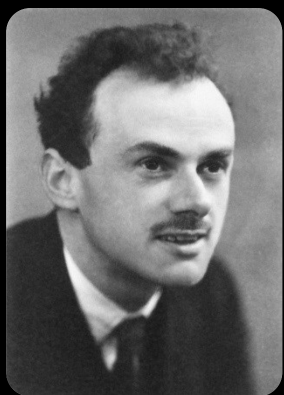
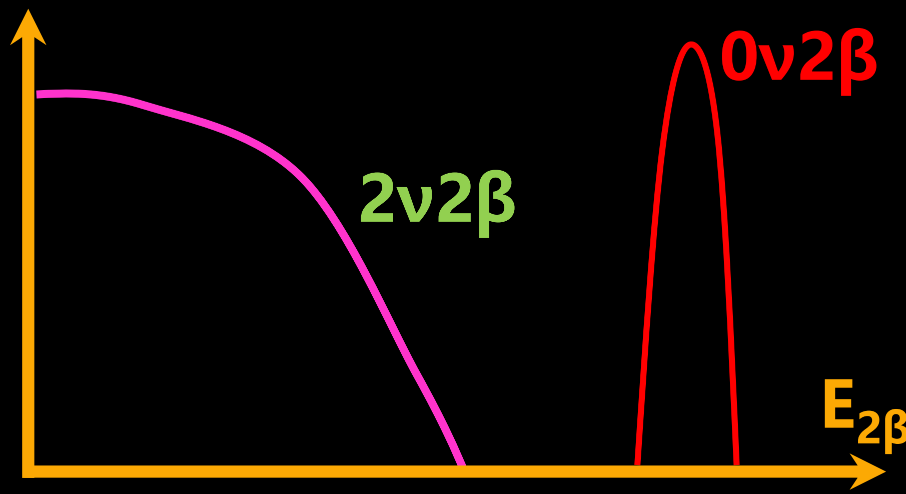
Neutrinoless Double-β Decays & ν Masses

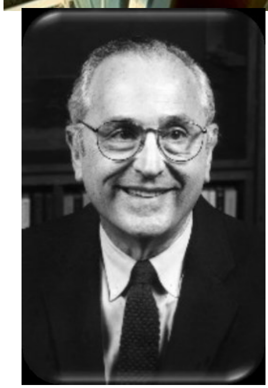




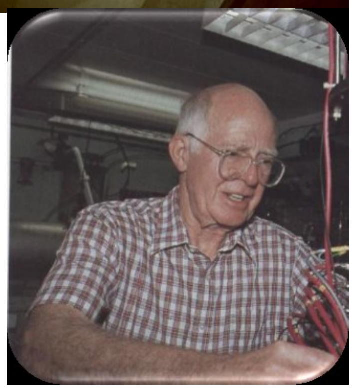
Shun Zhou (IHEP & UCAS)

Workshop on Neutrinoless Double-Beta Decays, Sun Yat-Sen University, Zhuhai, 2021/5/21

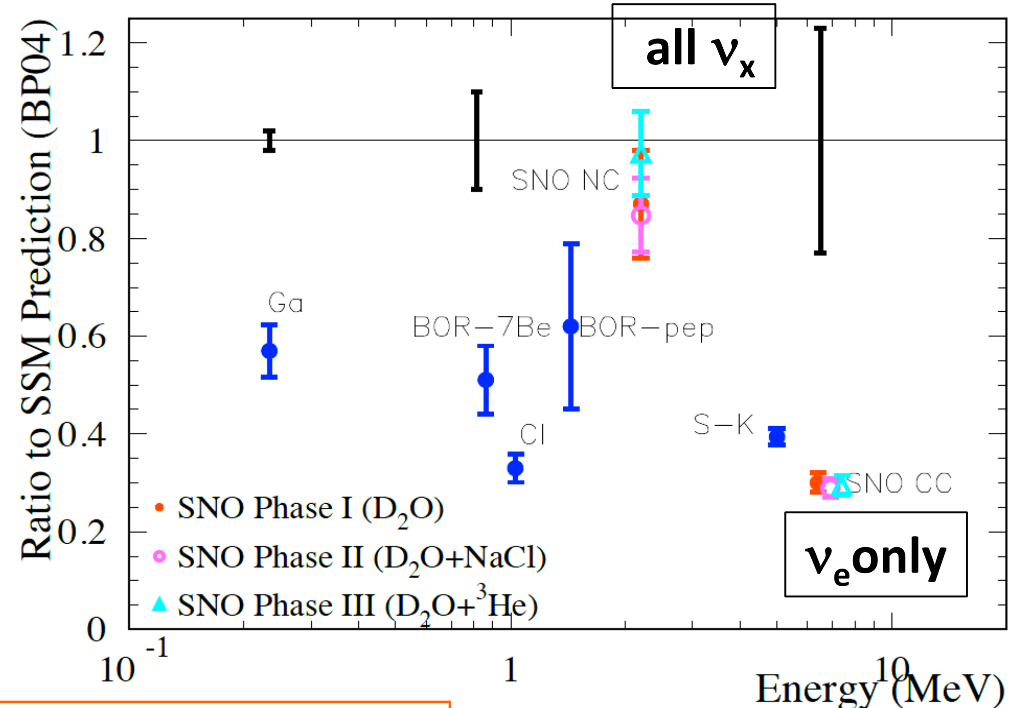
Solar Neutrino Oscillations



J. N. Bahcall



R. Davis Jr.



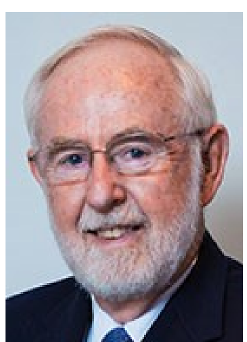
$$\text{CC}: \quad \nu_e + d \rightarrow p + p + e^-$$

$$\text{NC}: \quad \nu_\alpha + d \rightarrow p + n + \nu_\alpha$$

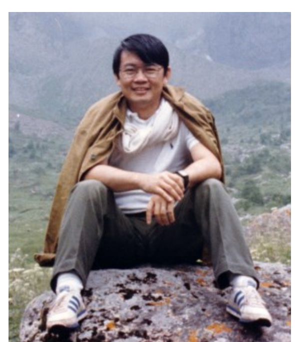
$$\text{ES}: \quad \nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$$

Discovery of solar neutrino oscillations

supported by KamLAND

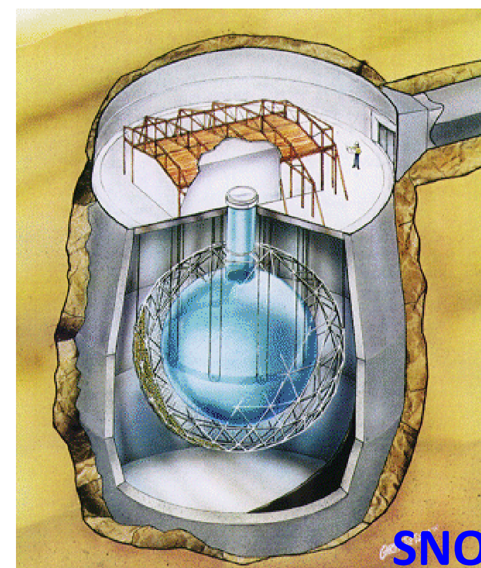


A. B. McDonald

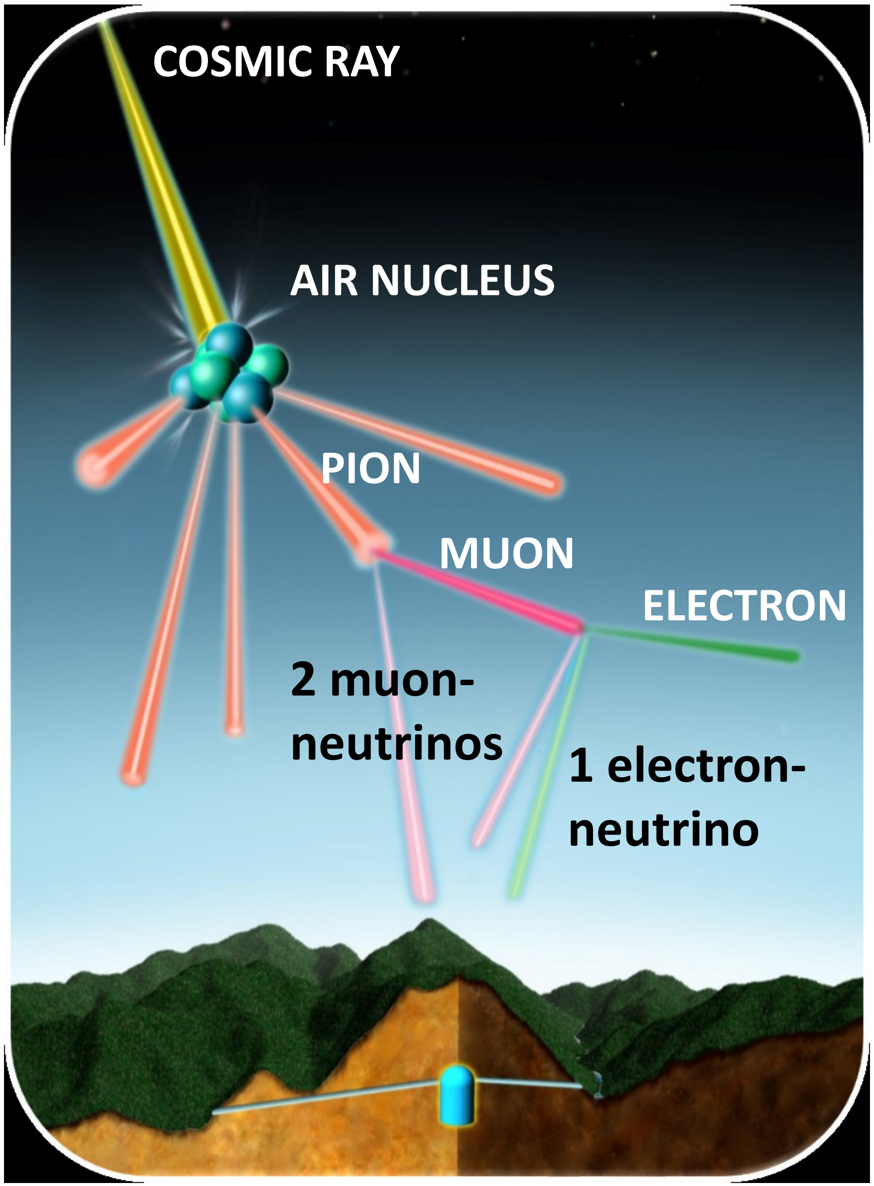


Phys. Rev. Lett. 55 (1985) 1534

Herbert H. Chen
陈华森
(1942-1987)

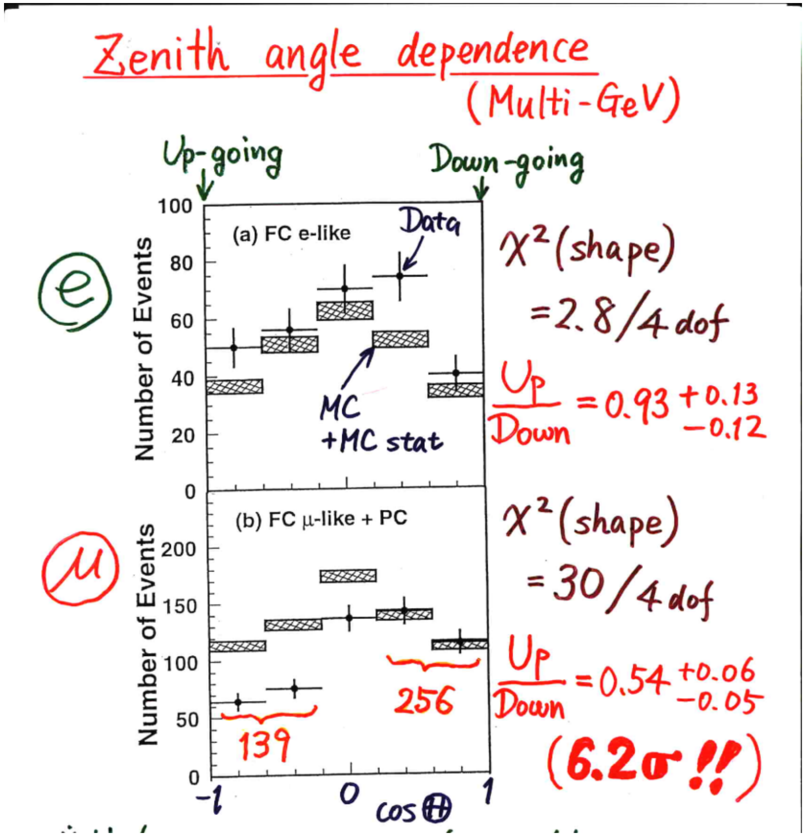


Atmospheric Neutrino Oscillations



From Kajita, ICHEP 16

Super-Kamiokande @ Neutrino 98



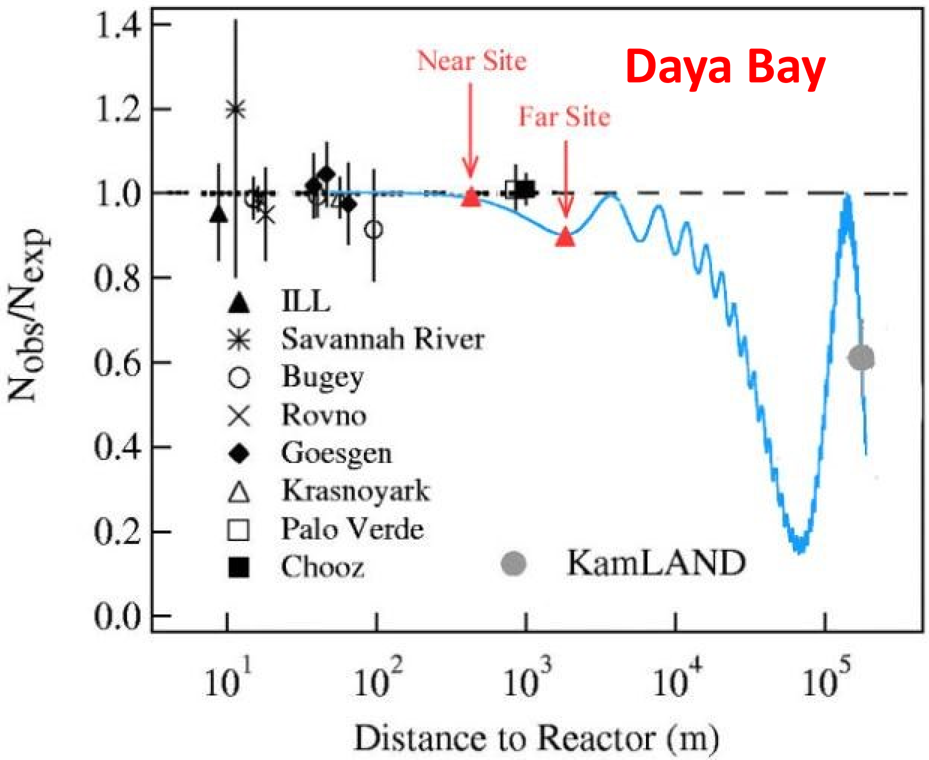
Discovery of atmospheric neutrino oscillations

