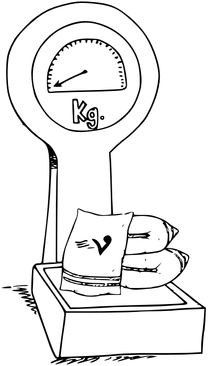
Brief overview of

# neutrino mass measurements

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*Third International Meeting*
*for Large Neutrino Infrastructures*

May 31, 2016 - KEK, Tsukuba, Japan

# Outline

See Valerius' talk

See Bellini, Inoue & Piepke's talks

See Murayama's talks

Review on direct measurement: G. Drexlin *et al.*, **Adv. High En. Phys. 2013, 293986**
Review on $0\nu\beta\beta$: S. D., S. Marcocci, M. Viel, F. Vissani, **Adv. High En. Phys. 2016, 2162659**

# What we (don't) know about neutrino masses

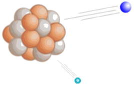
- what is the absolute neutrino mass scale?
- what is the neutrino mass ordering?
- what is the nature of the neutrino?
- what is the origin of neutrino masses?
- how many neutrinos besides the 3 known ones?


A starting point: thanks to oscillations,
we know that neutrinos have masses

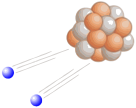
(Physics Nobel Prize 2015 to T. Kajita & A. B. McDonald)

# Assessing neutrino masses

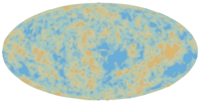
- direct measurement of neutrino mass



  - model independent: pure kinematics
  - sensitive to effective electron neutrino mass: $\langle m_\nu \rangle \equiv \sqrt{\sum_i |U_{ei}^2|\, m_i^2}$
- search for neutrinoless double beta decay



  - requires neutrinos to be Majorana particles
  - large theoretical uncertainties
  - sensitive to effective Majorana mass: $m_{\beta\beta} \equiv |\sum_i U_{ei}^2\, m_i|$
- cosmology



  - strong model dependence ($\Lambda$CDM, ...)
  - very stringent bounds
  - sensitive to sum of neutrino masses: $\Sigma \equiv \sum_i m_i$

# 3-flavor oscillations

- we know 3 light neutrinos: $\nu_e$, $\nu_\mu$ and $\nu_\tau$*
- the flavor eigenstates do not coincide with the mass eigenstates
  - it is possible to pass from the flavor basis to the mass basis by setting

$$|\nu_\ell\rangle = \sum_{i=1}^{3} U^*_{\ell i}\ |\nu_i\rangle$$

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

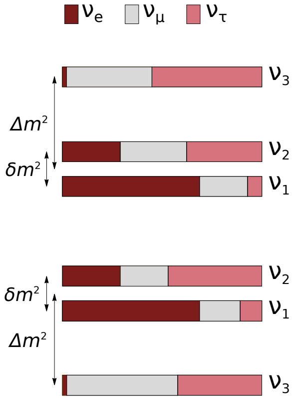
  $s_{ij}, c_{ij} \equiv \sin\theta_{ij}, \cos\theta_{ij}, \quad \phi =$ CP-violating phase

- $\delta m^2 = m_2^2 - m_1^2, \quad \Delta m^2 = m_3^2 - \dfrac{m_1^2 + m_2^2}{2}$

* These will be the only considered ones throughout this work.

# Oscillation parameters

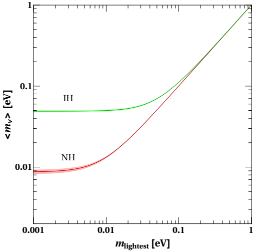
| Parameter | Best fit | $3\sigma$ range |
|---|---|---|
| NH | | |
| $\sin^2(\theta_{12})$ | $2.97 \cdot 10^{-1}$ | $(2.50 - 3.54) \cdot 10^{-1}$ |
| $\sin^2(\theta_{13})$ | $2.14 \cdot 10^{-2}$ | $(1.85 - 2.46) \cdot 10^{-2}$ |
| $\sin^2(\theta_{23})$ | $4.37 \cdot 10^{-1}$ | $(3.79 - 6.16) \cdot 10^{-1}$ |
| $\delta m^2$ [eV$^2$] | $7.37 \cdot 10^{-5}$ | $(6.93 - 7.97) \cdot 10^{-5}$ |
| $\Delta m^2$ [eV$^2$] | $2.50 \cdot 10^{-3}$ | $(2.37 - 2.63) \cdot 10^{-3}$ |
| IH | | |
| $\sin^2(\theta_{12})$ | $2.97 \cdot 10^{-1}$ | $(2.50 - 3.54) \cdot 10^{-1}$ |
| $\sin^2(\theta_{13})$ | $2.18 \cdot 10^{-2}$ | $(1.86 - 2.48) \cdot 10^{-2}$ |
| $\sin^2(\theta_{23})$ | $5.69 \cdot 10^{-1}$ | $(3.83 - 6.37) \cdot 10^{-1}$ |
| $\delta m^2$ [eV$^2$] | $7.37 \cdot 10^{-5}$ | $(6.93 - 7.97) \cdot 10^{-5}$ |
| $\Delta m^2$ [eV$^2$] | $2.46 \cdot 10^{-3}$ | $(2.33 - 2.60) \cdot 10^{-3}$ |




