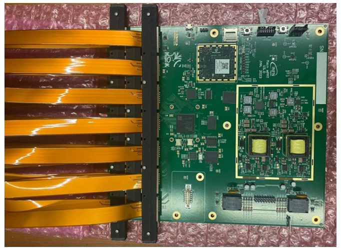




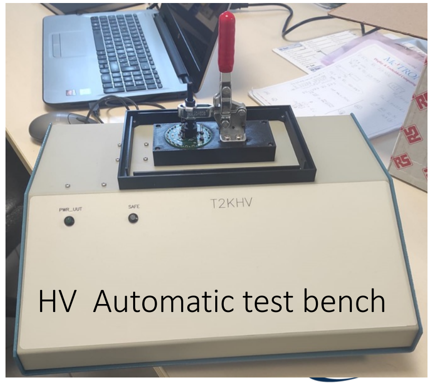


Electronics test station in Italy

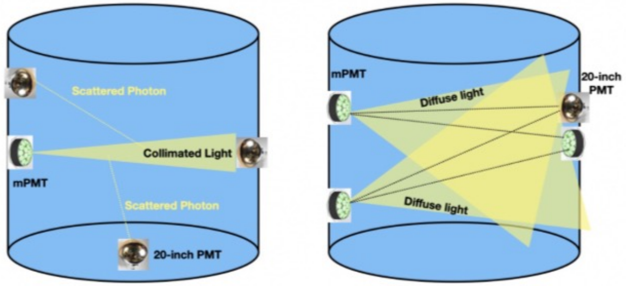
Preparation for testing station and procedures for testing during mass production ongoing



Test station during construction planned in Italy

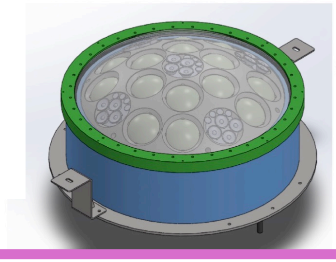


HV Automatic test bench



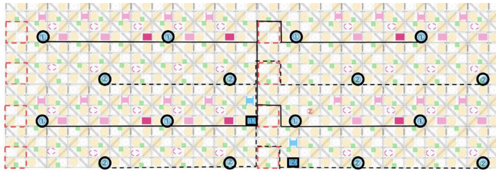
- 200 LED mPMTs
  - grid of 10m spacing
- Collimated light
  - water scattering/ absorption
    - Time of flight to identify the scattering position
  - Reflection measurement
- Wide-angle light
  - PMT angular response
  - timing select direct light

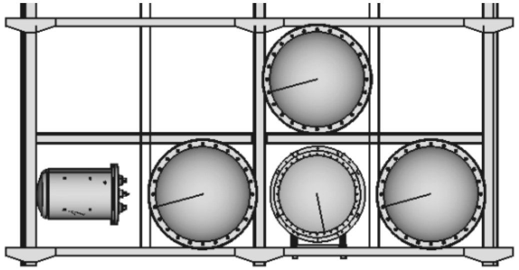
LED-focused mPMTs in Canada

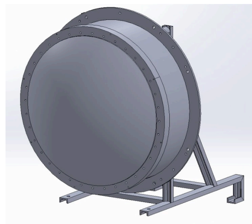


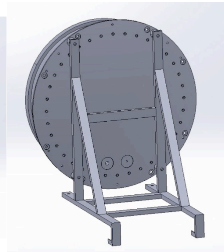
mPMT installation studies in Czech, Italy, Mexico

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









mPMT Packaging and Transportation Tests in Mexico

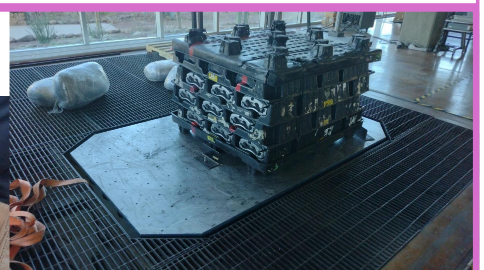
Studies on packaging

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

Studies for transportation

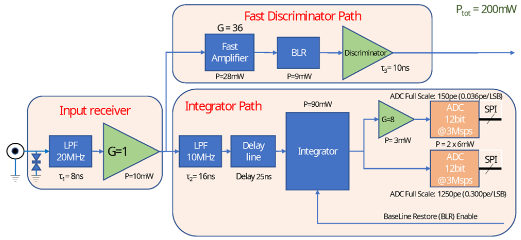
- Compression test to evaluate that the box is capable of withstanding the stowage
- Shock (drops) test
- Vibration tests: frequency based on transport frequencies
- Inclined impact test

First packing prototype built!



