Updated bounds for Neutrinoless Double Beta Decay

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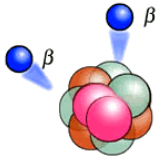
Presentation Outline

1. Theoretical Overview
2. Data
3. Results arXiv:1404.2616 [hep-ph]
4. Conclusions



Double Beta Decay

Theoretical Overview
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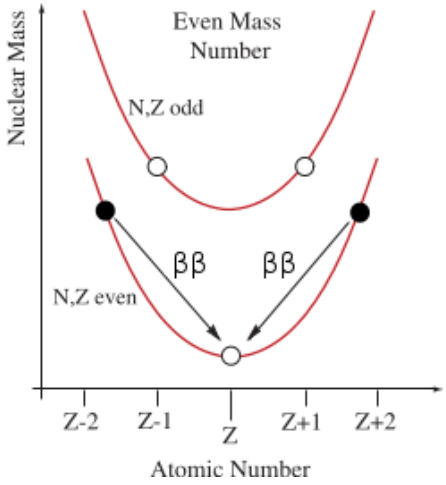
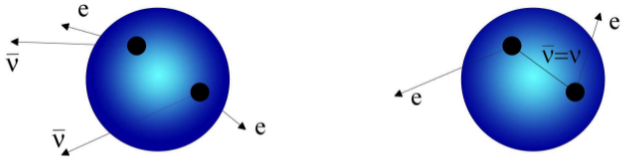


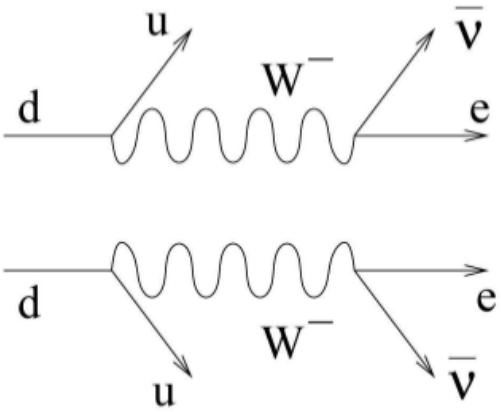
$$(A, Z) \to (A, Z+2) + 2e^- + 2\bar{\nu}_e \qquad (2\nu\beta\beta)$$

$$(A, Z) \to (A, Z+2) + 2e^- \qquad (0\nu\beta\beta)$$

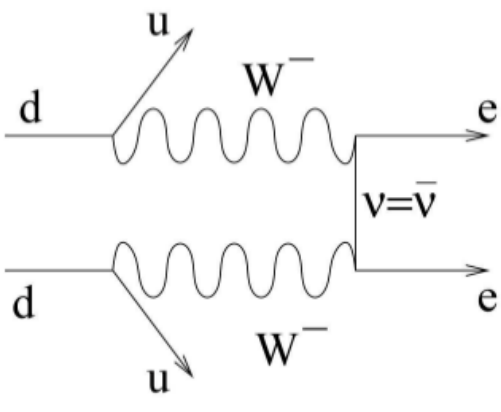


Wendell Hinkle Furry (1939)

Maria Goeppert-Mayer (1935)



$t^{1/2} \sim (10^{19} - 10^{25})$ yr



$t^{1/2} > 10^{25}$ yr

Half-life time

Theoretical Overview
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Conclusions

The half-life can be factorized as:

$$\left[t_i^{1/2}\right]^{-1} = G_{0\nu,i} \cdot \mathcal{M}_i^2 \cdot \left|f(m_k, U_{ek})\right|^2 *$$

$$\text{where} \quad \begin{cases} G_{0\nu,i} & = \text{space phase factor} \\ \mathcal{M}_i & = \text{nuclear matrix element} \\ f(m_i, U_{ei}) & = \text{physics beyond the SM} \end{cases}$$