F. Capozzi *et al.* **Nucl. Phys. B 908, 218 (2016)**

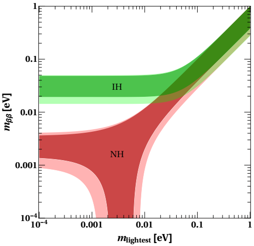
# Constraints from oscillations

## Direct measurement




$$\langle m_\nu \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}^2| \, m_i^2}$$

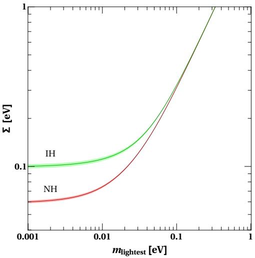
## Search for $0\nu\beta\beta$




$$m_{\beta\beta} = \left|\sum_{i=1}^{3} U_{ei}^2 \; m_i\right|$$

- bands due to Majorana phases (free)

## Cosmology




$$\Sigma \equiv \sum_{i=1}^{3} m_i$$

# Direct neutrino mass determination

- neutrino mass by relativistic energy-momentum relationship
  $E^2 = p^2 + m^2 \quad \Rightarrow$ sensitive to neutrino mass squared
- 2 methods if investigation
  - time-of-flight measurements
    - requires very long base-lines $\Rightarrow$ very strong sources
    - only cataclysmic astrophysical events (e. g. core-collapse supernovae)
  - precision investigations of weak decays

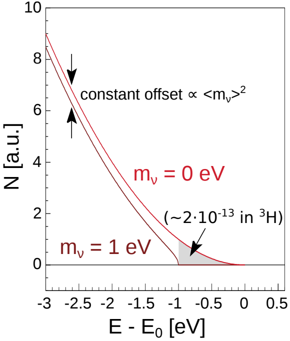
| Lepton | Mass limit (95% C. L.) | Reaction | Reference |
|---|---|---|---|
| $\nu_e$ | 2.05 eV | $^3H \rightarrow ^3He + e^- + \bar{\nu}_e$ | V. N. Aseev *et al.*, **Phys. Rev. D 84, 112003, (2011)** |
| $\nu_\mu$ | 0.17 MeV | $\pi^+ \rightarrow \mu^+ \nu_\mu$ | K. Assamagan *et al.*, **Phys. Rev. D 53, 6065, (1996)** |
| $\nu_\tau$ | 18.2 MeV | $\tau^- \rightarrow 2\pi^- \pi^+ \nu_\tau$<br>$\tau^- \rightarrow 3\pi^- 2\pi^+ (\pi^0) \nu_\tau$ | R. Barate *et al.*, **Eur. Phys. J. C 2, 395 (1998)** |

the most powerful way is the study of the $\beta$-decay spectrum

# $\beta$-decay and neutrino mass

- study of the *visible* energy of the decay
  - $\lambda = 2\pi \left|M\right|^2 \rho_f$ (Fermi Golden Rule)
  - $\frac{d\lambda}{dE} = (E_0 - E)\sqrt{(E_0 - E)^2 - \langle m_\nu \rangle^2}$

    $(E \equiv E_e - m_e, \quad E_0 \equiv \max(E) \text{ for } m_\nu = 0)$
- choice of an appropriate $\beta$-emitter
  - the total count rate rises strongly with $E_0$ (larger $e^-$ phase space)
  - the count rate in the region close to $E_0$ decreases with $E_0$
  - *experimentally*, it is easier to get better $\Delta E$ at lower energies

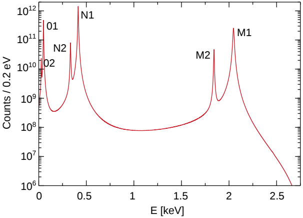



Requirements:

- low $E_0$
- short half-lives

# Candidate isotopes

- $^3$H: $^3\mathrm{H} \rightarrow {}^3\mathrm{He} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$ $(\beta^-)$
  - end-point: $E_0 = 18.6\,\mathrm{keV}$
  - half-life time: $12.3\,\mathrm{yr}$
    - super-allowed transition (no lepton carries away angular momentum)
    - rather simple electronic structure also for molecular $T_2$
- $^{163}$Ho: $^{163}\mathrm{Ho} + \mathrm{e}^- \rightarrow {}^{163}\mathrm{Dy} + \nu_\mathrm{e}$ $(EC)$
  - end-point: $E_0 = 2.83\,\mathrm{keV}$
  - half-life time: $4570\,\mathrm{yr}$
    - de-excitation spectrum of intermediate $^{163}\mathrm{Dy}^*$ ($\rightarrow$ series of lines)
- $^{187}$Re: $^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$ $(\beta^-)$
  - $E_0 = 2.47\,\mathrm{keV}$, $t^{1/2} = 4.3 \cdot 10^{10}\,\mathrm{yr}$




A. Nucciotti, **Adv. High En. Phys. 2016, 9153024**

# Experimental search

- task: resolve the tiny change of the spectral shape close to $E_0$

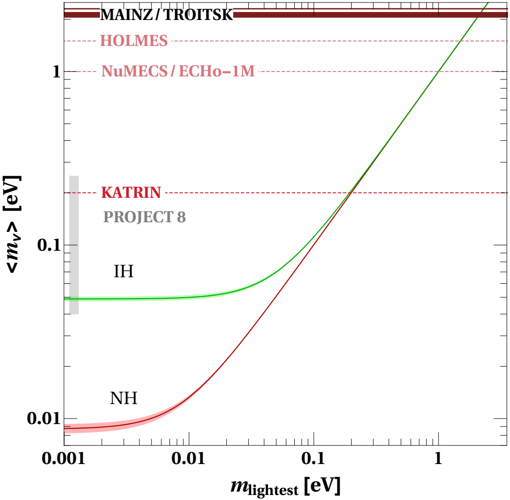
  $\Rightarrow$ tight requirements for a high sensitivity experiment

