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

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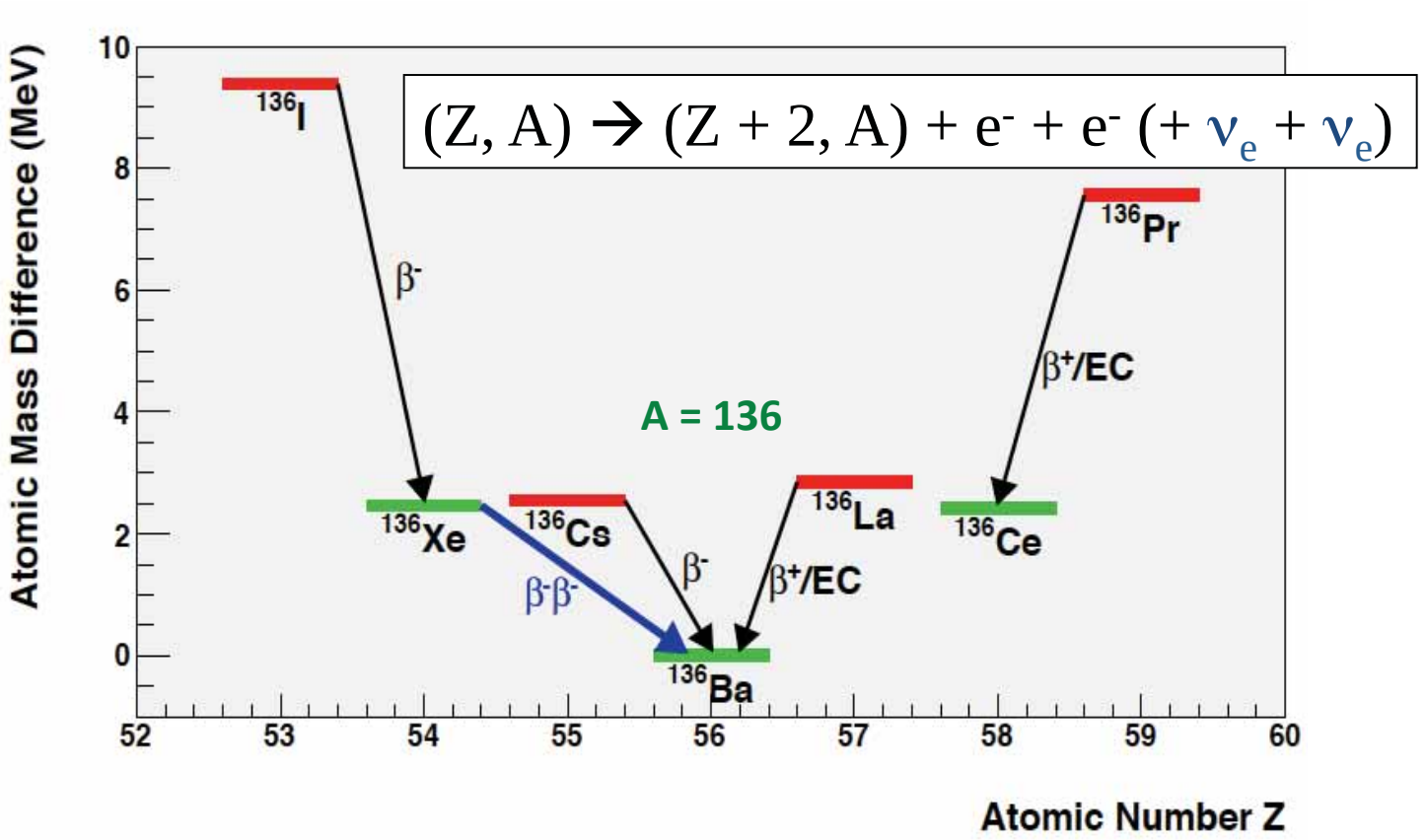
On behalf of the EXO-200 and nEXO collaborations
Drexel University
March 15, 2016

Double Beta Decay of ^{136}Xe



- ^{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**

Mass Measurement with ββ0ν

- Half-life depends on the effective mass,

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

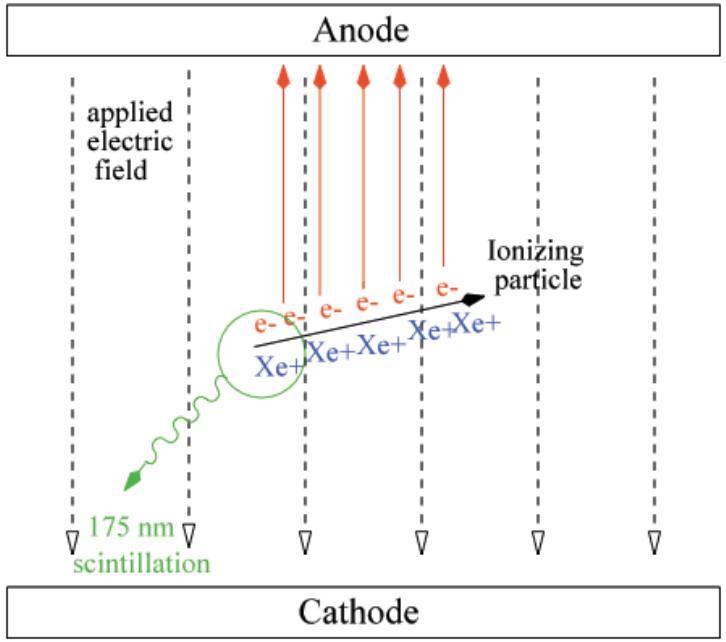
mass eigenvalues

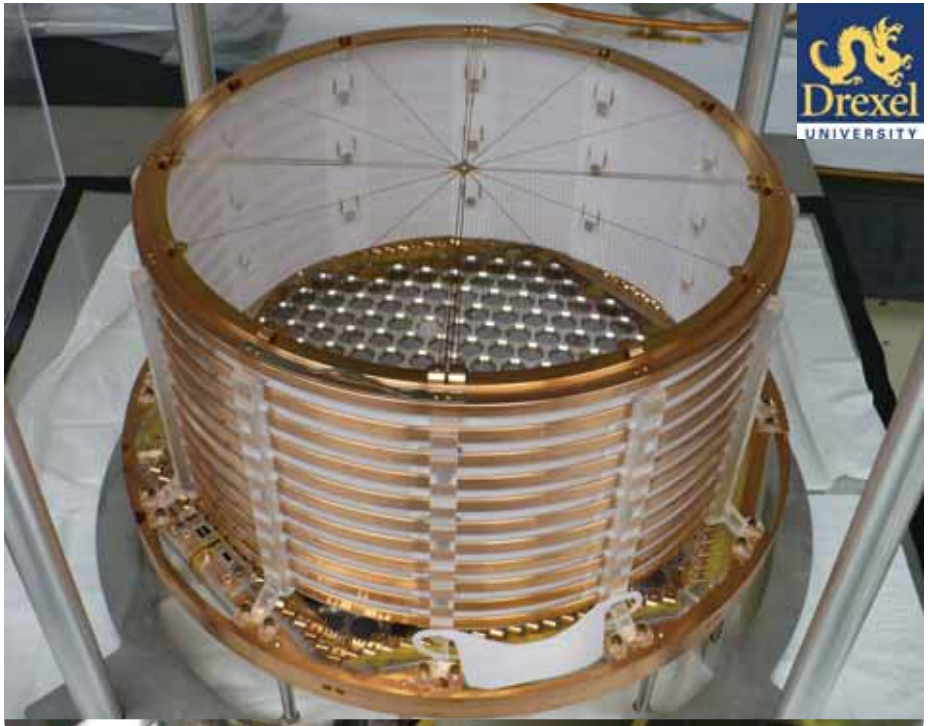
mixing matrix (with phases)

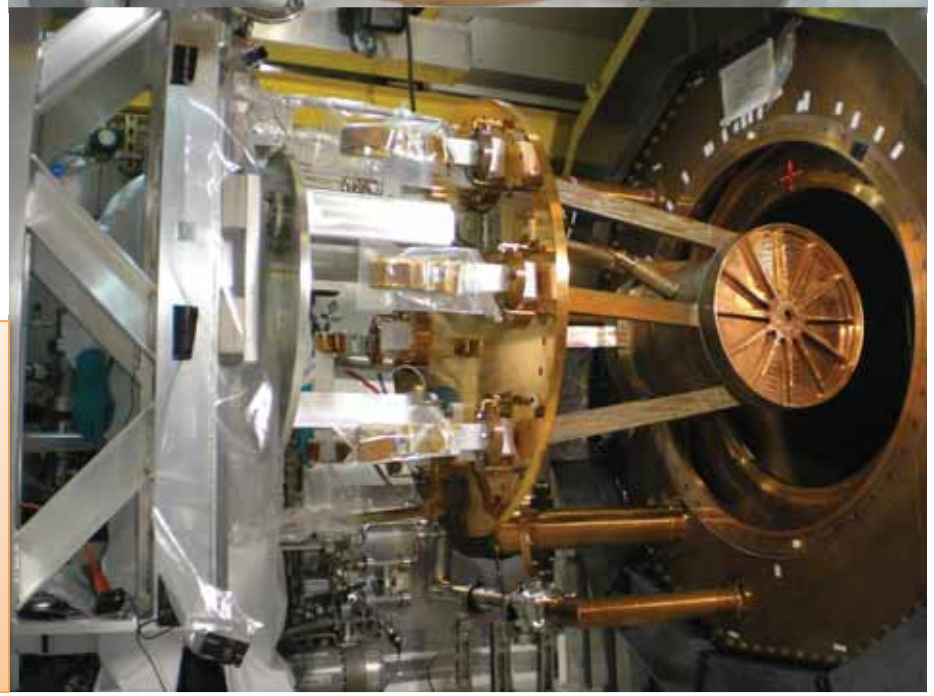
$$\frac{1}{t_{1/2}^{0\nu}} = G^{0\nu} \left| M^{0\nu} \right|^2 m_{\beta\beta}^2$$

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

EXO-200 Liquid Xe Time Projection Chamber







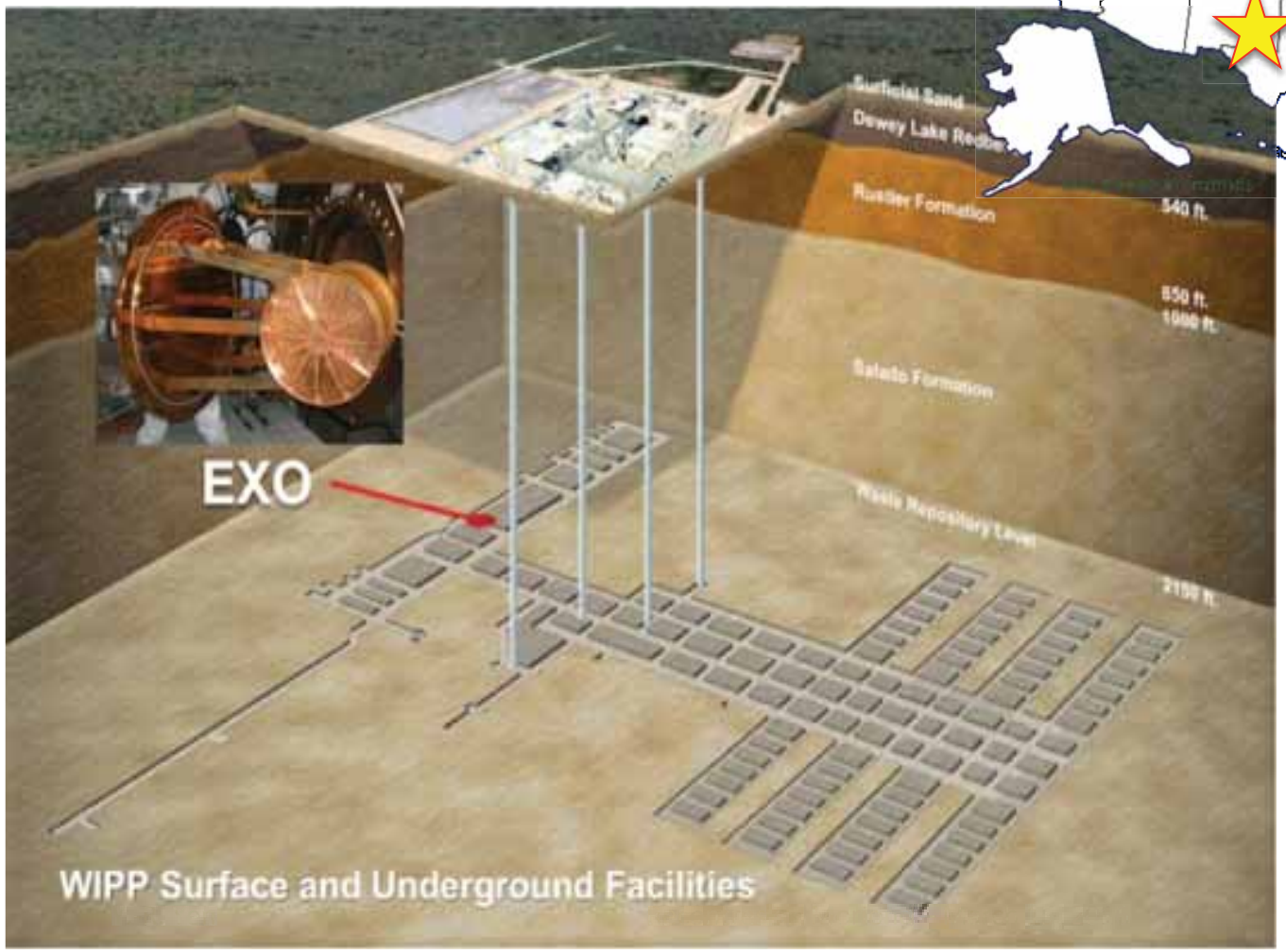
~110 kg active mass Xe enriched to 80% in ^{136}Xe, ultralow background construction

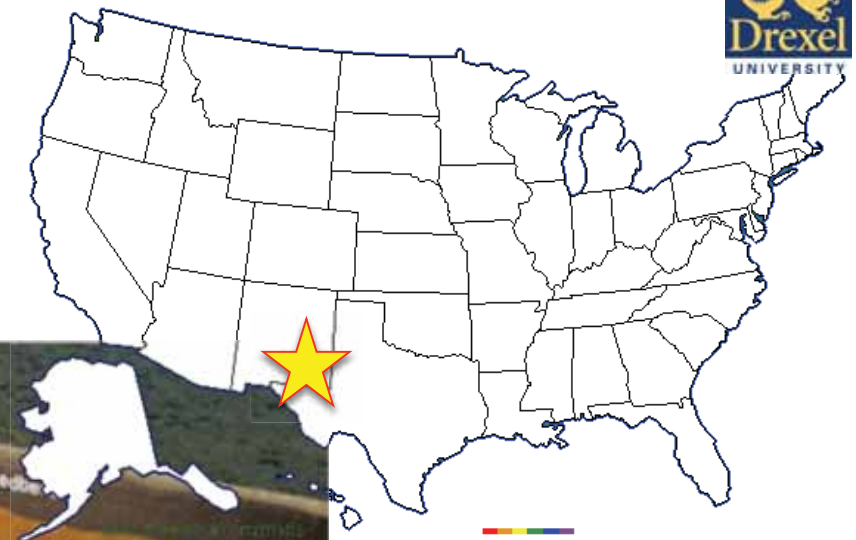
Readout plane is made up of LAAPDs (scintillation) + crossed wire grid (ionization)

