How to interpret a discovery or null result of the neutrinoless double beta decay

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(IHEP, Beijing)

- ★ Introduction and motivation
- ★ The coupling-rod geometry
- ★ The 3-dimensional diagram
- ★ Why beyond the $0\nu2\beta$ decay

Related theory talks:
S. Petcov: everything
J. Menendez: NMEs
...

@ Workshop on 2β Decays & Underground Science, 8-10/11, Osaka

1935: 2β decays

2β decay: certain even-even nuclei have a chance to decay into the second nearest neighbors via two simultaneous β decays (equivalent to the decays of two neutrons).

necessary conditions:

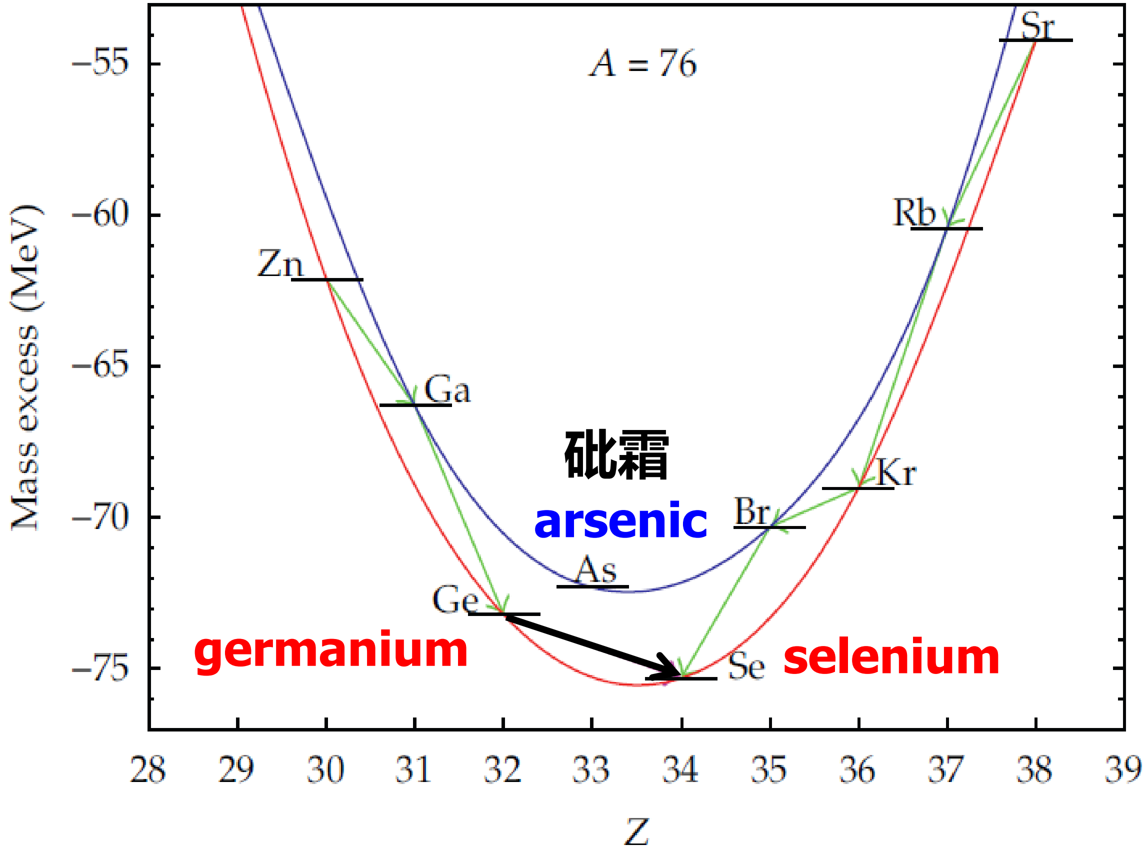
$$m(Z,A) > m(Z+2,A)$$

$$m(Z,A) < m(Z+1,A)$$

$$(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\bar{\nu}_e.$$

1935

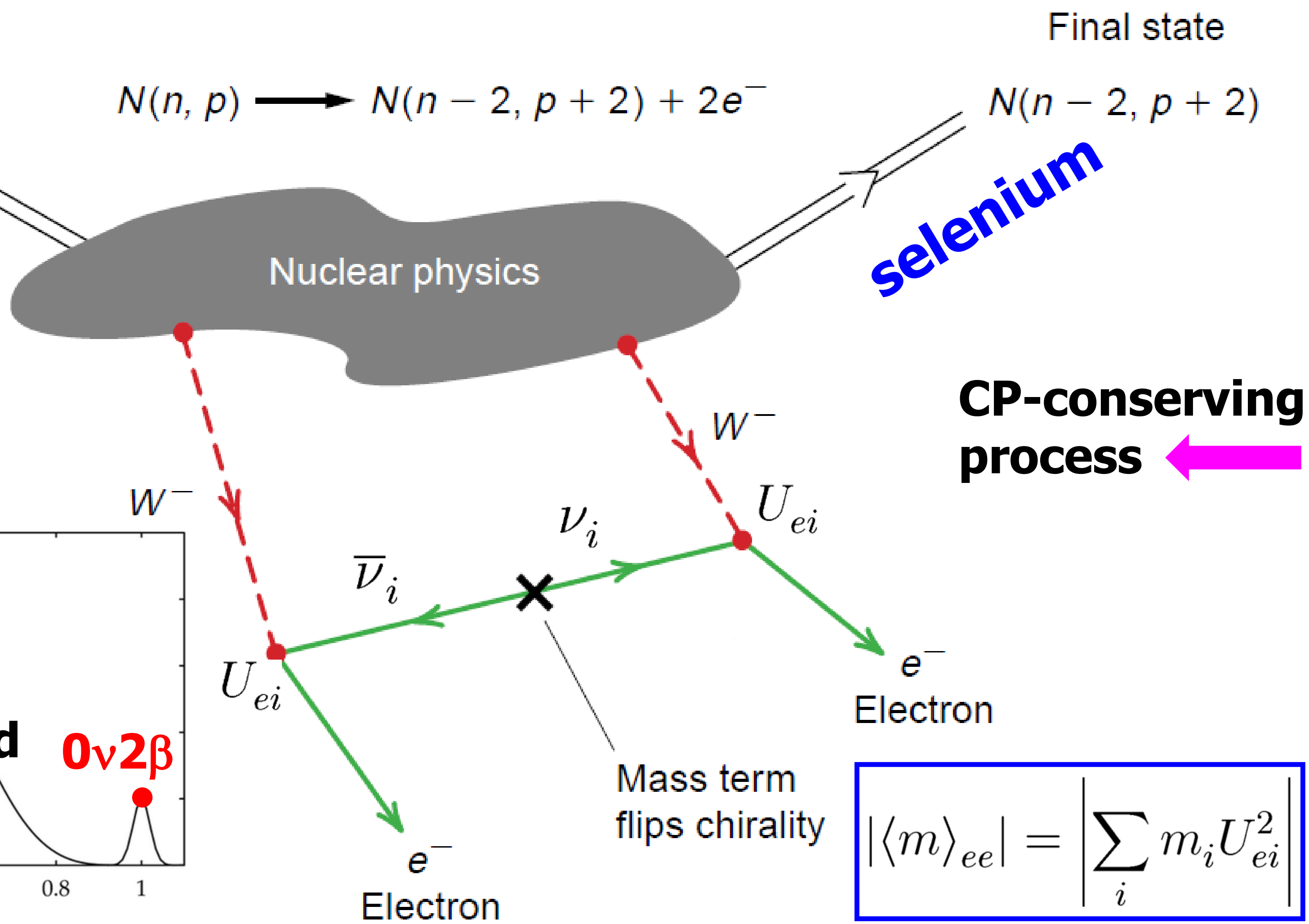
Maria Goeppert Mayer



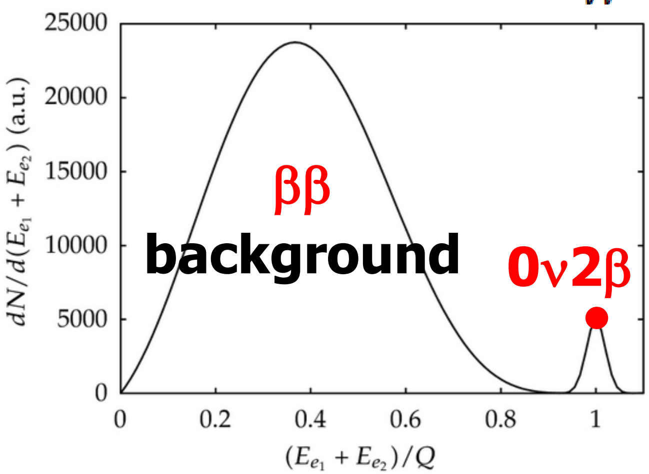
1939: 0ν2β decays

A 0ν2β decay can happen if massive ν's have the Majorana nature (W.H. Furry 1939):

