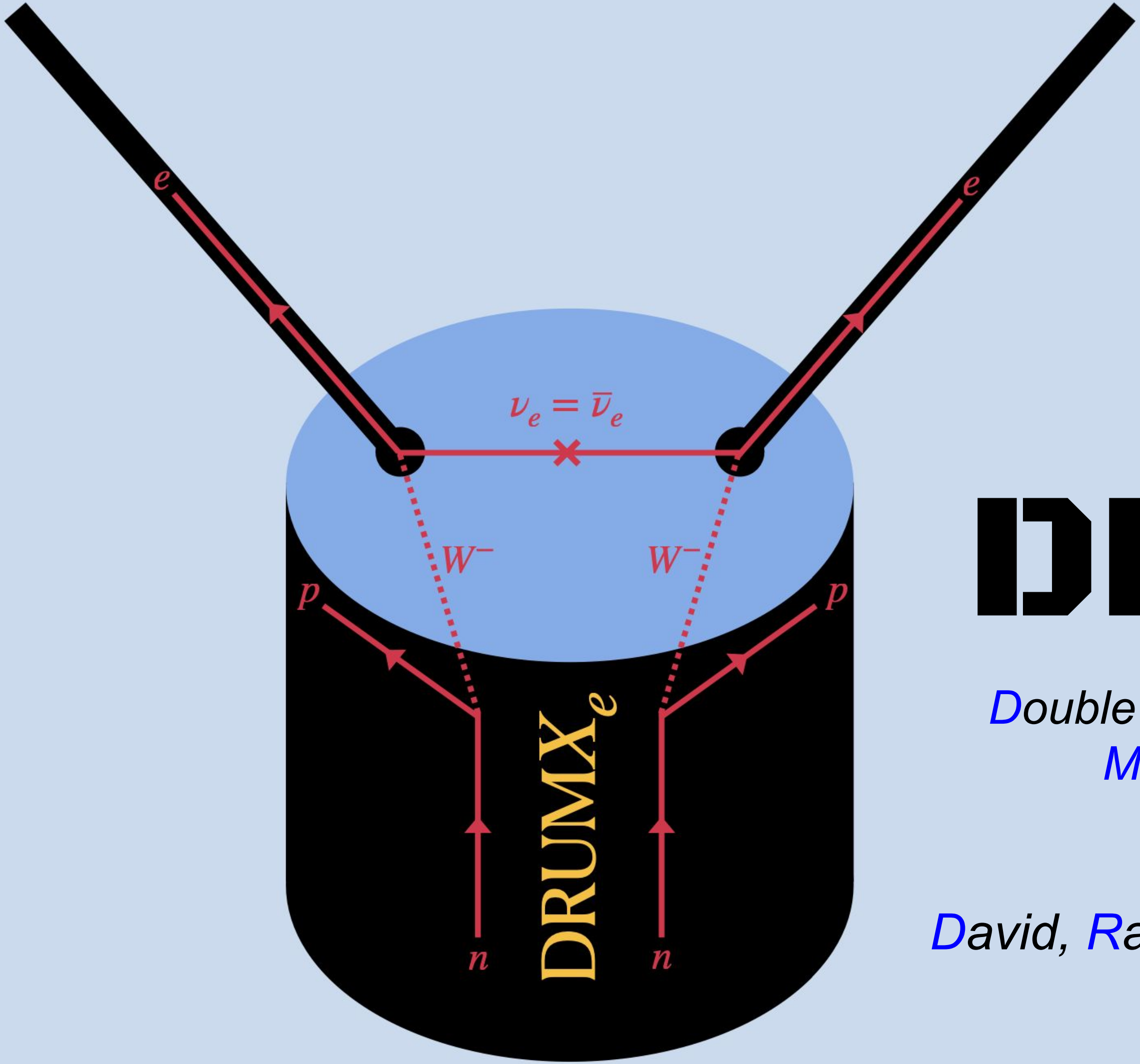


DRUMXe

Double beta decay Rate Underground Measurement using Xenon

David, Raghda, Ulysse, Mahnoor, Xiang:
$0\nu\beta\beta$ experimentalists

Outline

- (Neutrinoless) Double Beta Decay
- Mass Hierarchy
- Experimental Conditions & Setup
- Sensitivity
- EDI Scenario

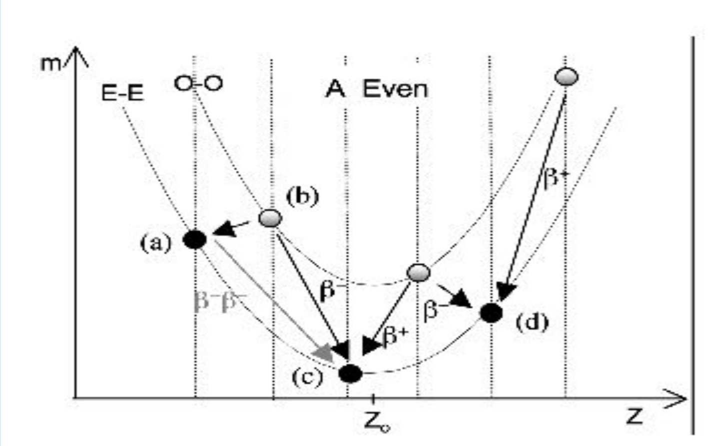
Double Beta $\beta\beta$ Decay

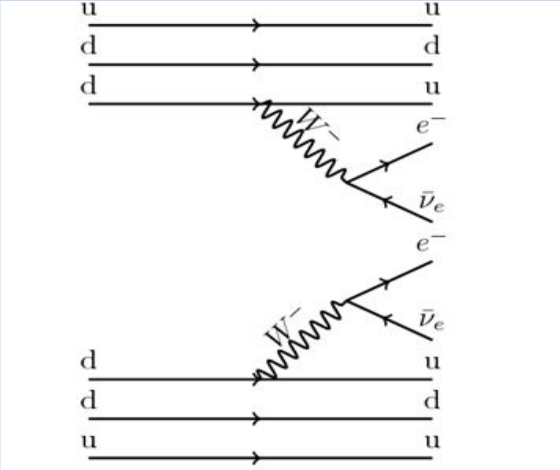
- This process occurs for isotopes with even-even nuclei.
- Q = M(A,Z) - M(A, Z+2)
- Conditions:
  a. Positive Q value :

     m(Z, A) > m(Z - 1, A) + 2me

  b. Forbidden Single beta decay :

     m(Z, A) < m(Z ± 1, A)

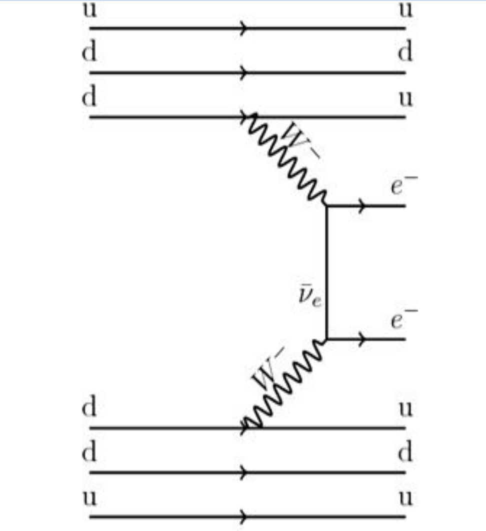




Neutrinoless Double Beta Decay $0\nu\beta\beta$

Theoretical motivation:

