Multi-Aspect Young-ORiented Advanced Neutrino Academy (MAYORANA) - International School&Workshop II edition

16–25 Jun 2025
Modica
Europe/Rome timezone

Neutrino physics at INFN

An incomplete biased review

Marco Pallavicini - Università degli Studi di Genova and INFN

Many slides stolen from Oliviero Cremonesi and CSN2 coordinators. Thanks!

INFN
Istituto Nazionale di Fisica Nucleare

State of the art in neutrino physics

- The 3 mixed massive-ν paradigm has been quite successful (modulo a few not understood “anomalies”)
  - However, knowledge and understanding of neutrino sector is far from being complete:

PDG

$$|\Delta m^2| = 2.49 \pm 0.04\ 10^{-3}\ eV^2 \quad [1.4\%] \qquad \delta m^2 = 7.73 \pm 0.18\ 10^{-5}\ eV^2 \quad [2.2\%]$$

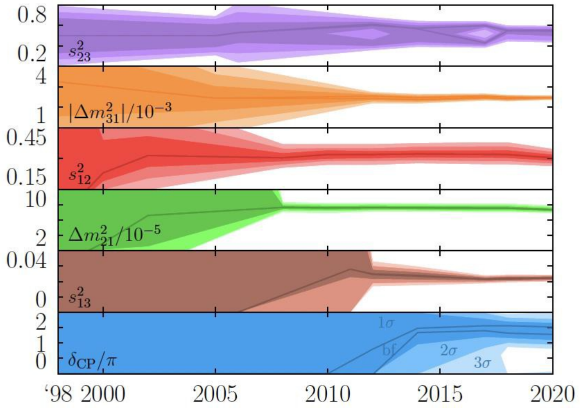
$$\sin^2(\theta_{23}) = 0.54 \pm 0.2 \quad [5\%] \qquad \sin^2(\theta_{13}) = 2.20 \pm 0.07\ 10^{-2} \quad [3.2\%] \qquad \sin^2(\theta_{12}) = 0.307 \pm 0.013 \quad [4\%]$$

UNKNOWN

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_D} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta_D} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

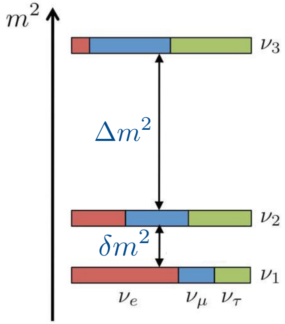
Majorana phases not relevant for oscillations

PROGRESS SINCE 1998 SK DISCOVERY

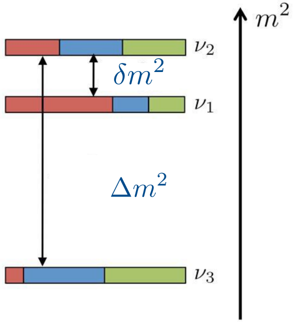


arXiv:2212.00809

Normal Ordering

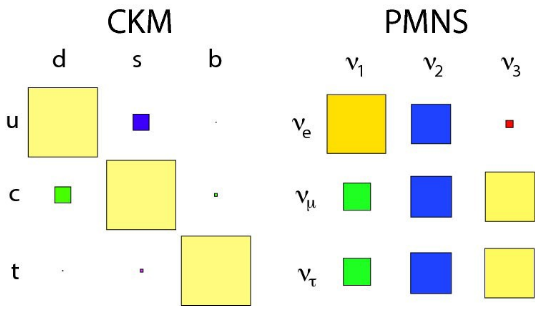


Inverted Ordering

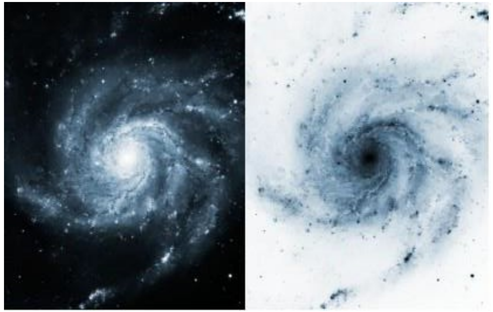


Fundamental Questions

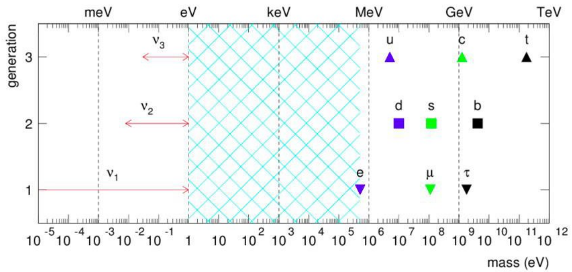
Can ν mixing teach us something about flavour ?
Are there underlying flavour symmetries ?



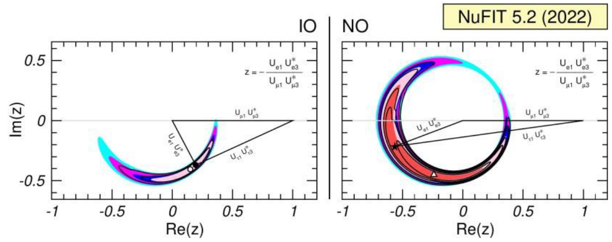
Is leptogenesis playing a role in BB matter-antimatter asymmetry ? Do protons decay ?



What is the origin of neutrino mass?
Why are the neutrinos so light? Is lepton number conserved ?



Are there light sterile neutrinos?
Can non-unitary reveal new physics BSM ?
Are there non standard neutrinos?



JHEP 09 (2020) 178

Oscillations: experimental efforts

Atmospheric ν

L ~10^3-10^4 km,
E~10^2-10^4 MeV
matter effects

- **KM3NeT**
- IceCube
- **JUNO**

Accelerator ν

L ~1 km or 10^2-10^3 km
E~10^3 MeV
matter effects

- **T2K**
- NOvA
- **ICARUS,** SBND
- **DUNE, HyperK**

Reactor ν

L ~1-10^2 km
E~MeV

- **JUNO**
- KamLAND
- RENO
- + short-baseline

Neutrino properties (from PDG 2024)

Exploring different sectors, based on experimental design

Experiment	Dominant	Important
Solar Experiments	θ_{12}	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	θ_{13}, $\|\Delta m^2_{31,32}\|$	
Atmospheric Experiments (SK, IC-DC)		θ_{23},$\|\Delta m^2_{31,32}\|$, θ_{13},δ_{CP}
Accel LBL ν_μ,$\bar{\nu}_\mu$, Disapp (K2K, MINOS, T2K, NOνA)	$\|\Delta m^2_{31,32}\|$, θ_{23}	
Accel LBL ν_e,$\bar{\nu}_e$ App (MINOS, T2K, NOνA)	δ_{CP}	θ_{13} , θ_{23}

S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)

Several experiments at a maturity stage,
others set to begin or be upgraded

Why measuring δ_{CP} is important ?

- We do not understand the **origin of matter-antimatter asymmetry in the Universe**
    - To get it you need CP violation (and baryon number violation)
    - Is the CP violation required explained by Standard Model + PMNS ?

- CP violation is proportional to so called Jarlskog invariant

$$J = \sin\vartheta_{12}\cos\vartheta_{12}\sin\vartheta_{23}\cos\vartheta_{23}\sin\vartheta_{13}\cos^2\vartheta_{13}\sin\delta_{CP} = J_{max}\sin\delta_{CP}$$

$$J_{max}^{quarks} = (3.18 \pm 0.15)\cdot 10^{-5}$$

$$J_{max}^{leptons} = (3.3 \pm 0.06)\cdot 10^{-2}$$

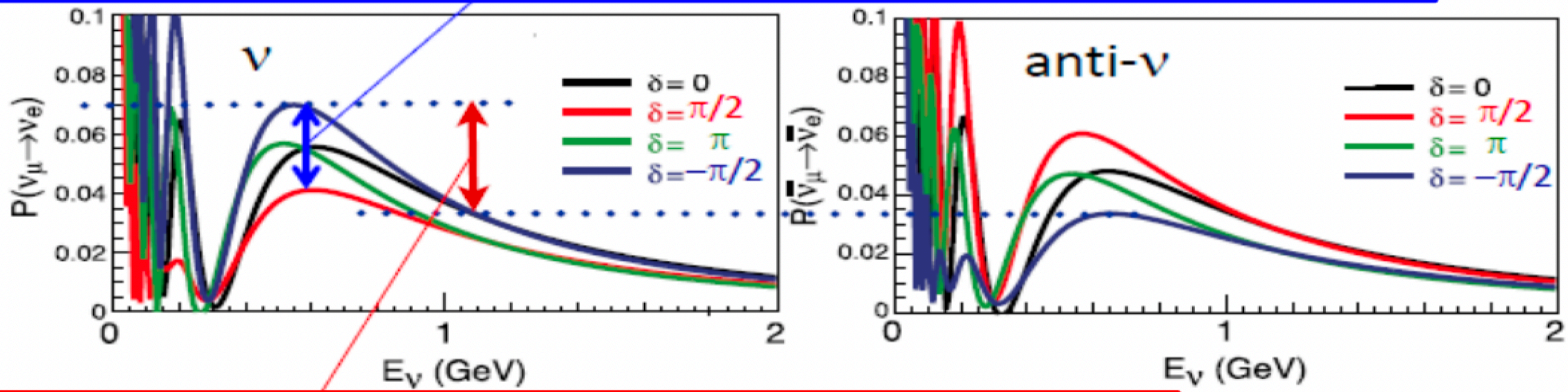
    - Quarks are ruled out
    - Leptons, not necessarily. They may play a role, possibly not unique.

- **Be aware:** you need, anyway, a **baryon number violation mechanism,** which cannot be related directly to lepton sector

Measuring CPV (1): electron neutrino appearance

- δ_{CP} → a modulation in the spectrum of the appeared ν_e
- The direction of the variation is opposite for ν and anti-ν beams → use both
- ~ change in normalization: @ 2nd maximum (at low E) → more "shape" info.
- Sub-leading: crucial role of systematics and statistics

method 1: use θ_{13} from reactor experiments and compare with data



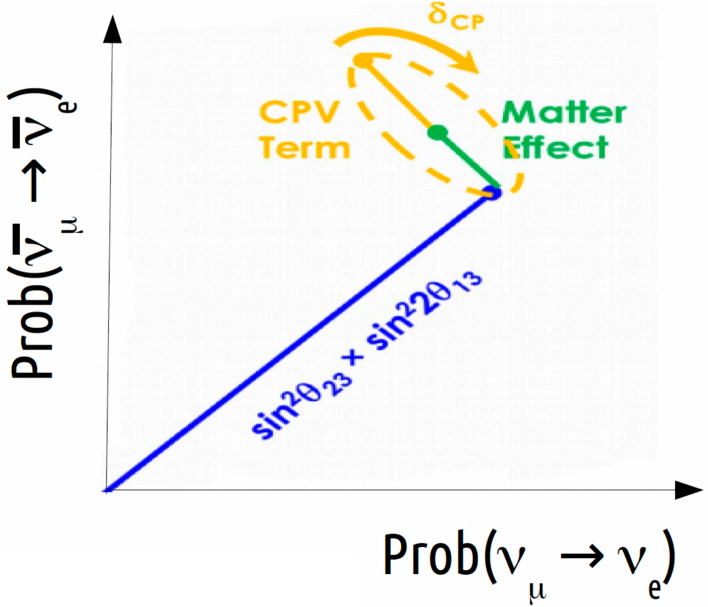
method 2: compare measured $P(\nu_\mu \to \nu_e)$ with $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

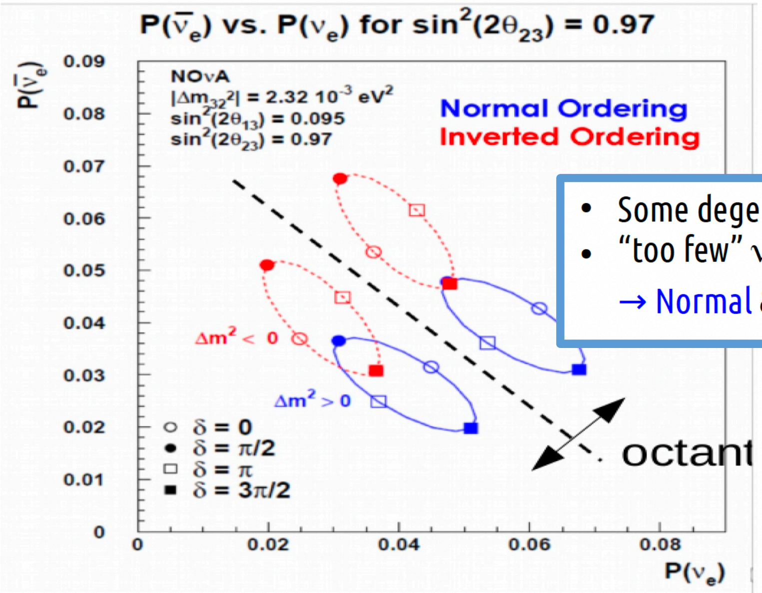
Courtesy: A. Longhin

Measuring CPV (2)

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) = & \, 4 c_{13}^2 \underline{s_{13}^2} s_{23}^2 \sin^2 \Delta_{31} \quad \text{dominant term} \\
& + 8 c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta_{CP} - s_{12} s_{13} s_{23}) \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \\
& - 8 c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \underline{\sin\delta_{CP}} \sin\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \quad \text{CP violation} \\
& + 4 s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2 c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta_{CP}) \sin^2\Delta_{21} \\
& - 8 c_{13}^2 s_{13}^2 s_{23}^2 \underline{\frac{a L}{4 E_\nu}} (1 - 2 s_{13}^2) \cos\Delta_{32} \sin\Delta_{31} + 8 c_{13}^2 s_{13}^2 s_{23}^2 \underline{\frac{a}{\Delta m_{31}^2}} (1 - 2 s_{13}^2) \sin^2\Delta_{31} \quad \text{matter}
\end{aligned}
$$

- θ_{13}
- CP violation,
- mass hierarchy
  - matter effects at large L
- the octant of θ_{23}





- Some degeneracy
- "too few" ν_e or "many" ν_e
  → Normal & $\delta_{CP} = 3/2\pi$

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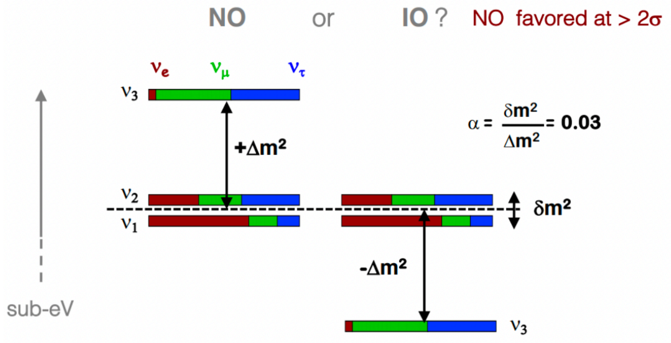
Courtesy: A. Longhin

Measuring mass ordering

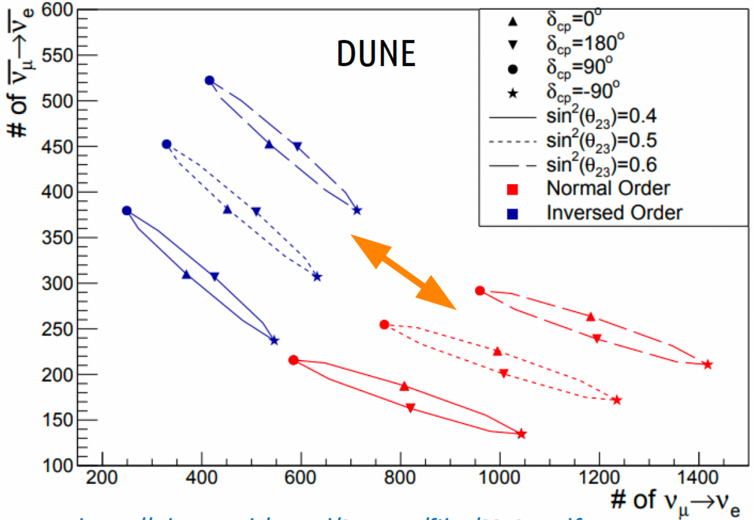
$$-8\,c_{13}^2 s_{13}^2 s_{23}^2 \frac{a L}{4 E_\nu}(1-2 s_{13}^2)\cos\Delta_{32}\sin\Delta_{31} + 8\,c_{13}^2 s_{13}^2 s_{23}^2 \frac{a}{\Delta m_{31}^2}(1-2 s_{13}^2)\sin^2\Delta_{31}$$

Matter term of $P(\nu_\mu \to \nu_e)$ is odd on the atmospheric Δm^2

Works well if matter effect is large (long baselines, i.e. DUNE, atmospheric neutrinos)



Terminology: Hierarchy ~ Ordering
NO or NH = normal
IO or IH = inverted



Courtesy: A. Longhin

https://cds.cern.ch/record/2641657/files/SS18-4.pdf

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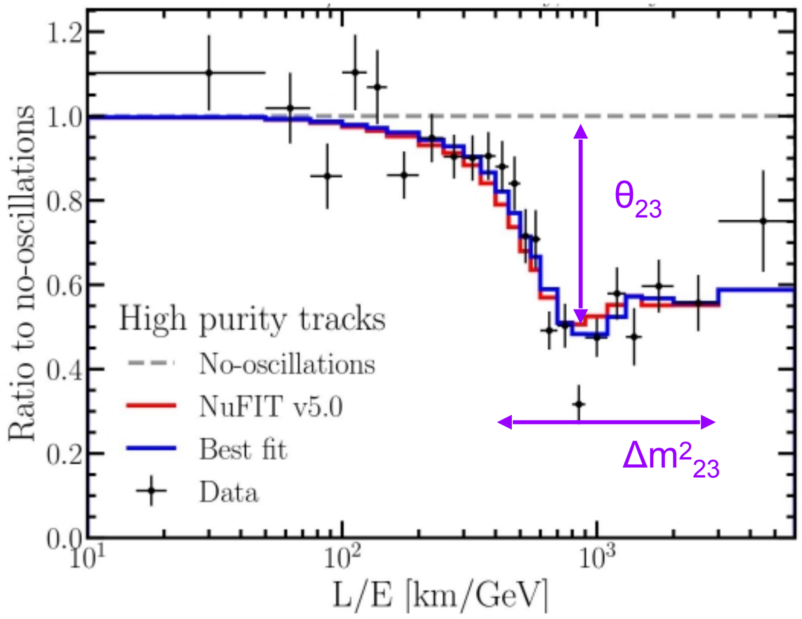
Atmospheric ν experiments

Leading order $\sin^2 2\theta_{23}$ and Δm^2_{32}

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \cdot \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$



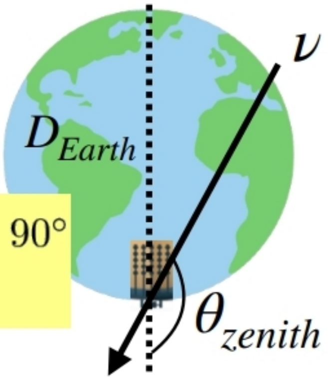
ν/anti-ν asymmetry in MSW resonance thanks to matter effects (4-30 GeV):
oscillation probabilities for NO and IO are different due to ν path through the Earth matter.

