NOW 2014

Searching for neutrino-less double beta decay with EXO-200 and nEXO

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on behalf of the
EXO-200 and nEXO collaborations

The EXO-200 Collaboration

Enriched Xenon Observatory for double beta decay

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Carleton University, Ottawa ON, Canada - V. Basque, M. Dunford, K. Graham, C. Hargrove, R. Killick, T. Koffas, F. Leonard, C. Licciardi, M.P. Rozo, D. Sinclair
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Duke University, Durham NC, USA - P.S. Barbeau
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University of Illinois, Urbana-Champaign IL, USA - D. Beck, M. Coon, J. Ling, M. Tarka, J. Walton, L. Yang
Indiana University, Bloomington IN, USA - J. Albert, S. Daugherty, T. Johnson, L.J. Kaufman, T. O'Conner
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ITEP Moscow, Russia - D. Akimov, I. Alexandrov, V. Belov, A. Burenkov, M. Danilov, A. Dolgolenko, A. Karelin, A. Kovalenko, A. Kuchenkov, V. Stekhanov, O. Zeldovich
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The nEXO Collaboration

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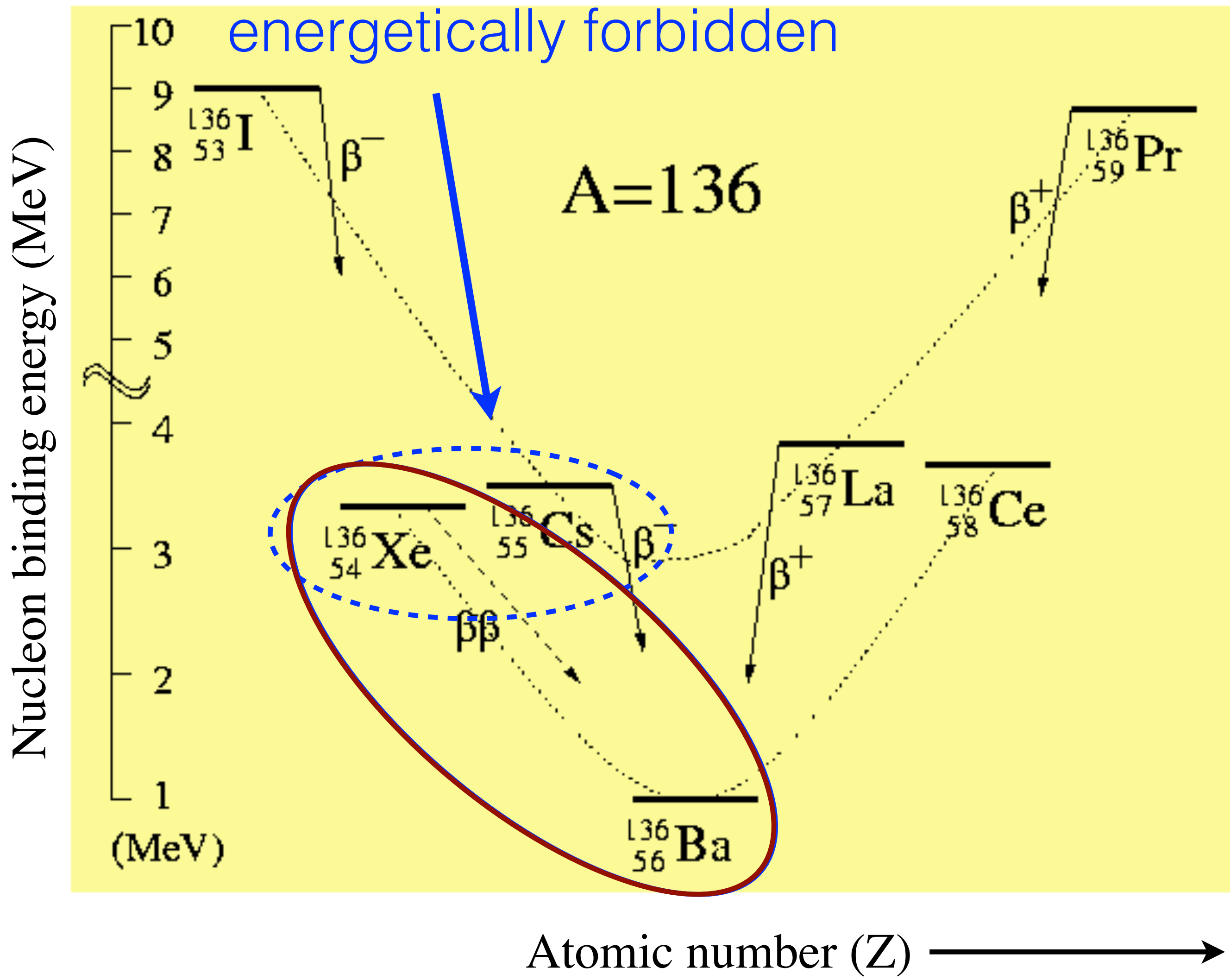
double beta decay

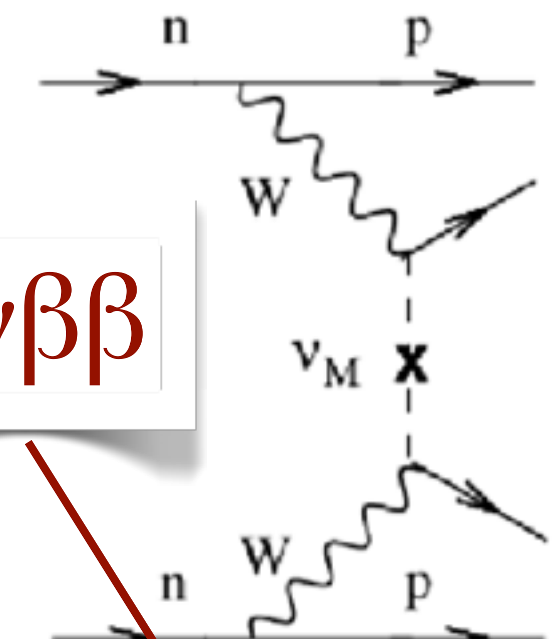
single β decay
energetically forbidden

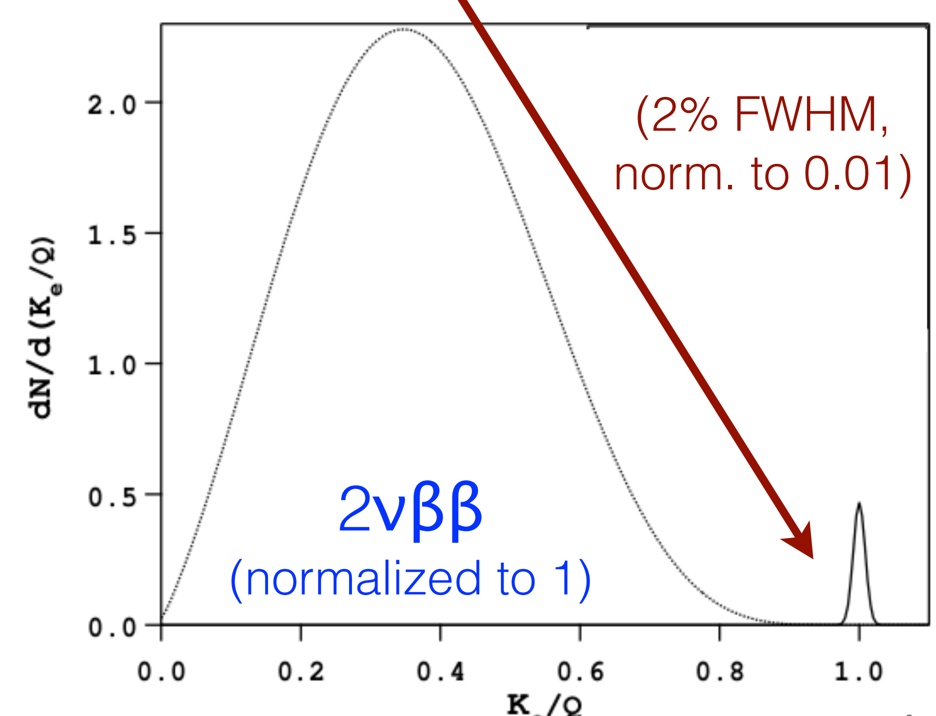


possibility of non-standard
0νββ process

electrons carry all of the
kinetic energy

0νββ





observation of 0νββ decay:

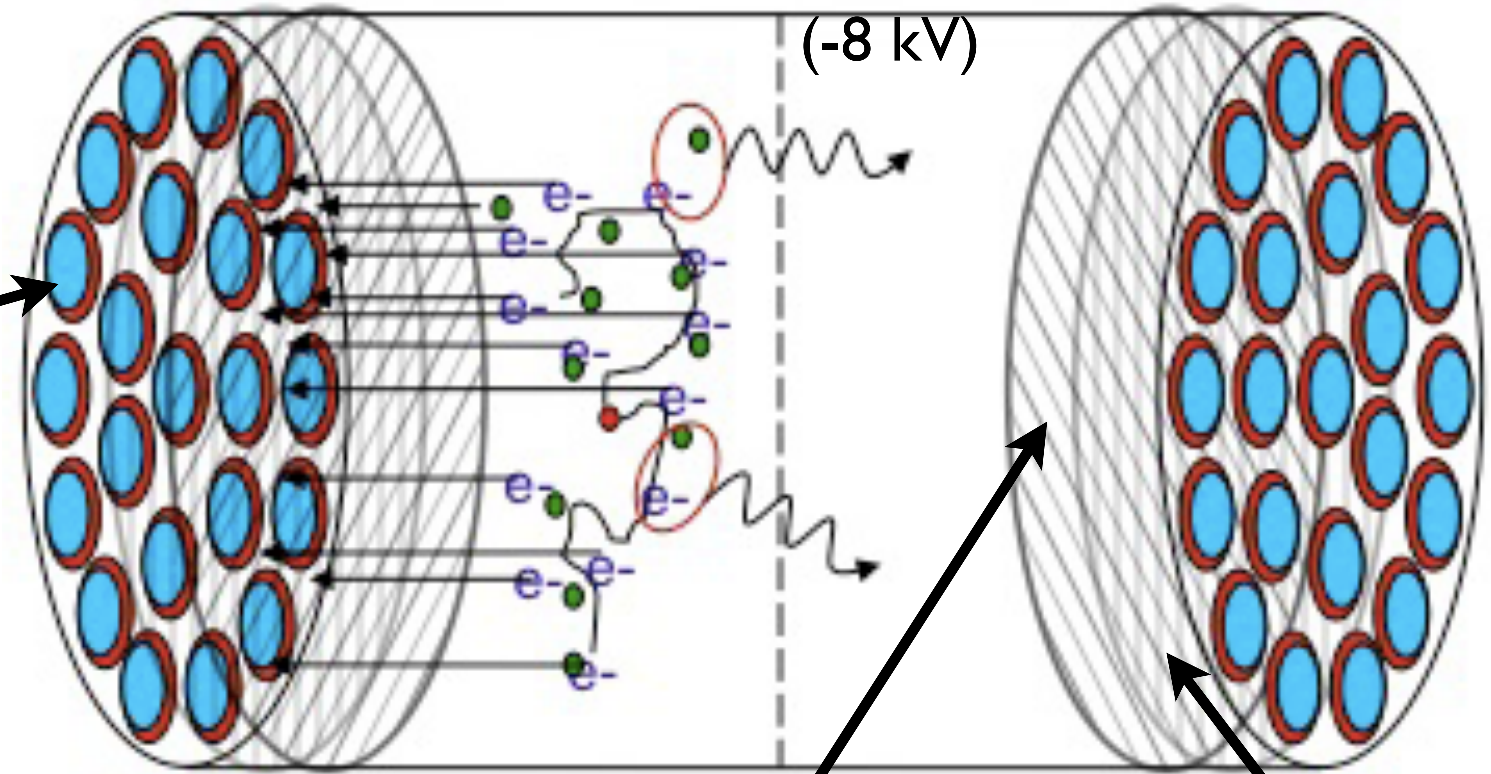
- massive, Majorana neutrinos
- lepton number violation

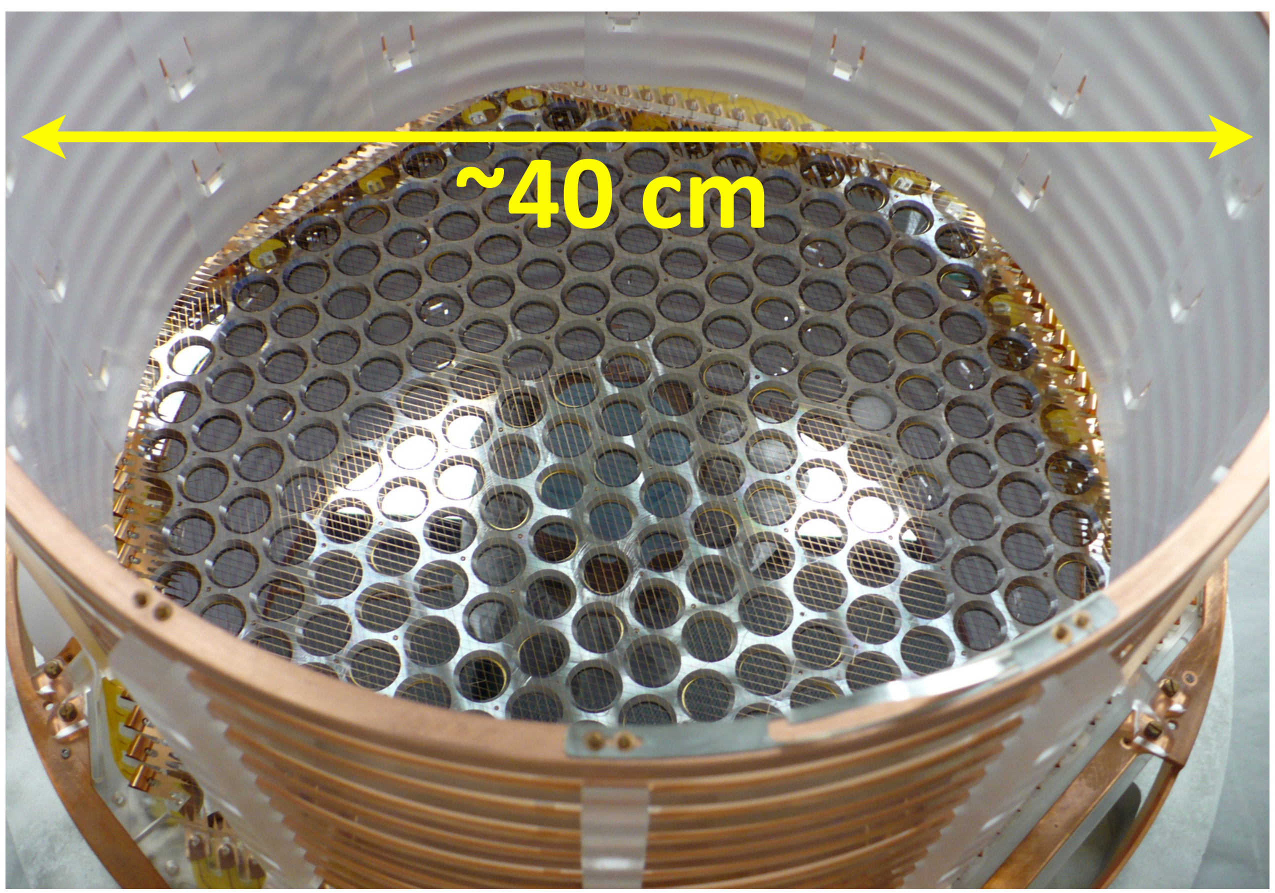
0νββ rate

- absolute neutrino mass (model dependent)

EXO-200 Time Projection Chamber

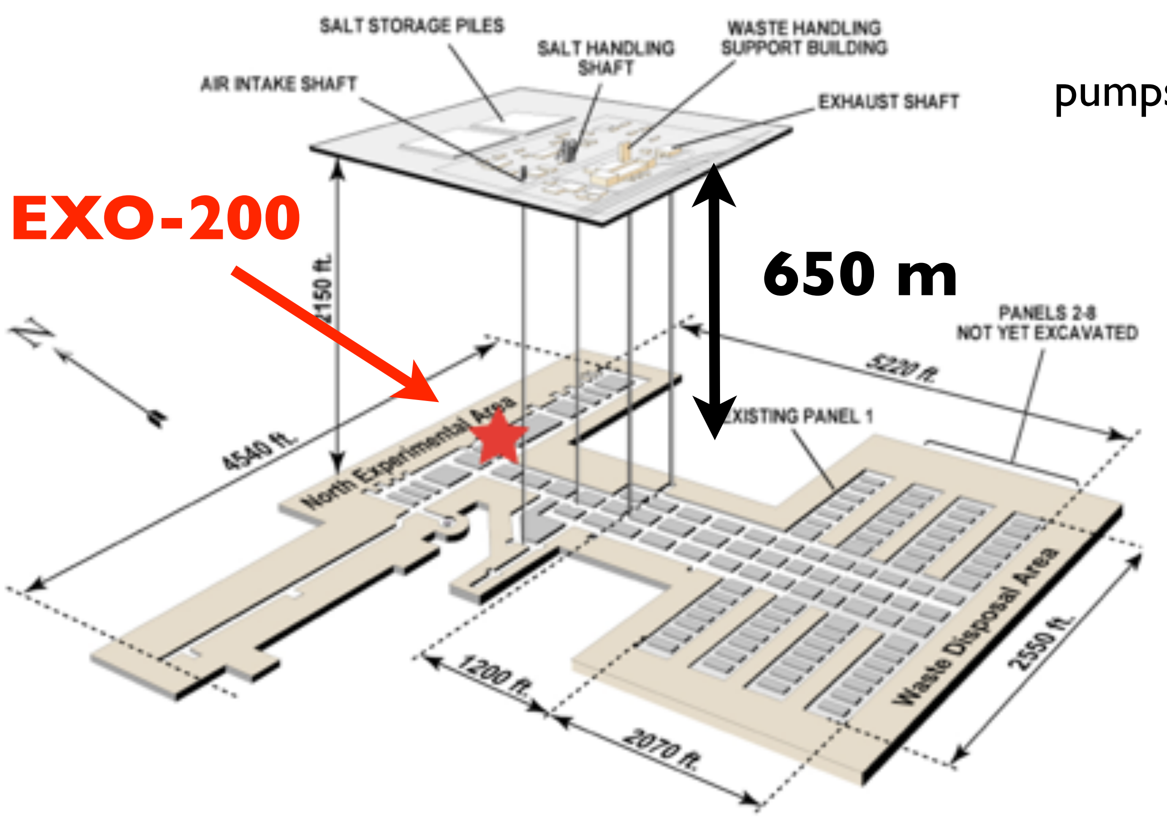
- Radio-pure, dual TPC (shared center cathode), filled with ~150 kg LXe, 80.6% ^{136}Xe)
- Scintillation detected by APDs at interaction time
- Rotated charge collection and shielding planes give x/y, z from electron drift time

