The 0νββ and its implications

邢志忠

高能所

★ Coming to the 0νββ decay

★ Its sensitivity to Majorana

★ New physics as pollution

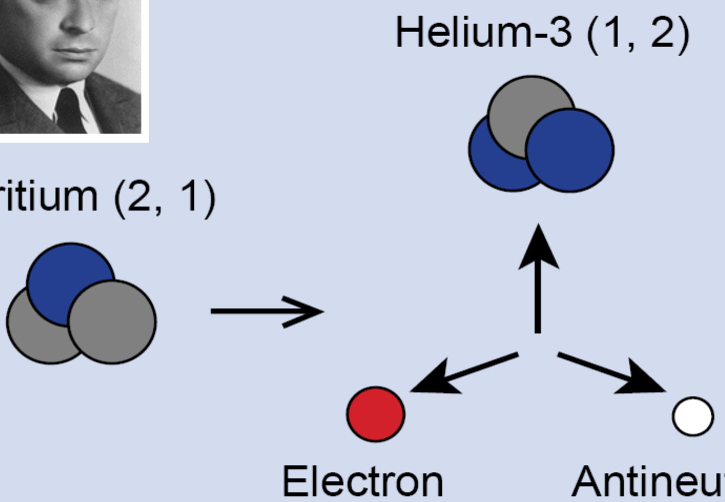
★ Other possible ways out?

Review 1: S. Elliot, M. Franz, 1403.4976 (Rev. Mod. Phys.)
Review 2: S. Bilenky, C. Giunti, arXiv:1411.4791

@ 中国科技大学，无中微子ββ衰变研讨会，2014年12月6日

1933

Three-Body Final State

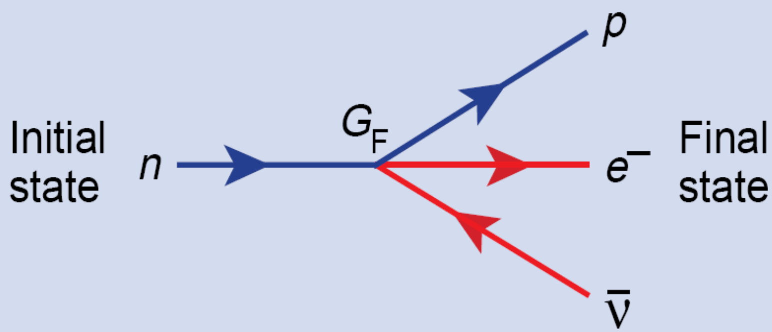


Electron and neutrino share the available energy.

$$(N, Z) \longrightarrow (N-1, Z+1) + e^- + \bar{\nu} \quad .$$

I will be remembered for this paper

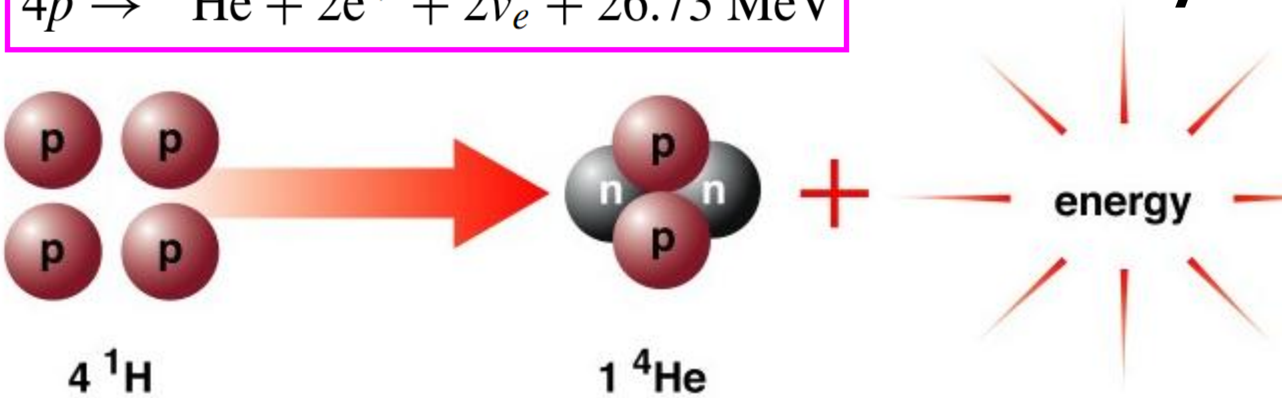
Neutron Beta Decay



$$n \rightarrow p + e^- + \bar{\nu}$$

$$4p \rightarrow {}^4\mathrm{He} + 2\mathrm{e}^+ + 2\nu_e + 26.73\ \mathrm{MeV}$$

Why the sun shines? Because blah blah blah



$$+\,2e^+ + 2\nu_e$$

1935

ββ 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:

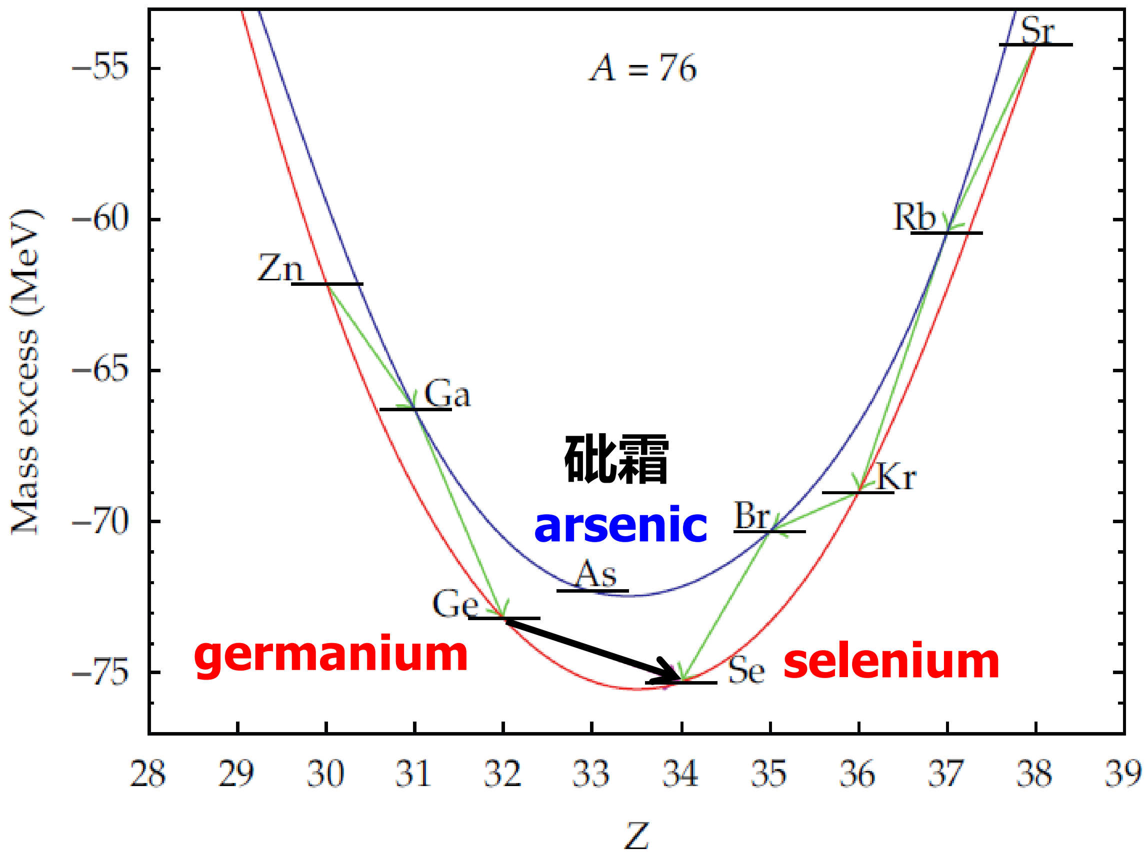
$$m(Z,A) > m(Z+2,A)$$

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

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

1935

Maria Goeppert Mayer



1937

★ Theory of the Symmetry of Electrons and Positrons

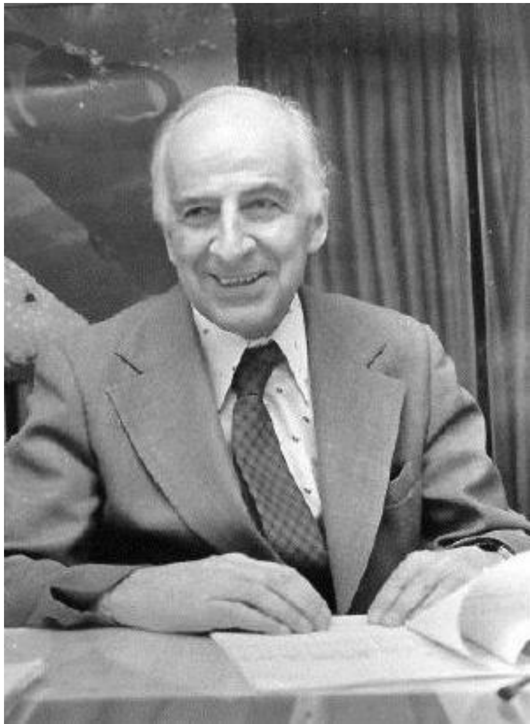
Ettore Majorana

Nuovo Cim. 14 (1937) 171

Are massive neutrinos and antineutrinos identical or different —— a fundamental puzzling question in particle physics.

