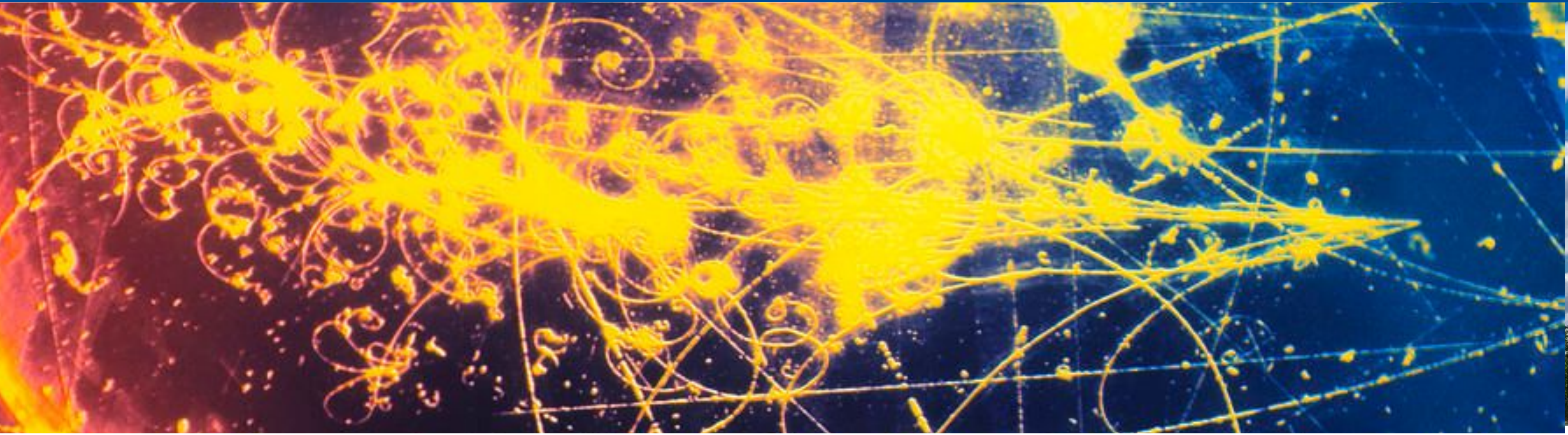


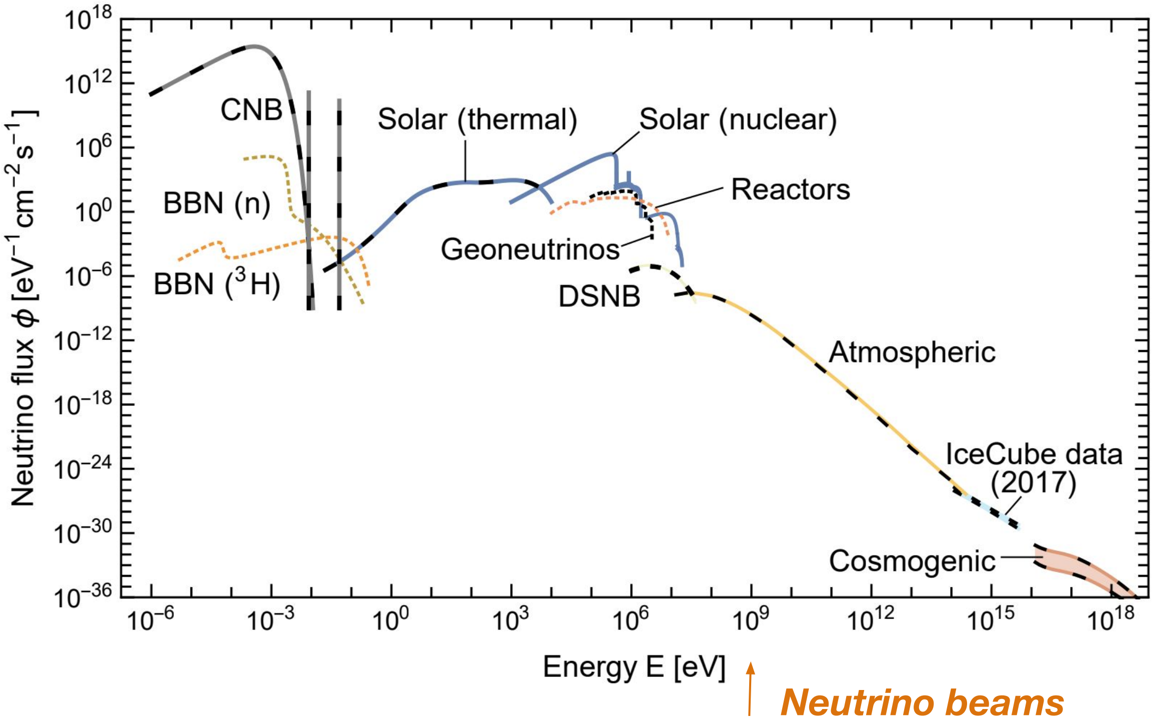
Advances and Perspectives of Neutrino Physics Experiments

Anne Schukraft

Lake Louise Winter Institute

Feb 21st 2024

Introduction

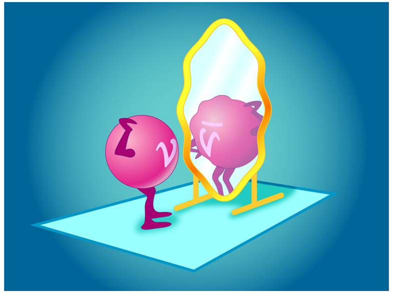


Source: [arXiv:1910.11878]

Neutrinos are among the most abundant particles in our Universe

- **Neutrino Physics** has strong ties to not only **Particle Physics**, but also **Astrophysics & Cosmology**, **Astroparticle Physics**, **Nuclear Physics**
- huge range in energies and fluxes requires very different experimental techniques
- most neutrino detectors are not single-purpose experiments and can search for interesting phenomena outside their main purpose

Open Questions in Neutrino Physics



Are neutrinos responsible for matter-antimatter asymmetry?

Are there > 3 flavours of neutrinos?

How do neutrinos get their mass?
What is their absolute mass?
What is the mass ordering?

Can we probe other BSM physics with neutrino detectors?

What can we learn about the Universe with neutrinos as messengers?

Open Questions in Neutrino Physics

	ν Oscillations	β-decay	$0\nu\beta\beta$	Astroparticle Phys.	Cosmology
Are neutrinos responsible for matter-antimatter asymmetry?	✓				
Are there > 3 flavours of neutrinos?	✓	✓	✓		✓
How do neutrinos get their mass?			✓		
What is their absolute mass?		✓	✓		✓
What is the mass ordering?	✓				✓
Can we probe other BSM physics with neutrino detectors?	✓	✓	✓	✓	✓
What can we learn about the Universe with neutrinos as messengers?				✓	✓

Open Questions in Neutrino Physics

Disclaimer:
This talk will focus on the discussion neutrino oscillations, mass measurements and neutrinoless double beta decay, and unfortunately neglect the wonderful physics at the very low and very high end of the neutrino energy spectrum.

	ν Oscillations	*β-decay*	*0νββ*	*Astroparticle Phys.*	*Cosmology*
Are neutrinos responsible for matter-antimatter asymmetry?	✓				
Are there > 3 flavours of neutrinos?	✓	✓	✓		✓
How do neutrinos get their mass?			✓		
What is their absolute mass?		✓	✓		✓
What is the mass ordering?	✓				✓
Can we probe other BSM physics with neutrino detectors?	✓	✓	✓	✓	✓
What can we learn about the Universe with neutrinos as messengers?				✓	✓

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Let's start with these:

Are neutrinos responsible for matter-antimatter asymmetry?

Are there > 3 flavours of neutrinos?

How do neutrinos get their mass?
What is their absolute mass?
What is the mass ordering?

Can we probe other BSM physics with neutrino detectors?

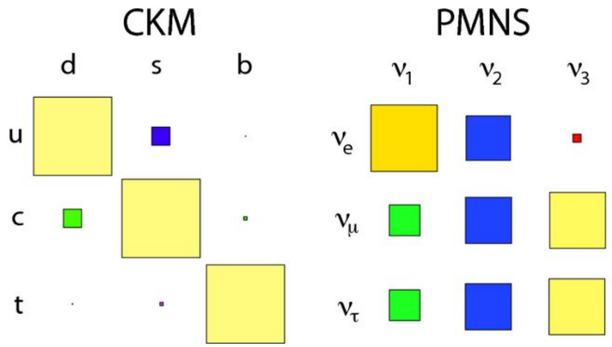
What can we learn about the Universe with neutrinos as messengers?

Introduction to 3-flavor Neutrino Oscillations

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

PMNS Matrix

The PMNS matrix is the analog to the CKM matrix in quark mixing.



- Are they related?
- Are they connected to their masses?
- They appear to be very different - why?

Introduction to 3-flavor Neutrino Oscillations

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

PMNS Matrix

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Atmospheric/ Accelerator

Accelerator/ Reactor

Solar/ Reactor

3 mixing angles: θ_{12}, θ_{13}, θ_{23}

CP violating phase: δ_{CP}

\+ 2 Majorana phases (not shown here)

c = cos θ; s = sin θ

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The fundamental neutrino parameters

Neutrino experiments measure neutrino mixing parameters through appearance and/or disappearance observations of neutrino flavor eigenstates

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$
$$+ 2\sum_{i>j}\mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right),$$
$$\alpha, \beta \in (\nu_e, \nu_\mu, \nu_\tau)$$

Appearance
$\alpha \neq \beta$
Disappearance
$\alpha = \beta$

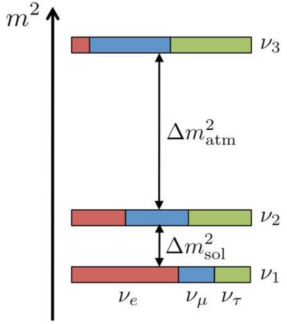
3 mixing angles: θ_{12}, θ_{13}, θ_{23}

CP violating phase: δ_{CP}

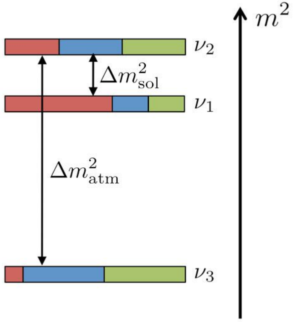
2 mass differences: Δm^2_{31}, Δm^2_{21}

Sign of Δm^2_{31}

Normal Ordering (NO)



Inverted Ordering (IO)



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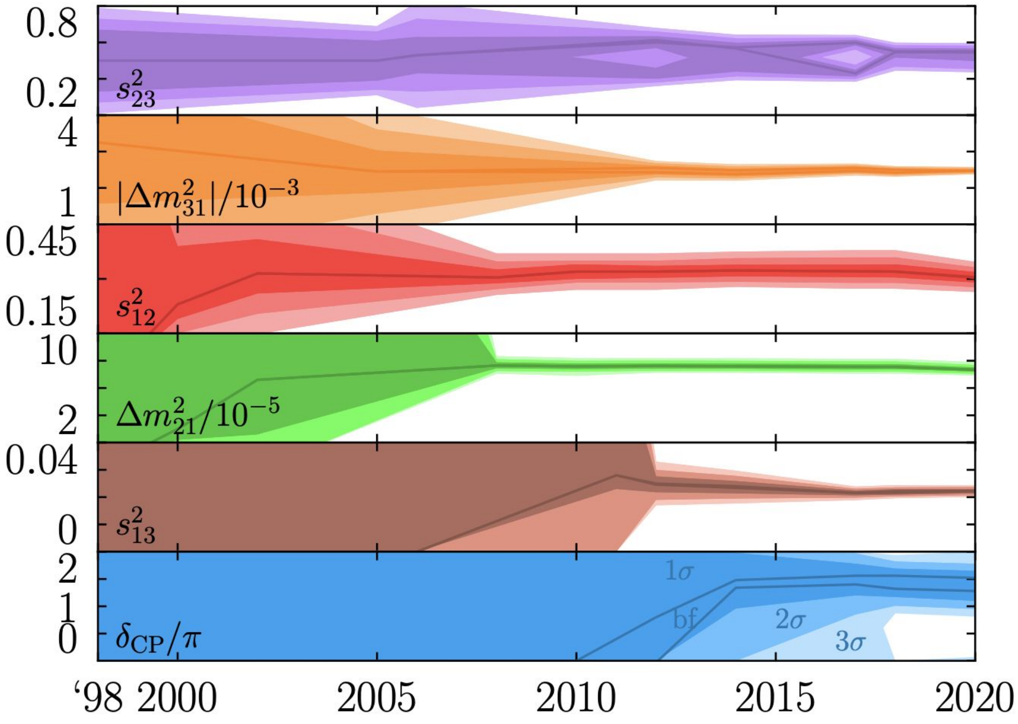
Mixing parameter evolution



known to

5%

1%

4%

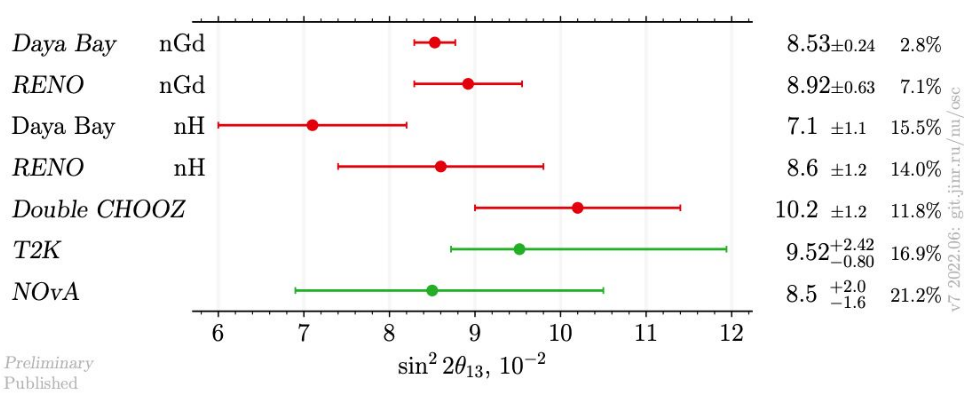
3%

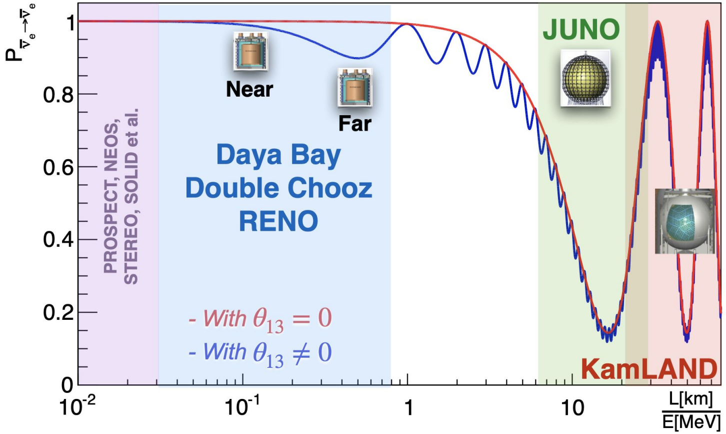
3%

Source:
Snowmass NF01 Topical Group Report, 2022
& Sanchez@TAUP2023

Status of reactor measurements on θ_{13}

The success story of θ_{13}:
From unknown to non-zero to one of the best known parameters thanks to reactor experiments.





