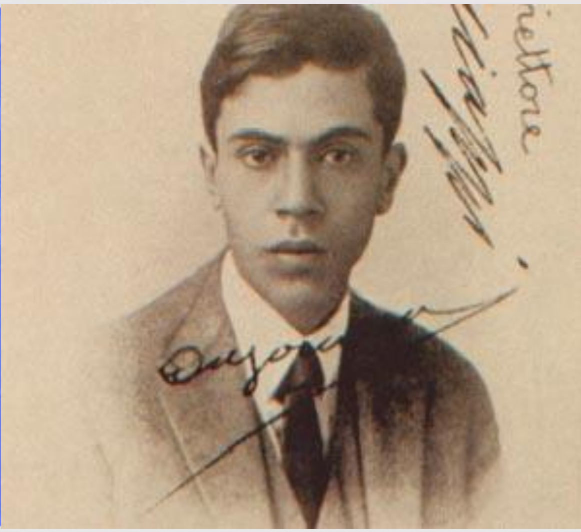
Majorana中微子物理



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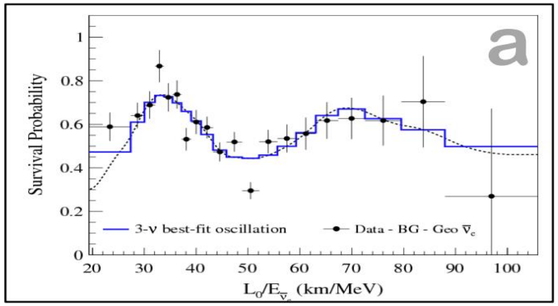
2022-08-02

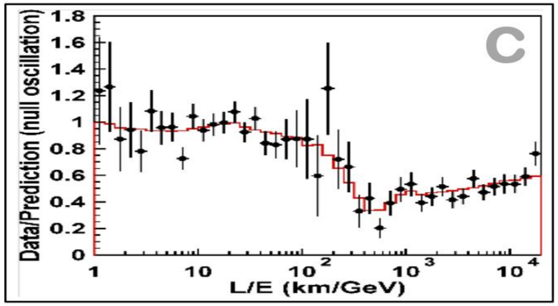
第十一届威海新物理研讨会

ν Oscillations

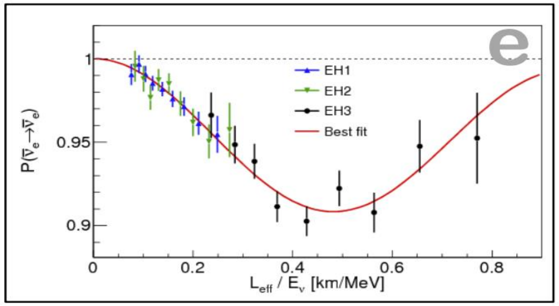
e→e



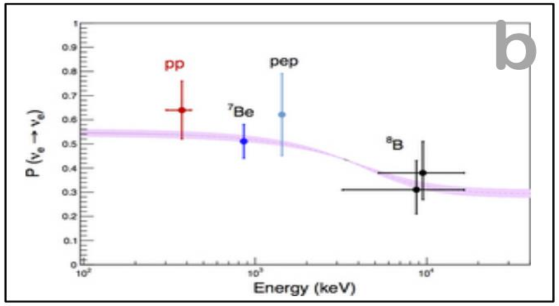
μ→μ



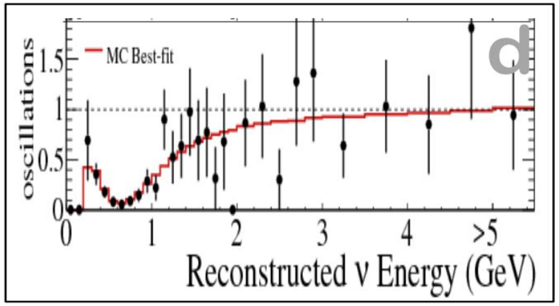
e→e



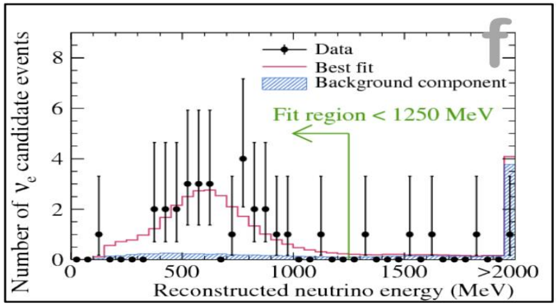
e→e



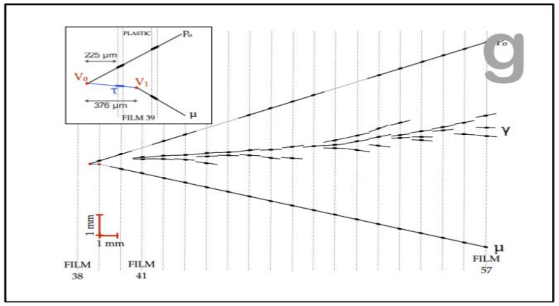
μ→μ



μ→e



μ→τ

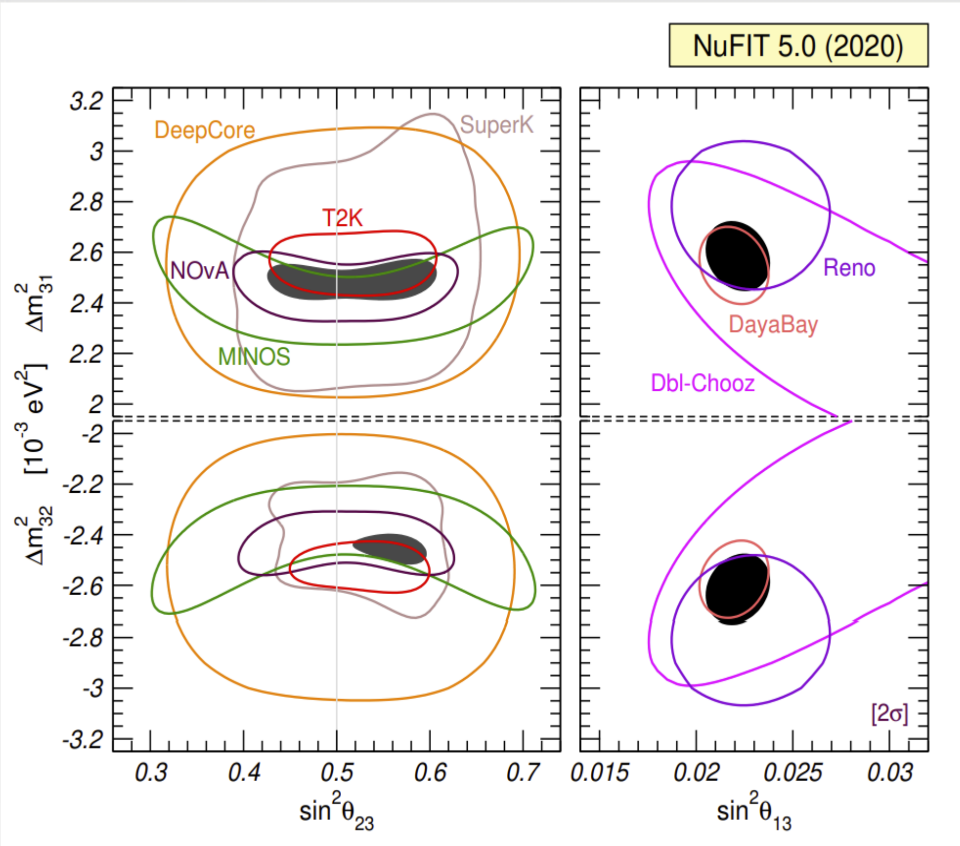


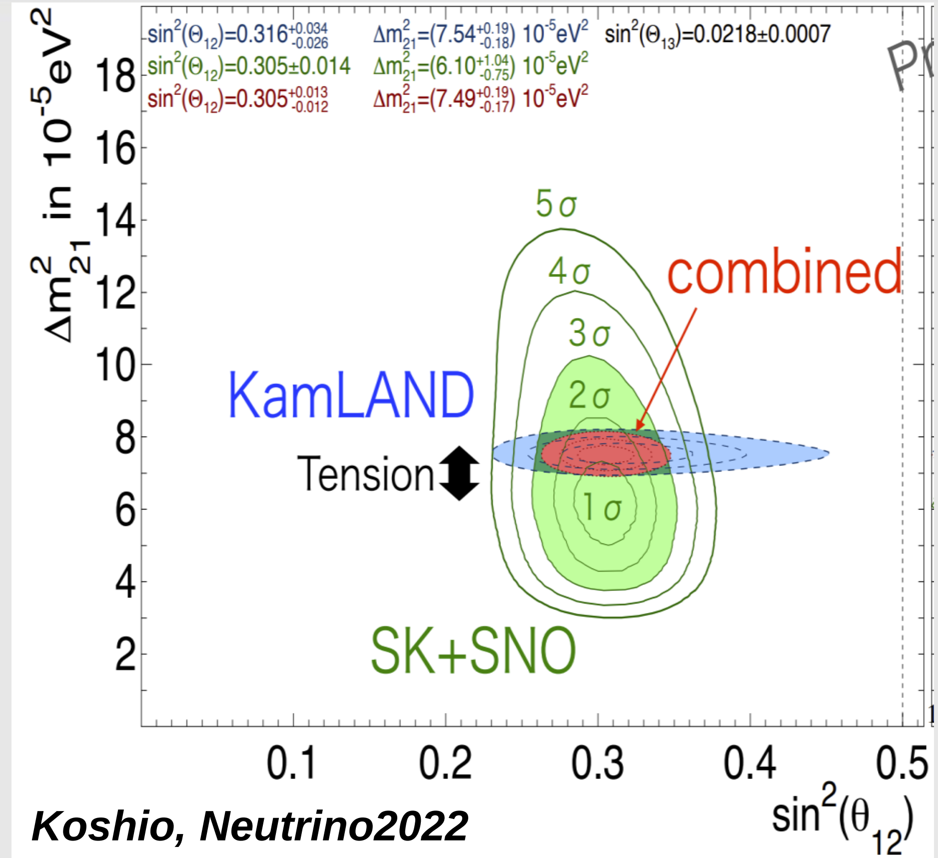
Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline accelerator, (e) short-baseline reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

(a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS, NOvA; (g) OPERA [plot], Super-K atmospheric.

From E. Lisi

ν Oscillations: robustness





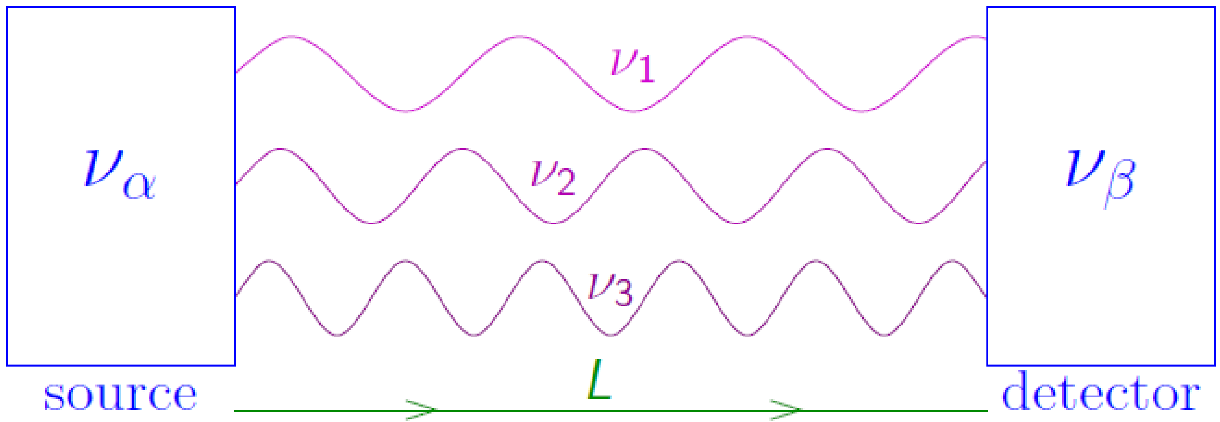
Koshio, Neutrino2022

Neutrino Oscillations:

- **Different neutrino sources and oscillation channels point to the same set of mass and mixing parameters → 3 flavor mixing**

Quantum mechanical ν Oscillations

$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = U_{\alpha 1}\,|\nu_1\rangle + U_{\alpha 2}\,|\nu_2\rangle + U_{\alpha 3}\,|\nu_3\rangle$$



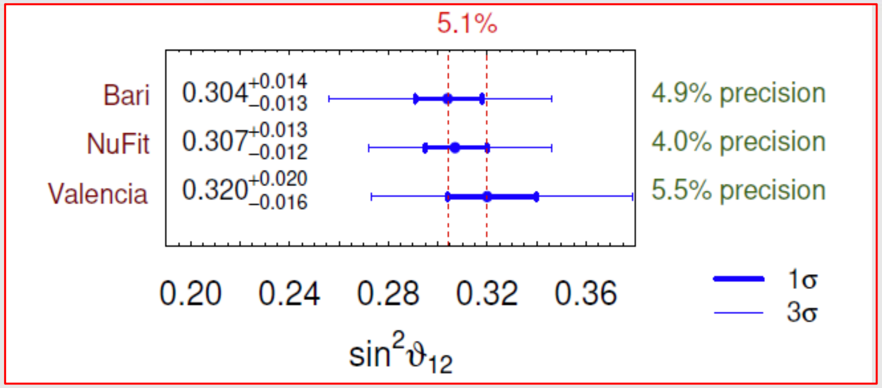
$$|\nu(t>0)\rangle = U_{\alpha 1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{\alpha 2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{\alpha 3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_\alpha\rangle$$

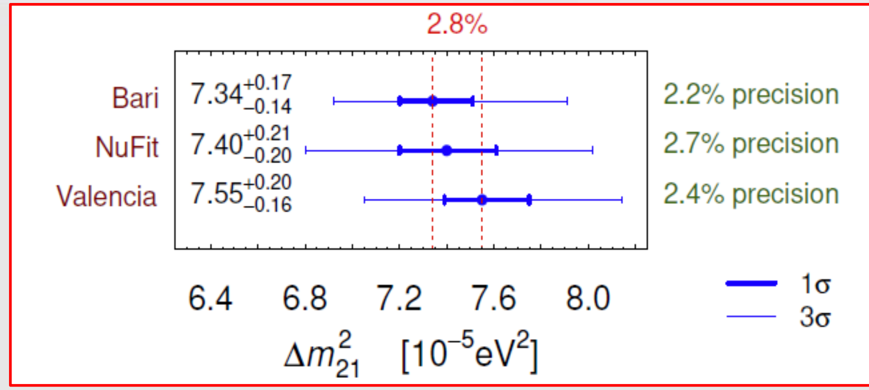
$$E_k^2 = p^2 + m_k^2 \qquad\qquad t = L$$

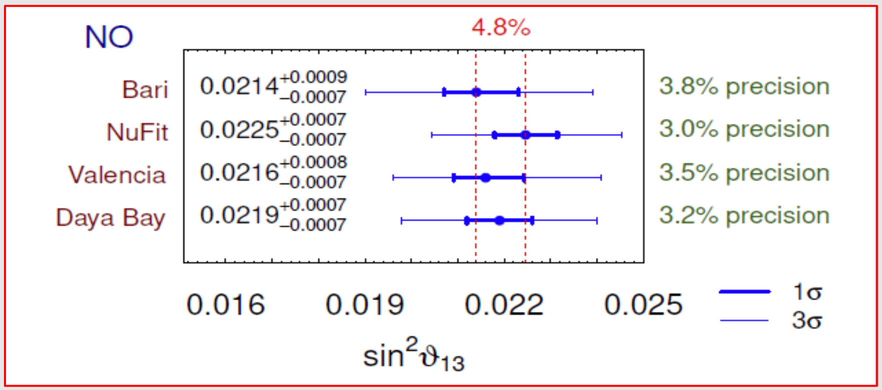
$$P_{\nu_\alpha\to\nu_\beta}(L) = |\langle\nu_\beta|\nu(L)\rangle|^2 = \sum_{k,j} U_{\beta k}\,U^*_{\alpha k}\,U^*_{\beta j}\,U_{\alpha j}\,\exp\left(-i\frac{\Delta m^2_{kj} L}{2E}\right)$$

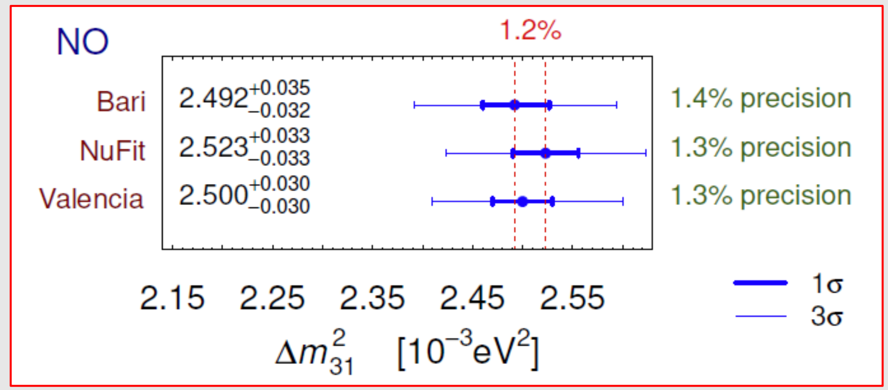
The oscillation probabilities depend on U and $\Delta m^2_{kj} \equiv m_k^2 - m_j^2$

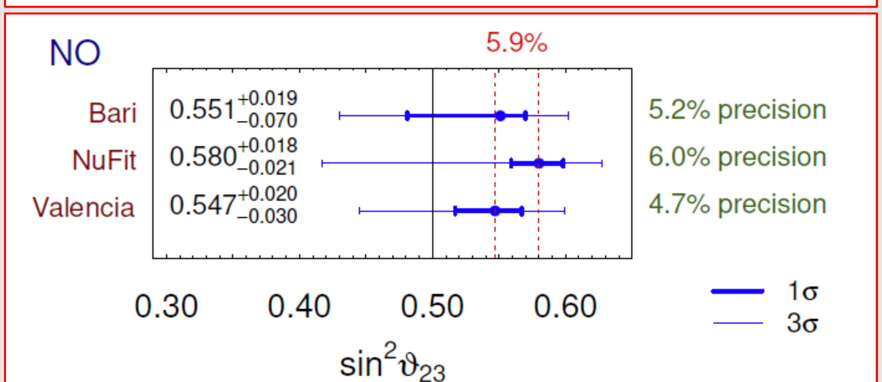
Global picture





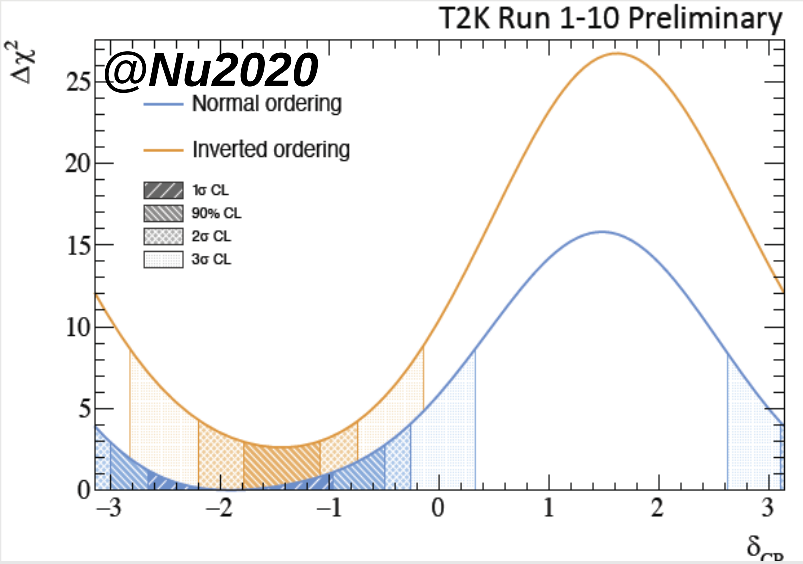


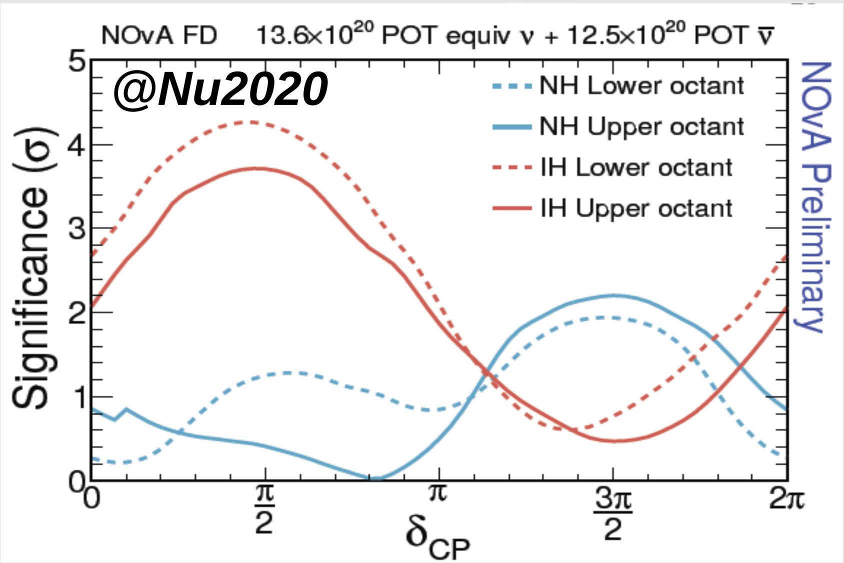


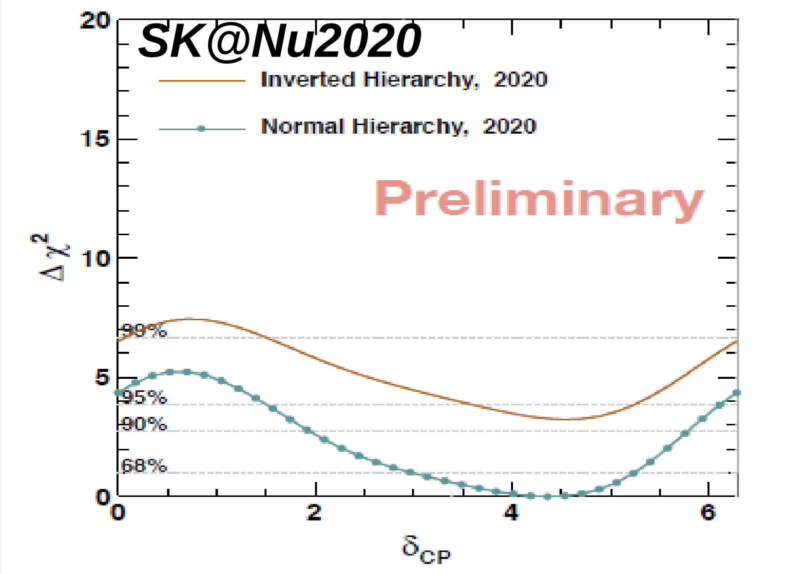


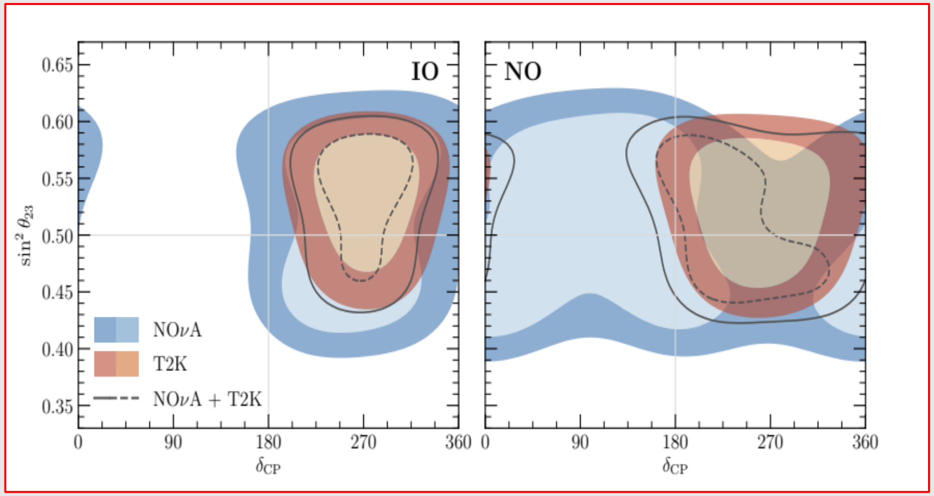
- **5 parameters: measured with rather high accuracies**
- **Mass ordering, CP violation to be determined**

