Neutrinoless Double Beta Decay: Your 0νββ future (2030)

Vincent Basque, Bruno Gelli, Joshua Martin, Michal Rigan, Jared Vann
Group 9

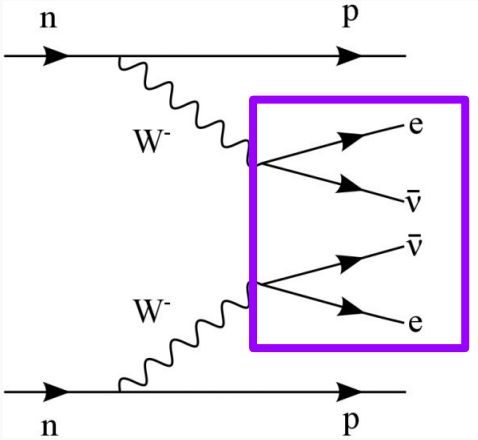
Neutrinoless Double Beta Decay:

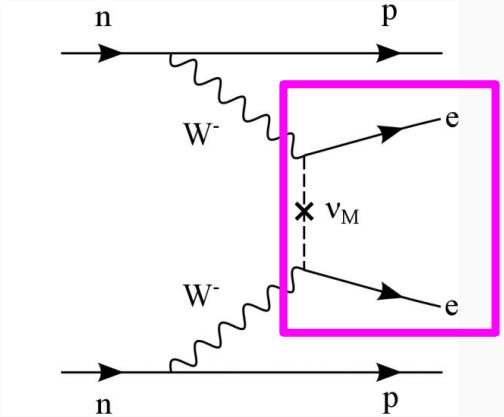
Yo[illegible] -> Our 0νββ present

Dr. Vincent Basque, Dr. Bruno Gelli,
Dr. Joshua Martin, Dr. Michal Rigan,
Dr. Jared Vann

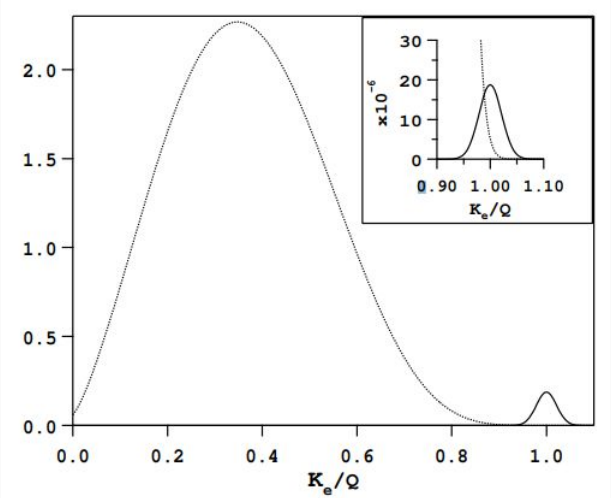
England winning the World Cup -->

Double beta decay mechanism

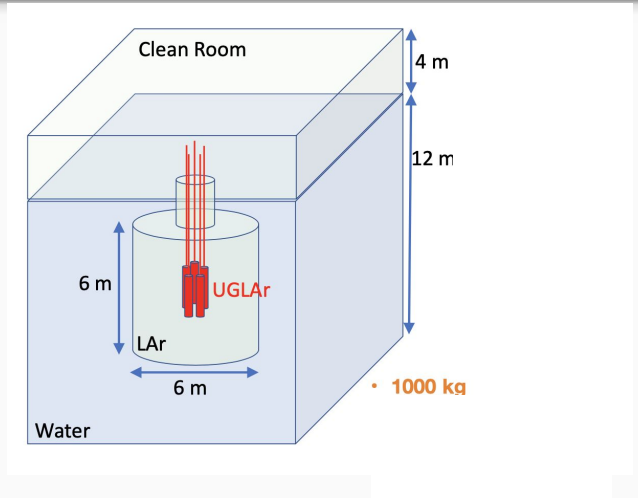




- 0νββ has been hypothesised for decades
- neutrinoLESS (learning by absence)
- electrons carry full Q
- ΔL = 2 => violates fundamental symmetry of SM
- 2019's lower limit on $T_{1/2} = 10^{25}$-10^{26}
- only possible if neutrinos are Majorana