★ Mesonium and Anti-mesonium

Bruno Pontecorvo

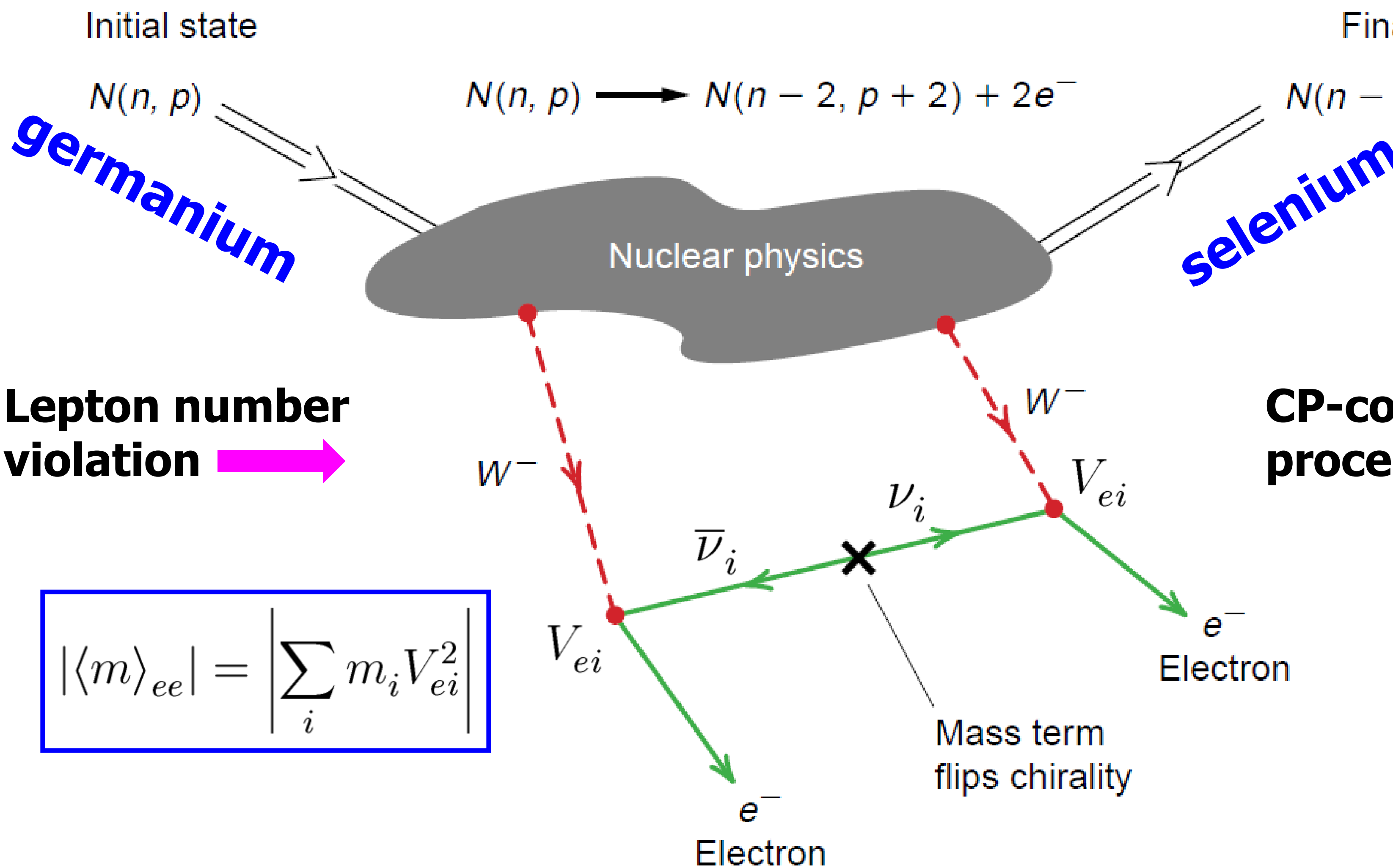


Zh. Eksp. Teor. Fiz. 33 (1957) 549
Sov. Phys. JETP 6 (1957) 429

If the two-component neutrino theory turned out to be incorrect and if the conservation law of neutrino charge didn't apply, then neutrino -antineutrino transitions would in principle be possible to take place in vacuum.

1939

The neutrinoless double beta decay can happen if massive neutrinos are the Majorana particles (W.H. Furry 1939):



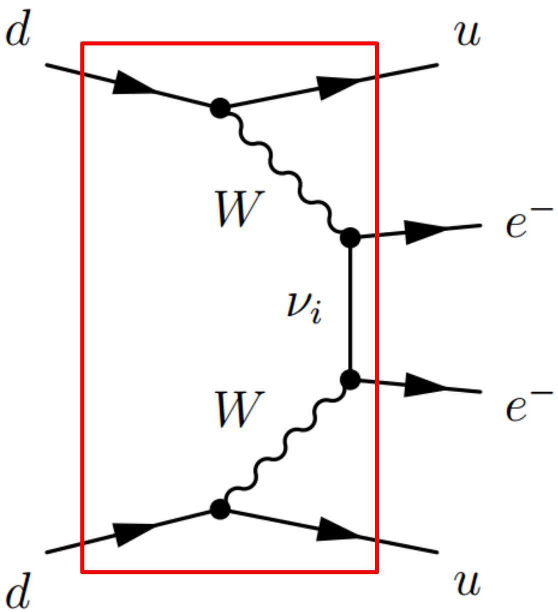
Lepton number violation →

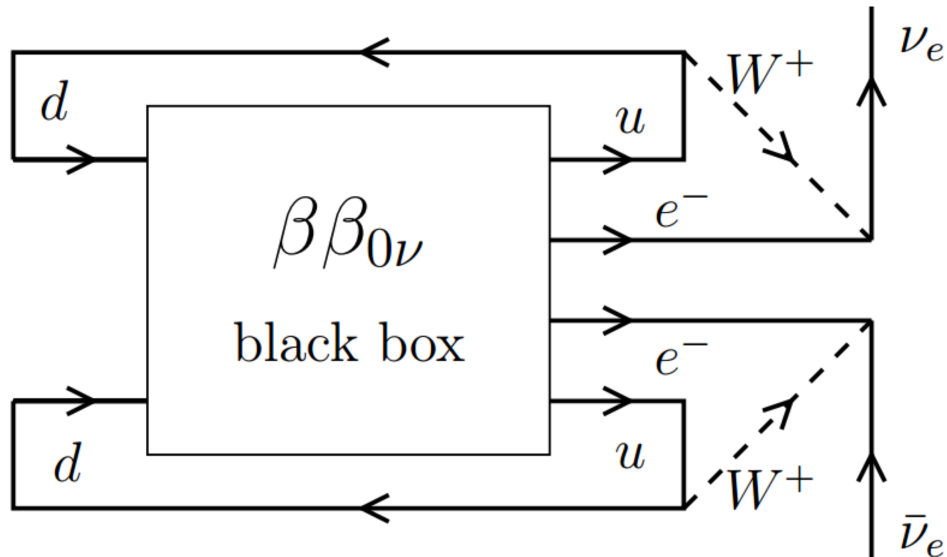
CP-conserving process ←

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

Schechter-Valle theorem

THEOREM (1982): if a 0νββ decay happens, there must be an effective Majorana mass term.





Bruno Pontecorvo's Prediction

指导我们试验的理论基础是SV定理

Four-loop ν mass:

$$\delta m_\nu = \mathcal{O}(10^{-24}\,\mathrm{eV})$$

(Duerr, Lindner, Merle, 2011)

Note: The black box can in principle have many different processes (new physics). Only in the simplest case, which is most interesting, it's likely to constrain neutrino masses

Simplest case

GERDA has killed the Heidelberg-Moscow's claim on 0νββ.