Neutrino mass ordering & CP



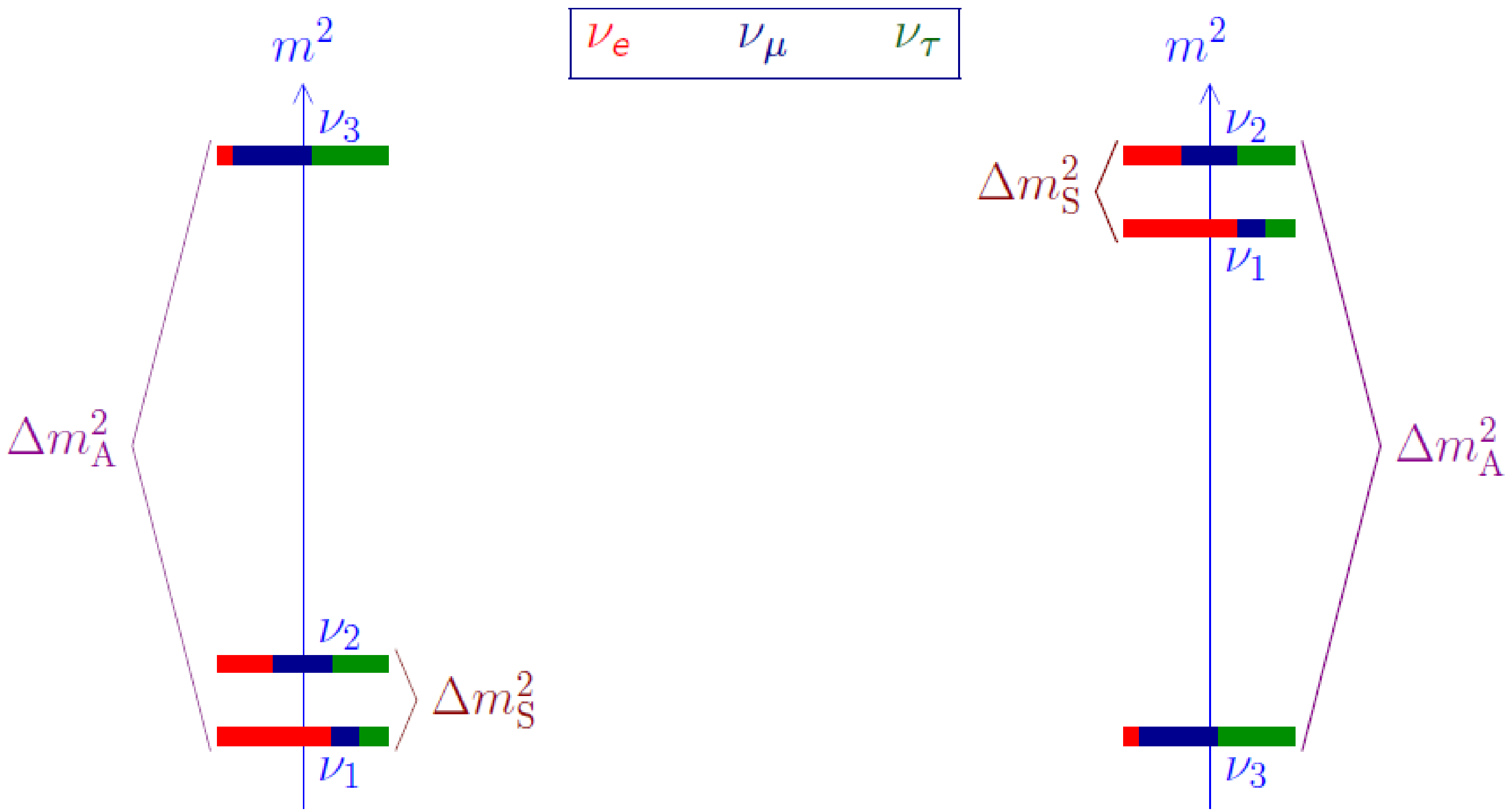






Schwetz@Nu2022

Neutrino mass spectrum



Normal Ordering

$\Delta m^2_{31} > \Delta m^2_{32} > 0$

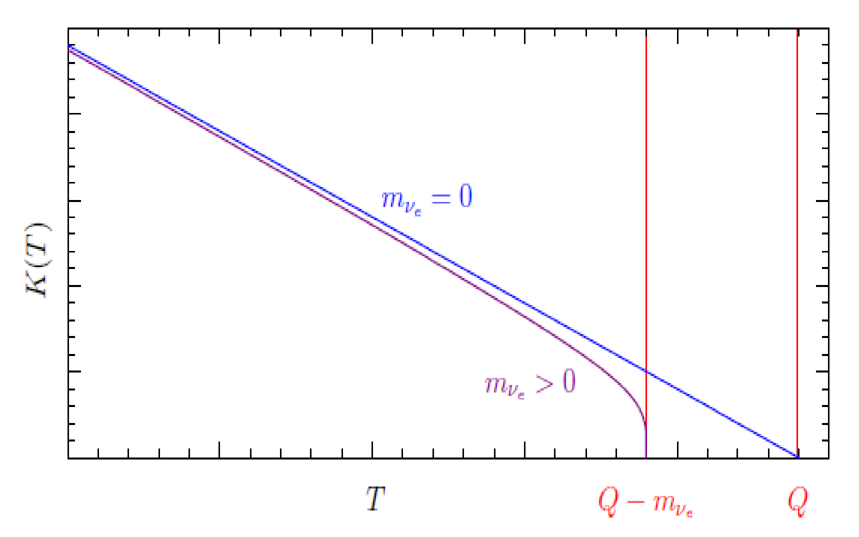
Inverted Ordering

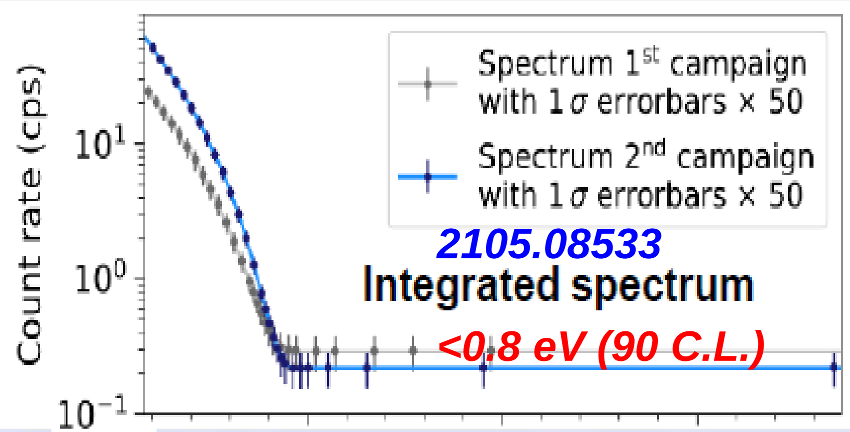
$\Delta m^2_{32} < \Delta m^2_{31} < 0$

absolute scale is not determined by neutrino oscillation data

Absolute neutrino masses: beta-decay

$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_e$$





2105.08533

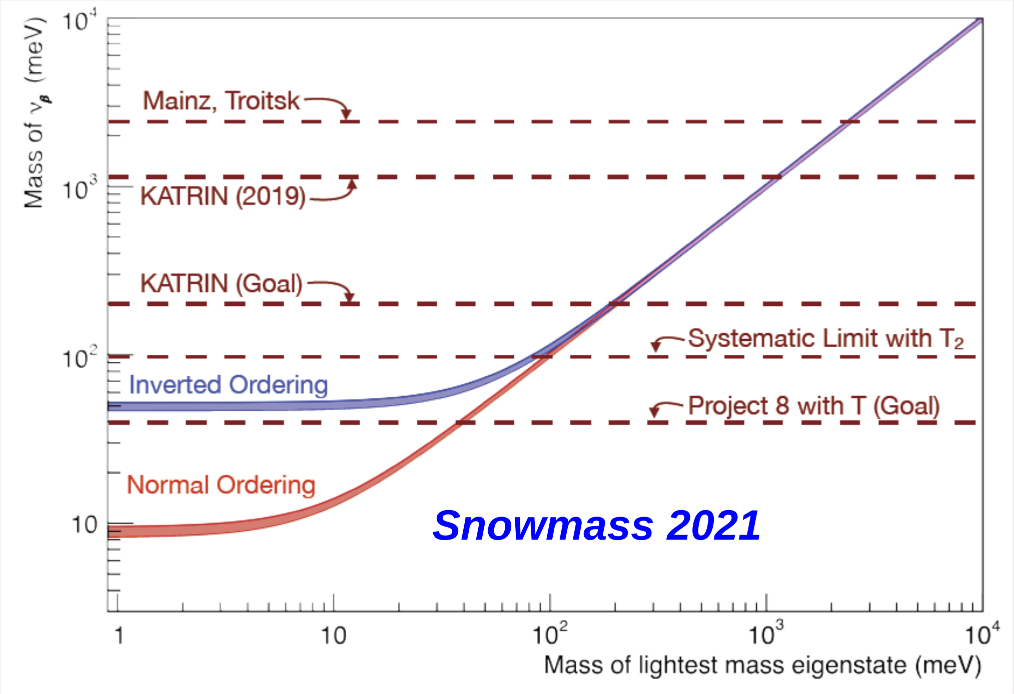
Integrated spectrum

<0.8 eV (90 C.L.)

Future Prospect:

$$m_\beta^2 = \sum_k |U_{ek}|^2 m_k^2$$

- **KATRIN: 200 meV**
- **Systematic limit: ~100 meV**
- **Project 8: 40 meV**



Snowmass 2021

Absolute neutrino masses: cosmology

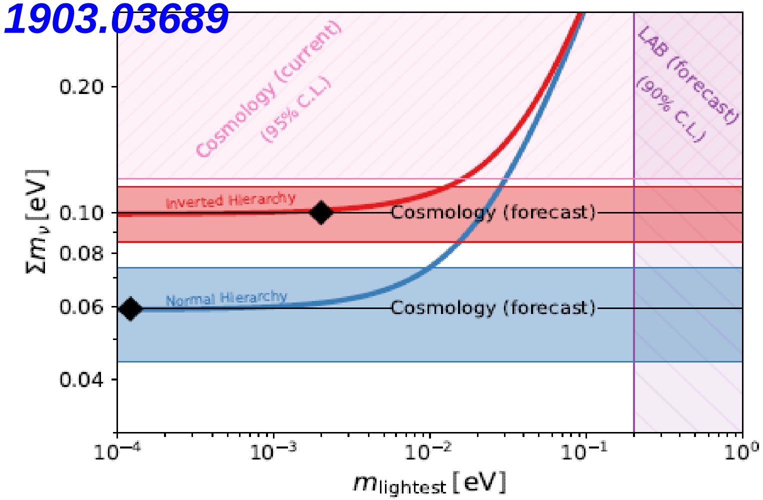
PDG 2020

	Model	95% CL (eV)	Ref.
CMB alone			
Pl18[TT+lowE]	ΛCDM+$\sum m_\nu$	< 0.54	[16]
Pl18[TT,TE,EE+lowE]	ΛCDM+$\sum m_\nu$	< 0.26	[16]
CMB + probes of background evolution			
Pl18[TT+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.16	[16]
Pl18[TT,TE,EE+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.13	[16]
Pl18[TT,TE,EE+lowE]+BAO	ΛCDM+$\sum m_\nu$+5 params.	< 0.515	[18]
CMB + LSS			
Pl18[TT+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.44	[16]
Pl18[TT,TE,EE+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.24	[16]
CMB + probes of background evolution + LSS			
Pl18[TT+lowE+lensing] + BAO	ΛCDM+$\sum m_\nu$	< 0.13	[16]
Pl18[TT,TE,EE+lowE+lensing] + BAO	ΛCDM+$\sum m_\nu$	< 0.12	[16]
Pl18[TT,TE,EE+lowE+lensing] + BAO+Pantheon	ΛCDM+$\sum m_\nu$	< 0.11	[16]

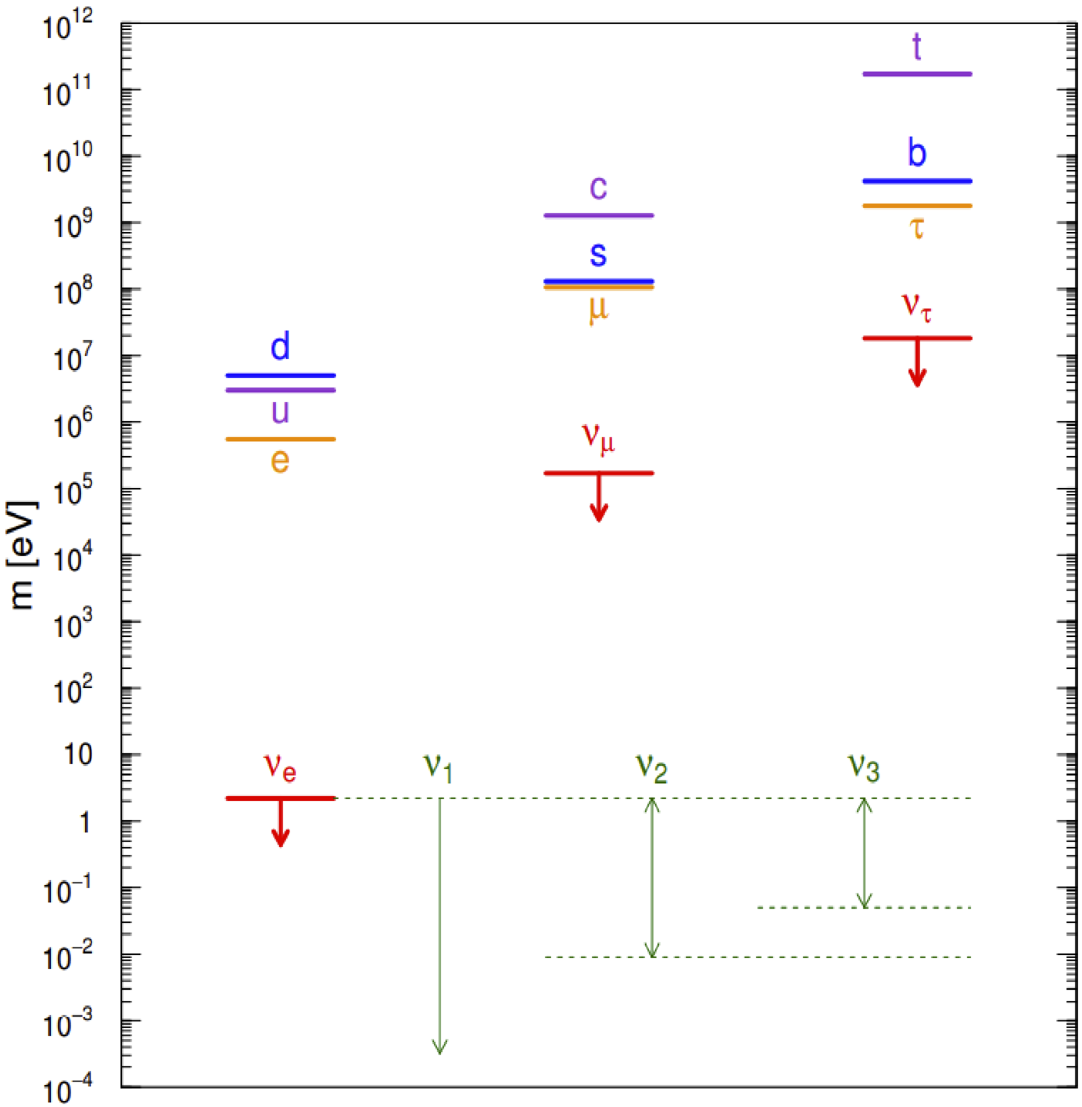
Cosmology: sum of neutrino masses

- **Data sets and model dependence**
- **Current best limit: ~120 meV**
- **Future projection → 60 meV**

1903.03689

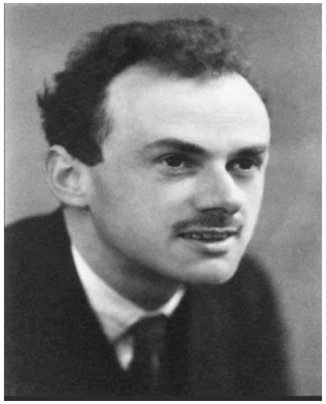


ν masses: Dirac versus Majorana



Two possibilities to define neutrino mass:

- **Dirac mass**



Left & right handed ν's

Lepton number conservation

- **Majorana mass**

Only left handed ν's

Lepton number violation

ν masses: Dirac versus Majorana

	1st Generation	2nd Generation	3rd Generation
Quarks:	$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{matrix} u_R \\ d_R \end{matrix}$	$\begin{pmatrix} c_L \\ s_L \end{pmatrix} \quad \begin{matrix} c_R \\ s_R \end{matrix}$	$\begin{pmatrix} t_L \\ b_L \end{pmatrix} \quad \begin{matrix} t_R \\ b_R \end{matrix}$
Leptons:	$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \quad \begin{matrix} \boxed{\nu_{eR}} \\ e_R \end{matrix}$	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix} \quad \begin{matrix} \boxed{\nu_{\mu R}} \\ \mu_R \end{matrix}$	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix} \quad \begin{matrix} \boxed{\nu_{\tau R}} \\ \tau_R \end{matrix}$

Standard Model extension: $\nu_R \Rightarrow$ Dirac mass Lagrangian

$$\mathscr{L}_{\mathrm{D}} \sim m_{\mathrm{D}} \, \overline{\nu_L} \nu_R$$

$$\mathscr{L}_{\mathrm{Y}} \sim y \, \overline{L_L} \widetilde{\Phi} \nu_R \xrightarrow[\text{Breaking}]{\text{Symmetry}} y \, v \, \overline{\nu_L} \nu_R$$

Extremely small Yukawa couplings are needed to get $m_{\mathrm{D}} \lesssim 1\,\mathrm{eV}$:

$$y \lesssim 10^{-11}$$

It is considered unnatural, unless there is a protecting BSM symmetry.

ν masses: Dirac versus Majorana

	1^{st} Generation		2^{nd} Generation		3^{rd} Generation	
Quarks:	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{matrix} u_R \\ d_R \end{matrix}$	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$	$\begin{matrix} c_R \\ s_R \end{matrix}$	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$	$\begin{matrix} t_R \\ b_R \end{matrix}$
Leptons:	$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	$\begin{matrix} \boxed{\nu_{eR}} \\ e_R \end{matrix}$	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$	$\begin{matrix} \boxed{\nu_{\mu R}} \\ \mu_R \end{matrix}$	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	$\begin{matrix} \boxed{\nu_{\tau R}} \\ \tau_R \end{matrix}$

Majorana Mass Lagrangian for SM ν_L

$$\mathscr{L}_L^{\mathrm{M}} \sim m_L \, \overline{\nu_L^c} \nu_L = -\nu_L^T \, \mathcal{C}^\dagger \, \nu_L$$

No Majorana Neutrino Mass in the SM

$$\nu_L^T \, \mathcal{C}^\dagger \, \nu_L \text{ has } I_3 = 1 \text{ and } Y = -2 \Longrightarrow$$

Needs Y= +2 Higgs triplet (type II), or (type I)

The introduction of ν_R leads

$$\mathscr{L}_R^{\mathrm{M}} \sim m_R \, \overline{\nu_R^c} \nu_R \qquad \text{singlet under SM symmetries!}$$

Dirac and Majorana mass Lagrangian

$$\mathscr{L}_{\text{mass}}^{\text{D+M}} = \mathscr{L}_{\text{mass}}^{\text{D}} + \mathscr{L}_{\text{mass}}^{R}$$

$$= -\, m_{\text{D}} \left(\overline{\nu_L}\, \nu_R + \overline{\nu_R}\, \nu_L \right) - \frac{1}{2}\, m_R \left(\overline{\nu_R^c}\, \nu_R + \overline{\nu_R}\, \nu_R^c \right)$$

$$= -\frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_{\text{D}} \\ m_{\text{D}} & m_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} - \frac{1}{2} \begin{pmatrix} \overline{\nu_L^c} & \overline{\nu_R} \end{pmatrix} \begin{pmatrix} 0 & m_{\text{D}} \\ m_{\text{D}} & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}$$

$\boxed{\text{Seesaw } m_R \gg m_{\text{D}}}$

$$\mathscr{L}_{\text{mass}}^{\text{D+M}} = -\frac{1}{2}\, \overline{n_L^c}\, U^T\, M\, U\, n_L + \text{H.c.}$$

$$U^T\, M\, U = \begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix} \quad \text{with real} \quad m_k \geq 0$$

$\boxed{\nu \simeq -i \left(\nu_L - \nu_L^c \right) \qquad N \simeq \nu_R + \nu_R^c}$

$$\mathscr{L}_{\text{mass}}^{\text{D+M}} = -\frac{1}{2} \sum_{k=1,2} m_k \left(\overline{\nu_{kL}^c}\, \nu_{kL} + \overline{\nu_{kL}}\, \nu_{kL}^c \right) = -\frac{1}{2} \sum_{k=1,2} m_k\, \overline{\nu_k}\, \nu_k$$

$\nu_k = \nu_{kL} + \nu_{kL}^c \quad \Longrightarrow \quad \boxed{\nu_k = \nu_k^c}$ Massive neutrinos are Majorana!

Low energy 3ν Majorana mixing

$$\nu_\alpha = \sum_{k=1}^{3} U_{\alpha k} \nu_k \quad \text{for} \quad \alpha = e, \mu, \tau \quad \text{with} \quad \boxed{\nu_k = \nu_k^c}$$

Standard Parameterization of Mixing Matrix (as CKM)

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$$c_{ab} \equiv \cos\vartheta_{ab} \qquad s_{ab} \equiv \sin\vartheta_{ab} \qquad 0 \leq \vartheta_{ab} \leq \frac{\pi}{2} \qquad 0 \leq \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi$$

OSCILLATION PARAMETERS

- 3 Mixing Angles: ϑ_{12}, ϑ_{23}, ϑ_{13}
- 1 CPV Dirac Phase: δ_{13}
- 2 independent $\Delta m^2_{kj} \equiv m^2_k - m^2_j$: Δm^2_{21}, Δm^2_{31}

2 CPV Majorana Phases: λ_{21}, λ_{31} $\Longleftrightarrow$ $\boxed{|\Delta L| = 2}$ processes

In ν Oscillations Dirac = Majorana

Evolution of Amplitudes: $$i\,\frac{\mathrm{d}\psi_\alpha}{\mathrm{d}x} = \frac{1}{2E}\sum_\beta \left(UM^2U^\dagger + 2EV\right)_{\alpha\beta}\psi_\beta$$

difference: $$\begin{cases} \text{Dirac:} & U^{(\mathrm{D})} \\ \text{Majorana:} & U^{(\mathrm{M})} = U^{(\mathrm{D})} D(\lambda) \end{cases}$$

$$D(\lambda) = \begin{pmatrix} 1 & 0 & \cdots & 0 \\ 0 & e^{i\lambda_{21}} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & e^{i\lambda_{N1}} \end{pmatrix} \quad \Rightarrow \quad D^\dagger = D^{-1}$$

$$M^2 = \begin{pmatrix} m_1^2 & 0 & \cdots & 0 \\ 0 & m_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & m_N^2 \end{pmatrix} \quad \Longrightarrow \quad DM^2 = M^2D \quad \Longrightarrow \quad DM^2D^\dagger = M^2$$

$$U^{(\mathrm{M})}M^2(U^{(\mathrm{M})})^\dagger = U^{(\mathrm{D})}DM^2D^\dagger(U^{(\mathrm{D})})^\dagger = U^{(\mathrm{D})}M^2(U^{(\mathrm{D})})^\dagger$$

Majorana-Dirac confusion theorem

Majorana neutrinos and their electromagnetic properties

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(Received 29 January 1982)

Phys.Rev.D 26 (1982) 1662

$SU(2)_L \times U(1)$ to one-loop order. Lastly, we compare the electromagnetic interactions of a Majorana and a Dirac neutrino in the massless limit. We find that they conform to what seems to be a general rule: If all weak currents are left-handed, then the difference between a Majorana and a Dirac neutrino becomes invisible as the mass goes to zero. This occurs in spite of gross differences between these particles when the mass is not negligible.

