A sterile neutrino signal in the neutrinoless double beta decay?

Jacobo López-Pavón



IFIC, Valencia, 17th October, 2013

Based on:

Blennow, Fernández-Martínez, JLP, Menéndez

ArXiv:1005.3240 (JHEP 1007 (2010) 096)

JLP, Pascoli and Wong

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

Outline

- Motivations

- Neutrinoless double beta decay, experimental bounds, nuclear matrix elements and standard approach

- Neutrinoless double beta decay in the context of seesaw models

- Can we expect a sterile neutrino signal in future neutrinoless doble beta decay experiments?

- What can we learn combining information from neutrinoless double beta decay, neutrino oscillations and cosmology?

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.

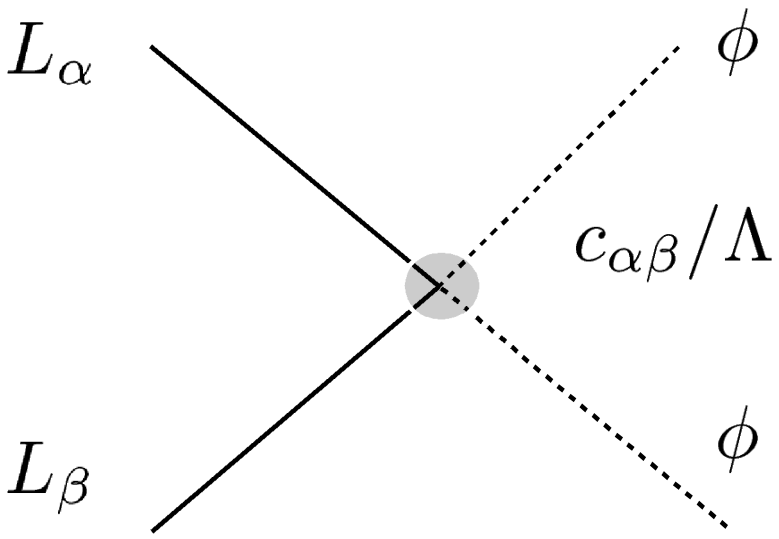
- Although the light neutrino masses could also be generated through the Higgs mechanism, their smallness in comparison with the SM particles calls for another explanation.

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



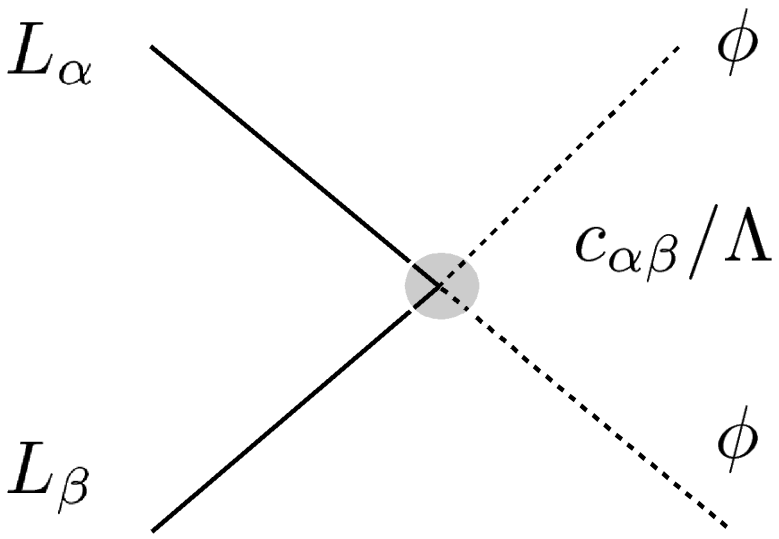
☺ Smallnes of neutrino masses can be explained

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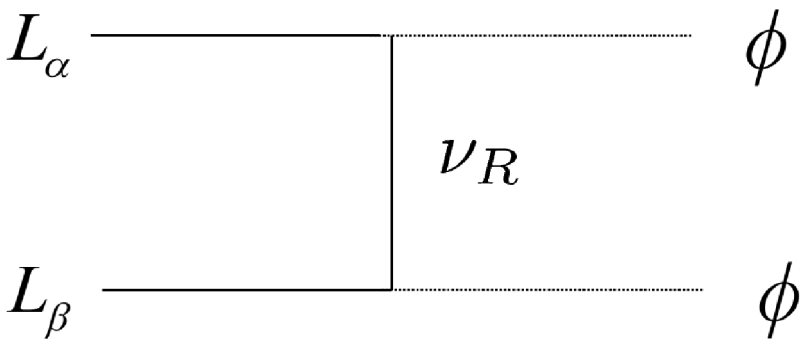


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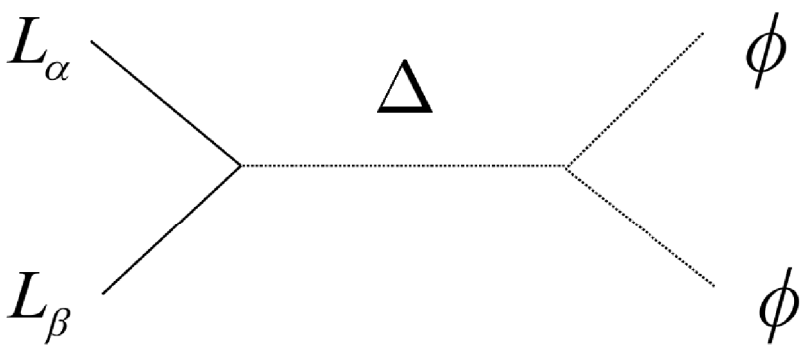
☺ Majorana masses
Lepton number is violated

$0\nu\beta\beta$ decay

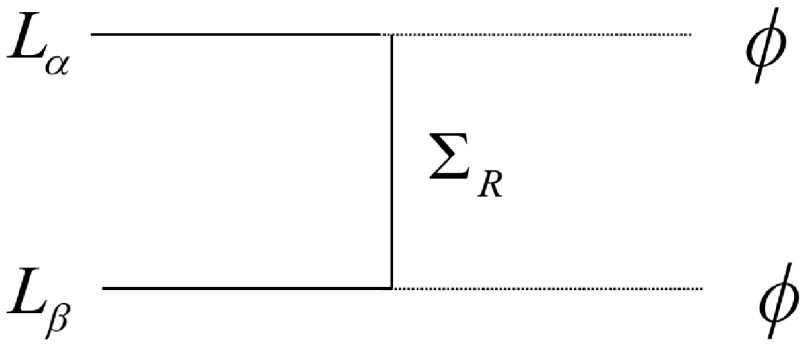
Seesaw Models



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

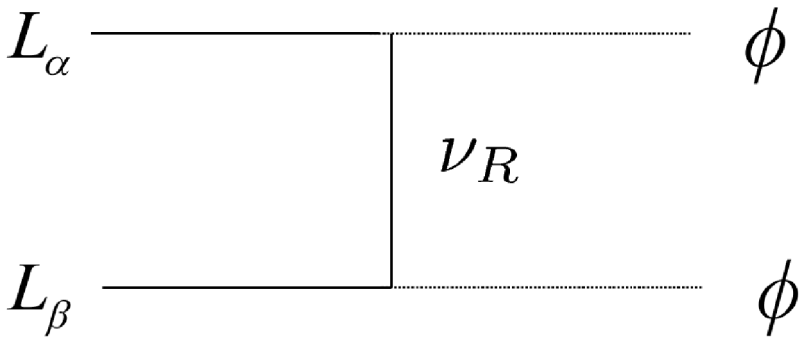


Heavy scalar triplet: Δ. Type II *seesaw.*
Magg, Wetterich 80; Schecter, Valle 80; Lazarides, Shafi, Wetterich 81; Mohapatra, Senjanovic 81.



Heavy fermion triplet: Σ
Type III *seesaw*. Foot, Lew, Joshi 89

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

- Are neutrinos Dirac or Majorana? Most models accounting for ν- masses, as the seesaw, point to Majorana neutrinos.

- The neutrinoless double beta decay ($0\nu\beta\beta$) is one of the most promising experiments in this context.

$$(Z, A) \Rightarrow (Z \pm 2, A) + 2e^{\mp} + X$$

- $0\nu\beta\beta$ can be also sensitive to the absolute ν - mass scale through some combination of parameters.

Experimental bounds

Isotope	0νββ half life	Experiment	<m> eV
^{48}Ca	> 1.4*10^{22} (90%CL)	ELEGANT-VI	< 7 - 44
^{76}Ge	> 1.9*10^{25} (90%CL)	Heidelberg-Moscow	< 0.35
^{76}Ge	2230^{+440}_{-310} (90%CL)	Subset of HM coll.	0.32 +/- 0.03
^{76}Ge	> 2.1*10^{25} (90%CL)	*GERDA*[†]	< 0.2 – 0.4
^{82}Se	> 2.1*10^{23} (90%CL)	NEMO-3	<1.2 – 3.2
^{100}Mo	> 5.8*10^{23} (90%CL)	NEMO-3	< 0.6 – 2.7
^{116}Cd	> 1.7*10^{23} (90%CL)	Solotvino	< 1.7
^{130}Te	> 2.8*10^{24} (90%CL)	Cuoricino	< 0.41 – 0.98
^{136}Xe	> 1.9*10^{25} (90%CL)	*KamLAND-Zen*[††]	< 0.12 – 0.25
^{136}Xe	> 1.6×10^{25} (90%CL)	*EXO-200*[†††]	< 0.14 – 0.38
^{150}Nd	> 1.8*10^{22} (90%CL)	NEMO-3	

Future experiments

NEXT, MAJORANA, CUORE, KamLAND-Zen, Super-Nemo, SNO+, GERDA, etc

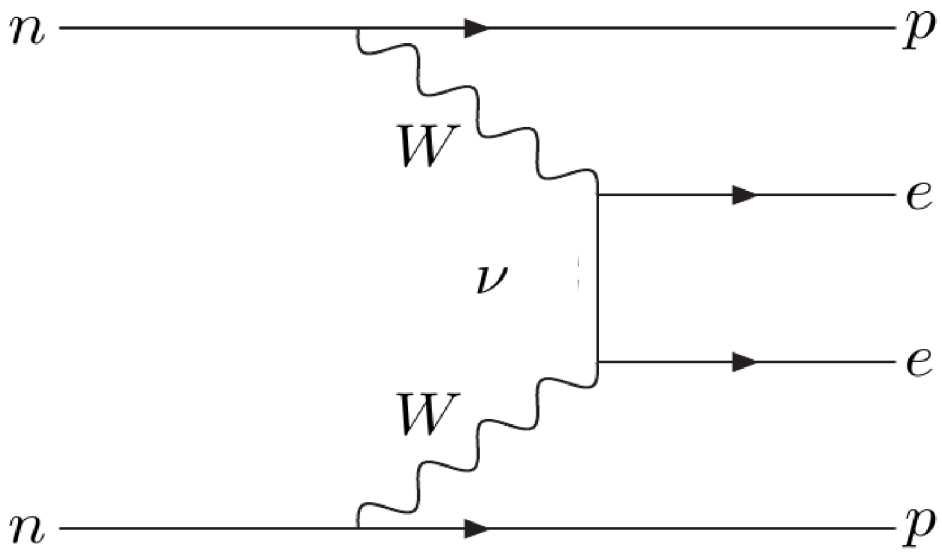
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Future experiments

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Neutrinoless double beta decay



