

The contribution of light Majorana neutrinos to neutrinoless double beta decay and cosmology



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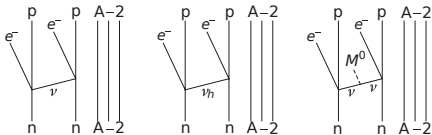
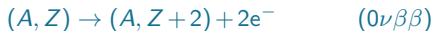
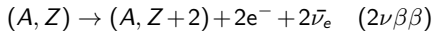
September 7, 2015

Outline

- Introduction
- Present situation on neutrinoless double beta decay
- Limits from cosmology
- Contributions from other mechanisms
- Summary



(Some) neutrinoless double beta decay mechanisms



$$\left[t_{0\nu,i}^{1/2} \right]^{-1} = G_{0\nu,i} |\mathcal{M}_i|^2 |f|^2$$

- $G_{0\nu,i}$ = phase space factor (atomic physics)
- \mathcal{M}_i = nuclear matrix element (nuclear physics)
- f = mechanism (particle physics)
 - light neutrino exchange $\rightarrow |f| = m_e^{-1} m_{\beta\beta}$
 - heavy neutrino exchange
 - Majoron emission
 - ...

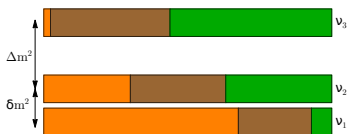
See Cremonesi's talk

Majorana effective mass

$$m_{\beta\beta} \equiv \left| \sum_{k=1,2,3} U_{ek}^2 m_k \right| = \left| e^{i\alpha_1} |U_{e1}^2| m_1 + e^{i\alpha_2} |U_{e2}^2| m_2 + |U_{e3}^2| m_3 \right|$$

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

Normal Hierarchy

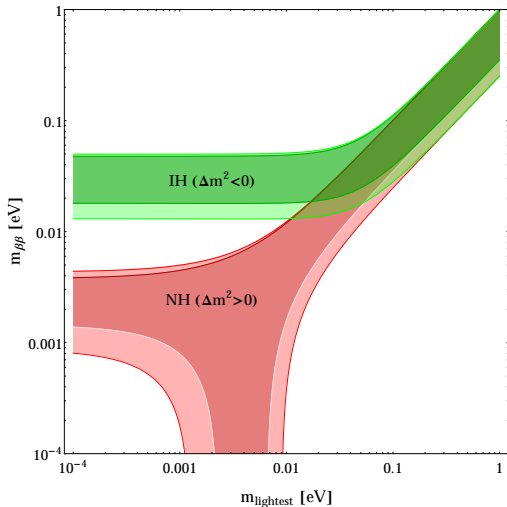


Inverted Hierarchy



Oscillation parameters: F. Capozzi *et al.*, *Phys. Rev. D* **89**, 093018 (2014)

Constraints from oscillations: $m_{\beta\beta}$ vs. m_{lightest}



Thanks to the knowledge of the oscillation parameters, we can put constraints on $m_{\beta\beta}$:

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

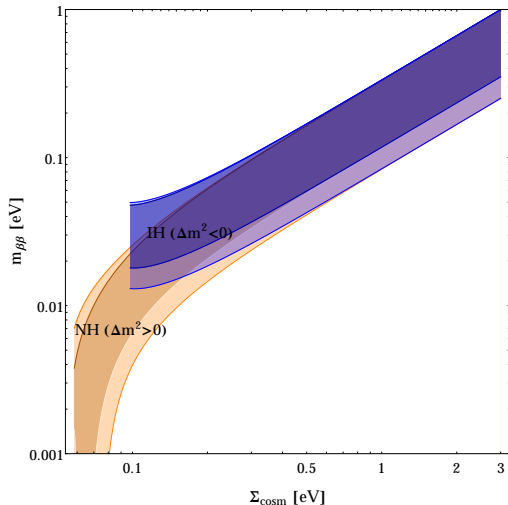
$$\diamond m_{\beta\beta}^{\min} = \max \left\{ 2 |U_{ei}^2| m_i - m_{\beta\beta}^{\max}, 0 \right\}$$

