Can heavy neutrinos dominate Neutrinoless double beta decay?

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IPPP
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Invisibles ITN pre-meeting

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Based on a collaboration with:

M. Blennow, E. Fernández-Martínez and J. Menéndez

arXiv:1005.3240 [hep-ph]

S. Pascoli and Chan-Fai Wong

work in progress...

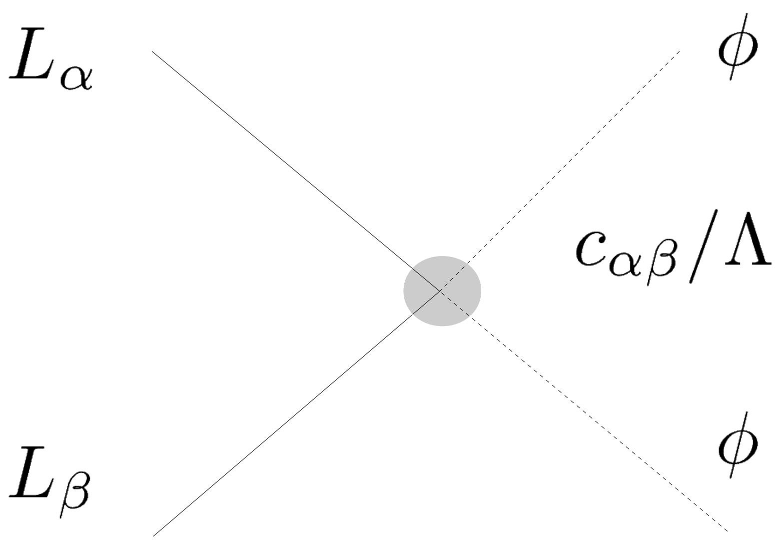
Very Brief Motivation

- Neutrino masses and mixing: evidence of physics Beyond the SM.

- 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



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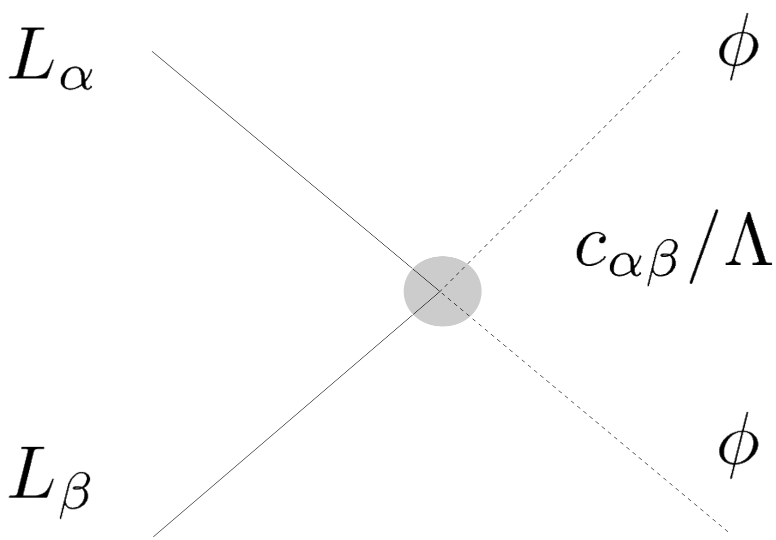

Smallnes of neutrino masses can be explained

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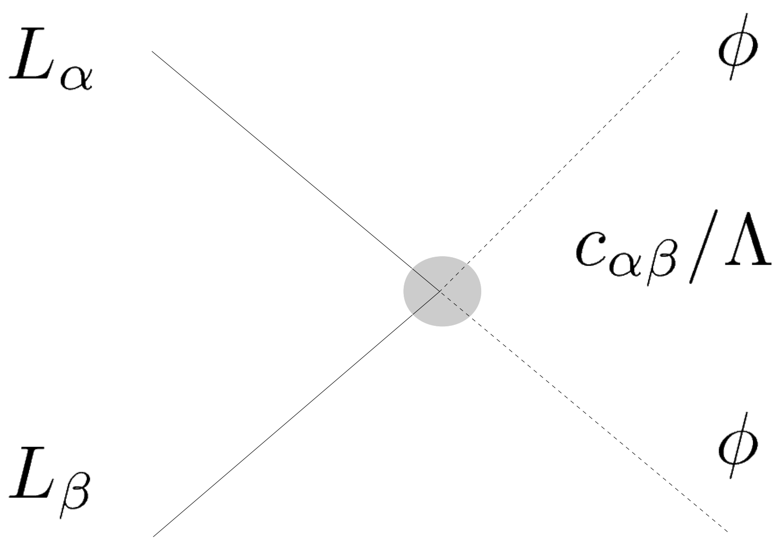
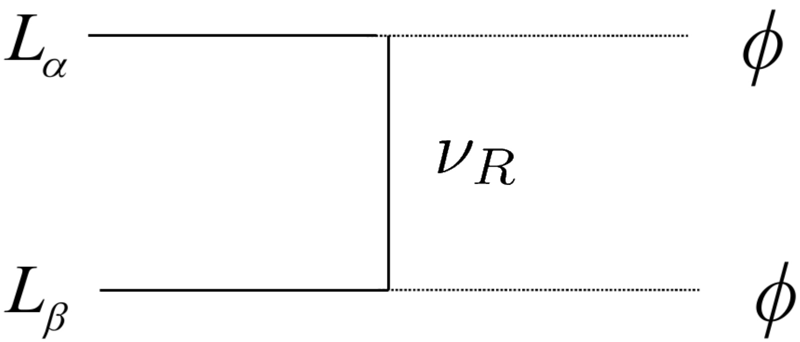


Smallnes of neutrino masses can be explained

$\not{L}$ required for neutrinoless double beta decay ($0\nu\beta\beta$)

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:

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

Neutrinoless double beta decay

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

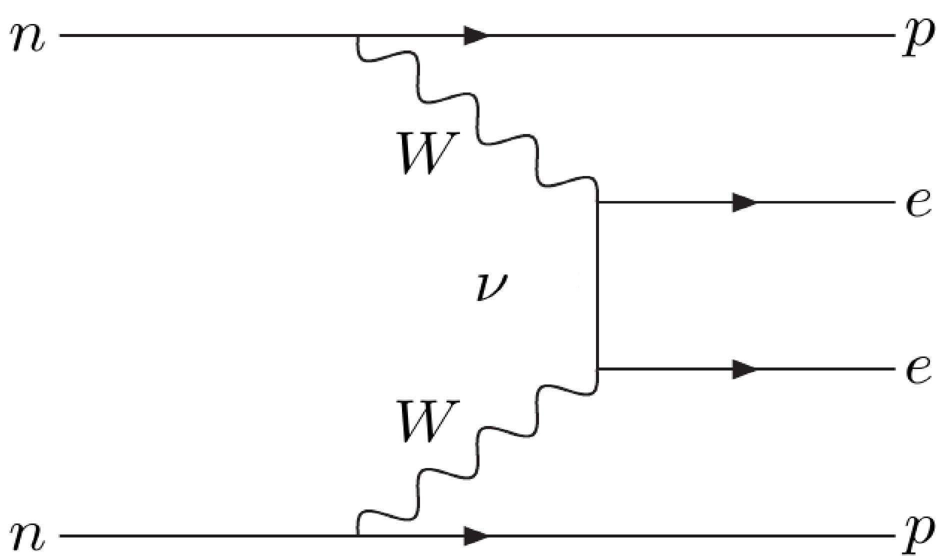
- The neutrinoless double beta decay ($0\nu\beta\beta$) is one of the most promising experiments in this context.

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

Its observation would imply ν's are Majorana fermions
Schechter and Valle 82

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

Neutrinoless double beta decay



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

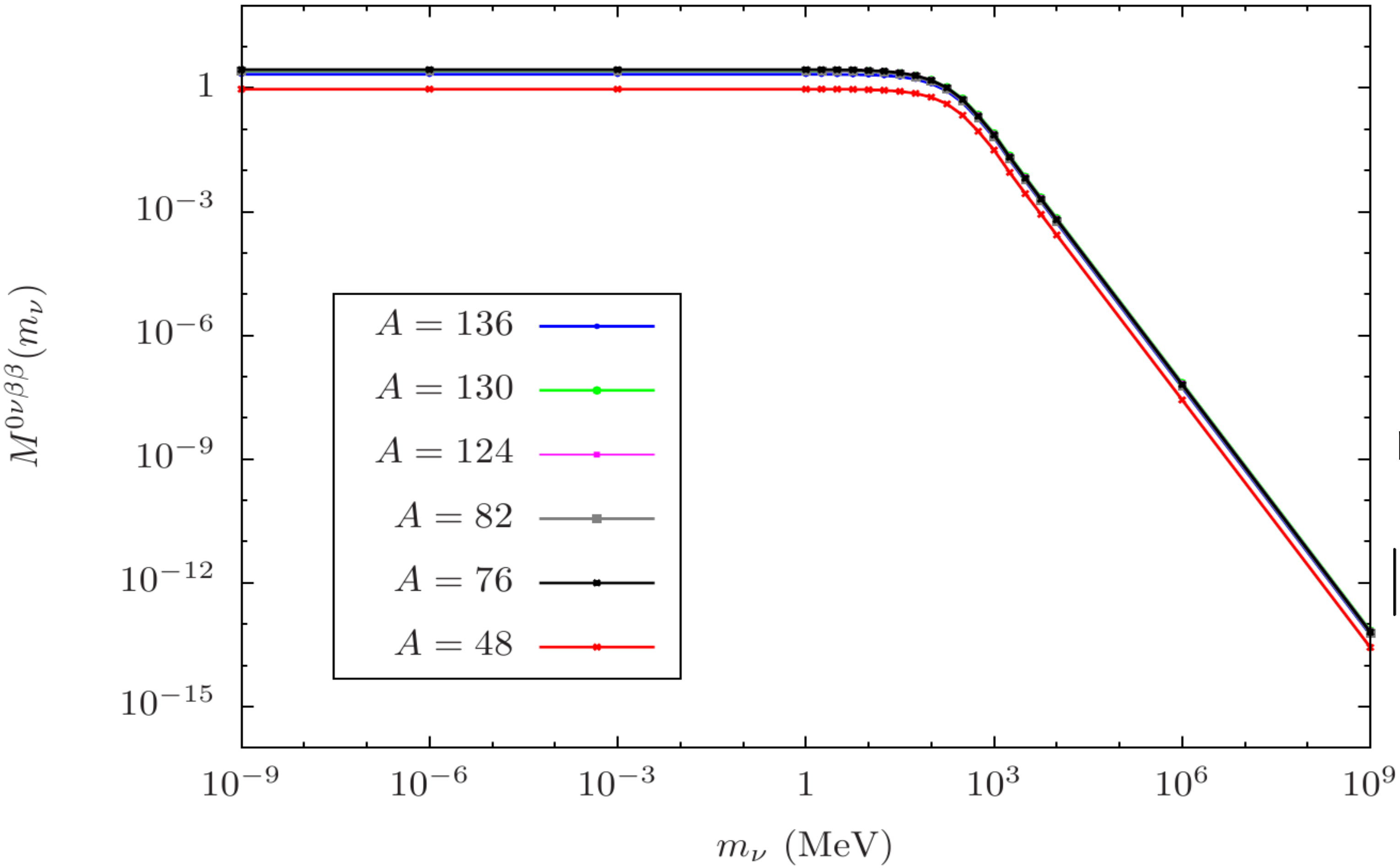
$$A_i \propto m_i U_{ei}^2 M^{0\nu\beta\beta}(m_i)$$

mass of propagating neutrino

Lepton mixing matrix

NME

Nuclear Matrix Element (NME)