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

$$A_i \propto m_i U_{ei}^2 M^{0\nu\beta\beta}(m_i)$$

mass of propagating neutrino

Lepton mixing matrix

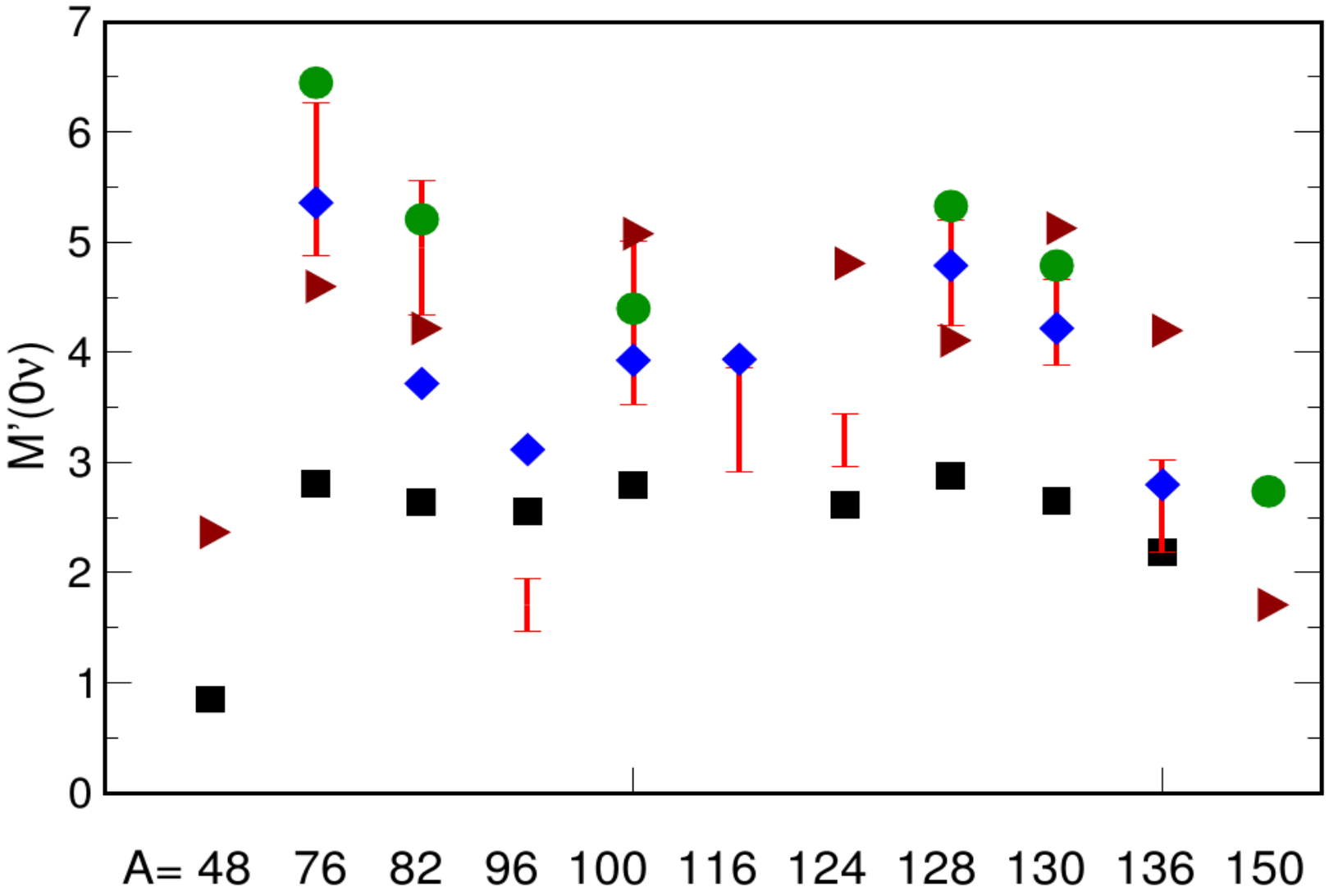
NME

Nuclear Matrix Elements (NMEs)

- *Quasiparticle random phase approximation* (QRPA): includes relatively large valence spaces but is not able to comprise all the possible configurations.

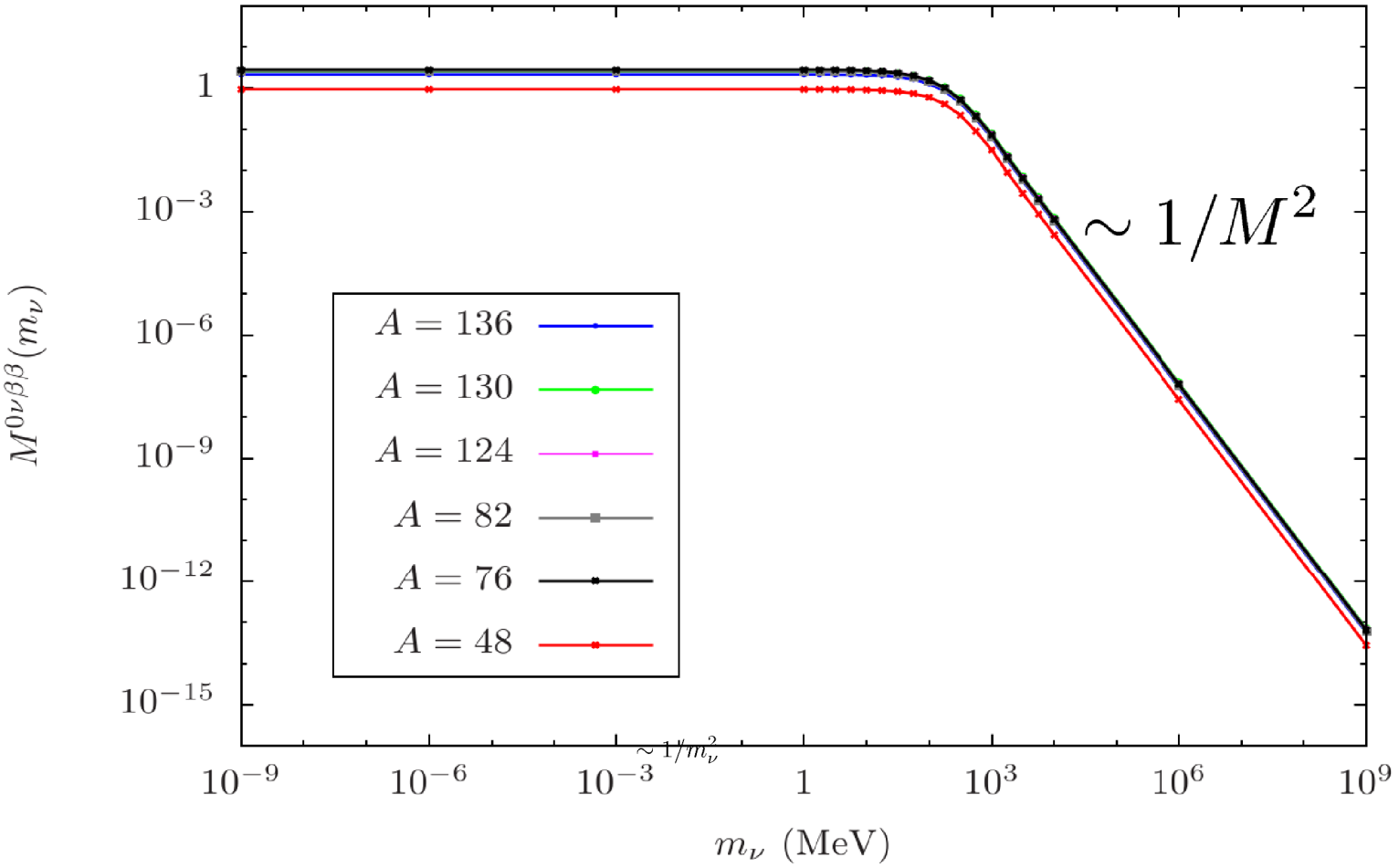
- *Interacting shell model* (ISM): limited to smaller configuration spaces, but all possible correlations within the space can be included.

Nuclear Matrix Elements (NMEs)



QRPA(Tu) (bars) QRPA(Jy)(lozenges) IBM(circles) ISM(squares)
GCM(triangles)

Nuclear Matrix Elements (NMEs)



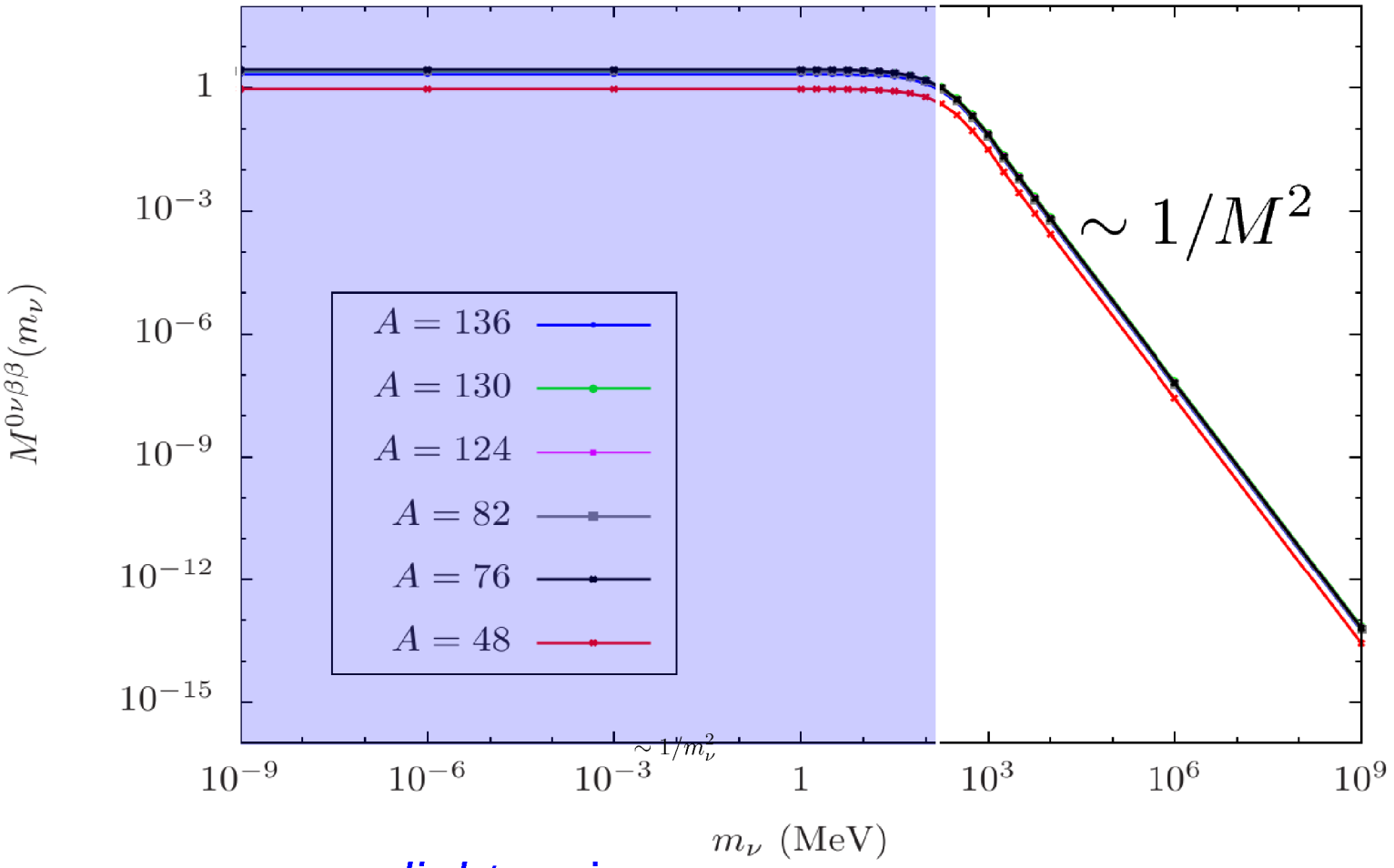
- Mild dependence on the nuclei

- Two different regions separated by nuclear scale

$$|p^2| \simeq 100\,\mathrm{MeV}$$

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

Nuclear Matrix Elements (NMEs)



