Neutrinos &
Neutrinoless double beta decay

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Half Day meeting IoP

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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:

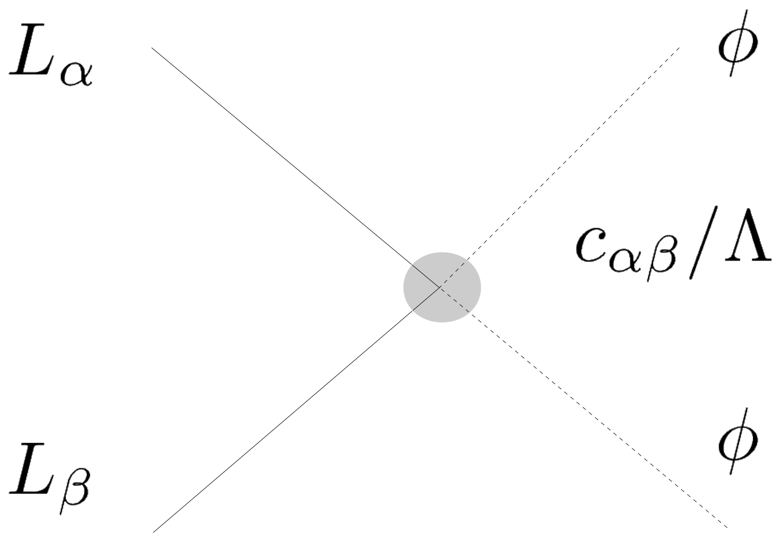
$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \delta\mathcal{L}^{d=5} + \delta\mathcal{L}^{d=6} + \ldots \text{ with } \delta\mathcal{L}^{d} \propto \frac{1}{\Lambda^{d-4}}$$

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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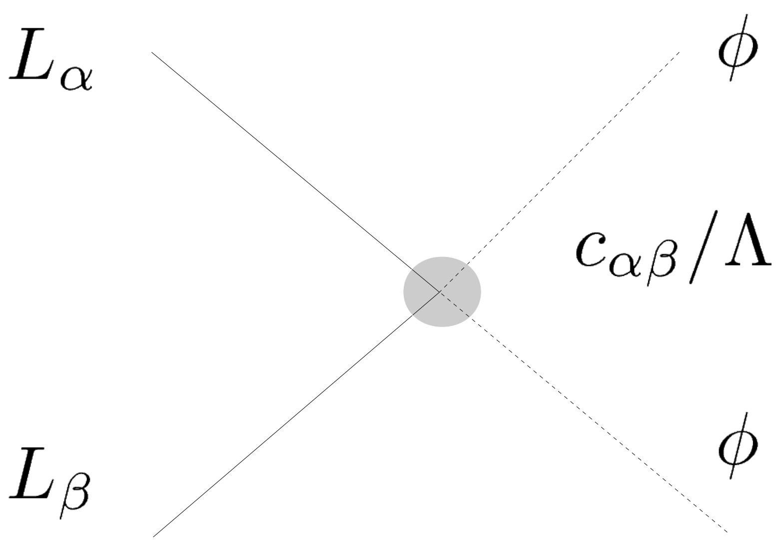

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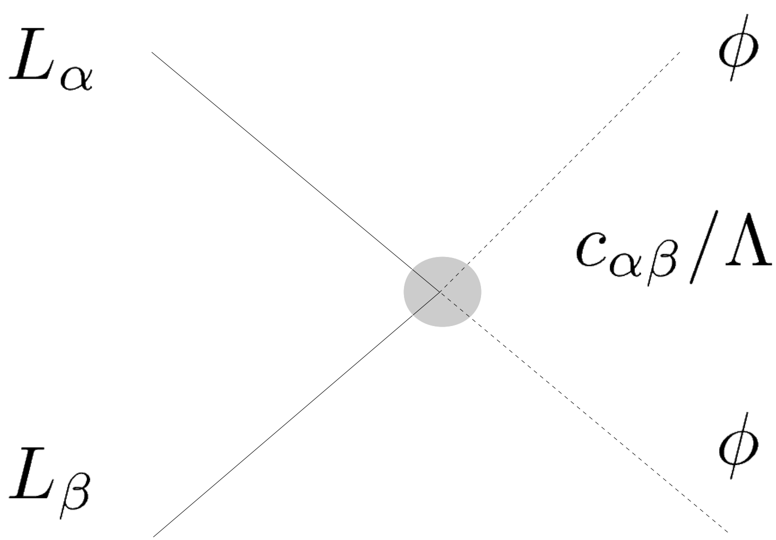


Smallnes of neutrino masses can be explained

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

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.

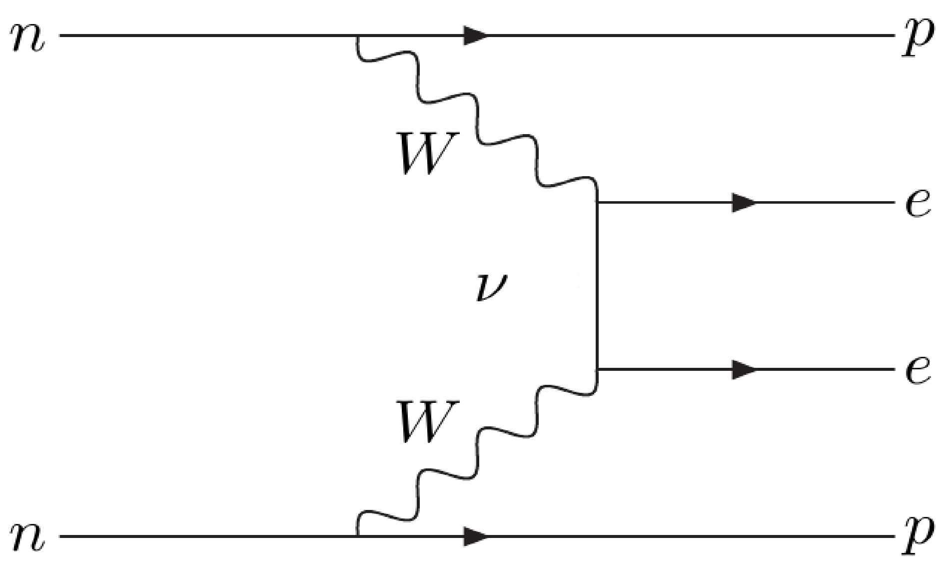
$$(Z, A) \Rightarrow (Z \pm 2, A) + 2e^{\mp} + X$$

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)

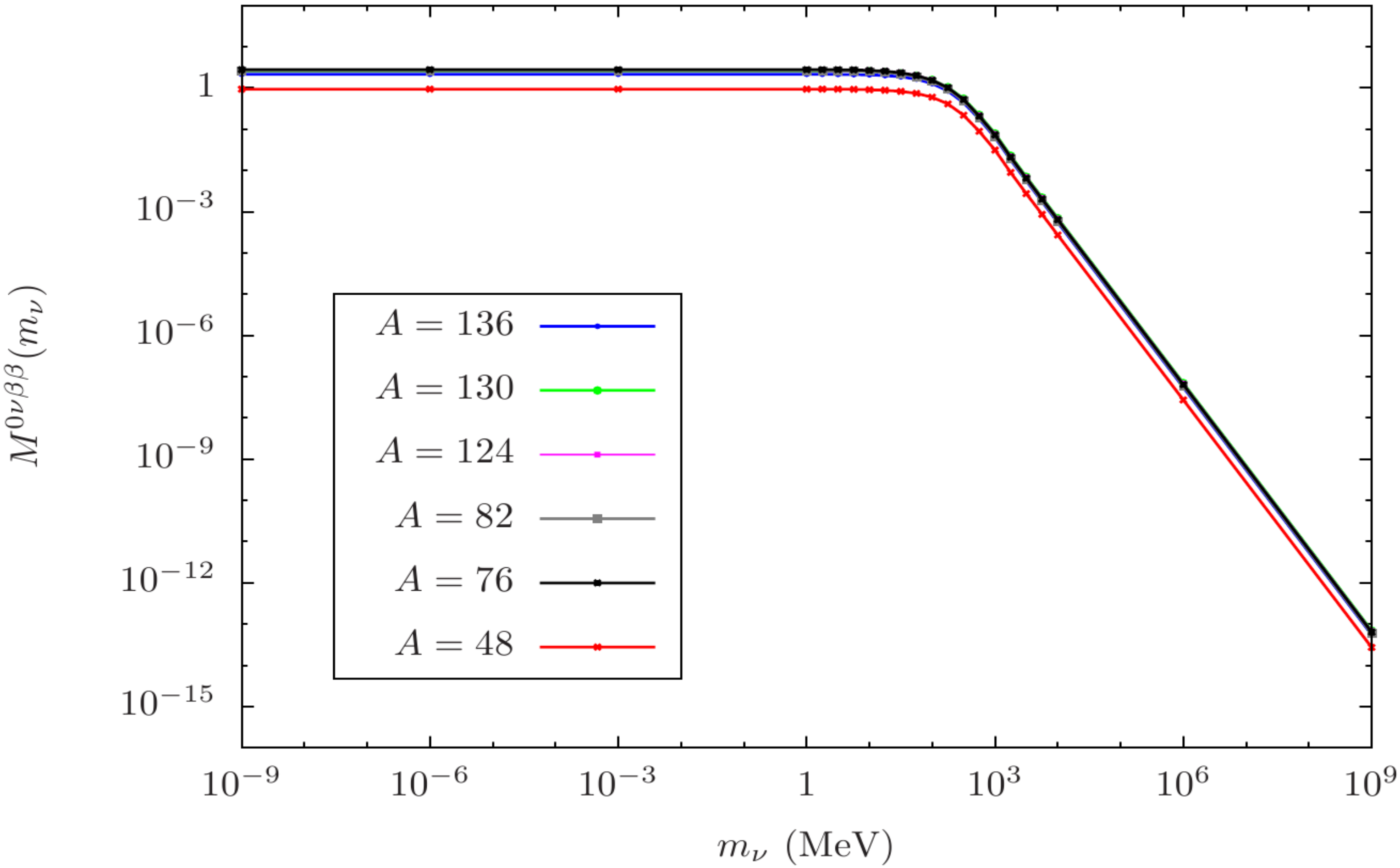
→ See talk by Vadim RODIN !

Basically, its computation can be performed within two models:

- *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 Element (NME)



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

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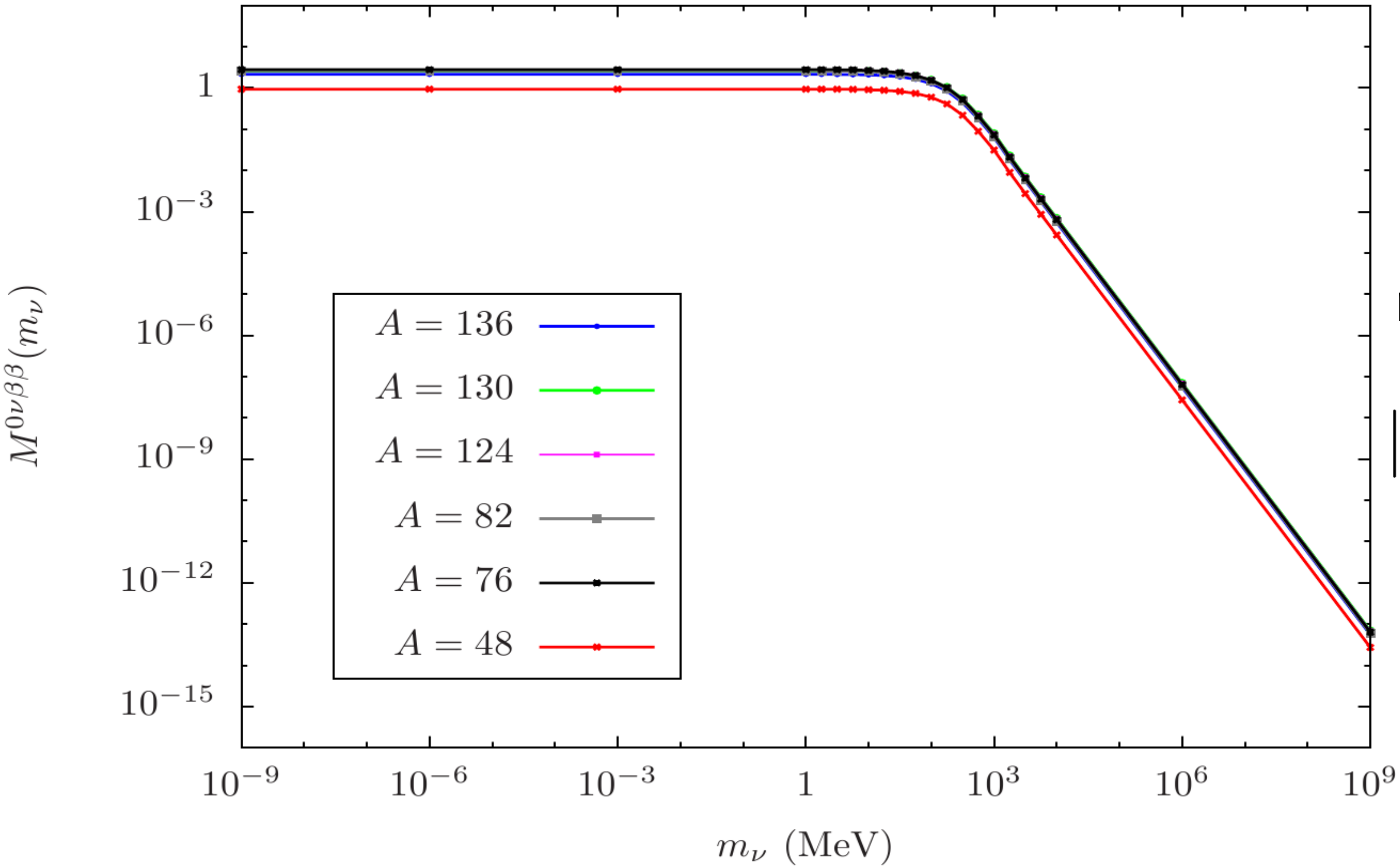