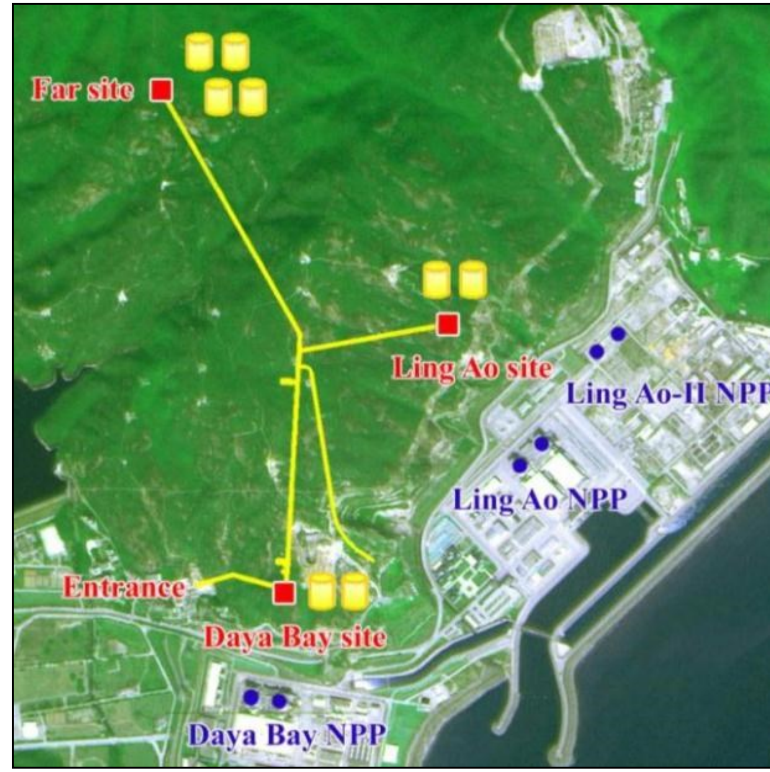
supported by K2K, MINOS, T2K, NOνA

Yoji Totsuka (1942-2008)

T. Kajita

Reactor Neutrino Oscillations





Dec. 2011 — **Double Chooz (far detector):**

$\sin^2\theta_{13} = 0.022 \pm 0.013$ — **1.7σ**

Mar. 2012 — **Daya Bay (near + far detectors):**

$\sin^2\theta_{13} = 0.024 \pm 0.004$ — **5.2σ**

Apr. 2012 — **RENO (near + far detectors):**

$\sin^2\theta_{13} = 0.029 \pm 0.006$ — **4.9σ**

Discovery of reactor neutrino oscillations

A complete picture of three-flavor neutrino oscillations!

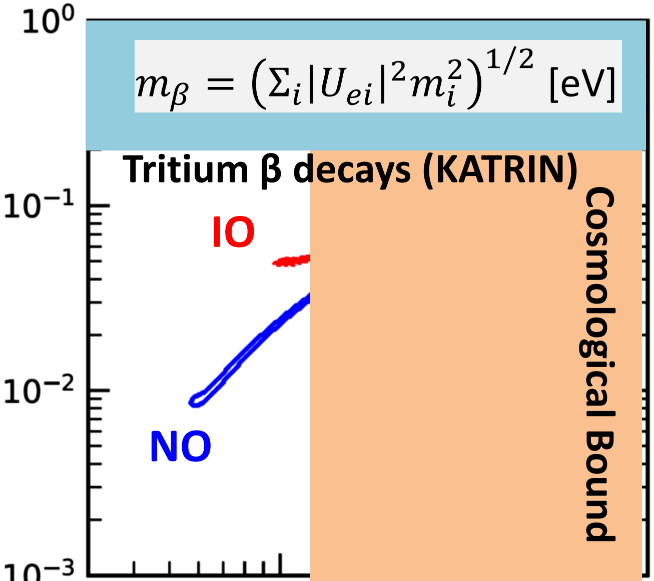
Basic neutrino parameters Esteban *et al.*, 2007.14792, NuFIT 5.0 (2020)

without SK atmospheric data

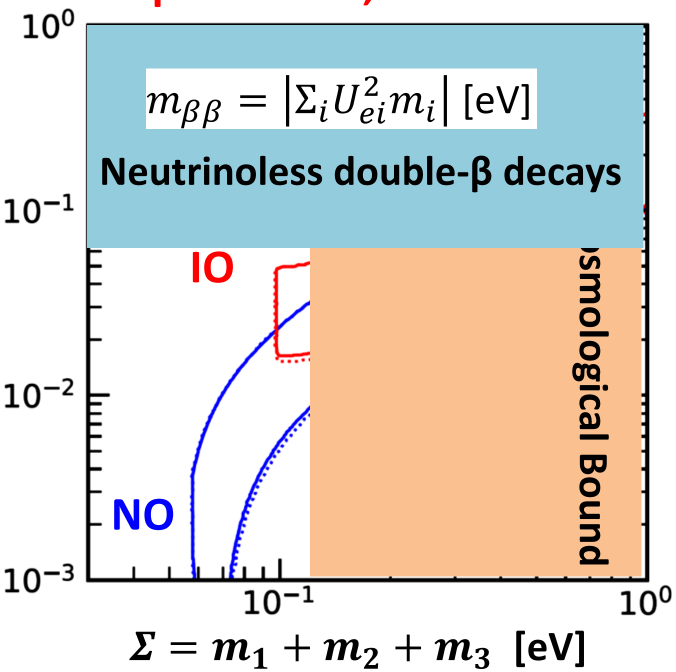
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
$\delta_{CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$

- **Future neutrino oscillation experiments will measure the octant of θ_{23}, the CP-violating phase δ, and the neutrino mass ordering**
- **The most restrictive bound on absolute neutrino masses is coming from cosmological observations: $m_1 + m_2 + m_3 < 0.12$ eV (Planck)**

Current Status of Absolute Neutrino Masses



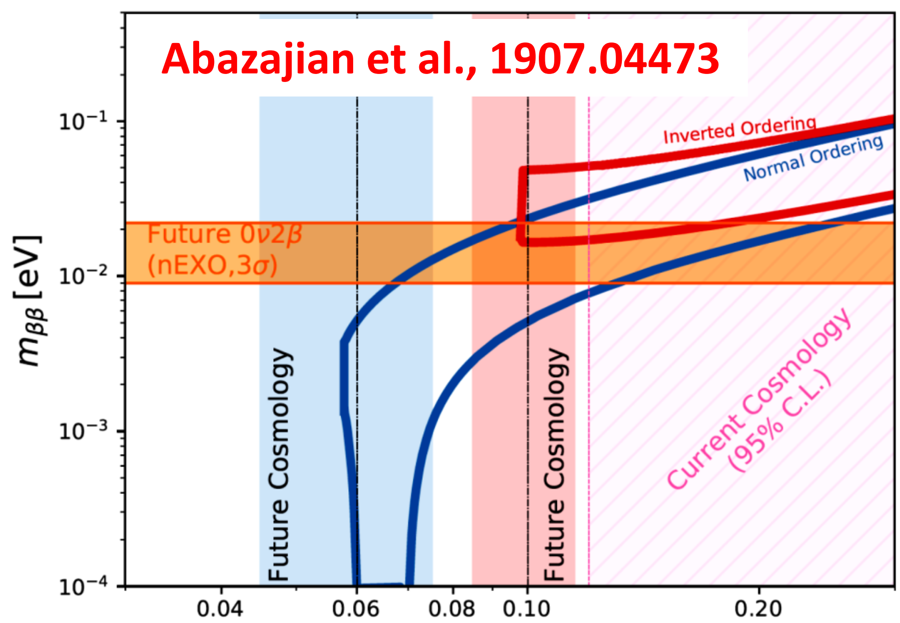
Capozzi et al., 2003.08511



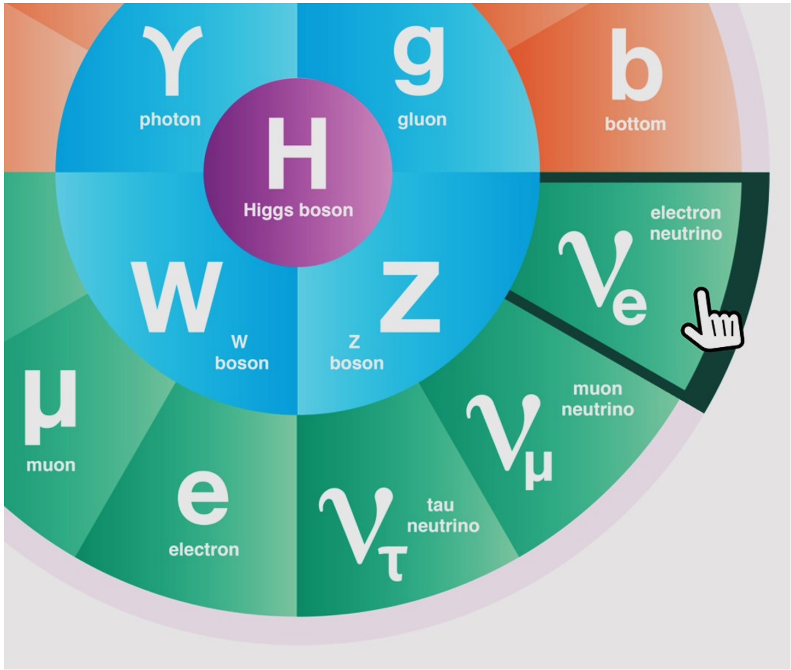
$m_1 < m_2 < m_3$ (NO) or $m_3 < m_1 < m_2$ (IO)

Constraints on absolute neutrino masses

- **Tritium β decays (95% C.L.)**
  $m_\beta < 0.8$ eV (KATRIN 2021)
- **Neutrinoless double-β decays (90% C.L.)**
  $m_{\beta\beta} < (0.06\sim0.16)$ eV (KamLAND-Zen)
  $(0.15\sim0.40)$ eV (EXO-200)
  $(0.08\sim0.18)$ eV (GERDA-II)
  $(0.08\sim0.35)$ eV (CUORE)
- **Cosmological observations (95% probability)**
  $\Sigma < 0.12$ eV (Planck)



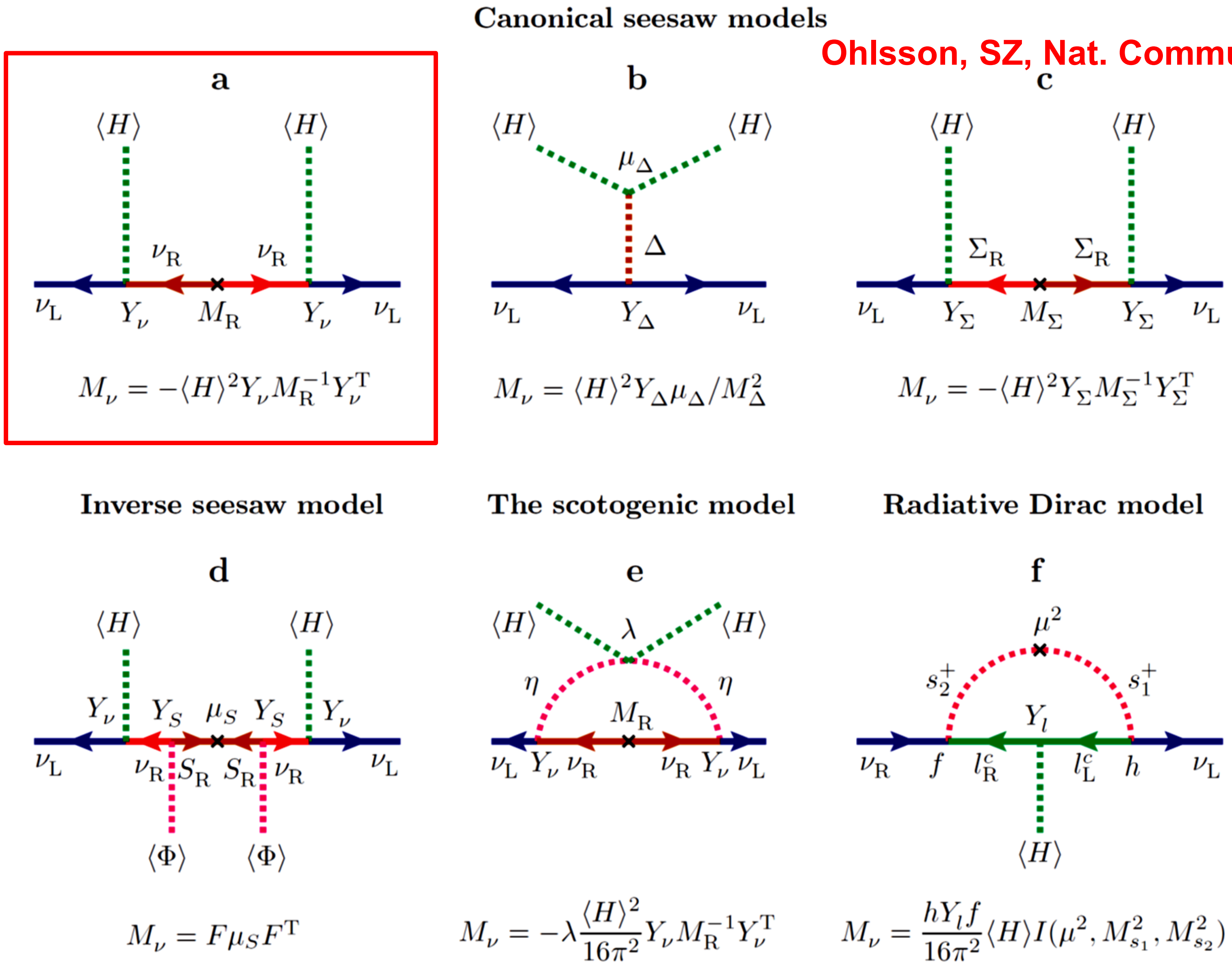
- **Normal or Inverted** (**sign of Δm^2_{31}?**)
- **Leptonic CP Violation** (**δ = ?**)
- **Octant of θ_{23}** (**> or < 45°?**)
- **Absolute Neutrino Masses** ($m_{\text{lightest}} = 0$?)
- **Majorana or Dirac Nature** (**$\nu = \nu^C$?**)
- **Majorana CP-Violating Phases** (**how?**)



- **Extra Neutrino Species**
- **Exotic Neutrino Interactions**
- **Various LNV & LFV Processes**
- **Leptonic Unitarity Violation**
- **Origin of Neutrino Masses**
- **Flavor Structure (Symmetry?)**
- **Quark-Lepton Connection**
- **Relations to DM, BAU, or NP**

Origin of Neutrino Masses

- Extend the SM with new particles but keep its gauge symmetries intact



Ohlsson, SZ, Nat. Commun., 2014

History of $0\nu2\beta$ Decays

SEPTEMBER 15, 1935 PHYSICAL REVIEW VOLUME 48

Double Beta-Disintegration

M. GOEPPERT-MAYER, *The Johns Hopkins University*

(Received May 20, 1935)

From the Fermi theory of β-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over 10^{17} years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass.

