

Can heavy neutrinos dominate Neutrinoless double beta decay?

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Invisibles ITN meeting

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Based on a collaboration with:

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

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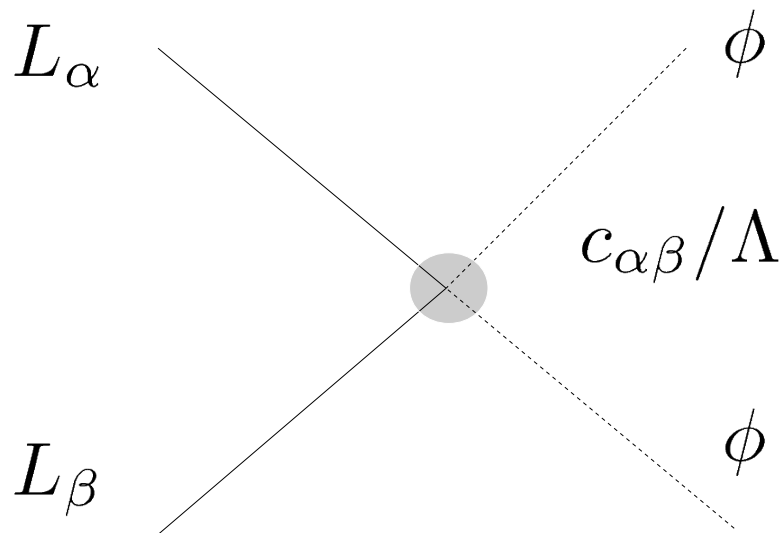
S. Pascoli and Chan-Fai Wong
work in progress...

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):

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

Weinberg 76

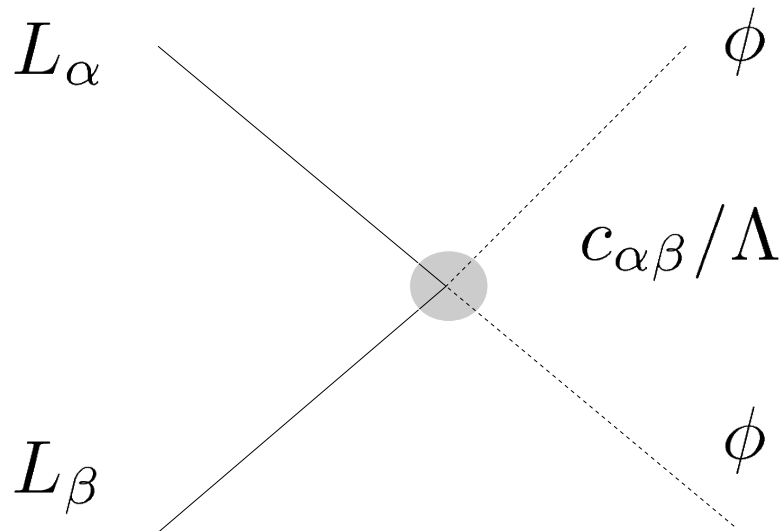


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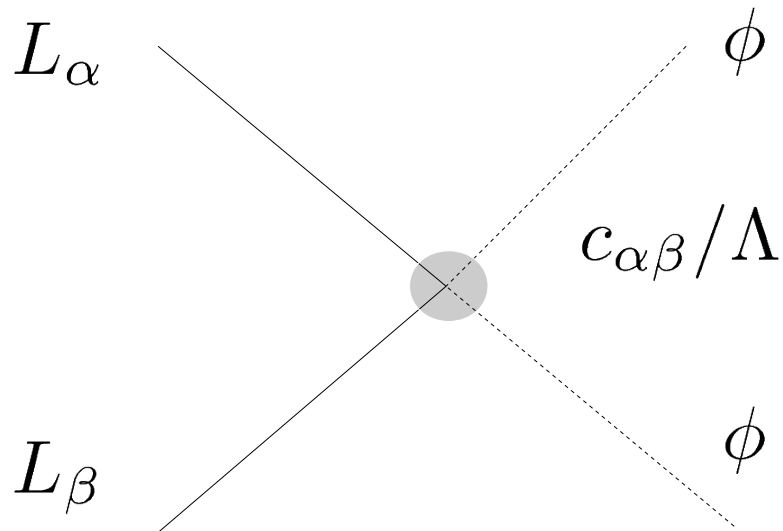
😊 Smallness of neutrino masses can be explained

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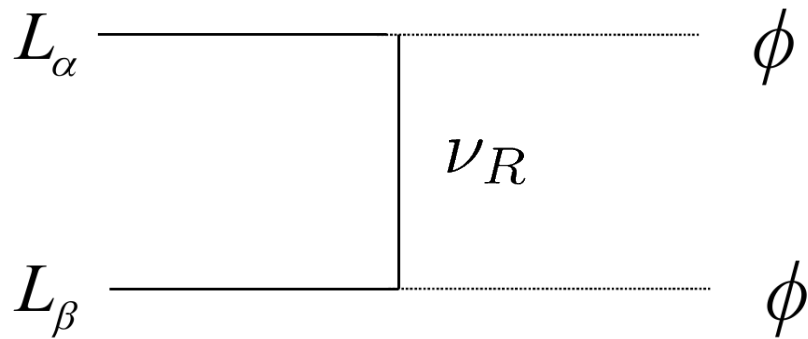
Weinberg 76



☺ Smallness of neutrino masses can be explained

☺ $\not\propto$ 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:

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

Neutrinoless double beta decay

- **Are neutrinos Dirac or Majorana?** Most models accounting for ν - masses, as the seesaw ones, point to Majorana neutrinos.
- The **neutrinoless double beta decay** ($0\nu\beta\beta$) is one of the most promising experiments in this context.

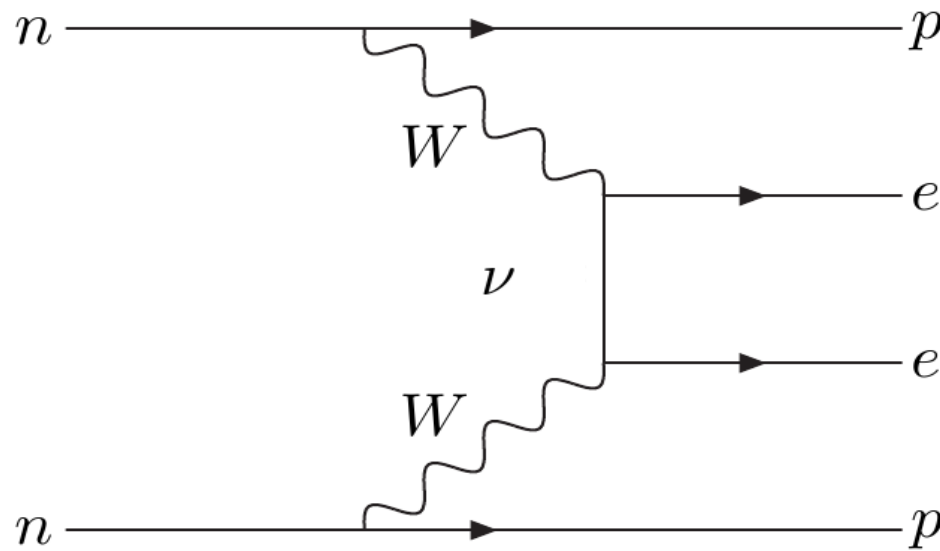
$$(Z, A) \Rightarrow (Z \pm 2, A) + 2e^{\mp} + X$$

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



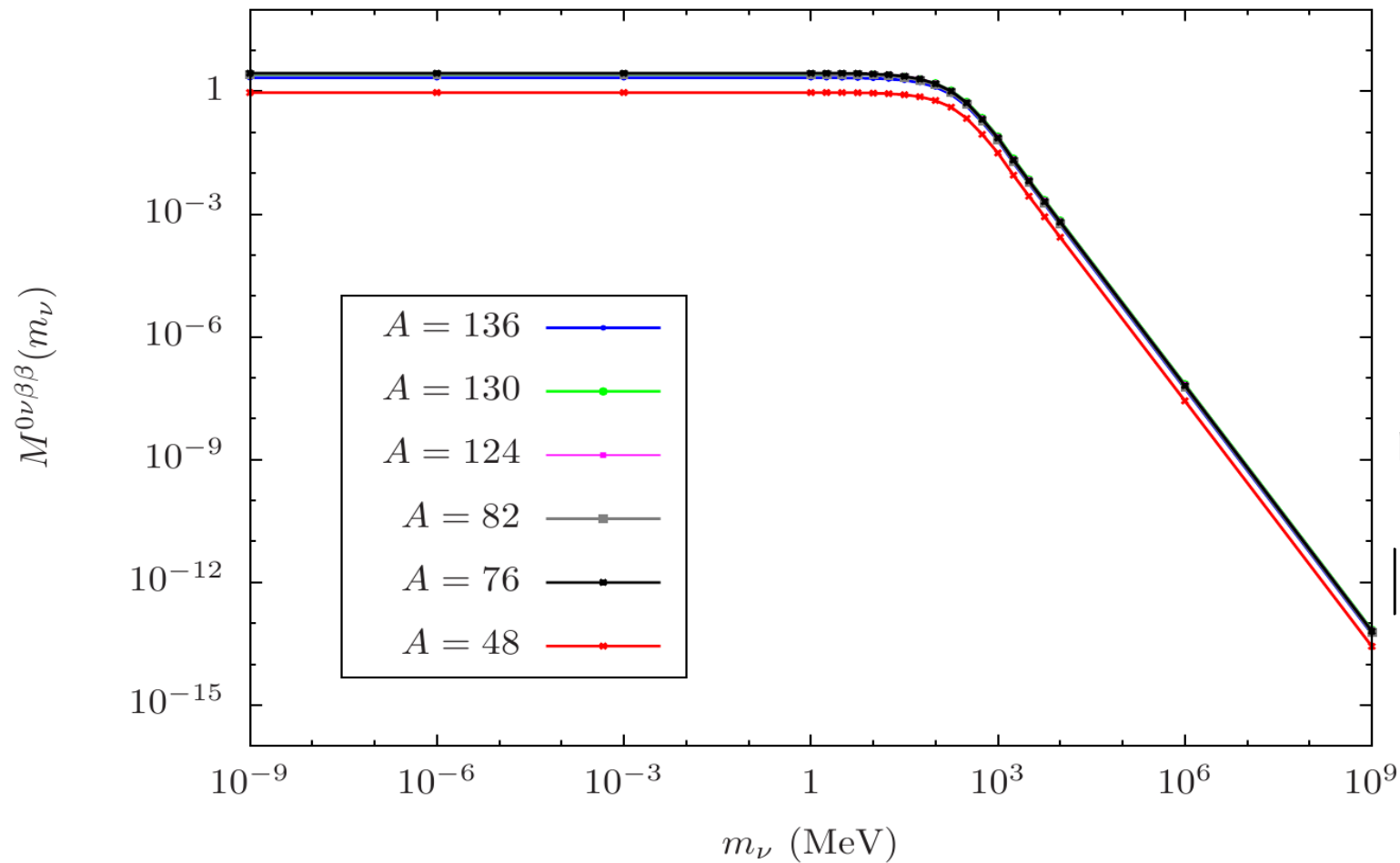
- Contribution of a single neutrino to the amplitude of $0\nu\beta\beta$ decay:

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

Diagram illustrating the components of the amplitude A_i for a single neutrino contribution to $0\nu\beta\beta$ decay:

- m_i : mass of propagating neutrino
- U_{ei}^2 : Lepton mixing matrix
- $M^{0\nu\beta\beta}(m_i)$: NME (Nuclear Matrix Element)

Nuclear Matrix Element (NME)



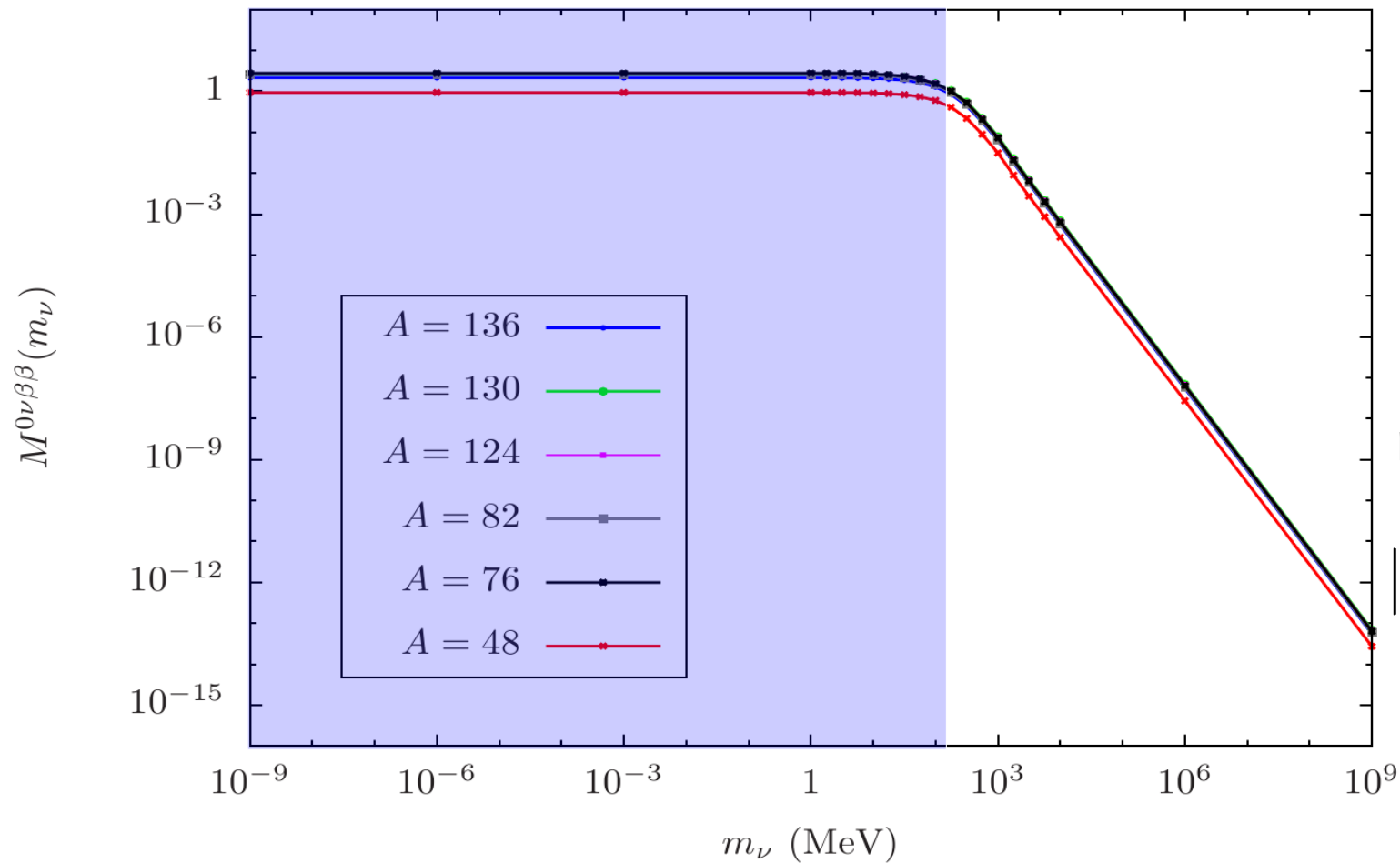
- Mild dependence on the nuclei

- 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

Nuclear Matrix Element (NME)



