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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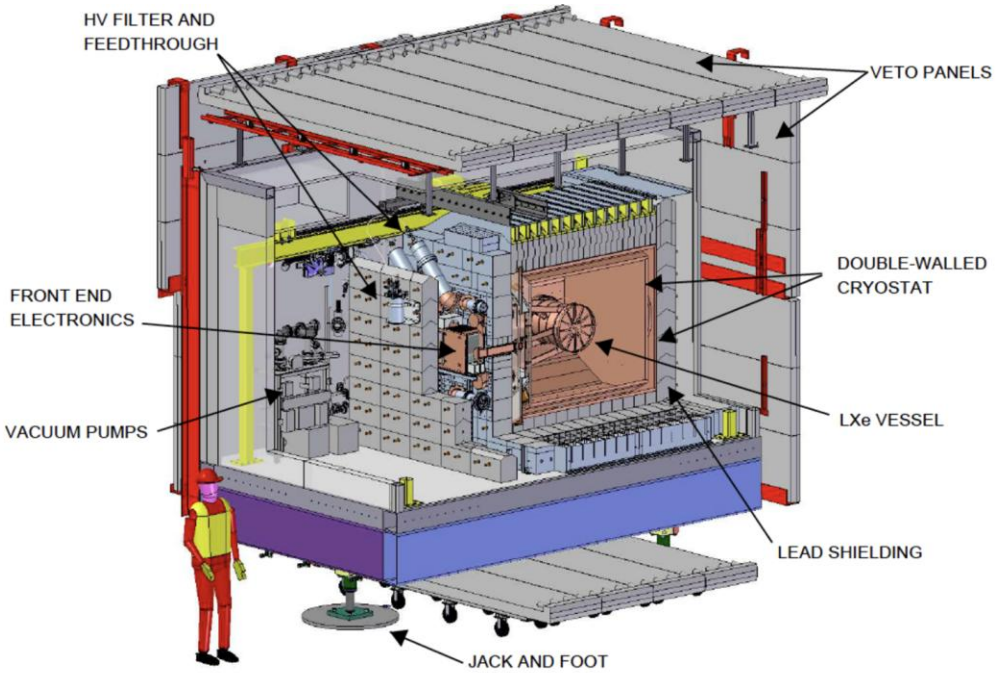
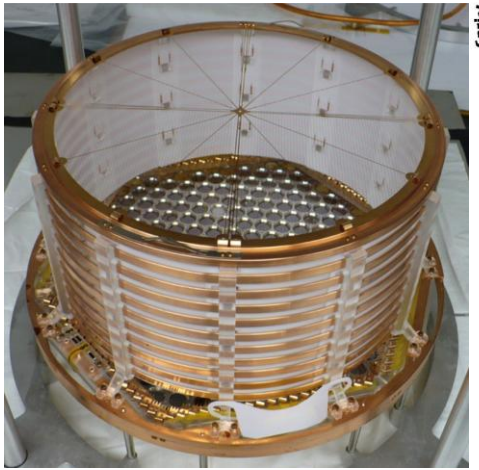
Outline

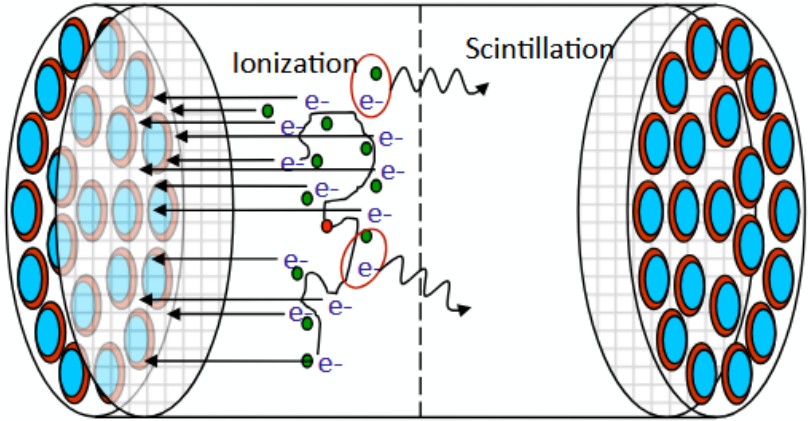
- The EXO-200 Experiment
- Double Beta Decay in ^{134}Xe
- Analysis Methodology
- Results
  - Sensitivity reach
  - ββ half-lives of ^{134}Xe
- Outlook



The EXO-200 TPC

- EXO-200 was active between 2011-2018 at the WIPP underground site in New Mexico
  - Phase I ended in 2014 → Phase II began in 2016
  - First observation of 2νββ decay of ^{136}Xe in 2011
  - Lower bound of 0νββ decay of ^{136}Xe: $> 3.5 \times 10^{25}$ 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.

