Neutrinoless double beta decay in the Type-I Seesaw model

Based on, Fang, YFL, Zhang
2112.12779 & 2305.xxxxx

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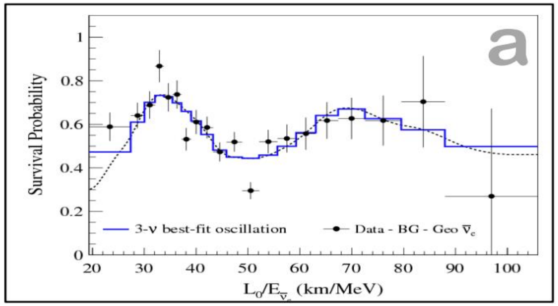
2023-05-20@珠海

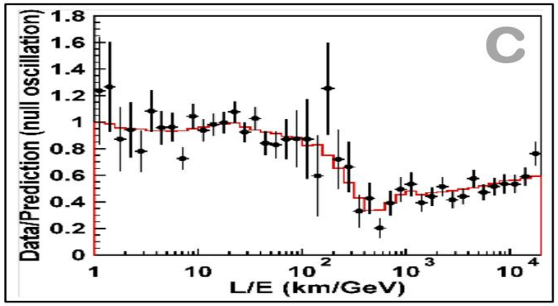
第二届“无中微子双贝塔衰变及相关物理研讨会”

νs do oscillate!

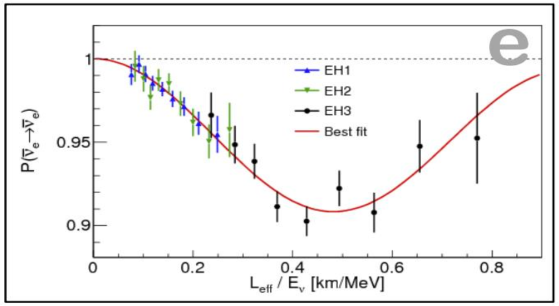
e→e



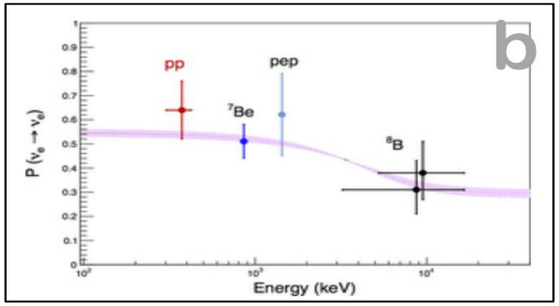
μ→μ



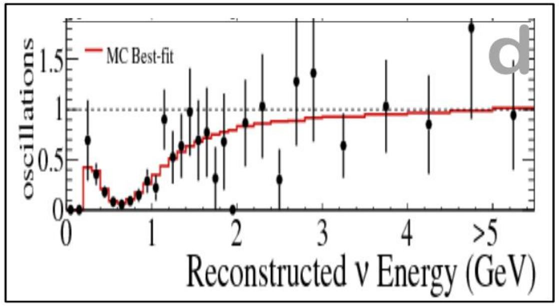
e→e



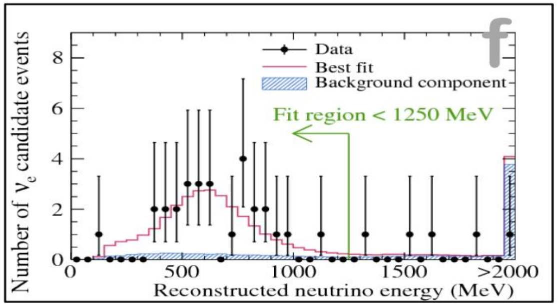
e→e



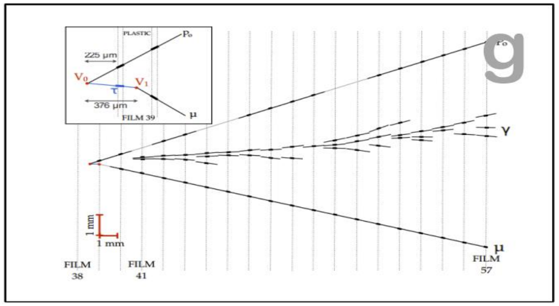
μ→μ



μ→e



μ→τ

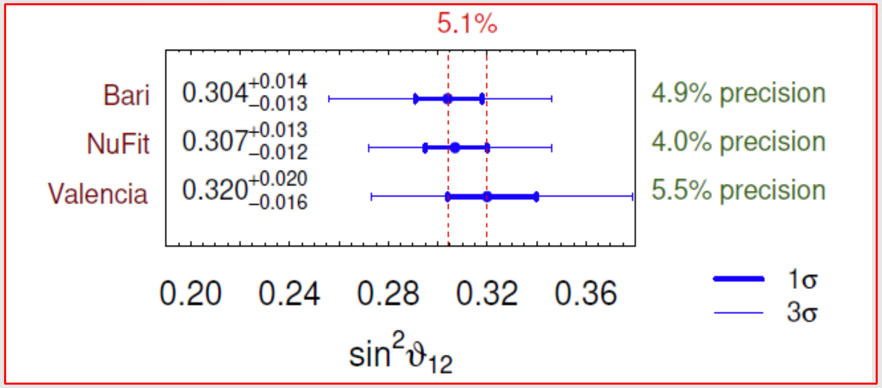


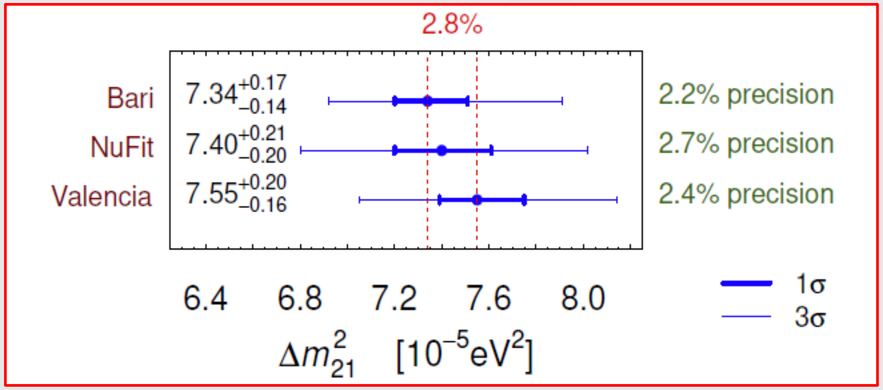
Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline accelerator, (e) short-baseline reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

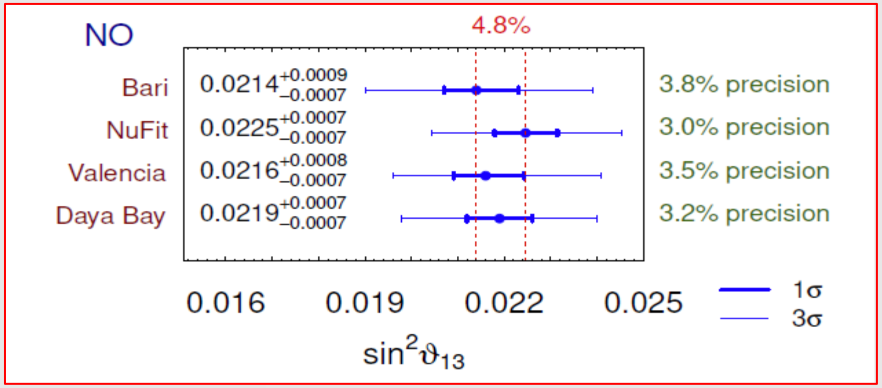
(a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS, NOvA; (g) OPERA [plot], Super-K atmospheric.

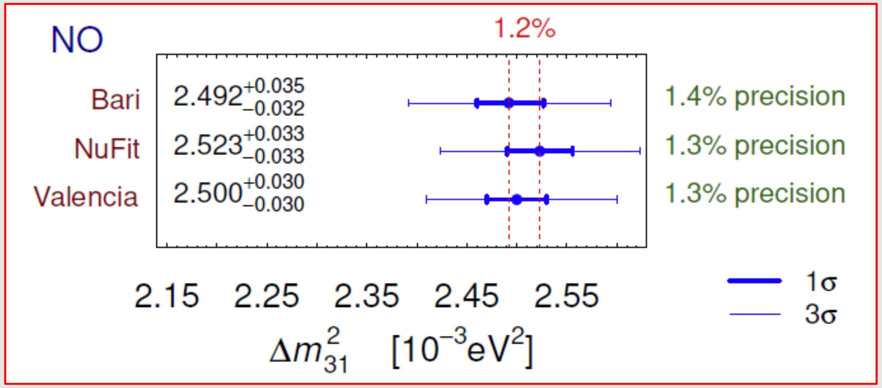
From Lisi

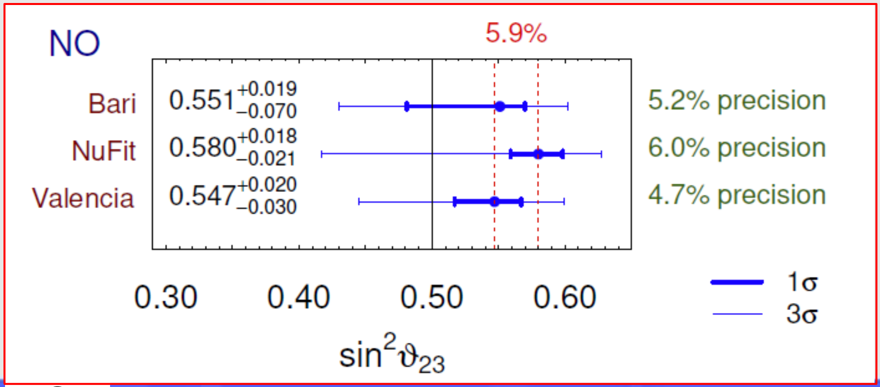
The current global picture





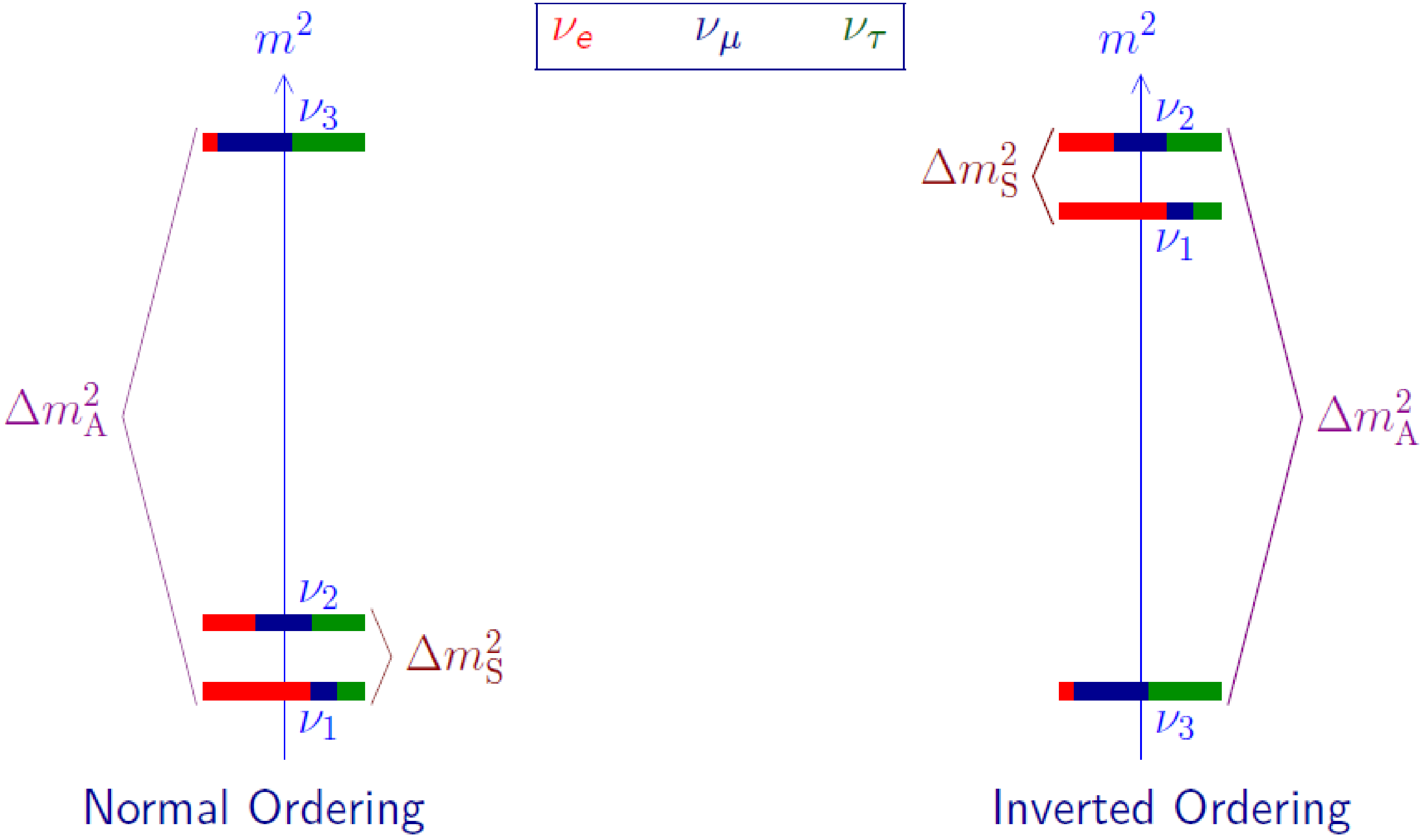






- **5 parameters: measured with high precision**
- **Mass ordering & CP violation to be determined**

