

# Multiple mechanisms in $\beta\beta0\nu$ -Decay

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Rencontres de Moriond EW 2012

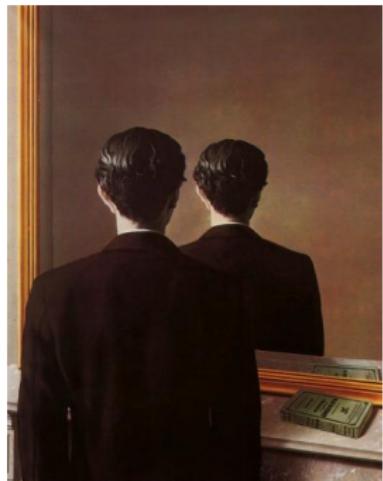


Based on Phys. Rev. D 83, 113003, 2011  
A. Faessler, A. M., S.T. Petcov, F. Simkovic, J. Vergados

$$\beta\beta0\nu : (A, Z) \rightarrow (A, Z + 2) + 2e^-$$

- Process forbidden in the SM
- Possible only if neutrinos are Majorana type
- Lepton number not conserved  $\Delta L = \pm 2$
- Second order in weak coupling constant of the SM
- Standard  $\beta\beta0\nu$ -decay amplitude is function of the effective Majorana mass parameter

$$|\langle m \rangle| = \sum_j^{light} (U_{ej}^{PMNS})^2 m_j, \quad m_j < 1\text{eV}$$

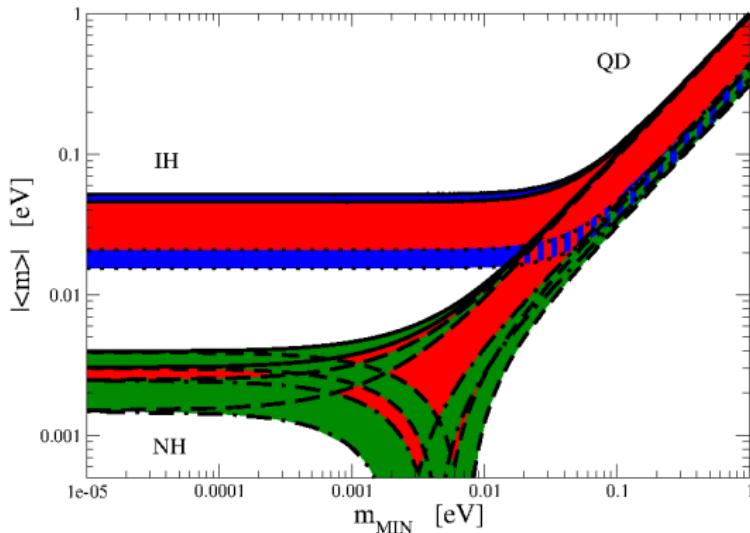


René Magritte, *Portrait of Edward James*.

## $\beta\beta0\nu$ Decay: effective mass

$$|\langle m \rangle| = |(U_{e1}^{PMNS})^2 m_1 + (U_{e2}^{PMNS})^2 m_2 + (U_{e3}^{PMNS})^2 m_3|, \text{ (all light } m_j \geq 0\text{)} ,$$

Figure: arXiv:0711.4993



$|\langle m \rangle|$  (including a prospective  $2\sigma$  uncertainty) as a function of  $m_{MIN}$  for  $\sin^2\theta_{13} = 0.01$ .  
NH Spectrum:  $(e^{\alpha_{21}}, e^{\alpha_{31}})$ :  $(+1,+1)$  solid,  $(-1,-1)$  short-dashed,  $(+1,-1)$  long-dashed, and  $(-1,+1)$  dash-dotted lines. IH spectrum (dotted) lines correspond to  $e^{\alpha_{21}} = +1$  ( $e^{\alpha_{21}} = -1$ )  
The regions shown in red correspond to **violation of CP-symmetry**.

