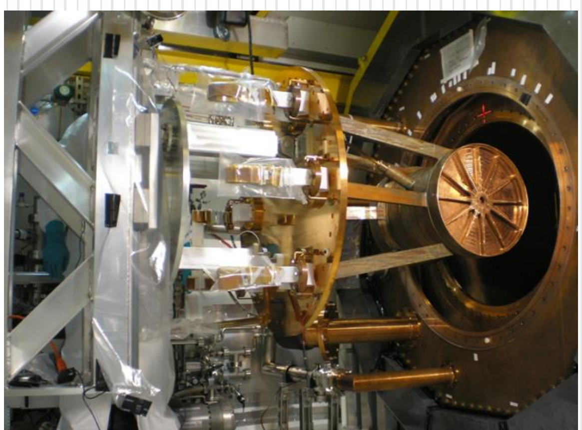
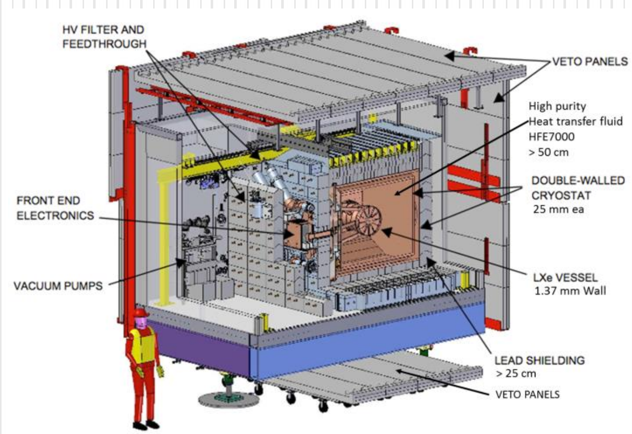
Recent Results and Status of EXO-200 and the nEXO Experiment

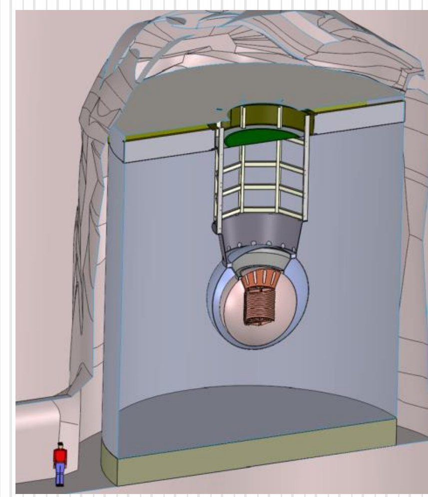
Caio Licciardi

Carleton University

for the EXO-200 and nEXO Collaborations

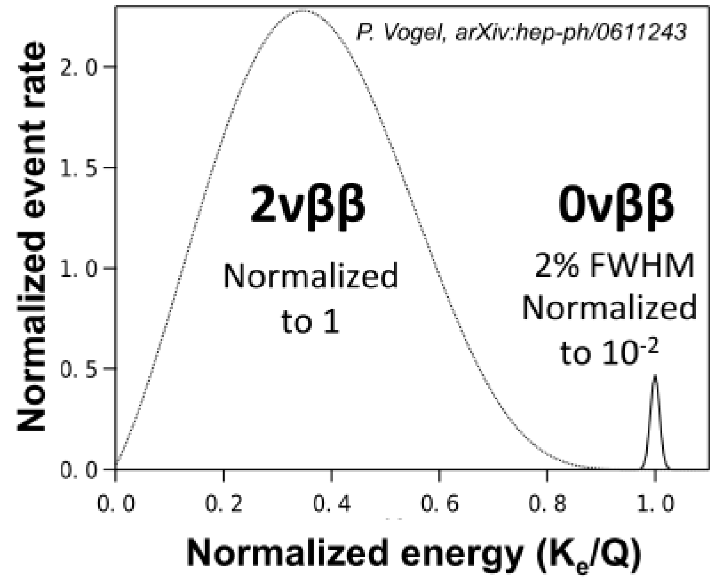






Enriched Xenon Observatory (EXO)

- Experimental program searching for neutrinoless double-beta decay ($0\nu\beta\beta$)
  - Current: EXO-200 Experiment
  - Next: nEXO Experiment



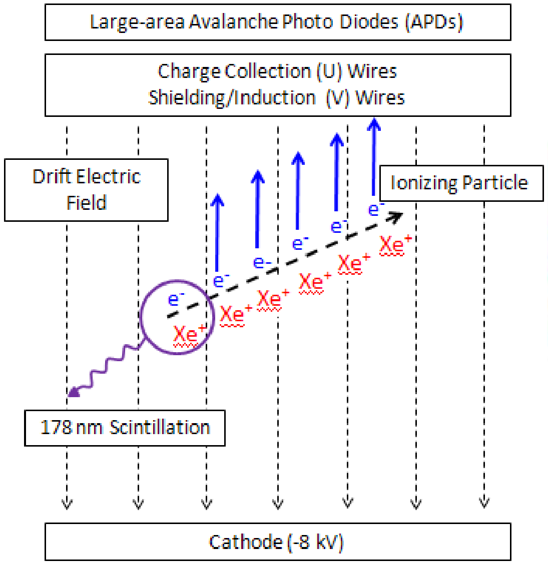
- Searching for $0\nu\beta\beta$ mode ($Q_{\beta\beta} = 2458$ keV):
  $$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^-$$

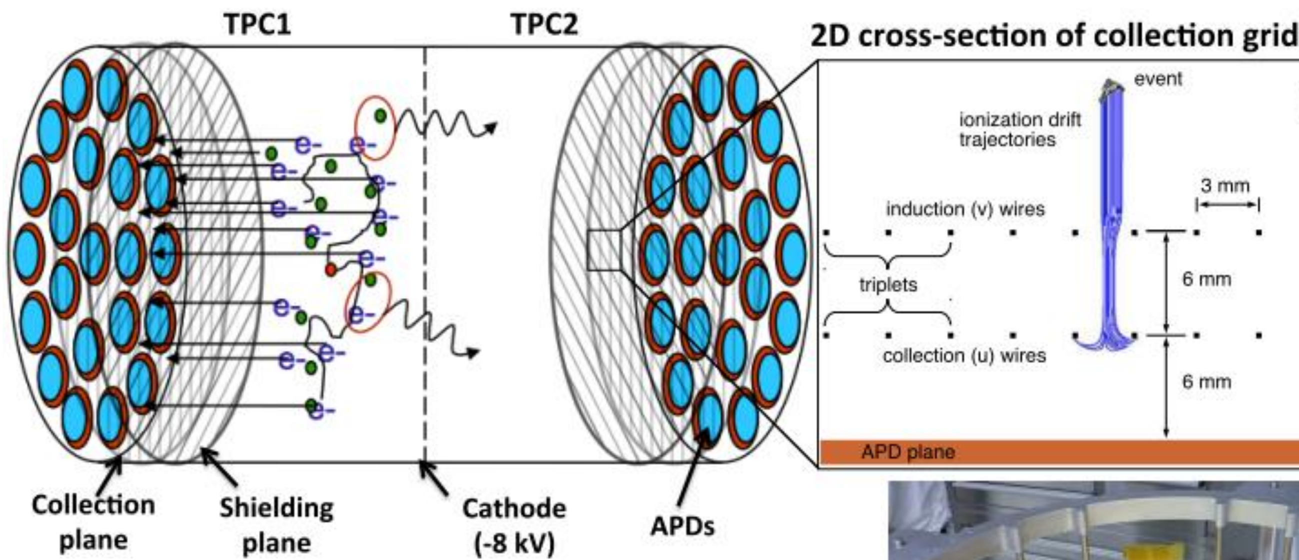
- Using a Time Projection Chamber (TPC)
  - Filled with liquid Xenon (LXe)
  - Constructed from radio-pure materials

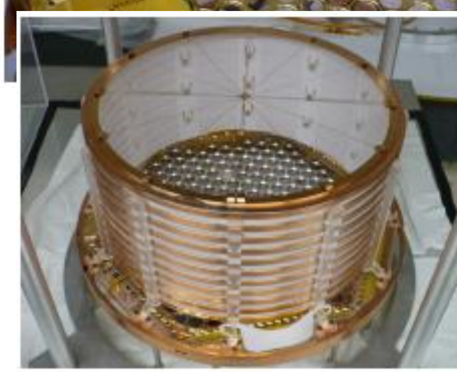
- Two measurements of the energy deposited in event
  - Scintillation light (178 nm)
  - Ionization electrons

- 3D position reconstruction
  - Third coordinate from time difference between scintillation and ionization signals

The EXO-200 TPC

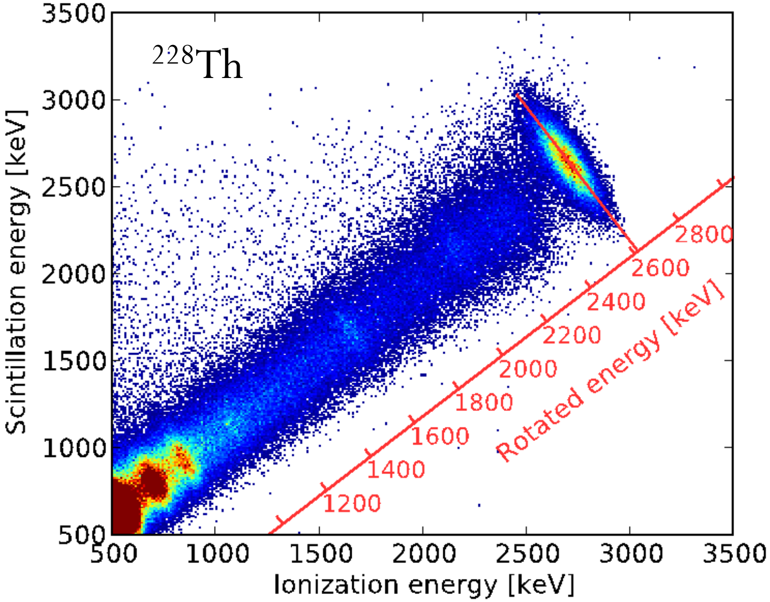




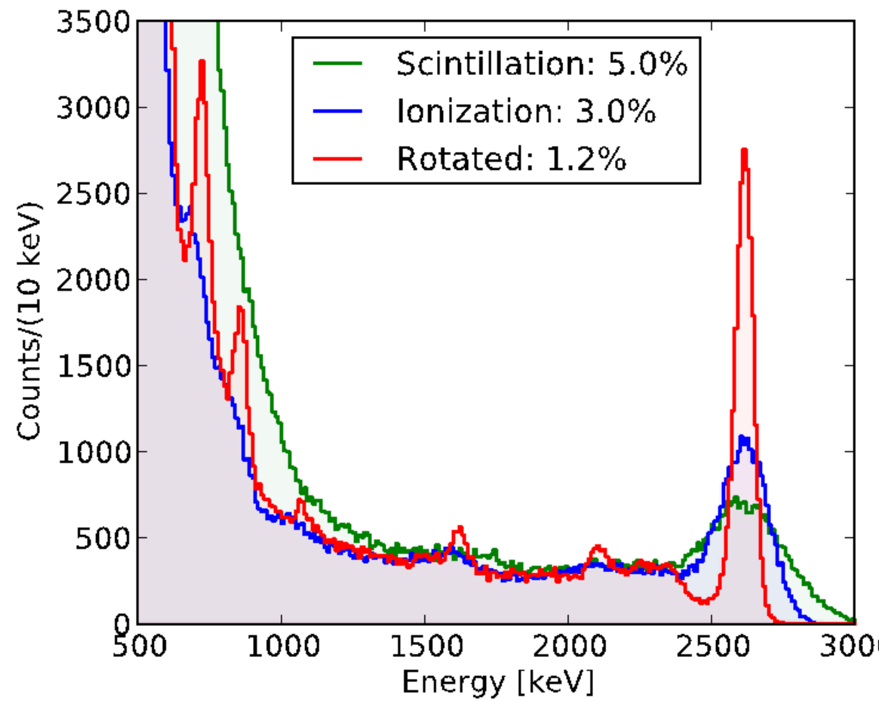


- ~150 kg LXe, enriched to 80.6% in ^{136}Xe
- High-voltage applied between cathode (center) and anodes (opposite ends)
- Scintillation collected by 234 large avalanche photo-diodes (APDs, in groups of 7) at interaction time
- Charge collected by 2 wire grids located on rotated planes after cloud drift
  - 38 U triplet wire channels: collection
  - 38 V triplet wire channels: induction

Detector Energy Resolution



- LXe scintillation light anti-correlates with ionization charge
- Anticorrelation allows a better energy resolution

