A sterile neutrino signal in the neutrinoless double beta decay?

Jacobo López-Pavón

SISSA

Nufact 13

IHEP, Beijing (China), August 19-24, 2013

Based on:

Blennow, Fernández-Martinez, JLP, Menéndez

ArXiv:1005.3240 (JHEP 1007 (2010) 096)

JLP, Pascoli and Wong

ArXiv:1209.5342 (PRD 87, 093007 (2013))

Very Brief Motivation

- The recent LHC results seem to indicate that the Higgs mechanism, with $m_H \sim 125$ GeV, is the responsible of the mass generation of the SM particles.

ATLAS, CMS 2012

- However, the origin of light neutrino masses, which existence is supported by neutrino oscillation experiments, still remains unknown.

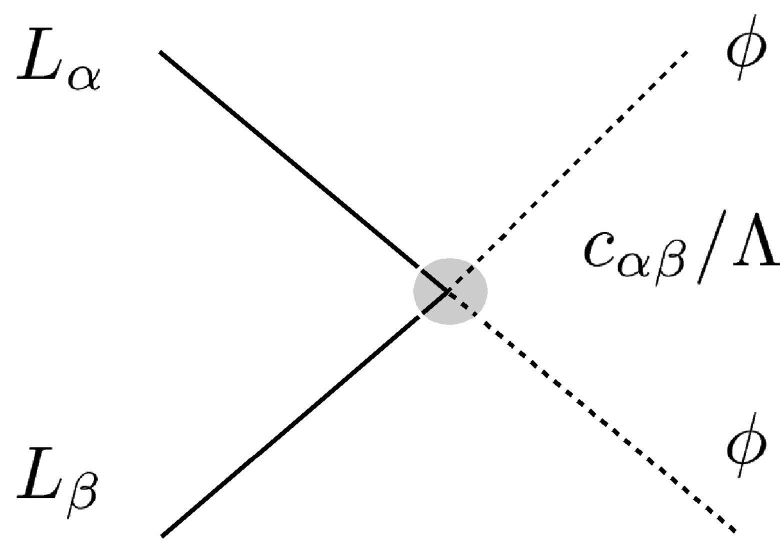
- Although the light neutrino masses could also be generated through the Higgs mechanism, their smallness in comparison with the SM particles calls for a more natural explanation.

Very Brief Motivation

- Consider SM as a low energy effective theory. With the SM field content, the lowest dimension effective operator is the following (d=5):

$$\frac{c_{\alpha\beta}}{\Lambda}\left(\overline{L^c}_{\alpha}\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger L_\beta\right) \xrightarrow[\text{SSB}]{} \frac{cv^2}{\Lambda}\overline{\nu^c_\alpha}\nu_\alpha$$

Weinberg 76



☺ Smallnes of neutrino masses can be explained

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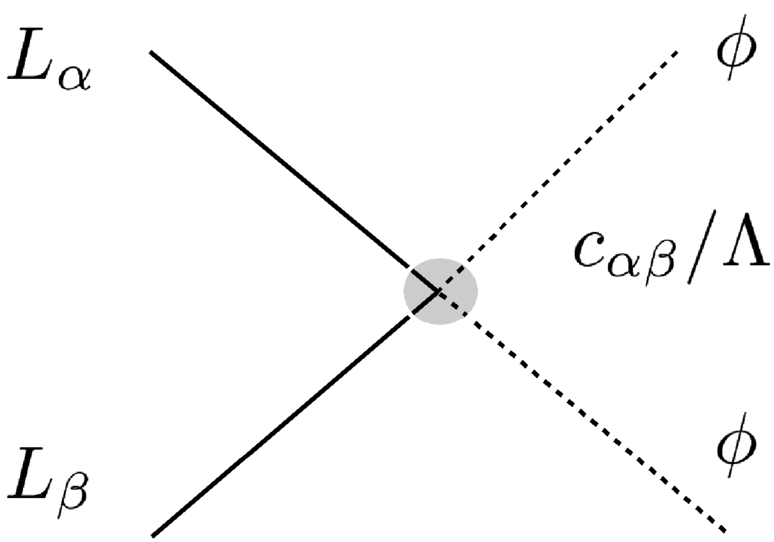
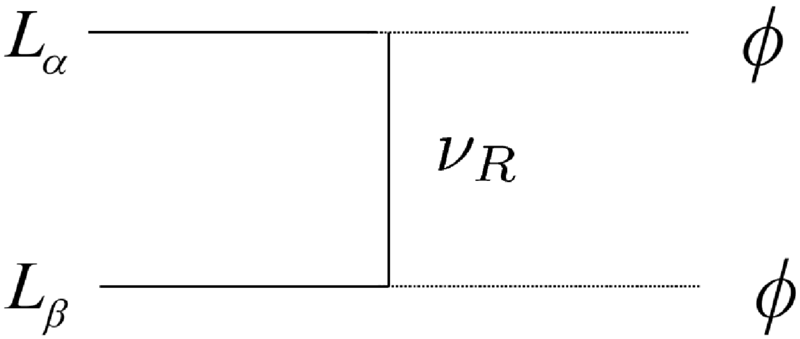


☺ Smallnes of neutrino masses can be explained

☺ Majorana masses
Lepton number is violated

$0\nu\beta\beta$ decay

Seesaw Models

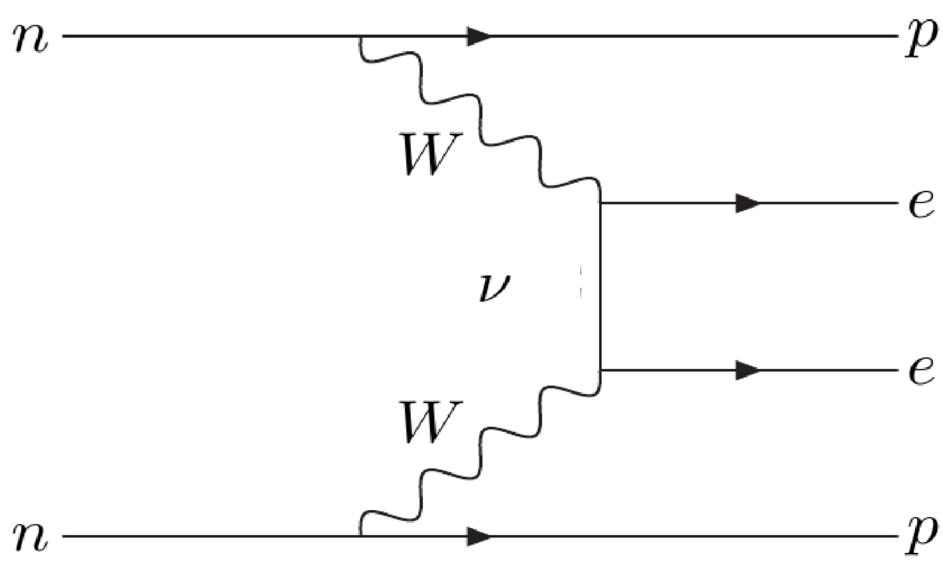


Heavy fermion singlet: ν_R. Type I *seesaw.*
Minkowski 77; Gell-Mann, Ramond, Slansky 79; Yanagida 79; Mohapatra, Senjanovic 80.

