The Normal ν Mass Ordering is Exactly What We Need!

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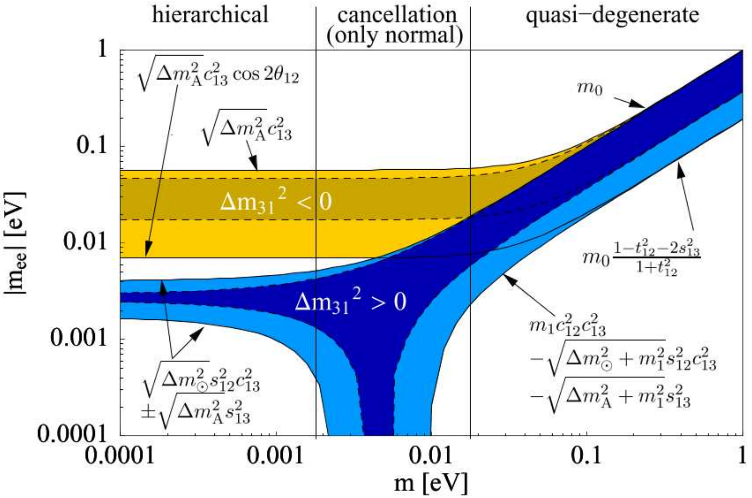
SFG and Manfred Lindner, PRD **95** (2017) No.3, 033003 [arXiv:1608.01618]

SFG and Jing-Yu Zhu, CPC **44** (2020) 8, 083103 [arXiv:1910.02666]

Dependence on Mass Ordering

$0\nu 2\beta$ Decay



Rodejohann, arXiv:1106.1334

Argument 1: Solar Octant

Degeneracy in MO, Solar Octant, CP & NSI

- **Hamiltonian reverses sign under combined transformations**

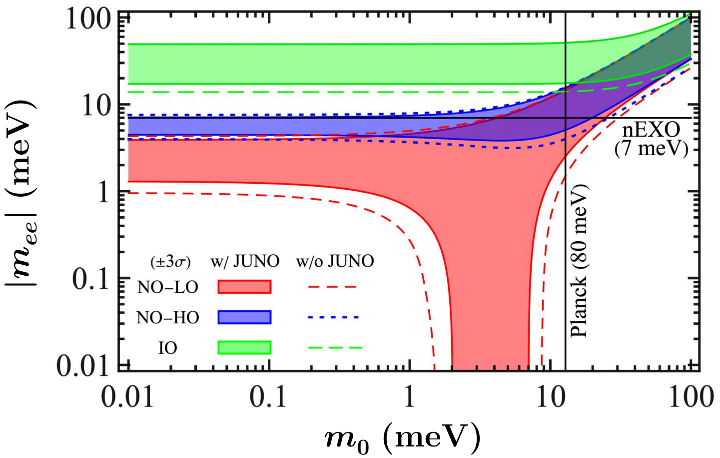
$$\begin{aligned} \sin\theta_s &\leftrightarrow \cos\theta_s\,, \\ \delta_D &\rightarrow \pi - \delta_D\,, \\ \Delta m_a^2 &\rightarrow -\Delta m_a^2 + \Delta m_s^2\,, \\ \epsilon_{ee} &\rightarrow -2 - \epsilon_{ee}\,, \end{aligned}$$

  together with a minus sign in the Dirac CP phase.

- **Degeneracy**
  - **Mass Ordering**: NO $\leftrightarrow$ IO
  - **Solar Octant**: $\theta_s \leftrightarrow \frac{\pi}{2} - \theta_s$
  - **CP Octant**: $\delta_D \leftrightarrow \pi - \delta_D$

- **Any unique way of distinguishing the solar octant!**

Distinguishing Solar Octant in the $0\nu2\beta$ Decay



w/o JUNO: $|m_{ee}| \geq 3.2\,\text{meV}$ @ $m_1 = 5.3\,\text{meV}$

with JUNO: $|m_{ee}| \geq 3.8\,\text{meV}$ @ $m_1 = 4.5\,\text{meV}$

SFG & Jing-Yu Zhu [arXiv:1910.02666]

also Choubey & Goswami [arXiv:1901.04313]

Argument 2

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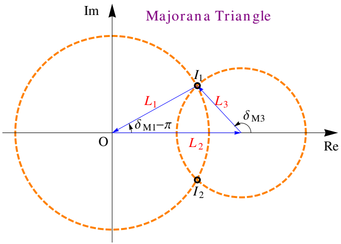
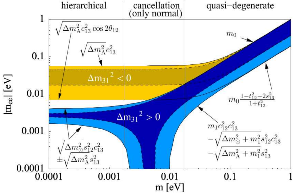
Majorana CP Phases

Any chance of obtaining some information?





