Present and future of double beta decay

EXO-200 and its successor nEXO

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on behalf of
the EXO-200 and the nEXO collaborations

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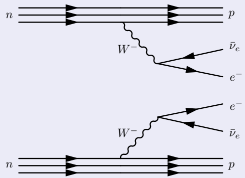
Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

- Observation of $0\nu\beta\beta$ would indicate that neutrinos are Majorana.
- $2\nu\beta\beta$ has been observed in some isotopes, including ^{136}Xe.

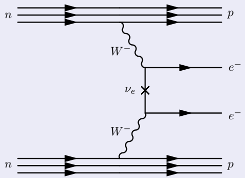
$$^{136}Xe \rightarrow {}^{136}Ba + 2e^{-} + 2\bar{\nu}_e \quad (Q = 2.458\ \text{MeV})$$

- However, $0\nu\beta\beta$ has never been observed, and that is the goal of EXO-200 and its successor nEXO.

$2\nu\beta\beta$



$0\nu\beta\beta$



EXO-200 and nEXO

This talk is about both EXO-200 and nEXO.

EXO-200:

- EXO-200 is a current $0\nu\beta\beta$ experiment.
- In operation since May 2011 until Feb 2014, now in hiatus
- Ongoing recovery effort after WIPP events
- Plan to run for 2 or 3 years after recovery

nEXO:

- nEXO is a planned experiment.
- Currently under R&D
- Will use about 5 tonnes of LXe
- Significantly better sensitivity

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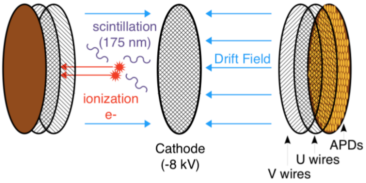
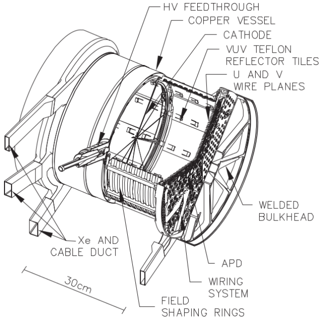
EXO-200 Detector

- Dual Time Projection Chamber (TPC).
- 110 kg LXe in active volume, enriched to 80.6% in ^{136}Xe.
- 468 Avalanche Photo-diodes (APD).





Energy:

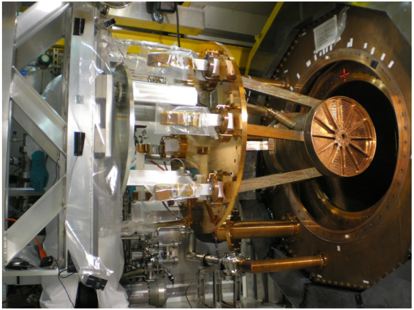
- APDs collect scintillation.
- U-wires collect charges, V-wires detect charge induction signals.

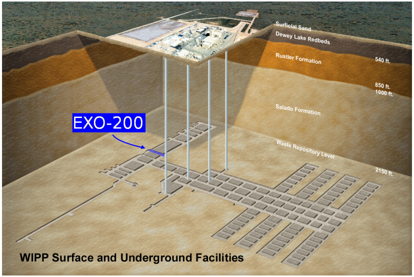
Position:

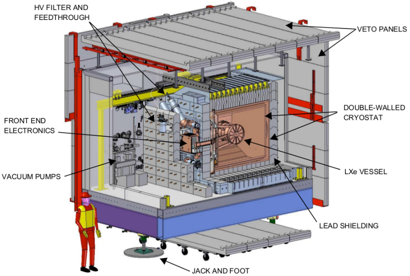
- U-wires and V-wires gives X,Y position.
- Time difference between scintillation and charge signals gives Z position.

