Neutrinoless double beta decay in seesaw models

Jacobo López-Pavón
IPPP
Durham University

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Based on a collaboration with:

M. Blennow,
(MPI, Munich)
E. Fernández-Martínez
(CERN)
and
J. Menéndez
(Institute for Nuclear Physics, TUD
EMM, GSI)

arXiv:1005.3240 [hep-ph]

Very Brief Motivation

- Neutrino masses and mixing ⇨ evidence of physics Beyond the SM

- Moreover, smallness of neutrino masses calls for a New Physics explanation coming from Higher Energies.

⇩

Consider SM as a low energy effective theory of a higher energy one able to explain this fact.

Heavy fields manifest in the low energy effective theory via higher dimension operators:

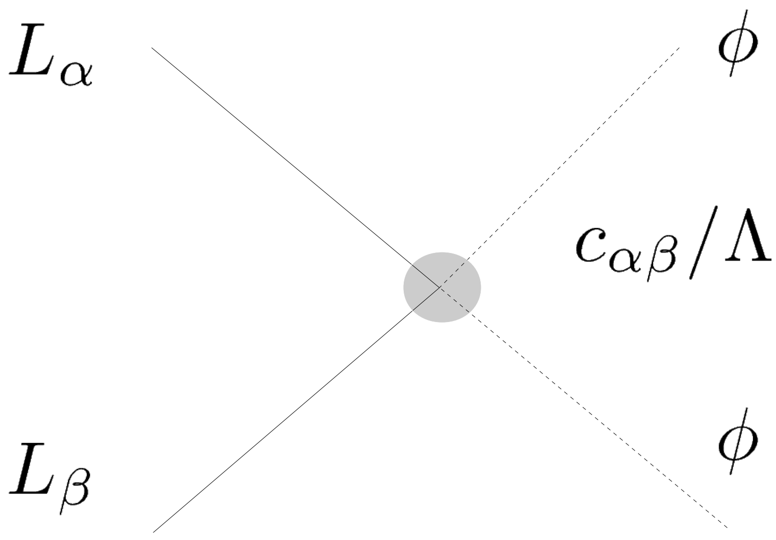
$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \delta\mathcal{L}^{d=5} + \delta\mathcal{L}^{d=6} + \ldots \text{ with } \delta\mathcal{L}^{d} \propto \frac{1}{\Lambda^{d-4}}$$

Very Brief Motivation

- With the SM field content, the lowest dimension operator which give neutrino masses 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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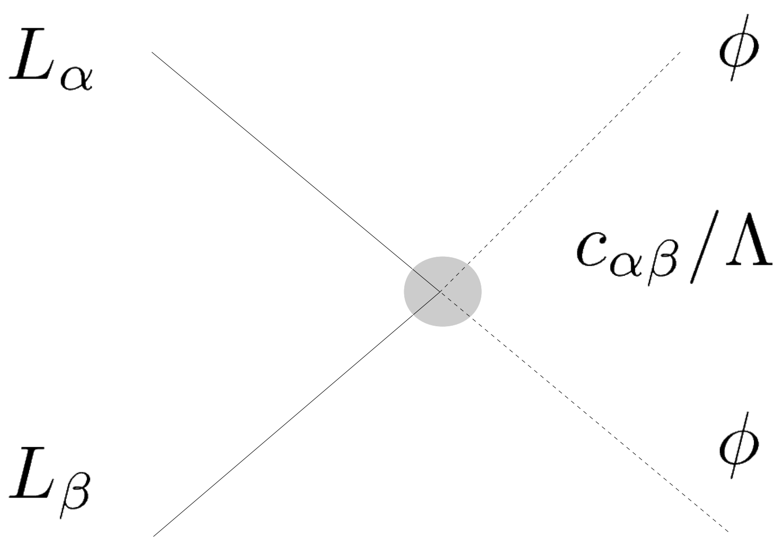

Smallnes of neutrino masses can be explained

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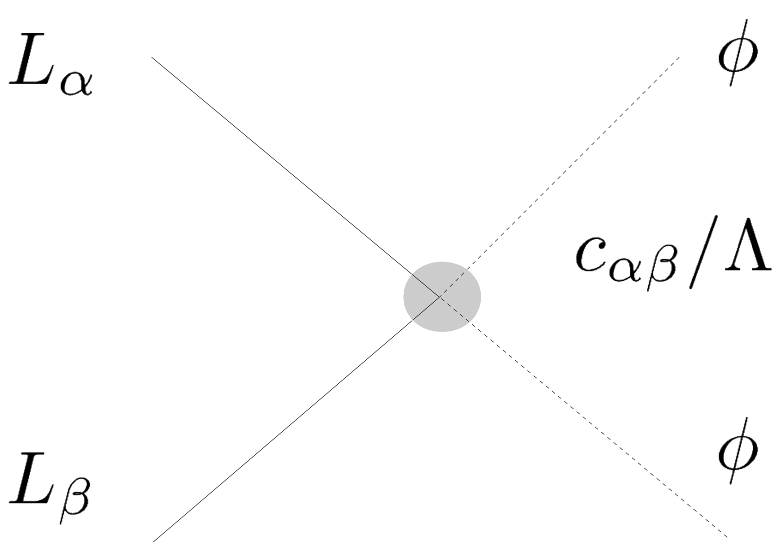
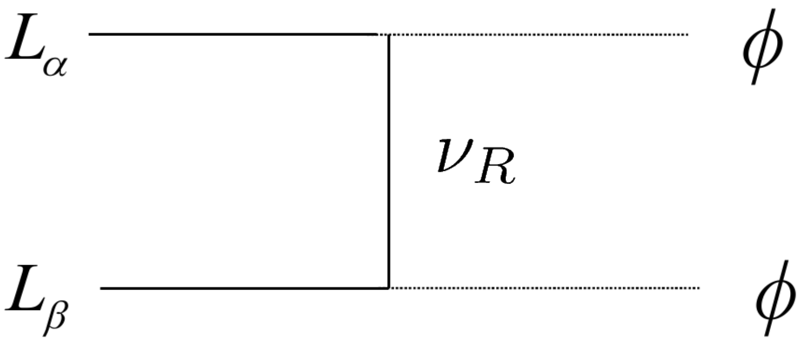


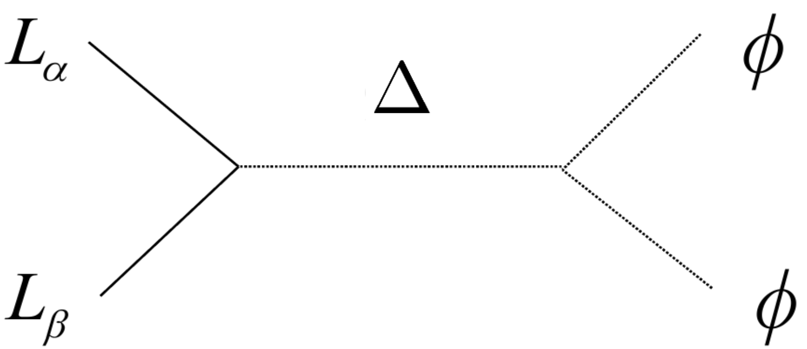
Smallnes of neutrino masses can be explained

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

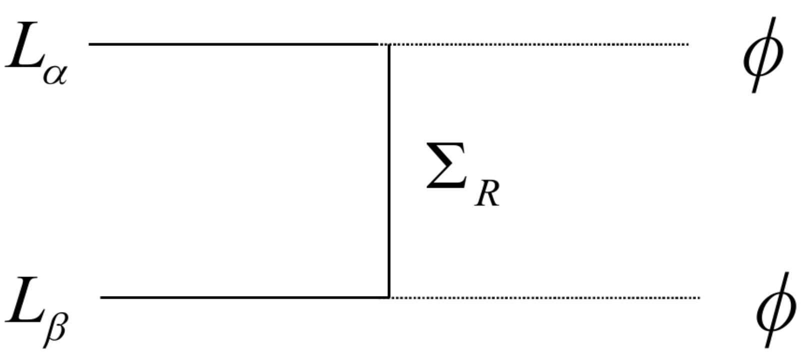
Tree level realisations of the Weinberg operator



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

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.

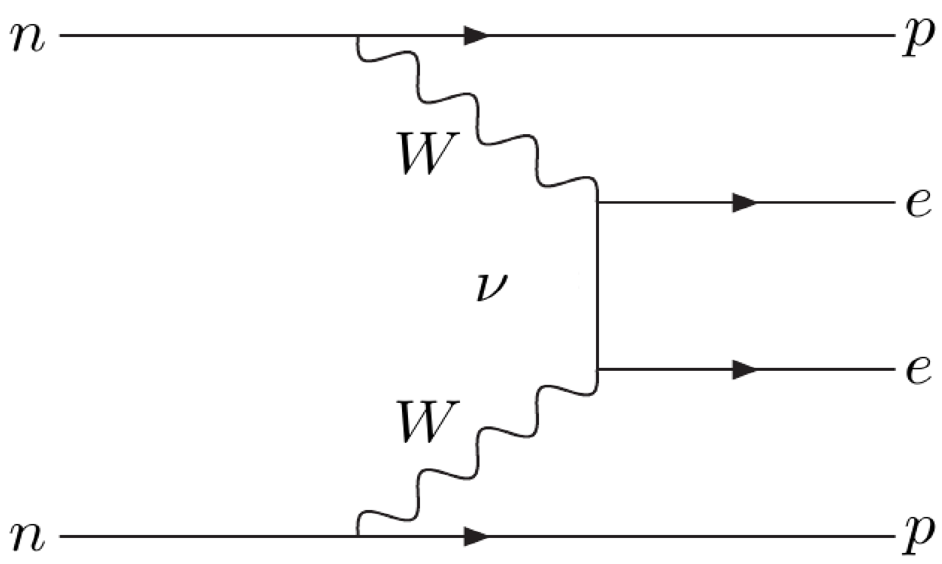
$$(Z, A) \Rightarrow (Z \pm 2, A) + 2e^{\mp} + X$$

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.

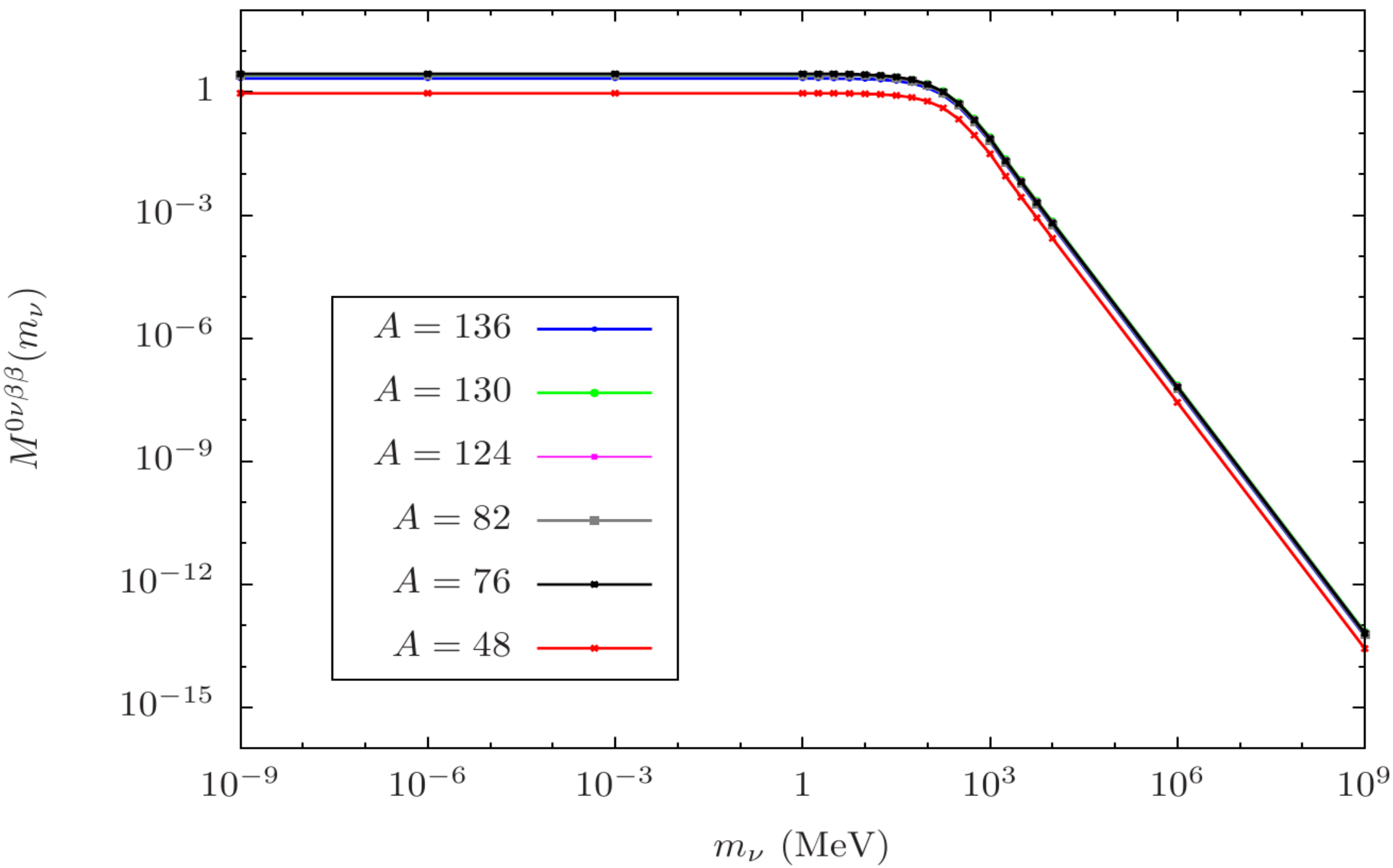
Neutrinoless double beta decay



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

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

Nuclear Matrix Element (NME)



