Synergy between neutrinoless double-beta decay & cosmology

Towards the discovery of Majorana neutrinos

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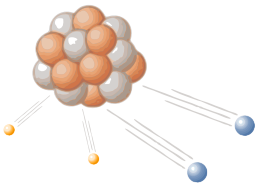
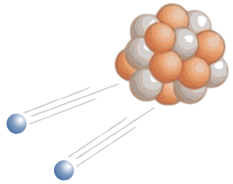
Double Beta Decay: real and virtual neutrinos



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

$$(A,Z) \rightarrow (A,Z+2) \; + \; 2e^- \quad (0\nu\beta\beta)$$



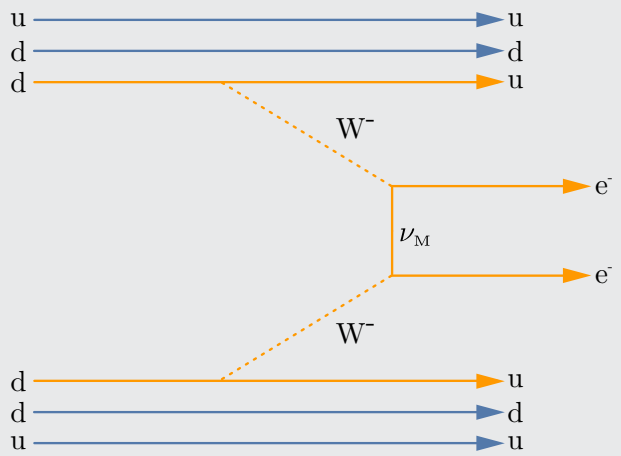
- L-violation: creation of a pair of electrons
  - discovery of $0\nu\beta\beta$

    $\Rightarrow$ L is not a symmetry of the universe

    $\Rightarrow$ link to baryon asymmetry in Universe (?)
- assume 3-ν exchange mechanism

  $\rightarrow$ $0\nu\beta\beta$ key tool for studying neutrinos
  - Majorana or Dirac nature
  - mass scale and ordering

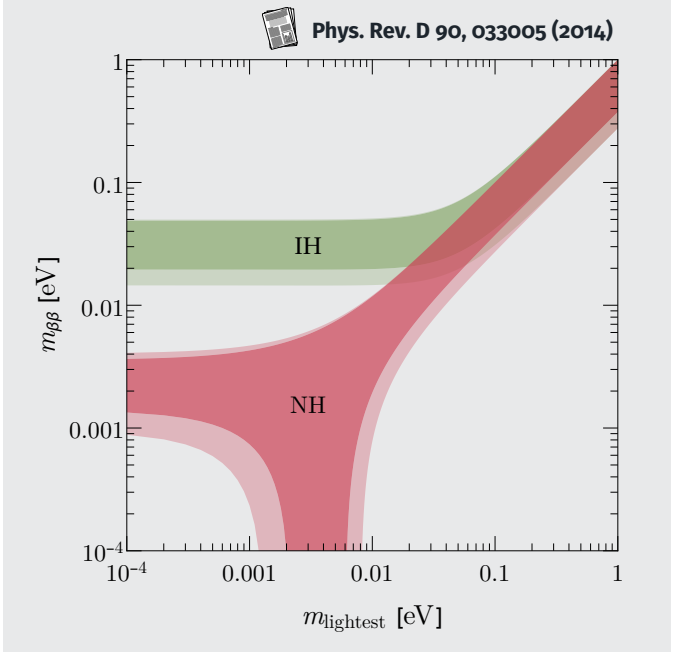
A possible diagram



Majorana effective mass

- $m_{\beta\beta}$ is the key quantity in 0νββ
  - absolute value of ee-entry of ν mass matrix
  - $m_{\beta\beta} \equiv |M_{ee}| = \left| \sum_{i=1,2,3} e^{i\xi_i} \, |U_{ei}^2| \, m_i \right|$
  - $U \equiv U|_{\text{osc.}} \cdot \text{diag}\left(e^{-i\xi_1/2}, e^{-i\xi_2/2}, e^{i\phi - i\xi_3/2}\right)$
    - 1 CP-violating + 3 Majorana phases
    - U mixing matrix of oscillation analysis
  - only two phases play a *physical* role

