Neutrinoless Double Beta Decay

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Phys 290E - UC Berkeley
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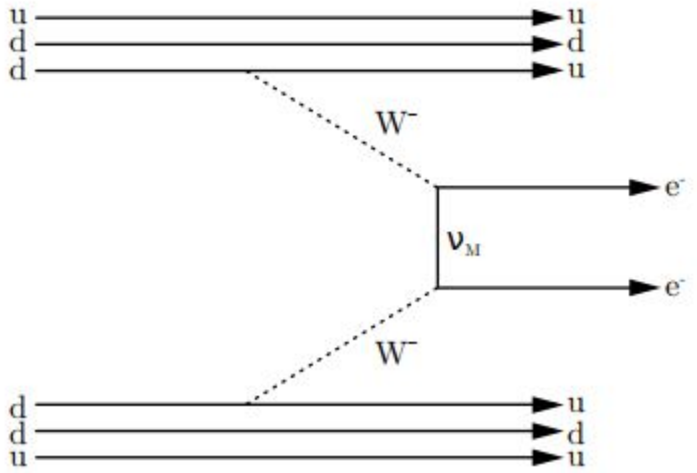
Overview

- Theoretical background
- Experimental design
- Selection of results

Why Should I Care?



- 0vββ: nuclear double beta decay where no neutrinos are in the final state (left)
- (A, Z) → (A, Z + 2) + 2e−
- SM conserves total lepton number L
- 0vββ would be direct evidence of BSM processes
- Premised on neutrinos being Majorana particles

Majorana what nows?

Ettore Majorana

- All SM particles are (so far) all Dirac
- Majorana particles are massive particles which are their own antiparticles
- Neutrinos are only SM candidates for Majorana particles (massive and neutral)
- Appear in Lagrangians as terms like

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

- Most interesting man alive?

Right Handed Neutrinos and the Seesaw Mechanism

How can I shove these cool new mass terms into the standard model?

Kill two birds with one stone!

$$\mathcal{L}_{\text{mass}} = -\bar{\nu}_{\mathrm{R}i}\; m_{\ell i}^{\mathrm{Dirac}}\; \nu_{\mathrm{L}\ell} + \frac{1}{2}\bar{\nu}_{\mathrm{R}i}\; M_i\, C\; \bar{\nu}_{\mathrm{R}i}^{t} + h.c.$$

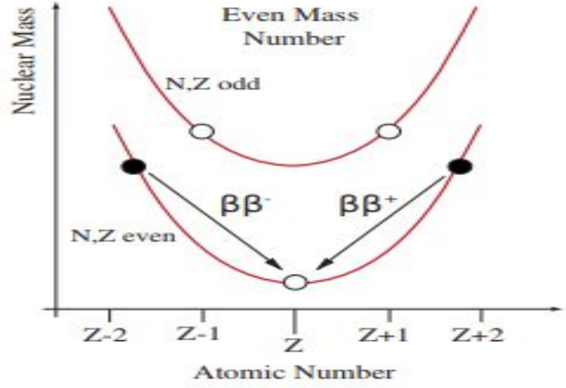
Heavy neutrinos have Majorana mass and at low energies, light neutrinos end up with effective Majorana mass inversely proportional to heavy neutrino mass

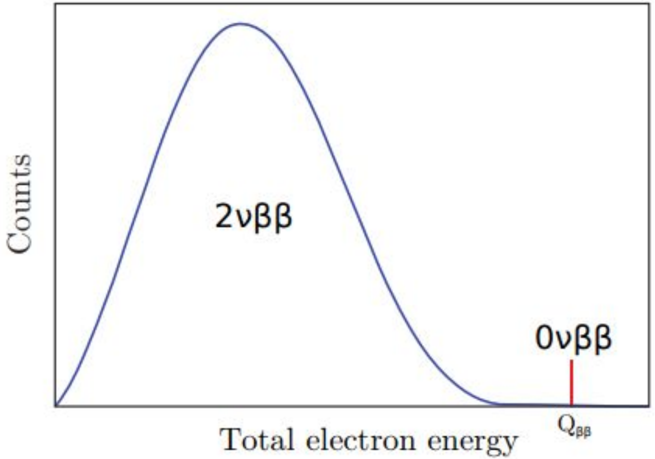
$$A = \begin{pmatrix} 0 & M \\ M & B \end{pmatrix}, \qquad \lambda_{\pm} = \frac{B \pm \sqrt{B^2 + 4M^2}}{2}. \qquad \lambda_{-} \approx -\frac{M^2}{B}.$$

Why haven't we already done this?