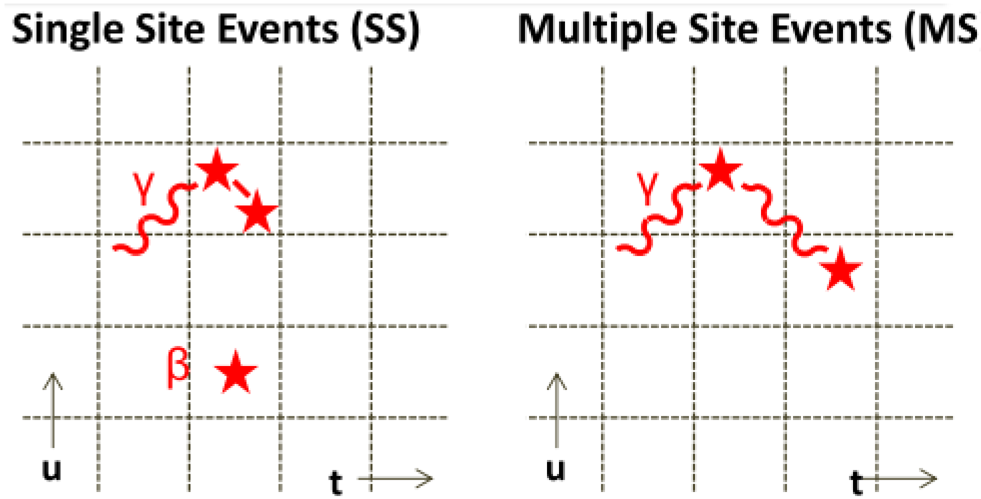


- **EXO-200 has achieved σ/E ~ 1.25% energy resolution at the Q value**

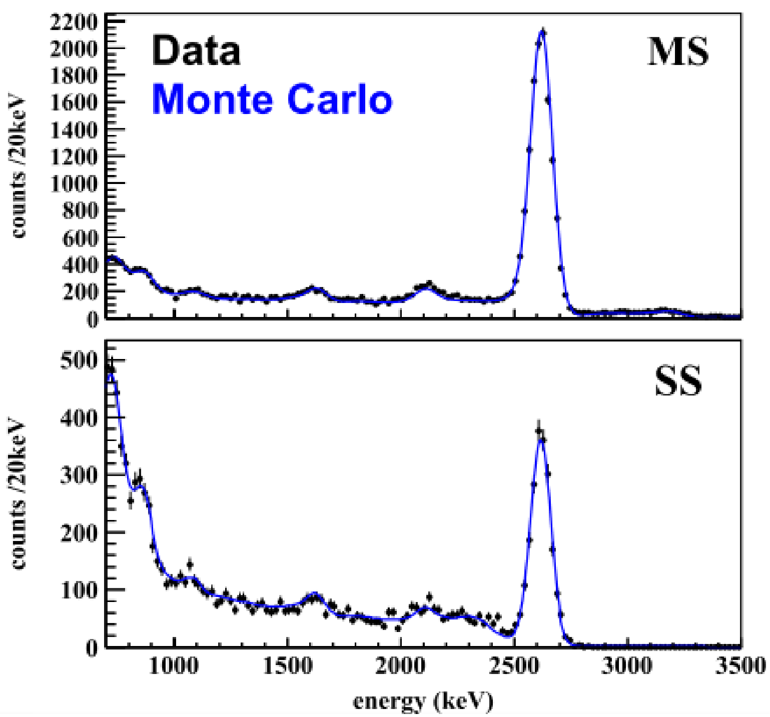
- *nEXO will reach resolution < 1%, sufficient to suppress background from 2νββ*

Position Discrimination

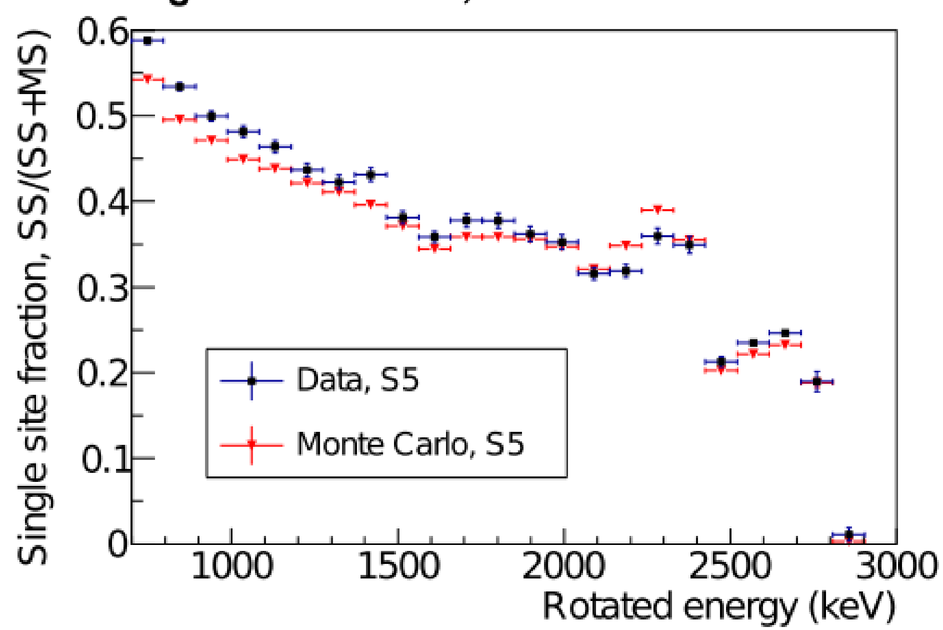
- Most gammas (backgrounds) deposit energy at multiple locations (multi-site, MS), while ββ's deposit energy at a single location (single-site, SS)
- Channel pitch is 9 mm in X/Y, while Z resolution is ~6 mm from timing



Energy spectrum, ^{228}Th calibration data:



Single-site fraction, ^{228}Th calibration data:



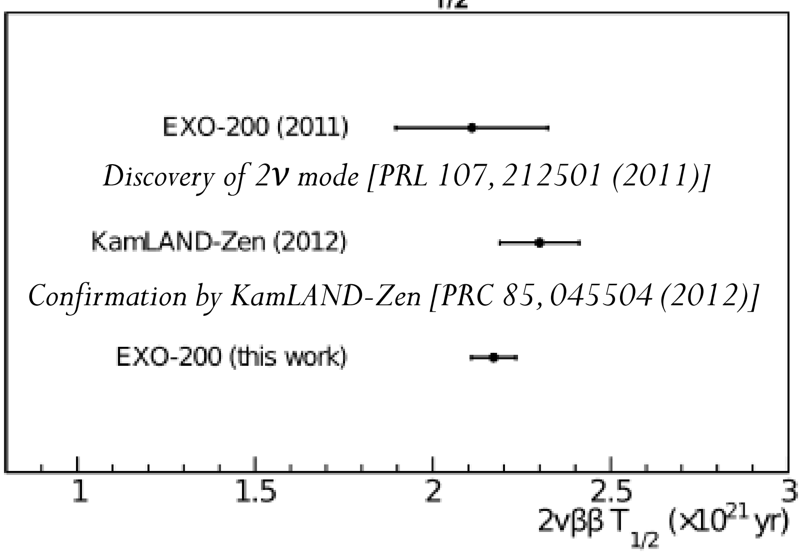
Precision 2νββ Measurement (2013)

Longest and most precisely measured 2νββ half life of any isotope to date

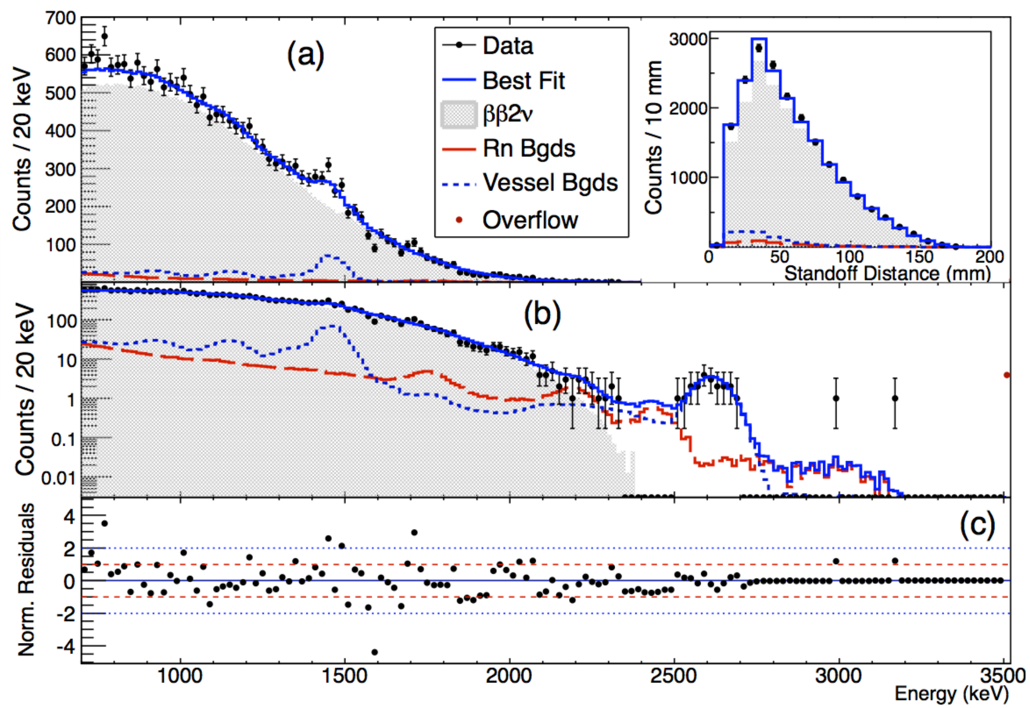
$T_{1/2}^{2\nu\beta\beta} = 2.165 \pm 0.016 \pm 0.059 \times 10^{21}$ yr
(stat) (syst)

[Phys. Rev. C 89 (2014) 015502]

Measurements of $T_{1/2}^{2\nu\beta\beta}$ for ^{136}Xe:



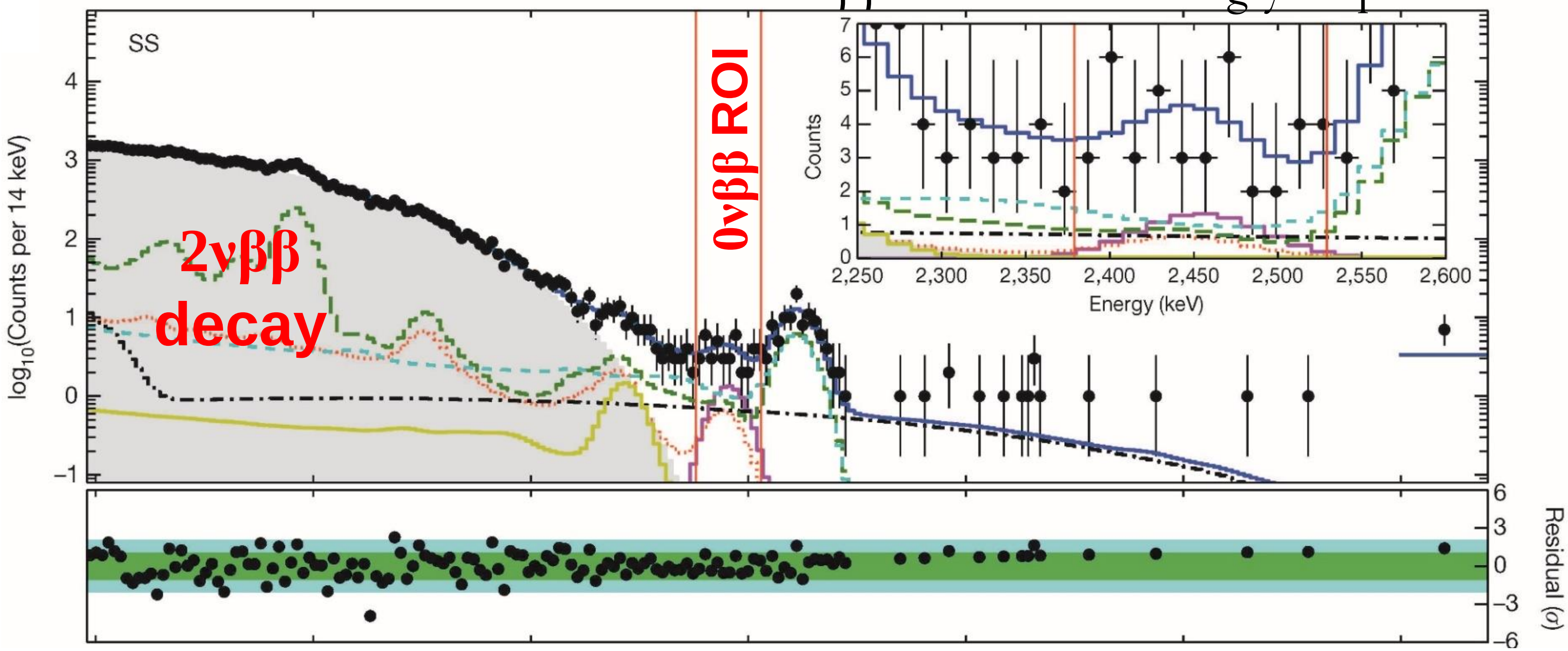
Single-site energy spectrum and fit:



Efficiency (2νββ)	57.88%
Systematic Uncertainty	2.83%
Partial Reconstruction	1.6%
Fiducial Volume	1.8%

0νββ Search (2014)

