What's new for ν?

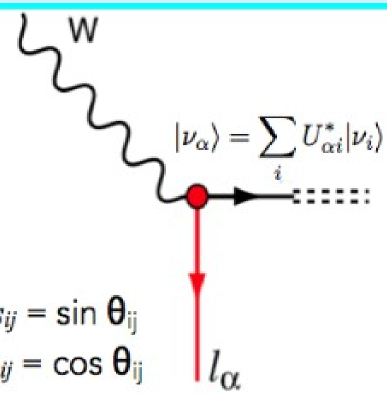
- Outline
  - What we know.
  - What we don't know.
  - How we might find out.
  - Can we help the world?

Users work on the Cryogenic Underground Test Facility at SNOLAB. Image by Gerry Kingsley.

About me

- Never took a physics course until I was 30
- T2K, SNO+, HK
- Cycling, hiking, camping, reading, singing, guitar
- flowers, vegan food
- XR

Things we know



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS mixing matrix

$s_{ij} = \sin\theta_{ij}$

$c_{ij} = \cos\theta_{ij}$

"standard" parametrization

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}$$

Current knowledge

$\theta_{12} \sim 33^o$

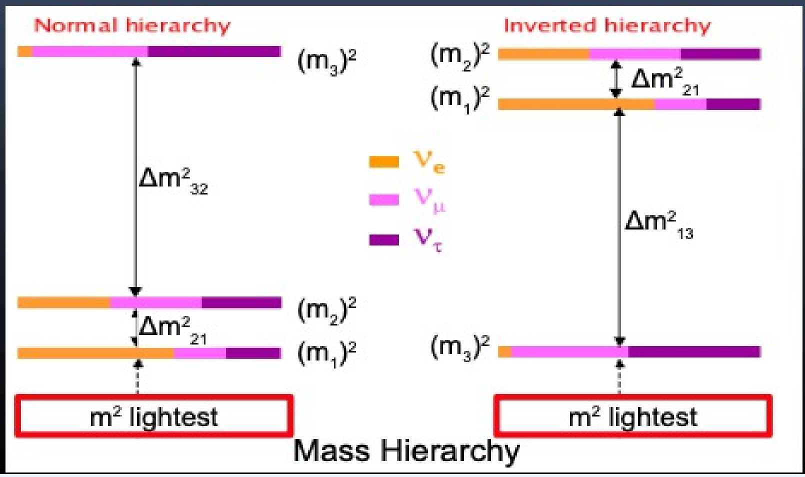
$\theta_{23} \sim 45^o$

$\theta_{13} \sim 9^o$

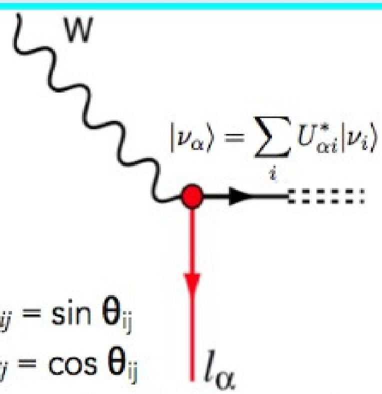
$\Delta m^2_{21} \sim 7.5 \times 10^{-5}\ eV^2$

$\Delta m^2_{32} \sim 2.5 \times 10^{-3}\ eV^2$

$\Delta m^2_{ij} = m_i^2 - m_j^2$



Things we know (kind of)