Neutrino mass spectrum

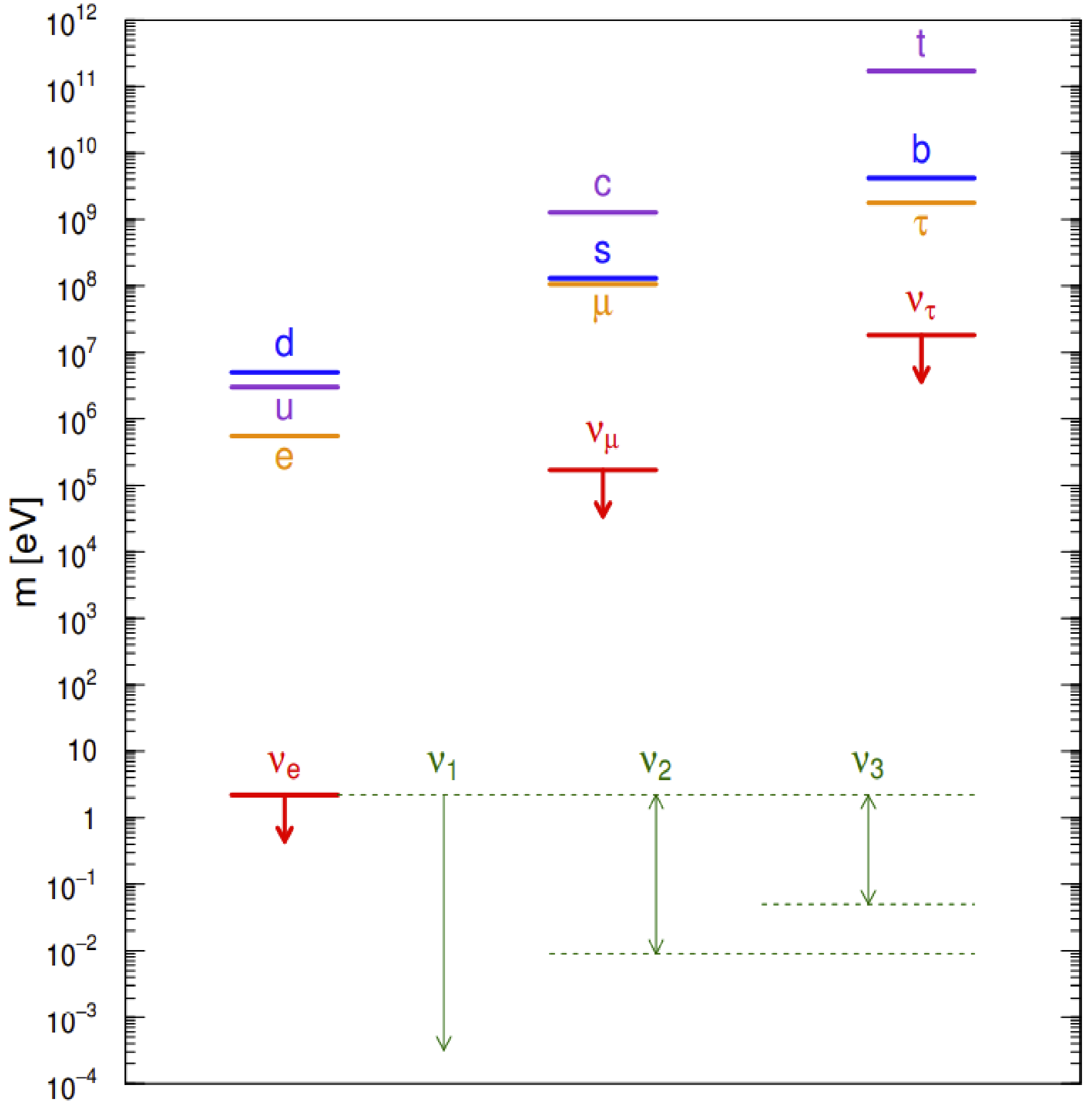


$\Delta m^2_{31} > \Delta m^2_{32} > 0$

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

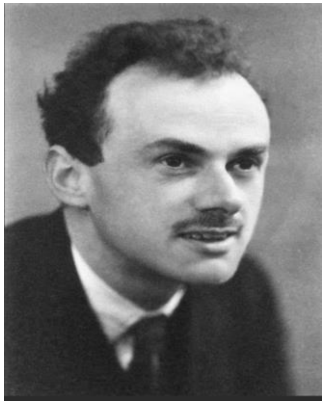
absolute scale is not determined by neutrino oscillation data

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

Double beta decay

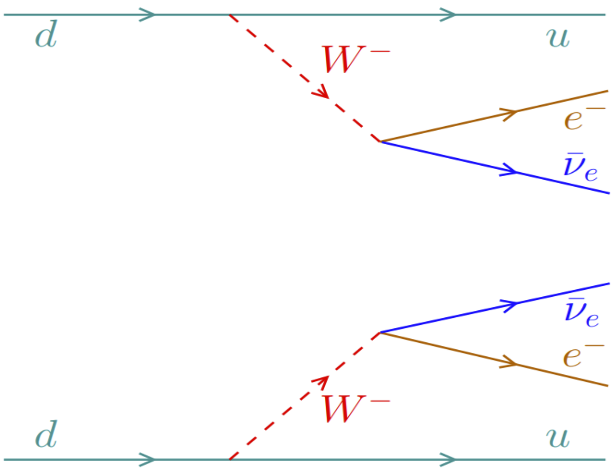
Two-Neutrino Double-β Decay: $\Delta L = 0$

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

Goeppert Mayer (1935)

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

second order weak interaction process in the Standard Model



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

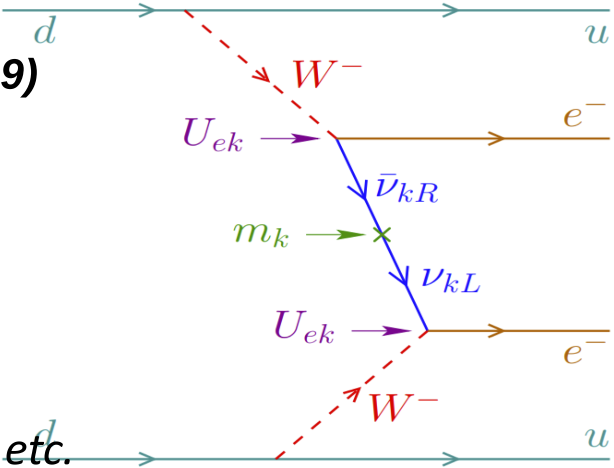
$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^-$$

Furry (1939)

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

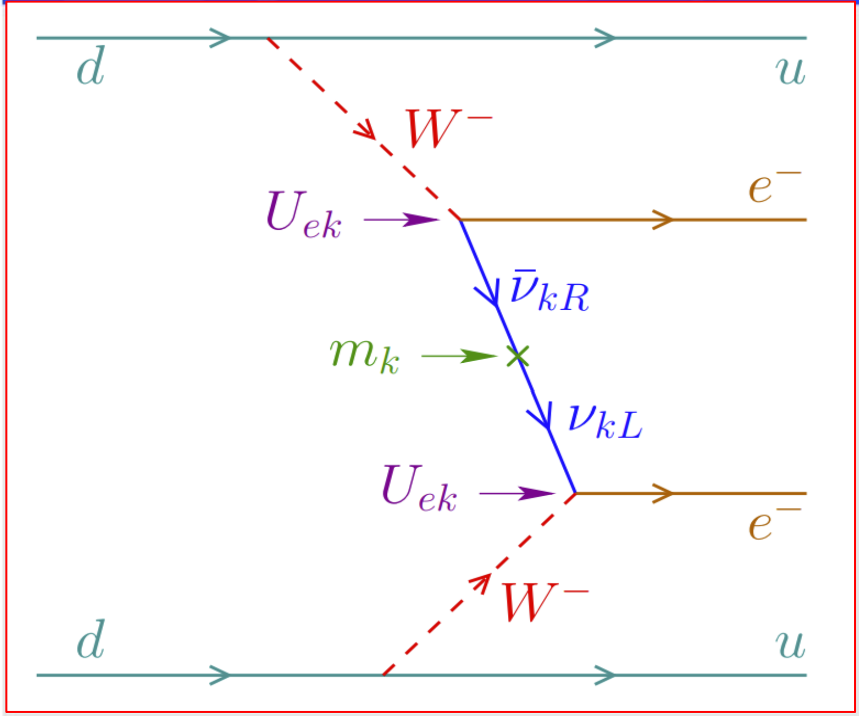
effective Majorana mass

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



See recent reviews: 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:

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

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

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

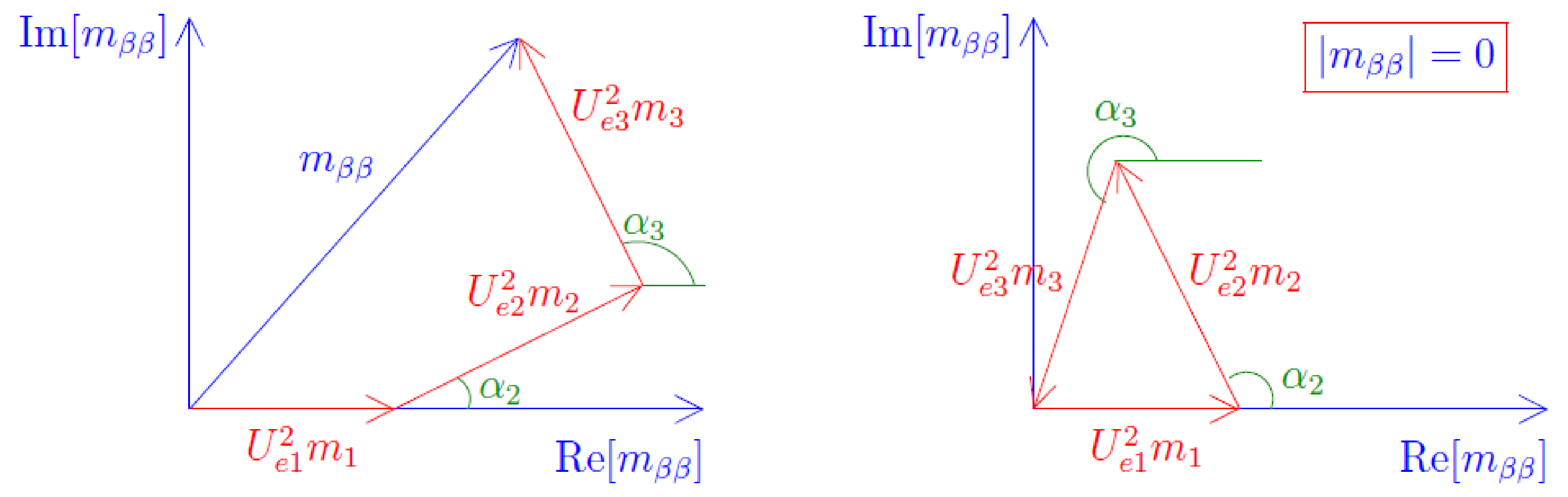
$$A_{\mu\nu} \propto \sum_k U_{ek}^2 \int \frac{d^4p}{(2\pi)^4}\overline{e}(x)\gamma_\mu\,(1-\gamma_5)\,\frac{\not{p}+m_k}{p^2-m_k^2}\,(1-\gamma_5)\,\gamma_\nu e^c(y)\,e^{-ip\cdot(x-y)}$$

Effective Majorana Neutrino Mass

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

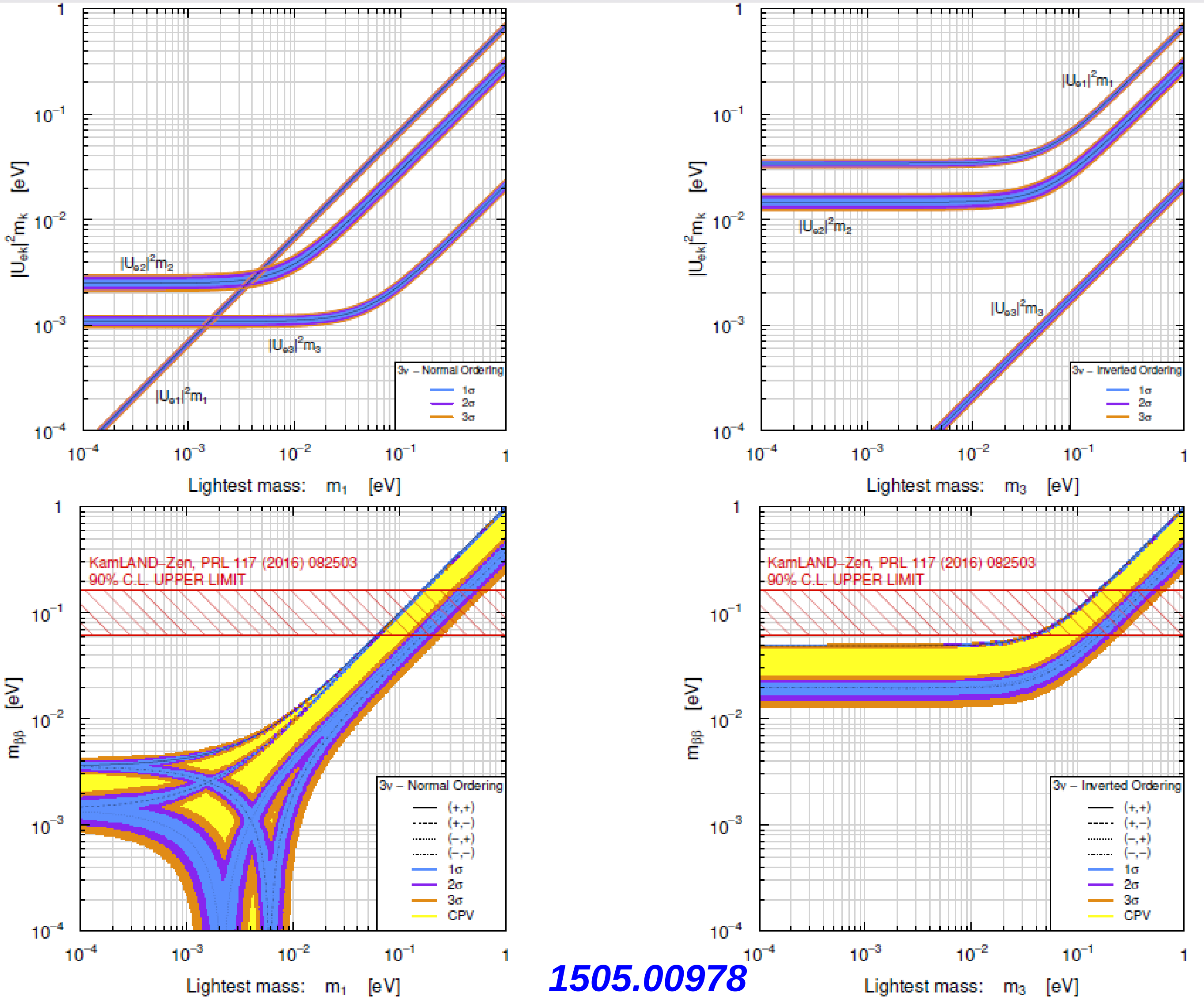
$$m_{\beta\beta} = |U_{e1}|^2 \, m_1 + |U_{e2}|^2 \, e^{i\alpha_2} \, m_2 + |U_{e3}|^2 \, e^{i\alpha_3} \, m_3$$