light regime

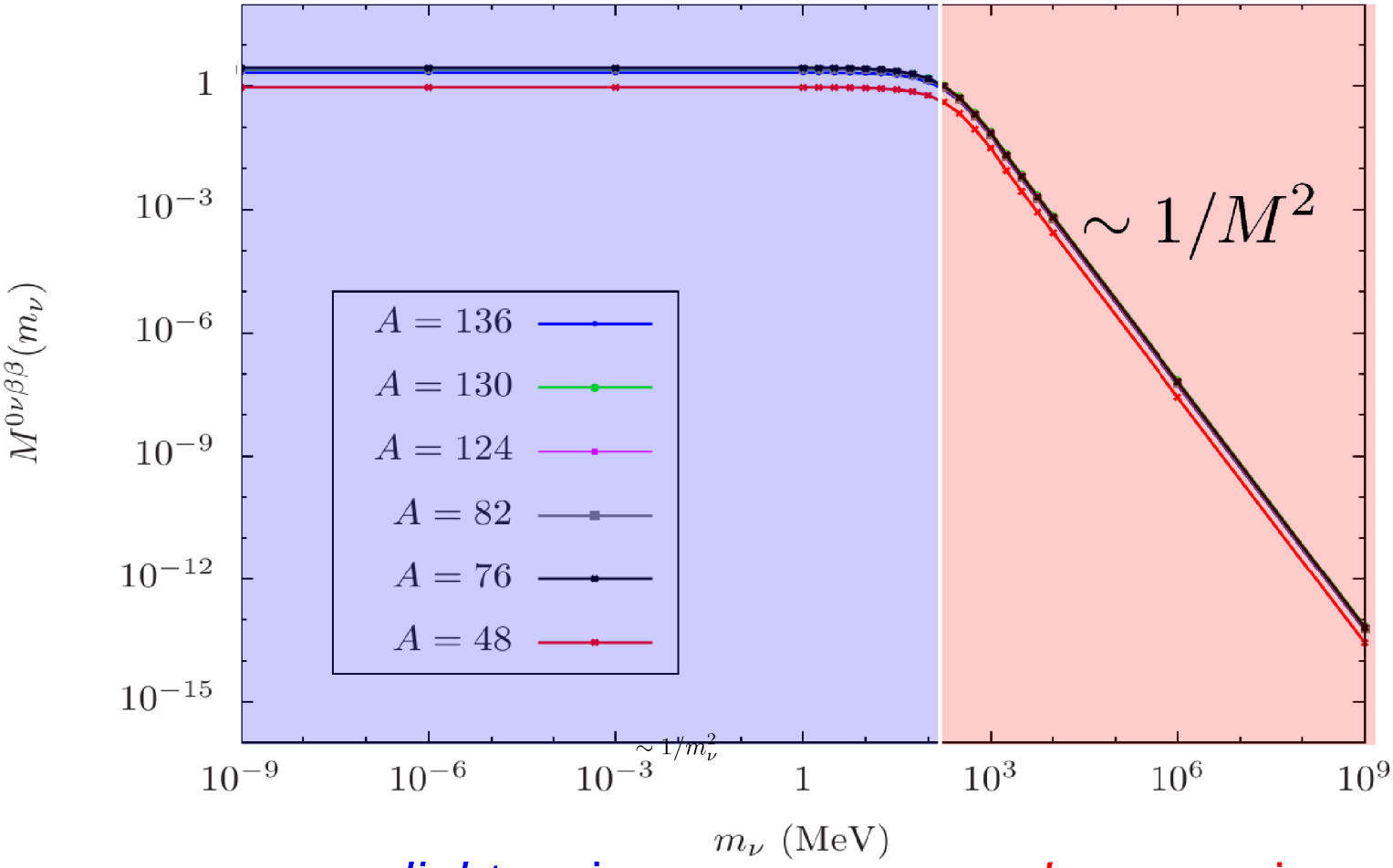
$m_i^2 \ll |p^2|$

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Nuclear Matrix Elements (NMEs)



- 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

Contribution of extra degrees of freedom is neglected

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

$m_{\beta\beta}$

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

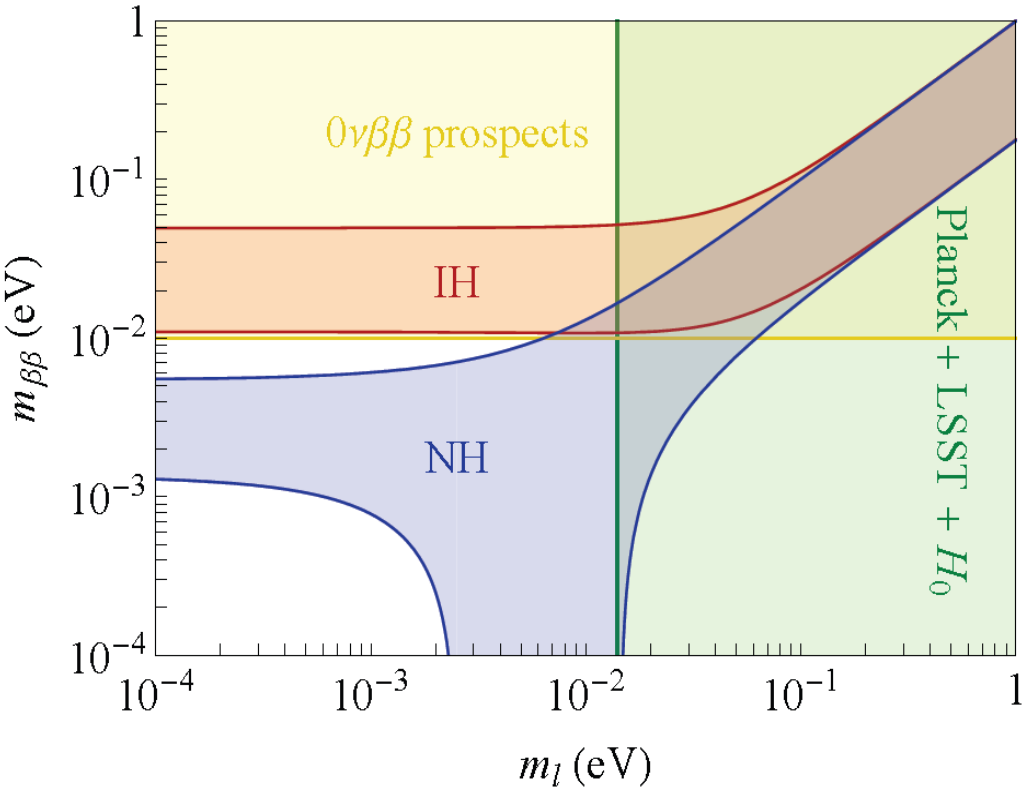
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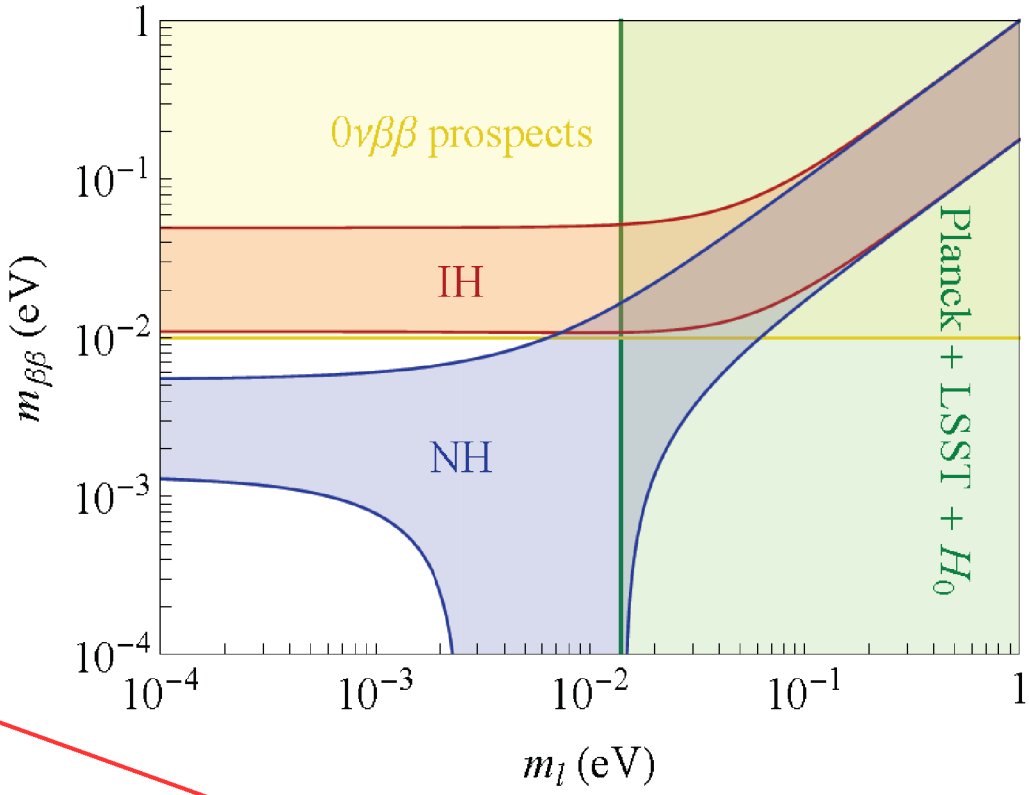
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$m_{\beta\beta}$

→ 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:

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

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

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$$U^* \,\mathrm{diag}\,\{m_1, m_2, ..., m_n\}\, U^\dagger = \begin{pmatrix} 0 & Y_N^* v/\sqrt{2} \\ Y_N^\dagger v/\sqrt{2} & M_N \end{pmatrix}.$$

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

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

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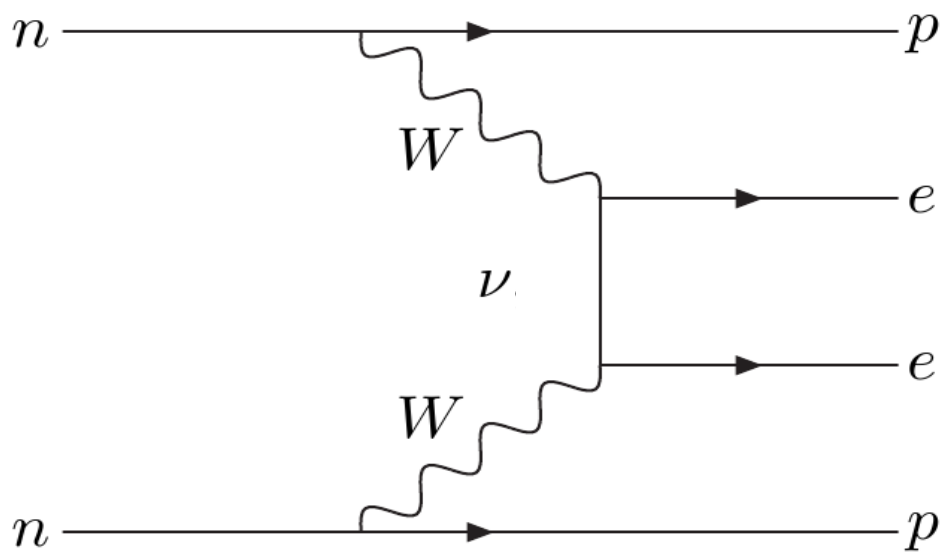
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$\overline{\nu_{\alpha L}}\nu^c_{\alpha L}$

$$\sum_i^{\mathrm{SM}} m_i U_{ei}^2 + \sum_I^{\mathrm{extra}} m_I U_{eI}^2 = 0$$

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

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



$$A \propto \sum_{i}^{\text{SM}} m_i U_{ei}^2 M^{0\nu\beta\beta}(0) + \sum_{I}^{\text{extra}} m_I U_{eI}^2 M^{0\nu\beta\beta}(m_I)$$

light mostly-active states

extra degrees of freedom

↓

Different phenomenologies depending on their mass regime

Sterile neutrinos in light regime

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

Remember

1. ~~$\overline{\nu_{\alpha L}} \nu^c_{\alpha L}$~~ $\quad \sum_i^{\text{SM}} m_i U_{ei}^2 + \sum_I^{\text{light}} m_I U_{eI}^2 = 0$

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

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

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

Sterile neutrinos in light regime

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

→ Analogy: GIM like cancellation between NME:

$$\sum_{i}^{\text{all}} U_{\alpha i} U_{\beta i}^* = 0 \quad \longleftrightarrow \quad \sum_{i}^{\text{all}} m_i U_{ei}^2 = 0$$