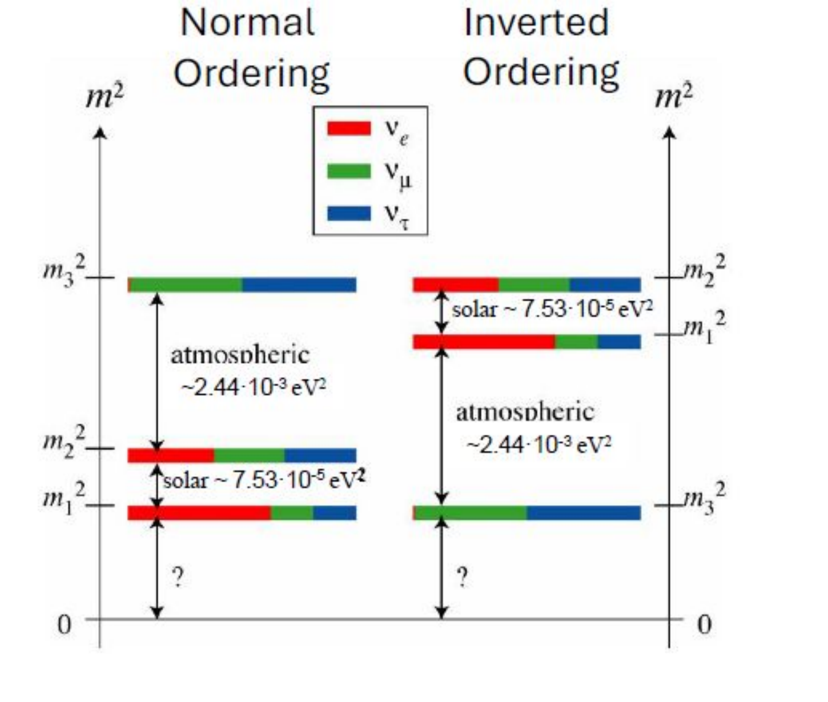
- Confirm if neutrino is a Majorana fermion
  - If so, we should see neutrino annihilation in double beta decay.
- Experimentally observe Lepton number violation.
- Provide insights into the seesaw* mechanism giving some constraints on the heavier (Right Handed) mass.



*See-Saw mechanism is a theoretical model explaining the low masses of neutrinos

Mass Hierarchy

- Neutrino flavors are linear combination of mass eigenstates time the transformation matrix
- Oscillation experiments have measured 2 mass squared differences (solar and atmospheric)
- At least two mass states have to be non zero.
- MSW effect occurring in the Sun showed $m_2 > m_1$ but the m_3 mass eigenstate is not yet determined to be the lightest (IO) or the heaviest (NO)



Experimental Conditions

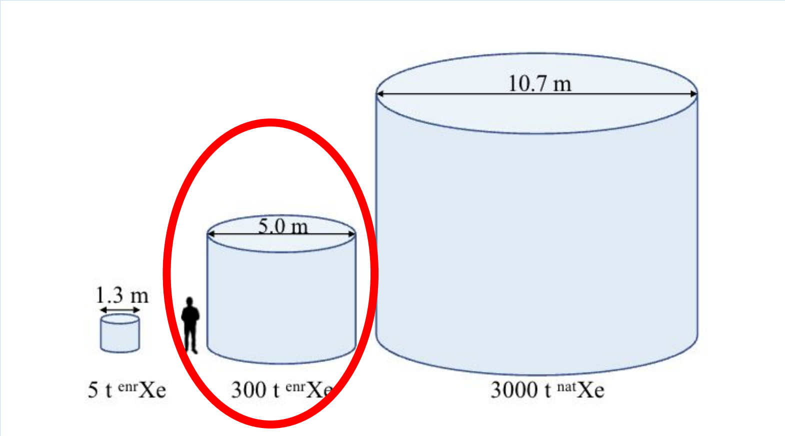
- Improve exposure (Enrichment vs more target mass)
  - Use ^{136}Xe. Wait longer.
  - Relatively large Q value $Q_{\beta\beta} \cong 2458.10$ keV.
  - LXe means we can pack more mass in smaller volume, LXe has density of 2.9 g/cm^3
- Understand background.
  - Solar neutrino background identification (Collaborate with XENONnT to exclude solar neutrino)
  - $2\nu\beta\beta$ continuum. Better energy resolution

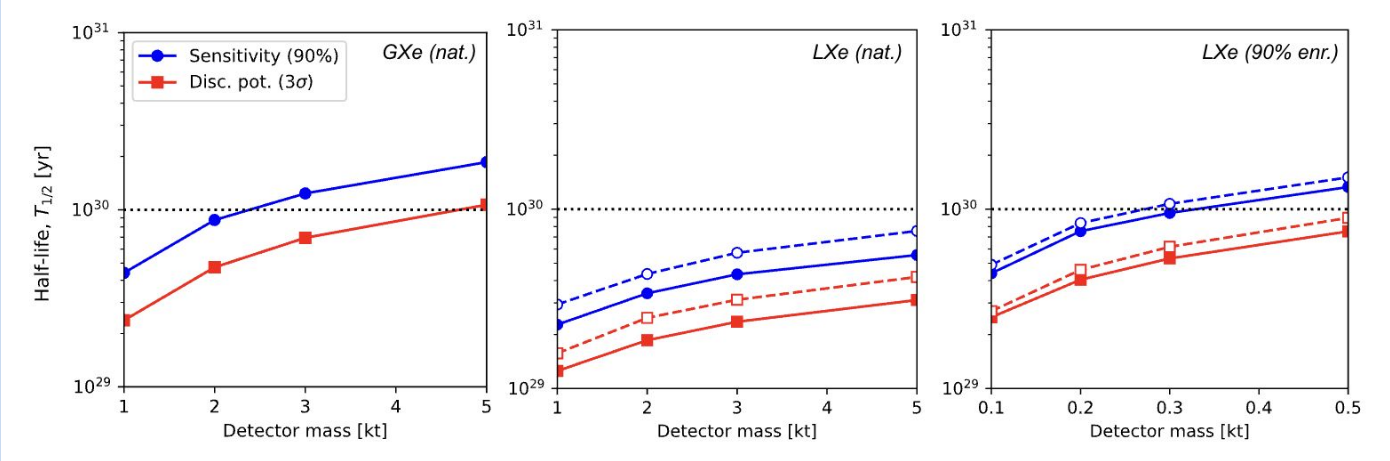
$$T_{1/2} \propto \frac{M \cdot \epsilon \cdot \sqrt{t}}{\sqrt{(b \cdot M + c)\Delta E}}$$

Isotope	Natural abundance [%]	$Q_{\beta\beta}$ [MeV]
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	8.7	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.8	3.035
^{116}Cd	7.5	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371

Xenon enrichment

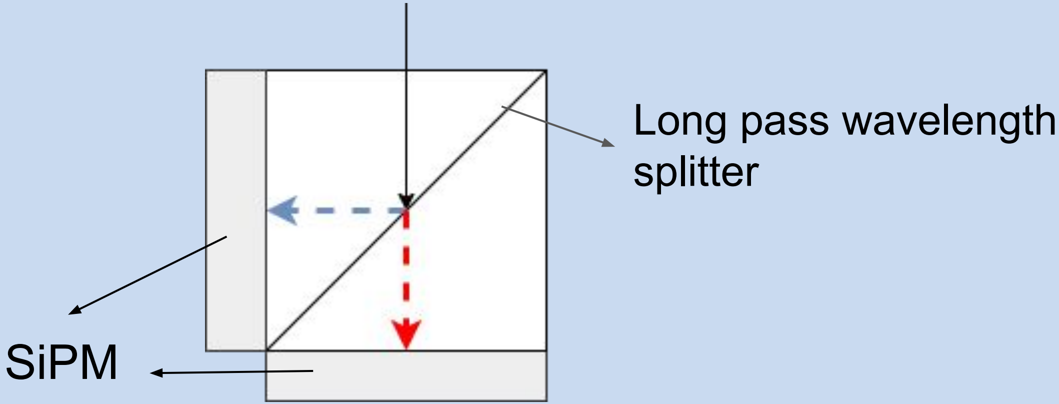
- Sensitivity as a function of detector mass, for natural Gaseous Xe, natural Liquid Xe and 90% enriched Liquid Xe
- 90% enrichment. ^{134}Xe is not a source of background in our search

