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Neutrino mass mechanisms of the 0νββ-decay

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OUTLINE

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- *Effect of non-standard ν-interactions on the $0\nu\beta\beta$-decay*
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- *Conclusions*

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Neutrino oscillations

Dubna, 60-years ago …

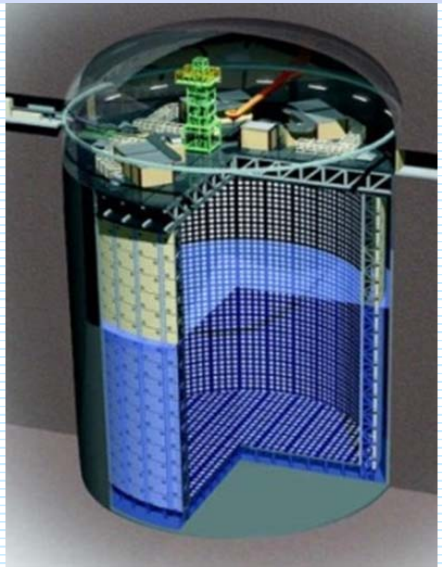
Zh.Eksp.Teor.Fiz, 32 (1957) 32

Bruno Pontecorvo

Mr. Neutrino

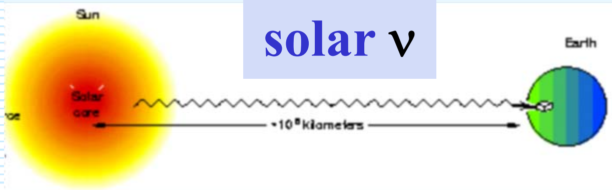
(22.8.1913-24.9.1993)

SuperKamiokande

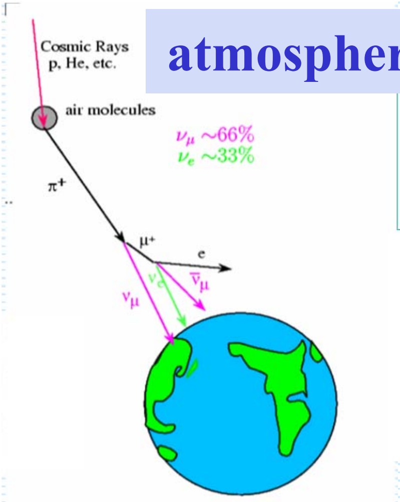


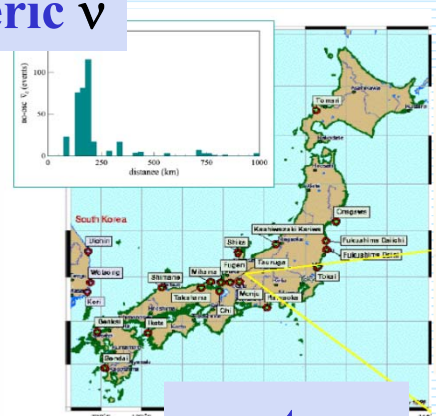
θ_{12}, θ_{23}

solar ν

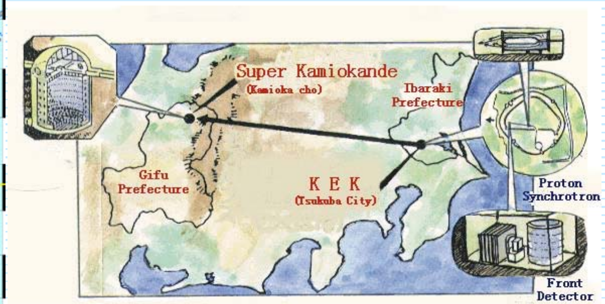


atmospheric ν

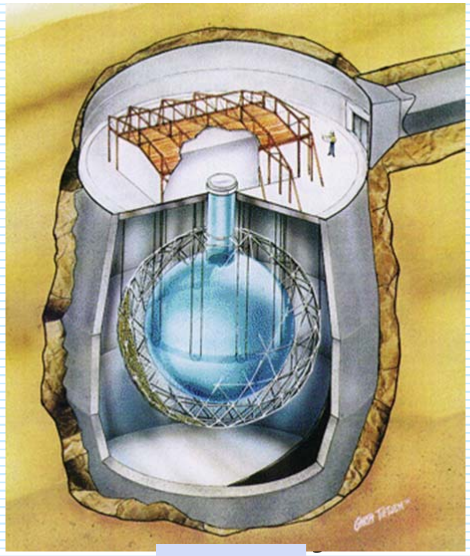




reactor ν



accelerator ν



SNO

Observation of ν-oscillations = the first prove of the BSM physics

mass-squared differences: $\Delta m^2_{SUN} \cong 7.5\ 10^{-5}\ eV^2$, $\Delta m^2_{ATM} \cong 2.4\ 10^{-3}\ eV^2$

The observed small neutrino masses (limits from tritium β-decay, cosmology) have profound implications for our understanding of the Universe and are now a major focus in astro, particle and nuclear physics and in cosmology.

PMNS unitary mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

large off-diagonal values

$$\begin{pmatrix} 0.82 & 0.54 & -0.15 \\ -0.35 & 0.70 & 0.62 \\ 0.44 & -0.45 & 0.77 \end{pmatrix}$$

3 angles: θ_{12}=33.36° (solar), θ_{13}=8.66° (reactor), θ_{23}=40.0° or 50.4° (atmospheric)

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

unknown (CP violating) phases: δ, α_1, α_2

Nσ ranges for single parameters (all data included):

[F. Capozzi, G.L. Fogli, E. Lisi, D. Montanino, A. Marrone, and A. Palazzo, arXiv:1312.2878]

TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. See also Fig. 3 for a graphical representation of the results. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH. The CP violating phase is taken in the (cyclic) interval $\delta/\pi \in [0, 2]$. The overall χ^2 difference between IH and NH is insignificant ($\Delta\chi^2_{\rm I-N} = +0.3$).

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.08	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.44	2.38 – 2.52	2.30 – 2.59	2.22 – 2.66
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.40	2.33 – 2.47	2.25 – 2.54	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34	2.16 – 2.56	1.97 – 2.76	1.77 – 2.97
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.39	2.18 – 2.60	1.98 – 2.80	1.78 – 3.00
$\sin^2\theta_{23}/10^{-1}$ (NH)	4.25	3.98 – 4.54	3.76 – 5.06	3.57 – 6.41
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.37	4.08 – 4.96 ⊕ 5.31 – 6.10	3.84 – 6.37	3.63 – 6.59
δ/π (NH)	1.39	1.12 – 1.72	0.00 – 0.11 ⊕ 0.88 – 2.00	—
δ/π (IH)	1.35	0.96 – 1.59	0.00 – 0.04 ⊕ 0.65 – 2.00	—

An indication of CP violation in neutrino sector

Fractional uncertainties (defined as 1/6 of 3σ ranges):

δm^2	=	Δm^2_{21}
$\theta_{12}, \theta_{23}, \theta_{13}, \delta$	=	as in PDB
δ range	=	$[0, 2\pi]$ (others prefer $[-\pi,+\pi]$)
Δm^2	=	$(\Delta m^2_{31} + \Delta m^2_{32})/2$

δm^2	2.6 %
Δm^2	3.0 %
$\sin^2\theta_{12}$	5.4 %
$\sin^2\theta_{13}$	8.5 %
$\sin^2\theta_{23}$	~ 11 %

Fundamental properties of ν

After 61 years from ν observation we know

- 3 families of light (V-A) neutrinos: ν_e, ν_μ, ν_τ
- ν are massive: we know mass squared differences
- relation between flavor states and mass states (neutrino mixing)

No answer yet

- Are ν Dirac or Majorana?
- Is there a CP violation in ν sector?
- Are neutrinos stable?
- What is the magnetic moment of ν?
- Sterile neutrinos?
- non-standard int. of ν
- Statistical properties of ν? Fermionic or partly bosonic?

Currently main issue

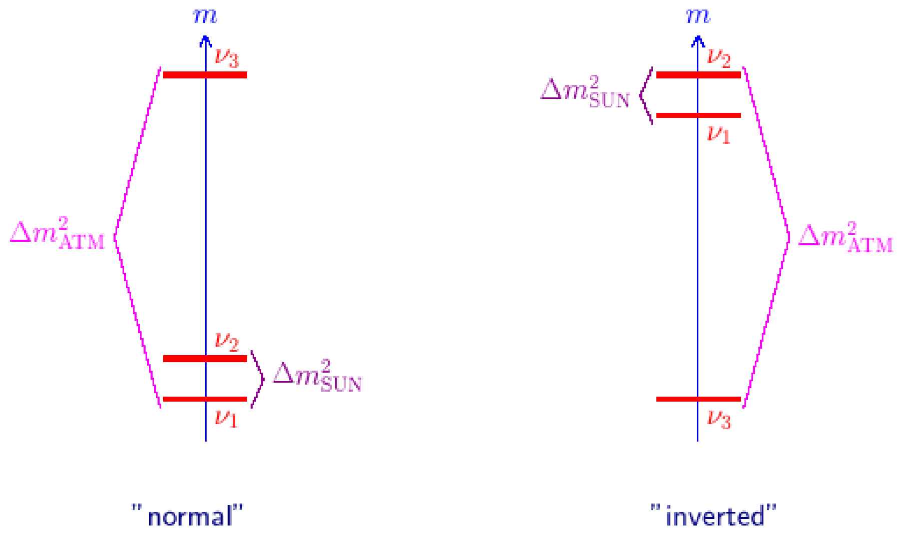
0νββ-decay: Nature, Mass hierarchy, CP-properties, sterile ν

The observation of neutrino oscillations has opened a new excited era in neutrino physics and represents a big step forward in our knowledge of neutrino properties

