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Ab initio Combined Neutrino Mass Limits from Neutrinoless Double-Beta Decay

Taiki Shickele

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CASST 2024

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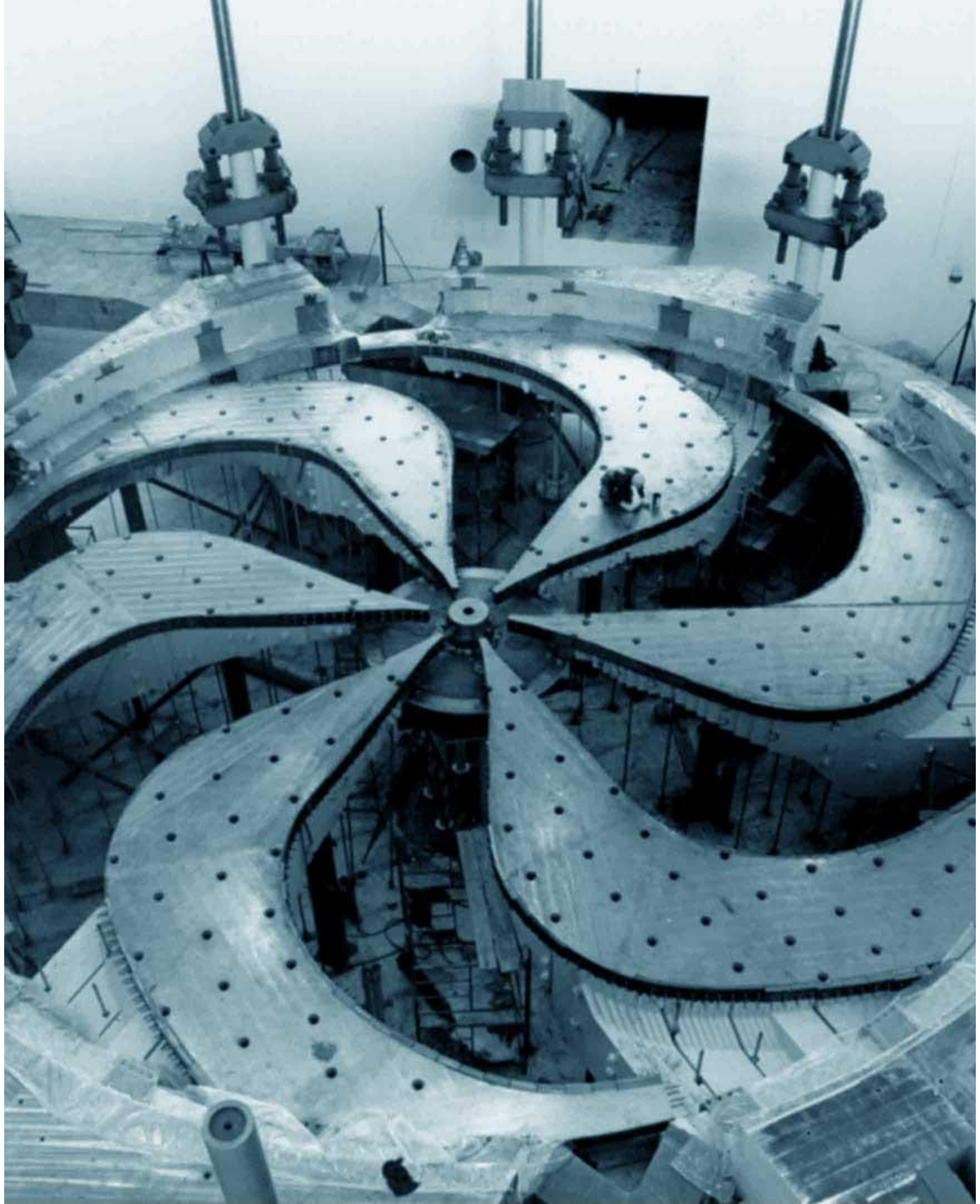

2024-08-19

Discovery, accelerated

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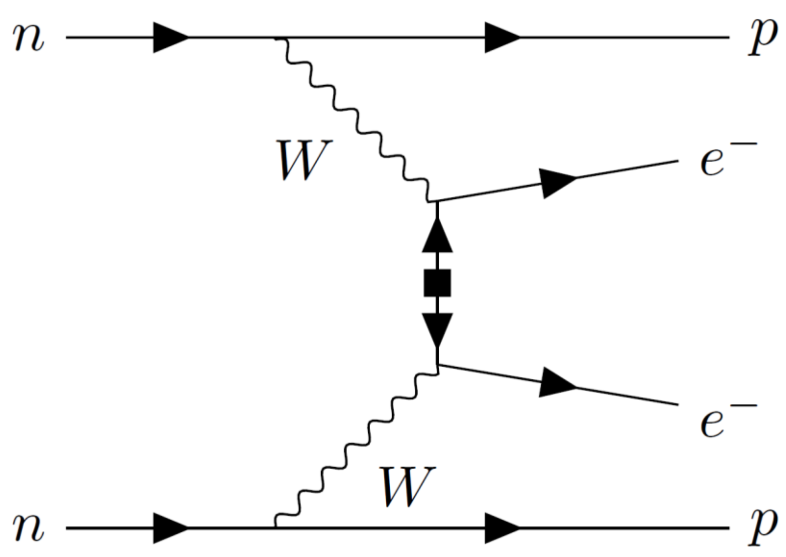
Neutrinoless Double-beta Decay (0νββ)

- Requires the neutrino to be its own antiparticle – Majorana particle
- A lepton-number violating process
  - Baryon asymmetry of the universe
- Other exotic new physics



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

Neutrinoless Double-beta Decay (0νββ)

$$\frac{1}{T_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M^{0\nu\beta\beta}|^2 \left(\frac{m_{\beta\beta}}{m_{\mathrm{e}}} \right)^2$$