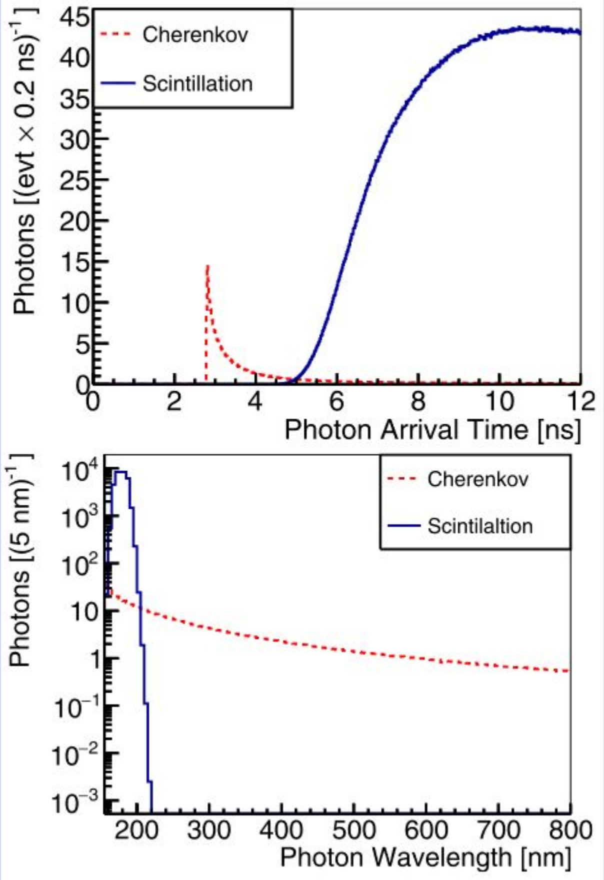




DRUMX Experimental Setup for $\beta\beta$ Decay

- Exposure: Hundred-ton scale LXe.
- Solar neutrino background
  - Directionality channel using Cherencov
    - Fast timing.
    - Dual SiPMs readout.

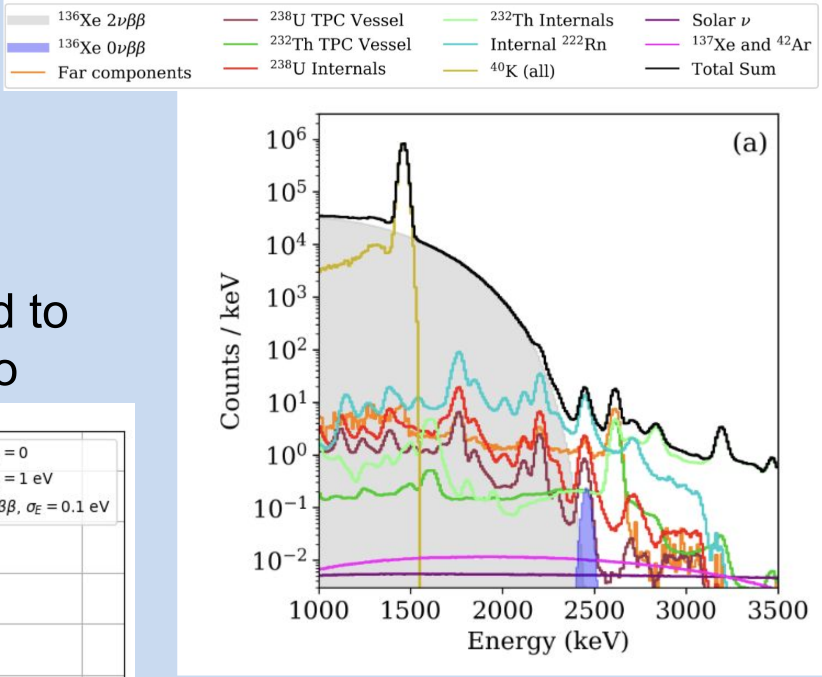




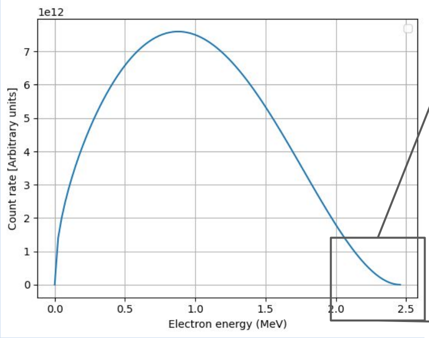
Energy resolution

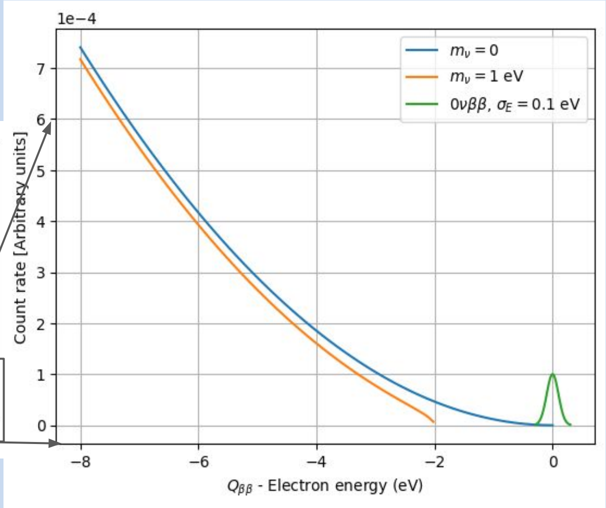
- High energy resolution is require to discriminate $0\nu\beta\beta$ event from $2\nu\beta\beta$ events and other background.
- To obtain neutrino mass, detector required to have the resolution in the order of neutrino mass.