Rodejohann, arXiv:1106.1334

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

with

$$\overrightarrow{L_1} \equiv m_1 U_{e1}^2 = m_1 c_r^2 c_s^2 e^{i\delta_{\mathrm{M1}}} \, ,$$

$$\overrightarrow{L_2} \equiv m_2 U_{e2}^2 = \sqrt{m_1^2 + \Delta m_s^2} c_r^2 s_s^2 \, ,$$

$$\overrightarrow{L_3} \equiv m_3 U_{e3}^2 = \sqrt{m_1^2 + \Delta m_a^2} s_r^2 e^{i\delta_{\mathrm{M3}}} \, .$$

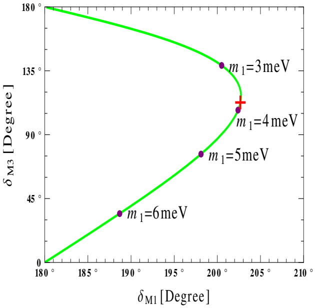
SFG and Manfred Lindner, PRD **95** (2017) No.3, 033003 [arXiv:1608.01618]

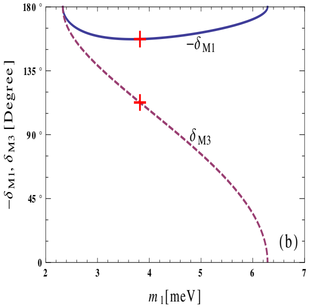
Determine 2 Majorana Phases Simultaneously

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

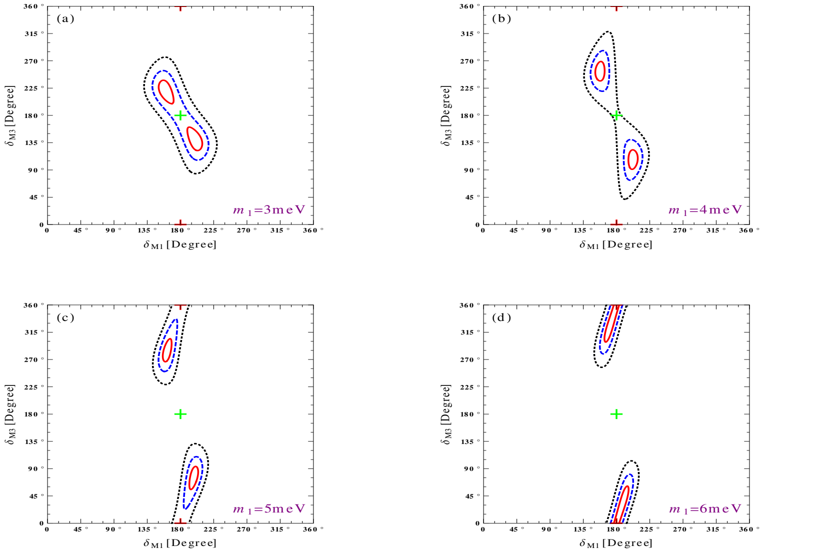
$$\cos \delta_{M1} \;=\; -\frac{L_1^2 + L_2^2 - L_3^2}{2 L_1 L_2} = -\frac{m_1^2 c_r^4 c_s^4 + m_2^2 c_r^4 s_s^4 - m_3^2 s_r^4}{2 m_1 m_2 c_r^4 c_s^2 s_s^2} \,,$$

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



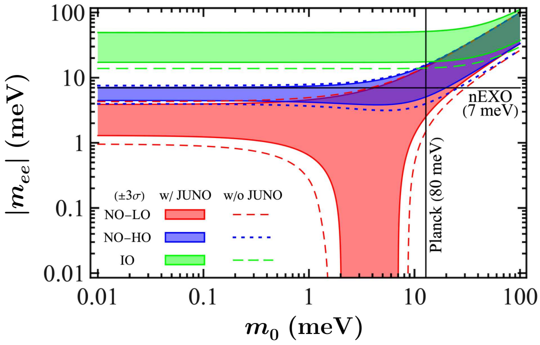


Uncertainties from $\langle m \rangle_{ee}$



also Xing, Zhao & Zhou [1504.05820]; Xing & Zhao [1612.08538]

Summary



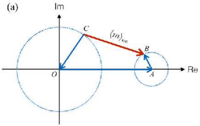
- There is no need to be scared of NO.
- At $\mathcal{O}$(meV), $0\nu2\beta$ can distinguish solar octant;
- At sub-meV scale, $0\nu2\beta$ can simultaneously determine the two Majorana CP phases.