Location

- Located at Waste Isolation Processing Plant (WIPP) near Carlsbad, New Mexico, USA
- 1600 m.w.e. flat overburden.
- Low levels of U and Th (<100 ppb)
- Low levels of Rn (20 Bq/m^3)

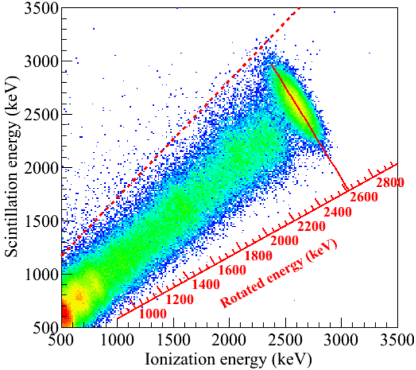






Energy Calibration

Response to ^{228}Th calibration source

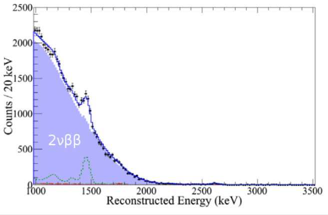


- Anti-correlation between scintillation and ionization in LXe is used to improve energy resolution.
- Rotation angle is chosen to optimize energy resolution at 2615 keV, and is time-dependent taking into account the noise variation in scintillation

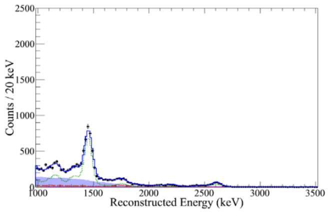
Event Multiplicity

Low Background Data

Single-site



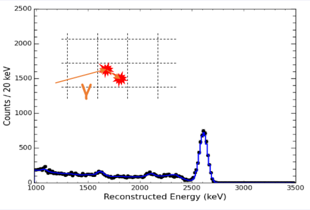
Multi-site



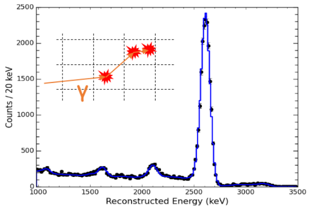
$\beta\beta$ events are predominantly single-site.

^{228}Th Calibration Data

Single-site



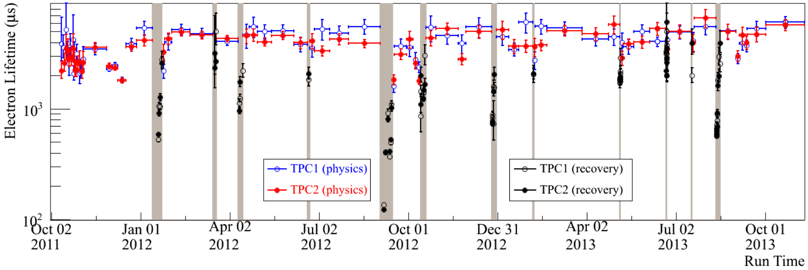
Multi-site



γ-like events are predominantly multi-site.

Xenon Purity

- Xenon purity is estimated by measuring electron lifetime (τ_e) using ^{228}Th calibration runs.
- τ_e is largely correlated with Xenon purification pump speed.
- At τ_e = 3 ms, drift time < 110 μs and loss of charge: 3.6% at full drift length.



Investigation of Radioactivity-induced Background

All materials used in detector construction were tested for radioactivity content before and during construction. With Monte Carlo detector model and actual data taken, two routes can be taken for verification[1]:

1. Radioassay results + Monte Carlo detector model } → Background expectation ↔ Low background data

   It was found that the expected background due to ^{238}U is consistent with observed rate in data, while for ^{232}Th, the expection is slightly lower than observed.

2. Low background data + Monte Carlo detector model } → Inferred radioactivity contents ↔ Radioassay results

   In general, radioassay gives a better constraints on the radioactivity contents than inferred from data. Except for the TPC vessel, where the two give comparable limits.

This study gives confidence in the background model, and it shows that radioassay of detector components can provide good guidance and constraint for its design.