In 1935, Maria Goeppert-Mayer published the first calculation of $2\nu2\beta$ decay rates based on the Fermi theory (proposed in 1934). It was acknowledged in her paper that Eugene Wigner suggested this problem.

DECEMBER 15, 1939 PHYSICAL REVIEW VOLUME 56

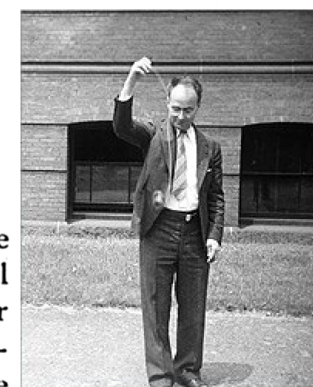
Ettore Majorana
($\nu=\nu^C$? 1937)

On Transition Probabilities in Double Beta-Disintegration

W. H. FURRY
Physics Research Laboratory, Harvard University, Cambridge, Massachusetts

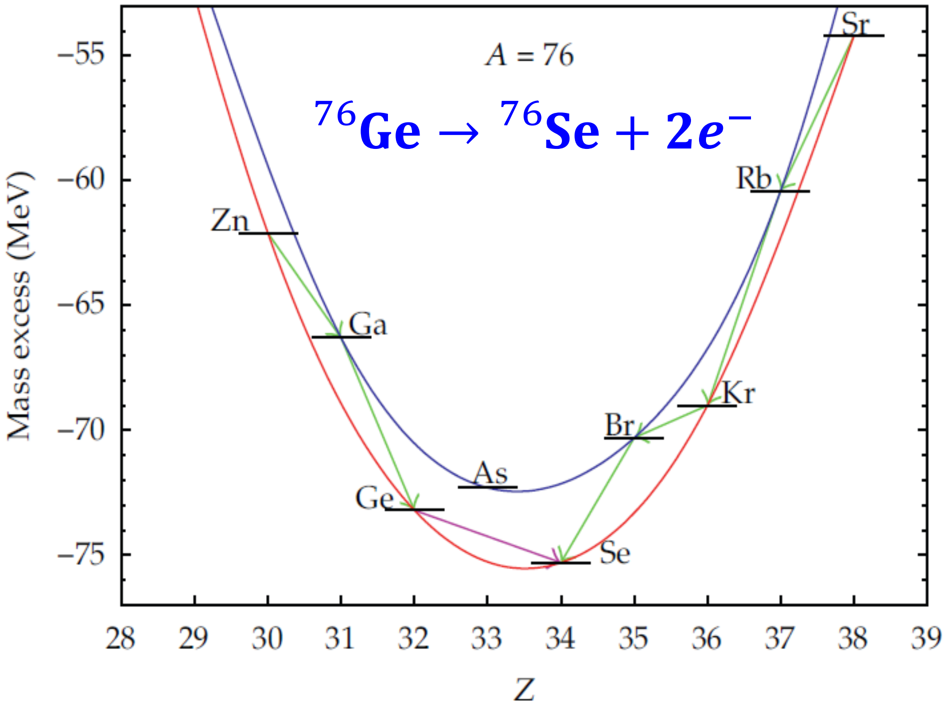
(Received October 16, 1939)

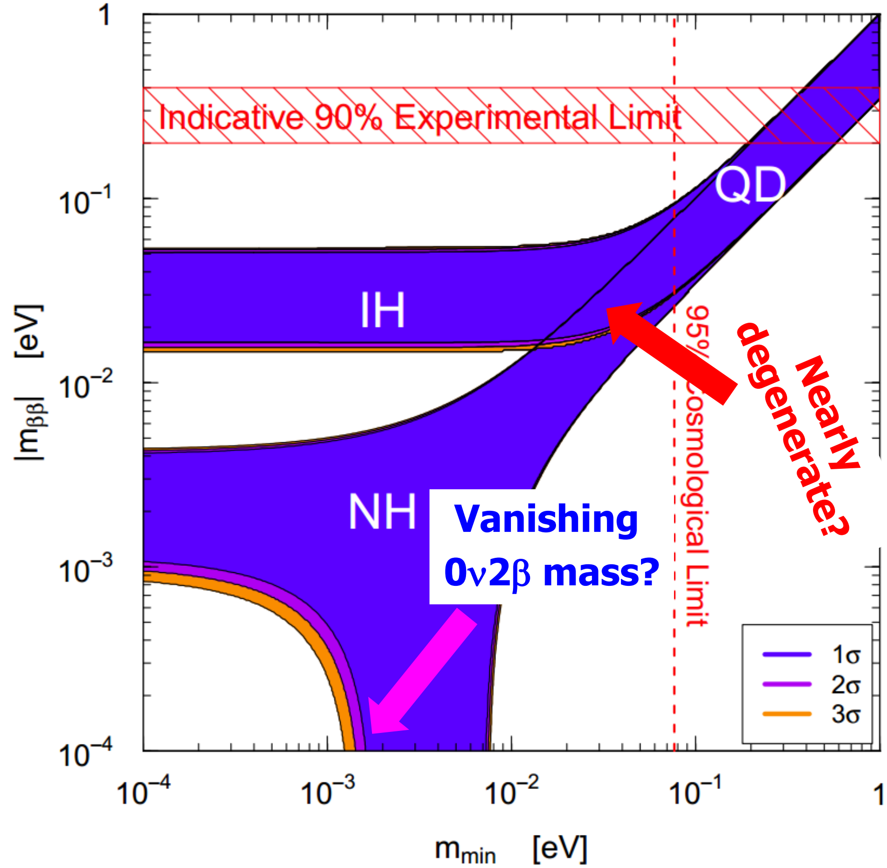
The phenomenon of double β-disintegration is one for which there is a marked difference between the results of Majorana's symmetrical theory of the neutrino and those of the original Dirac-Fermi theory. In the older theory double β-disintegration involves the emission of four particles, two electrons (or positrons) and two antineutrinos (or neutrinos), and the probability of disintegration is extremely small. In the Majorana theory only two particles—the electrons or positrons—have to be emitted, and the transition probability is much larger. Approximate values of this probability are calculated on the Majorana theory for the various Fermi and Konopinski-Uhlenbeck expressions for the interaction energy. The selection rules



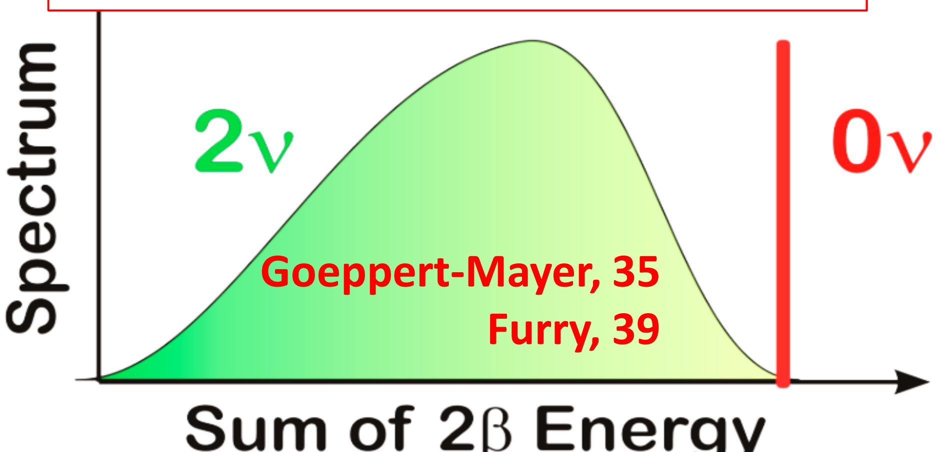
Wendell Furry
(1907 – 1984)

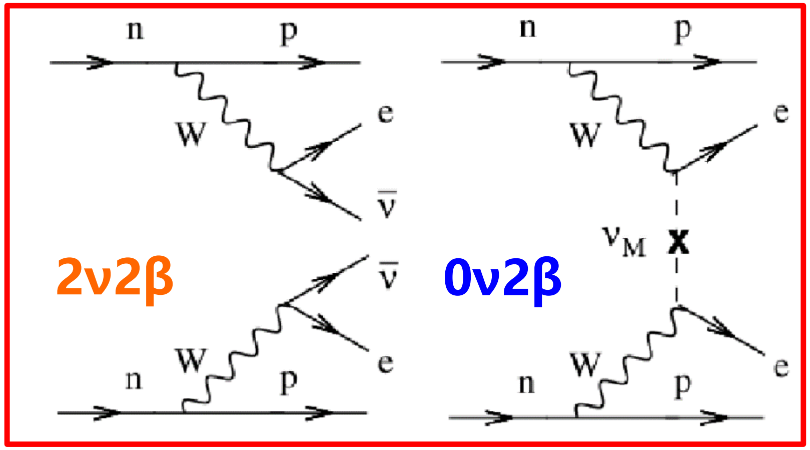
Basics of 0ν2β Decays



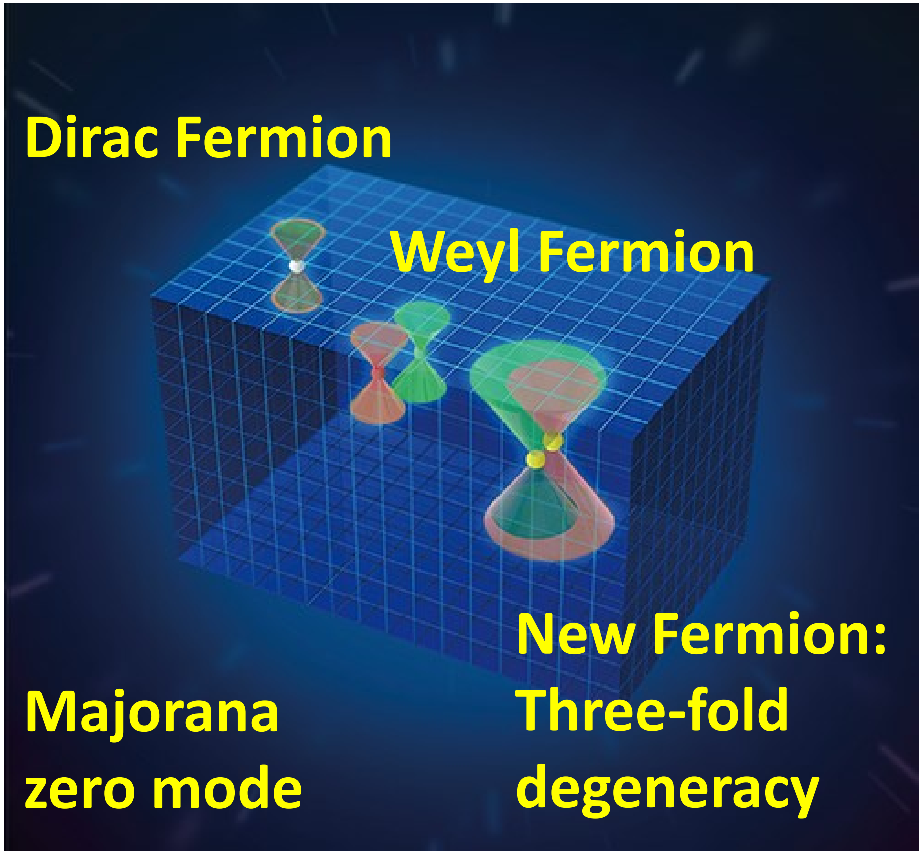


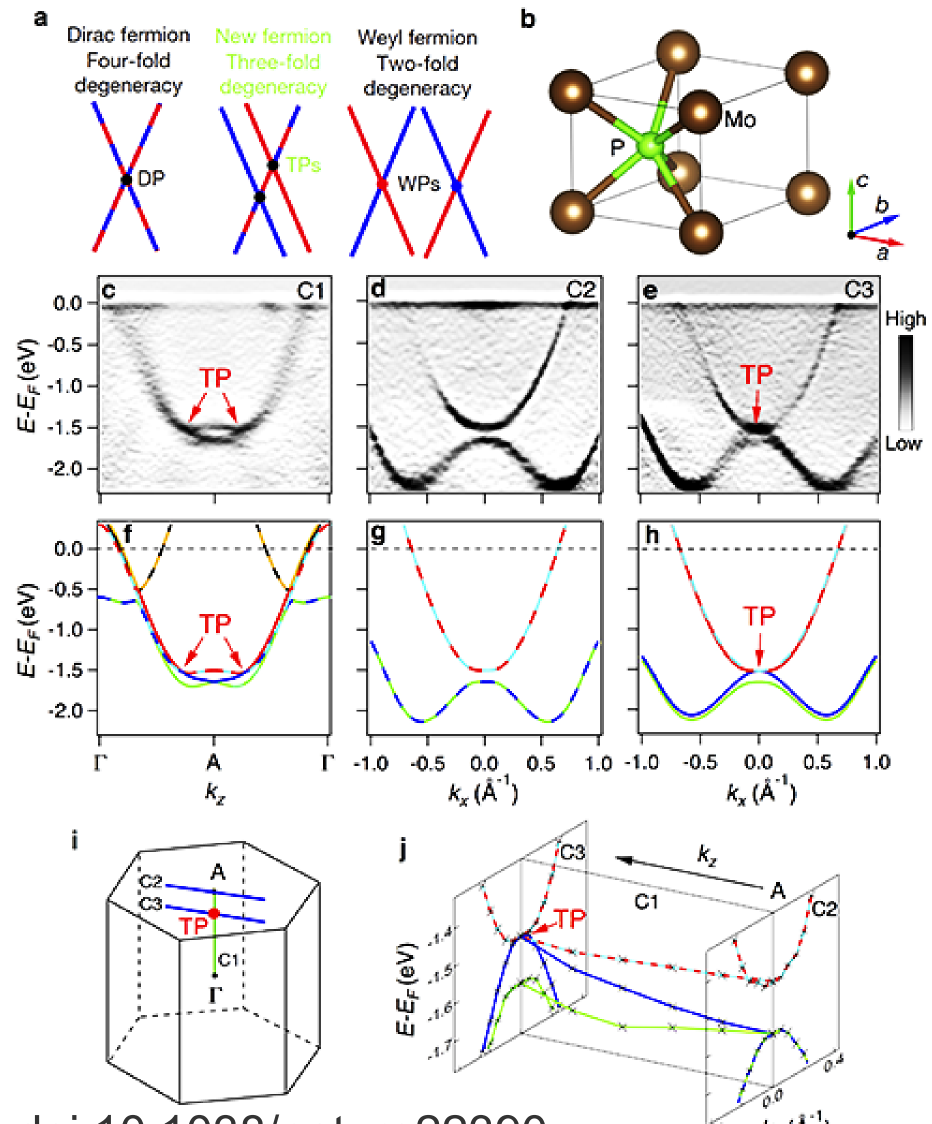
$$T^{0\nu}_{1/2} = G^{-1}_{0\nu} \cdot |\mathcal{M}_{0\nu}|^{-2} \cdot |m_{\beta\beta}|^{-2} \cdot m_e^2$$