Now we want to observe 0νββ, what's stopping us?

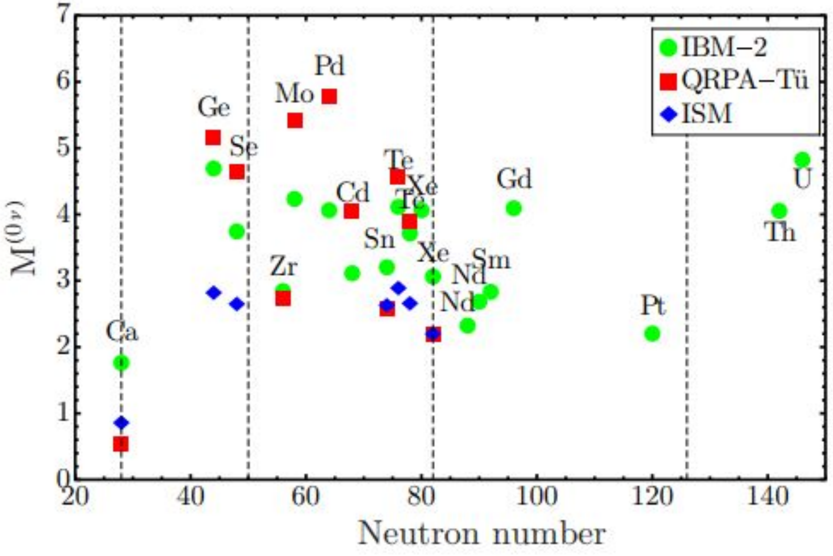
1. Nuclear matrix element calculations
2. Tiny rate
3. Energy resolution





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

NME: Why You Shouldn’t Try to Do Nuclear Physics

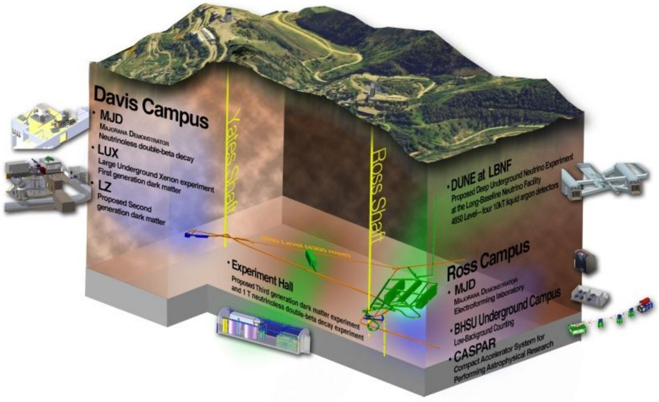


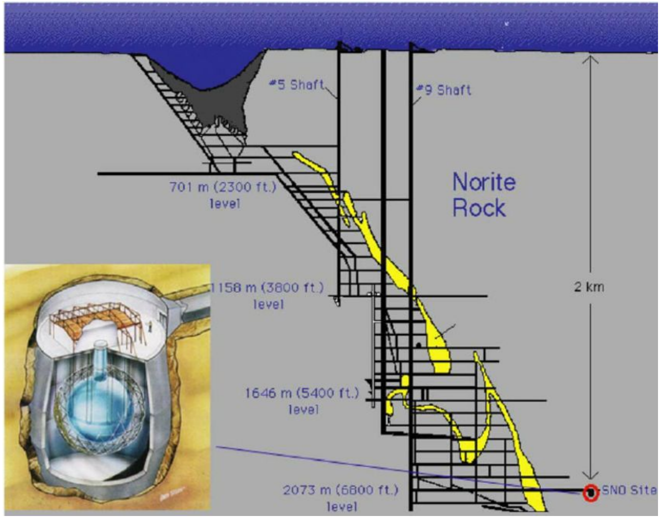
- Experiments are large piles of material in which this decay is possible.
- Simply measuring the energy of the decays
- Nuclear Matrix Element Calculations are very difficult
- Note that other processes give an idea of the error in 0vββ, its higher than it seems

Tiny Rate: Let’s Check Out This Abandoned Mine Scooby

NME is a theoretical issue, so why can’t we measure it and figure out the rest later? 2vββ and consequently 0vββ have very low probabilities of occuring, leading to very low rates.

