The searches for neutrinoless double beta decay and other physics with EXO-200

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On behalf of the EXO-200 and nEXO collaborations
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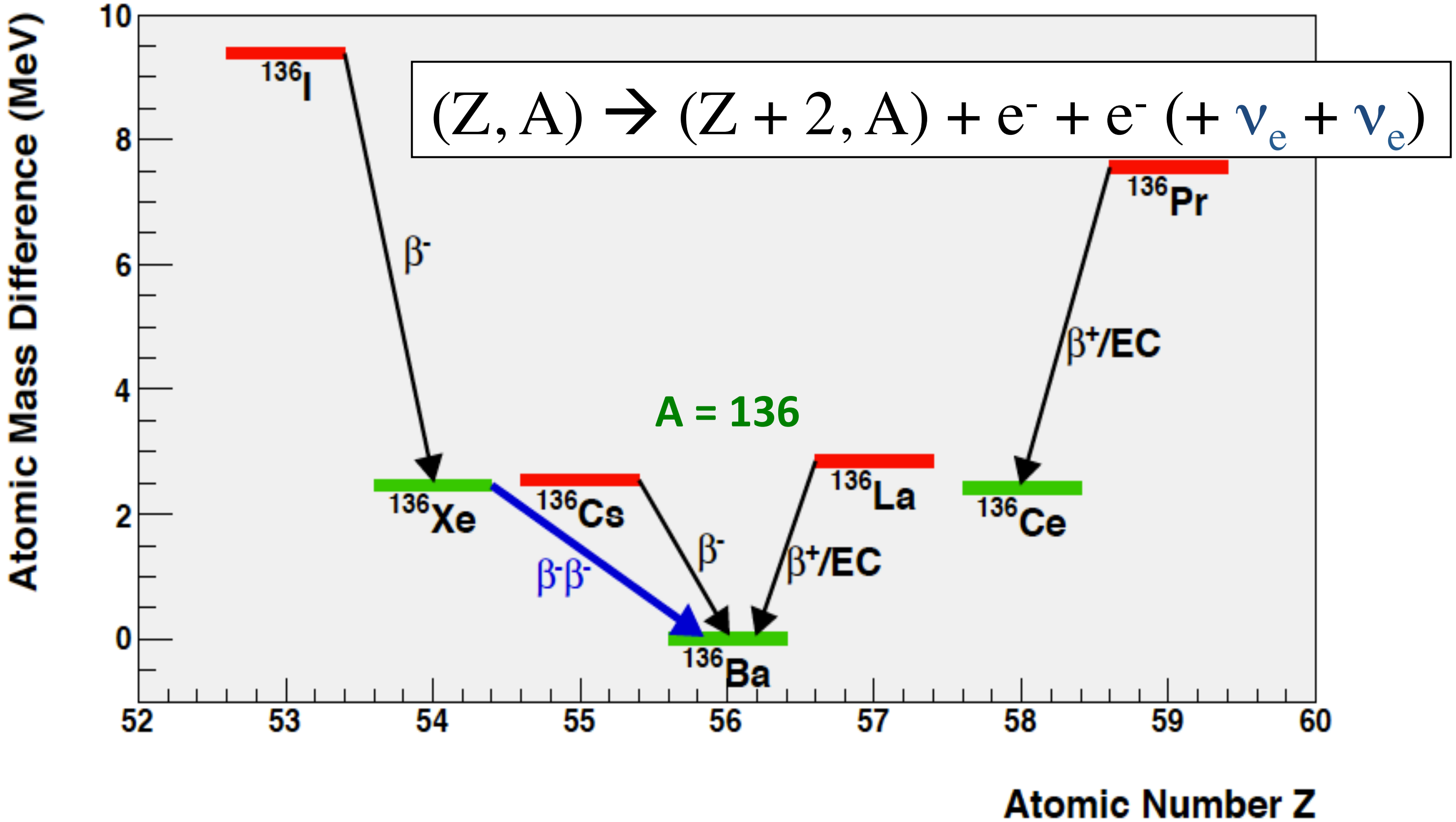
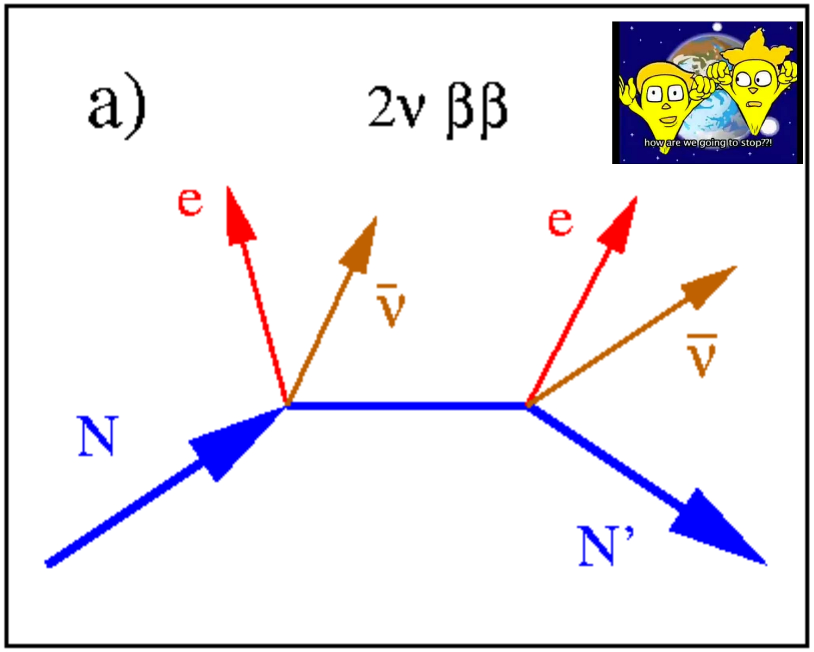
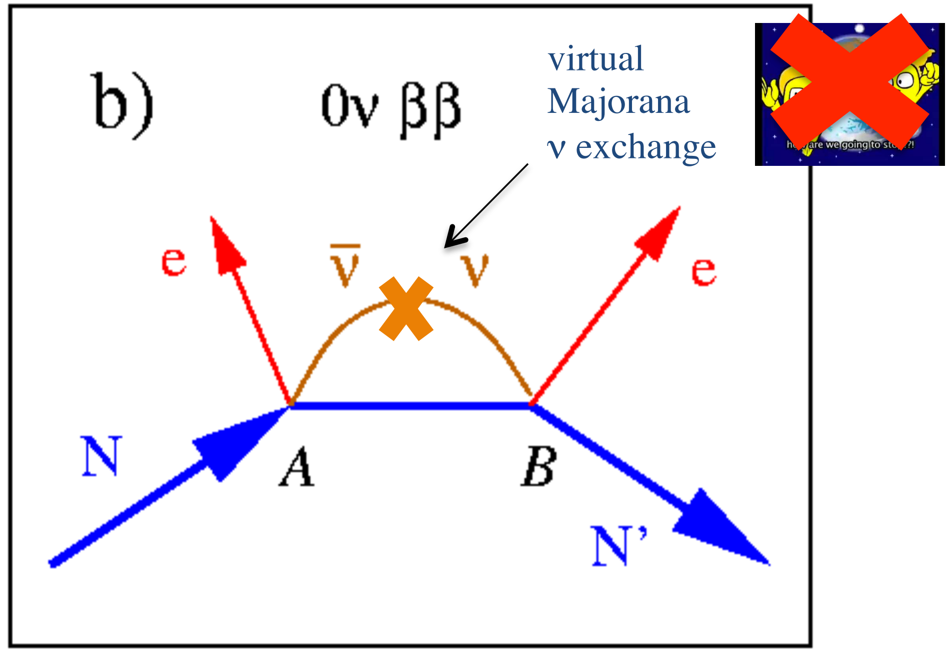
Double Beta Decay



- Double beta decay is possible for certain even-even nuclei, like ^{130}Te (CUORE), ^{76}Ge (GERDA, MAJORANA), ^{116}Cd (COBRA), etc.
- ^{136}Xe, being the heaviest xenon isotope, is relatively easy to enriched
  - Being a noble gas, xenon can be purified *in situ*
  - Relatively high Q-value of **2458 keV**

Two Modes of Double Beta Decay





Two neutrino mode:
•Standard model process
•Second order
•ΔL = 0 (lepton number conserved)

Neutrinoless mode:
•Hypothetical "Beyond the Standard Model" process
•Can happen if:
- neutrino has nonzero mass
- neutrino is its own antiparticle (Majorana neutrino)

•Total lepton number violating (ΔL = 2)

Mass Measurement with ββ0ν

- Half-life depends on the effective mass,

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$

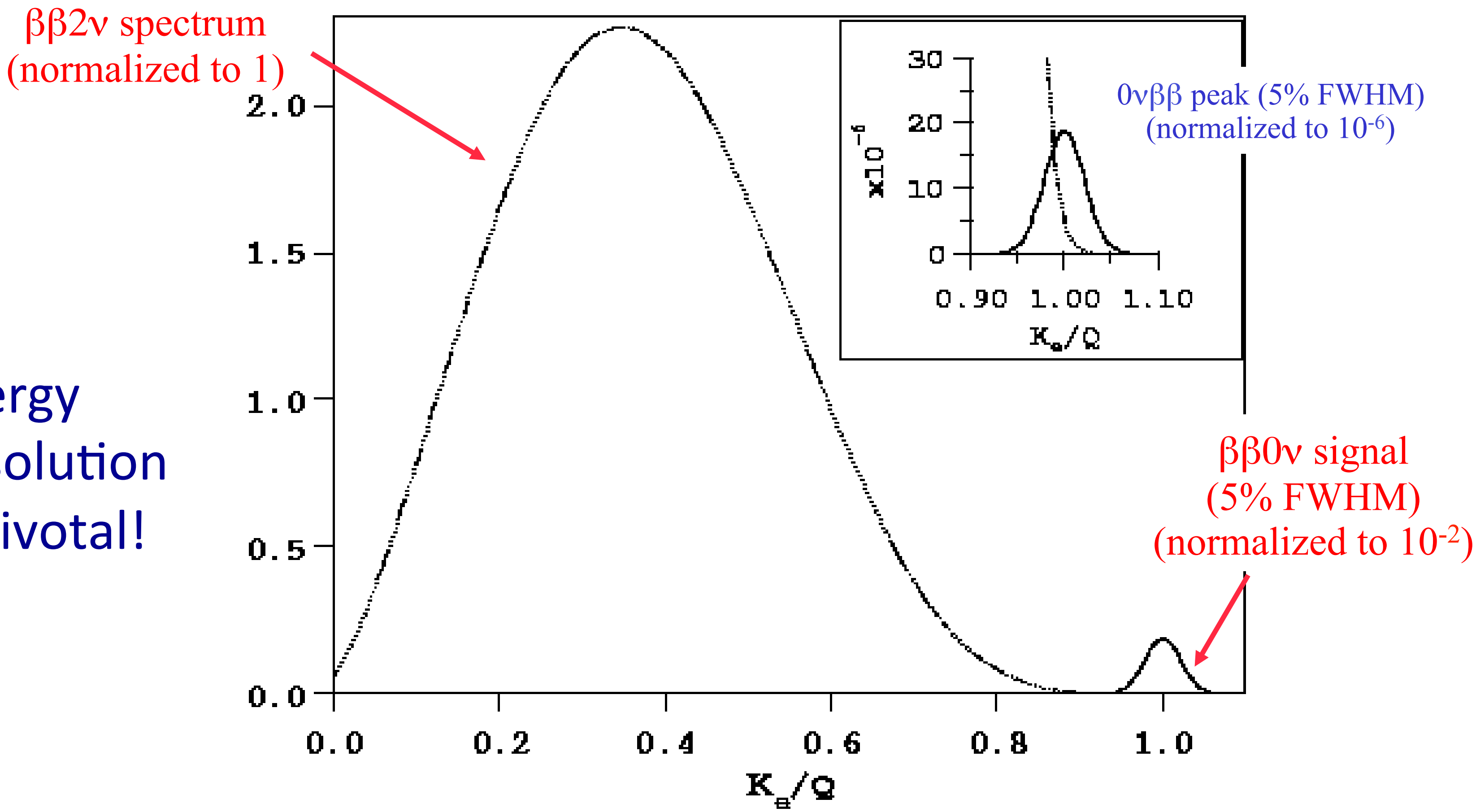
mass eigenvalues

mixing matrix (with phases)

$$\frac{1}{t_{1/2}^{0\nu}} = G^{0\nu} \left| M^{0\nu} \right|^2 m_{\beta\beta}^2$$

ββ0ν Half-life	Phase Space	Nuclear Matrix Element
To be measured	Calculable with high accuracy	Model dependent (largest source of uncertainty)

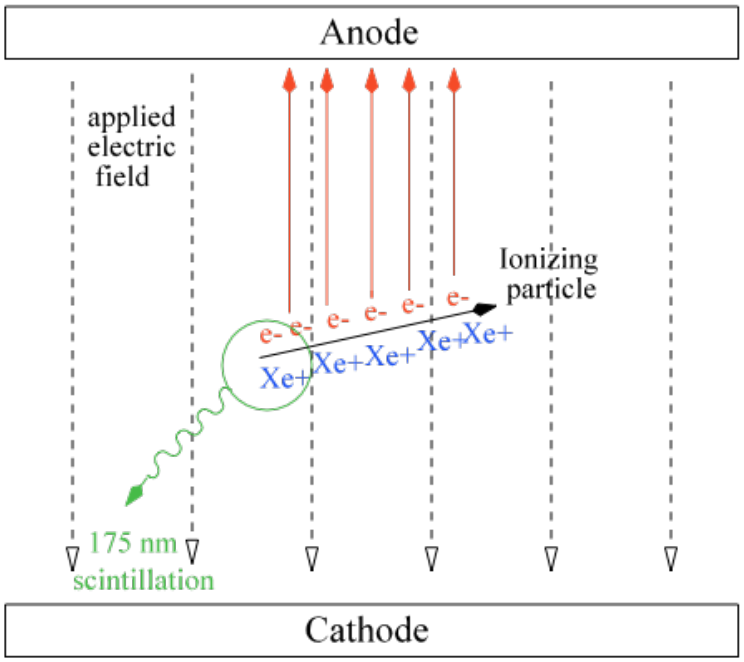
ββ0ν signature: a peak in the ββ energy spectrum



Energy Resolution is pivotal!