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS mixing matrix

$s_{ij} = \sin\theta_{ij}$

$c_{ij} = \cos\theta_{ij}$

"standard" parametrization

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}$$

Current knowledge

$\theta_{12} \sim 33^\circ$

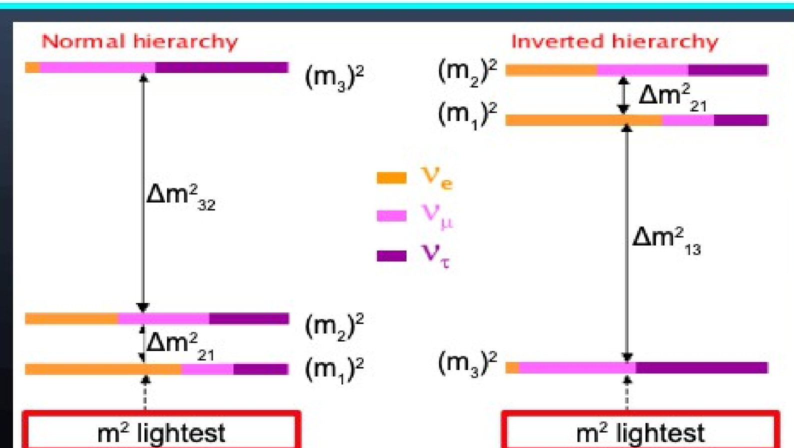
$\theta_{23} \sim 45^\circ$

$\theta_{13} \sim 9^\circ$

$\Delta m^2_{21} \sim 7.5 \times 10^{-5}\ eV^2$

$\Delta m^2_{32} \sim 2.5 \times 10^{-3}\ eV^2$

$\Delta m^2_{ij} = m_i^2 - m_j^2$



Mass Hierarchy

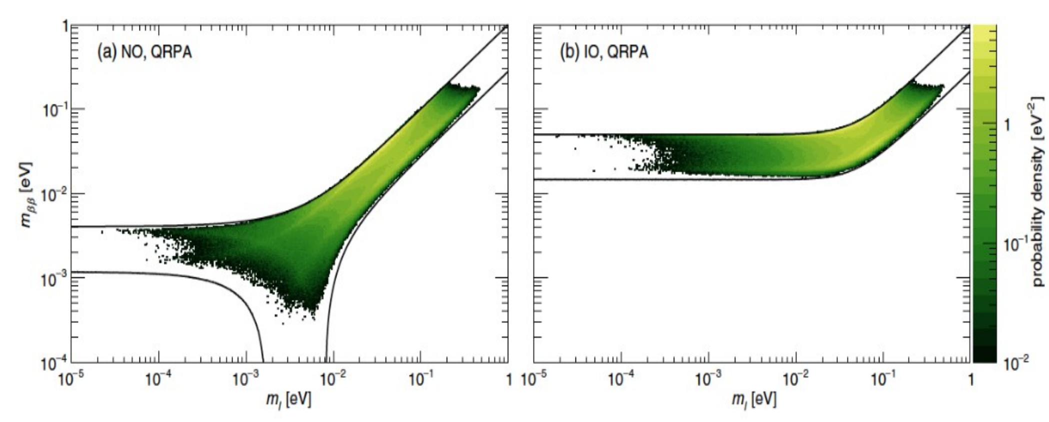
(Some) Things we don't know

Nature **580** 339 344 (2020)

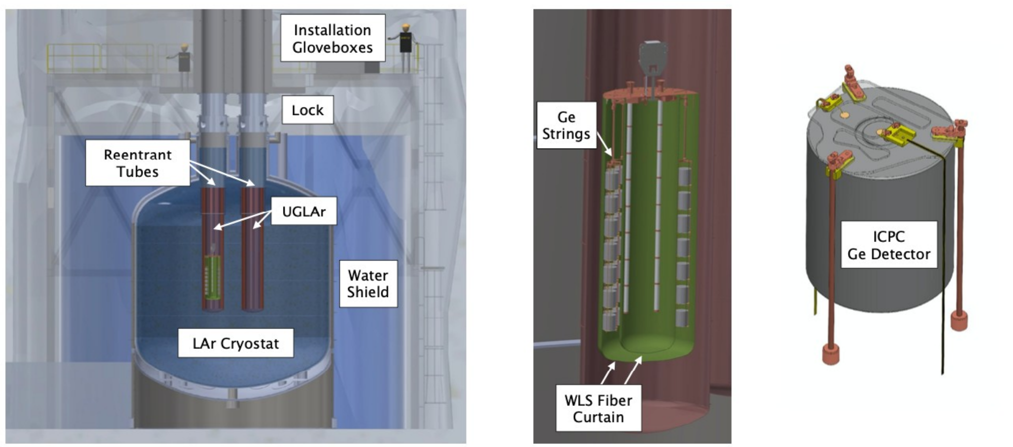
- $\nu = \bar{\nu}$
- m_ν
- ~~CP~~ (CPV)
- mass ordering/hierarchy (MO/MH)
- octant of θ_{23} (not discussed)

Things we don't know: $\nu = \bar{\nu}$

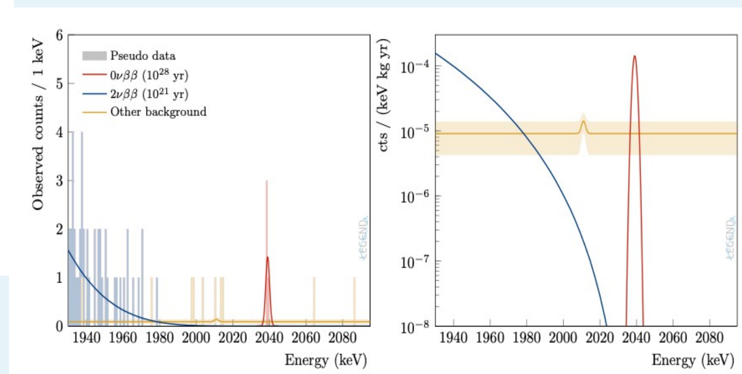
LEGEND200 starting to take calibration data. LEGEND 1000 at CDR stage.



- Current best bounds on $m_{\beta\beta}$ ~ 160-180 meV.
- To probe into IO, need 18.4 meV.
- LEGEND expects to see very little background in ROI and a 3-sigma discovery potential at 15.4 meV.
  - ^{76}Ge, semiconductor detectors.