Neutrinos mass spectrum

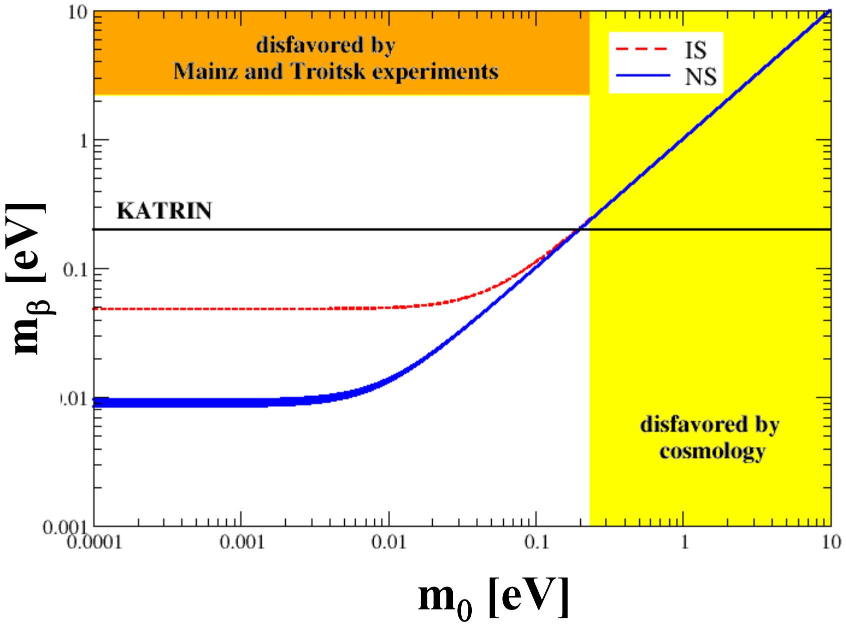
0νββ Measurements

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



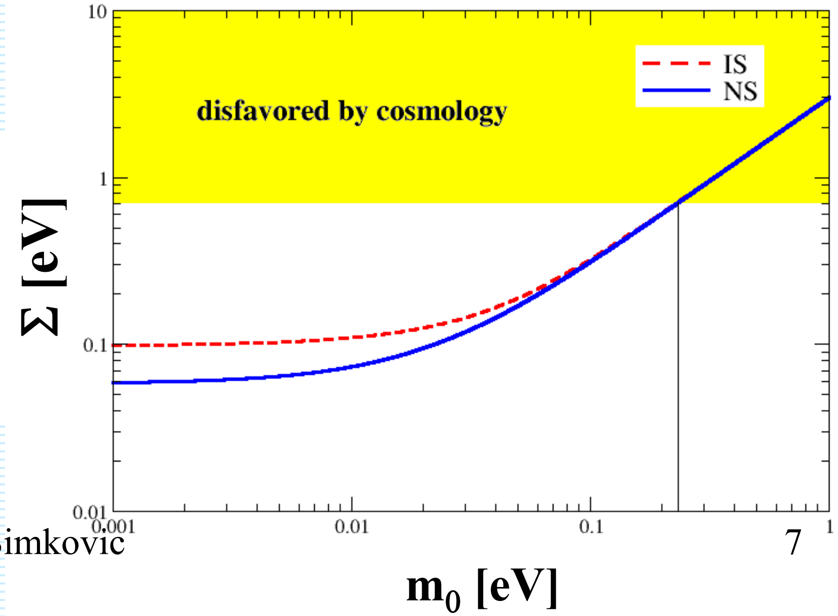
Beta Decay Measurements

$$m_\beta = \sqrt{c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2}$$



Cosmological Measurements

$$\Sigma = m_1 + m_2 + m_3$$



The answer to the question whether neutrinos are their own antiparticles is of central importance, not only to our understanding of neutrinos, but also to our understanding of the origin of mass.

What is the nature of neutrinos?

Actually, when NMEs will be needed to analyze data?

ν $\Rightarrow$

GUT's

Symmetric Theory of Electron and Positron
Nuovo Cim. 14 (1937) 171

Only the 0νββ-decay can answer this fundamental question

Analogy with kaons: K_0 and $\bar{K}_0$

Could we have both?
(light Dirac and heavy Majorana)

Analogy with π_0

Minimal SM + EFT

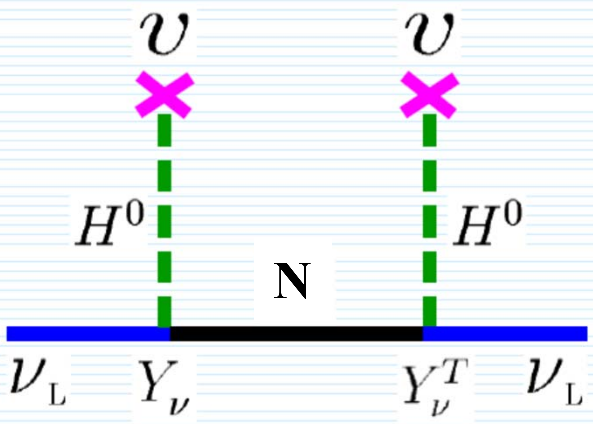
S.M. Bilenky,
Phys.Part.Nucl.Lett. 12 (2015) 453-461

The **absence of the right-handed neutrino fields** in the Standard Model is the simplest, most economical possibility. In such a scenario **Majorana mass term** is the only possibility for neutrinos to be massive and mixed. This mass term is generated by the **lepton number violating Weinberg effective Lagrangian.**

$$\mathcal{L}_5^{eff} = -\frac{1}{\Lambda}\sum_{l_1 l_2}\left(\overline{\Psi}^{lep}_{l_1 L}\tilde{\Phi}\right) \acute{Y}_{l_1 l_2}\left(\tilde{\Phi}^T(\Psi^{lep}_{l_2 L})^c\right)$$

$$m_i = \frac{v}{\Lambda}(y_i v), \quad i = 1, 2, 3$$

$\Lambda \geq 10^{15}$ GeV



Heavy Majorana leptons N_i ($N_i = N^c_i$)
singlet of $SU(2)_L x U(1)_Y$ group
Yukawa lepton number violating int.

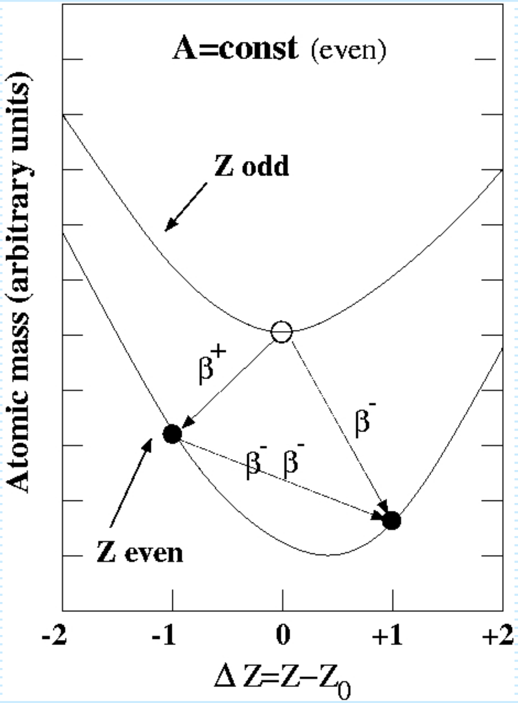
The three Majorana neutrino masses are suppressed by the ratio of the electroweak scale and a scale of a lepton-number violating physics.

The discovery of the ββ-decay and absence of transitions of flavor neutrinos into sterile states would be evidence in favor of this minimal scenario.

The simplest 0νββ-decay scenario
(SM + EFT scenario)

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

(A,Z) → (A,Z+2) + e$^-$ + e$^-$



transition	$G^{01}(E_0,Z)$ $\times 10^{14} y$	$Q_{\beta\beta}$ [MeV]	Abund. (%)	$\|M^{0\nu}\|^2$
$^{150}Nd \to {}^{150}Sm$	26.9	3.667	6	?
$^{48}Ca \to {}^{48}Ti$	8.04	4.271	0.2	?
$^{96}Zr \to {}^{96}Mo$	7.37	3.350	3	?
$^{116}Cd \to {}^{116}Sn$	6.24	2.802	7	?
$^{136}Xe \to {}^{136}Ba$	5.92	2.479	9	?
$^{100}Mo \to {}^{100}Ru$	5.74	3.034	10	?
$^{130}Te \to {}^{130}Xe$	5.55	2.533	34	?
$^{82}Se \to {}^{82}Kr$	3.53	2.995	9	?
$^{76}Ge \to {}^{76}Se$	0.79	2.040	8	?

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

I. Effective mass of Majorana neutrinos (in vacuum)

$$|m_{\beta\beta}| = |c^2_{12}c^2_{13}e^{i\alpha_1}m_1 + s^2_{12}c^2_{13}e^{i\alpha_2}m_2 + s^2_{13}m_3|$$

m_1, m_2, m_3, θ_{12}, θ_{13}, α_1, α_2
(3 unknown parameters)

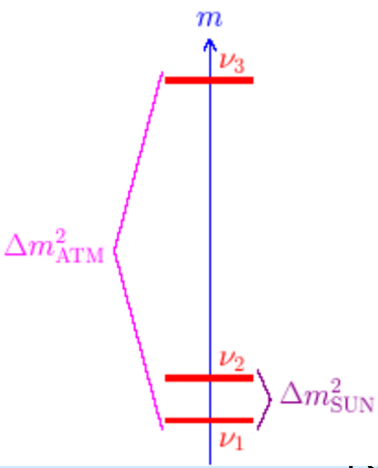
Measured quantity

$$|m_{\beta\beta}|^2 = c^4_{12}c^4_{13}m^2_1 + s^4_{12}c^4_{13}m^2_2 + s^4_{13}m^2_3 + 2c^2_{12}s^2_{12}c^4_{13}m_1m_2\cos(\alpha_1-\alpha_2) + 2c^2_{12}c^2_{13}s^2_{13}m_1m_3\cos\alpha_1 + 2s^2_{12}c^2_{13}s^2_{13}m_2m_3\cos\alpha_2 .$$

Limiting cases

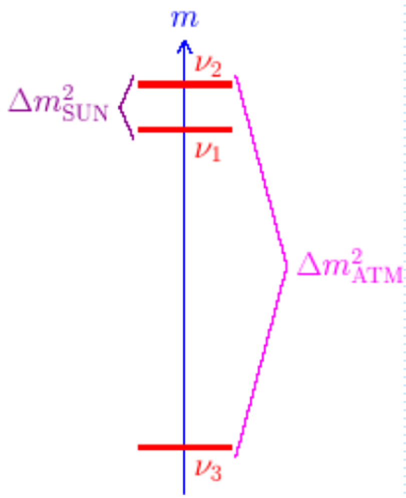
Normal hierarchy

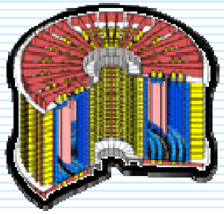
$$m_1 \ll \sqrt{\Delta m^2_{\rm SUN}}$$
$$m_2 \simeq \sqrt{\Delta m^2_{\rm SUN}}$$
$$m_3 \simeq \sqrt{\Delta m^2_{\rm ATM}}$$