nEXO collaboration

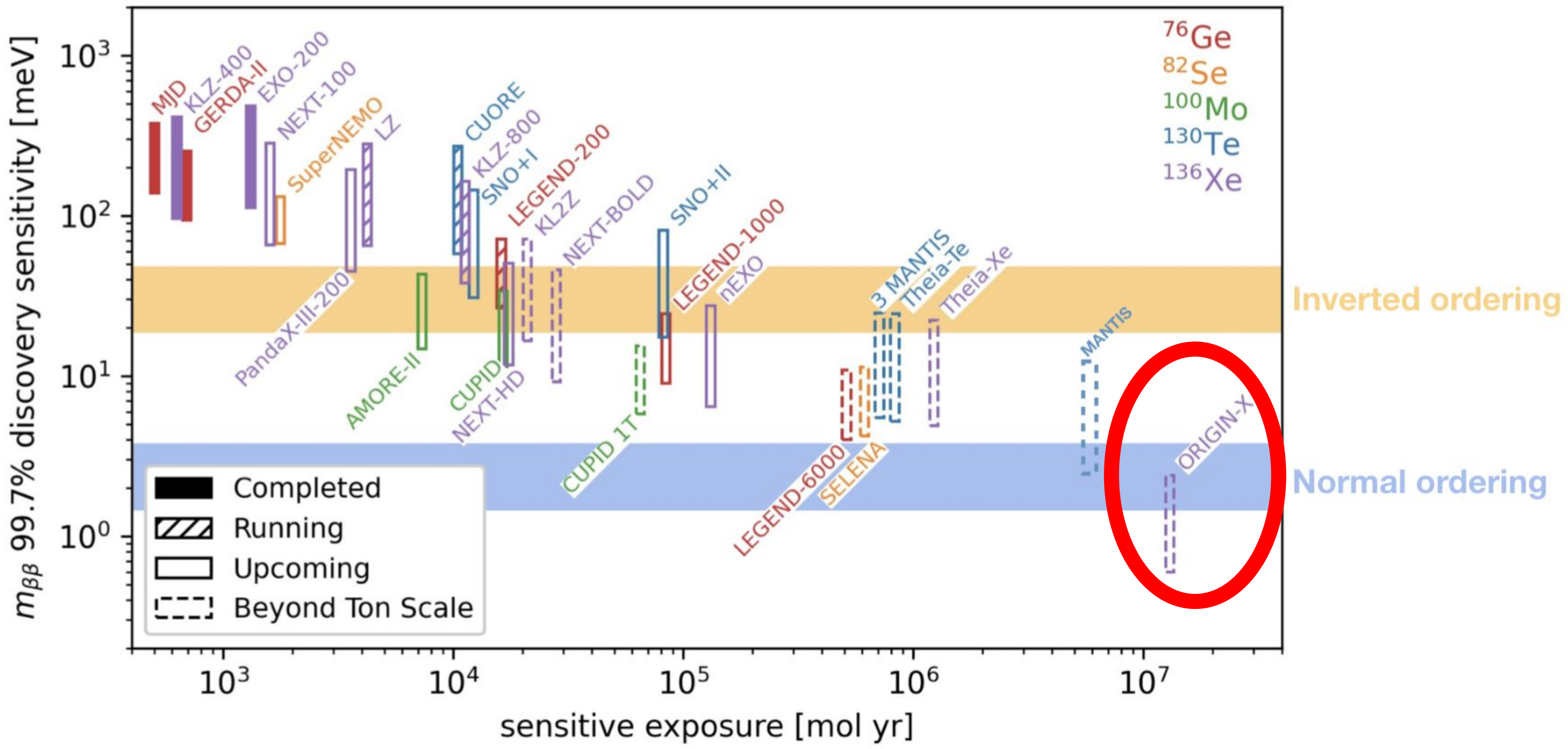


G Adhikari *et al* 2022 *J. Phys. G: Nucl. Part. Phys.* **49** 015104





Experiment Sensitivity

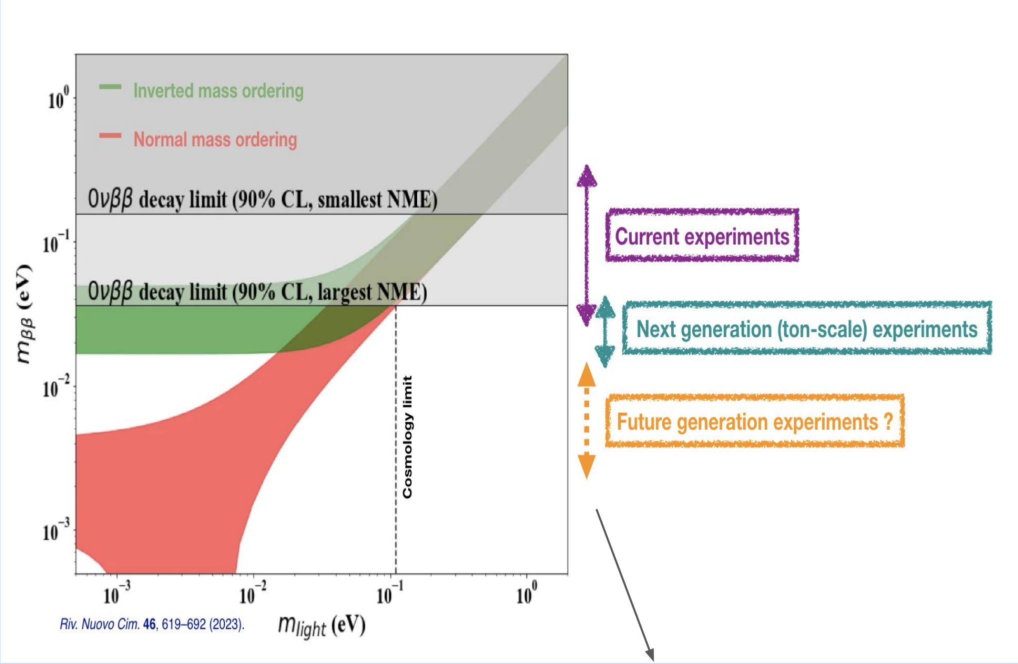


Adapted from arxiv:2304.03451 (Whitepaper for the 2023 NSAC Long Range Plan)

Experiment Sensitivity

$$T_{1/2}^{0\nu} = \left(G\,|\mathcal{M}|^2\,\langle m_{\beta\beta}\rangle^2\right)^{-1} \simeq 10^{27-28}\left(\frac{0.01\ \text{eV}}{\langle m_{\beta\beta}\rangle}\right)^2 \text{ years.}$$

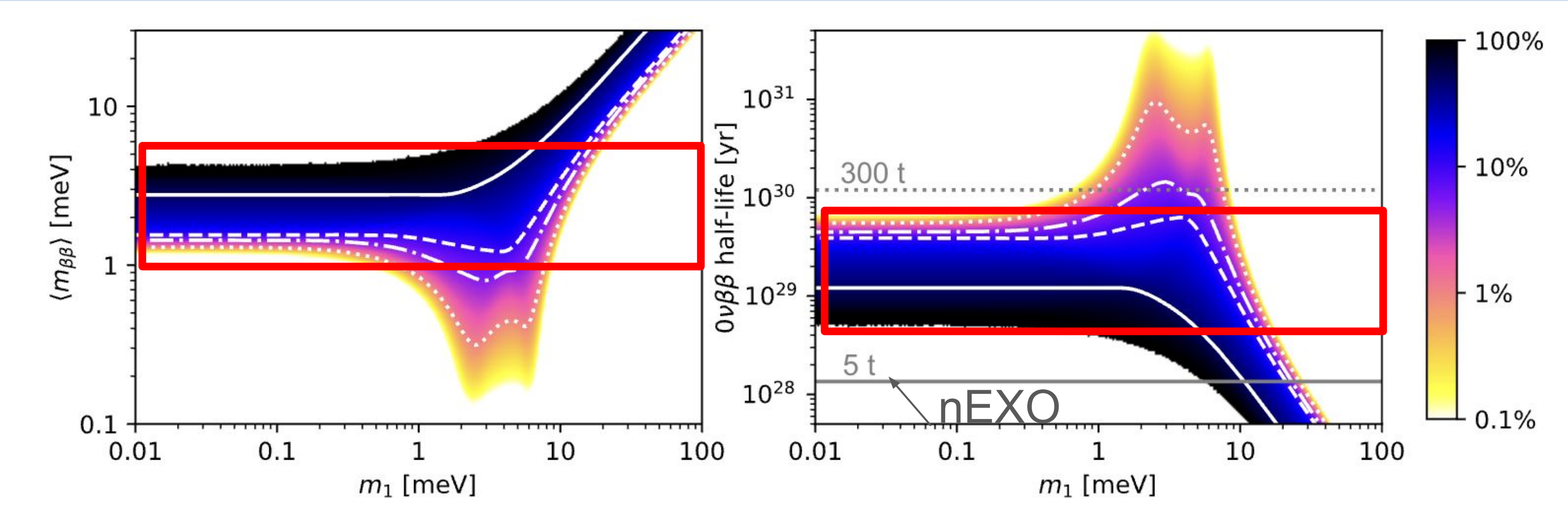
- Let's look at the plot together with the half life of our detector material.
- To reach the normal ordering regime requires lower $<m_{\beta\beta}>$ value (Plot)
- This requires a longer half-life and time for detector to run (half life equation)



OUR GOAL!

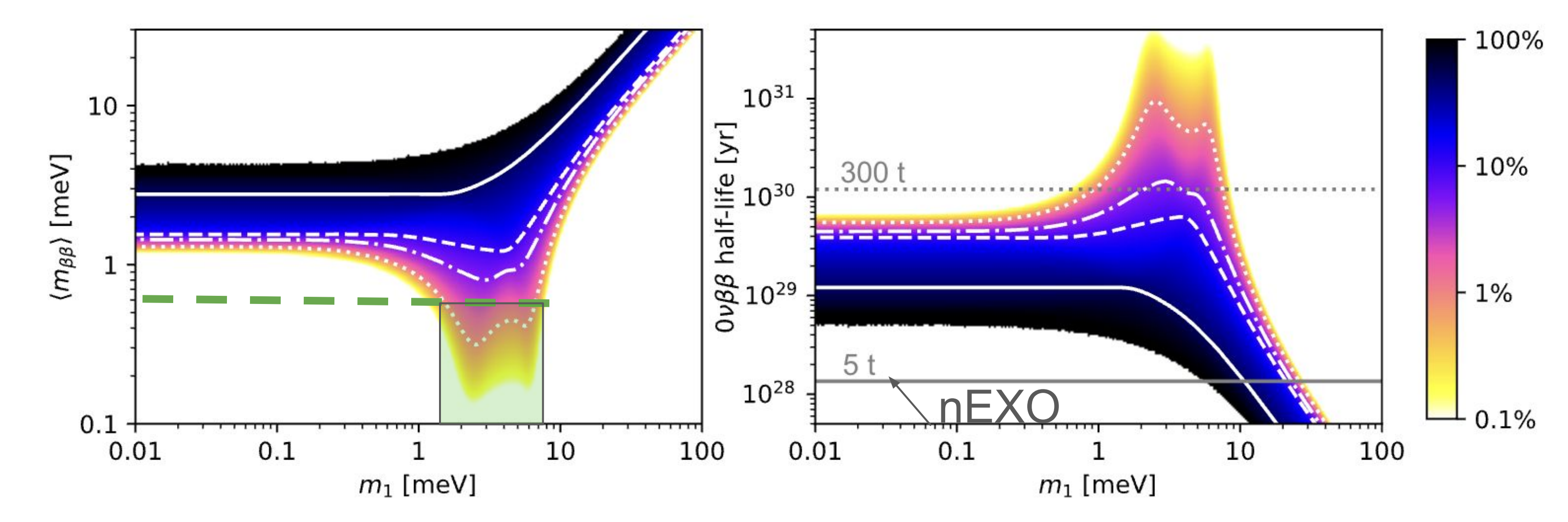
Experiment Sensitivity

- For given m1 (lightest mass state in the case of NO), colors represent the probability that mßß (half-life) would fall below (above) a given sensitivity
- IO parameter space not represented cause assumed to be ruled out by other experiments such as nEXO (5t of 90% enriched Xe)



