Current and Future Neutrino Experiments

Dan Dwyer
Brookhaven Forum
6 Oct. 2023

Outline

- The Era of Three-Flavor Mixing
- Pursuing Neutrino Mass
- Beyond Three-flavor Mixing

Neutrinos: The Era of Three-Flavor Mixing

History of Neutrino Masses and Mixing: Initial Evidence

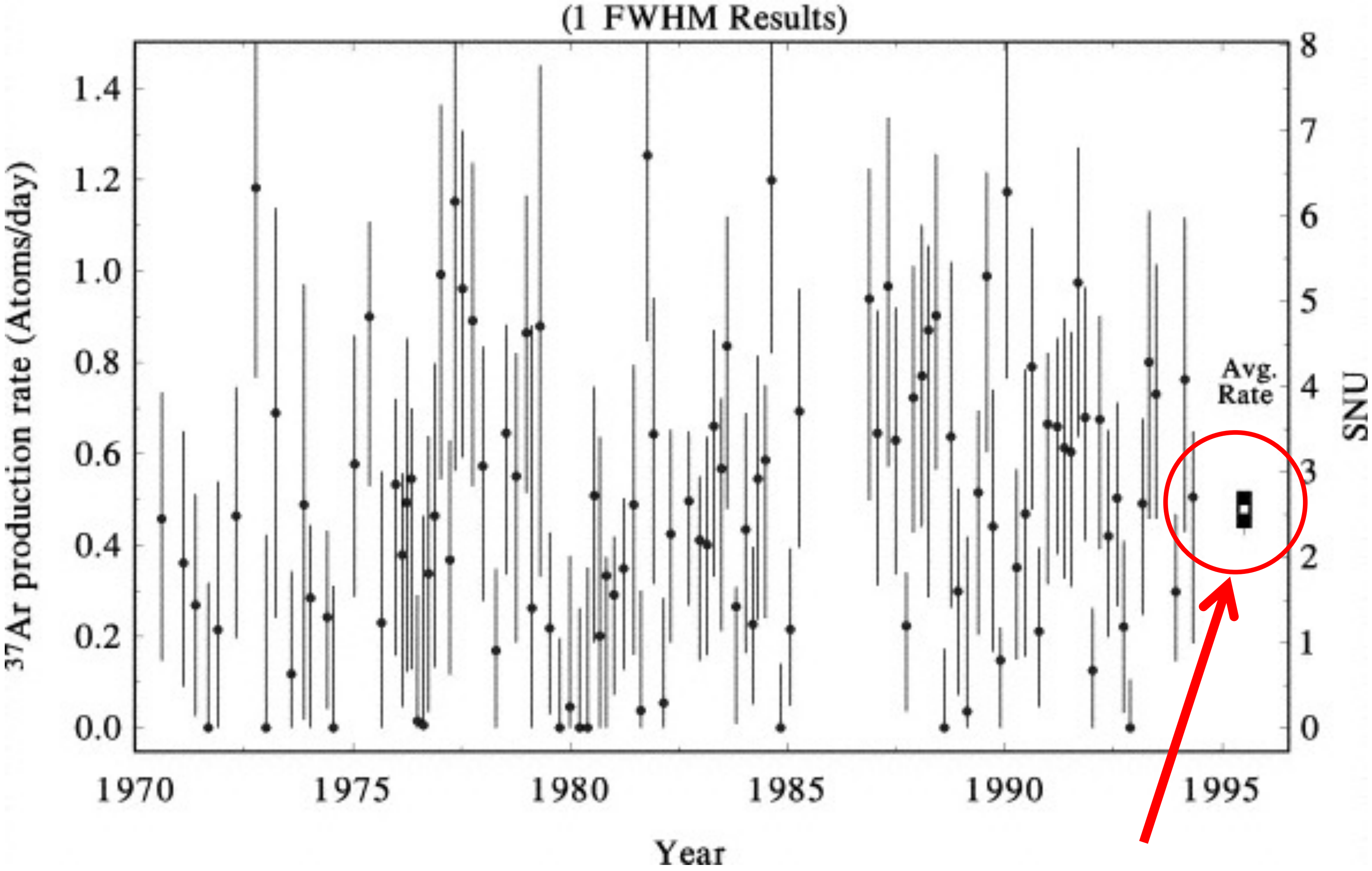
Homestake Experiment:

Ambitious radiochemical experiment

Search for argon atoms in 100,000 g of Cl

$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^- .$$

Observed deficit relative to prediction



Average rate: 1/3 of that expected from solar models.

History of Neutrino Masses and Mixing: Initial Evidence

Kamiokande Experiment:

1-kton Water Cherenkov detector

Observed electrons scattered by solar neutrinos, with deficit similar to Homestake Experiment.

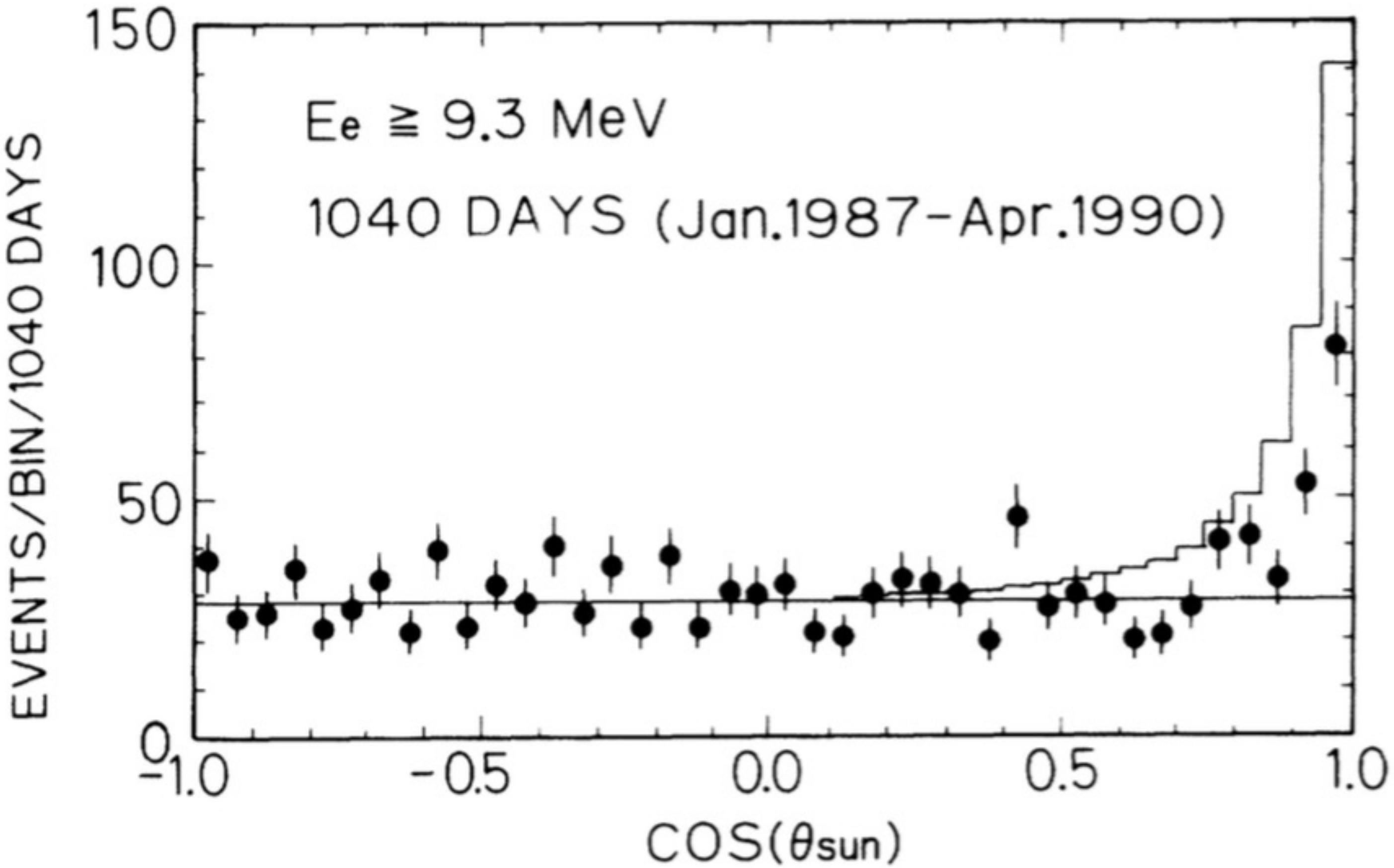
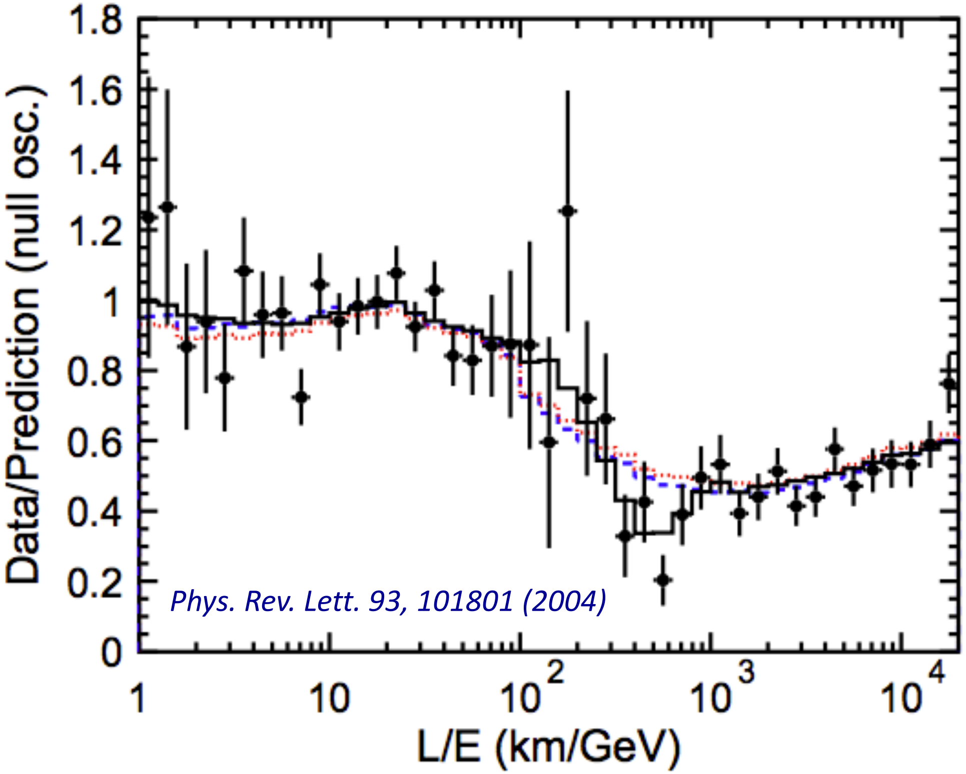


FIG. 3. Distribution in $\cos\theta_{\mathrm{Sun}}$ of the combined 1040-day sample for $E_e \geq 9.3$ MeV. The value of the ratio data/SSM from this figure is 0.43 ± 0.06.

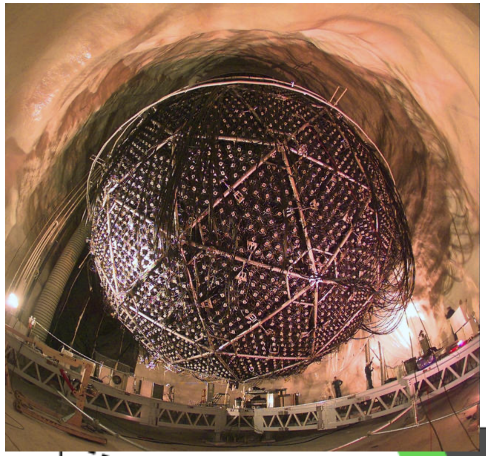
History of Neutrino Masses and Mixing

Super-Kamiokande:

Observes disappearance of neutrinos produced in atmosphere



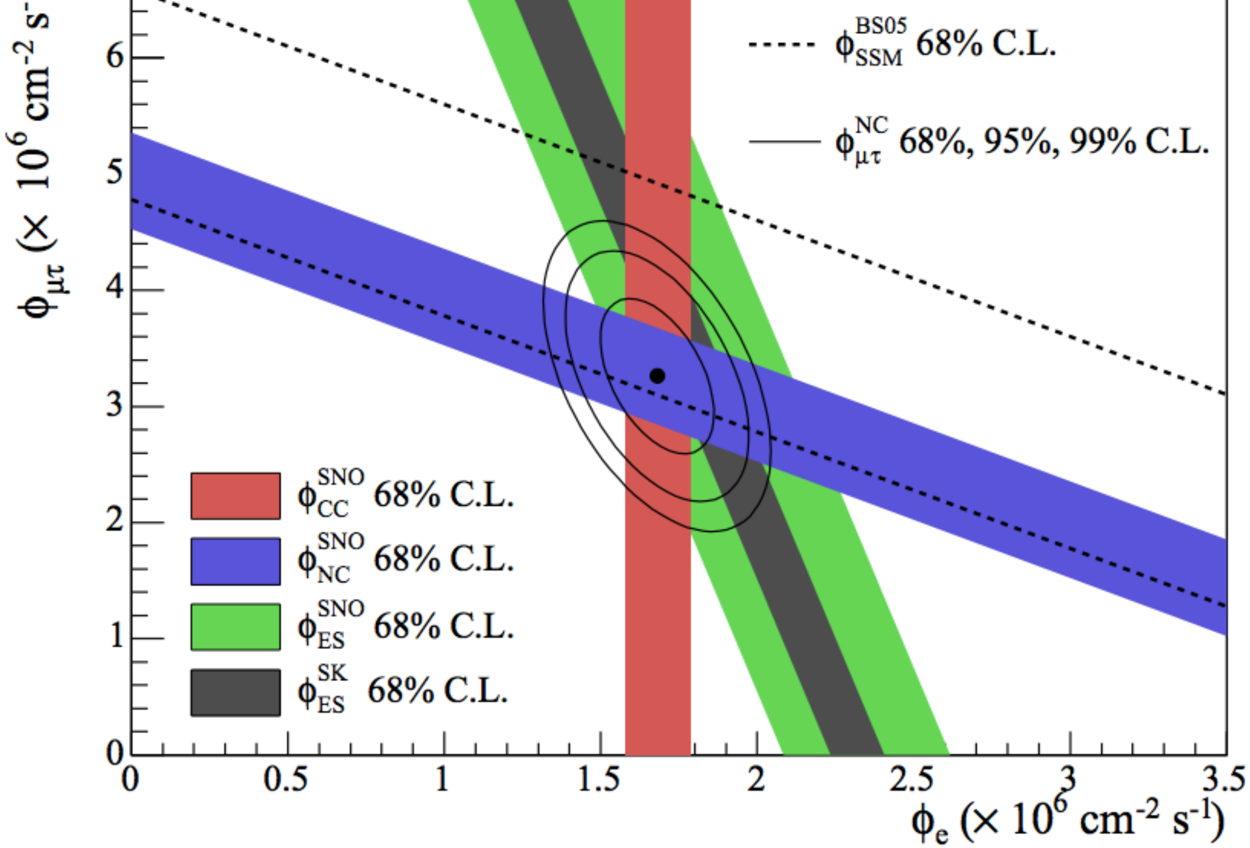
Phys. Rev. Lett. 93, 101801 (2004)



Sudbury Neutrino Observatory:

Observes flavor change for neutrinos from the sun.