The practical Majorana-Dirac confusion theorem

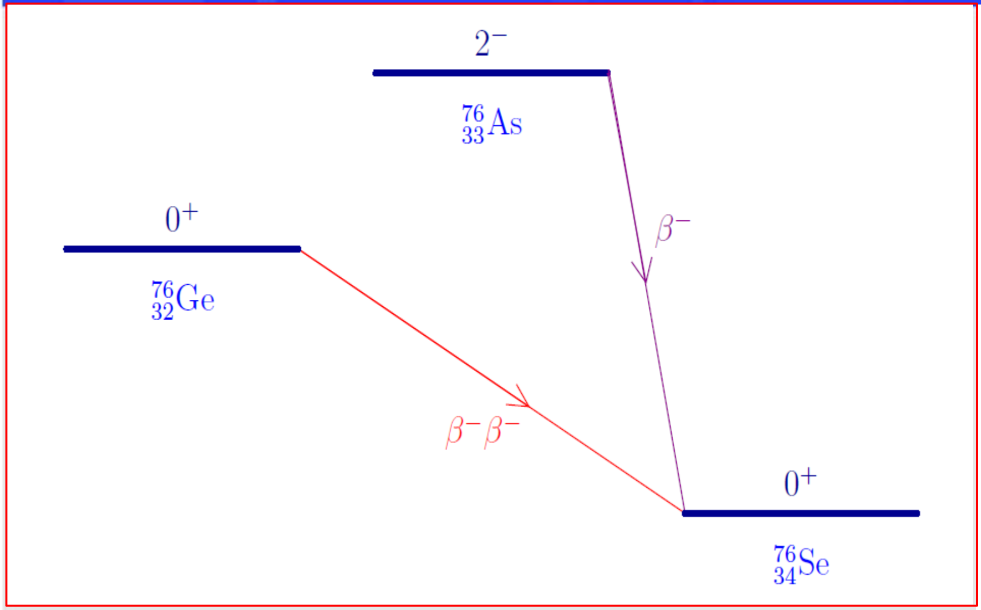
Practical Majorana-Dirac Confusion Theorem

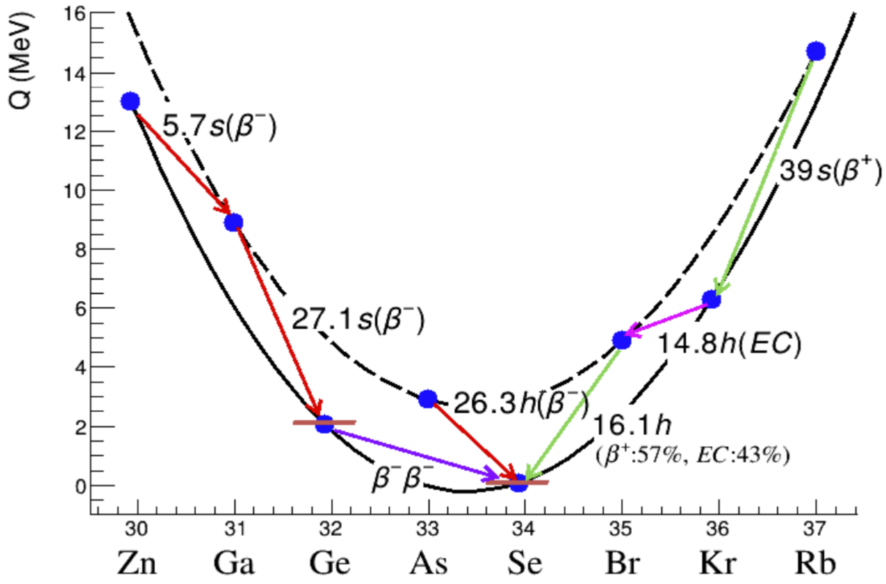
- **Only left-handed weak interactions exist**
- **Experiments with neutrinos of negative helicity and antineutrinos of positive helicity**
- **The Majorana Dirac difference ~ m^2_ν**

$$\boxed{|\nu_e\rangle \sim |L\rangle + \left(\frac{m}{E}\right)|R\rangle.}$$

- **Best Bet: $0\nu2\beta$-decay**

Neutrinoless Double-Beta Decay





$$M = Zm_p + Nm_n - E_{\mathrm{B}}(Z, N) \quad \leftarrow \quad \text{Binding Energy}$$

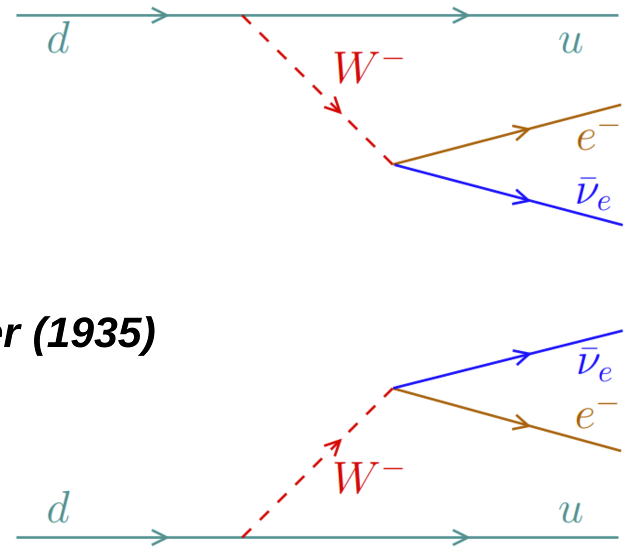
$$E_{\mathrm{B}}(Z, N) = a_{\mathrm{V}} A - a_{\mathrm{S}} A^{2/3} - a_{\mathrm{C}} \frac{Z(Z-1)}{A^{1/3}} - a_{\mathrm{A}} \frac{(N-Z)^2}{A} + \delta_{\mathrm{P}}(Z, N)$$

Pairing term due to spin-coupling:

$$\delta_{\mathrm{P}}(Z, N) = \begin{cases} a_{\mathrm{P}} A^{k_{\mathrm{P}}} & \text{if both } Z \text{ and } N \text{ are even } (A \text{ is even}) \\ -a_{\mathrm{P}} A^{k_{\mathrm{P}}} & \text{if both } Z \text{ and } N \text{ are odd } (A \text{ is even}) \\ 0 & \text{if } A \text{ is odd} \end{cases}$$

Two-Neutrino Double-β Decay: $\Delta L = 0$

$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$$



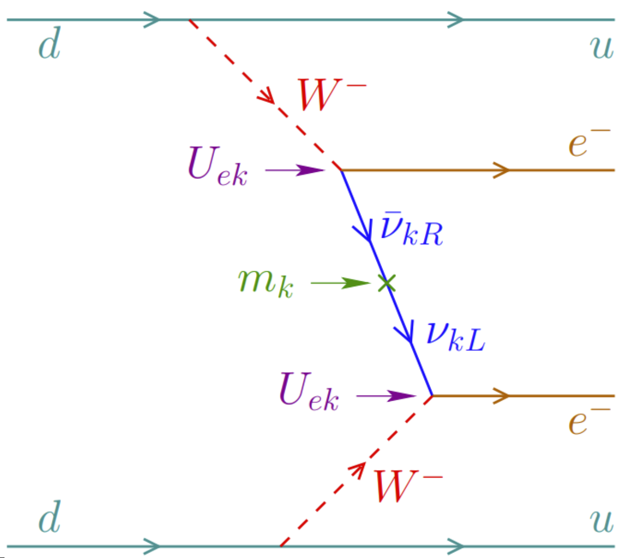
$$(T^{2\nu}_{1/2})^{-1} = G_{2\nu}\,|\mathcal{M}_{2\nu}|^2$$

Goeppert Mayer (1935)

second order weak interaction process in the Standard Model

Neutrinoless Double-β Decay: $\Delta L = 2$

$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^-$$



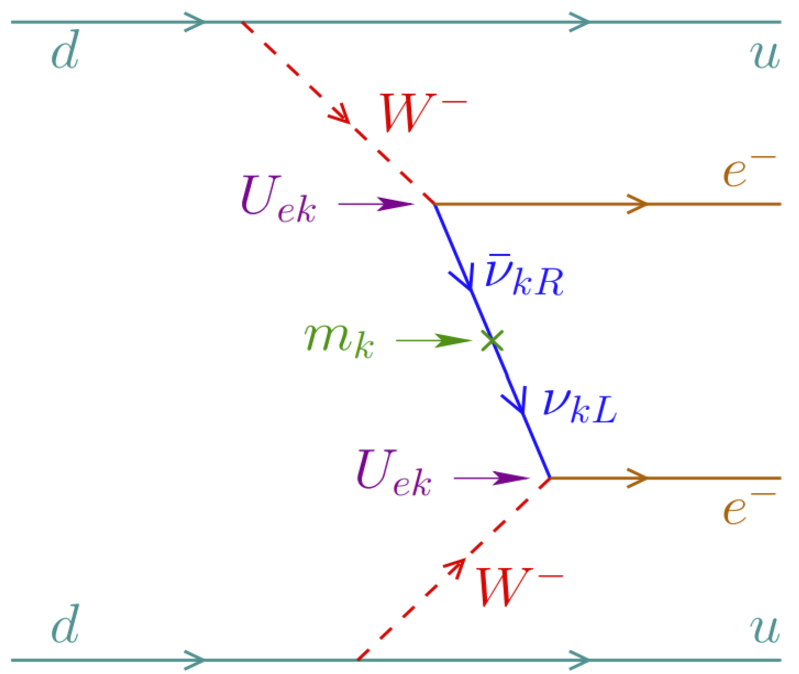
$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}\,|\mathcal{M}_{0\nu}|^2\,|m_{\beta\beta}|^2$$

Furry (1939)

effective Majorana mass $\quad |m_{\beta\beta}| = \left|\sum_k U_{ek}^2\, m_k\right|$

arXiv:2203.12169, 2203.12169, 1902.04097 etc.

The **0ν2β**-decay rate



- $\nu_k(x)\overline{\nu_j^c}(y)$ **gives a propagator only if ν and ν^c are the same field**

→ **Majorana neutrinos**

→ $\boxed{m_k > 0}$ needed!

→ **For light active neutrinos:**

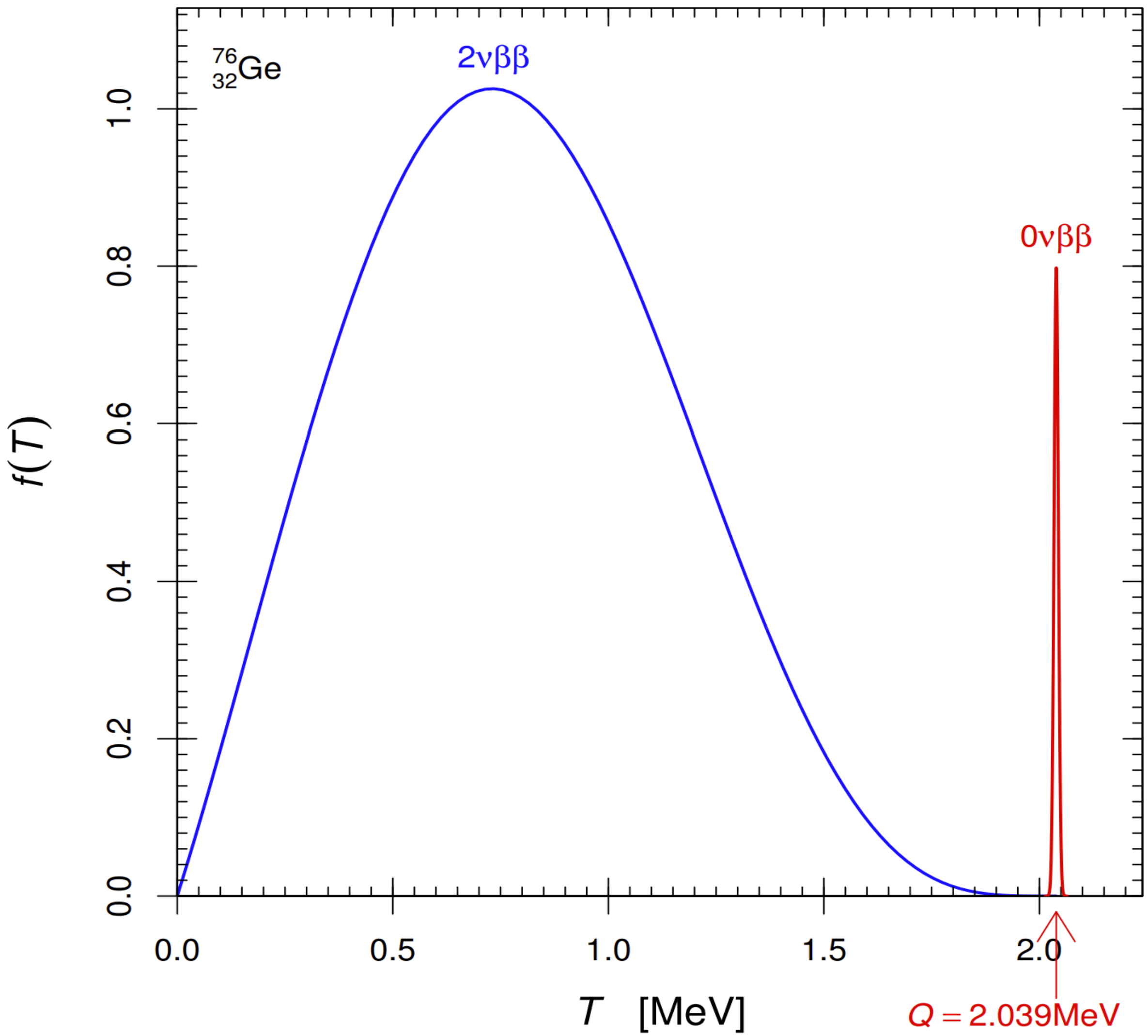
$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}\,|\mathcal{M}_{0\nu}|^2\,|m_{\beta\beta}|^2$$

Leptonic tensor in the $\beta\beta_{0\nu}$ amplitude:

$$A_{\mu\nu} = -\sum_{k,j} \overline{e}(x)\gamma_\mu\,(1-\gamma_5)\,U_{ek}\nu_k(x)\overline{\nu_j^c}(y)U_{ej}\,(1-\gamma_5)\,\gamma_\nu e^c(y)$$

$$A_{\mu\nu} \propto \sum_k U_{ek}^2 \int \frac{d^4p}{(2\pi)^4}\overline{e}(x)\gamma_\mu\,(1-\gamma_5)\,\frac{\not{p}+m_k}{p^2-m_k^2}\,(1-\gamma_5)\,\gamma_\nu e^c(y)\,e^{-ip\cdot(x-y)}$$

The 0ν2β-decay signature



Nuclear Matrix Elements

Light-ν Exchange in a Nucleus

$$[T^{0\nu}_{1/2}]^{-1} = G(Z,N)\,|M_{0\nu}|^2\, m^2_{\beta\beta}$$

Phase-space factor

Nuclear matrix element

"Traditional" part of matrix element:

$$\boxed{M_{0\nu} = M^{GT}_{0\nu} - \frac{g_V^2}{g_A^2} M^{F}_{0\nu} + \ldots} \quad \text{x } g_A{}^2$$

with

$$M^{GT}_{0\nu} = \langle F|\sum_{i,j} H(r_{ij})\, \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j\, \tau_i^+ \tau_j^+\ |I\rangle + \ldots$$

$$M^{F}_{0\nu} = \langle F\,|\sum_{i,j} H(r_{ij})\, \tau_i^+ \tau_j^+\ |I\rangle + \ldots$$

$$H(r) \approx \frac{2R}{\pi r}\int_0^\infty dq \frac{\sin qr}{q + \overline{E} - (E_i + E_f)/2} \quad \text{roughly} \propto 1/r$$

Corrections are from "forbidden" terms, weak nucleon form factors, many-body currents, other effects of high-energy physics that depend on framework.

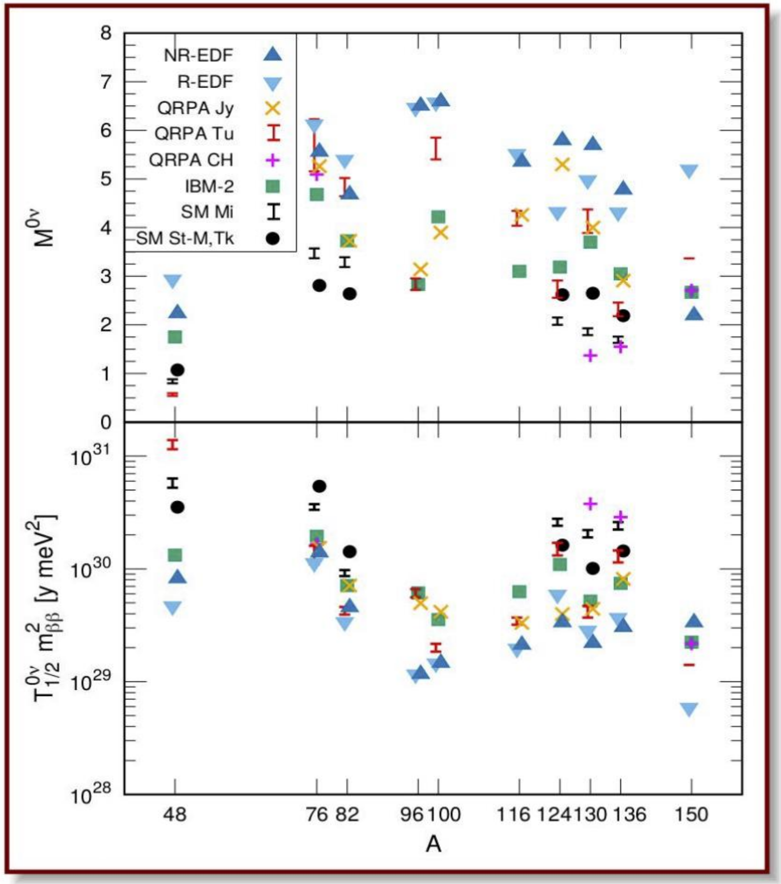
[Jonathan Engel @ Mini Workshop: Nuclear Theory of Neutrinoless Double-Beta Decay, 22 July 2020]

See also review, arXiv:1610.06548.

Nuclear Matrix Elements

Recent Values

Light-ν-Exchange Matrix Elements



Significant spread. And all the models may miss important physics.

Uncertainty hard to quantify.

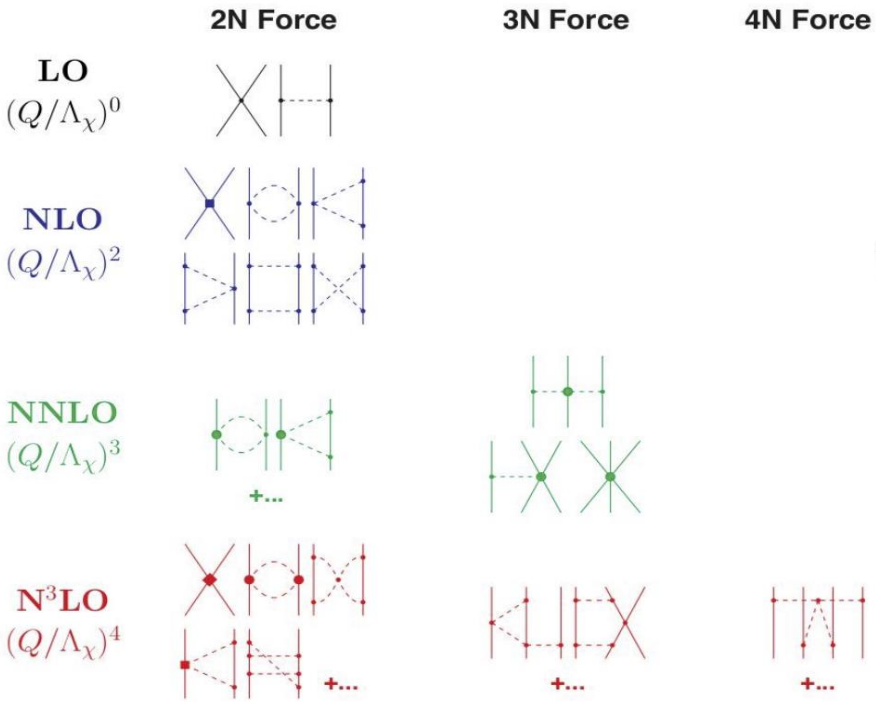
[Jonathan Engel @ Mini Workshop: Nuclear Theory of Neutrinoless Double-Beta Decay, 22 July 2020]

Nuclear Matrix Elements

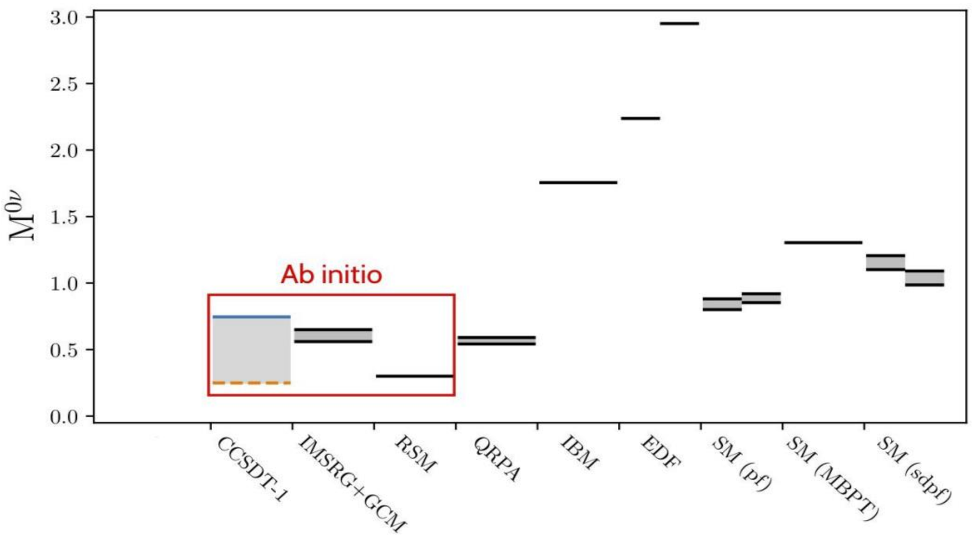
The Way Forward: Ab Initio Nuclear Theory

Starts with chiral effective field theory.

Nucleons, pions sufficient below chiral-symmetry breaking scale.



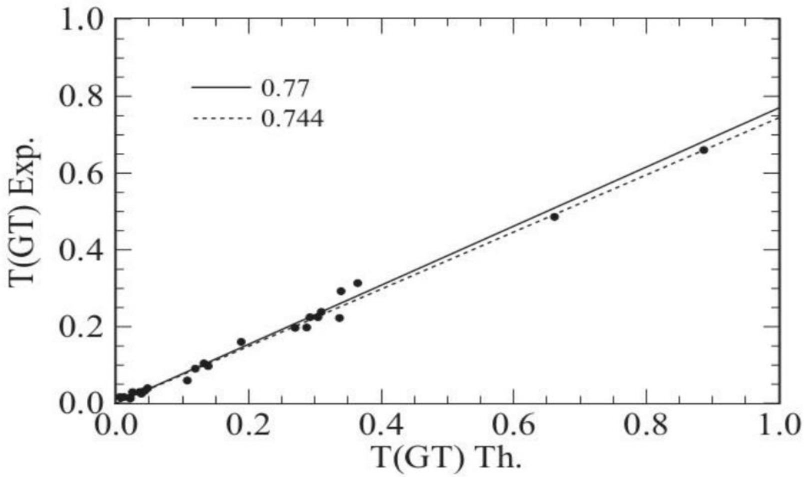
^{48}Ca: Ab-Inito $0\nu\beta\beta$ Matrix Elements vs. Older Ones



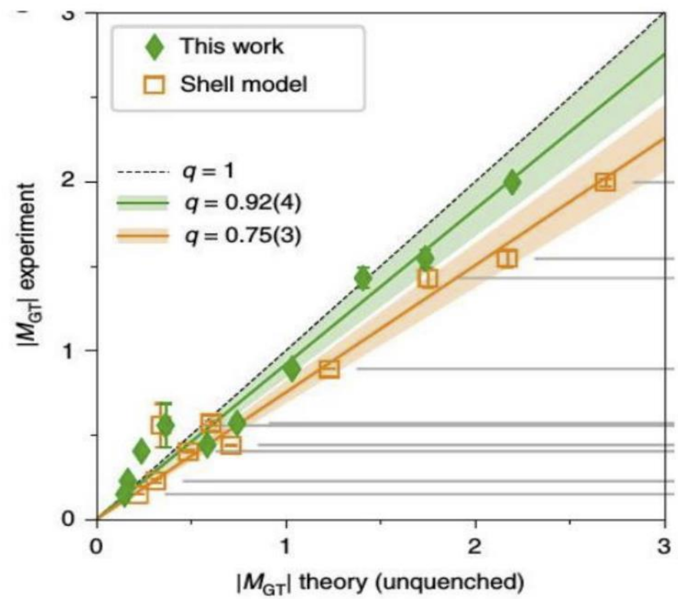
[Jonathan Engel @ Mini Workshop: Nuclear Theory of Neutrinoless Double-Beta Decay, 22 July 2020]

Nuclear Matrix Elements

β decays (e^- capture) challenge for nuclear theory



Martinez-Pinedo et al. PRC53 2602(1996)



Gysbers et al. Nature Phys. 15 428 (2019)

$$\langle F|\sum_i [g_A\,\boldsymbol{\sigma}_i\tau_i^-]^{\rm eff}\,|I\rangle\,,\quad [\boldsymbol{\sigma}_i\tau]^{\rm eff}\approx 0.7\boldsymbol{\sigma}_i\tau$$

Phenomenological models need $\boldsymbol{\sigma}_i\tau$ "quenching"

Ab initio calculations including meson-exchange currents do not need any "quenching"

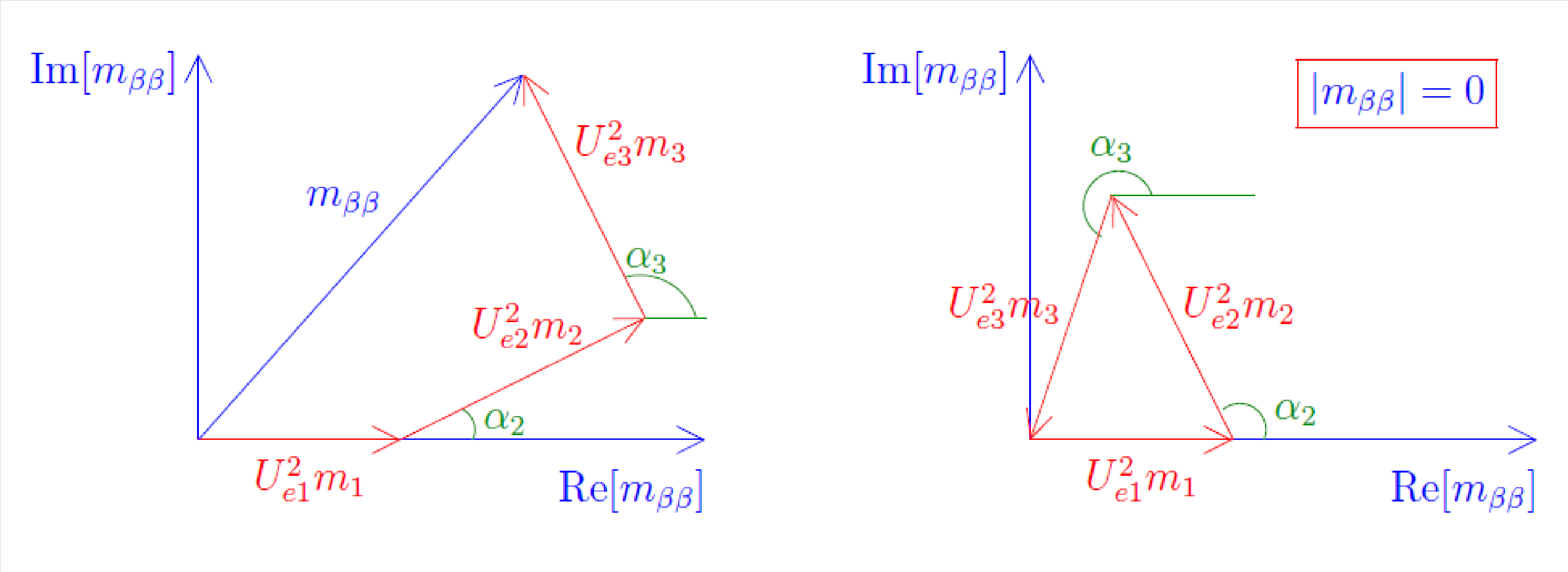
[Javier Menendez @ Mini Workshop: Nuclear Theory of Neutrinoless Double-Beta Decay, 22 July 2020]

Effective Majorana Neutrino Mass

$$m_{\beta\beta} = \sum_k U_{ek}^2 \, m_k$$

$$m_{\beta\beta} = |U_{e1}|^2 \, m_1 + |U_{e2}|^2 \, e^{i\alpha_2} \, m_2 + |U_{e3}|^2 \, e^{i\alpha_3} \, m_3$$

$$\alpha_2 = 2\lambda_2 \qquad \alpha_3 = 2\left(\lambda_3 - \delta_{13}\right)$$



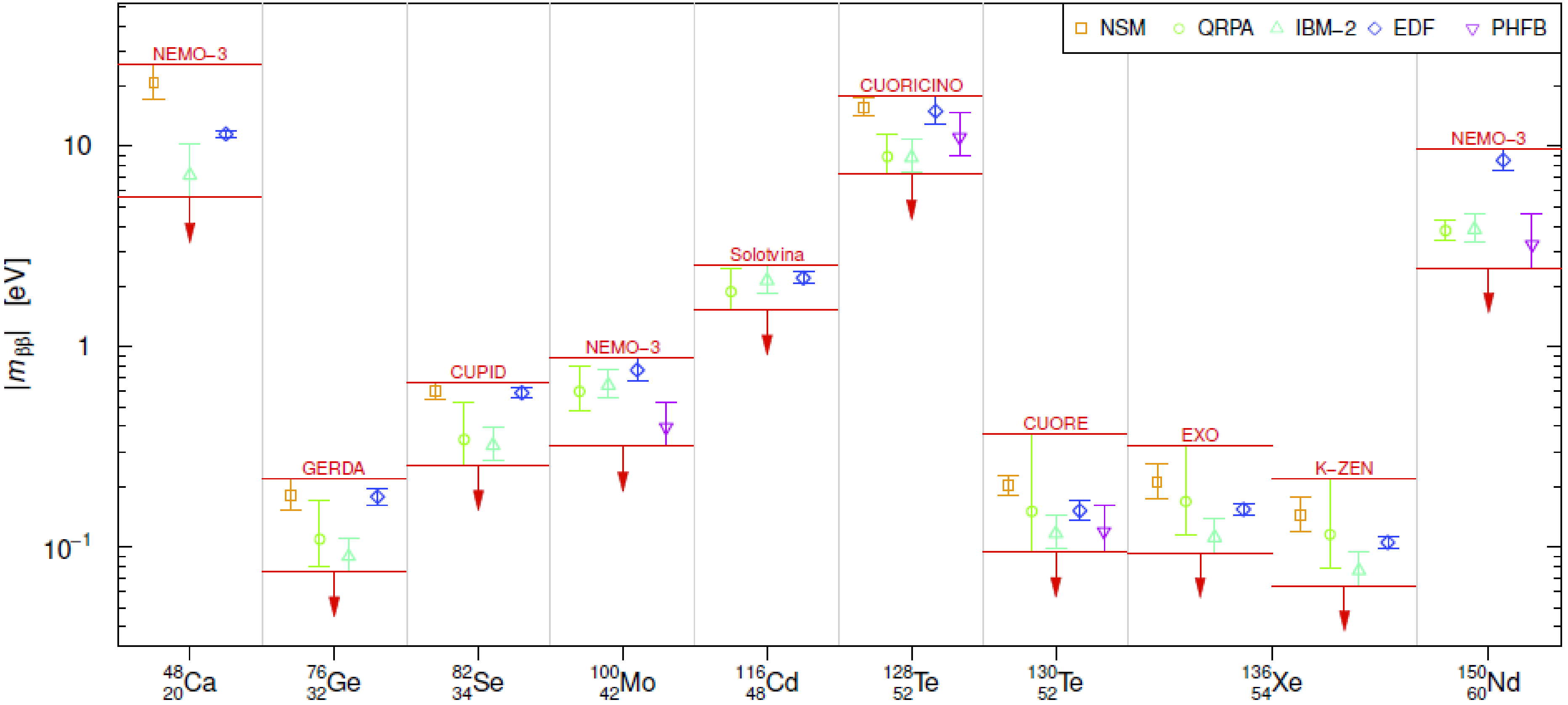
- **7 out of 9 parameters of light Majorana neutrinos !**
- **Neutrino oscillation and non-oscillation measurements contribute to the prediction of $m_{\beta\beta}$!**

Experimental Bounds (90 C.L.)