LEGEND preconceptual design report

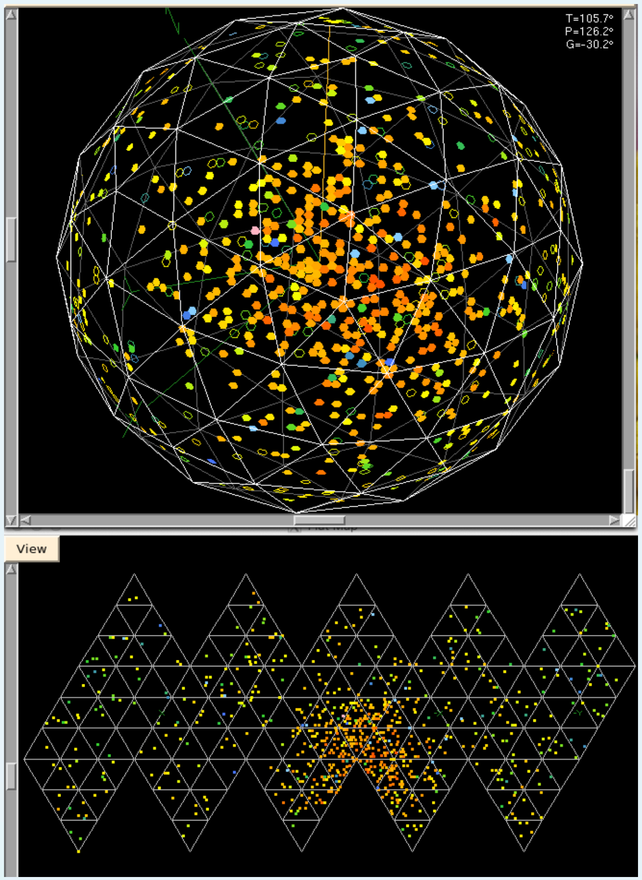


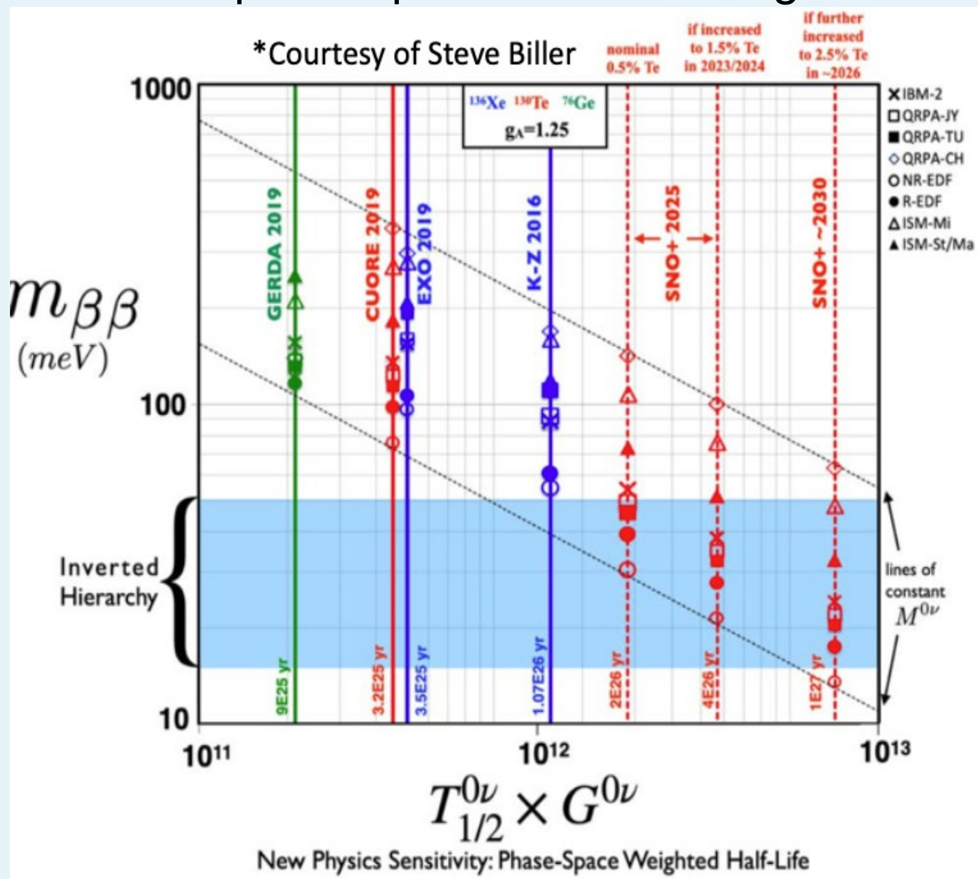
See talks by:
Jamie Grove
Syed Muhammad Adil Hussain
Shengzhao Yu
Pouya Khaghani
Serena Riccetto

Things we don't know: $\nu = \overline{\nu}$

SNO+

- ^{130}Te in liquid scintillator.
  - Easily scalable by adding more Te.
- Expect to probe below IO region.