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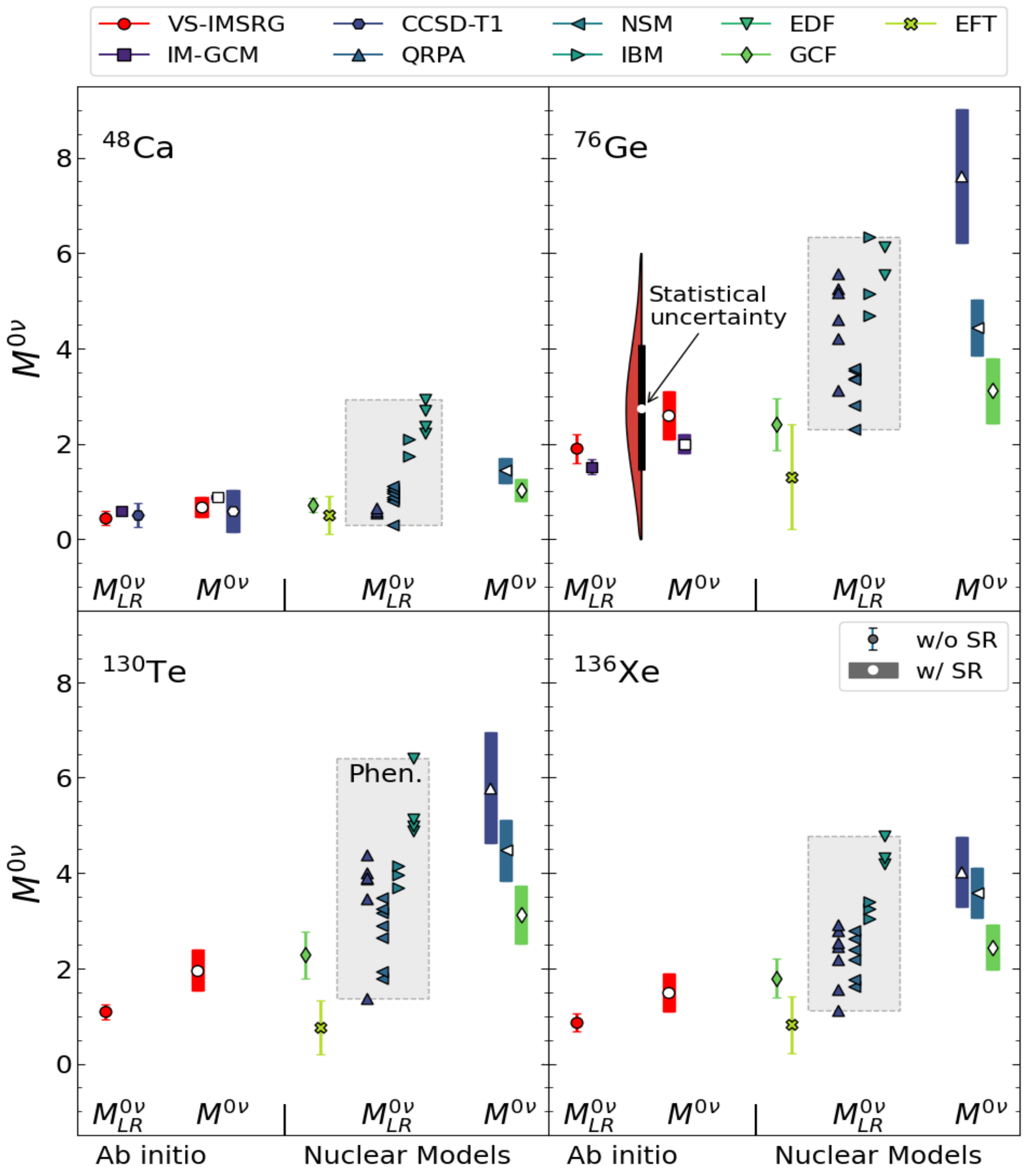
Nuclear Matrix Element (NME)

Nuclear Matrix Elements (NMEs) from *ab initio* Nuclear Theory

- Phenomenological methods make uncontrolled approximations – no way to obtain uncertainties
- *Ab initio* methods compute NMEs from first principles – controlled uncertainties



A. Belley, T. Miyagi, S.R. Stroberg, and J. D. Holt, arXiv:2307.15156

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Neutrinoless Double-beta Decay (0νββ)

$$\frac{1}{T_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M^{0\nu\beta\beta}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Nuclear Matrix Element (NME)

Effective Neutrino Mass

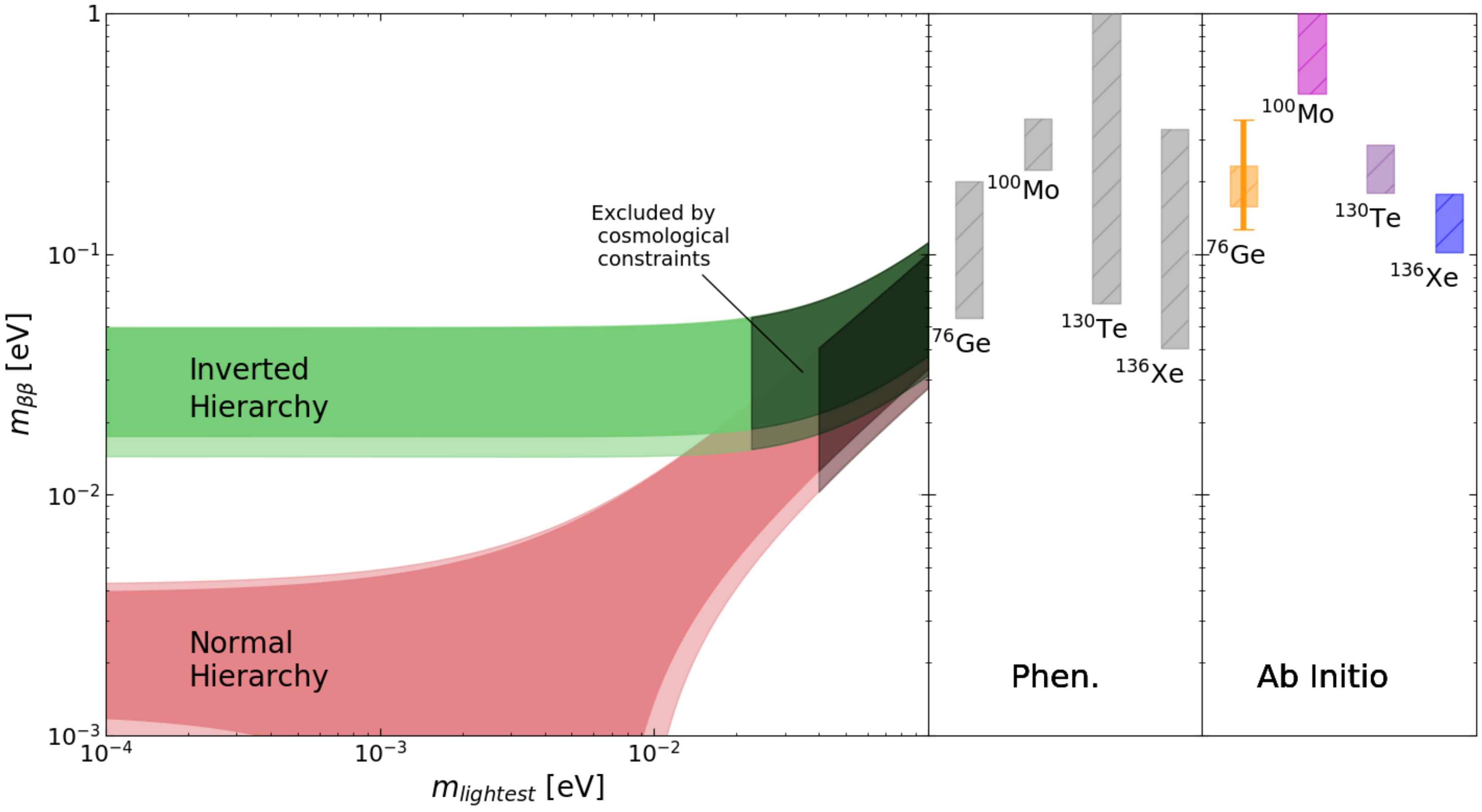
$$m_{\beta\beta} = \sum_i U_{ei}^2 m_i$$