$\beta\beta^-$ decay	experiment	$T^{0\nu}_{1/2}$ [y]	$m_{\beta\beta}$ [eV]
${}^{48}_{20}\mathrm{Ca} \to {}^{48}_{22}\mathrm{Ti}$	ELEGANT-VI	$> 1.4 \times 10^{22}$	$< 6.6 - 31$
${}^{76}_{32}\mathrm{Ge} \to {}^{76}_{34}\mathrm{Se}$	Heidelberg-Moscow	$> 1.9 \times 10^{25}$	$< 0.23 - 0.67$
	IGEX	$> 1.6 \times 10^{25}$	$< 0.25 - 0.73$
	Majorana	$> 4.8 \times 10^{25}$	$< 0.20 - 0.43$
	GERDA	$> 8.0 \times 10^{25}$	$< 0.12 - 0.26$
${}^{82}_{34}\mathrm{Se} \to {}^{82}_{36}\mathrm{Kr}$	NEMO-3	$> 1.0 \times 10^{23}$	$< 1.8 - 4.7$
${}^{100}_{42}\mathrm{Mo} \to {}^{100}_{44}\mathrm{Ru}$	NEMO-3	$> 2.1 \times 10^{25}$	$< 0.32 - 0.88$
${}^{116}_{48}\mathrm{Cd} \to {}^{116}_{50}\mathrm{Sn}$	Solotvina	$> 1.7 \times 10^{23}$	$< 1.5 - 2.5$
${}^{128}_{52}\mathrm{Te} \to {}^{128}_{54}\mathrm{Xe}$	CUORICINO	$> 1.1 \times 10^{23}$	$< 7.2 - 18$
${}^{130}_{52}\mathrm{Te} \to {}^{130}_{54}\mathrm{Xe}$	CUORE	$> 1.5 \times 10^{25}$	$< 0.11 - 0.52$
${}^{136}_{54}\mathrm{Xe} \to {}^{136}_{56}\mathrm{Ba}$	EXO	$> 1.1 \times 10^{25}$	$< 0.17 - 0.49$
	KamLAND-Zen	$> 1.1 \times 10^{26}$	$< 0.06 - 0.16$
${}^{150}_{60}\mathrm{Nd} \to {}^{150}_{62}\mathrm{Sm}$	NEMO-3	$> 2.1 \times 10^{25}$	$< 2.6 - 10$

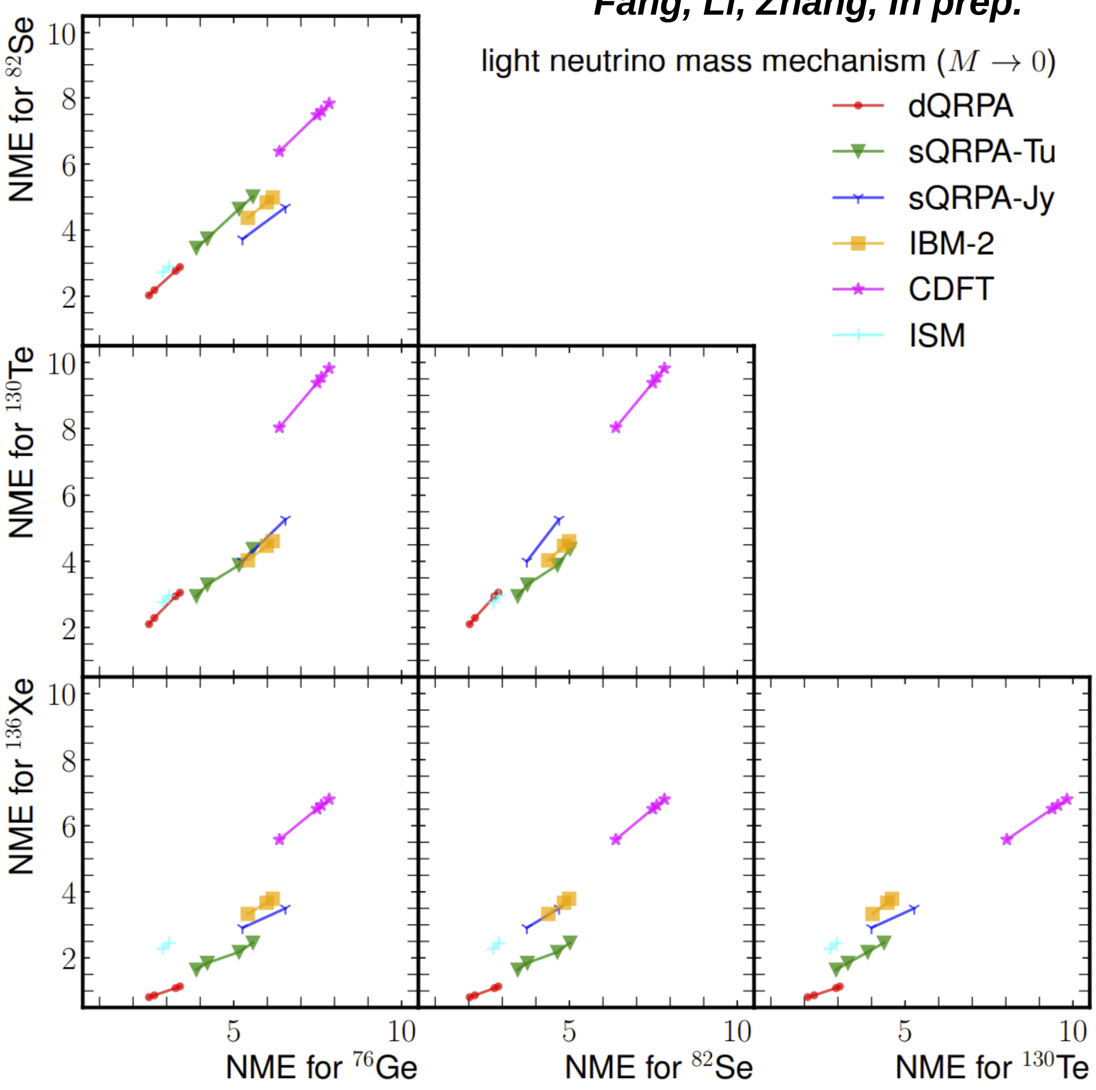
Effective neutrino mass from $0\nu2\beta$-decay

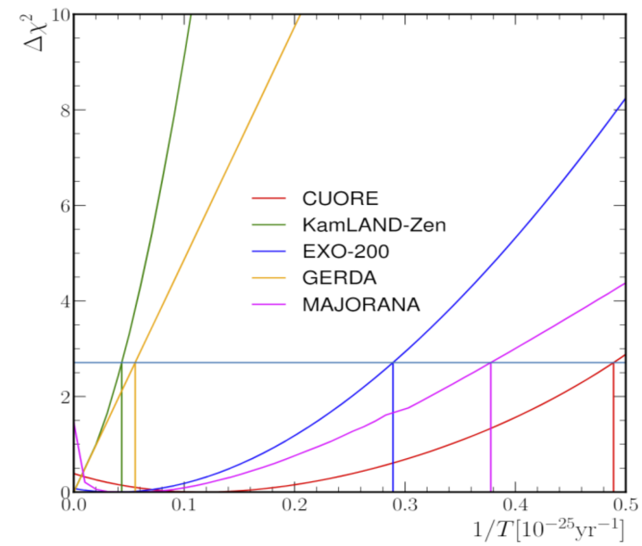
$0\nu2\beta$-decay: effective neutrino mass limit as in 2021

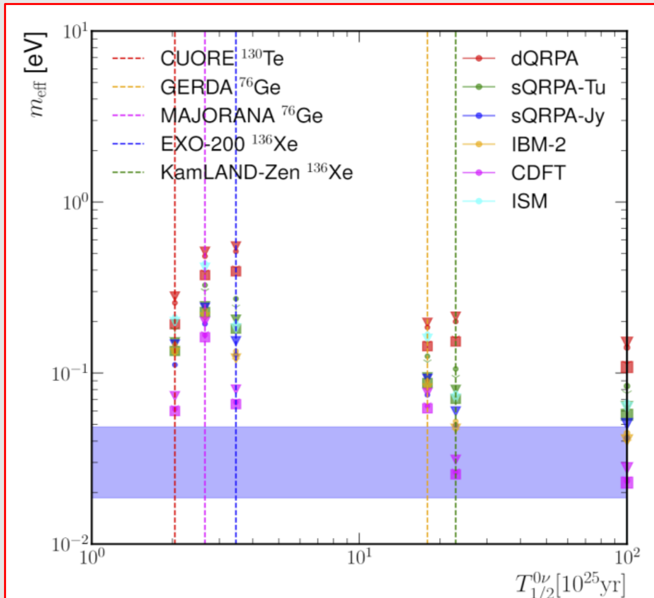


Light ν mechanism: current limits

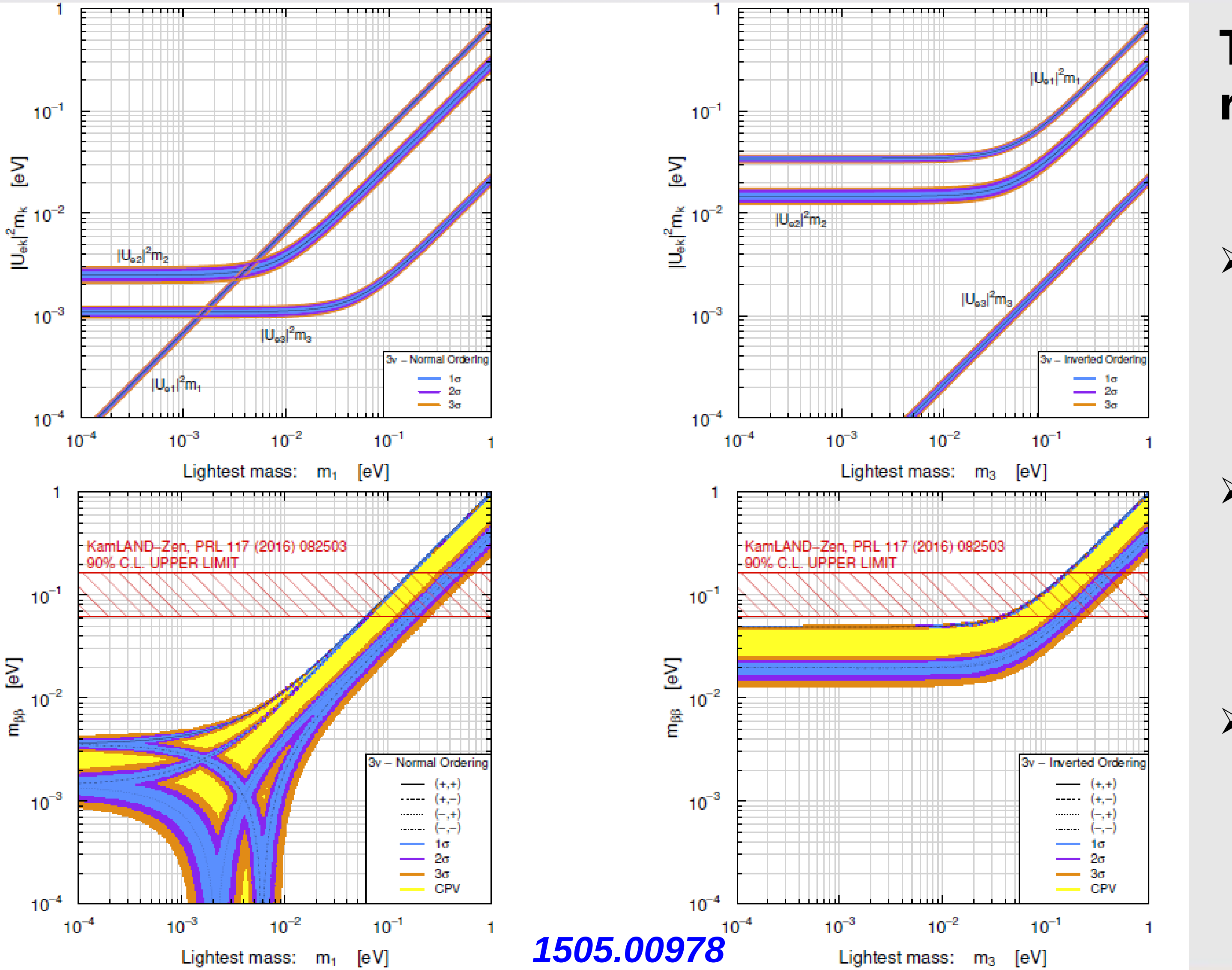
Fang, Li, Zhang, In prep.







$m_{\beta\beta}$: Decomposition



1505.00978

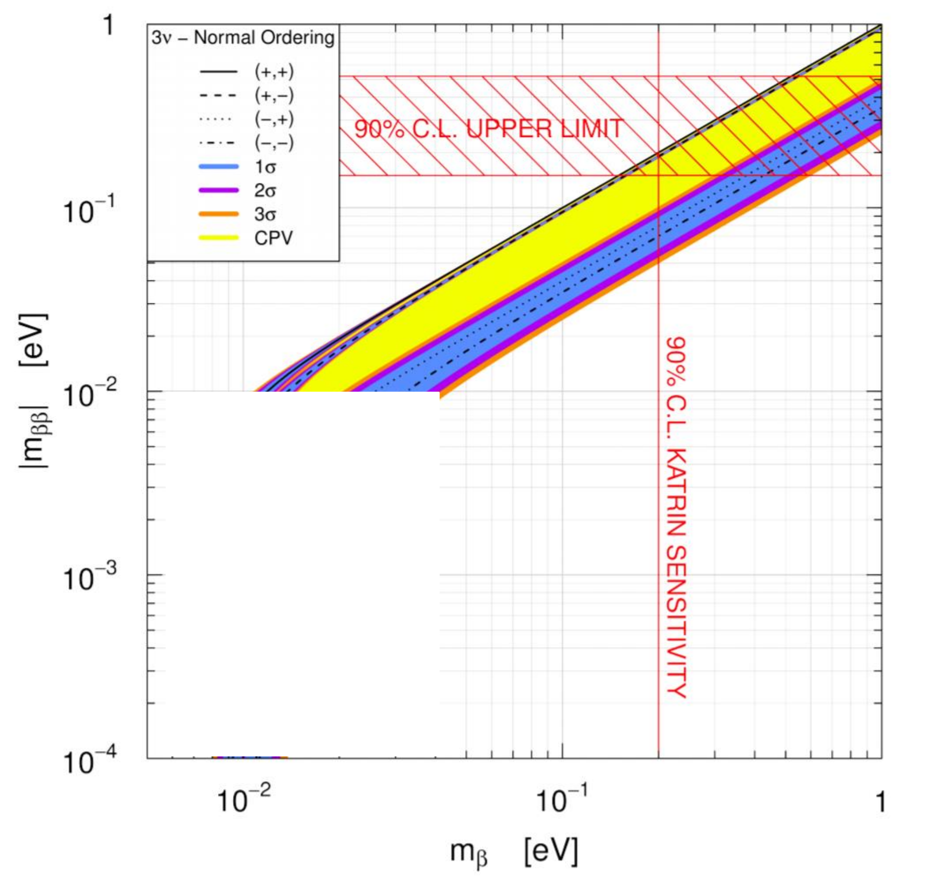
Three different regions:

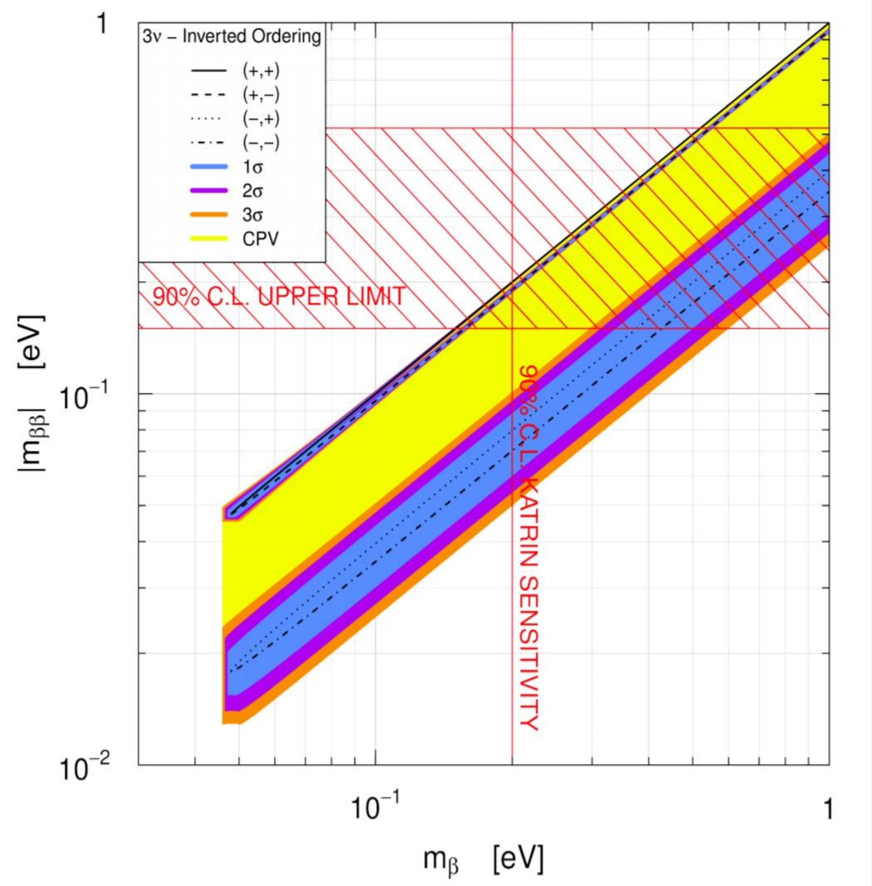
- **QD:** $m_{1/3}$>10 meV
- **Hierarchical:** $m_{1/3}$<1 meV
- **Cancelation:** [1, 10] meV

I: Quasi-Degenerate region

$$|m_{\beta\beta}| \simeq m_\nu \sqrt{1 - s^2_{2\vartheta_{12}} s^2_{\alpha_2}}$$

- **Extraction of the CP phase by comparing with beta decay or cosmology probe**



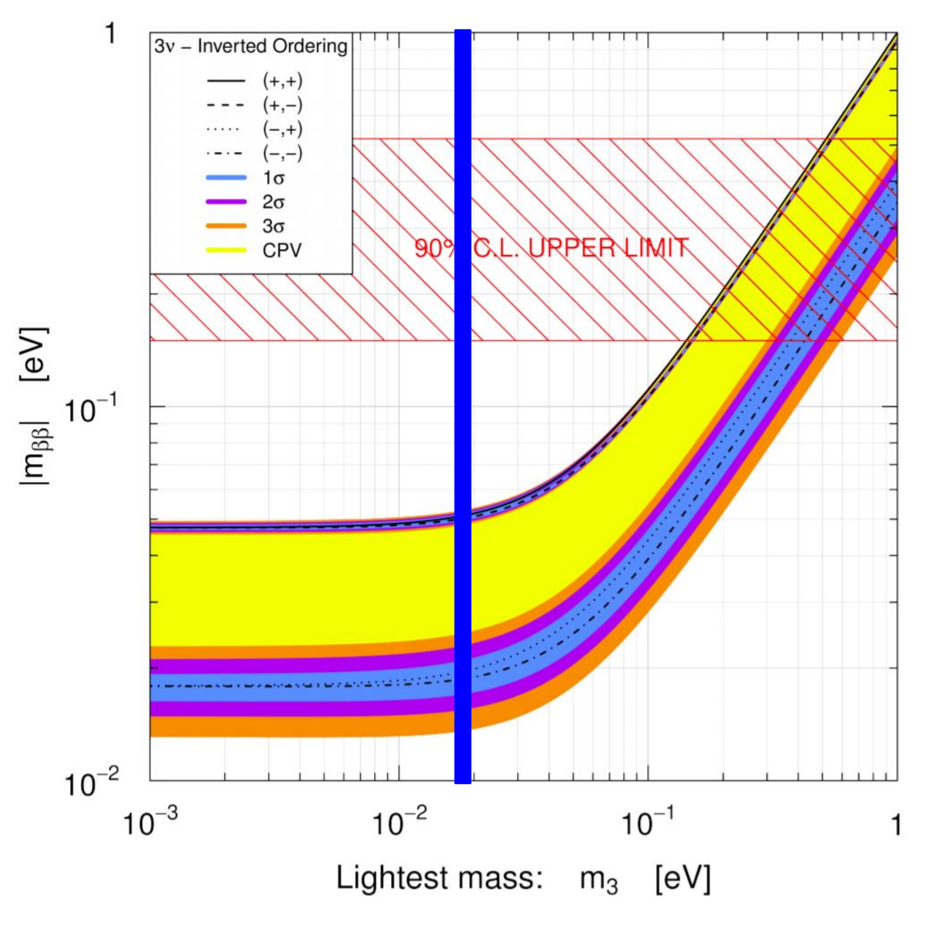


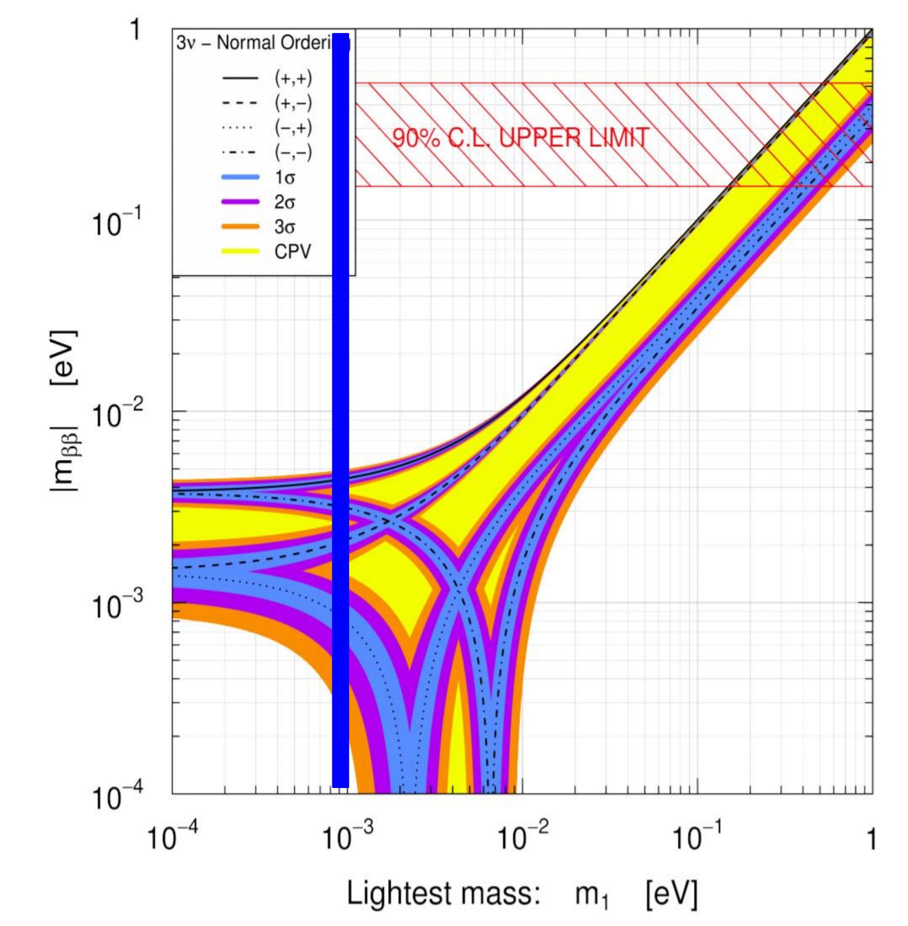
II: Hierarchical Region

- **Independent of the absolute neutrino masses (NO & IO)**

$$|m_{\beta\beta}| \simeq \sqrt{\Delta m^2_{\rm A}(1 - s^2_{2\vartheta_{12}} s^2_{\alpha_2})}$$