The LEGEND Experiment



From Cheryl Patrick's slides

Location: LNGS, Gran Sasso, Italy 🇮🇹

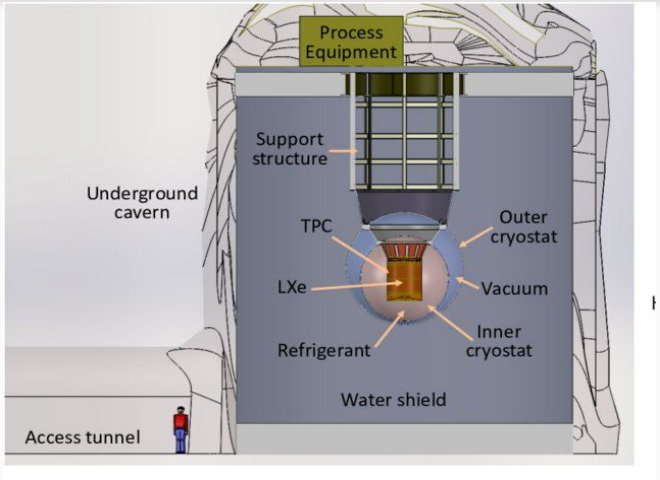
Technology: Germanium Crystal Detector

0νββ Isotope: ^{76}Ge

Active Mass: ~1000kg

$$T_{1/2}^{0\nu\beta\beta} = 5 \times 10^{27} years$$

The nEXO Experiment



nEXO Collaboration, Sensitivity and Discovery Potential of nEXO to Neutrinoless Double Beta Decay

Location: SNOLAB, Sudbury, Canada 🇨🇦

Technology: Liquid Xe TPC Detector

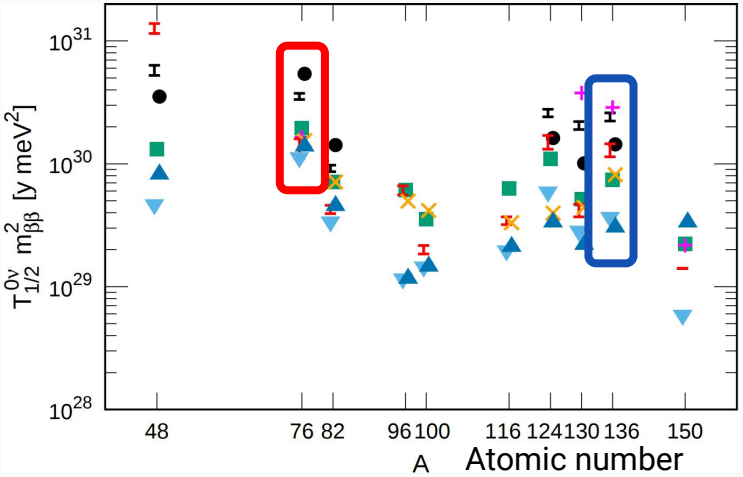
0νββ Isotope: ^{136}Xe enriched at ~90%

Active Mass: ~4036kg

$$T_{1/2}^{0\nu\beta\beta} = 7.5 \times 10^{27} years$$

Our Calculated Mass Limits from LEGEND and nEXO

- Using the found $T_{1/2}$ it is possible to obtain the effective neutrino mass (Majorana) through the equation below.
- The matrix elements were calculated using several models, producing different results.



$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}(Q,Z)\,|M_{0\nu}|^2\, m^2_{\beta\beta}$$