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

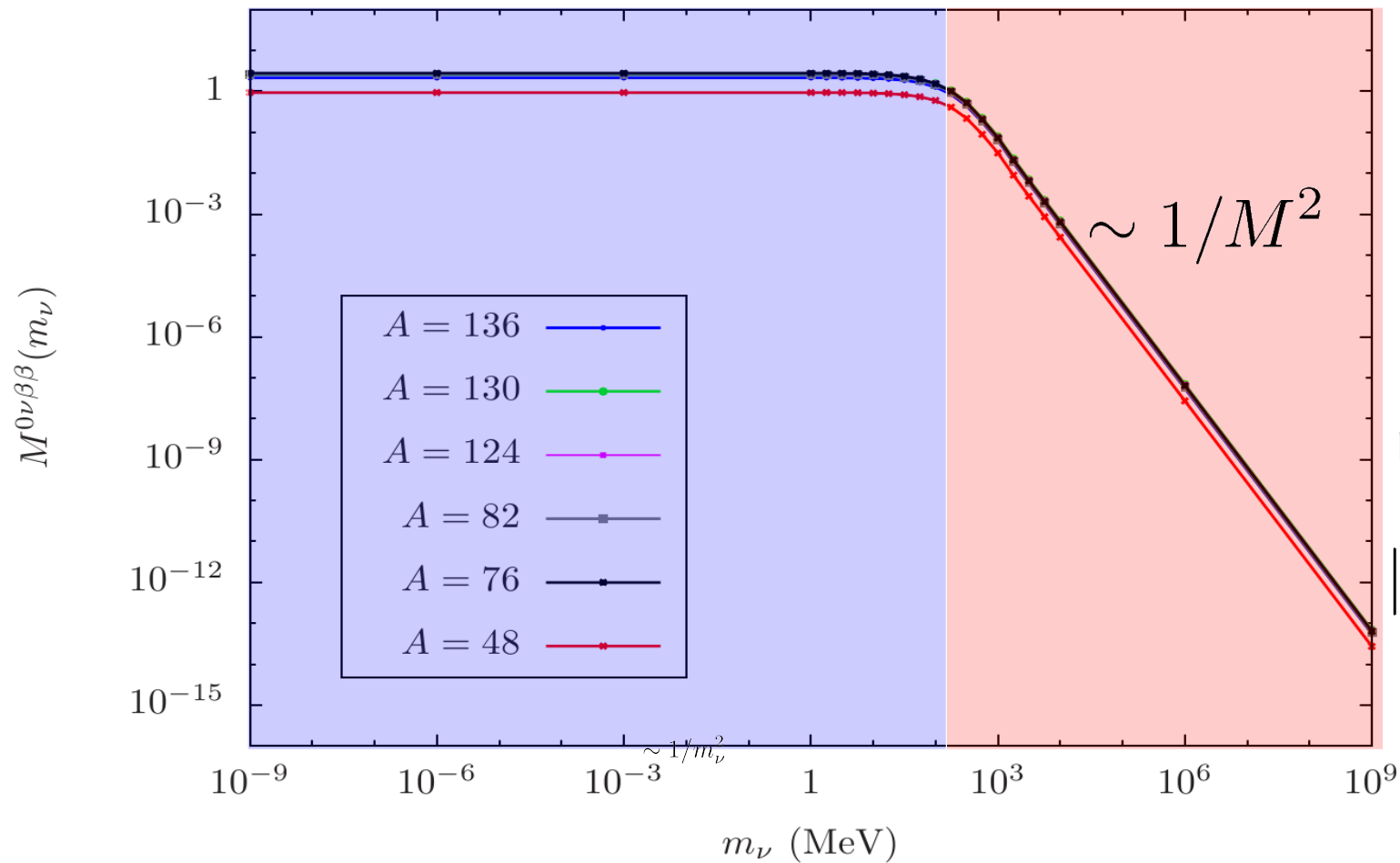
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light regime
 $m_i^2 \ll |p^2|$

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

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Standard approach

Usual assumption: neglect contribution of extra degrees of freedom.

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

$m_{\beta\beta}$

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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

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

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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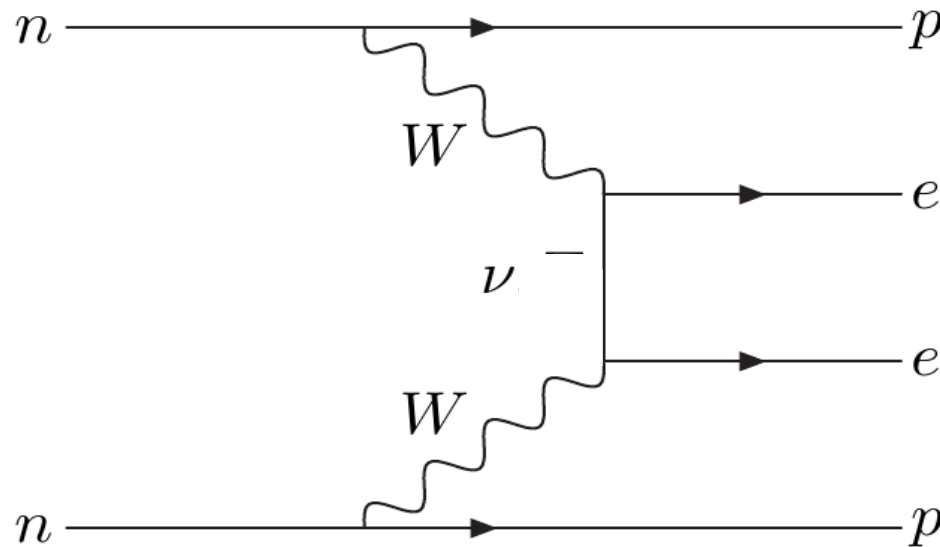
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~~$$\overline{\nu_{\alpha L}} \nu_{\alpha L}^c$$~~

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

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

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



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

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

- ~~$\overline{\nu_{\alpha L}} \nu_{\alpha L}^c$~~ $\sum_i^{\text{SM}} m_i U_{ei}^2 + \sum_I^{\text{light}} m_I U_{eI}^2 = 0$
- $M^{0\nu\beta\beta}(m_i) = M^{0\nu\beta\beta}(0)$ (light regime)

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

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

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



Type-I: All extra masses in heavy regime

"canonical" Type-I seesaw scenario

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

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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

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negligible!

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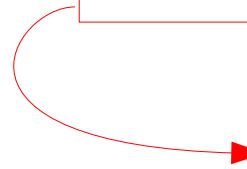
Extra states with masses below 100 MeV
can give a relevant contribution!
even
dominate the process

Is there any other case in which
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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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

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

- $\Lambda \gg \mu, \epsilon v, \mu'$ 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](#)

$$\tilde{M} \ll Y v / \sqrt{2}$$

Dirac

$$\tilde{M} \gg Y v / \sqrt{2}$$

seesaw

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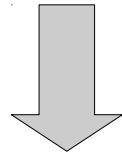
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seesaw

Tree level Cancellation of light contribution

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

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

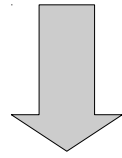


$$\mu Y_{1e}^2 + \epsilon Y_{2e} (\epsilon \mu' Y_{2e} - 2\Lambda Y_{1e}) = 0$$

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

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

▶ Tree level light active neutrino masses vanish !!

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

Heavy contribution

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

- 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:

Grimus, Lavoura 2000

Hettmansperger, Lindner, Rodejohann 2011

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

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0

when cancellation takes place

0

$$\mu = \epsilon = 0$$

Due to the suppression 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

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

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

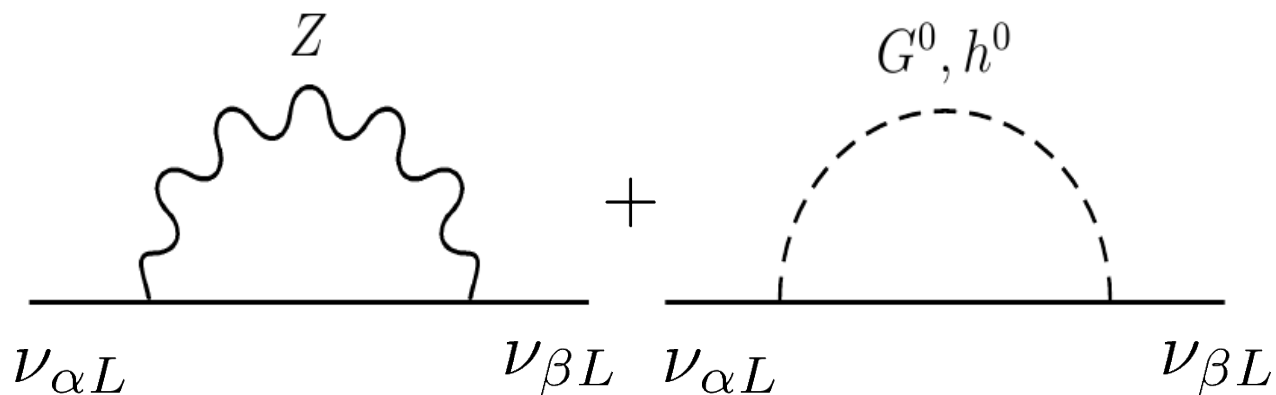
Running not relevant in this context.

1-loop corrections

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

Grimus & Lavoura 2002; Aristizabal Sierra & Yaguna 2011

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

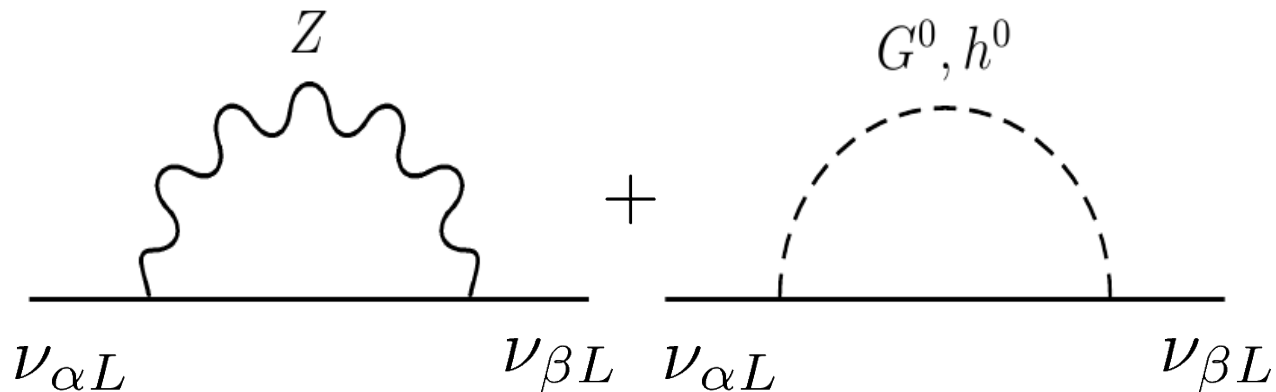


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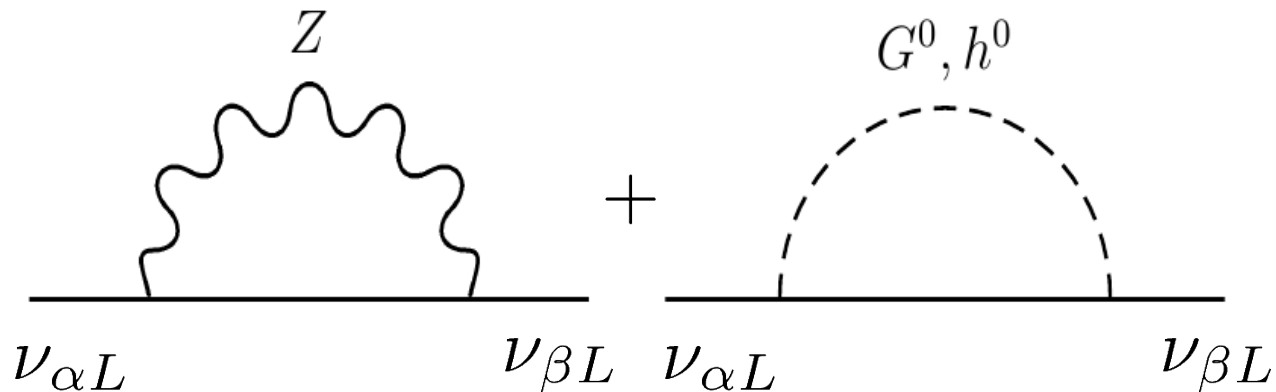
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→ Similar structure as tree level masses, but **no cancellation** for $\mu = \epsilon = 0$. Light masses generated at 1-loop.