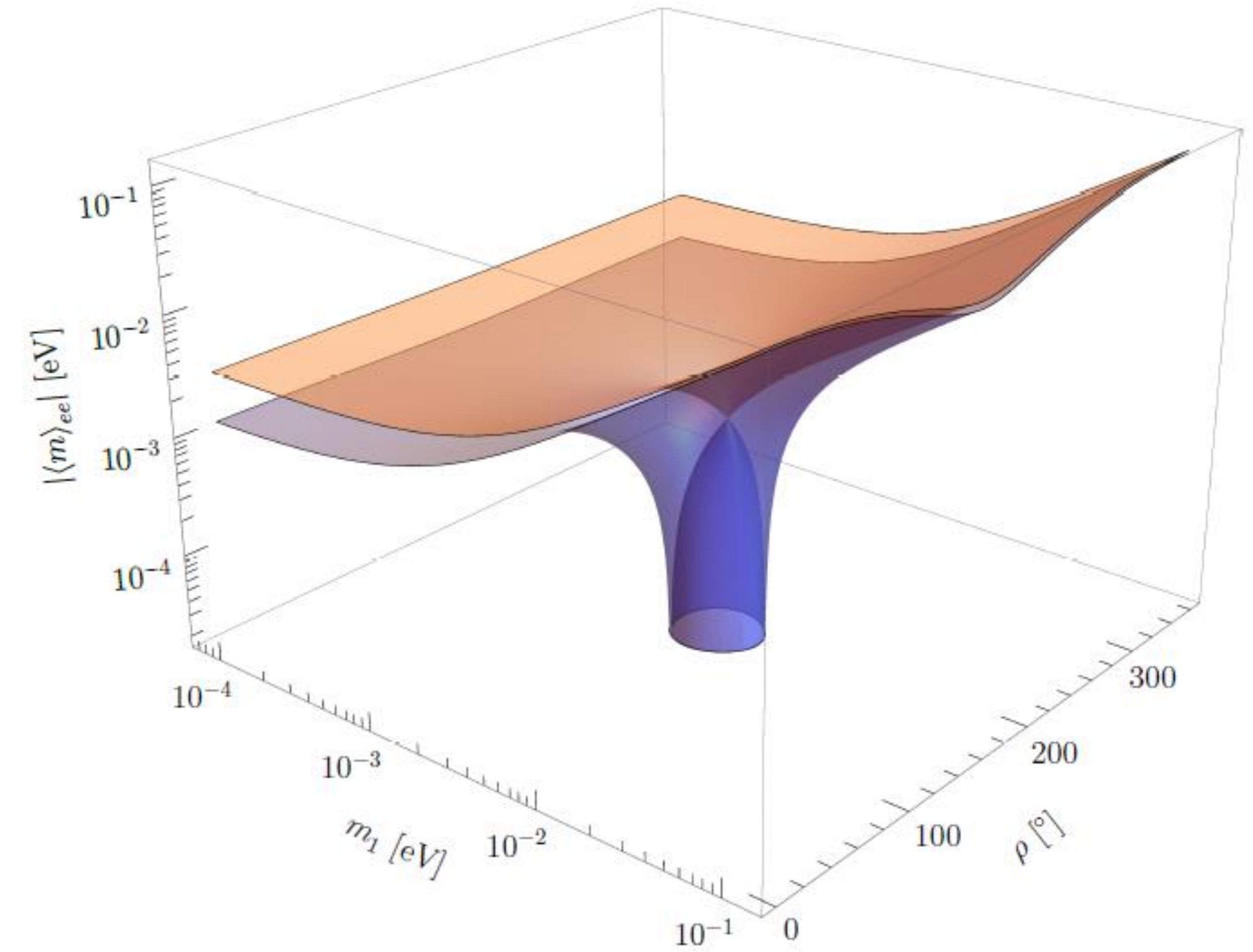
$$|m_{\beta\beta}| \simeq |s^2_{12}\sqrt{\Delta m^2_{\rm S}} + e^{i\alpha} s^2_{13}\sqrt{\Delta m^2_{\rm A}}|$$



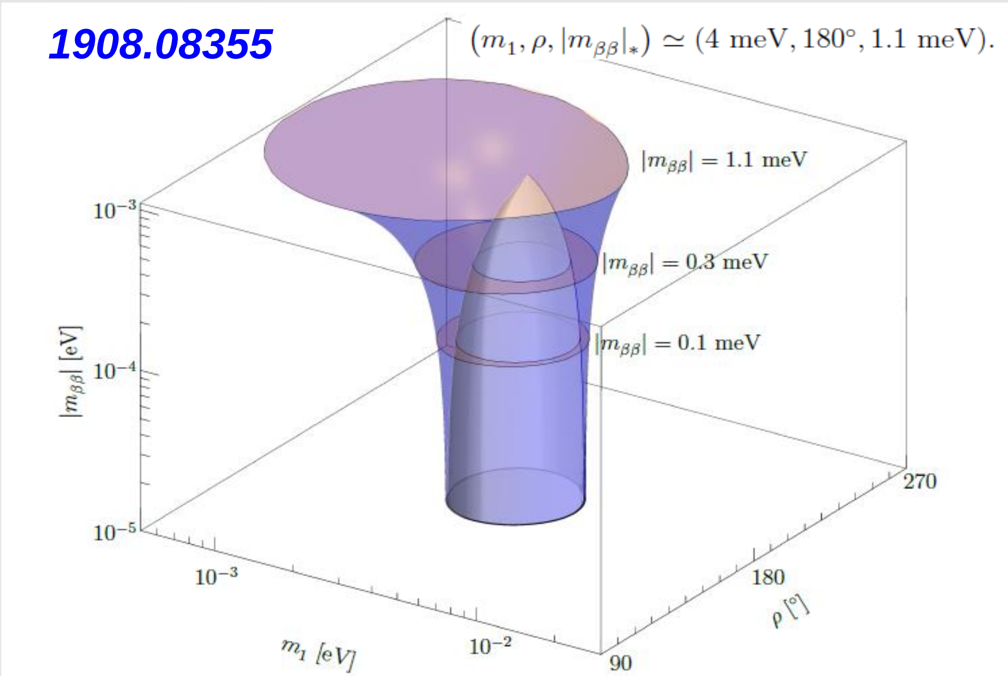


III: Cancelation region

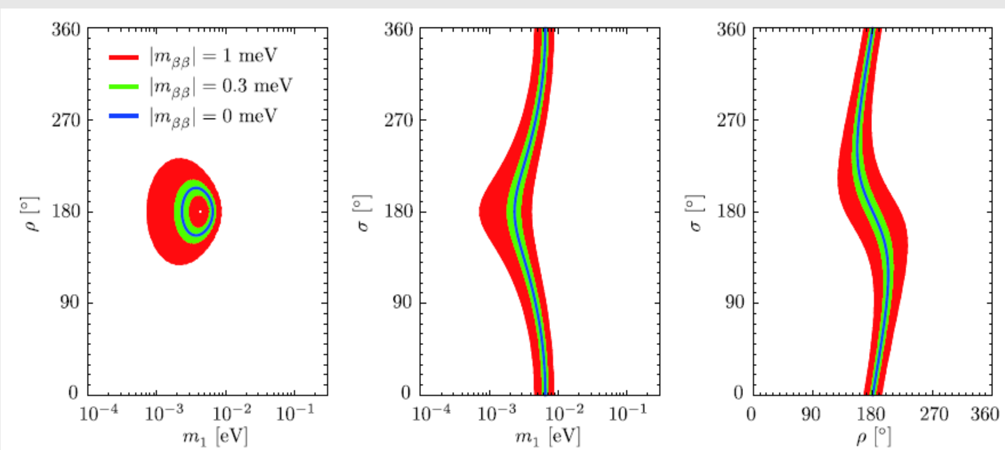
Xing & Zhao, 1612.08538: **The critical threshold point is just ~1 meV !**

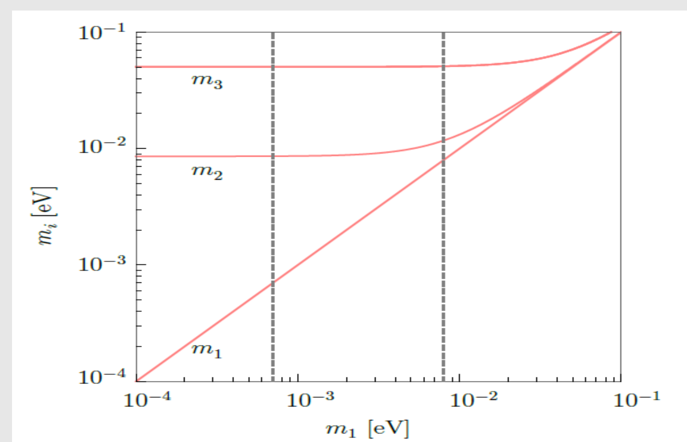


Fine structure: towards the meV goal

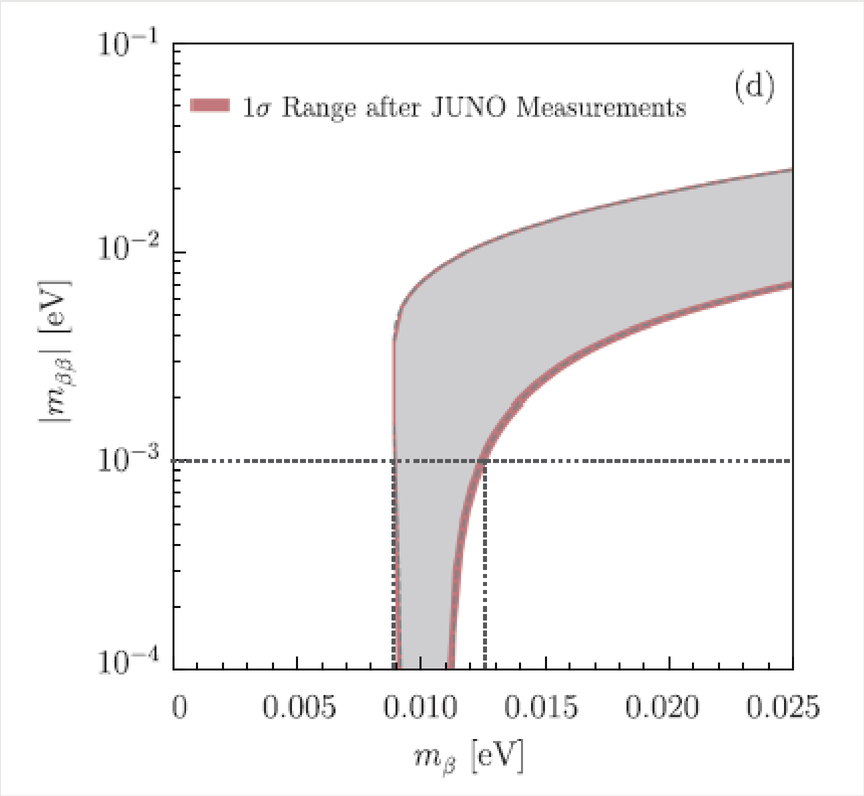


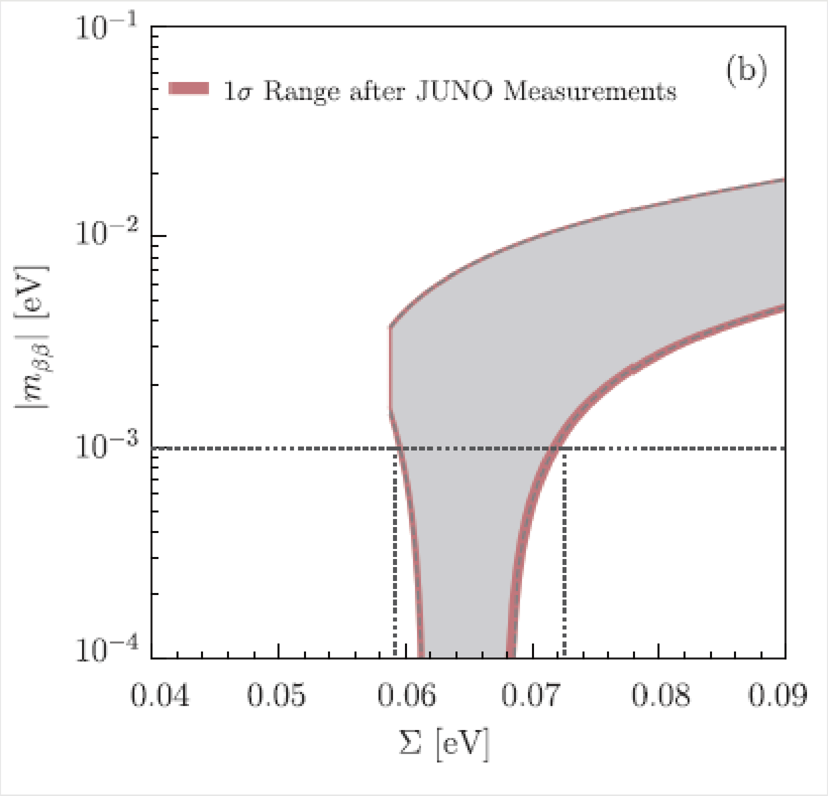
- The critical threshold point could serve as the **ultimate goal** for $0\nu2\beta$ searches.
- The possibility of **falling into the well** is very small.
- Have **unique (otherwise impossible) constraints** on non-oscillation parameters





Implications for beta-decay and cosmology

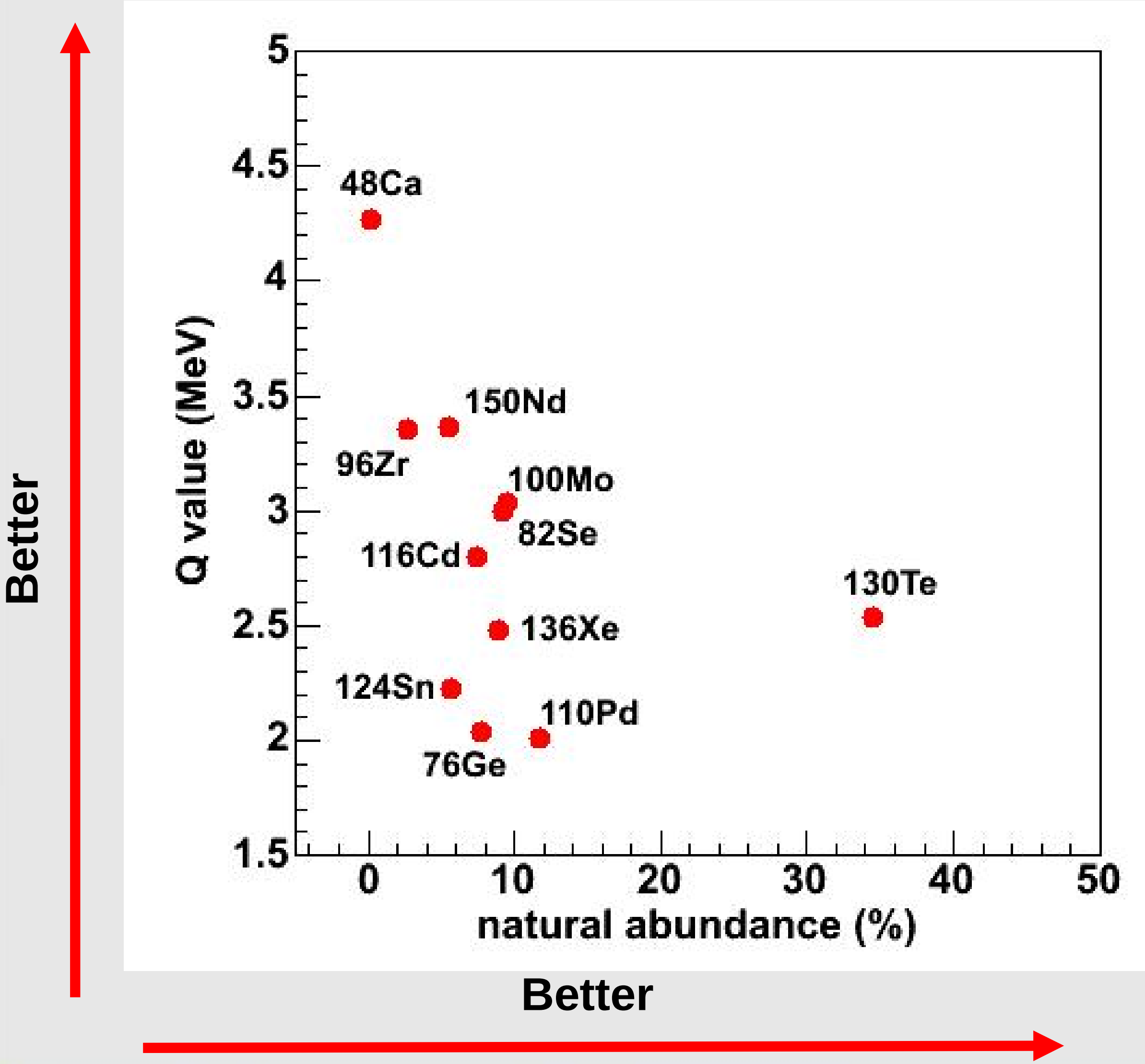




$$8.9\ \text{meV} \leq m_\beta \leq 12.6\ \text{meV}\ , \quad 59.2\ \text{meV} \leq \Sigma \leq 72.6\ \text{meV}$$

- **(much) better than the projected sensitivities of future beta decay and cosmology probes!**

Experimental Design



Sensitivity:

$$(T^{0\nu}_{1/2})^{-1} \propto \begin{cases} a\,M\,\varepsilon\,t \\ a\,\varepsilon\sqrt{\dfrac{M\,t}{B\,\Delta E}} \end{cases}$$

Background free
Background dominate

- **A factor of 2 on the mass needs factor of 16 in M × t × B × ΔE**
- **Very challenging improvement for ton-scale experiments or even more**

A brief history

- 1935 Mayer proposed double beta decay
- 1937 Majorana fermion proposed
- 1939 Furry proposed neutrinoless double beta decay
- 1948 – first counter experiment (Geiger counters, $T_{1/2}(0\nu) > 3 \cdot 10^{15}$ y)
- 1950 – first evidence for $2\beta2\nu$ decay of ^{130}Te in first geochemical experiment: $T_{1/2} \sim 1.4 \cdot 10^{21}$ y
- 1950-1965 – a few tens experiments with sensitivity $\sim 10^{16}$-10^{19} y
- $T_{1/2}(^{76}Ge) > 5 \cdot 10^{21}$ y; Ge(Li) detector, 1973 (E. Fiorini et al.)
- $T_{1/2}(^{48}Ca) > 2 \cdot 10^{21}$ y; streamer chamber + magnetic field + plastic scint., 1970 (C. Wu et al.)
- $T_{1/2}(^{82}Se) > 3.1 \cdot 10^{21}$ y; streamer chamber + magnetic field + plastic scint., 1975 (C. Wu et al.)
- 1987 first detection of evidence for $2\beta2\nu$ decay ^{82}Se

Beijing experiment

Physics Letters B 265 (1991) 53–56
North-Holland

PHYSICS LETTERS B

A search for neutrinoless double β decay of ^{48}Ca ☆

Ke You [a], Yucan Zhu [a], Junguang Lu [a], Hanseng Sun [a], Weihua Tian [a], Wenheng Zhao [a], Zhipeng Zheng [a,b], Minghan Ye [a,b], Chengrui Ching [b,c], Tsohsiu Ho [b,c], Fengzhu Cui [d], Changjiang Yu [d] and Guojing Jiang [d]

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Received 10 December 1990; revised manuscript received 5 June 1991

A search for the neutrinoless double β decay of ^{48}Ca is carried out in a coal mine near Beijing. Large scintillation crystals of natural CaF_2 were used as both detector and β source. Results obtained after a total of 7588.5 h of data taking give 9.5×10^{21} yr (76% confidence level) as the lower limit of the half-life of neutrinoless double β decay of ^{48}Ca.

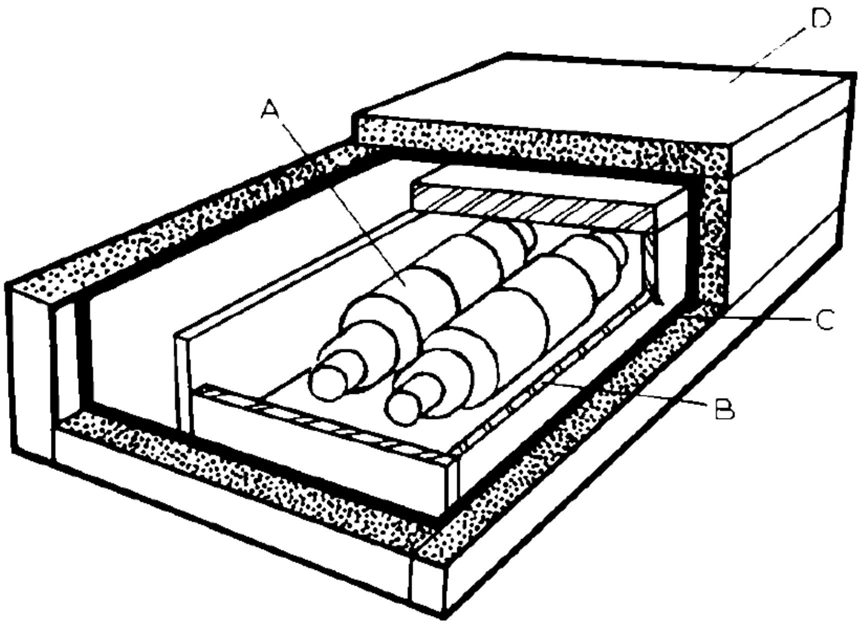
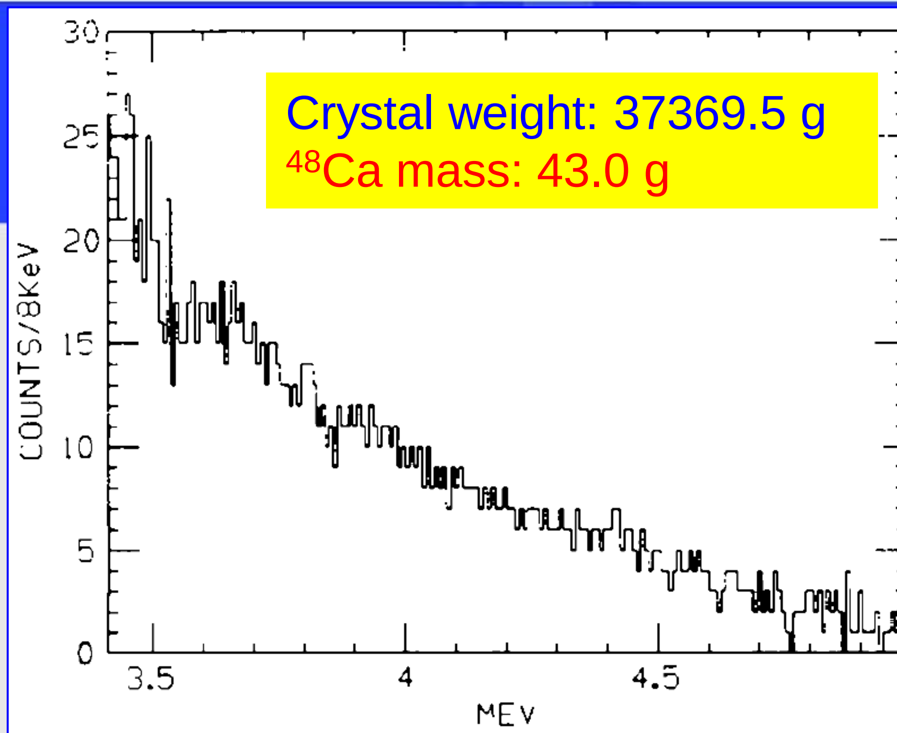


Fig. 1. Schematic drawing of detector assembly. A: CaF_2 crystal, B: plastic scintillator, C: steel shielding, D: lead shielding.



Crystal weight: 37369.5 g

^{48}Ca mass: 43.0 g

Fig. 3. Energy spectrum near 4.27 MeV underground.

$$\left.\begin{array}{ll} T_{1/2} \geq 1.4 \cdot 10^{22} & 95\% \ \ c.l. \\ \text{or} \ \ T \quad \geq 2.0 \cdot 10^{22} & 68\% \ \ c.l. \end{array}\right\} \quad (3)$$

ICHEP 90, proceedings

Table 1.

Authors	Goldhaber[4]	C.S.Wu[5]	of this paper
Quantity of ^{48}Ca	11.4 g	10.6 g	43.0 g
Data taking hours	689	1150	7588.5
Detector	$CaF_2(Eu)$	streamer Chamber	CaF_2
$T_{1/2}(y)$	$\geq 2 \times 10^{20}$	$\geq 2 \times 10^{21}$	$\geq 1.4 \times 10^{22}$

Phys. Lett. B 265 (1991) 53-56

Table 2

The light neutrino mass $\langle m_\nu \rangle$ and the right handed current mixing parameter η.

