Helmholtz International Summer School
Nuclear Theory and Astrophysical Applications
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I. Particle physics aspects of neutrinoless double beta decay

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OUTLINE

- ***Introduction***
- ***The simpliest $0\nu\beta\beta$-decay scenario***
- ***The sterile ν mechanism of the $0\nu\beta\beta$-decay***
  V-A int. ,limit on U_{eh} mixing
- ***$0\nu\beta\beta$-decay within the LR-symmetric theories***
  importance of light and heavy ν-exchange mechanisms
- ***Effect of non-standard ν-interactions on the $0\nu\beta\beta$-decay***
  complementarity of the cosmology, ν-mass, $0\nu\beta\beta$-decay observations
- ***The resonant neutrinoless double electron capture***
- ***Conclusions***

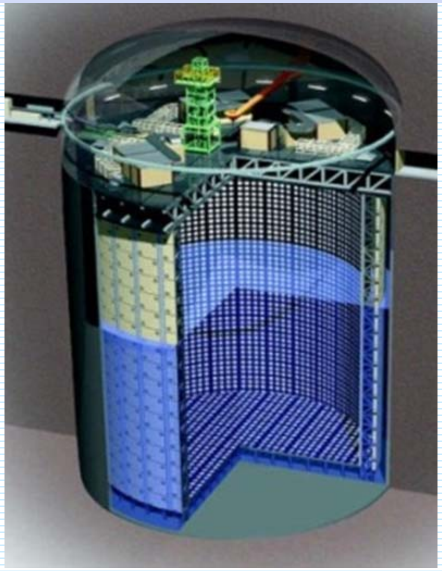
Acknowledgements: **A. Faesler (Tuebingen), P. Vogel (Caltech), S. Kovalenko (Valparaiso U.), M. Krivoruchenko (ITEP Moscow), S. Petcov (SISSA), D. Štefánik, R. Dvornický (Comenius U.) …**

Neutrino oscillations
Dubna, 60-years ago …

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

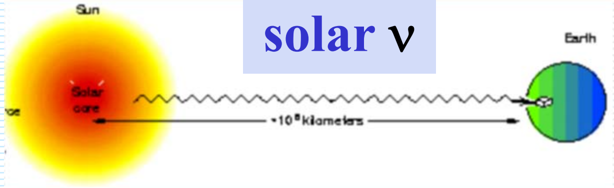
Bruno Pontecorvo
Mr. Neutrino
(22.8.1913-24.9.1993)

SuperKamiokande

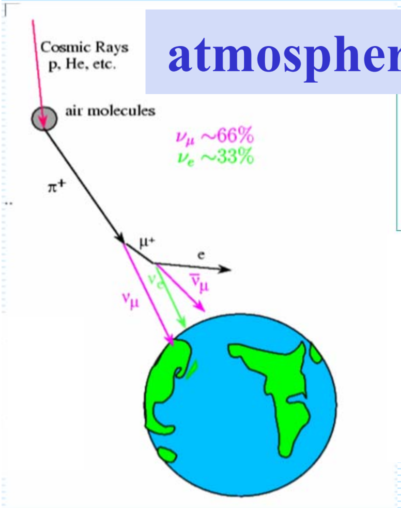


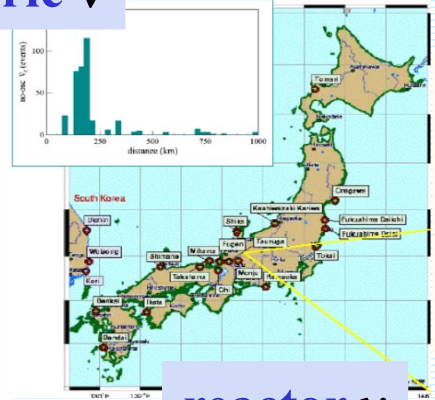
θ_{12}, θ_{23}

solar ν

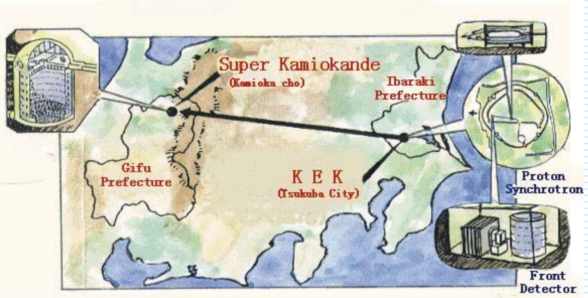


atmospheric ν

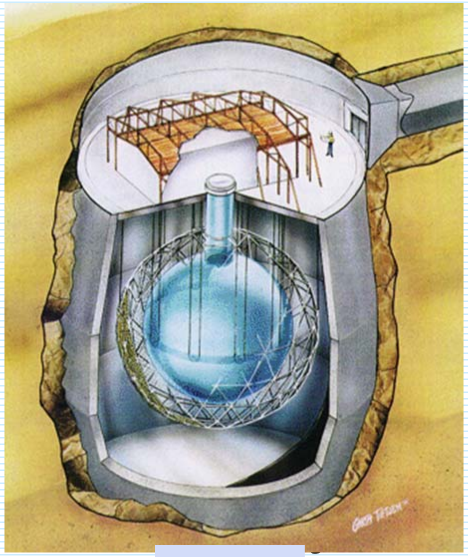




reactor ν



accelerator ν



SNO

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

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

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]

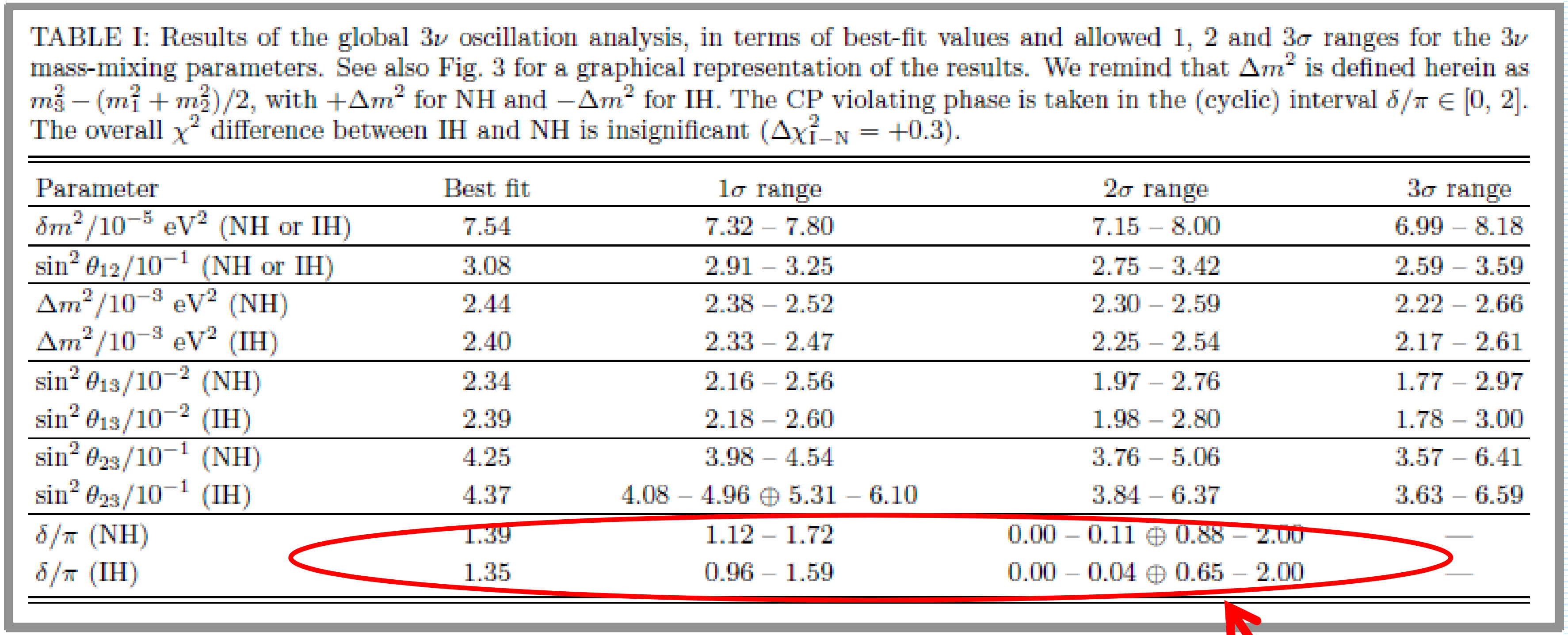


TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. See also Fig. 3 for a graphical representation of the results. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ 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 ($\Delta\chi^2_{\mathrm{I-N}} = +0.3$).

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	—

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 = $(\Delta m^2_{31} + \Delta m^2_{32})/2$

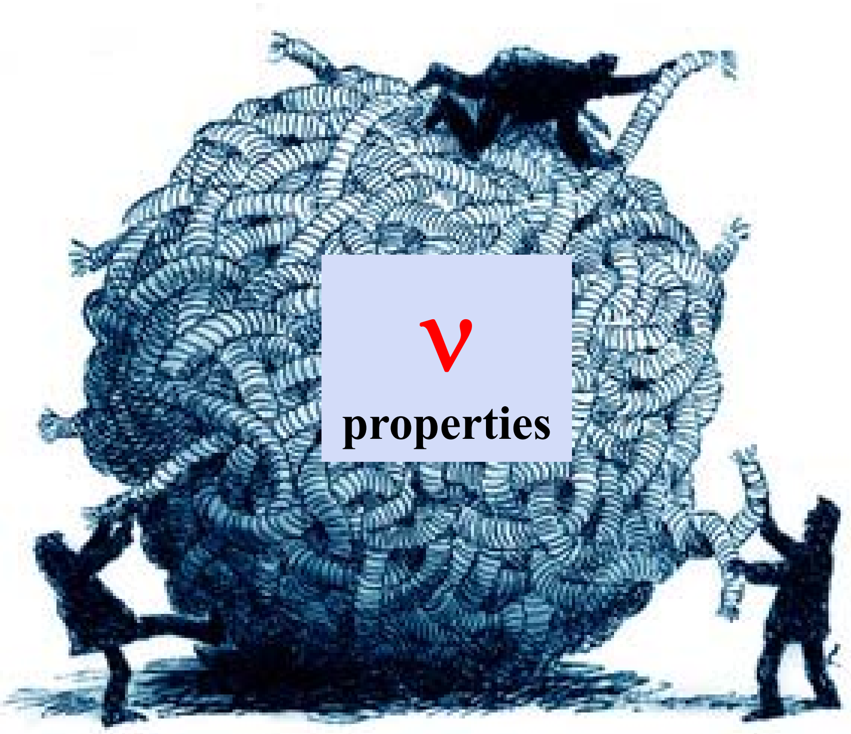
δm^2	2.6 %
Δm^2	3.0 %
$\sin^2\theta_{12}$	5.4 %
$\sin^2\theta_{13}$	8.5 %
$\sin^2\theta_{23}$	~ 11 %

An indication of CP violation in neutrino sector

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)**



ν
properties

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

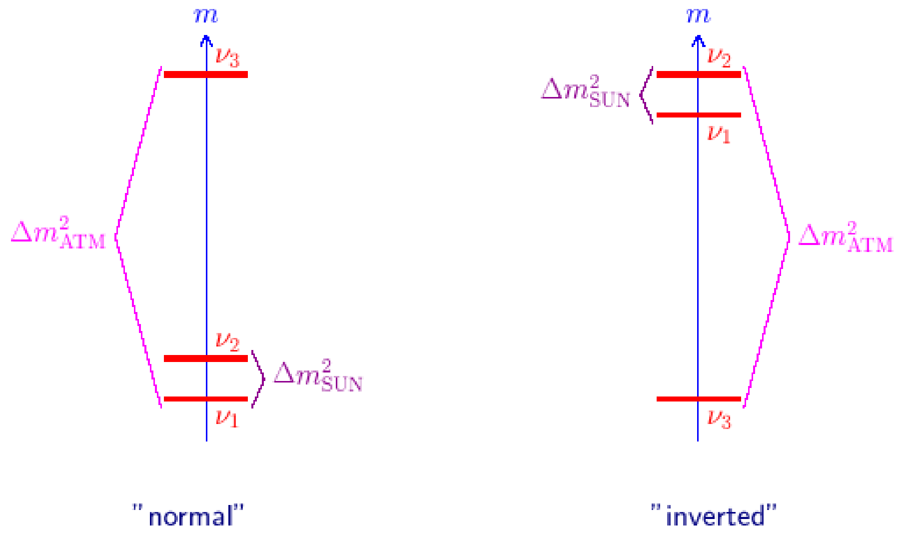
The observation of neutrino oscillations has opened a new excited era in neutrino physics and represents a big step forward in our knowledge of neutrino properties

Neutrinos mass spectrum

0νββ Measurements

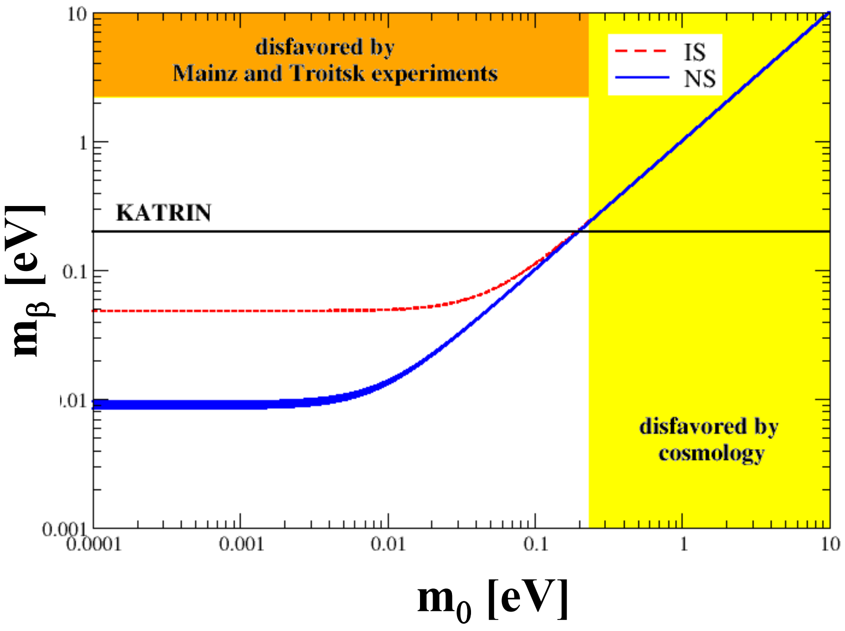
$$m_{\beta\beta} =$$

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



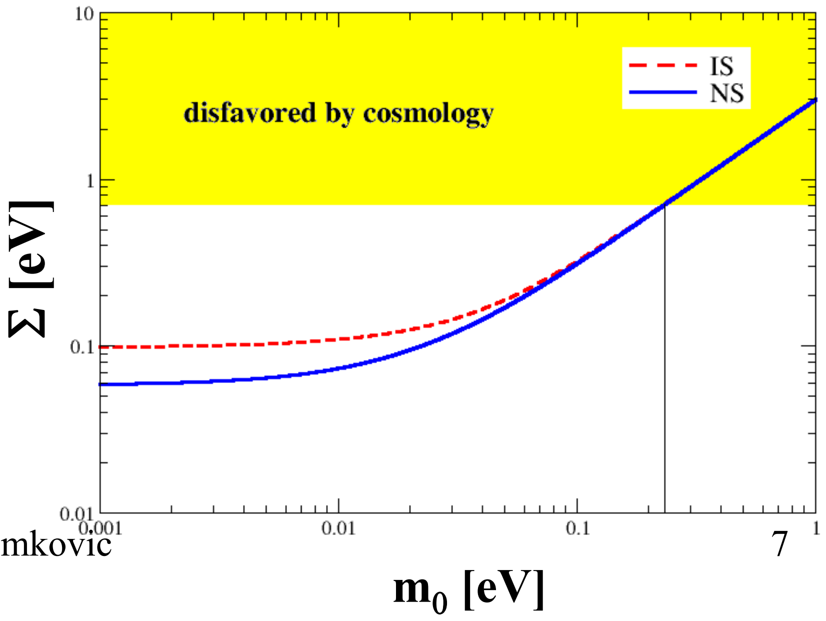
Beta Decay Measurements

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



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? 80 years old problem.

Actually, when NMEs will be needed to analyze data?