★ A new feature of elementary particles: Majorana fermions





doi:10.1038/nature22390

HOT!!! Weyl, Majorana, Dirac and new fermions in condensed matter physics,

but **NOT** really **elementary particles**

Importance of 0ν2β Decays

★ Discovery of lepton number violation: baryon vs. lepton numbers

- **Dirac Neutrinos**

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \overline{\nu_{\rm R}} {\rm i} \partial\!\!\!/ \nu_{\rm R} - \left[\overline{\ell_{\rm L}} Y_\nu \tilde{H} \nu_{\rm R} + {\rm h.c.} \right]$$

Generate Dirac ν masses in a similar way to that for quarks and charged leptons, after the spontaneous gauge symmetry breaking

$$M_\nu = Y_\nu v$$

M_ν: $O(0.1~{\rm eV})$; Y_ν: $O(10^{-12})$; v: $\approx 174~{\rm GeV}$

- ➢ Need to introduce additional symmetries to the SM to forbid a Majorana mass for right-handed neutrino singlets
- ➢ Need to explain a strong hierarchy for the Yukawa couplings of the SM fermions

- **Majorana Neutrinos**

$$- \left[\frac{1}{2} \overline{\nu^{\rm C}_{\rm R}} M_{\rm R} \nu_{\rm R} + {\rm h.c.} \right]$$

Generate tiny Majorana ν masses via the so-called seesaw mechanism

$$M_\nu = v^2 Y_\nu M_{\rm R}^{-1} Y_\nu^{\rm T}$$

M_ν: $O(0.1~{\rm eV})$; $M_{\rm R}$: $O(10^{14}~{\rm GeV})$

- ■ Retain the SM symmetries
- ■ GUT or TeV energy scale?

Guide the theorists to build a model for tiny ν masses

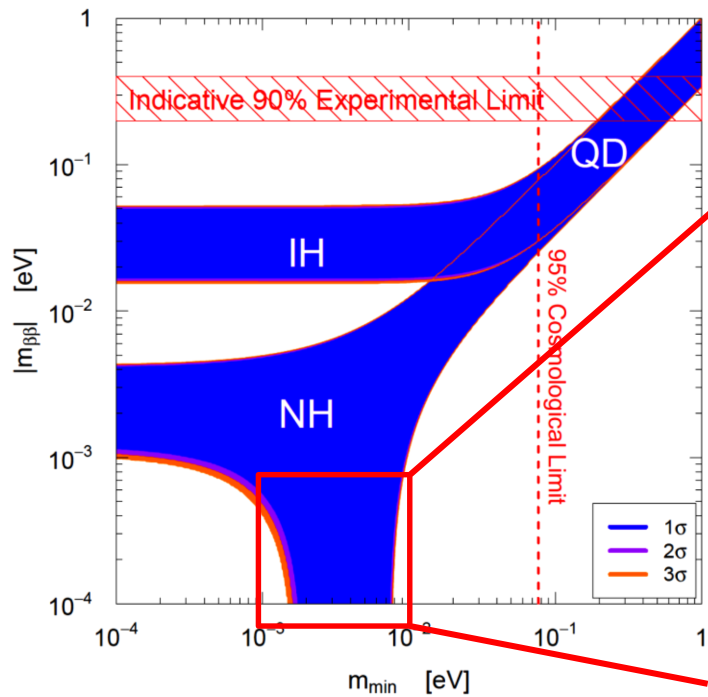
Importance of 0ν2β Decays

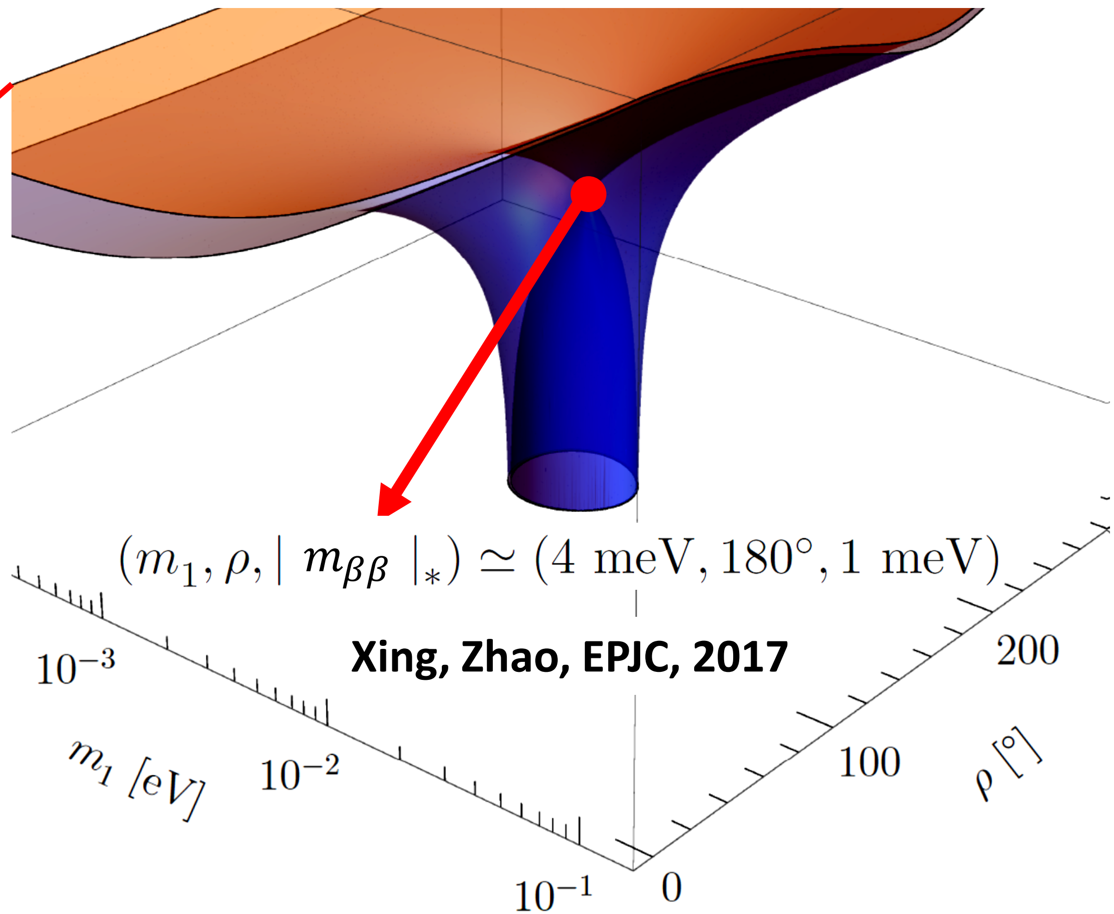
★ Constrain ν masses and mixing parameters: Majorana CP phases?

$$T^{0\nu}_{1/2} = G^{-1}_{0\nu} \cdot \left|\mathcal{M}_{0\nu}\right|^{-2} \cdot \left|m_{\beta\beta}\right|^{-2} \cdot m_e^2$$

Rodejohann, IJMPE, 2011; JPG, 2012; Bilenky, Giunti, MPLA, 2012; IJMPA, 2015

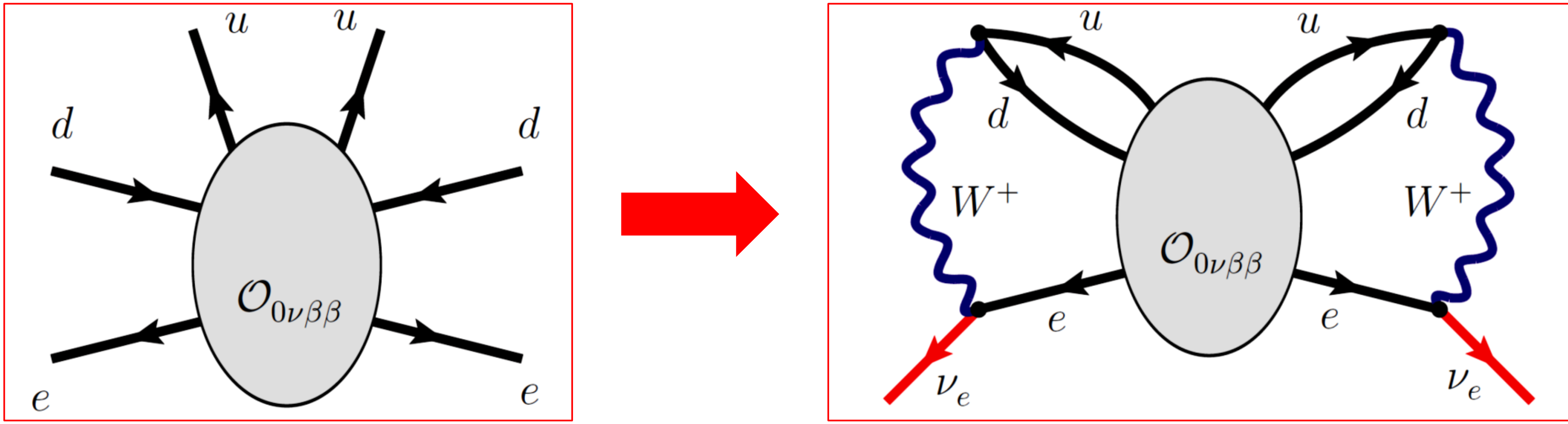
$$m_{\beta\beta} = m_1 |U_{e1}|^2 e^{i\rho} + m_2 |U_{e2}|^2 + m_3 |U_{e3}|^2 e^{i\sigma}$$





- **ν mass ordering, lightest ν mass, Majorana CP phases**
- **A unique way to constrain Majorana CP phases?**

Schechter-Valle Theorem



Schechter-Valle Theorem (82): If the 0ν2β decay happens, there must exist an effective Majorana neutrino mass term.

Question: How large is such a mass term?

Assumptions: (1) no tree-level neutrino masses; (2) 0ν2β decays are mediated by heavy particles, i.e., short-range interactions:

Pas et al., PLB, 2001

$$\mathcal{L}_{0\nu\beta\beta} = \frac{G_{\rm F}^2}{2m_p}\left(\epsilon_1 JJj + \epsilon_2 J^{\mu\nu}J_{\mu\nu}j + \epsilon_3 J^{\mu}J_{\mu}j + \epsilon_4 J^{\mu}J_{\mu\nu}j^{\nu} + \epsilon_5 J^{\mu}Jj_{\mu}\right)$$

Hadronic currents

$$J \equiv \bar{u}(1\pm\gamma_5)d\ , \quad J^{\mu} \equiv \bar{u}\gamma^{\mu}(1\pm\gamma_5)d\ , \quad J^{\mu\nu} \equiv \bar{u}\frac{\rm i}{2}[\gamma^{\mu},\gamma^{\nu}](1\pm\gamma_5)d$$

leptonic currents

$$j = \bar{e}(1\pm\gamma_5)e^{\rm c}\ , \quad j^{\mu} = \bar{e}\gamma^{\mu}(1\pm\gamma_5)e^{\rm c}\ , \quad j^{\mu\nu} = \bar{e}\frac{\rm i}{2}[\gamma^{\mu},\gamma^{\nu}](1\pm\gamma_5)e^{\rm c}$$

Schechter-Valle Theorem

- Current experimental upper bounds on the 0ν2β decay width can be translated into **upper limits** on the coefficients ϵ_i's
- Nonzero quark and electron masses are crucial for us to draw the butterfly diagram, since we don't know the chirality of (u, d, e)

Take one operator for example:

$$\epsilon_3 J^{\mu}_{\rm R} J_{\mu {\rm R}} j_{\rm L}$$

$$\epsilon_3 < 1.5 \times 10^{-8}$$

Upper bound

$$\delta m_\nu^{ee} = \frac{128 g^4 G_{\rm F}^2 \epsilon_3 m_u^2 m_d^2 m_e^2}{m_p} \mathcal{I}_{0\nu\beta\beta}$$

