Searches for Double Beta Decay of ^{134}Xe with EXO-200 Phase II Data

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on behalf of the EXO-200 Collaboration

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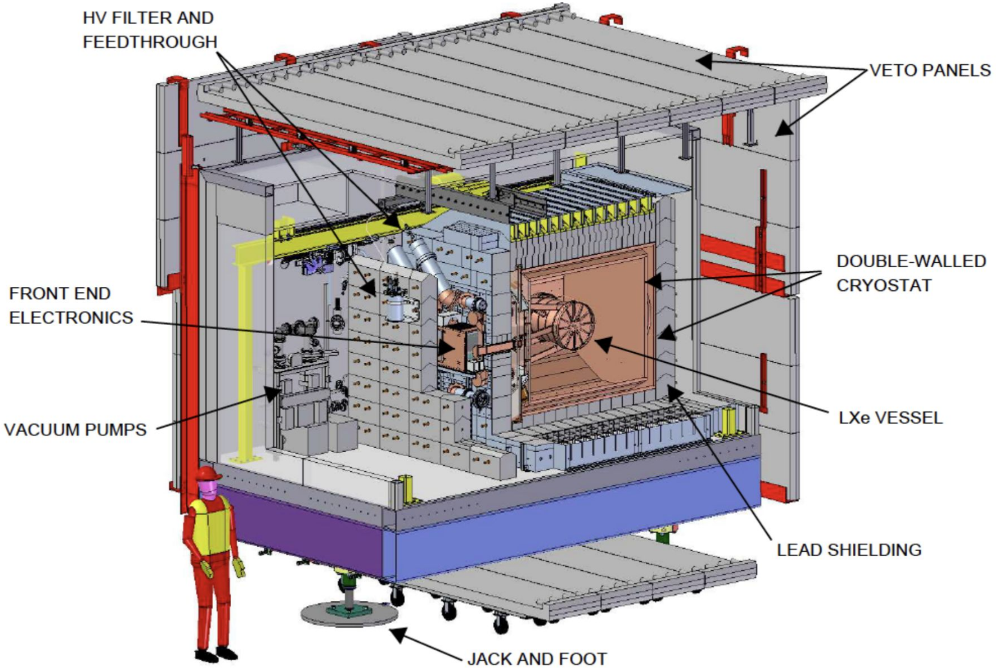
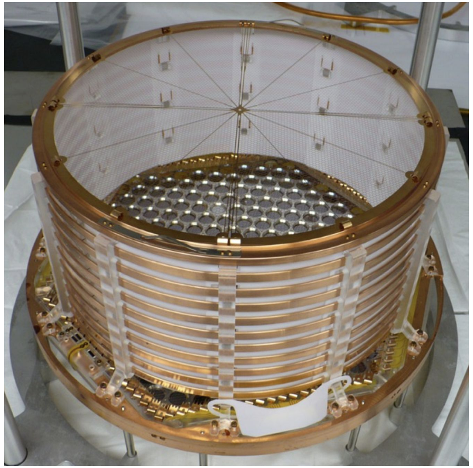
Outline

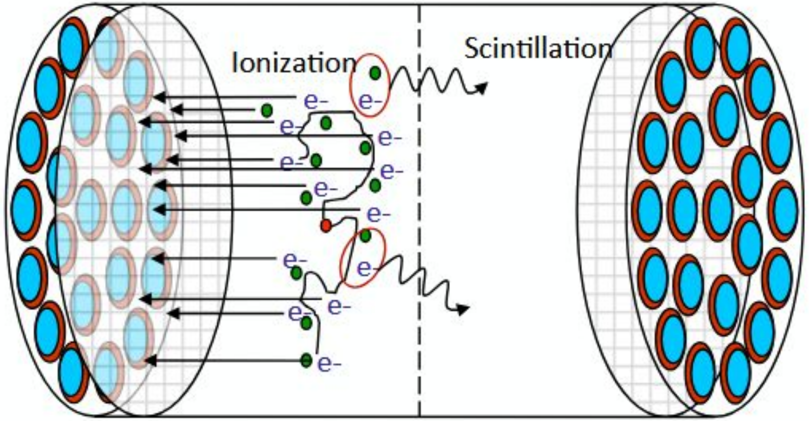
- The EXO-200 Experiment
- Double Beta Decay in ^{134}Xe
- Analysis Methodology
- Results
    - Sensitivity reach
    - $\beta\beta$ half-lives of ^{134}Xe
- Outlook & nEXO



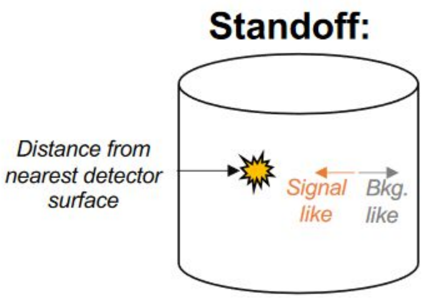
The EXO-200 TPC

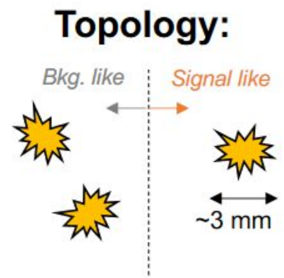
- Active 2011-2018 at WIPP underground site in New Mexico
  - Phase I ended in 2014 → Phase II began in 2016
  - First observation of $2\nu\beta\beta$ decay of ^{136}Xe in 2011
  - Lower bound of $0\nu\beta\beta$ decay of ^{136}Xe: > 3.5×10^{25} y
- 200 kg LXe (≈ 130 kg of LXe in active volume)
  - 80.672% ^{136}Xe and 19.098% ^{134}Xe
- TPC split into two drift regions sharing a common wire grid cathode
- Combination of scintillation and ionization signal allows full 3D reconstruction
- Prompt scintillation measured on two planes of Large Area Avalanche Photodiode (LAAPD)
- Delayed ionization signal measured by crossed wires for x-y plane reconstruction



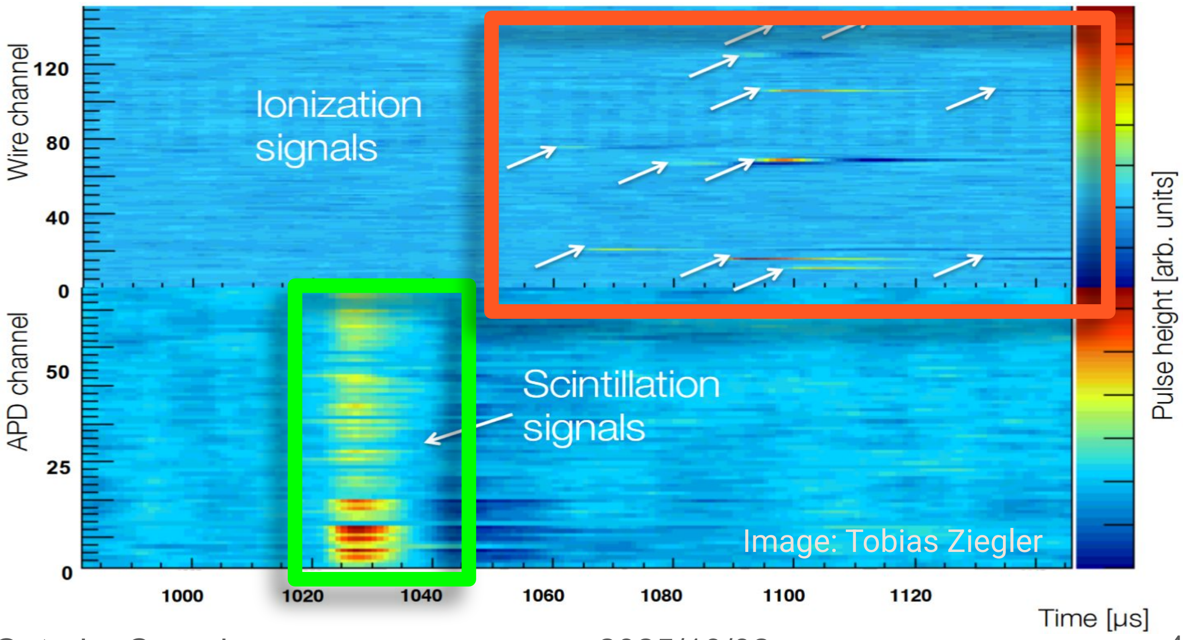


EXO-200





- ★ Single-phase LXe time projection chamber
  - Prompt scintillation
  - Delayed, distributed ionization
- ★ Topological discrimination between single-site (SS) and multi-site (MS) events



EXO-200

Number of electrons and photons from an event is anti-correlated and depends on electric field

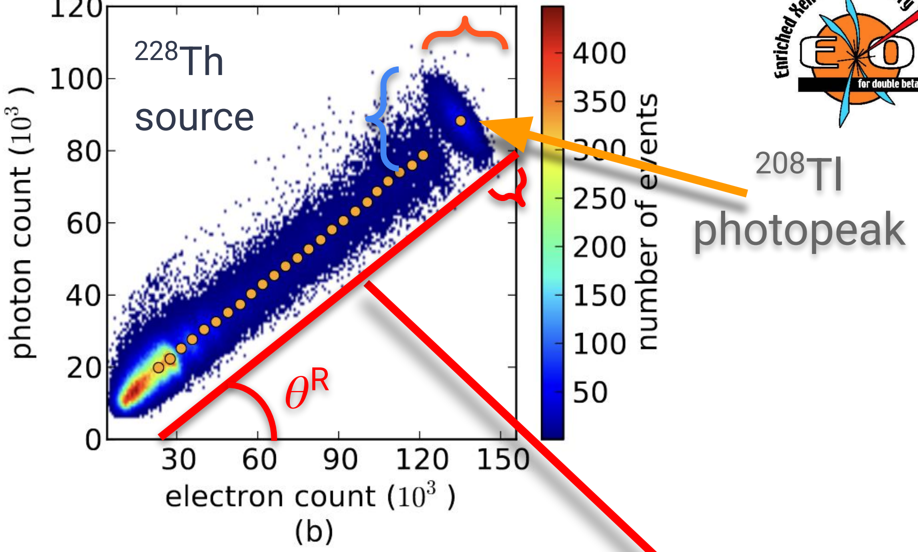
- ★ Larger E-field → more ionization

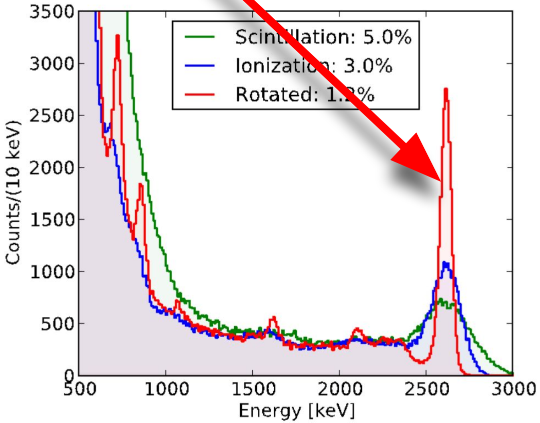
β, γ events deposit light + charge quanta characterized by θ^R