- Mild dependece 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

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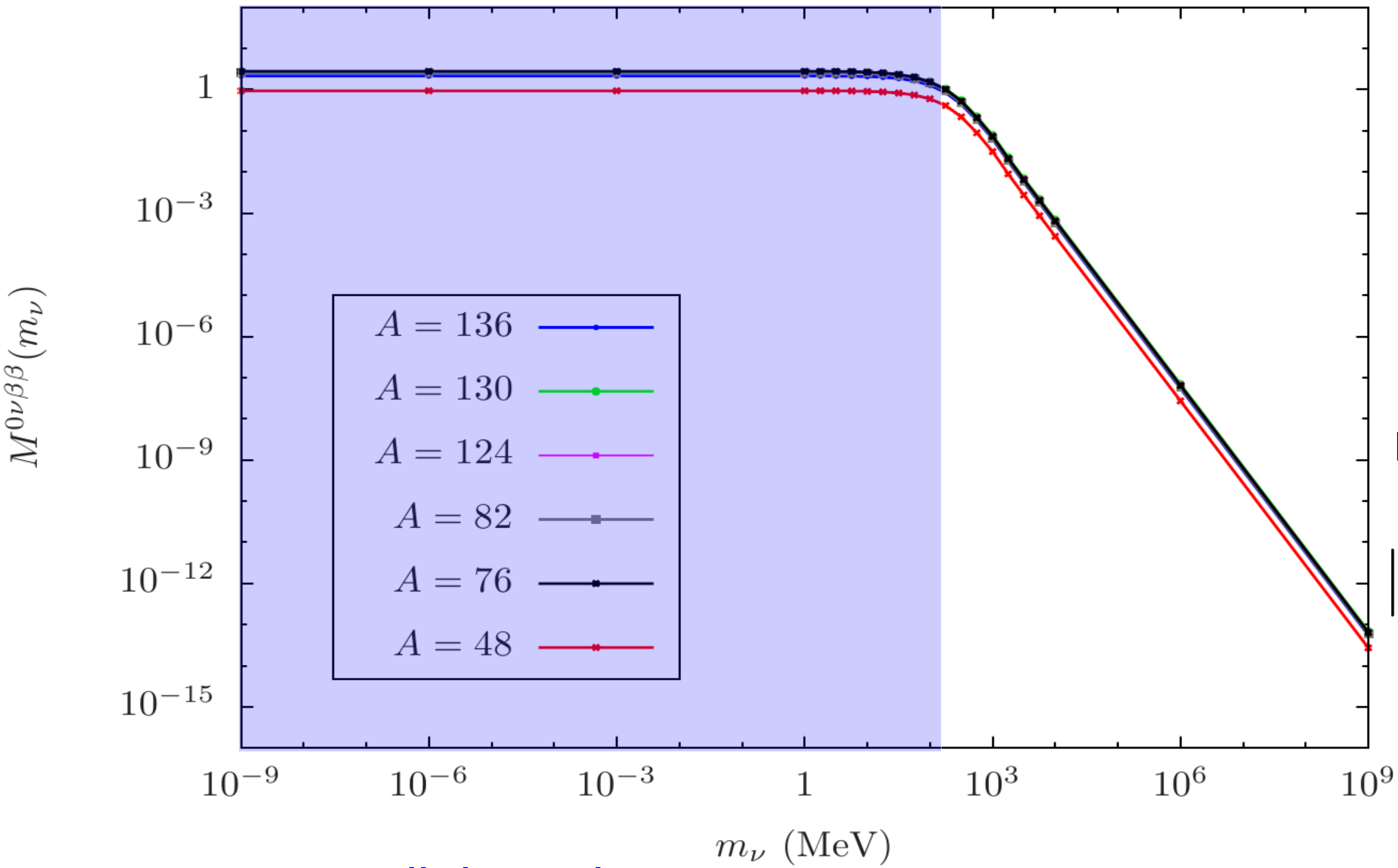

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light regime

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

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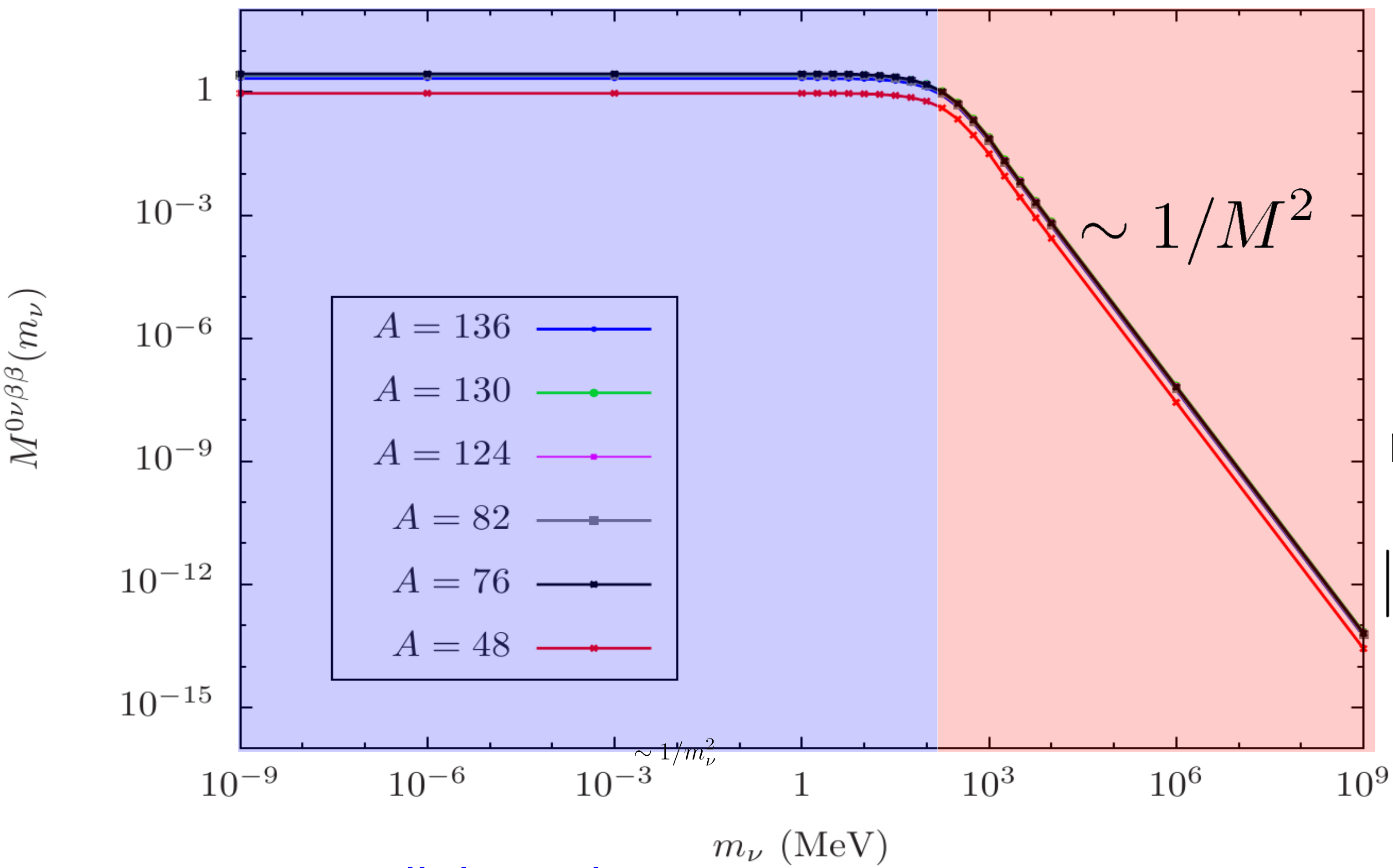

- Mild dependece on the nuclei
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light regime $m_i^2 \ll |p^2|$

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

Data available @
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standard approach

Usual assumption: neglect contribution of extra degrees of freedom.

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

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$\sum_{i=1}^{3} m_i U_{ei}^2 \rightarrow m_{\beta\beta}$

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$m_{\beta\beta}$

Using PMNS matrix parameterisation:

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

- Holds when "SM" neutrinos dominate the process

They can be very relevant !!

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

$0\nu\beta\beta$ in Type-I 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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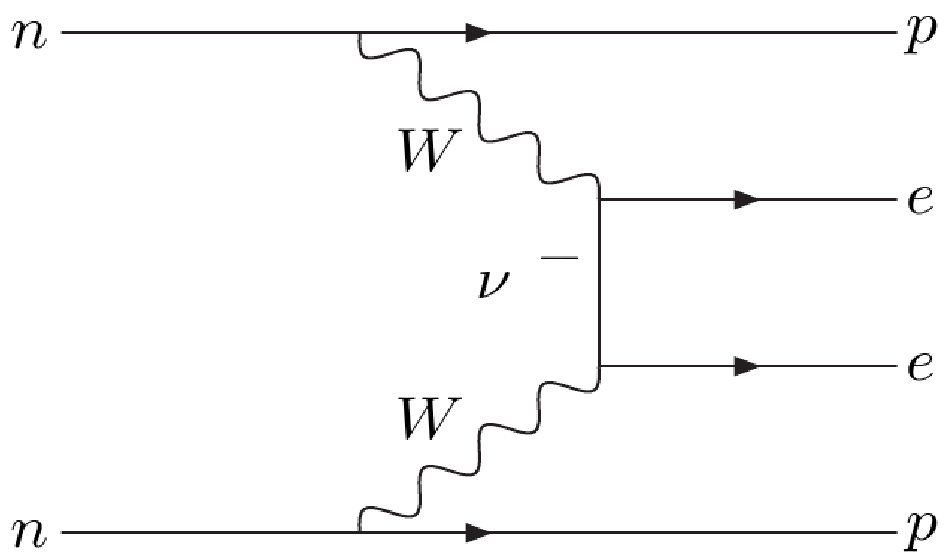
$$\overline{\nu_{\alpha L}}\nu^c_{\alpha L}$$

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

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

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



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

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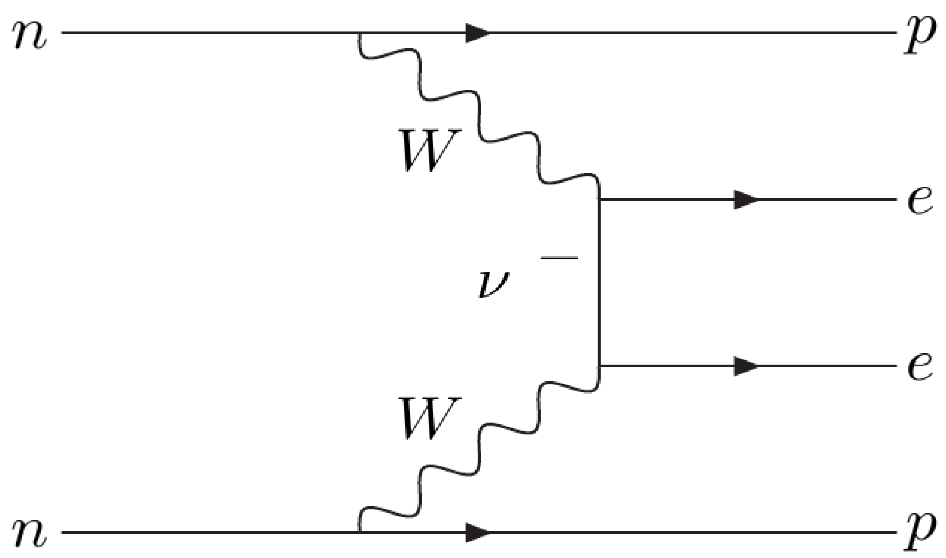

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light mostly-active states

extra degrees of freedom

Different phenomenologies depending on their mass regime

Type-I: All extra masses in light regime

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

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Remember

1. $\overline{\nu_{\alpha L}} \nu_{\alpha L}^c$ (crossed out) $\quad \sum_i^{\text{SM}} m_i U_{ei}^2 + \sum_I^{\text{light}} m_I U_{eI}^2 = 0$

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

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

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

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

Type-I: All extra masses 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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Constrain mixing with heavy neutrinos through light contribution!!

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

Type-I: Extra masses in heavy & light regime

negligible!

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

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

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Extra states with masses below 100 MeV
can give a relevant contribution!
even
dominate the process (fine-tuning required)

Is there any other case in wich the heavy neutrino contribution might dominate?

JLP, S. Pascoli and Chan-Fai Wang

Yes, there is an important exception

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

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Heavy neutrinos dominate process at tree level...

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

Parameterization

- In the appropriate basis, without loss of generality

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

- $\Lambda \gg \mu, \epsilon v, \mu'$ Minimal Flavour Violation models (*inverse seesaw*, etc)

arXiv:0906.1461; Gavela, Hambye, D. Hernandez, P. Hernandez 2009.

Quasi-degenerate heavy neutrino spectrum

arXiv:1103.6217
Ibarra, Molinaro, Petcov 2010

$$\tilde{M}_2 \approx -\tilde{M}_1 \approx \Lambda \qquad \Delta\tilde{M} \approx \mu' + \mu$$

- $\mu' \gg \Lambda, \mu, \epsilon v$ *Extended seesaw model*

Kang, Kim 2007
Majee, Parida, Raychaudhuri 2008

Hierarchical heavy neutrino spectrum

arXiv:1108.0004
Mitra, Senjanovic, Vissani 2011

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

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- We will not restrict the study to any input of the parameters but...

→ For simplicity, we consider just 2 fermion singlets

→ From neutrino oscillations we know the allowed regions are:

Donini, P. Hernandez, JLP, Maltoni 2011

$$\tilde{M} \ll Yv/\sqrt{2}$$

Dirac

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seesaw

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seesaw

Tree level Cancellation of light contribution

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

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

$$\Downarrow$$

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

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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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0 when cancellation takes place 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 masses vanish when cancellation takes place. They should be generated at loop level

?

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

$$Q\frac{d\mu}{dQ} = \frac{2\epsilon}{(4\pi)^2}\left[\Lambda\, Y^*_{1\beta} Y_{2\beta} + \mu\epsilon\, Y^*_{2\beta} Y_{2\beta}\right]$$

$$Q\frac{d\left(\epsilon Y_{2\alpha}\right)}{dQ} \propto \epsilon$$

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

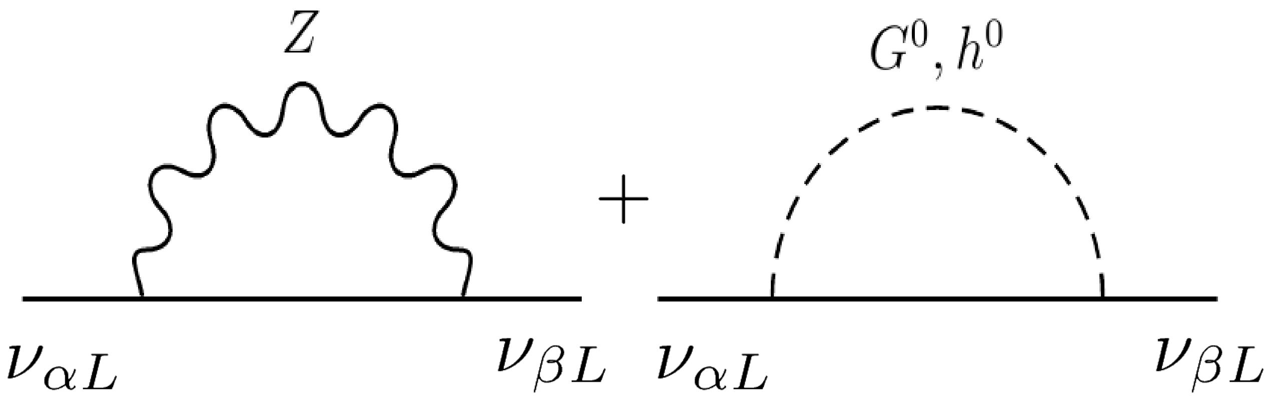
Running not relevant in this context.