$\nu \Rightarrow$

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

1937 Beginning of Majorana neutrino physics

Ettore Majorana discoveres the possiility of existence of truly neutral fermions

Charged fermion (electron) + electromagnetic field

$$\left(i\gamma^{\mu}\partial_{\mu} - e\gamma^{\mu}A_{\mu} - m\right)\Psi = 0$$

$$\left(i\gamma^{\mu}\partial_{\mu} + e\gamma^{\mu}A_{\mu} - m\right)\Psi^{c} = 0$$

$\Psi^{c} = \Psi$ **forbidden**

Neutral fermion (neutrino) + electromagnetic field

$$\left(i\gamma^{\mu}\partial_{\mu} - m\right)\nu = 0$$

$$\left(i\gamma^{\mu}\partial_{\mu} - m\right)\nu^{c} = 0$$

$\nu^{c} = \nu$ **allowed**

Majorana condition

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

Here is the beginning of Nonstandard Neutrino Properties

The chiral fields ν_L and ν_R (it it exists) are building blocks of neutrino Lagrangian

only ν_L => Majorana mass term

$$\mathcal{L}_L^M = -\frac{1}{2} m_L \bar{\nu}\nu = -\frac{1}{2} m_L (\overline{\nu_L} + \overline{\nu_L^c})(\nu_L + \nu_L^c) \quad = \quad -\frac{1}{2} m_L (\overline{\nu_L^c} \nu_L + \overline{\nu_L} \nu_L^c)$$

$$= \quad \frac{1}{2} m_L (\nu_L^T C^\dagger \nu_L \underbrace{- \overline{\nu_L} C \overline{\nu_L}^T}_{\nu_L^\dagger C \nu_L^*})$$

$$\nu_L^c = C \overline{\nu_L}^T, \quad \overline{\nu_L^c} = -\nu_L^T C^\dagger$$

ν_L and ν_R => Dirac mass term

$$\mathcal{L}^D = -m_D \bar{\nu}\nu = -m_D (\overline{\nu_L} + \overline{\nu_R})(\nu_L + \nu_R)$$

$$= -m_D (\overline{\nu_L} \nu_R + \overline{\nu_R} \nu_L)$$

ν_L and ν_R => Dirac-Majorana mass term

$$\begin{aligned}\mathcal{L}^{D+M} &= \mathcal{L}^M_L + \mathcal{L}^M_R + \mathcal{L}^D \\ &= -\frac{1}{2}(\overline{\nu^c_L} \quad \overline{\nu_R}) \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu^c_R \end{pmatrix} + H.c. \\ &= \frac{1}{2} N^T_L C^\dagger M N_L + H.c.\end{aligned}$$

$$M = \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$$

$$N_L = \begin{pmatrix} \nu_L \\ \nu^c_R \end{pmatrix}$$

Diagonalization => fields with definite masses

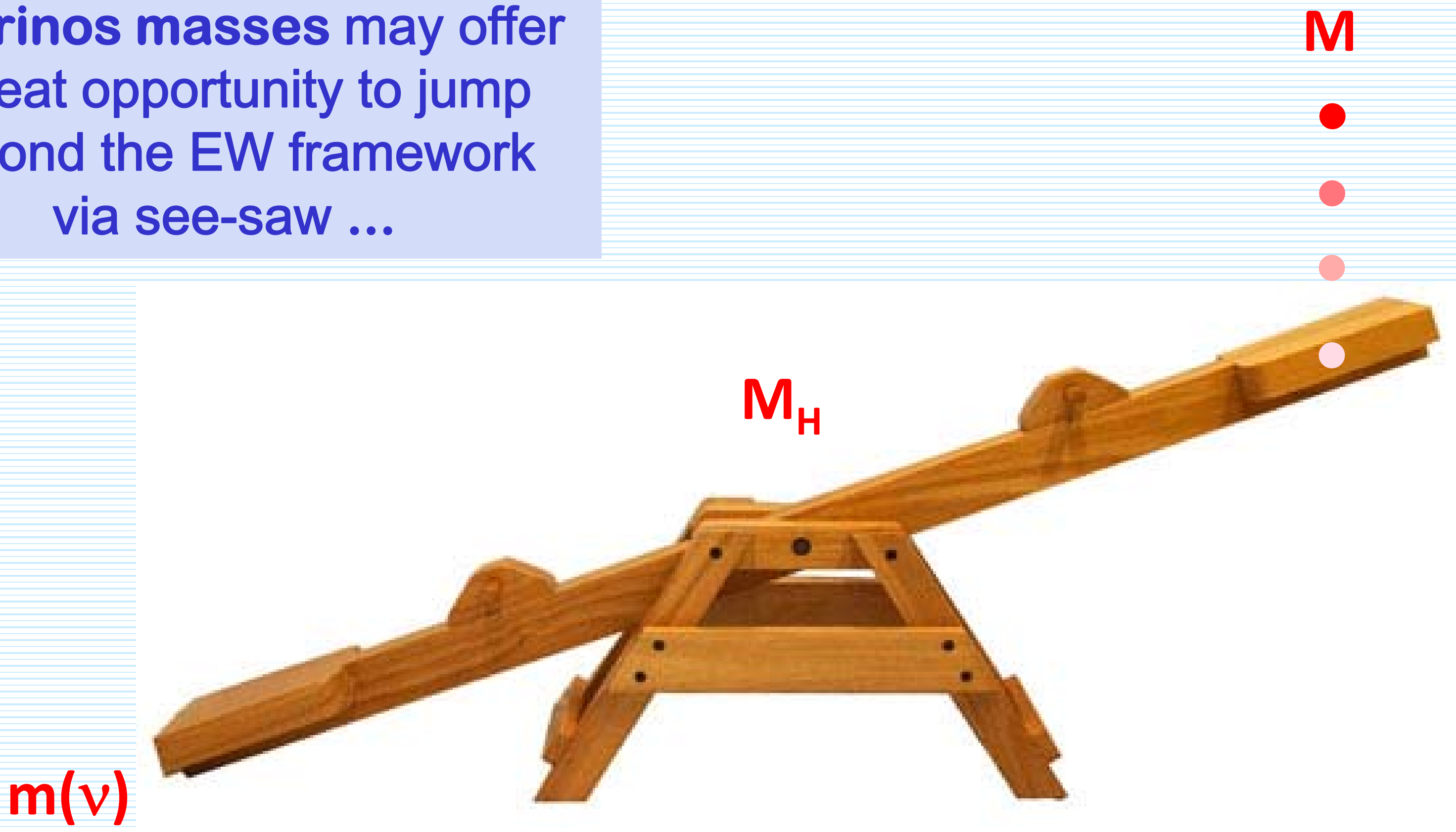
$$N_L = U n_L, \quad n_L = \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \end{pmatrix} \quad \Longrightarrow \quad U^T M U = \begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix}$$

$$\mathcal{L}^{D+M} = \frac{1}{2} \sum_{k=1,2} m_k \nu^T_{kL} C^\dagger \nu_{kL} + h.c. = -\frac{1}{2} \sum_{k=1,2} m_k \overline{\nu_k} \nu_k$$

$$\nu_k = \nu_{kL} + \nu^c_{kL}$$

Massive ν are Majorana particles!

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



... and to address fundamental physics issues, such as:

- **new sources of CP violation at low and high energies**
- **lepton number violation and associated phenomena**
- **matter-antimatter asymmetry of the universe ...**

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.**

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

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

m_3 =0.1 eV, $y_3 \approx 1$, v=246 GeV $\Rightarrow$ $\Lambda \geq 10^{15}$ GeV

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

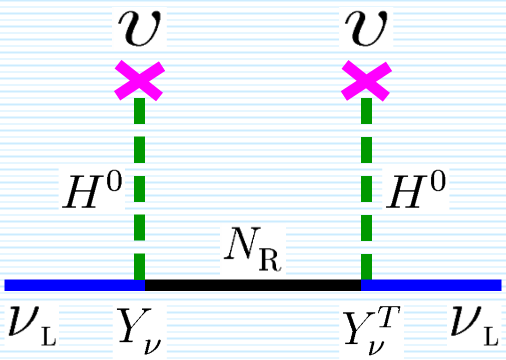
The discovery of the ββ-decay and absence of transitions of flavor neutrinos into sterile states would be evidence in favor of this minimal scenario.

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.

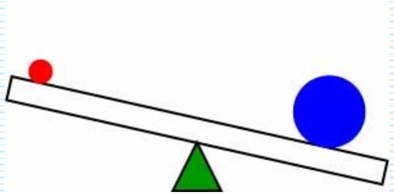
See-saws

A natural theoretical way to understand why 3 ν-masses are very small.

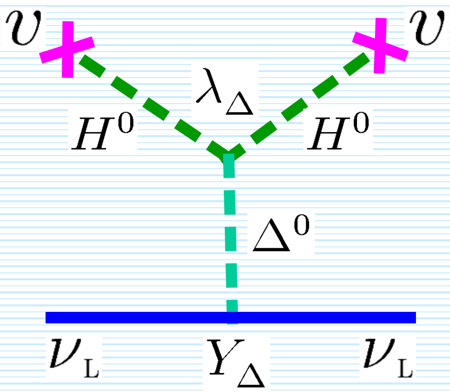
Type-I Seesaw



$$\boxed{M_\nu \approx -v^2 Y_\nu \frac{1}{M_R} Y_\nu^T}$$



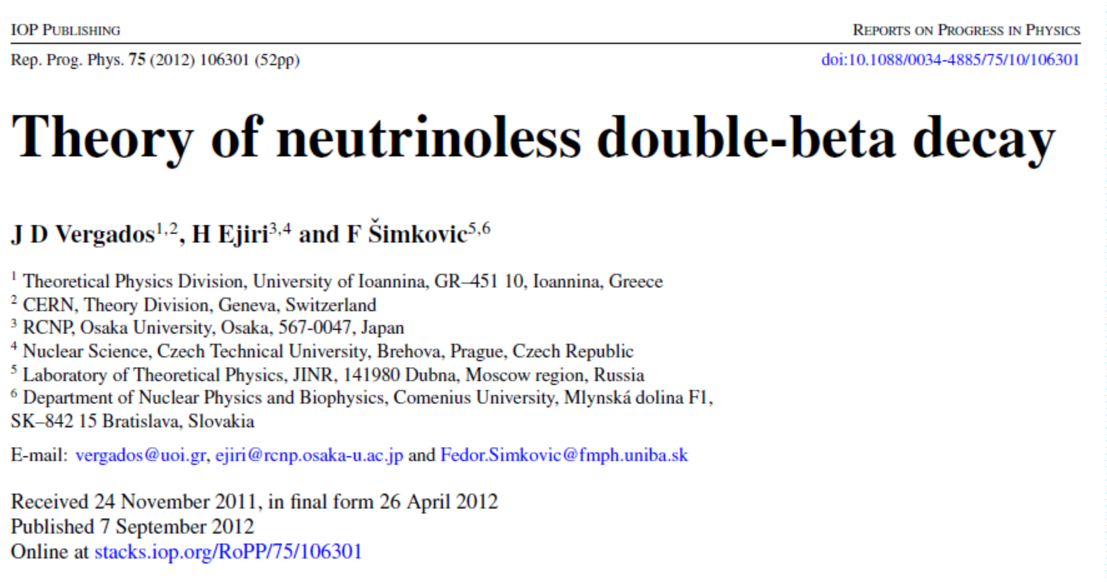
Type-II Seesaw



$$\boxed{M_\nu \approx \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta}}$$

Type-I Seesaw: a right-handed Majorana neutrinos is added into the SM.

Type-II Seesaw: a few right-handed Majorana neutrinos and one Higgs triplet are both added into the SM.



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Theory of neutrinoless double-beta decay

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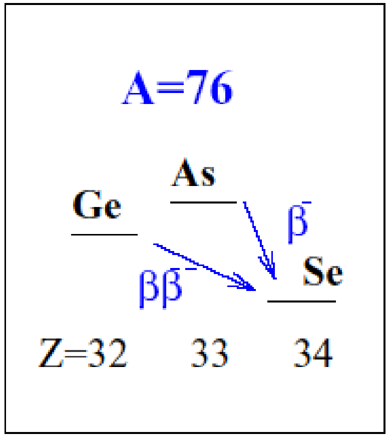
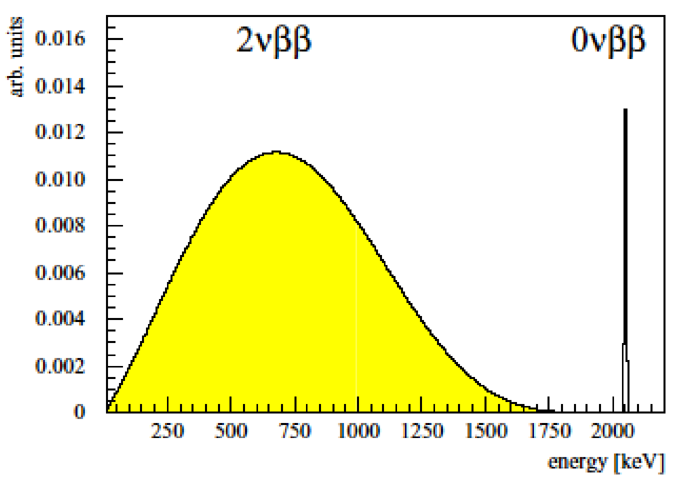
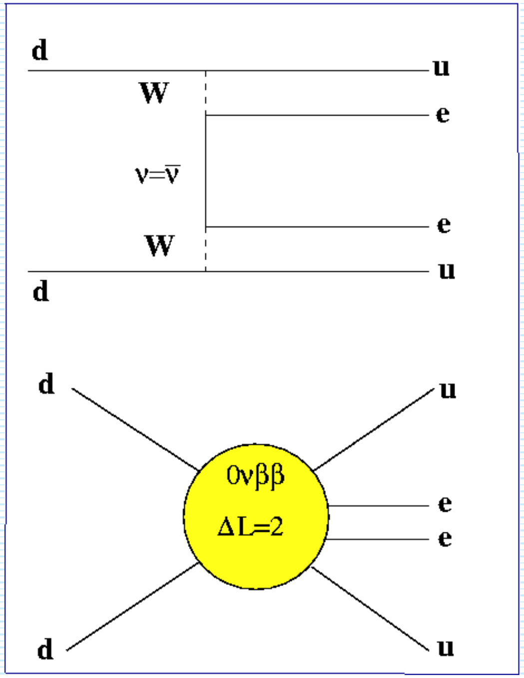
Neutrinoless Double-Beta Decay

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





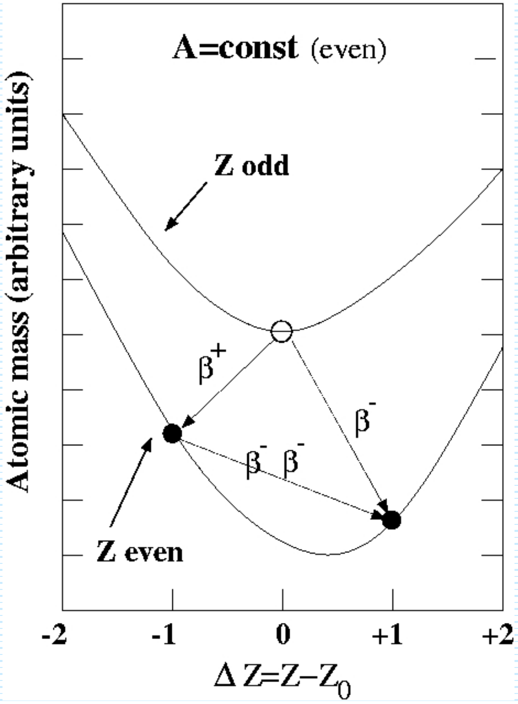


The simplest $0\nu\beta\beta$-decay scenario

(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. (%)	$\lvert M^{0\nu}\rvert^2$
$^{150}Nd \rightarrow {}^{150}Sm$	26.9	3.667	6	?
$^{48}Ca \rightarrow {}^{48}Ti$	8.04	4.271	0.2	?
$^{96}Zr \rightarrow {}^{96}Mo$	7.37	3.350	3	?
$^{116}Cd \rightarrow {}^{116}Sn$	6.24	2.802	7	?
$^{136}Xe \rightarrow {}^{136}Ba$	5.92	2.479	9	?
$^{100}Mo \rightarrow {}^{100}Ru$	5.74	3.034	10	?
$^{130}Te \rightarrow {}^{130}Xe$	5.55	2.533	34	?
$^{82}Se \rightarrow {}^{82}Kr$	3.53	2.995	9	?
$^{76}Ge \rightarrow {}^{76}Se$	0.79	2.040	8	?