  - high energy resolution
  - low background rate
  - large $\beta$-decay source strength and acceptance

- experimental techniques

  - spectrometers ($^3$H) MAINZ TROITSK KATRIN
  - low temperature detectors ($^{187}$Re, $^{163}$Ho) MARE ECHo HOLMES NUMECS
  - microwave-antennas ($^3$H) PROJECT 8

# Sensitivity on $\langle m_\nu \rangle$



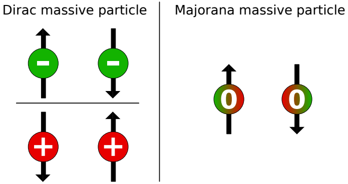

- present: $\sim 2\,\mathrm{eV}$
- near future: sub-eV region
- furhter future:

  hierarchy discrimination
  - R&Ds and new ideas

Osc. parameters: F. Capozzi *et al.*, **Nucl. Phys. B 908, 218 (2016)**

MAINZ: C. Kraus *et al.*, **Eur. Phys. J. C 40, 447 (2005)**
TROITSK: V. N. Aseev *et al.*, **Phys. Rev. D 84, 112003, (2011)**
KATRIN: J. Angrik *et al.*, *KATRIN design report 2004*
PROJECT 8: P. J. Doe *et al.*, `arXiv:1309.7093 [nucl-ex]` (2013)
ECHo: C. Enss, *Presentation at ECT* (2016)*
HOLMES: A. Nucciotti, **Adv. High En. Phys. 2016, 9153024**
NuMECS: A. Nucciotti, **Adv. High En. Phys. 2016, 9153024**

# Majorana neutrinos




- E. Majorana (1937):
  theory of massive and real fermions
  - $\chi = C\bar{\chi}^t \quad (\bar{\chi} \equiv \chi^\dagger\gamma_0, \quad C\gamma_0^t = 1)$
  - $\mathcal{L}_{\text{Majorana}} = \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - m)\chi$
  - $\chi(x) = \sum_{\mathbf{p},\lambda} [a(\mathbf{p}\lambda)\ \psi(x;\mathbf{p}\lambda) + a^*(\mathbf{p}\lambda)\ \psi^*(x;\mathbf{p}\lambda)]$

    $\rightarrow$ for any value of **p**, there are 2 helicity states: $|\mathbf{p}\uparrow\rangle$ and $|\mathbf{p}\downarrow\rangle$
- *L* will be violated by the presence of Majorana mass
- the Majorana hypothesis can be implemented in the SM
  - $\chi \equiv \psi_L + C\bar{\psi}_L^t$
  - to obtain the "usual" SM field: $\psi_L \equiv P_L\chi \qquad \left(P_L \equiv \frac{1-\gamma_5}{2}\right)$

# Effective Majorana mass

- the Majorana mass in the Lagrangian density can be written as

$$\mathcal{L}_{\text{mass}} = \frac{1}{2} \sum_{\ell,\ell'=\mathrm{e},\mu,\tau} \nu_\ell^t \, C^{-1} M_{\ell\ell'} \, \nu_{\ell'} + h.\,c.$$

- the only term that violates the electronic number by 2 units is $M_{\text{ee}}$
- diagonalization: $M = U^t \, \text{diag}(m_1, m_2, m_3) \, U^\dagger \qquad (U\,U^\dagger = 1)$
- in the $0\nu\beta\beta$ the observable is not $M_{\text{ee}}$, but just $|M_{\text{ee}}|$
  - 1 CP-violating + 2 new *physical* phases (Majorana phases)
  - we can rewrite: $m_{\beta\beta} = |M_{\text{ee}}| = \left| \sum_{i=1}^{3} \mathrm{e}^{i\xi_i} \; |U_{\mathrm{e}i}^2| \; m_i \right|$
  - $U \equiv U|_{\text{osc.}} \cdot \text{diag}\left(1,\, \mathrm{e}^{-i\xi_2/2},\, \mathrm{e}^{i\phi - i\xi_3/2}\right)$

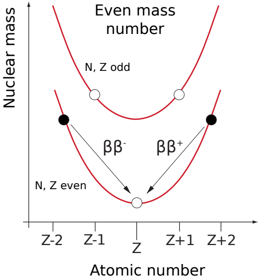
    $\rightarrow$ recall that oscillations cannot probe the Majorana phases

# $0\nu\beta\beta$ half-life time

- $0\nu\beta\beta$ is first of all a nuclear process
  - 2nd order transition: $(A, Z) \rightarrow (A, Z + 2)$
  - even-even nuclei: $\beta$-decay can be suppressed
- half-life expression can be factorized as

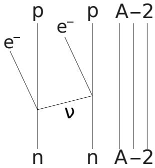
$$\left[t_{0\nu}^{1/2}\right]^{-1} = G_{0\nu}\,|\mathcal{M}|^2\,|f(m_i, U_{ei})|^2$$

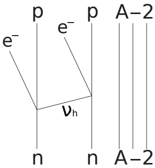
  - $G_{0\nu}$ = phase space factor (atomic physics)
  - $\mathcal{M}$ = nuclear matrix element (nuclear physics)
  - $f(m_i, U_{ei})$ = mechanism (particle physics)