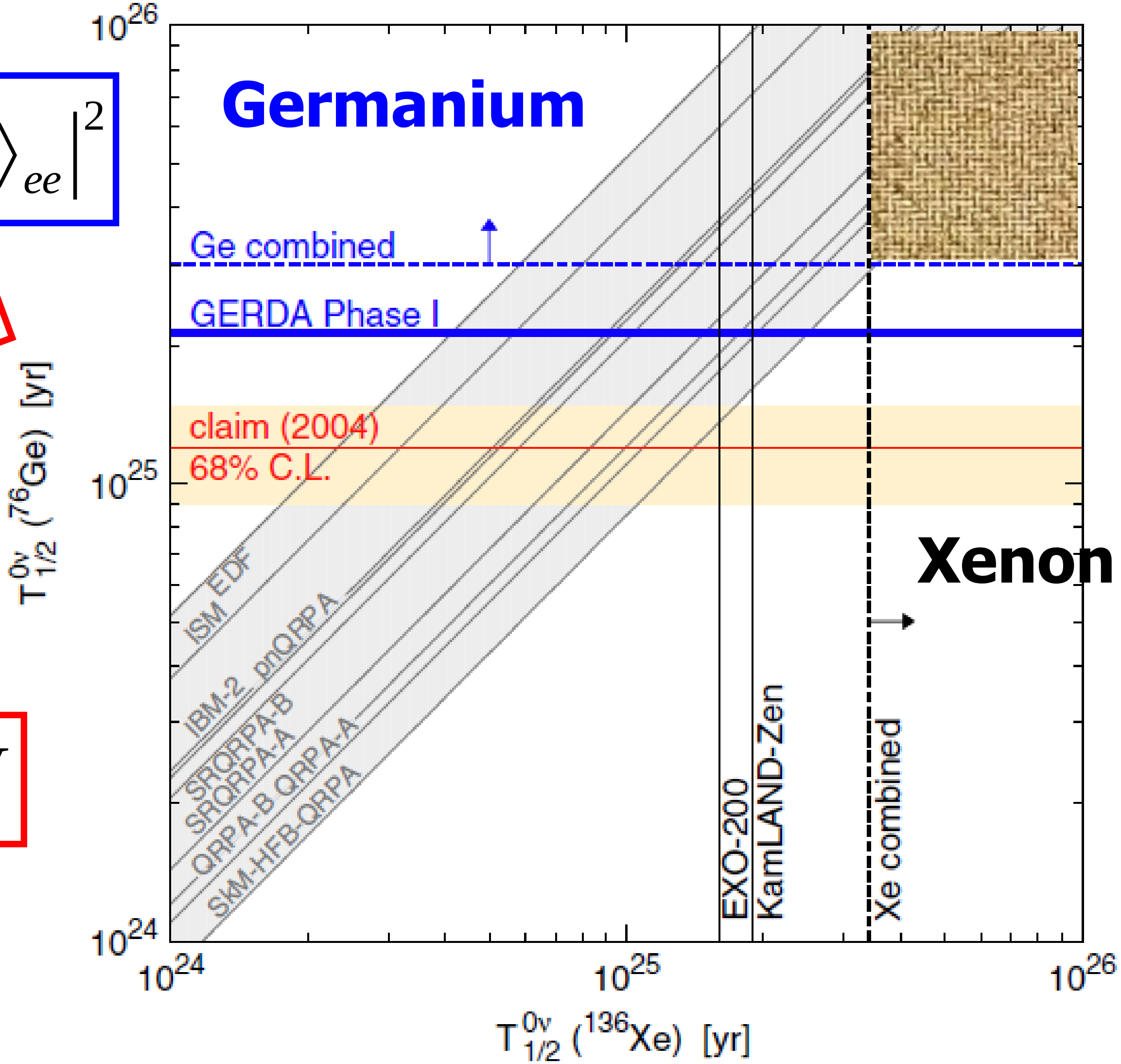
PRL **111**, 122503 (2013)

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

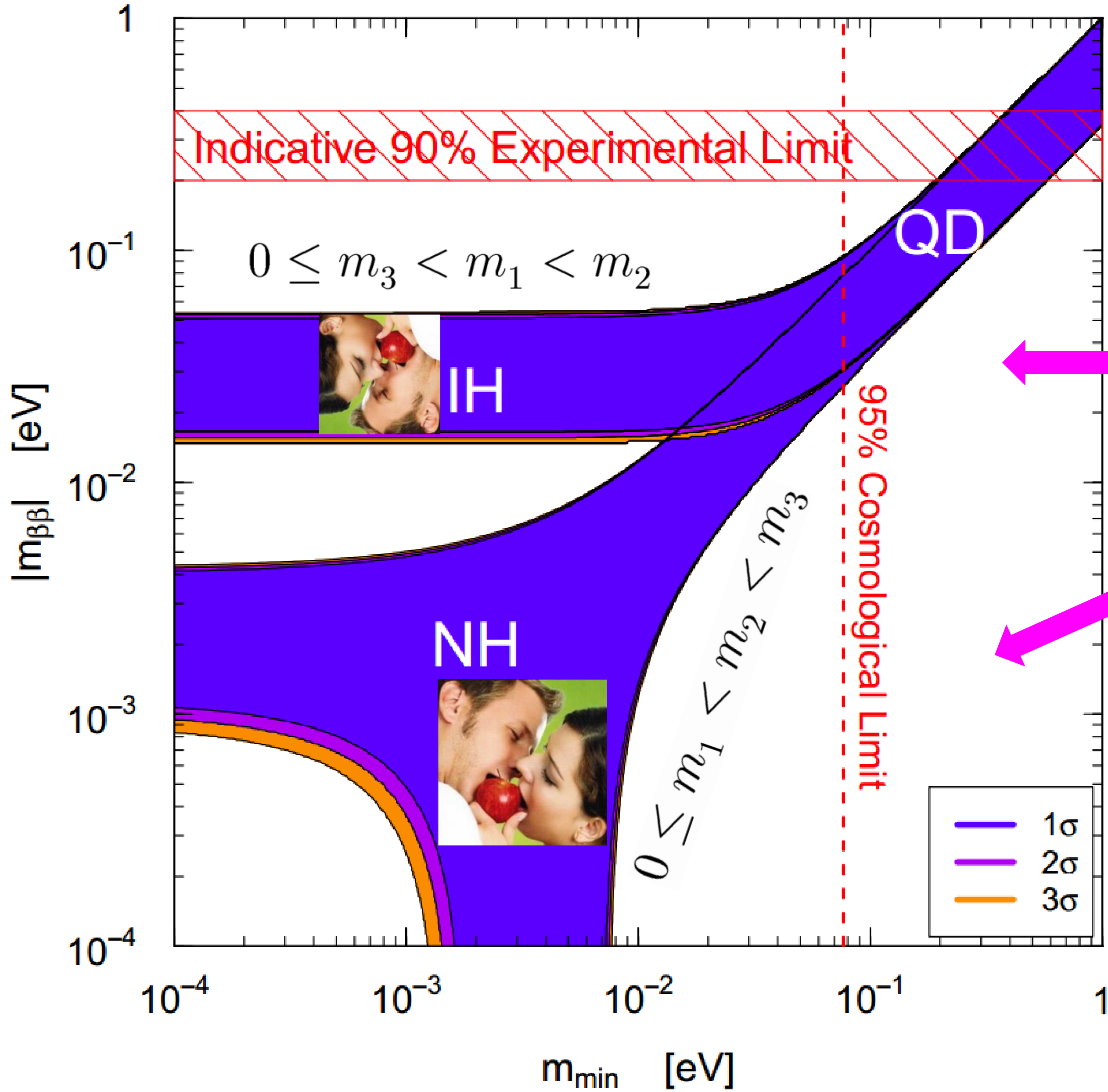
$$T_{1/2}^{0\nu} > 3.0 \times 10^{25}\ \text{yr (90\% C.L.)}.$$

$$\left|\langle m\rangle_{ee}\right| < 0.2 \rightarrow 0.4\ \text{eV}$$

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



Effective 0νββ mass



The effective mass

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

Maury Goodman asks

An intelligent design?

I asked myself in 2003

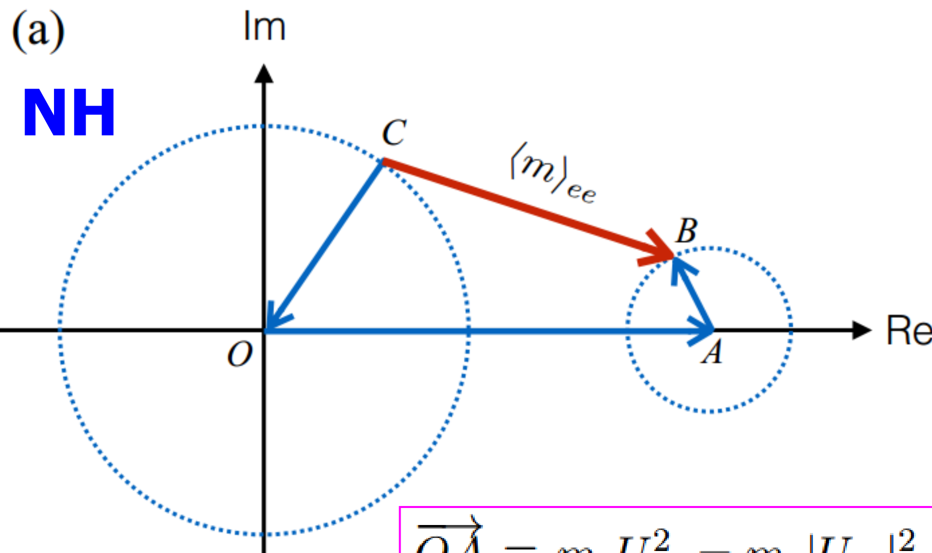
Vanishing 0νββ mass?

