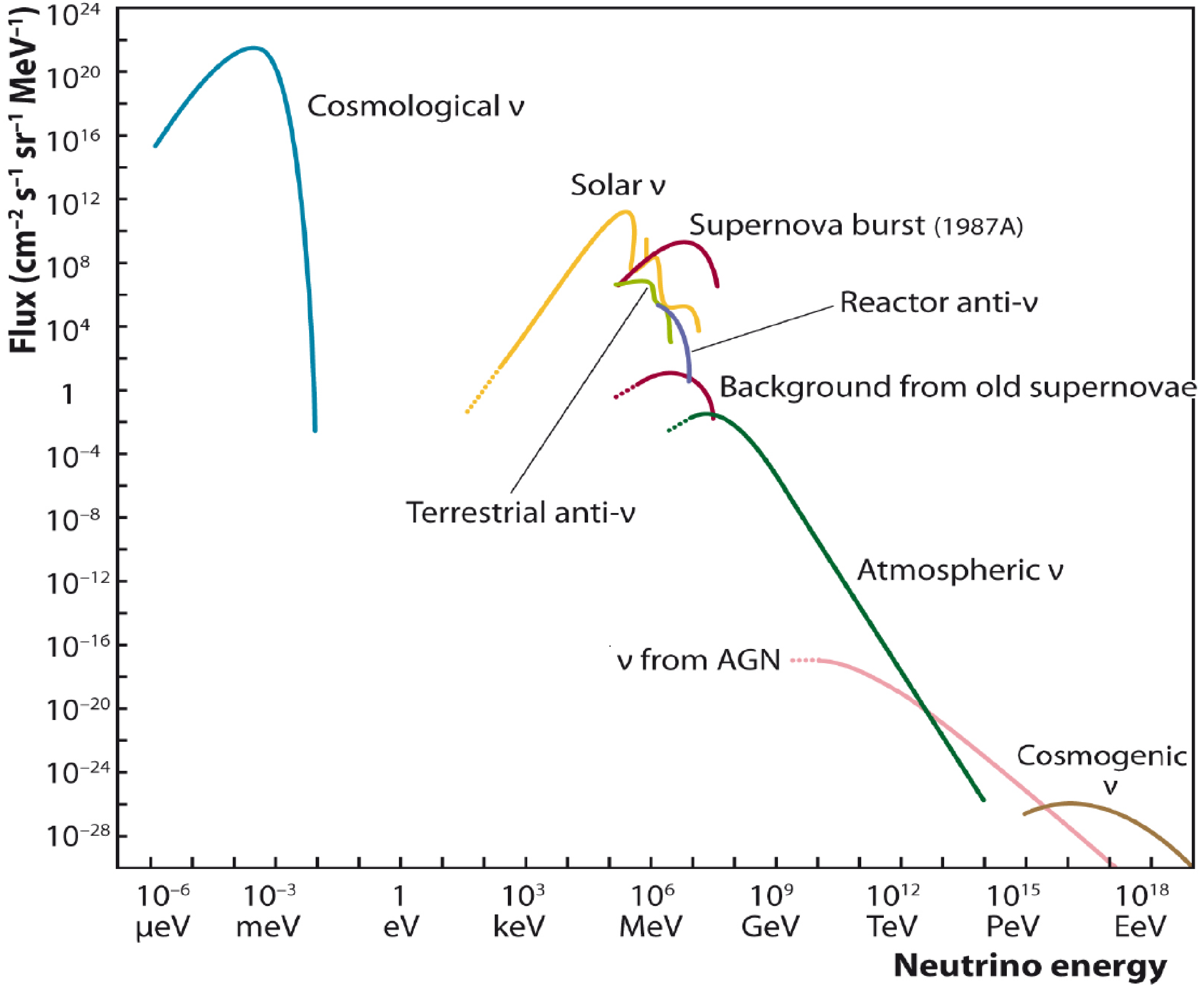
Neutrino 2024

Opening Talk: Where are we?

Art McDonald
Queen's University, Canada

Milan, Italy
June 17, 2024

Neutrinos Reaching the Earth



Topics of the Conference

- Neutrino Oscillations (CP violation, Hierarchy, Sterile neutrinos)
  - Long Baseline
  - Short Baseline
  - Reactor
  - Atmospheric, Solar, Geo
- Neutrino Properties
  - Majorana: Neutrino-less Double Beta
  - Mass: Direct, Cosmological
- Neutrino and Multi-messenger Astronomy
- Neutrino-Matter Interactions, including coherent scattering
- Theory
  - Beyond Standard Model
  - Neutrino Mass
  - Neutrino Cosmology

As of today: Oscillation of 3 massive active neutrinos is clearly the dominant effect:

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$

Flavor (e, μ, τ) — Mass 1,2.3

For 3 Active neutrinos.

Pontecorvo-Maki-Nakagawa-Sakata matrix

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

(Double β decay only)

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

✓ Atmospheric, Accel. | ? CP Violating Phase | ✓ Reactor, Accel. | ✓ Solar,Reactor | ? Majorana CP Phases

where $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$

✓ Range defined for Δm_{12}, Δm_{23}

For two neutrino oscillation in a vacuum: (a valid approximation in many cases)

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 (1.27 \frac{\Delta m^2 L}{E})$$

MSW

Interactions with high electron density can influence the process in the sun and the earth

SUMMARY OF OSCILLATION RESULTS FOR THREE ACTIVE ν TYPES

Particle Data Group

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$
$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2

Solar, Reactor

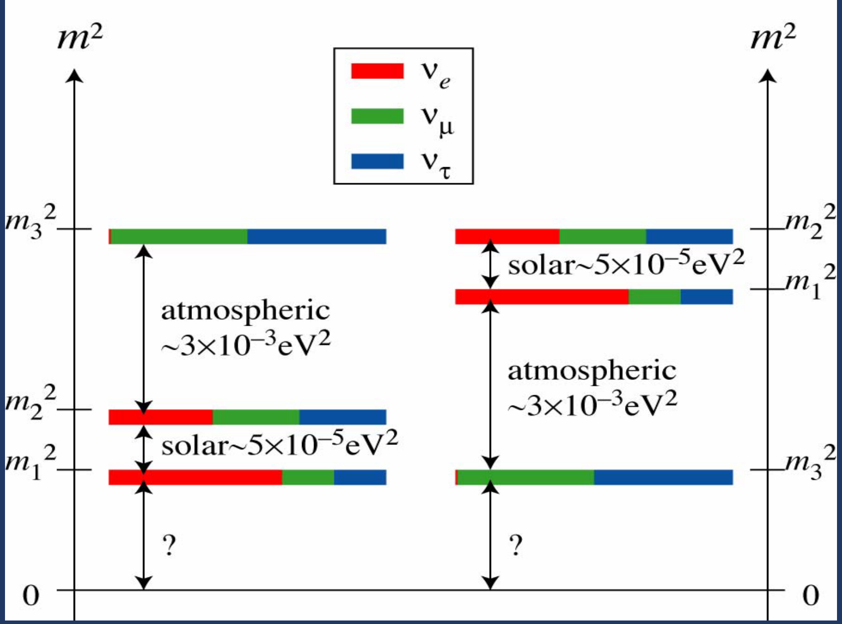
$\sin^2(\theta_{23}) = 0.539 \pm 0.022$ (S = 1.1) (Inverted order)
$\sin^2(\theta_{23}) = 0.546 \pm 0.021$ (Normal order)
$\Delta m^2_{32} = (-2.536 \pm 0.034) \times 10^{-3}$ eV^2 (Inverted order)
$\Delta m^2_{32} = (2.453 \pm 0.033) \times 10^{-3}$ eV^2 (Normal order)

Atmospheric,Accelerator

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

Reactor, Accelerator

Mass Hierarchies



Normal Inverted

Future objectives:

- δ_{CP}
- θ_{23} max?
- Hierarchy?

Accelerator,Reactor, Atmospheric

- Majorana ν?
- Absolute mass

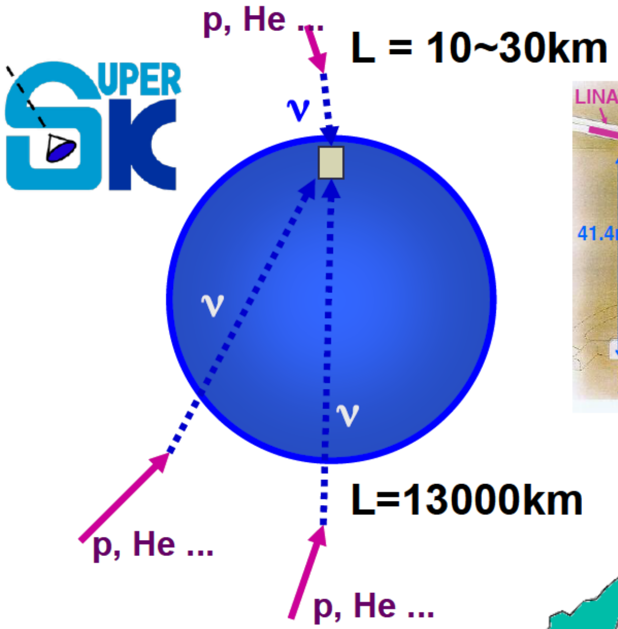
$0\nu\beta\beta$, Cosmology, Electron spectrometers,

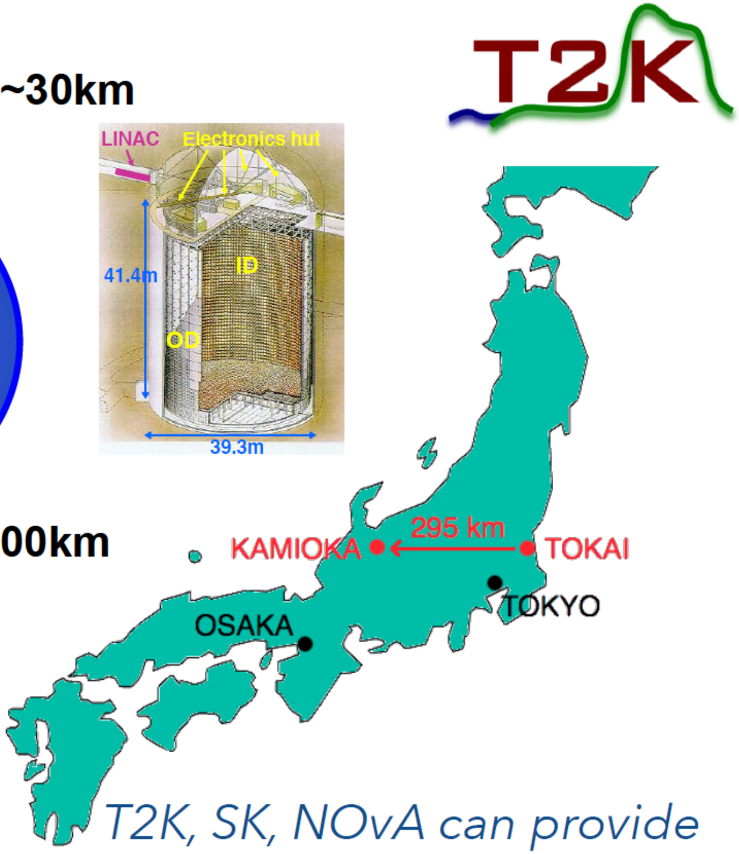
- Sterile ν?