Decay half-life

Phase space factor

Nuclear matrix element

Majorana neutrino effective mass

$$m^2_{\beta\beta} = \frac{C}{T_{1/2}}$$

$$\sigma_{m_{\beta\beta}} = \frac{\sigma_T}{2}\sqrt{\frac{C}{T^3_{1/2}}}$$

Our Calculated Mass Limits from LEGEND and nEXO

Using the found $T_{1/2}$ it
neutrino effective mass

$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}$$

The matrix elem
several models, resulti

$$m^2_{\beta\beta} = \frac{C}{T_{1/2}}$$

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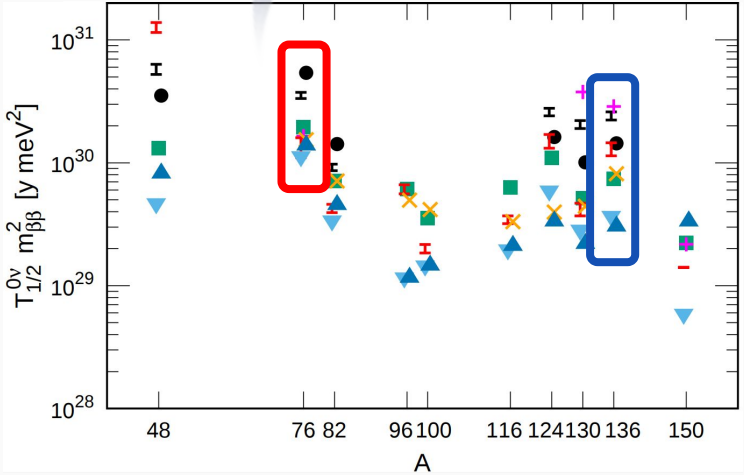
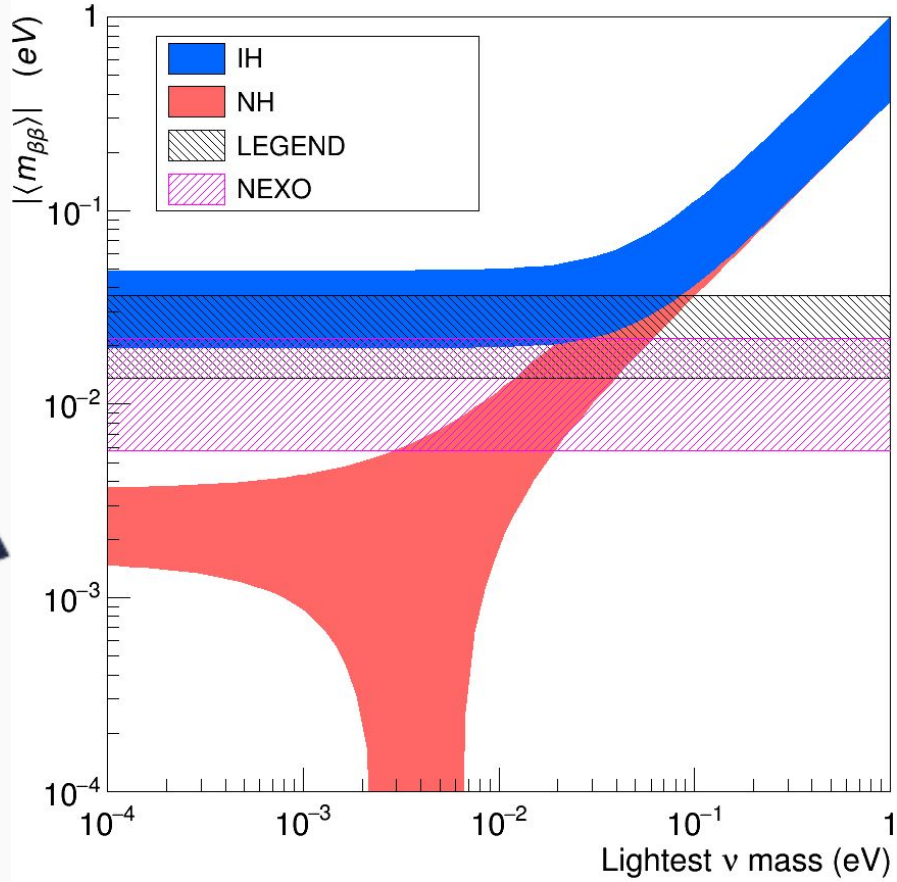
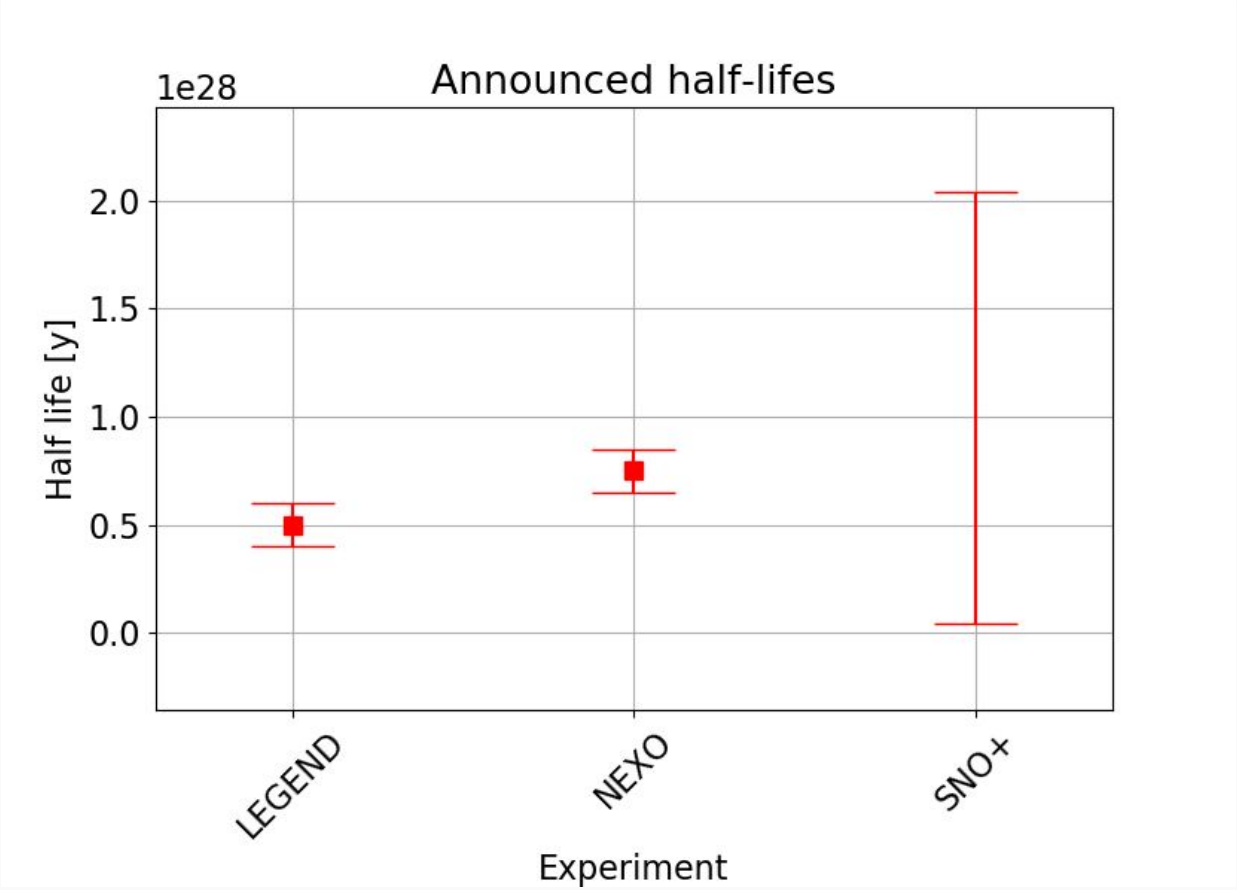




