Neutrino Experiments in 2026

Peter Shanahan
SAC Neutrino Working Group
5 April 2018

Overview

- Request from SAC Neutrino WG was to present the future
  - What we will know in 2026

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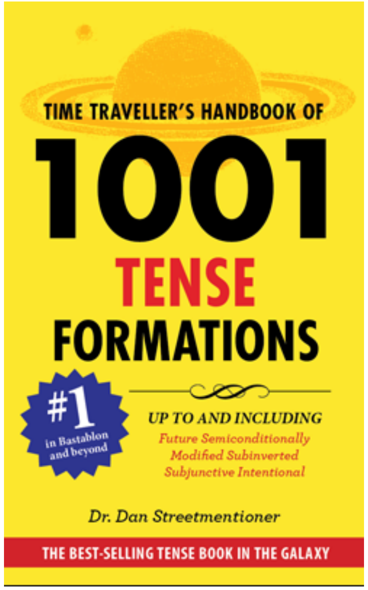

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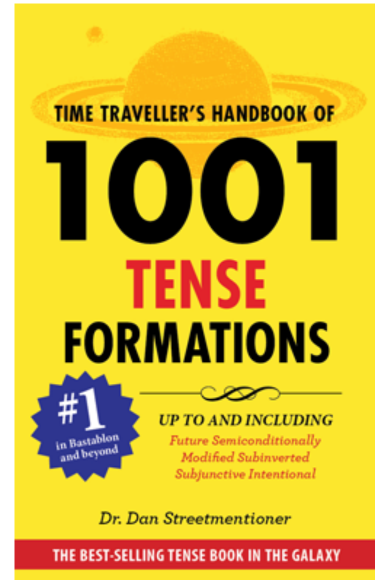


- Caveat: Prognostications fall in a spectrum

Informed Guess

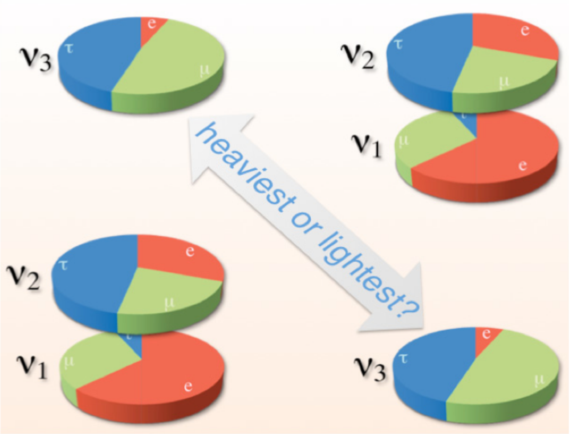
Guess

The Important Questions

- Explicit or implicit in the P5 Science Driver:

  Understand the Physics Associated with Neutrino Mass

  - What is the origin of neutrino masses?
  - What is the structure of the mixing?
    - Is θ_{23} maximal ($\pi/4$)?
      If not, what is the octant? Lower: $\theta_{23}<\pi/4$ more ν_τ in ν_3, Upper: $\theta_{23}>\pi/4$, more ν_μ in ν_3
  - What is the ordering of the masses?
    - ν_3 heavier (normal) or heavier (inverted) than ν_1, ν_2



  - What are the (absolute) masses?
  - Do neutrinos violate CP symmetry?
    - CP-phase δ nontrivial?
  - Are neutrinos their own antiparticle?
    - Majorana Particles vs. Dirac
  - Are there additional neutrino types and interactions?
    - BSM interactions, sterile neutrinos?

The Important Questions and Long-baseline Oscillations

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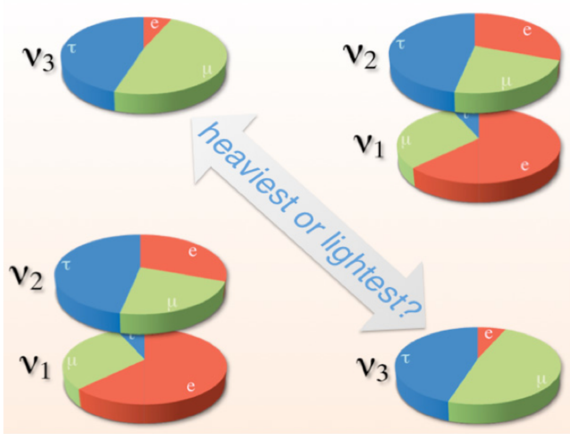

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The Open Questions and Long-baseline Oscillation Experiments

- Long-baseline Muon Neutrino Disappearance
  - Primarily sensitive to $|\Delta m^2_{31}|$, $\sin^2(2\theta_{23})$
  - Not sensitive to Mass Hierarchy
  - Probes maximality/degree of non-maximality, but not octant of θ_{23}
  - Not sensitive to CP violation (unless CPT is violated)
- Electron (anti)Neutrino Appearance
  - Sensitive to

    CP violation through effect of δ_{CP}

    Mass Hierarchy via the matter effect

    θ_{23} octant due to $\sin(\theta_{23})$ in leading term of appearance probability

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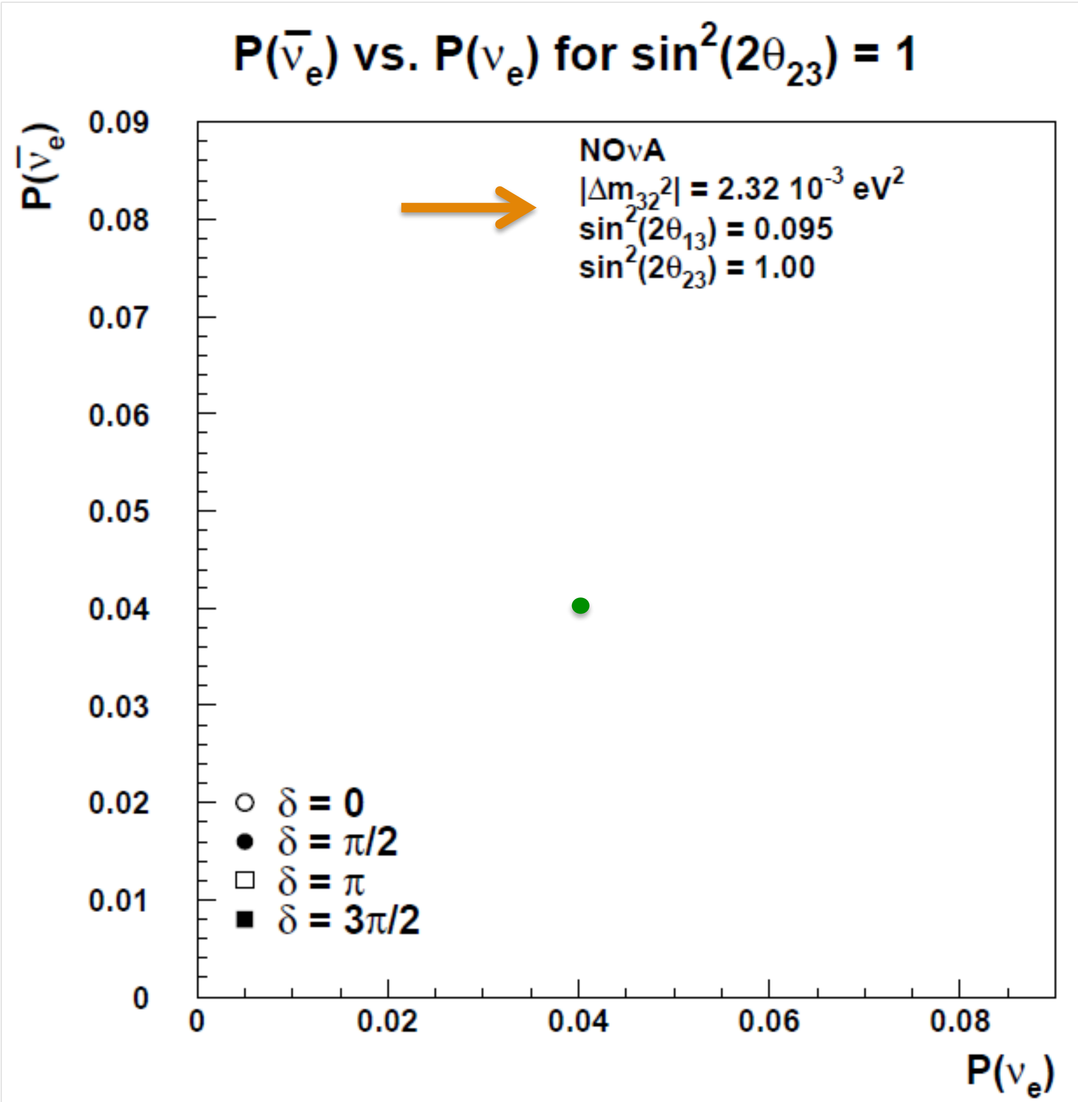
ν_e and $\bar{\nu}_e$ Appearance Probabilities

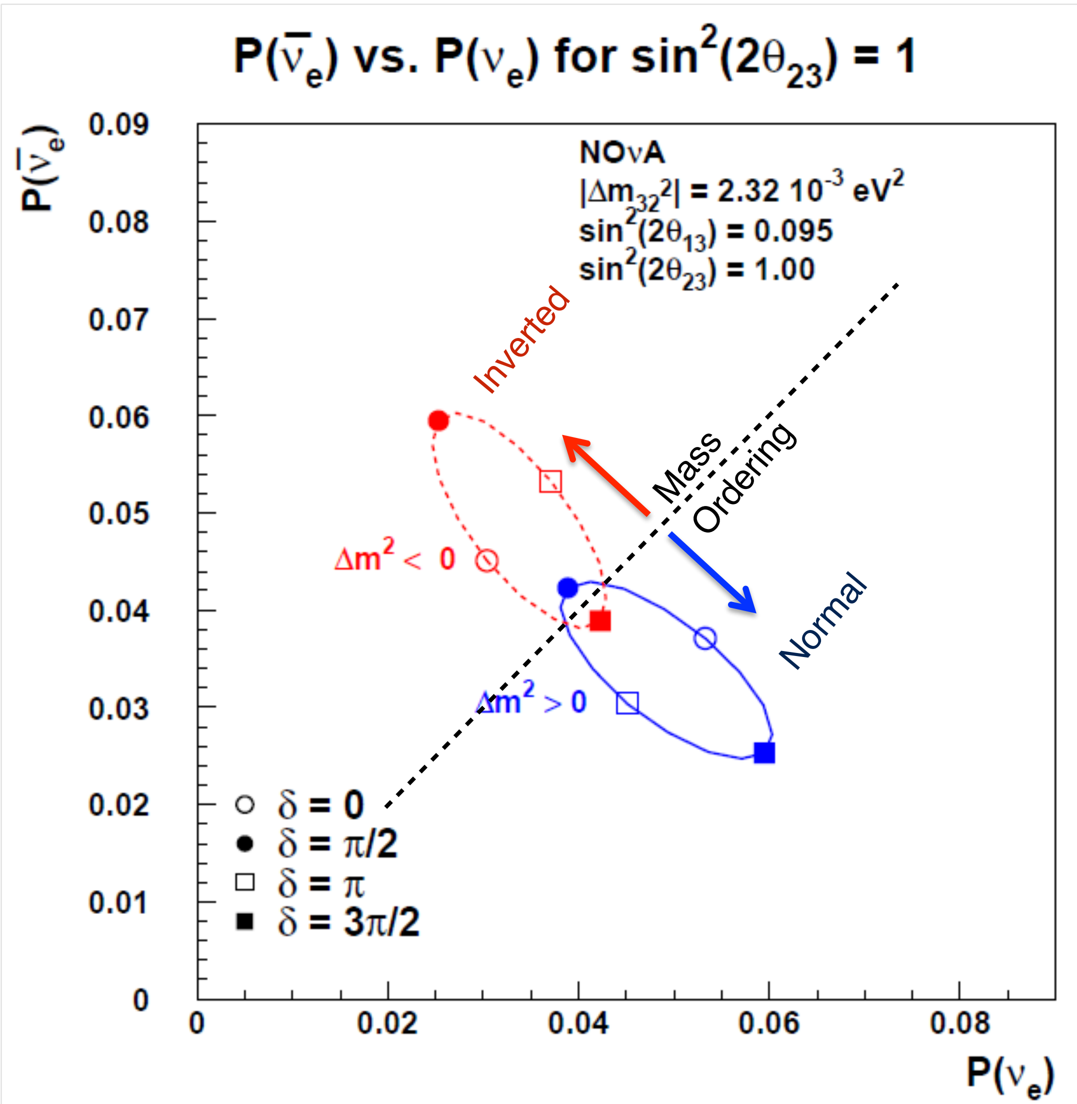


Comparison of neutrino and antineutrino appearance for a specific baseline and energy