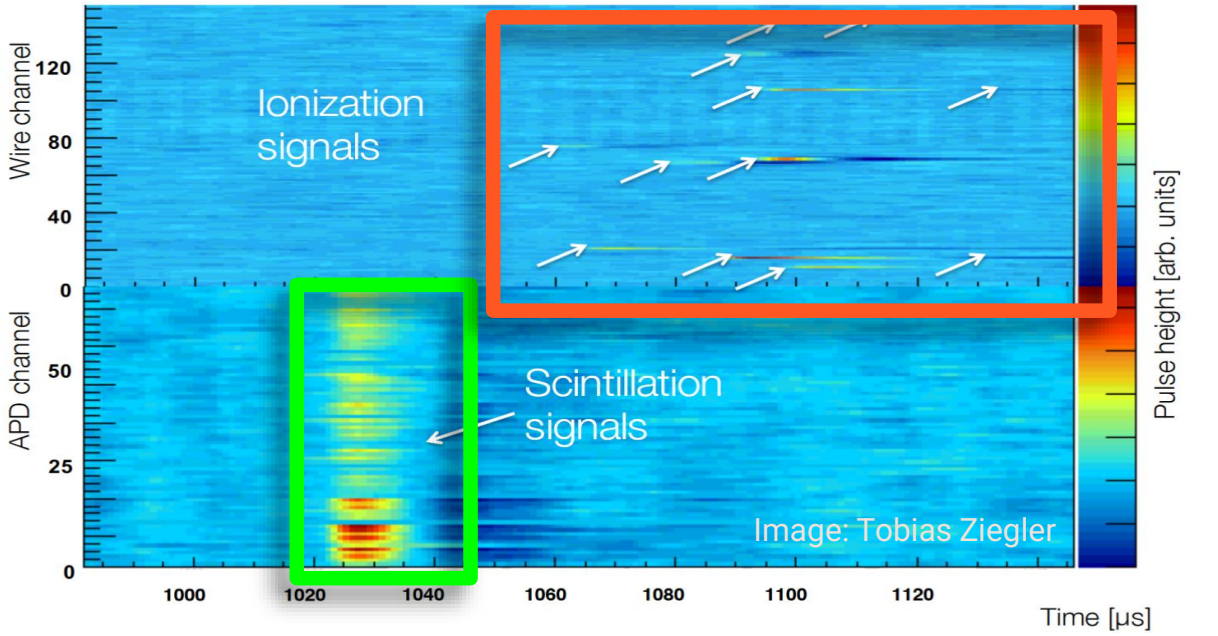


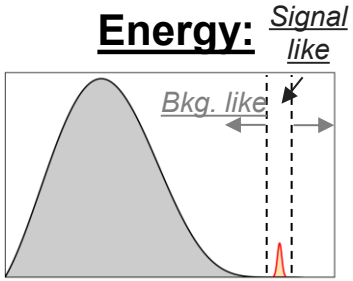


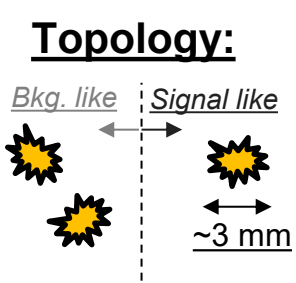
EXO-200 Signals

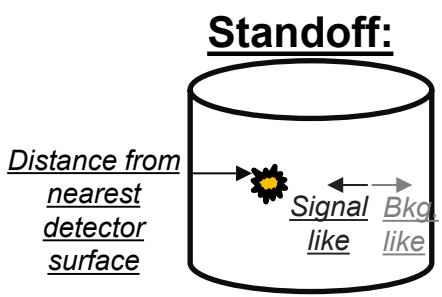
- Single-phase LXe time projection chamber:
  - ➢ Prompt scintillation
  - ➢ Delayed, distributed ionization

- Multiparameter measurement:
  - ➢ Energy from combined scintillation/ionization signal
  - ➢ Topology, e.g., single-site (SS) or multi-site (MS) event
  - ➢ Position distribution from 3D event reconstruction
  - ➢ Particle identification from scintillation/ionization ratio







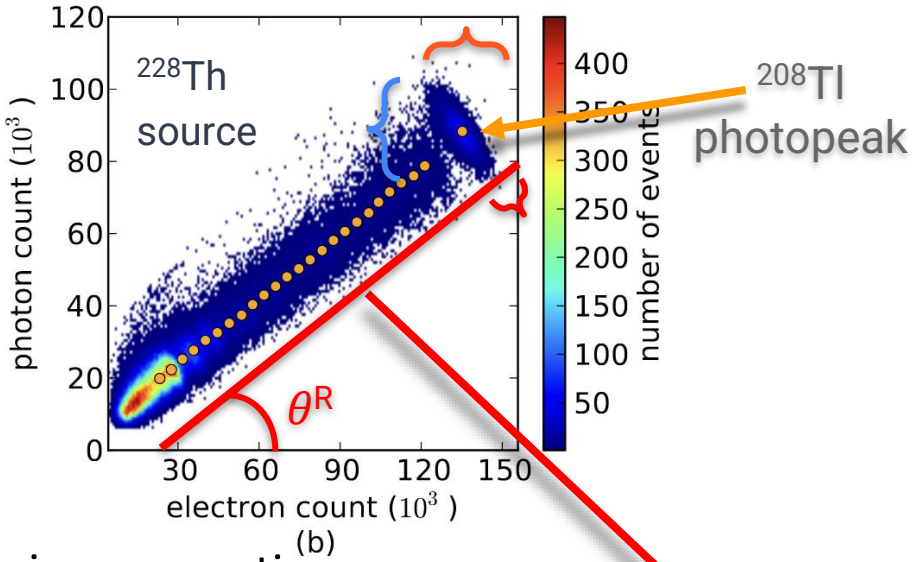


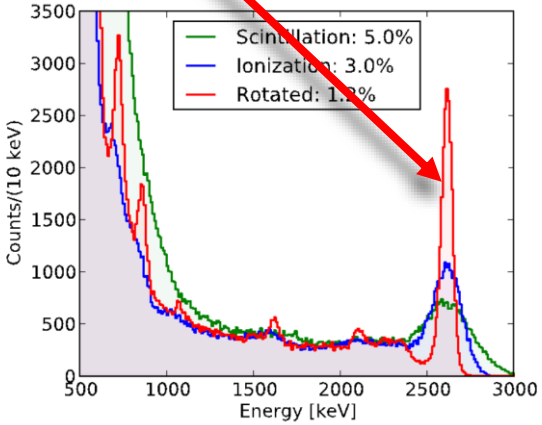
EXO-200 Energy Scale

- 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 in a proportion 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



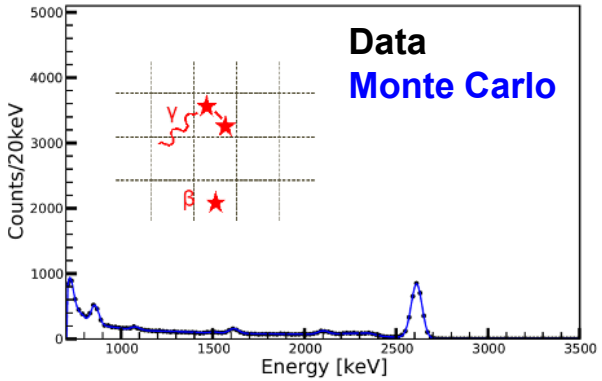


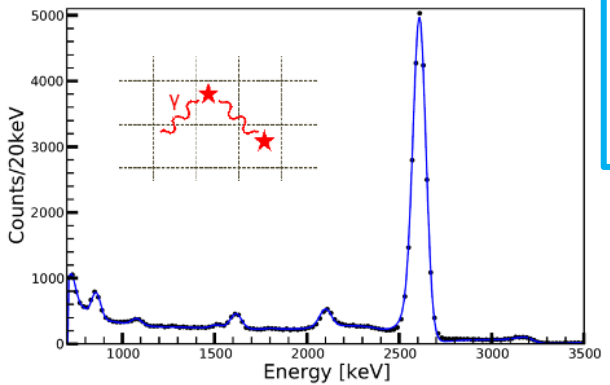
Event Topology and Multiplicity (EXO-200 data)