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

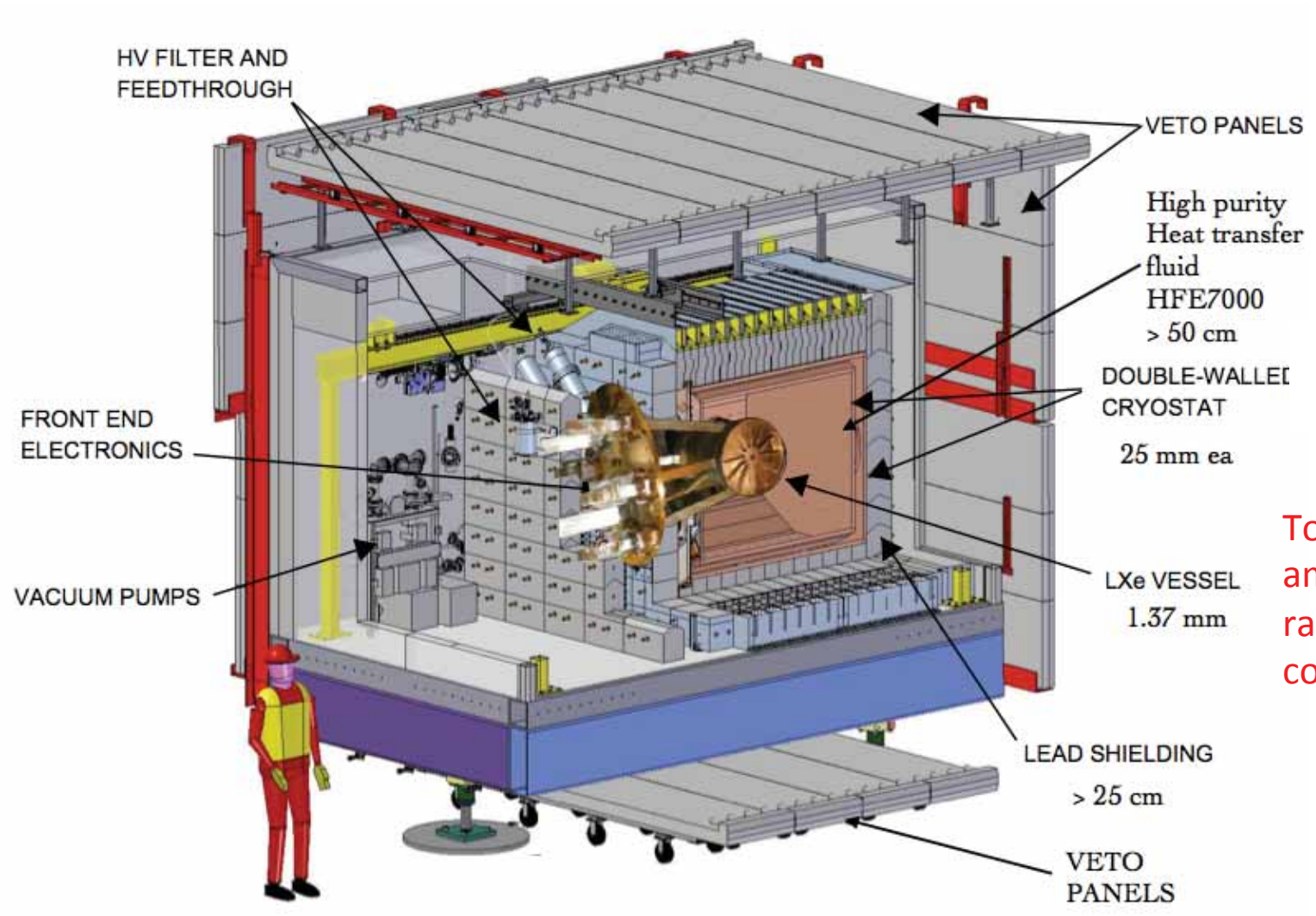
Underground Detector Site





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

Active and Passive Shielding

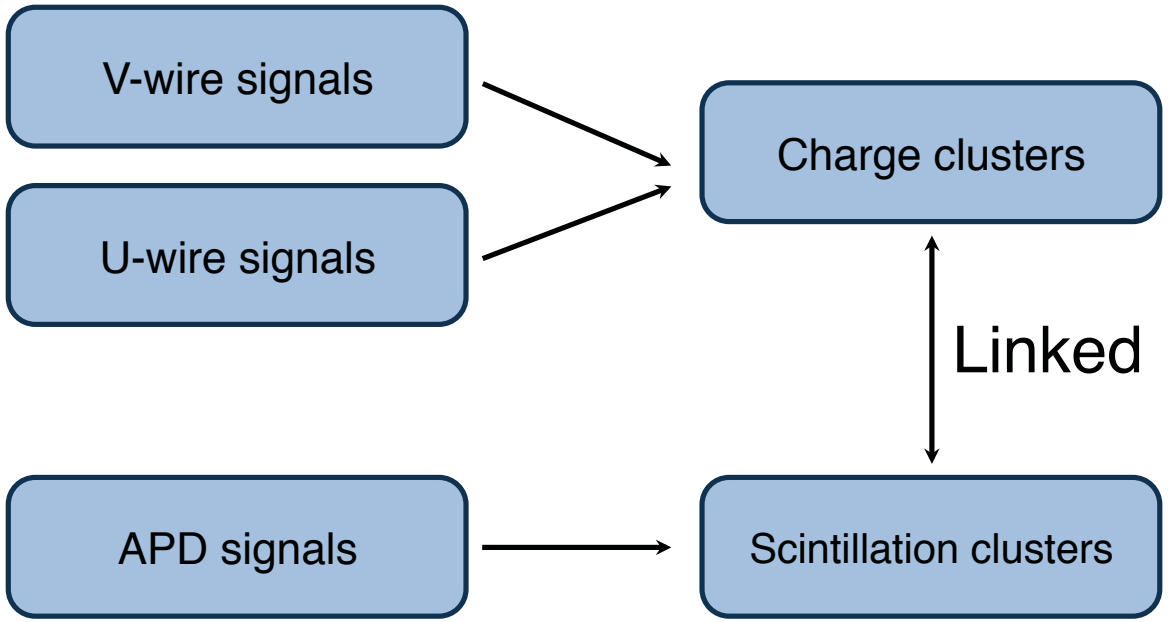


LXe Vessel
1.37 mm

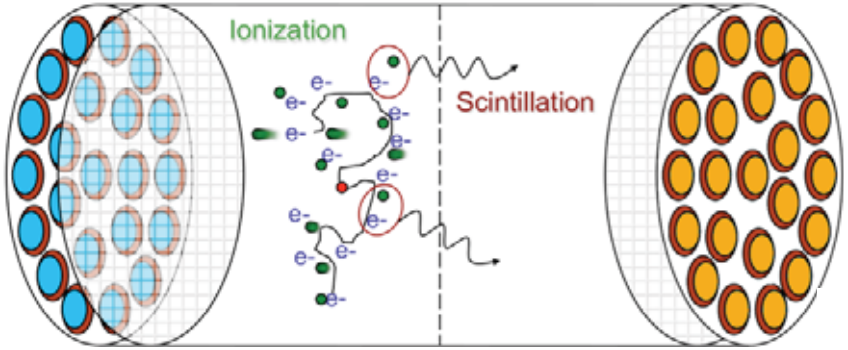
To minimize the amount of natural radioactivity in the copper "balloon"

Event reconstruction

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

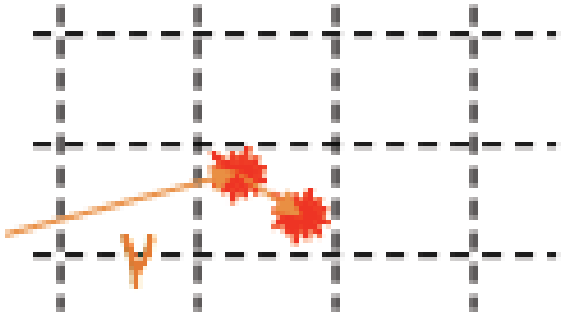


Ability to 100% reconstruct in 3D individual charge cluster down to ~200 keV (limited by induction signal)

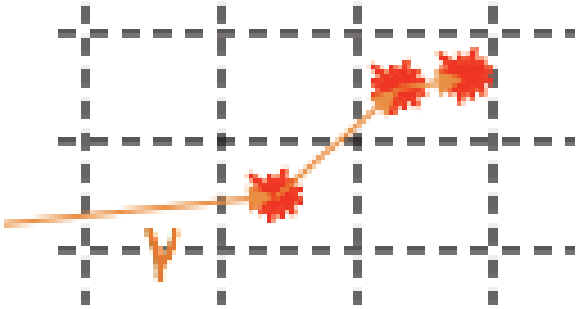


Position and multiplicity reconstruction

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

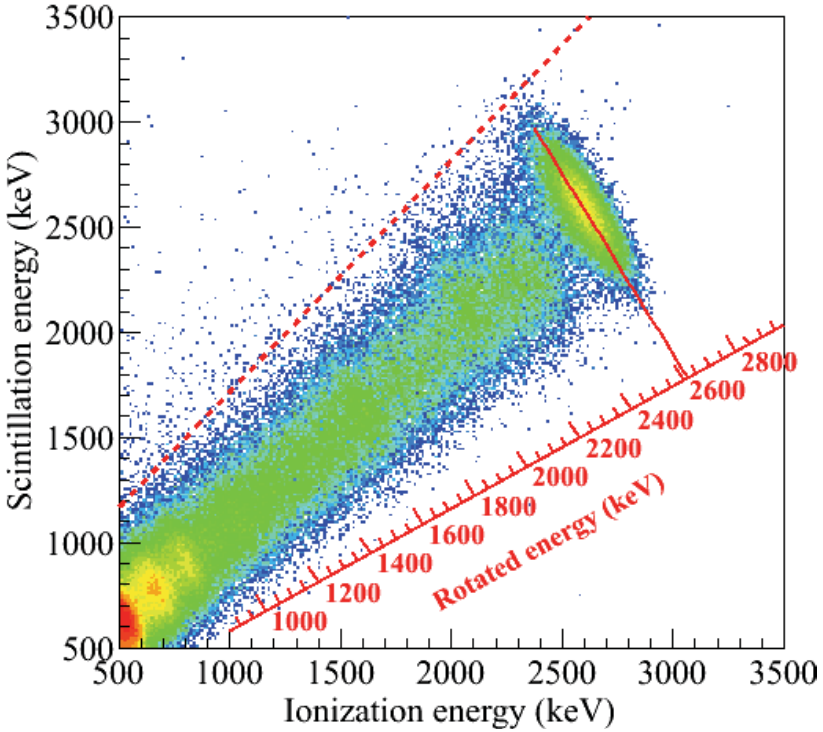
Wires are ~1 cm apart

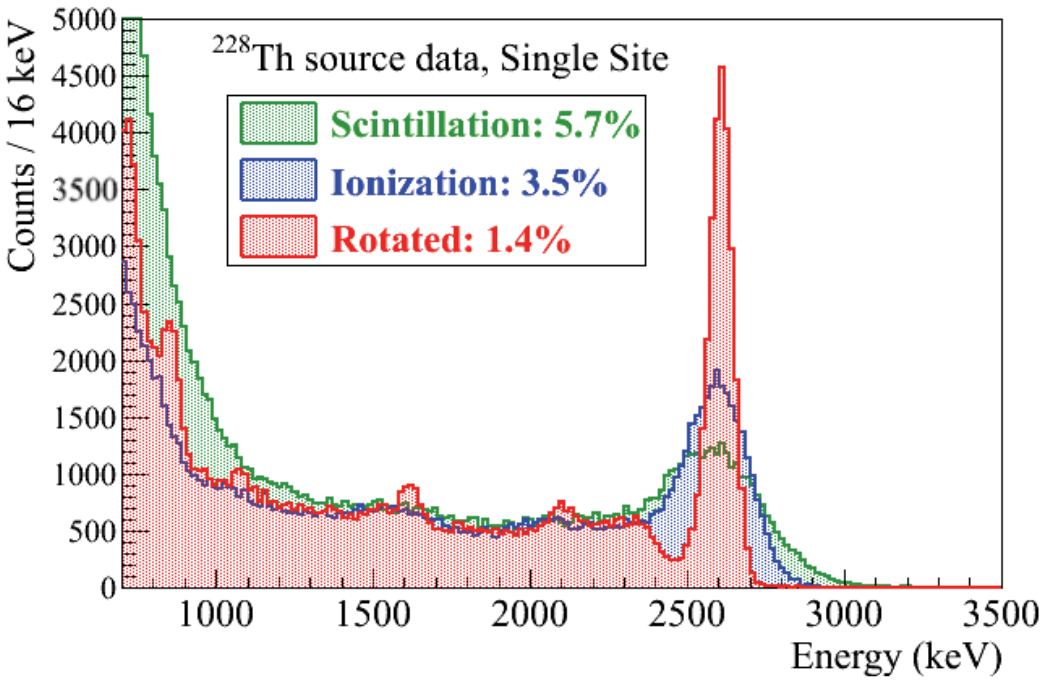
γ-rays: ~30% SS at $0\nu\beta\beta$ Q-value

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

Energy measurement

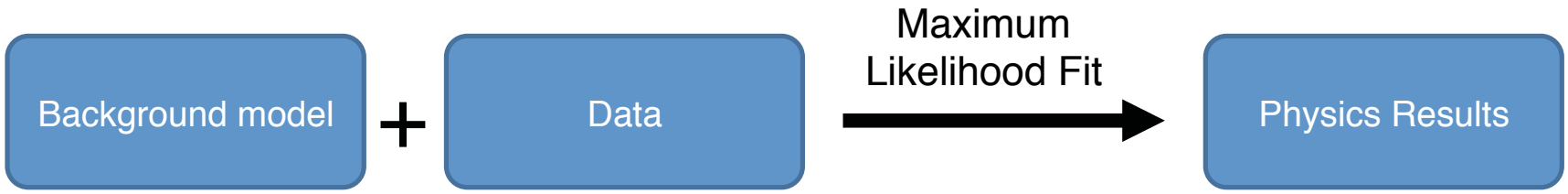
Anti-correlation of charge and light

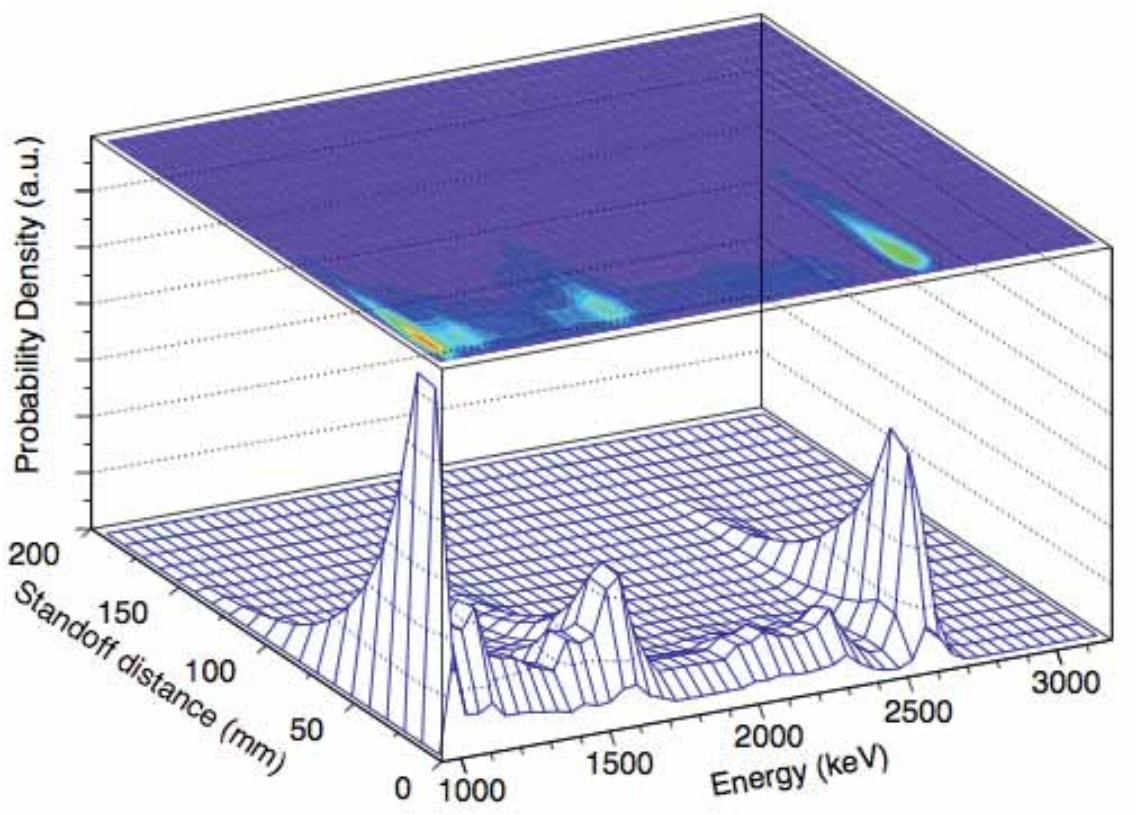




- Rotation angle determined weekly using ^{228}Th source data, defined as angle which gives best rotated resolution
- Energy resolution is dominated by APD noise

Extracting physics results





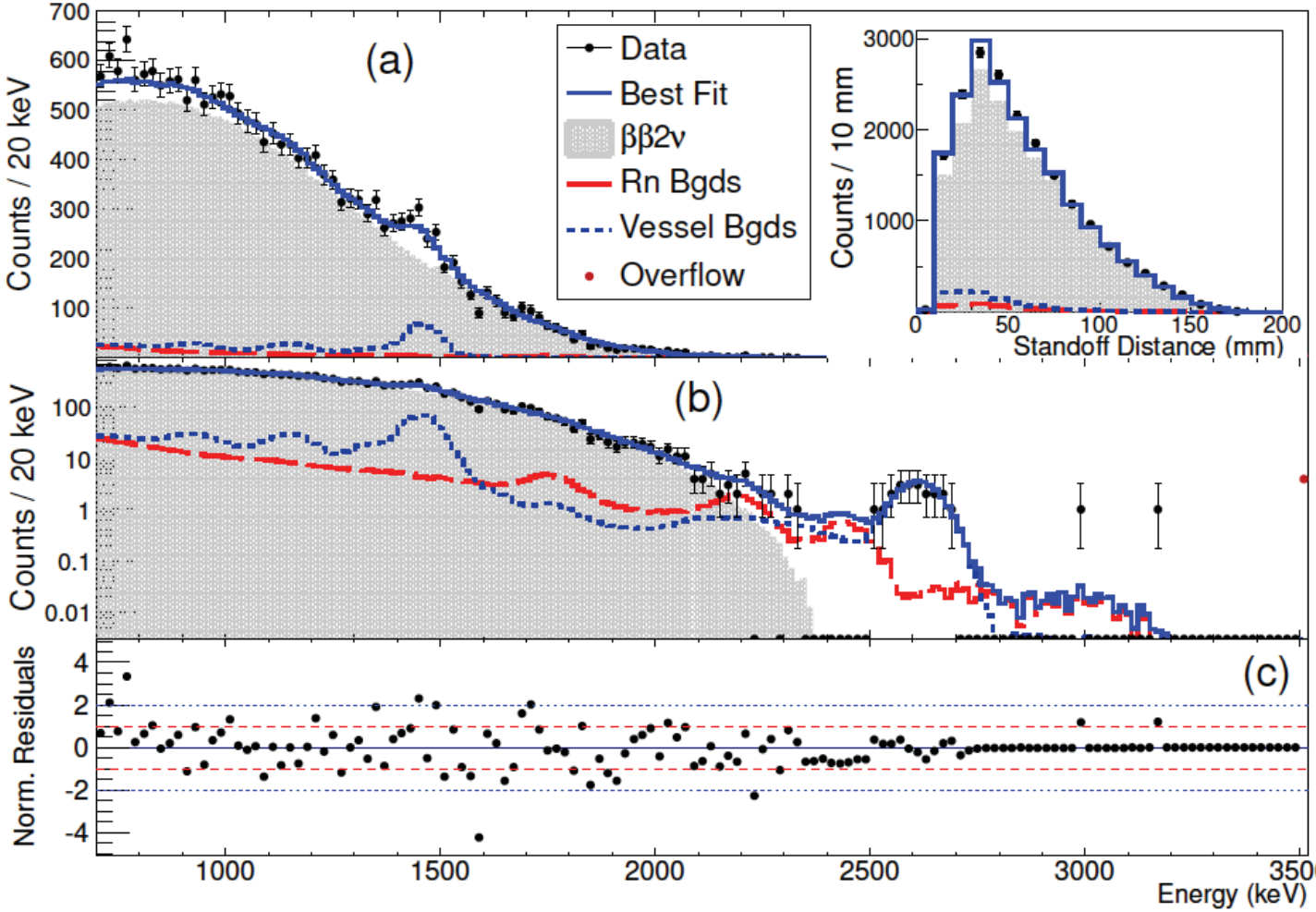
Single site ^{232}Th Probability Density Function in copper vessel