Bonus: lightest neutrino mass determination

- Hypothetical, but let's say 0v$\beta\beta$ is observed at $<m_{\beta\beta}>$ lower that 1 meV, we would start to reach lobster plot "vertical" branch, and constrain m1
- m and m3 could then be directly determined using Δm^2_{21} and Δm^2_{32}



EDI Scenario

You are in a collaboration with about 100 people from 6 different counties and 16 different institutions. Your collaboration has been together for 10 years already and recently performed a survey that showed a lack of gender diversity.

- *You are part of the task force that was formed to come up with **2 or 3 initiatives** to improve the situation over the next **5 years**.*

Countries/institutions involved

ARC Centre of Excellence for Dark Matter Particle Physics, School of Physics, The University of Melbourne, VIC 3010, Australia
School of Physics, The University of Sydney, NSW 2006 Camperdown, Sydney, Australia
Université de Sherbrooke, Sherbrooke, Québec J1K 2R1, Canada
Department of Physics and Astronomy, Simon Fraser University, Burnaby, BC V5A 1S6, Canada
TRIUMF, Vancouver, BC V6T 2A3, Canada
Department of Physics, Carleton University, Ottawa, Ontario, K1S 5B6, Canada
Department of Physics and Astronomy, Laurentian University, Sudbury ON, P3E 2C6 Canada
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, 100049 China
SUBATECH, IMT Atlantique, CNRS/IN2P3, Nantes Université, Nantes, France
LPNHE, Sorbonne Université, CNRS/IN2P3, Paris, France
IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
Physics Department, COMSATS University Islamabad (CUI), Islamabad 45550, Pakistan
Quaid-e-Azam University, Islamabad Capital Territory 15320, Pakistan
Cairo University, Oula, Al Giza, Giza Governorate 12613, Egypt
Center for Fundamental Physics, Zewail City of Science and Technology, 6th of October City, Giza 12578, Egypt
Department of Physics, University of Florida, FL 32611, United States

EDI Initiative #1

Gender equity on hiring committees → certain percentage of hiring committees are female or gender-diverse, e.g. 30%.

- Unconscious bias training - learn about EDI, gender bias/discrimination, making workplaces safe, etc.
- Implement hiring quotas - i.e. will hire a certain number of women/gender-diverse people in the next hiring round, e.g. 30% → can also have female-only positions.

Reading 1, 2, 3, 4

EDI Initiative #2

Detailed & clear grievance/complaint procedure - includes multiple pathways to raise an issue

- As part of the grievance procedure documentation, include clear information about confidentiality, pathways to resolving grievances, about possible accountability actions, etc.
- Can potentially have an anonymous grievance pathway, in case members are worries about being identified.

EDI Initiatives - Data Keeping

Keeping data on gender equity and member experiences over the five years, making annual reports. Use

- Anonymous surveys on gender experiences and their effect on mental health, productivity, career development, etc.
- Collection of data on changes in annual gender representation + distribution over different academic levels

Case Study: ASTRO 3D (Australia)
Achieved 50/50 gender representation in 2022
https://astro3d.org.au/diversity/

Backup Slides

Back up - Semi-empirical Formula

- Semi-empirical mass formula

$$B(N, Z) = aA - bA^{\frac{2}{3}} - s\frac{(N-Z)^2}{A} - \frac{dZ^2}{A^{\frac{1}{3}}} - \frac{\delta}{A^{\frac{1}{2}}}$$

- $$\begin{aligned} a &= 15.835\text{MeV} \\ b &= 18.33\text{MeV} \\ s &= 23.20\text{MeV} \\ d &= 0.714\text{MeV} \end{aligned}$$

- $$\delta = \begin{cases} .2\text{MeV}\ for\ odd - odd\ nuclei\ (i.e., odd\ N, odd\ Z) \\ +110\ for\ even - odd\ nuclei\ (even\ N\ odd\ Z, or\ even\ Z, odd\ N) \\ -11.2\text{MeV}\ for\ even - even\ nuclei\ (even\ N, even\ Z) \end{cases}$$

W. N. Cottingham and D. A. Greenwood, *An introduction to nuclear physics*. Cambridge University Press, 2004.

Back up - Majorana mass

- Begin with Lagrangian :

$$\mathcal{L}_M = i\nu_L^\dagger \sigma_\mu \partial_\mu \nu_L + i\frac{m}{2}\left(\nu_L^\dagger \sigma_2 \psi_L^\star - \nu_L^T \sigma_2 \nu_L\right)$$

$$\mathcal{L}_{\mathrm{M,m}} = i\frac{m}{2}\left(\nu_L^\dagger \sigma_2 \nu_L^\star - \nu_L^T \nu_2 \psi_L\right) = \frac{m}{2}\,\bar{\nu}\nu$$

$$\mathcal{L}_{\mathrm{M,m}} = \frac{m}{2}\,\bar{\nu}\nu$$

- Where $\nu = \begin{pmatrix} \nu_L \\ i\sigma_2 \nu_L^\star \end{pmatrix}$.
- The spinor have the property that

$$C: \nu \rightarrow -i\gamma_2 \nu^\star \equiv \nu_c$$

$$-i\gamma_2 \nu^\star = \nu$$

- The antiparticle of Majorana fermion is itself.

Back up - Seesaw mechanism

$$\mathcal{L}_{\text{mass}} = \mathcal{L}_{\text{D,m}} + \mathcal{L}_{\text{M,m}} = m(\nu_L^\dagger \nu_R + \nu_R^\dagger \nu_L) + i\frac{M}{2}(\nu_L^\dagger \sigma_2 \nu_L^\star - \nu_L^T \sigma_2 \nu_L)$$

- Where ϕ_L and ϕ_R is the same spinor defined in last page

$$\psi_L = \begin{pmatrix} \nu_L \\ i\sigma_2 \nu_L^\star \end{pmatrix}, \quad \psi_R = \begin{pmatrix} -i\sigma_2 \nu_R^\star \\ \nu_R \end{pmatrix}$$