Source: Ochoa-Ricoux@NuFact23

- A large value of θ_{13} is good for our sensitivity to δ_{CP}
- A good knowledge of θ_{13} is important for determining δ_{CP} and mass ordering in long-baseline experiments

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Accelerator Neutrino Oscillation Experiments

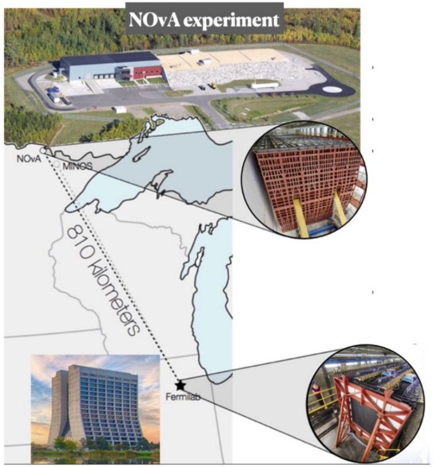
- ν_μ and/or $\bar{\nu}_\mu$ beams (with some contamination of other flavors)

- Measure the **disappearance of $\nu_\mu/\bar{\nu}_\mu$** and the **appearance of $\nu_e/\bar{\nu}_e$** at the detector location

- Typically have a near detector to constrain the initial flux and uncertainties

Current long baseline experiments

	T2K	NOvA
Proton energy & power	30 GeV / ~500 kW	120 GeV / ~700 kW
Peak neutrino energy	0.6 GeV	1.8 GeV
Baseline	295 km	810 km
Far detector mass	50 kton	14 kton
Detector technique	Water Cherenkov	Segmented liquid scintillator bar
Run period	2010 – (~2027)	2014 – (~2026)



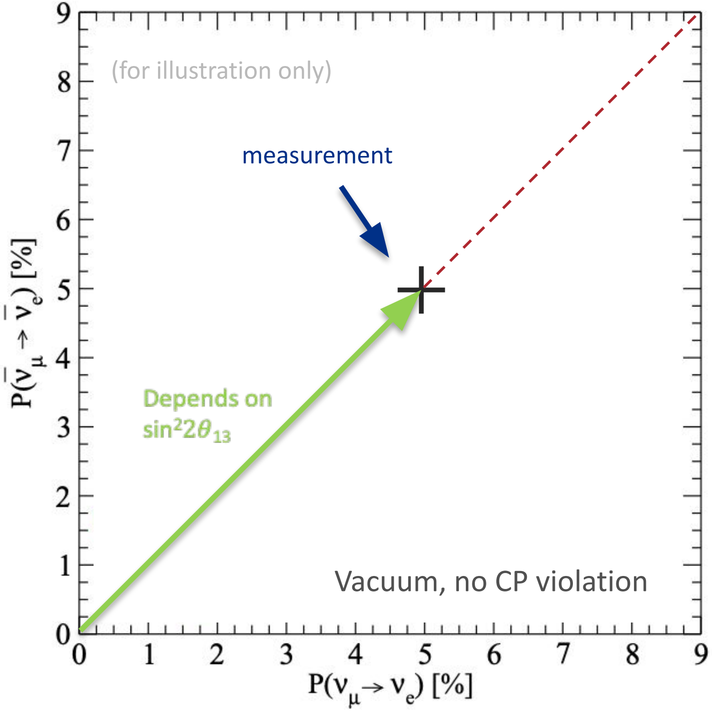
Source: [S. Cao, arXiv:2310.09855, 2023]

- Several ambiguities between oscillation parameters
  - measure several channels simultaneously and calculate a best fit of oscillation parameters
  - **Input from multiple experiments at different baselines & energies is crucial!**
  - Use other (reactor) measurements to constrain parameters the accelerator experiments are less sensitive to

Long Baseline Oscillation Measurements

- Very simplified, the oscillation analysis is a counting experiment

- **In vacuum, no CP violation**, expect same probability for neutrino and antineutrino appearance/disappearance



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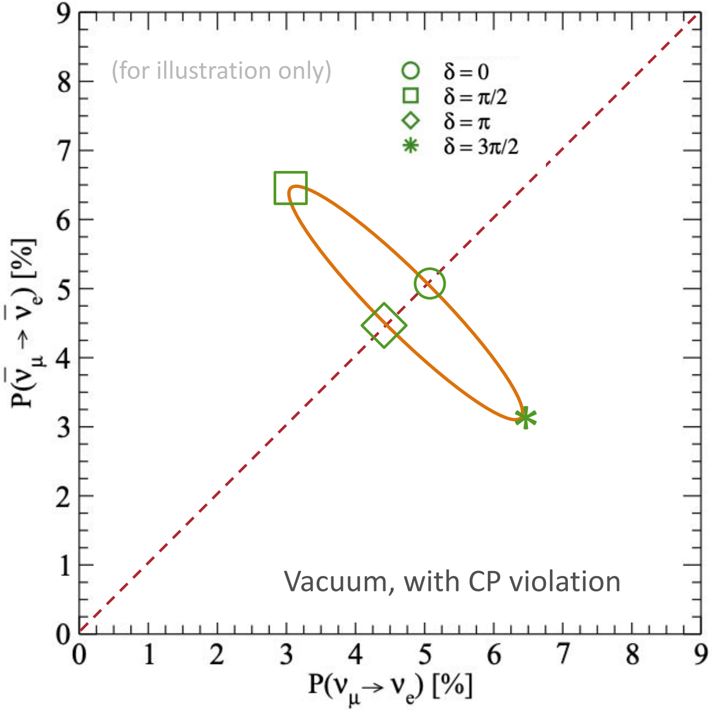
Long Baseline Oscillation Measurements

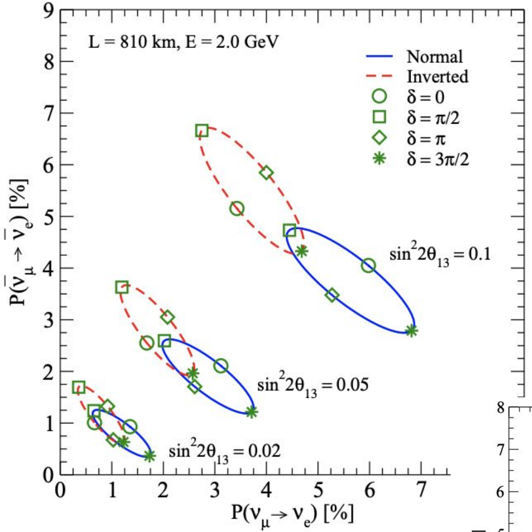
- Very simplified, the oscillation analysis is a counting experiment
- **In vacuum, no CP violation**, expect same probability for neutrino and antineutrino appearance/disappearance
- **With CP violation**, the measurement will be located on an **ellipse**



Long Baseline Oscillation Measurements

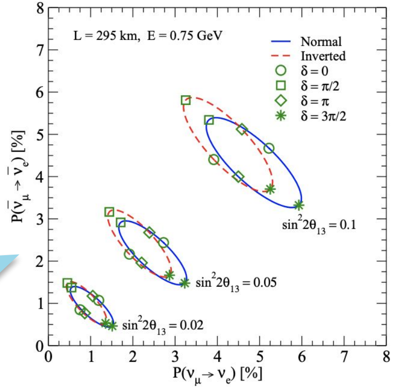
- Very simplified, the oscillation analysis is a counting experiment
- **In vacuum, no CP violation**, expect same probability for neutrino and antineutrino appearance/disappearance
- **With CP violation**, the measurement will be located on an **ellipse**
- Including **matter effects** (which are different for neutrinos and antineutrinos), the ellipses separate for the two **mass ordering** scenarios
  - Different baselines lead to different ambiguities

NOvA-like



arXiv:0710.0554

T2K-like



Shorter baseline
= less matter effects

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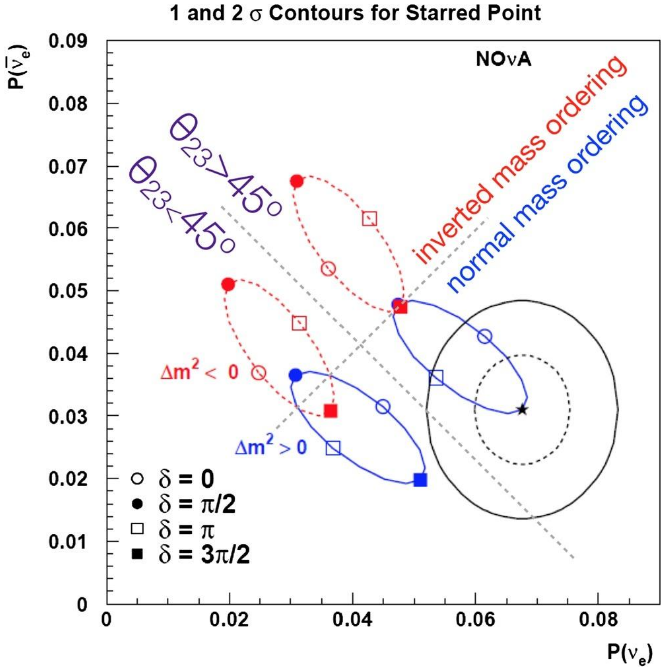
Long Baseline Oscillation Measurements

- Very simplified, the oscillation analysis is a counting experiment
- **In vacuum, no CP violation**, expect same probability for neutrino and antineutrino appearance/disappearance
- **With CP violation**, the measurement will be located on an **ellipse**
- Including **matter effects** (which are different for neutrinos and antineutrinos), the ellipses separate for the two **mass ordering** scenarios
  - Different baselines lead to different ambiguities
- The θ_{23} octant leads to another set of solutions



https://www.sciencedirect.com/science/article/pii/S0550321316300657

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NOvA & T2K results

→ See T2K (Nugent) and NOvA (Wu) talks tomorrow

δ_{CP}

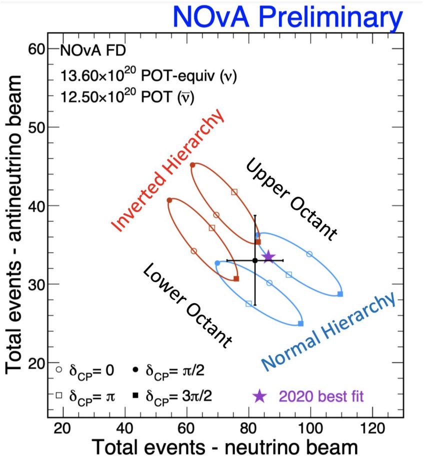
- NOvA doesn't observe asymmetry; Disfavor IO+δ_{CP} = π/2 by > 3σ and NO+δ_{CP} = 3π/2 by > 2σ
- T2K favors maximal CP violation; δ_{CP} = 0 or π excluded at > 90% CL

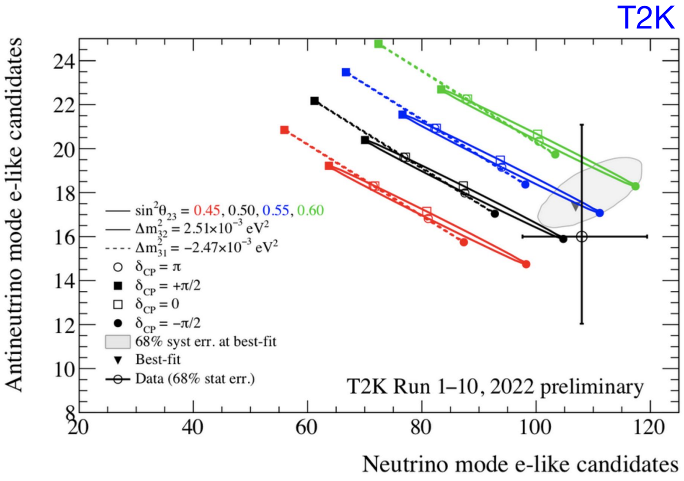
Mass Ordering

- both NOvA and T2K favor normal mass ordering

Octant θ_{23}

- slight preference for the upper Octant is driven by reactor constraints





Last week's Outlook

Outlook

- NOvA and T2K working towards a joint fit to quantify consistency of their results
- Both experiments expected to double statistics before the end of runtime
- Next-generation experiments DUNE and Hyper-K for definitive answers under construction

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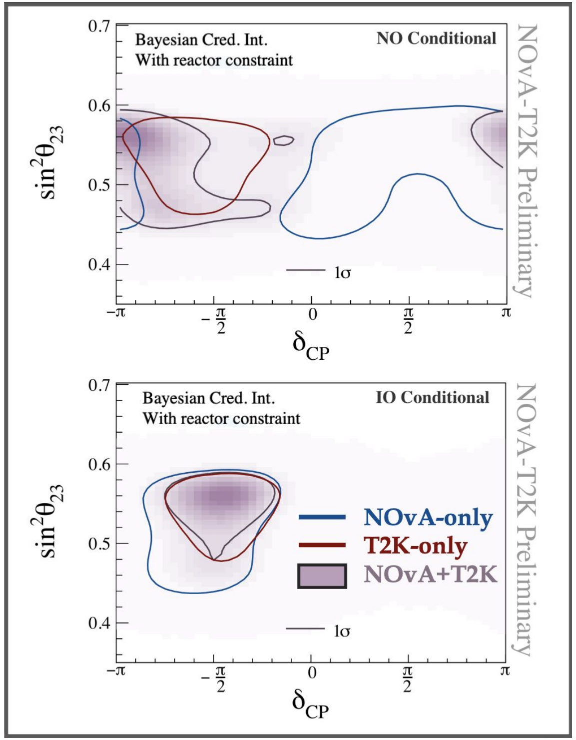
NOvA & T2K joint fit results

Why NOvA-T2K joint fit?