In this talk, we will focus on the following extension of SM:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} - \frac{1}{2}\overline{\nu_{si}} M_{ij} \nu^c_{sj} - (Y)_{i\alpha}\overline{\nu_{si}}\widetilde{\phi}^\dagger L_\alpha + \text{h.c.}$$

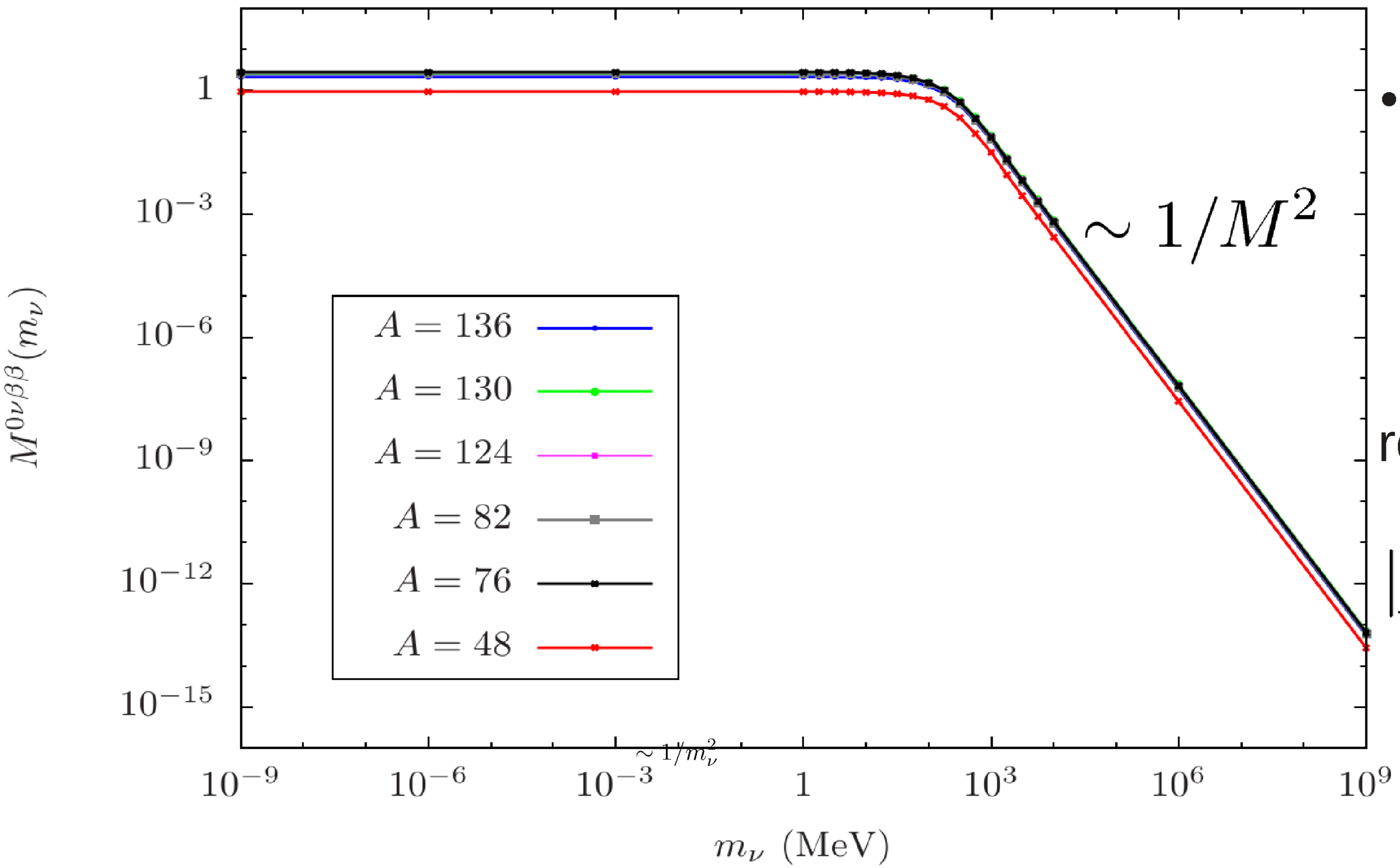
Neutrinoless double beta decay



- Contribution of a single neutrino to the amplitude of $0\nu\beta\beta$ decay:

$$A_i \propto \underbrace{m_i}_{\text{mass of propagating neutrino}} \underbrace{U_{ei}^2}_{\text{Lepton mixing matrix}} \underbrace{M^{0\nu\beta\beta}(m_i)}_{\text{NME}}$$

Nuclear Matrix Elements (NME)



- Mild dependence on the nuclei

- Two different regions separated by nuclear scale $|p^2| \simeq 100\,\text{MeV}$

Data available @
http://www.th.mppmu.mpg.de/members/blennow/nme_mnu.dat

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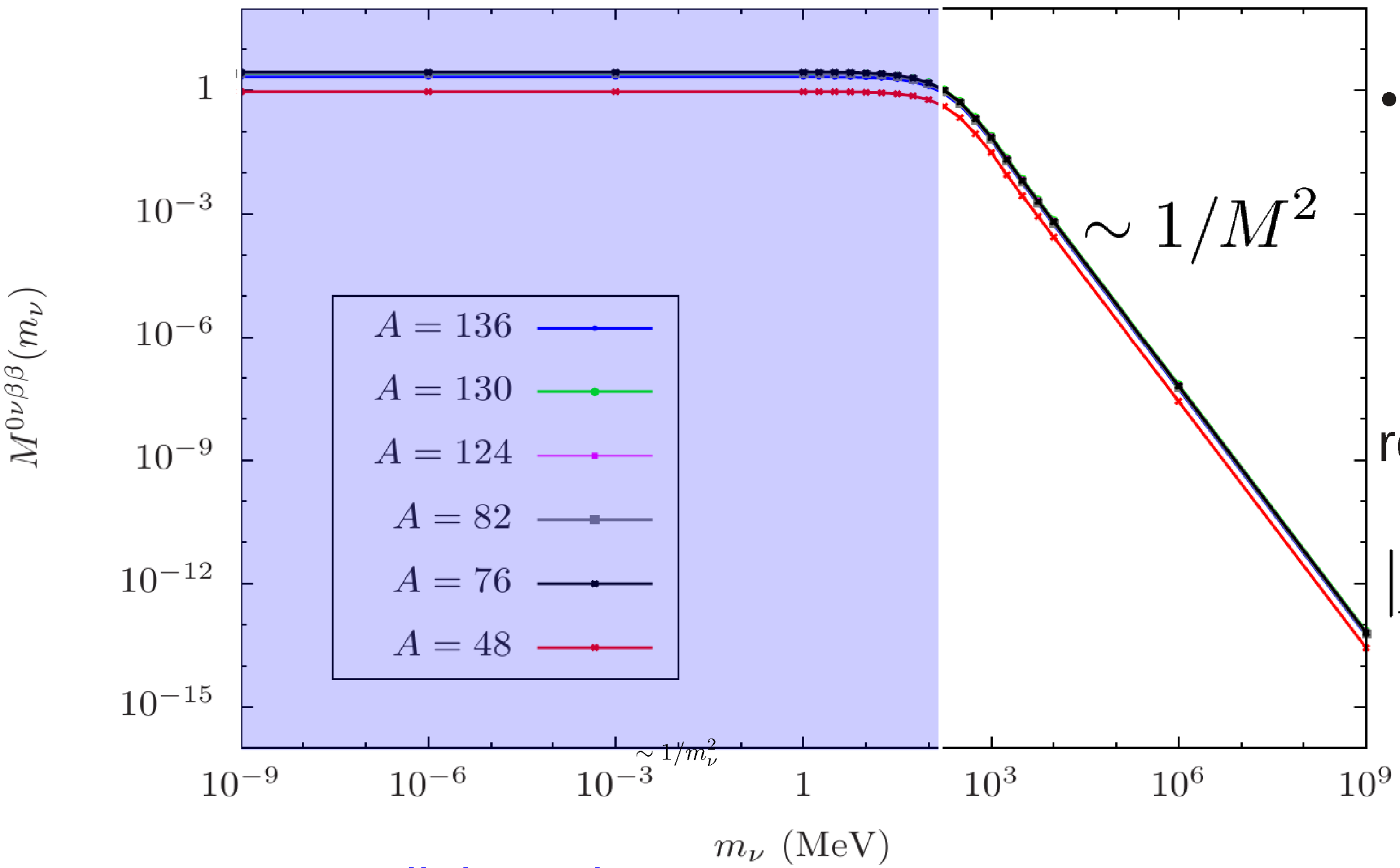

