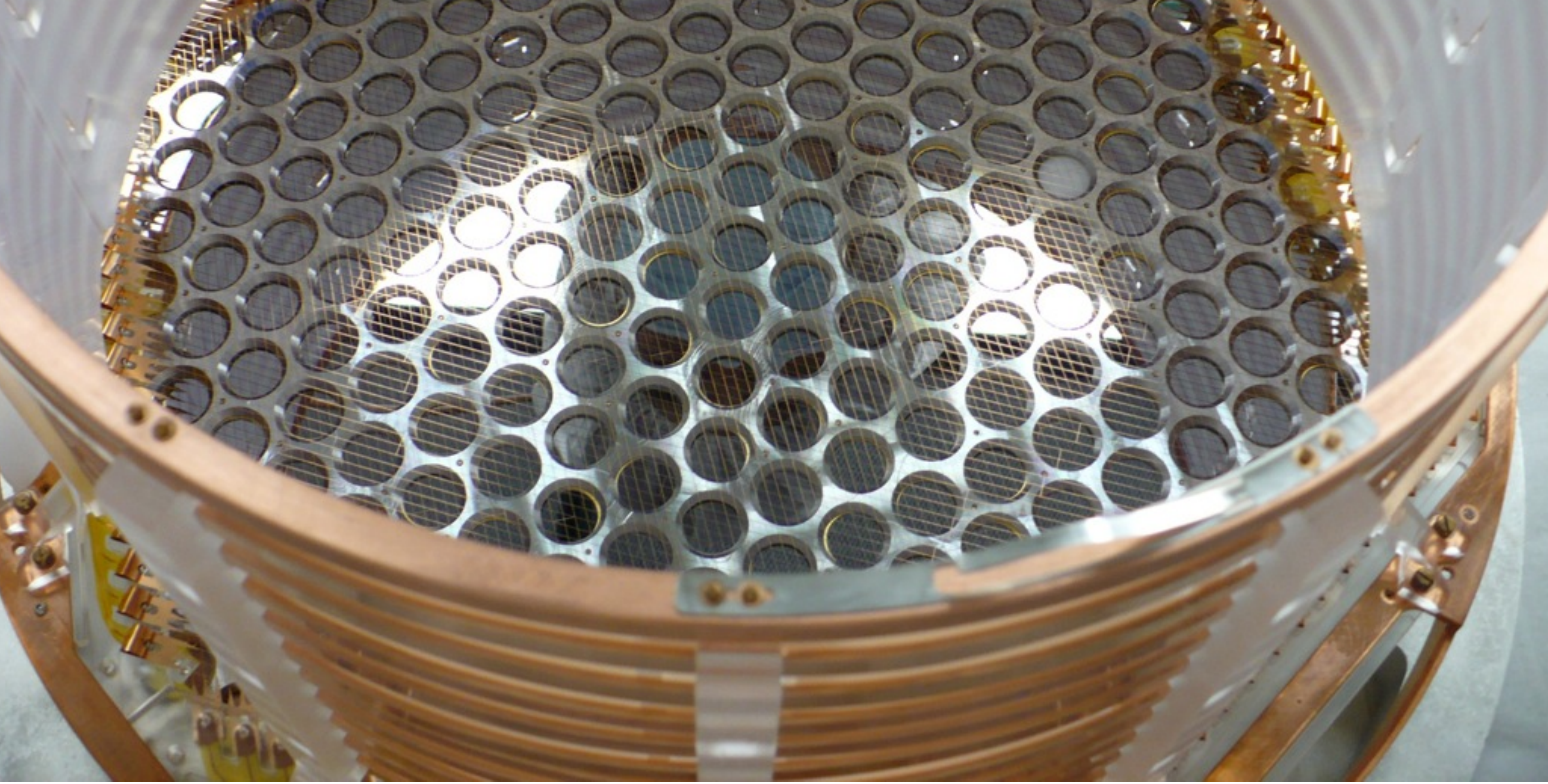

EXO-200 and nEXO: Searches for neutrinoless double-beta decay with Xenon-136

Alexis Schubert
Stanford University