✅ The complementarity between the experiments provides the power to **break degeneracies.**

- Full implementation of:
  - ✅ **Energy reconstruction and detector response**
  - ✅ **Detailed likelihood** from each experiment
  - ✅ Consistent **statistical inference across the full dimensionality**
- In-depth review of:
  - ✅ **Models, systematic uncertainties and possible correlations**
  - ✅ **Different analysis approaches** driven by contrasting detector designs.



Normal Ordering
(tension between T2K and NOvA individual results):

→ joint fit splits the difference

Inverted Ordering
(agreement between T2K and NOvA individual results):

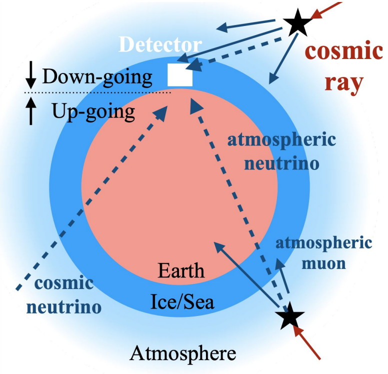
→ joint fit places tighter constraint on δ_{CP}

Source: Z. Vallari,
[Fermilab Joint Experimental-Theoretical Physics Seminar, Feb 16, 2024]

- Joint fit has smallest uncertainty on $|\Delta m^2_{32}|$: 1.5%
- Joint fit results on mass ordering and θ_{23} Octant still inconclusive

Atmospheric Neutrino Oscillations

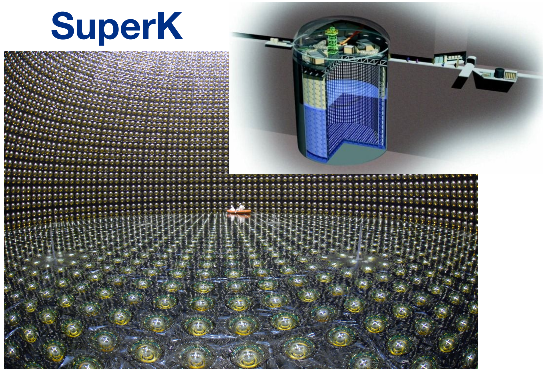
→ *See IceCube LE (Blot) and KM3NeT (Lamoureux) talks tomorrow*



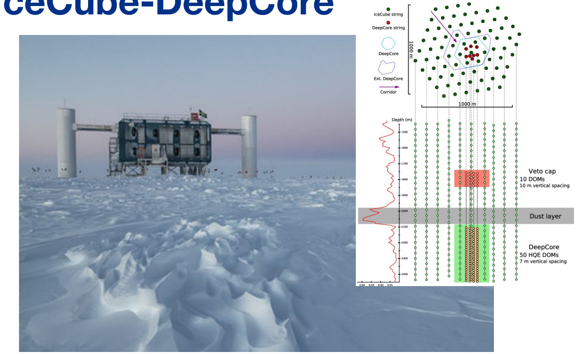
Atmospheric Neutrinos provide a complementary approach to measure oscillations parameters

- Huge statistics with extremely large detectors
- Large range of very long baselines → matter effects
- In addition to ν_μ disappearance can observe $\nu_\mu \rightarrow \nu_\tau$ appearance with ν_τ detection
- Higher neutrino energies and different systematics than accelerator neutrino experiments

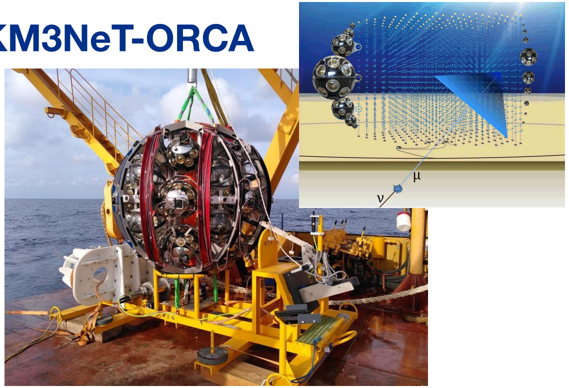
SuperK



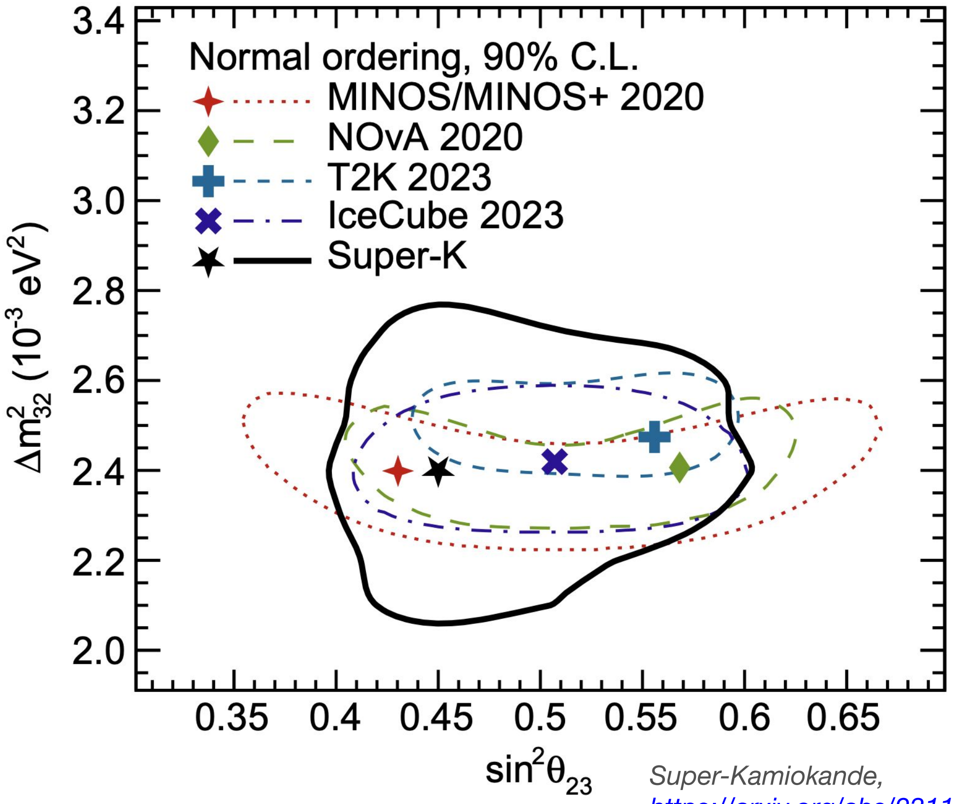
IceCube-DeepCore



KM3NeT-ORCA

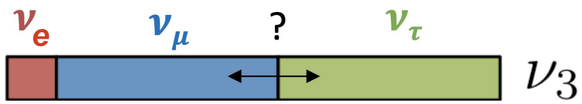


Status of θ_{23} Octant measurement



Super-Kamiokande, https://arxiv.org/abs/2311.05105 (2023)

How much ν_μ is in ν_3?



- ν_μ disappearance channel alone has little power to distinguish the octant. Observing ν_e or ν_τ appearance at the same time enables Octant separation in a joint fit of oscillation parameters

- Atmospheric mass splitting and large mixing angle results using atmospheric neutrinos very competitive with latest with long-baseline accelerator measurements.

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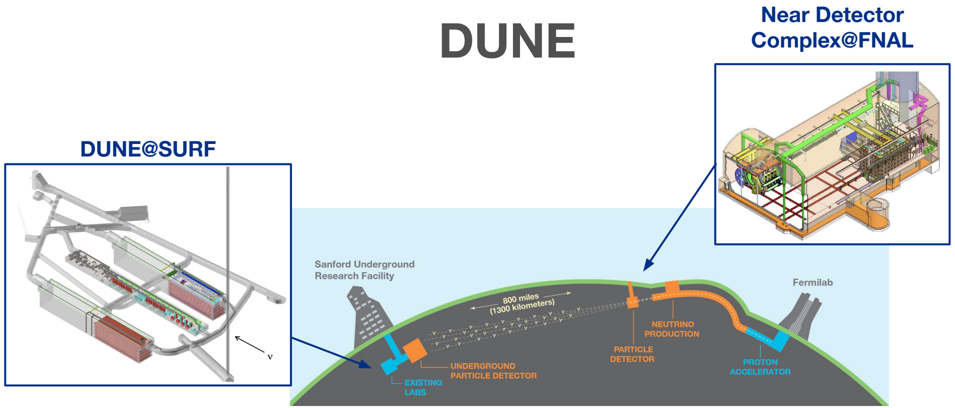
Next Generation Long Baseline Experiments

→ See Hyper-K (Koerich) and DUNE (Maricic) talks tomorrow

Hyper-K

- Upgraded 1.3 MW J-PARC beam over 295 km baseline
- 258 kt Water Cherenkov Far Detector
- Upgraded off-axis near detector
  (ND280-upgrade + new intermediate Water Cherenkov Detector (IWCD))

DUNE



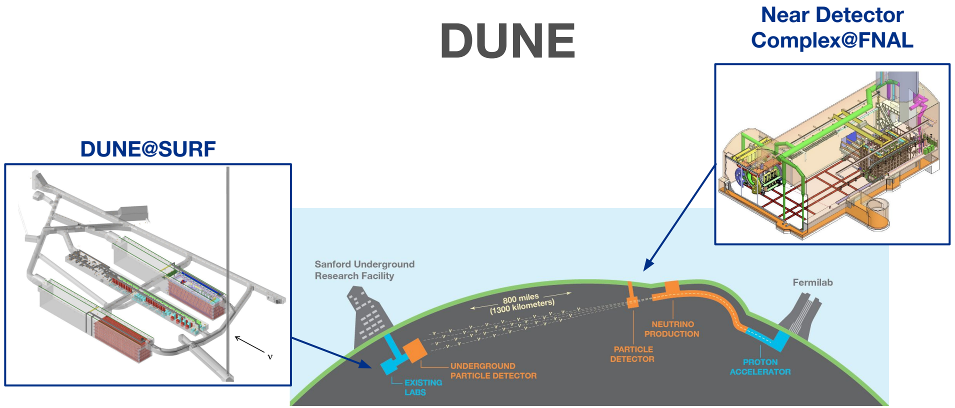
- New 1.2 MW neutrino beam from Fermilab to South Dakota over 1285 km baseline
  (upgradable to > 2 MW in Phase II)
- Two 17 kt liquid Argon Time Projection Chamber (LArTPC) far detector modules in Phase I (Phase II upgrade with more far detector mass planned)
- Movable LArTPC near detector with muon catcher + on-axis detector (with plans for upgrade)

Complementarity between Hyper-K and DUNE

Hyper-K

- short baseline → small matter effect
- off-axis detector, narrower beam
- lower energy range, dominantly charged-current quasi-elastic scattering
- very large Water Cherenkov detector