^{136}Xe 0νββ search with 100 kg·yr exposure



Background in the 0ν ROI: (1.7±0.2)·keV^{-1} ton^{-1} yr^{-1}

Sensitivity: 1.9·10^{25} yr

$T_{1/2}^{0\nu\beta\beta} > 1.1\cdot10^{25}$ yr (90%CL)

[Nature 510, 229 (2014)]

$\langle m_{\beta\beta} \rangle < 190 - 450$ meV (90% CL)

Backgrounds in ± 2σ ROI	
Th-228 chain	16.0
U-232 chain	8.1
Xe-137	7.0
Total	**31.1 ± 3.8**

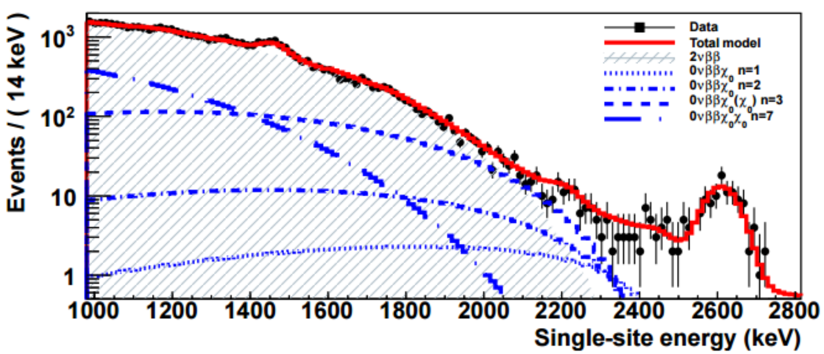
Other Double-beta Decay Results

- Majoron-mediated Decays

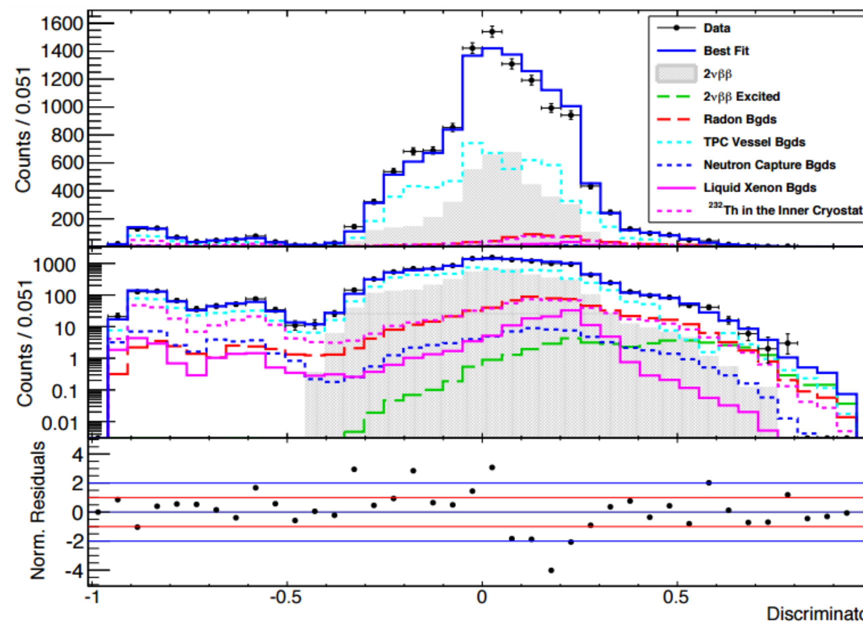
$$(A, Z) \rightarrow (A, Z+2) + 2e^- + \chi_0$$
$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\chi_0$$

← Massless or light boson ("Majoron")

  - No significant evidence is found
  - Limits on coupling constants among strongest to date
  - *PRD 90, 092004 (2014)*



- 2νββ Decay to the 0_1^+ Excited State of ^{136}Ba
  - Machine learning discriminator
  - $T_{1/2}^{2\nu}(0^+ \rightarrow 0_1^+) > 6.9 \cdot 10^{23}$ yr (90%CL)
  - *PRC 93, 035501 (2016)*



Recent Publications

Many other recent publications by the EXO-200 Collaboration

- Investigation of Radioactivity-induced Backgrounds in EXO-200
  - *PRC 92, 015503 (2015)*
- Measurements of the Ion Fraction and Mobility of Alpha and Beta Decay Products in Liquid Xenon Using EXO-200
  - *PRC 92, 045504 (2015)*
- First Search for Lorentz and CPT Violation in Double-beta Decay with EXO-200
  - *PRD 93, 072001 (2016)*
- Cosmogenic Backgrounds to $0\nu\beta\beta$ in EXO-200
  - *JCAP, April 2016*
- An Optimal Energy Estimator to Reduce Correlated Noise for the EXO-200 Light Readout
  - *JINST, Vol. 11, July 2016*

And others soon to be published …

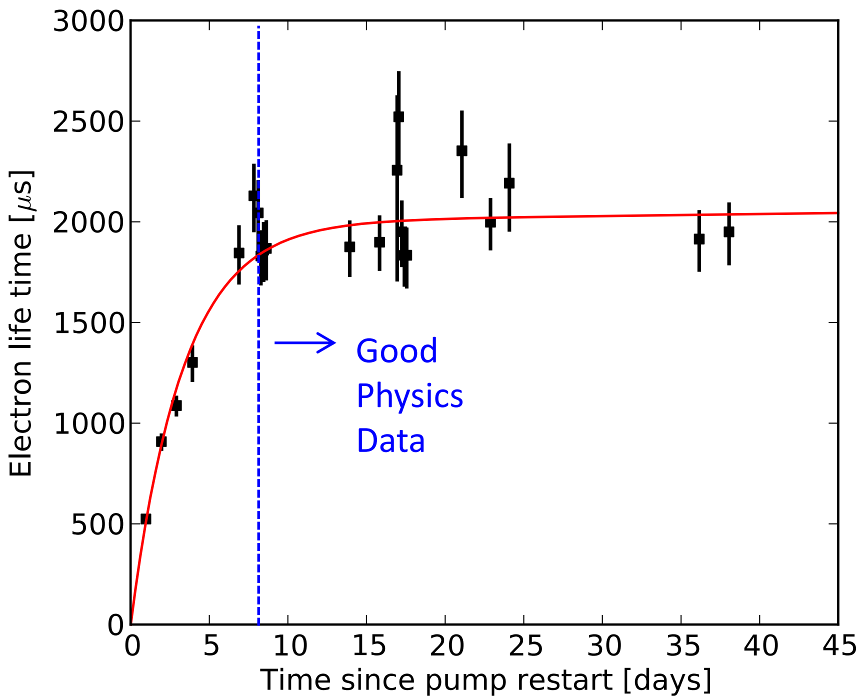
Recovery from Underground Incidents

DOE Accident Inv. Rep., Mar 2014

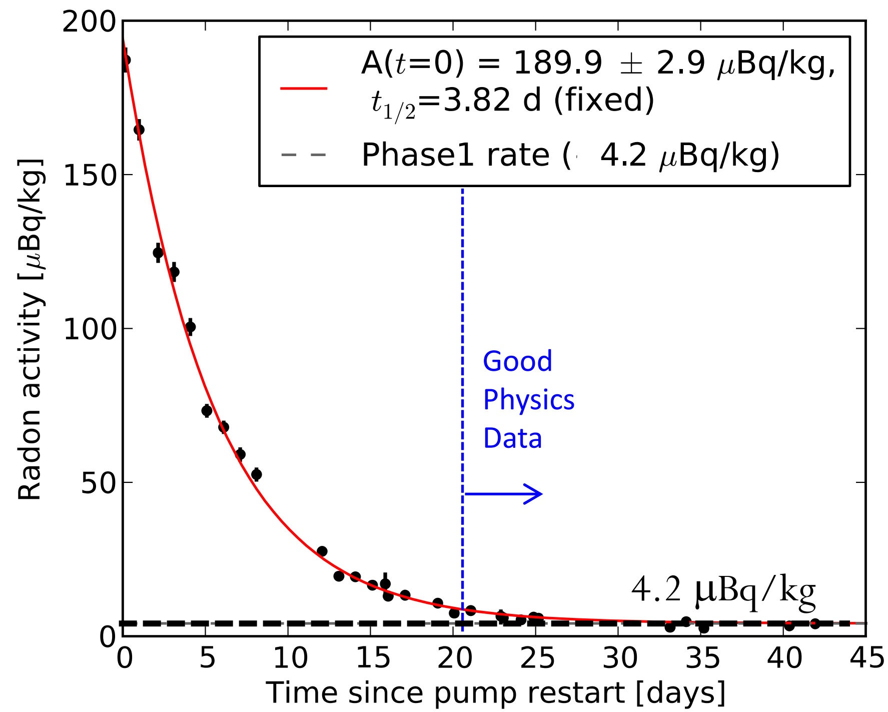
- **WIPP Events:**
  - 5 Feb. 2014
    - Fire in WIPP underground
  - 14 Feb. 2014
    - Unrelated airborne radiological event
- **Recovery**:
  - 18 Feb 2014, remote recovery of enriched xenon
  - Sept. 2014 – June 2015, drift and clean room cleanup and TPC health diagnostics (no measureable radioactive contamination inside or outside the cleanrooms.
  - June – Oct. 2015, equipment repair and Infrastructure maintenance
- **Phase-II Restart**:
  - Oct. 2015 – Jan. 2016, system cooldown, gas purification and liquid xenon filling
  - Feb. – April 2016, detector upgrades (electronics and derandonator)
  - April 2016, Phase-II Physics data taking begins

EXO-200 Phase-II Operation

- EXO-200 Phase-II operation begins on 1/31/2016, after enriched liquid xenon fill
- Data shows that the detector reached excellent xenon purity and ultra-low internal Rn level shortly after restart

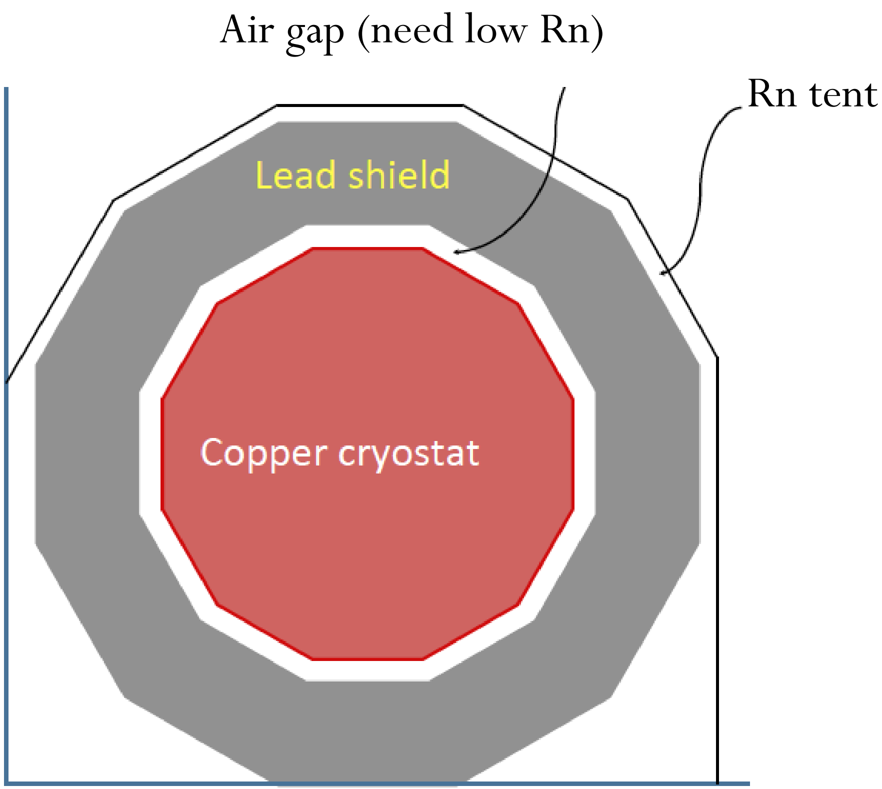


Xenon purity since Jan. 31, 2016



Rn level in TPC since Jan. 31, 2016

Upgrade Performance (Deradonator)



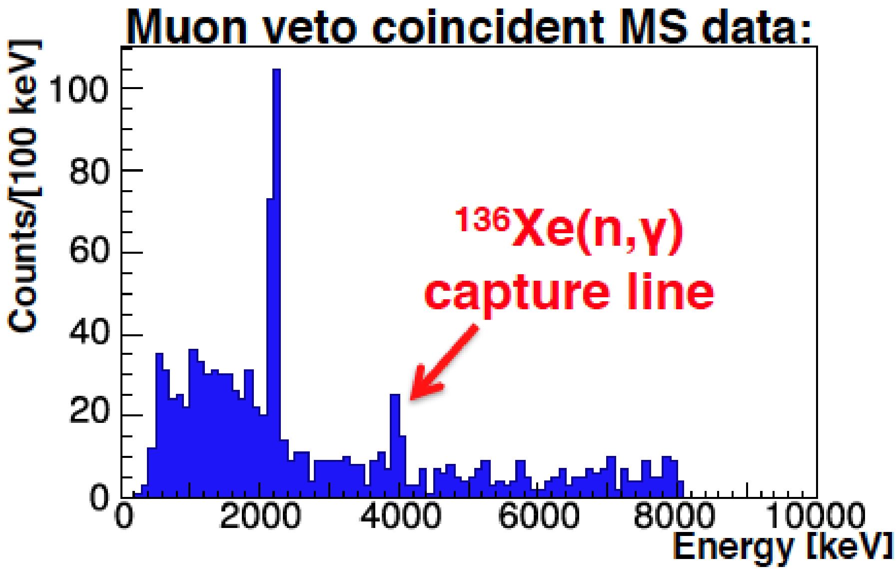
EXO-200 Clean Room Module 1

Deradonator can deliver 0.85 m^3/min of low Rn air

- Measurements show that the Rn level in the air gap has been reduced by a factor ~ 10, sufficient to suppress this background for $0\nu\beta\beta$ search.