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

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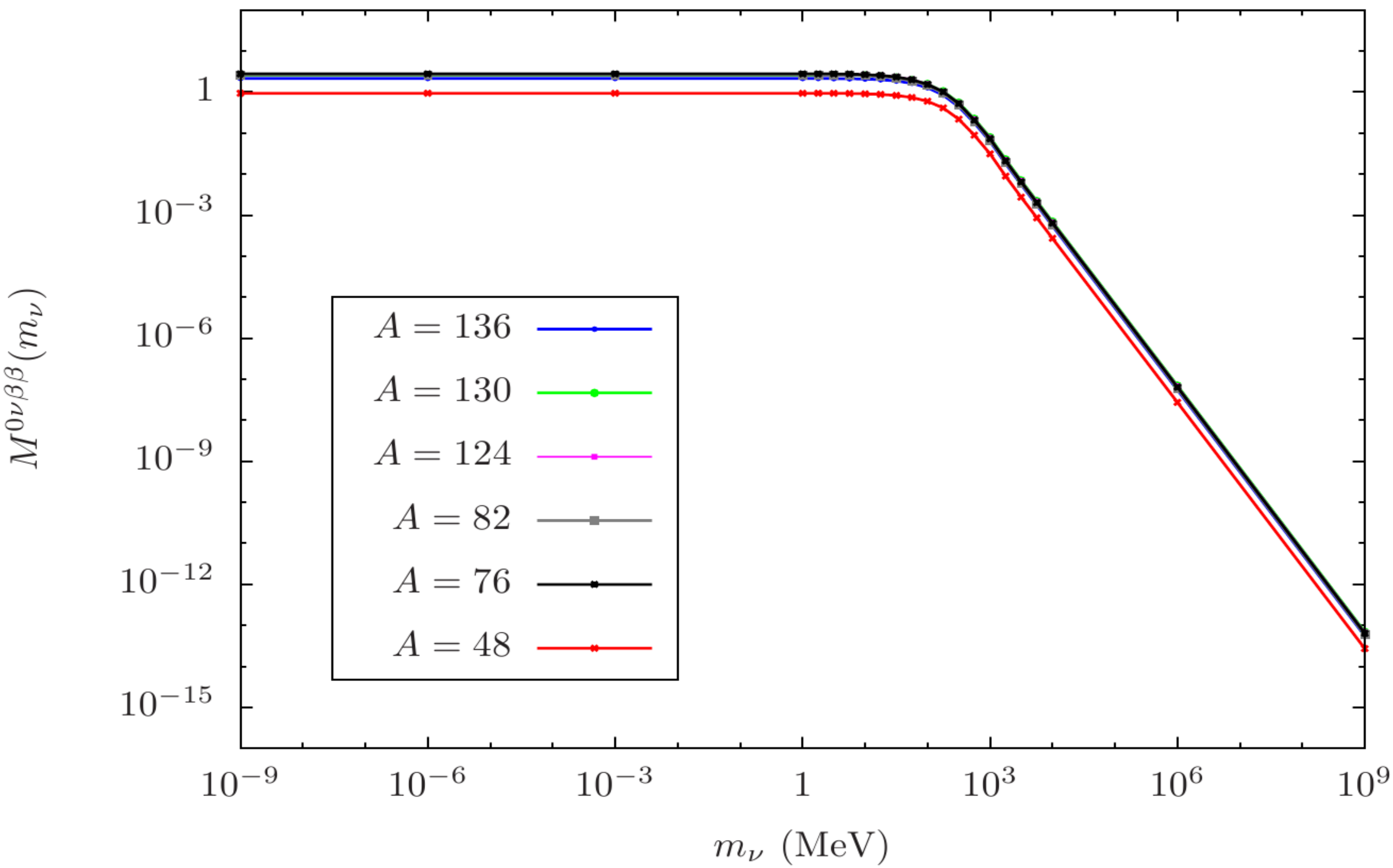

- Mild dependece on the nuclei

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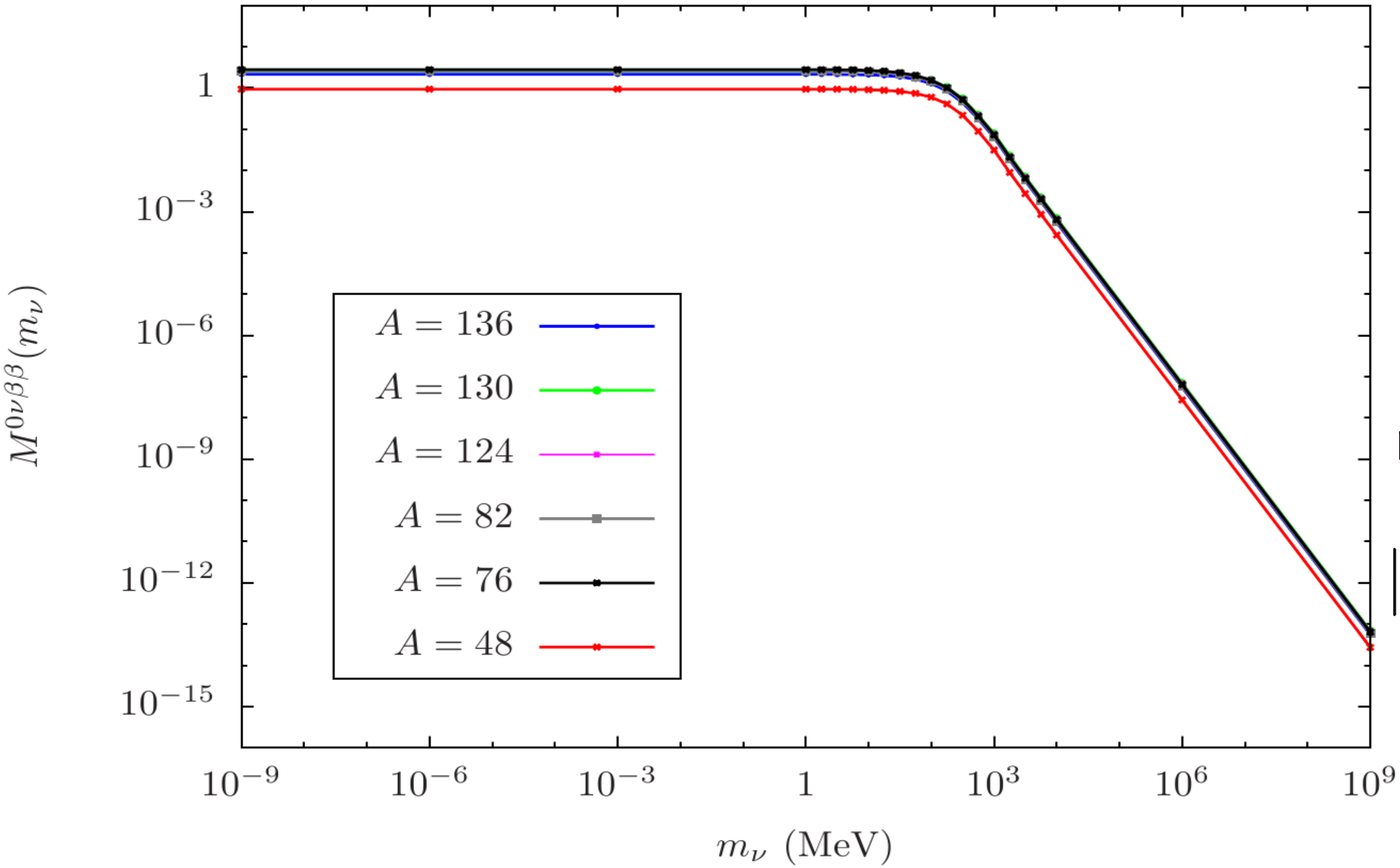

- Mild dependece on the nuclei

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

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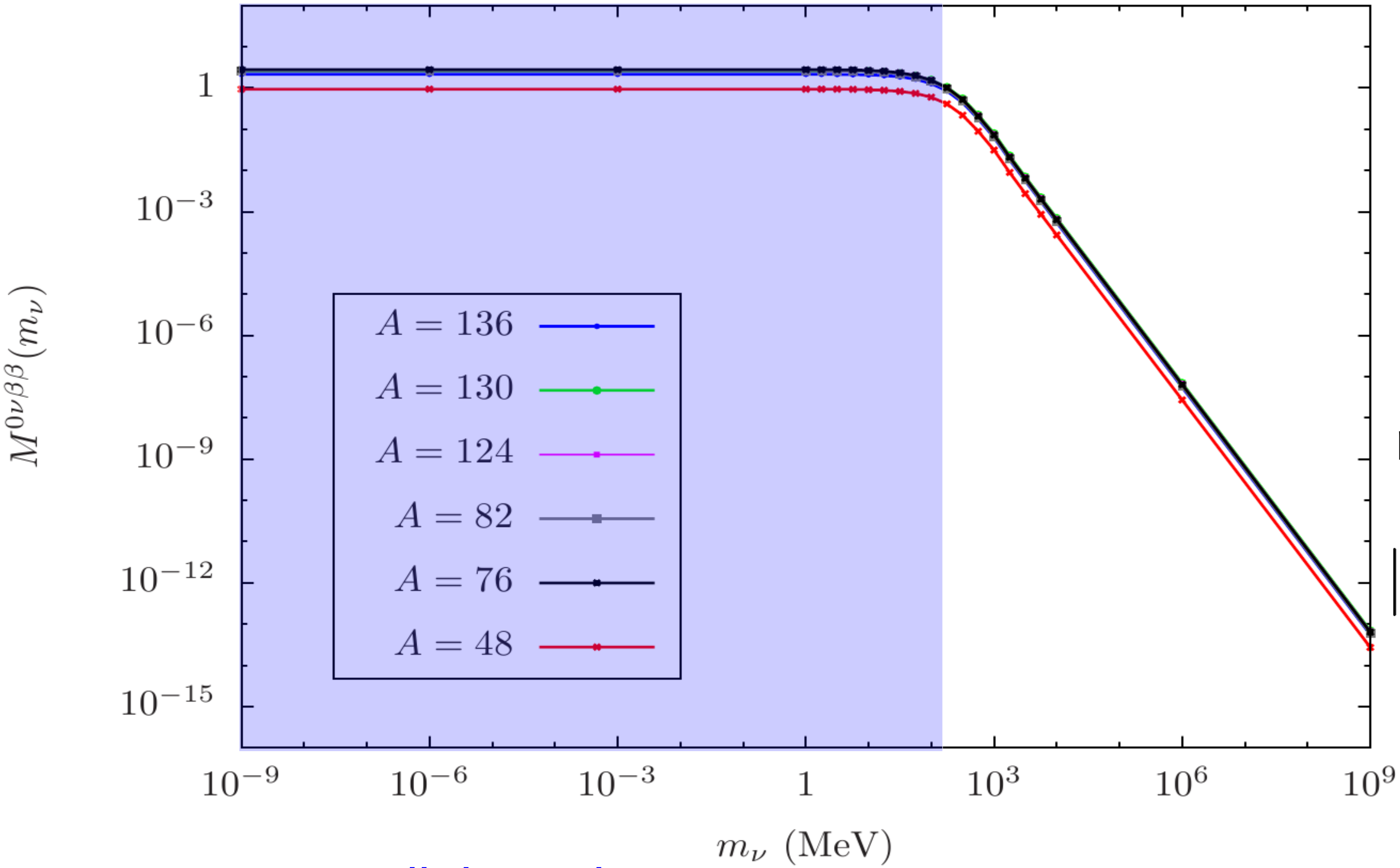