If  $\beta\beta0\nu$  decay will be **observed**, the question will inevitably arise:

**Which mechanism is triggering the decay?**  
**How many mechanisms are involved?**

A number of different mechanisms is possible:

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}(E, Z) \left| \sum_i \eta_i^{LNV} M_i^{0\nu} \right|^2$$

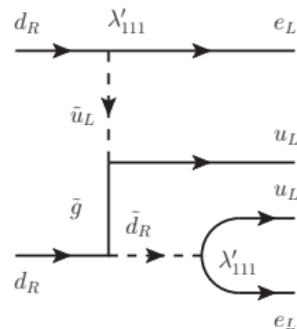
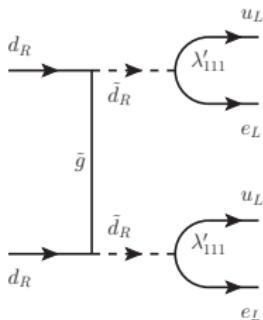
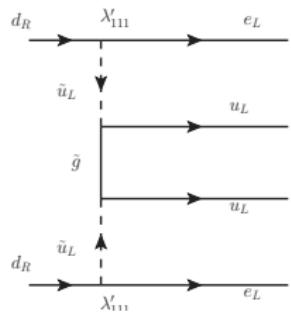
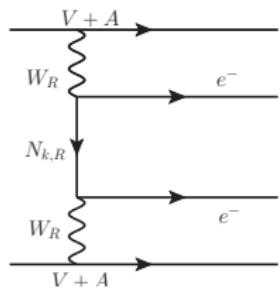
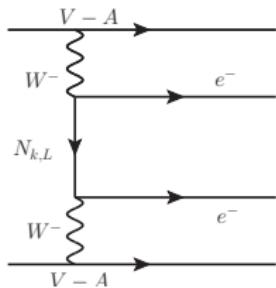
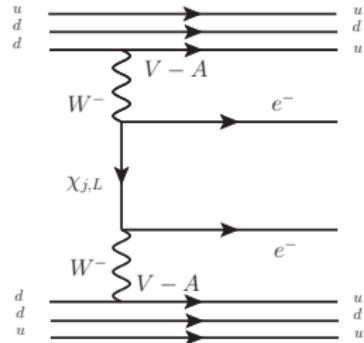
These mechanisms might trigger  $\beta\beta0\nu$ -decay **individually or together and can interfere or not.**

- $\eta_i^{LNV}$  is the fundamental LNV parameter characterizing the mechanism *i*.  $\eta_i^{LNV}$  can be **real or complex** → CPV.
- $G^{0\nu}(E, Z)$  is the phase space factor
- $M_i^{0\nu}$  is the nuclear matrix element (NME)

$\beta\beta0\nu$  decay is allowed by a number of different models: Left-Right Symmetry, R parity violating SUSY...

# Possible Mechanisms

Standard, Heavy Neutrino exchange, SUSY particles...



# Multiple mechanisms: Two **Not** interfering mechanisms Analysis

**Example.** We assume light LH and heavy RH Majorana neutrino exchanges  $\rightarrow$  LNV fundamental parameters  $|\eta_\nu|$  and  $|\eta_R|$

$$\begin{cases} \frac{1}{T_1 G_1} = |\eta_\nu|^2 |M'^{0\nu}_{1,\nu}|^2 + |\eta_R|^2 |M'^{0\nu}_{1,N}|^2, \\ \frac{1}{T_2 G_2} = |\eta_\nu|^2 |M'^{0\nu}_{2,\nu}|^2 + |\eta_R|^2 |M'^{0\nu}_{2,N}|^2 \end{cases}$$

$|\eta_\nu|^2, |\eta_R|^2 > 0$  ( $A_1 < A_2$ ) only if:

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

Positivity Conditions:

$$|\eta_\nu|^2 > 0$$

$$|\eta_R|^2 > 0$$

If one of the two solutions is zero then **only one mechanism is active**.