SNO+ Expected Results

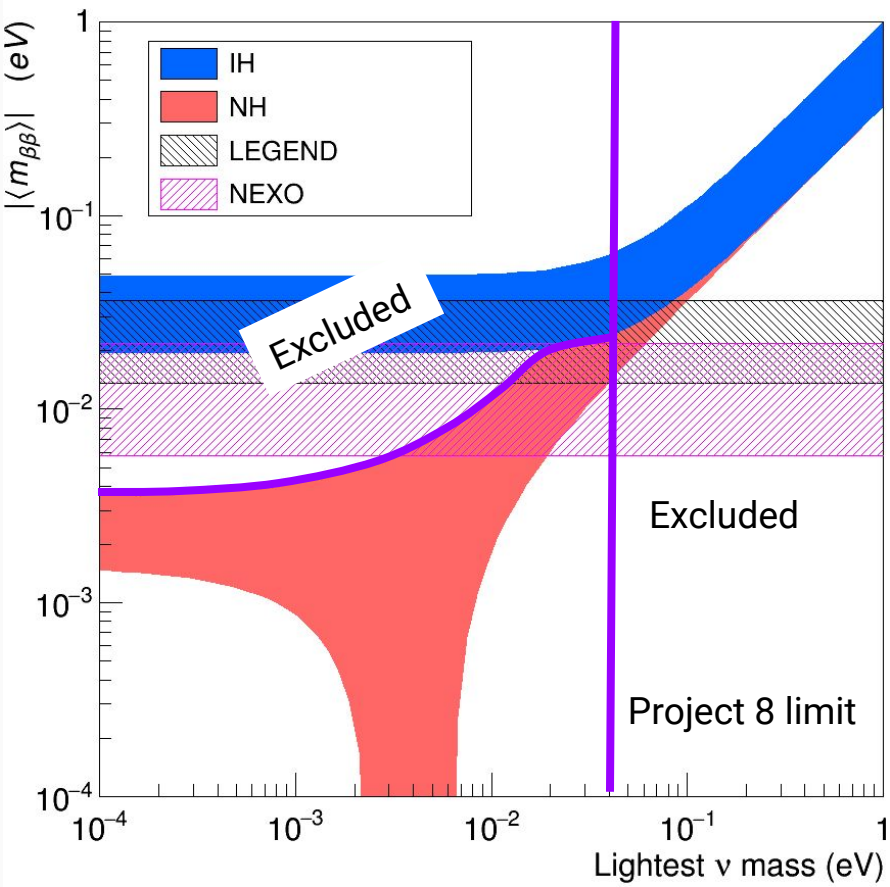
- From highest and lowest limit from LEGEND and nEXO, one can estimate the SNO+ half life prediction using the appropriate nuclear matrix element.
- Large uncertainty dominated by range in matrix elements.



Nature of the Neutrino and its properties

- Neutrinos are now determined to be Majorana due to the discovery in 2 different isotopes!
- Unfortunately, the hierarchy problem has not been solved in respect of the discovery of the $0\nu\beta\beta$.
- What do we do now?

- DUNE -> Normal Hierarchy at 4.94 σ!
- Project 8 (et al.) -> < 0.04 eV!



“How much will it cost? What can you save or reuse?” - Investors

- Thanks to DUNE, location, facilities, even large 10kTon LAr detector available! Free of charge!
- All we need is to modify a LArTPC to a LXeTPC by replacing the LAr with LXe (plus some purification & circulation…).
- LXe is at higher temperature (~162 K) compared to LAr (~90K).
- LXe is about twice dense as LAr, therefore we need twice more! A ~20kTon LXe supply is required!