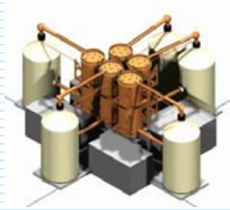


Inverted hierarchy

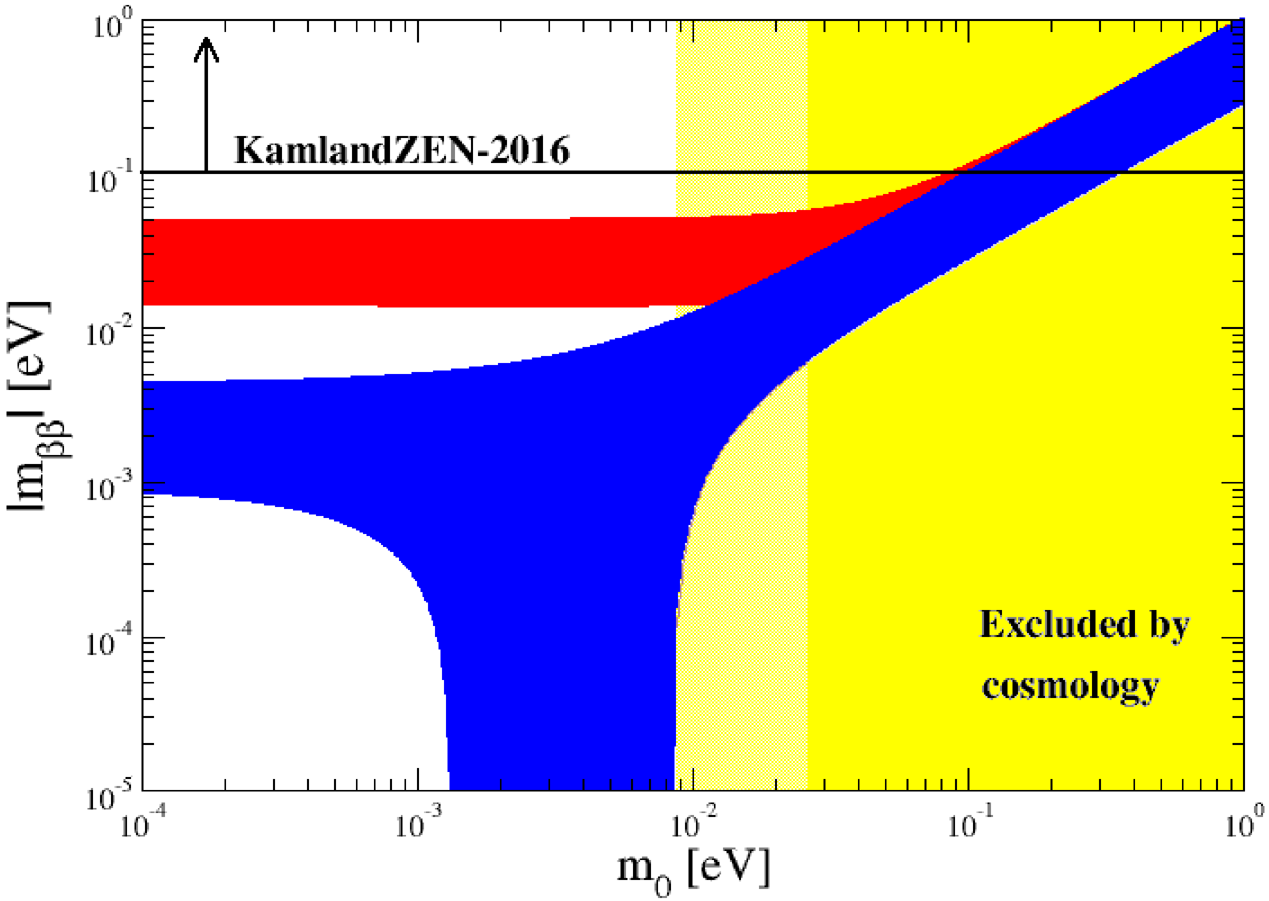
$$m_3 \ll \sqrt{\Delta m^2_{\rm ATM}}$$
$$m_1 \simeq m_2 \simeq \sqrt{\Delta m^2_{\rm ATM}}$$







Issue: Lightest neutrino mass m_0



GUT's

Complementarity of 0νββ-decay, β-decay and cosmology

β-decay (Mainz, Troitsk)

$$m_\beta^2 = \sum_i |U^L_{ei}|^2 m_i^2 \leq (2.2\ \mathrm{eV})^2$$

KATRIN: $(0.2\ \mathrm{eV})^2$

Cosmology (Planck)

$$\Sigma < 110\ \mathrm{meV}$$

$$m_0 > 26\ \mathrm{meV}\ (\mathrm{NS})$$
$$87\ \mathrm{meV}\ (\mathrm{IS})$$

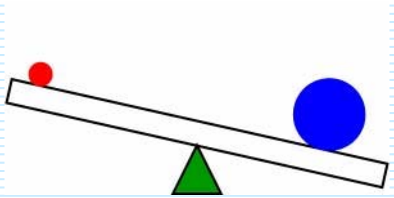
II. *The sterile ν mechanism of the 0νββ-decay*
(D-M mass term, V-A SM int.)

$$N = \sum_{\alpha=s,e,\mu,\tau} U_{N\alpha}\ \nu_\alpha$$

Mixing of active-sterile neutrinos

Dirac-Majorana mass term

$$\begin{pmatrix} 0 & m_D \\ m_D & m_{LNV} \end{pmatrix}$$



Light ν mass ≈ $(m_D/m_{LNV})\, m_D$
Heavy ν mass ≈ m_{LNV}

small ν masees due to see-saw mechanism

Possible lepton number violating scale - m_{LNV}

Neutrinos masses may offer a great opportunity to jump beyond the EW framework via see-saw ...

10^{19} GeV — **Planck**

How heavy are the heavy Majorana neutrinos?

10^{16} GeV — **GUT**

to unify strong, weak & electromagnetic forces?

Conventional (Type-one) Seesaw Picture: close to the GUT scale

10^{3} GeV — **TeV**

TeV Seesaw Idea: driven by testability at LHC

to solve the unnatural gauge hierarchy problem?

GeV/5 — **Fermi**

10^{-6} GeV — **kev**

Hot dark mattter

Left-handed neutrinos: Majorana neutrino mass eigenstate N with arbitrary mass m_N

Faessler, Gonzales, Kovalenko, F. Š., PRD 90 (2014) 096010]

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

General case

$$M'^{0\nu}(m_N, g_A^{eff}) = \frac{1}{m_p m_e} \frac{R}{2\pi^2 g_A^2} \sum_n \int d^3x \, d^3y \, d^3p$$

$$\times e^{ip\cdot(\mathbf{x}-\mathbf{y})} \frac{\langle 0_F^+ | J^{\mu\dagger}(\mathbf{x}) | n \rangle \langle n | J^\dagger_\mu(\mathbf{y}) | 0_I^+ \rangle}{\sqrt{p^2 + {m_N}^2} \left(\sqrt{p^2 + {m_N}^2} + E_n - \frac{E_I - E_F}{2} \right)}$$

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

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

Particular cases

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu} g_A^4 \times$$

$$\times \begin{cases} \left| \frac{\langle m_\nu \rangle}{m_e} \right|^2 \left| M'^{0\nu}_\nu(g_A^{eff}) \right|^2 & \text{for } m_N \ll p_F \\ \left| \langle \frac{1}{m_N} \rangle m_p \right|^2 \left| M'^{0\nu}_N(g_A^{eff}) \right|^2 & \text{for } m_N \gg p_F \end{cases}$$

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

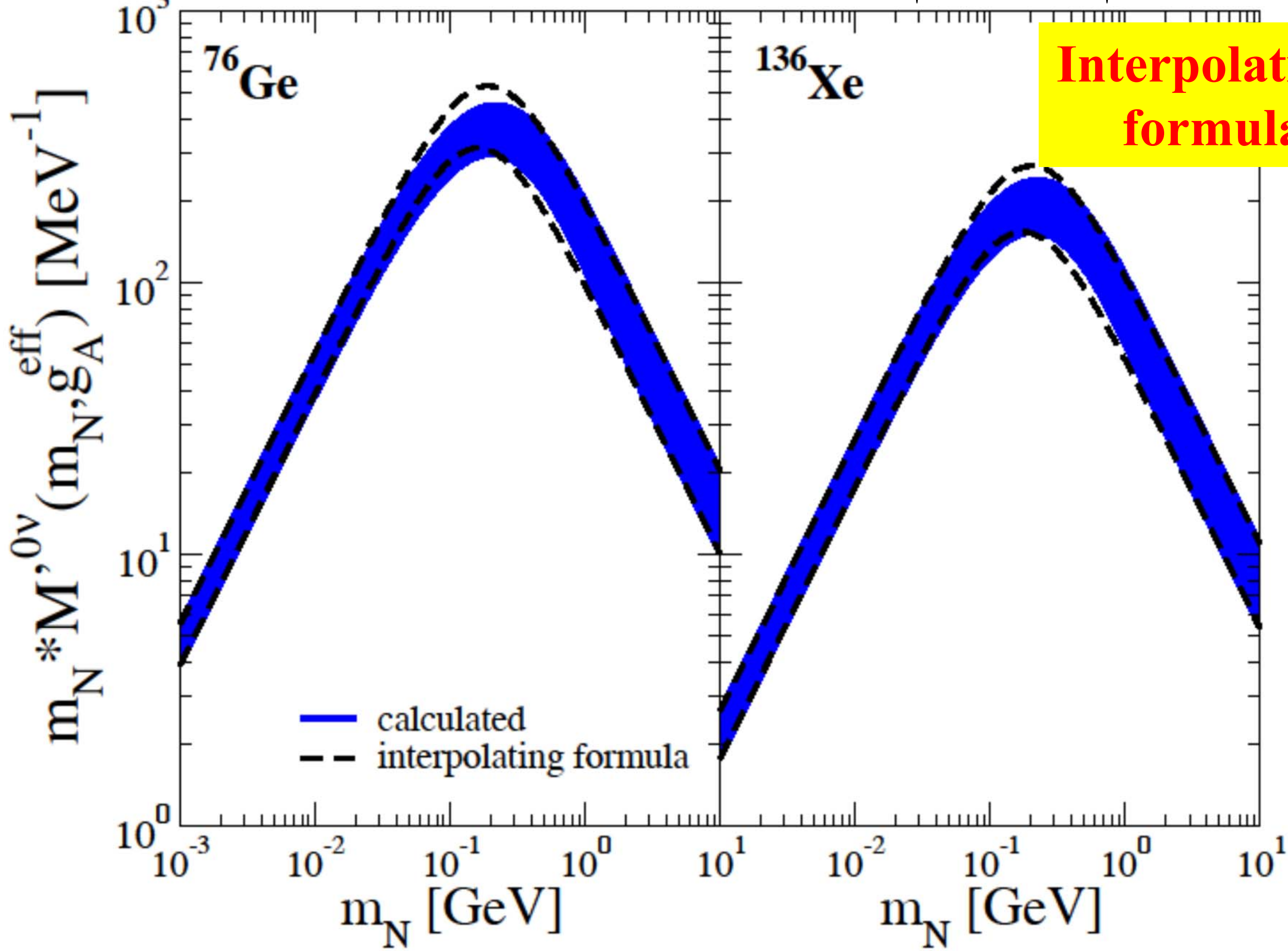
$$\left\langle \frac{1}{m_N} \right\rangle = \sum_N \frac{U^2_{eN}}{m_N}$$