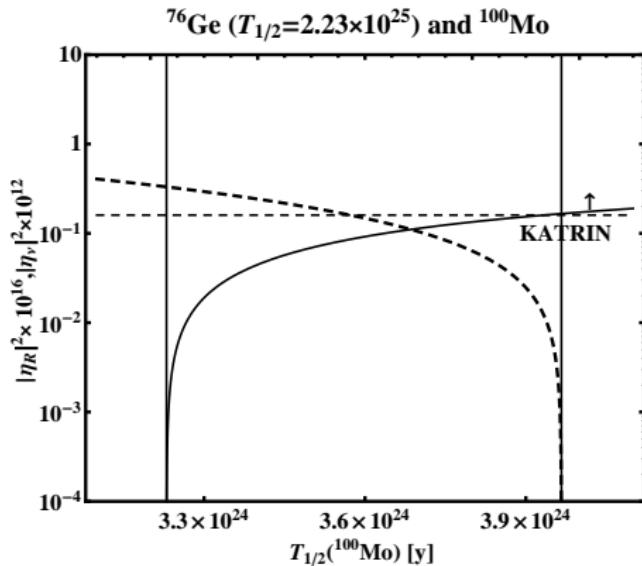
Using the values "CD-Bonn, large,  $g_A = 1.25$ ", we get the positivity conditions:

$$0.15 \leq \frac{T_{1/2}^{0\nu}({}^{100}\text{Mo})}{T_{1/2}^{0\nu}({}^{76}\text{Ge})} \leq 0.18, 0.17 \leq \frac{T_{1/2}^{0\nu}({}^{130}\text{Te})}{T_{1/2}^{0\nu}({}^{76}\text{Ge})} \leq 0.22, 1.14 \leq \frac{T_{1/2}^{0\nu}({}^{130}\text{Te})}{T_{1/2}^{0\nu}({}^{100}\text{Mo})} \leq 1.24$$

**Very narrow intervals!**

# Two not interfering mechanisms

## Results



The values of the rescaled parameters  $|\eta_\nu|^2$  (solid line) and  $|\eta_R|^2$  (dashed line), for  $T_{1/2}^{0\nu}(^{76}\text{Ge})$  and  $T_{1/2}^{0\nu}(^{100}\text{Mo})$  lying in a specific interval. The physical (positive) solutions are delimited by the two vertical lines. The horizontal dashed line corresponds to the prospective upper limit from the upcoming  $^3H$   $\beta$ -decay experiment KATRIN.

## Two not interfering mechanisms- Conclusion

Phys. Rev. D 83, 113003, 2011 - A. Faessler, A. M., S.T. Petcov, F. Simkovic, J. Vergados

- All cases of **two non-interfering mechanisms** have the same features.
- The indicated specific half-life intervals for the various isotopes, are **stable** with respect to the change of the NMEs (Argonne or CD- Bonn Potentials and  $g_A = 1, 1.25$ ).
- The intervals of  $T_2/T_1$  depend on the type of the two non-interfering mechanisms. However, the differences in the cases of the exchange of heavy Majorana neutrinos coupled to (V+A) currents and i) light Majorana neutrino exchange, or ii) the gluino exchange mechanism, are extremely small for the isotopes considered.
- **if it will be possible to rule out one of these mechanisms as the cause of  $\beta\beta0\nu$  decay, most likely one will be able to rule out all three of them (the NMEs are too similar).**
- We need extremely high precision measurement of the  $\beta\beta0\nu$  decay half-lives of the isotopes considered but this seem **impossible to achieve in the near future**.
- If taking into account all relevant uncertainties, experimental data lie outside the interval of physical solutions  $\Rightarrow \beta\beta0\nu$  decay is not generated by the two mechanisms considered.
- This is not valid if the two mechanisms are **interfering**.