- After long negotiation with Xe providers, we managed to secure 2kTon of Xe-136 and 18kTon of the other isotopes! For the sum of $700/kg!

20kTons of LXe you say? How much will this REALLY cost? Worth it?

Assuming the following:

- 7.5x10^27 years half life
- 10% detection efficiency
- 20kTon mass of Xe-136
- 100% enrichment of Xe-136

Advantage:

- Probe better Xe-136

$14B → 1.03 days/event For Xe-136

Assuming the following:

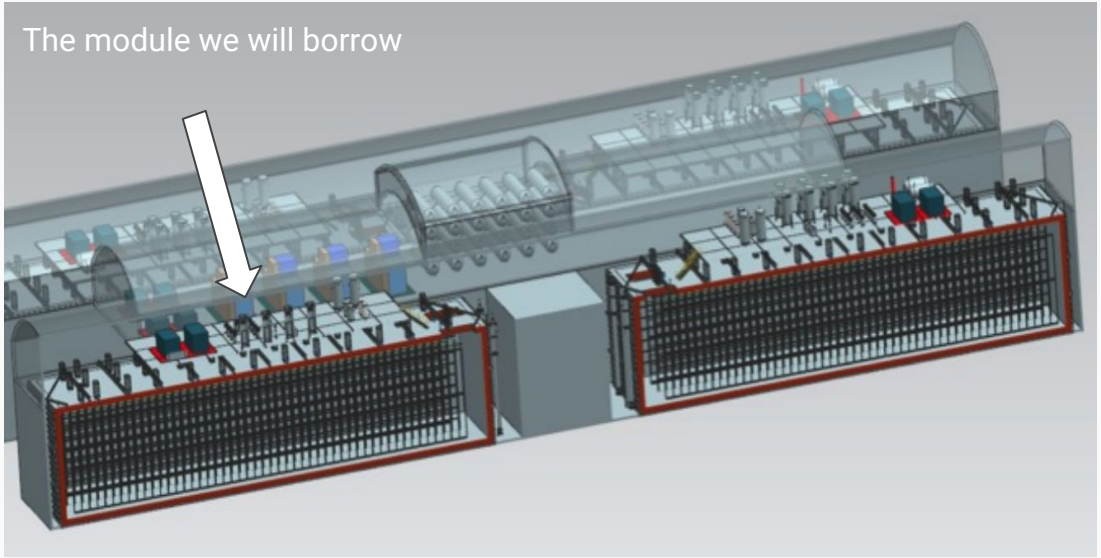
- 7.5x10^27 years half life
- 1% detection efficiency
- 2kTon mass of Xe-136
- 10% enrichment of Xe-136

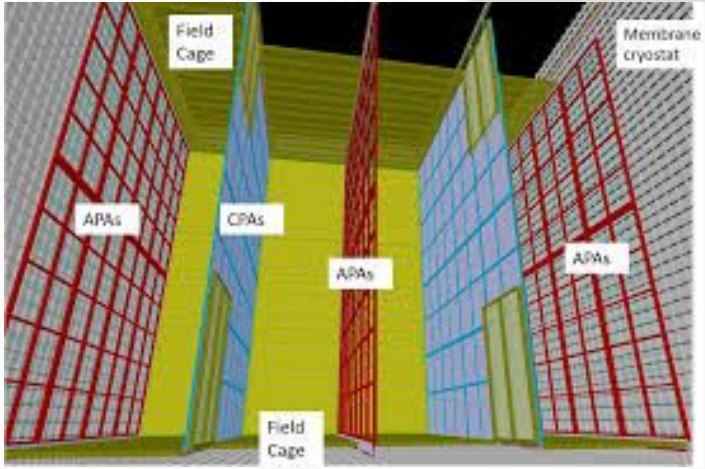
Advantages:

- 10 times Cheaper
- Can probe other Xe isotopes

$1.4B → 103 days/event For Xe-136

Our New Experiment Proposal: Dun(X)e





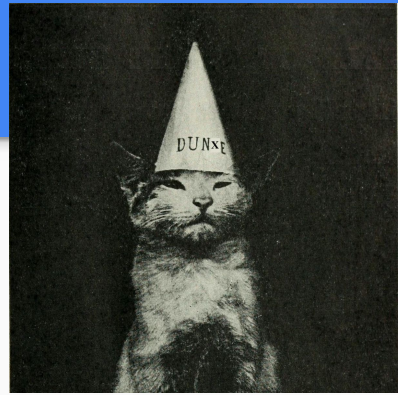
- "Borrow" one of the 10kTon LAr module.
- (We have connections with Dune leadership).
- Empty the LAr, install a LXe purification and recirculation system on the side.
- Fill with LXe.
- Take data!