$m_{\beta\beta}$ vs. m_{lightest}



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

No definitive indication on definitive value of $m_{\beta\beta}$ from theory

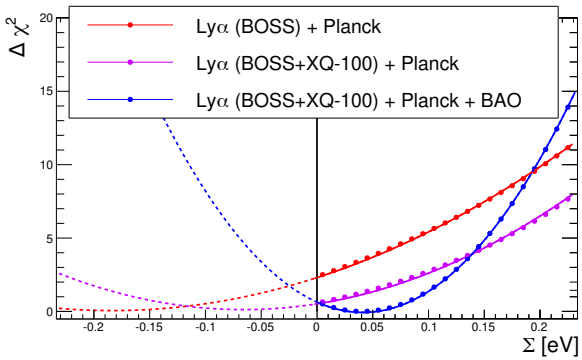
Need to exploit information from the experimental observations

Neutrino mass from cosmology

- Linear sum of ν masses: $\Sigma \equiv m_1 + m_2 + m_3 \quad \Rightarrow \quad \Sigma = m_l + \sqrt{m_l^2 + a} + \sqrt{m_l^2 + b}$

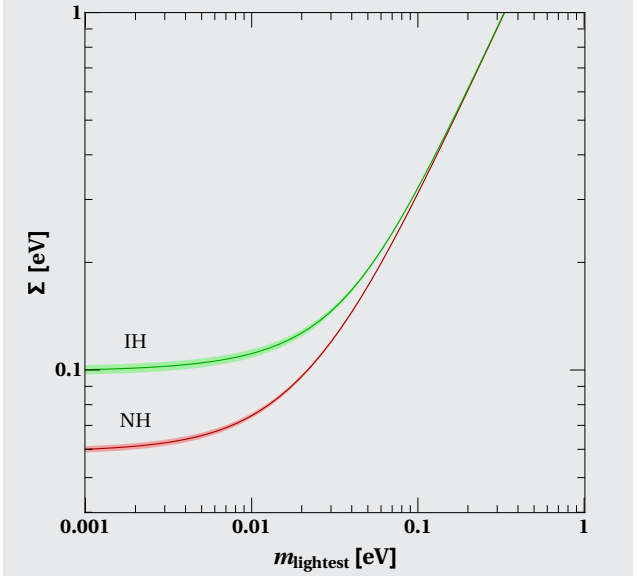
$$\text{where} \quad \text{NH:} \begin{cases} a = \delta m^2 \\ b = \Delta m^2 + \delta m^2/2 \end{cases} \quad \text{or} \quad \text{IH:} \begin{cases} a = \Delta m^2 - \delta m^2/2 \\ b = \Delta m^2 + \delta m^2/2 \end{cases}$$

- Limits of the order of 100 meV
  - from data probing different scales (CMB, Lyman-α, ...)
  - within the ΛCDM model
  - unavoidable systematics (*not* laboratory measurements)



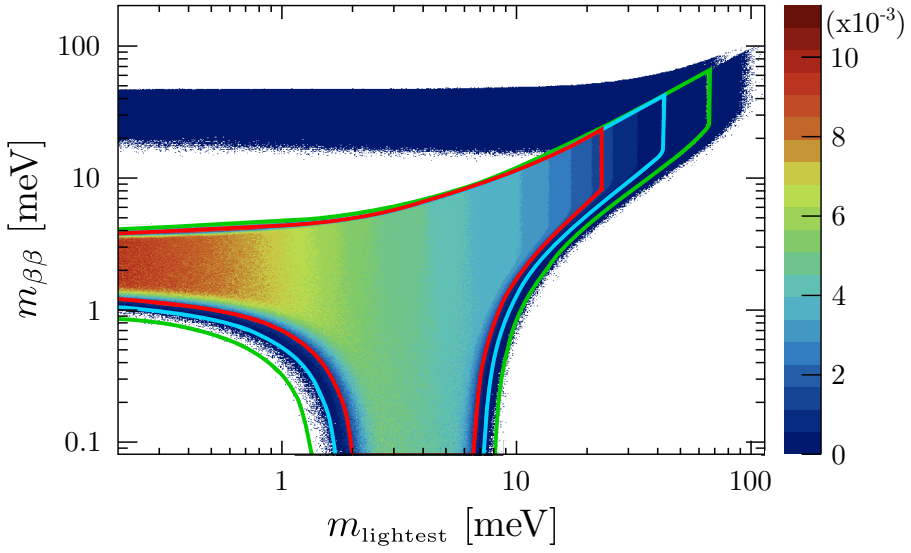
J. Cosmol. Astropart. Phys. 06, 047 (2017)