* J. Barea, J. Kotila and F. Iachello, *Phys. Rev. C*, 2013, 87, 014315
J. Kotila and F. Iachello, *Phys. Rev. C*, 2012, 85, 034316

g_A quenching

Theoretical Overview
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In particular, the nuclear matrix element can be expressed emphasizing the role of the axial coupling constant:

$$\mathcal{M}_i = g_A^2 \cdot \mathcal{M}_{0\nu,i}$$

$$\begin{cases} g_{\text{nucleon}} & = 1.269 \\ g_{\text{quark}} & = 1 \\ g_{\text{phen.}} & = g_{\text{nucleon}} \cdot A^{-0.18} \end{cases}$$

Majorana effective mass

Theoretical Overview
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Light neutrino exchange $\rightarrow f$ proportional to $m_{\beta\beta}$

$$m_{\beta\beta} \equiv m_e \cdot f(m_k, U_{ek}) = \left| \sum_{k=1,2,3} U_{ek}^2 m_k \right|$$

$$= \left| e^{i\alpha_1} |U_{e1}^2| m_1 + e^{i\alpha_2} |U_{e2}^2| m_2 + e^{-2i\delta} |U_{e3}^2| m_3 \right|$$

$$= \left| e^{i\alpha_1} c_{12} c_{13} m_1 + e^{i\alpha_2} c_{13} s_{12} m_2 + e^{-i\delta} s_{13} m_3 \right|$$

m_e = electron mass, s_{ij} and $c_{ij} = \sin\theta_{ij}$ and $\cos\theta_{ij}$,
δ = CP-violating phase and $\alpha_{1,2}$ = Majorana phases.
This parametrization holds for $\theta_{ij} = [0, \pi/2]$ and $\phi = [0, 2\pi]$.

Oscillation parameters and cosmological mass

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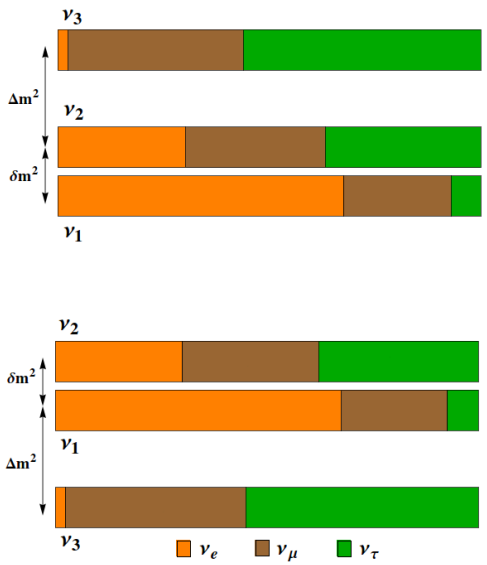
3ν mass-mixing parameters (global data analysis):†

Parameter	Best fit	1σ range
$\mathcal{NH}$		
$\sin^2(\theta_{12})$	$3.08 \cdot 10^{-1}$	$(2.91 - 3.25) \cdot 10^{-1}$
$\sin^2(\theta_{13})$	$2.34 \cdot 10^{-2}$	$(2.16 - 2.56) \cdot 10^{-2}$
$\sin^2(\theta_{23})$	$4.25 \cdot 10^{-1}$	$(3.98 - 4.54) \cdot 10^{-1}$
δm^2 [eV^2]	$7.54 \cdot 10^{-5}$	$(7.32 - 7.80) \cdot 10^{-5}$
Δm^2 [eV^2]	$2.44 \cdot 10^{-3}$	$(2.38 - 2.52) \cdot 10^{-3}$
$\mathcal{IH}$		
$\sin^2(\theta_{12})$	$3.08 \cdot 10^{-1}$	$(2.91 - 3.25) \cdot 10^{-1}$
$\sin^2(\theta_{13})$	$2.39 \cdot 10^{-2}$	$(2.18 - 2.60) \cdot 10^{-2}$
$\sin^2(\theta_{23})$	$4.37 \cdot 10^{-1}$	$(4.08 - 4.96 \oplus 5.31 - 6.10) \cdot 10^{-1}$
δm^2 [eV^2]	$7.54 \cdot 10^{-5}$	$(7.32 - 7.80) \cdot 10^{-5}$
Δm^2 [eV^2]	$2.40 \cdot 10^{-3}$	$(2.33 - 2.47) \cdot 10^{-3}$



cosmological mass (Planck):‡ $\Sigma = m_1 + m_2 + m_3 < 0.23\,\text{eV}$ (95% C. L.)