One crucial requirement: low background rate





Energy Resolution: Squint, Alot

There are two broad classes of experiment

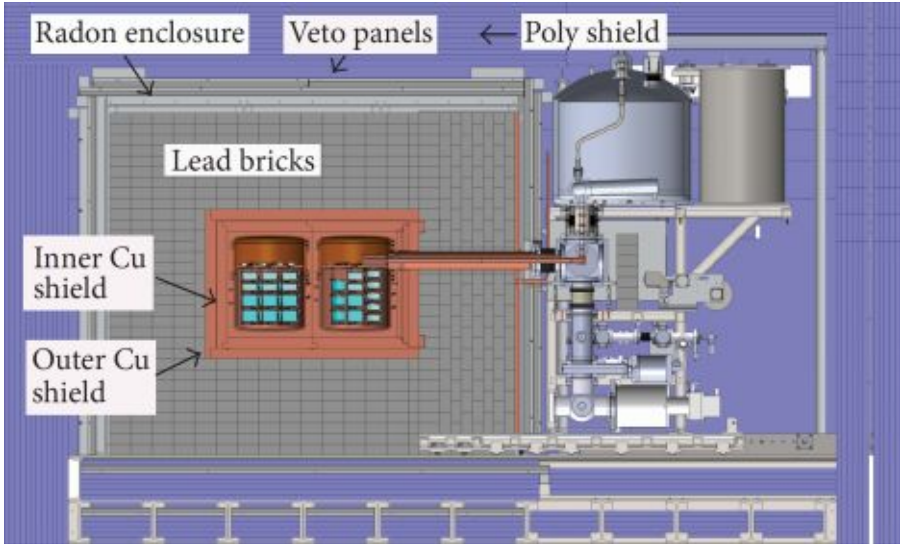
Detector + Source

- Fully reconstructible event topology enabling background reduction (good)
- Low energy resolution and intrinsic limits on the size of the source material (bad)

Detector = Source

- Good energy resolution (good)
- Scalable (good)
- Not generally able to reconstruct the event topology (bad)
- Limited in choices of material (bad)

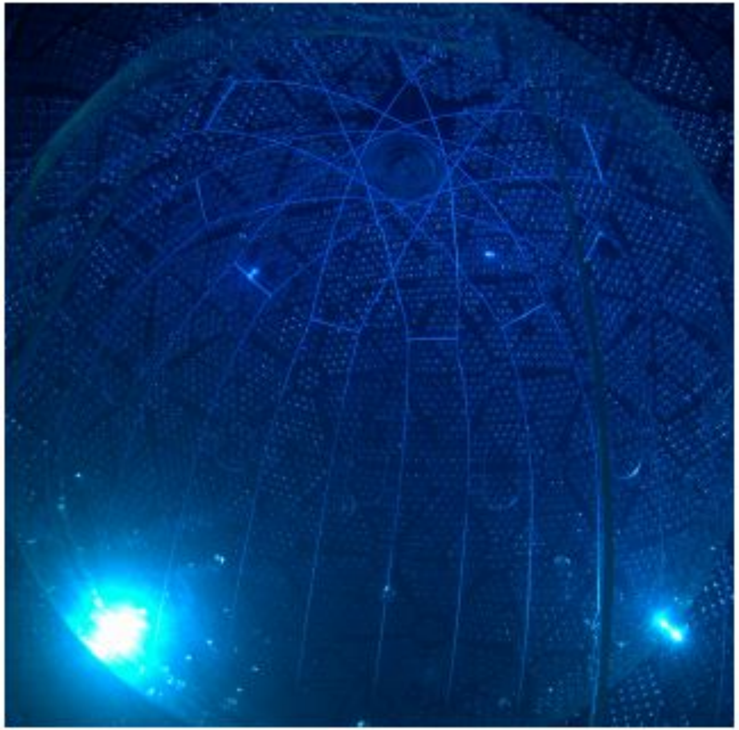
Experiment Example: Majorana Demonstrator