$i = 1, 2, 3$

obs. $\alpha_{1,2}$ are left free

S. D., S. M., F. Vissani, *Phys. Rev. D* **90**, 033005 (2014)

Constraints from oscillations: $m_{\beta\beta}$ vs. Σ



$$\Sigma \equiv m_1 + m_2 + m_3$$

Therefore:

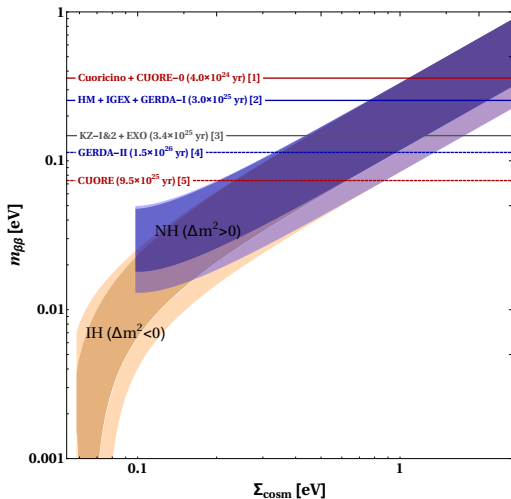
$$\Sigma = m_l + \sqrt{m_l^2 + a} + \sqrt{m_l^2 + b}$$

$$\mathcal{NH}: \begin{cases} a = \delta m^2 \\ b = \Delta m^2 + \delta m^2/2 \end{cases}$$

$$\mathcal{IH}: \begin{cases} a = \Delta m^2 - \delta m^2/2 \\ b = \Delta m^2 + \delta m^2/2 \end{cases}$$

S. D., S. M., F. Vissani, *Phys. Rev. D* **90**, 033005 (2014)

Experimental bounds on $m_{\beta\beta}$



$$m_{\beta\beta} \leq \frac{m_e}{\mathcal{M}_i \sqrt{G_{0\nu,i} t_{0\nu,i}^{1/2}(\text{exp.})}}$$

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

obs. NMEs calculated with IBM-2 model

$$g_A = 1.269 \text{ (free nucleons)}$$

NMEs: J. Barea *et al.*, *Phys. Rev. C* 91, 034304 (2015)

PSFs: J. Kotila & F. Iachello, *Phys. Rev. C* 85, 034316 (2012)

Experiment sensitivities:

[1] K. Alfonso *et al.*, *Phys. Rev. Lett.* 115, 102502 (2015)

[2] M. Agostini *et al.*, *Phys. Rev. Lett.* 111, 122503, (2013)

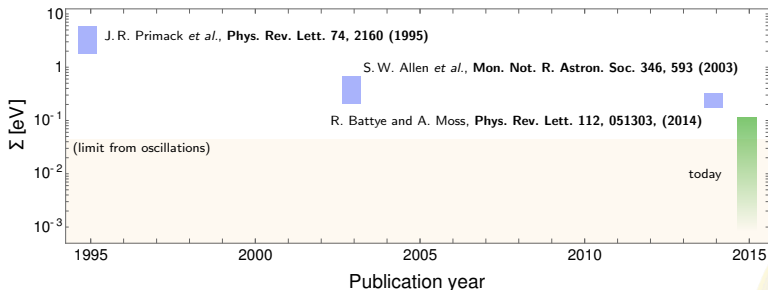
[3] A. Gando *et al.*, *Phys. Rev. Lett.* 110, 062502, (2013)

[4] R. Brugnera *et al.*, *Adv. High En. Phys.* 2013, 506186, (2013)

[5] D. R. Artusa *et al.*, *Adv. High En. Phys.* 2015, 879871, (2015)

