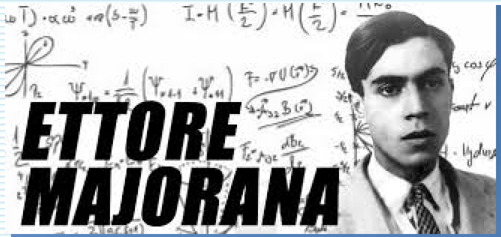
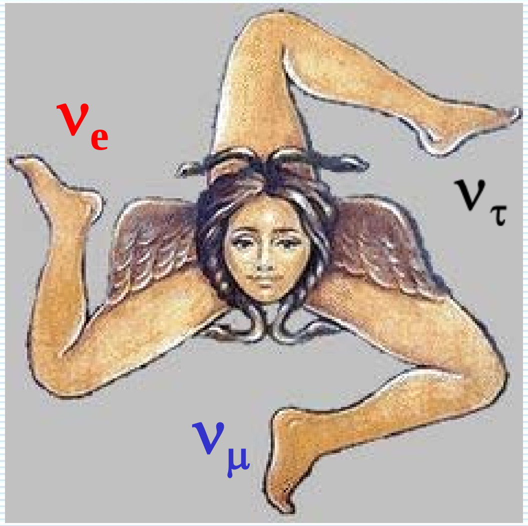
VIENNA, September 5 (Mon) – 9 (Fri), 2022

Double Beta Decay (status and future)

Fedor Šimkovic



OUTLINE



I. *Introduction* ***(brief history, Majorana ν's,)***

II. The *0νββ-decay experiments, status and perspectives*

(Gerda/Majorana/Legend, EXO,KamLAND-Zen, NEXT, CUORE, CUPID, etc.)

III. ν-mass *0νββ-decay mechanisms*

(QCSS scenario, sterile ν, LR symmetric model, LNV at LHC)

IV. *The 2νββ-decay and new physics*

(sterile heavy ν, right-handed ν)

V. The *0νββ-decay NMEs, current status*

(nuclear structure approaches, uncertainties, contact term)

VI. *Supporting nuclear experiments and effective* g_A

(β-decay, 2νββ-decay, muon capture, heavy-ion DCX)

V. *Outlook*

Acknowledgements:

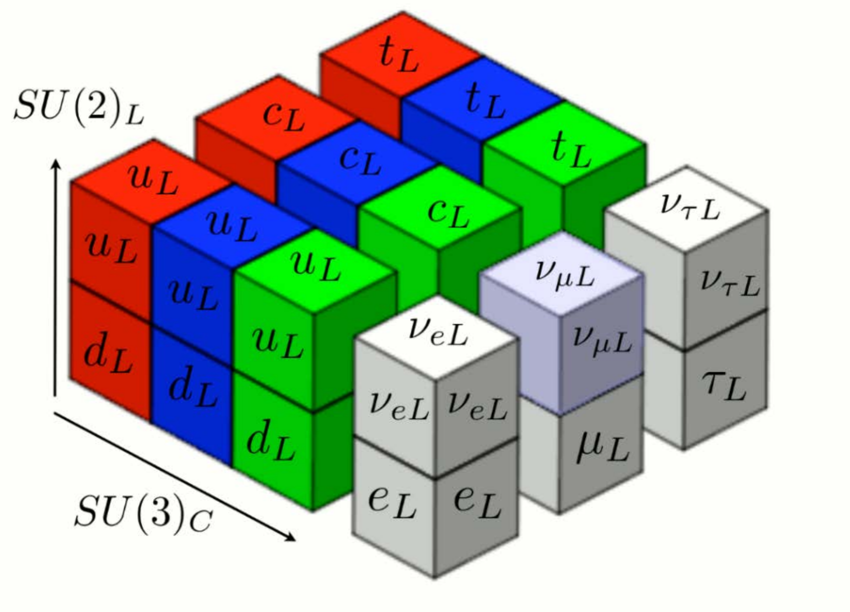
0νββ-decay exp.: *A. Giuliani, G. Gratta, Ch. Marques, I. Shimizu, L. Szimard, D. Waters*

0νββ-decay theory: *S. Bilenky, V. Cirigliano, S. Kovalenko, M. Krivoruchenko, S. Petcov, A. Smetana*

0νββ-decay NMEs: *C. Agodi, F. Cappuzzello, J. Engel, E. Lisi, P. Vogel,*

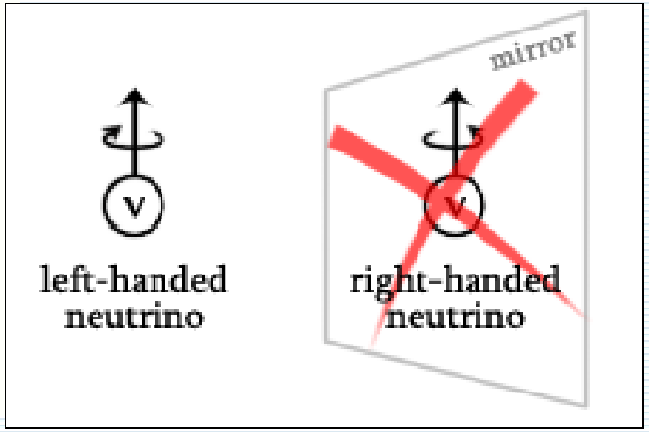
and other colleagues and friends.

Standard Model
(an astonishing successful theory,
based on few principles)



ν is a special particle in SM:

- **It is the only fermion that does not carry electric charge (like γ, g, H^0)**
- **There are only left-handed ν's (ν_{eL}, $\nu_{\mu L}$, $\nu_{\tau L}$)**
- **ν-mass can not be generated with any renormalizable coupling with the Higgs fields through SSB**



ν's oscillations experiments
⇒ tiny neutrino masses (!)
⇒ Beyond SM physics (!)

, etc

Majorana fermions

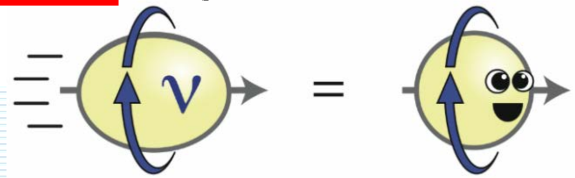
Ettore Majorana
Teoria simmetrica dell'elettrone e del positrone
(A symmetric theory of electrons and positrons).
Il Nuovo Cimento, 14: 171–184, 1937.) 171

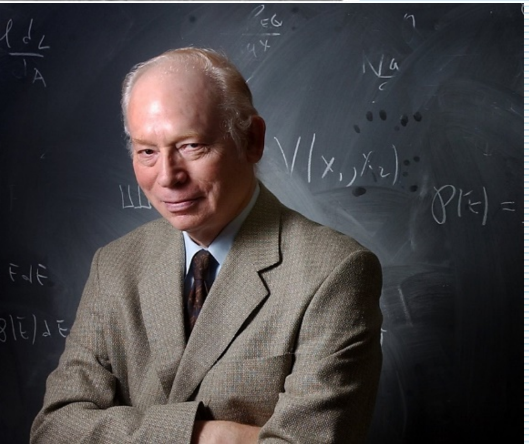
ν is its own antiparticle

It follows from the above assumptions that in vacuum a neutrino can be transformed into an antineutrino and vice versa. This means that the neutrino and antineutrino are "mixed" particles, i.e., a symmetric and antisymmetric combination of two truly neutral Majorana particles ν_1 and ν_2 of different combined parity.[5]

Bruno Pontecorvo
Inverse beta processes and nonconservation of lepton charge
Zhur. Eksptl'. i Teoret. Fiz. 34, 247 (1958)

ν ↔ anti-ν oscillation



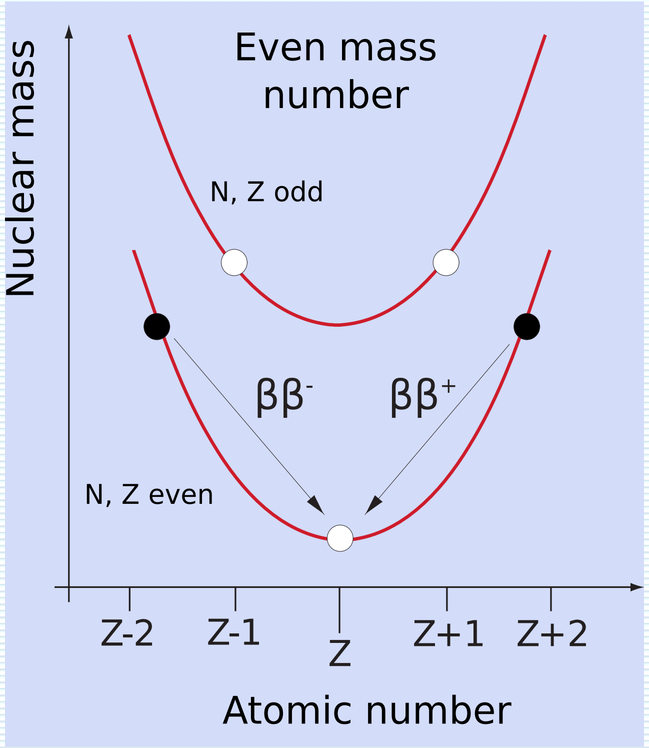


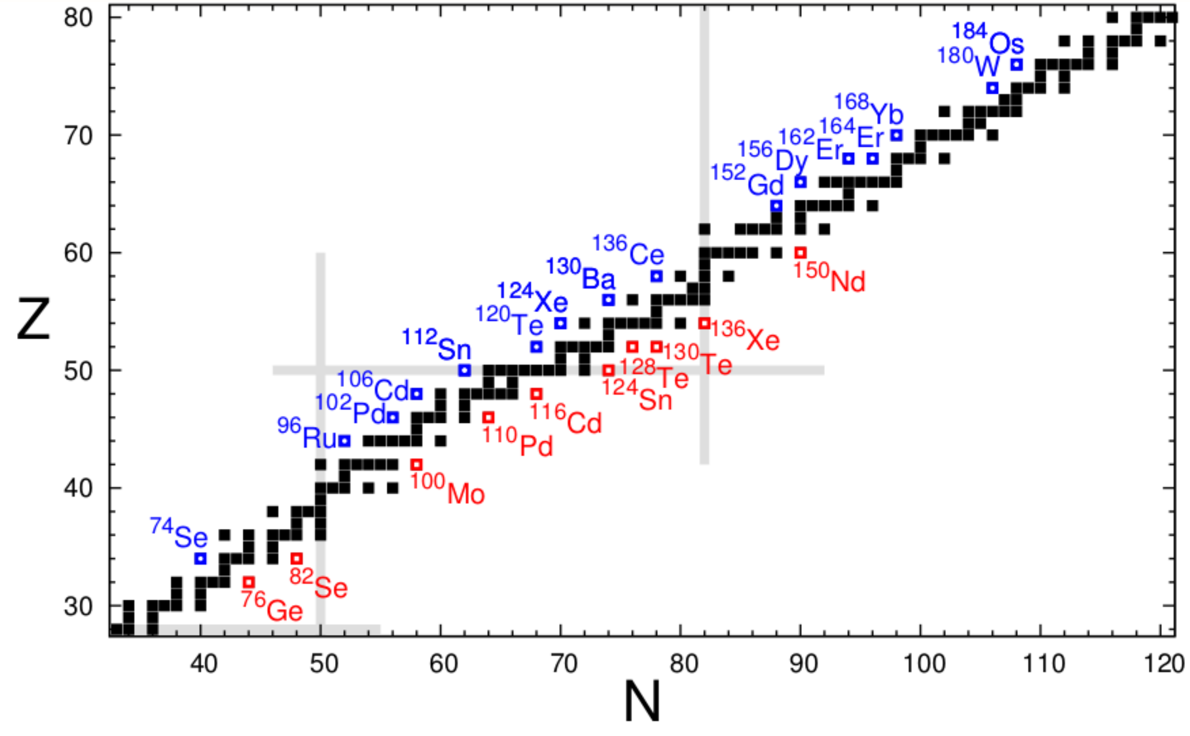
Steve Weinberg
ν-mass generation via d=5 eff. oper. related to unknown high energy scale (GUT?)

thought massless back in 1979. Weinberg does not take credit for predicting neutrino masses, but he thinks it's the right interpretation. What's more, he says, the non-renormalisable interaction that produces the neutrino masses is probably also accompanied with non-renormalisable interactions that produce proton decay and other things that haven't been observed, such as violation of baryon-number conservations. "We don't know anything about the details of those terms, but I'll swear they are there."

Nuclear double-β decay

(even-even nuclei, pairing int.)





Phys. Rev. 48, 512 (1935)

Two-neutrino double-β decay – LN conserved

$(A,Z) \rightarrow (A,Z+2) + e^- + e^- + \nu_e + \nu_e$

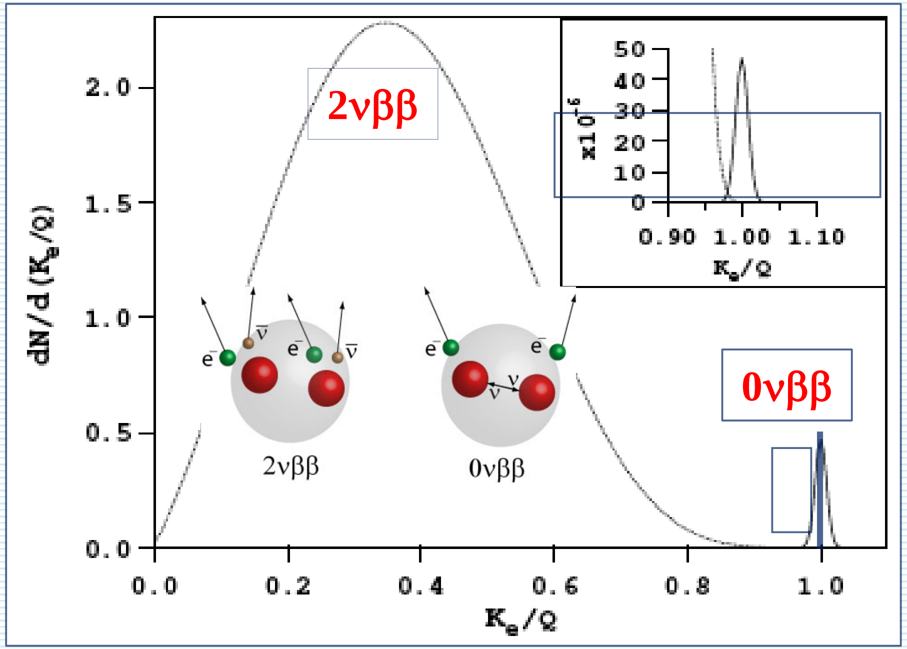
Goepert-Mayer – 1935. 1st observation in 1987

Nuovo Cim. 14, 322 (1937)   Phys. Rev. 56, 1184 (1939)

Neutrinoless double-β decay – LN violated

$(A,Z) \rightarrow (A,Z+2) + e^- + e^-$ (Furry 1937)

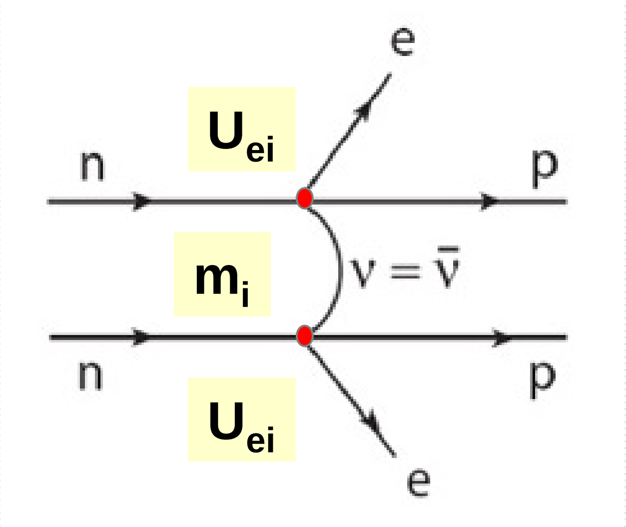
Not observed yet. Requires massive Majorana ν's



$(A,Z) \rightarrow (A,Z+2) + e^- + e^-$

$0\nu\beta\beta$-decay

(LNV at ≈GUT scale, exchange of three light ν)



$$\left(T^{0\nu}_{1/2}\right)^{-1} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 g_A^4 \left|M^{0\nu}_{\nu}\right|^2 G^{0\nu}$$

?

Phase space factor well understood

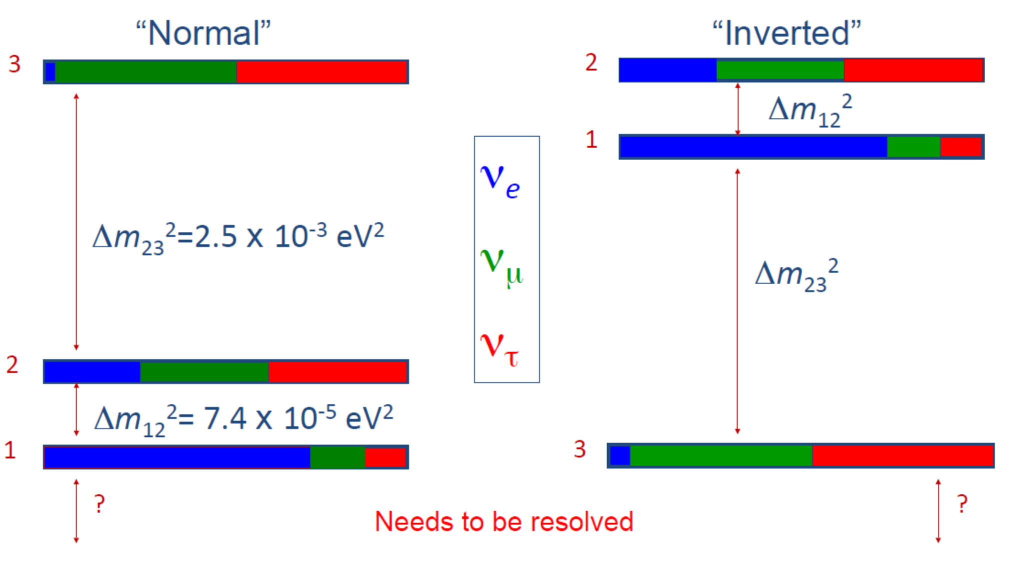
NME must be evaluated using tools of nuclear theory

Effective Majorana mass can be evaluated. It depends on

$m_1, m_2, m_3, \theta_{12}, \theta_{13}, \alpha_1, \alpha_2$

(3 unknown parameters: m_1/m_3, α_1, α_2 and ν-mass hierarchy)

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 e^{i\alpha_1} m_1 + c_{13}^2 s_{12}^2 e^{i\alpha_2} m_2 + s_{13}^2 m_3\right|$$

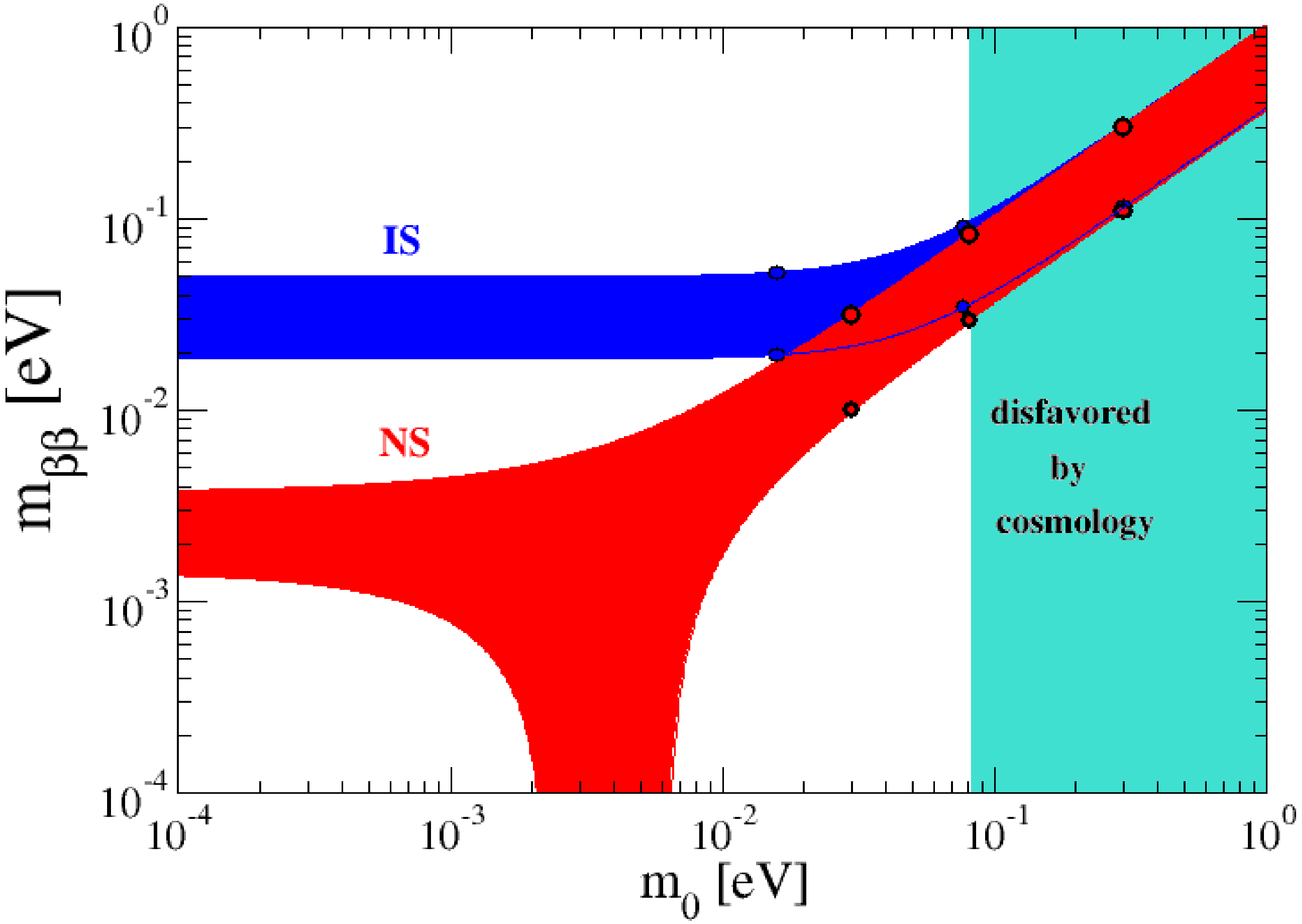


$$U^{PMNS} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -c_{23}s_{12} - e^{i\delta}c_{12}s_{13}s_{23} & c_{12}c_{23} - e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - e^{i\delta}c_{12}c_{23}s_{13} & -e^{i\delta}c_{23}s_{12}s_{13} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Effective Majorana ν-mass $m_{\beta\beta}$
(prediction due ν-oscillations)

Constraint from cosmology
$\Sigma = m_1 + m_2 + m_3$
< 0.90 eV
< 0.26 eV (Planck coll.)
< 0.12 eV

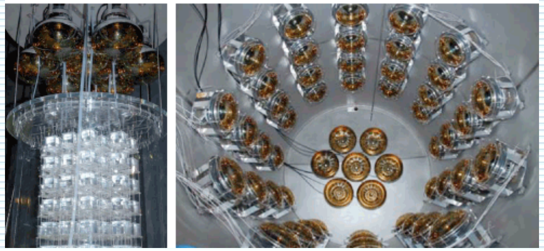
Contrary, the constraint from $0\nu\beta\beta$-decay (KLZ)
$m_{\beta\beta} < 0.036$-0.156 eV
implies
$\Sigma < 0.12$ eV



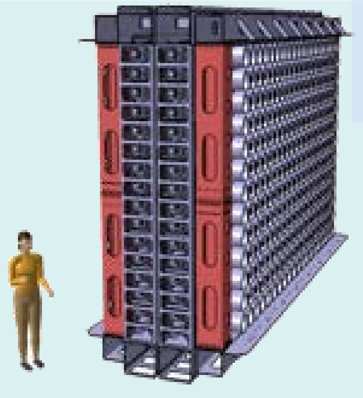
$0\nu\beta\beta$ decay isotopes and experiments

Candidates	$Q_{\beta\beta}$(MeV)	N.A. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.268	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.039	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.998	8.8
$^{96}Zr \rightarrow ^{96}Mo$	3.356	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.7
$^{110}Pd \rightarrow ^{110}Cd$	2.017	11.7
$^{116}Cd \rightarrow ^{116}Sn$	2.813	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.293	5.8
$^{130}Te \rightarrow ^{130}Xe$	2.528	34.1
$^{136}Xe \rightarrow ^{136}Ba$	2.458	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.371	5.6

【Current CANDLES detector】

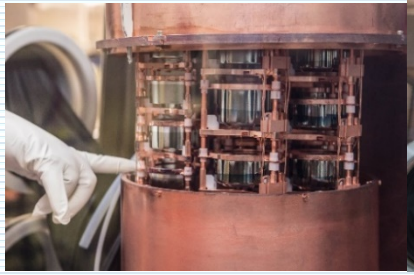


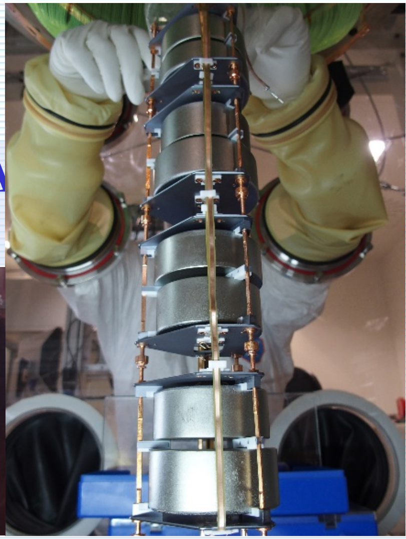
CANDLE
CaF scintillating crystal



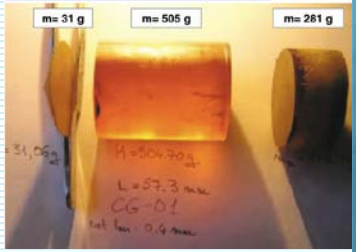
SuperNEMO
Se source foil

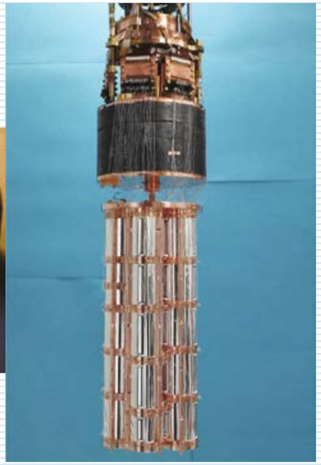
GERDA, MAJORANA
Ge crystal



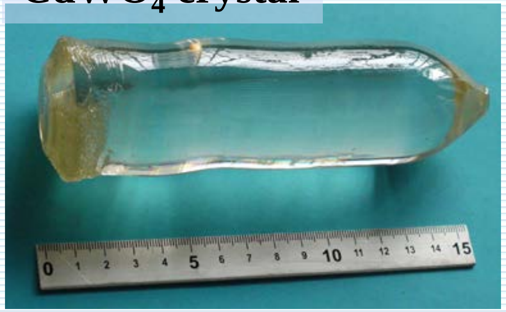


CUPID-0
ZnSe scintillating crystal

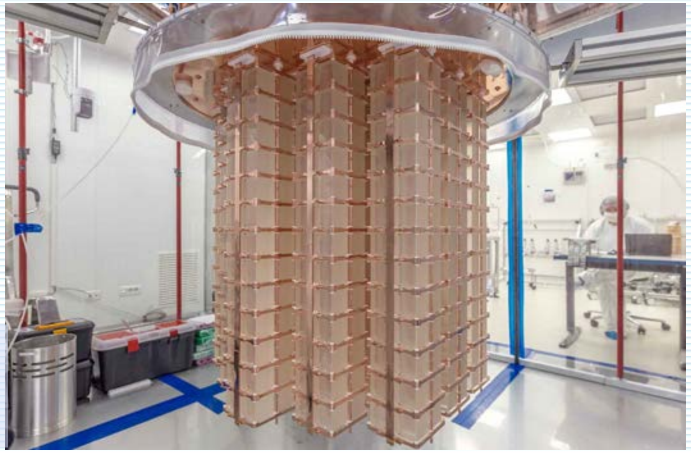




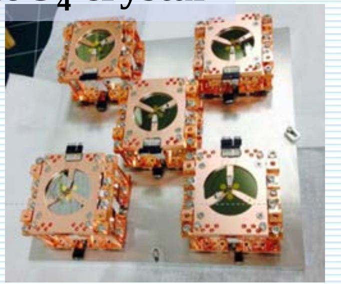
Aurora
$CdWO_4$ crystal



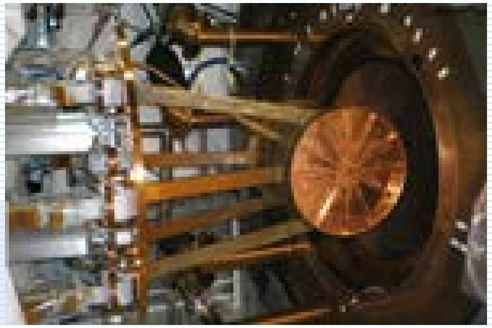
CUORE
TeO_2 crystal



Amore
$CaMoO_4$ crystal



EXO, KamLAND-Zen
Liquid Xe



Quite challenging 100 kg-class 0νββ experiment
(zero background, large mass, long time measurement, very good energy resolution)

