Determine the Two Majorana CP Phases with the help of Neutrino Electromagnetic Measurements

Shao-Feng Ge

(gesf02@gmail.com)

TDLI-SJTU, Kavli IPMU & UC Berkeley

2019-4-25

SFG, Manfred Lindner, PRD **95** (2017) No.3, 033003 [arXiv:1608.01618]

Minimal Neutrinos

Georg G. Raffelt

Stars as Laboratories for Fundamental Physics

The Astrophysics of Neutrinos, Axions, and Other Weakly Interacting Particles

In the standard model, neutrinos have been assigned the most minimal properties compatible with experimental data: zero mass, zero charge, zero dipole moments, zero decay rate, zero almost everything.

Neutrinos are not just invisible but very boring!

Lazy Neutrino

Nothing can interest me!!!

Daya Bay & LHC changed Physics in 2012

- **Higgs boson** $\Rightarrow$ electroweak symmetry breaking & mass.
- **Chiral symmetry breaking** $\Rightarrow$ majority of mass.
- **The world seems not affected by the tiny neutrino mass?**
  - Neutrino mass $\Rightarrow$ Mixing
  - 3 Neutrino $\Rightarrow$ possible **CP violation**
  - CP violation $\Rightarrow$ **Leptogenesis**
  - **Leptogenesis** $\Rightarrow$ **Matter-Antimatter Asymmetry**
  - There is something left in the Universe.
  - Baryogenesis from quark mixing is not enough.
- Majorana $\nu \Leftrightarrow$ **Lepton Number Violation**
- **Residual $\mathbb{Z}_2$ Symmetries:** $\cos \delta_D = \frac{(s_s^2 - c_s^2 s_r^2)(c_a^2 - s_a^2)}{4 c_a s_a c_s s_s s_r}$ 1108.0964 1104.0602

ν Oscillation Data

(for NH)	-1σ	Best Value	$+1\sigma$
$\mathbf{\Delta m_s^2} \equiv \Delta m_{12}^2\,(\mathbf{10^{-5}}\mathrm{eV}^{\mathbf{2}})$	7.37	**7.56**	7.75
$\lvert \mathbf{\Delta m_a^2} \equiv \Delta m_{13}^2 \rvert\ (\mathbf{10^{-3}}\mathrm{eV}^{\mathbf{2}})$	2.51	**2.55**	2.59
$\sin^2 \boldsymbol{\theta_s}\ (\boldsymbol{\theta_s} \equiv \boldsymbol{\theta_{12}})$	0.305 (33.5°)	0.321 (**34.5°**)	0.339 (35.6°)
$\sin^2 \boldsymbol{\theta_a}\ (\boldsymbol{\theta_a} \equiv \boldsymbol{\theta_{23}})$	0.412 (39.9°)	0.430 (**41.0°**)	0.450 (42.1°)
$\sin^2 \boldsymbol{\theta_r}\ (\boldsymbol{\theta_r} \equiv \boldsymbol{\theta_{13}})$	0.02080 (8.29°)	0.02155 (**8.44°**)	0.02245 (8.62°)
δ_D, δ_{Mi}	?, **??**	?, **??**	?, **??**

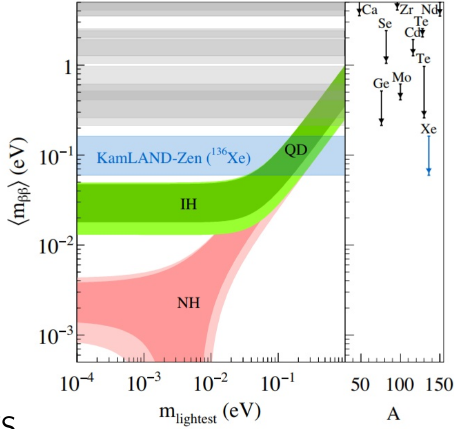
Salas, Forero, Ternes, Tortola & Valle, arXiv:1708.01186

The Current $0\nu2\beta$ Experiments are Approaching IH

KamLAND-Zen 400 Phase 1+2 combined

$$T^{0\nu}_{1/2} > 1.07 \times 10^{26}\ \text{yr}$$

(sensitivity 5.6×10^{25} yr)



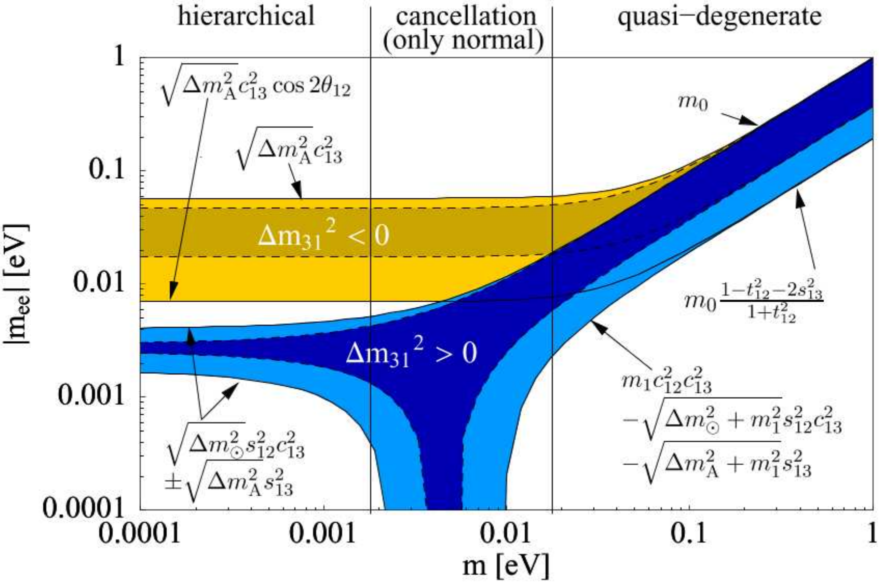
It also provides upper limit of m_{lightest} at 180-480 meV.