$$E_R = E_S \cdot \sin(\theta^R) + E_I \cdot \cos(\theta^R)$$

“Rotated energy” = linear combination of light and charge

θ^R measured every week with ^{228}Th source





EXO-200 Phase II

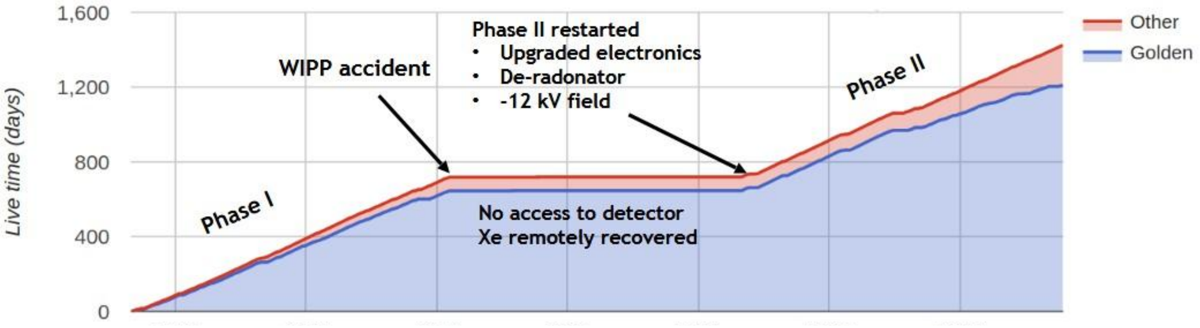
Upgrades during shutdown

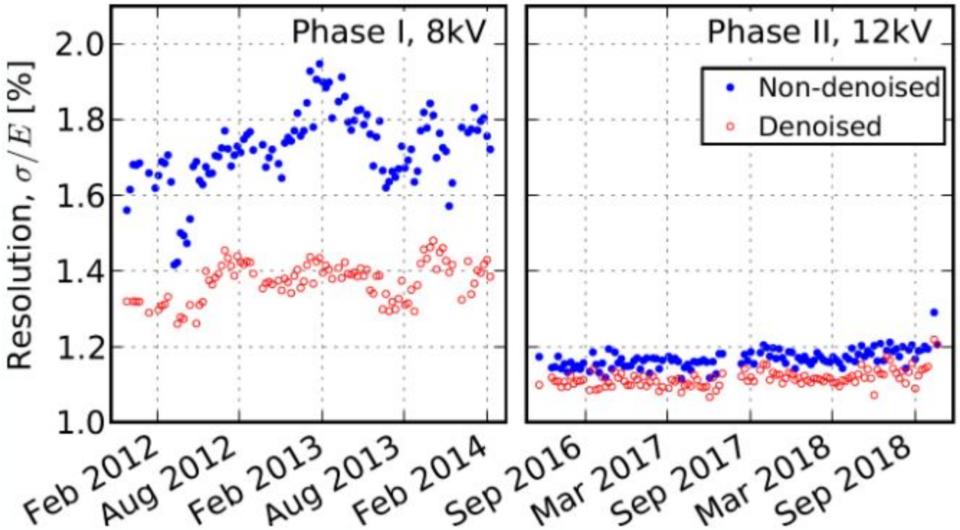
- ➢ Upgraded APD Readout → Reduced Noise
- ➢ 50% stronger drift field
- ➢ De-radonator added to reduce radon in air surrounding cryostat

❖ Improved energy resolution

- ➢ 1.35%→1.15% @ 2458 keV

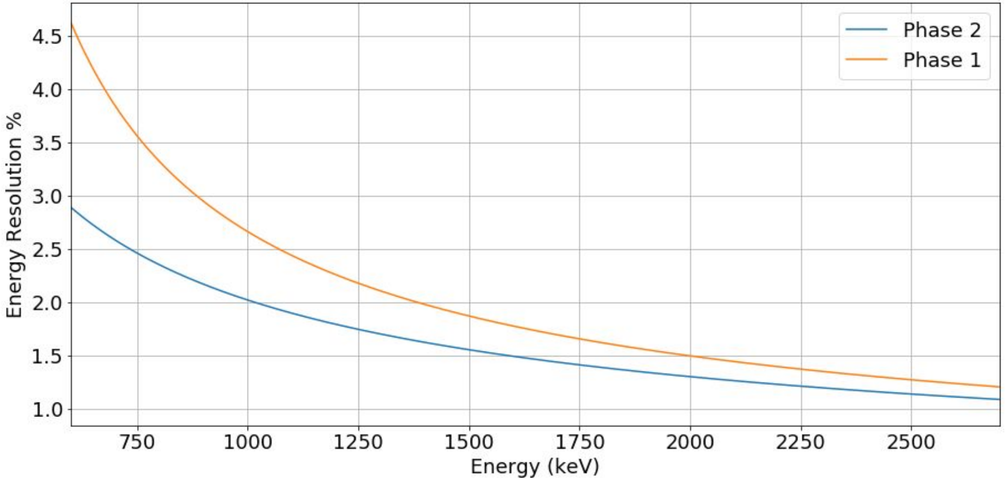
❖ Total Phase II exposure is 28.5 kg·yr (212.8 mol·yr)





Phase II Sensitivity Improvements

- With upgraded APD readout, can search at lower energies
  - 460 keV → 320 keV threshold
  - Increased sensitivity to $2\nu\beta\beta$ spectrum
- Improved energy resolution → better background discrimination



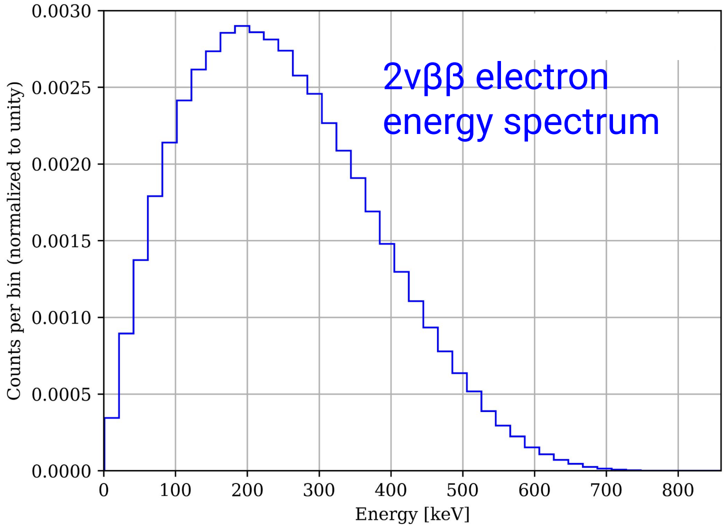
New ^{134}Xe analysis uses Phase II data only due to these substantial improvements

Status of Double Beta Decay Searches in ^{134}Xe

^{134}Xe is a double beta decay candidate

$Q_{\beta\beta}$ = 825.8 ± 0.9 keV

	EXO-200 Phase-I (2017)	PandaX-4T (2024)
2νββ	**≥ 8.7 x 10^{20} yr**	**≥ 2.8 x 10^{22} yr**
0νββ	**≥ 1.1 x 10^{23} yr**	**≥ 3.0 x 10^{23} yr**



EXOSim code implementing Schenter & Vogel parameterization

G. K. Schenter et al. A simple approximation of the Fermi function in nuclear beta decay. Nucl. Sci. Eng., 83:393–396, 1983.

Double Beta Decay in ^{134}Xe

$$\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} = G_{0\nu}\,|M^{0\nu}|^2\,|\langle m_{\beta\beta}\rangle|^2$$

- ❖ $M^{0\nu}$ calculations have a large theoretical uncertainty
- ❖ $M^{0\nu}_{134}$ ~ 3-4
- ❖ Constrain $M^{0\nu}$ by comparing isotopes
  - ➢ $M^{2\nu}$ might be correlated with $M^{0\nu}$
- ❖ Half-life of ***2νββ*** ~ order 10^{24}-10^{25} years depending on $M^{2\nu}$, $G_{2\nu}$ – within exclusion sensitivity of future detectors

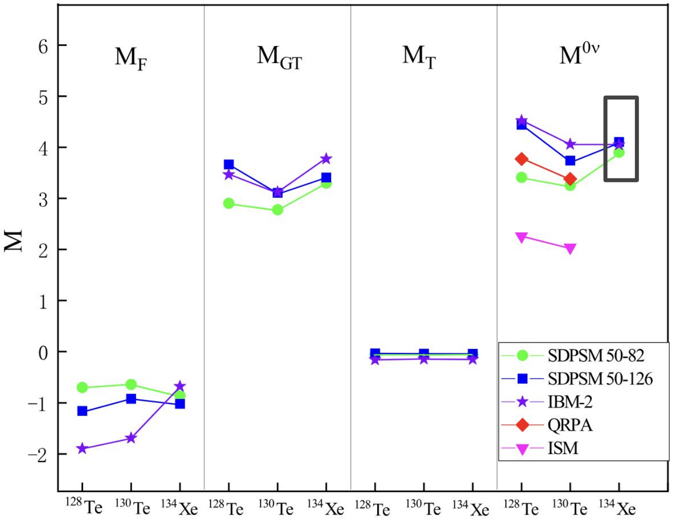


FIG. 2. The NMEs of the $0\nu\beta\beta$ decay in different models.