Assuming

- **No Matter Effect**
- **No CP Violation**
- **Maximal μ-τ mixing**

CP Violation and Neutrino Mass Ordering

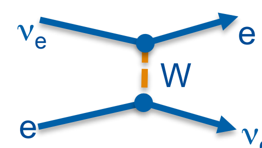


CP Violation

- *CPT theorem requires ν_μ and $\bar{\nu}_\mu$ disappearance to be equal in vacuum*
- ν_e appearance probabilities vary on an ellipse with δ_{CP}

Mass Ordering

- *ν_μ disappearance largely sensitive to $|\Delta m^2|$*
- ν_e appearance is sensitive to sign(Δm^2) via matter effect
  - due to presence of electrons in matter

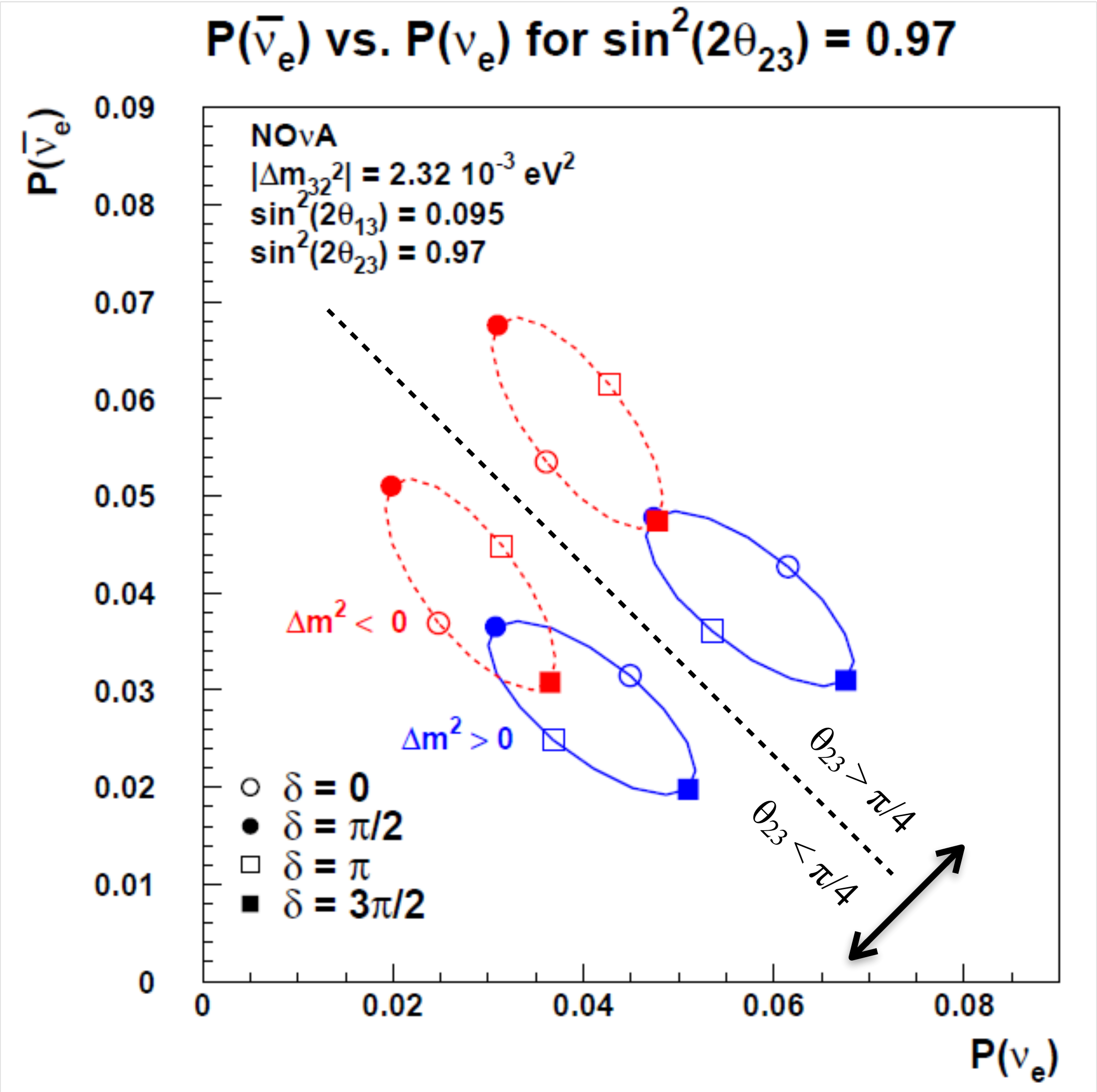


$\sqrt{2}G_F N_e 2E/\Delta m^2_{31}$

- ~22% effect for NOvA baseline, 11% for T2K

Shown for maximal θ_{23}

θ_{23} Octant



ν_μ disappearance measures $\sin^2(2\theta_{23})$

ν_e appearance depends in leading order on $\sin^2(\theta_{23})$

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    - θ_{23} octant due to $\sin(\theta_{23})$ in leading term of appearance probability
  - Sensitivity to the above depends strongly on external constraint for θ_{13} (from reactors)
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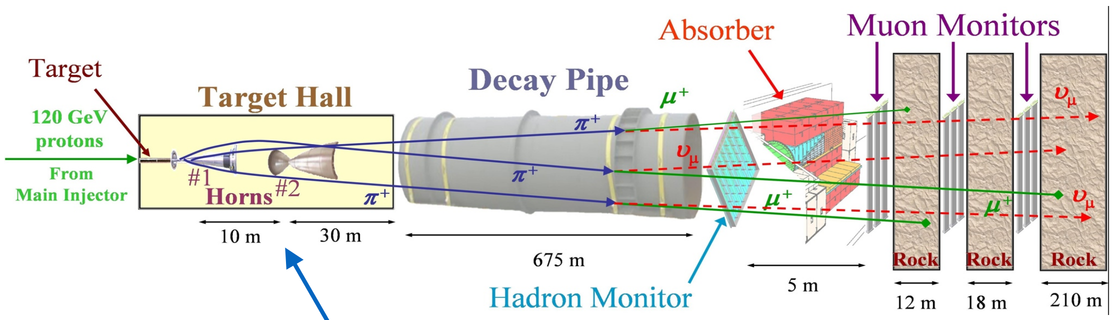
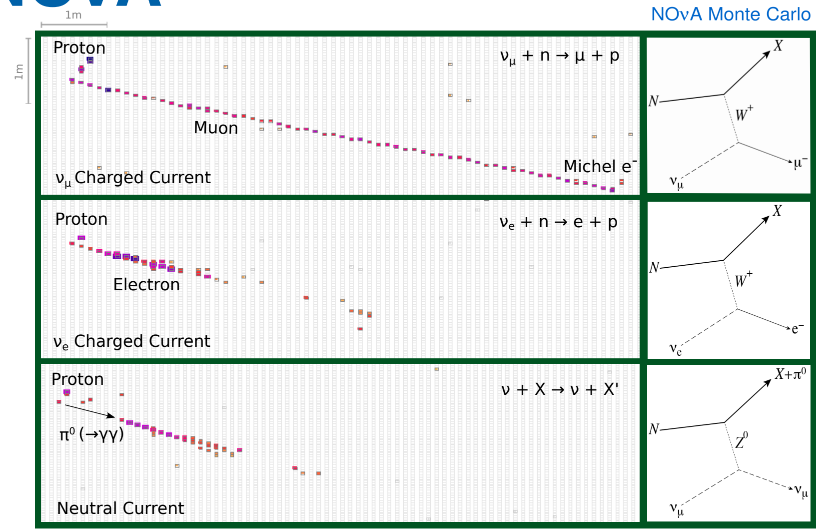
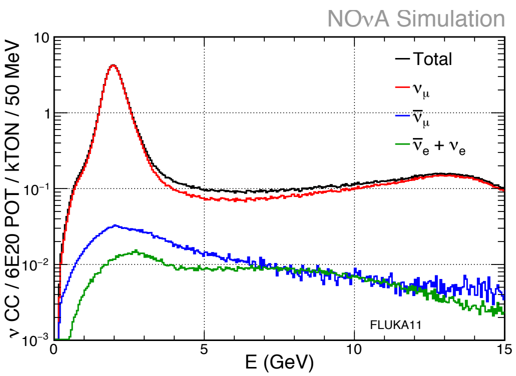
    θ_{23} octant due to $\sin(\theta_{23})$ in leading term of appearance probability
  - Sensitivity to the above depends strongly on external constraint for θ_{13} (from reactors)
  - ν_μ disappearance improved sensitivity
- Neutral Current Disappearance
  - Sensitivity to effect of sterile neutrinos, e.g. constraints on θ_{24}, θ_{34}
- Non-standard interactions
  - Alternative interpretation of ν_e vs $\overline{\nu}_e$ appearance

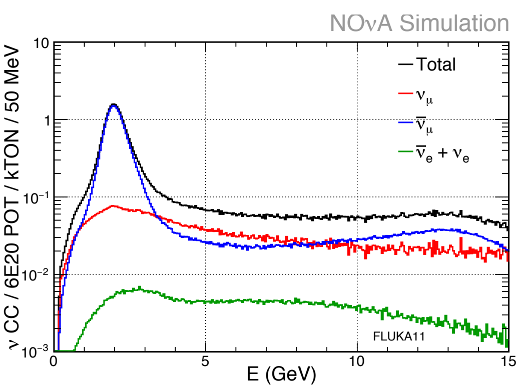
Current Long-Baseline Experiments - NOvA