Duerr, Lindner, Merle, JHEP, 2011

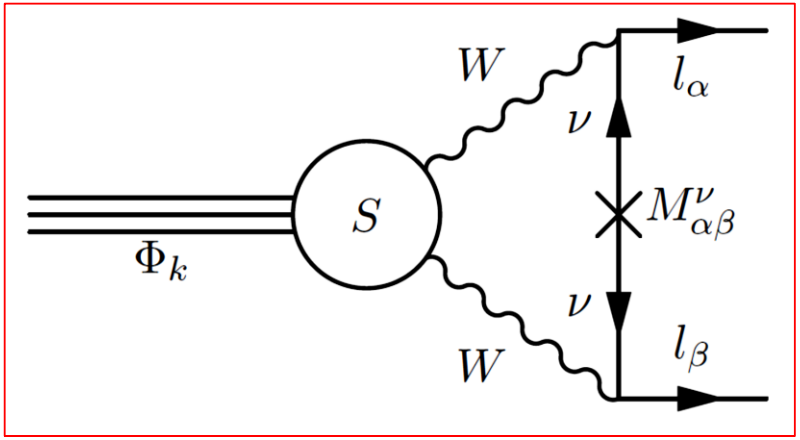
Quantitatively, the 4-loop Majorana mass from the butterfly diagram is EXTREMELY small:

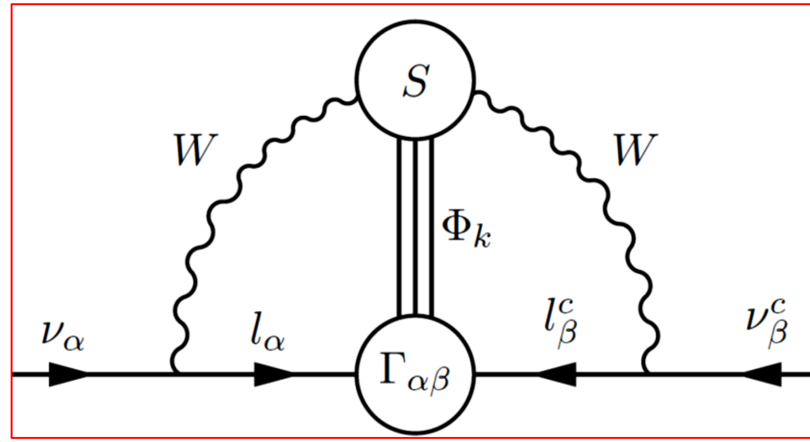
$$\delta m_\nu \lesssim \mathcal{O}(10^{-28}\ \text{eV})$$

Duerr, Lindner, Merle, JHEP, 2011; Liu, Zhang, Zhou, PLB, 2016

- Assume 0ν2β decays are governed by short-distance operators
- The Schechter-Valle (Black Box) theorem is qualitatively correct, but the induced Majorana masses are **too small to be relevant** for neutrino oscillations
- Other mechanisms are needed to generate neutrino masses

Extended Schechter-Valle Theorem





Hirsch, Kovalenko, Schmidt (06): One-to-one correspondence relation between LNV processes and corresponding elements of the Majorana neutrino mass matrix

Conclusion:

current neutrino oscillation data indicate a finite 0ν2β rate

$$\mathcal{M}_\nu^{(1)} = \begin{pmatrix} 0 & x & y \\ x & 0 & 0 \\ y & 0 & 0 \end{pmatrix} \quad \mathcal{M}_\nu^{(2)} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x & y \\ 0 & y & z \end{pmatrix} \quad \mathcal{M}_\nu^{(3)} = \begin{pmatrix} 0 & x & 0 \\ x & 0 & y \\ 0 & y & 0 \end{pmatrix}$$

All possible mass matrices with $(M_\nu)_{ee} = 0$

$$\mathcal{M}_\nu^{(4)} = \begin{pmatrix} 0 & 0 & y \\ 0 & x & 0 \\ y & 0 & 0 \end{pmatrix} \quad \mathcal{M}_\nu^{(5)} = \begin{pmatrix} 0 & x & 0 \\ x & 0 & 0 \\ 0 & 0 & y \end{pmatrix}$$

$$\mathbf{A}_1 : \begin{pmatrix} \mathbf{0} & \mathbf{0} & a \\ \mathbf{0} & b & c \\ a & c & d \end{pmatrix}$$

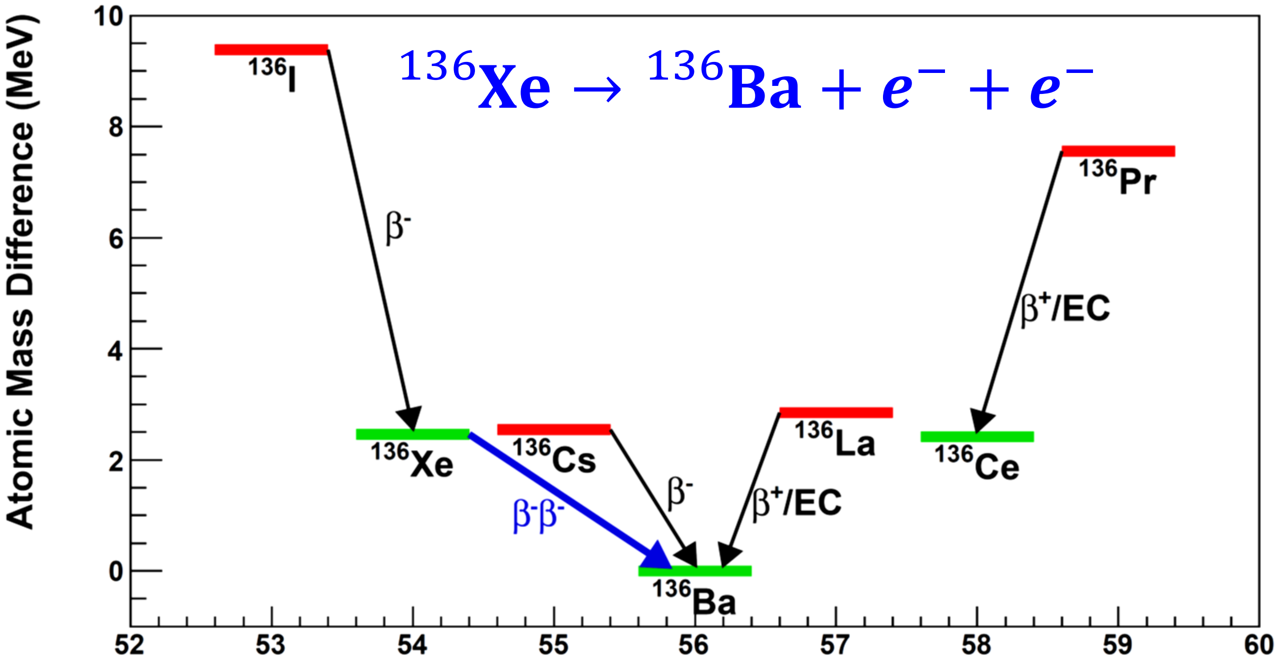
The Majorana neutrino mass matrix A_1 is allowed by oscillation data, leading to a nonzero 0ν2β rate!

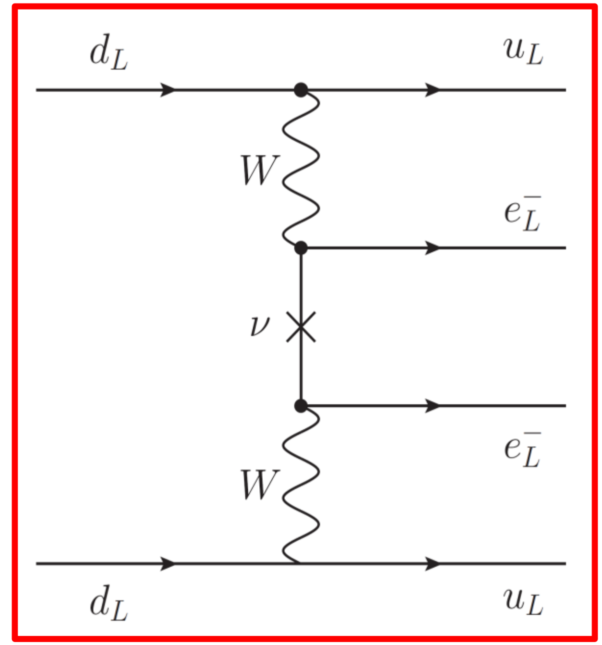
Other Lepton-Number-Violating Decays

Meson Decays: $\mathcal{L}_{\rm MD} = \varepsilon_{\alpha\beta} \frac{G_{\rm F}^2}{2m_p} J^{\mu}_{\rm R} J'_{\mu{\rm R}} j_{\rm L}$ **Liu, Zhang, Zhou, PLB, 2016**

Decay modes	Branching ratios	Upper bounds on $\varepsilon_{\alpha\beta}$	Upper bounds on $\lvert\delta m_\nu^{\alpha\beta}\rvert$ (eV)
$K^- \to \pi^+ e^- e^-$	$< 6.4 \times 10^{-10}$	9.0×10^2	9.7×10^{-18}
$K^- \to \pi^+ \mu^- \mu^-$	$< 1.1 \times 10^{-9}$	2.2×10^3	1.0×10^{-12}
$K^- \to \pi^+ e^- \mu^-$	$< 5.0 \times 10^{-10}$	7.3×10^2	1.6×10^{-15}
$D^- \to \pi^+ e^- e^-$	$< 1.1 \times 10^{-6}$	2.4×10^4	7.3×10^{-15}
$D^- \to \pi^+ \mu^- \mu^-$	$< 2.2 \times 10^{-8}$	3.5×10^3	4.6×10^{-11}
$D^- \to \pi^+ e^- \mu^-$	$< 2.0 \times 10^{-6}$	2.4×10^4	1.5×10^{-12}
$D^- \to \rho^+ \mu^- \mu^-$	$< 5.6 \times 10^{-4}$	1.0×10^6	1.3×10^{-8}
$D^- \to K^+ e^- e^-$	$< 9 \times 10^{-7}$	2.1×10^4	2.5×10^{-13}
$D^- \to K^+ \mu^- \mu^-$	$< 1.0 \times 10^{-5}$	7.2×10^4	3.7×10^{-8}
$D^- \to K^+ e^- \mu^-$	$< 1.9 \times 10^{-6}$	2.2×10^4	5.5×10^{-11}
$D^- \to K^{*+} \mu^- \mu^-$	$< 8.5 \times 10^{-4}$	1.7×10^6	8.7×10^{-7}
$D_s^- \to \pi^+ e^- e^-$	$< 4.1 \times 10^{-6}$	4.5×10^4	5.5×10^{-13}
$D_s^- \to \pi^+ \mu^- \mu^-$	$< 1.2 \times 10^{-7}$	7.9×10^3	4.1×10^{-9}
$D_s^- \to \pi^+ e^- \mu^-$	$< 8.4 \times 10^{-6}$	4.6×10^4	1.2×10^{-10}
$D_s^- \to K^+ e^- e^-$	$< 5.2 \times 10^{-6}$	4.7×10^4	5.6×10^{-12}
$D_s^- \to K^+ \mu^- \mu^-$	$< 1.3 \times 10^{-5}$	7.7×10^4	3.9×10^{-7}
$D_s^- \to K^+ e^- \mu^-$	$< 6.1 \times 10^{-6}$	3.7×10^4	8.9×10^{-10}
$D_s^- \to K^{*+} \mu^- \mu^-$	$< 1.4 \times 10^{-3}$	1.8×10^6	9.1×10^{-6}

Experimental Sensitivities





Gomez-Cadenas *et al.*, 1109.5155

Atomic Number Z

Light ν mediated 0νββ

The 0νββ-decay half-life

$$T_{1/2}^{0\nu} = G_{0\nu}^{-1} \cdot |\mathcal{M}_{0\nu}|^{-2} \cdot |m_{\beta\beta}|^{-2} \cdot m_e^2$$

Phase space

Nuclear **M**atrix **E**lement

Effective ν mass

$$|m_{\beta\beta}| \equiv |m_1 \cos^2\theta_{13} \cos^2\theta_{12} e^{i\rho} + m_2 \cos^2\theta_{13} \sin^2\theta_{12} + m_3 \sin^2\theta_{13} e^{i\sigma}|$$

- Experimentalists: fix the half-life
- Nuclear theorists: calculate NME
- Particle theorists: effective mass ν masses & Majorana CP phases

Experimental Sensitivities

How to extract the 0νββ-decay half-life:

Number of events

$$N = \frac{\ln 2}{T^{0\nu}_{1/2}} \cdot t \cdot \frac{M_{\text{iso}} \cdot N_{\text{A}}}{m_{\text{iso}}} \cdot \epsilon$$

Detection efficiency

Decay rate   Number of nuclei

Toy model:

$$T^{0\nu}_{1/2} = G^{-1}_{0\nu} \cdot |\mathcal{M}_{0\nu}|^{-2} \cdot |m_{\beta\beta}|^{-2} \cdot m_e^2$$

- **Background-free setup:** $N = S$
- **Require** $N < 1$ ➡ $T^{0\nu}_{1/2} > \ln 2 \cdot t \cdot \frac{M_{\text{iso}} \cdot N_{\text{A}}}{m_{\text{iso}}} \cdot \epsilon$ ➡ **Upper limit on effective mass**

Realistic case:

$$T^{0\nu}_{1/2} = \ln 2 \cdot \frac{N_{\text{A}} \cdot \xi \cdot \epsilon}{m_{\text{iso}} \cdot S(B)}$$

$\xi \equiv M_{\text{iso}} \cdot t$ **exposure**

$S(B)$ **Number of signal events given background *B* in ROI**

$$\text{PDF}_{\text{Poisson}}(n, \mu) = e^{-\mu}\mu^n/n!$$

$$\text{CDF}_{\text{Poisson}}(n, \mu) \equiv \sum_{k=0}^{n} \text{PDF}_{\text{Poisson}}(k, \mu)$$