† **F. Capozzi et al.** arXiv:1312.2878 [hep-ph] **(2013)**
‡ **P. A. R. Ade et al.** arXiv:1303.5076 [astro-ph.CO] **(2013)**

Constraints from oscillations

Theoretical Overview
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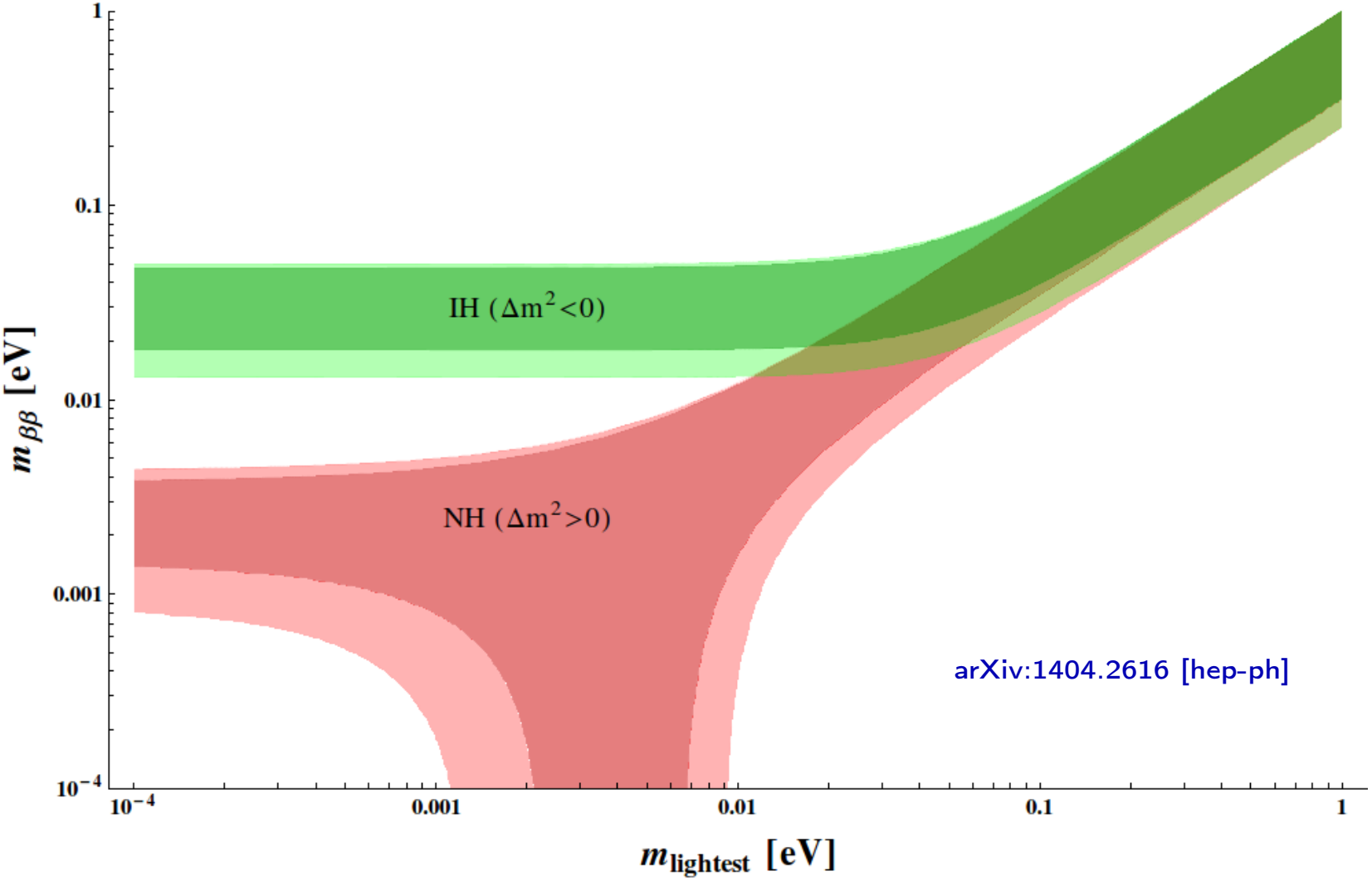

arXiv:1404.2616 [hep-ph]