- Ge 76 (enriched and natural)
- Calorimetric approach (source coincides with detector)
- Competitive predictive limits for Ge with full lifetime
- Ge Diode detection principle

arXiv:1711.11145

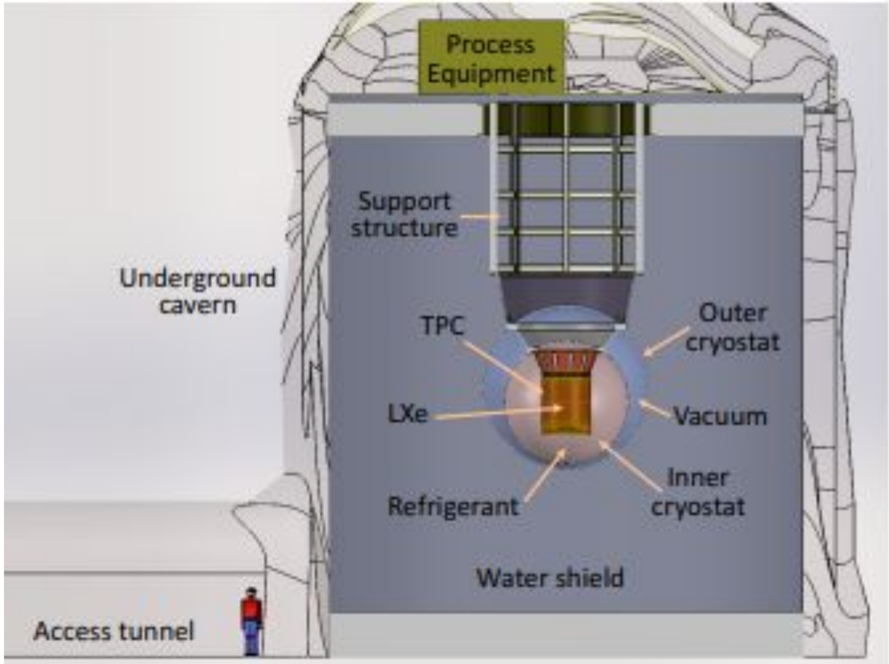
Experiment Example: SNO+



arXiv:1711.11094

- Te based experiment
- The isotope is mixed with water (liquid scintillator)
- Read out by pmts
- Water veto on the outside