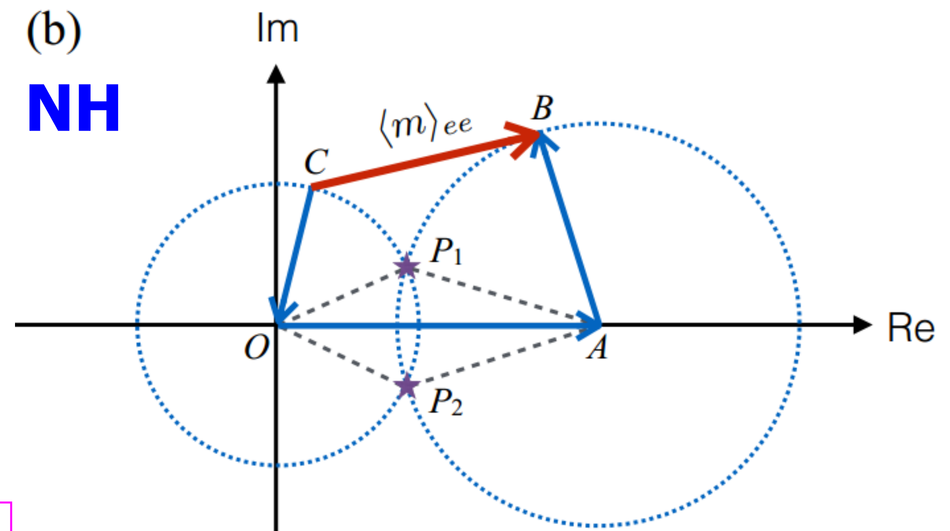
hep-ph/0305195, PRD

CP phases also matter

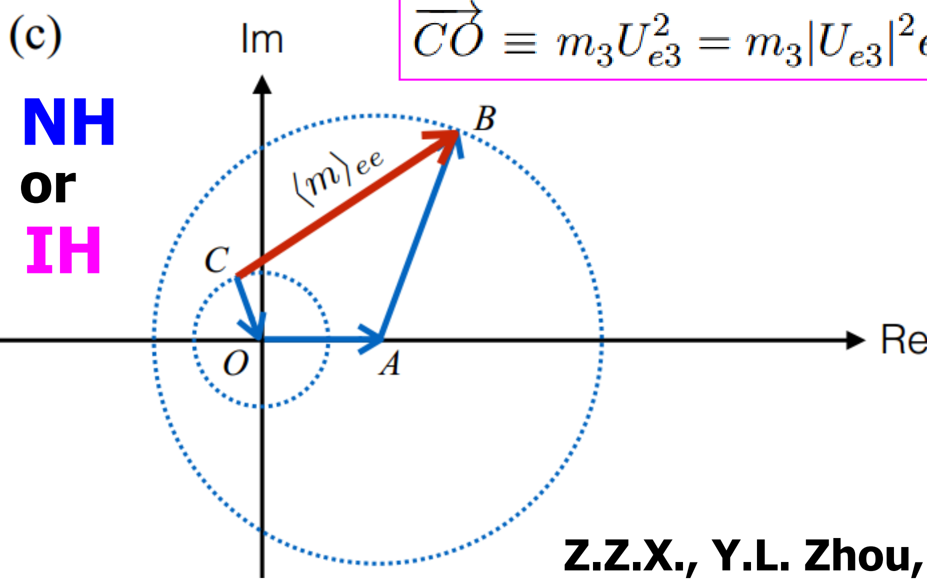
In case of new physics, is it destructive or constructive?

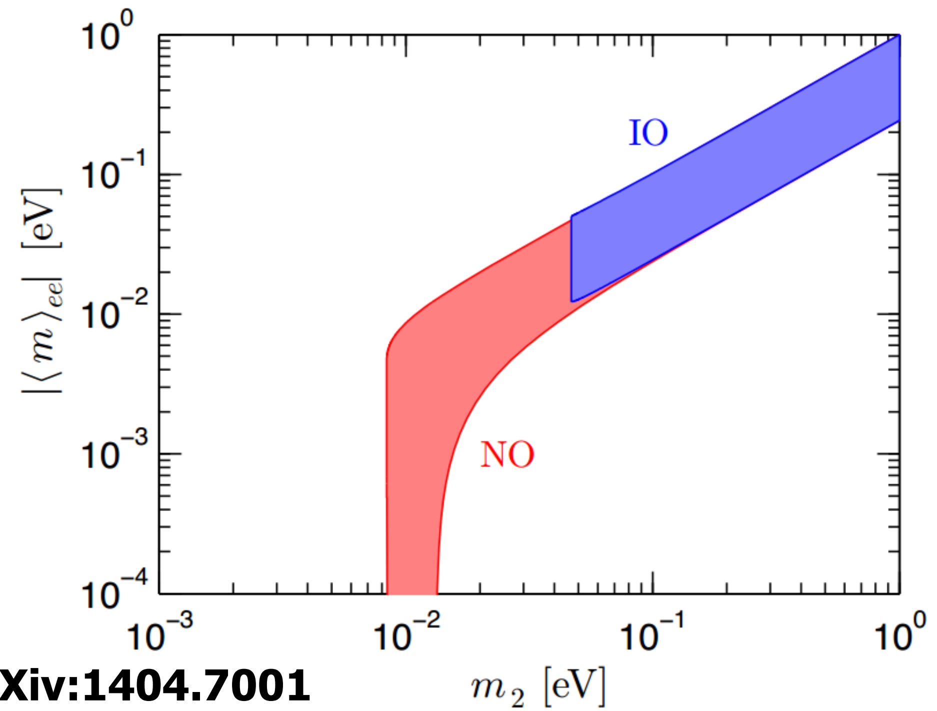
Coupling-rod diagram





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





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

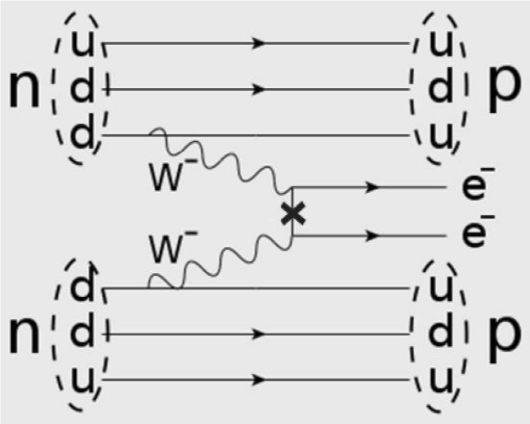
New physics

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

Example 1: heavy Majorana neutrinos from type-I seesaw

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

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



In most cases the heavy contribution is negligible

Example 2: light sterile neutrinos from LSND etc

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

In this case the new contribution might be constructive or destructive

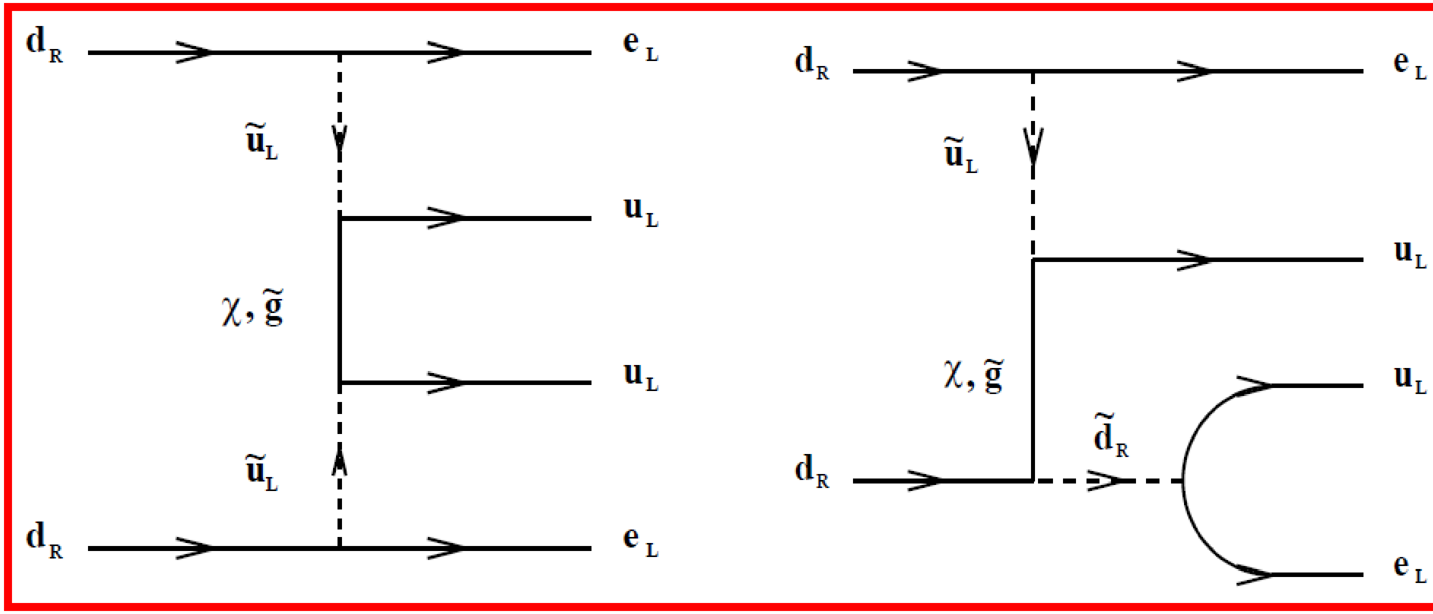
Type (B): NP has little to do with the neutrino mass issue.