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



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

$m_{\beta\beta}$: Decomposition



1505.00978

Three different regions:

- **QD:**

  $m_{1/3} > 10$ meV

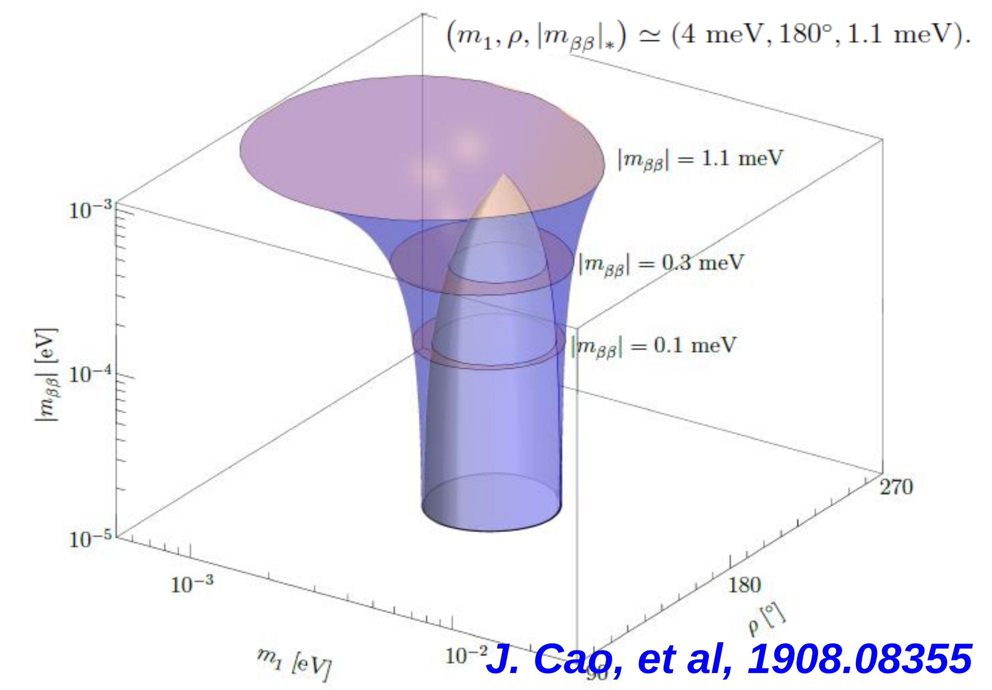
- **Hierarchical:**

  $m_{1/3} < 1$ meV

- **Cancelation:**

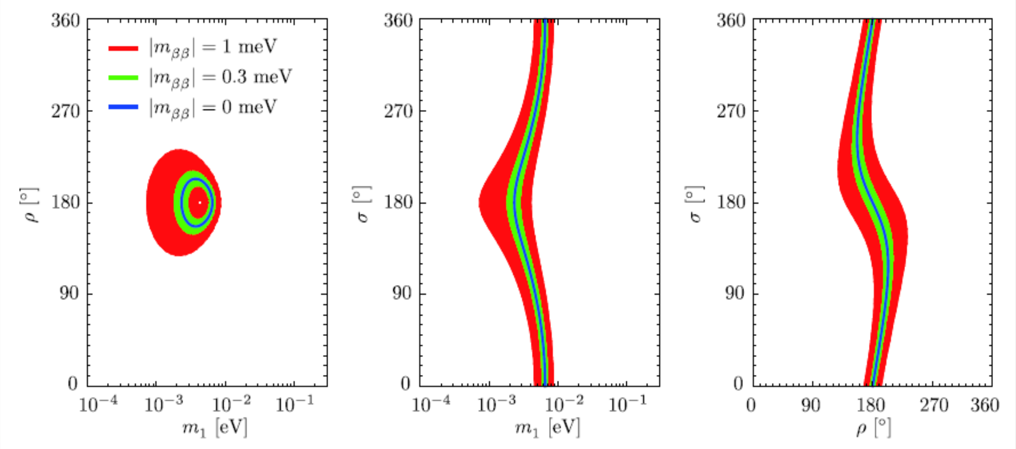
  [1, 10] meV

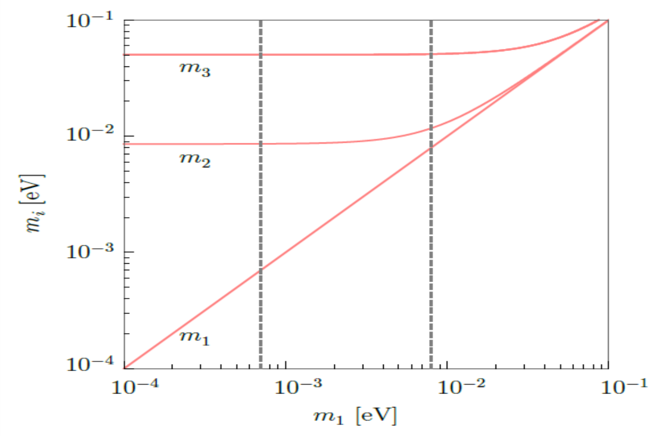
Fine structure: towards the meV goal



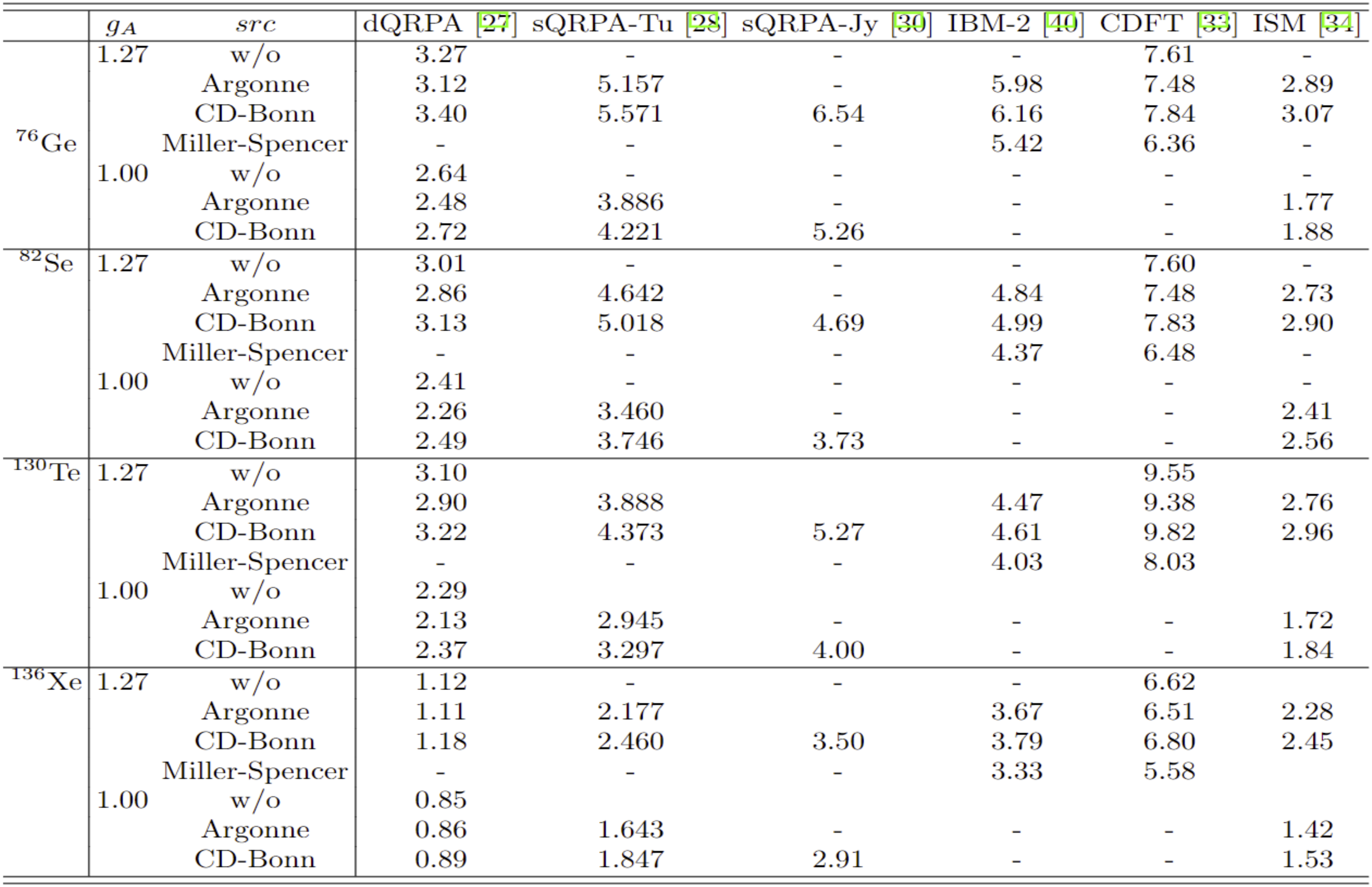
J. Cao, et al, 1908.08355

- 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



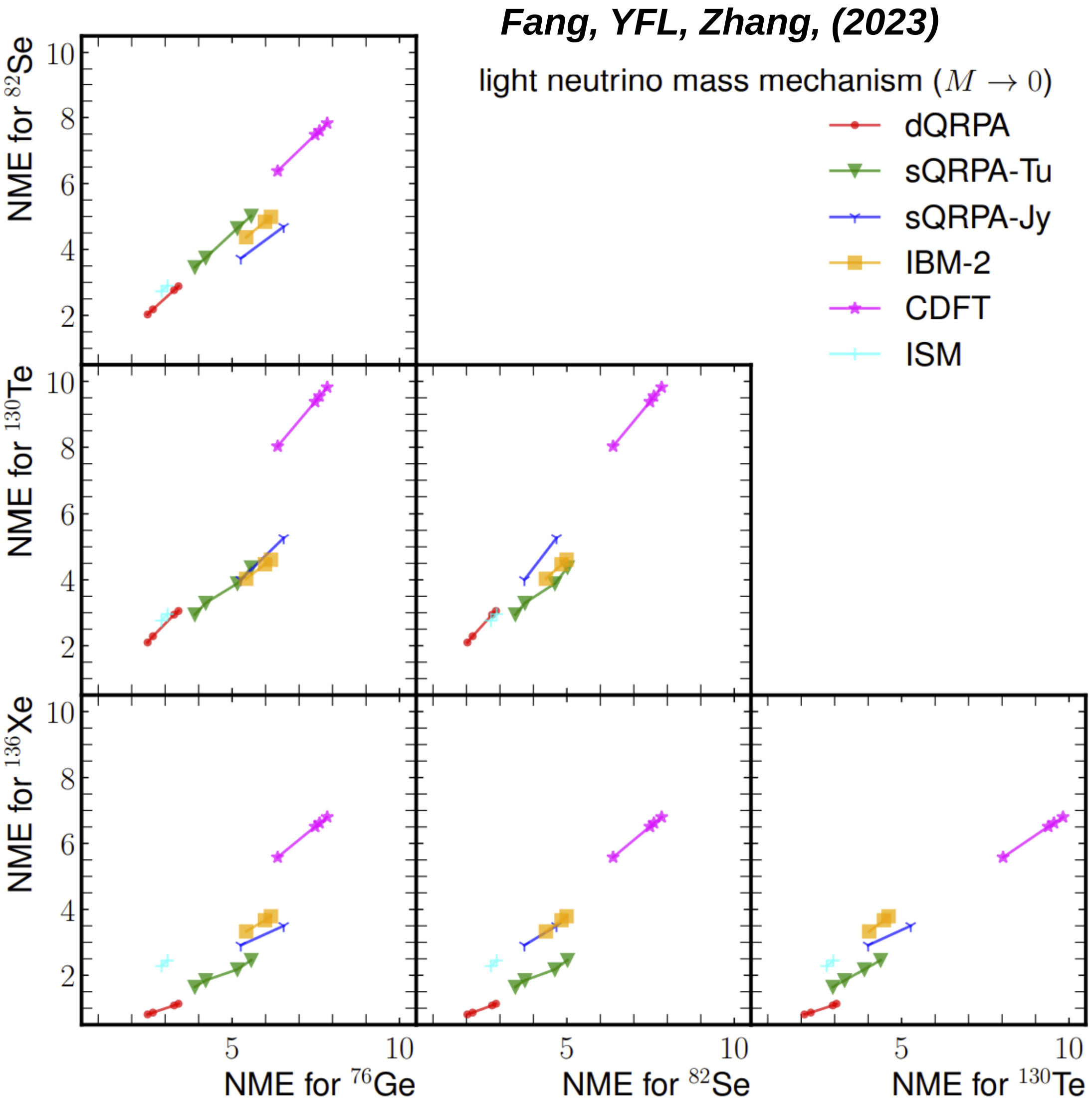


Nuclear Matrix Element (light νs)