- 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

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

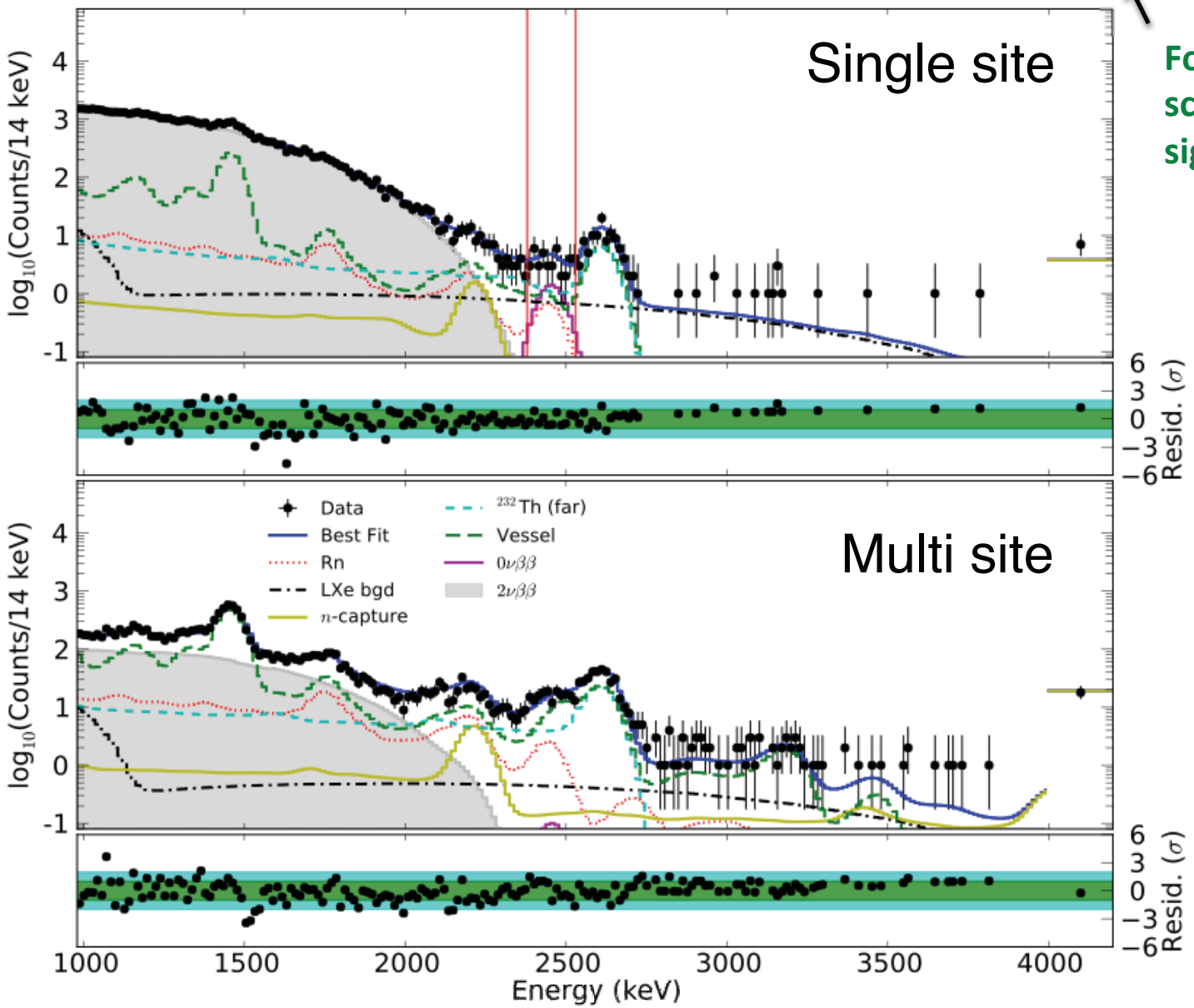
[PRC **89**, 015502 (2014)]

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

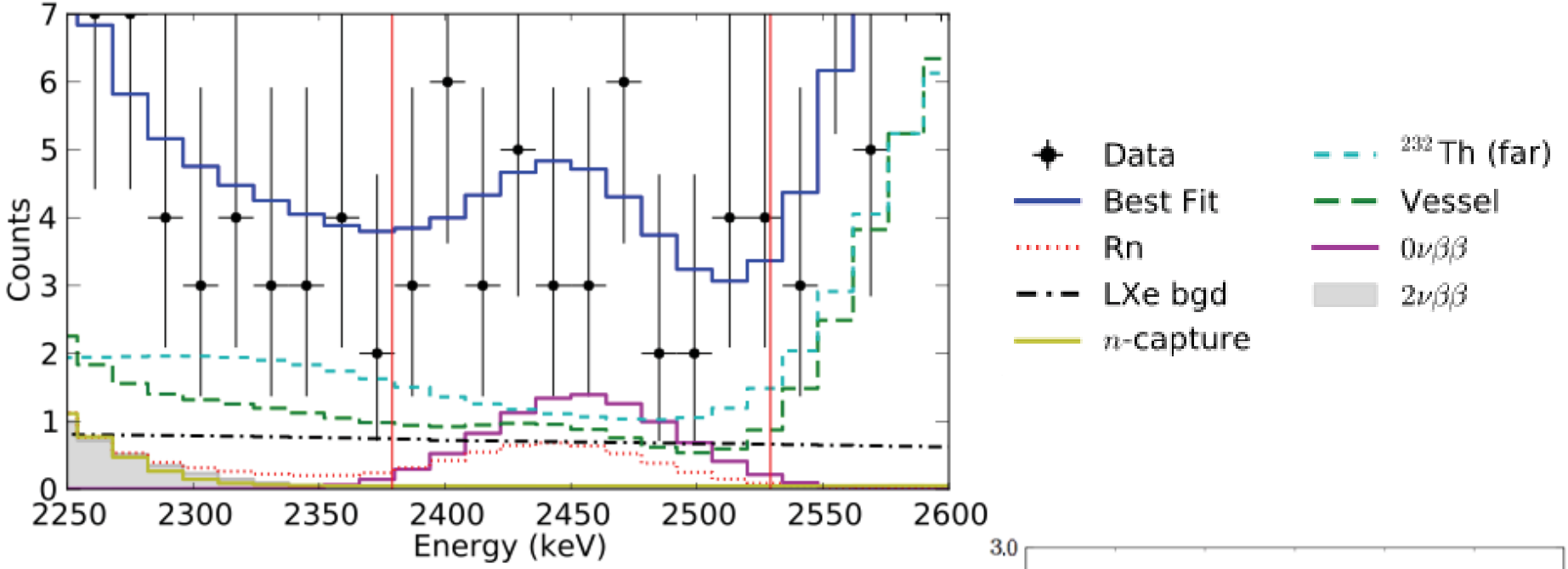
$0\nu\beta\beta$ Search

Analysis range:
980 keV to 9800 keV

For 100% scintillation signal efficiency



$0\nu\beta\beta$ Search

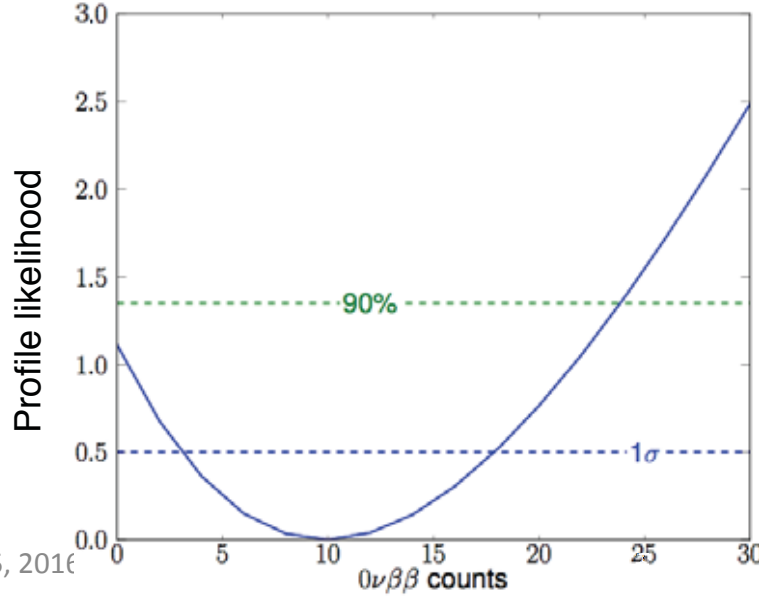


$T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{25}$ yr

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

(90% C.L.)

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

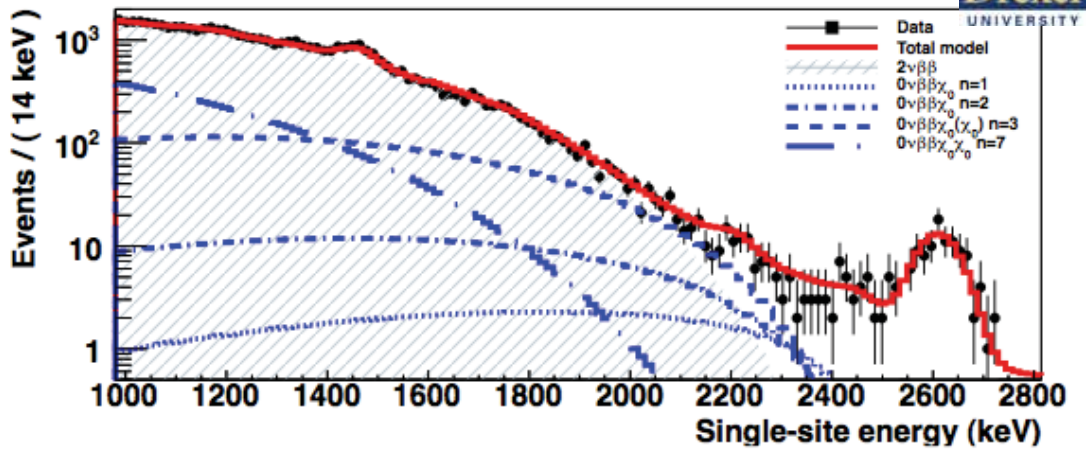


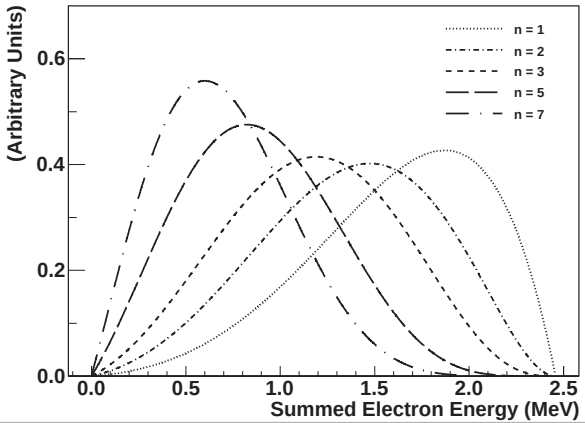
Majoron Mode Search Results

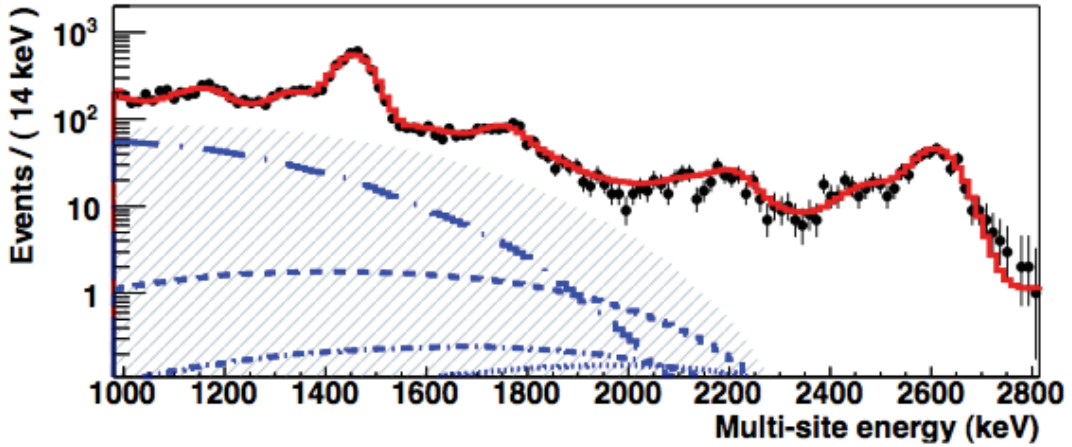
Phys. Rev. D 90, 092004 (2014)

*Data fit for each Majoron mode separately

*Background shown is for fit to n=1 mode

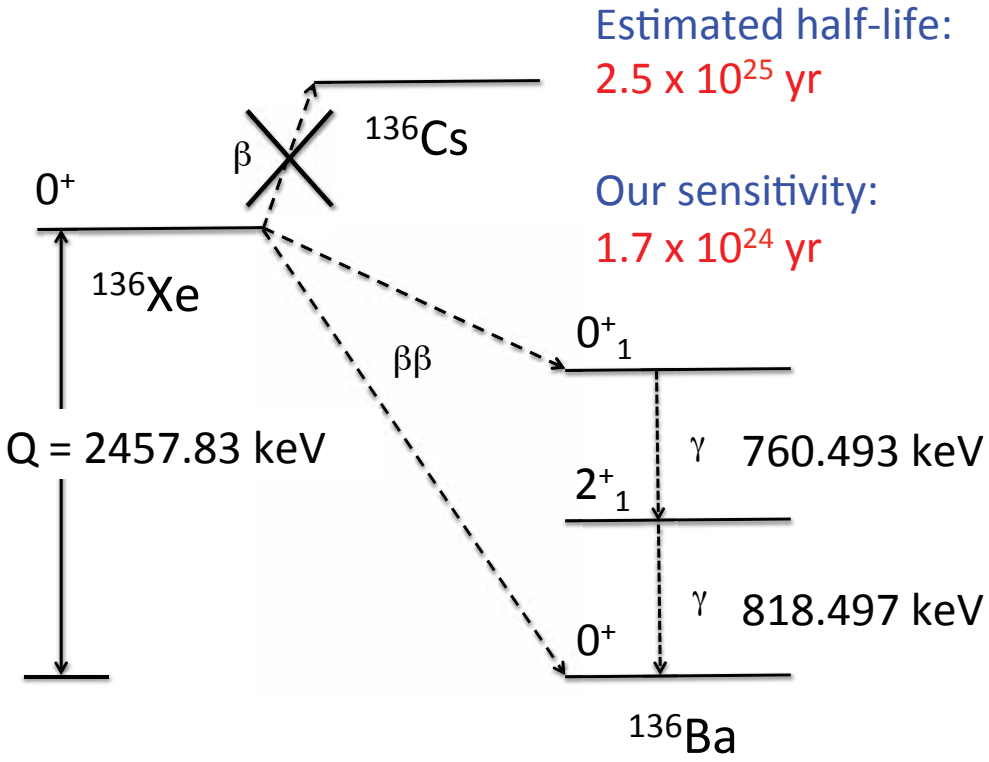






Decay mode	Spectral index, n	Model types	$T_{1/2}$, yr	$\lvert\langle g_{ee}^{M}\rangle\rvert$
$0\nu\beta\beta\chi_0$	1	IB, IC, IIB	$>1.2\cdot10^{24}$	$<(0.8\text{-}1.7)\cdot10^{-5}$
$0\nu\beta\beta\chi_0$	2	"Bulk"	$>2.5\cdot10^{23}$	–
$0\nu\beta\beta\chi_0\chi_0$	3	ID, IE, IID	$>2.7\cdot10^{22}$	$<(0.6\text{-}5.5)$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