Experiment	Life-time [yr]	$\langle m_\nu \rangle (\eta=0)$ [eV]	$\eta(\langle m_\nu \rangle=0)$
Goldhaber	2×10^{20}	$\leqslant 59.5$	$\leqslant 5.09 \times 10^{-5}$
Wu	2×10^{21}	$\leqslant 18.8$	$\leqslant 1.61 \times 10^{-5}$
this experiment	9.5×10^{21}	$\leqslant 8.3$	$\leqslant 0.74 \times 10^{-5}$

38

Latest ^{48}Ca

Table I: Present results on neutrinoless DBD

Ettore Fiorini, Nuclear Physics B (Proc. Suppl.) 168 (2007) 11–16

Nucleus	Experiment	%	$Q_{\beta\beta}$	Enrich (%)	Technique	$T_{0\nu}$ (y)	$<m_\nu>$
^{48}Ca	Elegant IV	0.19	4271		scintillator	$>1.4\times10^{22}$	7-45
^{76}Ge	Heidelberg-Moscow	7.8	2039	87	ionization	$>1.9\times10^{25}$	0.12 - 1
^{76}Ge	IGEX	7.8	2039	87	Ionization	$>1.6\times10^{25}$	0.14 – 1.2
[illegible]	[illegible]	[illegible]	[illegible]	87	ionization	1.2×10^{25}	0.44
[illegible]	[illegible]	[illegible]	[illegible]	97	tracking	$>1.x10^{23}$	1.8-4.9
[illegible]	[illegible]	[illegible]	[illegible]	95-99	tracking	$>4.6\times10^{23}$	0.7-2.8
[illegible]	[illegible]	[illegible]	[illegible]	83	scintillator	$>1.7\times10^{23}$	1.7 - ?

Search for neutrino-less double beta decay of ^{48}Ca by CaF_2 scintillator

I. Ogawa [a,*], R. Hazama [a], H. Miyawaki [a], S. Shiomi [a], N. Suzuki [a], Y. Ishikawa [a], G. Kunitomi [a], Y. Tanaka [a], M. Itamura [a], K. Matsuoka [a], S. Ajimura [a], T. Kishimoto [a], H. Ejiri [b], N. Kudomi [b], K. Kume [b], H. Ohsumi [c], K. Fushimi [d]

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[b] Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan
[c] Faculty of Culture and Education, Saga University, Honjo, Saga 840-8502, Japan
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Received 24 March 2003; received in revised form 21 October 2003; accepted 27 October 2003

Nuclear Physics A 730 (2004) 215–22

Abstract

A CaF_2 scintillation detector system (ELEGANT VI) has been operating at Oto Cosmo Observatory to study double beta decays of ^{48}Ca. No events were observed around the Q-value energy region after the analysis of 4.23 kg yr data. To derive the lower limit for the half-life of the neutrino-less double beta decay of ^{48}Ca, the expected number of background events in that energy region was estimated by a Monte Carlo simulation using the measured activities of ^{214}Bi and ^{220}Rn inside CaF_2 crystals. A new lower limit is obtained to be 1.4×10^{22} yr at the 90% C.L. An experimental sensitivity is 5.9×10^{21} yr at the 90% C.L.

The most stringent lower limit for the half-life of 0νDBD ($T^{0\nu}_{1/2}$) of ^{48}Ca was obtained by Beijing group [6] using 37 kg of CaF_2 scintillation crystals. They derived the limit of 9.5×10^{21} yr at the 76% C.L. from the statistical error of background (365 events in signal window). For the 2νDBD of ^{48}Ca, there are two experiments that have measured the half-life with $(4.3^{+2.4}_{-1.1}[\mathrm{stat}]\pm1.4[\mathrm{syst}])\times10^{19}$ yr [7] and $(4.2^{+3.3}_{-1.3})\times10^{19}$ yr [8], respectively. The lower limits of DBD to the excited states of ^{48}Ti and single β decay to ^{48}Sc have been obtained to be around 10^{20} yr by the experiment [9].

An active and competitive community (2010s-2020s)

Tracking Detector

^{136}Xe

supernemo collaboration

Feature: Topological information
Challenge: very large size

^{82}Se (^{130}Te, ^{116}Cd, ^{48}Ca, ^{96}Zr, ^{150}Nd, ^{100}Mo)

^{136}Xe Zero neutrino double beta decay search KamLAND-Zen

^{130}Te SNO+

Feature: existing large clean detector; self-shielding
Challenge: 2νββ background, internal purity

Liquid Scintillator

^{76}Ge GERDA

^{130}Te CUORE

LEGEND

Crystals

Feature: excellent energy resolution
Challenge: very large size; segmented

Enriched Xenon Observatory for double beta decay

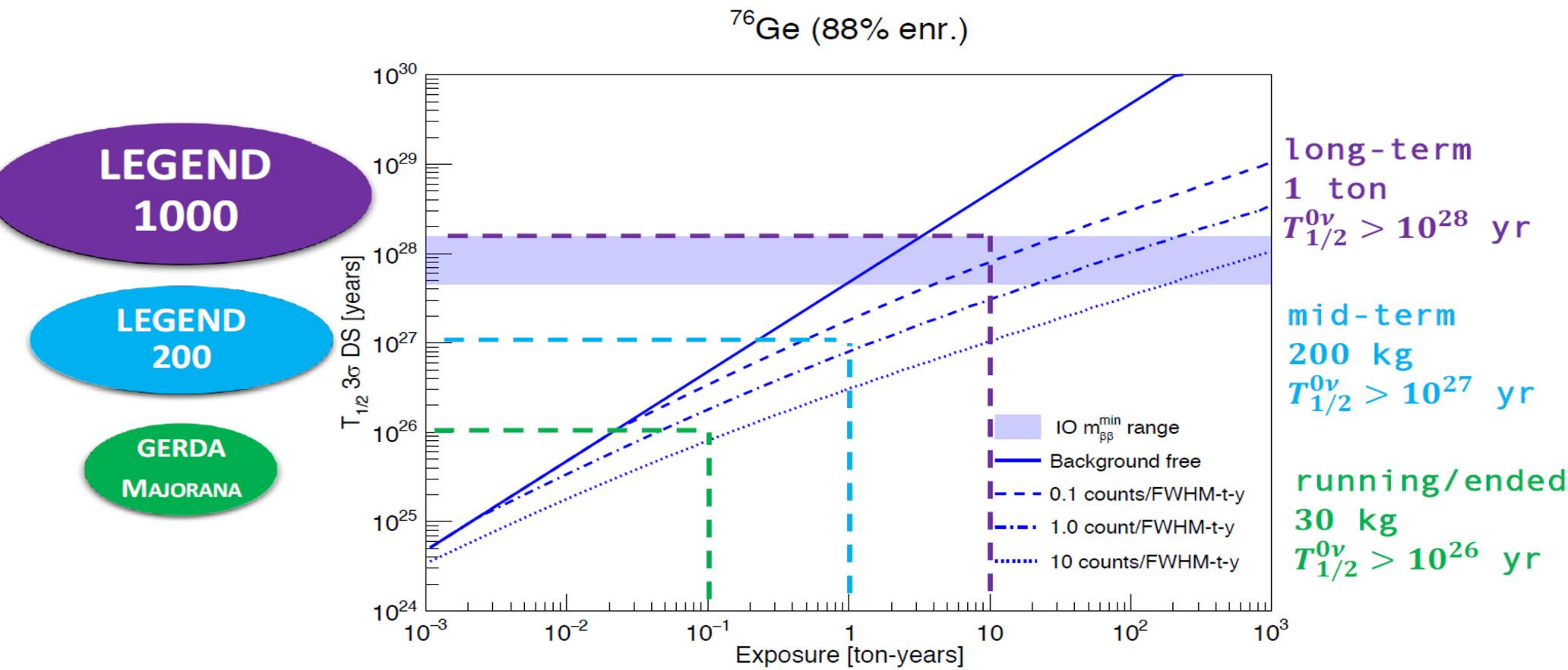
^{136}Xe

Feature: homogeneous; decent energy resolution; 3D toponology
Challenge: 2νββ background, internal purity

Liquid TPC

CUPID ($Zn^{82}Se$, $Li_2{}^{100}MoO_4$, TeO_2), AMoRE (^{100}Mo), CANDLES (^{48}Ca), ZICOS (^{96}Zr), AXEL (^{136}Xe), DCBA (^{100}Mo/ ^{150}Nd), COBRA (CdZnTe), …

Ge Roadmap

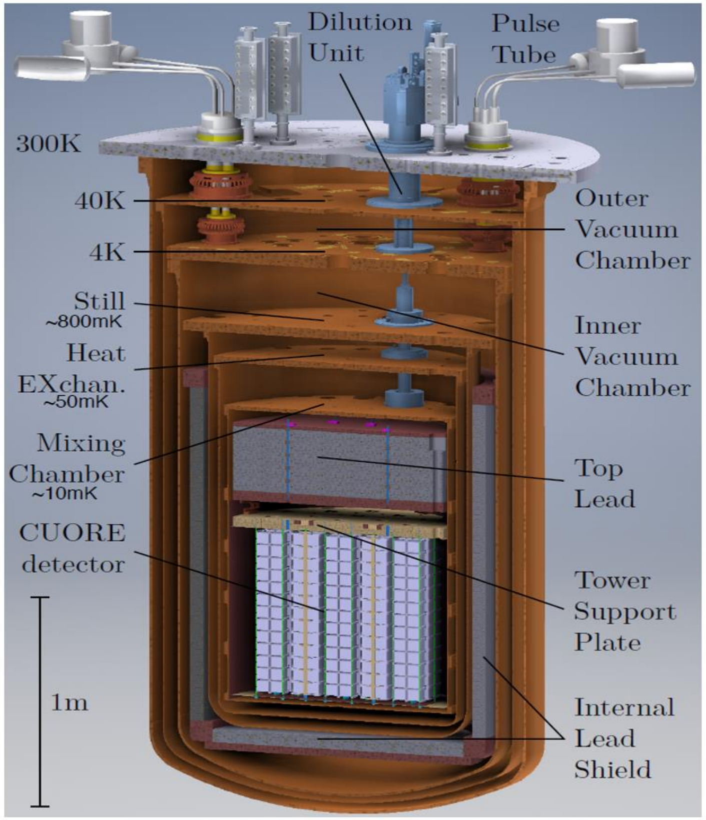


Yoann KERMAIDIC @ Neutrino2020

^{100}Mo

CUORE： > 3.2 x 10^{25} yrs (90% C.L.)

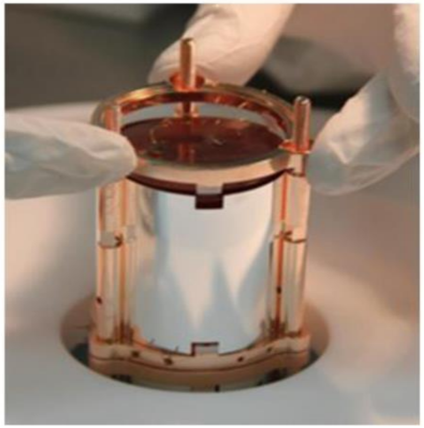
- Enriched to >95% in ^{100}Mo
- ^{100}Mo Q-value: 3034 keV



CUPID preCDR

https://arxiv.org/abs/1907.09376

Parameter	CUPID Baseline
Crystal	$Li_2{}^{100}MoO_4$
Detector mass (kg)	472
^{100}Mo mass (kg)	253
Energy resolution FWHM (keV)	5
Background index (counts/(keV·kg·yr))	10^{-4}
Containment efficiency	79%
Selection efficiency	90%
Livetime (years)	10
Half-life exclusion sensitivity (90% C.L.)	1.5×10^{27} y
Half-life discovery sensitivity (3σ)	1.1×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	10–17 meV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV

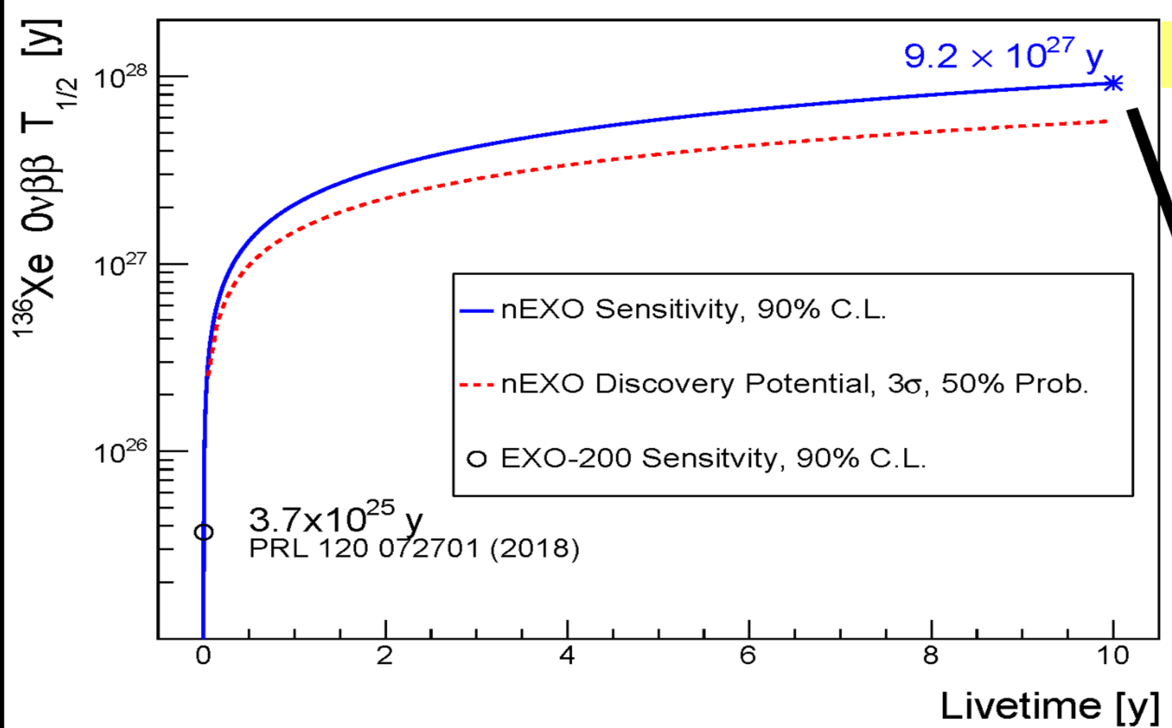


T. O'Donnell @ Neutrino2020

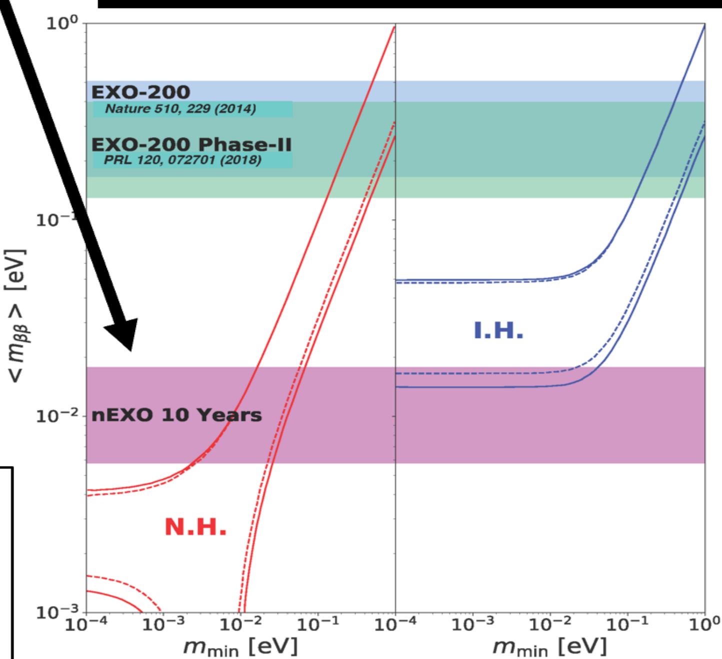
^{136}Xe

nEXO Sensitivity

Sensitivity as a function of time for the baseline design



Phys. Rev. C 97.065503



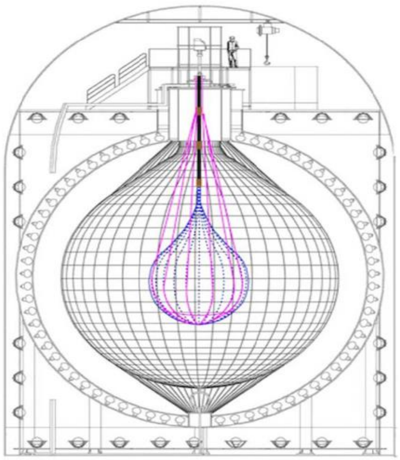
- $g_A = g_A^{free} = -1.2723$
- Band is the envelope of NME:

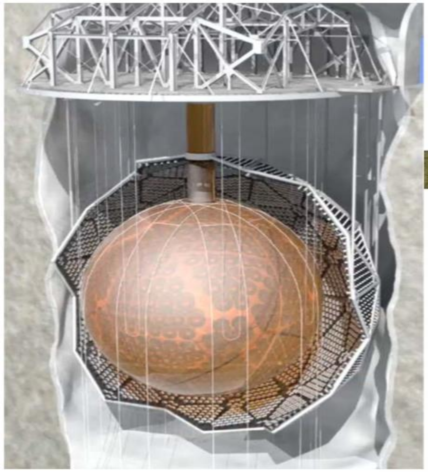
EDF: T.R. Rodríguez and G. Martínez-Pinedo, PRL 105, 252503 (2010)
ISM: J. Menendez et al., Nucl Phys A 818, 139 (2009)
IBM-2: J. Barea, J. Kotila, and F. Iachello, PRC 91, 034304 (2015)
QRPA: F. Šimkovic et al., PRC 87 045501 (2013)
SkyrmeQRPA: M.T. Mustonen and J. Engel PRC 87 064302 (2013)

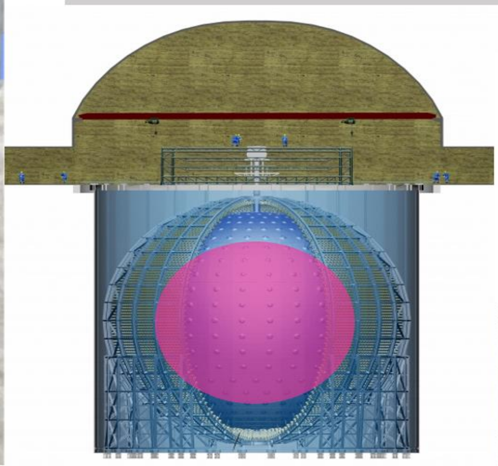
^{136}Xe or ^{130}Te

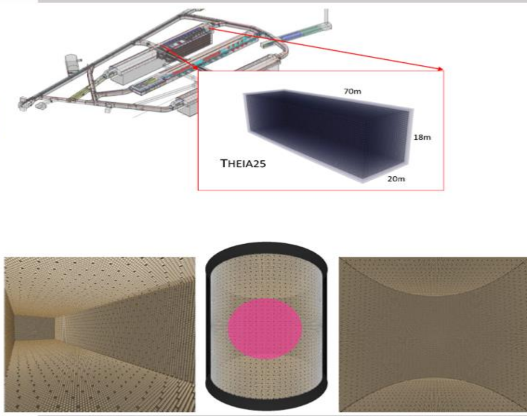
Present

Future









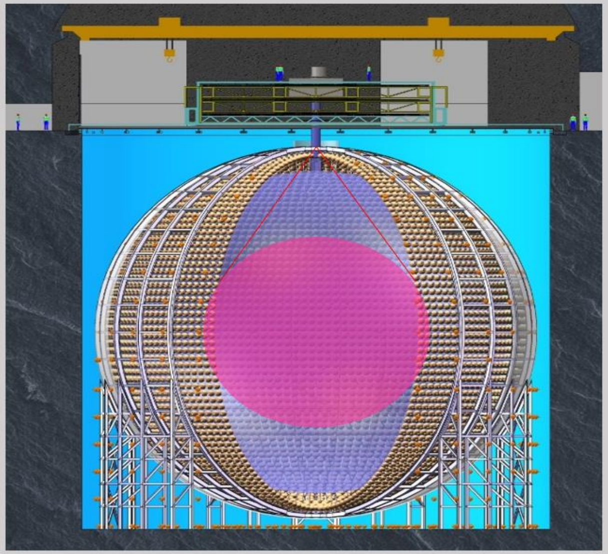
KamLAND-Zen	SNO+	JUNO-ββ	THEIA
			(THEIA-25: 25 kton) (THEIA-100: 100 kton)
KLZ-800 (2020): > 8×10^{25} yrs	Commissioning (47% full@2020.04)	Chin. Phys. C 41 (2017) 053001	Eur. Phys. J. C (2020) 80:416
KLZ-800 (5 yrs): > 5×10^{26} yrs	0.5% loading (3 yrs): > 2×10^{26} yrs	50 tons ^{136}Xe (5 yrs): > 1.8×10^{28} yrs	49.5 tons ^{136}Xe (10 yrs): > 2.0×10^{28} yrs
KamLAND2-Zen: > 2×10^{27} yrs	2.5% loading (4 yrs): > 1×10^{27} yrs	JUNO can hold >100 tons ^{130}Te	~31.4 tons ^{130}Te (10 yrs): > 1.1×10^{28} yrs

JUNO-ββ

Future prospect of JUNO

After the completion of the primary physics goals, JUNO can be upgraded by loading ^{136}Xe or ^{130}Te into LS, for searching for 0νββ (~2030)

The most sensitive to probe the Majorana nature of neutrinos, aiming at a sensitivity level of $|m_{\beta\beta}|$~ meV



Chin. Phys. C 41 (2017) 053001

~10^2 tons of 0νββ target;

best LS shielding;

excellent energy resolution (3%/√E);

ultra-low background

	Isotope	mass (ton)	$<m_{\beta\beta}>$, meV
KamLAND-Zen	^{136}Xe	1	61-165
EXO	^{136}Xe	0.2	93-286
nEXO	^{136}Xe	5	7-22
GERDA	^{76}Ge	1	10-40
Majorana	^{76}Ge	1	10-40
SNO+	^{130}Te	8	19-46
JUNO-ββ	^{136}Xe	50	4-12
	^{130}Te	100-200	2-6 ?

国内研究

无中微子双β衰变（NLDBD）– 国内研究

From Liangjian Wen

第268期双清论坛
"深地前沿物理研讨会"，2020.11

- 低温晶体量热器（^{100}Mo）
- 高压气体TPC （^{82}Se，^{136}Xe）
- 高纯锗（^{76}Ge）
- 液体闪烁体（^{130}Te）

CJPL

JUNO

国内实验结果$T_{1/2}^{0\nu}$ (90% C.L.)

- PandaX-II *(2019, CPC)*:
  > 2.1 x 10^{23} yrs
- CDEX *(2017, Sci.China)*：
  > 6.4 x 10^{22} yrs

CUPID-CJPL

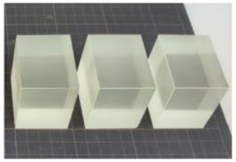
地面/地下晶体测试
(2021-2022)
6-12自然丰度晶体

↓

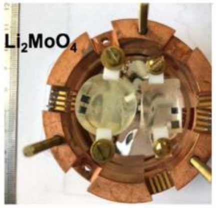
CUPID-CJPL-Demo样机实验
(2022-2024)
10 kg, 36块富集晶体

↓

CUPID-CJPL-200
(2024+)
>1000块富集晶体



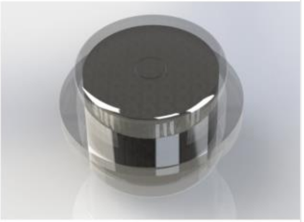
45×45×45 mm³ high purity LMO crystal



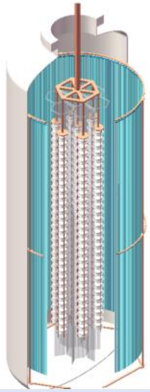
Sens: 9 x 10^{26} yrs @ 5 yrs

CDEX-300ν

- BEGe和ICPC探测器自主研制
- 富集Ge探测器研制，首批2021底到CJPL



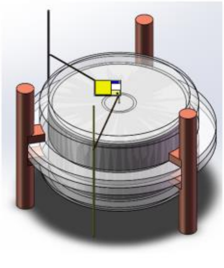
BEGe + LAr active shielding



PandaX-III

- 高压气氙TPC，原型探测器验证阶段
- 灵敏度分析: 2.7 x 10^{26} yrs (90% CL, 140 kg*5 yrs)

JHEP 06 (2021) 106

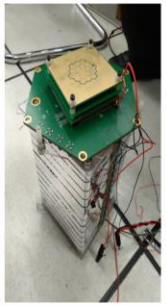


19

- PandaX-4T暗物质探测器也可寻找0νββ，预期灵敏度10^{25} yrs水平

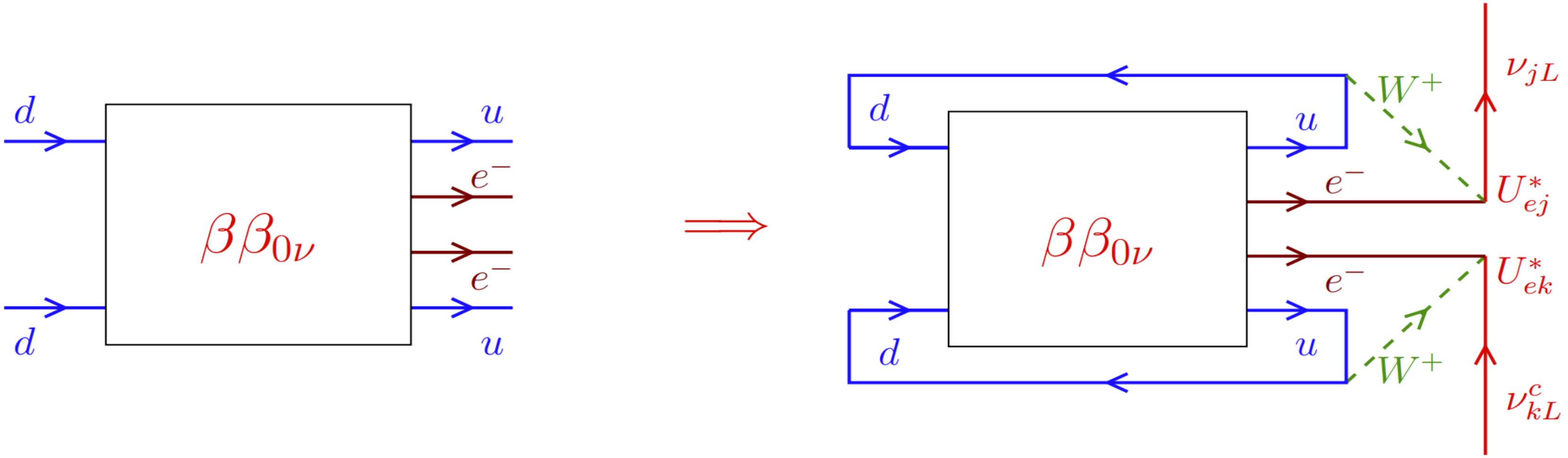
NvDEx

- 关键技术：Topmetal-S芯片
  - 目标：30 e-
  - 实测：~ 50 e-
- 100 kg样机 (2022)