# (Some) particle physics mechanisms

$$\left[t_{0\nu}^{1/2}\right]^{-1} = G_{0\nu}\,|\mathcal{M}|^2\,|f(m_i, U_{ei})|^2$$




- light neutrino exchange:

$$f(m_i, U_{ei}) \equiv \frac{m_{\beta\beta}}{m_e} = \frac{1}{m_e}\left|\sum_{i=1,2,3} U_{ei}^2 m_i\right|$$

- heavy neutrino exchange:

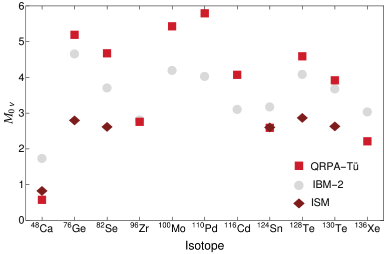
$$f(m_i, U_{ei}) \equiv m_p \left\langle M_H^{-1}\right\rangle = m_p \left|\sum_{I=\text{heavy}} U_{eI}^2 \frac{1}{M_I}\right|$$

- ...

# Models for the nuclear matrix elements

- Nucleus = p and n interacting, bound in a potential well
  - definition of the valence space
  - derivation of an effective Hamiltonian
  - ground state wave functions by solving the equations of motion
- different theoretical models
  - Quasiparticle Random Phase Approximation
  - Intermediate Boson Model
  - Interacting Shell Model
  - ...

QRPA / IBM-2 within ∼ 30%




QRPA-Tü: F. Šimkovic *et al.*, **Phys. Rev. C 87, 045501 (2013)**
IBM-2: J. Barea *et al.*, **Phys. Rev. C 91, 034304 (2015)**
ISM: J. Menéndez *et al.*, **Nucl. Phys. A 818, 139 (2009)**

# Assessing the uncertainties

- a convenient parametrization for the NME can be:

$$\mathcal{M} \equiv g_A^2\, \mathcal{M}_{0\nu} = g_A^2 \left( \mathcal{M}_{GT}^{(0\nu)} - \left(\frac{g_V}{g_A}\right)^2 \mathcal{M}_F^{(0\nu)} + \mathcal{M}_T^{(0\nu)} \right)$$

  - $\mathcal{M}_{0\nu}$ mildly depends on $g_A$
  - relatively small intrinsic error of $\sim 20\%$
  - still hard to give an overall error including all the models
- differences between calculations and rates $\gg 20\%$ for other processes "similar" to $0\nu\beta\beta$ ($\beta$, $EC$, $2\nu\beta\beta$)
- important role of $g_A$
  - any uncertainty on its values $\Rightarrow$ a larger uncertainty factor on $\mathcal{M}$

# Relevance of $g_A$ for the experimental searches

- $\left[t_{0\nu}^{1/2}\right]^{-1} = g_A^4\, G_{0\nu}\, |\mathcal{M}_{0\nu}|^2\, |f(m_i, U_{ei})|^2$
- let us suppose that the axial coupling in the nuclear medium is decreased by a factor $\delta$: $g_A \to g_A \cdot (1-\delta)$
- the expected decay rate ($\Rightarrow$ the number of signal events $S$) will also decrease: $S \to S \cdot (1-\delta)^4$
- compensation by increasing the time of data taking $T$
  - but $\frac{S}{\sqrt{B}} \sim \sqrt{T}$ (statistical significance of the measurement)
  - $T \to (1-\delta)^{-8}\, T$
- example: $\delta = 10\%\ (20\%) \quad \Rightarrow \quad T' = 2.3\ (6)\, T$

# Size of $g_A$

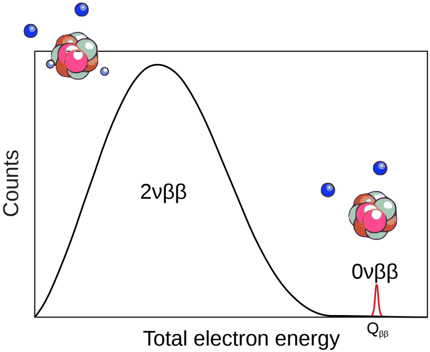
- $g_A \simeq 1.27$ in weak interactions and decays of nucleons (measured)
- *renormalization* in nuclear medium, value appropriate for quarks
- *strong quenching*: $g_A < 1$
  - limited model space of the calculation
  - contribution of non-nucleonic degrees of freedom
  - renormalization of the GT operator due to two-body currents
- still unknown if the quenching in $0\nu\beta\beta$ and $2\nu\beta\beta$ is the same

a conservative description of the uncertainty
should consider (at least) the 3 cases:

$$g_A \overset{?}{=} \begin{cases} g_{A,\,\text{nucleon}} & = 1.269 \\ g_{A,\,\text{quark}} & = 1 \\ g_{A,\,\text{phen.}} & = 1.269 \cdot A^{-0.18} \quad \text{(fit from } 2\nu\beta\beta) \end{cases}$$

# $0\nu\beta\beta$ signature

- detection of the 2 emitted $e^-$
  - monochromatic peak at $Q_{\beta\beta}$
- background events in the region of interest can mask the $0\nu\beta\beta$ signal
  - cosmic rays
    $\Rightarrow$ go underground
  - environmental radioactivity
  - $2\nu\beta\beta$ (unavoidable)

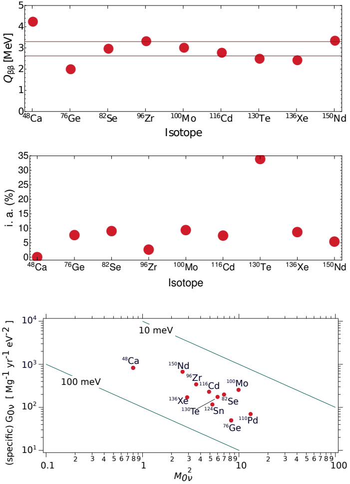



$$(A, Z) \to (A, Z+2) + 2e^-$$

# Choice of the isotope

- high $Q_{\beta\beta} \rightarrow$ influences the bkg
  - 2.6 MeV $\gamma$-line from $^{208}$Tl
  - 3.3 MeV $\beta$-line from $^{214}$Bi
- high isotopic abundance
  - ease of enrichment
- compatibility with a suitable detection technique
- maximization of PSF and NME
  - no preferred isotope ...