Summed electron energy in units of the kinematic endpoint (Q)

EXO-200
Liquid Xe Time Projection Chamber

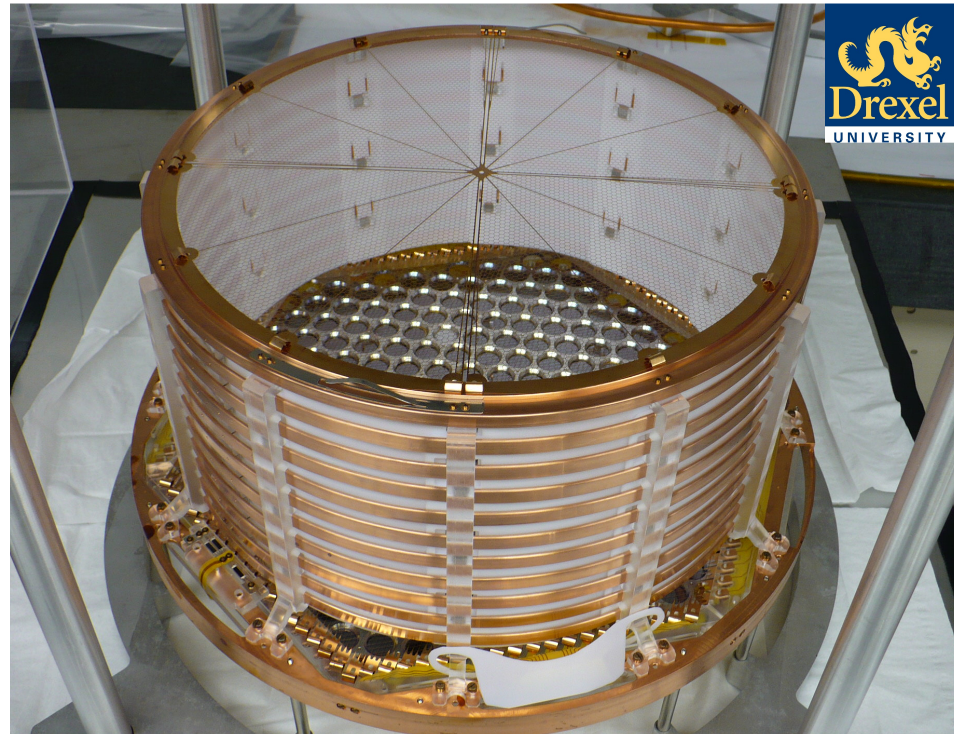


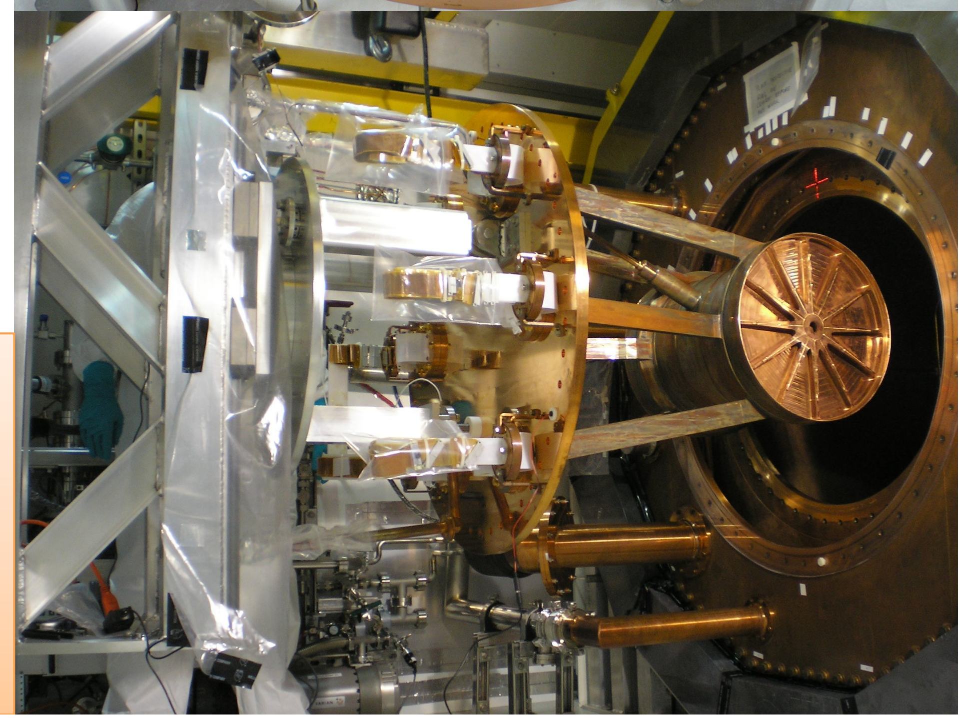
~110 kg active mass Xe enriched to 80% in ^{136}Xe, ultralow background construction

Readout plane is made up of LAAPDs (scintillation) + crossed wire grid (ionization)

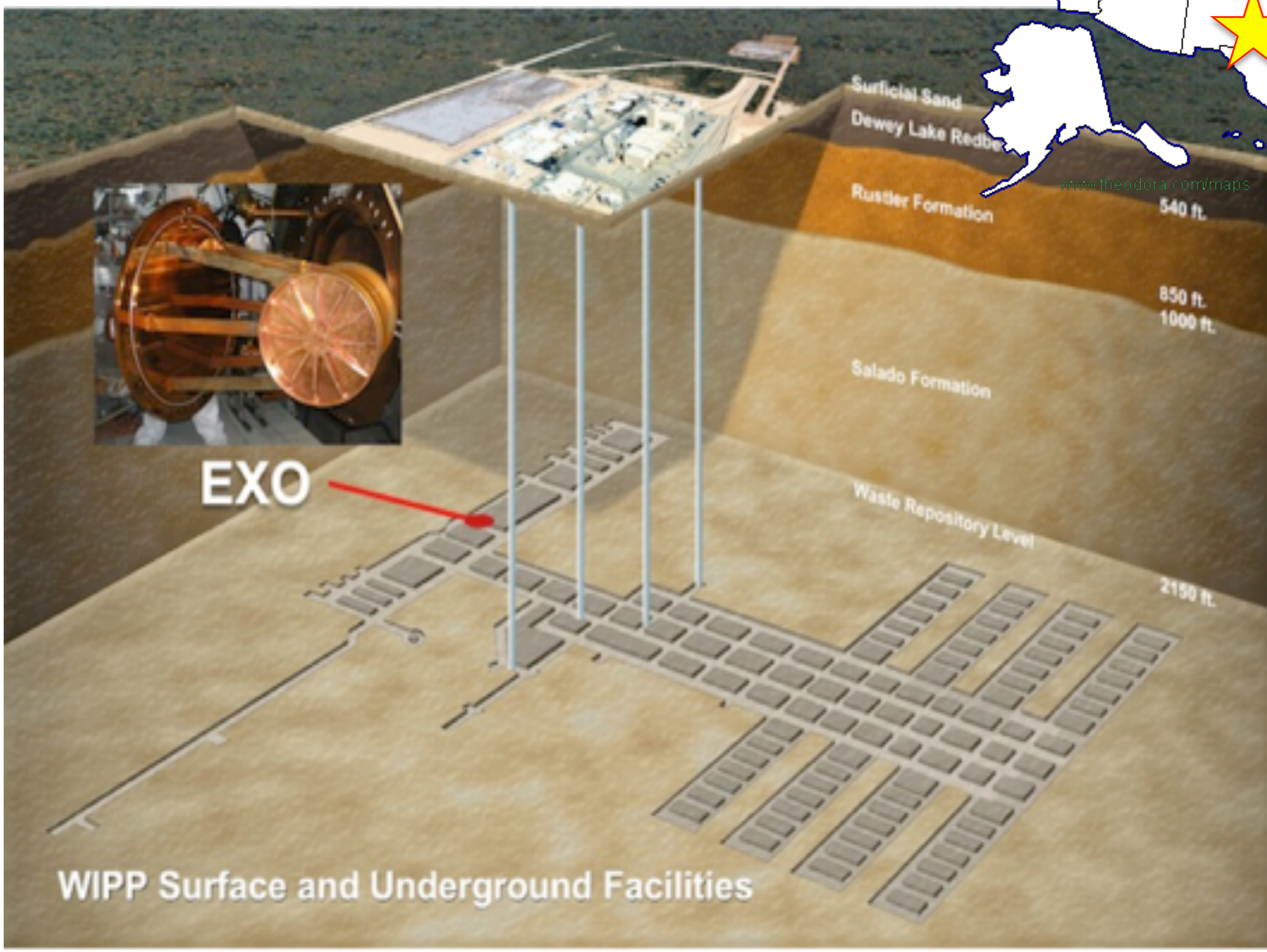
Achieve electron lifetime in liquid xenon $\tau_e > 3$ ms

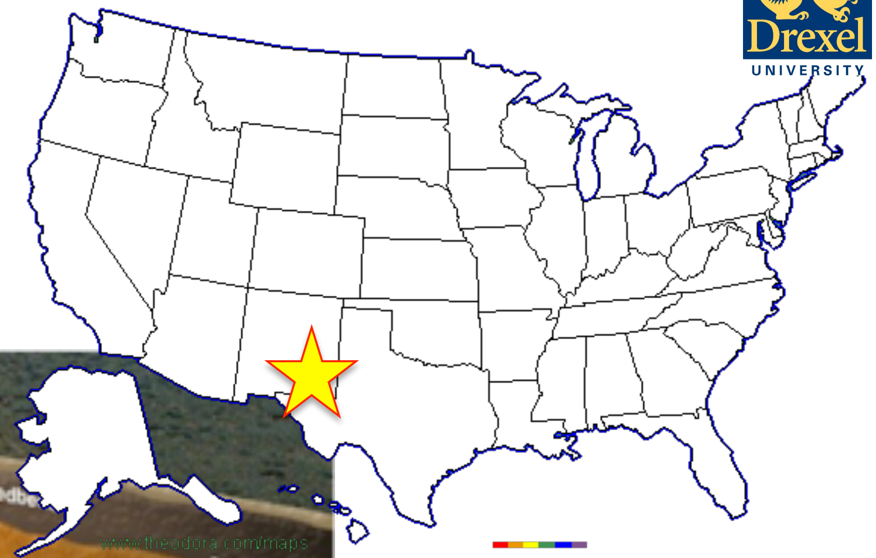
Began operating with enriched Xe at the Waste Isolation Pilot Plant (WIPP) in May 2011





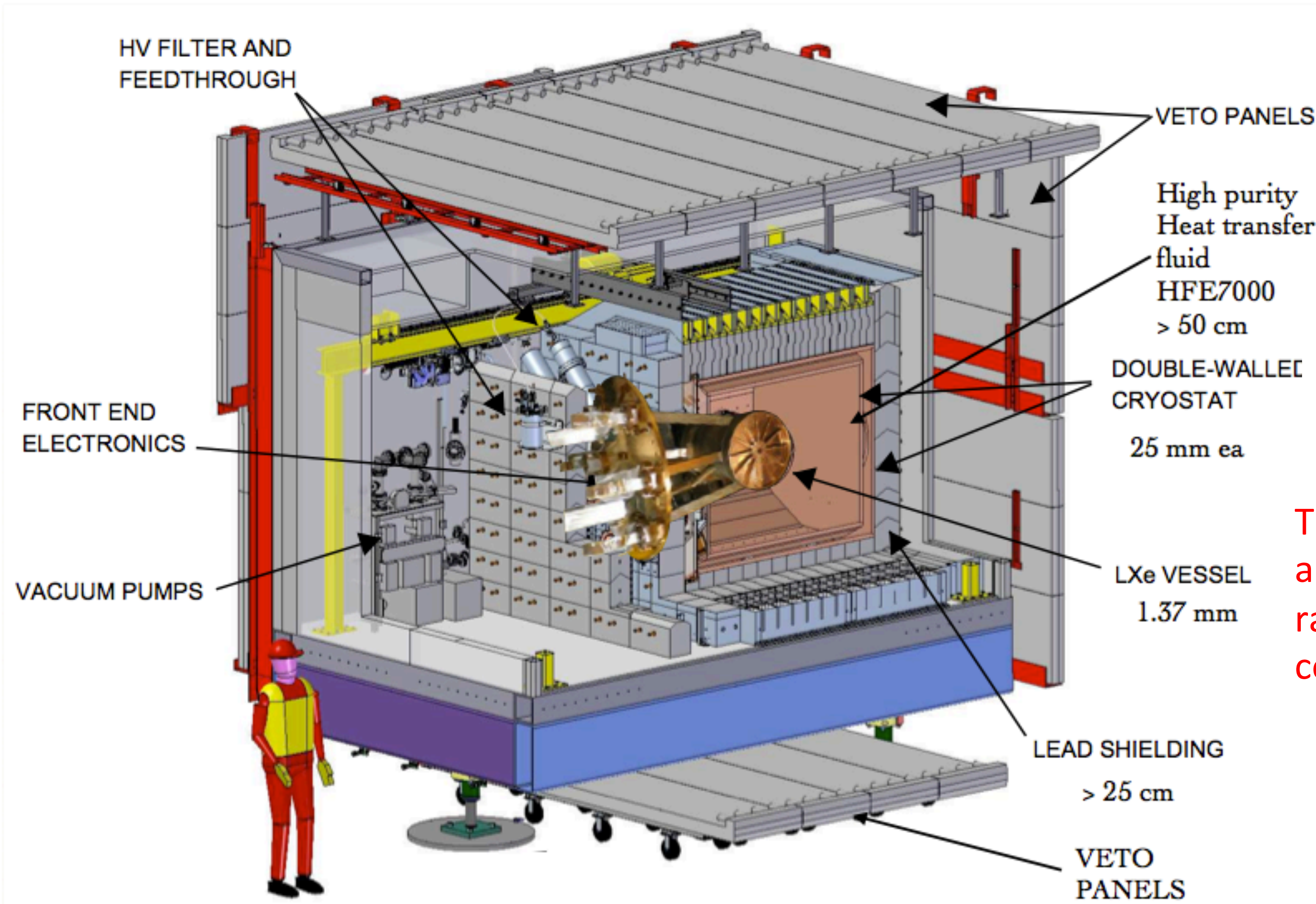
Underground Detector Site





- Waste Isolation Pilot Plant in New Mexico, USA
- Overburden of 1585 meters water equivalent
- low salt radioactivity

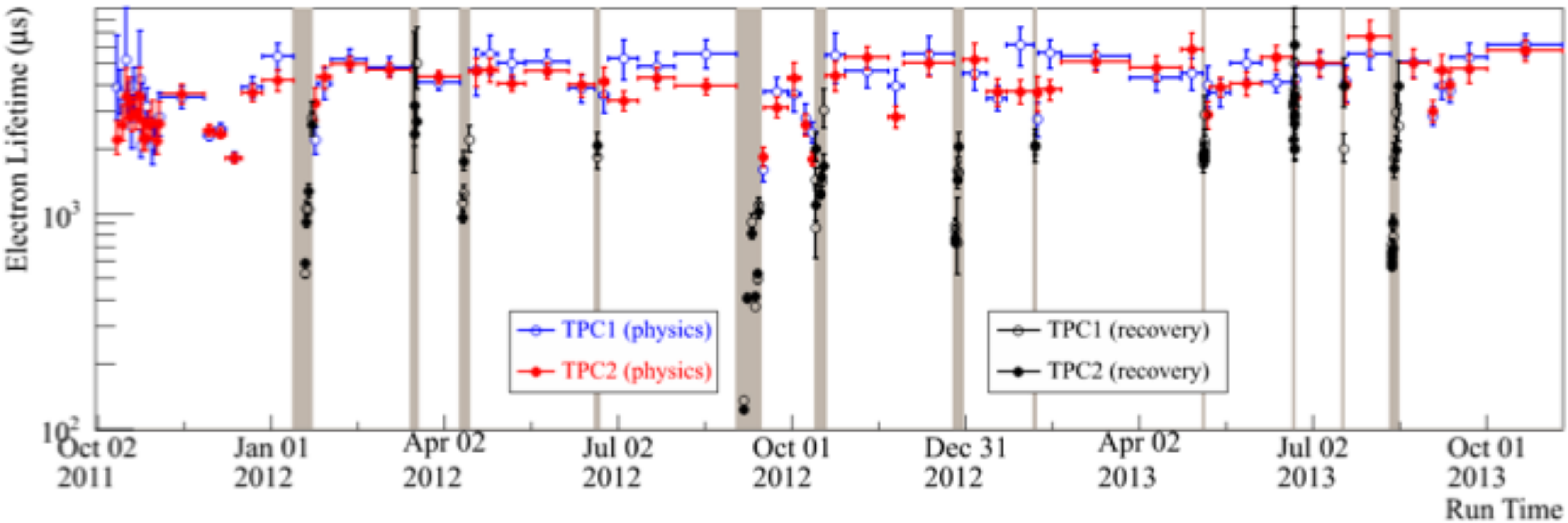
Active and Passive Shielding



LXe Vessel 1.37 mm

To minimize the amount of natural radioactivity in the copper "balloon"