1-loop corrections

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

Grimus & Lavoura 2002; Aristizabal Sierra & Yaguna 2011

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



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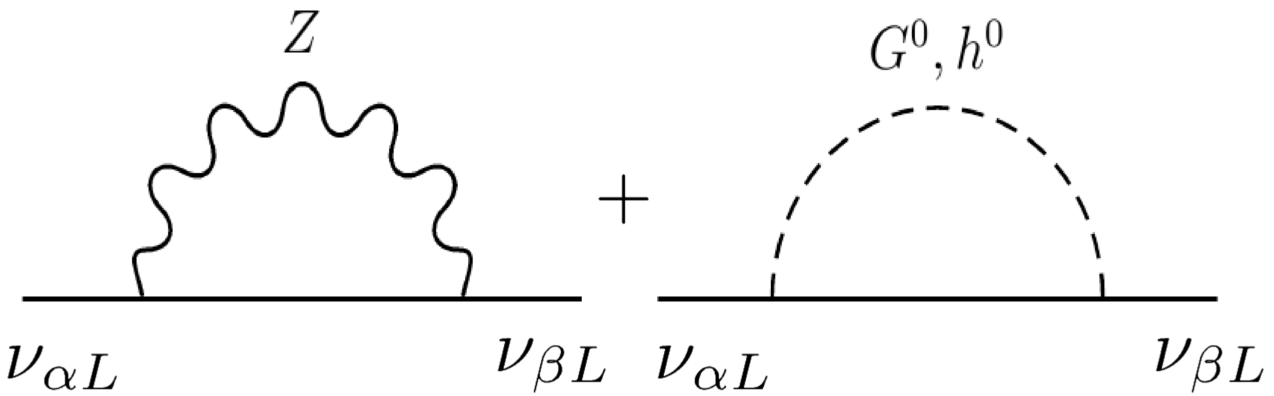

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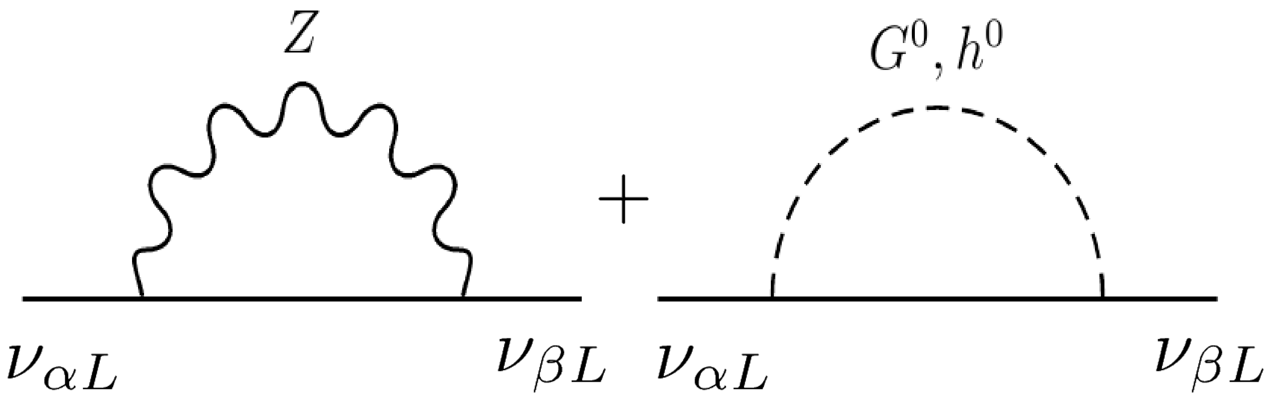

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→ No m_D/M expansion considered.

1-loop corrections

$$-\mathcal{L}_{mass} = \frac{1}{2}\overline{\nu_{Ri}}(M_N)_{ij}\nu^c_{Rj} + (\delta m_{LL})_{\alpha\beta}\overline{\nu_{\alpha L}}\nu^c_{\beta L} - (Y_\nu)_{i\alpha}\overline{\nu_R}\nu_{\alpha L}$$

The neutrino mass matrix is then given by:

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$$\overline{\nu_{\alpha L}}\nu^c_{\alpha L} : \qquad \sum_i^{\mathrm{SM}} m_i U_{ei}^2 + \sum_I^{\mathrm{extra}} m_I U_{eI}^2 = (\delta m_{LL})_{ee}$$

Relation between "light" parameters and extra degrees of freedom is modified

1-loop corrections

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

cancellation condition
$\mu = \epsilon = 0$

$$(\delta m_{LL})_{ee} + \sum_I^{\text{extra}} m_I U^2_{eI} \approx (\delta m_{LL})_{ee}$$

Relation between "light" parameters and extra degrees of freedom is modified

1-loop corrections

$$-\mathcal{L}_{mass} = \frac{1}{2}\overline{\nu_{Ri}}(M_N)_{ij}\nu^c_{Rj} + (\delta m_{LL})_{\alpha\beta}\overline{\nu_{\alpha L}}\nu^c_{\beta L} - (Y_\nu)_{i\alpha}\overline{\nu_R}\nu_{\alpha L}$$

The neutrino mass matrix is then given by:

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

cancellation condition $\mu = \epsilon = 0$ ⇒

$$\sum_I^{\text{extra}} m_I U_{eI}^2 \approx 0$$

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

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

Constraints

1 Neutrino oscillations $\sqrt{\delta m^2_{solar}} < \delta m_{LL} < 0.54\, eV$ Absolute mass scale experiments (WMAP7)

$2\, eV$ (^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 sizable, to be phenomenologically interesting

$$10^{-2}\, eV < m_{\beta\beta}^{heavy} < 0.58\, eV$$

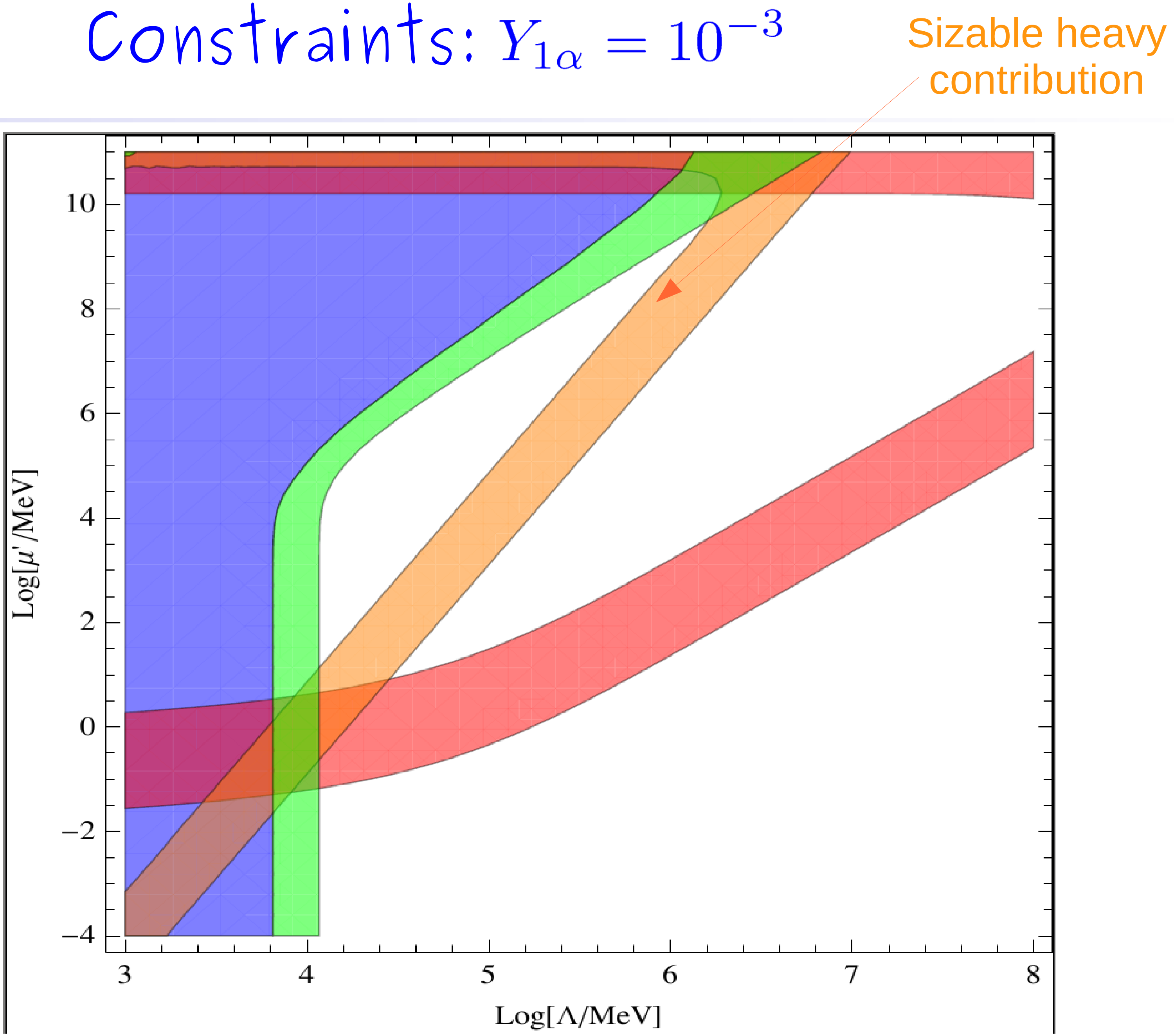
Present bound
CURICINO using ISM NME

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

$$m_{\beta\beta}^{heavy} = |\sum_{I=4,5} U_{eI}^2 m_I M^{0\nu\beta\beta}(m_I)/M^{0\nu\beta\beta}(0)|$$

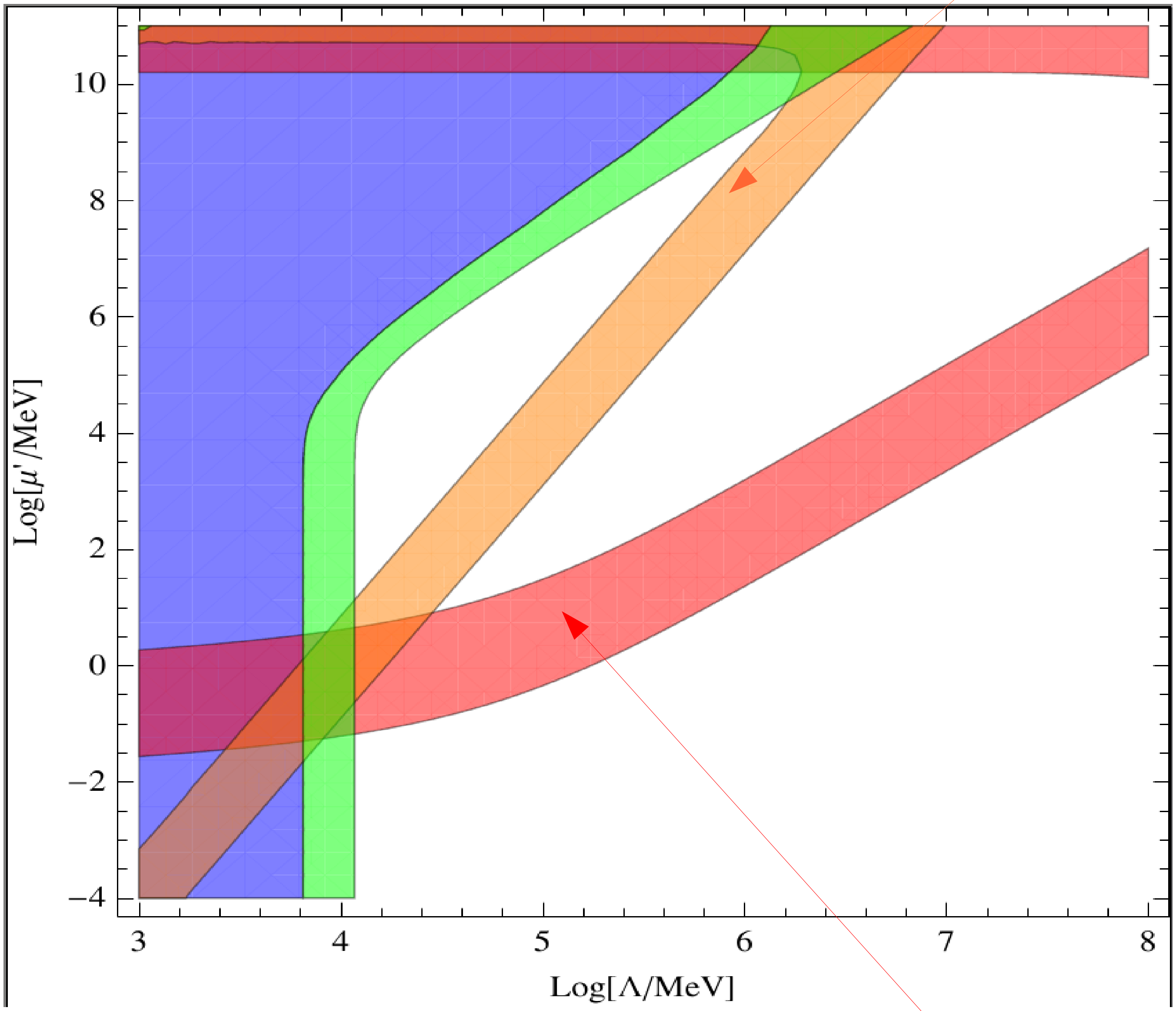
computed in the ISM
Blennow, Fernandez-Martinez, Menendez, JLP. arXiv:1005.324