DUNE



- long baseline → large matter effect
- on-axis detector, broadband beam
- broad energy range, high statistics over full oscillation region
- LArTPC technology

credit:
Marshall@NuFact2023

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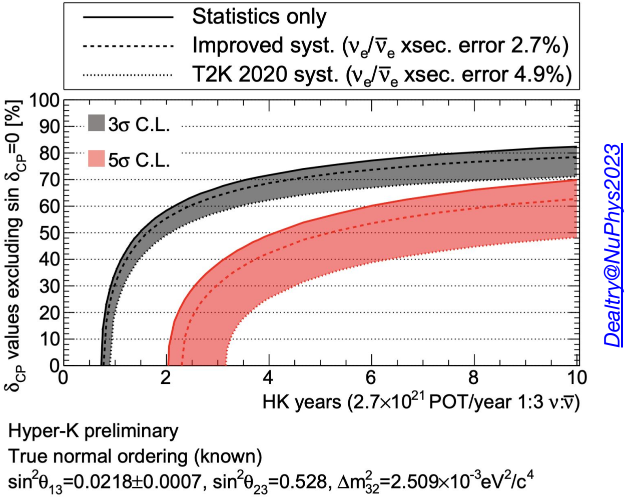
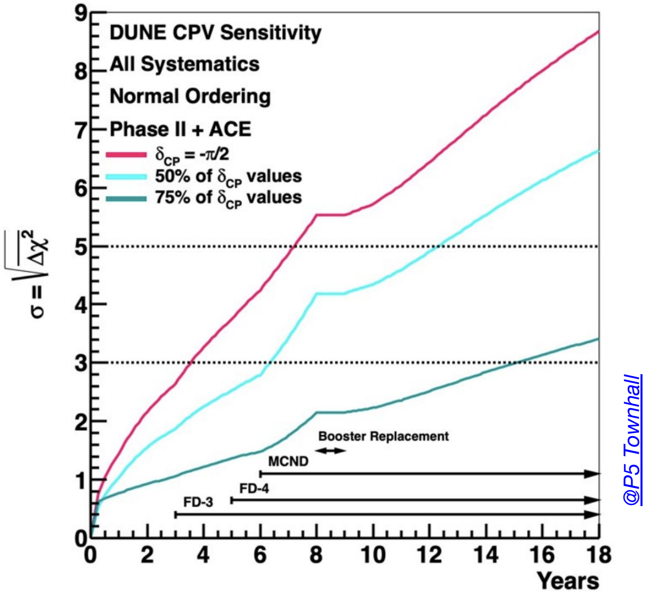
Sensitivities to δ_{CP}

Hyper-K



DUNE



Hyper-K can exclude 50% of true δ_{CP} values in < 2 years @ 3σ **if the mass ordering is known**

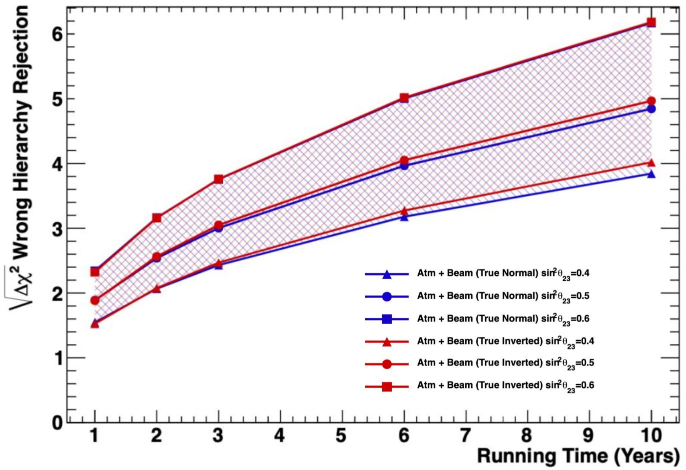
- addition of atmospheric data help if mass ordering is not known

If δ_{CP} is maximal, DUNE reaches 3σ CP violation in 3.5 years of running

- other scenarios are reachable with DUNE Phase II

Sensitivities to Mass Ordering and Octant

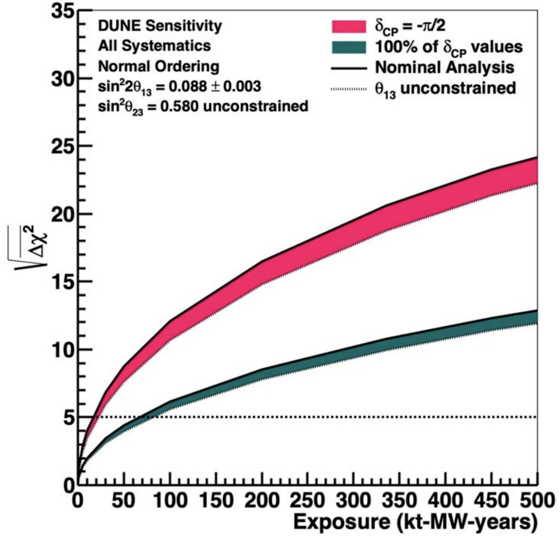
Hyper-K



Dealtry@NuPhys2023

- Hyper-K can determine the mass ordering using a combination of beam and atmospheric neutrinos
  - atmospheric neutrinos typically have longer baselines → increased matter effect
- The incorrect mass ordering can be excluded with 4-6σ in 10 years

DUNE



Marshall@NuFact2023

- DUNE can determine the mass ordering above 5σ for all values of δ_{CP} in 1-4 years
- Excellent resolution to θ_{23}, including octant discovery potential

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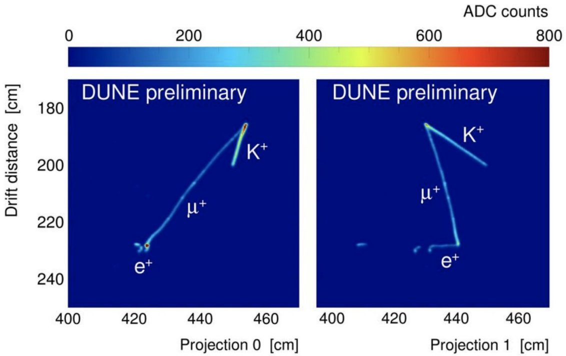
More Physics with Hyper-K and DUNE

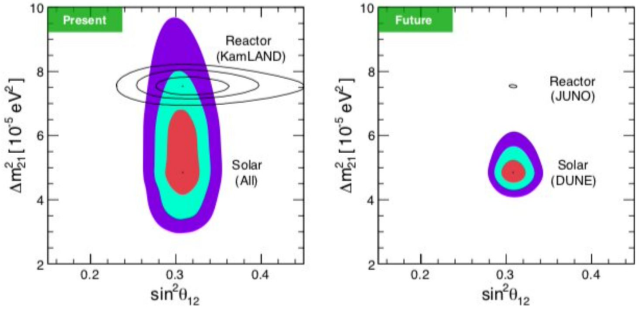
New large underground neutrino detectors with excellent imaging capabilities enable a huge physics program beyond long baseline oscillations



Complementary sensitivity to various nucleon decay channels

Study the core collapse mechanism and supernova evolution

Source: Capozzi et al.

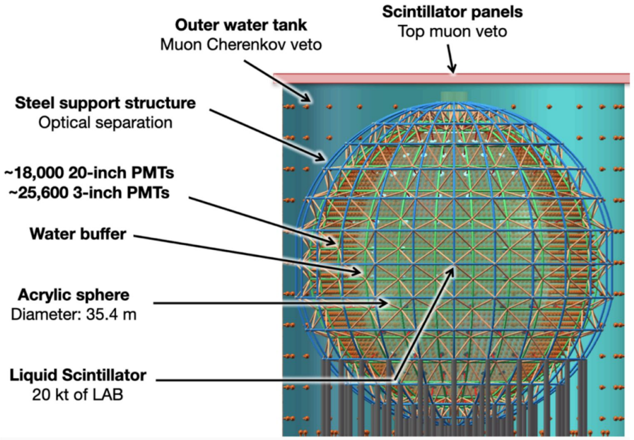


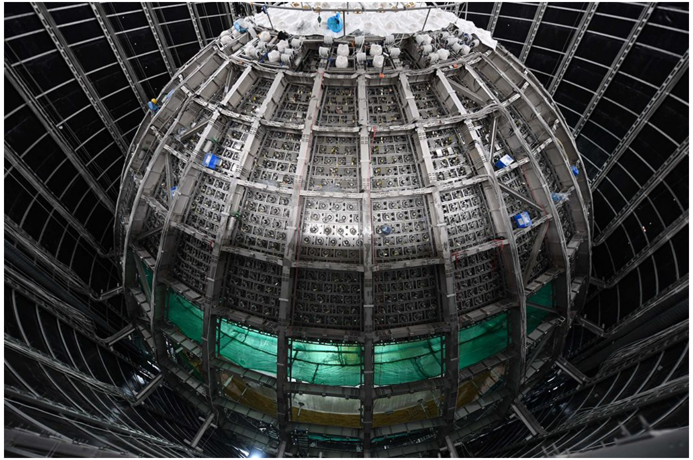
Measurement of solar neutrino oscillation parameters in comparison with other experiments (JUNO) sensitive to new physics

… and more

JUNO

- The world's largest liquid scintillator neutrino detector (20 kt, 35 m diameter)
- Instrumented with 43k PMTs for 75% photo-cathode coverage
- Aiming at 3% energy resolution
- Undergoing construction in Kaiping, South China
- Observing reactor neutrinos at 53 km baseline
  - Will also detect solar, atmospheric and geo neutrinos
- Expect data taking to begin soon





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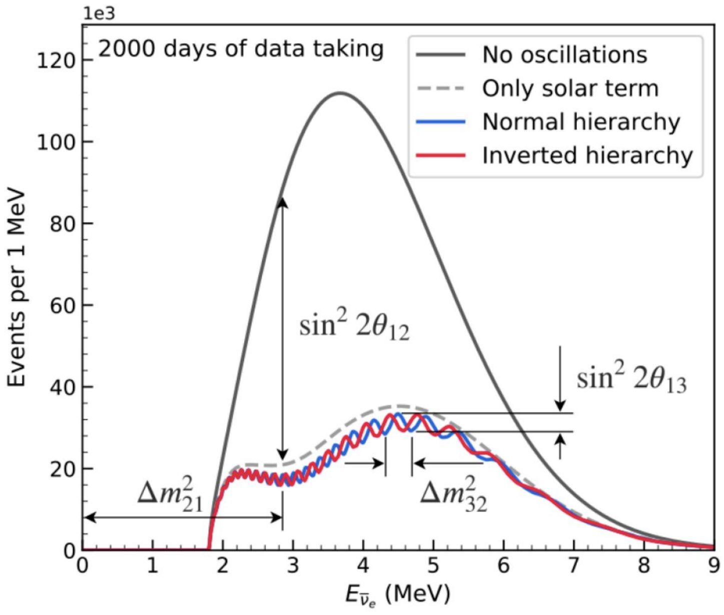
JUNO Physics Potential

- Simultaneous observation of two oscillation modes driven by (θ_{12}, Δm^2_{21}) and (θ_{13}, Δm^2_{31}) for the first time

- Optimized baseline to determine the Neutrino Mass Ordering via reactor disappearance
  - vacuum oscillation driven, independent of θ_{23} and δ_{CP}
  - This is complementary to long baseline accelerator or atmospheric neutrino experiments, dominated by matter effects

- JUNO projects that measurements of $\sin^2 2\theta_{12}$, Δm^2_{21}, and Δm^2_{32} will reach ~1% precision in six years of data taking



Source: Snowmass NF01 Topical Group Report, 2022

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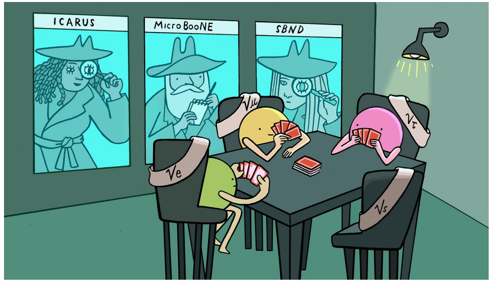
Let’s talk about anomalies:



Are neutrinos responsible for matter-antimatter asymmetry?

Are there > 3 flavours of neutrinos?

How do neutrinos get their mass?
What is their absolute mass?
What is the mass ordering?

Can we probe other BSM physics with neutrino detectors?

What can we learn about the Universe with neutrinos as messengers?

Motivation for Sterile Neutrino Searches (last decade)

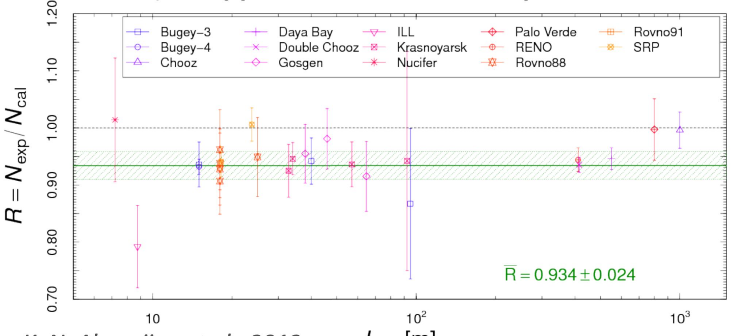
- Sterile neutrinos motivated by anomalies observed in neutrino experiments at very short baselines (L/E ~ 1 km/GeV), i.e. before 3-flavor oscillations set in
  - $\bar{\nu}_e$ disappearance in reactor experiments
  - ν_e disappearance in source calibrations of solar ν experiments
  - Appearance of ν_e and $\bar{\nu}_e$ in neutrino beam experiments
  - but no anomalies in ν_μ disappearance experiments so far

credit: A. Fava

Experiment	Type	Channel	Significance
LSND	DAR accelerator	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8 σ
MiniBooNE	SBL accelerator	$\nu_\mu \rightarrow \nu_e$	4.5 σ
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.8 σ
GALLEX/SAGE	Source – e capture	ν_e disappearance	2.8 σ
Reactors	β decay	$\bar{\nu}_e$ disappearance	3.0 σ

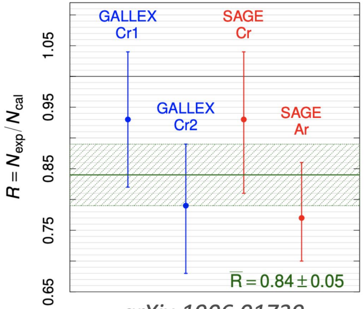
- Believed that observations can possibly be explained by sterile neutrinos (1 or more) with a Δm^2 of ~ 1 eV^2.