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

$$\mathcal{A} = G^{0\nu} g_A^4 \left| M'^{0\nu}_N (g_A^{\text{eff}}) \right|^2,$$

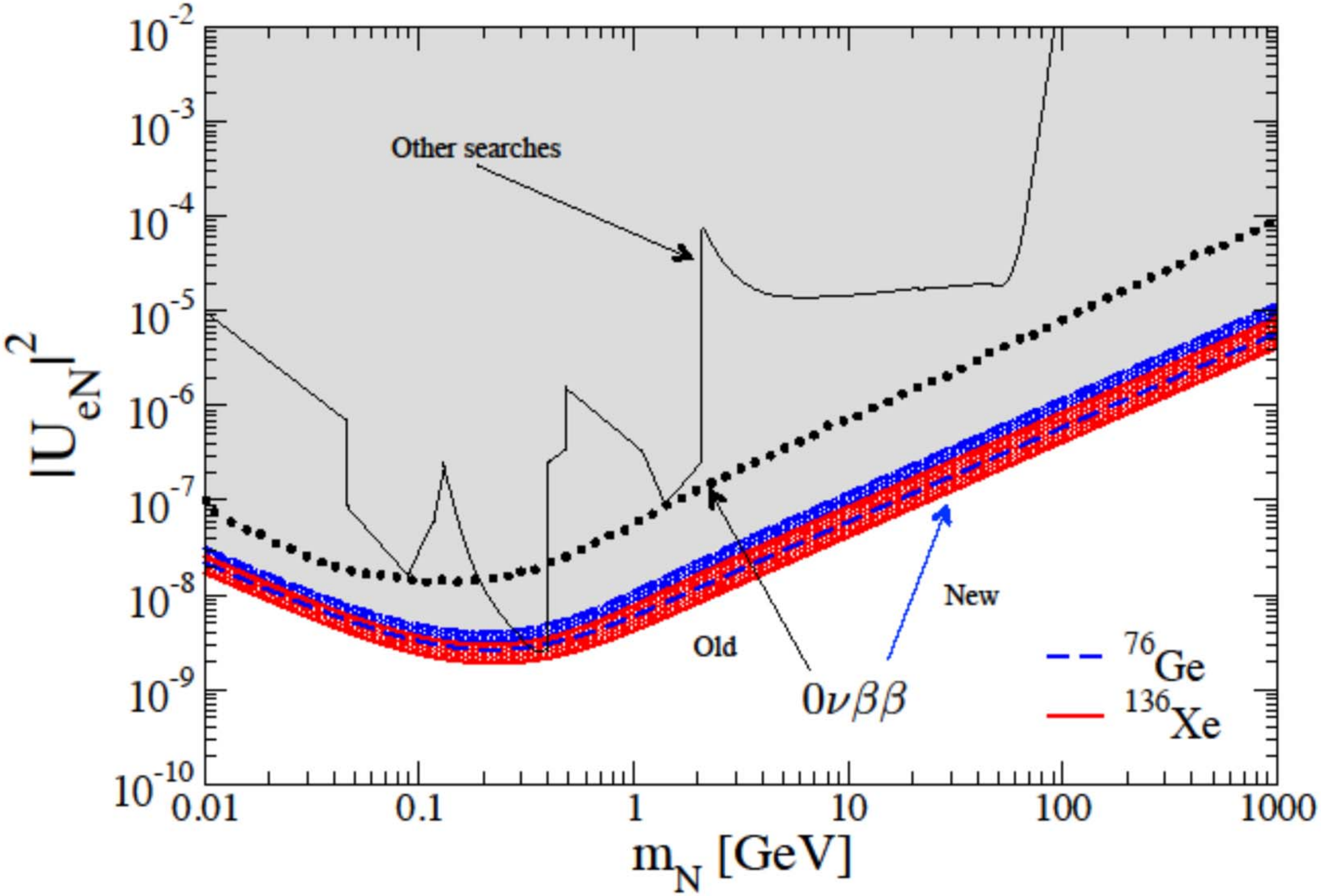
$$\langle p^2 \rangle = m_p m_e \left| \frac{M'^{0\nu}_N (g_A^{\text{eff}})}{M'^{0\nu}_\nu (g_A^{\text{eff}})} \right| \approx 200 \quad MeV$$

Interpolating formula



Exclusion plot in $|U_{eN}|^2 - m_N$ plane

$T^{0\nu}_{1/2}(^{76}Ge) \geq 3.0\ 10^{25}$ yr
$T^{0\nu}_{1/2}(^{136}Xe) \geq 3.4\ 10^{25}$ yr



Improvements: i) QRPA (constrained Hamiltonian by 2νββ half-life, self-consistent treatment of src, restoration of isospin symmetry …), ii) More stringent limits on the 0νββ half-life

III. *The 0νββ-decay within L-R symmetric theories*

(D-M mass term, see-saw, V-A and V+A int., exchange of light neutrinos)

Effective β-decay Hamiltonian

$$H^\beta = \frac{G_\beta}{\sqrt{2}} \left[j_L^{\ \rho} J_{L\rho} + \chi\, j_L^{\ \rho} J_{R\rho} + \eta\, j_R^{\rho} J_{L\rho} + \lambda\, j_R^{\rho} J_{R\rho} + h.c. \right].$$

left- and right-handed lept. currents

$$j_L^{\ \rho} = \bar{e}\gamma^\rho (1-\gamma_5)\nu_{eL}$$
$$j_R^{\ \rho} = \bar{e}\gamma^\rho (1+\gamma_5)\nu_{eR}$$

Mixing of vector bosons W_L and W_R

$$\begin{pmatrix} W_L^- \\ W_R^- \end{pmatrix} = \begin{pmatrix} \cos\zeta & \sin\zeta \\ -\sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W_1^- \\ W_2^- \end{pmatrix}$$

$$\eta = -\tan\zeta, \quad \chi = \eta,$$
$$\lambda = (M_{W_1}/M_{W_2})^2$$

The 0νββ-decay half-life

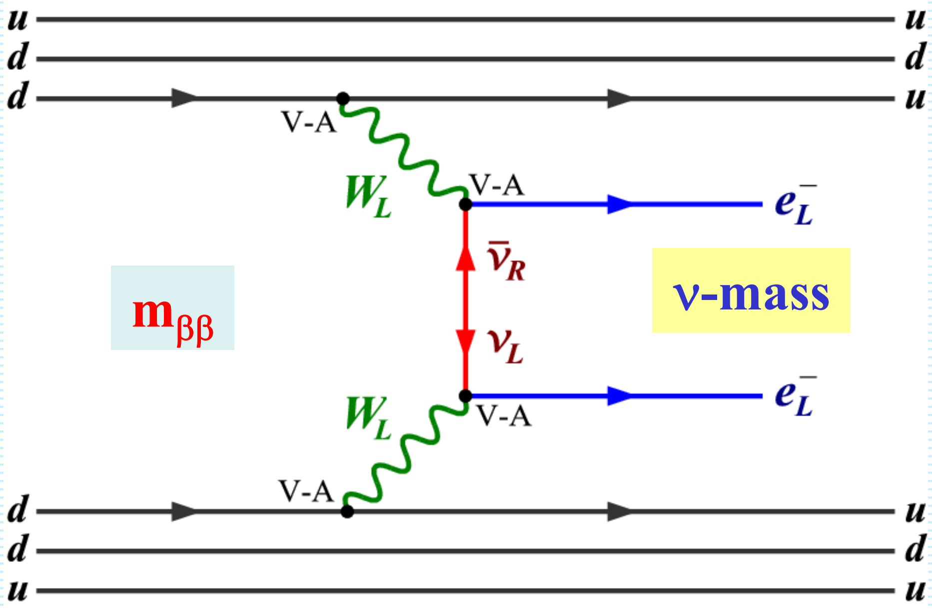
$$\left[T_{1/2}^{0\nu}\right]^{-1} = \frac{\Gamma^{0\nu}}{\ln 2} = g_A^4 \left|M_{GT}\right|^2 \left\{ C_{mm} \frac{|m_{\beta\beta}|^2}{m_e} + C_{m\lambda}\frac{|m_{\beta\beta}|}{m_e}\langle\lambda\rangle \cos\psi_1 + C_{m\eta}\frac{|m_{\beta\beta}|}{m_e}\langle\eta\rangle\cos\psi_2 + C_{\lambda\lambda}\langle\lambda\rangle^2 + C_{\eta\eta}\langle\eta\rangle^2 + C_{\lambda\eta}\langle\lambda\rangle\langle\eta\rangle\cos(\psi_1-\psi_2) \right\}$$

$\langle\lambda\rangle$ - W_L-W_R exch.