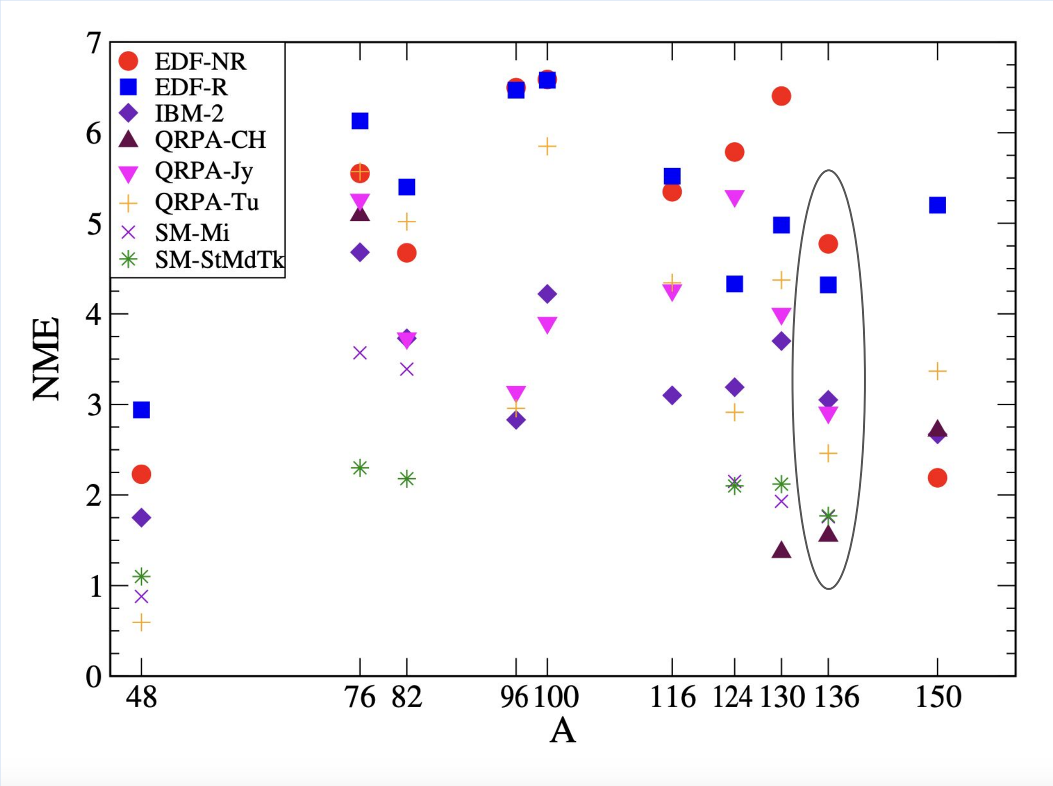
- The mass term becomes

$$\mathcal{L}_{\text{mass}} = -m\bar{\psi}_L \psi_R - \frac{M}{2}\bar{\psi}_R \phi_R = (\bar{\psi}_R \quad \bar{\psi}_L)\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}\begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

- Eigenvalue:

$$M_+ = \sqrt{m^2 + \frac{1}{4}M^2} + \frac{1}{2}M \approx M, \qquad M_- = \sqrt{m^2 + \frac{1}{4}M^2} - \frac{1}{2}M \approx m^2/M$$

Back up - NME



Compilation of nuclear matrix element calculations (arXiv:1902.04097)

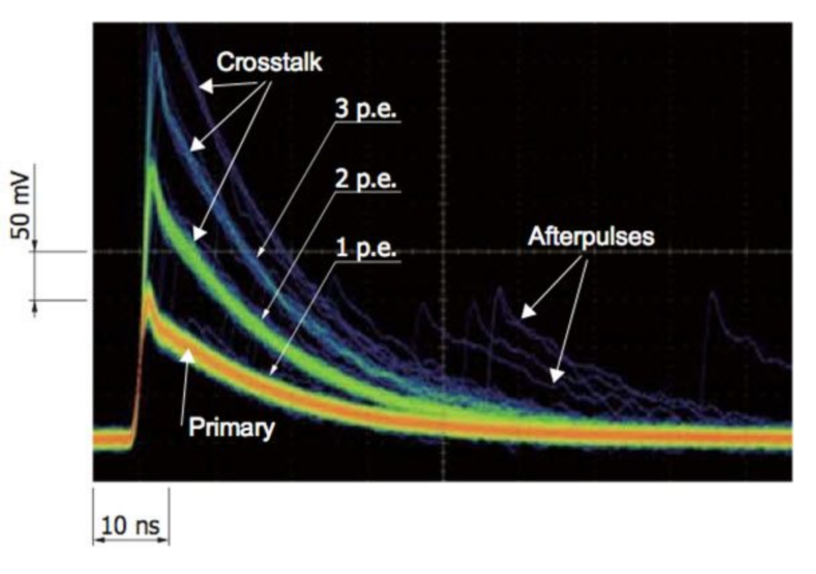
$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} g_A^4 |M^{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

Nuclear matrix element (NME) - range of values. arXiv:2106.16243 cites a range of nuclear approaches: Interacting Shell Model (ISM), QRPA, EDF, Interacting Boson Model (IBM-2),...

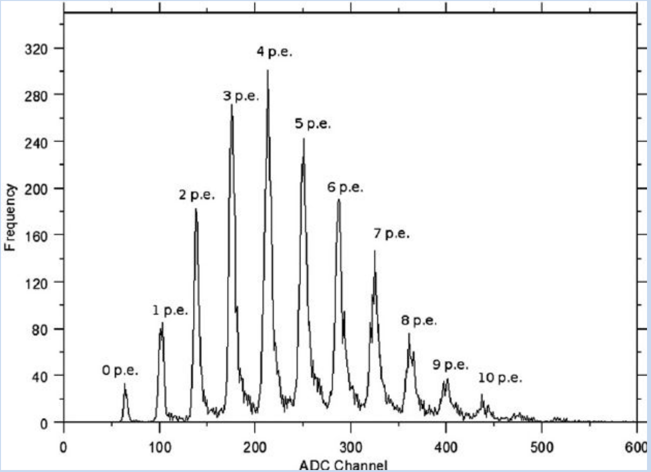
Summary

- DRUMXe - $0\nu\beta\beta$ experiment underground, using ton-scale liquid ^{136}Xe as target
  - Xe target material is enriched, such that ^{136}Xe makes up a large %
- Aiming to probe normal ordering regime for neutrino mass

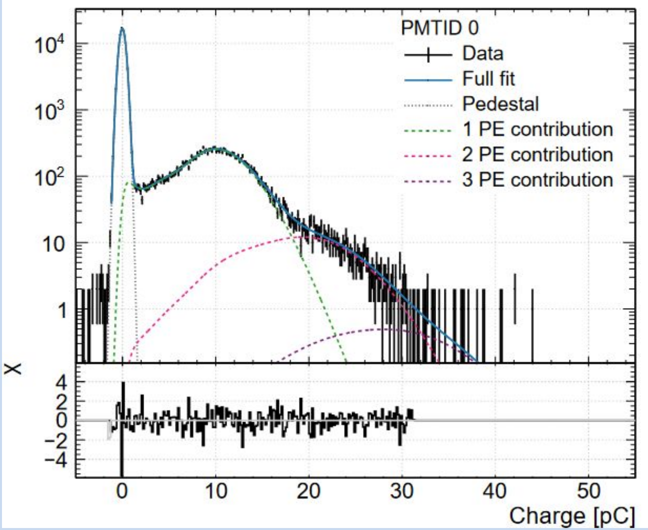
SiPM vs PMT



Crosstalk
3 p.e.
2 p.e.
1 p.e.
Afterpulses
Primary
50 mV
10 ns



0 p.e.
1 p.e.
2 p.e.
3 p.e.
4 p.e.
5 p.e.
6 p.e.
7 p.e.
8 p.e.
9 p.e.
10 p.e.
Frequency
ADC Channel