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light regime

$m_i^2 \ll |p^2|$

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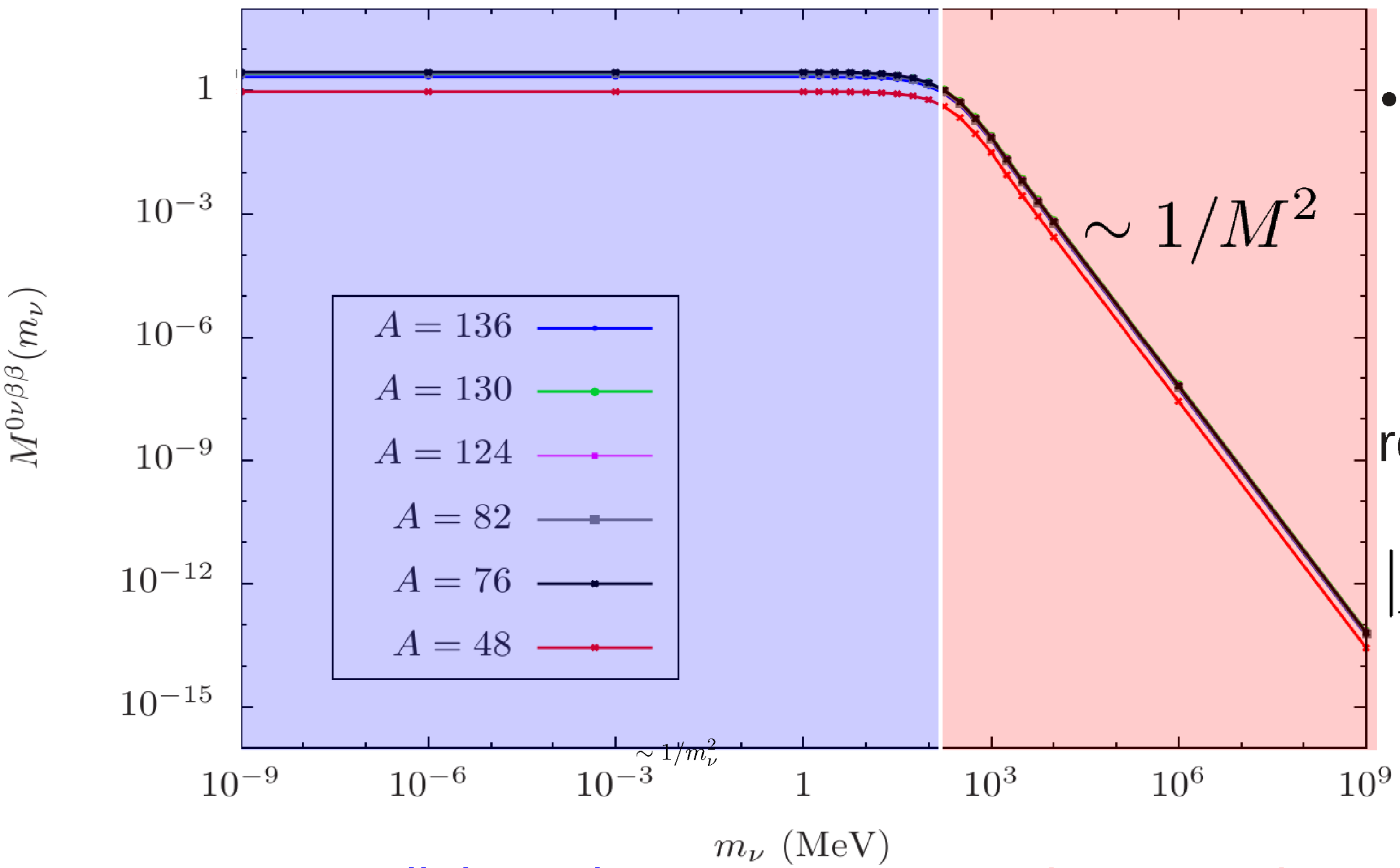

- Mild dependence on the nuclei
- Two different regions separated by nuclear scale $|p^2| \simeq 100\,\mathrm{MeV}$

light regime $m_i^2 \ll |p^2|$

heavy regime $m_i^2 \gg |p^2|$

Data available @
http://www.th.mppmu.mpg.de/members/blennow/nme_mnu.dat

Standard approach

$m_{\beta\beta}$

Contribution of extra degrees of freedom is neglected

$$A_{0\nu\beta\beta} = \sum_{i=1}^{3} A_i \propto \sum_{i=1}^{3} m_i U_{ei}^2 M^{0\nu\beta\beta}(m_i) \simeq M^{0\nu\beta\beta}(0) \sum_{i=1}^{3} m_i U_{ei}^2$$

Using PMNS matrix parameterisation:

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

→ Valid if "SM" neutrinos dominate the process

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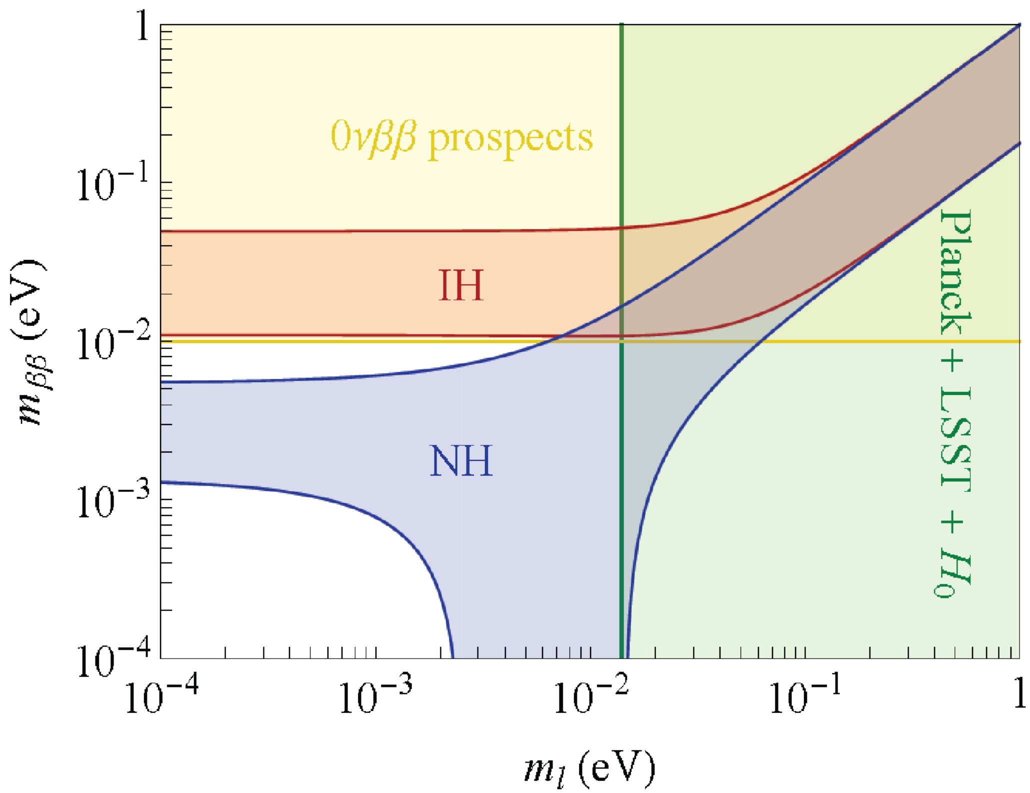

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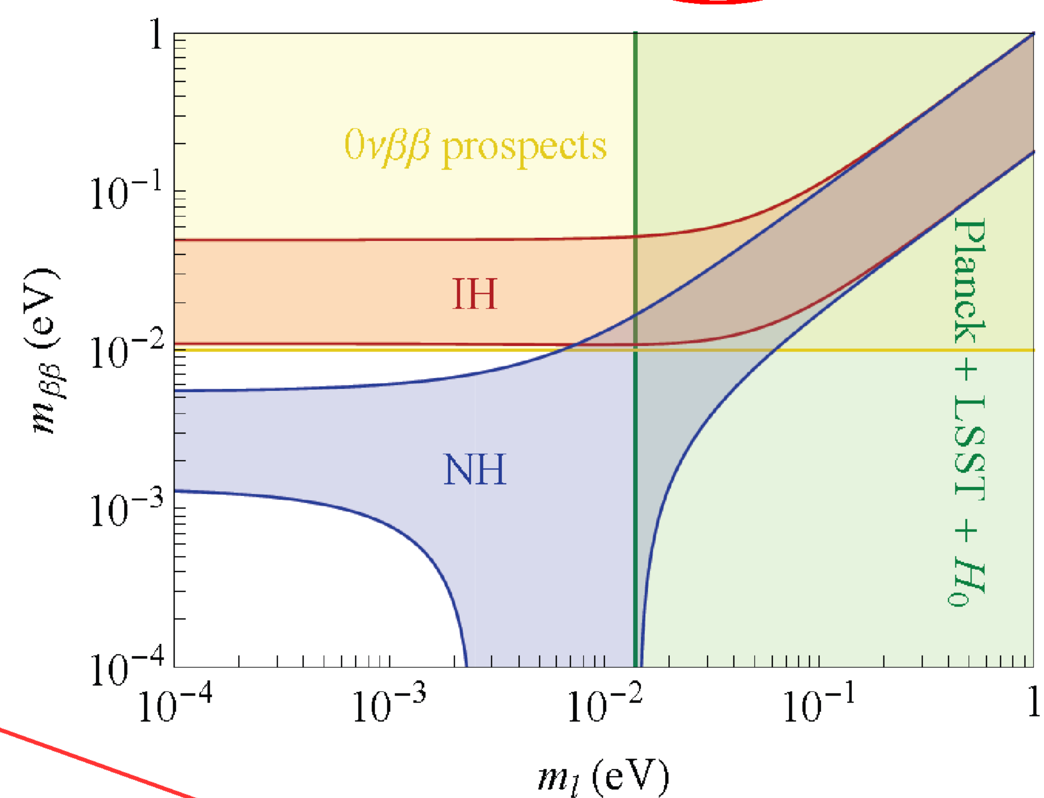

→ Valid if "SM" neutrinos dominate the process

→ But the SM has to be extended with *heavy* degrees of freedom, not considered above, otherwise $0\nu\beta\beta$ decay would be forbidden.