The Majorana Neutrino Mass and Combined Limits

$$m_{\beta\beta} = \sum_i U_{ei}^2 m_i$$

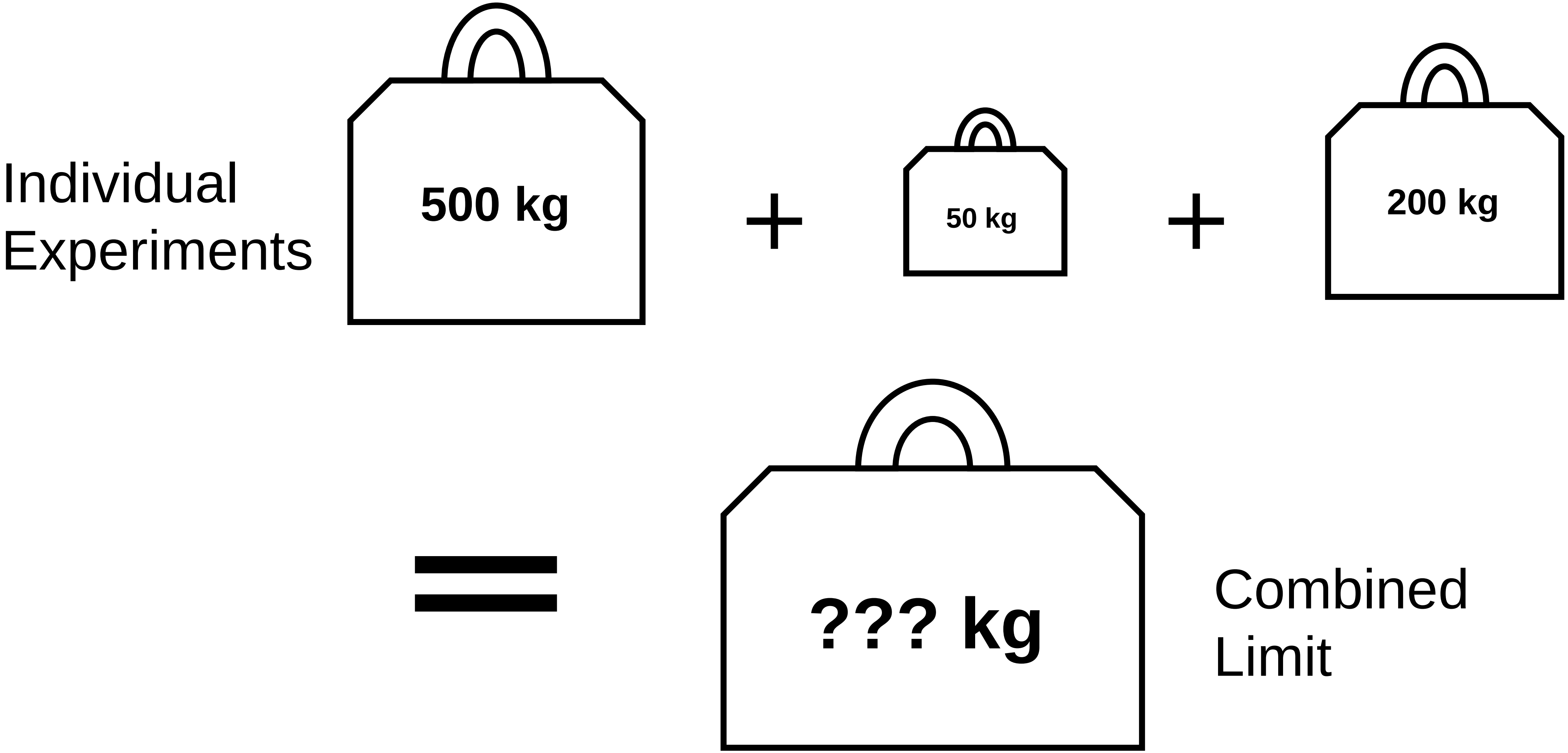
$$m_3 < m_1 < m_2$$

$$m_1 < m_2 < m_3$$

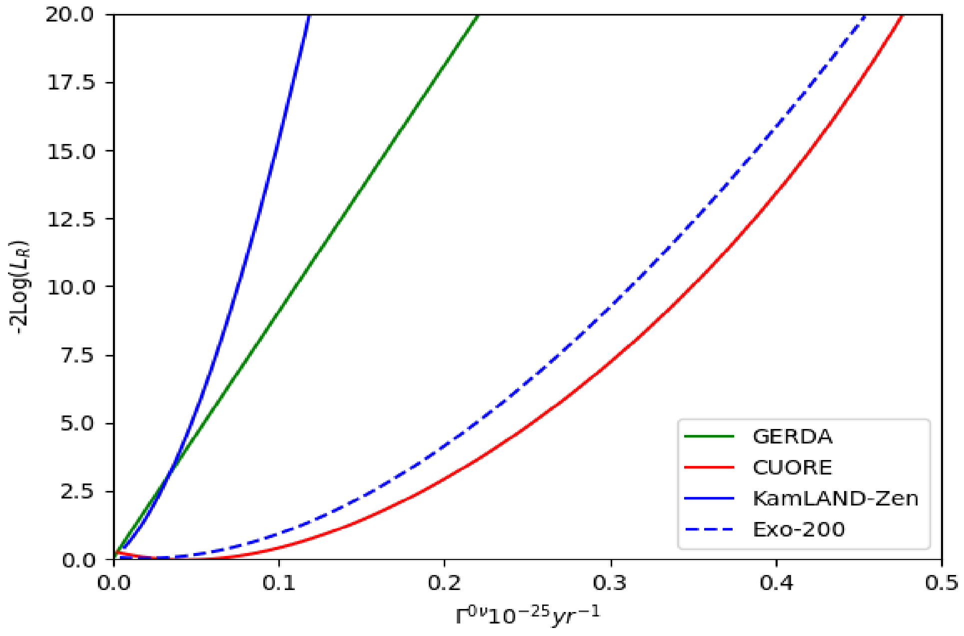


A. Belley et al. Phys. Rev. Lett. 132 (2024) 18, 182502, M. Agostini et al. Phys. Rev. Lett. 125 (2020) 25 252502, D. Q. Adams, et al. arXiv:2404.04453, A. Gisela, et al. Phys. Rev. Lett. 123 (2019) 16, 161802, S. Abe, et al. arXiv:2406.11438 (2024).