	g_A	*src*	dQRPA [27]	sQRPA-Tu [28]	sQRPA-Jy [30]	IBM-2 [40]	CDFT [33]	ISM [34]
^{76}Ge	1.27	w/o	3.27	-	-	-	7.61	-
		Argonne	3.12	5.157	-	5.98	7.48	2.89
		CD-Bonn	3.40	5.571	6.54	6.16	7.84	3.07
		Miller-Spencer	-	-	-	5.42	6.36	-
	1.00	w/o	2.64	-	-	-	-	-
		Argonne	2.48	3.886	-	-	-	1.77
		CD-Bonn	2.72	4.221	5.26	-	-	1.88
^{82}Se	1.27	w/o	3.01	-	-	-	7.60	-
		Argonne	2.86	4.642	-	4.84	7.48	2.73
		CD-Bonn	3.13	5.018	4.69	4.99	7.83	2.90
		Miller-Spencer	-	-	-	4.37	6.48	-
	1.00	w/o	2.41	-	-	-	-	-
		Argonne	2.26	3.460	-	-	-	2.41
		CD-Bonn	2.49	3.746	3.73	-	-	2.56
^{130}Te	1.27	w/o	3.10				9.55	
		Argonne	2.90	3.888		4.47	9.38	2.76
		CD-Bonn	3.22	4.373	5.27	4.61	9.82	2.96
		Miller-Spencer	-	-	-	4.03	8.03	
	1.00	w/o	2.29					
		Argonne	2.13	2.945	-	-	-	1.72
		CD-Bonn	2.37	3.297	4.00	-	-	1.84
^{136}Xe	1.27	w/o	1.12	-	-	-	6.62	
		Argonne	1.11	2.177		3.67	6.51	2.28
		CD-Bonn	1.18	2.460	3.50	3.79	6.80	2.45
		Miller-Spencer	-	-	-	3.33	5.58	
	1.00	w/o	0.85					
		Argonne	0.86	1.643	-	-	-	1.42
		CD-Bonn	0.89	1.847	2.91	-	-	1.53

Nuclear Matrix Element (light νs)



- Correlation of different isotopes
- Each model has rather small uncertainty
- Different models differ by a factor of 3
- CDFT tends to have the largest values
- ISM predicts most of the lowest values
- QRPA has the lowest value for Xe

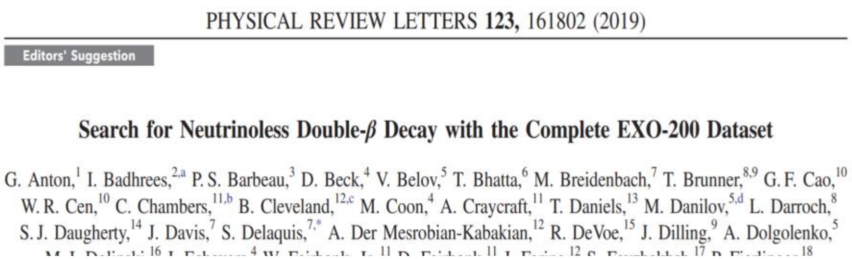
Current experimental results

PHYSICAL REVIEW LETTERS **125,** 252502 (2020)

Editors' Suggestion | Featured in Physics

Final Results of GERDA on the Search for Neutrinoless Double-β Decay

M. Agostini,[9,17] G. R. Araujo,[21] A. M. Bakalyarov,[15] M. Balata,[1] I. Barabanov,[13] L. Baudis,[21] C. Bauer,[8] E. Bellotti,[10,11] S. Belogurov,[14,13,†] A. Bettini,[18,19] L. Bezrukov,[13] V. Biancacci,[18,19] D. Borowicz,[6] E. Bossio,[17] V. Bothe,[8] V. Brudanin,[6] R. Brugnera,[18,19] A. Caldwell,[16] C. Cattadori,[11] A. Chernogorov,[14,15] T. Comellato,[17] V. D'Andrea,[2] E. V. Demidova,[14] N. Di Marco,[1] E. Doroshkevich,[13] F. Fischer,[16] M. Fomina,[6] A. Gangapshev,[13,8] A. Garfagnini,[18,19] C. Gooch,[16] P. Grabmayr,[20] V. Gurentsov,[13] K. Gusev,[6,15,17] J. Hakenmüller,[8] S. Hemmer,[19] R. Hiller,[21] W. Hofmann,[8] J. Huang,[21]

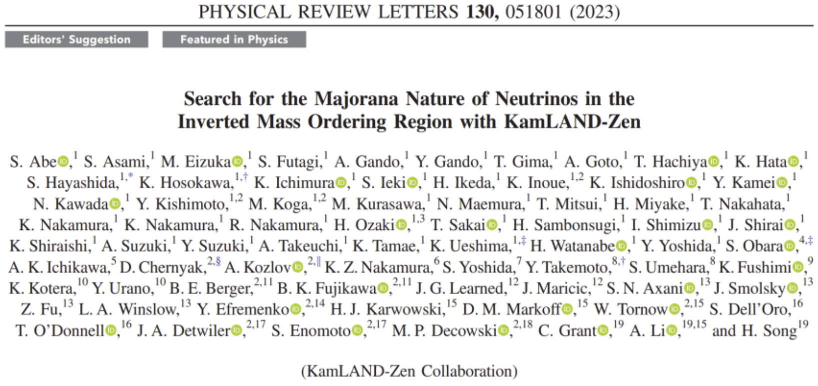


PHYSICAL REVIEW LETTERS **123,** 161802 (2019)

Editors' Suggestion

Search for Neutrinoless Double-β Decay with the Complete EXO-200 Dataset

G. Anton,[1] I. Badhrees,[2,a] P. S. Barbeau,[3] D. Beck,[4] V. Belov,[5] T. Bhatta,[6] M. Breidenbach,[7] T. Brunner,[8,9] G. F. Cao,[10] W. R. Cen,[10] C. Chambers,[11,b] B. Cleveland,[12,c] M. Coon,[4] A. Craycraft,[11] T. Daniels,[13] M. Danilov,[5,d] L. Darroch,[8] S. J. Daugherty,[14] J. Davis,[7] S. Delaquis,[7,*] A. Der Mesrobian-Kabakian,[12] R. DeVoe,[15] J. Dilling,[9] A. Dolgolenko,[5]



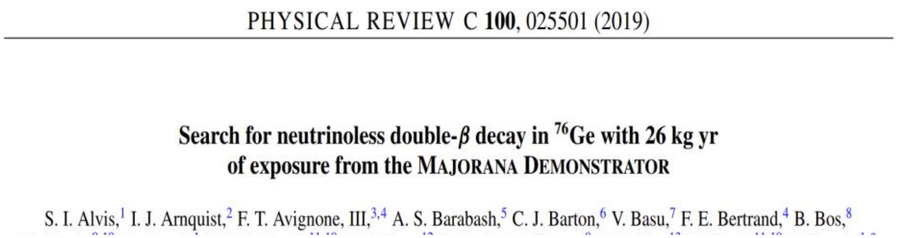
PHYSICAL REVIEW LETTERS **130,** 051801 (2023)

Editors' Suggestion | Featured in Physics

Search for the Majorana Nature of Neutrinos in the Inverted Mass Ordering Region with KamLAND-Zen

S. Abe,[1] S. Asami,[1] M. Eizuka,[1] S. Futagi,[1] A. Gando,[1] Y. Gando,[1] T. Gima,[1] A. Goto,[1] T. Hachiya,[1] K. Hata,[1] S. Hayashida,[1,*] K. Hosokawa,[1,†] K. Ichimura,[1] S. Ieki,[1] H. Ikeda,[1] K. Inoue,[1,2] K. Ishidoshiro,[1] Y. Kamei,[1] N. Kawada,[1] Y. Kishimoto,[1,2] M. Koga,[1,2] M. Kurasawa,[1] N. Maemura,[1] T. Mitsui,[1] H. Miyake,[1] T. Nakahata,[1] K. Nakamura,[1] K. Nakamura,[1] R. Nakamura,[1] H. Ozaki,[1,3] T. Sakai,[1] H. Sambonsugi,[1] I. Shimizu,[1] J. Shirai,[1] K. Shiraishi,[1] A. Suzuki,[1] Y. Suzuki,[1] A. Takeuchi,[1] K. Tamae,[1] K. Ueshima,[1,‡] H. Watanabe,[1] Y. Yoshida,[1] S. Obara,[4,‡] A. K. Ichikawa,[5] D. Chernyak,[2,§] A. Kozlov,[2,∥] K. Z. Nakamura,[6] S. Yoshida,[7] Y. Takemoto,[8,†] S. Umehara,[8] K. Fushimi,[9] K. Kotera,[10] Y. Urano,[10] B. E. Berger,[2,11] B. K. Fujikawa,[2,11] J. G. Learned,[12] J. Maricic,[12] S. N. Axani,[13] J. Smolsky,[13] Z. Fu,[13] L. A. Winslow,[13] Y. Efremenko,[2,14] H. J. Karwowski,[15] D. M. Markoff,[15] W. Tornow,[2,15] S. Dell'Oro,[16] T. O'Donnell,[16] J. A. Detwiler,[2,17] S. Enomoto,[2,17] M. P. Decowski,[2,18] C. Grant,[19] A. Li,[19,15] and H. Song[19]

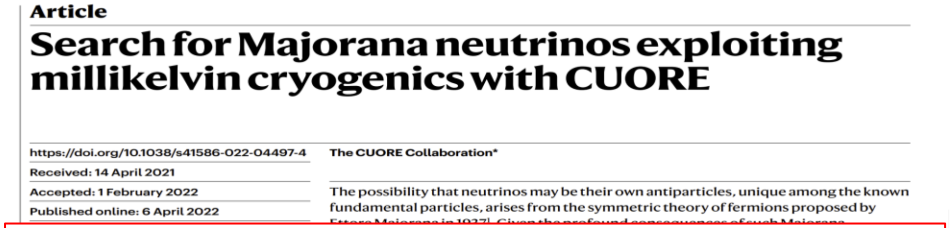
(KamLAND-Zen Collaboration)



PHYSICAL REVIEW C **100**, 025501 (2019)

Search for neutrinoless double-β decay in ^{76}Ge with 26 kg yr of exposure from the MAJORANA DEMONSTRATOR

S. I. Alvis,[1] I. J. Arnquist,[2] F. T. Avignone, III,[3,4] A. S. Barabash,[5] C. J. Barton,[6] V. Basu,[7] F. E. Bertrand,[4] B. Bos,[8]