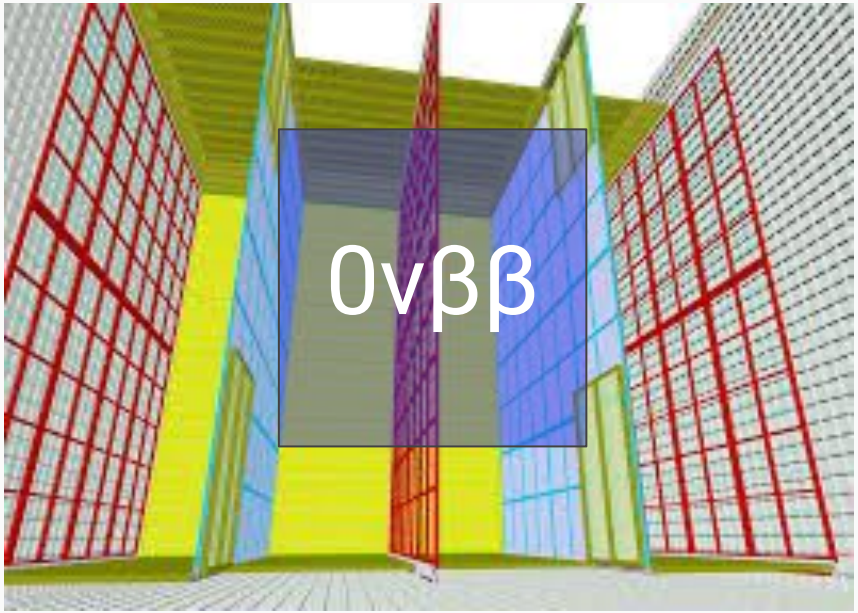
- Use current module configuration.
- Change configuration to make drift region smaller (more TPCs).
- Replace wires for pixel readout (less ambiguity due to pixel size, low noise, overcome pileup)

Overview of Dun(X)e

- Xenon is both the source and detection medium.
- It is also monolithic and self-shielding.

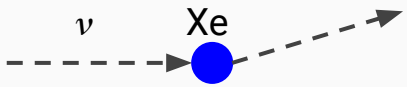
	Xe
Boiling Point [K] @ 1atm	165.0
Density [g/cm^3]	3.0
Radiation Length [cm]	2.8
dE/dx [MeV/cm]	3.8
Scintillation [γ/MeV]	42,000
Scintillation λ [nm]	175



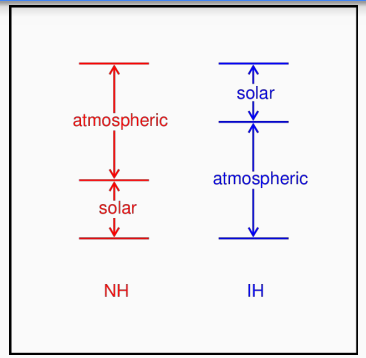


- Important background: ~2.5 MeV gammas from the rock with attenuation length of ~8.3 cm.
- Limiting the 0νββ Xe-136 region to the middle of the detector will greatly help (up to 3.6 m of shielding on either side).
- Use barium tagging concept from nEXO.
- Cathode wavelength-shifting reflectors increase amount of scintillation seen).

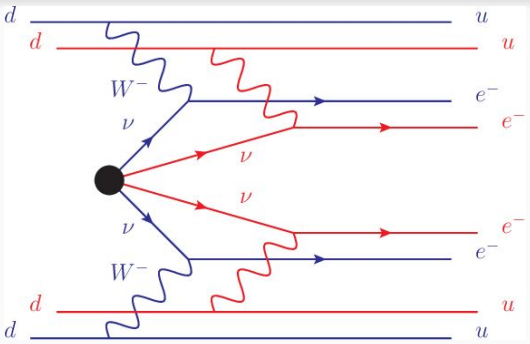
Other physics beyond 0νββ:



Neutrino cross-section with xenon (beam, atmospheric, supernova)



Better hierarchy determination



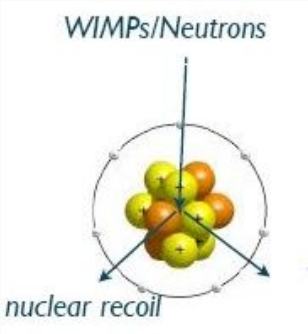
Neutrinoless Quadruple Beta Decay

$$^{134}Xe \rightarrow ^{134}Ba^{++} + e + e + \nu + \nu$$

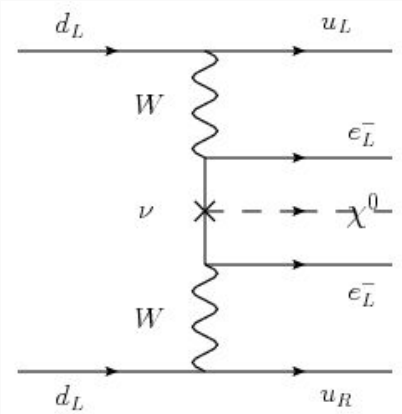
Observation of Xe-134 2νββ decay

$$^{124}Xe + 2e^- \rightarrow ^{124}Te + 2\nu_e$$

Xe-124 decay through double-electron capture



Nuclear recoil due to possible dark matter



Majoron emission

How to make money and perform particle physics research? We invest it in Xenon!