They can be very relevant !!

$0\nu\beta\beta$ in seesaw models

$$-\mathcal{L}_{mass} = \frac{1}{2}\overline{\nu_{Ri}}(M_N)_{ij}\nu^c_{Rj} - (Y_\nu)_{i\alpha}\overline{\nu_R}\widetilde{\phi}^\dagger L_\alpha$$

The neutrino mass matrix is then given by:

$$\begin{pmatrix} 0 & Y_N^* v/\sqrt{2} \\ Y_N^\dagger v/\sqrt{2} & M_N \end{pmatrix}.$$

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$(3+n_R)\times(3+n_R)$ unitary mixing matrix

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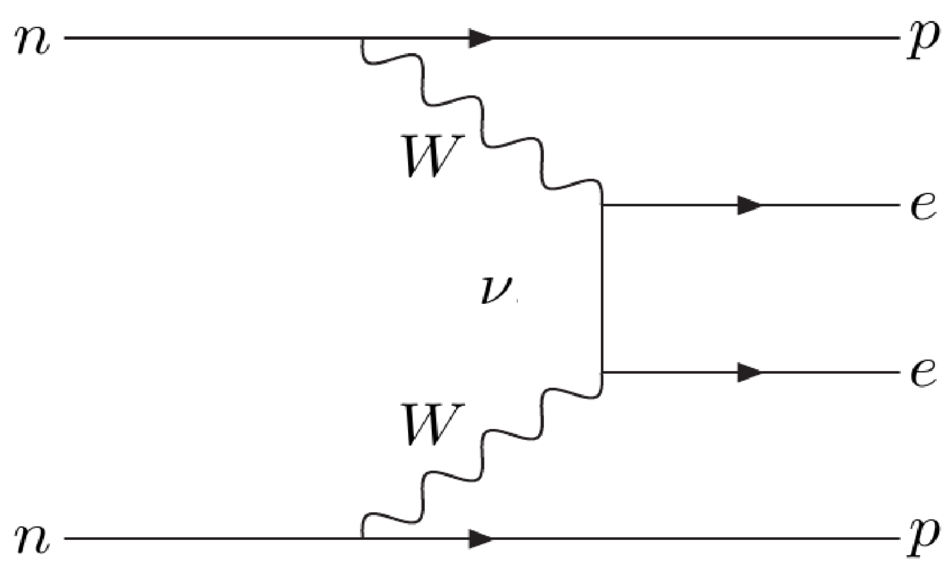
$$\cancel{\overline{\nu_{\alpha L}}\nu^c_{\alpha L}} \qquad \sum_i^{\mathrm{SM}} m_i U_{ei}^2 + \sum_I^{\mathrm{extra}} m_I U_{eI}^2 = 0$$

Simple relation between "light" parameters and extra degrees of freedom!

$0\nu\beta\beta$ decay in seesaw models



$$A \propto \sum_i^{\mathrm{SM}} m_i U_{ei}^2 M^{0\nu\beta\beta}(0) + \sum_I^{\mathrm{extra}} m_I U_{eI}^2 M^{0\nu\beta\beta}(m_I)$$

light mostly-active states

extra degrees of freedom

↓

Different phenomenologies depending on their mass regime

Sterile neutrinos in light regime

$$A \propto \sum_i^{\mathrm{SM}} m_i U_{ei}^2 M^{0\nu\beta\beta}(m_i) + \sum_I^{\mathrm{light}} m_I U_{eI}^2 M^{0\nu\beta\beta}(m_I)$$

Remember

1. $\cancel{\overline{\nu_{\alpha L}} \nu_{\alpha L}^c}$ $\quad \displaystyle\sum_i^{\mathrm{SM}} m_i U_{ei}^2 + \sum_I^{\mathrm{light}} m_I U_{eI}^2 = 0$

2. $M^{0\nu\beta\beta}(m_i) = M^{0\nu\beta\beta}(0)$ (light regime)

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$$A \propto -\sum_I^{\text{light}} m_I U_{eI}^2 \boxed{\left(M^{0\nu\beta\beta}(0) - M^{0\nu\beta\beta}(m_I)\right)}$$

strong suppression for $m_{\text{extra}} < 100\text{MeV}$!

Sterile neutrinos in heavy regime

”canonical” Type-I seesaw scenario

$$A \propto - \sum_{I}^{\text{heavy}} m_I U_{eI}^2 \left(M^{0\nu\beta\beta}(0) - M^{0\nu\beta\beta}(m_I) \right)$$

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negligible!

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$$\approx - \sum_I^{\text{heavy}} m_I U_{eI}^2 M^{0\nu\beta\beta}(0) = \boxed{\sum_i^{\text{SM}} m_i U_{ei}^2 M^{0\nu\beta\beta}(0).}$$

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Constrain mixing with heavy neutrinos
through light contribution!!

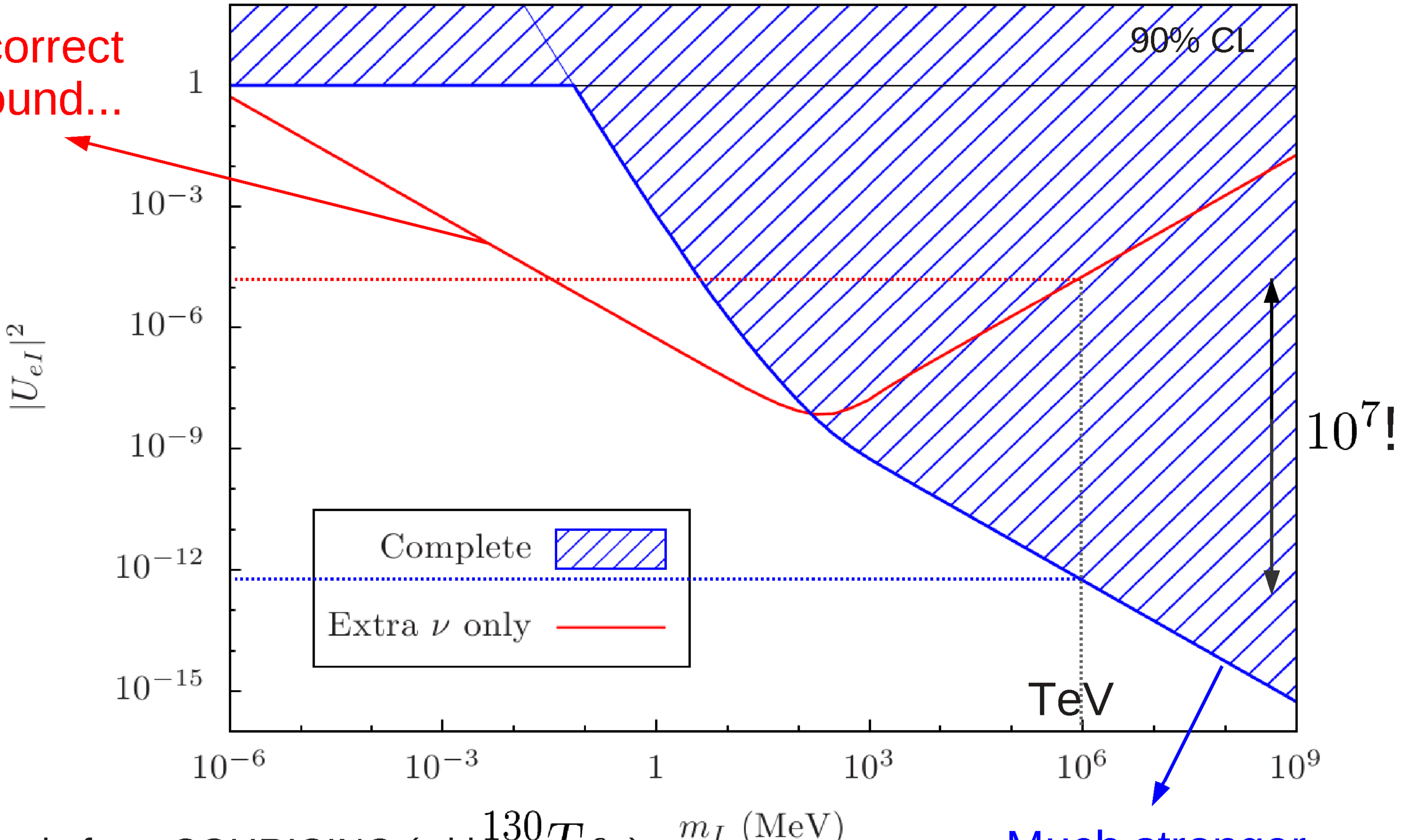
(Much stronger than the bounds usually considered in the literature)

Zhi- Zhong Xing 09

Blennow, Fernandez-Martinez, Menendez, JLP 10
arXiv:1005.324

Bound on mixing active-sterile neutrino

Incorrect bound...