Thank you

# Back up slides

# Multiple mechanisms

NMEs

Nuclear transition	$G^{0\nu}(E_0, Z)$ [ $y^{-1}$ ]	$ M'^{0\nu}_\nu $		$ M'^{0\nu}_N $		$ M'^{0\nu}_{\lambda'} $		$ M'^{0\nu}_{\tilde{q}} $	
		NN pot.	m.s.	$\frac{g_A}{1.0} =$	$\frac{g_A}{1.25} =$	$\frac{g_A}{1.0} =$	$\frac{g_A}{1.25} =$	$\frac{g_A}{1.0} =$	$\frac{g_A}{1.25} =$
$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$	$7.98 \cdot 10^{-15}$	Argonne	intm.	3.85	4.75	172.2	232.8	387.3	587.2
			large	4.39	5.44	196.4	264.9	461.1	699.6
		CD-Bonn	intm.	4.15	5.11	269.4	351.1	339.7	514.6
			large	4.69	5.82	317.3	411.5	392.8	595.6
$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$	$3.53 \cdot 10^{-14}$	Argonne	intm.	3.59	4.54	164.8	225.7	374.5	574.2
			large	4.18	5.29	193.1	262.9	454.9	697.7
		CD-Bonn	intm.	3.86	4.88	258.7	340.4	328.7	503.7
			large	4.48	5.66	312.4	408.4	388.0	594.4
$^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$	$5.73 \cdot 10^{-14}$	Argonne	intm.	3.62	4.39	184.9	249.8	412.0	629.4
			large	3.91	4.79	191.8	259.8	450.4	690.3
		CD-Bonn	intm.	3.96	4.81	298.6	388.4	356.3	543.7
			large	4.20	5.15	310.5	404.3	384.4	588.6
$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$	$5.54 \cdot 10^{-14}$	Argonne	intm.	3.29	4.16	171.6	234.1	385.1	595.2
			large	3.34	4.18	176.5	239.7	405.5	626.0
		CD-Bonn	intm.	3.64	4.62	276.8	364.3	335.8	518.8
			large	3.74	4.70	293.8	384.5	350.1	540.3

The NMEs were obtained within the Self-consistent Renormalized Quasiparticle Random Phase Approximation (SRQRPA). From Faessler, Simkovic

# Multiple mechanisms

## Numerical constraints and NMEs

The NMEs were obtained within the Self-consistent Renormalized Quasiparticle Random Phase Approximation (SRQRPA). From Faessler, Simkovic

Important feature of the NMEs considered: they differ relatively little!:

$$|M_{i\kappa} - M_{j\kappa}| \ll M_{i\kappa}, M_{j\kappa}$$

$$|M_{i\kappa} - M_{j,\kappa}| / (0.5(M_{i\kappa} + M_{j,\kappa})) \sim 0.1 \quad i \neq j = {}^{76}\text{Ge}, {}^{82}\text{Se}, {}^{100}\text{Mo}, {}^{130}\text{Te}$$

### $\beta\beta0\nu$ Decay Experiments: Constraints on isotopes half-lives:

- $T_{1/2}^{0\nu}({}^{76}\text{Ge}) = 2.23^{+0.44}_{-0.31} \times 10^{25}\text{y}$  H. V. Klapdor-Kleingrothaus and I. V. Krivosheina, Mod. Phys. Lett. A **21** (2006) 1547
- $T_{1/2}^{0\nu}({}^{76}\text{Ge}) \geq 1.9 \times 10^{25}\text{y}$  L. Baudis *et al.*, Phys. Rev. Lett. **83** (1999) 41
- $T_{1/2}^{0\nu}({}^{100}\text{Mo}) \geq 5.8 \times 10^{23}\text{y}$  [NEMO Collaboration], arXiv:0807.2336 [nucl-ex].
- $T_{1/2}^{0\nu}({}^{130}\text{Te}) \geq 3.0 \times 10^{24}\text{y}$  [CUORICINO Collaboration], Phys. Rev. C **78**, 035502 (2008).

### From Tritium $\beta$ decay:

- Troitzk and Mainz experiments  $\Rightarrow |<m>| < 2.3$  eV at 95% C.L.
- **KATRIN** experiment  $\Leftrightarrow$  sensitivity of  $|<m>| \simeq 0.20$  eV,  $\Rightarrow$  it will probe the region of the QD spectrum.