[1] J.B. Albert et al. "Investigation of radioactivity-induced backgrounds in EXO-200". Submitted to PRC. arxiv:1503.06241

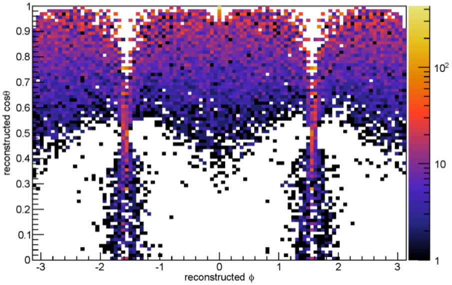
Muon Flux Measurement

- Muon-induced spallation neutrons capture on detector or nearby materials. β and γ from the decay of the activated isotopes cause background.
- Muon flux measurement enables estimation of
  - Neutron yields
  - Cosmogenic isotope production rates
  - Backgrounds for $0\nu\beta\beta$ analysis

Muon flux and vertical intensity at WIPP has been measured with TPC. [2]

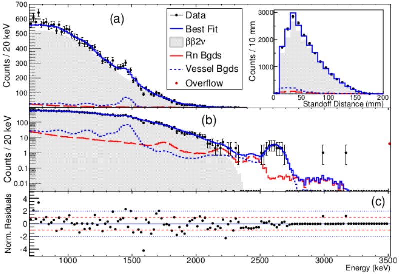
$\Phi = 4.04^{+0.15}_{-0.14} \times 10^{-7}(cm^2\ s)^{-1}$

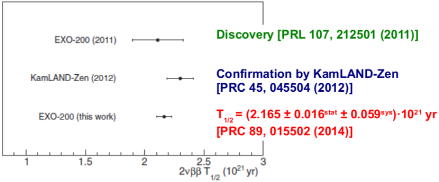
$I_v = 2.95^{+0.14}_{-0.13} \times 10^{-7}(cm^2\ s\ sr)^{-1}$



[2] "Study of Cosmogenic Backgrounds for $0\nu\beta\beta$ in EXO-200", in preparation

Precision Measurement of $2\nu\beta\beta$ Half-life



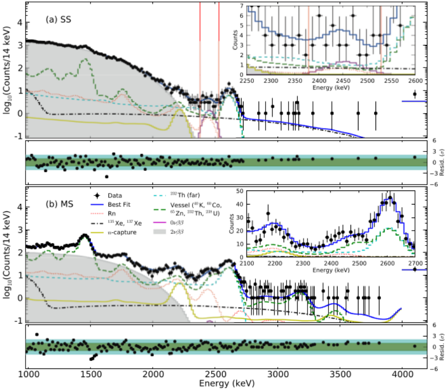


Nuclide	$T^{2\nu\beta\beta}_{1/2} \pm$ stat $\pm$ sys [y]	rel. uncert. [%]	$G^{2\nu}$ $[10^{-21}\ y^{-1}]$	$M^{2\nu}$ $[MeV^{-1}]$	rel. uncert. [%]	Experiment (year)
^{136}Xe	$2.165 \pm 0.016 \pm 0.059 \cdot 10^{21}$	± 2.83	1433	0.0218	± 1.4	EXO-200 (this work)
^{76}Ge	$1.84^{+0.09+0.11}_{-0.08-0.06} \cdot 10^{21}$	$^{+7.7}_{-5.4}$	48.17	0.129	$^{+3.9}_{-2.8}$	GERDA [39] (2013)
^{130}Te	$7.0 \pm 0.9 \pm 1.1 \cdot 10^{20}$	± 20.3	1529	0.0371	± 10.2	NEMO-3 [40] (2011)
^{116}Cd	$2.8 \pm 0.1 \pm 0.3 \cdot 10^{19}$	± 11.3	2764	0.138	± 5.7	NEMO-3 [41] (2010)
^{48}Ca	$4.4^{+0.5}_{-0.4} \pm 0.4 \cdot 10^{19}$	$^{+14.6}_{-12.9}$	15550	0.0464	$^{+7.3}_{-6.4}$	NEMO-3 [41] (2010)
^{96}Zr	$2.35 \pm 0.14 \pm 0.16 \cdot 10^{19}$	± 9.1	6816	0.0959	± 4.5	NEMO-3 [42](2010)
^{150}Nd	$9.11^{+0.25}_{-0.22} \pm 0.63 \cdot 10^{18}$	$^{+7.4}_{-7.3}$	36430	0.0666	$^{+3.7}_{-3.7}$	NEMO-3 [43](2009)
^{100}Mo	$7.11 \pm 0.02 \pm 0.54 \cdot 10^{18}$	± 7.6	3308	0.250	± 3.8	NEMO-3 [44](2005)
^{82}Se	$9.6 \pm 0.3 \pm 1.0 \cdot 10^{19}$	± 10.9	1596	0.0980	± 5.4	NEMO-3 [44](2005)