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



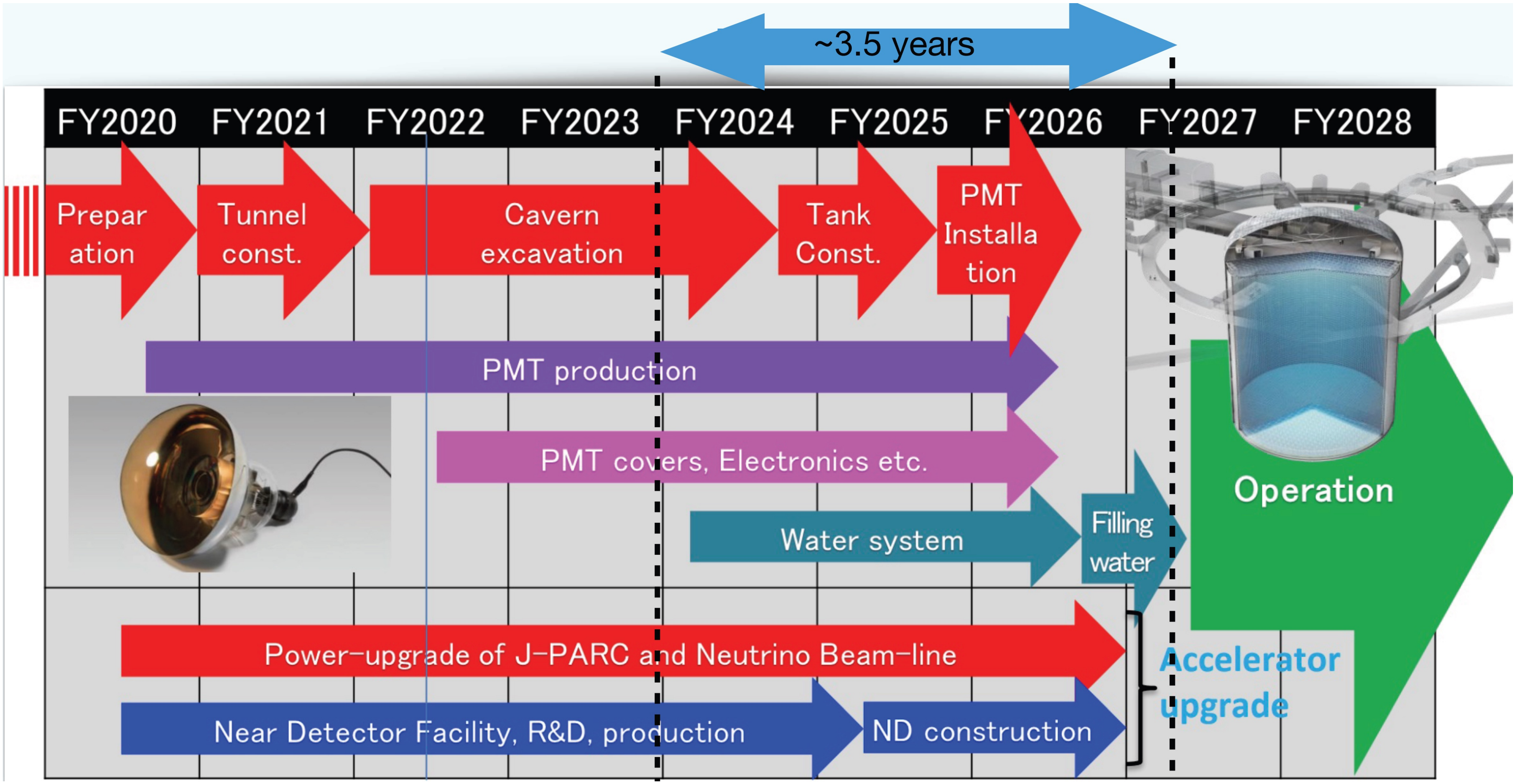
Critical components reviewed and procurement and tendering started in 2023

