Null Observation of $0\nu2\beta$ is Even Better!

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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:** $\cos \delta_D = \dfrac{(s_s^2 - c_s^2 s_r^2)(c_a^2 - s_a^2)}{4 c_a s_a c_s s_s s_r}$ 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

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

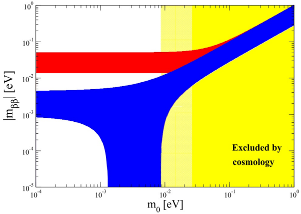
8 God's mistake

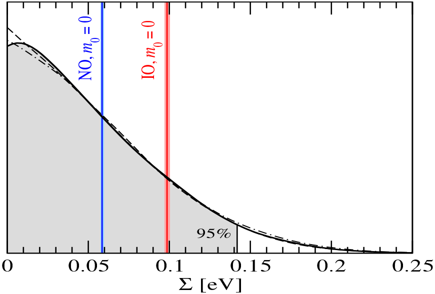
So in 2012 I extrapolated the intelligent design concept to the still unanswered questions about neutrinos. This implied (1) the CP violation parameter $\delta \sim 3\pi/2$ to most quickly determine the mass ordering and to get large CP violation; (2) the inverted mass order so that we can more readily 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.

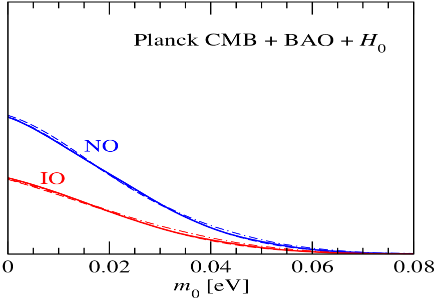
Question 3 hasn't been answered yet, but early comparisons of T2K, NOvA and reactor data suggest $\delta \sim 3\pi/2$ may be close to the answer. However there is increasing evidence that the mass order is normal, in contradiction to the apparent "Intelligent Design" answer. Did god make a mistake? The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

Cosmological Data on Mass Sum

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

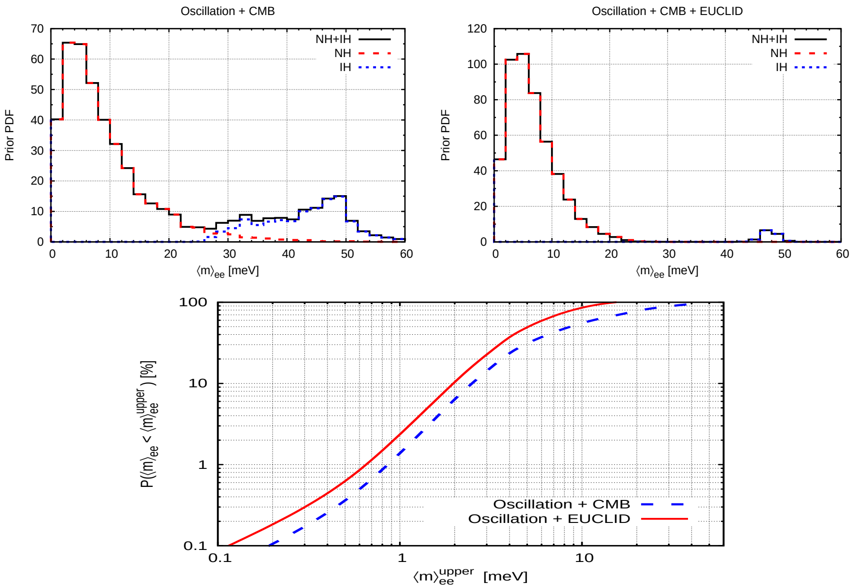




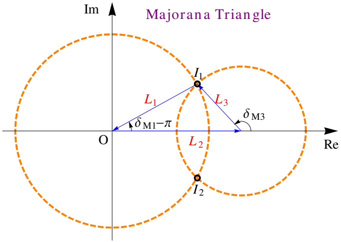


Hannestad & Schwetz [1606.04691]

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



Any chance of obtaining some information?