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

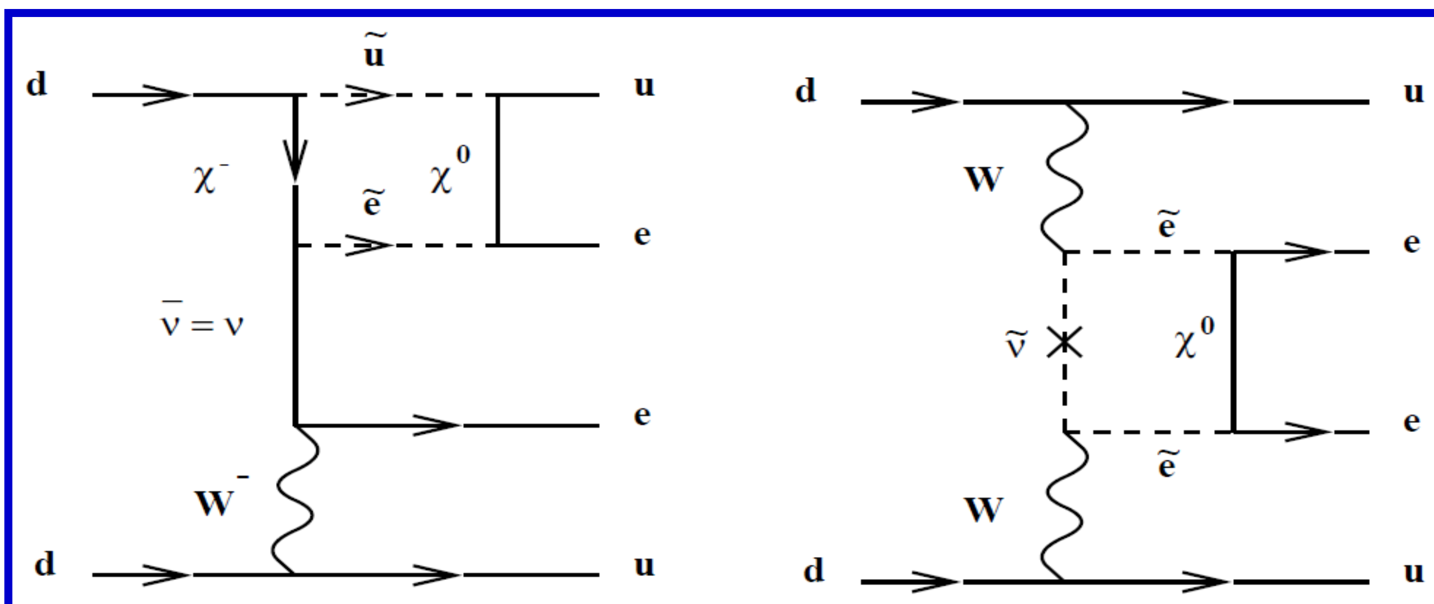
Part C

SUSY?

Example (A):
R-parity violation



Example (B):
R-parity conservation



H.V. Klapdor, hep-ex/9901021

YES or NO?

QUESTION: are massive neutrinos the Majorana particles?

One might be able to answer YES through a measurement of the 0νββ 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 0νββ decay is currently the only possibility.**

Answer 2: **In principle their dipole moments are different.**

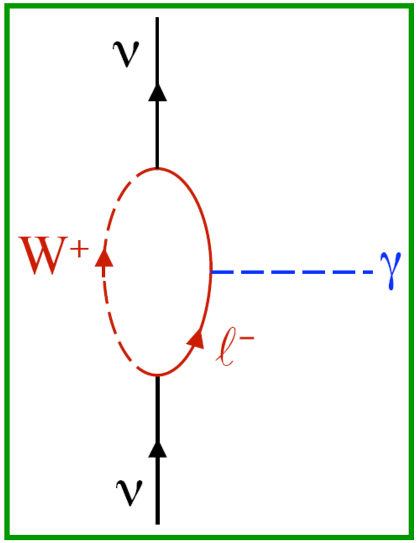
Answer 3: **They show different behavior if nonrelativistic.**

Electromagnetic properties

Without electric charges, neutrinos have electromagnetic interactions with the photon via quantum loops.

Given the SM interactions, a massive Dirac neutrino can only have a tiny magnetic dipole moment:

$$\mu_\nu \sim \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu = 3\times10^{-20} \frac{m_\nu}{0.1\,\mathrm{eV}} \mu_B$$



A massive Majorana neutrino can not have magnetic & electric dipole moments, as its antiparticle is itself.

Proof: Dirac neutrino's electromagnetic vertex can be parametrized as

$$\Gamma_\mu(p,p') = f_Q(q^2)\gamma_\mu + f_M(q^2) i\sigma_{\mu\nu}q^\nu + f_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + f_A(q^2)\left(q^2\gamma_\mu - q_\mu q^\nu\gamma_\nu\right)\gamma_5$$

Majorana neutrinos

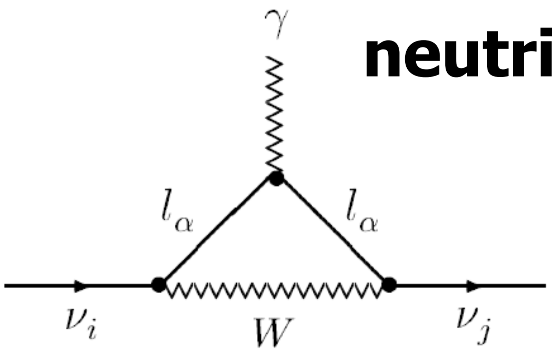
$$\overline{\psi}\Gamma_\mu\psi = \overline{\psi^c}\Gamma_\mu\psi^c = \psi^T \mathcal{C}\Gamma_\mu \mathcal{C}\overline{\psi}^T = \left(\psi^T \mathcal{C}\Gamma_\mu \mathcal{C}\overline{\psi}^T\right)^T = -\overline{\psi}\mathcal{C}^T\Gamma_\mu^T \mathcal{C}^T\psi = \overline{\psi}\mathcal{C}\Gamma_\mu^T \mathcal{C}^{-1}\psi$$

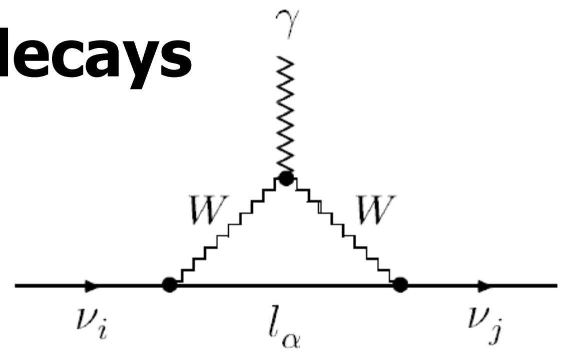
$\Rightarrow$ $f_Q(q^2) = f_M(q^2) = f_E(q^2) = 0$ **intrinsic property of Majorana ν's.**

Transition dipole moments

Both Dirac & Majorana neutrinos can have *transition* dipole moments (of a size comparable with μ_ν) that may give rise to neutrino decays, scattering with electrons, interactions with external magnetic field & contributions to ν masses. (Data: < a few × 10^-11 Bohr magneton).