$\bar{\nu}_e$ disappearance in reactor experiments



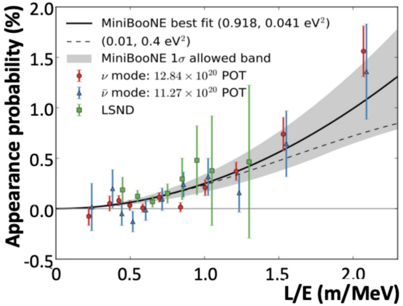
K. N. Abazajian et al., 2012

ν_e disappearance in solar ν experiments



arXiv:1906.01739

ν_e and $\bar{\nu}_e$ appearance in neutrino beam experiments

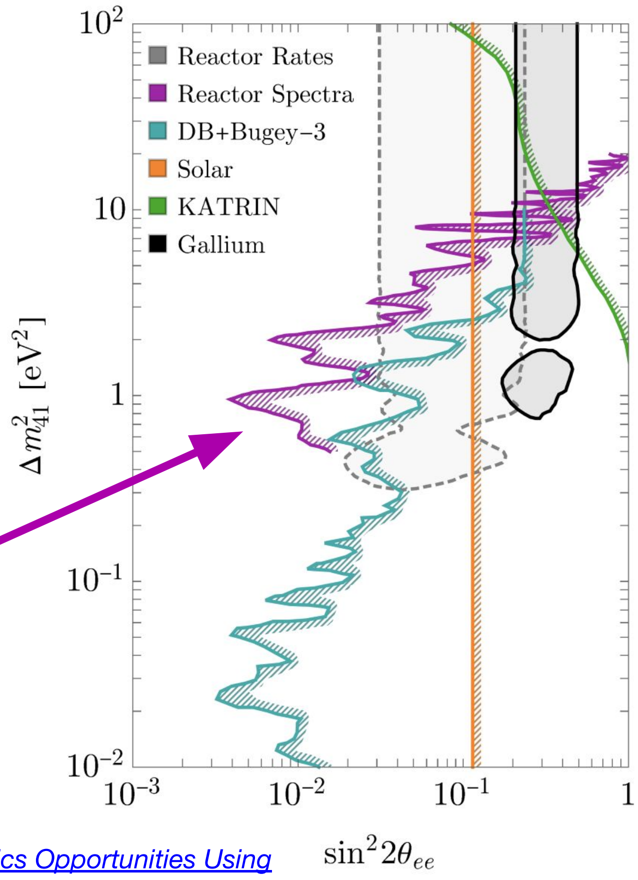


Phys. Rev. Lett., vol. 121, no. 22, p. 221801, 2018

Reactor Antineutrino Anomaly status

- $\bar{\nu}_e$ rate deficit of ~ 6% (known as Reactor Antineutrino Anomaly (RAA)) established by more recent measurements from STEREO, Double Chooz, Daya Bay, RENO
- New data suggests that ^{235}U beta spectrum underlying all rate predictions is largely responsible for the RAA
This weakens sterile neutrino hypothesis
- New spectral measurements (in particular ratios of antineutrino spectra at different baselines) are less sensitive to input flux model

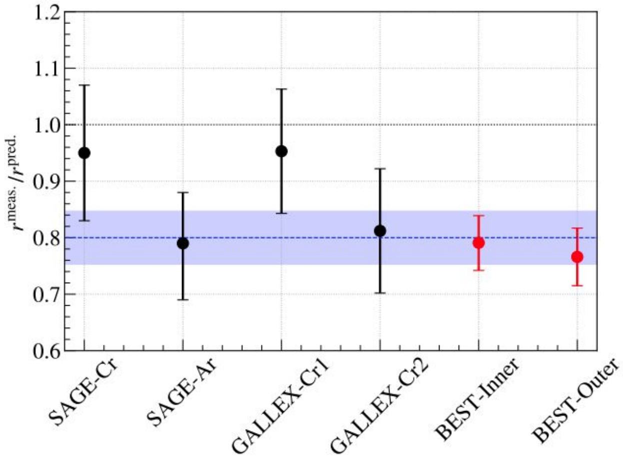
→ ***No significant evidence for sterile neutrino hypothesis so far***

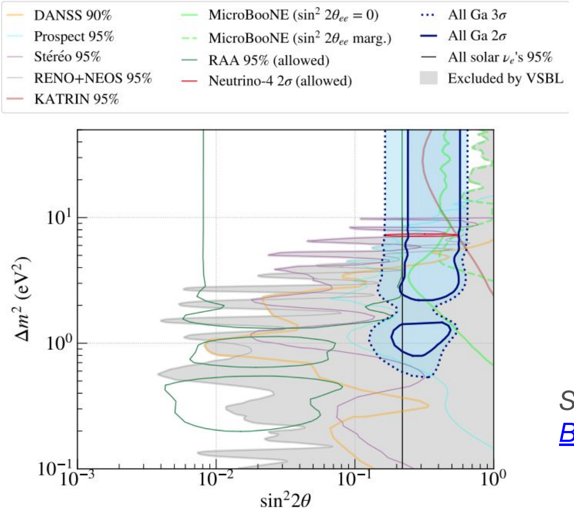


Source: [HEP Physics Opportunities Using Reactor Antineutrinos: A Snowmass 2021 White Paper Submission, 2022]

Gallium anomaly status

- BEST experiment confirms 20% deficit in ratio of measured and predicted ^{71}Ge production rates in all Ga source experiments, bringing the significance of the anomaly to 5-6σ



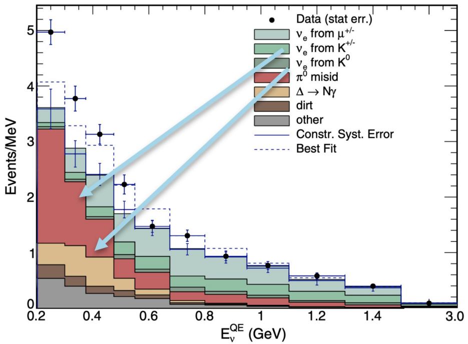


Source:
[Barinov et al., 2022]

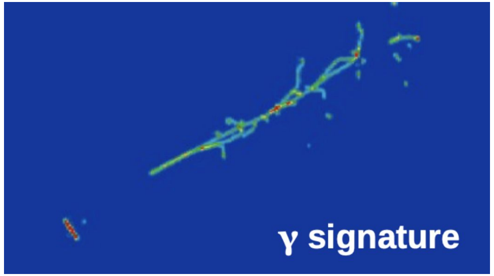
- However:
  - No distance dependence in BEST measurements → no hint for oscillatory behavior
  - tension between the Gallium Anomaly and other experiments in the 3+1 scenario

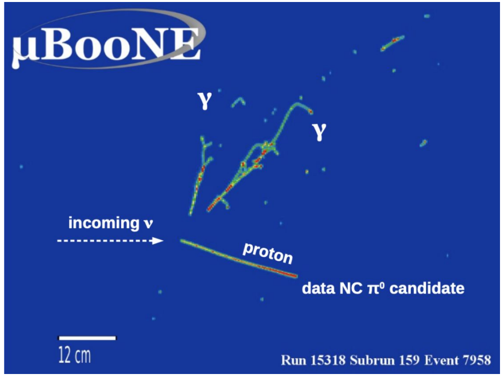
Accelerator Low Energy Excess (LEE) Anomaly

- **MicroBooNE** designed to probe the anomaly in ν_e and $\bar{\nu}_e$ appearance measurements in neutrino beam experiments, specifically **MiniBooNE**:
  - same beam
  - same baseline
  - but different detection technology



PHYSICAL REVIEW LETTERS 121, 221801 (2018)





MicroBooNE is a Liquid Argon TPC

- Particle ID through calorimetry & great resolution
- electron/photon separation possible

MiniBooNE result limited by Particle ID capabilities of the detector

- electrons and photons both show as fuzzy rings in a Cherenkov detector like MiniBooNE

MicroBooNE Initial Results

→ *See MicroBooNE (Wu) talk tomorrow*

Single γ channels:

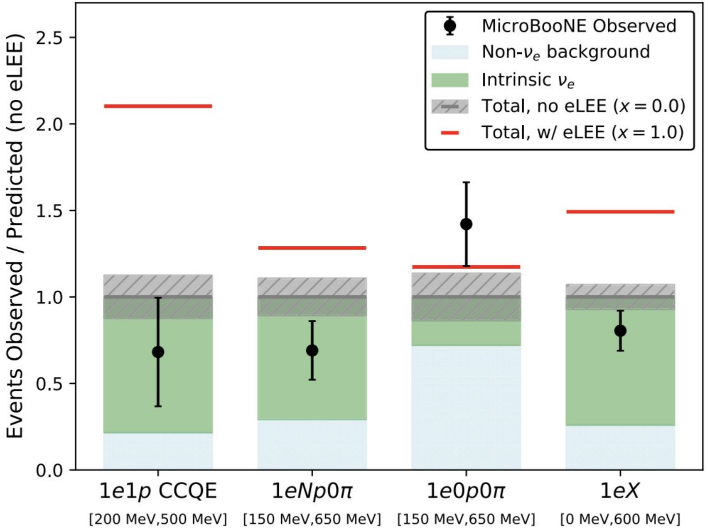
- No excess in NCΔ → 1γ + 0p and NCΔ → 1γ + 1p channels

  → **Photons from NCΔ → Nγ as sole explanation for the LEE is rejected at > 90% CL**

Single e channels:

- No significant excess in 1e1p, 1eNp, 1e0p0π, and 1eX channels

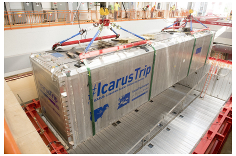
  → **single electrons from ν_e as sole explanation for the LEE is rejected at > 97% CL**



Source: PRL 128, 241801 (2022)

Upcoming MicroBooNE results will use the final dataset (~ 2x more statistics) and a combination of BNB and NuMI beam

Short Baseline Neutrino (SBN) Program at Fermilab

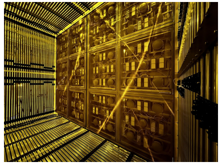


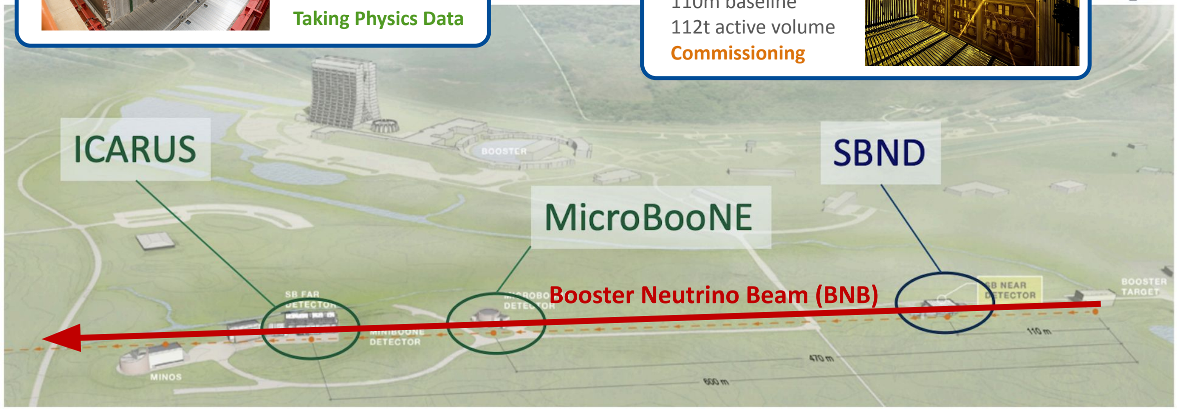
ICARUS

600m baseline
470t active volume
Taking Physics Data

SBND

110m baseline
112t active volume
Commissioning



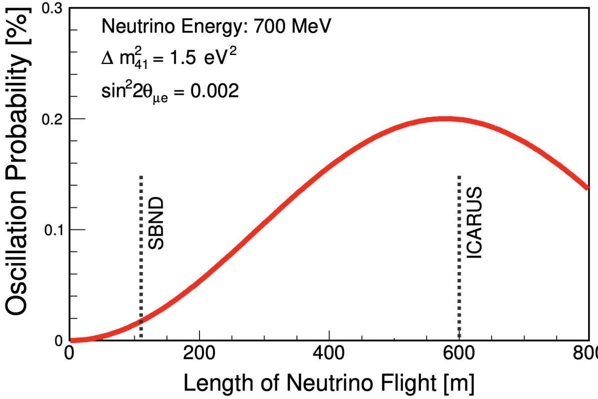


Relative Neutrino Interaction Rates	3.3	1	23
ν_μ-CC interactions per 1×10^{20} POT	90k	27k	625k
ν_e-CC interactions per 1×10^{20} POT	0.6k	0.2k	4k

All detectors sampling the *same neutrino beam* at different distances

Same nuclear target (Ar) and *detector technology* (LArTPC)