Sell all the xenon at >$701/kg when we are done! ⇒ $$$$:)

Option #2: What else is there?

- Since we are in it for the physics AND the money (to fund future experiment), a plan b as been thought through very carefully.
- Looking at the list of possible double beta decay isotopes there is only one more viable solution other than Xe...

$2\beta^-$-decay	$Q_{2\beta}$ [keV]	$T^{2\nu}_{1/2}$ [y]	$T^{0\nu}_{1/2}$ [y]
$^{46}Ca \to {}^{46}Ti$	990.4 ± 2.4		$> 1.0 \times 10^{17}$ (90%)
$^{48}Ca \to {}^{48}Ti$[a]	4272 ± 4	$4.2^{+3.3}_{-1.3} \times 10^{19}$	$> 1.5 \times 10^{21}$ (90%)
$^{70}Zn \to {}^{70}Ge$	1000.9 ± 3.4		$> 4.8 \times 10^{14}$
$^{76}Ge \to {}^{76}Se$	2039.006 ± 0.050	$(1.8 \pm 0.1) \times 10^{21}$	$> 1.9 \times 10^{25}$ (90%)
$^{80}Se \to {}^{80}Kr$	133.9 ± 3.7		
$^{82}Se \to {}^{82}Kr$	2995.1 ± 2.0	$(8.3 \pm 1.2) \times 10^{19}$	$> 2.7 \times 10^{22}$ (68%)
$^{86}Kr \to {}^{86}Sr$	1255.6 ± 2.4		
$^{94}Zr \to {}^{94}Mo$	1144.1 ± 2.0	$> 1.1 \times 10^{17}$ (90%)	$> 1.9 \times 10^{19}$ (90%)
$^{96}Zr \to {}^{96}Mo$[a]	3350.4 ± 2.9	$2.1^{+0.8}_{-0.4} \times 10^{19}$	$> 1.0 \times 10^{21}$ (90%)
$^{98}Mo \to {}^{98}Ru$	112 ± 6		$> 1.0 \times 10^{14}$
$^{100}Mo \to {}^{100}Ru$	3034 ± 6	$6.8^{+0.8}_{-0.9} \times 10^{18}$	$> 5.5 \times 10^{22}$ (90%)
$^{104}Ru \to {}^{104}Pd$	1300 ± 4		
$^{110}Pd \to {}^{110}Cd$	2000 ± 11	$> 6.0 \times 10^{16}$	$> 6.0 \times 10^{16}$
$^{114}Cd \to {}^{114}Sn$	536.8 ± 3.3	$> 9.2 \times 10^{16}$ (99%)	$> 2.0 \times 10^{20}$ (90%)
$^{116}Cd \to {}^{116}Sn$	2805.0 ± 3.8	$2.6^{+0.7}_{-0.4} \times 10^{19}$	$> 7.0 \times 10^{22}$ (90%)
$^{122}Sn \to {}^{122}Te$	366.2 ± 2.8		$> 5.8 \times 10^{13}$
$^{124}Sn \to {}^{124}Te$	2287.0 ± 1.5	$> 1.0 \times 10^{17}$	$> 2.4 \times 10^{17}$ (95%)
$^{128}Te \to {}^{128}Xe$	867.2 ± 1.0	$(2.2 \pm 0.3) \times 10^{24}$ (G)	$> 8.6 \times 10^{22}$ (90%)
$^{130}Te \to {}^{130}Xe$	2528.8 ± 1.3	$(7.9 \pm 1.0) \times 10^{20}$ (G)	$> 1.4 \times 10^{23}$ (90%)
$^{134}Xe \to {}^{134}Ba$	830.1 ± 3.0	$> 1.1 \times 10^{16}$	$> 8.2 \times 10^{19}$ (68%)
$^{136}Xe \to {}^{136}Ba$	2468 ± 7	$> 8.1 \times 10^{20}$ (90%)	$> 4.4 \times 10^{23}$ (90%)
$^{142}Ce \to {}^{142}Nd$	1416.9 ± 2.1	$> 1.6 \times 10^{17}$ (90%)	$> 1.5 \times 10^{19}$ (68%)
$^{146}Nd \to {}^{146}Sm$	70.2 ± 2.9		
$^{148}Nd \to {}^{148}Sm$	1928.8 ± 1.9	$> 3.0 \times 10^{18}$ (90%)	$> 3.0 \times 10^{18}$ (90%)
$^{150}Nd \to {}^{150}Sm$	3367.5 ± 2.2	$(6.8 \pm 0.8) \times 10^{18}$	$> 1.2 \times 10^{21}$ (90%)
$^{154}Sm \to {}^{154}Gd$	1251.0 ± 1.3	$> 2.3 \times 10^{18}$ (68%)	$> 2.3 \times 10^{18}$ (68%)
$^{160}Gd \to {}^{160}Dy$	1729.7 ± 1.3	$> 1.9 \times 10^{19}$ (90%)	$> 1.3 \times 10^{21}$ (90%)
$^{170}Er \to {}^{170}Yb$	653.6 ± 1.7	$> 3.2 \times 10^{17}$ (68%)	$> 3.2 \times 10^{17}$ (68%)
$^{176}Yb \to {}^{176}Hf$	1086.7 ± 1.9	$> 1.6 \times 10^{17}$ (68%)	$> 1.6 \times 10^{17}$ (68%)
$^{186}W \to {}^{186}Os$	488.0 ± 1.7	$> 5.9 \times 10^{17}$ (90%)	$> 2.7 \times 10^{20}$ (90%)
$^{192}Os \to {}^{192}Pt$	413.5 ± 3.0		$> 9.8 \times 10^{12}$
$^{198}Pt \to {}^{198}Hg$	1047 ± 3		$> 3.2 \times 10^{14}$
$^{204}Hg \to {}^{204}Pb$	416.3 ± 1.5		
$^{232}Th \to {}^{232}U$	842.2 ± 2.5		
$^{238}U \to {}^{238}Pu$	1145.0 ± 1.3	$(2.0 \pm 0.6) \times 10^{21}$ (R)	