The NMEs for $0\nu\beta\beta$-decay must be evaluated using tools of nuclear theory

Light ν-exchange 0νββ–decay mechanism

S.M. Bilenky, S. Petcov, Rev. Mod. Phys. 59, 671 (1987)

Majorana condition

$$C\,\overline{\chi_k}^T(x) \;=\; \xi_k\,\chi_k(x)$$

Majorana particle propagator

$$\begin{aligned} <\chi_\alpha(x_1)\overline{\chi}_\beta(x_2)> &= \frac{-1}{(2\pi)^4}\int\left(\frac{1}{\gamma p - im}\right)_{\alpha\beta} e^{ip(x_1-x_2)}dp \\ &= S_{\alpha\beta}(x_1-x_2) \end{aligned}$$

$$\begin{aligned} <\chi(x_1)\chi^T(x_2)> &= -\xi S(x_1-x_2)C \\ <\overline{\chi}^T(x_1)\overline{\chi}(x_2)> &= \xi C^{-1}S(x_1-x_2) \end{aligned}$$

Weak β-decay Hamiltonian

$$\mathcal{H}^\beta_W = \frac{G_F}{\sqrt{2}}\,\bar{e}\gamma_\alpha(1+\gamma_5)\nu_e\;j_\alpha + h.c.$$

Neutrino mixing

$$\nu_{eL} \;=\; \sum_k U^L_{lk}\;\chi_{kL}$$

S-matrix term

$$S^{(2)} = -\frac{(-i)^2}{2} 4 \left(\frac{G_F}{\sqrt{2}}\right)^2 \int N\left[\overline{e_L}(x_1)\gamma_\alpha < \nu_{eL}(x_1)\nu^T_{eL}(x_2) > \gamma^T_\beta \overline{e_L}^T(x_2)\right] \times$$

$$T\left(j_\alpha(x_1) j_\beta(x_2) e^{-i\int \mathcal{H}_{str}(x)dx}\right) dx_1 dx_2$$

Contraction of ν-fields

$$< \nu_{eL}(x_1)\nu_{eL}{}^T(x_2) > = -\sum_k \left(U^L_{ek}\right)^2 \xi_k \frac{1+\gamma_5}{2} S_k(x_1 - x_2) \frac{1+\gamma_5}{2} C$$

$$= \frac{i}{(2\pi)^4} \sum_k \left(U^L_{ek}\right)^2 \xi_k m_k \int \frac{e^{iq(x_1-x_2)} dq}{q^2 + m_k^2} \frac{1+\gamma_5}{2} C$$

Effective mass of Majorana neutrinos

$$m_{\beta\beta} = \sum_k \left(U^L_{ek}\right)^2 \xi_k m_k$$

0νββ-decay matrix element

$$< f|S^{(2)}|i > \; = \; m_{\beta\beta}\left(\frac{G_F}{\sqrt{2}}\right)^2 N_{p_1}N_{p_2}\overline{u}(p_1)\gamma_\alpha(1+\gamma_5)\gamma_\beta C\overline{u}^T(p_2)\times$$

$$\int e^{-ip_1x_1}e^{-ip_2x_2}\frac{-i}{(2\pi)^4}\int\frac{e^{iq(x_1-x_2)}dq}{q^2}\times$$

$$< A'|T\left[J_\alpha(x_1)J_\beta(x_2)\right]|A > dx_1dx_2 - (p_1\leftrightarrow p_2)$$

Use of completeness 1=Σ_n|n><n|

$$< A'|J_\alpha(x_1)J_\beta(x_2)|A > \; = \; \sum_n < A'|J_\alpha(0,\vec{x}_1)|n >< n|J_\beta(0,\vec{x}_2)|A > \times$$

$$e^{-i(E'-E_n)x_{10}}e^{-i(E_n-E)x_{20}}$$

$$< f|S^{(2)}|i > \; = \; im_{\beta\beta}\left(\frac{G_F}{\sqrt{2}}\right)^2 N_{p_1}N_{p_2}\overline{u}(p_1)\gamma_\alpha(1+\gamma_5)\gamma_\beta C\overline{u}^T(p_2)$$

After integration over time variables

$$\times\int d\vec{x}_1 d\vec{x}_2 e^{-i\vec{p}_1\cdot\vec{x}_1}e^{-i\vec{p}_2\cdot\vec{x}_2}\frac{1}{(2\pi)^3}\int\frac{e^{i\vec{q}\cdot(\vec{x}_1-\vec{x}_2)}d\vec{q}}{\vec{q}^2}\times$$

$$\sum_n\left(\frac{< A'|J_\alpha(0,\vec{x}_1)|n >< n|J_\beta(0,\vec{x}_2)|A >}{E_n+q_0+p_{20}-E}+\right.$$

$$\left.\frac{< A'|J_\beta(0,\vec{x}_1)|n >< n|J_\alpha(0,\vec{x}_2)|A >}{E_n+q_0+p_{10}-E}\right)$$

$$\times\;2\pi\delta(E'+p_{10}+p_{20}-E)$$

Approximations and simplifications

1) Non-relativistic impulse approx. for nuclear current

$$J_\alpha(0,\vec{x}) = \sum_n \tau_n^+ (\delta_{\alpha 4} + i g_A (\vec{\sigma})_k \delta_{\alpha k}) \delta(\vec{x} - \vec{x}_n)$$

2) Long-wave approximation for lepton wave functions

$$e^{-i\vec{p}_1\cdot\vec{x}_1 - i\vec{p}_2\cdot\vec{x}_2} \longrightarrow 1$$

3) Closure approximation

$$E_n \;\longrightarrow\; < E_n >$$

$$< f|S^{(2)}|i > = \overline{u}(p_1)\gamma_\alpha(1+\gamma_5)\gamma_\beta C\overline{u}^T(p_2) A_{\alpha\beta}, \quad A_{\alpha\beta} = A_{\beta\alpha}$$

Hadron part is symmetric

$$J_\alpha(0,\vec{x}_1)J_\beta(0,\vec{x}_2) = J_\beta(0,\vec{x}_2)J_\alpha(0,\vec{x}_1)$$

contribute

$$\gamma_\alpha\gamma_\beta = \delta_{\alpha\beta} + \frac{1}{2}(\gamma_\alpha\gamma_\beta - \gamma_\beta\gamma_\alpha)$$

0νββ-decay matrix element

$$\begin{aligned} < f|S^{(2)}|i > \quad &= \quad i\, m_{\beta\beta} \left(\frac{G_F}{\sqrt{2}}\right)^2 N_{p_1} N_{p_2} \overline{u}(p_1)(1-\gamma_5)C\overline{u}^T(p_2)\frac{1}{R} \\ &\times \left(M_F - g_A^2 M_{GT}\right)\delta(p_{10} + p_{20} + M' - M) \end{aligned}$$

Nuclear matrix elements

$$M_F = < A'|\sum_{n,m}\tau_n^+\tau_m^+ h(|\vec{x}_n - \vec{x}_m|)|A >$$

$$M_F = < A'|\sum_{n,m}\tau_n^+\tau_m^+ h(|\vec{x}_n - \vec{x}_m|)\vec{\sigma}_n\cdot\vec{\sigma}_m|A >$$

Neutrino exchange potential

$$\begin{aligned} h(|\vec{x}_n - \vec{x}_m|) &= \frac{1}{2\pi^2}\int \frac{e^{i\vec{q}\cdot\vec{x}}d\vec{q}}{q_0(q_0 + < E_n > -(E + E')/2)} \\ &\approx \frac{1}{|\vec{x}|} \end{aligned}$$

Differential 0νββ-decay rate

$$\begin{aligned} d\Gamma_{0\nu} &= \frac{1}{2}\frac{G_F^4 m_e^5}{(2\pi)^5}\,|m_{\beta\beta}|^2\,\frac{1}{R^2}|M_F - g_A^2 M_{GT}|^2(1-\cos\theta) \\ &\quad F^2(Z)(\varepsilon_0 - \varepsilon + 1)^2(\varepsilon + 1)d\varepsilon\sin\theta d\theta \end{aligned}$$

$$F(Z) = \frac{2\pi\alpha(Z+2)}{1 - exp[-2\pi\alpha(Z+2)]}$$

$$\varepsilon_0 = \frac{1}{m_e}(M - M' - 2m_e)$$

Full 0νββ-decay rate

$$\begin{aligned} \Gamma_{0\nu} &= \frac{1}{2}\frac{G_F^4 m_e^5}{(2\pi)^5}\,|m_{\beta\beta}|^2\,\frac{1}{R^2}|M_F - g_A^2 M_{GT}|^2 F^2(Z) \\ &\quad \times\frac{1}{15}\left(\varepsilon_0^5 + 10\varepsilon_0^4 + 40\varepsilon_0^3 + 60\varepsilon_0^2 + 30\varepsilon_0\right) \end{aligned}$$

I. Effective mass of Majorana neutrinos (in vacuum)

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

m_1, m_2, m_3, θ_{12}, θ_{13}, α_1, α_2

(3 unknown parameters)

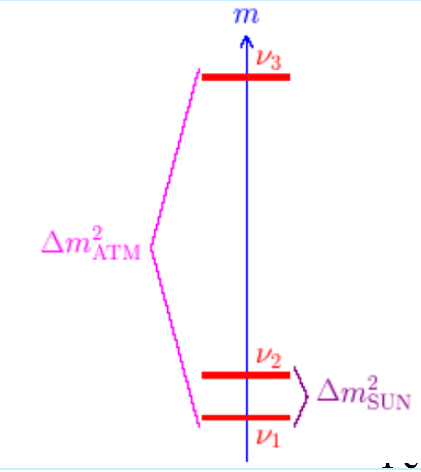
Measured quantity

$$\begin{aligned}|m_{\beta\beta}|^2 &= c_{12}^4 c_{13}^4 m_1^2 + s_{12}^4 c_{13}^4 m_2^2 + s_{13}^4 m_3^2 \\ &+2c_{12}^2 s_{12}^2 c_{13}^4 m_1 m_2 \cos(\alpha_1 - \alpha_2) \\ &+2c_{12}^2 c_{13}^2 s_{13}^2 m_1 m_3 \cos\alpha_1 + 2s_{12}^2 c_{13}^2 s_{13}^2 m_2 m_3 \cos\alpha_2 .\end{aligned}$$

Limiting cases

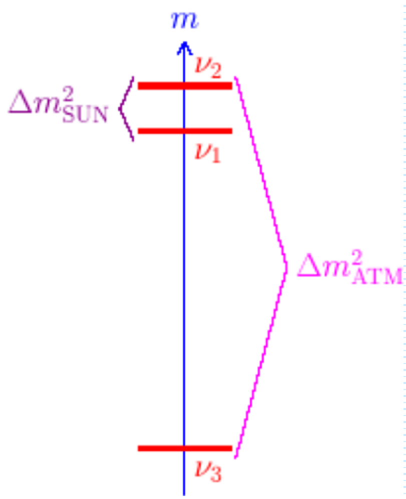
Normal hierarchy

$$\begin{aligned} m_1 &\ll \sqrt{\Delta m^2_{\mathrm{SUN}}} \\ m_2 &\simeq \sqrt{\Delta m^2_{\mathrm{SUN}}} \\ m_3 &\simeq \sqrt{\Delta m^2_{\mathrm{ATM}}} \end{aligned}$$



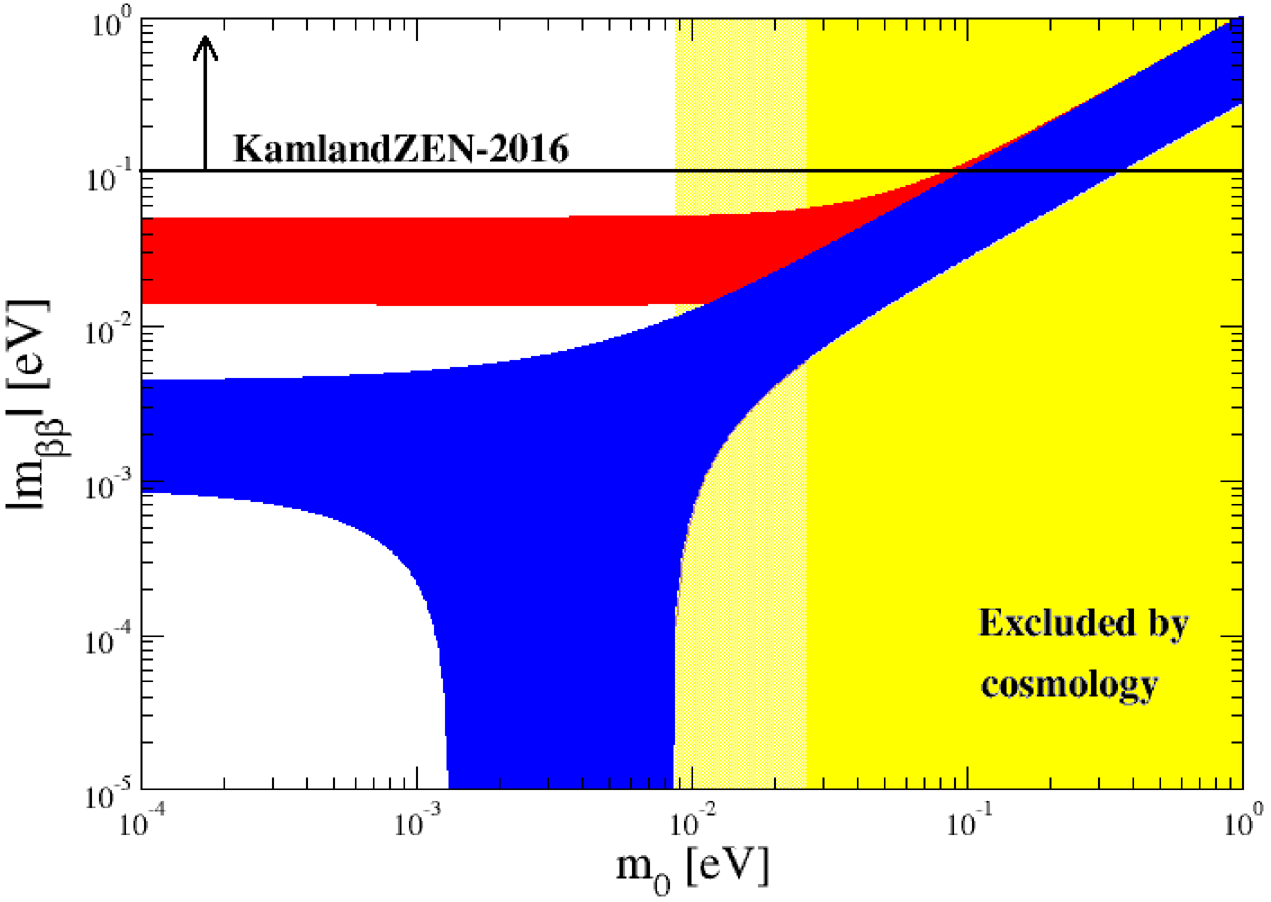
Inverted hierarchy

$$\begin{aligned} m_3 &\ll \sqrt{\Delta m^2_{\mathrm{ATM}}} \\ m_1 &\simeq m_2 \simeq \sqrt{\Delta m^2_{\mathrm{ATM}}} \end{aligned}$$



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

Issue: Lightest neutrino mass m_0



GUT's

β-decay (Mainz, Troitsk)