neutrino decays



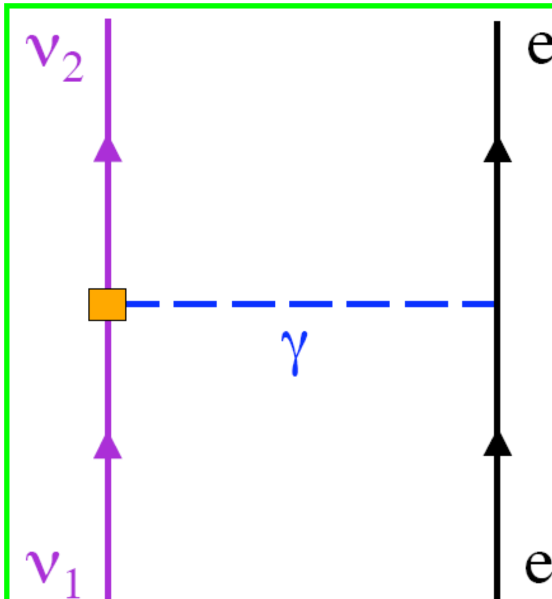


$$\mu_{\text{eff}} \equiv \sqrt{\left|\mu_{ij}\right|^2 + \left|\epsilon_{ij}\right|^2}$$

$$\Gamma_{\nu_i \to \nu_j + \gamma} = 5.3 \times \left(1 - \frac{m_j^2}{m_i^2}\right)^3 \left(\frac{m_i}{1\ \text{eV}}\right)^3 \left(\frac{\mu_{\text{eff}}}{\mu_{\text{B}}}\right)^2 \text{s}^{-1}$$

$$\frac{d\sigma'_\mu}{dT} = \frac{\alpha^2 \pi}{m_e^2} \sum_{k=1}^{3} \left| \sum_{j=1}^{3} e^{i q_j L} V_{ej} \left(i \frac{\mu_{jk}}{\mu_{\text{B}}} + \frac{\epsilon_{jk}}{\mu_{\text{B}}} \right) \right|^2 \left(\frac{1}{T} - \frac{1}{E_\nu} \right)$$

scattering



Nonrelativistic CνB

When $T \sim 1$ MeV after the Big Bang, the neutrinos became decoupled from thermal plasma, formed a ν background in the Universe. Today the relic neutrinos are nonrelativistic.

Temperature today

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \simeq 1.945\ \mathrm{K}$$

Mean momentum today

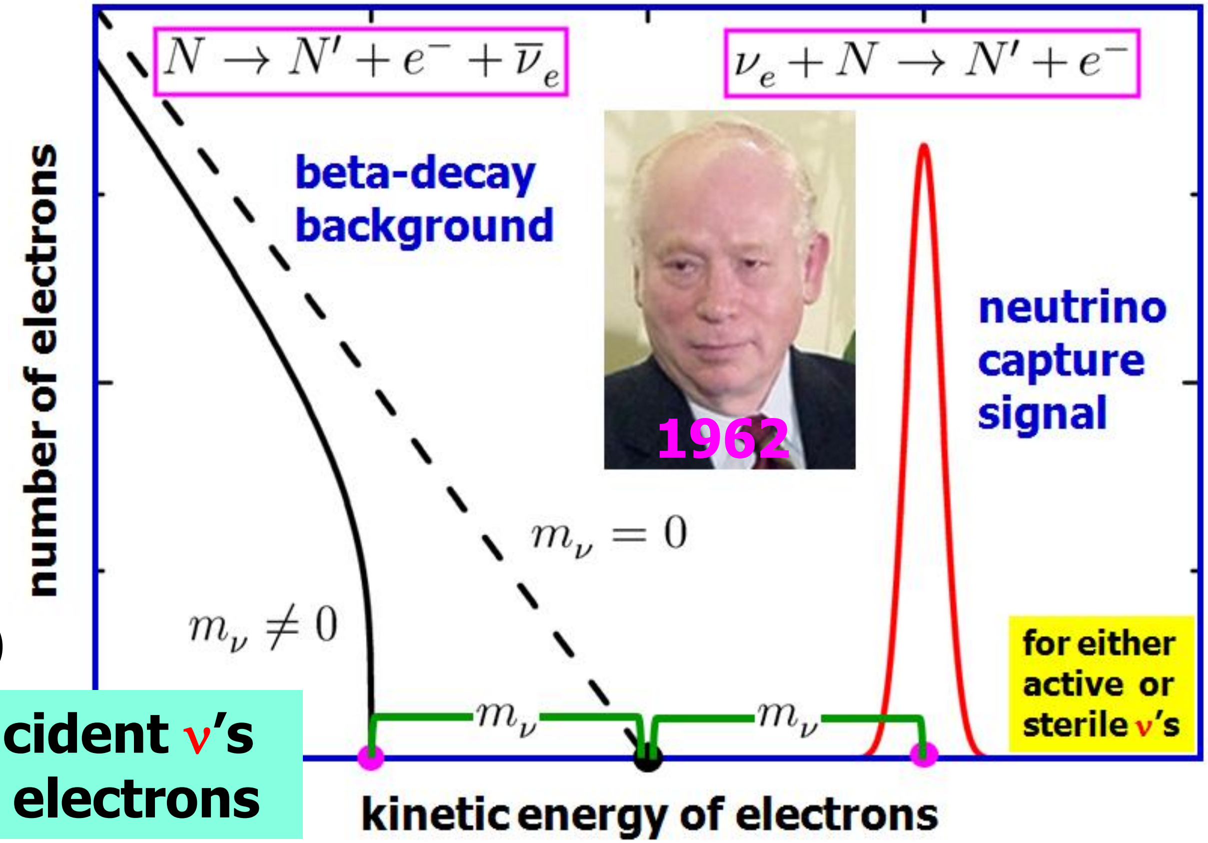
$$\langle p_\nu \rangle \simeq 3.151 T_\nu \simeq 5.281 \times 10^{-4}\ \mathrm{eV}$$

At least 2 ν's cold today

Non-relativistic ν's!

(Irvine & Humphreys, 83)

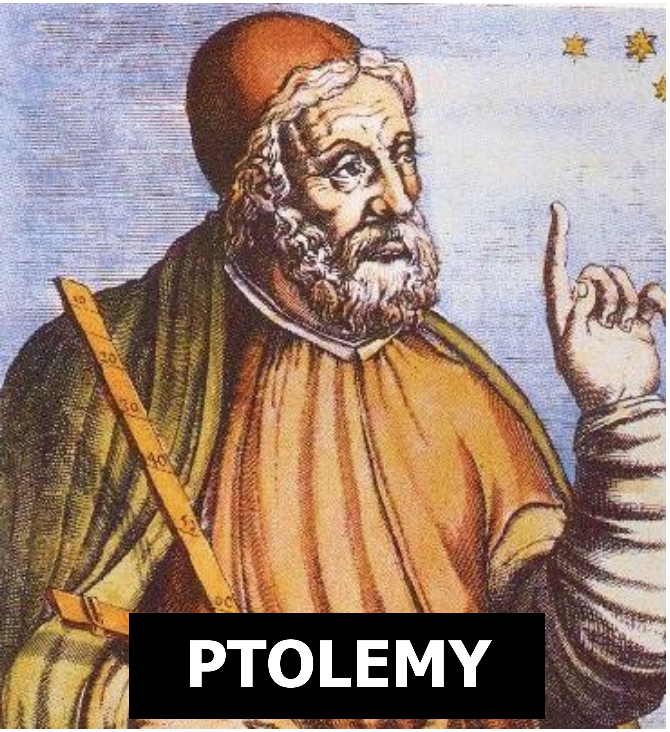
Relic neutrino capture on β-decaying nuclei

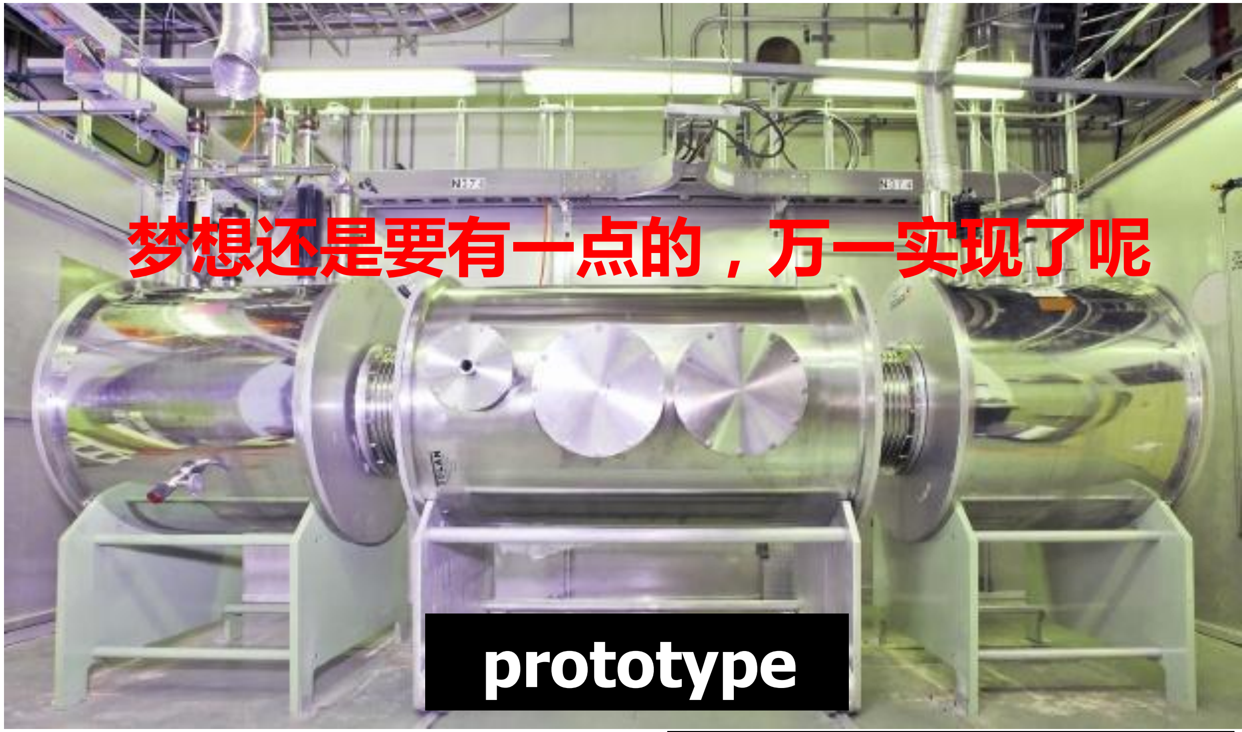


no energy threshold on incident ν's

mono-energetic outgoing electrons

Towards a real experiment?