Decay to Excited State

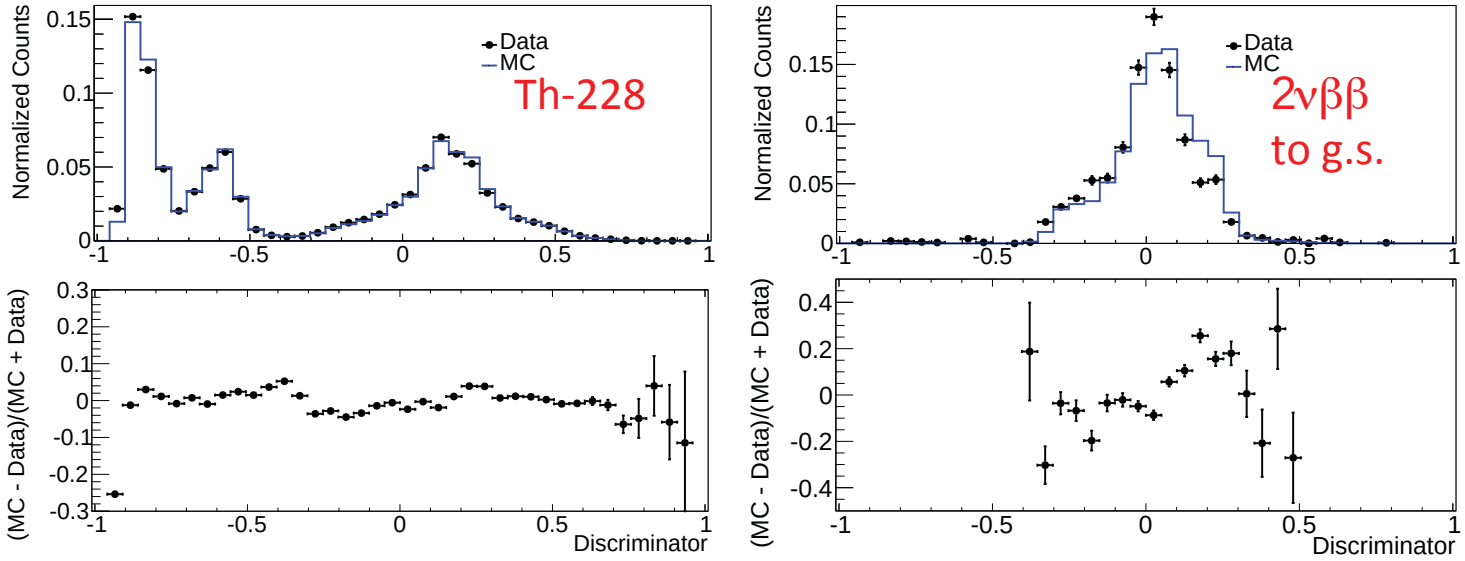


- Search for the $2\nu\beta\beta$ decay to the excited state, 0^+_1, of ^{136}Ba
- Decays to excited state has been observed in two isotopes: ^{100}Mo and ^{150}Nd
- De-excitation from the 0^+_1 state produce two γs – unique signature
- Main background is $2\nu\beta\beta$ to the ground state

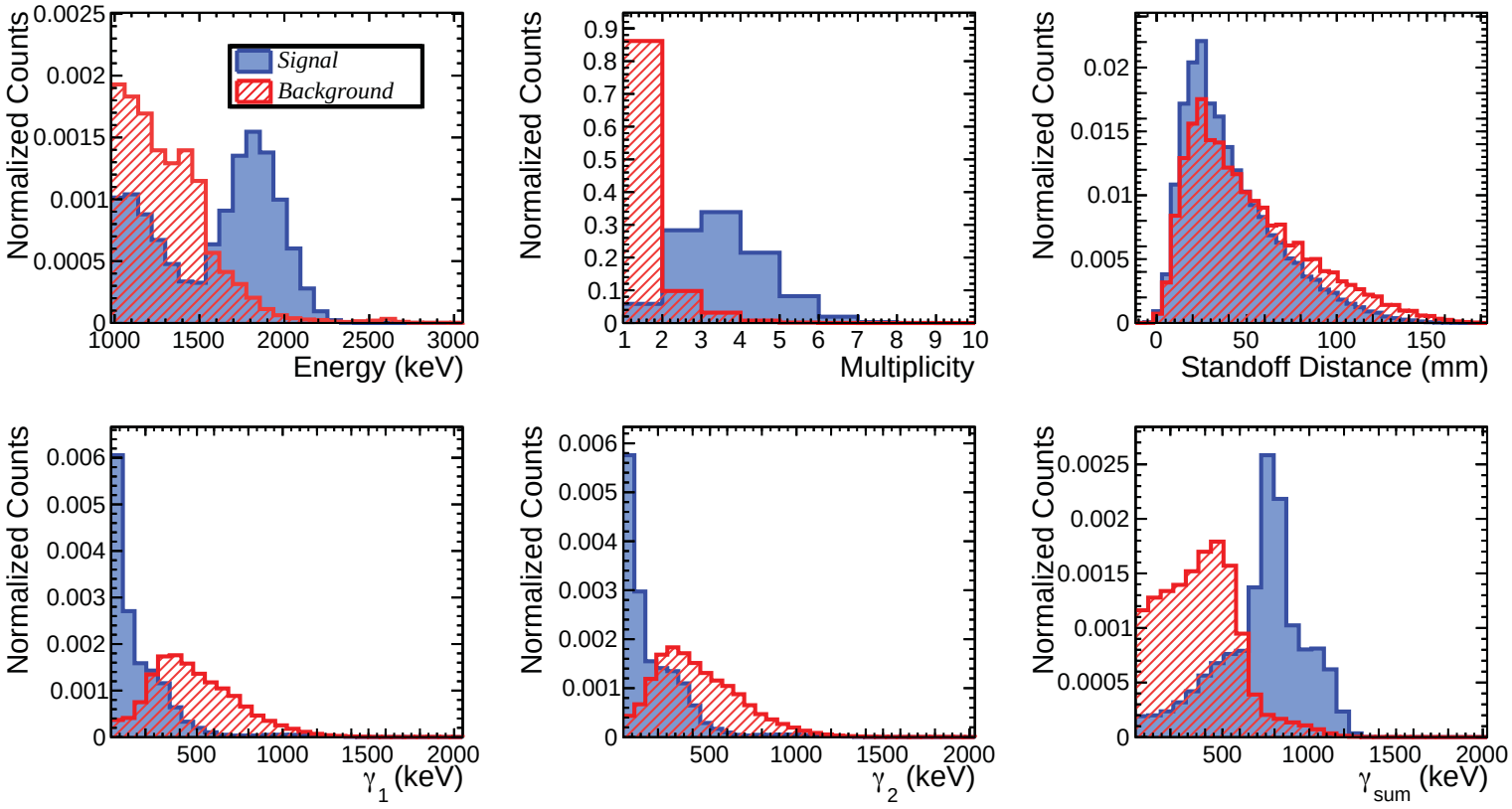
Knowledge of the decay to excited state rate check the various Nuclear Matrix Element calculations -> smaller uncertainty on the effective neutrino mass

Decay to Excited State

- 1st EXO-200 physics analysis to use machine learning
- Beware (the Ides of March!) and 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



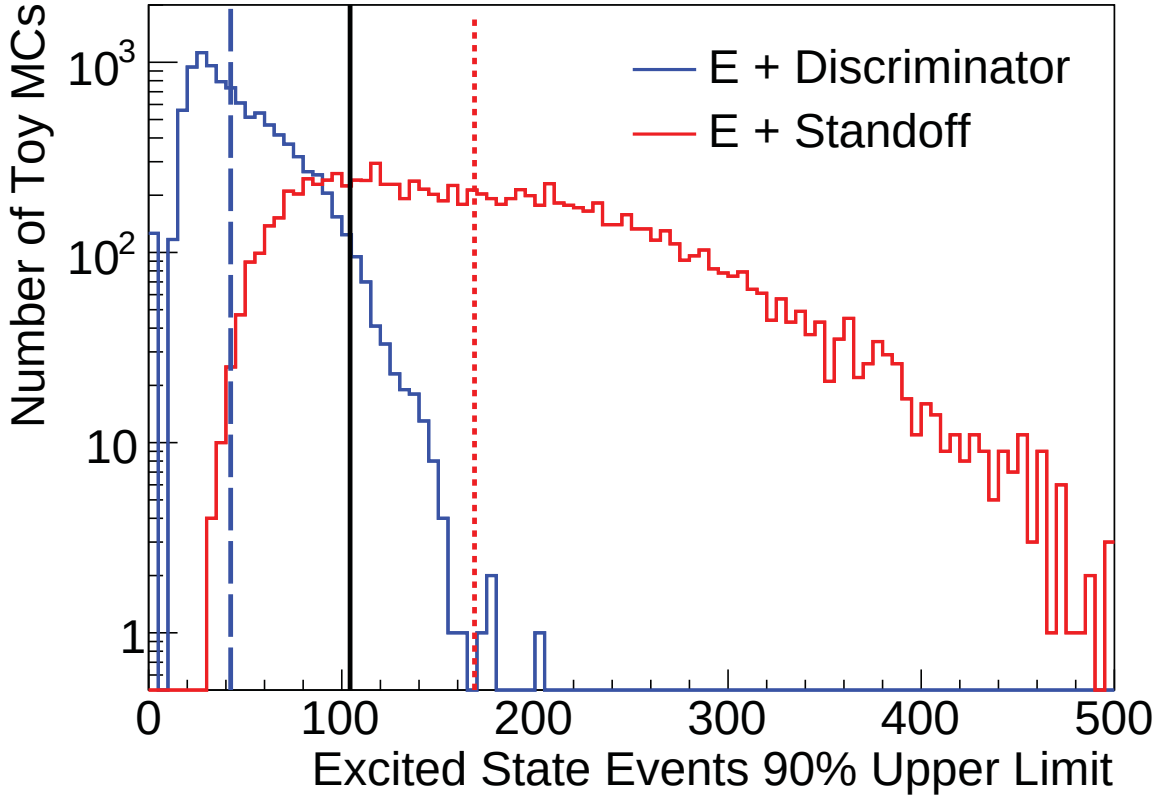
Decay to Excited State



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

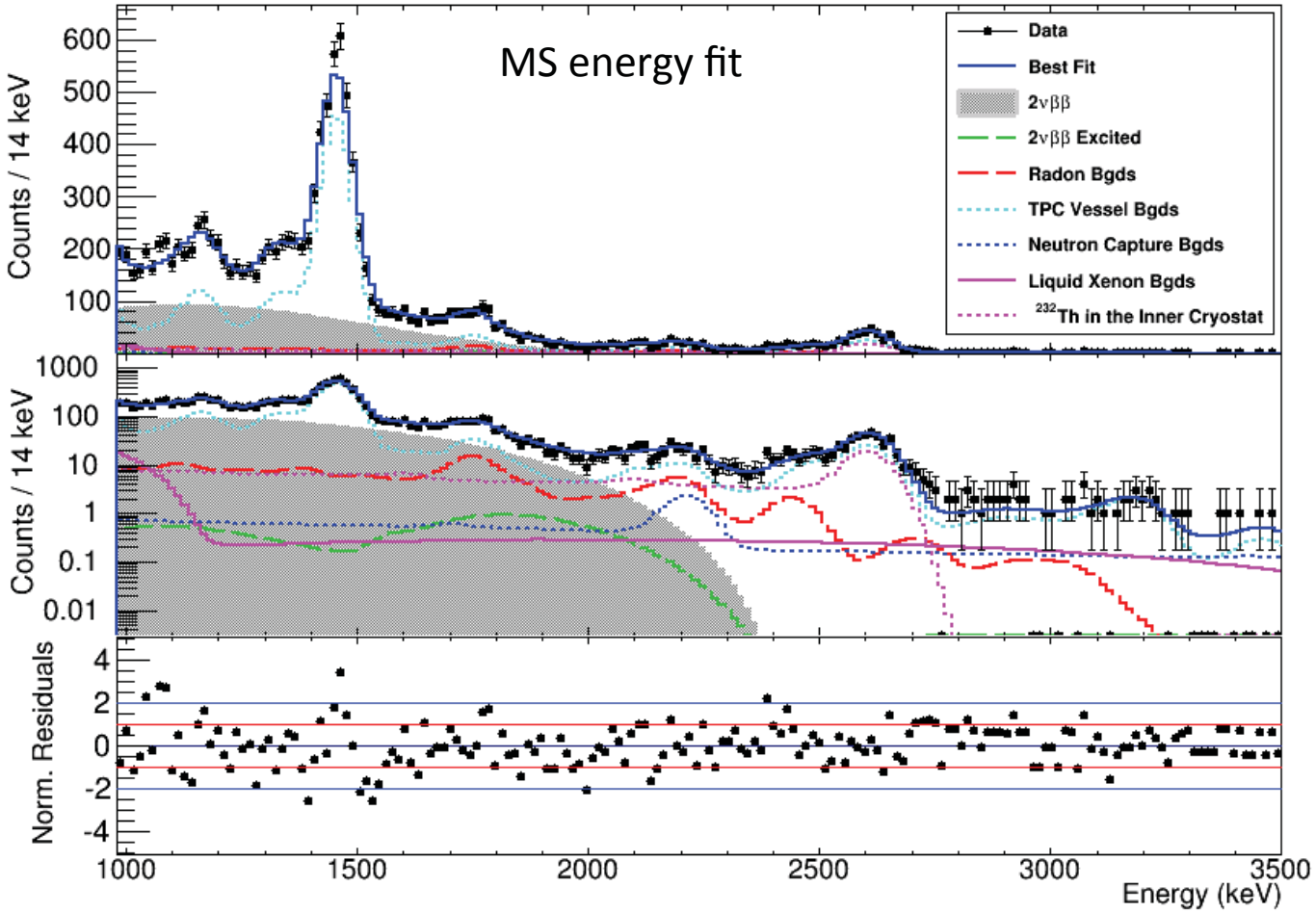
- Machine learning improves our sensitivity compares to traditional EXO-200 method



Sensitivity of
1.7×10^{24} yr

Phys Rev C 93 035501 (2016)

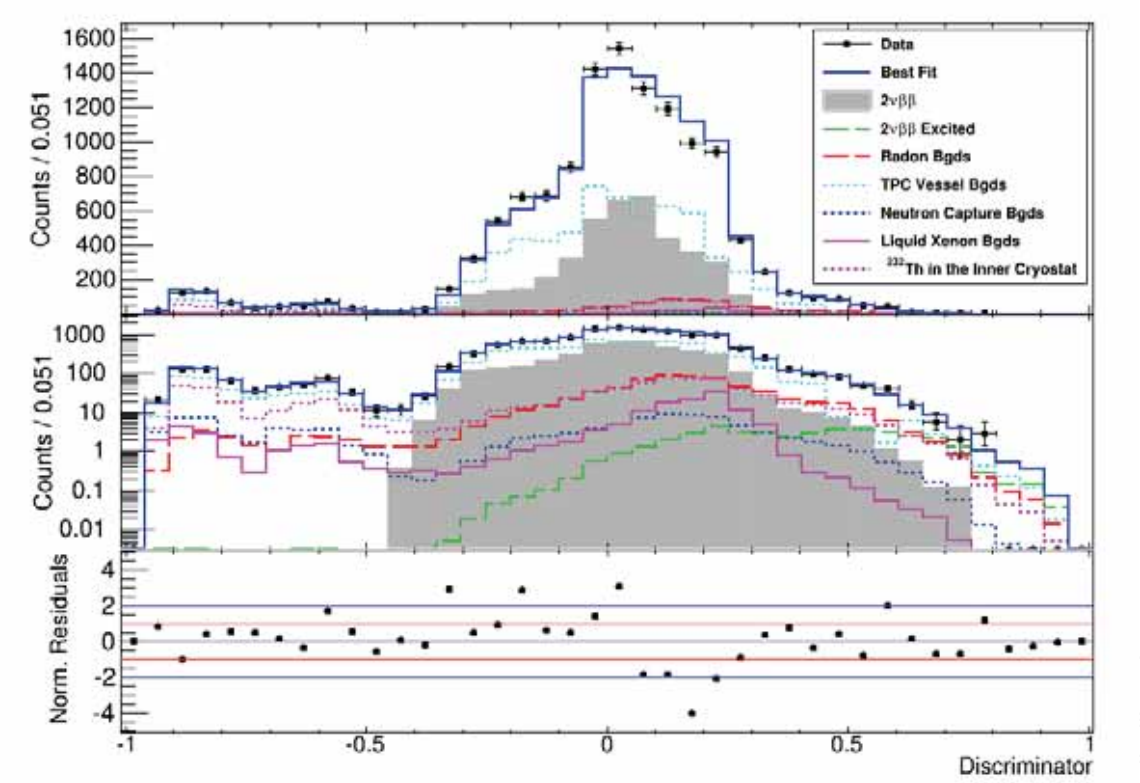
Decay to Excited State



- 2D Maximum Likelihood fit in Energy + Discriminator

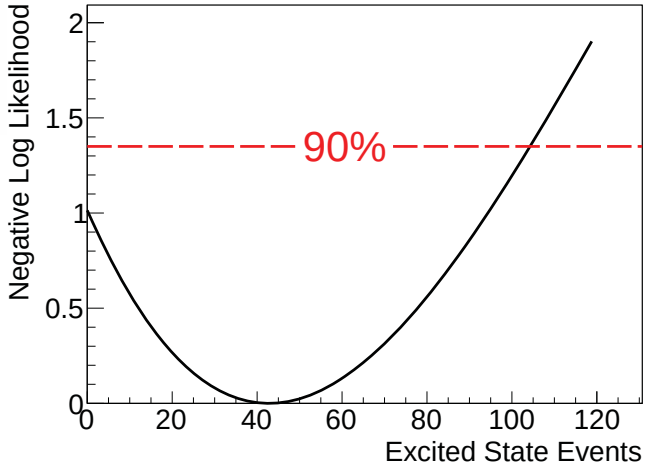
Phys Rev C 93 035501 (2016)