$0\nu\beta\beta$ experiment sensitivities

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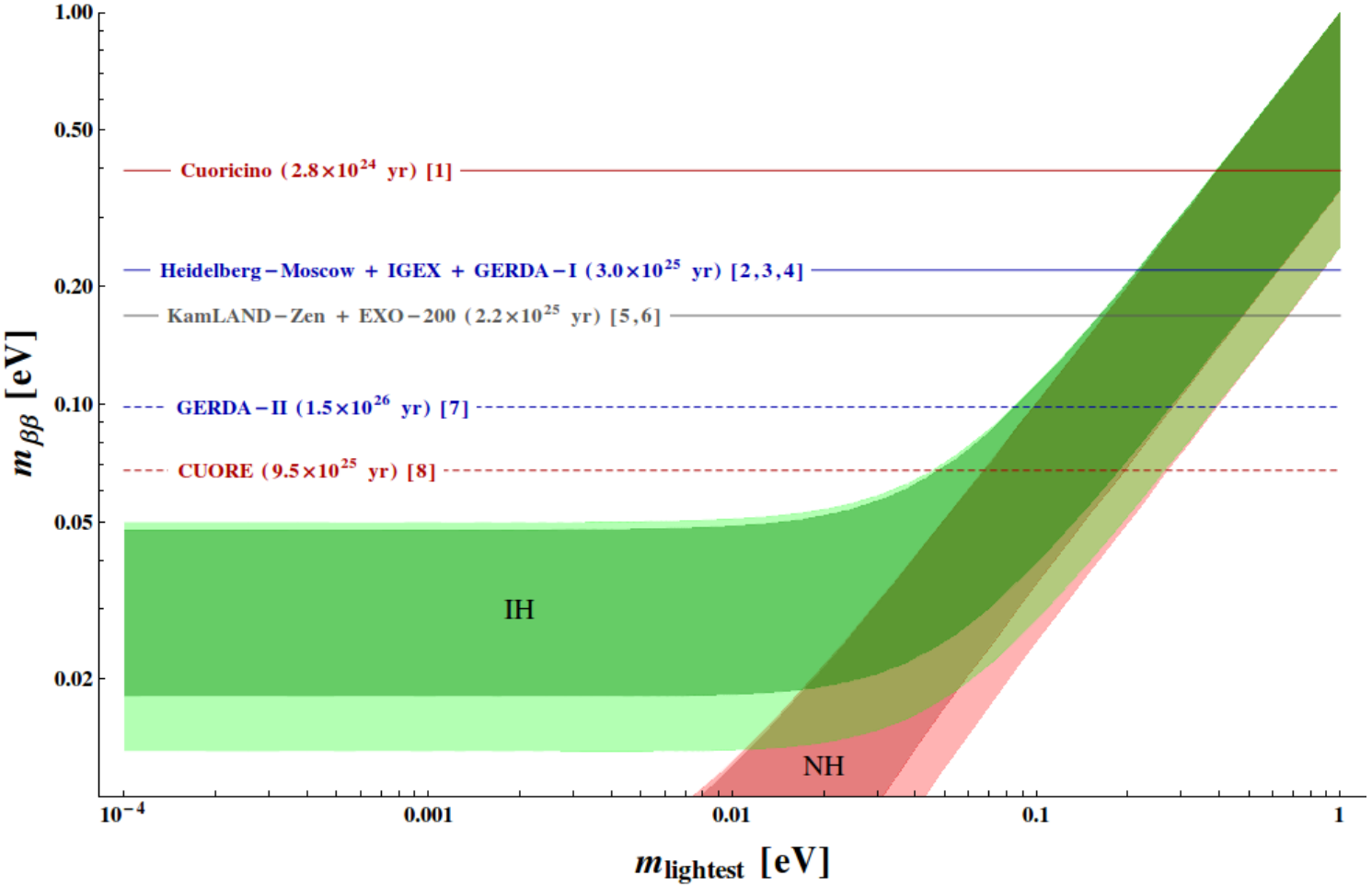