$T^{2\nu\beta\beta}_{1/2}$ of ^{136}Xe has been precisely measured: 2.165 ± 0.016(stat) $\pm$ 0.059(sys) $\times 10^{21}$ yr. [3]

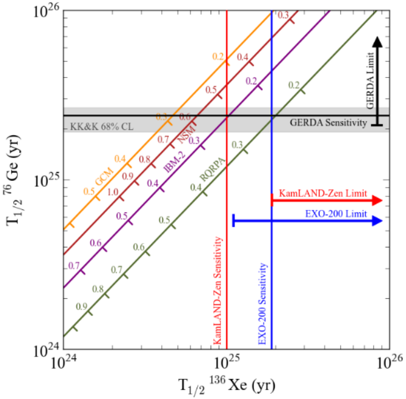
[3] J.B. Albert, et al. "An improved measurement of the $2\nu\beta\beta$ half-life of Xe-136 with EXO-200", Phys. Rev. C 89 (2014) 015502

Constraint on $0\nu\beta\beta$ Half-life



$T_{1/2}^{0\nu\beta\beta}$ of ^{136}Xe has been constrained:

$T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{25}$ yr at 90% CL. corresponding to a limit on the neutrino mass of 0.2-0.4 eV.



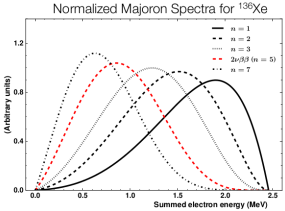
References:

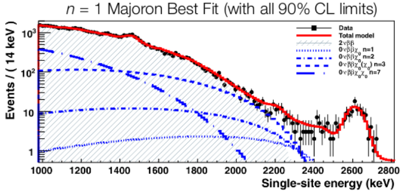
- EXO-200: Nature 510 (2014) 229
- GERDA Phase 1: PRL 111 (2013) 122503
- KamLAND-Zen: PRL 110 (2013) 062502
- KK&K claim: Mod. Phys. Lett., A21 (2006) 1547

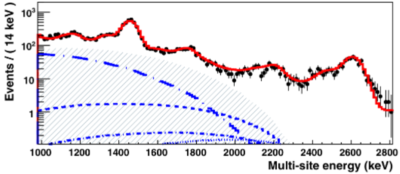
Constraints on Majoron Emitting Modes

EXO-200 has searched [4] for Majoron-emitting $0\nu\beta\beta$ modes such as,

$$^{136}Xe \rightarrow {}^{136}Ba + 2e^- + \chi_0$$
$$^{136}Xe \rightarrow {}^{136}Ba + 2e^- + 2\chi_0$$





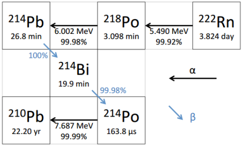


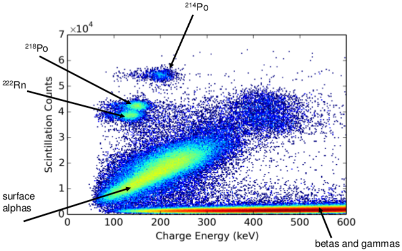
Decay Mode	Spectral index, n	Model types	$T_{1/2}$ (yr)	$\lvert\langle g^M_{ee}\rangle\rvert$
$0\nu\beta\beta\chi_0$	1	IB, IC, IIB	$> 1.2 \times 10^{24}$	$<(0.8\text{-}1.7)\times10^{-5}$
$0\nu\beta\beta\chi_0$	2	Bulk	$> 2.5 \times 10^{23}$	...
$0\nu\beta\beta\chi_0\chi_0$	3	ID, IE, IID	$> 2.7 \times 10^{22}$	<(0.6-5.5)
$0\nu\beta\beta\chi_0$	3	IIC, IIF	$> 2.7 \times 10^{22}$	<0.66
$0\nu\beta\beta\chi_0\chi_0$	7	IIE	$> 6.1 \times 10^{21}$	<(0.5-4.7)