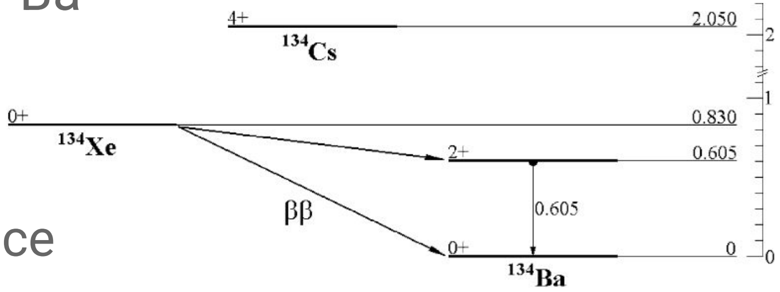
Figure: Z.W. Li, S. Y. Zhang, H. T. Xue, B. C. He, Y. A. Luo, Lei Li, F. Pan, and J. P. Draayer. Nuclear matrix elements of neutrinoless double-β decay in the SD-pair shell model with expanded model space. Phys. Rev. C, 111(2):024318, 2025.

IBM-2: J. Barea, J. Kotila, and F. Iachello, 0νββ and 2νββ nuclear matrix elements in the interacting boson model 447 with isospin restoration, Phys. Rev. C 91, 034304 (2015),448 arXiv:1506.08530 [nucl-th].

Phase space factors: J. Kotila and F. Iachello. Phase space factors for double-β decay. Phys. Rev. C, 85:034316, 2012.

Double Beta Decay to 2^+ Excited State of ^{134}Xe

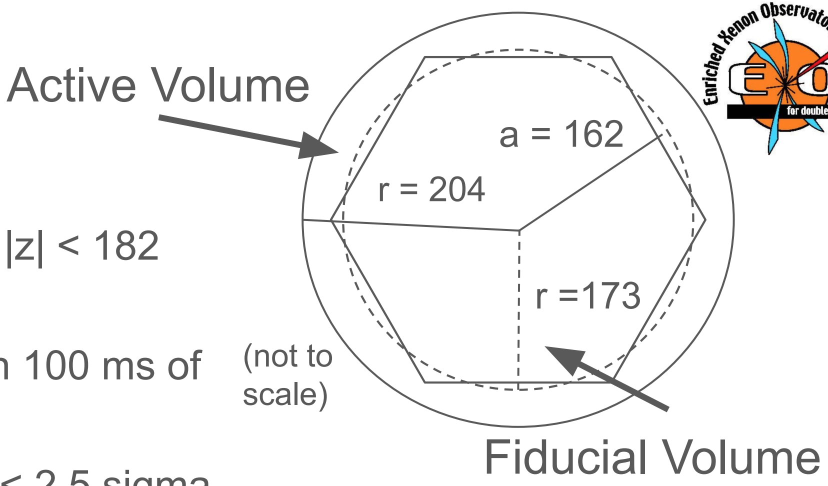
- ^{134}Xe can decay to a 2^+ excited state of ^{134}Ba
  - **$Q_{\beta\beta}$ = 225 keV**
  - **605 keV** gamma in de-excitation $2^+ \rightarrow 0^+$
- Estimate $T_{1/2}$ **≳ 10^{30} yr** based on phase space and ^{136}Xe $T_{1/2}(2\nu\beta\beta)$
  - J. Kotila and F. Iachello. Phase space factors for double-β decay. Phys. Rev. C, 85:034316, 2012
- $T_{1/2}\,(0\nu\beta\beta, 2^+) > 2.6 \times 10^{22}$ yr
  - R Bernabei, P Belli, F Cappella, R Cerulli, F Montecchia, A Incicchitti, D Prosperi, and C.J Dai. Investigation of decay modes in 134Xe and 136Xe. Physics Letters B, 546(1):23–28, 2002

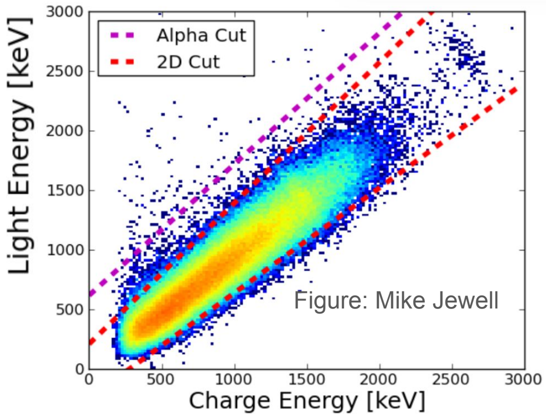


Search for ββ decay modes to the 2^+ excited state is in progress.

Data Quality Cuts

- **Fiducial volume:** hexagon with a = 162 mm, 10 < |z| < 182 mm, r < 173 mm
- **Coincidence cut:** removes events occurring within 100 ms of one another
- **Diagonal light/charge:** light-charge ratio must be < 2.5 sigma from the mean
- **Muon Veto:** cuts data taken 1 ms before and 25 ms after a trigger of the muon veto system
- **3D position reconstruction:**
  - For decays to the ground state of ^{134}Ba, require full 3D position reconstruction (signal is dominantly single-site)
  - For decays to the excited state of ^{134}Ba, cut is relaxed to allow events with at least 60% of their charge energy coming from fully reconstructed clusters (“partial 3D”) (signal is largely multi-site)





Fitting Methodology

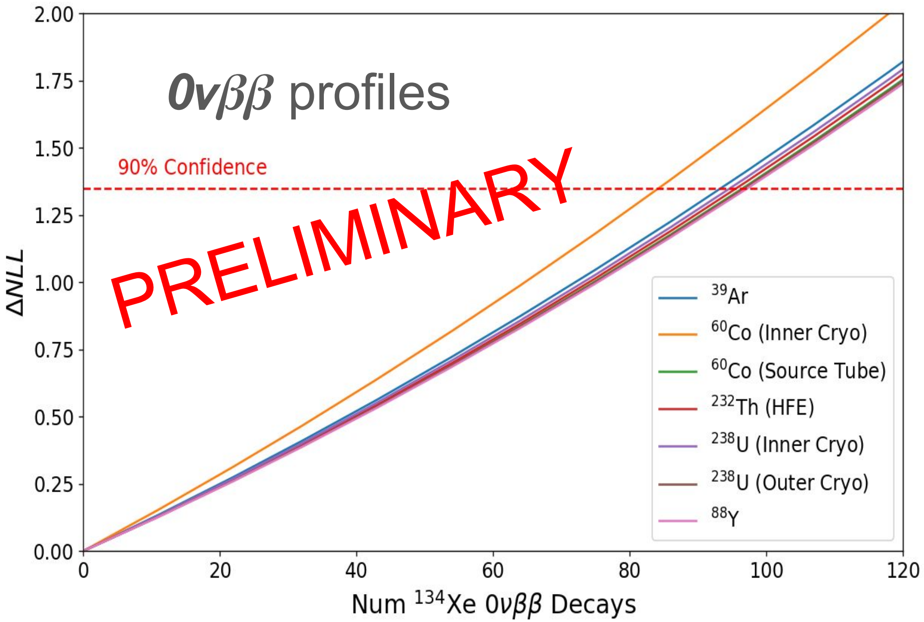
- Probability Distribution Functions (PDFs) for all background + signal components based on simulation and smeared by energy resolution
- Simultaneous multidimensional fit over both the single site and multi site data using the rotated energy, standoff distance, and constraining the fraction of events that are single site for each PDF
- Limits are calculated by the difference of log likelihood using a critical value of 1.35 from Wilks' theorem.
- This corresponds to a 90% Confidence limit

Systematics

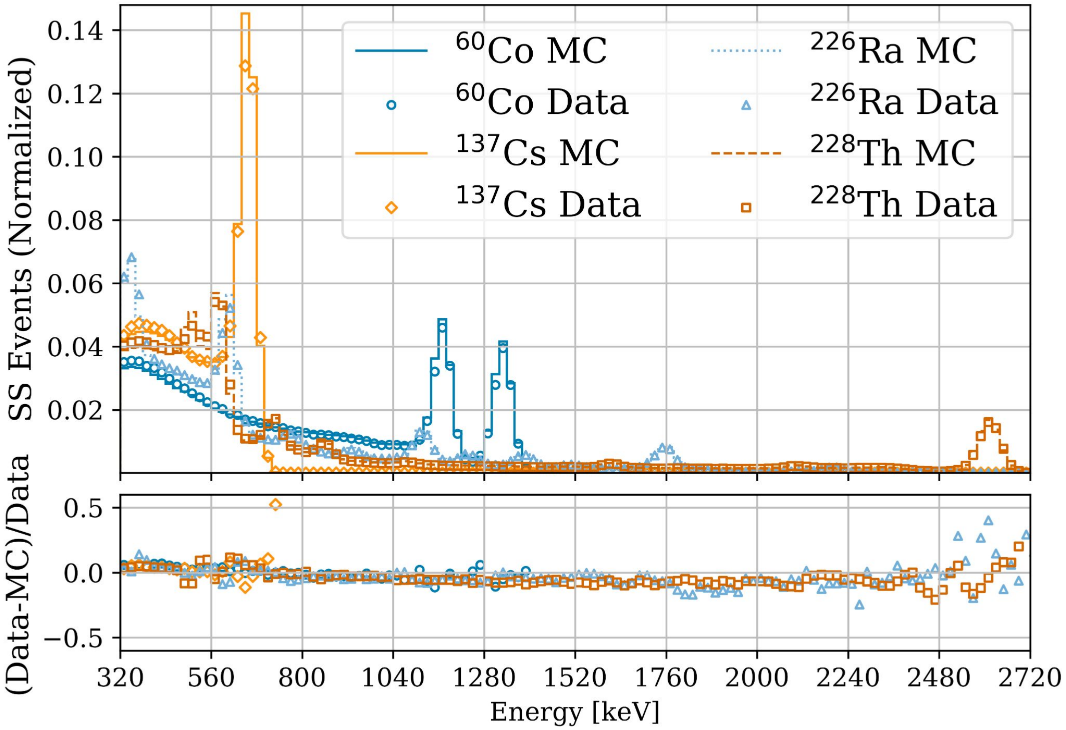
- Data quality cuts carry known systematic errors
  - Coincidence Cut, Fiducial Volume, 3D Reconstruction, Diagonal Cut
- Uncertainty in the location of certain background components is investigated by swapping corresponding PDFs in the fit
- Differences between simulation and data are quantified through source shape agreement
- Applied constraints on known components
  - Neutron capture fraction, Radon chain, Single Site Fraction, Normalization

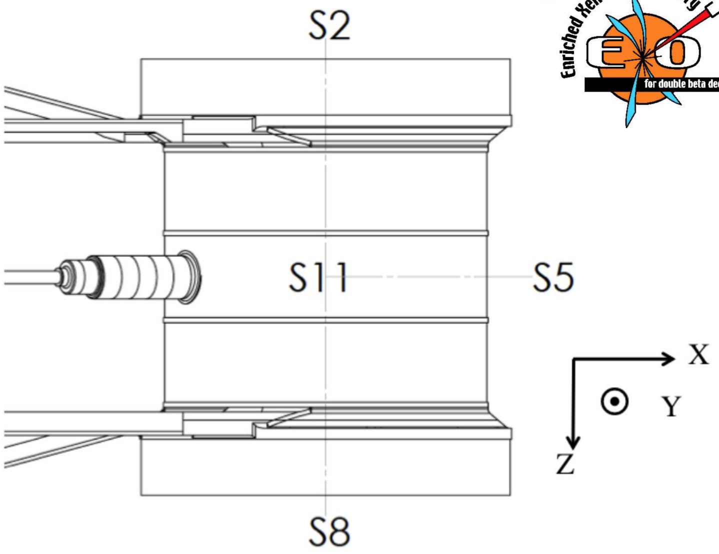
Background Model

- Location of some background components is not known precisely.
- Use different background models and check how this impacts the 90% CL upper limit on signal counts.
- Also allow for exotic backgrounds not expected to be present but that could influence result.