Thank You!

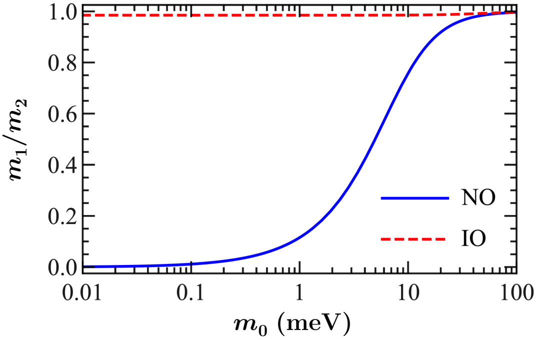
Solar Octant & Mass Degeneracy

The **octant transformation**, $c_s \leftrightarrow s_s$ is **equivalent** to $m_1 \leftrightarrow m_2$,

$$m_{ee} = c_r^2 c_s^2 m_1 e^{i\tilde{\delta}_{\rm M1}} + c_r^2 s_s^2 m_2 + s_r^2 m_3 e^{i\tilde{\delta}_{\rm M}}$$



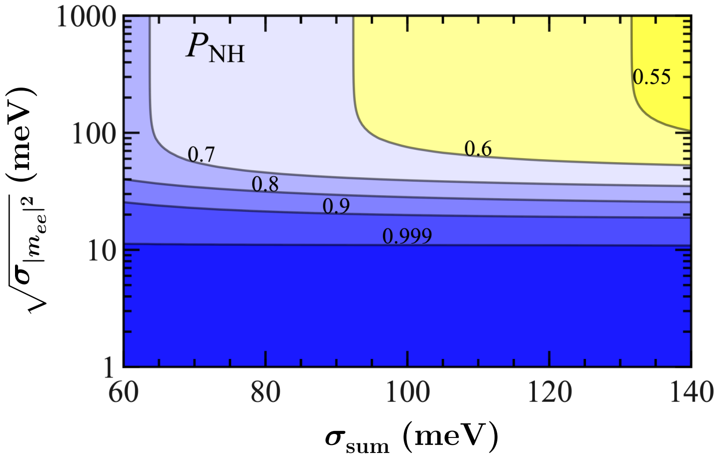
where $\tilde{\delta}_{\rm Mi} \equiv \delta_{\rm Mi} - \delta_D$.



$c_s^2 m_1 \leftrightarrow s_s^2 m_2$

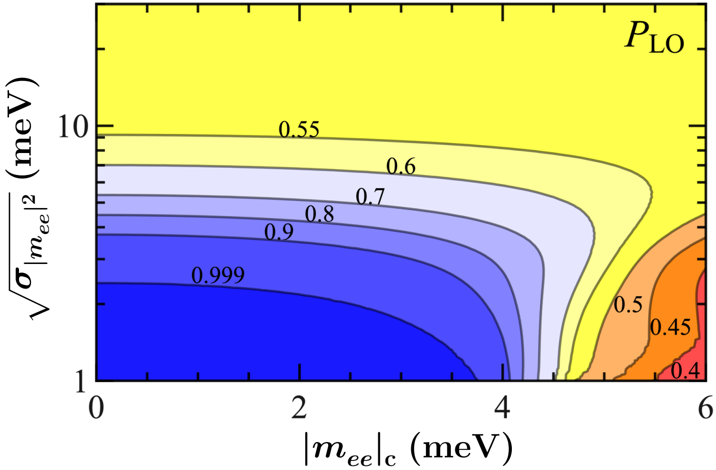
SFG & Jing-Yu Zhu [arXiv:1910.02666]