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light regime

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

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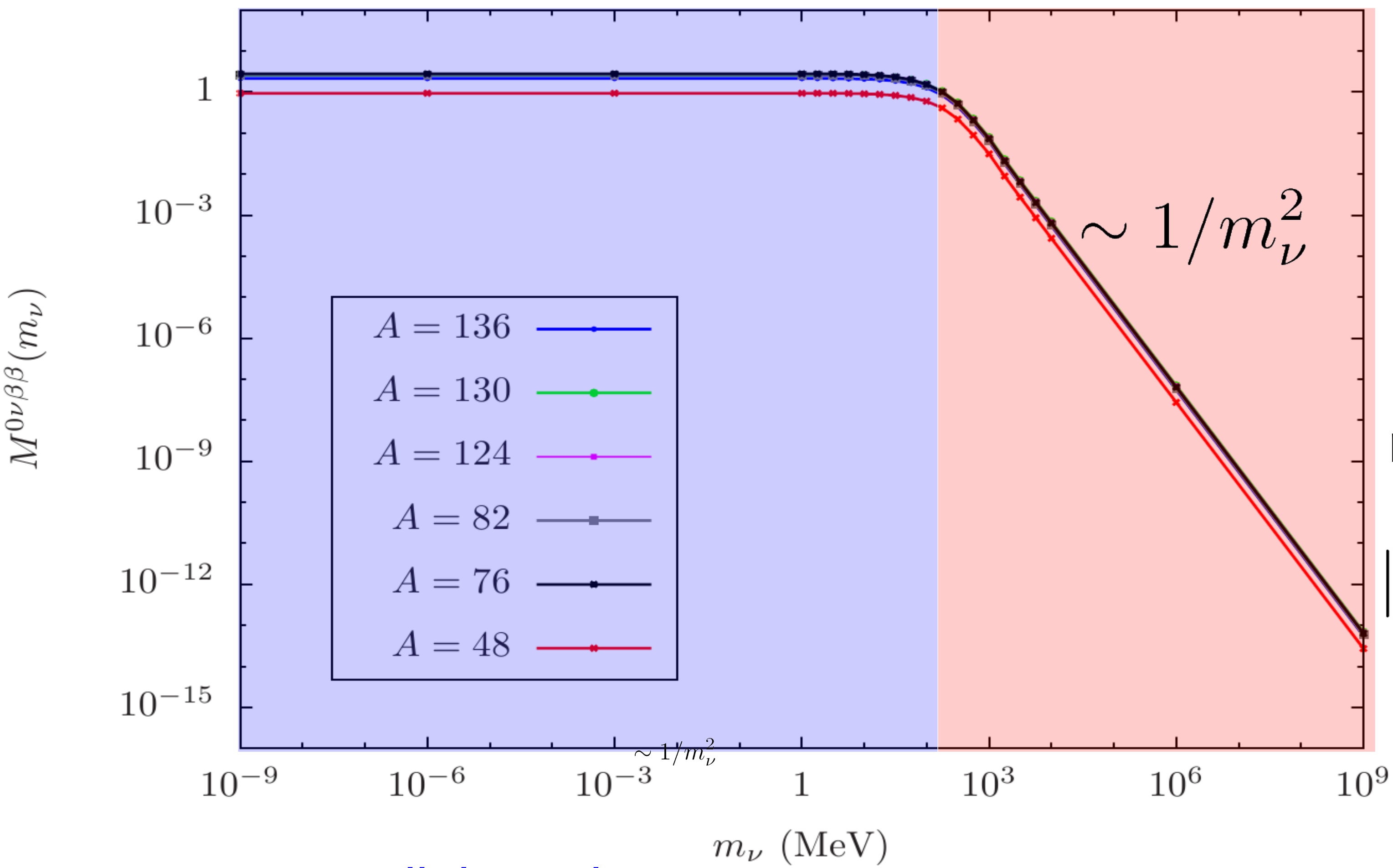

- Mild dependece on the nuclei
- Two different regions separated by nuclear scale $|p^2| \simeq 100\,\mathrm{MeV}$

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

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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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:

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

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

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The neutrino mass matrix is then given by:

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

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

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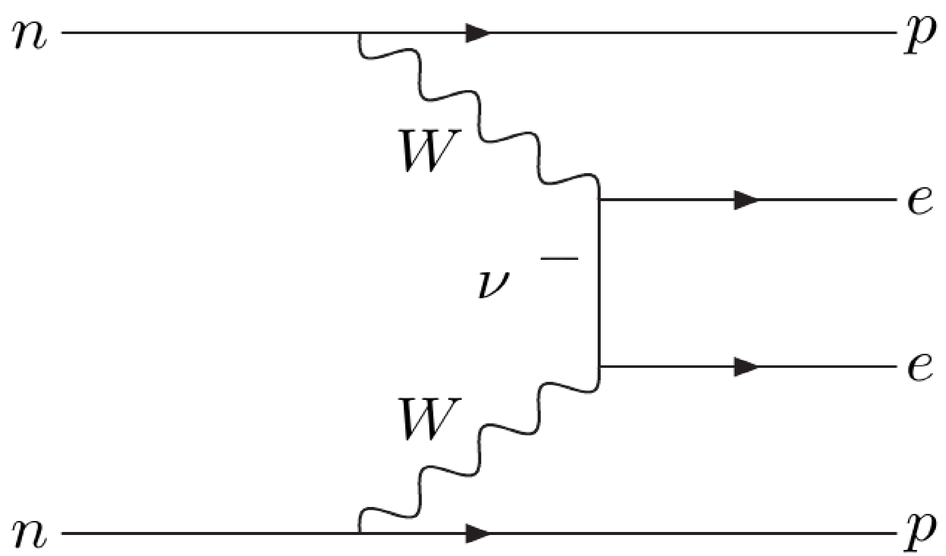
$$\cancel{\overline{\nu_{\alpha L}}\nu^c_{\alpha L}}$$

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

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

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



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

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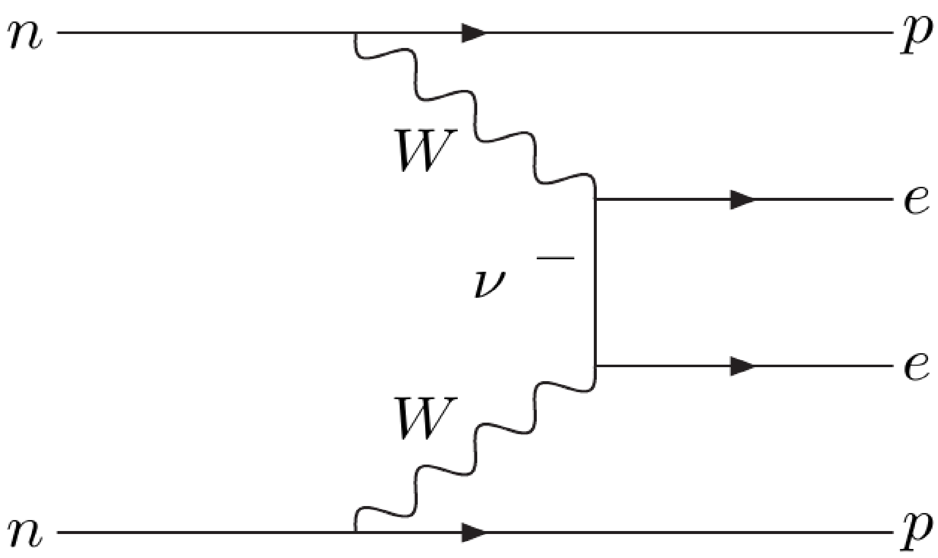

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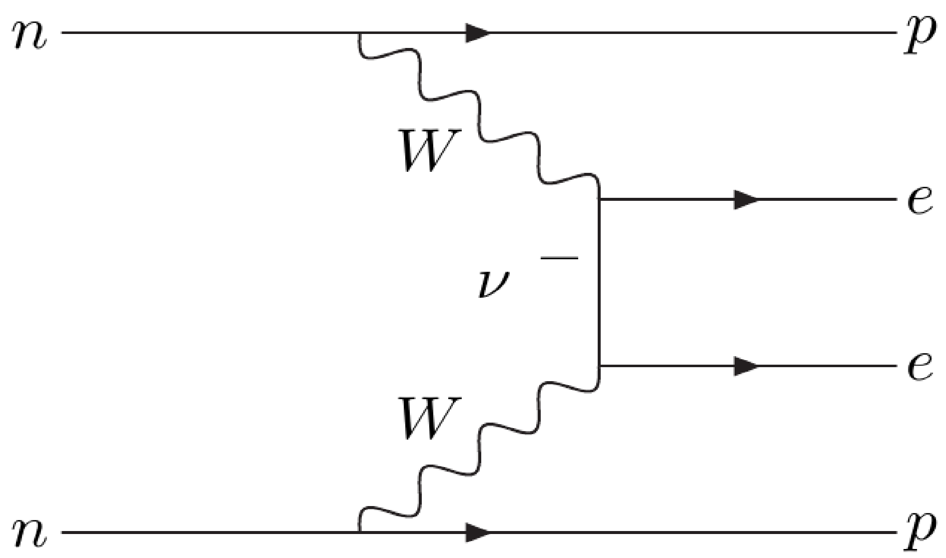
light mostly active states

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



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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. $\cancel{\overline{\nu_{\alpha L}} \nu_{\alpha L}^c}$ $\quad \sum_{i}^{\text{SM}} m_i U_{ei}^2 + \sum_{I}^{\text{light}} m_I U_{eI}^2 = 0$

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

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

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→ 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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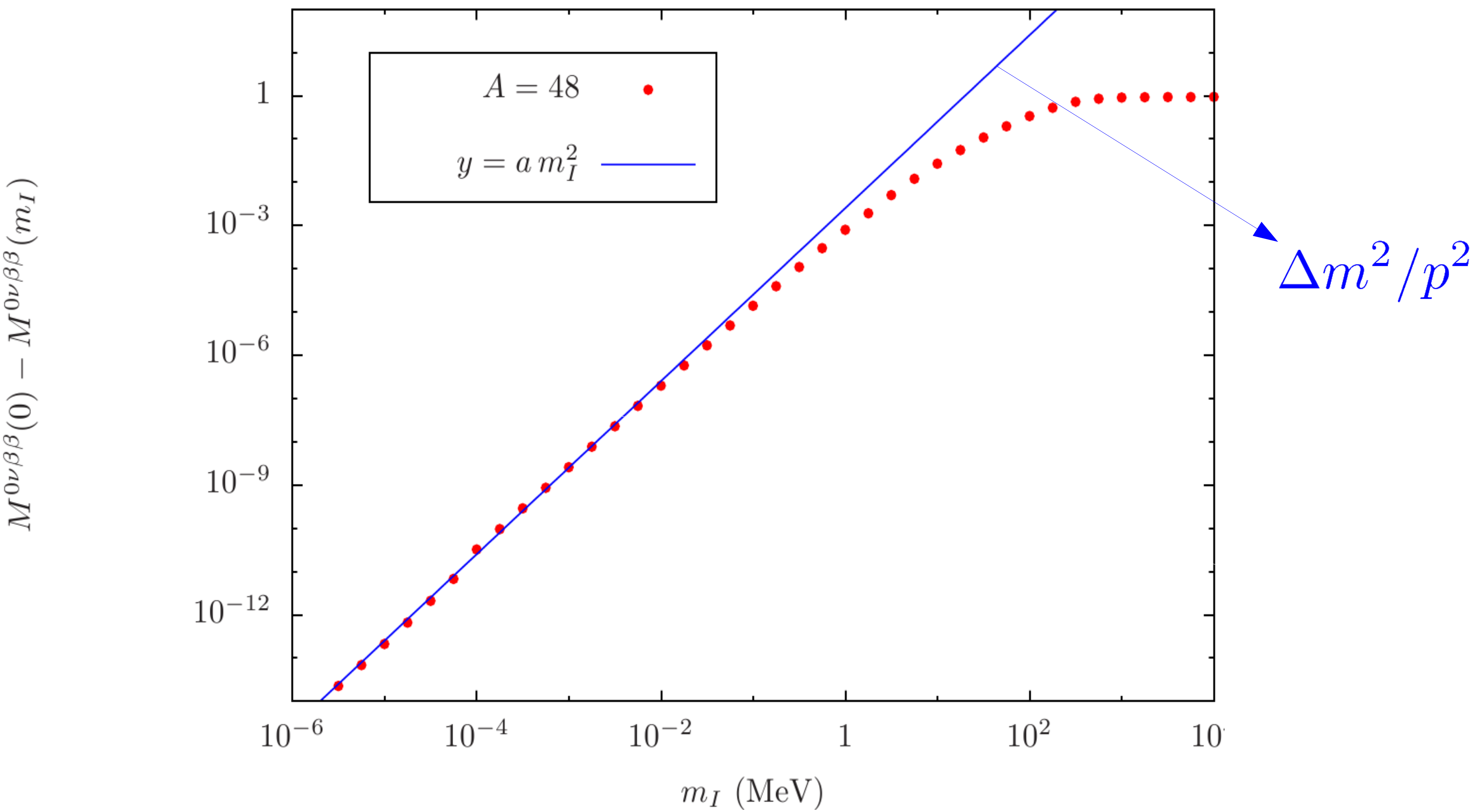