[1] S. Di Domizio, *J. Phys. Conf. Ser*, 2012, 375, 042014; [2] H. Klapdor-Kleingrothaus et al., *Eur. Phys. J. A*, 2001, 12, 147–154; [3] C. E. Aalseth et al., *Phys. Rev. D*, 2002, 65, 092007; [4] M. Agostini et al., *Phys. Rev. Lett.*, 2013, 111, 122503; [5] A. Gando et al., *Phys. Rev. Lett.*, 2013, 110, 062502; [6] J. Albert et al. arXiv:1402.6956 [nucl-ex] (2014); [7] F. Alessandria et al. arXiv:1109.0494 [nucl-ex] (2011); [8] R. Brugnera and A. Garfagnini, *Adv. High Energy Phys.*, 2013, 2013, 506186

Importance of quenching

Theoretical Overview
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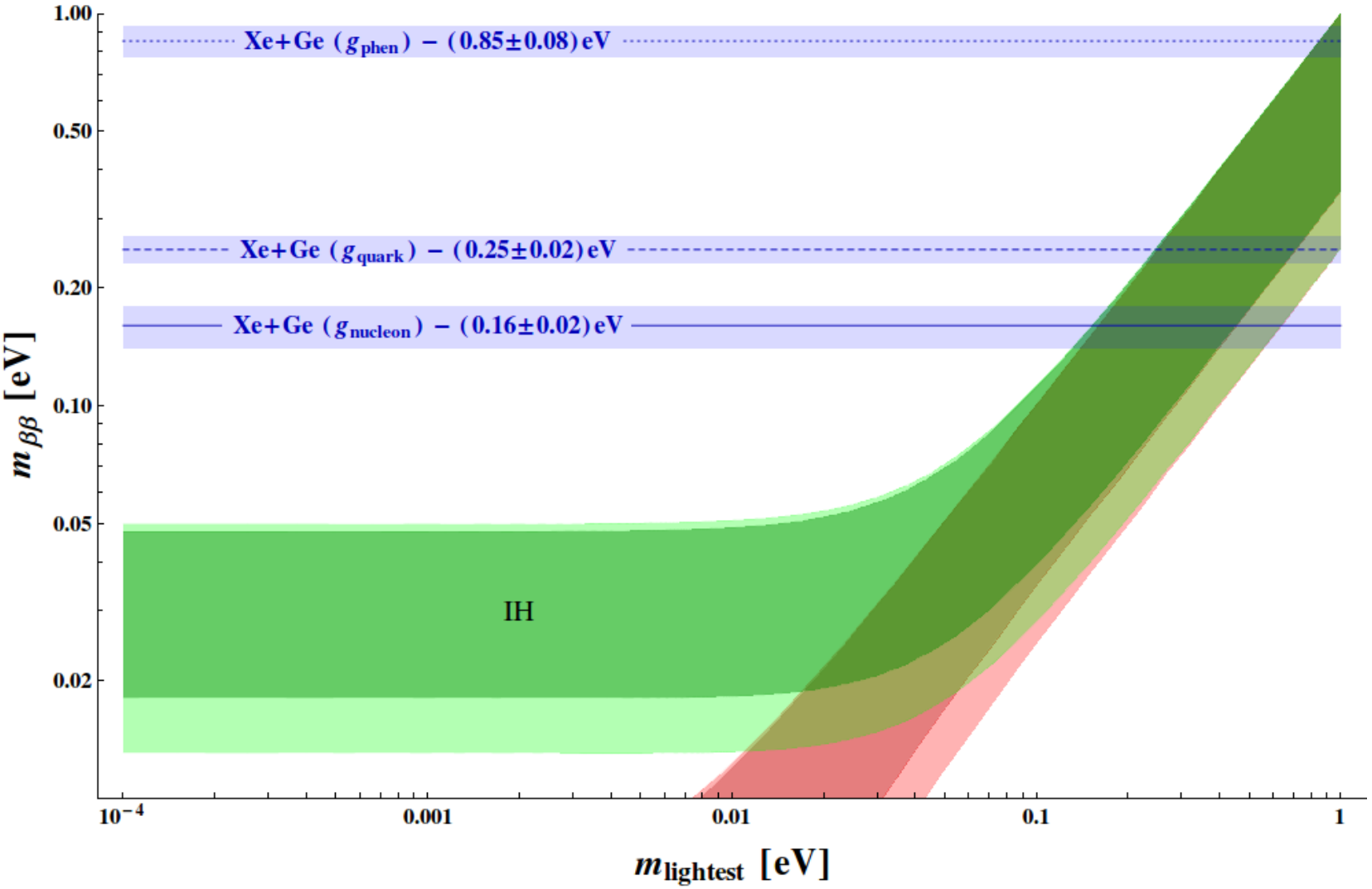