Kunio Inoue @ IPMU ν WS

$$\langle m_{\beta\beta} \rangle < (61 - 165)\ \text{meV}$$

PRL117, 082503 (2016)

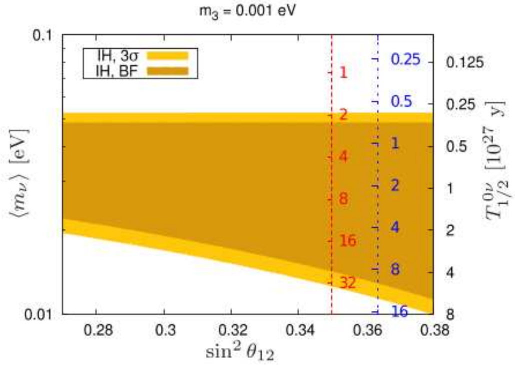
Dependence on Mass Hierarchy



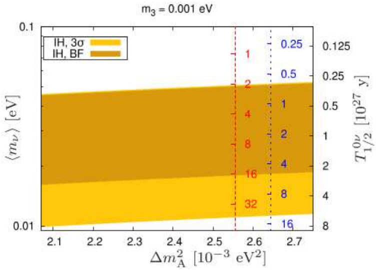
Uncertainty from Neutrino Mixing

- **Effective Mass** – **Large Uncertainty**

$$\text{IH} \quad : \quad c_r^2(1-2s_s^2)\sqrt{\Delta m_a^2} \leq |m_{ee}^{\rm IH}| \leq c_r^2\sqrt{\Delta m_a^2}$$



	$\langle m_\nu\rangle^{\rm IH}_{\rm min}$ [eV]	
$\sin^2\theta_{12}$	minimal	maximal
0.270	0.0196	0.0240
0.318	0.0154	0.0189
0.380	0.0100	0.0123



Dueck, Rodejohann & Zuber, arXiv:1103.4152

Uncertainty Reduction with Reactor Neutrino

- **Neutrinoless Double Beta Decay**

$$|m_{ee}| = \left| c_s^2 c_r^2 m_1 e^{i\delta_{M1}} + s_s^2 c_r^2 m_2 + s_r^2 m_3 e^{i\delta_{M3}} \right|$$

- **Reactor Neutrino**

$$P_{ee} = 1 - 4c_r^4 c_s^2 s_s^2 \sin^2\Delta_{21} - 4c_s^2 c_r^2 s_r^2 \sin^2\Delta_{31} - 4s_s^2 c_r^2 s_r^2 \sin^2\Delta_{32}$$