Source Shape Agreement

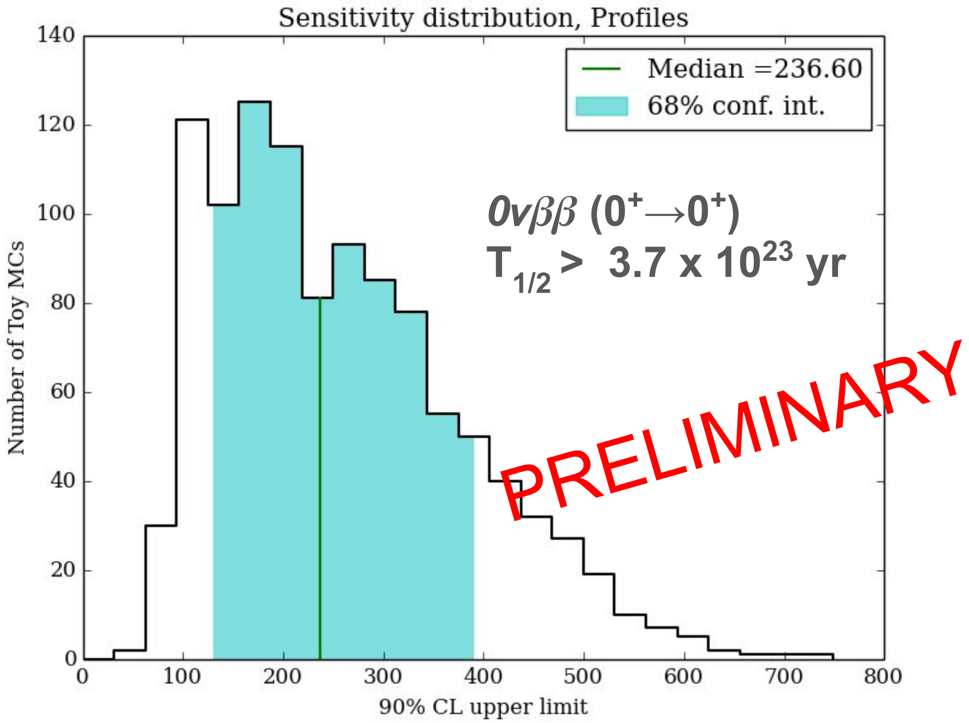




- Source data was collected for weekly energy calibration
- Ratio Data/MC also used to reweight PDF shapes
- Use reweighted PDFs to calculate spectral shape error

Median 90% C.L. Sensitivity (0νββ to ground state)

- Sensitivity evaluated with background-only fits to Toy MC resampled from a fit to the data
- Measure 90% Confidence upper limits on detected signal counts of multiple Toy MC
- Median upper limits of toy MC simulation is taken as sensitivity



Fit to Data

- Simultaneously minimize NLL with respect to rotated energy, standoff distance, and single-site fraction
- Limits are calculated by profiling NLL as a function of signal counts
- Systematic uncertainties are folded into the fit as Gaussian constraints

Mean of residuals between source data and simulation → Single-Site Fraction

Uncertainties in efficiency of selection cuts → Event Rate Norm.

Background model error (a) + Spectral shape error (b) → Signal-Specific Normalization

From background studies → Neutron Capture Fraction, Radon in LXe

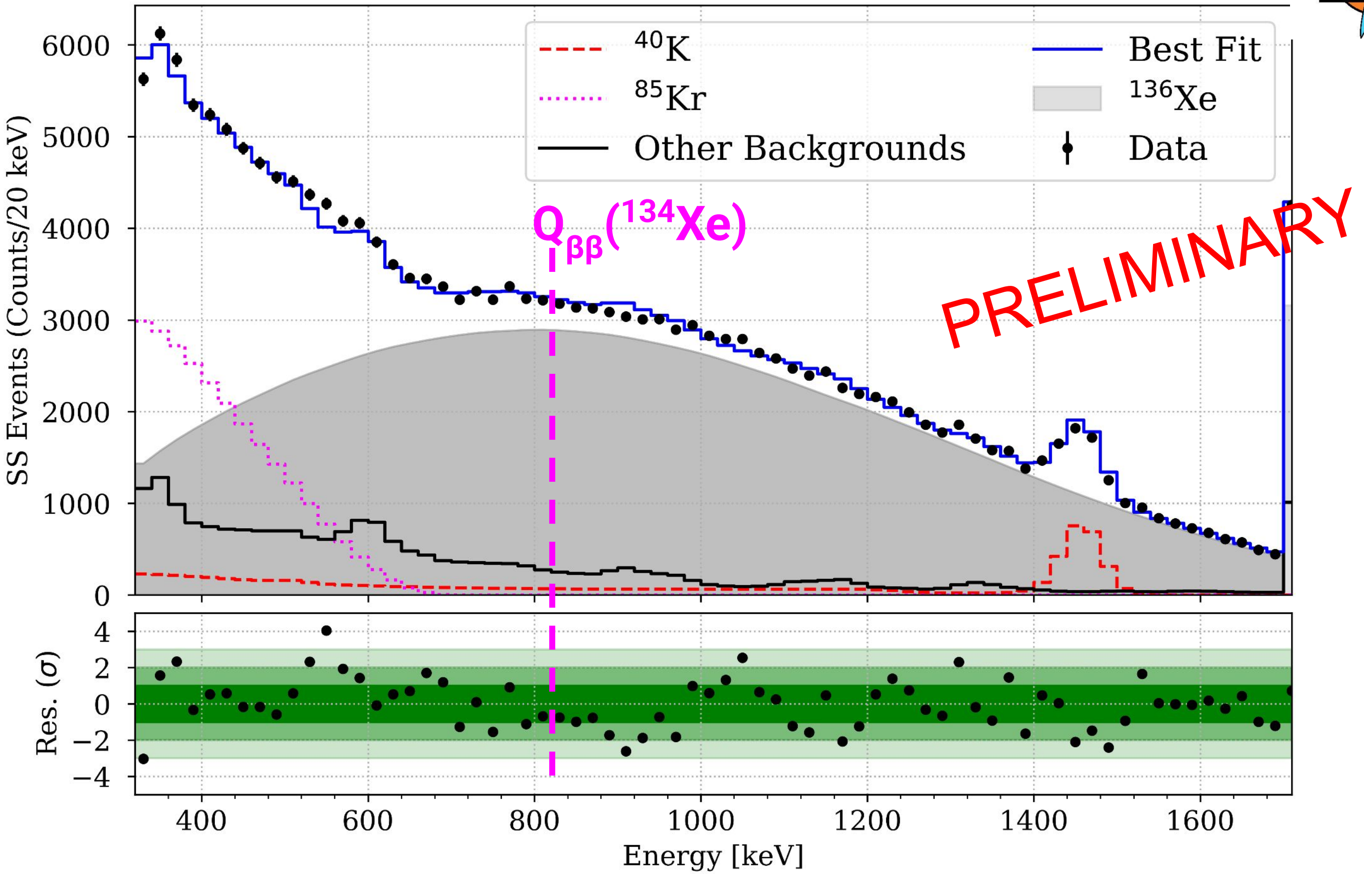
Constraint	**Value (*0νββ*)**
Single-Site Fraction	3.4%
Event Rate Norm.	3.4%
Signal-Specific Normalization	a = 16.3% b = 16 counts
Neutron Capture Fraction	10%
Radon in LXe	20%

Fit to Data

Both 0ν and 2ν ββ signal PDFs fit to zero

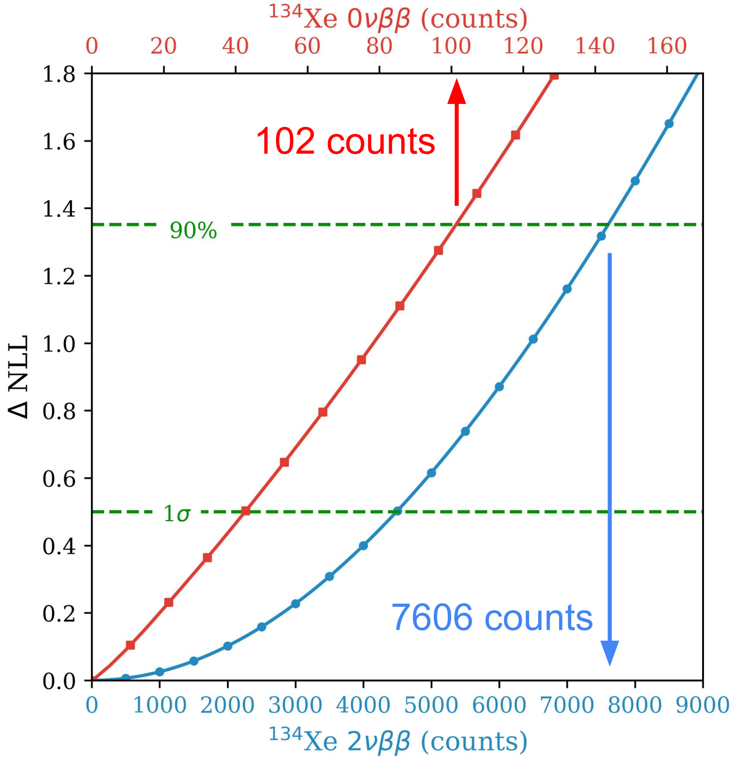
$$\chi^2_{\mathbf{Red,SS}} = \mathbf{1.57}$$