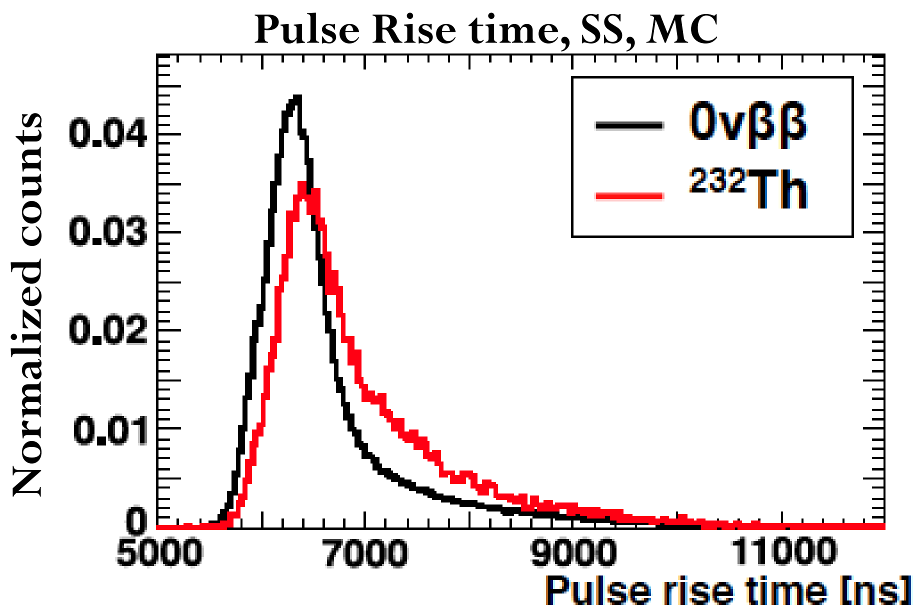
Analysis Improvements

Xe-137 Veto



Tagging neutron capture events using both veto panel and prompt gamma information can suppress ^{137}Xe

Improved SS/MS discriminators

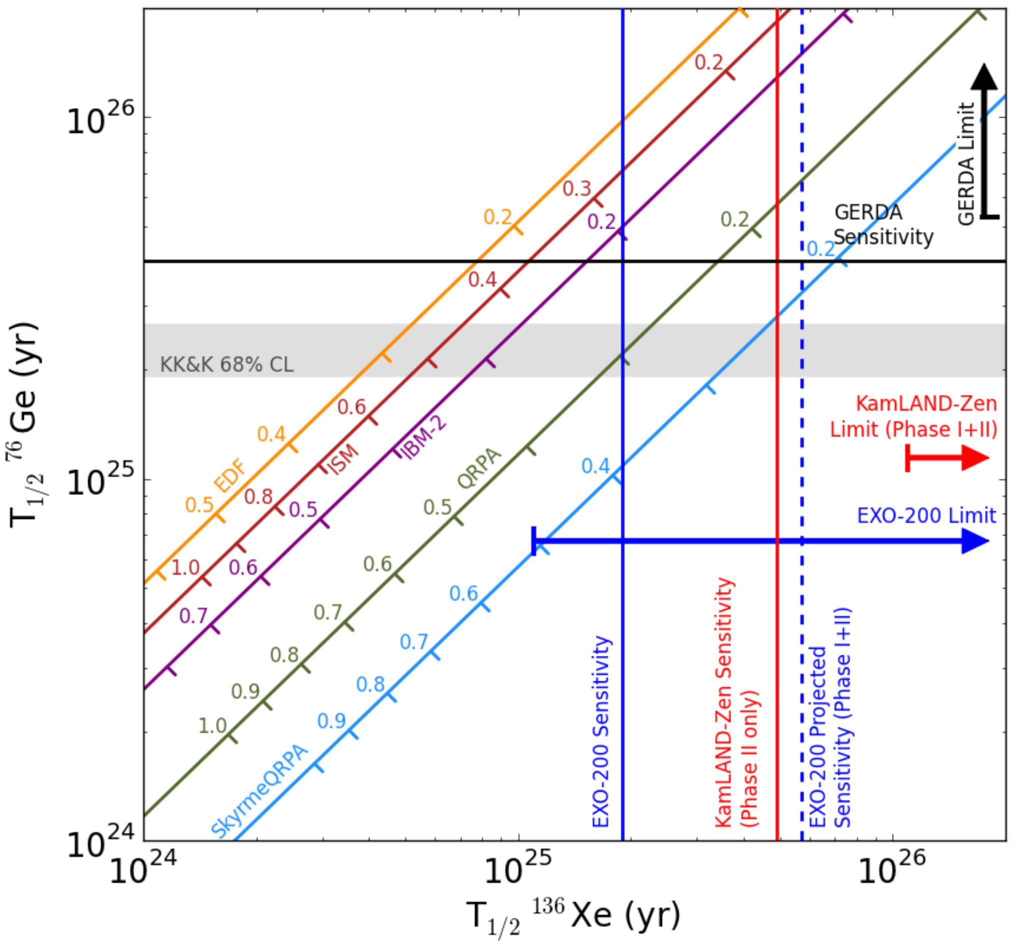


Discriminating gamma/beta events using the pulse rise time can suppress U and Th backgrounds

Many other analysis techniques under study:

- Enhance energy resolution through corrections of spatial and temporal non-uniformity
- Reduce systematics through detector simulation and calibration
- Implement continuous multiplicity metrics to improve event classification
- Develop multivariate discriminators and other machine learning algorithms

Sensitivity to 0νββ



- EXO-200 can reach 0νββ half-life sensitivity of **5.7x10^{25} yrs**
- With lower threshold, EXO-200 can improve measurement of ^{136}Xe 2νββ and searches in other physics channels

EXO-200:
Nature (2014),
doi:10.1038/nature13432

GERDA Phase 2:
Public released result. June, 2016
(frequentist limit)

KamLAND-Zen:
arXiv:1605.02889 (2016)

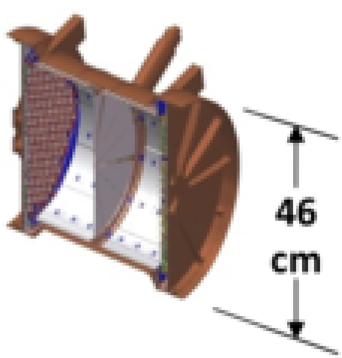
Next Generation Experiment: nEXO

- EXO-200 has surpassed design energy resolution and SS/MS rejection capability, and is expected to suppassed the design background goals

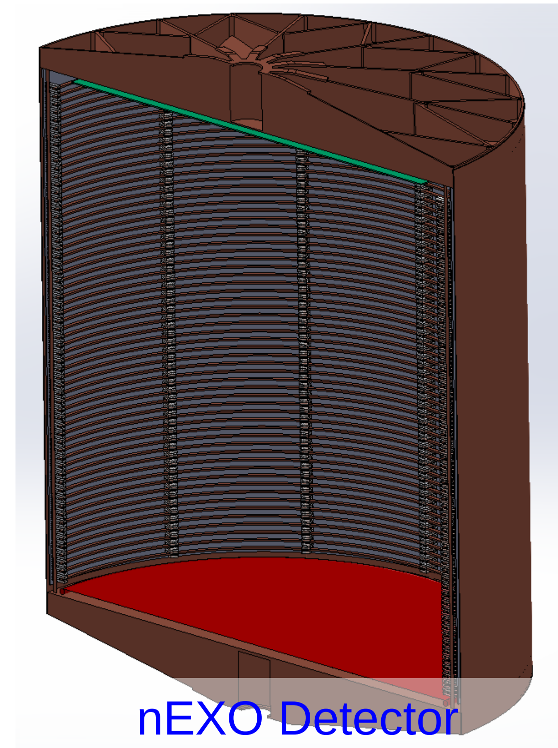
- nEXO design:
  - ~ 5 tonne LXe TPC
  - 4.7 tonnes of active enrXe (90% or higher)
  - < 1.0% (σ/E) energy resolution
  - cover inverted hierarchy
  - options for Ba-tagging

Poster 1364 on nEXO by **J. Albert**
The Next-generation Neutrinoless Double-beta Decay Experiment nEXO
Saturday, August 6^{th} (tomorrow)

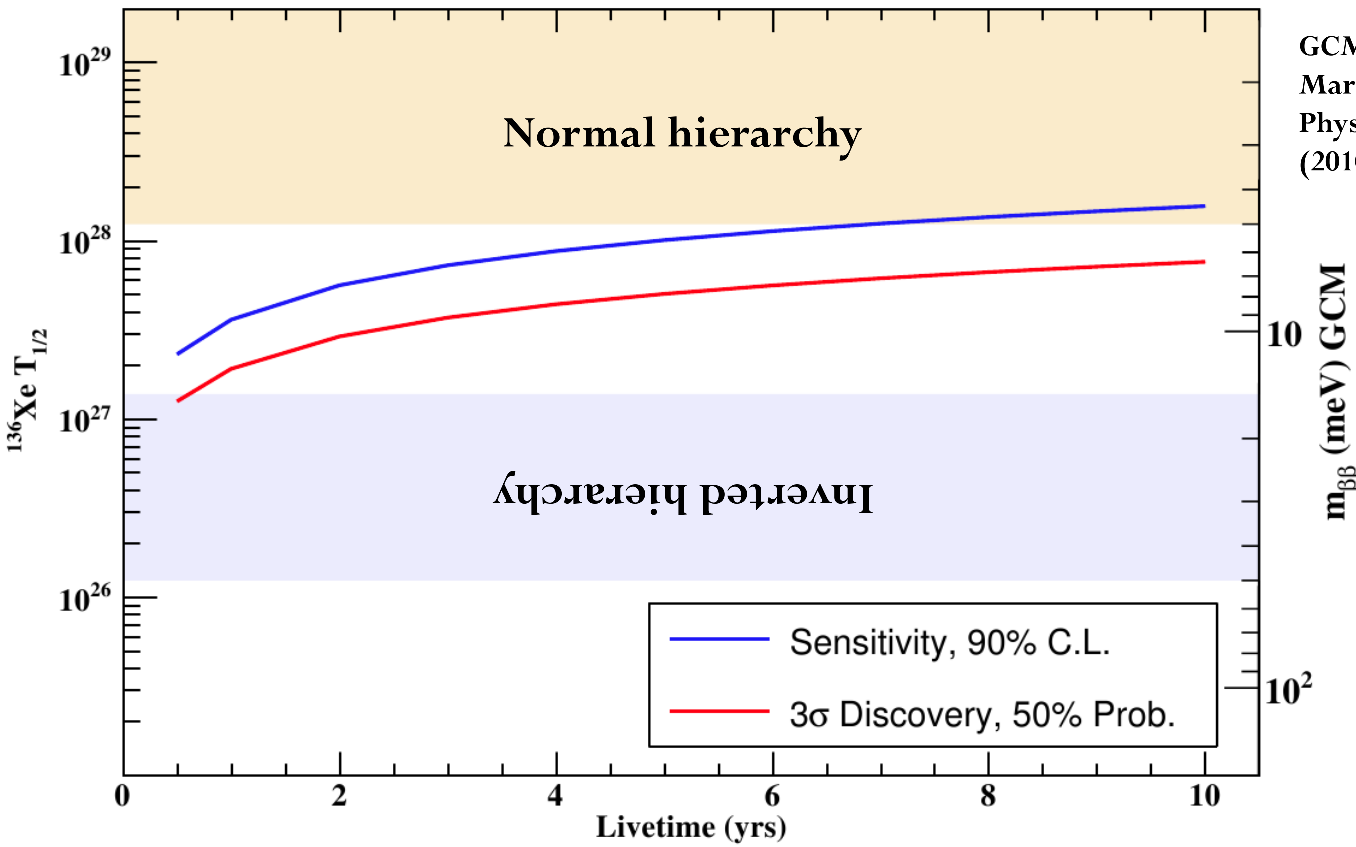
EXO-200 Detector



1.3 m



nEXO Sensitivity to 0νββ

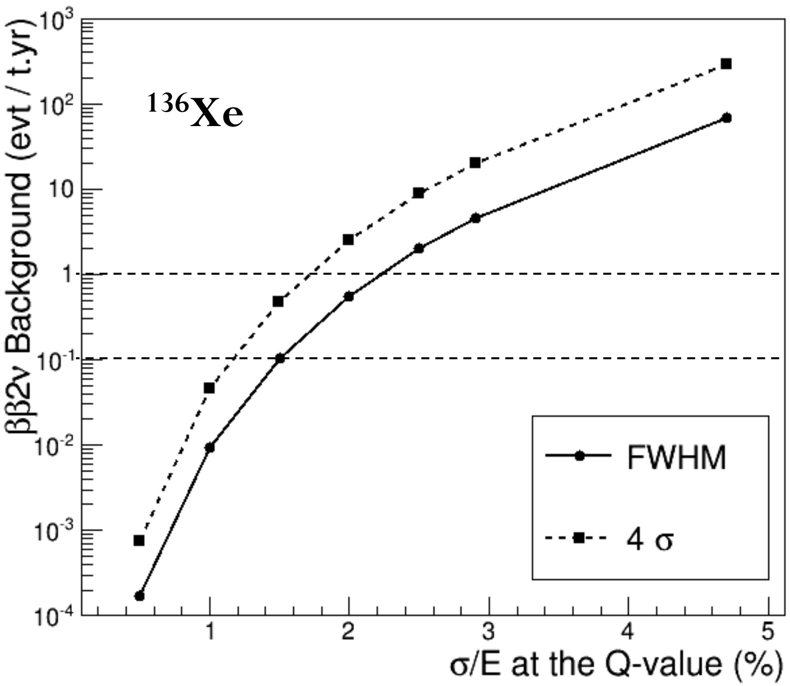


GCM: Rodriguez, Martinez-Pinedo, Phys. Rev. Lett. 105 (2010) 252503

nEXO sensitivity as a function of time for the best-case nuclear matrix element (GCM).