Article

Search for Majorana neutrinos exploiting millikelvin cryogenics with CUORE

https://doi.org/10.1038/s41586-022-04497-4

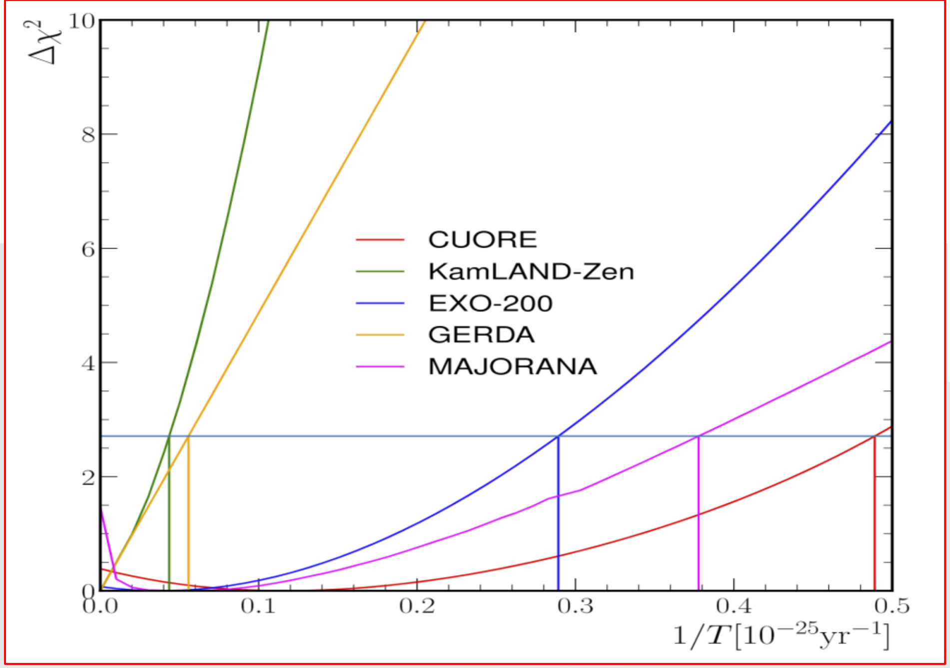
Received: 14 April 2021

Accepted: 1 February 2022

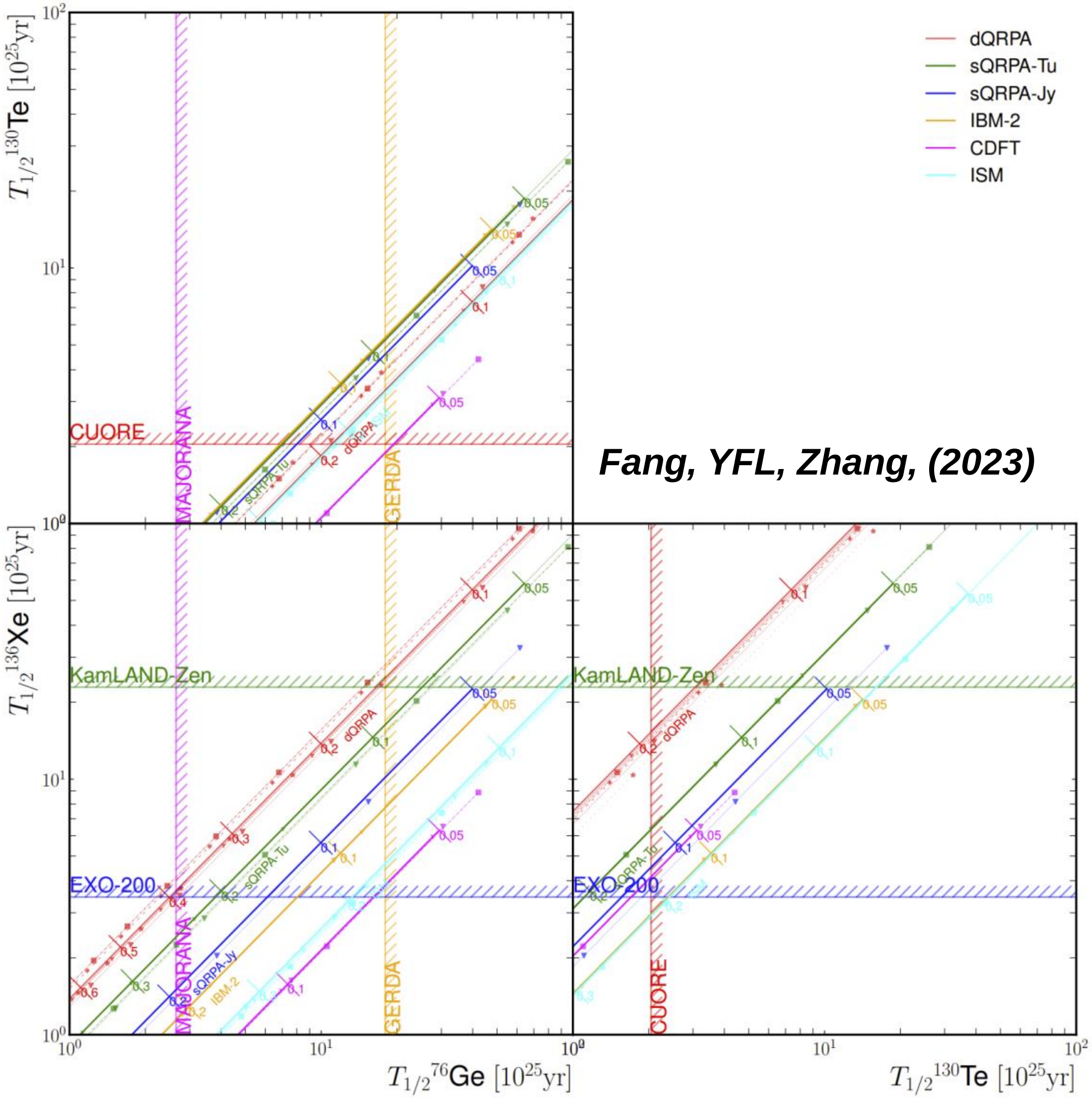
Published online: 6 April 2022

The CUORE Collaboration*

The possibility that neutrinos may be their own antiparticles, unique among the known fundamental particles, arises from the symmetric theory of fermions proposed by

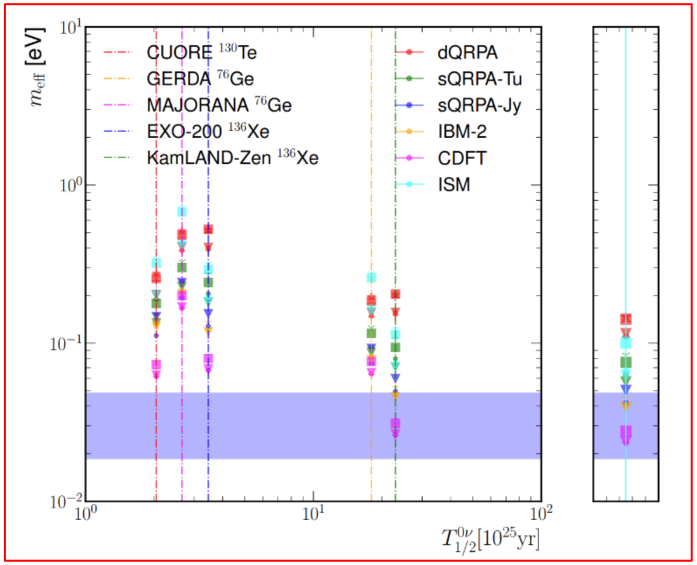


Current experimental results



Fang, YFL, Zhang, (2023)

- **Results of Both Ge & Xe have reached 100 meV**
- **KamLAND-Zen even entered the boundary of IMO (50 meV)**
- **Important implications on the parameter space, and even additional contributions!**



Dirac and Majorana mass Lagrangian

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

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

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

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

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

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

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

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

Seesaw Mechanism

- **The smallness of light neutrino masses ←**

Seesaw: $m_R \gg m_D$

$$\text{diagonalization of } \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \Longrightarrow m_\nu \simeq \frac{m_D^2}{m_R} \qquad m_N \simeq m_R$$

- **In general, the light and heavy mass eigenstates are mixed:**

$$\begin{pmatrix} 0 & M_\mathrm{D} \\ M_\mathrm{D}^\mathrm{T} & M_\mathrm{R} \end{pmatrix} = \begin{pmatrix} U & R \\ S & V \end{pmatrix} \begin{pmatrix} \hat{M}_\nu & 0 \\ 0 & \hat{M}_\mathrm{R} \end{pmatrix} \begin{pmatrix} U & R \\ S & V \end{pmatrix}^\mathrm{T}$$

- **Exact seesaw relation:**

$$\sum_i U_{\alpha i}^2 m_i + \sum_I R_{\alpha I}^2 M_I = 0.$$

- **Connection of the low energy and high energy parameters**

- **A minimal (3+2) seesaw: two heavy neutrinos** ***(hep-ph/0208157)***

“Seesaw fair play rule” [0706.0052]: one massless active neutrino !

How to include heavy neutrinos?

- **To include the contribution of heavy neutrinos (aka, right handed neutrinos, or sterile neutrinos):**
- **Mass Dependent Nuclear Matrix Elements**

$$\boxed{f_\beta(M) = \frac{M_{0\nu}(M)}{M_{0\nu}(0)} \simeq \frac{\langle p^2\rangle}{\langle p^2\rangle + M^2}\,.}$$

Faessler et al, 1408.6077
See also 2303.04168

(a) When the masses are small enough

$$\boxed{\sum_i U_{\alpha i}^2 m_i + \sum_I R_{\alpha I}^2 M_I = 0.}$$

(b) When the masses are large enough

$$\boxed{m_{\rm eff} \simeq m_{\rm eff}^\nu}$$

e.g., Xing, 0907.3014

(c) One light enough & others large enough (e.g., eV sterile neutrino)

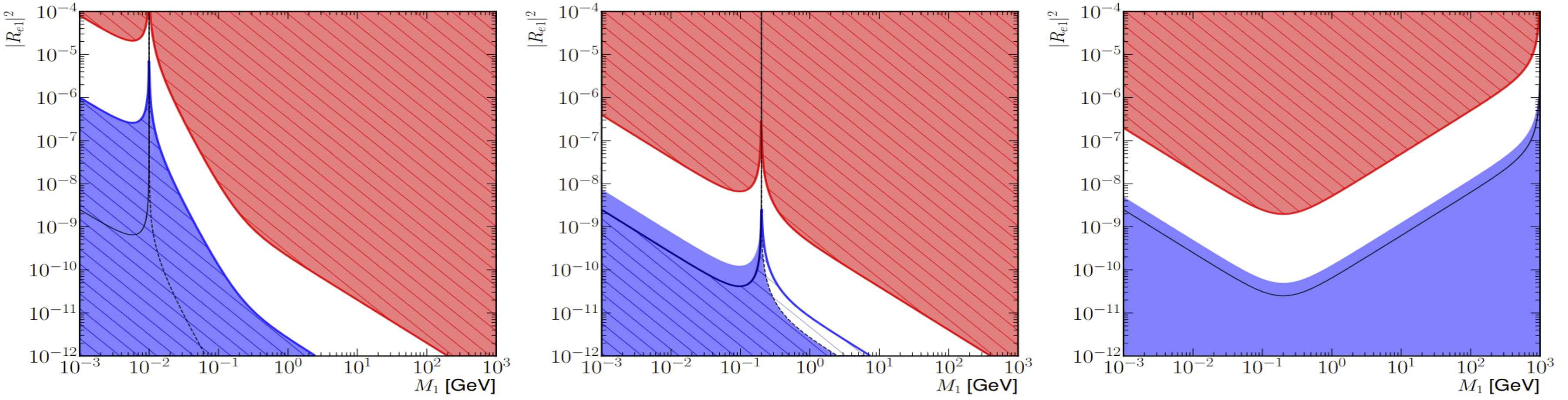
(d) Minimal 3+2 seesaw for a general study

Fang, YFL, Zhang, 2112.12779

$$\boxed{m_{\rm eff} = m_{\rm eff}^\nu - m_{\rm eff}^\nu f_\beta(M_2) + R_{e1}^2 M_1 \left[f_\beta(M_1) - f_\beta(M_2)\right]}$$

Generalized $m_{\beta\beta}$

$$m_{\text{eff}} = m^{\nu}_{\text{eff}} + m^{N}_{\text{eff}} = \sum_{i=1}^{3} U_{ei}^2 m_i + \sum_{I=1}^{2} R_{eI}^2 M_I f_\beta(M_I)$$