# Light Majorana neutrino exchange

$\beta\beta0\nu$ -Decay contribution comes from the standard  $\mathcal{L}^{CC}(V - A)$  weak interaction.  
The LNV parameter is given by:

$$\eta_\nu = \frac{\langle m \rangle}{m_e}, \quad \langle m \rangle = \sum_j^{\text{light}} (U_{ej}^{\text{PMNS}})^2 m_j, \quad (\text{all light } m_j \geq 0),$$

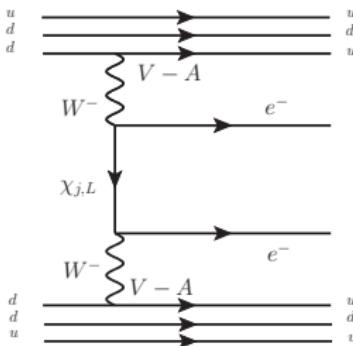
$U$  is **CP-violating**, in general:  $(U_{ej})^2 = |U_{ej}|^2 e^{i\alpha_j}$ ,  $j = 1, 2, 3$ ,  $\alpha_{21}$ ,  $\alpha_{31}$  - **Majorana CPV phases**.

Using  $-\nu_k^T C^\dagger = \overline{\nu_k^c} = \xi_k \nu_k$  and  $C^{-1} \gamma_\alpha C = -\gamma_\alpha^T$  and  
 $\nu_{eL} = \sum_j^{\text{light}} U_{ej} \nu_{jL}$  one may write:

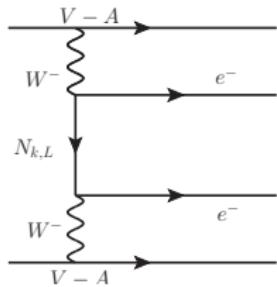
$$Tr[(\bar{e}_L \gamma_\alpha \nu_{eL})(\bar{e}_L \gamma_\beta \nu_{eL})] \Rightarrow \\ - \sum_k \xi_k (U_{ek})^2 \bar{e} \gamma_\alpha P_L(-i) \frac{\int e^{iq(x_1 - x_2)} (q + m_k) dq}{q^2 - m_k^2} P_L \gamma_\beta C \bar{e}^T$$

**Only the  $(U_{ek})^2 m_k$  term survives!**  
 Notice the leptonic chiral structure in the final amplitude **S+PS**:

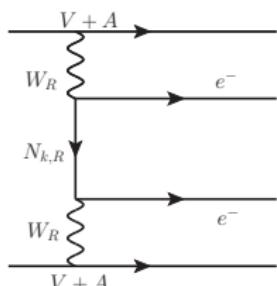
$$\mathcal{M} \propto \langle m \rangle [\bar{e}(1 + \gamma_5)e^c] A_{\alpha\beta}^{h.\text{current}}$$



# Heavy Majorana neutrino exchange: $M_k \gtrsim 10$ GeV



$$\eta_N^L [\bar{e}(1 + \gamma_5)e^c]$$



$$\eta_N^R [\bar{e}(1 - \gamma_5)e^c]$$

- **$V-A$  coupling:** The LNV parameter due to the exchange of LH  $N_k$ , is:

$$\eta_N^L = \sum_k^{heavy} U_{ek}^2 \frac{m_p}{M_k},$$

$m_p$  = proton mass,  $U_{ek}$  is the mixing matrix due to  $V-A$  coupling.

- **$V+A$  coupling:**  $\mathcal{L}_{weak} \supset (\bar{e}\gamma_\alpha(1 + \gamma_5)\nu_{eR})W_{\mu R}^-$  where  $\nu_{eR} = \sum_k V_{ek} N_{kR}$ ,  $C\bar{N}_k^T = \xi N_k$ . The LNV parameter is:

$$\eta_N^R = \left(\frac{M_W}{M_{WR}}\right)^4 \sum_k^{heavy} V_{ek}^2 \frac{m_p}{M_k}. \quad M_{W_R} \gtrsim 2.5 \text{ TeV}.$$

Here  $V_{ek}$  is the mixing matrix by which  $N_k$  couple to the electron in the  $(V+A)$  charged lepton current.