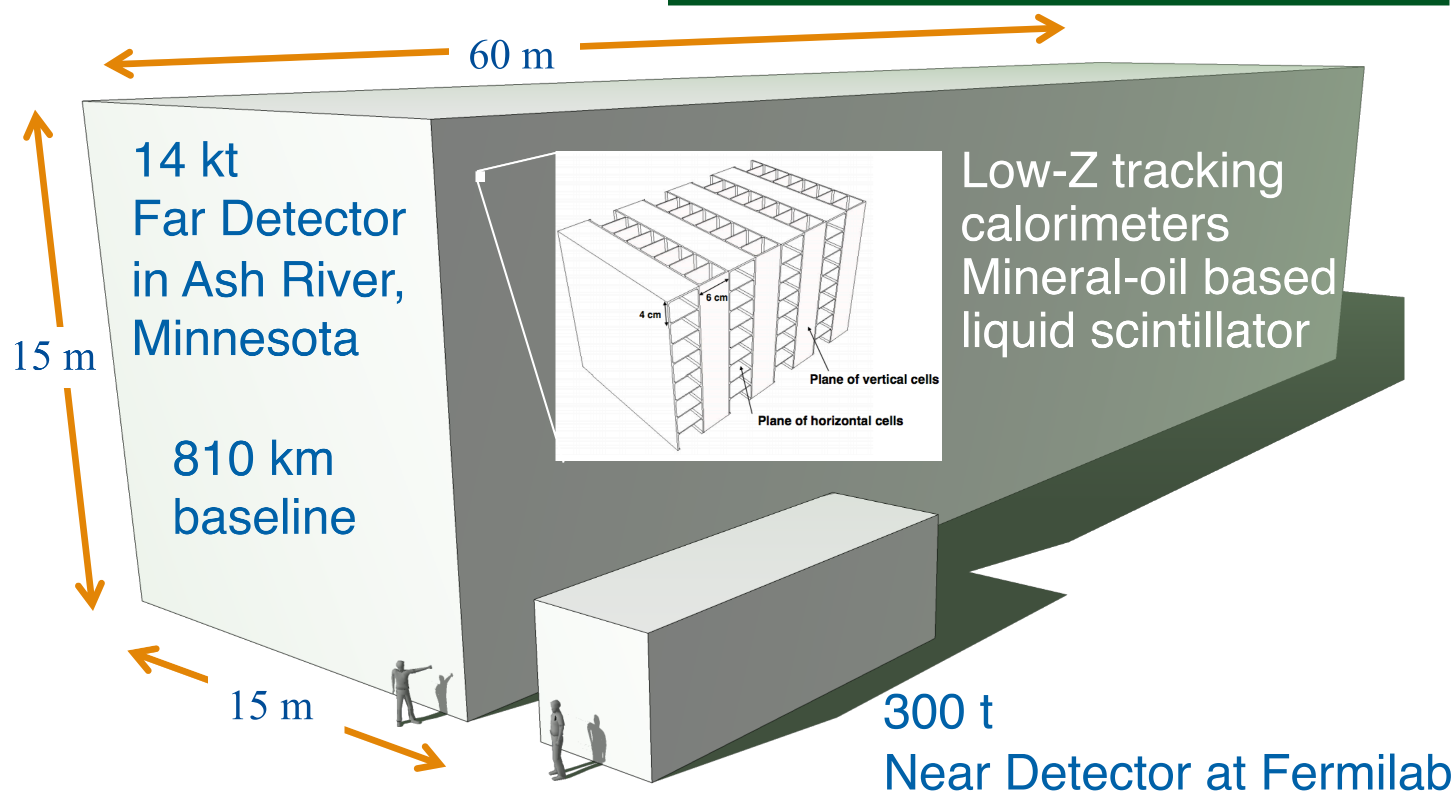




Horn-current polarity selects high-purity ν_μ or $\overline{\nu}_\mu$







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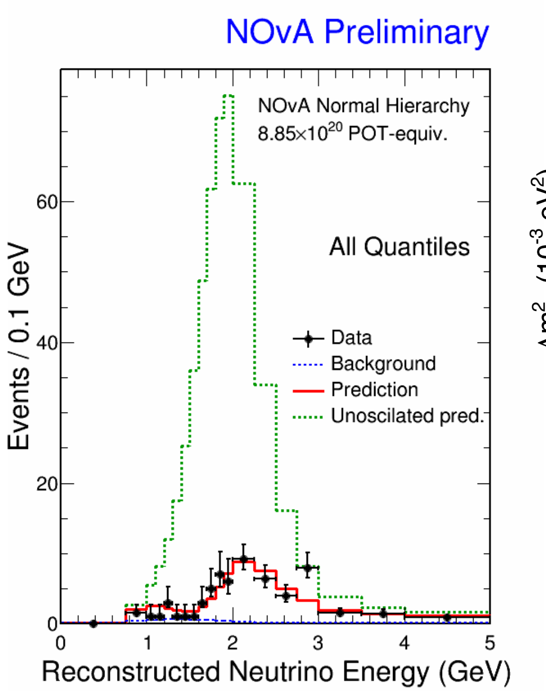
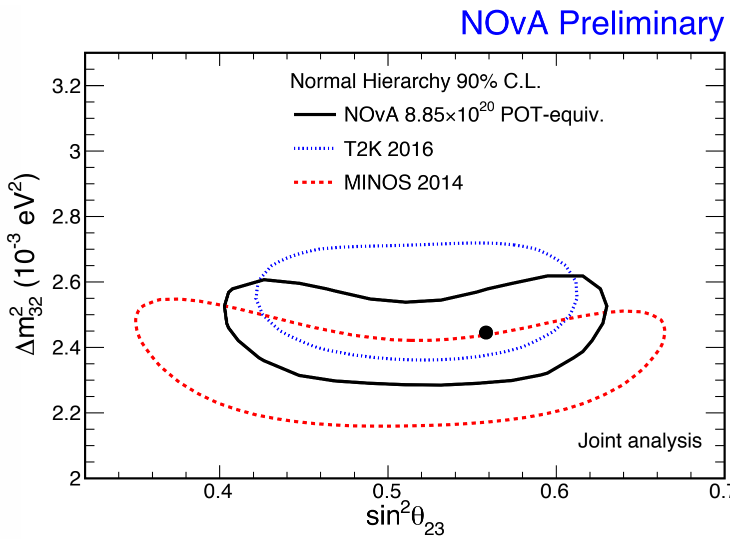
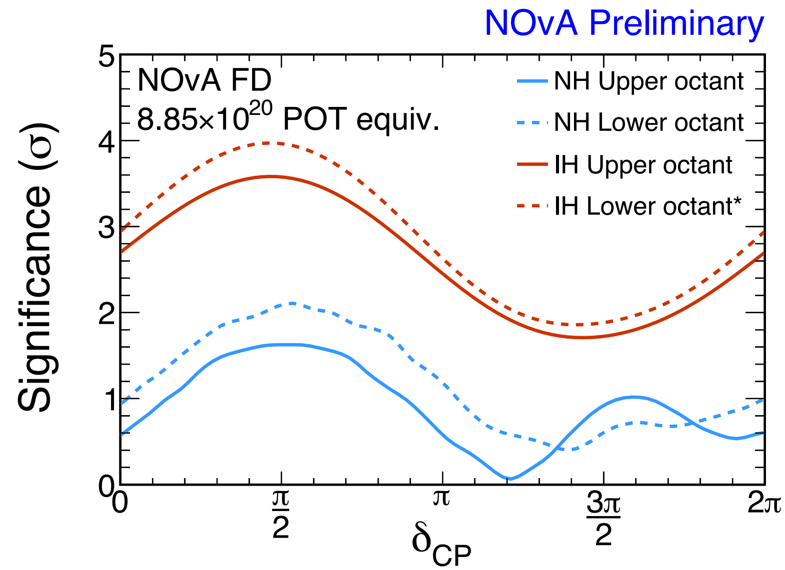
Recent NOvA Results

- Based on all neutrino-mode data to-date
  - 8.85×10^{20} protons-on-target (14-kt equivalent), collected since Feb. 2014





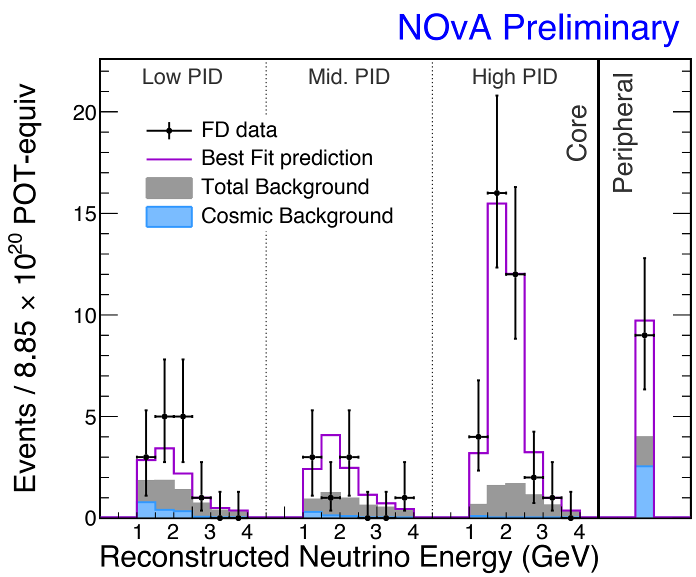


Observe

$126\ \nu_\mu$ on background of 9

763 +/- 33 without oscillations

$66\ \nu_e$ on background of 21

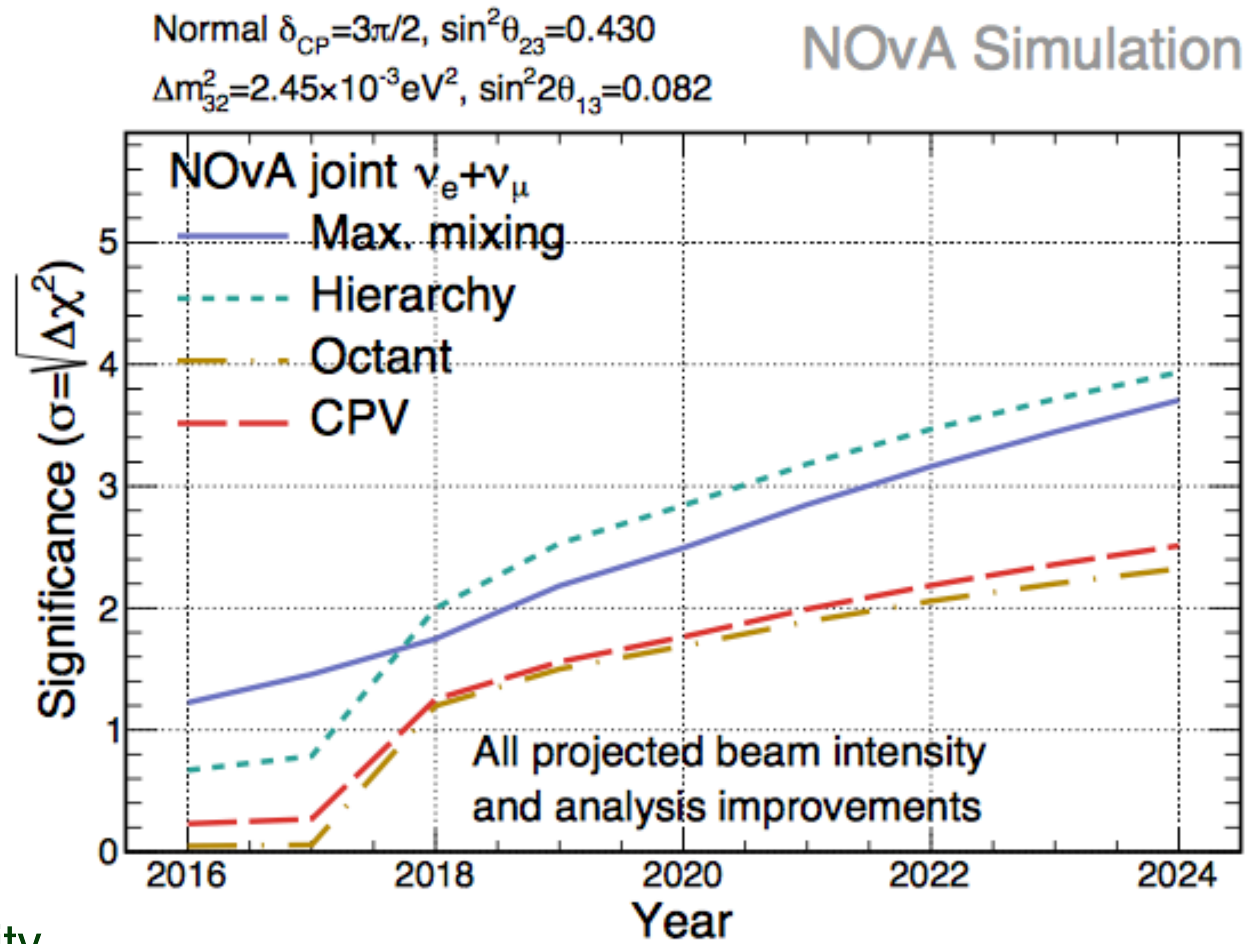


- **Compatible with maximal θ_{23} at 0.8σ**
- **No significant octant preference**
- **Normal Hierarchy is preferred at nearly 2σ**
- **Compatible with CP conservation**

  Best fit implies strong CPV effect

NOvA in the Future

- NOvA has been collecting antineutrino-mode data since Feb. 2017 at 700 kW
- Working on first antineutrino results with ~7x10^{20} protons-on-target
- Guidance from Program Planning: expect to run until 2024.
- Projected sensitivities: assume 800 kW in FY19, 900 kW in FY21, target and analysis improvements
- Sensitivities depend heavily on the assumed values of the parameters
  - Choose scenario that illustrates capabilities on all questions
  - ~1 sigma from our current best fit point
  - Other scenarios that are compatible with the data have better or worse sensitivity to Mass Hierarchy, Octant, maximality, generally weaker for CPV



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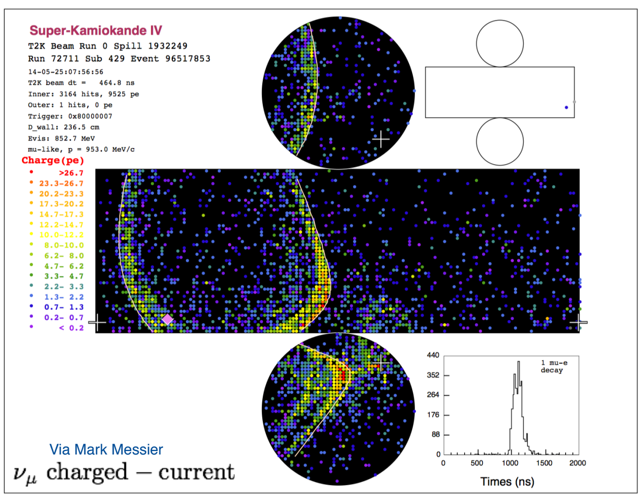
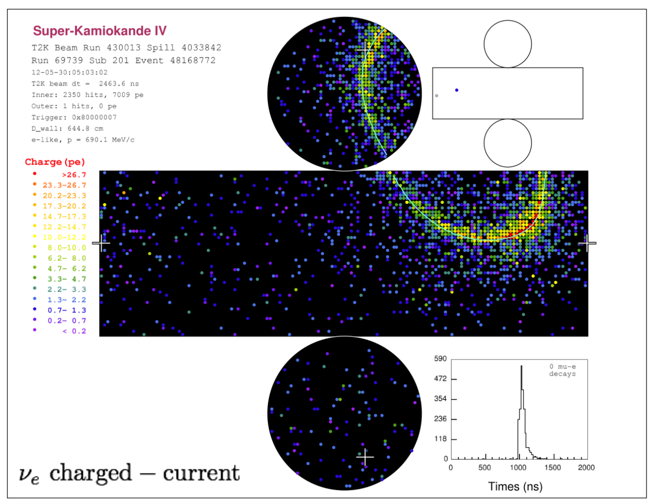
Current Long-Baseline Experiments - T2K