- Two different regions separated by nuclear scale

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

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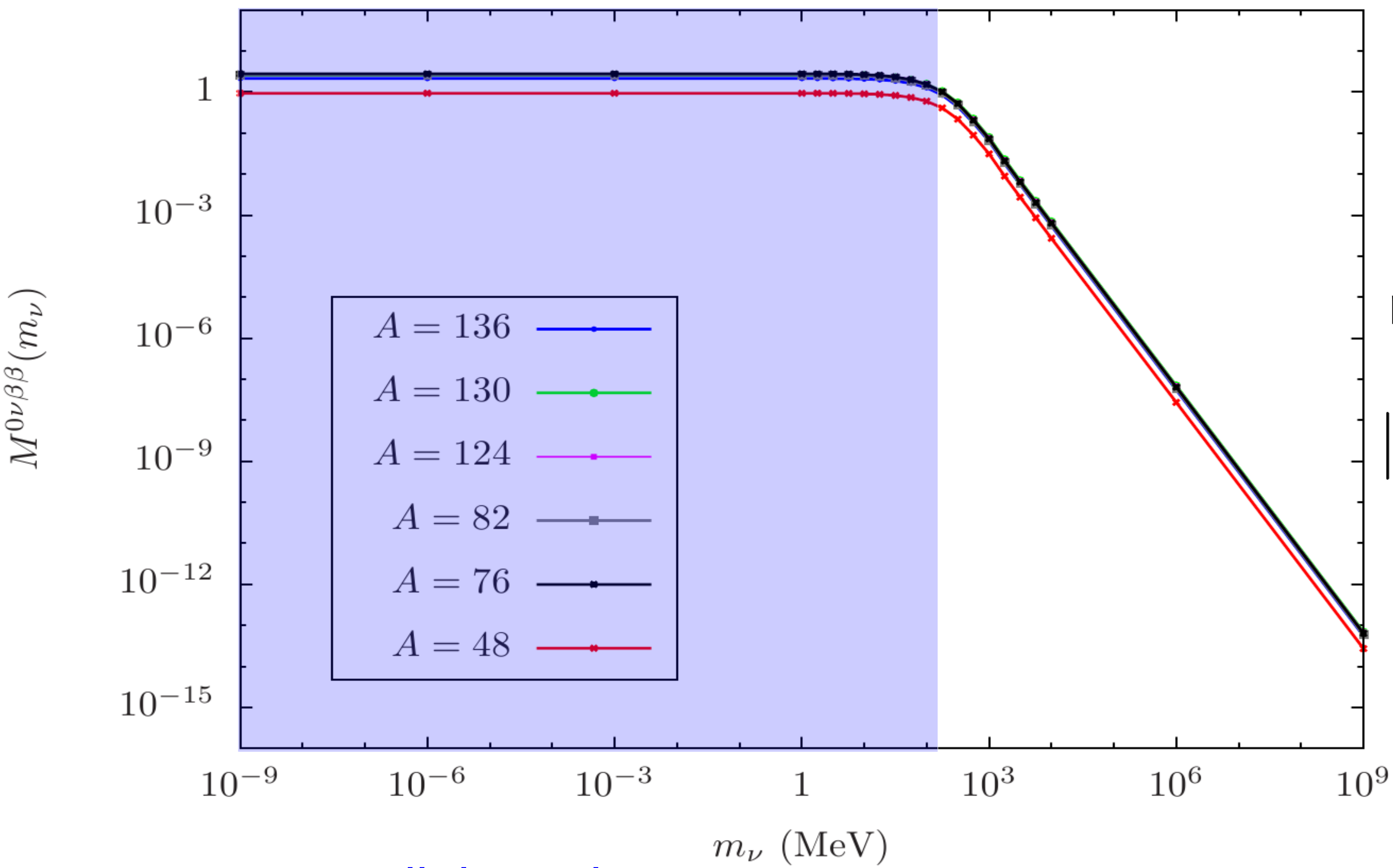

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light regime

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

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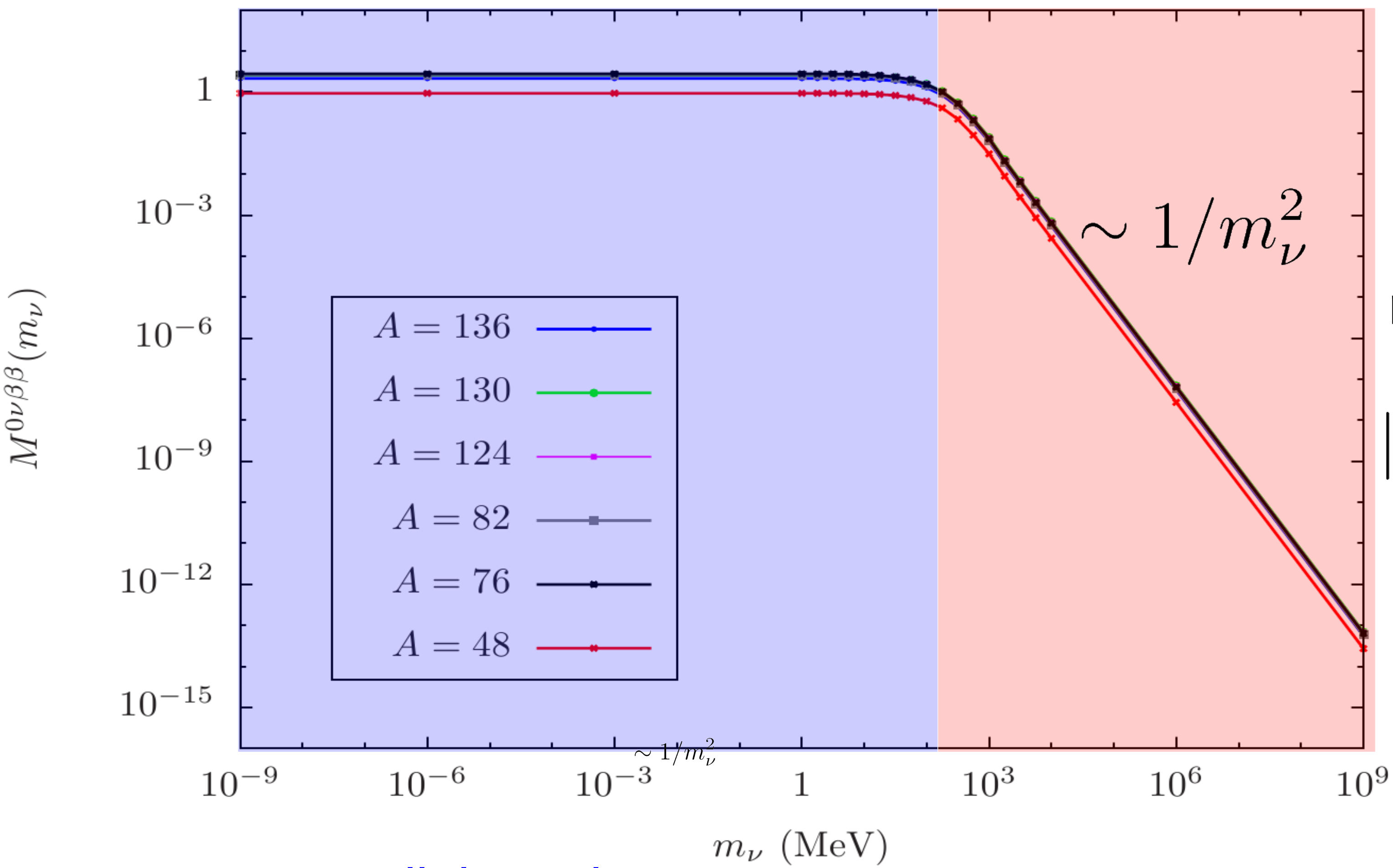

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light regime
$m_i^2 \ll |p^2|$

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

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Standard approach

Usual assumption: neglect contribution of extra degrees of freedom.

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

$$\left[T_{0\nu}^{1/2}\right]^{-1} \propto |m_{\beta\beta}|^2$$

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$m_{\beta\beta}$

Using PMNS matrix parameterisation:

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

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→ Holds when light active neutrinos dominate the process

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

→ See talk by Martin HIRSCH !

standard approach

$0\nu\beta\beta$ sensitive to the following combination of parameters:

$$|m_{\beta\beta}| = |m_1 \cos^2\theta_{12}\cos^2\theta_{13} + m_2 \sin^2\theta_{12}\cos^2\theta_{13} e^{2i\alpha_1} + m_3 \sin^2\theta_{13} e^{2i\alpha_2}|$$

- Light neutrino masses: m_1, m_2, m_3
- Two lepton mixing angles: θ_{12}, θ_{13}
- Two Majorana phases: α_1, α_2

What we know from neutrino oscillations...

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric sector

Interference

Solar sector

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Atmospheric sector | Interference | Solar sector

$$\sin^2\theta_{12} = 0.312^{+0.017}_{-0.015} \quad (1\sigma)$$

$$\Delta m^2_{21} = (7.59^{+0.20}_{-0.18}) \times 10^{-5}\,\mathrm{eV}^2$$

Schwetz, Tortola, Valle, 1103.0734 [hep-ph]

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Atmospheric sector — Interference — Solar sector

$$\sin^2\theta_{23} = \begin{array}{c} 0.51 \pm 0.06 \\ 0.52 \pm 0.06 \end{array} \quad (1\sigma)$$

$$\Delta m^2_{31} = \begin{array}{c} 2.45 \pm 0.09 \\ -2.34^{+0.10}_{-0.09} \end{array} \times 10^{-3}\mathrm{eV}^2$$

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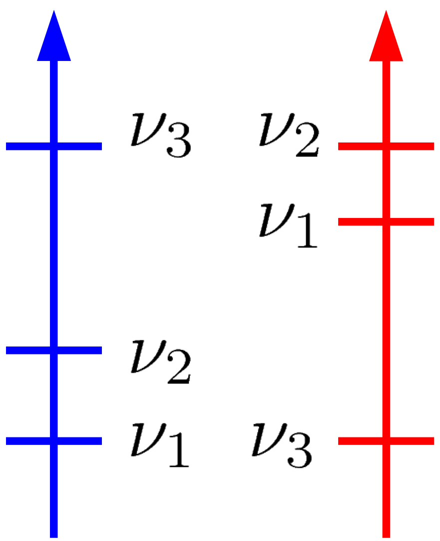
$$\sin^2\theta_{13} \le \begin{matrix} 0.027 \\ 0.031 \end{matrix} \quad (2\sigma)$$

Schwetz, Tortola, Valle, 1103.0734 [hep-ph]

What we don't know...



Normal Hierarchy (NH)

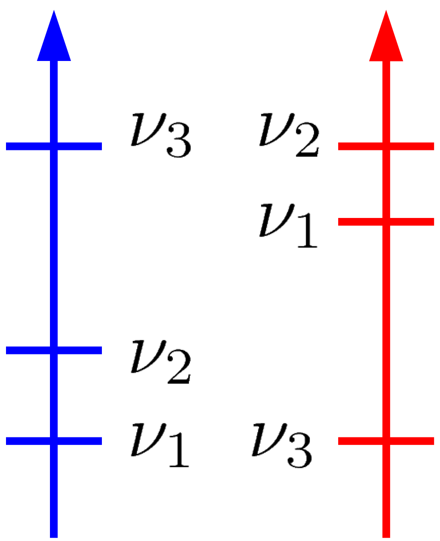
Inverted Hierarchy (IH)

No information about the Majorana phases

$\theta_{13},\ \delta,\ \mathrm{sgn}(\Delta m^2_{31}),\ \theta_{23} - \pi/4$

interference effects

What we don't know...



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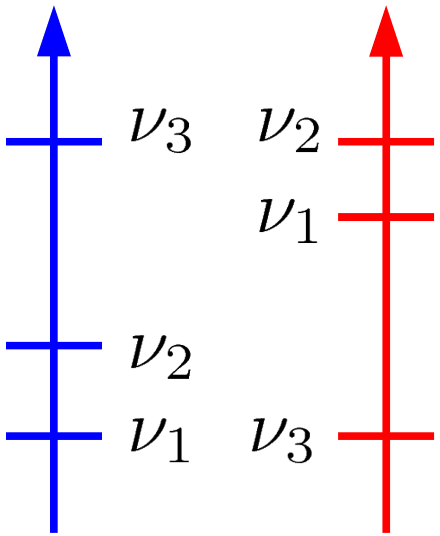

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Inverted Hierarchy (IH)

Specially relevant !

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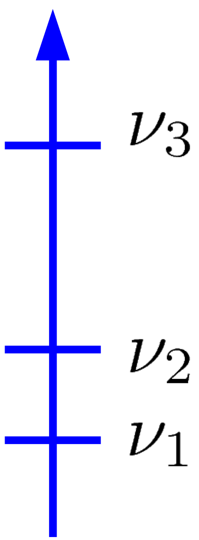
$$m_{\beta\beta} = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\alpha_1} + m_3 s_{13}^2 e^{2i\alpha_2}$$



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$$\Delta m_{31}^2 > 0$$

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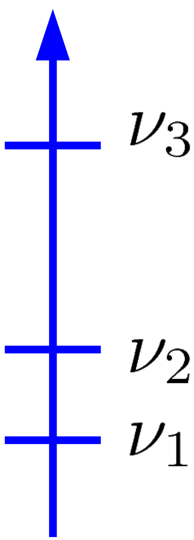
$$s_{13}^2 \ll 1$$



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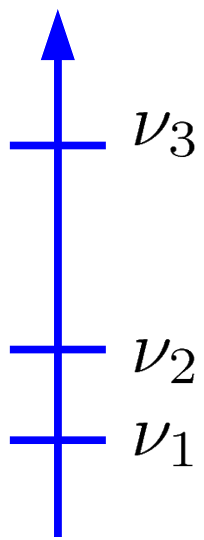

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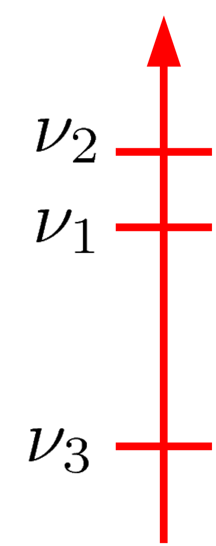

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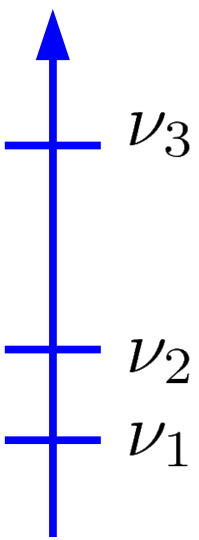
No suppresed by s_{13}^2



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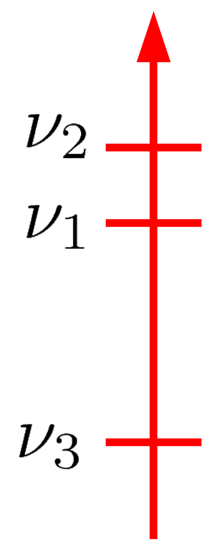

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- Inverted Hierarchy (IH): $\Delta m_{31}^2 < 0$