Single-site

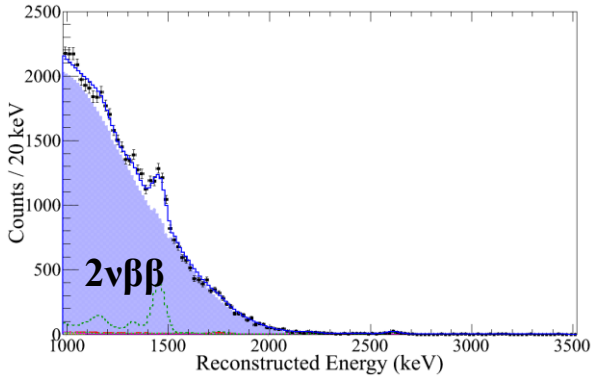
Multi-site

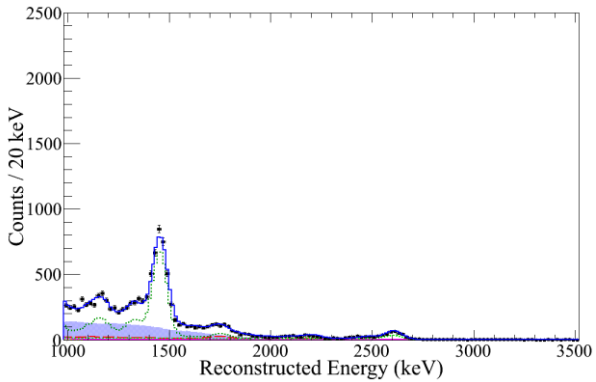
^{228}Th calibration source





Low background data



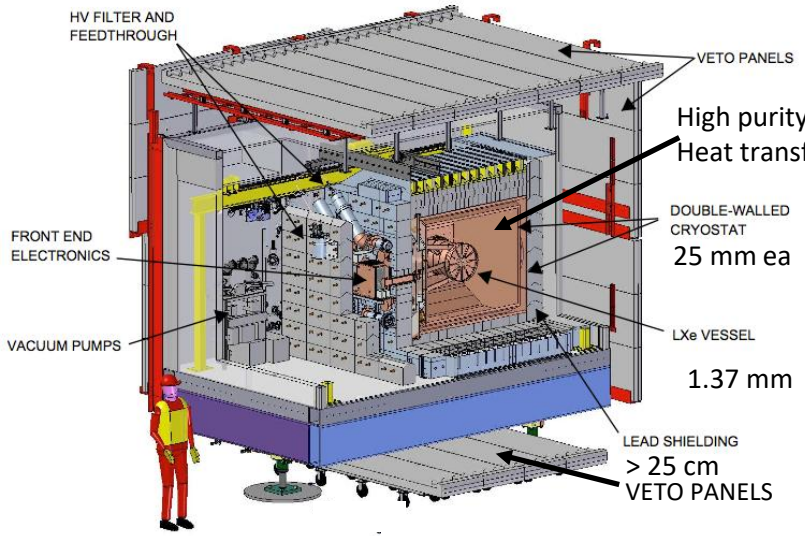


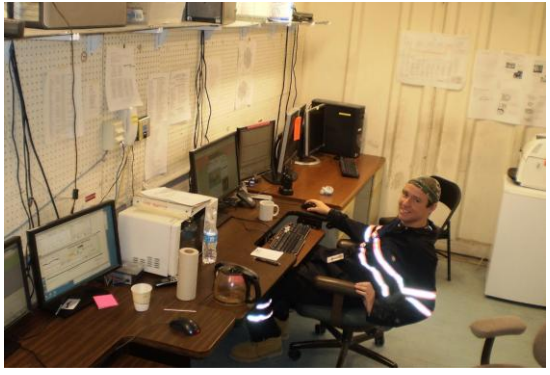
Allows for background measurement and reduction

Events with **> 1** charge cluster: multi-site events (MS)
Events with **1** charge cluster: single-site events (SS)

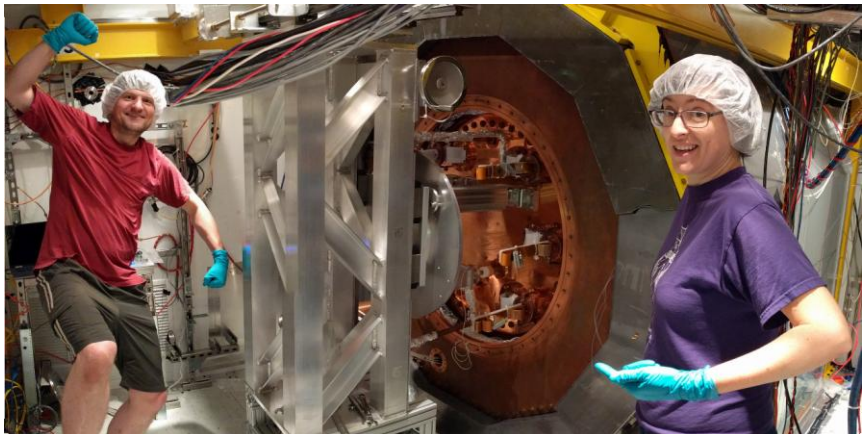
EXO-200 simulations:
$0\nu\beta\beta$: ~90% SS
γ-rays: ~15% SS at $0\nu\beta\beta$ Q-value