Accelerator,Reactor, Atmospheric

Joint oscillation analysis

- Different energies, baselines can resolve the degeneracies between mass ordering and δ_{CP} and/or θ_{23} octant and δ_{CP}
- It is important to study possible correlations in the systematics errors between the experiments





Slide from A. Himmel, Neutrino 2020

atmospheric
+ accelerator

T2K, SK, NOvA can provide complementary information

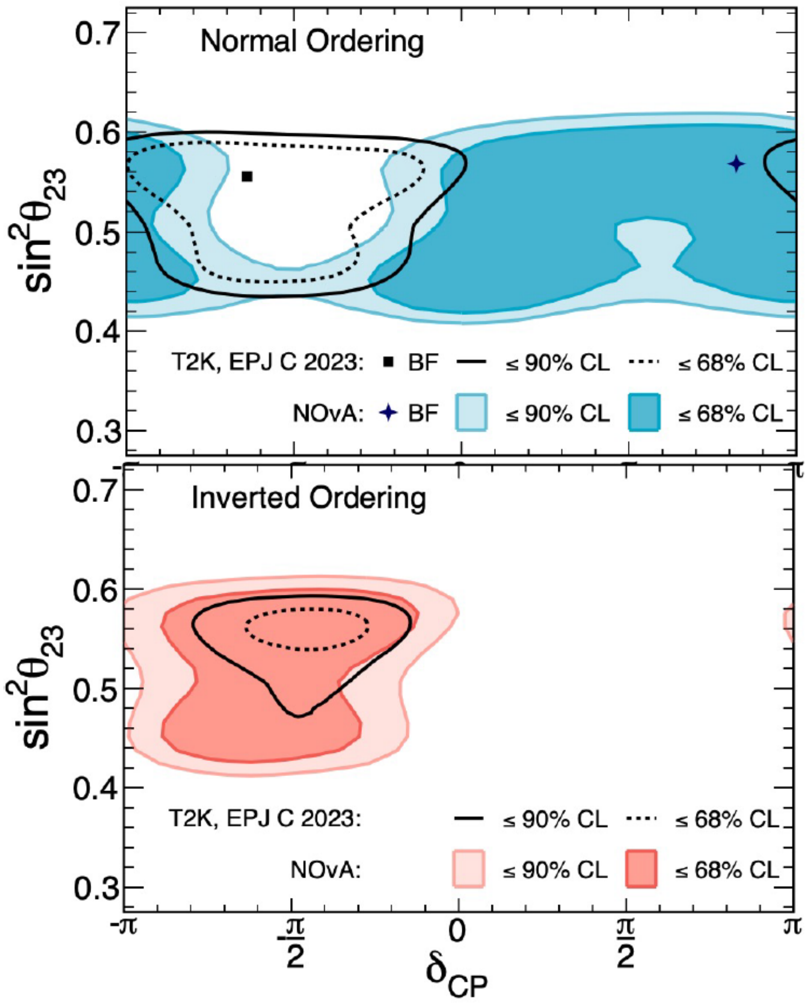
	T2K	NOvA
Baseline	295km	810km
Peak neutrino energy	0.6 GeV	2 GeV
CP effect	32%	22%
Matter effect	9%	29%

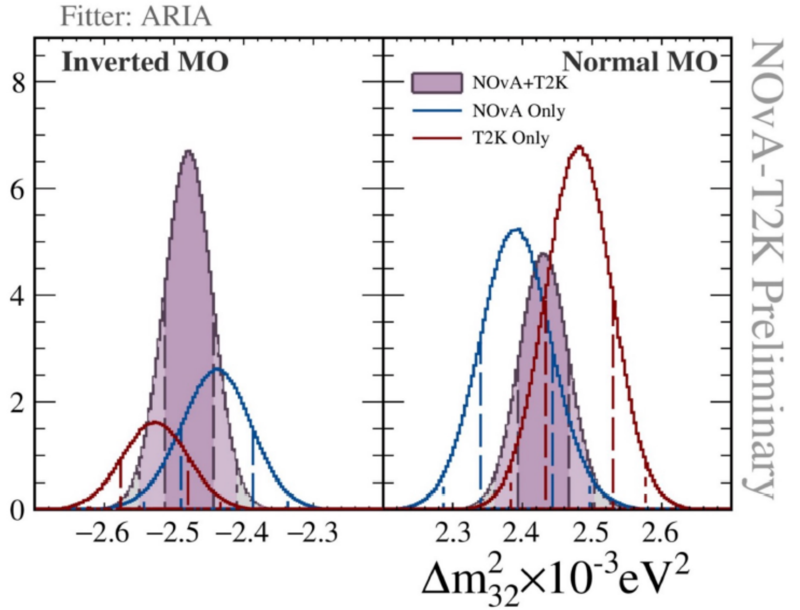
Long-Baseline Neutrino Oscillation Measurements in Progress

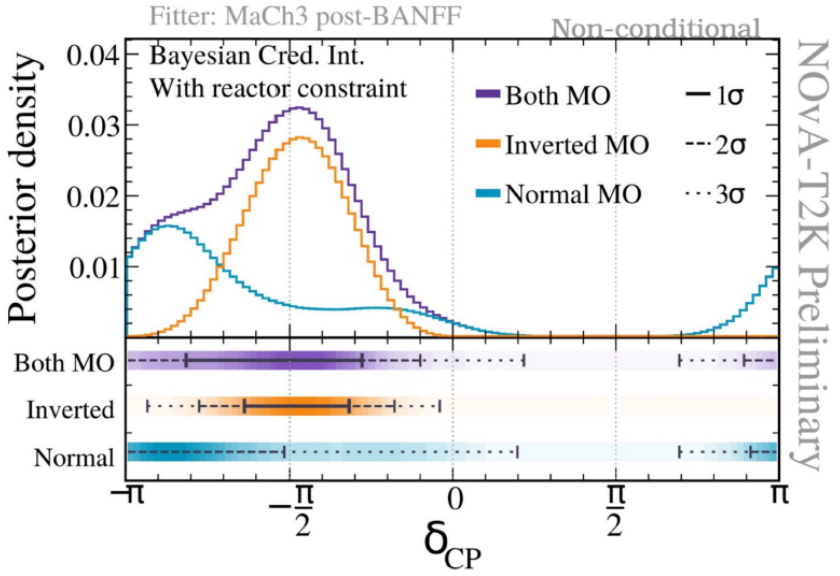
K. Sakashita at NPB2024, Hong Kong, Feb 2024

N0vA and T2K joint results
(Mayly Sanchez)

T2K measurements isolate the impact of CP violation whereas NOvA has more mass ordering sensitivity







Including the Δm^2_{32} constraint from the Daya Bay experiment reverses the preference back to NO

The ν mass ordering remains inconclusive

$\delta_{CP} = \pi/2$ lies outside 3σ interval for both mass orderings

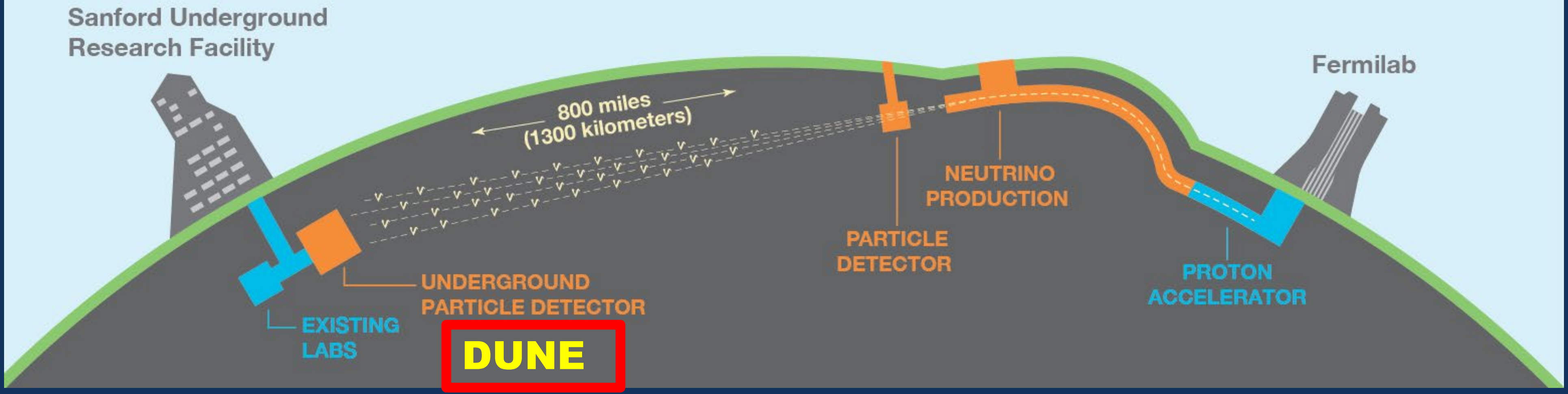
CP conserving values for the IO fall outside the 3σ range

B. Clerbeau Summary Talk Moriond Mar 2024

→ Need more data

Future improvements and more running at both experiments. Next Talks!

In progress: Next-Gen Long-Baseline experiments: Different neutrino interactions in the earth. Combined analysis will be valuable.