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



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

Other Recent EXO-200 Physics Papers

- Lorentz and CPT violation: *arXiv:1601.07266, submitted to PRD*
  - 1st double beta decay experiment to set this limit
- 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

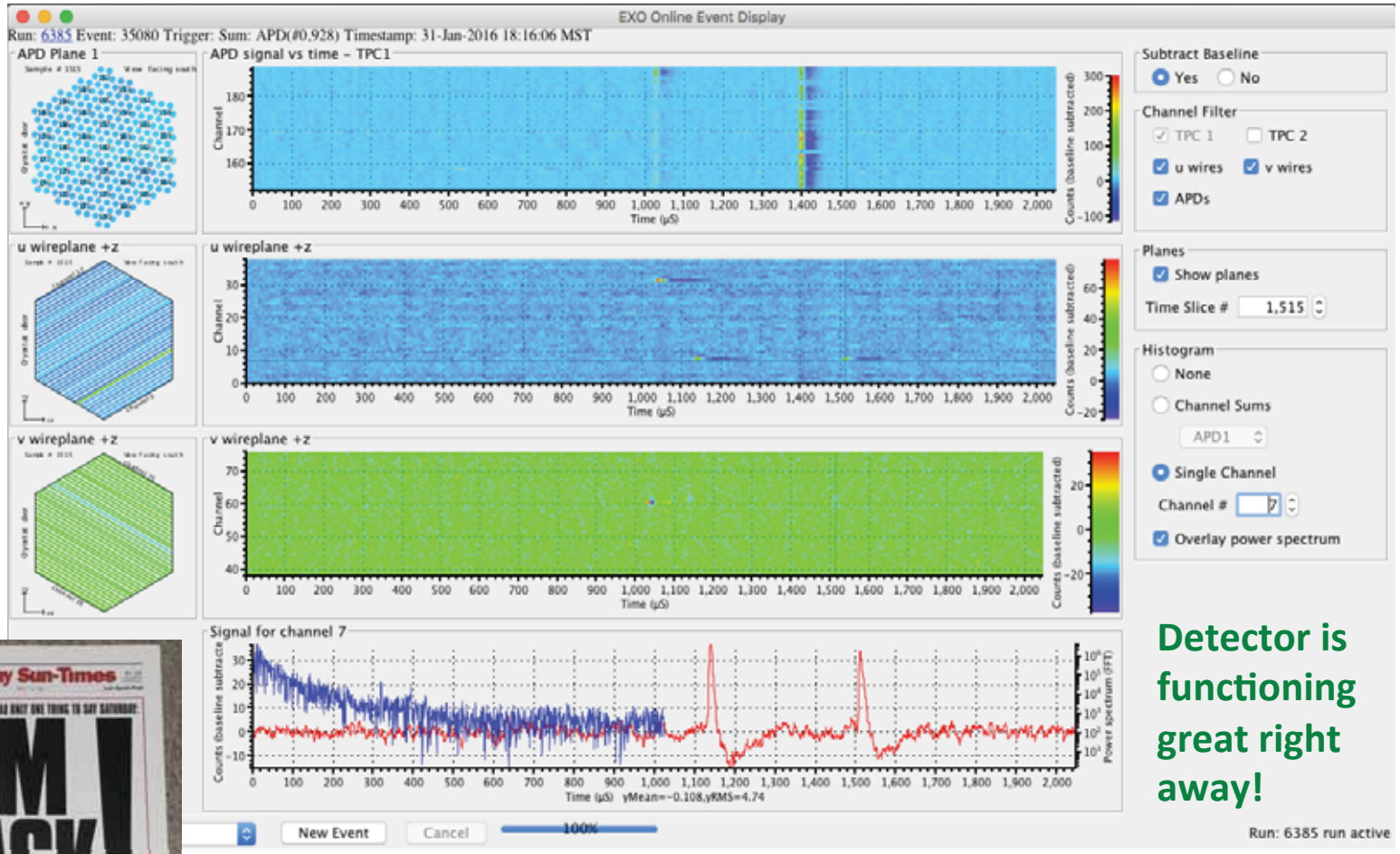
- WIPP incidents (NOT OUR FAULT!):
  - Feb. 5 2014 – Fire in WIPP underground
  - Feb. 14 2014 – Airborne radiological event

- 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

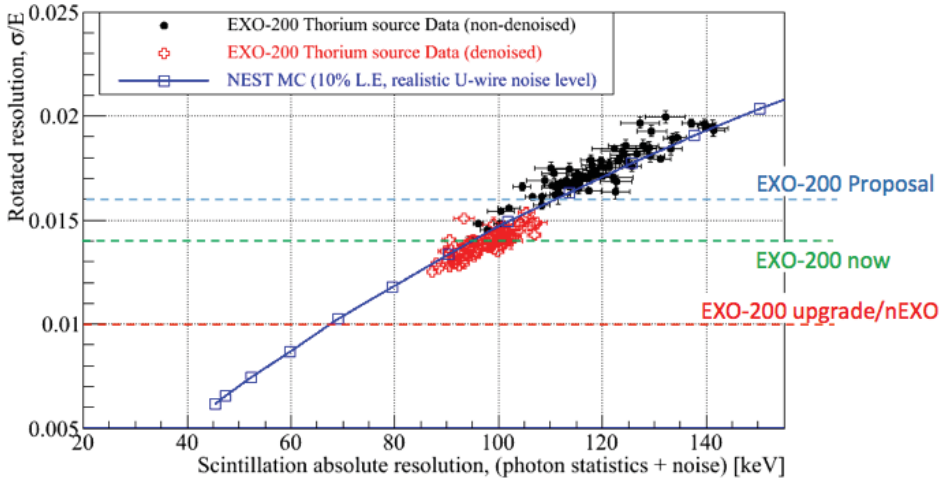


Detector is functioning great right away!

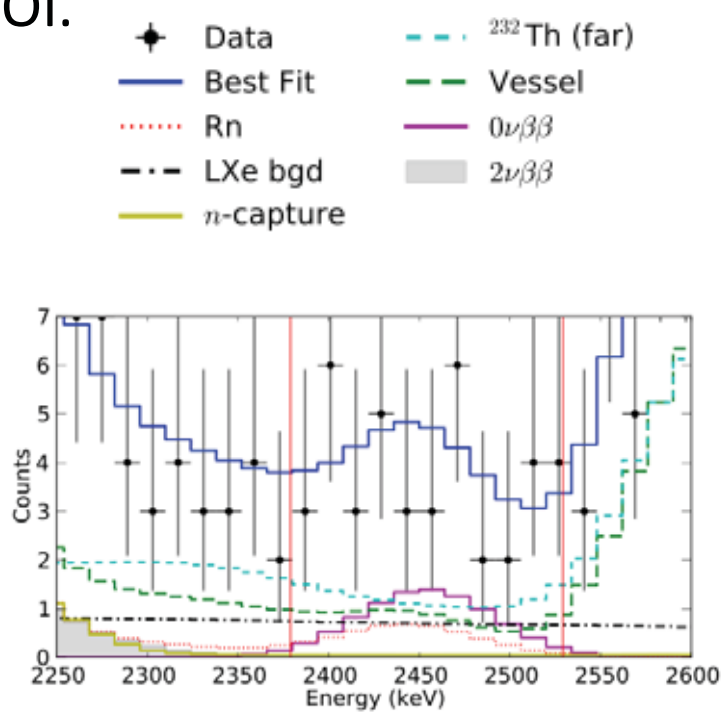
Data taking has resuming since January 31st, 2016

Current EXO-200 Improvements

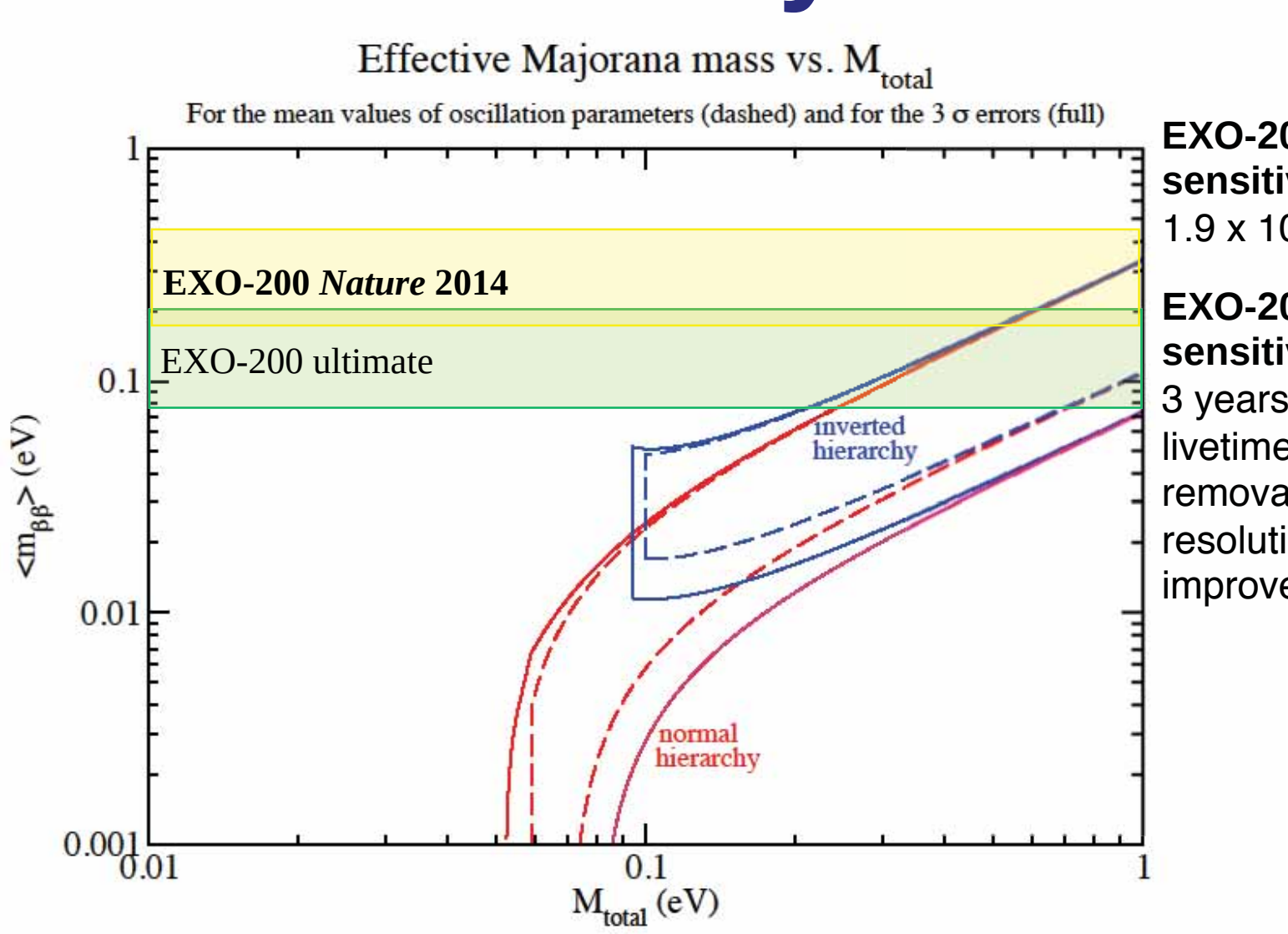
- Hardware upgrade to improve energy resolution at Q-value to 1% via improvement in minimizing APD noise
- Many of the ROI background counts come from radon daughters external to the detector. Deradonator should improve our background in the ROI.



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

The EXO-200 Collaboration

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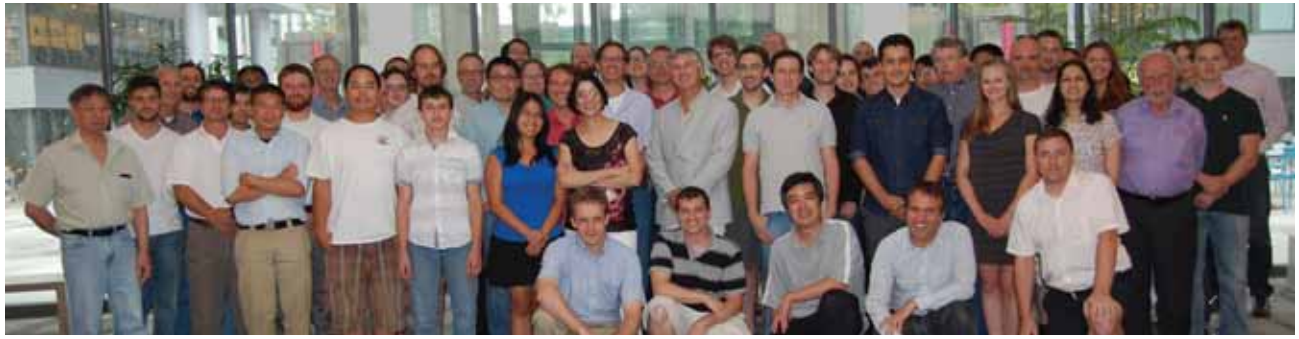

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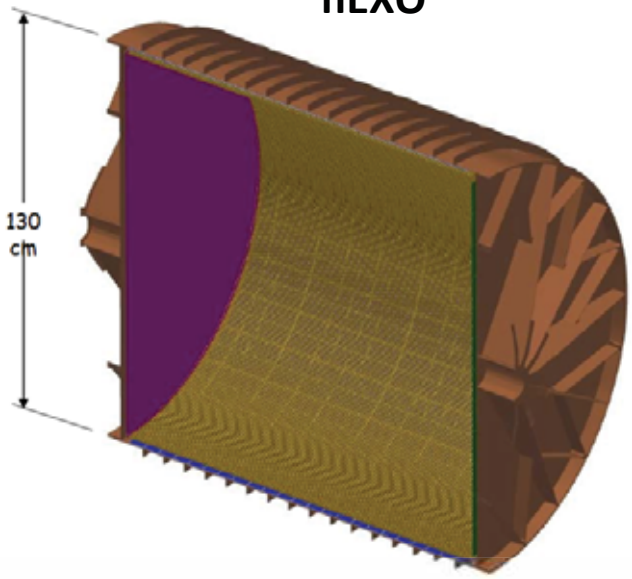
SLAC National Accelerator Laboratory, Menlo Park CA, USA — T Daniels,- K Fouts, G Haller, R Herbst, M Kwiatkowski, K Nishimura, A Odian, M Oriunno, PC Rowson, K Skarpaas
University of South Dakota, Vermillion SD, USA — R MacLellan
Stanford University, Stanford CA, USA — R DeVoe, D Fudenberg, G Gratta, M Jewell, S Kravitz, D Moore, I Ostrovskiy, A Schubert, K Twelker, M Weber
Stony Brook University, SUNY, StonyBrook, NY, USA — K Kumar, O Njoya, M Tarka
Technical University of Munich, Garching, Germany — P Fierlinger, M Marino
TRIUMF, Vancouver BC, Canada — J Dilling, P Gumplinger, R Krücken, F Retière, V Strickland

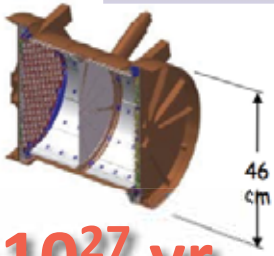
nEXO ("next EXO")

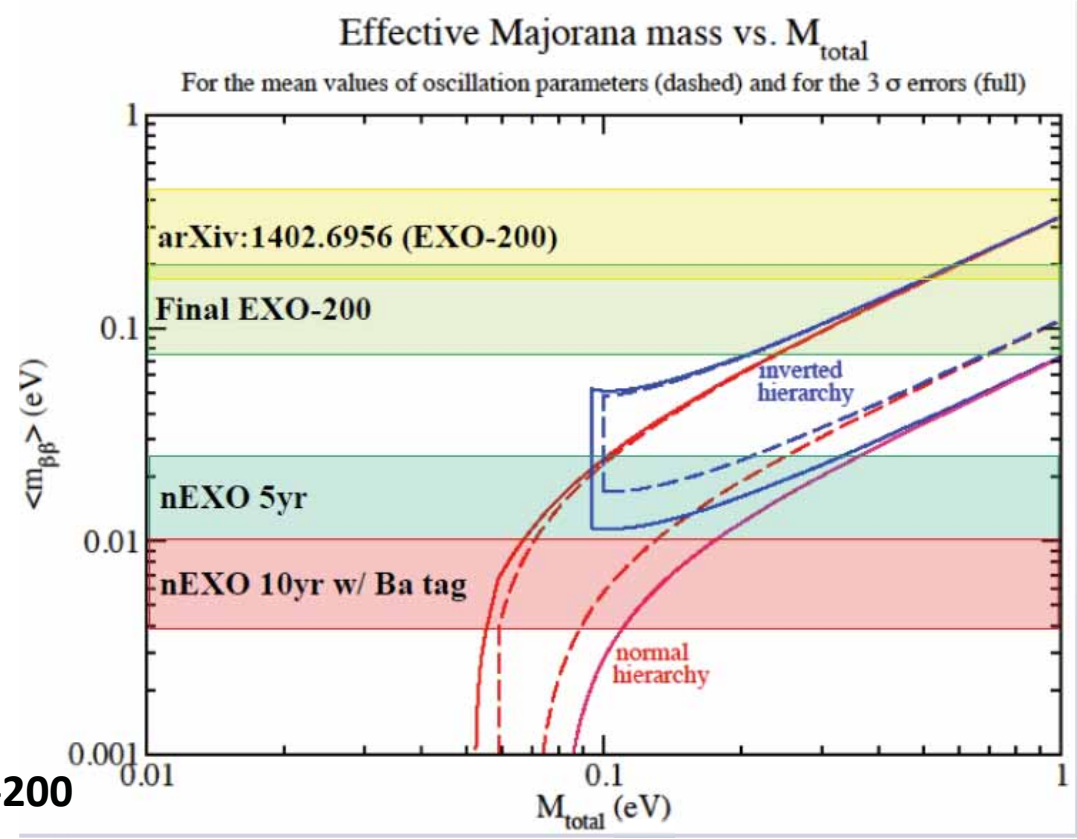
A detector 50x the size of EXO-200 is being designed