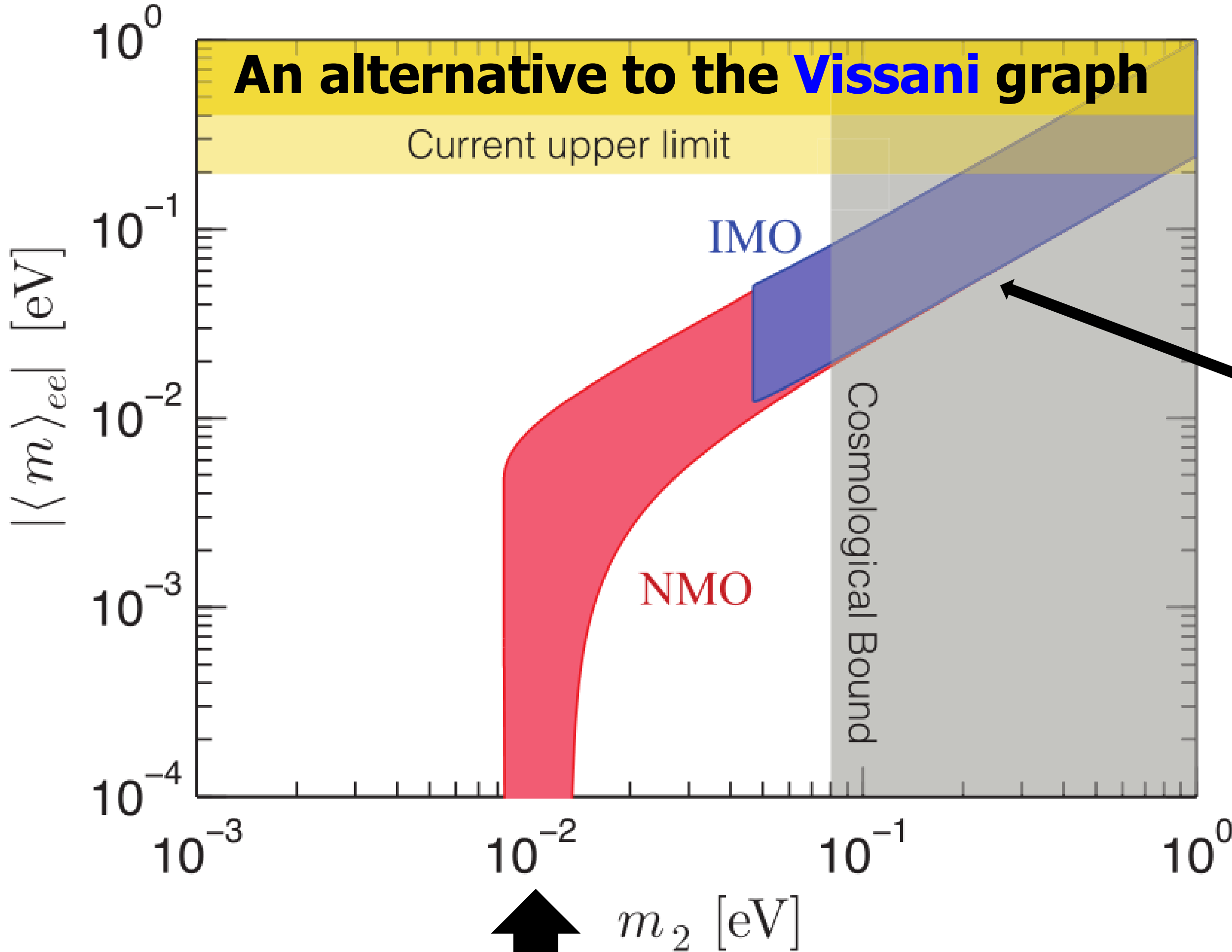
$$T^{0\nu}_{1/2} = \left(G^{0\nu}\right)^{-1} \left|M^{0\nu}\right|^{-2} \left|\langle m\rangle_{ee}\right|^{-2}$$



$$|\langle m\rangle_{ee}| = \left|\sum_i m_i U^2_{ei}\right|$$



The effective mass



The effective mass

$$|\langle m \rangle_{ee}| = \left|\sum_i m_i U_{ei}^2\right|$$

Maury Goodman asks:
An intelligent design?

Einstein (1921):
Subtle is the Lord, but malicious He is not.

The dark well

Vanishing 0ν2β mass?
Xing, hep-ph/0305195

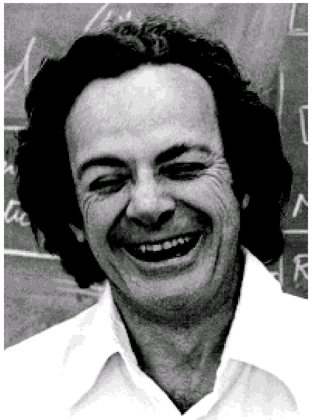
Burning Question:
how to interpret a discovery or a null result of 0ν2β?

Part A

Motivation of this talk

- to look at the effective $0\nu2\beta$ mass in a geometric way;
- to show the effects of Majorana phases in a 3-d graph;
- to explain why we have to go beyond the $0\nu2\beta$ decays.

I won't tell you anything that you don't know. I'll tell you something that you have known in a slightly (psychologically) different way.

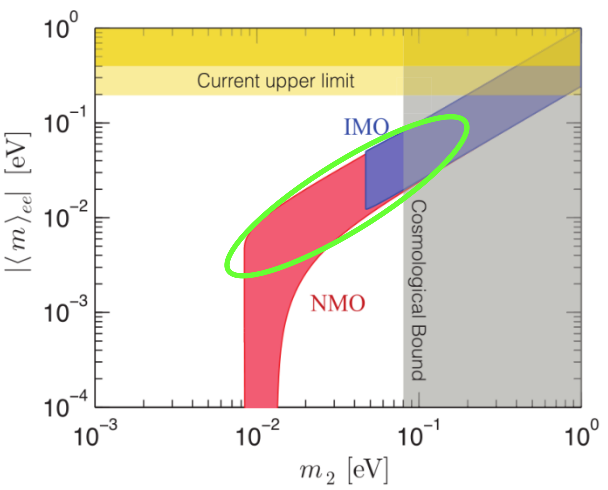


Example: the language of unitarity triangles in the quark sector proves to be very useful.

A naïve question: if the accelerator and reactor neutrino (antineutrino) oscillation experiments point to the normal neutrino mass hierarchy, is it still promising to look for the $0\nu2\beta$ decays?

Sure!