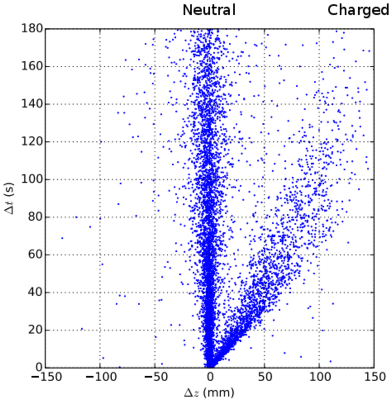
[4] J.B. Albert, et al., "Search for Majoron-emitting modes of $\beta\beta$ decay of ^{136}Xe with EXO-200", Phys. Rev. D 90 (2014) 092004.

Ion Studies Using Alpha Decays

- ^{218}Po and ^{214}Bi created from ^{222}Rn decays can be neutral or charged.
- By measuring drift velocity, the fractions of charged ^{218}Po and ^{214}Bi were estimated.[5]
- $^{218}Po^{+}$: $50.3 \pm 3.0\%$
  $^{214}Bi^{+}$: $76.4 \pm 5.7\%$







[5] J.B. Albert, et al.,"Measurements of the ion fraction and mobility of alpha and beta decay products in liquid xenon using EXO-200". Submitted to PRX. arxiv:1506.00317

Current Status and Recovery

WIPP incidents and impact to EXO-200:

- Feb 5, 2014: Haul truck fire. (Lost access to the underground.)
- Feb 14, 2014: Airbourne radiological event. (No direct impact on EXO-200. Salt sample near experiment showed virtually zero contamination.)
- Feb 18, 2014: Xenon recovered into high pressure cylinders.
- Aug 21, 2014: First underground entry in 6 months.
- Sep 12, 2014 - Feb 7, 2015: Power outage.

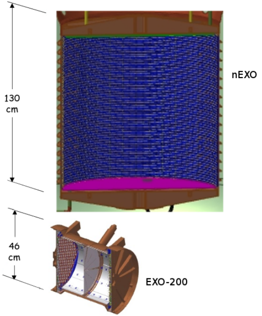
EXO-200 status and outlook:

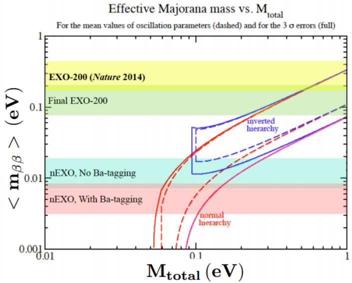
- Ongoing cleanup/repair/replacement effort.
- Cooling and filling LXe to TPC in summer 2015.
- Upgrades: Electronics, deradonator and analysis improvements.
- Expected to resume data taking in fall 2015.

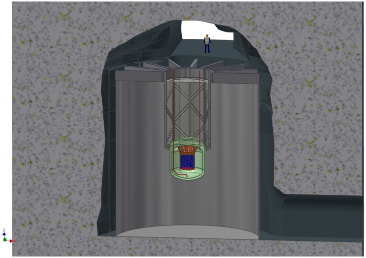
nEXO: Next Generation of EXO-200

nEXO will continue to search for $0\nu\beta\beta$ of ^{136}Xe with better sensitivity.