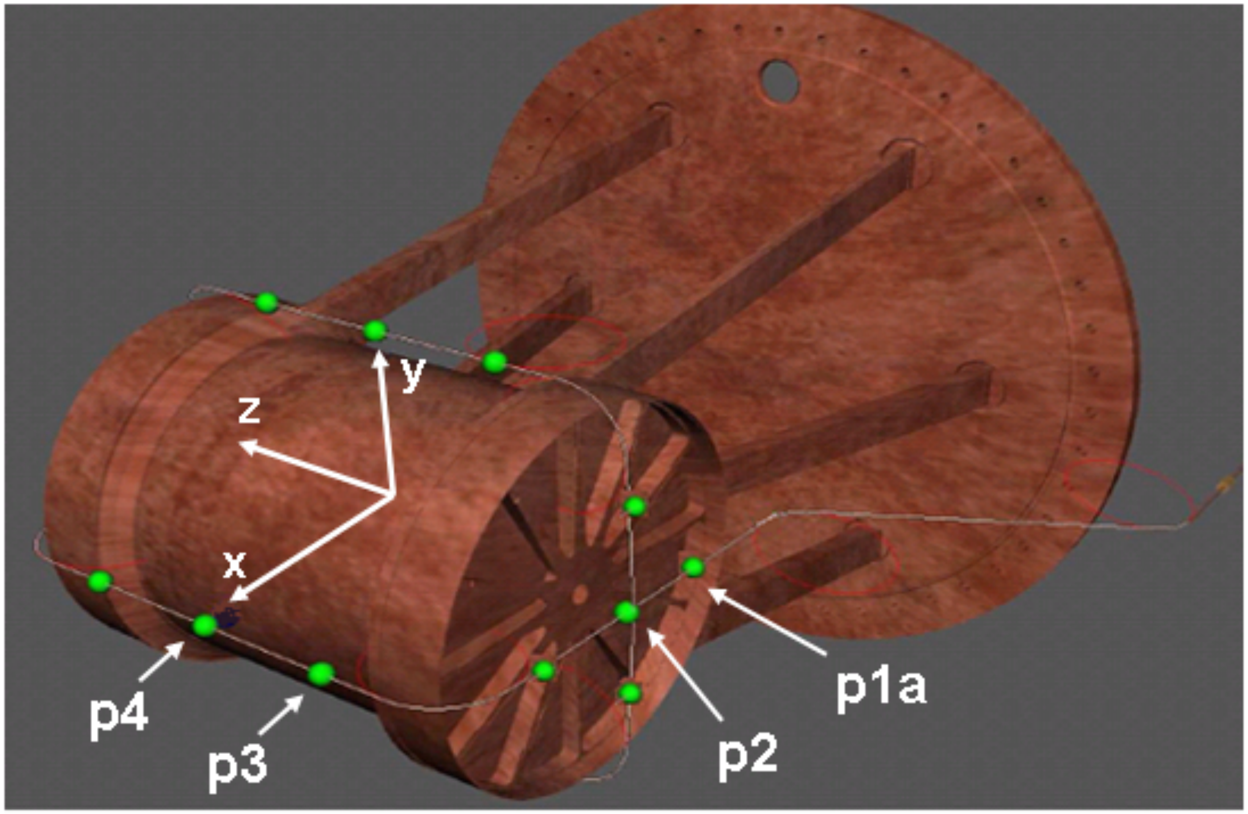
Xe Purity over Run 2



- Estimation based upon data from ^{228}Th source runs
- Purity strongly correlated with circulation pump speed
- At τ_e = 3 ms: drift time <110 μs, loss of charge: 3.6% at full drift length

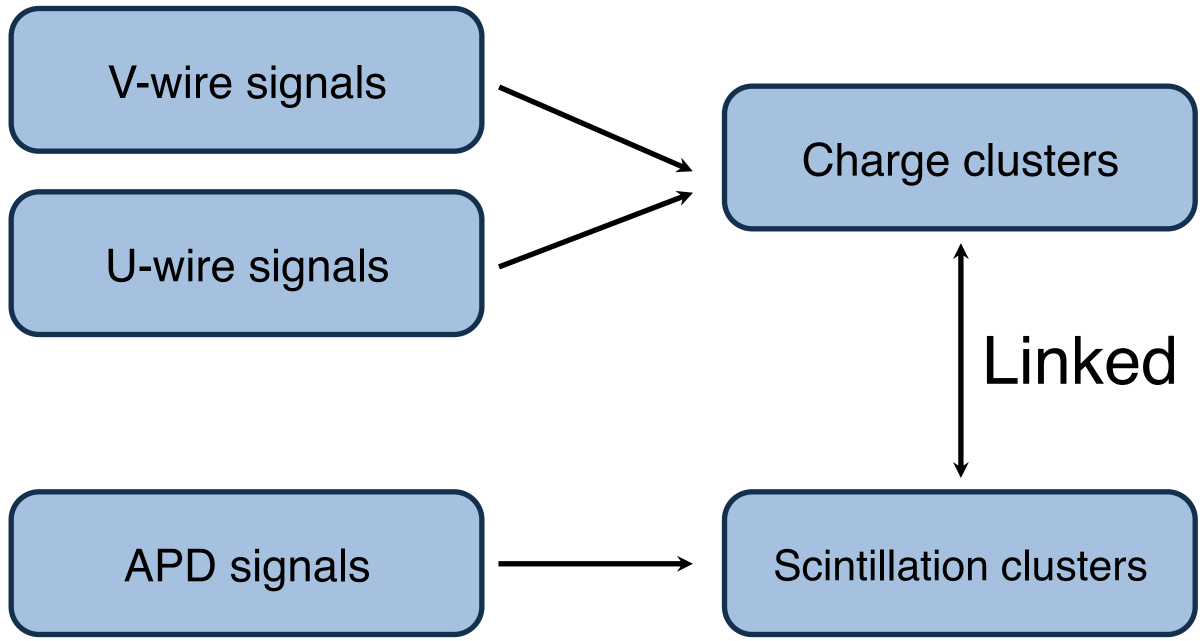
Calibration System

- Periodic campaigns with ^{228}Th, ^{60}Co, and ^{137}Cs, ^{226}Ra
- Main calibration is done with 2615 keV gamma line from ^{228}Th source.

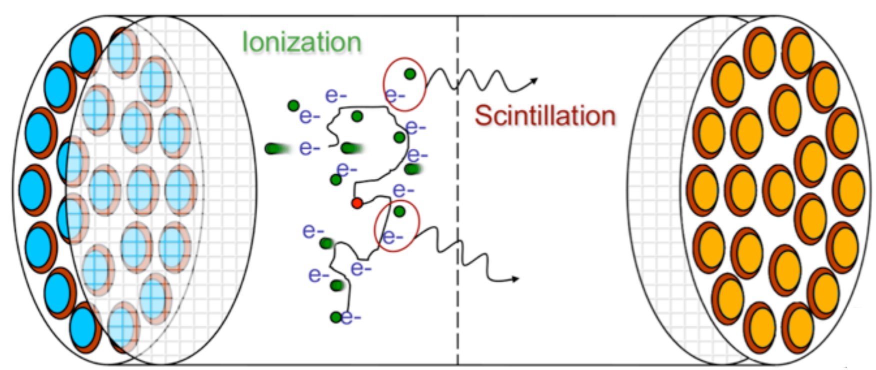


Event reconstruction

1. Event position
2. Event multiplicity
3. Energy measurement

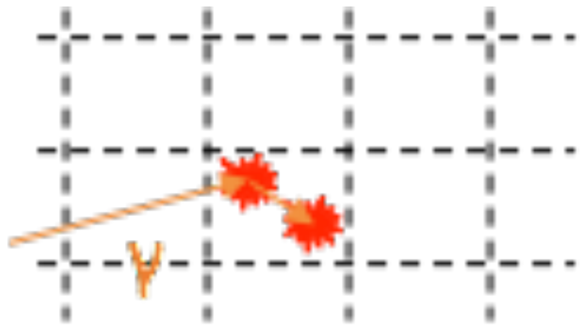


Ability to 100% reconstruct in 3D individual charge cluster down to ~200 keV (limited by induction signal)

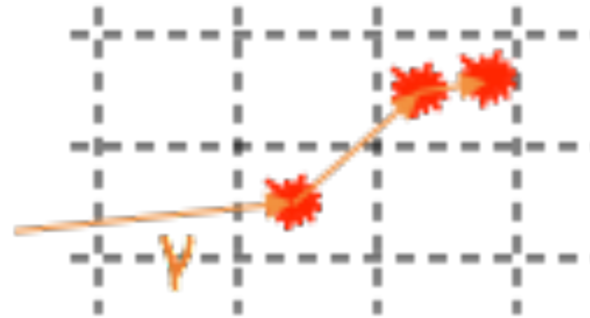


Position and multiplicity reconstruction

Allows for background measurement and reduction



Single-Site (SS) event
(1 charge cluster)



Multi-Site (MS) event
(>1 charge cluster)

$0\nu\beta\beta$: ~90% SS

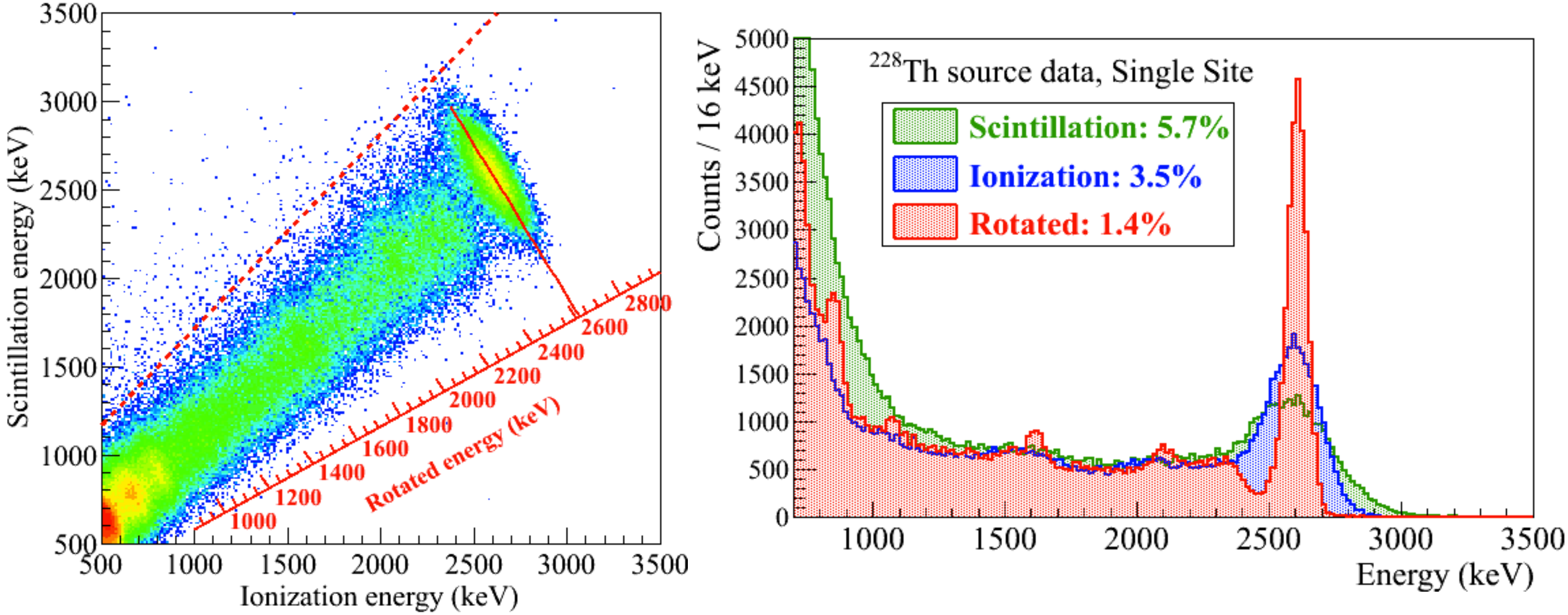
Wires are ~1 cm apart

γ-rays: ~30% SS at $0\nu\beta\beta$ Q-value

Total error in fiducial volume from position reconstruction: **1.73%**

Energy measurement

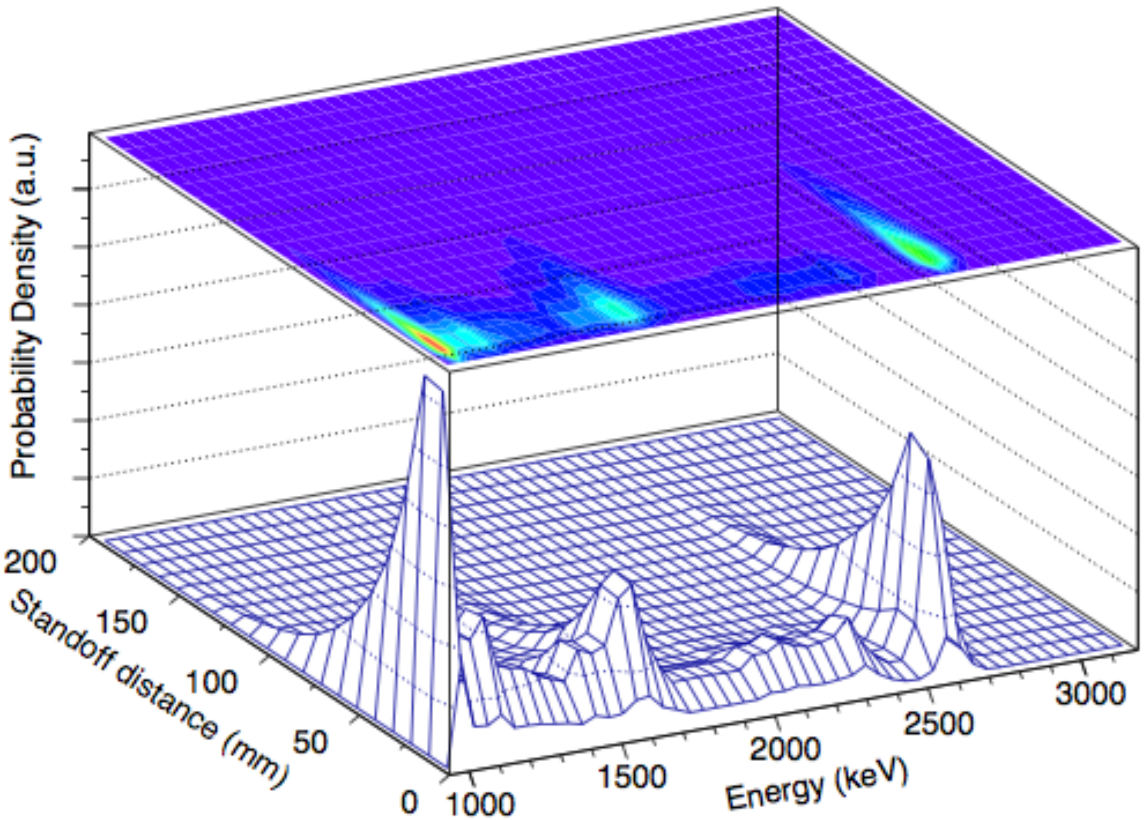
Anti-correlation of charge and light



- Rotation angle determined weekly using ^{228}Th source data, defined as angle which gives best rotated resolution
- Energy resolution is dominated by APD noise

Extracting physics results

Background model + Data → (Maximum Likelihood Fit) → Physics Results



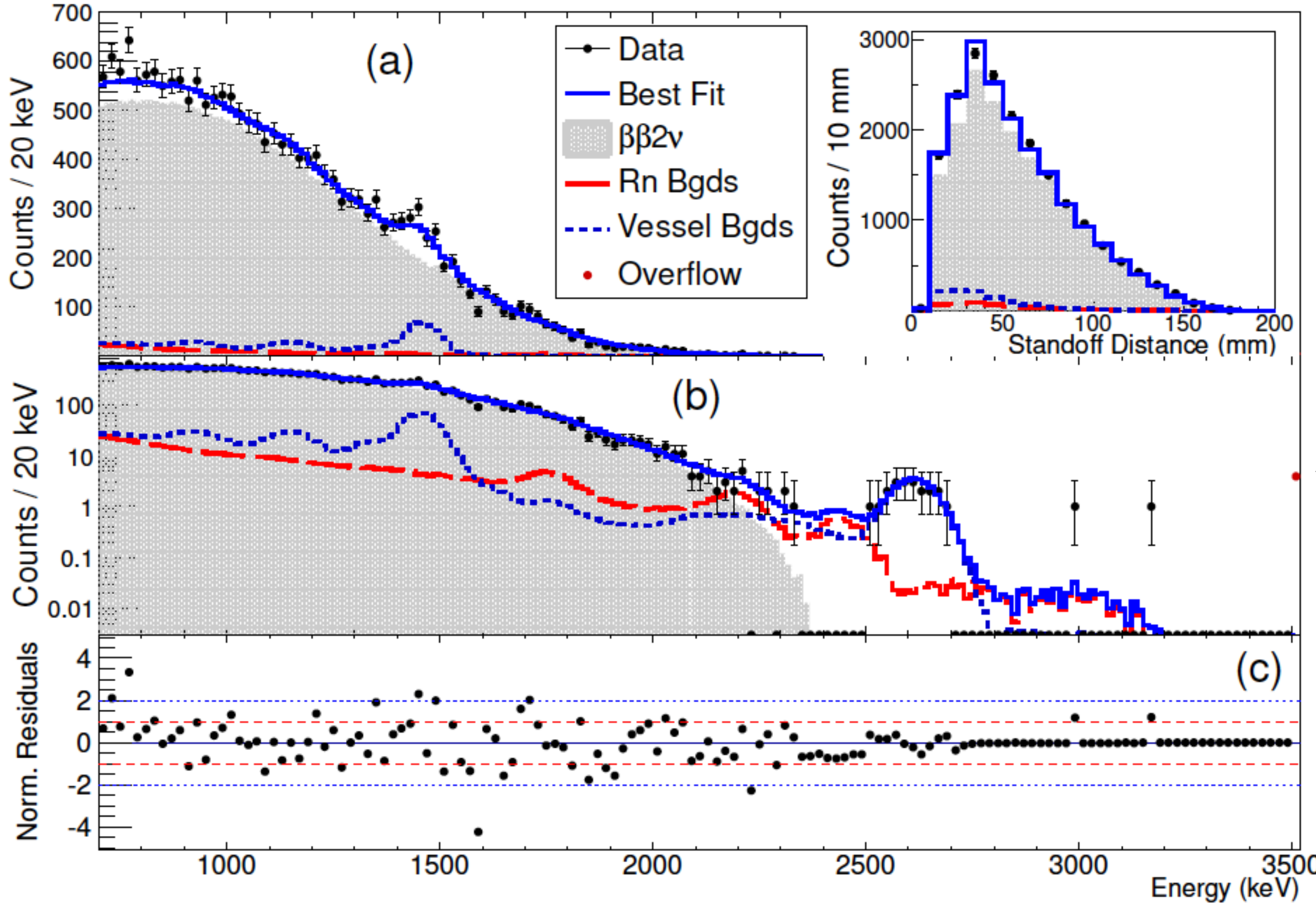
Single site ^{232}Th Probability Density Function in copper vessel