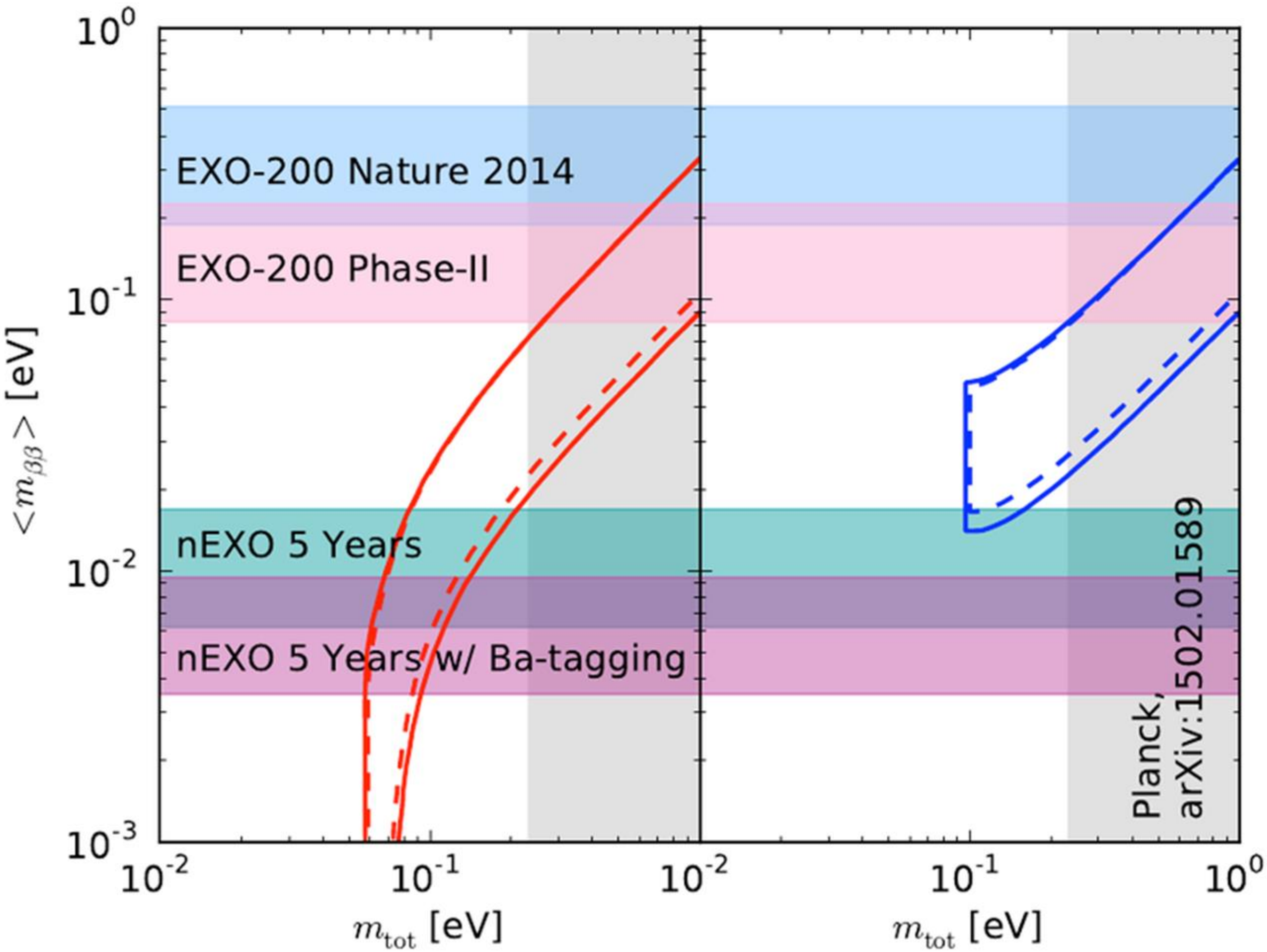
Tagging the Daughter Ba

- ^{136}Xe offers a unique possibility of the daughter identification
  - In this scenario, the only backgrounds arise from $2\nu\beta\beta$
- While LXe TPCs provide many handles to discriminate backgrounds, energy resolution is the only handle to discriminate $2\nu\beta\beta$ background
  - Future very large scale detectors should have sufficient energy resolution to suppress the $2\nu\beta\beta$ mode



The $2\nu\beta\beta$ background is smallest for ^{136}Xe, as it has the longest $2\nu\beta\beta$ half-life.

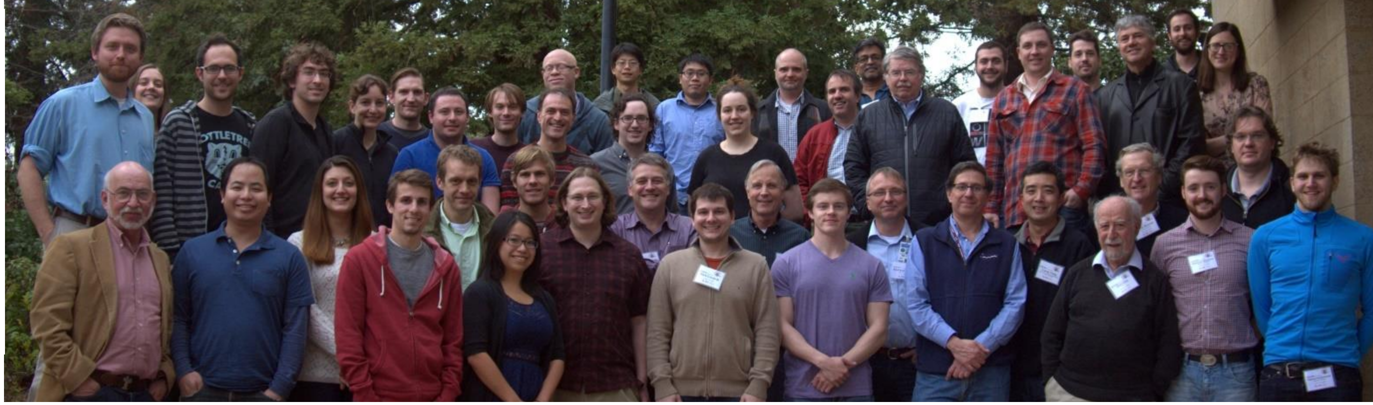
Summary



EXO-200 Nature 2014
EXO-200 Phase-II
nEXO 5 Years
nEXO 5 Years w/ Ba-tagging
Planck, arXiv:1502.01589
$<m_{\beta\beta}>$ [eV]
m_{tot} [eV]
10^0
10^{-1}
10^{-2}
10^{-3}

The EXO-200 Collaboration

Enriched Xenon Observatory EXO for double beta decay



University of Alabama, Tuscaloosa AL, USA — T Didberidze, M Hughes, A Piepke, R Tsang
University of Bern, Switzerland — J-L Vuilleumier
University of California, Irvine, Irvine CA, USA — M Moe
California Institute of Technology, Pasadena CA, USA — P Vogel
Carleton University, Ottawa ON, Canada — M Dunford, R Gornea, K Graham, R Killick, T Koffas, C Licciardi, D Sinclair
Colorado State University, Fort Collins CO, USA — C Chambers, A Craycraft, W Fairbank Jr., T Walton
Drexel University, Philadelphia PA, USA — E Callaghan, MJ Dolinski, YH Lin, E Smith, Y-R Yen
Duke University, Durham NC, USA — PS Barbeau
Friedrich-Alexander-University Erlangen, Nuremberg, Germany — G. Anton, R. Bayerlein, J. Hoessl, P. Hufschmidt, A. Jamil, T. Michel, M. Wagenpfeil, G. Wrede, T. Ziegler
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ITEP Moscow, Russia — V Belov, A Burenkov, M Danilov, A Dolgolenko, A Karelin, A Kuchenkov, V Stekhanov, O Zeldovich
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Stanford University, Stanford CA, USA — R DeVoe, D Fudenberg, G Gratta, M Jewell, S Kravitz, D Moore, I Ostrovskiy, A Schubert, M Weber
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Technical University of Munich, Garching, Germany — W Feldmeier, P Fierlinger, M Marino
TRIUMF, Vancouver BC, Canada — J Dilling, R Krücken, Y Lan, F Retière, V Strickland

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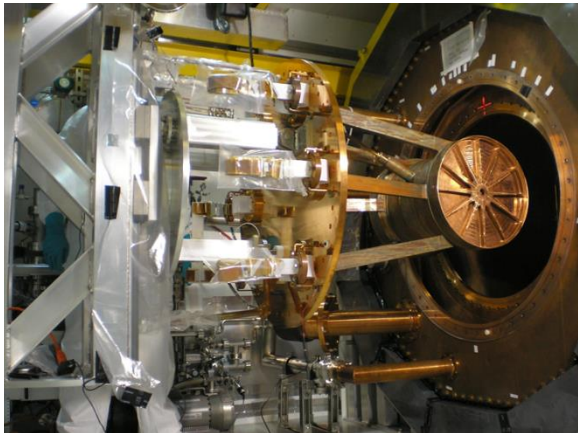
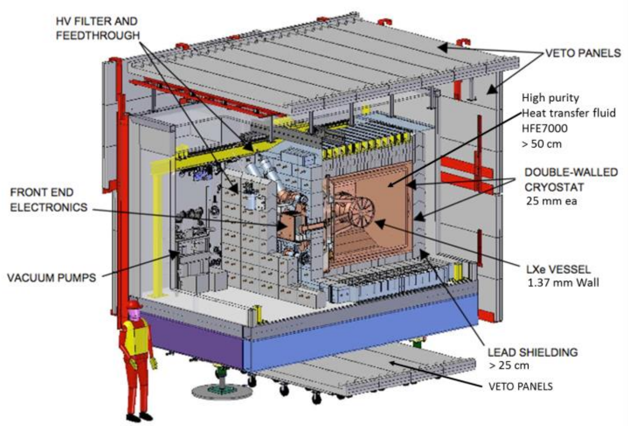
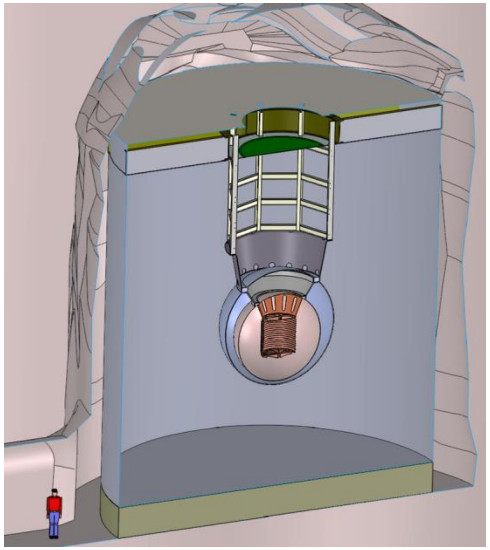
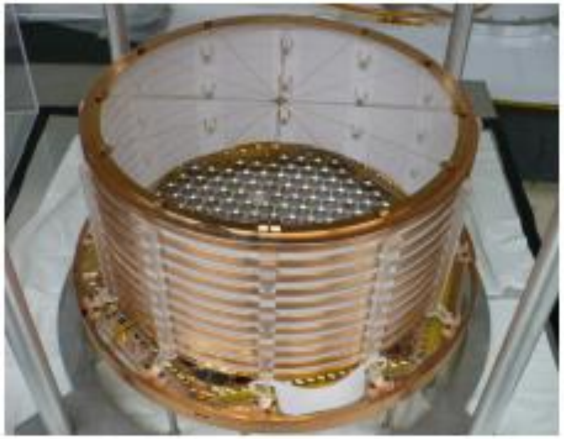
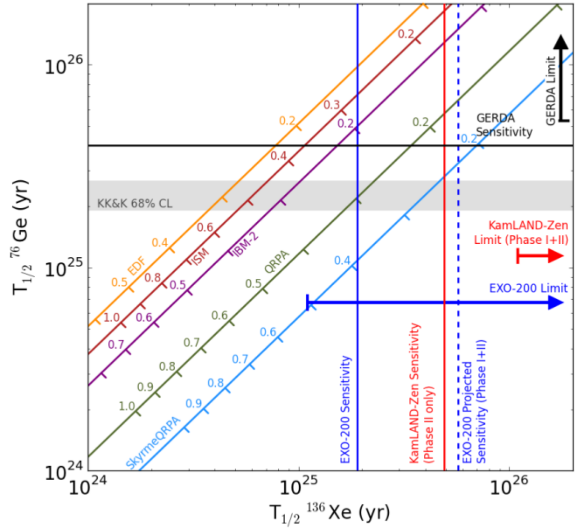
Thank You – Questions?