Phys. Rev. C 72, 055502 (2005)



History of Neutrino Masses and Mixing

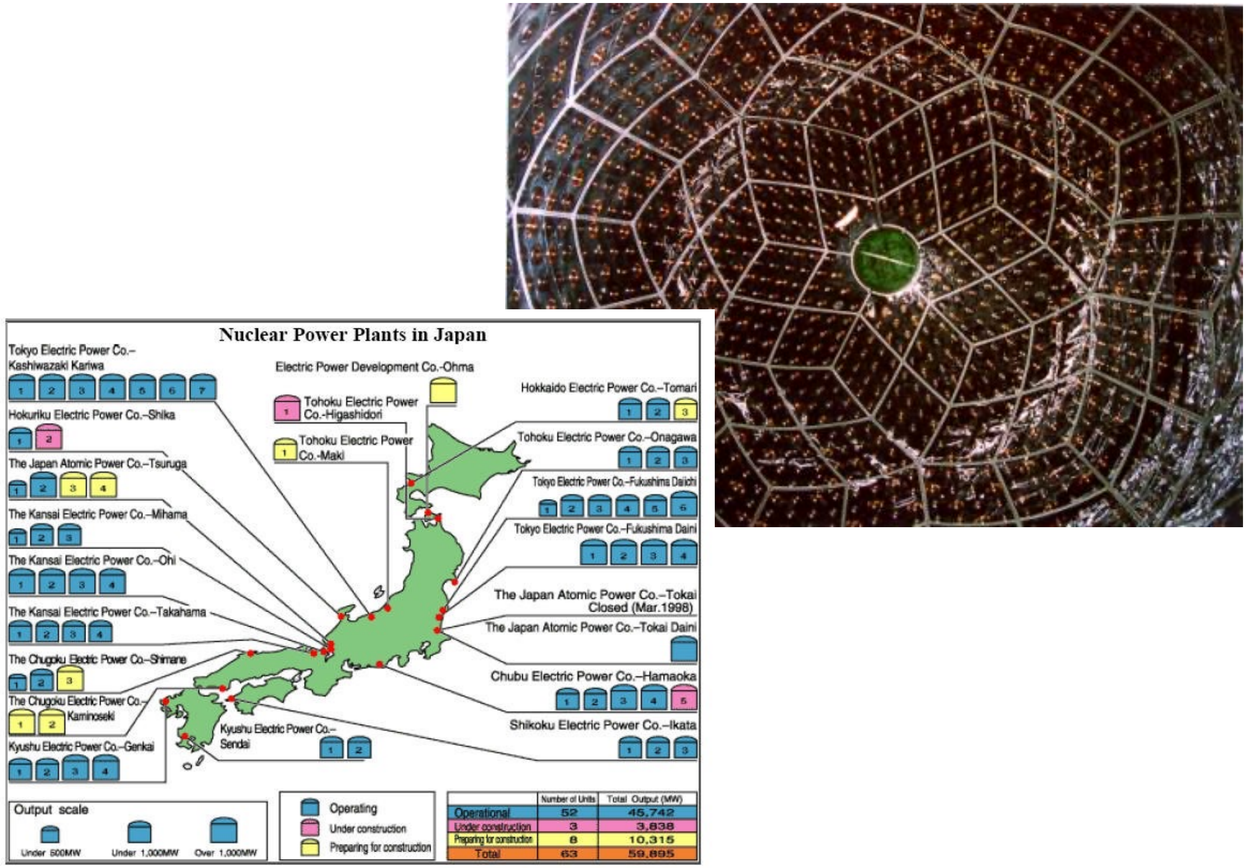
KamLAND:

1 kton of liquid scintillator detects antineutrinos emitted by nuclear reactors

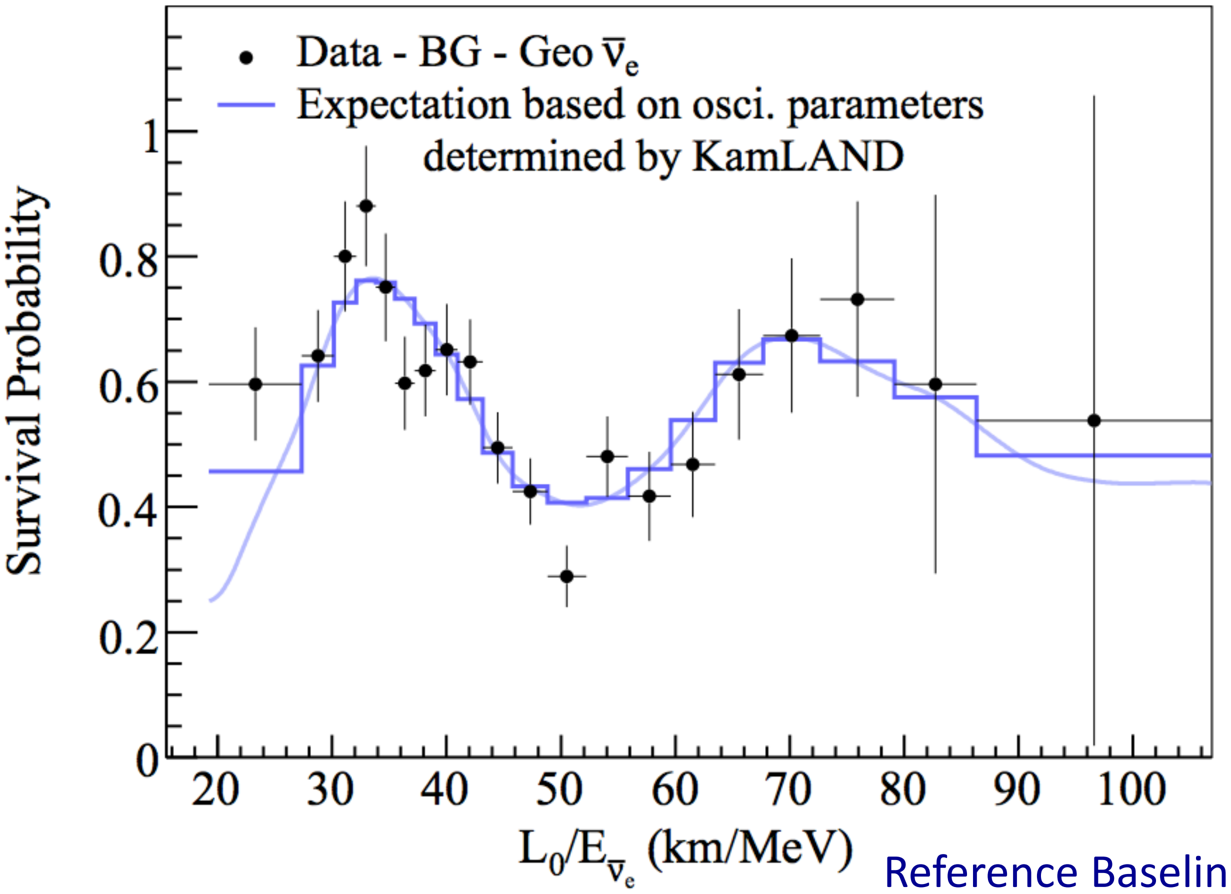
Observes energy-dependent disappearance / reappearance

-> Neutrino flavor oscillation!

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{12}) \sin^2 \frac{\Delta m^2_{12} L}{4E}$$



	Number of Units	Total Output (MW)
Operational	52	45,742
Under construction	3	3,838
Preparing for construction	8	10,315
Total	63	59,895



Phys. Rev. Lett. 100, 221803 (2008)

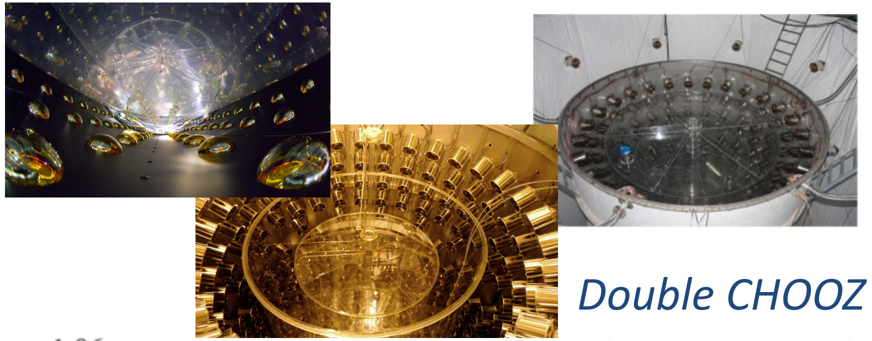
Reference Baseline:
L_0 = 180 km

History of Neutrino Masses and Mixing

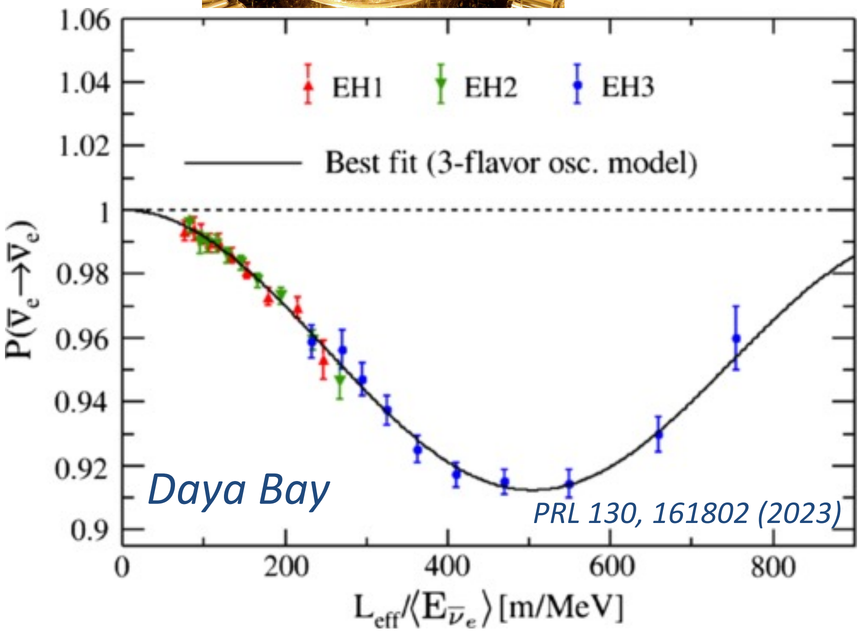
Reactor Antineutrinos

Daya Bay

RENO



Double CHOOZ

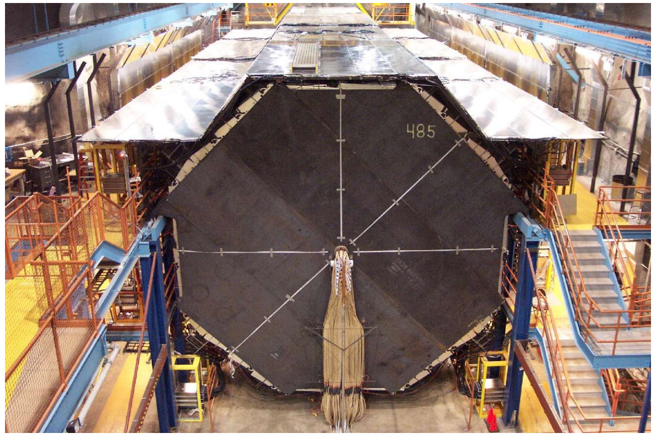


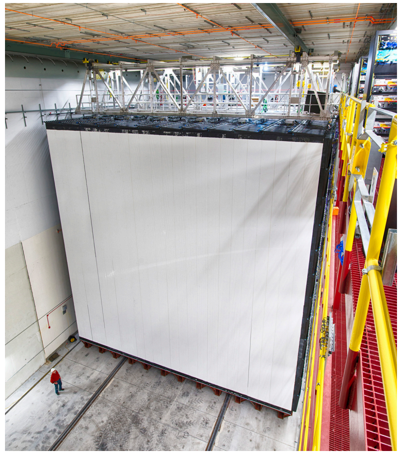
Daya Bay

PRL 130, 161802 (2023)