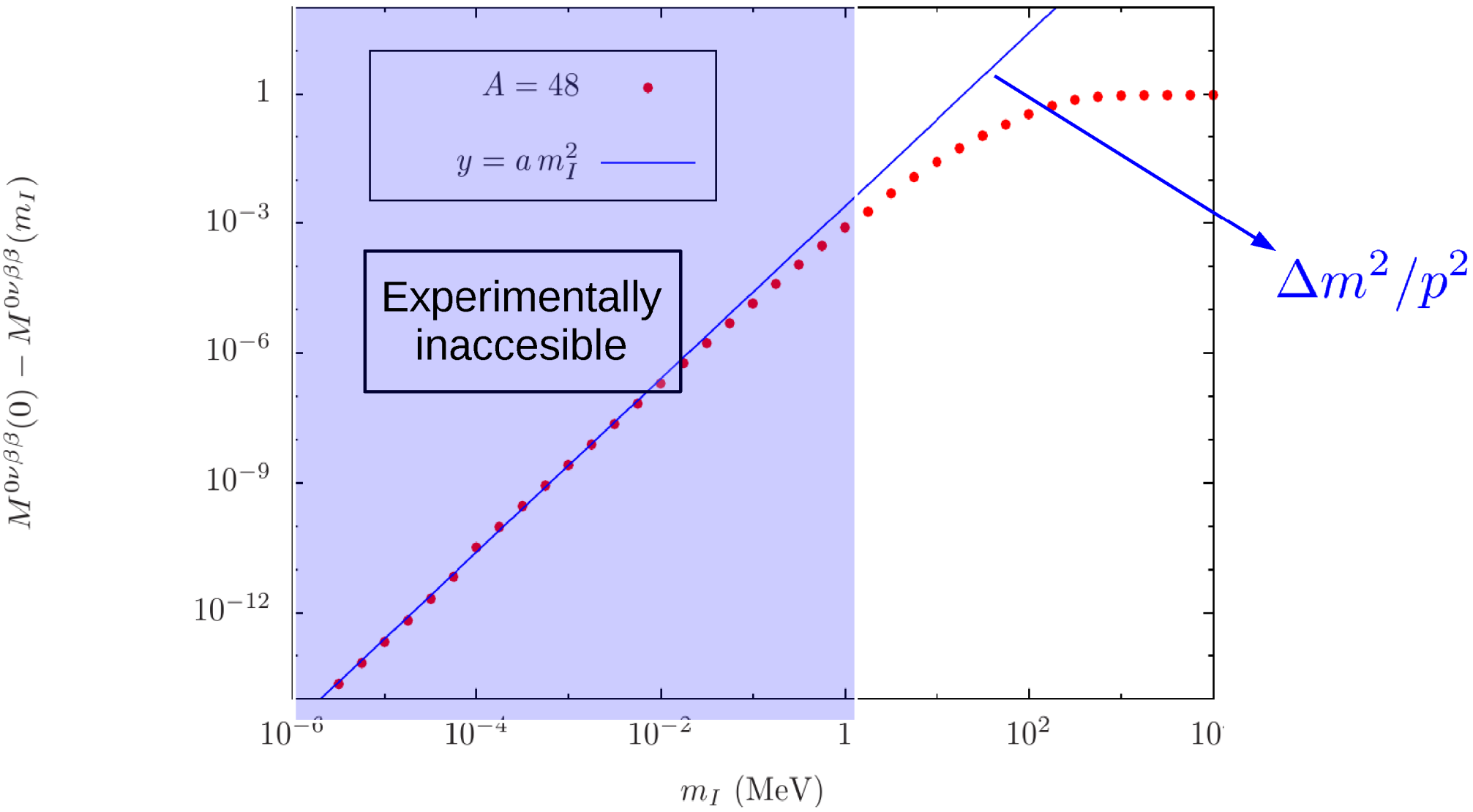
$$\Delta m^2 / M_W^2 \quad \longleftrightarrow \quad \Delta M^{0\nu\beta\beta}$$

driven by the $\Delta m^2 / p^2$ dependence of the NME's

→ Strong suppression for $m_{\text{extra}} < 100\text{MeV}$

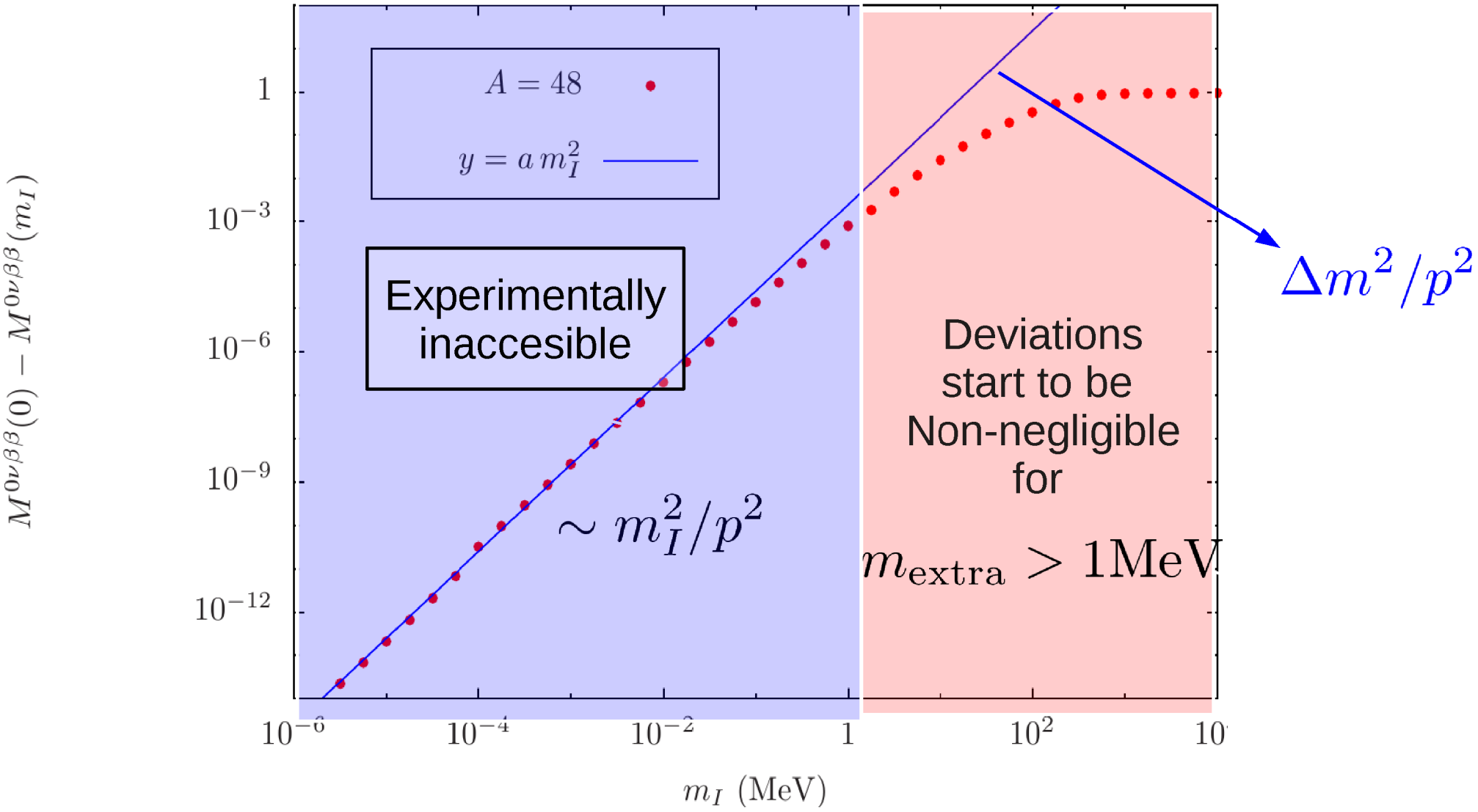
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Sterile neutrinos in heavy regime

”canonical” Type-I seesaw scenario

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

Sterile neutrinos in heavy regime

"canonical" Type-I seesaw scenario

negligible!

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

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

Sterile neutrinos in heavy regime

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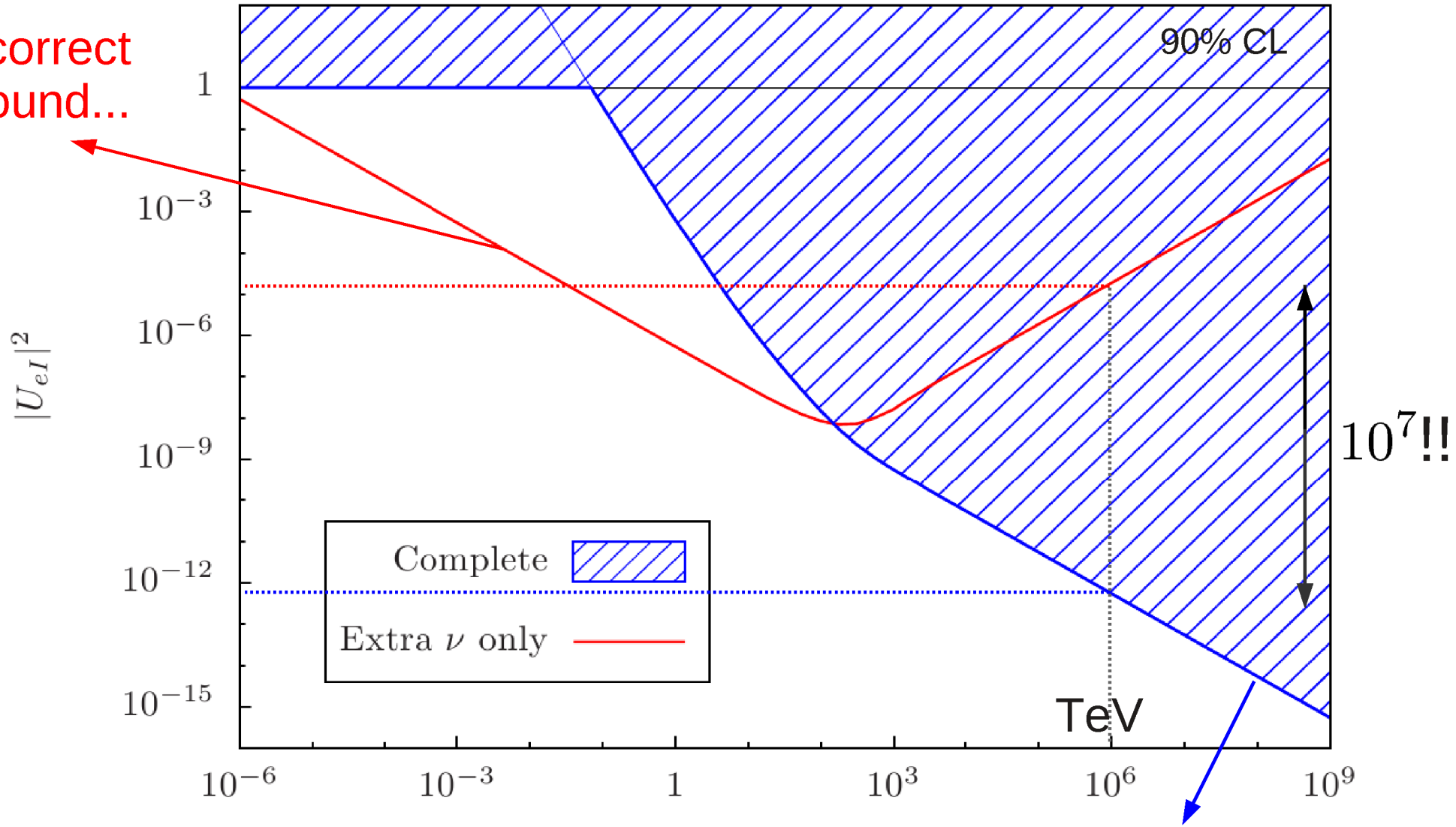
Constrain mixing with heavy neutrinos through light contribution!!