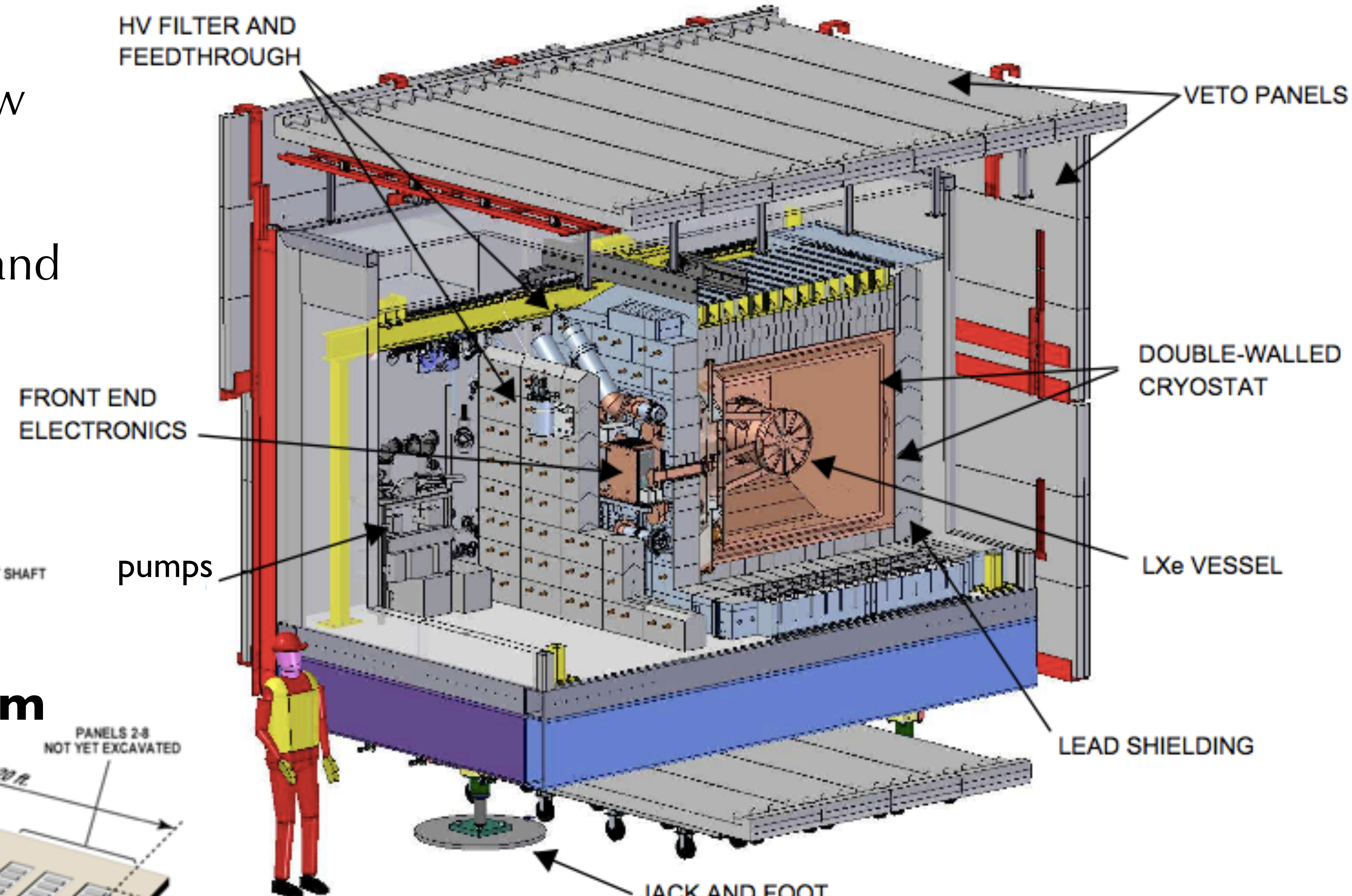




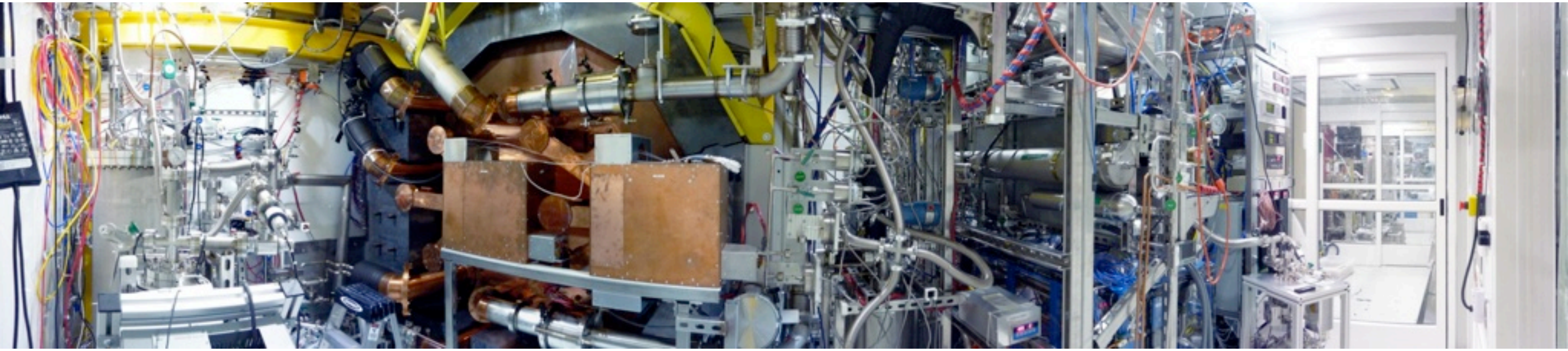
The EXO-200 detector at WIPP

- Detector installed at WIPP, near Carlsbad, NM in 2010
- Salt mine with relatively low Th/U and Rn
- TPC surrounded by active and passive shielding, inside a clean room

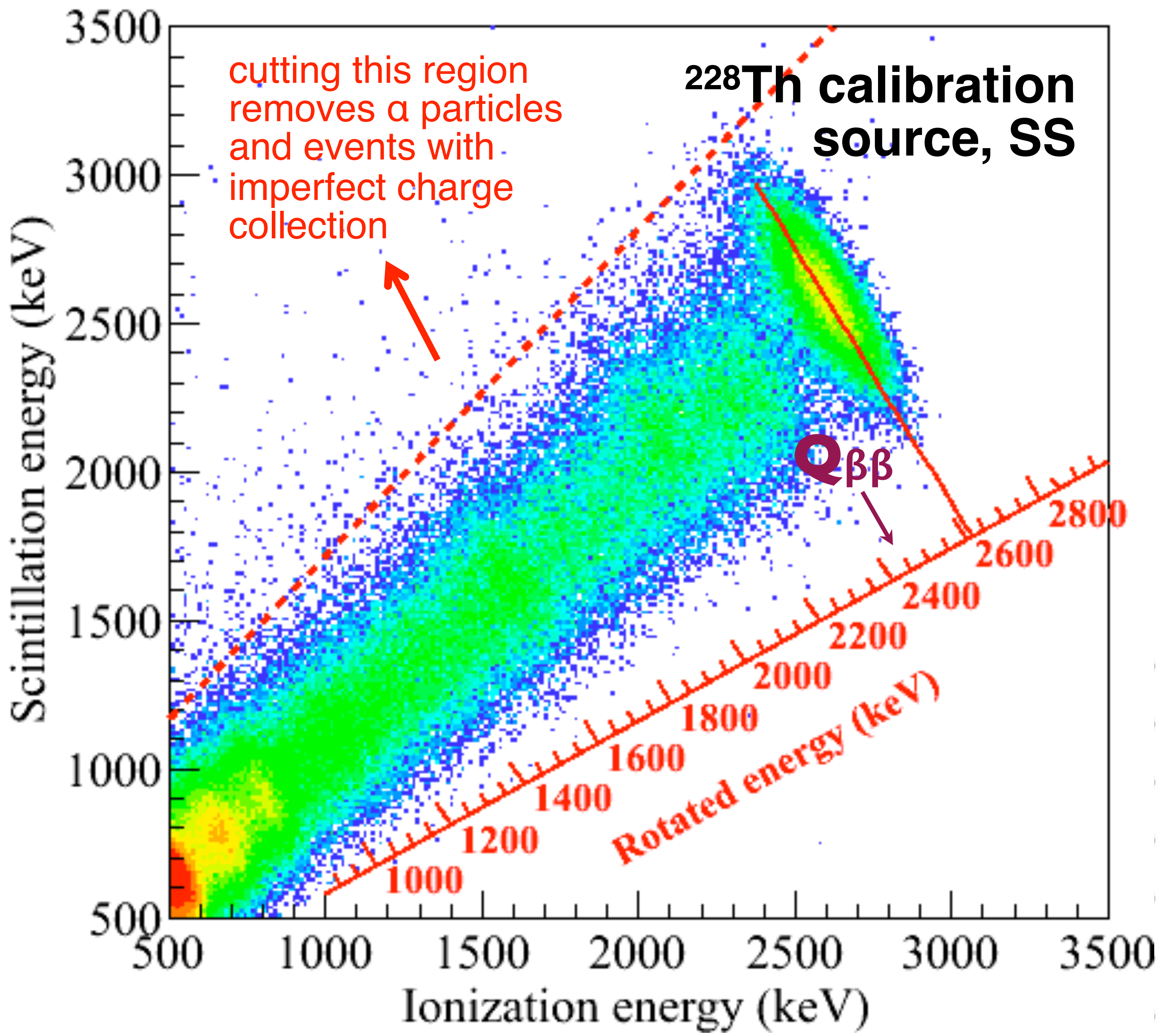




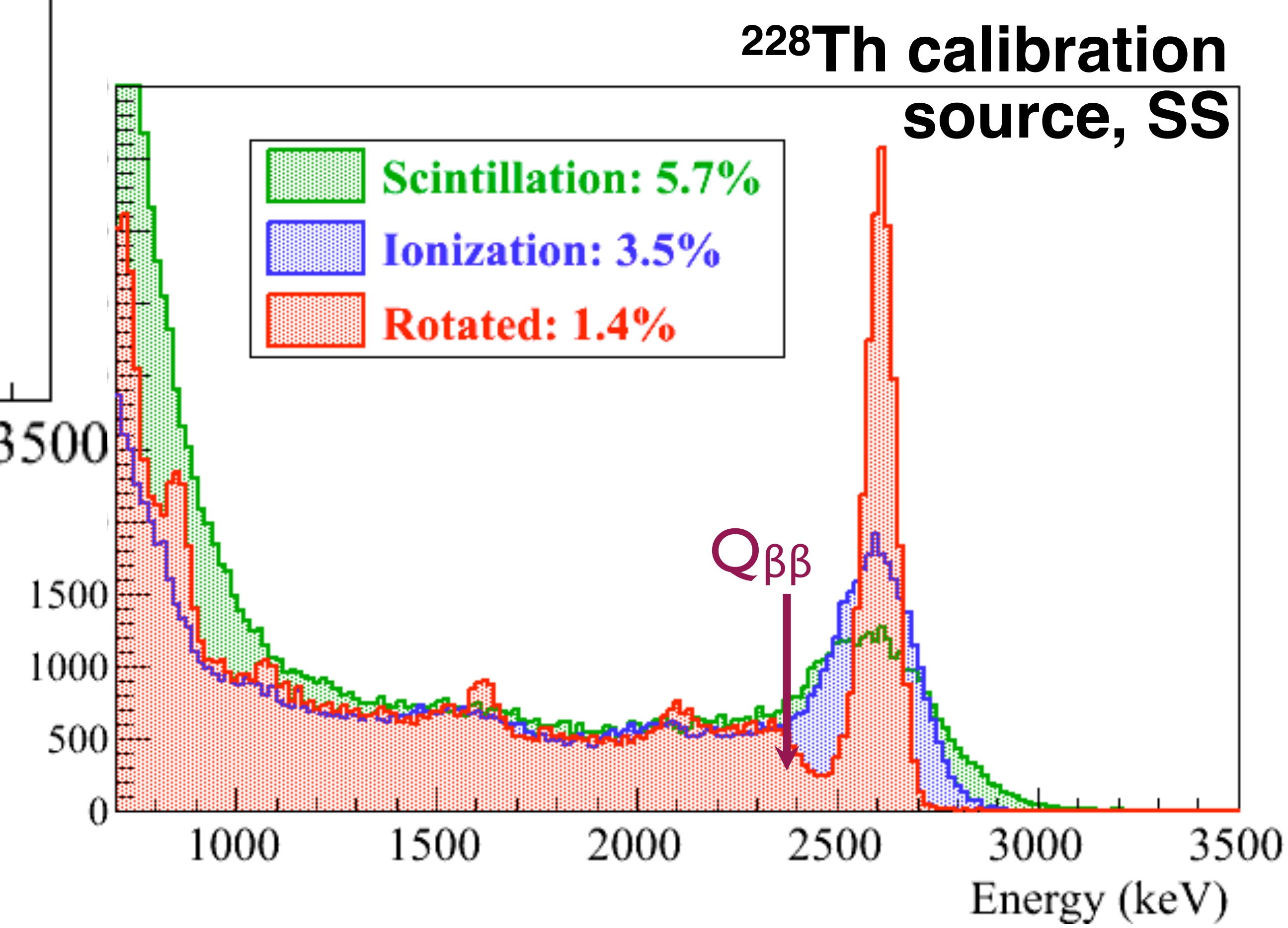
EXO-200 @ WIPP



Energy reconstruction



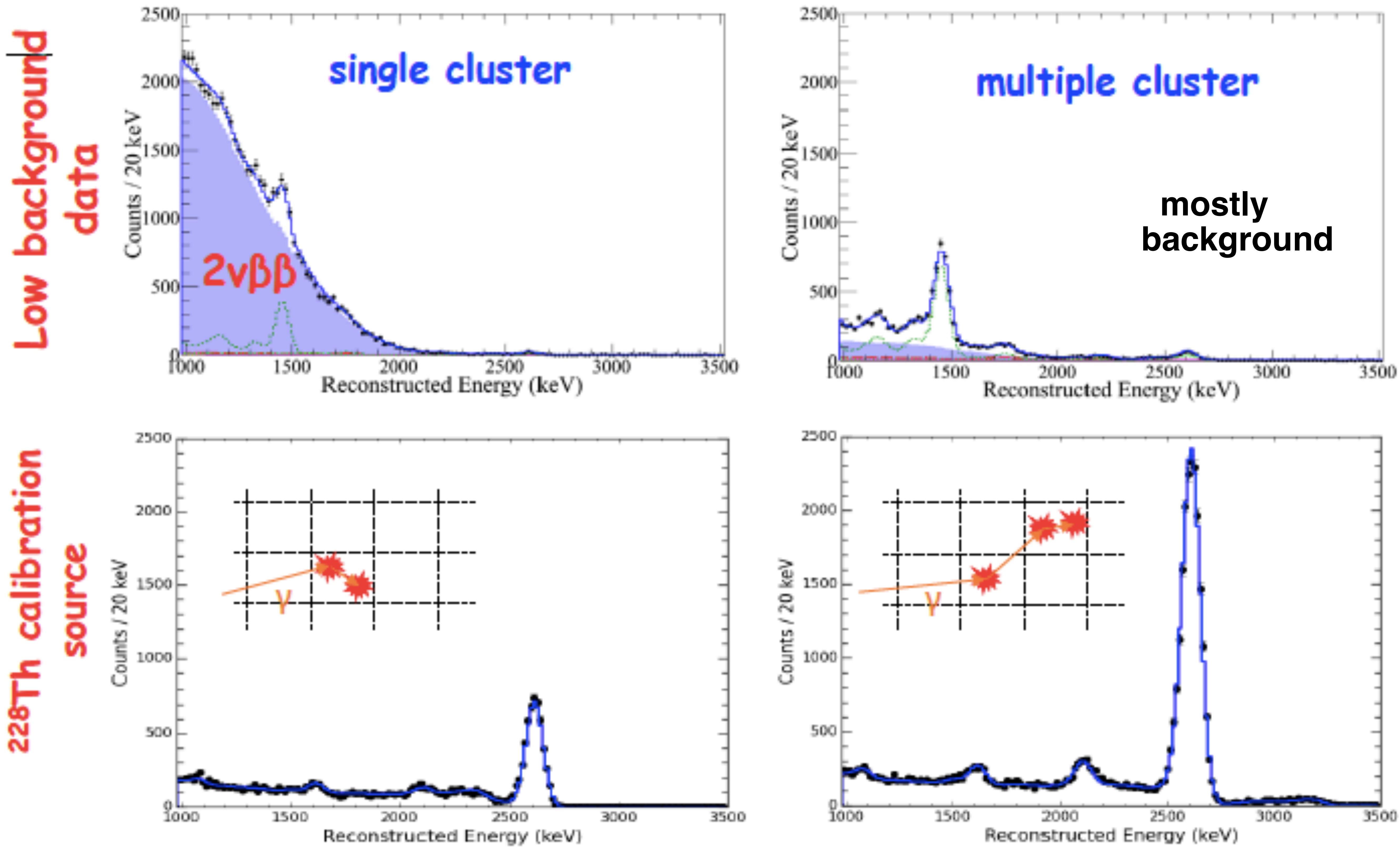
- Reconstruct "rotated" energy measured in scintillation versus ionization plane
- Takes into account anti-correlation of charge and scintillation response to improve energy resolution
- Calibration performed with ^{60}Co, ^{137}Cs, ^{226}Ra, and ^{228}Th
- Denoised LAAPD signals



Molecular properties of xenon cause increased scintillation to be associated with decreased ionization (and vice-versa)

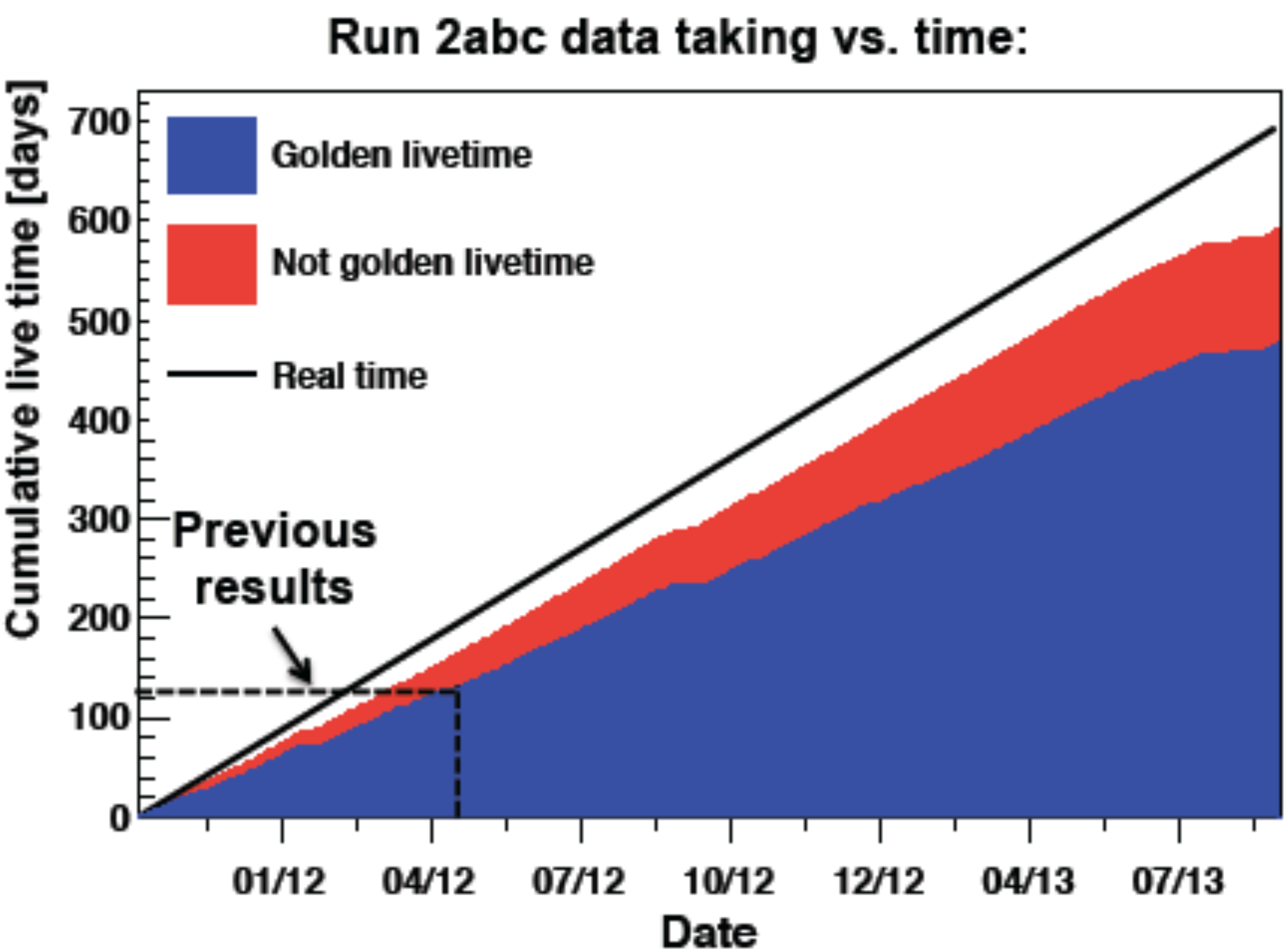
[E. Conti et al. Phys. Rev. B 68 (2003) 054201]