★ first experiment

★ 100 g of tritium

★ graphene target

★ planned energy resolution 0.15 eV

★ CνB capture rate

$$\Gamma^{D}_{C\nu B} \sim 4\ \mathrm{yr}^{-1}$$

$$\Gamma^{M}_{C\nu B} \sim 8\ \mathrm{yr}^{-1}$$

D = Dirac

M = Majorana

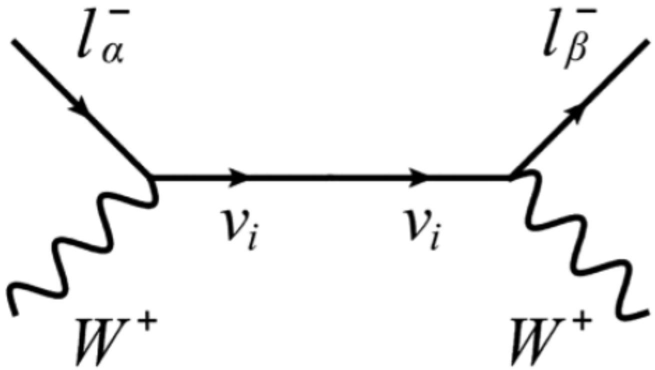
PTOLEMY

Princeton **T**ritium **O**bservatory for **L**ight, **E**arly-Universe, **M**assive-Neutrino **Y**ield (Betts et al, arXiv:1307.4738)

Part D

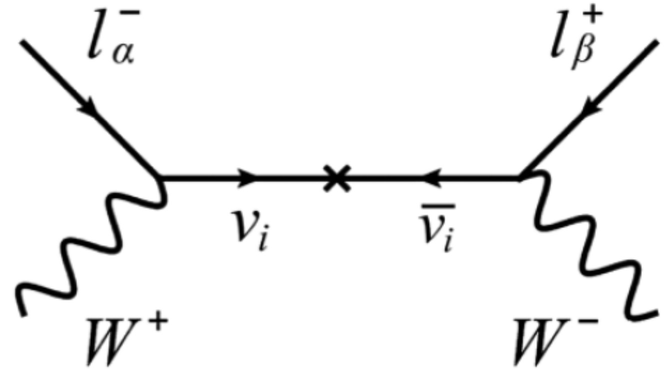
$\nu \Leftrightarrow \overline{\nu}$ oscillations?

Comparison: neutrino-neutrino and neutrino-antineutrino oscillation experiments.



neutrino → neutrino

$$A = \sum_{k=1}^{3} V_{\alpha k}^{*} V_{\beta k} e^{-iE_k t}$$



neutrino → antineutrino

$$A = \frac{1}{E} \sum_{k=1}^{3} V_{\alpha k} V_{\beta k} m_k e^{-iE_k t}$$

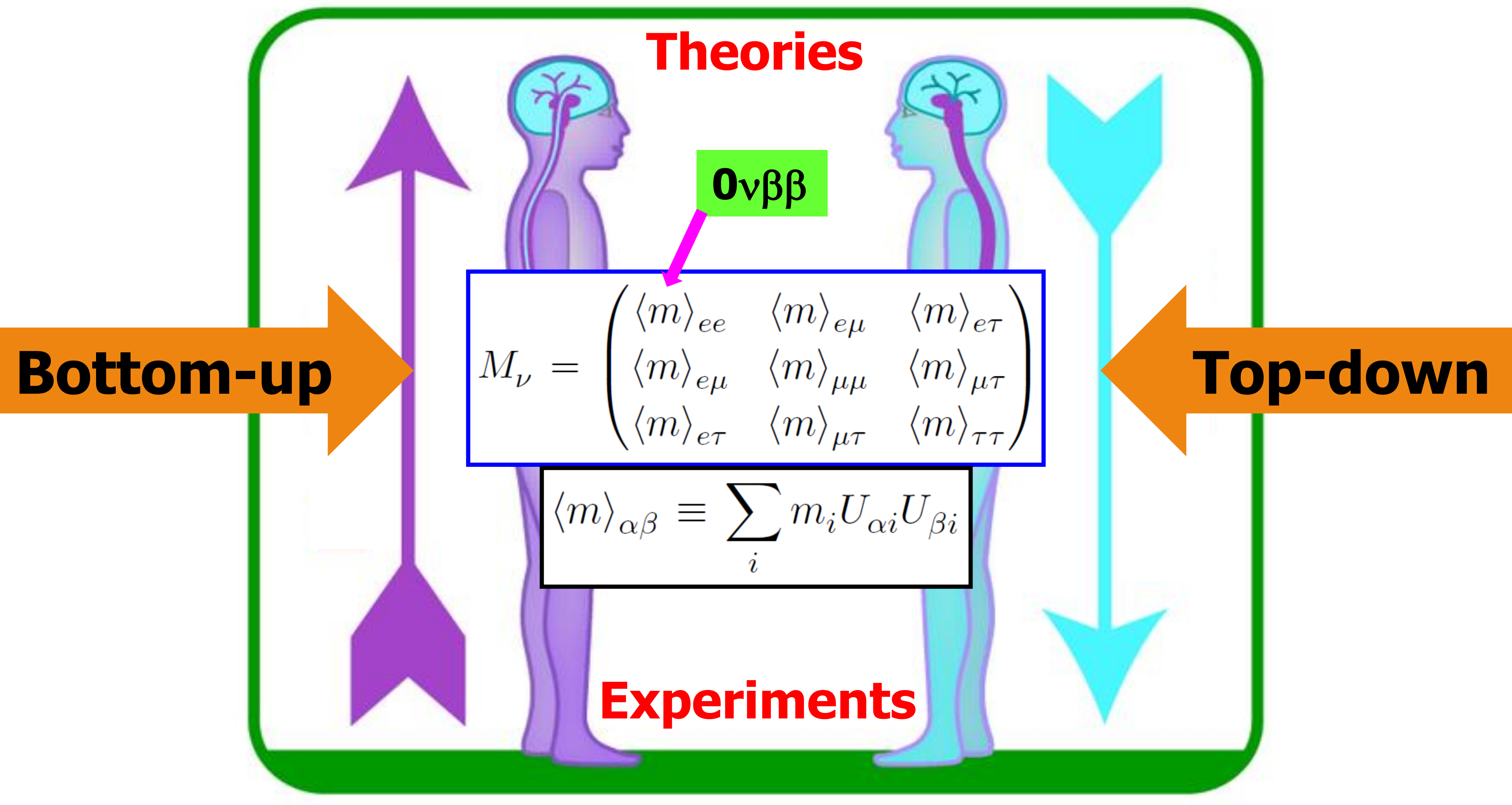
Feasible and successful today!

Unfeasible, a hope tomorrow?