$$\chi^2_{\mathbf{Red,MS}} = \mathbf{1.09}$$



Results

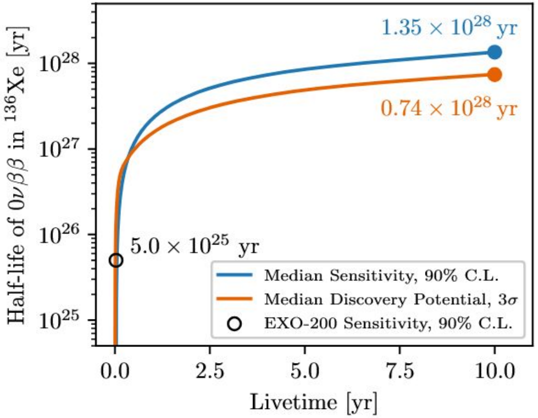
PRELIMINARY

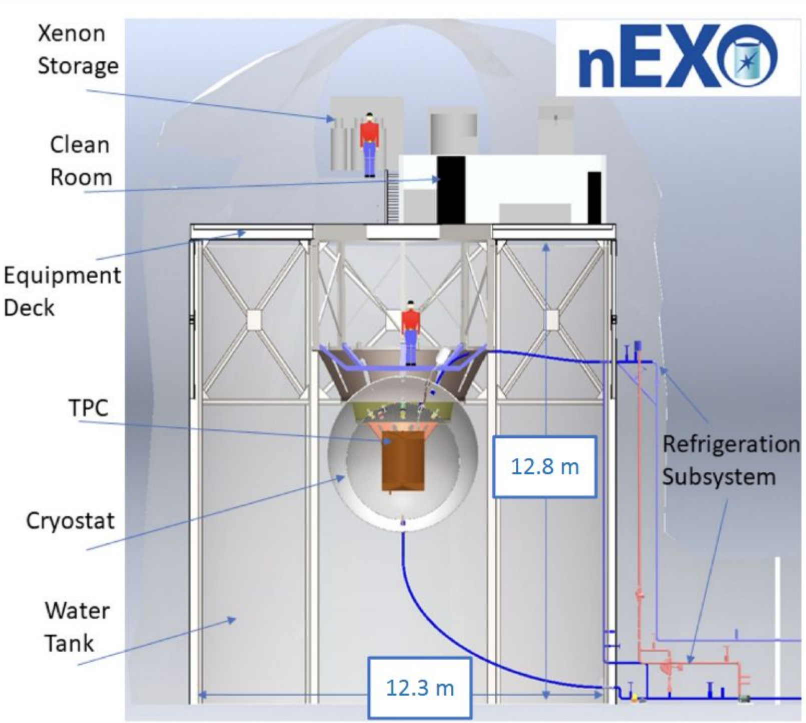


	EXO-200 Phase-II	PandaX-4T
2νββ ($0^+ \to 0^+$)	≥ 2.9 x 10^{21} yr	≥ 2.8 x 10^{22} yr
0νββ ($0^+ \to 0^+$)	**≥ 8.7 x 10^{23} yr**	≥ 3.0 x 10^{23} yr
0ν/2ν ββ ($0^+ \to 2^+$)	In progress	–

nEXO

- nEXO is the proposed successor experiment to EXO-200
- Tonne scale liquid xenon TPC
- 5 tonnes of enriched liquid xenon, 90%/10%:^{136}Xe/^{134}Xe





Proposed for the SNOLab Cryopit

nEXO

	EXO-200	nEXO
Xenon Mass	175 kg	**5000 kg**
Enrichment	81% / 19% :^{136}Xe/^{134}Xe	**90% / 10%:^{136}Xe/^{134}Xe**
Charge Readout	Anode Wire Plane	Charge Tiles
Light Readout	APDs	SiPMs
Energy Resolution $Q_{\beta\beta}$	1.15% @ 2458 keV	0.8% @ 2458 keV*
Detector Livetime	3 years	**10 years**

*Proposed

Sensitivity to ^{134}Xe $0\nu\beta\beta$

- Primary background is ^{136}Xe $2\nu\beta\beta$, can scale using formula for DBD half-life sensitivity in presence of background
- Simplify calculation by taking the sensitivity from EXO-200 and scale relevant parameters
- Assume ϵ=1, very unlikely to miss an 824 keV DBD
  - 96 kg $\rightarrow$ 3000 kg fiducial mass
  - ^{136}Xe enrichment increases the background by fraction (.9*3000)/(.8*96)
  - 1.61 yr (Phase II) $\rightarrow$ 10 yr livetime

EXO-200 Phase II Sensitivity

Scaling factor for nEXO

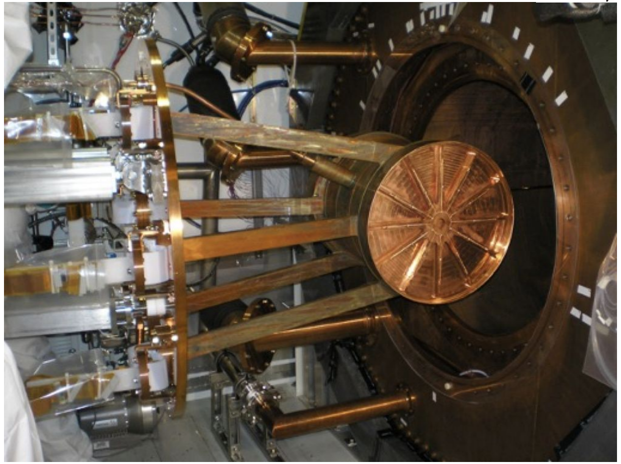
$$T_{1/2}^{0\nu\beta\beta} = ln2 N_X \epsilon \sqrt{\frac{T_{livetime}}{M_X B \sigma}} \rightarrow 3.7 \times 10^{23} \cdot 74.5 = 2.8 \times 10^{25} yr$$

Sensitivity to ^{134}Xe $2\nu\beta\beta$

- Based on a theoretical half-life of ~10^{24*}, could see ~1000 decays per year
  - If $T_{1/2}$ ~ 10^{25}, ~100 decays per year
  - Based on phase space, $T_{1/2}$(136) and NMEs, $T_{1/2}$ is probably not longer than order 10^{25}
- ^{136}Xe $2\nu\beta\beta$ is a major background–natural Xe experiment would have advantage
- Other major background is ^{85}Kr
- Based on the sensitivity of EXO-200, if scaled up to nEXO exposure, could exclude half-lives of order 10^{24} years
  - Assumes similar systematic error contributions and energy threshold

*optimistic estimate–could be longer

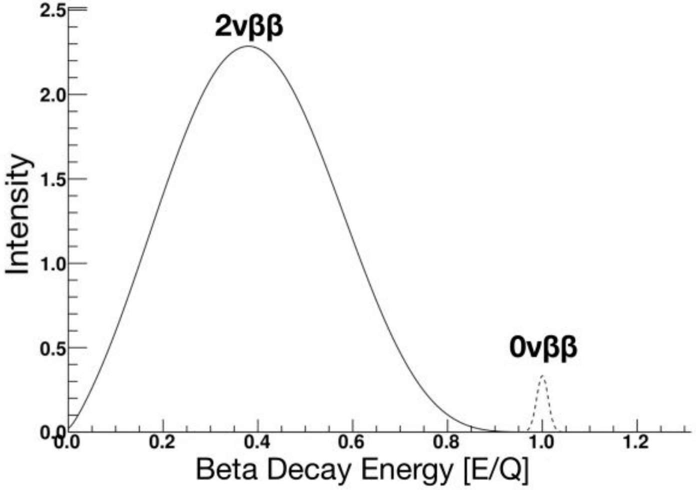
Conclusions

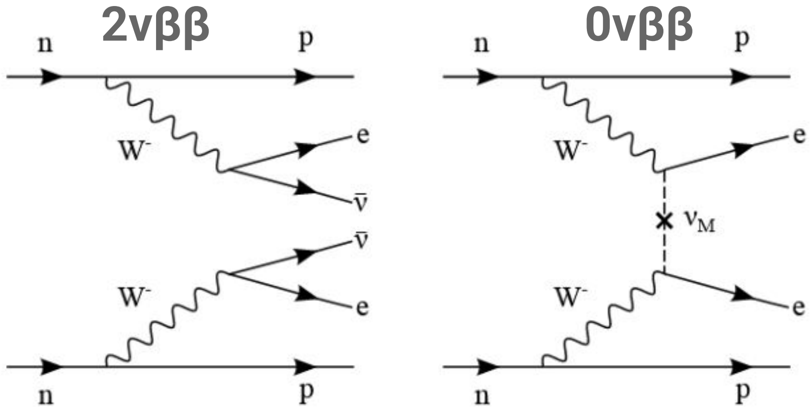


- ❖ We report new world leading limit on the ^{134}Xe ***0νββ*** ($0^+ \rightarrow 0^+$) decay
- ❖ Also improved on the EXO-200 Phase I limit for the ***2νββ*** ($0^+ \rightarrow 0^+$) decay of ^{134}Xe
- ❖ Search for the ***ββ*** ($0^+ \rightarrow 2^+$) decays is in progress
- ❖ Tonne scale experiments could reach sensitivities as high as 10^{24} years, approaching theoretical half-life of ***2νββ*** ($0^+ \rightarrow 0^+$) decay of ^{134}Xe
  - ➢ ***2νββ*** discovery may be within reach of tonne-scale detectors!
  - ➢ Exclusion for ***0νββ*** still an order of magnitude off current limits for ^{136}Xe