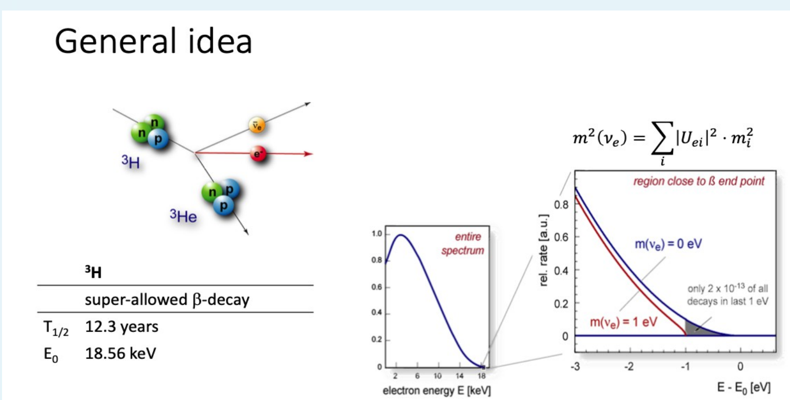




Christopher Grant Neutrino 2020

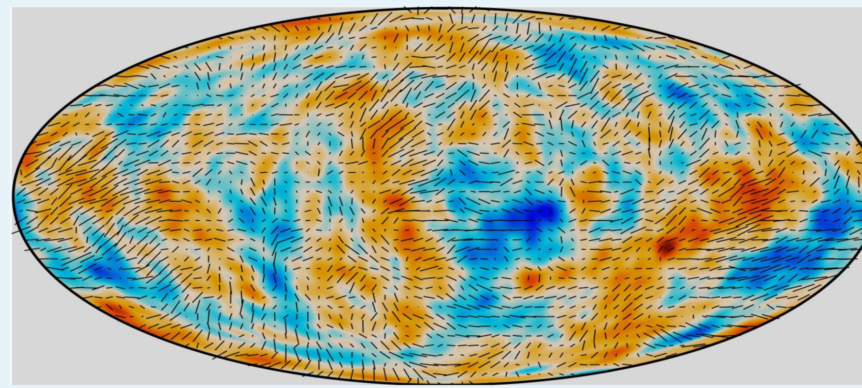
Things we don't know: m_ν

- m_ν < 1.1 eV (90% CL) KATRIN



Suzanne Mertens Neutrino 2020

- Cosmology
  - Planck 2018 □ $\Sigma\, m_\nu$ < 0.26 eV (95% CL)



  - KATRIN plans to reach 0.2 eV

Things we don't know: CPV, MO

T2K NOvA

Appearance

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \times \left(1 \pm \frac{2a}{\Delta m_{31}^2}(1-s_{13}^2)\right)$$ ← Leading term

$$+8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ ← CP Conserving

$$\mp 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\Delta_{32}\sin\Delta_{31}\frac{aL}{4E}(1-2s_{13}^2)$$ ← Matter effect

$$\mp 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ ← CP Violating

$$+4s_{12}^2 c_{13}^2(c_{12}c_{23}+s_{12}^2 s_{13}^2 s_{23}^2 - 2c_{12}c_{23}s_{12}s_{13}s_{23}\cos\delta)\sin^2\Delta_{21}$$ ← Solar term

ν vs. $\bar{\nu}$ sign change

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ $\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$ $a = 2\sqrt{2}G_F n_e E$

θ_{13} dependence | Octant sensitivity | CP-odd phase

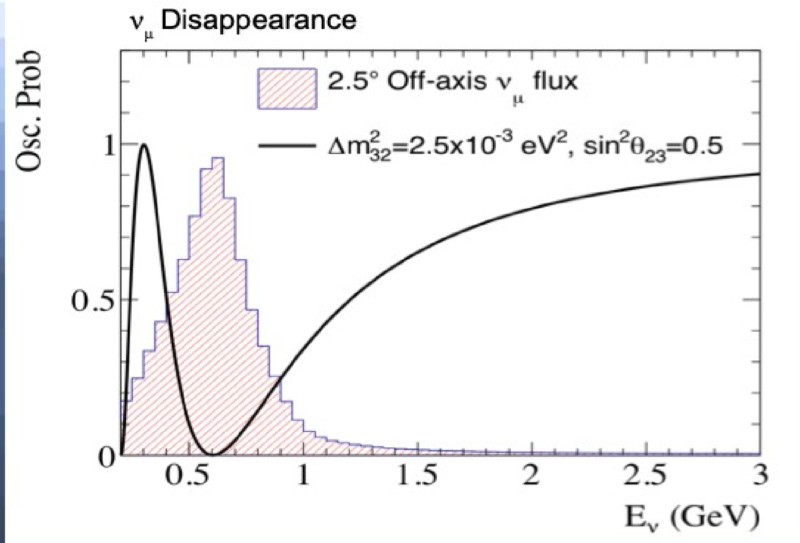
Disappearance

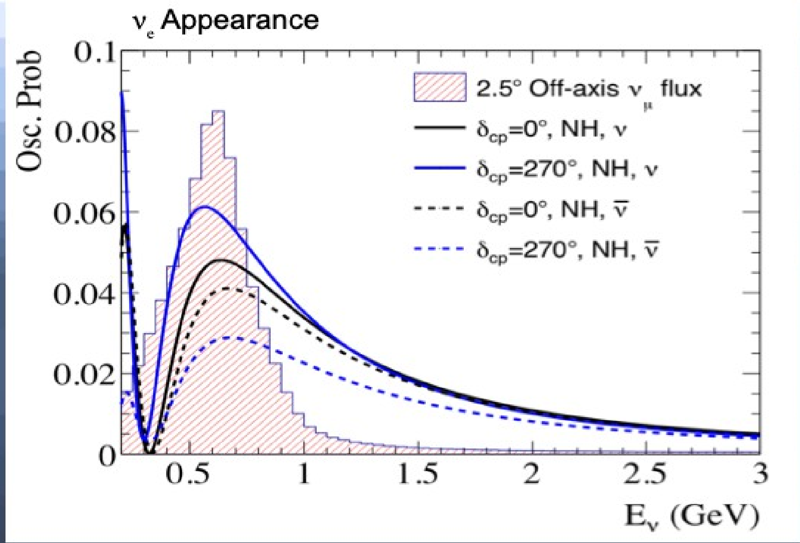
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \left(\cos^4\theta_{13}\cdot\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\cdot\sin^2\theta_{23}\right)\cdot\sin^2\frac{\Delta m_{32}^2 \cdot L}{4E_\nu}$$

(Leading and next terms only)