Bounds on Σ

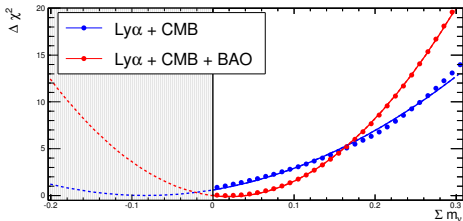
- cosmology is producing more and more stringent bounds on Σ
- requirements/evidences for $\Sigma \neq 0$ involve always smaller values
- today, the bound is pushed down to hundreds or tens of meV
- all the predictions are model dependent. A cautious attitude is advisable



Recent results, N. Palanque-Delabrouille *et al.*, JCAP 1502, 045 (2015)

$\Sigma < 0.14 \text{ eV}$ (95% C. L.)[†] by combining different data:

- Ly α -forest 1-D power spectrum from Baryon Oscillation Spectroscopic Survey (BOSS) of SDSS-III (N. Palanque-Delabrouille *et al.*, *Astron. Astrophys.* 559, A 85 (2013))
- CMB data from Planck 2013 (P. Ade *et al.*, *Astron. Astrophys.* 571, A 16 (2014))
- BAO data from BOSS (L. Anderson *et al.*, *Mon. Not. R. Astron. Soc.* 441, 24 (2014))



$$\Delta\chi^2(\Sigma) \simeq \frac{(\Sigma - 22 \text{ meV})^2}{(62 \text{ meV})^2}$$

$$\Sigma < 84 \text{ meV} \quad (1\sigma \text{ C. L.})$$

$$\Sigma < 146 \text{ meV} \quad (2\sigma \text{ C. L.})$$

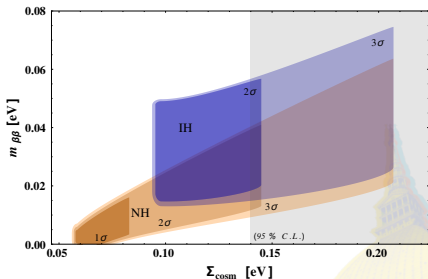
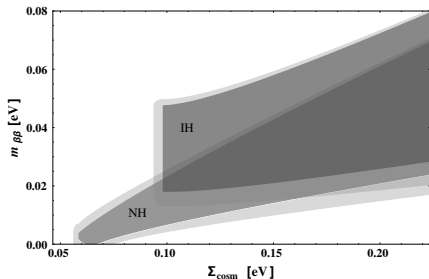
$$\Sigma < 208 \text{ meV} \quad (3\sigma \text{ C. L.})$$

[†] The limit $\Sigma < 0.12 \text{ eV}$ (95% C. L.) is set by a newer analysis (N. Palanque-Delabrouille *et al.*, arXiv:1506.05976 [astro-ph.CO] (2015))

Implications for $m_{\beta\beta}$

It is possible to include the new constraints on Σ by considering:

$$\frac{(y - m_{\beta\beta}(\Sigma))^2}{(n\sigma[m_{\beta\beta}(\Sigma)])^2} + \frac{(\Sigma - \Sigma(0))^2}{(\Sigma_n - \Sigma(0))^2} < 1$$



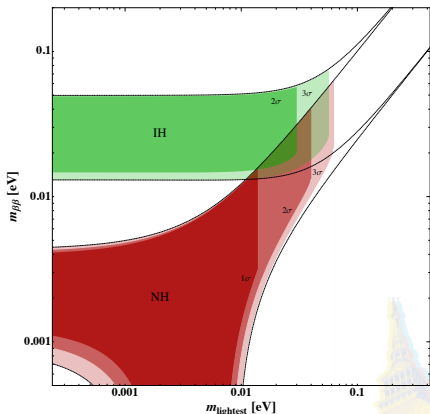
S. D., S. M., M. Viel, F. Vissani, arXiv:1505.02722 [hep-ph] (2015)

