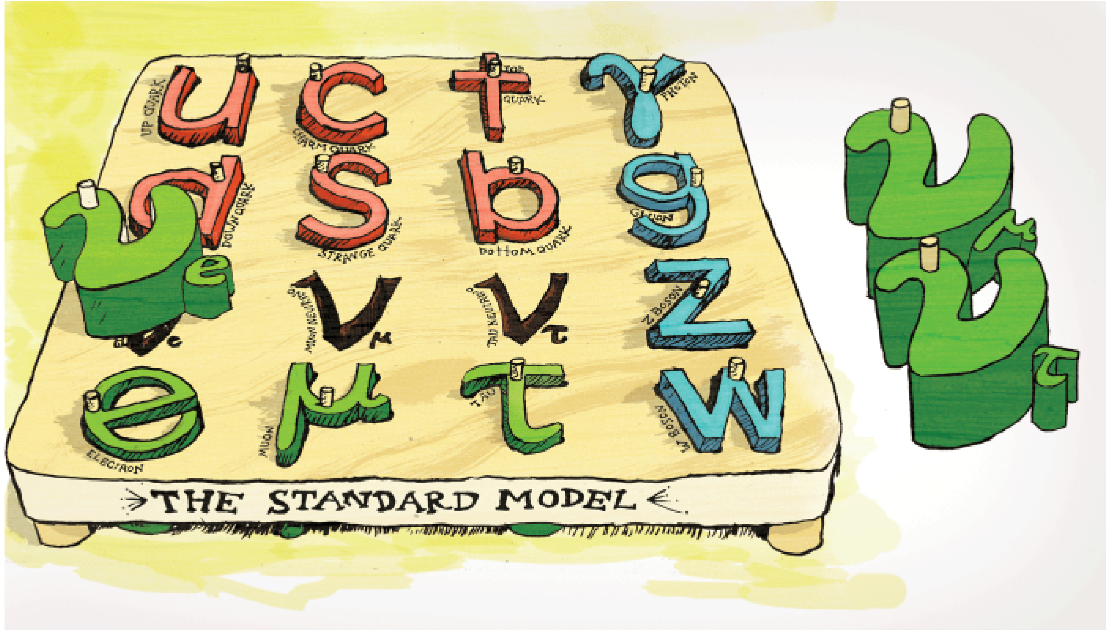
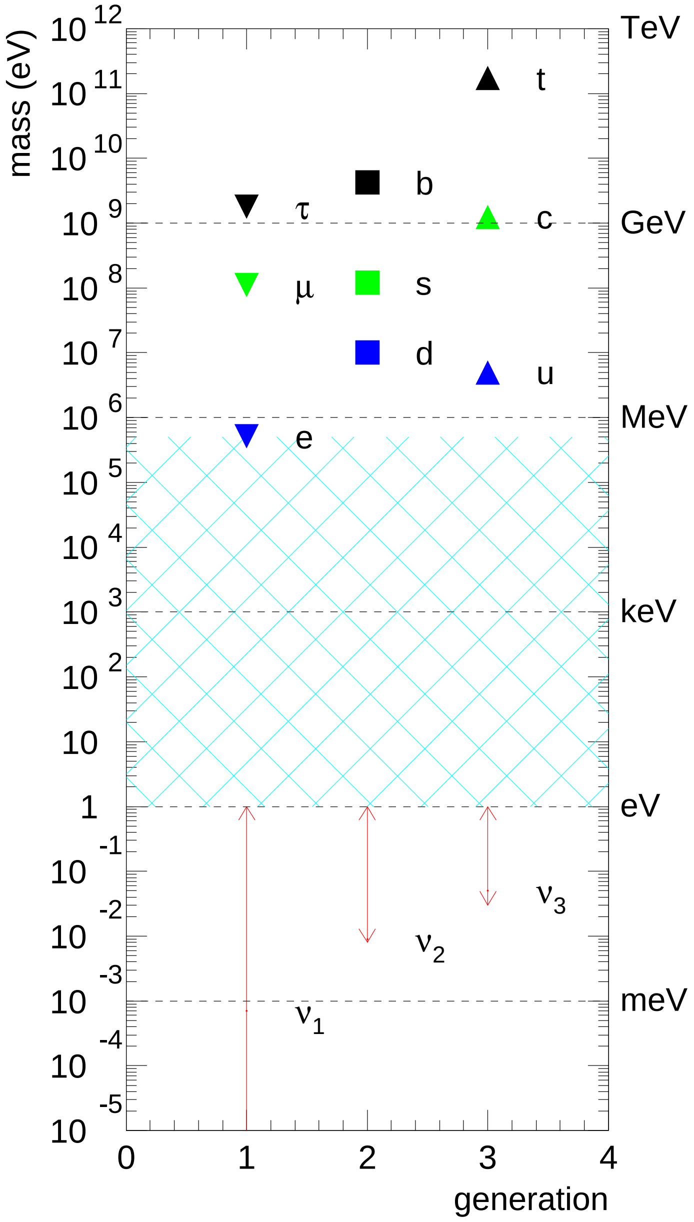
“Pursue the Physics Associated with Neutrino Mass” – 5-Year Update



André de Gouvêa – Northwestern University

HEPAP Meeting, Betheda, MA

November 21–22, 2019



What We Are Trying To Understand:

$\Leftarrow$ **NEUTRINOS HAVE TINY MASSES**

$\Downarrow$ **LEPTON MIXING IS "WEIRD"** $\Downarrow$

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

$\boxed{\textbf{What Does It Mean?}}$

Neutrino Masses: Only* "Palpable" Evidence of Physics Beyond the Standard Model

Nonzero neutrino masses imply new degrees of freedom. We don't know what they are nor what are their masses. They may be very light sterile fermions, very heavy sterile fermions, a Higgs boson triplet, a set of new charged fermions and scalars with TeV masses, new vector bosons, etc.

Ultimately, the SM has to be replaced by something qualitatively different.

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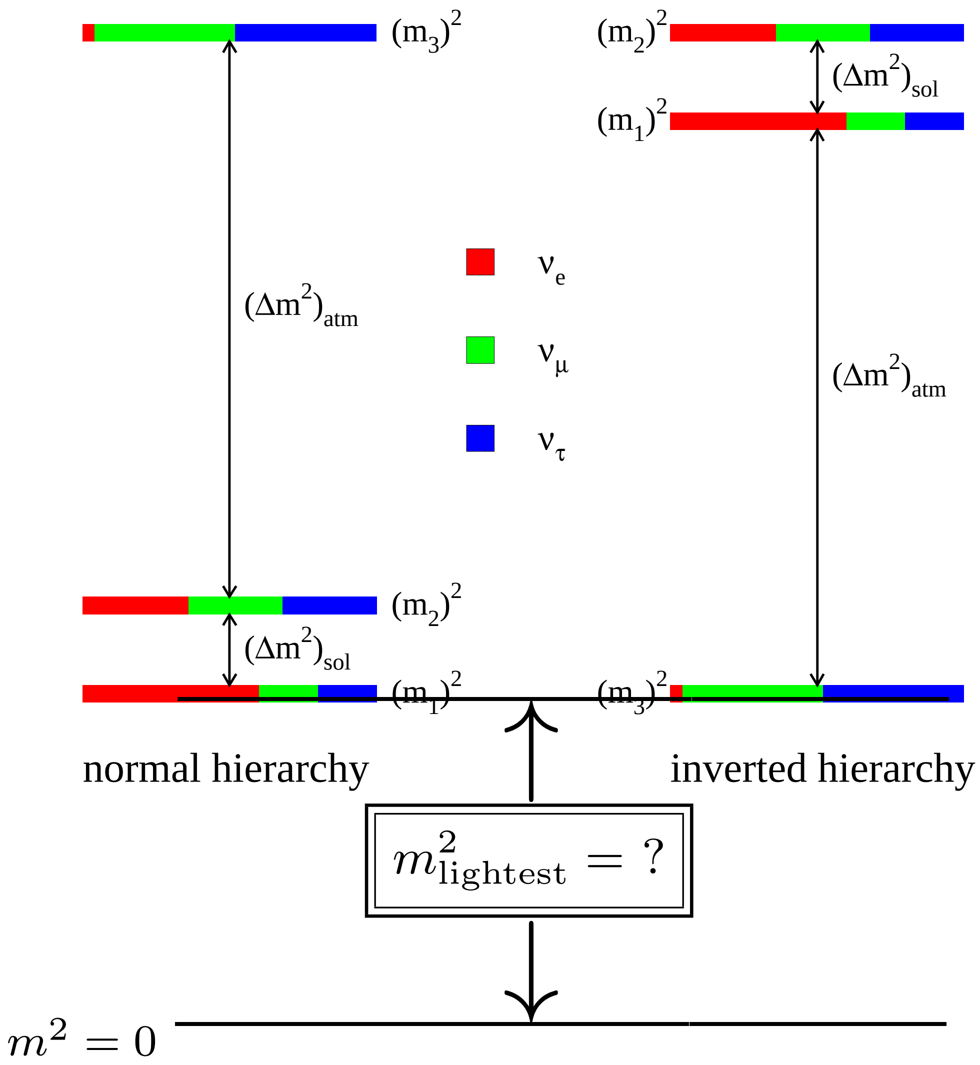
* There is only a handful of questions our model for fundamental physics cannot explain (these are personal. Feel free to complain).