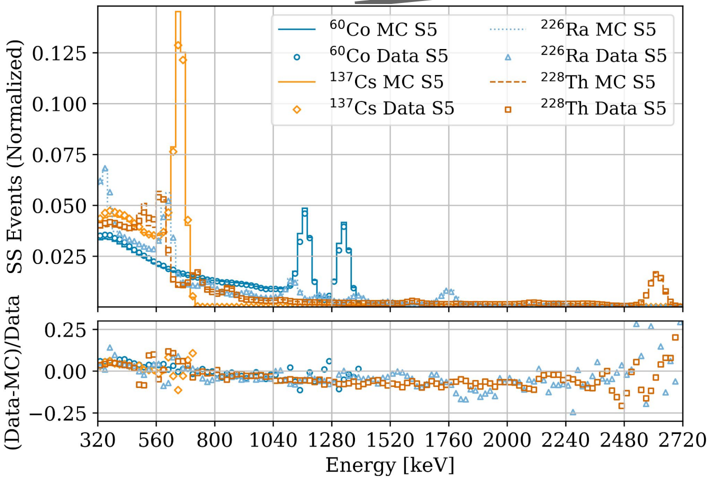
Backup Slides

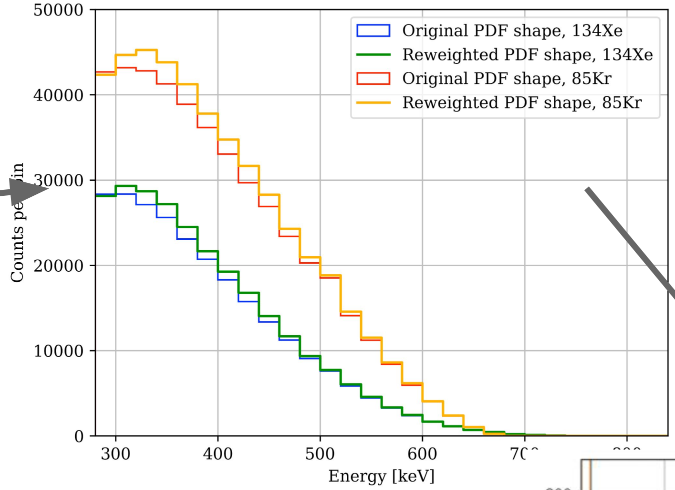
General Double Beta Decay





- Compare data from calibration runs to simulated data to quantify the fidelity of simulation

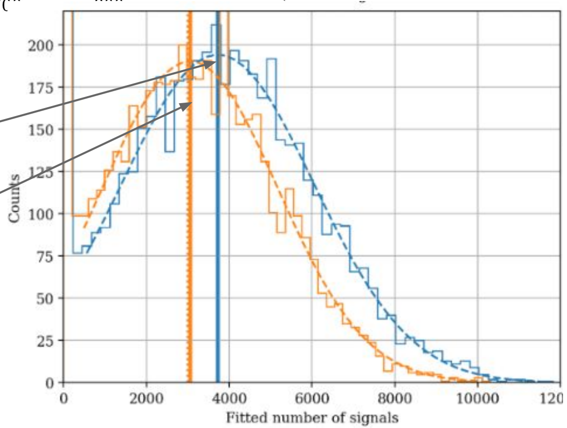




"Re-weight" PDFs to reflect data-MC discrepancy by multiplying by MC/Data bin-by-bin

Fitted number

True number

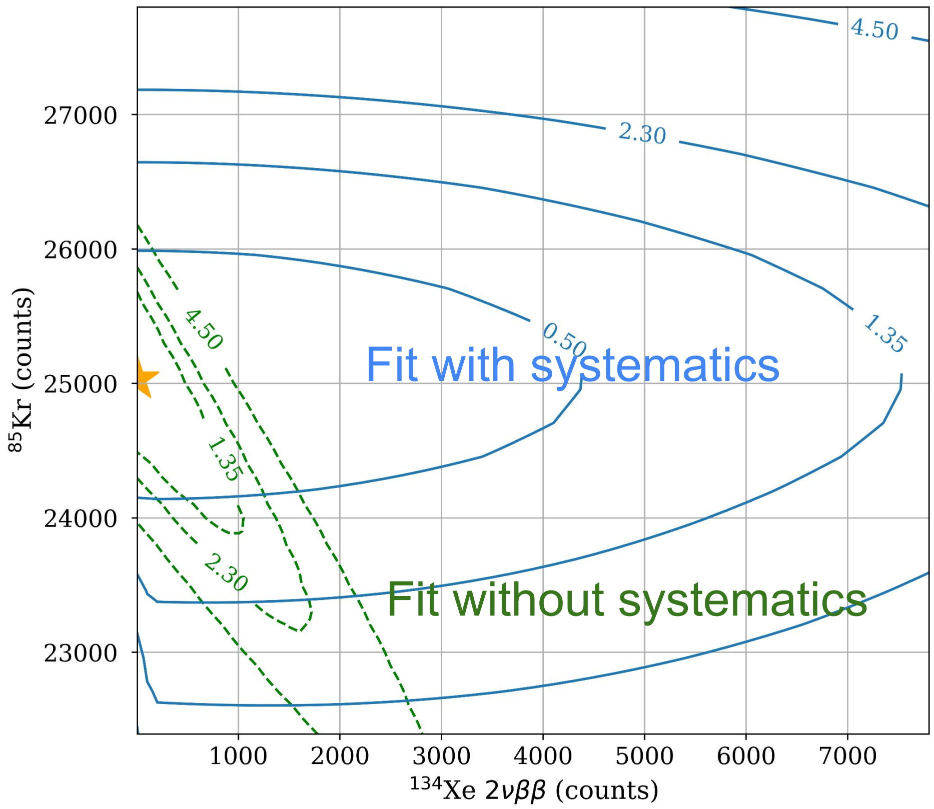


- Test the result of the fit on toy data drawn from the reweighted PDFs for a known number of "injected" signals
- Toy data is generated from the reweighted PDFs based on source agreement data, then fit with standard PDFs with a fixed injected number of signal counts

Krypton correlation

- ***2νββ*** ($0^+ \rightarrow 0^+$) decay spectrum is degenerate with ^{85}Kr

After all systematics are accounted for, fit values of ^{85}Kr and ^{134}Xe are uncorrelated



2D NLL profile scan

NMEs

Formalism	Channel	g_A	Mechani...	M(136)	M(134)	Ratio T_1/2	T(134) [1e25 ...
QRPA @ Tübingen, 2002	0ν	1.25	Light neutrino	0.66	1.66	3.84	1591.66
QRPA @ Tübingen, 2002	0ν	1.25	Heavy neutrino	14.1	23	9.13	0.41
QRPA + isospin @ Tübingen, 2013	0ν	1.27	Light neutrino	2.177	3.664	8.58	326.70
QRPA + isospin + CD Bonn @ Tübingen, 20	0ν	1.27	Light neutrino	2.46	4.119	8.67	258.51
IBM-2 @ Yale, 2015	0ν	1.269	Light neutrino	3.05	4.05	13.78	267.40
IBM-2 @ Yale, 2015	0ν	1.269	Heavy neutrino	72.6	91.2	15.40	0.03
IBM-2 @ Yale, 2015	$0\nu \rightarrow 0_2^+$	1.269	Light neutrino	1.6	2.35	11.26	794.20
IBM-2 @ Yale, 2015	$0\nu \rightarrow 0_2^+$	1.269	Heavy neutrino	28.3	41.5	11.30	0.13
SDPSM+BCS, 2022	0ν	1.25	Light neutrino	0.88	1.11	15.27	3559.75
SDPSM+SDI, 2022	0ν	1.25	Light neutrino	0.93	1.17	15.35	3204.01
SDPSM+SDI+SDG, 2022	0ν	1.25	Light neutrino	0.88	0.99	19.20	4475.02
SDPSM+SDI+degeneracy, 2022	0ν	1.25	Light neutrino	1.52	2.12	12.49	975.87

Half-life estimate (ground state 2nu)

2ν mode

The relationship between the NMEs and the half-life in the 2nu mode is

$$\frac{1}{T_{1/2}^{2\nu}} = g_A^4 m_e^2 G_{2\nu}|M_{2\nu}|^2$$

From the Yale group (https://nucleartheory.yale.edu/double-beta-decay-phase-space-factors#npsf): $G_{2\nu}(134) = 0.226 \times 10^{-21}\mathrm{yr}^{-1}$ and $G_{2\nu}(136) = 1430 \times 10^{-21}\mathrm{yr}^{-1}$

$$\frac{G_{2\nu}(136)}{G_{2\nu}(134)} = 6327$$

The NMEs are related as

$$|\frac{M_{2\nu}^{(2)}}{M_{2\nu}^{(1)}}|^2 \times 6327 = \frac{T_{1/2}^{2\nu}(N_1)}{T_{1/2}^{2\nu}(N_2)}.$$

In this case $T_{1/2}^{2\nu}(136) = 2.165 \times 10^{21}$ (not including error bars)

$$|\frac{M_{2\nu}^{(2)}}{M_{2\nu}^{(1)}}|^2 \times 6327 = \frac{T_{1/2}^{2\nu}(134)}{2.165 \times 10^{21}}$$

$$T_{1/2}^{2\nu}(134) = 2.165 \times 10^{21} \times 6327 \times |\frac{M_{2\nu}^{(2)}}{M_{2\nu}^{(1)}}|^2$$

If the ratio is 1 then $T_{1/2}^{2\nu}(134) = 2.165 \times 10^{21} \times 6327 = 1.37 \times 10^{25}$

Half-life estimate (excited state)

From the Yale group: $G_{2\nu,0_2^+}(136) = 0.3622 \times 10^{-21}\text{yr}^{-1}$ and $G_{0\nu,0_2^+}(136) = 0.6127 \times 10^{-21}\text{yr}^{-1}$

^{134}Xe is not reported.

In general, the phase space factor is proportional to Q^{11} (for neutrinofull)

In the case of ^{134}Xe, Q of the excited decay is 225 keV.

By the argument above we expect $T_{1/2}^{2\nu}(134) \leq 1.37 \times 10^{25}$ based on the ratio of NMEs and known half-life of neutrinofull ^{136}Xe.

We can extrapolate from the above an expected half-life for the excited state neutrinofull decay.

$$T_{1/2}^{2\nu,0_2^+}/T_{1/2}^{2\nu} = (G_{2\nu}|M_{2\nu}|^2)/(G_{2\nu,0_2^+}|M_{2\nu,0_2^+}|^2)$$

For the light neutrino, the only published value of $M_{2\nu,0_2^+}$ is 2.34 (Yale). (1.65 for 136). This is only 0.01 different from the decay to the ground state so let's just say the matrix elements are equal:

$$T_{1/2}^{2\nu,0_2^+} \approx G_{2\nu}/G_{2\nu,0_2^+} \cdot T_{1/2}^{2\nu}$$

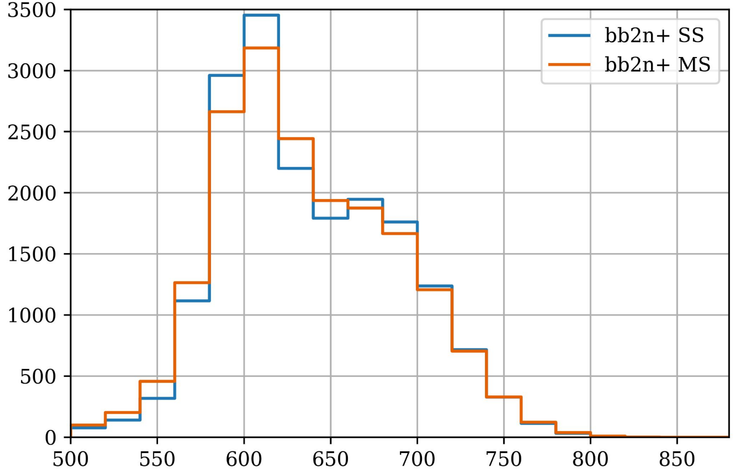
Let's take 1.37×10^{25} as an upper bound on $T_{1/2}^{2\nu}$ and define a factor $w \leq 1$ (for "weight") to represent the ratio of the matrix elements discussed above.