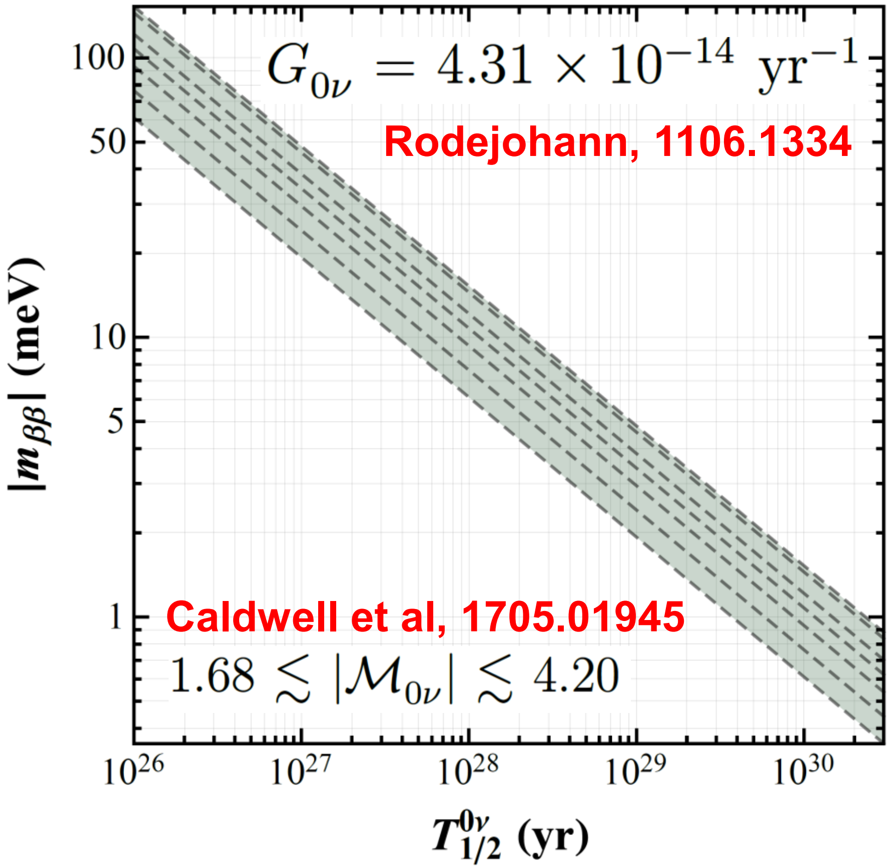
$$\text{CDF}_{\text{Poisson}}(n_p, B) \geq p$$

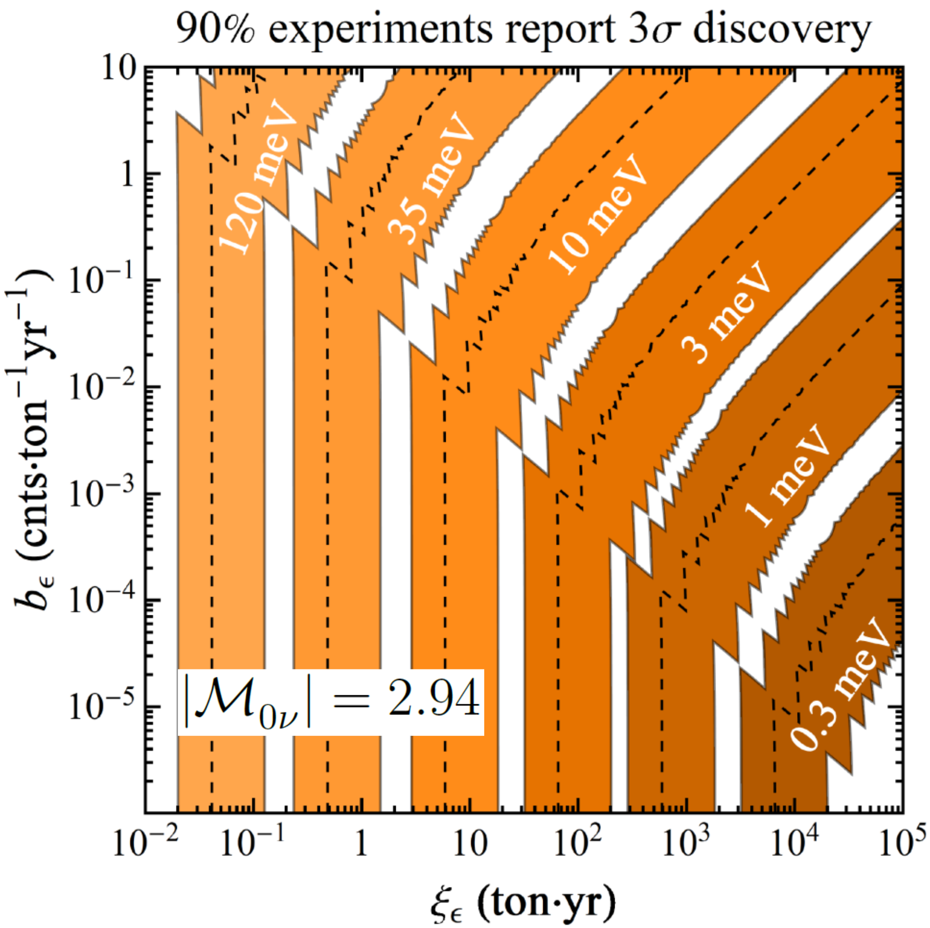
$$\overline{\text{CDF}}_{\text{Poisson}}(n_p, B + S) = q$$

$$\overline{\text{CDF}}_{\text{Poisson}} = 1 - \text{CDF}_{\text{Poisson}}$$

$^{136}Xe \rightarrow {}^{136}Ba + e^- + e^-$

G.Y. Huang, SZ, 2010.16281





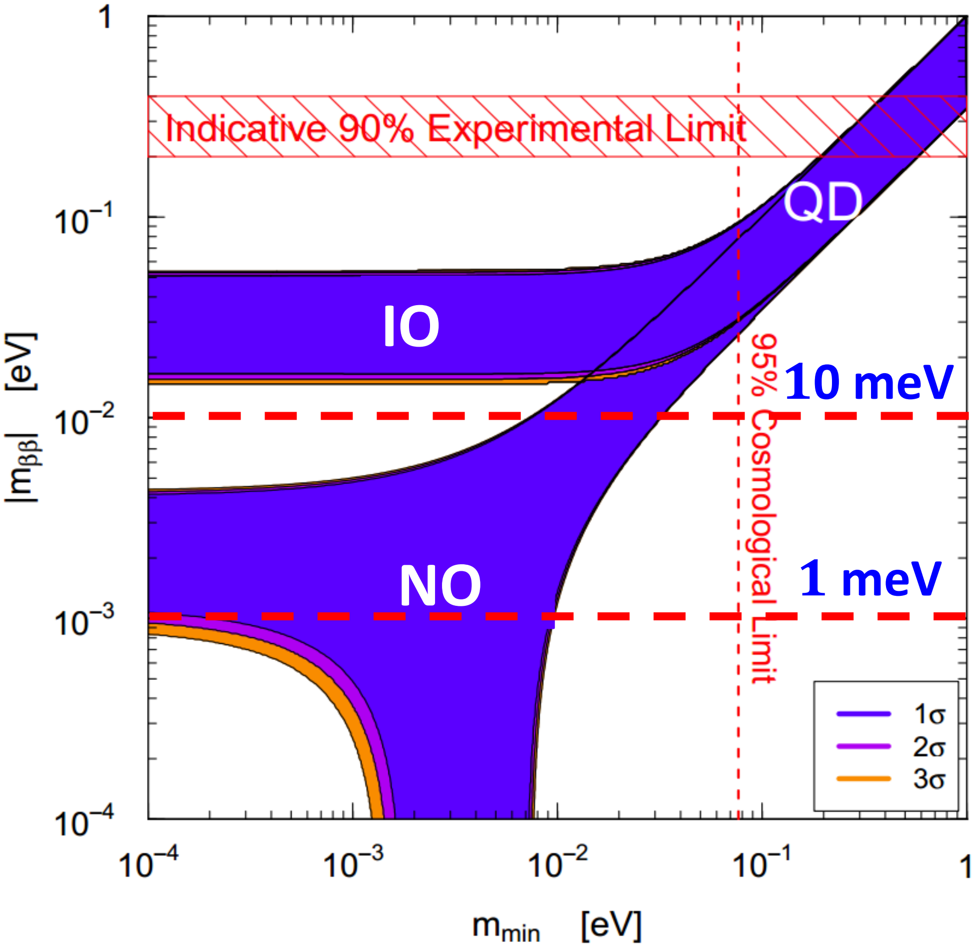
$$|m_{\beta\beta}| = 10 \text{ meV} \Rightarrow T^{0\nu}_{1/2} \in (3.8 \times 10^{27} \cdots 2.5 \times 10^{28}) \text{ yr}$$

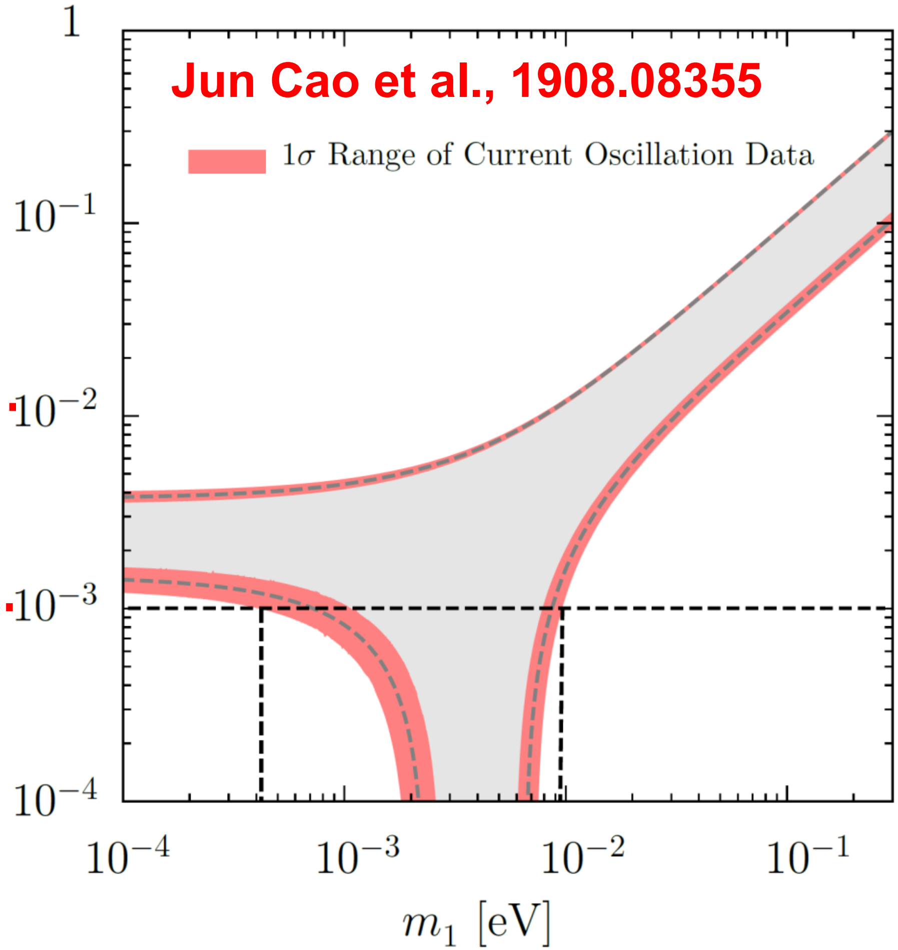
$$|m_{\beta\beta}| = 1 \text{ meV} \Rightarrow T^{0\nu}_{1/2} \in (3.8 \times 10^{29} \cdots 2.5 \times 10^{30}) \text{ yr}$$

1 meV sensitivity

$\xi_\epsilon \simeq 300$ ton · yr

Probe ν Masses & Majorana CP Phases





Effective ν mass $|m_{\beta\beta}| \equiv \left|m_1 \cos^2\theta_{13}\cos^2\theta_{12} e^{i\rho} + m_2\cos^2\theta_{13}\sin^2\theta_{12} + m_3\sin^2\theta_{13}e^{i\sigma}\right|$

- **We assume Majorana neutrinos with NO, and observe no signal events**
- **If this is true even for future 1 meV sensitivity, then what can we learn?**

Bayesian Approach

Bayes' Theorem $P(\mathcal{H}_i|\mathcal{D}) = \frac{P(\mathcal{D}|\mathcal{H}_i)P(\mathcal{H}_i)}{P(\mathcal{D})}$

- $P(\mathcal{H}_i)$ → **Prior probability**
- $P(\mathcal{D})$ → **normalization**
- $P(\mathcal{D}|\mathcal{H}_i)$ → **likelihood**
- $P(\mathcal{H}_i|\mathcal{D})$: **Posterior probability**

Model selection: $\frac{P(\mathcal{H}_i|\mathcal{D})}{P(\mathcal{H}_j|\mathcal{D})} = \frac{\mathcal{Z}_i}{\mathcal{Z}_j}\frac{P(\mathcal{H}_i)}{P(\mathcal{H}_j)}$

Bayes' factor $\mathcal{B} \equiv \mathcal{Z}_i/\mathcal{Z}_j$

Parameter estimation: $P(\Theta|\mathcal{H}_i,\mathcal{D}) = \frac{P(\mathcal{D}|\mathcal{H}_i,\Theta)P(\Theta|\mathcal{H}_i)}{P(\mathcal{D}|\mathcal{H}_i)}$

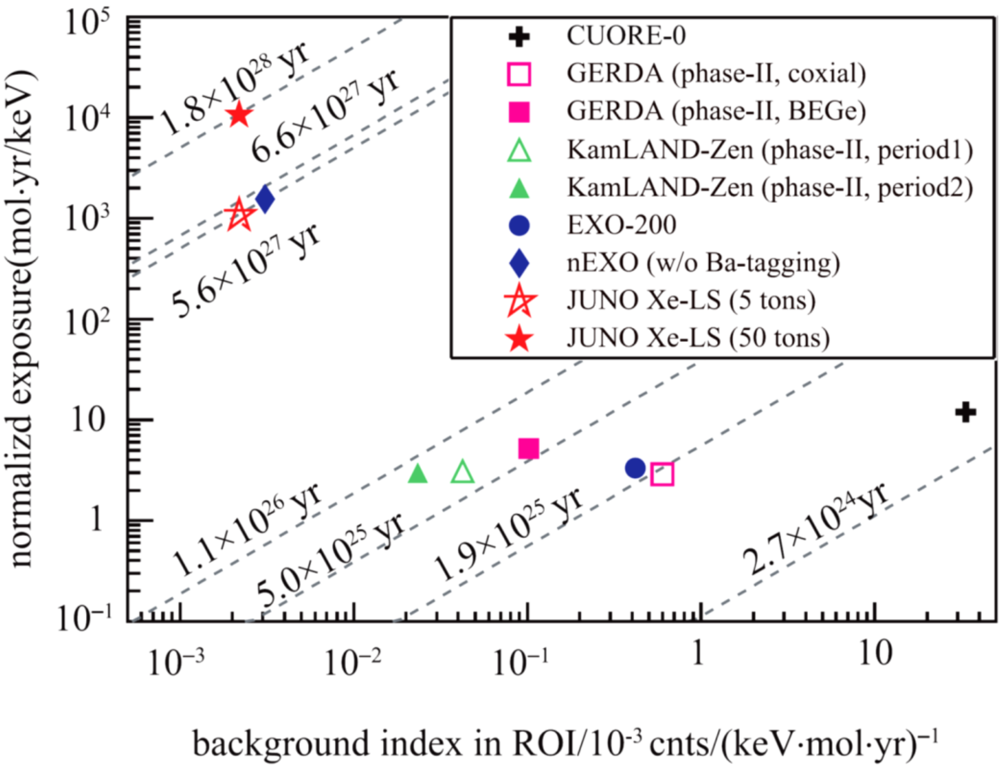
Calculate the evidence $\mathcal{Z}_i = \int P(\mathcal{D}|\mathcal{H}_i,\Theta)P(\Theta|\mathcal{H}_i)\mathrm{d}\Theta$