- Normal Hierarchy (NH): $\Delta m_{31}^2 > 0$

$$\boxed{(m_{\beta\beta})_{QD} > (m_{\beta\beta})_{IH} > (m_{\beta\beta})_{NH}}$$

Dependence on the mixing angles

- Normal Hierarchy (NH), $\Delta m^2_{31} > 0$, and $m_1^2 \ll \Delta m^2_{21}$

$$|m_{\beta\beta}| \approx |\sin^2\theta_{12}\sqrt{\Delta m^2_{21}} + \sin^2\theta_{13}\sqrt{\Delta m^2_{31}}e^{2i\alpha_1}|$$

- Inverted Hierarchy (IH): $\Delta m^2_{31} < 0$

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- Quasi-degenerate spectrum (QD):

subdominant

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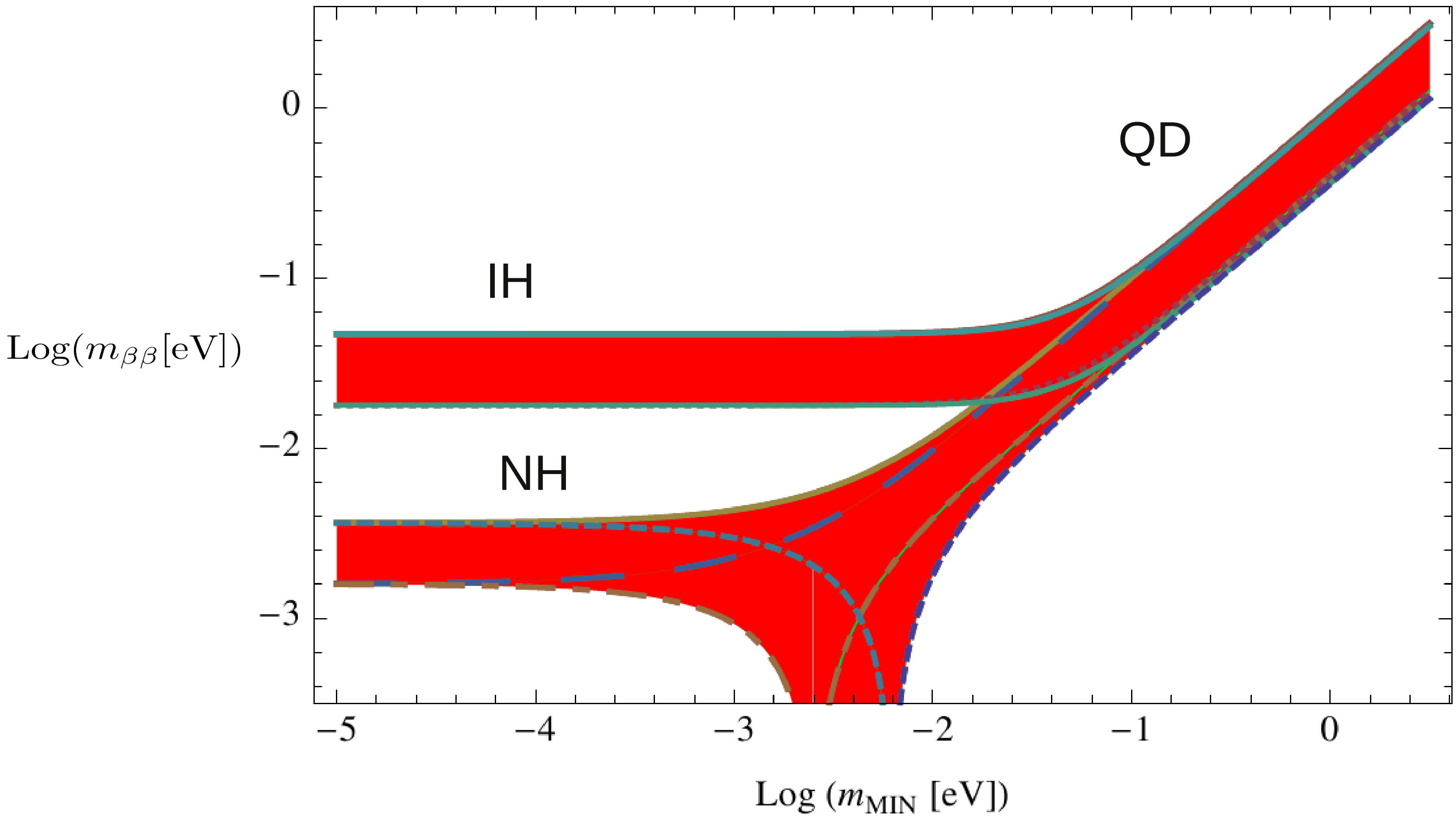
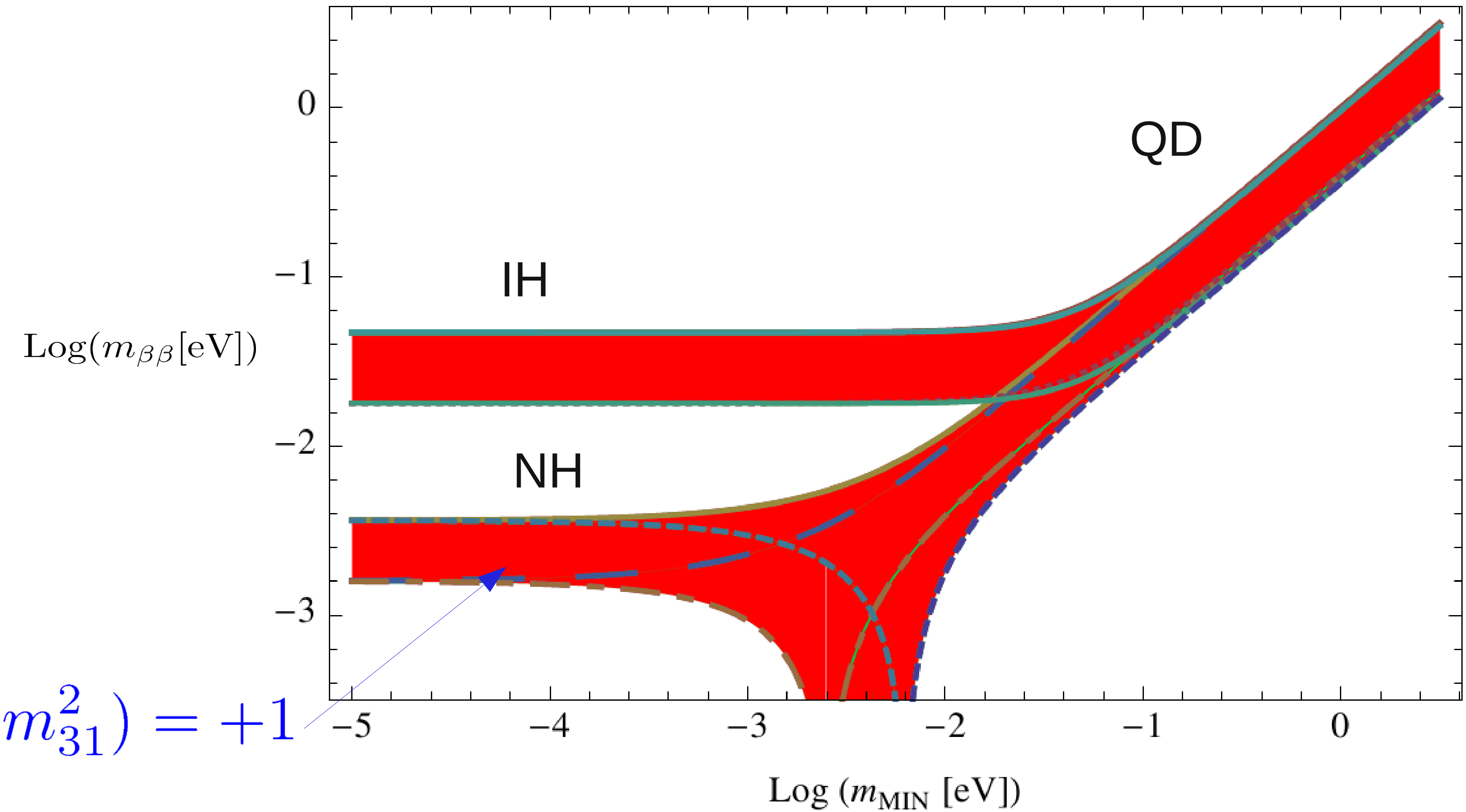
Impact of neutrino oscillations precission



Allowed regions considering BEST FIT values for the mixing parameters

Courtesy of Silvia Pascoli

Impact of neutrino oscillations precission



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

Allowed regions considering BEST FIT values for the mixing parameters

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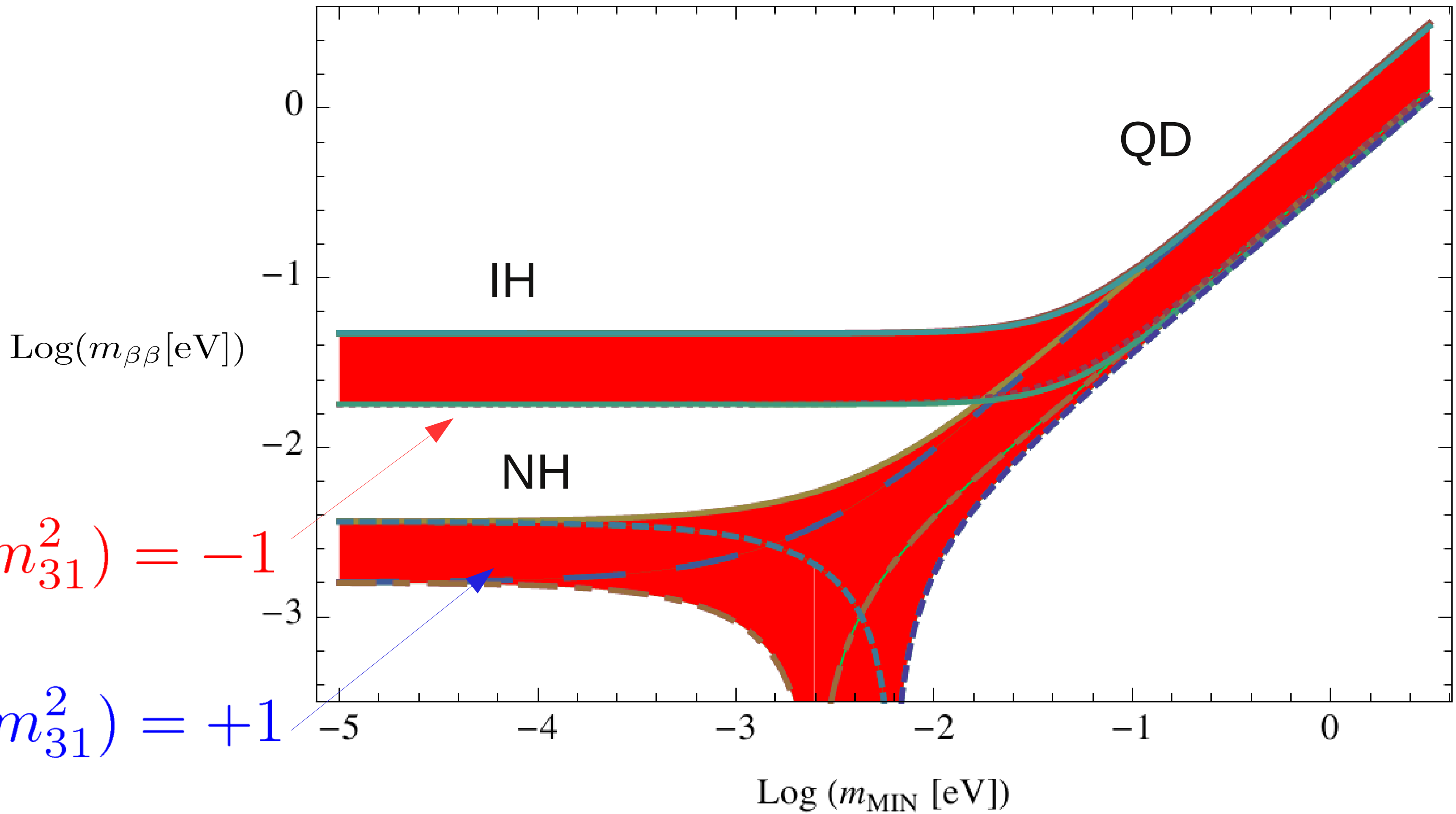
Impact of neutrino oscillations precission

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

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



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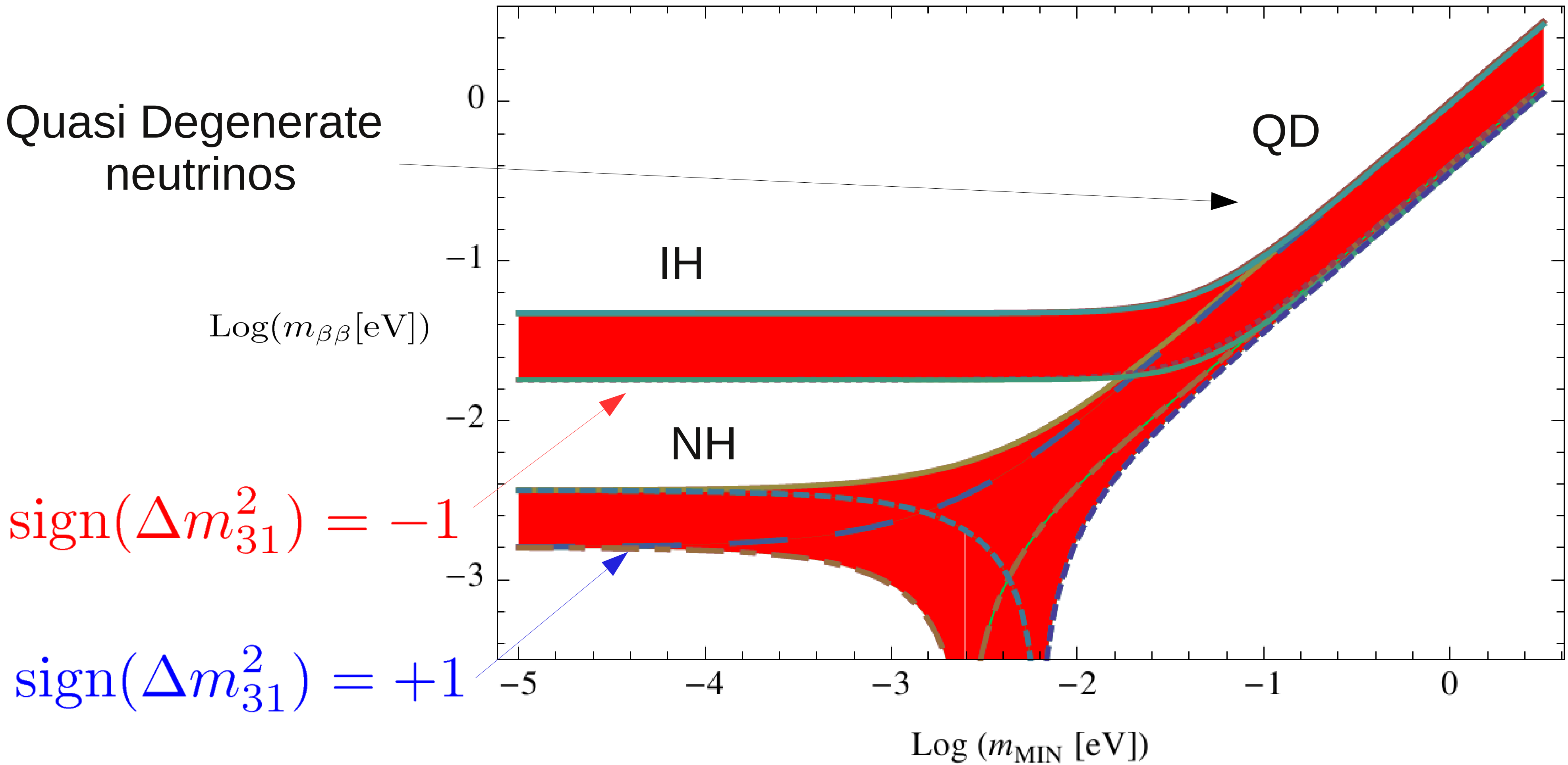