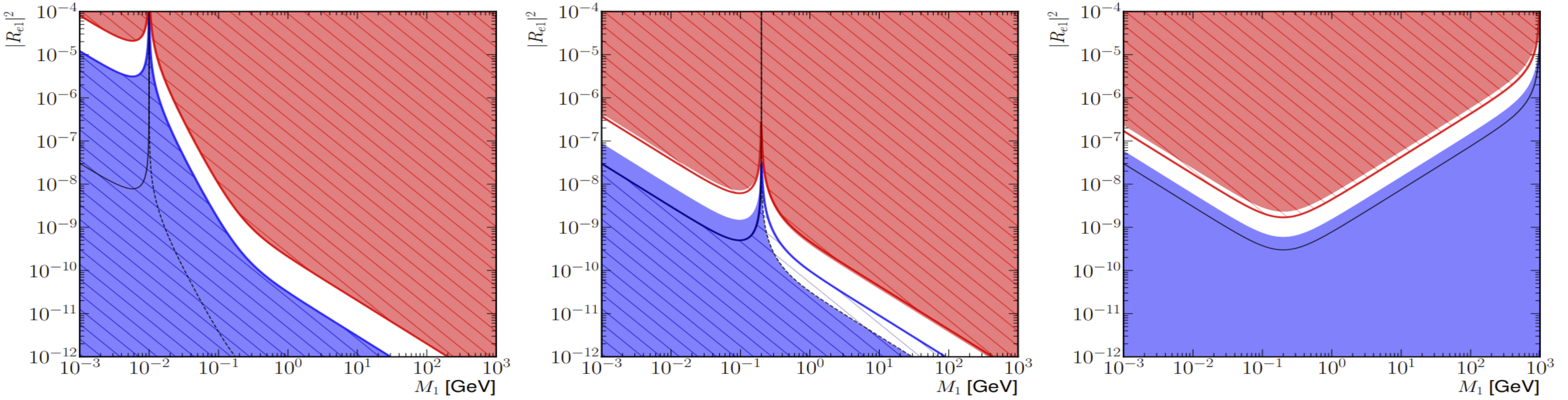


(a)NH, $M_2 = 10$ MeV

(b)NH, $M_2 = 200$ MeV

(c)NH, $M_2 = 1$ TeV

Fang, YFL, Zhang, 2112.12779

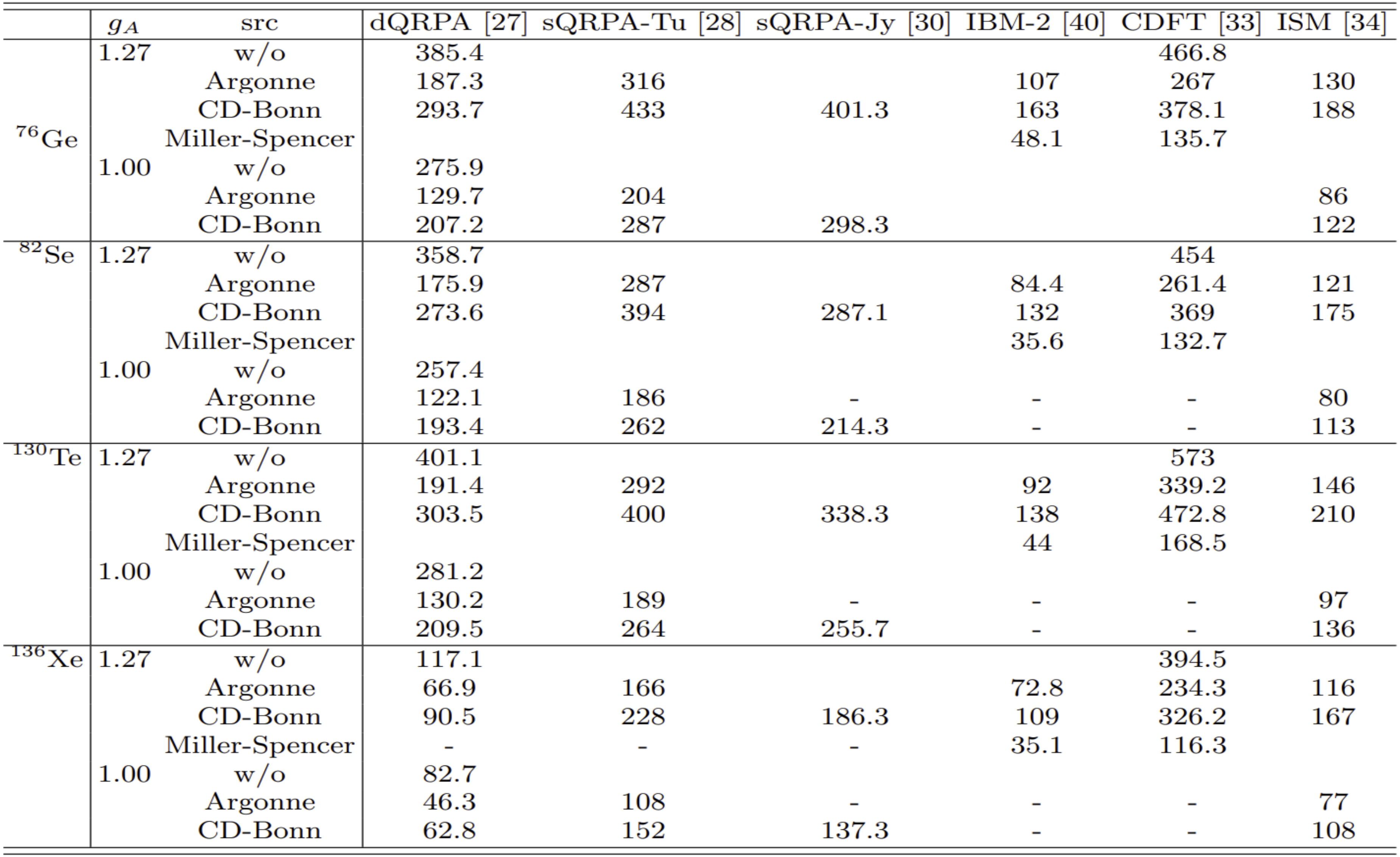


(d)IH, $M_2 = 10$ MeV

(e)IH, $M_2 = 200$ MeV

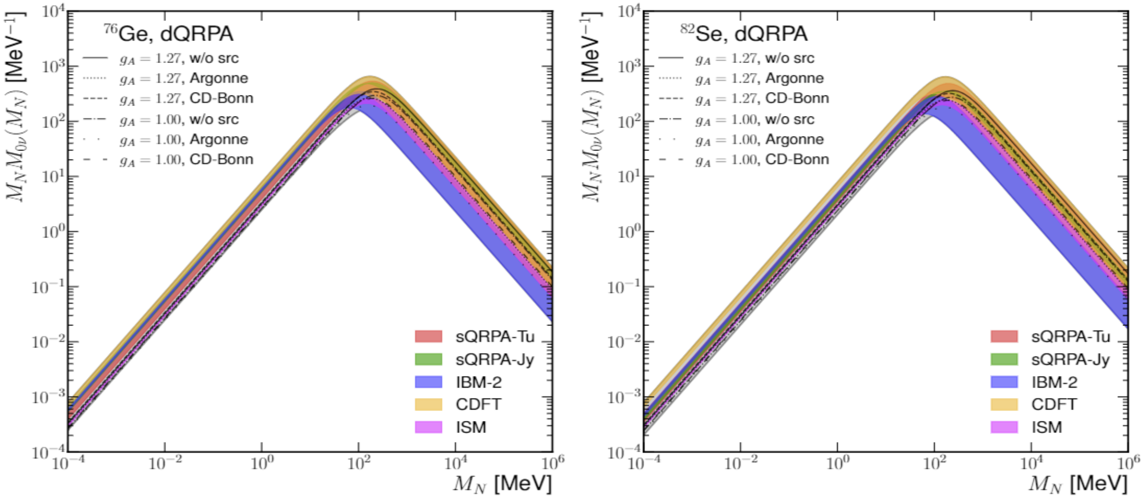
(f)IH, $M_2 = 1$ TeV

Nuclear Matrix Element (heavy νs)

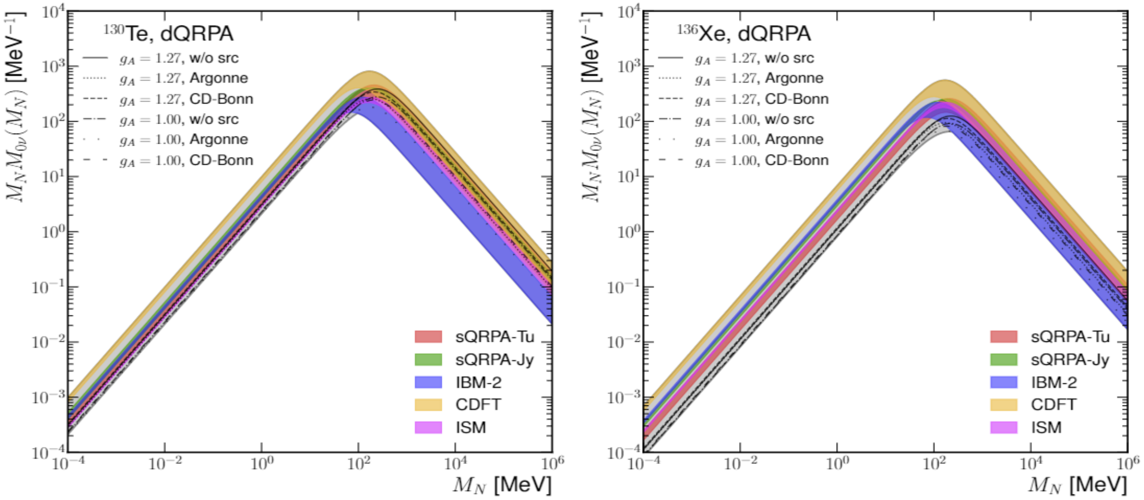


	g_A	src	dQRPA [27]	sQRPA-Tu [28]	sQRPA-Jy [30]	IBM-2 [40]	CDFT [33]	ISM [34]
^{76}Ge	1.27	w/o	385.4				466.8	
		Argonne	187.3	316		107	267	130
		CD-Bonn	293.7	433	401.3	163	378.1	188
		Miller-Spencer				48.1	135.7	
	1.00	w/o	275.9					
		Argonne	129.7	204				86
		CD-Bonn	207.2	287	298.3			122
^{82}Se	1.27	w/o	358.7				454	
		Argonne	175.9	287		84.4	261.4	121
		CD-Bonn	273.6	394	287.1	132	369	175
		Miller-Spencer				35.6	132.7	
	1.00	w/o	257.4					
		Argonne	122.1	186	-	-	-	80
		CD-Bonn	193.4	262	214.3	-	-	113
^{130}Te	1.27	w/o	401.1				573	
		Argonne	191.4	292		92	339.2	146
		CD-Bonn	303.5	400	338.3	138	472.8	210
		Miller-Spencer				44	168.5	
	1.00	w/o	281.2					
		Argonne	130.2	189	-	-	-	97
		CD-Bonn	209.5	264	255.7	-	-	136
^{136}Xe	1.27	w/o	117.1				394.5	
		Argonne	66.9	166		72.8	234.3	116
		CD-Bonn	90.5	228	186.3	109	326.2	167
		Miller-Spencer	-	-	-	35.1	116.3	
	1.00	w/o	82.7					
		Argonne	46.3	108	-	-	-	77
		CD-Bonn	62.8	152	137.3	-	-	108

Mass Dependent Nuclear Matrix Elements



Fang, YFL, Zhang (2023)



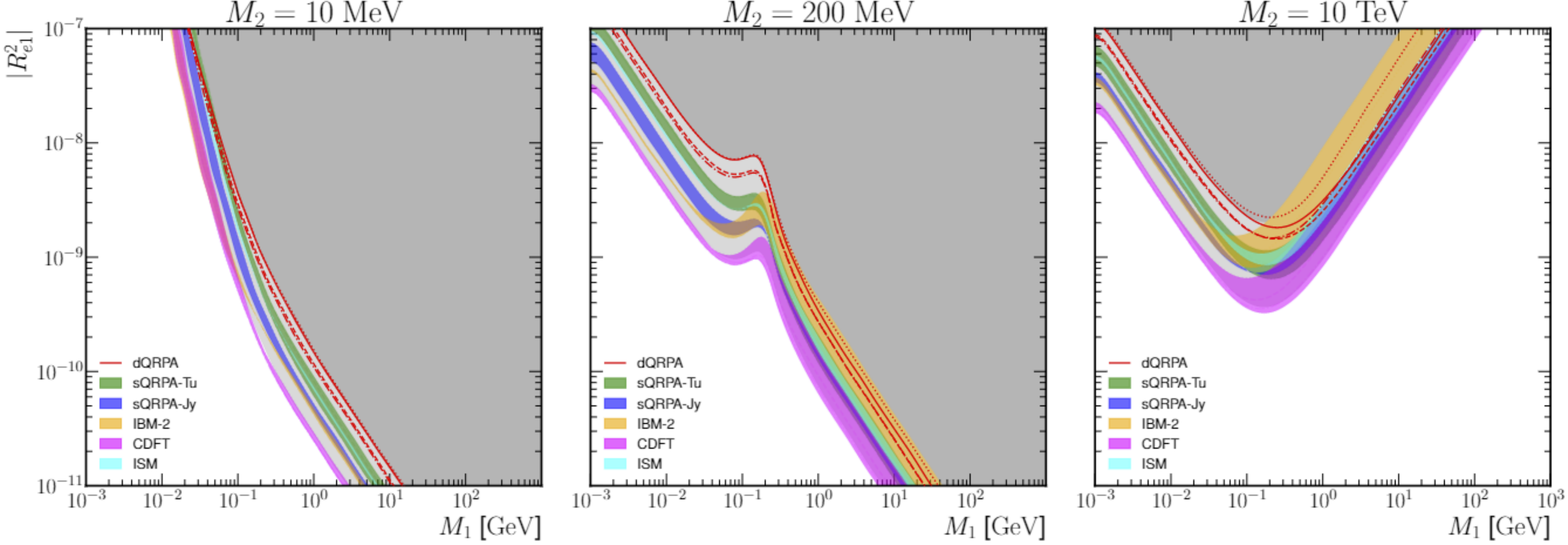
- **dQRPA: Numerical calculation**
- **Others: interpolation with two extreme values**

$$f_\beta(M) = \frac{M_{0\nu}(M)}{M_{0\nu}(0)} \simeq \frac{\langle p^2 \rangle}{\langle p^2 \rangle + M^2} .$$

- **dQRPA, agrees with ISM for light νs and tends to be consistent with CDFT for heavy νs**
- **At high mass region, IBM-2 tends to have the smallest values**

Minimal seesaw: current limits

Normal ordering



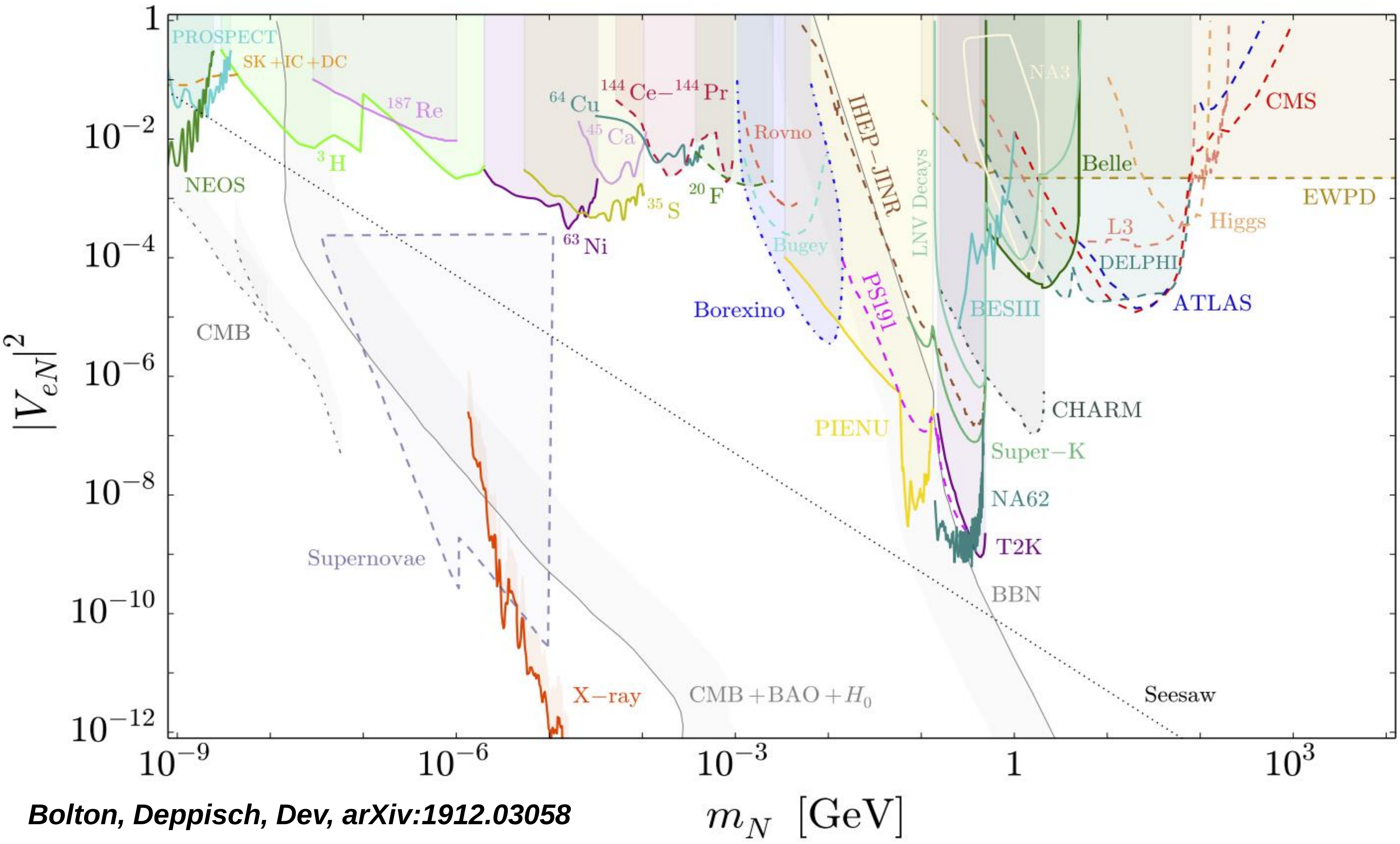
Fang, YFL, Zhang, To appear

- **Different choices of parameters and models are scanned (not as Guassian)**
- **Both the $0\nu2\beta$-decay and oscillation data are used**
- **Interpretations of three benchmark scenarios: two different roles!**

$$m_{\rm eff} = m^{\nu}_{\rm eff} - m^{\nu}_{\rm eff} f_\beta(M_2) + R^2_{e1} M_1 \left[f_\beta(M_1) - f_\beta(M_2)\right]$$

$$f_\beta(M) = \frac{\mathcal{M}_{0\nu}(M)}{\mathcal{M}_{0\nu}(0)} \simeq \frac{\langle p^2\rangle}{\langle p^2\rangle + M^2} \, .$$