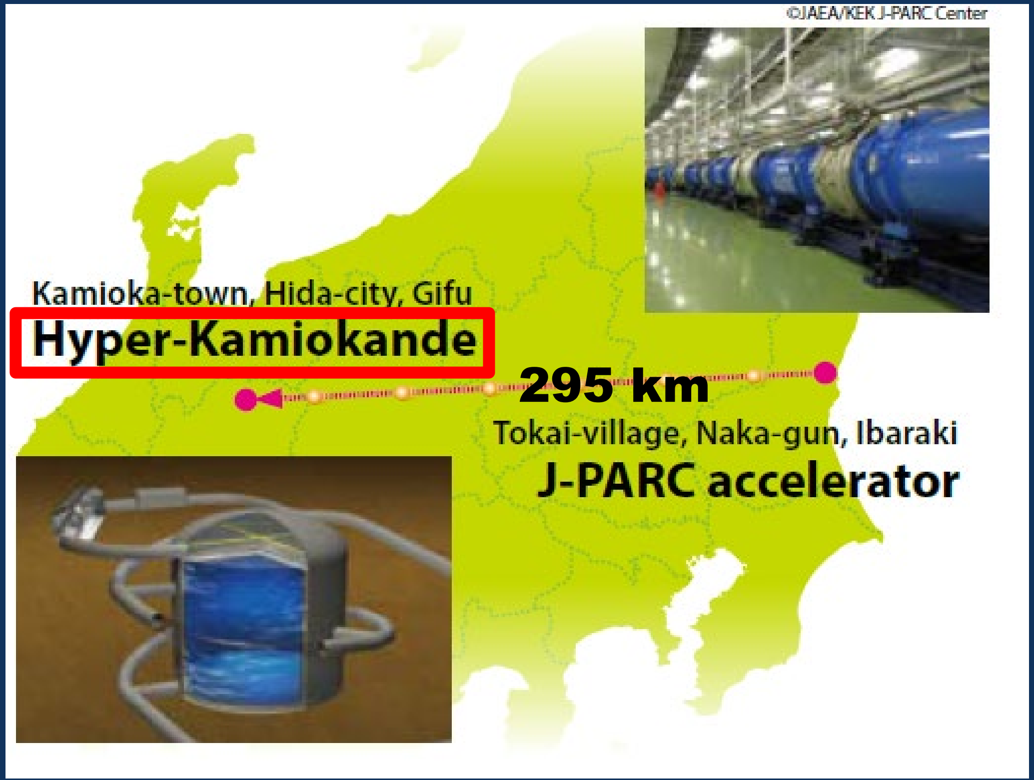


- DUNE in the US and Hyper-Kamiokande in Japan

Compare neutrino oscillations initiated by muon neutrinos and their anti-particles.

δ_{CP}, θ_{23} max?, Hierarchy?

Status of each experiment will be presented, including schedules.



Conclusions

Sterile Neutrinos

- **Short Baseline**

- LSND and MiniBooNE anomalies are disfavored by MicroBooNE
- ν_s explanation of LEE is still possible but contradicts disapp. experiments
- MicroBooNE(NuMI), SBNP and $JSNS^2$ will soon clarify the situation

- **Gallium**

-GA is in serious tension with many experiments but agrees with Neutrino-4
-Many ideas of possible conventional or BSM explanation but not convincing
- ν_s explanation of GA is still marginally possible
- BEST with ^{65}Zn source – smoking gun test for many explanations

- **Reactor Neutrinos**

- RAA is probably explained by smaller ^{235}U contribution preferred by new experiments (with exception of DANSS) and new Reactor flux models
- Spectral analysis still indicates ν_s with a small $\sin^2 2\theta_{ee}$ at ~3σ
- Neutrino-4 claim of ν_s observation is in tension with many results but not excluded
- Upgraded VSBL reactor experiments will clarify the situation
  Upgraded Neutrino-4+ is already taking data, Neutrino-4M will start in 2024

Cosmological constraints were not discussed but models exist which remove them
See e.g. Davoudiasl,Denton arXiv:2301.09651   Explains Ga, LSND, MiniBooNE, DM

Experimental evidence for ν_s is fading away but not excluded

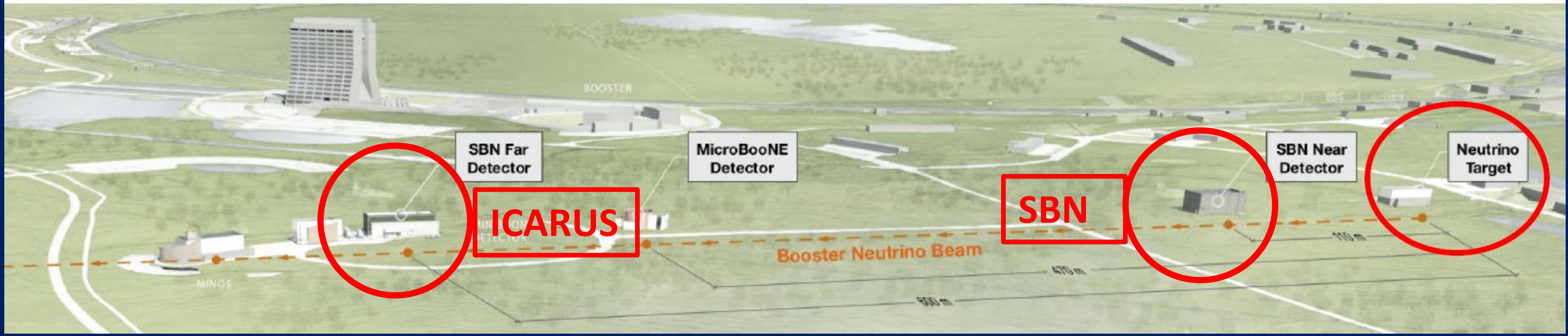
Sterile Neutrinos

Short-Baseline Neutrino Oscillation + Source Measurements in Progress

Summary Talk by M. Danilov at Moriond Mar 2024

The SBN program: Booster beam

Fermilab Short Baseline program



- Two similar Liquid Argon Detectors
- Search for neutrino oscillations at O(Δm2) ~ 0.1-10 eV^2
- Measure ν-Ar interactions
- Search for physics beyond the Standard Model
- ICARUS in operation
- SBN about to cool down

Jiangmen Underground Neutrino Observatory

Z. Yu at NPB 2024

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \frac{\Delta m^2_{21} L}{4E}$$

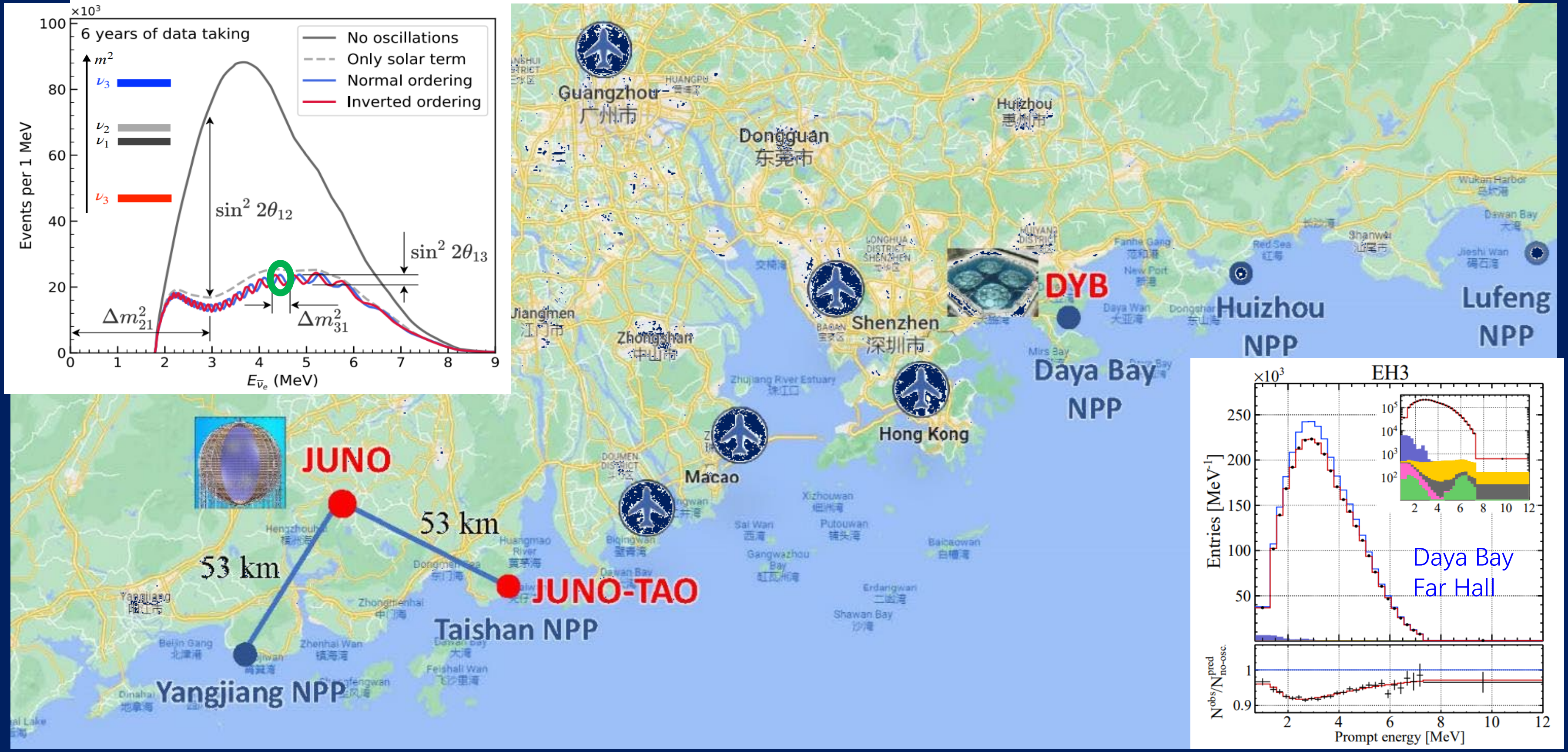
← **Leading term at JUNO**

$$- \frac{1}{2} \sin^2 2\theta_{13} \left[\sin^2 \frac{\Delta m^2_{31} L}{4E} + \sin^2 \frac{\Delta m^2_{32} L}{4E} \right]$$

← **Leading term at Daya Bay**

$$- \frac{1}{2} \cos 2\theta_{12} \sin^2 2\theta_{13} \sin \frac{\Delta m^2_{21} L}{4E} \sin \frac{(\Delta m^2_{31} + \Delta m^2_{32}) L}{4E}$$

← **Sensitive to mass ordering**



Key for NMO:

1、20 kton liquid scintillator detector

2、3% energy resolution at 1 MeV energy deposit

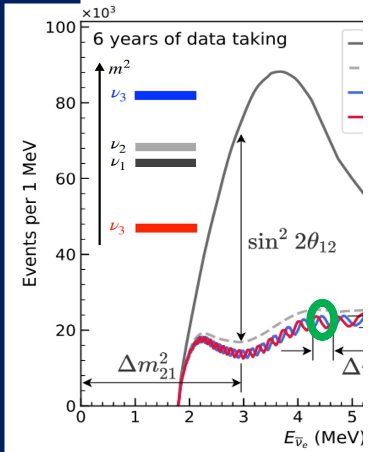
3、low background

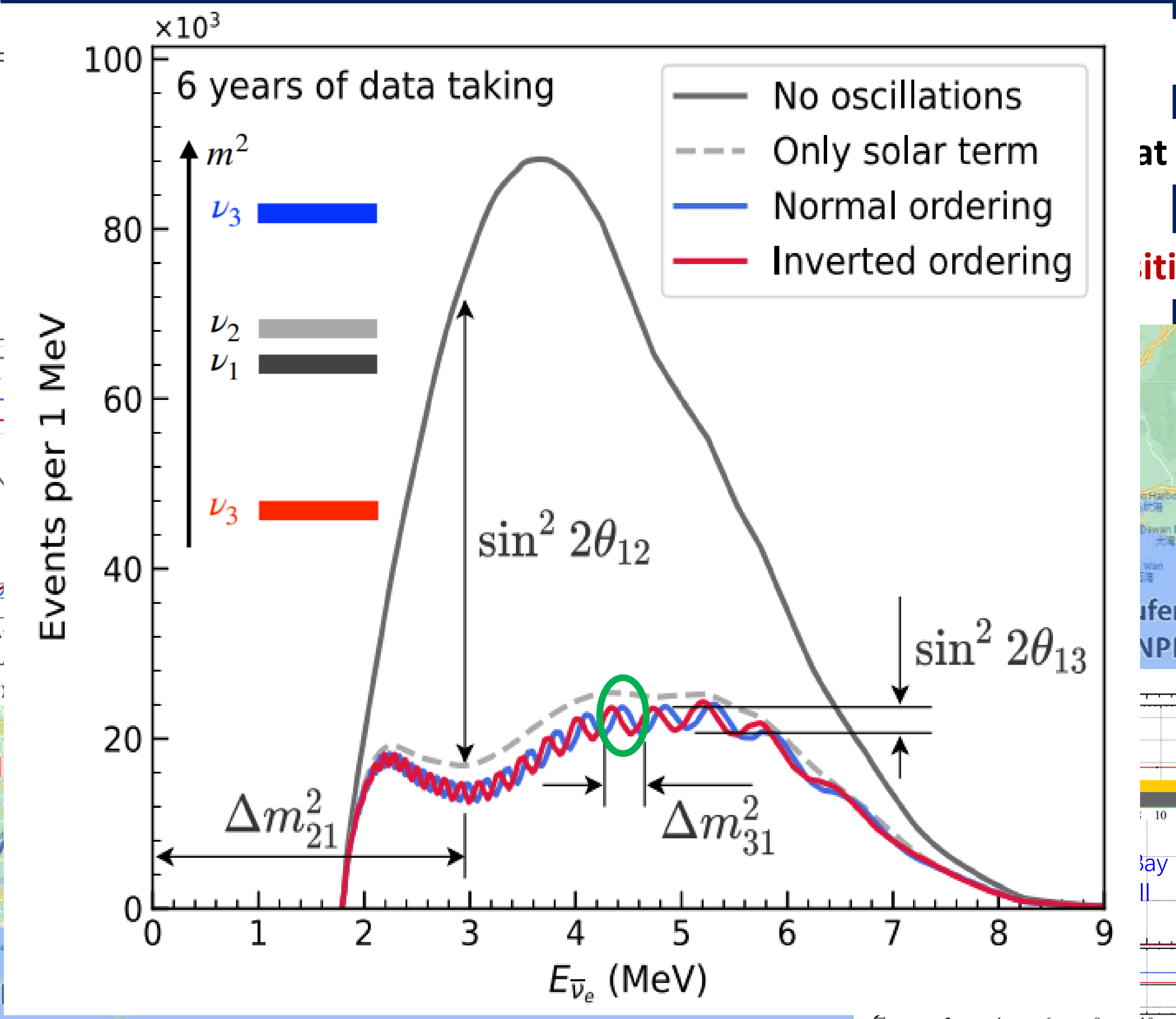
Jiangmen Underground Neutrino Observatory

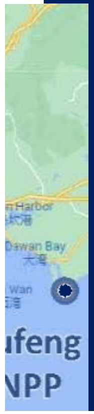
$P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$ =

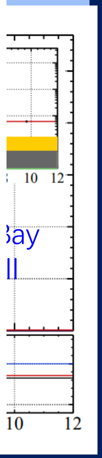
at Daya Bay

itive to mass ordering









Key for NMO:

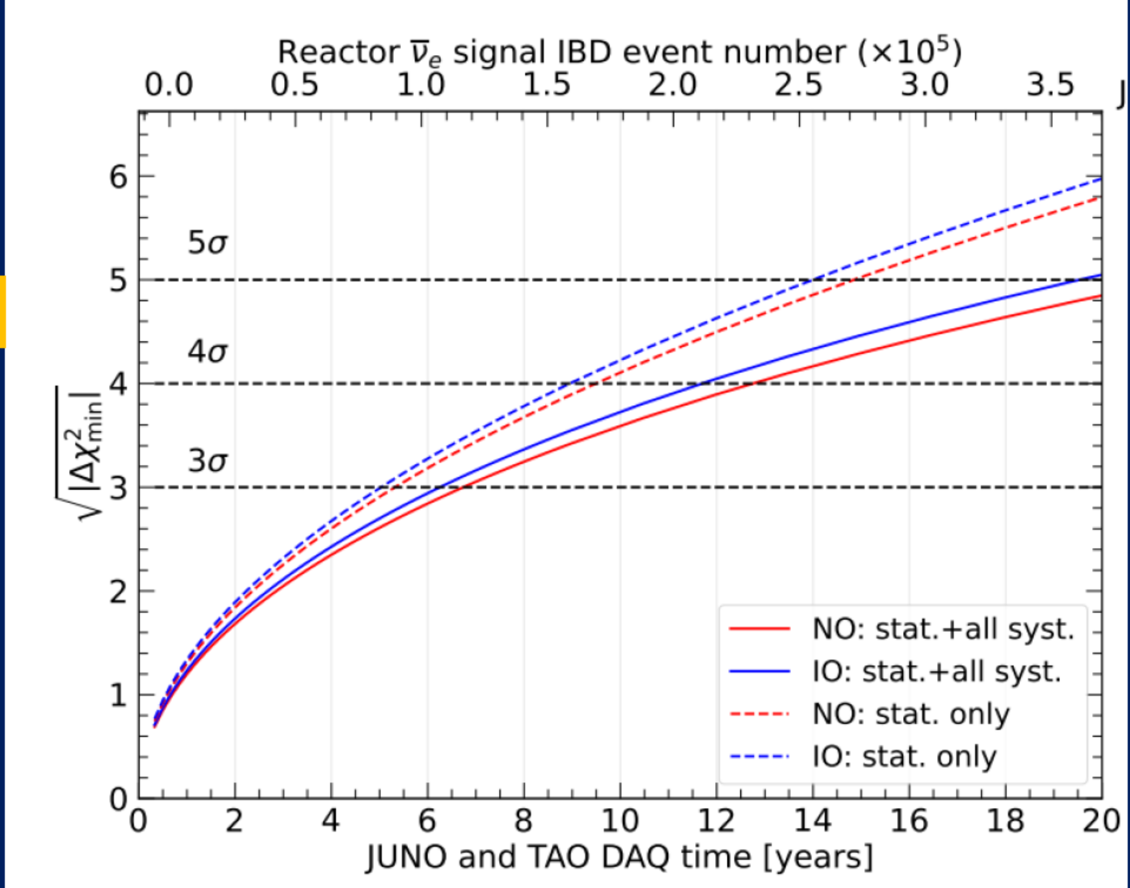
1、20 kton liquid scintillator detector

2、3% energy resolution at 1 MeV energy deposit

3、low background

Neutrino Mass Ordering

Preliminary



JUNO NMO median sensitivity: **3σ (reactors only) @ ~6 yrs * 26.6 GW_{th} exposure**

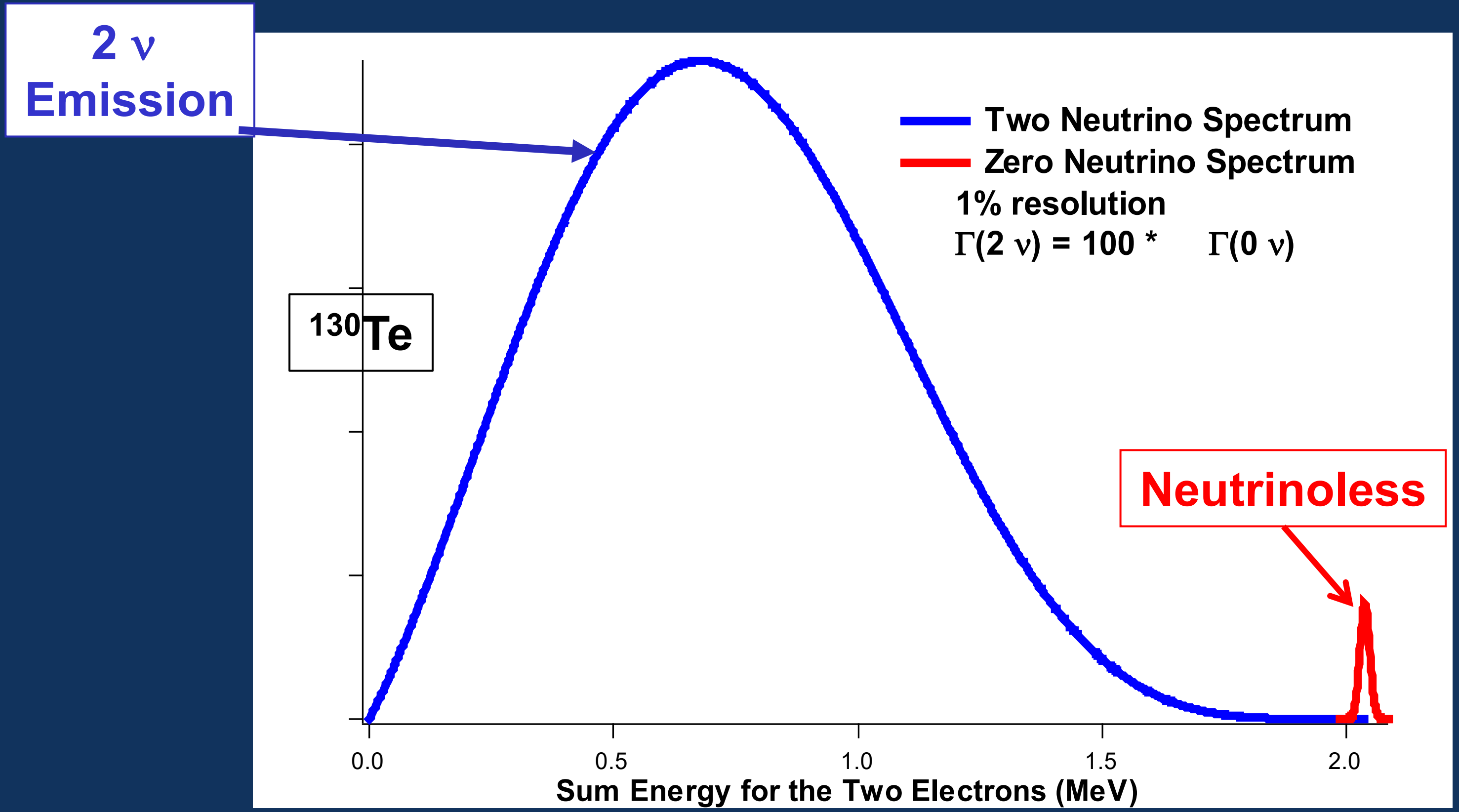
Combined reactor+atmospheric neutrino analysis in progress: further improve the Neutrino Mass Ordering sensitivity