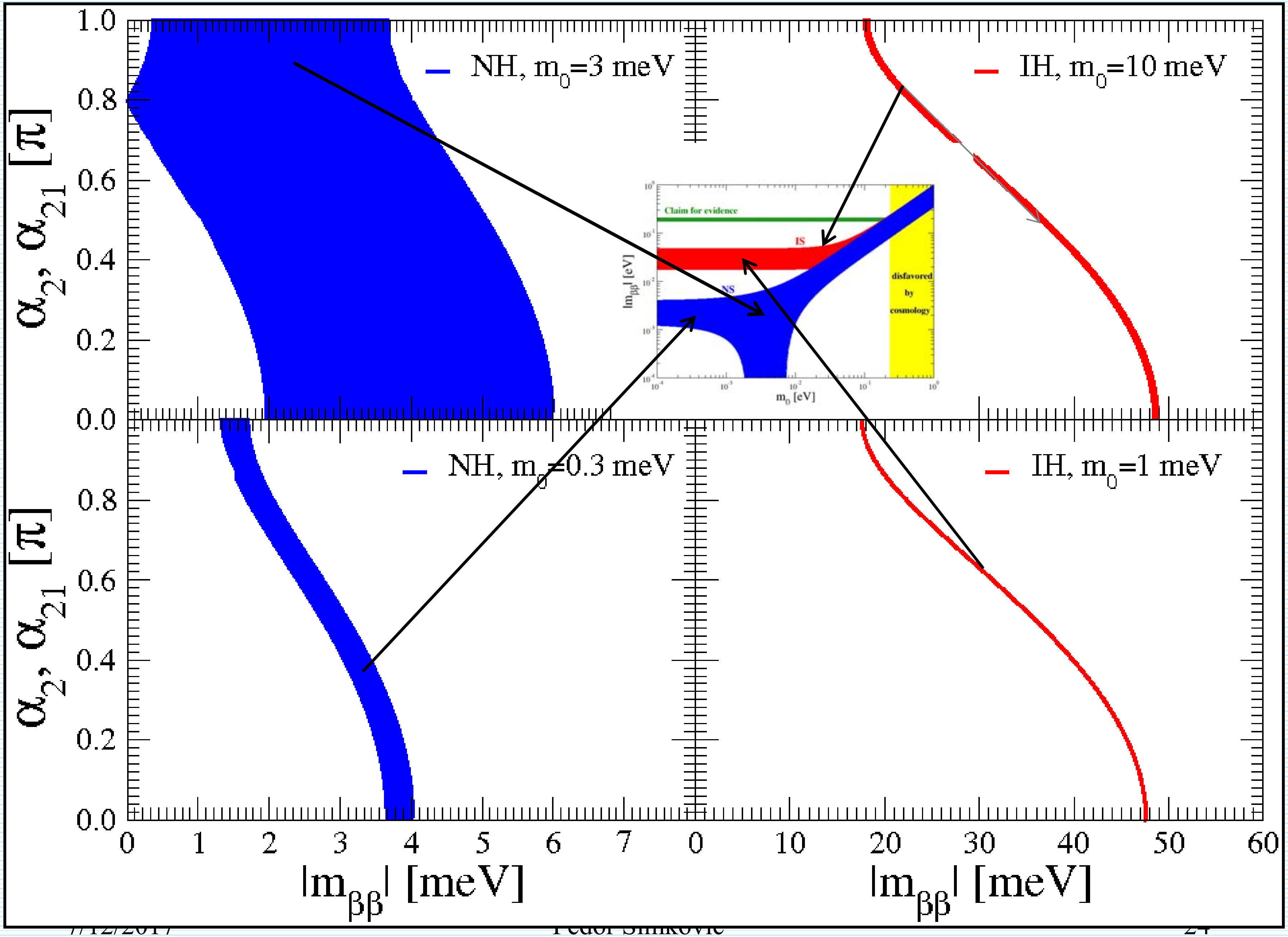
$$m_\beta^2 = \sum_i |U^L_{ei}|^2 m_i^2 \lesssim (2.2\ \mathrm{eV})^2$$

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

Cosmology (Planck)

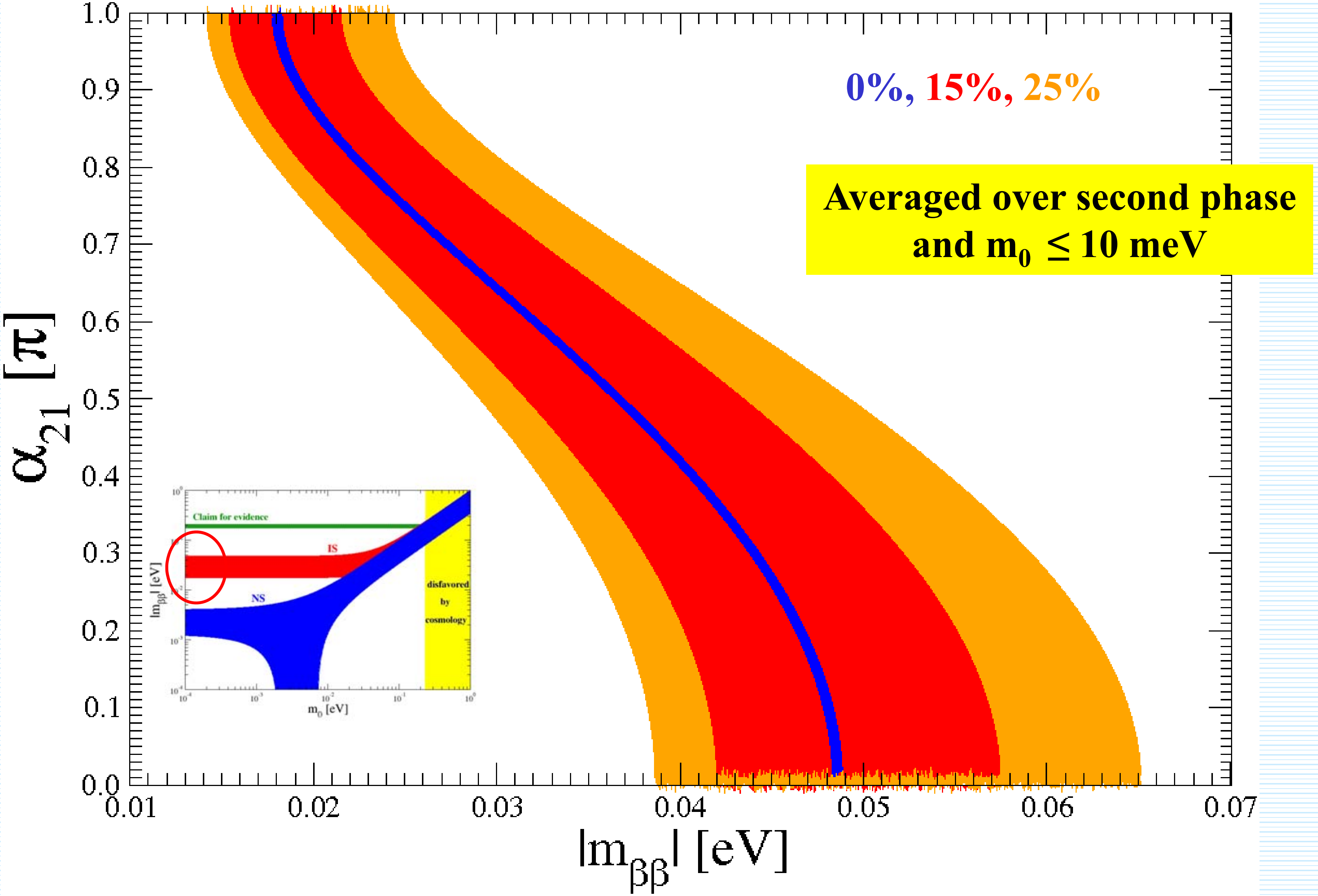
$$\Sigma < 110\ \mathrm{meV}$$

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


NH, m_0=3 meV
IH, m_0=10 meV
NH, m_0=0.3 meV
IH, m_0=1 meV
α_2, α_{21} [π]
$|m_{\beta\beta}|$ [meV]
0.0
0.2
0.4
0.6
0.8
1.0
0 1 2 3 4 5 6 7
0 10 20 30 40 50 60
Claim for evidence
IS
NS
disfavored by cosmology
$|m_{\beta\beta}|$ [eV]
m_0 [eV]

$$|m_{\beta\beta}| = \frac{1}{\sqrt{T^{0\nu}_{1/2} G^{0\nu}(Q_{\beta\beta}, Z)}|M'^{0\nu}|}$$

$$\frac{\sigma_{\beta\beta}}{|m_{\beta\beta}|^{obs}} = \sqrt{\frac{1}{4}\left(\frac{\sigma_{exp}}{T^{0\nu-obs}_{1/2}}\right)^2 + \left(\frac{\sigma_{th}}{|M'^{0\nu}|}\right)^2}$$



Averaged over second phase and $m_0 \leq 10$ meV

II. *The sterile ν mechanism of the 0νββ-decay*

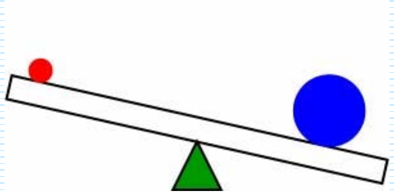
(D-M mass term, V-A SM int.)

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

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]

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu} g^4_{\rm A} \left| \sum_{\rm N} \left(U^2_{e\rm N} m_{\rm N} \right) m_{\rm p}\, M'^{\,0\nu}(m_{\rm N}, g^{\rm eff}_{\rm A}) \right|^2$$

General case

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

$$M'^{0\nu}(m_{\rm N} \to 0, g^{\rm eff}_{\rm A}) = \frac{1}{m_{\rm p} m_{\rm e}} M'^{0\nu}_\nu(g^{\rm eff}_{\rm A})$$

$$M'^{0\nu}(m_{\rm N} \to \infty, g^{\rm eff}_{\rm A}) = \frac{1}{m^2_{\rm N}} M'^{0\nu}_{\rm N}(g^{\rm eff}_{\rm A})$$

Particular cases

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu} g^4_{\rm A} \times \times \begin{cases} \left| \frac{\langle m_\nu \rangle}{m_e} \right|^2 \left| M'^{0\nu}_\nu(g^{\rm eff}_{\rm A}) \right|^2 & \text{for } m_{\rm N} \ll p_{\rm F} \\ \left| \langle \frac{1}{m_{\rm N}} \rangle m_{\rm p} \right|^2 \left| M'^{0\nu}_{\rm N}(g^{\rm eff}_{\rm A}) \right|^2 & \text{for } m_{\rm N} \gg p_{\rm F} \end{cases}$$

$$\langle m_\nu \rangle = \sum_{\rm N} U^2_{\rm eN} m_{\rm N}$$

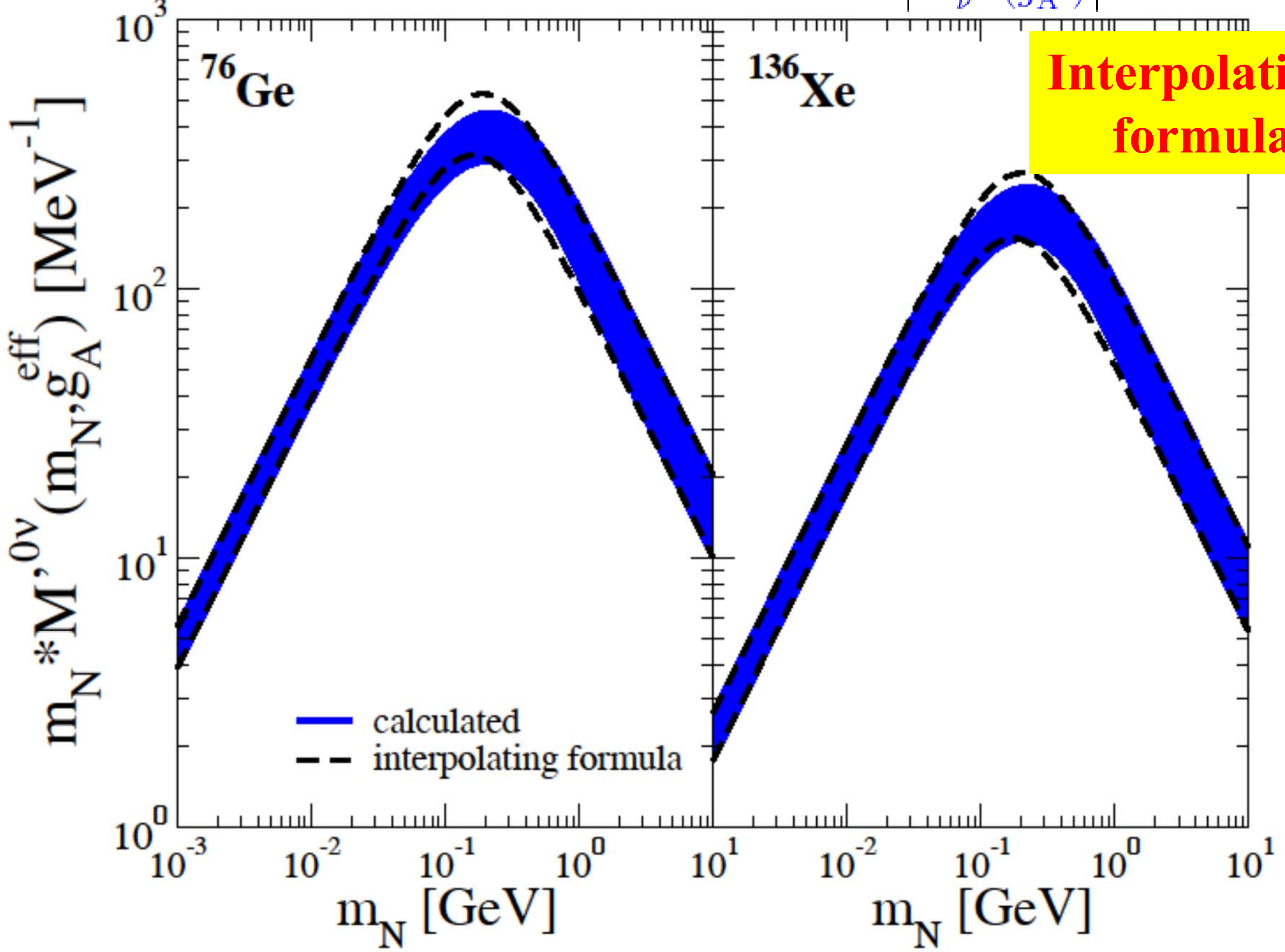
$$\left\langle \frac{1}{m_{\rm N}} \right\rangle = \sum_{\rm N} \frac{U^2_{\rm eN}}{m_{\rm N}}$$

$$[T^{0\nu}_{1/2}]^{-1} = \mathcal{A}\cdot\left|m_{\mathrm{p}}\sum_{\mathrm{N}} U^2_{e\mathrm{N}}\frac{m_{\mathrm{N}}}{\langle p^2\rangle + m^2_{\mathrm{N}}}\right|^2,$$

$$\mathcal{A} = G^{0\nu}g^4_{\mathrm{A}}\left|M'^{0\nu}_{\mathrm{N}}(g^{\mathrm{eff}}_{\mathrm{A}})\right|^2,$$