Final prototype early 2024

The tender for the board production will start early 2024

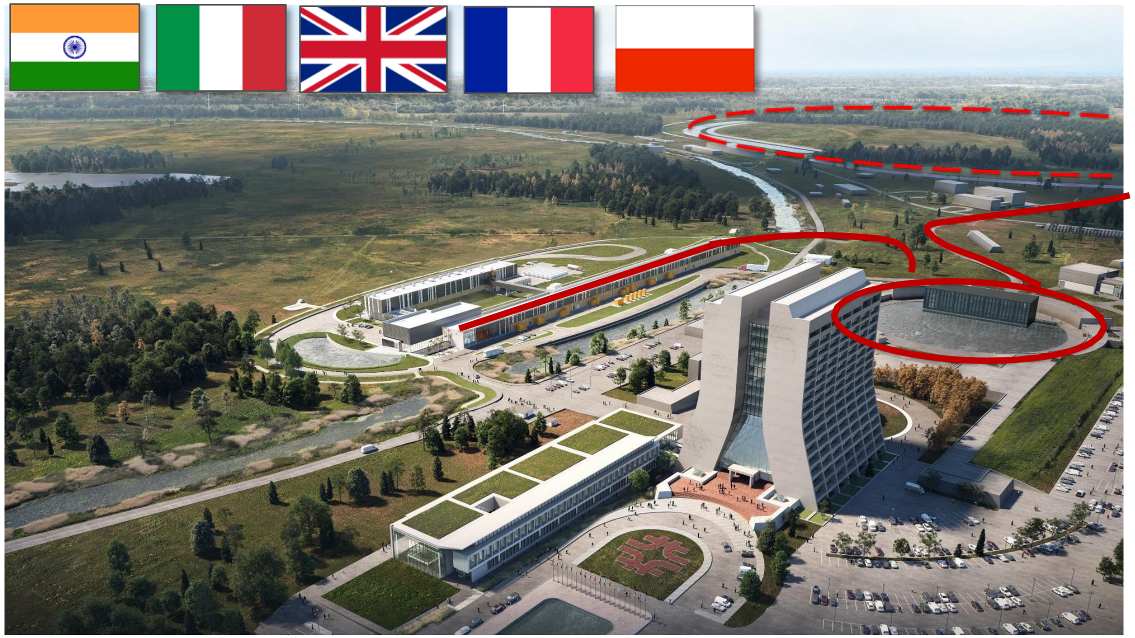
Start mass production by the end of 2024

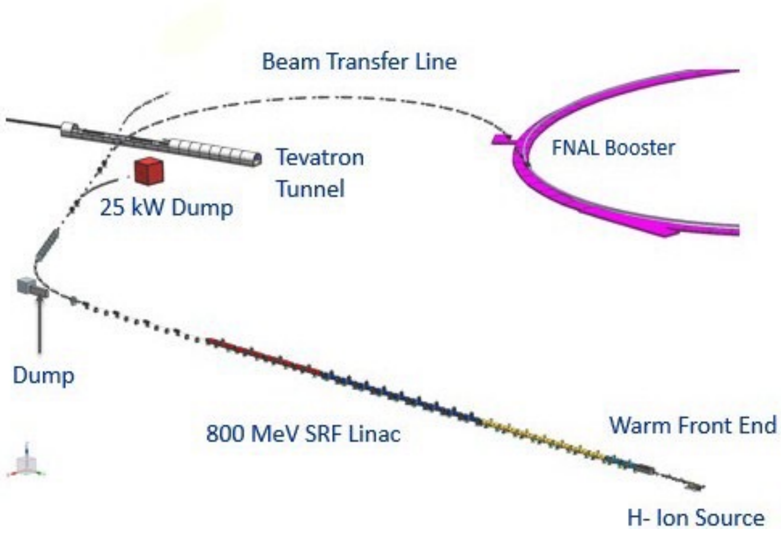
Hyper-K timetable



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

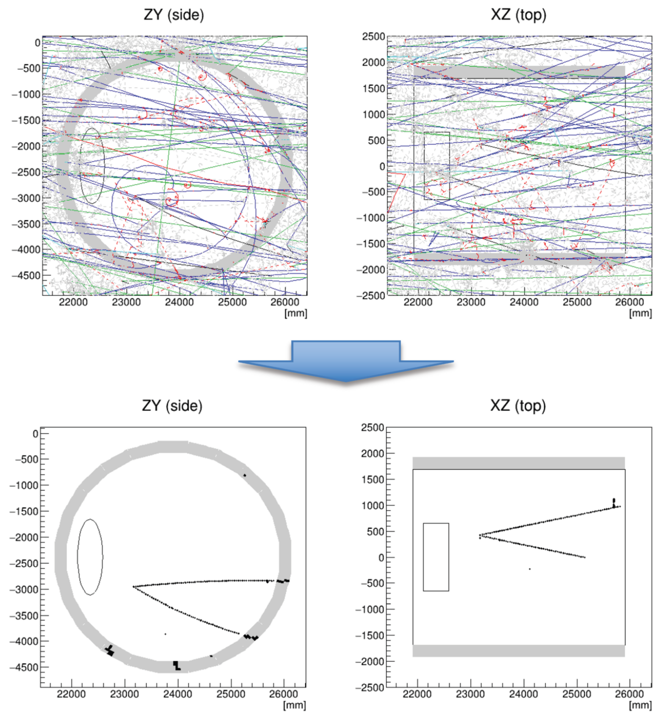
SAND Tracker

Two options: STT (Straw Tube Tracker)
DC (Drift chambers)