- What is the physics behind electroweak symmetry breaking? (Higgs ✓).
- What is the dark matter? (not in SM).
- Why is there so much ordinary matter in the universe? (not in SM).
- Why does the Universe appear to be accelerating? Why does it appear that the Universe underwent rapid acceleration in the past? (not in SM).

What We Know We Don't Know: How Light is the Lightest Neutrino?



So far, we've only been able to measure neutrino mass-squared differences.

The lightest neutrino mass is only poorly constrained: $m^2_{\text{lightest}} < 1$ eV^2

qualitatively different scenarios allowed:

- $m^2_{\text{lightest}} \equiv 0$;
- $m^2_{\text{lightest}} \ll \Delta m^2_{12,13}$;
- $m^2_{\text{lightest}} \gg \Delta m^2_{12,13}$.

Need information outside of neutrino oscillations:

$\rightarrow$ cosmology, β-decay, $0\nu\beta\beta$

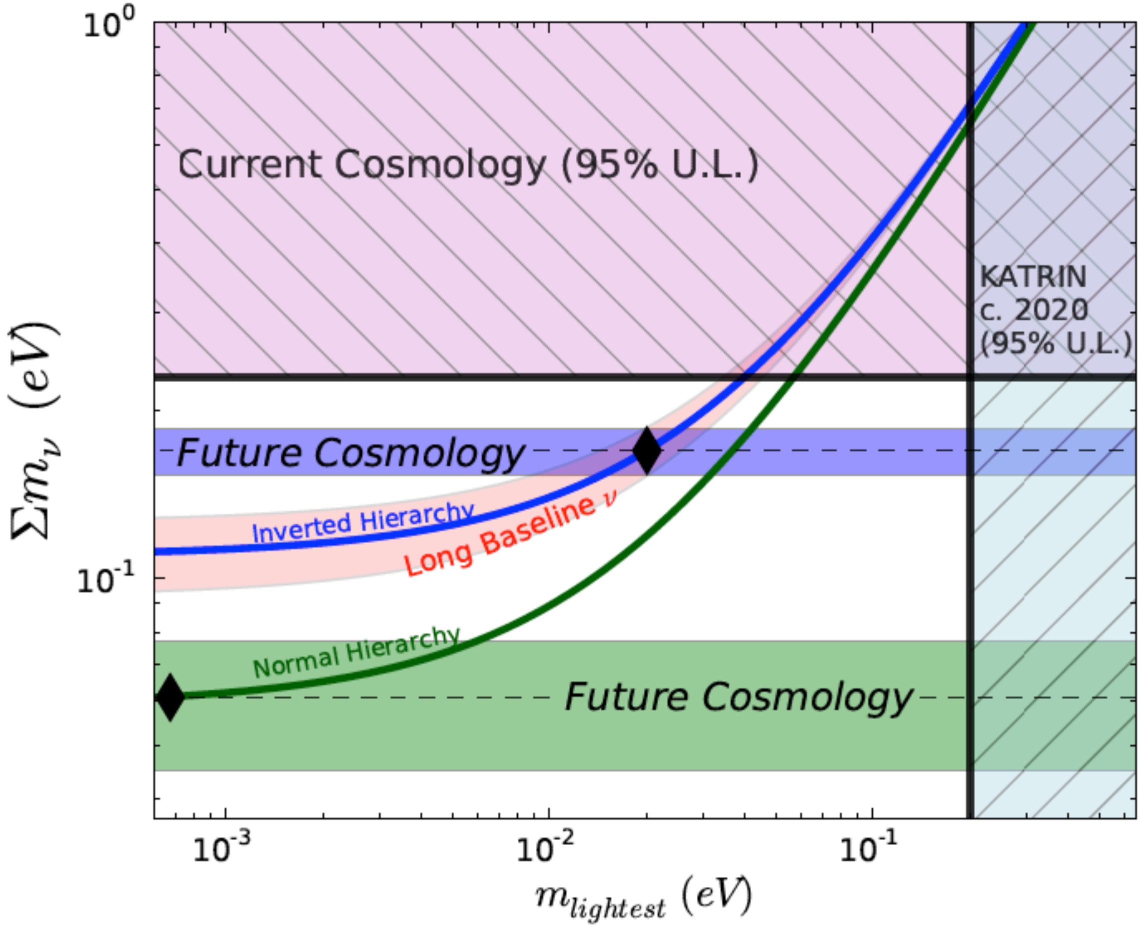


Figure 7. *Current constraints and forecast sensitivity of cosmology to the sum of neutrino masses. In the case of an "inverted hierarchy," with an example case marked as a diamond in the upper curve, future combined cosmological constraints would have a very high-significance detection, with 1-σ error shown as a blue band. In the case of a normal neutrino mass hierarchy with an example case marked as diamond on the lower curve, future cosmology would still detect the lowest $\sum m_\nu$ at greater than 3-σ.*

[K. Abazajian *et al.* arXiv:1309.5386]

New in 2019 (finally!): The Karlsruhe Tritium Neutrino (KATRIN) Experiment:

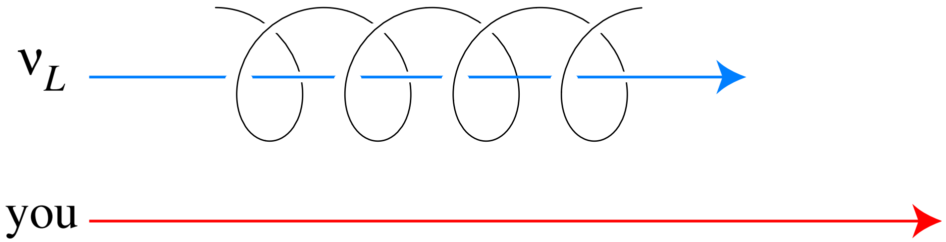
(not your grandmother's table top experiment!)

$\boxed{\text{sensitivity } m^2_{\nu_e} > (0.2 \text{ eV})^2}$

NEW DEVELOPMENTS:

- Project 8 – long term R&D project to measure the energy of the β-ray in situ. Improve on KATRIN by a factor of 5 (ultimately needs atomic tritium).
- PTOLEMY – ultimate goal is to measure the cosmic neutrino background. Measurement of tritium spectrum as a "side-effect."

What We Know We Don't Know: Are Neutrinos Majorana Fermions?