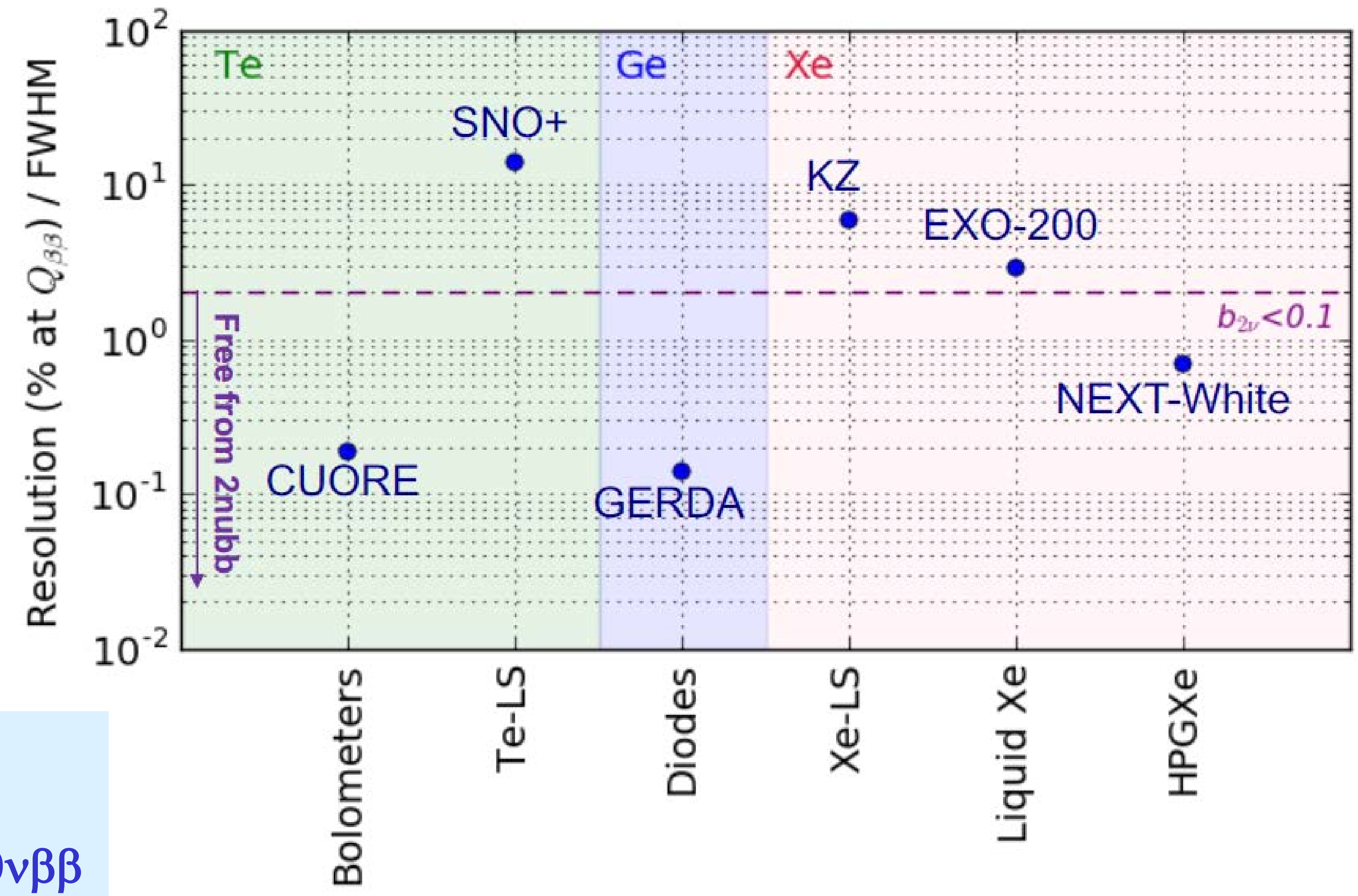
Enrichments of isotopes

^{76}Ge: Semiconductor industry enriches Ge already – ^{76}Ge can in principle be extracted as by product.

^{100}Mo: New capacity for enrichment of Mo in ^{100}Mo for nuclear medicine is needed. Parasitic?

^{130}Te: Comes naturally enriched. Natural Te is the most viable for an unenriched experiment.

^{136}Xe: Atmospheric carbon capture technology based on metal oxide has plausible extendibility to capture atmospheric Xe. Free from steel industry capacity limit?



- Resolution better than **2% FWHM** to fully reject **2νββ** mode
- **solar ν** is not an issue for 100 kg-class 0νββ experiment

Leading limits in each $0\nu\beta\beta$ isotope

A monoenergetic peak at the Q-value is searched for.
Need a large amount of decay isotope and low radioactive environment

Experiment	Isotope	Exposure [kg yr]	$T^{0\nu}_{1/2}[10^{25}$ yr]	$m_{\beta\beta}$ [meV]
Gerda	^{76}Ge	127.2	18	79-180
Majorana	^{76}Ge	26	2.7	200-433
CUPID-0	^{82}Se	5.29	0.47	276-570
NEMO3	^{100}Mo	34.3	0.15	620-1000
CUPID-Mo	^{100}Mo	2.71	0.18	280-490
Amore	^{100}Mo	111	0.095	1200-2100
CUORE	^{130}Te	1038.4	2.2	90-305
EXO-200	^{136}Xe	234.1	3.5	93-286
KamLAND-Zen	^{136}Xe	970	23	36-156

Zero background experiment

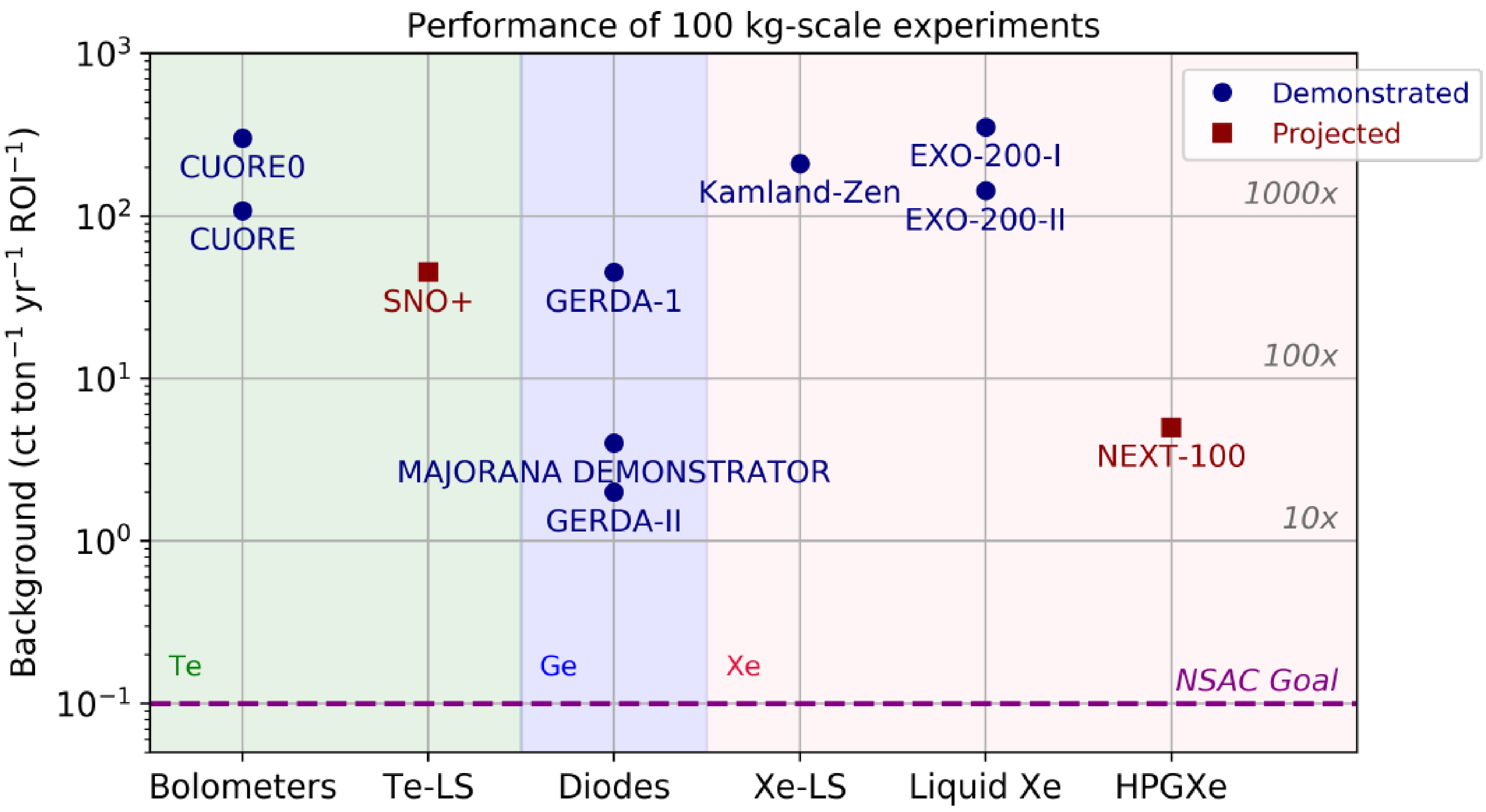
$$T_{1/2}^{0\nu}(\exp) = (\ln 2) N_a \frac{a}{A} \varepsilon \sqrt{\frac{MT}{b\Delta E}}$$

M - mass of detector in kg,
A - mass number of candidate isotope
a - $\beta\beta$ isotope concentration (enrichment)
T - measured time in years
ε – detection efficiency
b - events in ROI
***ΔE* - detector performance**

When b = 0

$$T_{1/2}^{0\nu}(\exp) = (\ln 2) N_a \frac{a}{A} \varepsilon \frac{MT}{n_{CL}}$$

"100kg-class" experiments:



KamLAND-Zen

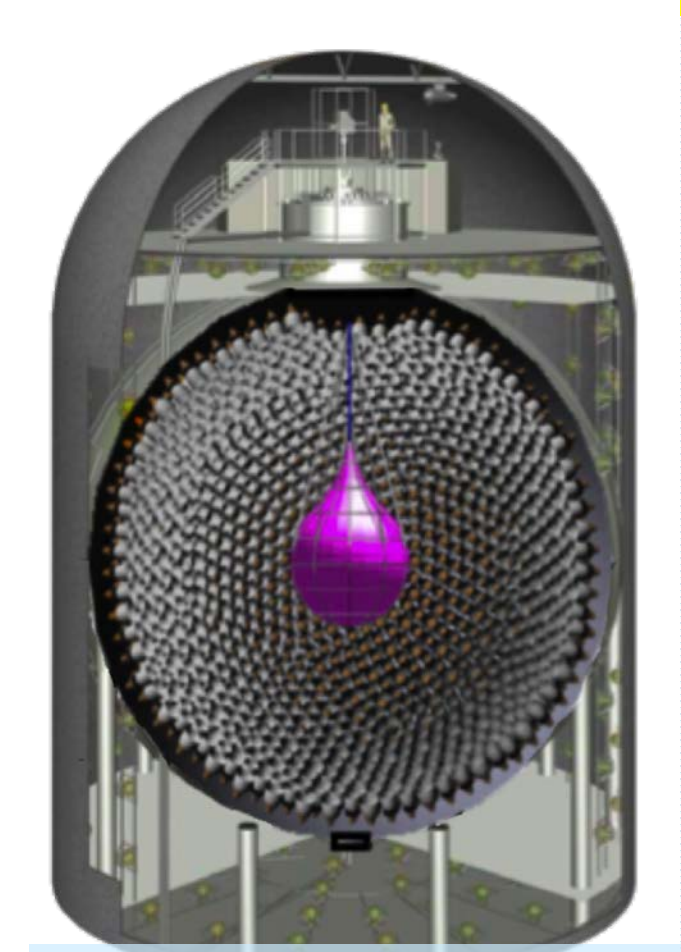
1 ton-class ^{136}Xe 0νββ experiment reaching IH region

KamLAND-Zen 400 and KamLAND-Zen 800 combined results

Limit: $T^{0\nu}_{1/2} > 2.3 \times 10^{26}$ year (90%C.L.), $m_{\beta\beta} < 36$–156 meV

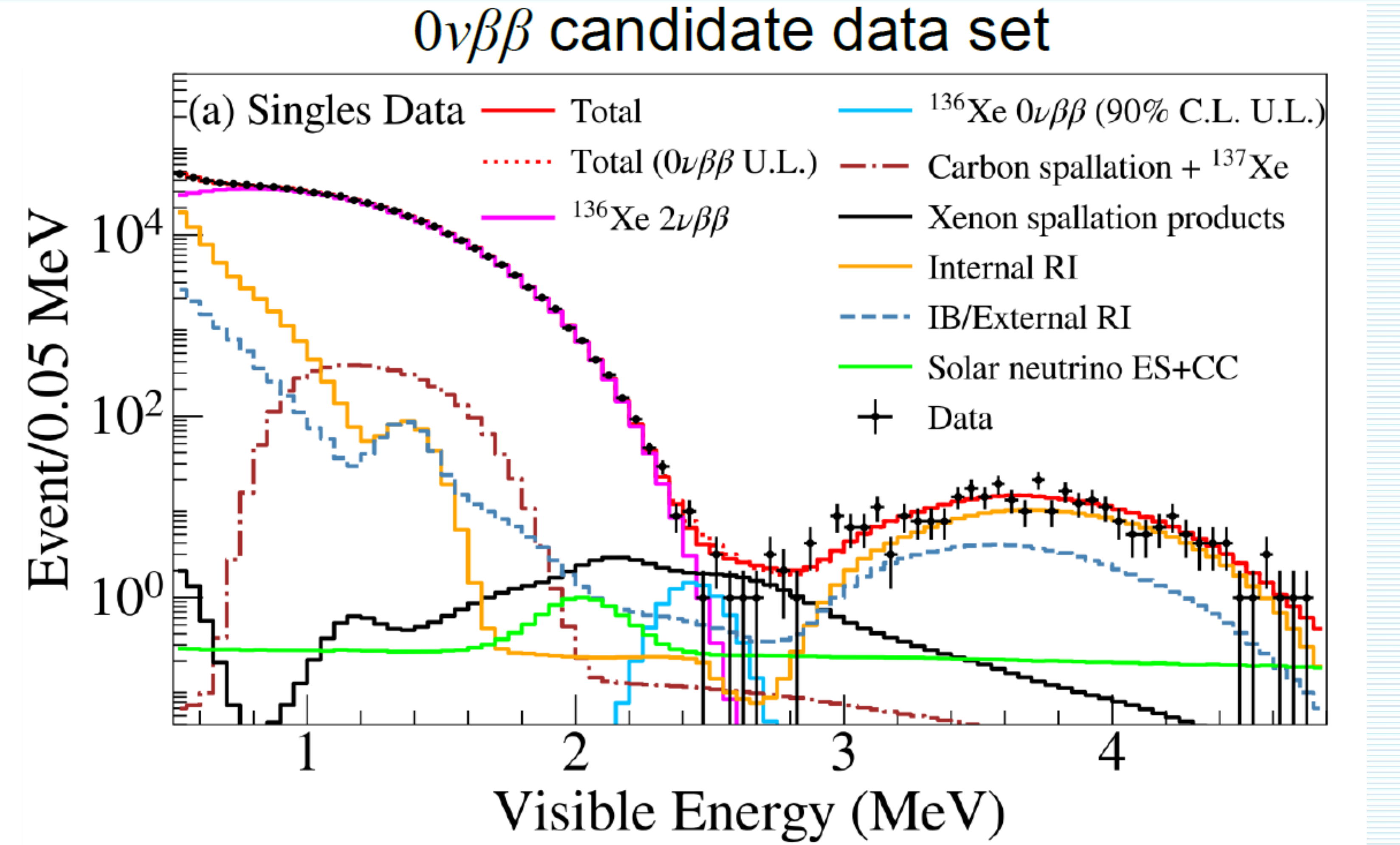
(g_A=1.27, NME = 1.11-4.77 are assumed)

Currently, the most strict 0νββ limit



Large volume liquid scintillator detector

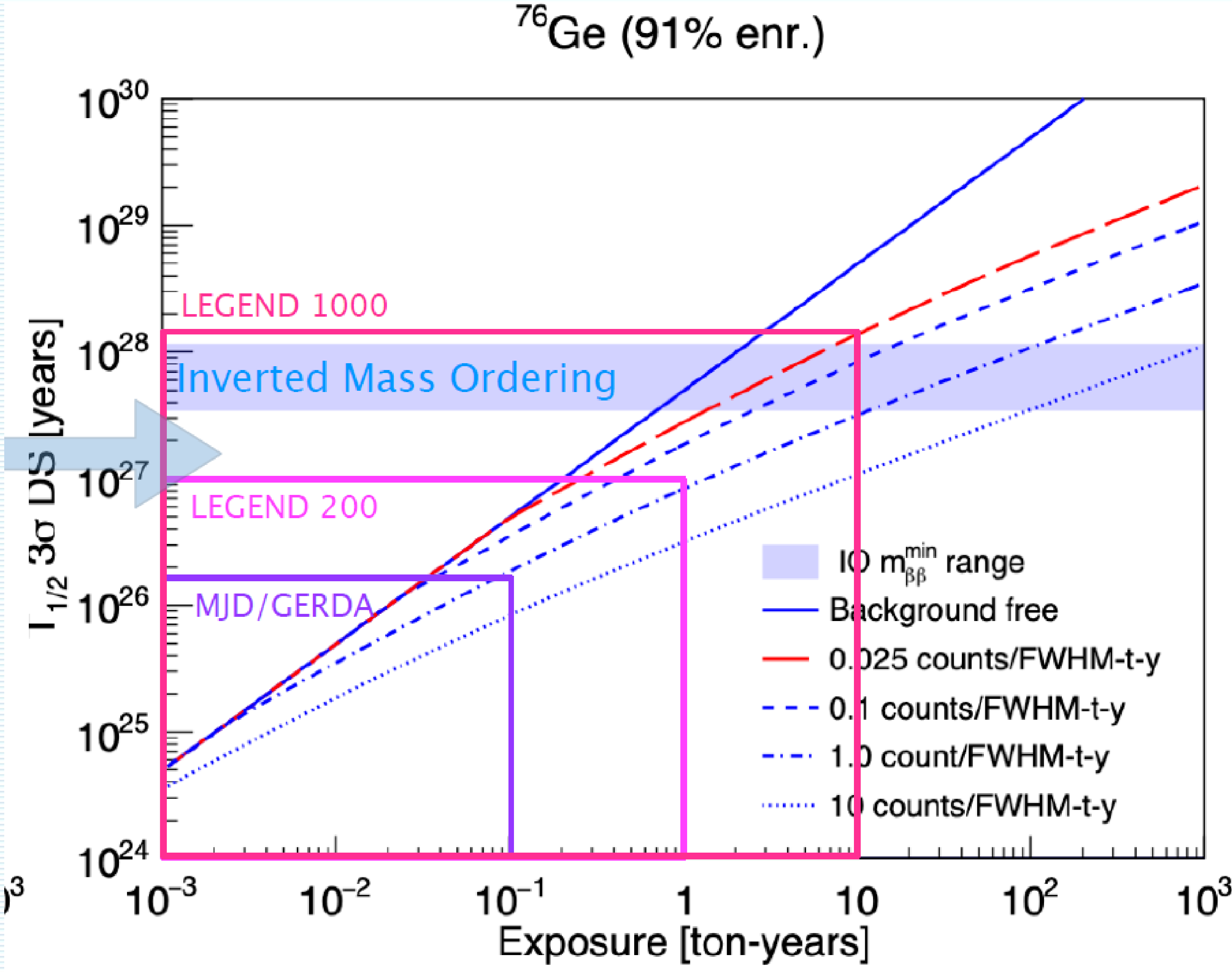
LS: 30.5 m^3, ^{136}Xe: 677 kg



LEGEND
1 ton-class ^{76}Ge 0νββ experiment

LEGEND-200

- Builds on the past successes of the MAJORANA DEMONSTRATOR and GERDA
- Low-risk approach to meeting background and sensitivity goals
- LEGEND-200: start data taking in 2022



LEGEND-1000 is a next-generation Experiment aiming for unambiguous discovery of 0νββ with 10^{28} years of sensitivity targeting 10 years of exposure

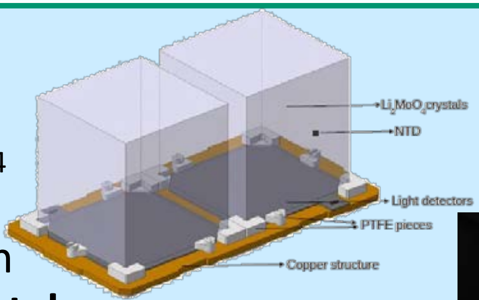
- in Conceptual Design phase
- 20x reduction to LEGEND-200 background goal
- Next-generation R&D efforts including Germanium Machine learning in progress

CUORE + CUPID-Mo
→ CUPID: 1 ton-class ^{100}Mo 0νββ experiment

Small scale demonstrators

- CUPID-Mo
- CUPID-0
- CUORE

→ CUPID → CUPID Reach / CUPID-1T



prototype tower

- Single module: $Li_2{}^{100}MoO_4$ **45×45x45 mm – ~280 g**
- 57 towers of 14 floors with 2 crystals each - **1596 crystals**
- **~240 kg of ^{100}Mo** with >95% enrichment
- **~1.6×10^{27}** ^{100}Mo atoms
- **Bolometric Ge light detectors** as in CUPID-Mo, CUPID-0

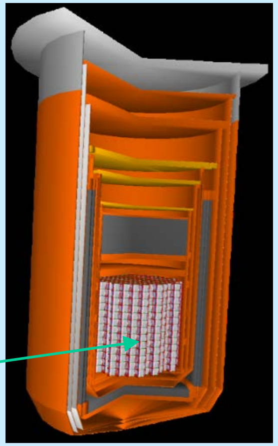
arXiv:1907.09376

J. Ouellet, TAUP 2021

CUPID is built on successful CUPID-Mo + CUORE

Li_2MoO_4 scintillating bolometer technology, with demonstration of energy resolution, crystal radiopurity and α rejection

Ton-scale bolometric experiment is possible
Electronics and data analysis tools
Reuse CUORE infrastructure



CUPID sensitivity

Data driven background model

- Information from CUPID-Mo, CUPID-0
- CUORE background model (same infrastructure!)