# SUSY with $\mathcal{R}_p$ : gluino exchange mechanism

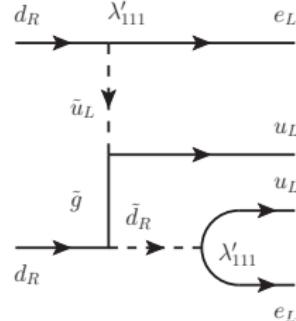
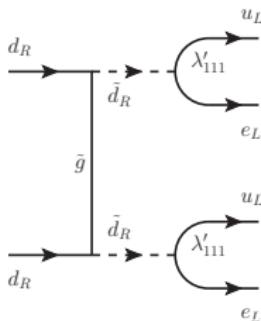
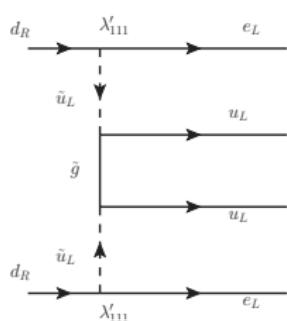
SUSY +  $\mathcal{R}_p$ : The LNV couplings emerge in SUSY models from the **R-parity breaking part of the superpotential**:

$$W_{\mathcal{R}_p} \sim \lambda'_{ijk} L_i Q_j D_k^c$$

Assuming the **dominance of the gluino exchange** the LNV parameter is:

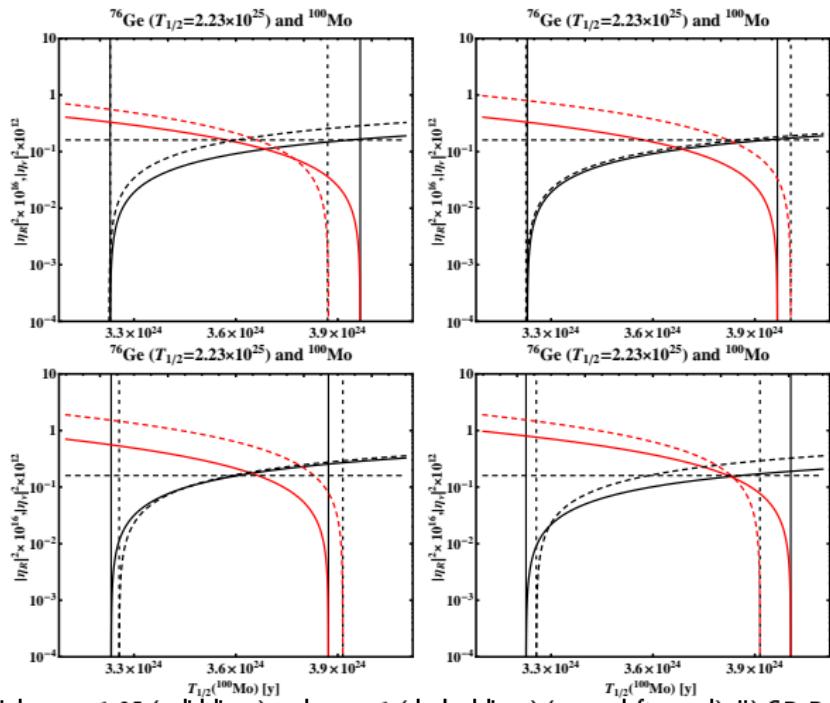
$$\eta_{\lambda'} = \frac{\pi \alpha_s}{6} \frac{\lambda'^2_{111}}{G_F^2 m_{\tilde{d}_R}^4} \frac{m_p}{m_{\tilde{g}}} \left[ 1 + \left( \frac{m_{\tilde{d}_R}}{m_{\tilde{u}_L}} \right)^2 \right]^2, \quad \alpha_s = \frac{g_3^2}{4\pi}$$

**Same Chiral structure** of the "standard" light  $\nu$  mechanism. hep-ph/9502385



# Two not interfering mechanisms

## Results



i) CD-Bonn potential,  $g_A = 1.25$  (solid lines) and  $g_A = 1$  (dashed lines) (upper left panel); ii) CD-Bonn (solid lines) and Argonne (dashed lines) potentials with  $g_A = 1.25$  (upper right panel); iii) CD-Bonn (solid lines) and Argonne (dashed lines) potentials with  $g_A = 1.0$  (lower left panel); iv) Argonne potential with  $g_A = 1.25$  (solid lines) and  $g_A = 1$  (dashed lines) (lower right panel).