50 kt Water Cherenkov Far Detector

295 km baseline



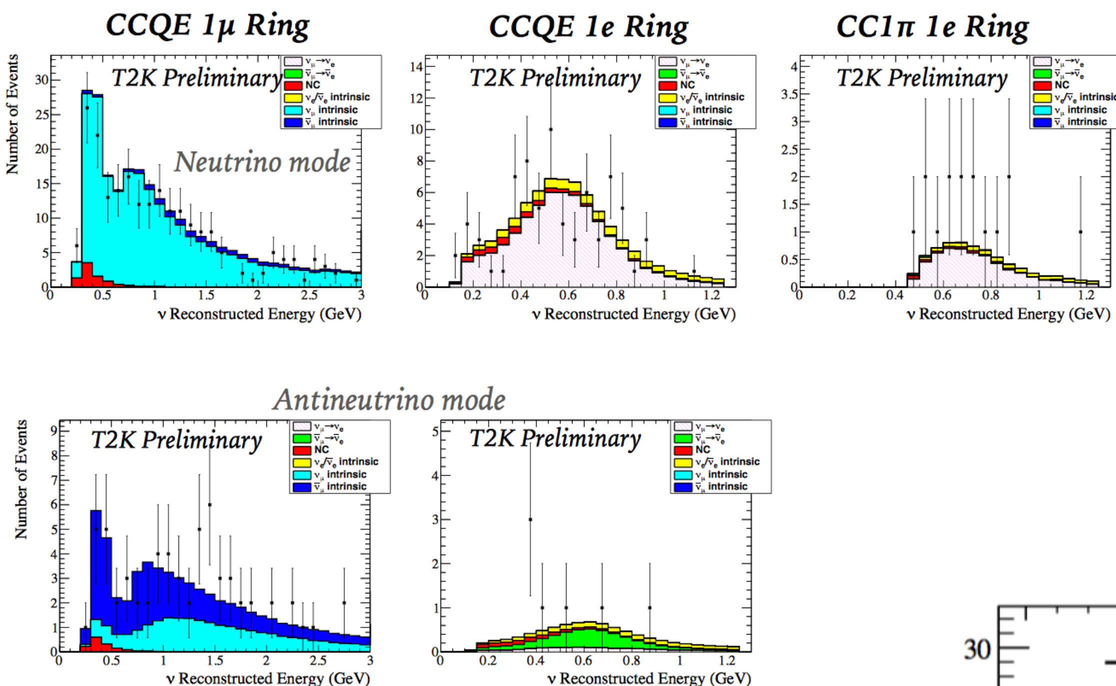


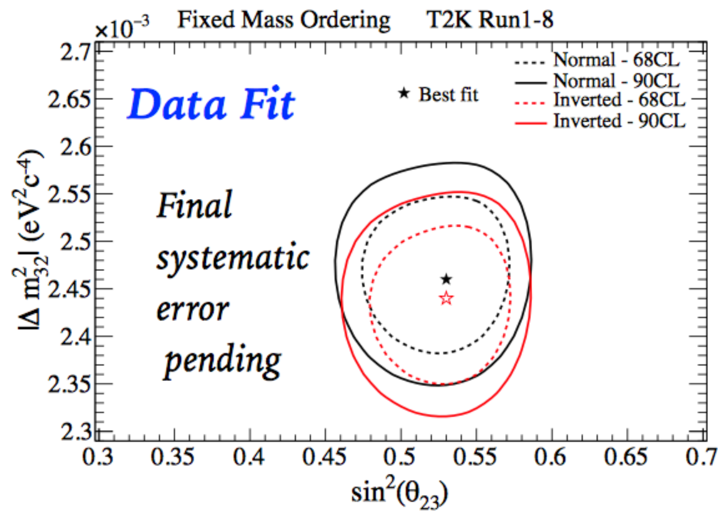
Neutrino and antineutrino mode from polarity of

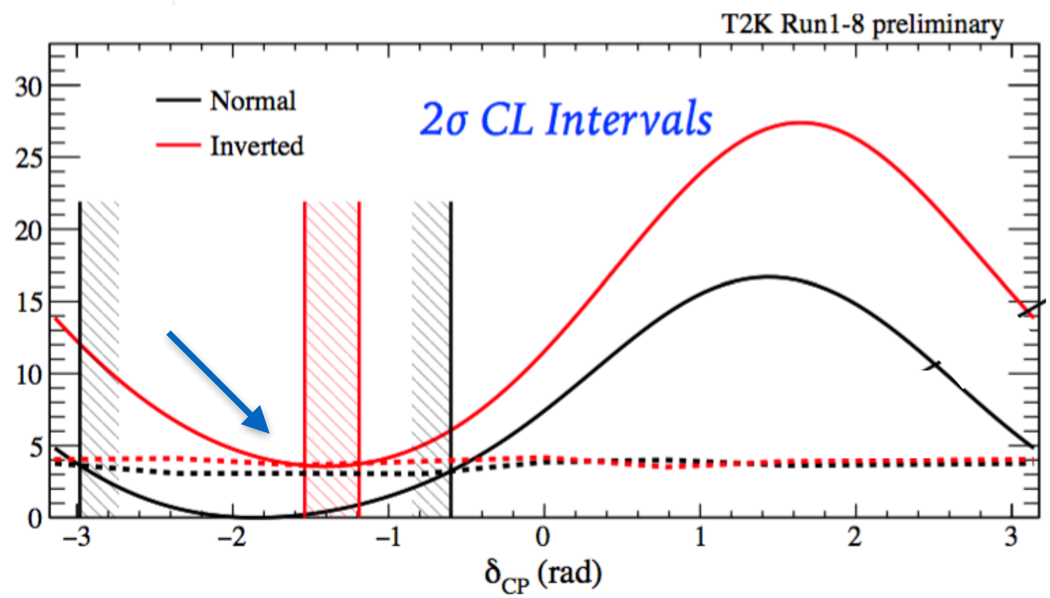
T2K Recent Results

- 14x10[20] protons-on-target neutrino-mode, 7x10[20] POT antineutrino-mode

Mark Hartz, KEK Colloquium, 8/4/17







89 (7) "ν_e" candidates in (anti)neutrino-mode

240 (68) "ν_μ" candidates in (anti)neutrino-mode

- **Compatible with maximal θ_{23}**
- **Weak preference for upper octant**
- **CP conservation disfavored at 2σ**
- **Normal Hierarchy appears to be preferred at nearly 2σ**

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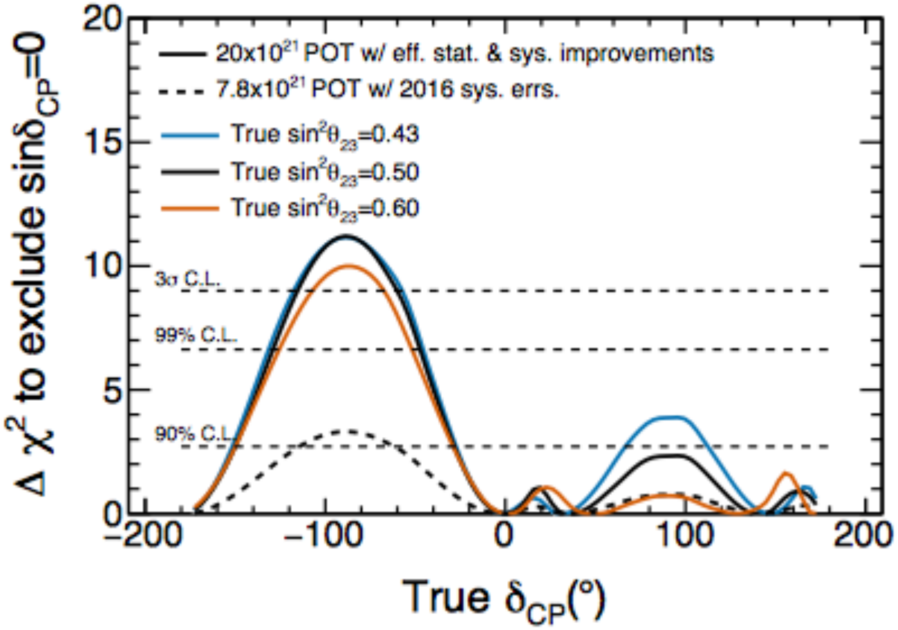
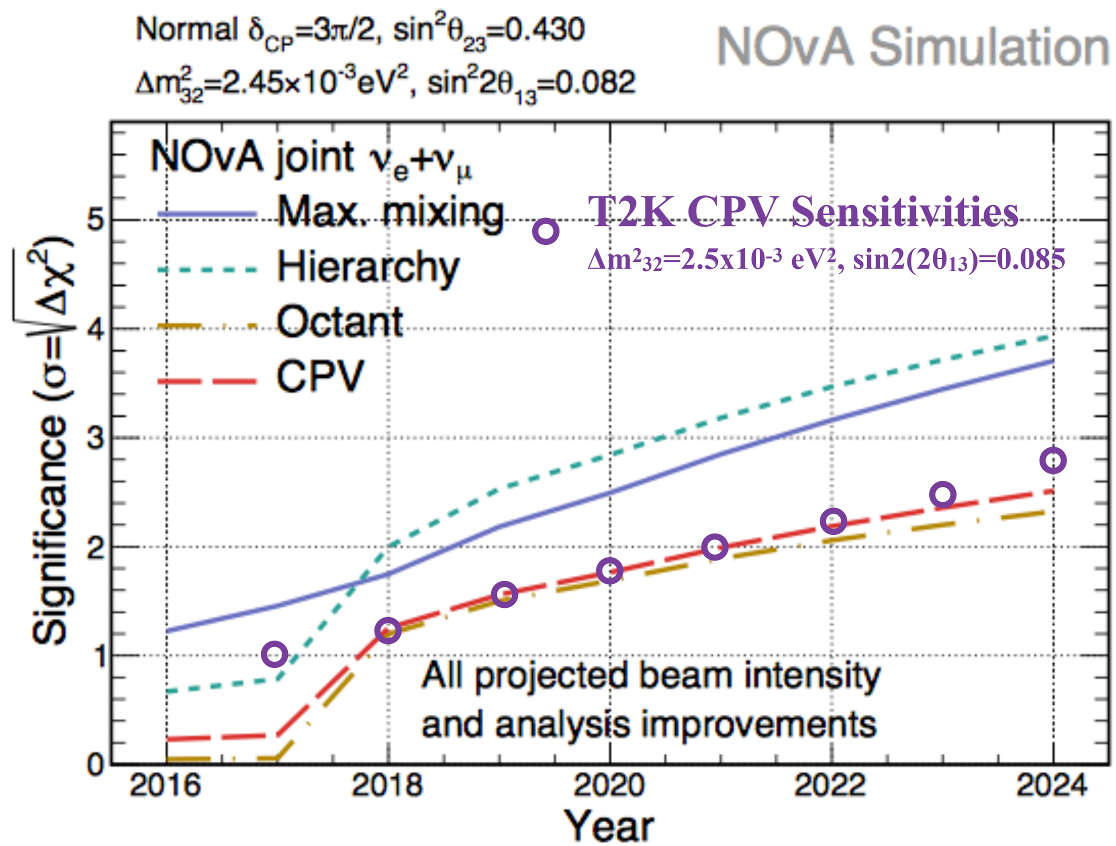
T2K and the Future

- T2K-II proposal
  - Go from approved 78e20 POT to 200e20 POT, with beam upgrades to1.3 MW and running through 2026
  - Other beam and analysis improvements, reduction of systematic uncertainties by 1/3

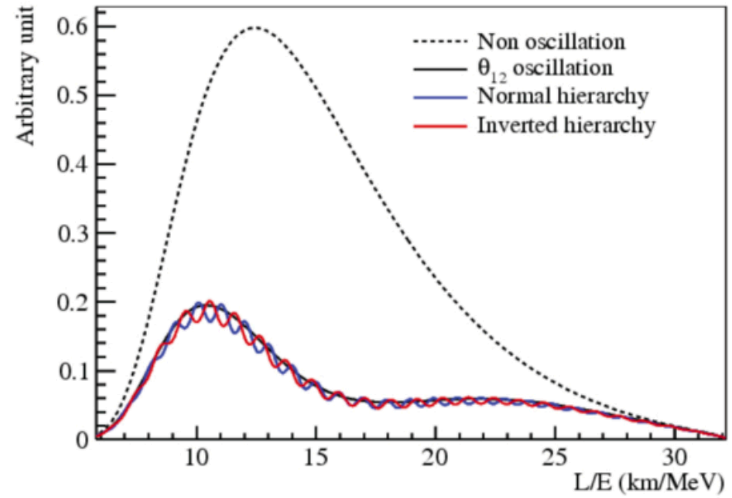
T2K-II CP-Violation Sensitivity by 2026 (arXiv:1609.0411)