EXO-200


HV FILTER AND
FEEDTHROUGH
VETO PANELS
High purity
Heat transfer fluid
DOUBLE-WALLED
CRYOSTAT
25 mm ea
FRONT END
ELECTRONICS
VACUUM PUMPS
LXe VESSEL
1.37 mm
LEAD SHIELDING
> 25 cm
VETO PANELS



EXO-200 decommissioning



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
- $M^{0\nu}_{\text{Xe-134}}$ ~ 3-4
- Constrain M by comparing isotopes
  - ➢ $M^{2\nu}$ might be correlated with $M^{0\nu}$
- Half-life of ^{134}Xe $\boldsymbol{2\nu\beta\beta}$ ~ order 10^{24}-10^{25} years depending on $M^{2\nu}$, $G_{2\nu}$– might be in reach of future detectors

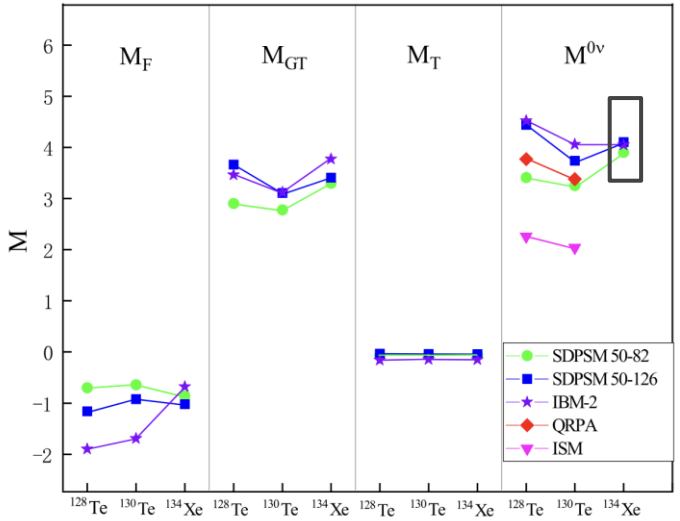


FIG. 2. The NMEs of the $0\nu\beta\beta$ decay in different models.

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.

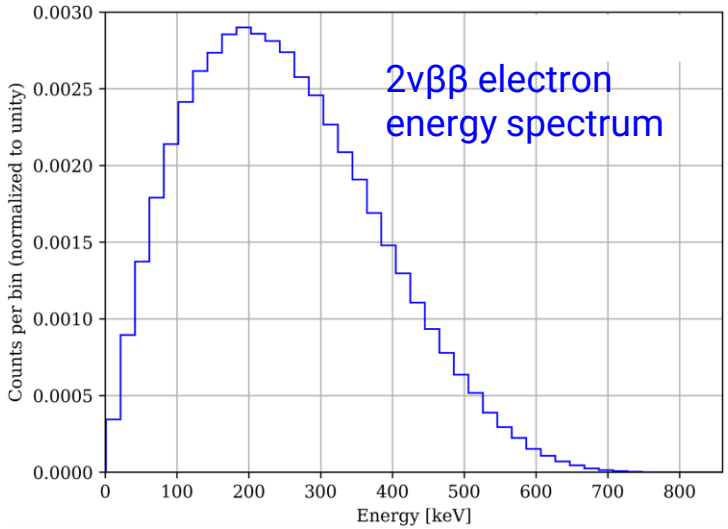
Status of Double Beta Decay Searches in ^{134}Xe

^{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**

PandaX: Phys. Rev. Lett. **132**, 152502 (2024)
EXO-200: Phys. Rev. D **96**, 092001 (2017)

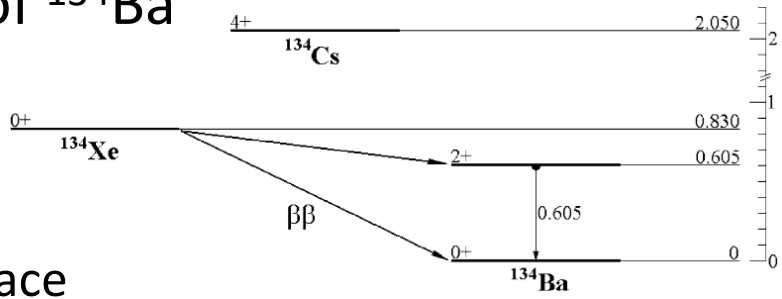


EXOSim code implementing Schenter & Vogel parameterization

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 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 **$T_{1/2} \gtrsim 10^{30}$ 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 ^{134}Xe and ^{136}Xe. Physics Letters B, 546(1):23–28, 2002



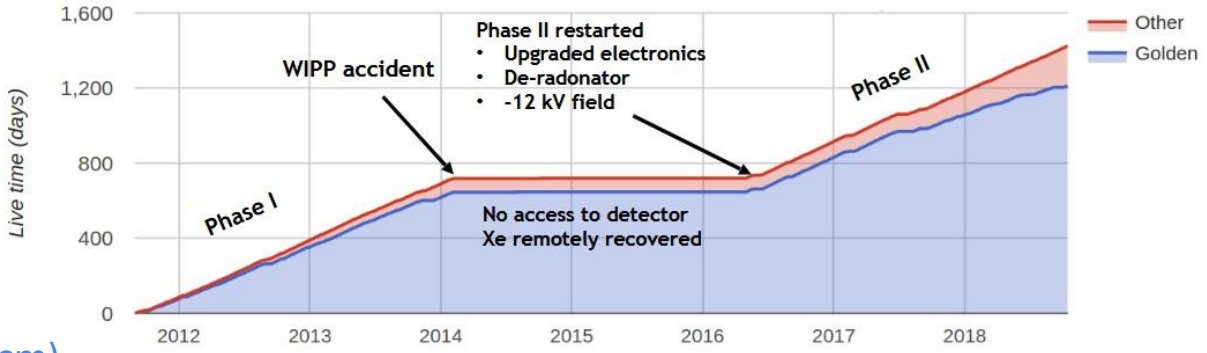
Search for ββ decay modes to the 2^+ excited state is in progress.