θ_{23} dependence | Octant sensitivity | $P_{PMNS}(\bar{\nu}_\mu \to \bar{\nu}_\mu) = P_{PMNS}(\nu_\mu \to \nu_\mu)$ Test of CPT

Things we don't know: CPV, MO



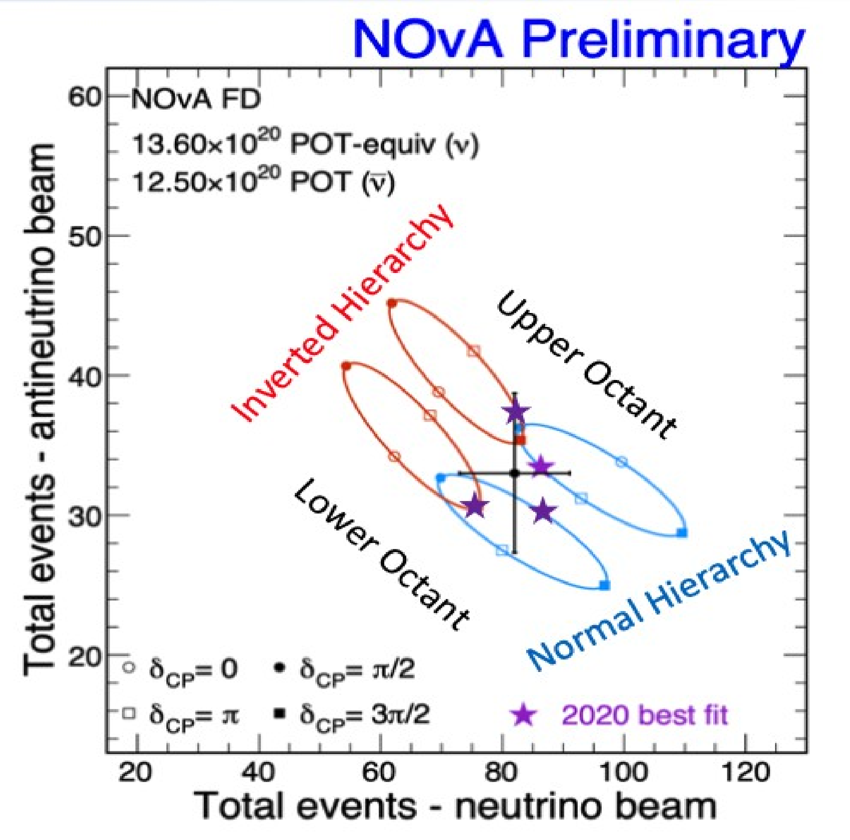


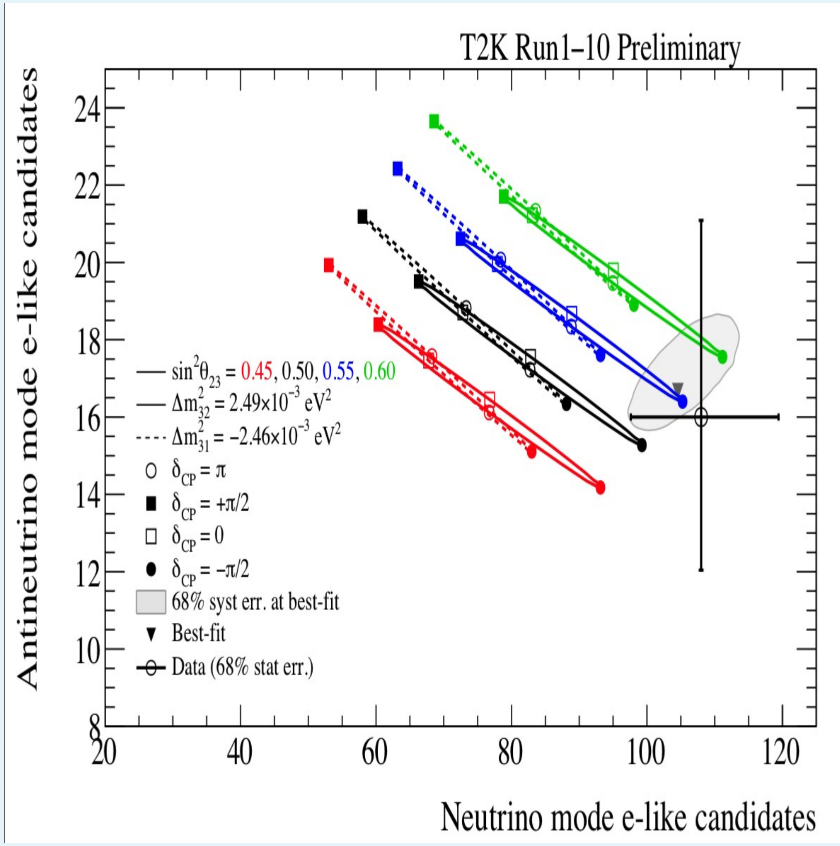
- Tests CPT symmetry
- LO* dependence on $\sin^2 2\theta_{23}$
  - hard to distinguish $\theta_{23}>45°$ from $\theta_{23}<45°$
- LO dependence on $|\Delta m^2_{32}|$
  - doesn't depend on sign of mass splitting

(* Leading Order)