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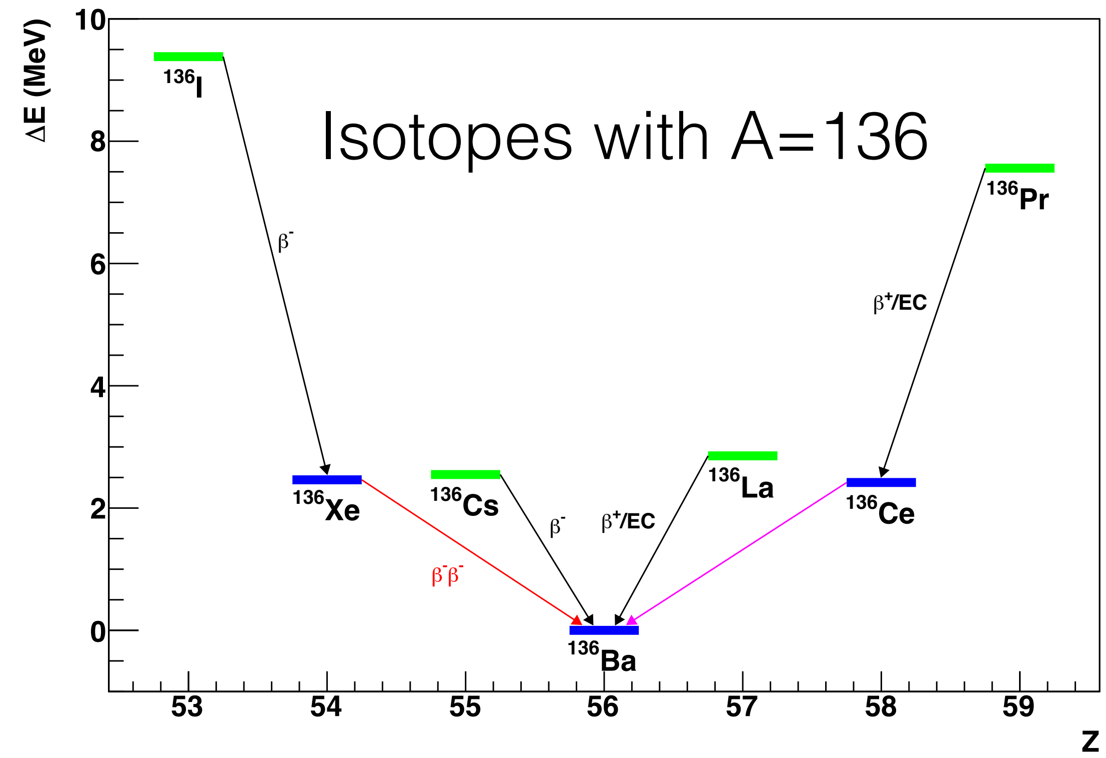
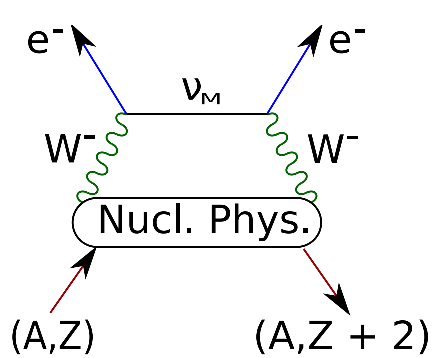
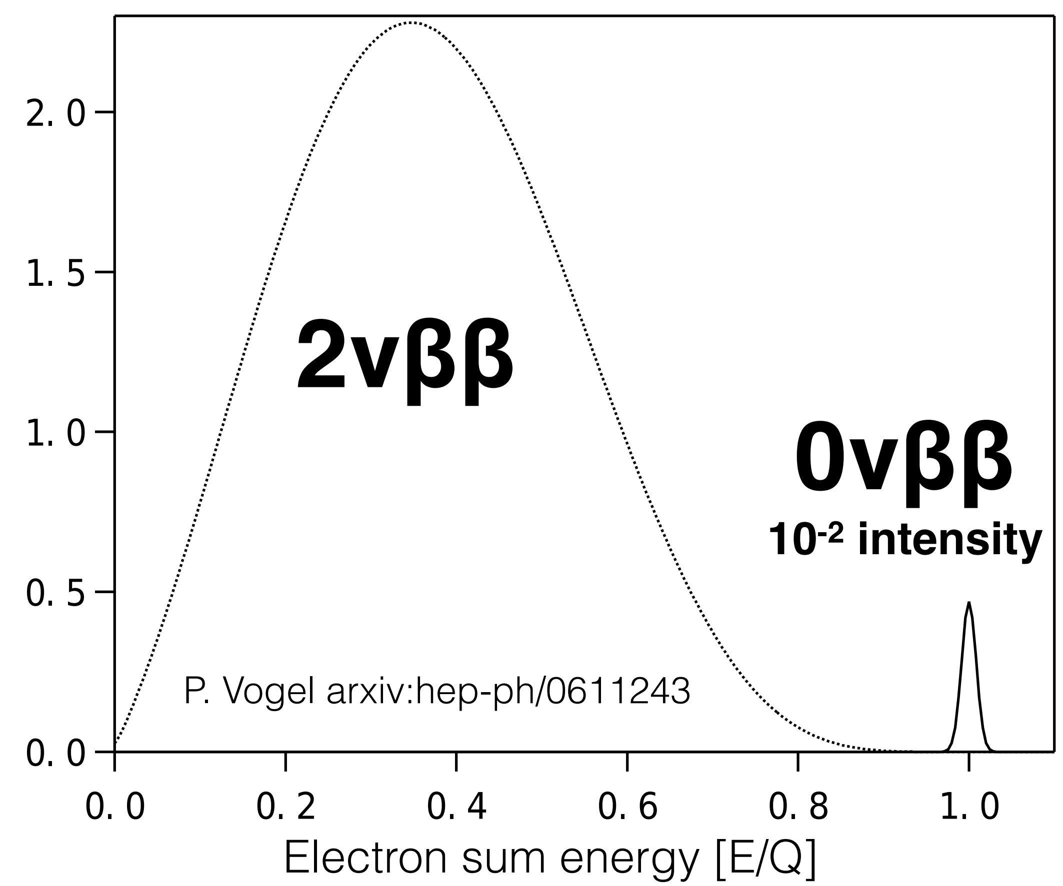
20 February 2015