  - **Short Baseline – Daya Bay**

$$P_{ee} \approx 1 - 4\mathbf{c_r^2 s_r^2} \sin^2\boldsymbol{\Delta}_{31}$$

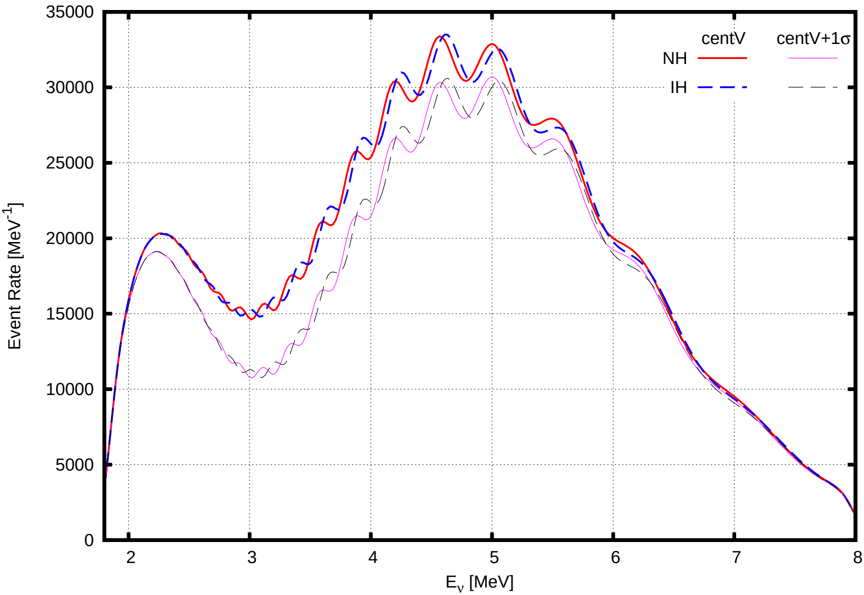
  - **Medium Baseline – JUNO**

$$\begin{aligned} P_{ee} &= 1 - 4c_r^4 \mathbf{c_s^2 s_s^2} \sin^2\boldsymbol{\Delta}_{21} - 4c_r^2 s_r^2 \sin^2|\boldsymbol{\Delta}_{31}| \\ &\quad - 4s_s^2 c_r^2 s_r^2 \sin^2\boldsymbol{\Delta}_{21} \cos(2|\boldsymbol{\Delta}_{31}|) \\ &\quad \pm 2s_s^2 c_r^2 s_s^2 \sin(2\boldsymbol{\Delta}_{21}) \sin(2|\boldsymbol{\Delta}_{31}|), \end{aligned}$$

with $\Delta_{ij} \equiv \Delta m_{ij}^2 L/2E$.