→ No m_D/M expansion considered.

1-loop corrections

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

The neutrino mass matrix is then given by:

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

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

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

1-loop corrections

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cancellation
condition
 $\mu = \epsilon = 0$

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

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

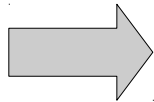
1-loop corrections

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

The neutrino mass matrix is then given by:

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

cancellation
condition
 $\mu = \epsilon = 0$



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

1-loop corrections

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

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

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

Constraints

1

Neutrino
oscillations

$$\sqrt{\delta m_{solar}^2} < \delta m_{LL} < 0.54 \text{ eV}$$

Absolute mass
scale experiments
(WMAP7)

2 eV (${}^3\text{H}$ β -decay)

Constraints

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

$2 eV$ (3H β -decay)
- Dominant or not, the heavy contribution should respect the present constraint and be measurable, to be phenomenologically interesting

$$10^{-2} eV < m_{\beta\beta}^{heavy} < 0.58 eV \rightarrow \text{Present bound CURICINO using ISM NME}$$

Next-to-Next generation sensitivity

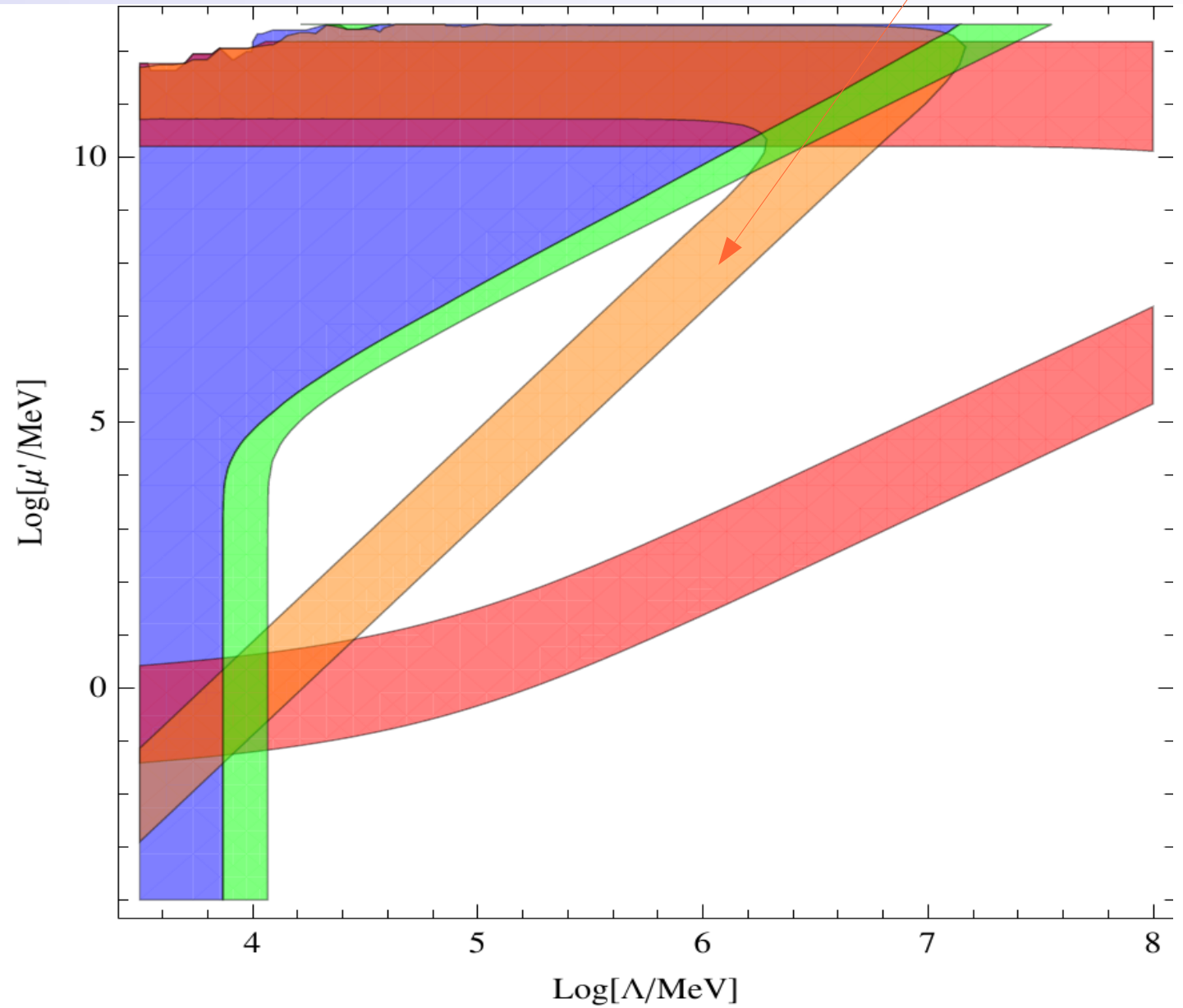
MAJORANA, Super-Nemo, etc, etc

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

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

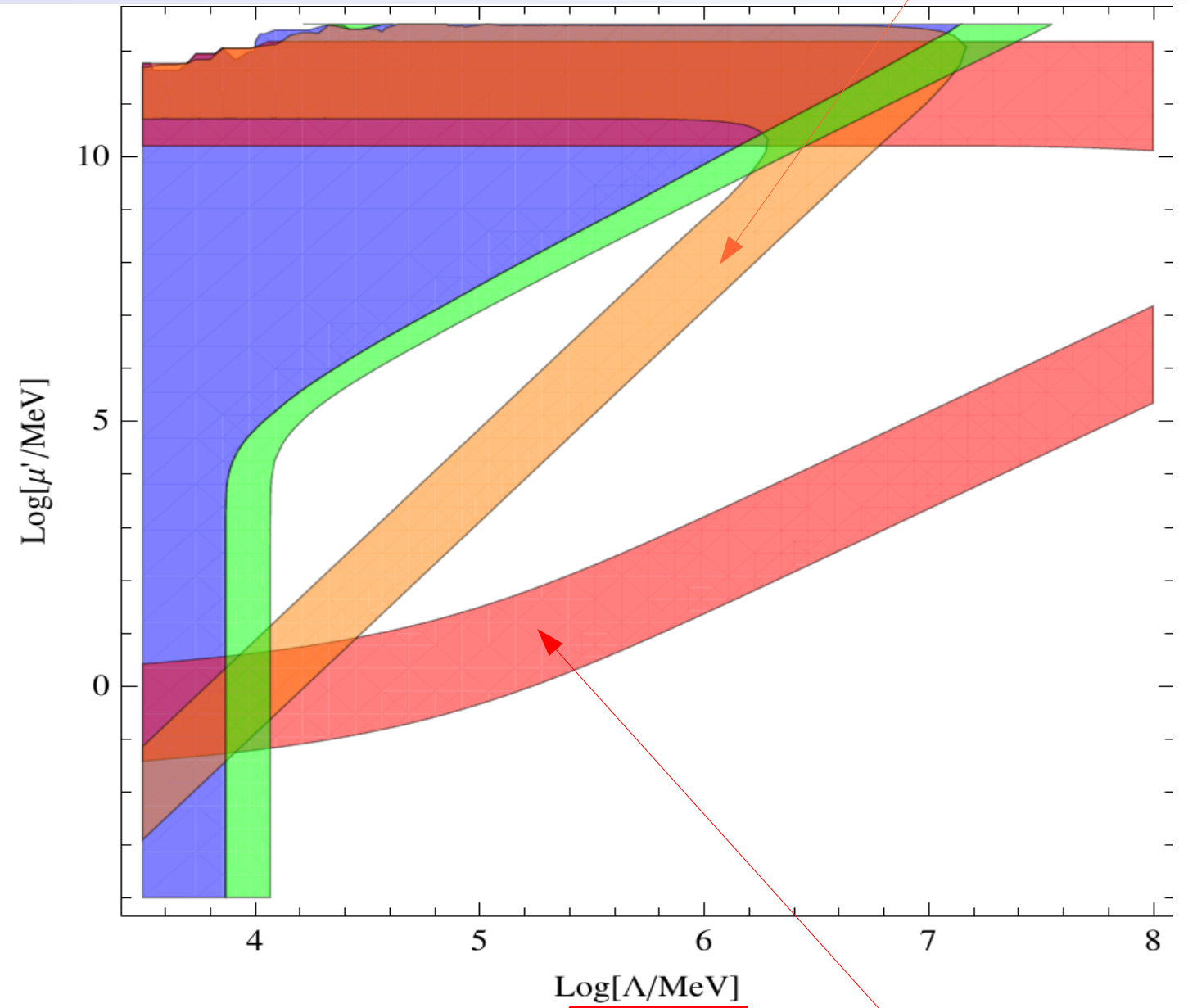
Constraints: $Y_{1\alpha} = 10^{-3}$

Measurable heavy contribution



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Measurable heavy contribution