Heavy νs: different probes



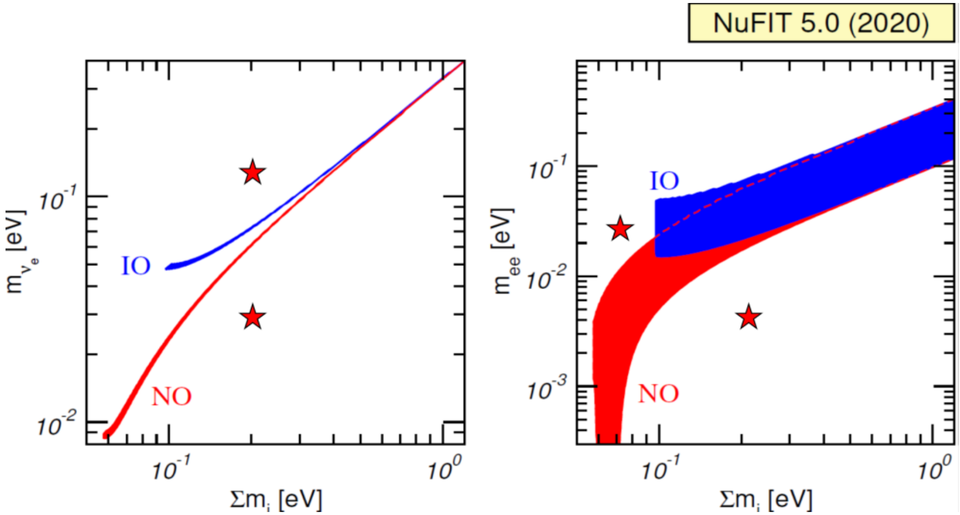
Bolton, Deppisch, Dev, arXiv:1912.03058

Conclusion

- **Neutrino-less double decay:**

  A smoking gun of the neutrino Majorana nature!

- **After the observation of $0\nu2\beta$, what is the true mechanism for neutrino mass generation and the $0\nu2\beta$ process ?**



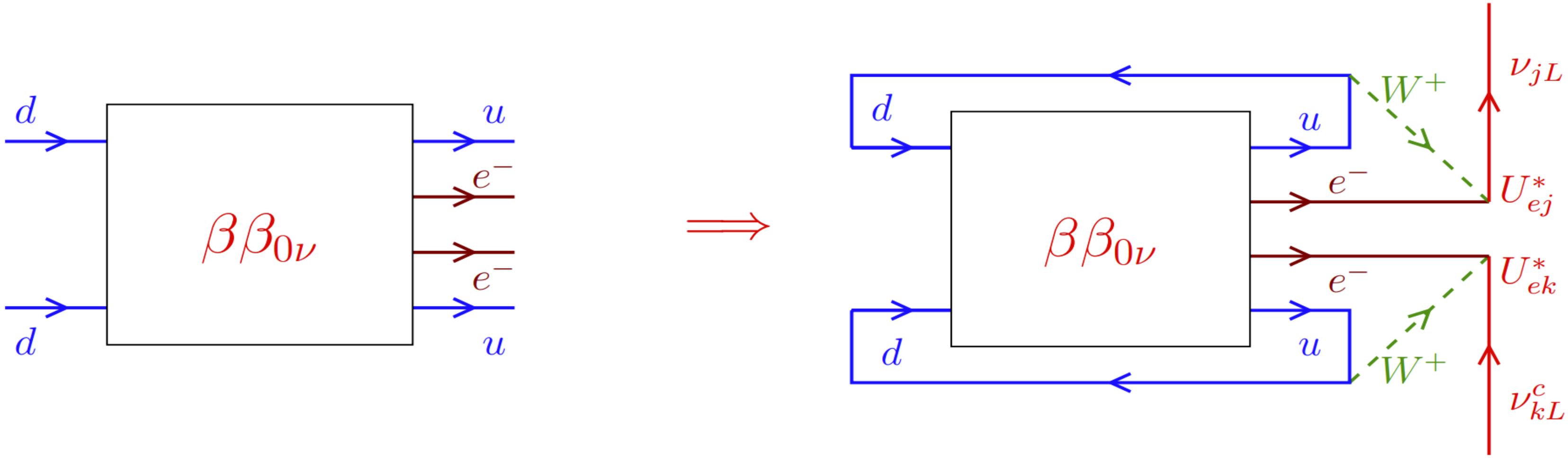
- **In the type-I seesaw model, we have obtained the experimental limits on the seesaw parameters by using**

  a) the $0\nu2\beta$ data and neutrino oscillation data,
  b) global model predictions of nuclear matrix elements,
  c) and seesaw relation of light and heavy neutrino masses.

Thank you!

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:



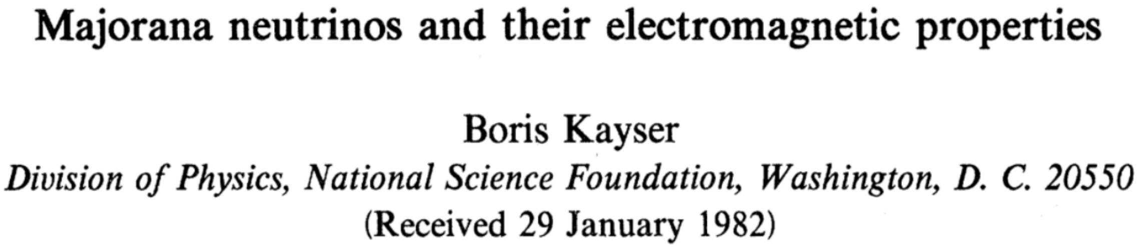
[Schechter, Valle, PRD 25 (1982) 2951; Takasugi, PLB 149 (1984) 372]

- 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]

Majorana-Dirac confusion theorem



Majorana neutrinos and their electromagnetic properties

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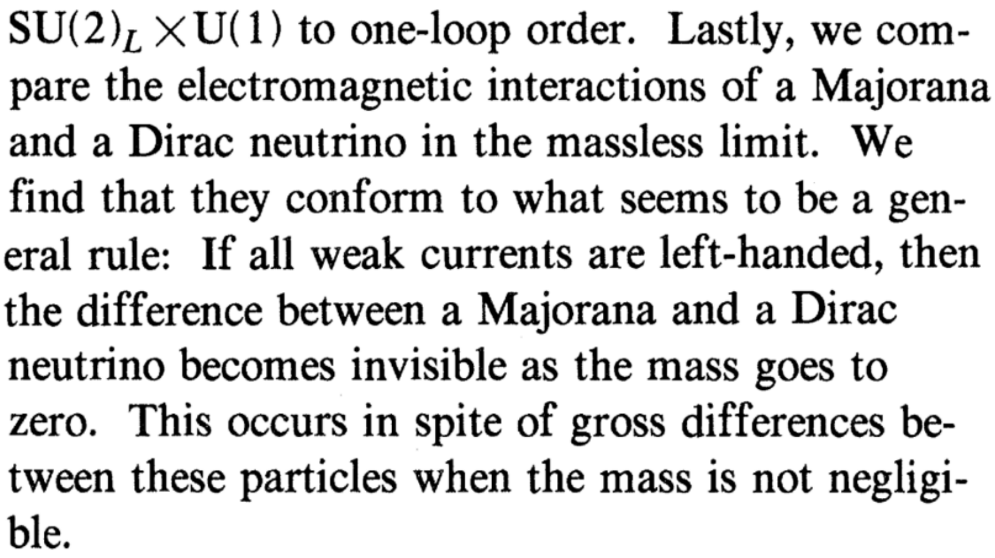
(Received 29 January 1982)

Phys.Rev.D 26 (1982) 1662



SU(2)$_L$ × 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

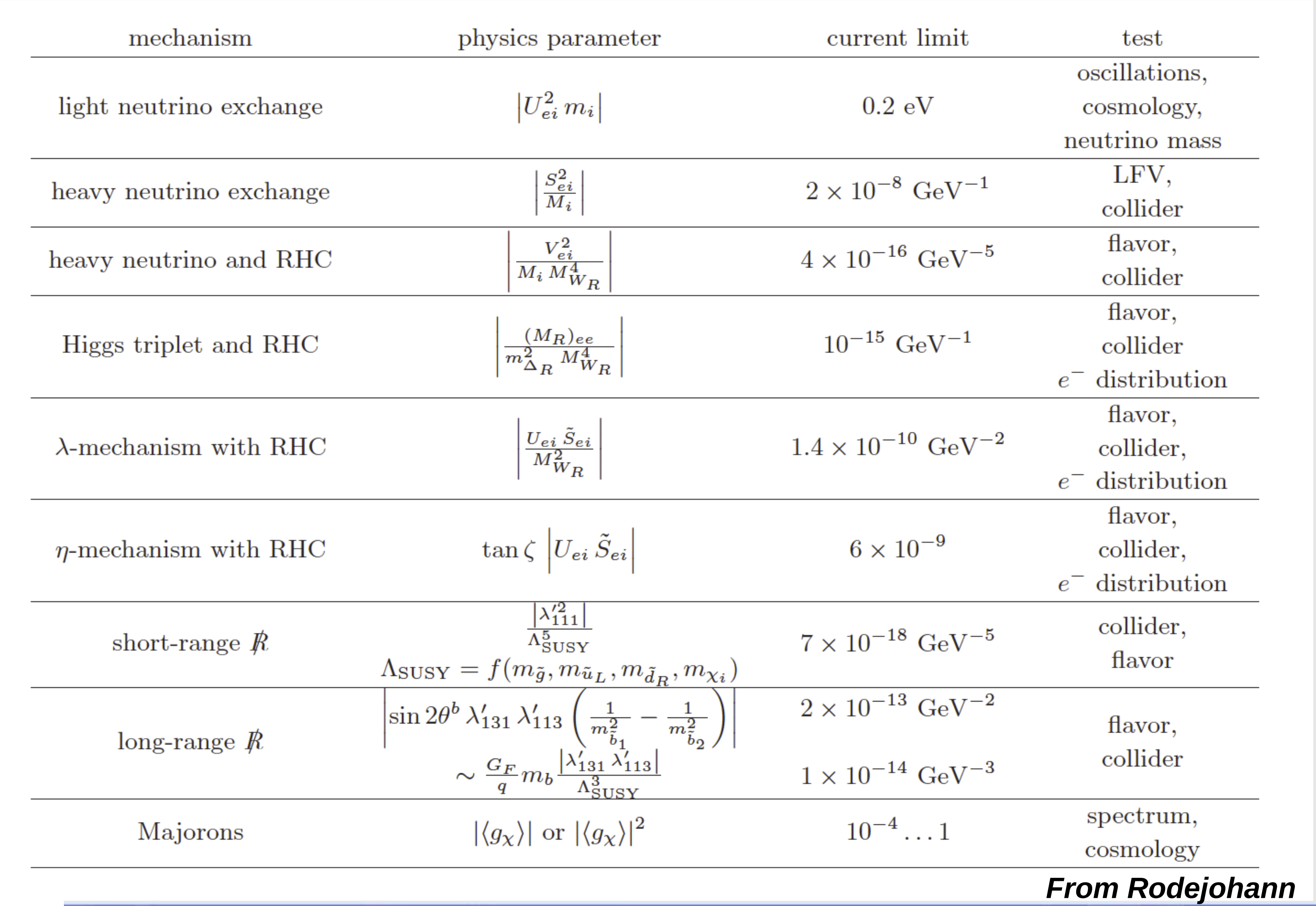
Practical Majorana-Dirac Confusion Theorem