Much stronger Constraint !!

Bounds from COURICINO (with ^{130}Te)

Non-hierarchical extra neutrinos assumed

Blennow, Fernandez-Martinez, Menendez, JLP 10

Sterile neutrinos in heavy & light regime

negligible!

$$\boxed{A \propto} - \sum_{I}^{\text{heavy}} m_I U_{eI}^2 \left(M^{0\nu\beta\beta}(0) - \cancel{M^{0\nu\beta\beta}(m_I)} \right)$$

$$\approx \left(\sum_{i}^{\text{SM}} m_i U_{ei}^2 + \sum_{extra}^{\text{light}} m_I U_{eI}^2 \right) M^{0\nu\beta\beta}(0)$$

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$$\approx \left(\sum_{i}^{\text{SM}} m_i U_{ei}^2 + \sum_{extra}^{\text{light}} m_I U_{eI}^2 \right) M^{0\nu\beta\beta}(0)$$

Extra states with masses below 100 MeV
can give a relevant contribution!

The sterile neutrinos can dominate the process

Blennow, Fernandez-Martinez, Menendez, JLP. arXiv:1005.324

Is there any other case in wich
the sterile neutrinos
can dominate the decay rate?

JLP, Pascoli and Wong
ArXiv:1209.5342 (PRD **87,** 093007 (2013))

Yes, there is an important exception

$$A \propto \boxed{\sum_i^{SM} m_i U_{ei}^2} M^{0\nu\beta\beta}(0) + \sum_I^{\text{heavy}} m_I U_{eI}^2 M^{0\nu\beta\beta}(m_I)$$

$$\sum_i^{SM} m_i U_{ei}^2 = \sum_I^{\text{heavy}} m_I U_{eI}^2 = 0$$

Ibarra, Molinaro, Petcov 2010

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Heavy neutrinos dominate process at tree level...

...is it really possible to have a dominant and measurable contribution once the one-loop corrections are considered?

Parameterization

In the appropriate basis, without loss of generality

$$M_\nu = \begin{pmatrix} 0 & Y_1^T v/\sqrt{2} & \epsilon Y_2^T v/\sqrt{2} \\ Y_1 v/\sqrt{2} & \mu' & \Lambda \\ \epsilon Y_2 v/\sqrt{2} & \Lambda^T & \mu \end{pmatrix}$$

$\epsilon, \mu, \mu' = \text{lepton number violation parameters}$

$0\nu\beta\beta$ decay rate should depend on them

Also light majorana masses

Tree level Cancellation of light contribution

At tree level in the seesaw limit, the cancellation condition reads:

$$A_{light} \propto -\left(m_D^T M^{-1} m_D\right)_{ee} M^{0\nu\beta\beta}(0) = 0$$

$$\Downarrow$$

SM + $2 \times \nu_R$

$$\mu Y_{1e}^2 + \epsilon Y_{2e}\left(\epsilon\mu' Y_{2e} - 2\Lambda Y_{1e}\right) = 0$$

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SM + $2 \times \nu_R$

$$\mu Y_{1e}^2 + \epsilon Y_{2e} \left(\epsilon \mu' Y_{2e} - 2\Lambda Y_{1e}\right) = 0$$

$\mu = \epsilon = 0$ is the most stable solution under corrections

Tree level light active neutrino masses vanish !!

$$A_{heavy} \propto -\left(m_D^T M^{-3} m_D\right) = \frac{v^2 \mu' Y_{1e}^2}{2\Lambda^4}$$

Heavy contribution

$$A_{heavy} \propto -\left(m_D^T M^{-3} m_D\right) = \frac{v^2 \mu' Y_{1e}^2}{2\Lambda^4}$$

→ To have a phenomenologically relevant contribution, a large μ' and/or a rather small Λ are in principle required.

Does it induce too large radiative corrections?

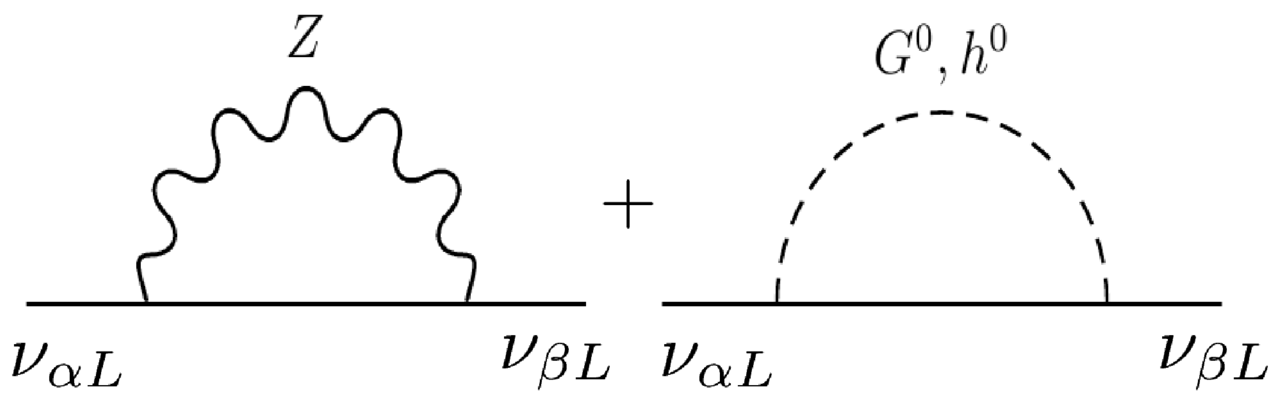
What about the higher order corrections in the seesaw expansion? NO, they vanish for $\mu = \epsilon = 0$

1-loop corrections

- Finite corrections. 1-loop generated Majorana mass term for the active neutrinos is the dominant contribution:

Pilaftsis 92; Grimus & Lavoura 2002; Aristizabal Sierra & Yaguna 2011

$$\delta m_{LL} = \frac{1}{(4\pi)^2} m_D^T M \left\{ \frac{3 \ln\left(M^2/M_Z^2\right)}{M^2/M_Z^2 - 1} + \frac{\ln\left(M^2/M_h^2\right)}{M^2/M_h^2 - 1} \right\} m_D$$



Similar structure as tree level masses, but no cancellation for $\mu = \epsilon = 0$. Light masses generated at 1-loop.