- Variables
  - Energy
  - Position (standoff distance)
- Multiplicity
  - SS
  - MS

Standoff Distance

- "Standoff" = closest distance between a charge cluster and detector component
- Gammas will be closer to detector sides, $\beta\beta0\nu$ will be evenly distributed in detector

$2\nu\beta\beta$ precision measurement



$2\nu\beta\beta$ signal to background ratio: **11: 1**

Inner 40% fiducial volume signal to background ratio: **19: 1**

Most precise measurement of the $2\nu\beta\beta$ half-life

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

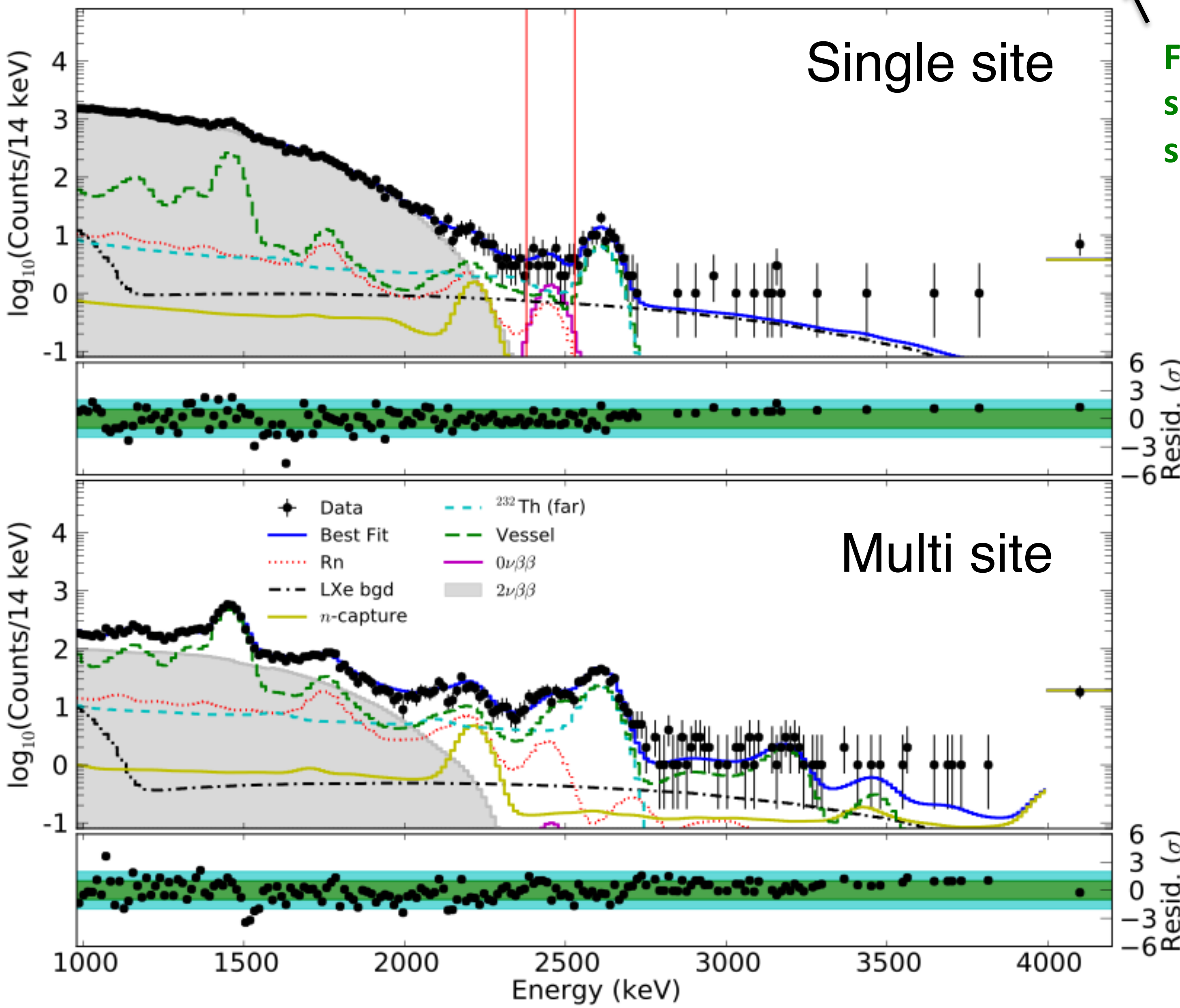
[PRC **89**, 015502 (2014)]

100 kg · yr
736 mol · yr ^{136}Xe exposure

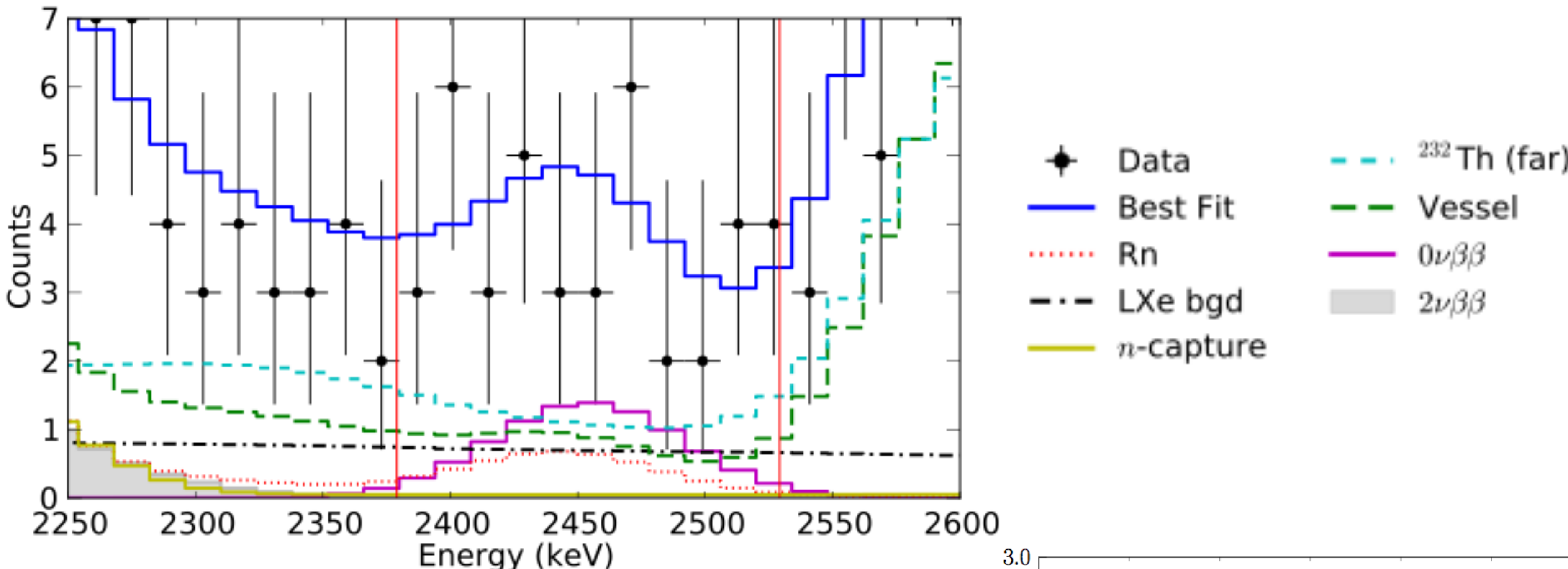
$0\nu\beta\beta$ Search

Analysis range:
980 keV to 9800 keV

For 100% scintillation signal efficiency



$0\nu\beta\beta$ Search

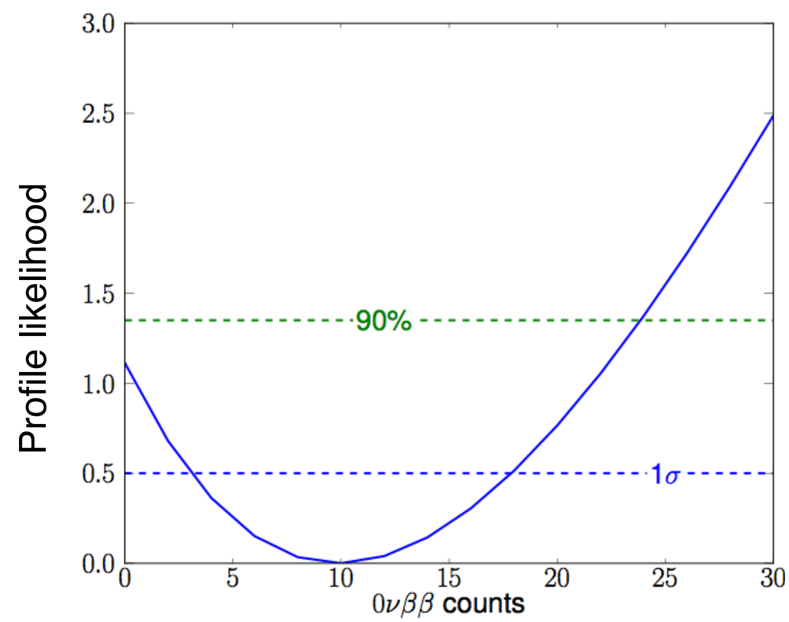


$T_{1/2}^{0\nu\beta\beta} > 1.1 \text{ x } 10^{25}$ yr

$\langle m_{\beta\beta} \rangle < 190 - 450$ meV

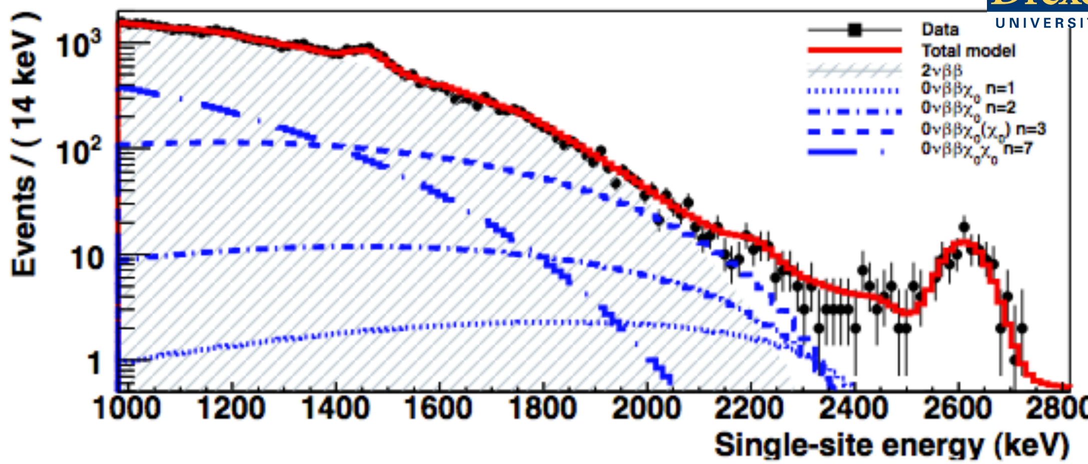
(90% C.L.)

[*Nature* **510**, 229 (2014)]



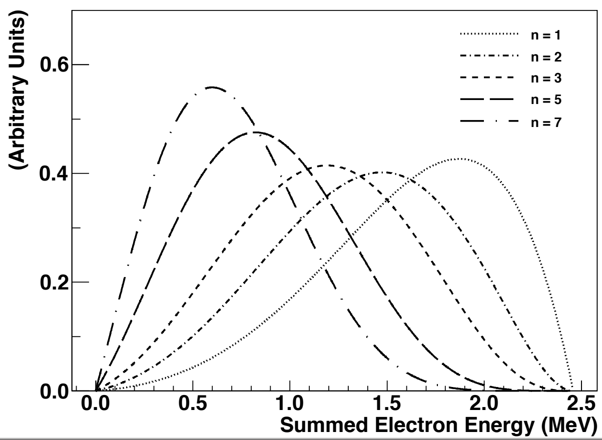
Majoron Mode Search Results

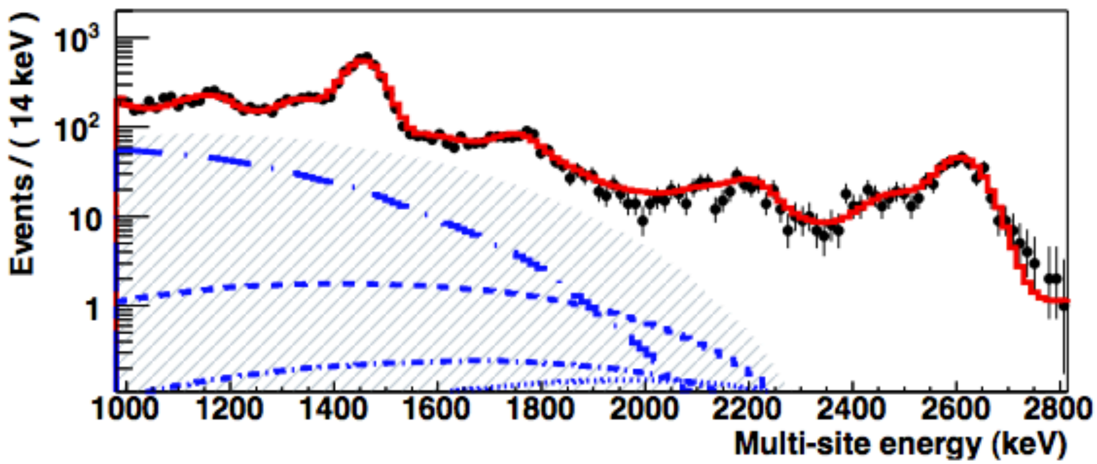
Phys. Rev. D 90, 092004 (2014)



*Data fit for each Majoron mode separately

*Background shown is for fit to n=1 mode

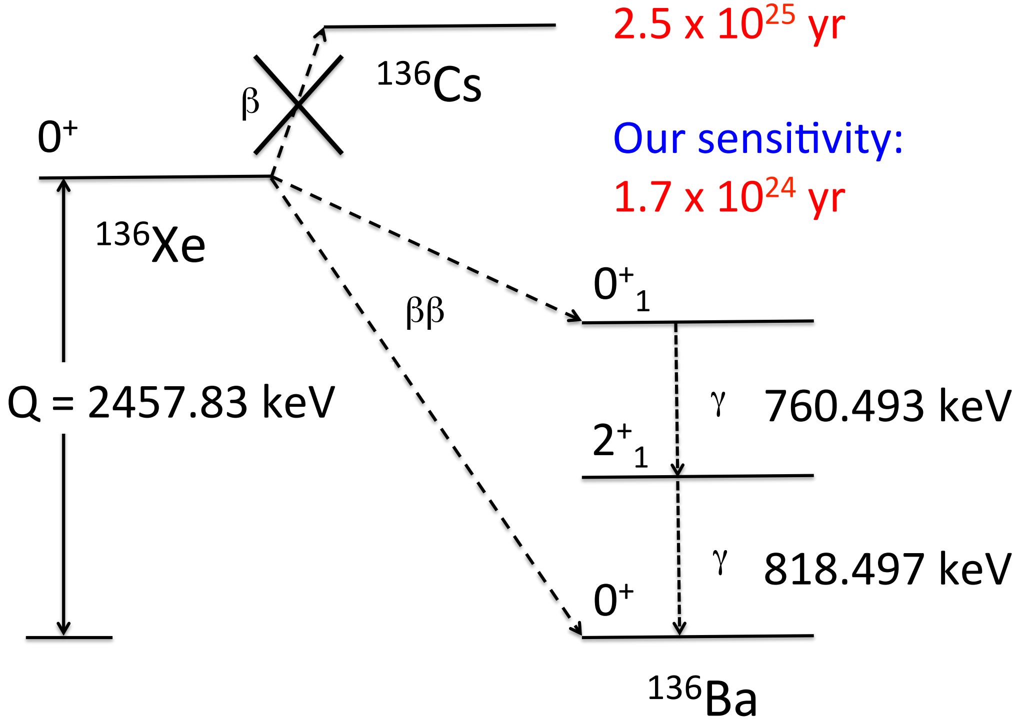




Decay mode	Spectral index, n	Model types	$T_{1/2}$, yr	$\lvert\langle g_{ee}^{M}\rangle\rvert$
$0\nu\beta\beta\chi_0$	1	IB, IC, IIB	$>1.2\cdot10^{24}$	$<(0.8\text{-}1.7)\cdot10^{-5}$
$0\nu\beta\beta\chi_0$	2	"Bulk"	$>2.5\cdot10^{23}$	–
$0\nu\beta\beta\chi_0\chi_0$	3	ID, IE, IID	$>2.7\cdot10^{22}$	$<(0.6\text{-}5.5)$
$0\nu\beta\beta\chi_0$	3	IIC, IIF	$>2.7\cdot10^{22}$	<0.06
$0\nu\beta\beta\chi_0\chi_0$	7	IIE	$>6.1\cdot10^{21}$	$<(0.5\text{-}4.7)$