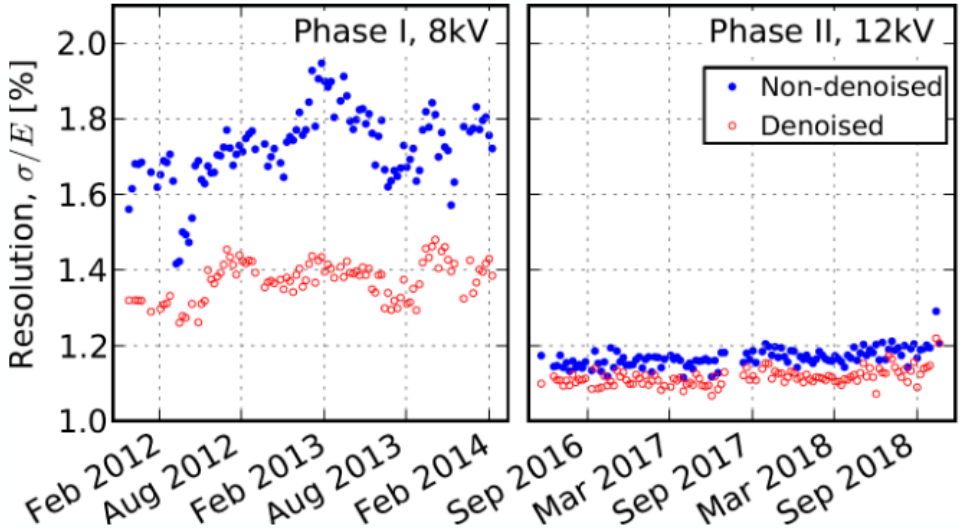
EXO-200 Phase II

Upgrades during shutdown

- ➢ Upgraded APD Readout → Reduced Noise
- ➢ 50% stronger drift field (567 V/cm)
- ➢ De-radonator added to reduce radon in air surrounding cryostat

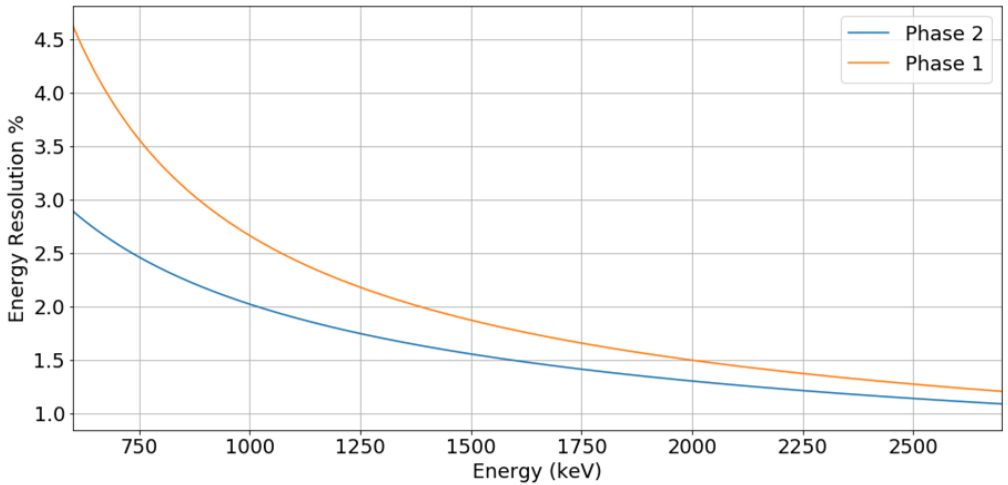
- Improved energy resolution
  - ➢ 1.35%→1.15% @ 2458 keV
- Total Phase II exposure is 28.5 kg·yr (212.8 mol·yr)





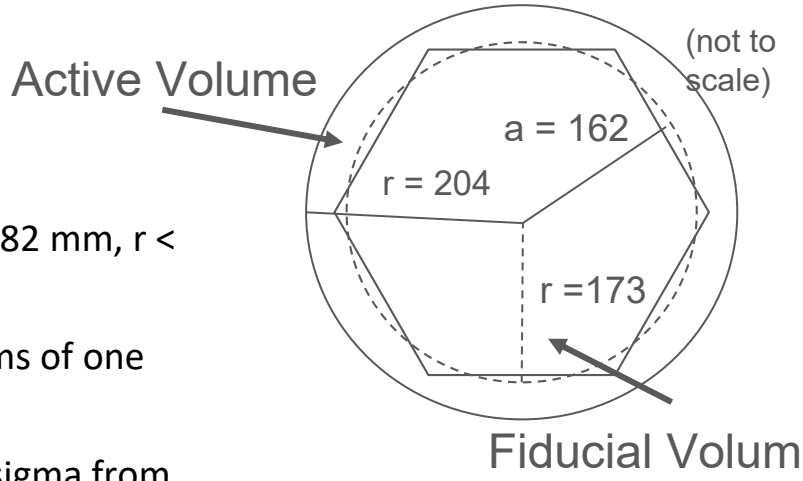
Phase II Sensitivity Improvements

- 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

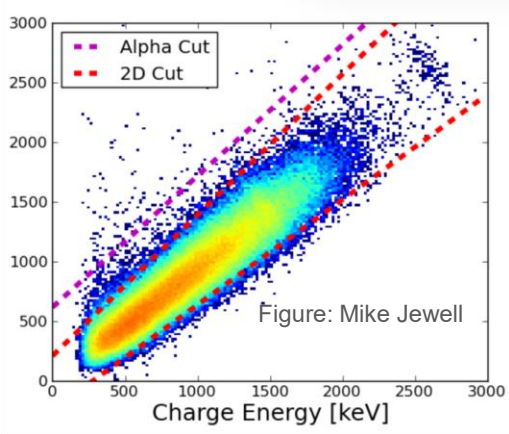


New ^{134}Xe analysis uses Phase II data only due to these substantial improvements