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



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

Sizable heavy contribution

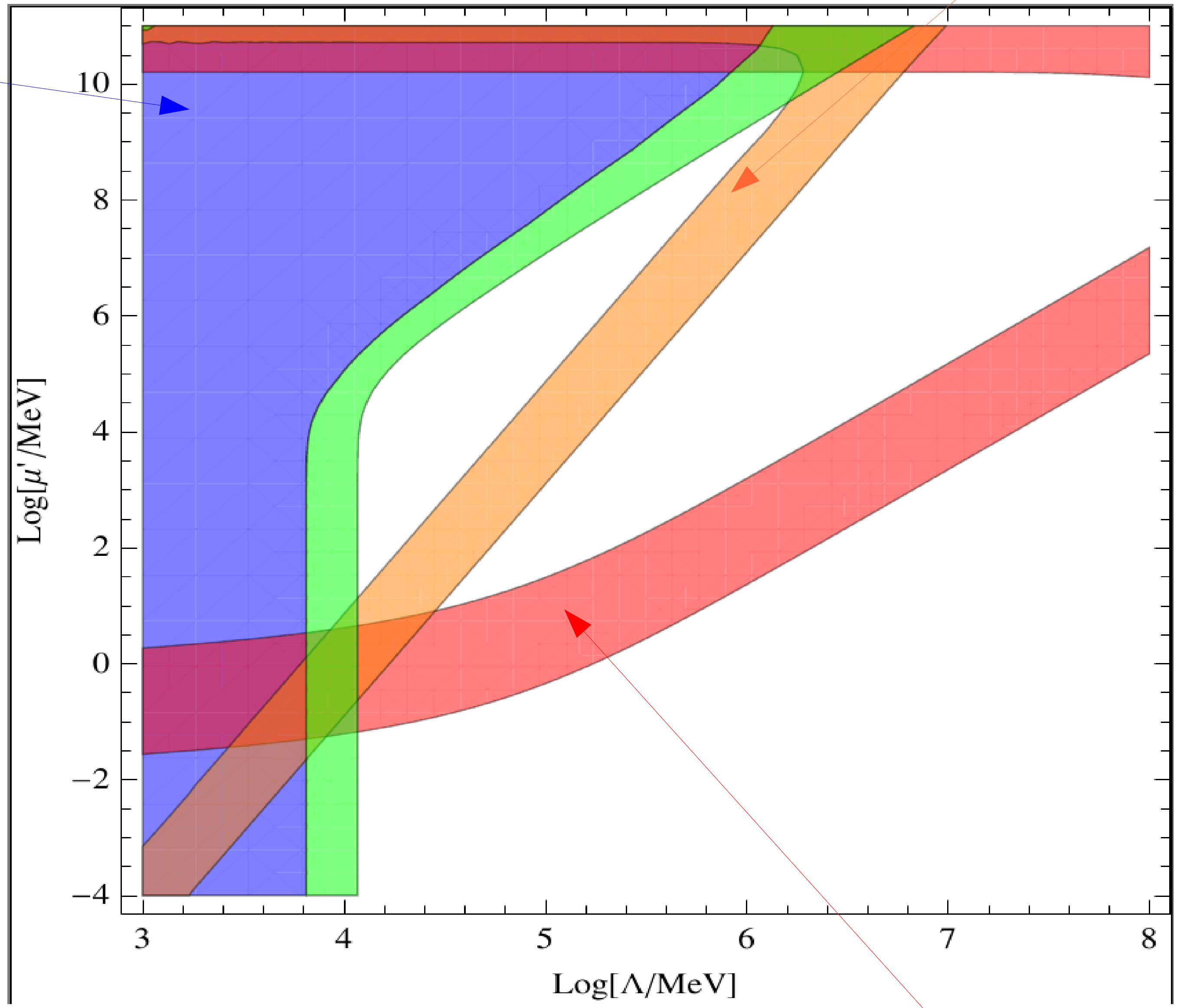


$$\sqrt{\delta m^2_{solar}} < \delta m_{LL} < 0.58\, eV$$

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

Sizable heavy contribution

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



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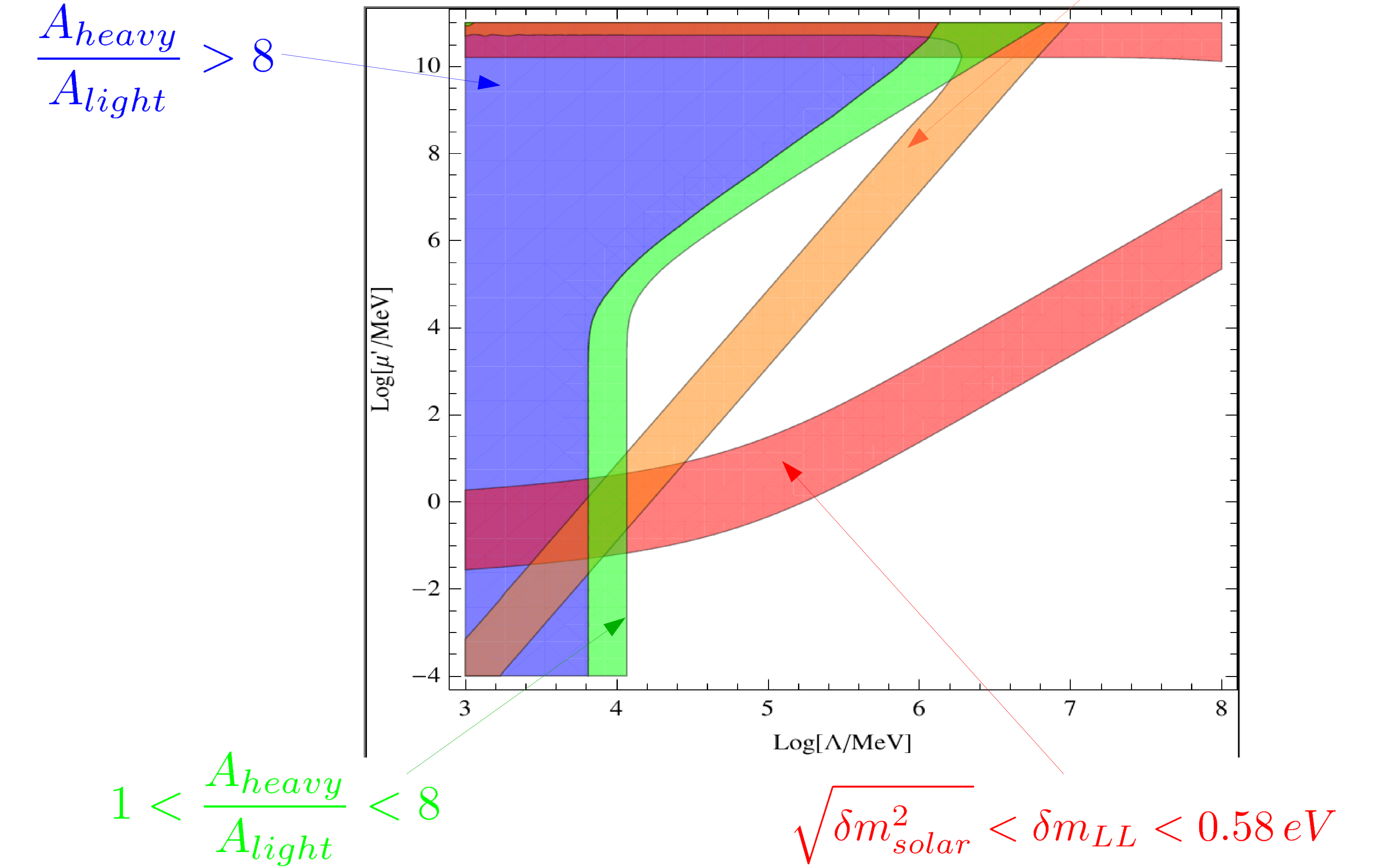
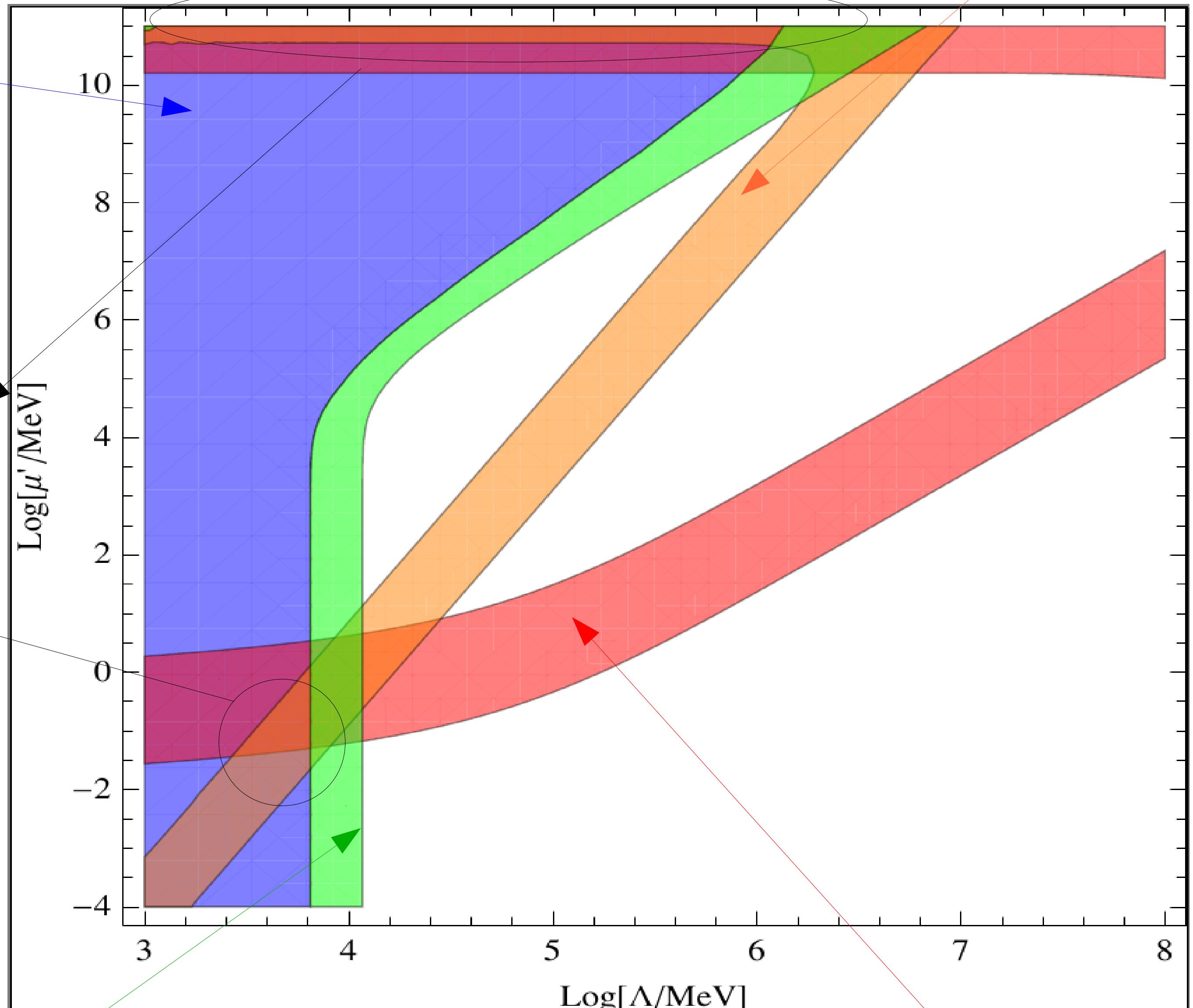


Constraints: $Y_{1\alpha} = 10^{-3}$

Sizable heavy contribution

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



Heavy neutrinos dominate keeping light masses under control

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

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

Heavy dominant contribution

In principle, it can take place in two limits:

- "Hierarchical" seesaw: $\Lambda \ll \mu'$ $\quad$ $\tilde{M}_2 \approx \mu' \gg \tilde{M}_1 \approx \frac{\Lambda^2}{\mu'}$