(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



Bounds from COURICINO (with ^{130}Te)

Non-hierarchical extra neutrinos assumed

Much stronger Constraint !!

Blennow, Fernandez-Martinez, Menendez, JLP 10

Sterile neutrinos in heavy & light regime

negligible!

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

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

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

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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

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

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

Ibarra, Molinaro, Petcov 2010
Mitra, Senjanovic, Vissani 2011

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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

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

$\epsilon, \mu, \mu' =$ 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:

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

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 + $2 \times \nu_R$

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$\mu = \epsilon = 0$ 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?

Higher order corrections to the expansion

→ Next to leading order correction to the light active neutrino masses:

Hettmansperger, Lindner, Rodejohann 2011

$$\delta m = \frac{1}{2} m_{tree}\, m_D^{\dagger} M^{-2} m_D + \frac{1}{2} \left(m_{tree}\, m_D^{\dagger} M^{-2} m_D \right)^T$$

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$m_{tree} \to 0$ when cancellation takes place $\to m_{tree} \to 0$

$$\mu = \epsilon = 0$$

Due to the suppresion with ϵ and μ, light neutrino masses are stable under higher order corrections in expansion.



Still, light neutrino contribution vanish when cancellation takes place.

1-loop corrections

Two different effects that should be taken into account:

- Renormalizable corrections (running of the parameters):

Casas *et al.*; Pirogov *et al.*; Haba *et al.* 1999

$$\left.\begin{aligned} Q\frac{d\mu}{dQ} &= \frac{2\epsilon}{(4\pi)^2}\left[\Lambda\, Y_{1\beta}^{*} Y_{2\beta} + \mu\epsilon\, Y_{2\beta}^{*} Y_{2\beta}\right] \\ Q\frac{d\left(\epsilon Y_{2\alpha}\right)}{dQ} &\propto \epsilon \end{aligned}\right\}$$

Light neutrino masses cancellation still holds when running is taken into account.

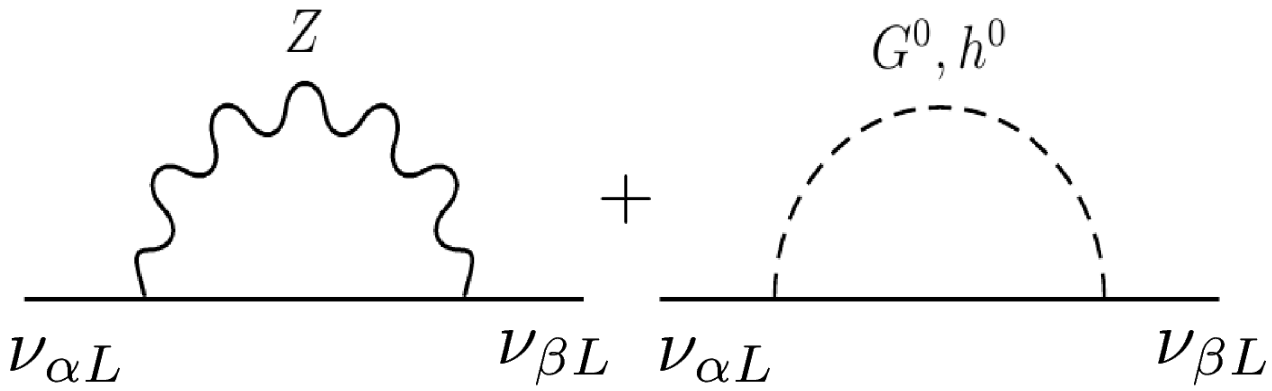
Running not relevant in this context.

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 $(\mu = \epsilon = 0)$:

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

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)

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)

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 (optimistic) sensitivity

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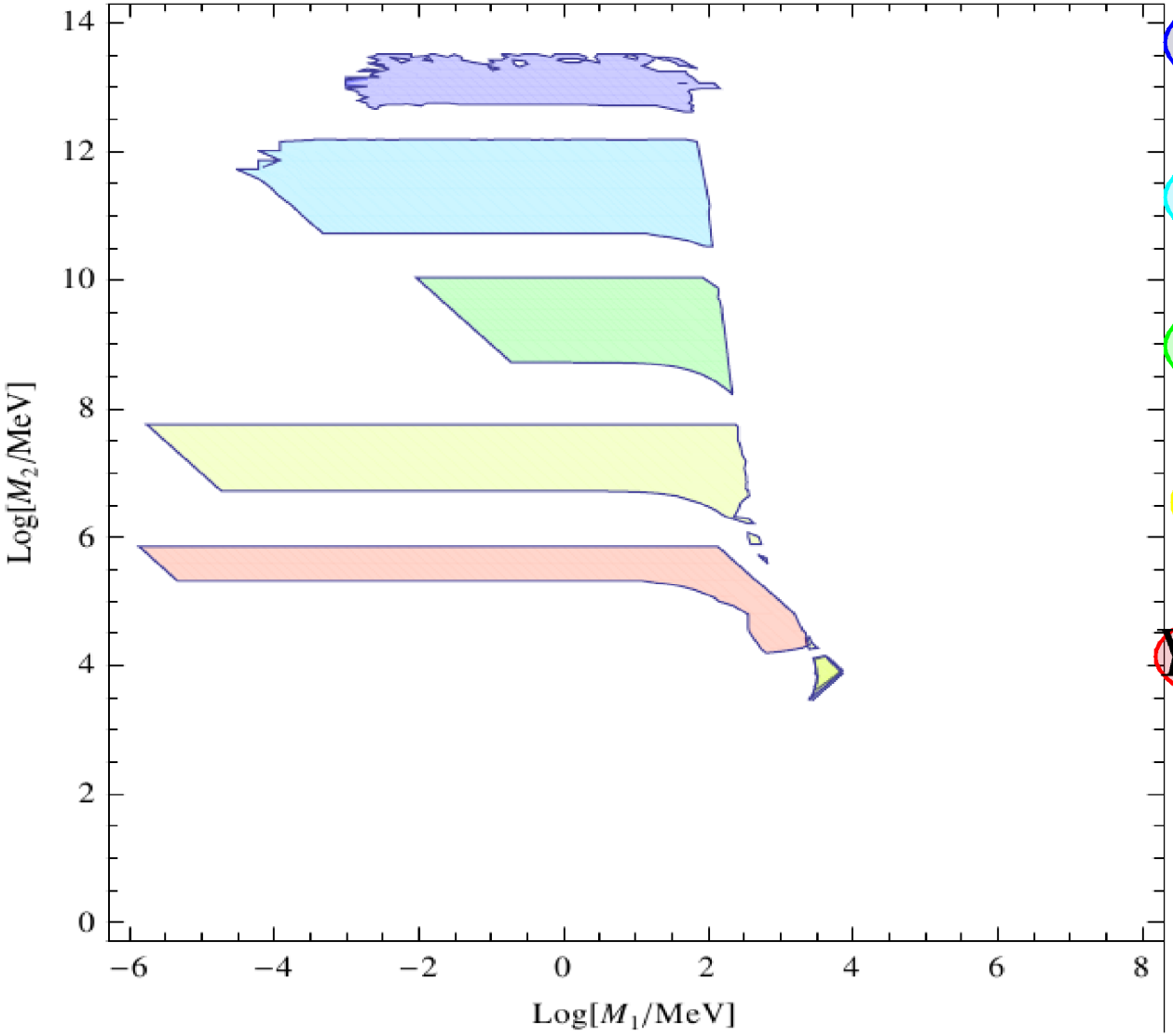
3 Constraints on the mixing with heavy neutrinos from weak decays, lepton number violating processes and non-unitarity.