ν-less Double Beta Decay: Measuring Effective ν Mass

$(T_{1/2})^{-1} = F(Q_{\beta\beta},Z)\,|M^{0\nu}|^2 \,\langle m_{\nu\beta\beta}\rangle^2$

Additional phases

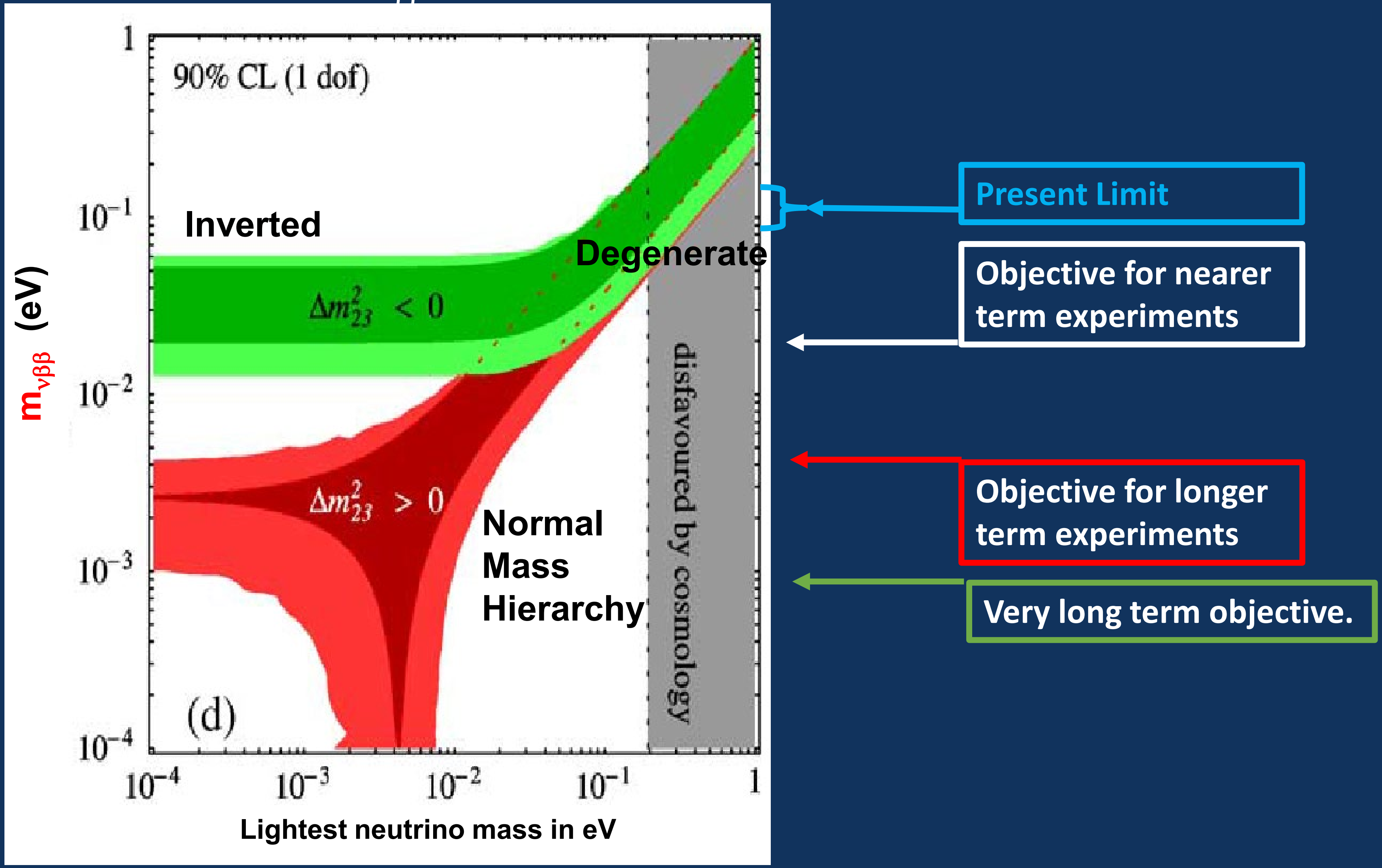
$$m_{\nu\beta\beta} = |m_1 \cos^2\theta_{13}\cos^2\theta_{12} + m_2\, e^{2i\alpha} \cos^2\theta_{13}\sin^2\theta_{12} + m_3\, e^{2i\beta} \sin^2\theta_{13}|$$



Requires: Neutrinos to be their own antiparticle (Majorana particles)

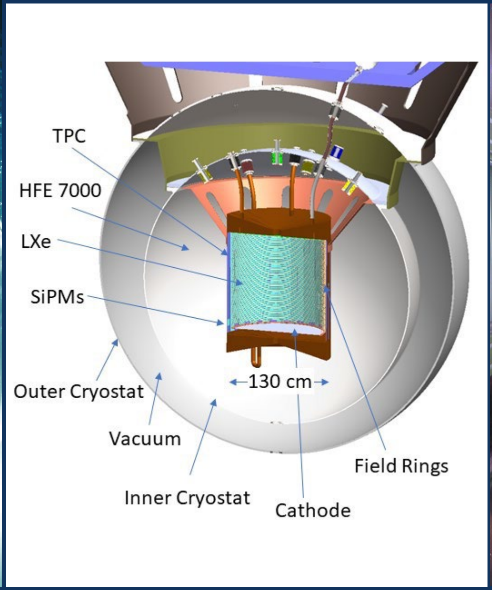
- **Finite ν mass: Lifetimes > ~10^{26} years imply ν mass < 0.1 eV**

Variation of $m_{\beta\beta}$ vs Lightest ν mass



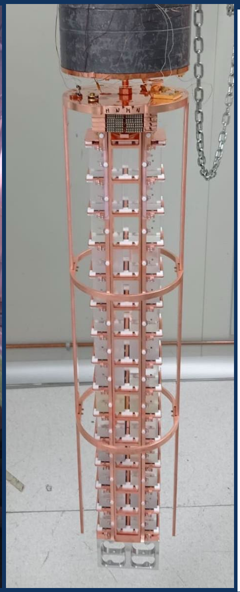
Neutrino-less Double Beta Decay

SNO+ (Te)

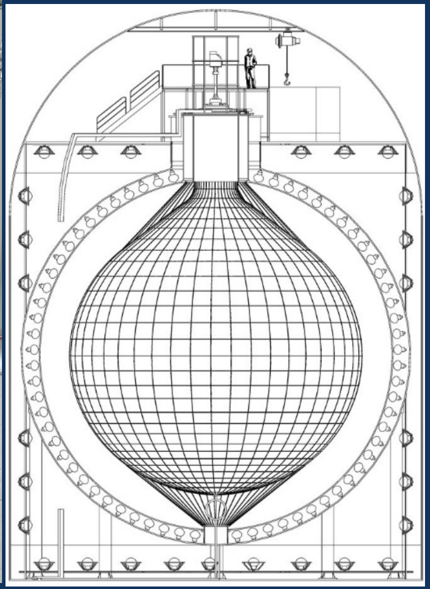


nEXO (Xe)

LEGEND (Ge)



CUPID (Mo)