Combined Neutrino Mass Limits



Bayes' Theorem and Likelihood Functions



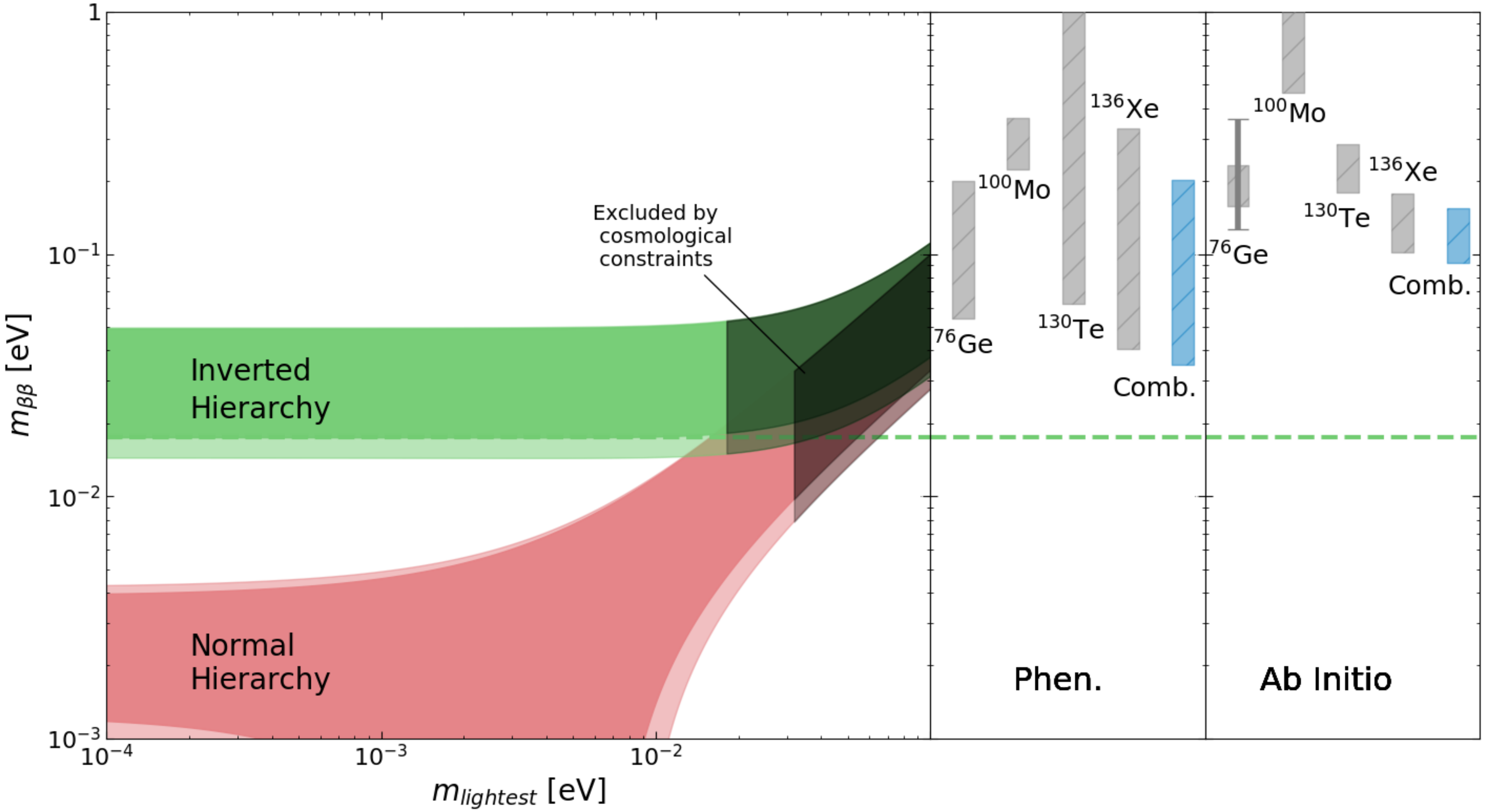
- Likelihoods from experiments in terms of decay rate converted to $m_{\beta\beta}$

$$m_{\beta\beta} = \frac{m_e}{g_A^2 |M^{0\nu}|} \sqrt{\frac{\Gamma^{0\nu}}{G^{0\nu} \log 2}}$$

- Likelihoods allow us to obtain a combined limit on $m_{\beta\beta}$ thru Bayes' theorem:

S. D. Biller, Phys. Rev. D 104 (2021) 1 012002.

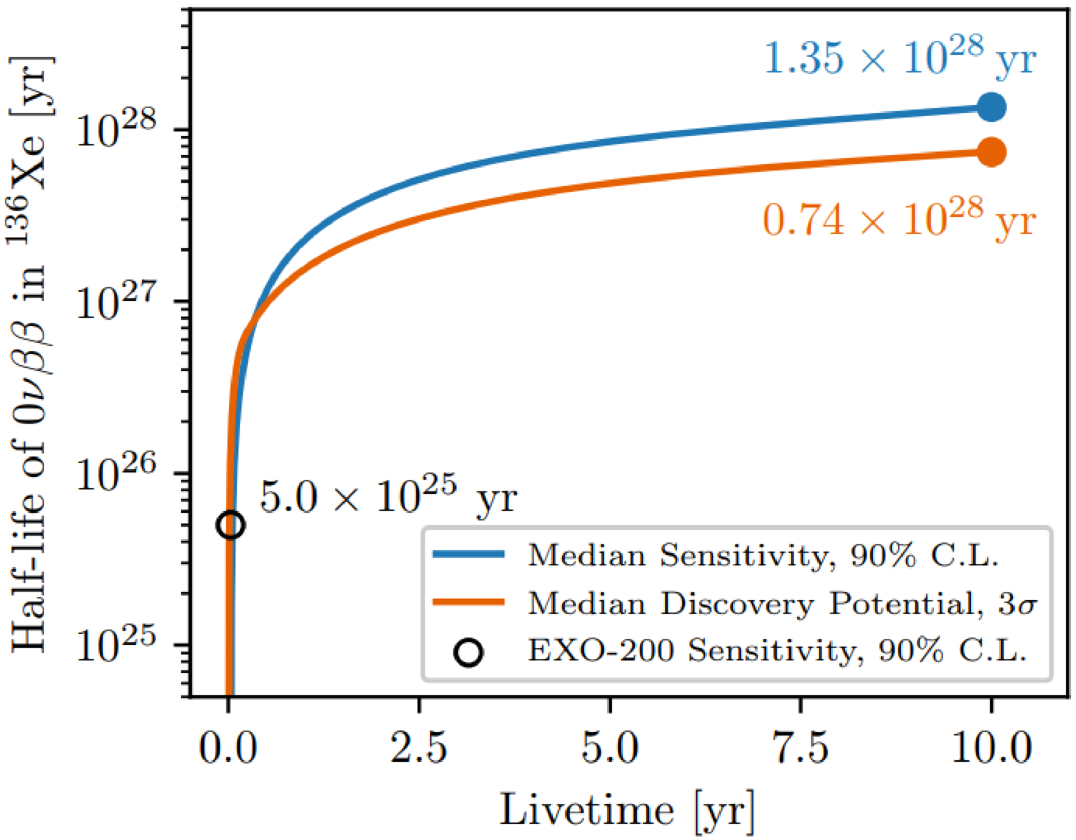
Combined Neutrino Mass Limits



$$m_{\beta\beta} \leq 113 \text{ meV}$$

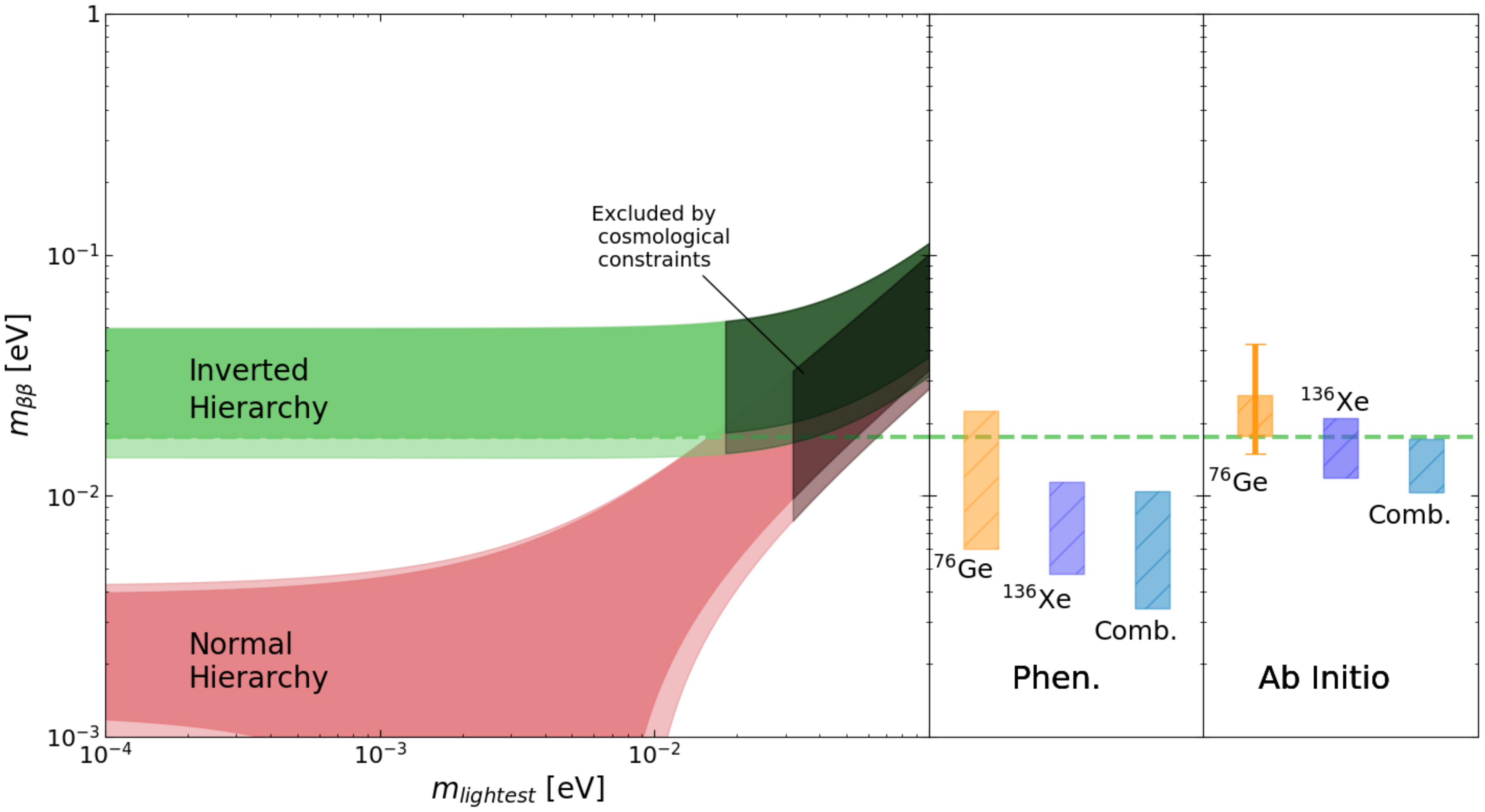
Next-Generation Sensitivities

- A predicted exclusion reach of next-generation experiments
- Poisson counting analysis utilized to obtain sensitivities