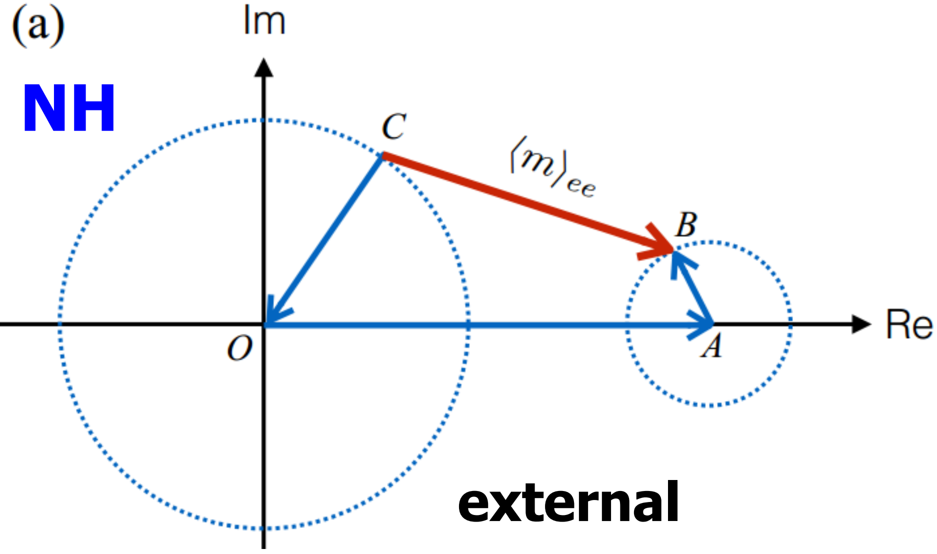
I have bet 50 Euro (~5000 Yen) on the **normal mass hierarchy** ---- better nearly degenerate!



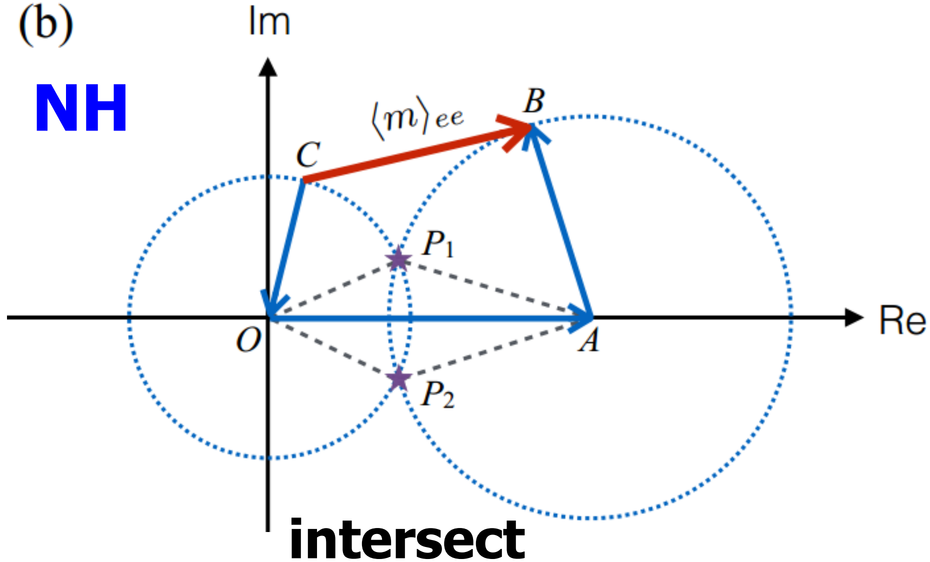
Part B

Coupling-rod diagram

(a)

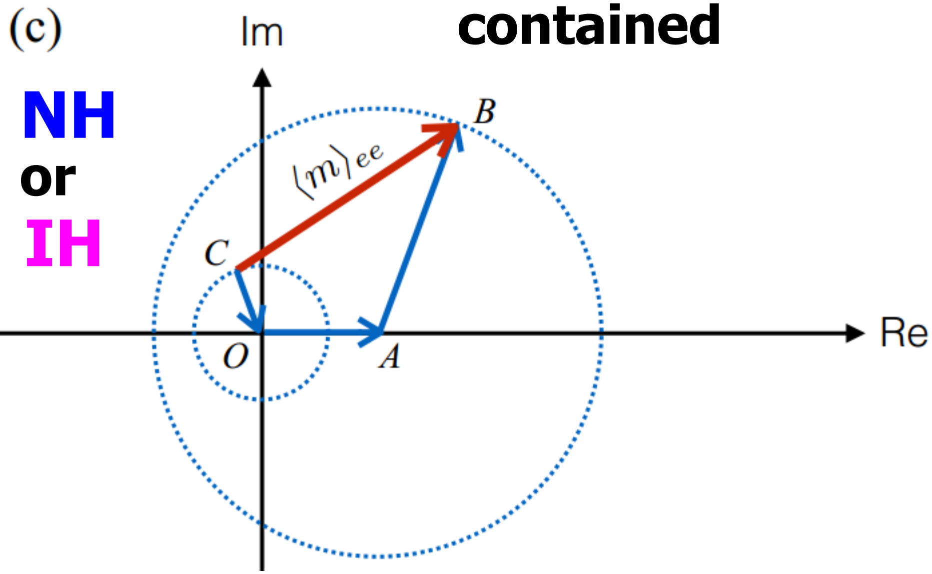


(b)



(c)

contained



$$\langle m \rangle_{ee} \equiv \overrightarrow{CB} = \overrightarrow{OA} + \overrightarrow{AB} + \overrightarrow{CO}$$

$$\overrightarrow{OA} \equiv m_2 U_{e2}^2 = m_2 |U_{e2}|^2 \,,$$
$$\overrightarrow{AB} \equiv m_1 U_{e1}^2 = m_1 |U_{e1}|^2 e^{i\rho}$$
$$\overrightarrow{CO} \equiv m_3 U_{e3}^2 = m_3 |U_{e3}|^2 e^{i\sigma}$$

Z.Z.X., Y.L. Zhou, arXiv:1404.7001

Maximum + Minimum

The above diagrams allow us to obtain the maximum/minimum limit:

Maximum in either hierarchy: $|\langle m\rangle_{ee}|_{\max} = OA + AB + OC$

$$|\langle m\rangle_{ee}|_{\max} = m_2 \sin^2\theta_{12}\cos^2\theta_{13}\left[1 + \sqrt{1 - \frac{\Delta m^2_{21}}{m^2_2}\cot^2\theta_{12}} + \sqrt{1 - \frac{\Delta m^2_{21}}{m^2_2} + \frac{\Delta m^2_{31}}{m^2_2}\frac{\tan^2\theta_{13}}{\sin^2\theta_{12}}}\right]$$

Minimum in normal hierarchy (1) : $|\langle m\rangle_{ee}|^{(\mathrm{a})}_{\min} = OA - AB - OC$

$$|\langle m\rangle_{ee}|^{(\mathrm{a})}_{\min} = m_2 \sin^2\theta_{12}\cos^2\theta_{13}\left[1 - \sqrt{1 - \frac{\Delta m^2_{21}}{m^2_2}\cot^2\theta_{12}} - \sqrt{1 - \frac{\Delta m^2_{21}}{m^2_2} + \frac{\Delta m^2_{31}}{m^2_2}\frac{\tan^2\theta_{13}}{\sin^2\theta_{12}}}\right]$$

Minimum in normal hierarchy (2): $|\langle m\rangle_{ee}|^{(\mathrm{c})}_{\min} = AB - OA - OC$