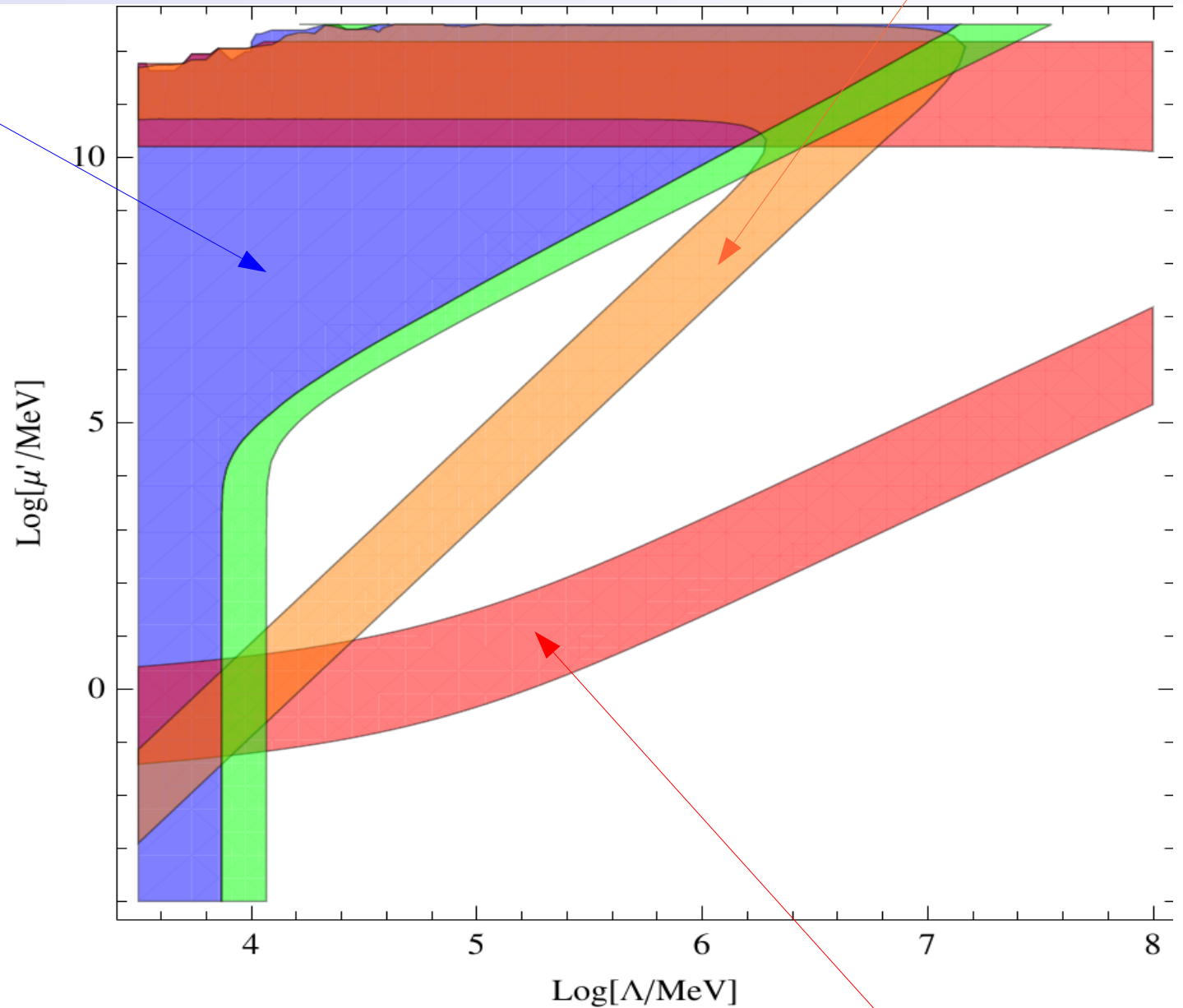


$$\sqrt{\delta m_{solar}^2} < \delta m_{LL} < 0.58 \text{ eV}$$

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

Measurable heavy contribution

$$\frac{A_{heavy}}{A_{light}} > 5$$

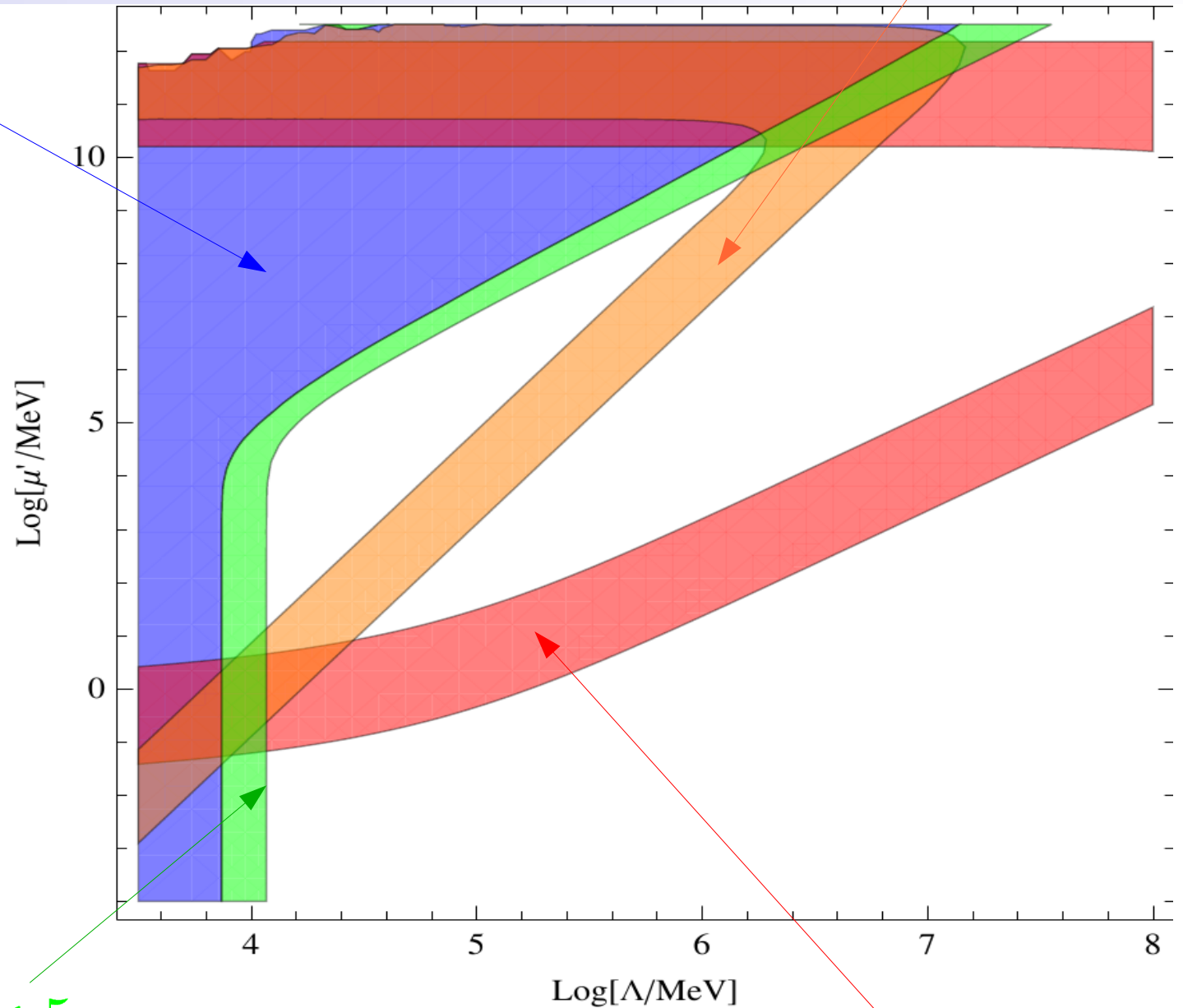


$$\sqrt{\delta m_{solar}^2} < \delta m_{LL} < 0.58 \text{ eV}$$

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

Measurable heavy contribution

$$\frac{A_{heavy}}{A_{light}} > 5$$



$$1 < \frac{A_{heavy}}{A_{light}} < 5$$

$$\sqrt{\delta m_{solar}^2} < \delta m_{LL} < 0.58 \text{ eV}$$

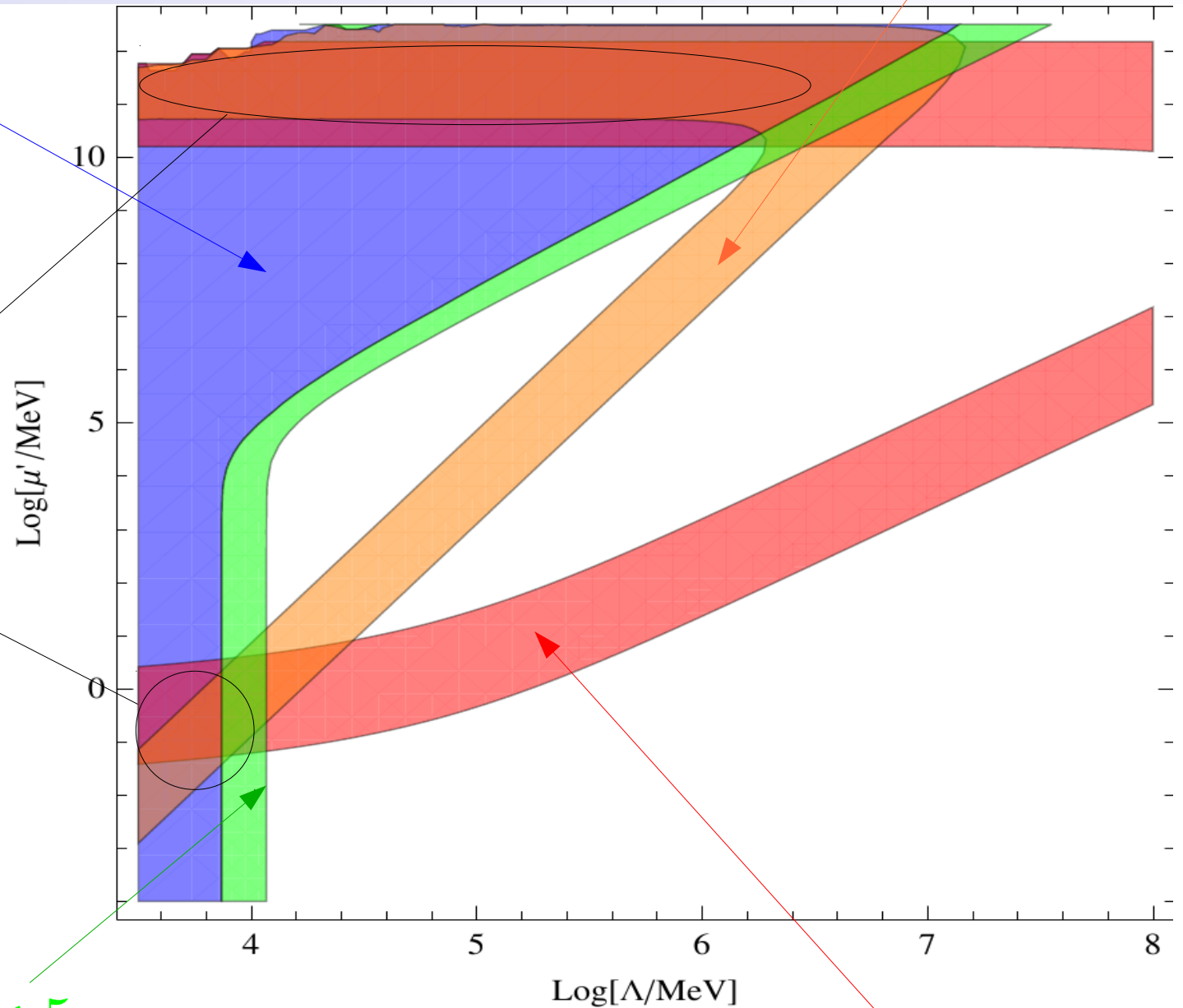
Constraints: $Y_{1\alpha} = 10^{-3}$

Measurable heavy contribution

$$\frac{A_{heavy}}{A_{light}} > 5$$

Heavy neutrinos dominate keeping light masses under control

$$1 < \frac{A_{heavy}}{A_{light}} < 5$$



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

Heavy dominant contribution

In principle, it can take place in two limits:

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

Heavy dominant contribution

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

But, there are additional constraints not considered before:

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

Atre, Han, Pascoli, Zhang 2009

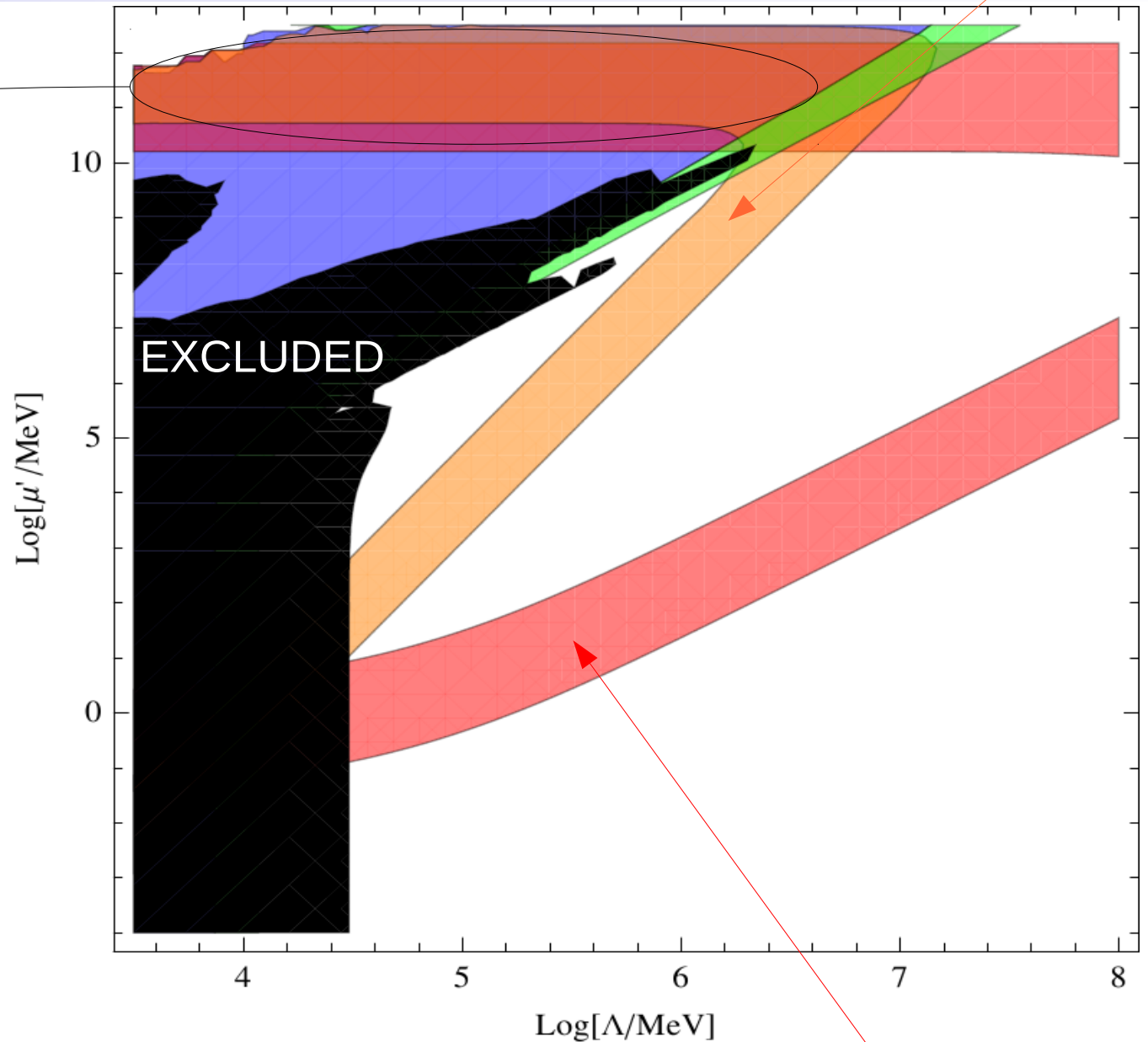
Antusch, Biggio, Fernandez-Martinez, Gavela, JLP 2006

etc

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

Measurable heavy contribution

Only the hierarchical case survives!!