Up-going muon ν: MSW resonance takes place according to sign($\boldsymbol{A/\Delta m^2_{3\ell}}$), where A = ν-matter potential

$$P(\nu_e \to \nu_e) \approx 1 - \sin^2 2\theta_{13}^{m} \sin^2\left[1.27\left(\Delta m^2_{31}\right)^{m} \frac{L}{E_\nu}\right];$$

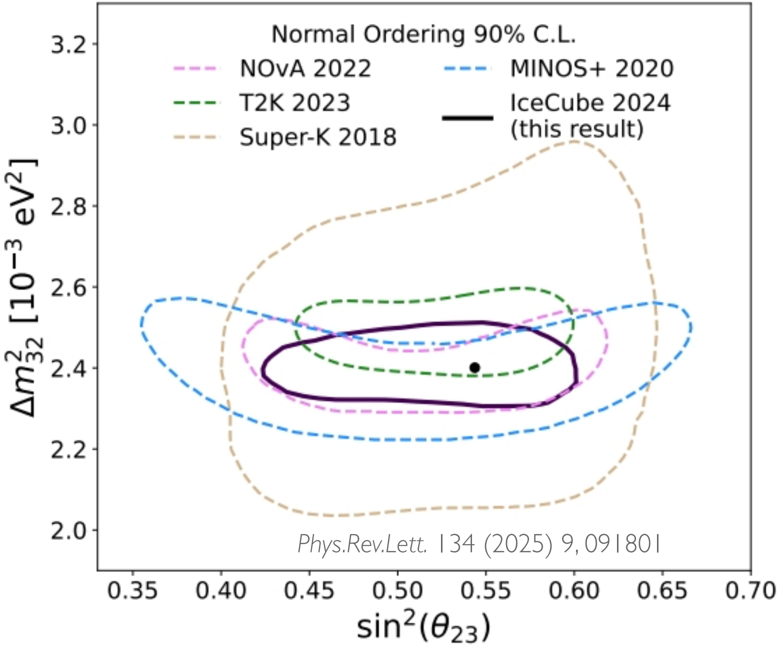
$$\sin^2 2\theta_{13}^{m} = \frac{\sin^2 2\theta_{13}}{\left(\cos 2\theta_{13} - A/\Delta m^2_{31}\right)^2 + \sin^2 2\theta_{13}}.$$

$$L \approx -D_{Earth}\cos(\theta), \quad \theta > 90^\circ$$
$$L \approx 0, \text{ otherwise}$$



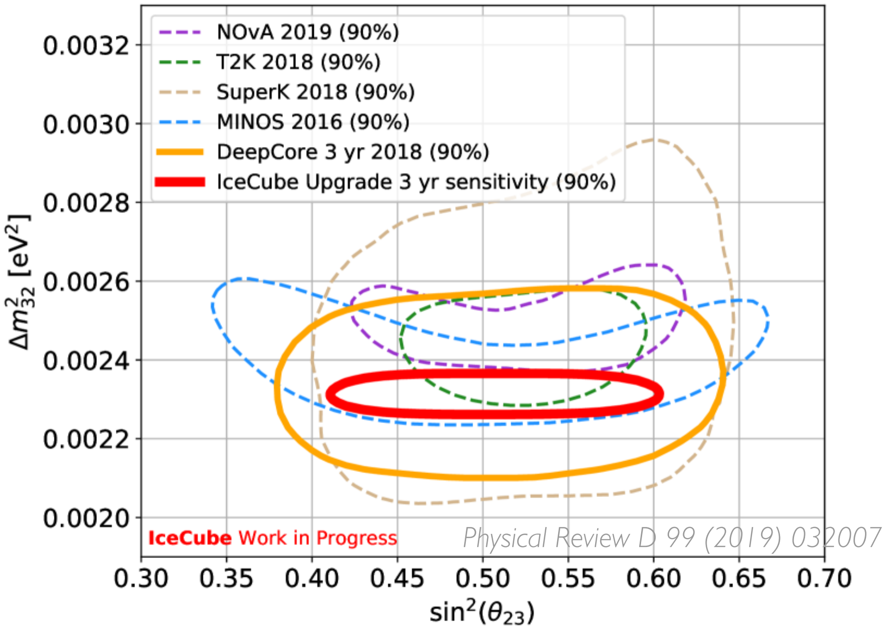
ν:	$A > 0$	MSW if $\Delta m^2_{3\ell} > 0$	NO
anti-ν:	$A < 0$	MSW if $\Delta m^2_{3\ell} < 0$	IO

9.3 years of data in IceCube DeepCore



Comparable θ_{23} and mass splitting precision to LBL experiments

Icecube Upgrade proposal



Conservative estimates predict world-leading results within 1 year of data-taking

KM3neT

KM3NeT is a research infrastructure in the Mediterranean Sea hosting two neutrino detectors

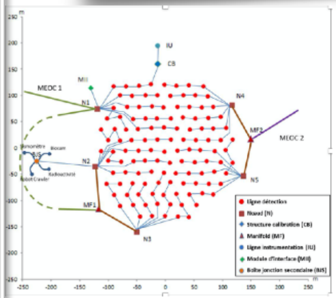
KM3NeT/ORCA: Study of the physical proper5es of the neutrino – neutrino mass ordering

KM3NeT/ARCA: Discovery and observation of cosmic neutrino sources

Two different detectors with the same technology and operated by the same collaboration

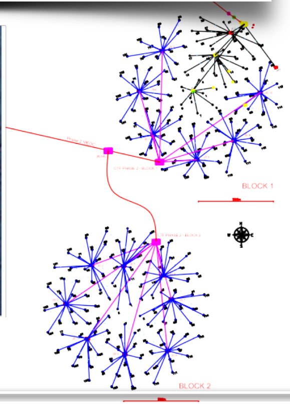
ORCA (Oscillation Research with Cosmic in the Abyss)

- Depth ~2500 m
- One block of 115 Detection Units
- Average distance between Detection Units ~20 m
- Average vertical distance between DOMs ~9 m
- Volume ≈ 7 Mton

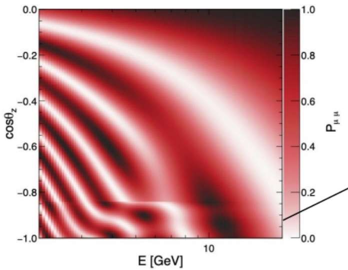


ARCA (Astroparticle Research with Cosmic in the Abyss)

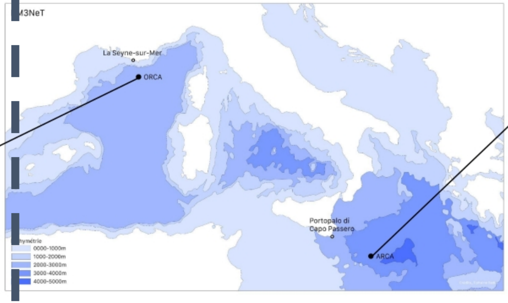
- Depth ~3500 m
- Two blocks of 115 Detection Units each
- Average distance between Detection Units ~90 m
- Vertical distance between DOMs ~36 m
- Volume $(0.5 \times 2)\ km^3 \approx 1$ Gton

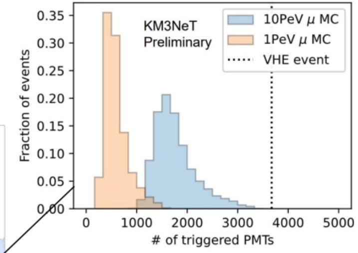


Atmospheric ν : KM3NeT

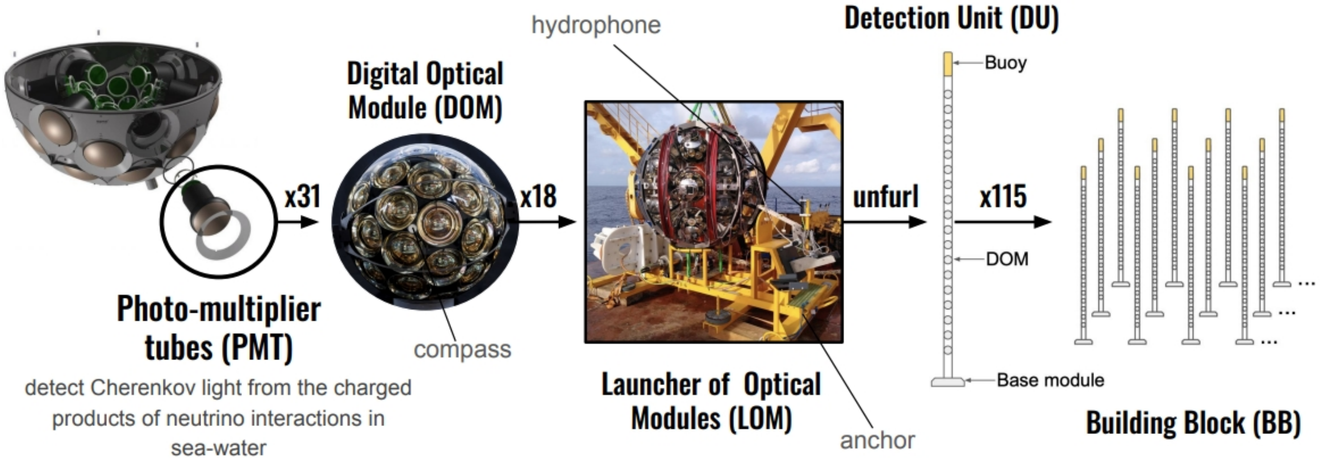


probe GeV neutrinos
ORCA



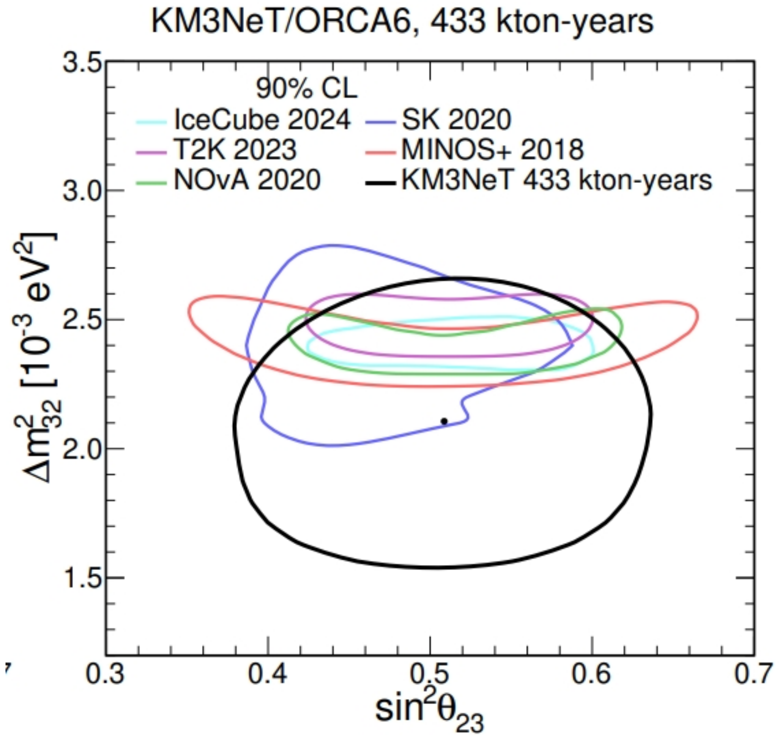


probe TeV-EeV neutrinos
ARCA



detect Cherenkov light from the charged products of neutrino interactions in sea-water

Atmospheric ν : KM3NeT (ORCA) today

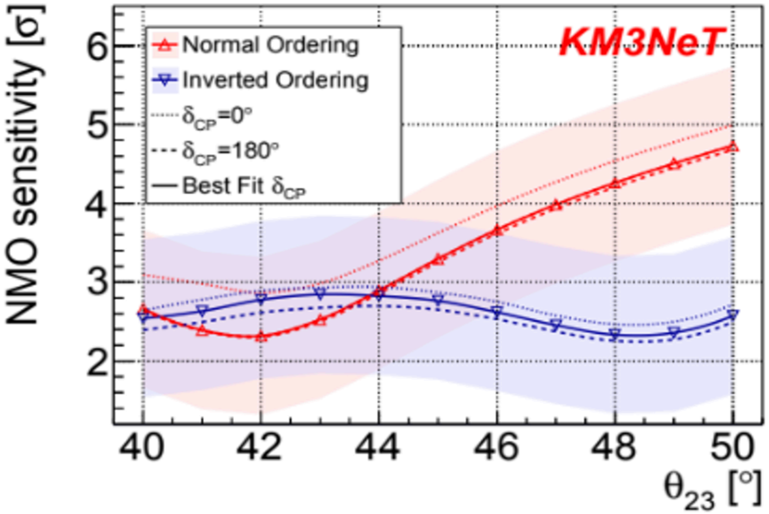


- low preference for IO
- maximum mixing preferred

Measurement of neutrino oscillation parameters with the first six detection units of KM3NeT/ORCA JHEP 10 (2024) 206

ORCA perspectives

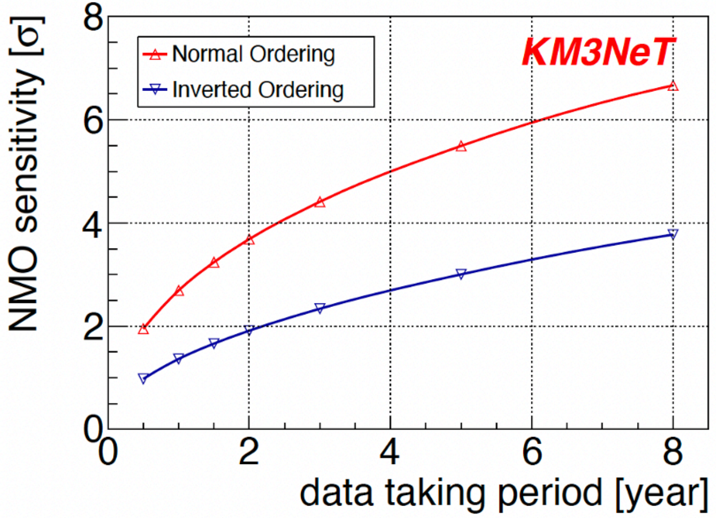
3 years



With full detector: 2.5-5σ determination of NMO possible in 3 years

S. Aiello et al. [KM3NeT], "Determining the neutrino mass ordering and oscillation parameters with KM3NeT/ORCA", Eur. Phys. J. C 82 (2022) no.1, 26, doi:10.1140/epjc/s10052-021-09893-0 [arXiv:2103.09885 [hep-ex]].

Theta23=48 deg



S. Aiello et al. [KM3NeT and JUNO], "Combined sensitivity of JUNO and KM3NeT/ORCA to the neutrino mass ordering", JHEP 03 (2022), 055, doi:10.1007/JHEP03(2022)055 [arXiv:2108.06293 [hep-ex]].

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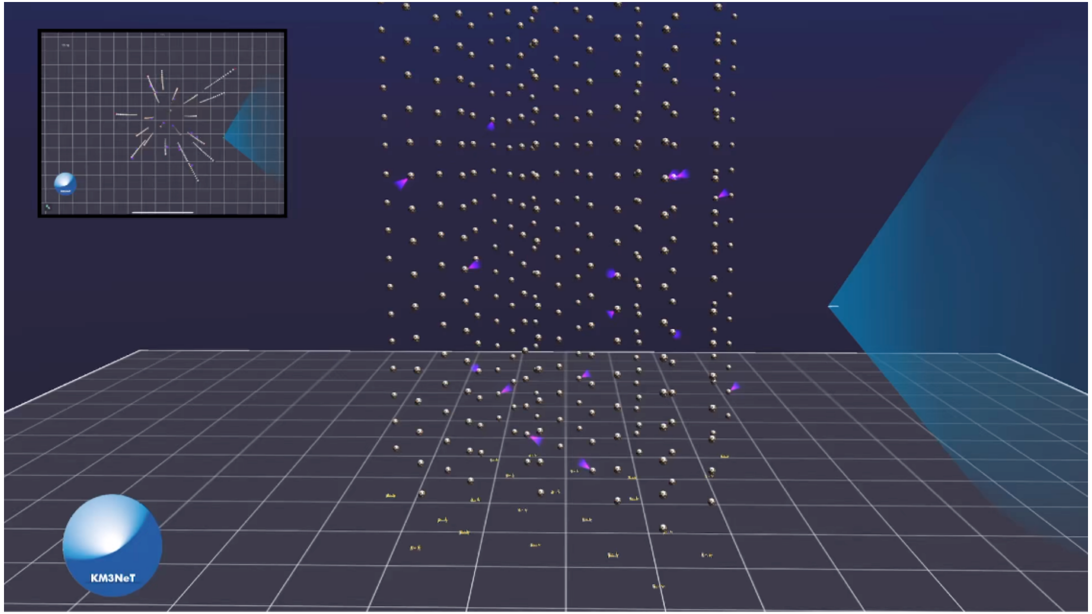
KM3neT: the highest energy event ever observed

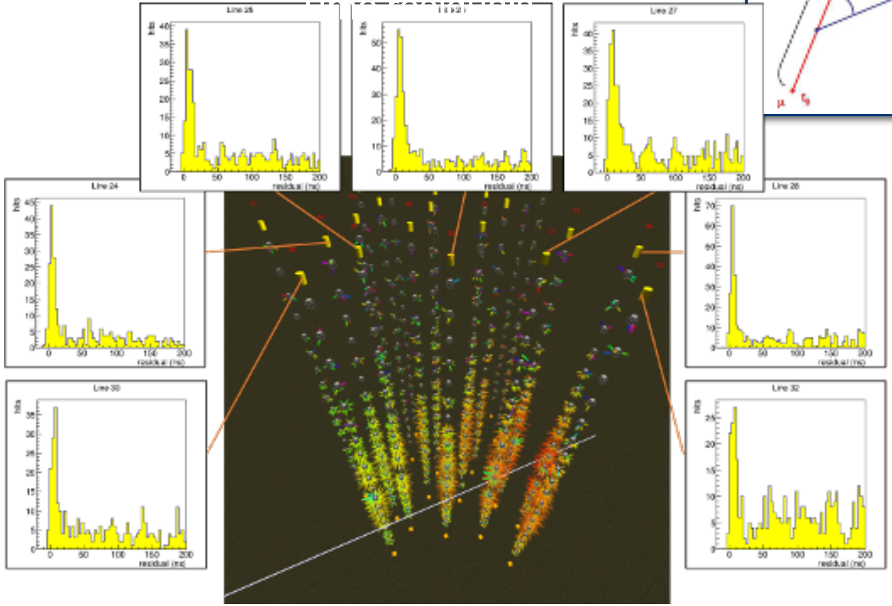
The February 13 2023 an event with the highest energy ever seen has been detected with ARCA when it consisted of 21 Lines

- Huge amount of light detected 35% of the total number of PMTs were triggered

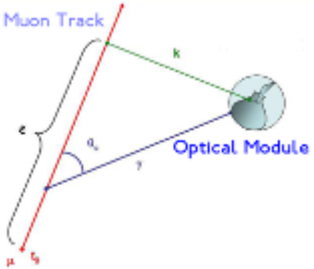


Nature 638, 376–382 (2025) (https://www.youtube.com/watch?v=2jgyZIBpkI8)

KM3neT: the highest energy event ever observed



$$t_{th} = t_0 + \frac{1}{c}\left(\ell - \frac{k}{\tan\theta_C}\right) + \frac{1}{v_g}\left(\frac{k}{\sin\theta_C}\right)$$

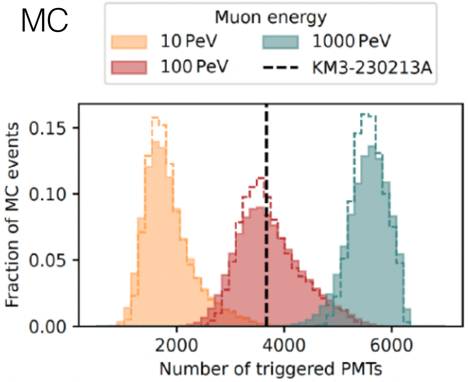


$$t_{res} = t_{det} - t_{th}$$

A cosmic neutrino!

- With a very high energy
  - the muon energy is estimated by counting the number of PMTs participating at the triggering of the event

MC



- **Energy is measured from the amount of light:**

$$E_\mu = 120^{+110}_{-60} \text{ PeV}$$

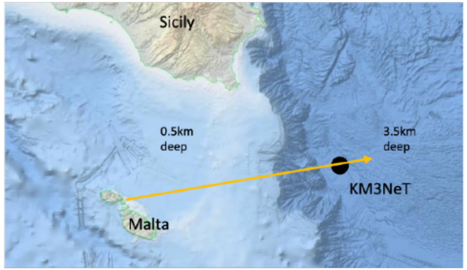
(10 000 times the energy of the LHC)

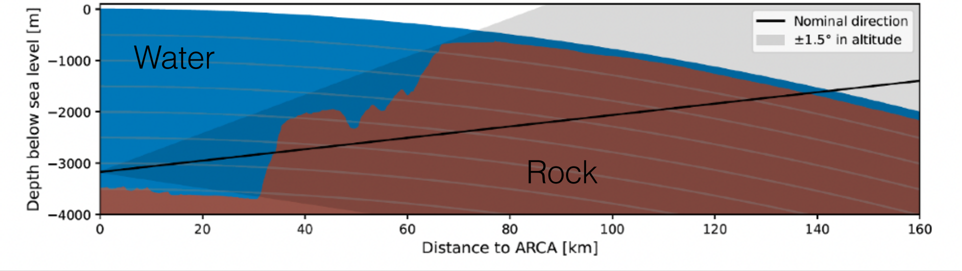
- **The neutrino Energy is higher:**

$$E_\nu = 220^{+570}_{-100} \text{ PeV}$$

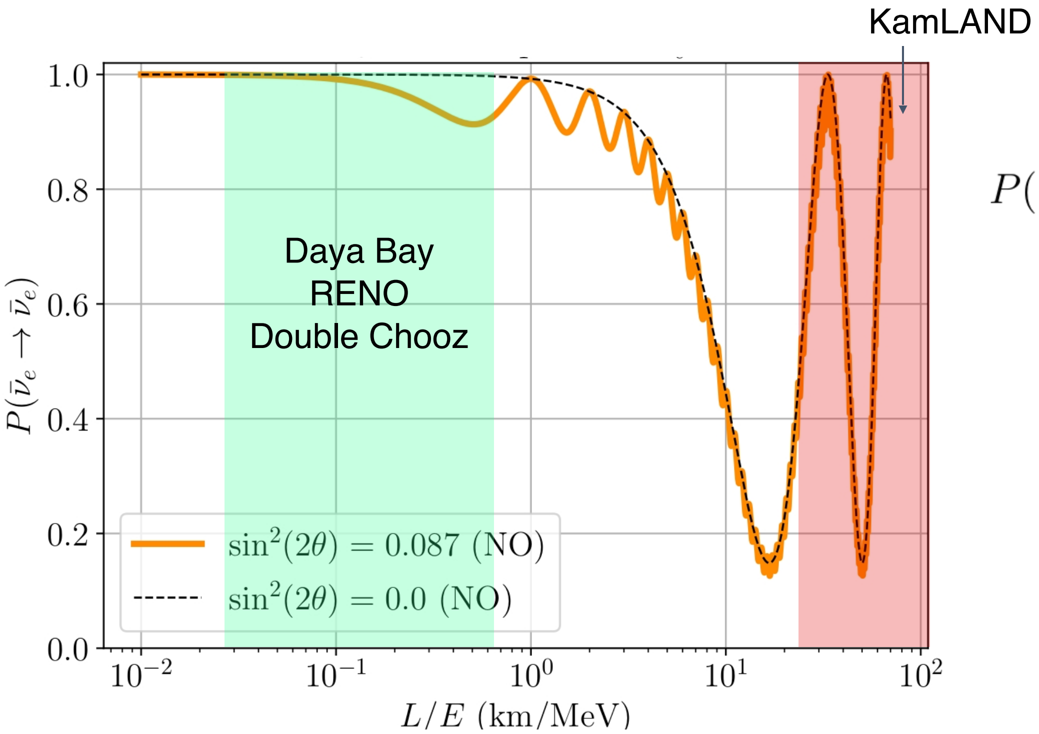
Assuming a E^{-2} muon neutrino spectrum

- It is a horizontal event (0.6° above the horizon) traversing ~140km of rock&water