Σ vs. m_{lightest}

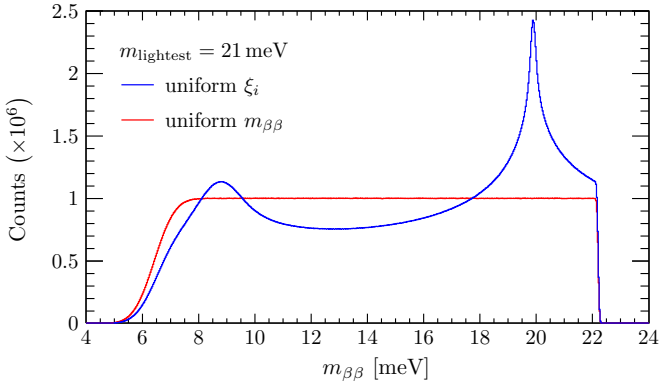


From Σ to $m_{\beta\beta}$

- extract value of m_{lightest}
  - (δm^2, Δm^2 from best-fit values)
  - $G(\Sigma) \propto \exp\left[-\frac{1}{2}\frac{(\Sigma-\bar{\Sigma})^2}{\delta\Sigma^2}\right]$
  - choice for mass ordering (NH preferred)



- generate compatible value of $m_{\beta\beta}$
  - limited by: $\begin{cases} m_{\beta\beta}^{\min} = \max\left\{2\left|U_{ei}^2\right|m_i - m_{\beta\beta}^{\max}, 0\right\} & i = 1,2,3 \\ m_{\beta\beta}^{\max} = \sum_{i=1}^{3}\left|U_{ei}^2\right|m_i \end{cases}$
  - select from possible *prior* distributions
    - non-negligible impact



Phys. Rev. D 96, 073001 (2017) Phys. Rev. D 96, 053001 (2017)

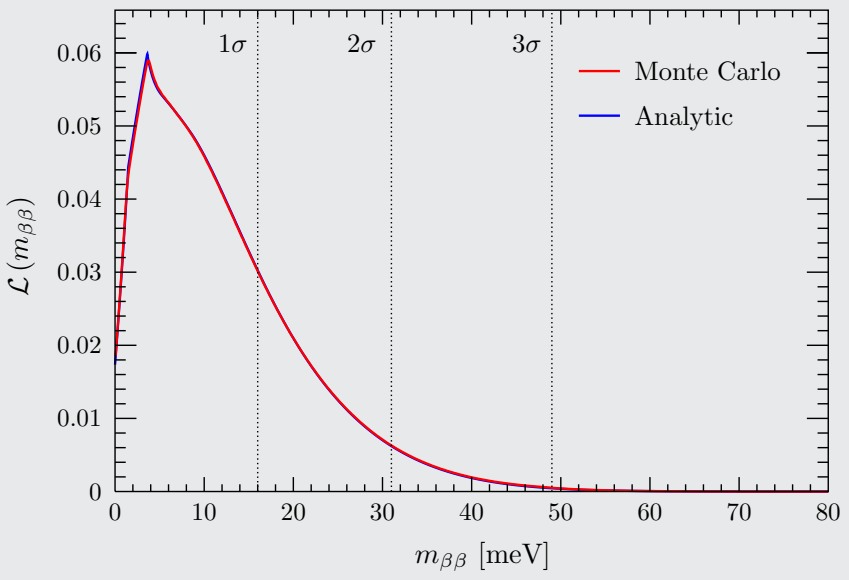
Phys. Rev. D 100, 073003 (2019)