Truly international involvement: US, Georgia, India, Kazakistan, INFN

Prototyping and test undergoing

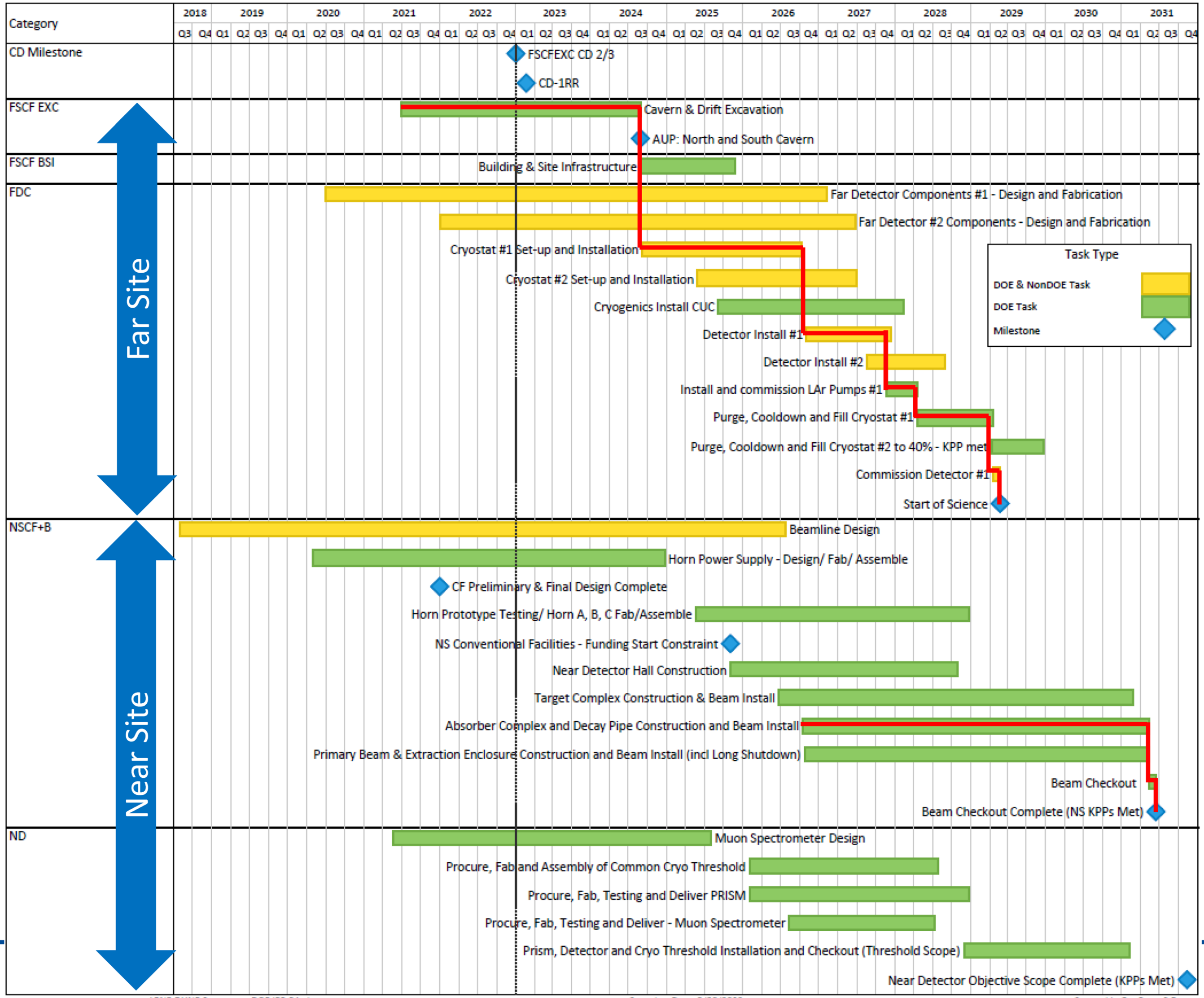
From here



To here

10 µsec spill of ν_μ beam

Summary Schedule with Critical Paths through Start of Science (FD1) and Beam-on



Favorable execution schedule enabled by new DOE funding profile in March 2022

Notes:
- Fiscal Year display
- Early completion dates shown