Projected background index: **1×10^{-4} c/(keV kg y)**

Critical background component: random coincidence of 2νββ events (^{100}Mo fastest 2νββ emitter: $T_{1/2}$ = 7.1×10^{18} y)

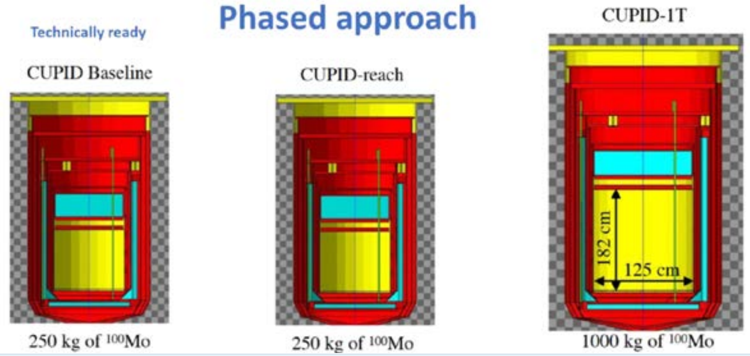
10 y discovery sensitivity 1.1×10^{27} $m_{\beta\beta}$ < 12 – 20 meV

Possible follow-up of CUPID

CUPID-reach - Same sensitive mass and cryostat as CUPID
Background improvement by factor 5
2.3 × 10^{27} y → $m_{\beta\beta}$ < 7.9 – 14 meV

CUPID-1T - 1 ton isotope → new cryostat
Background improvement by factor 20
9.2 × 10^{27} y → $m_{\beta\beta}$ < 4.0 – 6.9 meV

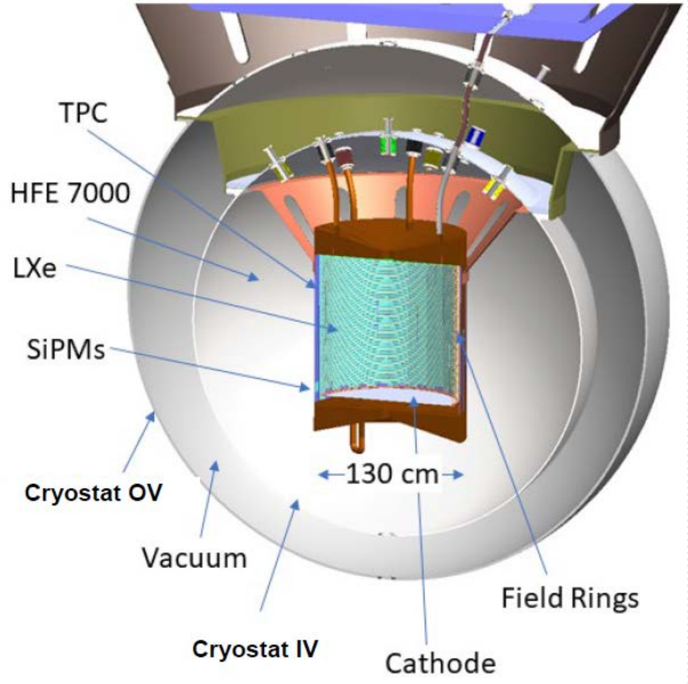
- Surface events

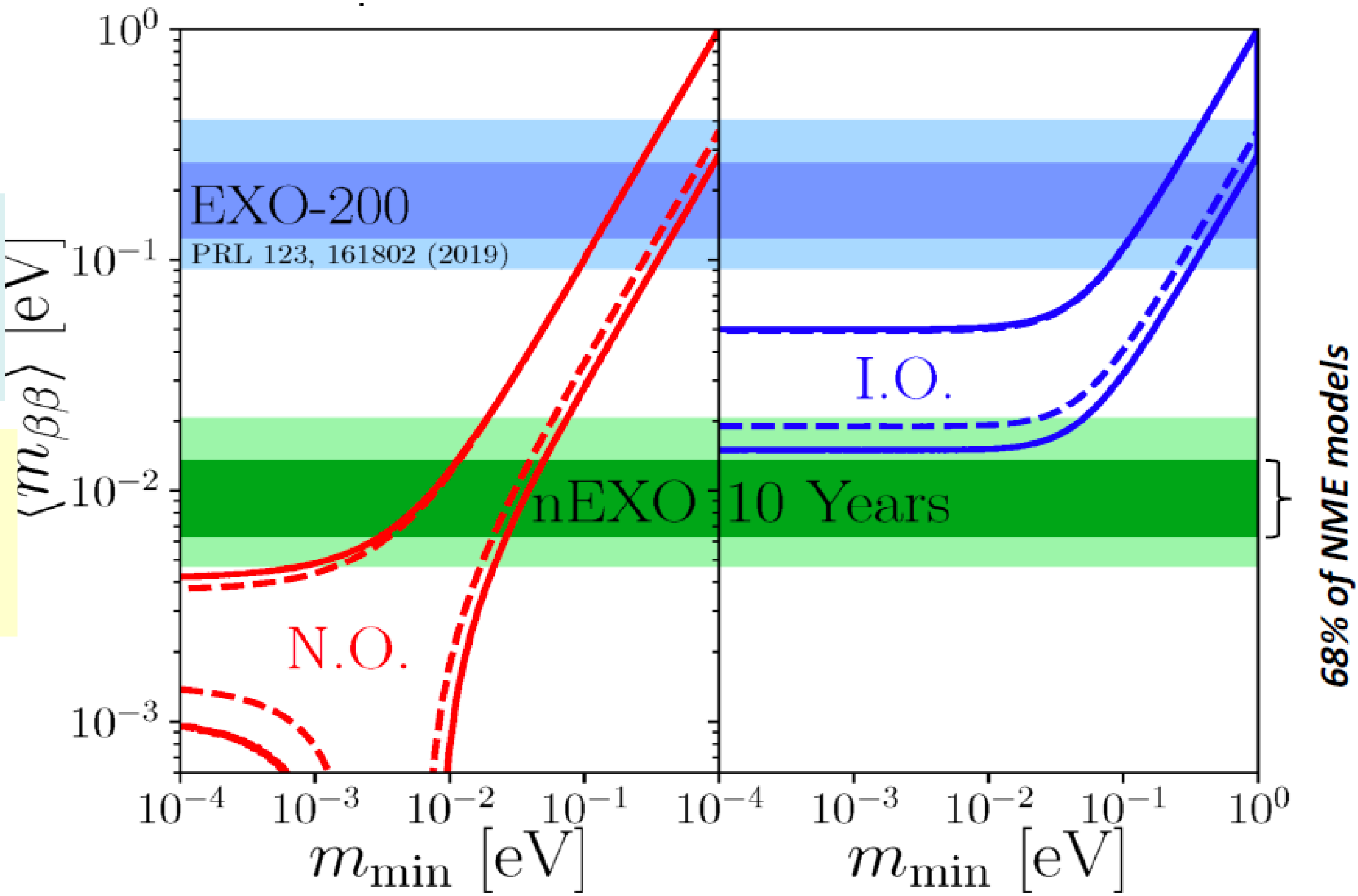


nEXO
5 ton-class ^{136}Xe 0νββ experiment

EXO-200, 1st 100 kg-class 0νββ-experiment, excellent background-essential for nEXO design, Sensitivity increased linearly with exposure.

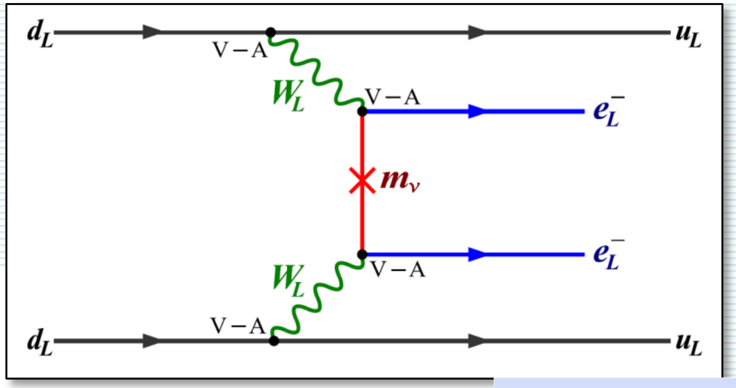
nEXO, discovery 0νββ experiment, reaches sensitivity of 10^{28} yr in 6.5 yr data taking, probes $m_{\beta\beta}$ down to 15 meV, scalable experiment.

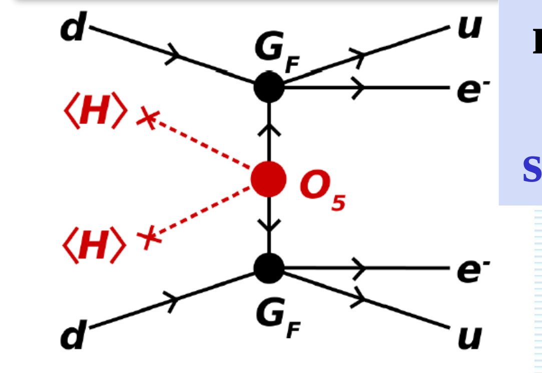




	isotope	$m_{\beta\beta}$ [meV] 90% excl. sensitivity	$m_{\beta\beta}$ [meV] 3 σ discovery potential
Legend	^{76}Se	8.2	11.1
CUPID	^{100}Mo	11.1	12.0
nEXO	^{136}Xe	12.9	15.0

0νββ governed by exotic mechanisms

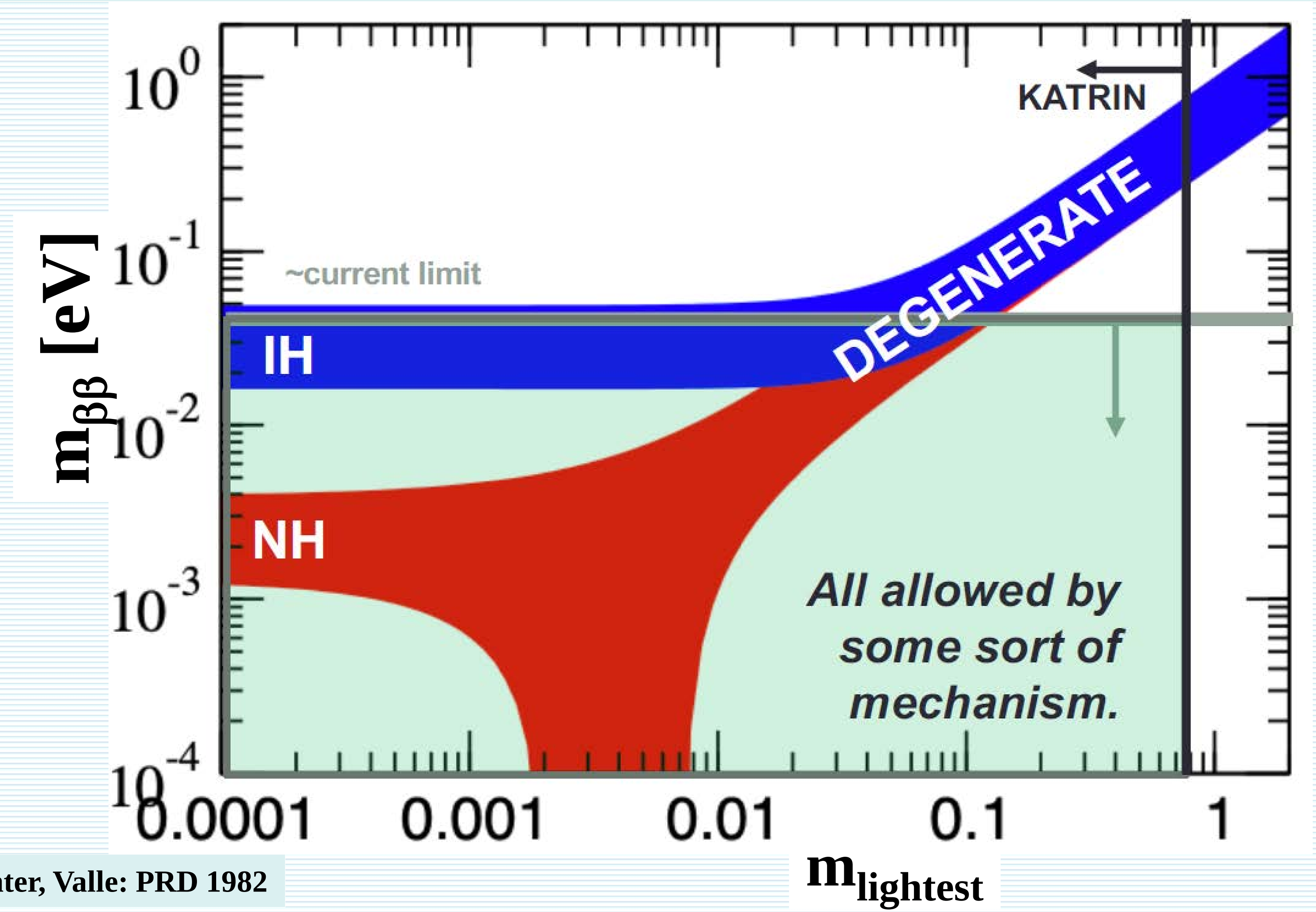




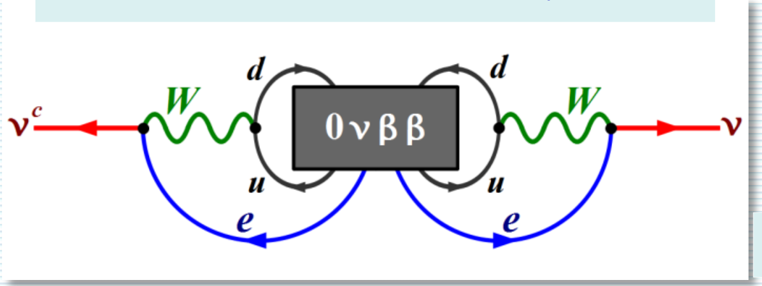
$m_{\beta\beta}$ mech. strongly suppressed

Light ν-mass mechanism can be strongly suppressed: $m_{\beta\beta}$ < 1 meV

- It is not possible to discover 0νββ with 10-100 ton-class experiment
- It should be a subject of theory to justify it
- There might be a dominance of other 0νββ mechanisms



Any 0νββ mech. generates a small correction to ν-mass



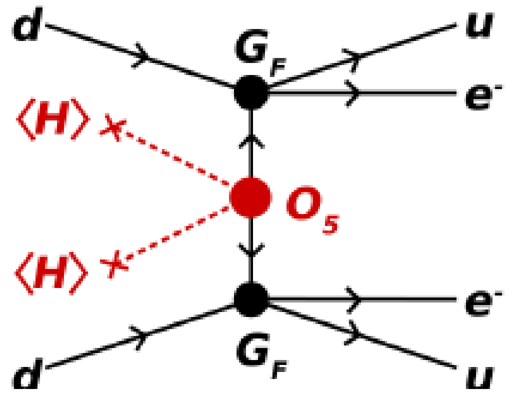
Schechter, Valle: PRD 1982

Beyond the SM physics

$$\mathcal{L} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_i c_i^{(5)}\mathcal{O}_i^{(5)} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)}\mathcal{O}_i^{(6)} + O(\frac{1}{\Lambda^3})$$

Amplitude for (A,Z)→(A,Z+2)+2e⁻ can be divided into:

mass mechanism: d=5

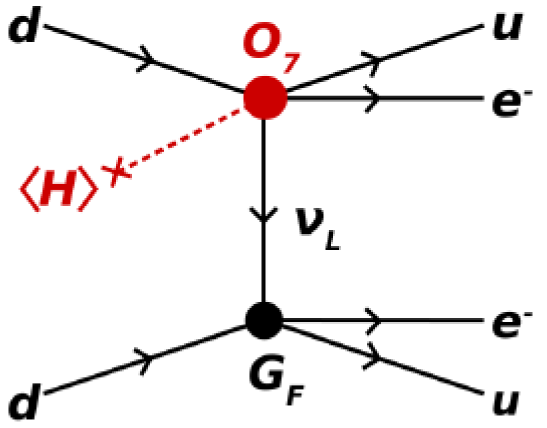


$$\mathcal{O}_W \propto \frac{c_{ij}}{\Lambda}(L_i H)(L_j H)$$

Weinberg, 1979

+

long range: d=7

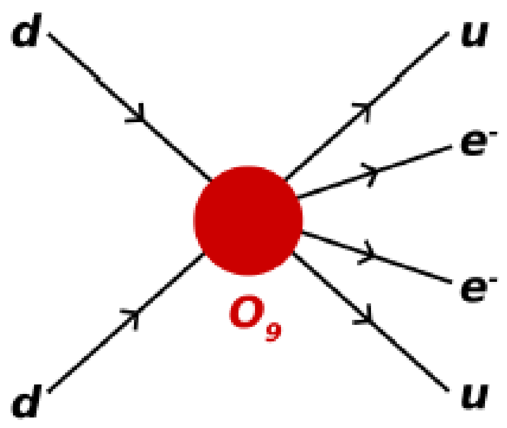


$$\mathcal{O}_2 \propto LLLe^cH$$
$$\mathcal{O}_3 \propto LLQd^cH$$
$$\mathcal{O}_4 \propto LL\bar{Q}\bar{u}^cH$$
$$\mathcal{O}_8 \propto L\bar{e}^c\bar{u}^cd^cH$$

Babu, Leung: 2001
de Gouvea, Jenkins: 2007

+

short range: d=9 (d=11)



$$\mathcal{O}_5 \propto LLQd^cHHH^\dagger$$
$$\mathcal{O}_6 \propto LL\bar{Q}\bar{u}^cHH^\dagger H$$
$$\mathcal{O}_7 \propto LQ\bar{e}^c\bar{Q}HHH^\dagger$$
$$\mathcal{O}_9 \propto LLLe^cLe^c$$
$$\mathcal{O}_{10} \propto LLLe^cQd^c$$
$$\mathcal{O}_{11} \propto LLQd^cQd^c$$
......

Valle

Quark Condensate Seesaw Mechanism for Neutrino Mass

PRD 103, 015007 (2021).

This operator contributes to the Majorana-neutrino mass matrix due to chiral symmetry breaking via the light-quark condensate.

The SM gauge-invariant effective operators

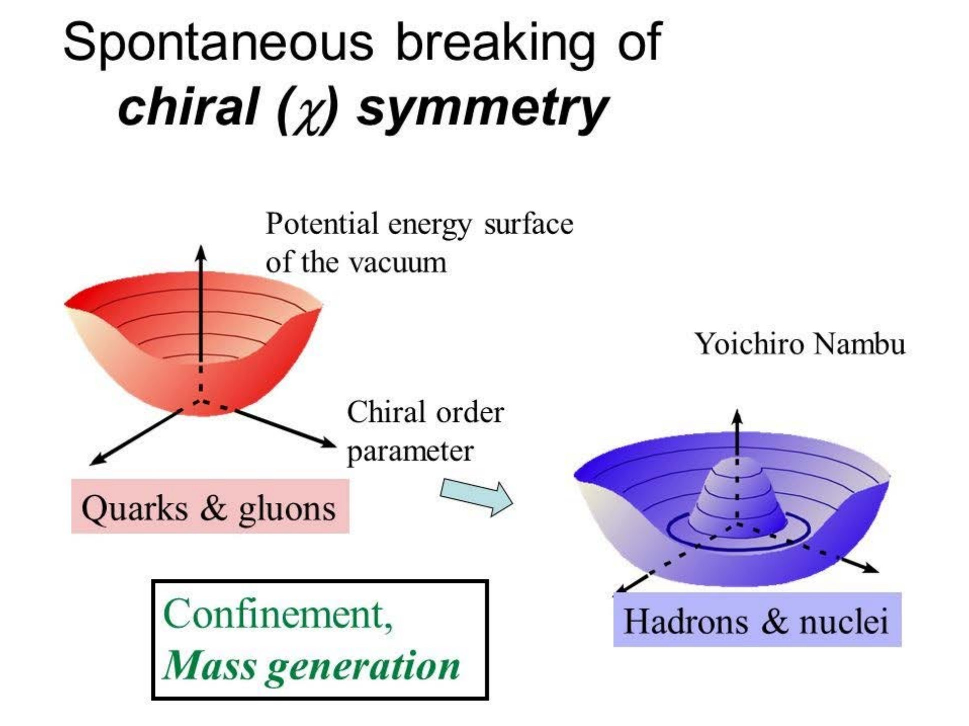
$$\mathcal{O}_7^{u,d} = \frac{\tilde{g}^{u,d}_{\alpha\beta}}{\Lambda^3}\, \overline{L^C_\alpha}\, L_\beta\, H \left\{ (\overline{Q}\, u_R),\ (\overline{d_R}\, Q) \right\}$$

After the EWSB and ChSB one arrives at the Majorana mass matrix of active neutrinos

$$m_{\alpha\beta}{}^{\nu} = g_{\alpha\beta}\, v\, \frac{\langle \overline{q} q \rangle}{\Lambda^3} = g_{\alpha\beta}\, v \left(\frac{\omega}{\Lambda} \right)^3$$

$$g_{\alpha\beta} = g^u_{\alpha\beta} + g^d_{\alpha\beta}, \quad v/\sqrt{2} = \langle H^0 \rangle$$

$$\omega = -\langle \overline{q} q \rangle^{1/3}, \quad \langle \overline{q} q \rangle^{1/3} \approx -283\ \mathrm{MeV}$$



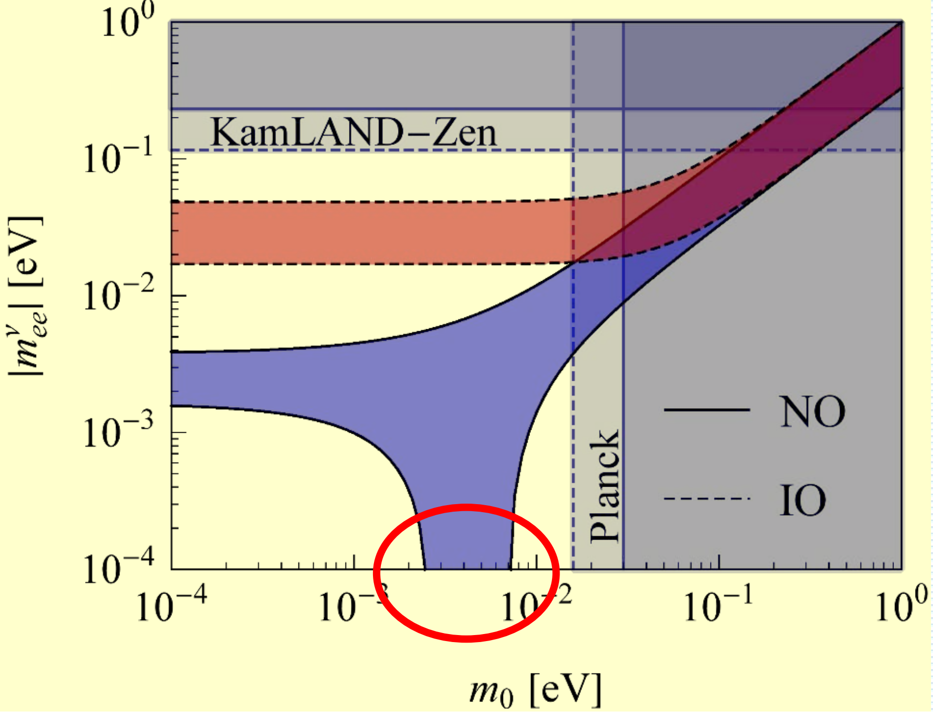
$\Lambda \sim$ a few TeV
we get the neutrino mass in the sub-eV ballpark

The genuine QCSS scenario

(predicts NH and ν-mass spectrum)

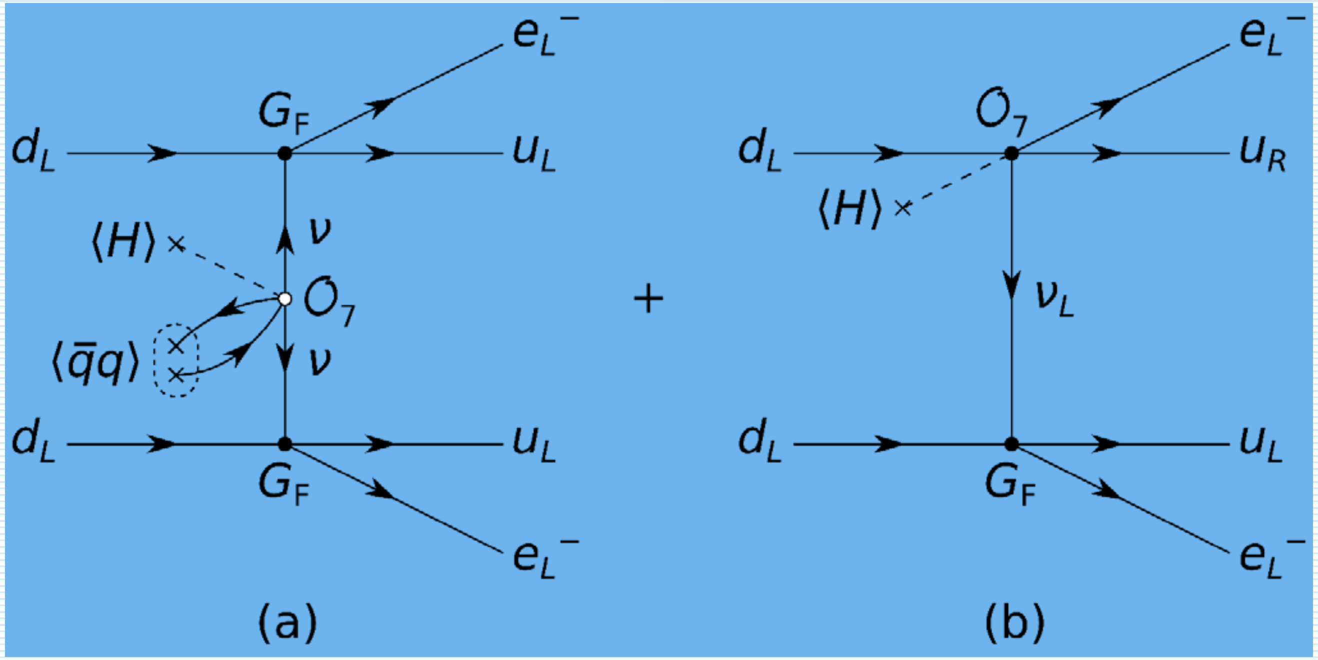
$$\mathcal{L}_7 = \frac{1}{\sqrt{2}} \sum_{\alpha\beta} \frac{v}{\Lambda^3} \overline{\nu^C_{\alpha L}} \nu_{\beta L} (g^u_{\alpha\beta} \overline{u_L} u_R + g^d_{\alpha\beta} \overline{d_R} d_L) + \text{H.c.}$$

$$m^\nu_{\alpha\beta} = -\frac{g_{\alpha\beta}}{\sqrt{2}} v \frac{\langle \bar{q} q \rangle}{\Lambda^3} = \frac{g_{\alpha\beta}}{\sqrt{2}} v \left(\frac{\omega}{\Lambda}\right)^3$$



(a) PRL 112, 142503 (2014).

(b) PLB 453, 194 (1999).



Neutrino spectrum (NH) !!!