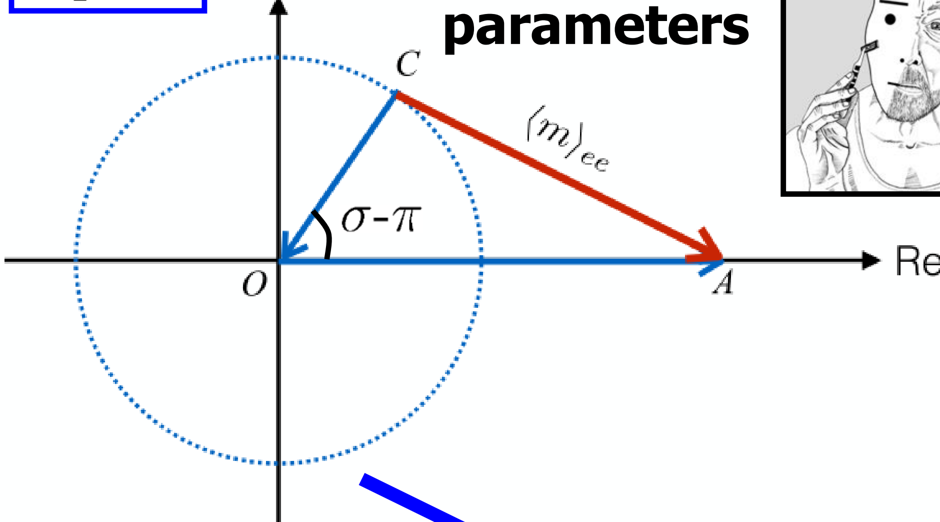
$$|\langle m\rangle_{ee}|^{(\mathrm{c})}_{\min} = m_2 \sin^2\theta_{12}\cos^2\theta_{13}\left[\sqrt{1 - \frac{\Delta m^2_{21}}{m^2_2}\cot^2\theta_{12}} - 1 - \sqrt{1 - \frac{\Delta m^2_{21}}{m^2_2} + \frac{\Delta m^2_{31}}{m^2_2}\frac{\tan^2\theta_{13}}{\sin^2\theta_{12}}}\right]$$

Minimum in inverted hierarchy: $|\langle m\rangle_{ee}|^{(\mathrm{c})}_{\min} = AB - OA - OC$

$$|\langle m\rangle_{ee}|^{(\mathrm{c})}_{\min} = m_2 \sin^2\theta_{12}\cos^2\theta_{13}\left[\sqrt{1 - \frac{\Delta m^2_{21}}{m^2_2}\cot^2\theta_{12}} - 1 - \sqrt{1 - \frac{\Delta m^2_{21}}{m^2_2} + \frac{\Delta m^2_{31}}{m^2_2}\frac{\tan^2\theta_{13}}{\sin^2\theta_{12}}}\right]$$

Occam's razor

$m_1 = 0$

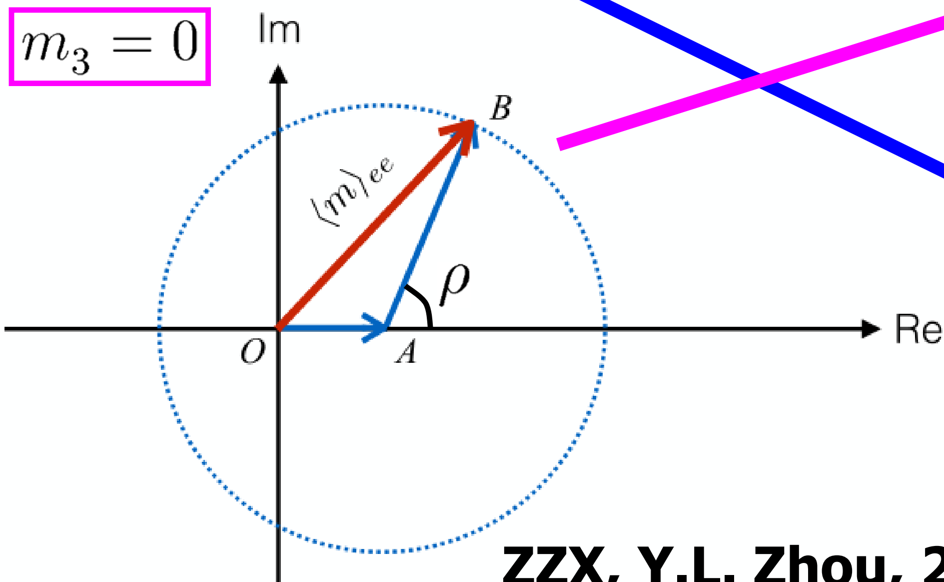


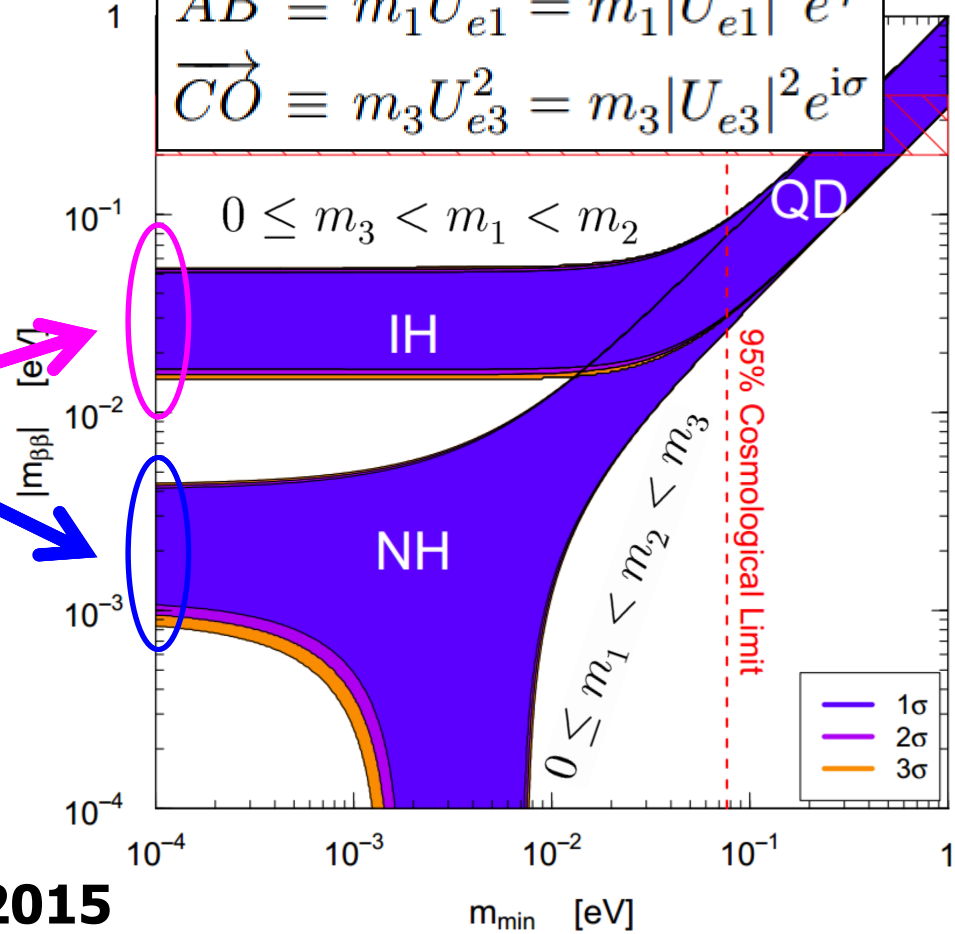
Fewer facial parameters

Entities must not be multiplied beyond necessity.

$$\overrightarrow{OA} \equiv m_2 U_{e2}^2 = m_2 |U_{e2}|^2 \,,$$
$$\overrightarrow{AB} \equiv m_1 U_{e1}^2 = m_1 |U_{e1}|^2 e^{i\rho}$$
$$\overrightarrow{CO} \equiv m_3 U_{e3}^2 = m_3 |U_{e3}|^2 e^{i\sigma}$$