A wide L/E range to explore different oscillation features



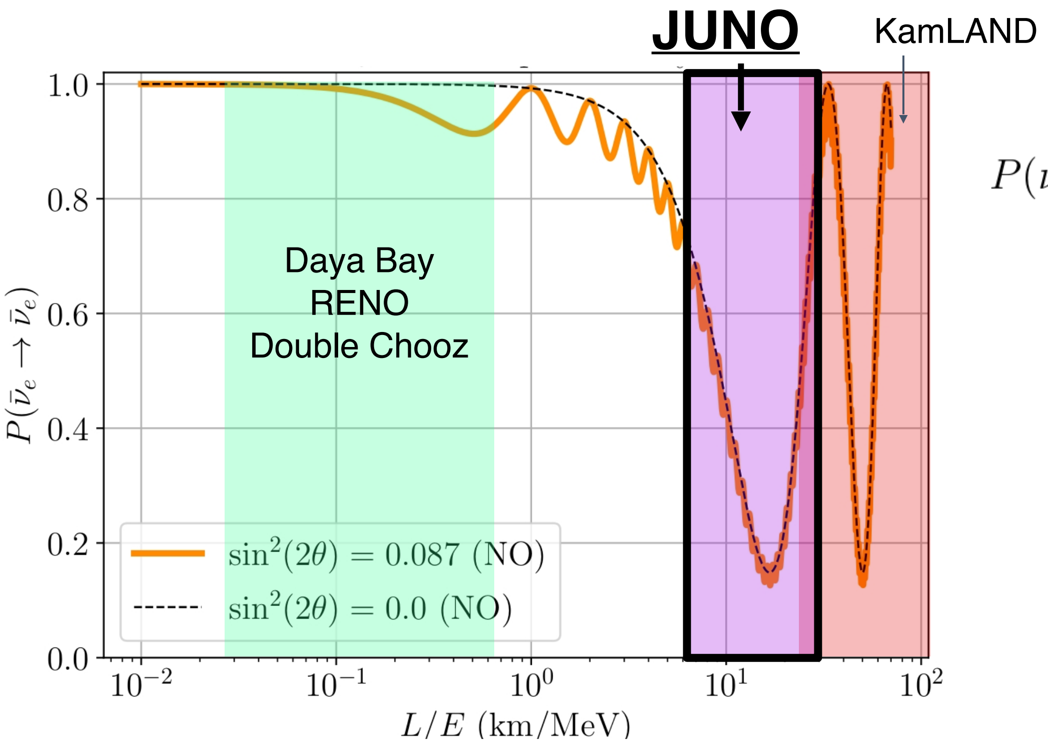
Medium baseline (θ_{12}, Δm^2_{21})

$$P(\nu_e \to \nu_e) = 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) - \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) - \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})$$

Short baseline (θ_{13}, Δm^2_{3l})

$$\Delta_{kj} = 1.27 \Delta m^2_{kj} [\mathrm{eV}^2] \frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}$$

A wide L/E range to explore different oscillation features



Medium baseline (θ_{12}, Δm^2_{21})

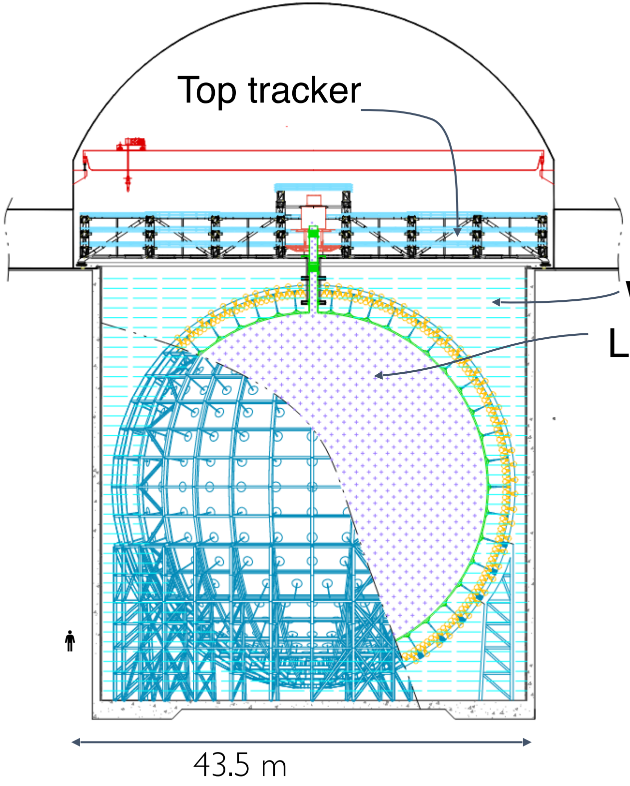
$$P(\nu_e \to \nu_e) = 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) - \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) - \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$

Short baseline (θ_{13}, Δm^2_{3l})

$$\Delta_{kj} = 1.27\Delta m^2_{kj}[\mathrm{eV}^2]\frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}$$

Reactor ν: JUNO

- **Medum baseline,** L = 52 km, E ~ MeV
- **Largest liquid scintillator ever (20 kton)**, equipped with 17612 large PMTs + 25600 small PMTs to collect scintillation light
- Data taking started in December 2024



Experiment	Daya Bay	Borexino	KamLAND	JUNO
Target mass [kt]	0.16	~0.3	~1	**~20**
Photo electrons / MeV	~160	~500	~250	**~1600**
Energy resolution @MeV	~8.5%	~5%	~6%	**~3%**
Photocathode coverage	12%	34%	34%	**78%**
Energy cal. Uncert.	0.5%	1.0%	2.0%	**<1%**

Reactor ν: JUNO, experimental challenges

1) Large statistics

→ huge scintillator mass, powerful nuclear reactors

2) Energy resolution: 2.95% @ 1MeV + 1% understanding of the intrinsically non-linear energy scale

→ LS optical properties + light collection + calibrations

3) Low background

→ underground + scintillator purification system + material screening + veto systems

4) Knowledge of reactor spectra at sub-% level

→ near detector: Taishan Antineutrino Observatory (TAO) at 44 m from Taishan reactor

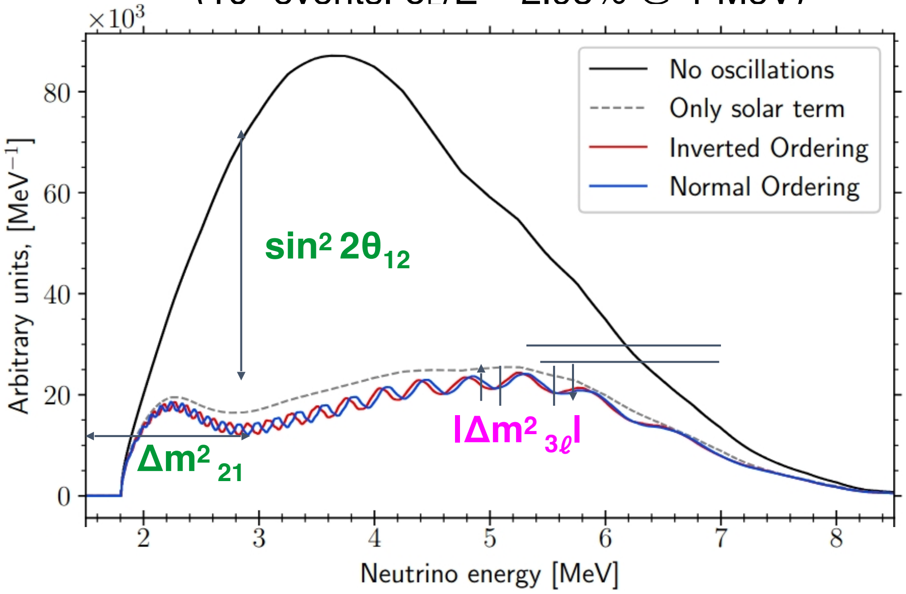
→ reduce spectral shape systematics

Reactor ν: JUNO

First experiment to observe both **fast** ($\sin^2\theta_{13}$, $|\Delta m^2_{3\ell}|$) and **slow** ($\sin^2\theta_{12}$, Δm^2_{21}) oscillations **in vacuum**

→ **interference pattern depends on NMO**
… no dependence on θ_{23} , δ_{CP}, small dependence on matter effects: **no degeneracies.**

Exemplary spectrum, 6y
(10^5 events. σ_E/E = 2.95% @ 1 MeV)

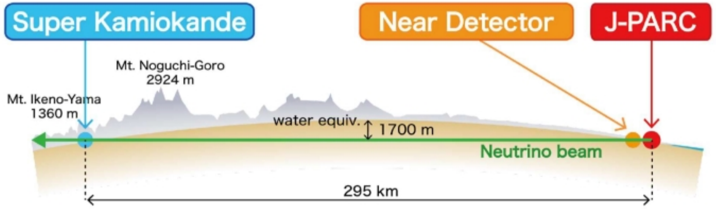


Chin. Phys. C46 (2022) 12, 123001

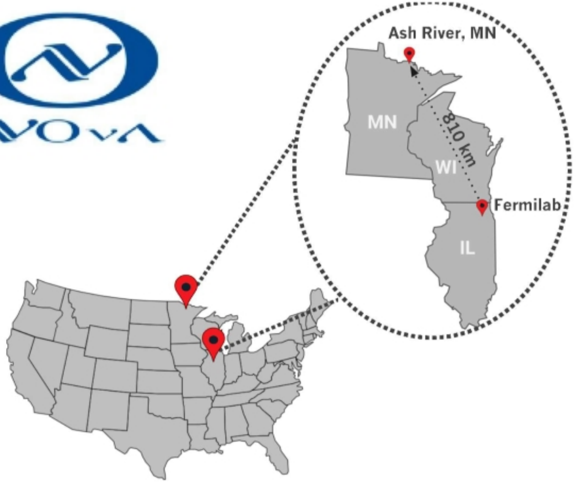
	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)	±0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)	±0.0016 (7.3%)

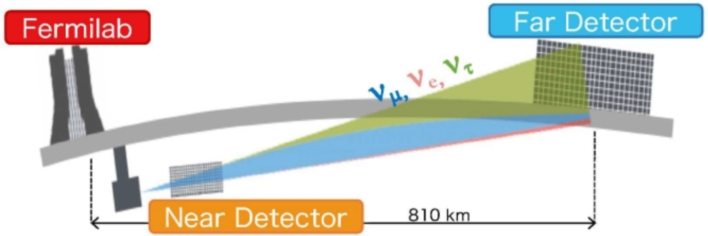
Long base line: Noνa and T2K

T2K



NOvA





L = 295 km, E_{peak} = 0.6 GeV

L = 810 km, E_{peak} = 2 GeV

Long base line: Noνa and T2K

Leading order $\sin^2\theta_{23}, \sin^2 2\theta_{13}$ and Δm^2_{32} in vacuum

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

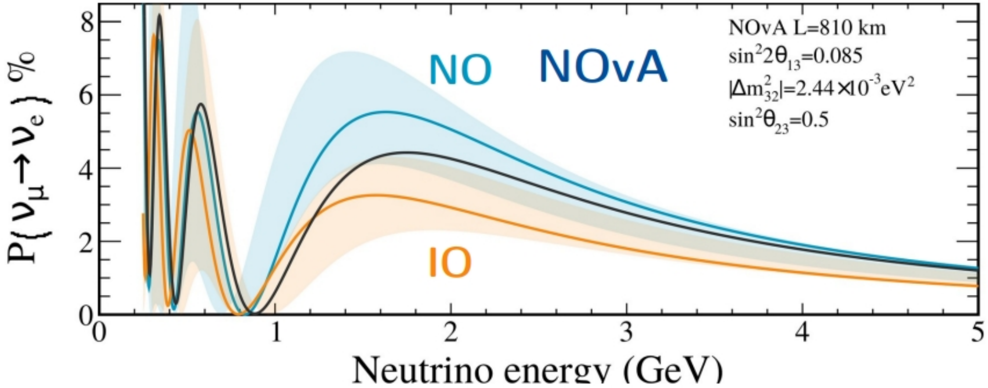
$+\ \delta_{CP}$ dependent terms CP violating

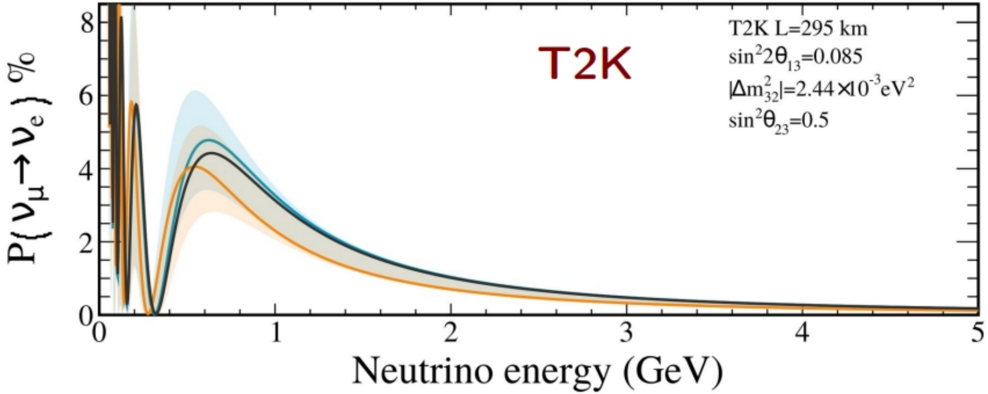
$+\ \delta_{CP}$ dependent terms CP conserving

$+$ other terms

- In many LBL neutrino oscillation experiments matter effect and CP violation are degenerate
  - Not for DUNE, which has a wide beam and long distance, allowing to separate the two effects

Long base line: Noνa and T2K





NOvA: lower E and shorter L reduces the matter effects → less degenerate CPV values of δ_{CP}

T2K: higher E and longer L enhances the NMO dependent matter effects

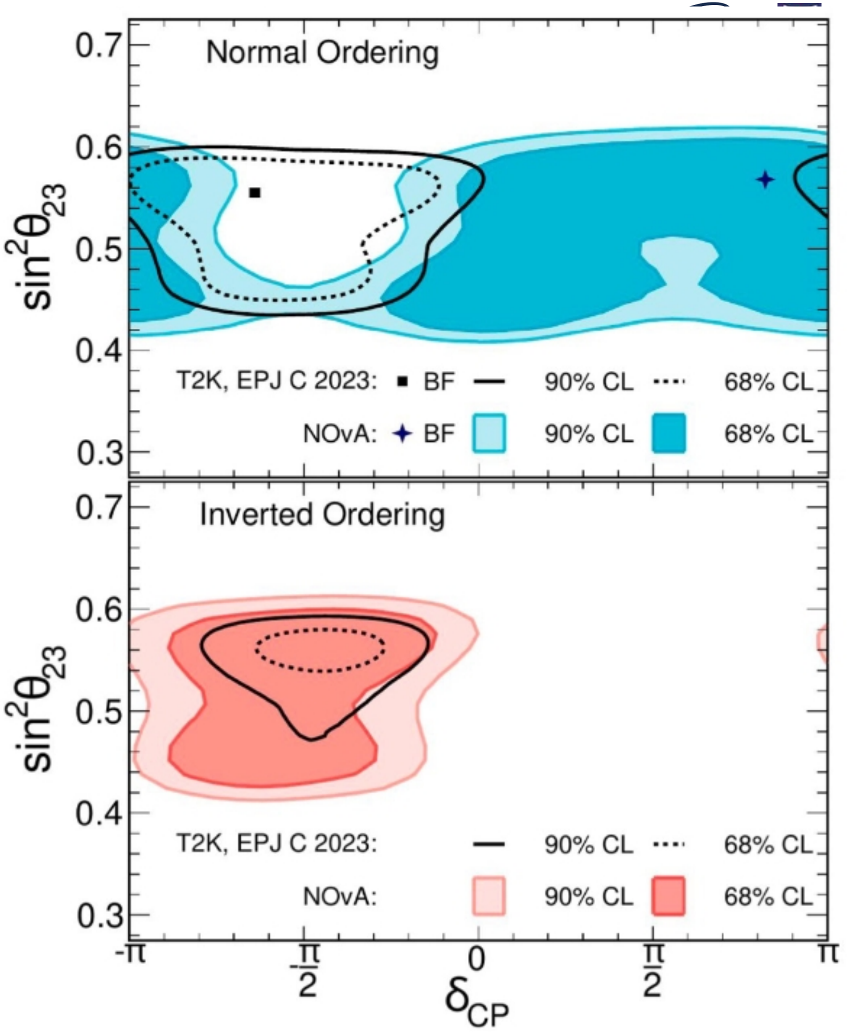
→ impact on P(v*μ* → ve) and P(anti-v*μ* → anti-ve) differs for each experiment

Long base line: Noνa and T2K

Joint analysis lifts degeneracies of individual experiments.
Based on Eur. Phys. J. C (2023) 83: 782 and Phys. Rev. D 110, 012005

NMO:
- Joint analysis flips the preference for the IO: T2K and NOvA individually prefer NO
- Very weak preference for IO, Bayes factor 1.3

δCP:
- Degeneracy between δCP and MO
- NO: allows for a broad range of possible δCP
- IO: CP-conserving outside 3σ CIs
- Neither NMO points to δCP ~ +π/2 (outside 3σ CI)

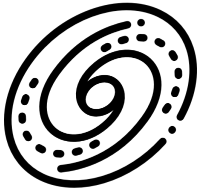


Anomalies?

New physics from oscillations?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Unitarity of mixing matrix → eV-scale sterile ν?



Interplay with cosmology → Neutrino masses: ΛCDM tension?

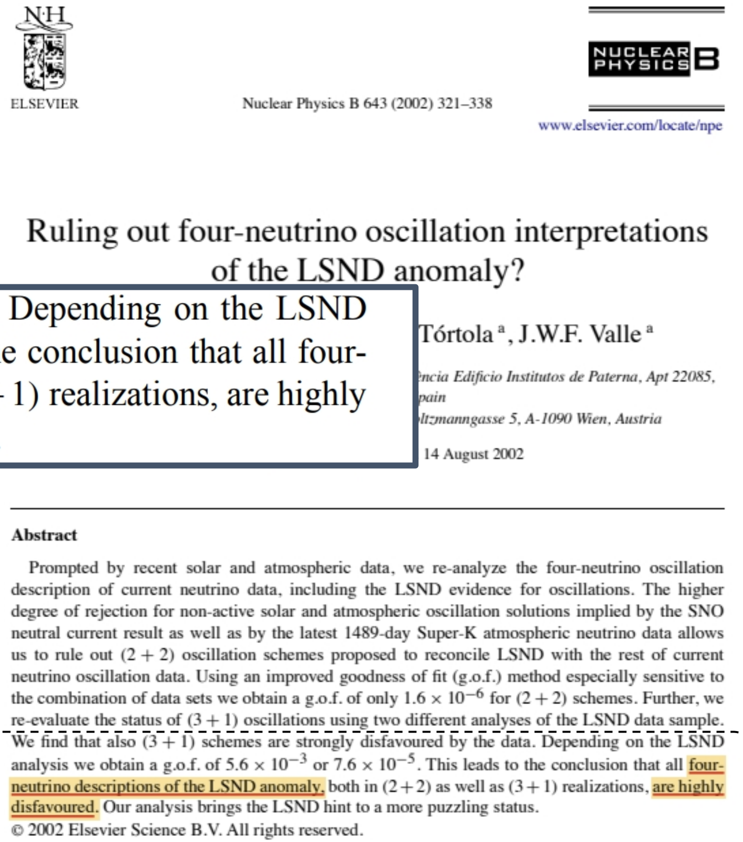
Sterile neutrinos …

Global analyses disfavoured eV sterile neutrino oscillations already 20 years ago

We find that also (3 + 1) schemes are strongly disfavoured by the data. Depending on the LSND analysis we obtain a g.o.f. of 5.6×10^{-3} or 7.6×10^{-5}. This leads to the conclusion that all four-neutrino descriptions of the LSND anomaly, both in (2 + 2) as well as (3 + 1) realizations, are highly disfavoured. Our analysis brings the LSND hint to a more puzzling status.

In 20 years…

- **reactor anomaly**: came and went away
- **LSND/MiniBoone**: (largely) unsolved
- **Gallium** anomaly: unsolved
- Strong tension with **cosmology**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Nuclear Physics B 643 (2002) 321–338

NUCLEAR PHYSICS B

www.elsevier.com/locate/npe

Ruling out four-neutrino oscillation interpretations of the LSND anomaly?

Tórtola [a], J.W.F. Valle [a]

…ncia Edificio Institutos de Paterna, Apt 22085, …pain

…ltzmanngasse 5, A-1090 Wien, Austria

14 August 2002

Abstract

Prompted by recent solar and atmospheric data, we re-analyze the four-neutrino oscillation description of current neutrino data, including the LSND evidence for oscillations. The higher degree of rejection for non-active solar and atmospheric oscillation solutions implied by the SNO neutral current result as well as by the latest 1489-day Super-K atmospheric neutrino data allows us to rule out (2 + 2) oscillation schemes proposed to reconcile LSND with the rest of current neutrino oscillation data. Using an improved goodness of fit (g.o.f.) method especially sensitive to the combination of data sets we obtain a g.o.f. of only 1.6×10^{-6} for (2 + 2) schemes. Further, we re-evaluate the status of (3 + 1) oscillations using two different analyses of the LSND data sample. We find that also (3 + 1) schemes are strongly disfavoured by the data. Depending on the LSND analysis we obtain a g.o.f. of 5.6×10^{-3} or 7.6×10^{-5}. This leads to the conclusion that all four-neutrino descriptions of the LSND anomaly, both in (2 + 2) as well as (3 + 1) realizations, are highly disfavoured. Our analysis brings the LSND hint to a more puzzling status.