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

with

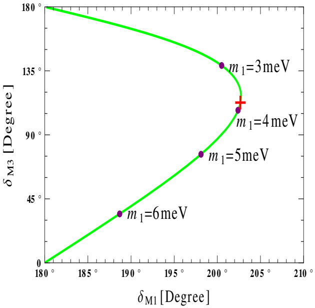
$$\overrightarrow{L_1} \equiv m_1 U_{e1}^2 = m_1 c_r^2 c_s^2 e^{i\boldsymbol{\delta_{\mathrm{M1}}}} \,,$$
$$\overrightarrow{L_2} \equiv m_2 U_{e2}^2 = \sqrt{m_1^2 + \Delta m_s^2} c_r^2 s_s^2 \,,$$
$$\overrightarrow{L_3} \equiv m_3 U_{e3}^2 = \sqrt{m_1^2 + \Delta m_a^2} s_r^2 e^{i\boldsymbol{\delta_{\mathrm{M3}}}}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

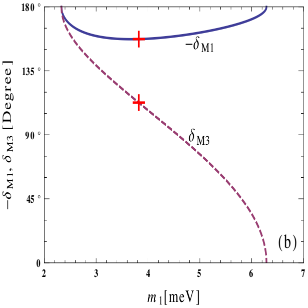
Determine 2 Majorana Phases Simultaneously

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

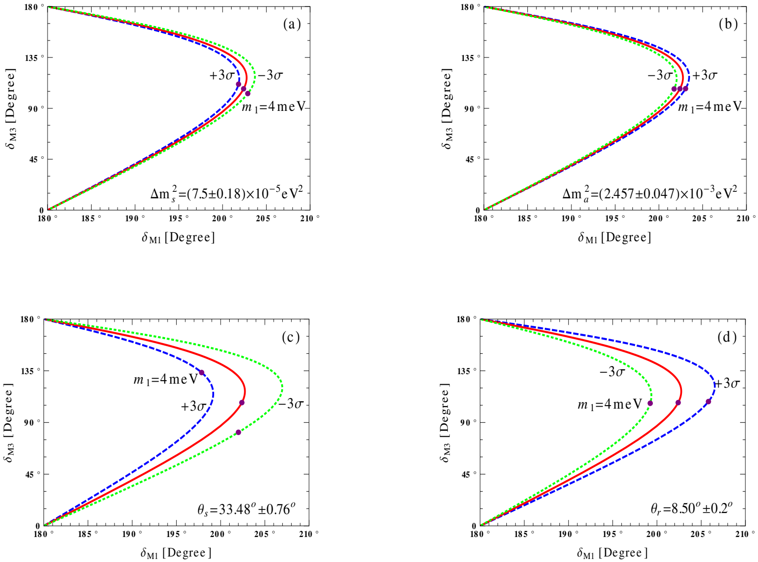
$$\cos \delta_{M1} = -\frac{L_1^2 + L_2^2 - L_3^2}{2L_1L_2} = -\frac{m_1^2 c_r^4 c_s^4 + m_2^2 c_r^4 s_s^4 - m_3^2 s_r^4}{2m_1 m_2 c_r^4 c_s^2 s_s^2} \,,$$

$$\cos \delta_{M3} = +\frac{L_1^2 - L_2^2 - L_3^2}{2L_2L_3} = +\frac{m_1^2 c_r^4 c_s^4 - m_2^2 c_r^4 s_s^4 - m_3^2 s_r^4}{2m_2 m_3 c_r^2 s_r^2 s_s^2} \,.$$