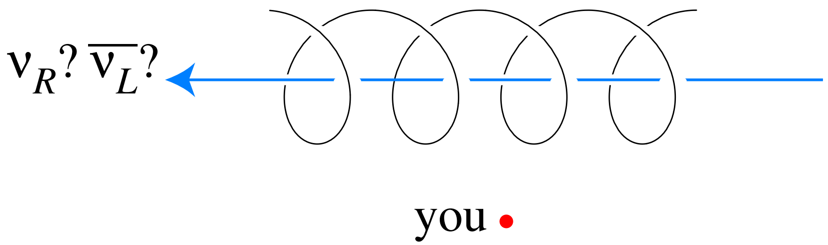


A massive charged fermion (s=1/2) is described by 4 degrees of freedom:

$$(e^-_L \leftarrow \text{CPT} \rightarrow e^+_R)$$
$$\updownarrow \text{ “Lorentz”}$$
$$(e^-_R \leftarrow \text{CPT} \rightarrow e^+_L)$$

A massive neutral fermion (s=1/2) is described by 4 or 2 degrees of freedom:

$$(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R)$$
$$\updownarrow \text{ “Lorentz”} \qquad \text{‘DIRAC’}$$
$$(\nu_R \leftarrow \text{CPT} \rightarrow \bar{\nu}_L)$$



‘MAJORANA’

$$(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R)$$
$$\updownarrow \text{ “Lorentz”}$$
$$(\bar{\nu}_R \leftarrow \text{CPT} \rightarrow \nu_L)$$

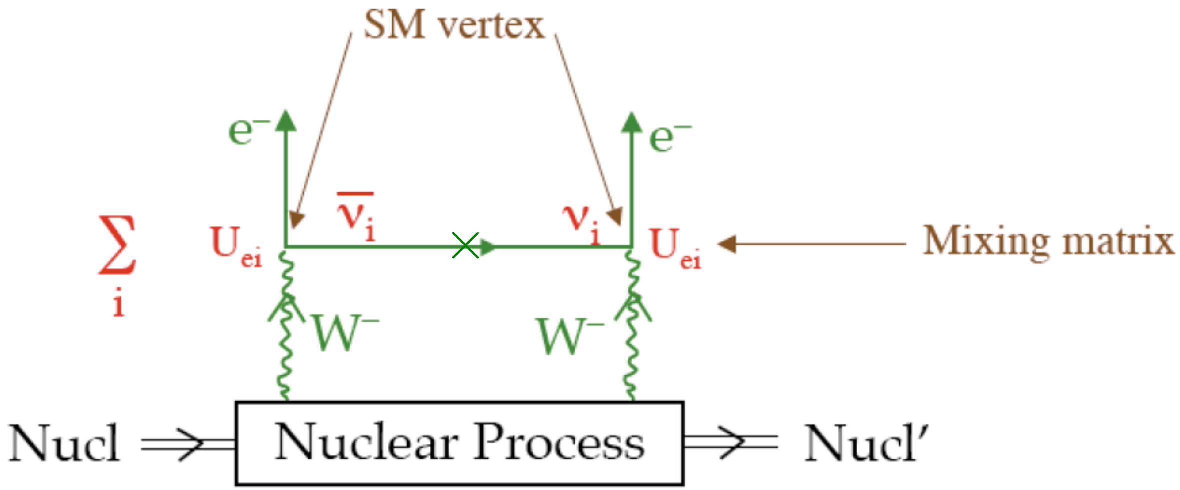
How many degrees of freedom are required to describe massive neutrinos?

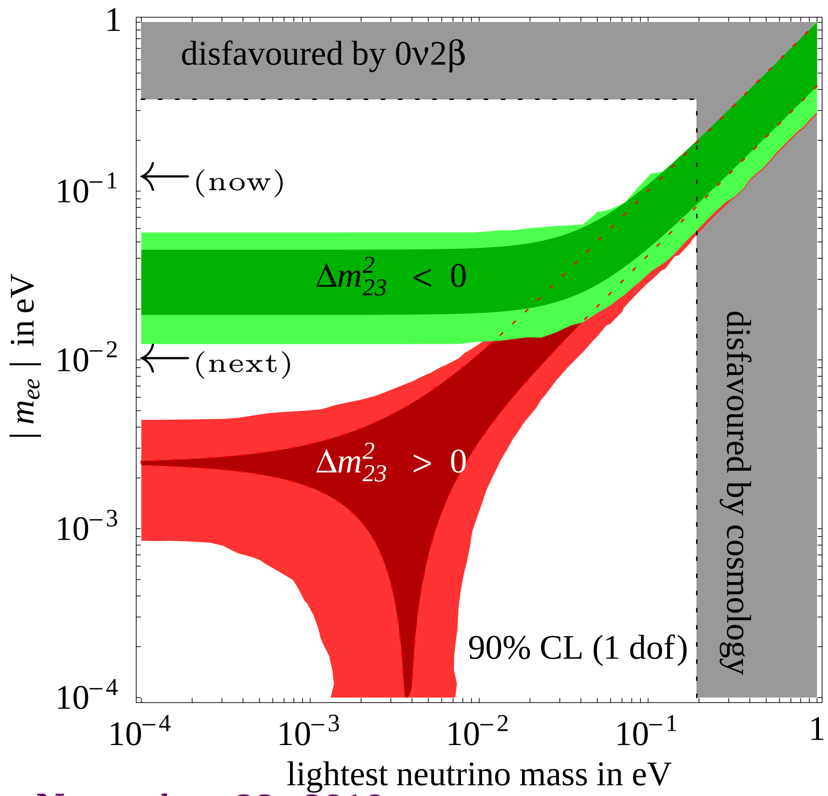
Search for the Violation of Lepton Number (or $B-L$)

Best Bet: search for

Neutrinoless Double-Beta

Decay: $\boxed{Z \to (Z+2)e^- e^-}$





Helicity Suppressed Amplitude $\propto \frac{m_{ee}}{E}$

Observable: $m_{ee} \equiv \sum_i U_{ei}^2 m_i$

$\Leftarrow$ **not "lamp-post" physics!**

NEW DEVELOPMENTS:

- "Second" results from current generation of experiments: KamLAND-ZEN, EXO, GERDA, CUORE;
- Some progress on nuclear matrix elements. Lattice effort on $nn \to ppee$;
- Robust plans to reach the bottom of the inverted hierarchy in progress;
- Ideas about the normal-hierarchy;
- Daughter tagging;
- New target when/if cosmic surveys measure a nonzero neutrino mass?

Understanding Neutrino Oscillations

- After twenty years, it is still true that we have only managed to observe the effect of non-zero neutrino masses in neutrino oscillations.
- There are still many outstanding questions, and there is still room – with a lot of effort from theorists and experimentalists, including nuclear physicists – to do qualitatively better.
- It stands to reason that pursing a vigorous neutrino oscillation program is a no brainer.
- How will these experiments inform the neutrino mass puzzle? We don't know.
- Can these experiments inform the neutrino mass puzzle? Absolutely. We won't know the answer until we are done.

Three Flavor Mixing Hypothesis Fits All* Data Really Well.