Neutrinoless double-beta decay

- Double-beta decay is a second order process allowed by the Standard Model
- If the neutrino is a Majorana particle, the decay can occur without emitting neutrinos (0νββ)
- Observation of 0νββ would indicate:
  - Lepton number is not conserved
  - Neutrino is a Majorana particle
- Information about neutrino mass



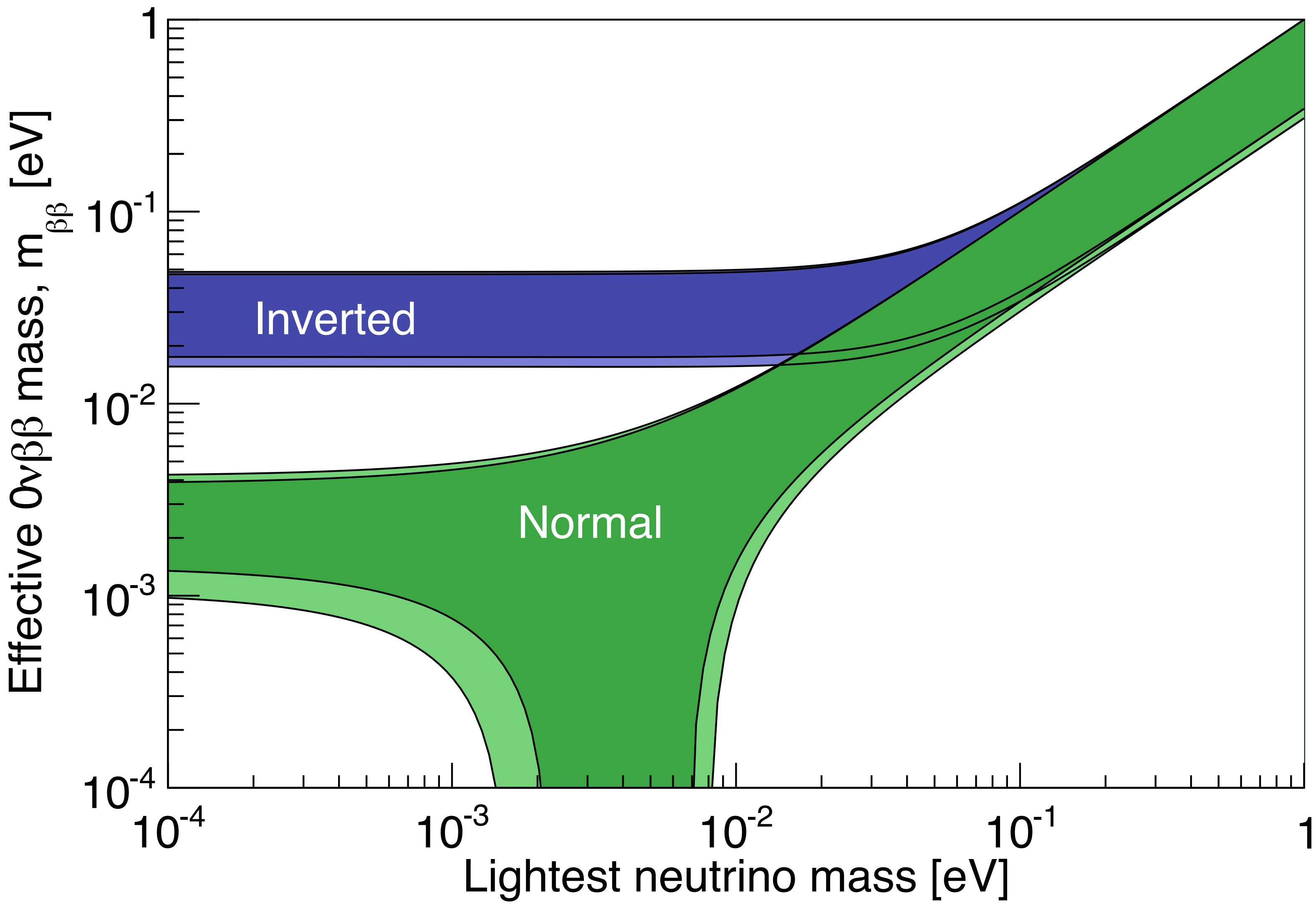


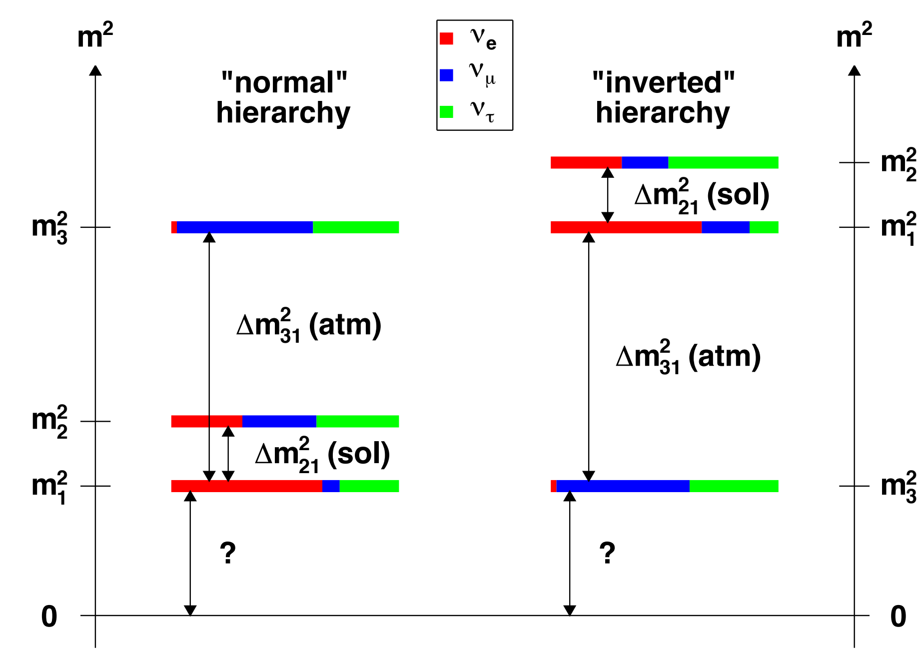


Neutrinoless double-beta decay and neutrino mass

decay rate: $[T_{1/2}^{0\nu\beta\beta}]^{-1} = G^{0\nu\beta\beta}(E_0,Z)\ (M^{0\nu\beta\beta})^2\ \langle m_{0\nu\beta\beta}\rangle^2$

eff. mass: $m_{0\nu\beta\beta} = \left|\, |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2\, e^{i\Phi 2} + |U_{e3}|^2 m_3\, e^{i\Phi 3} \right|$