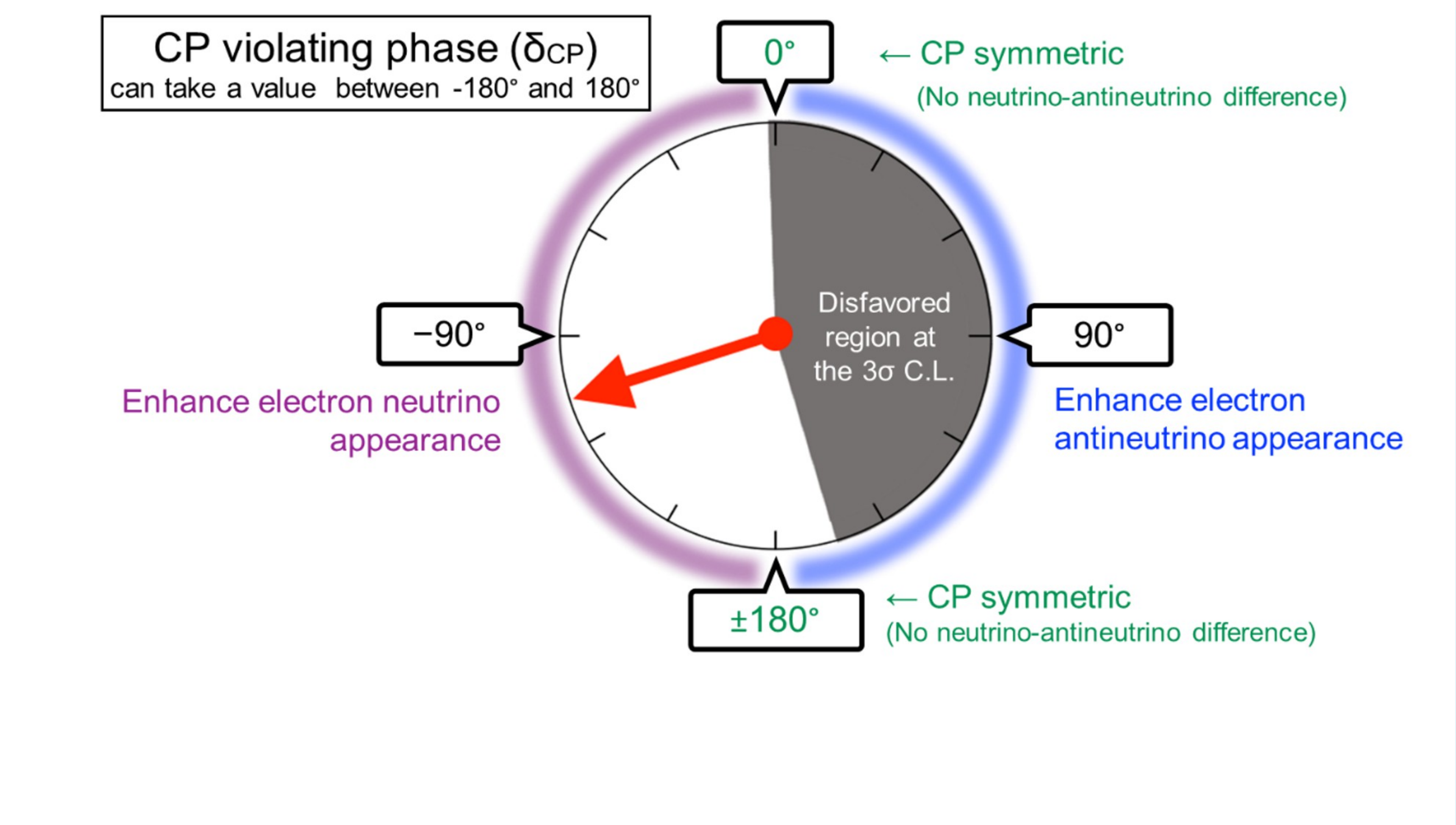
- Tests CP symmetry
- LO dependence on $\sin^2 2\theta_{13}$, $\sin^2\theta_{23}$
  - can separate $\theta_{23}>45°$ from $\theta_{23}<45°$
- Sub-leading dependence on $\sin(\delta_{CP})$
  - can detect CP violation (~27% effect)
- Sub-leading dependence on $\pm\Delta m^2_{32}$
  - ~10% matter effect