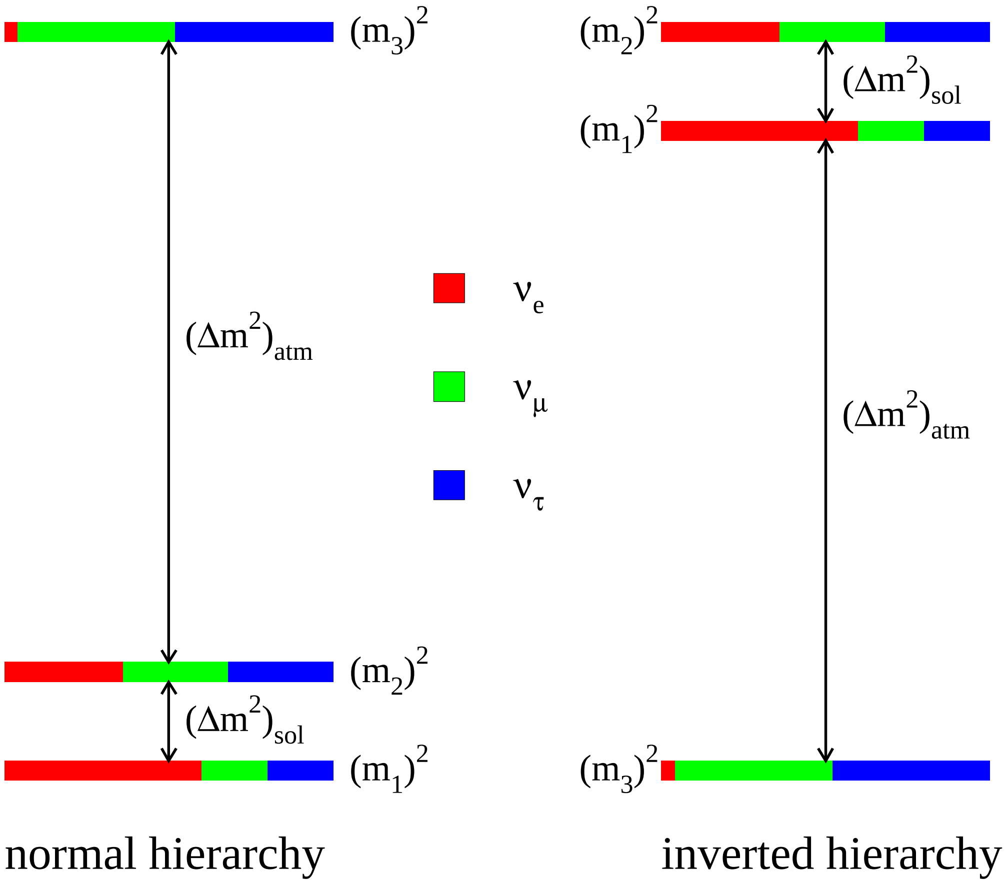
NuFIT 3.2 (2018)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$	$33.62^{+0.78}_{-0.76}$	$31.43 \to 36.06$	$31.42 \to 36.05$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$	$0.554^{+0.023}_{-0.033}$	$0.435 \to 0.616$	$0.418 \to 0.613$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$	$48.1^{+1.4}_{-1.9}$	$41.3 \to 51.7$	$40.3 \to 51.5$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.01981 \to 0.02436$	$0.02227^{+0.00074}_{-0.00074}$	$0.02006 \to 0.02452$	$0.01981 \to 0.02436$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$	$8.09 \to 8.98$
$\delta_{CP}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$	$144 \to 374$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$	$\begin{bmatrix}+2.399 \to +2.593 \\ -2.536 \to -2.395\end{bmatrix}$

[Esteban *et al*, JHEP 01 (2017) 087, http://www.nu-fit.org]

*Modulo the short-baseline anomalies.

Understanding Neutrino Oscillations: Are We There Yet? [NO!]

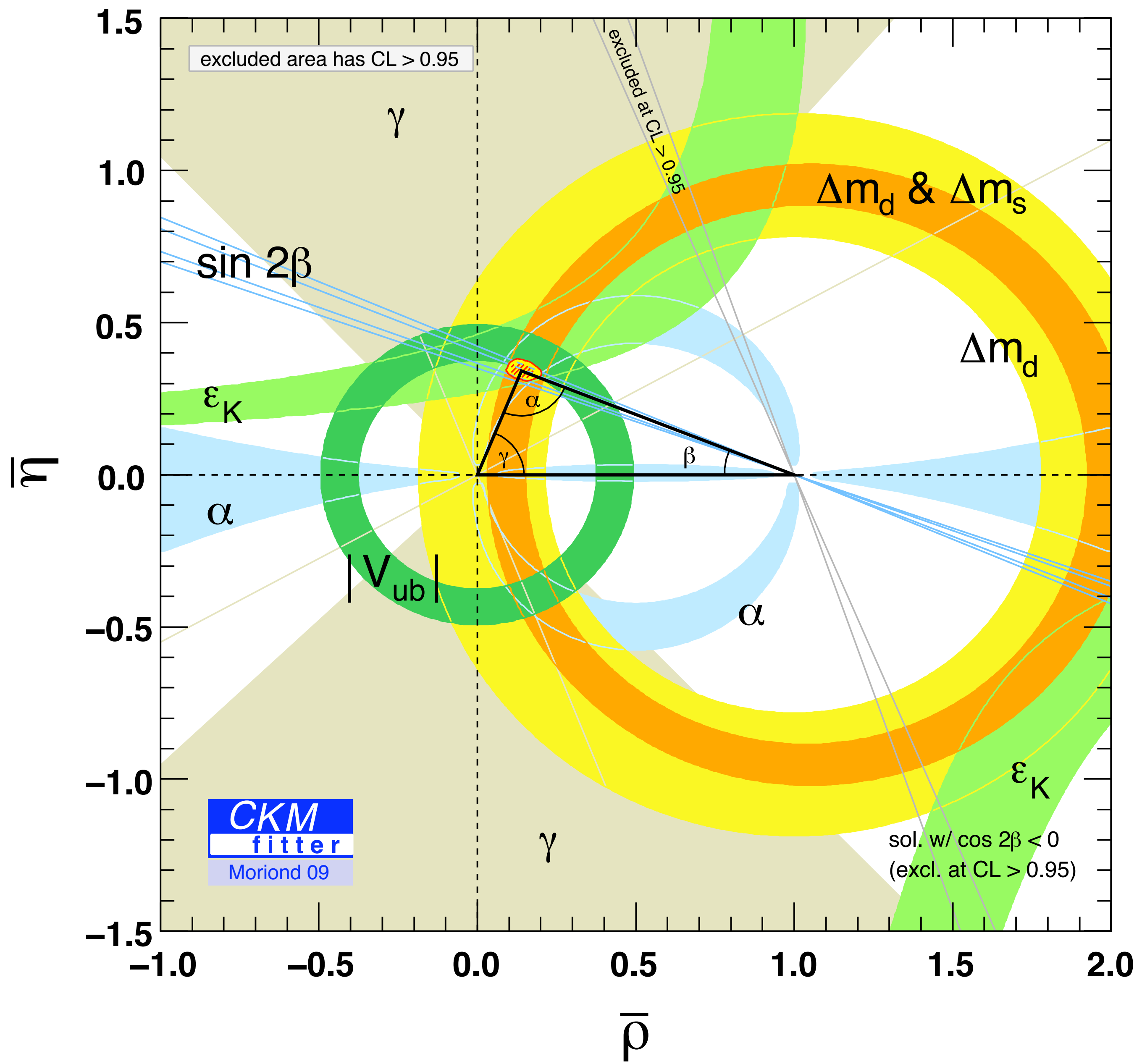


- ~~What is the ν_e component of ν_3?~~ ($\theta_{13} \neq 0$!)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?) ['yes' hint]
- Is ν_3 mostly ν_μ or ν_τ? [$\theta_{23} \neq \pi/4$ hint]
- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?) [NH hint]

$\Rightarrow$ All of the above can "only" be addressed with new neutrino oscillation experiments

Ultimate Goal: Not Measure Parameters but Test the Formalism (Over-Constrain Parameter Space)

What we ultimately want to achieve:



We need to do this in the lepton sector!

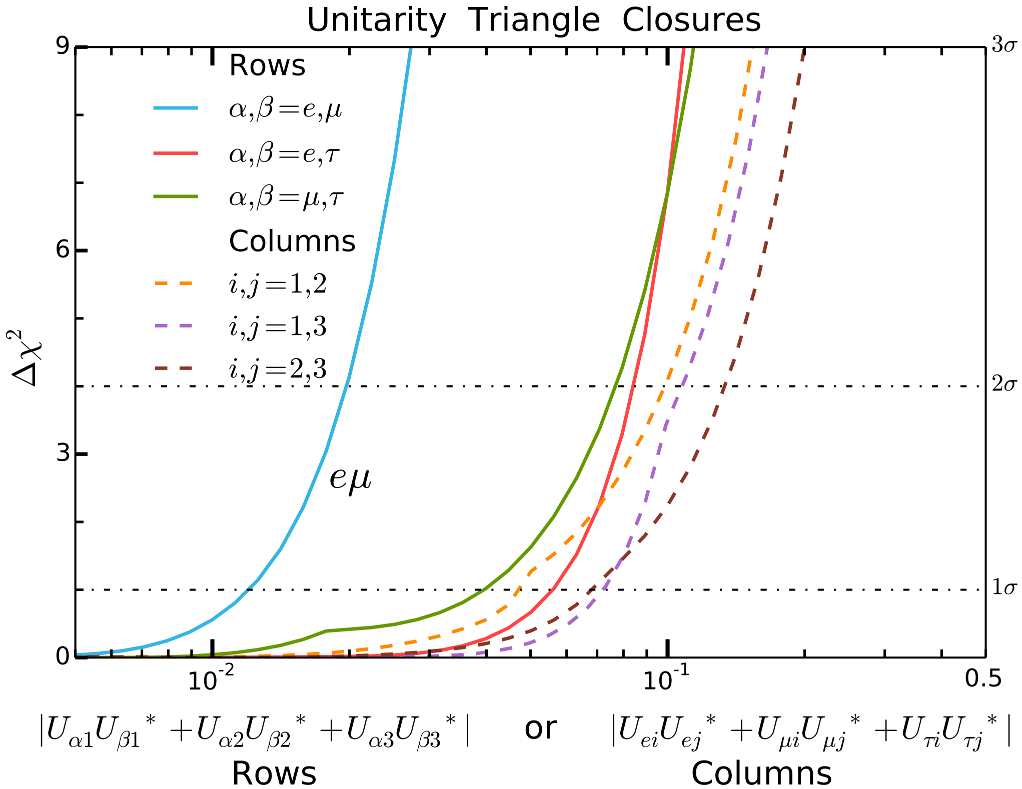
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