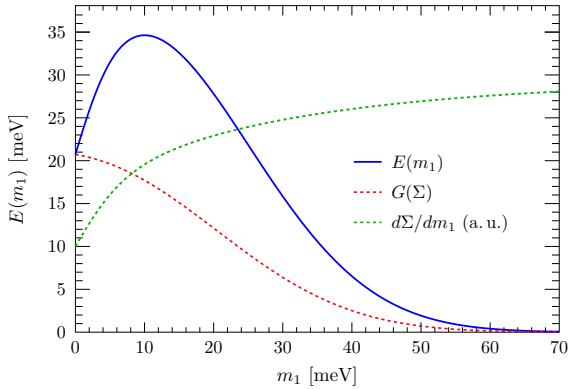
Density distribution

- consider NH case
- projection (integral over m_1)
  - mode around 4 meV
  - cuts: 16 meV (1σ) / 50 meV (3σ)
- OR equivalent analytic procedure
  - $d\mathcal{L}(\Sigma \mid \text{cosm}) = G(\Sigma)\, d\Sigma$
  - $d\mathcal{L}(m_1 \mid \text{cosm}) = G(\Sigma)\, \dfrac{d\Sigma}{dm_1}\, dm_1$
  - $d\mathcal{L}(m_{\beta\beta}, m_1) = d\mathcal{L}^{\text{prior}}(m_{\beta\beta}) \times d\mathcal{L}(m_1 \mid \text{cosm})$
  - $d\mathcal{L}(m_{\beta\beta} \mid \text{cosm}) = \displaystyle\int_{m_1^{\text{min}}(m_{\beta\beta})}^{m_1^{\text{max}}(m_{\beta\beta})} d\mathcal{L}(m_{\beta\beta}, m_1)\, dm_{\beta\beta}$

… let us now try to remove any need of priors

Differential $m_{\beta\beta}$ (posterior)





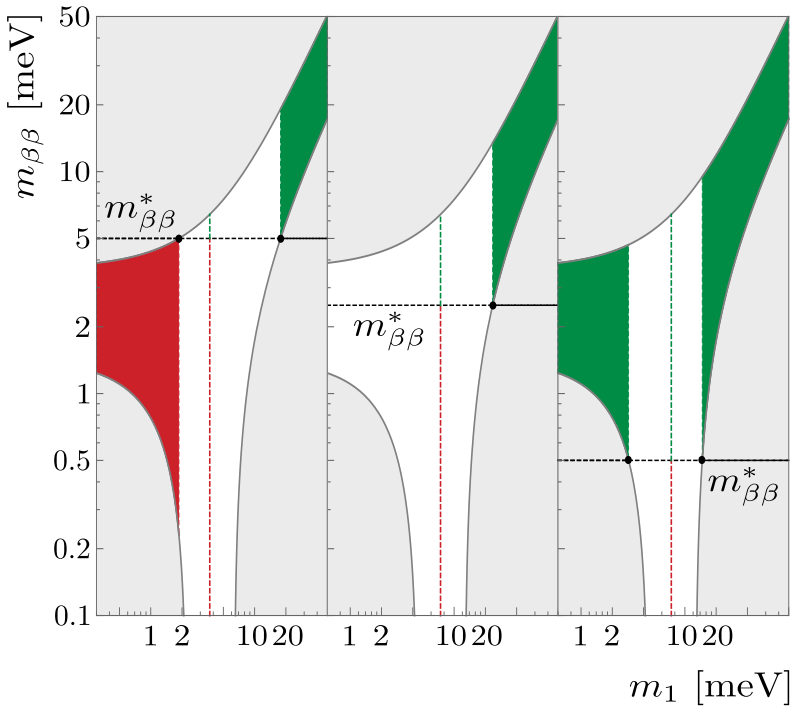
A different perspective

- whatever the *true value* of $m_{\beta\beta}$: $m_{\beta\beta}^{\min}(m_1) \leq m_{\beta\beta} \leq m_{\beta\beta}^{\max}(m_1)$
- we get $m_1^{\min}(m_{\beta\beta})$ and $m_1^{\max}(m_{\beta\beta})$
  - $m_1^{\min} = 0$ when $m_{\beta\beta}$ in $(1.4 - 3.7)$ meV

For an experiment of sensitivity $m_{\beta\beta}^*$

- $m_{\beta\beta}^* \geq m_{\beta\beta}^{\max}(m_1)$: inaccessibility
- $m_{\beta\beta}^* \leq m_{\beta\beta}^{\min}(m_1)$: observation
- $m_{\beta\beta}^{\min}(m_1) < m_{\beta\beta}^* < m_{\beta\beta}^{\max}(m_1)$: exploration
  - outcome depends on α_1, α_2

Phys. Rev. D 103, 033008 (2021)