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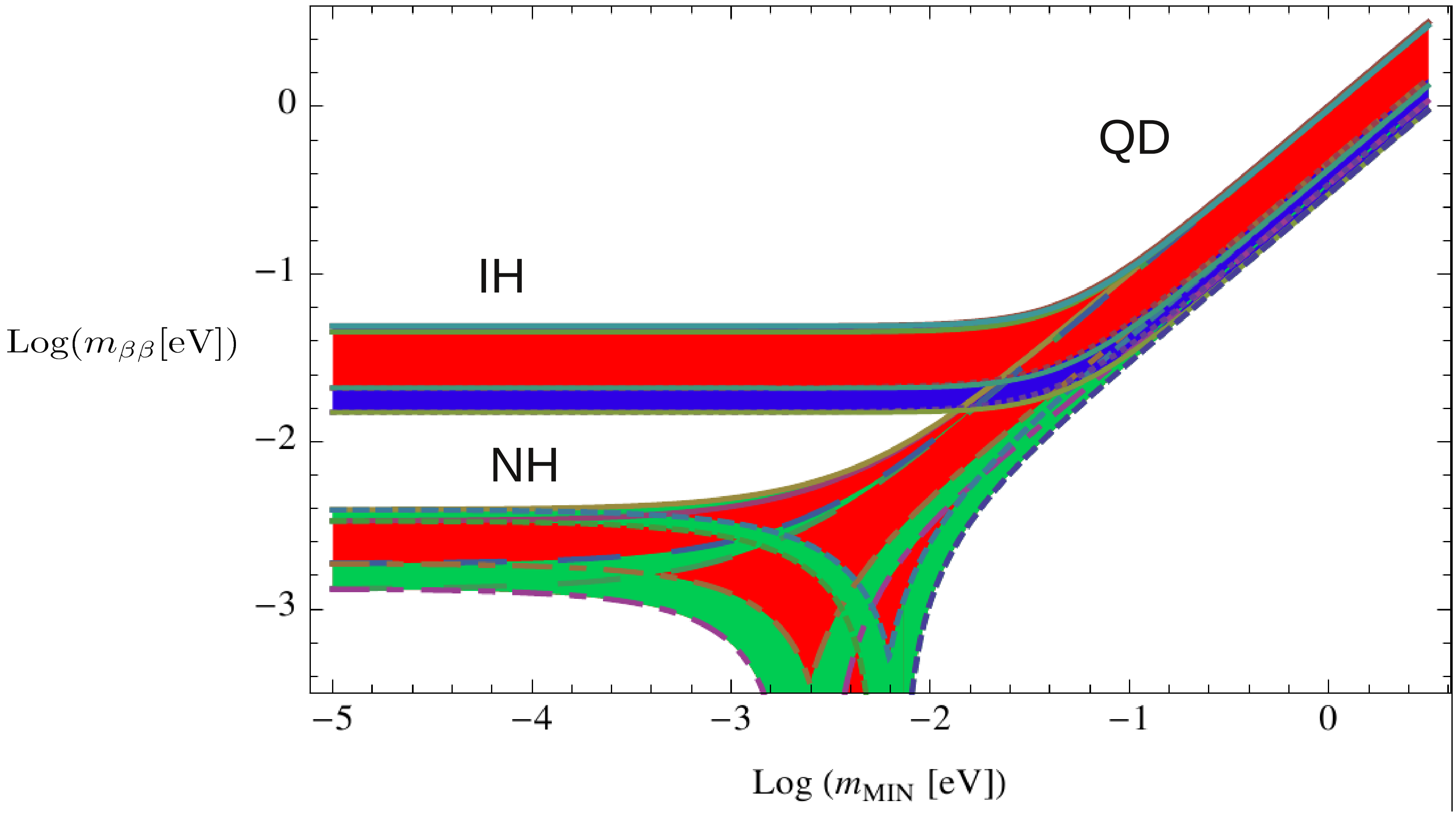
2σ



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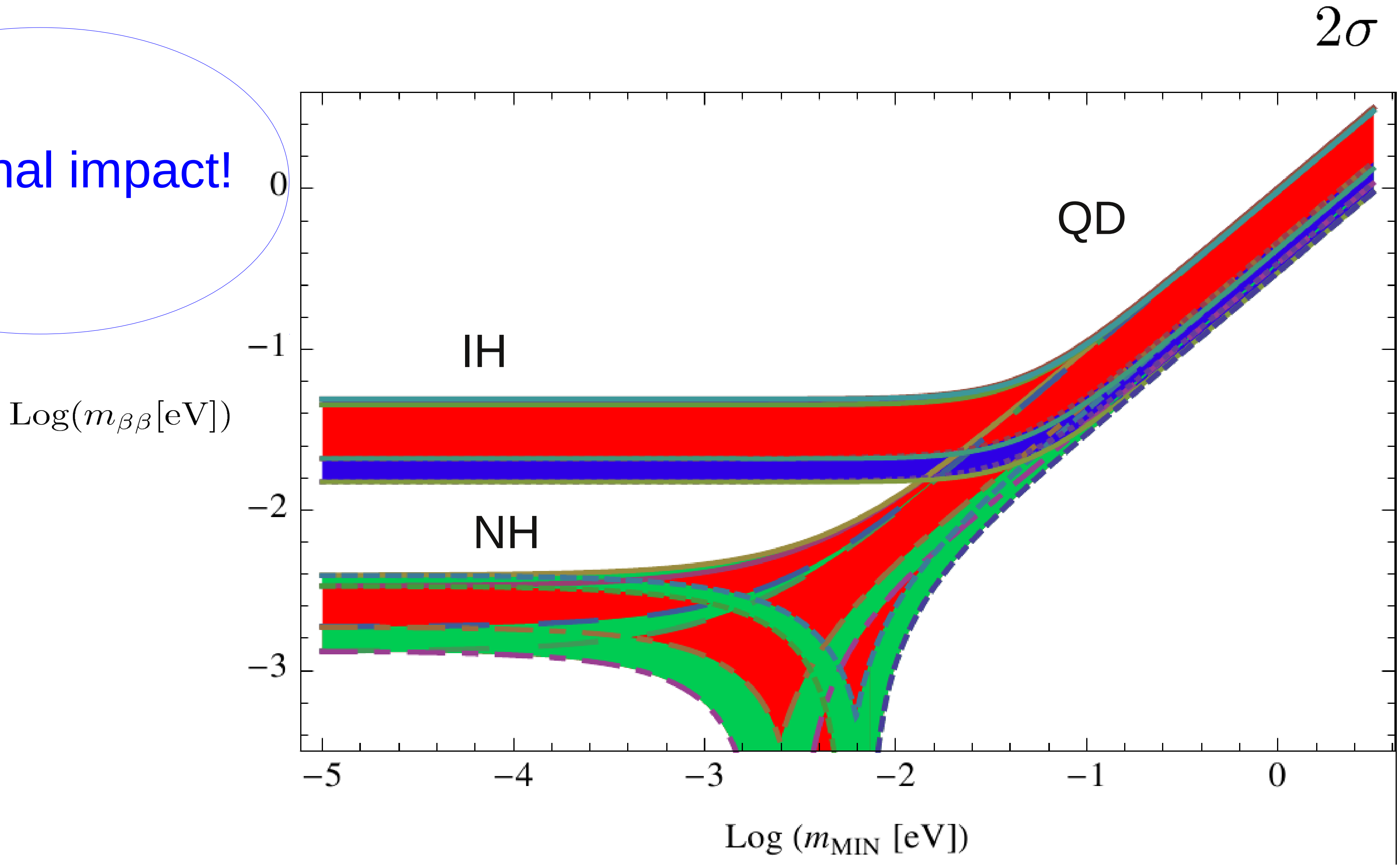
Impact of neutrino oscillations precission

Marginal impact!



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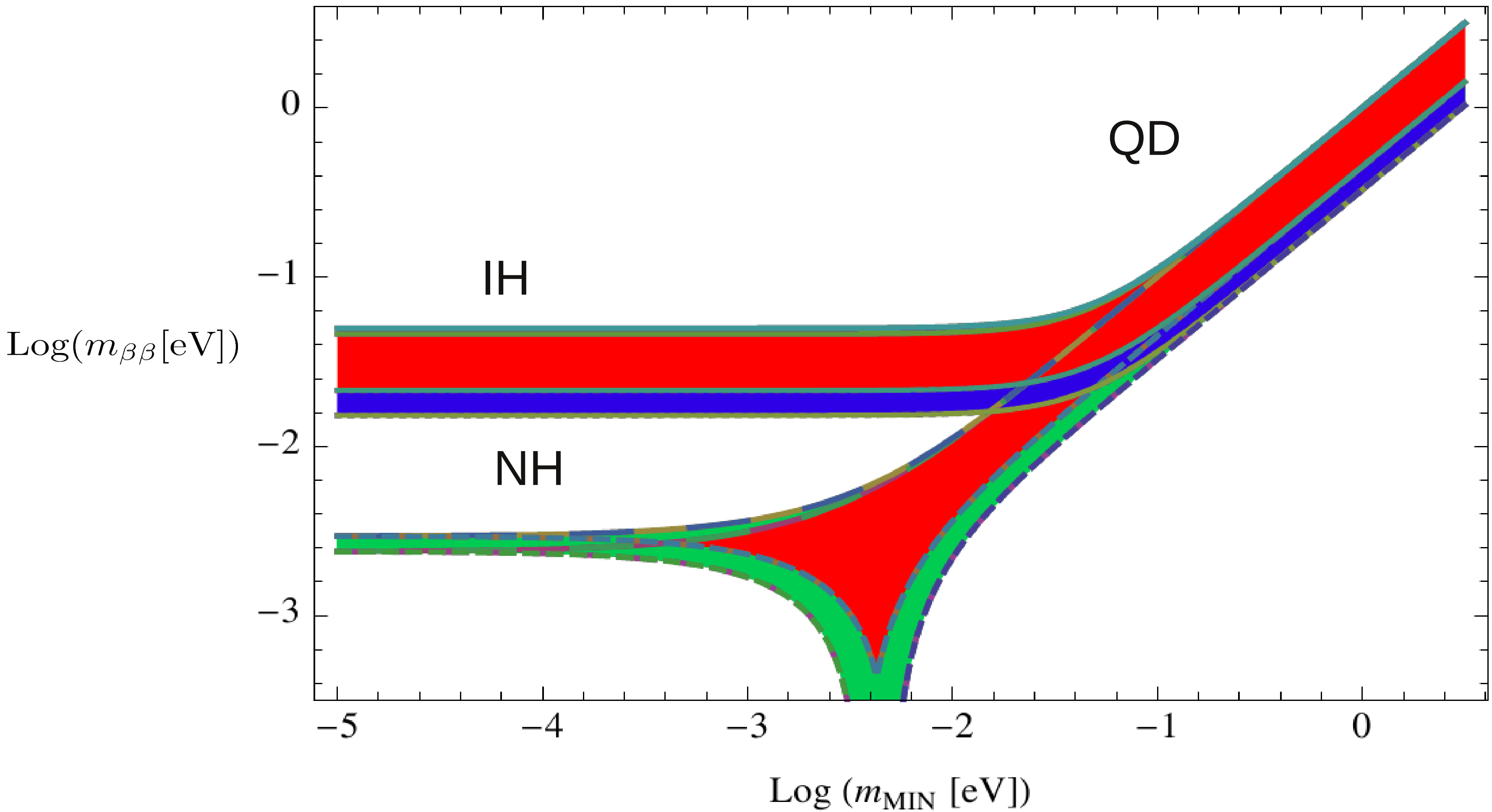
Courtesy of Silvia Pascoli