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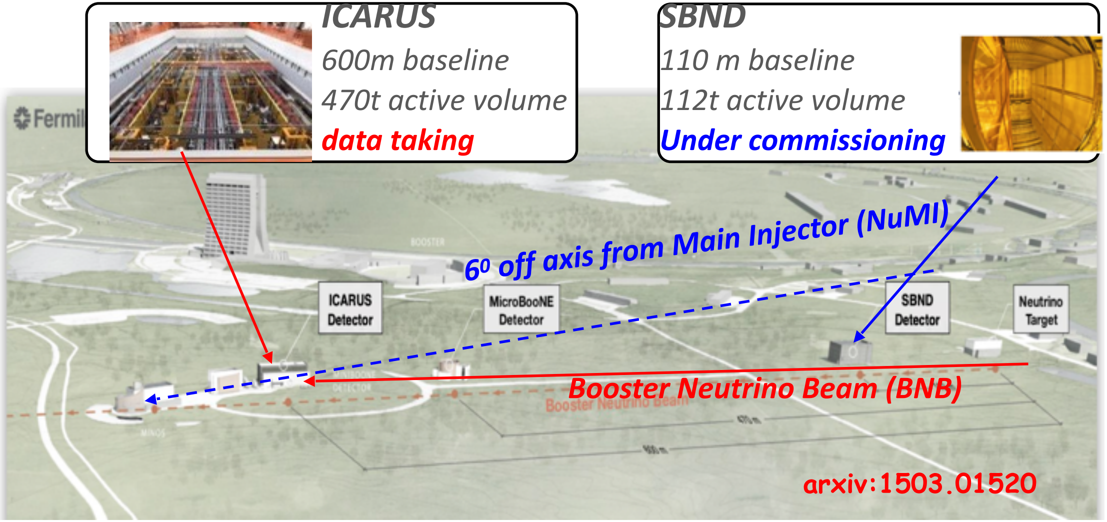
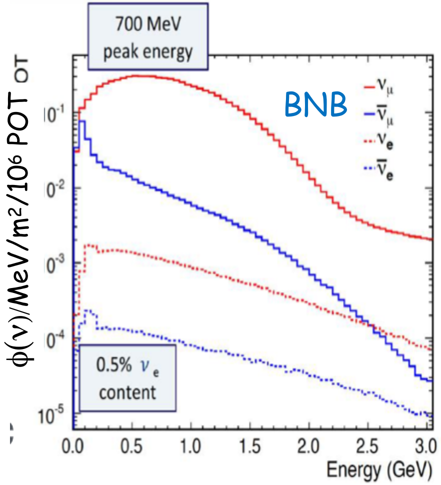
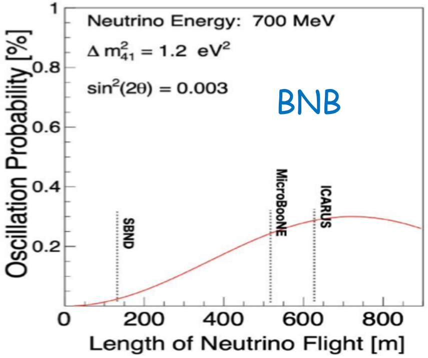
Short Baseline Neutrino (SBN) at FNAL BNB and NuMi beams: *a definitive answer to sterile neutrinos ?*





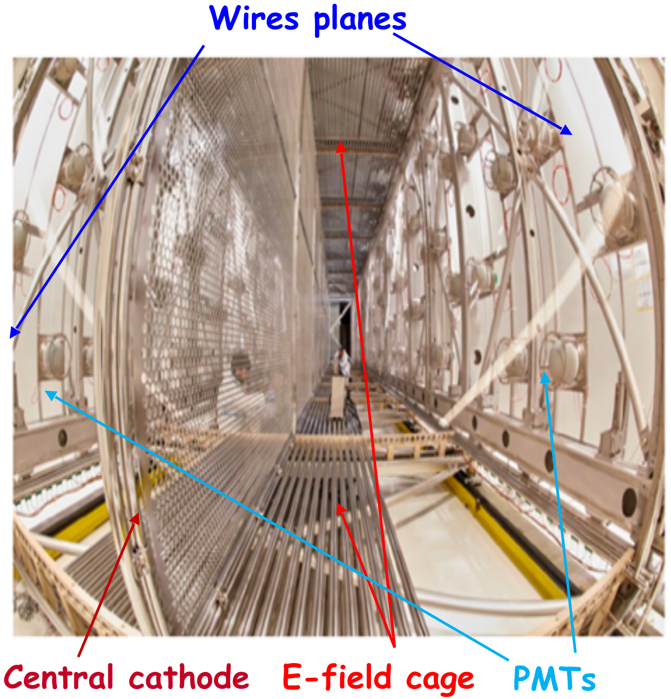
- ICARUS and SBND LAr-TPC's are installed at 600 and 110 m from the Booster target, searching for sterile-ν oscillations both in appearance and disappearance channels.
- In addition high-statistics ν-Ar cross-section measurements and event identification/reconstruction studies in view of DUNE:
  - ➢ ~10^6 events/y in SBND < 1 GeV from Booster
  - ➢ ~10^5 events/y in ICARUS > 1 GeV from off-axis NuMI beam.



ICARUS LAr-TPC at Fermilab

- ICARUS-T600 was overhauled at CERN in 2014-18 within the Neutrino Platform, introducing technology developments while maintaining the already achieved performance in view of the shallow depth operation at Fermilab:

  - 2 modules, 2 TPCs per module with central cathode (1.5 m drift, E_D= 0.5 kV/cm);
  - 3 readout wire planes per TPC, in total 54000 wires at 0, ± 60^0, 3 mm pitch; new faster, higher-performance read-out electronics;
  - Upgraded light collection system: 360 8" PMTs, TPB coated detecting scintillation light by particles in LAr;
  - New cold vessels, purely passive insulation and refurbished cryogenics and purification equipment;
  - Surrounded by ~4π Cosmic Ray Tagger system, protected by ~3 m thick concrete overburden.

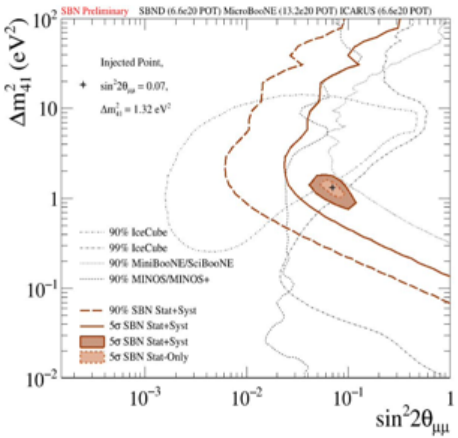


Structure of one module with 2 TPC chambers

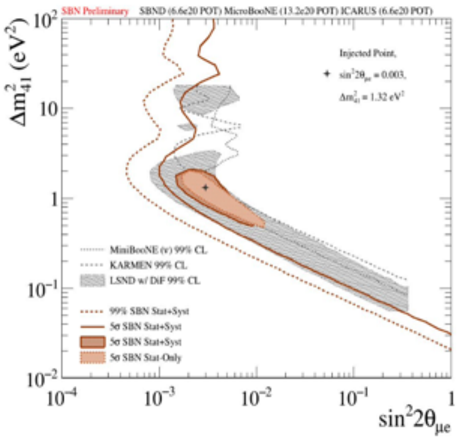
SBN Program: sterile neutrino sensitivity, 3 years (6.6 x10^{20} pot)

- 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:
  - ➢ High νe identification capability of LAr-TPCs rejecting NC event background;
  - ➢ "Initial" BNB beam composition and spectrum provided by SBND detector.

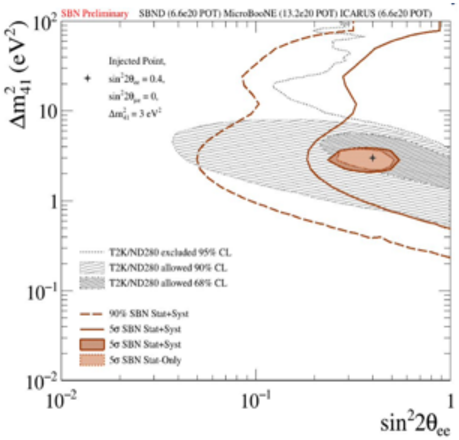
νμ disappearance



νe appearance



νe disappearance

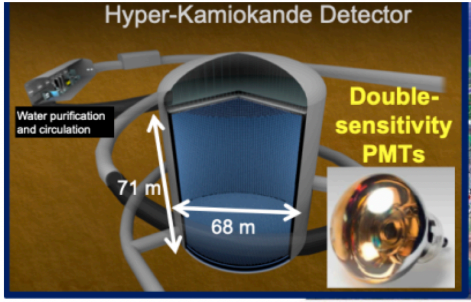


5σ coverage of the parameter area relevant to LSND anomaly

Probing the parameter area relevant to reactor and gallium anomalies.

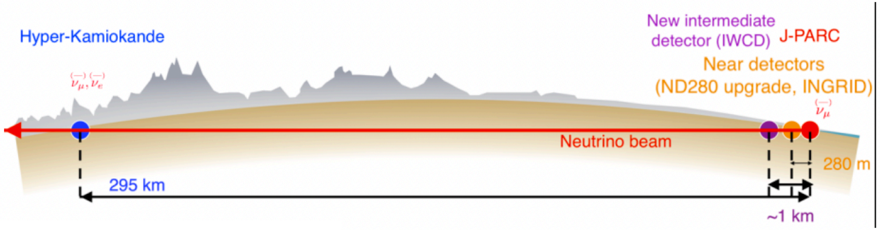
Unique capability to study neutrino appearance and disappearance simultaneously

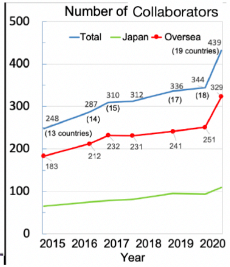
Hyper-Kamiokande



190 kton fiducial mass (8.4 x SK)
Sensitivity PMT (2x)
J-PARC beam upgrade (x2.5, 0.5 → 1.3 MW)
New Intermediate Water Cherenkov + upgraded T2K near detector @ 280 m

~440 collaborators, 93 inst. 19 countries





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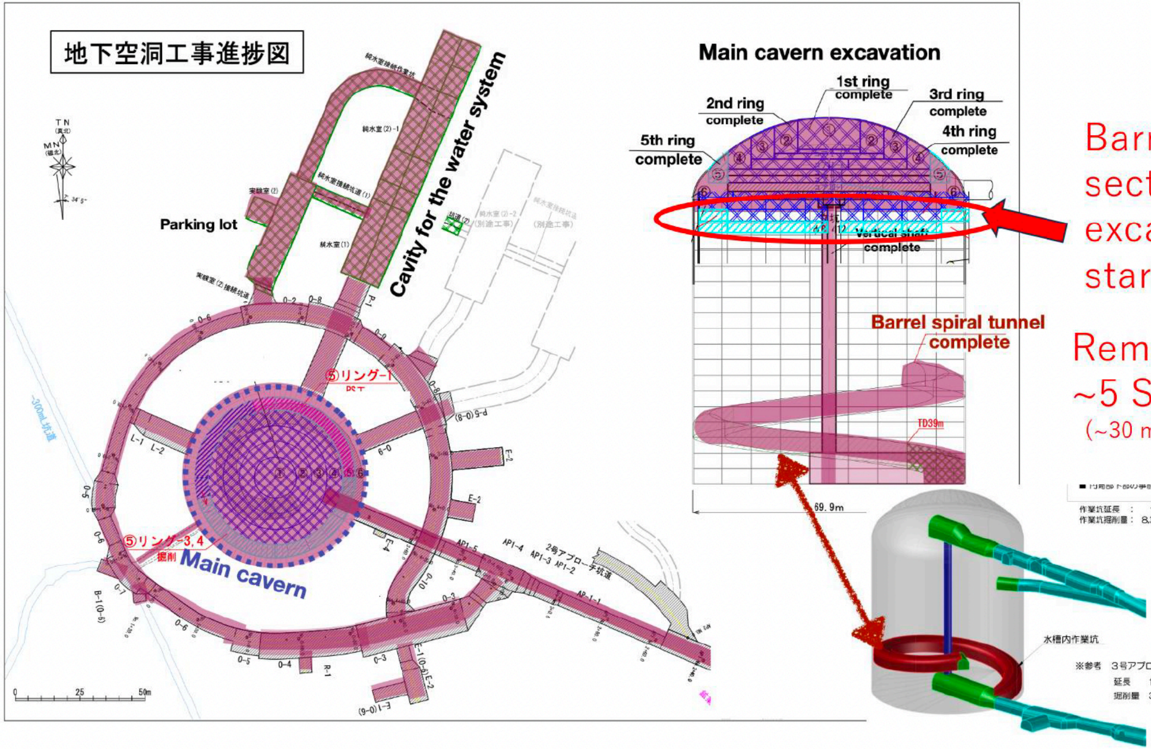
Status of cavern excavation



Barrel section excavation started!

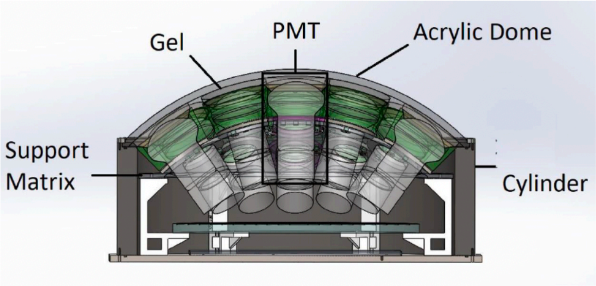
Remaining ~5 SK tank
(~30 m^3/hr ave)

cf.
Super-K Cavern
69 000 m^3
Super-K Tank
50 000 m^3

multi-PMT

- Proposti dall'INFN che ne ha la leadership (Poland, Canada, Czech Rep., Mexico)
- HK INFN R&D dal 2015 (~200k€)
- Flagship della proposta italiana per il far detector, insieme al frontend dei PMTs 20''
- Informazioni uniche e complementari ai PMTs 20''
- Riduzione delle sistematiche sui parametri dell'acqua e sulla scala di energia

	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



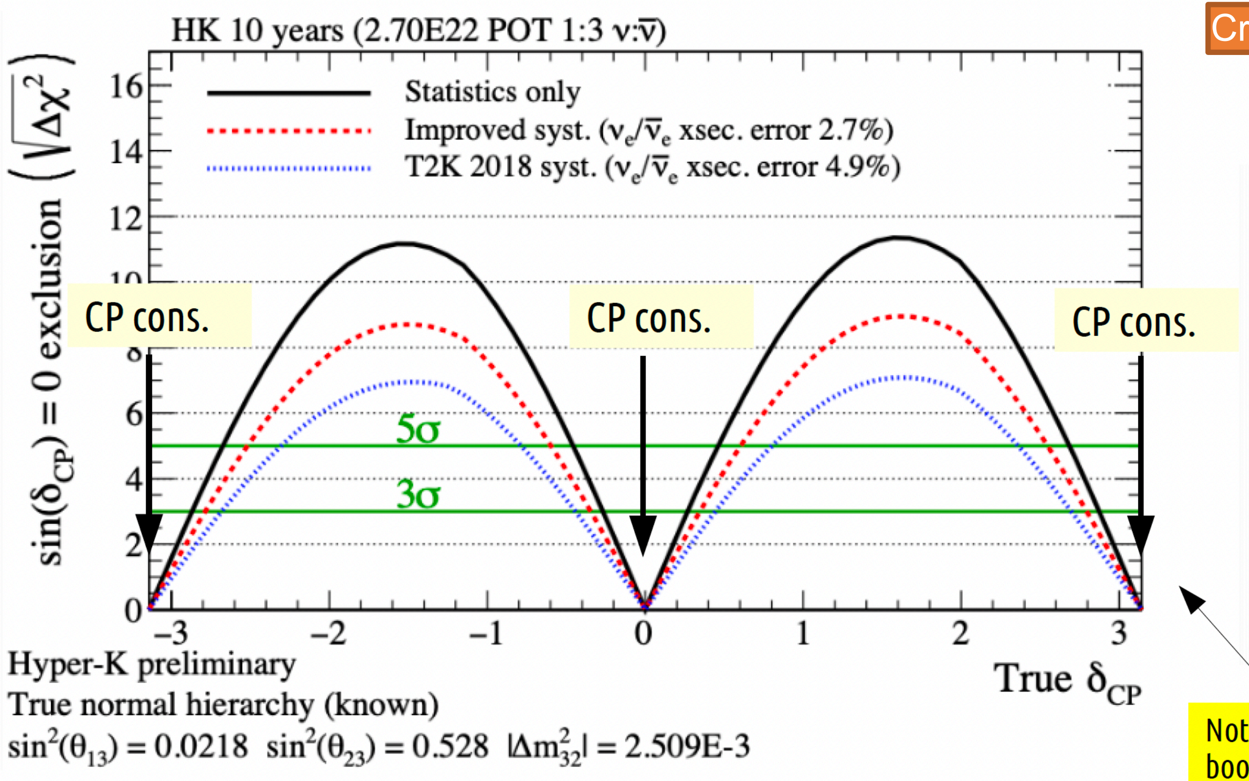
mPMT design review

Final prototypes, contracts & procurement

Mass production 2024-26

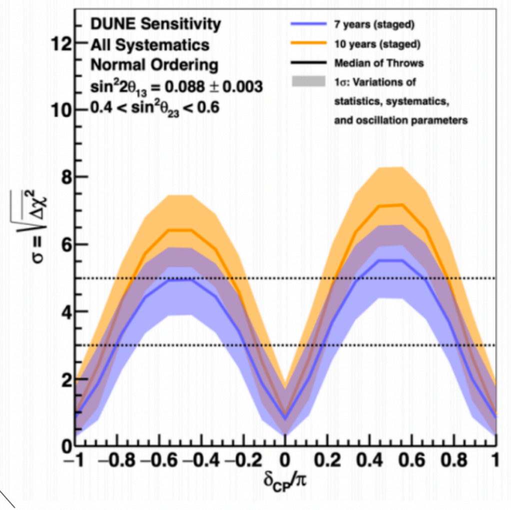
17

HK: Sensitivity to CPV



Critically depends on δ_{CP}

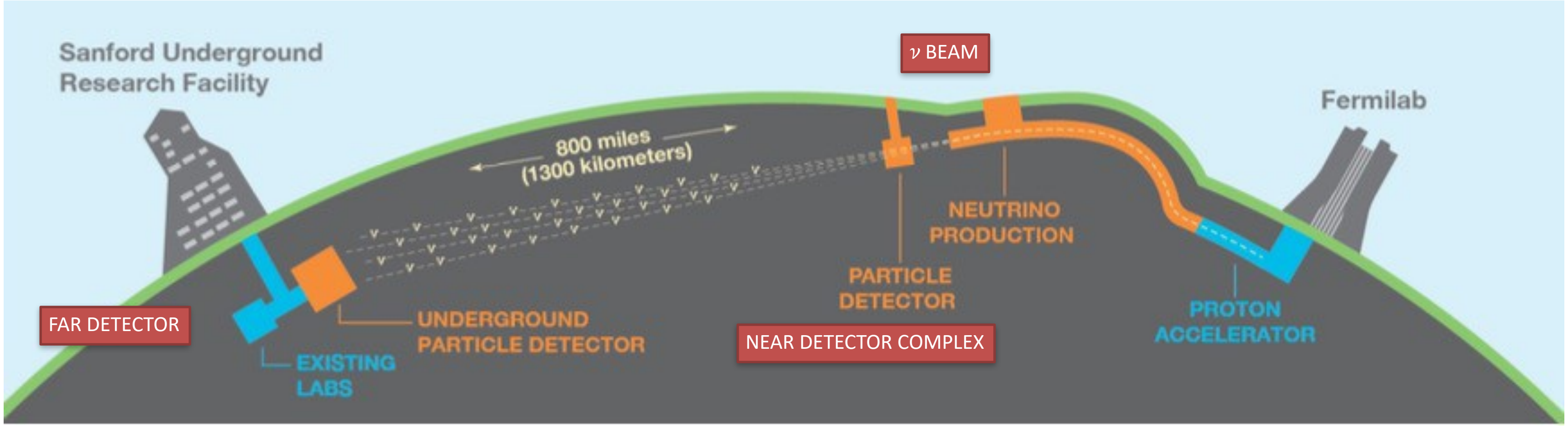
True Normal Ordering



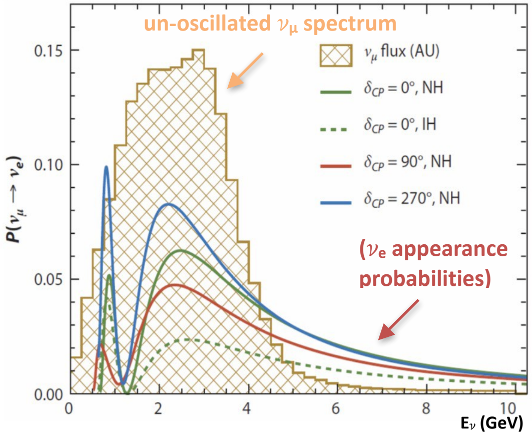
Notice how the reduction in systematics can boost the performance

35

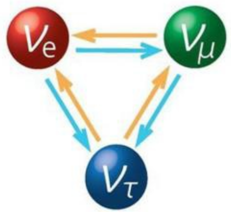
DUNE: the ultimate proton-driven long-baseline experiment

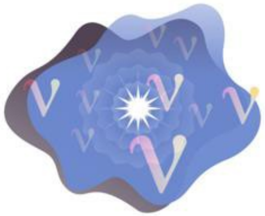


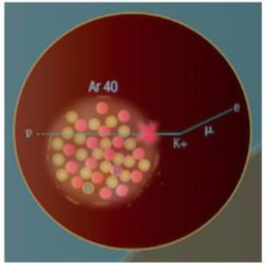
- High precision measurements of ν mixing in a **single experiment.**
- Determination of the ν **mass ordering** in the first few years.
- Observation and measurement of **CPV** in the ν **sector.**
- Test of the **3-ν paradigm** (PMNS unitarity).
- Observatory for **astrophysical ν sources** (solar, atmospheric, SN).
- Search for **physics Beyond Standard Model** with and without **νs**