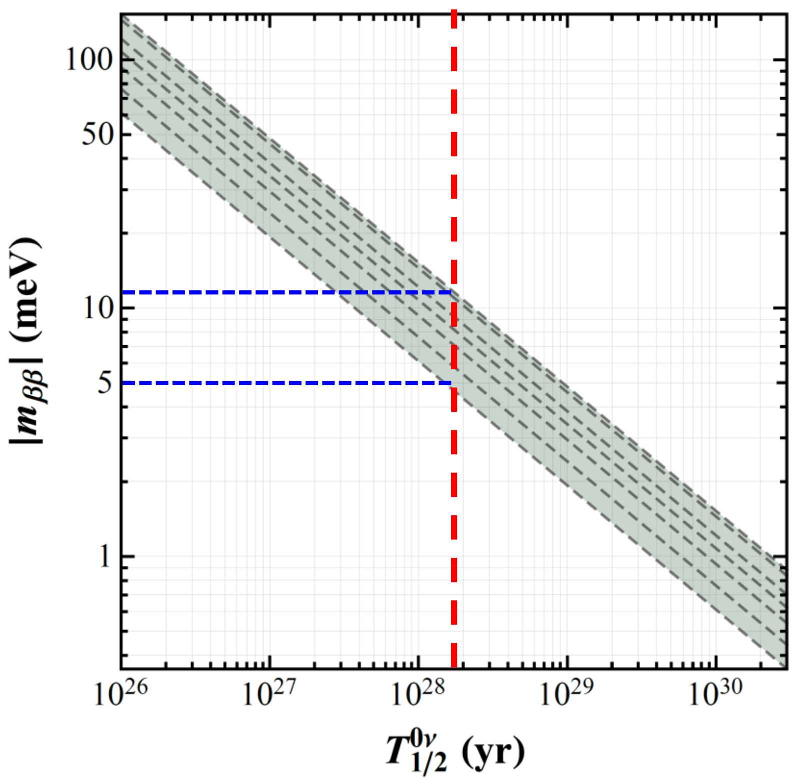
Central idea: Sivia & Skilling, *Data Analysis: A Bayesian Tutorial*, 2006

- **Before including the new experimental data, we have to specify prior info.**
- **Update our knowledge by using the posterior of previous expts. as priors**

Motivation for two setups

J. Zhao, L.J. Wen, Y.F. Wang, J. Cao, 1610.07143





Setup I: JUNO Xe-LS $\xi = 50\ \text{ton}\cdot 5\ \text{yr}$ $\epsilon = 0.634$ $b = 1.35\ \text{ton}^{-1}\cdot\text{yr}^{-1}$

$$T^{0\nu}_{1/2} = 6.24\times 10^{27}\ \text{yr} \quad |m_{\beta\beta}| = (7.9\cdots 19.7)\ \text{meV}$$ @3σ C.L.

Setup II: Ideal scenario $\xi = 400\ \text{ton}\cdot 5\ \text{yr}$ $\epsilon = 1$ $b = 0\ \text{ton}^{-1}\cdot\text{yr}^{-1}$

$$T^{0\nu}_{1/2} = 2.67\times 10^{30}\ \text{yr} \quad |m_{\beta\beta}| = (0.38\cdots 0.95)\ \text{meV}$$ @3σ C.L.

- **First, we specify the model (i.e., Majorana neutrinos & NO) and the model parameters are the lightest neutrino mass m_1, two neutrino mass-squared differences $\{\Delta m^2_{21}, \Delta m^2_{31}\}$, two mixing angles $\{\theta_{12}, \theta_{13}\}$ and two Majorana CP phases $\{\rho, \sigma\}$**

- **Second, we state our current knowledge on these parameters, i.e., priors. Neutrino oscillations: $\{\Delta m^2_{21}, \Delta m^2_{31}\}$ and $\{\theta_{12}, \theta_{13}\}$; Uniform distribution: $\{\rho, \sigma\}$ in the whole range [0, 2π); Uniform distribution for NME in whole range [1.68, 4.20]; Gaussian distribution for the phase factor; Uniform distribution: m_1**

Flat: $m_1/\mathrm{eV} \in [10^{-7}, 10]$ **Log:** $\log_{10}(m_1/\mathrm{eV}) \in [-7, 1]$

- **Third, given the parameters, we calculate the expected number $N^{0\nu}$ of the signal events; the data $n_{\rm tot}$ can be simulated and we simply take $n_{\rm tot} = B$; then the likelihood is**

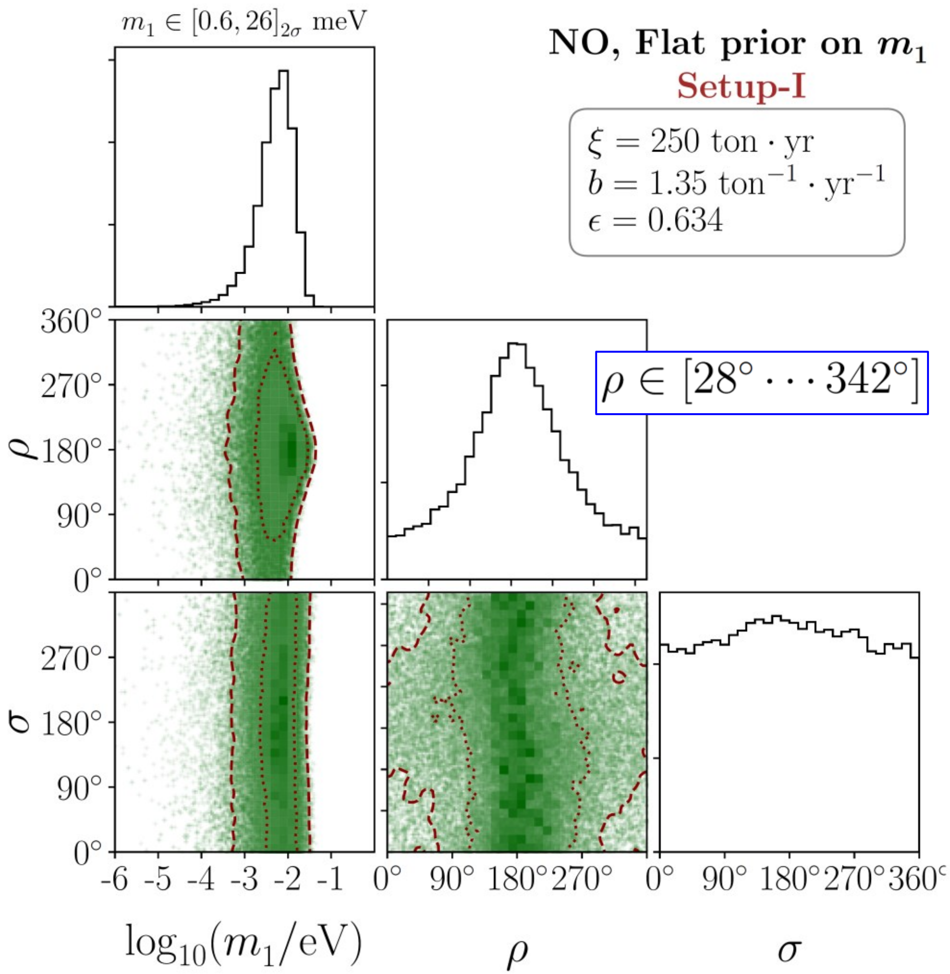
$$\mathcal{L}^{\rm meV}_{0\nu\beta\beta}(N^{0\nu}) = \frac{(N^{0\nu} + B)^{n_{\rm tot}}}{n_{\rm tot}!} \cdot e^{-(N^{0\nu}+B)}$$

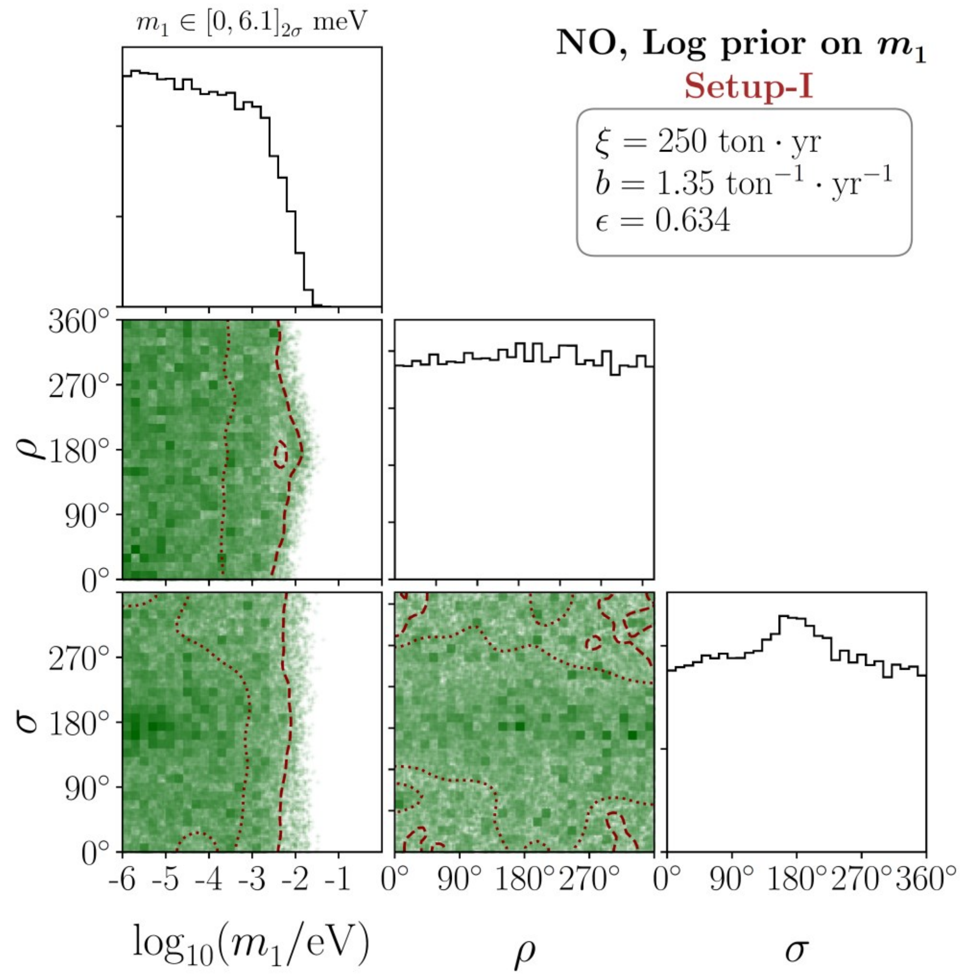
- **Fourth, calculate the posterior probabilities for the model parameters and project them onto one or two-dimensional parameter space**

Bayesian Analysis: Masses & Majorana CP Phases

Final Results for Setup-I

G.Y. Huang, SZ, 2010.16281

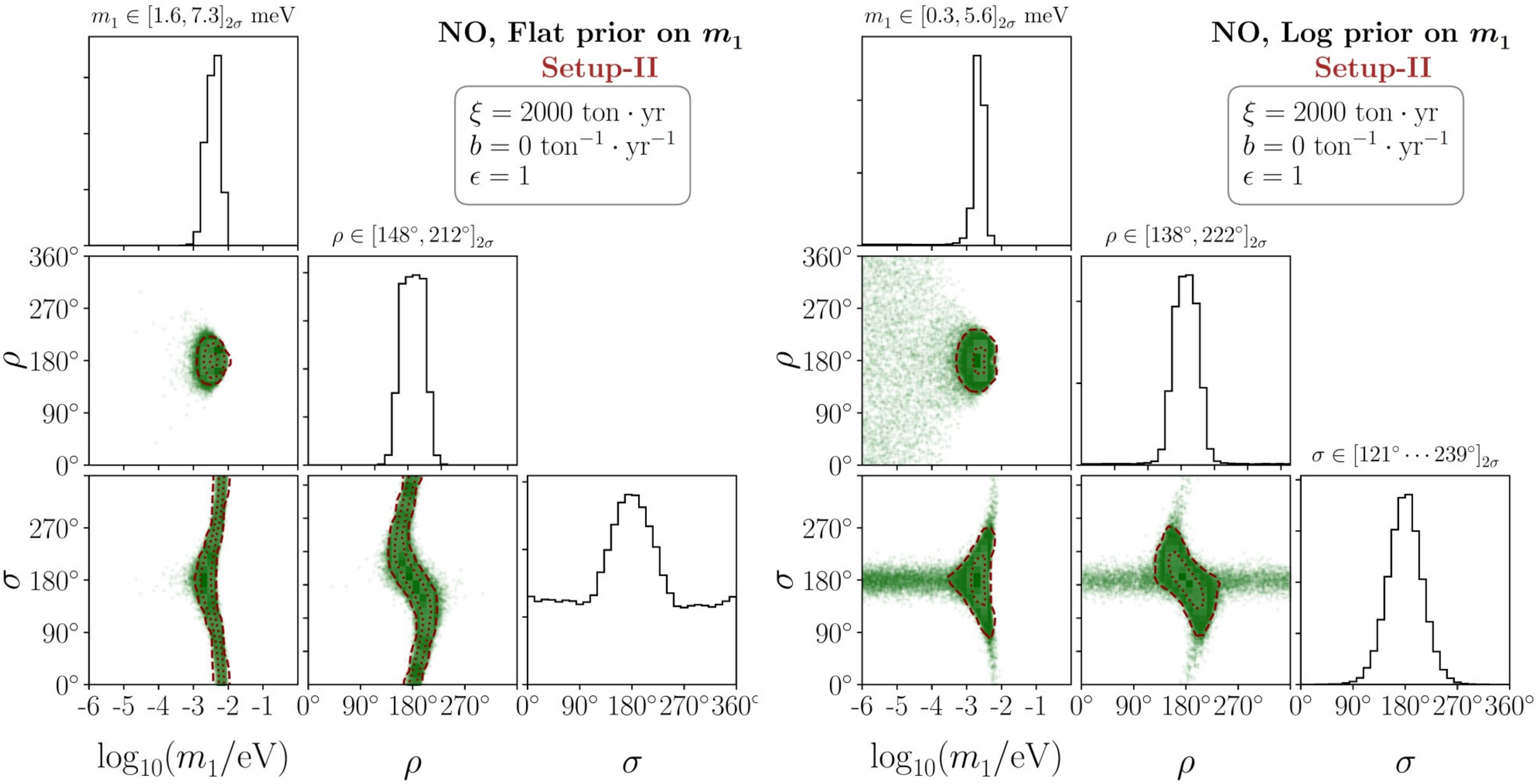




$$\begin{cases} m_1 \in [0.6 \cdots 26]\ \mathrm{meV}\ , \\ m_1 \in [0 \cdots 6.1]\ \mathrm{meV}\ , \end{cases} \quad \begin{cases} \Sigma \equiv m_1 + m_2 + m_3 < 0.11\ \mathrm{eV}\ , & \text{for flat prior on } m_1 \\ \Sigma \equiv m_1 + m_2 + m_3 < 0.067\ \mathrm{eV}\ , & \text{for log prior on } m_1 \end{cases}$$