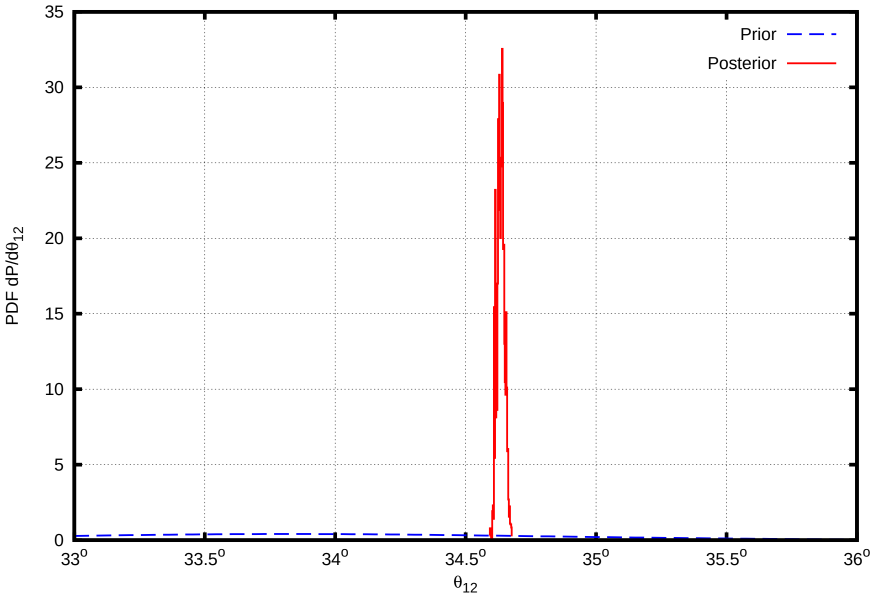
Precision Measurement @ JUNO

SFG & Rodejohann, arXiv:1507.05514



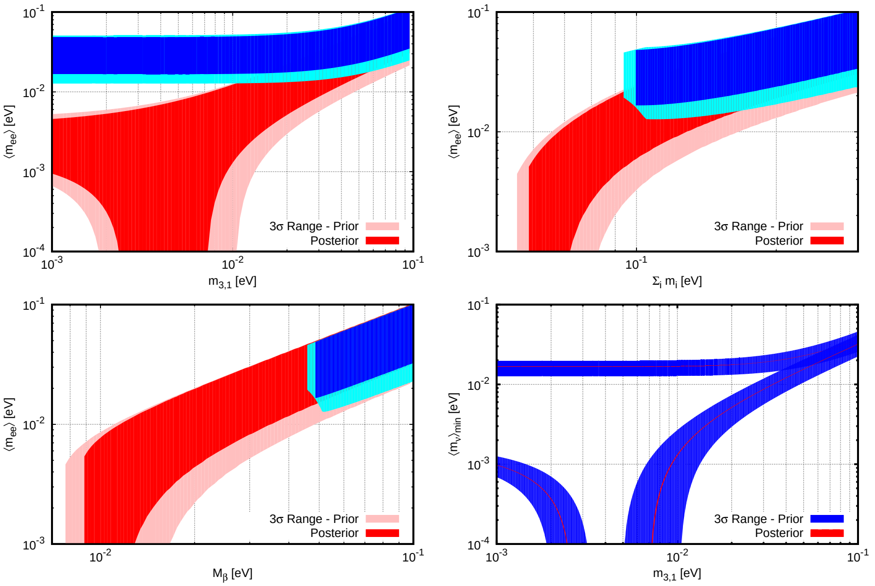
Precision Measurement @ JUNO

SFG & Rodejohann, arXiv:1507.05514



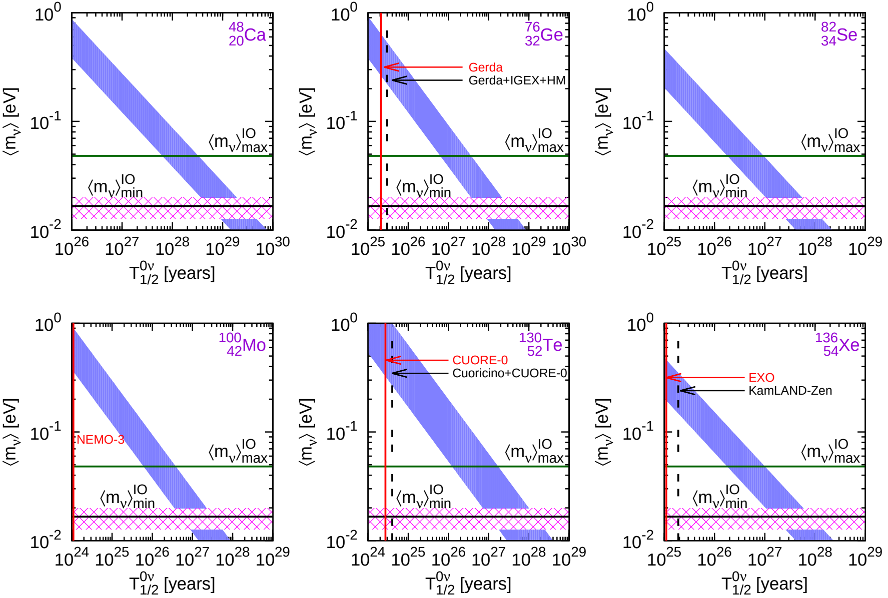
Effect on Effective Mass

SFG & Rodejohann, arXiv:1507.05514



Effect on Lifetime

SFG & Rodejohann, arXiv:1507.05514



Bright Future with Daya Bay + JUNO

Heart Breaking Time!

NH is Preferred by Global Fit

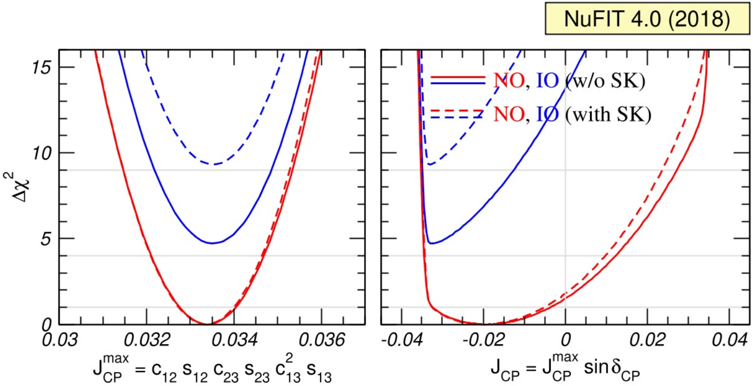
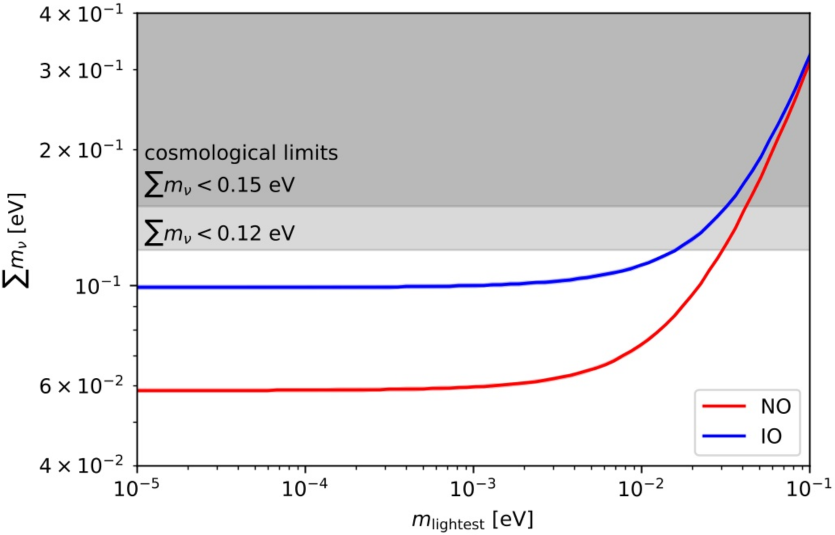


Figure 3. Dependence of the global $\Delta\chi^2$ function on the Jarlskog invariant. The red (blue) curves are for NO (IO). Solid (dashed) curves are without (with) adding the tabulated SK-atm $\Delta\chi^2$.

Esteban, Gonzalez-Garcia, Hernandez-Cabezudo, Maltoni & Schwetz [arXiv:1811.05487]

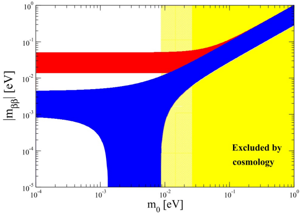
NH is Preferred by Cosmological Data

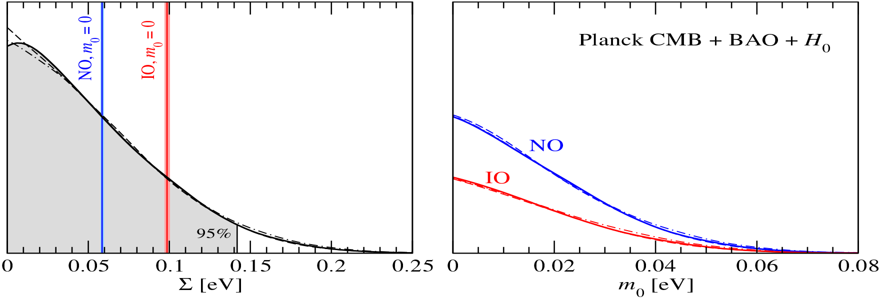


Salas, Gariazzo, Mena, Ternes & Tortola [arXiv:1806.11051]