2 meV < m_1 < 7 meV

9 meV < m_2 < 11 meV

50 meV < m_2 < 51 meV

Prediction for m_β

9 meV < m_b < 12 meV

Prediction for cosmology (Σ)

62 meV < $m_1 + m_2 + m_3$ < 69 meV

Majorana neutrino mass eigenstate N
with arbitrary mass m_N mixed with 3 active neutrinos (U_{eN})

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu} g_A^4 \left| \sum_N \left(U^2_{eN} m_N \right) m_p \, M'^{0\nu}(m_N, g_A^{\rm eff}) \right|^2$$

General case

$$M'^{0\nu}(m_N, g_A^{\rm eff}) = \frac{1}{m_p m_e} \frac{R}{2\pi^2 g_A^2} \sum_n \int d^3x \, d^3y \, d^3p$$
$$\times e^{i\mathbf{p}\cdot(\mathbf{x}-\mathbf{y})} \frac{\langle 0^+_F | J^{\mu\dagger}(\mathbf{x}) | n \rangle \langle n | J^\dagger_\mu(\mathbf{y}) | 0^+_I \rangle}{\sqrt{p^2 + m_N{}^2}\left(\sqrt{p^2 + m_N{}^2} + E_n - \frac{E_I - E_F}{2}\right)}$$

light ν exchange

$$M'^{0\nu}(m_N \to 0, g_A^{\rm eff}) = \frac{1}{m_p m_e} M'^{0\nu}_\nu(g_A^{\rm eff})$$

$$M'^{0\nu}(m_N \to \infty, g_A^{\rm eff}) = \frac{1}{m_N^2} M'^{0\nu}_N(g_A^{\rm eff})$$

heavy ν exchange

Particular cases

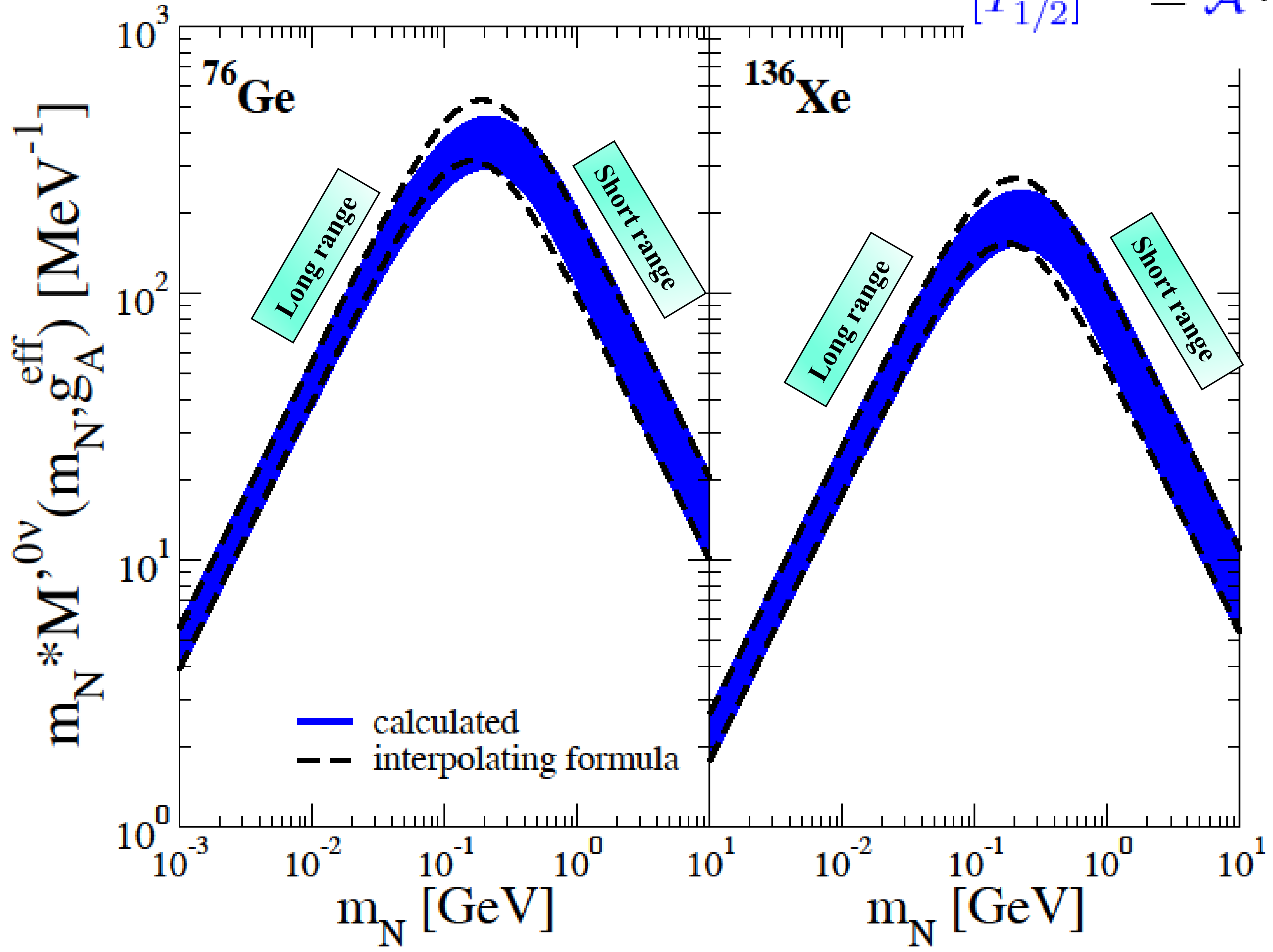
$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu} g_A^4 \times$$
$$\times \begin{cases} \left| \frac{\langle m_\nu \rangle}{m_e} \right|^2 \left| M'^{0\nu}_\nu(g_A^{\rm eff}) \right|^2 & \text{for } m_N \ll p_F \\ \left| \langle \frac{1}{m_N} \rangle m_p \right|^2 \left| M'^{0\nu}_N(g_A^{\rm eff}) \right|^2 & \text{for } m_N \gg p_F \end{cases}$$

$$\langle m_\nu \rangle = \sum_N U^2_{eN} m_N$$

$$\left\langle \frac{1}{m_N} \right\rangle = \sum_N \frac{U^2_{eN}}{m_N}$$

or Simkovic

$$[T^{0\nu}_{1/2}]^{-1} = \mathcal{A} \cdot \left| m_p \sum_N U^2_{eN} \frac{m_N}{\langle p^2 \rangle + m_N^2} \right|^2,$$



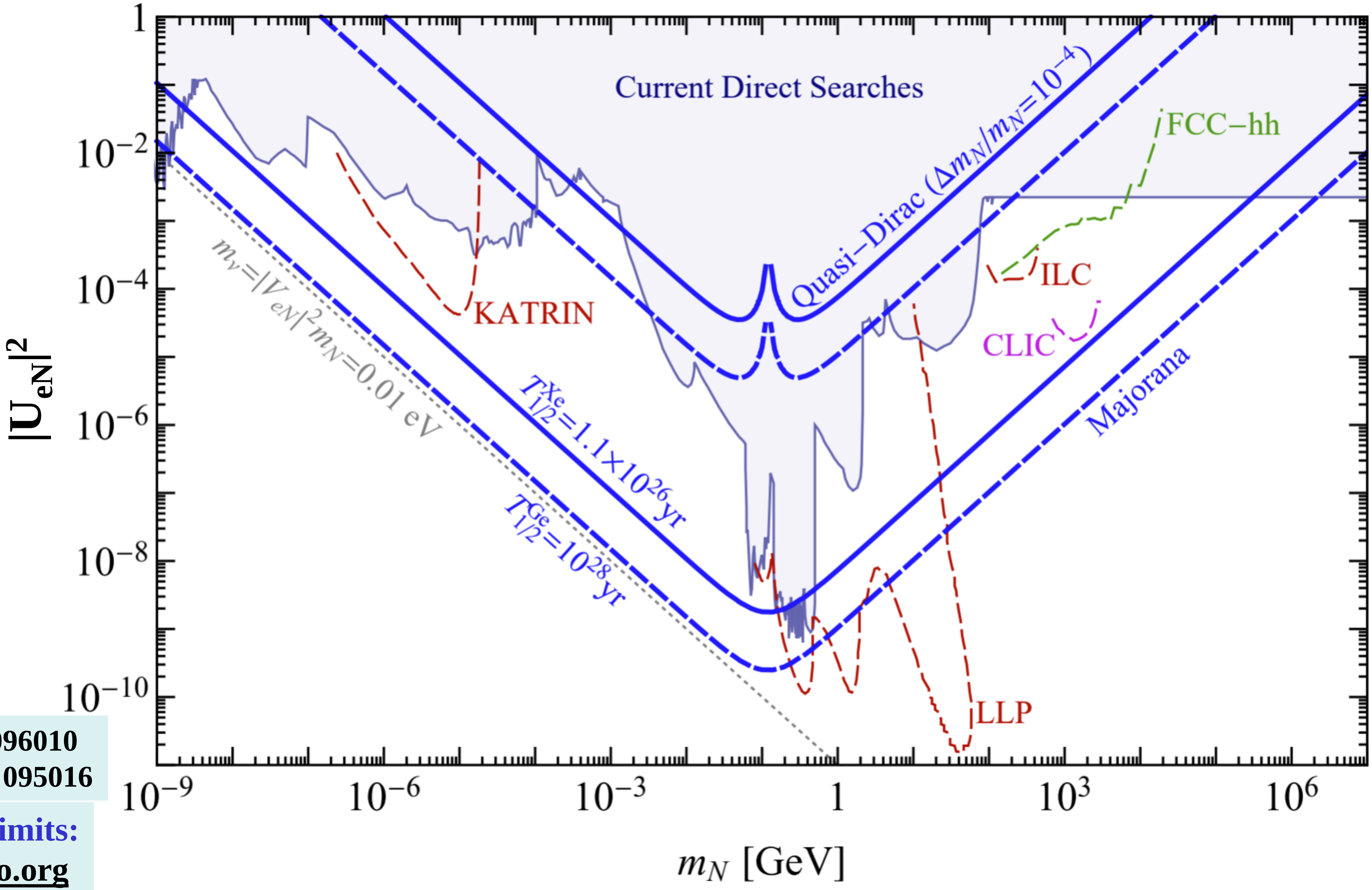
$$\langle p^2 \rangle = m_p m_e \frac{M'^{0\nu}_N}{M'^{0\nu}_\nu}$$

Interpolating formula

PRD 90 (2014) 096010]

Sterile ν (U_{en}, m_N)

Constraints from Direct Searches are less Stringent as those from 0νββ



PRD 90 (2014) 096010
PRD 102 (2020) 095016

Direct search limits:
sterile-neutrino.org

The 0νββ-decay within L-R symmetric theories (interpolating formula)
(D-M mass term, see-saw, V-A and V+A int., exchange of heavy neutrinos)

$$[T^{0\nu}_{1/2}]^{-1} = \eta^2_{\nu N}\ C_{\nu N}$$

$$C_{\nu N} = g^4_{\rm A}\ \left|M'^{0\nu}_{\nu}\right|^2\ G^{0\nu}$$

$$\nu_{eL} = \sum_{j=1}^{3}\left(U_{ej}\nu_{jL} + S_{ej}(N_{jR})^C\right),$$

$$\nu_{eR} = \sum_{j=1}^{3}\left(T^*_{ej}(\nu_{jL})^C + V^*_{ej}N_{jR}\right)$$

Mixing of 3 light and 3 heavy neutrinos generally parametrized with 15 angles + 15 phases

$$\mathcal{U} = \begin{pmatrix} U & S \\ T & V \end{pmatrix}$$

Effective LNV parameter within LRS model (due interpolating formula)

$$\langle p^2\rangle = m_{\rm p} m_{\rm e}\frac{M'^{0\nu}_{\rm N}}{M'^{0\nu}_{\nu}}$$

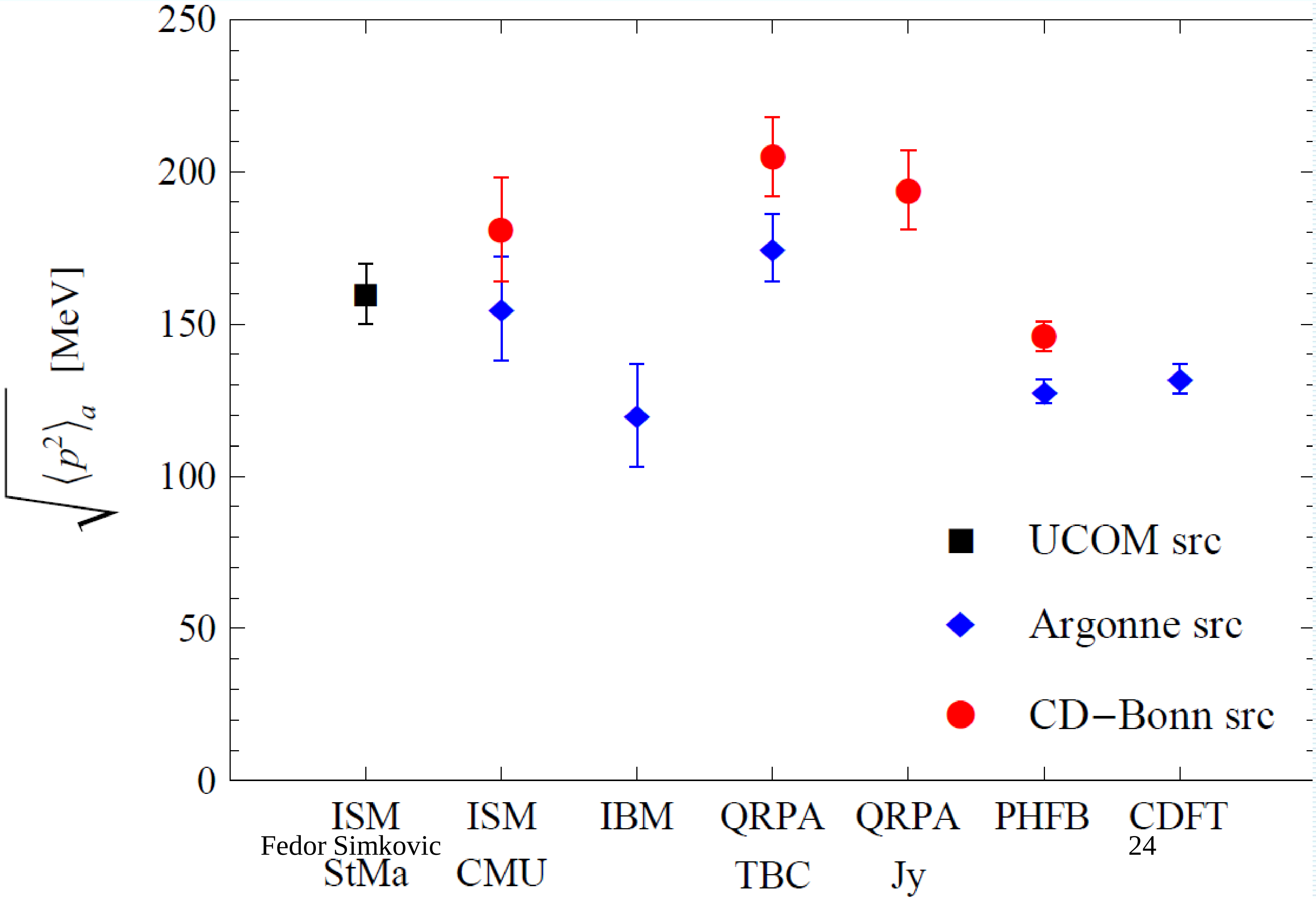
$$\eta^2_{\nu N} = \left|\sum_{j=1}^{3}\left(U^2_{ej}\ \frac{m_j}{m_e}\ +\ S^2_{ej}\ \frac{\langle p^2\rangle_a}{\langle p^2\rangle_a + M^2_j}\ \frac{M_j}{m_e}\right)\right|^2 + \lambda^2\left|\sum_{j=1}^{3}\left(T^2_{ej}\ \frac{m_j}{m_e}\ +\ V^2_{ej}\ \frac{\langle p^2\rangle_a}{\langle p^2\rangle_a + M^2_j}\ \frac{M_j}{m_e}\right)\right|^2$$

The dominance of light and heavy ν-mass contributions to 0nbb-decay rate can not be established by observing this process at different nuclei.

$\langle p^2 \rangle$ only weakly depends on A

$$\langle p^2 \rangle = m_p m_e \frac{M_N'^{0\nu}}{M_\nu'^{0\nu}}$$

Supported by detailed analysis:
Degeneracies of particle and nuclear physics uncertainties in 0νββ–decay
PRD 92, 093004 (2018)



As a consequence contributions to 0νββ decay rate from light and heavy neutrino mass mechanisms can not be distinquished.

PRD 98, 015003 (2018)

6x6 PMNS see-saw ν-mixing matrix
(the most economical one)

$$\mathcal{U} = \begin{pmatrix} U_0 & \zeta\, 1 \\ -\zeta\, 1 & V_0 \end{pmatrix}$$

ζ - see-saw parameter

$U_0 = U_{\rm PMNS}$

PRD 98, 015003 (2018)

$$\eta^2_{\nu N} = \frac{1}{m_e^2}\left({m_{\beta\beta}}^2 + (M^R_{\beta\beta})^2 \right)$$

The mixing for heavy ν follows from the unitarity of *U*

$$V_0 = U^\dagger_{\rm PMNS} =$$

$$\begin{pmatrix} c_{12}\, c_{13}\, e^{-i\alpha_1} & \left(-s_{12}\, c_{23} - c_{12}\, s_{13}\, s_{23}\, e^{-i\delta}\right) e^{-i\alpha_1} & \left(s_{12}\, s_{23} - c_{12}\, s_{13}\, c_{23}\, e^{-i\delta}\right) e^{-i\alpha_1} \\ s_{12}\, c_{13}\, e^{-i\alpha_2} & \left(c_{12}\, c_{23} - s_{12}\, s_{13}\, s_{23}\, e^{-i\delta}\right) e^{-i\alpha_2} & \left(-c_{12}\, s_{23} - s_{12}\, s_{13}\, c_{23}\, e^{-i\delta}\right) e^{-i\alpha_2} \\ s_{13}\, e^{i\delta} & c_{13}\, s_{23} & c_{13}\, c_{23} \end{pmatrix}$$

Assumption about heavy neutrino masses M_i (by assuming see-saw)

Inverse proportional

$$m_i M_i \simeq m_D^2$$

$$M^{\rm R}_{\beta\beta} = \lambda\, \frac{\langle p^2\rangle_a}{m_D^2} \left| \sum_{j=1}^{3} (U_0^\dagger)^2_{ej}\; m_j \right|$$

$M^R_{\beta\beta}$ depends on "Dirac" CP phase δ unlike "Majorana" CP phases α_1 and α_2

Proportional

$$m_i \simeq \zeta^2 M_i$$

$$M^{\rm R}_{\beta\beta} = \lambda\, \zeta^2 \left| \sum_{j=1}^{3} (U_0^\dagger)^2_{ej}\, \frac{\langle p^2\rangle_a}{m_j} \right|$$

Heavy Majorana mass $M^R_{\beta\beta}$ depends on the "Dirac" CP violating phase δ

Contribution from exchange of heavy neutrino to 0νββ-decay rate might be large

Inverse proportional

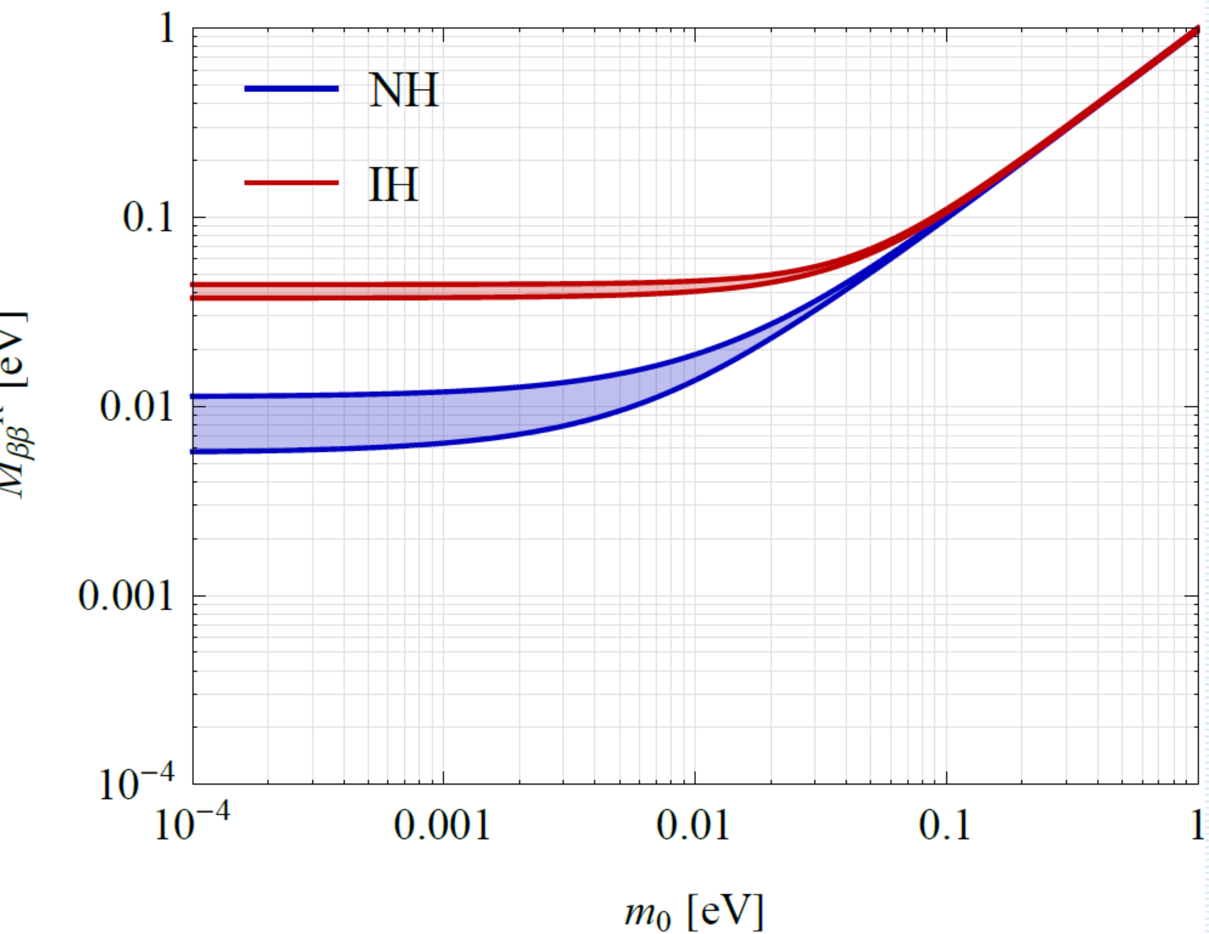
$$m_i M_i \simeq m_D^2$$

$$M_{\beta\beta}^{\rm R} = \lambda \frac{\langle p^2 \rangle_a}{m_D^2} \left| \sum_{j=1}^{3} (U_0^\dagger)_{ej}^2 \, m_j \right|$$

$V_0 = U_{PMNS}^\dagger$

$M_i = m_D^2/m_i \quad m_D \simeq 5$ MeV

$\lambda = 7.7 \times 10^{-4}$



Proportional

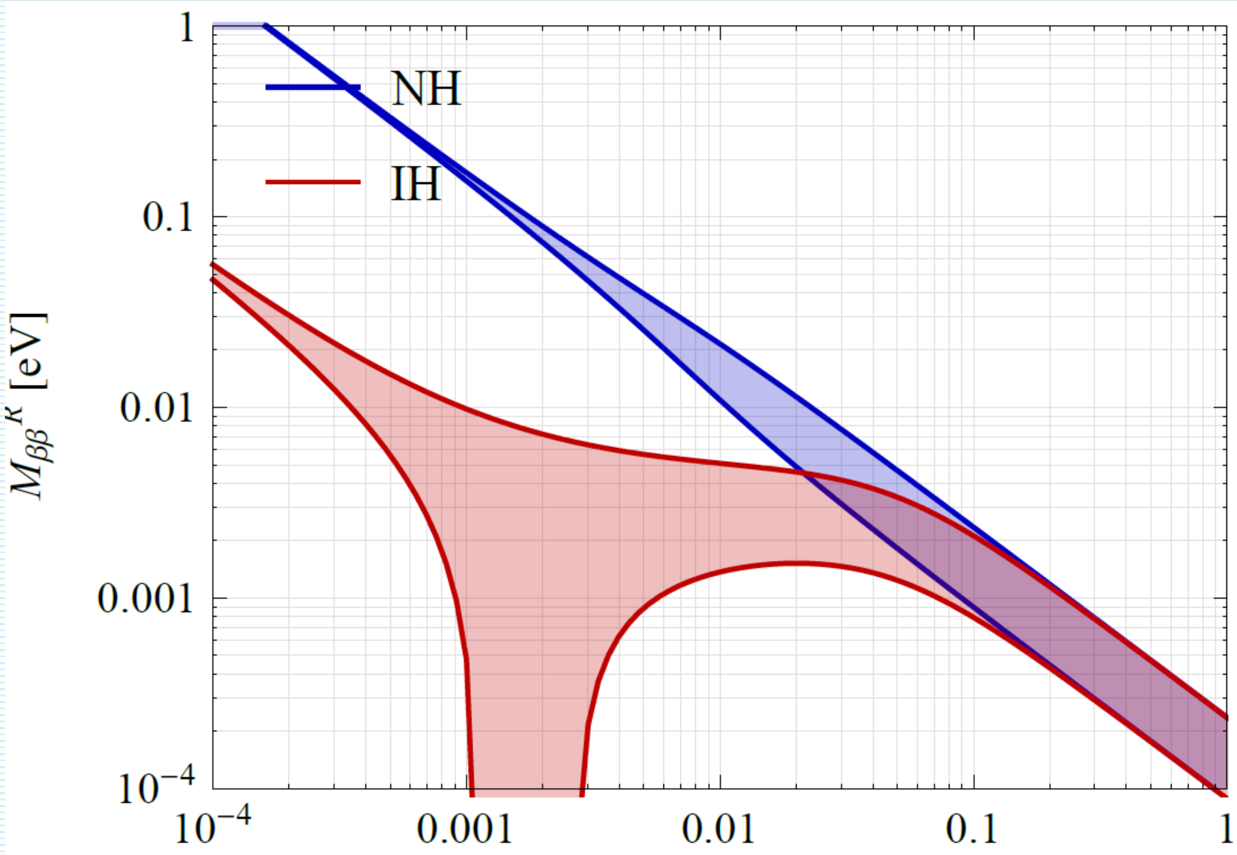
$$m_i \simeq \zeta^2 M_i$$

$$M_{\beta\beta}^{\rm R} = \lambda \, \zeta^2 \left| \sum_{j=1}^{3} (U_0^\dagger)_{ej}^2 \frac{\langle p^2 \rangle_a}{m_j} \right|$$

$V_0 = U_{PMNS}^\dagger$

$\zeta = m_i/M_i \quad \zeta^2 \simeq 5 \times 10^{-17}$

$\lambda = 7.7 \times 10^{-4}$



m_0 constrained from bottom.

Introduction to Quasi-Dirac nature of Neutrino

We do not yet know whether neutrino is Dirac or Majorana particle.