$^{48}$Ca $^{76}$Ge $^{82}$Se $^{96}$Zr $^{100}$Mo
$^{116}$Cd $^{130}$Te $^{136}$Xe $^{150}$Nd




R. G. H. Robertson, **Mod. Phys. Lett. A 28, 1350021 (2013)**

# Half-life time Sensitivity

- in the (fortunate) event of a peak in the energy spectrum

$$t_{0\nu}^{1/2} = \ln 2 \cdot T \cdot \varepsilon \cdot \frac{N_{\beta\beta}}{N_{\mathrm{peak}}} \qquad \left( \frac{\delta t_{0\nu}^{1/2}}{t_{0\nu}^{1/2}} = \frac{\delta N_{\mathrm{peak}}}{N_{\mathrm{peak}}} \right)$$

- if no peak is detected*

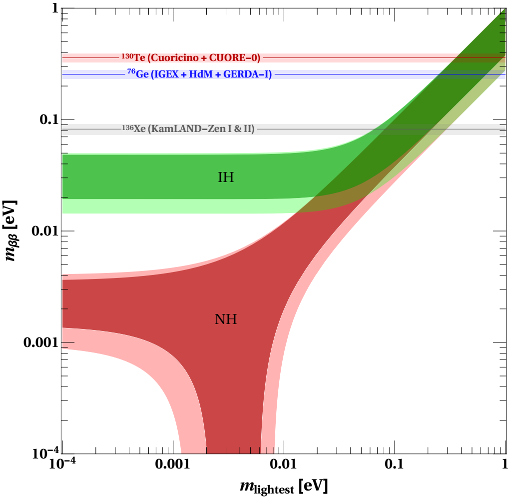
$$S_{0\nu}^{1/2} = \ln 2 \cdot T \cdot \varepsilon \cdot \frac{n_{\beta\beta}}{n_\sigma \cdot n_B} = \ln 2 \cdot \varepsilon \cdot \frac{1}{n_\sigma} \cdot \frac{x\,\eta\,N_A}{\mathcal{M}_A} \cdot \sqrt{\frac{M\,T}{B\,\Delta}}$$

  - *zero background* condition: $M\ T\ B\ \Delta \lesssim 1$

$$S_{0\nu,\,0B}^{1/2} = \ln 2 \cdot T \cdot \varepsilon \cdot \frac{N_{\beta\beta}}{n_\sigma \cdot n_B} = \ln 2 \cdot \varepsilon \cdot \frac{x\,\eta\,N_A}{\mathcal{M}_A} \cdot \frac{M\,T}{N_{\mathrm{s}}}$$

* the sensitivity is defined as the process half-life corresponding to the maximum signal that could be hidden by the bkg fluctuations $n_B$

# Experimental limits on $m_{\beta\beta}$




$$m_{\beta\beta} \leq \frac{m_e}{g_A^2\, \mathcal{M}_{0\nu} \sqrt{G_{0\nu}\, S_{0\nu}^{1/2}}}$$

| Isotope | $S_{0\nu}^{1/2}$ (90% C. L.) [yr] | $m_{\beta\beta}^{\min}$ [eV] |
|---|---|---|
| $^{130}$Te | $4.0 \cdot 10^{24}$ | $0.36 \pm 0.03$ |
| $^{76}$Ge | $3.0 \cdot 10^{25}$ | $0.25 \pm 0.02$ |
| $^{136}$Xe | $1.1 \cdot 10^{26}$ | $0.08 \pm 0.01$ |

Osc. parameters: F. Capozzi *et al.*, **Nucl. Phys. B 908, 218 (2016)**
NMEs (IBM-2): J. Barea *et al.*, **Phys. Rev. C 91, 034304 (2015)**
PSFs: J. Kotila, F. Iachello, **Phys. Rev. C 85, 034316 (2012)**
$g_A = 1.269$

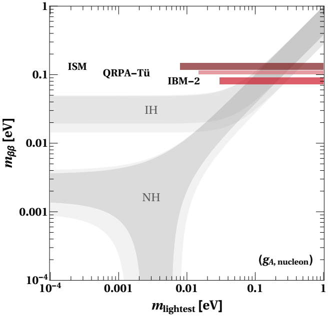
Experiment sensitivities:
$^{130}$Te: K. Alfonso *et al.*, **Phys. Rev. Lett. 115, 102502 (2015)**
$^{76}$Ge: M. Agostini *et al.*, **Phys. Rev. Lett. 111, 122503, (2013)**
$^{136}$Xe: A. Gando *et al.*, `arXiv:1605.02889 [hep-ex]` (2016)