$\langle\eta\rangle$ - W_L-W_R mixing

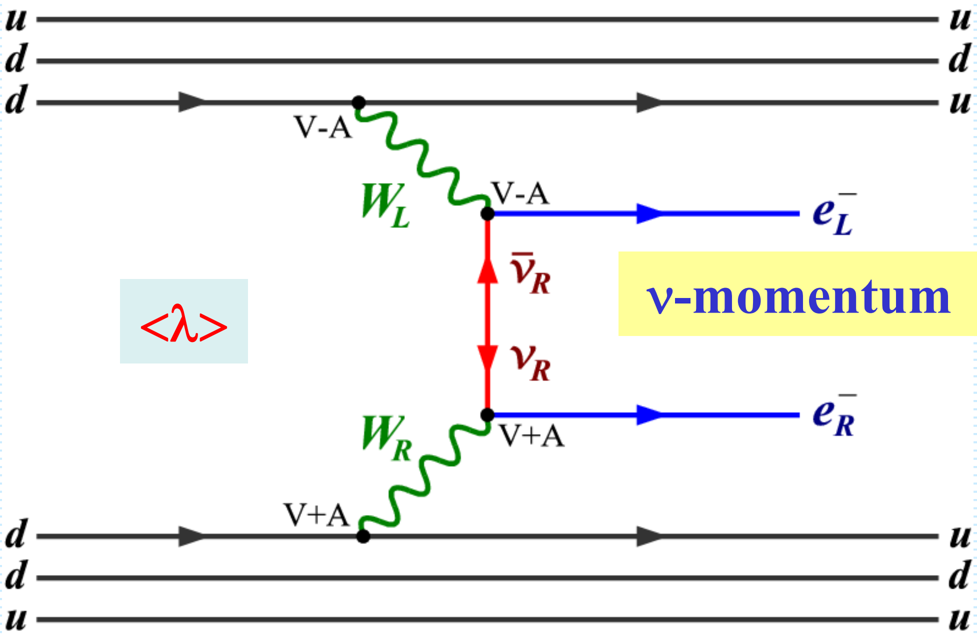
D. Štefánik, R. Dvornický, F.Š., P. Vogel, PRC 92, 055502 (2015)

Left-right symmetric models SO(10)



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

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



$$\langle\lambda\rangle = \lambda \, |\sum_{j=1}^{3} U_{ej}T_{ej}^{*}|$$

$$\langle\eta\rangle = \eta \, |\sum_{j=1}^{3} U_{ej}T_{ej}^{*}|$$

3x3 block matrices
U, S, T, V are
generalization of PMNS matrix

Zhi-zhong Xing, Phys. Rev. D **85**, 013008 (2012)

6x6 neutrino mass matrix

Basis

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

$$(\nu_L, (N_R)^c)^T$$

$$\mathcal{M} = \begin{pmatrix} M_L & M_D \\ M_D & M_R \end{pmatrix}$$

15 angles, 10+5 phases

Decomposition

$$\mathcal{U} = \begin{pmatrix} \mathbf{1} & \mathbf{0} \\ \mathbf{0} & U_0 \end{pmatrix} \begin{pmatrix} A & R \\ S & B \end{pmatrix} \begin{pmatrix} V_0 & \mathbf{0} \\ \mathbf{0} & \mathbf{1} \end{pmatrix}$$

The see-saw structure and neglecting mixing between different generations

Approximation

$$A \approx \mathbf{1}, \quad B \approx \mathbf{1}, \quad R \approx \frac{m_D}{m_{LNV}}\,\mathbf{1}, \quad S \approx -\frac{m_D}{m_{LNV}}\,\mathbf{1}$$

$$U_0 \simeq V_0$$

LNV parameters

$$|\langle\lambda\rangle| \approx \frac{m_D}{m_{LNV}} \left(\frac{M_{W_1}}{M_{W_2}}\right)^2 |\xi|$$

$$|\langle\eta\rangle| \approx \frac{m_D}{m_{LNV}} \tan(\zeta)\, |\xi|$$

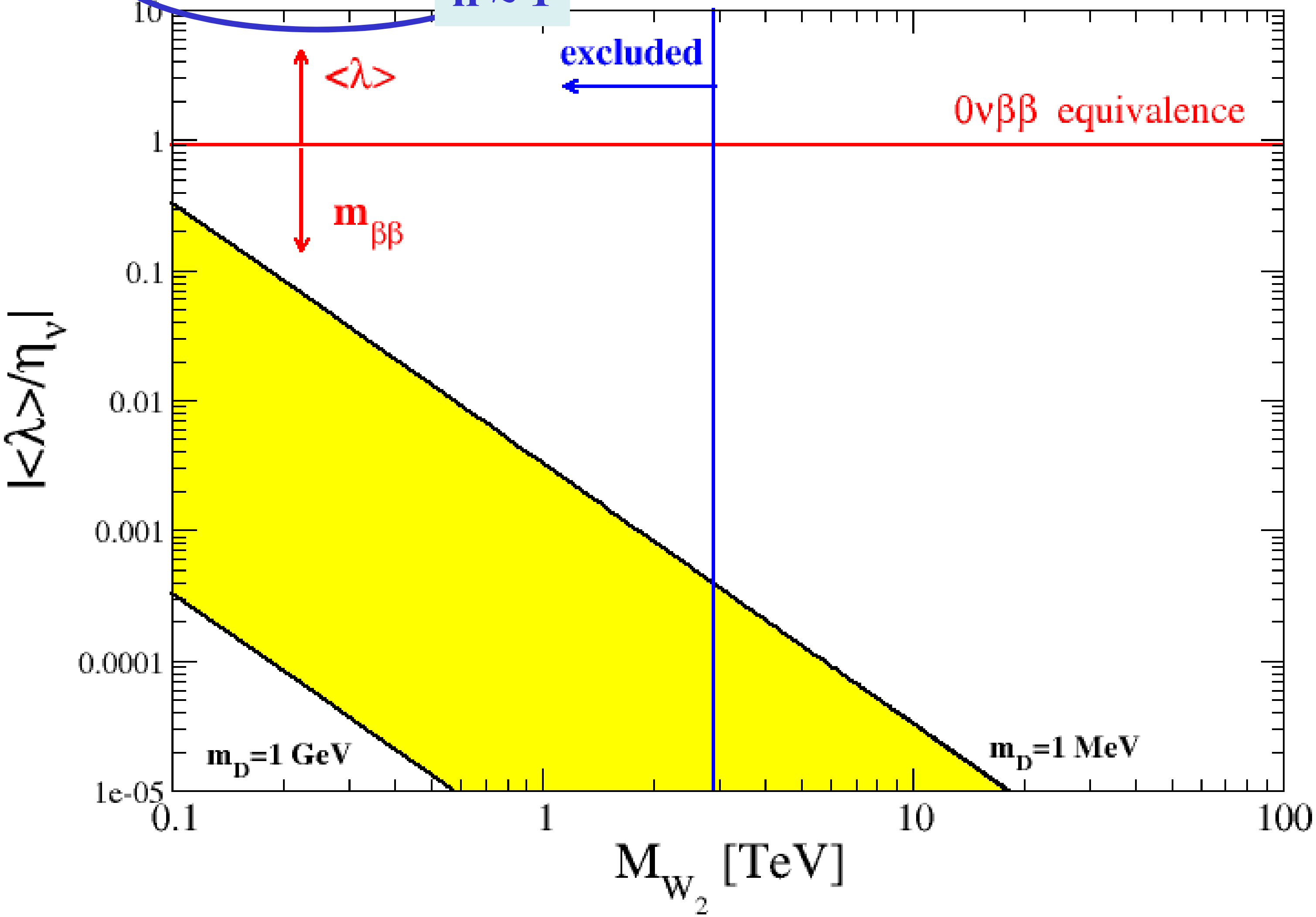
$$|\xi| \simeq 0.82$$

$$\eta_\nu = \frac{m_{\beta\beta}}{m_e} = \sum_i ((U_0)_{ei})^2 \frac{m_i}{m_e}$$

$$\approx \frac{m_D}{m_{LNV}} \frac{m_D}{m_e} \sum_i (U_0)^2_{ei} \frac{m_i \, m_{LNV}}{m_D^2}$$

if ≈ 1

$$|\langle\lambda\rangle| \approx \frac{m_D}{m_{LNV}} \left(\frac{M_{W_1}}{M_{W_2}}\right)^2 |\xi|$$



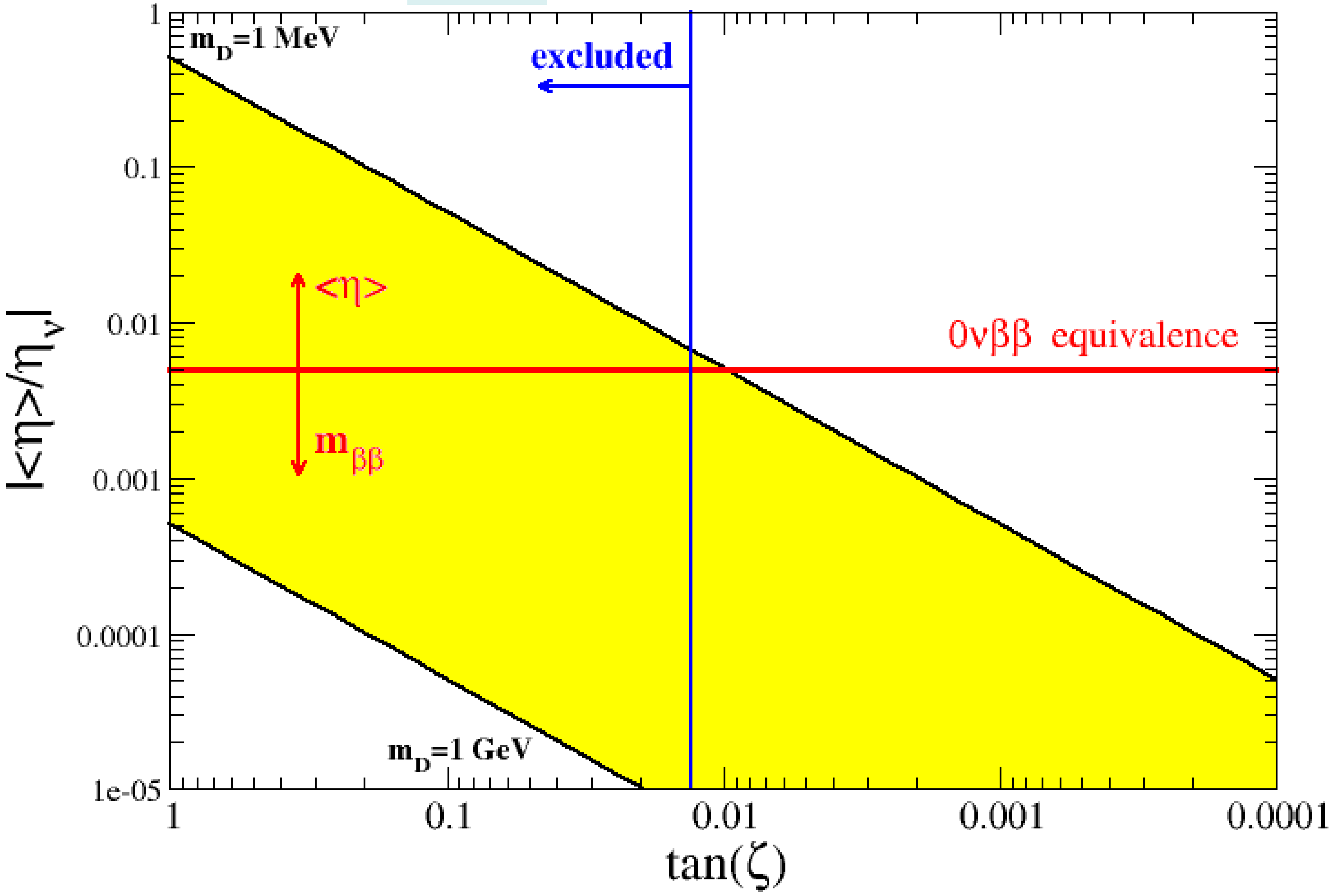
Clear dominance of $m_{\beta\beta}$ over <λ> mechanism by current constraint on mass of heavy vector boson

$$\eta_\nu = \frac{m_{\beta\beta}}{m_e} = \sum_i ((U_0)_{ei})^2 \frac{m_i}{m_e}$$

$$\approx \frac{m_D}{m_{LNV}} \frac{m_D}{m_e} \sum_i (U_0)^2_{ei} \frac{m_i\, m_{LNV}}{m_D^2}$$

if ≈ 1

$$|\langle\eta\rangle| \approx \frac{m_D}{m_{LNV}} \tan(\zeta)\, |\xi|$$



Dominance of $m_{\beta\beta}$ over <λ> mech., but might be also comparable

IV. *The 0νββ-decay within L-R symmetric theories*

(D-M mass term, see-saw, V-A and V+A int., exchange of heavy neutrinos)