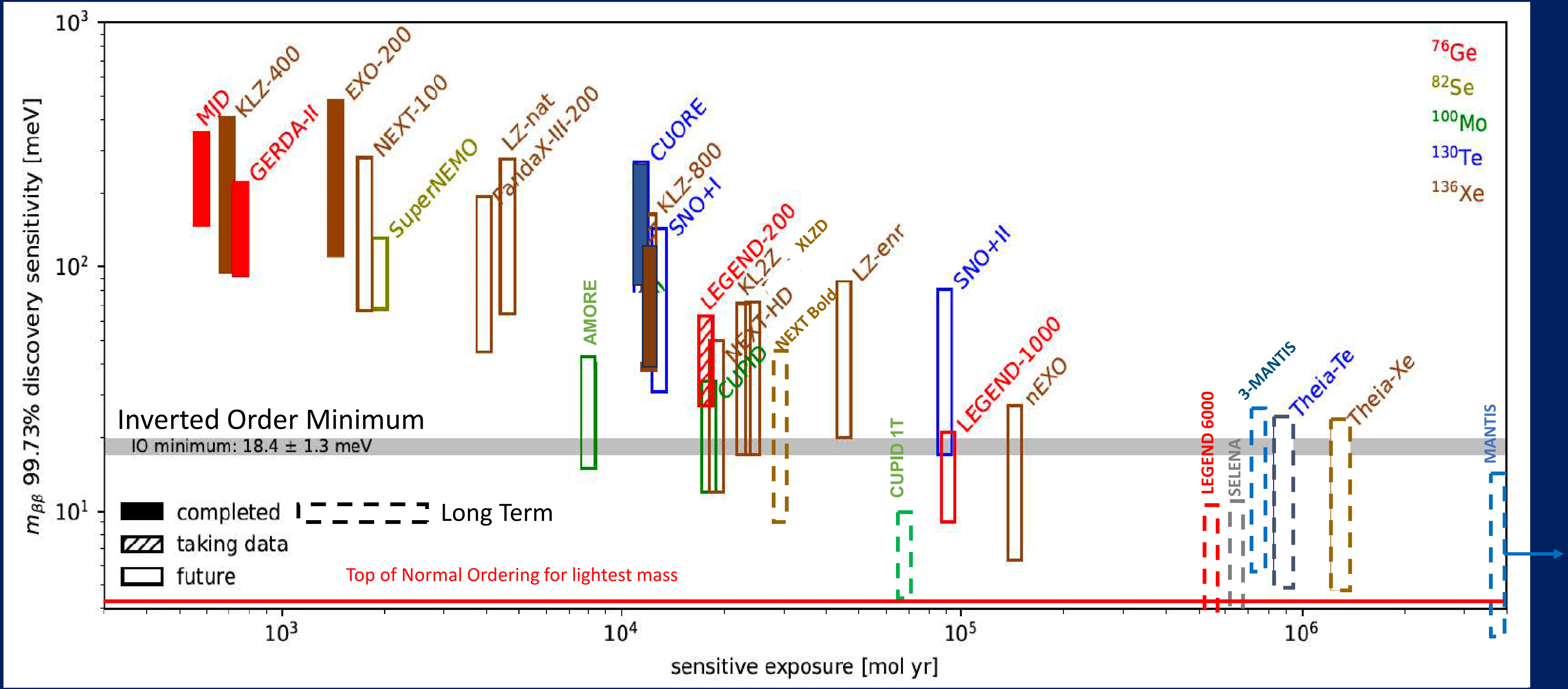


KAM-ZEN (Xe)

- There are a number of experiments in operation and others in development with several different isotopes. This will be an advantage in the advent of a discovery

- Detailed nuclear theory calculations are needed to interpret these measurements and are an important part of the field.
- There is a question of quenching of g_A that could reduce the sensitivity of these experiments to effective neutrino mass by a factor of 2 to 4.

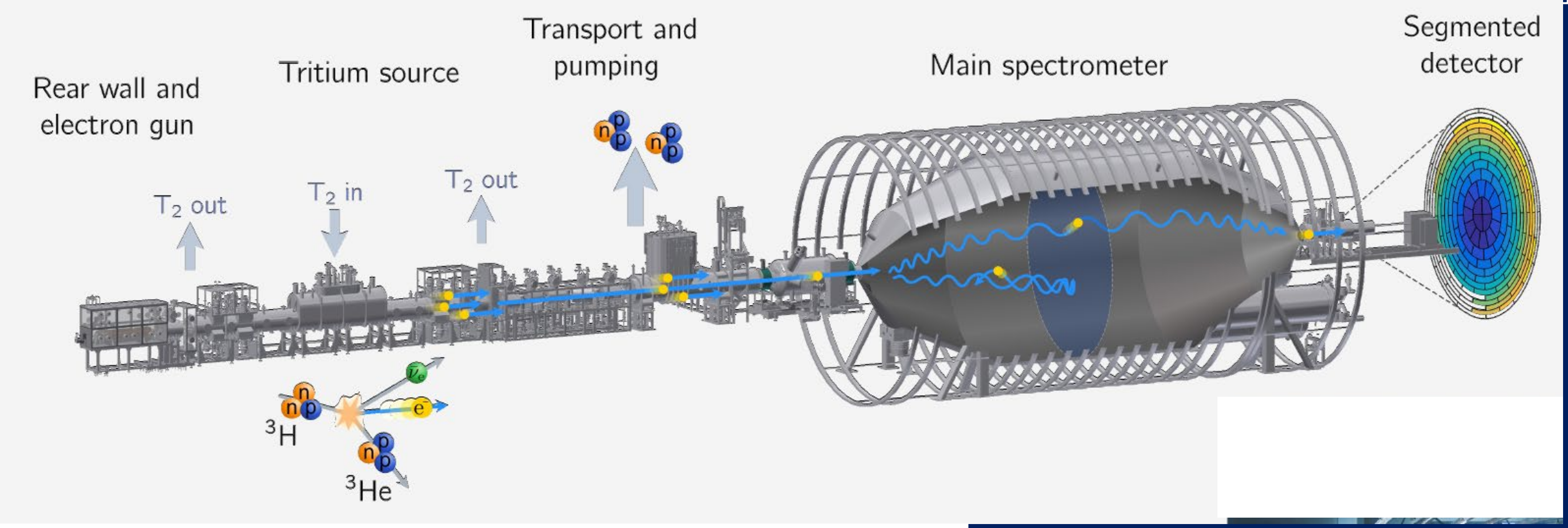
Summary plot from NSAC LRP White Paper (Augmented) (Values provided by experiments)
(Assuming that process is mediated by low mass neutrinos and g_A is not quensched)



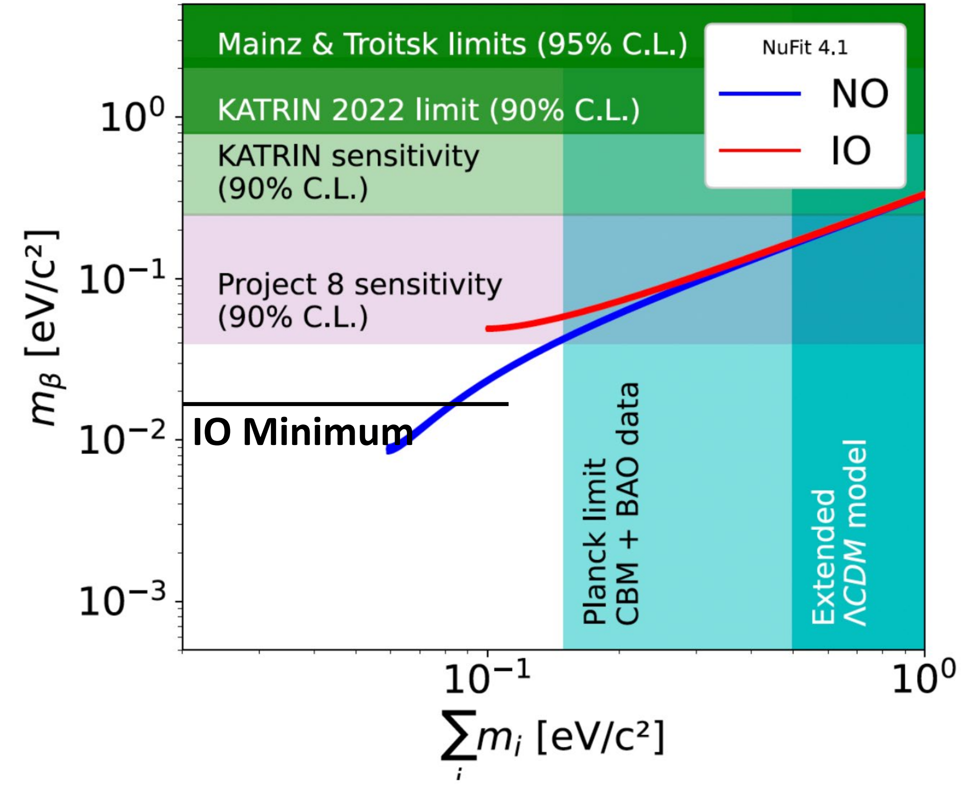
From: Fundamental Symmetries, Neutrons, and Neutrinos (FSNN):
Whitepaper for the 2023 Nuclear Science Advisory Committee Long Range Plan: arXiv:2304.03451iv:2304.03451

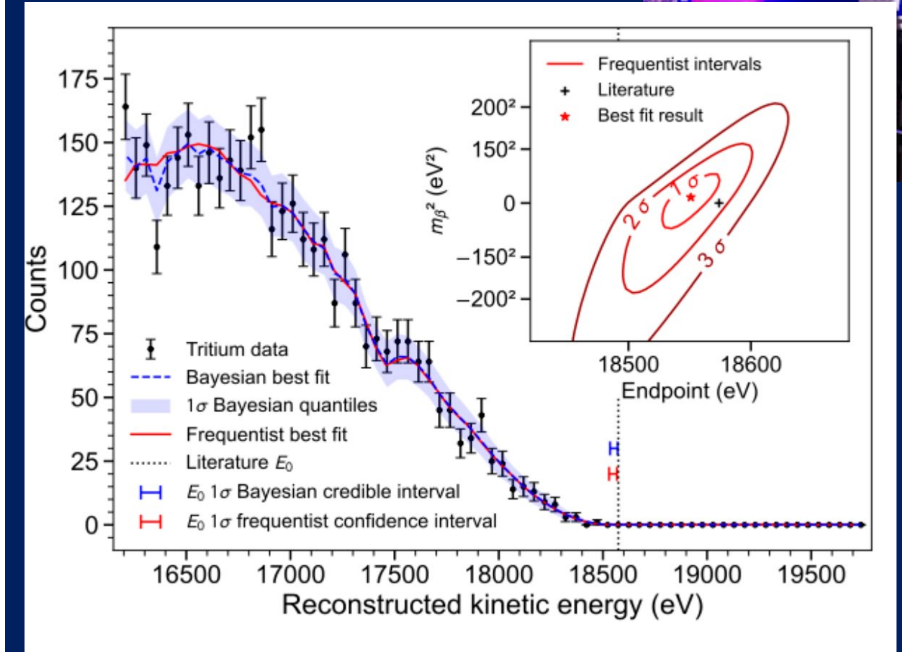
Neutrino Mass from Tritium Beta decay

KATRIN



Both Projects will also search for kinks in the spectra at lower energy to look for sterile neutrinos: KATRIN Next Phase





Phys.Rev.Lett. 131 (2023) 10, 102502

PROJECT 8

Cyclotron Radiation Emission Spectrometry (CRES)
Published result:
Neutrino Mass < 150 ev/c^2
Future: Atomic Tritium, greater statistics:
Projected reach: ~ 0.040 ev/c^2