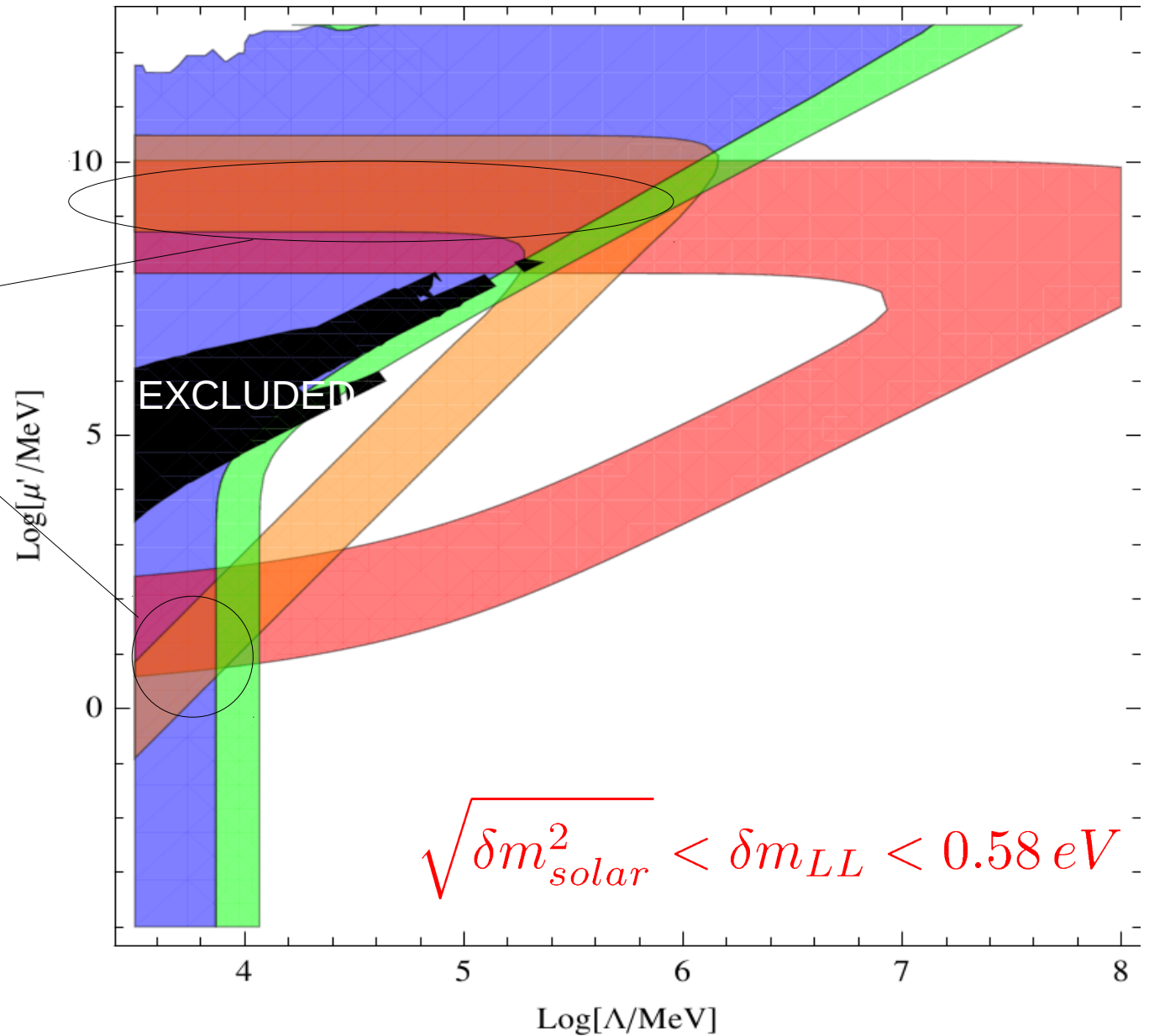


$$\sqrt{\delta m_{solar}^2} < \delta m_{LL} < 0.58 \text{ eV}$$

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

Measurable heavy
contribution

Heavy neutrinos
dominate keeping
light masses under
control



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

Measurable heavy contribution

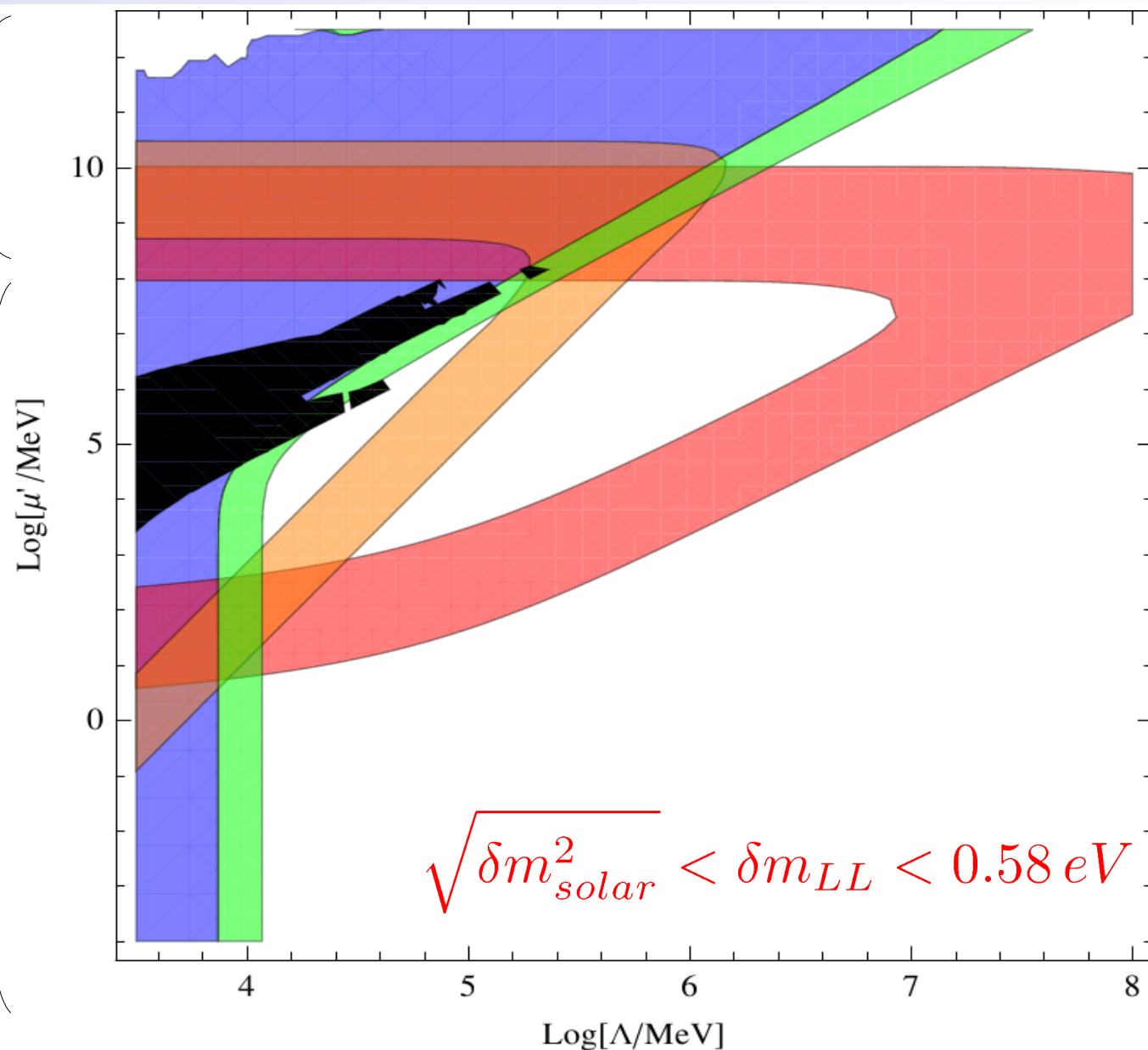
$$\tilde{M}_1 \lesssim 100 \text{ MeV} \ll \tilde{M}_2$$

Lightest sterile neutrino below 100 MeV dominates

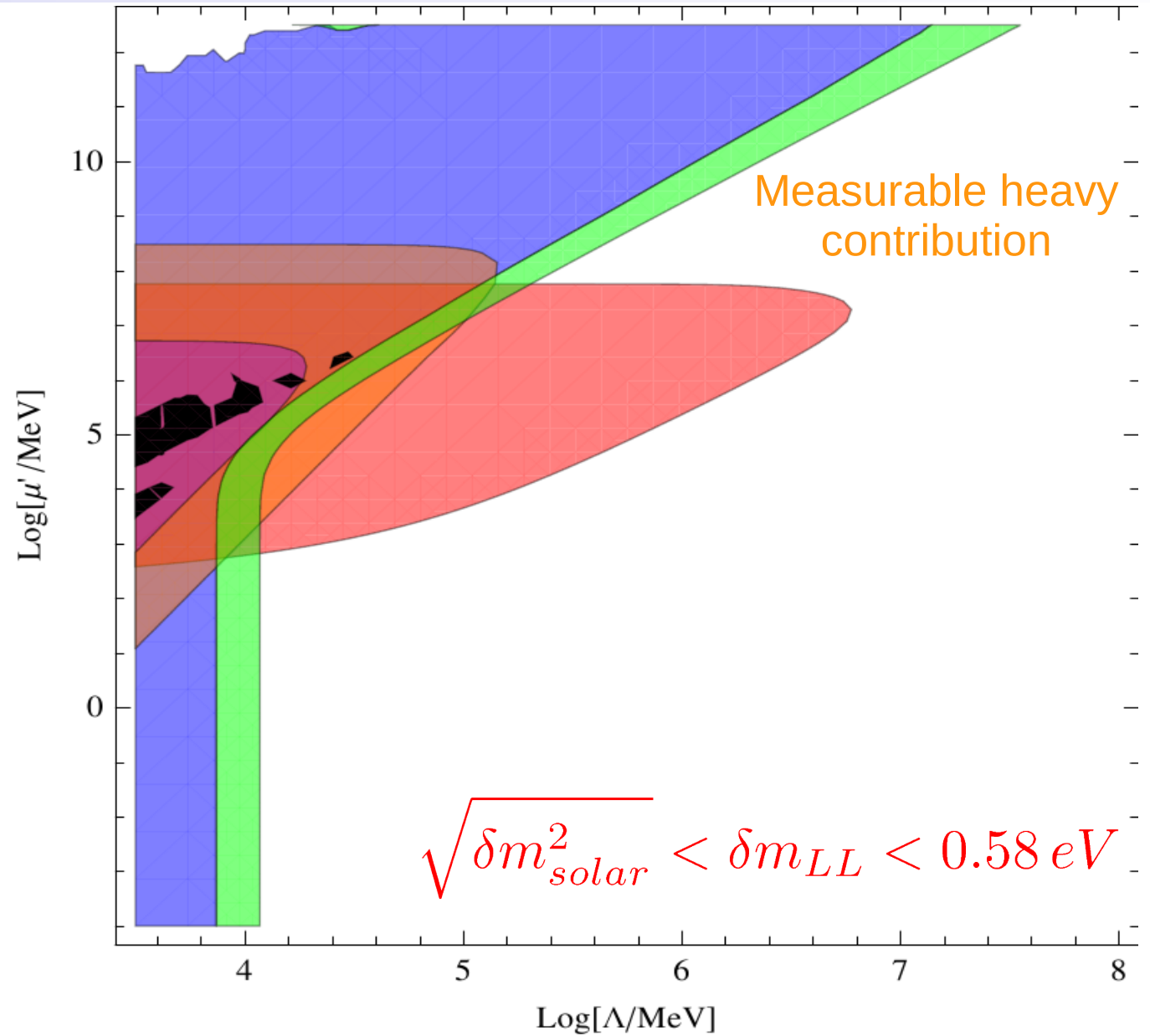
$$A_{heavy} \propto \frac{Y_{1e}^2 v^2}{8\mu'}$$

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

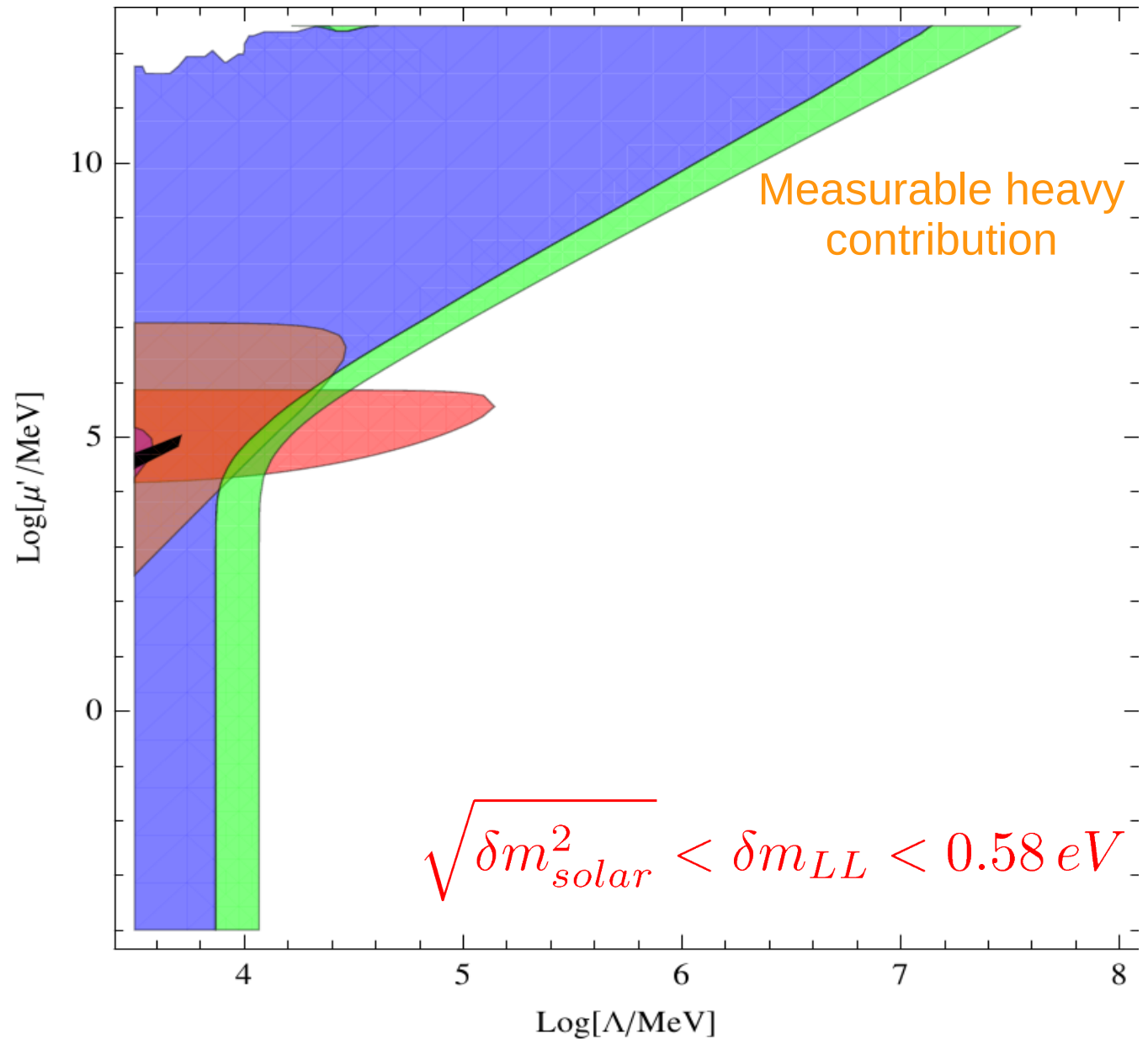
$$A_{heavy} \propto \frac{v^2 \mu' Y_{1e}^2}{2\Lambda^4}$$