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

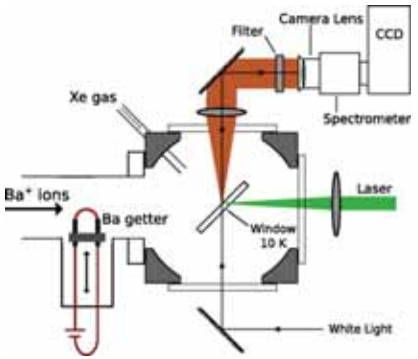
Summary

- 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

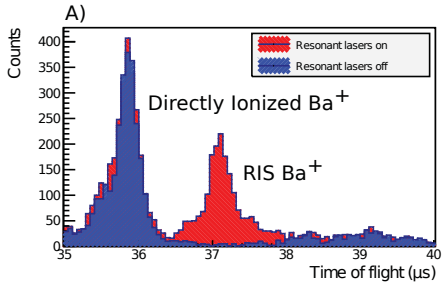
EXTRA SLIDES

nEXO R&D

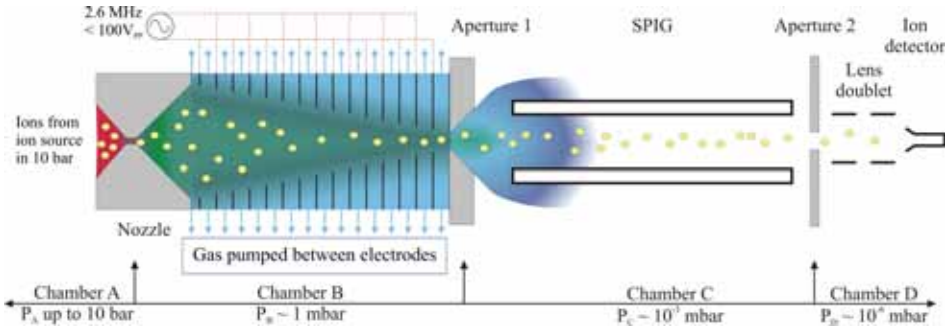
Barium Tagging (0 background possible if we can ID the daughter barium ion)



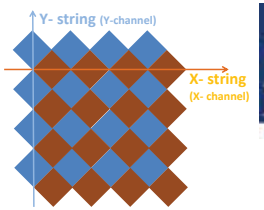
Ba deposit in solid Xe
(Phys. Rev. A, V91, 2, 2015)



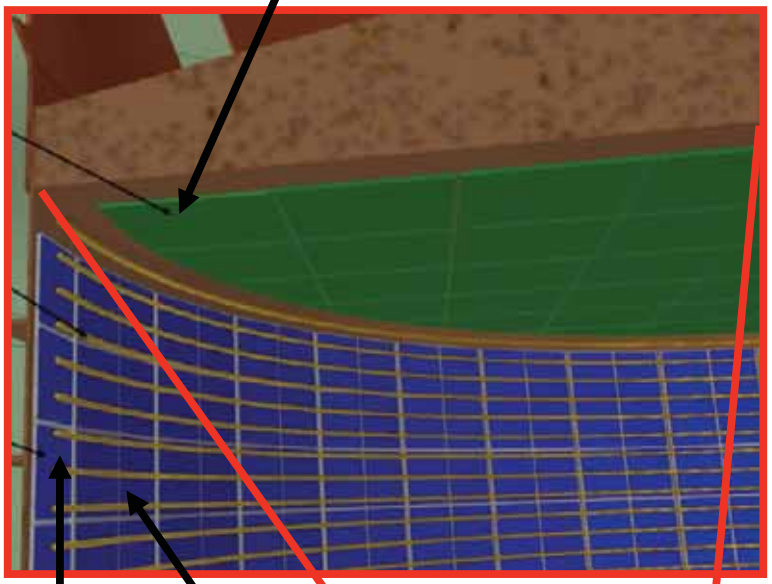
Ba ID in liquid Xe via Resonance Ionization Spectroscopy
(Rev. of Sc.i Inst., V85, 9, 2014)



RF Funnel for Gas
(Int. J. of Mass. Spec., V379, 110, 2015)



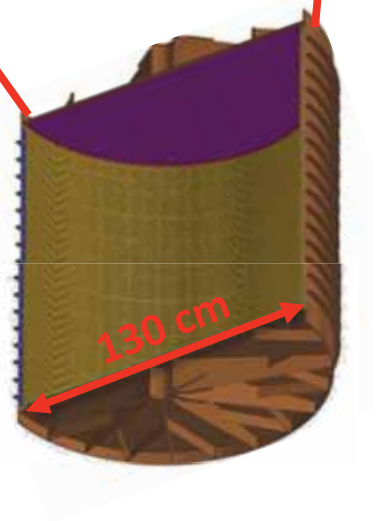
Charge readout tiles



Light sensors

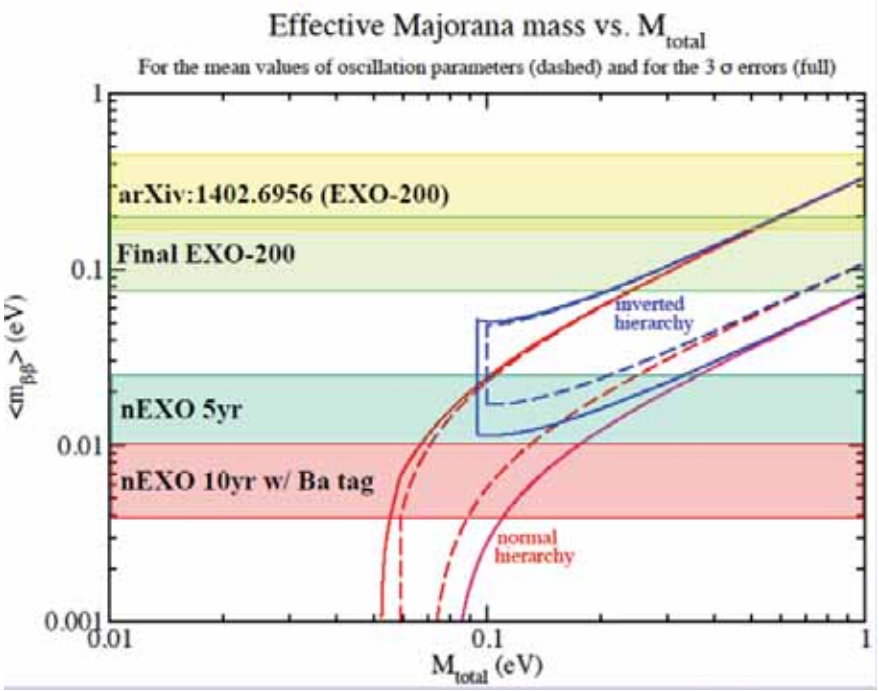
Field shaping rings

SiPM (arXiv 1502.07837)

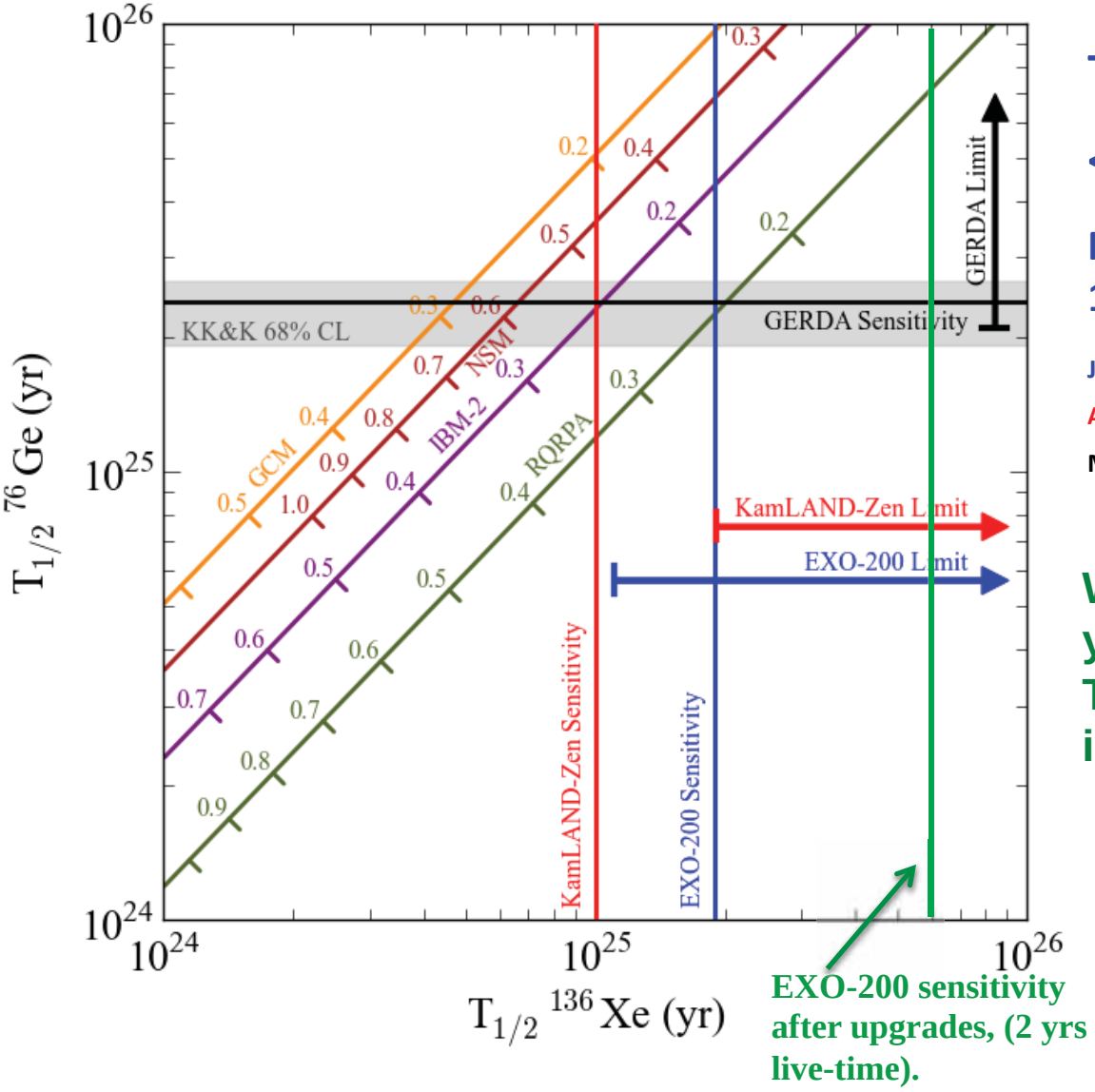


nEXO vs. EXO-200

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}	



EXO-200 0νββ Half-life Sensitivity



$T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25}$yr (90%CL)

$\langle m_\nu \rangle < 190 - 450$ meV

Median $T_{1/2}^{0\nu\beta\beta}$ sensitivity: $1.9 \cdot 10^{25}$ yr

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

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

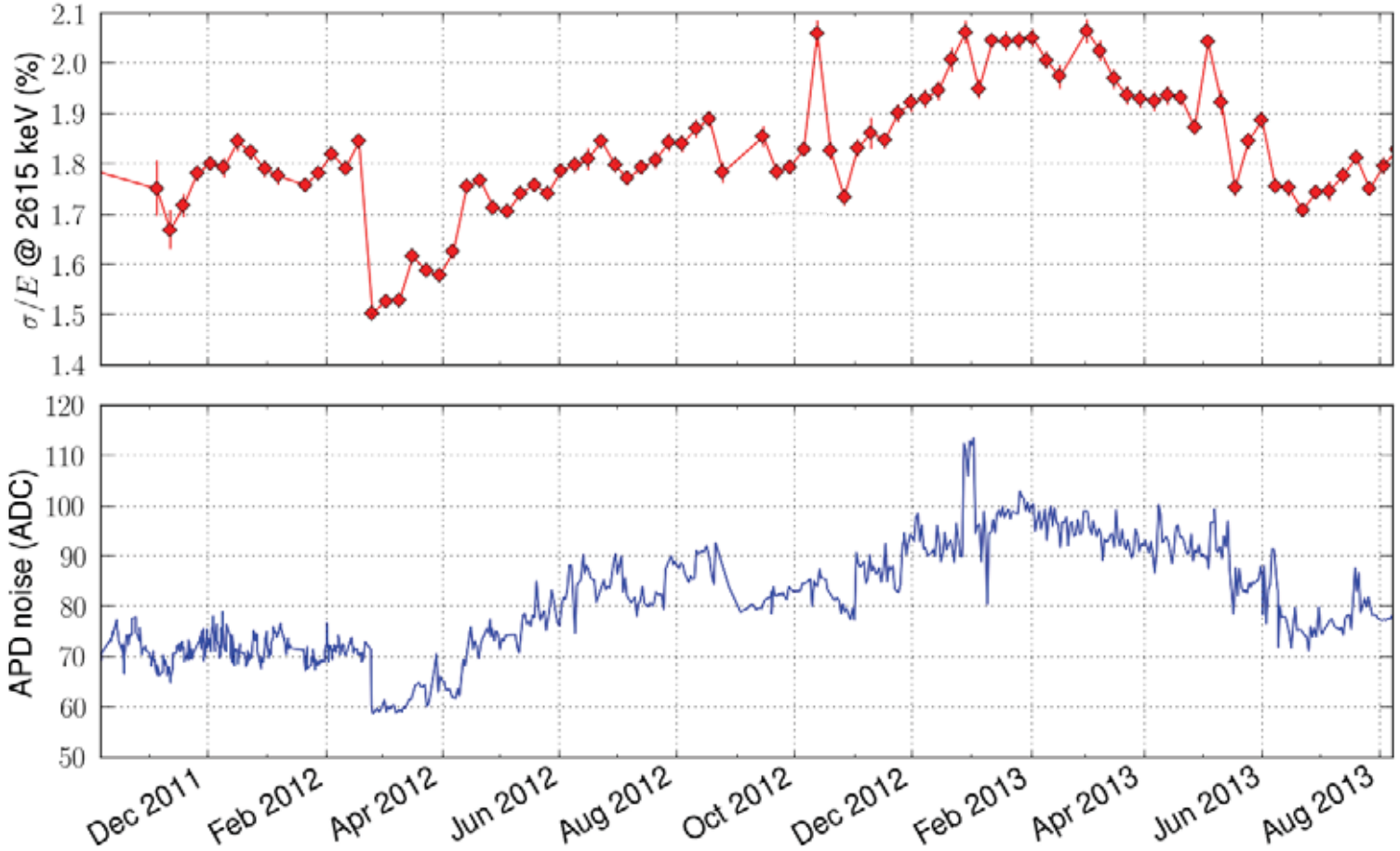
M. Agostini et al. (GERDA), PRL 111 (2013) 122503

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.