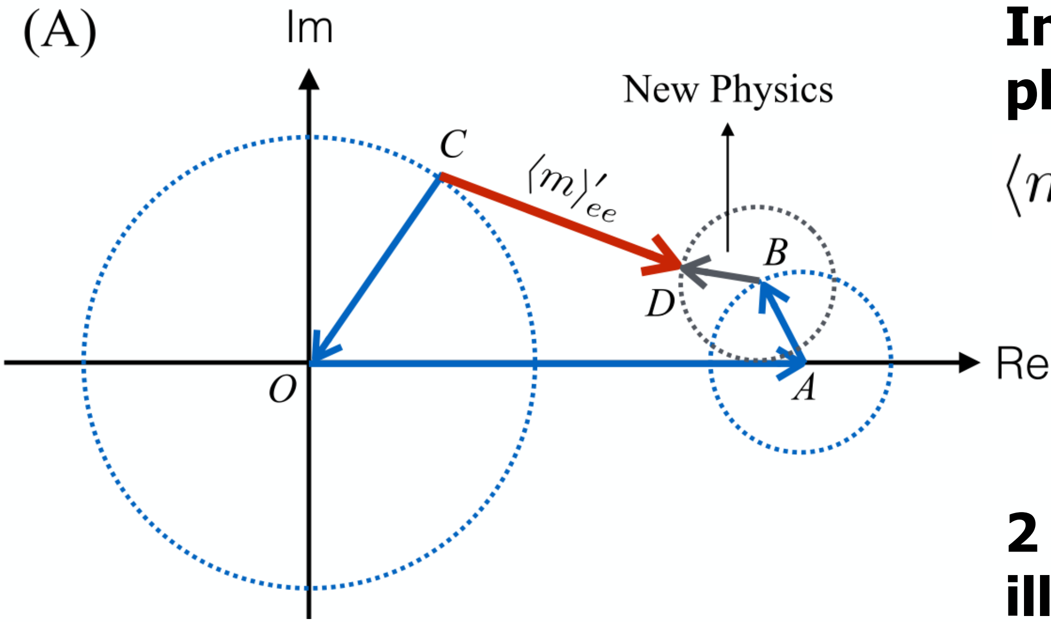
$m_3 = 0$

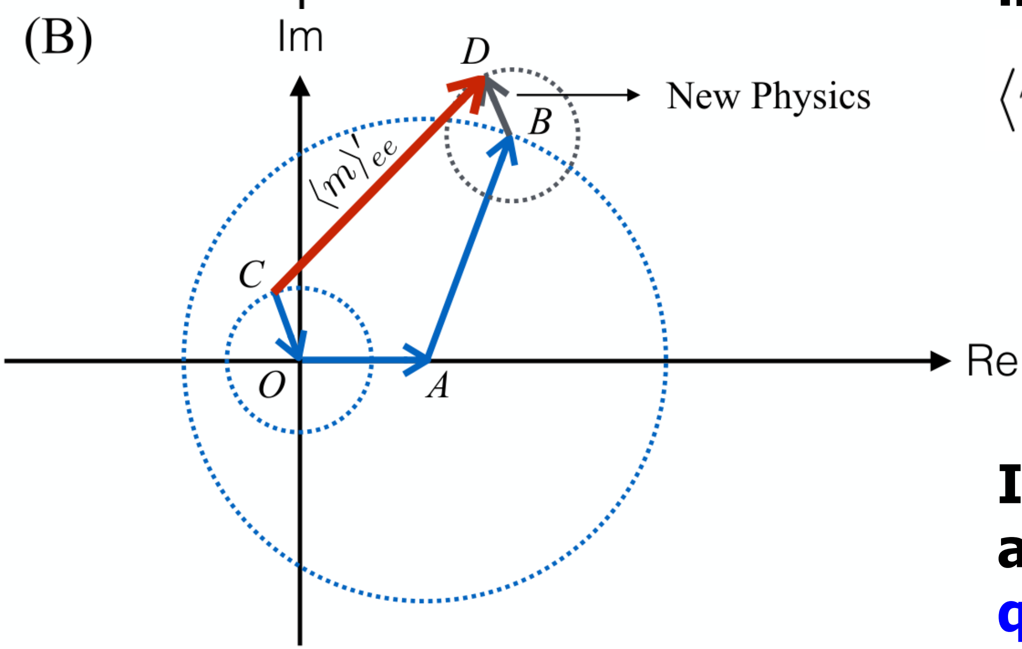




ZZX, Y.L. Zhou, 2015

New physics





In the presence of a kind of new physics, we denote:

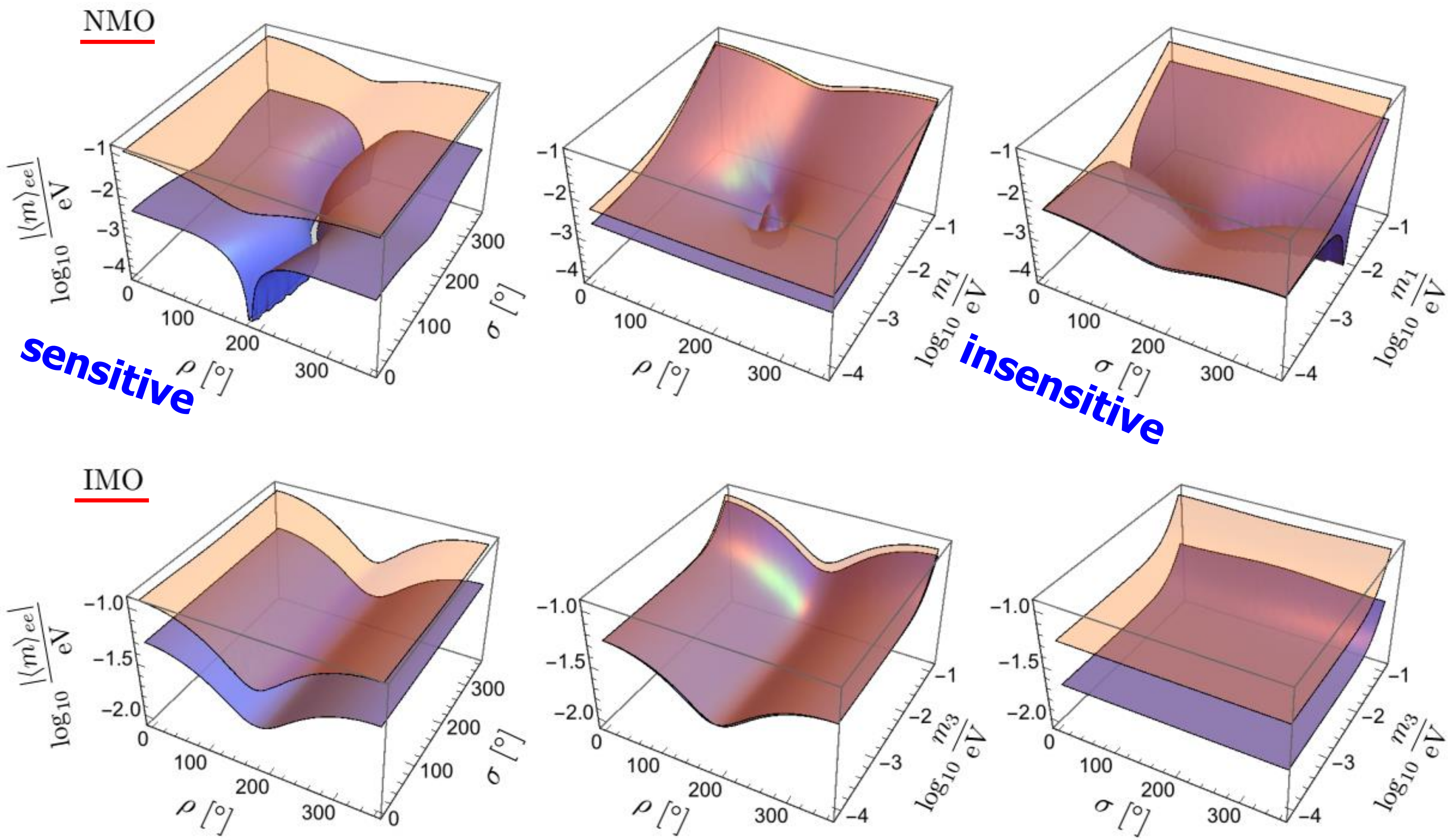
$$\langle m \rangle'_{\alpha\beta} = \langle m \rangle_{\alpha\beta} + \text{new physics}$$

2 very simple configurations are illustrated on the left-hand side:

$$\begin{aligned} \langle m \rangle'_{\alpha\beta} &\equiv \overrightarrow{CD} = \langle m \rangle_{\alpha\beta} + \overrightarrow{BD} \\ &= \overrightarrow{CO} + \overrightarrow{OA} + \overrightarrow{AB} + \overrightarrow{BD} \end{aligned}$$

In the above Occam's razor case, a pentagon can be simplified to a quadrangle.