Accelerator Neutrinos

MINOS

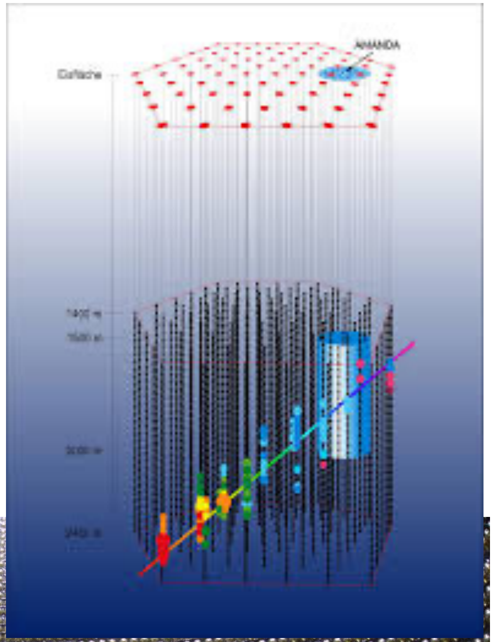


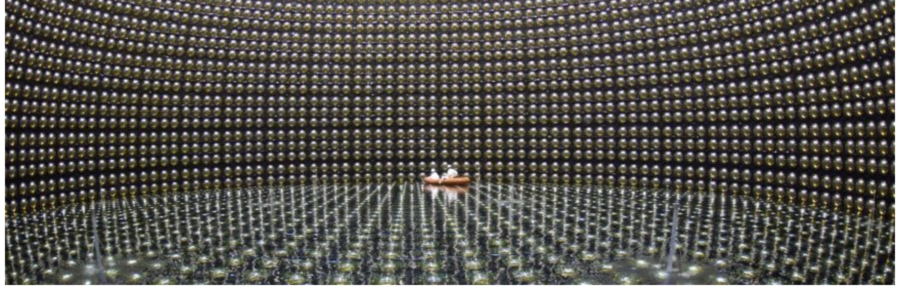


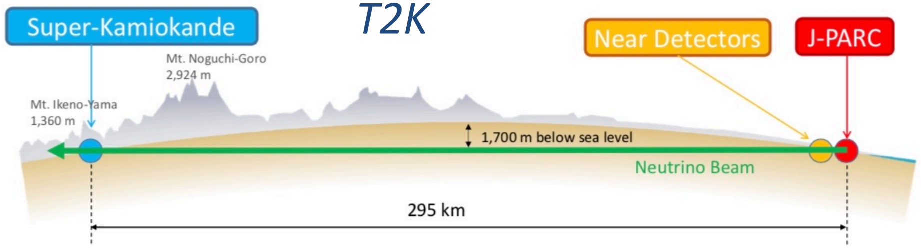
NOvA

Atmospheric Neutrinos

IceCUBE

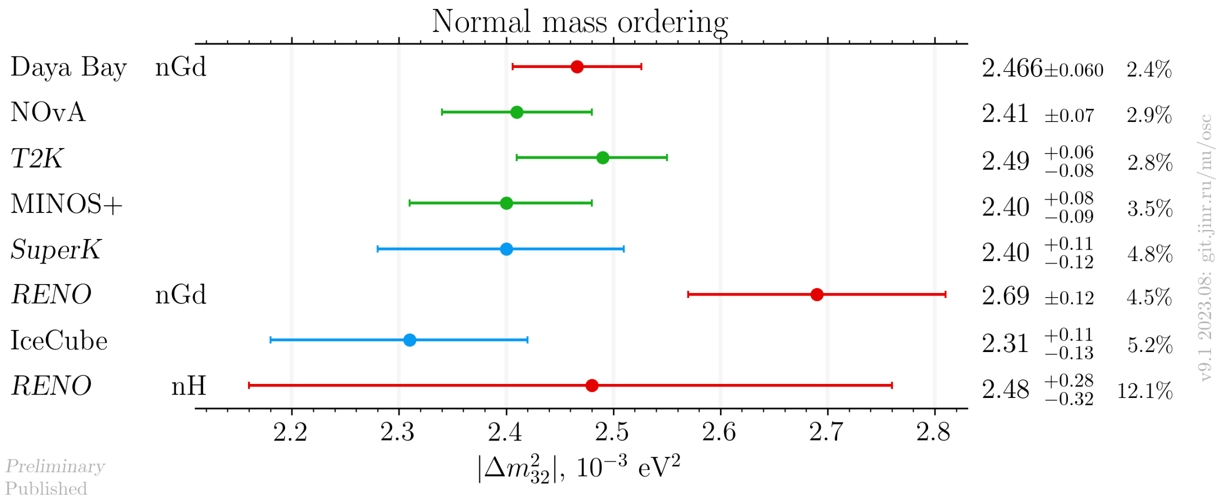


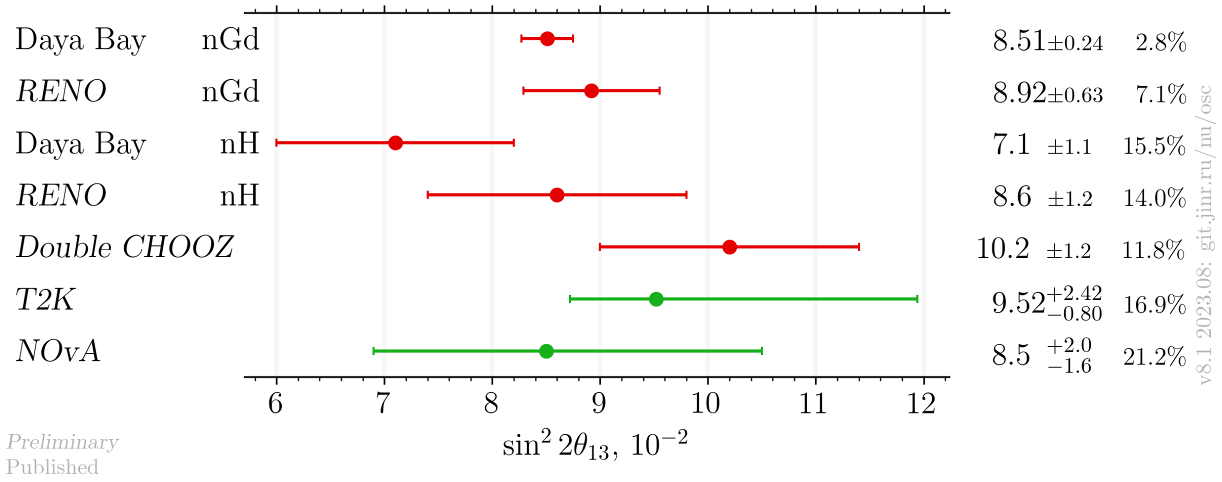


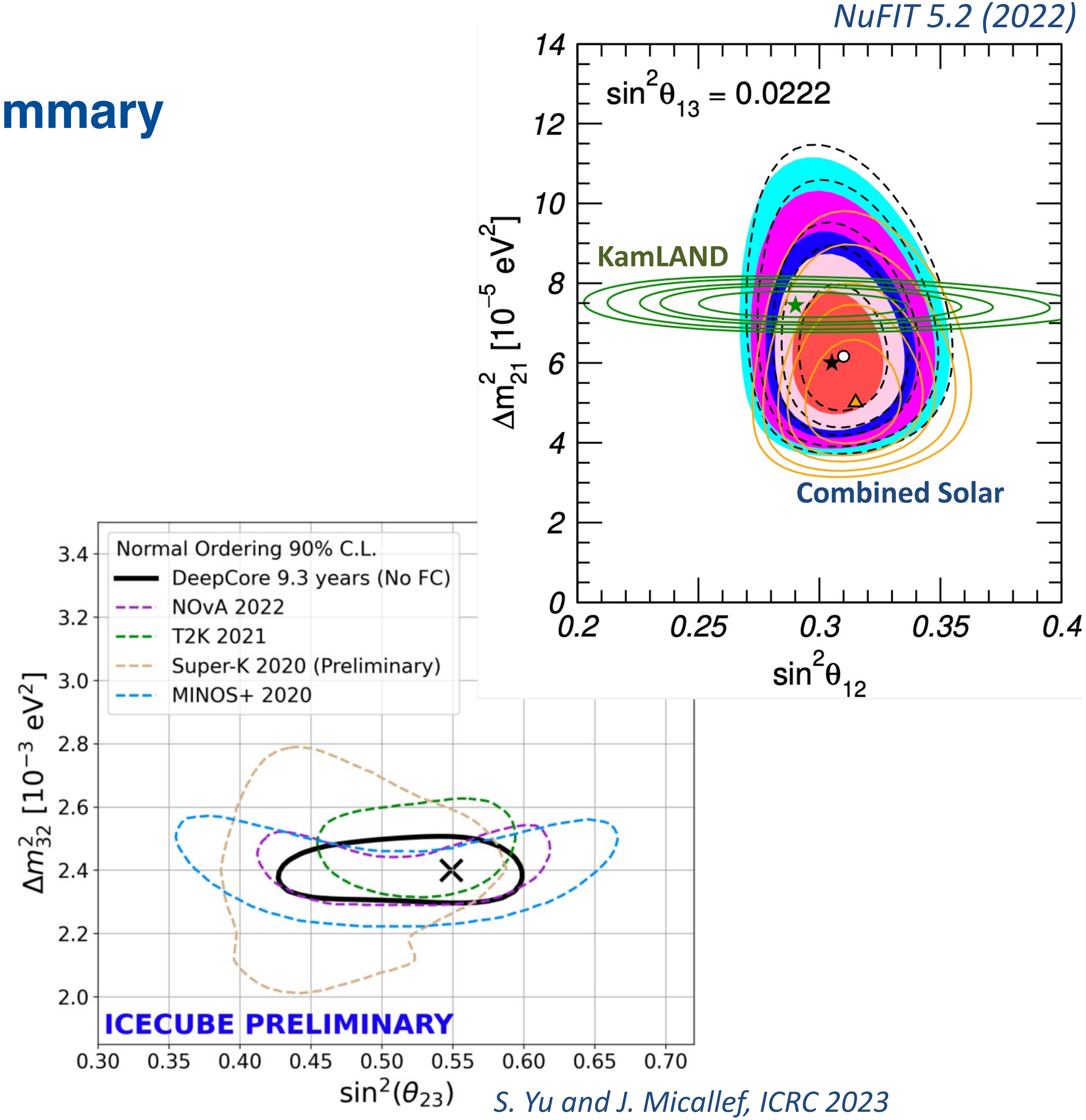


T2K

Neutrino Masses and Mixing: Results Summary





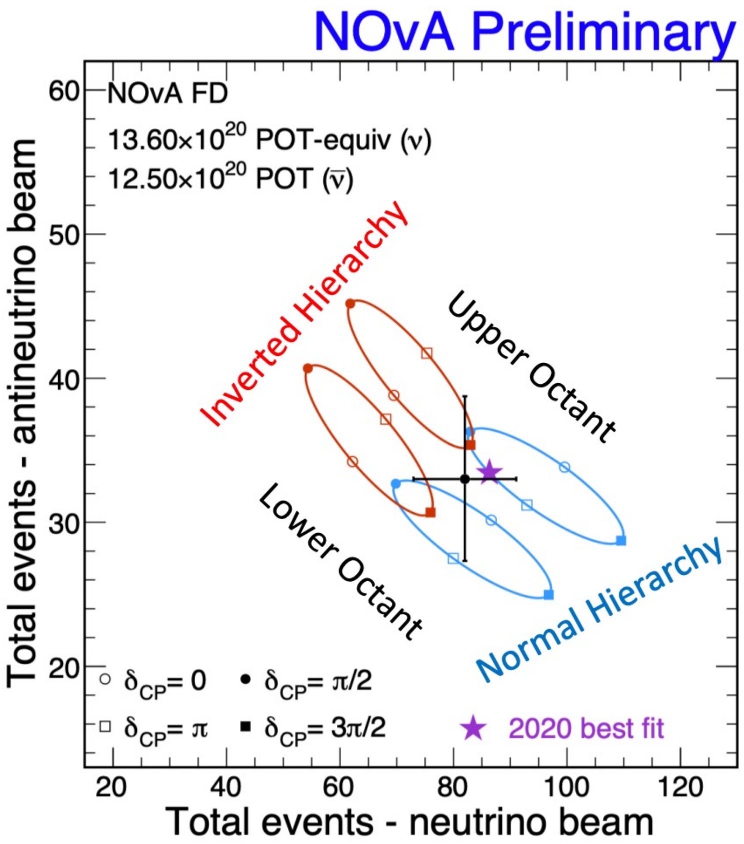


NuFIT 5.2 (2022)

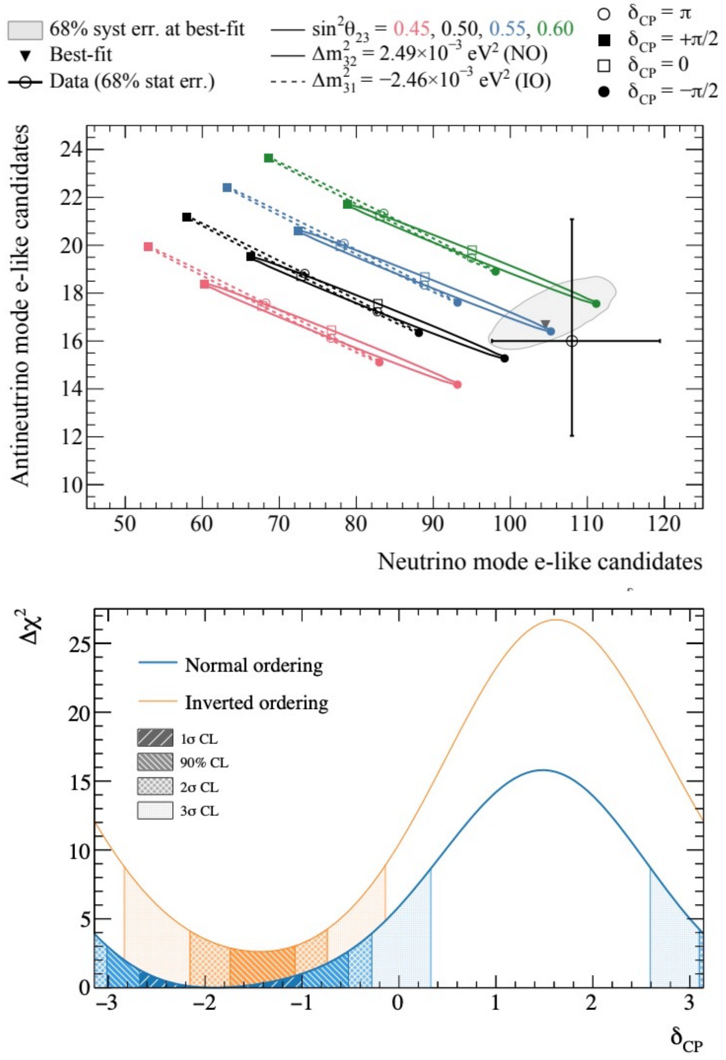
S. Yu and J. Micallef, ICRC 2023

Neutrino Masses and Mixing: Latest Results

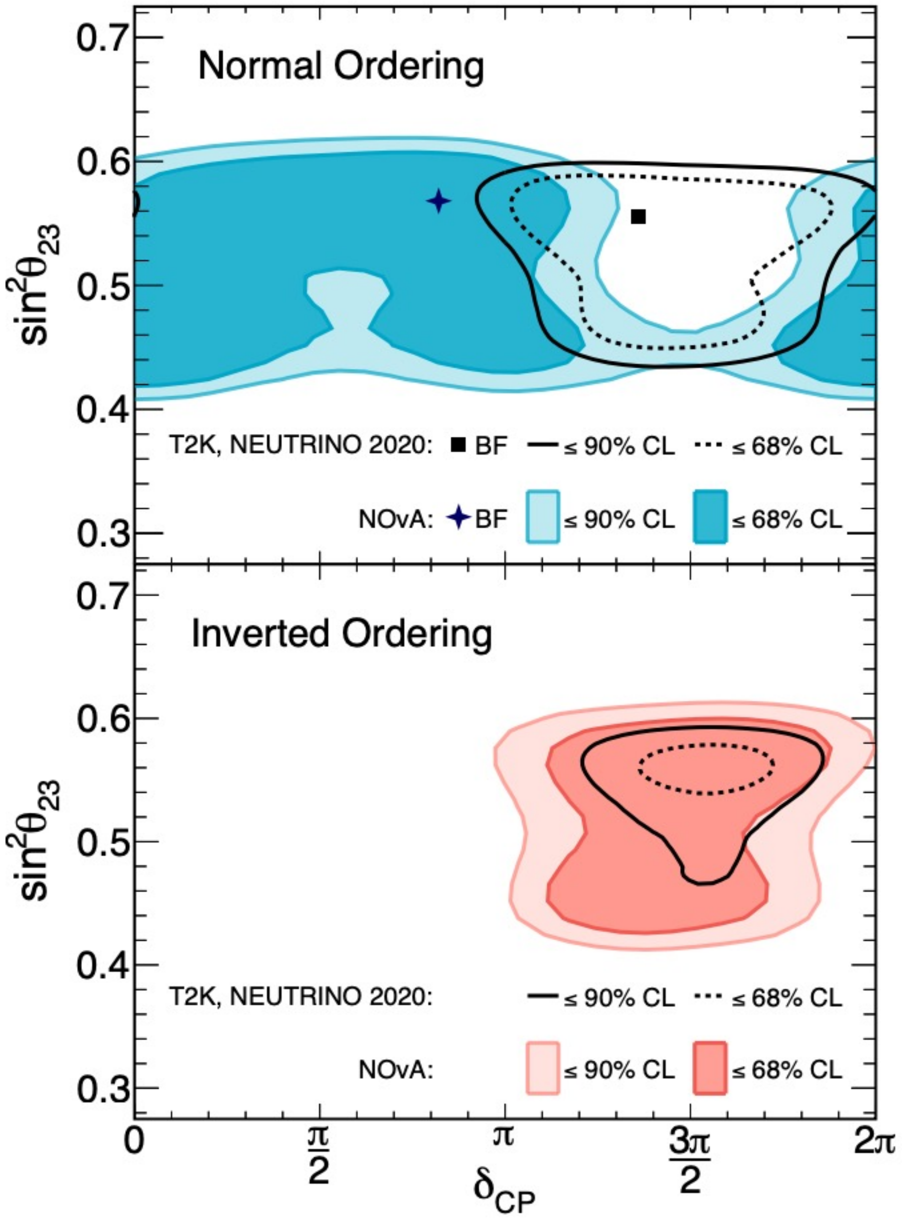
Gaining sensitivity to the neutrino mass ordering and possible CP Violation



M. Sanchez, TAUP 2023

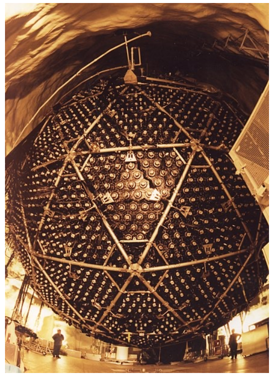


arxiv:2303.03222



M. Sanchez, TAUP 2023

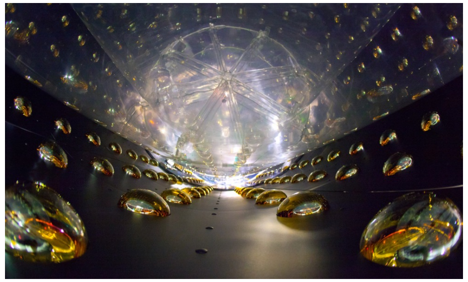
Current Status of Three-flavor Neutrino Oscillation Model



R.L. Workman et al. (Particle Data Group),
Prog. Theor. Exp. Phys. 2022, 083C01 (2022) and 2023 update

Neutrino Mixing

The following values are obtained through data analyses based on the 3-neutrino mixing scheme described in the review "Neutrino Masses, Mixing, and Oscillations."



Leading Measurements:

SNO, SuperK → $\sin^2(\theta_{12}) = 0.307 \pm 0.013$

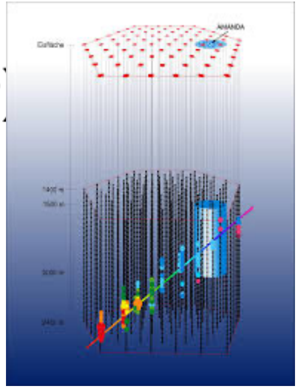
KamLAND → $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \text{eV}^2$

T2K, NOvA, IceCUBE →
$\sin^2(\theta_{23}) = 0.534^{+0.021}_{-0.024}$ (Inverted order)
$\sin^2(\theta_{23}) = 0.547^{+0.018}_{-0.024}$ (Normal order)

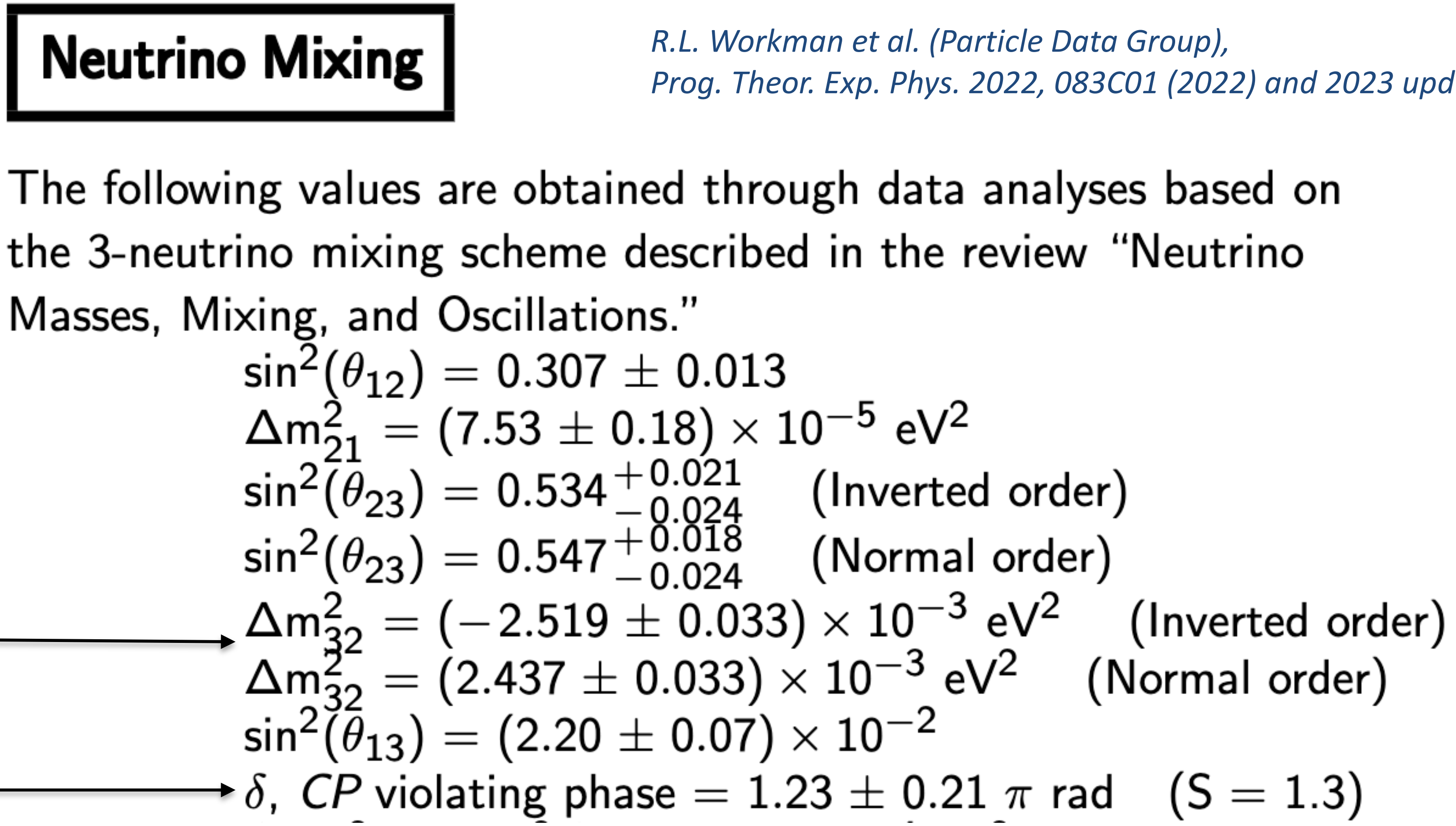
Daya Bay, IceCUBE, T2K, NOvA →
$\Delta m^2_{32} = (-2.519 \pm 0.033) \times 10^{-3}\ \text{eV}^2$ (Inverted order)
$\Delta m^2_{32} = (2.437 \pm 0.033) \times 10^{-3}\ \text{eV}^2$ (Normal order)

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

T2K, NOvA → δ, CP violating phase $= 1.23 \pm 0.21\ \pi$ rad (S = 1.3)



Neutrino Masses and Mixing: Future Experiments



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R.L. Workman et al. (Particle Data Group),
Prog. Theor. Exp. Phys. 2022, 083C01 (2022) and 2023 update

Upcoming Measurements:

Mass Ordering:

T2K, NOvA, JUNO, T2HK, IceCUBE upgrade, DUNE →

Search for CP-Violation:

T2K, NOvA, T2HK, DUNE →

Neutrino Masses and Mixing: Future Experiments

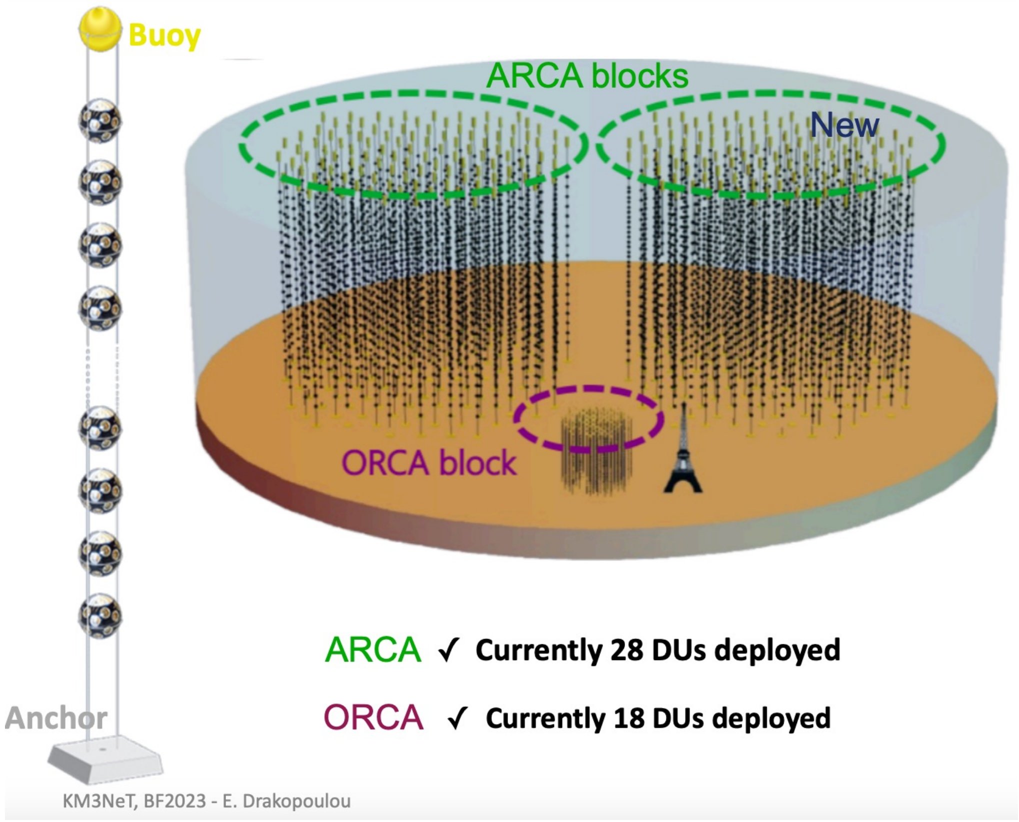
E. Drakapoulou, BNL Forum 2023

KM3Net-ORCA:

- 7 Mton water Cherenkov detector in the Mediterranean Sea
- **ORCA:** Dense distribution of photodetectors for ~GeV threshold
- Atmospheric neutrinos with few-GeV energy particularly sensitive to neutrino mass ordering due to matter-enhanced oscillation in earth.

Status:

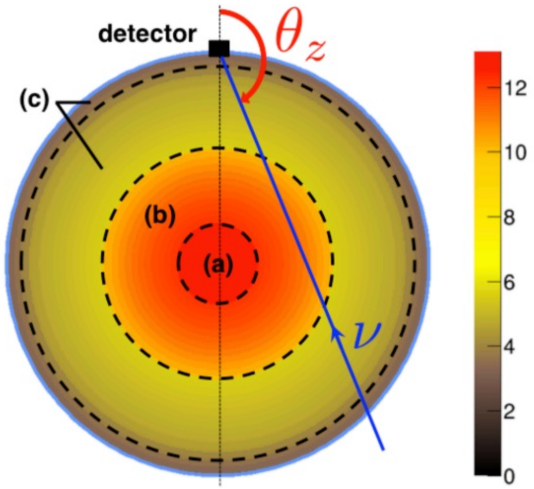
- 18 (of 155) DUs installed, and initial measurement of atmospheric neutrino disappearance released

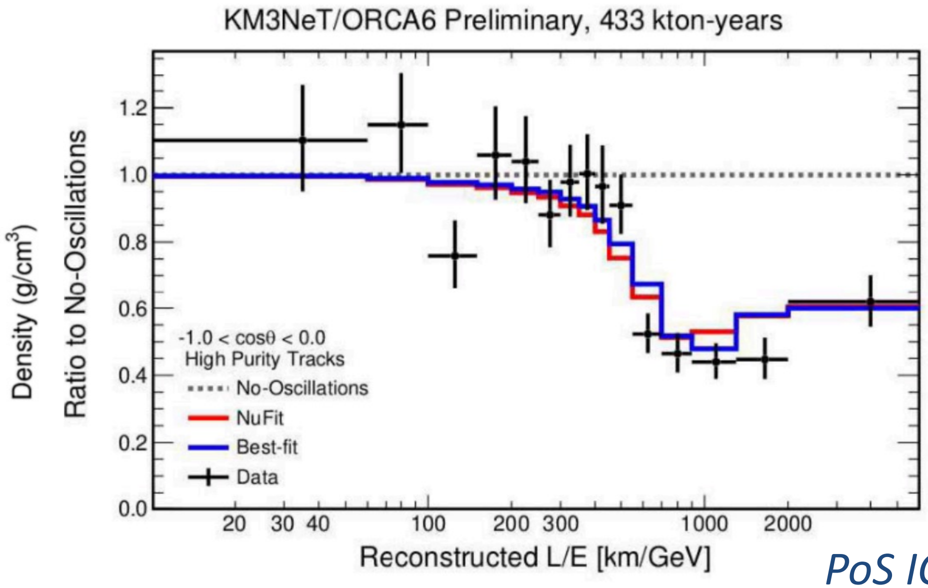


ARCA ✓ **Currently 28 DUs deployed**

ORCA ✓ **Currently 18 DUs deployed**

KM3NeT, BF2023 - E. Drakopoulou





PoS ICRC2023 (2023) 996

Instruments 2022, 6(3), 26

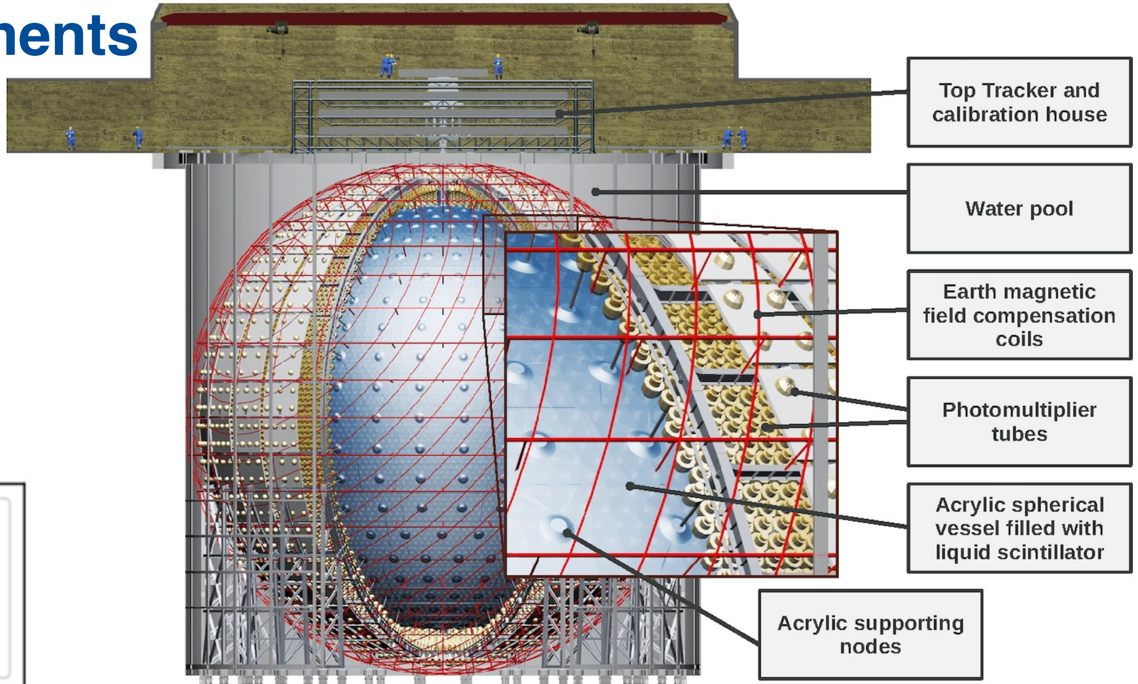
Neutrino Masses and Mixing: Future Experiments

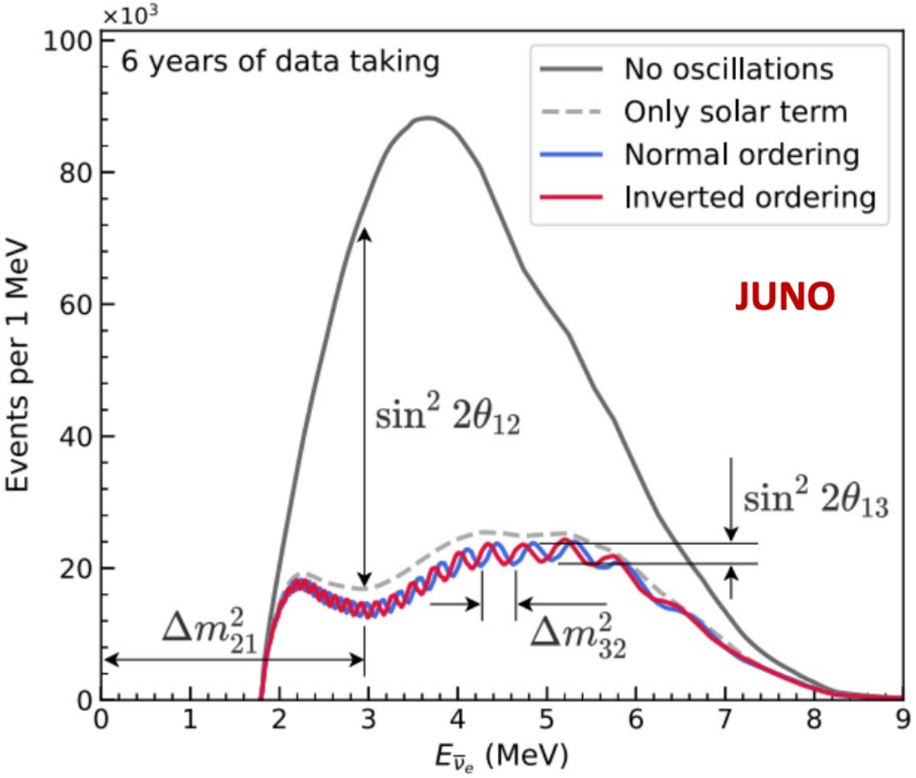
JUNO:

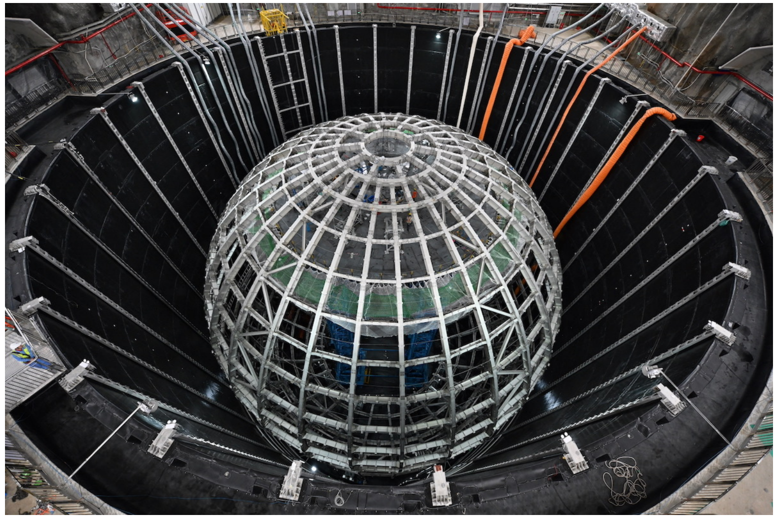
- Measure reactor electron antineutrino disappearance at 52.5 km
- Detect via inverse-beta decay in 20 kt liquid scintillator detector

Status:

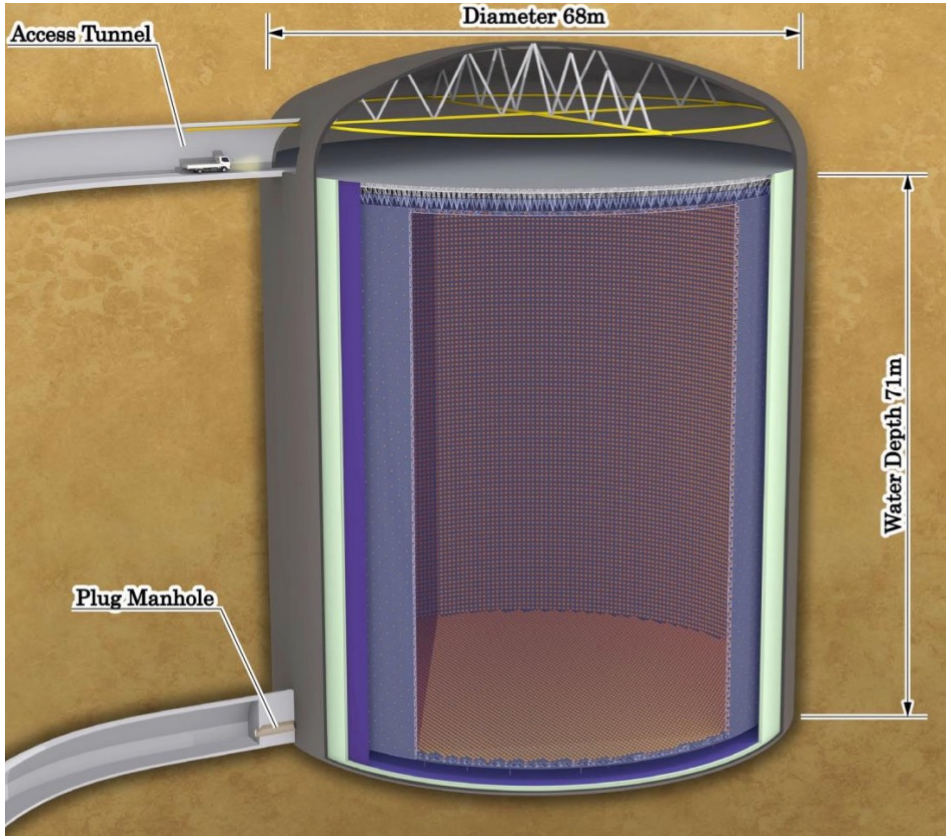
- Under construction, aiming for first data in 2024





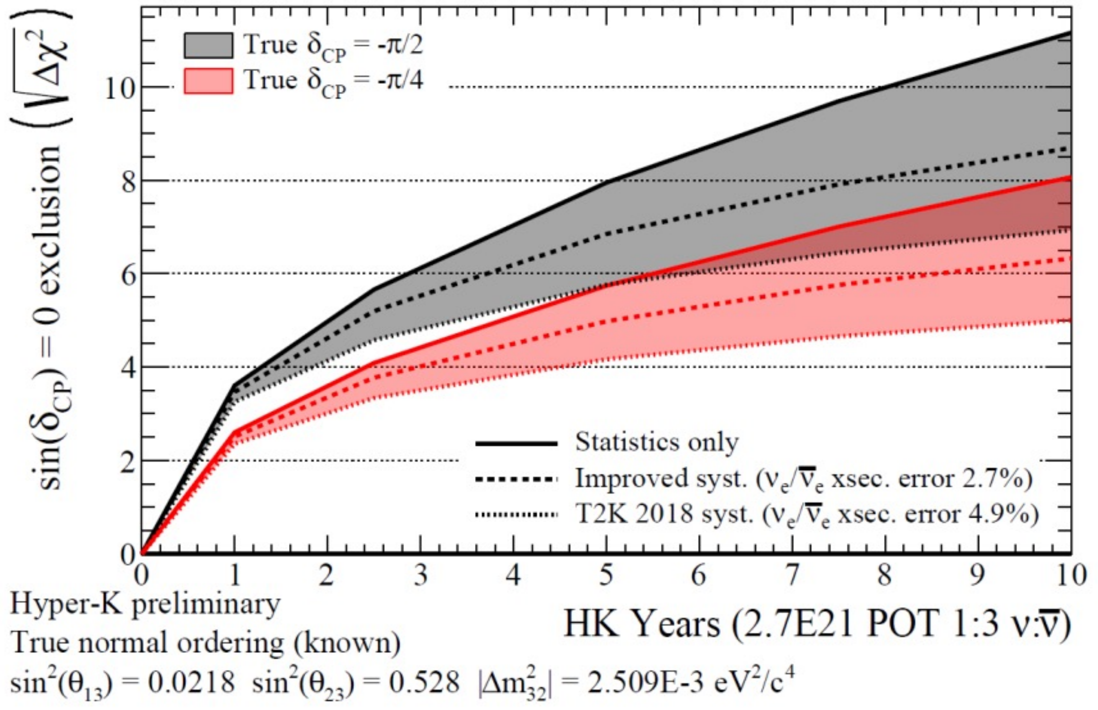


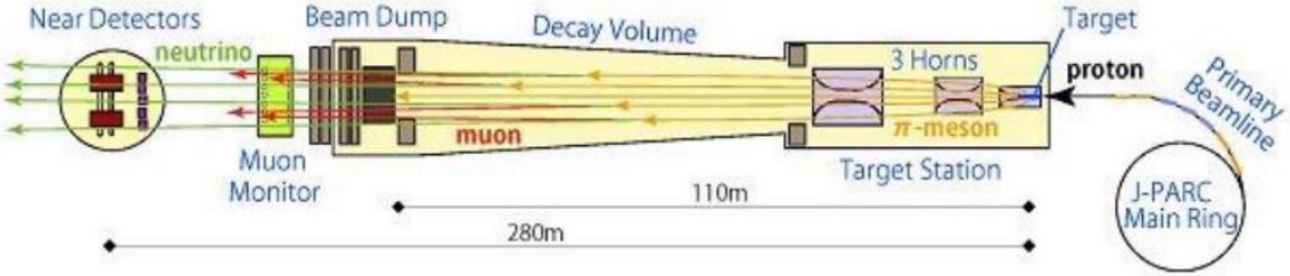
Neutrino Masses and Mixing: Future Experiments