Things we don't know: CPV, MO

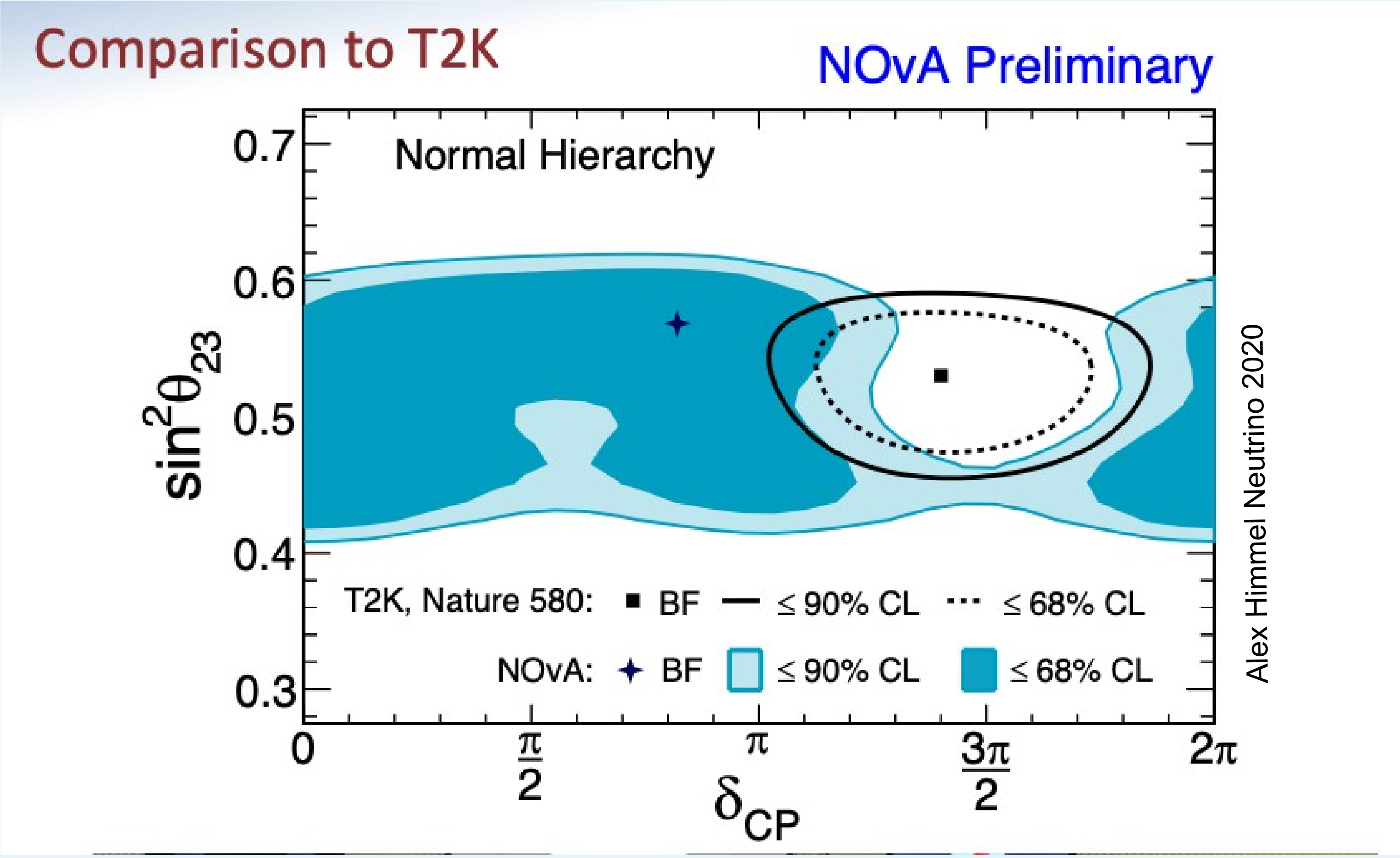




Things we don't know: CPV



Things we don't know: CPV



Future long-baseline experiments

- Reduce both statistical and systematic uncertainties.
  - More powerful beams and larger detectors
    - More neutrinos
  - Better detectors and more near detectors

Hyper-Kamiokande

In construction

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

- ~8 x FD of SK, WC far detector, ~295 km
- high-power beam from JPARC
- new near detectors
  - ND280 upgrade
  - IWCD
- Gd (now also in SK)

- very large liquid Argon (LAr) near/far detectors, ~1300 km
- high-power beam from FNAL
- Proto-DUNE detectors tested at CERN.

Can we help the world?

Science, technology, and the neutrino

"I don't say that the neutrino is going to be a practical thing, but it has been a time-honored pattern that science leads, and then technology comes along, and then, put together, these things make an enormous difference in how we live."

—Fredrick Reines, winner of the Nobel Prize and co-discoverer of the neutrino, NYT interview, 1997

http://library.lanl.gov/cgi-bin/getfile?00326606.pdf

Can we help the world?

A practical thing: ‘near-field’ reactor monitoring

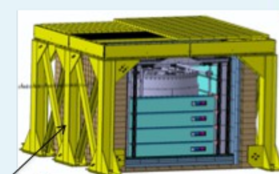
- Monitor reactor operational status, power and fuel consumption and composition
- ‘Near’: less than 1 km, typically 10-100 meters – plant access granted by operators
- High statistics: a few thousand events per day per ton per GWt, sufficient to populate a spectrum
- Reactor power of interest is > ~50-3000 MWt

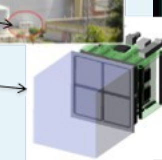
Technology: cubic meter scale scintillator detectors

The Rovno experiment was the first to provide a dedicated monitoring detector in the mid-1980s – based on concepts from Mikelyan (‘77)

Numerous experiments have significantly improved efficiency, resolution and deployability

Group	Country	Technology	Application
SNL/LLNL	USA	Segmented	Compact/Aboveground/Portable
‘PANDA’	Japan		
‘Mars’	UK		
‘CORMORAD	Italy		
‘Nucifer’	France	Gd-doped liquid scintillator	‘Industrial design’
Tohoku U.	Japan		Aboveground
AECL	CA/US		CANDU reactor
Angra	Brazil	Gd-doped Water	Aboveground
Niigata U.	Japan	Gd-doped Plastic	Deployable
U. Hawaii	USA	Fast Liquid Scint.	Directional





Can we help the world?