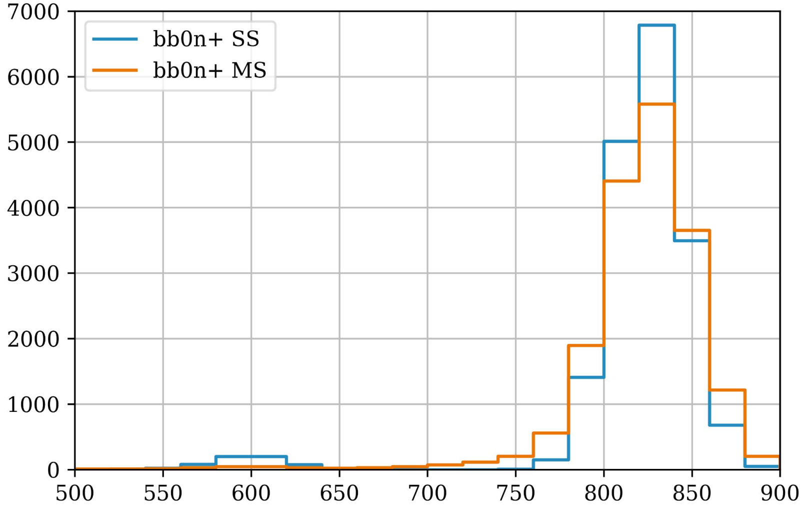
$$G_{2\nu,0_2^+}/G_{2\nu} \approx Q(0)^{11}/Q(0_2^+)^{11} \approx 1.6 \times 10^6$$

$$T_{1/2}^{2\nu,0_2^+} \approx 1.6 \times 10^6 \cdot 1.37 \times 10^{25} \cdot w \approx 2.2 \times 10^{31} \cdot w \text{ yr}$$

Where w is a number between 0 and 1 (and in most cases is more than 0.5). This implies a half-life of order 10^{31} years, not accounting for any subtleties that may apply.

Double Beta Decay to Excited States in ^{134}Xe

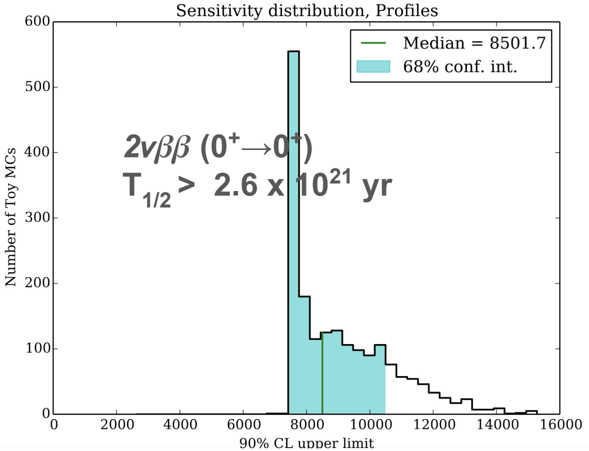


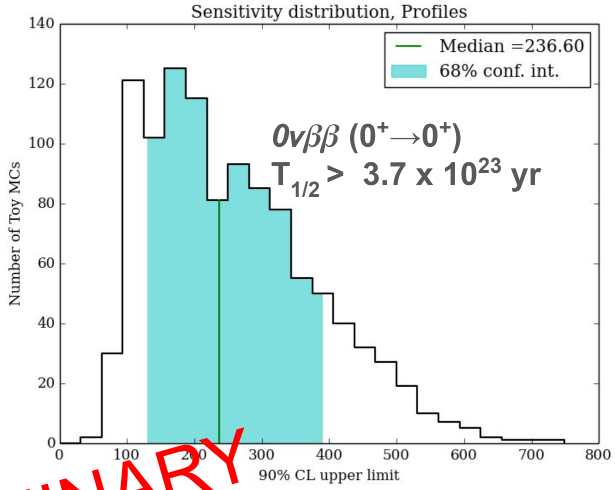


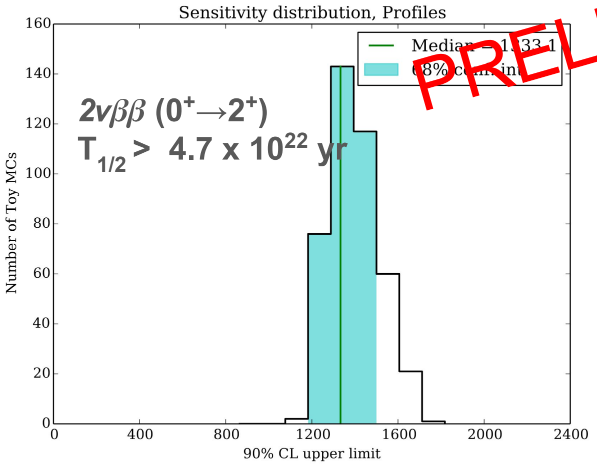
Probability Distributions Functions (PDFs) of excited decay spectra, smeared by realistic detector energy resolution

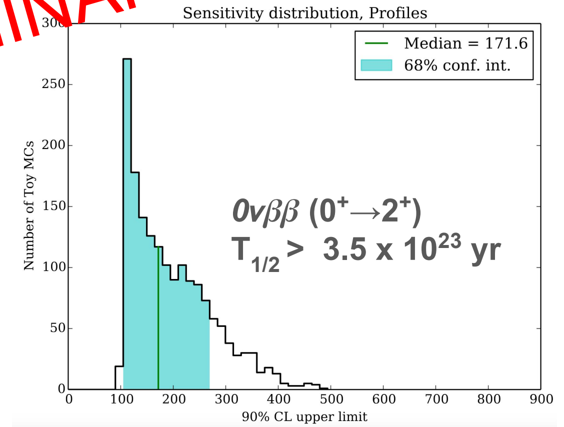
Median Sensitivity

- Sensitivity evaluated with background only fits to Toy MC
- Measure 90% Confidence upper limits on detected signal counts
- Median upper limits of toys is taken as sensitivity

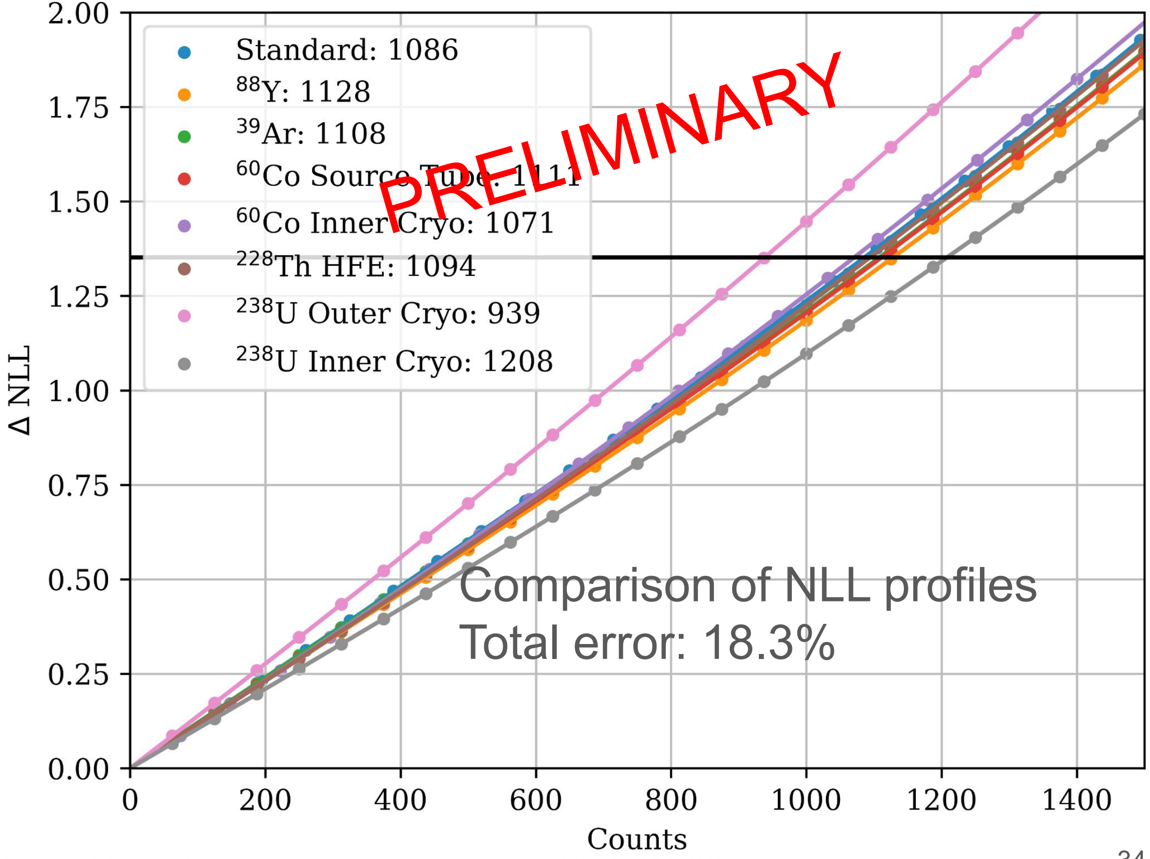








$2\nu\beta\beta$ ground state



Comparison of NLL profiles
Total error: 18.3%

Constraint	$2\nu\beta\beta$ (2^+)	$0\nu\beta\beta$ (2^+)
Single-Site Fraction	3.4% (4.4%)	3.4% (4.4%)
Event Rate Norm.	3.4% (3.3%)	3.4% (3.3%)
Signal-Specific Normalization	$a = 18.3\%$ (44.6%) $b = 4411$ (514) cts	$a = 16.3\%$ (28.2%) $b = 16$ (57) cts
Neutron Capture Fraction [25]	10%	10%
Radon in the LXe [3]	20%	20%