Hyper-Kamiokande:

- 258 kton Water Cherenkov detector
- Upgraded off-axis neutrino beam from J-PARC, ~0.6 GeV, 295 km away
- Status: Excavation in progress, aiming for start of operations in 2027



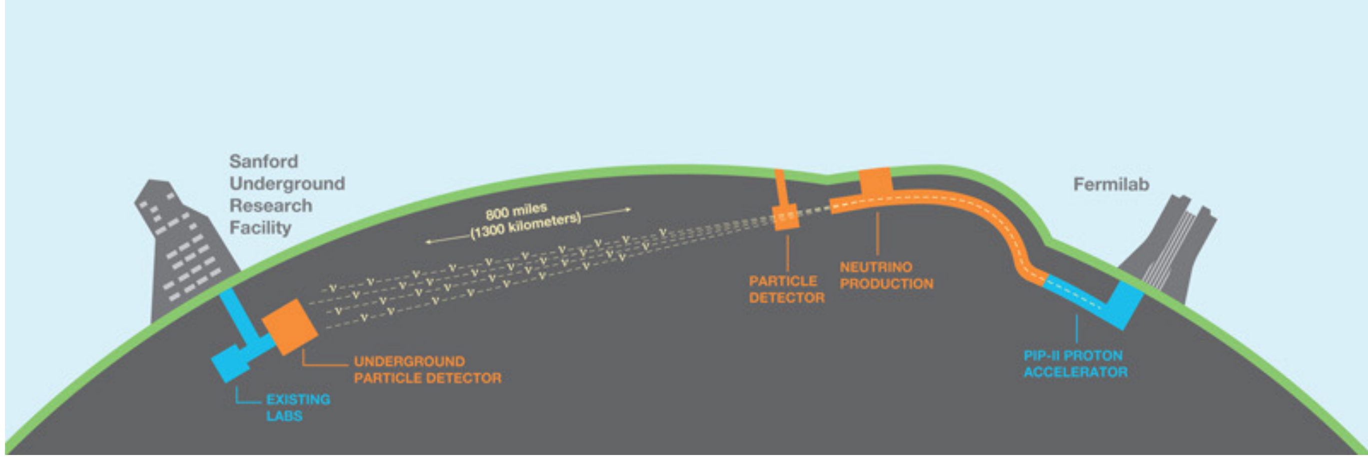


N. McCauley, NuFact 2023

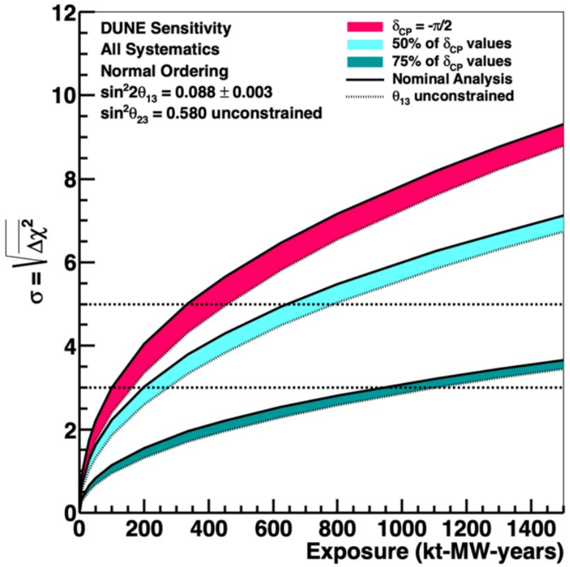
Neutrino Masses and Mixing: Future Experiments

Deep Underground Neutrino Experiment (DUNE)

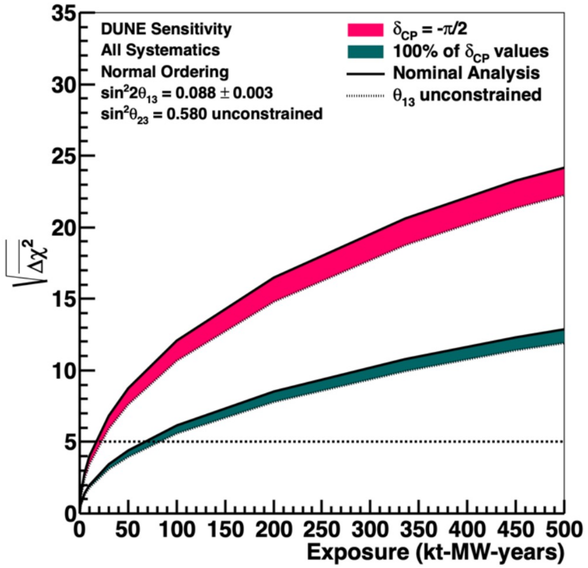
- Multiple 10 kton Liquid Argon Time-Projection Chambers at SURF
- New on-axis neutrino beam from FNAL, ~1-5 GeV, 1300 km
- Physics goals:
    - Mass ordering, CP-Violation, Precision Oscillation
    - Supernova Neutrinos, Nucleon Decay, BSM Searches
- Status: Far site excavation nearly complete,
  First 10 kton TPC production starting now

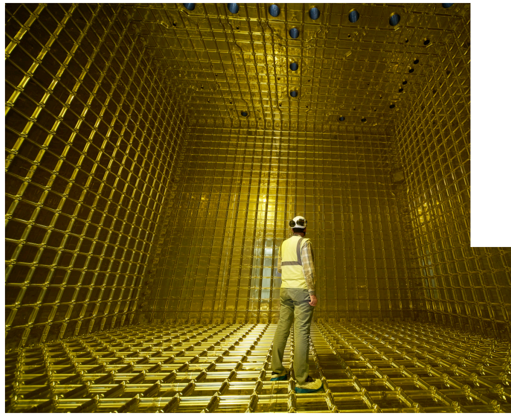


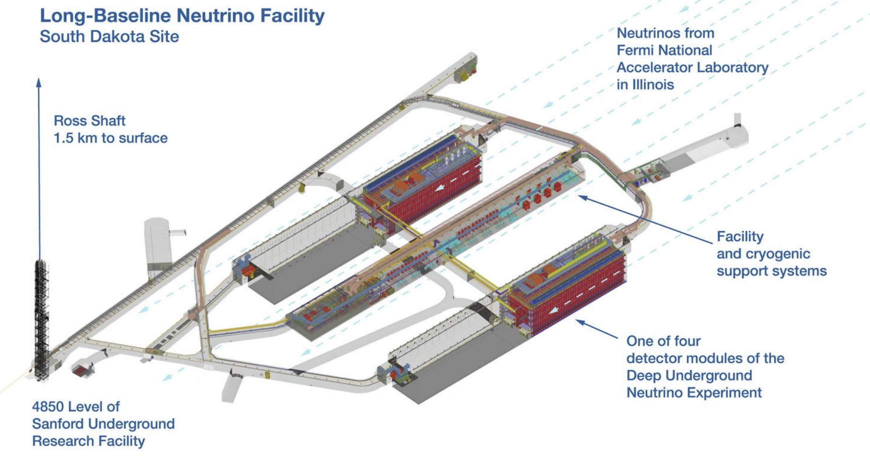
CP Violation Sensitivity



Mass Ordering Sensitivity







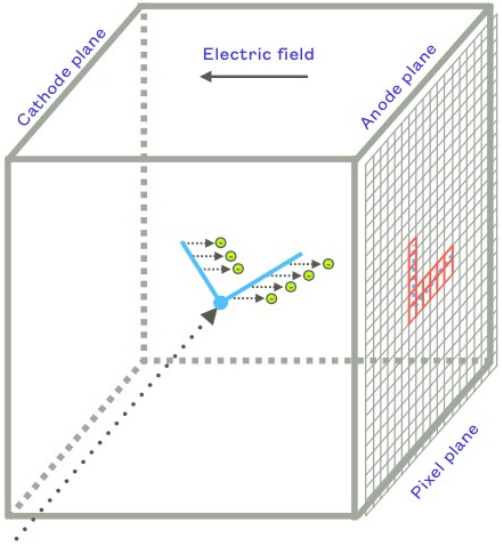
Interlude: Development of 3D LArTPC

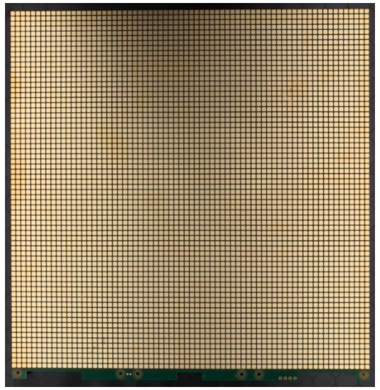
3D Pixel LArTPC (LArPix):

- True 3D imaging
- Continuous readout, ~100% uptime
- Intrinsically sparse data, low data volume

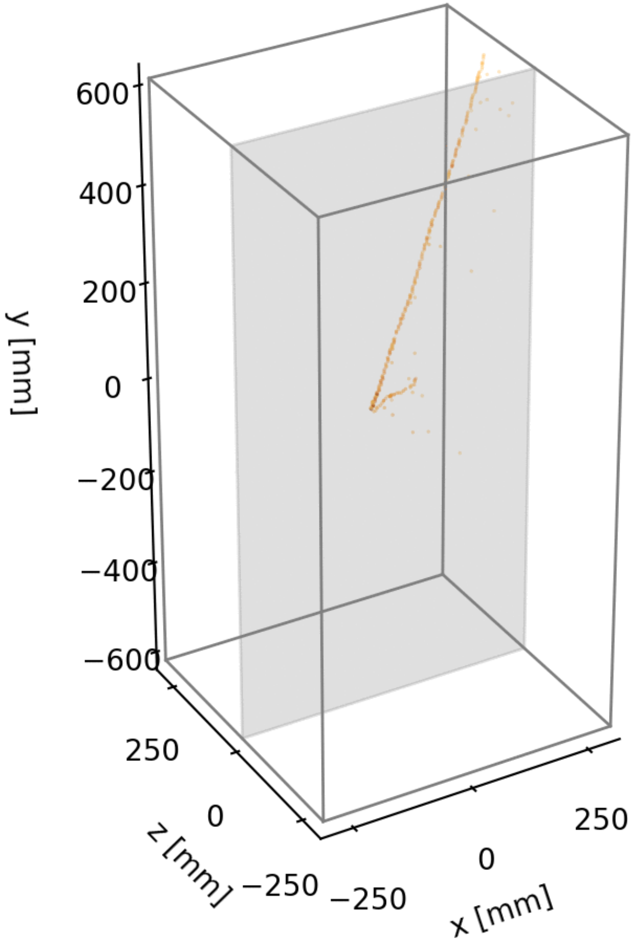
Recent Progress:

- Operation of four ton-scale 100k-pixel prototype LArTPCs

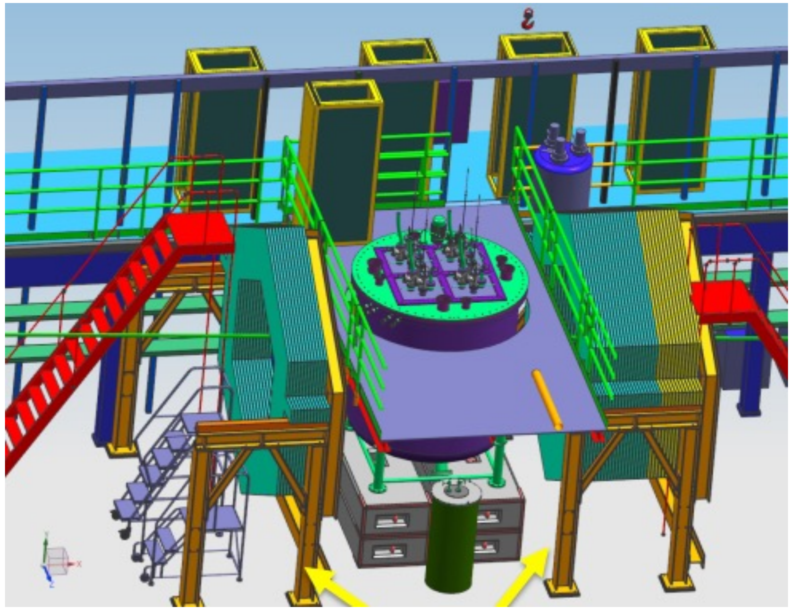




LArPix-v2 Pixel Tile



Actual raw cosmic ray data imaged in ton-scale prototype pixel TPC



Next Steps:

- Currently installing a 300k-pixel LArTPC in NuMI neutrino beam
- Use to characterize neutrino-nuclear interactions in the few-GeV energy regime, relevant for DUNE program
- Serve as prototype for the DUNE Liquid Argon Near Detector (ND-LAr)

Pursuing Neutrino Mass

Neutrino Masses and Mixing: Direct Mass Measurements

Kinematic Measurement:

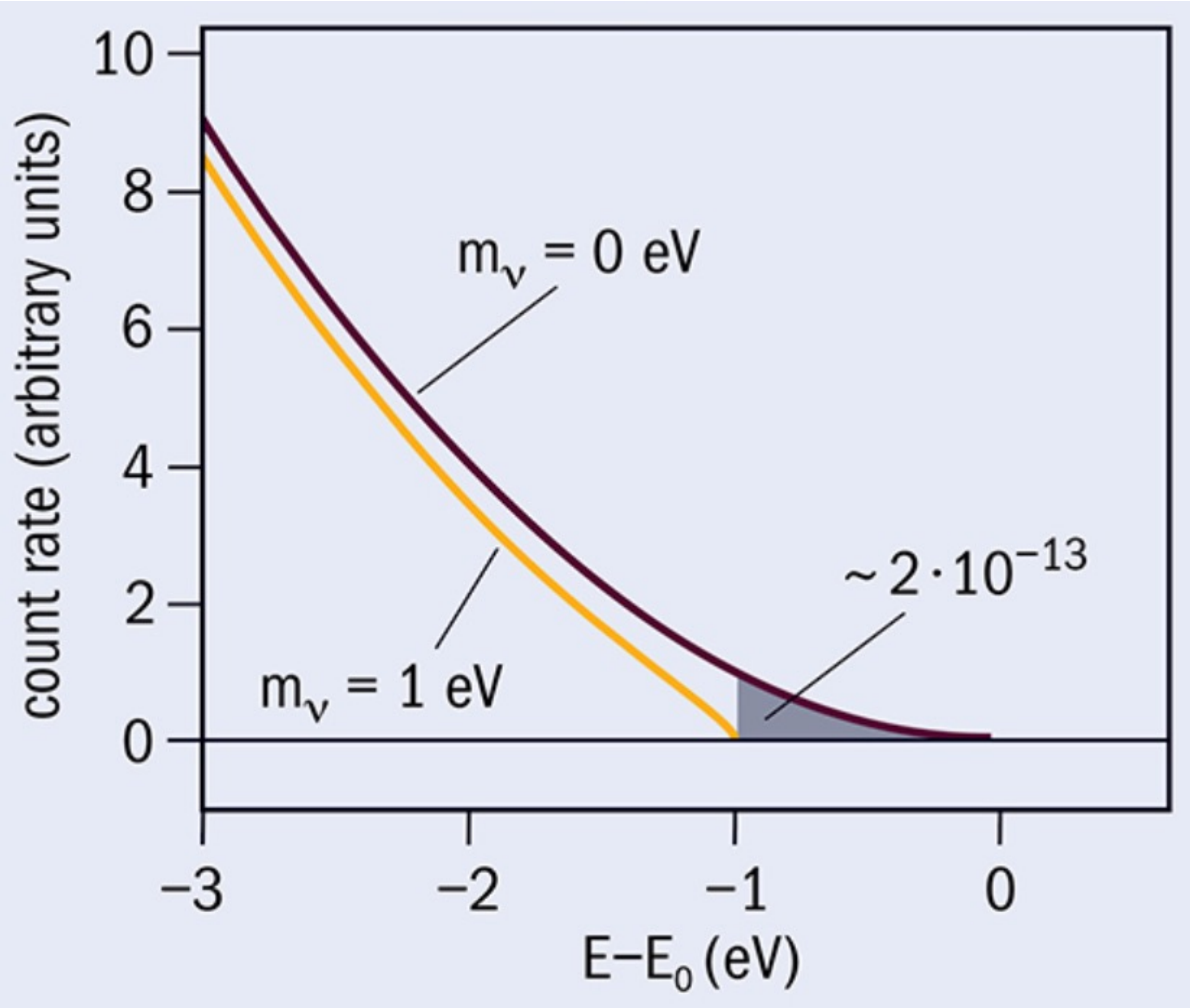
- Neutrino mass distorts the spectrum of beta-decay electrons

- Small neutrino mass only visible in very tail of decay spectrum

Effective Neutrino Mass: $m_\beta = \sqrt{\sum_i |U_{ei}^2| m_i^2}$

- ^{3}H (beta-decay), ^{163}Ho (EC) are preferred isotopes, due to lower half-life and decay endpoint.