Majorana effective mass and cosmological mass

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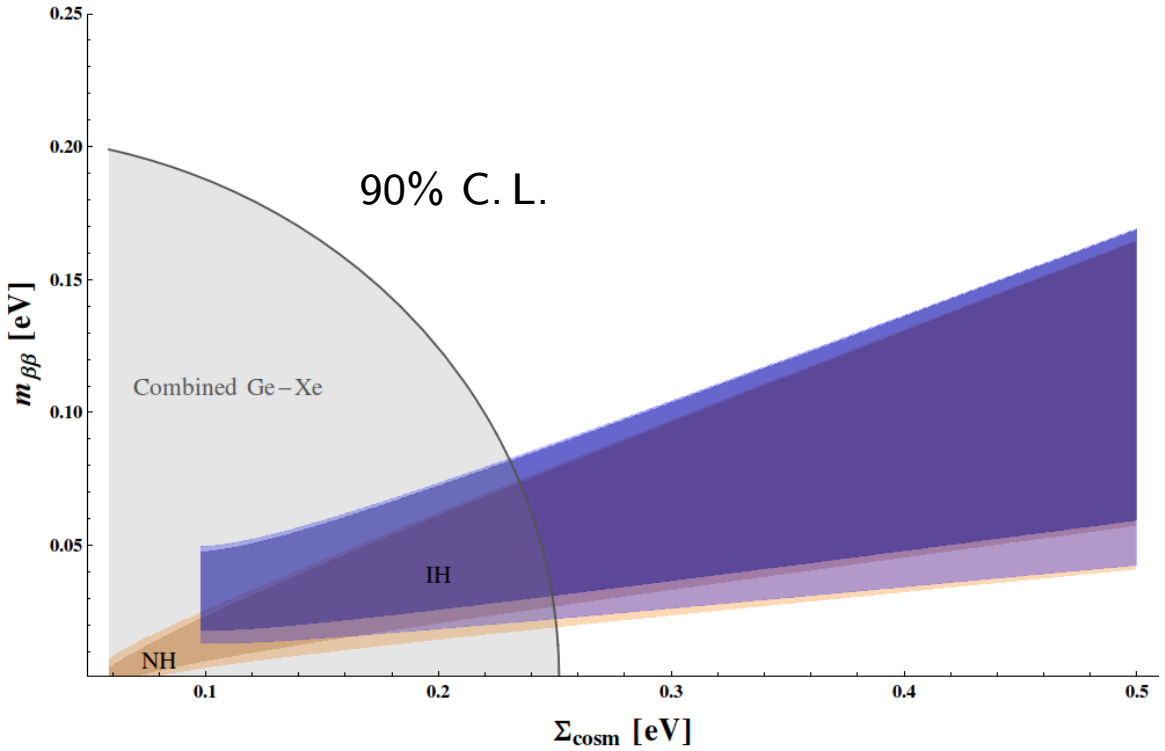
- $m_{\beta\beta}$ is a function of the mass of one of the neutrinos
- Σ is the sum of the three active neutrino masses

$$\Rightarrow \Sigma = \begin{cases} m_l + \sqrt{m_l^2 + \delta m^2} + \sqrt{m_l^2 + \Delta m^2 + \frac{\delta m^2}{2}}, & \text{for } \mathcal{NH} \\ m_l + \sqrt{m_l^2 + \Delta m^2 - \frac{\delta m^2}{2}} + \sqrt{m_l^2 + \Delta m^2 + \frac{\delta m^2}{2}}, & \text{for } \mathcal{IH} \end{cases}$$