The EXO-200 Collaboration

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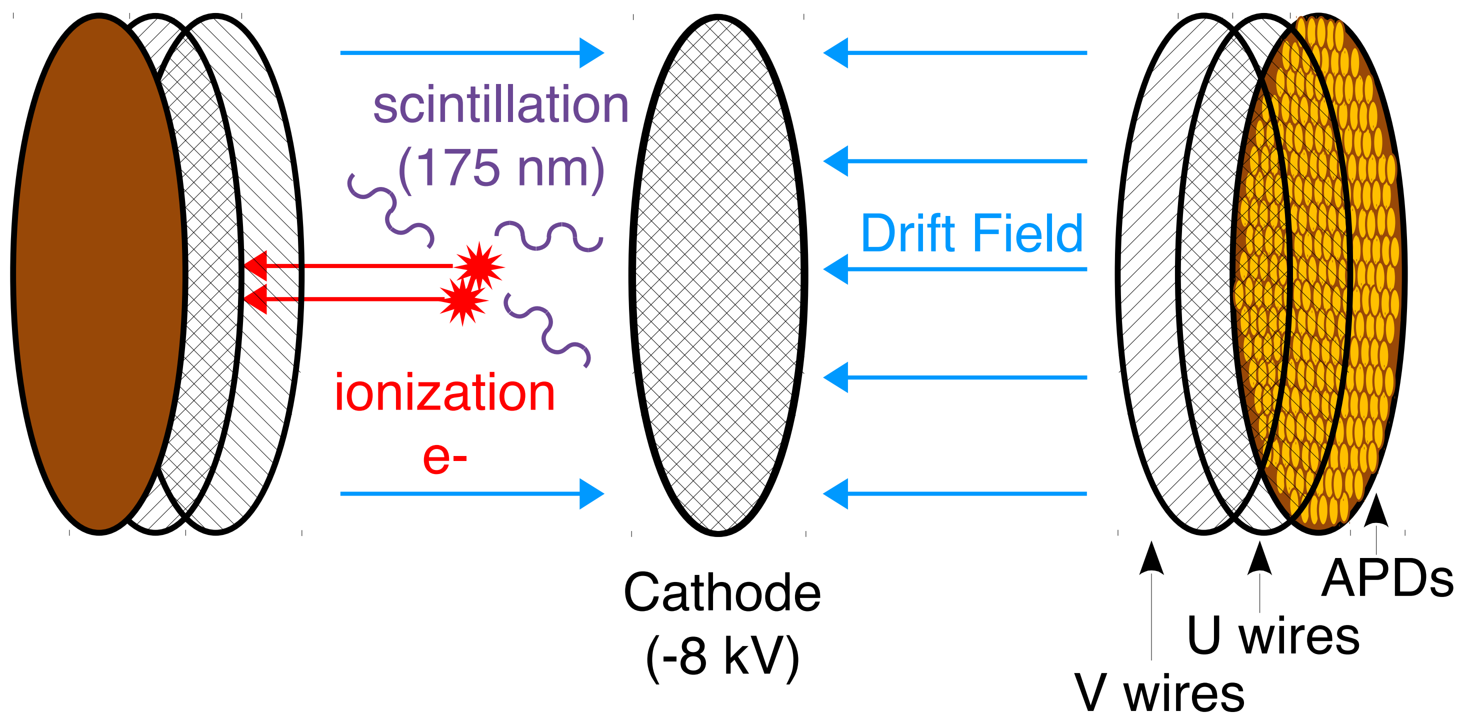
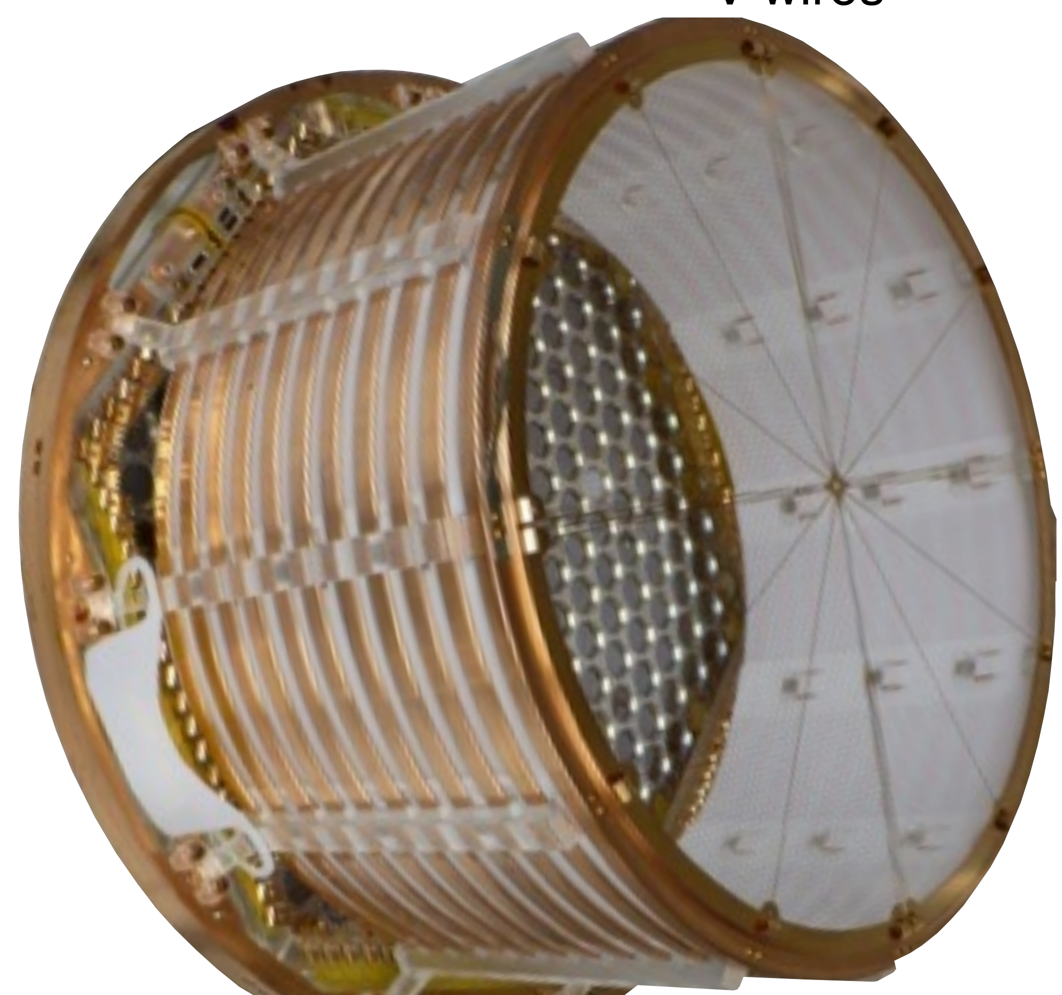
The EXO-200 detector

- Cylindrical liquid xenon time projection chamber (TPC)
- 40cm in diameter, 44cm long
- Enriched to 80.6% in the 0νββ candidate isotope: 136-xenon
- Collect ionization charge and scintillation light to determine energy and position information
- 38 charge collection wire channels
- 38 charge induction triplet wire channels, at 60 degrees
- 234 large area Avalanche Photo Diodes (in gangs of 7)