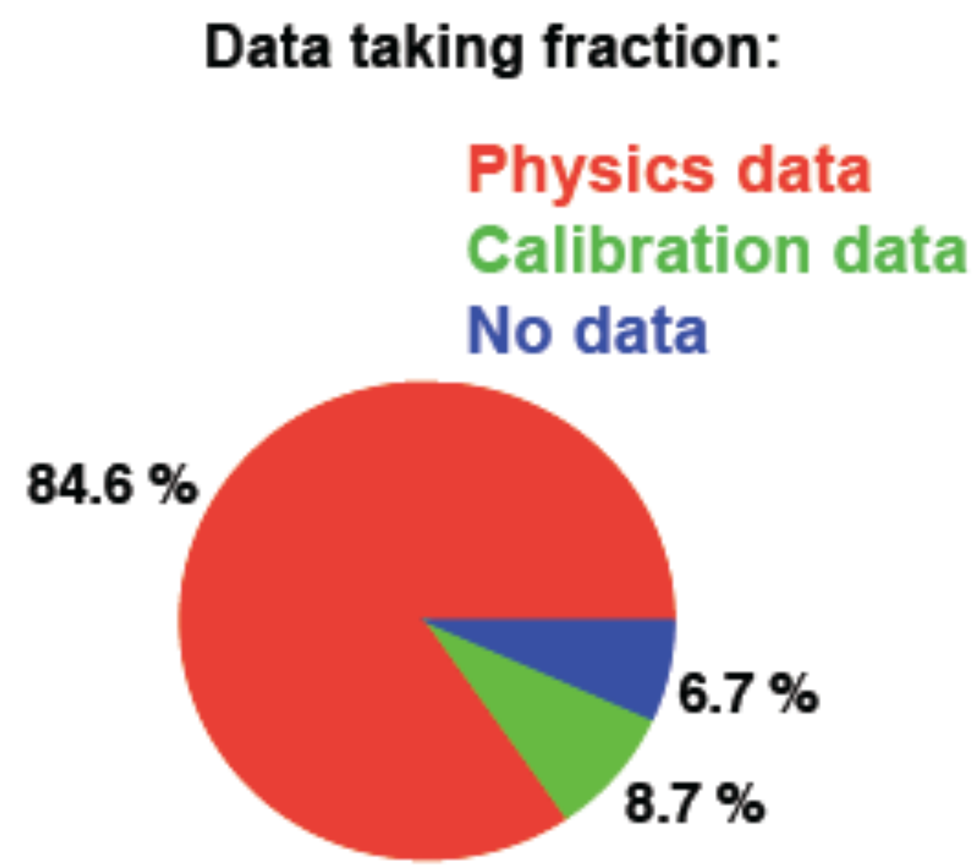
Background discrimination and tracking



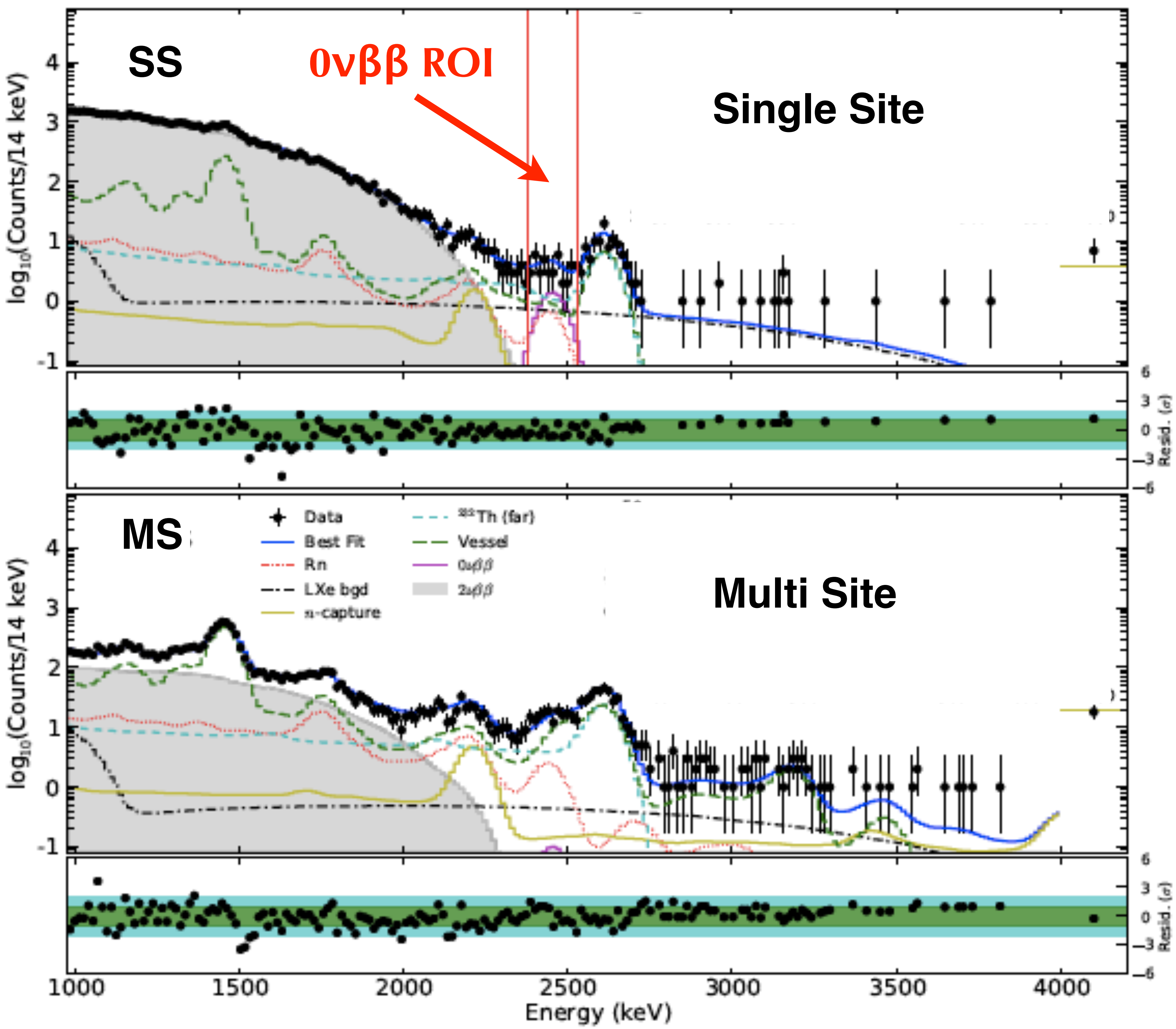
Run 2 dataset

- Data analyzed in this work were taken between Oct. 2011 and Sept. 2013
- Total accumulated "Golden" data was 447.60 ± 0.01 days, corresponding to a ^{136}Xe exposure of 100 kg · yr





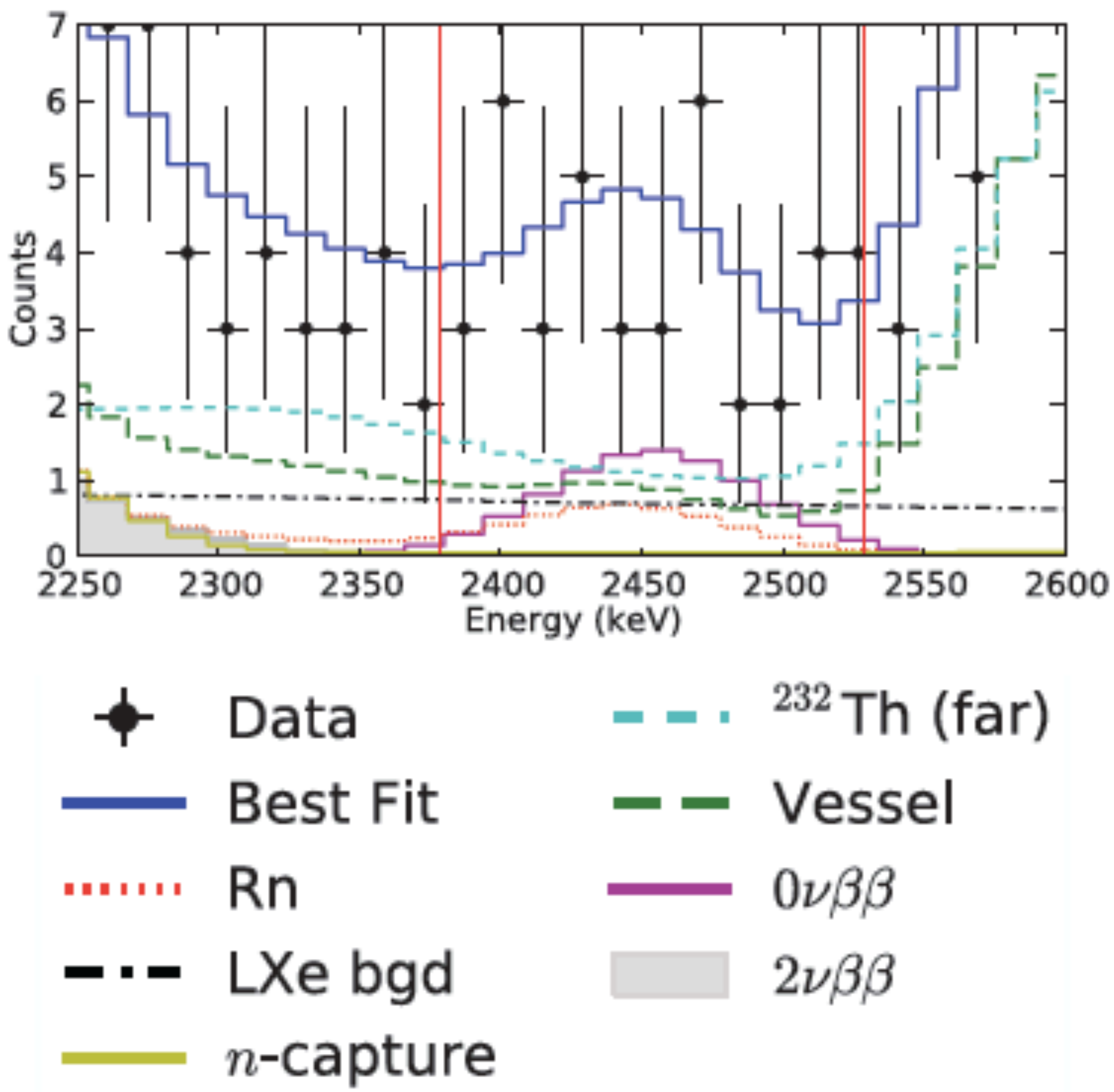
0νββ results - Nature 510, 9 (2014) (arXiv:1402.6956)



- Fit energy spectrum in 980-9800 keV range
- Multi-site (MS) data constrain backgrounds, while 0νββ ROI in in single site (SS) data.
- Fit also includes the "standoff distance" from nearest TPC surface to better constrain backgrounds (and identify signal)

0νββ results - Nature 510, 9 (2014) (arXiv:1402.6956)

Fit to single site spectrum near 0νββ ROI:



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

$T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25}$ yr
$\langle m_{\beta\beta} \rangle < 190 - 450$ meV
(90% C.L.)

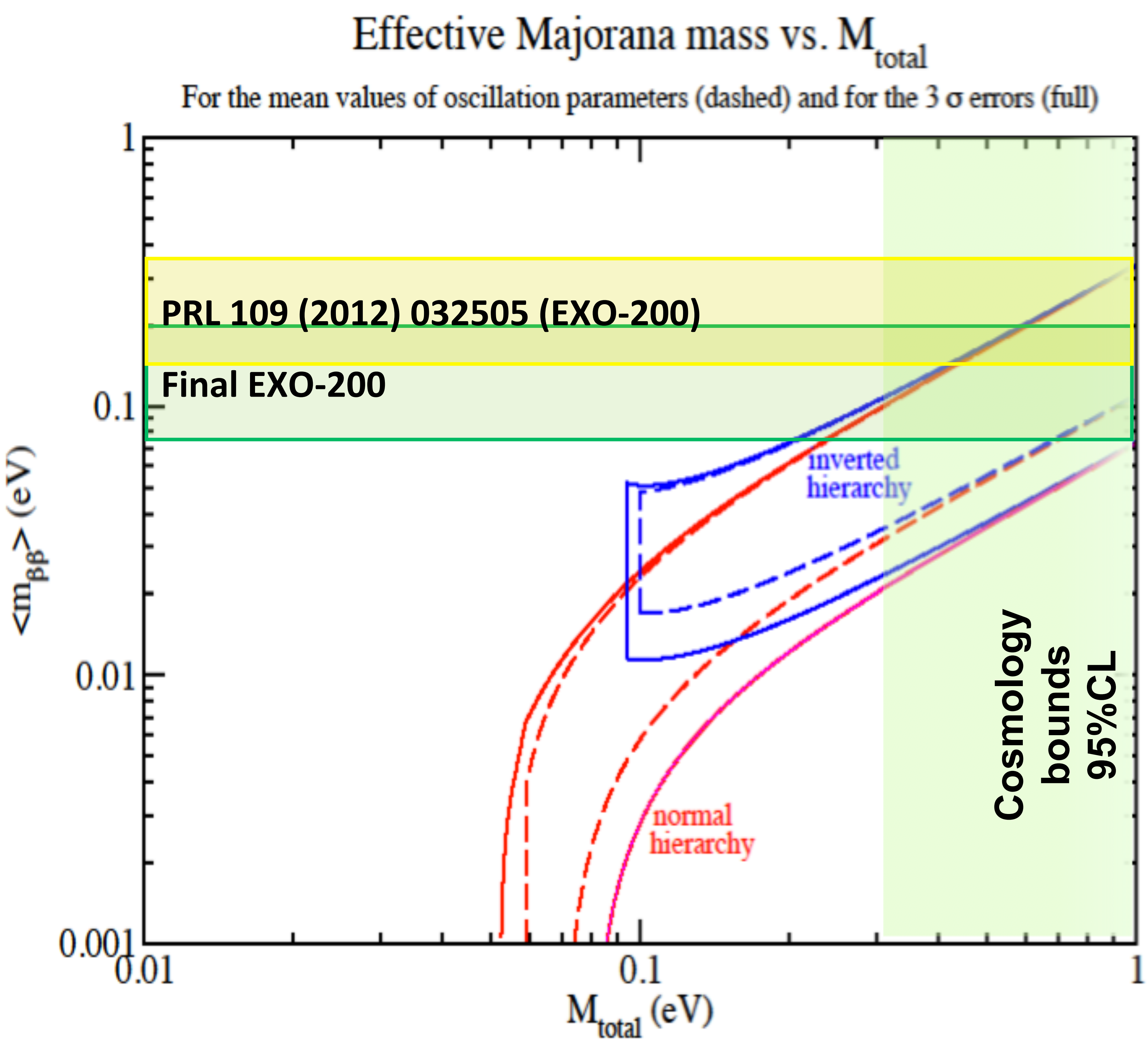
energy resolution

$$\frac{\sigma}{E}(Q) = 1.53$$

background index

$$(1.7 \pm 0.2) \times 10^{-3} \ \mathrm{cts/(keV \cdot kg \cdot y)}$$

Current and projected sensitivity



Final EXO-200:

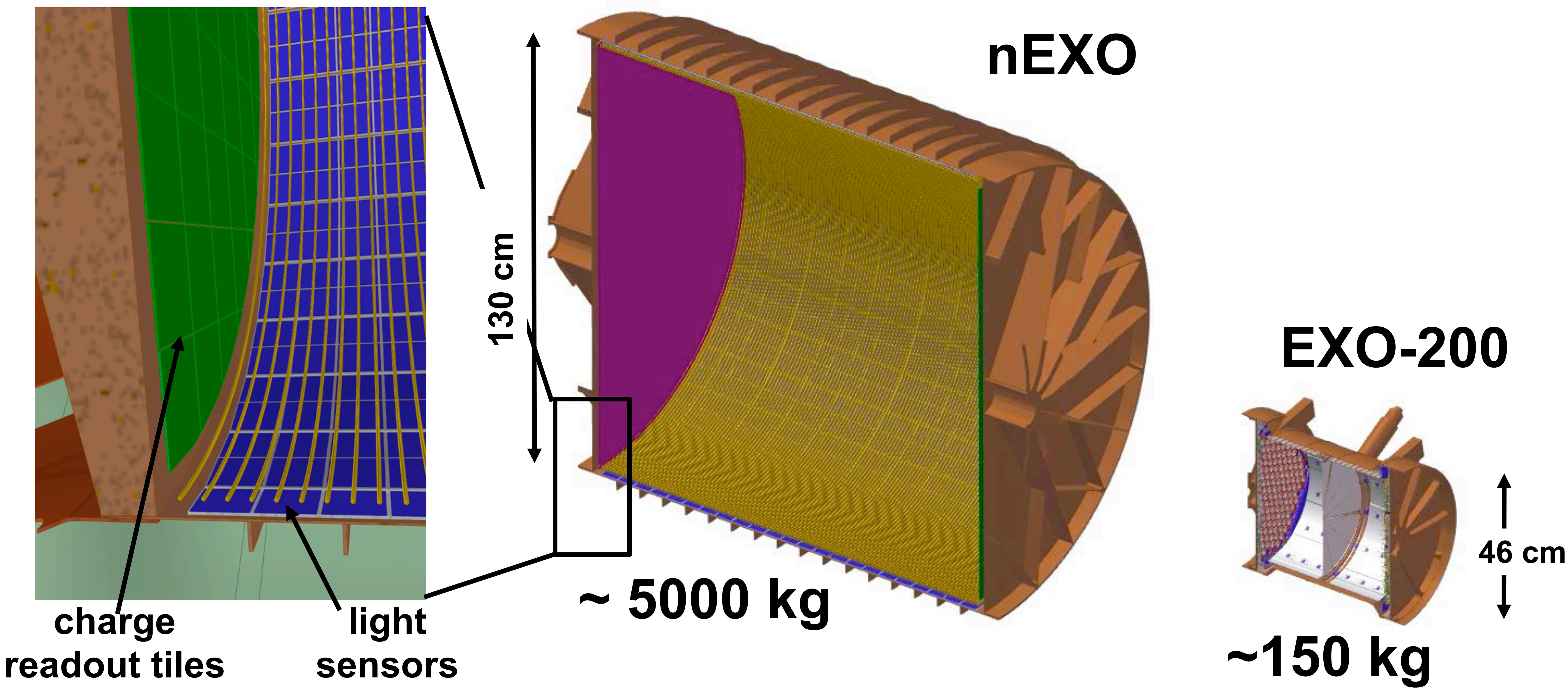
- Assume 2 more years with Rn suppression around the cryostat
- Upgrade of APD electronics to lower the noise
- Access to WIPP site has partially resumed

Next generation:

- Push sensitivity to cover the inverted neutrino mass hierarchy
- >10 tonne-year exposure with corresponding background reduction

nEXO TPC design concept

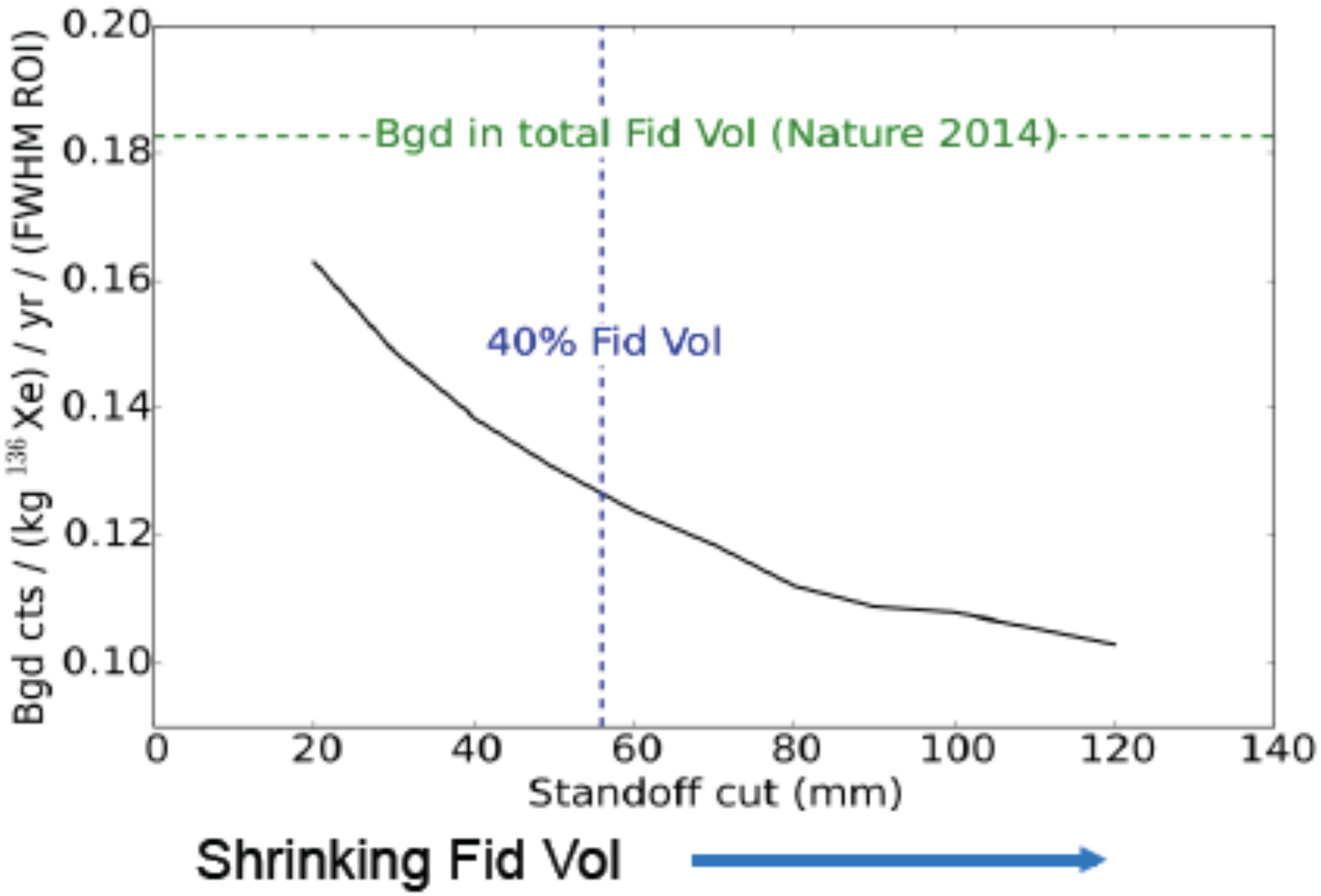
- Large (5 tonne) homogeneous enriched LXe TPC can allow large exposure and background suppression
- Inspired by EXO-200 design, and based on its demonstrated technology
- More powerful thanks to self-shielding

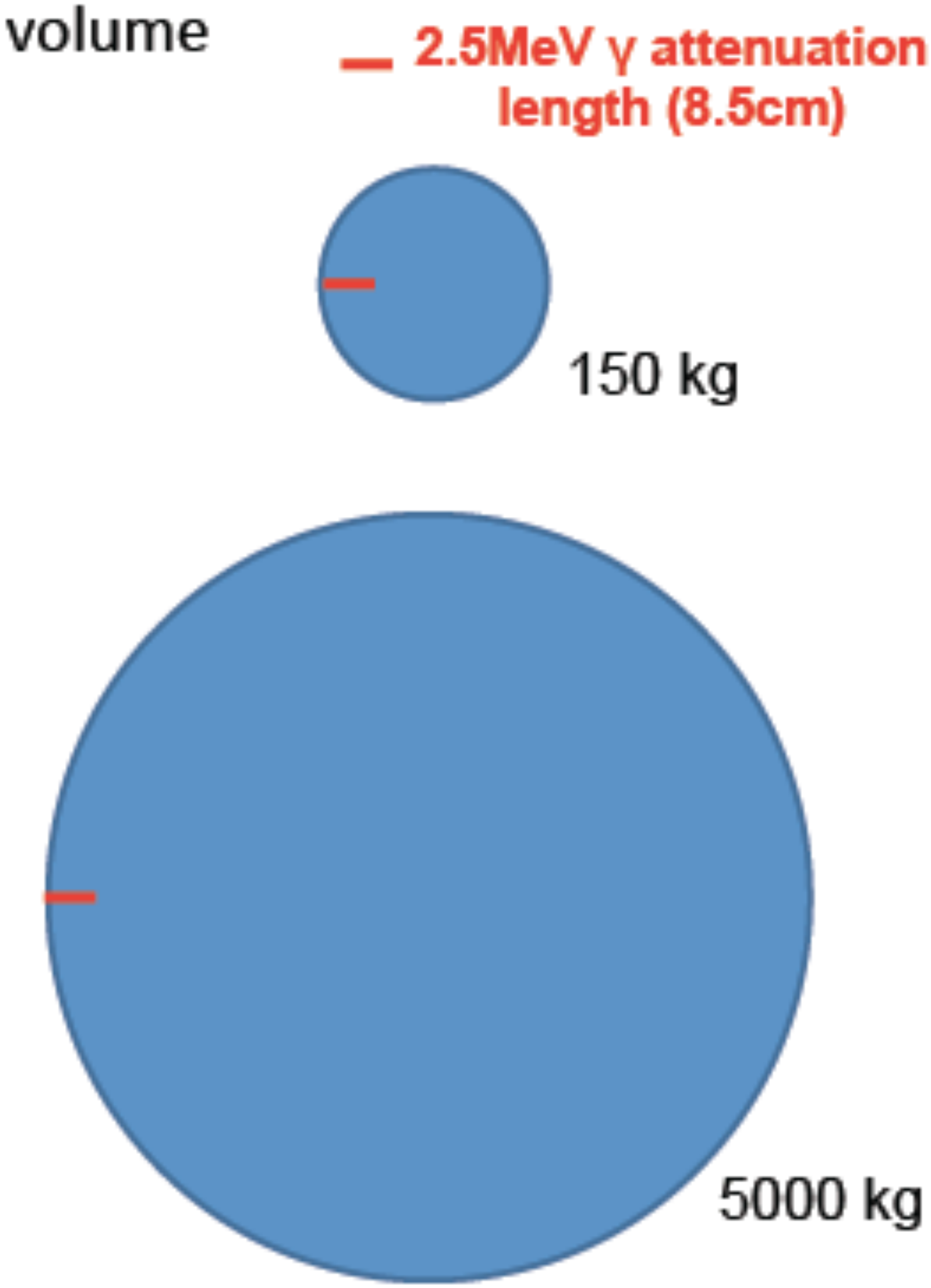


Self shielding

- A large, monolithic detector provides significant attenuation of external backgrounds in the central volume

Measured reduction in backgrounds vs. standoff, EXO-200:



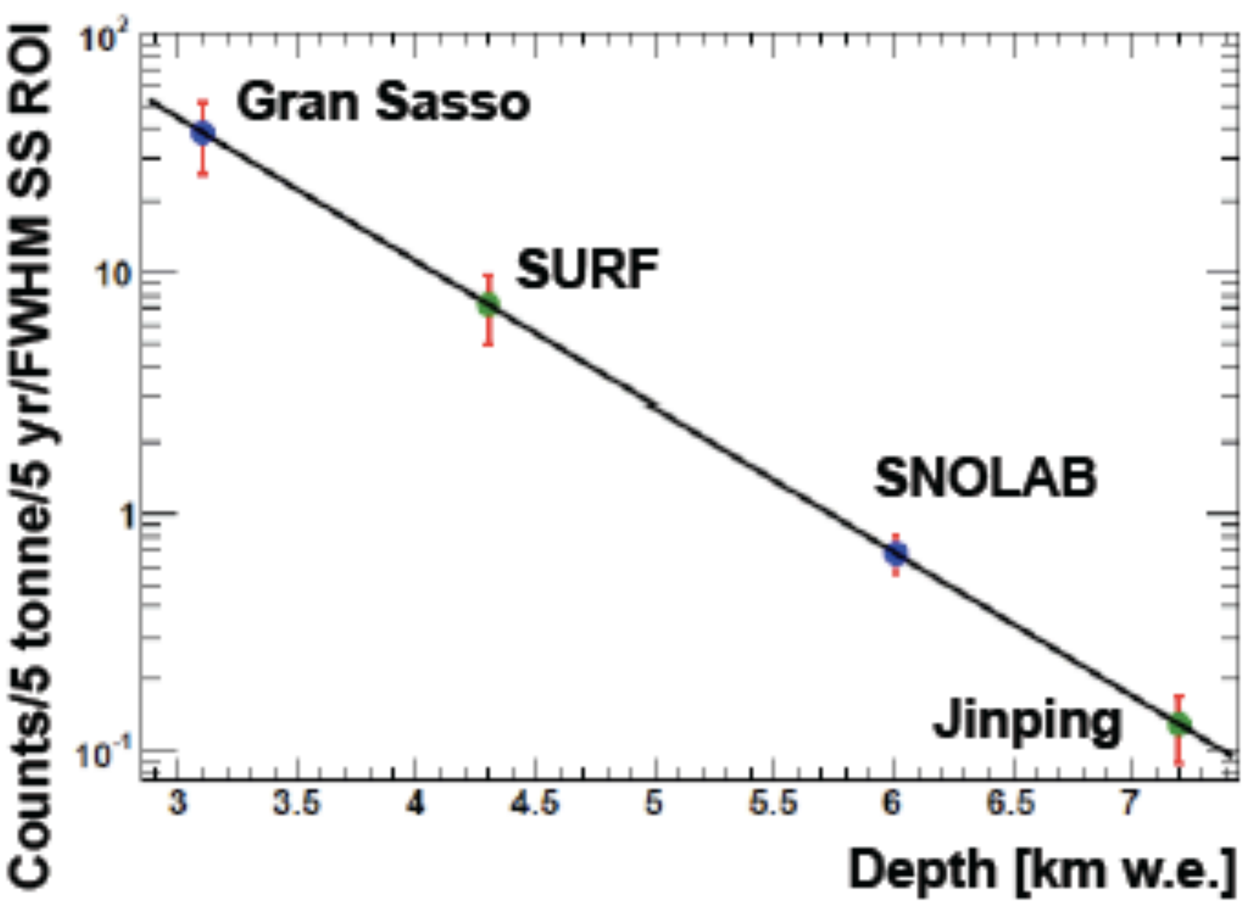


Choice of experimental site

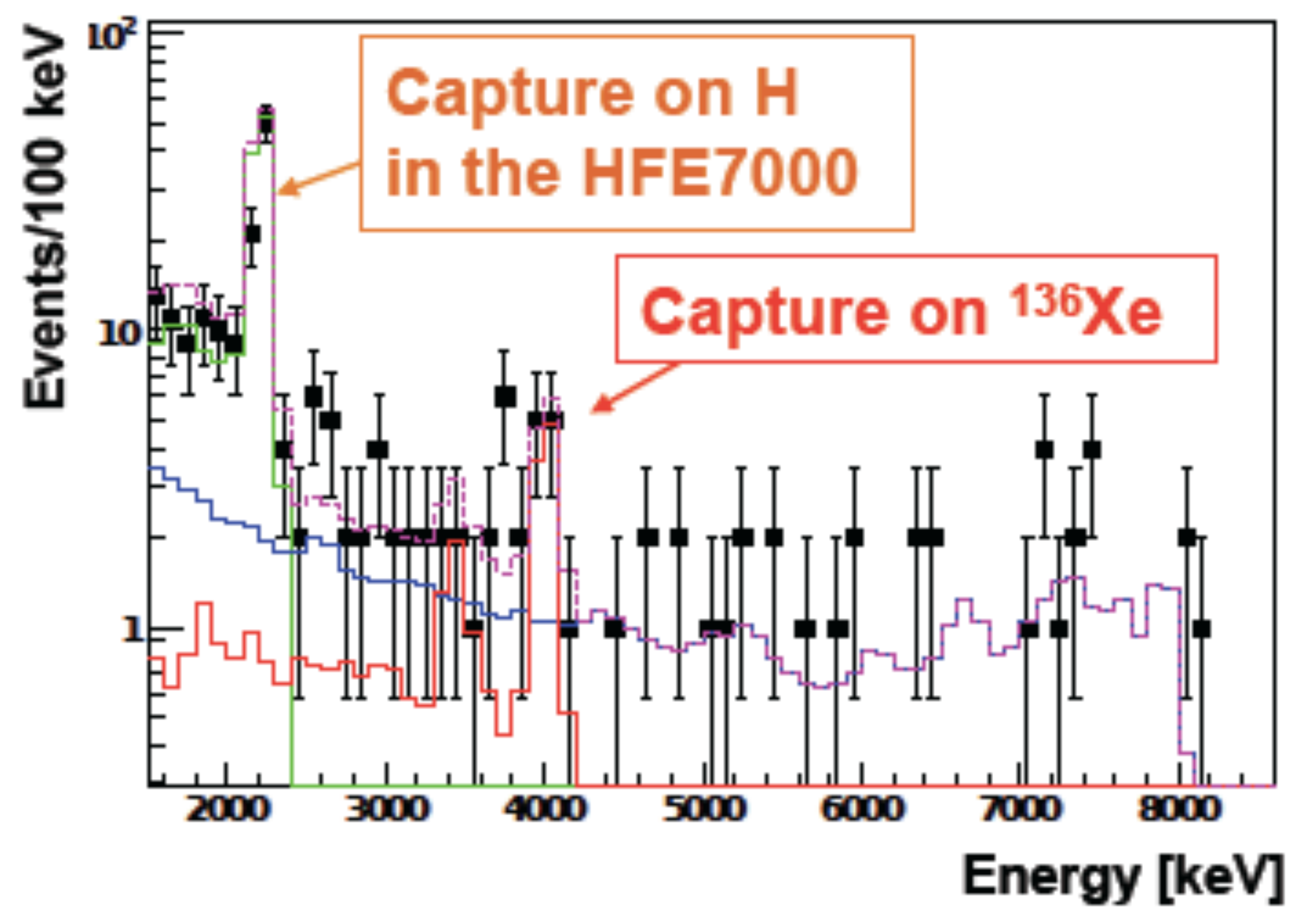
- Have simulated cosmogenic backgrounds for nEXO (cross-checked with EXO-200 data)
- Problematic backgrounds include β/γ emitters from n-capture (e.g. ^{137}Xe)

Site:	μ flux: [m^{-2} day]	Rock radioactivity: [Bq/kg] ^{232}Th:	^{238}U:
Gran Sasso (Italy)	22.3	0.25	5.18
SNOLAB (Canada)	**0.33**	**22.7**	**40.2**
Jinping (China)	~0.14	<0.27	1.8±0.2 (^{226}Ra)

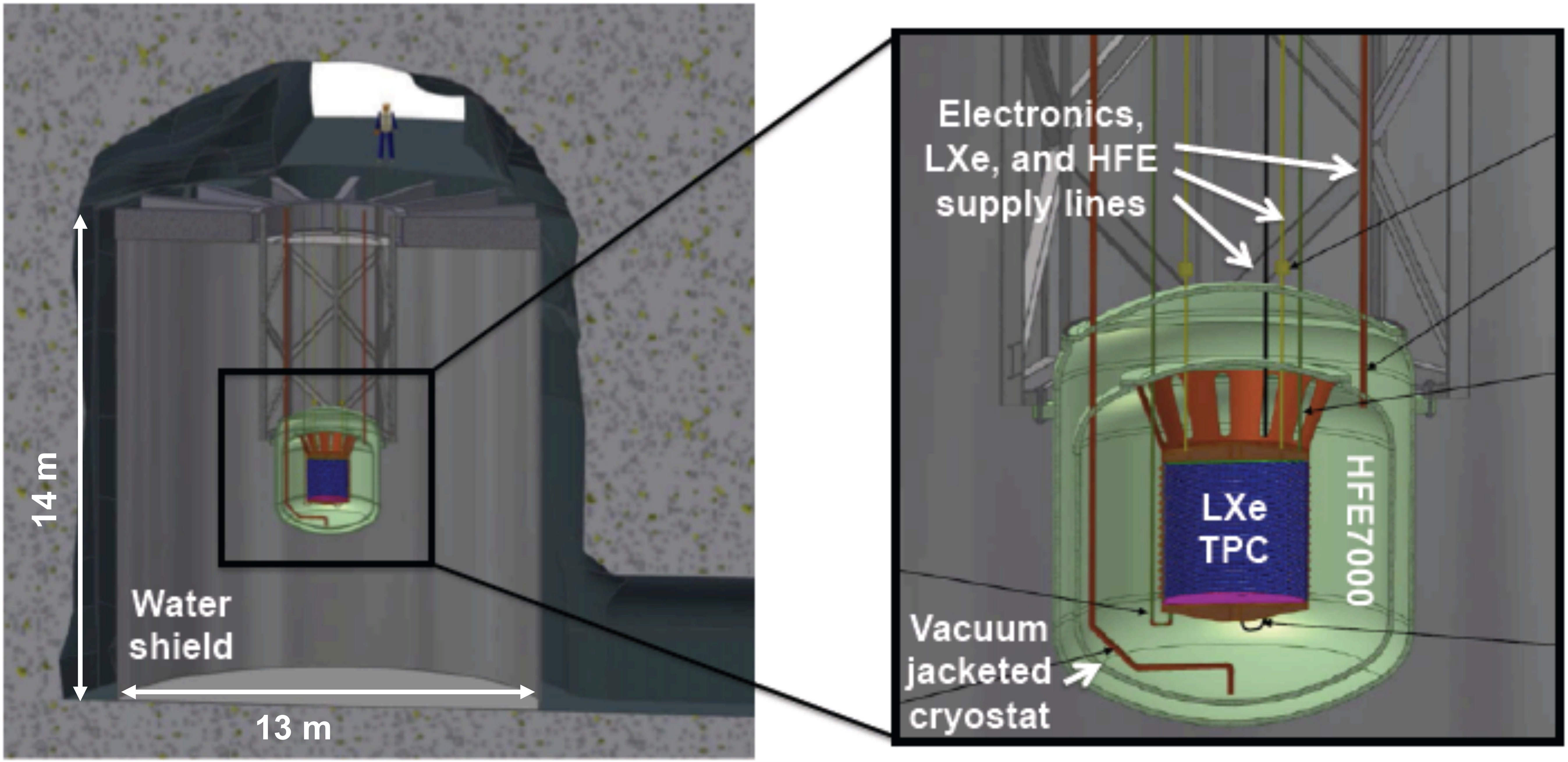
Cosmogenic background rate vs. site:



EXO-200 veto coincident spectrum:



Conceptual nEXO design at SNOLab

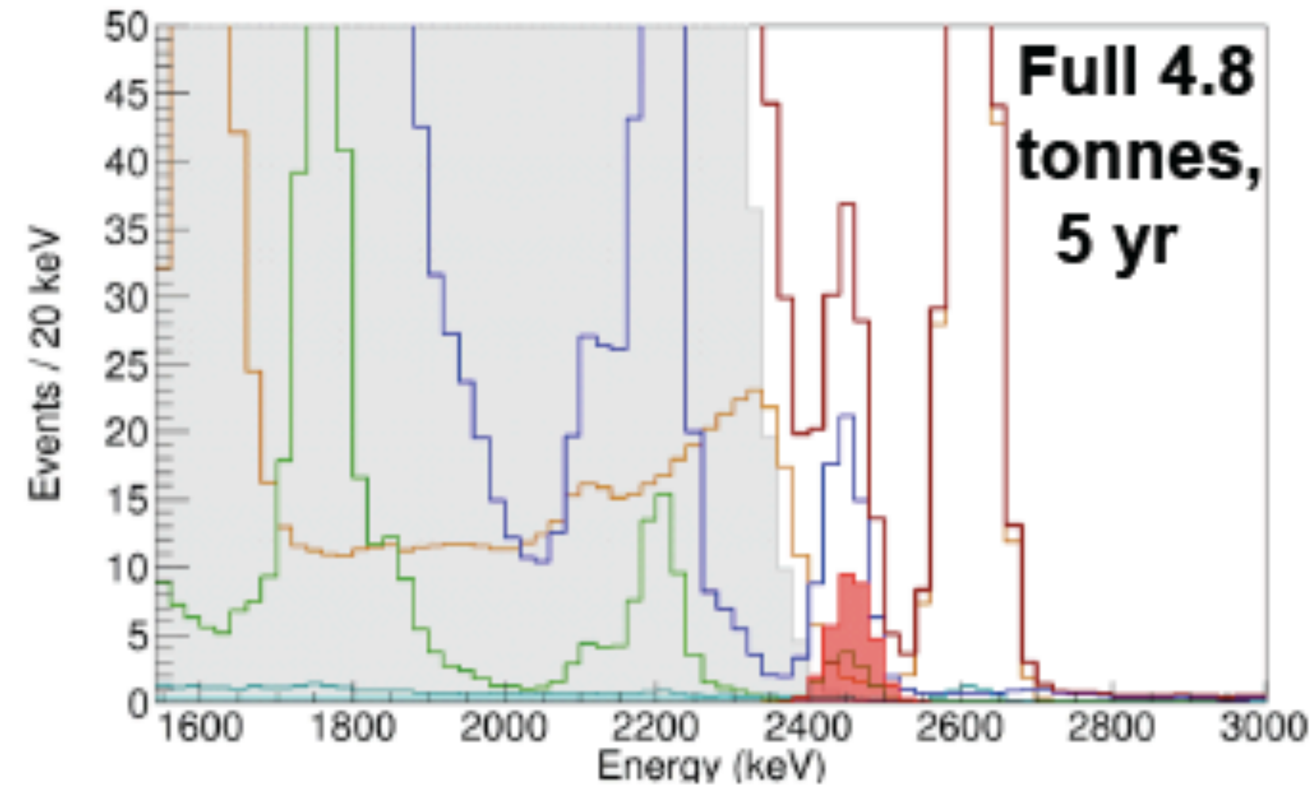


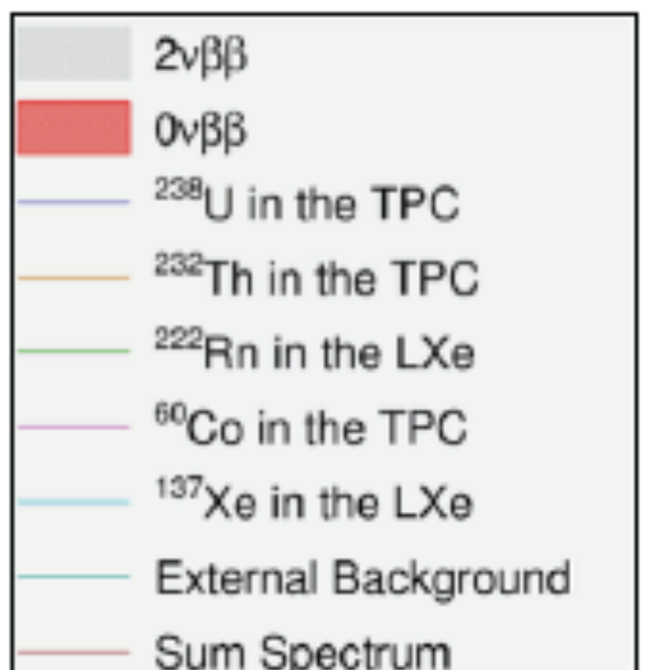
TPC: ~ 1.3 m x 1.3 m

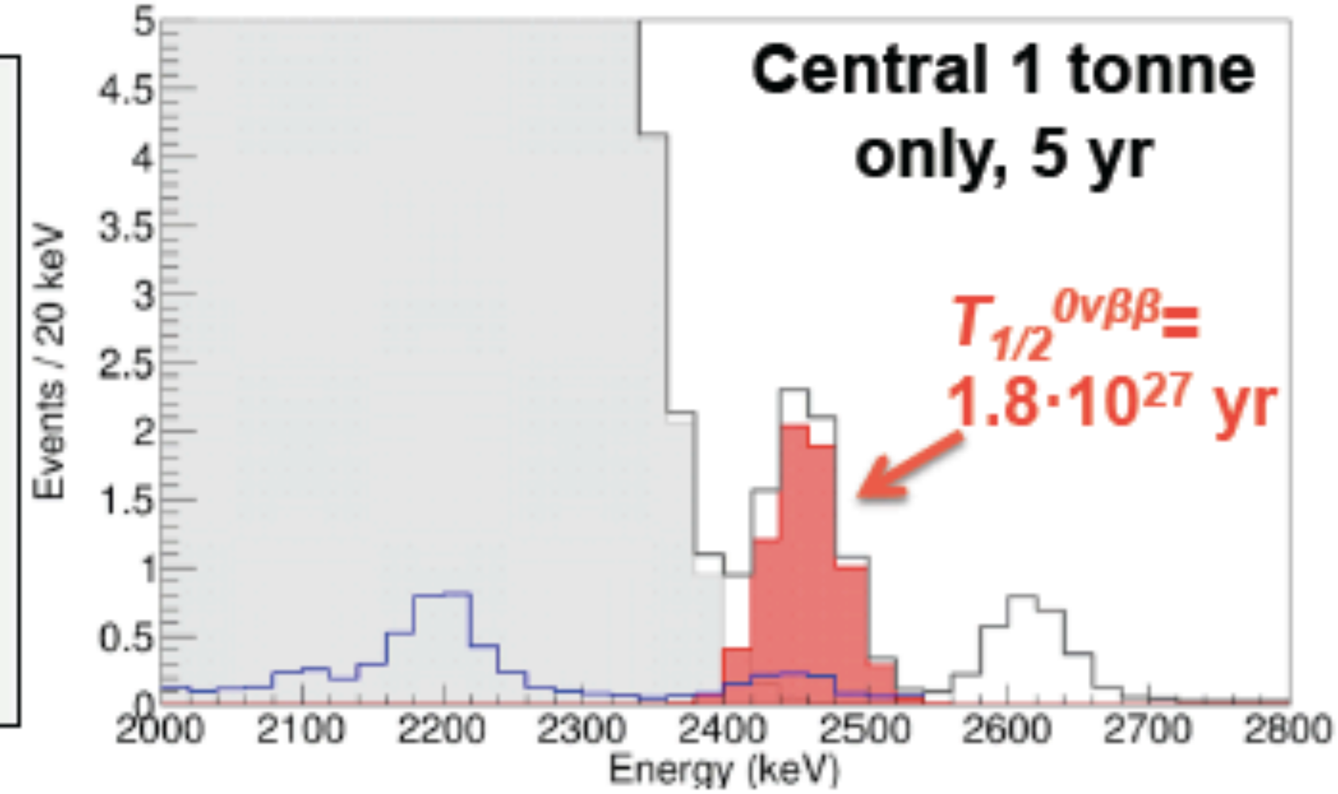
nEXO expected backgrounds and signals

- Have developed Geant4 simulation for nEXO, using experience gained from EXO-200
- Spectra on right show expected backgrounds in 5 yr exposure, and 0νββ at discovery threshold
- Background calculation assumes measured activity for detector materials
- This procedure was verified with EXO-200 data, and assumes several improvements for nEXO

Simulated nEXO spectrum near single-site ROI:







nEXO background simulation

- nEXO backgrounds assume measured activities for all detector materials

from EXO-200:

- have compared with EXO-200 data to confirm validity of our assumptions
- Measured background rate from EXO-200 is ***$B_{EXO\text{-}200}$ = 151±19 counts/(ROI t yr)***
  (ROI = $Q_{\beta\beta}$ ± 0.5 FWHM, Nature 510, 9 (2014))
- Agrees with predicted nEXO rate in outer 16.2 cm under the same assumptions

nEXO improvements:

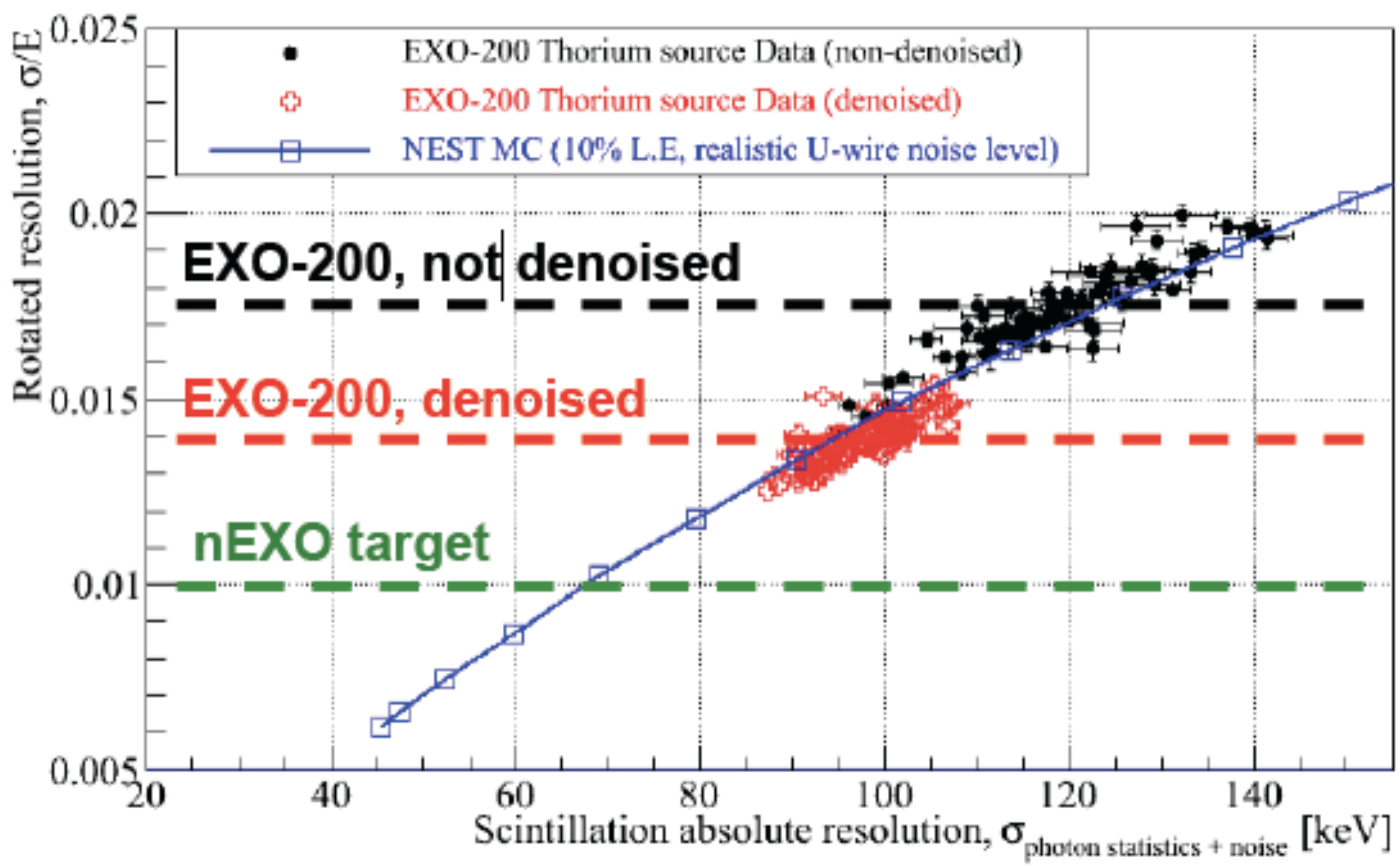
  - improved energy resolution ($\sigma/Q_{\beta\beta}$ = 0.01)
  - improved SS/MS discrimination (wire pitch = 3mm)
  - improved Cu activity from more sensitive radio assay (done)
  - lower 136Xe rate at SNOLab
  - reduced Rn density (lower surface/volume), longer 214BiPo cut
  - no kapton cables (cold electronics)

- total nEXO background prediction in outer 16.2 cm = ***Bn_{EXO} = 3.7 counts/(ROI t yr)***,
  a 40x background index improvement with respect to EXO-200

Energy resolution

- $\sigma/Q_{\beta\beta}$ = 1% requires minimal readout noise in scintillation and charge readout
- Have demonstrated 1.4% resolution in EXO-200; simulations indicate that 1% resolution is attainable with improved readout electronics for light channels
- This will be tested with EXO-200 upgrades

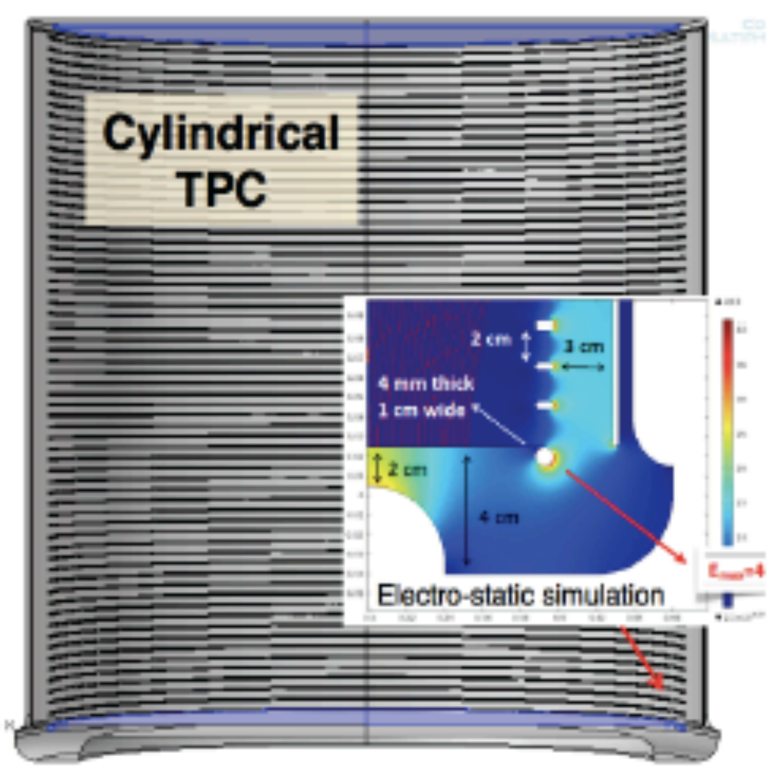
Simulated rotated resolution vs. readout noise:



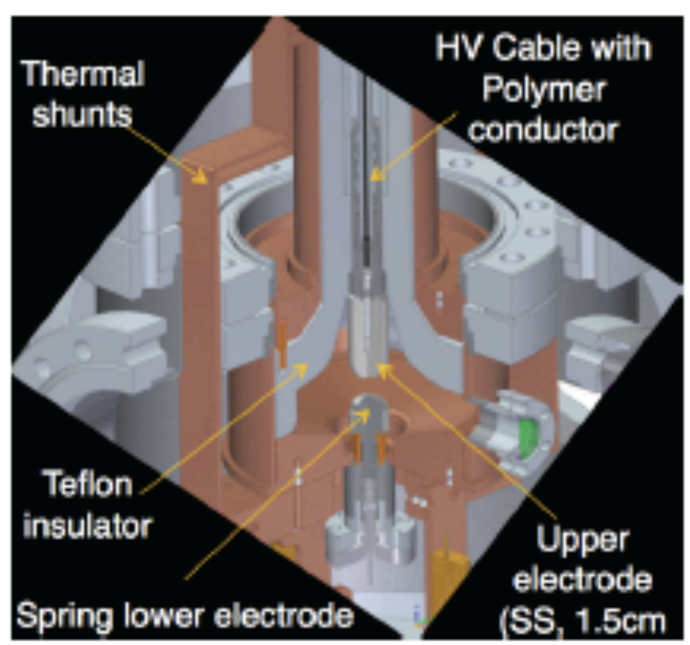
nEXO R&D in progress

- Field Cage and Xe vessel design, electrostatic simulations, light collection simulations
- Characterization of light sensors (Silicon Photo Multipliers)
- Passive optics (reflectors, no PTFE)
- Design and testing of charge readout tiles
- Low radioactivity, in-Xenon readout electronics
- High voltage testing and prototyping
- Cryostat design

TPC E-field simulations:

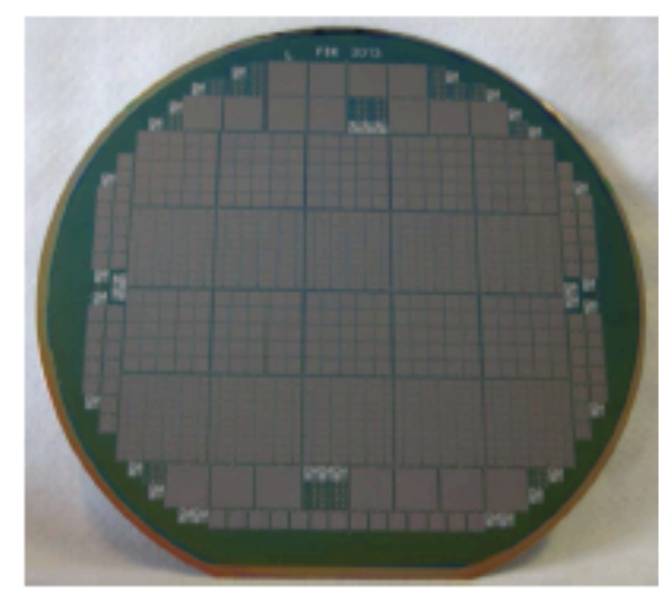


HV testing setup:



Charge readout LXe test cell:

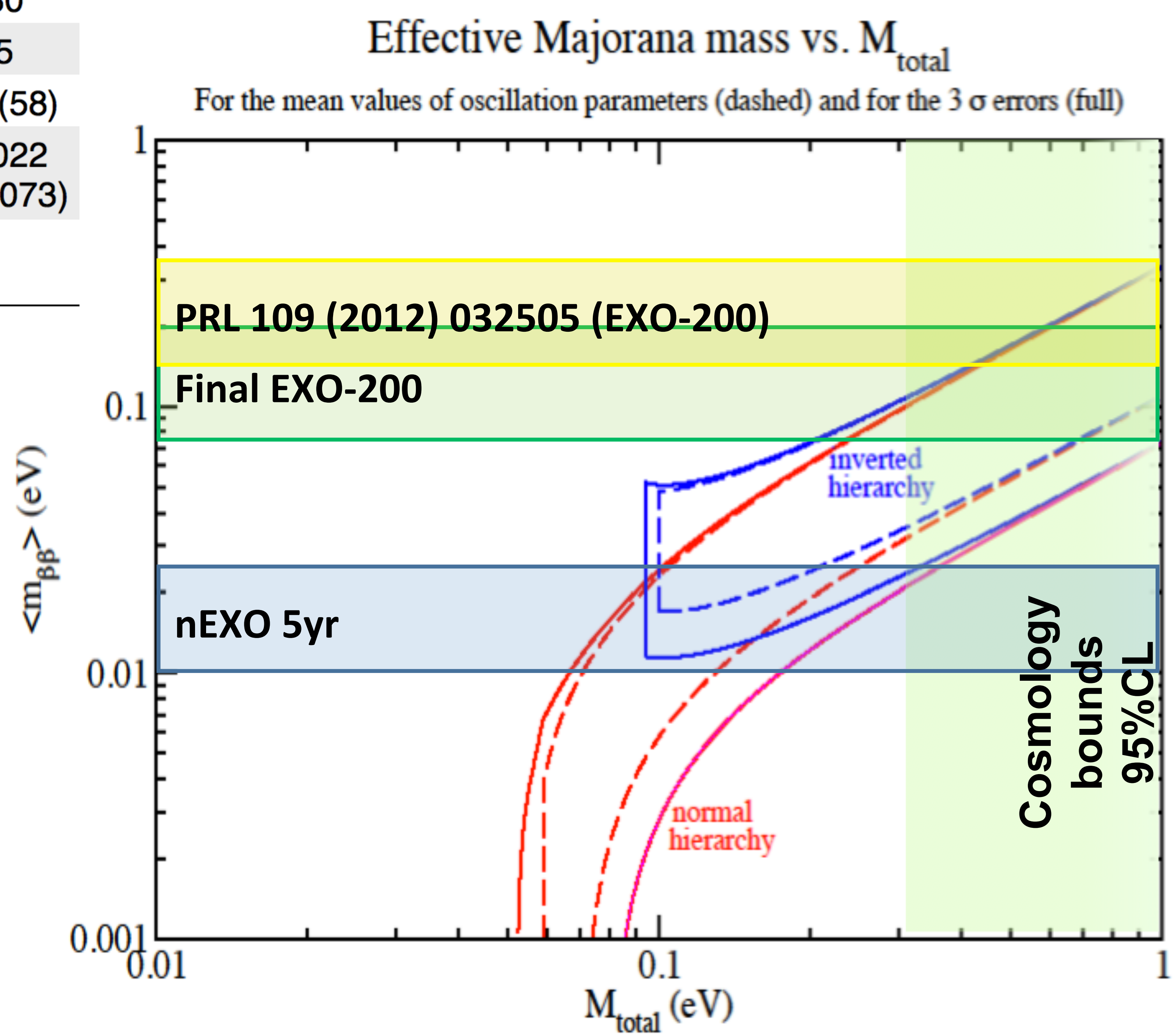
SiPMs:



nEXO sensitivity

Parameter	nEXO	EXO-200
Fiducial Mass (kg)	4780	98.5
Enrichment (%)	90	80
Data taking time (yr)	5	5
Energy resolution @ $Q_{\beta\beta}$ (keV)	58	88 (58)
Background wthin FWHM of endpoint ($evts/yr/mol_{136}$)	$6.1 \cdot 10^{-4}$	0.022 (0.0073)
Background within FWHM of endpoint inner 3000kg ($evts/yr/mol_{136}$)	$1.6 \cdot 10^{-4}$	

- Sensitivity computed using background simulations
- Self shielding gives significantly lower backgrounds, especially in innermost volume
- Possible upgrade to include daughter Ba tagging



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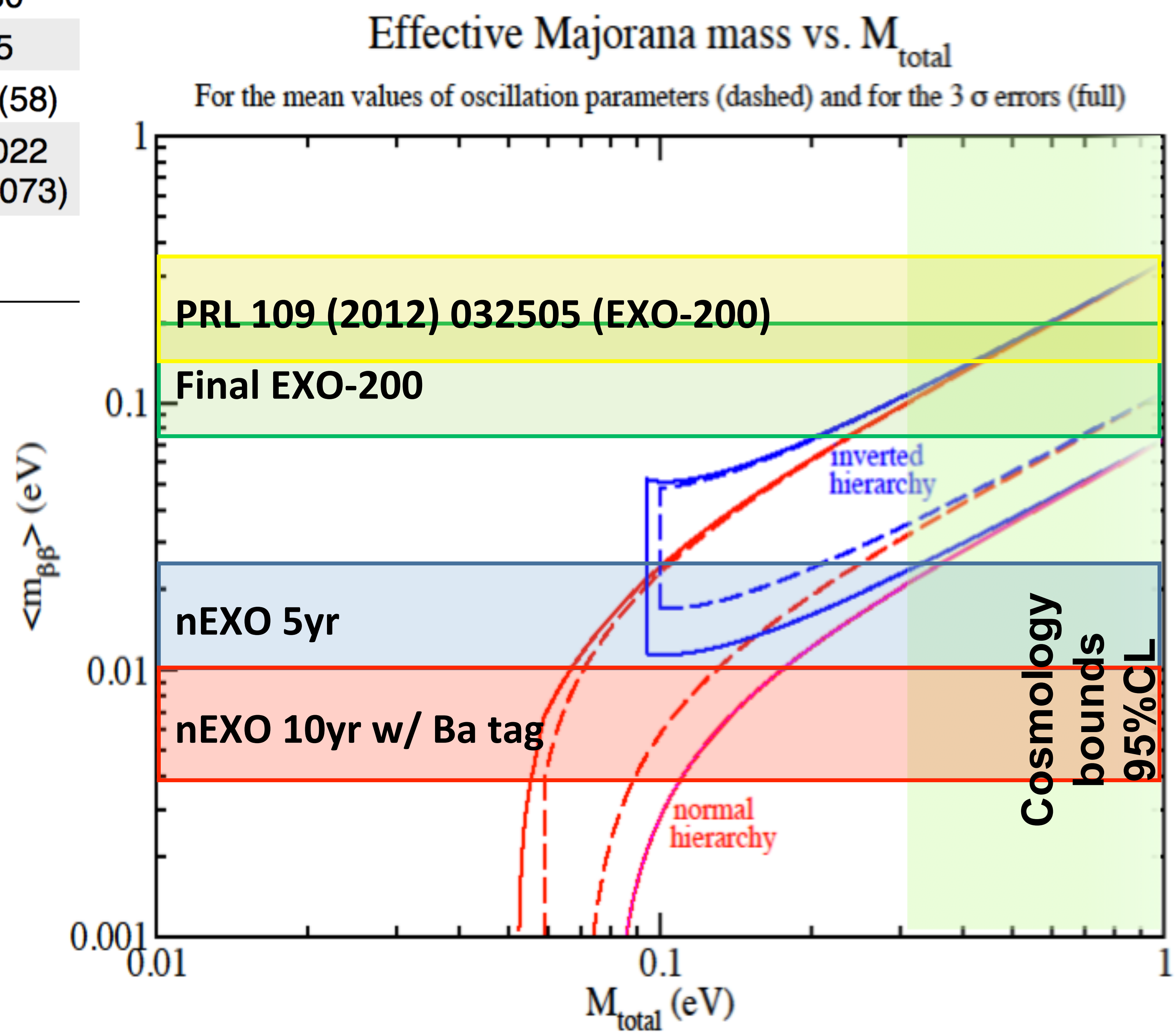
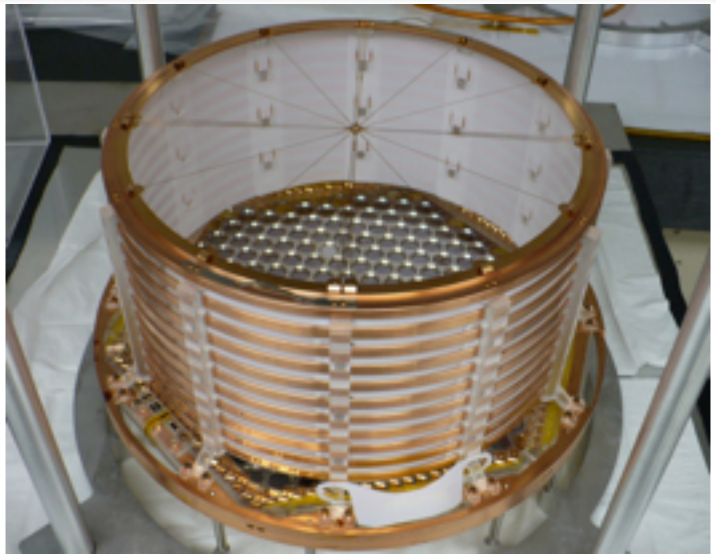
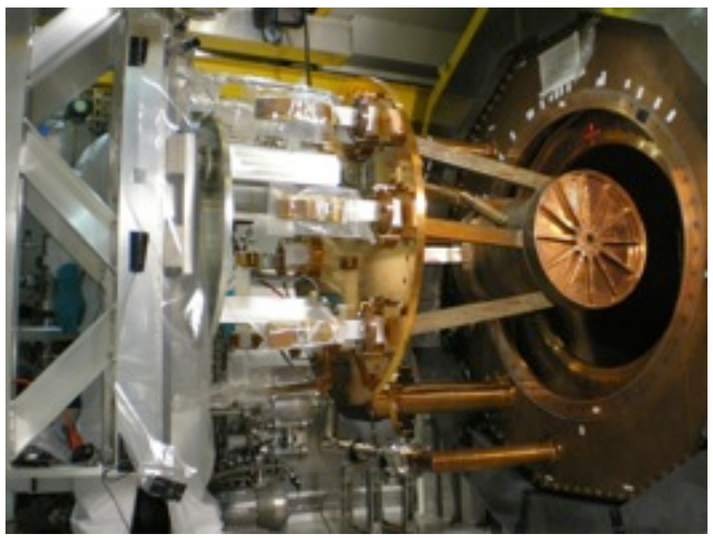
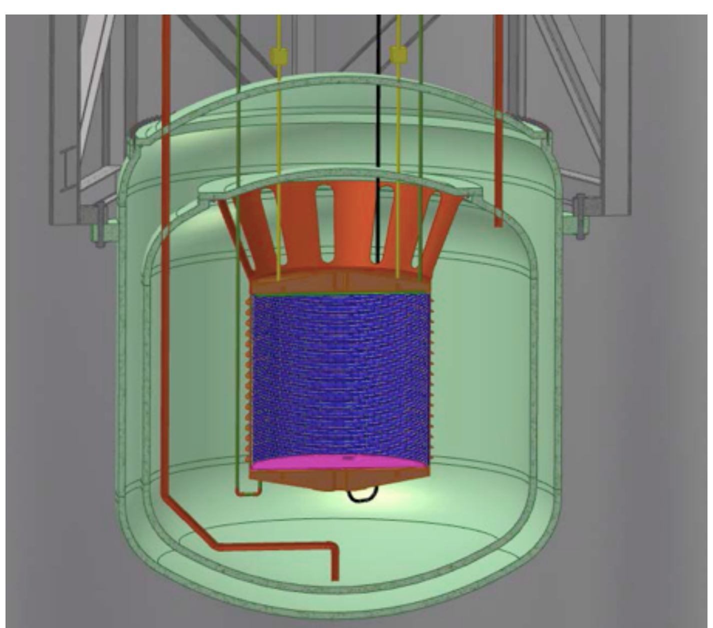


Summary

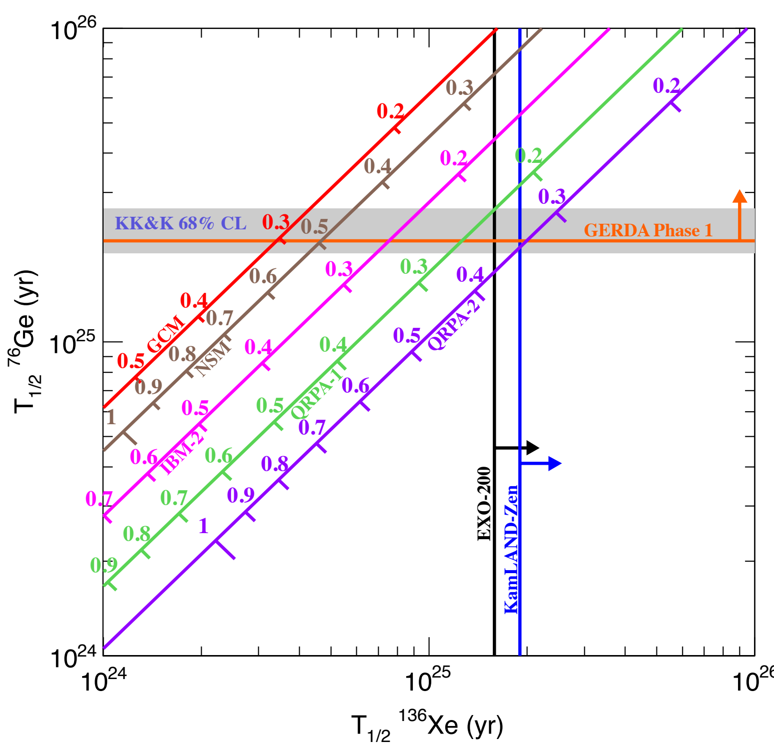
stay hungry, my friend

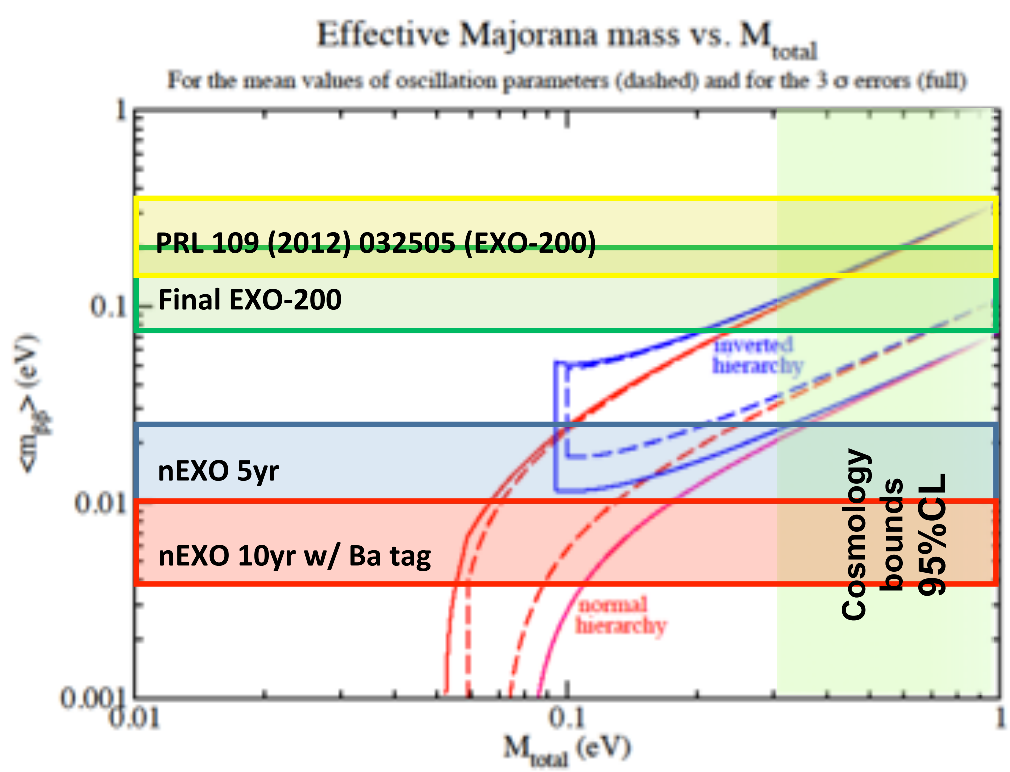




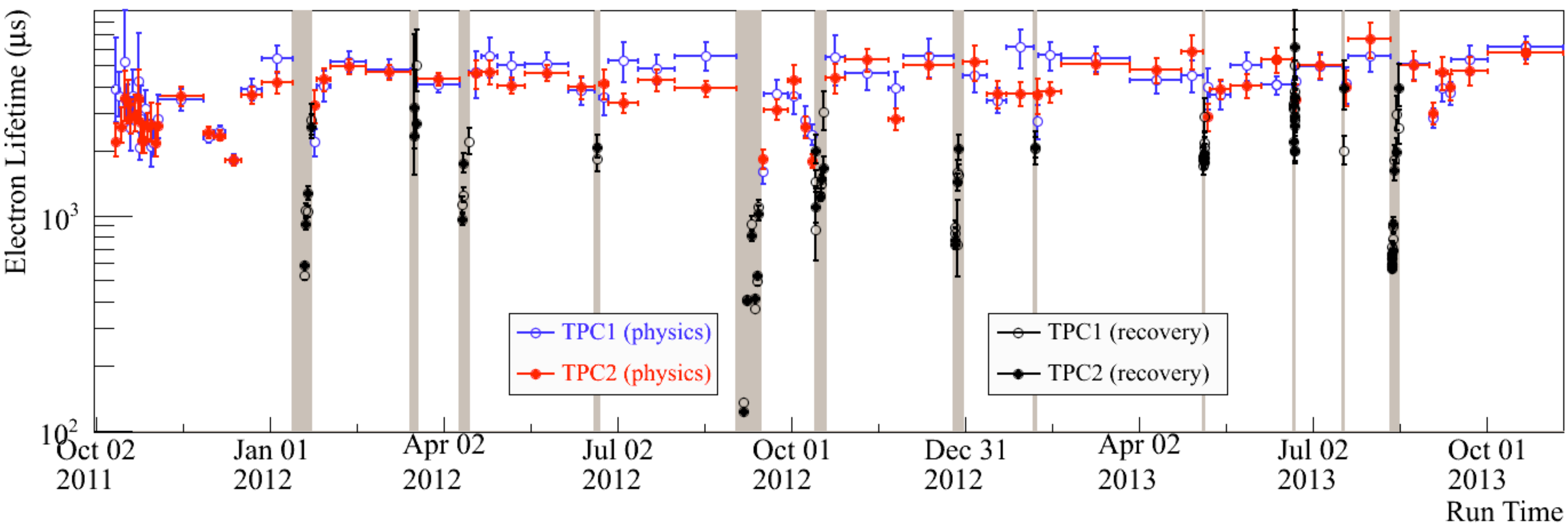


- EXO-200 has been continuously taking data since June 2011, and has met the design goals
- Announced first observation of 2νββ in ^{136}Xe in 2011, most precise one (3% uncertainty) in 2013 (not covered in this talk)
- Competitive limits on the 0νββ mode with 2011-13 run: $T_{1/2}^{0\nu\beta\beta} > 1.1\ 10^{25}$ yr
- EXO-200 data taking stopped due to WIPP closure, run with upgraded could resume as early as Fall 2014
- R&D for a 5 tonne nEXO experiment well under way
- Design based on EXO-200, but makes full use of self shielding and EXO-200 experience