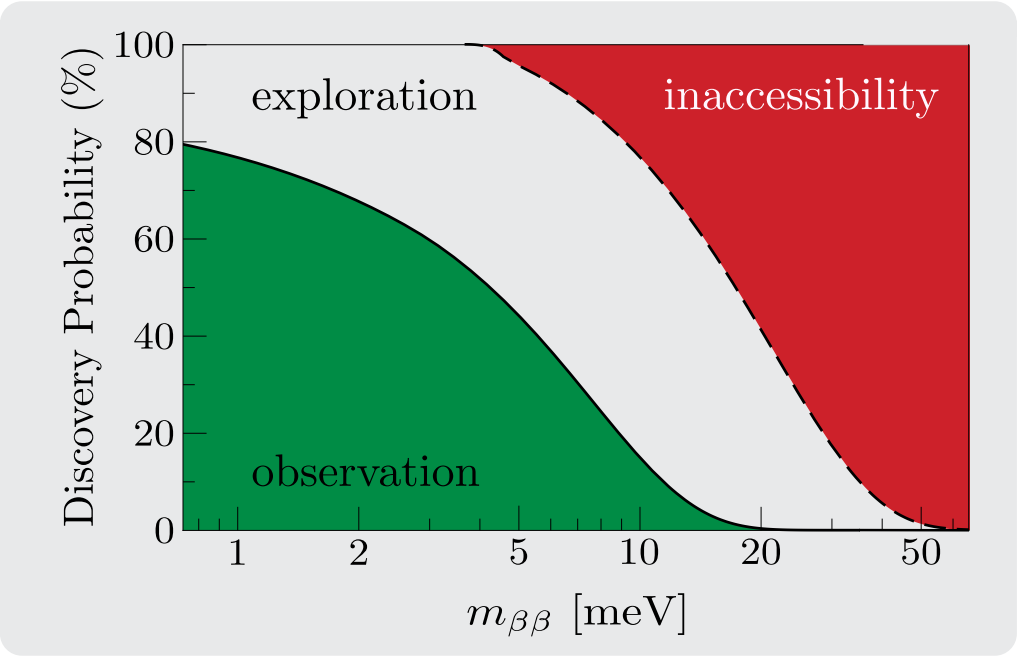
We can use the results of cosmology ...

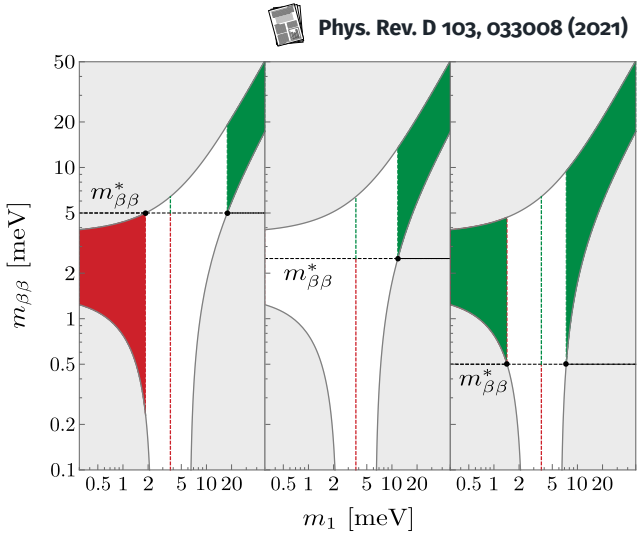
- let us approximate a constraint on Σ with a Gaussian pdf
  - parabolic chi-square: $\chi^2 \approx \dfrac{(\Sigma - \overline{\Sigma})^2}{(\delta\Sigma)^2}$
  - (today $\delta\Sigma$ is about 50 meV)
  - actual impact of functional form is $\sim$ 10%
- restrict to physical range $\Sigma \geq \Sigma_{\rm min} \equiv \Sigma(m_1 = 0)$ (i. e. $\sim$ 59 meV)
- obtain cumulative $F_{\boldsymbol{\Sigma}}(\Sigma) \equiv P(\boldsymbol{\Sigma} \leq \Sigma) = 1 - \dfrac{f(\Sigma)}{f(\Sigma_{\rm min})}$
  - $f(\Sigma) = \mathrm{erfc}\left(\dfrac{\Sigma - \overline{\Sigma}}{\sqrt{2}\,\delta\Sigma}\right)$