Prospects for the measurement of the absolute neutrino mass in cosmology

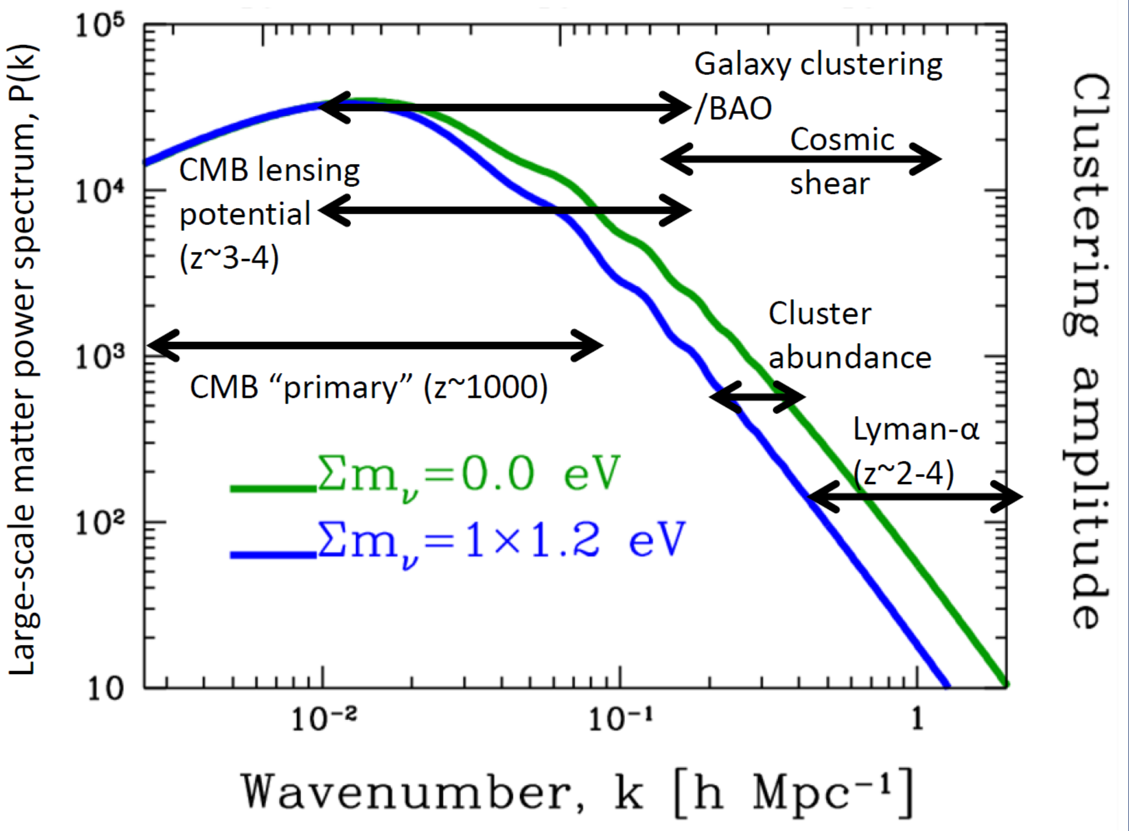
Yvonne Y. Y. Wong

UNSW Sydney

International Symposium on Neutrino Physics and Beyond, HKUST,

February 19 – 21, 2024

Studies of the Large-scale Matter Power Spectrum are sensitive to the sum of ν masses



- ΛCDM+neutrino mass 7-parameter fit; 95% C.L. on $\sum m_\nu$ in [eV].

Planck 2018 TT+TE+EE+ lowE+lensing+BAO

$\sum m_\nu < 0.121$ eV	Degenerate
$\sum m_\nu < 0.146$ eV	Normal hierarchy
$\sum m_\nu < 0.172$ eV	Inverted hierarchy

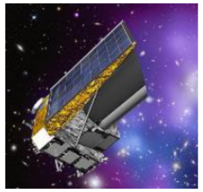
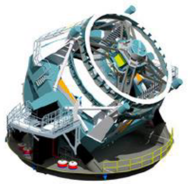
Official Planck benchmark: $\sum m_\nu < 0.12$ eV

Roy Choudhury & Hannestad 2019

Future Measurements will improve this sensitivity

What to expect in the future?

Galaxies, cosmic shear, clusters, etc.

			1σ sensitivity to $\sum m_\nu$	1σ sensitivity to N_{eff}
	**ESA Euclid**	Launched 2023	$0.011 - 0.02$ eV	0.05
	**LSST**	202X	0.015 eV	0.05

These numbers mean, if the true neutrino mass sum is $\sum m_\nu = 0.06$ eV, then it is possible to measure it with $(3-5)\sigma$ significance.

Summary…

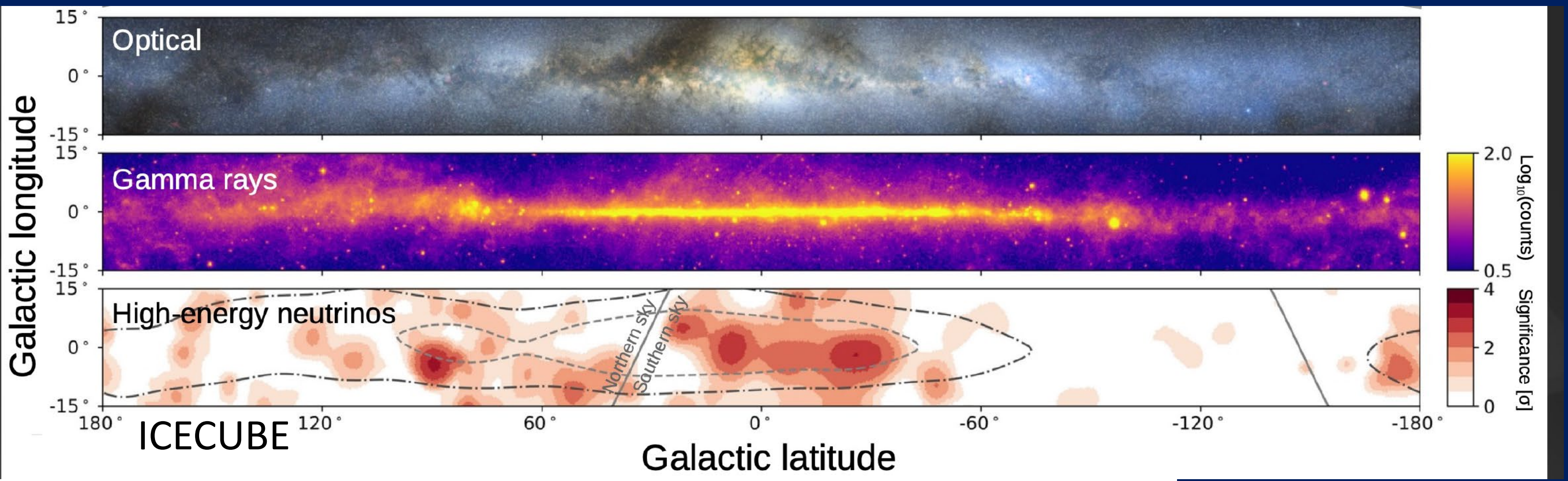
Yvonne Y. Y. Wong

UNSW Sydney

These is no doubt that neutrino masses induce some non-trivial effects on cosmological observables.

- You can even turn this around and use cosmological observables to "measure" the neutrino mass.
- But please please please don't over-interpret bounds or forecasted sensitivities. They are best treated as ballpark figures.
- Until **multiple observations** have measured the same neutrino mass sum value, take all "measurements" *cum grano salis*.

Also summarised in Antel et al., Feebly Interacting Particles: FIPs 2022 workshop report, *Eur.Phys.J.C* 83 (2023) 1122 [arXiv:2305.01715 [hep-ph]].



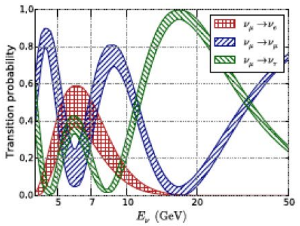
ICECUBE

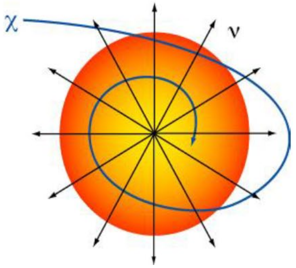
ICECUBE And KM3NET

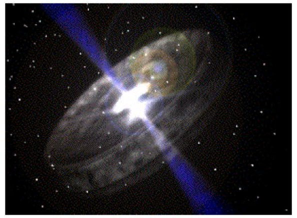
Future P-ONE?

Neutrino telescopes: science

MeV to PeV energies





Supernova
Solar flares

Atmos neutrinos
ν oscillations
ν mass ordering
Sterile, NSI, …

Dark matter
Monopoles,
Nuclearites,…

Cosmic neutrinos

Cosmic rays

Origin and production mechanism of HE CR

[Coyle for KM3NET at NPB 2024]

KM3NeT-ORCA ANTARES KM3NeT-ARCA

+ oceanography, biology, bioacoustics, seismology,…

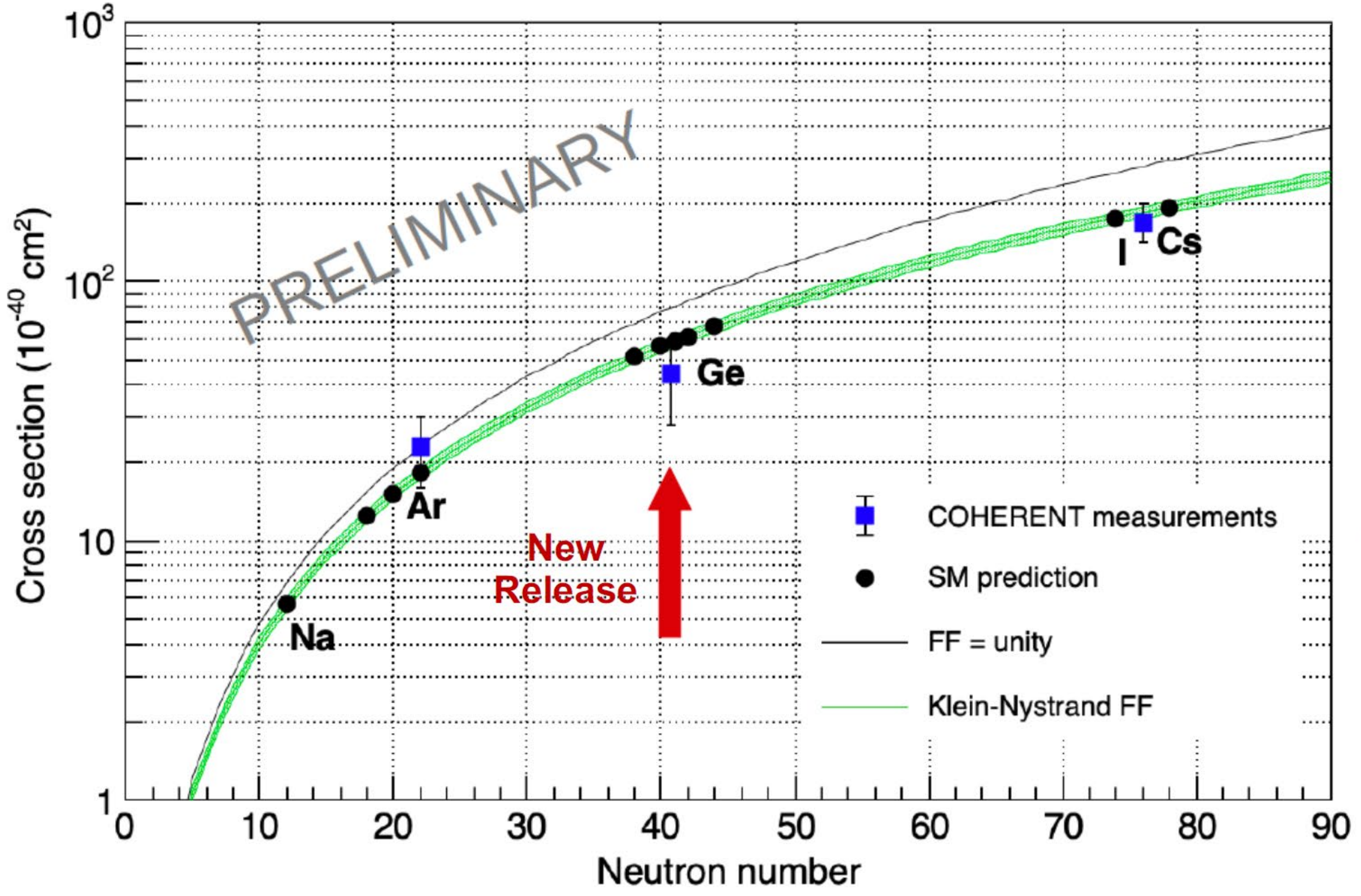
High-Energy Neutrinos and Multi-messenger Astronomy