# Near future sensitivity (summary)

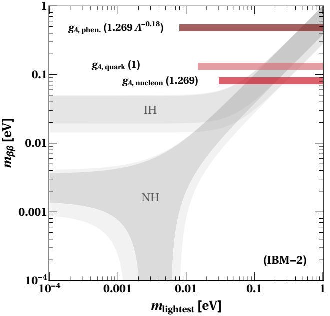
| Experiment | Isotope | $S_{0\nu}^{1/2}$ [yr] | $m_{\beta\beta}^{\min}$ [eV] | Reference |
|---|---|---|---|---|
| CUORE | $^{130}Te$ | $9.5 \cdot 10^{25}$ | $0.073 \pm 0.008$ | D. R. Artusa *et al.*, **Adv. High En. Phys. 2015, 879871** |
| GERDA-II | $^{76}Ge$ | $1.5 \cdot 10^{26}$ | $0.11 \pm 0.01$ | R. Brugnera and A. Garfagnini, **Adv. High En. Phys. 2013, 506186** |
| LUCIFER | $^{82}Se$ | $1.8 \cdot 10^{25}$ | $0.20 \pm 0.02$ | L. Pattavina, Presentation at TAUP 2015 |
| MAJORANA D. | $^{76}Ge$ | $1.2 \cdot 10^{26}$ | $0.13 \pm 0.01$ | N. Abgrall *et al.*, **Adv. High En. Phys. 2014, 365432** |
| NEXT | $^{136}Xe$ | $5.0 \cdot 10^{25}$ | $0.12 \pm 0.01$ | A. Laing, Presentation at TAUP 2015 |
| AMoRE | $^{100}Mo$ | $5.0 \cdot 10^{25}$ | $0.084 \pm 0.008$ | Y. H. Lim, Presentation at TAUP 2015 |
| nEXO | $^{136}Xe$ | $6.6 \cdot 10^{27}$ | $0.011 \pm 0.001$ | I. Ostrovsky, Presentation at TAUP 2015 |
| SNO+ | $^{130}Te$ | $9.0 \cdot 10^{25}$ | $0.076 \pm 0.007$ | S. Andringa *et al.*, **Adv. High En. Phys. 2016, 6194250** |
| SuperNEMO | $^{82}Se$ | $1.0 \cdot 10^{26}$ | $0.084 \pm 0.008$ | R. Arnold *et al.*, **Phys. Rev. D 92, 072011, (2015)** |

# Effect of the nuclear uncertainties: Xe case

- different NMEs / fixed $g_A$
  - $73\,\text{meV} < m_{\beta\beta} < 147\,\text{meV}$




- different $g_A$ / fixed NMEs
  - $73\,\text{meV} < m_{\beta\beta} < (147)\,535\,\text{meV}$

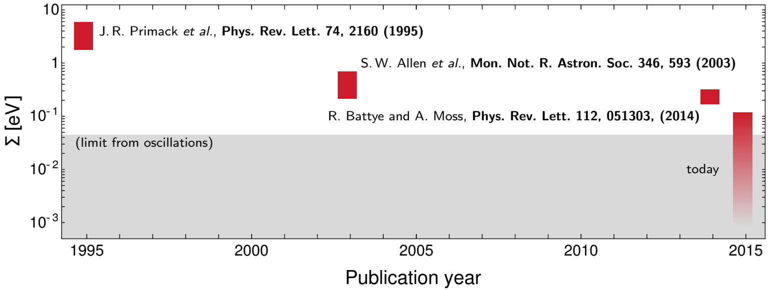



$$t_{0\nu}^{1/2} \propto \mathcal{M} = g_A^{-4}\mathcal{M}_{0\nu}^{-2}$$

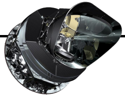
the main uncertainty consists in the determination of the "true value" of $g_A$

# Bounds on Σ: evolution

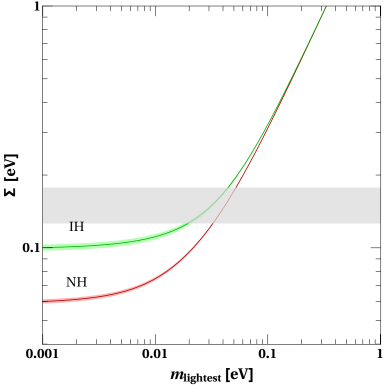
- cosmology is producing more and more stringent bounds on Σ
- requirements/evidences for $\Sigma \neq 0$ involve always smaller values
- today, the bound is pushed down to hundreds or tens of meV
- all the predictions are model dependent. A cautious attitude is advisable



# Bounds on Σ: today



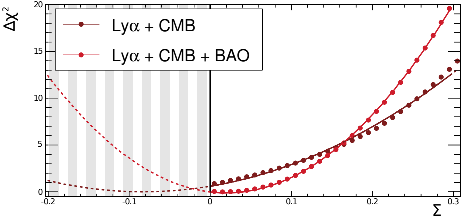
| $\Sigma^{max}$ (95% C. L.) | Reference |
|---|---|
| 153 meV | P. A. R. Ade *et al.* (Planck Collaboration), `arXiv:1502.01589 [astro-ph.CO]` (2015) |
| 130 meV | A. J. Cuesta *et al.*, **Phys. Dark Universe 13, 77 (2016)** |
| 126 meV | E. Di Valentino *et al.*, **Phys. Rev. D 93, 083527 (2016)** |
| 176 meV | E. Giusarma *et al.*, `arXiv:1605.04320 [astro-ph.CO]` (2016) |
| 120 meV | N. Palanque-Delabrouille *et al.*, **J. Cosm. Astropart. Phys. 1511, 011 (2015)** |
| 177 meV | X. Zhang, **Phys. Rev. D 93, 083011 (2016)** |