DUNE and its Physics Program in one slide







- **Long- baseline wide-band neutrino beam**
  - Measurement of CP violation phase and determination of the neutrino mass ordering in a single experiment using spectral information
- **Underground location → access to astrophysical neutrinos**
  - Supernova neutrino burst detection – sensitive to the ν_e component
  - Atmospheric neutrino – capability of ν_τ identification
  - Solar neutrinos – potential for detection of hep flux
- **Massive detectors with tracking and calorimetric information**
  - Search for baryon number violating processes – p ⟶ ν K+, n ꝏ
- **Long baseline + higher energy neutrino beam**
  - ν_τ appearance, NSI searches
- **Capable Near Detector Complex**
  - Precise neutrino physics (cross sections, nuclear effects)
  - BSM searches

arXiv 1807.10334

Experimental Strategy for oscillations

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta m^2}{a-\Delta m^2}\right)\sin^2\left(\frac{a-\Delta m^2}{4E}L\right) + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\left(\frac{\delta m^2}{a}\right)\left(\frac{\Delta m^2}{a-\Delta m^2}\right)\sin\left(\frac{aL}{4E}\right)\sin\left(\frac{a-\Delta m^2}{4E}L\right)\cos\left(\frac{\Delta m^2 L}{4E}\right)\cos\delta \; +$$

$$+\cos^2\theta_{13}\sin^2 2\theta_{12}\left(\frac{\delta m^2}{a}\right)^2\sin^2\left(\frac{aL}{4E}\right) - \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\left(\frac{\delta m^2}{a}\right)\left(\frac{\Delta m^2}{a-\Delta m^2}\right)\sin\left(\frac{aL}{4E}\right)\sin\left(\frac{a-\Delta m^2}{4E}L\right)\cos\left(\frac{\Delta m^2 L}{4E}\right)\sin\delta$$

$\overline{\nu}_\mu \to \overline{\nu}_e$

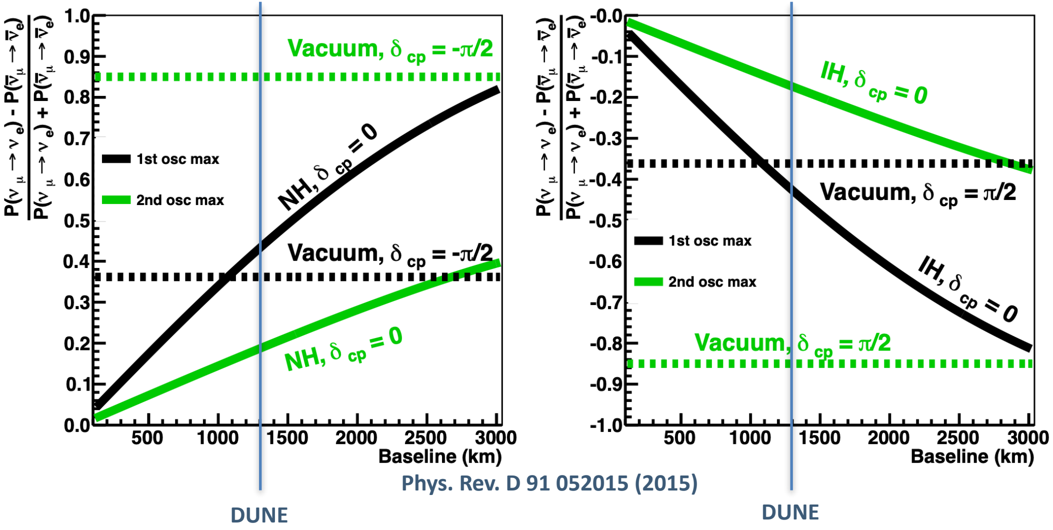
$a \to -a$

$\delta \to -\delta$

Leading order approximation

$$\mathcal{A}_{cp}(E_\nu) = \left[\frac{P(\nu_\mu \to \nu_e) - P(\bar\nu_\mu \to \bar\nu_e)}{P(\nu_\mu \to \nu_e) + P(\bar\nu_\mu \to \bar\nu_e)}\right] \approx \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta_{CP}}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right) + \text{ matter effects.}$$

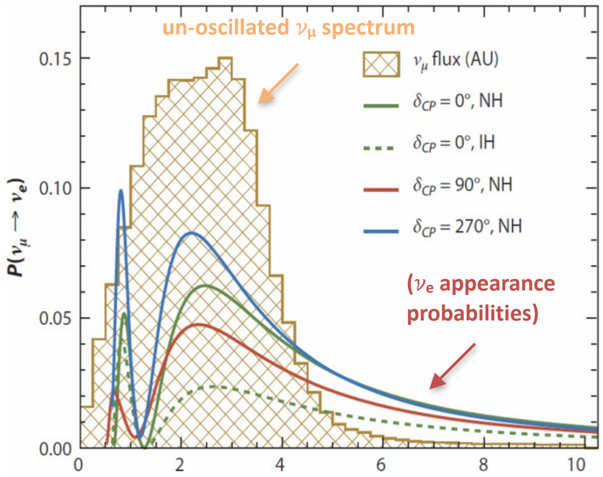
- Long baseline + wide-band beam: **unfold CPV and matter effects** using information from the **first** and **second oscillation maxima**
    - Baseline ~ 1300 km
        - 1^{st} peak at ~ 2.6 GeV
        - 2^{nd} peak at ~ 0.65 GeV



Phys. Rev. D 91 052015 (2015)

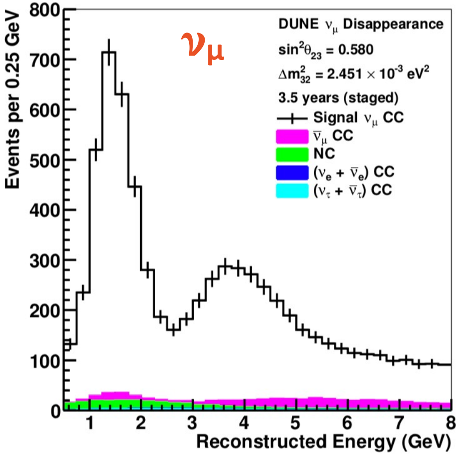
DUNE Oscillation physics

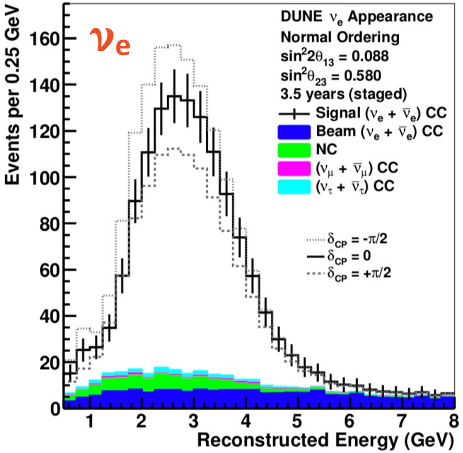
DUNE Collaboration, Eur. J. Phys. C80, 978 (2020)



ν_μ disappearance

$\nu_\mu \rightarrow \nu_e$ appearance



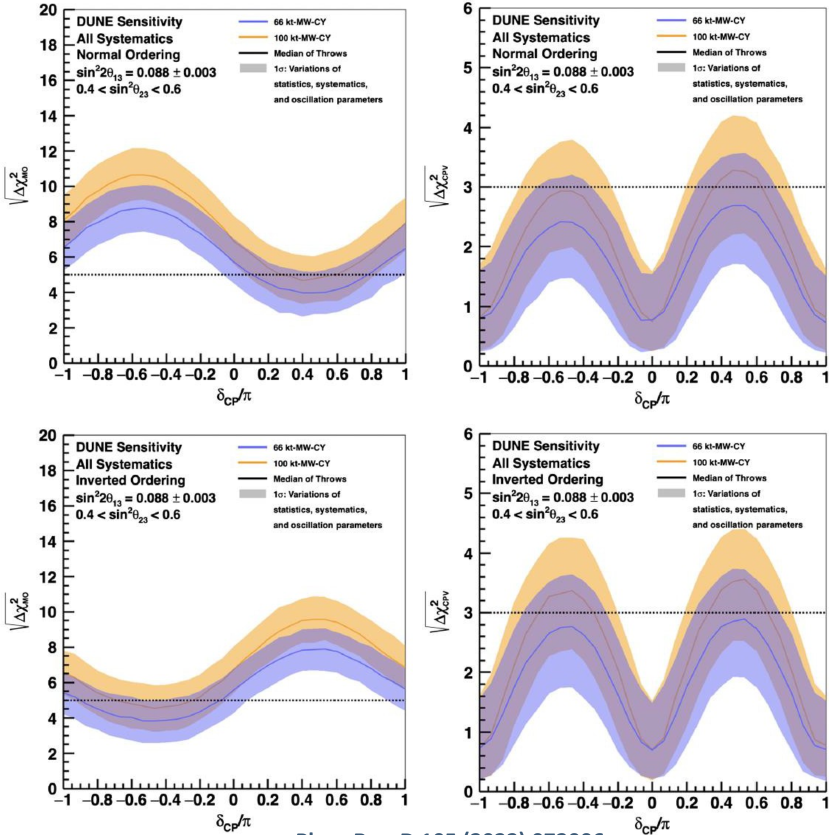


In year 1 alone, DUNE will collect ~150 oscillated ν_e events. This is approx. the sum of T2K + NOvA

- *assuming a beam ramp-up to 1.2 MW, 2 FDs, normal ordering, θ_{CP}=0*
- *expected range is 70-180 ν_e events in FHC, depending on true MO, CP*
- *a factor 1.75 more with ACE-MIRT*

Sensitivity to CPV - Phase I

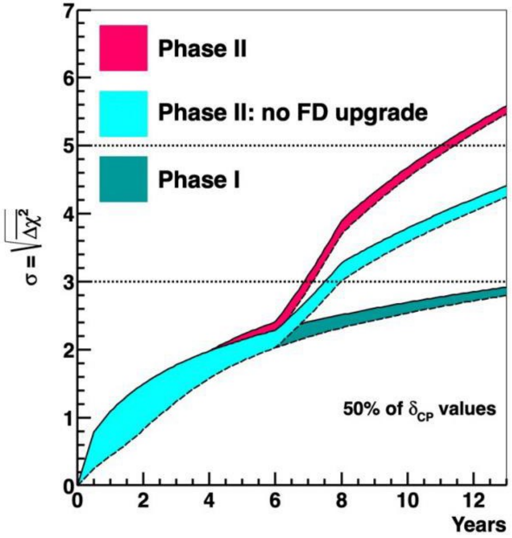
- DUNE Phase-I will:
  - unambiguously resolve the neutrino mass ordering at **3σ** **(5σ)** level with a **66** **(100)** kt · MW · yr exposure
  - measure CPV at 3σ level with a **100 kt · MW · yr** exposure for the maximally CP-violating values $\delta_{CP} = \pm \pi/2$

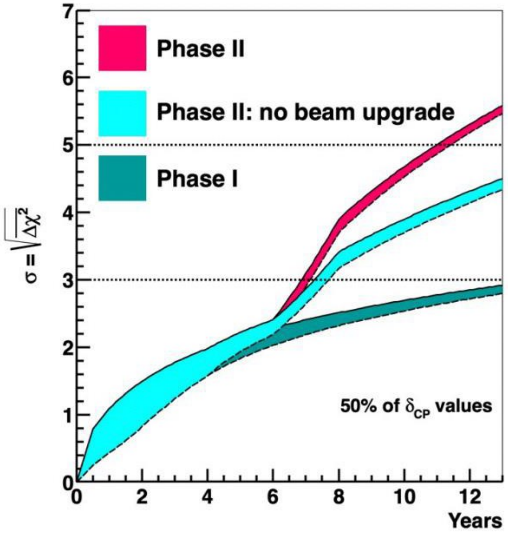


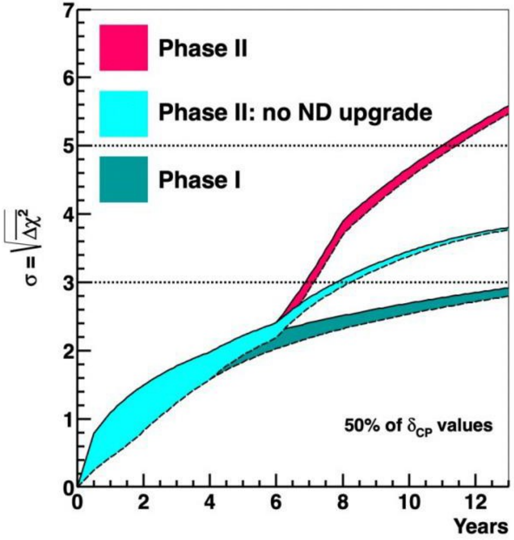
Phys. Rev. D 105 (2022) 072006

DUNE sensitivities at higher exposures (Phase II)

To achieve all P5 goals it is need : Detector Mass 40 kton (4 modules) + Beam power upgrade to 2.4MW + Improved Systematics (Near detector upgrade)





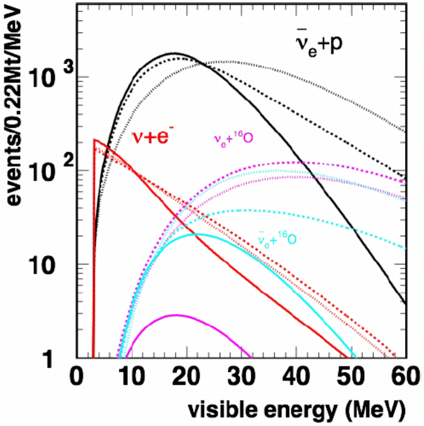


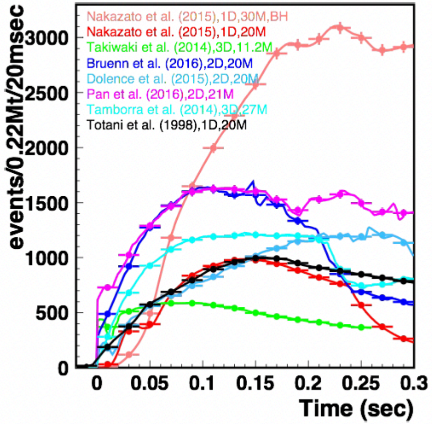
If $\delta_{CP} = \pm 90°$, CP violation at 3σ in Phase I

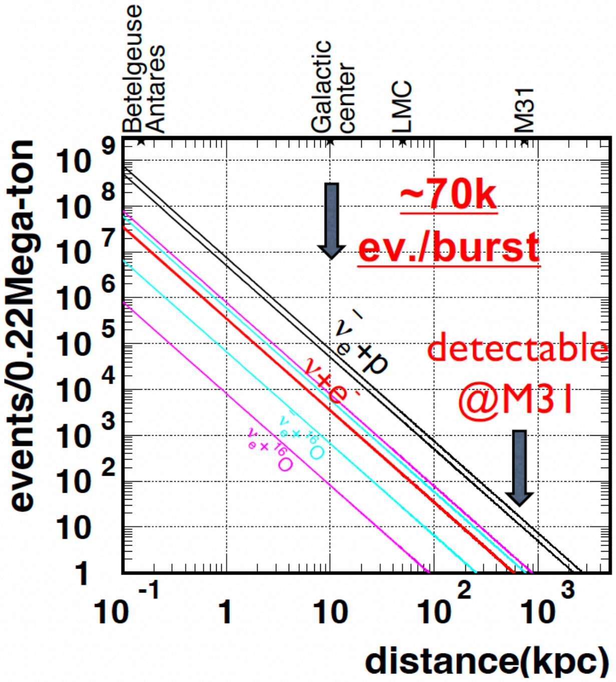
Phase II: If $\delta_{CP} = \pm 90°$ 5σ in 7 years

For 50% of δ_{CP} values 5σ CPV in 12 years

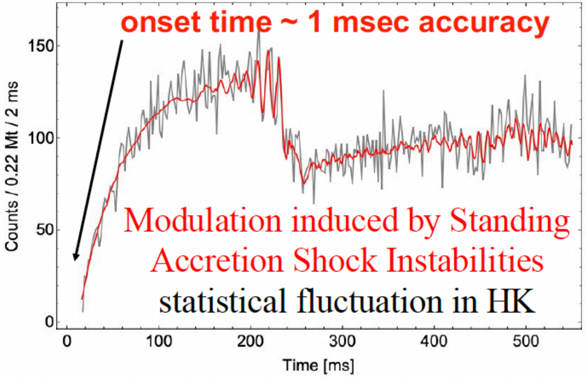
SN neutrino burst in HK

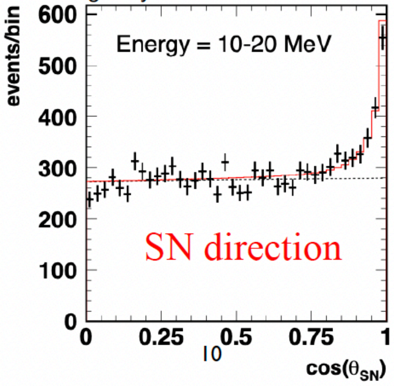






galactic supernova at 10 kpc (our r_{galaxy}= 8 kpc)



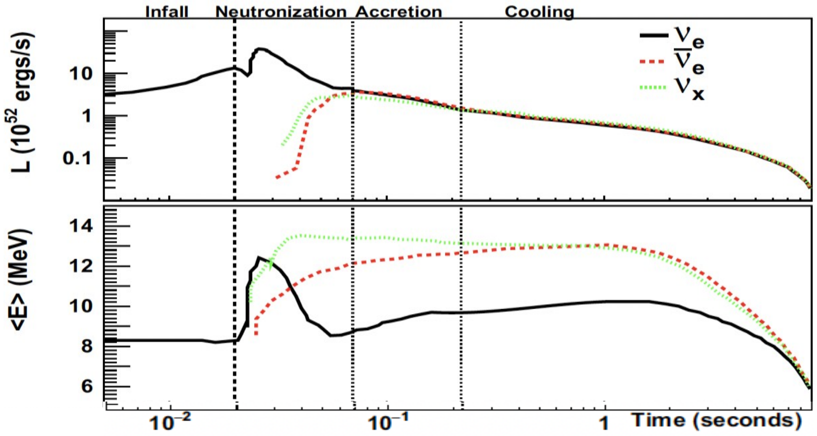


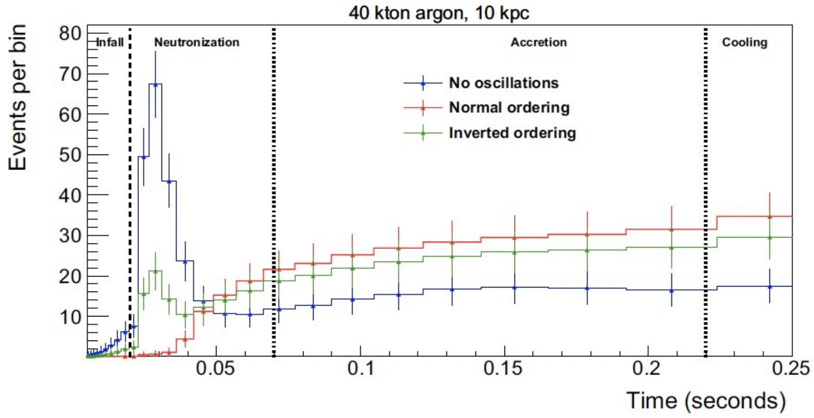
~70k events/burst at 10 kpc

- explosion mechanism,
- BH/NS formation,
- alert with 1° pointing

10

SN neutrino burst in DUNE



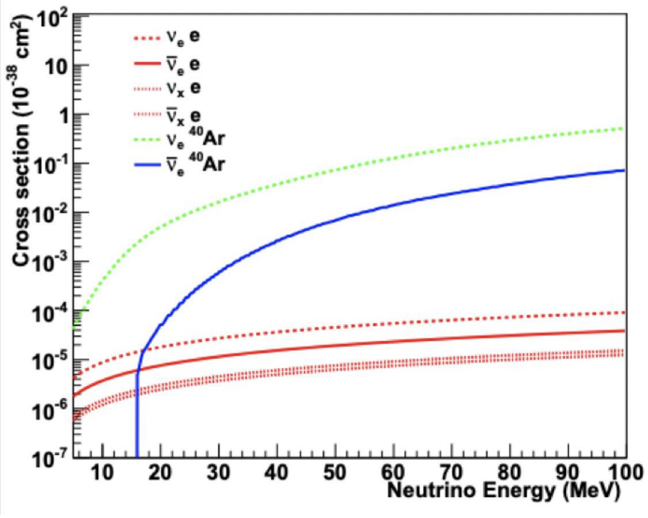


DUNE sensitive to ν_e CC events by

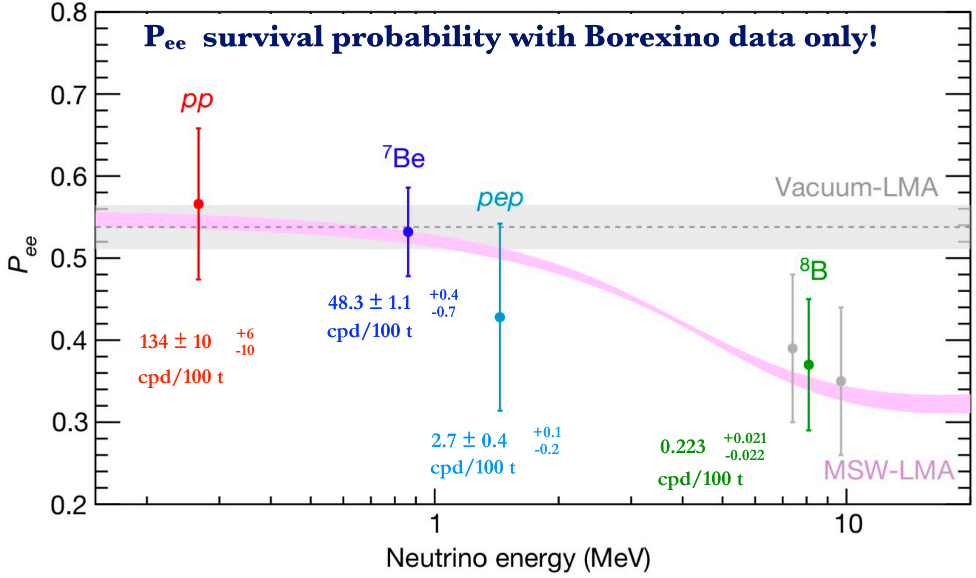
$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

exploiting the Ar target and to ν ES on electrons thanks to its large mass

Eur. Phys. J. C (2021) 81



Borexino: Summary of pp chain study (2007-2018)



Comprehensive chain:
Nature 562 (2018) 7728, 505.
Phys. Rev. D (2019)

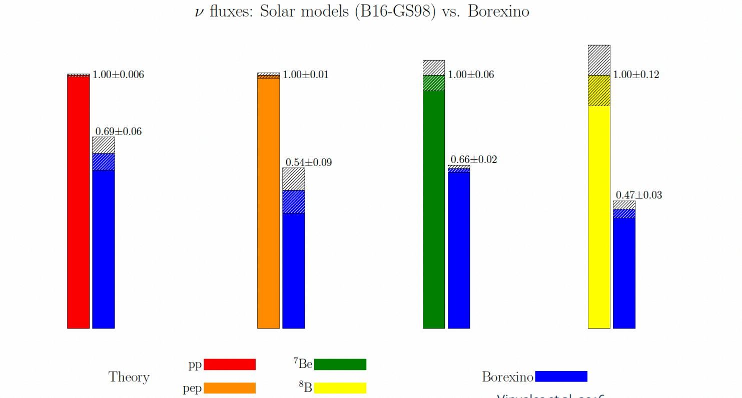
pp:
Nature 512 (2014) 7515, 383.