Impact of neutrino oscillations precission

2σ



Allowed regions for $s_{13}^2 = 0$

Courtesy of Silvia Pascoli

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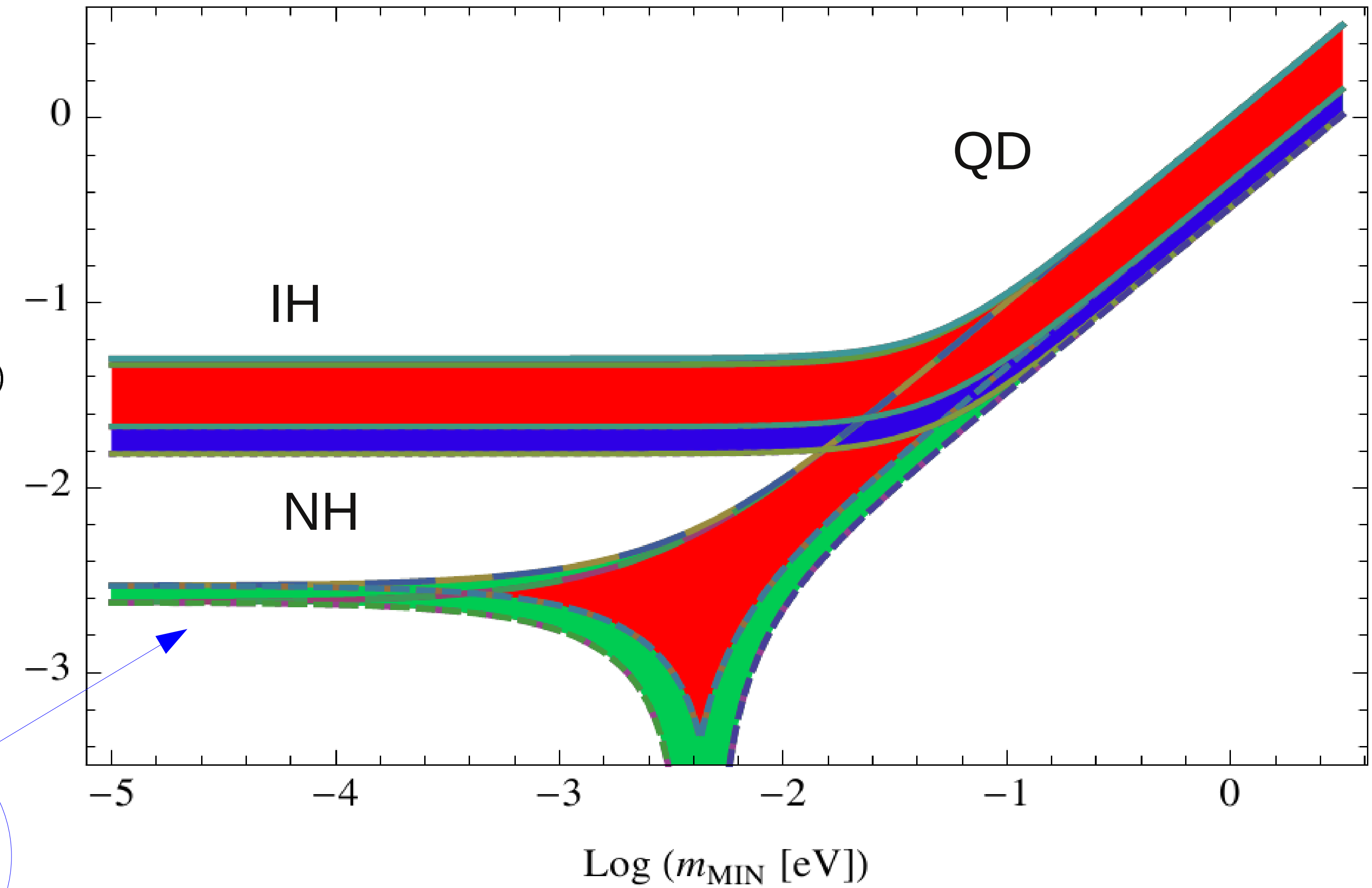


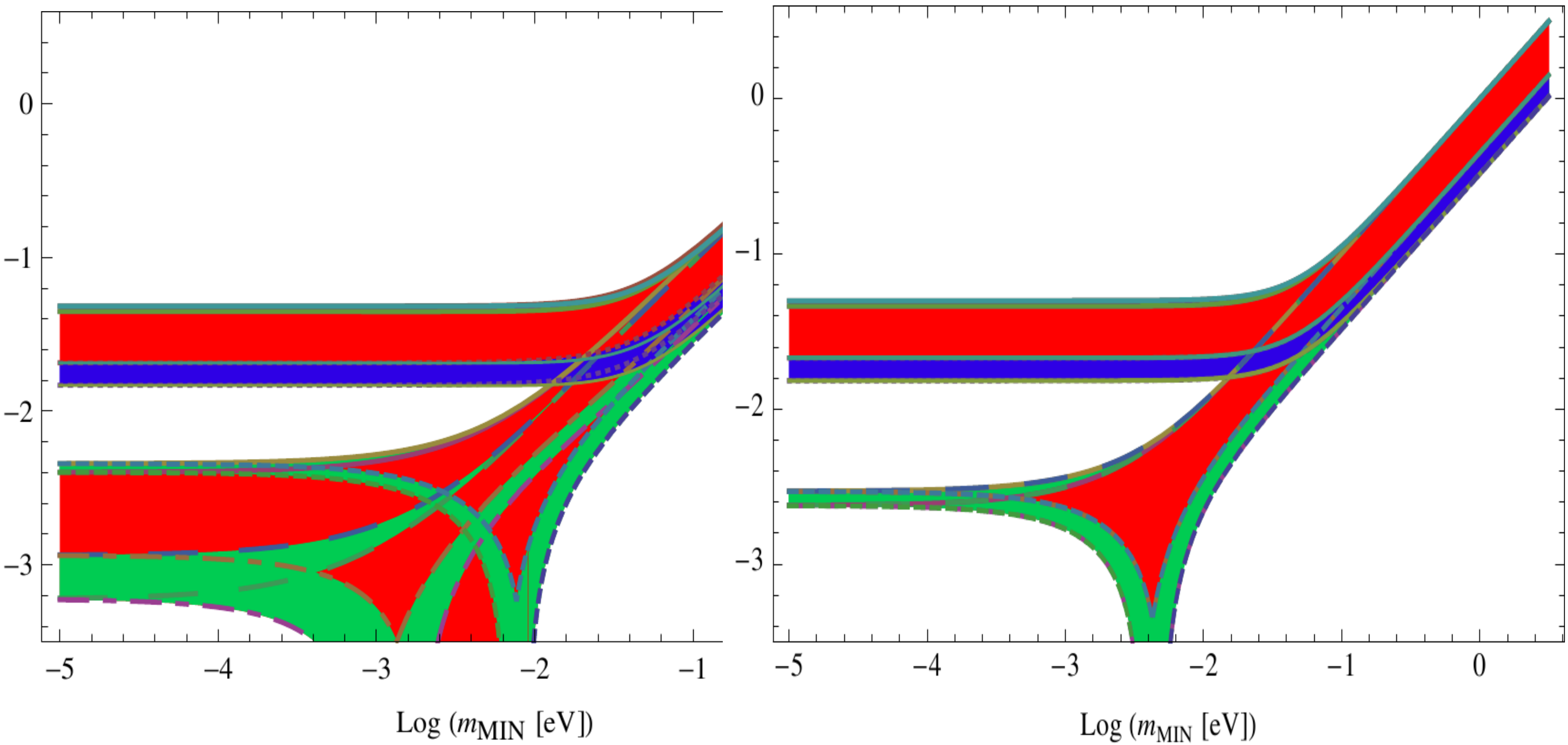
A small value of θ_{13} would reduce uncertanty In NH case

Allowed regions for $s^2_{13} = 0$

Courtesy of Silvia Pascoli

Impact of neutrino oscillations precission

2σ



$s_{13}^2 = 0.035$

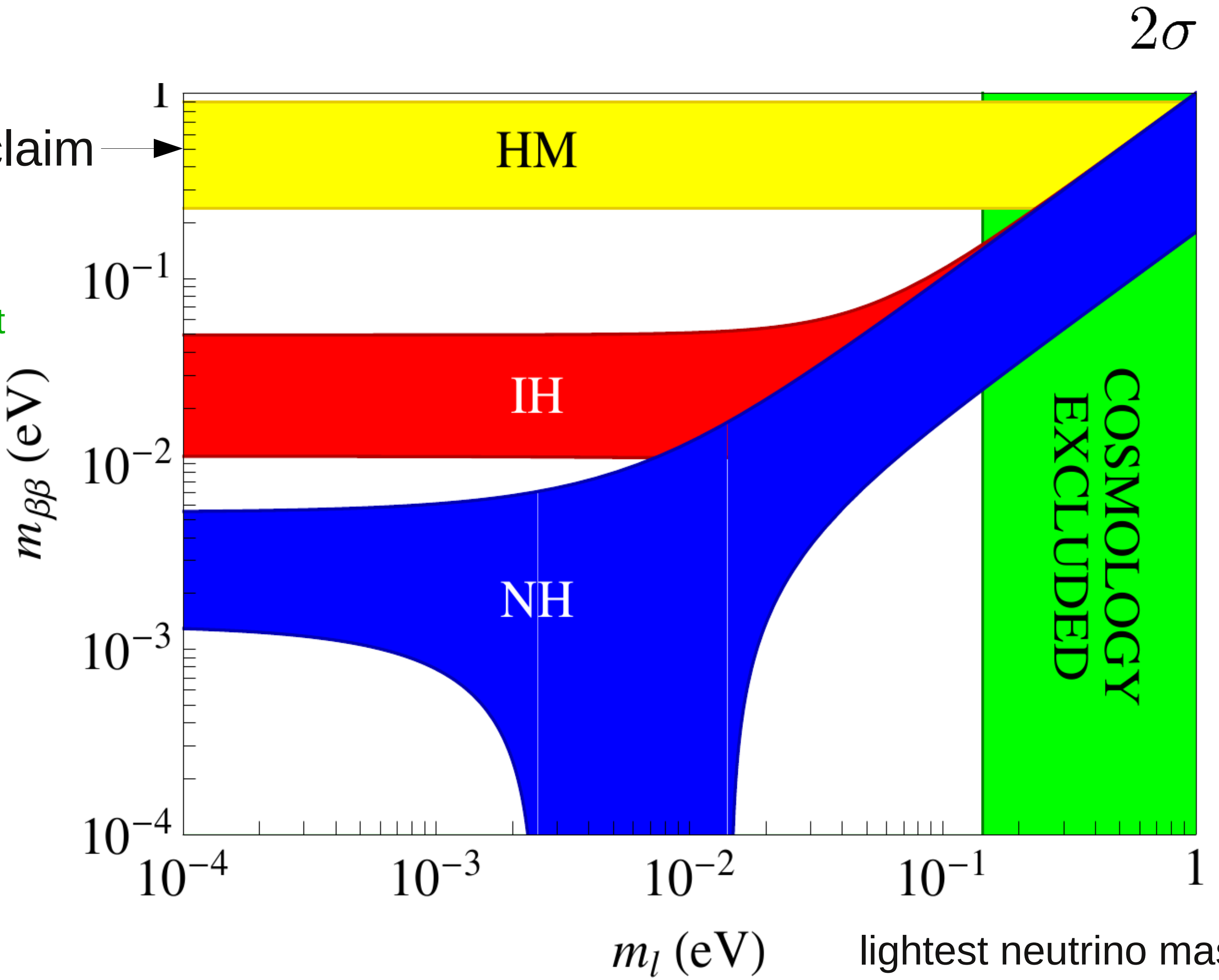
$s_{13}^2 = 0$

Courtesy of Silvia Pascoli

Combination of data

Heidelberg-Moscow claim

H.V. Klapdor-Kleingrothaus et al 06

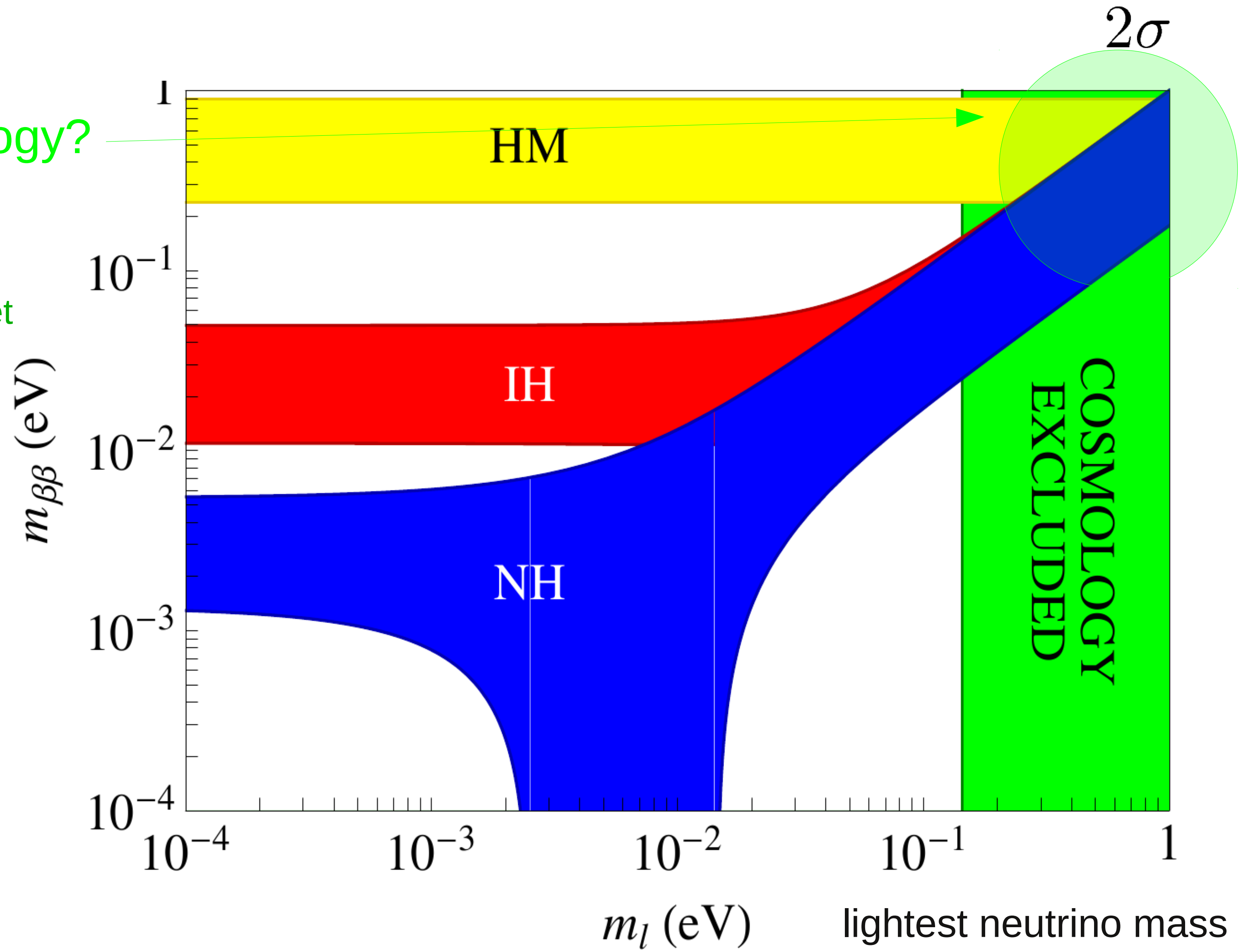


lightest neutrino mass

Combination of data

Ruled out by cosmology?

H.V. Klapdor-Kleingrothaus et al 06



lightest neutrino mass

Combination of data

Combination of different future neutrino experiments will shed light on the origin of neutrino masses:

- $0\nu\beta\beta$ may tell us if neutrinos are Majorana or Dirac particles.

- Future long base line oscillation experiments using matter effects can measure the mass hierarchy.