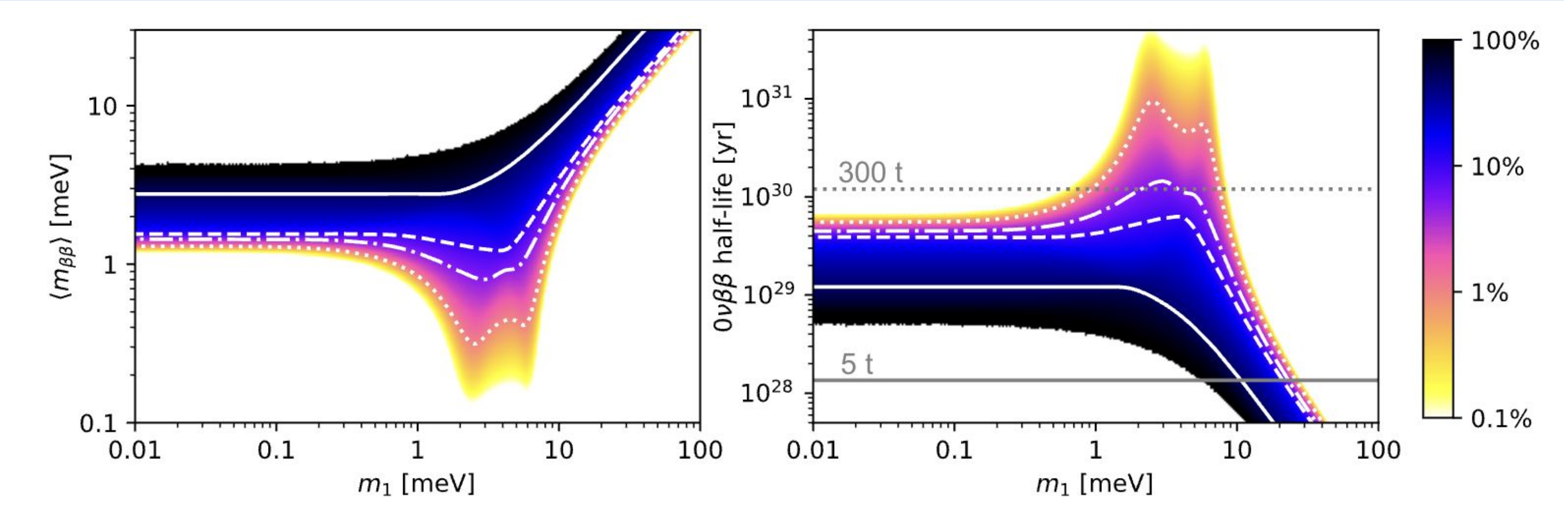


PMTID 0
Data
Full fit
Pedestal
1 PE contribution
2 PE contribution
3 PE contribution
χ
Charge [pC]

Experiment Sensitivity

- Enrichment vs increasing target mass given that you chose a good target already
- Reach lower energy threshold
- Eliminate/understand your background
- Think of the physics processes involved. What about using heavy neutrino

$$T^{0\nu}_{1/2} = \left(G\,|\mathcal{M}|^2\,\langle m_{\beta\beta}\rangle^2\right)^{-1} \simeq 10^{27-28}\left(\frac{0.01\,\text{eV}}{\langle m_{\beta\beta}\rangle}\right)^2 \text{years.}$$



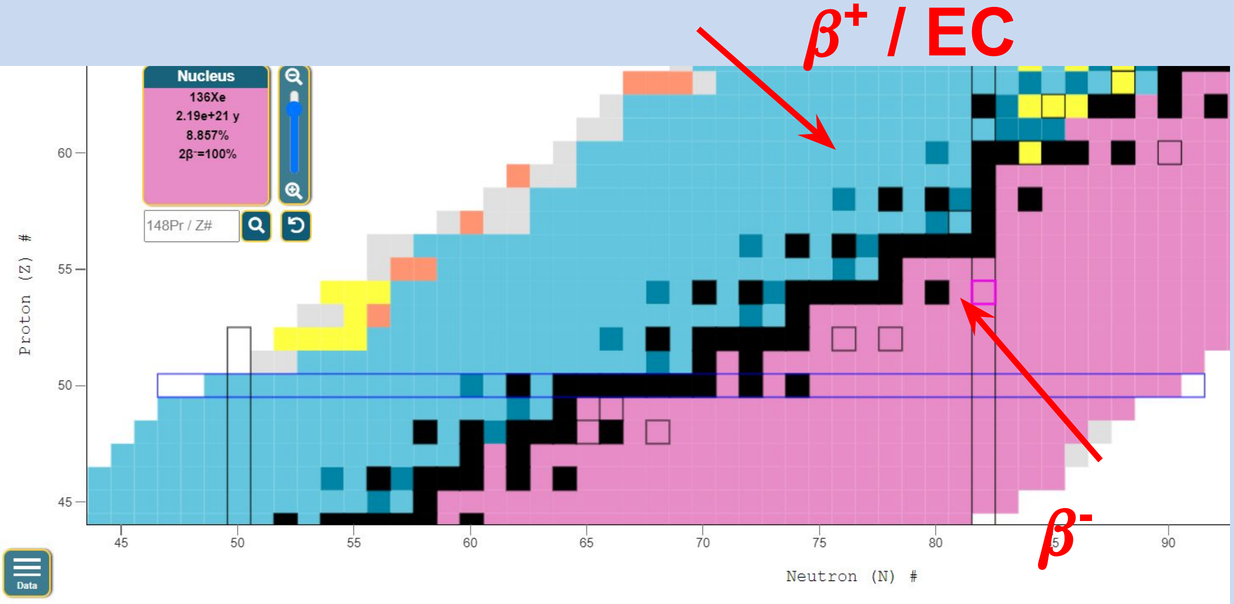
EDI Initiative #3

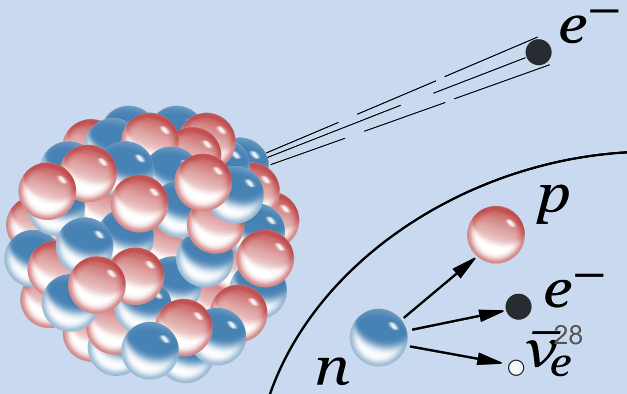
Set up an EDI committee for the collaboration

- Ensure member diversity
- Set up “representative” roles that target different academic levels, i.e. one that deals with undergraduate researchers, graduate researches, postdocs, academics, etc.

Beta β Decay

β decay involves the conversion of a proton to a neutron (or vice versa), and can go through either:

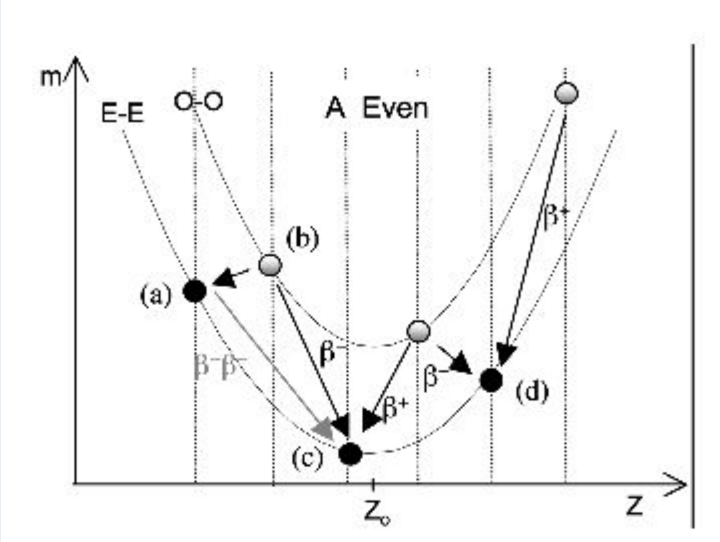


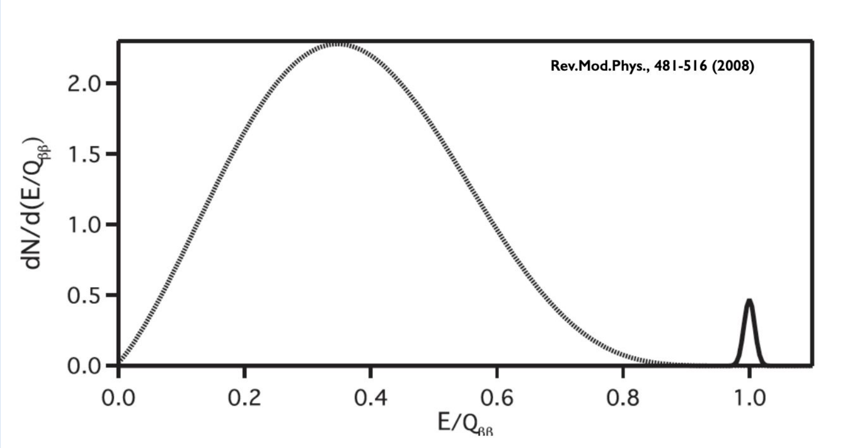


NNDC

Double Beta *ββ* Decay

- This process occurs for even-even nuclei, for which the ground state wave function has 0^+. Typically decay process is of $0^+ \rightarrow 0^+$.
-