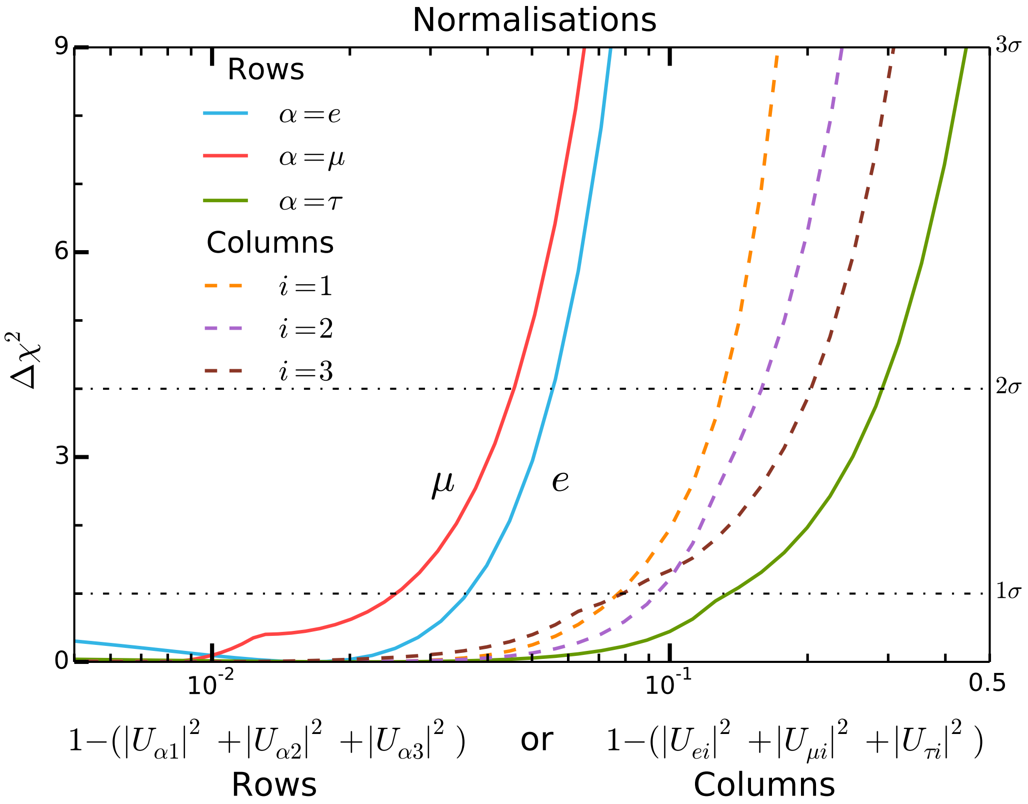
What we have **really measured** (very roughly):

- Two mass-squared differences, at several percent level – many probes;
- $|U_{e2}|^2$ – solar data;
- $|U_{\mu 2}|^2 + |U_{\tau 2}|^2$ – solar data;
- $|U_{e2}|^2 |U_{e1}|^2$ – KamLAND;
- $|U_{\mu 3}|^2 (1 - |U_{\mu 3}|^2)$ – atmospheric data, K2K, MINOS, T2K, NOνA;
- $|U_{e3}|^2 (1 - |U_{e3}|^2)$ – Double Chooz, Daya Bay, RENO;
- $|U_{e3}|^2 |U_{\mu 3}|^2$ – MINOS, T2K, NOνA;
- $|U_{\mu 3}|^2 |U_{\tau 3}|^2$ (evidence) – atmospheric data, OPERA.

We still have a ways to go!

A little more quantitative:

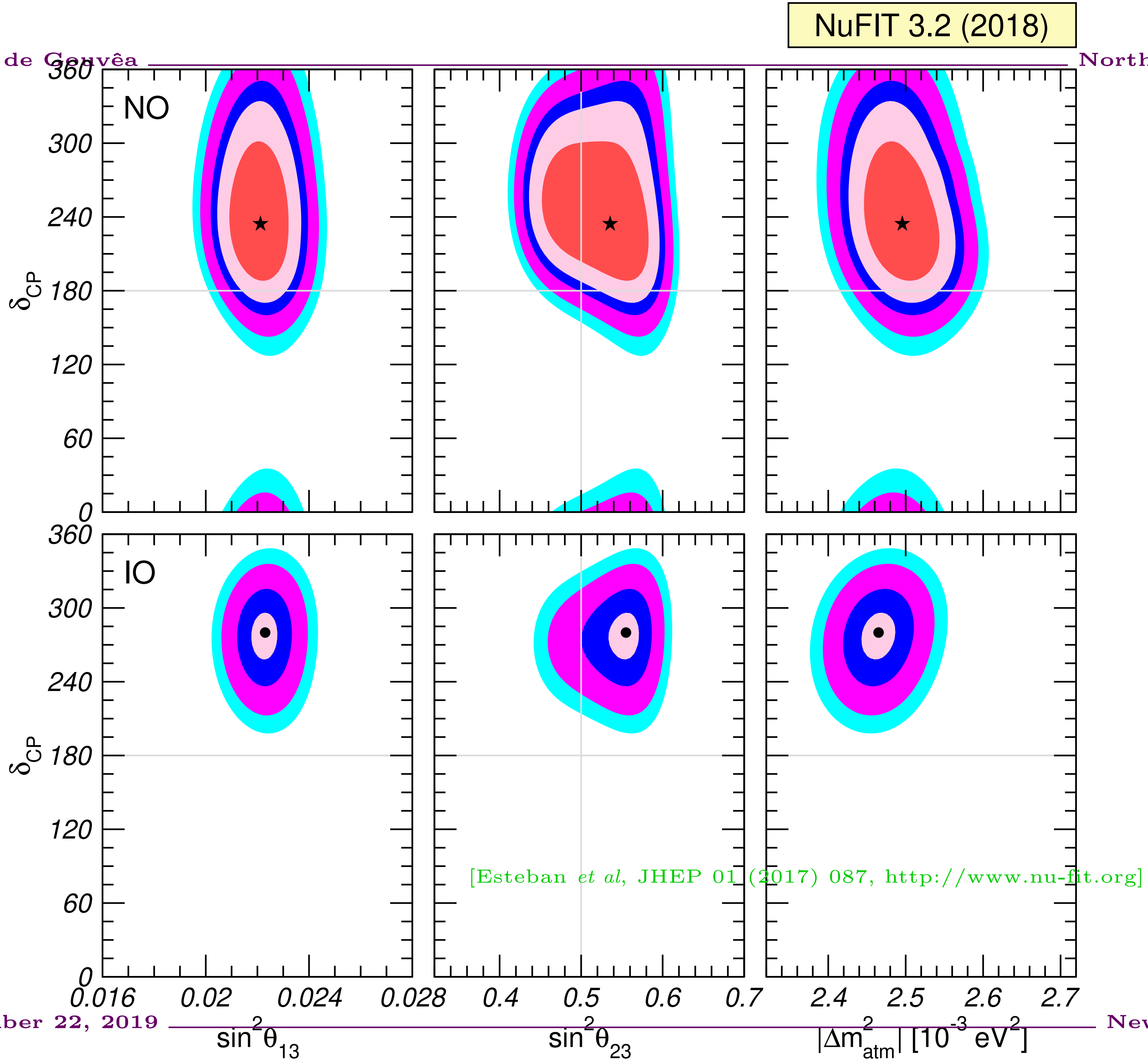


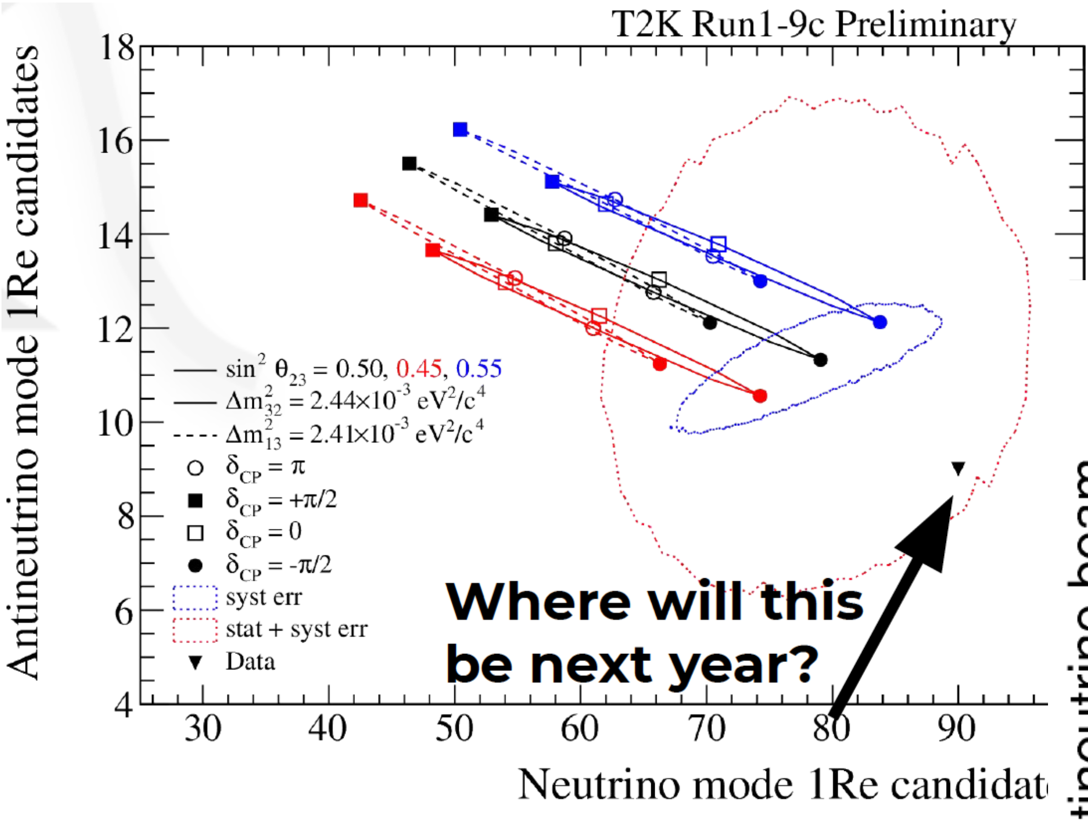


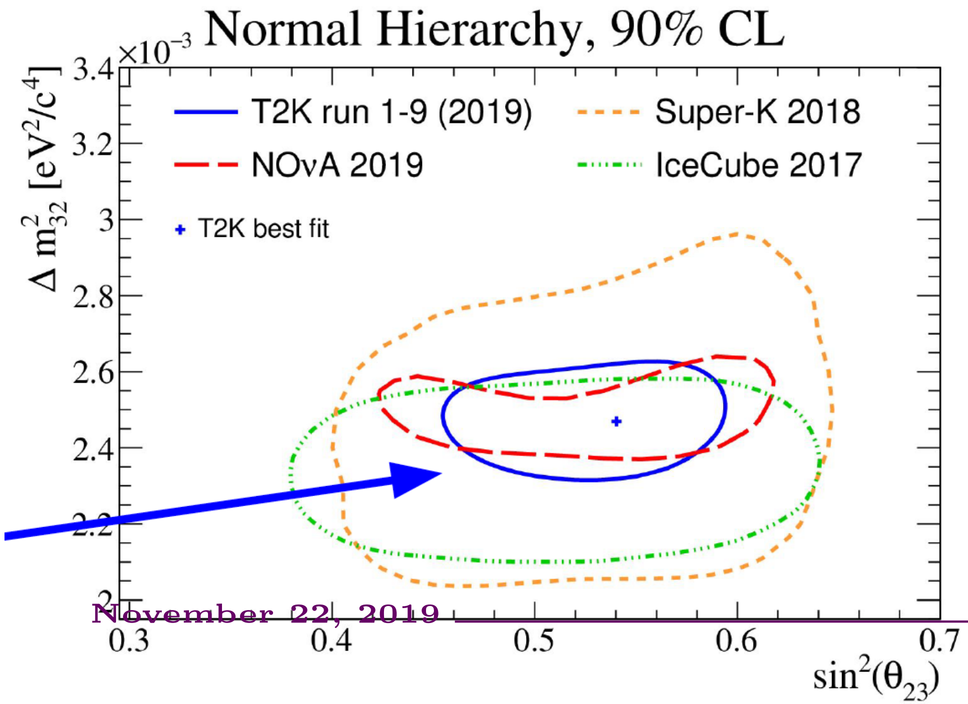
[Parke and Ross-Lonergan, arXiv:1508.05095]

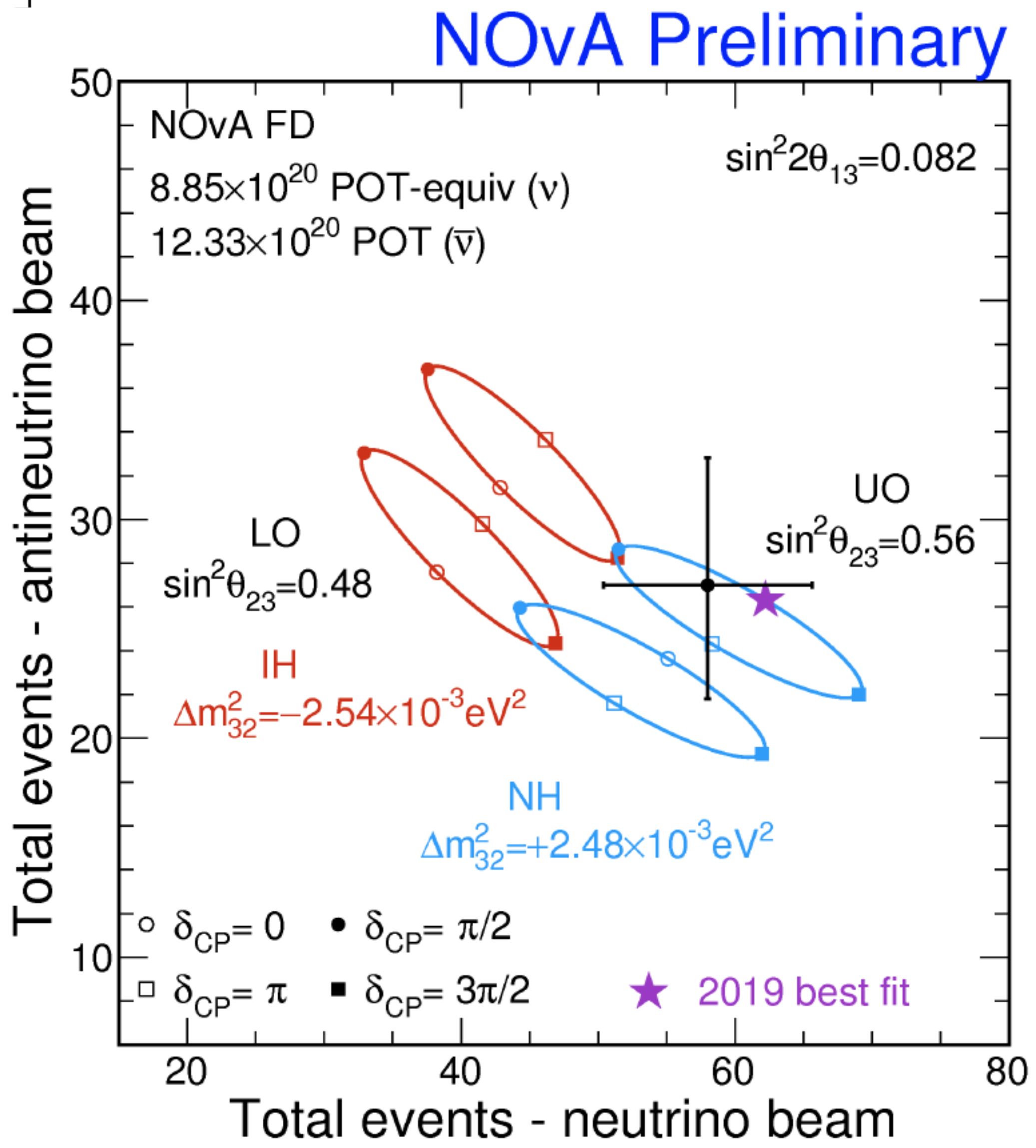
What Could We Run Into?