Atre,Han, Pascoli, Zhang 2009

Antusch, Biggio, Fernandez-Martinez, Gavela, JLP 2006

etc

Sterile Neutrino signal



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

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

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

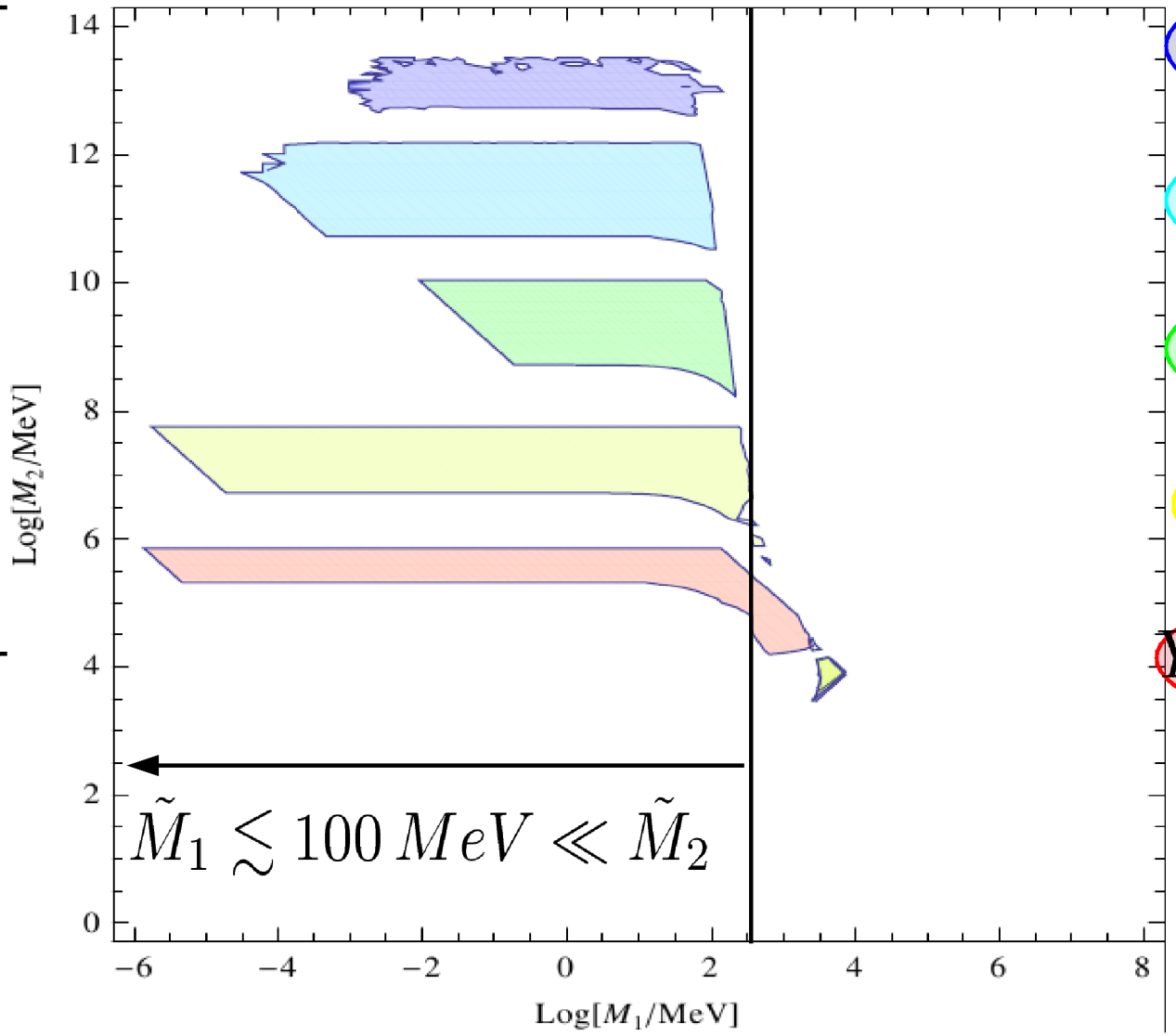
$Y_{1\alpha} = 10^{-5}$

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

Sterile Neutrino signal

Hierarchical seesaw

ESS



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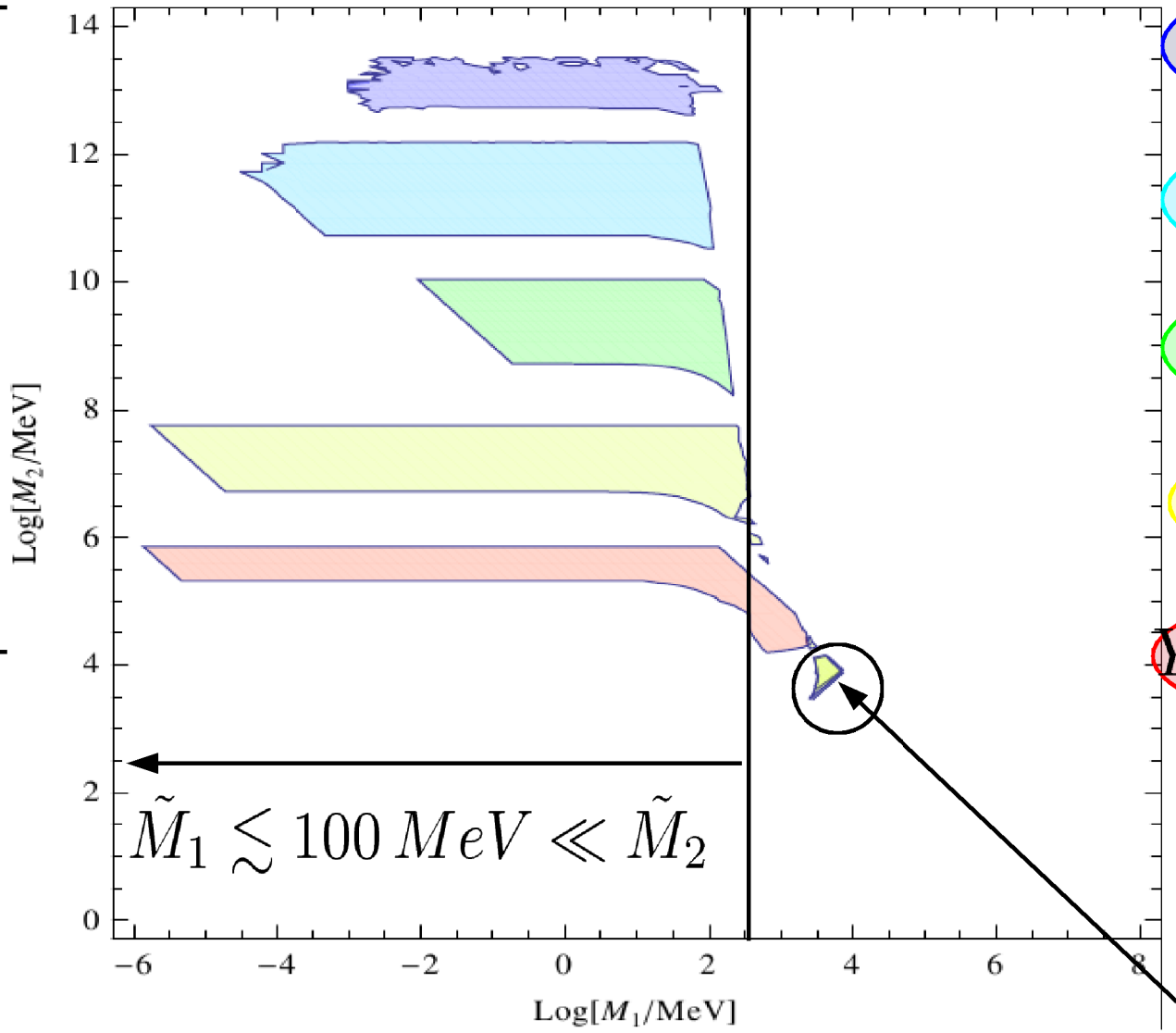
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Sterile Neutrino signal

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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 heavy 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

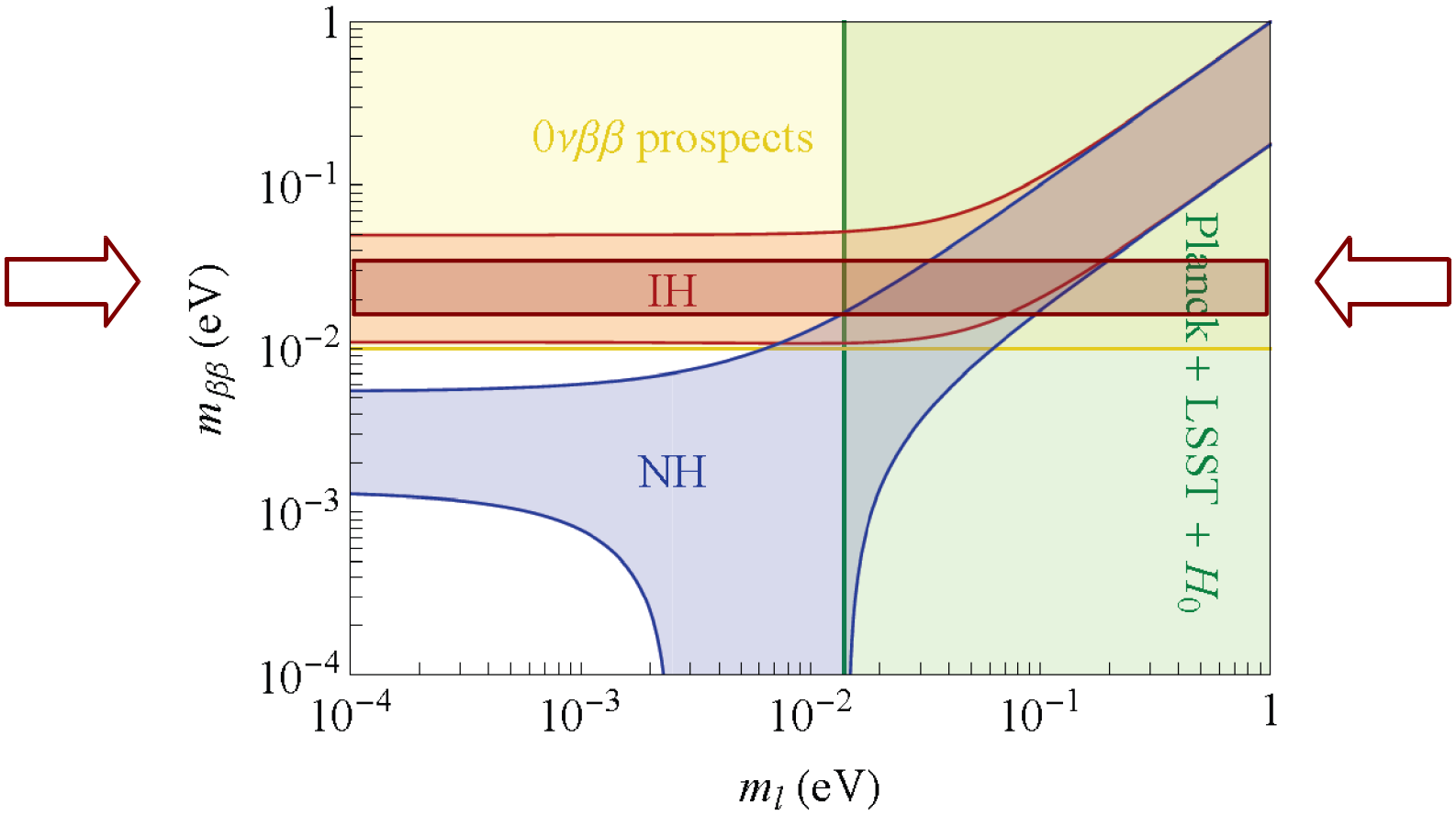
$$\tilde{M}_2 \approx \mu' \gg \tilde{M}_1 \approx \frac{\Lambda^2}{\mu'}$$

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

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

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

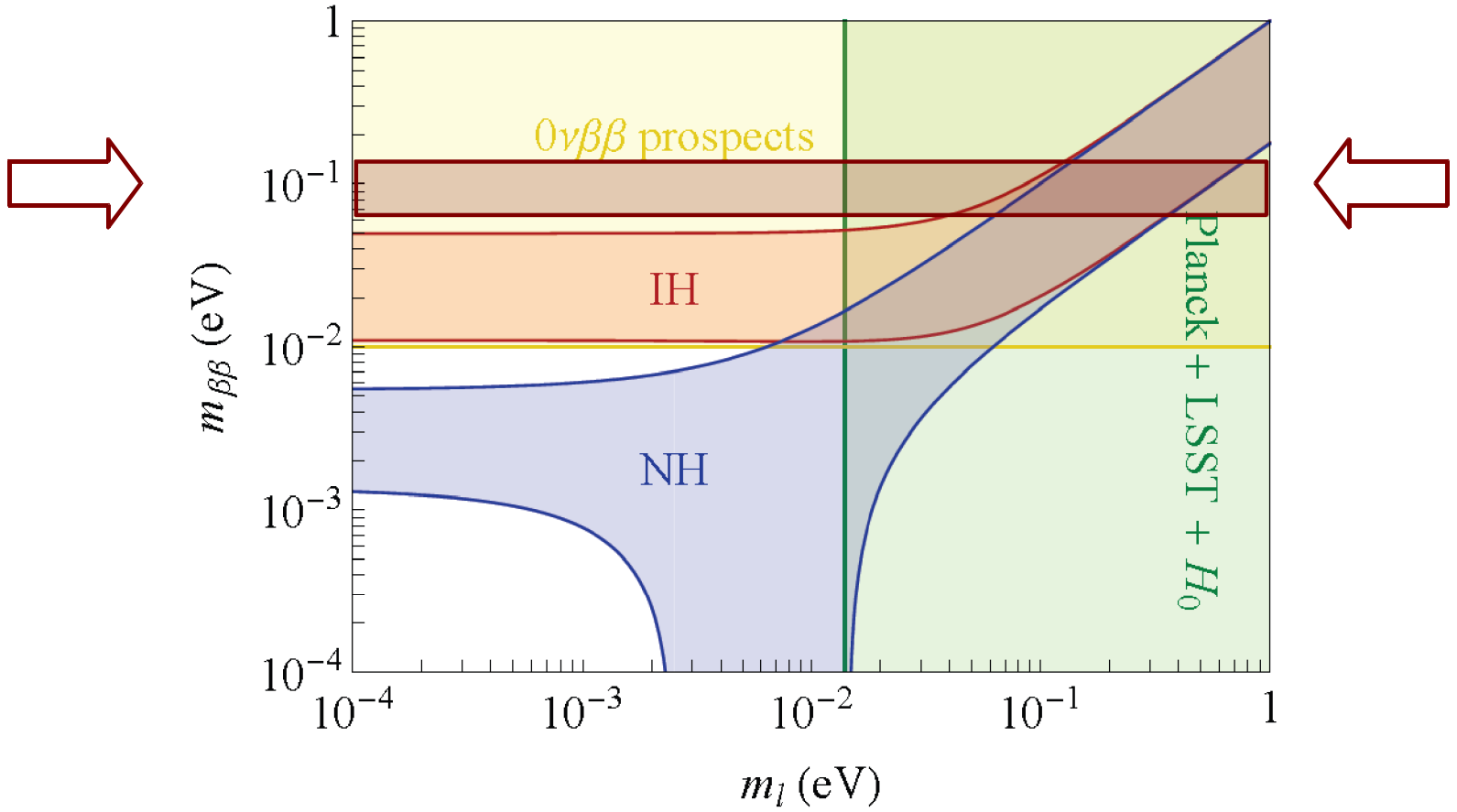
- Light active neutrinos dominate the 0νββ
- New physics above the nuclear scale, but its contribution is suppressed.