- Dirac mass term $\mathcal{L}^D = -\bar{\nu}_R \, m_D \, \nu_L + \text{H.c.}$
- Majorana mass term $\mathcal{L}^M = \frac{1}{2}(\bar{\nu}_L)^c \, m_L \nu_L + (\bar{\nu}_R)^c \, m_R \nu_R + \text{H.c.}$
- Dirac-Majorana mass term $\mathcal{L}^{D+M} = \frac{1}{2}(\bar{n}_L)^c \, \mathcal{M} \, n_L + \text{H.C. with } n_L = \begin{pmatrix} \nu_L \\ (\nu_R)^c \end{pmatrix}$

  and $\mathcal{M} = \begin{pmatrix} m_L & m_D \\ m_D^T & m_R \end{pmatrix}$
- If $m_L = m_R = 0 \Rightarrow$ neutrinos are Dirac particle.
- Small deviation of m_L or m_R from 0 $\Rightarrow$ neutrinos are Quasi-Dirac

$$\mathcal{U}^{\mathrm{T}} \tilde{\mathcal{M}} \mathcal{U} = \mathcal{M} \text{ with } \tilde{\mathcal{M}} = \begin{pmatrix} m_i + \epsilon_i & 0 \\ 0 & -m_i + \epsilon_i \end{pmatrix}$$

6x6 PMNS quasi-dirac ν-mixing matrix)

Theoretical Framework

$$\tilde{\mathcal{M}} = \begin{pmatrix} m_i + \epsilon & 0 \\ 0 & -m_i + \epsilon \end{pmatrix} \text{ and } \mathcal{U} = \begin{pmatrix} U_{PMNS} & U_{PMNS} \\ V & V \end{pmatrix}$$

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(\epsilon \neq 0) = 1 - P_1 - 4\, c_{13}^4 c_{12}^2 s_{12}^2 F_{21} - 4\, s_{13}^2 c_{13}^2 (c_{12}^2 F_{31} + s_{12}^2 F_{32})$$

with

$$P_1 = c_{13}^4 c_{12}^4 \sin^2 \frac{m_1 \epsilon L}{E} + c_{13}^4 s_{12}^4 \sin^2 \frac{m_2 \epsilon L}{E} + s_{13}^4 \sin^2 \frac{m_3 \epsilon L}{E}$$

$$F_{ij} = \frac{1}{4}\Big(\sin^2 \frac{\Delta m_{ij}^2 + 2\epsilon \Delta m_{ij}}{4E} L + \sin^2 \frac{\Delta m_{ij}^2 - 2\epsilon \Delta m_{ij}}{4E} L + \sin^2 \frac{\Delta m_{ij}^2 + 2\epsilon \sum m_{ij}}{4E} L + \sin^2 \frac{\Delta m_{ij}^2 - 2\epsilon \sum m_{ij}}{4E} L \Big)$$

6x6 PMNS quasi-dirac ν-mixing matrix

(the most economical one)

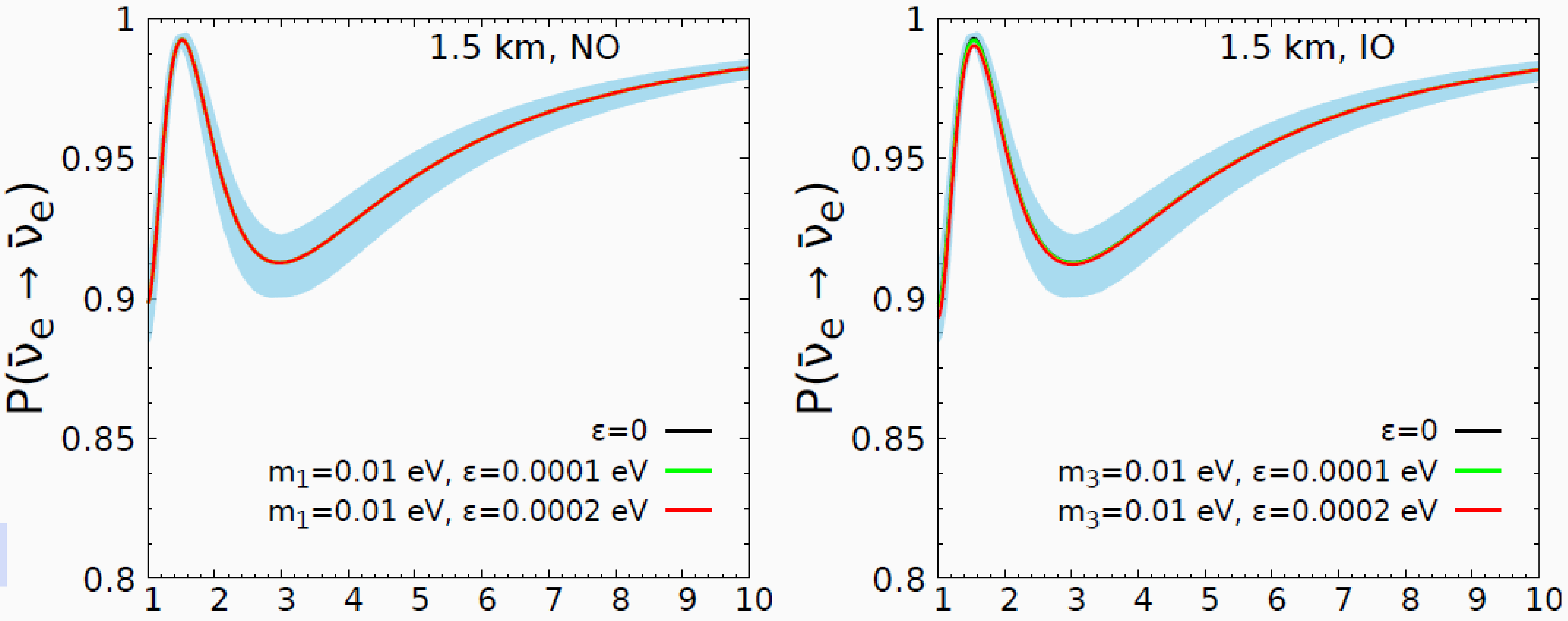
Symmetry 12, 1310 (2020)

Survival probabilities of reactor $\bar{\nu}_e$

quasi-dirac
ν-mixing matrix
(the most economical one)

Restriction from Daya-Bay data (3σ)

Symmetry 12, 1310 (2020)



The survival probabilities of $\bar{\nu}_e$ with non-zero ϵ are same as in 3ν cases.

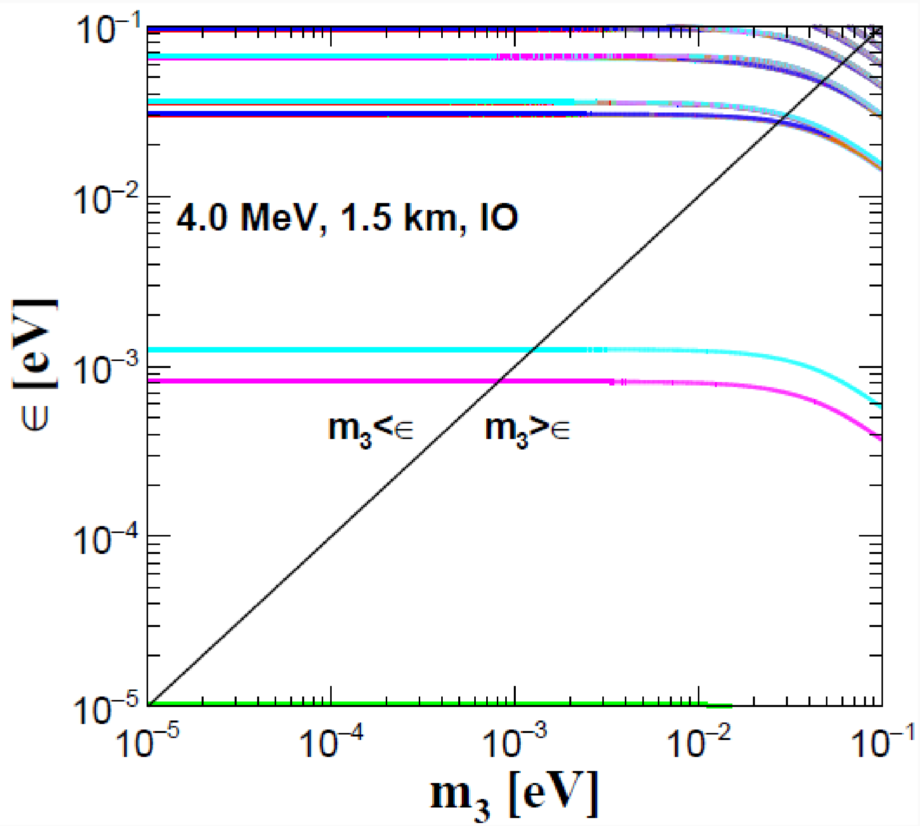
Expected Constraints on Majorana contribution ϵ

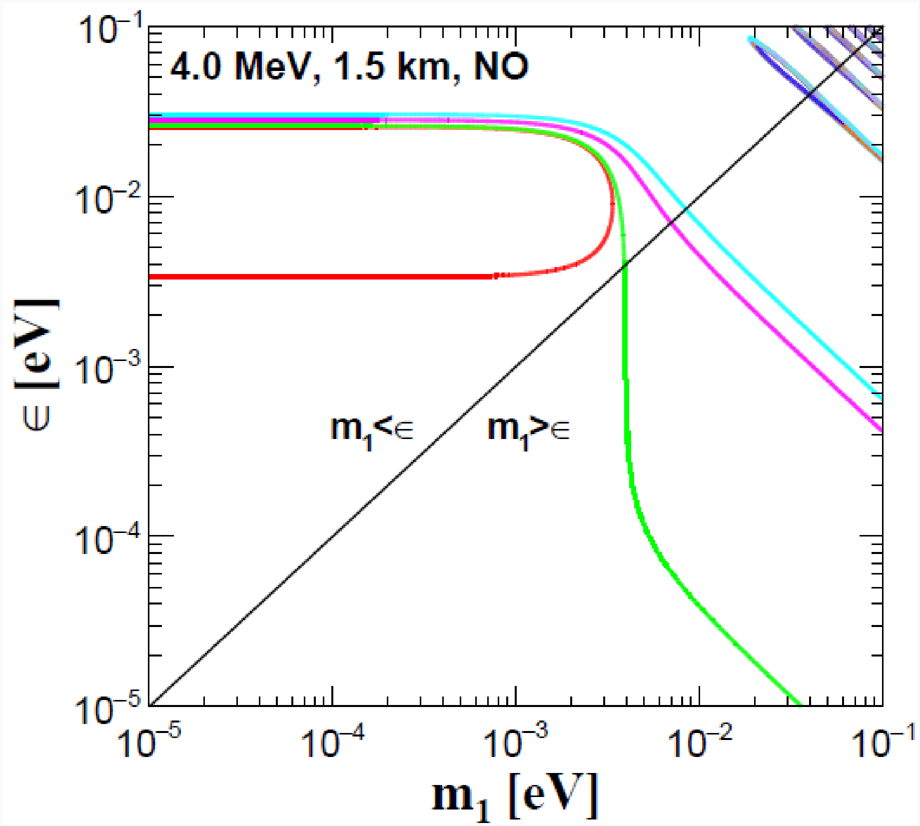
Quasi-dirac ν-mixing
(the most economical one)

Restriction from Daya-Bay data (3σ)

Constraint on 0νββ

Symmetry 12, 1310 (2020)





$$m_{\beta\beta} = \left|\sum_{i=1}^{3} U_{ei}^2 \epsilon\right| = \epsilon\left|c_{12}^2 c_{13}^2 + e^{2i\alpha_{21}} c_{13}^2 s_{12}^2 + e^{2i\alpha_{31}} s_{13}^2\right|$$

$$m_{\beta\beta} \lesssim 0.03\,\text{eV} \quad \text{for NO}$$
$$\lesssim 0.001\,\text{eV} \quad \text{for IO}$$

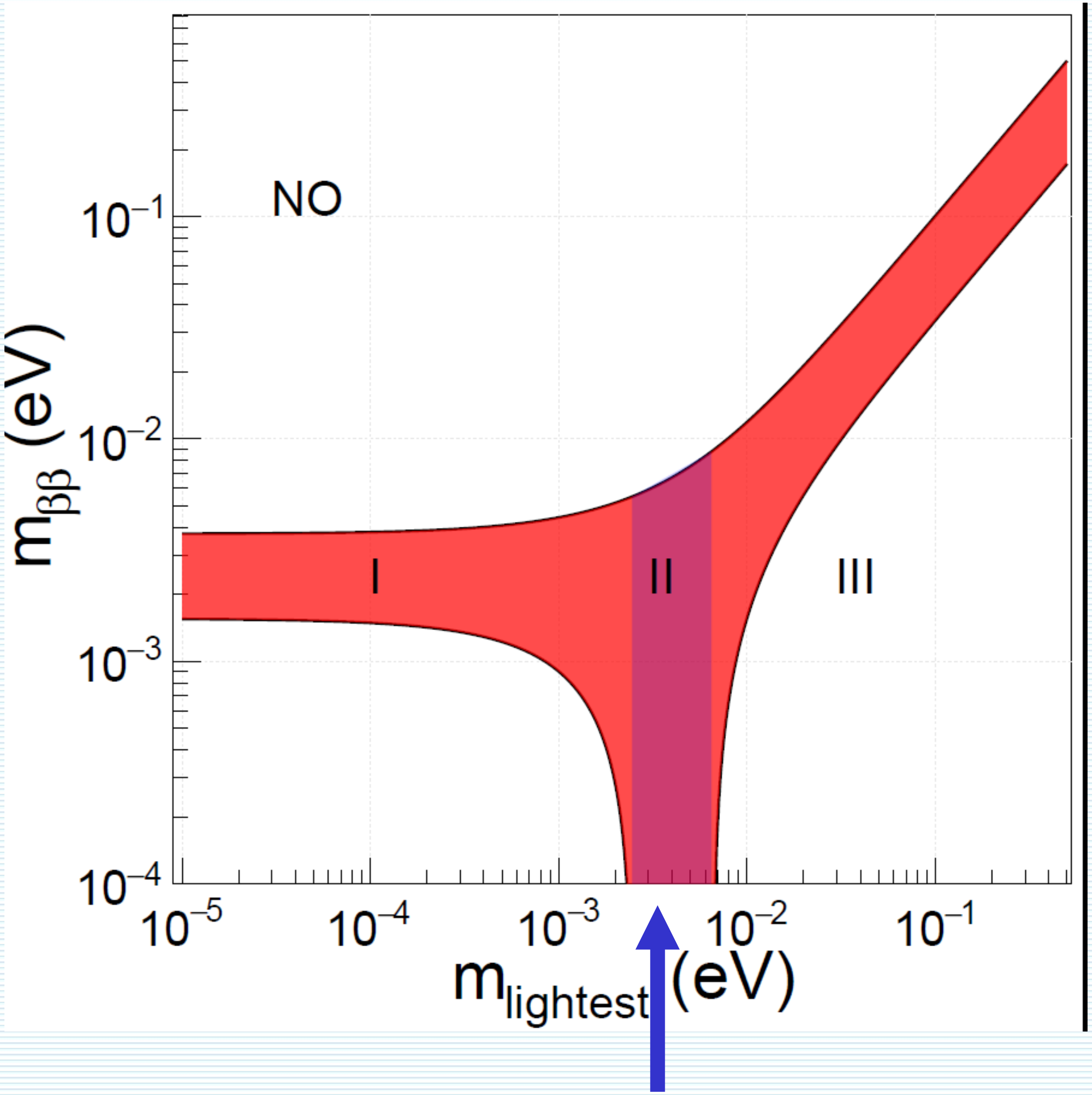
neutrino ↔ antineutrinos oscillations

governed by a related parameter

m^L_{ee} (L=0) = $m_{\beta\beta}$

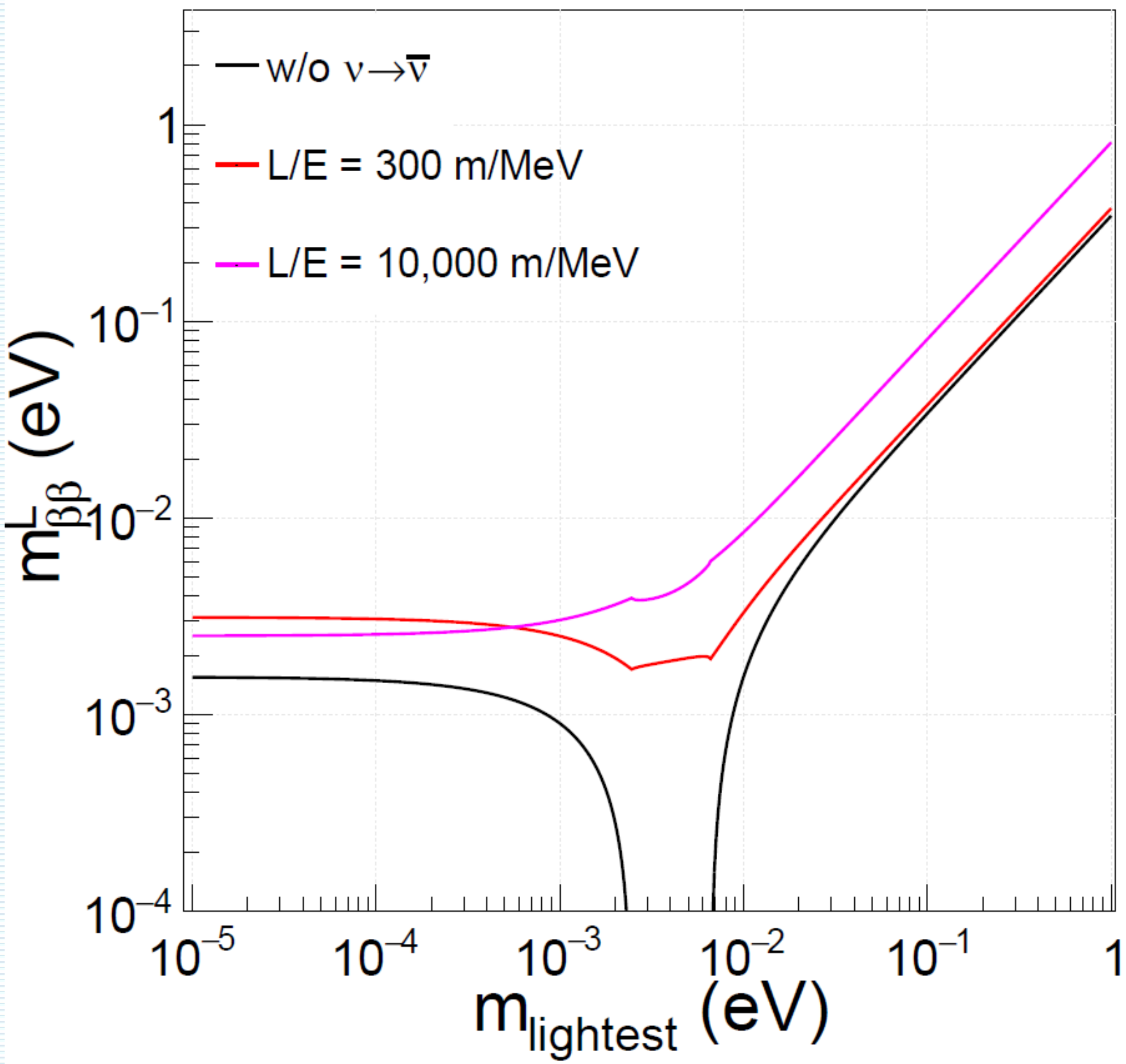
$$P(\bar{\nu}_\alpha \to \nu_\gamma) = \frac{|K|^2}{E^2}(m^L_{\alpha\gamma})^2$$

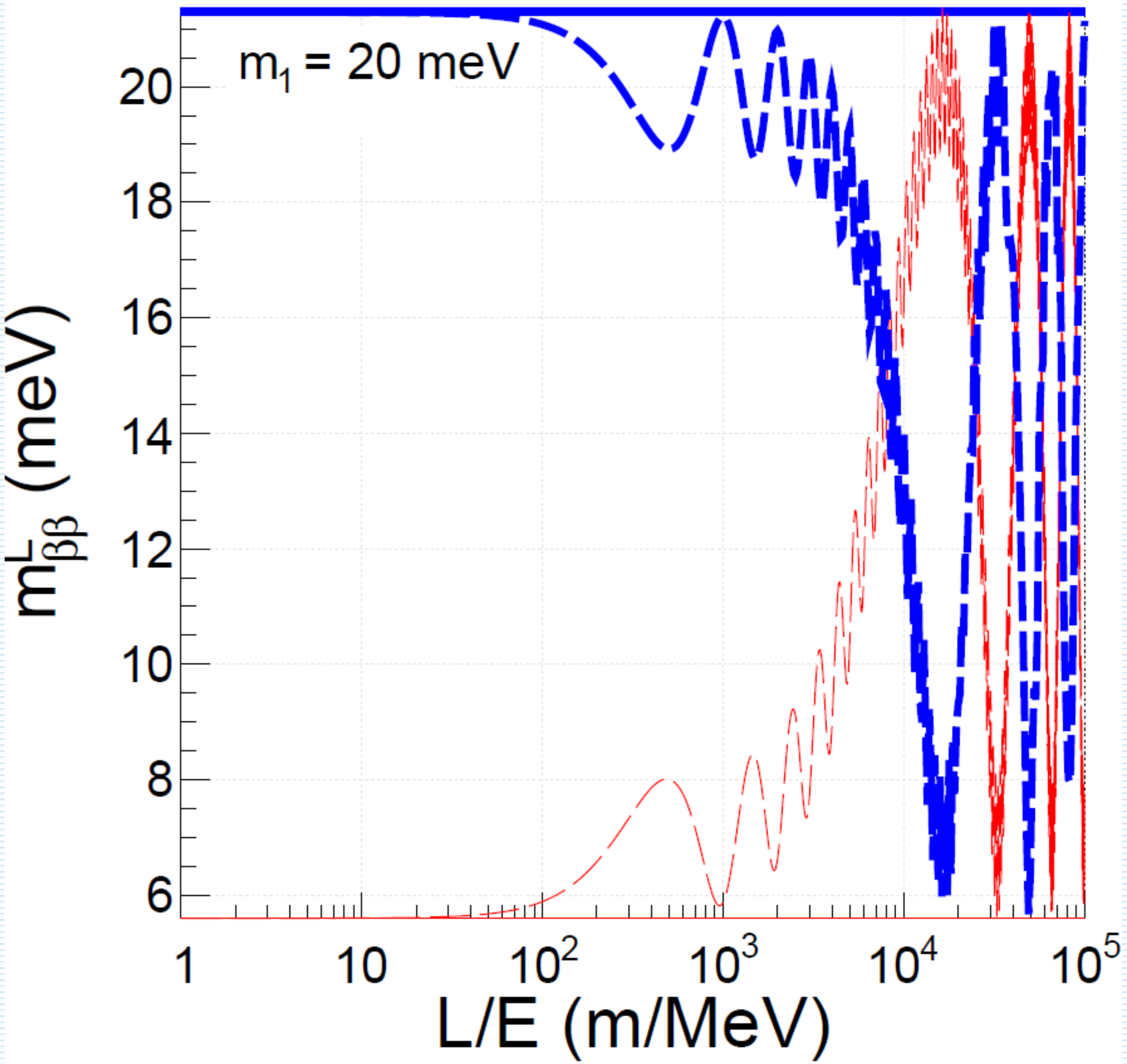
$$m^L_{\alpha\gamma} = \left|\sum_i [U_{\alpha i} U_{\gamma i} m_i exp(-i\frac{m_i^2}{2E}L)\right|$$



0νββ can be strongly suppressed (?!) …

Dependence of m^L_{ee} on $m_{lightest}$ and L/E

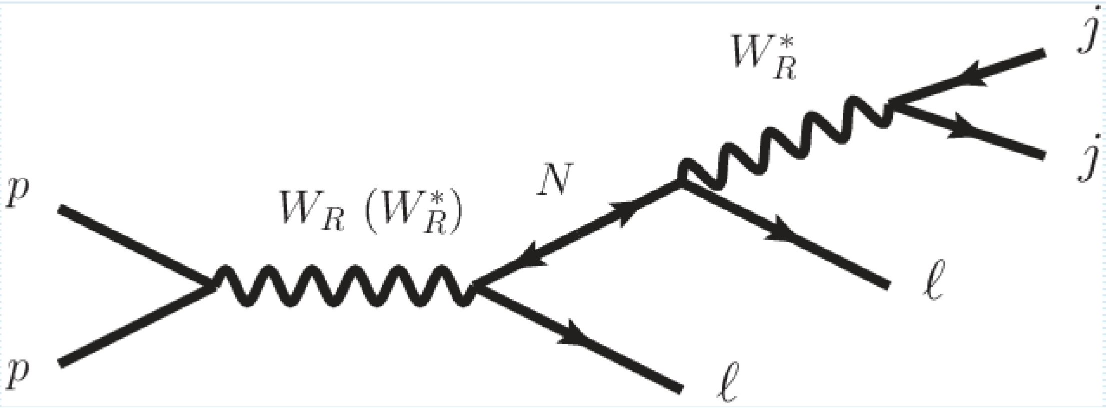


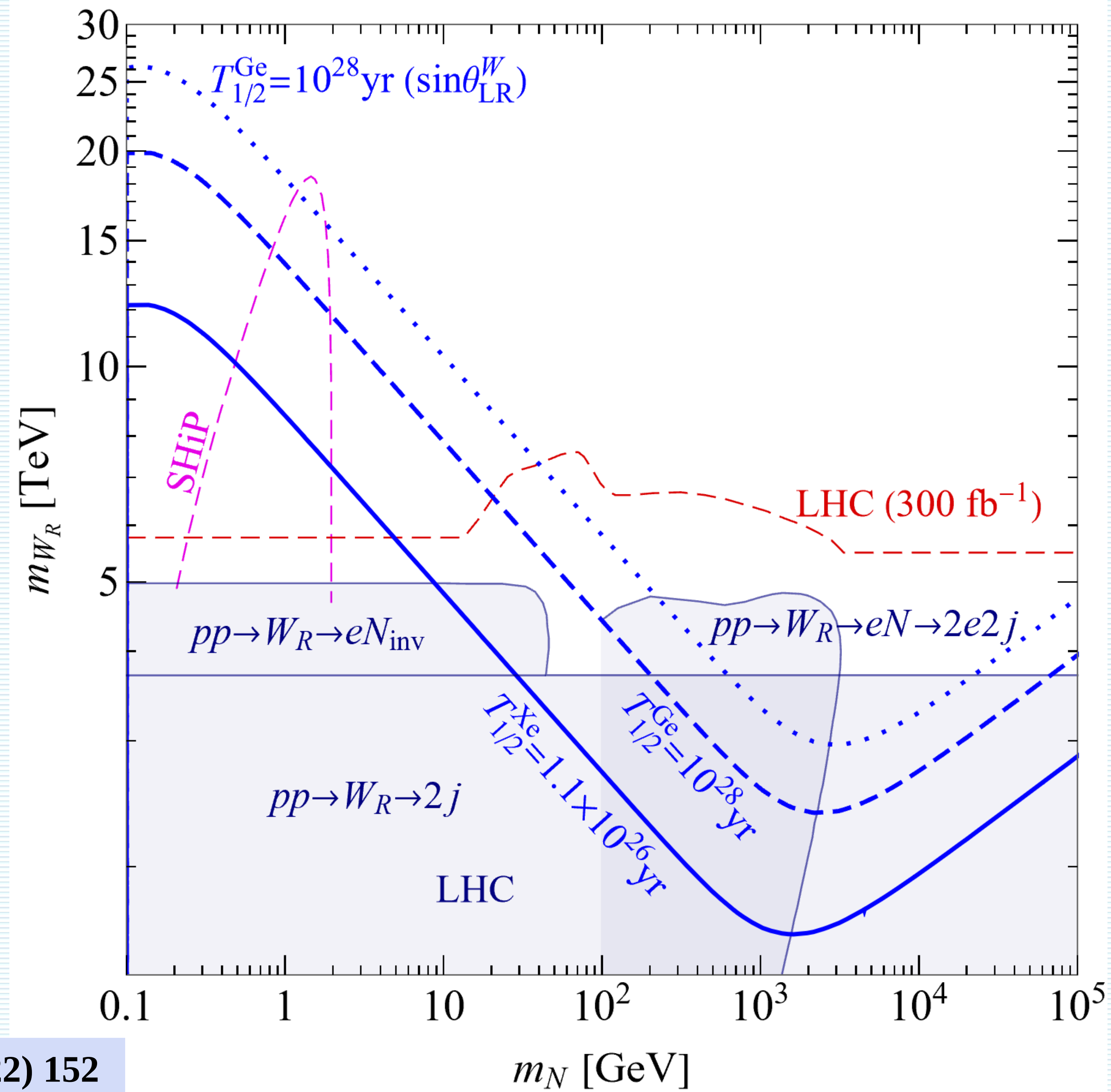


Symmetry 14, 1383 (2022)

Direct probe of Majorana nature of heavy neutrino (or HNL) at LHC

Keung-Senjanovic processes:
$pp \rightarrow W_R \rightarrow eN \rightarrow 2e2j$
or
$pp \rightarrow W_R \rightarrow \mu N \rightarrow 2\mu 2j$





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2νββ is sensitive to New Physics as well

All 100 kg- and ton-class 0νββ experiments can also study a diverse range of exotic phenomena, e.g. through spectral distortion in $2\nu\beta\beta$.
Future searches will probe the $2\nu\beta\beta$ with high statistics about 10^5-10^6 events.