- New neutrino states. In this case, the 3×3 mixing matrix would not be unitary.
- New short-range neutrino interactions. These lead to, for example, new matter effects. If we don't take these into account, there is no reason for the three flavor paradigm to "close."
- New, unexpected neutrino properties. Do they have nonzero magnetic moments? Do they decay? The answer is 'yes' to both, but nature might deviate dramatically from νSM expectations.
- Weird stuff. CPT-violation. Decoherence effects (aka "violations of Quantum Mechanics.")
- etc.


NuFIT 3.2 (2018)
NO
IO
δ_{CP}
0
60
120
180
240
300
360
0.016
0.02
0.024
0.028
0.4
0.5
0.6
0.7
2.4
2.5
2.6
2.7
$\sin^2\theta_{13}$
$\sin^2\theta_{23}$
$|\Delta m^2_{atm}|$ [10^{-3} eV^2]
[Esteban *et al*, JHEP 01 (2017) 087, http://www.nu-fit.org]

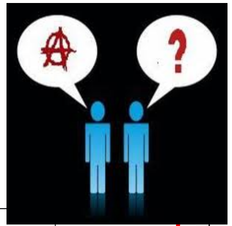

T2K Run1-9c Preliminary
Antineutrino mode 1Re candidates
Neutrino mode 1Re candidat
$\sin^2\theta_{23}$ = 0.50, 0.45, 0.55
$\Delta m^2_{32} = 2.44\times10^{-3}$ eV^2/c^4
$\Delta m^2_{13} = 2.41\times10^{-3}$ eV^2/c^4
$\delta_{CP} = \pi$
$\delta_{CP} = +\pi/2$
$\delta_{CP} = 0$
$\delta_{CP} = -\pi/2$
syst err
stat + syst err
Data
Where will this be next year?


Normal Hierarchy, 90% CL
Δm^2_{32} [eV^2/c^4]
$\times10^{-3}$
T2K run 1-9 (2019)
Super-K 2018
NOvA 2019
IceCube 2017
T2K best fit
$\sin^2(\theta_{23})$

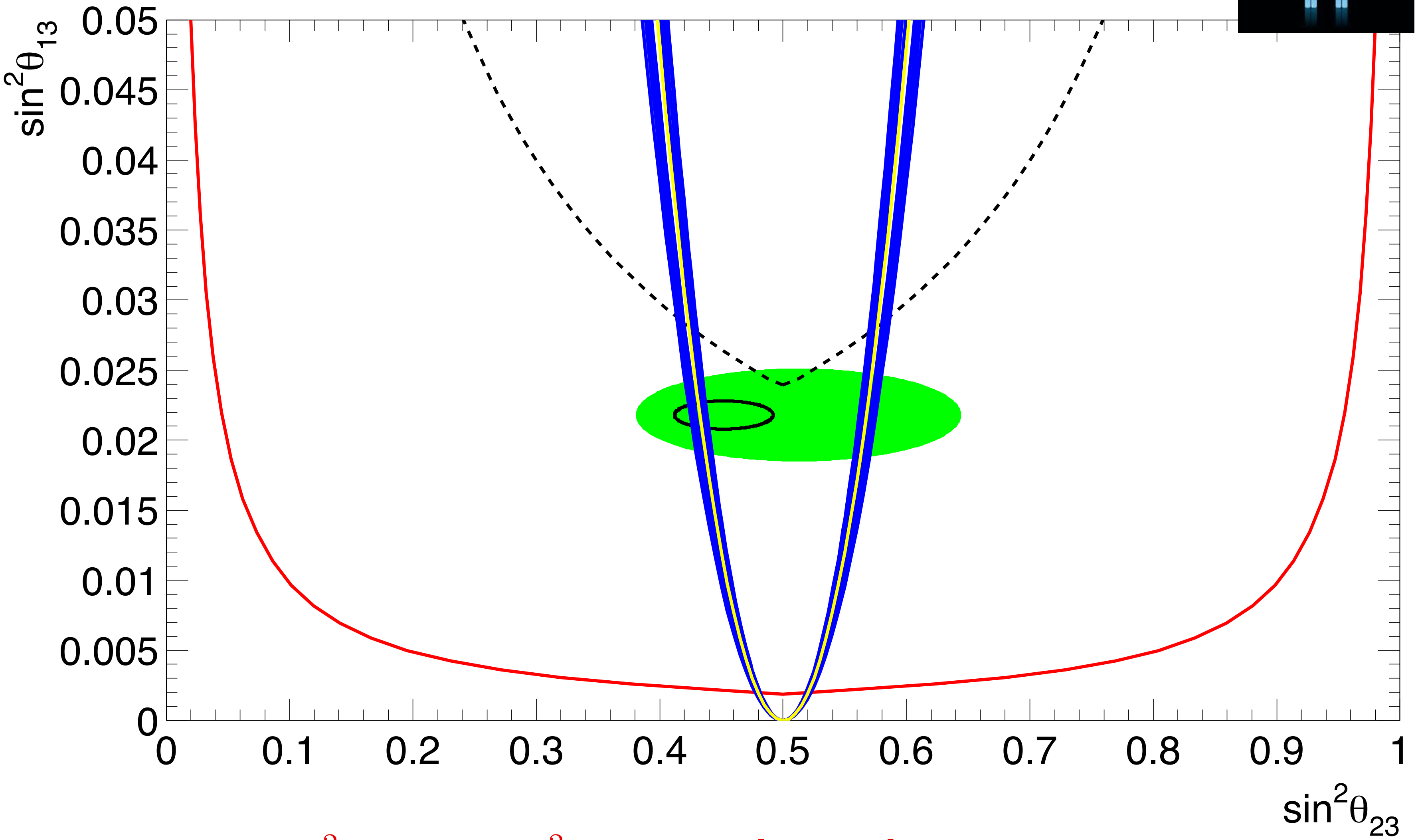

NOvA Preliminary
NOvA FD
8.85×10^{20} POT-equiv (ν)
12.33×10^{20} POT ($\bar{\nu}$)
$\sin^2 2\theta_{13}$=0.082
LO
$\sin^2\theta_{23}$=0.48
UO
$\sin^2\theta_{23}$=0.56
IH
$\Delta m^2_{32}=-2.54\times10^{-3}$eV^2
NH
$\Delta m^2_{32}=+2.48\times10^{-3}$eV^2
δ_{CP}= 0
δ_{CP}= $\pi/2$
δ_{CP}= π
δ_{CP}= $3\pi/2$
2019 best fit
Total events - antineutrino beam
Total events - neutrino beam

How Well Do We "Need" to Measure Oscillation Parameters?