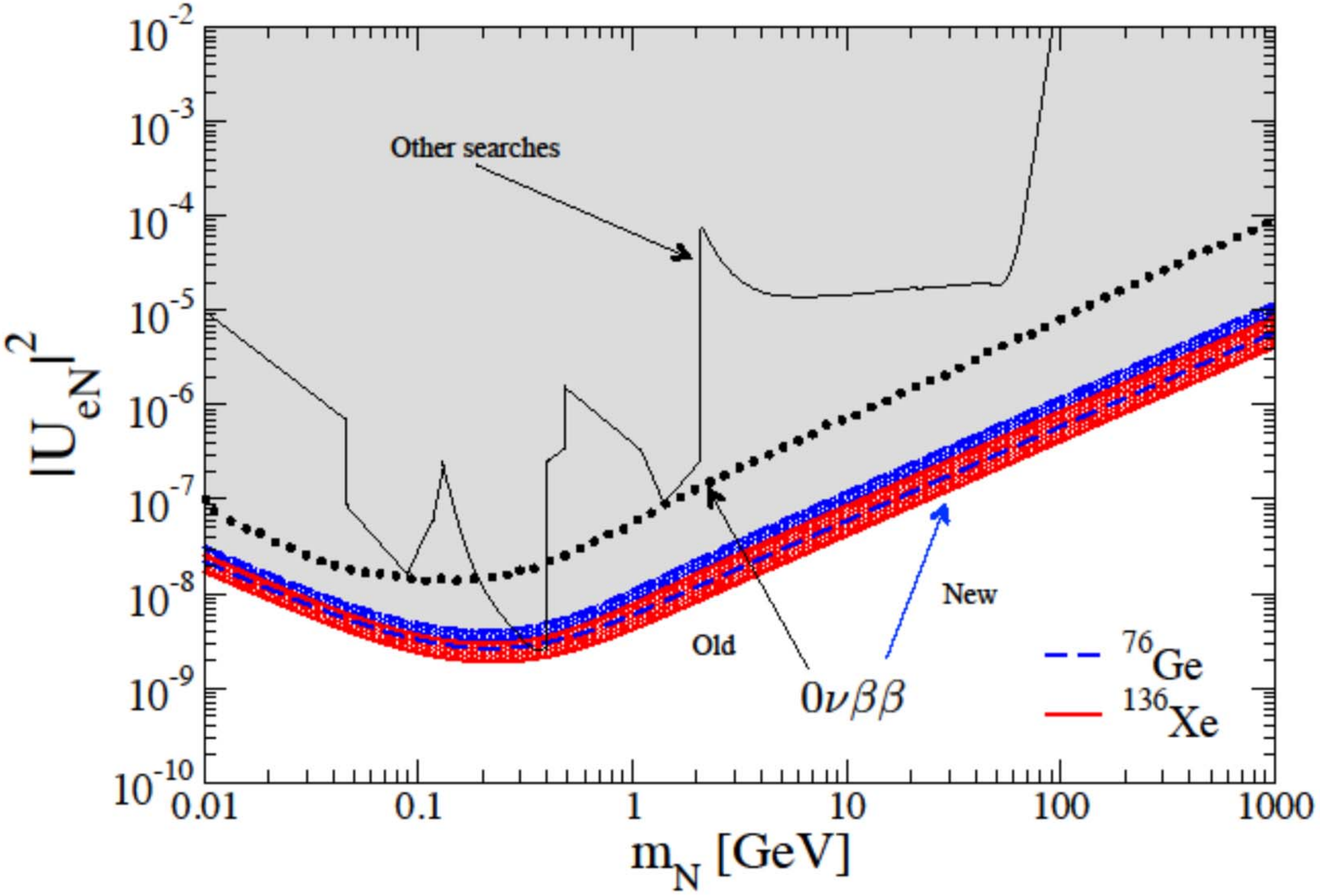
$$\langle p^2\rangle = m_{\mathrm{p}}m_{\mathrm{e}}\left|\frac{M'^{0\nu}_{\mathrm{N}}(g^{\mathrm{eff}}_{\mathrm{A}})}{M'^{0\nu}_{\nu}(g^{\mathrm{eff}}_{\mathrm{A}})}\right|^{\cancel{2}} \approx 200\ \ MeV$$

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

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

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

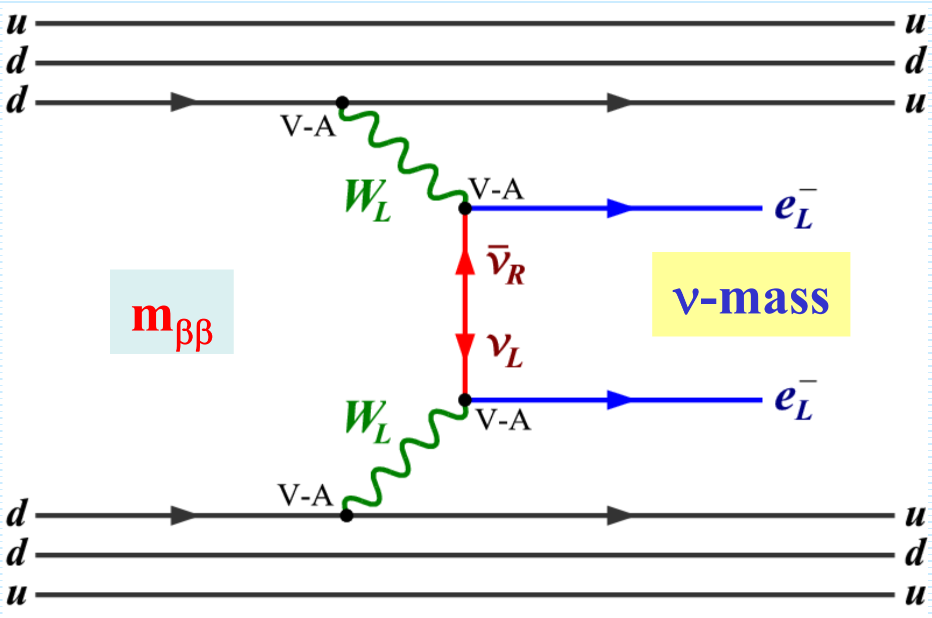
$$\left[T^{0\nu}_{1/2}\right]^{-1} = \frac{\Gamma^{0\nu}}{\ln 2} = g_A^4\,|M_{GT}|^2 \left\{ C_{mm} \frac{|m_{\beta\beta}|}{m_e}^2 \right.$$
$$+ C_{m\lambda}\frac{|m_{\beta\beta}|}{m_e}\langle\lambda\rangle\cos\psi_1 + C_{m\eta}\frac{|m_{\beta\beta}|}{m_e}\langle\eta\rangle\cos\psi_2$$
$$\left. + C_{\lambda\lambda}\langle\lambda\rangle^2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

<λ> - W$_L$-W$_R$ exch.

<η> - W$_L$-W$_R$ mixing

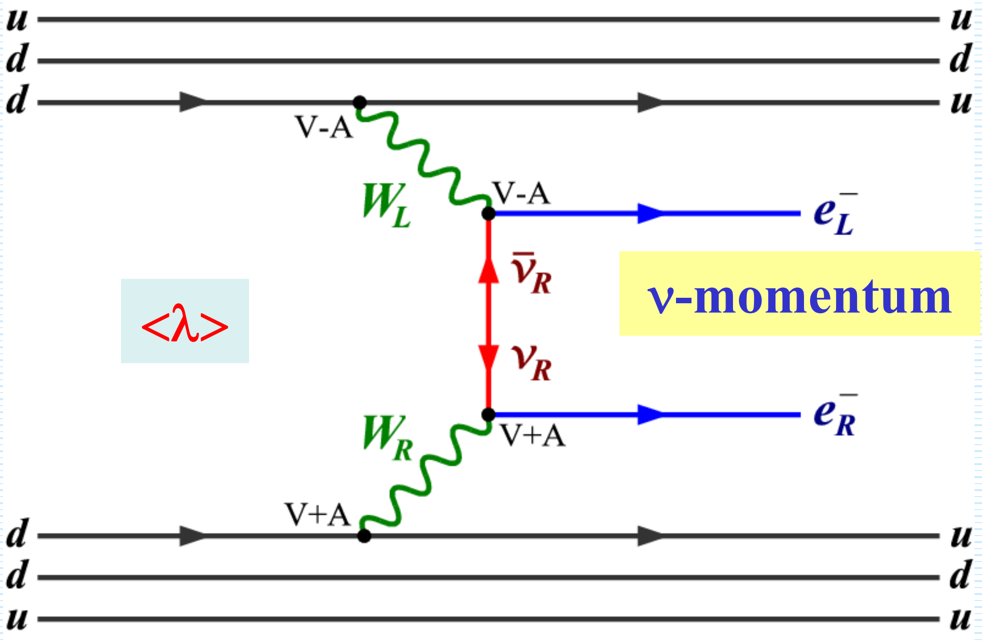
D. Štefánik, R. Dvornický, F.Š., P. Vogel, PRC 92, 055502 (2015)

Left-right symmetric models SO(10)



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

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



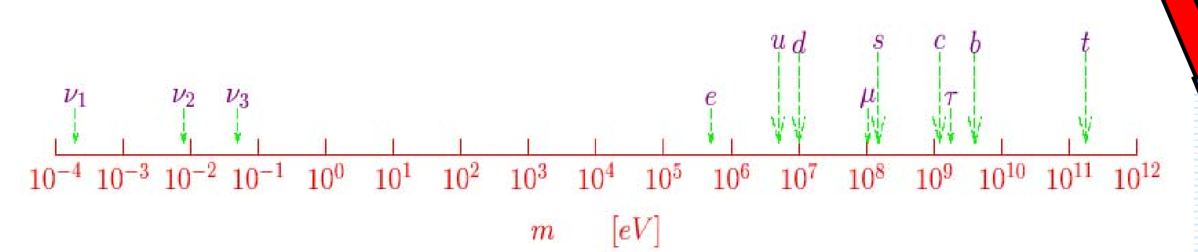
$$\langle\lambda\rangle = \lambda\,\left|\sum_{j=1}^{3} U_{ej}T^*_{ej}\right|$$

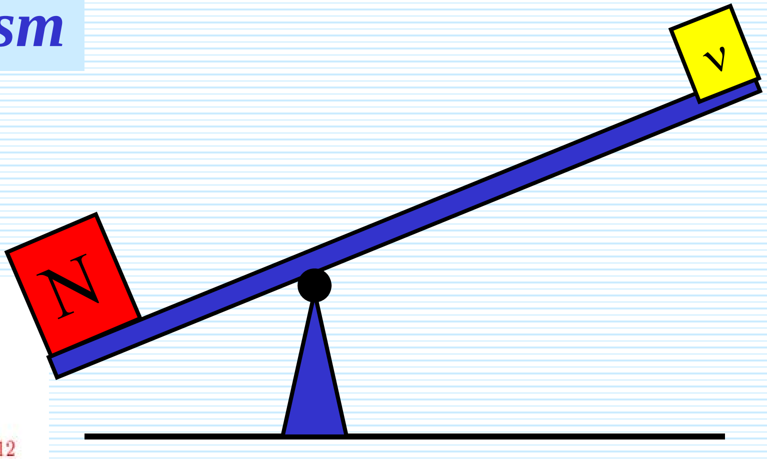
$$\langle\eta\rangle = \eta\,\left|\sum_{j=1}^{3} U_{ej}T^*_{ej}\right|$$

Assumption $M_R \gg m_D$

See-Saw mechanism

$$\begin{pmatrix} \overline{\nu}_L & \overline{(\nu_R)^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} (\nu_L)^c \\ \nu_R \end{pmatrix}$$





Left-right symmetric models SO(10)

$$\nu_{eL} = \sum_{i=1}^{light} \underset{\underset{\textbf{large}}{\uparrow}}{U_{ei}\chi_{iL}} + \sum_{i=1}^{heavy} \underset{\underset{\textbf{small}}{\uparrow}}{U_{ei}N_{iL}}$$

$$(\nu_{eR})^c = \sum_{i=1}^{light} \underset{\underset{\textbf{small}}{\uparrow}}{V_{ei}\chi_{iL}} + \sum_{i=1}^{heavy} \underset{\underset{\textbf{large}}{\uparrow}}{V_{ei}N_{iL}}$$

Probability of Neutrino Oscillations

As N increases, the formalism gets rapidly more complicated!

N	Δm_{ij}^2	θ_{ij}	CP
2	1	1	0+1
3	2	3	1+2
6	5	15	10+5

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

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

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

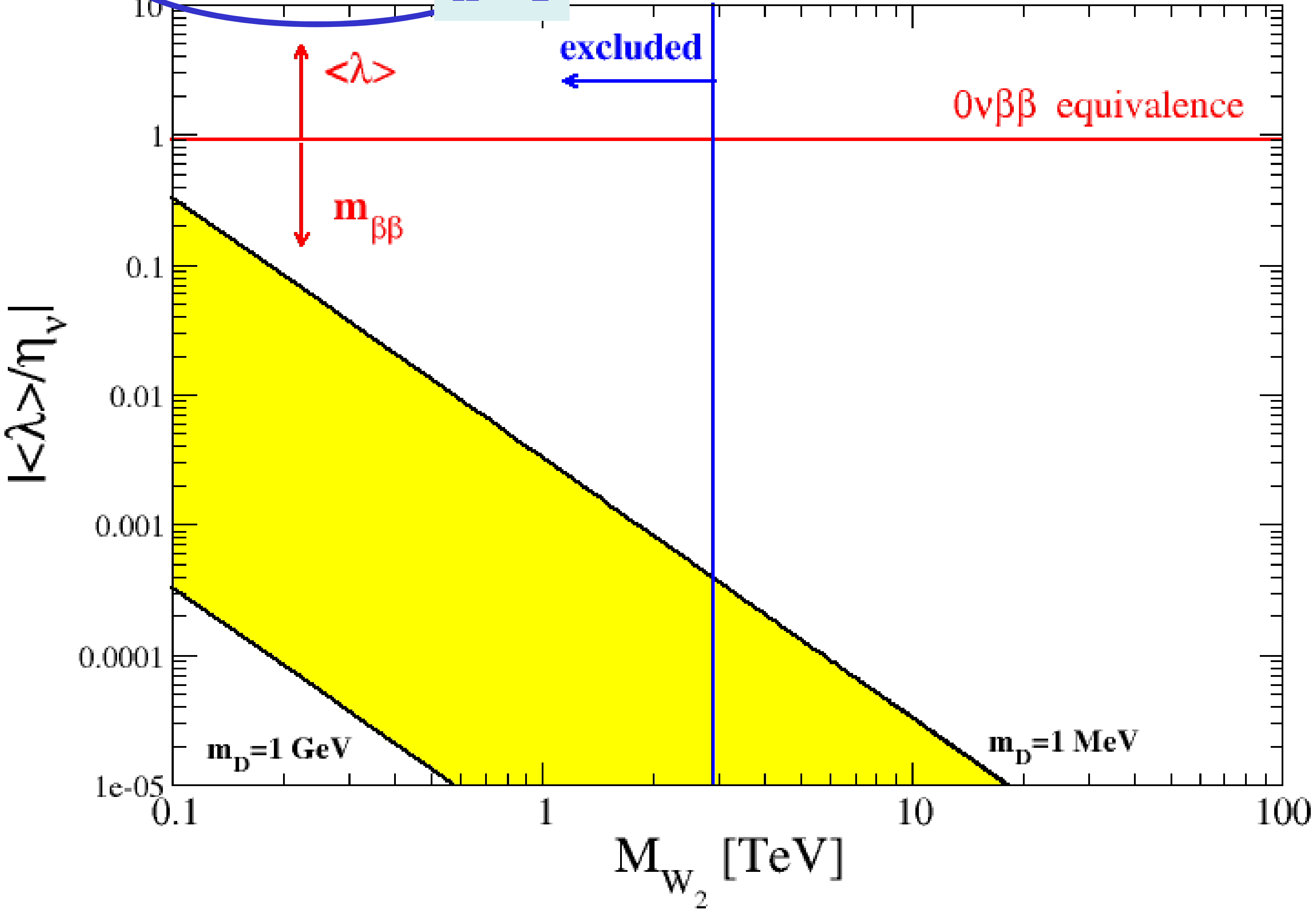
$$|\xi| \simeq 0.82$$

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

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

if ≈ 1

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



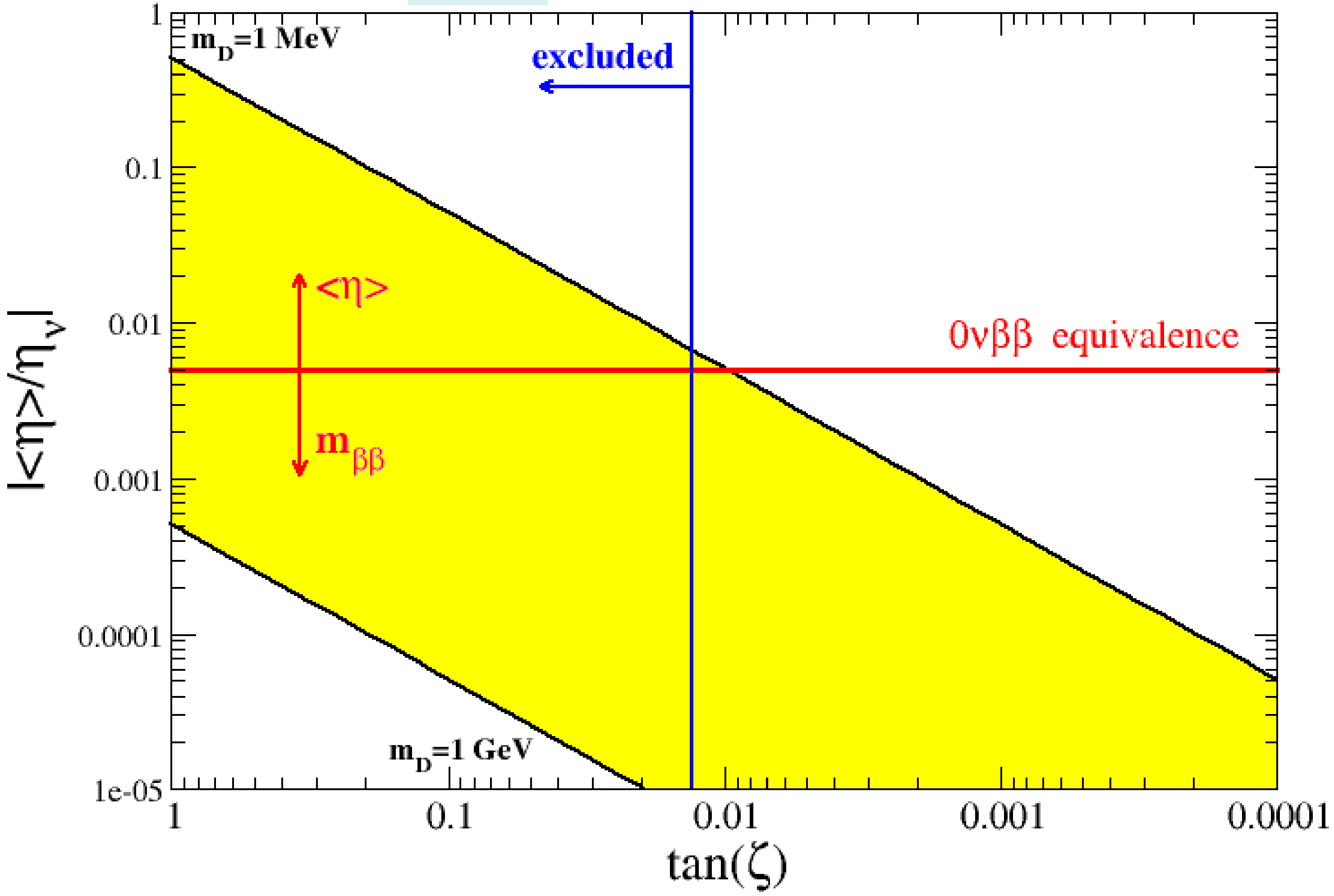
Clear dominance of $m_{\beta\beta}$ over <λ> mechanism
by current constraint on mass of heavy vector boson