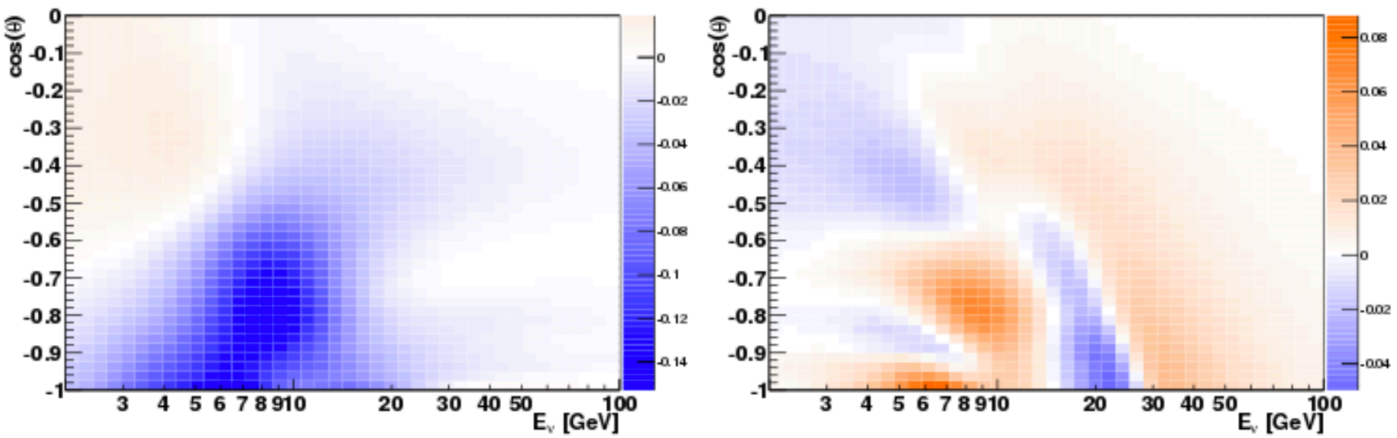


Other Potential Mass Hierarchy Measurements

- JUNO - medium baseline reactor measurement
  - 50 km baseline, from 36 GW reactor complex, far from others. Daya Bay-style detectors
  - Use interference between the two fast atmospheric components
  - 3 σ by 2022/3



- ORCA-KM3Net - underwater atmospheric neutrino experiment
  - 3 σ sensitivity in 3 years for a variety of scenarios, possibly by 2025



ν_e ν_μ

P. Coyle, arXiv:1701.01382

ORCA-KM3NET
Event Rate Asymmetry from matter effect
$(N_{NH}-N_{IH})/N_{NH}$

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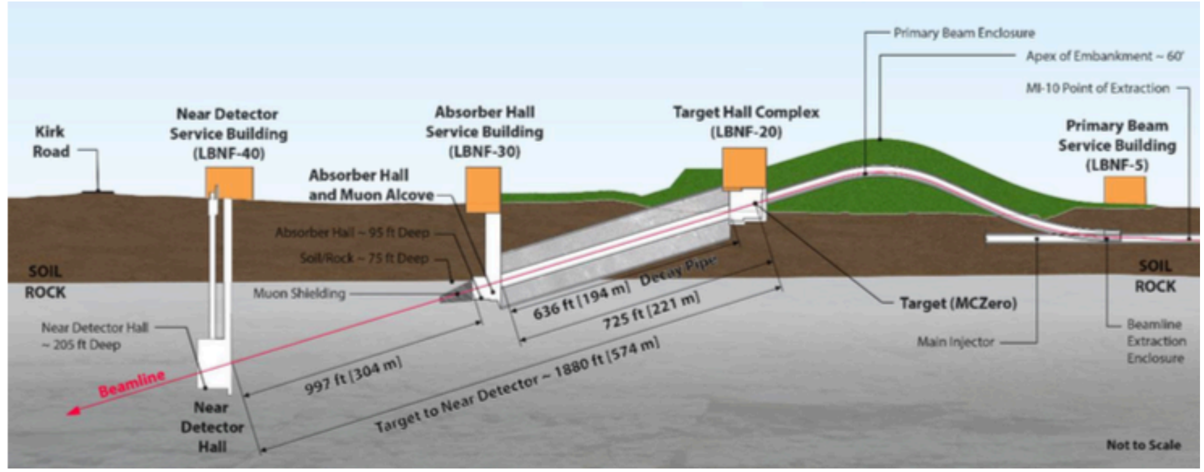
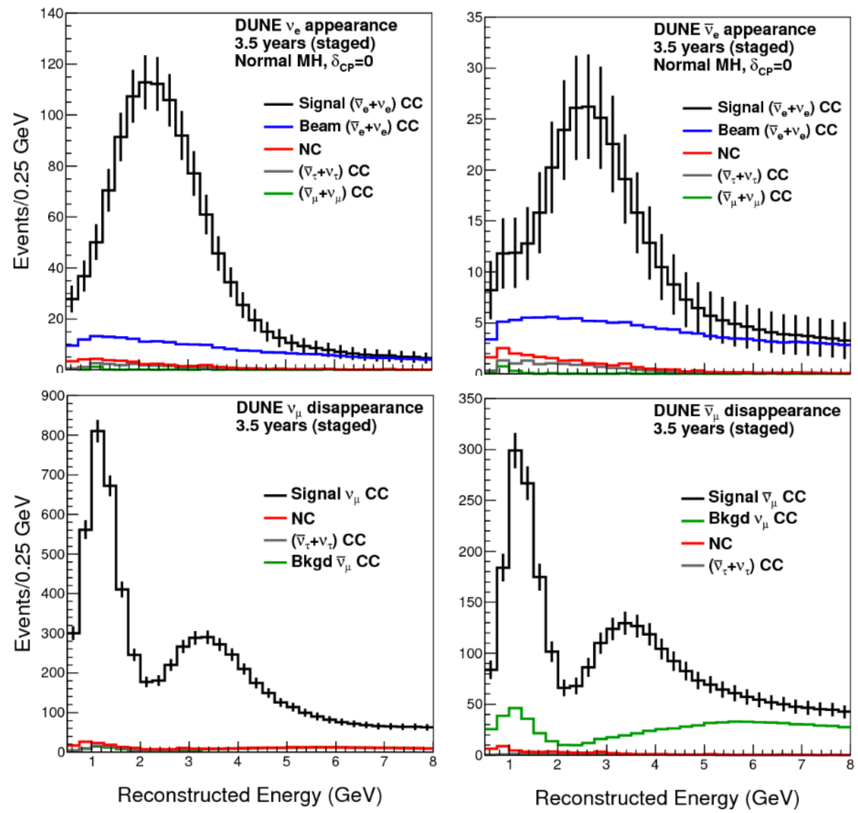
L. Whitehead Koerner TAUP 2017

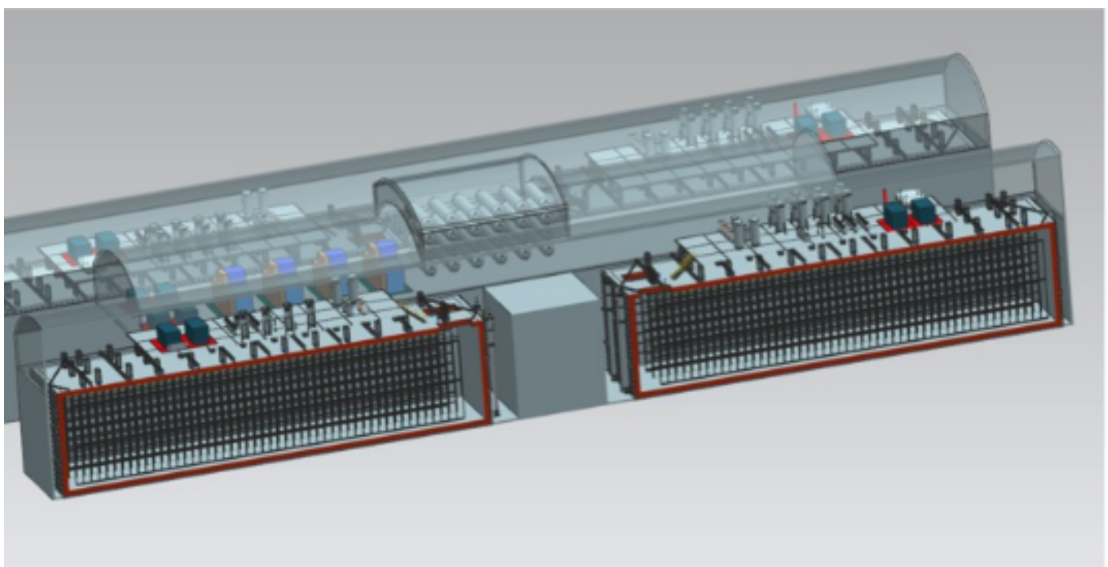
DUNE

- 1.2 MW beam, upgradable to 2.4 MW
- Wide-band flux
- Near Detector at Fermilab
- Far Detector at SURF, 1300 km baseline
  - 40kt LArTPC modules in 4x10kt modules
  - Staging: 20kt in 2026, 30 kt in 2027, 40 kt in 2029 2.1 MW in 2032 (technically limited schedule)



~1000 ν_e appearance events in 7 years





Dune CDR, arXiv:1601.02984

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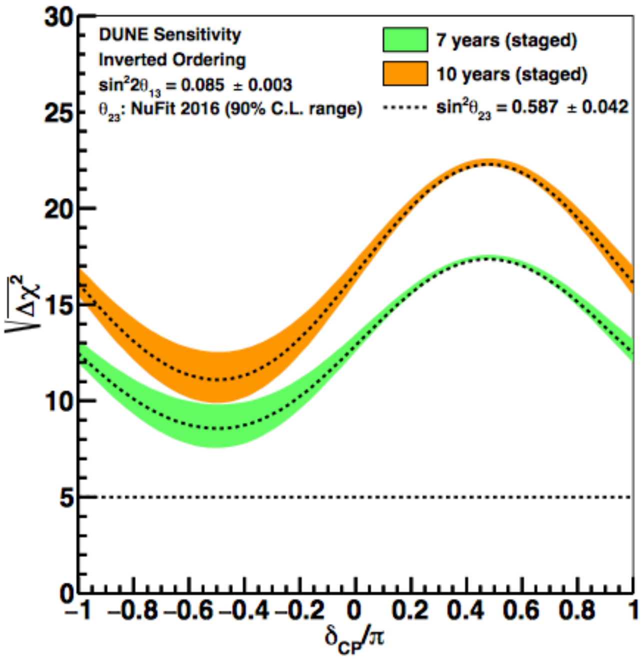
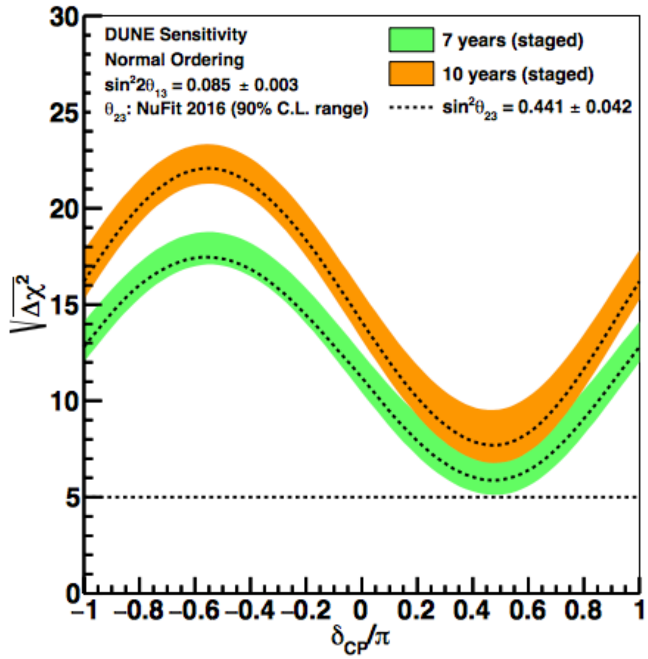
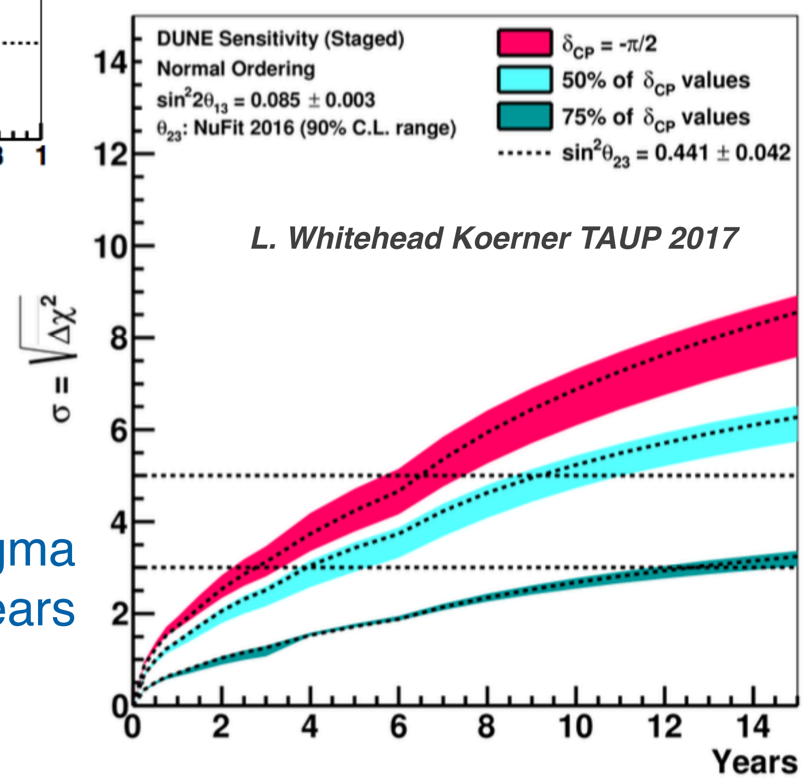
DUNE Reach