- data probing different scales (CMB, BAOs, Lyman-$\alpha$, lensing, ...)
- limits within the ΛCDM model

# Implication for the $0\nu\beta\beta$ search (I)

- $\Sigma < 140\,\text{meV}$ (95% C. L.) by combining different data:
  - Ly$\alpha$-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)**)




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

$$\begin{aligned} \Sigma &< 84\,\text{meV} & (1\sigma\ \text{C. L.}) \\ \Sigma &< 146\,\text{meV} & (2\sigma\ \text{C. L.}) \\ \Sigma &< 208\,\text{meV} & (3\sigma\ \text{C. L.}) \end{aligned}$$

N. Palanque-Delabrouille *et al.*, **J. Cosm. Astropart. Phys. 1502, 045 (2015)**

# Implication for the $0\nu\beta\beta$ search (II)

- $\Sigma = m_1 + m_2 + m_3$

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

  - NH: $a = \delta m^2$

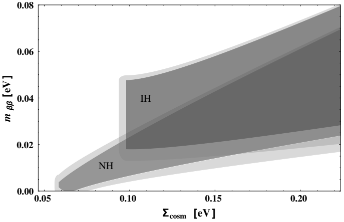
    $b = \Delta m^2 + \delta m^2/2$

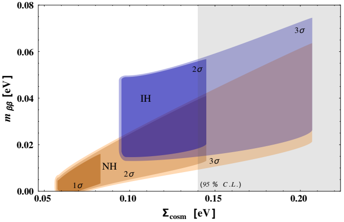
  - IH: $a = \Delta m^2 - \delta m^2/2$

    $b = \Delta m^2 + \delta m^2/2$

- it is possible to include the new constraints on $\Sigma$ by considering:

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

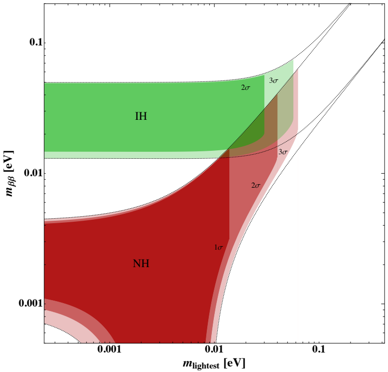


# Implication for the $0\nu\beta\beta$ search (III)

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

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



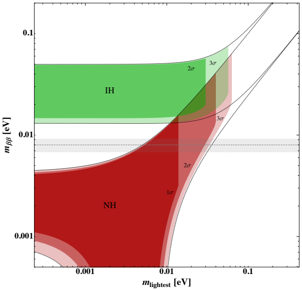

The IH region is excluded at $1\sigma$

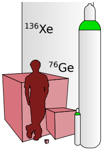
S. D., S. Marcocci, M. Viel, F. Vissani, **J. Cosm. Astropart. Phys. 1512, 023 (2015)**

# Further future prospects

- let us require a sensitivity $m_{\beta\beta} = 8\,\text{meV}$ (hierarchy discrimination)
  - $M\,T\,B\,\Delta \lesssim 1$ (zero bkg condition)
  - $t^{1/2}_{0\nu} \sim M\,T$

| Isotope | $t^{1/2}_{0\nu}$ [yr] | Exposure [ton · yr] | $(B \cdot \Delta)_{0B}$ [kg$^{-1}$ · yr$^{-1}$] |
|---|---|---|---|
| $g_A$, 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 | $3.2 \cdot 10^{-4}$ |
| $g_A$, 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 | $9.2 \cdot 10^{-6}$ |




Ton (many-ton) scale detectors would be needed!

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

# Summary

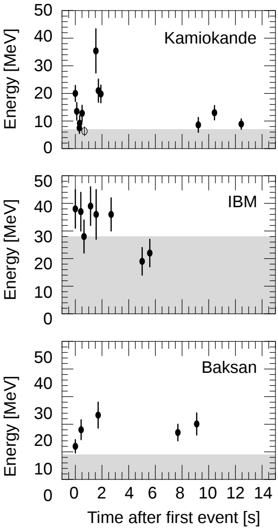
- a series of open question are still open concerning neutrino masses
- the direct measurement is the only model-independent approach to determine the neutrino mass value
  - we will soon enter the sub-eV mass region
- $0\nu\beta\beta$ is a unique tool to study $L$-violation and neutrino masses
  - we need a better understanding of the uncertainties (especially of $g_A$)
- cosmology is making impressive progress and it is producing stringent bounds on $\Sigma$
  - the $\mathrm{IH}$ region is excluded at $1\sigma$, but a cautious attitude is advisable
- probing $\mathrm{IH}$ will require a strong experimental effort for both the studies of $\beta$ and $0\nu\beta\beta$ decays, but the sensitivities are improving

# Neutrino mass limit from SN1987A

- 1987-02-23: detected $\nu$s from SN1987A (Large Magellanic Cloud, $L = 50\,\text{kpc}$)
  - $\bar{\nu}_e + p \rightarrow n + e^+$
- $\Delta t = L \dfrac{m^2}{2E^2}$ $\left(m^2 = E^2 - p^2 \rightarrow \beta = 1 - \frac{m^2}{2E^2}\right)$
  - expected hyperbolas $E$ *vs.* $\sqrt{t_{\text{arrival}}}$ for each $\nu_i$ if the emission is sharp
- bound on neutrino mass: 5.8 eV (95%C. L.)