Data Quality Cuts

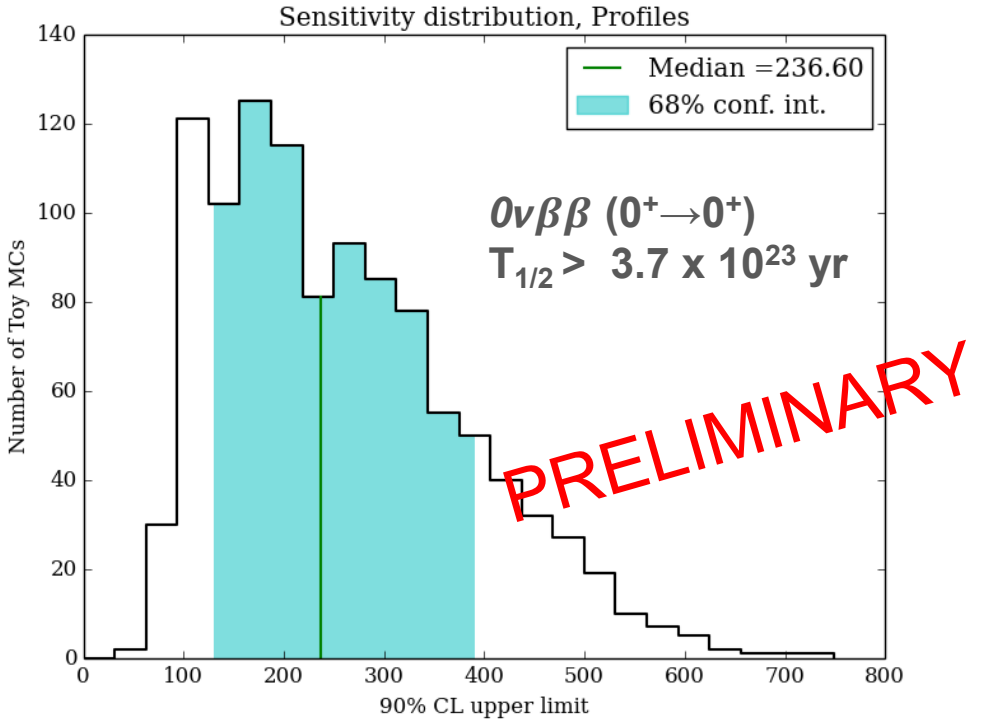


- **Fiducial volume:** hexagon with a = 162 mm, 10 < |z| < 182 mm, r < 173 mm
- **Coincidence cut:** removes events occurring within 100 ms of one another
- **Diagonal light/charge:** light-charge ratio must be < 2.5 sigma from the mean
- **Muon Veto:** cuts data taken 1 ms before and 25 ms after a trigger 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)



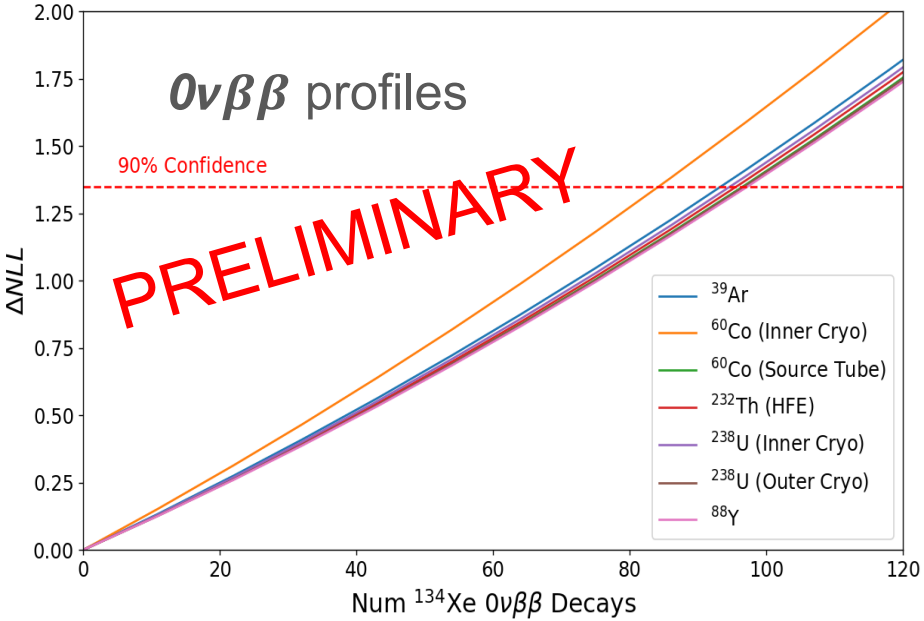
Median 90% C.L. Sensitivity (0νββ decay to ground state)