xenon purity from electronegative species

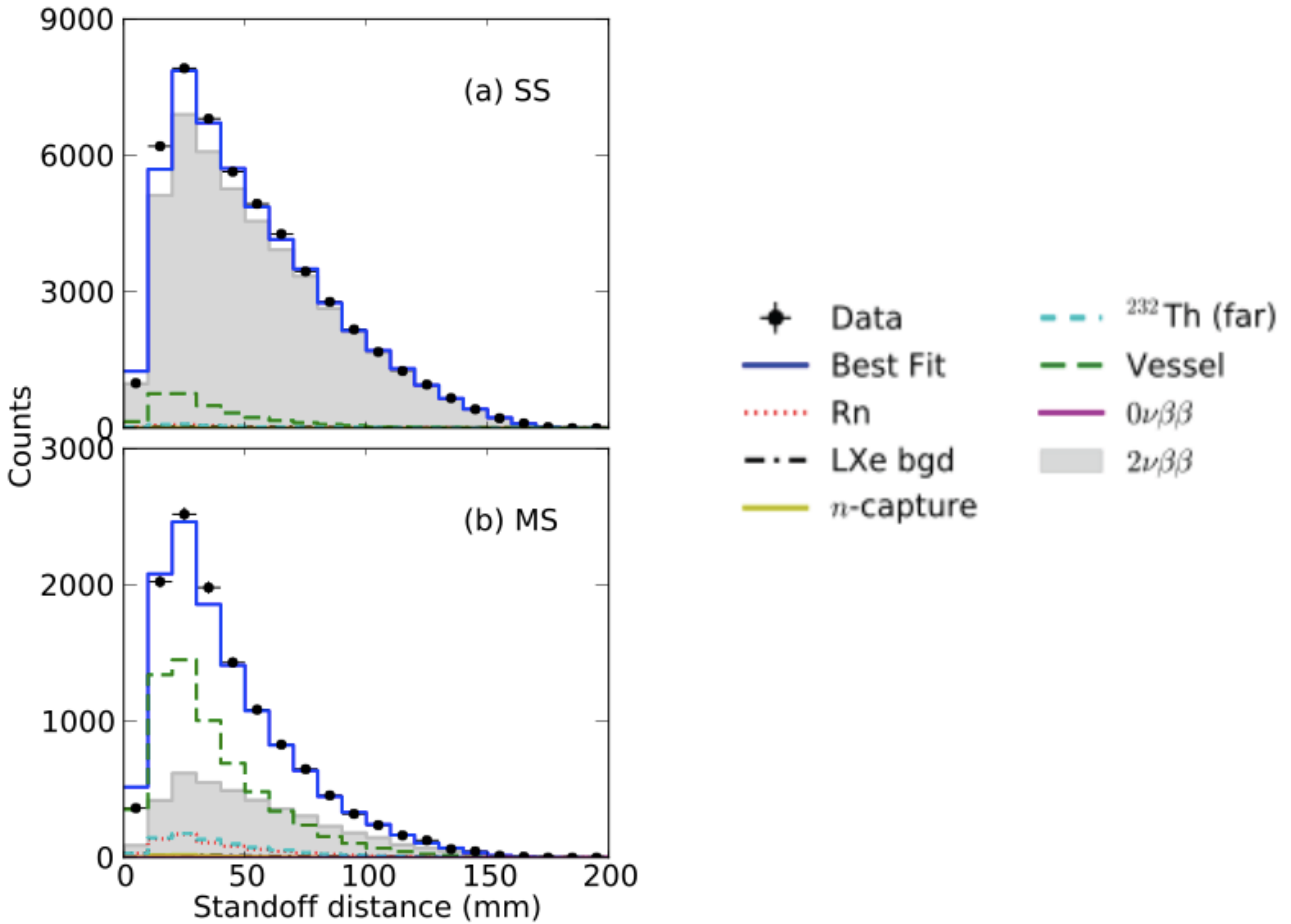


Xenon gas is forced through heated Zr getter by a custom ultraclean pump.

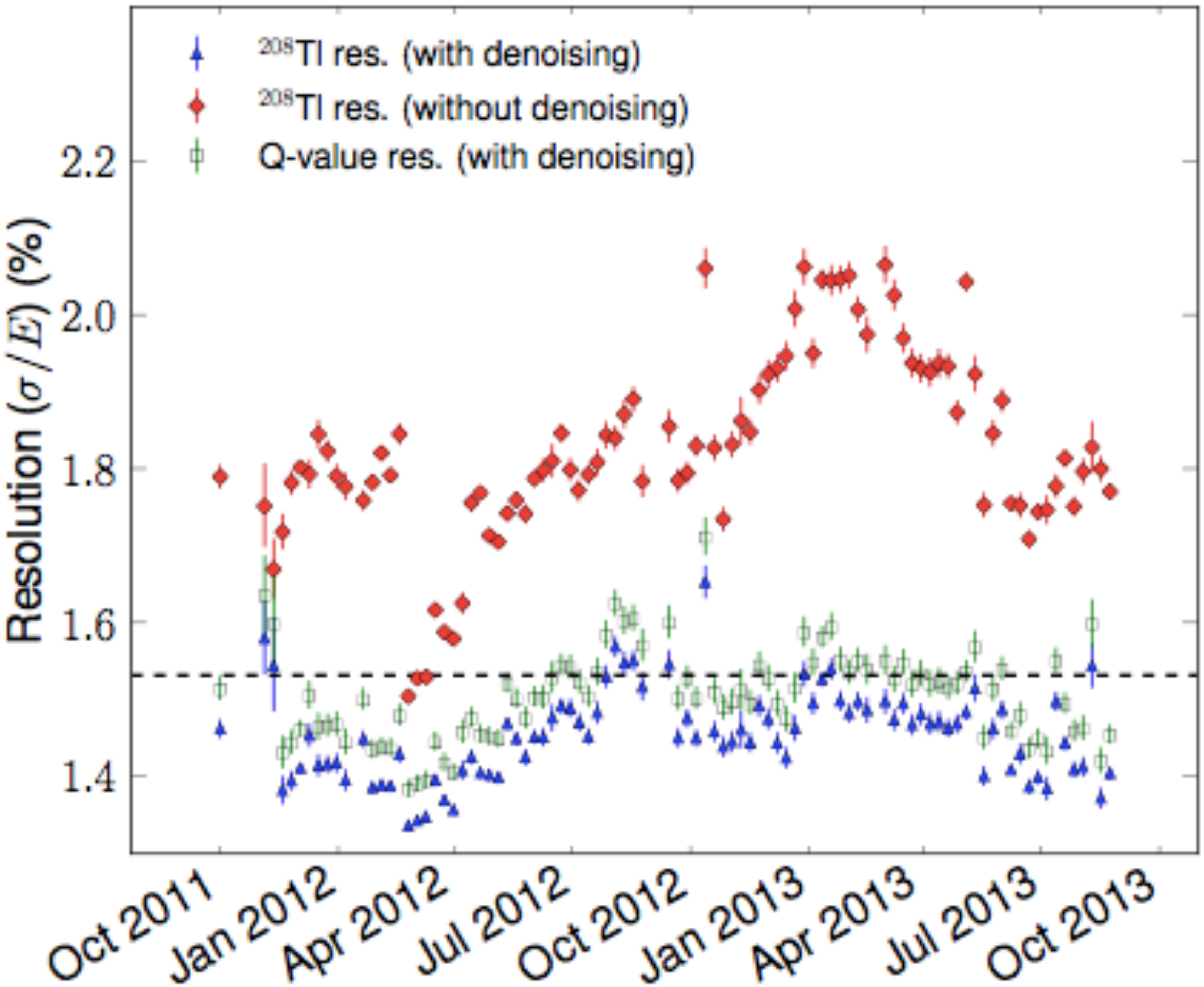
At τ_e = 3 ms:
- drift time <110 μs
- loss of charge: 3.6% at full drift length

Ultraclean pump: *Rev SciInstr. 82 (10) 105114*
Xenon purity with mass spec: *NIM A675 (2012) 40*
Gas purity monitors: *NIM A659 (2011) 215*

Run 2, standoff distance projection

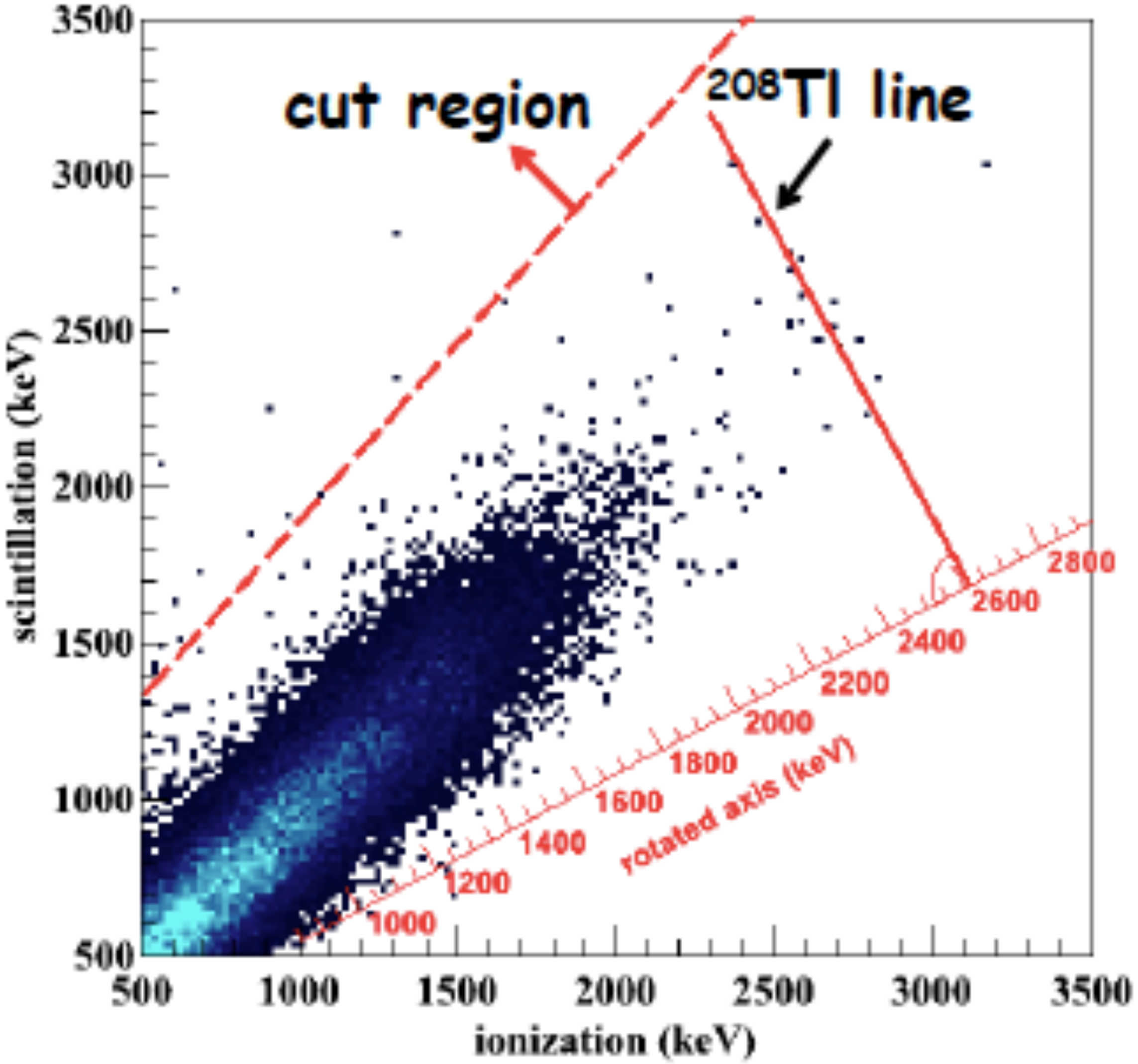


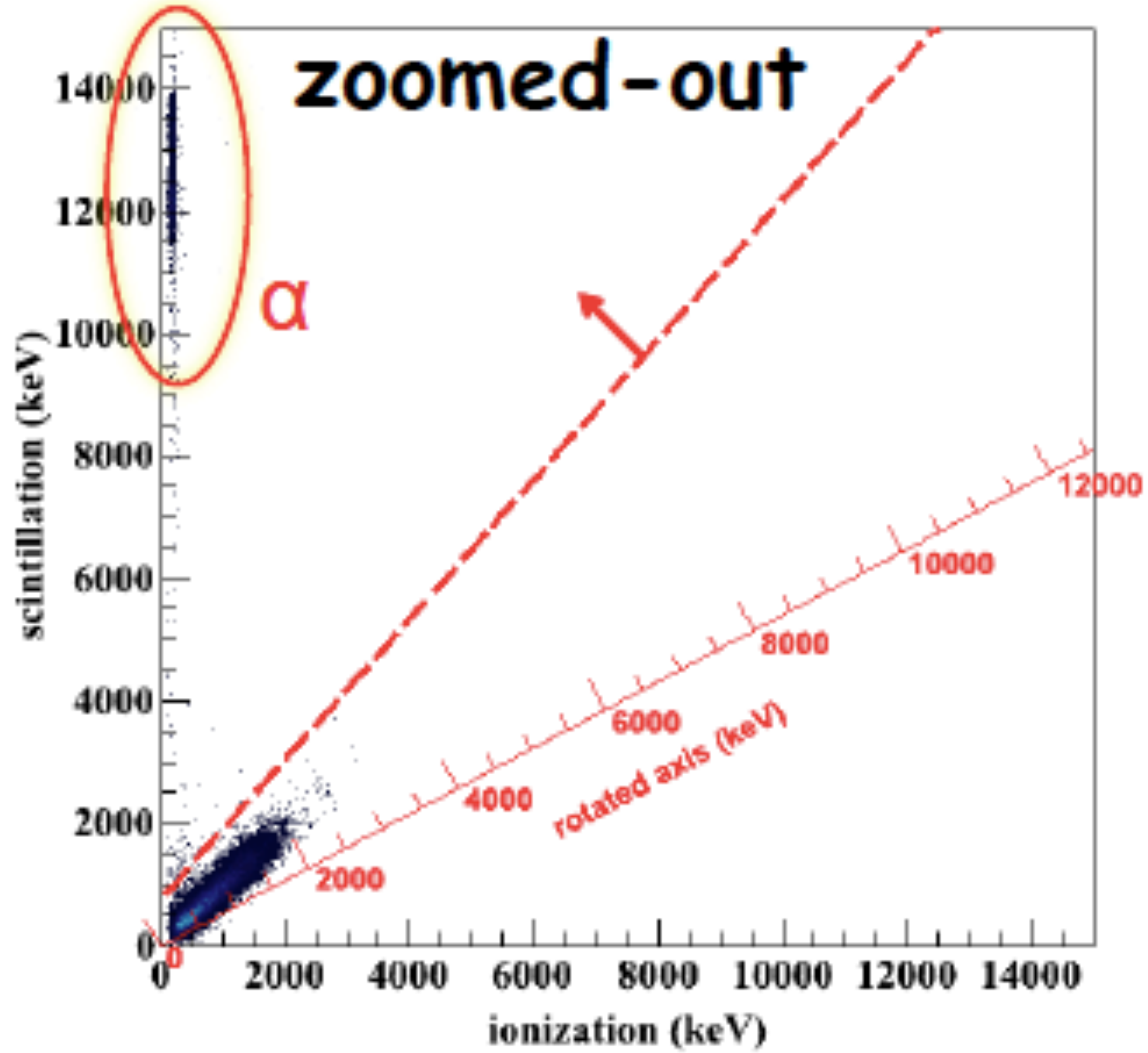
LAAPD denoising



1.53 % in SS at 0νββ Q-value

alpha decay identification



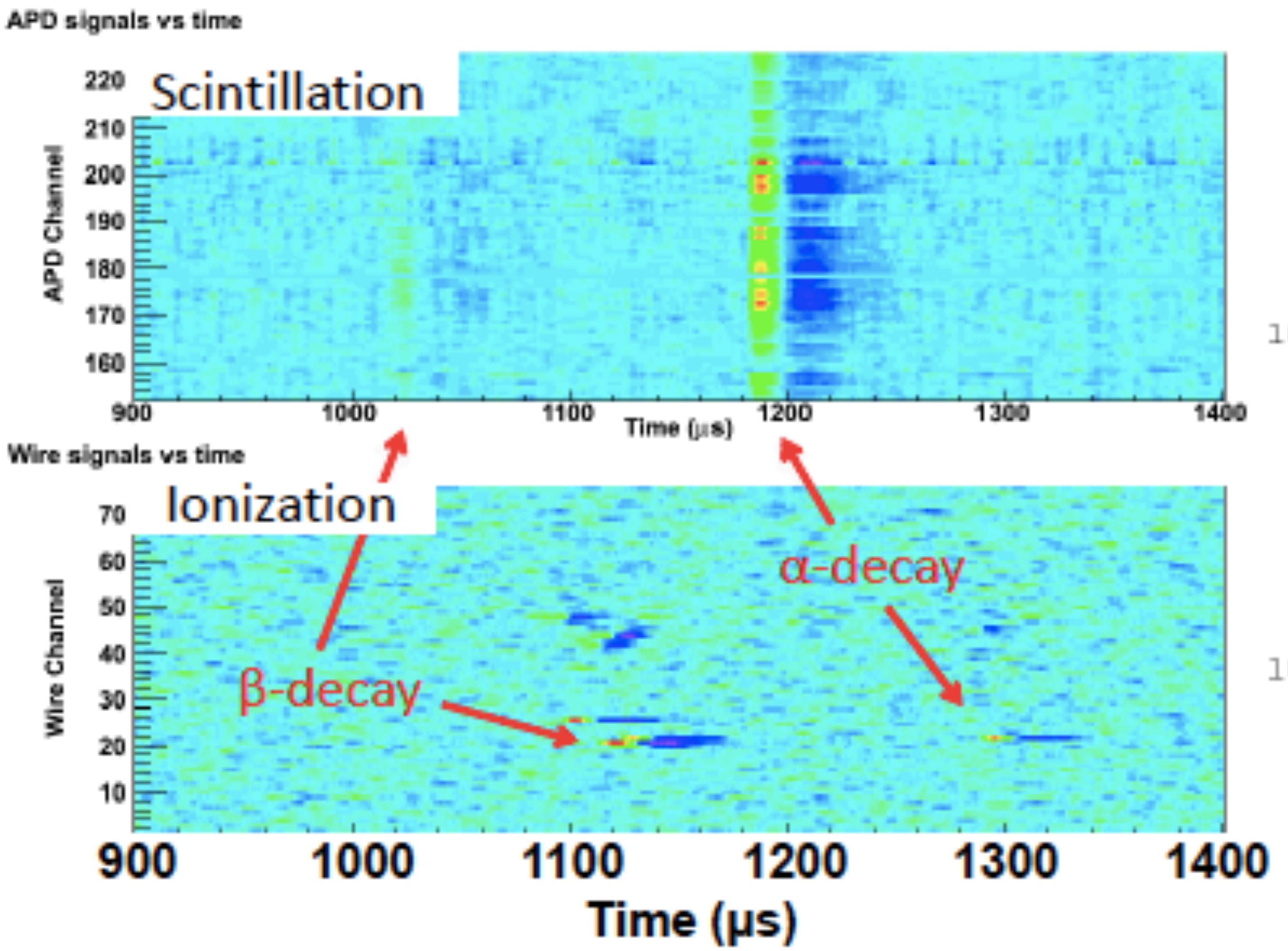


a diagonal cut (large scintillation, low charge) eliminates:

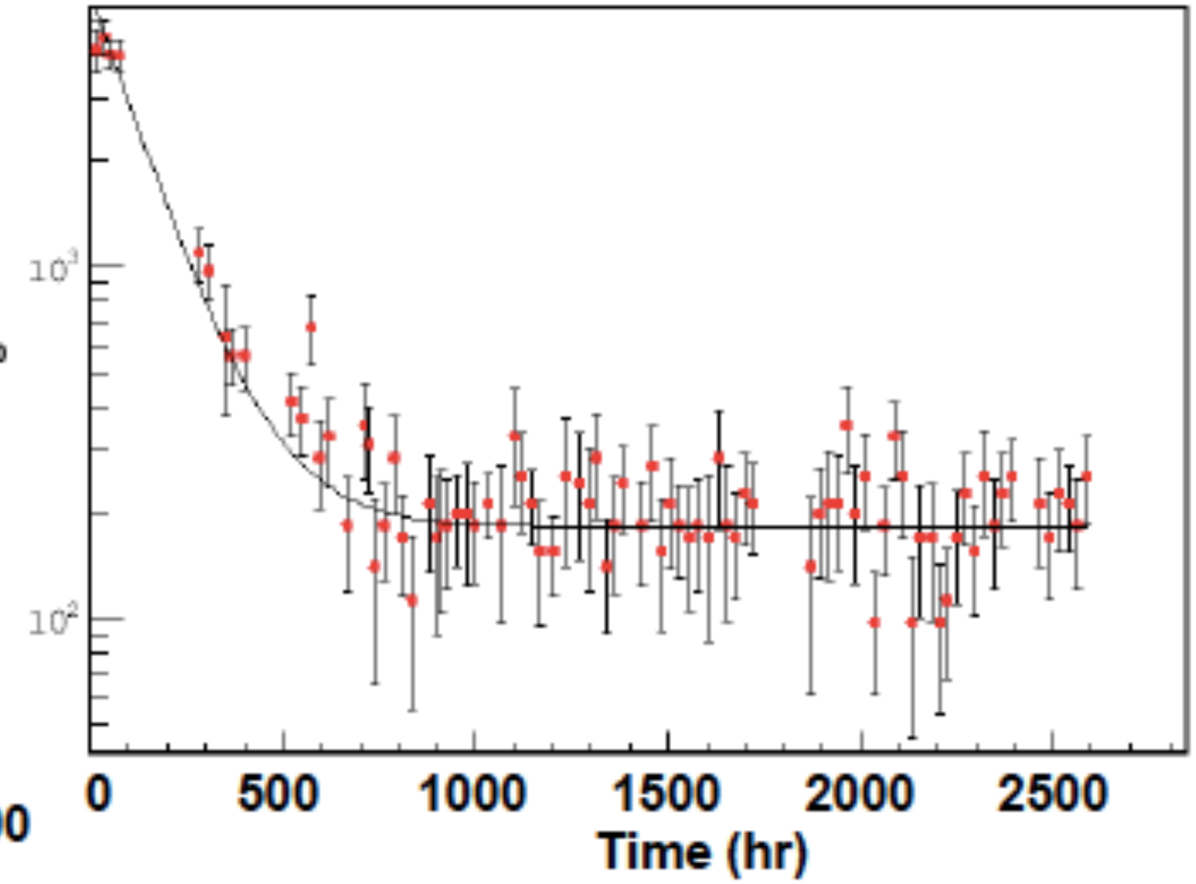
1) alphas

2) edge events (partial charge collection)

Radon in EXO-200



^{214}Bi – ^{214}Po correlations in the EXO-200 detector



Total ^{222}Rn in LXe after initial fill

Long term study shows a constant source of ^{222}Rn dissolving in ^{enr}LXe: 360 ± 65 μBq (Fid. vol.)

or 200 atoms of ^{222}Rn in our Xenon!