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

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

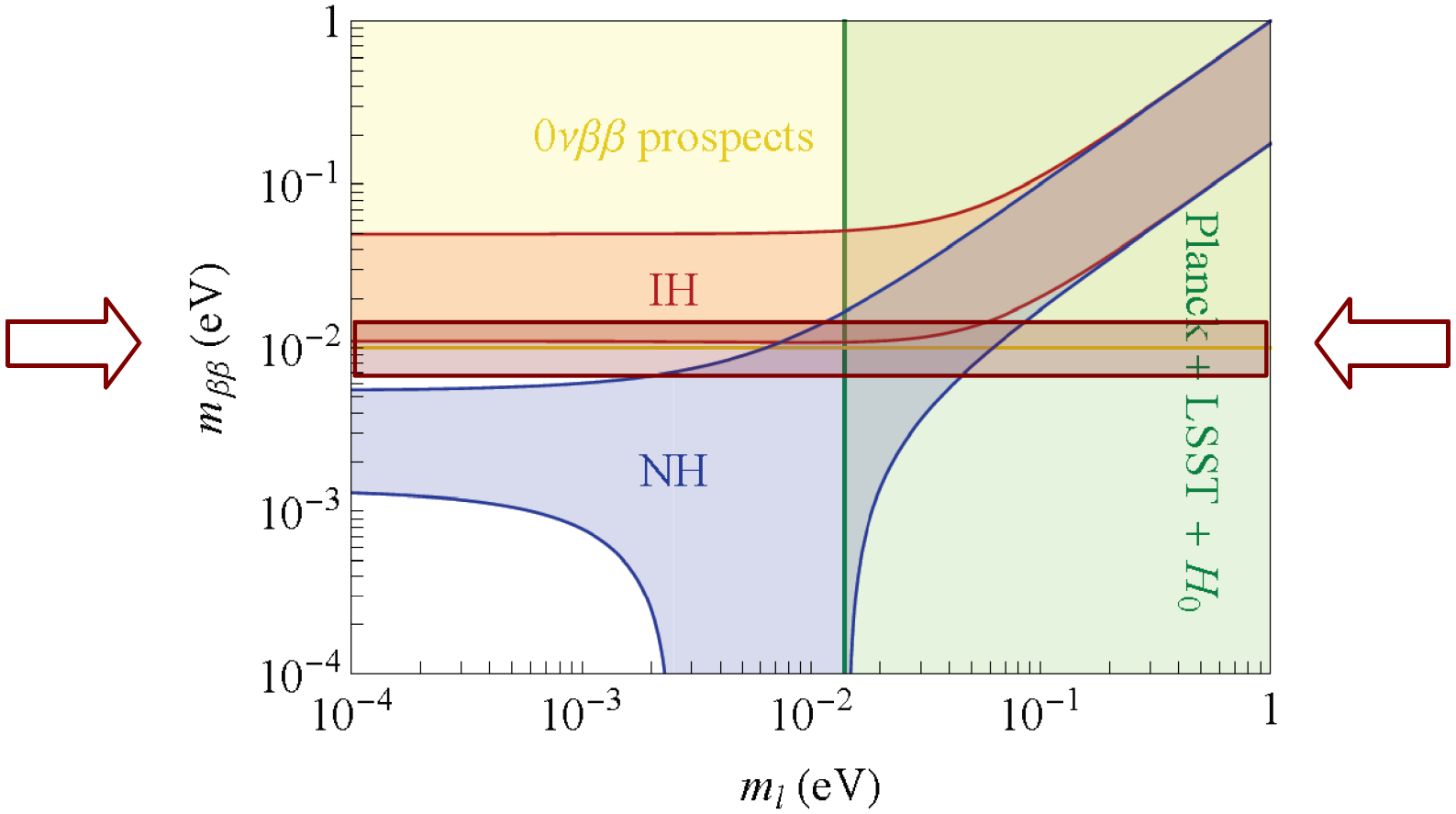
- Light active neutrinos do not dominate the 0νββ
- A dominant New physics contribution is required



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

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

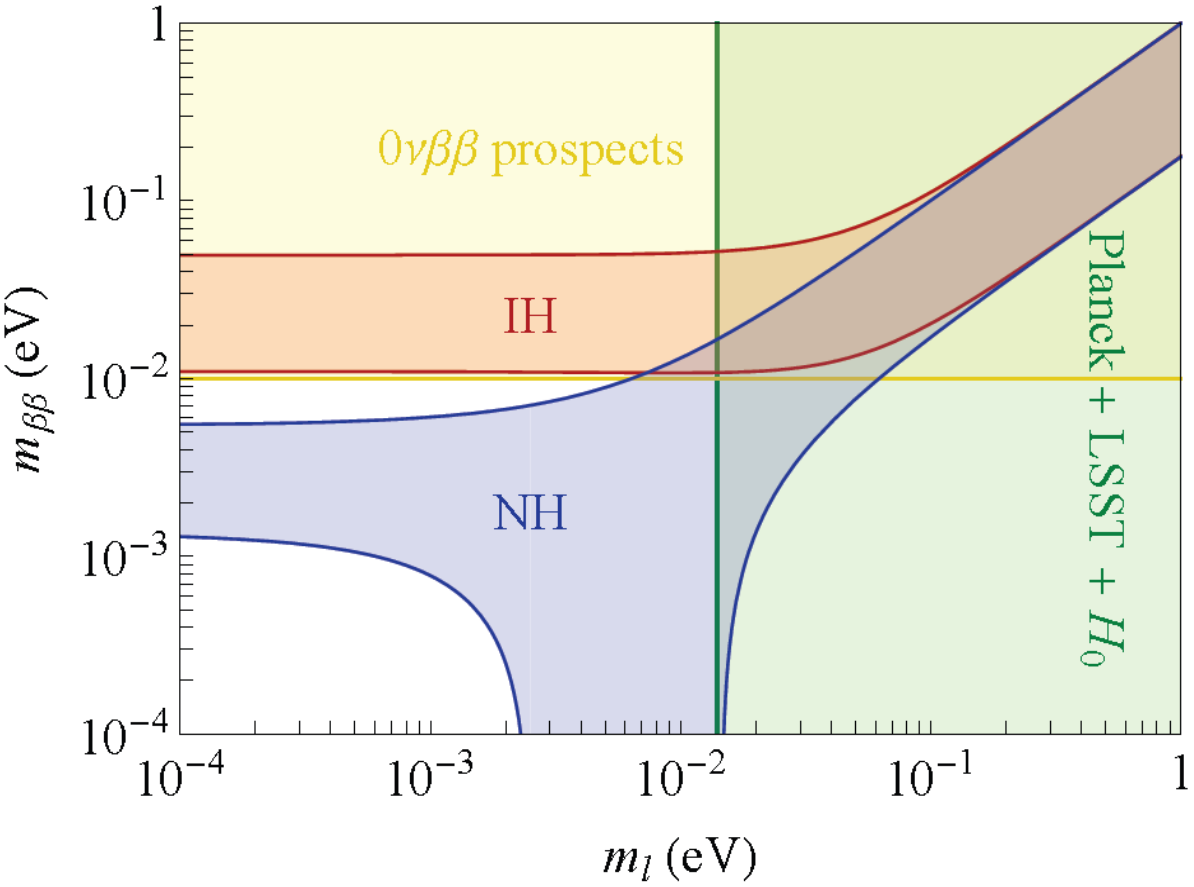
- Parcial cancellation between light active neutrino contribution and extra degrees of freedom (example: sterile neutrinos around the nuclear scale)



$0\nu\beta\beta$ 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



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

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 0νββ decay. This basically requires a hierarchical spectrum with (at least) one sterile neutrino lighter than the 0νββ 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

- Strong complementarity among neutrino oscillations, neutrinoless double beta decay experiments and cosmology. Warning: very relevant role of BBN constraints...they might rule out the light sterile neutrino contribution!!

  Work in progress in collaboration with Pilar and Marija

Thank you!

Back-up

What about the other seesaw realisations?

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

Adding a heavy $SU(2)$ scalar triplet:

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

$$\mathcal{L} = \mathcal{L}_{\rm SM} - (Y_\Delta)_{\alpha\beta}\overline{L^c}_\alpha i\tau_2 \Delta L_\beta$$

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

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$$\mathcal{L} = \mathcal{L}_{\rm SM} - (Y_\Delta)_{\alpha\beta}\overline{L^c}_\alpha i\tau_2 \Delta L_\beta$$

SSB

- Light neutrino masses ("SM"): $m_\nu^\Delta = 2Y_\Delta v_\Delta = Y_\Delta \dfrac{\mu v^2}{M_\Delta^2}$

- Relation between light neutrino masses and extra grades of freedom:

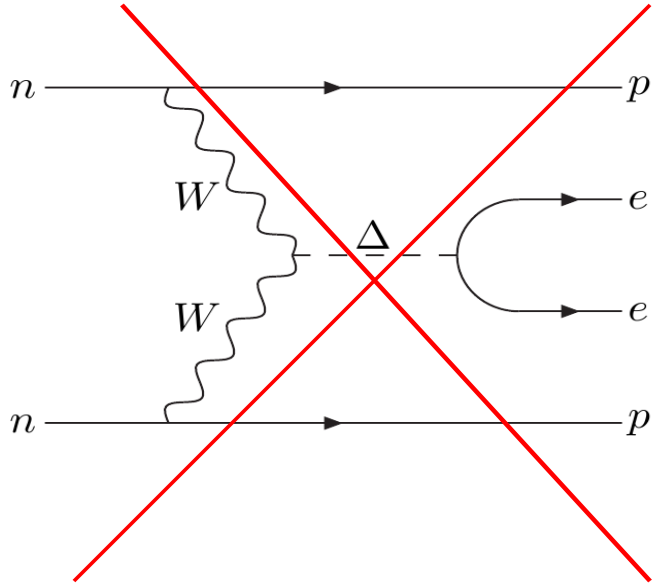
$$\sum_i^{\rm SM} m_i U_{ei}^2 + \sum_I^{\rm heavy} m_I U_{eI}^2 = 0 \quad \longleftrightarrow \quad \sum_i^{\rm SM} m_i U_{ei}^2 = \left(m_\nu^\Delta\right)_{ee}$$

Type-I

Type-II

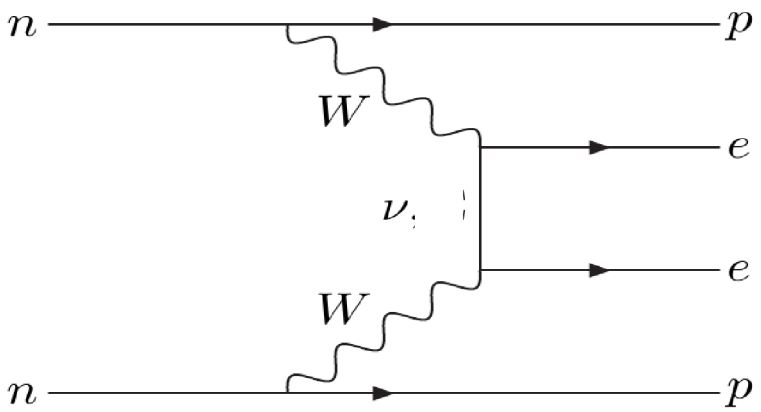
$0\nu\beta\beta$ in Type-II seesaw models

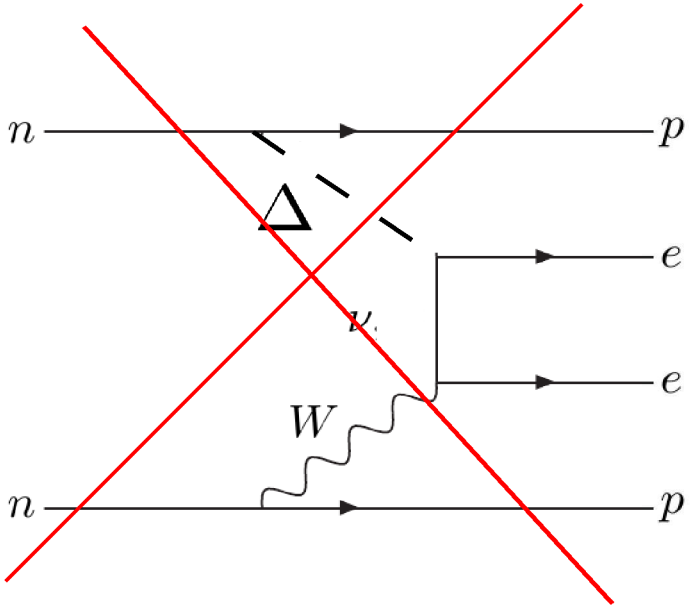
But the scalars can also mediate the process:



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

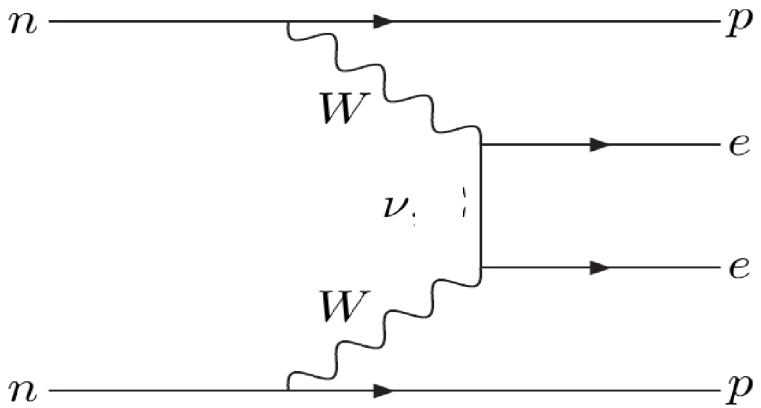
$$< 10^{-6}$$





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

$$< 10^{-5}$$



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

Therefore, in this scenario, as in the Type-I seesaw with all extra states heavy, the light active neutrino contribution dominates and the usual description of 0νββ decay applies:

$$A \approx \left(m_\nu^\Delta\right)_{ee} M^{0\nu\beta\beta}(0) = \sum_i^{\mathrm{SM}} m_i U_{ei}^2 M^{0\nu\beta\beta}(0).$$

- Bounds from light active contribution can be obtained for the extra degrees of freedom:

$$m_\nu^\Delta = (Y_\Delta)_{ee} \frac{\mu v^2}{M_\Delta^2}$$

- The neutrinoless claim and the cosmological data can not be reconciled within this model

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

Adding a heavy $SU(2)$ fermion triplet: $\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}$

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{2}(M_\Sigma)_{ij}\,{\rm Tr}\left(\overline{\Sigma}_i \Sigma_j^c\right) - (Y_\Sigma)_{i\alpha}\tilde{\phi}^\dagger \overline{\Sigma}_i i\tau_2 L_\alpha$$

↓ SSB

- Light neutrino masses ("SM"): $m_\nu^\Sigma = \frac{v^2}{2} Y_\Sigma^T M_\Sigma^{-1} Y_\Sigma$

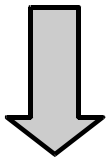
- Relation between light neutrino parameters and extra degrees of freedom:

$$\sum_i^{\rm SM} m_i U_{ei}^2 + \sum_I^{\rm heavy} m_I U_{eI}^2 = 0 \quad \longleftrightarrow \quad \sum_i^{\rm SM} m_i U_{ei}^2 = \left(m_\nu^\Sigma\right)_{ee}$$

Type-I Type-III

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

In addition: Stringent lower bounds in $\sum$ mass



$0\nu\beta\beta$ phenomenology of type III seesaw reduces in practise to Type-II seesaw case, simply doing:

$$m_\nu^\Delta \longrightarrow m_\nu^\Sigma = \frac{v^2}{2} Y_\Sigma^T M_\Sigma^{-1} Y_\Sigma .$$

Nuclear Matrix Element (NME)

Easy to understand expanding the propagator:

- Light netrino regime; $m_i^2 \leq 100\,\mathrm{MeV}$: the NME is constant

$$\frac{1}{p^2 - m_i^2} = \frac{1}{p^2} - \frac{m_i^2}{p^4} + \ldots \qquad M^{0\nu\beta\beta}(m_i) = M^{0\nu\beta\beta}(0)\left[1 - \frac{m_i^2}{p^2} + \ldots\right]$$

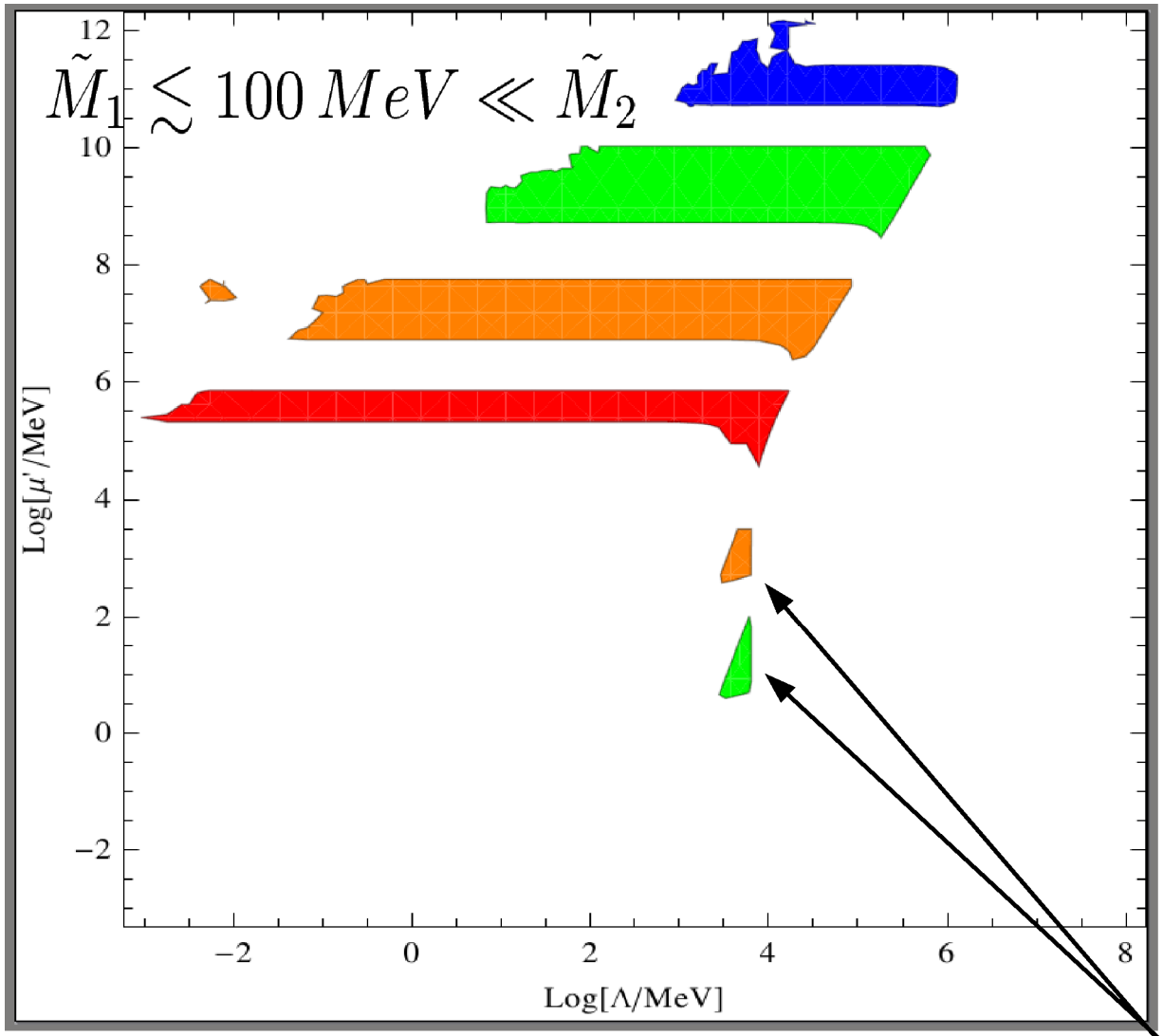
- Heavy netrino regime; $m_i^2 \geq 100\,\mathrm{MeV}$: the NME decreases as $1/m_i^2$

$$\frac{1}{p^2 - m_i^2} = -\frac{1}{m_i^2} + \mathcal{O}\left(\frac{p^2}{m_i^4}\right)$$

- No resonance for $|p^2| \simeq m_i^2$! (t-channel type diagram: $p^2 < 0$)

Dominant Heavy Neutrino Contribution

Hierarchical seesaw



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

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

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

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

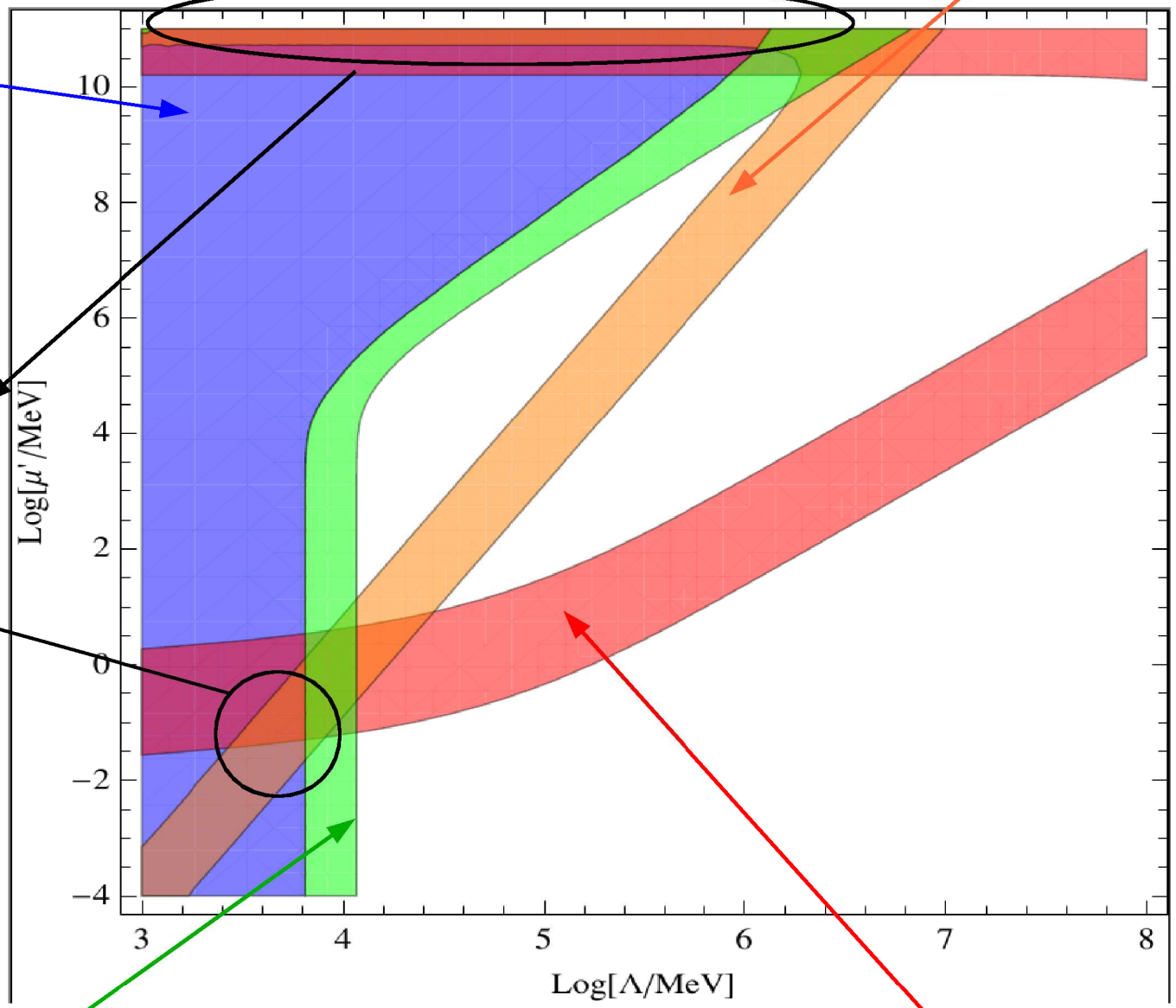
Quasi-Degenerate heavy spectrum

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

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

Sizable heavy contribution

$\frac{A_{heavy}}{A_{light}} > 8$



Heavy neutrinos dominate keeping light masses under control

$1 < \frac{A_{heavy}}{A_{light}} < 8$

$\sqrt{\delta m^2_{solar}} < \delta m_{LL} < 0.58\,eV$