Cosmological Data on Mass Sum

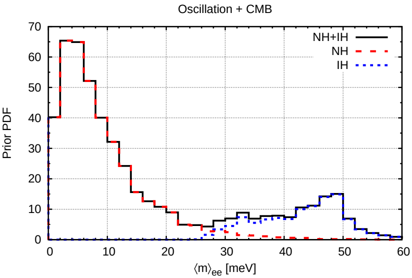
$$\Sigma \equiv m_1 + m_2 + m_3$$

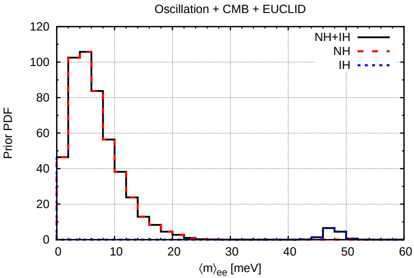


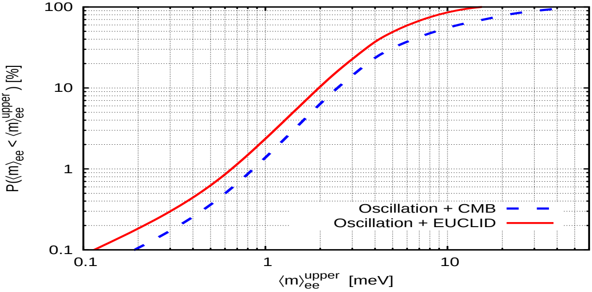


Hannestad & Schwetz [arXiv:1606.04691]

Preference of NH ⇒ Non-Observation of $0\nu2\beta$?







Intelligent Design of Neutrino Parameters

- $\Delta m^2_{21} = 7.5 \times 10^{-5}$ eV^2 $\Rightarrow$ resonant MSW effect @ solar ν
- $\theta_{12} = 34.5^\circ$ $\Rightarrow$ big enough effect @ KamLAND
- $\Delta m^2_{32} = 2.6 \times 10^{-3}$ eV^2 $\Rightarrow$ 0$\sim$ full oscillation @ atmospheric ν
- $\theta_{23} \approx 45^\circ$ $\Rightarrow$ dramatic large effects to be easily seen @ atmospheric ν
- θ_{13} is large enough to be seen @ reactor ν
- $\delta_D \approx -90^\circ$ $\Rightarrow$ most quickly determine MO & large CP
- IH $\Rightarrow$ we can more readily measure $0\nu\beta\beta$ & beta decay endpoint
- Neutrinos are Majorana type.

Only that IH is not preferred now!

NH is preferred for the chance of determining the two Majorana CP phases

S. Wojcicki (1995) & M. Goodman (2012)

God's Mistake?

Neutrino Mistakes: Wrong tracks and Hints, Hopes and Failures

1901.07068

Maury C. Goodman

8 God's mistake

So in 2012 I extrapolated the intelligent design concept to the still unanswered questions about neutrinos. This implied (1) the CP violation parameter $\delta \sim 3\pi/2$ to most quickly determine the mass ordering and to get large CP violation; (2) the inverted mass order so that we can more readily measure $0\nu\beta\beta$ to distinguish Dirac and Majorana neutrinos, and perhaps measure the beta decay endpoint, and (3) neutrinos should be Majorana which seems to be the more interesting case for theorists, and we want our theorists to be happy.

Question 3 hasn't been answered yet, but early comparisons of T2K, NOvA and reactor data suggest $\delta \sim 3\pi/2$ may be close to the answer. However there is increasing evidence that the mass order is normal, in contradiction to the apparent "Intelligent Design" answer. Did god make a mistake? The more likely answer is that the normal mass order is just what we want and we aren't intelligent enough to realize why yet.

Maury Goodman's talk @ Neutrino History WS (2018) in Paris

Let's Cheer Up!

God Didn't Make a Mistake!

God Didn't Make a Mistake!

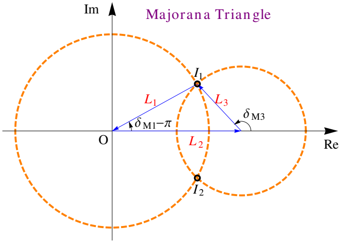
www.hep.anl.gov/ndk/longbnews/1901.html

Long-Baseline news, January 2019

*** Neutrino mistakes

In my article on neutrino mistakes for the nu history workshop, arXiv:1901.07068, I playfully attributed the increasing evidence for the normal mass order as god's mistake. New experiments on neutrinoless double beta decay are targeting the region suggested by the inverted mass order. But I added, "The more likely answer is that the normal mass order is just what we want and we aren't intelligent enough to realize why yet." I have been pointed to arXiv:1608.01618 which points out that if the order is normal, we can have a chance to simultaneously pin down the two Majorana CP phases which is not possible if it's inverted.