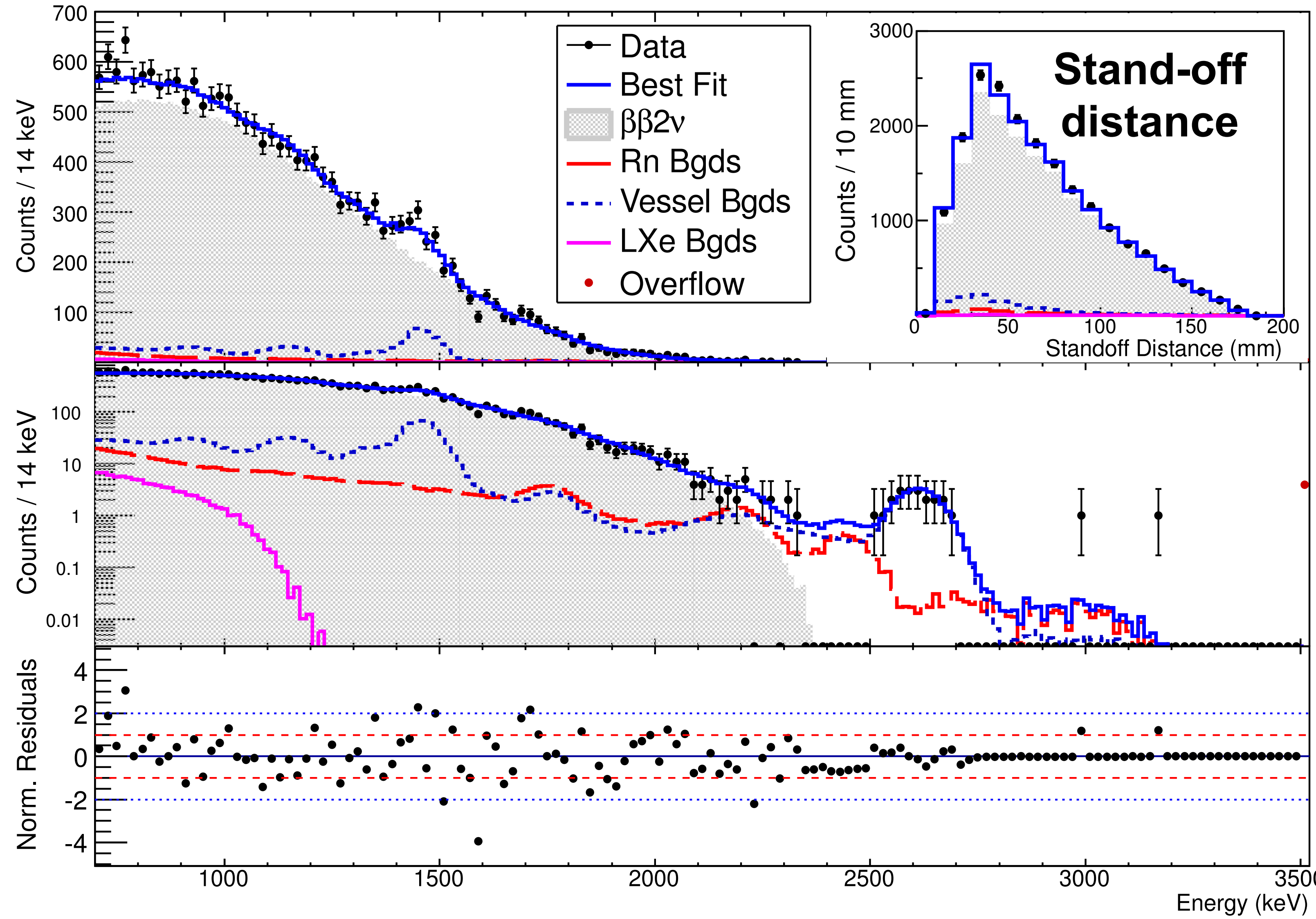
precision measurement of $T_{1/2}^{2\nu\beta\beta}$ (2013)

Run 2a data set (previously analyzed in PRL **109**, 032505 [2012]) reanalyzed with improvements to event reconstruction and reduced fiducial volume uncertainty

$T_{1/2}^{2\nu\beta\beta}$ measured with total relative uncertainty of 2.85 %

Most precisely measured 2νββ half life of any isotope to date

Single-site energy spectrum and fit:



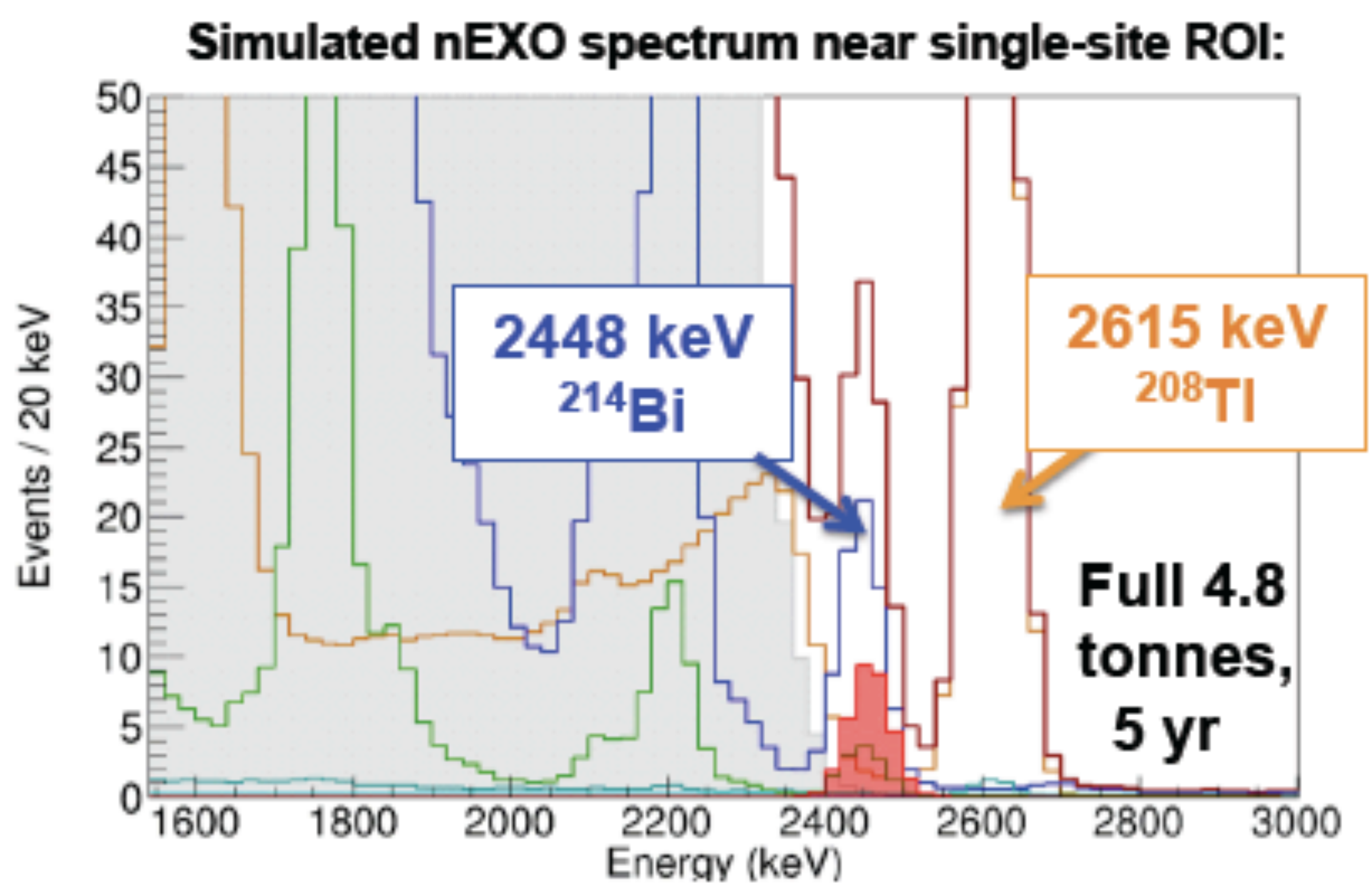
PRC 89 (2014) 015502

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

(stat..) (syst.)

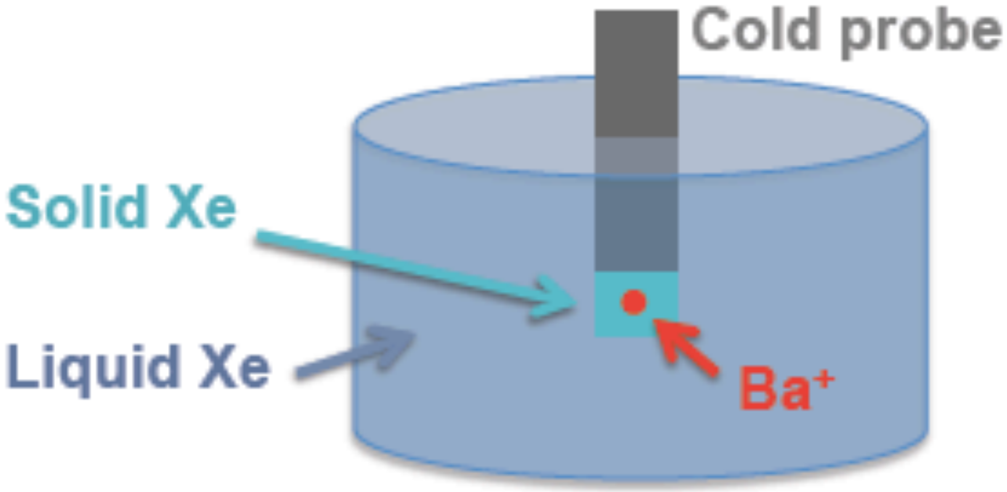
nEXO sensitivity with Ba tagging

- In addition, R&D to develop techniques to identify Ba daughter nucleus of $0\nu\beta\beta$ decay ("Ba tagging") is continuing
- Candidate $0\nu\beta\beta$ events would be identified in real time and daughter Ba ion collected by probe inserted into the TPC at the decay location
- Identity of Ba daughter can be confirmed spectroscopically
- This technology would eliminate all non-$\beta\beta$ backgrounds near ROI
- Could extend ultimate reach of nEXO into the normal hierarchy since full 5 tonne mass would be background free

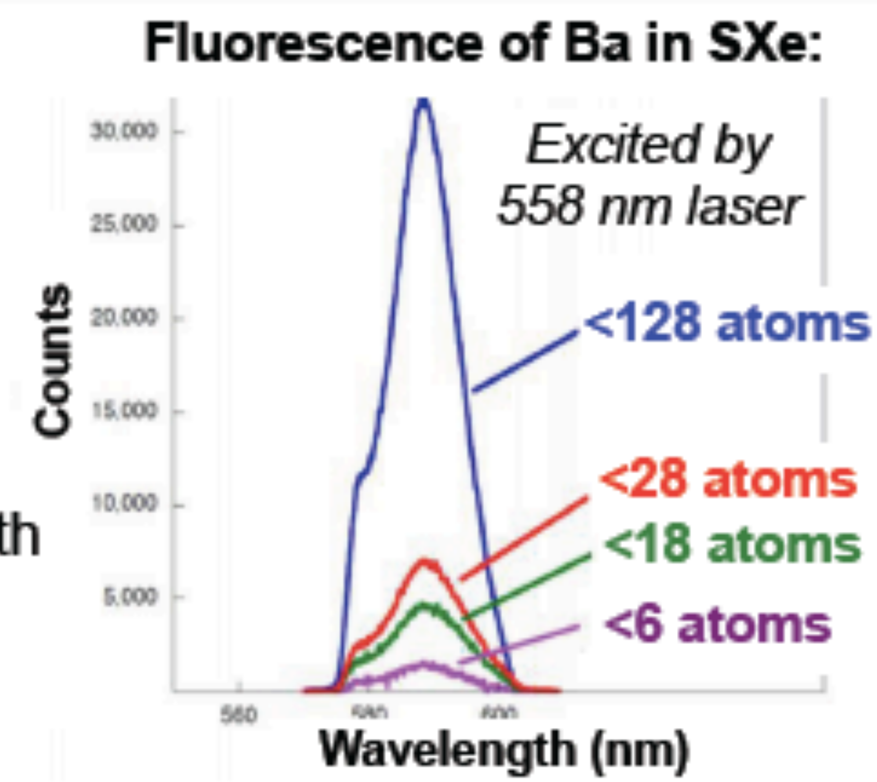


Ba tagging R&D

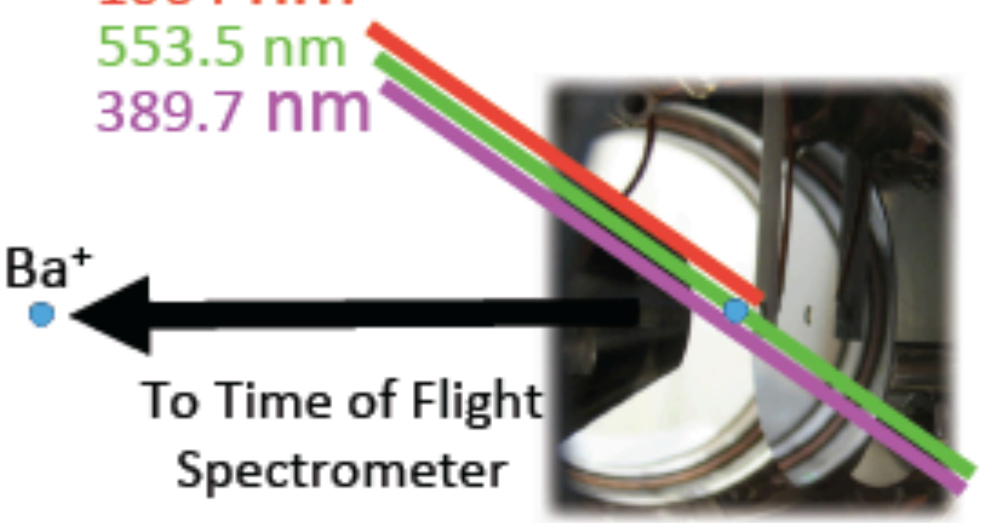
- Several techniques are currently being pursued:
  - Tagging from solid Xe by fluorescence spectrum

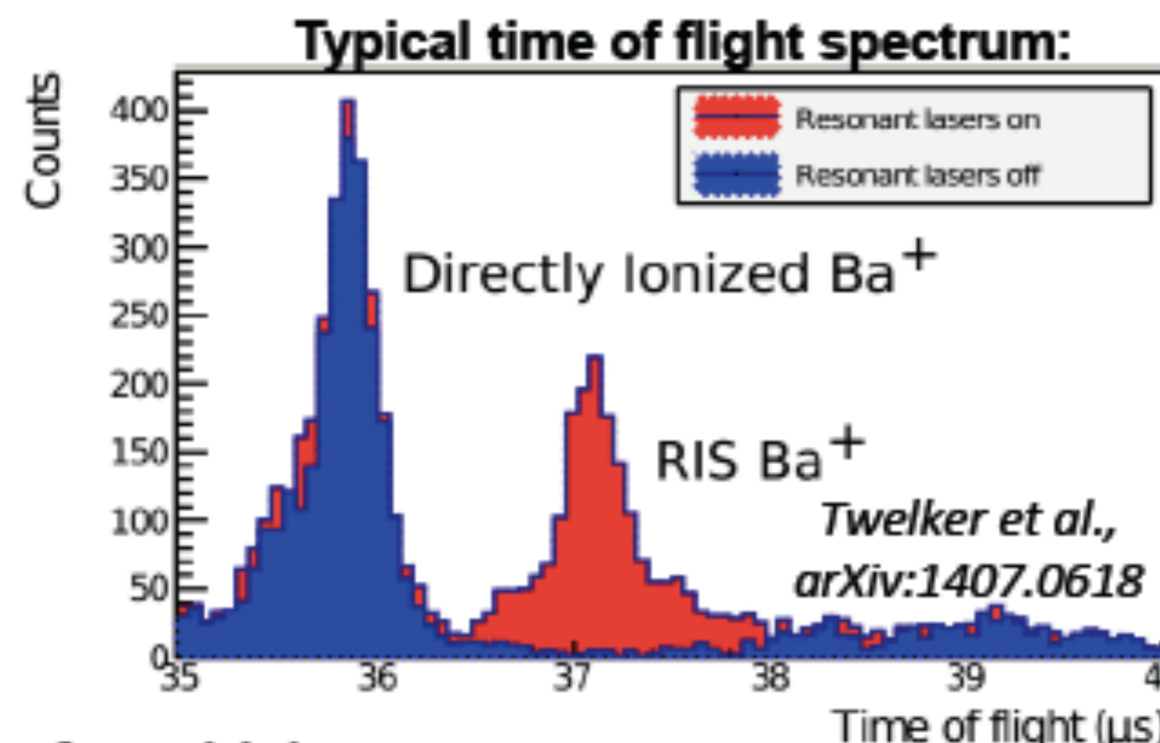


Detect single ion or atom on the probe with laser-induced fluorescence



  - Resonance ionization spectroscopy (RIS):





- Also studying ion extraction and tagging from high pressure Xe gas