3-d description



Lower bound: blue; upper bound: light orange. Clearer sensitivities to mass and phase parameters (Xing, Zhao, Zhou, arXiv:1504.05820)

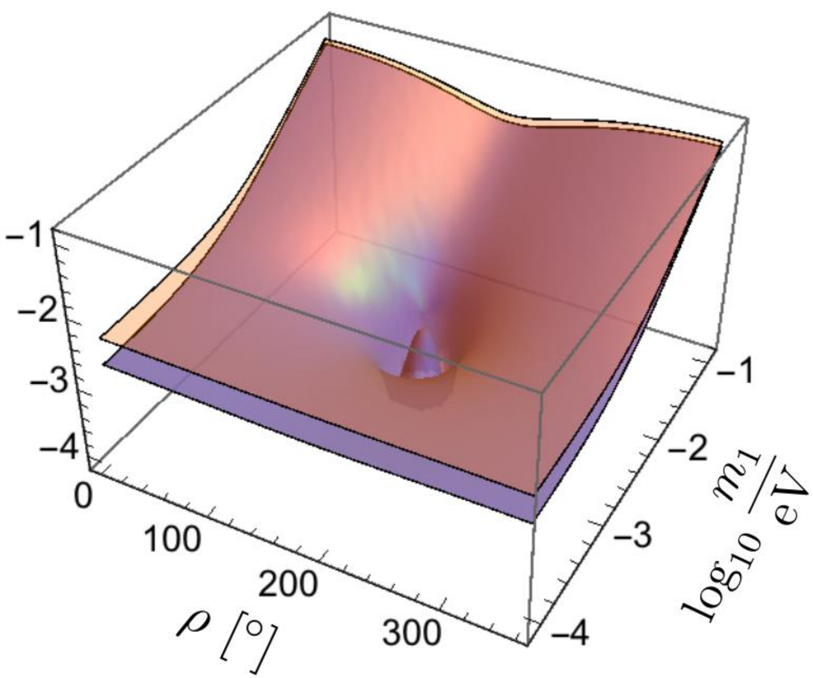
Contour of the well

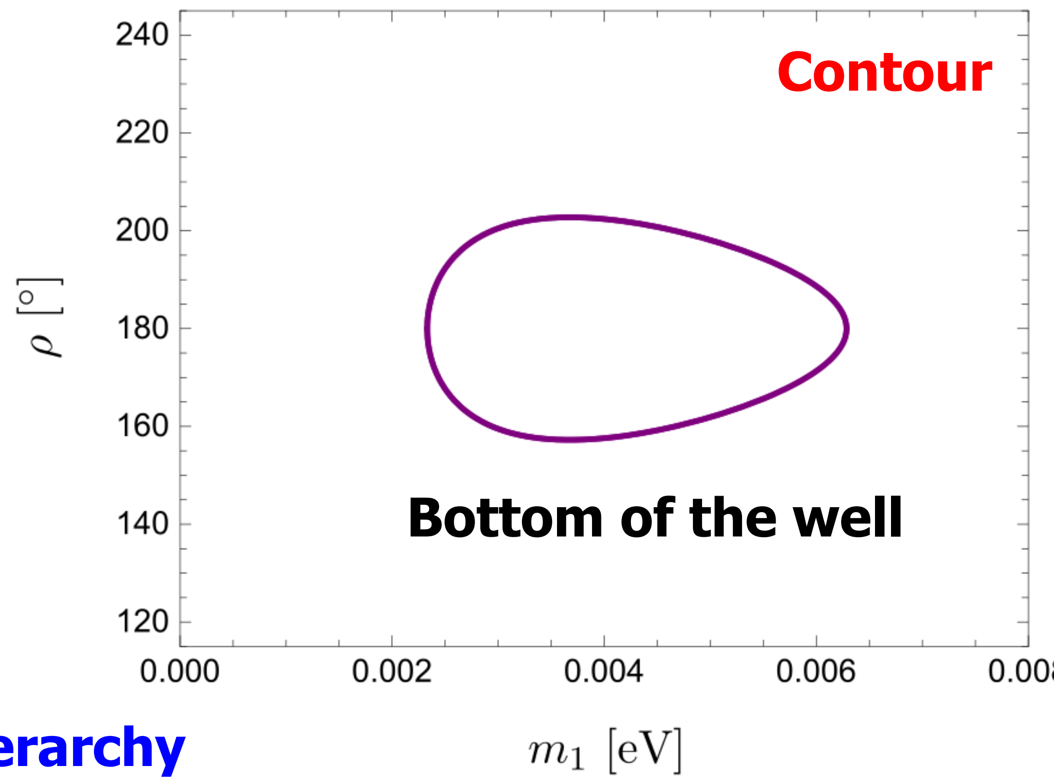
Let us understand the champagne-bottle profile of the effective 0ν2β mass term in the normal hierarchy case:

$$\langle m \rangle_{ee} = m_1 c_{12}^2 c_{13}^2 e^{i\rho} + m_2 s_{12}^2 c_{13}^2 + m_3 s_{13}^2 e^{i\sigma} = 0$$

$$\Downarrow$$

$$m_1^2 c_{12}^4 c_{13}^4 + 2 m_1 m_2 c_{12}^2 s_{12}^2 c_{13}^4 \cos\rho + m_2^2 s_{12}^4 c_{13}^4 = m_3^2 s_{13}^4$$





The dark well in the normal hierarchy

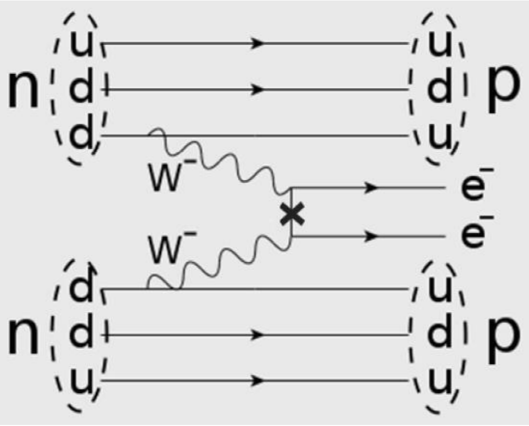
What new physics?

Type (A): NP directly related to extra species of neutrinos.

Example 1: heavy Majorana neutrinos from type-I seesaw

$$-\mathcal{L}_{\rm lepton} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \overline{l_{\rm L}} Y_\nu \tilde{H} N_{\rm R} + \frac{1}{2}\overline{N^{\rm c}_{\rm R}} M_{\rm R} N_{\rm R} + {\rm h.c.}$$

$$\Gamma_{0\nu\beta\beta} \propto \left| \sum_{i=1}^{3} m_i U_{ei}^2 \;-\; \sum_{k=1}^{n} \frac{R_{ek}^2}{M_k} M_A^2 \mathcal{F}(A, M_k) \right|^2$$



In most cases the heavy contribution is negligible

Example 2: light sterile neutrinos from LSND etc

$$\langle m\rangle'_{ee} \equiv \sum_{i=1}^{6} m_i U_{ei}^2 = \langle m\rangle_{ee} \left(c_{14}c_{15}c_{16}\right)^2 + m_4 \left(\hat{s}^*_{14}c_{15}c_{16}\right)^2 + m_5 \left(\hat{s}^*_{15}c_{16}\right)^2 + m_6 \left(\hat{s}^*_{16}\right)^2$$