J.D.Vergados, H. Ejiri, , F.Š., Int. J. Mod. Phys. E25, 1630007(2016)

$$\left(T^{0\nu}_{1/2} G^{0\nu} g_A^2\right)^{-1} = \left|\eta_\nu \; M^{0\nu}_\nu + \eta^L_N \; M^{0\nu}_N\right|^2 \; + \; \left|\eta^R_N \; M^{0\nu}_N\right|^2$$

$$\eta_\nu = \frac{m_{\beta\beta}}{m_e} = \sum_i ((U_0)_{ei})^2 \frac{m_i}{m_e} \approx \frac{m_p}{m_{LNV}} \frac{m_D^2}{m_e m_p} \sum_i (U_0)^2_{ei} \frac{m_i \, m_{LNV}}{m_D^2}$$

$$\eta^L_N = \frac{m_p}{m_{LNV}} \sum_i (U^{(12)}_{ei})^2 \frac{m_{LNV}}{M_i} \approx \frac{m_p}{m_{LNV}} \left(\frac{m_D}{m_{LNV}}\right)^2 \sum_i \frac{m_{LNV}}{M_i}$$

$$\eta^R_N = \frac{m_p}{m_{LNV}} \left(\frac{M_{W_1}}{M_{W_2}}\right)^2 \sum_i (U^{22}_{ei})^2 \frac{m_{LNV}}{M_i} \approx \frac{m_p}{m_{LNV}} \left(\frac{M_{W_1}}{M_{W_2}}\right)^2 \sum_i (V_0)^2_{ei} \frac{m_{LNV}}{M_i}$$

$\eta_\nu >> \eta^L_N$

η_ν and η^R_N might be comparable, if e.g.

$$\sum_i (U_0)^2_{ei} \frac{m_i \, m_{LNV}}{m_D^2} \simeq \sum_i (V_0)^2_{ei} \frac{m_{LNV}}{M_i}$$

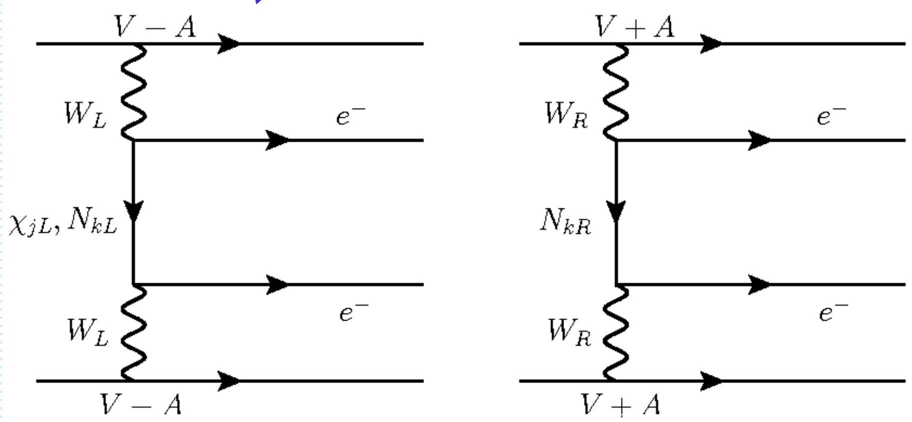
$$\frac{m_D^2}{m_e m_p} M^{0\nu}_\nu \simeq \left(\frac{M_{W_1}}{M_{W_2}}\right)^2 M^{0\nu}_N$$

Two non-interfering mechanisms of the $0\nu\beta\beta$-decay (light LH and heavy RH neutrino exchange)

Half-life:

$$\frac{1}{T^{0\nu}_{1/2,i}G^{0\nu}_i(E,Z)} \cong |\eta_\nu|^2|M'^{0\nu}_{i,\nu}|^2 + |\eta_R|^2|M'^{0\nu}_{i,N}|^2$$

$$\eta_\nu = \frac{m_{\beta\beta}}{m_e}$$



Set of equations:

$$\frac{1}{T_1G_1} = |\eta_\nu|^2|M'^{0\nu}_{1,\nu}|^2 + |\eta_R|^2|M'^{0\nu}_{1,N}|^2$$

$$\frac{1}{T_2G_2} = |\eta_\nu|^2|M'^{0\nu}_{2,\nu}|^2 + |\eta_R|^2|M'^{0\nu}_{2,N}|^2$$

Solutions:

$$|\eta_\nu|^2 = \frac{|M'^{0\nu}_{2,N}|^2/T_1G_1 - |M'^{0\nu}_{1,N}|^2/T_2G_2}{|M'^{0\nu}_{1,\nu}|^2|M'^{0\nu}_{2,N}|^2 - |M'^{0\nu}_{1,N}|^2|M'^{0\nu}_{2,\nu}|^2}$$

$$|\eta_R|^2 = \frac{|M'^{0\nu}_{1,\nu}|^2/T_2G_2 - |M'^{0\nu}_{2,\nu}|^2/T_1G_1}{|M'^{0\nu}_{1,\nu}|^2|M'^{0\nu}_{2,N}|^2 - |M'^{0\nu}_{1,N}|^2|M'^{0\nu}_{2,\nu}|^2}$$

$$\eta^R_N = \left(\frac{M_W}{M_{WR}}\right)^4 \sum_k^{heavy} V^2_{ek}\,\frac{m_p}{M_k}$$

A. Faessler, A. Meroni, S.T. Petcov, F. Š., J.D. Vergados, Phys. Rev. D 83, 113003 (2011); JHEP 1302, 025 (2013)

Two non-interfering mechanisms of the $0\nu\beta\beta$-decay
(light LH and heavy RH neutrino exchange)

Pure $m_{\beta\beta}$ mech.

The positivity condition:

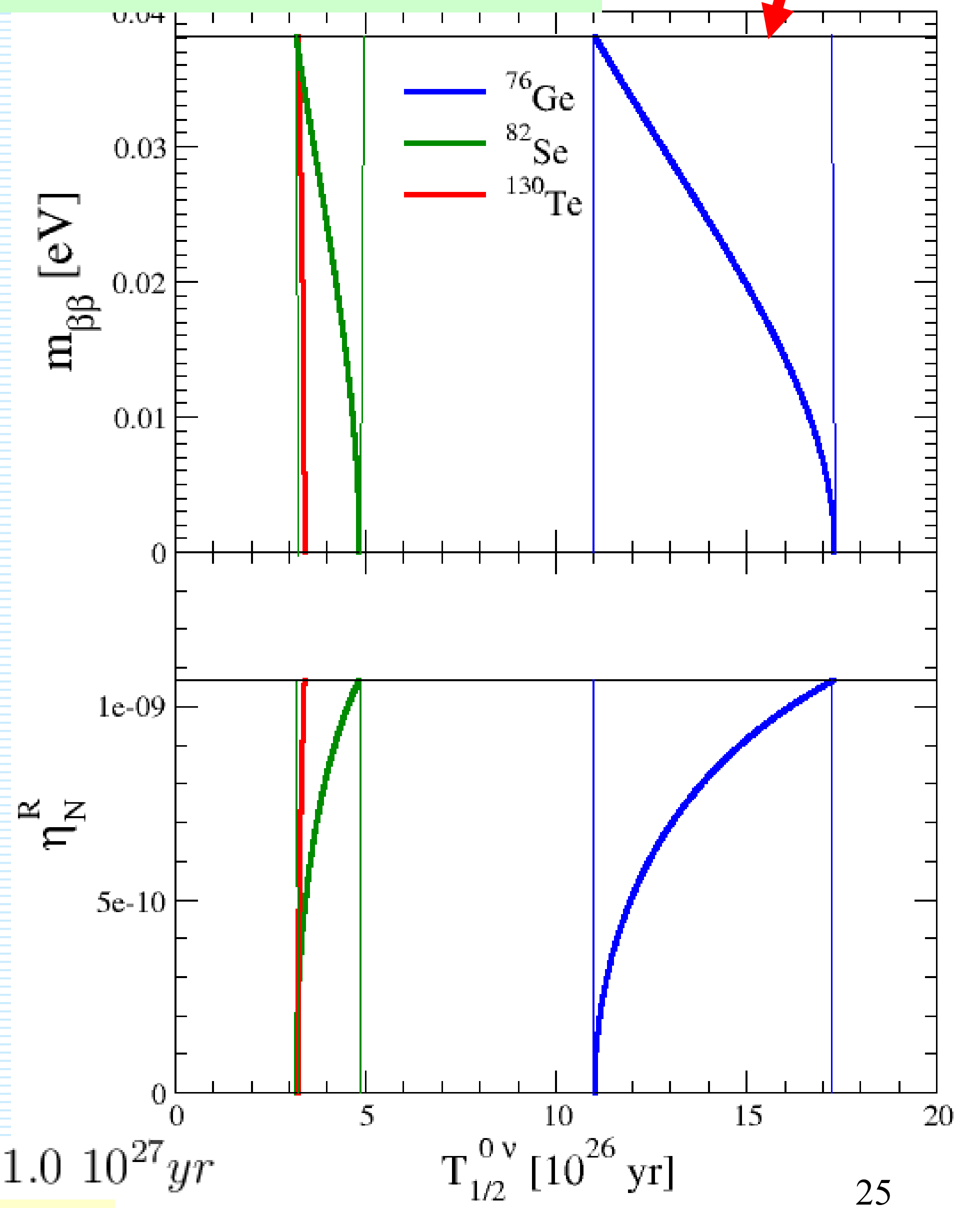
$$\frac{T_1 G_1 |M'^{0\nu}_{1,N}|^2}{G_2 |M'^{0\nu}_{2,N}|^2} \leq T_2 \leq \frac{T_1 G_1 |M'^{0\nu}_{1,\nu}|^2}{G_2 |M'^{0\nu}_{2,\nu}|^2}$$