- Experiments sensitive to absolute neutrino mass scale, m_{MIN} :

- ^3H β-decay experiments sensitive to: $m_{\nu_e} = \sum |U_{\alpha i}|^2 m_i < 2\,\mathrm{eV}$

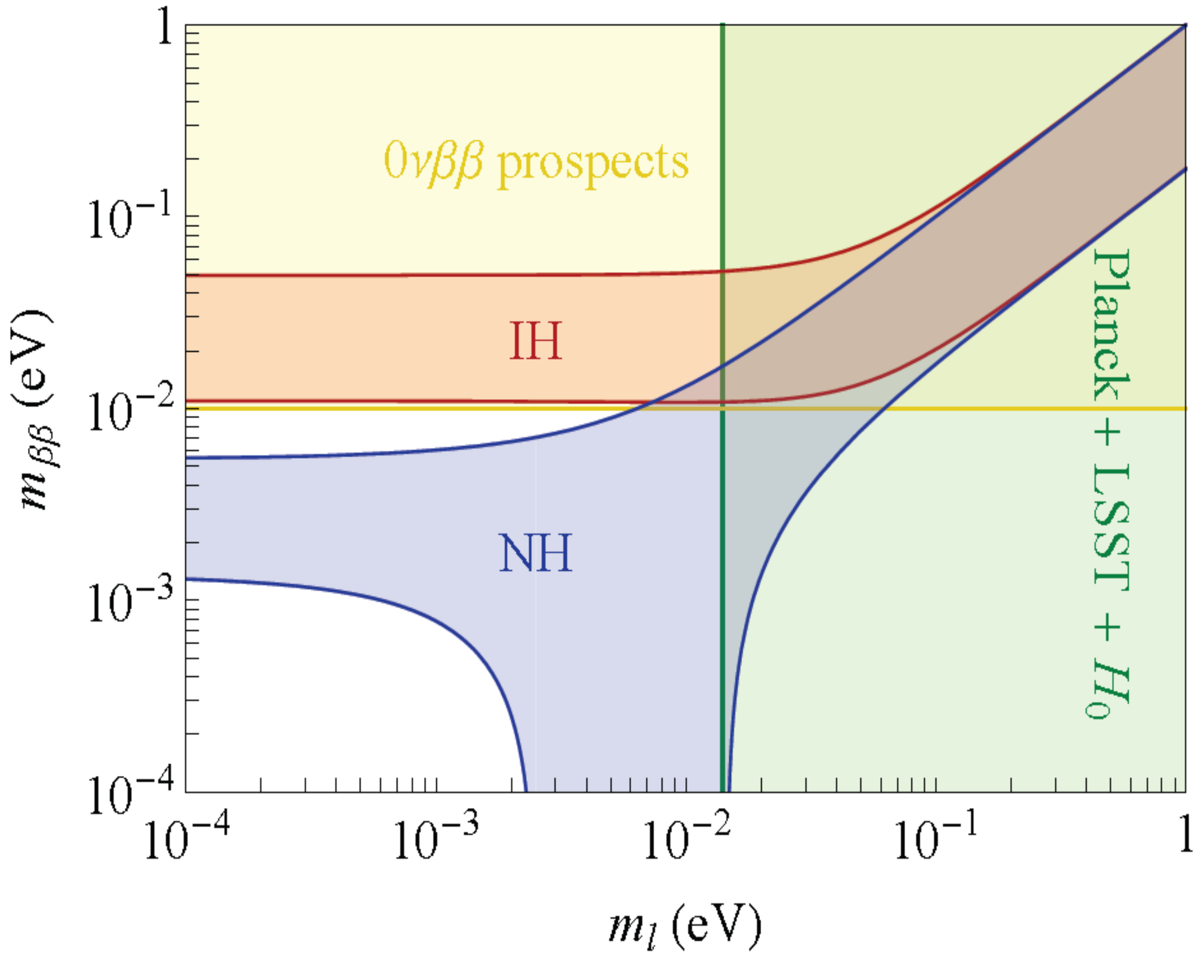
KATRIN future sensitivity: 0.2 eV

- Cosmological data: $\sum m_i < 0.58\,\mathrm{eV}$

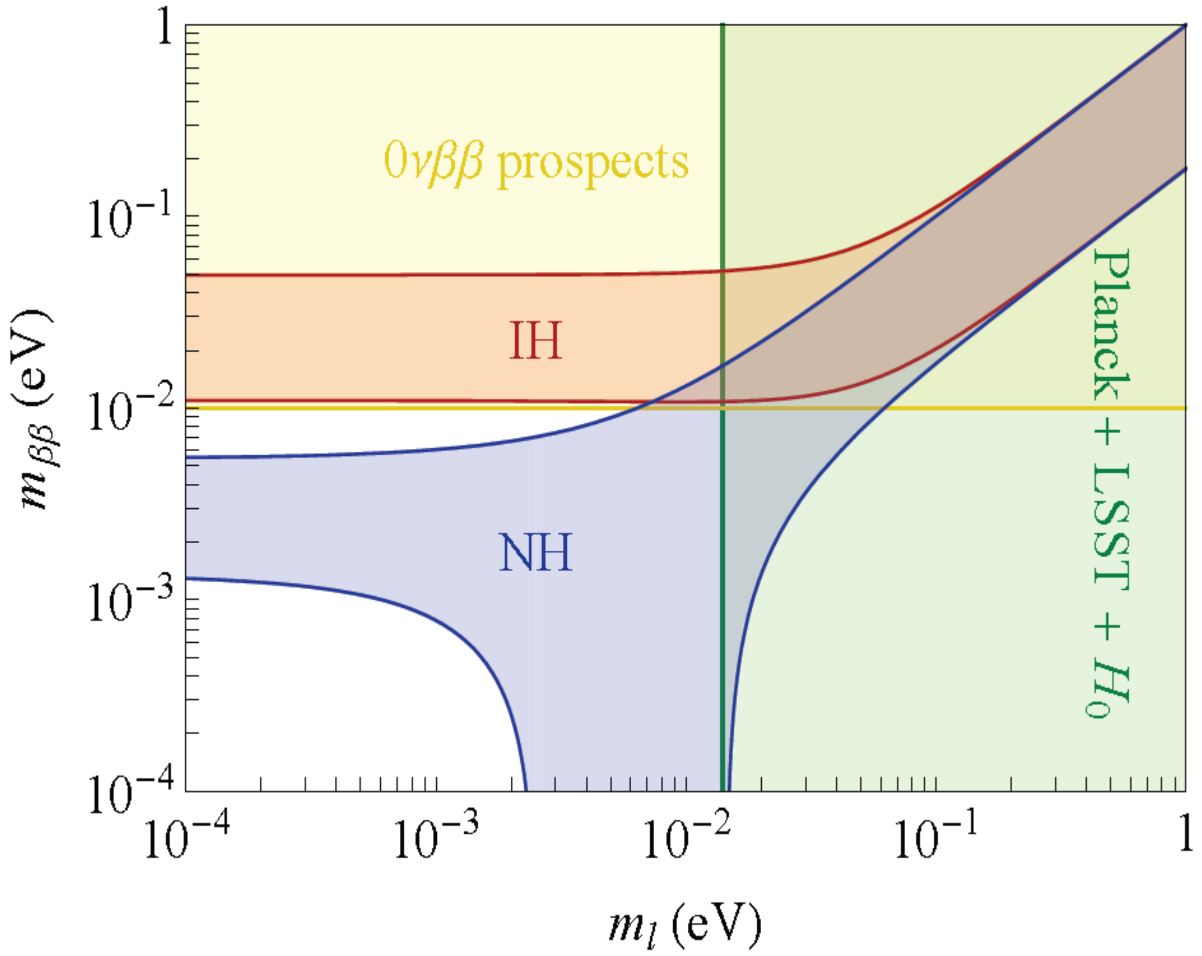
WMAP7; arXiv:1001.4538

→ See talk by Ofer LAHAV !

Future prospects

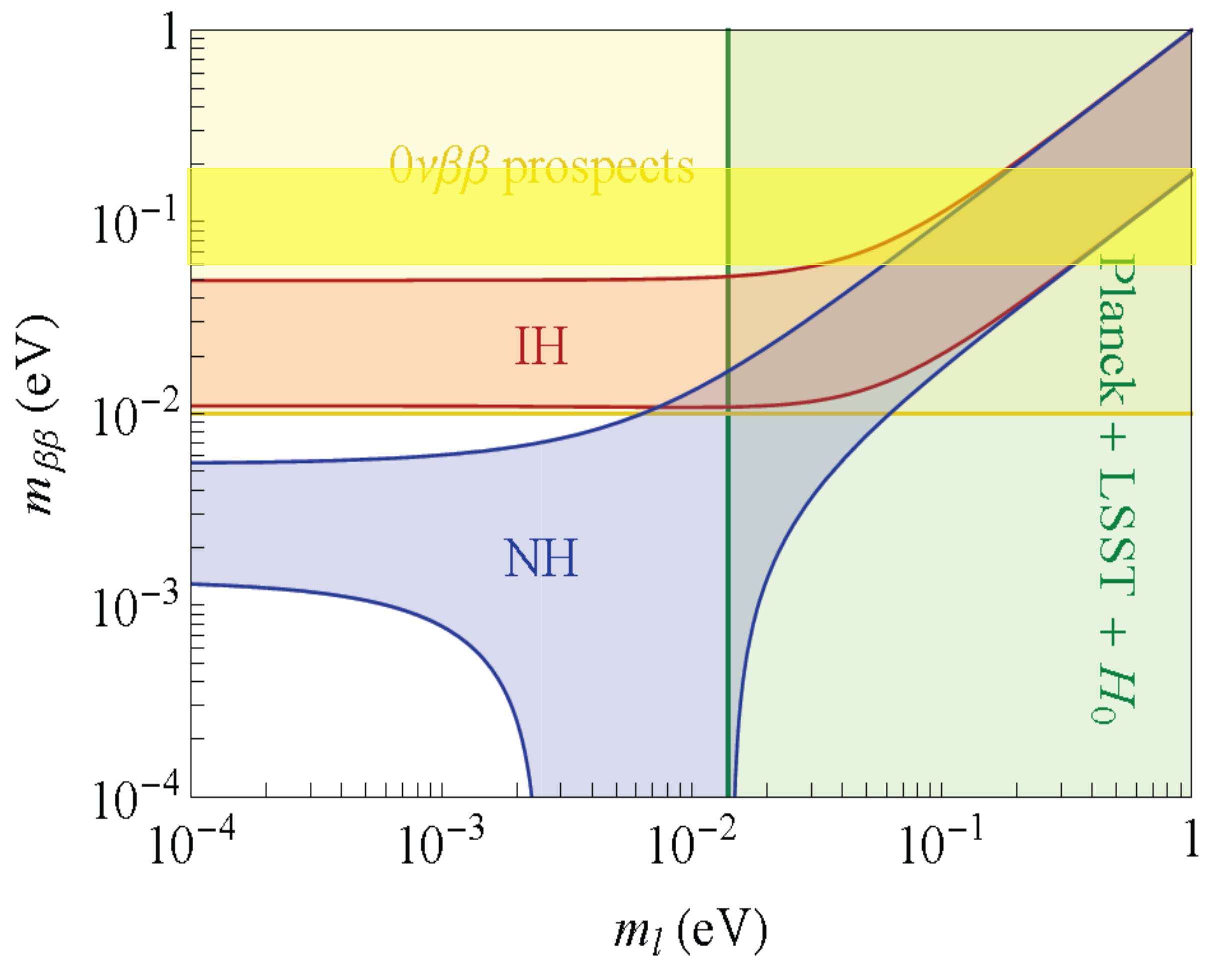


Future prospects



- Future cosmology bounds + present neutrino oscillation data can rule out the QD spectrum.

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



Hypothetical $0\nu\beta\beta$ signal

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

Combination of data

- The contribution to $0\nu\beta\beta$ decay from the light active neutrinos can be forecasted by combining present and future neutrino oscillation data on the neutrino mixing and mass hierarchy with probes of the absolute neutrino mass scale such as cosmology.

- These predictions can be compared to future $0\nu\beta\beta$ decay searches so as to gain information on the origin and nature of the neutrino masses.

Combination of data

We can distinguiss the following scenarios:

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

- Light active neutrinos dominate the $0\nu\beta\beta$
- New physics above the nuclear scale, but its contribution is suppressed.

Combination of data

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

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

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

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

Combination of data

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

- Neutrinos are Dirac particles
- Neutrinos are Majorana particles within *mini-seesaw model with* all the neutrinos below nuclear scale.

Combination of data

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

- Neutrinos are Dirac particles
- Neutrinos are Majorana particles within *mini-seesaw model with* all the neutrinos below nuclear scale.

5. No $0\nu\beta\beta$ signal observed and NOT forecasted.

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

Conclusions

- Neutrino masses signal of Physics Beyond the SM. Its smallness points to New Physics at high energies. Most of the moldels accounting for neutrinos masses predict that neutrinos are Majorana particles.

- Neutrinoless double beta decay experiments can probe the Majorana or Dirac nature of neutrinos. Its observation would imply that neutrinos are Majorana and Lepton number is not conserved.

- Neutrino oscillation experiments can meassure some of the lepton mixing parameters. We have already meassured: θ_{12}, θ_{23} , Δm^2_{21} and $|\Delta m^2_{31}|$. But we still don't know:

$\theta_{13},\ \delta,\ \mathrm{sgn}(\Delta m^2_{31}),\ \theta_{23}-\pi/4$ & absolute neutrino mass scale

$\theta_{13},\ \delta,\ \mathrm{sgn}(\Delta m^2_{31}),\ \theta_{23}-\pi/4 \longrightarrow$ Future neutrino oscillation data

absolute neutrino mass scale $\longrightarrow$ Cosmology and Tritium β-decay

Conclusions

- $0\nu\beta\beta$ depend on the mixing parameters:

  - The hierarchy, $\mathrm{sgn}(\Delta m_{31}^2)$, is a key parameter.

  - Marginal impact of the uncertanties in the already meassured mixing parameters.

  - A stronger future upper bound on θ_{13} would reduce the uncertanty in the NH case.

- Combination of neutrino oscillations, cosmology and $0\nu\beta\beta$ data will give us precious information about the origin and nature of neutrino masses !!!

Thank you!