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

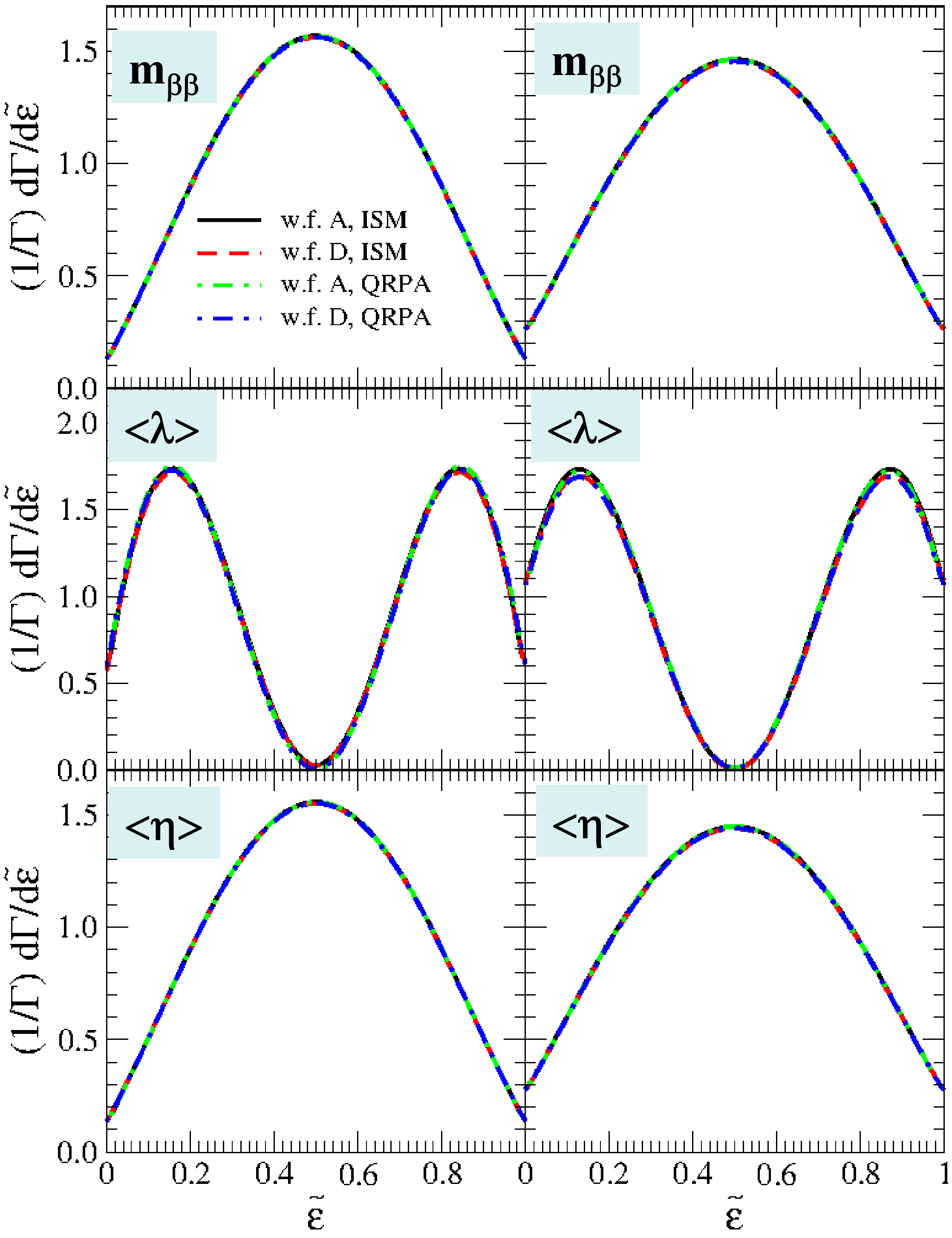
$$\approx \frac{m_D}{m_{LNV}} \frac{m_D}{m_e} \boxed{\sum_i (U_0)^2_{ei} \frac{m_i \, m_{LNV}}{m_D^2}}$$

if ≈ 1

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

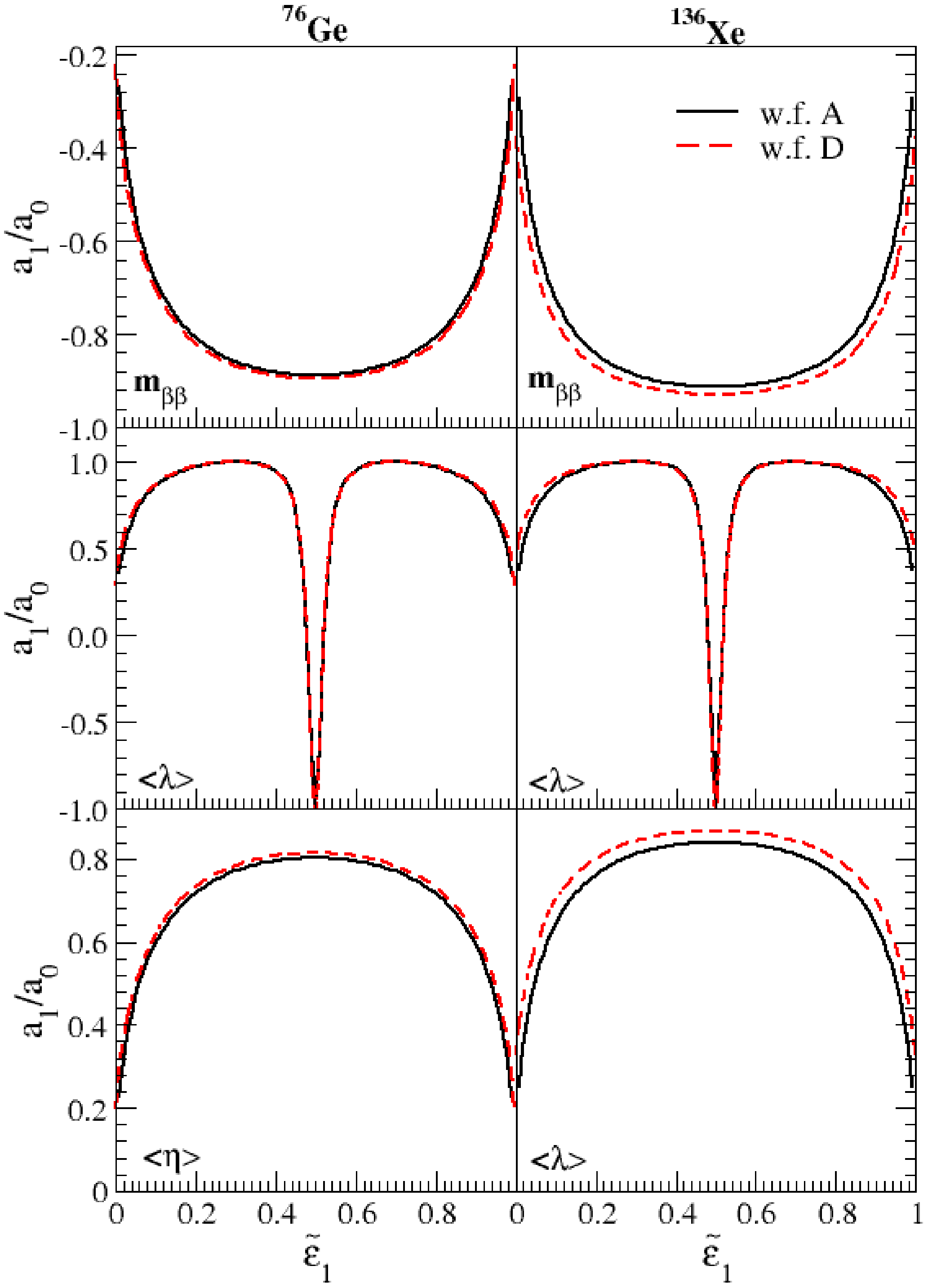


Dominance of $m_{\beta\beta}$ over <λ> mech., but might be also comparable



The single differential decay rate normalized to the total decay rate as function of electron energy for 3 limiting cases:

^{82}Se



Angular correlation factor as function of electron energy

$$\frac{d\Gamma}{d\cos\theta d\tilde{\varepsilon}_1} = a_0\left(1 + a_1/a_0\cos\theta\right)$$

SuperNEMO experiment could see it

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)

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

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

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

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

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

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 0νββ-decay
(light LH and heavy RH neutrino exchange)

Half-life:

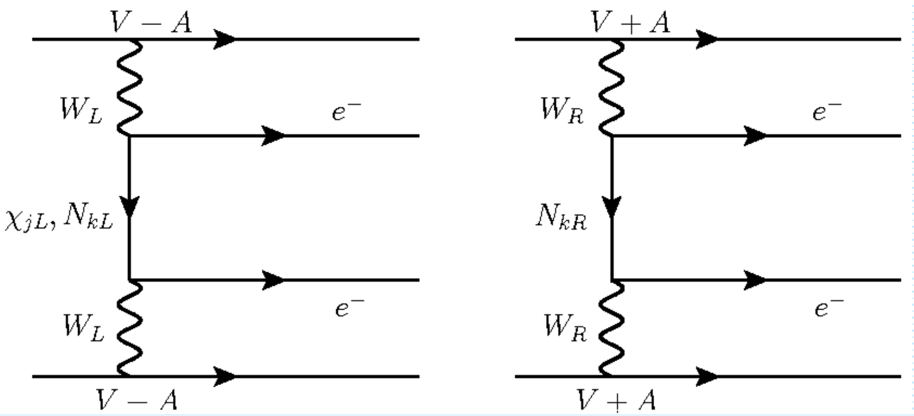
$$\frac{1}{T^{0\nu}_{1/2,i}\, G^{0\nu}_i(E,Z)} \cong |\eta_\nu|^2 |M'^{0\nu}_{i,\nu}|^2 + |\eta_R|^2 |M'^{0\nu}_{i,N}|^2$$

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

Set of equations:

$$\frac{1}{T_1 G_1} = |\eta_\nu|^2 |M'^{0\nu}_{1,\nu}|^2 + |\eta_R|^2 |M'^{0\nu}_{1,N}|^2$$

$$\frac{1}{T_2 G_2} = |\eta_\nu|^2 |M'^{0\nu}_{2,\nu}|^2 + |\eta_R|^2 |M'^{0\nu}_{2,N}|^2$$



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)

The positivity condition:

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

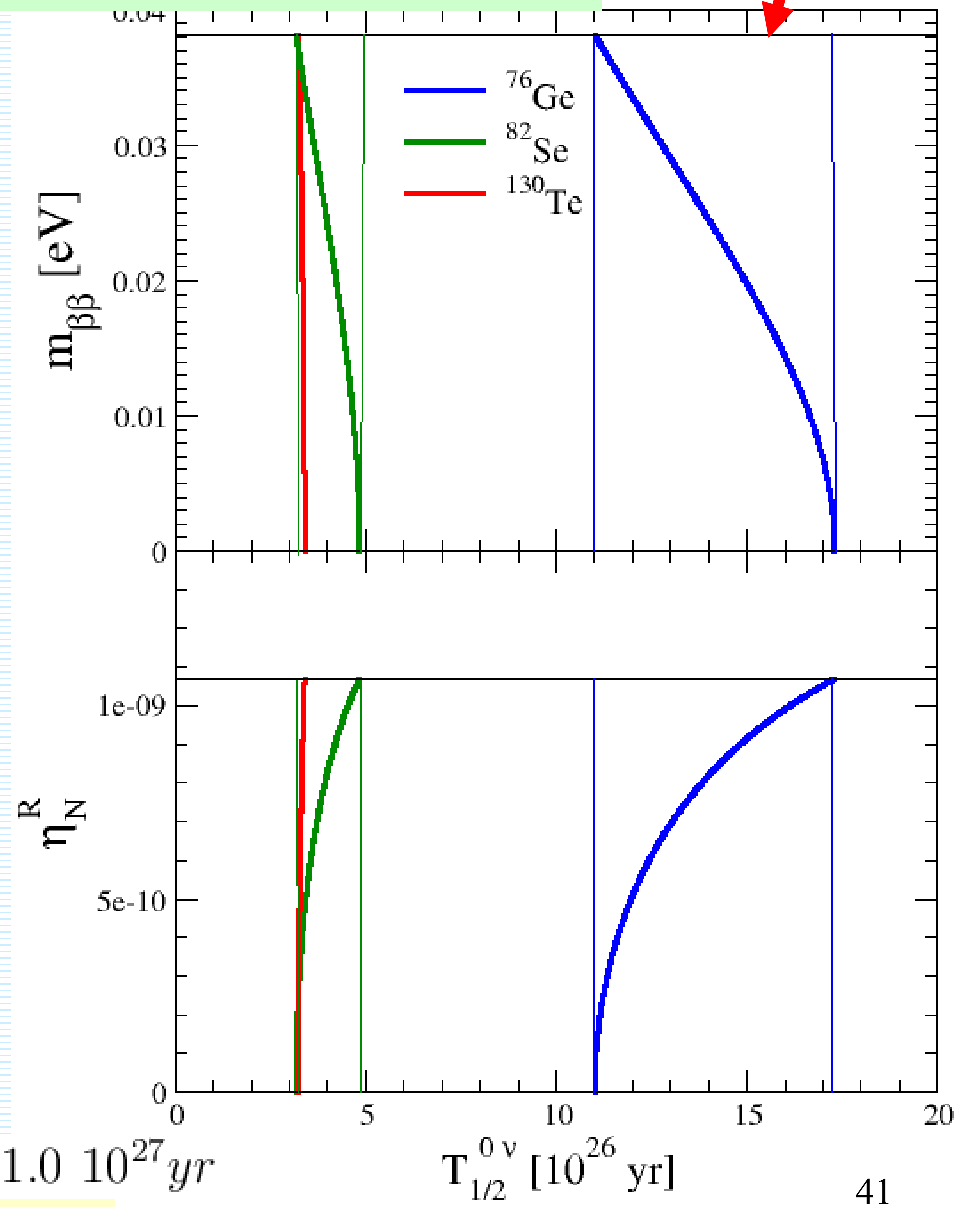
Very narrow ranges!