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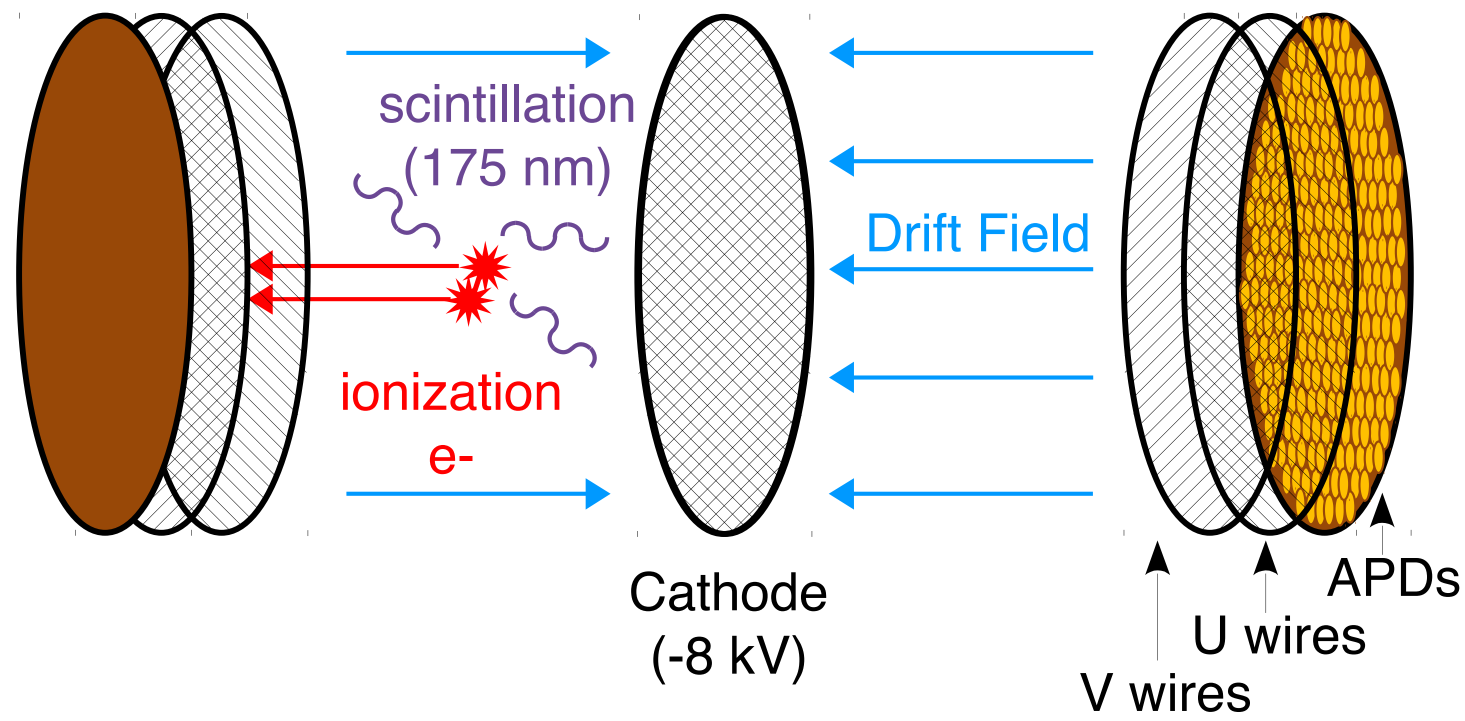