- **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: $0\nu 2\beta$-decay**

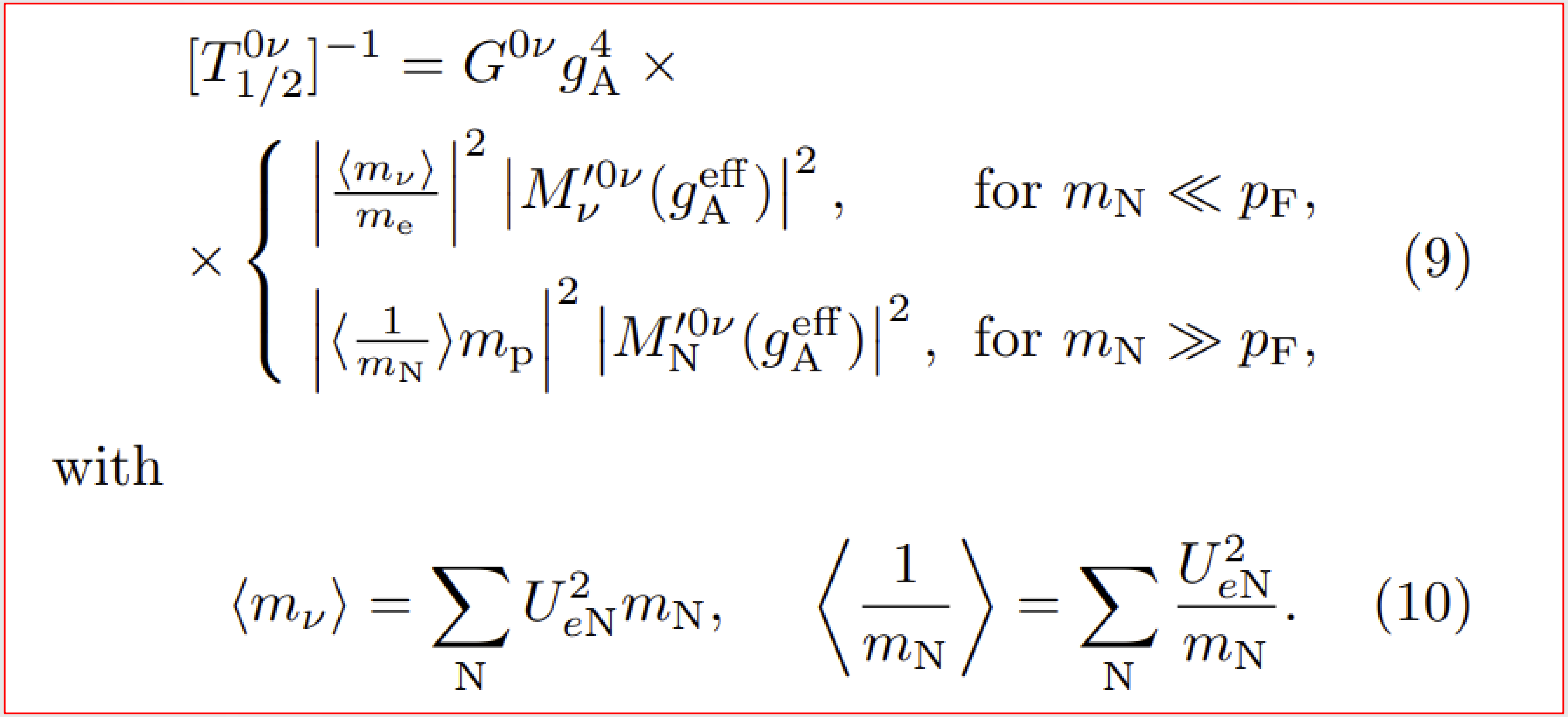
Other mechanisms



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

From Rodejohann

Convention of nuclear matrix element



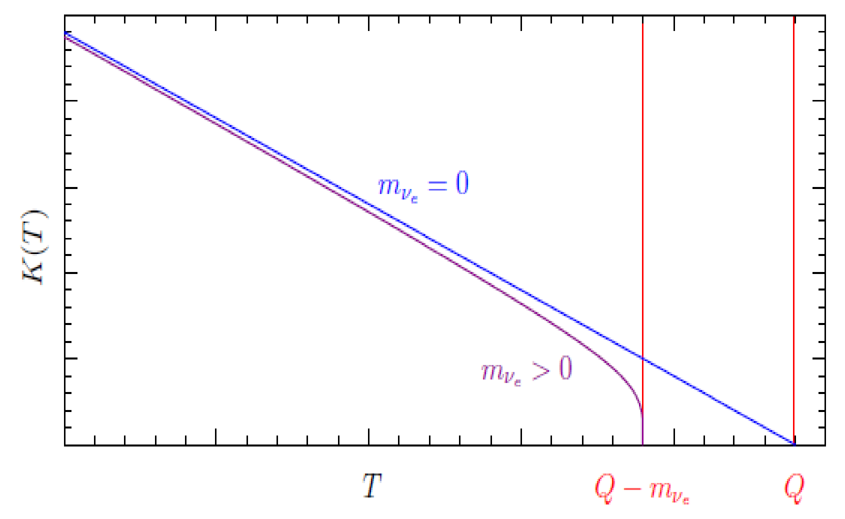
$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu} g_{\mathrm{A}}^{4} \times \times \begin{cases} \left|\frac{\langle m_\nu \rangle}{m_{\mathrm{e}}}\right|^2 \left|M_\nu'^{0\nu}(g_{\mathrm{A}}^{\mathrm{eff}})\right|^2, & \text{for } m_{\mathrm{N}} \ll p_{\mathrm{F}}, \\ \left|\langle \frac{1}{m_{\mathrm{N}}} \rangle m_{\mathrm{p}}\right|^2 \left|M_{\mathrm{N}}'^{0\nu}(g_{\mathrm{A}}^{\mathrm{eff}})\right|^2, & \text{for } m_{\mathrm{N}} \gg p_{\mathrm{F}}, \end{cases} \tag{9}$$

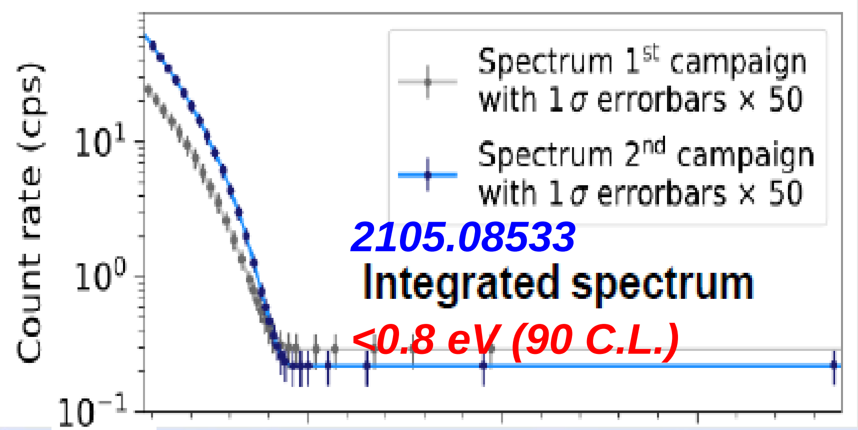
with

$$\langle m_\nu \rangle = \sum_{\mathrm{N}} U_{e\mathrm{N}}^2 m_{\mathrm{N}}, \quad \left\langle \frac{1}{m_{\mathrm{N}}} \right\rangle = \sum_{\mathrm{N}} \frac{U_{e\mathrm{N}}^2}{m_{\mathrm{N}}}. \tag{10}$$

Absolute neutrino masses: beta-decay

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





2105.08533

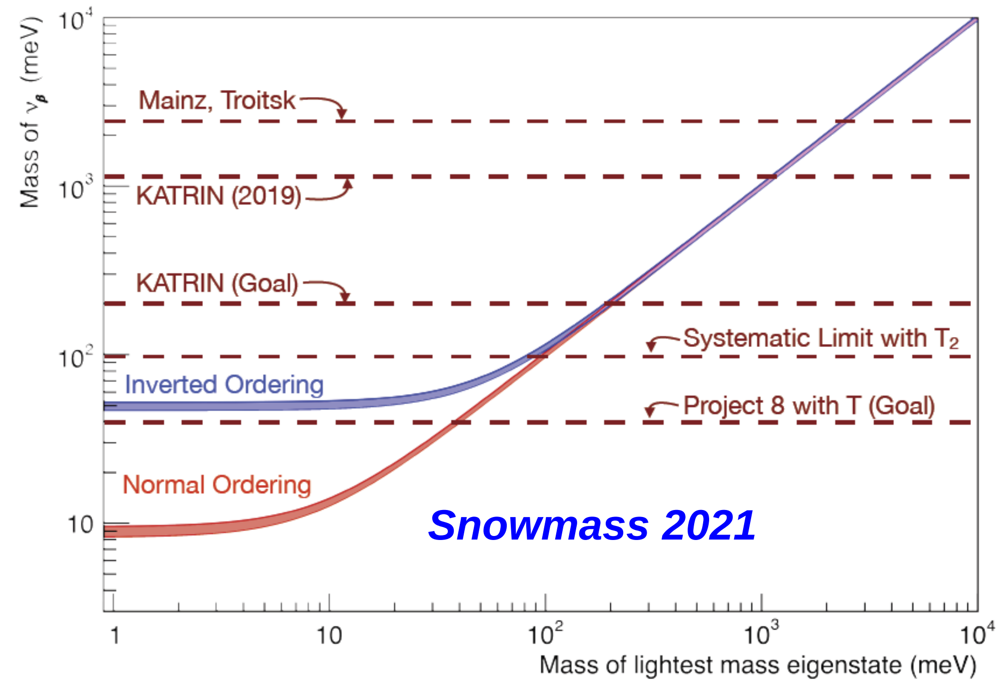
Integrated spectrum

<0.8 eV (90 C.L.)

Future Prospect:

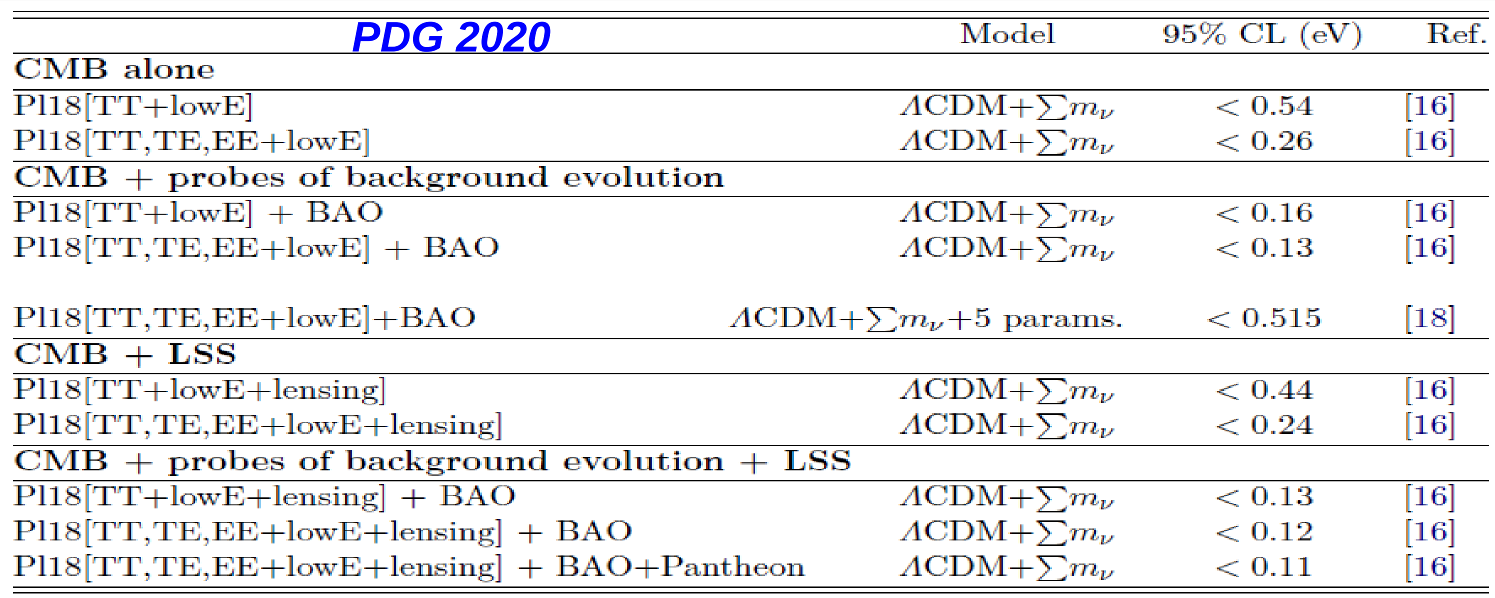
$$m_\beta^2 = \sum_k |U_{ek}|^2 m_k^2$$

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



Snowmass 2021

Absolute neutrino masses: cosmology



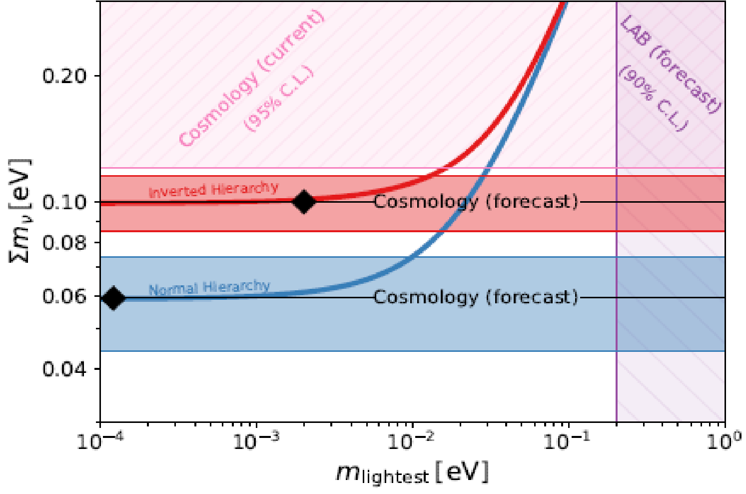
PDG 2020

	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



Low energy 3ν mixing

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

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