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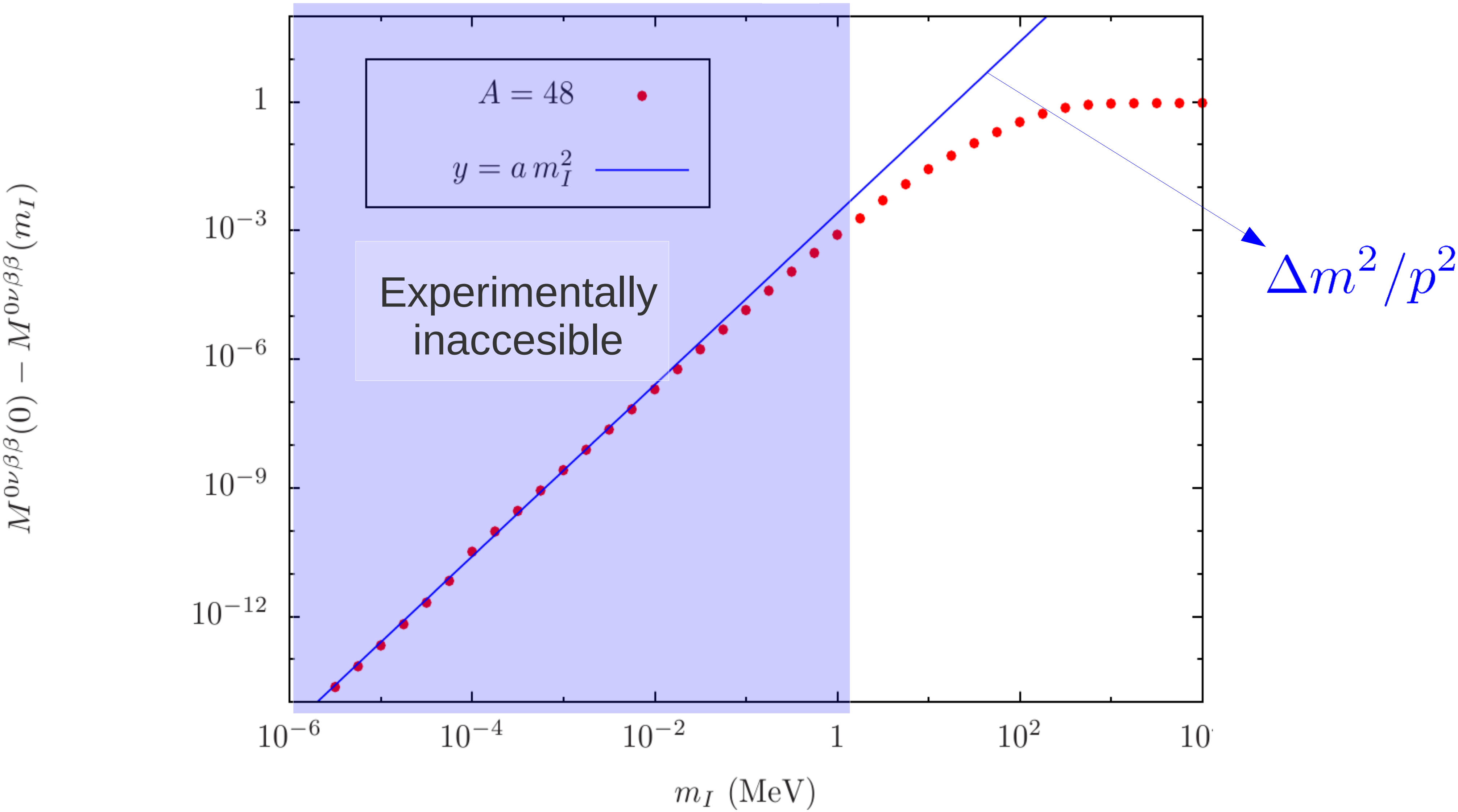

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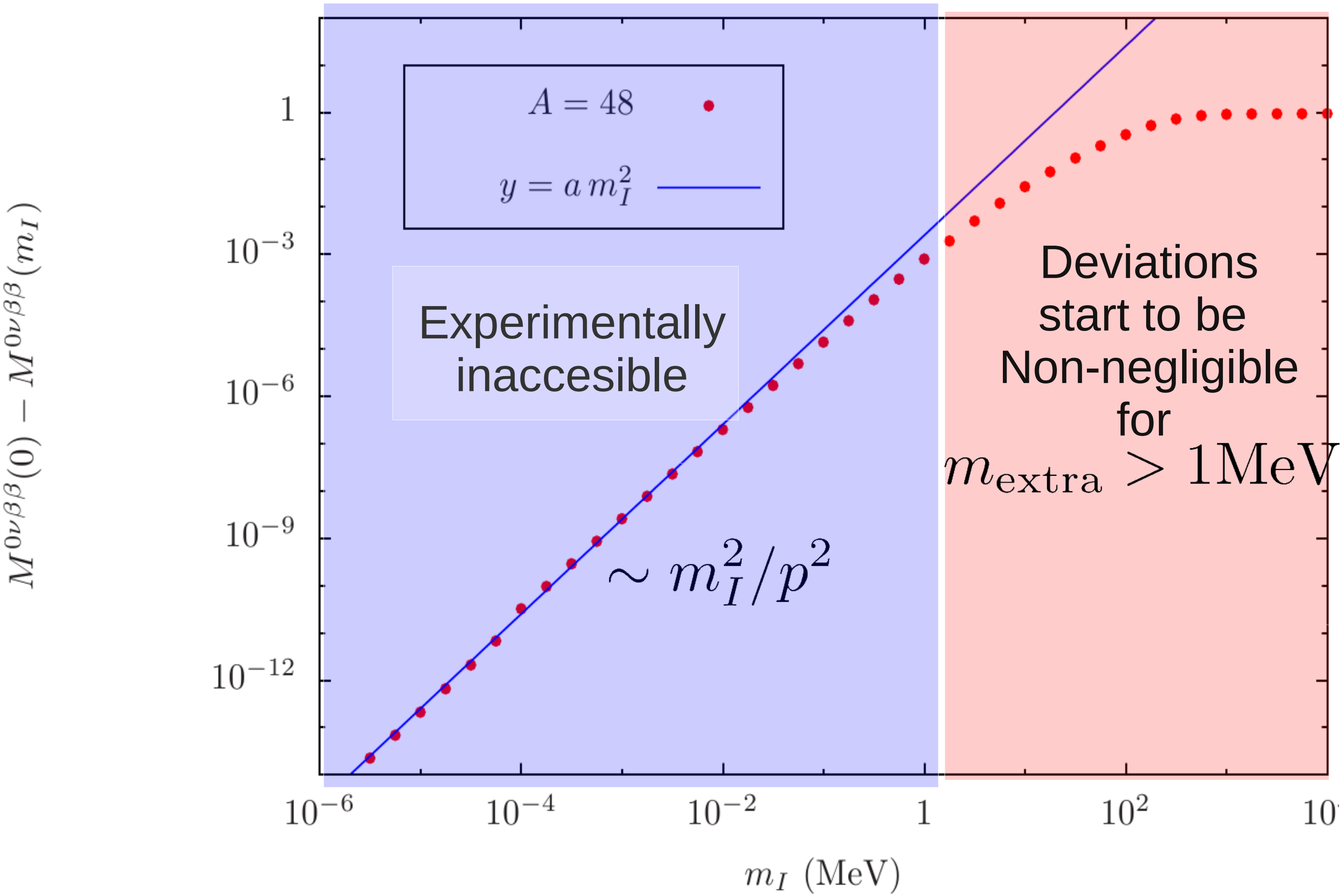

Type-I: All extra masses in heavy regime

"canonical" Type-I seesaw scenario

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

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Usually treated as separeted sectors when constraints are extracted from experiments. But they are related !!

Type-I: All extra masses in heavy regime

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

Type-I: All extra masses in heavy regime

"canonical" Type-I seesaw scenario

negligible!

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Type-I: All extra masses in heavy regime

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negligible

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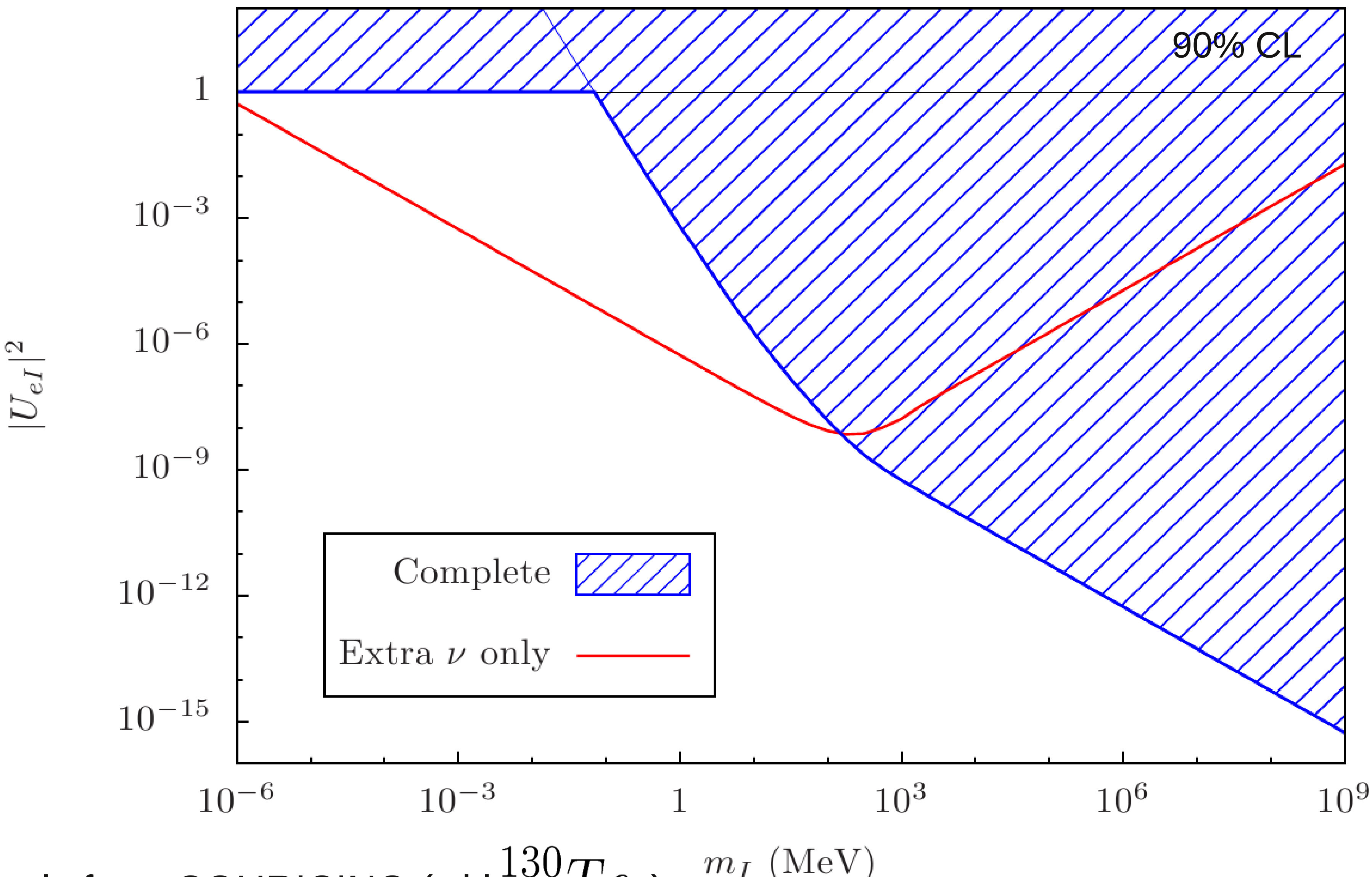
Constraint on mixing with heavy neutrinos
through light contribution!!