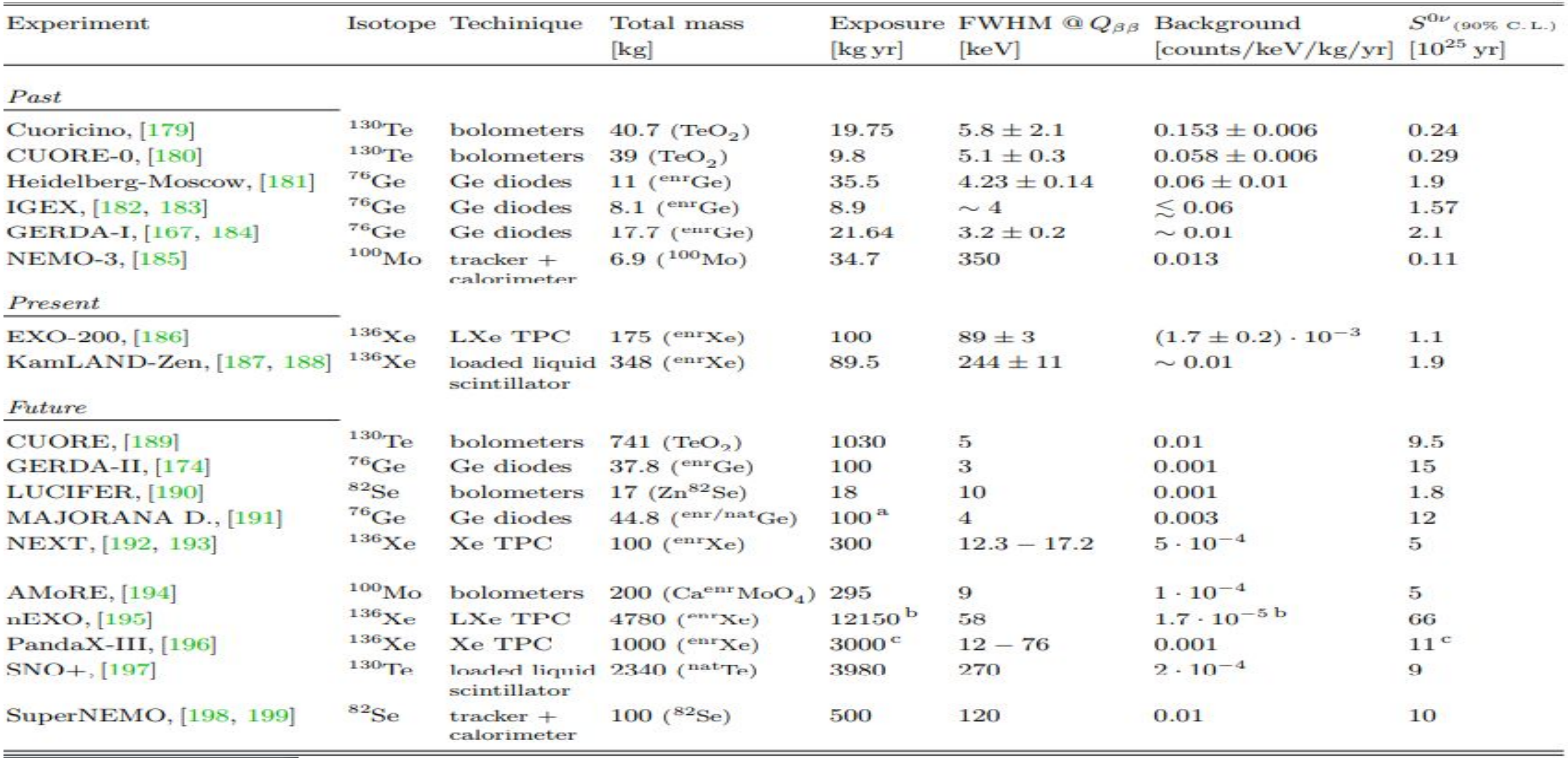
Experiment Example: (n)EXO



arXiv:1710.05075

- Liquid Xenon based detector
- Uses both scintillation light and a TPC to detect events
- Full event topology is reconstructed with good energy resolution
- Able to tag background processes for veto to further suppress backgrounds
- Predicted best limits