Allowed values for $m_{\beta\beta}$

$$\frac{(y - m_{\beta\beta}(m))^2}{(n\sigma[m_{\beta\beta}(m)])^2} + \frac{m^2}{m(\Sigma_n)^2} < 1$$

Mass spectrum	$m_{\beta\beta}^{\max}$ [meV] (C. L. on Σ)		
	1σ	2σ	3σ
\mathcal{NH}	16	41	64
\mathcal{IH}	-	57	75

The \mathcal{IH} region is excluded at 1σ



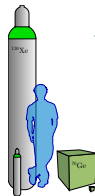
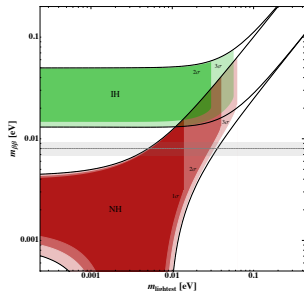
S. D., S. M., M. Viel, F. Vissani, arXiv:1505.02722 [hep-ph] (2015)

Future prospects

- the next generation of $0\nu\beta\beta$ experiments will probe the region $m_{\beta\beta} > 70$ meV
- let us require a sensitivity $m_{\beta\beta} = 8$ meV (hierarchy discrimination)
 - $M \cdot T \cdot B \cdot \Delta \lesssim 1$ (0-bkg condition)
 - $M \cdot T = \frac{\mathcal{M}_A \cdot t^{1/2}}{\ln 2 \cdot N_A}$

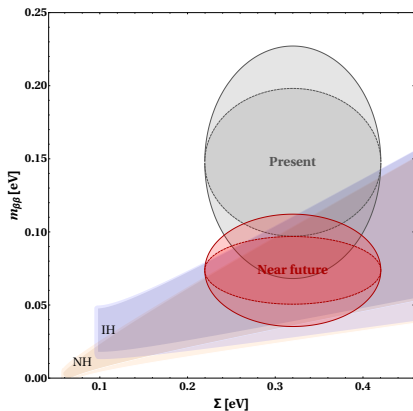
Isotope	$t^{1/2}$ [yr]	Exposure [ton · yr]	$(B \cdot \Delta)_{0\text{-bkg}}$ [$\text{kg}^{-1} \cdot \text{yr}^{-1}$]
^{76}Ge	$2.3 \cdot 10^{28}$	4.1	$2.4 \cdot 10^{-4}$
^{130}Te	$6.8 \cdot 10^{27}$	2.1	$4.7 \cdot 10^{-4}$
^{136}Xe	$9.7 \cdot 10^{27}$	3.2	$3.2 \cdot 10^{-4}$

obs. the quenching of g_A would worsen the situation very much



Ton or multi-ton scale detectors will be needed

The case of non-null Σ best fit



- some studies suggest a non-null best fit value for Σ in the range (0.3-0.4) eV
- let us suppose that Σ and $m_{\beta\beta}$ are measured with non zero values
- we assume $\Sigma = (0.320 \pm 0.081)$ eV
(R. Battye and A. Moss, *Phys. Rev. Lett.* 112, 051303, (2014))
- we consider the present [3] and the forthcoming future [5] sensitivities
- the statistical contribution to the determination of $m_{\beta\beta}$ cannot be neglected ($\delta N_s/N_s = \delta t^{1/2}/t^{1/2}$)

There is the opportunity to learn something on Majorana phases!