- So far, experiments have placed limits at the < 1 eV scale, approaching oscillation measurement mass regime.



CERN Courier, Jan. 2020

Neutrino Masses and Mixing: Direct Mass Measurements

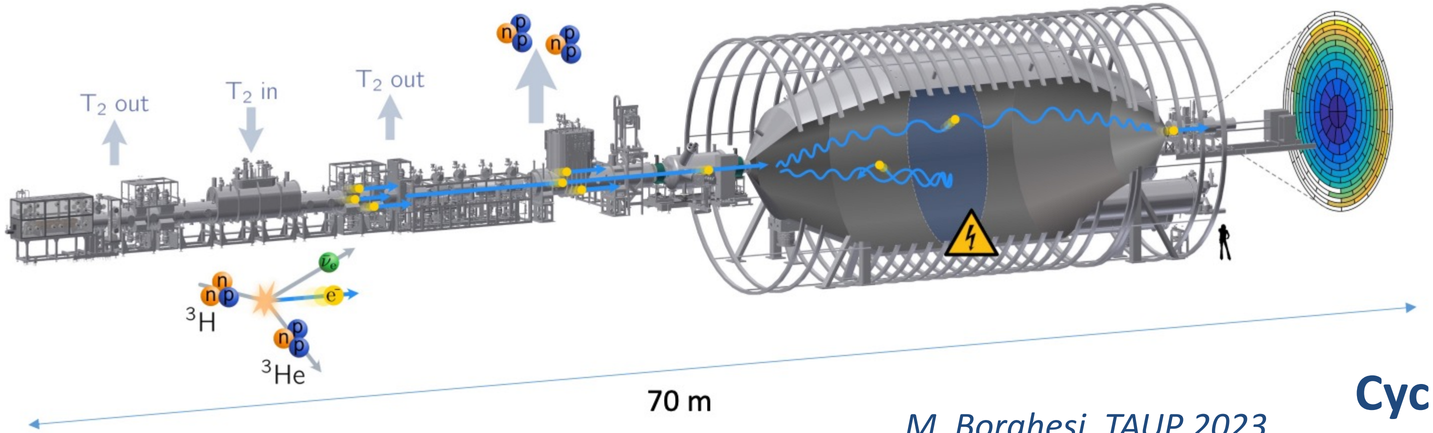
Spectrometer:

KATRIN: Electrostatic filtering spectrometer measuring ^{3}H decay

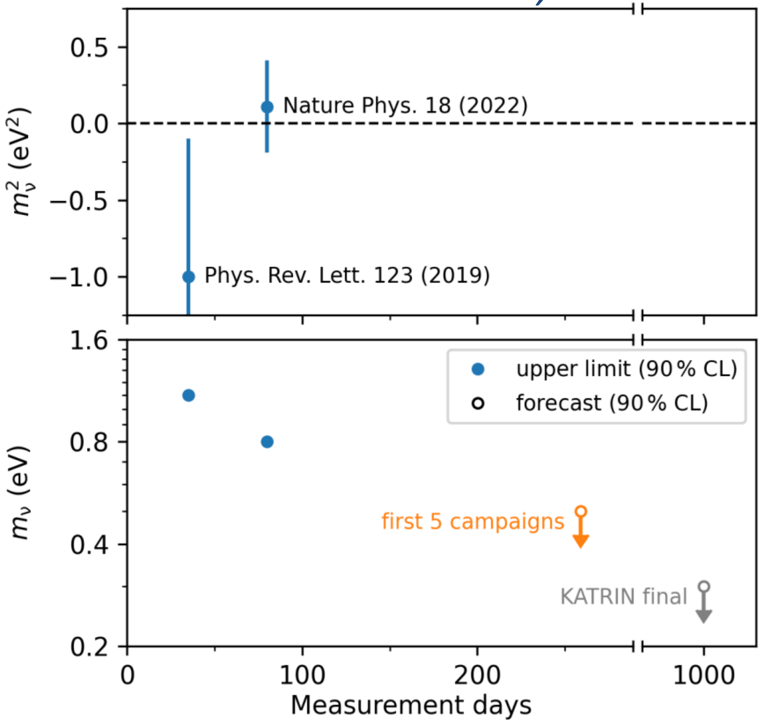
Tritium source
- Gaseous T_2
- 10^{11} T_2 decays/s

Spectrometer
- Electrostatic filter
- MAC-E filter principle

Detector
- Si-PIN detector
- Rate vs filter voltage



S. Mertens, TAUP 2023



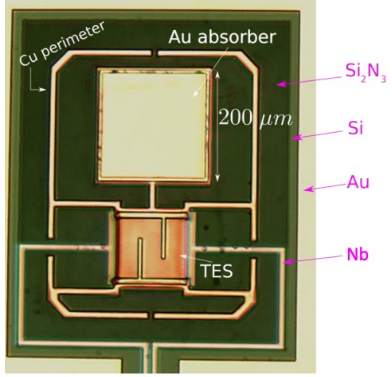
Microcalorimeters:

HOLMES: ^{163}Ho embedded in Au absorber, coupled to TES

ECHo: ^{163}Ho embedded in magnetic micro-calorimeter (MMC)

Eur. Phys. J. Special Topics 226, 1623–1694 (2017)

M. Borghesi, TAUP 2023



Cyclotron Resonance Spectrometer: *PRD 80, 051301 (2009)*

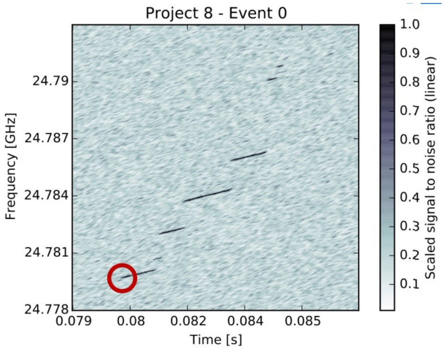
Cyclotron emission frequency sensitive to electron energy

Project-8: *Y.H. Sun, BNL Forum 2023*

^{3}H in atom trap resonant cavity

QTNM:

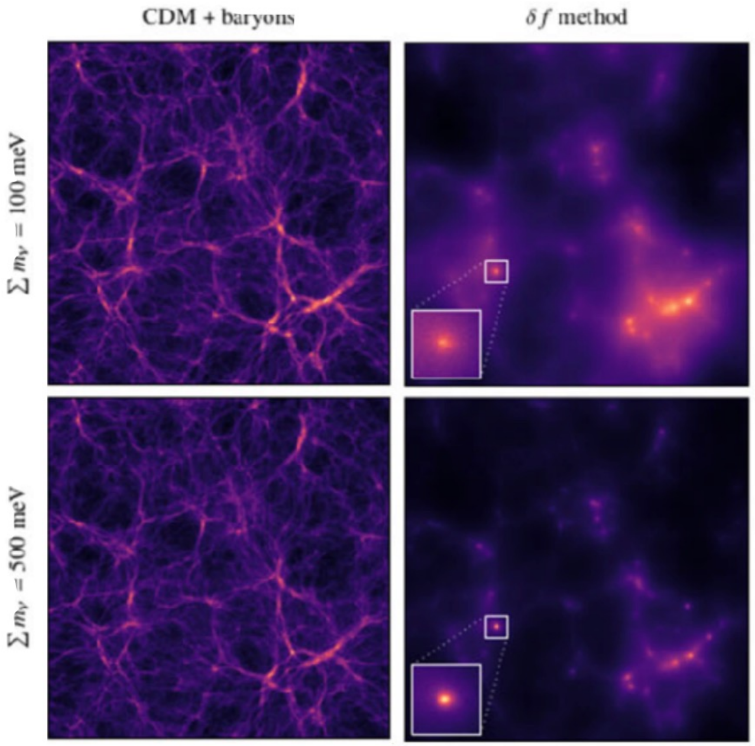
^{3}H storage ring



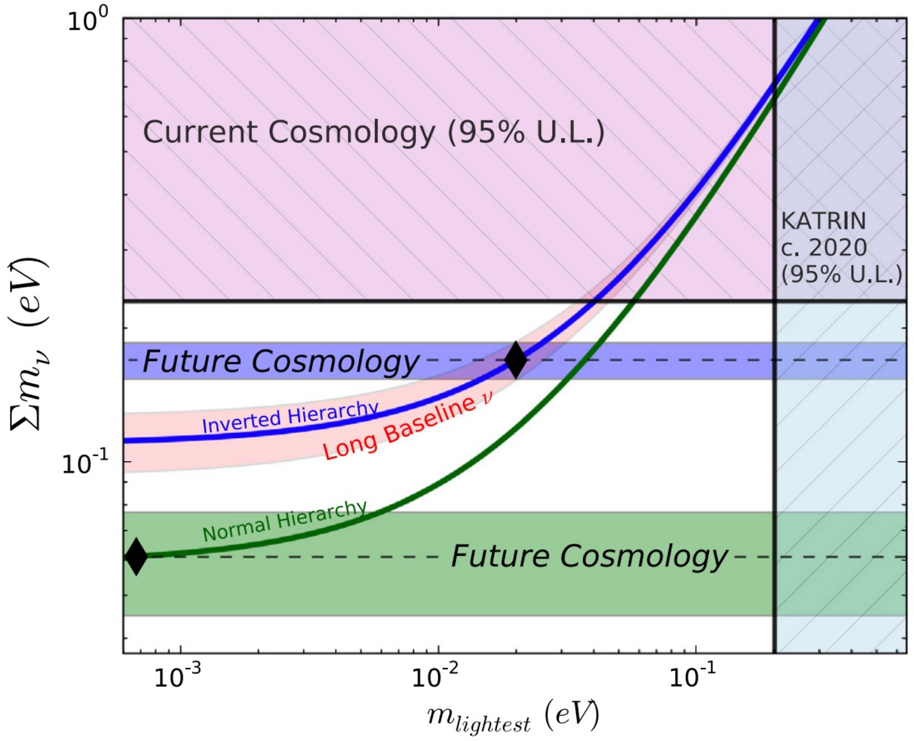
Neutrino Masses and Mixing: Cosmological Probes

Large Scale Structure:

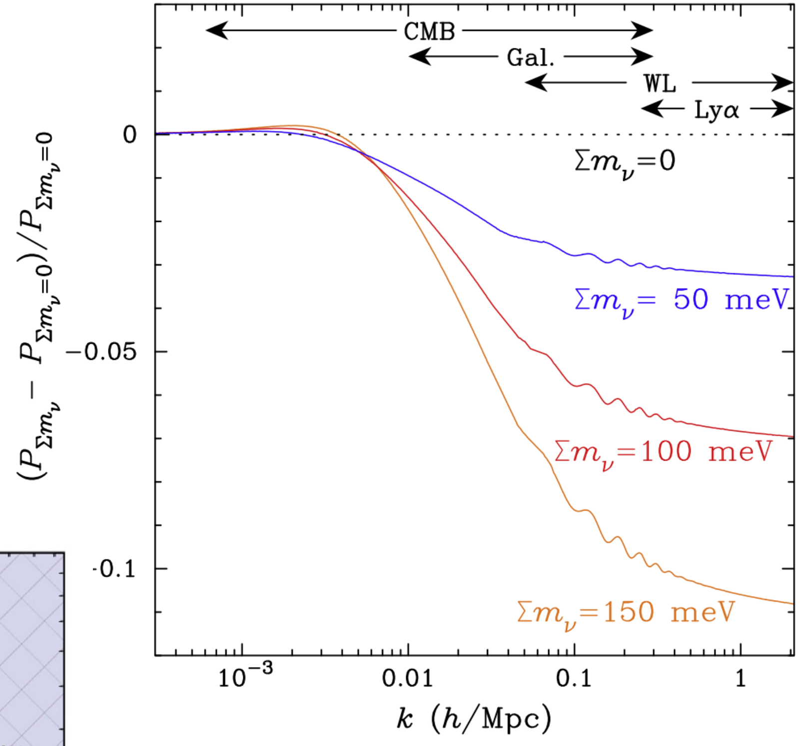
- Free-streaming of massive neutrinos suppresses clustering in early universe
- Measurable using CMB, Galaxy surveys, Weak Lensing, and Lyman-alpha forest
- Sensitive to the sum of neutrino masses



MNRAS 507(2) 2614 (2015)



Astropart. Phys. 63, 66 (2015)



Current combined limit:

Sum(m_{nu}) < 0.12 eV

Next-generation experiments (CMB-S4 and Spectroscopic surveys) aim for a resolution of 0.01 eV

Implications of Neutrino Masses and Mixing

Lepton flavor is not a conserved quantity.

Neutrinos have mass.

- Mass is at least 6 orders of magnitude smaller than known particles.
- Currently unknown how to correctly incorporate neutrino mass into the Standard Model.

Dirac Mass

$$- m\psi_R\psi_L - m\psi_R\psi_L$$

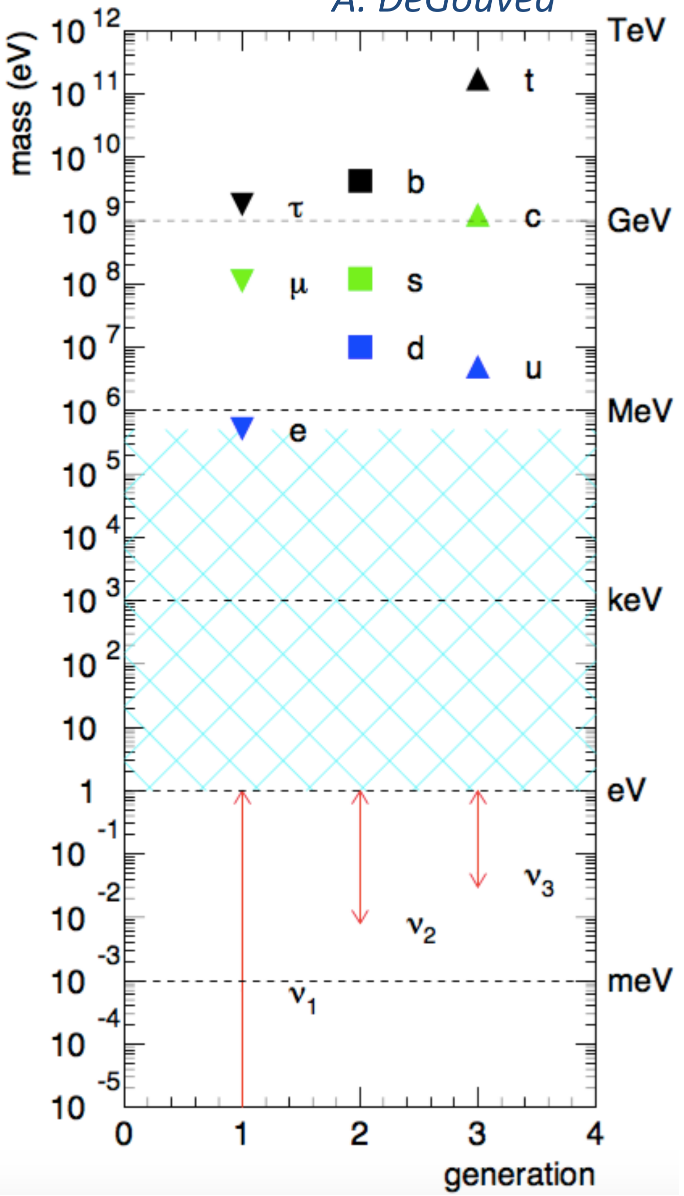
Majorana Mass

$$- m_L\chi_L\chi_L - m_R\chi_R\chi_R$$

- **Dirac mass:**
  Similar to other known particles, but difficult to motivate small mass

- **Majorana mass:**
  Possible for neutral neutrino, and seesaw mechanism can generate small mass, but violates lepton number conservation

A. DeGouvea



The Nature of Neutrino Mass

Neutrino mass and Lepton Number Violation:

- Neutrinoless double beta decay:
  Currently the most sensitive probe of possible LNV

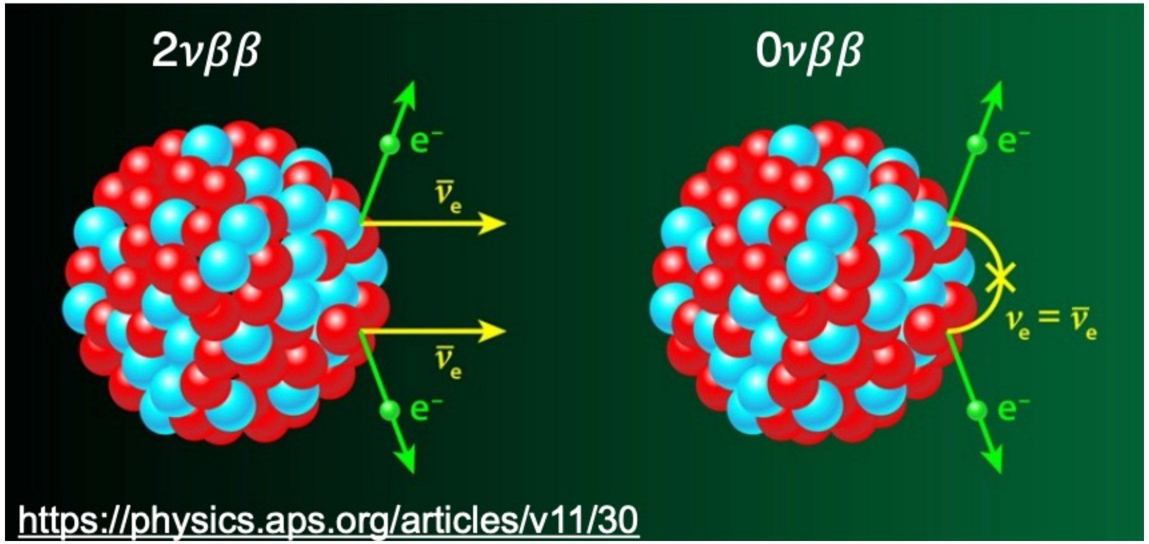
- Experiments aim to measure/limit half-life of isotope decay