… to get the implications for double-beta decay

- convert distribution from Σ to $m_{\beta\beta}$
  - not univocal (Majorana phases)
  - defined for $m_{\beta\beta}^{\max}$ and $m_{\beta\beta}^{\min}$
- get discovery probabilities
  - $F_{\Sigma}^{\max} \equiv F_{\Sigma}\left(\Sigma\left(m_1^{\max}\left(m_{\beta\beta}^{*}\right)\right)\right)$
  - $F_{\Sigma}^{\min} \equiv F_{\Sigma}\left(\Sigma\left(m_1^{\min}\left(m_{\beta\beta}^{*}\right)\right)\right)$
    - $0 \leq F_{\Sigma}^{\min} < F_{\Sigma}^{\max} < 1$ (monotonic nondecreasing)
    - $0 \leq m_1^{\min} < m_1^{\max}$

A novel graphical representation!



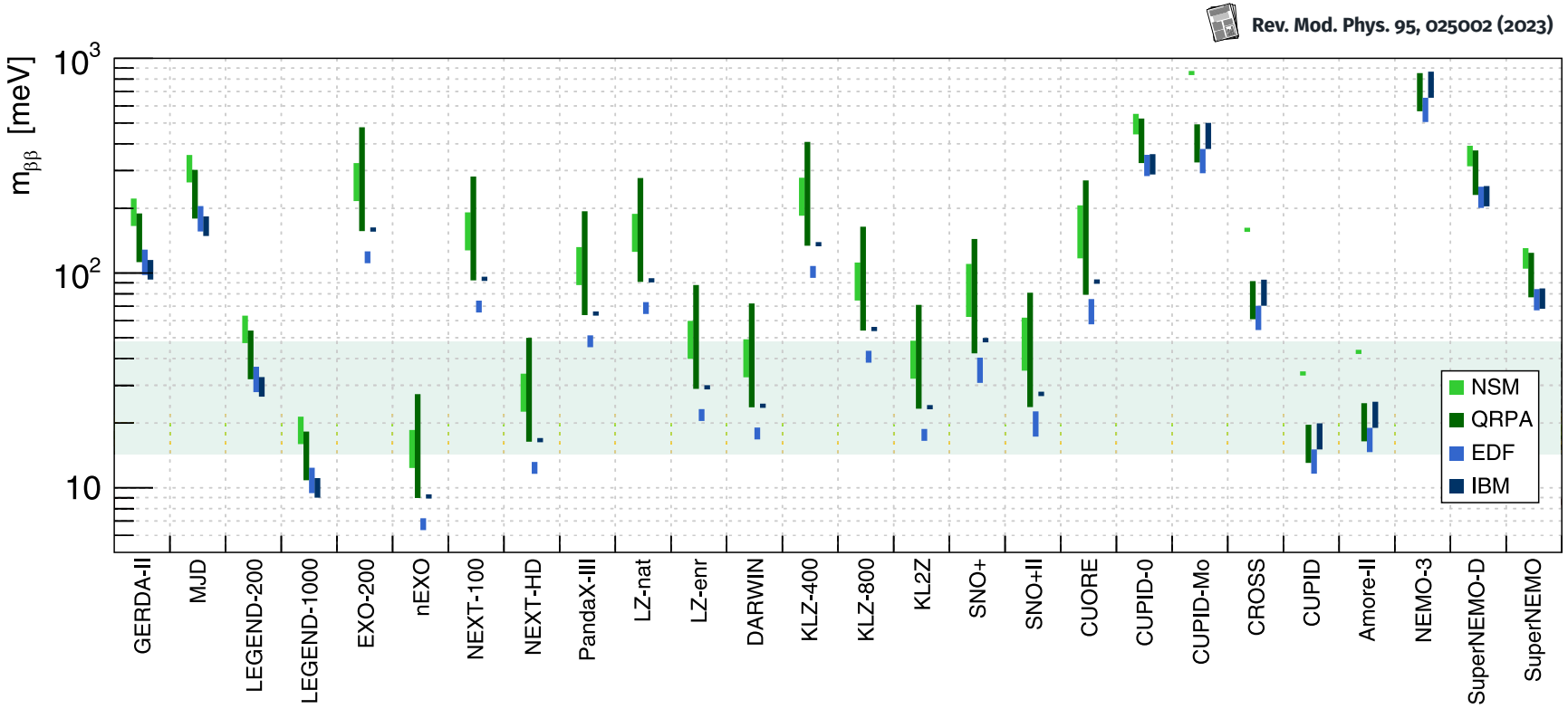


only underlying hypotheses

- 3 light neutrinos
- Majorana mass
- known Σ distribution (no priors)