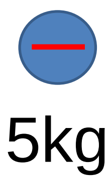


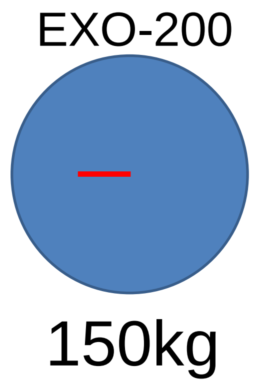
Poster by **J. Albert**

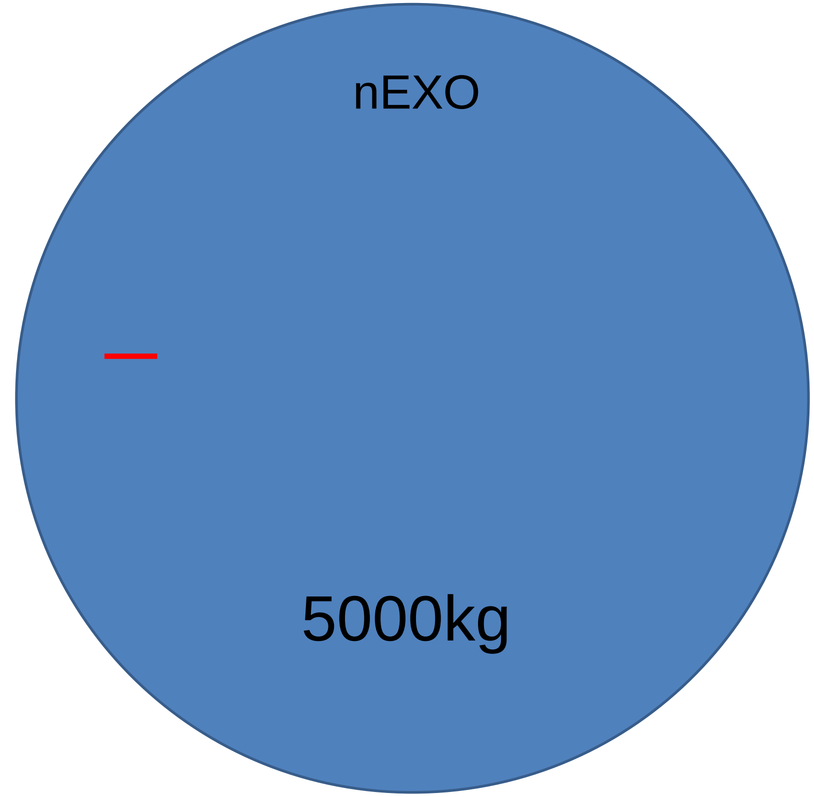
The Next-generation Neutrinoless Double-beta Decay Experiment nEXO

Saturday, August 6^{th}

Monolithic Detectors







2.5MeV gamma ray attenuation length 8.5 cm = —

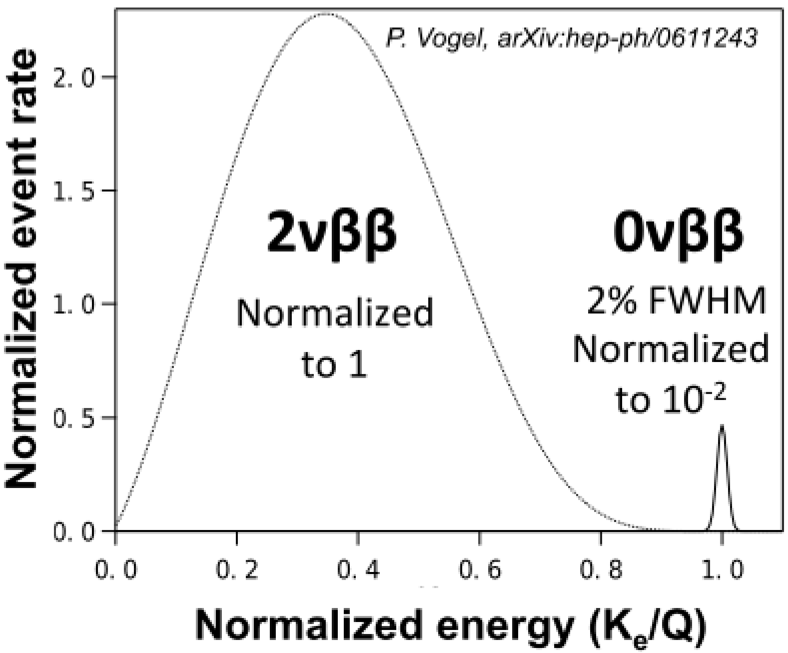
LXe mass (kg)	Diam. or length (cm)
5000	130
150	40
5	13

Monolithic detector is essential for background rejection:

- Rejection of surface background
- Self-shielding, containment of Compton scattering
- Inner fiducial volume extremely clean

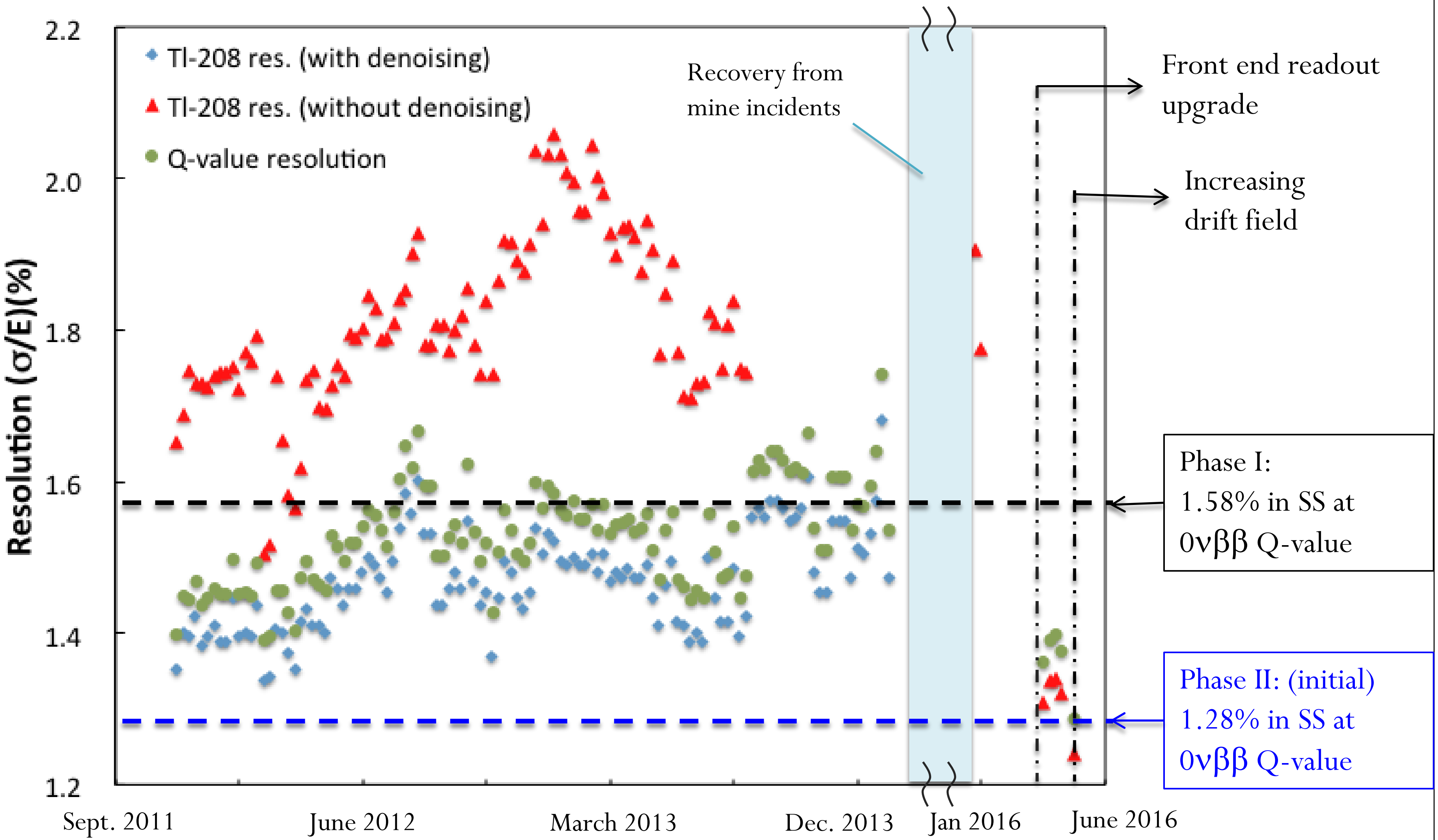
Motivations

- Physics (observation of 0νββ mode would provide):
  - Majorana nature of the neutrinos
  - Neutrino mass scale
  - A lepton number violating process
  - Beyond the Standard Model physics



- Material (LXe):
  - Easier enrichment (noble gas)
  - Reusable: can be purified and recycled
  - Self-shielding: reduces effect of surface contamination
  - Minimal cosmogenic activation: no long-lived radioactive isotopes
  - Good energy resolution: ~1% at Q-value by using the anticorrelation between scintillation light and ionization charge
  - Identification of daughter nucleus: identification of Ba daughter would eliminate all non-ββ backgrounds (on-going research)

EXO-200 Phase II Upgrade Performance (Front End Readout Upgrade)



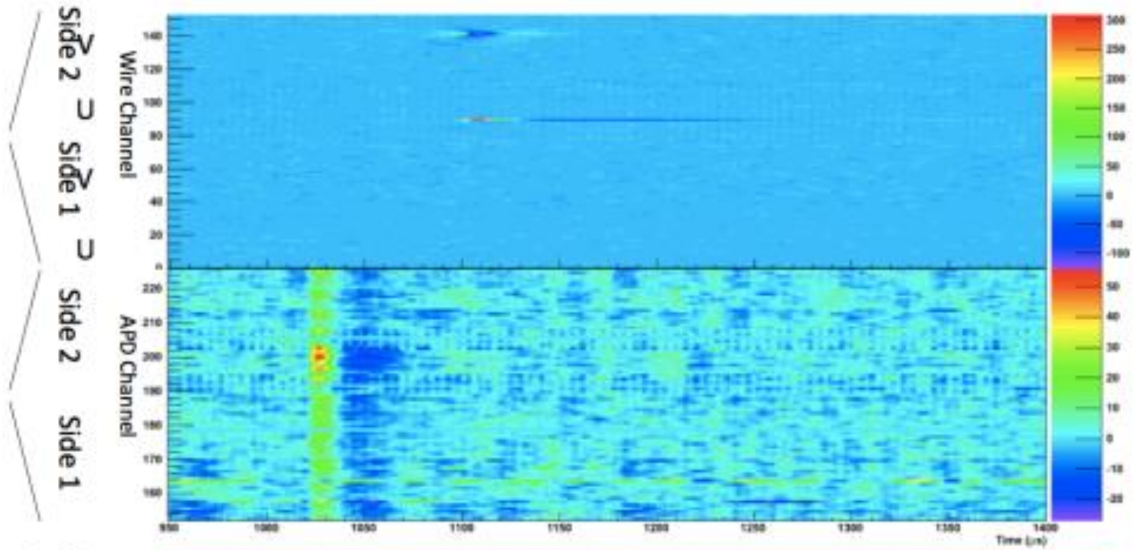
Further improvements in detector energy resolution may be possible with better signal reconstruction and detector non-uniformity corrections.