- Quasi-Degenerate: $\Lambda \gg \mu'$ $\quad$ $\tilde{M}_2 \approx -\tilde{M}_1 \approx \Lambda$

Heavy dominant contribution

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- "Hierarchical" seesaw: $\Lambda \ll \mu'$ $\qquad$ $\tilde{M}_2 \approx \mu' \gg \tilde{M}_1 \approx \dfrac{\Lambda^2}{\mu'}$

- Quasi-Degenerate: $\Lambda \gg \mu'$ $\qquad$ $\tilde{M}_2 \approx -\tilde{M}_1 \approx \Lambda$

But, there are additional constraints not considered before:

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

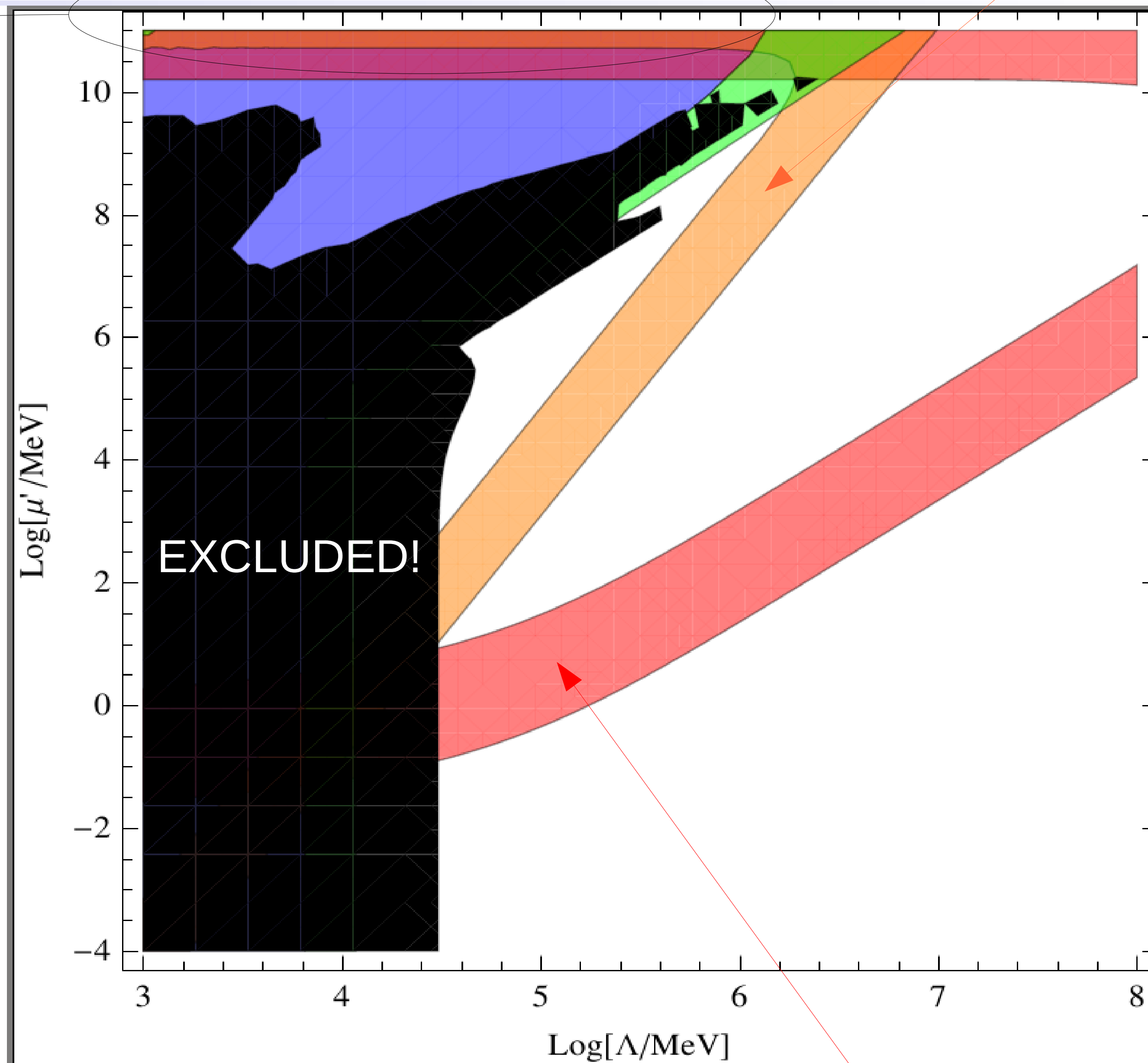
Atre,Han, Pascoli, Zhang 2009

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

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

Sizable heavy contribution

Only the hierarchical case survives!!

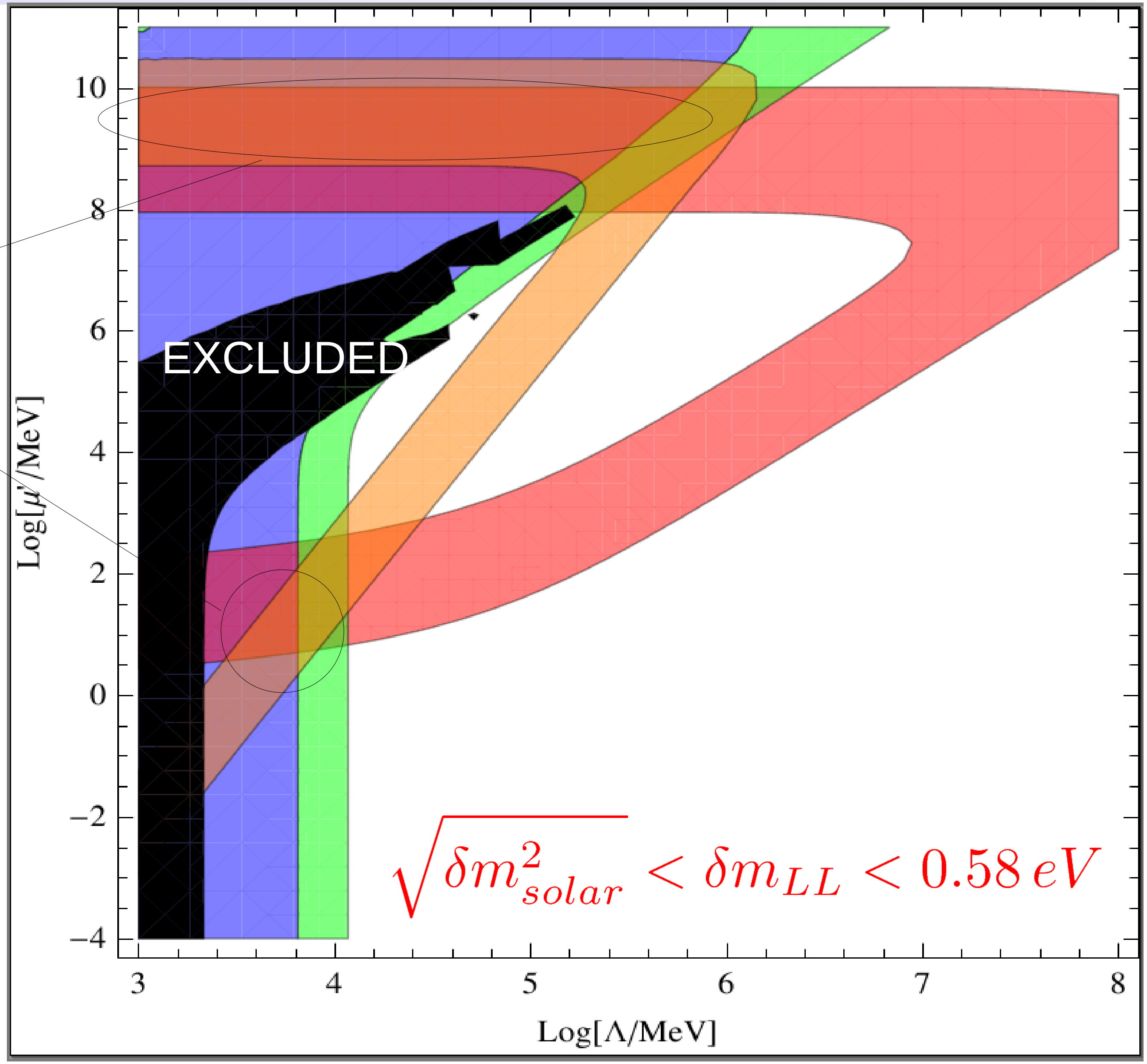


$$\sqrt{\delta m^2_{solar}} < \delta m_{LL} < 0.58\, eV$$

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

Sizable heavy contribution

Heavy neutrinos dominate keeping light masses under control



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

Sizable heavy contribution

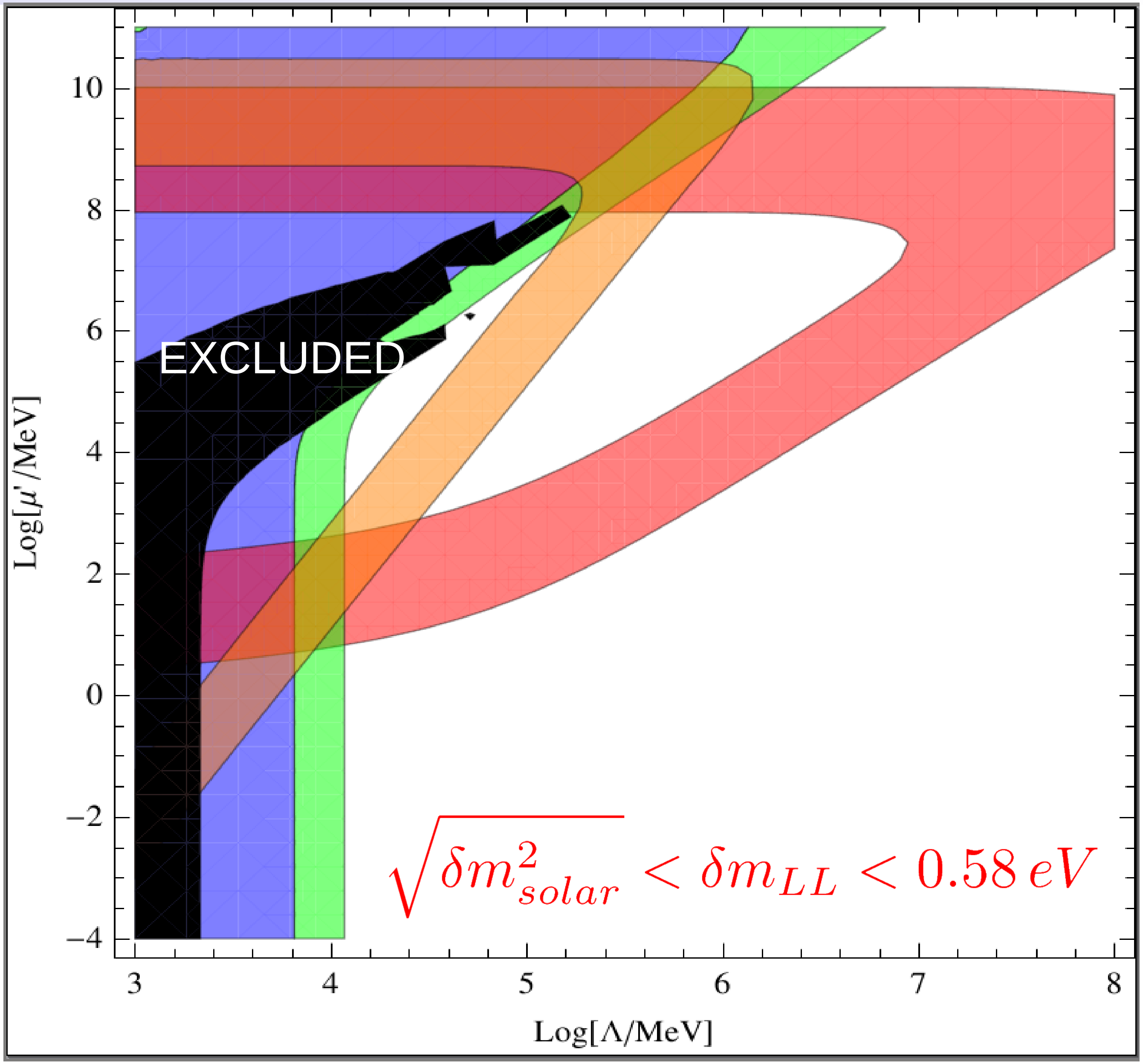
$$\tilde{M}_1 \lesssim 100\, MeV \ll \tilde{M}_2$$