Alternative Thorium Hypothesis

Largest deviations in residuals in the fit are at energies corresponding to gamma rays in thorium decay chain

Investigated possibility of different thorium background positions as well as broken stochastic equilibrium

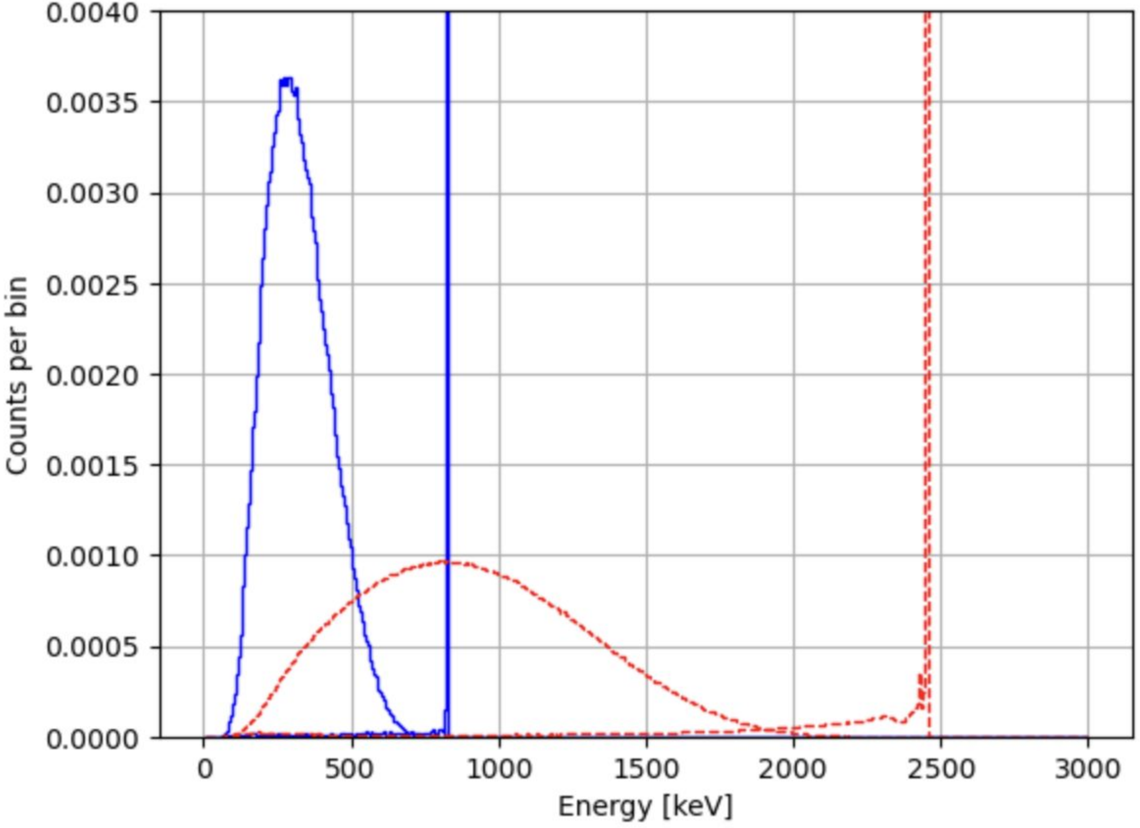
No evidence that either of these possibilities showed improvement in quality of fit

Config.	E-SS	E-MS	SD-SS	SD-MS	Vessel	ST	HFE	IC
V+IC	1.10	1.57	1.65	2.04	6692 ± 415	-	-	1759 ± 407
V only	1.14	1.54	1.82	446.23	7940 ± 304	-	-	-
V+IC+HFE	1.10	1.58	1.64	2.04	6297 ± 500	-	747 ± 539	1398 ± 477
IC+HFE	1.38	1.69	1.31	2.09	-	-	5290 ± 455	2218 ± 461
HFE only	1.28	1.65	1.35	2.10	-	-	7005 ± 294	-
IC+ST	1.21	1.69	1.47	2.07	-	8573 ± 350	-	0 ± 141
V+ST+HFE	1.13	1.59	1.66	2.05	4860 ± 761	2712 ± 1010	788 ± 537	-

Table 8: χ^2_{Red} on each fit dimension in each configuration of ^{232}Th components, as well as the best fit numbers of counts in each component. ST = Source Tube, V = Vessel, IC = Inner Cryo.

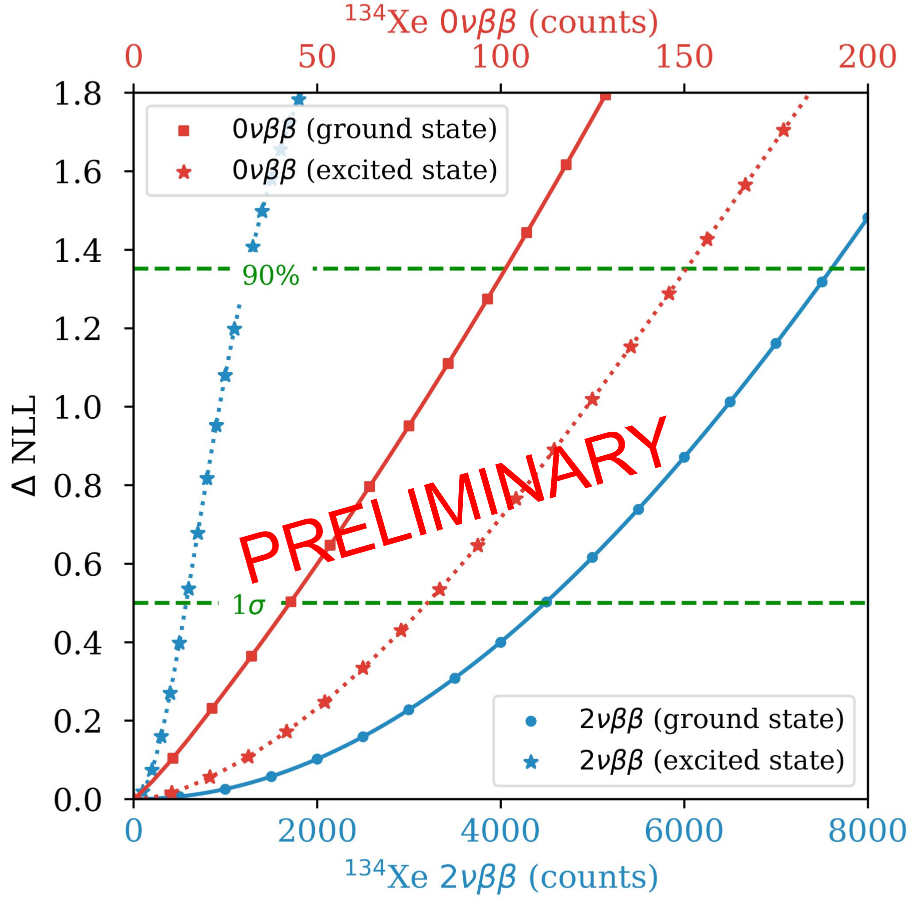
Broken equilibrium	E-MS	E-SS	SD-MS	SD-SS
Vessel + IC	1.10	1.47	1.80	2.06
Vessel	1.09	1.55	1.62	2.06
IC	1.14	1.49	1.96	2.03

Table 11: χ^2_{Red} on each fit dimension in each configuration of ^{232}Th components with broken equilibrium.

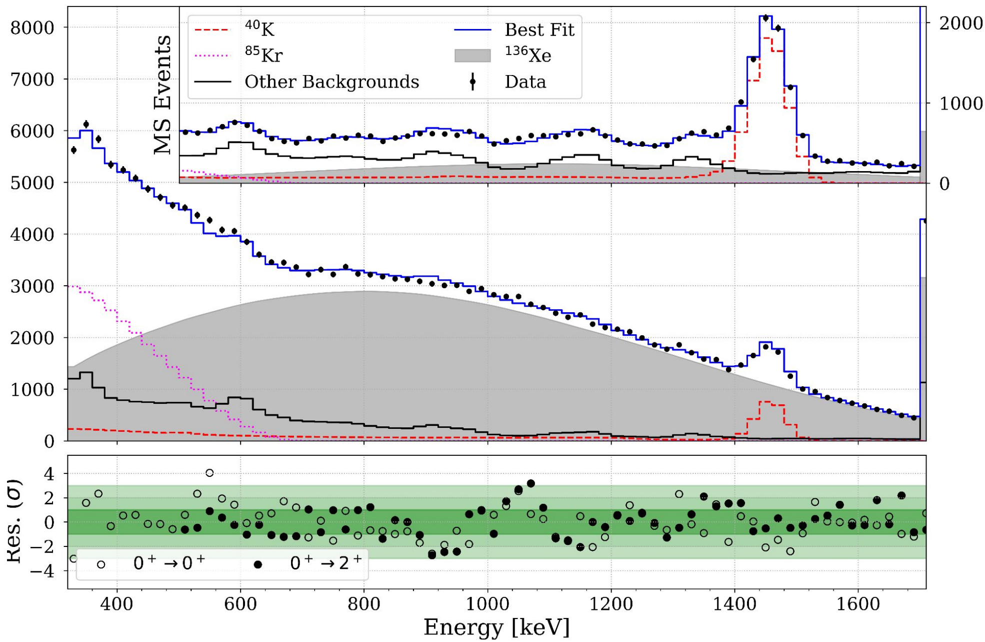


Simulated 2v spectra of 136 and 134, plotted together

Includes detector/reconstruction effects



^{134}Xe $0\nu\beta\beta$ (counts)
$0\nu\beta\beta$ (ground state)
$0\nu\beta\beta$ (excited state)
90%
1σ
PRELIMINARY
Δ NLL
$2\nu\beta\beta$ (ground state)
$2\nu\beta\beta$ (excited state)
^{134}Xe $2\nu\beta\beta$ (counts)



^{40}K
^{85}Kr
Other Backgrounds
Best Fit
^{136}Xe
Data
MS Events
Res. (σ)
$0^+ \to 0^+$
$0^+ \to 2^+$
Energy [keV]