Reduces systematic uncertainties to the %-level

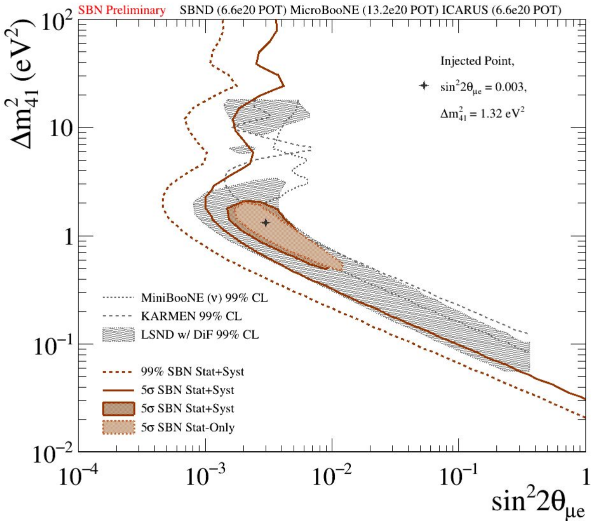


Fermilab

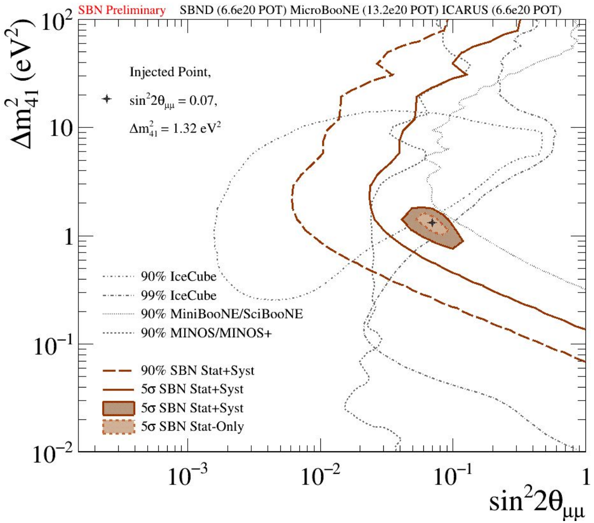
SBN Oscillation Potential

- SBND + ICARUS can cover the parameter space favored by past anomalies with 5σ significance
- **Search for appearance of ν_e and disappearance of ν_μ within the same experiment is key**
  - current results show a 4.7σ tension between ν_e appearance and ν_μ disappearance channels

ν_e appearance



ν_μ disappearance



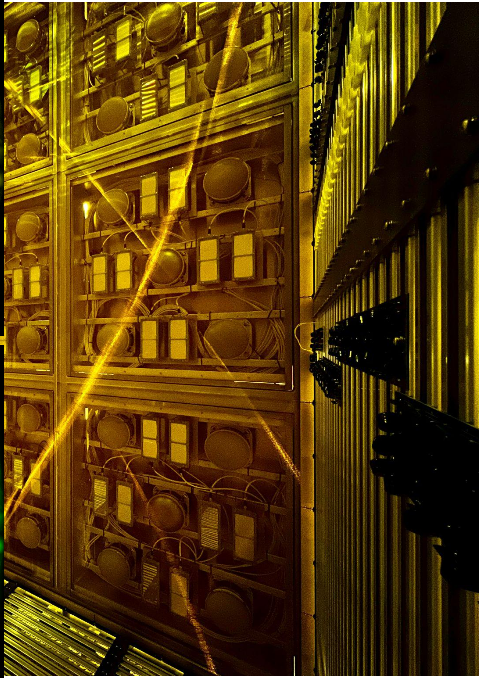
SBND under Commissioning

SBND completed construction in January.

SBND under Commissioning

Feb 7, 2024

Feb 18, 2024



The cryostat is right now being filled with liquid Argon and will be ready to power on the detector in a couple of weeks!

Fermilab

Alternative explanations

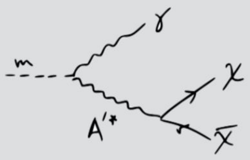
- With recent results, a 3+1 or 3+N flavor conversion hypothesis as joint explanation for the observed anomalies is weakening
  - but most observed anomalies remain to be explained!

- Many BSM physics ideas have been suggested that can explain one or more of the observations
  - current experiments exploring alternative explanations with high sensitivity

- New experiments continue to probe 3+N flavor conversion hypothesis
  - in addition to categories previously discussed, this includes also **meson decay-at-rest** experiments, **muon decay-in-flight** experiments, **beta decay and electron capture** experiments

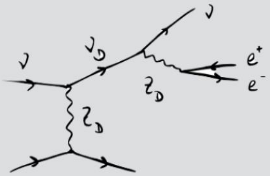
→ See BeEST (Lennarz) and other talks today/tomorrow

Light Dark Matter



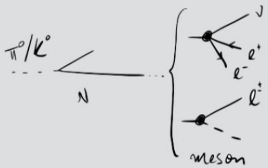
Romeri Kelley Machado PRD 2019

Dark Neutrinos



Bertuzzo Jana Machado Zukanovich PRL 2018, PLB 2019
Arguelles Hostert Tsai PRL 2019
Ballett Pascoli Ross-Lonergan PRD 2019
Ballett Hostert Pascoli PRD 2020

Heavy Neutral Leptons



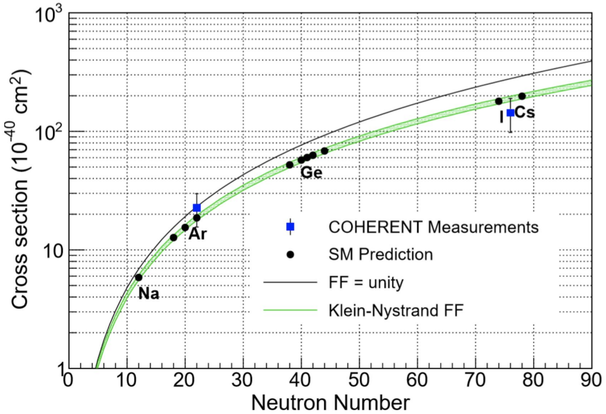
Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021

…

Neutrino Cross Section Measurements

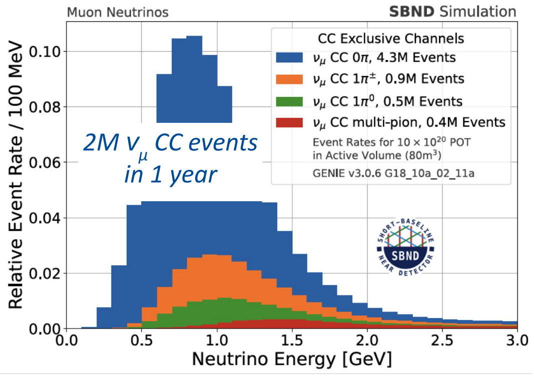
→ *See FASERν (Ohashi), SND@LHC (Conaboy), MINERvA (Mehmood) and MicroBooNE (Wu) talks tomorrow*

- Refined neutrino cross section measurements are important to develop nuclear models and to constrain uncertainties in precision neutrino experiments
- Many recent measurements have been presented by T2K, NOvA, MINERvA, MicroBooNE

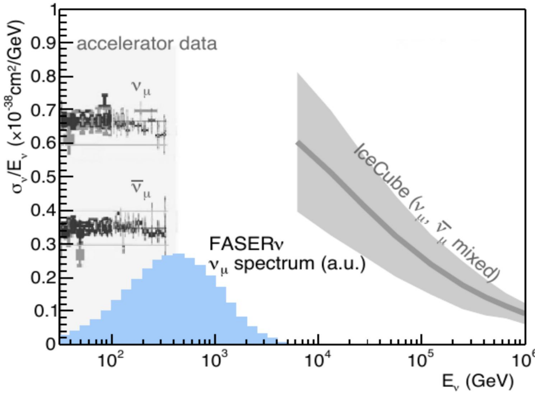


Source: arXiv:2003.10630 (2021)

First measurements of CEvNS by COHERENT and other experiments, extending cross section measurements into sub-keV energies



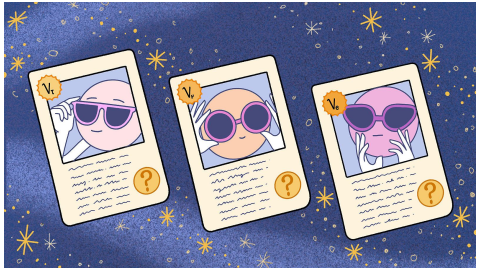
Huge datasets expected from SBND and other future short baseline and near detectors



Source: Kose@TAU2023

Cross section measurements exploiting intense neutrino flux of forward experiments at the LHC with FASERν, SND@LHC extending the energy range of current data into TeV energies

We talked mostly about these:



Are neutrinos responsible for matter-antimatter asymmetry?

Are there > 3 flavours of neutrinos?

How do neutrinos get their mass?
What is their absolute mass?
What is the mass ordering?

Can we probe other BSM physics with neutrino detectors?

What can we learn about the Universe with neutrinos as messengers?

Now let's talk about these:

Are neutrinos responsible for matter-antimatter asymmetry?

Are there > 3 flavours of neutrinos?

How do neutrinos get their mass?

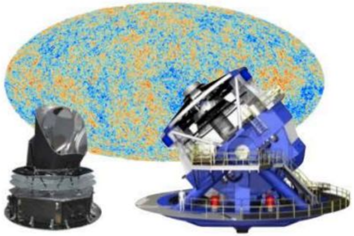
What is their absolute mass?

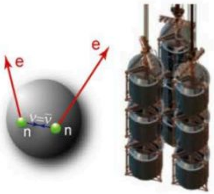
What is the mass ordering?

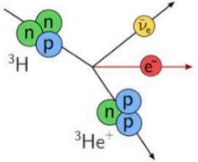
Can we probe other BSM physics with neutrino detectors?

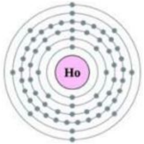
What can we learn about the Universe with neutrinos as messengers?

Neutrino Mass Measurements







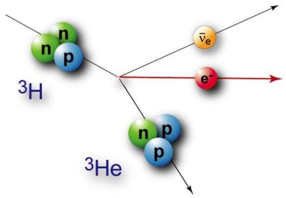


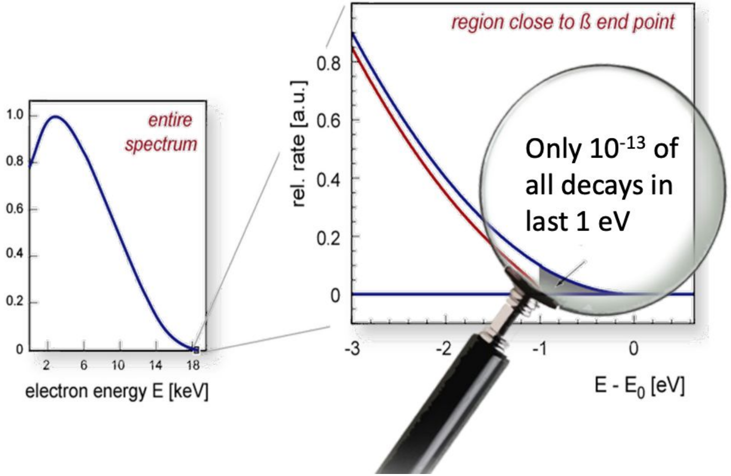
	Cosmology	Search for 0νββ	β-decay & electron capture
Observable	$M_\nu = \sum_i m_i$	$m^2_{\beta\beta} = \left\lvert \sum_i U^2_{ei}\, m_i \right\rvert^2$	$m^2_\beta = \sum_i \lvert U_{ei} \rvert^2 m^2_i$
Present upper limit	~0.1 – 0.6 eV	~0.1 – 0.4 eV	~~2 eV~~ **0.8 eV**
Potential: near-term (long-term)	60 meV (15 meV)	50 – 200 meV (20 – 40 meV)	200 meV (40 – 100 meV)
Model dependence	Multi-parameter cosmological model	- Majorana nature of ν, lepton number violation - BSM contributions other than m(ν)? - Nuclear matrix elements	**Direct**, only kinematics; no cancellations in incoherent sum

Source: K. Valerius

Results from KATRIN

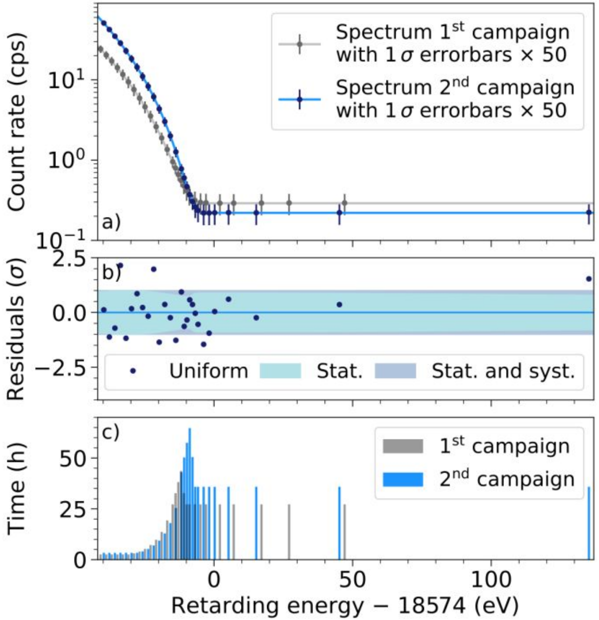
- endpoint measurement of the tritium β-spectrum with an electrostatic filter (MAC-E)





Source: [Mertens@TAUP2023]

→ *See KATRIN (Block) talk tonight*



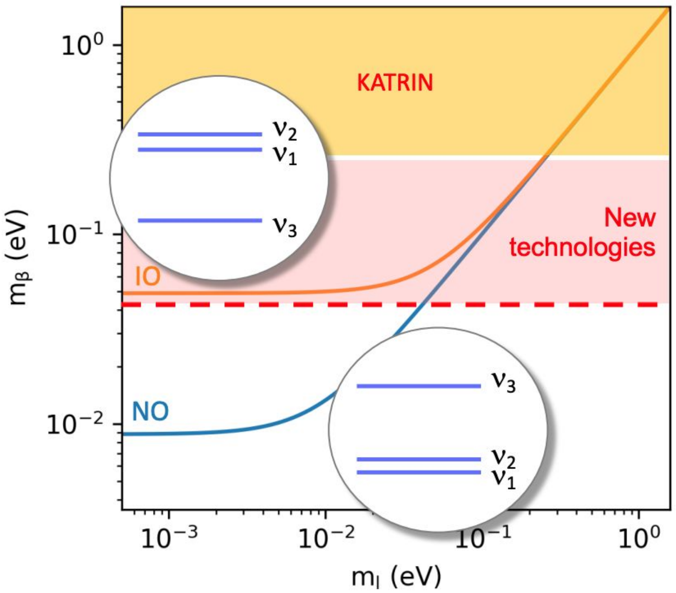
Source: [Nat. Phys. 18, 160–166 (2022)]