J. Martin-Albo, arXiv:1710.08964





We should know the Mass Hierarchy to 5 sigma with 7 years of DUNE running

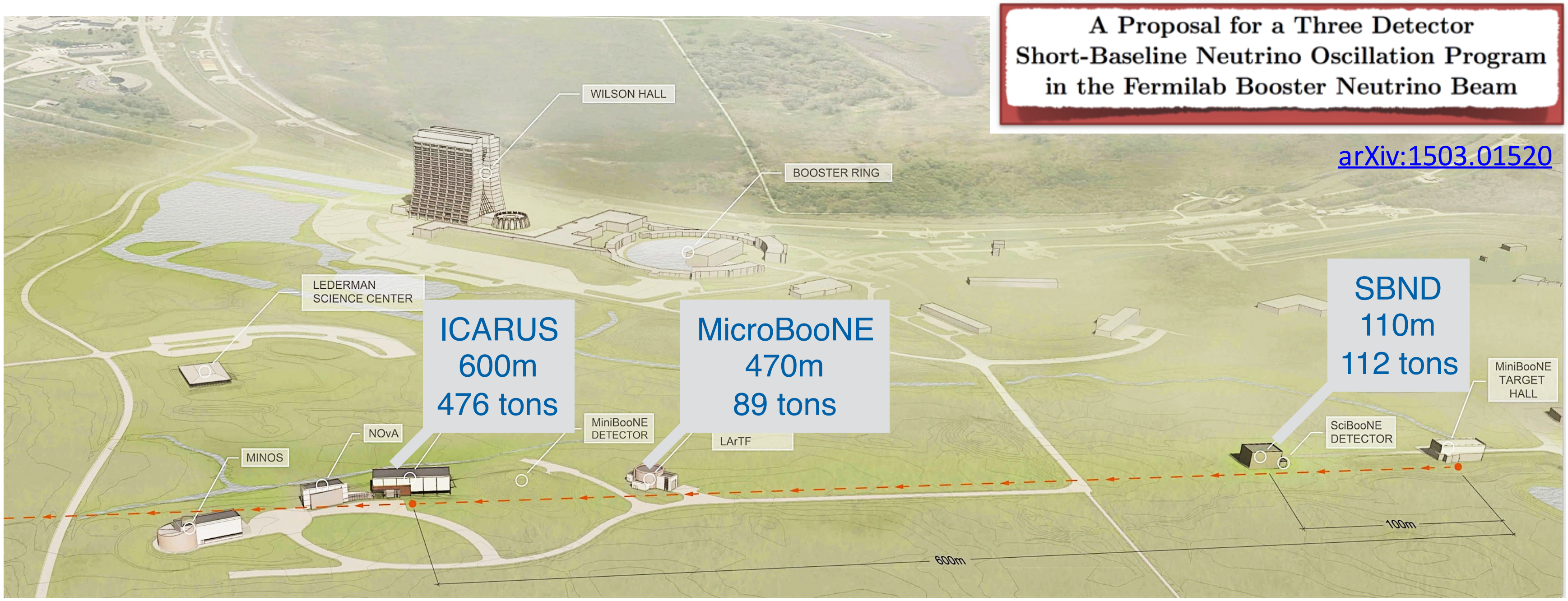


L. Whitehead Koerner TAUP 2017

"Equal odds" of observing CP violation at 3 sigma or greater in 5 years, high chance in 12 years

SBN

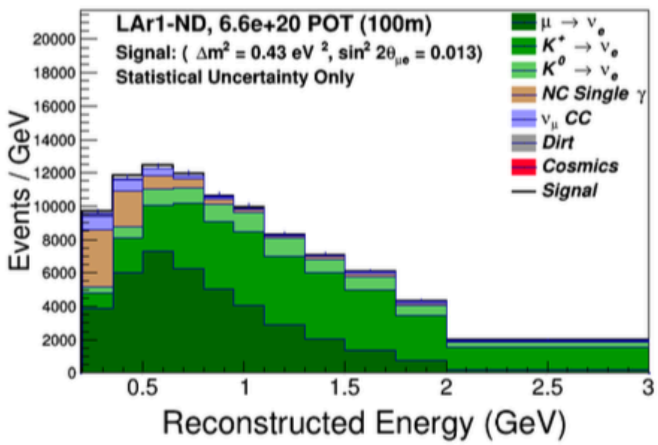
Courtesy P. Wilson



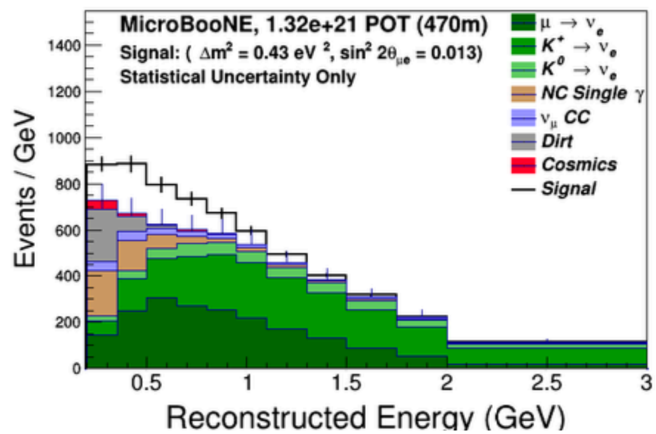
- 3 LArTPC Detectors in Booster Neutrino Beam
  - MicroBooNE, SBND,
- World-leading neutrino oscillation search at $\Delta m^2 \sim 1$ eV^2
- Status
  - MicroBooNE - taking data since 2015
  - Icarus - Detectors on site, expect installation this summer, ready for LAr fill and commissioning in 2019 (technical schedule)
  - SBND - TPC assembly Summer 2018, electronics production Fall 2018, complete cryostat 2018, to start cryostat & detector installation in 2019

SBN Reach

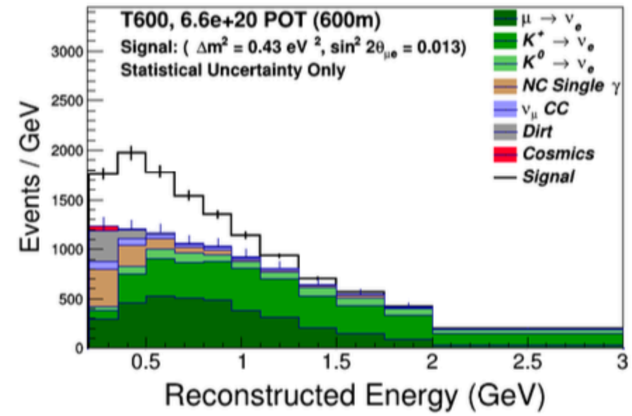
SBND



MicroBooNE

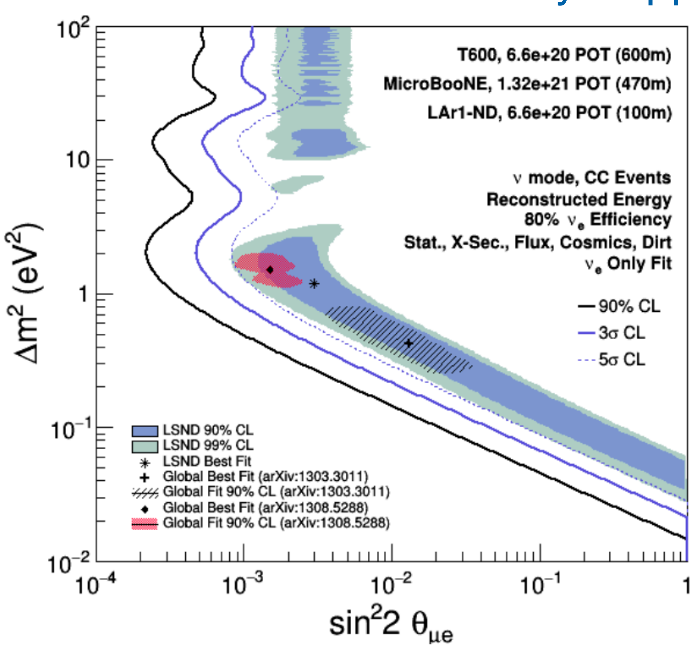


ICARUS [arXiv:1503.01520]



ν_e candidate spectra for 3-year nominal exposure (+existing MicroBooNE data)

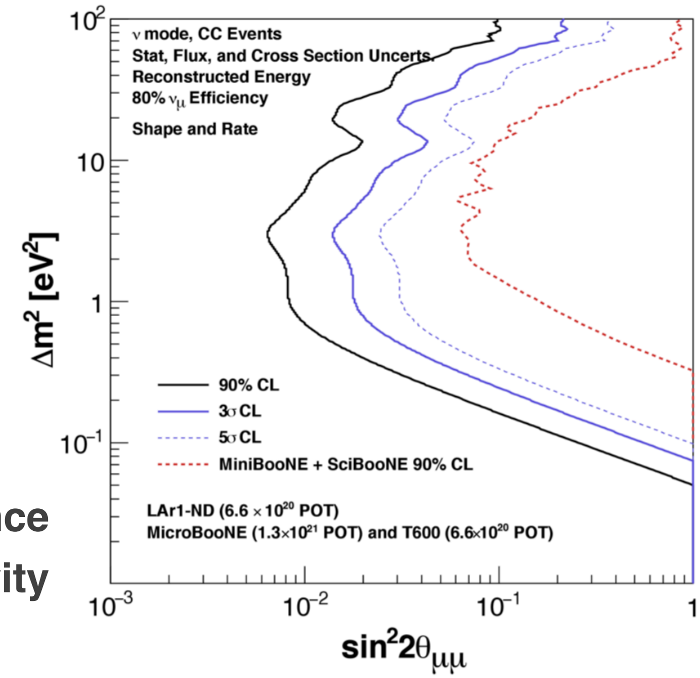
ν_e appearance signal (white histogram) corresponds to central value of global fit to eV scale effects by Kopp, et al., ***JHEP 1305, 050 (2013)***



SBN ν_e appearance sensitivity

By 2022-2023, could have ~definitive answer on question of eV-scale sterile neutrino

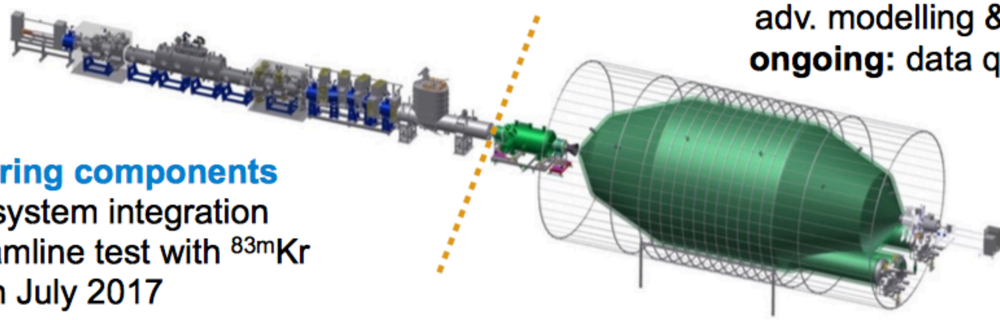
SBN ν_μ disappearance sensitivity



Beta Decay and Absolute Mass Measurement

- Measurement of β-decay endpoint spectra - challenge akin to $0\nu\beta\beta$

Preparing KATRIN for neutrino-mass measurements:



Analysis chain
adv. modelling & analysis framework
ongoing: data quality filters, blinding

Tritium-bearing components
- now: final system integration
- overall beamline test with ^{83m}Kr achieved in July 2017
- **next:** inactive commissioning with D_2, then $D_2(T_2)$

Spectrometer & detector section
2 successful commissioning phases already done
ongoing: background investigations