Conclusions

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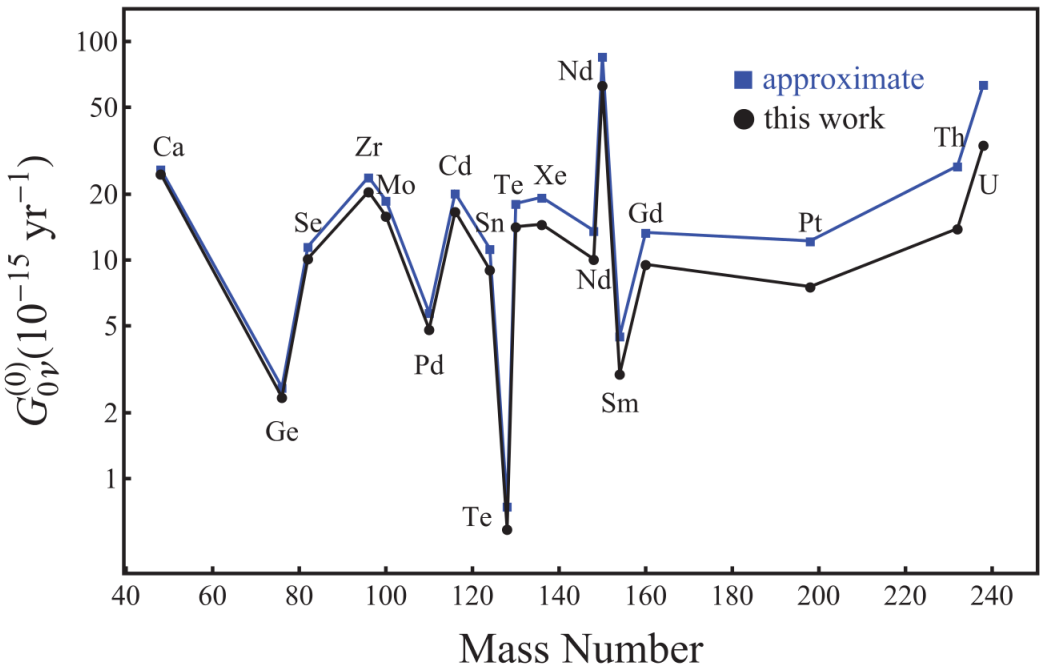
- Need of studying the quenching
- Probing $\mathcal{IH}$ will require a strong experimental effort
- Experimental sensitivities are improving fast
- Stay tuned on new constraints from Σ
- $0\nu\beta\beta$ is a unique tool to study lepton number violation and neutrino masses

Backup: phase space factors

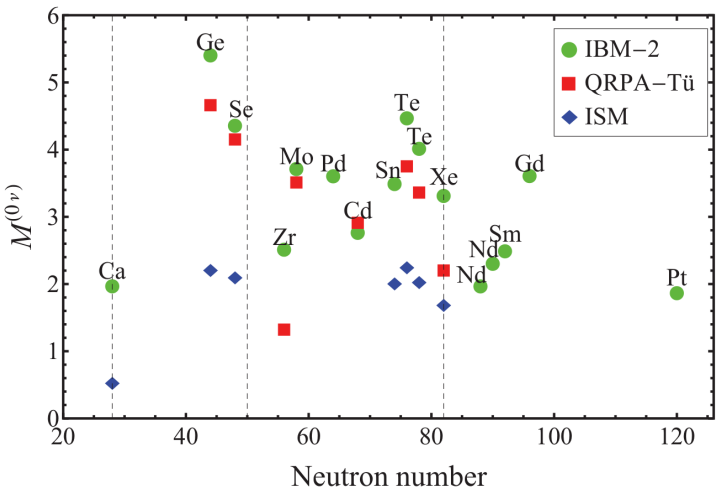


Obs. Main corrections in heavy nuclei (Z large), where relativistic and screening corrections play a major role.