$m^*_{\beta\beta}$	Inaccess.	Exploration	Observation
5.0 meV (L)	$F_\Sigma^{\min}$	$F_\Sigma^{\max} - F_\Sigma^{\min}$	$1 - F_\Sigma^{\max}$
2.5 meV (C)	0	$F_\Sigma^{\max}$	$1 - F_\Sigma^{\max}$
0.5 meV (R)	0	$F_\Sigma^{\max} - F_\Sigma^{\min}$	$1 - (F_\Sigma^{\max} - F_\Sigma^{\min})$

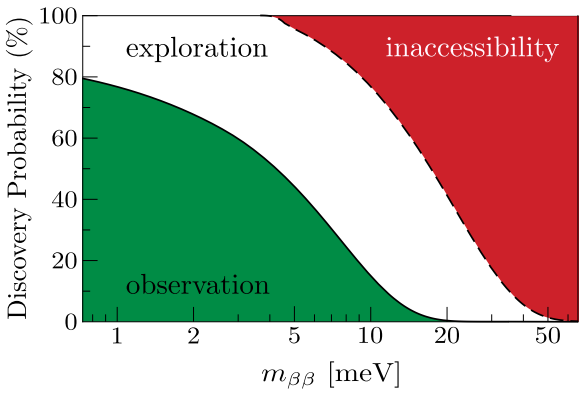
Present & future sensitivities



- present limit: $(36 - 156)$ meV [KLZ-2022] $\rightarrow$ future searches: $(6 - 20)$ meV
  - *bands* ($m_{\mathrm{lightest}} = 0$): IH: $(19 - 48)$ meV / NH: $(1.4 - 3.7)$ meV
- theoretical uncertainties mostly from nuclear physics

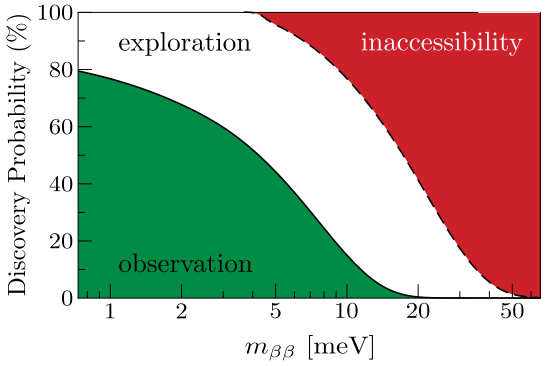
Discovery probability

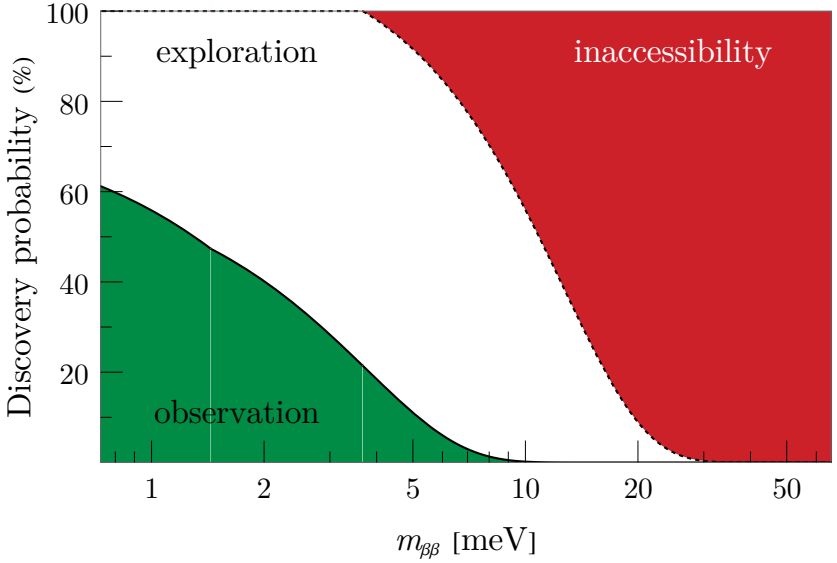
$m^*_{\beta\beta}$ [meV]		Inaccess.	Exploration	Observation
	50	98.7 %	1.3 %	0.0 %
(pres.)	35	89.7 %	10.3 %	0.0 %
	20	58.6 %	41.1 %	0.3 %
	15	41.9 %	55.1 %	3.0 %
	10	23.1 %	62.0 %	14.9 %
(future)	5	4.4 %	51.4 %	44.2 %
	2	0.0 %	32.3 %	67.7 %
	0	0.0 %	12.4 %	87.6 %