1-loop corrections

$$U^* \mathrm{diag}\{m_1, m_2, ..., m_n\}\, U^\dagger = \begin{pmatrix} \delta m_{LL} & Y_N^* v/\sqrt{2} \\ Y_N^\dagger v/\sqrt{2} & M_N \end{pmatrix}.$$

If tree level cancelation takes place $(\mu = \epsilon = 0)$:

$$\begin{cases} \boxed{A_{extra}} \propto \sum_I^{\mathrm{extra}} U_{eI}^2 m_I M^{0\nu\beta\beta}(m_I) \boxed{\neq 0} \\ \boxed{A_{active}} \propto (\delta m_{LL})_{ee} M^{0\nu\beta\beta}(0) \boxed{\neq 0} \end{cases}$$

Constraints

1 Neutrino oscillations $\sqrt{\delta m^2_{solar}} < \delta m_{LL} < 0.23\, eV$ Absolute mass scale experiments (PLANCK)

$2\, eV$ (^3H β- decay)

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$2\, eV$ (^3H β- decay)

2 Dominant or not, the heavy contribution should respect the present constraint and be measurable, to be phenomenologically interesting

$$10^{-2}\, eV < m^{heavy}_{\beta\beta} < 0.38\, eV$$

Present bound
EXO using
ISM NME

Next-to-Next generation sensitivity
MAJORANA, Super-Nemo, etc, etc

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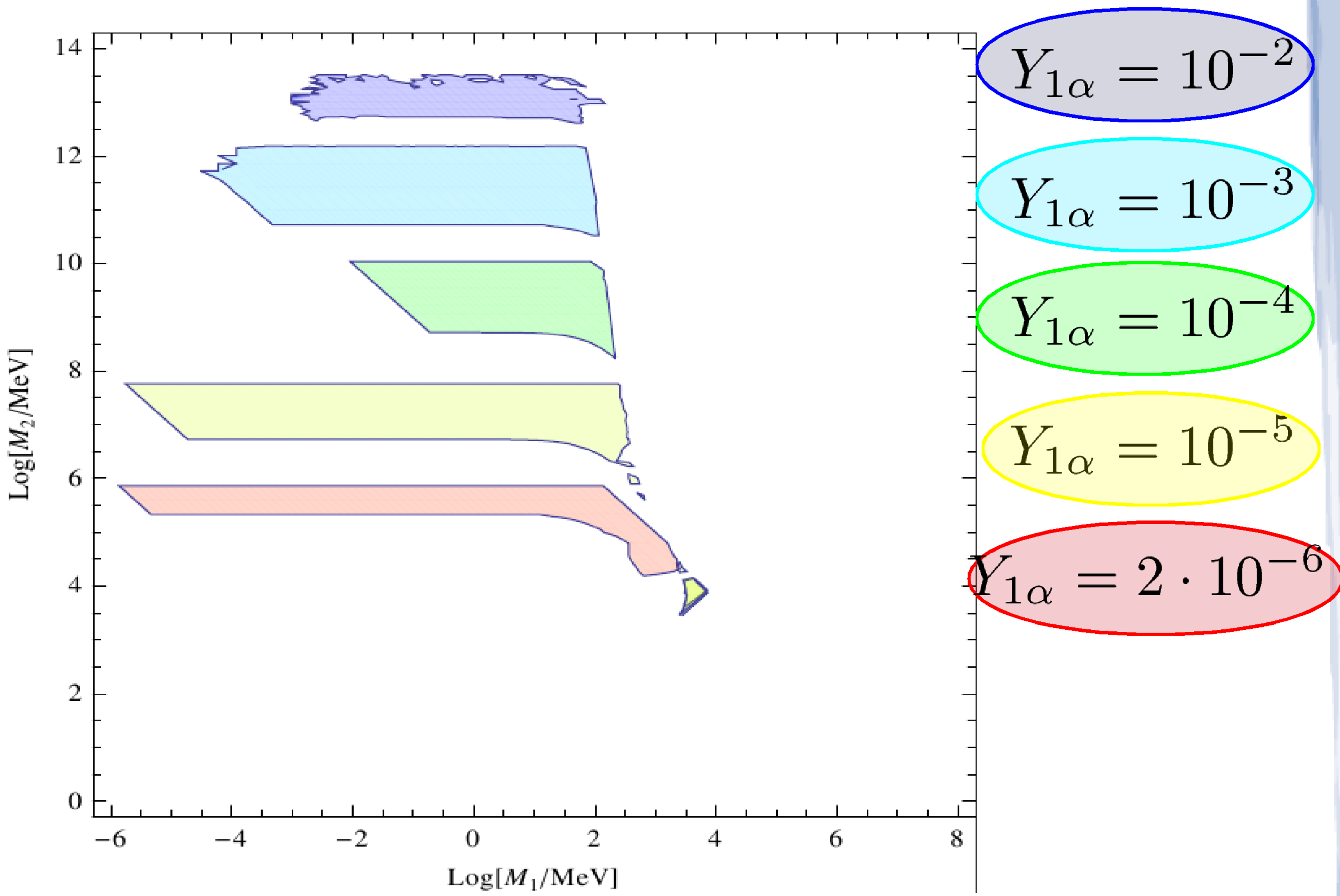
3 Constraints on the mixing with heavy neutrinos from weak decays, lepton number violation processes and non-unitarity.

Atre,Han, Pascoli, Zhang 2009
Antusch, Biggio, Fernandez-Martinez, Gavela, JLP 2006
etc