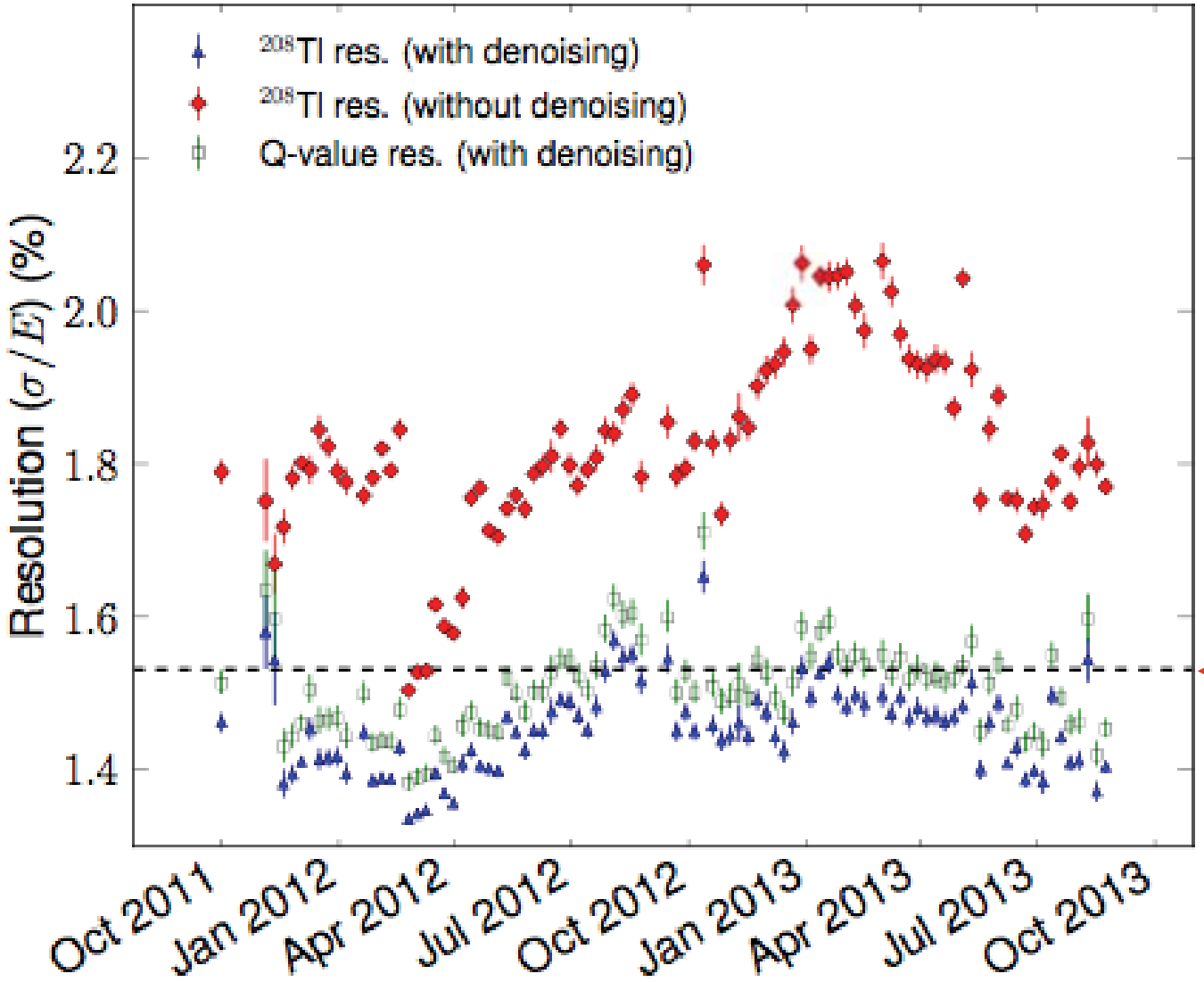
APD Denoising

Problem: Noise and resolution is dependent on the varying (correlated) noise of the APDs



(Current) solution: Find the optimum combination of APD signals *per event*, given position and noise

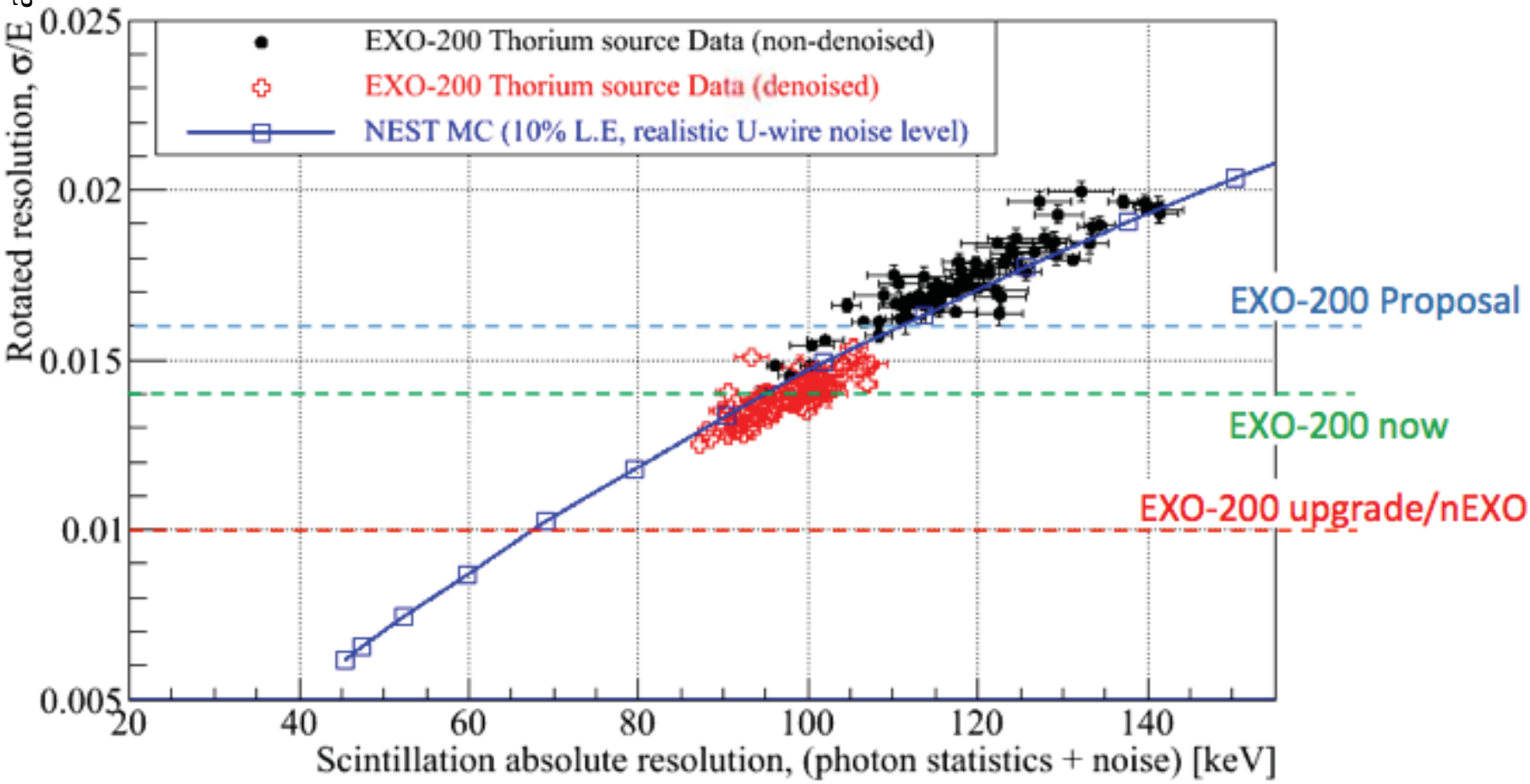
APD Denoising



1.53 % in SS at 0νββ Q-value

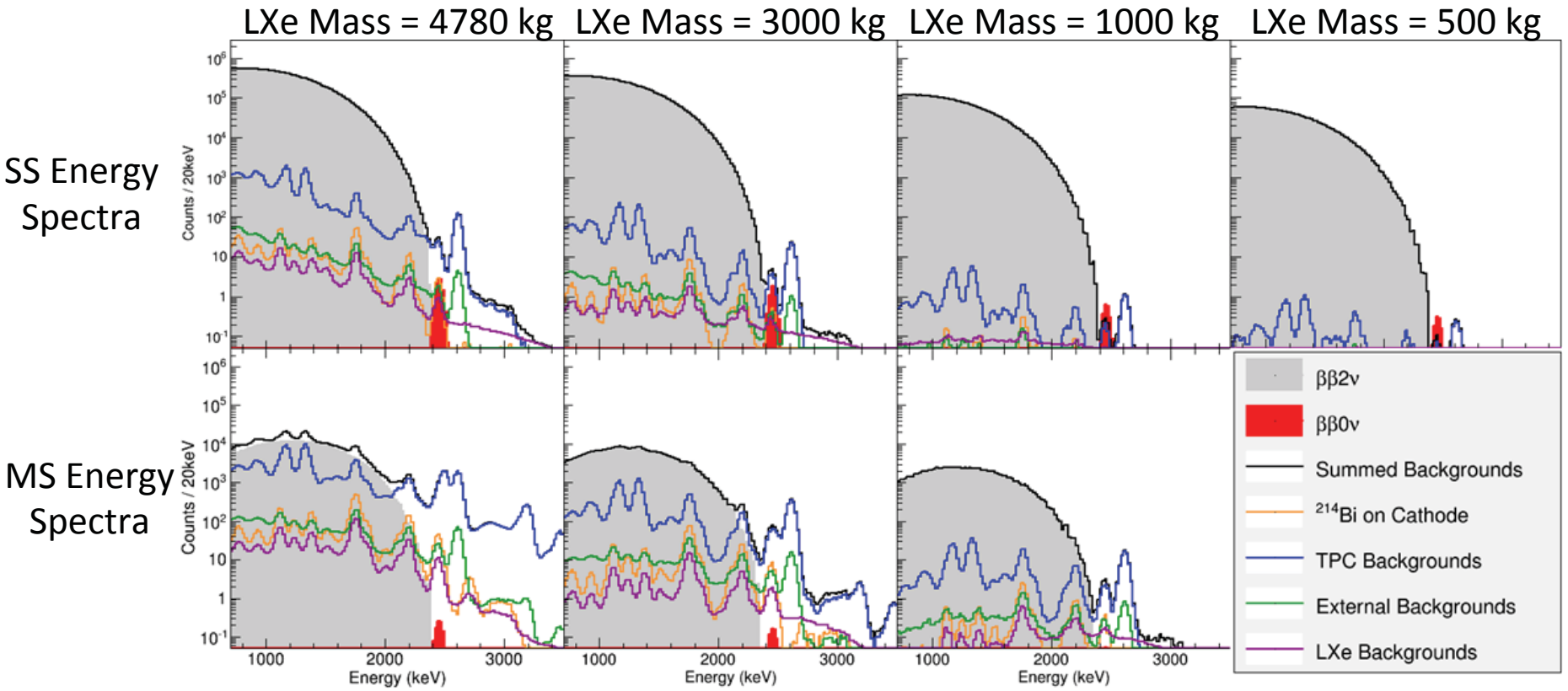
APD Denoising

Problem: Resolution is dependent on the time-varying correlated noise of the APDs
Software solution (past): Find the optimum combination of APD signals *per event,* given position and noise
Hardware solution (current): Planned upgrade of APD readout electronics to reduce noise



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

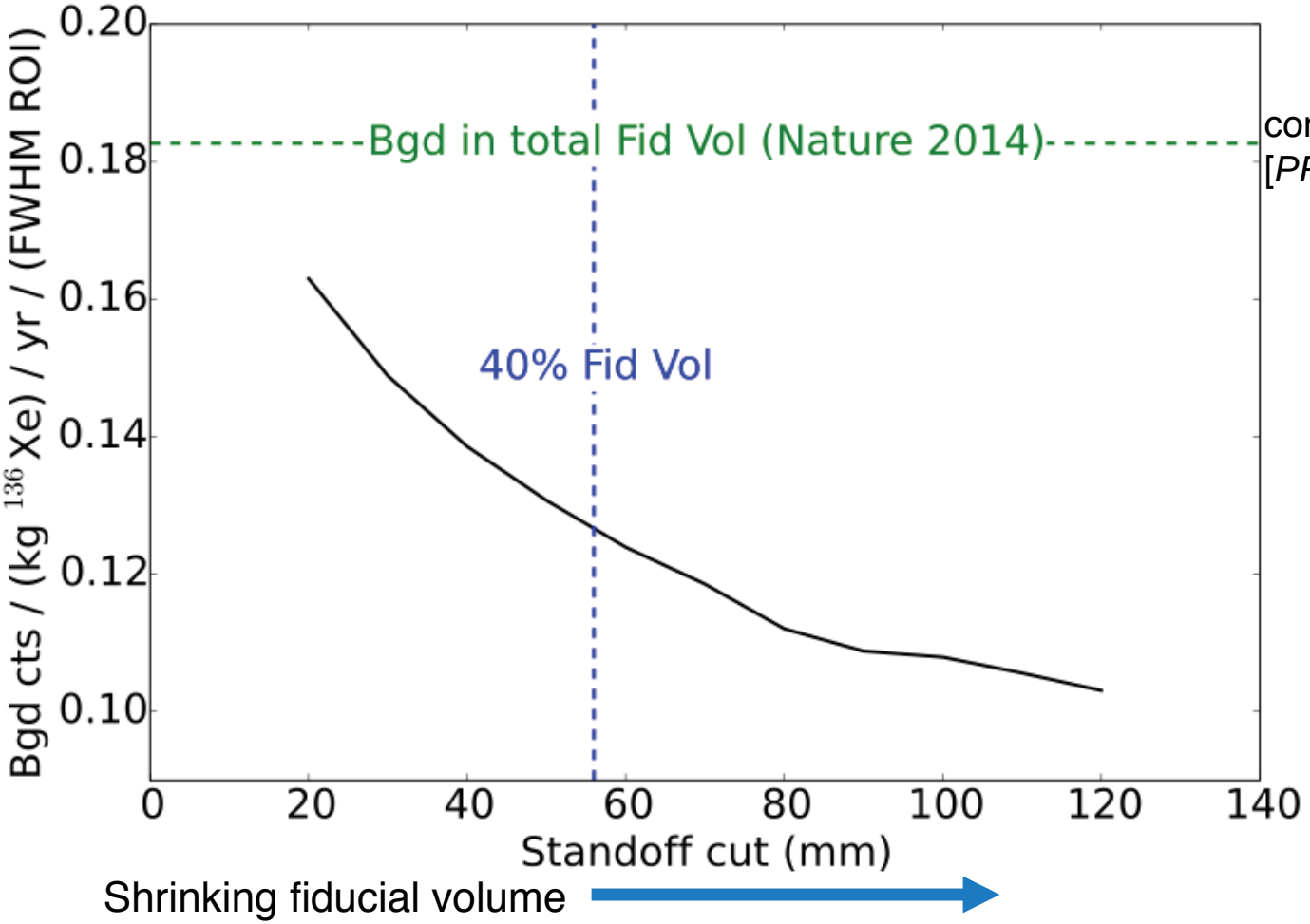
Backgrounds and Signal



Energy spectra for different LXe masses, with energy discrimination at different positions in the detector without statistical fluctuations, after 5 year exposure.

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

Backgrounds in the ROI



consistent with previous result [*PRL* **109**, 032505 (2012)]

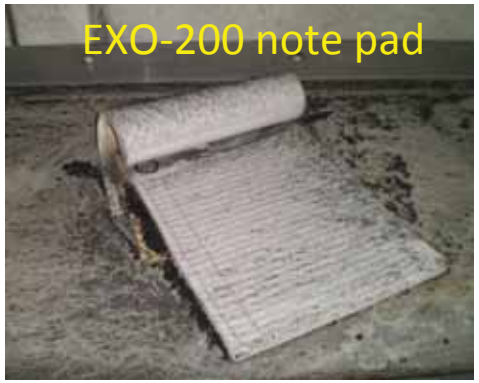
39 counts in $\pm 2\sigma$ ROI

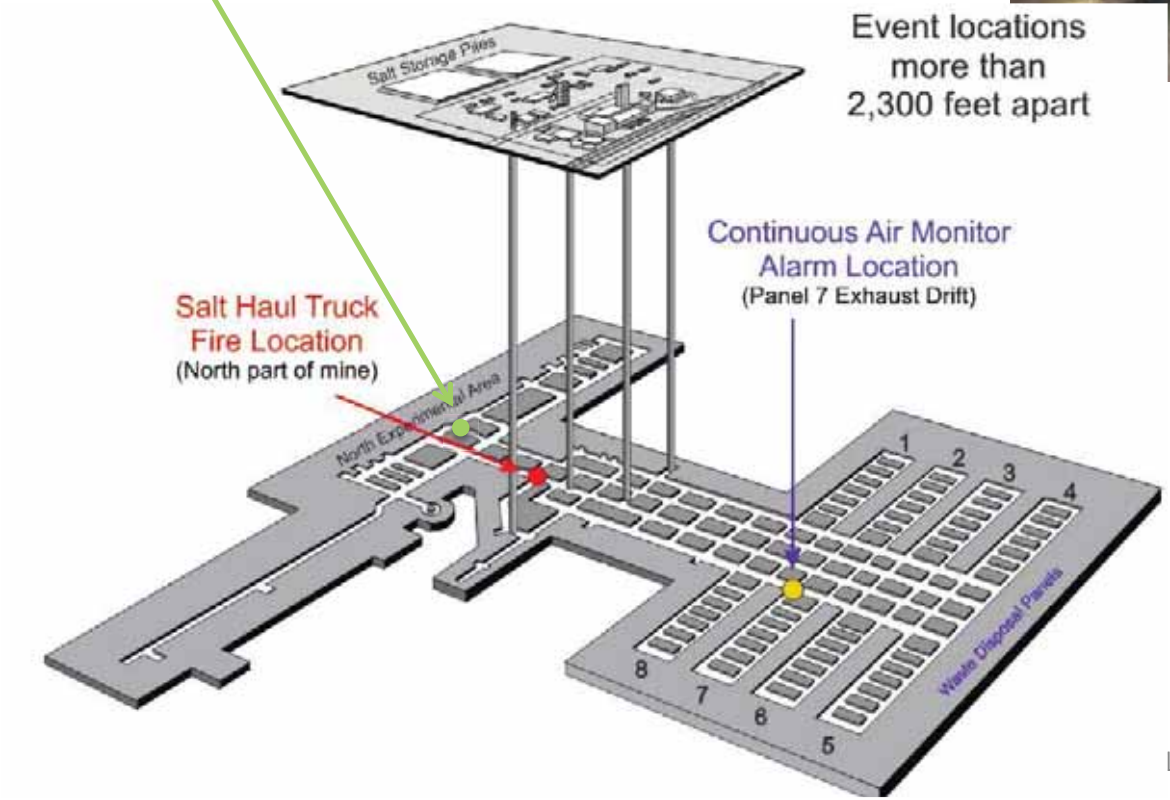
Backgrounds in $\pm 2\sigma$ R.O.I.	
Th-228 chain	16.0
U-232 chain	8.1
Xe-137	7.0
Total	31.1 ± 3.8