# Multiple mechanisms: Interfering mechanisms

**Example:** light Majorana neutrino and gluino exchange mechanisms

$$[T_{1/2,i}^{0\nu} G_i^{0\nu}(E, Z)]^{-1} = |\eta_\nu|^2 (M'^{0\nu}_{i,\nu})^2 + |\eta_{\lambda'}|^2 (M'^{0\nu}_{i,\lambda'})^2 + 2 \cos \alpha M'^{0\nu}_{i,\lambda'} M'^{0\nu}_{i,\nu} |\eta_\nu| |\eta_{\lambda'}|.$$

$$|\eta_\nu|^2 = \frac{D_1}{D}, \quad |\eta_{\lambda'}|^2 = \frac{D_2}{D}, \quad z \equiv 2 \cos \alpha |\eta_\nu| |\eta_{\lambda'}| = \frac{D_3}{D},$$

$$D = \begin{vmatrix} (M'^{0\nu}_{1,\nu})^2 & (M'^{0\nu}_{1,\lambda'})^2 & M'^{0\nu}_{1,\lambda'} M'^{0\nu}_{1,\nu} \\ (M'^{0\nu}_{2,\nu})^2 & (M'^{0\nu}_{2,\lambda'})^2 & M'^{0\nu}_{2,\lambda'} M'^{0\nu}_{2,\nu} \\ (M'^{0\nu}_{3,\nu})^2 & (M'^{0\nu}_{3,\lambda'})^2 & M'^{0\nu}_{3,\lambda'} M'^{0\nu}_{3,\nu} \end{vmatrix}, \quad D_1 = \begin{vmatrix} 1/T_1 G_1 & (M'^{0\nu}_{1,\lambda'})^2 & M'^{0\nu}_{1,\lambda'} M'^{0\nu}_{1,\nu} \\ 1/T_2 G_2 & (M'^{0\nu}_{2,\lambda'})^2 & M'^{0\nu}_{2,\lambda'} M'^{0\nu}_{2,\nu} \\ 1/T_3 G_3 & (M'^{0\nu}_{3,\lambda'})^2 & M'^{0\nu}_{3,\lambda'} M'^{0\nu}_{3,\nu} \end{vmatrix}$$

$$D_2 = \begin{vmatrix} (M'^{0\nu}_{1,\nu})^2 & 1/T_1 G_1 & M'^{0\nu}_{1,\lambda'} M'^{0\nu}_{1,\nu} \\ (M'^{0\nu}_{2,\nu})^2 & 1/T_2 G_2 & M'^{0\nu}_{2,\lambda'} M'^{0\nu}_{2,\nu} \\ (M'^{0\nu}_{3,\nu})^2 & 1/T_3 G_3 & M'^{0\nu}_{3,\lambda'} M'^{0\nu}_{3,\nu} \end{vmatrix}, \quad D_3 = \begin{vmatrix} (M'^{0\nu}_{1,\nu})^2 & (M'^{0\nu}_{1,\lambda'})^2 & 1/T_1 G_1 \\ (M'^{0\nu}_{2,\nu})^2 & (M'^{0\nu}_{2,\lambda'})^2 & 1/T_2 G_2 \\ (M'^{0\nu}_{3,\nu})^2 & (M'^{0\nu}_{3,\lambda'})^2 & 1/T_3 G_3 \end{vmatrix}.$$

Positivity conditions:

$$|\eta_\nu|^2 > 0 \quad |\eta_{\lambda'}|^2 > 0$$

$$-2|\eta_\nu| |\eta_{\lambda'}| \leq 2 \cos \alpha |\eta_\nu| |\eta_{\lambda'}| \leq 2|\eta_\nu| |\eta_{\lambda'}|.$$

# Multiple mechanisms: two interfering mechanisms

## Results

**Comment:** in most of the cases analyzed destructive interference was found.

$|\eta_\nu|^2 \times 10^{10}$  (thick line),  $|\eta_{\lambda'}|^2 \times 10^{14}$  (dashed line) and  $z = 2 \cos \alpha |\eta_\nu| |\eta_{\lambda'}| \times 10^{12}$  (dot-dashed line).