➜ **First tritium runs starting in 2018, inauguration ceremony: 11 June 2018**

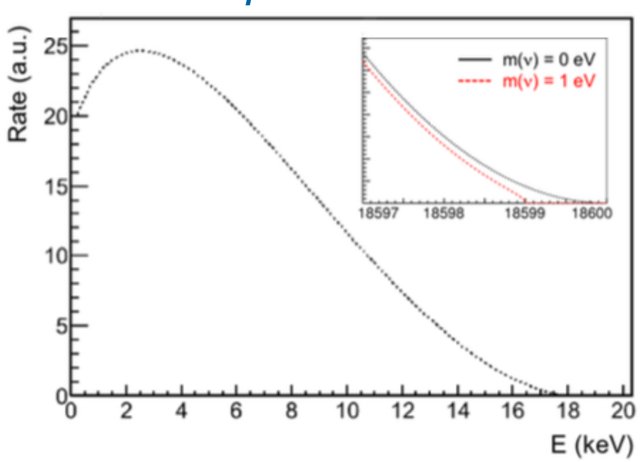
K. Valerius, Erice, 17 Sept. 2017

KATRIN ^3H run to start this year

10^{11} e-/s from Gaseous T_2 source

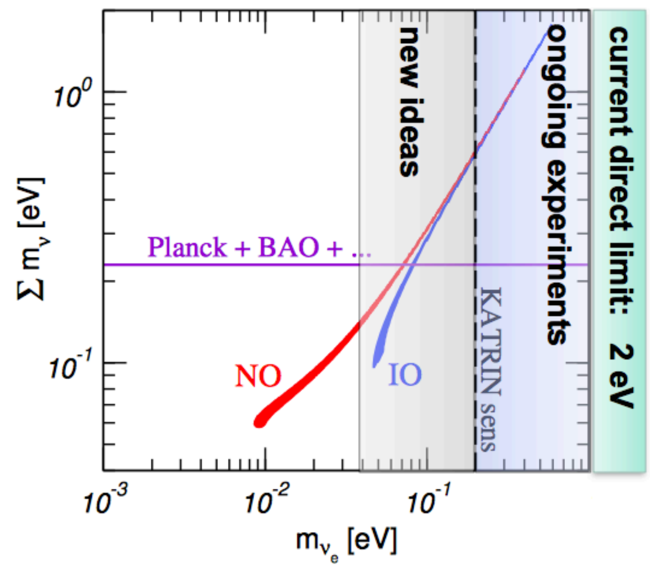
<1 e-/s in detector

^3H endpoint illustration



S. Martens
arXiv:605.01579

K. Valerius, Erice, 17 Sept. 2017



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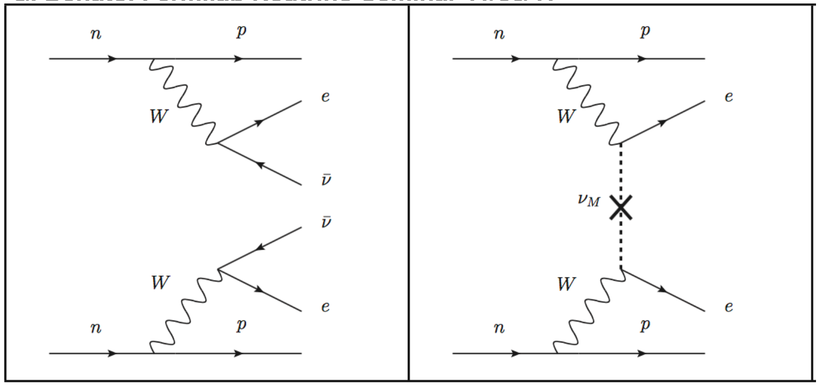
Neutrinoless Double Beta Decay

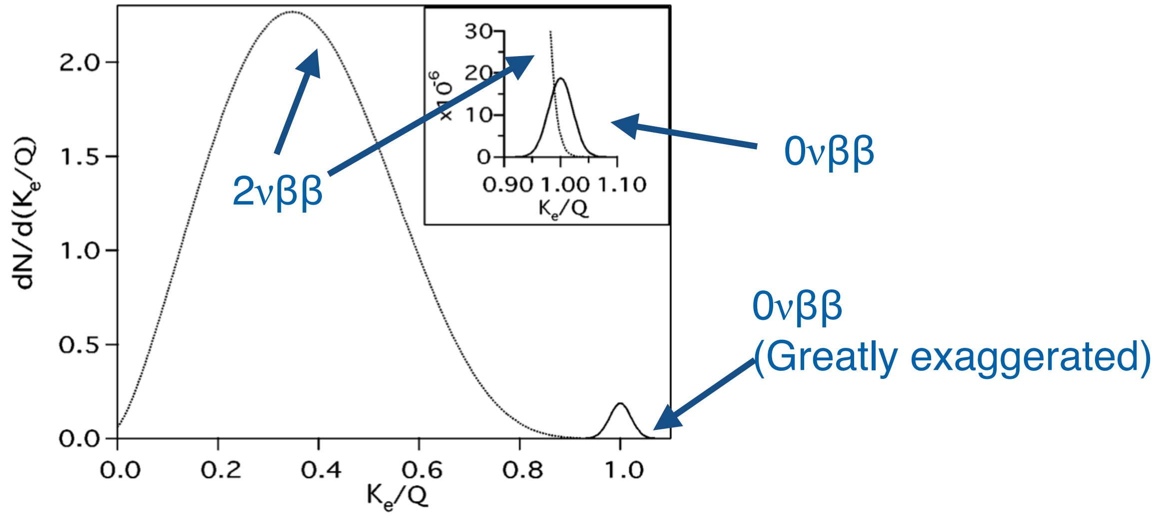
G. Benato. Fermilab Neutrino Seminar 11/30/17



2νββ

0νββ
Majorana Neutrinos only.
Violation of total lepton number

Ann.Rev.Nucl.Part.Sci. 52 (2002)



- Assuming the 3 light neutrinos as Majorana particles, rate

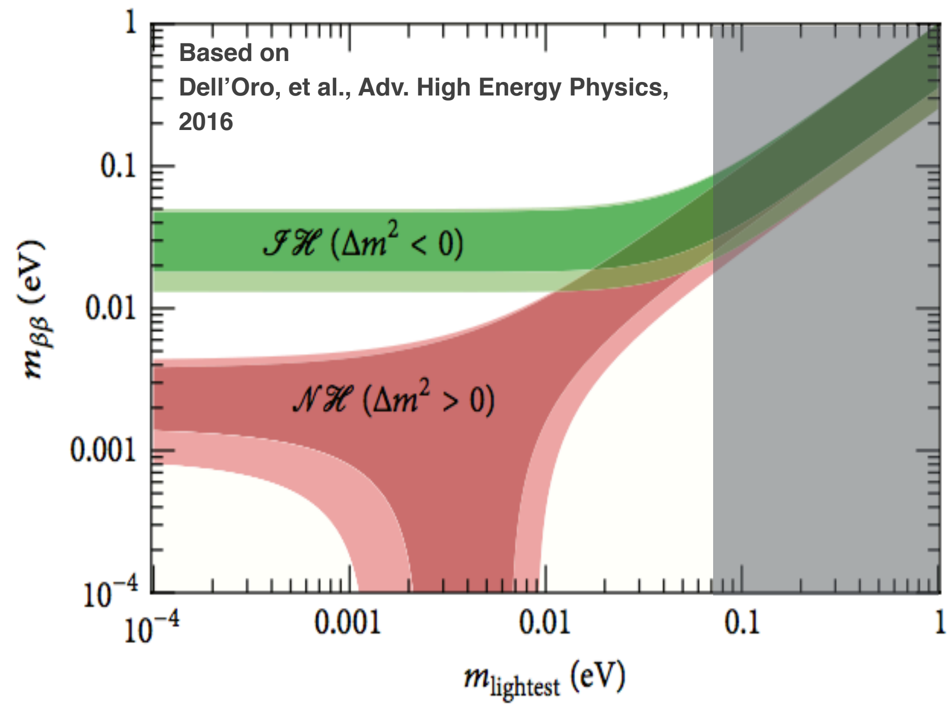
$$(T_{1/2})^{-1} = G_{0\nu} |\mathcal{M}_{0\nu}|^2 m_{\beta\beta}^2$$

  - Phase space factor G
  - Effective neutrino mass

$$m_{\beta\beta} \equiv |m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i(\alpha_{31}-\delta)}|$$

  - Nuclear Matrix Elements $\mathcal{M}$ - known to ~x2

(The NME of precise calculation)



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0νββ Experimental Design

- Following Sisti *et al.*, Nuclear Physics B Proceedings Supplement 00 (2015) 1–7
- Figure of Merit

$$F \propto \eta\epsilon\sqrt{\frac{MT}{B\Delta}}$$

Source Mass

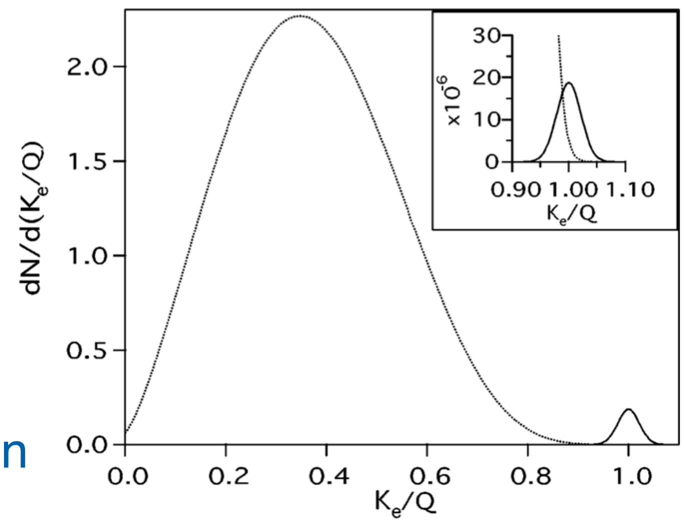
Exposure Time

Candidate 0νββ isotope abundance

Energy Resolution

Detection Efficiency

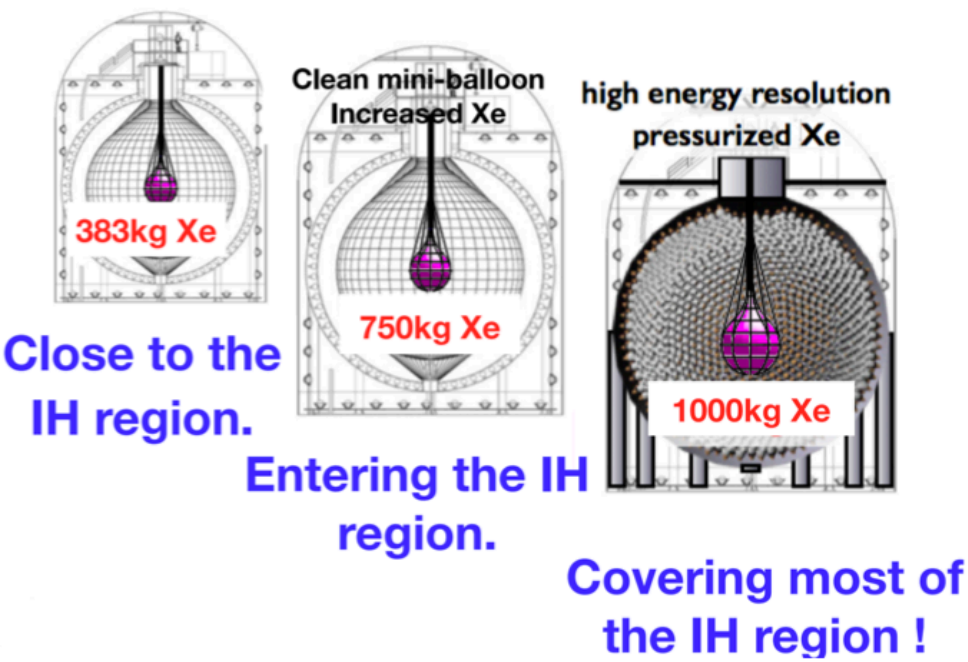
Background Rate



- Can trade Mass for Energy Resolution

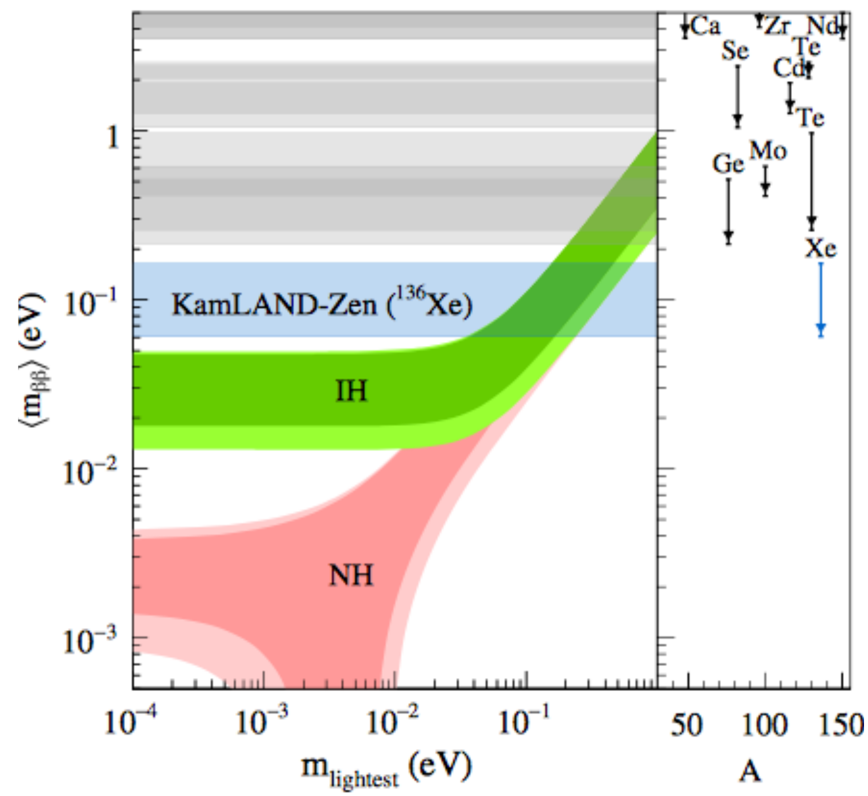
KamLAND-ZEN

- Best limits to-date
  - ^{136}Xe in Nylon ballon
  - Poorer resolution, huge mass
  - KamLAND-Zen 800 delayed due to balloon issues