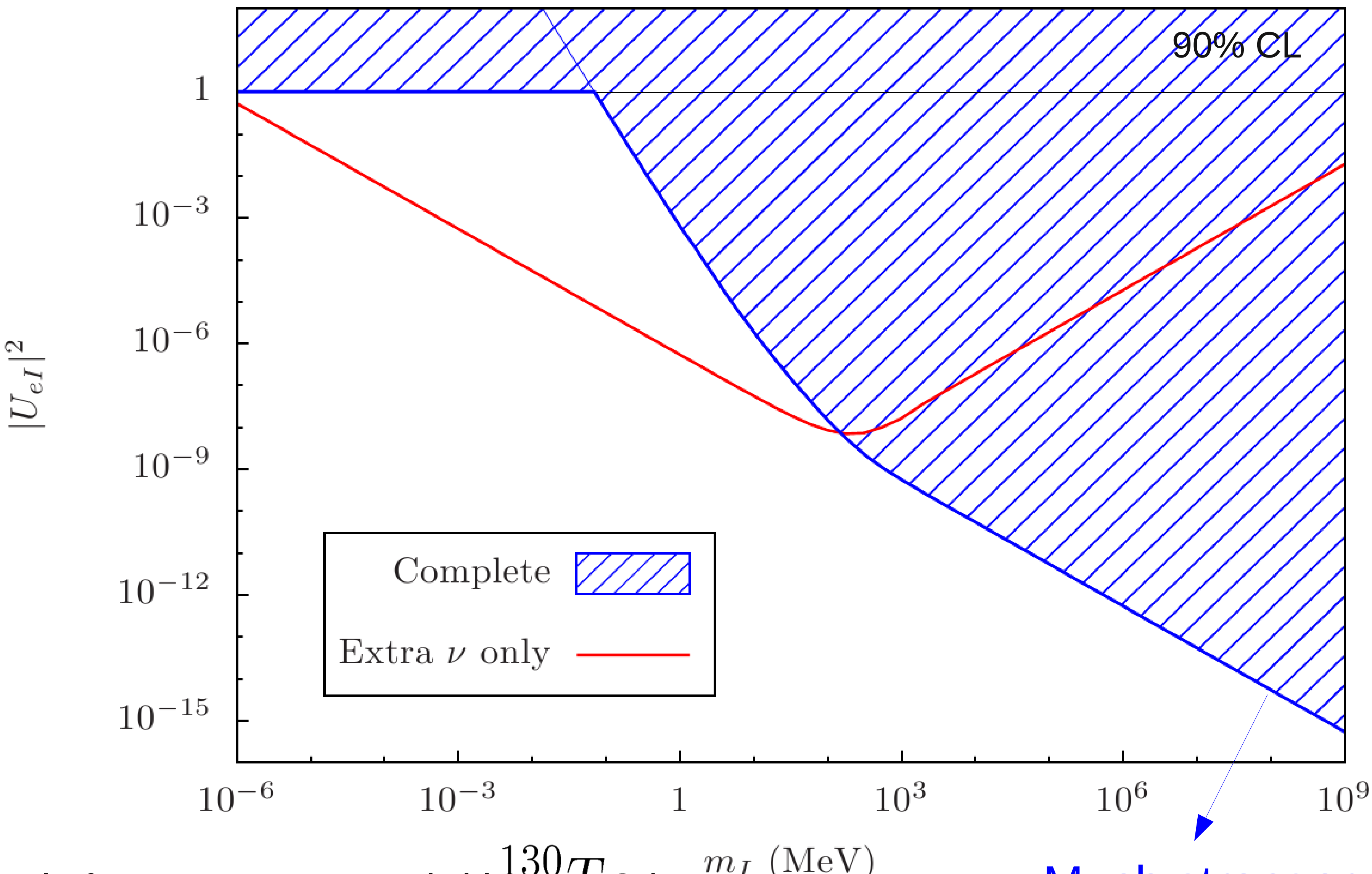
Constraint on mixing with extra neutrino



Bounds from COURICINO (with ^{130}Te)

Non-hierarchical extra neutrinos assumed

Constraint on mixing with extra neutrino



Much stronger Constraint !!

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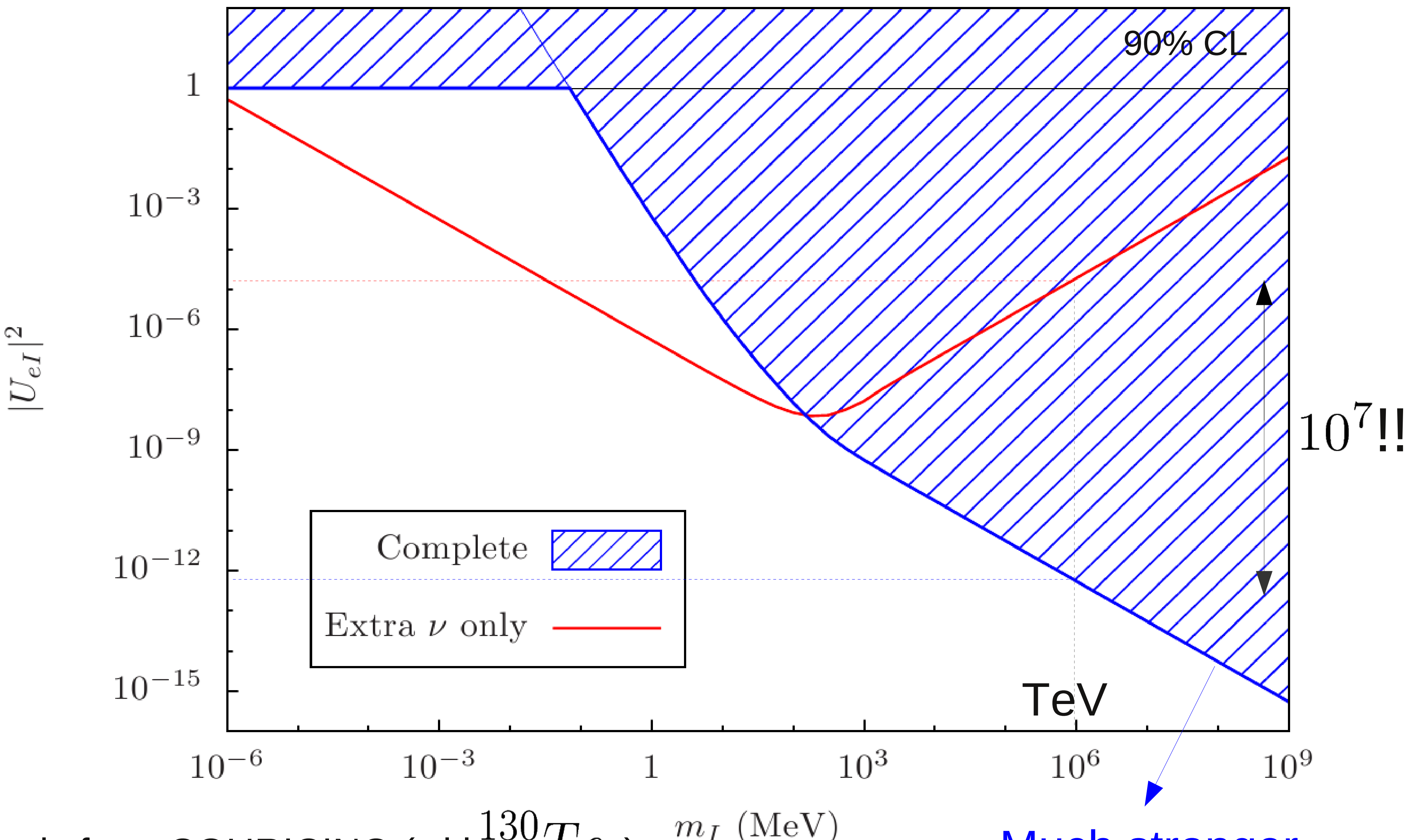

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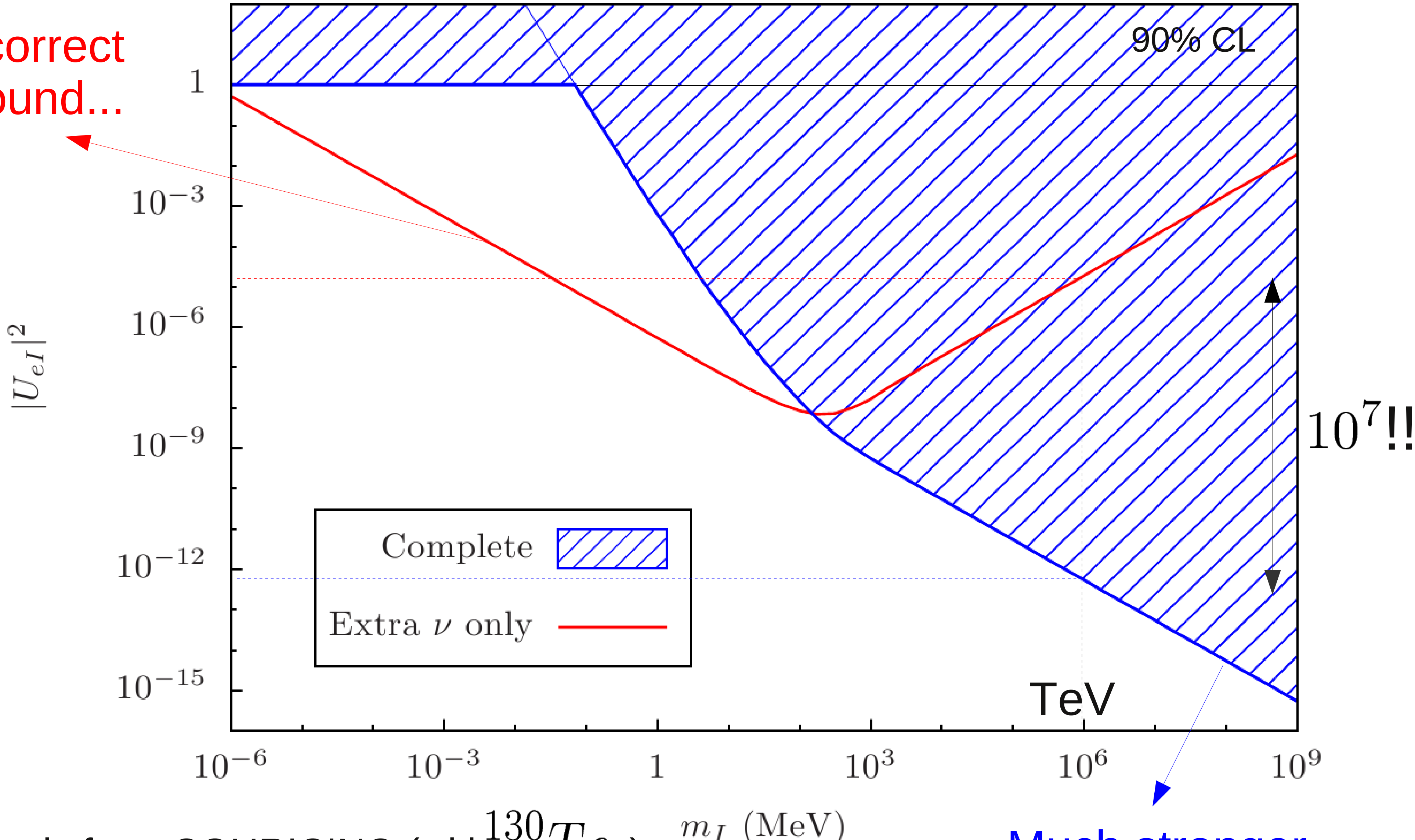
Incorrect bound...



Much stronger Constraint !!

Bounds from COURICINO (with ^{130}Te)

Non-hierarchical extra neutrinos assumed

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 would be independent:

  - Light contribution 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 GIM like cancellation leads to an experimentally inaccessible result.

- Future tension between $0\nu\beta\beta$ and cosmological data may put the canonical seesaw models in trouble.

Conclusions

• This tension could be removed in a non-canonical seesaw scenario with extra light and heavy states.

• Some cancellation level required between both contributions in order to keep the smallness of neutrino masses explained.

50% cancellation needed when H-M claim and present cosmology bounds are considered

• Same phenomenology for the type-II and type-III seesaws as for the type I seesaw (even in the mixed light and heavy version).

Thank you!

Back-up

Nuclear Matrix Element (NME)

Easy to understand expanding the propagator:

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

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

- 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: $p^2 < 0$)

Standard approach

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

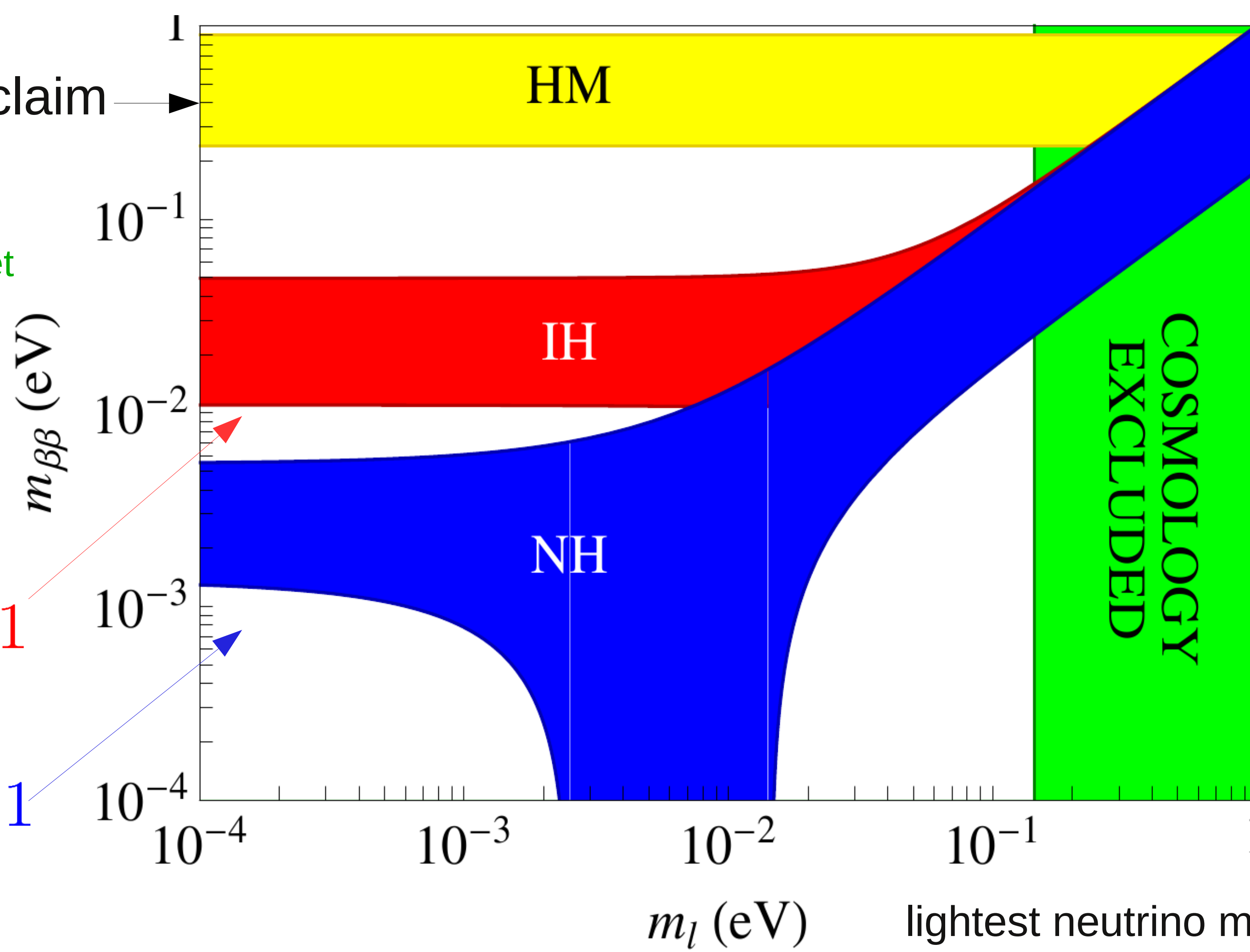
2σ

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

Standard approach

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

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Heidelberg-Moscow Claim excluded by cosmology?