Phys Rev C 93 035501 (2016)

Decay to Excited State



Estimated half-life:
2.5×10^{25} yr

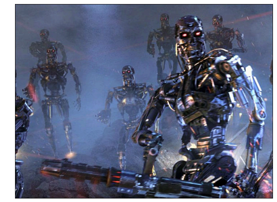
Our sensitivity:
1.7×10^{24} yr

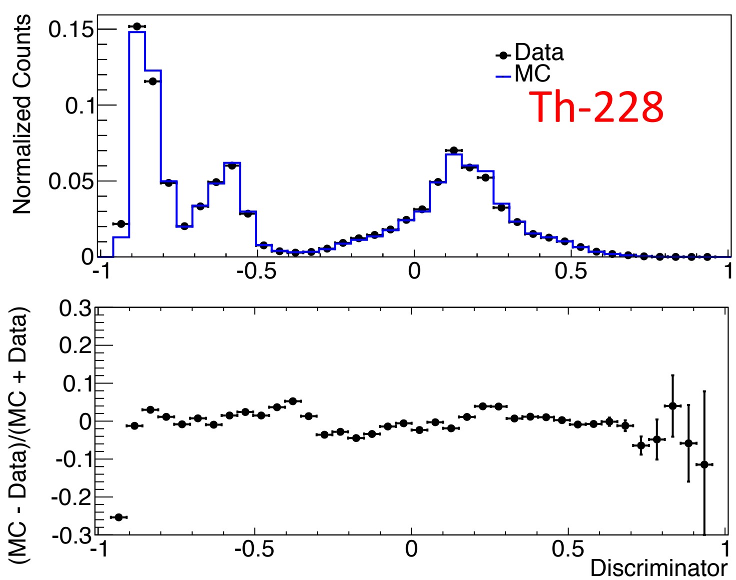
- Search for the $2\nu\beta\beta$ decay to the excited state, 0^+_1, of ^{136}Ba
- Decays to excited state has been observed in two isotopes: ^{100}Mo and ^{150}Nd
- De-excitation from the 0^+_1 state produce two γs – unique signature
- Main background is $2\nu\beta\beta$ to the ground state

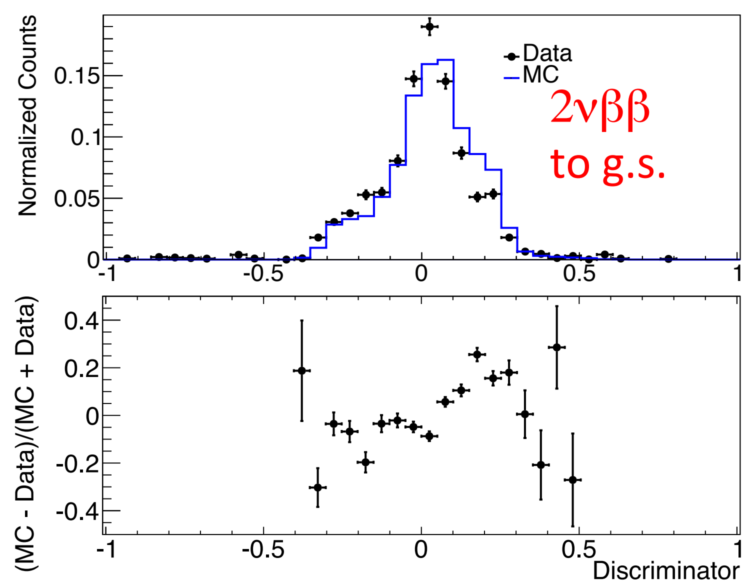
Knowledge of the decay to excited state rate check the various Nuclear Matrix Element calculations -> smaller uncertainty on the effective neutrino mass

Decay to Excited State

- 1st EXO-200 physics analysis to use machine learning
- Being healthily skeptical of our robotic friends
  - Algorithm and input variables decided **prior to the final fit**
  - Method is chosen based on the **toy MC studies** of uncertainty (excited state normalization) after the "unskewing" of source agreements applied to PDFs

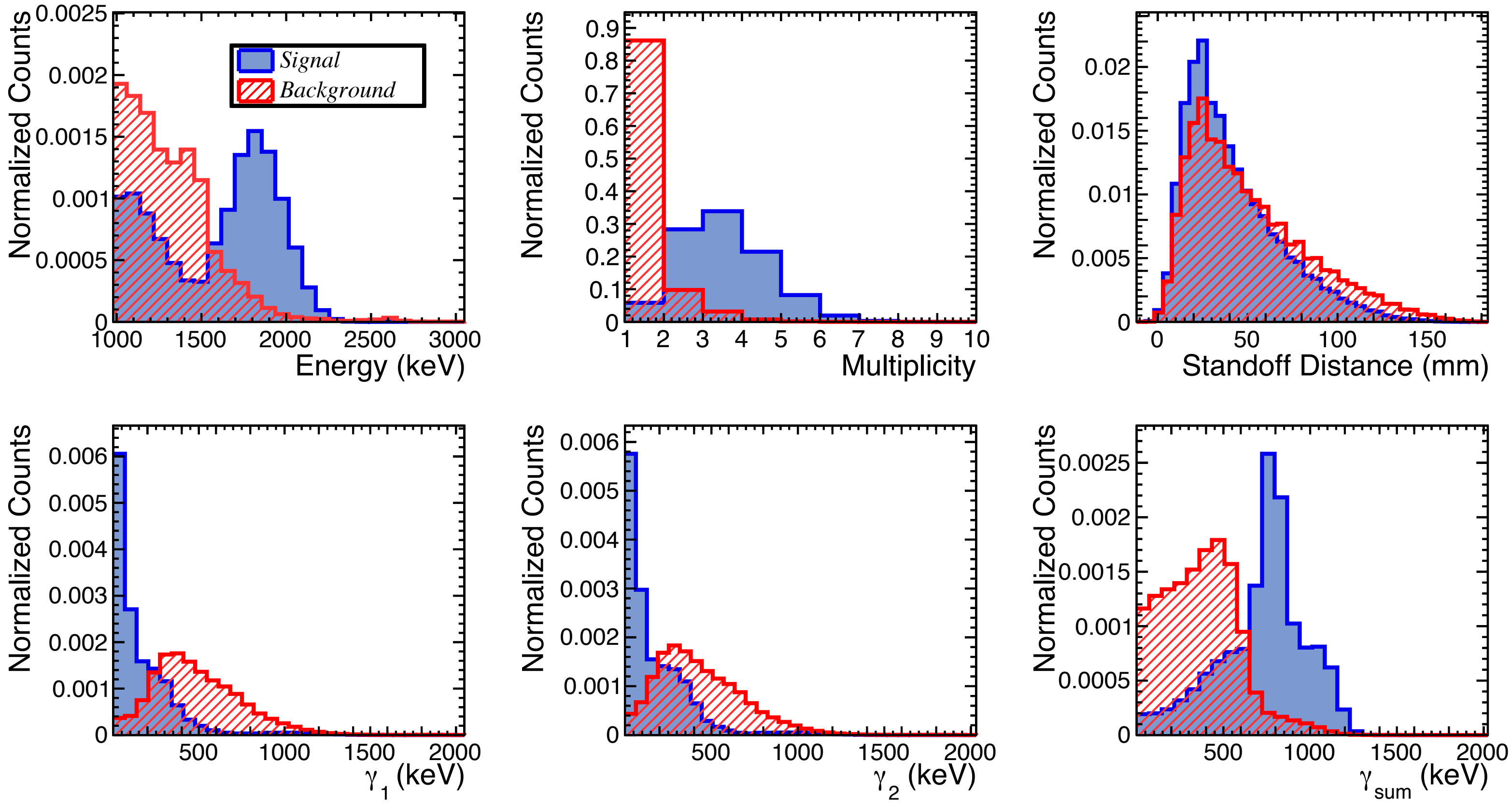






Phys Rev C 93 035501 (2016)

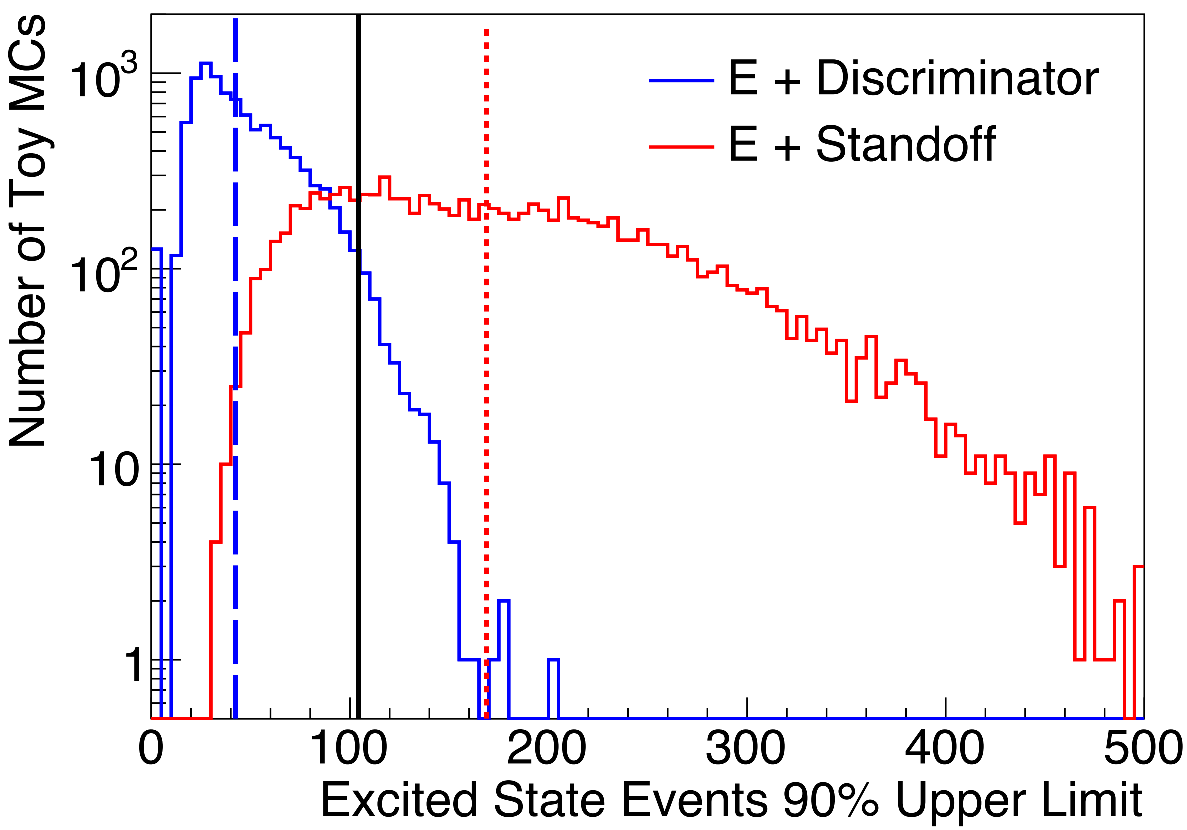
Decay to Excited State



The “discriminator” variable is produced from a combination of 6 variables as determined by BDT, boosted decision tree , machine learning algorithm,

Decay to Excited State

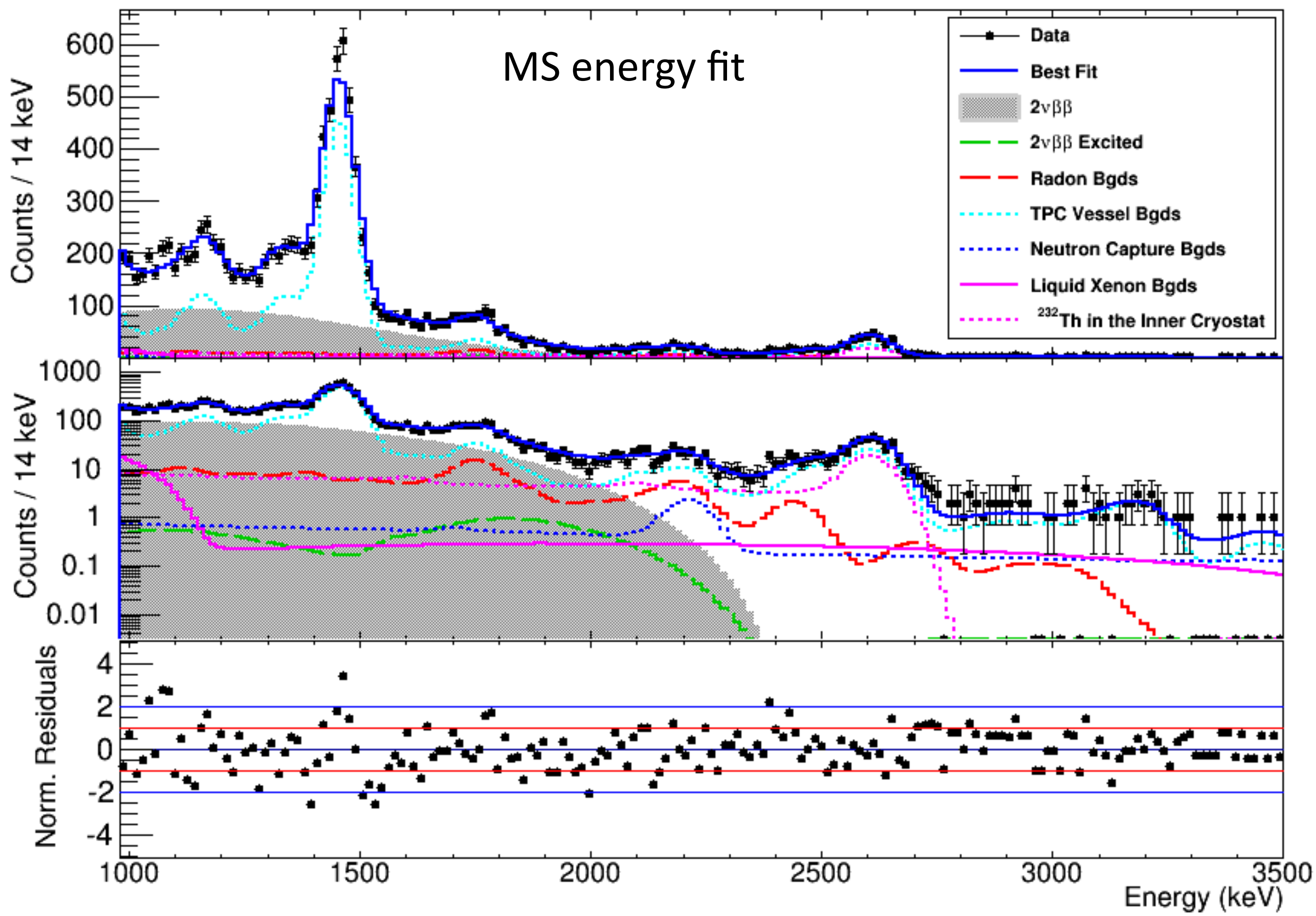
- Machine learning improves our sensitivity compares to traditional EXO-200 method



Sensitivity of 1.7×10^{24} yr

Phys Rev C 93 035501 (2016)