Event Topology

Single site:

Charge readout
V: Induction
U: Collection

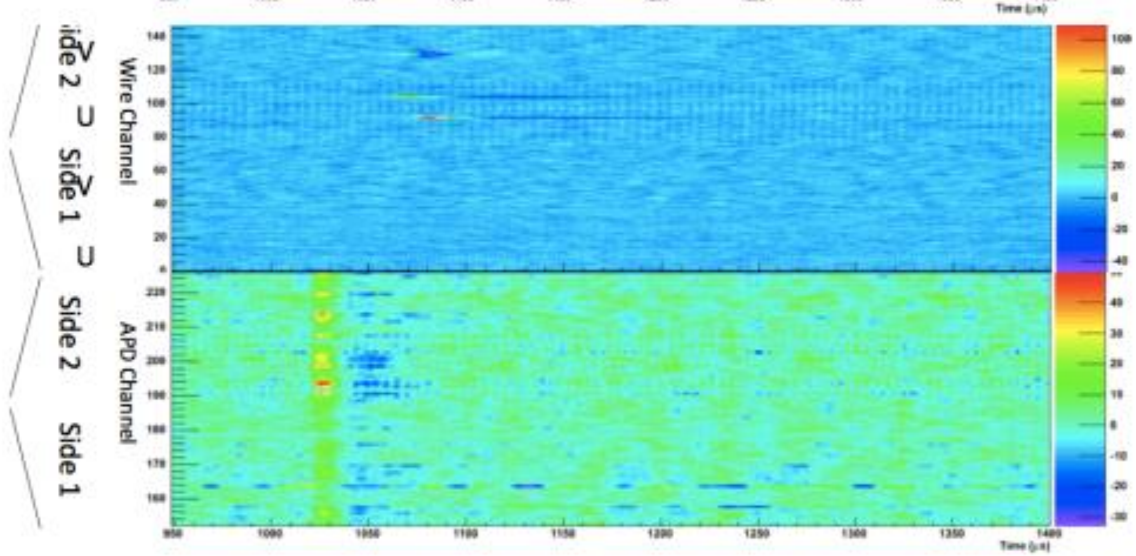
Light readout



Multi site:

Charge readout
V: Induction
U: Collection

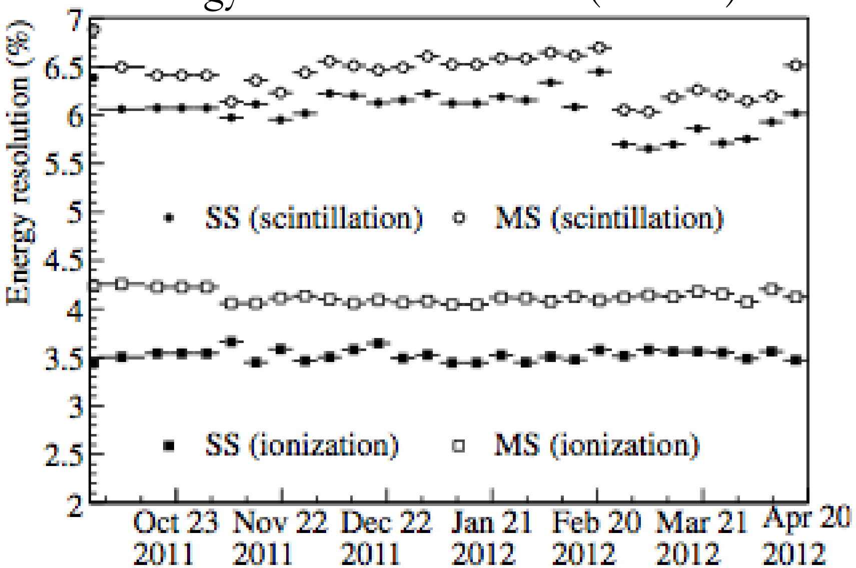
Light readout



Deradonator and Electronics Upgrade

- Designed and built at UMass
- "Vacuum-swing adsorption" (VSA) Rn filter for air.
- Air forced through activated charcoal to filter Rn at atmospheric pressure, then regenerated by purge at vacuum
- Dual charcoal columns allow continuous operation at 10-30cfm.
- Installation at WIPP nearly complete!
- Electronics upgrade later this year

Energy resolution vs. time (Run 2a)



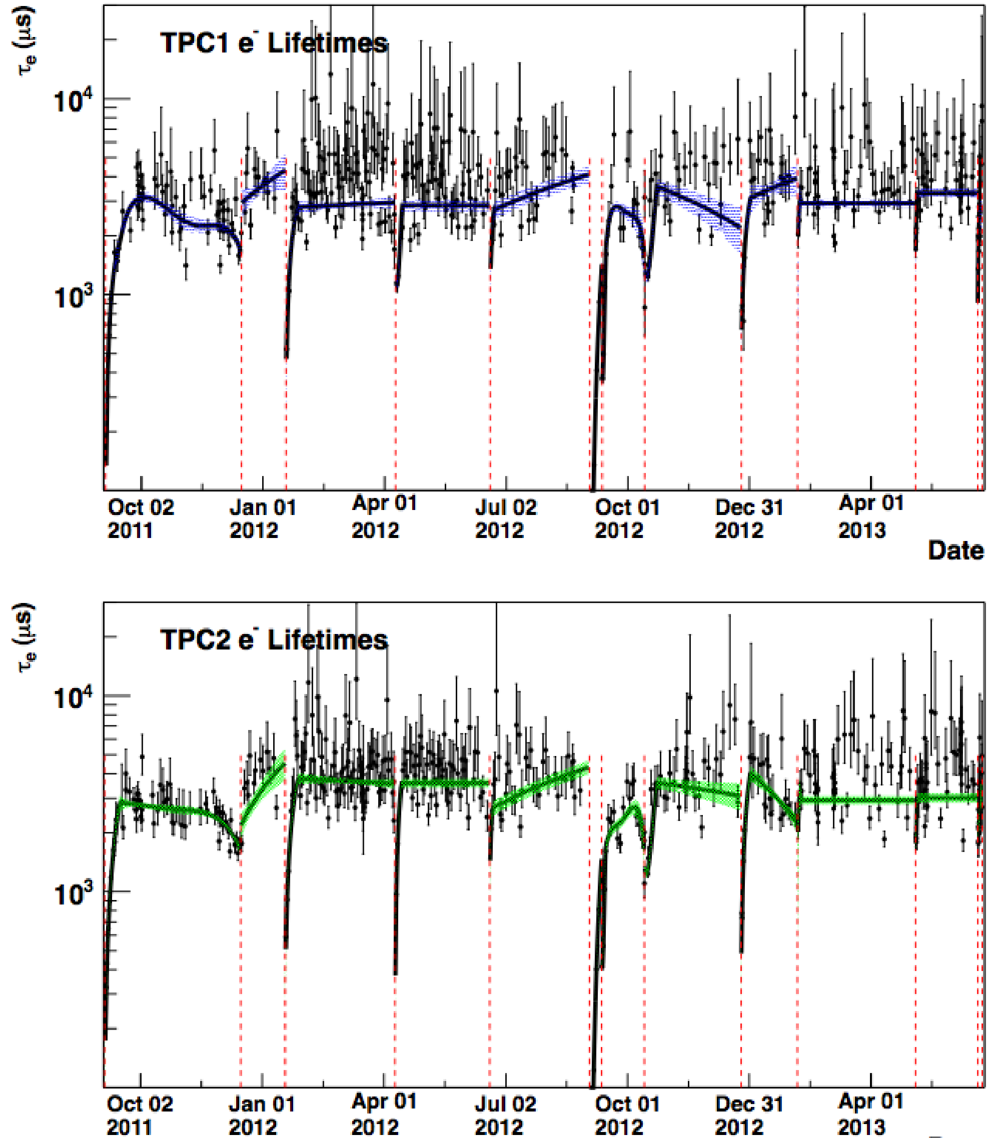
Deradonator at WIPP

Xenon Purity

• Continuously recirculate Xe through SAES high temperature purifiers using a custom designed magnetic piston pump. [Neilson et al. (2011) arXiv:1104.5041v1].

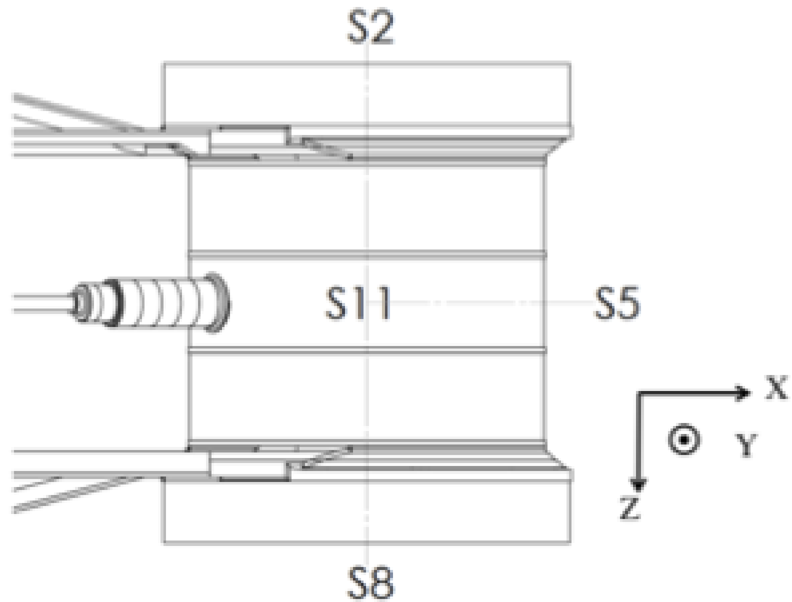
• Average electron lifetime for $0\nu\beta\beta$ data set was ~ 3 ms with maximum drift time of 110 us.

• Power outages and other events occasionally require a small fraction of the Xe to be removed from and replaced into the detector, resulting in ~few day recovery times



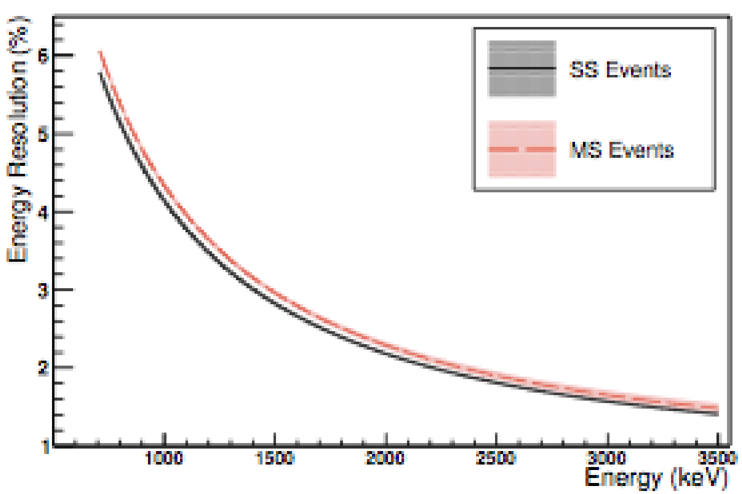
Source Calibration

- Use 4 gamma sources, spanning the energy range 662 – 2615 keV (^{60}Co, ^{137}Cs, ^{226}Ra, and ^{228}Th)
- Calibrate 2-3 times a week using ^{228}Th source at the S5 position
- Every few months, calibrate with additional sources

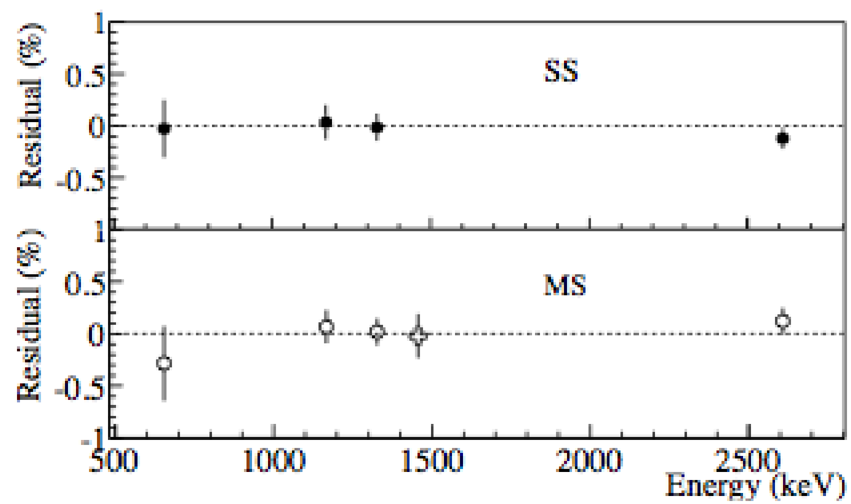


Source	Activity (Bq)	Half-life (years)
^{60}Co	530 ± 6	5.27
^{137}Cs	2820 ± 33	30.1
^{228}Th	1417 ± 17	1.91