- Combined result from 1st and 2nd campaign: **m_ν < 0.8 eV (90% CL)**

- Expected sensitivity of final result: **m_ν < 0.3 eV (90% CL)**

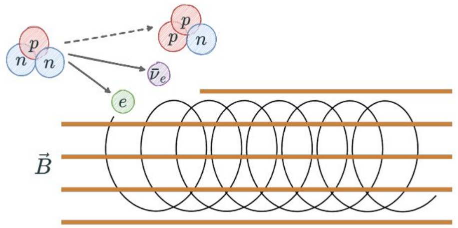
Neutrino Mass Measurements

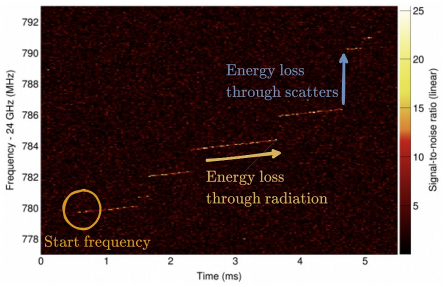
Covering the Inverted Ordering requires new technologies:



Source:
[Mertens@TAUP2023]

- Cyclotron Radiation Emission Spectroscopy (CRES): **Project-8, QTNM**





- Low-temperature micro-calorimetry with holmium: **ECHo, HOLMES**

Next generation experiments aim for sensitivities of $\mathbf{m_\nu < 0.05}$ **eV**

Fermilab

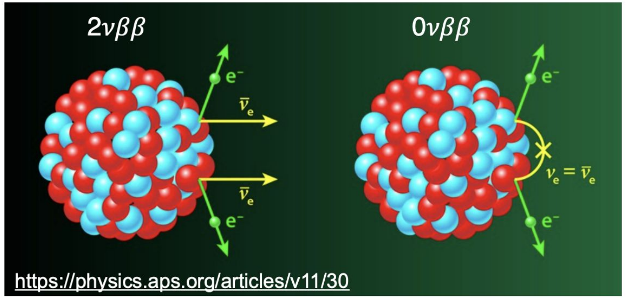
Neutrinoless double-beta decay

- Observation of 0νββ is proof that neutrinos and antineutrinos are the same object
  - only known method with plausible sensitivity to determine neutrinos are Majorana fermions

- 0νββ would be a demonstration of creation of matter without antimatter
  - direct violation of L and B-L

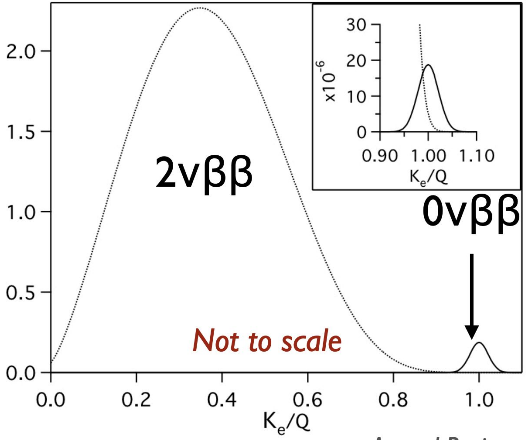
- Searches for 0νββ are a powerful experimental probe of lepton number violation (LNV) and other BSM physics

Schematic of $\beta\beta$ decay processes:



$2\nu\beta\beta$: (A,Z) -> (A, Z+2) + $2e^-$ + $2\bar{\nu}_e$

$0\nu\beta\beta$: (A,Z) -> (A, Z+2) + $2e^-$

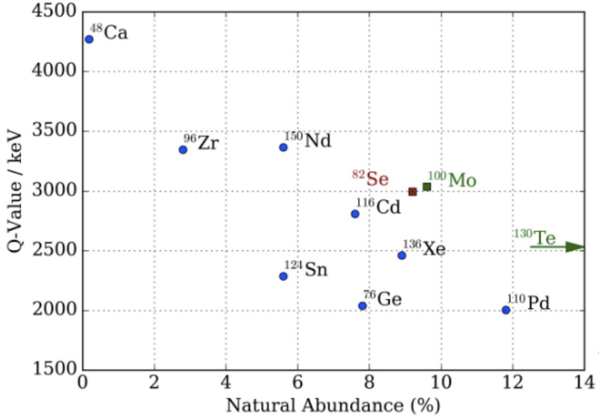


Annual Reviews: 52:115-151

Detection technologies

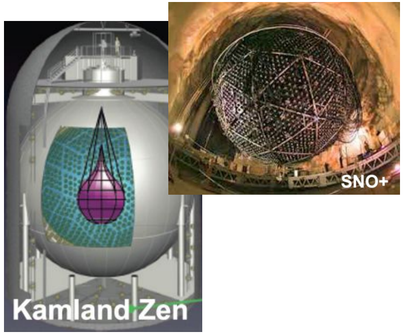
Isotope choice

2νββ with long half-life to reduce background
high Q-value → shorter half-life for 0νββ
high natural abundance
enrichment & large scale production possible



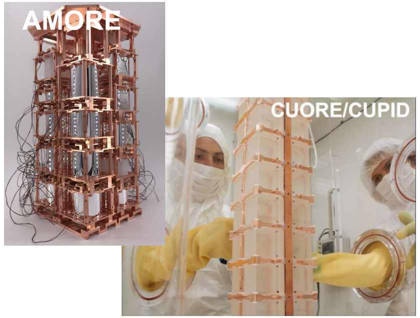
Source: *Patrick@NuPhys2023*

Liquid Scintillators

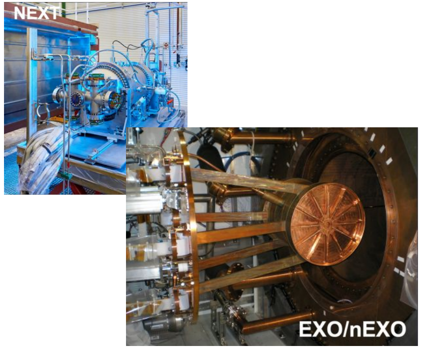


Semiconductor detectors

Cryogenic Calorimeters



Xe TPCs



(not exhaustive)

Neutrinoless double-beta decay outlook

- Most sensitive search to date for 0νββ from KamLAND-Zen: $m_{\beta\beta}$ < 36-156 meV

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}\, g_A^4 |M^{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} \; *$$

Measurement

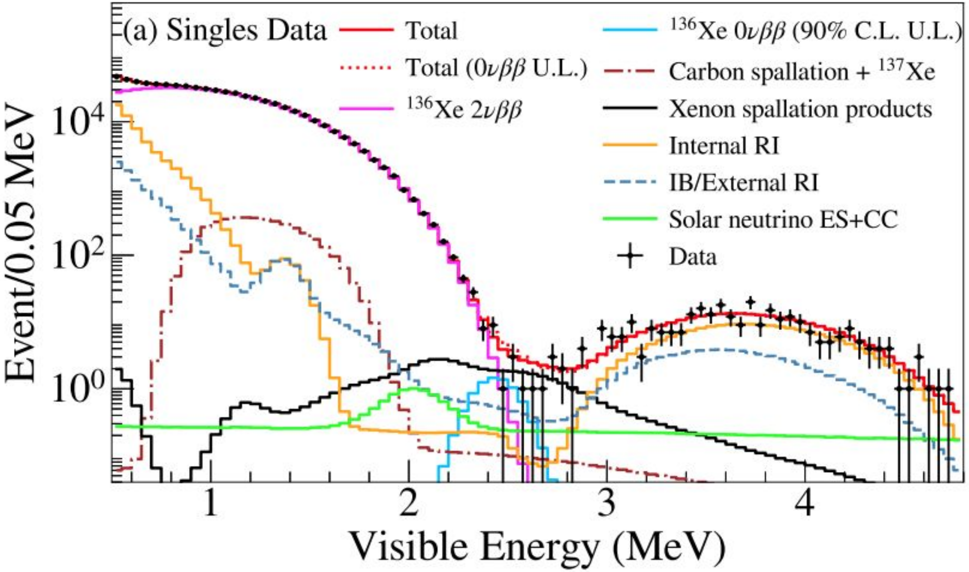
Phase space (computational)

Nuclear Matrix Element (significant theory uncertainty)

Effective Majorana Mass (model dependent)

Source: [Moore@TAUP2023]

Source: [arXiv:2203.02139v2] (2023)

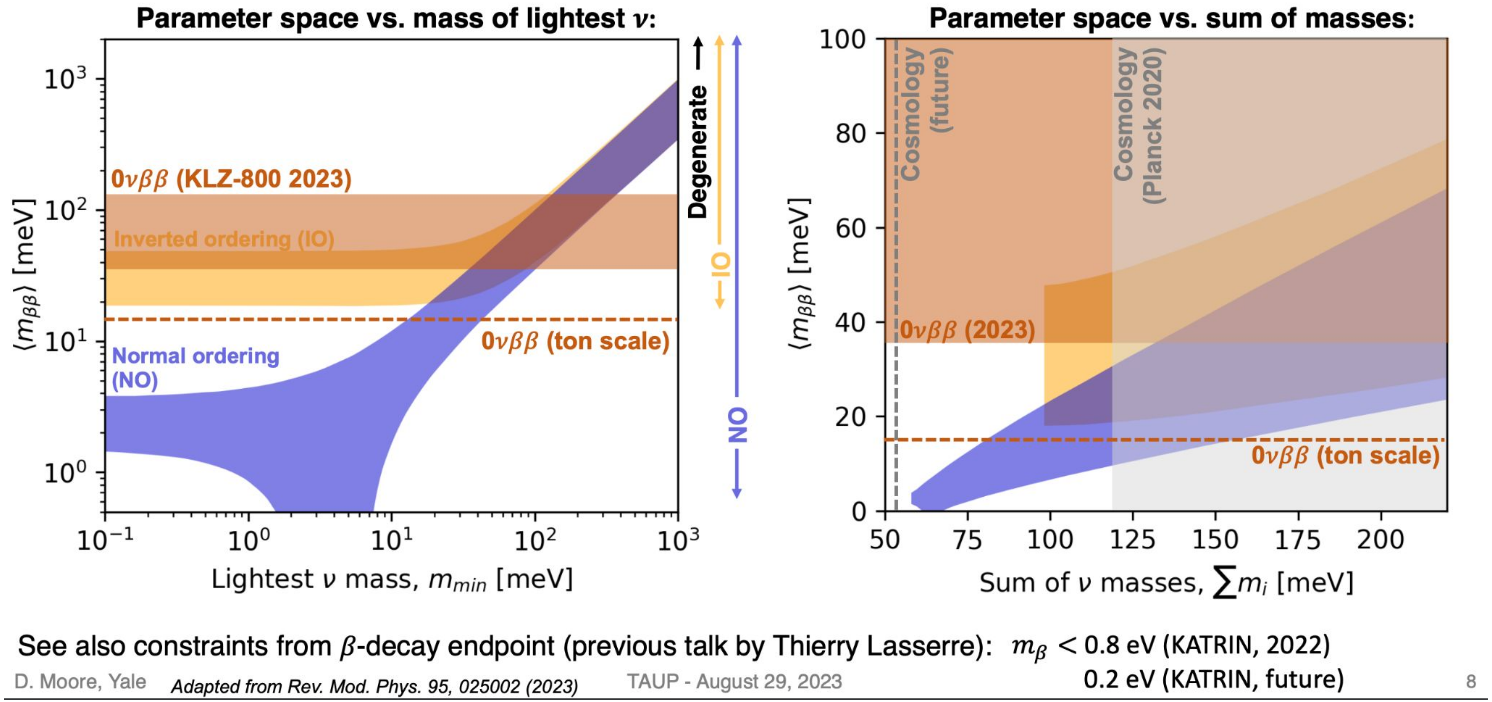


*Sensitive also to 3+N sterile neutrino oscillation scenario!

→ See KamLAND-Zen (Miyake) talk today

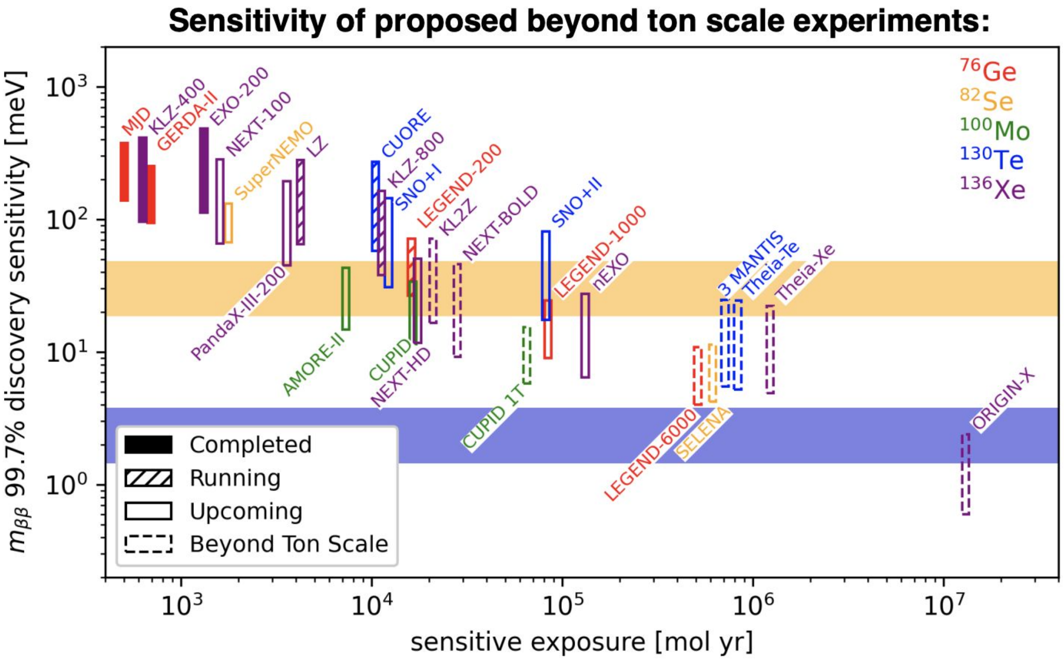
Neutrinoless double-beta decay outlook

- Most sensitive search to date for $0\nu\beta\beta$ from KamLAND-Zen: $m_{\beta\beta}$ < 36-156 meV



Source: Moore@TAUP2023

Neutrinoless double-beta decay outlook



Plot adapted from arXiv:2212.11099,
https://indico.cern.ch/event/1242655/contributions/5377665/
R. Saldanha (private comm.)