Very narrow ranges!

$$1.10 \leq \frac{T^{0\nu}_{1/2}(^{76}Ge)}{T^{0\nu}_{1/2}(^{136}Xe)} \leq 1.73$$

$$3.17 \leq \frac{T^{0\nu}_{1/2}(^{82}Se)}{T^{0\nu}_{1/2}(^{136}Xe)} \leq 4.83$$

$$3.22 \leq \frac{T^{0\nu}_{1/2}(^{130}Te)}{T^{0\nu}_{1/2}(^{136}Xe)} \leq 3.40$$



$T^{0\nu}_{1/2}(^{136}Xe) = 1.0\ 10^{27} yr$

Assumption

V. *Nuclear medium effect on the light neutrino mass exchange mechanism of the 0νββ-decay*

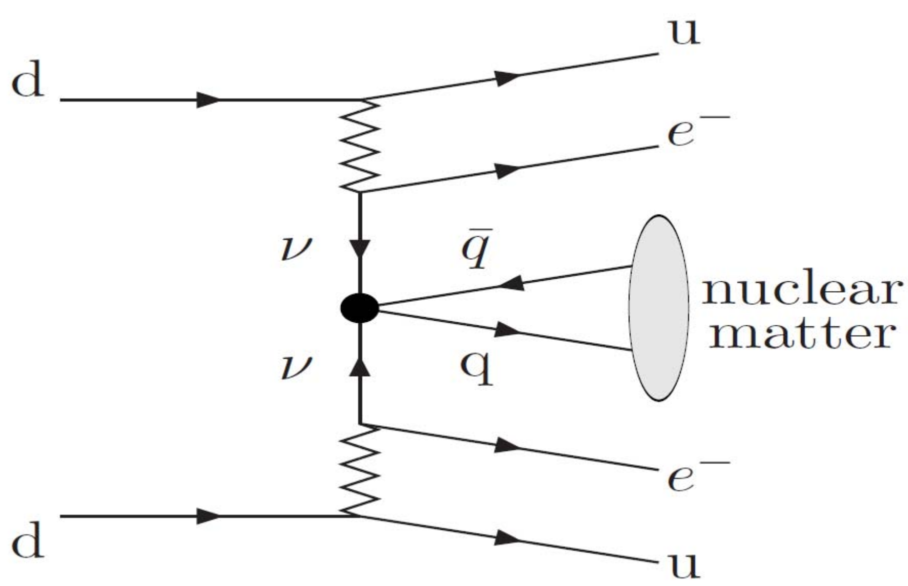
S.G. Kovalenko, M.I. Krivoruchenko, F. Š., Phys. Rev. Lett. 112 (2014) 142503

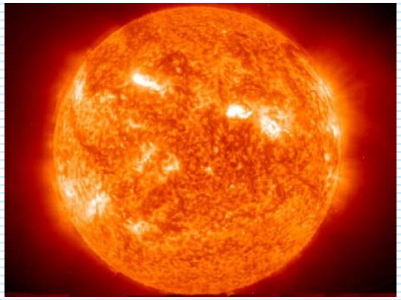
A novel effect in 0νββ decay related with the fact, that its underlying mechanisms take place in the nuclear matter environment:

+ Low energy 4-fermion ΔL ≠ 0 Lagrangian

+ In-medium Majorana mass of neutrino

+ 0νββ constraints on the universal scalar couplings





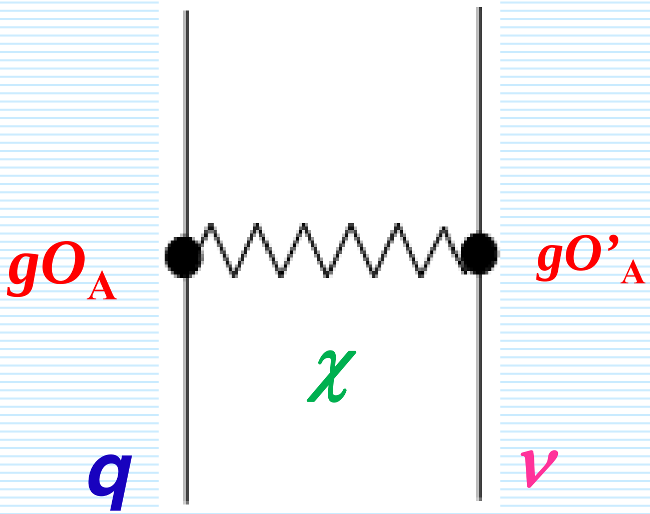
Non-standard ν−int. discussed e.g., in the context of ν−osc. at Sun

$\rho_{Sun} = 1.4$ g/cm^3

$\rho_{Earth} = 5.5$ g/cm^3

$\rho_{nucleus} = 2.3\ 10^{14}$ g/cm^3

Non-standard interactions might be easily detected in nucleus rather than in vacuum



Low energy 4-fermion $\Delta L \neq 0$ Lagrangian

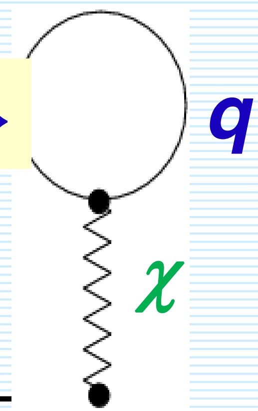
$$L_{\text{eff}} = \frac{g^2}{m_\chi^2} \sum_A (\bar{q} O_A q)(\bar{\nu} O'_A \nu),$$

$$m_\chi \gtrsim M_W.$$

oscillation experiments
tritium β-decay, cosmology

0νββ-decay

density →



$$\Sigma_\nu^{\text{vac}} = \text{-}\times\text{-},$$

$$\Sigma_\nu^{\text{medium}} = \text{-}\times\text{-} +$$

Classification of the vertices gO_A and gO'_A

$$\mathcal{L}_{\mathrm{free},\nu} = \frac{1}{4}\sum_i \bar{\nu}_i i\gamma^\mu \overleftrightarrow{\partial}_\mu \nu_i - \frac{1}{2}\sum_i m_i \bar{\nu}_i \nu_i .$$

$$\mathcal{L}_{\mathrm{eff}} = \frac{g_\chi}{m_\chi^2}\bar{q}q \sum_{a=1}^{6}\sum_{ij} g^a_{ij} J^a_{ij}$$

In nuclei, mean fields are created by scalar and vector currents (σ, ω).

Vector currents do not flip the spin of neutrinos and do not contribute to the 0νββ decay.

Symmetric and antisymmetric scalar neutrino currents J^a_{ij}

a	S	a	S	a	A
1	$\bar{\nu}_i^c \nu_j$	3	$\partial_\mu(\bar{\nu}_i^c \gamma_5 \gamma^\mu \nu_j)$	5	$\partial_\mu(\bar{\nu}_i^c \gamma^\mu \nu_j)$
2	$\bar{\nu}_i^c i\gamma_5 \nu_j$	4	$\bar{\nu}_i^c \gamma^\mu i \overleftrightarrow{\partial}_\mu \nu_j$	6	$\bar{\nu}_i^c \gamma_5 \gamma^\mu i \overleftrightarrow{\partial}_\mu \nu_j$

g^a_{ij} are real symmetric for a = 1,2,3,4 and imaginary antisymmetric for a = 5,6. In the limit of $R = \infty$, the currents a = 3,5 vanish.

Mean field: $\bar{q}q \to \langle \bar{q}q \rangle$ **and** $\langle \bar{q}q \rangle \approx 0.5 \langle q^{\dagger} q \rangle \approx 0.25\,\mathrm{fm}^{-3}$

The effect depends on $\langle \chi \rangle = -\frac{g_{\chi}}{m_{\chi}^{2}} \langle \bar{q}q \rangle$

A comparison with G_F:

$$\frac{g_{\chi} g_{ij}^{a}}{m_{\chi}^{2}} = \frac{G_F}{\sqrt{2}} \varepsilon_{ij}^{a}$$

Typical scale: $\langle \chi \rangle g_{ij}^{a} = -\frac{G_F}{\sqrt{2}} \langle \bar{q}q \rangle \varepsilon_{ij}^{a} \approx -25\,\varepsilon_{ij}^{a}\ \mathrm{eV}$

We expect:

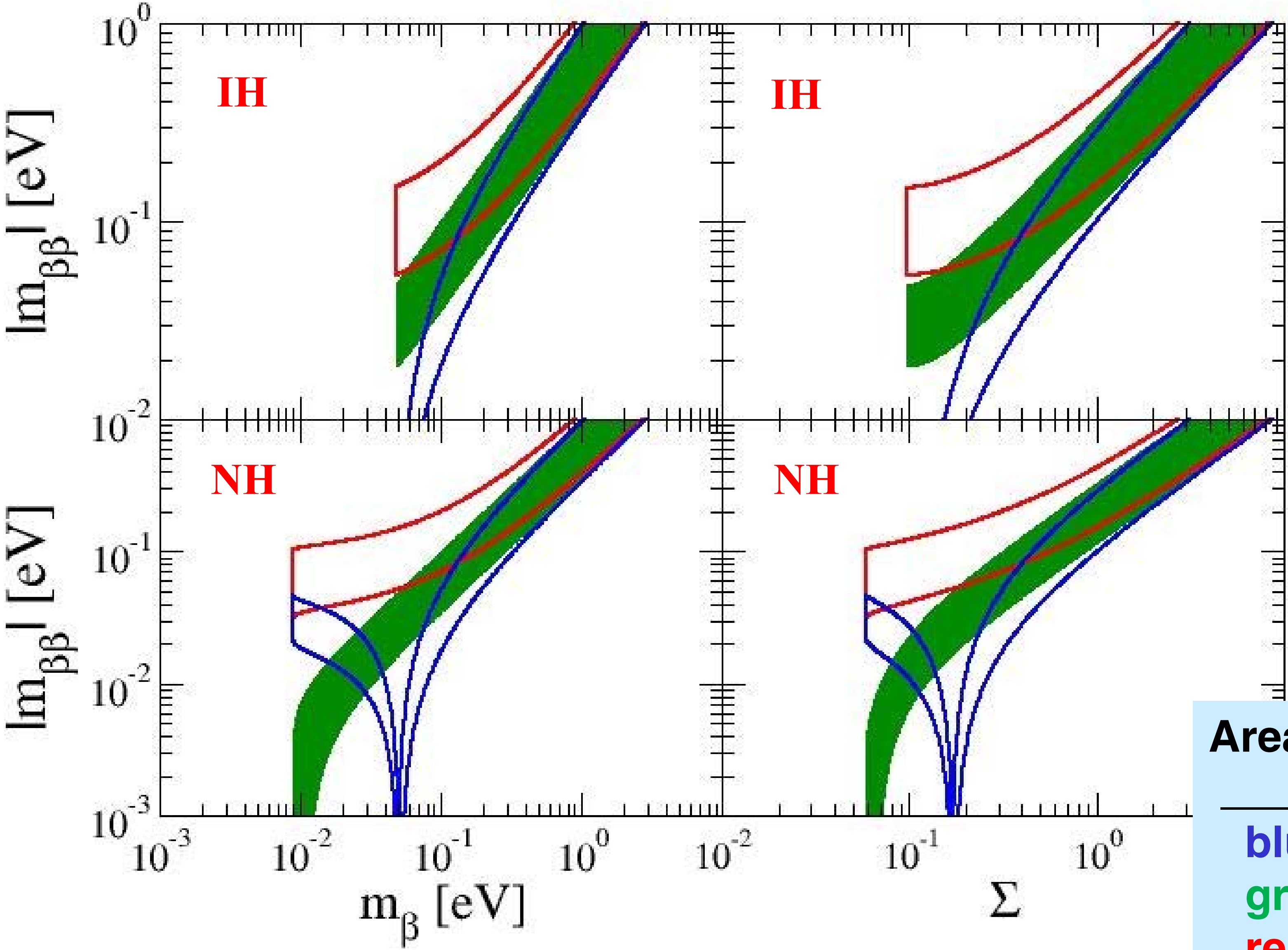
$$25\,\varepsilon_{ij}^{a} < 1 \to m_{\chi}^{2} > 25 \frac{g_{\chi} g_{ij}^{a} \sqrt{2}}{G_F} \sim 1\,\mathrm{TeV}^{2}$$