Lightest sterile neutrino below 100 MeV dominates

$$A_{heavy} \propto \frac{Y_{1e}^2 v^2}{8\mu'}$$

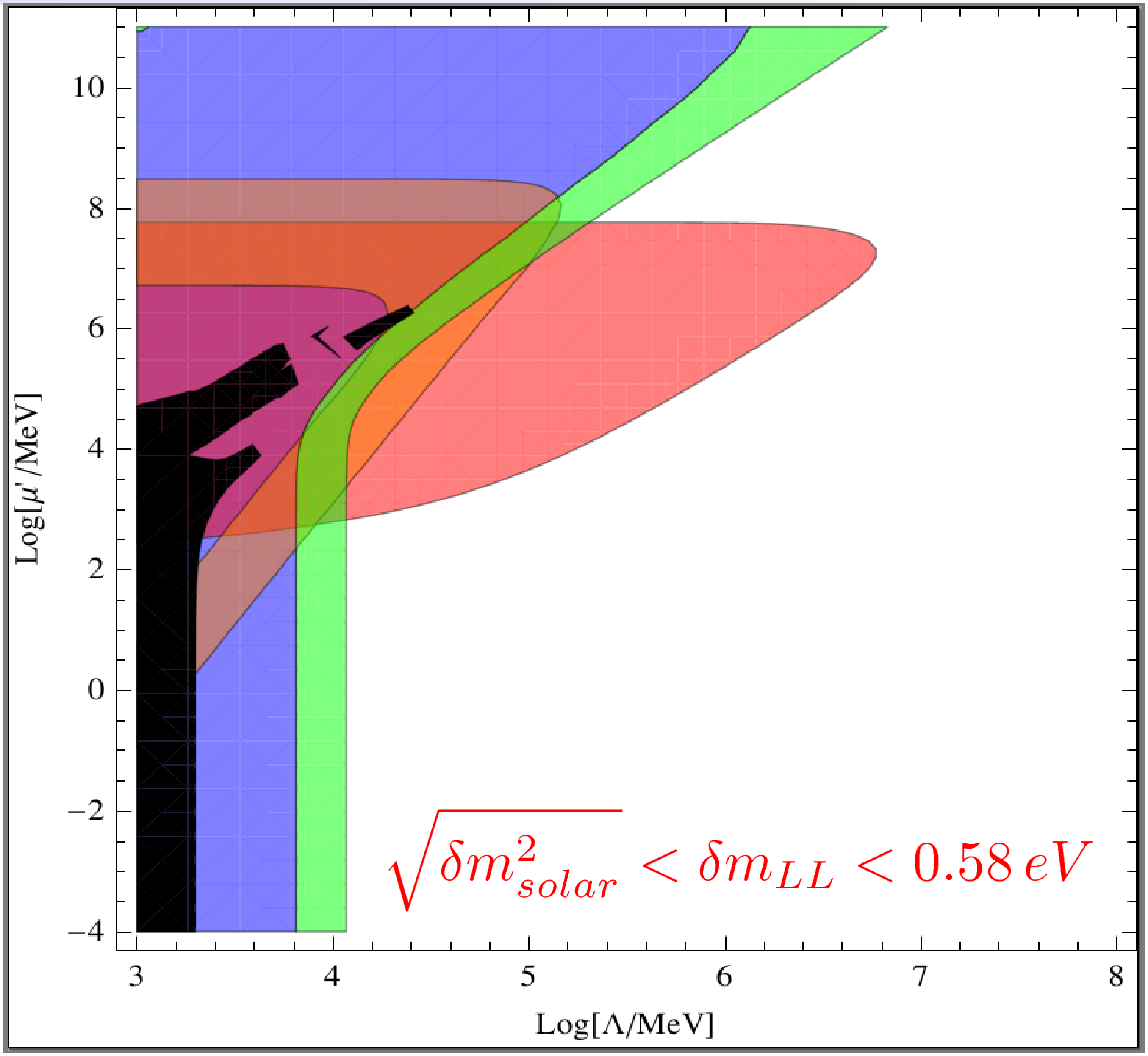
$$\tilde{M}_1, \tilde{M}_2 > 100\, MeV$$

$$A_{heavy} \propto \frac{v^2 \mu' Y_{1e}^2}{2\Lambda^4}$$

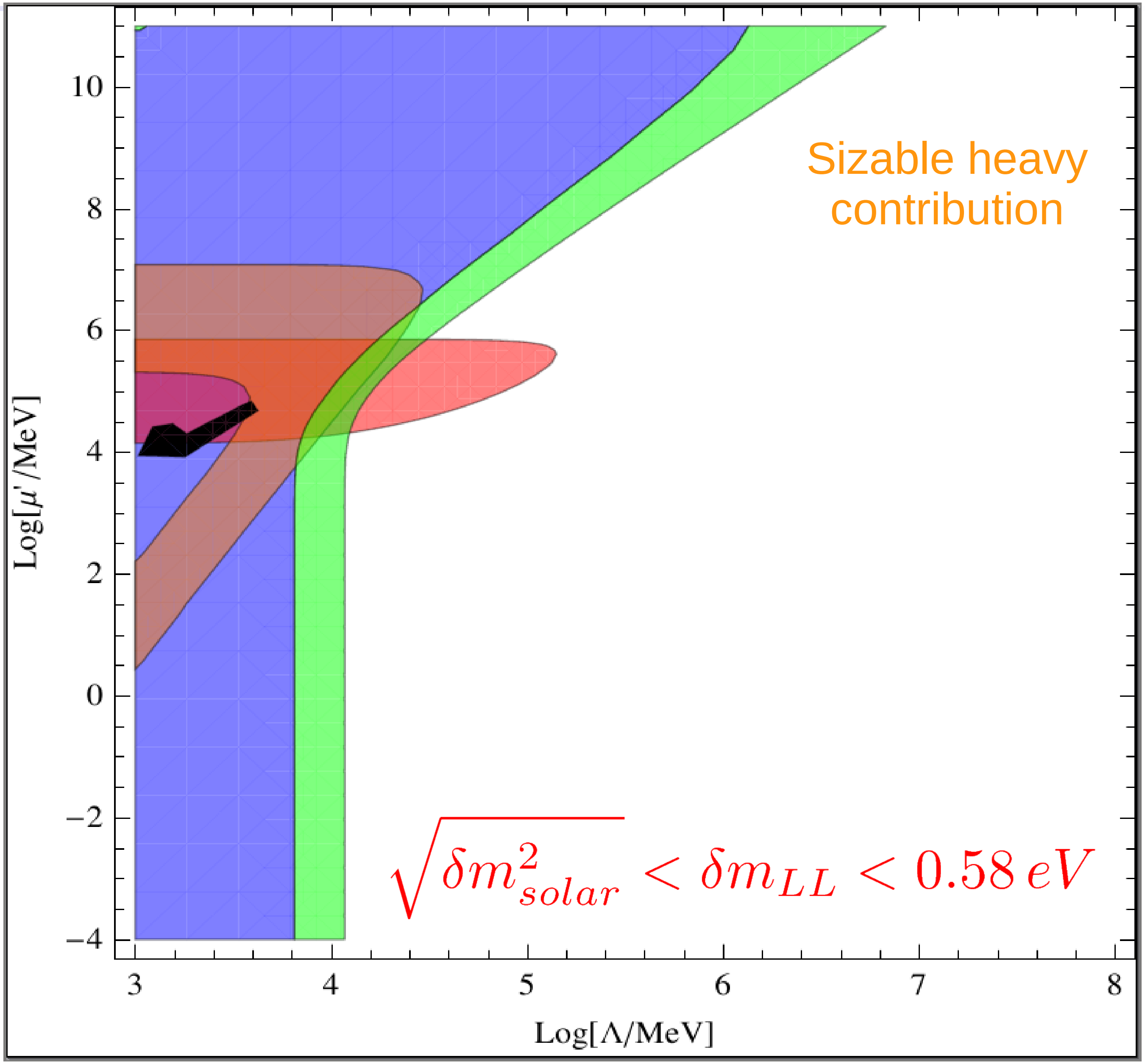


Constraints: $Y_{1\alpha} = 10^{-5}$

Sizable heavy contribution



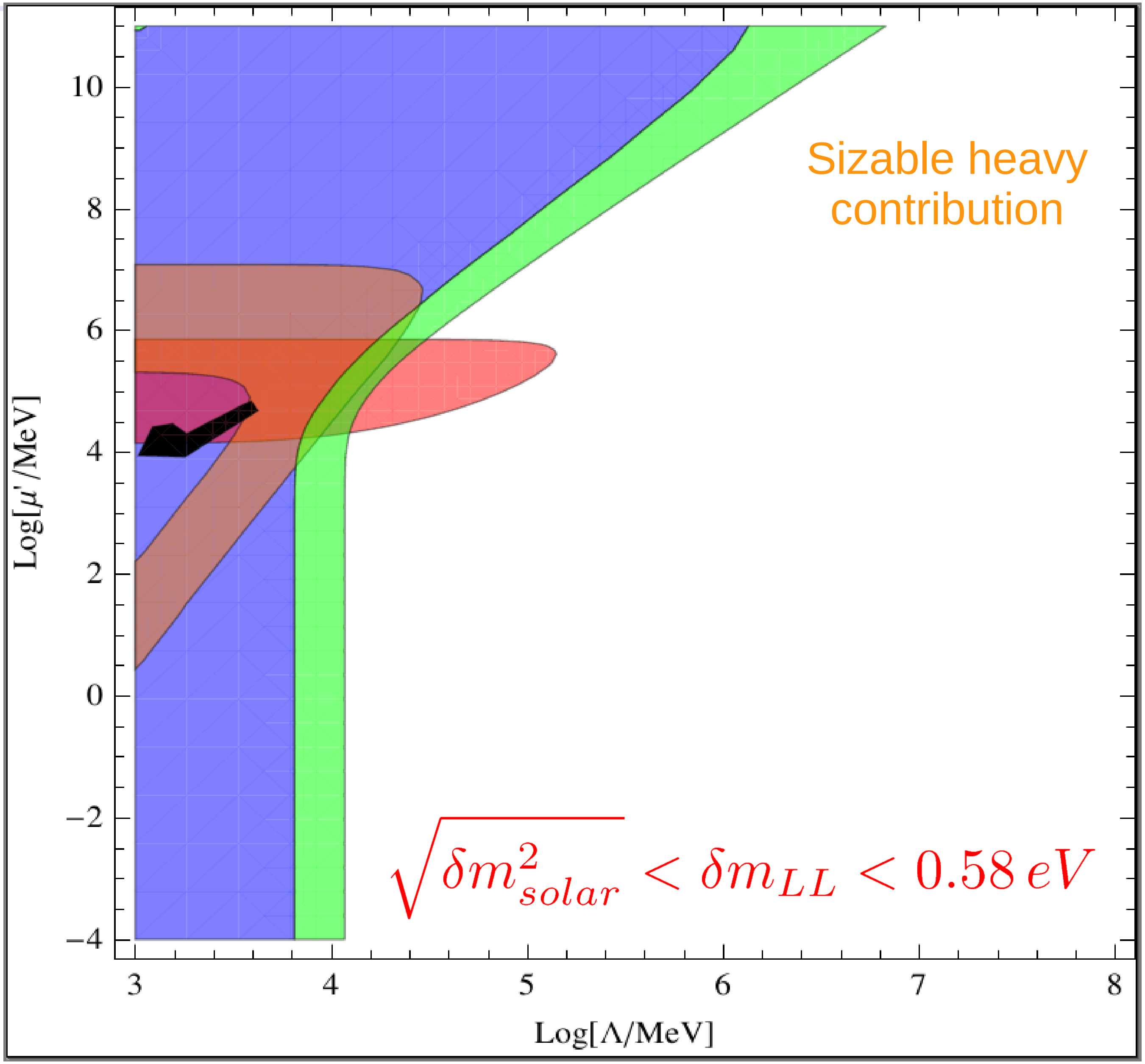
Constraints: $Y_{1\alpha} = 2 \cdot 10^{-6}$



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

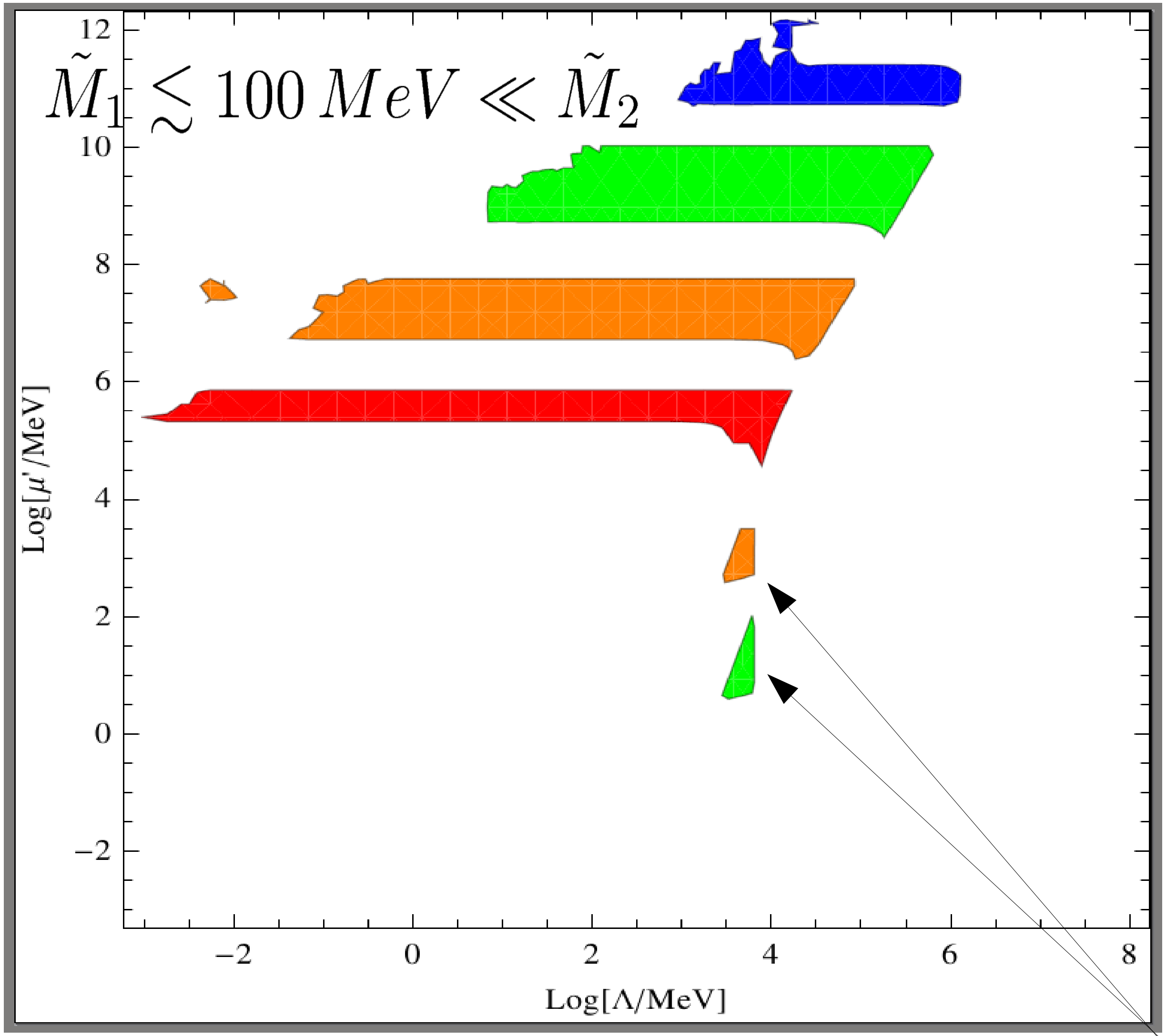
A_{heavy}/A_{light}
independent
of $Y_{1\alpha}$

Both too
suppressed
for
smaller
Yukawa
couplings



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

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

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 regimes 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.