- In the simplest SM extention:
  e.g. Exchange of a light Majorana neutrino

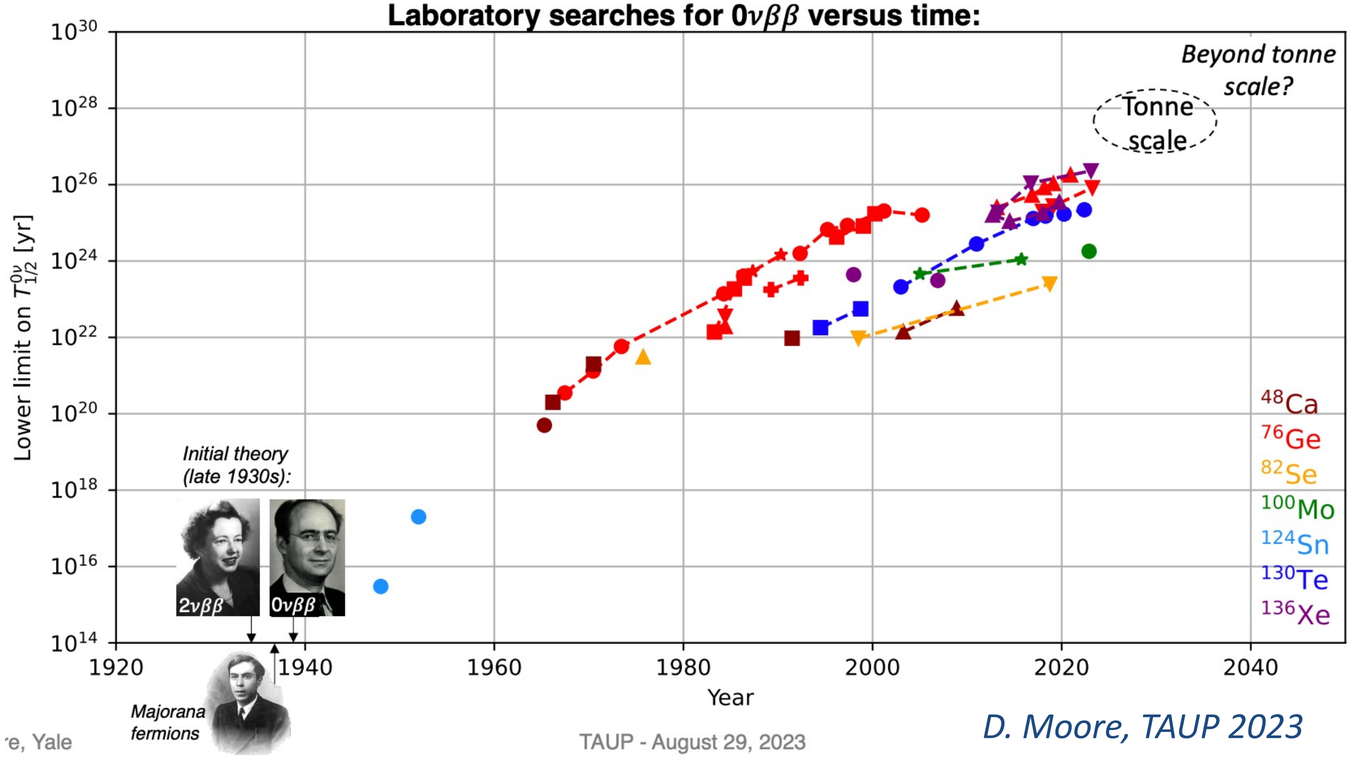
$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu} g_A^4 \mathcal{M}^2 |f|^2$$

$$|f| = \frac{m_{\beta\beta}}{m_e} = \frac{\left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|}{m_e}$$

-> Sensitive to coherent sum of neutrino masses



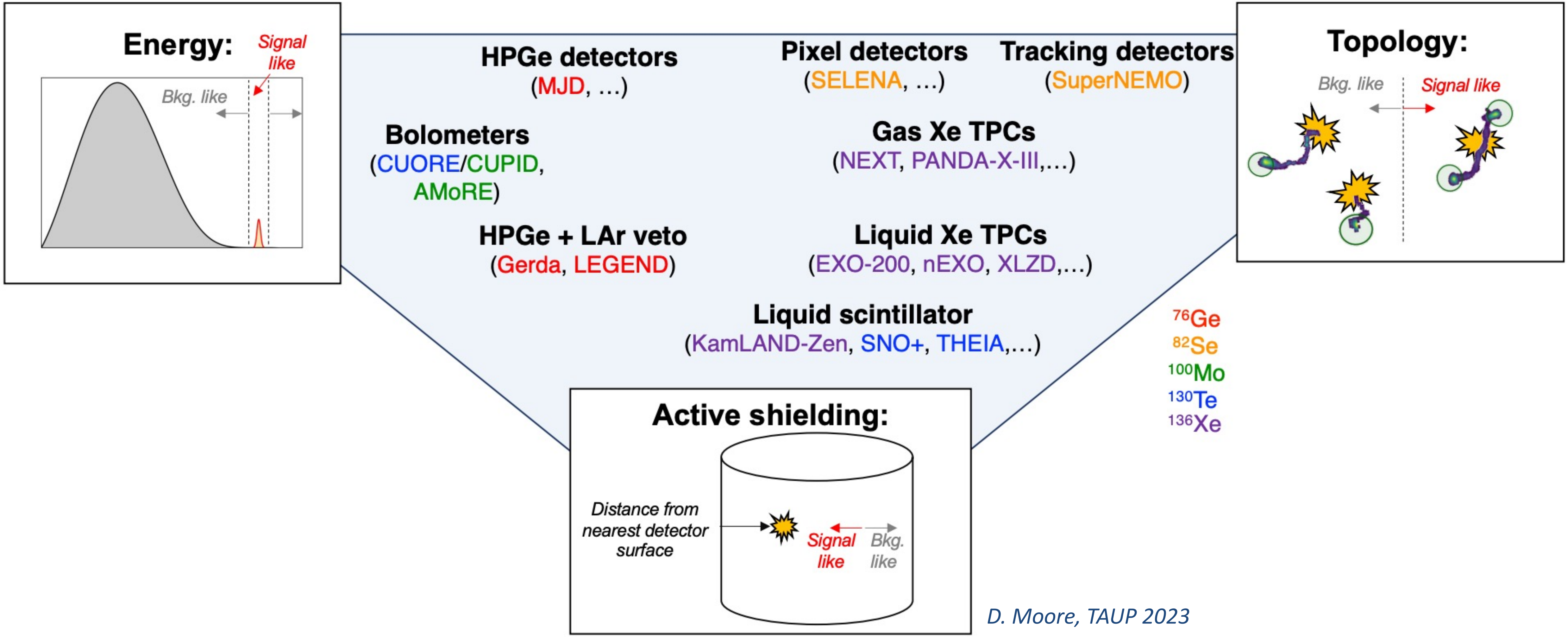
https://physics.aps.org/articles/v11/30



D. Moore, TAUP 2023

The Nature of Neutrino Mass: Techniques

Rich experimental field leveraging a wide range of detection technologies.



HPGe detectors
(MJD, …)

Pixel detectors
(SELENA, …)

Tracking detectors
(SuperNEMO)

Bolometers
(CUORE/CUPID,
AMoRE)

Gas Xe TPCs
(NEXT, PANDA-X-III,…)

HPGe + LAr veto
(Gerda, LEGEND)

Liquid Xe TPCs
(EXO-200, nEXO, XLZD,…)

Liquid scintillator
(KamLAND-Zen, SNO+, THEIA,…)

^{76}Ge
^{82}Se
^{100}Mo
^{130}Te
^{136}Xe

D. Moore, TAUP 2023

The Nature of Neutrino Mass: Current Limits

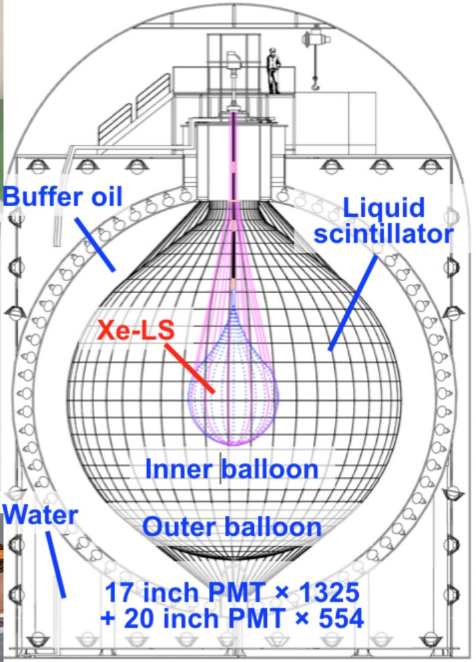
GERDA

^{76}Ge

PRL 125, 252502 (2020)

Isotope	Technique	$T^{0\nu}_{1/2}$	$m_{\beta\beta}$ (eV)	Year Published
^{48}Ca	CaF_2 scint. crystals	$> 5.8 \times 10^{22}$ y	<3.5-22	2008 [65]
^{76}Ge	^{76}Ge detectors	$> 1.8 \times 10^{26}$ y	<0.079-0.180	2020 [12]
^{82}Se	$Zn^{82}Se$ bolometers	$> 4.6 \times 10^{24}$ y	<0.263-0.545	2022 [19]
^{96}Zr	Thin metal foil within TPC	$> 9.2 \times 10^{21}$ y	<3.9 - 19.5	2009 [66]
^{100}Mo	$Li_2{}^{100}MoO_4$ bolometers	$> 1.8 \times 10^{24}$ y	<0.28-0.49	2022 [18]
^{116}Cd	$^{116}CdWO_4$ scint. crystals	$> 2.2 \times 10^{23}$ y	<1.0-1.7	2018 [67]
^{128}Te	TeO_2 bolometers	$> 3.6 \times 10^{24}$ y	<1.5-4.0	2022 [68]
^{130}Te	TeO_2 bolometers	$> 2.2 \times 10^{25}$ y	<0.090-0.305	2022 [69]
^{136}Xe	Liquid Xe scintillators	$> 2.3 \times 10^{26}$ y	<0.036-0.156	2022 [13]
^{150}Nd	Thin metal foil within TPC	$> 2 \times 10^{22}$ y	1.6-5.3	2016 [70]

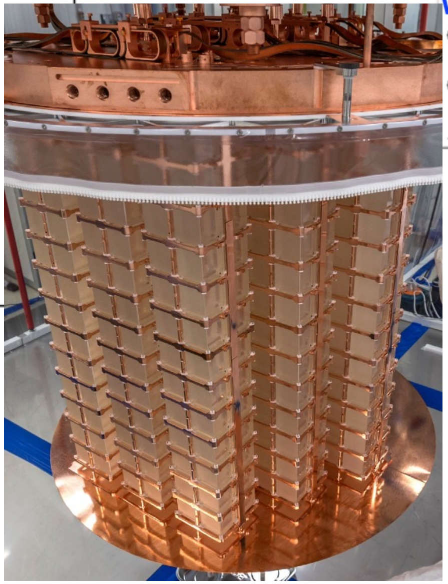
arXiv:2212.11099



KamLAND-Zen 800

^{136}Xe

JPCS 1468 (2020) 012142

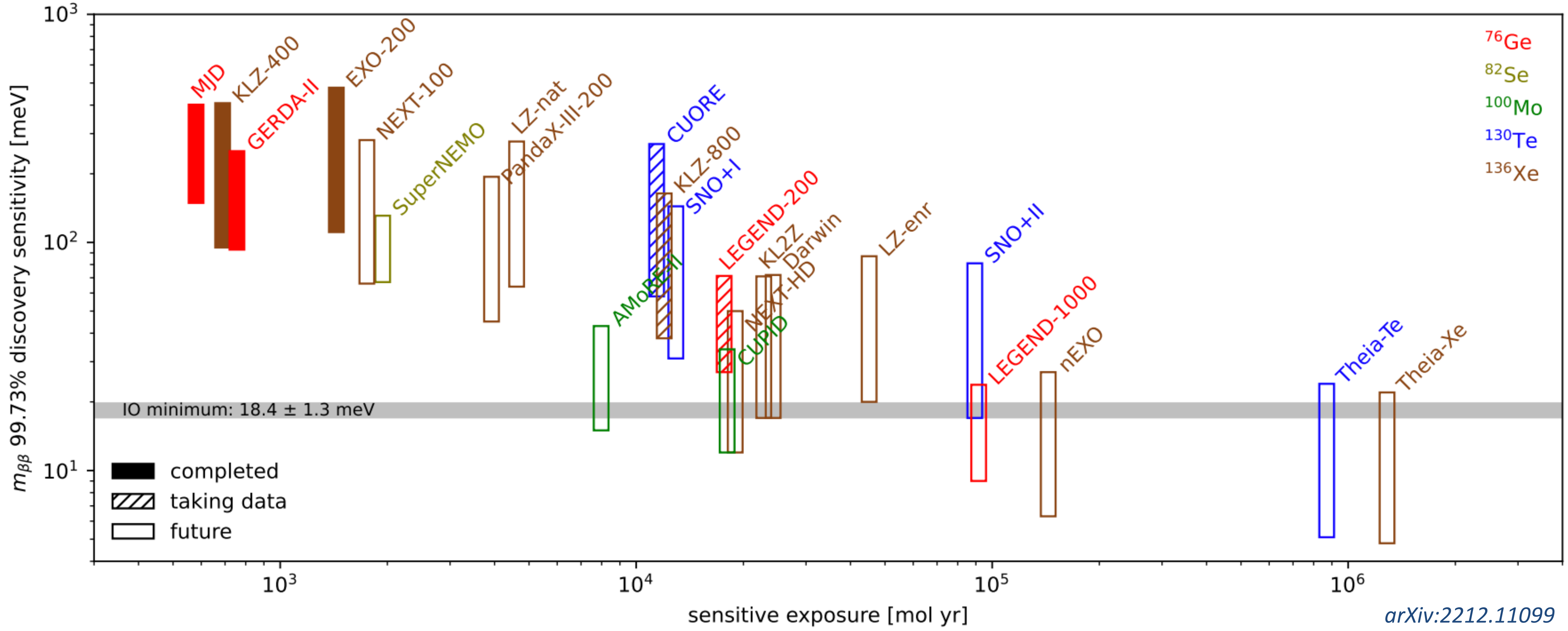


CUORE

^{130}Te

Nature 604 53 (2022)

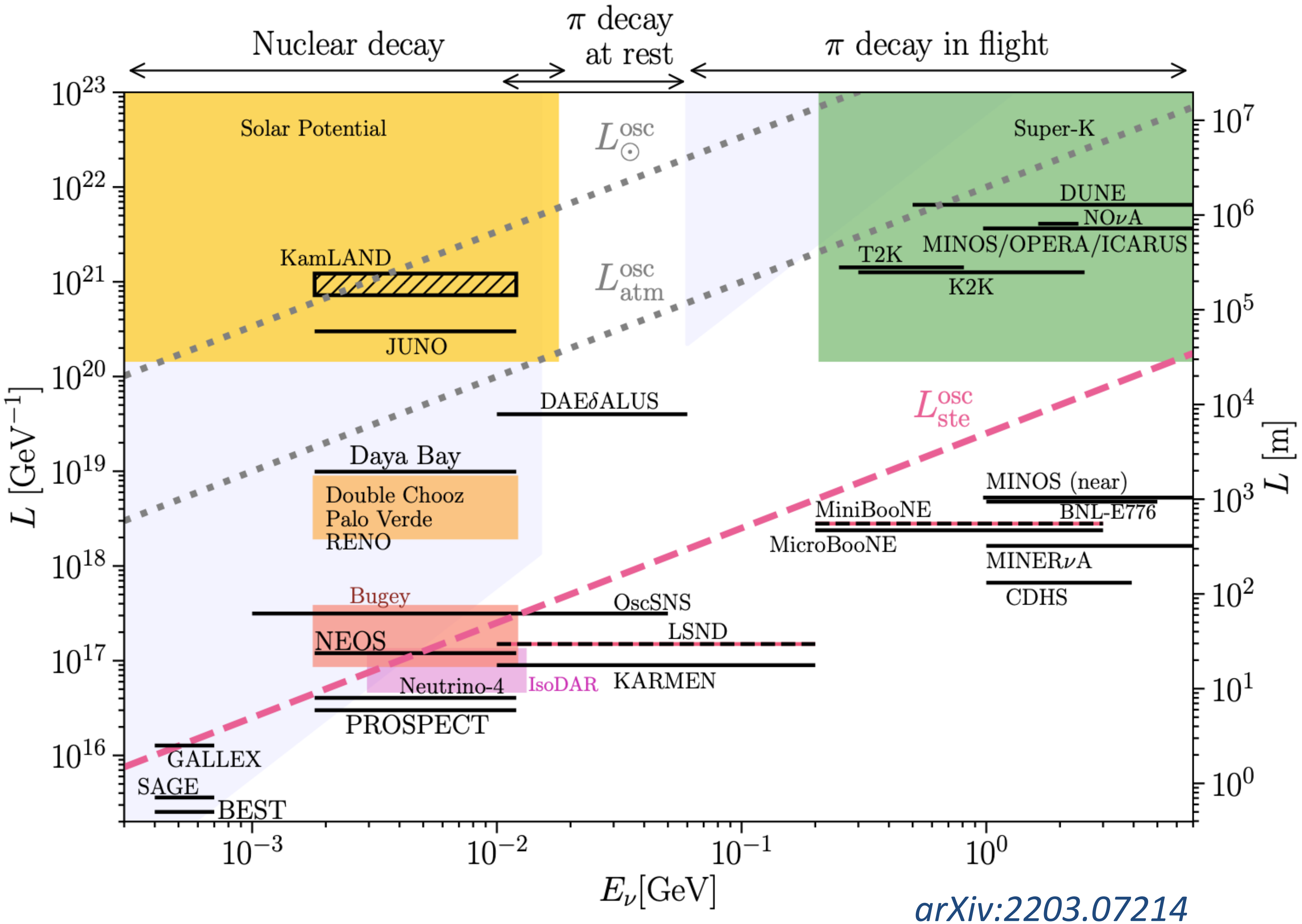
The Nature of Neutrino Mass: Current and Future Reach