ICECUBE: Potential correlation between active galaxy NGC 1068 and neutrino hot spot (with 79 +22 -21 events). Significance 4.2 sigma. [Halzen at NPB 2024 Hong Kong]

Two Major Talks at this conference

Neutrino-Matter Interactions, including coherent scattering

Collaboration Published Detection of CEvNS on Three Targets



COHERENT Collaboration

All three individual results agree with the Standard Model within one sigma

However, accuracy is limited so far

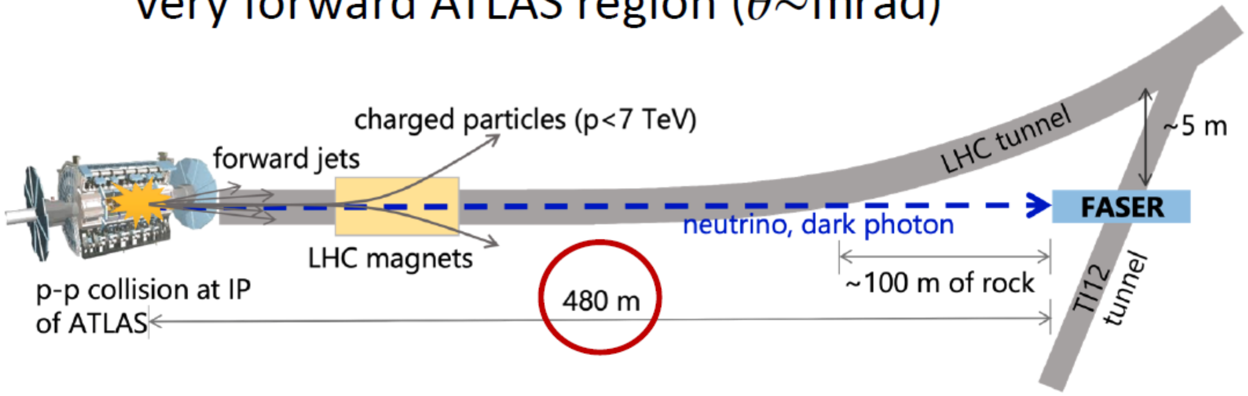
Dominant source of uncertainty is the knowledge of Neutrino Flux at the SNS
Which we believe is known within 10% accuracy. Phys. Rev. D, 106(3):032003, 2022, 2109.11049.

Efremenko at NPB 2024

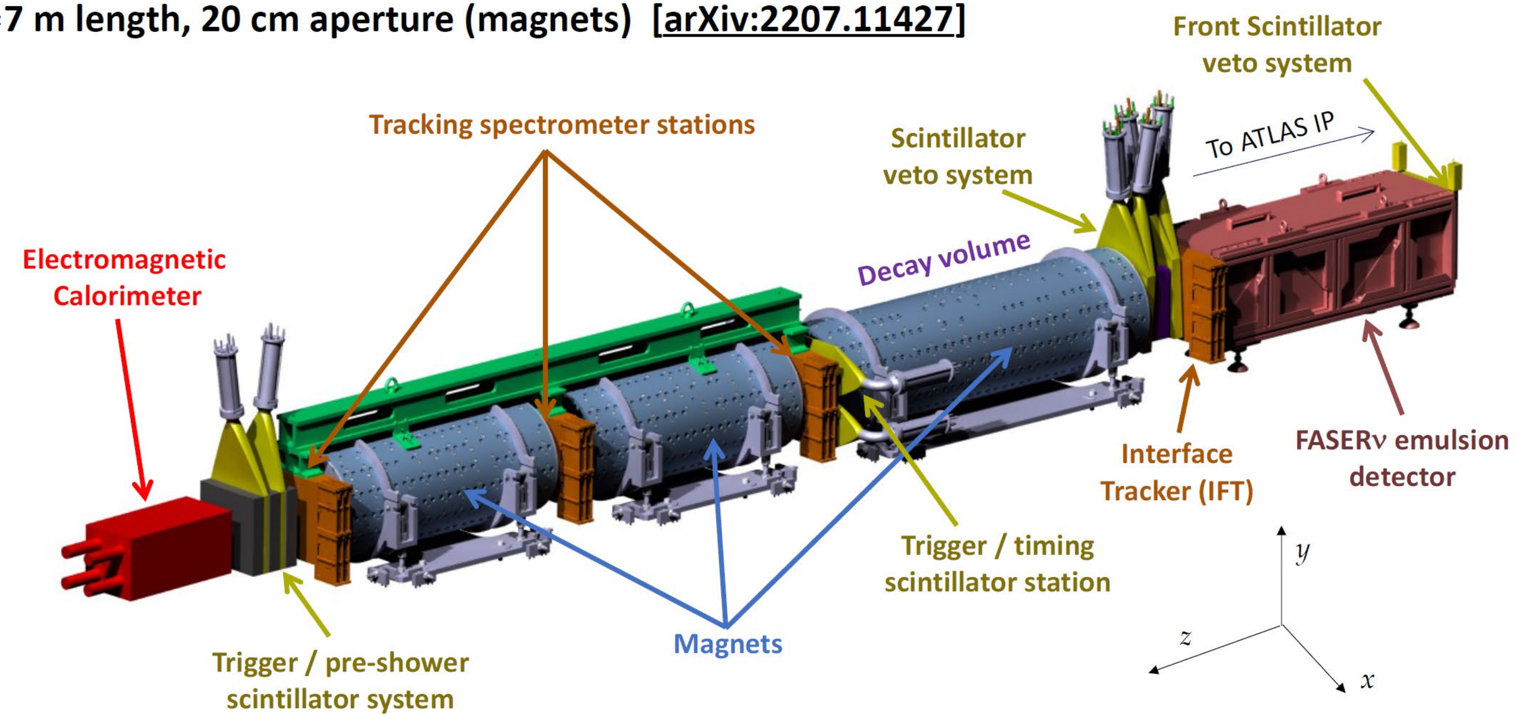
The ForwArd Search ExpeRiment at the LHC

Search for light, weakly interacting (LLP) new particles

↳ stemming from rare meson decays (π, η, K, D …) in very forward ATLAS region (θ~mrad)

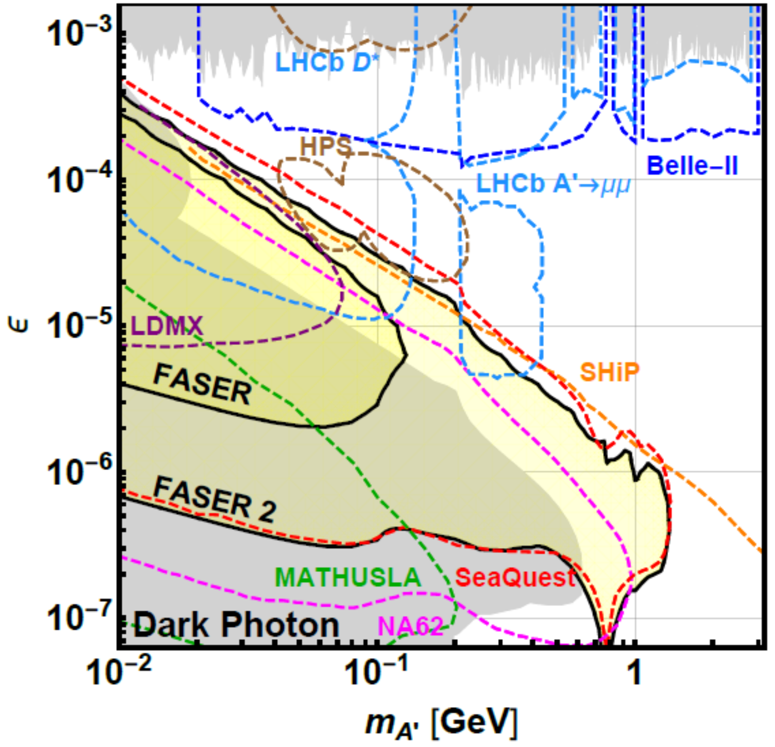


≃7 m length, 20 cm aperture (magnets) [arXiv:2207.11427]



Beyond Standard Model Searches

Talk at the Conference: Neutrinos @ LHC: de Roeck



- Theory
  - Beyond Standard Model
  - Neutrino Mass
  - Neutrino Cosmology
  - Leptogenesis

- Theory Talks at the conference:
  - Theory of Leptonic Flavor Mixing: Ding
  - Nu Mass and the Origins of Baryons: Shaposhnikov
  - Open Problems in Neutrino Astrophysics: Spurio
  - 0νDBD searches: theory and motivation: Mendendez
  - Single/Double Beta Decay spectral shapes and theory:
  - Beyond Standard Model: Overview (Theory): Fernanandez-Martinez

This will be an interesting week

Have fun!