- 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

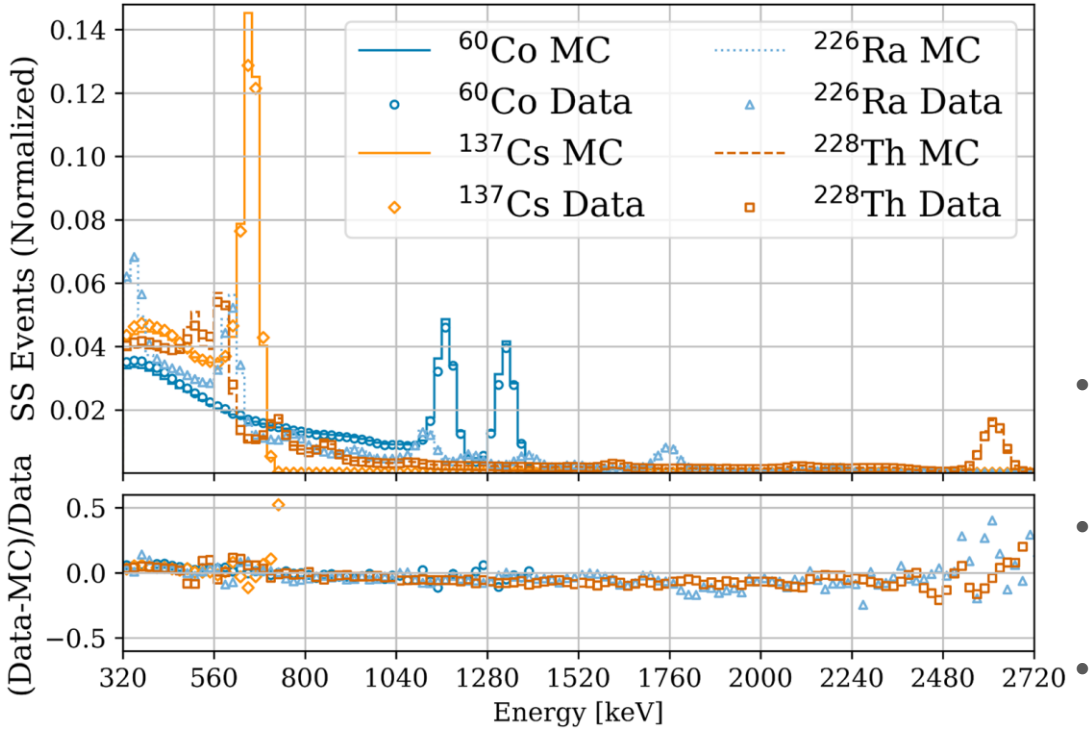


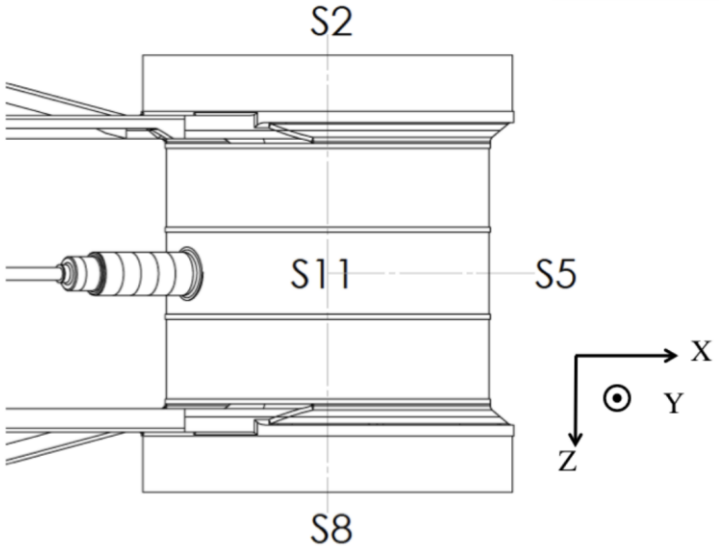
Background Model

- 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

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 source data/simulation residuals

Uncertainties in efficiency of selection cuts

Background model error (a)
+ Spectral shape error (b)

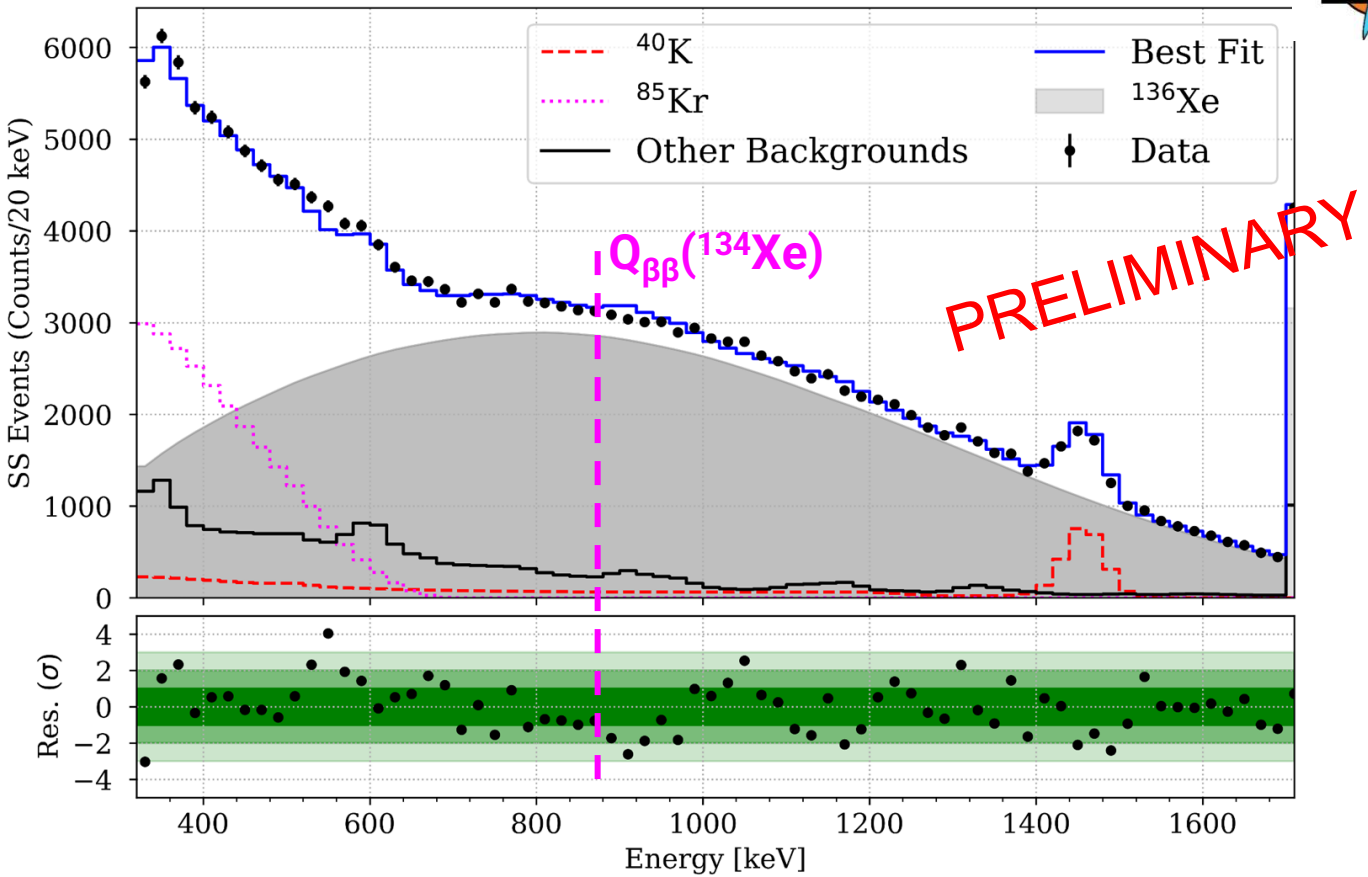
Constraint	Value
Single-Site Fraction	3.4%
Event Rate Norm.	3.4%
Signal-Specific Normalization	a = 16.3% b = 16 counts
Neutron Capture Fraction	10%
Radon in LXe	20%