Any chance of obtaining some information?



$$\langle m \rangle_{ee} \equiv \overrightarrow{L_1} + \overrightarrow{L_2} + \overrightarrow{L_3} \,,$$

with

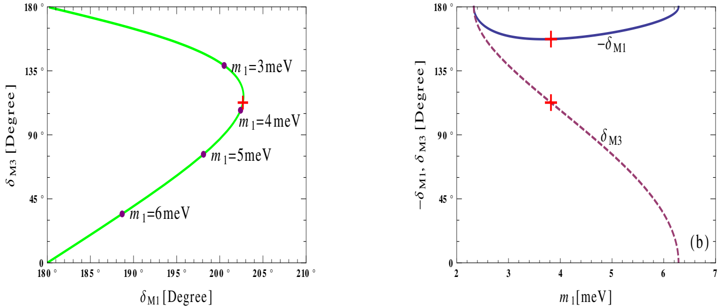
$$\overrightarrow{L_1} \equiv m_1 U_{e1}^2 = m_1 c_r^2 c_s^2 e^{i\delta_{M1}} \,,$$
$$\overrightarrow{L_2} \equiv m_2 U_{e2}^2 = \sqrt{m_1^2 + \Delta m_s^2} c_r^2 s_s^2 \,,$$
$$\overrightarrow{L_3} \equiv m_3 U_{e3}^2 = \sqrt{m_1^2 + \Delta m_a^2} s_r^2 e^{i\delta_{M3}} \,.$$

Determine 2 Majorana Phases Simultaneously

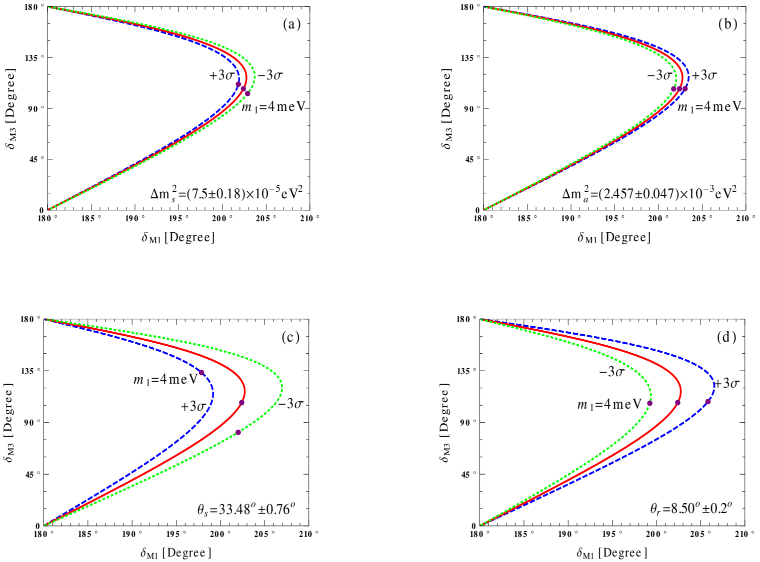
$$|L_1 - L_3| \leq L_2 \leq L_1 + L_3 \,.$$

$$\cos \delta_{\rm M1} = -\frac{L_1^2 + L_2^2 - L_3^2}{2 L_1 L_2} = -\frac{m_1^2 c_r^4 c_s^4 + m_2^2 c_r^4 s_s^4 - m_3^2 s_r^4}{2 m_1 m_2 c_r^4 c_s^2 s_s^2} \,,$$

$$\cos \delta_{\rm M3} = +\frac{L_1^2 - L_2^2 - L_3^2}{2 L_2 L_3} = +\frac{m_1^2 c_r^4 c_s^4 - m_2^2 c_r^4 s_s^4 - m_3^2 s_r^4}{2 m_2 m_3 c_r^2 s_r^2 s_s^2} \,.$$