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

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

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

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



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

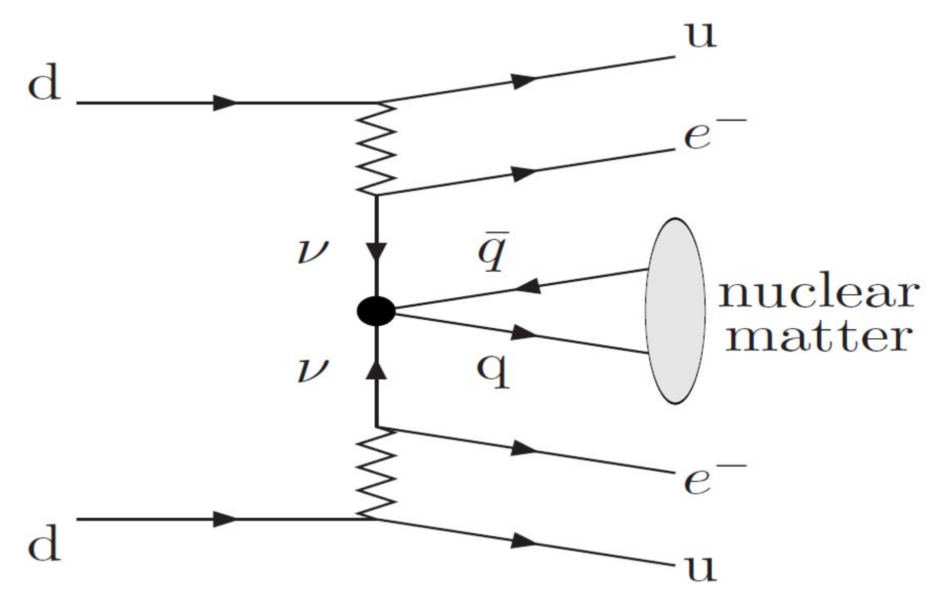
Assumption

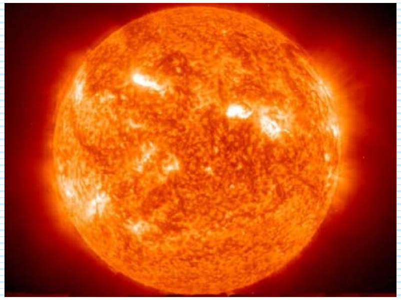
V. *Nuclear medium effect on the light neutrino mass exchange mechanism of the $0\nu\beta\beta$-decay*

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

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

+ Low energy 4-fermion $\Delta L \neq 0$ Lagrangian
+ In-medium Majorana mass of neutrino
+ $0\nu\beta\beta$ constraints on the universal scalar couplings

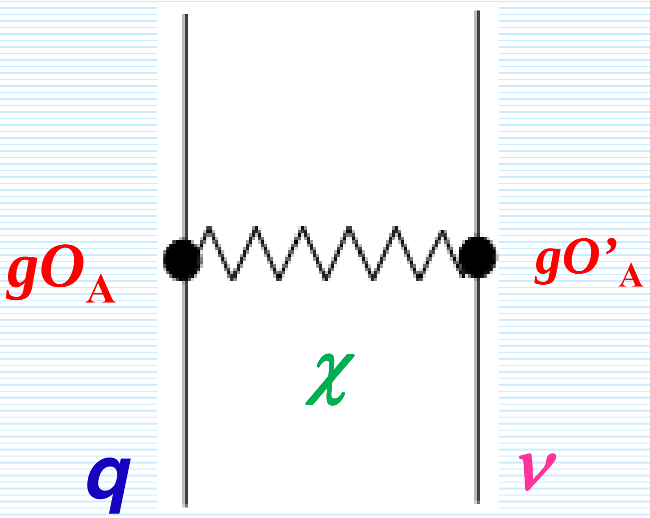




Non-standard ν–int. discussed e.g., in the context of ν–osc. at Sun

$\rho_{Sun} = 1.4$ 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
ΔL ≠ 0 Lagrangian

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

$$m_\chi \gtrsim M_W .$$

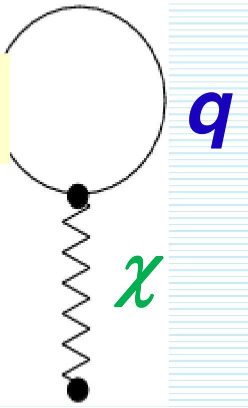
0νββ-decay

density →

oscillation experiments
tritium β-decay, cosmology

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

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



Classification of the vertices gO_A and gO'_A

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

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

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

A comparison with G_F:

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

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

We expect:

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

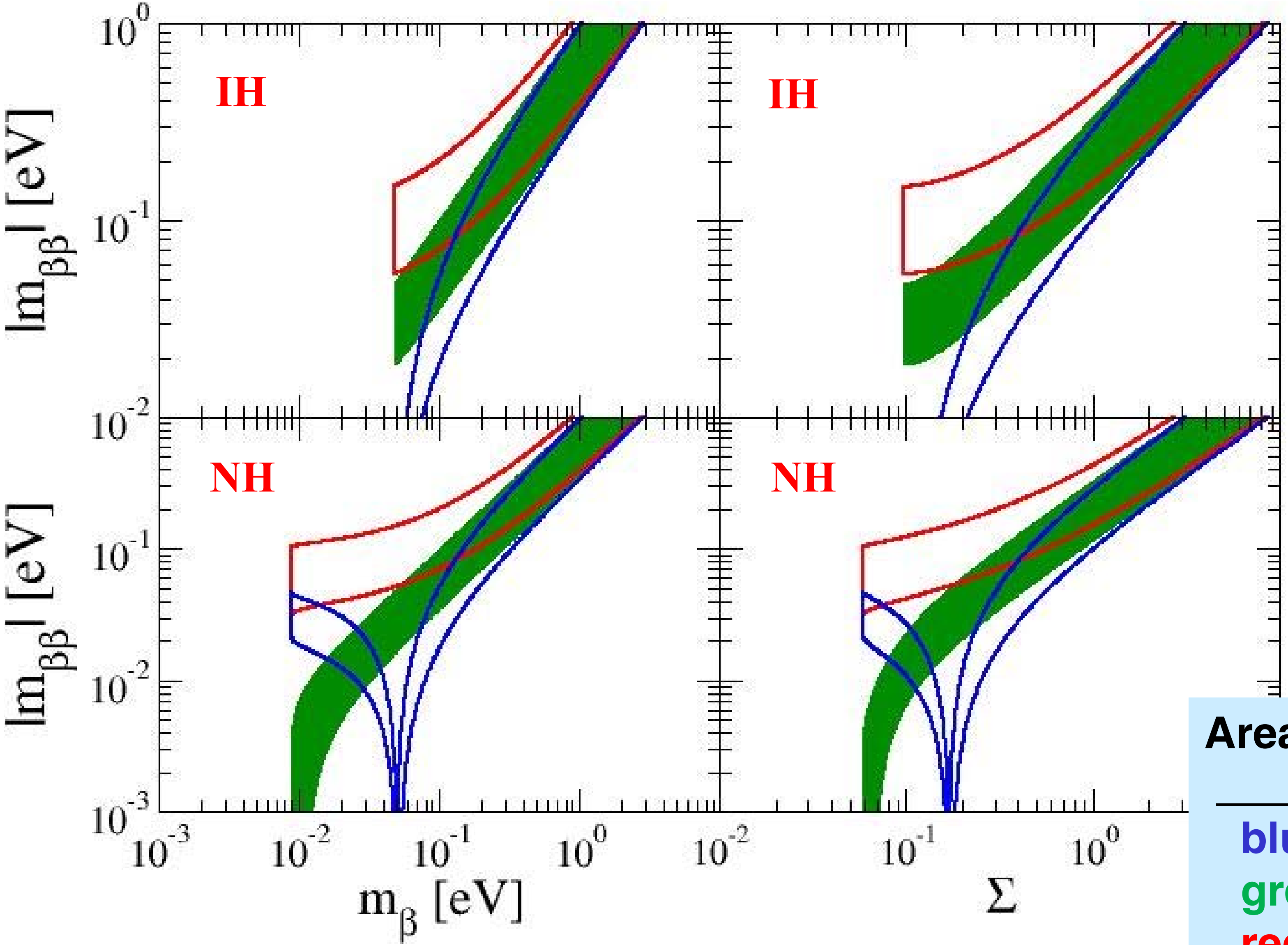
Universal scalar interaction

$$g_{ij}^a = \delta_{ij} g_a \quad \varepsilon_{ij}^a = \delta_{ij} \varepsilon_a$$

In medium effective Majorana ν mass

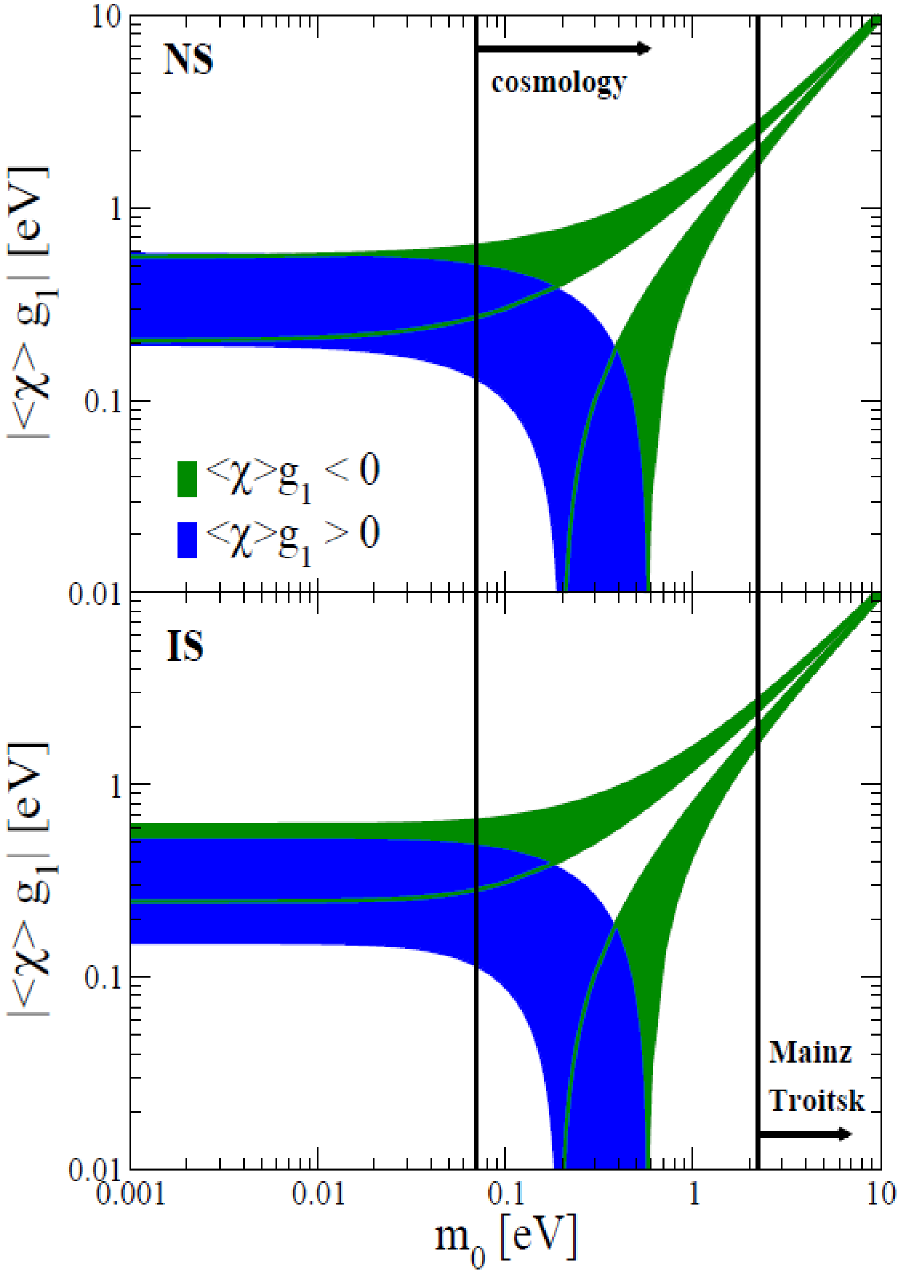
$$m_{\beta\beta} = \sum_{i=1}^{n} U_{ei}^2 \xi_i \frac{\sqrt{(m_i + \langle \chi \rangle g_1)^2 + (\langle \chi \rangle g_2)^2}}{(1 - \langle \chi \rangle g_4)^2}.$$

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



Area	$\langle\chi\rangle g_1$ [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($\pi^0 \rightarrow \nu\nu$) ≤ 2.7 10^{-7}

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

Resonant Neutrinoless Double-Electron Capture

$$(A,Z) \rightarrow (A,Z-2)^{**}$$

Additional modes of the 0νECEC-decay:

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

The 0νββ-decay is an atomic physics problem

Oscillations of atoms

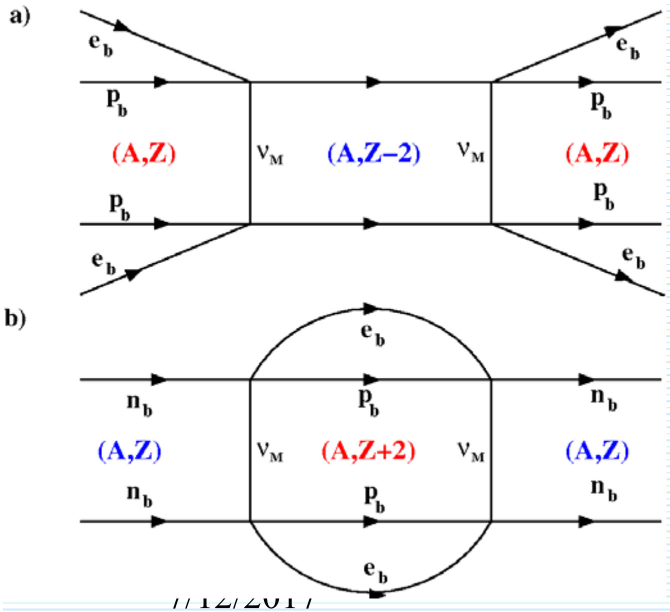
$$H^{atom}_{eff} = \begin{pmatrix} M_i & V^{LNV} \\ V^{LNV} & M_f - \frac{i}{2}\Gamma \end{pmatrix}$$

Oscillation of atoms
(lepton number violation)

F.Š., M. Krivoruchenko, Phys.Part.Nucl.Lett. 6 (2009) 485.

In analogy with oscillations of
n-anti{n} (baryon number violation)

$$H^{n\bar{n}}_{eff} = \begin{pmatrix} M & V^{BNV} \\ V^{BNV} & M - \frac{i}{2}\Gamma \end{pmatrix}$$



***Oscillations of stable atoms* (Γ=0)**

$$| < f|e^{-iH_{eff}t}|i > |^2 = \frac{4V^2}{(M_i - M_f)^2} \sin^2 [t\ (M_i - M_f)/2]$$

$$^{164}_{68}Er \rightarrow {}^{164}_{66}Dy$$

$$(M_i - M_f) = 24.1\ keV$$

$$| < f|e^{-iH_{eff}t}|i > |^2 \leq 3\ 10^{-55}$$

***Oscillations of unstable atoms* (Γ≠0)**

Double electron capture
(resonant enhancement)

Different types of Oscillations (Effective Hamiltonian)

$$H_{eff}^{K_0\overline{K_0}} = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \Gamma_{12} \\ M_{12}^* - \Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}$$

Oscillations of ν_l-$\nu_{l'}$
(lepton flavor)

Oscillation of K_0-anti$\{K_0\}$
(strangeness)

$$H_{eff}^{n\bar{n}} = \begin{pmatrix} M & V^{BNV} \\ V^{BNV} & M - \frac{i}{2}\Gamma \end{pmatrix}$$

Oscillation of n-anti{n}
(baryon number)

$$H_{eff}^{atom} = \begin{pmatrix} M_i & V^{LNV} \\ V^{LNV} & M_f - \frac{i}{2}\Gamma \end{pmatrix}$$

Oscillation of **Atoms** (OoA)
(total lepton number)

F.Š., M. Krivoruchenko, Phys.Part.Nucl.Lett. 6 (2009) 485.