Heavy neutrino(s) exchange

- the observation of a $0\nu\beta\beta$ signal in the next generation of experiments would indicate that some other mechanisms compatible with a faster decay rate are at work
- heavy neutrinos compatible with the seesaw Type I could constitute a valid candidate (M. Mitra et al., Nucl. Phys. B 856, 26 (2012))
- the radiative stability of the tree-level neutrino masses implies that the heavy neutrino masses cannot exceed ~ 10 GeV

Let us consider a more general expression for the $0\nu\beta\beta$ half-life:

$$[t^{1/2}]^{-1} = \mathcal{G}_{0\nu} \left| \mathcal{M}_{0\nu} \sum_{i=1}^3 U_{ei}^2 \frac{m_i}{m_e} + \mathcal{M}_{0N} \sum_I V_{ei}^2 \frac{m_p}{m_I} \right|^2$$



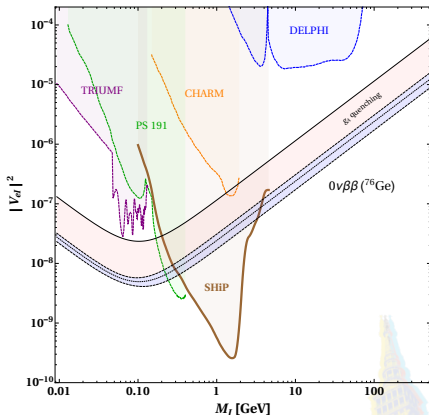
Mixing vs. heavy neutrino mass

$$\left| \sum_I \frac{V_{eI}^2}{M_I} \right| < \frac{7.8 \cdot 10^{-8}}{m_p} \left[\frac{104}{\mathcal{M}_{\text{GeV}}} \right] \left[\frac{3 \cdot 10^{25} \text{ yr}}{t^{1/2}} \right]^{1/2}$$

- an appropriate parametrization is needed to match the heavy and light neutrino exchange regimes

(S. Kovalenko *et al.*, *Phys. Rev. D* 80, 073014 (2009))

- $0\nu\beta\beta$ provides very competitive limits in the search for heavy neutrinos
- theoretical uncertainties (in particular those from nuclear physics) still play a significant role

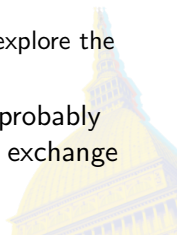


S. Alekhin *et al.*, arXiv:1504.04855 [hep-ph] (2015)

The interplay between $0\nu\beta\beta$ and searches at accelerators can be powerful!

Summary

- Thanks to the precise knowledge of the oscillation parameters, it is possible to stringently constrain $m_{\beta\beta}$
- Probing \mathcal{IH} will require a strong experimental effort, but experimental sensitivities are improving
- Cosmology is making impressive progress and it is producing stringent bounds on Σ
 - The \mathcal{IH} region is excluded at 1σ . A cautious attitude is anyway advisable
 - Ton or multi-ton scale detectors will be needed in order to explore the new $m_{\beta\beta}$ allowed region
- A $0\nu\beta\beta$ signal in the next generation experiments would probably mean new physics other than the light Majorana neutrino exchange





Possible quenching of g_A ?

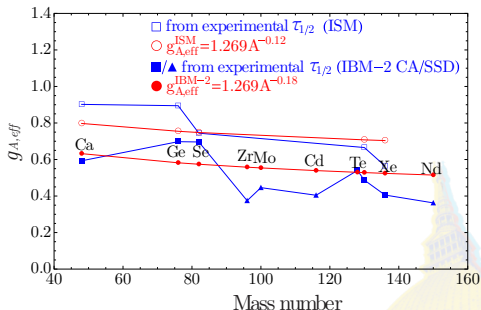
\mathcal{M}_i can be rewritten emphasizing the axial coupling g_A :