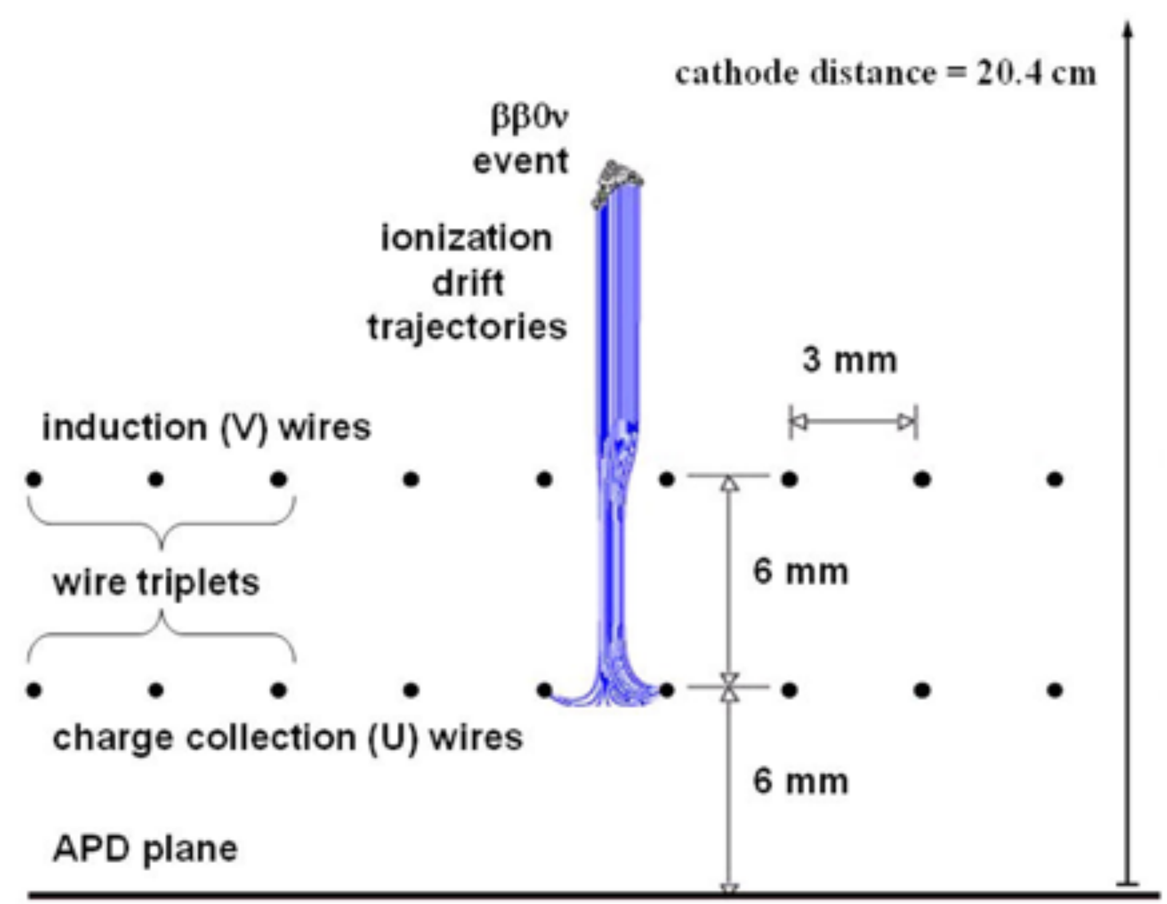
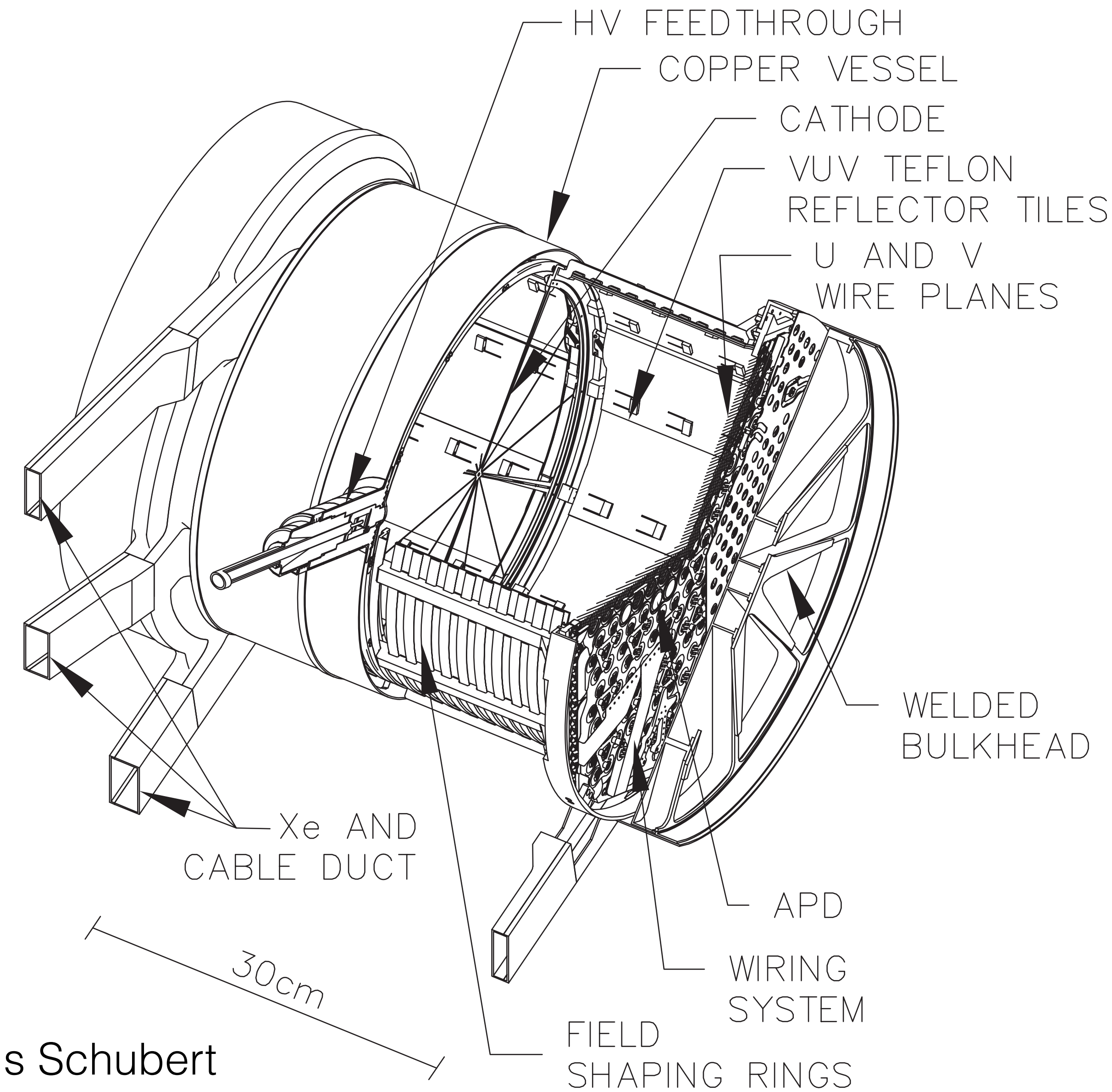