Fit to Data

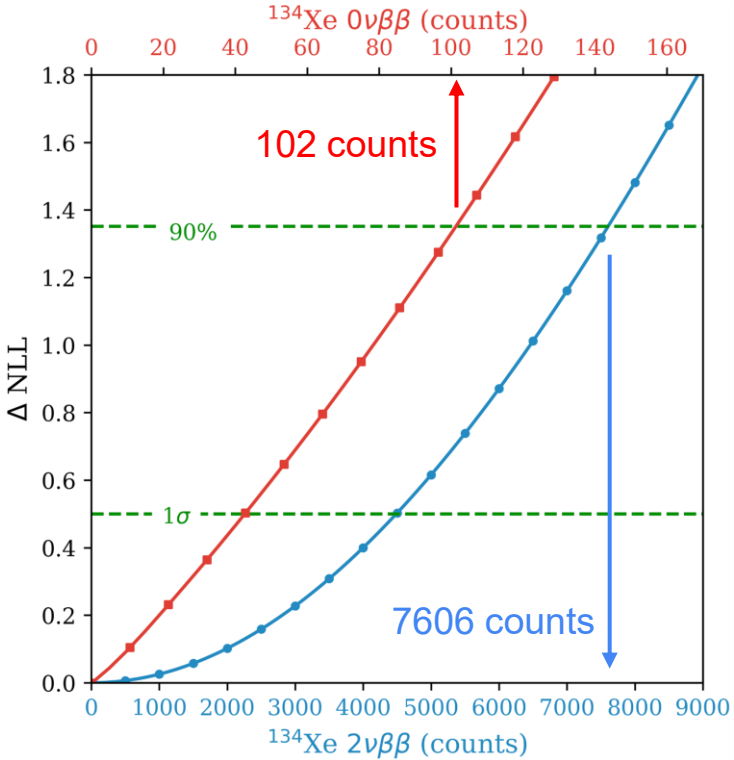
Both 0ν and 2ν ββ signal PDFs fit to zero

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

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



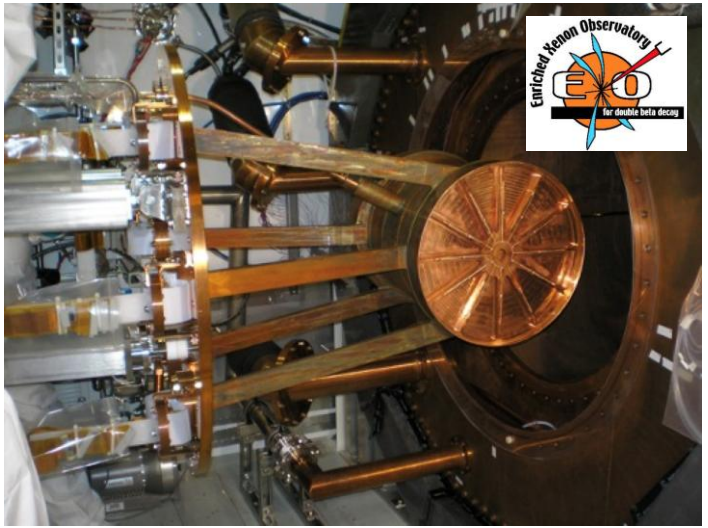
Results



PRELIMINARY

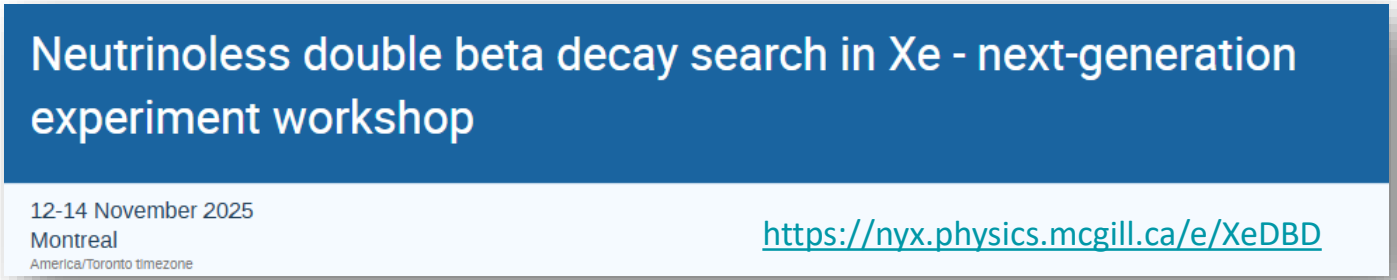
	EXO-200 Phase-II	PandaX-4T
2νββ ($0^+ \rightarrow 0^+$)	≥ 2.9 x 10^{21} yr	≥ 2.8 x 10^{22} yr
0νββ ($0^+ \rightarrow 0^+$)	**≥ 8.7 x 10^{23} yr**	≥ 3.0 x 10^{23} yr
0ν/2ν ββ ($0^+ \rightarrow 2^+$)	In progress	–

Conclusions



- We report on new world leading results on the ^{134}Xe $\boldsymbol{0\nu\beta\beta}$ ($0^+ \rightarrow 0^+$) decay
- We also improved on the EXO-200 Phase I measurement for the $\boldsymbol{2\nu\beta\beta}$ ($0^+ \rightarrow 0^+$) decay of ^{134}Xe
- Search for the $\boldsymbol{\beta\beta}$ ($0^+ \rightarrow 2^+$) decays in ^{134}Xe is in progress
- Tonne scale experiments could reach sensitivities as high as 10^{24} years, with realistic chance of observing the $\boldsymbol{2\nu\beta\beta}$ ($0^+ \rightarrow 0^+$) decay of ^{134}Xe

Advertisement: Neutrinoless double beta decay search in Xe - next-generation experiment workshop



Xe-focused 0νββ workshop planned in Montreal on November 12-14, 2025!