G. Adhikari et al 2022 J. Phys. G: Nucl. Part. Phys. 49 015104

Next-Generation Sensitivities



N. Abgrall, et al. arXiv:2107.11462 (2021), G. Adhikari et al 2022 J. Phys. G: Nucl. Part. Phys. 49 015104

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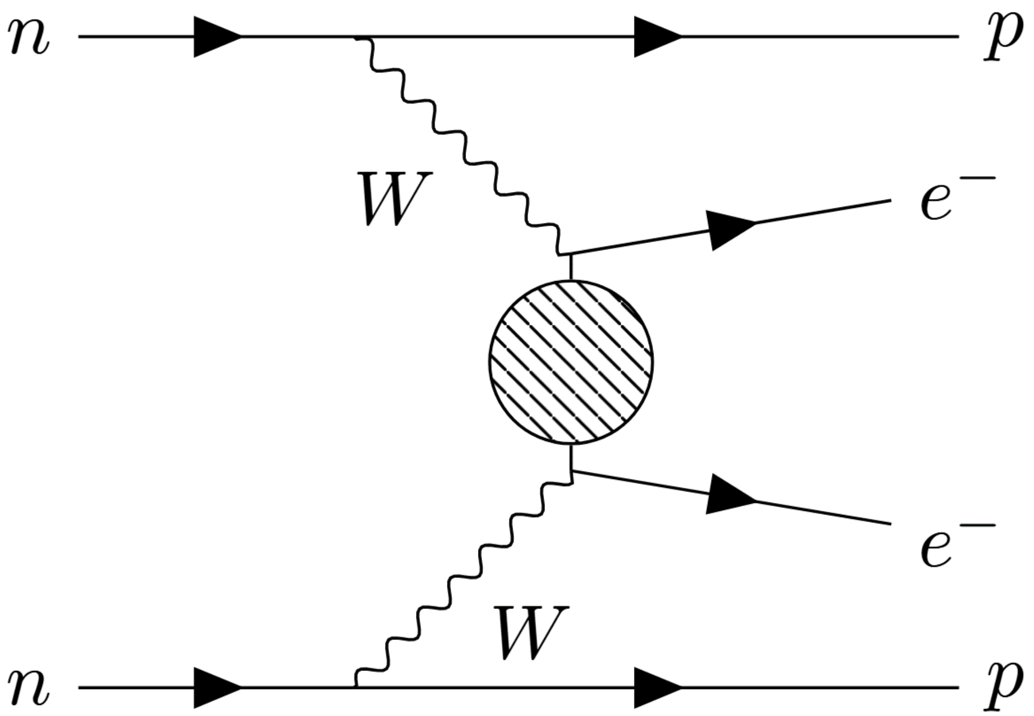
Heavy Sterile Neutrino Exchange



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Heavy Sterile Neutrino Exchange

$$\frac{1}{T_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M^{0\nu\beta\beta}|^2 \left(\frac{m_{\beta\beta}}{m_{\mathrm{e}}}\right)^2$$

$$\Downarrow$$

$$\frac{1}{T_{1/2}^{0\nu}} = g_A^4 G^{0\nu} \left(|M_L^{0\nu}| \frac{m_{\beta\beta}}{m_{\mathrm{e}}} + \underline{|M_H^{0\nu}| \frac{m_{\mathrm{p}}}{M_{\beta\beta}}}\right)^2$$

V. Cirigliano, W. Dekens, J. de Vries et al. J. High Energ. Phys. 2018, 97 (2018)

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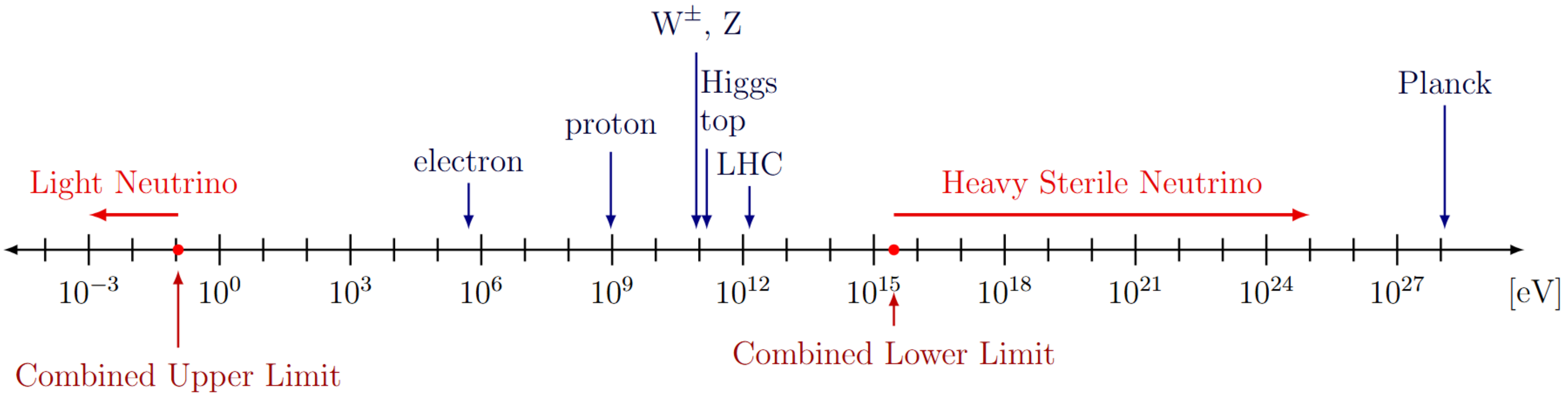
Heavy Sterile Neutrino Exchange

- Combined constraint on heavy neutrino mass of $M_{\beta\beta} \geq 2.87 \times 10^8$ GeV
- Orders of magnitude above energies accessible to accelerators
- Potential candidate for dark matter at $> 10^8$ GeV scale



A. Todd, T. Shickele, A. Belley, J.D. Holt (in progress)

Summary

- The combined constraint on the effective neutrino mass from current and next-generation experiments is $\boldsymbol{m_{\beta\beta}} \leq$ **113meV** and $\boldsymbol{m_{\beta\beta}} \leq$ **13meV** respectively
- Combined limits lead to **>10% improvement over the most stringent individual constraints**

Outlook

- Propagation of uncertainties from NMEs to final combined limits
- Sensitivities for other next-generation experiments
- Varying uninformative Bayesian priors

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Thank you
Merci

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Jason Holt

Discovery, accelerated

Questions?