^{7}Be:
Phys. Lett. B658 (2008) 101
PRL 107 (2011) 141302

pep:
PRL 108 (2012) 051302

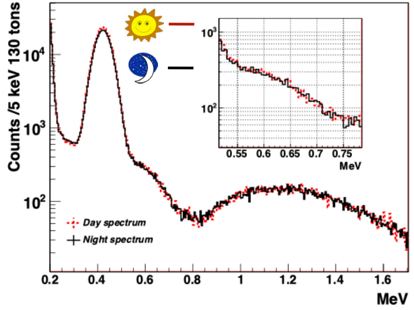
^{8}B:
Phys. Rev. D82 (2010) 033006

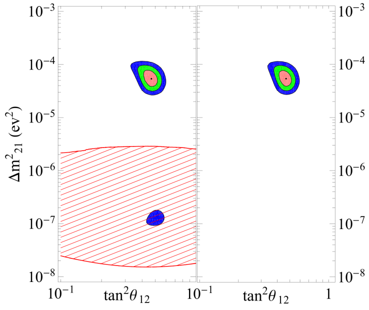
The Solar Neutrino Problem viewed by Borexino



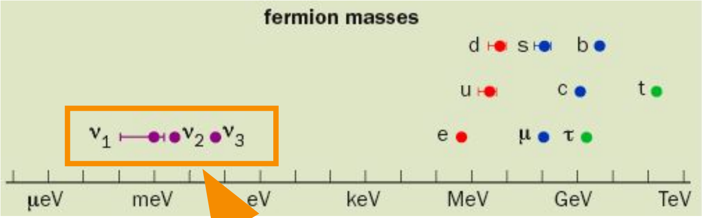
Vinyoles et al. 2016
http://www.ice.csic.es/personal/aldos

No day-night ^{7}Be: confirmation of LMA [Phys. Lett. B707 (2012) 401.]





Why mass is important: three ways, three "masses" !

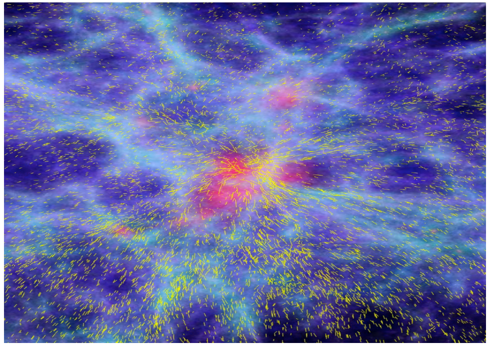


NEUTRINOS
ARE DIFFERENT ?

0.2 eV @ 90% CL
(Lisi et al, arXiv 2503.07752)

GRAVITY

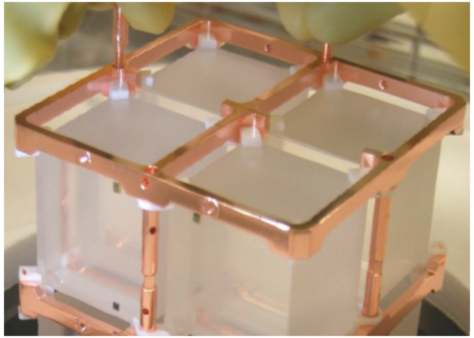
$$\Sigma_\nu = m_1 + m_2 + m_3$$



β **DECAY KINEMATICS**

$$m_\beta = \sqrt{|U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2}$$

0.45 eV @ 90% CL (KATRIN, arXiv 2406.13516)



0.028-0.122 eV @ 90% CL
(KLDZ, arXiv 2406.11438)

LEPTON NUMBER VIOLATION ($0\nu\beta\beta$ DECAY)

$$m_{\beta\beta} = \left| U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3 \right|$$

Neutrino masses and cosmology

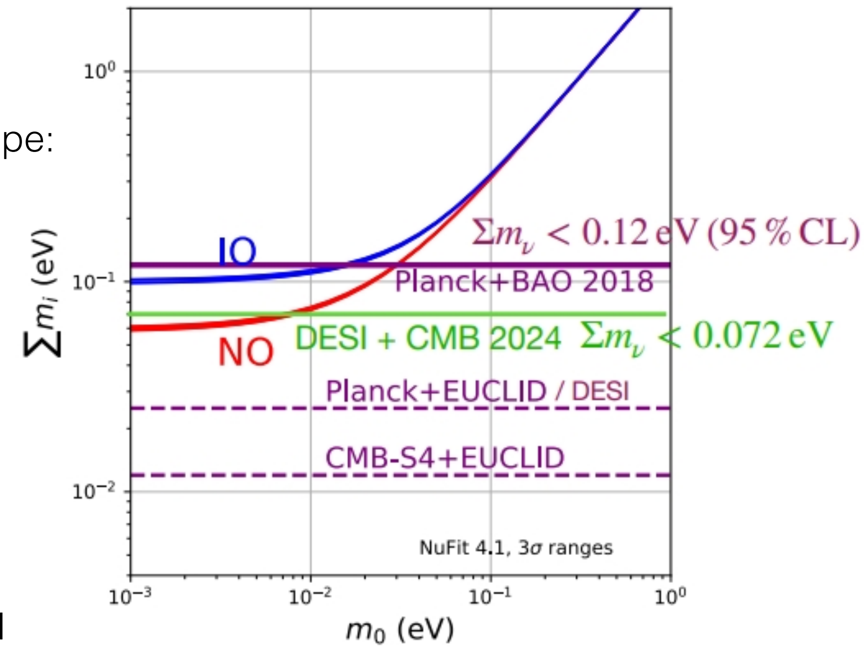
Cosmology provides tight constraints on the sum of neutrino masses Σ in ΛCDM model. Too tight?

DESI (April 2024) + CMB Planck + CMB Atacama Telescope:
- Best fit value: Σ = 0 , and Σ < 0.072 eV at 95% CL
- Relaxing the Σ > 0 prior, negative neutrino masses are favoured.

Long list of possible interpretations:

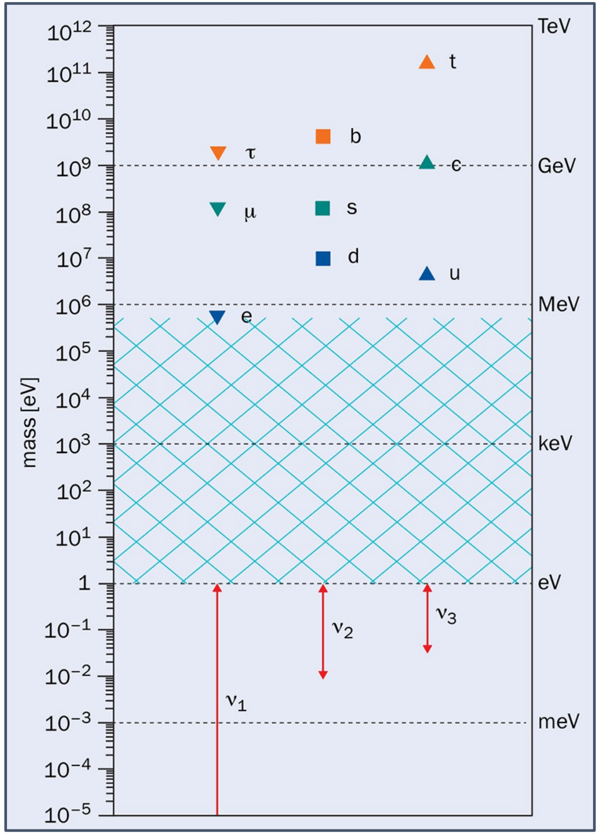
- Undetected systematics in DESI BAO data?
- Non-standard cosmology?
- New physics beyond the ΛCDM model?
- Exotic neutrino properties?

direct mass determinations crucial ⇒ KATRIN and beyond

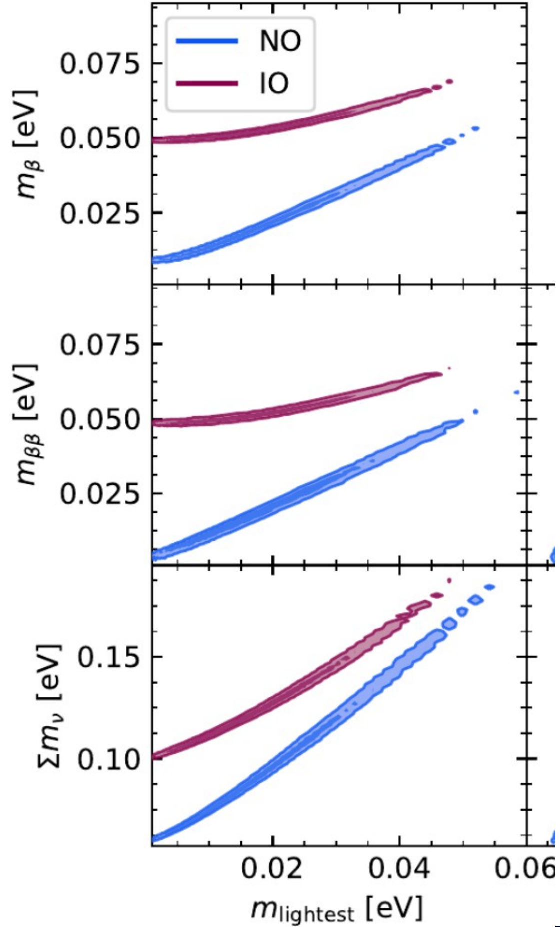


Neutrino mass: a gap (?)

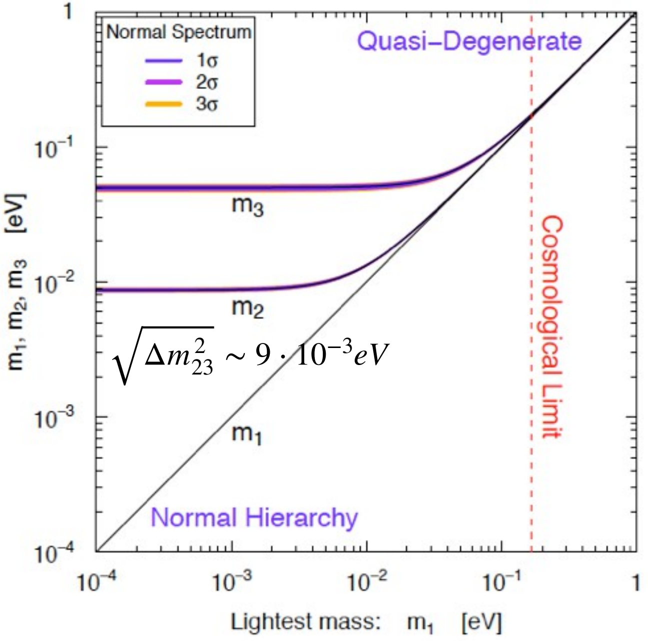
Is this a hint for a different mass generation mechanism ?

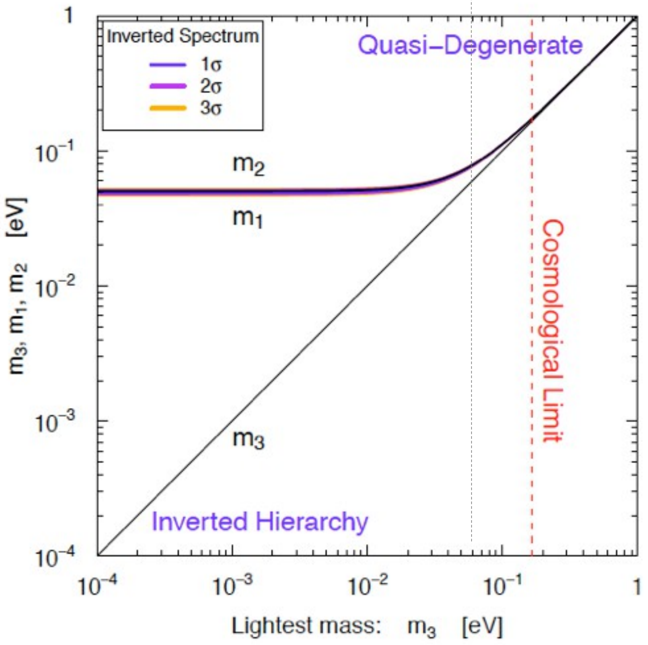


https://globalfit.astroparticles.es/2020/06/24/neutrino-masses/



Absolute neutrino masses





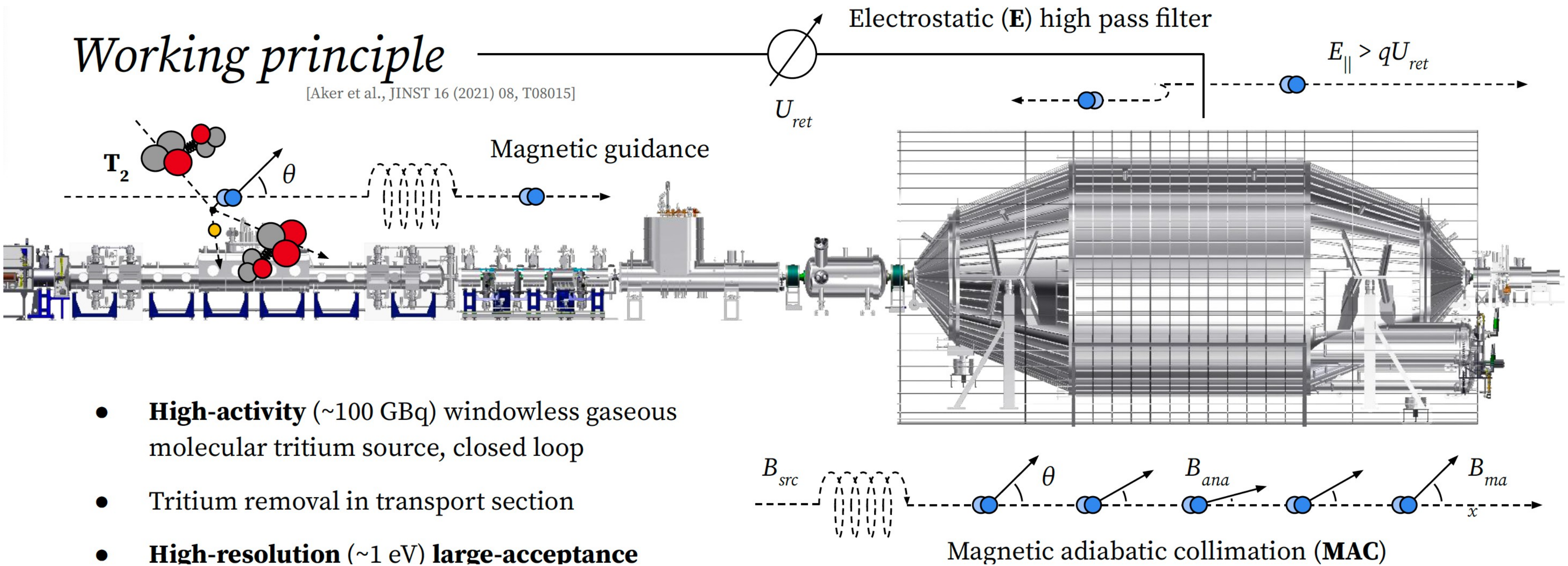
$$\sqrt{\Delta m^2_{23}} \sim 9 \cdot 10^{-3} eV$$

$$m_2^2 = m_1^2 + \Delta m_{21}^2 = m_1^2 + \Delta m_S^2$$
$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_A^2$$

$$m_1^2 = m_3^2 - \Delta m_{31}^2 = m_3^2 + \Delta m_A^2$$
$$m_2^2 = m_1^2 + \Delta m_{21}^2 \simeq m_3^2 + \Delta m_A^2$$

Quasi-Degenerate for $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \gg \sqrt{\Delta m_A^2} \simeq 5 \times 10^{-2}$ eV

KATRIN



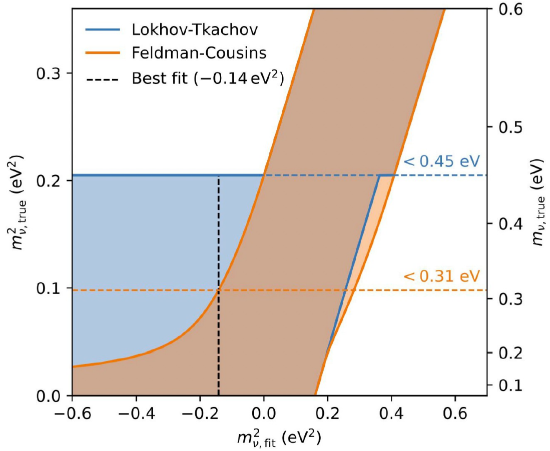
- **High-activity** (~100 GBq) windowless gaseous molecular tritium source, closed loop
- Tritium removal in transport section
- **High-resolution** (~1 eV) **large-acceptance**

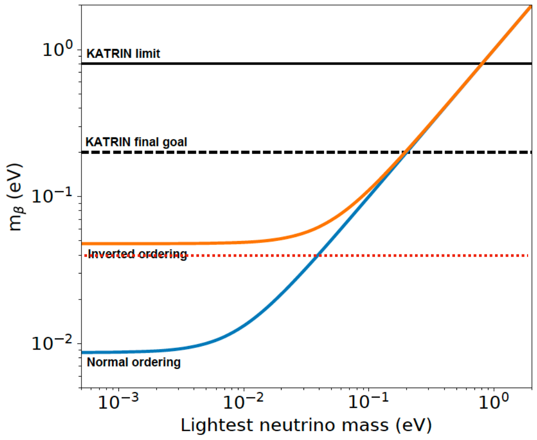
➔ Discrete **retarding potential steps**, measurement time distribution, **integral spectra**

KATRIN++

2019-2025 (PoF-IV)	2026-2027 (PoF-IV)	2028-2034 (PoF-V)	Scientific goal
Phase 1 (Integral) Neutrino mass	Phase 2 (Differential) keV sterile ν	R&D Phase KATRIN ++: Atomic Tritium Demonstrator; Quantum Sensor Demonstrator	Neutrino mass

- **KATRIN** on way to achieve 1000 d measurement time **(final sensitivity m_β < 0.3 eV).** Next m_β result : ~ **0.5 eV sensitivity**
- We will be ready for **TRISTAN**-Operation at the end of 2025 (**Search for keV sterile neutrinos)**
- Ultimate neutrino mass experiment (Normal Ordering; **sensitivity on m_β < 40 meV**) requires **differential detector principle** und **an atomic tritium source → R&D Plan for PoF-V**



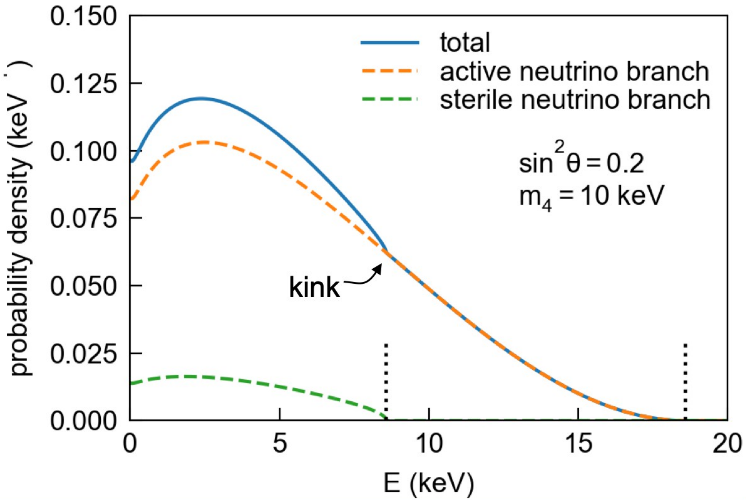


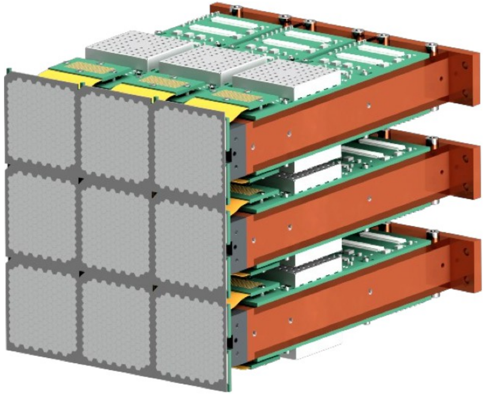
Today

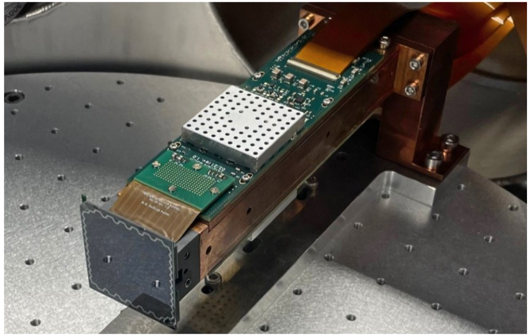
KATRIN final

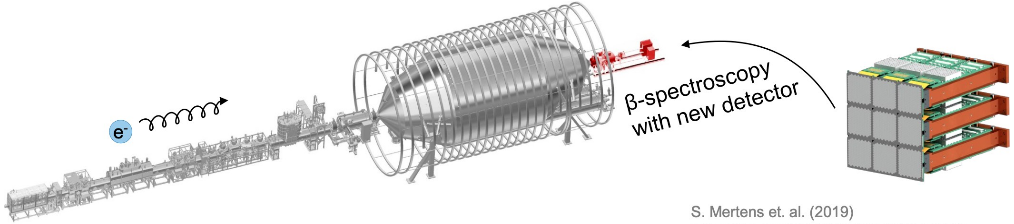
KATRIN++ ?