[a] β^--decay energetically allowed but enormously suppressed.

Option #2: DUUUNE (Deep Underground Uranium Unique Neutrino Experiment) --->

DUUUNE

$^{238}U \rightarrow {}^{238}Pu \quad 1145.0 \pm 1.3 \quad (2.0 \pm 0.6) \times 10^{21}$ (R)

~50$/ kg for U-238!
>5 times more dense! :)

Uranium Ore

1,289 customer reviews | 300 answered questions

Patrick J. McGovern

Great reviews, long legivity!

Great Product, Poor Packaging

May 14, 2009

I purchased this product 4.47 Billion Years ago and when I opened it today, it was half empty.

27,447 people found this helpful

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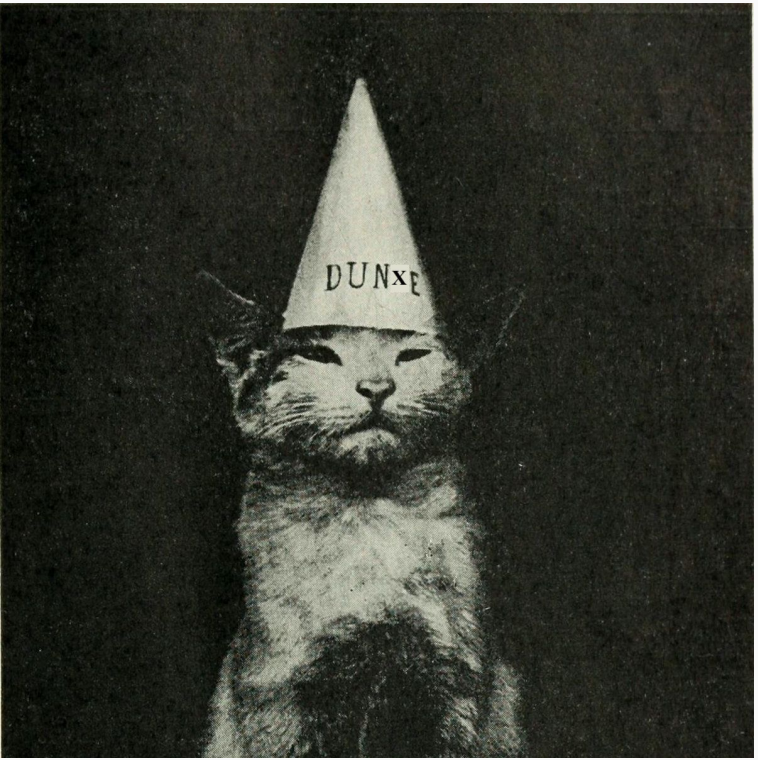
Important choice to make...



OR

DUUUNE

Thanks!

Contact us with funding opportunities:

Dun(X)e/DUUUNE Collaboration
Kirk Street and Wilson Road
Batavia, IL 60510

Questions?