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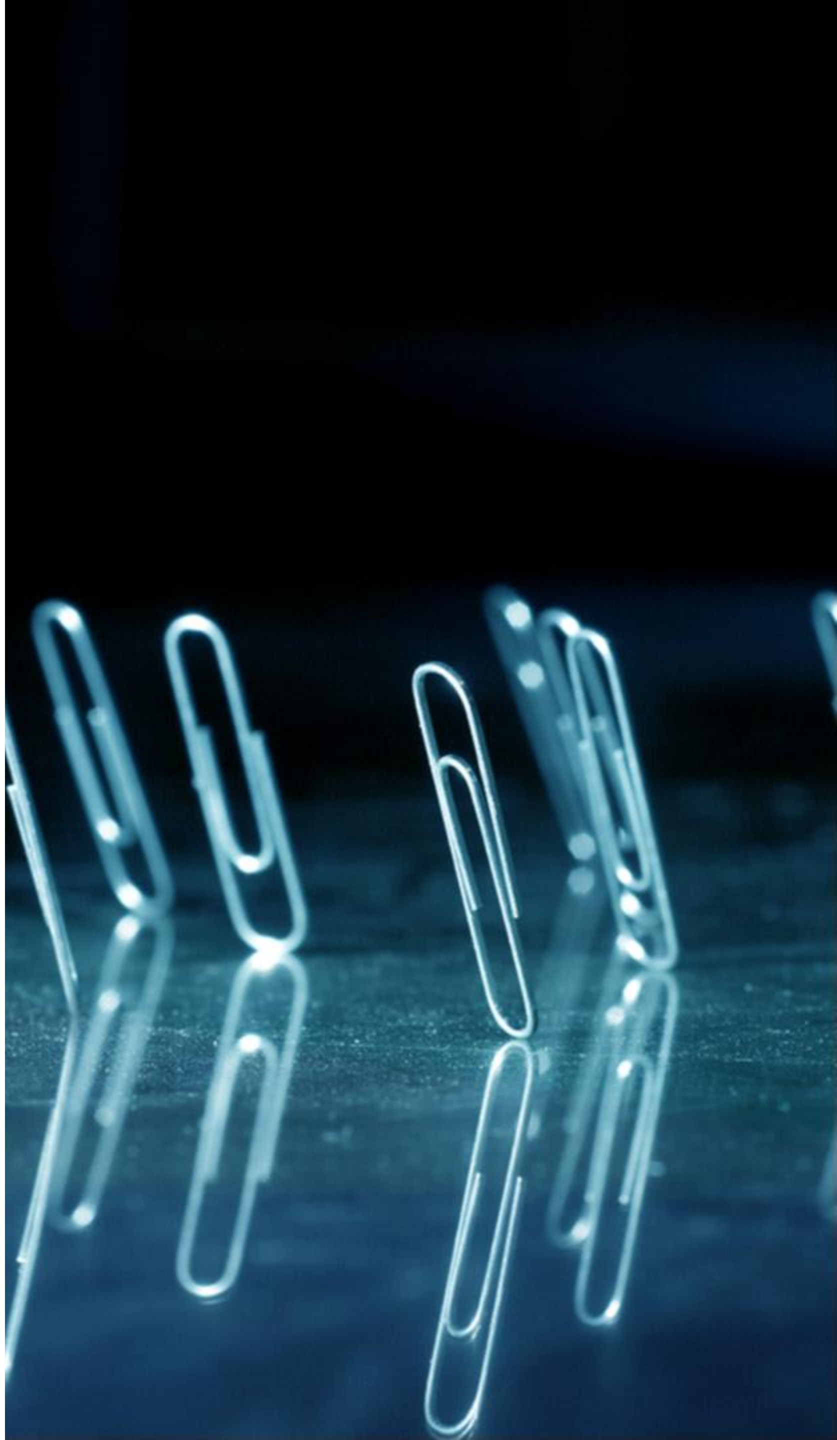
Backup Slides



Bayes' Theorem and Likelihood Functions

$$P(\theta|\text{Data}) = \frac{P(\text{Data}|\theta)P(\text{Data})}{P(\theta)}$$

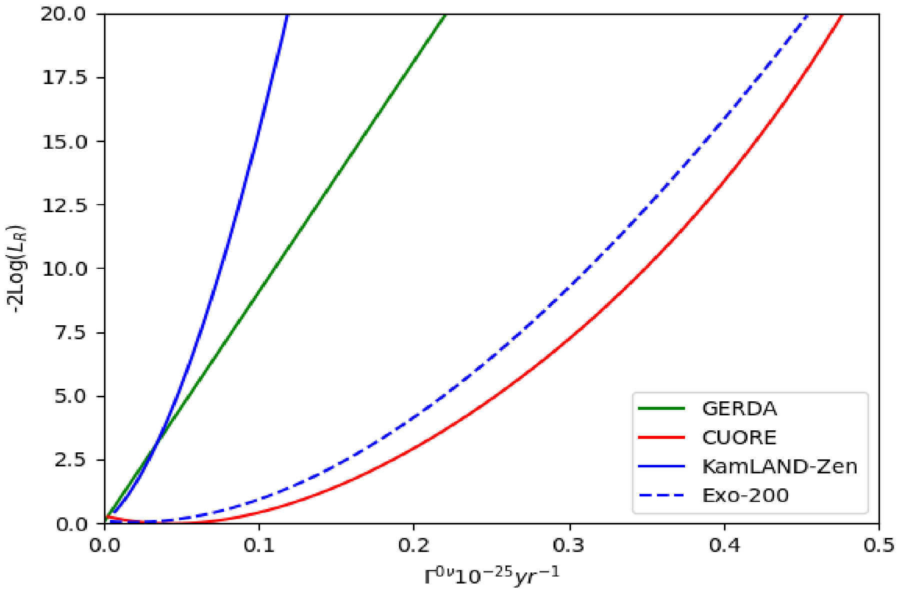
$$\mathcal{L}(\theta)$$

- Each experiment has an associated likelihood function

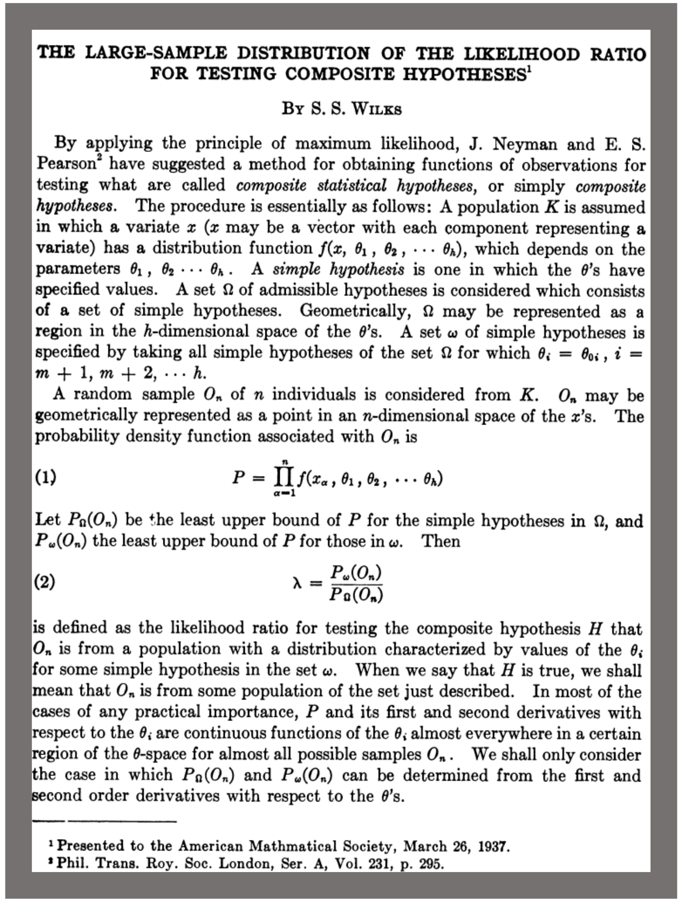
Constructing Likelihood Functions

- Wilks' theorem allows us to obtain likelihoods from $\Delta\chi^2$ profiles

$$-2\log\left(L_R\right) \approx \frac{1}{2}\Delta\chi^2_{m=1} + \frac{1}{2}\delta(0)$$