H.V. Klapdor-Kleingrothaus et al 06

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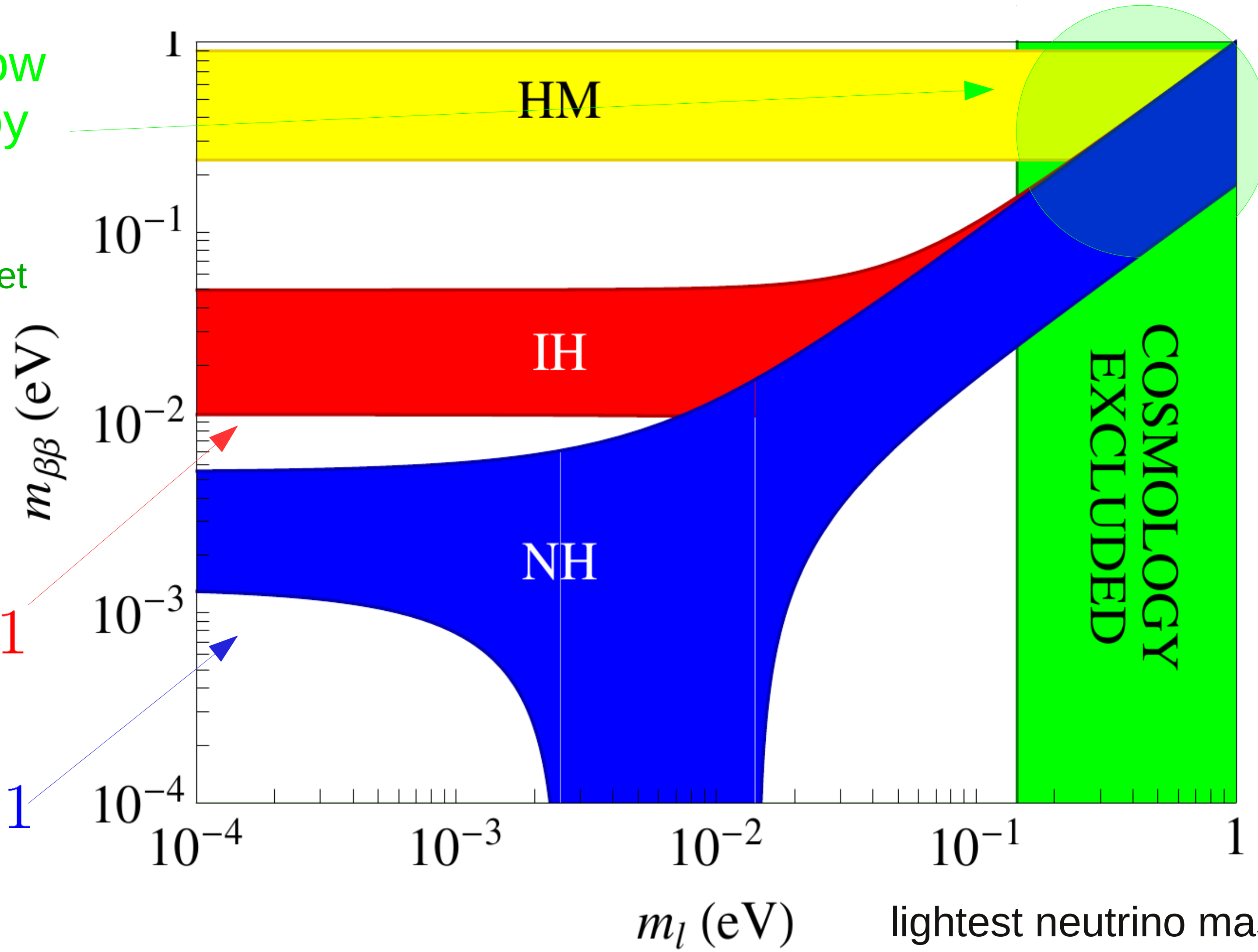

lightest neutrino mass

What about the other seesaw realisations?

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

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

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

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

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Type-I

Type-II

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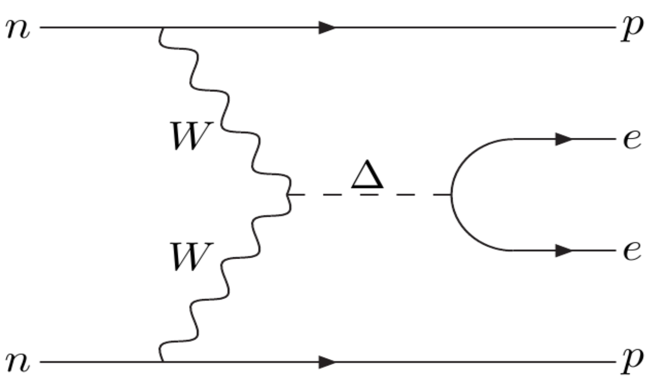
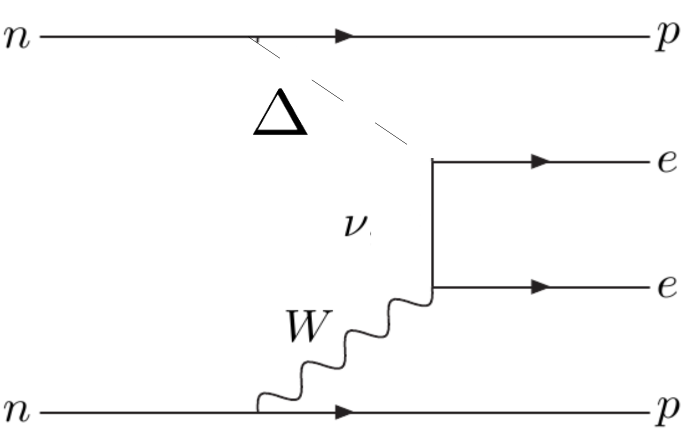
Type-I

Type-II

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

But the scalars can also mediate the process:





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

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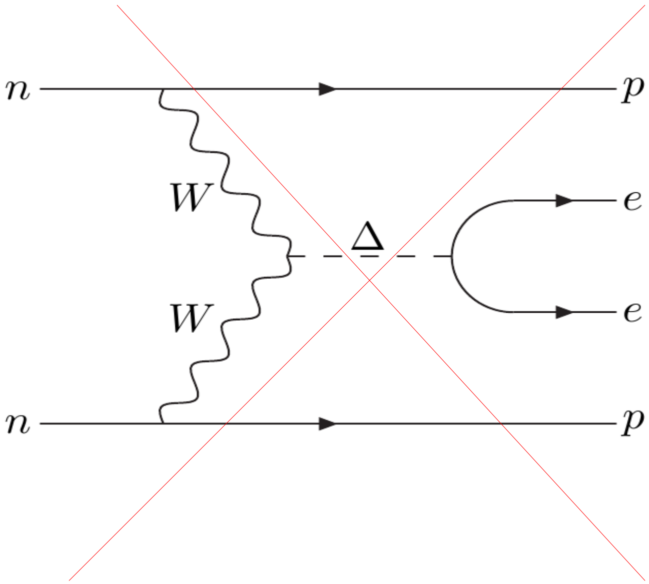
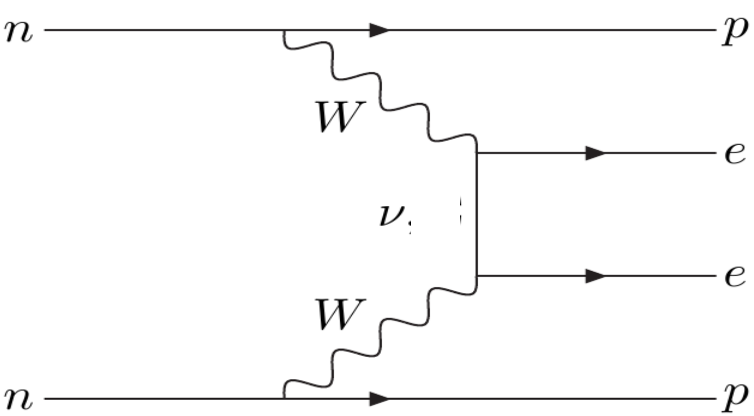
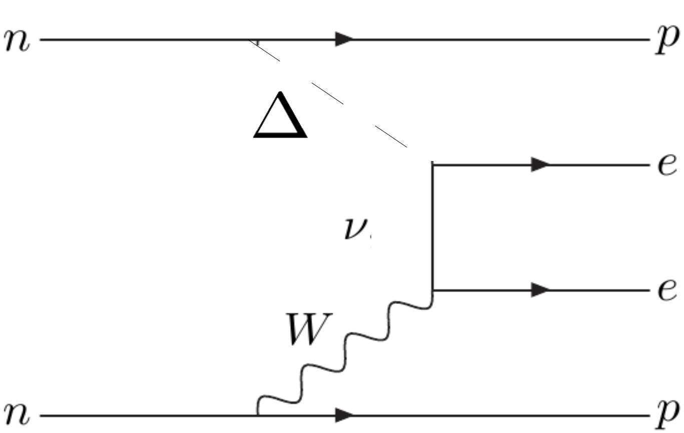


$$\sim p^2/M_\Delta^2 \times$$

$$< 10^{-6}$$





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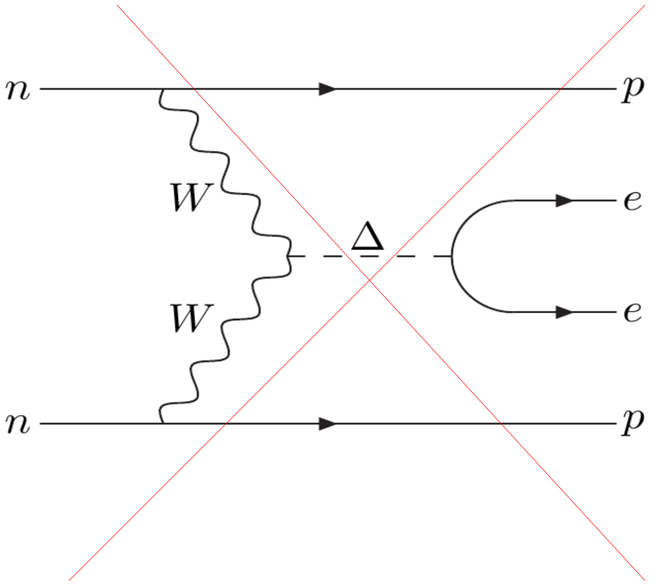