- That is a stupid question…or is it?
- Precision measurements of mass-squared differences, combined with non-oscillation experiments will allow one to reconstruct the values of the neutrino masses themselves.
- GUTs relate quarks and leptons so $V_{\rm CKM}$ is related to $U_{\rm PMNS}$. Similar precision is required for meaningful comparisons. Currently, precision with for $V_{\rm CKM}$ varies from 0.2% (for V_{us}) to 5% (for V_{ub}). The unitarity-triangle phase γ is known at the 10% $\to$ 2% (Belle-II).
- Flavor models predict relations among the different mixing parameters. In many cases, all parameters can be determined once a subset is know.
  E.g. sum rules like
  $$f(\theta_{12},\theta_{13},\theta_{23},\delta)=0.$$
  Ability to test different sum rules limited by "weakest link." Nowadays, these are δ and θ_{23}.



Anarchy vs. Order — more precision required!



Order: $\sin^2\theta_{13} = C\cos^2 2\theta_{23}$, $C \in [0.8, 1.2]$

[AdG, Murayama, 1204.1249]

Long-Baseline Experiments, Present and Future

- [NOW] T2K (Japan), NOνA (USA) – $\nu_\mu \to \nu_e$ appearance, ν_μ disappearance – precision measurements of "atmospheric parameters" $(\Delta m^2_{13}, \sin^2\theta_{23})$. Pursue mass hierarchy via matter effects. Nontrivial tests of paradigm. First step towards CP-invariance violation.

- [$\sim$2021] JUNO (China) – $\bar{\nu}_e$ disappearance – precision measurements of "solar parameters" $(\Delta m^2_{12}, \sin^2\theta_{12})$. Pursue the mass hierarchy via precision measurements of oscillations.

- [$\sim$2021?] PINGU (South Pole) and ORCA (Mediterranean)– atmospheric neutrinos – pursue mass hierarchy via matter effects.

- [$\sim$2027] Tokai-to-HyperK (Japan), LBNF/DUNE (USA) – Second (real opportunity for discovery!) step towards CP-invariance violation. Nontrivial tests of the paradigm. Ultimate "super-beam" experiments.

- [>2035?] What comes next?

With greater precision come greater headaches!

(Already Now and Definitely In the Future!)

- How well do we need to reconstruct the neutrino energy (remember everything goes like L/E)?
- How well do we need to understand or at least describe neutrino-nucleus scattering?
- How well do we need to know the pion-decay-in-flight neutrino flux?

With greater precision come greater headaches!

- Increasingly coherent effort to address the cross-sections issue. Theory, generators, and different types of experiments;
- More and better neutrino data. E.g, right now, MINERνA and MicroBooNE, MiniBooNE in the recent past, SBND in the near future.
- Significant developments in analysis and event reconstruction;
- Better instruments allow more information;
- Better near-detector complexes.

BONUS: better measurements, different observables, more detectors open the door for more opportunities to make measurements and look for new phenomena.

The Short Baseline Anomalies

Different data sets, sensitive to L/E values small enough that the known oscillation frequencies do not have "time" to operate, point to unexpected neutrino behavior. These include

- $\nu_\mu \to \nu_e$ appearance — LSND, MiniBooNE;
- $\nu_e \to \nu_{\rm other}$ disappearance — radioactive sources;
- $\bar{\nu}_e \to \bar{\nu}_{\rm other}$ disappearance — reactor experiments.

None are entirely convincing, either individually or combined. However, there may be something very very interesting going on here…

What is Going on Here?

- Are these “anomalies” related?
- Is this neutrino oscillations, other new physics, or something else?
- Are these related to the origin of neutrino masses and lepton mixing?
- How do clear this up **definitively**?

Need new clever experiments, of the short-baseline type (and we are working on it)!

Observable wish list:

- ν_μ disappearance (and antineutrino);
- ν_e disappearance (and antineutrino);
- $\nu_\mu \leftrightarrow \nu_e$ appearance;
- $\nu_{\mu,e} \to \nu_\tau$ appearance.

If the oscillation interpretation of the short-baseline anomalies turns out to be correct – big if, given existing constraints – . . .

- We would have found new particle(s)!!!!!! [cannot overemphasize this!]
- Lots of Questions! What is it? Who ordered that? Is it related to the origin of neutrino masses? Is it related to dark matter?
- Lots of Work to do! Discovery, beyond reasonable doubt, will be followed by a panacea of new oscillation experiments. If, for example, there were one extra neutrino state the 4×4 mixing matrix would require three more mixing angles and three more CP-odd phases. Incredibly challenging. For example, two of the three CP-odd parameters, to zeroth order, can only be "seen" in tau-appearance.

RECENT and EXPECTED DEVELOPMENTS

- MicroBooNE – getting there – one year (?) – on photons versus electrons for the MiniBooNE anomaly?
- SBN Program – address the oscillation interpretation, plus a few others – five years (?).
- IceCUBE – interesting null results in the recent past (only one year of data). Looking forward to results from eight-year data set.
- Reactor Anomaly – a lot of progress from current reactor experiments. It is becoming clear we don't understand reactors as neutrino sources at better than the 5% level (normalization and spectrum).
- Gallium Anomaly – source experiments (?).

And there's more!

- Solar Neutrinos. We are not done yet. Day-night effect, solar models, tension with KamLAND? This could become a big deal with JUNO data;
- Supernova neutrinos: bursts and the diffuse background. SuperK with gadolinium poised to make the first observation of the DSNB;
- Ultra-High Energy Neutrinos; IceCUBE; ANITA anomaly; using UHE neutrinos to learn about neutrino properties;
- New detector technologies;
- Neutrino theory;
- News from CERN: LHC, new experiments (e.g. FASER), SHiP;
- New neutrino sources. π and K decay-at-rest: JSNS^2 in J-PARC; MiniBooNE detection of neutrinos from KDAR.
- COHERENT: First observation of coherent elastic neutrino-nucleus scattering (CEνNS). A lot of other efforts ongoing. $\Rightarrow$


Dinosaur heretic looks for redemption p. 1088
Increase inclusion to increase STEM diversity p. 1101
Fluorescent or magnetic cotton fibers p. 1138
Science
$15
15 SEPTEMBER 2017
sciencemag.org
AAAS
SPOTTING A GHOST
A compact detector spies neutrinos scattering from nuclei
pp. 1098 & 1123

Piecing the Neutrino Mass Puzzle

Understanding the origin of neutrino masses and exploring the new physics in the lepton sector will require unique **theoretical** and **experimental** efforts . . .

- understanding the fate of lepton-number. Neutrinoless double beta decay!
- A comprehensive long-baseline neutrino program. (On-going T2K and $NO\nu$A. DUNE and HyperK next steps towards the ultimate "superbeam" experiment.)
- The next-step is to develop a qualitatively better neutrino beam – e.g. muon storage rings (neutrino factories).
- Different baselines and detector technologies a must for both over-constraining the system and looking for new phenomena.
- Probes of neutrino properties, including neutrino scattering experiments.
- Precision measurements of charged-lepton properties ($g-2$, edm) and searches for rare processes ($\mu \to e$-conversion the best bet at the moment).
- Collider experiments. The LHC and beyond may end up revealing the new physics behind small neutrino masses.
- Neutrino properties affect, in a significant way, the history of the universe (Cosmology). Will we learn about neutrinos from cosmology, or about cosmology from neutrinos?

In Conclusion

The venerable Standard Model sprang a leak in the end of the last century: neutrinos are not massless! (and we are still trying to patch it)

1. We know very little about the new physics uncovered by neutrino oscillations.

2. **neutrino masses are very small** – we don't know why, but we think it means something important.

3. **neutrino mixing is "weird"** – we don't know why, but we think it means something important.

4. We **need more experimental input** These will come from a rich, diverse experimental program which relies heavily on the existence of underground facilities capable of hosting large detectors (**double-beta decay, precision neutrino oscillations, supernova neutrinos, nucleon decay**). Also "required"
   - Powerful neutrino beam;
   - Precision studies of charged-lepton lepton properties and processes;
   - High energy collider experiments (the LHC will do for now);
5. There is plenty of **room for surprises**, as neutrinos are potentially very deep probes of all sorts of physical phenomena. Remember that neutrino oscillations are "quantum interference devices" – potentially very sensitive to whatever else may be out there (e.g., $\Lambda \simeq 10^{14}$ GeV).