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



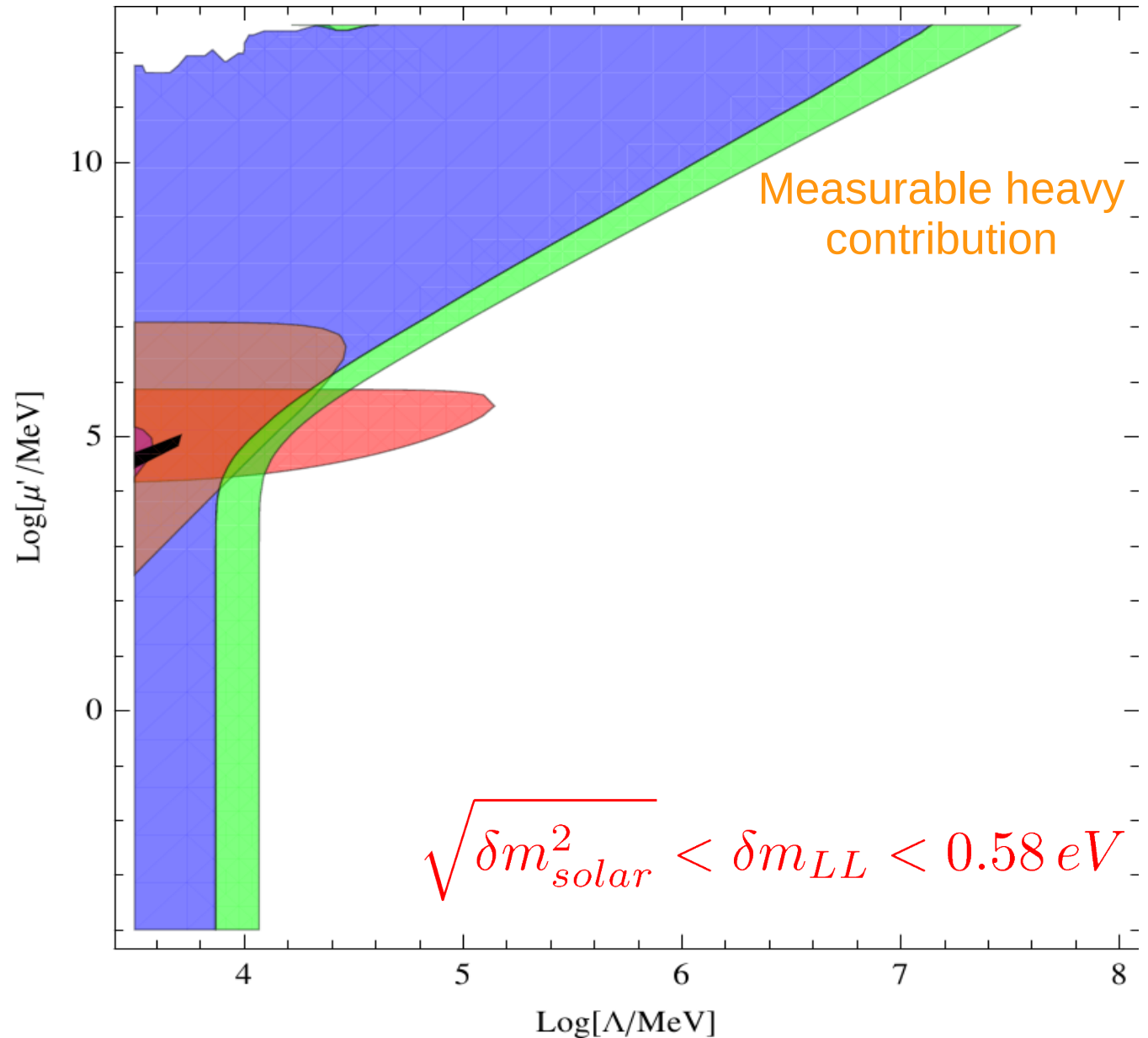
Constraints: $Y_{1\alpha} = 2 \cdot 10^{-6}$



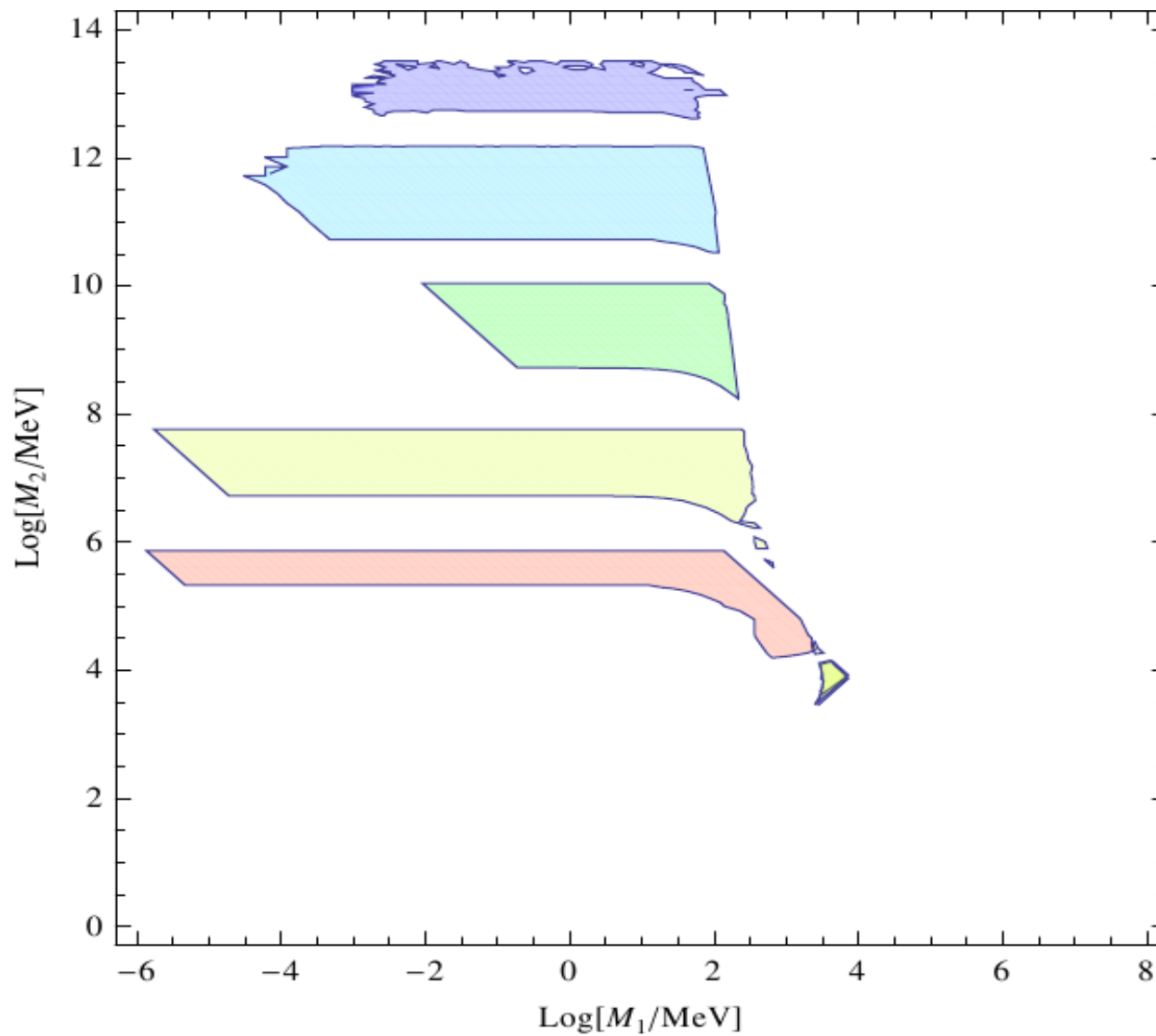
Constraints: $Y_{1\alpha} = 2 \cdot 10^{-6}$