$$\sim p^2/M_\Delta^2 \times$$

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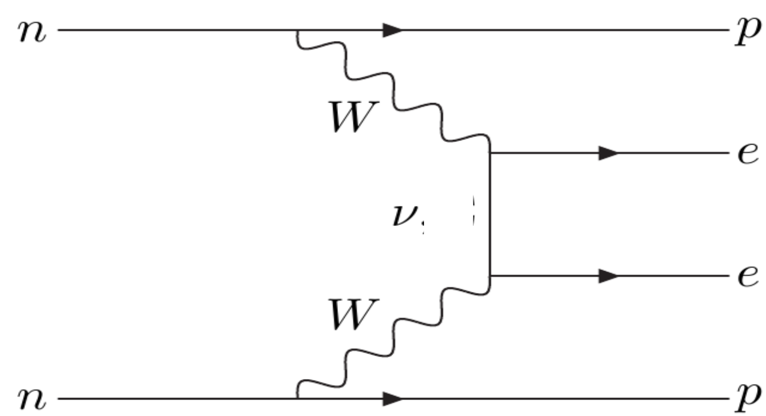
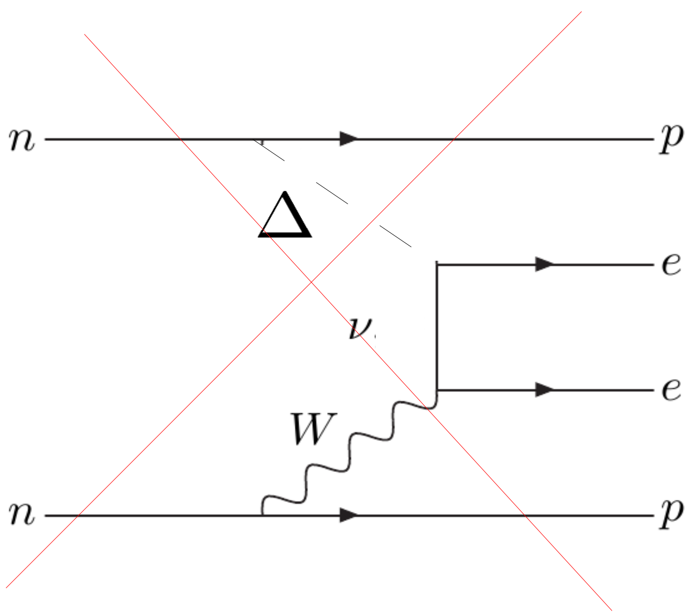
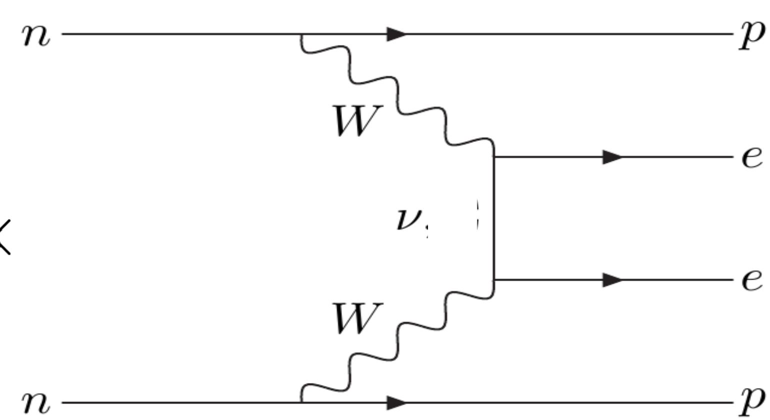




$$\sim m_q/M_\Delta \times$$

$$< 10^{-5}$$



$0\nu\beta\beta$ 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:

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

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

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$$\Big\downarrow \text{SSB}$$

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

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

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

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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:

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

Tension between $0\nu\beta\beta$ and cosmo data

- In the standard framework: implicitely assumed the existence of ”heavy” degrees of freedom.

- Bounds from cosmology only apply to the light contribution, which dominates the $0\nu\beta\beta$

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

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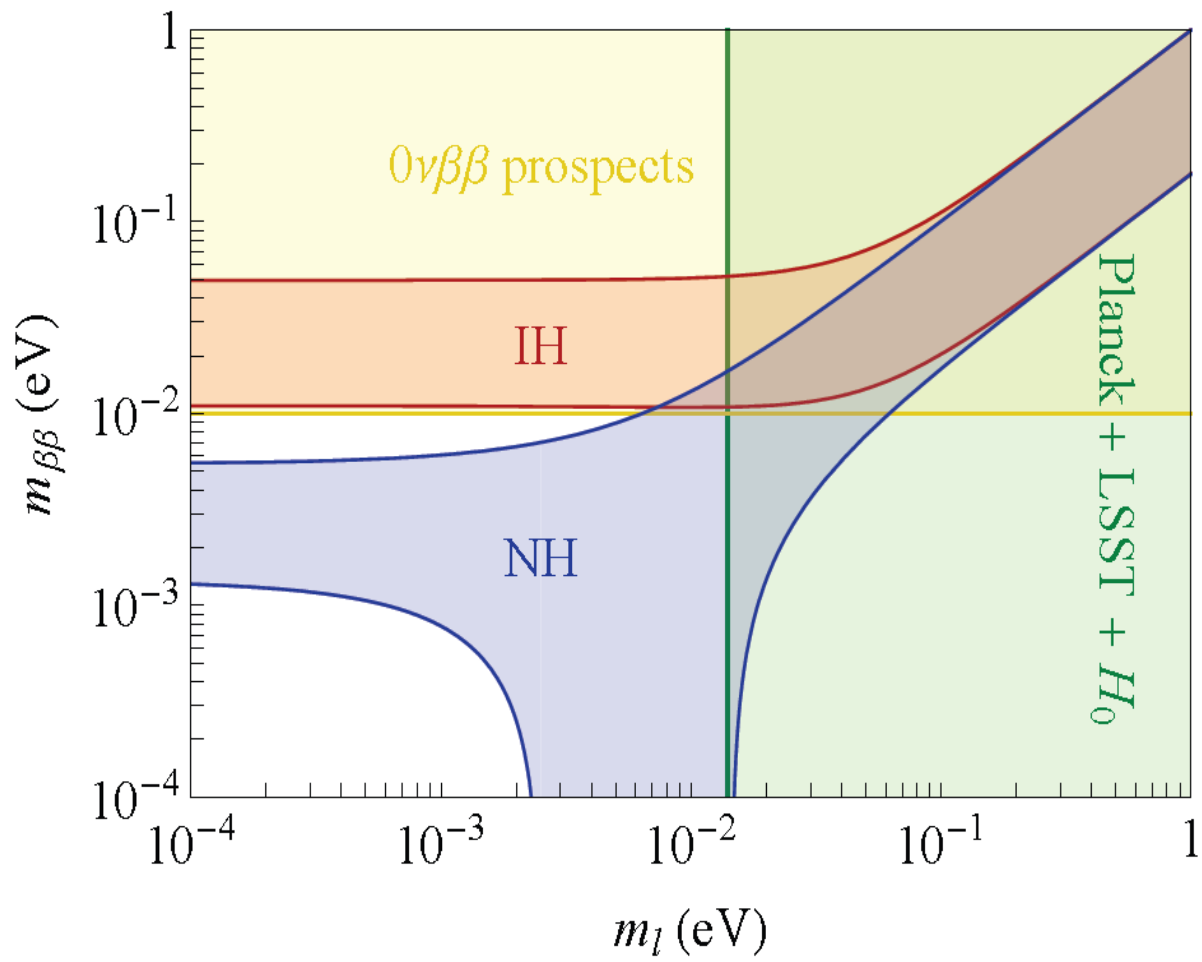
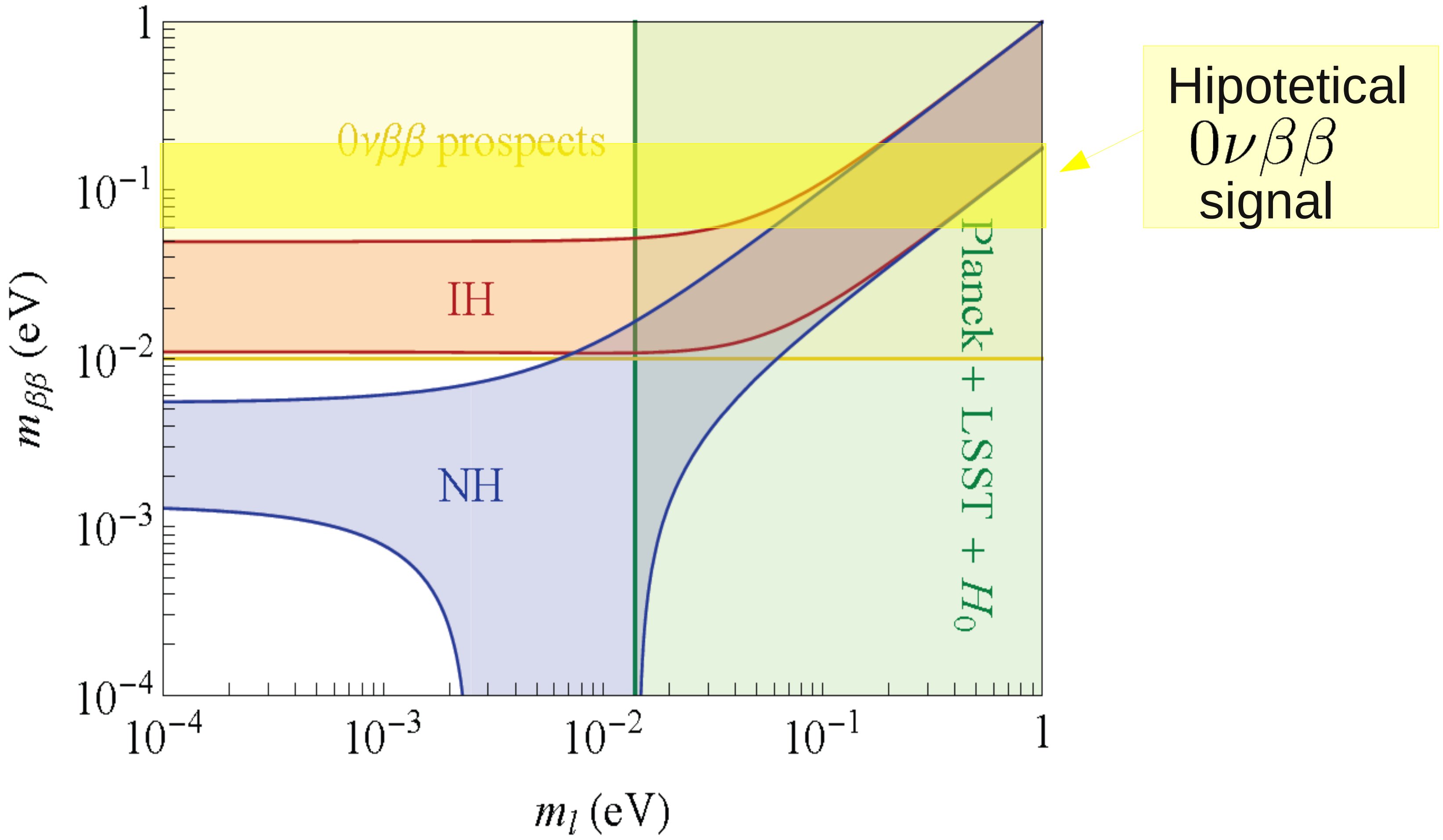
- The $0\nu\beta\beta$ bounds on the heavy contribution are not affected by cosmology but correlated with the light contribution.

No escape from the cosmology bound for the canocial seesaw!

Tension between $0\nu\beta\beta$ and cosmo data



Tension between $0\nu\beta\beta$ and cosmo data



- In the standard framework, a future $0\nu\beta\beta$ measurement could be in conflict with cosmology!!

What would happen then
if we do meassure the $0\nu\beta\beta$?

Tension between $0\nu\beta\beta$ and cosmo data

- Let's consider the claim by the Heidelberg-Moscow collaboration and the present cosmology constraints on neutrino masses (from WMAP7+SDSS).

Tension between $0\nu\beta\beta$ and cosmo data

- Let's consider the claim by the Heidelberg-Moscow collaboration and the present cosmology constraints on neutrino masses (from WMAP7+SDSS).

- If we have only extra light states: $0\nu\beta\beta$ would be very suppresed!

No signal!

- If we have only extra heavy states: light active and heavy contribution correlated

No scape from cosmology bounds
Ruled out!

Idea: Extra states in light & heavy regimes

- In this way we could satisfy:

1 $0\nu\beta\beta$ signal

$+$

2 cosmology constraints

$+$

3 Relation between "light" parameters and extra degrees of freedom:

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

cancellation between EXTRA Light & heavy contribution

explaining at the same time smallness of neutrino masses observed in neutrino oscillations.