In this case the new contribution might be constructive or destructive

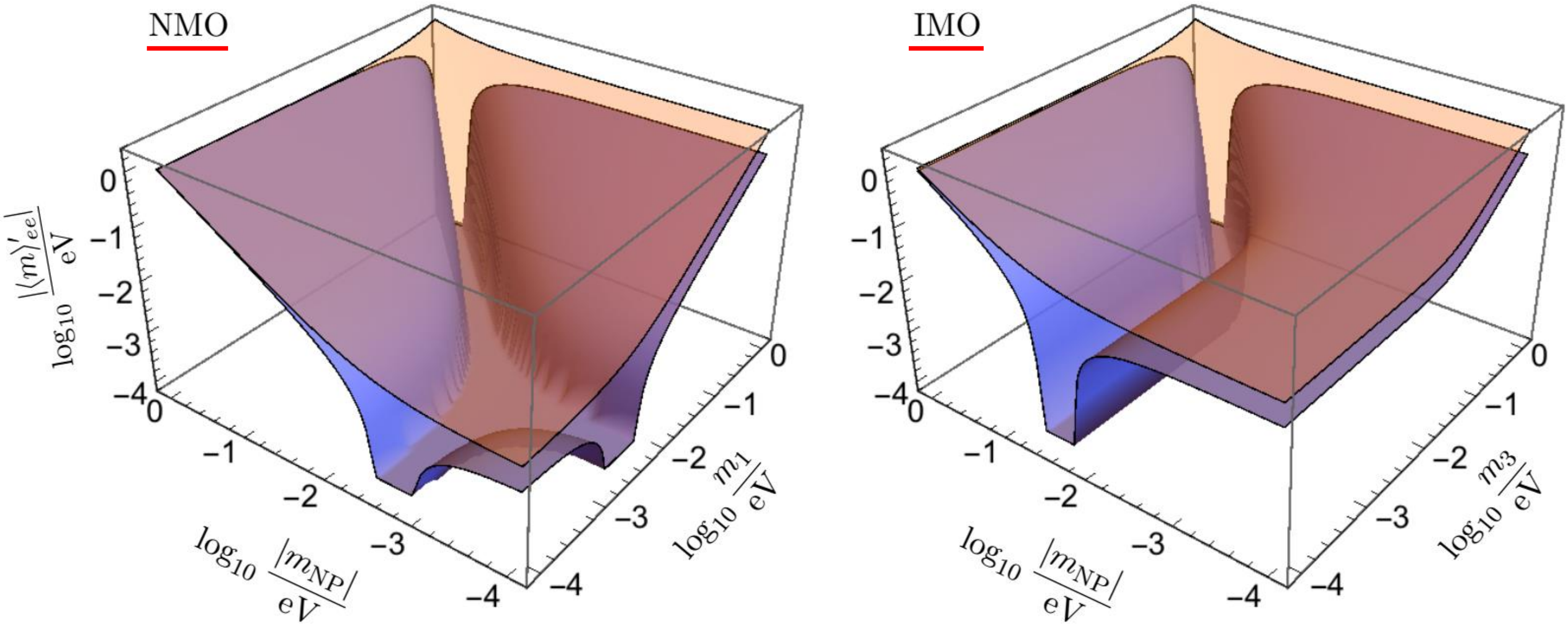
Type (B): NP has little to do with the neutrino mass issue.

SUSY, Left-right, and some others that I don't understand

Possible effects

New physics effects:

$$\langle m\rangle'_{ee} = m_1 U_{e1}^2 + m_2 U_{e2}^2 + m_3 U_{e3}^2 + m_{\rm NP}$$



Lower bound: blue; upper bound: light orange. Clearer sensitivities to mass and phase parameters (Xing, Zhao, Zhou, arXiv:1504.05820)

$$\left|\langle m\rangle'_{ee}\right|_{\rm upper} = m_1 \left|U_{e1}\right|^2 + m_2 \left|U_{e2}\right|^2 + m_3 \left|U_{e3}\right|^2 + \left|m_{\rm NP}\right| ,$$

$$\left|\langle m\rangle'_{ee}\right|_{\rm lower} = \max\left\{0,\ 2m_i \left|U_{ei}\right|^2 - \left|\langle m\rangle'_{ee}\right|_{\rm upper},\ 2\left|m_{\rm NP}\right| - \left|\langle m\rangle'_{ee}\right|_{\rm upper}\right\}$$

It is hard to tell much

YES or NO?

QUESTION: are massive neutrinos the Majorana particles?

One might be able to answer YES through a measurement of the 0ν2β decay or other LNV processes someday, but how to answer with NO?

YES
or
I don't know!

The same question: how to distinguish between Dirac and Majorana neutrinos in a realistic experiment?

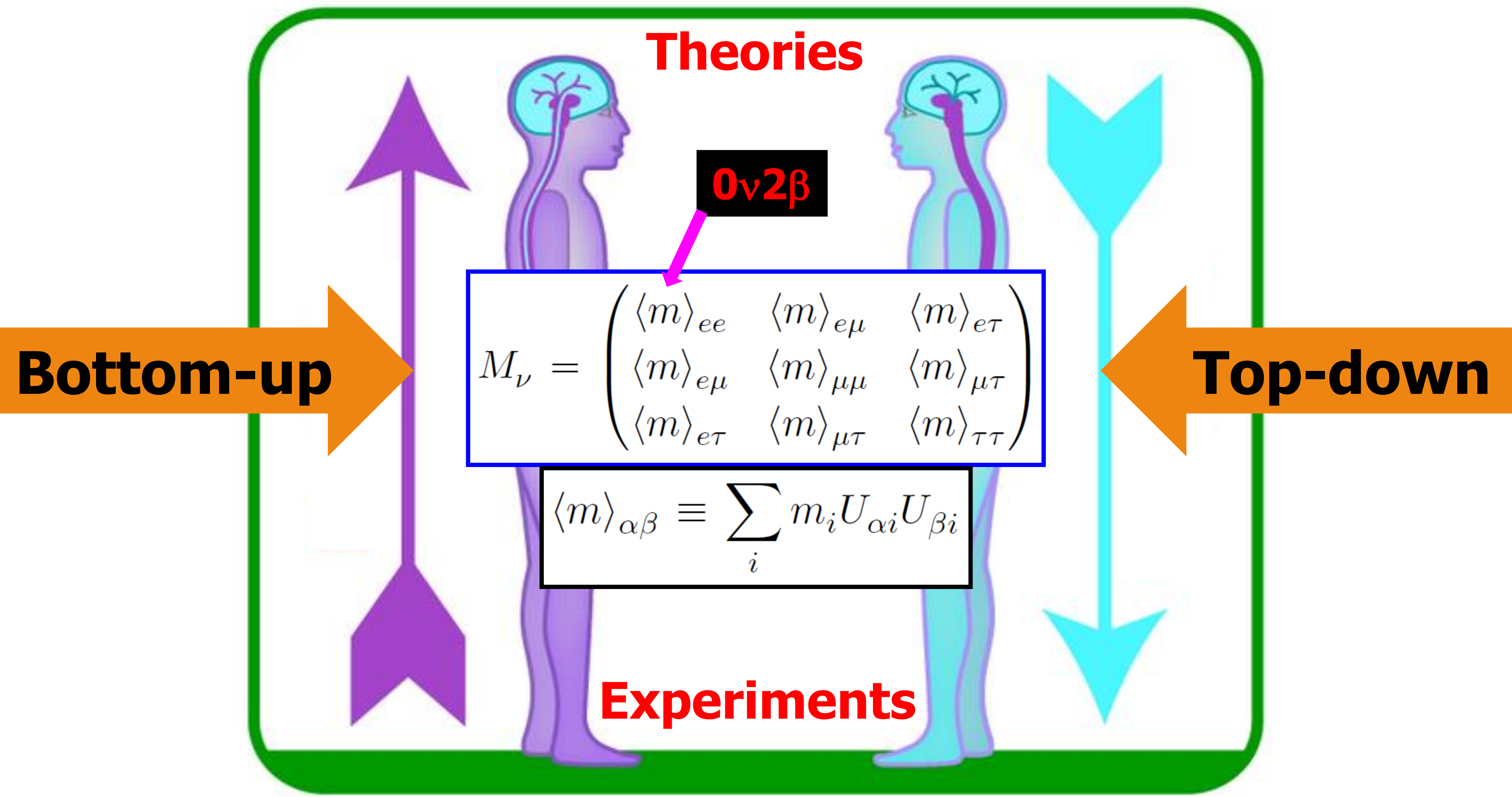
Answer 1: The 0ν2β decay is currently the only possibility.