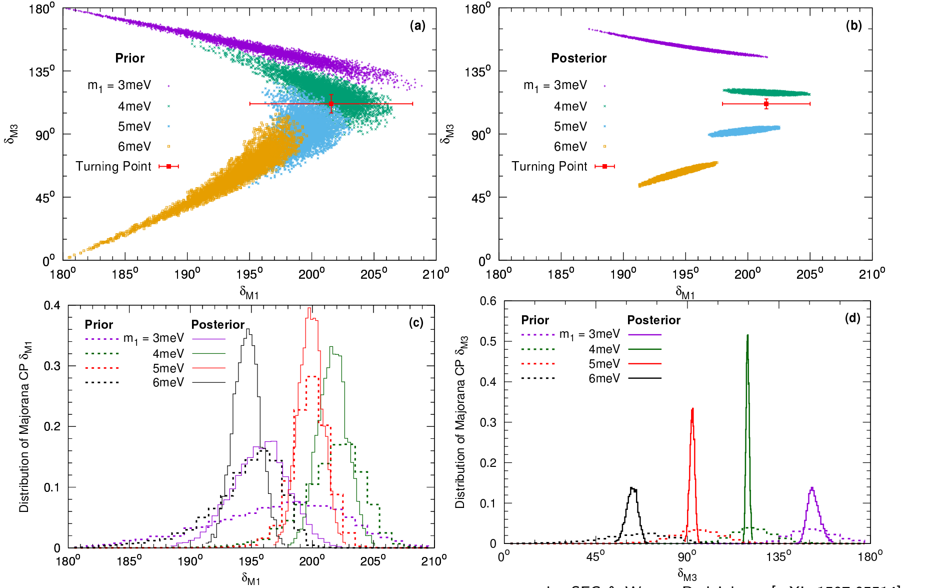


Uncertainties from Oscillation Parameters



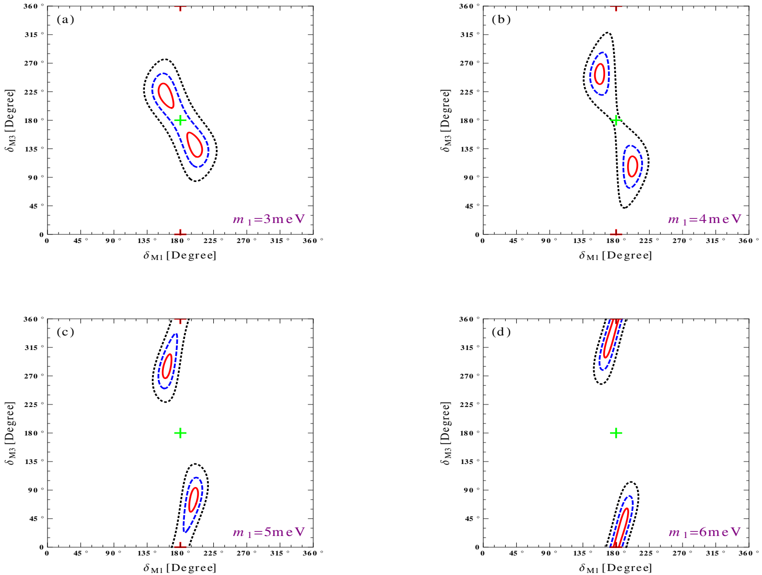
see also SFG & Werner Rodejohann [arXiv:1507.05514]

Uncertainties from Oscillation Parameters

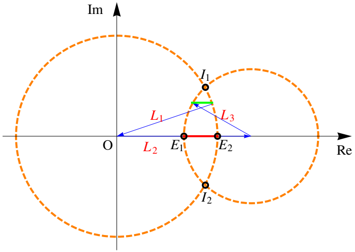


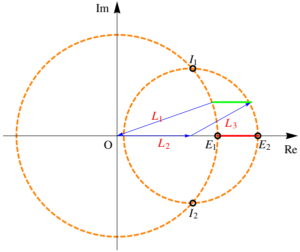
see also SFG & Werner Rodejohann [arXiv:1507.05514]

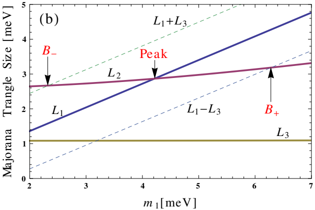
Uncertainties from $\langle m \rangle_{ee}$

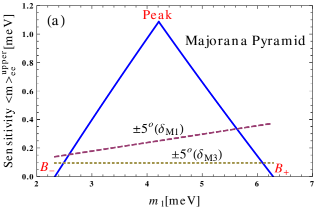


Majorana Pyramid & Projected Uncertainty









Prey of Leptonic CP Phases

TNT2K for better Dirac CP measurement [1506.05023, 1605.01670, 1607.08513, 1704.08518]

Extracting Majorana CP Phases from Nothing

- Null observation seems to be very unfortunate!
- But **not bad at all!**
- Vanishing m_{ee} $\Rightarrow$ Determine the **2** Majorana CP Phases Simultaneously!

$$|\mathbf{m_{ee}}| = \mathbf{0} \quad \Rightarrow \quad \mathbb{R}(\mathbf{m_{ee}}) = \mathbb{I}(\mathbf{m_{ee}}) = \mathbf{0}$$
$$|\mathbf{m_{ee}}| < \mathbf{f} \quad \Rightarrow \quad \mathbb{R}(\mathbf{m_{ee}}) < \mathbf{f} \quad \& \quad \mathbb{I}(\mathbf{m_{ee}}) < \mathbf{f}$$

- Non-zero m_{ee} can only determine a **single** degree of freedom

$$|\mathbf{m_{ee}}| = \mathbf{f}$$

- **Missing Piece**
  - Null observation of $0\nu2\beta \nRightarrow$ 2 Majorana CP phases;
  - Neutrinos have to be Majorana type in the first place!
  - Either assumption or independent measurement.

External Input – Dirac or Majorana?