Idea: Extra states in light & heavy regimes

- Add extra heavy states to have a non-negligible $0\nu\beta\beta$
- Add extra states in the light regime which could dominate in $0\nu\beta\beta$:

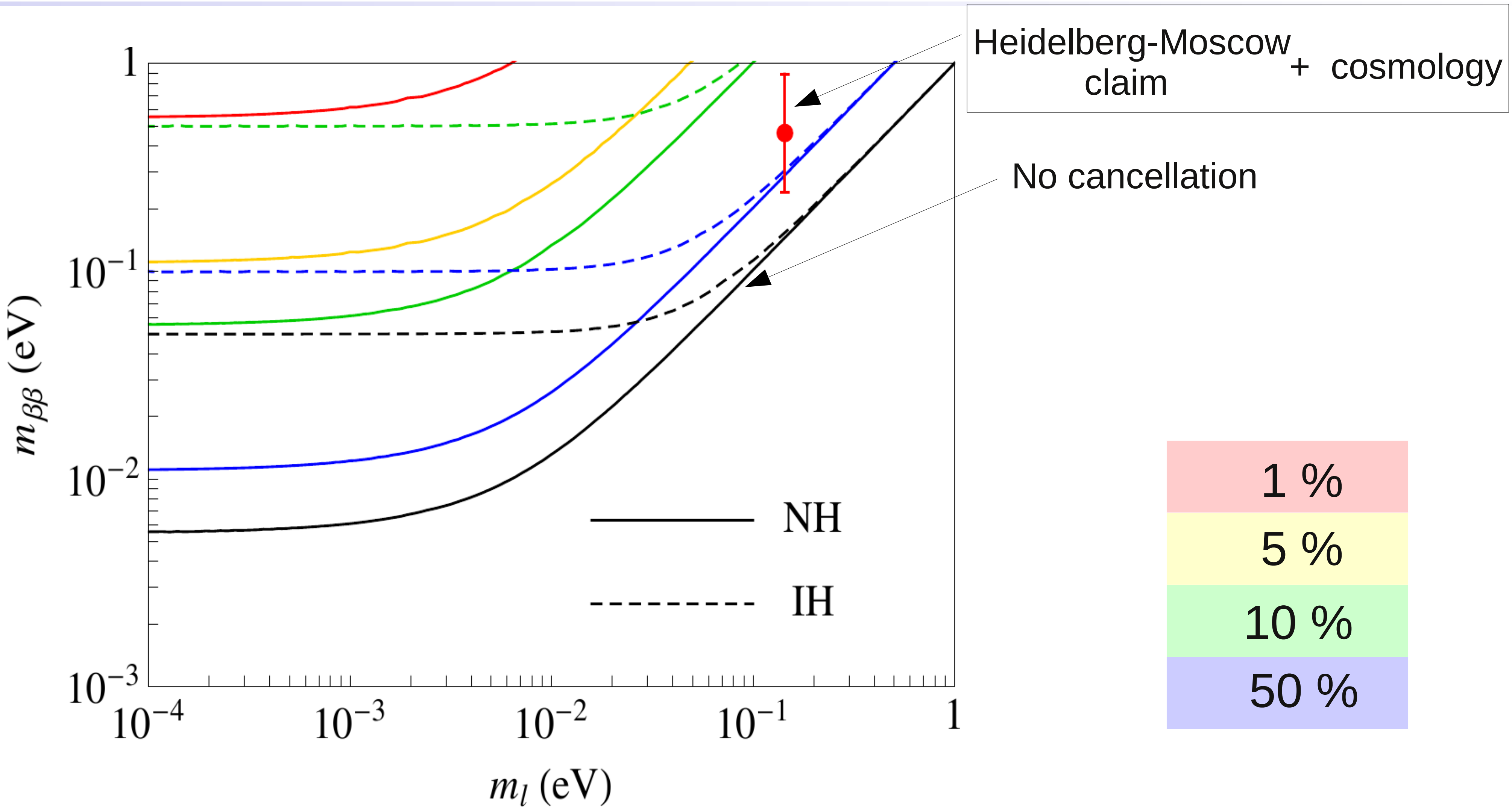
$$A = \sum_{i}^{\mathrm{SM}} m_i U_{ei}^2 M^{0\nu\beta\beta}(0) + \sum_{I}^{\mathrm{light}} m_I U_{eI}^2 M^{0\nu\beta\beta}(0)$$

$$\simeq - \sum_{I}^{\mathrm{heavy}} m_I U_{eI}^2 M^{0\nu\beta\beta}(0)$$

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

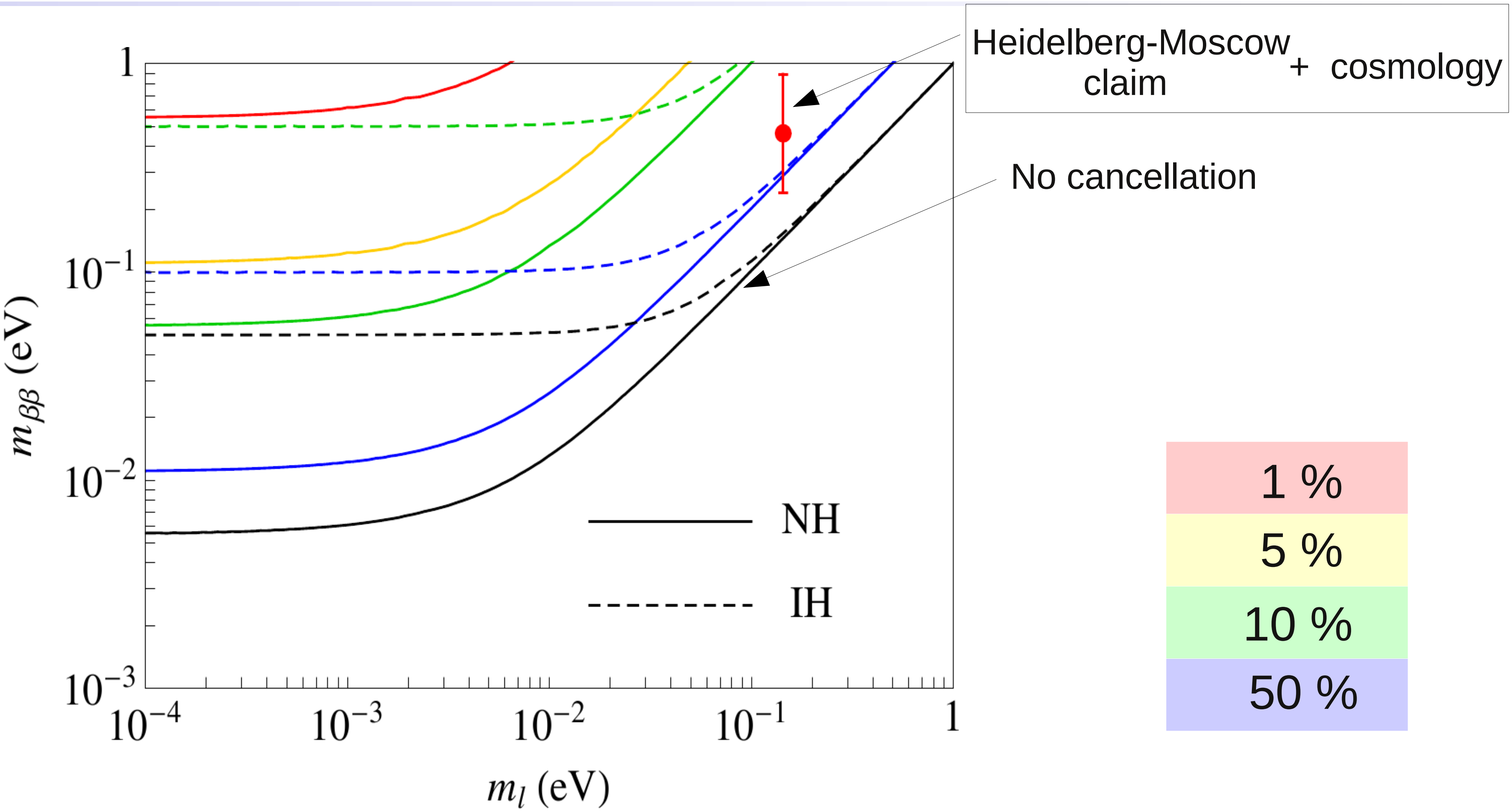
- The cosmology constraints may not apply to these masses!!

Required cancellation level



lightest neutrino mass

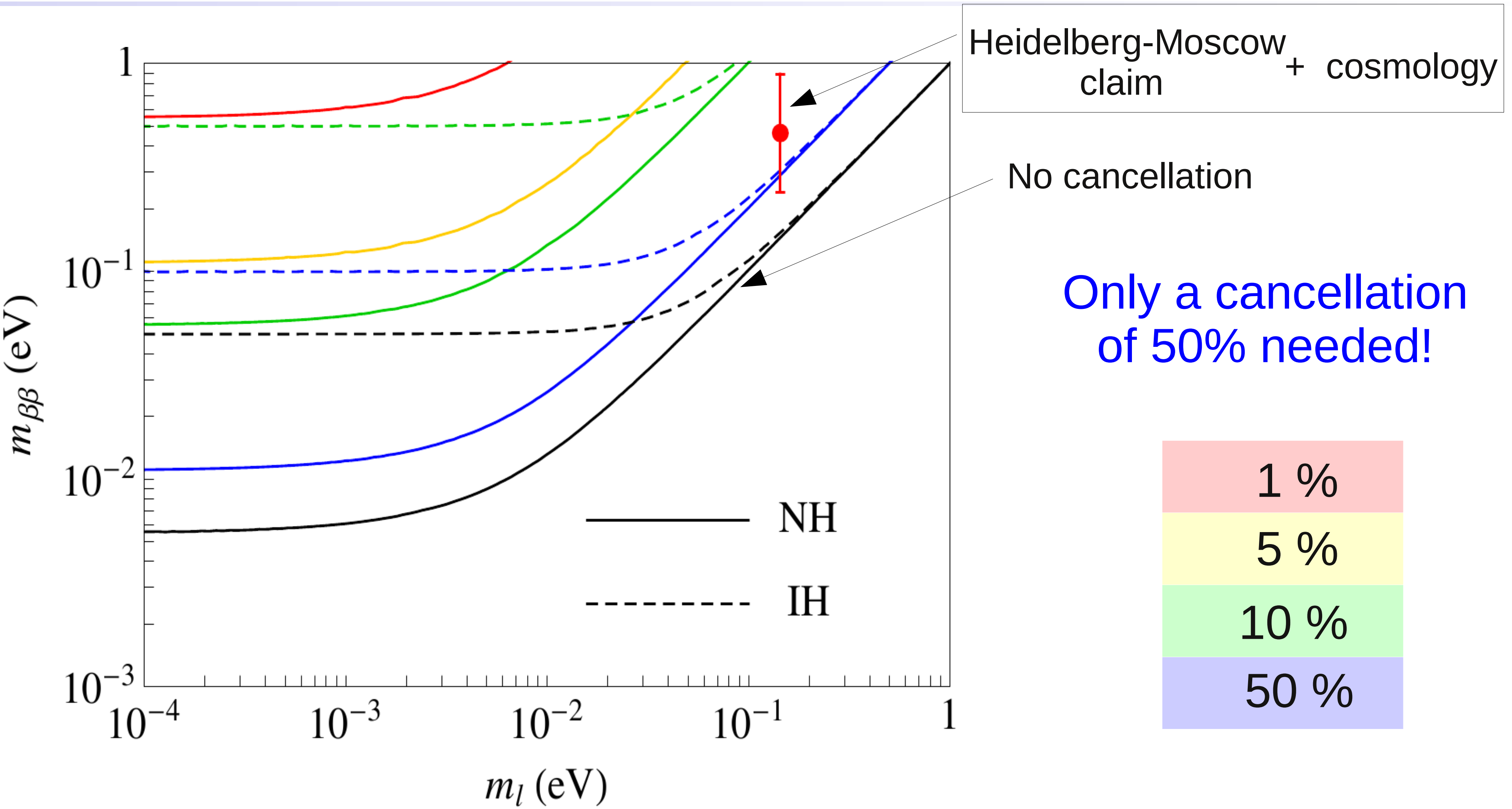
Required cancellation level



lightest neutrino mass

Note that the usual interpretation of $m_{\beta\beta}$ (no cancellation case), as it comes from canonical seesaw would fail!

Required cancellation level



lightest neutrino mass

Only a cancellation of 50% needed!

1 %
5 %
10 %
50 %

Note that the usual interpretation of $m_{\beta\beta}$ (no cancellation case), as it comes from canonical seesaw would fail!

Cancellation level

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

For different cancellation levels:

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

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

Information from neutrino oscillations

Idea: Extra states in light & heavy regimes

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

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

Heidelberg-Moscow claim + our calculation NME (including NME error):

$$0.24 \text{ eV} < \left| \sum_I^{\text{heavy}} m_I U_{eI}^2 \right| < 0.89 \text{ eV}.$$

$0\nu\beta\beta$ 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 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.

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

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

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

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

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

- The Heidelberg-Moscow claim can be interepreted as:

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

- 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.

Absolute neutrino mass scale

- Information coming from kinematic studies of well known processes:

$$m_{\nu_\alpha} = \sum |U_{\alpha i}|^2 m_i$$

$$\begin{array}{llll} \mathrm{m}_{\nu_e} & < & 2 \text{ eV} & \text{from} \quad {}^3H \rightarrow {}^3He + e + \overline{\nu}_e \\ \mathrm{m}_{\nu_\mu} & < & 0.190 \text{ MeV} & \text{from} \quad \pi^+ \rightarrow \mu^+ \nu_\mu \quad [12] \\ \mathrm{m}_{\nu_\tau} & < & 18.2 \text{ MeV} & \text{from} \quad \tau^+ \rightarrow \pi^+ \nu_\tau \quad [12] \end{array}$$

PDG; Phys.Lett.B667:1-1340,2008

- Information coming from cosmology:

$$\sum m_i < 0.58 eV$$

WMAP7; arXiv:1001.4538 [astro-ph.CO]