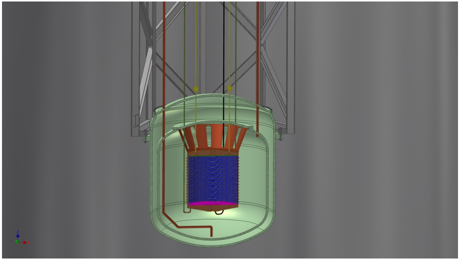
- 5 tonnes of enriched LXe
- Built upon known technology with possible Ba tagging upgrade
- Proposed location: SNOLAB's cryopit (6010 m.w.e.)
- Potential to probe inverted hierarchy

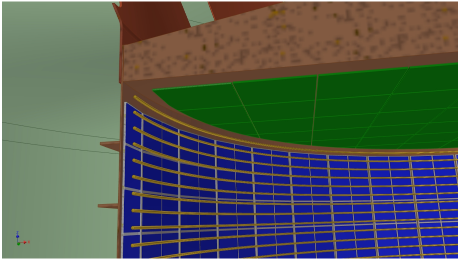






Detector Design



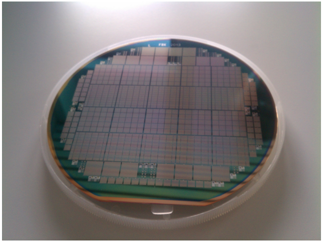


- TPC submerged in cryofluid in dual layer cryostat.
- Water shield surrounds detector.
- Light sensors on the barrel
- Charge readout on the anode
- Field shaping rings
- In-xenon electronics
- Expect σ/E of 1% at Q-value.

Light Sensors and Charge Sensors

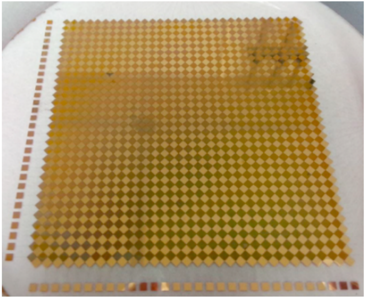
Silicon Photomultipliers (SiPM)

- Diameter about 128 mm
- Sensitive to VUV
- Low radioactivity
- More testing underway



Charge sensor tiles:

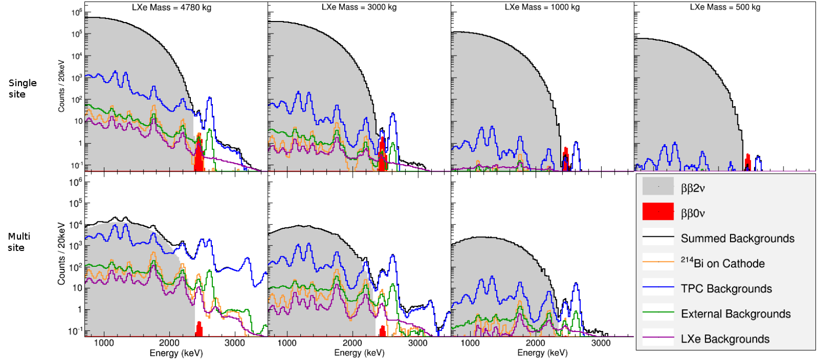
- Orthogonal noble metal chains of 10 cm length on a quartz substrate
- Being fabricated and tested.



Signal and Background

Effect of Self-shielding

Sensitivity study with GEANT4+NEST model and toy Monte Carlo.



90% C.L. sensitivity with 5-year exposure: 6.6×10^{27} yr

Barium Tagging

Goal of barium tagging:

- Recover and identify xenon decay daughter barium if present
- Suppress background towards a background free detector

Approaches being investigated:

- Sending probe into LXe, identify Ba^+ with Resonance Ionization Spectroscopy (RIS).
- Ba^+ extraction from a high pressure xenon gas detector through a supersonic nozzle and identification through laser spectroscopy. [6]
- Freeze LXe with a cold probe, identify Ba^+ by fluorescence using tunable laser. [7]

(Currently not in baseline design.)

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[6] T. Brunner et al., “An RF-only ion-funnel for extraction from high-pressure gases”, Int J. Mass Spec., 379, 110-120 (2015)

[7] B. Mong et al., “Spectroscopy of Ba and Ba^+ deposits in solid xenon for barium tagging in nEXO”, Phys. Rev. A 91, (2015) 022505

Summary

- EXO-200 has precisely measured $2\nu\beta\beta$ half-life of ^{136}Xe and has placed a strong limit on $0\nu\beta\beta$ half-life.
- EXO-200 is undergoing recovery and upgrade and is expected to resume data taking in fall 2015.
- nEXO is the next generation $0\nu\beta\beta$ experiment with ongoing R&D.
- nEXO will have discovery potential in the IH region.