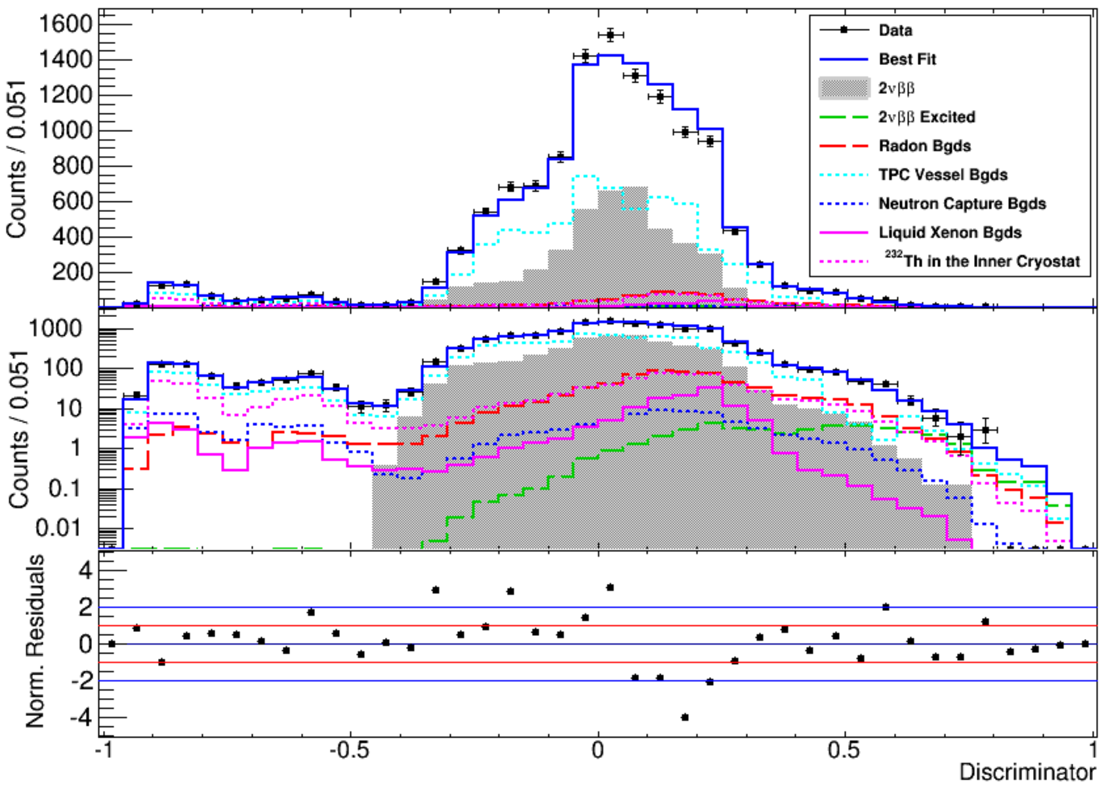
Decay to Excited State



- 2D Maximum Likelihood fit in Energy + Discriminator

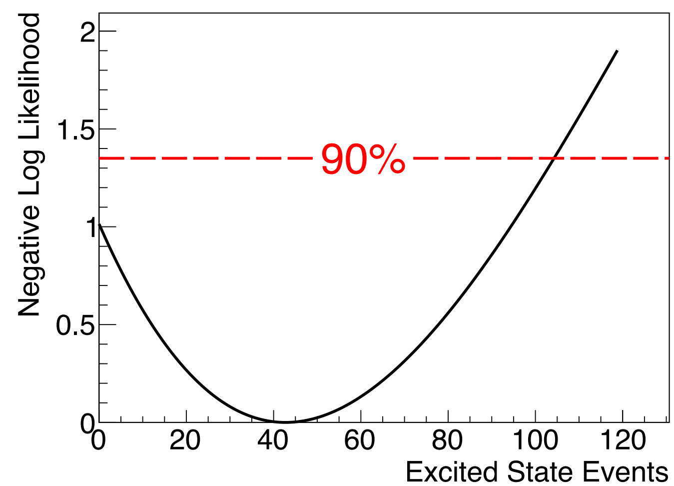
Phys Rev C 93 035501 (2016)

Decay to Excited State



MS discriminator fit

- Best fit value of 43 events
  - 90% CL of 104 events
  - Consistent with null hypothesis at 1.6σ



$T_{1/2}\,(0^+ \text{-->} 0^+_1) > 6.9 \times 10^{23}$ yr

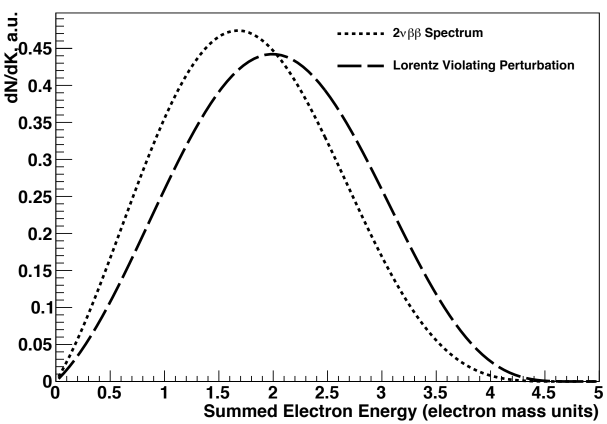
Search for Lorentz- and CPT- violation in double beta decay within the Standard-Model Extension

- First search for Lorentz-violation in double beta decay within the Standard-Model Extension framework
- Able to search for an oscillation-free, momentum independent neutrino coupling parameter, $\mathring{a}_{\text{of}}^{(3)}$
- A perturbation to the standard 2spectrum defines the magnitude of $\mathring{a}_{\text{of}}^{(3)}$

$$\Gamma = \Gamma_0 + \delta\Gamma \longrightarrow$$

$$\Gamma_0 = g_A^4 m_e^2 |M^{2\nu}|^2 G_0^{2\nu}$$

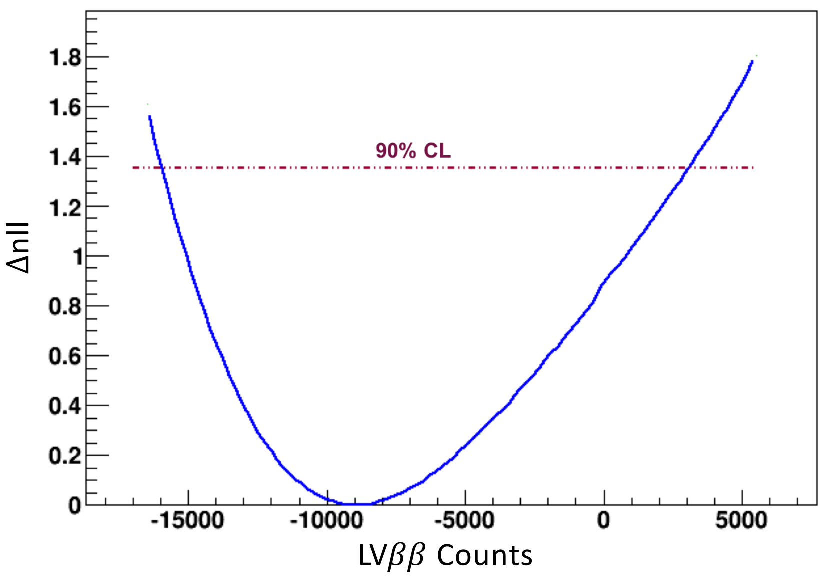
$$\delta\Gamma = g_A^4 m_e^2 |M^{2\nu}|^2 \delta G^{2\nu}$$

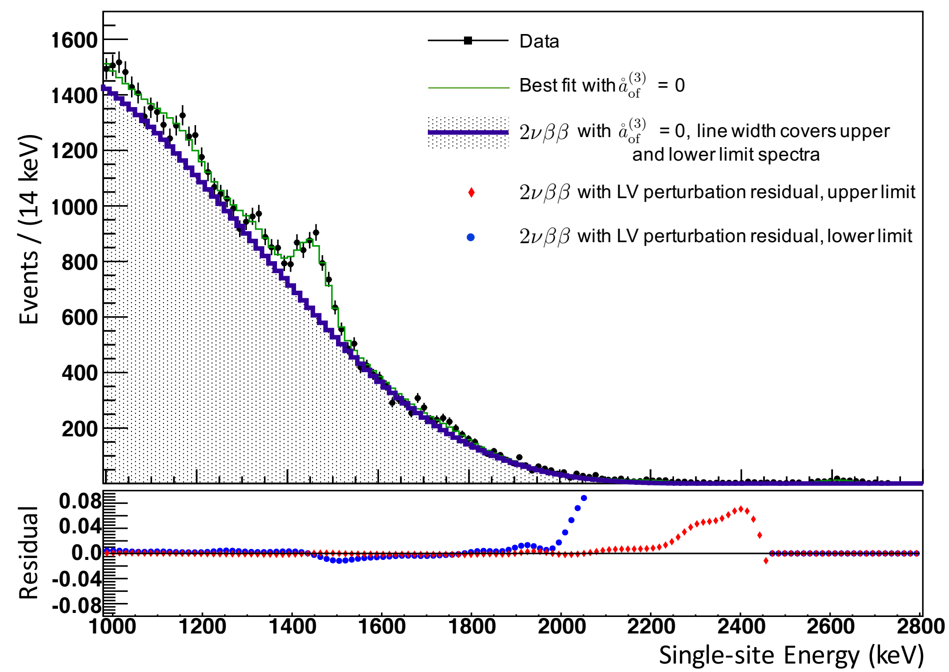


$$\delta G^{2\nu} \propto \mathring{a}_{\text{of}}^{(3)}$$

arXiv:1601.07266, accepted by PRD

Search for Lorentz- and CPT- violation in double beta decay within the Standard-Model Extension





$$-2.65 \times 10^{-5}\ \mathrm{GeV} < \mathring{a}^{(3)}_{\mathrm{of}} < 7.60 \times 10^{-6}\ \mathrm{GeV}$$

* First limit on this parameter set by a direct search

Other Recent EXO-200 Physics Papers

- Cosmological background: *arXiv:1512.06835, accepted by JCAP*
  - Improved understanding of Xe-137 (a muon induced background above our $0\nu\beta\beta$ Q-value)
- Alphaion fraction and mobility: *PRC 92 4 (2015)*
  - Interesting info for potential future Ba tagging work
- Radioactivity-induced background: *PRC 92 1 (2015)*
  - Understanding of our backgrounds are detailed

EXO-200 Status to Jan. 2016

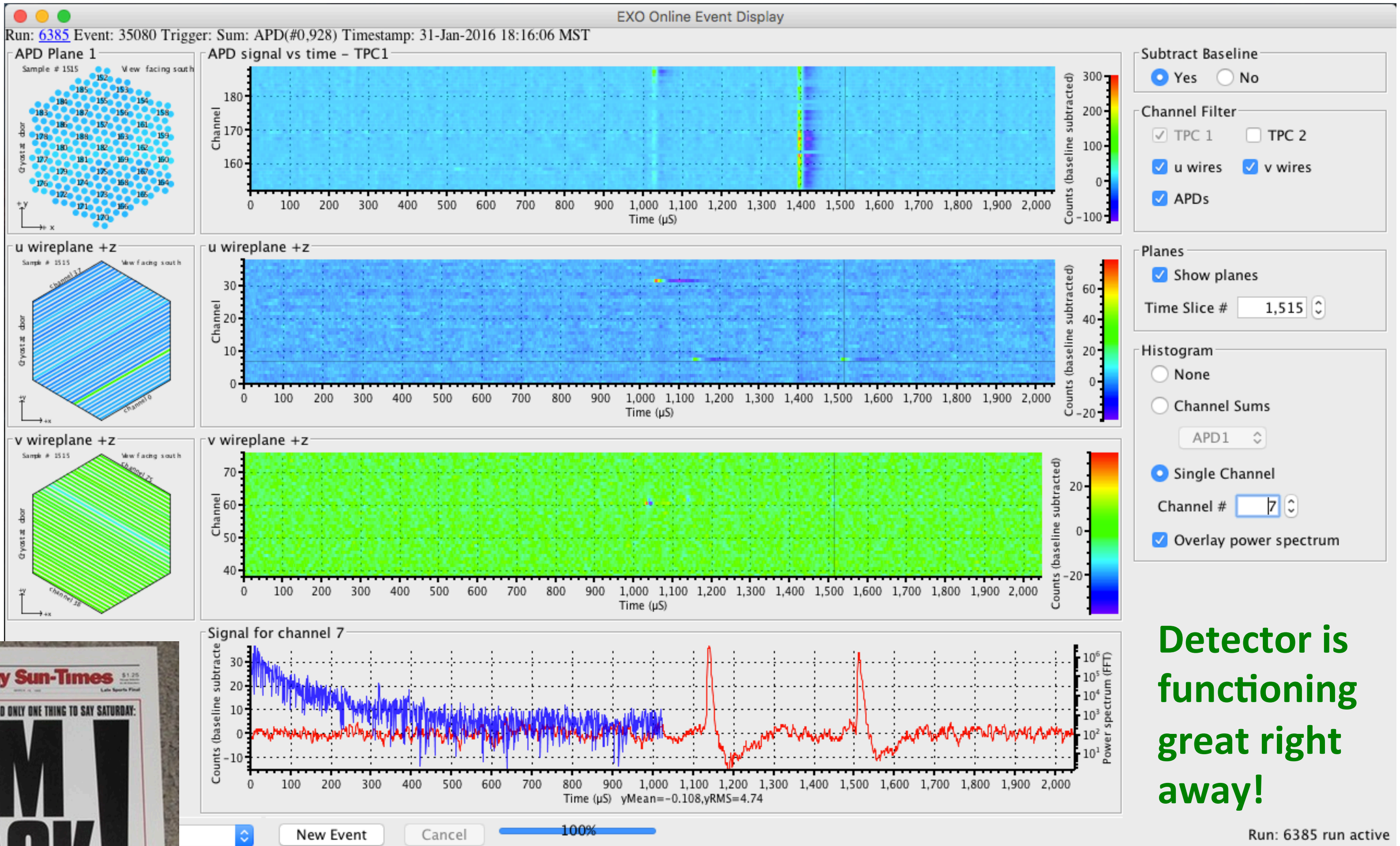
- WIPP incidents (NOT OUR FAULT!):
  - Feb. 5 2014 – Fire in WIPP underground
  - Feb. 14 2014 – Airborne radiological event

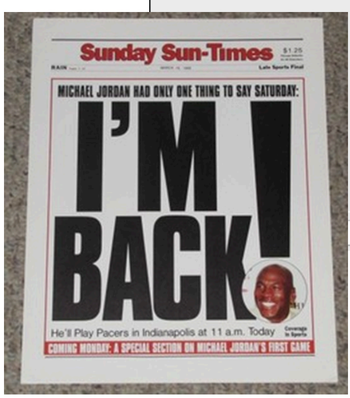
- EXO-200 timeline:
  - In late Feb. 2014, with remote system access, Xe was successfully recovered (as designed), followed by controlled warm up of TPC/Cryostat.
  - In Sept. 2014, lost underground power but regained access.
  - Power restored in Feb. 2015
  - Sample salt near the experiment show virtually zero contamination from the radiological event
  - Ongoing cleanup and equipment repair/replacement
  - Cooling and filling LXe TPC in the winter 2015/2016

EXO-200 is nearly 4000 feet from the radiation event

EXO-200 is Back!

A Bi-Po alpha event right after turning the detector back on



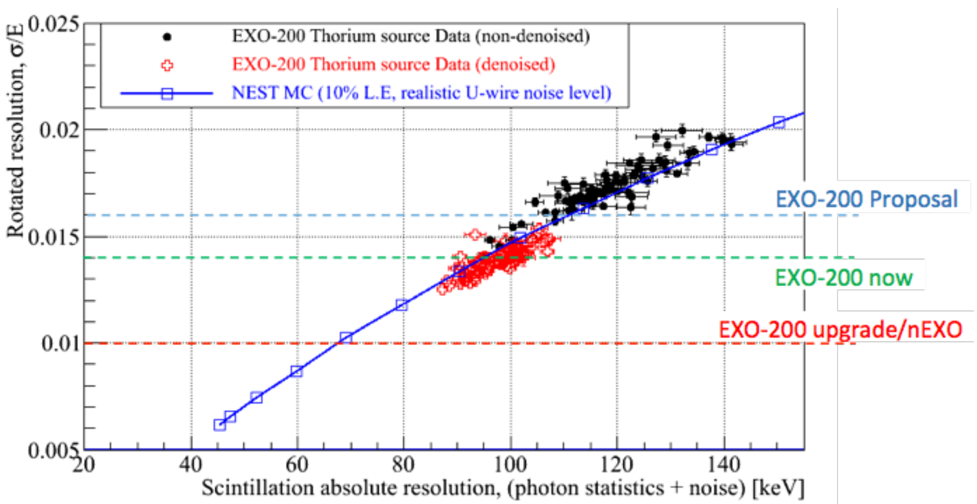


Detector is functioning great right away!