TAUP - August 29, 2023 30

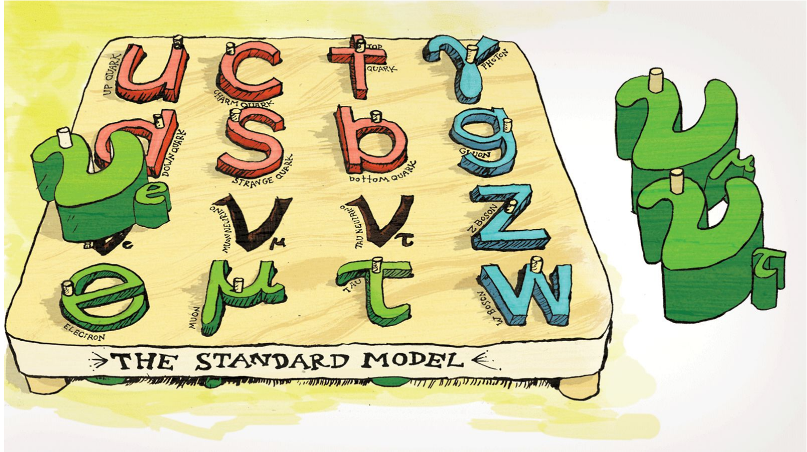
Several new ton-scale experimental efforts ongoing

- Sensitivity will cover inverted ordering!

Source:
[Moore@TAUP2023]

→ See KamLAND-Zen (Miyake), LEGEND (Bos), CUORE (Kowalski), CUPID (Torres) and AMoRE (Kim) talks today/tomorrow

Summary



- Neutrino physics holds answers to several open questions in and beyond the Standard Model
- Current and future oscillation experiments probing the three-flavor model and beyond from all angles
- Coming neutrino mass and $0\nu\beta\beta$ experiments closing in on mass mechanism and absolute scale
- Large & sensitive (neutrino) experiments are always good for surprises!
- **Looking forward to exciting talks at this conference!**

Backup Material

Category	Model	Signature	Anomalies				References
			LSND	MiniBooNE	Reactor	Gallium	
Flavor Conversion: Transitions	(3+N) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [19–22]
	(3+N) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[23, 24]
	(3+N) w/ sterile decay	$\nu_4 \to \phi \nu_e$	✓	✓	✓	✓	[25–29]
Flavor Conversion: Matter Effects	(3+N) w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	✗	✗	[30–34]
	(3+N) w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[35]
Flavor Conversion: Flavor Violation	lepton-flavor-violating μ decays	$\mu^+ \to e^+ \nu_\alpha \overline{\nu_e}$	✓	✗	✗	✗	[36–38]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to e \phi A$	✓	✓	✗	✗	[39]
Dark Sector: Decays in Flight	transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	✗	✗	[40]
	dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-)$ or $N \to \nu(X \to \gamma\gamma)$	✗	✓	✗	✗	[41]
Dark Sector: Neutrino Scattering	neutrino-induced up-scattering	$\nu A \to NA$, $N \to \nu e^+ e^-$ or $N \to \nu\gamma\gamma$	✓	✓	✗	✗	[42–51]
	neutrino dipole up-scattering	$\nu A \to NA$, $N \to \nu\gamma$	✓	✓	✗	✗	[52–59]
Dark Sector: Dark Matter Scattering	dark particle-induced up-scattering	γ or e^+e^-	✗	✓	✗	✗	[60]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[60]

Source: Snowmass NF02 Topical Group Report, 2021

<table>
<tr><th>Source</th><th>Flavor Conversion:
3+N Oscillations</th><th>Flavor Conversion:
Anomalous Matter Effects</th><th>Flavor Conversion:
Lepton Flavor Violation</th><th>Dark Sector:
Decays in Flight</th><th>Dark Sector:
Neutrino-induced Up-scattering</th><th>Dark Sector:
Dark-particle-induced Up-scattering</th></tr>
<tr><td>Reactor</td><td>DANSS Upgrade, JUNO-TAO, NEOS-II, Neutrino-4 Upgrade, PROSPECT-II</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Radioactive Source</td><td>BEST-2, IsoDAR, THEIA, Jinping</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Atmospheric</td><td colspan="2">IceCube Upgrade, KM3NET, ORCA and ARCA, DUNE, Hyper-Kamiokande, THEIA</td><td></td><td></td><td colspan="2">IceCube Upgrade, KM3NET, ORCA and ARCA, DUNE, Hyper-Kamiokande, THEIA</td></tr>
<tr><td>Pion/Kaon Decay-At-Rest</td><td>$JSNS^2$, COHERENT, Coherent-Captain-Mills, KPIPE</td><td></td><td>$JSNS^2$, COHERENT, Coherent-Captain-Mills, KPIPE, PIP2-BD</td><td></td><td></td><td>COHERENT, Coherent-Captain-Mills, KPIPE, PIP2-BD, SBN-BD</td></tr>
<tr><td>Beam Short Baseline</td><td>SBN</td><td></td><td></td><td colspan="3">SBN, FASERν, SND@LHC, FLArE</td></tr>
<tr><td>Beam Long Baseline</td><td colspan="3">DUNE, Hyper-Kamiokande, ESSnuSB</td><td colspan="3">DUNE, Hyper-Kamiokande, ESSnuSB</td></tr>
<tr><td>Muon Decay-In-Flight</td><td colspan="3">nuSTORM</td><td></td><td>nuSTORM</td><td></td></tr>
<tr><td>Beta Decay and Electron Capture</td><td>KATRIN/TRISTAN, Project-8, HUNTER, BeEST, DUNE (^{39}Ar), PTOLEMY, $2\nu\beta\beta$</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Source: Snowmass NF02 Topical Group Report, 2021

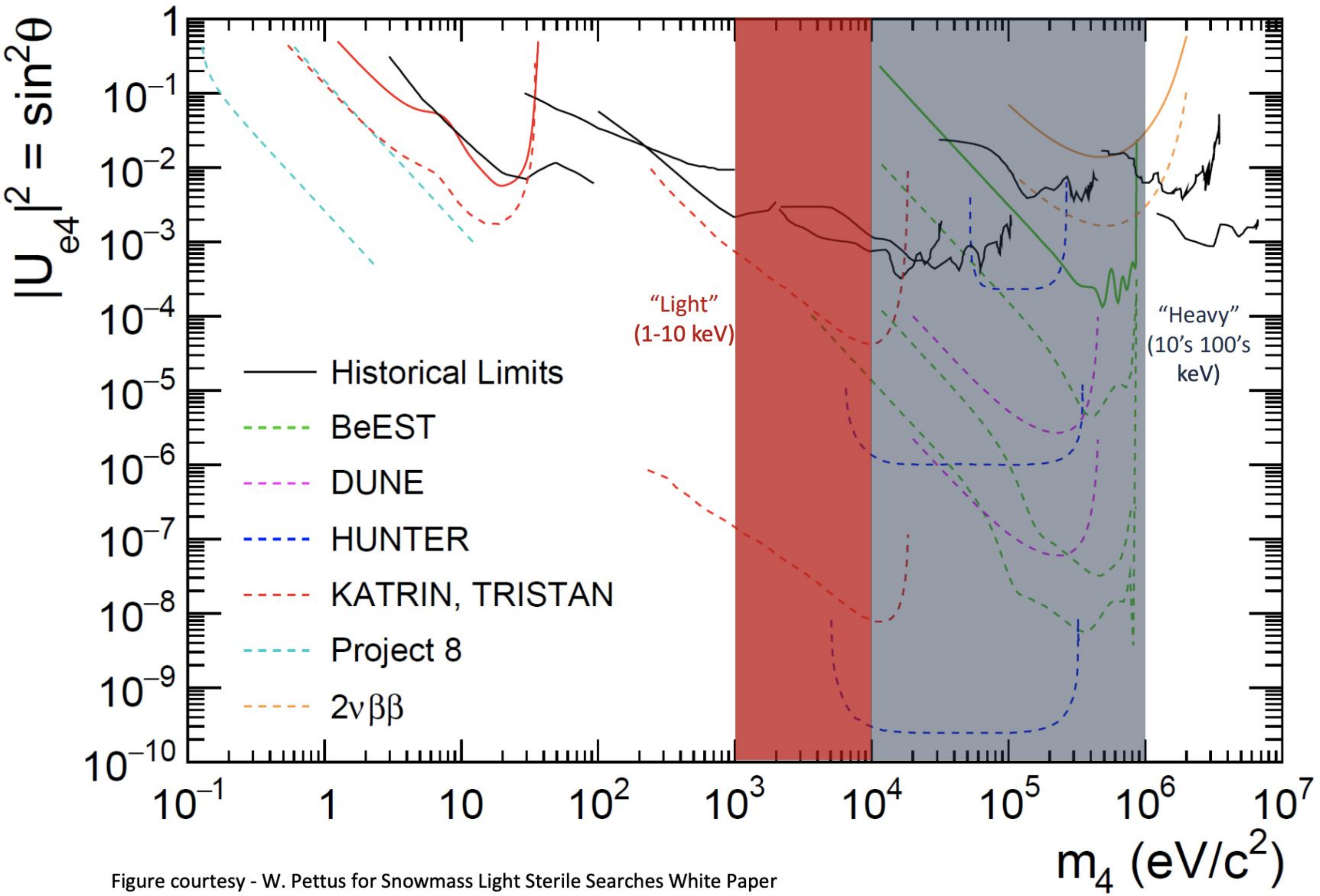


Figure courtesy - W. Pettus for Snowmass Light Sterile Searches White Paper

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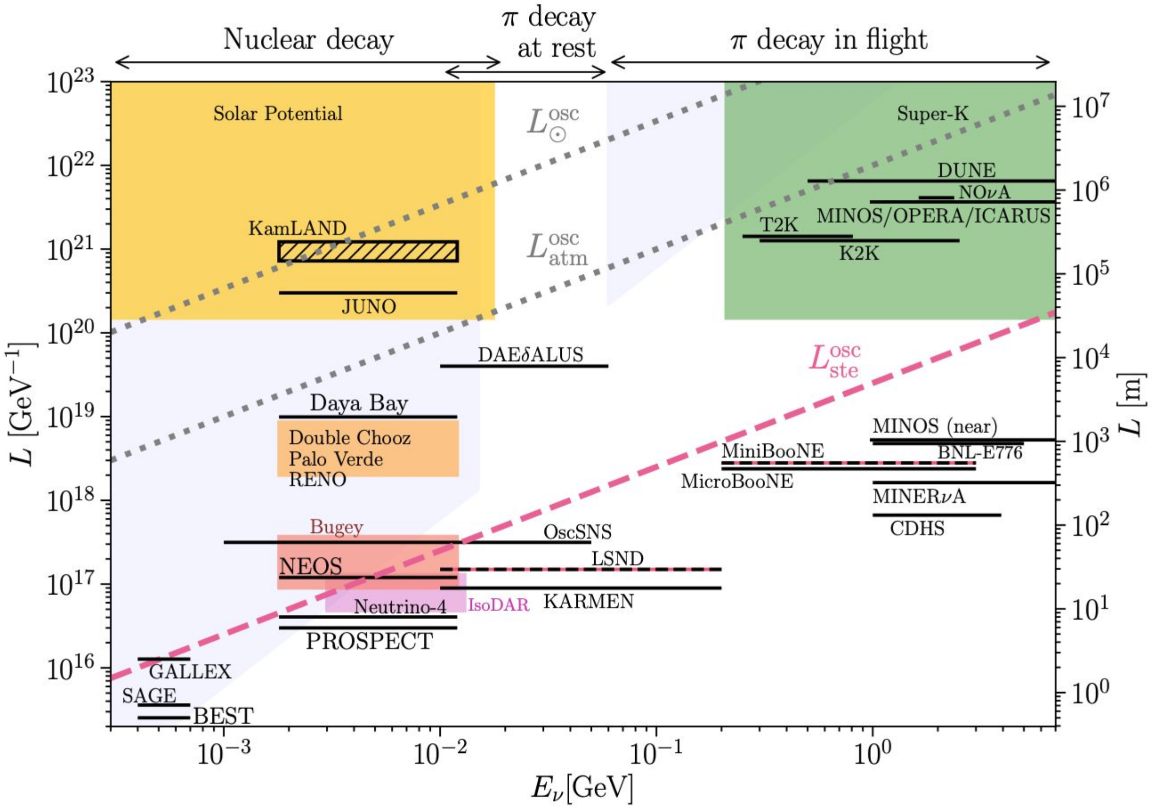
Landscape of Neutrino Oscillation Experiments



(not complete)

Source: [HEP Physics Opportunities Using Reactor Antineutrinos: A Snowmass 2021 White Paper Submission, 2022]

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