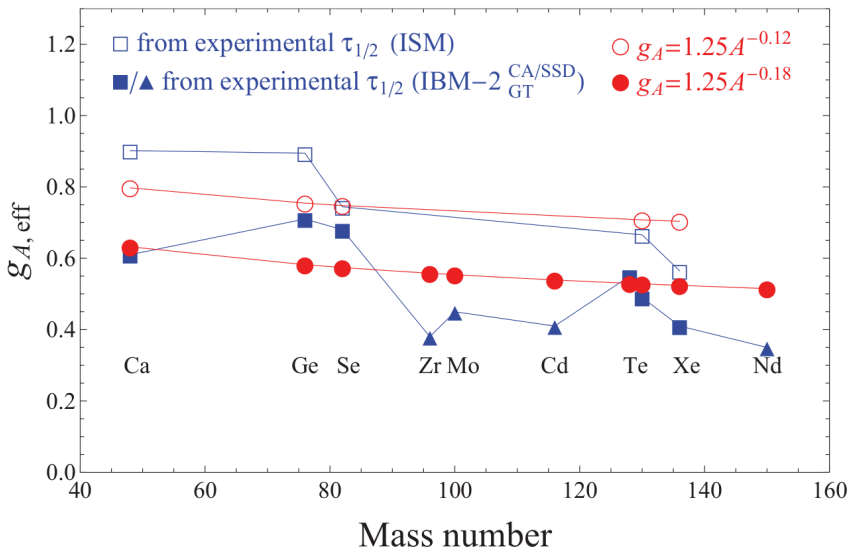
(*approximate* refers to the results obtained by the use of approximate electron wave functions)[§]

[§] J. Kotila and F. Iachello, *Phys. Rev. C*, 2012, 85, 034316

Backup: nuclear matrix elements



IBM-2 results for $0\nu\beta\beta$ compared with QRPAand the ISM.



Value of $g_{A,eff}$ extracted from experiment for IBM-2 and the ISM.

IBM-2: J. Kotila and F. Iachello, ***Phys. Rev. C***, 2012, 85, 034316
QRPA: F. Šimkovic et al., ***Phys. Rev. C***, 2008, 77, 045503
ISM: E. Caurier et al., ***Phys. Rev. Lett.***, 2008, 100, 052503.

Backup: combined experiment sensitivity

- the combined Gaussian bound for the half-life is:

$$t^{1/2} = \sqrt{\sum_{i=\mathrm{Ge,Te,\ \ldots}} \left(t_i^{1/2}\,(\mathrm{exp.})\right)^2}$$

- the combination of results from different nuclei is more delicate and depends on the uncertain matrix elements (the (relative) matrix elements are assumed to be known precisely):

$$\frac{1}{m_{\beta\beta}} = \left[\sum_{i=\mathrm{Ge,Te,\ \ldots}} \left(\frac{t_i^{1/2}\,(\mathrm{exp.})\, G_{0\nu,i}\, \mathcal{M}_i^2}{m_e^2}\right)^2\right]^{1/4}$$

Backup: likelihood

- for a simultaneous observation of some values for Σ and $m_{\beta\beta}$:

$$\mathcal{L} \sim \exp\left[-\frac{(\Sigma - \Sigma^{\text{meas}})^2}{2\sigma(\Sigma^{\text{meas}})^2}\right] \exp\left[-\frac{(m_{\beta\beta} - m_{\beta\beta}^{\text{meas}})^2}{2\sigma(m_{\beta\beta}^{\text{meas}})^2}\right]$$

- since $\mathcal{L} = \mathrm{e}^{-\chi^2/2}$:

$$\chi^2 = \frac{(\Sigma - \Sigma^{\text{meas}})^2}{\sigma(\Sigma^{\text{meas}})^2} + \frac{(m_{\beta\beta} - m_{\beta\beta}^{\text{meas}})^2}{\sigma(m_{\beta\beta}^{\text{meas}})^2}$$

- to define the confidence intervals:

$$\text{C. L.} = \iint_{\chi^2 < \chi_0^2} dx\, dy\, \mathrm{e}^{-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}}$$

$$\Rightarrow \quad \chi_0^2 = -2\ \ln(1 - \text{C. L.})$$