The nEXO Collaboration

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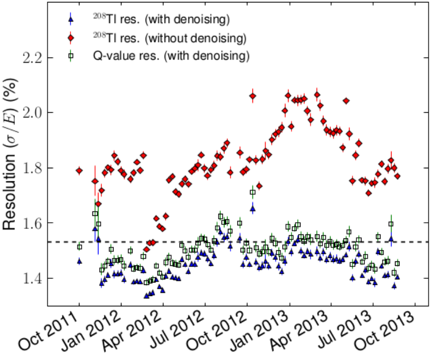
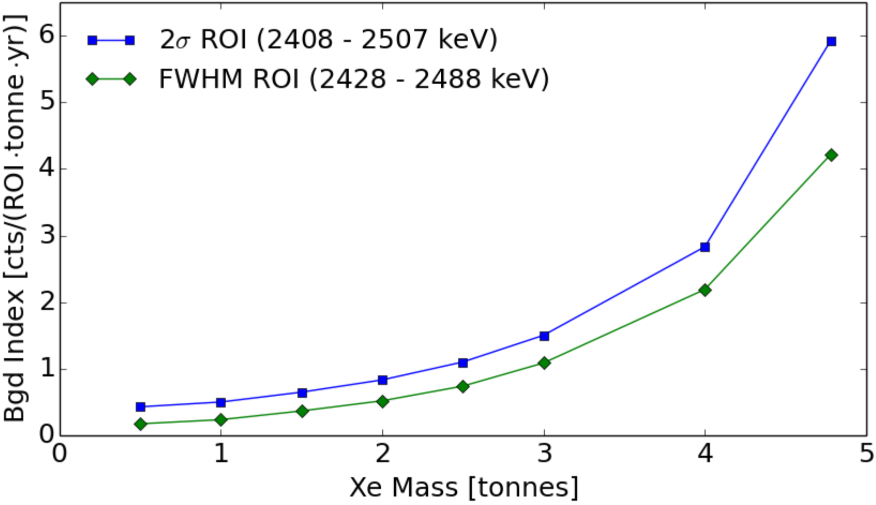
Thank you for your attention!
Any questions?

Denoising and Energy Resolution

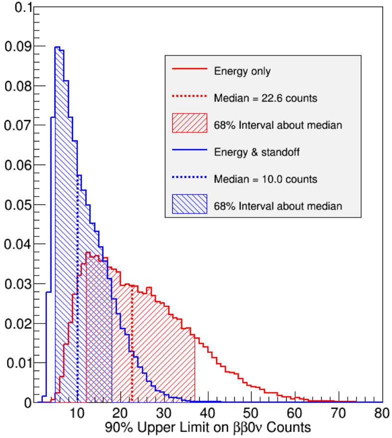
Denoising improves energy resolution by selecting an optimal linear combination of APD signals with proper weights.

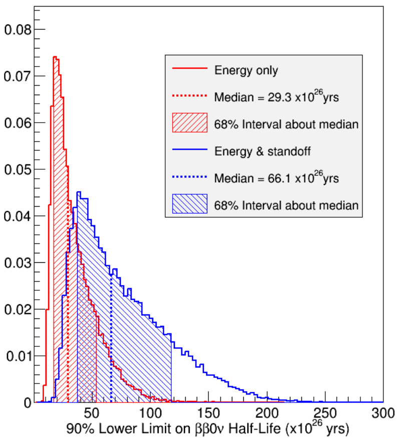


nEXO: Background Index



nEXO: Toy Monte Carlo





nEXO: Background Improvements over EXO-200

Planned Improvement in nEXO	**Bg Reduction (%)**
Improved energy resolution ($\sigma/Q_{\beta\beta}$ = 0.01)	18
Improved SS/MS discrimination.	35
Improved Cu activity with more sensitive radioassay.	22
Reduced ^{137}Xe rate at SNOLAB (vs WIPP).	50
Reduced ^{222}Rn concentration.	48
Replaced Kapton cables with cold electronics.	58
Total background reduction	95.5