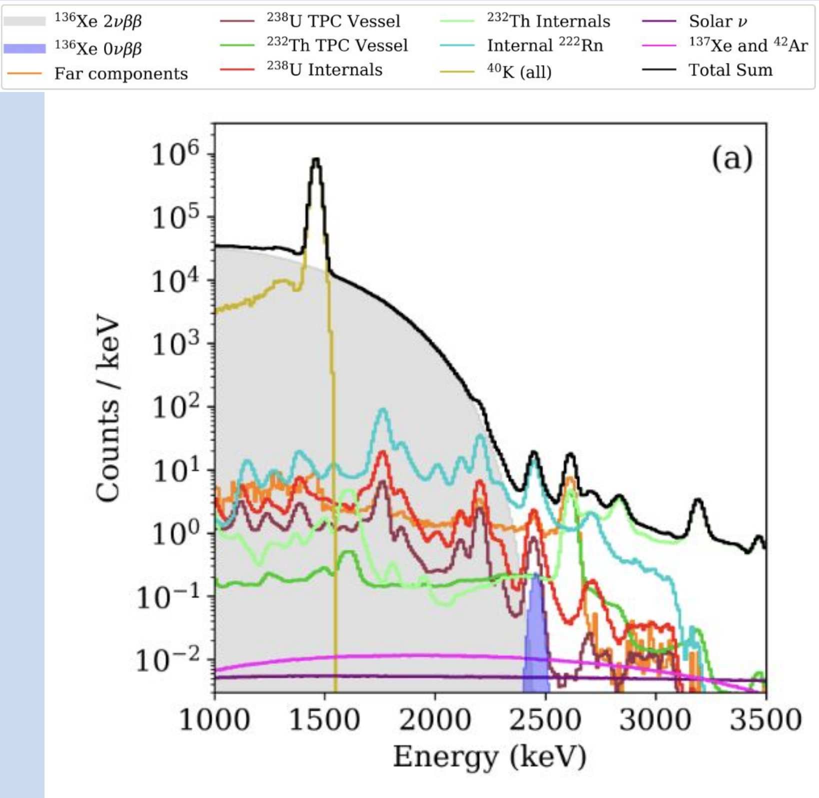
Double Beta $\beta\beta$ Decay

- This process occurs for even-even nuclei, for which the ground state wave function has 0^+. Typically decay process is of $0^+ \rightarrow 0^+$.
- Need $m(Z, A) > m(Z + 2, A)$ & $m(Z, A) < m(Z + 1, A)$

Nuclide	Half-life, 10^{21} years	Mode
^{48}Ca	$0.064^{+0.007}_{-0.006} \pm ^{+0.012}_{-0.009}$	$\beta^-\beta^-$
^{76}Ge	1.926 ± 0.094	$\beta^-\beta^-$
^{78}Kr	$9.2^{+5.5}_{-2.6} \pm 1.3$	εε
^{82}Se	$0.096 \pm 0.003 \pm 0.010$	$\beta^-\beta^-$
^{96}Zr	$0.0235 \pm 0.0014 \pm 0.0016$	$\beta^-\beta^-$
^{100}Mo	0.00693 ± 0.00004	$\beta^-\beta^-$
	$0.69^{+0.10}_{-0.08} \pm 0.07$	$\beta^-\beta^-$
^{116}Cd	$0.028 \pm 0.001 \pm 0.003$ $0.026^{+0.009}_{-0.005}$	$\beta^-\beta^-$
^{128}Te	7200 ± 400 1800 ± 700	$\beta^-\beta^-$
^{130}Te	$0.82 \pm 0.02 \pm 0.06$	$\beta^-\beta^-$
^{124}Xe	$18 \pm 5 \pm 1$	εε
^{136}Xe	$2.165 \pm 0.016 \pm 0.059$	$\beta^-\beta^-$
^{130}Ba	(0.5 – 2.7)	εε
^{150}Nd	$0.00911^{+0.00025}_{-0.00022} \pm 0.00063$	$\beta^-\beta^-$
	$0.107^{+0.046}_{-0.026}$	$\beta^-\beta^-$
^{238}U	2.0 ± 0.6	$\beta^-\beta^-$

Sources of background

- Plot produced by nEXO collaboration, showing the main sources of background for $0\nu\beta\beta$ search using Xe



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$0\nu\beta\beta$ Experimental Requirement

Theoretical motivation:

Nuclide	Half-life, 10^{21} years	Mode
^{48}Ca	$0.064^{+0.007}_{-0.006} \pm ^{+0.012}_{-0.009}$	$\beta^-\beta^-$
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^{100}Mo	0.00693 ± 0.00004	$\beta^-\beta^-$
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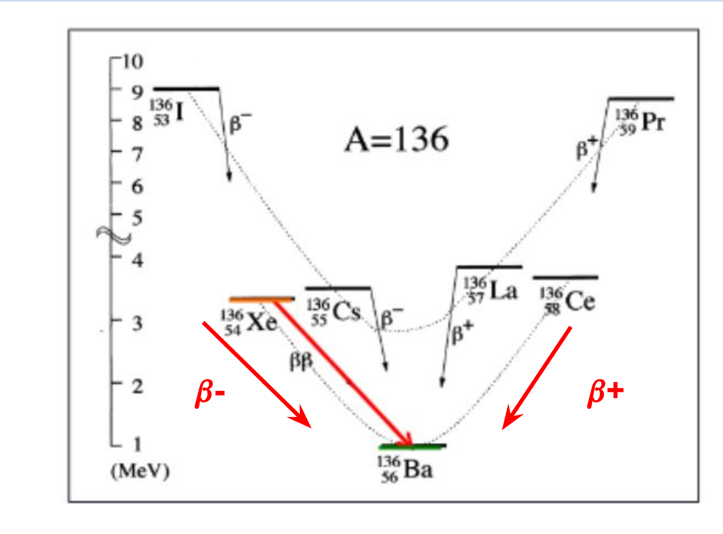
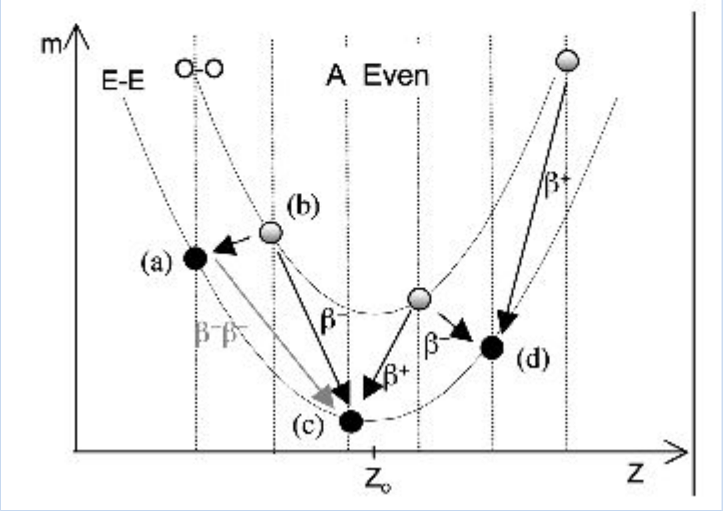
	$0.107^{+0.046}_{-0.026}$	$\beta^-\beta^-$
^{238}U	2.0 ± 0.6	$\beta^-\beta^-$

Double Beta $\beta\beta$ Decay

- Isotope decays from higher to lower excess mass.
- Need $m(Z, A) > m(Z \pm 2, A)$ & $m(Z, A) < m(Z \pm 1, A)$
- This process occurs for even-even nuclei, for which the ground state wave function has 0^+. Typically decay process is of $0^+ \rightarrow 0^+$.





Neutrinoless Double Beta Decay $0\nu\beta\beta$

Theoretical motivation:

- Neutrino might be Majorana fermion
    - It’s is its own antiparticle
- If so, we should see neutrino annihilation in double beta decay.
- Lead to the explanation of low neutrino mass and introduce right-handed neutrinos (Sterile neutrino).