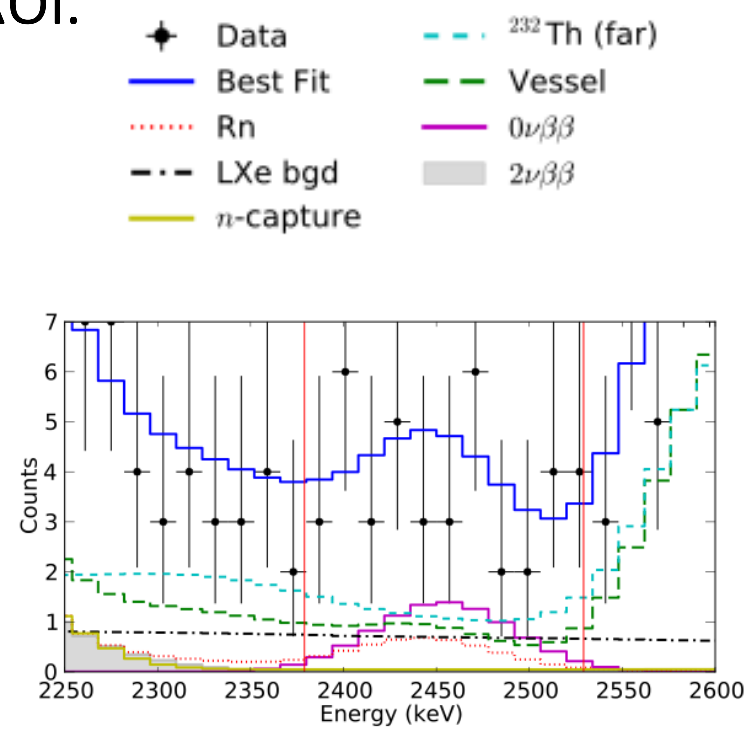
Data taking has resuming since January 31st, 2016

Current EXO-200 Improvements

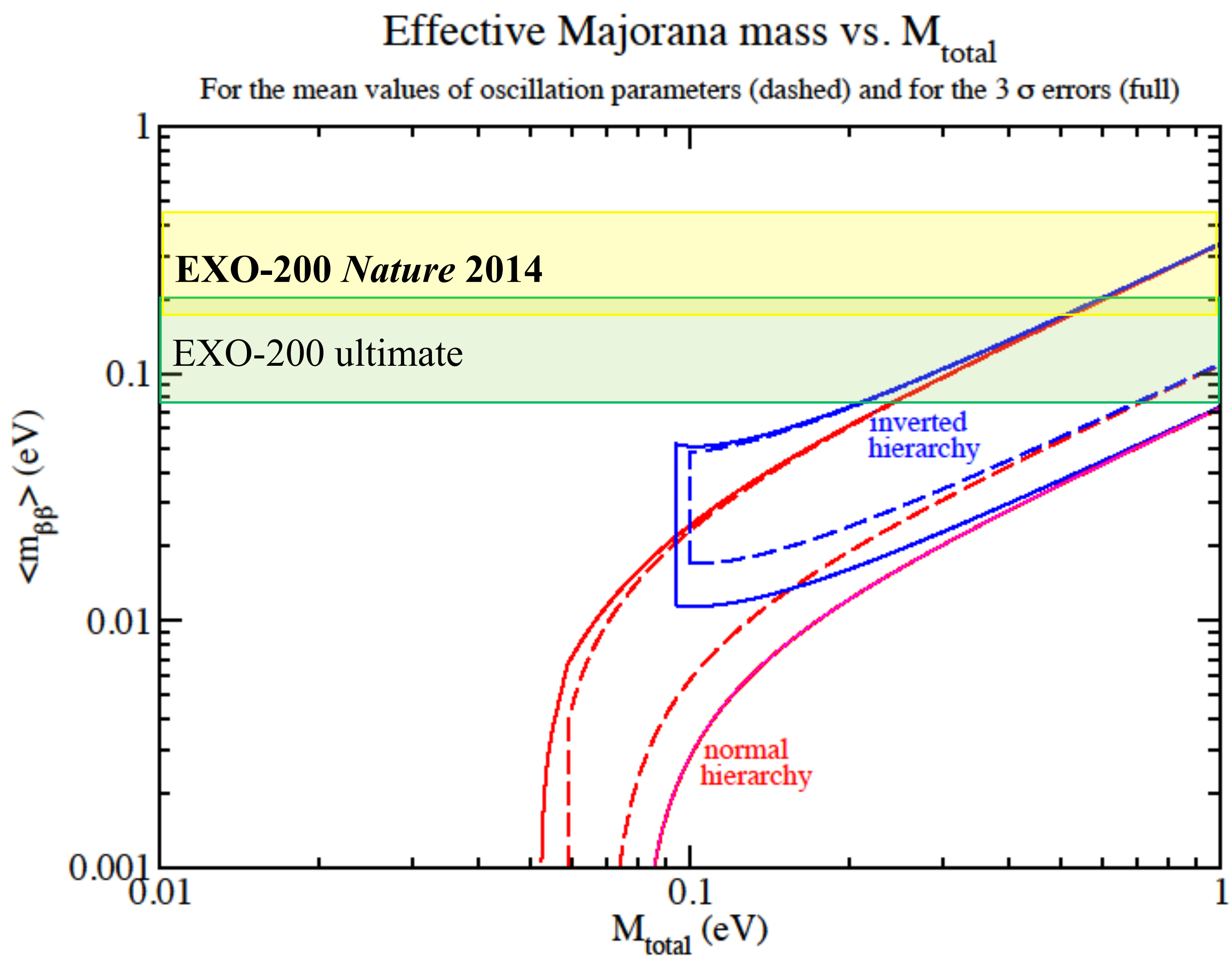
- Hardware upgrade to improve energy resolution at Q-value to 1% via improvement in minimizing APD noise
- Many of the ROI background counts come from radon daughters external to the detector. Deradonator should improve our background in the ROI.



Resolution curve from simulation using NEST:
http://nest.physics.ucdavis.edu/



Sensitivity outlook



EXO-200 current sensitivity (90%CL):
1.9×10^{25} yr

EXO-200 ultimate sensitivity (90%CL):
3 years additional livetime with Rn removal and energy resolution improvement

Enriched Xenon Observatory
EXO for double beta decay

The EXO-200 Collaboration

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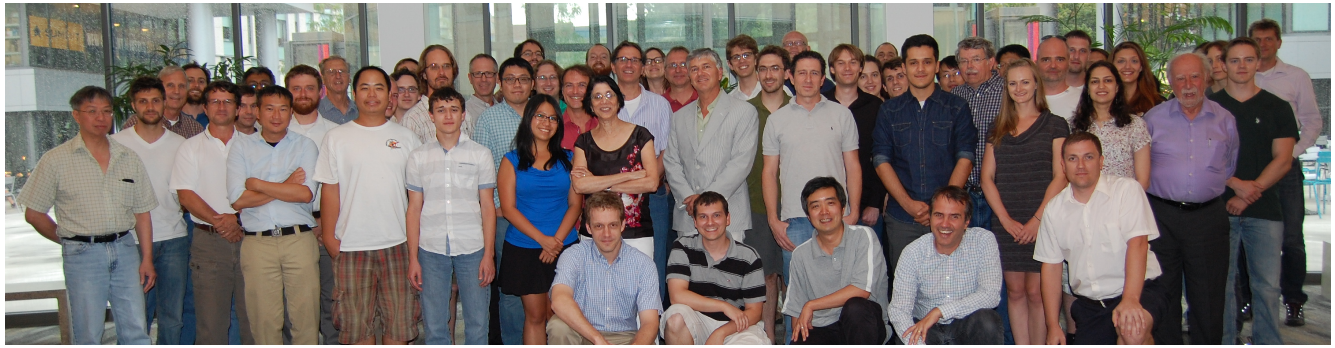
The nEXO Collaboration

Enriched Xenon Observatory for double beta decay



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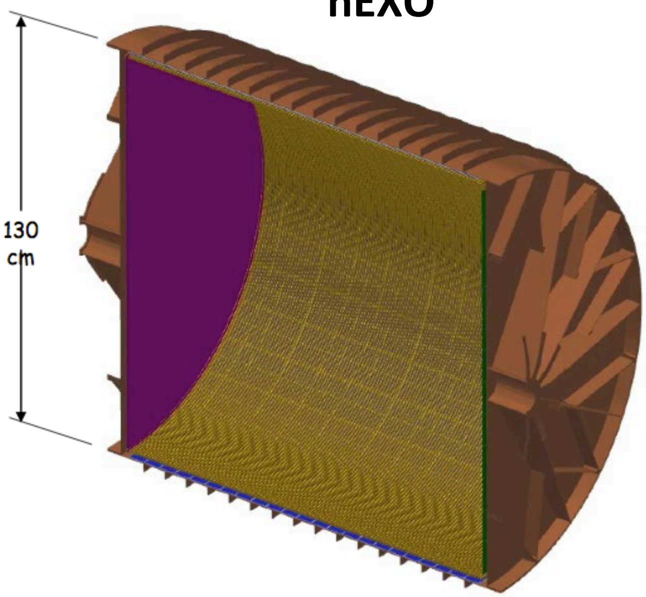
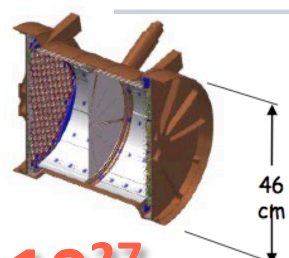
nEXO (“next EXO”)

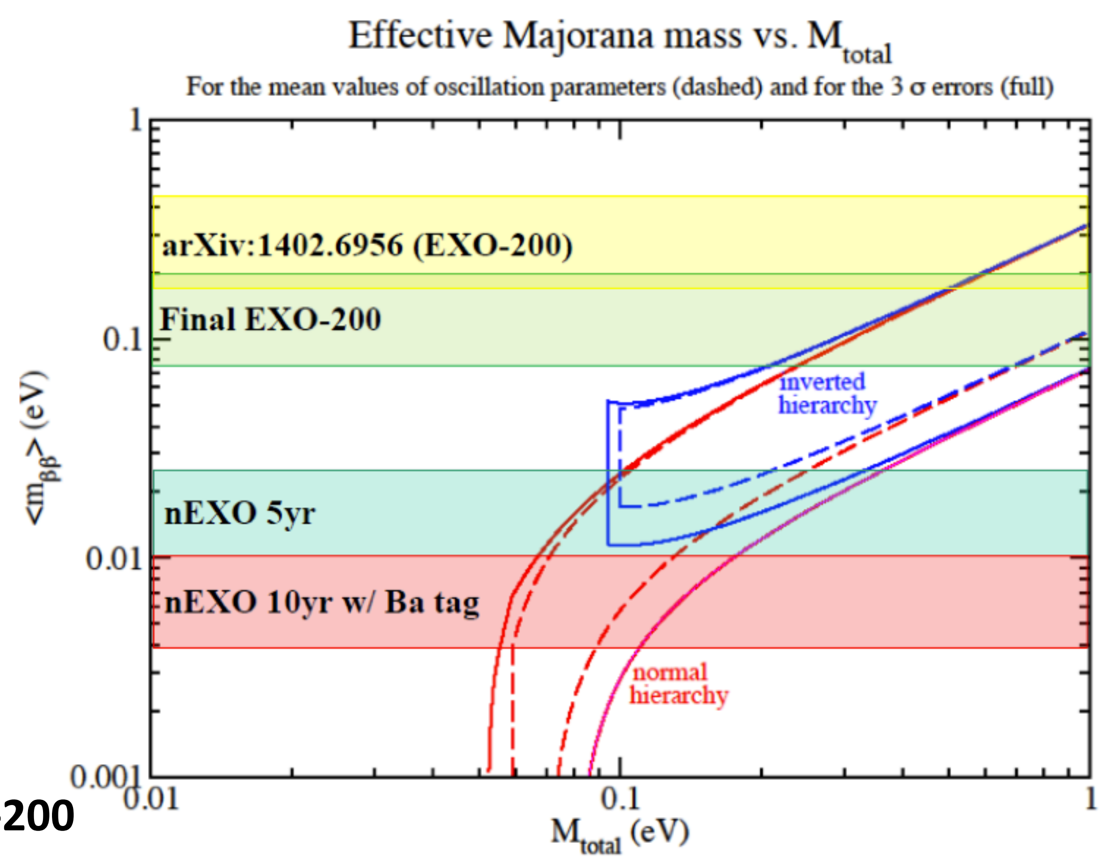
A detector 50x the size of EXO-200 is being designed

nEXO



EXO-200

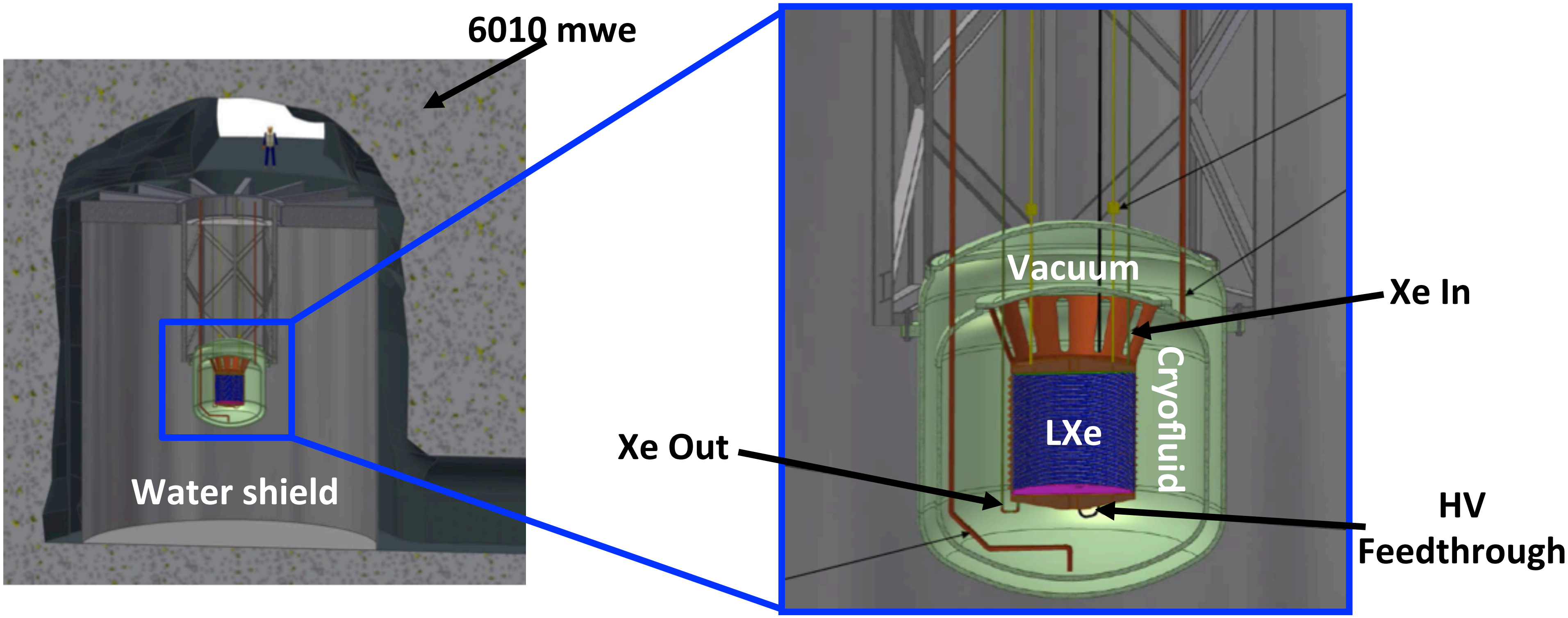




nEXO sensitivity: $6.6 \cdot 10^{27}$ yr

Projected sensitivity will probe the inverted hierarchy, and cover the inverted hierarchy with implemented **^{136}Ba tagging**