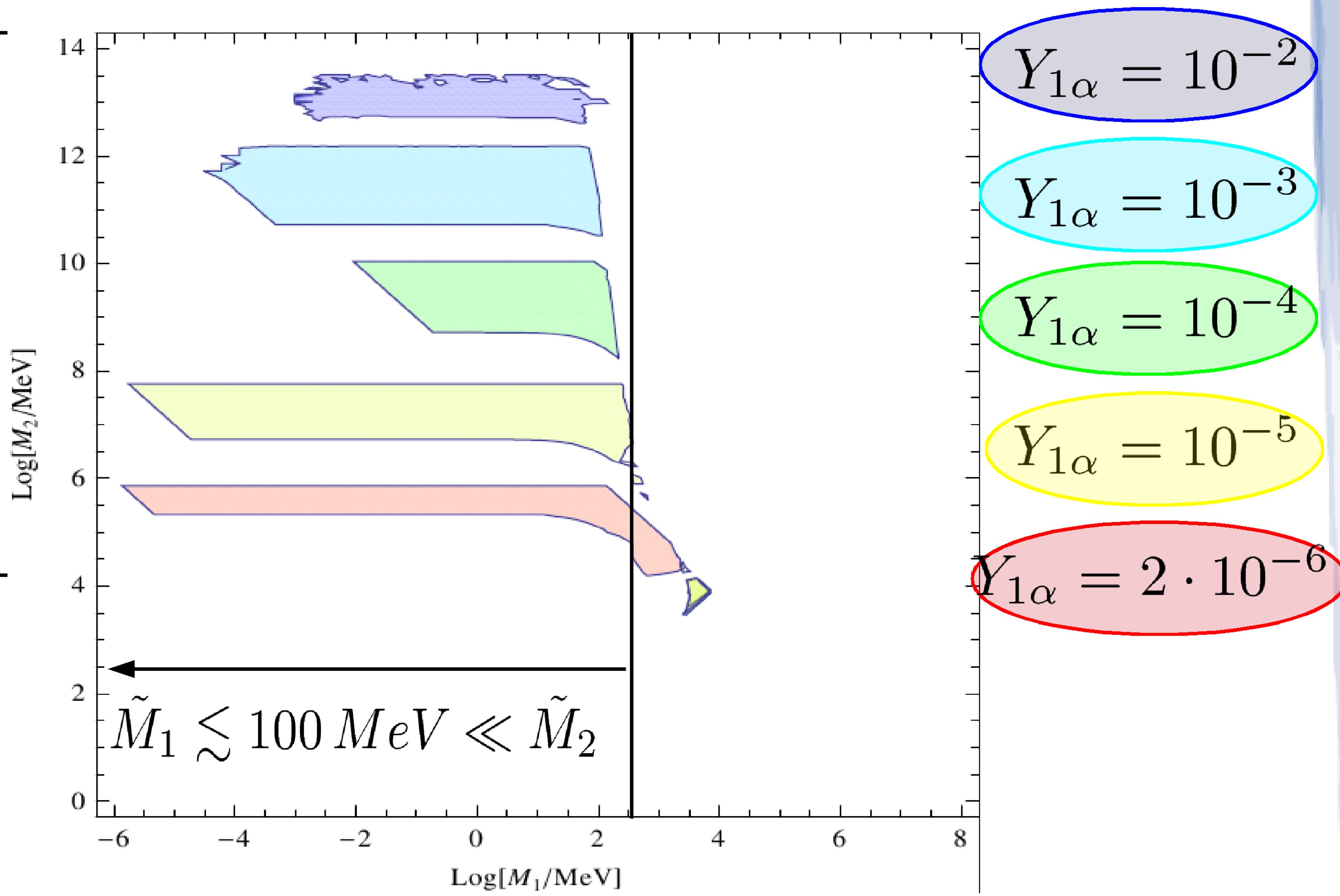
Sterile Neutrino signal



Sterile Neutrino signal

Hierarchical seesaw

ESS



Sterile Neutrino signal

Hierarchical seesaw

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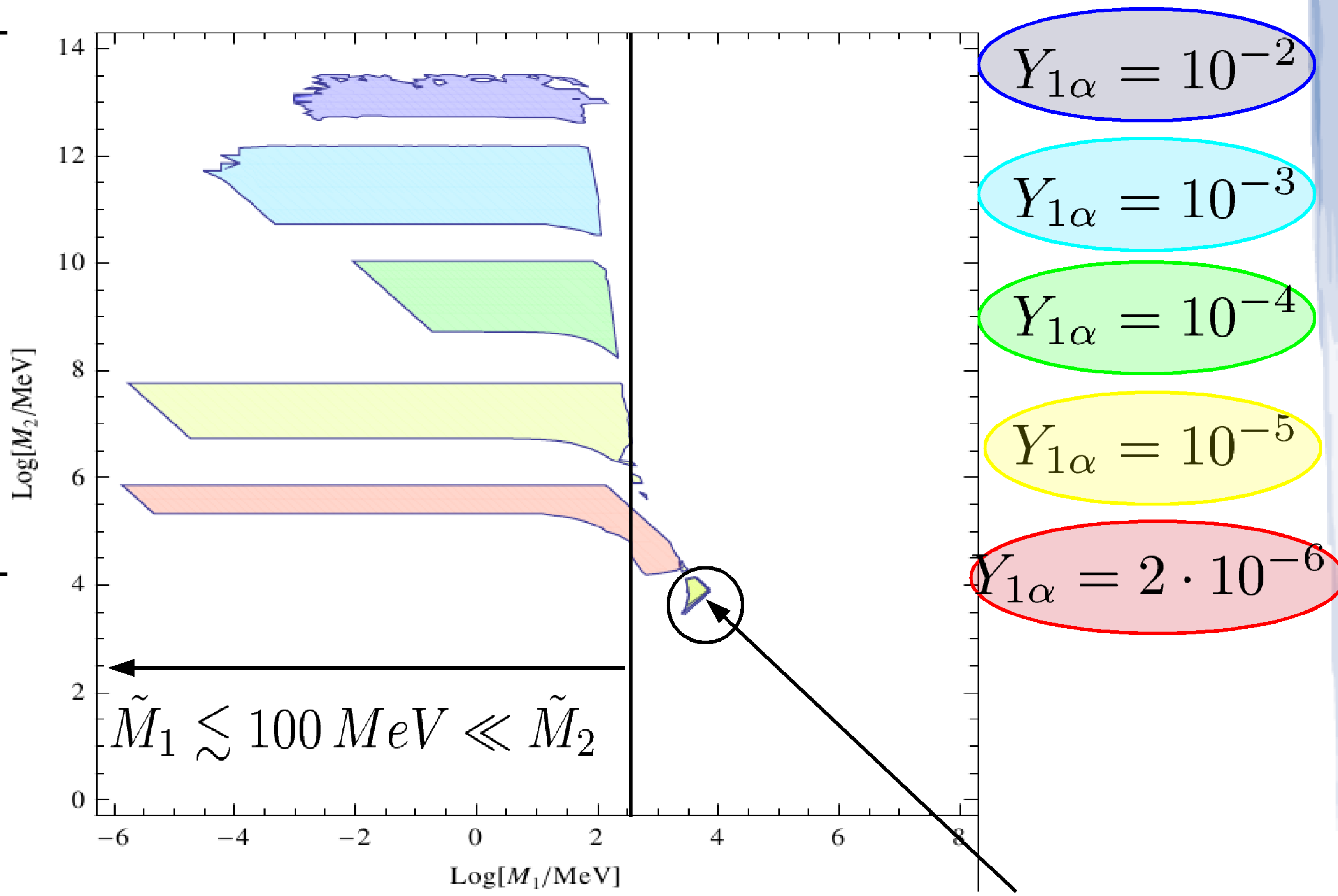

Quasi-Degenerate spectrum

ISS

$$\tilde{M}_2 \approx \tilde{M}_1 \approx \Lambda \sim 5\, GeV$$

Sterile Neutrino signal

It can take place in two limits:

- Quasi-Degenerate havy spectrum (ISS limit): $\Lambda \gg \mu'$

  Mohapatra, Valle 86; Branco, Grimus, Lavoura 89

$$\tilde{M}_2 \approx -\tilde{M}_1 \approx \Lambda$$

$$\delta m_{LL} \approx \frac{1}{(4\pi)^2} \frac{Y_1^T Y_1}{2} \frac{M_H^2 + 3M_Z^2}{\Lambda^2} \mu'$$

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- "Hierarchical" heavy spectrum (ESS limit): $\Lambda \ll \mu'$

  Kang, Kim 2007; Majee, Parida, Raychaudhuri 2008

$$\tilde{M}_2 \approx \mu' \gg \tilde{M}_1 \approx \frac{\Lambda^2}{\mu'}$$

$$\delta m_{LL} \approx \frac{1}{(4\pi)^2} \frac{Y_1^T Y_1}{2} \left[\frac{3M_Z^2}{\mu'} \ln\left(\frac{\Lambda^4}{M_Z^4}\right) + \frac{M_H^2}{\mu'} \ln\left(\frac{\Lambda^4}{M_H^4}\right) \right]$$

$0\nu\beta\beta$ decay+Neutrino Oscillations+Cosmology

1. $0\nu\beta\beta$ signal in agreement with the forecasted rates

- Light active neutrinos dominate the 0νββ
- New physics above the nuclear scale, but its contribution is suppressed.

2. $m_{\beta\beta}$ meassured in $0\nu\beta\beta$ larger than the forecasted rates

- Light active neutrinos do not dominate the 0νββ
- A dominant New physics contribution is required

3. $m_{\beta\beta}$ meassured in $0\nu\beta\beta$ smaller than the forecasted rates

- Parcial cancellation between light active neutrino contribution and extra degrees of freedom (example: sterile neutrinos around the nuclear scale)

$0\nu\beta\beta$ decay+Neutrino Oscillations+Cosmology

4. No $0\nu\beta\beta$ signal observed but forcasted.

- Neutrinos are Dirac particles
- Neutrinos are Majorana particles but all masses below nuclear scale

5. NO $0\nu\beta\beta$ signal observed and NOT forcasted.

- Very pesimistic!
- Impossible to draw any conclusion about origin and nature of neutrino masses.

Conclusions

- Computed the NME as a function of the mass of the mediating fermions, estimating its relevant theoretical error.

  Data available @ http://www.th.mppmu.mpg.de/members/blennow/nme_mnu.dat

- Contributions of light and heavy neutrinos should not be treated as if they were independent:

  - Light contribution usually dominates the process.

  - ***Much stronger constraints*** on heavy mixing obtained considering relation between light and heavy degrees of freedom

  - If all extra states are in the light regime: strong cancellation leads to an experimentally inaccessible result.

- Same phenomenology for the type-II and type-III seesaws as for the type I seesaw.

Blennow, Fernandez-Martinez, Menendez, JLP. arXiv:1005.324

Conclusions

- Sterile neutrinos can give a signal in $0\nu\beta\beta$ decay. This basically requires a hierarchical spectrum with (at least) one sterile neutrino lighter than the $0\nu\beta\beta$ decay scale (around 100 MeV) and (at least) other sterile neutrino heavier than 100 MeV.

Blennow, Fernandez-Martinez, Menendez, JLP. arXiv:1005.324

- Even if the light neutrino contribution cancels out at tree-level, a measurable heavy neutrino contribution requires to introduce violation of L through the heavy sector, which appears naturally at the one-loop level making very difficult a dominant heavy contribution.

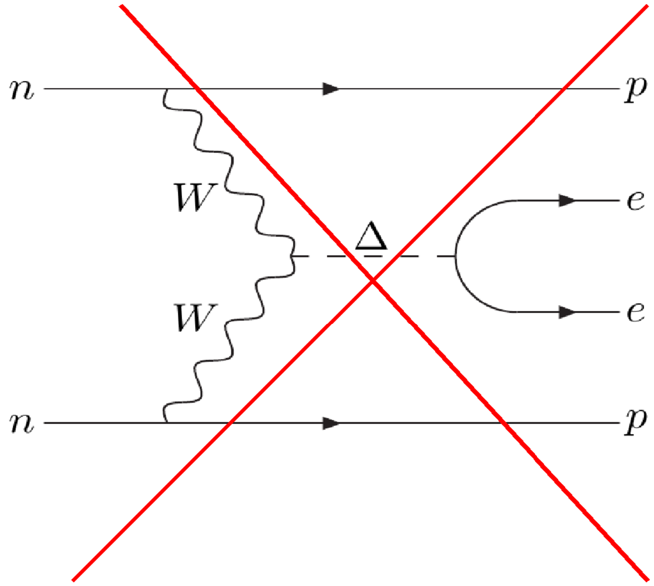
JLP, Pascoli and Wong, arXiv:1209.5342

Thank you!