(G. Pagliaroli *et al.*, **Astropart. Phys. 33, 287 (2010)**)

- main limiting factors: time and energy spectra of the neutrino emission of a core-collapse SN




G. Drexlin *et al.*, **Adv. High En. Phys. 2013, 293986**

# $L$-violation in the SM

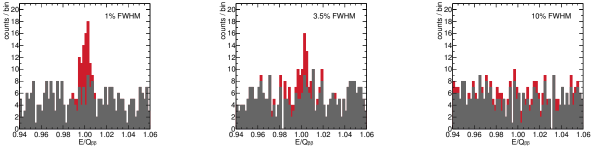
- in the SM language, the violation of $L$ (and $B$) can be expressed as:

$$\mathcal{H}_{\text{Weinberg}} = \frac{(l_L H)^2}{M} + \frac{l_L q_L q_L q_L}{M'^2} + \frac{(l_L q_L d_R^c)^2}{M''^5}$$

  - the first (dimension-5) operator generates Majorana neutrino masses ($m_\nu < 0.1\,\text{eV} \Rightarrow M < 10^{11}$ TeV)
  - the dimension-6 operator leads to proton decay ($\rightarrow M' > 10^{12}$ TeV)
  - the dimension-9 operator contribution can be relevant if the scale of $L$-violation is low ($\rightarrow M'' > 5\,\text{TeV}$)
- if the scale of new physics is $\gg$ than the electroweak scale
  $\rightarrow$ light neutrinos exchange "behind" a $L$-violating process

# $0\nu\beta\beta$ detector requirements

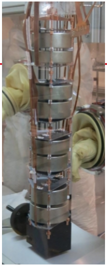
- good energy resolution
  - only protection against the bkg from the $2\nu\beta\beta$ spectrum tail



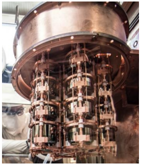

J. J. Gómez-Cadenas *et al.*, **PoS (GSSI2014), 004 (2015)**

- very low background
  - underground location
  - radio-pure materials for detector and surrounding parts ($(10^9$–$10^{10})$ yr from natural chains *vs.* $\gtrsim 10^{25}$ yr of $0\nu\beta\beta$)
- large isotope mass
  - present: some tens of kg up to a few hundreds kg
  - tons required to cover the IH region

# $0\nu\beta\beta$ search: experimental techniques (I)



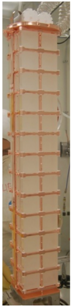
- Ge-diodes
  - high-purity
  - high-energy resolution

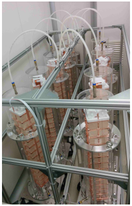


Heidelberg-Moscow IGEX

GERDA Majorana Demonstrator

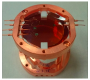
- bolometers
  - large source masses
  - good energy resolution (close to Ge-diodes)
  - many compounds with $0\nu\beta\beta$ emitters



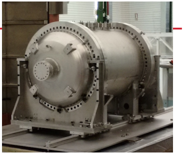


Cuoricino CUORE-0

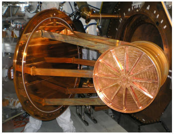
AMoRE LUCIFER CUORE



# $0\nu\beta\beta$ search: experimental techniques (II)

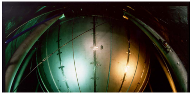


- Xe liquid and gaseous TPC
  - lower energy resolution
  - event topology reconstruction



EXO-200 NEXT nEXO

- liquid scintillators loaded with $0\nu\beta\beta$ isotope
  - poor energy resolution
  - huge amount of material
  - very low background



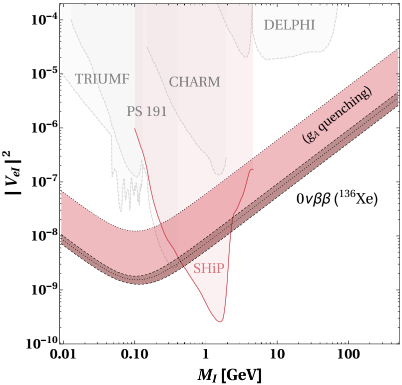
KamLAND-Zen SNO+

- tracker + calorimeter (external $0\nu\beta\beta$ source)
  - low energy resolution
  - large isotope masses hardly achievable
  - event topology reconstruction


NEMO-3 SuperNEMO

# Search at accelerators: mixing *vs.* heavy $\nu$ mass

- observation of a $0\nu\beta\beta$ signal in the next generation of experiments
  $\rightarrow$ other mechanisms with faster decay rate at work (e. g. Type I ss $\nu$s)
- $\left[t_{0\nu}^{1/2}\right]^{-1} = \mathcal{G}_{0\nu} \left| \mathcal{M}_{0\nu} \sum_{i=1}^{3} U_{ei}^2 \frac{m_i}{m_e} + \mathcal{M}_{0N} \sum_I V_{ei}^2 \frac{m_p}{M_I} \right|^2$
- $\left| \sum_I \frac{V_{eI}^2}{M_I} \right| < \frac{1.2 \cdot 10^{-8}}{m_p} \left[ \frac{67}{\mathcal{M}_{Xe}} \right] \left[ \frac{1.1 \cdot 10^{26}\ \mathrm{yr}}{t_{0\nu}^{1/2}} \right]^{1/2}$
- theoretical uncertainties (in particular those from nuclear physics) still play a significant role




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

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