- today we see limited possibility of observation
- next-generation 0νββ experiments will have much larger room for a signal
- even *ultimate* experiment at sub-meV gets $\sim$ 20% probability in exploration
  - canceling α_1, $\alpha_2 \to \Sigma$ in the interval (61.4–67.5) meV

Tighter bounds from cosmology





- forthcoming cosmological investigation will push $\delta\Sigma$ down to $\sim$ 20 meV
- let us assume the minimal value of Σ compatible with oscillations
  - we take $\Sigma = \Sigma_{\text{min}}$ (59 meV)
- *broadening* of the exploration region at the expense of the observation region

Summary

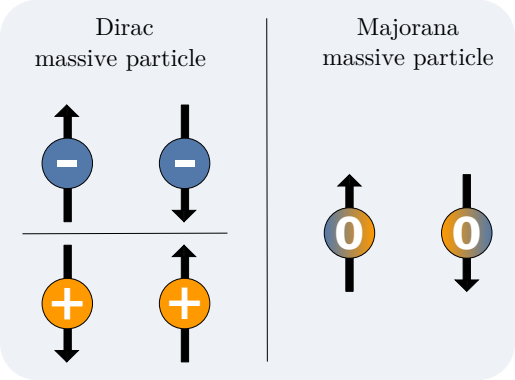
- the Majorana effective mass is the key parameter in the search for 0νββ
- information on $m_{\beta\beta}$ can be extracted from oscillations & cosmology
  - distribution tends toward low values (few meV)
- it is possible to construct a pdf for $m_{\beta\beta}$ which relies on no priors
  - only assumptions: 3 light neutrinos, Majorana mass, known Σ
- next-generation 0νββ experiments will have high discovery power even in NH scenario

Thank you!

Majorana neutrinos

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

    $\rightarrow \forall \mathbf{p}$, 2 helicity states: $|\mathbf{p}\uparrow\rangle$ and $|\mathbf{p}\downarrow\rangle$

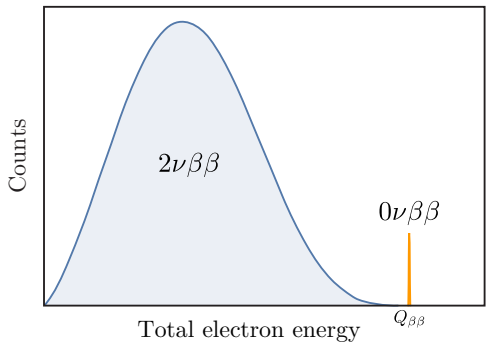


Adv. High Energy Phys. 2016, 2162659 (2016)

- could fully describe massive neutrinos (G. Racah, 1937)
- Majorana's hypothesis can be implemented in the SM
  - $\chi \equiv \psi_L + C\bar{\psi}_L^t \quad \rightarrow \quad \psi_L = P_L\, \chi \equiv \frac{(1-\gamma_5)}{2}\, \chi \quad$ (*usual* field)
- *L*-violation due to Majorana mass
  - $\mathcal{L}_{\text{mass}} = \frac{1}{2} \sum_{\ell,\ell'=e,\mu,\tau} \nu_\ell^t\, C^{-1} M_{\ell\ell'}\, \nu_{\ell'} + h.c. \quad \Rightarrow \quad$ ovββ proportional to $|M_{ee}| \equiv m_{\beta\beta}$

Experimental search for 0νββ

- detection of 2 emitted e^-
  - monochromatic peak at $Q_{\beta\beta}$
- observable is decay half-life $t_{1/2}^{0\nu}$ of a specific isotope



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

M = detector mass T = measuring time
B = background level Δ = energy resolution

- information on neutrino mass from theory

$$\left[t_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\,|\mathcal{M}|^2\,\frac{m_{\beta\beta}^2}{m_e^2}$$

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

- $G_{0\nu}$ = Phase Space Factor (atomic physics)
- $\mathcal{M}$ = Nuclear Matrix Element (nuclear physics)
- $m_{\beta\beta}$ = effective Majorana mass (particle physics)