Back-up

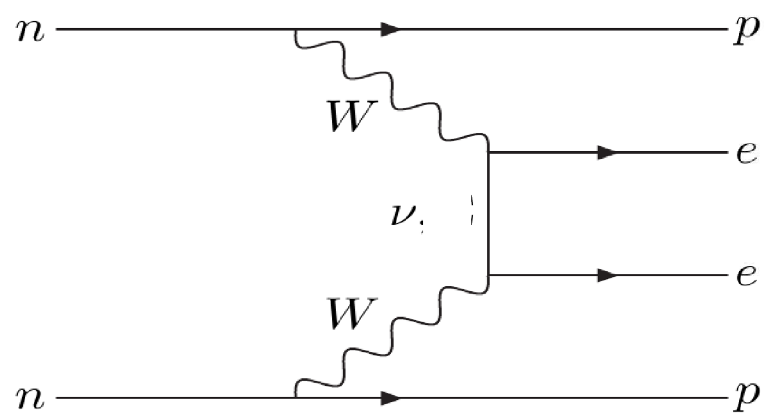
$0\nu\beta\beta$ in Type-II seesaw models

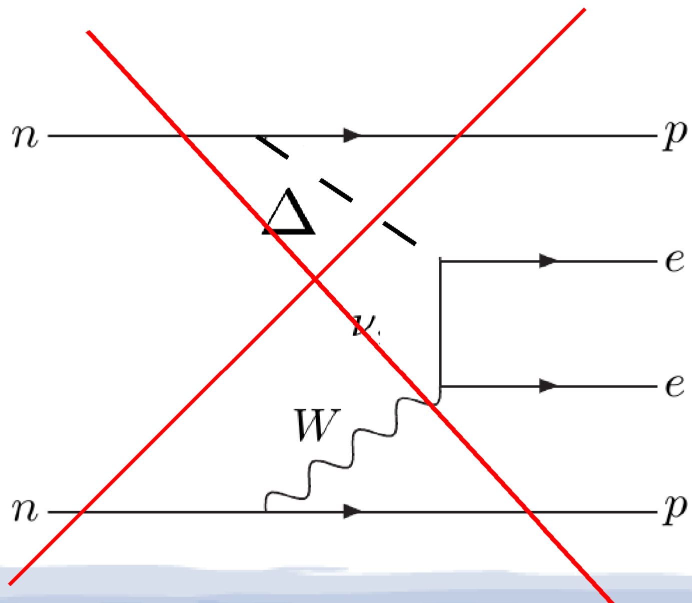
But the scalars can also mediate the process:



$$\sim p^2/M_\Delta^2 \times$$

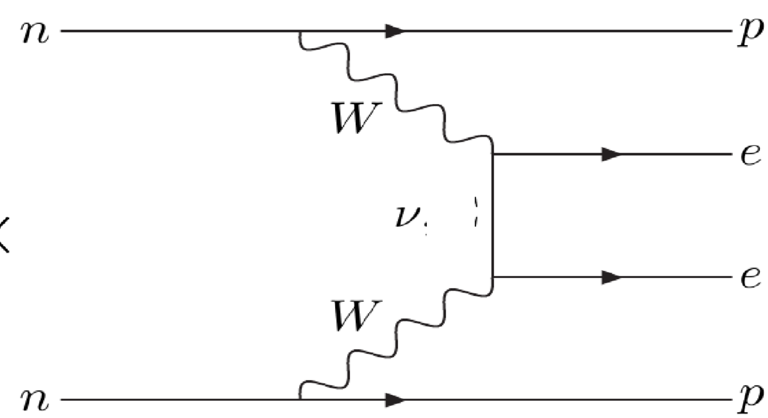
$$< 10^{-6}$$





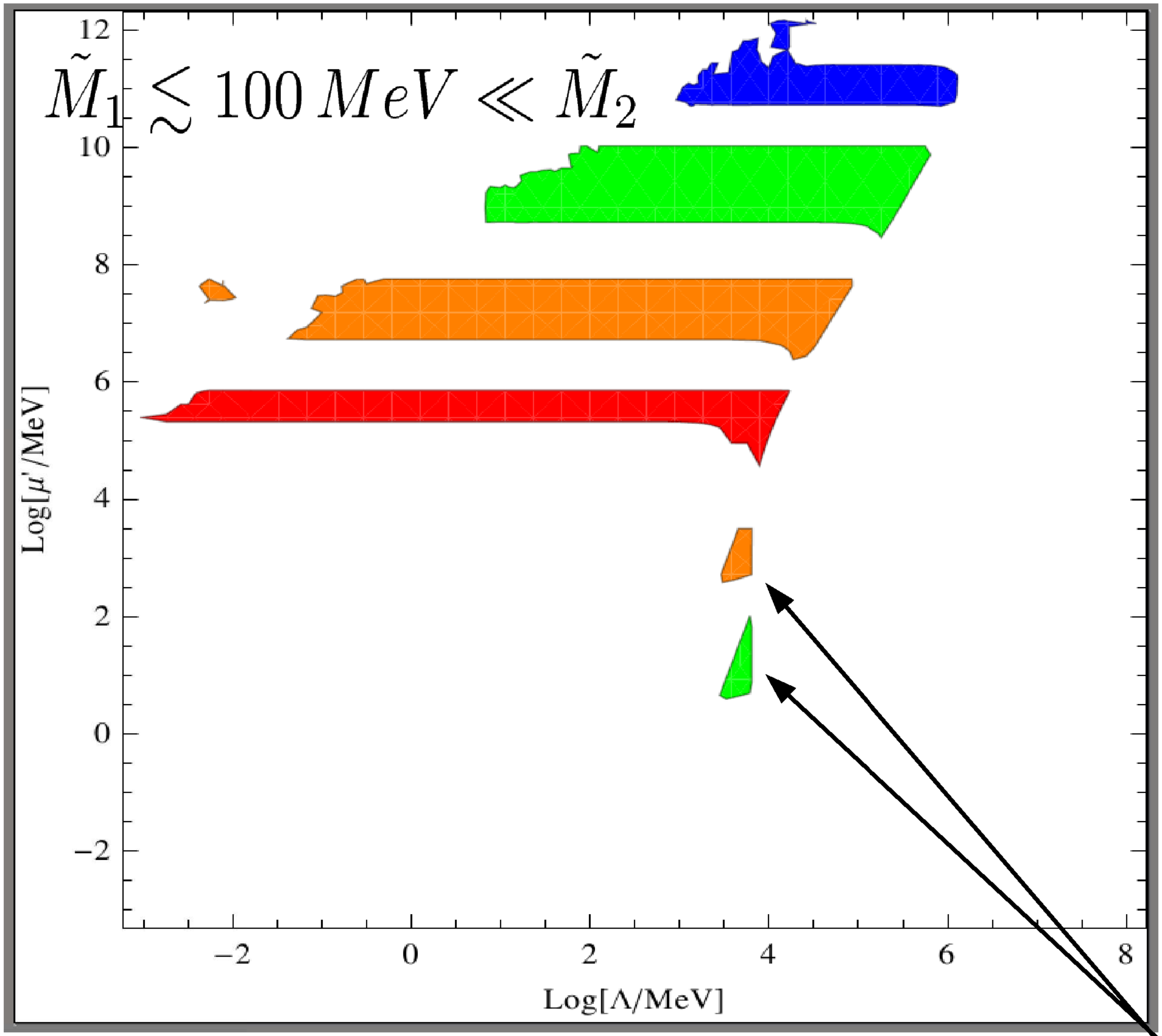
$$\sim m_q/M_\Delta \times$$

$$< 10^{-5}$$



Dominant Heavy Neutrino Contribution

Hierarchical seesaw



$Y_{1\alpha} = 10^{-3}$

$Y_{1\alpha} = 10^{-4}$

$Y_{1\alpha} = 10^{-5}$

$Y_{1\alpha} = 2 \cdot 10^{-6}$

Quasi-Degenerate heavy spectrum

$$\tilde{M}_2 \approx \tilde{M}_1 \approx \Lambda \sim 5\,GeV$$

Type-I: All extra masses in light regime

$$A \propto -\sum_{I}^{\text{light}} m_I U_{eI}^2 \left(M^{0\nu\beta\beta}(0) - M^{0\nu\beta\beta}(m_I)\right)$$