arXiv:2212.11099

Beyond Three-flavor Mixing

Beyond Three Flavor Mixing

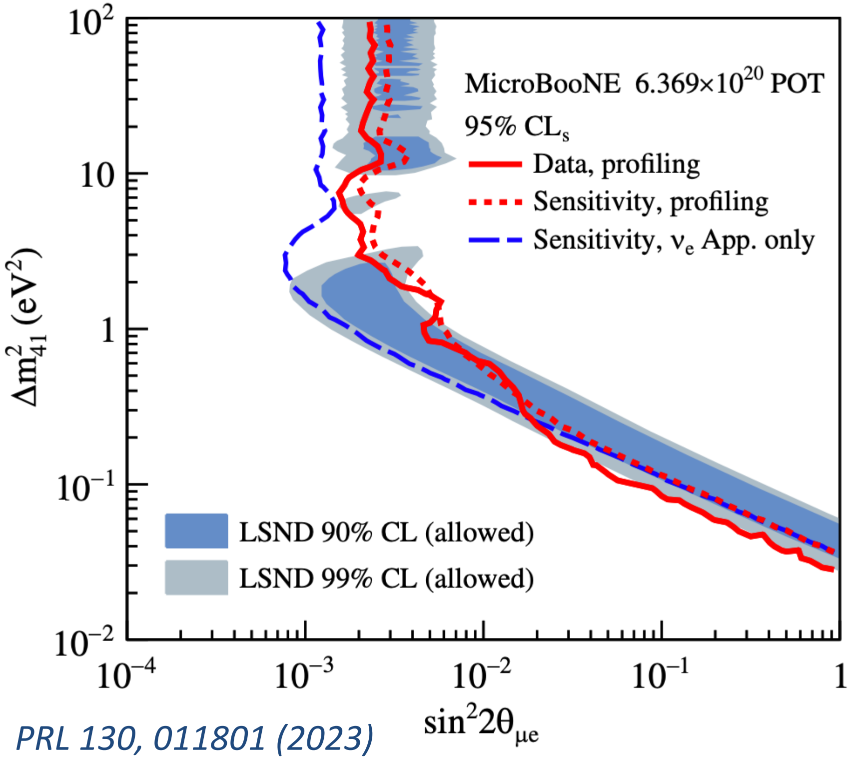


arXiv:2203.07214

Beyond Three Flavors: Accelerator and Radiochemical Experiments

Short-baseline Accelerator Experiments

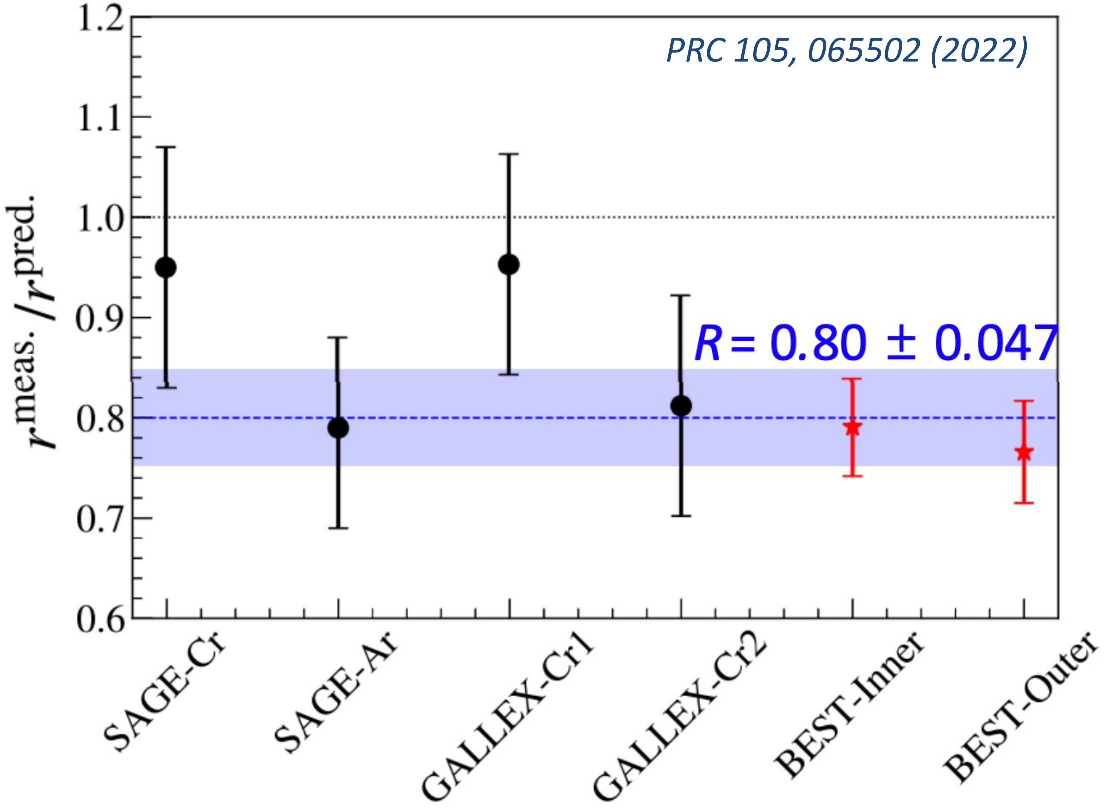
- LSND and MiniBooNE observed an excess of electron neutrino-like events from muon neutrino sources
- Data is in strong tension with other oscillation results
- Recent MicroBooNE measurement does not observe any excess
- Expect more results soon from the Short-Baseline Neutrino Program (SBN)



PRL 130, 011801 (2023)

Radiochemical Experiments

- Look for the conversion of ^{71}Ga to ^{71}Ge when exposed to an intense neutrino source (e.g. ^{51}Cr, ^{37}Ar)
- Less ^{71}Ge measured than predicted



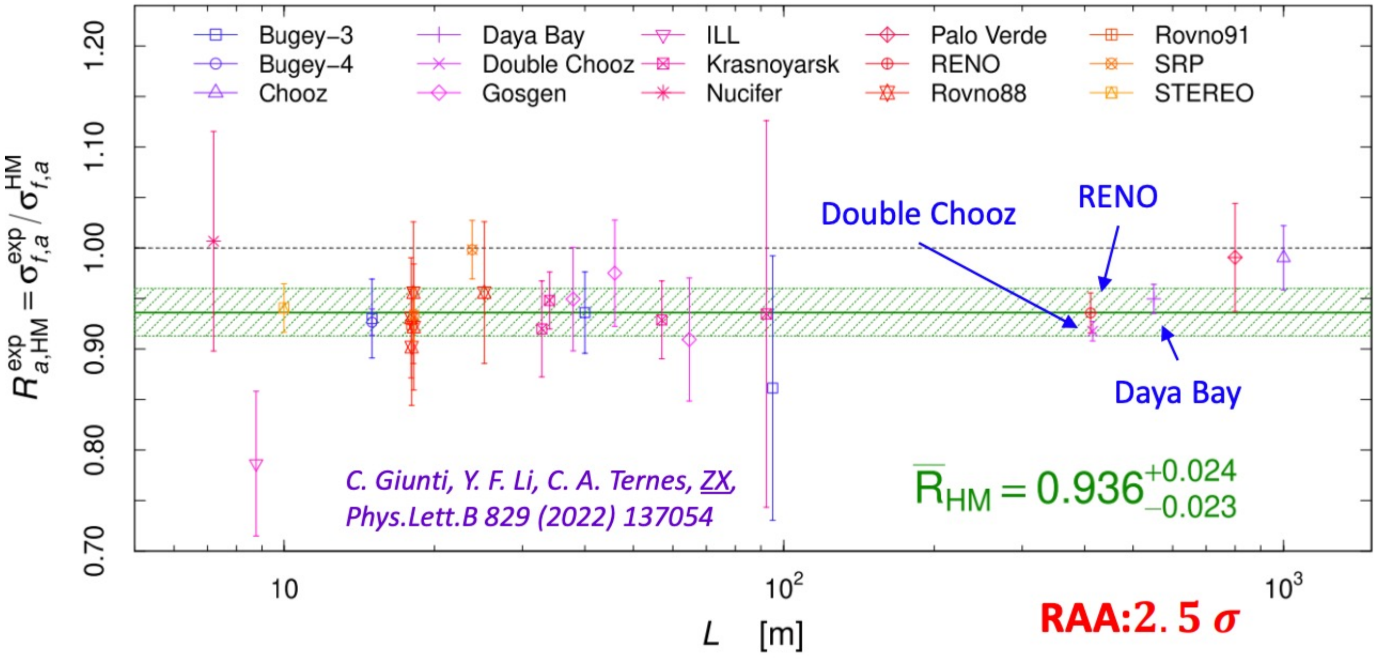
Beyond Three Flavors: Reactor Antineutrinos

Discrepancy between observed vs predicted antineutrino rate

- Considered potential evidence for a light (eV-scale) sterile neutrino
- Consistent across multiple experiments
- Model prediction was semi-empirical; based on fission electron spectra
- Predicted energy spectrum also inconsistent with data (5 MeV shoulder)

Recent Progress

- Variation of rate vs. reactor fuel composition inconsistent with semi-empirical model
- New models based on summation of nuclear decay data are consistent

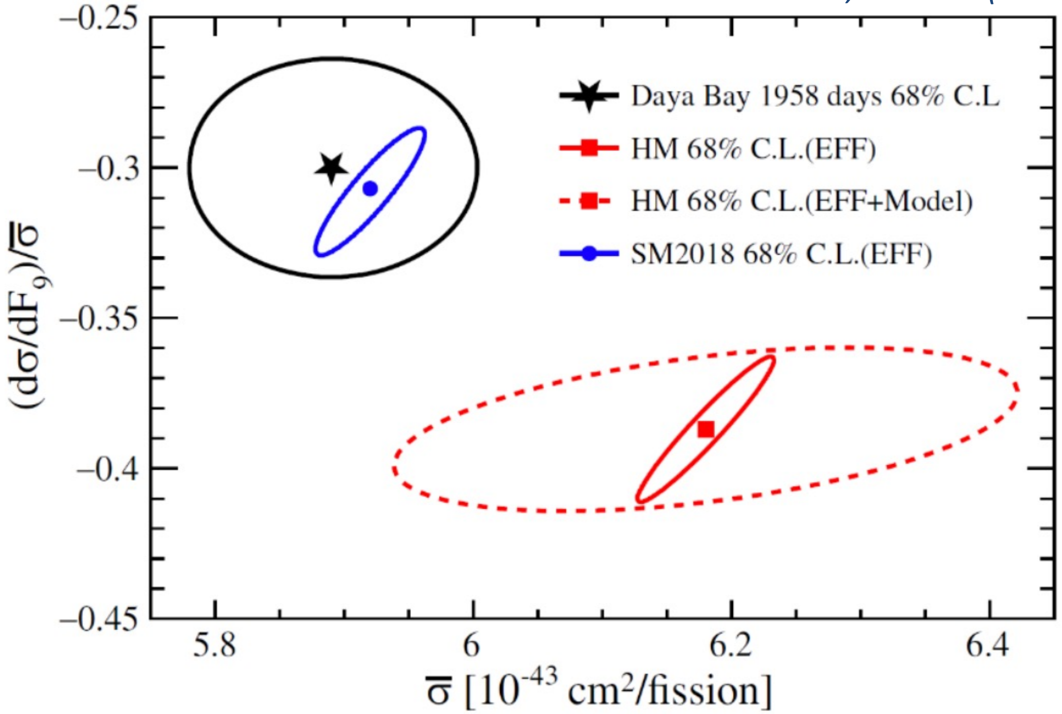


C. Giunti, Y. F. Li, C. A. Ternes, ZX, Phys.Lett.B 829 (2022) 137054

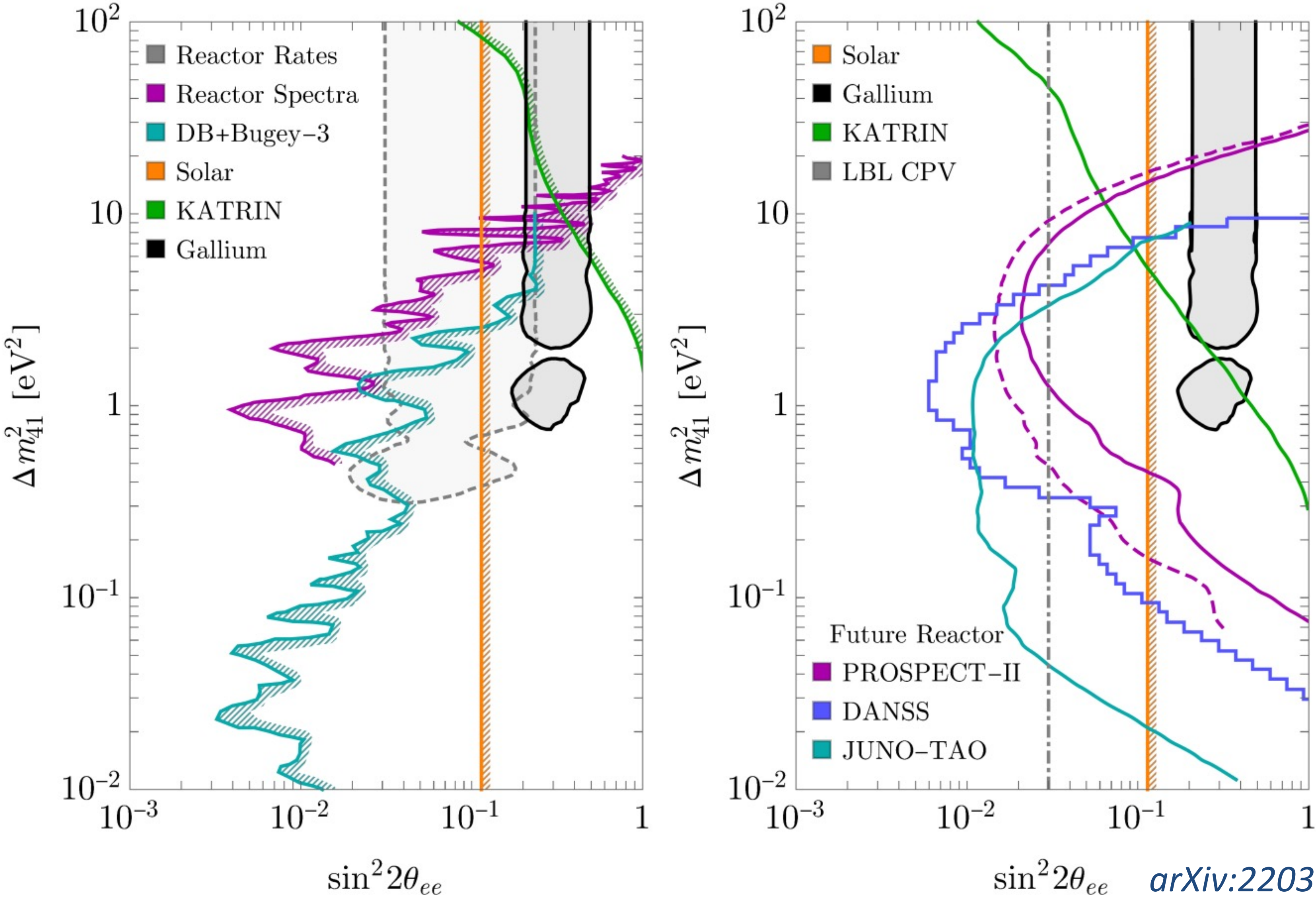
$\overline{R}_{\rm HM} = 0.936^{+0.024}_{-0.023}$

RAA:2.5 σ

PRL 130, 211801 (2023)



Sterile Neutrinos: Current and Future Sensitivities



arXiv:2203.07214

Neutrino Experiments: Summary

Neutrino Masses and Mixing:

- Measurements sensitive to neutrino mass differences <10^{-2} eV^2 present a remarkably consistent picture of three-flavor neutrino mixing
- Upcoming measurements from KM3NeT-ORCA, JUNO, Hyper-K, and DUNE will pursue the neutrino mass ordering and CP-violation, while also providing a new level of precision of the three-flavor model

Pursuing Neutrino Mass

- Kinematic and cosmic probes of neutrino mass are entering the regime suggested by oscillation measurements
- Neutrino oscillation proves neutrinos have mass, but we do not know the correct manner for inclusion in a new Standard Model
- Searches for neutrinoless double beta decay may provide direction, as well as determine if neutrinos violate lepton number conservation

Beyond Three Flavors

- Oscillation searches at O(1) eV^2 present an inconsistent picture, but current and upcoming accelerator and reactor neutrino experiments are providing clearer answers.