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

obs. since $2\nu\beta\beta$ has been observed in different nuclei, in this case we can write:

$$\mathcal{M}_{2\nu}(\text{exp.}) = \left(\frac{g_{A,\text{eff}}}{g_{A,\text{nucleon}}} \right)^2 \mathcal{M}_{2\nu,i}$$

where $g_{A,\text{nucleon}} \simeq 1.269$

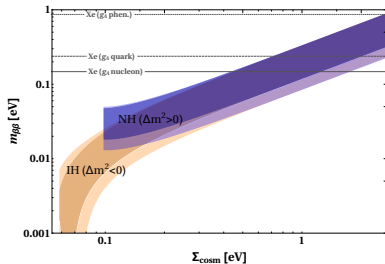


The effect of quenching on $0\nu\beta\beta$

$$t_i^{1/2} \sim \mathcal{M}_i^{-2} = g_A^{-4} \cdot \mathcal{M}_{0\nu,i}^{-2} *$$

A conservative treatment of the uncertainties should consider at least three cases: †

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



g_A	$m_{\beta\beta}^{\min}$ [eV]
$g_{A, \text{nucleon}}$	0.15 ± 0.03
$g_{A, \text{quark}}$	0.24 ± 0.05
$g_{A, \text{phen.}}$	0.87 ± 0.17

* Other studies suggest that the NME dependence on g_A should be milder than quadratic (E. Lisi *et al.*, arXiv:1506.04058 [hep-ph] (2015))

† S. D., S. M., F. Vissani, *Phys. Rev. D* **90**, 033005 (2014)

NMEs: J. Barea *et al.*, *Phys. Rev. C* **91**, 034304 (2015)

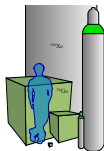
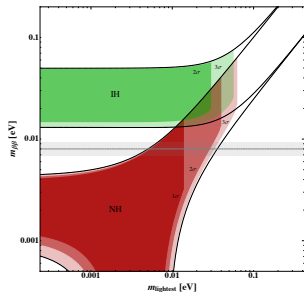
PSFs: J. Kotila & F. Iachello, *Phys. Rev. C* **85**, 034316 (2012)

The issue of the coupling of the nucleons in the nuclear medium is still open!

(More pessimistic) future prospects

- let us still require a sensitivity $m_{\beta\beta} = 8 \text{ meV}$ (hierarchy discrimination)
- we consider the case of unquenched and maximally quenched g_A

Isotope	$t^{1/2}$ [yr]	Exposure [ton · yr]	$(B \cdot \Delta)_{0\text{-bkg}}$ [$\text{kg}^{-1} \cdot \text{yr}^{-1}$]
$g_A, \text{nucleon}$			
^{76}Ge	$2.3 \cdot 10^{28}$	4.1	$2.4 \cdot 10^{-4}$
^{130}Te	$6.8 \cdot 10^{27}$	2.1	$4.7 \cdot 10^{-4}$
^{136}Xe	$9.7 \cdot 10^{27}$	3.2	$3.2 \cdot 10^{-4}$
$g_A, \text{phen.}$			
^{76}Ge	$5.1 \cdot 10^{29}$	93	$1.1 \cdot 10^{-5}$
^{130}Te	$2.3 \cdot 10^{29}$	71	$1.4 \cdot 10^{-5}$
^{136}Xe	$3.3 \cdot 10^{29}$	109	$9.2 \cdot 10^{-6}$



Many-ton scale detectors would be needed!

Confidence intervals

- we use the definition of likelihood function:

$$\mathcal{L} \propto \exp -(\Delta\chi^2/2)$$

- left side:*

$$\Delta\chi^2 = \frac{(y - m_{\beta\beta}(0))^2}{(\delta m_{\beta\beta}(0))^2} + \frac{(\Sigma - \Sigma(0))^2}{(\delta \Sigma(0))^2} = \sigma^2$$

where $m_{\beta\beta}(0) = m_{\beta\beta}(\Sigma = 0)$

- right side:*

$$\Delta\chi^2 = \frac{(y - m_{\beta\beta}(\Sigma))^2}{(n \sigma[m_{\beta\beta}(\Sigma)])^2} + \frac{(\Sigma - \Sigma(0))^2}{(\Sigma_n - \Sigma(0))^2} = 1$$