$0\nu\beta\beta$ in simplest extension of the SM

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

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:

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

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

$0\nu\beta\beta$ in simplest extension of the SM

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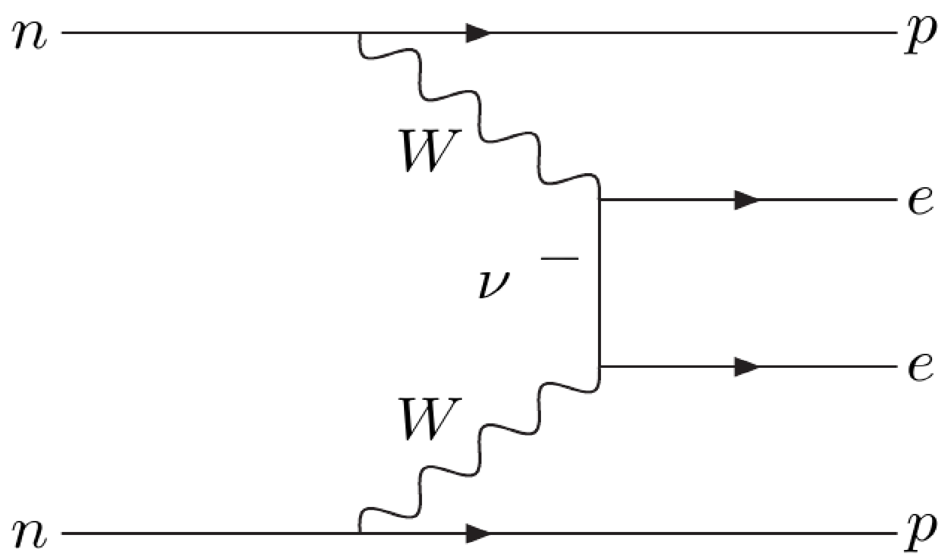
$$\cancel{\overline{\nu_{\alpha L}}\nu^c_{\alpha L}} \qquad \sum_i^{\text{SM}} m_i U^2_{ei} + \sum_I^{\text{extra}} m_I U^2_{eI} = 0$$

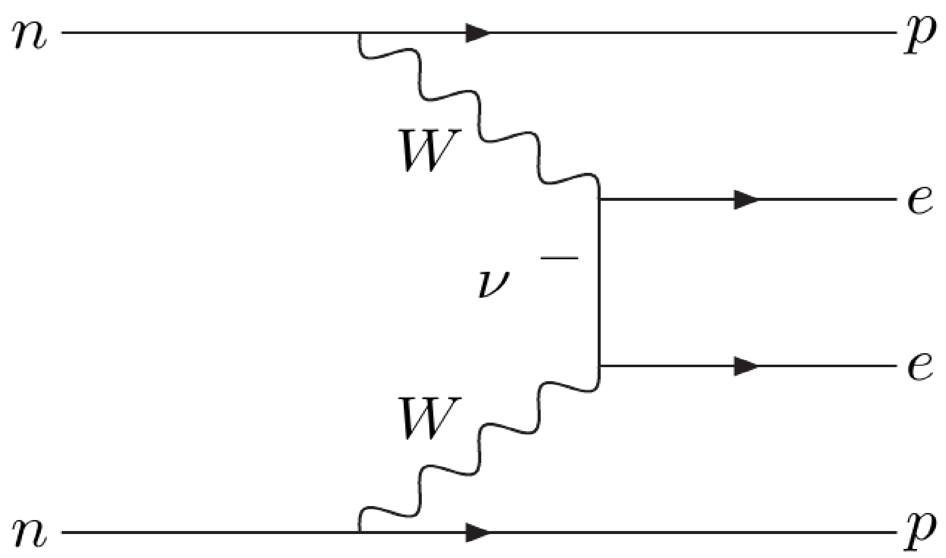
Simple relation between "light" parameters
and extra degrees of freedom!

$0\nu\beta\beta$ in simplest extension of the SM



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

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



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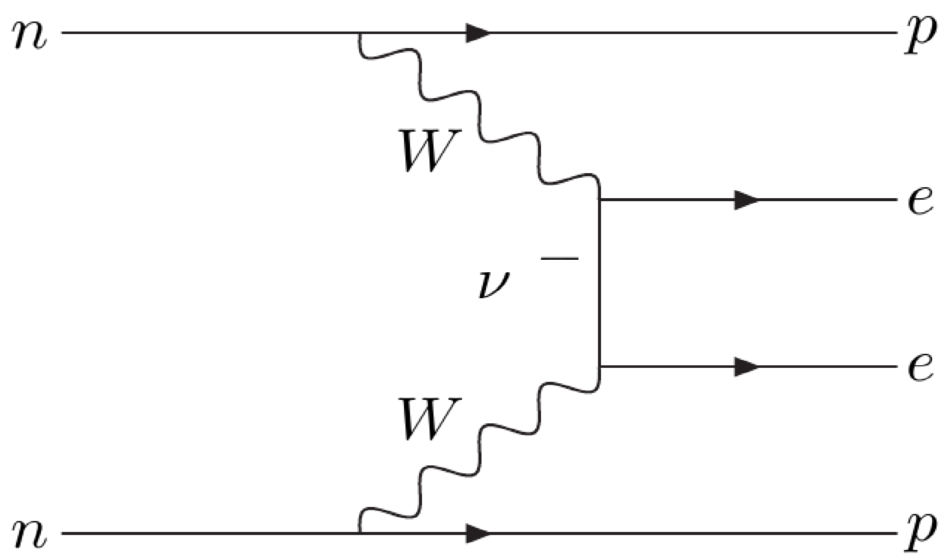
light mostly active states

$0\nu\beta\beta$ in simplest extension of the SM



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light mostly active states

extra degrees of freedom

Different phenomenologies depending on their mass regime

All extra masses in light regime

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

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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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→ Cancellation between NME: GIM *analogy*

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

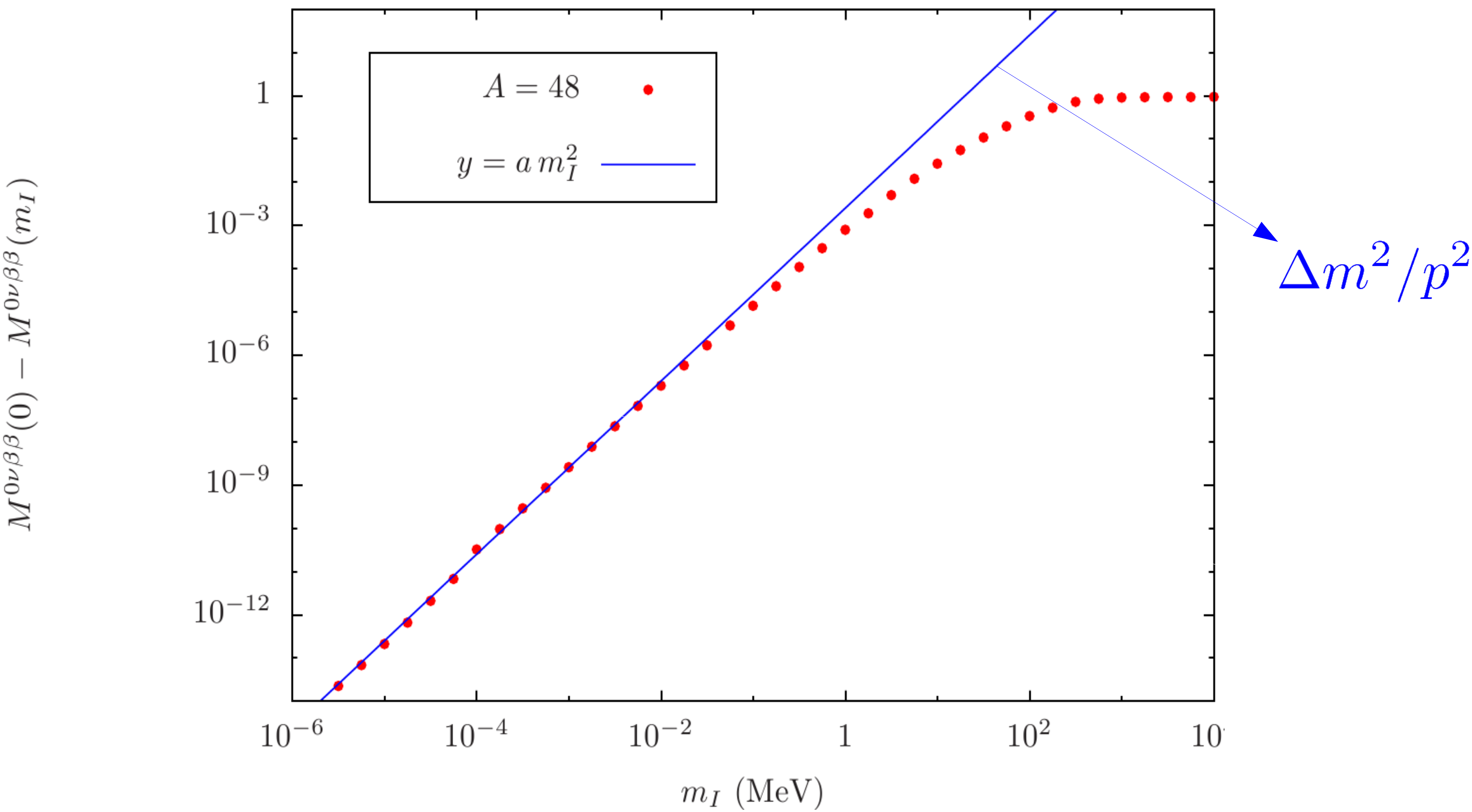
$$\Delta m^2 / M_W^2 \quad \longleftrightarrow \quad \Delta M^{0\nu\beta\beta}$$

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

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

All extra masses in light regime

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



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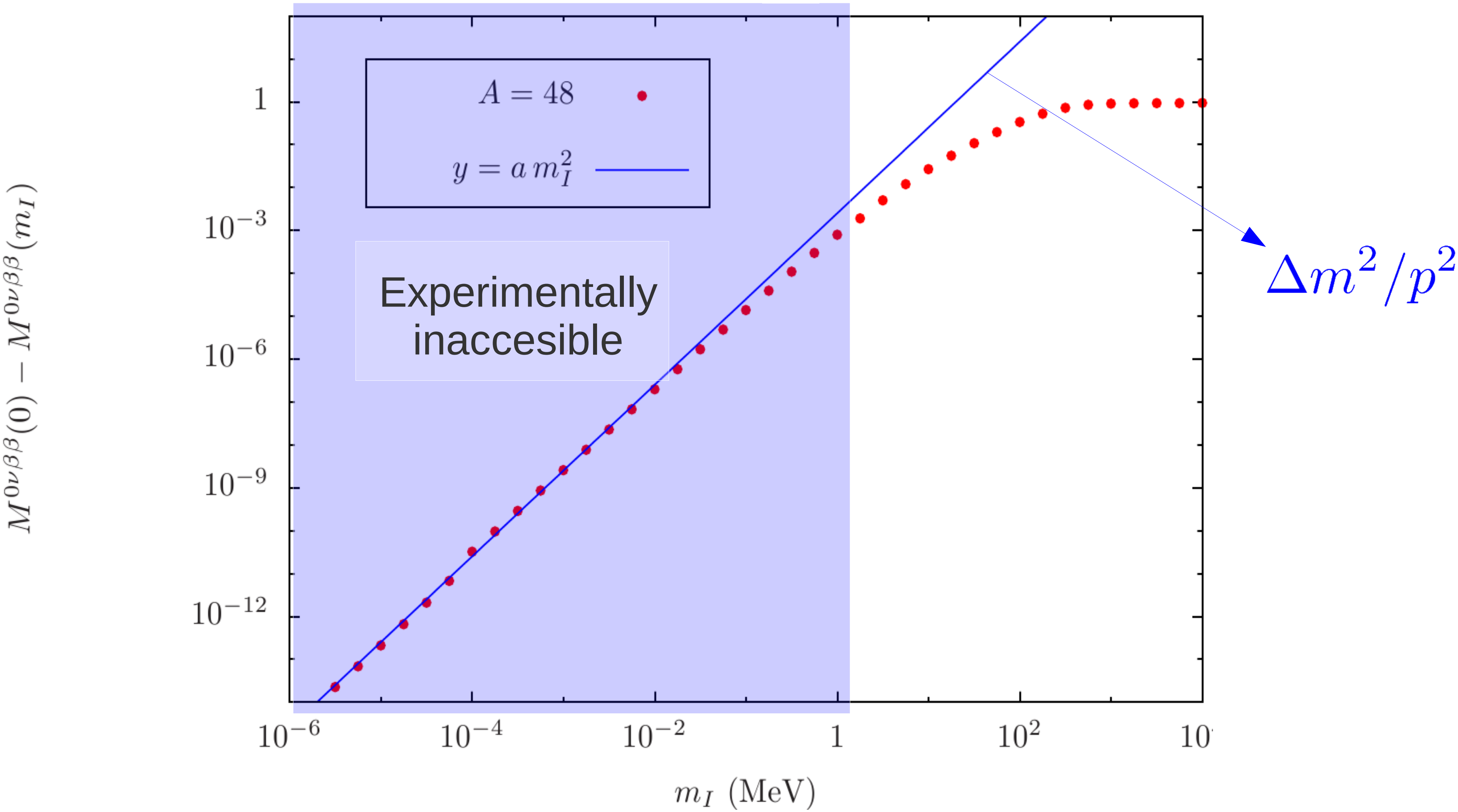