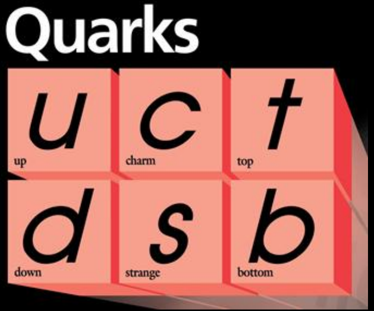
Sensitivity to CP-violating phase(s): δ (neutrino-neutrino); δ, ρ, σ (neutrino-antineutrino)

Remarks

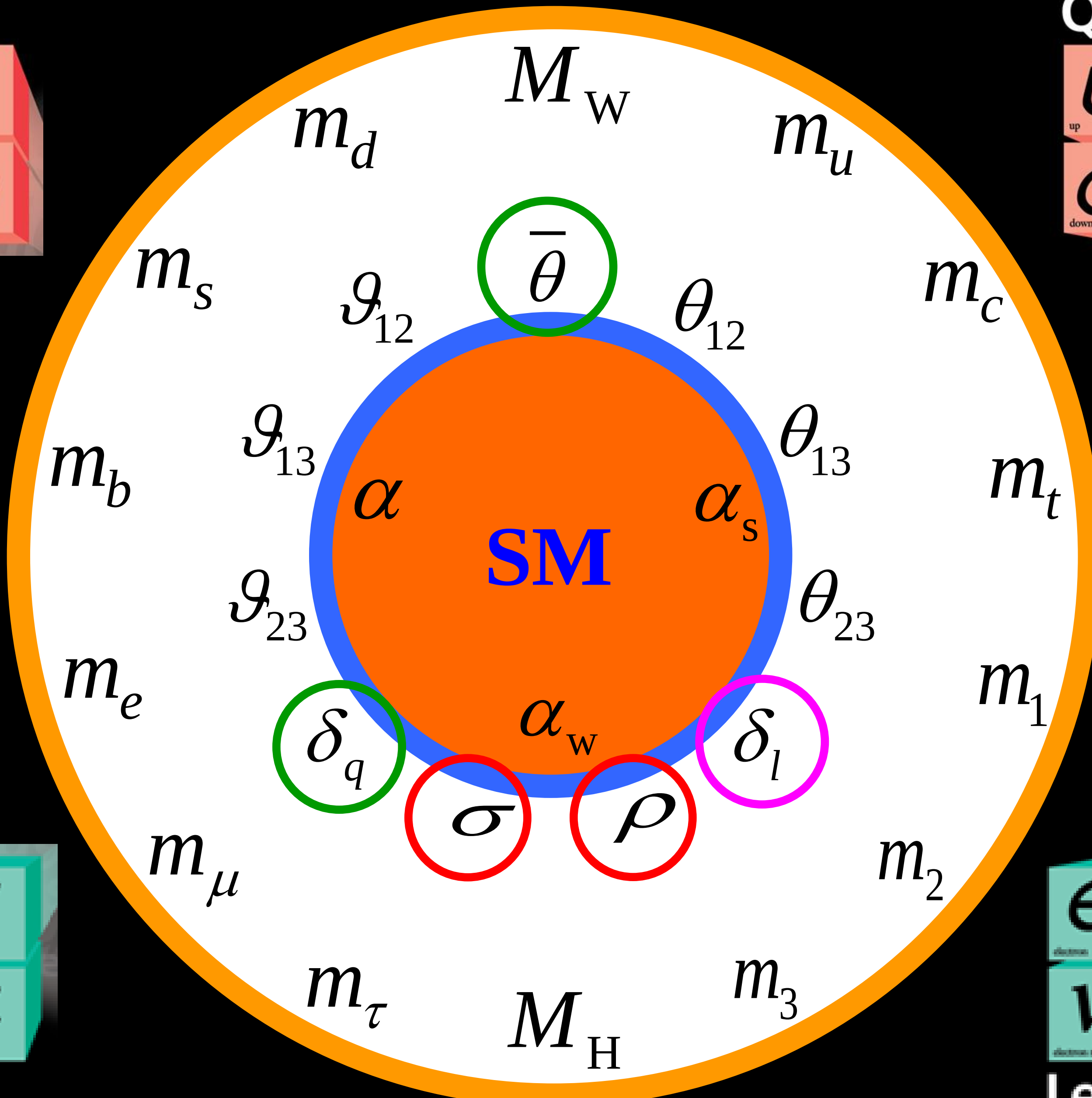
Without information on the nature of massive neutrinos (Majorana or not) and all the CP-violating phases, one will have no way to establish a full theory of ν masses and flavor mixing. Give 0νββ a chance!



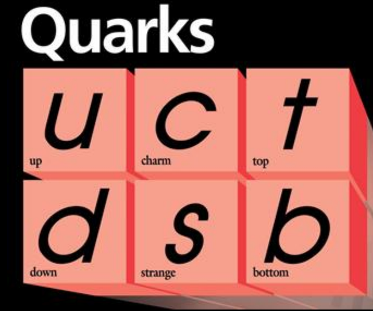
OUTLOOK: How about the Majorana phases?

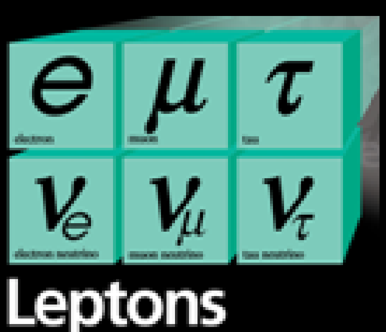


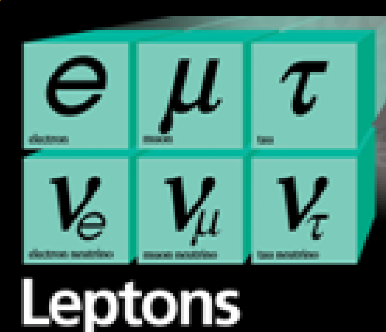
1/5
OK!

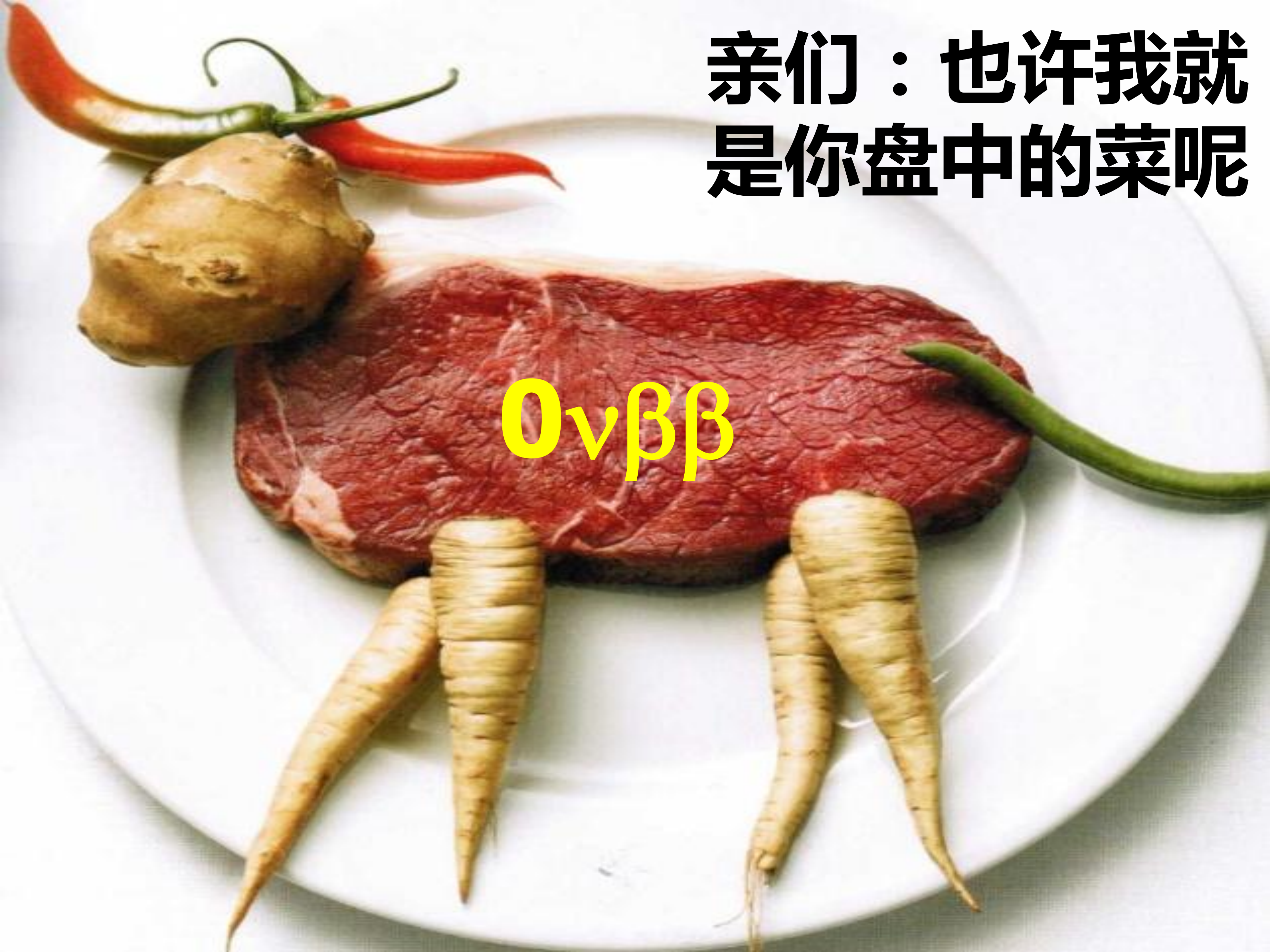


4/5
NO!








亲们：也许我就
是你盘中的菜呢
0νββ