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

Both too
suppressed
for
smaller
Yukawa
couplings



Dominant Heavy Neutrino Contribution



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

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

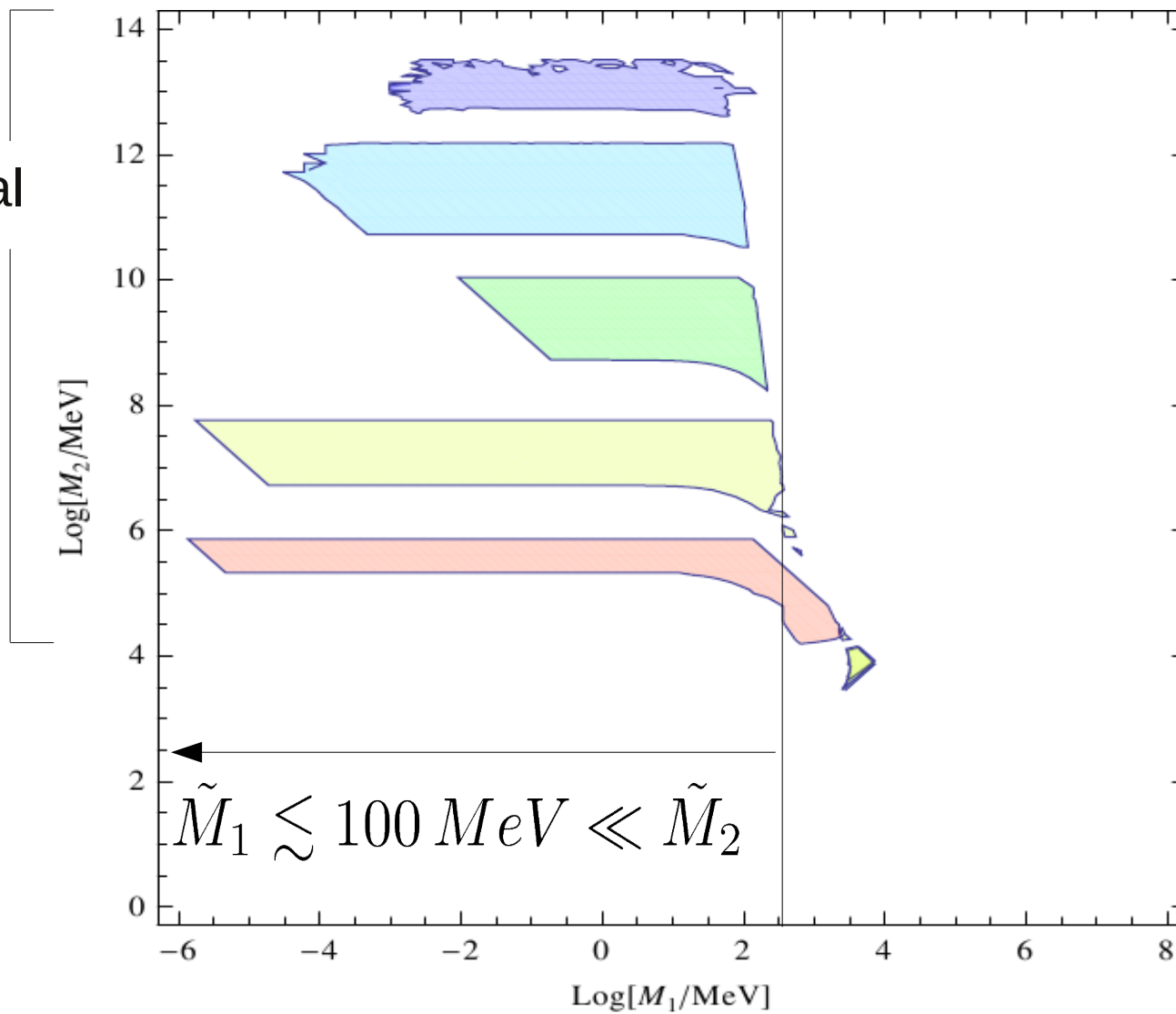
$$Y_{1\alpha} = 10^{-4}$$

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

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

Dominant Heavy Neutrino Contribution

Hierarchical
seesaw



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

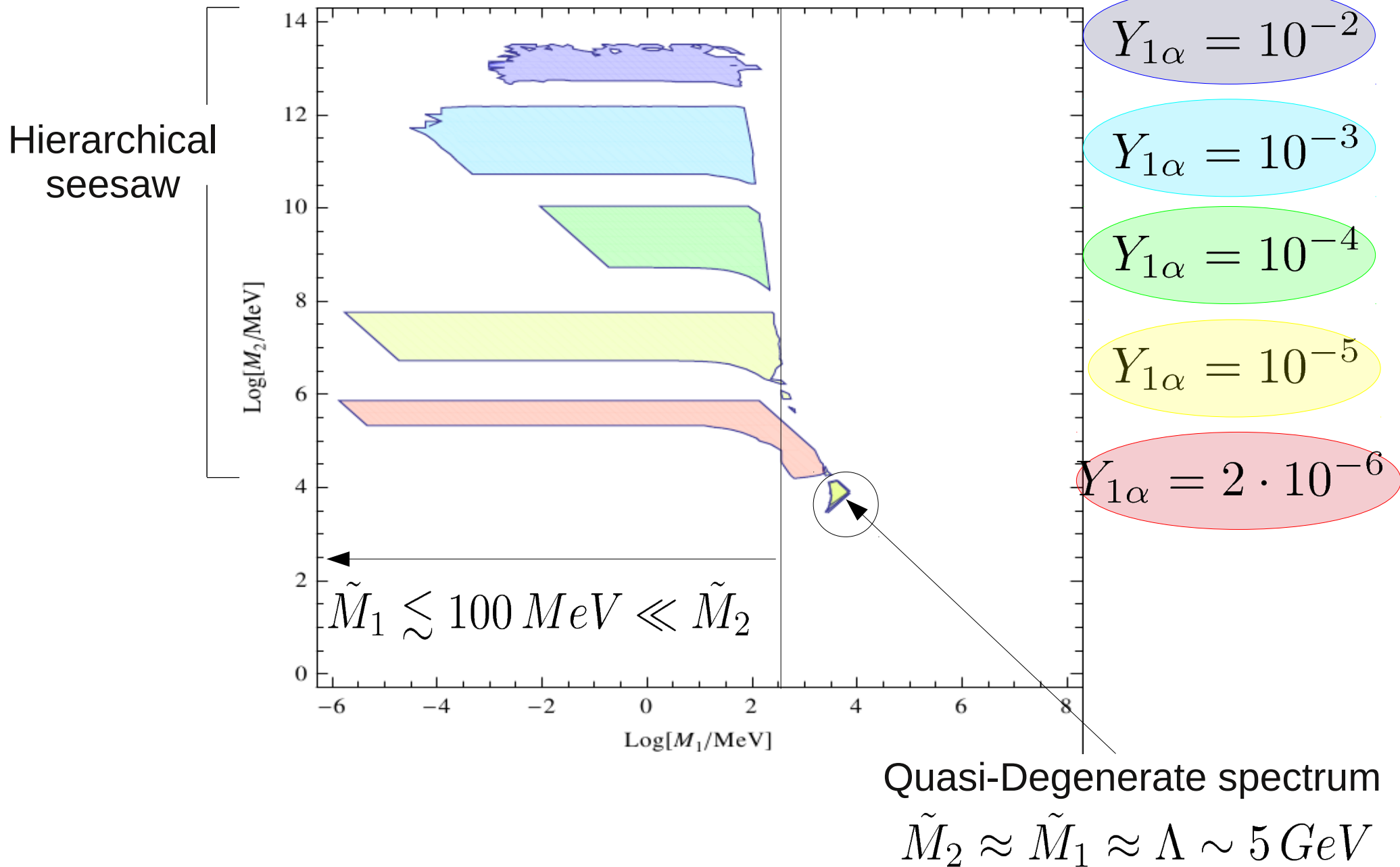
$$Y_{1\alpha} = 10^{-3}$$

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

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

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

Dominant Heavy Neutrino Contribution



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.**

Conclusions

- "Heavy" neutrinos may dominate $0\nu\beta\beta$ decay at tree level if they are in both light and heavy regime.

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

- "Heavy" neutrinos dominate $0\nu\beta\beta$ decay if the light contribution cancels at tree level and:

→ $10^{-6} \lesssim Y_{1\alpha} \lesssim 10^{-2}$

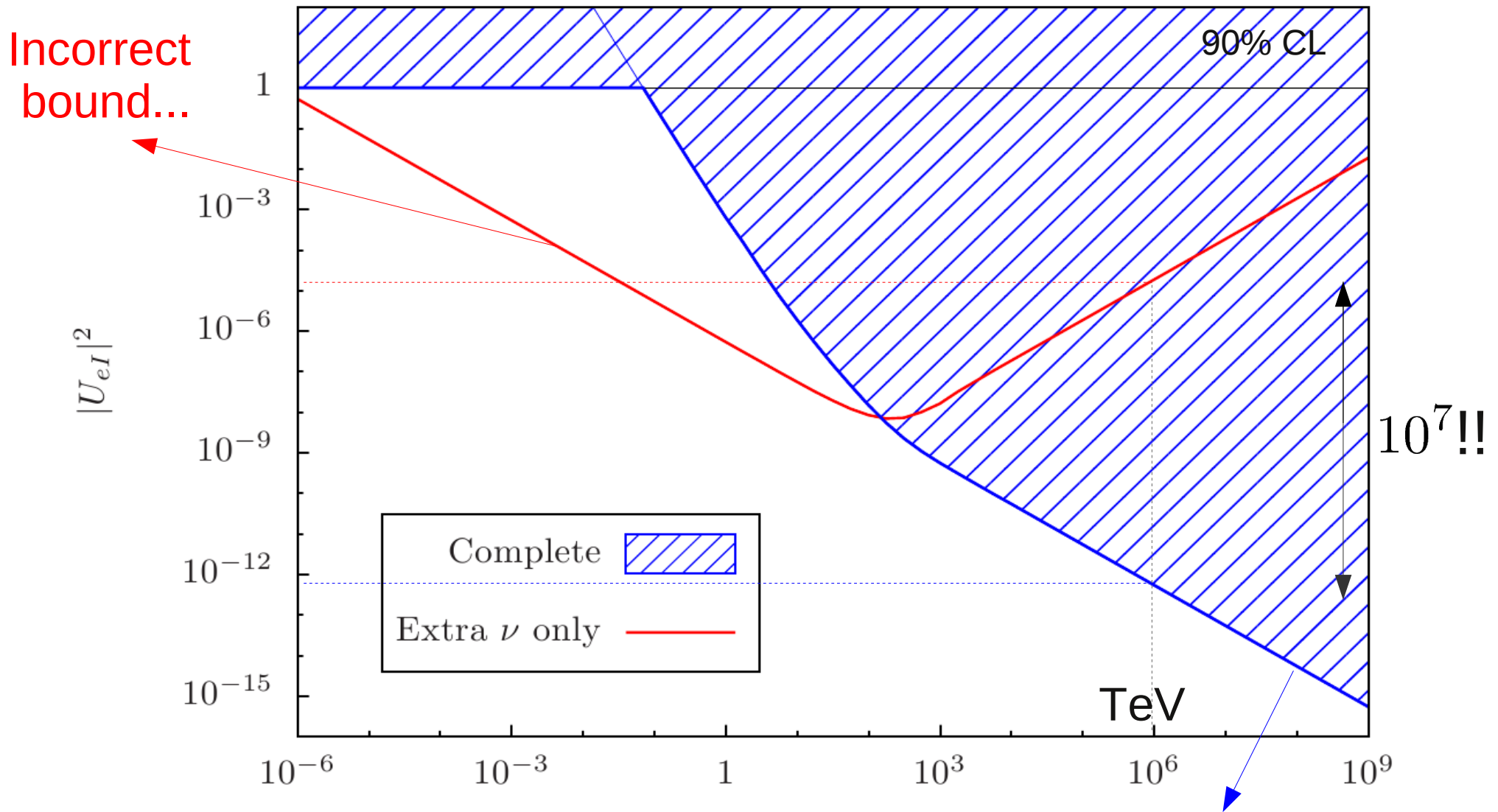
→ "Hierarchical" seesaw ($\Lambda \ll \mu'$). Lightest sterile ν dominates.
 $\tilde{M}_1 \lesssim 100 \text{ MeV} \ll \tilde{M}_2$

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

Thank you!

Back-up

Constraint on mixing with extra neutrino



Bounds from COURICINO (with ^{130}Te) m_I (MeV)