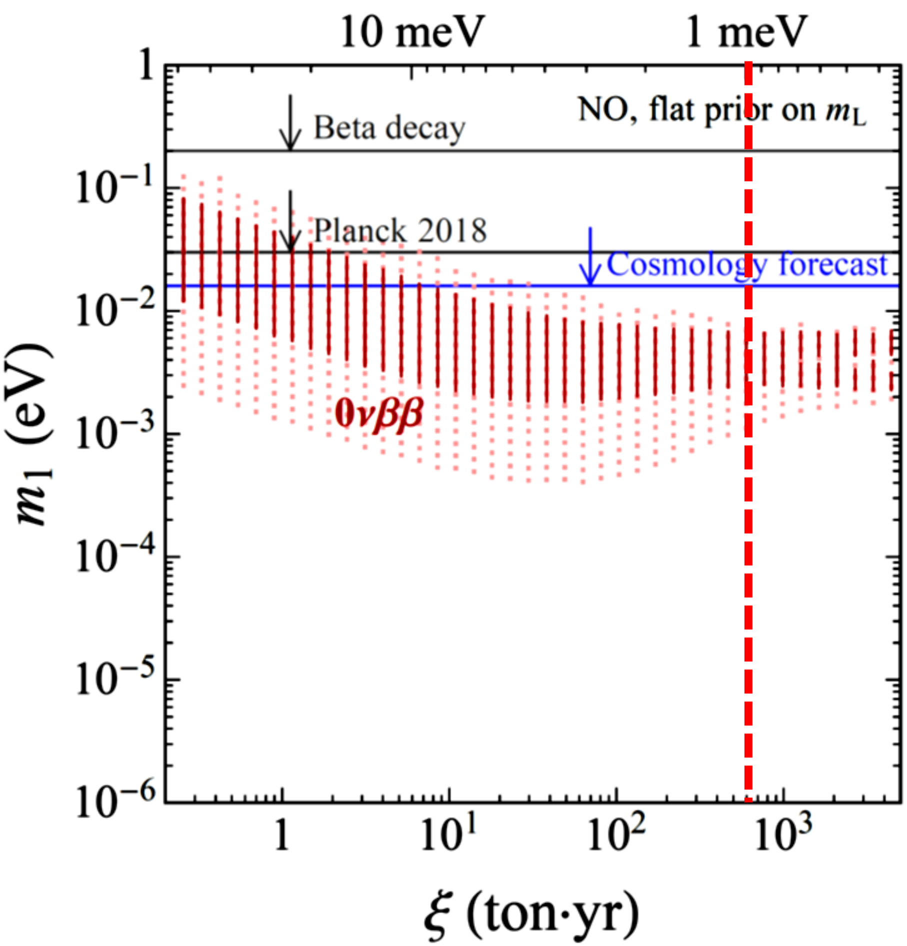
Final Results for Setup-II

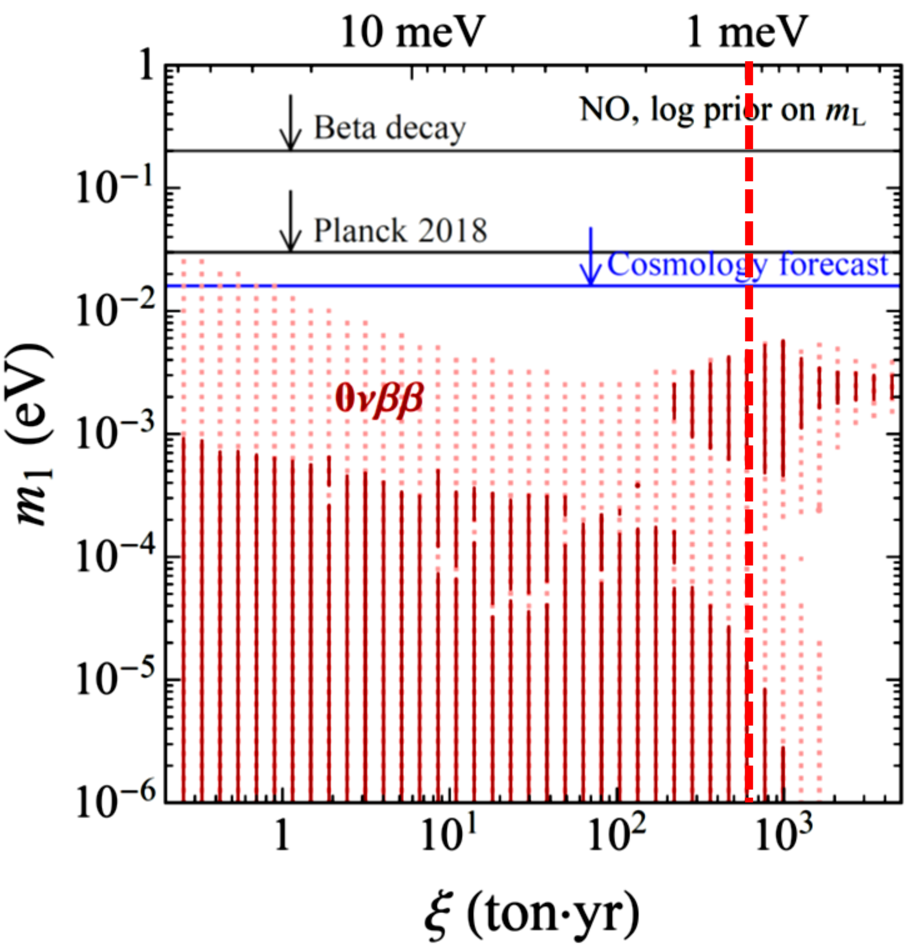
G.Y. Huang, SZ, 2010.16281



$$\begin{cases} m_1 \in [1.6 \cdots 7.3]\ \mathrm{meV}\ , \\ m_1 \in [0.3 \cdots 5.6]\ \mathrm{meV}\ , \end{cases} \quad \begin{cases} \rho \in [148° \cdots 212°]\ , & \text{for flat prior on } m_1 \\ \rho \in [138° \cdots 222°]\ , & \text{for log prior on } m_1 \end{cases}$$

Future sensitivity from cosmology $\sigma(\Sigma) \sim 14$ meV

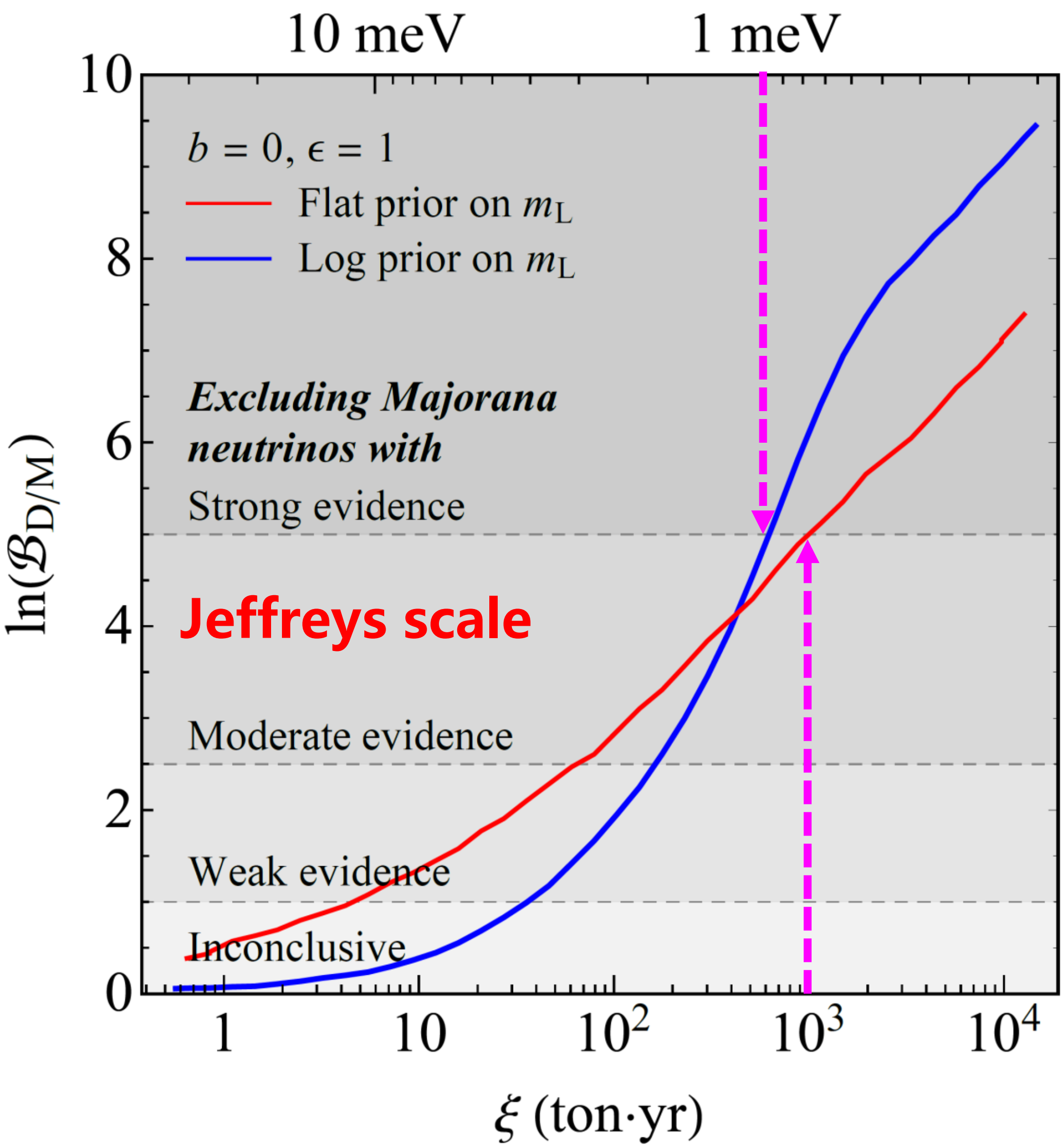




- **Background-free environment, average NME, and varying total exposure**
- **Better sensitivity to lightest ν mass than future cosmological observations**

Bayesian Analysis: Majorana vs. Dirac Neutrinos

If no signals observed, is it possible to exclude Majorana neutrinos?



Setup I: JUNO Xe-LS

NO

$\ln(\mathcal{B}_{D/M}) = 0.16$ **Log**

$\ln(\mathcal{B}_{D/M}) = 1.0$ **Flat**

Inconclusive

IO

$\ln(\mathcal{B}_{D/M}) = 11.7$ **Log**

$\ln(\mathcal{B}_{D/M}) = 12.3$ **Flat**

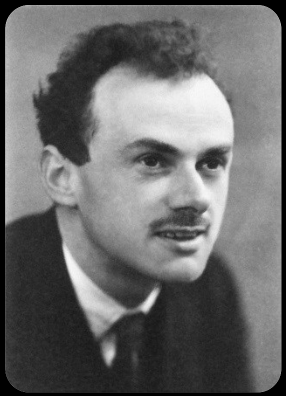
Very strong evidence

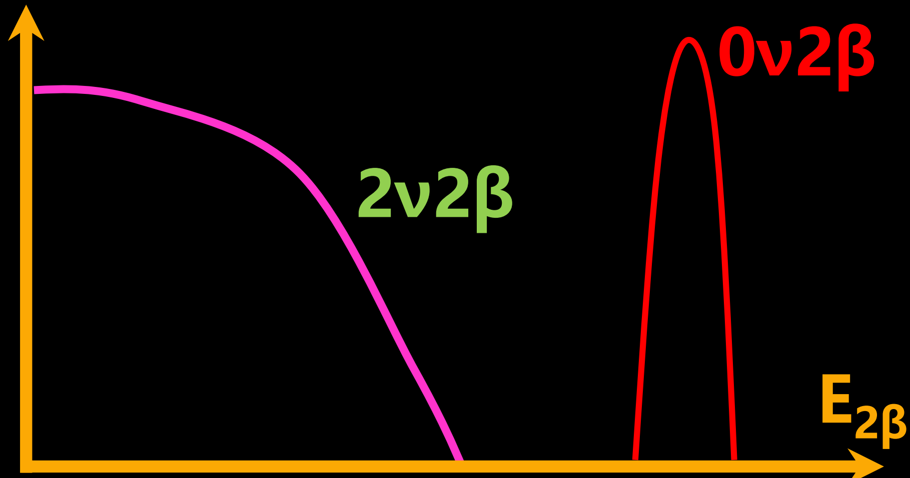
Setup II: NO case

Strong evidence $\ln(B_{D/M})=5$ requires the total exposure:

$$\xi = 1000\ \text{ton} \cdot \text{yr}$$

Summary





- **The 0ν2β decays offer a feasible and promising way to establish the Majorana nature of massive neutrinos**

★ Discovery of a new feature of elementary fermions	★ Discovery of LNV: a guide for theorists	★ Majorana CP Phases

- **The implications of the Schechter-Valle theorem are discussed and the extended to other LNV processes: a Majorana mass**

- **More efforts on experimental & theoretical sides hopefully help us explore the intrinsic properties of neutrinos**