30% reduction of background index in inner 40% fiducial volume

WIPP Incident

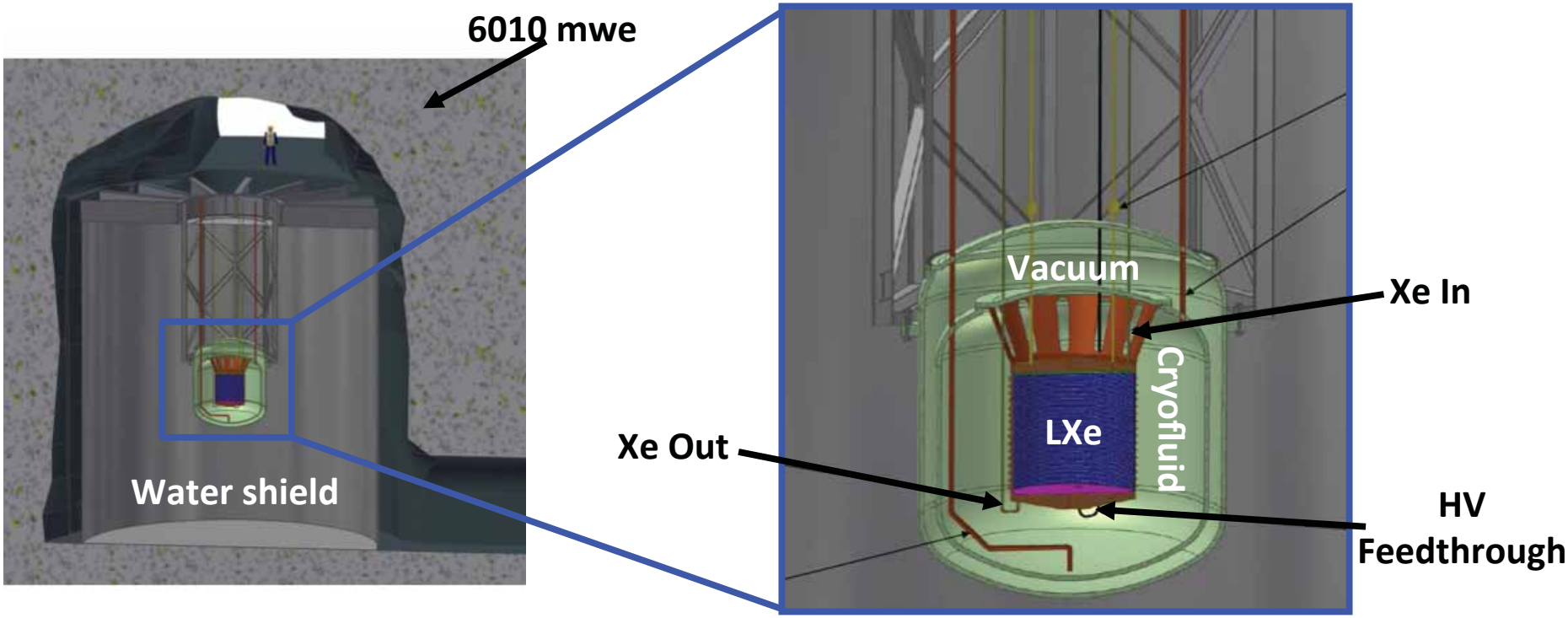
EXO-200 is nearly 4000 feet from the radiation event





- **Feb. 5 2014:** Fire in WIPP underground
- **Feb. 14, 2014:** Radiation release event
- No radioactivity has been measured at EXO-200

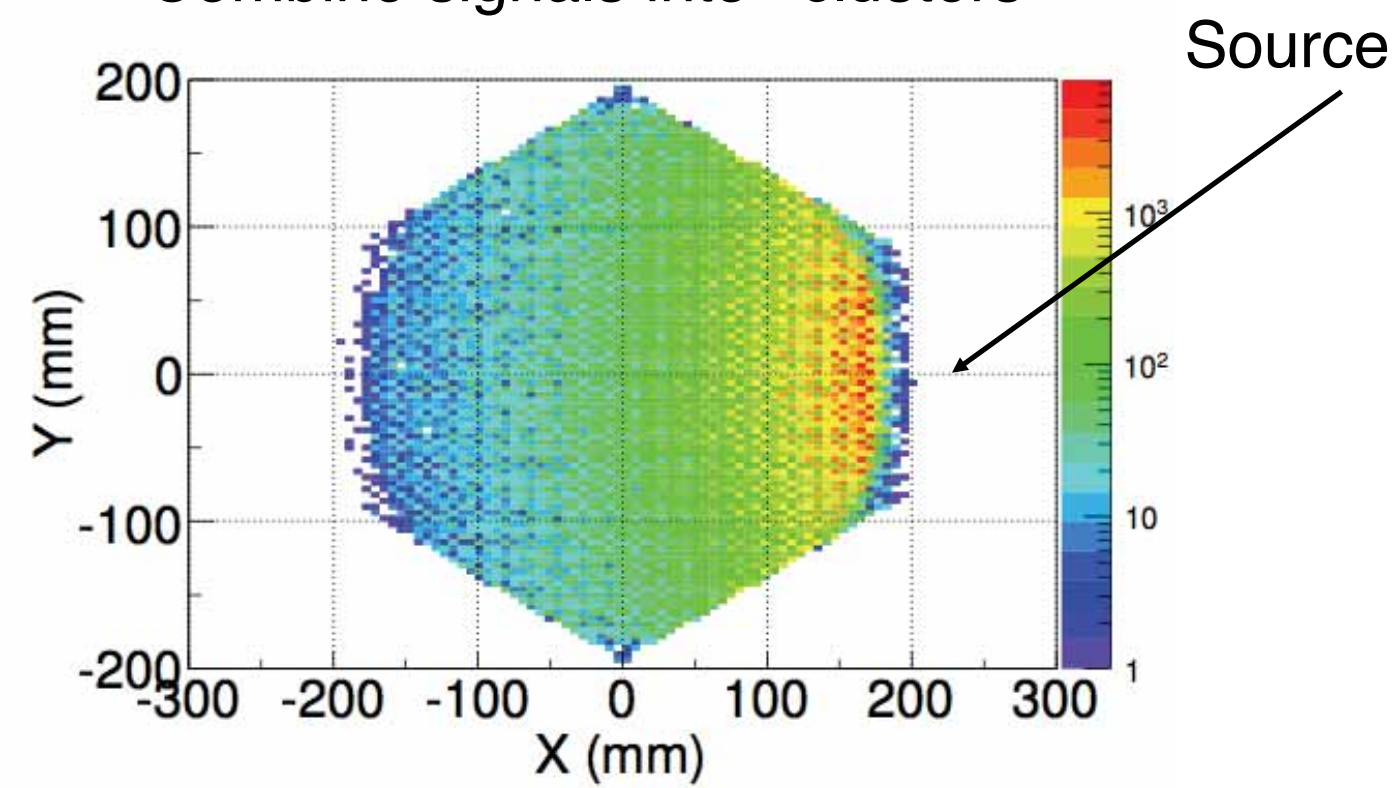
Preliminary design of nEXO



Preliminary design of the nEXO detector in SNOLab's cryopit

Position/multiplicity reconstruction

Combine signals into “clusters”



Uncertainty, 2.4 (1.2) mm U (V) + 1.5 mm shift (taken as systematic error), Z (0.5 mm), measured using internal decays on the cathode

Total error in fiducial volume due to position reconstruction: **1.73%**

Systematic errors

- 0νββ detection efficiency:

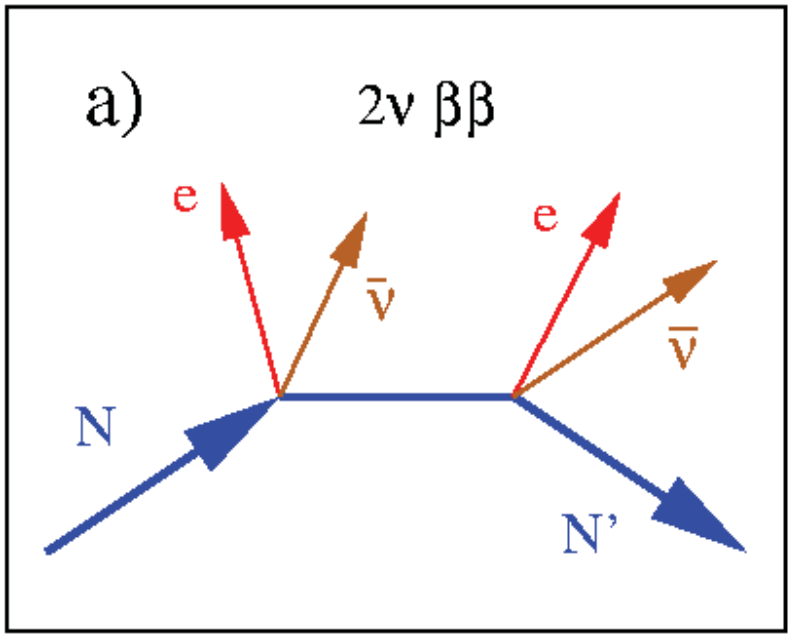
Source:	Signal efficiency [%]:	Relative error [%]:
Summary from PRC **89**, 015502 (2014)	93.1	0.9
Partial reconstruction	90.9	7.8
Fiducial volume/rate agreement		3.4
Total:	**84.6**	**8.6**

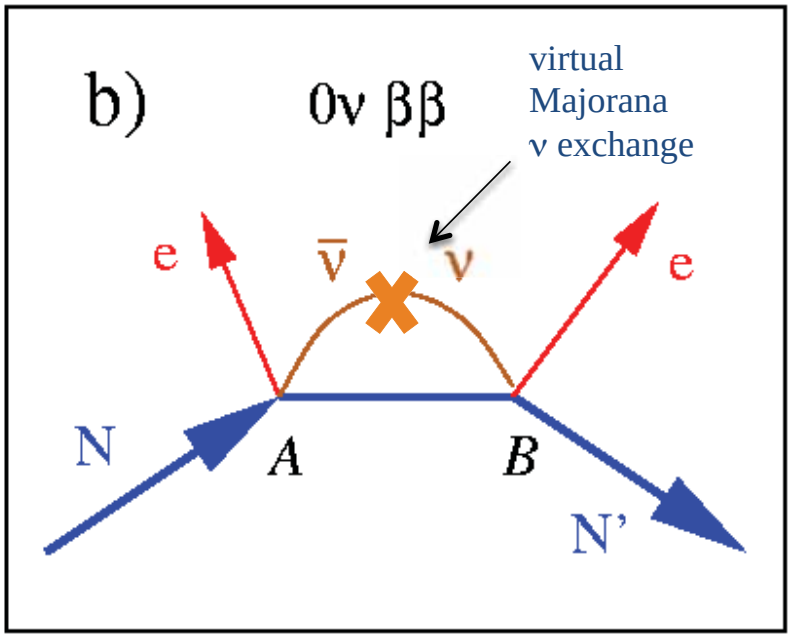
- Region-of-interest (ROI) backgrounds:

Source:	Relative error [%]:
Background shape distortion	9.2
Choice of background model components	5.7
Variation of energy resolution over time	1.5
Total:	**10.9**

- Location of 0νββ ROI: "β-scale" allowed to float in fit
  - Deviations between β and γ energy scale: $E_\beta = B \cdot E_\gamma \Rightarrow$ ***B* = 0.999 ±0.002**
- Single-site fraction error: **9.6%** SS/MS fraction allowed to vary within this error in fit

Two Modes of Double Beta Decay





Two neutrino mode:
- Standard model process
- Second order
- $\Delta L = 0$ (lepton number conserved)

Neutrinoless mode:
- Hypothetical "Beyond the Standard Model" process
- Can only happen if:
  - neutrino has nonzero mass
  - neutrino is its own antiparticle (Majorana neutrino)
- Total lepton number violating ($\Delta L = 2$)

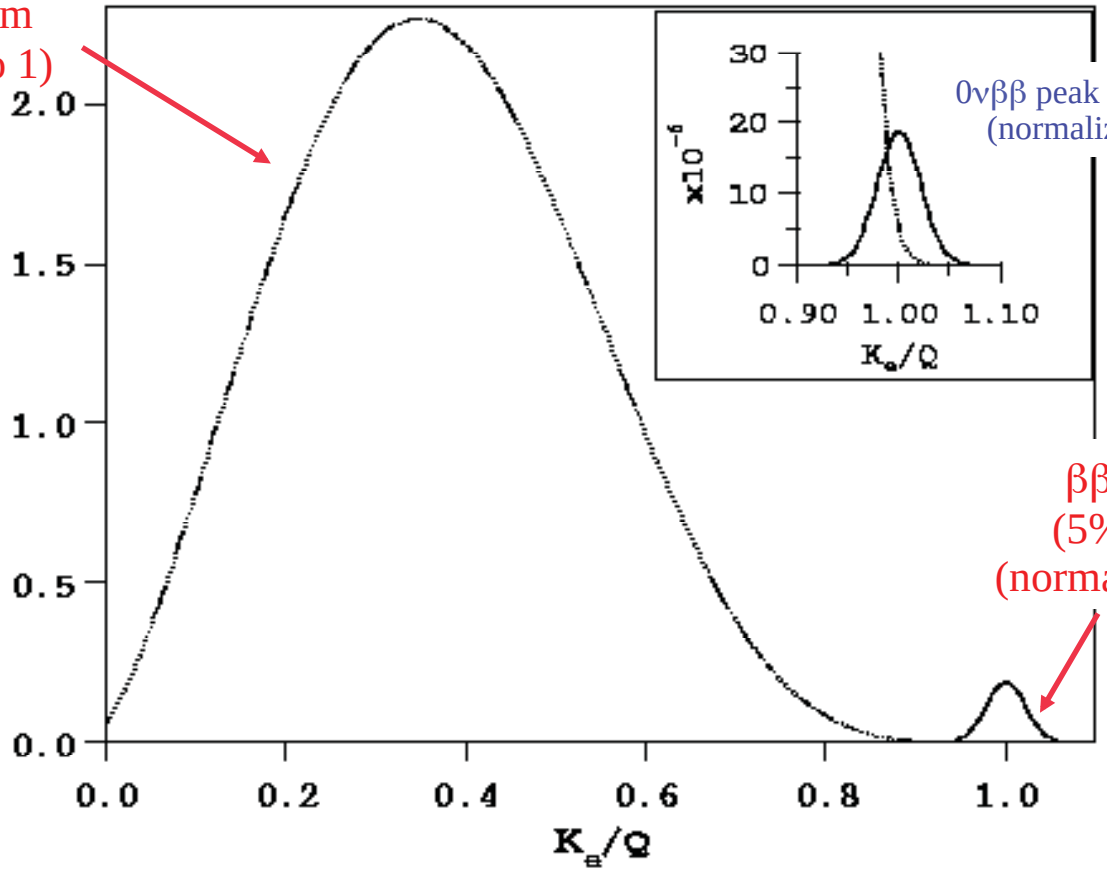
ββ0ν signature: a peak in the ββ energy spectrum

ββ2ν spectrum
(normalized to 1)

0νββ peak (5% FWHM)
(normalized to 10^{-6})

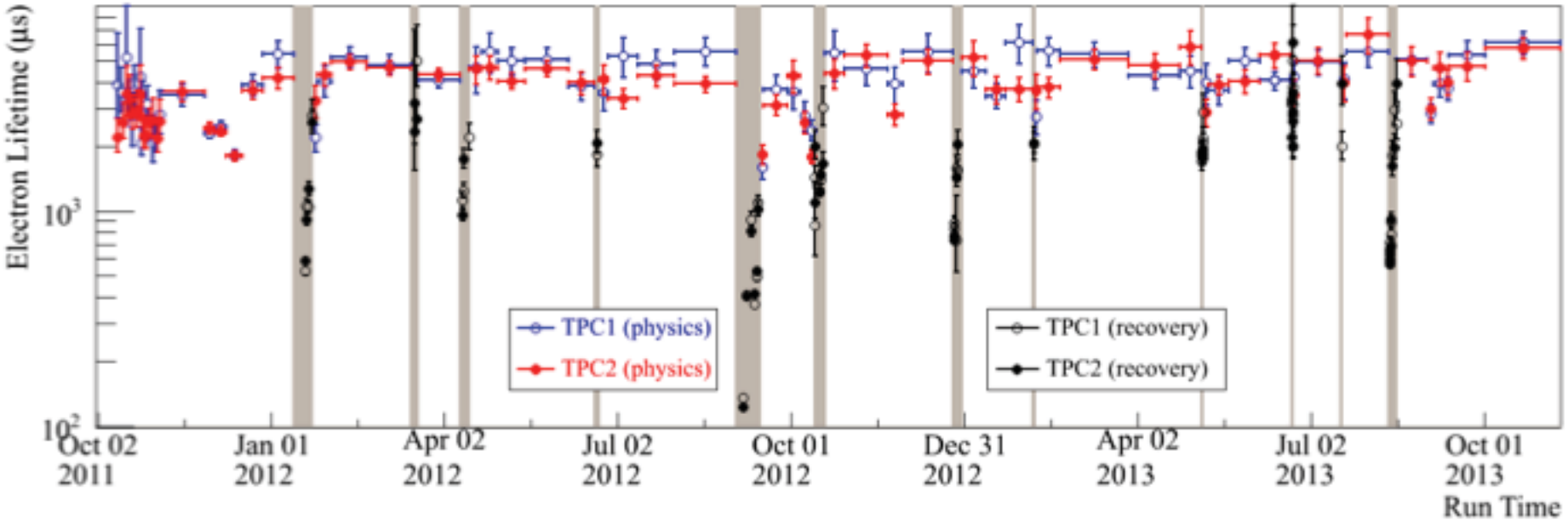
ββ0ν signal
(5% FWHM)
(normalized to 10^{-2})

Energy
Resolution
is pivotal



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

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.