Conclusions

- "*Heavy*" neutrinos may dominate 0νββ decay at tree level if they are in both light and heavy regime (some level of fine-tuning required)

- "*heavy*" neutrinos dominate 0νββ decay if the light contribution cancels at tree level and:

  → $10^{-6} \lesssim Y_{1\alpha} \lesssim 10^{-3}$

  → "Hierarchical" seesaw $(\Lambda \ll \mu')$. Lightest sterile ν dominates.
  $\tilde{M}_1 \lesssim 100\, MeV \ll \tilde{M}_2$

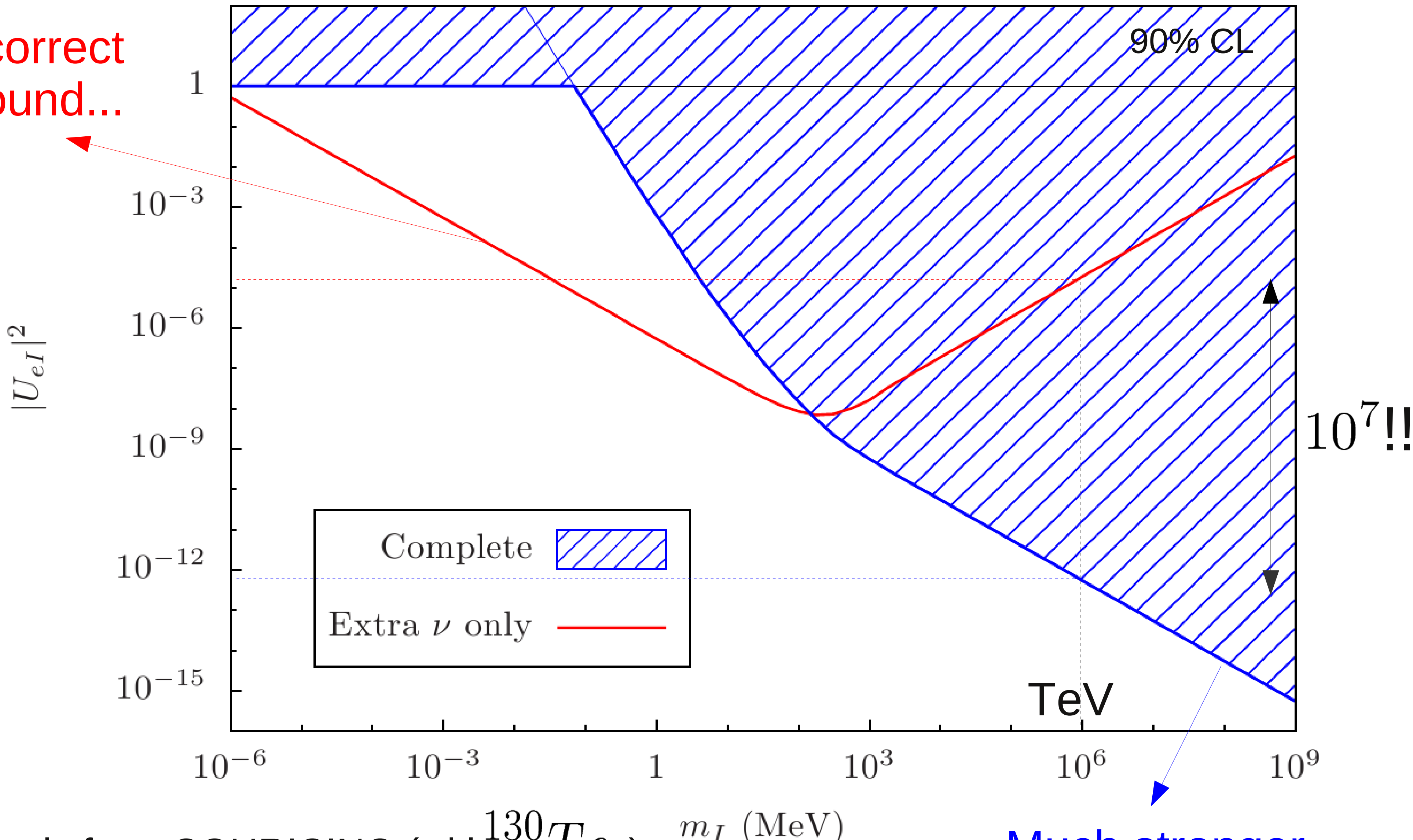
  → Quasi-Degenerate heavy neutrinos $(\Lambda \gg \mu')$ with
  $\tilde{M}_2 \approx \tilde{M}_1 \approx \Lambda \sim 5\, GeV$ (*only for tiny region in parameter space*)

Thank you!

Back-up

Constraint on mixing with extra neutrino

Incorrect bound...



Much stronger Constraint !!

Bounds from COURICINO (with ^{130}Te)

Non-hierarchical extra neutrinos assumed

Type-I: All extra masses in light regime

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

→ Cancellation between NME: GIM *analogy*

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

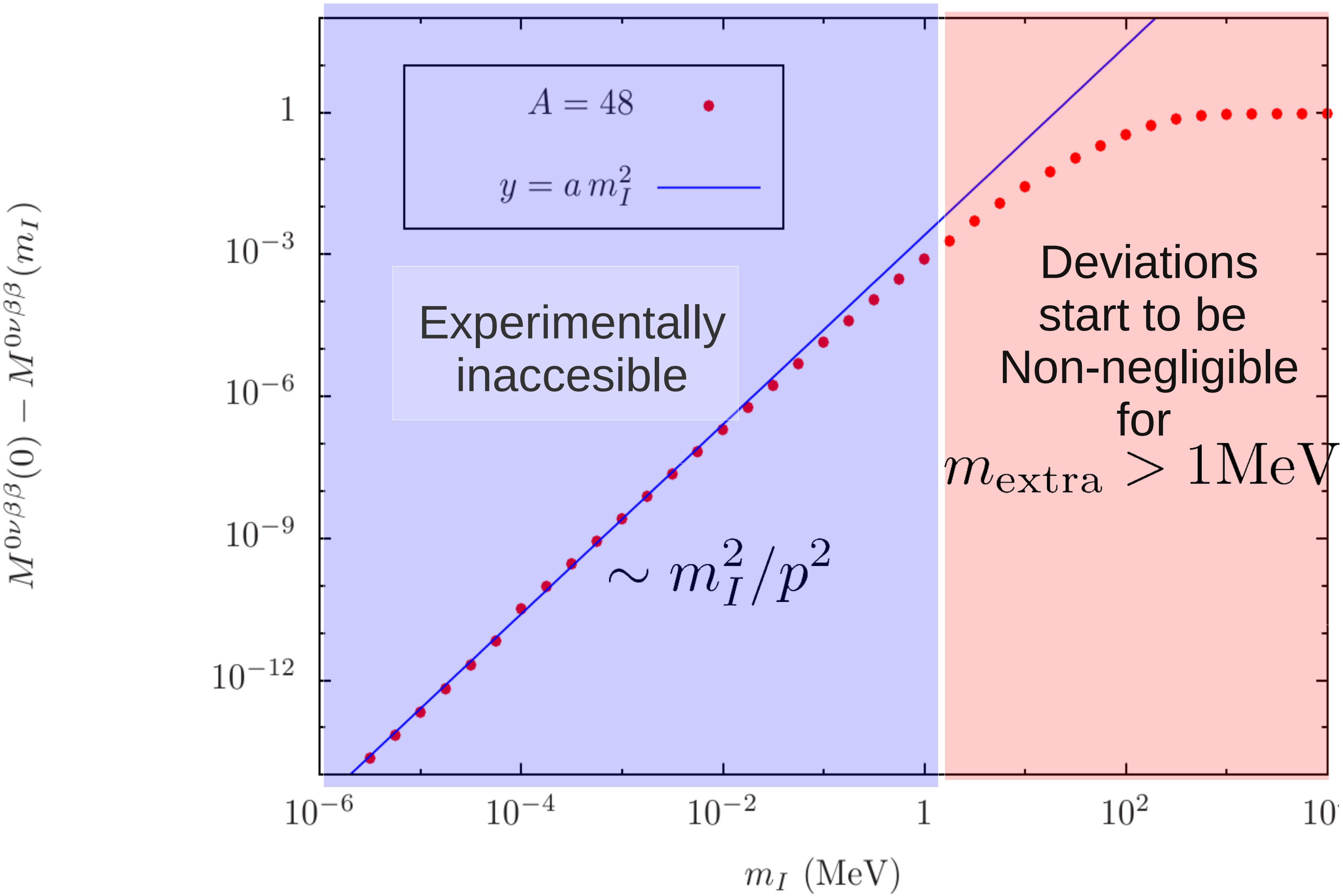
$$\Delta m^2 / M_W^2 \quad \longleftrightarrow \quad \Delta M^{0\nu\beta\beta}$$

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

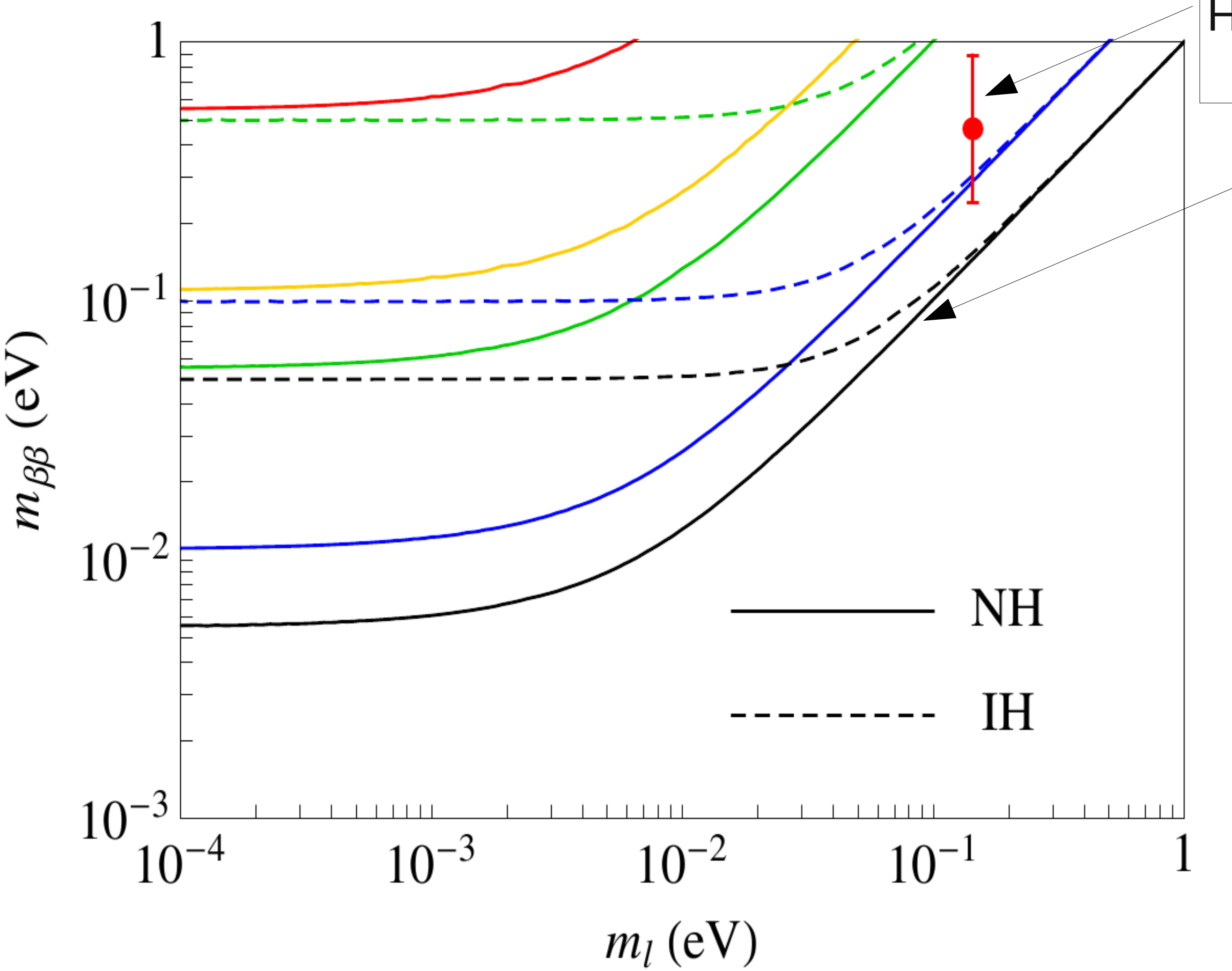
→ Strong suppression for $m_{\text{extra}} < 100\text{MeV}$

Type-I: All extra masses in light regime

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



Extra states in light & heavy regime



$\frac{A_{heavy}}{A_{light}}$	fine-tuning level
100	1 %
20	5 %
10	10 %
2	50 %

Note that the usual interpretation of $m_{\beta\beta}$ (light active neutrinos only), as comes from canonical seesaw (extra states in heavy regime) would fail!