Probability of NO



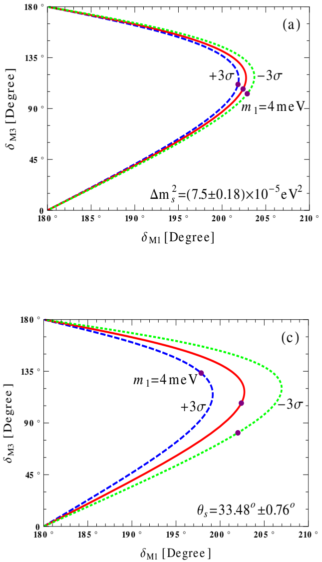
SFG & Jing-Yu Zhu [arXiv:1910.02666]

Probability of LO



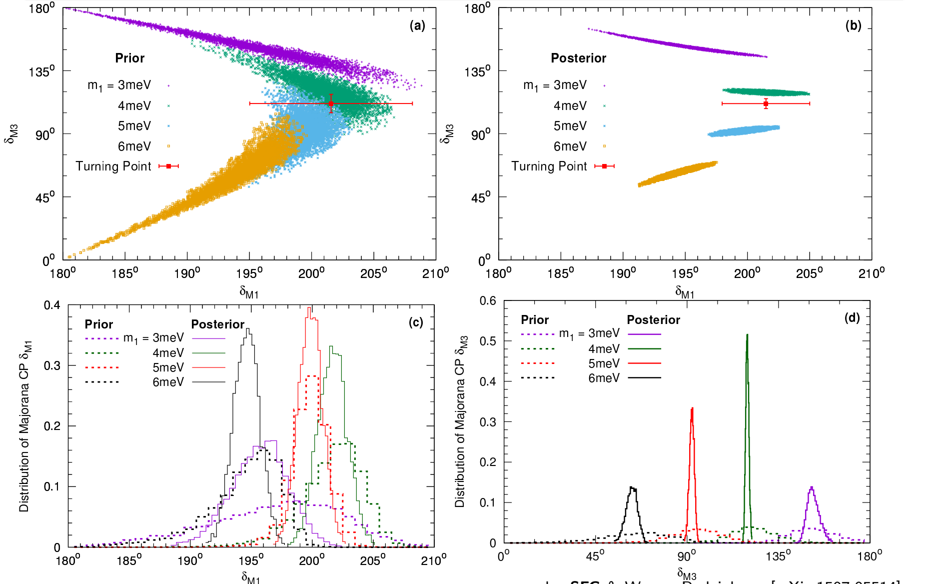
SFG & Jing-Yu Zhu [arXiv:1910.02666]

Uncertainties from Oscillation Parameters



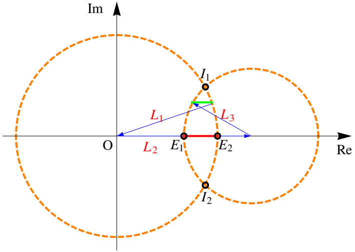
see also **SFG** & Werner Rodejohann [arXiv:1507.05514]

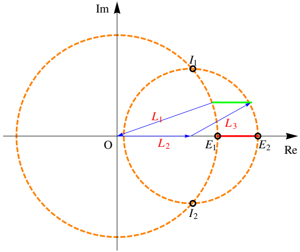
Uncertainties from Oscillation Parameters

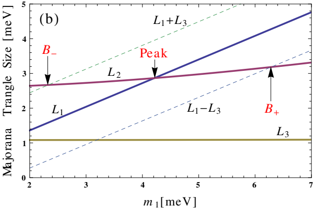


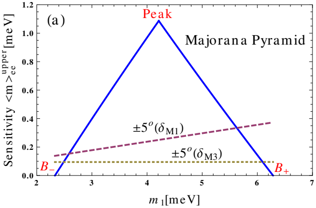
see also **SFG** & Werner Rodejohann [arXiv:1507.05514]

Majorana Pyramid & Projected Uncertainty









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!

$$|\mathrm{m}_{ee}| = 0 \quad \Rightarrow \quad \mathbb{R}(\mathrm{m}_{ee}) = \mathbb{I}(\mathrm{m}_{ee}) = 0$$
$$|\mathrm{m}_{ee}| < \mathrm{f} \quad \Rightarrow \quad \mathbb{R}(\mathrm{m}_{ee}) < \mathrm{f} \quad \& \quad \mathbb{I}(\mathrm{m}_{ee}) < \mathrm{f}$$

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

$$|\mathrm{m}_{ee}| = \mathrm{f}$$

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