Common subjects:

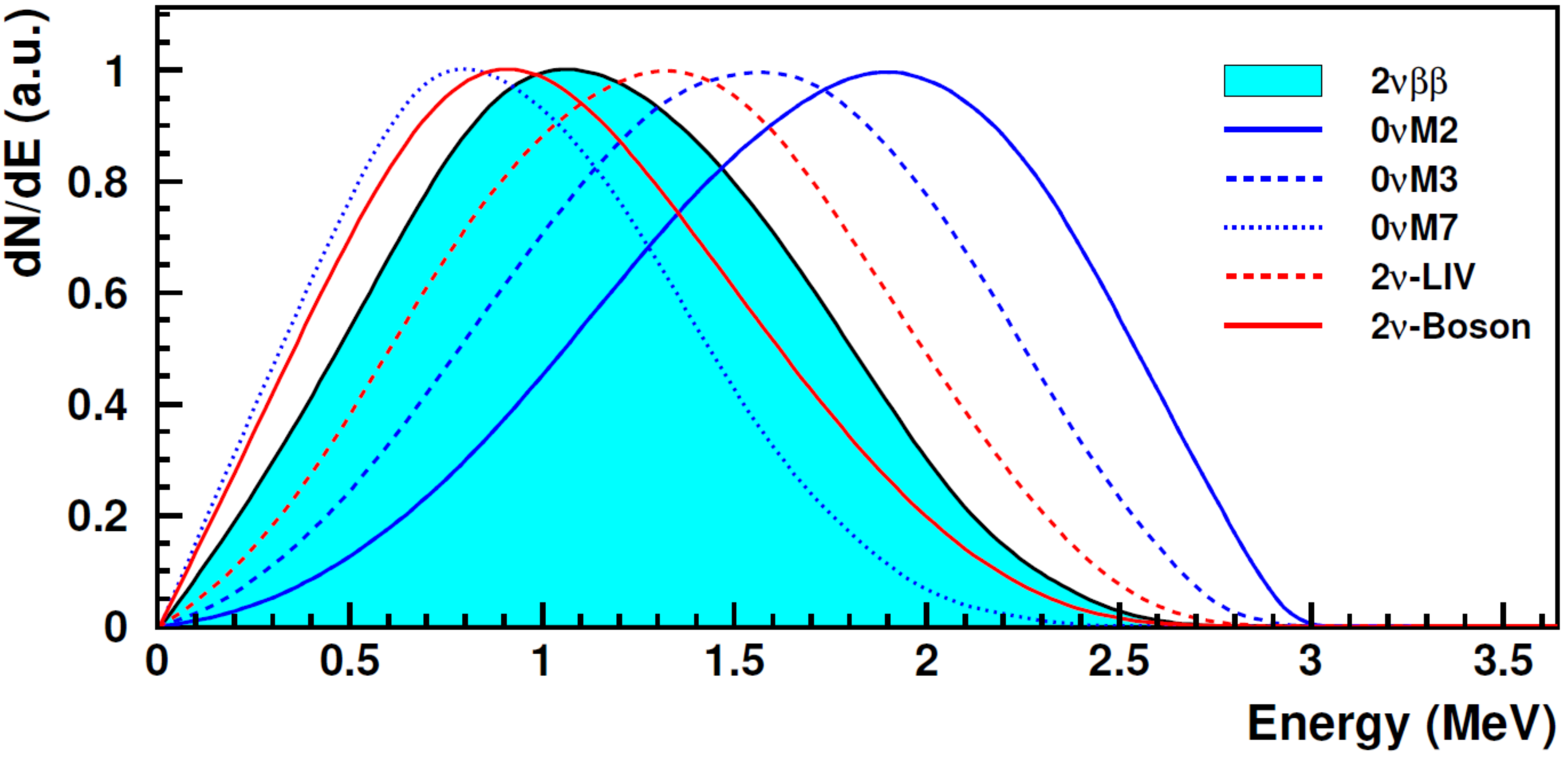
Majoron(s) emission
(partly)bosonic neutrinos,
Lorentz invariance violation

Recent subjects:

Lepton-number conserving right-handed currents
(PRL 125 (2020) 17, 171801)

Neutrino self-interactions
(PRD 102 (2020) 5, 051701)

Sterile neutrino and light fermion searches through energy end point
(PRD 103 (2021) 5, 055019;
PLB 815 (2021) 136127)



$$\frac{d\Gamma}{d\varepsilon_1 d\varepsilon_2} = C(Q-\varepsilon_1-\varepsilon_2)^n \left[p_1\varepsilon_1 F(\varepsilon_1)\right] \left[p_2\varepsilon_2 F(\varepsilon_2)\right]$$

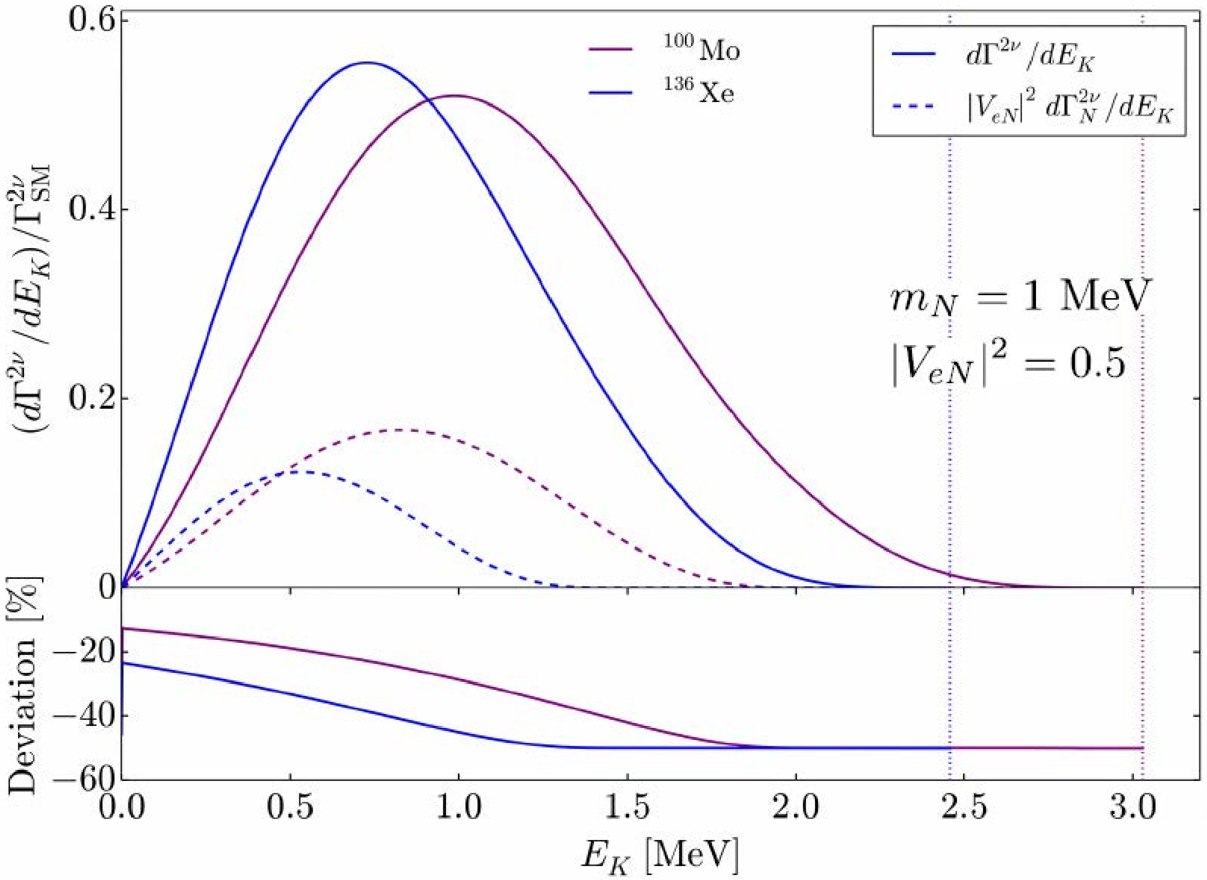
Spectral index **n**

$$\mathcal{L} = \frac{G_F \cos\theta_C}{\sqrt{2}} \left[(1+\delta_{\rm SM}) j_L^\mu J_{L\mu} + V_{eN} j_L^{N\mu} J_{L\mu} + \epsilon_{LR} j_R^{N\mu} J_{L\mu} + \epsilon_{RR} j_R^{N\mu} J_{R\mu} \right] + \text{h.c.}$$

Exotic 2νββ Sterile Neutrino (or HNL)

Consider either mixing of sterile ν with active ν, or right-handed currents

Phys.Rev.D 103 (2021) 055019



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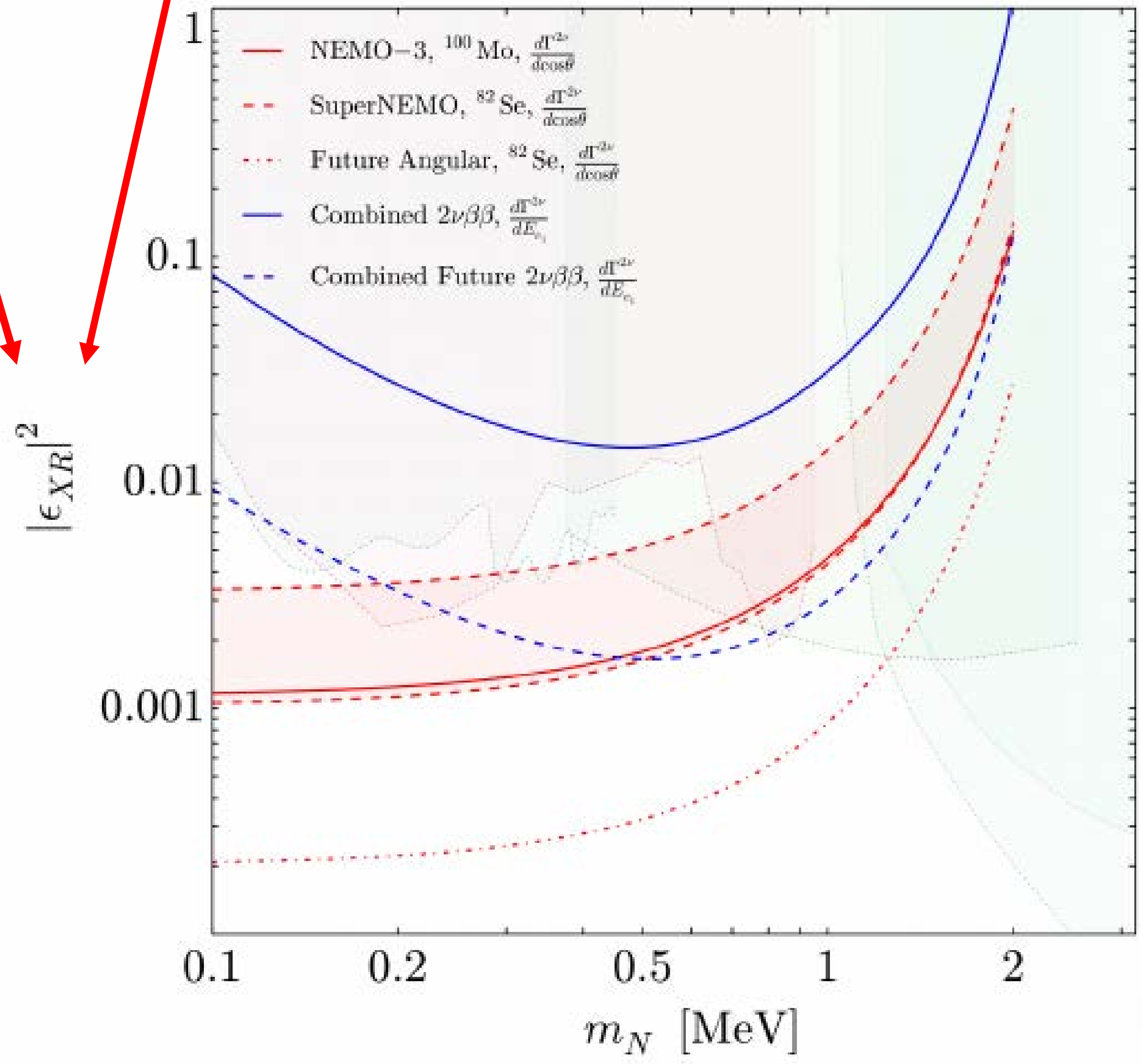
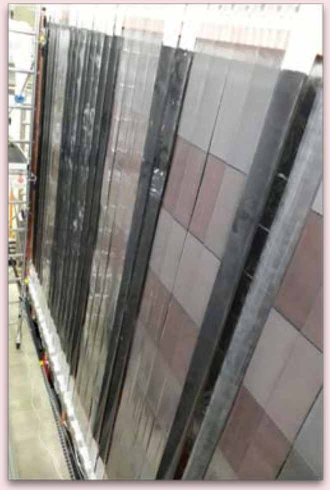


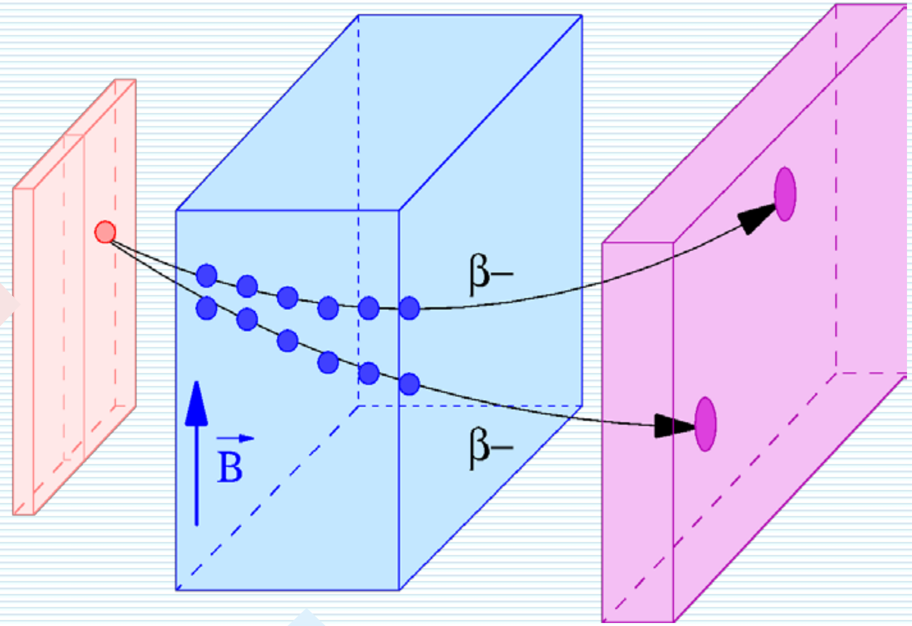
SuperNEMO Double-Beta Decay Experiment

Unique tracker-calorimeter technology

Source foil

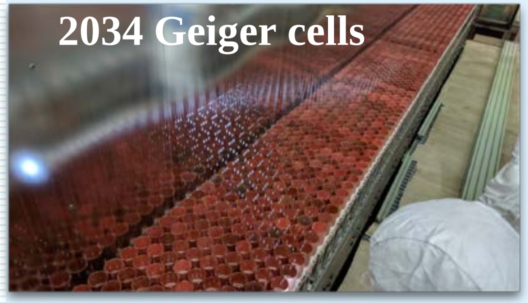
^{82}Se or any $\beta\beta$ isotope





Segmented calorimeter

Individual e^- & γ energies



Tracker

Identification of e^-, e^+, γ and α

Full $\beta\beta$ kinematics & topology

- **Excellent background rejection**
- Disentangle $0\nu\beta\beta$ **mechanisms:** V+A, sterile ν…
- Nuclear physics: constrain g_A in $2\nu\beta\beta$
- e-γ separation **probes** decays to excited states

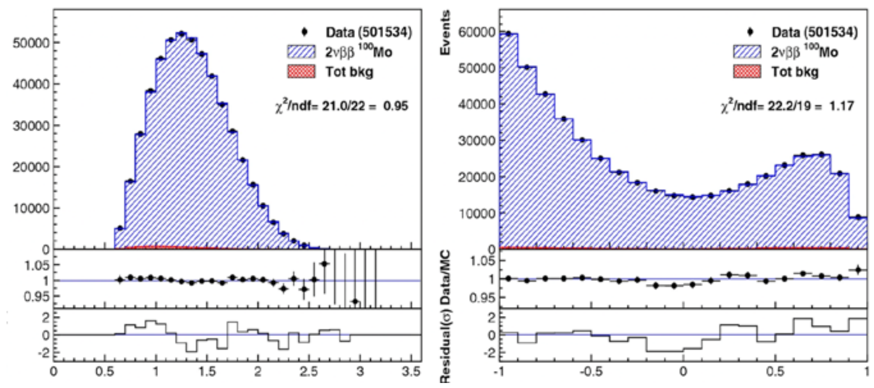
Role of SuperNEMO

Full kinematics and precision measurements of *2νββ*

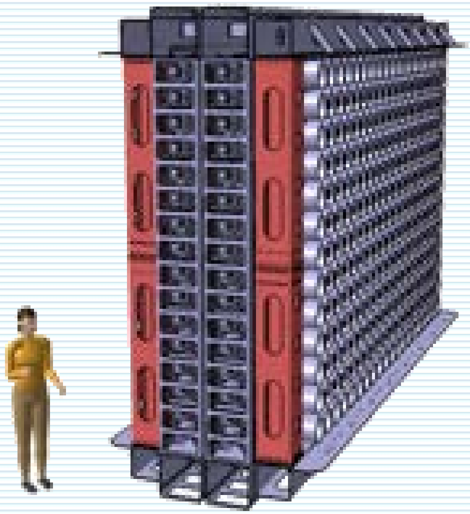
- Nuclear model constraints
- g_A quenching constraints
- Sterile neutrinos
- Right-handed currents
- *2νββ* with emission of single e^-, etc

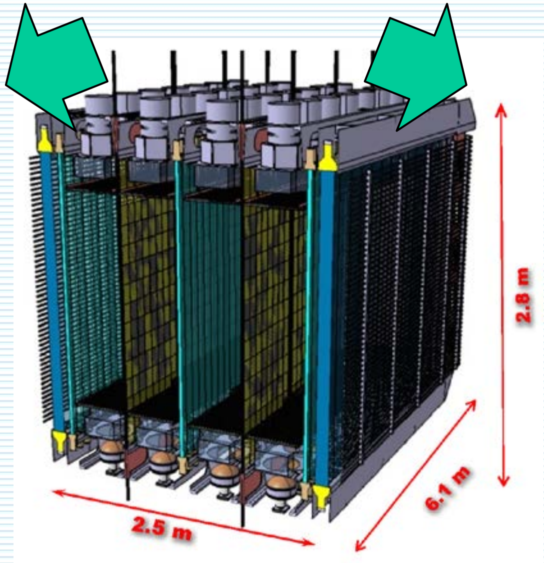
(NEMO-3 analysis in preparation)

NEMO3 100Mo total data



Esum (MeV) cosθ





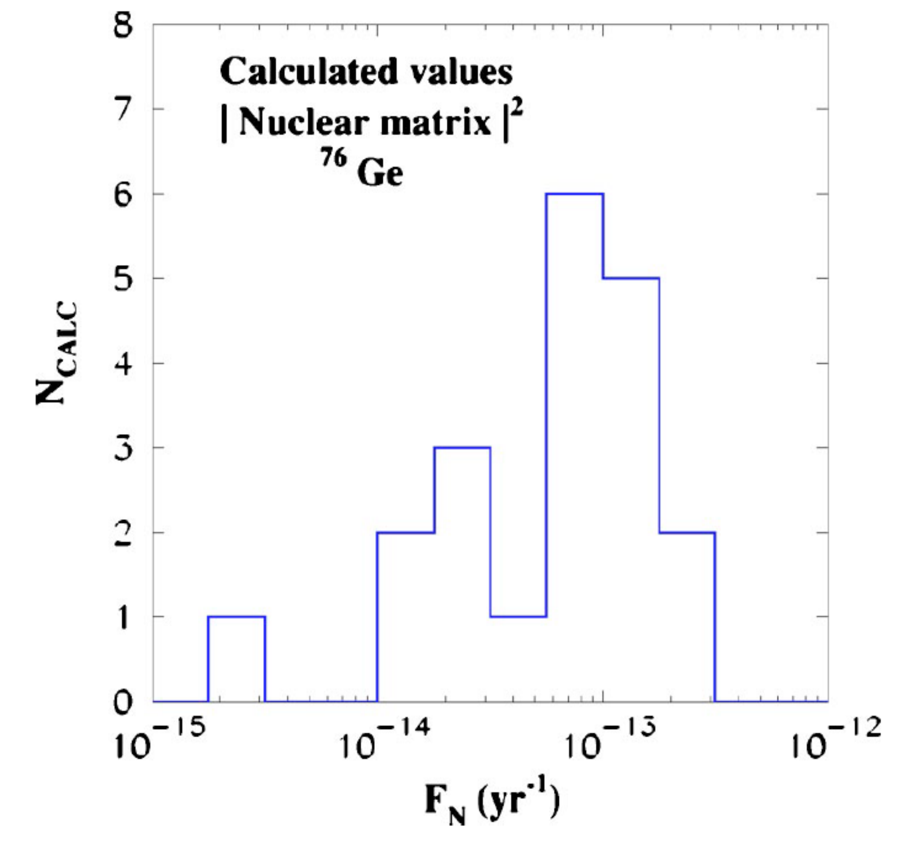
Understanding the Ultimate Reach of the Tracker-Calorimeter Technique

- Can the technique be used to confirm & probe a signal found in the next generation of *0νββ* experiments?
- Explore alternative tracker-calorimeter technologies & different isotopes

SuperNEMO Collaboration

0νββ decay NMEs

Before: 2004 (factor 10 uncertainty)
few groups, 2 nuclear structure methods:
Nuclear Shell Model, QRPA



PRC 70, 033012 (2004)

Present: 2022 (factor 2-3)
Recognized priority task in nuclear physics
many groups, many nuclear structure methods:
Nuclear Shell Model, QRPA, PHFB, IBM, EDF

Attempts (light nuclear systems):
Ab initio calculations by different approaches – No Core Shell Model, Green's Function Monte Carlo, Coupled Cluster Method, Lattice QCD etc

Additional problems:
+ Effective weak coupling constant
$g^{eff}_A \approx 0.4 - 1.27$ (factor ≈ 3)
+ contact term (factor ≈ 2)

Evaluation of the 0νββ-decay NMEs calculation - Approximations needed

The nuclear w. f. of
(A,Z), (A,Z+1)*, (A,Z+2)
Many-body methods
of choice:

Nuclear Shell Model (Madrid-Strasbourg, Michigan, Tokyo): Relatively small model space (1 shell), all correlations included, solved by direct diagonalization
QRPA (Tuebingen-Bratislava-Calltech, Jyvaskyla, Chapel Hill, Lanzhou): Several major shells, only simple correlations included
Interacting Boson Method (Yale-Concepcion): Small space, important proton-neutron Pairing correlations missing
Projected Hartree-Fock-Bogoliubov Method (Lucknow): Several major shells, missing GT proton-neutron residual interaction.
Energy Density Functional theory (Madrid, Beijing): >10 shells, important proton-neutron pairing missing
An initio approaches:

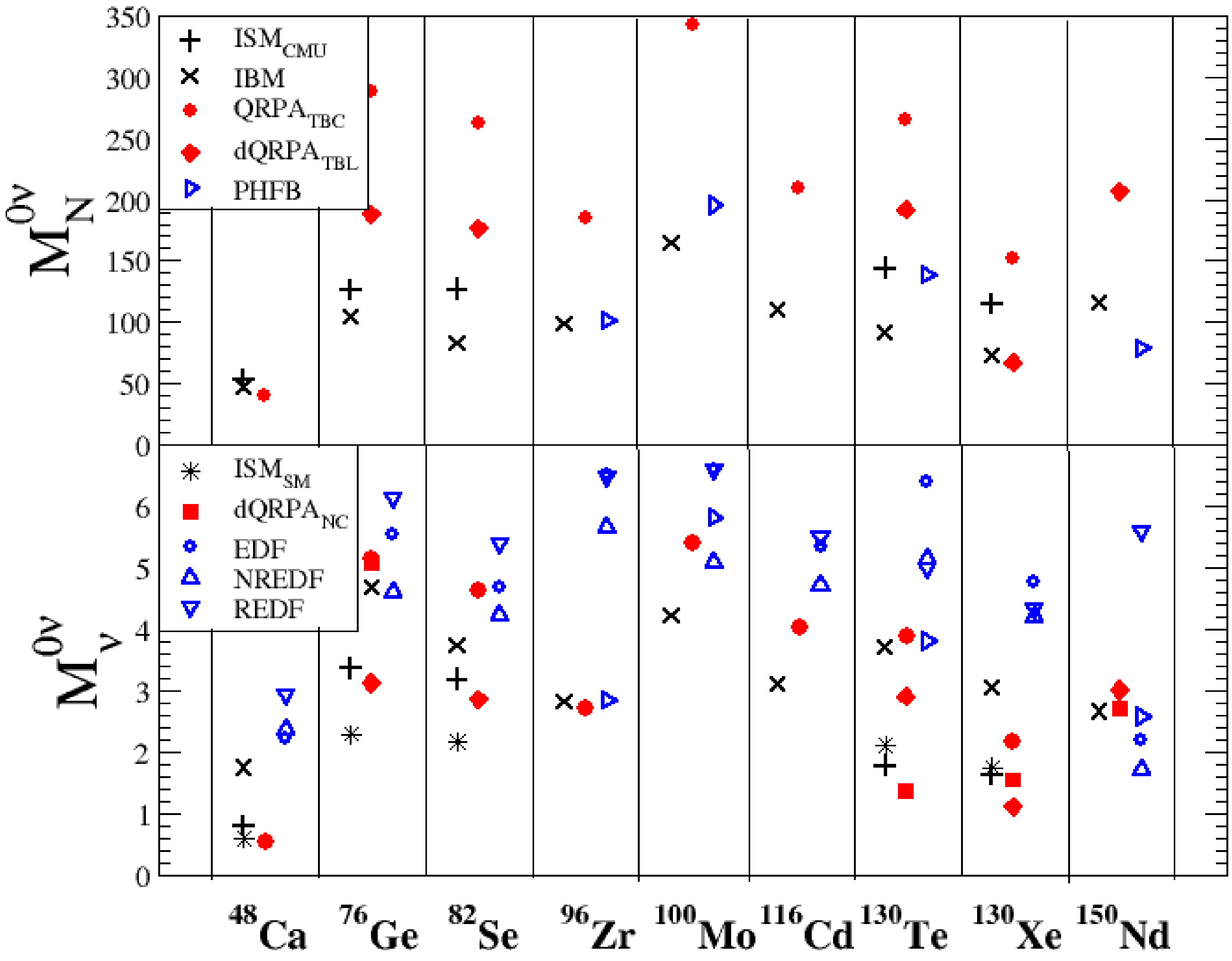
The 0νββ nuclear transition operators
(F, GT, and tensor type):

+ Transiton operators involving complete set of states of intermediate nucleus
+ Transition operators in closure approximation – just two-body operators
+ Chiral effective field theory two-body transition operators with contact term
+

! Isospin, and spin-isospin symmetries
(M_{Fcl}≈0, M_{GTcl} strongly suppressed):

Initial 0^+ g.s.: (T, T)
Final 0^+ g.s.: (T-2, T-2) ⇒ ΔT = 2 (!)