Schechter Valle theorem

- $|m_{\beta\beta}|$ can vanish because of unfortunate cancellations among the ν_1, ν_2, ν_3 contributions or because neutrinos are Dirac particles.
- However, $\beta\beta_{0\nu}$ decay can be generated by another BSM mechanism.
- In this case, Majorana masses are generated by radiative corrections:

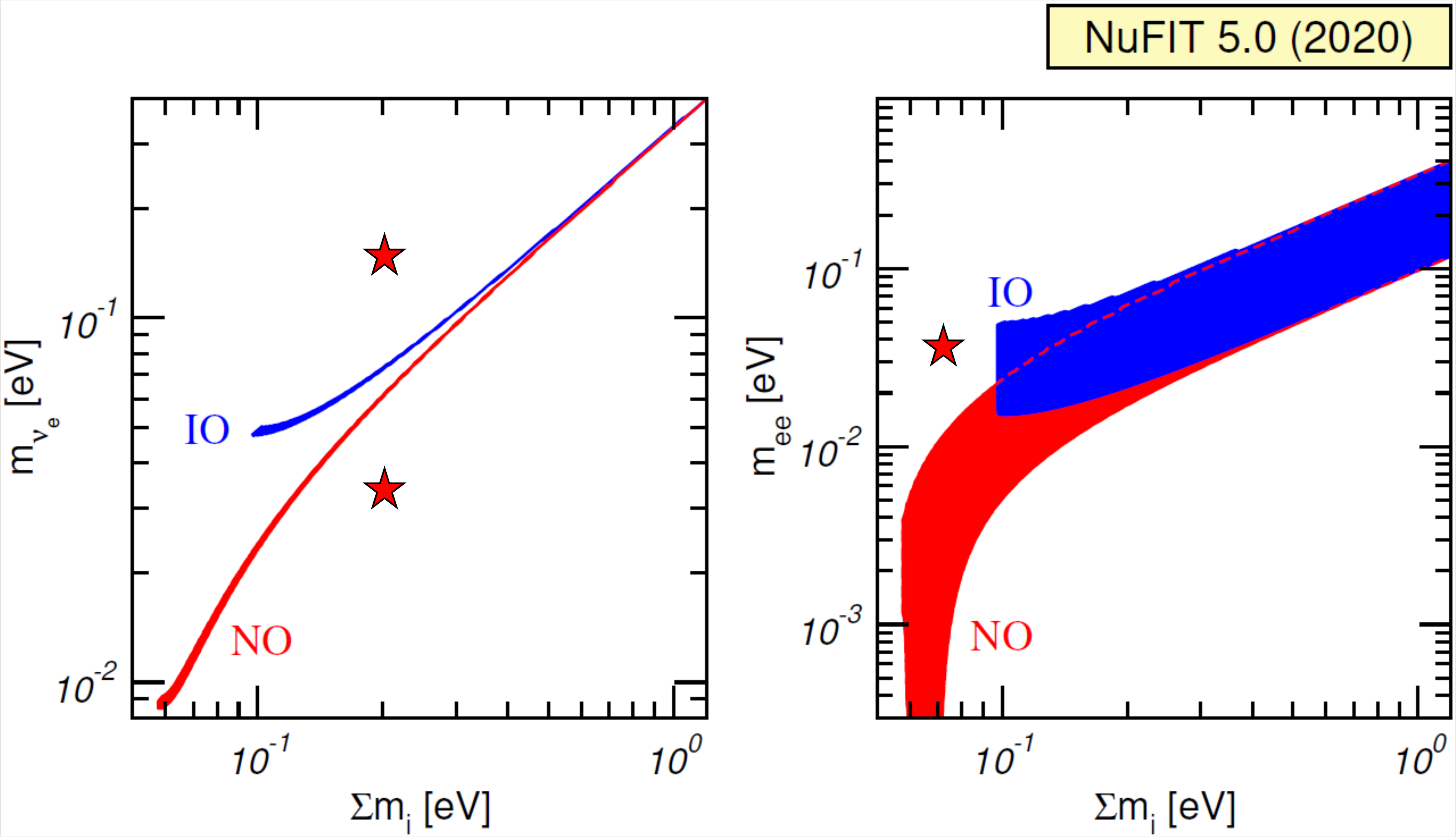


[Schechter, Valle, PRD 25 (1982) 2951; Takasugi, PLB 149 (1984) 372]

- Majorana Mass Lagrangian: $\boxed{\mathscr{L}^{\mathrm{M}}_{\mathrm{mass}} = -\frac{1}{2}\, m_{\mathrm{box}} \sum_{j,k} U^*_{ej} U^*_{ek} \overline{\nu_{jL}} \nu^c_{kL} + \mathrm{H.c.}}$
- Very small four-loop diagram contribution: $m_{\mathrm{box}} \sim 10^{-24}$ eV

Liu, Zhang, Zhou 10^{-28} eV (2016) [Duerr, Lindner, Merle, arXiv:1105.0901]

Mass probe correlation



- What is the interpretation if out of the standard region?

Non-Standard Interpretations

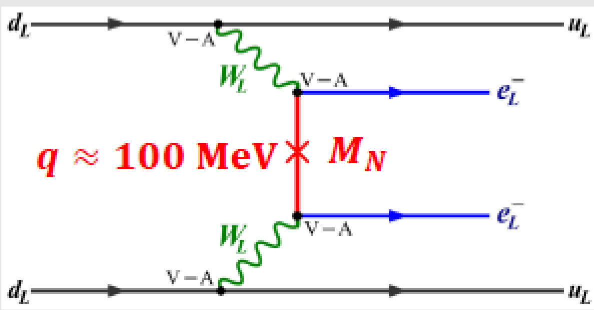
mechanism	physics parameter	current limit	test
light neutrino exchange	$\left\vert U_{ei}^2\, m_i \right\vert$	0.2 eV	oscillations, cosmology, neutrino mass
heavy neutrino exchange	$\left\vert \frac{S_{ei}^2}{M_i} \right\vert$	2×10^{-8} GeV^{-1}	LFV, collider
heavy neutrino and RHC	$\left\vert \frac{V_{ei}^2}{M_i\, M_{W_R}^4} \right\vert$	4×10^{-16} GeV^{-5}	flavor, collider
Higgs triplet and RHC	$\left\vert \frac{(M_R)_{ee}}{m_{\Delta_R}^2\, M_{W_R}^4} \right\vert$	10^{-15} GeV^{-1}	flavor, collider e^- distribution
λ-mechanism with RHC	$\left\vert \frac{U_{ei}\, \tilde{S}_{ei}}{M_{W_R}^2} \right\vert$	1.4×10^{-10} GeV^{-2}	flavor, collider, e^- distribution
η-mechanism with RHC	$\tan\zeta \left\vert U_{ei}\, \tilde{S}_{ei} \right\vert$	6×10^{-9}	flavor, collider, e^- distribution
short-range $\not{R}$	$\frac{\vert\lambda_{111}'^2\vert}{\Lambda_{\rm SUSY}^5}$ $\Lambda_{\rm SUSY} = f(m_{\tilde{g}}, m_{\tilde{u}_L}, m_{\tilde{d}_R}, m_{\chi_i})$	7×10^{-18} GeV^{-5}	collider, flavor
long-range $\not{R}$	$\left\vert \sin 2\theta^b\, \lambda_{131}'\, \lambda_{113}' \left(\frac{1}{m_{\tilde{b}_1}^2} - \frac{1}{m_{\tilde{b}_2}^2} \right) \right\vert$ $\sim \frac{G_F}{q} m_b \frac{\vert\lambda_{131}'\, \lambda_{113}'\vert}{\Lambda_{\rm SUSY}^3}$	2×10^{-13} GeV^{-2} 1×10^{-14} GeV^{-3}	flavor, collider
Majorons	$\vert\langle g_\chi \rangle\vert$ or $\vert\langle g_\chi \rangle\vert^2$	$10^{-4} \ldots 1$	spectrum, cosmology

From Rodejohann

Heavy ν mechanism: different probes

- with mass larger than ≈ 100 MeV

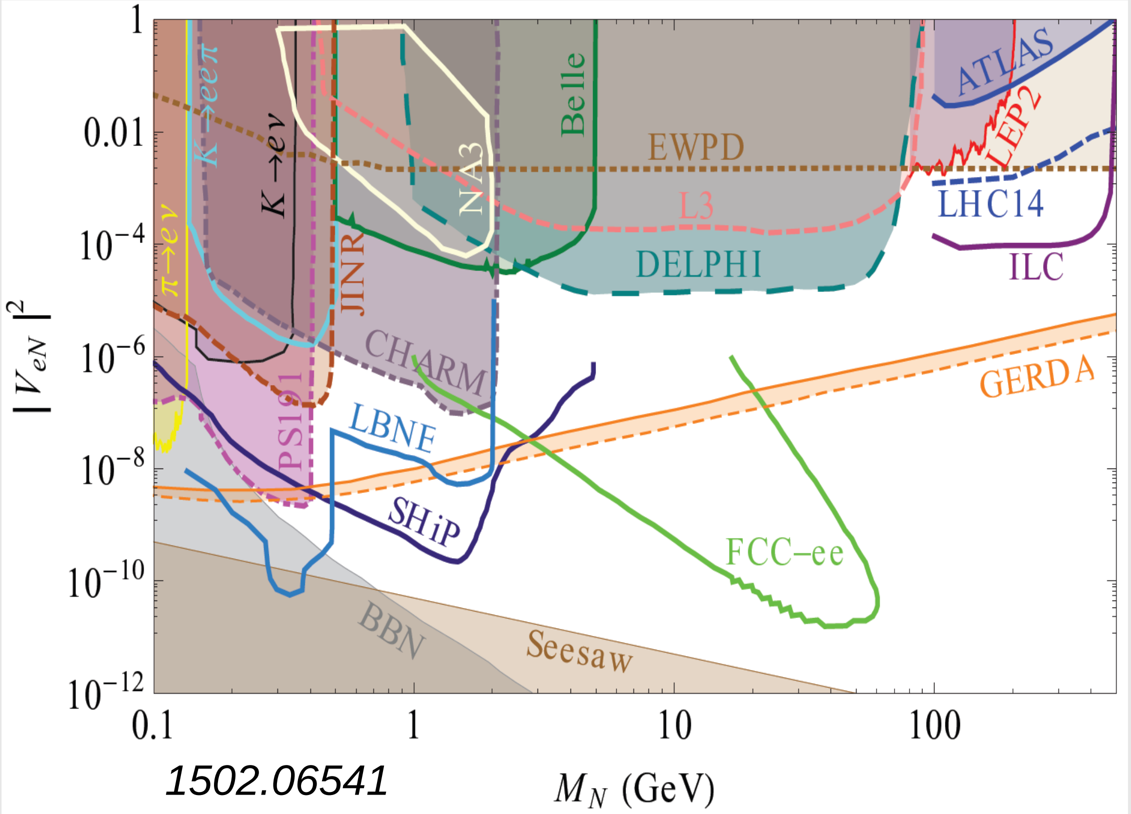
$$\mathcal{A}^{lep}_{\mu\nu} = \frac{1}{4}\sum_{i=1}^{3} V_{ei}^2\,\gamma_\mu(1+\gamma_5)\frac{\not{q} + M_{N_i}}{q^2 - M_{N_i}^2}\gamma_\nu(1-\gamma_5) \approx \frac{-\gamma_\mu(1+\gamma_5)\gamma_\nu}{4}\boxed{\sum_{i=1}^{3}\frac{V_{ei}^2}{M_{N_i}}} \rightarrow \left\langle \frac{1}{M_N} \right\rangle_{\beta\beta}$$



Nuclear matrix element exchange: Short range operators

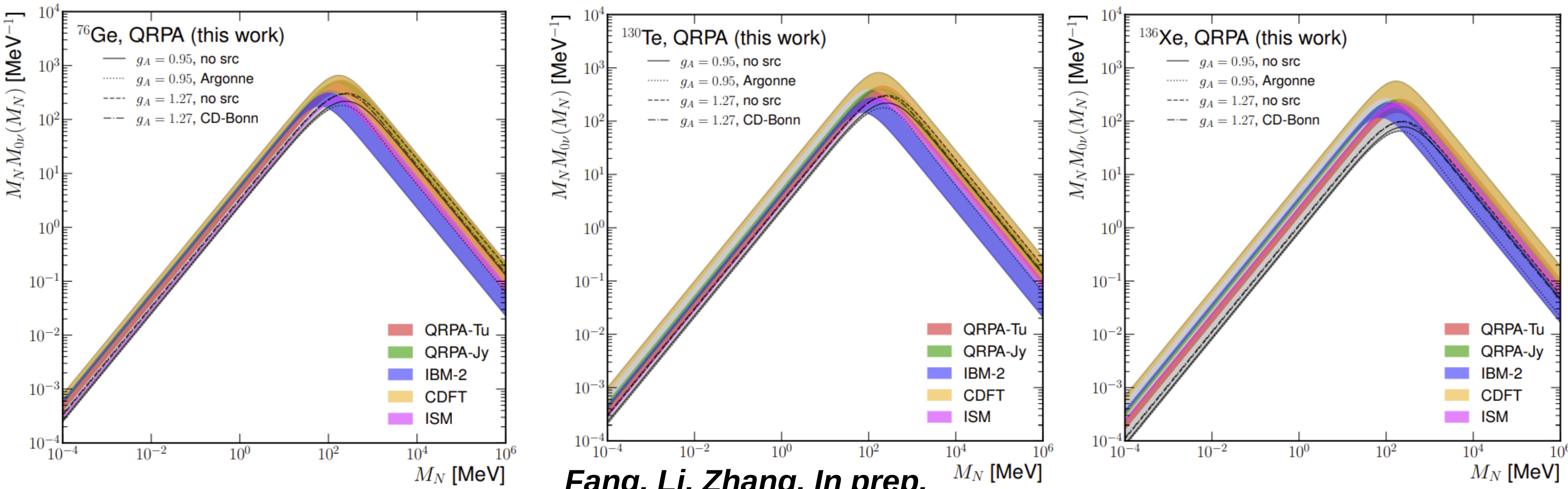
Can also be probed in other experiments.

Seesaw relation gives another constraint.

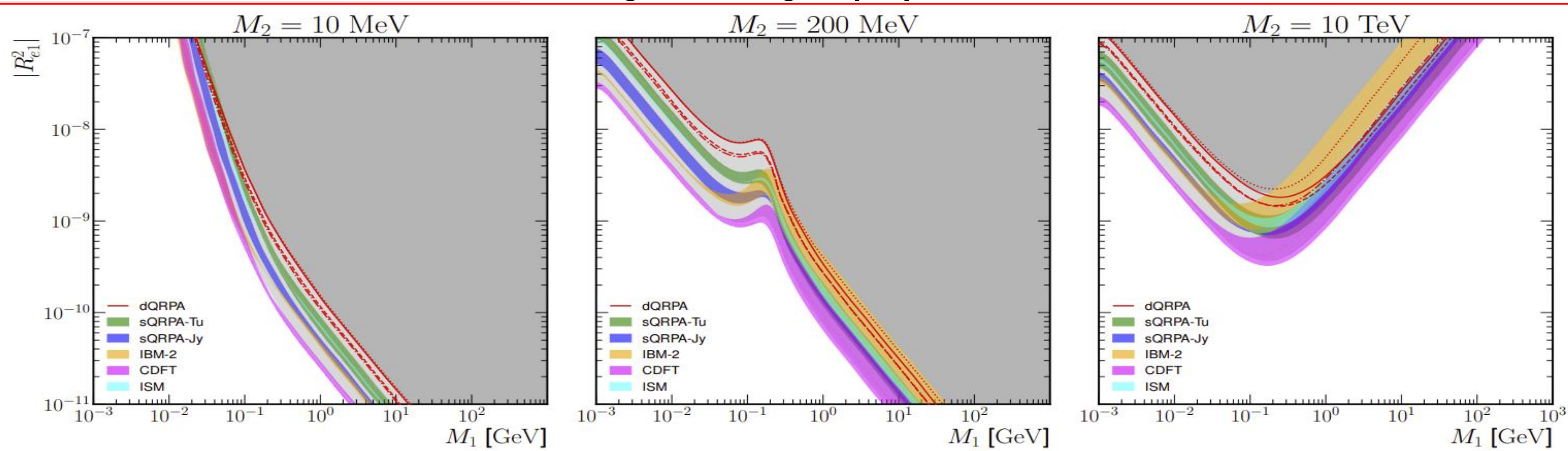


1502.06541

Heavy ν mechanism: current limits



Fang, Li, Zhang, In prep.



LNV process beyond $0\nu\beta\beta$?

Other process may test the Majorana-Dirac properties:

(1) LNV rare decay of B and D mesons

(2) Neutrino-antineutrino oscillation process (Pontecorvo's initial dream)

(3) LNV same-sign di-lepton signal at collider

(4) Cosmic neutrino background detection

(5) Neutrino electro-magnetic properties

(6) Atomic process

Ultra-relativistic nus always with $(m/E)^2$

- Z-decay:

$$\frac{\Gamma(Z \to \nu_{\rm D}\nu_{\rm D})}{\Gamma(Z \to \nu_{\rm M}\nu_{\rm M})} \simeq 1 - 3\frac{m_\nu^2}{m_Z^2}$$

- Meson decays

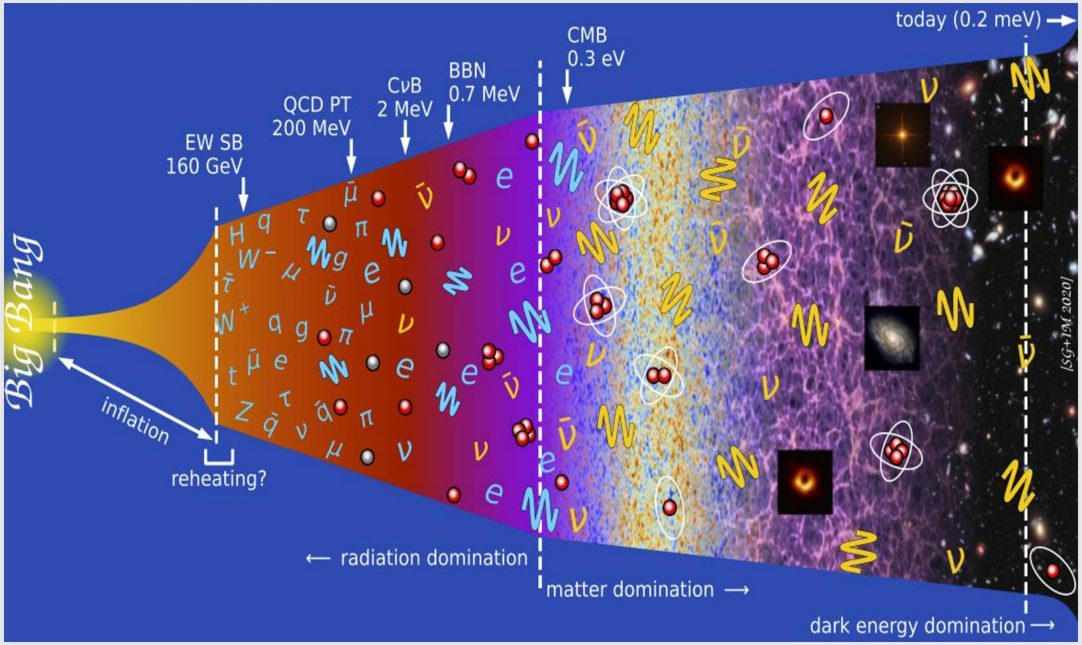
$$\mathrm{BR}(K^+ \to \pi^- e^+ \mu^+) \propto |m_{e\mu}|^2 = \left|\sum U_{ei}\, U_{\mu i}\, m_i\right|^2 \sim 10^{-30} \left(\frac{|m_{e\mu}|}{\mathrm{eV}}\right)^2$$

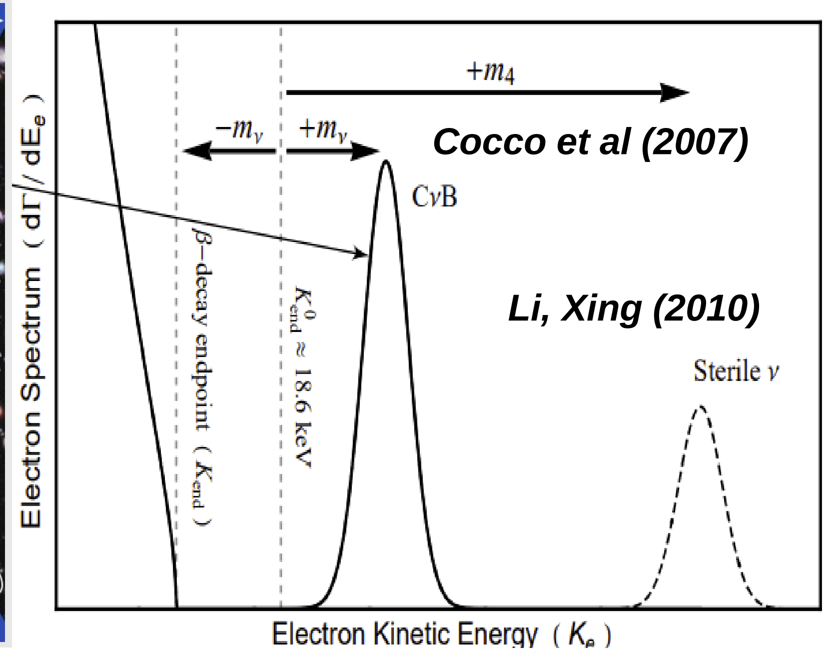
- neutrino-antineutrino oscillations

$$P(\nu_\alpha \to \bar{\nu}_\beta) = \frac{1}{E^2}\left|\sum_{i,j} U_{\alpha j} U_{\beta j} U^*_{\alpha i} U^*_{\beta i}\, m_i m_j\, \mathrm{e}^{-i(E_j - E_i)t}\right|$$

From W. Rodejohann

Detection of CNB





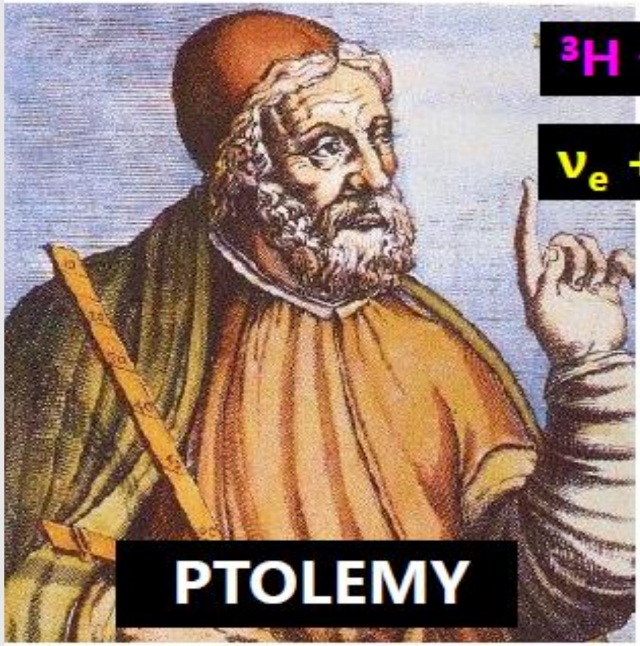
How to directly detect non-relativistic neutrinos?

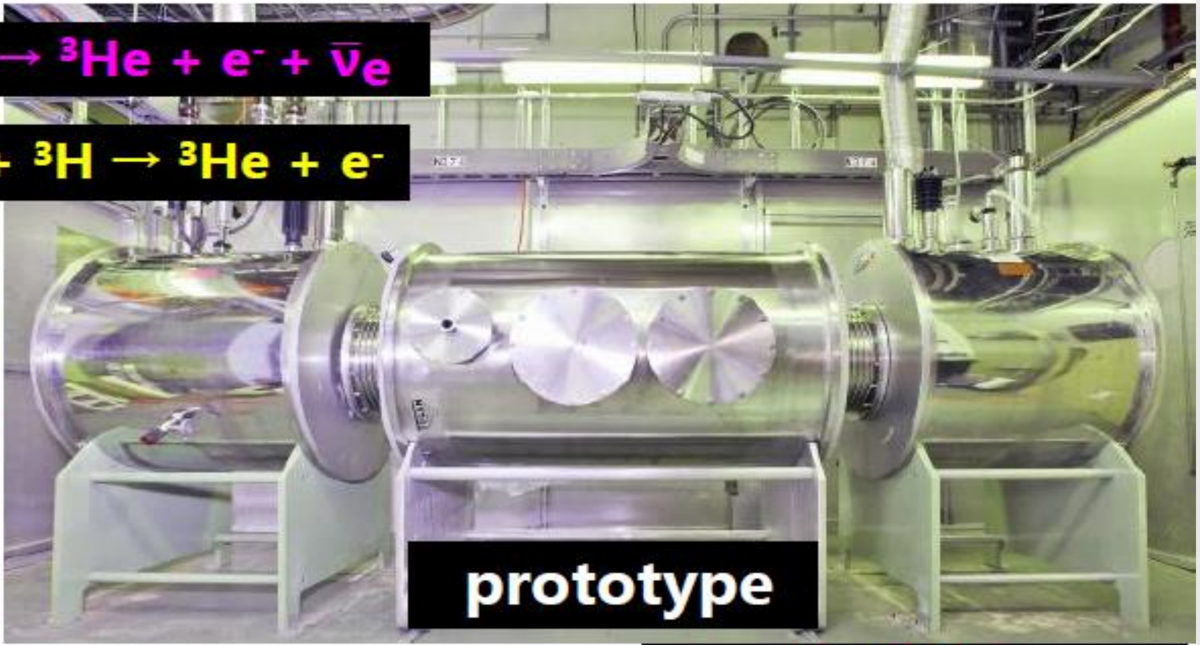
Remember that $\langle E_\nu \rangle \simeq \mathcal{O}(10^{-4})$ eV today $\longrightarrow$ a process without energy threshold is necessary

[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

Main background: β decay $n \to p + e^- + \bar{\nu}$!