Cancellation level

$$m_{\beta\beta} = \left|\sum_i^{\text{SM}} m_i U_{ei} + \sum_I^{\text{light}} m_I U_{eI}^2\right| = \left|\sum_I^{\text{heavy}} m_I U_{eI}^2\right|$$

For different cancellation levels:

$$\alpha \equiv \frac{m_{\beta\beta}^{standard}}{m_{\beta\beta}} = \frac{\left|\sum_i^{\text{light}} m_I U_{eI} + \sum_I^{\text{heavy}} m_I U_{eI}^2\right|}{m_{\beta\beta}}$$

$$= \frac{\left|\sum_i^{\text{SM}} m_i U_{ei}\right|}{m_{\beta\beta}}$$

Information from neutrino oscillations

Standard approach

Usual assumption: neglect contribution of extra degrees of freedom. Using information from neutrino oscillations:

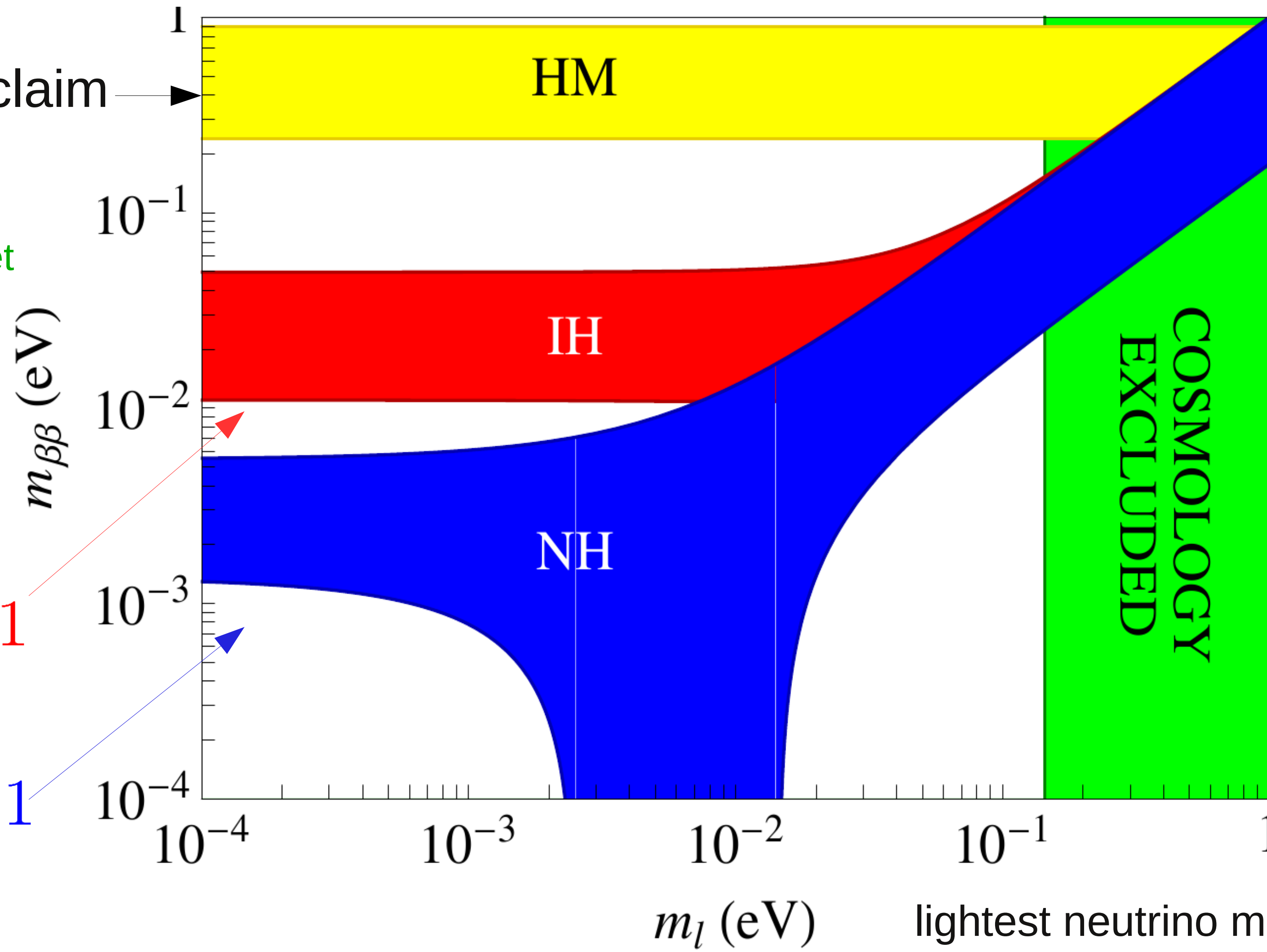
2σ

Heidelberg-Moscow claim

H.V. Klapdor-Kleingrothaus et al 06

$\mathrm{sign}(\Delta m^2_{31}) = -1$

$\mathrm{sign}(\Delta m^2_{31}) = +1$



lightest neutrino mass

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

Adding a heavy $SU(2)$ triplet:

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

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

↓ SSB

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

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

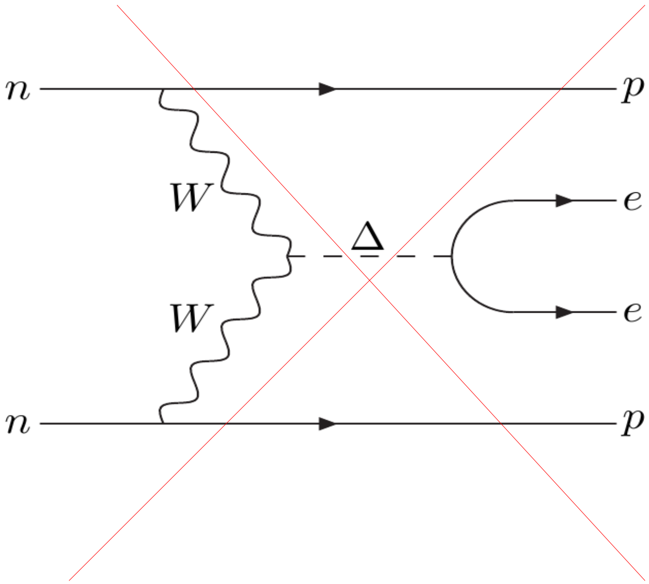
$$\sum_i^{\rm SM} m_i U_{ei}^2 + \sum_I^{\rm heavy} m_I U_{eI}^2 = 0 \quad \longleftrightarrow \quad \sum_i^{\rm SM} m_i U_{ei}^2 = \left(m_\nu^\Delta\right)_{ee}$$

Type-I

Type-II

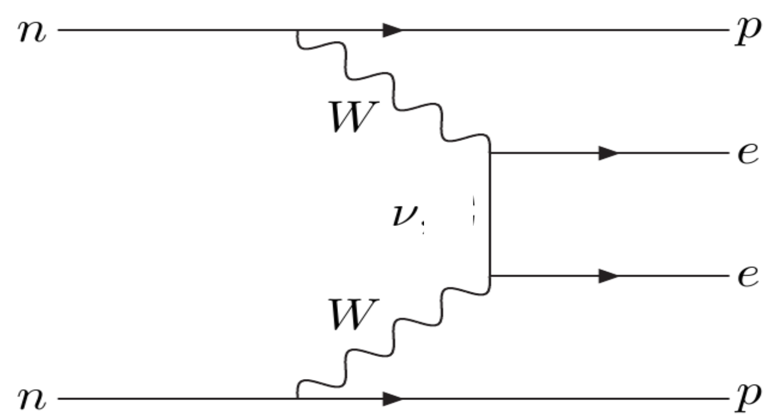
$0\nu\beta\beta$ in Type-II seesaw models

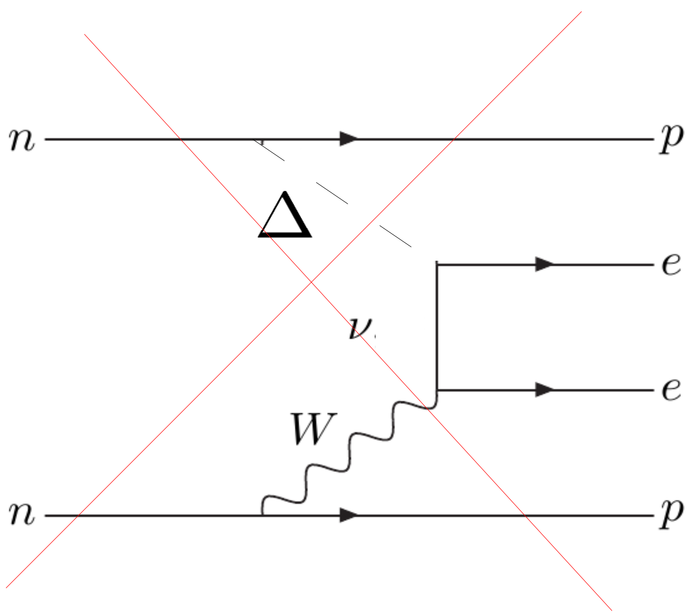
But the scalars can also mediate the process:



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

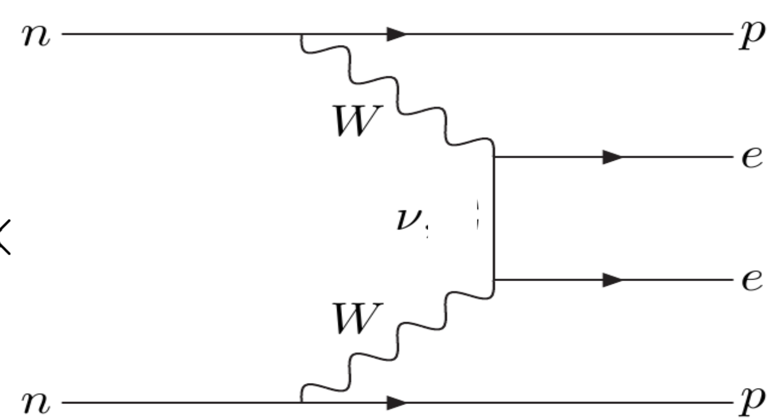
$< 10^{-6}$





$\sim m_q/M_\Delta \times$

$< 10^{-5}$



$0\nu\beta\beta$ 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: $\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}$

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

↓ 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 Σ mass

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

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

$0\nu\beta\beta$ in Mixed Seesaw Models

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

$$\simeq m_{ee}^{\Delta,\Sigma} M^{0\nu\beta\beta}(0)$$

- Can dominate the contribution to $0\nu\beta\beta$

- The cosmology Constraints don't apply to these masses!!

- The Heidelberg-Moscow claim can be interepreted as:

$$0.24 \text{ eV} < \left|m_{ee}^{\Delta,\Sigma}\right| < 0.89 \text{ eV}$$

- Same level of the cancellation as for the case of Type-I seesaw model with extra light and heavy neutrinos required to reconciliate with cosmo data.

$0\nu\beta\beta$ in Mixed Seesaw Models

• Same phenomenology from a type-I seesaw with both heavy and light extra eigenstates can also arise from a type-II or III seesaw in combination with type-I extra states in the light regime:

$$M_\nu = \begin{pmatrix} m^{\Delta,\Sigma} & Y_N v/\sqrt{2} \\ Y_N^T v/\sqrt{2} & M_N \end{pmatrix}.$$

$$\sum_i^{\mathrm{SM}} m_i U_{ei}^2 + \sum_I^{\mathrm{light}} m_I U_{eI}^2 = m_{ee}^{\Delta,\Sigma}$$

• Possible to have dominant contribution to 0νββ decay from the extra light sterile neutrinos while above equation and the smallness of masses is respected by a cancellation between extra states contribution.