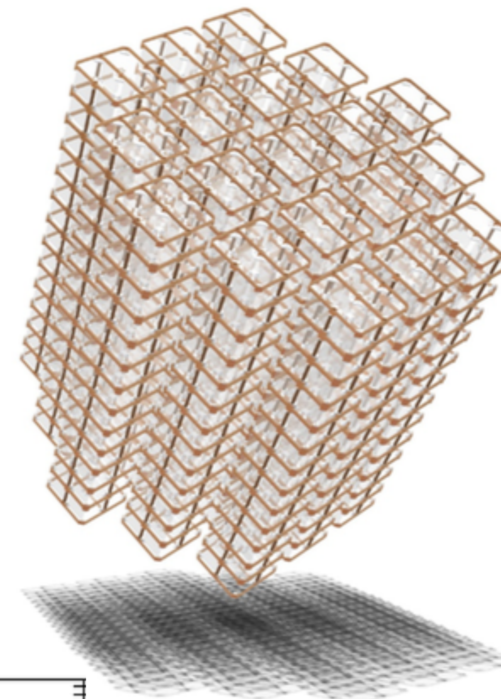
G. Benato, Fermilab Neutrino Seminar 11/30/17

Already approaching IH band

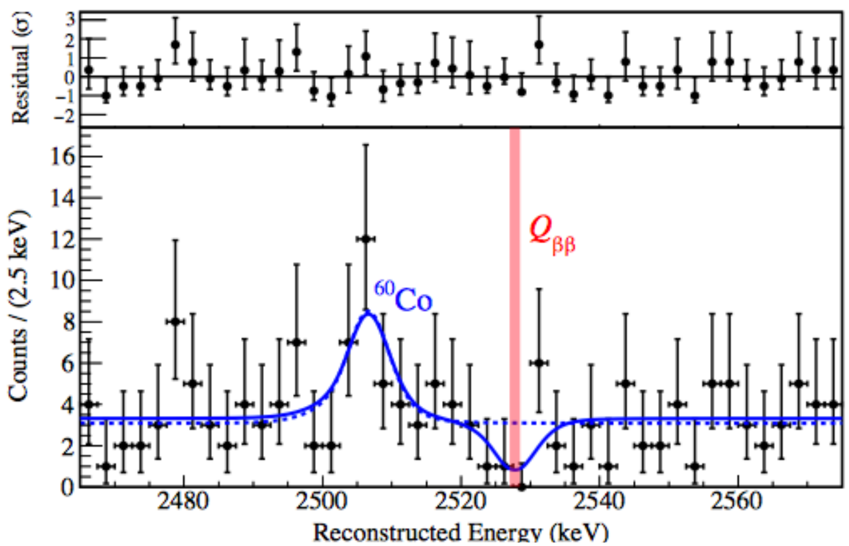


PRL 117, 082503 (2016)

CUORE

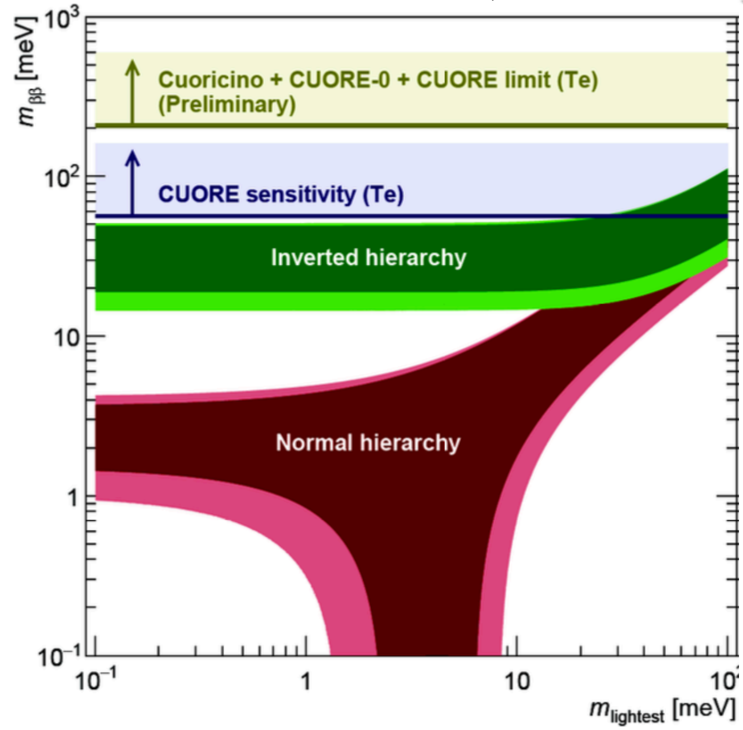


- TeO_2 bolometers - highly sensitive cryogenic thermometry
  - 741 kg total, 206 kg of ^{130}Te
  - Effective energy resolution 7.5 keV, for $Q_{\beta\beta}$ 2.5 MeV
  - With 86 kg-yr exposure to date, observe 151 events in ROI (2465-2575 keV)
  - Fit to 0νββ peak, floating 60Co BG γ peak, flat continuum BG
    - Best fit $\Gamma_{0\nu}$=(-1.0+(0.4-0.3)+/0.1)x10^{-25}/yr, $T^{0\nu}_{1/2}$>1.4x10^{25} yr



PRL 120, 132501 (2018)

M. Sisti, Erice 2017

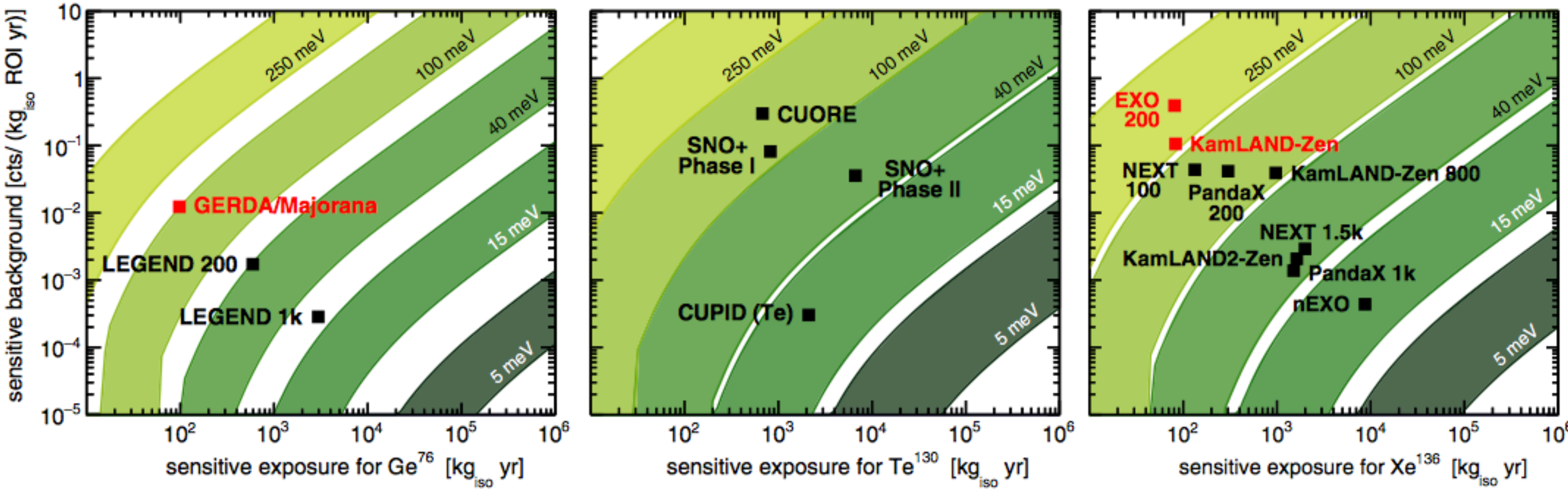


$m_{\beta\beta}$ limits from earlier preliminary result, with projection

Projection ~current KamLAND-ZEN limit

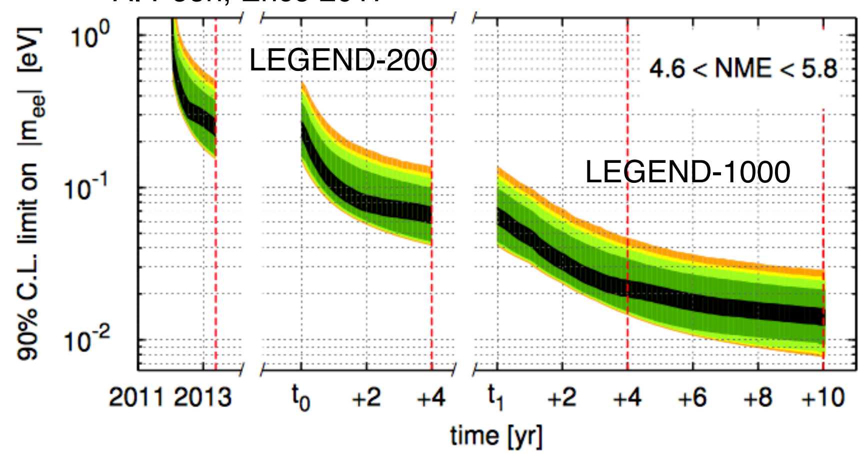
Overview

Agostini, Benato, Detwiler, PRD 96, 053001 (2017)



- 5-year discovery potential vs. signal exposure and background
  - Caveat: the relative strength of KamLAND-Zen and GERDA is not reflected in current limits
- Challenge is estimating $T_{0,1,2...}$
  - Technical schedule: LEGEND-200 start 2021 - cover IH by 2026
  - 5-10 years R&D for LEGEND-1000? Start in 2028 or later? Much of IH range by 2038?

A. Poon, Erice 2017



(LEGEND is follow-on of GERDA and MAJORANA)

Prognostications

- “Unless we’re unlucky” applies

2018 | 2026 | 2036

Possible 3+ σ
Mass Hierarchy Determination from several experiments, independent methods

Possible 2-3 σ
CP-violation from 2 experiments
Possible 3 σ Octant Determination

Definitive answer to eV-scale neutrino

Starting to probe 0νββ for Inverted Hierarchy

0.2 eV $m_{\beta\beta}$ sensitivity

5 σ
Mass Hierarchy Determination

Probable 3σ CP-violation

Likely 3σ CP-violation →

“Likely” to discover 0νββ if Inverted Hierarchy →

Extras

The Open Questions and Long-baseline Oscillation Experiments

- Long-baseline Muon Neutrino Disappearance
  - To leading order, neglecting Δm^2_{21}, θ_{13}

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{32}\frac{L}{E})$$

  - Note: degenerate in Δm^2_{32} <—> $-\Delta m^2_{32}$ (Mass Hierarchy), $\pi/4-\theta_{23}$ <—> $\theta_{23}-\pi/4$ (Octant)

- Electron Neutrino Appearance
  - $P(\nu_\mu \rightarrow \nu_e) \cong P_{Atm} + P_{\sin\delta} + P_{\cos\delta} + P_{Sol}$ *DUNE Science Report and References*

$$P_{Atm} = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2[(A-1)\Delta]}{(A-1)^2}$$

$$P_{Sol} = \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(A\Delta)}{A^2}$$

$$P_{\sin\delta} = \alpha 8 J_{CP}\sin\Delta\sin(A\Delta)\frac{\sin[(1-A)\Delta]}{A(1-A)}$$

$$P_{\cos\delta} = \alpha 8 J_{CP}\cot\delta_{CP}\cos\Delta\sin(A\Delta)\frac{\sin[(1-A)\Delta]}{A(1-A)}$$

$\Delta = \Delta m^2_{31}L/4E$

$\alpha = |\Delta m^2_{21}|/|\Delta m^2_{31}|$

$A = \sqrt{2}G_F N_e 2E/\Delta m^2_{31}$ *Matter Effect*

$J_{CP} \propto \sin\delta$ *CP violating phase*

A and δ change sign for antineutrinos
Δ depends explicitly on sign of Δm^2_{31}

Fermilab