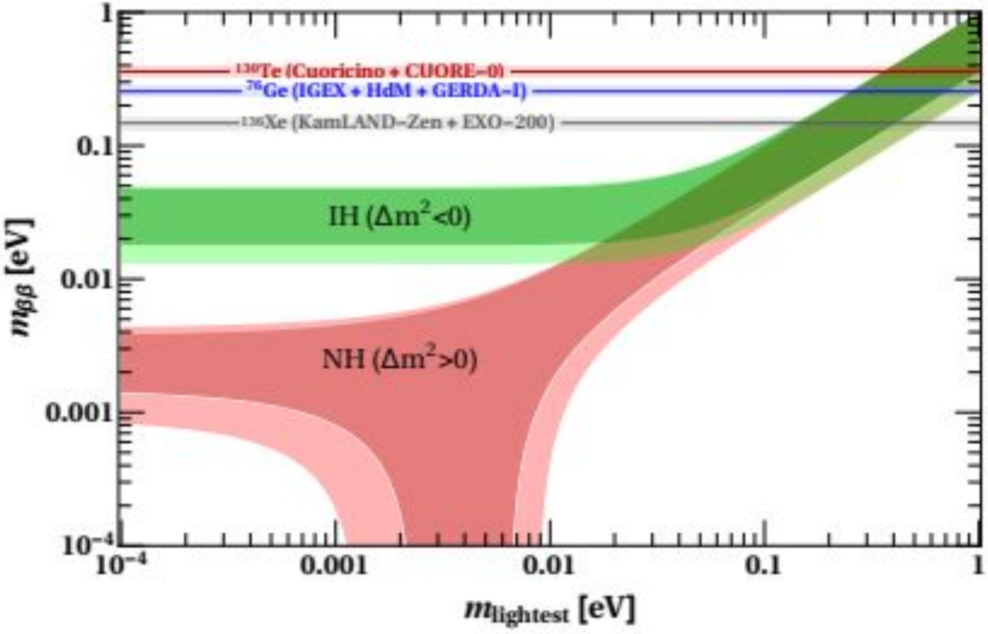
Table of Results



Experiment	Isotope	Techinique	Total mass [kg]	Exposure [kg yr]	FWHM @ $Q_{\beta\beta}$ [keV]	Background [counts/keV/kg/yr]	$S^{0\nu}$ (90% C.L.) [10^{25} yr]
Past							
Cuoricino, [179]	^{130}Te	bolometers	40.7 (TeO_2)	19.75	5.8 ± 2.1	0.153 ± 0.006	0.24
CUORE-0, [180]	^{130}Te	bolometers	39 (TeO_2)	9.8	5.1 ± 0.3	0.058 ± 0.006	0.29
Heidelberg-Moscow, [181]	^{76}Ge	Ge diodes	11 (^{enr}Ge)	35.5	4.23 ± 0.14	0.06 ± 0.01	1.9
IGEX, [182, 183]	^{76}Ge	Ge diodes	8.1 (^{enr}Ge)	8.9	~ 4	$\lesssim 0.06$	1.57
GERDA-I, [167, 184]	^{76}Ge	Ge diodes	17.7 (^{enr}Ge)	21.64	3.2 ± 0.2	~ 0.01	2.1
NEMO-3, [185]	^{100}Mo	tracker + calorimeter	6.9 (^{100}Mo)	34.7	350	0.013	0.11
Present							
EXO-200, [186]	^{136}Xe	LXe TPC	175 (^{enr}Xe)	100	89 ± 3	$(1.7 \pm 0.2) \cdot 10^{-3}$	1.1
KamLAND-Zen, [187, 188]	^{136}Xe	loaded liquid scintillator	348 (^{enr}Xe)	89.5	244 ± 11	~ 0.01	1.9
Future							
CUORE, [189]	^{130}Te	bolometers	741 (TeO_2)	1030	5	0.01	9.5
GERDA-II, [174]	^{76}Ge	Ge diodes	37.8 (^{enr}Ge)	100	3	0.001	15
LUCIFER, [190]	^{82}Se	bolometers	17 ($Zn^{82}Se$)	18	10	0.001	1.8
MAJORANA D., [191]	^{76}Ge	Ge diodes	44.8 ($^{enr/nat}$Ge)	100 [a]	4	0.003	12
NEXT, [192, 193]	^{136}Xe	Xe TPC	100 (^{enr}Xe)	300	$12.3 - 17.2$	$5 \cdot 10^{-4}$	5
AMoRE, [194]	^{100}Mo	bolometers	200 ($Ca^{enr}MoO_4$)	295	9	$1 \cdot 10^{-4}$	5
nEXO, [195]	^{136}Xe	LXe TPC	4780 (^{enr}Xe)	12150 [b]	58	$1.7 \cdot 10^{-5}$ [b]	66
PandaX-III, [196]	^{136}Xe	Xe TPC	1000 (^{enr}Xe)	3000 [c]	$12 - 76$	0.001	11 [c]
SNO+, [197]	^{130}Te	loaded liquid scintillator	2340 (^{nat}Te)	3980	270	$2 \cdot 10^{-4}$	9
SuperNEMO, [198, 199]	^{82}Se	tracker + calorimeter	100 (^{82}Se)	500	120	0.01	10

Current Limits

- Common to consider intersection of oscillations and 0νββ
- Different 0νββ limits lead to different implications for mass splitting scenarios
- Cosmological constraints and different models, also play a role in the full physics of this search



Questions

Reference

1. S. Dell'Oro, S. Marcocci, M. Viel, F. Vissani. Neutrinoless double beta decay: 2015 review. Advances in High Energy Physics, Volume 2016 (2016).