A not-yet-practical, but still promising thing: ‘far-field’’ reactor monitoring

- Monitor, find indications of, or exclude the existence of, operating reactors
- ‘Far’: more than 1 km, less than 200 km with megaton detectors, 1000 km only with directionality in megaton detectors – varying degrees of access
- low statistics: a few events per week, month or year
- Reactor power ~50 MWt – roughly generating 8 kg/one ‘Significant Quantity’ per year (SQ = international standard for monitoring)

Technology: Variations on KamLAND, Super-Kamiokande, Borexino and other large detectors

Can we help the world?

The Advanced Instrumentation Testbed (AIT) is the location of the world's first dedicated remote reactor monitoring demonstration - 'Neutrino Experiment One, or NEO

- AIT is a site and and organizational structure that will enable real-world, at-scale testing of enhanced antineutrino-based monitoring technologies for nuclear reactors
- AIT will house NEO and follow-on experiments for nonproliferation or physics – NE2,NEn...
- **The Boulby Mine in Northern England is the preferred deployment location for AIT**
- AIT requires **new excavation** of a 25 meter cylindrical cavern to accommodate the first neutrino experiment

Can we help the world?

Neutrino Experiment 1 at AIT

Main Project Objectives:

- Demonstrate monitoring at a single reactor complex
  - at 25 km standoff
  - With a kiloton-scale Gd-H_2O or Gd-WbLS detector
- At-scale test-bed for advances in large water-based detectors relevant for fundamental physics and nonproliferation

HARTLEPOOL Reactors

- 2 cores
- 1570 MWt per core
- 25 km standoff

Doping the water with gadolinium greatly increases sensitivity to inverse beta interactions of antineutrinos

$$\bar{\nu} + p \rightarrow e^{+} + n$$

A high-level look at the experiment

- Water Cherenkov detector, doped with gadolinium and/or scintillator (Gd-WbLS)
- 16-20 m cylindrical detector with veto and buffer regions
- kiloton scale fiducial inside buffer
- several thousand PMTs

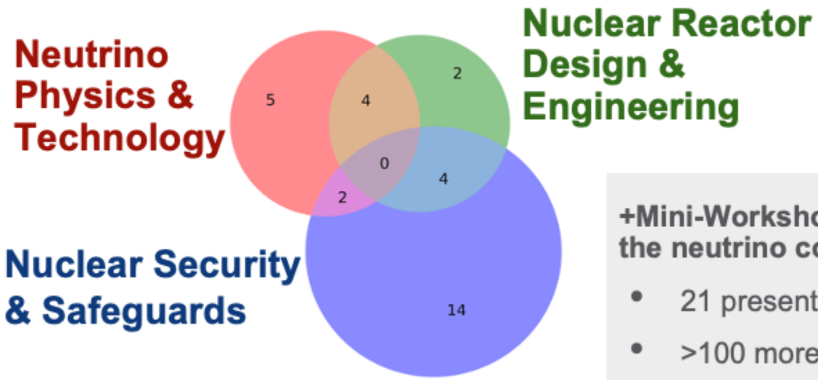
Can we help the world?

Nu Tools: Exploring Practical Roles For Neutrinos In Nuclear Energy And Security

In FY20, a committee of US DOE National Lab scientists and academics were charged by the DOE NNSA Office of Defense Nuclear Nonproliferation Research and Development:

> *"...to facilitate broad engagement with interested communities on the topic of antineutrino-based monitoring of nuclear reactors and associated post-irradiation fuel cycle activities. The particular focus... should be on the* ***potential utility of antineutrino detection technologies****… in the context of existing or potential policy needs."*

Stakeholders interviewed across multiple sectors:



+Mini-Workshop with the neutrino community:

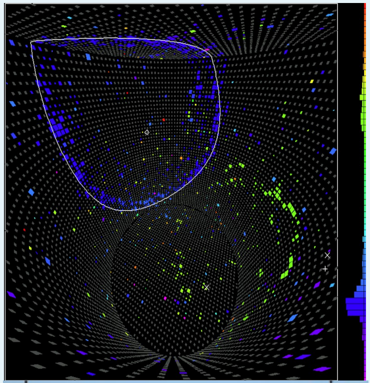
- 21 presenters
- >100 more attendees

Utility criteria	*Determined by...*
Need for a new or improved capability	*… End user*
Existence of a neutrino signal	*… Tech development community*
Availability of a neutrino detection technology	*… Tech development community*
Compatibility with implementation constraints	*… End user*

Final Report to be released to the public at the INMM Annual Meeting on August 31, 2021

Things not covered here

- Neutrinos in multimessenger astronomy.
  - IceCube/DeepCore.
- Detection of neutrinos from the CNO cycle
  - Borexino.
- Reactor neutrinos
  - RENO, Double Chooz, Daya Bay, (JUNO).
- Astrophysical neutrinos
  - Antares, KM3Net.
- Farther-future experiments
  - Theia, HKK
- and a lot more!



Summary and Conclusion

- Key questions about neutrinos are as yet unanswered BUT some tantalising hints are beginning to emerge (normal mass ordering, CPV, θ_{23} upper octant).
  - will they remain?
- Setting better and better limits on the paramaters of 0νββ. "Discovery" sensitivities in next-generation experiments.
- Neutrino experiments/detectors are contributing to a broad range of physics (not covered here)
  - multimessenger astronomy, UHE neutrinos, SN neutrinos, etc.
- There's a lot to do.