Relative resolution (σ/E) vs. energy

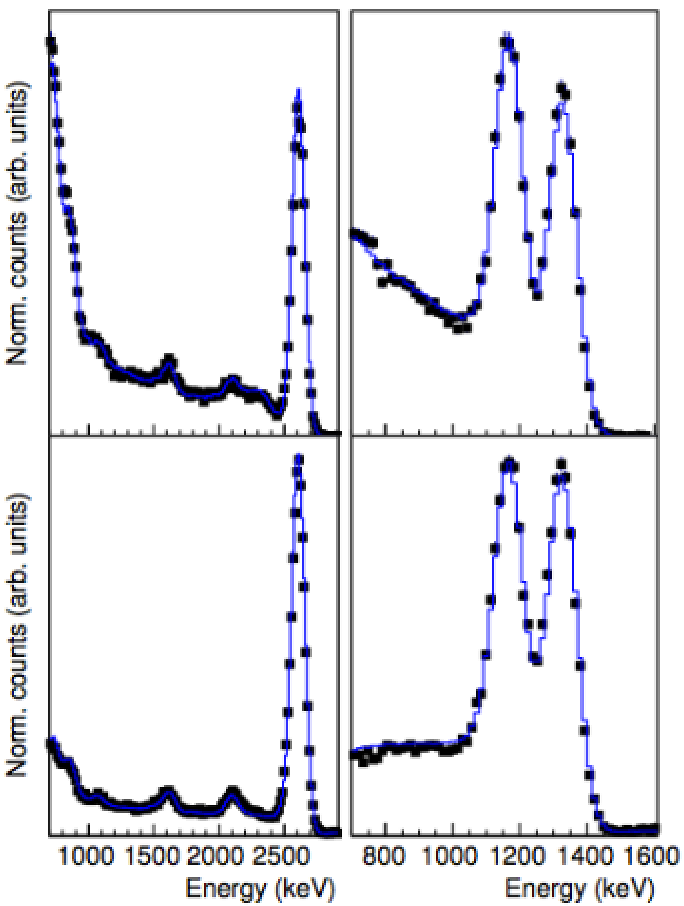


Residual between reconstructed and true energy



Source Agreement

Source shape agreement:



Source rate agreement:

Source location	Source type	Absolute rate agreement (Data − (MC Sim))/Data [%]
S2 (anode)	^{228}Th	$3.5^{+0.8}_{-1.3}$
	^{60}Co	$2.4^{+0.4}_{-1.6}$
S5 (cathode)	^{228}Th	$1.1^{+1.0}_{-0.9}$
	^{60}Co	$-3.7^{+1.5}_{-1.2}$
S8 (anode)	^{228}Th	$-3.2^{+0.8}_{-0.9}$
	^{60}Co	$1.8^{+0.8}_{-1.1}$
S11 (cathode)	^{228}Th	$3.1^{+2.3}_{-2.7}$
	^{60}Co	$1.3^{+3.1}_{-4.0}$

- Excellent spectral shape agreement between data and MC for calibration with external Th and Co sources
- Absolute rate agreement with known source activities better than ~4%

2νββ systematics

Component	Error [%]
Normalization errors	2.60
Single-site fraction	0.77
Backgrounds	1.3
Statistical	0.76
Total	**2.83**

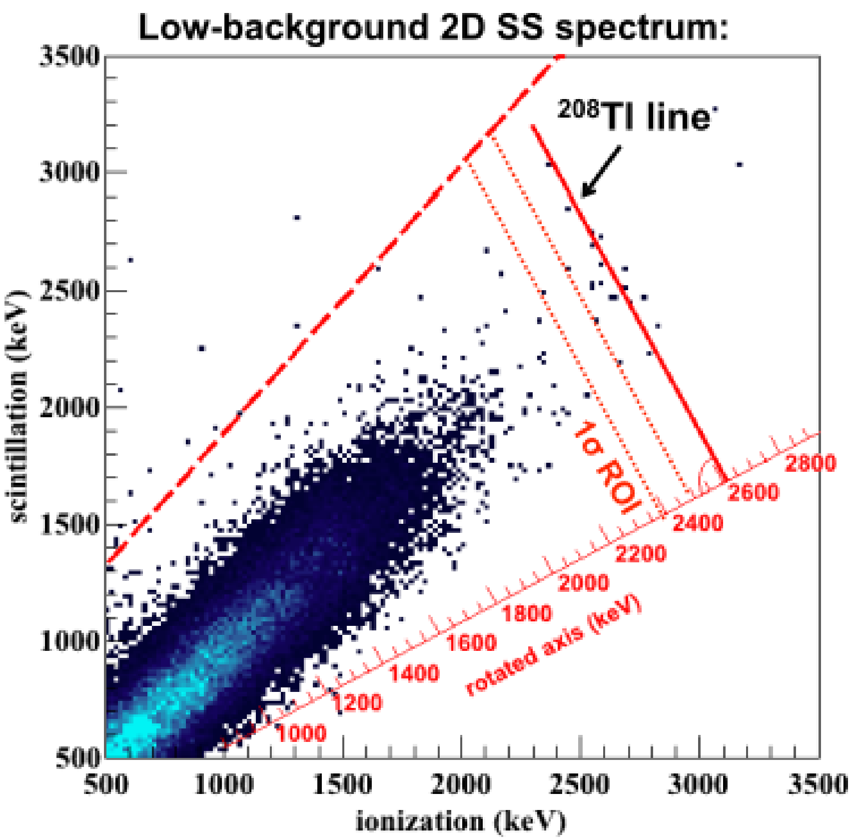
Normalization errors	Error [%]
Failed event reconstruction	<0.18
Shape distortion	0.33
Missing U-wire channel	<0.1
Beta-scale	0.24
Background model	0.25
Xe parameters	0.26
Event selection	2.53

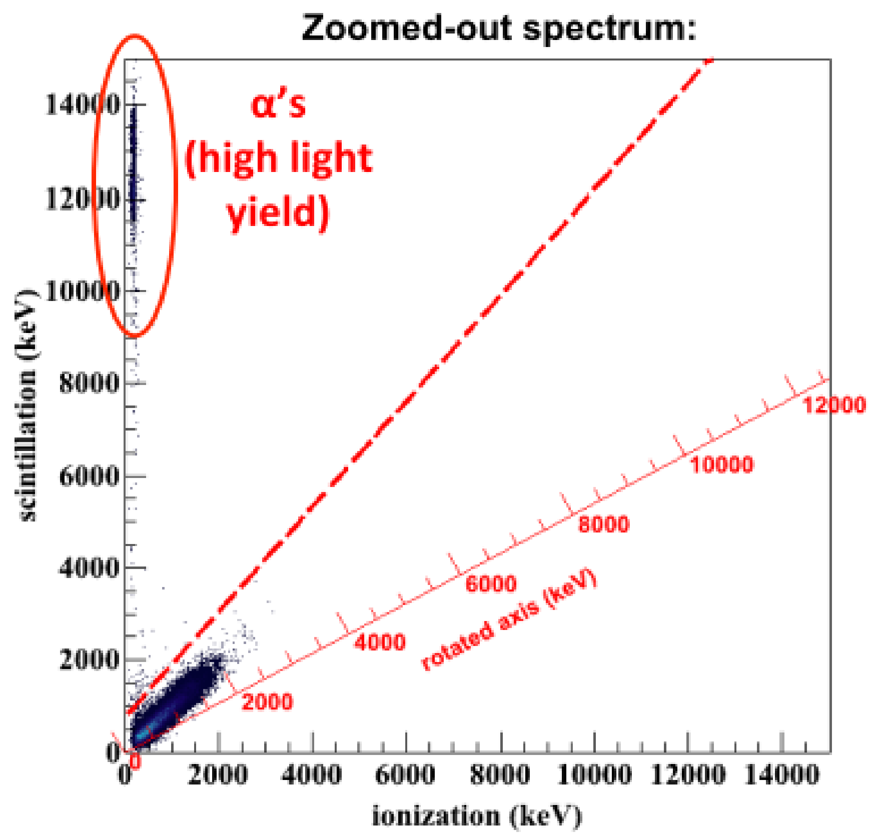
Event cut type	Signal efficiency [%]	Error [%]
Solicited triggers	99.99	-
Noise	100.0	<0.06
1 s coincidence	93.1	0.2
$>$ 1 scintillation signal	100.0	+0.07/-0.0
Partial reconstruction	93.9	1.6
Fiducial volume	-	1.77
Light-to-charge ratio	100	0.15
Energy $>$ 700 keV	-	0.4

- Overall systematics reduced by factor of ~3.5 relative to 2νββ discover (2011)
- Systematics dominated by normalization (signal efficiency) errors
- Relative error on fiducial volume of 1.77% (volume reduced to central 66.2 kg ^{136}Xe)
- Error on signal reconstruction efficiency of 1.6%

Low Background Spectrum

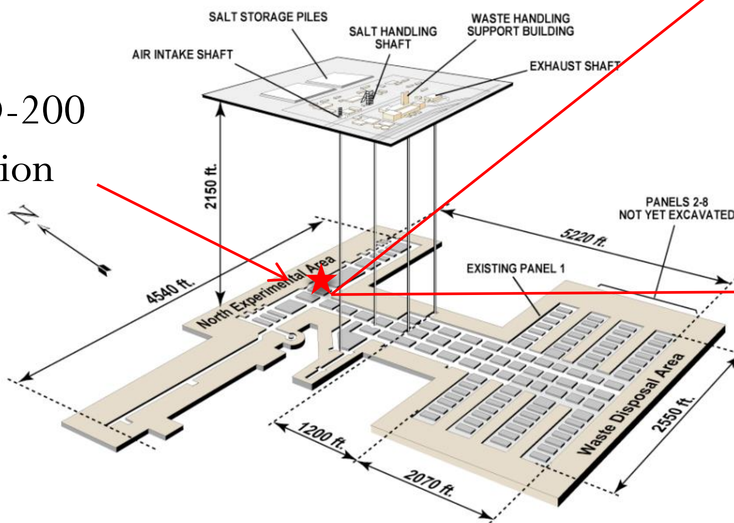
- ROI defined in rotated energy plane
- Diagonal cut in 2D plane removes higher light yield α's



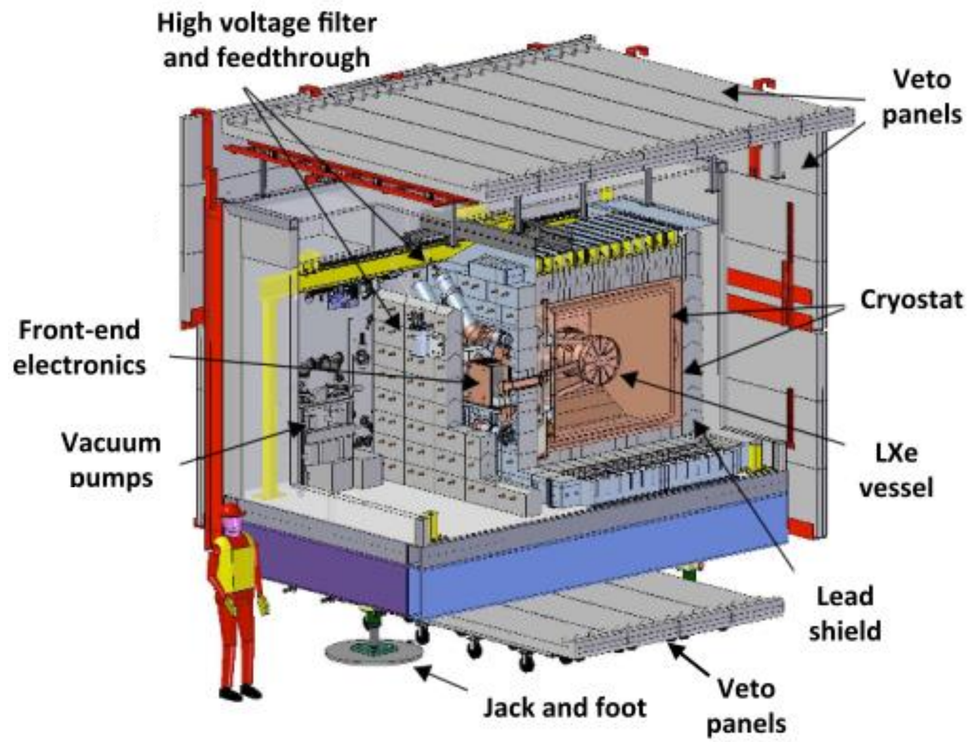


EXO-200 Location

EXO-200 location



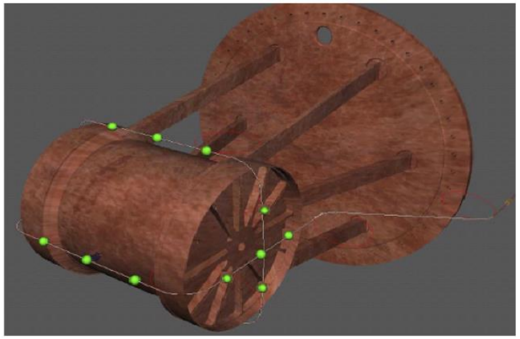
Detector schematic:



- Detector installed at WIPP facility near Carlsbad, NM (~1600 mwe)
- Salt mine with relatively low levels of U/Th and Rn
- TPC additionally surrounded by active and passive shielding

Detector Calibration

- Calibration performed with ^{60}Co, ^{137}Cs, ^{226}Ra, and ^{228}Th
- Calibration sources are deployed through a guide tube



- Weekly calibration data taking provides:
  - Xenon purity
  - Energy scale and resolution
- Dedicated charge injection runs to measure channel gains