S. Algeri, et al. Nat. Rev. Phys. 2, 245–252 (2020).



THE LARGE-SAMPLE DISTRIBUTION OF THE LIKELIHOOD RATIO FOR TESTING COMPOSITE HYPOTHESES[1]

BY S. S. WILKS

By applying the principle of maximum likelihood, J. Neyman and E. S. Pearson[2] have suggested a method for obtaining functions of observations for testing what are called *composite statistical hypotheses*, or simply *composite hypotheses*. The procedure is essentially as follows: A population K is assumed in which a variate x (x may be a vector with each component representing a variate) has a distribution function $f(x, \theta_1, \theta_2, \cdots \theta_h)$, which depends on the parameters $\theta_1, \theta_2 \cdots \theta_h$. A *simple hypothesis* is one in which the θ's have specified values. A set Ω of admissible hypotheses is considered which consists of a set of simple hypotheses. Geometrically, Ω may be represented as a region in the h-dimensional space of the θ's. A set ω of simple hypotheses is specified by taking all simple hypotheses of the set Ω for which $\theta_i = \theta_{0i}$, $i = m+1, m+2, \cdots h$.

A random sample O_n of n individuals is considered from K. O_n may be geometrically represented as a point in an n-dimensional space of the x's. The probability density function associated with O_n is

(1) $$P = \prod_{\alpha=1}^{n} f(x_\alpha, \theta_1, \theta_2, \cdots \theta_h)$$

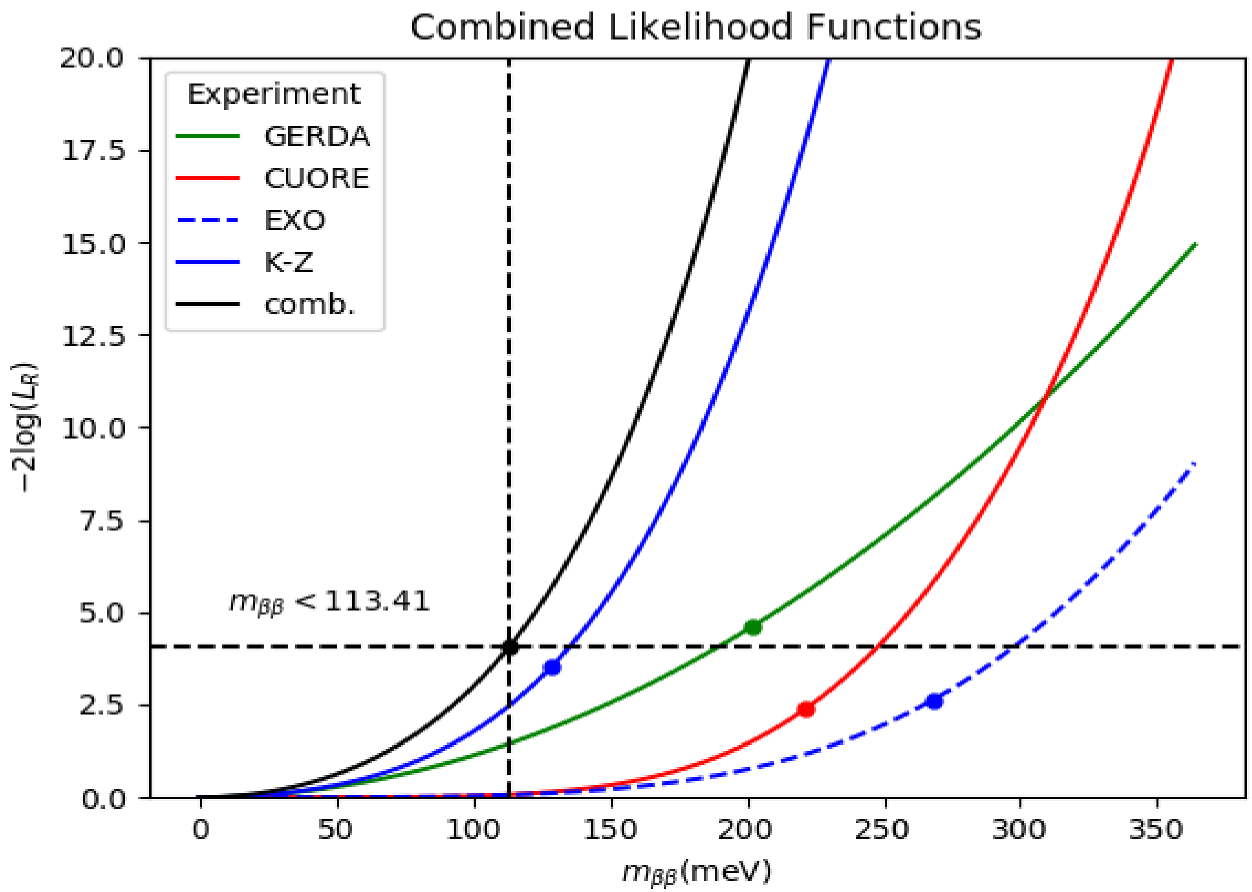
Let $P_\Omega(O_n)$ be the least upper bound of P for the simple hypotheses in Ω, and $P_\omega(O_n)$ the least upper bound of P for those in ω. Then

(2) $$\lambda = \frac{P_\omega(O_n)}{P_\Omega(O_n)}$$

is defined as the likelihood ratio for testing the composite hypothesis H that O_n is from a population with a distribution characterized by values of the θ_i for some simple hypothesis in the set ω. When we say that H is true, we shall mean that O_n is from some population of the set just described. In most of the cases of any practical importance, P and its first and second derivatives with respect to the θ_i are continuous functions of the θ_i almost everywhere in a certain region of the θ-space for almost all possible samples O_n. We shall only consider the case in which $P_\Omega(O_n)$ and $P_\omega(O_n)$ can be determined from the first and second order derivatives with respect to the θ's.

[1] Presented to the American Mathmatical Society, March 26, 1937.
[2] Phil. Trans. Roy. Soc. London, Ser. A, Vol. 231, p. 295.

Combined Neutrino Mass Limits



S. D. Biller, Phys. Rev. D 104 (2021) 1 012002.

Heavy Sterile Neutrino Exchange

Heavy Sterile Neutrino Mass Lower Bounds

	Phenomenological Limit (GeV)	Ab initio Limit (GeV)
GERDA	2.28×10^8	1.35×10^8
CUORE	2.58×10^8	1.29×10^8
KamLAND-Zen	3.16×10^8	2.78×10^8
Exo-200	1.51×10^8	1.33×10^8
Combined	3.73×10^8	2.87×10^8