Non-hierarchical extra neutrinos assumed

Type-I: All extra masses in light regime

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

→ Cancellation between NME: GIM *analogy*

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

$$\Delta m^2 / M_W^2$$



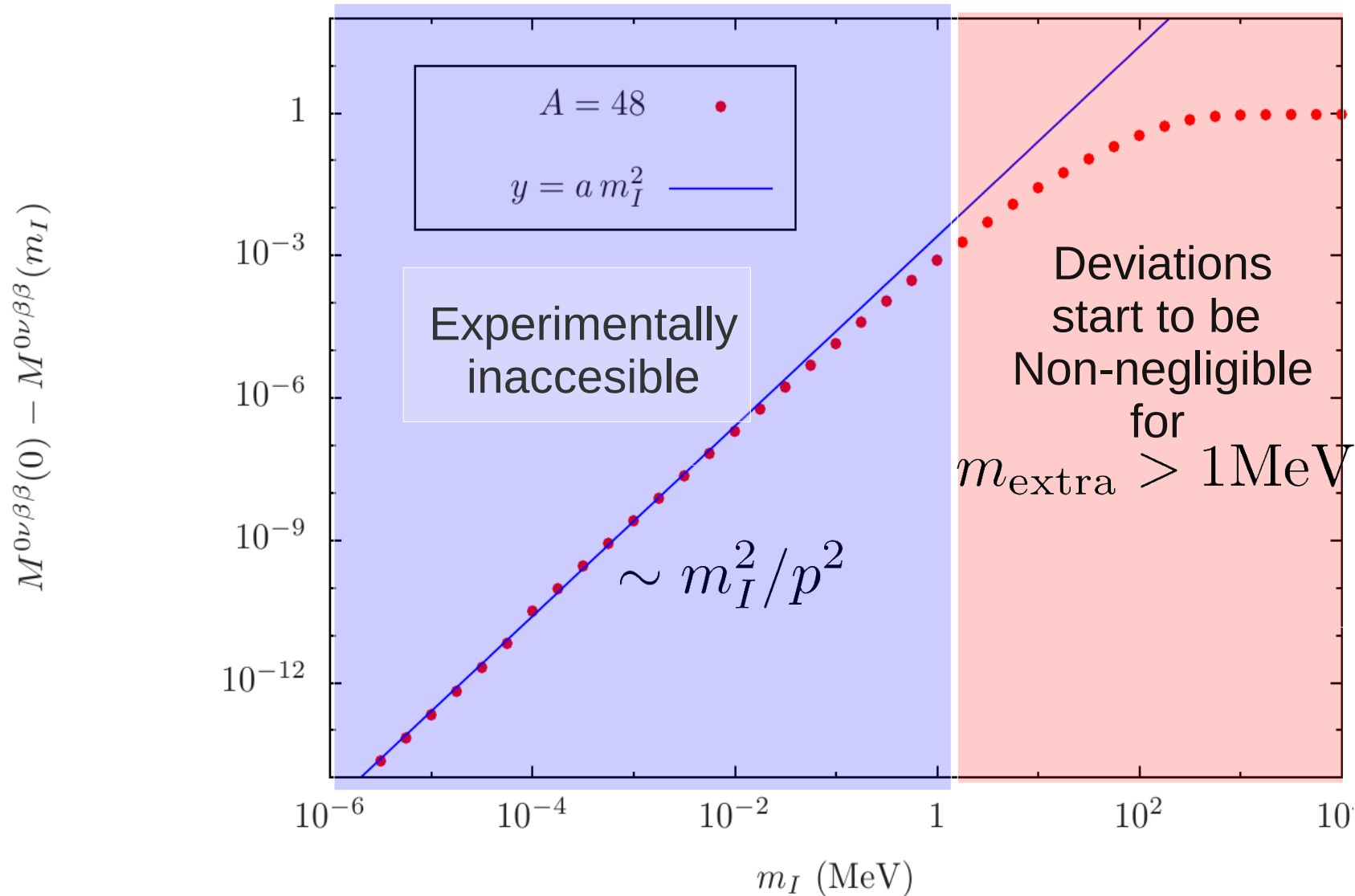
$$\Delta M^{0\nu\beta\beta}$$

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

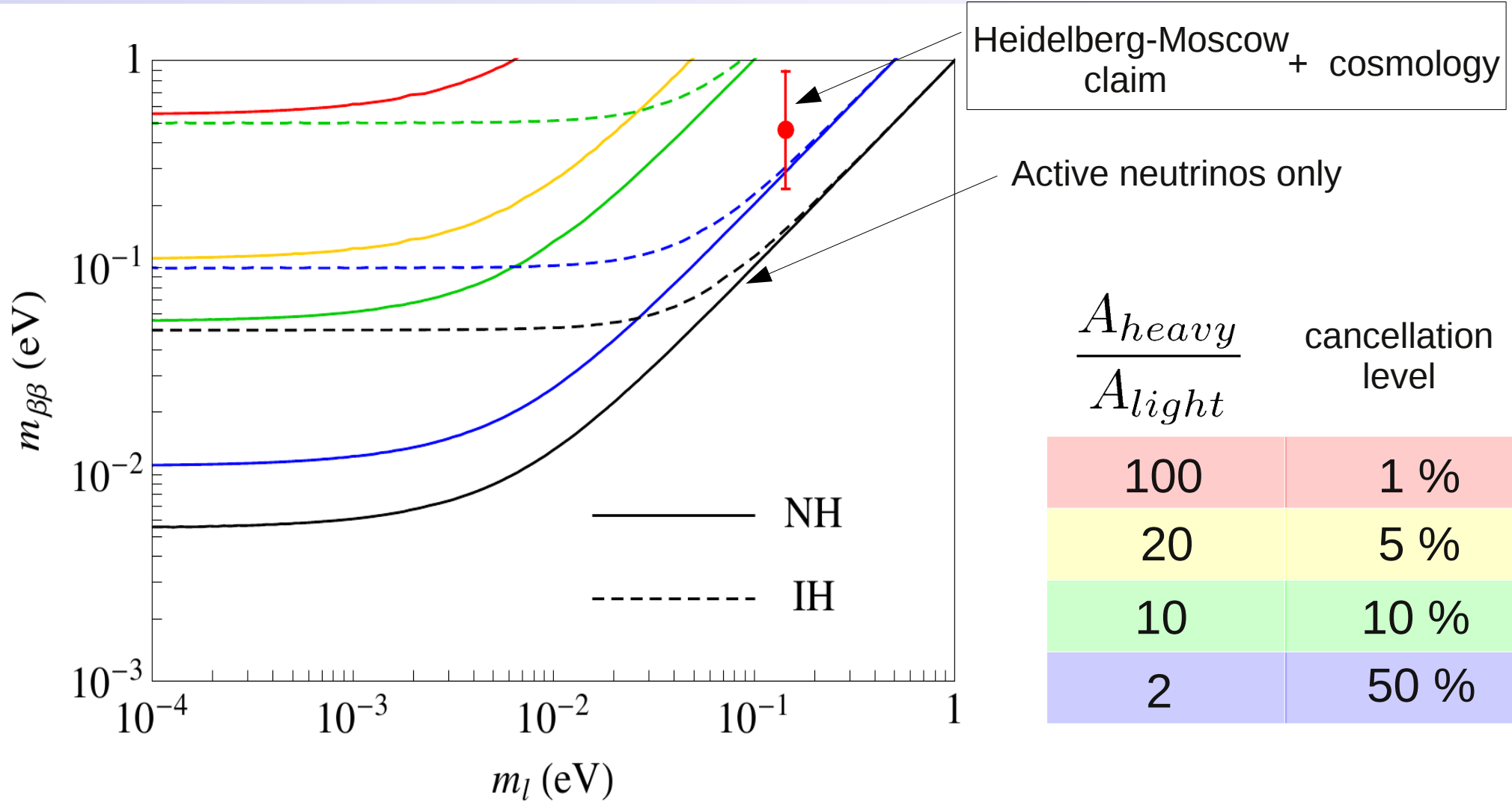
→ Strong suppression for $m_{\text{extra}} < 100\text{MeV}$

Type-I: All extra masses in light regime

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



Extra states in light & heavy regime



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

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

For different cancellation levels:

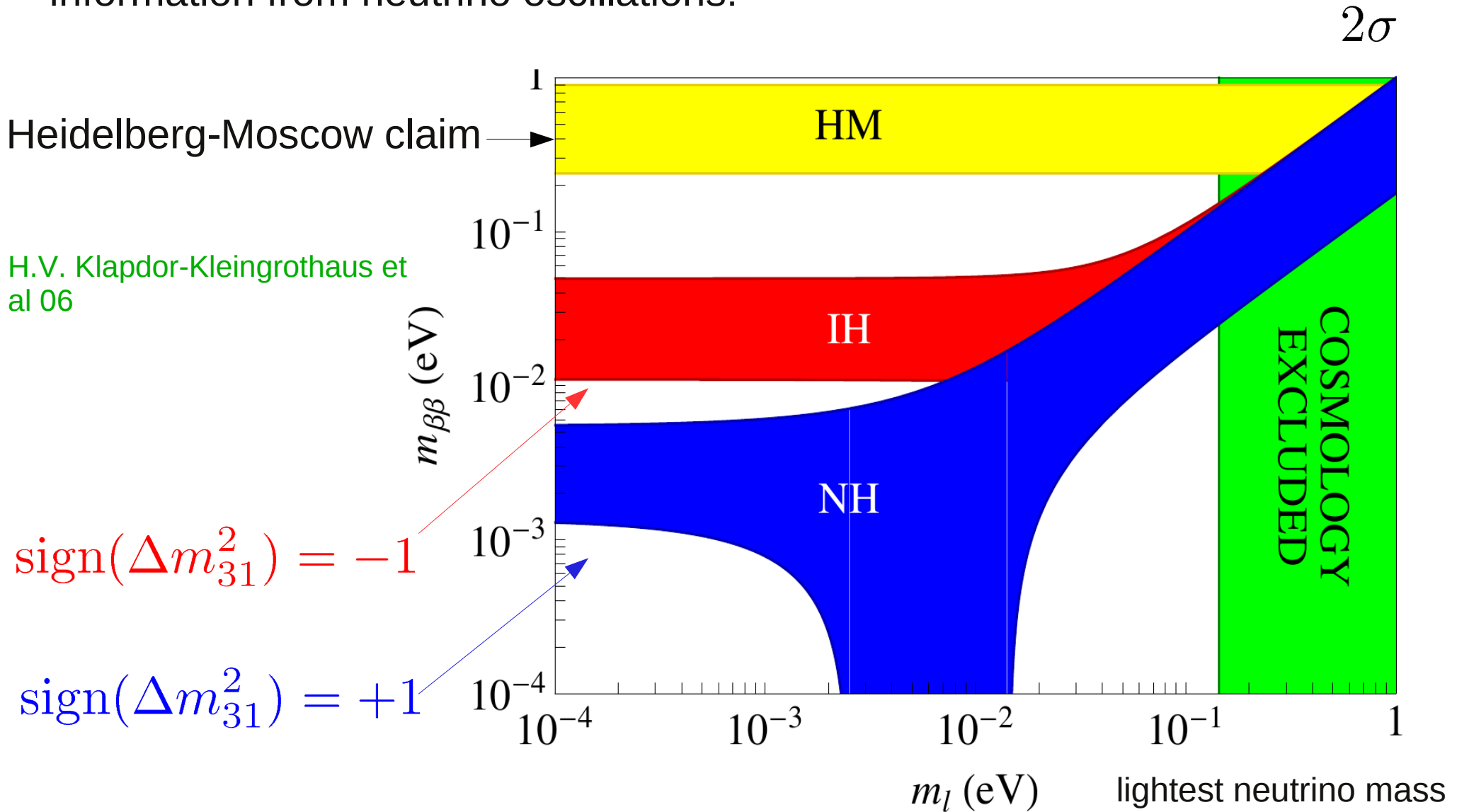
$$\alpha \equiv \frac{m_{\beta\beta}^{\text{standard}}}{m_{\beta\beta}} = \frac{\left| \sum_i^{\text{light}} m_I U_{eI} + \sum_I^{\text{heavy}} m_I U_{eI}^2 \right|}{m_{\beta\beta}}$$

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

Information from neutrino oscillations

Standard approach

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



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

Adding a heavy $SU(2)$ triplet:

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

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

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:

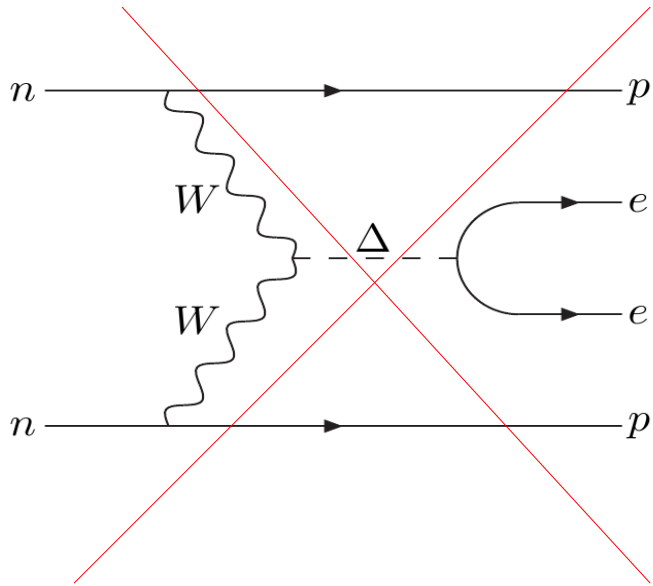
$$\sum_i^{\text{SM}} m_i U_{ei}^2 + \sum_I^{\text{heavy}} m_I U_{eI}^2 = 0 \quad \longleftrightarrow \quad \sum_i^{\text{SM}} m_i U_{ei}^2 = (m_\nu^\Delta)_{ee}$$

Type-I

Type-II

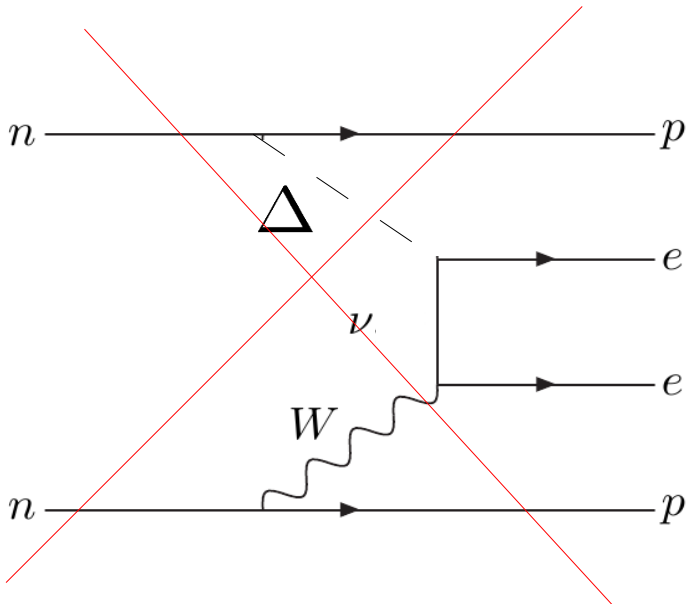
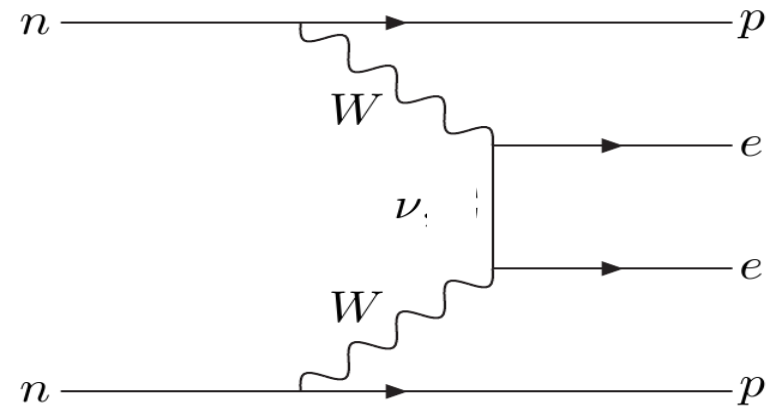
$0\nu\beta\beta$ in Type-II seesaw models

But the scalars can also mediate the process:



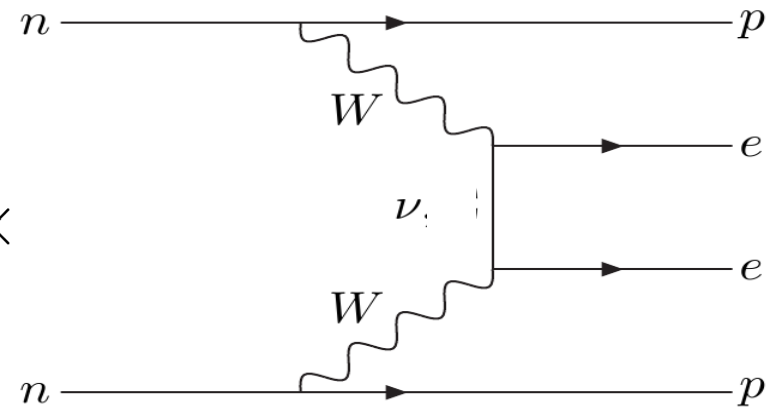
$$\sim \frac{p^2}{M_\Delta^2} \times$$

$$< 10^{-6}$$



$$\sim \frac{m_q}{M_\Delta} \times$$

$$< 10^{-5}$$



$0\nu\beta\beta$ 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 $0\nu\beta\beta$ decay applies:

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

- 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:

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

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

↓ SSB

- Light neutrino masses ("SM"):

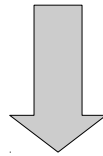
$$m_\nu^\Sigma = \frac{v^2}{2} Y_\Sigma^T M_\Sigma^{-1} Y_\Sigma$$

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

$$\sum_i^{\text{SM}} m_i U_{ei}^2 + \underbrace{\sum_I^{\text{heavy}} m_I U_{eI}^2}_{\text{Type-I}} = 0 \quad \longleftrightarrow \quad \sum_i^{\text{SM}} m_i U_{ei}^2 = \underbrace{(m_\nu^\Sigma)_{ee}}_{\text{Type-III}}$$

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

In addition: **Stringent lower bounds in Σ mass**



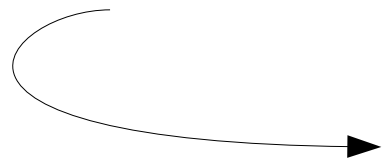
$0\nu\beta\beta$ phenomenology of type III seesaw reduces in practise to Type-II seesaw case, simply doing:

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

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

- 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:

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


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

- Possible to have **dominant contribution to $0\nu\beta\beta$ decay from the extra light sterile neutrinos while** above equation and the **smallness of masses is respected by a cancellation** between extra states contribution.