Full width of unstable atom/nucleus

Eigenvalues

$$\begin{aligned} \lambda_+ &= M_i + \Delta M - \frac{i}{2}\Gamma_1, \\ \lambda_- &= M_f - \frac{i}{2}\Gamma - \Delta M + \frac{i}{2}\Gamma_1 \end{aligned}$$

$$\begin{aligned} \Delta M &= \frac{V^2(M_i - M_f)}{(M_i - M_f)^2 + \frac{1}{4}\Gamma^2}, \\ \Gamma_1 &= \frac{V^2\Gamma}{(M_i - M_f)^2 + \frac{1}{4}\Gamma^2}. \end{aligned}$$

A comparison

Resonance enhancement of neutrinoless double electron capture
M.I. Krivoruchenko, F. Š., D. Frekers, and A. Faessler,
Nucl. Phys. A 859, 140-171 (2011)

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

Perturbation theory

$$\frac{1}{T^{0\nu}_{1/2}} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 G^{01}(E_0,Z)\left|M^{0\nu}\right|^2$$

- $2\nu\beta\beta$-decay background can be a problem
- Uncertainty in NMEs factor ~2, 3
- $0^+ \rightarrow 0^+, 2^+$ transitions
- Large Q-value
- ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe …
- Many exp. in construction, potential for observation in the case of inverted hierarchy (2020)

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

Breit-Wigner form

$$\Gamma^{0\nu ECEC}(J^\pi) = \frac{|V_{\alpha\beta}(J^\pi)|^2}{(M_i - M_f)^2 + \Gamma^2_{\alpha\beta}/4}\,\Gamma_{\alpha\beta}$$

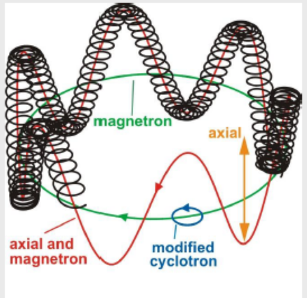
- $2\nu\varepsilon\varepsilon$-decay strongly suppressed
- NMEs need to be calculated
- $0^+ \rightarrow 0^+, 0^-, 1^+, 1^-$ transitions
- Small Q-value
- Q-value needs to be measured at least with 100 eV accuracy
- ^{152}Gd, looking for additional
- small experiments yet

Improved Q-value measurements
Klaus Blaum (MPI Heidelberg)

nucl. tr.	Q_{old}	$E = B + E_\gamma$	Orbit.	$\Delta = Q(old) - E$	Q_{new}	$\Delta = Q(new) - E$
$^{112}Sn \rightarrow ^{112}Cd$	1919.5(4.8)	1901.7	KL_1	17.8(4.8)	1919.82(16)	18.12(16)
		1924.4	KK	-4.9(4.8)		-4.56(16)
$^{152}Gd \rightarrow ^{152}Sm$	54.6(3.5)	54.79+0	KL_1	-0.19(3.50)	55.70(18)	0.91(18)
$^{164}Er \rightarrow ^{164}Dy$	23.3(3.9)	18.09	l_1L_1	5.21(3.90)		

^{152}Gd→^{152}Sm **(Eliseev, et al., F.Š, M. Krivoruchenko, PRL 106, 052504 (2011))**
(F.Š., Krivoruchenko, Faessler, PPNP 66, 446 (2011))

Penning Trap



ν_+ - modified cyclotron
ν_- - magnetron
ν_z - axial

$$\Gamma_{\varepsilon\varepsilon} = |V_{\varepsilon\varepsilon}|^2 \frac{\Gamma}{\Delta^2 + \Gamma^2/4} = |V_{\varepsilon\varepsilon}|^2 R$$

$$V_{\varepsilon\varepsilon} = m_{\beta\beta} \frac{\sqrt{2} g_A^2 G_\beta^2}{(4\pi)^2 R_{nucl}} \overline{f}_a \overline{f}_b M^{0\nu}$$

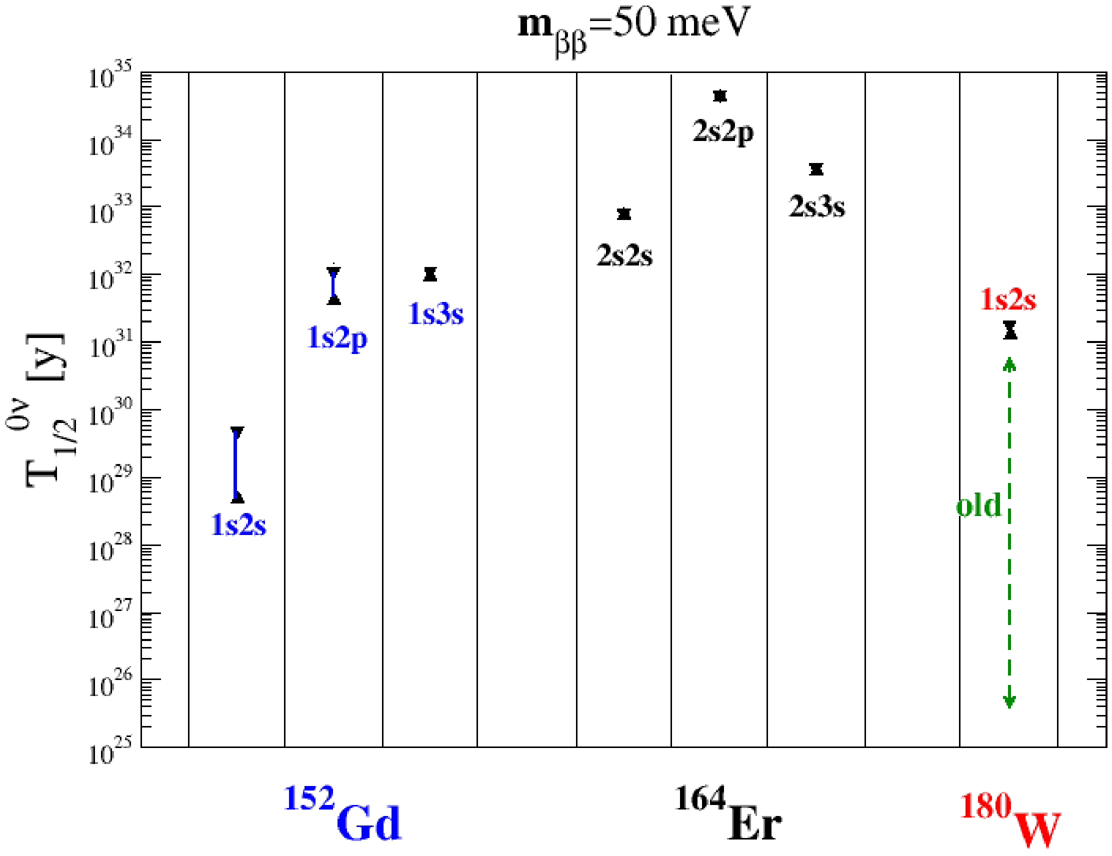
$$T_{1/2}^{0\nu} = 4 \times 10^{26} \left(\frac{1 \text{ eV}}{m_{\beta\beta}} \right)^2 \text{ years.}$$

Remeasured Q-value: **^{112}Sn, ^{74}Se, ^{136}Ce, ^{96}Ru, ^{152}Gd, ^{162}Er, ^{168}Yb, ^{106}Cd, ^{156}Dy, ^{180}W, ^{124}Xe, ^{130}Ba, ^{184}Os, ^{190}Pt**

$0\nu\varepsilon\varepsilon$
half-lives

$m_{\beta\beta}=50\,meV$

Ground state to ground state nuclear transitions



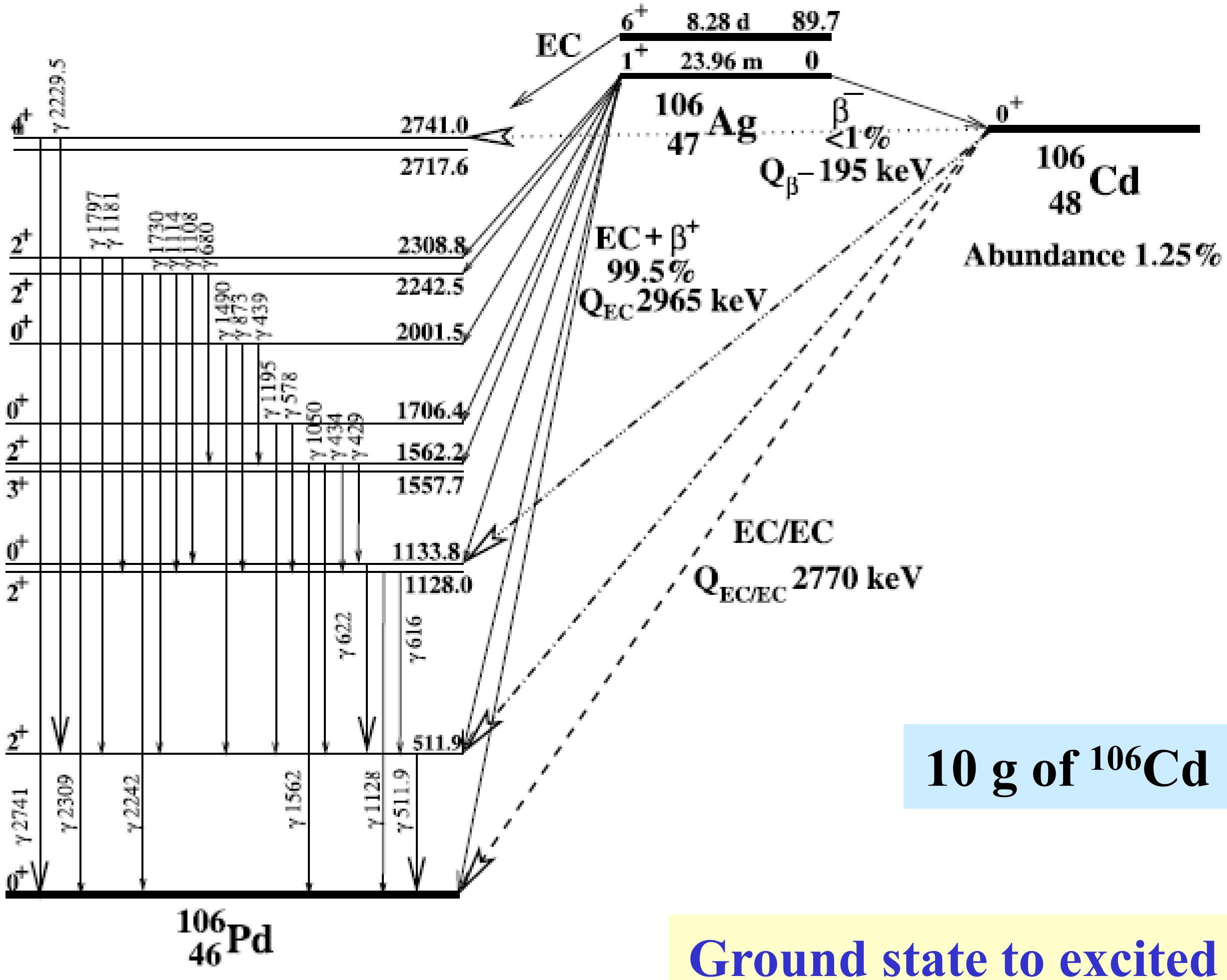
Nucleus	$(n2jl)_a$	$(n2jl)_b$	E_a	E_b	E_C	Γ_{ab} (keV)	Δ (keV)	$T^{\rm min}_{1/2}$ (y)	$T^{\rm max}_{1/2}$ (y)
^{152}Gd	110	210	46.83	7.74	0.34	2.3×10^{-2}	-0.83 ± 0.18	4.7×10^{28}	4.8×10^{29}
	110	211	46.83	7.31	0.32	2.3×10^{-2}	-1.27 ± 0.18	4.2×10^{31}	1.1×10^{32}
	110	310	46.83	1.72	0.11	3.2×10^{-2}	-7.07 ± 0.18	9.4×10^{31}	1.1×10^{32}
^{164}Er	210	210	9.05	9.05	0.22	8.6×10^{-3}	-6.82 ± 0.12	7.5×10^{32}	8.4×10^{32}
	210	211	9.05	8.58	0.23	8.3×10^{-3}	-7.28 ± 0.12	4.2×10^{34}	4.6×10^{34}
	210	310	9.05	2.05	0.11	1.8×10^{-2}	-13.92 ± 0.12	3.5×10^{33}	3.9×10^{33}
^{180}W	110	110	63.35	63.35	1.26	7.2×10^{-2}	-11.24 ± 0.27	1.3×10^{31}	1.8×10^{31}

0νεε experiments in Modane and Grand Sasso

New level

2737 keV

(J^{π}=?)



10 g of ^{106}Cd

TGV Coll.,
Rukhadze et al.,
NPA 852, 197 (2011)

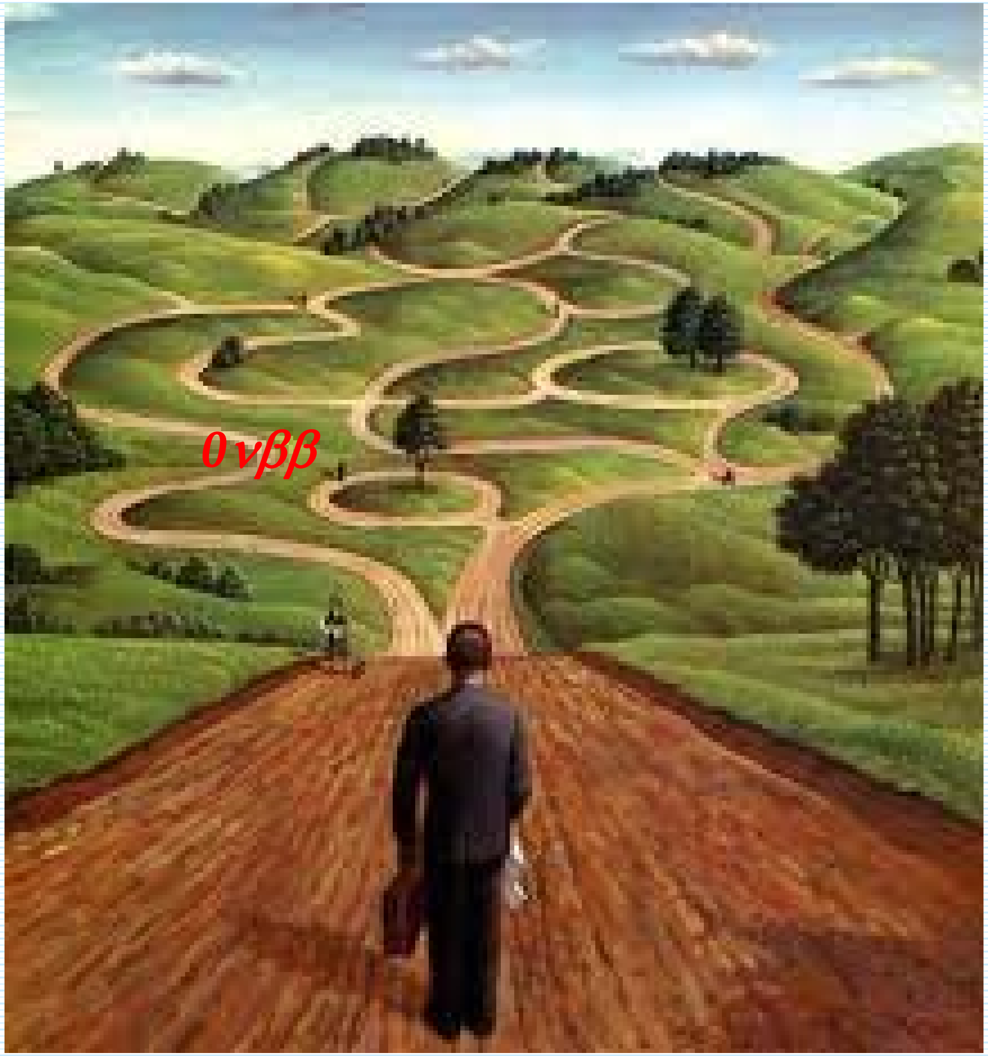
$T_{1/2}^{2\nu\varepsilon\varepsilon}$ (^{106}Cd) > 3.6 10^{20} y

$T_{1/2}^{0\nu\varepsilon\varepsilon}$ (^{106}Cd) > 1.1 10^{20} y

Ground state to excited 0^+ state nuclear transitions are strongly suppressed…

Kotila, Barea, Iachello, accepted in PRC

Instead of Conclusions



We are at the beginning of the BSM Road…

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Introduction to ν-physics
Theory of ν-masses and mixing
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
ν-astronomy
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Neutrino physics at CERN
Future colliders
Statistics for Nucl. and Particle Phys.

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