Universal scalar interaction $g_{ij}^{a} = \delta_{ij} g_{a} \quad \varepsilon_{ij}^{a} = \delta_{ij} \varepsilon_{a}$

In medium effective Majorana ν mass

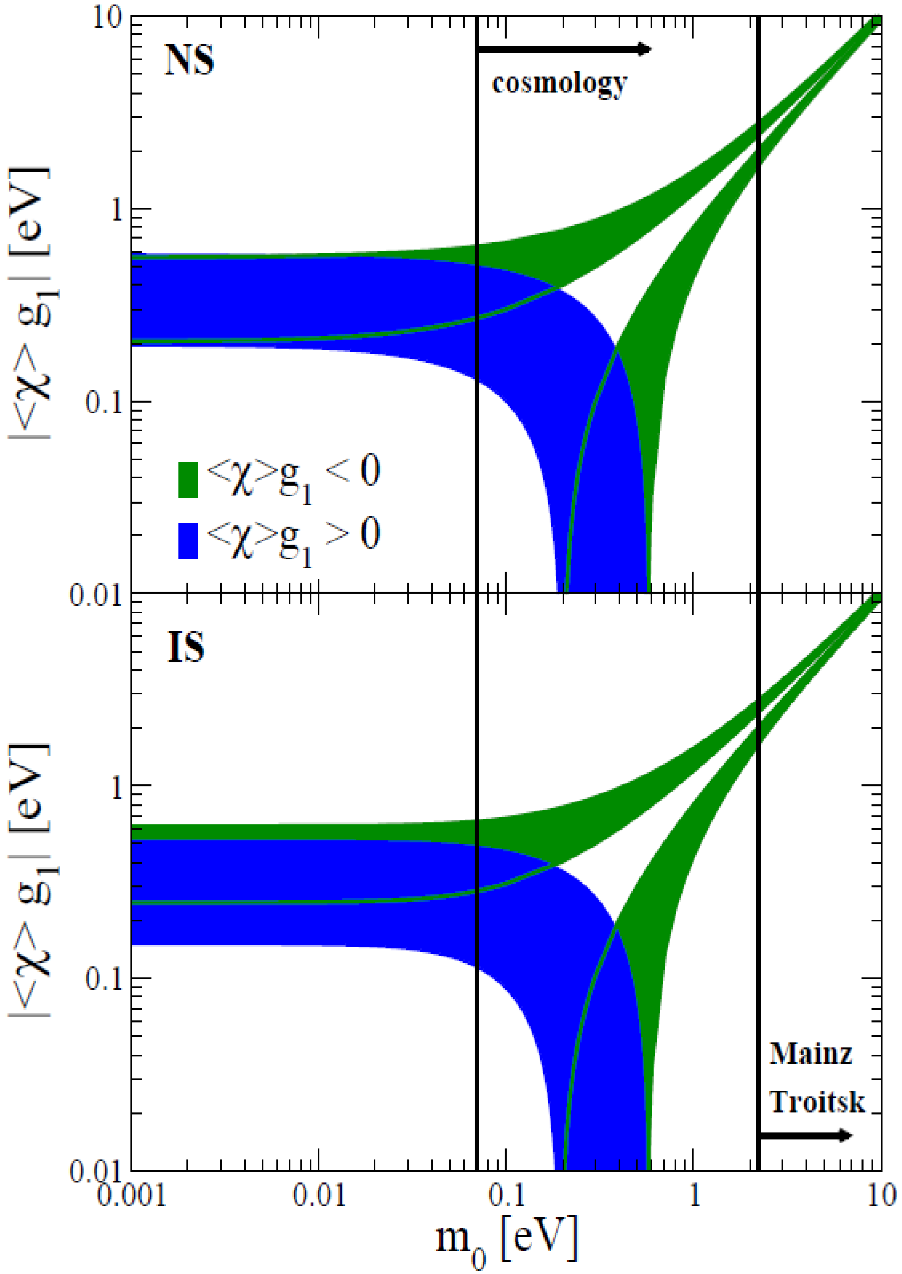
$$m_{\beta\beta} = \sum_{i=1}^{n} U_{ei}^{2} \xi_{i} \frac{\sqrt{(m_i + \langle \chi \rangle g_1)^2 + (\langle \chi \rangle g_2)^2}}{(1 - \langle \chi \rangle g_4)^2}.$$

Complementarity between β-decay, 0νββ –decay and cosmological measurements might be spoiled



Area	⟨χ⟩g_1 [eV]
blue	-0.05
green	0
red	1

Regions of admissible values of $\langle\chi\rangle g_1$ and m_0 ($m_{\beta\beta}$=0.2 eV)



$$\langle\chi\rangle = 0.17\ fm^{-3} = \frac{0.17}{(5.07)^3} GeV^3$$

$$\Lambda_{LNV} \geq 2.4\ \text{TeV (Planck)}$$

$$1.1\ \text{TeV (Tritium)}$$

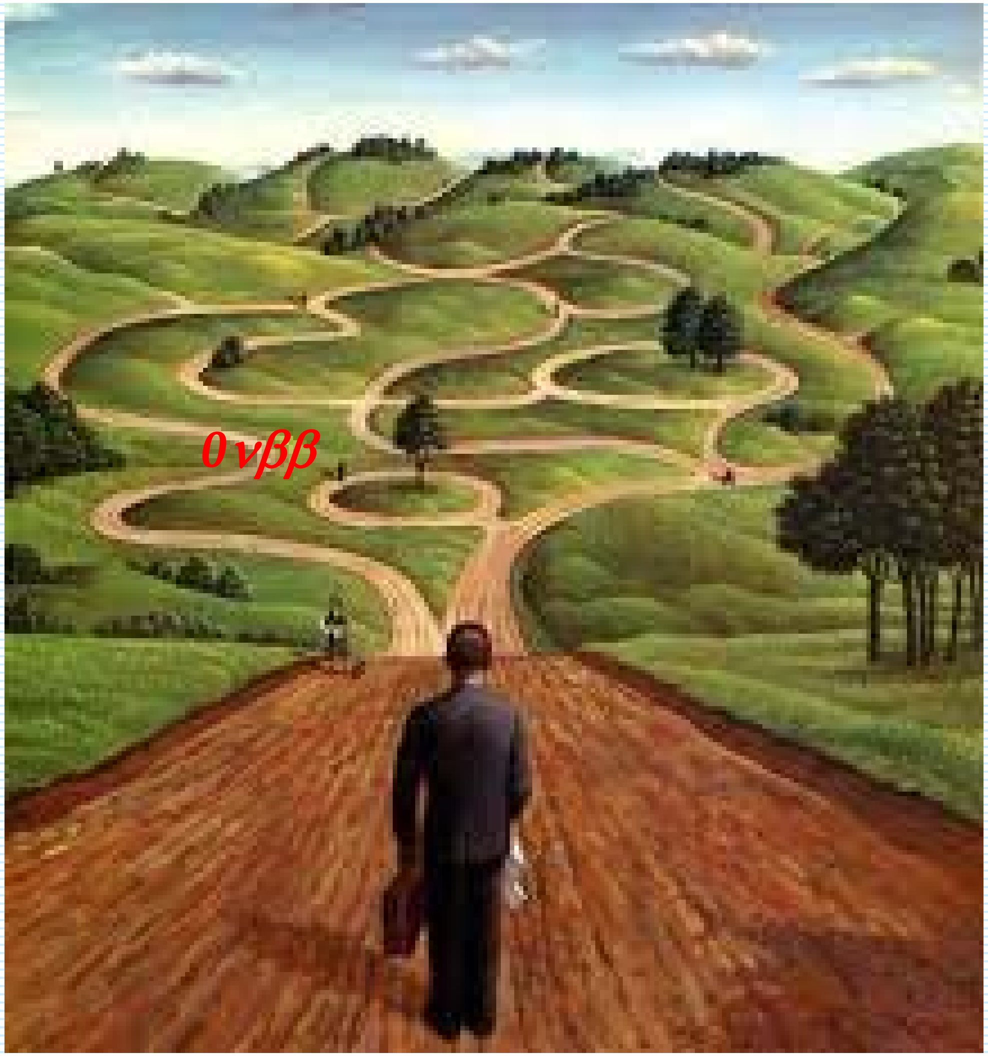
$$\varepsilon_{ij} \leq 0.02\ \text{(Planck)},\ 0.1\ \text{(Tritium)}$$

Using experimental data on the $0\nu\beta\beta$ decay in combination with β-decay and cosmological data we evaluated the characteristic scales of 4-fermion neutrino-quark operators, which is Λ_{LNV} > 2.4 TeV.

Pion decay: BR($\pi^0 \to \nu\nu$) ≤ 2.7 10^{-7}

$$\Lambda_{LNV} \geq 560\ \text{GeV}$$

Instead of Conclusions



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ν-oscillation phenomenology
Solar ν-experiments and theory
Accelerator ν-experiments
Reactor ν-experiments
Measurement of ν-mass

0νββ-decay experiments
0νββ-decay nuclear matrix elements
ν-nucleus interactions
Sterile neutrinos

Leptogenesis
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