- Cosmic Neutrino Background
  - Capture by tritium [PTOLEMY]
  - Pendulum [Domcke & Spinrath 2017]
  - Atom?
- Neutrino Magnetic Moment

Neutrino Magnetic Moment – Dirac

hep-ph/0504134

How Magnetic is the Dirac Neutrino?

Nicole F. Bell, V. Cirigliano, M. J. Ramsey-Musolf, P. Vogel, and Mark B. Wise
California Institute of Technology, Pasadena, CA 91125, USA
(Dated: December 16, 2005)

We derive model-independent, "naturalness" upper bounds on the magnetic moments μ_ν of Dirac neutrinos generated by physics above the scale of electroweak symmetry breaking. In the absence of fine-tuning of effective operator coefficients, we find that current information on neutrino mass implies that $|\mu_\nu| \lesssim 10^{-14}$ Bohr magnetons. This bound is several orders of magnitude stronger than those obtained from analyses of solar and reactor neutrino data and astrophysical observations.

$$\begin{cases} \mathcal{O}_1^{(6)} = g_1 \bar{L} \tilde{\phi} \sigma^{\mu\nu} \nu_R B_{\mu\nu} \\ \mathcal{O}_2^{(6)} = g_2 \bar{L} \tau^a \tilde{\phi} \sigma^{\mu\nu} \nu_R W^a_{\mu\nu} \\ \mathcal{O}_3^{(6)} = \bar{L} \tilde{\phi} \nu_R (\phi^\dagger \phi) \end{cases} \Rightarrow \begin{cases} \frac{\mu_\nu}{\mu_B} = -4\sqrt{2} \left(\frac{m_e v}{\Lambda^2} \right) \left[C_1^6(v) + C_2^6(v) \right] \\ \delta m_\nu = -C_2^6(v) \frac{v^3}{2\sqrt{2}\Lambda^2} \end{cases}$$

$$\frac{|\mu_\nu|}{\mu_B} \lesssim 8 \times 10^{-15} \times \left(\frac{\delta m_\nu}{1 \text{ eV}} \right) \frac{1}{|f|}$$

Neutrino Magnetic Moment – Majorana

hep-ph/0606248

Model Independent Bounds on Magnetic Moments of Majorana Neutrinos

Nicole F. Bell, Mikhail Gorchtein, Michael J. Ramsey-Musolf, Petr Vogel, and Peng Wang
California Institute of Technology, Pasadena, CA 91125, USA
(Dated: September 23, 2006)

We analyze the implications of neutrino masses for the magnitude of neutrino magnetic moments. By considering electroweak radiative corrections to the neutrino mass, we derive model-independent naturalness upper bounds on neutrino magnetic moments, μ_ν, generated by physics above the electroweak scale. For Dirac neutrinos, the bound is several orders of magnitude more stringent than present experimental limits. However, for Majorana neutrinos the magnetic moment contribution to the mass is Yukawa suppressed. The bounds we derive for magnetic moments of Majorana neutrinos are weaker than present experimental limits if μ_ν is generated by new physics at ~ 1 TeV, and surpass current experimental sensitivity only for new physics scales $> 10 - 100$ TeV. The discovery of a neutrino magnetic moment near present limits would thus signify that neutrinos are Majorana particles.

i) 1-loop, 7D	$\mu^W_{\alpha\beta}$	$\leq 1 \times 10^{-10} \mu_B \left(\frac{[m_\nu]_{\alpha\beta}}{1 \text{ eV}}\right) \ln^{-1} \frac{\Lambda^2}{M_W^2} R_{\alpha\beta}$
ii) 2-loop, 5D	$\mu^W_{\alpha\beta}$	$\leq 1 \times 10^{-9} \mu_B \left(\frac{[m_\nu]_{\alpha\beta}}{1 \text{ eV}}\right) \left(\frac{1 \text{ TeV}}{\Lambda}\right)^2 R_{\alpha\beta}$
iii) 2-loop, 7D	$\mu^B_{\alpha\beta}$	$\leq 1 \times 10^{-7} \mu_B \left(\frac{[m_\nu]_{\alpha\beta}}{1 \text{ eV}}\right) \ln^{-1} \frac{\Lambda^2}{M_W^2} R_{\alpha\beta}$
iv) 2-loop, 5D	$\mu^B_{\alpha\beta}$	$\leq 4 \times 10^{-9} \mu_B \left(\frac{[m_\nu]_{\alpha\beta}}{1 \text{ eV}}\right) \left(\frac{1 \text{ TeV}}{\Lambda}\right)^2 R_{\alpha\beta}$

Summary

- Neutrino has very important responsibility of explaining the existence of matter and the world.
- We need to try hard to squeeze out information of them.
- Intelligent design behind the neutrino parameters, including NH.
- **God didn't make a mistake** for NH, but probably just want us to **measure all the physical information from neutrinos.**
- 1 meV sensitivity is needed to touch down to the Majorana Pyramid.
  - Short + Intermediate baseline reactor exps reduce oscillation uncertainties to 0!
  - Nuclear Matrix Element calculation
  - Experimental uncertainty on half-lifetime.
- We shall not just investing on $0\nu 2\beta$, but also other ways
  - Cosmic Neutrino Background
  - Neutrino Magnetic Moment

Thank You!