Answer 2: In principle their dipole moments are different.

Answer 3: They show different behavior if nonrelativistic.

Remarks

Without information on the nature of massive neutrinos (Majorana or not) and all the CP-violating phases, one will have no way to establish a full theory of ν masses and flavor mixing. Give 0ν2β a chance!



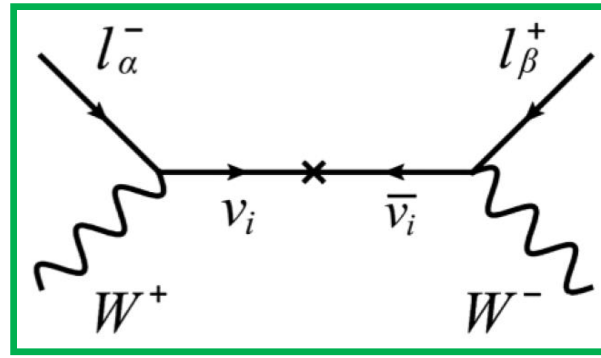
$\nu \Leftrightarrow \overline{\nu}$ oscillations?

The neutrino-antineutrino oscillation can in principle help.

Neutrino-Antineutrino Oscillations:

$$A(\nu_\alpha \to \overline{\nu}_\beta) = \sum_i \left[U^*_{\alpha i} U^*_{\beta i} \frac{m_i}{E} \exp\left(-\mathrm{i}\frac{m_i^2}{2E} L\right)\right] K$$

$$A(\overline{\nu}_\alpha \to \nu_\beta) = \sum_i \left[U_{\alpha i} U_{\beta i} \frac{m_i}{E} \exp\left(-\mathrm{i}\frac{m_i^2}{2E} L\right)\right] \overline{K}$$



$$\phi_{ji} \equiv \Delta m^2_{ji} L/(4E)$$

$$P(\nu_\alpha \to \overline{\nu}_\beta) = \frac{|K|^2}{E^2} \left[\left|\langle m\rangle_{\alpha\beta}\right|^2 - 4\sum_{i<j} m_i m_j \mathcal{C}^{ij}_{\alpha\beta} \sin^2\phi_{ji} + 2\sum_{i<j} m_i m_j \mathcal{V}^{ij}_{\alpha\beta} \sin 2\phi_{ji}\right]$$

$$P(\overline{\nu}_\alpha \to \nu_\beta) = \frac{|\overline{K}|^2}{E^2} \left[\left|\langle m\rangle_{\alpha\beta}\right|^2 - 4\sum_{i<j} m_i m_j \mathcal{C}^{ij}_{\alpha\beta} \sin^2\phi_{ji} - 2\sum_{i<j} m_i m_j \mathcal{V}^{ij}_{\alpha\beta} \sin 2\phi_{ji}\right]$$

mass **CP-conserving** **CP-violating**

Effective mass terms:

$$\langle m\rangle_{\alpha\beta} \equiv \sum_i m_i U_{\alpha i} U_{\beta i}$$

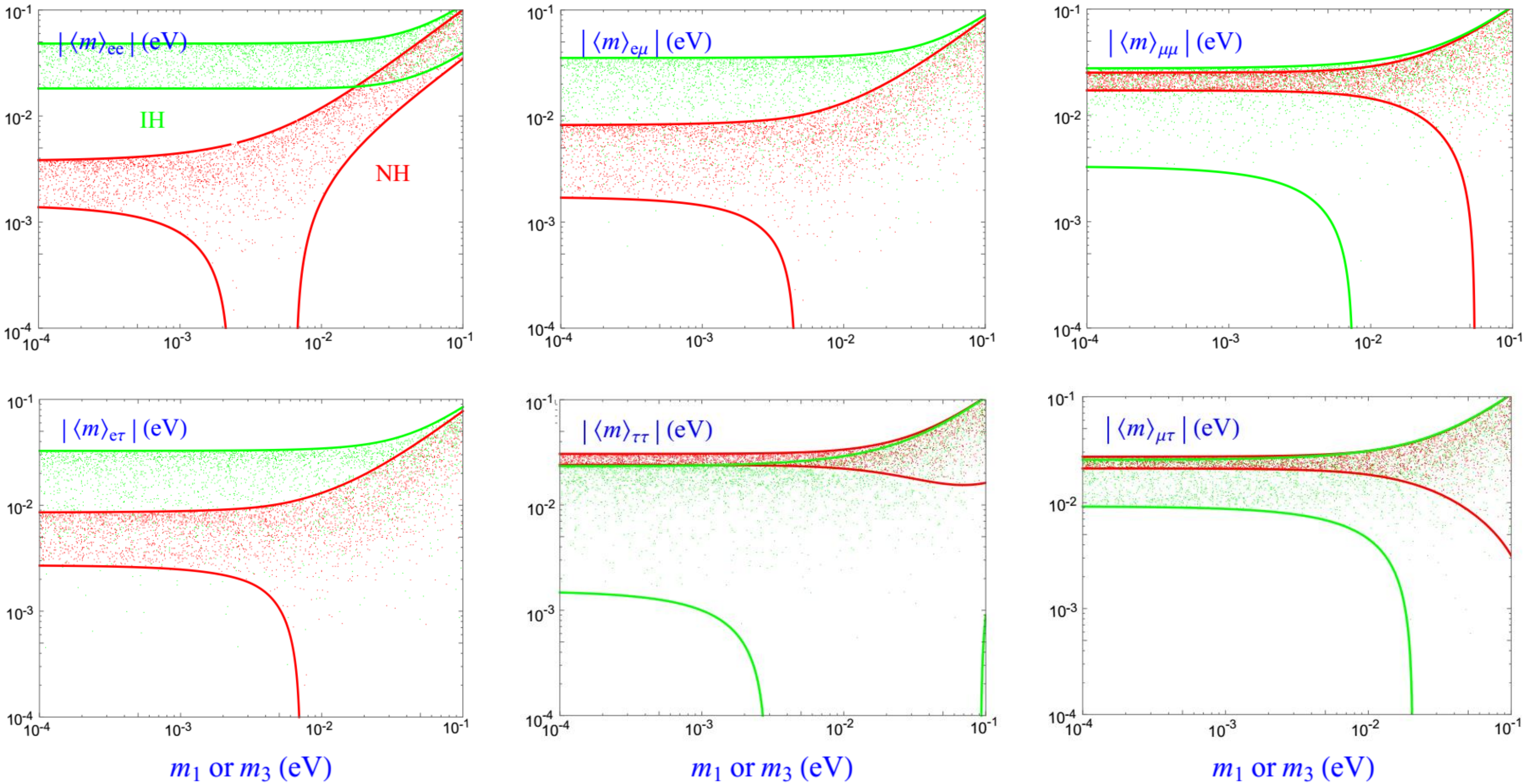
Jarlskog-like parameters:

$$\mathcal{C}^{ij}_{\alpha\beta} \equiv \mathrm{Re}\left(U_{\alpha i} U_{\beta i} U^*_{\alpha j} U^*_{\beta j}\right)$$

$$\mathcal{V}^{ij}_{\alpha\beta} \equiv \mathrm{Im}\left(U_{\alpha i} U_{\beta i} U^*_{\alpha j} U^*_{\beta j}\right)$$

Part D

More LNV processes



To identify the Majorana nature, CP-violating phases and new physics it is imperative to observe the 0ν2β decays and other lepton-number-violating processes (e.g., neutrino-antineutrino oscillations, the relic neutrino background, doubly-charged Higgs decays). None is realistic

Concluding remark

All of us expect the massive neutrinos to be the Majorana particles. If this expectation comes true someday thanks to the 0ν2β decay, then we will be required to have some new or good or right ideas to probe the Majorana phases.

I.I. Rabi: Physics needs new ideas. But to have a new idea is a very difficult task....

L.C. Pauling: The best way to have a good idea is to have a lot of ideas.

C.S. Wu: It is easy to do the right thing once you have the right ideas.