Till now, this issue addressed only within the QRPA
PRC 98, 064325 (2018)



unquenched g_A

0νββ-decay NME status 2022

All models missing essential physics

Impossible to assign rigorous uncertainties

Differencies:

- **Many-body approxim.**
- **Size of the m.s.**
- **Residual interactions**

Chiral effective-field theory approach – contact term

PRL 126, 172002 (2021)

Assuming that the $0\nu\beta\beta$ process is mediated by a light-Majorana-neutrino exchange, a systematic analysis in chiral effective field theory shows that already at leading order a contact operator is required to ensure renormalizability of the amplitude for nn -> pp + ee process. Without the strong $^1S_0$ short range interaction (which appears universally in all nuclear potentials) there would be no need of contact term.

Nuclear matrix element

$$M^{0\nu} = \langle \Psi_f | O^{0\nu} | \Psi_i \rangle$$

Standard type contrib.

$$O_F^{0\nu} = (4\pi R_A) \sum_{a\neq b} V_F^{0\nu}(r_{ab}) \tau_a^+ \tau_b^+ ,$$

$$O_{GT}^{0\nu} = (4\pi R_A) \sum_{a\neq b} V_{GT}^{0\nu}(r_{ab})\, \sigma_{ab}\, \tau_a^+ \tau_b^+ ,$$

$$O_T^{0\nu} = (4\pi R_A) \sum_{a\neq b} V_T^{0\nu}(r_{ab}) S_{ab}\, \tau_a^+ \tau_b^+ .$$

$$V_\alpha^{0\nu}(r_{ab}) = \frac{1}{g_A^2} \int \frac{d^3\mathbf{q}}{(2\pi)^3} e^{i\mathbf{q}\cdot\mathbf{r}_{ab}} V_\alpha^{0\nu}(\mathbf{q}^2)$$

$$V_\alpha^{0\nu}(\mathbf{q}^2) = \frac{1}{\mathbf{q}^2} v_\alpha(\mathbf{q}^2)$$

ν-potential (< $E_{aver.}$> = 0).

regularized with a dipole form-factors

$$v_F(\mathbf{q}^2) = -g_V^2(\mathbf{q}^2) ,$$

$$v_{GT}(\mathbf{q}^2) = g_A^2(\mathbf{q}^2) + \frac{2}{3}\frac{\mathbf{q}^2}{2m_N} g_A(\mathbf{q}^2) g_P(\mathbf{q}^2) + \frac{1}{3}\frac{\mathbf{q}^4}{4m_N^2} g_P^2(\mathbf{q}^2) + \frac{2}{3}\frac{\mathbf{q}^2}{4m_N^2} g_M^2(\mathbf{q}^2) ,$$

$$v_T(\mathbf{q}^2) = -\frac{2}{3}\frac{\mathbf{q}^2}{2m_N} g_A(\mathbf{q}^2) g_P(\mathbf{q}^2) - \frac{1}{3}\frac{\mathbf{q}^4}{4m_N^2} g_P^2(\mathbf{q}^2) + \frac{1}{3}\frac{\mathbf{q}^2}{4m_N^2} g_M^2(\mathbf{q}^2) ,$$

Contact term contrib.

$$O_S^{0\nu} = (4\pi R_A) \sum_{a\neq b} V_S^{0\nu}(r_{ab}) \tau_a^+ \tau_b^+$$

$$V_S^{0\nu}(r_{ab}) = 2\frac{g_\nu^{NN}}{g_A^2} \delta_R^{(3)}(\mathbf{r}_{ab}),$$

PPNP 112, 1037 (2020)

Magnitude of the contact term 0νββ-decay NME

PLB 823, 136720 (2021)

Nucleus	QRPA $M_S^{0\nu}/M_L^{0\nu}$ (%)	NSM $M_S^{0\nu}/M_L^{0\nu}$ (%)
^{48}Ca		23 – 62
^{76}Ge	32 – 73	15 – 42
^{82}Se	30 – 70	15 – 41
^{96}Zr	29 – 69	
^{100}Mo	49 – 108	
^{116}Cd	26 – 61	
^{124}Sn	36 – 81	17 – 46
^{128}Te	35 – 77	17 – 46
^{130}Te	34 – 77	17 – 47
^{136}Xe	30 – 70	17 – 47

$$[t^{0\nu}_{1/2}]^{-1} = G_{0\nu}\, g_A^4\, |M_L^{0\nu} + M_S^{0\nu}|^2 \frac{m^2_{\beta\beta}}{m_e^2}$$

Long-range $$M_L^{0\nu} = M_{GT}^{0\nu} - \left(\frac{g_V}{g_A}\right)^2 M_F^{0\nu} + M_T^{0\nu}$$

Short-range $$M_S^{0\nu} = \frac{2R}{\pi g_A^2} \langle 0_f^+ | \sum_{m,n} \tau_m^- \tau_n^- \int j_0(qr) h_S(q^2)\, q^2 dq | 0_i^+ \rangle$$

$$h_S(q^2) = -2 g_\nu^{NN}\, e^{-q^2/(2\Lambda^2)}$$

Regularized with Gaussian
(maybe better with dipole form-f. like weak magn. contr.)

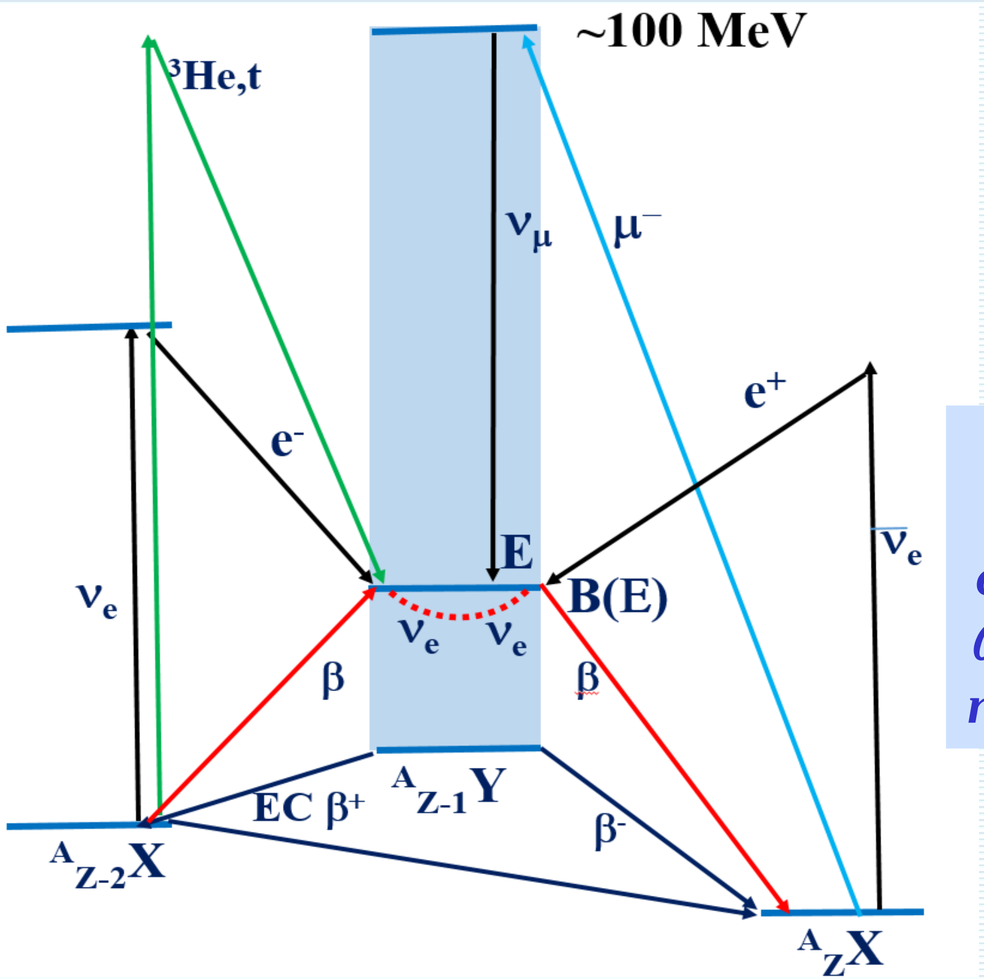
Open urgent questions:

- **A correspondence of the standard and the chiral field theory formalisms. Is contact term involved in the standard mechanism (completeness …).**
- **What is the magnitude of the contact term NME? Can it be large? Justification with other phenomenology needed – pion and heavy-ion DCX, etc.**

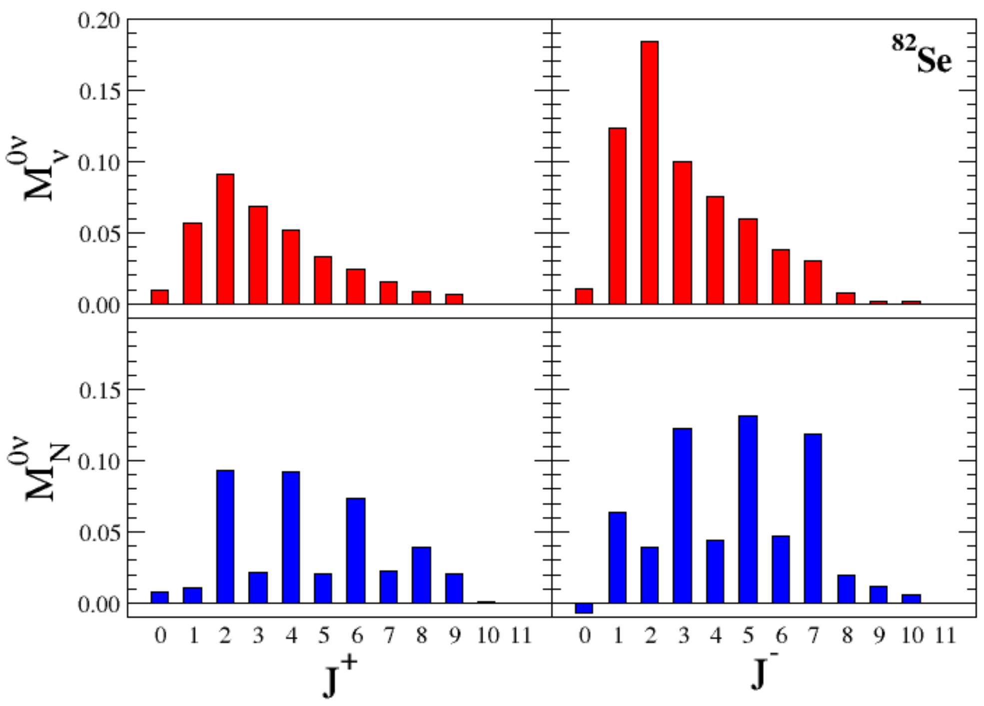
Supporting nuclear physics experiments

(Measurements still not conclusive for 0νββ NME)

- ✓ **β-decay, EC and 2νββ decay**
- ✓ **μ-capture**
- ✓ **(π^+, π^-), single charge exchange**
- ✓ **(^{3}He,t), (d,^{2}He), transfer reactions**
- ✓ **γ-ray spectroscopy, γγ-decay**
- ✓ **A promising experimental tool:**
  Heavy-Ion Double Charge-Exchange



Multipole decomposition of light and heavy 0νββ-decay NMEs normalized to unity

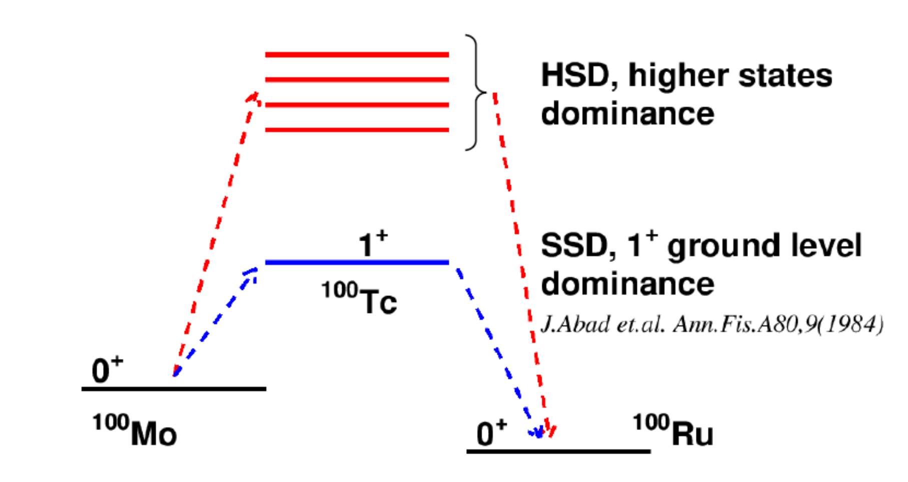


Higher multiploles are populated mostly due large ν-momenta transfer

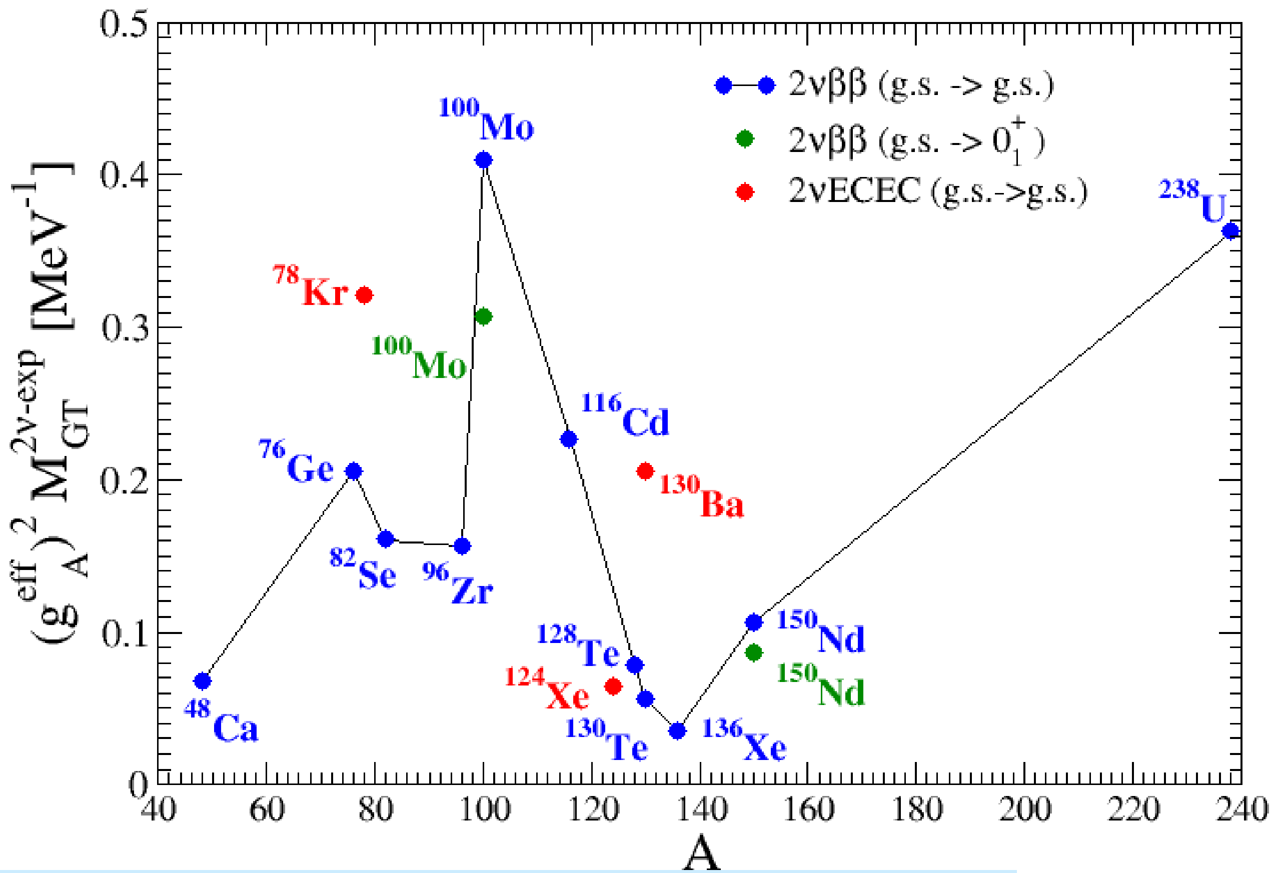
Fedor Simkovic

Understanding of the 2νββ-decay NMEs is of crucial importance for correct evaluation of the 0νββ-decay NMEs

There is no reliable calculation of the *2νββ-decay NMEs yet*



$$M_{GT}^{2\nu} = \sum_m \frac{< 0_f^+||\tau^+\sigma||1_m^+ >< 1_m^+||\tau^+\sigma||0_i^+ >}{E_m - E_i + \Delta}$$



The spread of 2νββ and 0νββ NMEs is large and small, respectively.
Reasons:

- **2νββ NMEs governed by contribution from single (1+) multipole unlike 0νββ NMEs by contributions from all multipoles (Jπ) of int. nucl.**
- **Neutrino potential vs 2νββ potential**

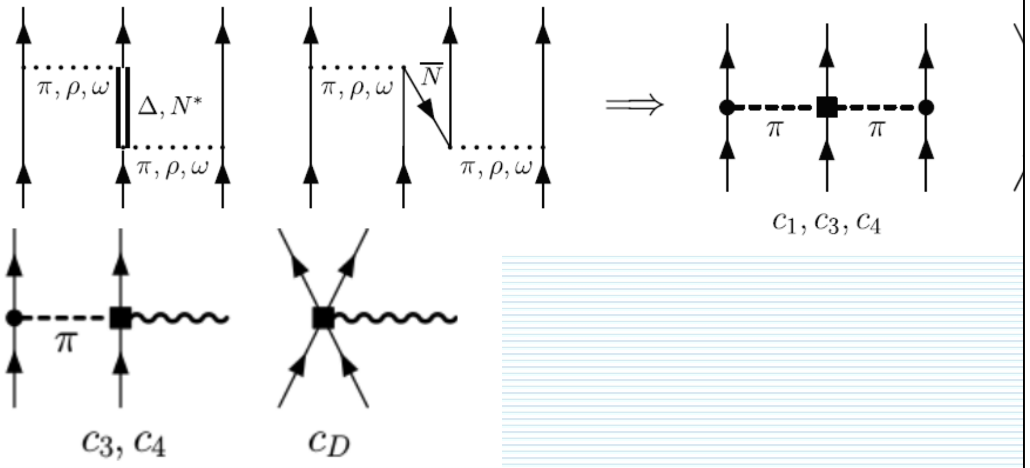
Both 2νββ and 0νββ operators connect the same states. Both change two neutrons into two protons. Explaining 2νββ-decay is necessary but not sufficient

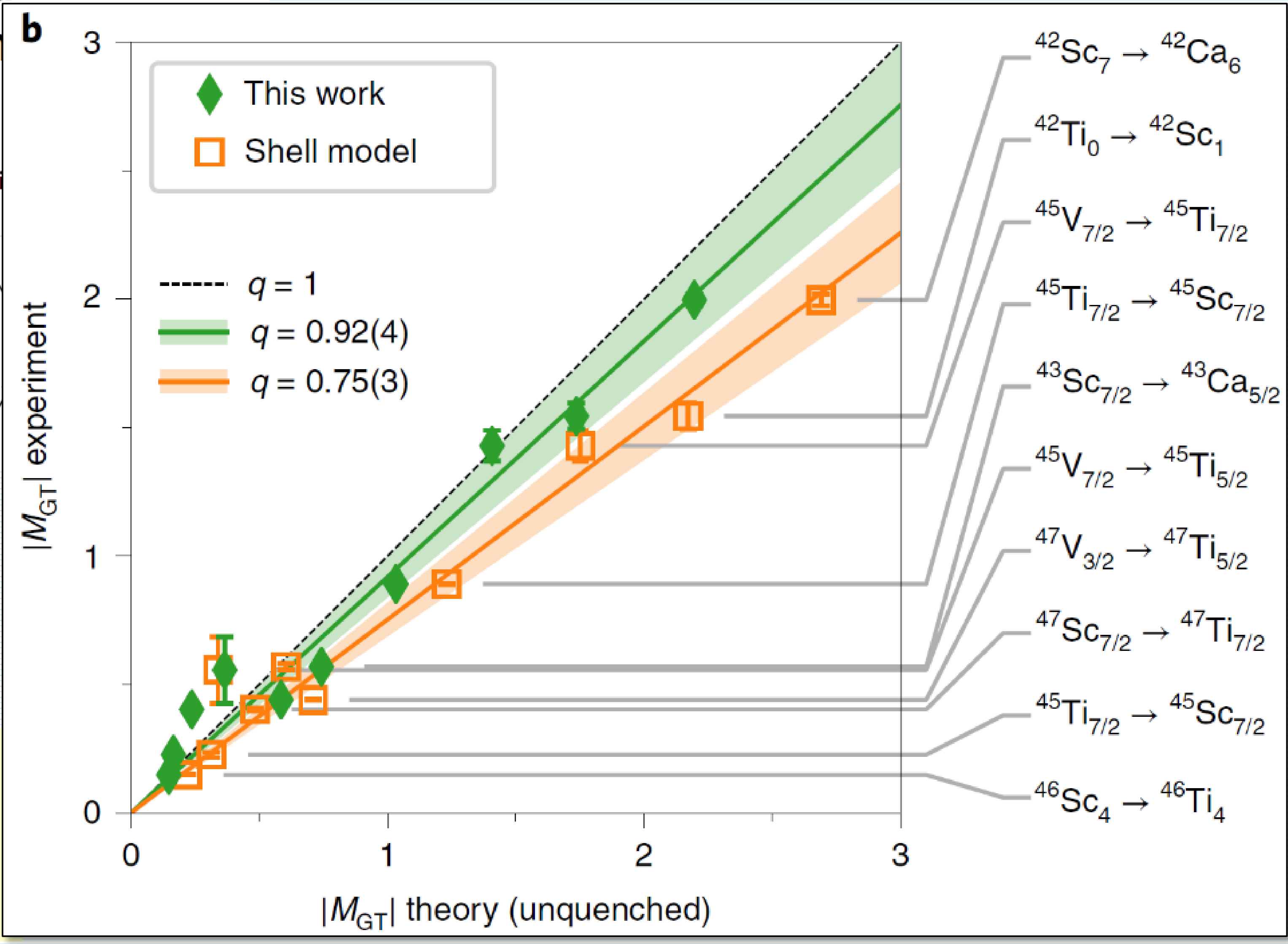
LETTERS
https://doi.org/10.1038/s41567-019-0450-7
nature physics

Ab initio β-decay study: g_A is unquenched (light nuclear systems)

Discrepancy between experimental and theoretical β-decay rates resolved from first principles

P. Gysbers[1,2], G. Hagen[3,4*], J. D. Holt[1], G. R. Jansen[3,5], T. D. Morris[3,4,6], P. Navráti
S. Quaglioni[7], A. Schwenk[8,9,10], S. R. Stroberg[1,11,12] and K. A. Wendt[7]





Once meson-exchange currents and 3-body forces are considered there is no need for any "quenching"

Measurement of GT strength via μ-capture

$\mu^-_b + (A,Z) \rightarrow (A,Z-1) + \nu_\mu$

J-PARC 3-50 GeV p, ν, μ

Contradicting results:

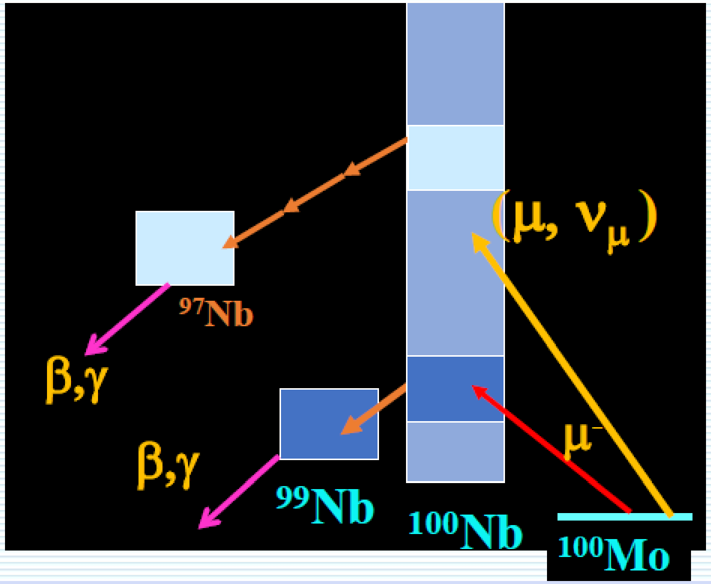
- **Strong quenching ($g_A \approx 0.6$)**

PRC 100, 014619 (2019)

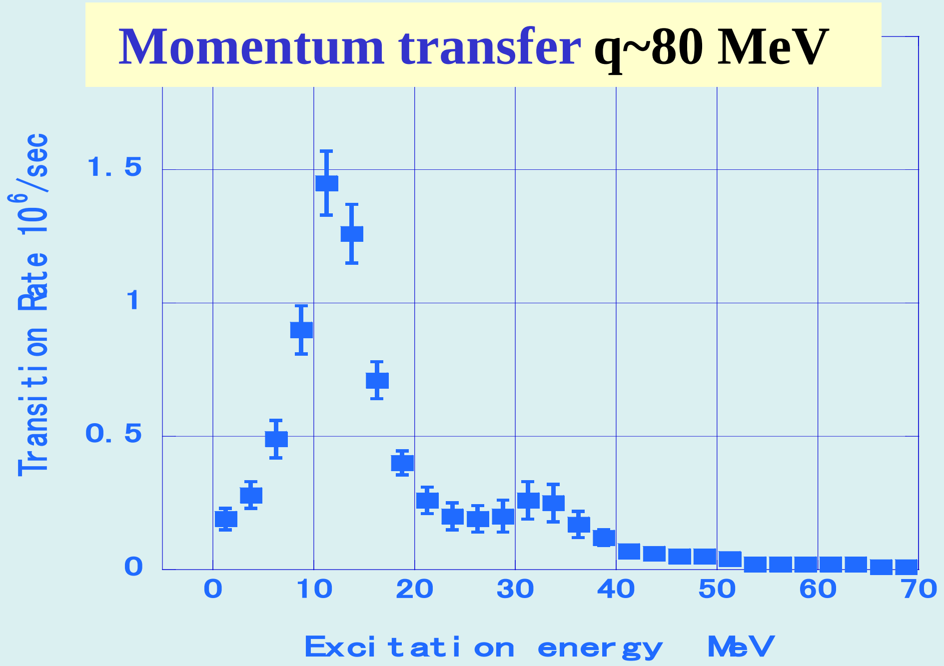
- **Weak quenching ($g_A \approx 1.1$)**

PRC 74, 024326 (2006)

PRC 79, 054323 (2009)