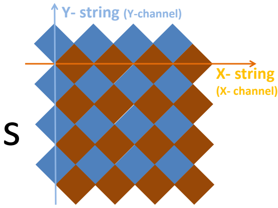
Preliminary design of nEXO

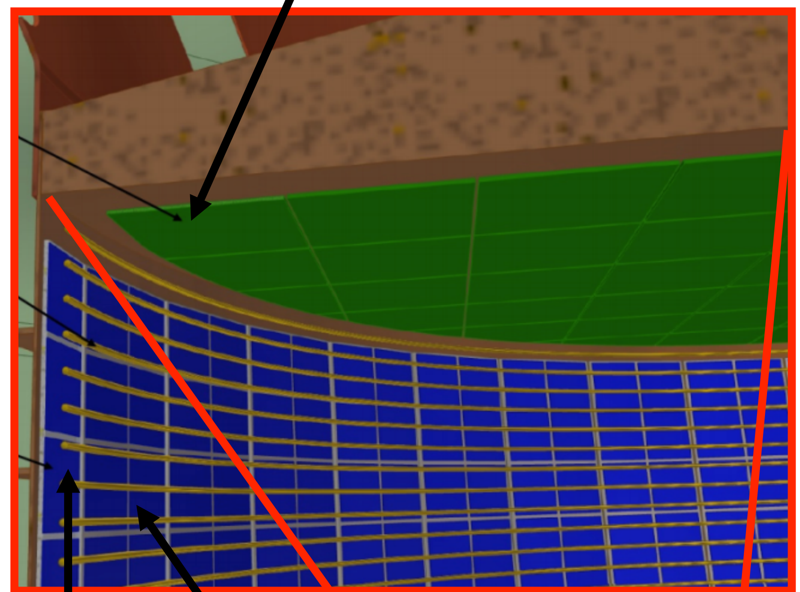


Preliminary design of the nEXO detector in SNOLab's cryopit

nEXO R&D

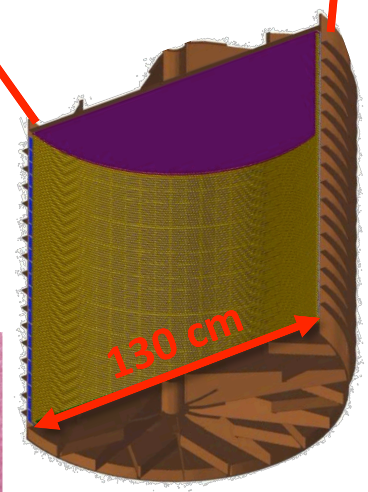
Charge readout tiles



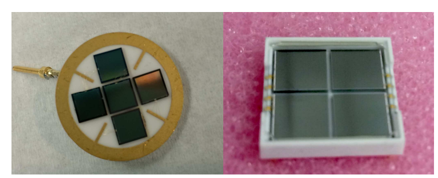


Light sensors

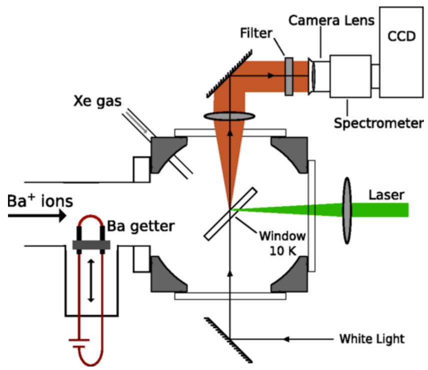
Field shaping rings



SiPM (arXiv 1502.07837)

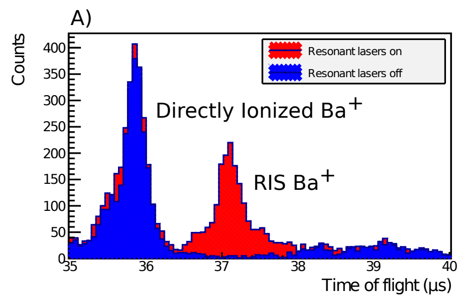


Barium Tagging (0 background possible if we can ID the daughter barium ion)



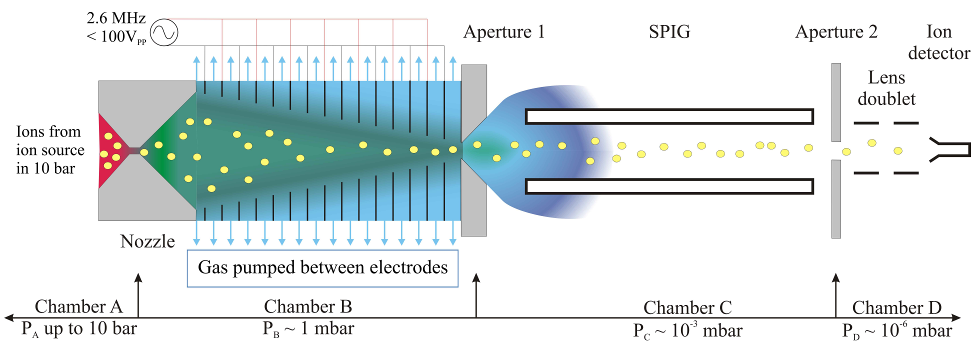
Ba deposit in solid Xe

(Phys. Rev. A, V91, 2, 2015)



Ba ID in liquid Xe via Resonance Ionization Spectroscopy

(Rev. of Sc.i Inst., V85, 9, 2014)

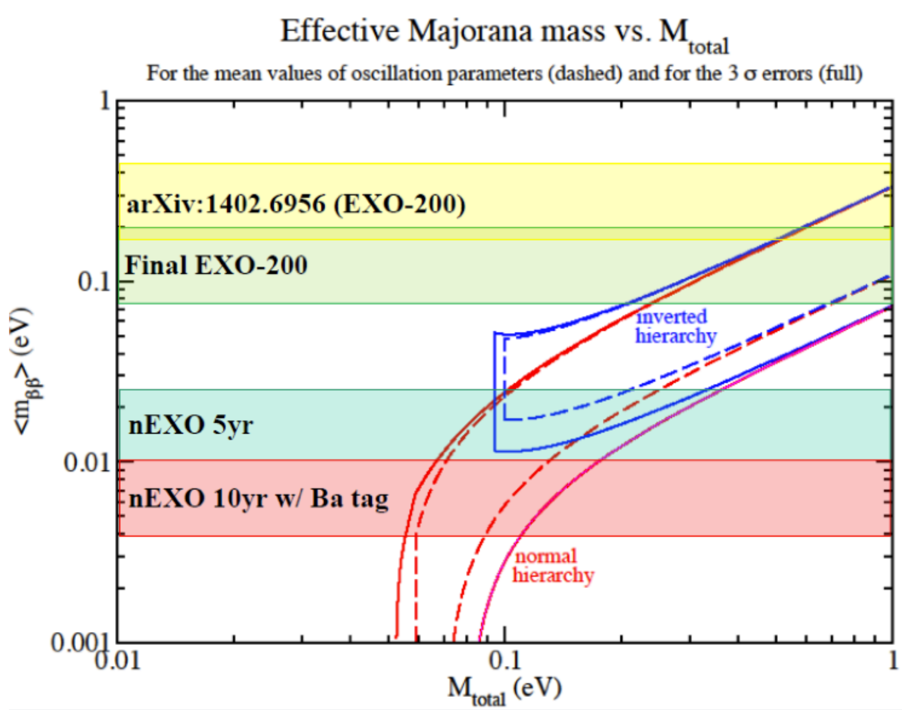


RF Funnel for Gas

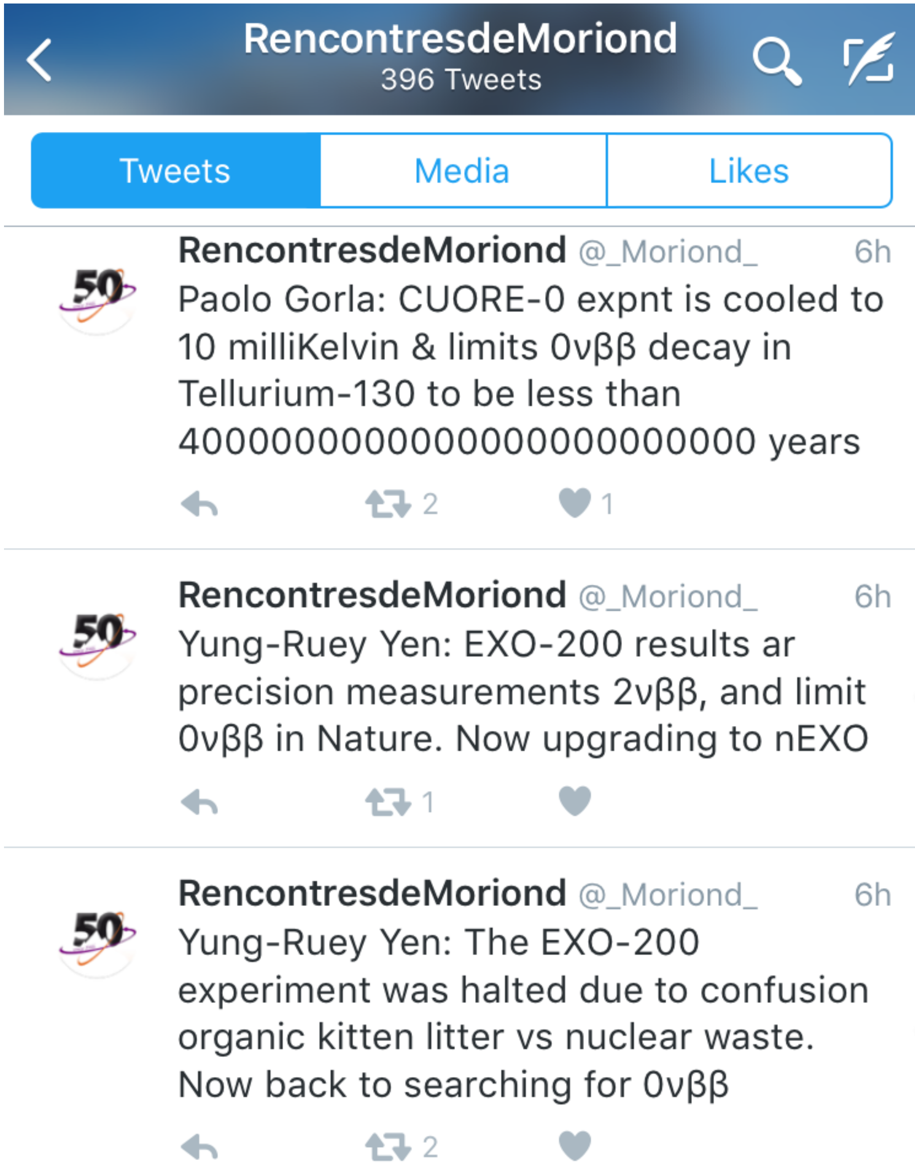
(Int. J. of Mass. Spec., V379, 110, 2015)

nEXO vs. EXO-200

Parameter	nEXO	EXO-200
Fiducial mass (kg)	4780	98.5
Enrichment (%)	80-90	80
Data taking time (yr)	5	5
Energy resolution @ $Q_{\beta\beta}$ (keV)	58	88 (58)
Depth (m.w.e)	6010	1500
Background within FWHM of endpoint (events/yr/mol_{136})	6.1×10^{-4}	0.022 (0.0073)
Background within FWHM of endpoint inner 3000kg (events/yr/mol_{136})	1.6×10^{-4}	



NOT the Summary



- EXO-200 has restarted and hope to do great physics in running for 3 more years.
- Effort toward nEXO R&D is just one of the byproduct.
- Problem at WIPP (yes, organic kitty litter - not EXO's fault!) caused a two year hiatus, but we have overcame that.
- (Yes, the organic kitty litter thing is rather memorable if not confusing.)

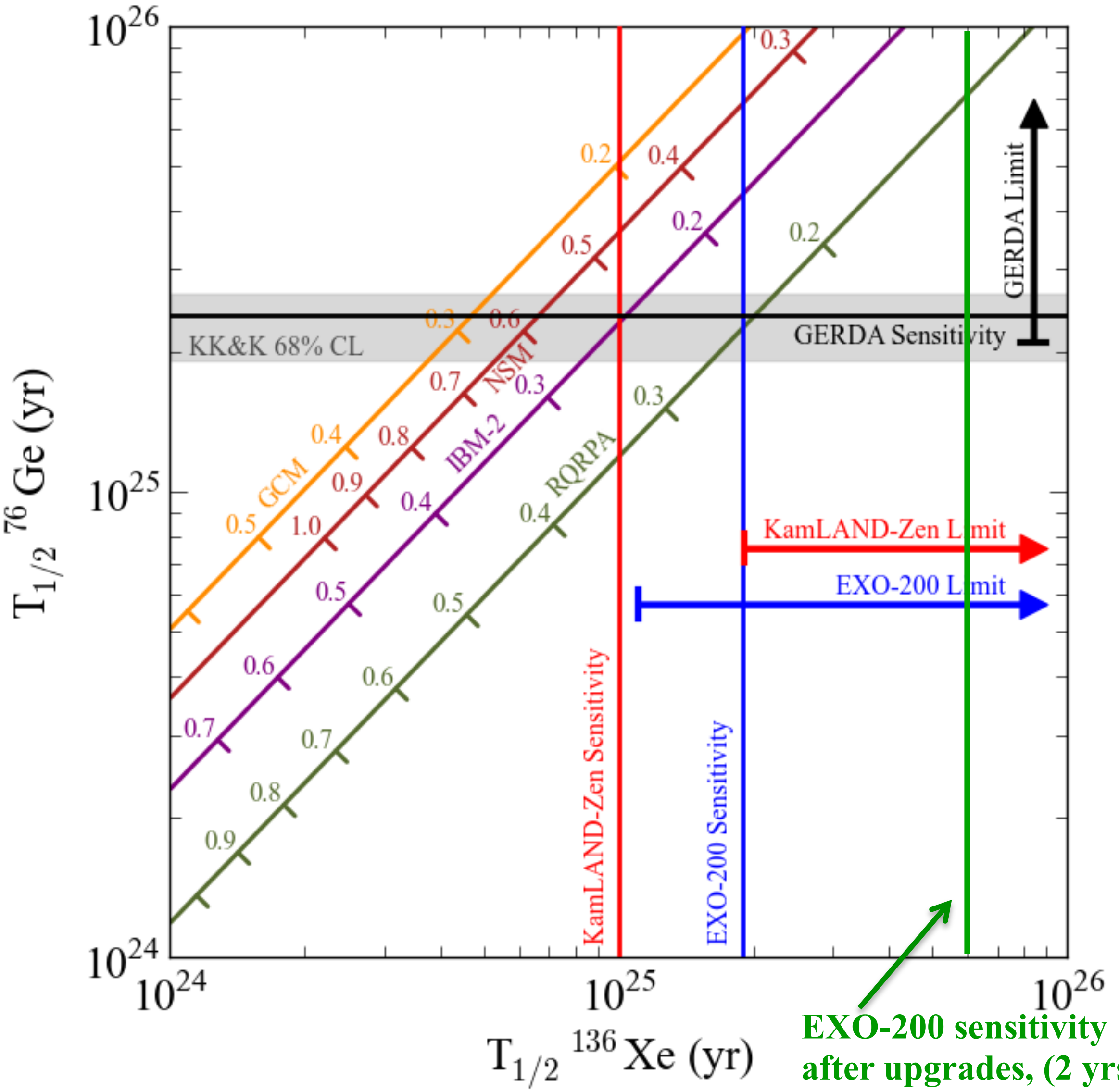
Summary

- 100 kg·yr (736 mol·yr) ^{136}Xe exposure of EXO-200 data have resulted in
  - Precision $2\nu\beta\beta$ measurement (*PRC* **89**, 015502 (2014))
  - $0\nu\beta\beta$ limit (*Nature* **510**, 229 (2014))
  - Majoron mode limits (*PRD* **90,** 092004 (2014))
  - $2\nu\beta\beta$ to the excited state limit (*PRC* **93,** 035501 (2016))
- After 2 yr hiatus, EXO-200, one of the most sensitive $0\nu\beta\beta$ experiment currently, has restarted to take more data (Jan. 2016)
- Upgrades (electronics and deradonator) will help with nEXO (5 ton next-gen LXe experiment) R&D currently in progress

THANK YOU FOR YOUR ATTENTION!

EXO-200 0νββ Half-life Sensitivity



EXO-200 sensitivity after upgrades, (2 yrs live-time).

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

$<m_\nu> < 190 – 450$ meV

Median $T_{1/2}^{0\nu\beta\beta}$ sensitivity: $1.9\cdot10^{25}$ yr

J.B.Albert et al. (EXO-200), Nature (6 June, 2014)

A. Gando et al. (KamLAND-ZEN), PRL 110 (2013) 062502

M. Agostini et al. (GERDA), PRL 111 (2013) 122503

With upgraded detector and 2 yrs of live-time, EXO-200 $T_{1/2}^{0\nu\beta\beta}$ median sensitivity will increase by a factor of 3.

One of the most sensitive 0νββ experiments in the next 3 - 5 years.