PTOLEMY





★ 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)

PTOLEMY

PTOLEMY

[PTOLEMY LoI, arxiv:1808.01892]

Pontecorvo Tritium Observatory for Light, Early-universe, Massive-neutrino Yield (PTOLEMY)

expected resolution $\Delta \simeq 0.1$ eV? 0.05 eV?

built mainly for CNB

can probe $m_\nu \simeq 1.4\Delta \simeq 0.1$ eV

$M_T = 100$ g of atomic ^{3}H

ehnancement from ν clustering in the galaxy?

ehnancement from other effects?

$$\Gamma_{\rm CNB} = \sum_{i=1}^{3} |U_{ei}|^2 [n_i(\nu_{h_R}) + n_i(\nu_{h_L})]\, N_T\, \bar\sigma \qquad \sim \mathcal{O}(10)\ \mathrm{yr}^{-1}$$

N_T number of ^{3}H nuclei in a sample of mass M_T $\quad \bar\sigma \simeq 3.834 \times 10^{-45}$ cm^2 $\quad n_i$ number density of neutrino i

- **Clustering effect:** [de Salas+, 2017] and [Zhang^2, 2018] (without clustering)
- **New physics effect:** Chen & Trautner (2015) Zhang & Zhou (2016)

What if $0\nu 2\beta$ is observed?

Neutrinoless double beta decay: neutrino nature and masses!

- **After the discovery of $0\nu 2\beta$**

  Distinguishing Mechanisms:

- **Comparison of different mass probes: agreement or not ?**

- **Other contributions: light/heavy sterile neutrinos, and more …**

- **Decay products**

  individual electron energies, angular correlations, spectrum

- **Nuclear aspects**

  multiple isotopes, decay to excited states, 0νECEC,

Thank you !

Discussion

a) Experimental efforts beyond 10^{28} years

isotope purchase, background etc.

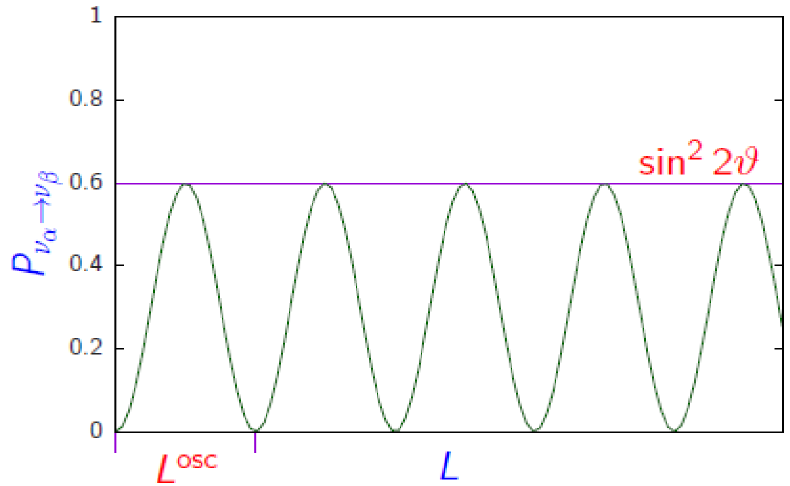
b) Nuclear matrix elements

c) Beyond $0\nu 2\beta$

d) If observed, what mechanism?

Oscillation Types

2ν-mixing: $P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\vartheta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \implies \boxed{L^{\text{osc}} = \frac{4\pi E}{\Delta m^2}}$



Tiny neutrino masses lead to observable macroscopic oscillation distances!

$$\frac{L}{E} \gtrsim \begin{cases} 10 \, \frac{\text{m}}{\text{MeV}} \left(\frac{\text{km}}{\text{GeV}}\right) & \text{short-baseline experiments} & \Delta m^2 \gtrsim 10^{-1}\,\text{eV}^2 \\ 10^3 \, \frac{\text{m}}{\text{MeV}} \left(\frac{\text{km}}{\text{GeV}}\right) & \text{long-baseline experiments} & \Delta m^2 \gtrsim 10^{-3}\,\text{eV}^2 \\ 10^4 \, \frac{\text{km}}{\text{GeV}} & \text{atmospheric neutrino experiments} & \Delta m^2 \gtrsim 10^{-4}\,\text{eV}^2 \\ 10^{11} \, \frac{\text{m}}{\text{MeV}} & \text{solar neutrino experiments} & \Delta m^2 \gtrsim 10^{-11}\,\text{eV}^2 \end{cases}$$

Neutrino oscillations are the optimal tool to reveal tiny neutrino masses!

Categories of neutrino oscillations-I

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

Solar $\nu_e \to \nu_\mu, \nu_\tau$	SNO, Borexino Super-Kamiokande GALLEX/GNO, SAGE Homestake, Kamiokande	
VLBL Reactor $\bar{\nu}_e$ disappearance	(KamLAND)	

$$\rightarrow \begin{cases} \Delta m^2_S = \Delta m^2_{21} \simeq 7.4 \times 10^{-5}\,\mathrm{eV}^2 \\ \sin^2\vartheta_S = \sin^2\vartheta_{12} \simeq 0.30 \end{cases}$$

Categories of neutrino oscillations-II

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

Atmospheric $\nu_\mu \to \nu_\tau$	(Super-Kamiokande Kamiokande, IMB MACRO, Soudan-2 IceCube, ANTARES)	
LBL Accelerator ν_μ disappearance	(K2K, MINOS T2K, NOνA)	
LBL Accelerator $\nu_\mu \to \nu_\tau$	(OPERA)	

$$\rightarrow \begin{cases} \Delta m^2_{\mathrm{A}} \simeq |\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\,\mathrm{eV}^2 \\ \sin^2\vartheta_{\mathrm{A}} = \sin^2\vartheta_{23} \simeq 0.50 \end{cases}$$

Categories of neutrino oscillations-III

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

LBL Accelerator
$\nu_\mu \to \nu_e$ (T2K, MINOS, NOνA)

LBL Reactor
$\bar{\nu}_e$ disappearance (Daya Bay, RENO, Double Chooz)

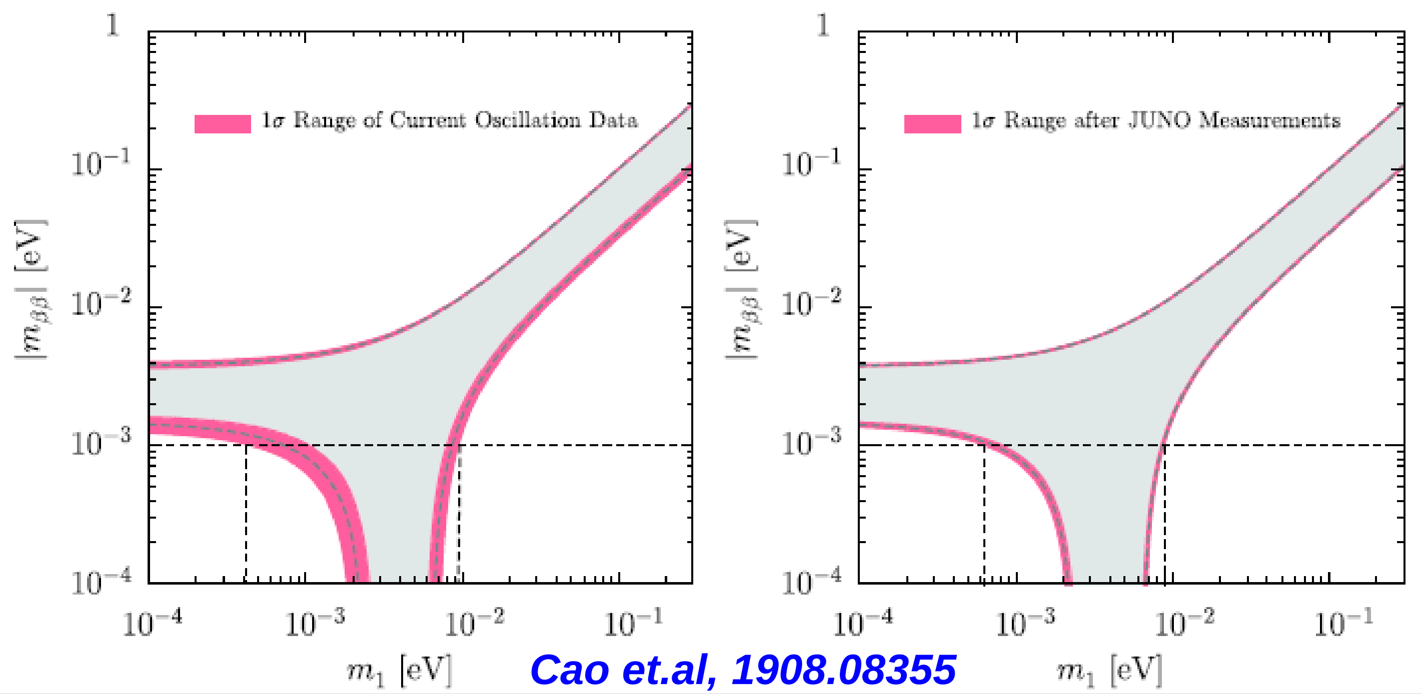
$\rightarrow$

$$\begin{cases} \Delta m^2_{\mathrm{A}} \simeq |\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\,\mathrm{eV}^2 \\ \sin^2 \vartheta_{13} \simeq 0.022 \end{cases}$$

Role of Precision Measurement (JUNO)

JUNO Physics Book: 1507.056131

	Nominal	+ B2B (1%)	+ BG	+ EL (1%)	+ NL (1%)
$\sin^2\theta_{12}$	0.54%	0.60%	0.62%	0.64%	0.67%
Δm^2_{21}	0.24%	0.27%	0.29%	0.44%	0.59%
$\lvert\Delta m^2_{ee}\rvert$	0.27%	0.31%	0.31%	0.35%	0.44%



Cao et.al, 1908.08355

- **Precision measurement can eliminate (almost) all the uncertainties from oscillation parameters**

Global picture

with SK atmospheric data	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

Unknowns

- **Mass ordering, CP violation, More new physics**
- **Dirac or Majorana Nature, Absolute neutrino masses, ……**

$\mathrm{Br}(K^+ \to \pi^- e^+ e^+) < 6.4 \times 10^{-10}$， $\mathrm{Br}(D^+ \to \pi^- e^+ e^+) < 1.1 \times 10^{-06}$；

$\mathrm{Br}(K^+ \to \pi^- e^+ \mu^+) < 5.0 \times 10^{-10}$， $\mathrm{Br}(D^+ \to \pi^- e^+ \mu^+) < 2.0 \times 10^{-06}$；

$\mathrm{Br}(K^+ \to \pi^- \mu^+ \mu^+) < 8.6 \times 10^{-11}$， $\mathrm{Br}(D^+ \to \pi^- \mu^+ \mu^+) < 2.2 \times 10^{-08}$；

$\mathrm{Br}(B^+ \to K^- e^+ e^+) < 3.0 \times 10^{-08}$， $\mathrm{Br}(B^+ \to \pi^- e^+ e^+) < 2.3 \times 10^{-08}$；

$\mathrm{Br}(B^+ \to K^- e^+ \mu^+) < 1.6 \times 10^{-07}$， $\mathrm{Br}(B^+ \to \pi^- e^+ \mu^+) < 1.5 \times 10^{-07}$；

$\mathrm{Br}(B^+ \to K^- \mu^+ \mu^+) < 4.1 \times 10^{-08}$， $\mathrm{Br}(B^+ \to \pi^- \mu^+ \mu^+) < 4.0 \times 10^{-09}$；

$\mathrm{Br}(\Xi^- \to p \mu^- \mu^-) < 4 \times 10^{-08}$， $\mathrm{Br}(\Lambda_c^+ \to \Sigma^- \mu^+ \mu^+) < 7.0 \times 10^{-04}$。

Why different?

Conservation of Helicity: $[\hat{H}, \hat{h}] = 0$ for free particles after decoupling

$$\hat{H} \equiv \gamma^0 m + \gamma^0 \vec{\gamma} \cdot \vec{p} = \begin{pmatrix} m & \vec{\sigma} \cdot \vec{p} \\ \vec{\sigma} \cdot \vec{p} & -m \end{pmatrix} \qquad \hat{h} \equiv \frac{\vec{\Sigma} \cdot \vec{p}}{|\vec{p}|} = \frac{1}{|\vec{p}|} \begin{pmatrix} \vec{\sigma} \cdot \vec{p} & 0 \\ 0 & \vec{\sigma} \cdot \vec{p} \end{pmatrix}$$

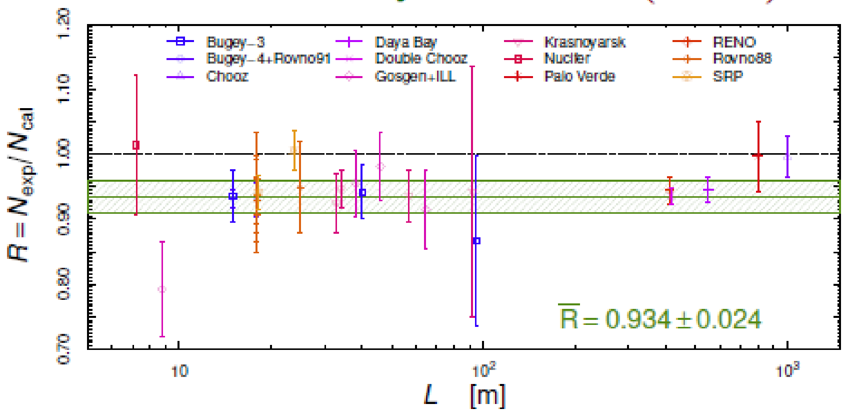
In the rest frame of CνB, the background neutrinos are isotropic

Long et al., 14;
Zhang, Zhou, 16

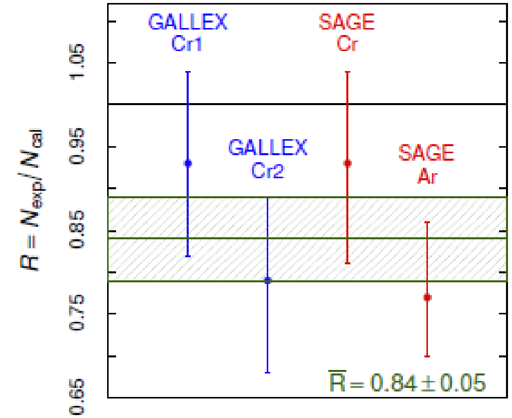
	Dirac Neutrinos		Majorana Neutrinos
Decoupling	$n(\nu_{\rm L}) = n(z)$, $n(\overline{\nu}_{\rm R}) = n(z)$,	$n(\nu_{\rm R}) \approx 0$ $n(\overline{\nu}_{\rm L}) \approx 0$	$n(\nu_{\rm L}) = n(z)$ $n(\nu_{\rm R}) = n(z)$
Nowadays	$n(\nu_{\rm hL}) = n_0$, $n(\overline{\nu}_{\rm hR}) = n_0$,	$n(\nu_{\rm hR}) \approx 0$ $n(\overline{\nu}_{\rm hL}) \approx 0$	$n(\nu_{\rm hL}) = n_0$ $n(\nu_{\rm hR}) = n_0$
Total Rates	$\boxed{\Gamma^{\rm D}_{\rm C\nu B} = \bar{\sigma} n_0 N_{\rm T}}$	$\bar{\sigma} \approx 3.8 \times 10^{-45}\ {\rm cm}^2$	$\boxed{\Gamma^{\rm M}_{\rm C\nu B} = 2\bar{\sigma} n_0 N_{\rm T}}$

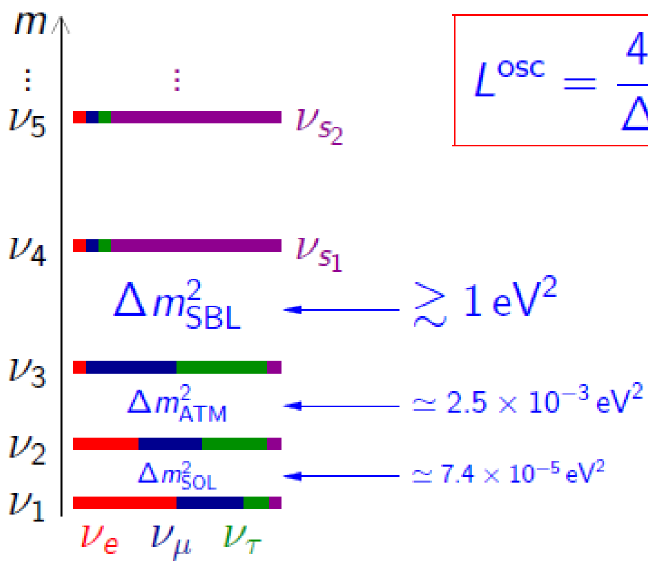
Short baseline oscillations: Anomalies?

Reactor Anomaly: $\bar{\nu}_e \to \bar{\nu}_x$ $(\sim 3\sigma)$



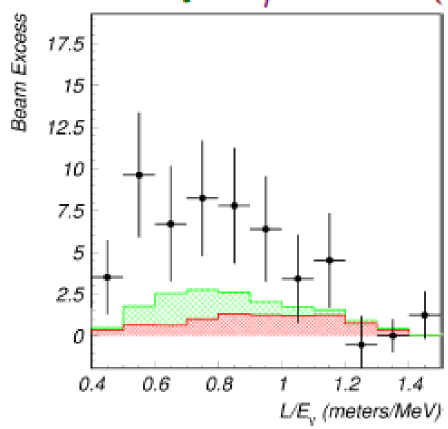
Gallium Anomaly: $\nu_e \to \nu_x$ $(\sim 3\sigma)$





$$\boxed{L^{osc} = \frac{4\pi E}{\Delta m^2}}$$

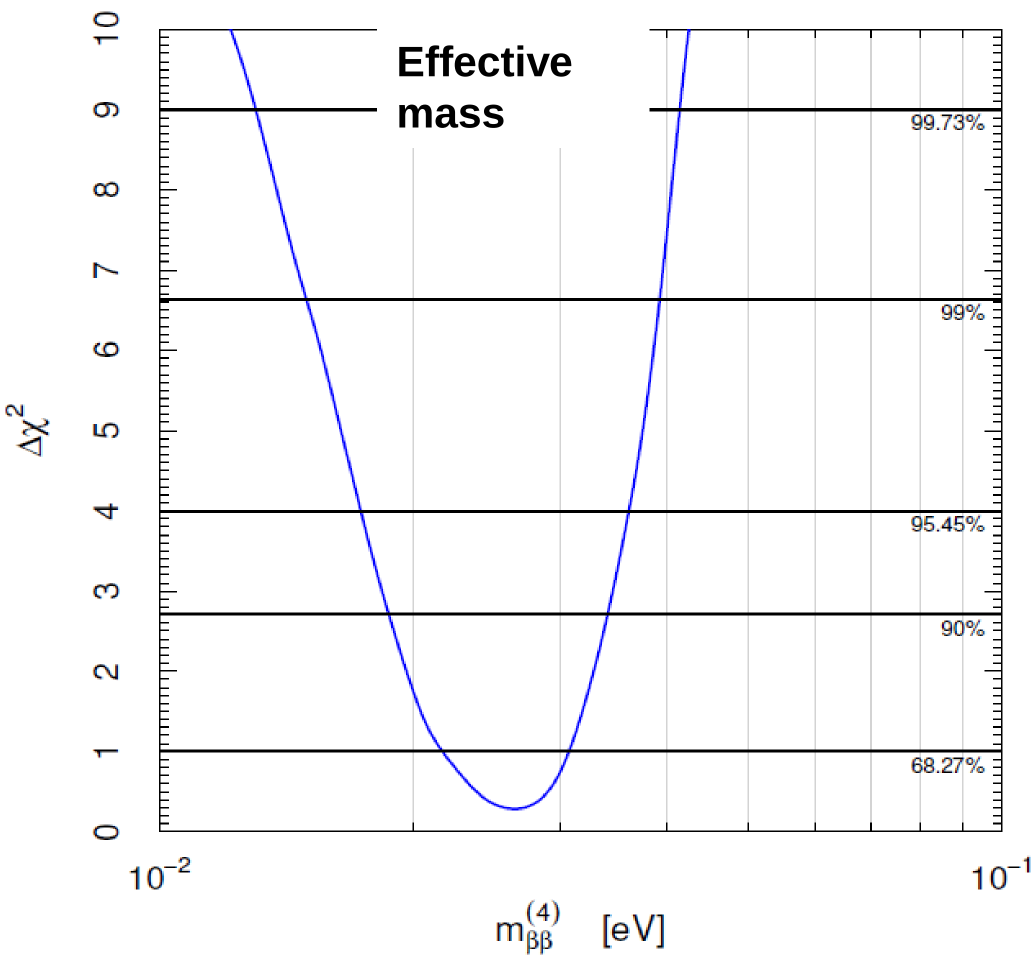
LSND Anomaly: $\bar{\nu}_\mu \to \bar{\nu}_e$ $(\sim 4\sigma)$



Minimal perturbation of 3ν mixing: effective 3+1 with $|U_{e4}|, |U_{\mu 4}|, |U_{\tau 4}| \ll 1$

$0\nu2\beta$-decay: the effective mass

$$m_{\beta\beta} = |U_{e1}|^2\, m_1 + |U_{e2}|^2\, e^{i\alpha_{21}}\, m_2 + |U_{e3}|^2\, e^{i\alpha_{31}}\, m_3 + |U_{e4}|^2\, e^{i\alpha_{41}}\, m_4$$



$$m_{\beta\beta}^{(k)} = |U_{ek}|^2 m_k$$

$$m_1 \ll m_4$$

$$\Downarrow$$

$$m_{\beta\beta}^{(4)} \simeq |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

warning:

possible cancellation with $m_{\beta\beta}^{(3\nu)}$

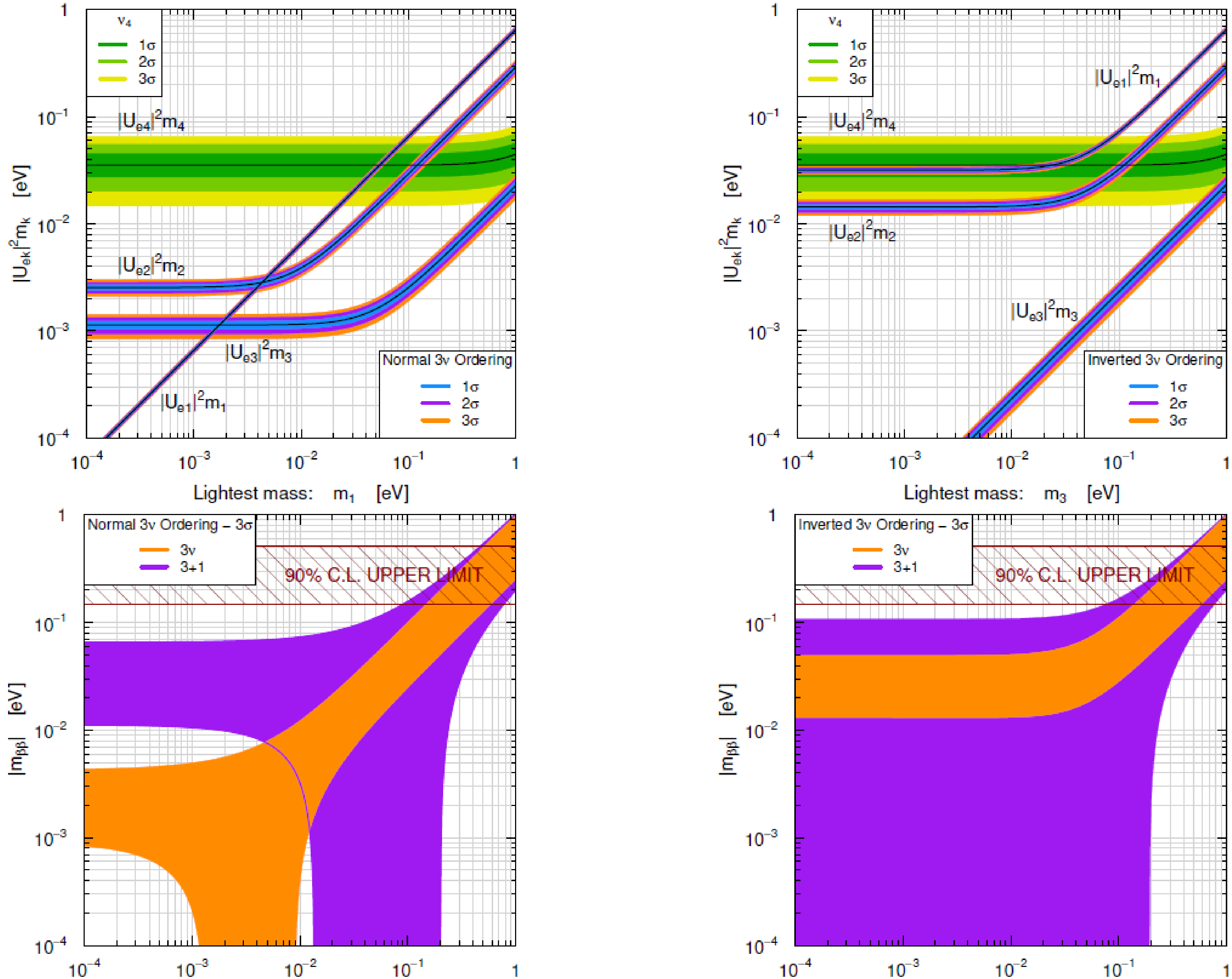
[Barry, Rodejohann, Zhang, JHEP 07 (2011) 091]

[Li, Liu, PLB 706 (2012) 406]

[Rodejohann, JPG 39 (2012) 124008]

[Girardi, Meroni, Petcov, JHEP 1311 (2013) 146]

[CG, Zavanin, JHEP 07 (2015) 171]


ν4
1σ
2σ
3σ
$|U_{e4}|^2 m_4$
$|U_{e2}|^2 m_2$
$|U_{e3}|^2 m_3$
$|U_{e1}|^2 m_1$
Normal 3ν Ordering
Inverted 3ν Ordering
$|U_{ek}|^2 m_k$ [eV]
Lightest mass: m_1 [eV]
Lightest mass: m_3 [eV]
Normal 3ν Ordering – 3σ
Inverted 3ν Ordering – 3σ
3ν
3+1
90% C.L. UPPER LIMIT
$|m_{\beta\beta}|$ [eV]