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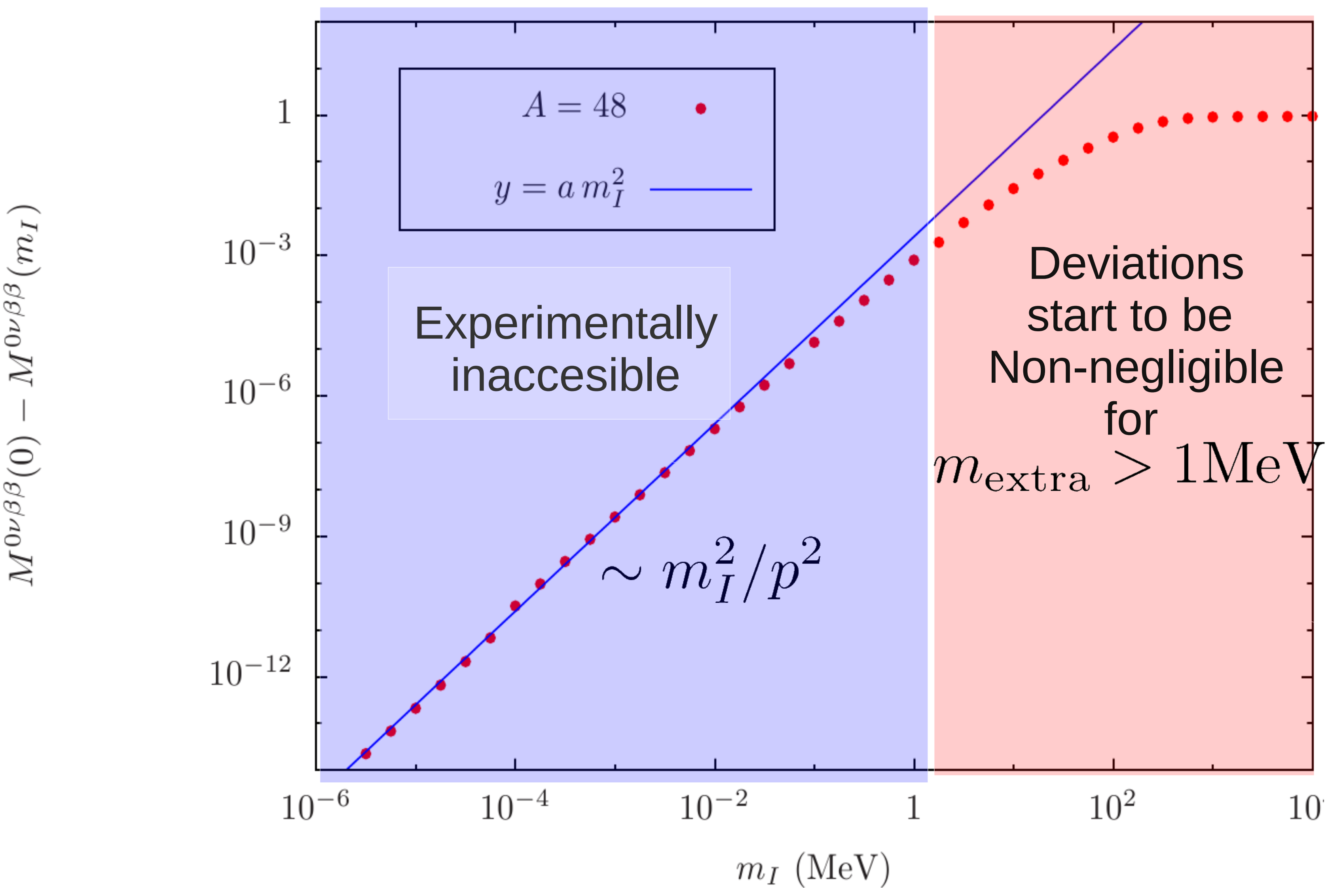

All extra masses in heavy regime

”canonical” Type-I seesaw scenario

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

All extra masses in heavy regime

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

All extra masses in heavy regime

"canonical" Type-I seesaw scenario

negligible!

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

All extra masses in heavy regime

"canonical" Type-I seesaw scenario

negligible!

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

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

$m_{\beta\beta}$

Light neutrino contribution dominates the process

All extra masses in heavy regime

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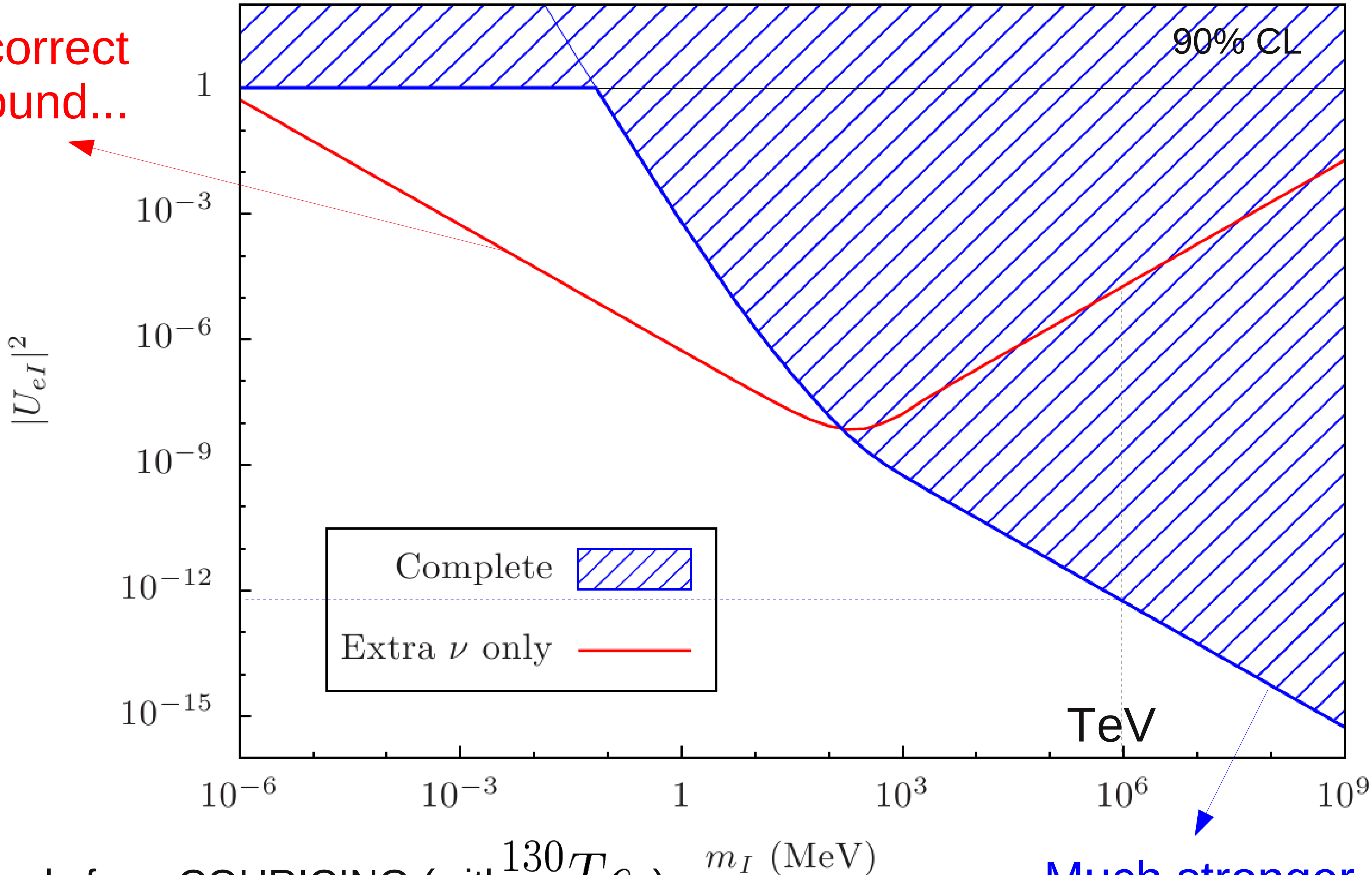
Constraint on mixing with heavy Neutrinos through light contribution!!

$m_{\beta\beta}$

Light neutrino contribution dominates the process

Constraint on mixing with extra neutrino

Incorrect bound...



Much stronger Constraint !!

Bounds from COURICINO (with ^{130}Te)

Non-hierarchical extra neutrinos assumed

Idea: Extra states in light & heavy regimes

- In this way we could satisfy:

1 $0\nu\beta\beta$ signal

$+$

2 cosmology constraints

$+$

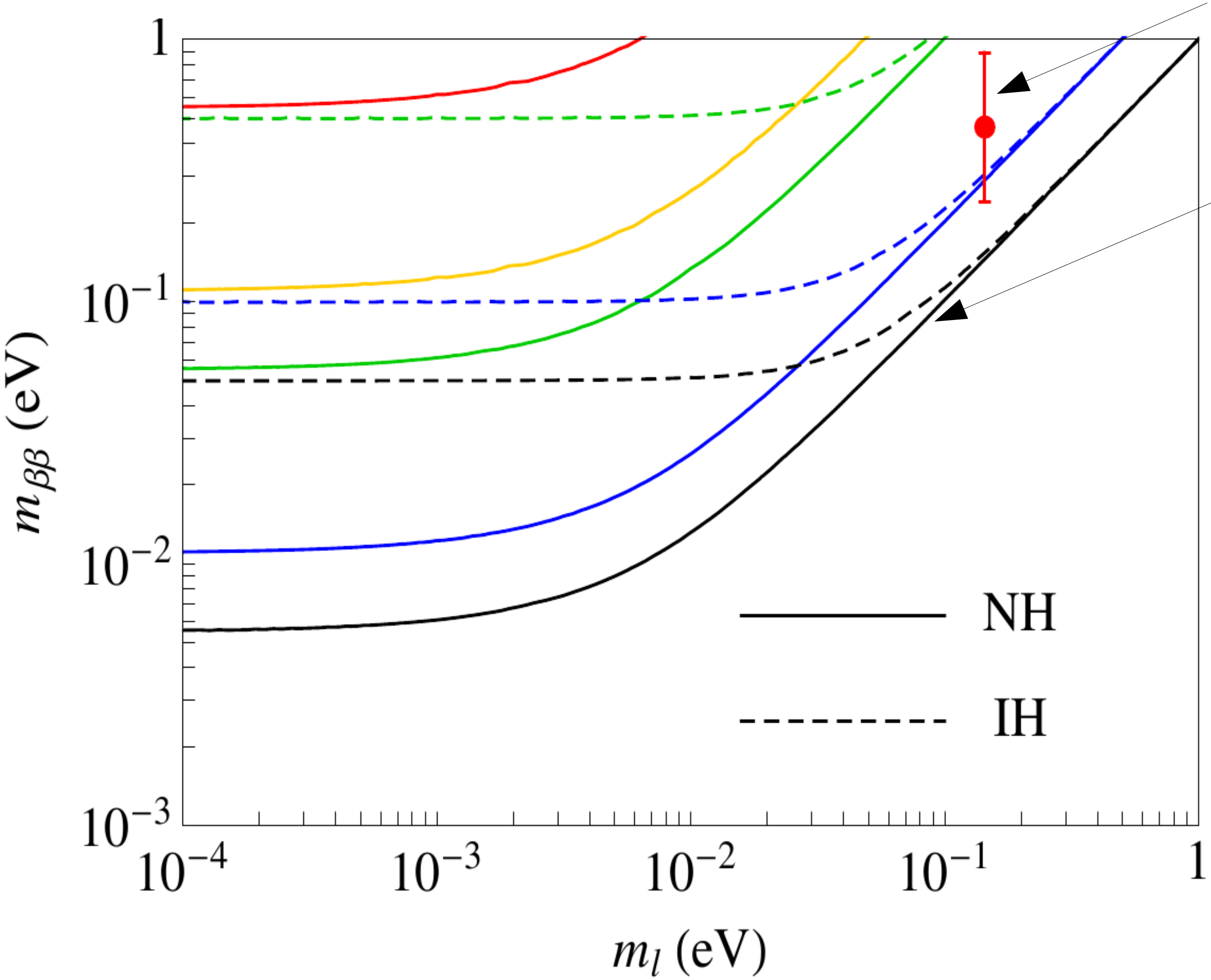
3 Relation between ”light” parameters and extra degrees of freedom:

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

cancellation between EXTRA Light & heavy contribution

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

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!

Important exception

This may be implemented at tree level in inverse seesaw models:

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

Gavela, Hambye, D. Hernandez, P. Hernandez 2009

$$\sum_I^{\mathrm{SM}} m_i U_{ei}^2 M^{0\nu\beta\beta}(0) \approx \left(Y \frac{v}{\Lambda} \mu \frac{v}{\Lambda} Y^T \right)_{ee}$$

$$\sum_I^{\mathrm{heavy}} m_I U_{eI}^2 M^{0\nu\beta\beta}(m_I) \sim \left(v^2 Y \frac{\mu + \mu'}{\Lambda^2} Y^T \right)_{ee} \frac{p^2}{\Lambda^2}$$

Cancellation level

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

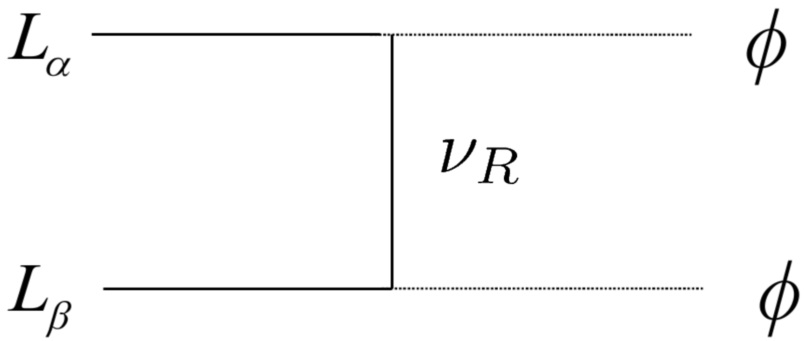
For different cancellation levels:

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

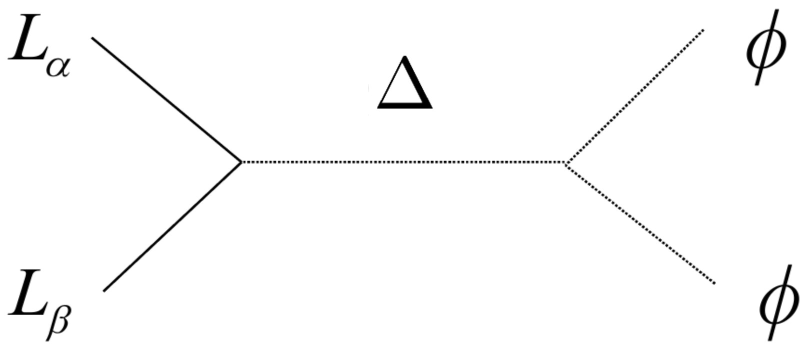
$$= \frac{\left| \sum_i^{\mathrm{SM}} m_i U_{ei} \right|}{m_{\beta\beta}}$$

Information from neutrino oscillations

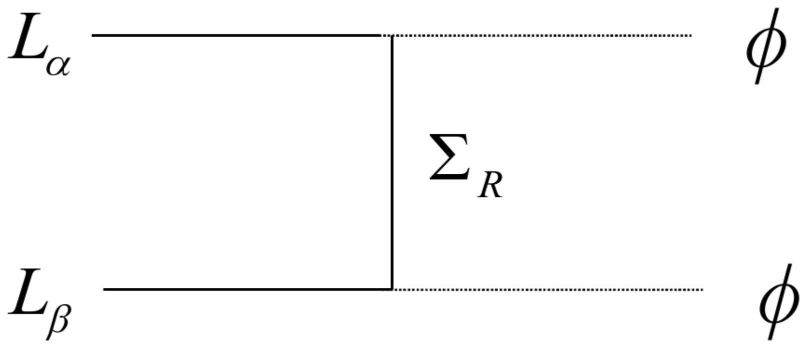
Tree level realisations of the Weinberg operator



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

Idea: Extra states in light & heavy regimes

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

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

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

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

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: $p^2 < 0$)