I. Hashim H. Ejiri , MXG16, PR C 97 2018

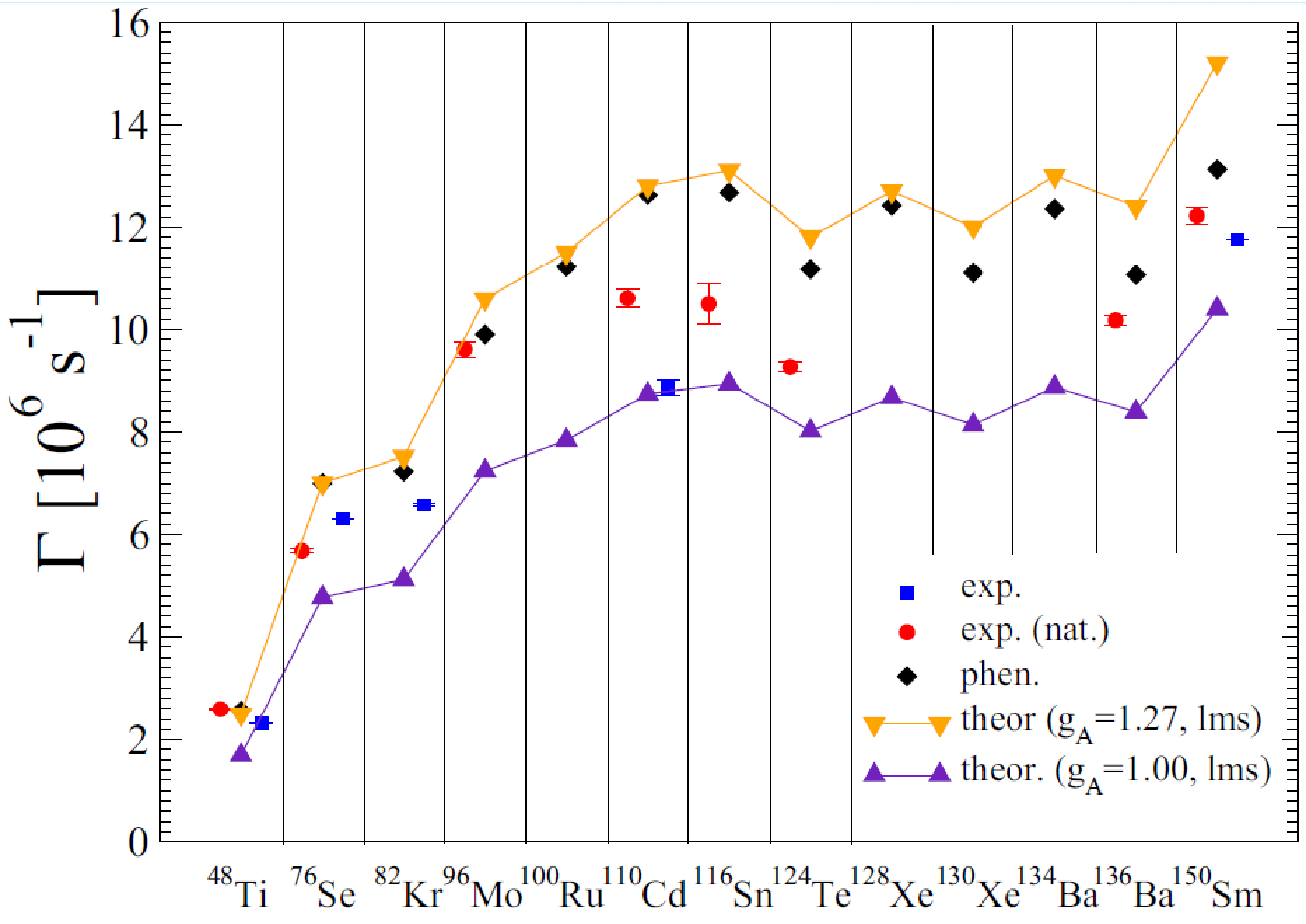


⇒ Small basis nuclear structure calculations (NSM, IBM) are disfavored. ⇒

Fedor S

Muon capture rates evaluated within QRPA

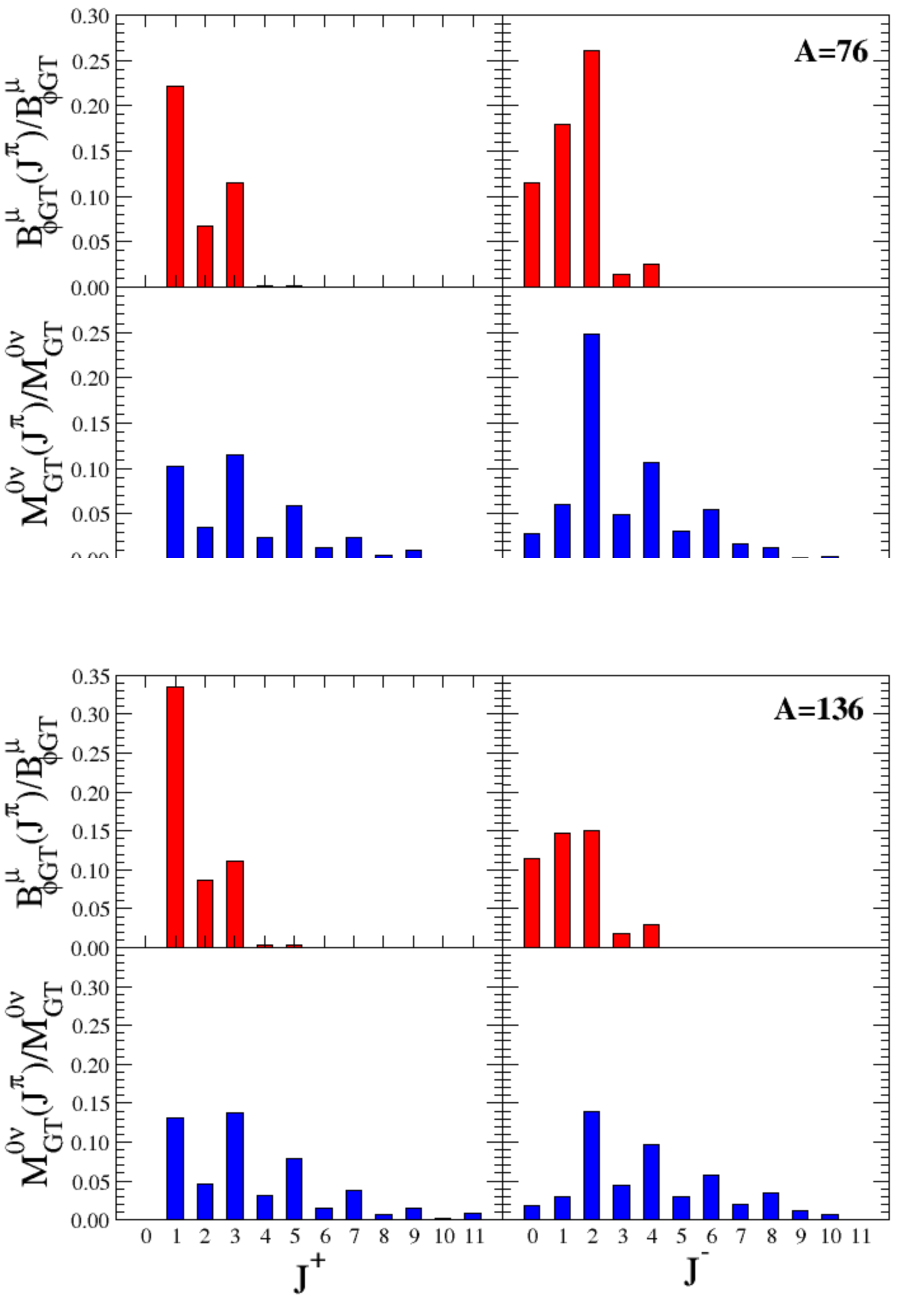
In agreement with soft quenching ($g_A \approx 1.1$)



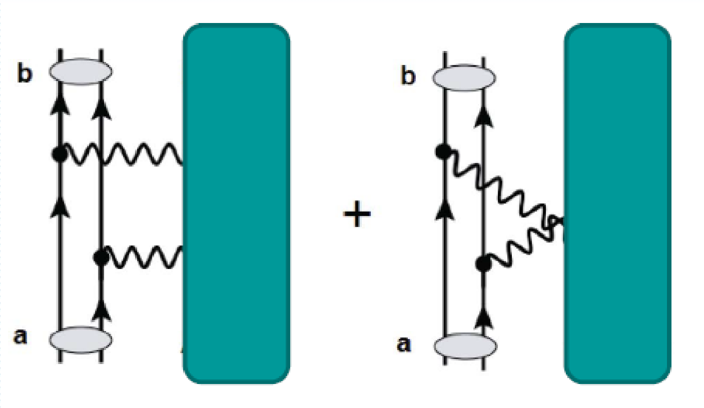
PRC 102, 034301 (2020).

9/7/2022

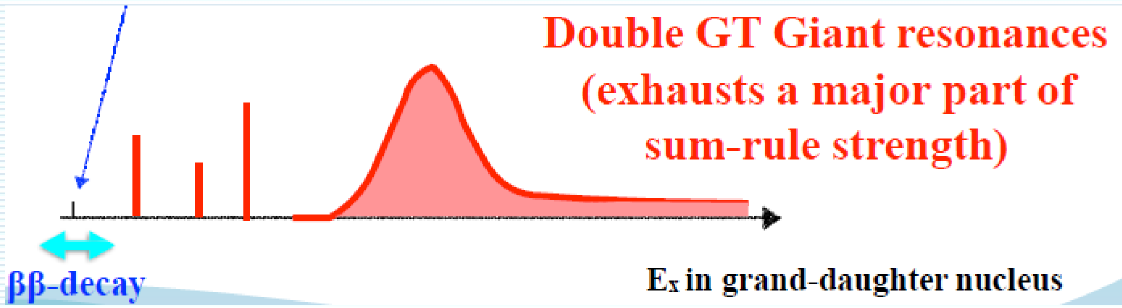
Experiment Monument at PSI will study contributions from all multipoles



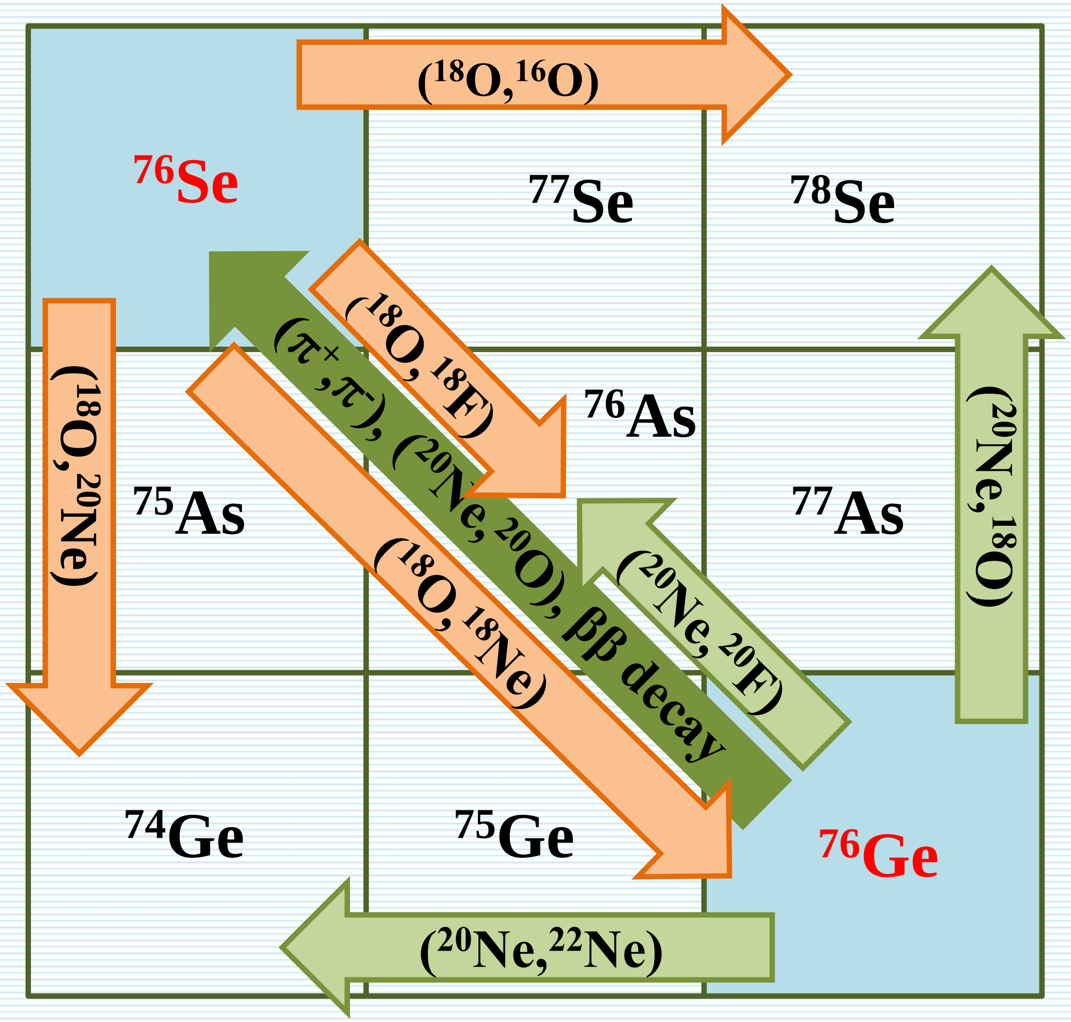
Multipole decomposition of B^{μ}_{GT} and $M^{0\nu}_{GT}$



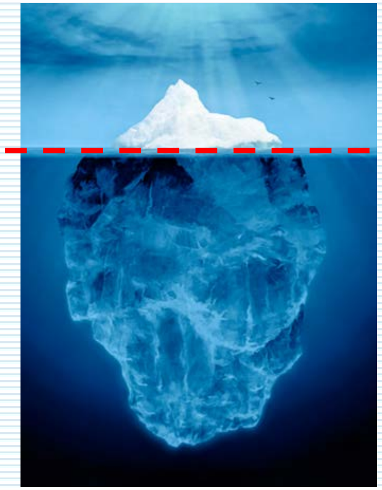
Heavy-ion DCE as surrogate processes of ββ-decay



- ✓ Induced by strong interaction
- ✓ Sequential nucleon transfer mechanism 4th order: Kinematical matching
- ✓ Meson exchange mechanism 1st or 2nd order
- ✓ Possibility to go in both directions
- ✓ Low cross section



Tiny amount of DGT strenght for low lying states



NUMEN

erc NURE

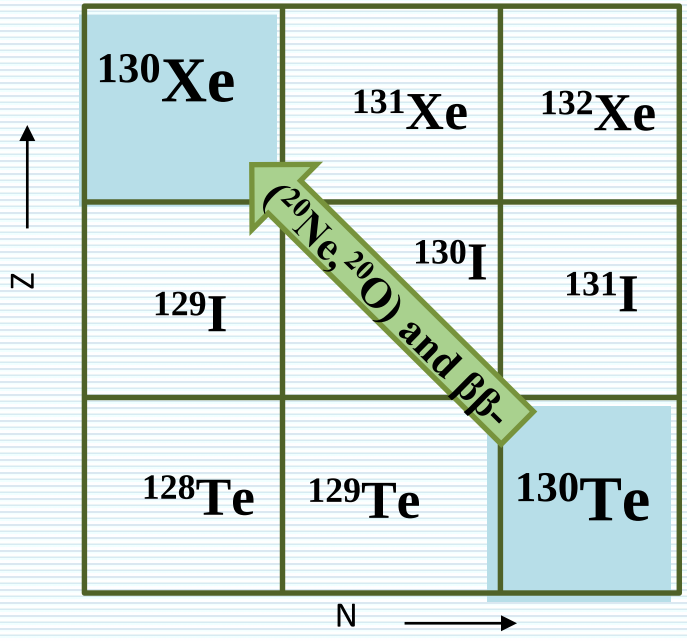
Sum rule almost exhausted by DGT Giant Mode, still not observed

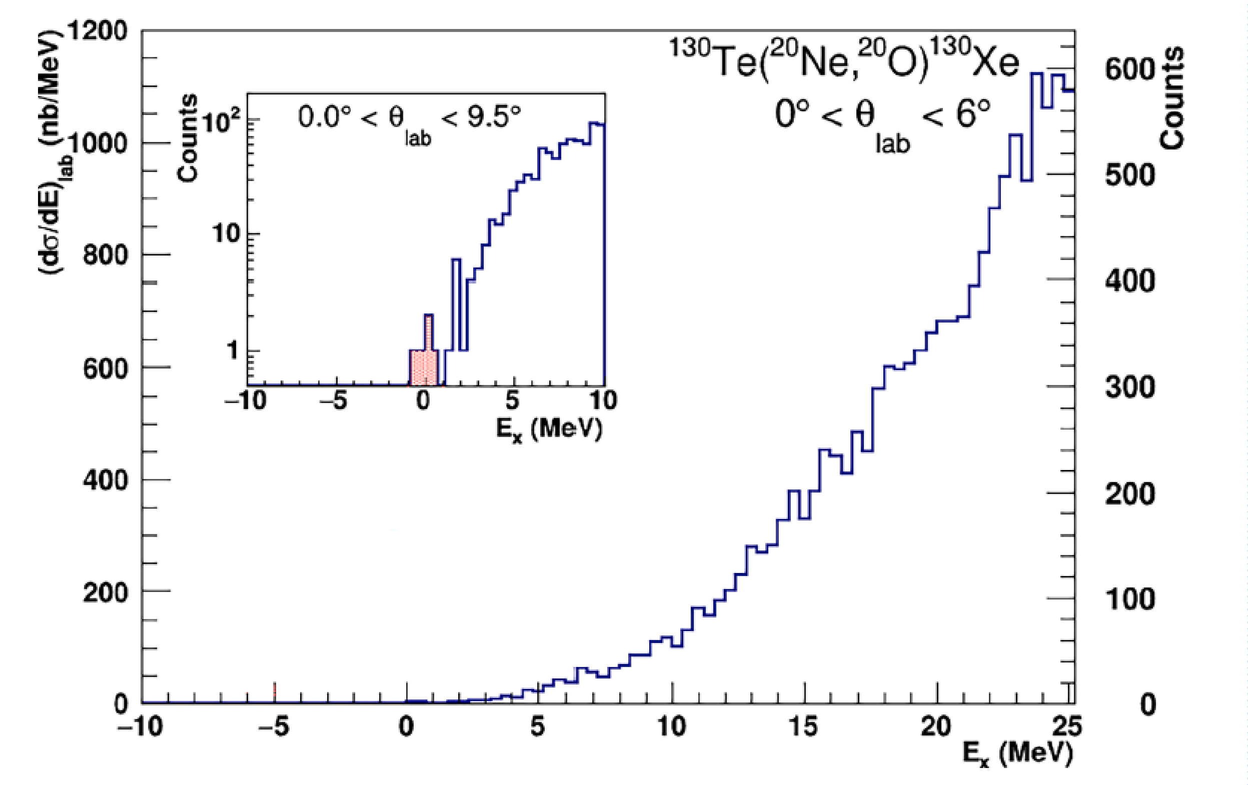
RIKEN

RCNP

Future: INFN-LNS

The ^{130}Te(^{20}Ne,^{20}O)^{130}Xe DCE reaction





- g.s. → g.s. transition maybe isolated
- Absolute cross section measured

Resolution ~ 500 keV FWHM

No spurious counts at $-10 < E_x < -2$ MeV

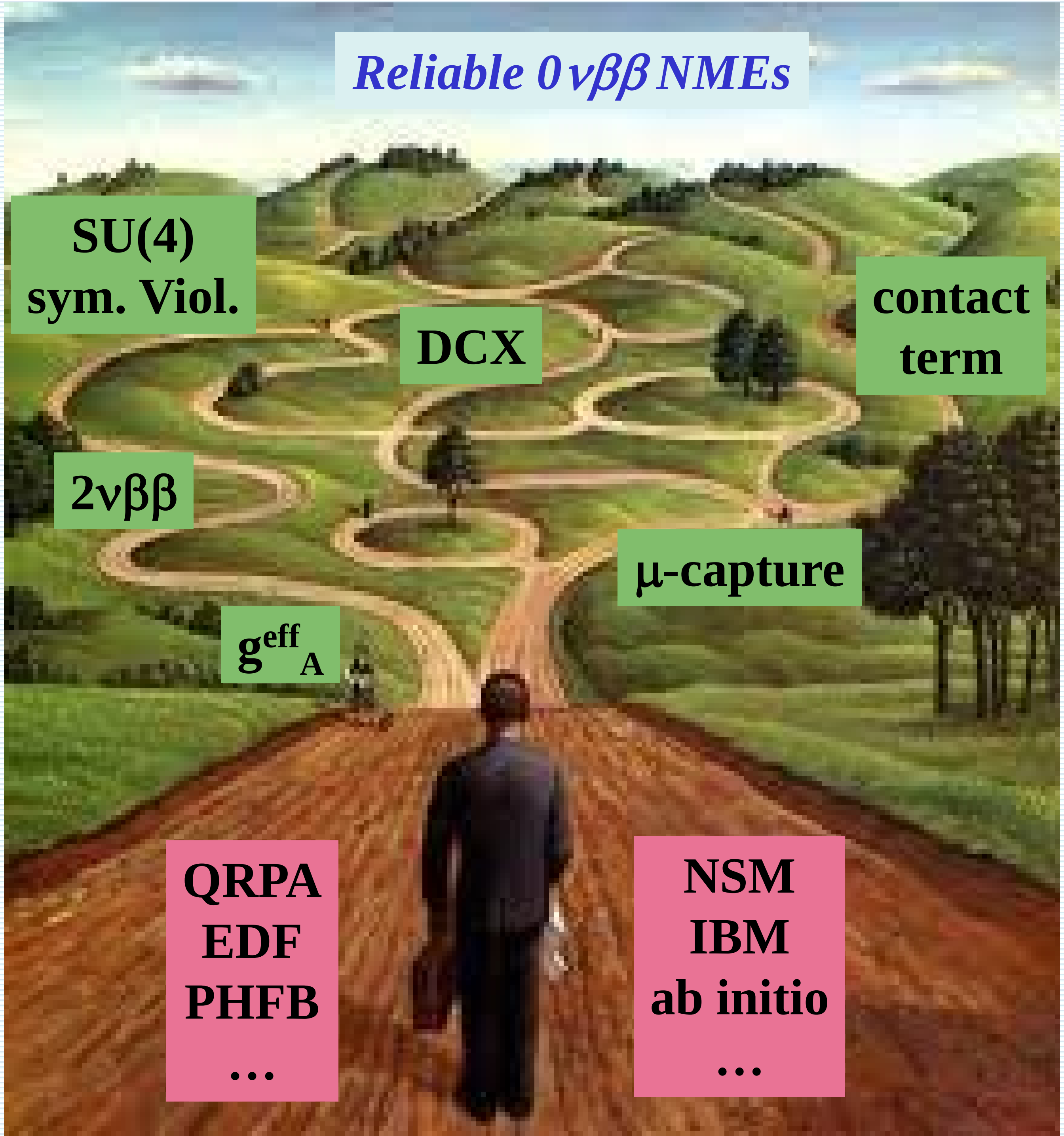
State (MeV)	Counts	Absolute coss section (nb)	Cross section 95% limit (nb)
g.s. (0^+) + 2^+ (536 keV)	5	13	[3--18]

Analysis of cross-section sensitivity < 0.1 nb in the Region Of Interest

There is still some time to complete the job

Waiting on observation of 0νββ

0νββ - NMEs must be evaluated using tools of nuclear theory



To complete information on 0νββ see reviews:

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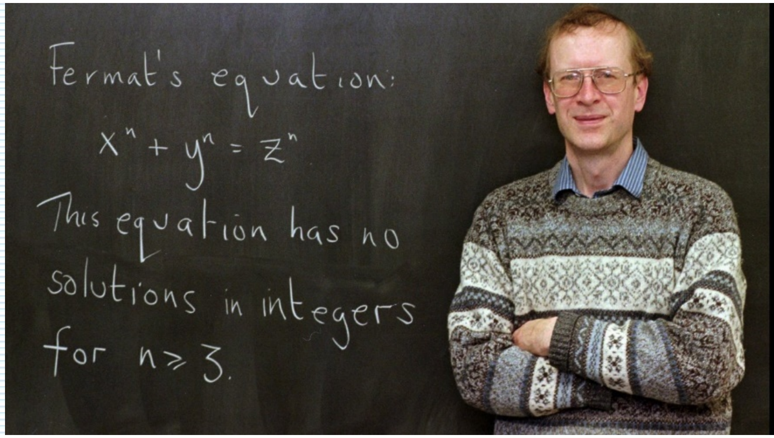
Around 1637, Pierre de Fermat wrote in the margin of a book that the more general equation

$$a^n + b^n = c^n$$

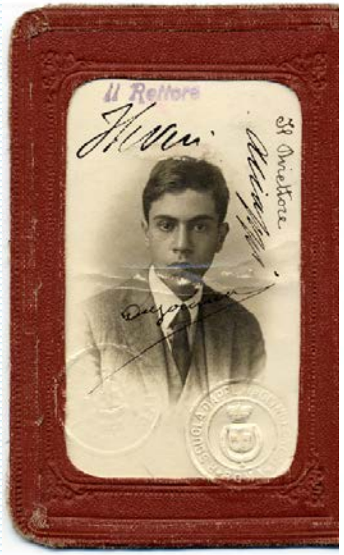
had no solutions in positive integers if *n* is an integer greater than 2.

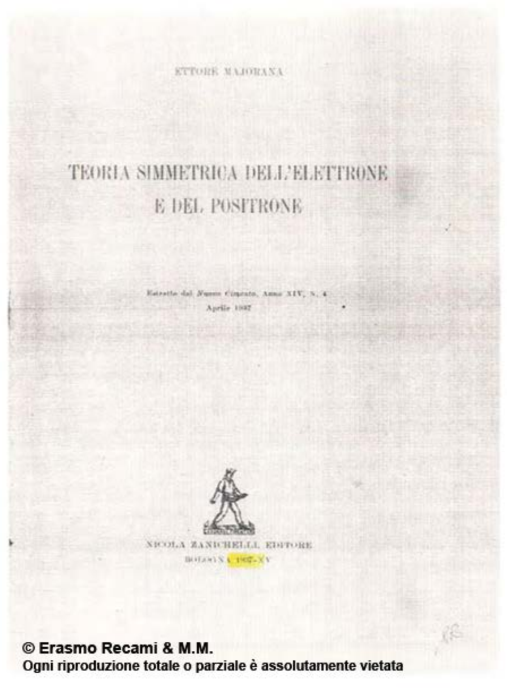


After 358 years

The proof was published by Andrew Wiles in 1995.

Some long-standing tasks of humanity …





1937

After 85 years

n-ton-class $0\nu\beta\beta$ exp.
with discovery potential
KamLAND-Zen 800
SNO+
LEGEND
nEXO
NEXT
CUPID
etc

After ? years

If $m_{\beta\beta}$ < 1 meV, what technology is needed for observation of $0\nu\beta\beta$?