TRISTAN









S. Mertens et. al. (2019)
https://doi.org/10.1088/1361-6471/ab12fe

- precise spectral shape measurement (**FWHM <300 eV**) across entire energy range
  Ability to handle high rates at the detector (~108 cps)

Challenges:

- scaling to focal plane array (>1000 pixels)
- electron spectroscopy
- difficult environment: UHV, magnetic fields, high voltage etc.

2025:
- 9 modules in replica of KATRIN detector section

2026:
- installation in KATRIN beam line
- start of sterile neutrino physics program (~1 year)

Holmes

low temperature **microcalorimeter arrays** with ion-implanted ^{163}Ho

scalable proof-of-principle for an experiment with **$\lesssim$0.1 eV m_ν sensitivity**

- 6.5×10^{13} atom/det → A_{EC}=300 c/s/det
- $\Delta E \approx 1$ eV and $\tau_R \approx 1$ μs
- 1000 TES microcalorimeters
  → 16 × 64-pixel arrays with
  microwave multiplexed read-out
- 6.5×10^{16} ^{163}Ho nuclei → ≈18 μg
  → 3×10^{13} events in 3 years
  → m_ν statistical sensitivity ≈1 eV

realistic rescaled intermediate target

- $A_{EC}\approx$1 c/s/det
- $\Delta E \approx 1$ eV and $\tau_R \approx 1$ μs
- 64-pixel array
  → 2×10^{9} events in 1 year
  → m_ν statistical sensitivity O(10 eV)

HOLMES

B. Alpert et al., Eur. Phys. J. C, (2015) 75:112

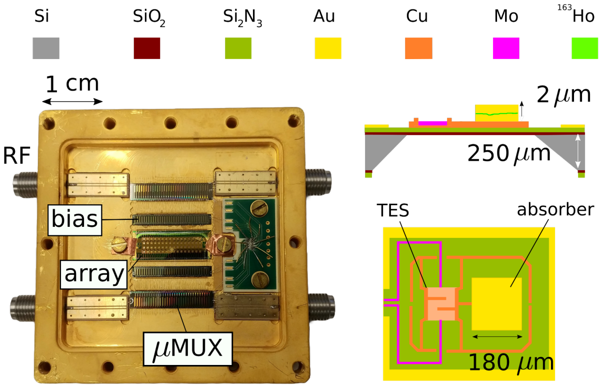
^{163}Ho: low T calorimeters (HOLMES)

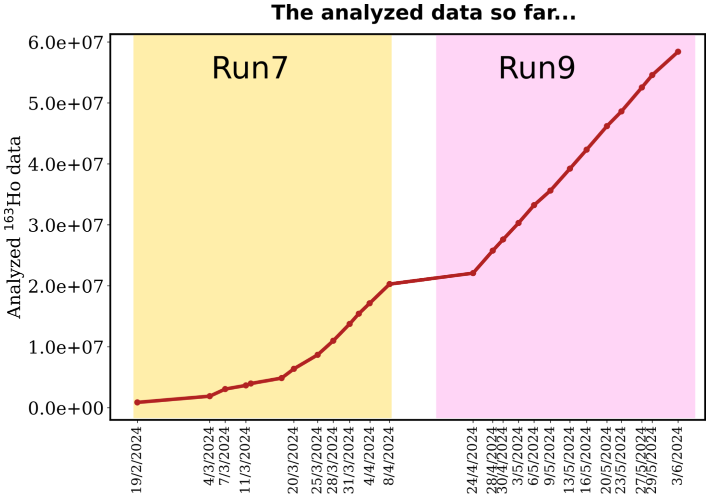
- 1st neutrino mass measurement of HOLMES (submitted to PRL): https://arxiv.org/pdf/ 2503.19920

Not competitive with KATRIN but

- validates the approach implemented in recent years by HOLMES and ECHo
- Can extract info on the neutrino mass using 163Ho even without knowing well the ^{163}Ho spectral shape

→m(nu) < 27 eV at 90% C.L. with





- 48 detectors (microwave multiplexed readout)
- 2 months
- 15 Bq total activity = 10^7 decadimenti

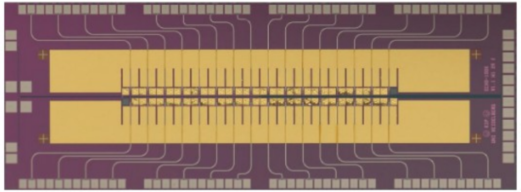
EChO: a competitive approach to ^{163}Ho

- Current unclear situation
- Good proof of principle in 2019: m<150 eV
- 163Ho spectra collected (E<2.5 keV for EC spectrum, E>3 keV for pileup) with a similar number of channels as HOLMES: no update on mass result

Towards ECHo-100K

ECHo-100k baseline: large arrays of MMCs

Number of detectors:	12000
Activity per pixel:	10 Bq



Present status:

MMCs arrays:	reliable fabrication of large MMC array succesfull characterization of arrays with ^{163}Ho
High Purity ^{163}Ho source:	available about 30 MBq
Ion implantation system:	demostrated co-deposition of Ag for larger activities

ECHo-1k chip-Ag

34 pixel with implanted ^{163}Ho

6 background pixels

average activity = 0.71 Bq

total activity of 25.9 Bq

- … working on improving to "EChO-100k"
- Latest news at Neutrino 2024
- But no plan to go beyond eV mass sensitivity

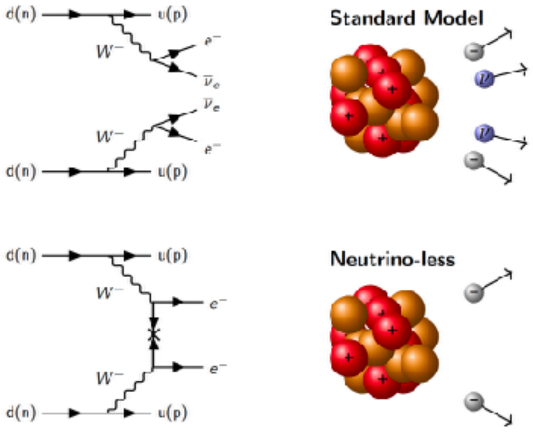
Neutrinoless double beta decay

- It is a very rare nuclear process (if it exists) in which a nucleus makes a “double” beta decay **without the emission of neutrinos**

Maria Göppert Mayer

  - The decay with 2 neutrinos exists and has been observed
    - It does not contain new physics

  - **That without neutrinos is super-interesting**



  -

Why $0\nu\beta\beta$ is important ?

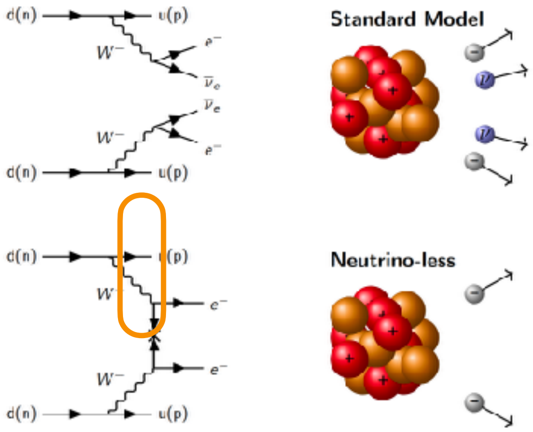
- The only known process that can **distinguish** between **Majorana and Dirac mass terms**

  - Other subdominant effects exist but much more difficult to measure

  - i.e. **$0\nu\beta\beta$** can happen only if neutrinos are their own anti-particle (truly neutral)

  - i.e. lepton number is violated

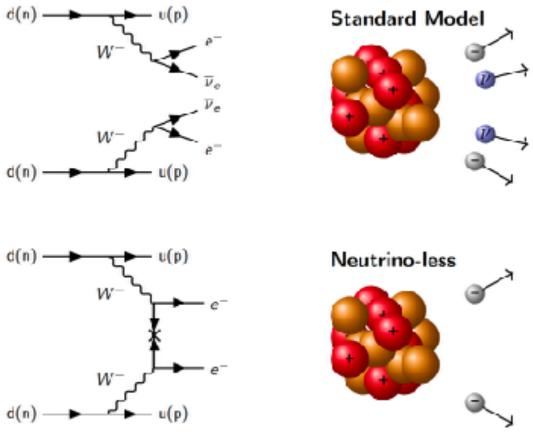
  - **In all scenarios $0\nu\beta\beta$ implies new physics**



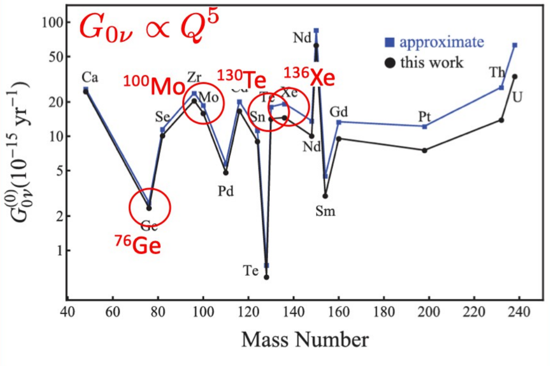
Why $0\nu\beta\beta$ is important ?

- The best process that can **distinguish** between **Majorana and Dirac mass terms**
  - i.e. $0\nu\beta\beta$ can happen only if neutrinos are their own anti-particle
  - i.e. lepton number is violated
  - **In all scenarios $0\nu\beta\beta$ implies new physics**

$$\Gamma^{0\nu}/\ln(2) = (T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)g_Z^4 |M^{0\nu}|^2 \frac{\langle m^2_{\beta\beta}\rangle}{m_e^2}$$

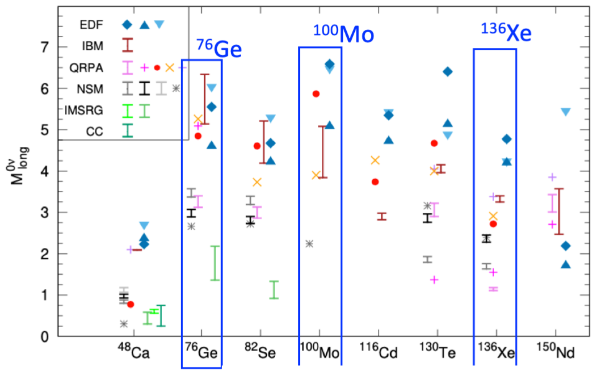


Phase space (accurately calculated):



Phys. Rev. C 85, 034316 (2012)

Nuclear Matrix Element (significant theory uncertainty):



Effective Majorana Mass (assumes "standard" mechanism):

$$\langle m_{\beta\beta}\rangle = \left|\sum |U_{ei}|^2 e^{i\phi_i} m_i\right|$$
$$= |c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i\alpha} + s_{13}^2 m_3 e^{i\beta}|$$

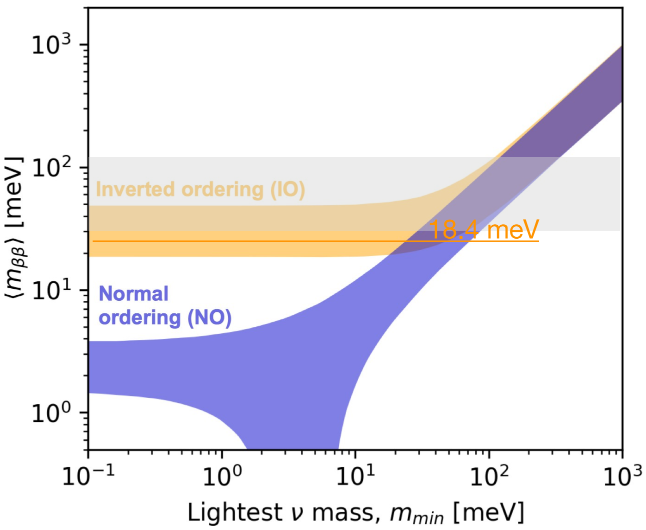
α, β are unknown Majorana phases

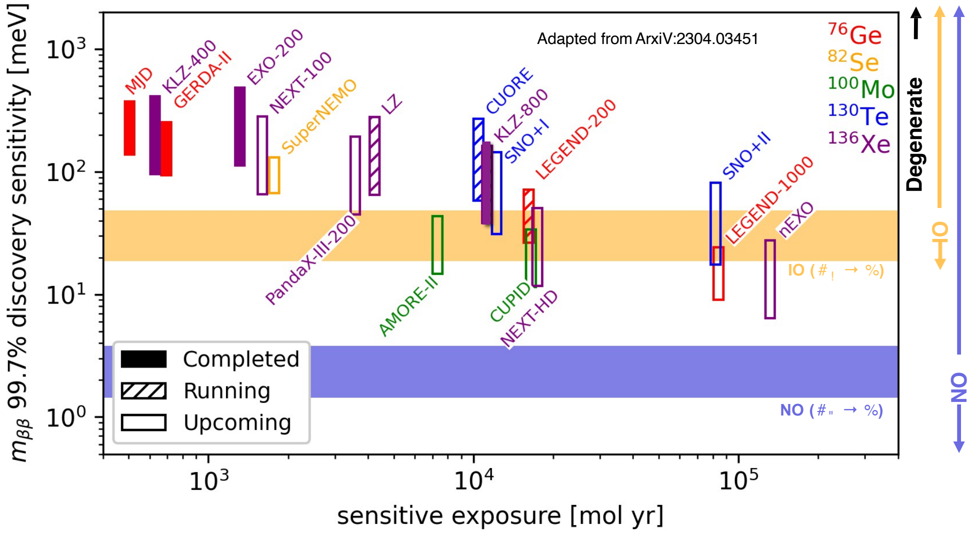
→ *Not measurable in oscillation experiments*

This is only one model -- other LNV physics also possible!

Discovery Sensitivity

Bkg free operation mode $\to \langle m_{\beta\beta} \rangle \propto [T_{1/2}]^{-1} \to T_{1/2} \propto \epsilon m_{iso}^{FV} t$ (isotope-weighted exposure)





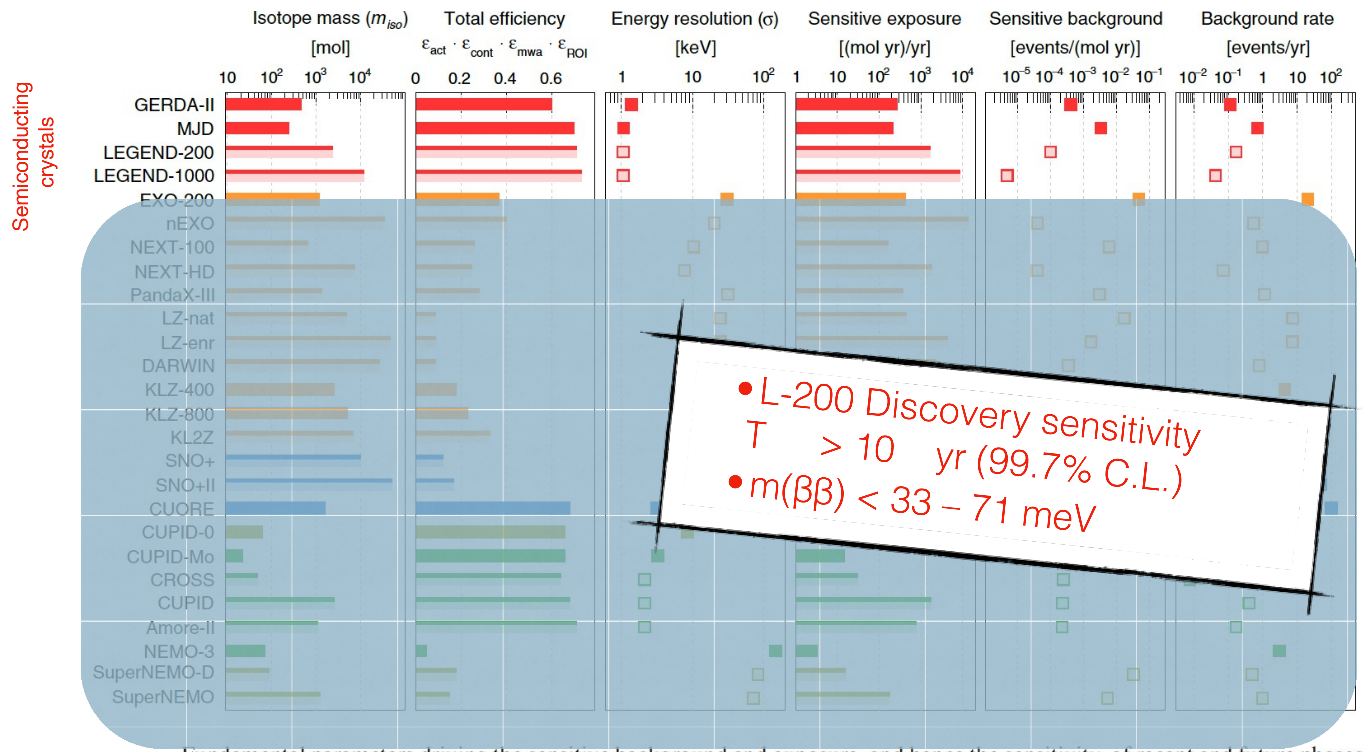
Experiments taking data currently (both at LNGS)

- CUORE:Ton·yr scale sensitivity now, but background dominated
- LEGEND-200: background-free mode,Ton scale sensitivity expected in few yrs

Future generation experiments designed to cover I.O. region fully (10 Ton·yr)

Lively experimental programme!

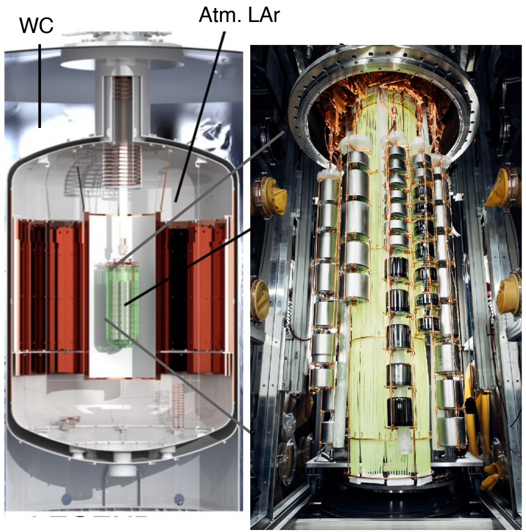
Rev. Mod. Phys. 95, 025002



- L-200 Discovery sensitivity T > 10 yr (99.7% C.L.)
- m(ββ) < 33 – 71 meV

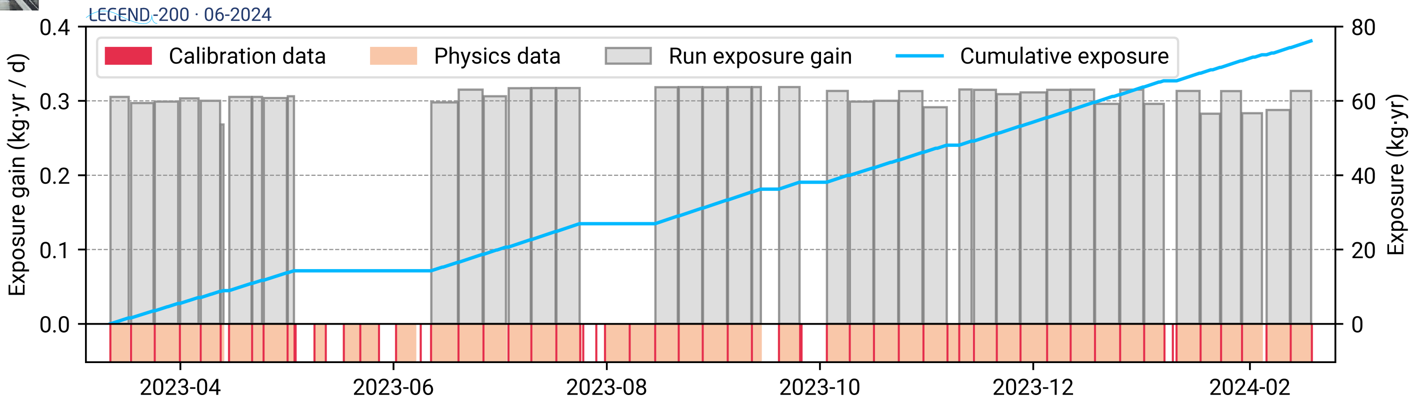
Fundamental parameters driving the sensitive background and exposure, and hence the sensitivity, of recent and future phases of existing experiments; see Eq. (38). Red bars are used for ^{76}Ge experiments, orange bars are used for ^{136}Xe, blue bars are used for ^{130}Te, green bars are used for ^{100}Mo, and sepia bars are used for ^{82}Se. Similar exposures are achieved with high mass but poorer energy resolution and efficiency using gas and liquid detectors, or with small mass but high resolution and efficiency by solid-state detectors. The sensitive exposure is computed for 1 yr of live time. Lighter shades indicate experiments that are either under construction or proposed.