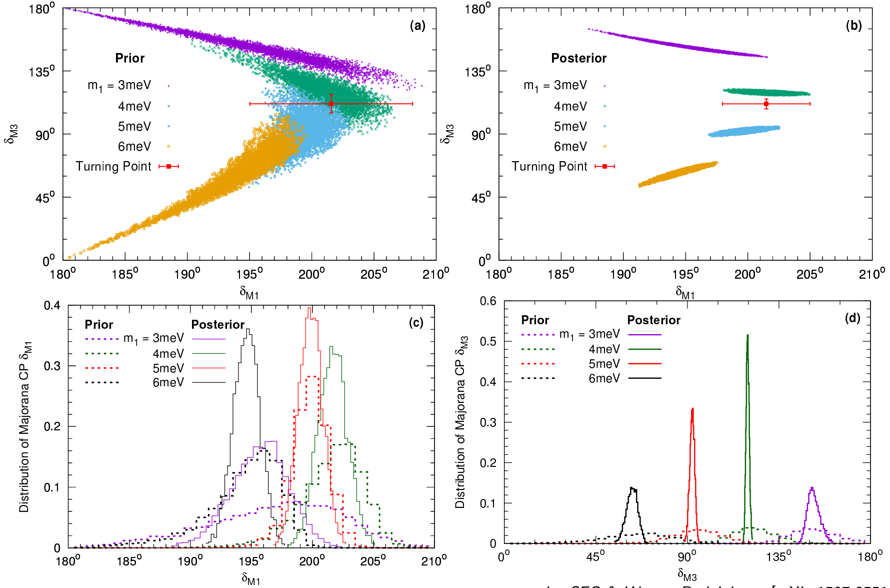


Uncertainties from Oscillation Parameters



see also SFG & Werner Rodejohann [arXiv:1507.05514]

Uncertainties from Oscillation Parameters



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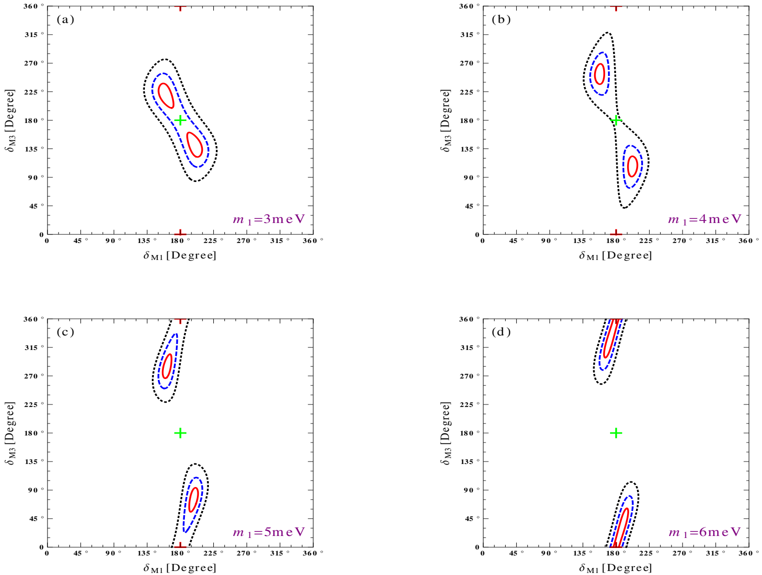
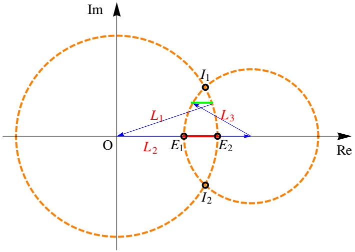
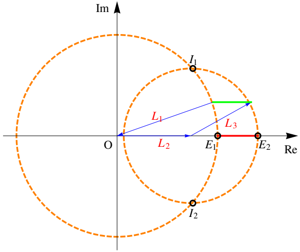
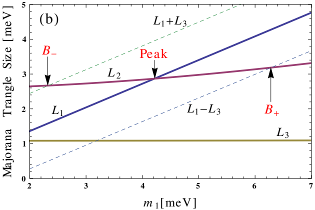
Uncertainties from $\langle m \rangle_{ee}$

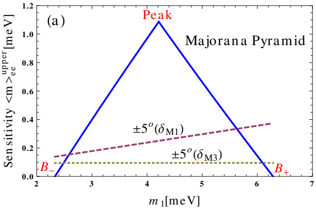


Majorana Pyramid









Prey of Leptonic CP Phases

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.
- Although there seems to have some intelligent design behind the neutrino parameters.
- Preference of NH from the current global fit & cosmology.
- The null observation of $0\nu2\beta$ can reconcile NH & Majorana neutrino.
- **God didn't make a mistake** but probably just want us to **measure all the 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.

Thank You!