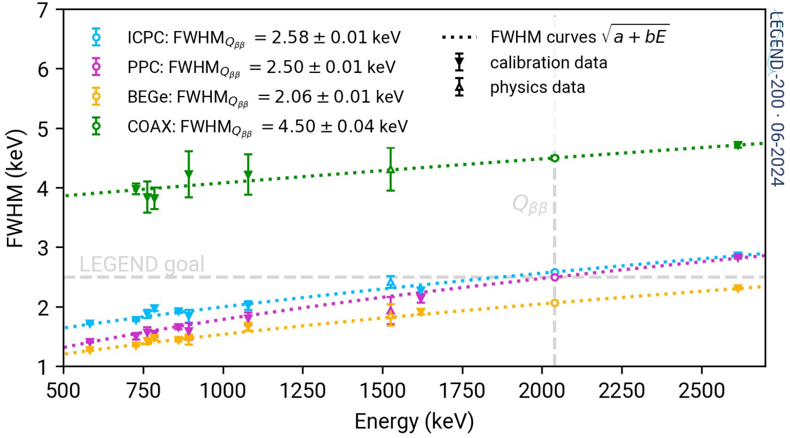
LEGEND-200



- ☑ Overall exposure so far ~ 80 kg×yr over about 0.7 years of live time (~130 kg active HPGe)
- ☑ "Golden" exposure for 0ν2β search = 48.3 kg×yr

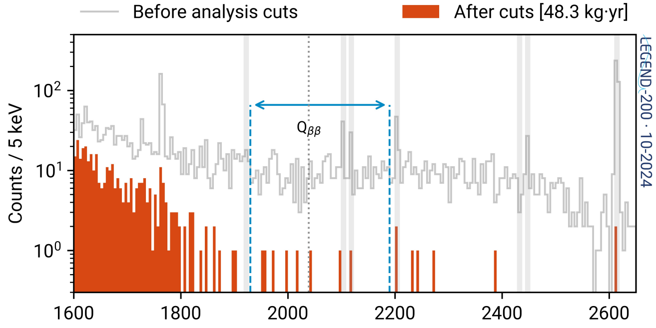
- Plus another about 30 kg yr of "silver" data for bkg characterisation
- About 1 year of maintenance and material screening to reduce background further towards target (^{228}Th contribution higher than expected, but effectively reduced)
- Almost ready to resume data taking
  - Additional about 35 kg of HPGe to be included

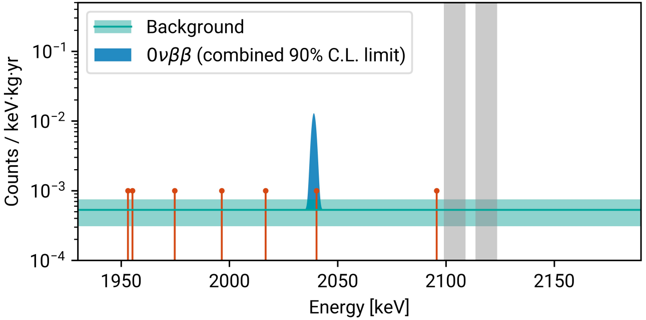




Overall resolution of 0.1% FWHM at $Q_{\beta\beta}$

- Energy scale stable over data taking with 0.3±0.2 keV bias at $Q_{\beta\beta}$
- ICPC show very good resolution even at higher masses ➙ promising for LEGEND-1000





World best exclusion limit from Ge

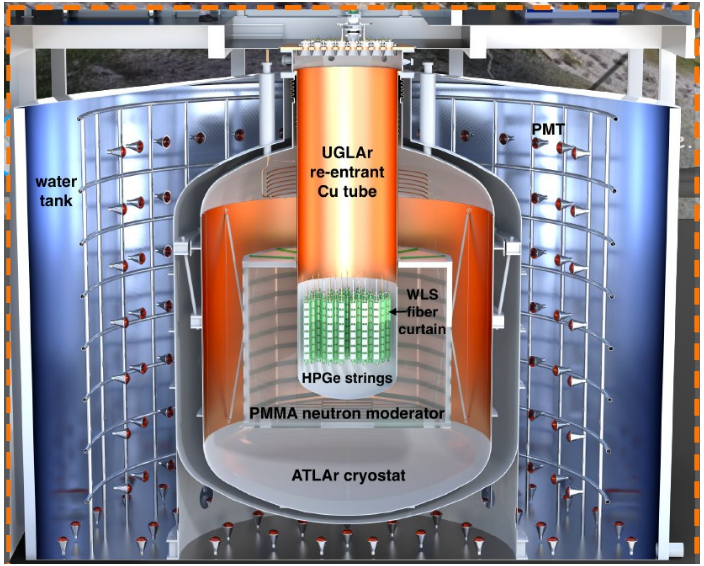
(L200+Gerda+Majorana Demonstrator, L200 improves by 30%):

- Sensitivity $T_{1/2} = 2.8 \times 10^{26}$ yr (90% CL)
- Observed $T_{1/2} > 1.9 \times 10^{26}$ yr (90% CL)

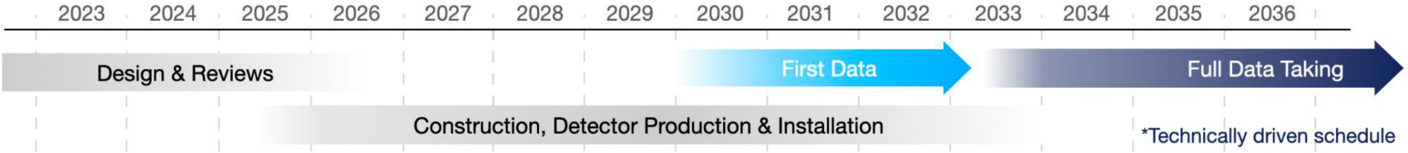
- BI = $(5.3 \pm 2.2) \times 10^{-4}$ cts/(keV·kg·yr)
  - Very low thanks to PSD in HPGe and high efficiency of LAr vetoing

https://agenda.infn.it/event/37867/contributions/233912/

LEGEND-1000



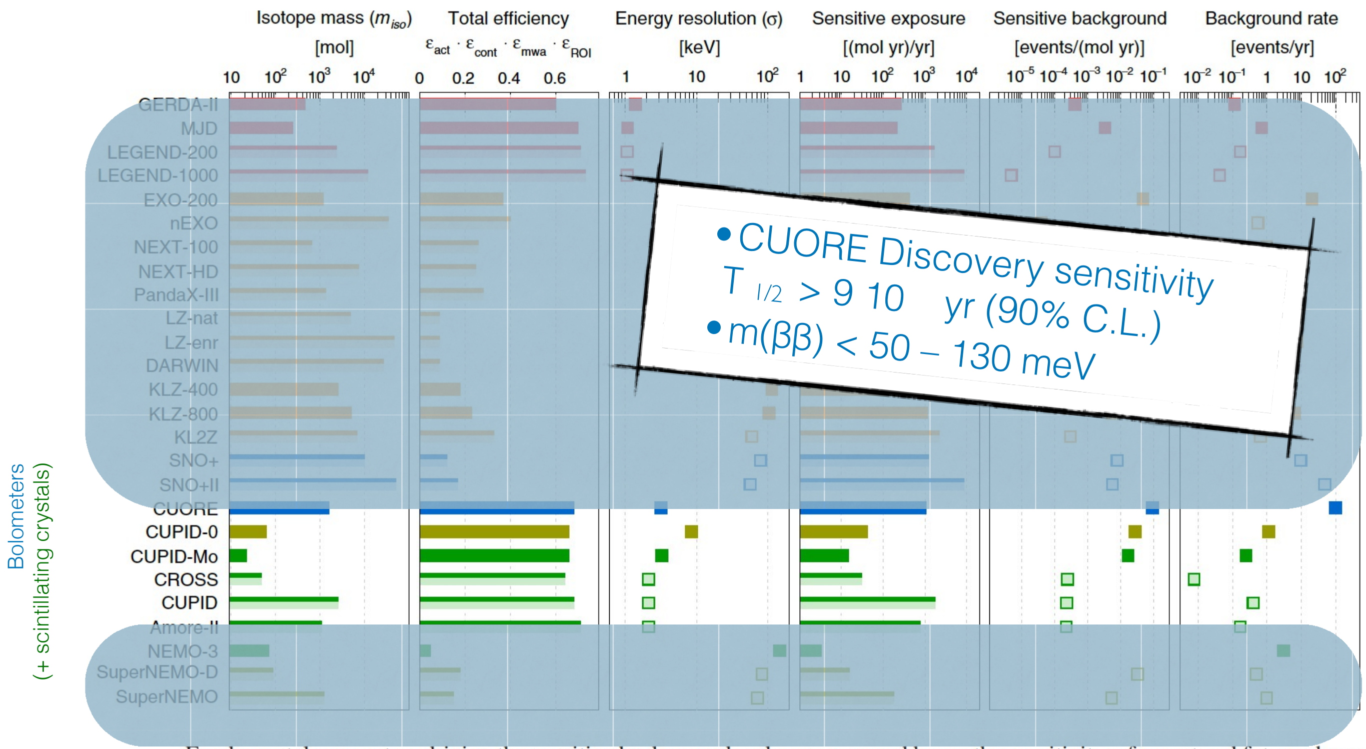
- Independent strings to allow production and independent installation of ~400 HPGe detectors
- Dedicated Underground Ar cryostat, contains HPGe and scintillation detectors, while (cosmogenic) neutron veto system in outer Atmospheric Ar volume
- Expect further improvements: larger ICPC, new electronics, radio-cleaner LAr detector fibers, cleaner Cu



- Projected background in the ROI around $Q_{\beta\beta}(^{76}Ge) = 10^{-5}$ counts/(keV·kg·yr)
- Expected sensitivity $T_{1/2} > 10^{28}$ yr (10 yrs data taking) ⇛ $m_{\beta\beta}$: [10-20] meV
- Brand new infrastructure at LNGS
- Expected start ~ 2030, but subject to HPGe procurement and international funding scenario

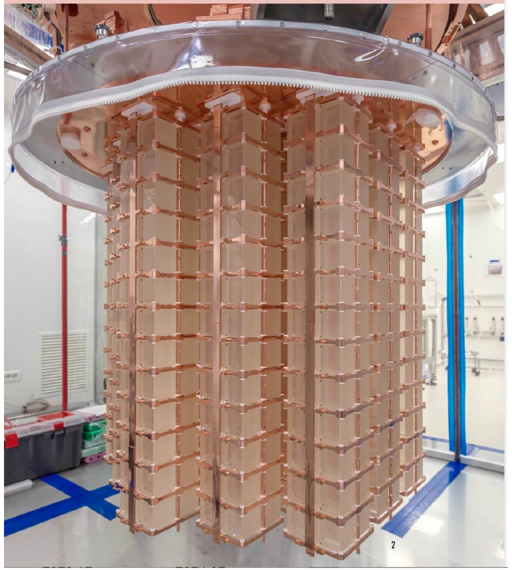
Lively experimental programme!

Rev. Mod. Phys. 95, 025002

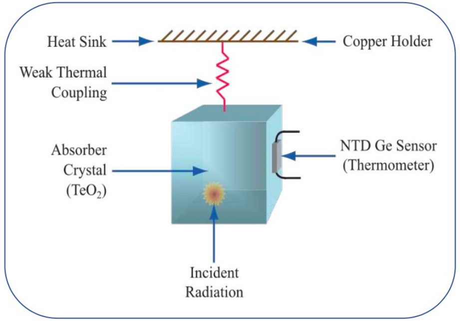


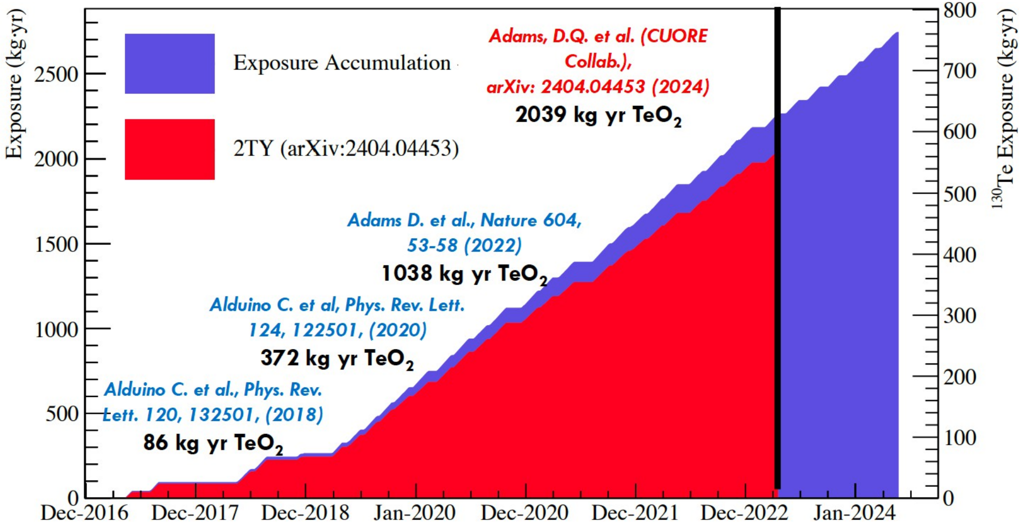
Fundamental parameters driving the sensitive background and exposure, and hence the sensitivity, of recent and future phases of existing experiments; see Eq. (38). Red bars are used for ^{76}Ge experiments, orange bars are used for ^{136}Xe, blue bars are used for ^{130}Te, green bars are used for ^{100}Mo, and sepia bars are used for ^{82}Se. Similar exposures are achieved with high mass but poorer energy resolution and efficiency using gas and liquid detectors, or with small mass but high resolution and efficiency by solid-state detectors. The sensitive exposure is computed for 1 yr of live time. Lighter shades indicate experiments that are either under construction or proposed.

CUORE



- Largest and coldest bolometer ever built
- 19 towers of 52 independent TeO_2 crystals, T=10 mK
  - Overall 742 kg total mass - 206 kg of ^{130}Te
- Steadily increasing data set since 2019 has lead to exposure for 0ν2β search = 2039 kg×yr worth of TeO_2 (567 kg×yr of ^{130}Te)

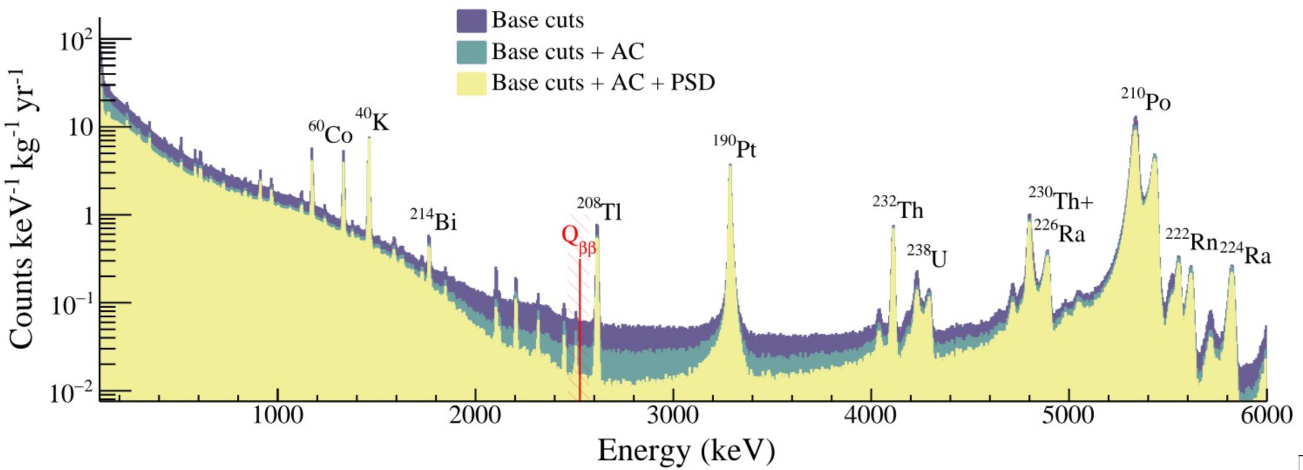




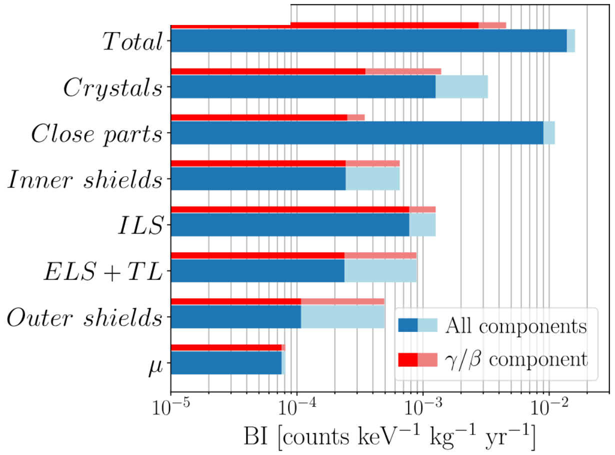
- ΔE_{FWHM} @ $Q_{\beta\beta}$ = 2527 keV: 7.3 keV
  - Continuously monitoring detector stability (NTD resistance and Pulse Tubes)

CUORE

arXiv:2404.04453



Phys. Rev. D **110**, 052003



☑ Results from Te (arXiv:2404.04453)

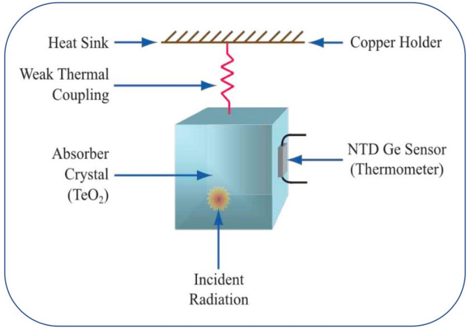
- Sensitivity $T_{1/2}$ = 4.4 × 10^{25} yr (90% CL)
- Observed $T_{1/2}$ > 3.8 × 10^{25} yr (90% CL)
- BI = (1.42 ± 0.02) × 10^{-2} cts/(keV·kg·yr)
- Mostly dominated by α particles from "close parts" (PTFE spacing, Cu supports, etc)

CUPID

arXiv:1907.09376

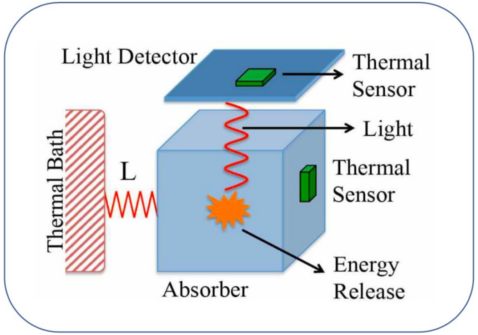
- Identify and suppress α radiation by conjugating scintillation capabilities and bolometer energy resolution
  → leverages on experience and achievements of CUORE and CUPID0/CUPID-Mo
- Re-use CUORE infrastructure + 1600 $Li_2{}^{100}MoO_4$ (⇛240 kg ^{100}Mo)

CUORE ^{130}Te
pure thermal detector (bolometer)

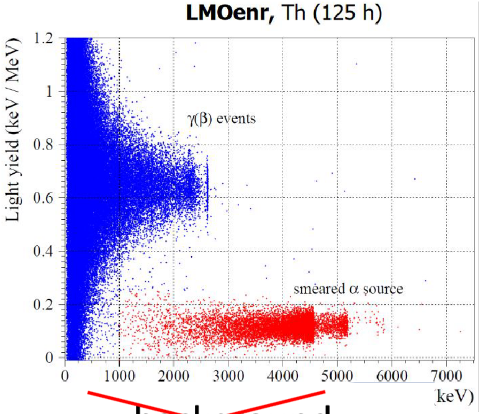


No PID
Q = 2527 keV **< 2615 keV**

CUPID ^{100}Mo
heat + light (scintillating bolometer)



PID
Q = 3034 keV > 2615 keV



~~α background~~
~~γ background~~

- Projected background in the ROI around $Q_{\beta\beta}(^{100}Mo)$ = 10^{-4} counts/(keV·kg·yr)
- Expected sensitivity $T_{1/2} > 10^{27}$ yr (10 yrs data taking) ⇛ $m_{\beta\beta}$: [12-20] meV
- Re-use CUORE infrastructure at LNGS
- Expected start ~ 2030, but subject to crystal procurement and international funding scenario

Lively experimental programme!

FIG. 20. Fundamental parameters driving the sensitive background and exposure, and hence the sensitivity, of recent and future phases of existing experiments; see Eq. (38). Red bars are used for ^{76}Ge experiments, orange bars are used for ^{136}Xe, blue bars are used for ^{130}Te, green bars are used for ^{100}Mo, and sepia bars are used for ^{82}Se. Similar exposures are achieved with high mass but poorer energy resolution and efficiency using gas and liquid detectors, or with small mass but high resolution and efficiency by solid-state detectors. The sensitive exposure is computed for 1 yr of live time. Lighter shades indicate experiments that are either under construction or proposed.

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Conclusions

Apologies: not covered
- Solar neutrinos — S. Zavatarelli
- Geo-neutrinos — L. Ludhova
- Coherent scattering
- see other talks

- A **huge** work in progress:
  - Neutrino mass ordering (NMO) and δ_{CP} likely to be measured relatively soon
    - **JUNO** and **ORCA** leading the effort on NMO
    - Better hints on δ_{CP} will come from **T2K/NOvA**, first measurement likely from **HK**, precision era with **HK & DUNE** (capable to measure both without degeneracies)
  - **A new generation of $0\nu\beta\beta$** (ton scale) is underway to cover IMO completely
  - News on mass might come from cosmology and/or direct measurement
  - **Investigation on unitarity** will come from precision measurements (**JUNO**) and search for short distance anomalous effects (**SBN** program at FNAL, reactors)
  - **Ready for surprises !**