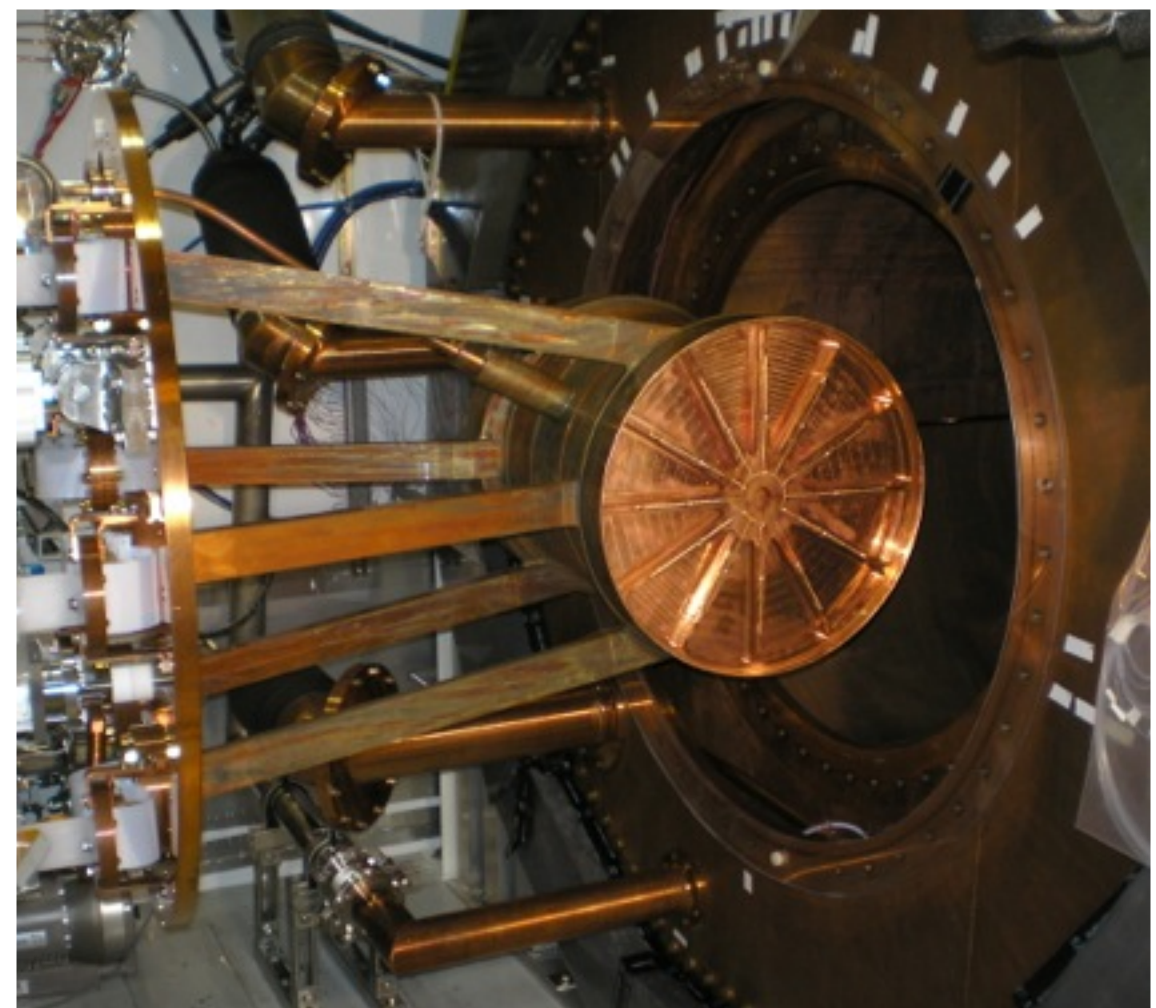




The EXO-200 detector

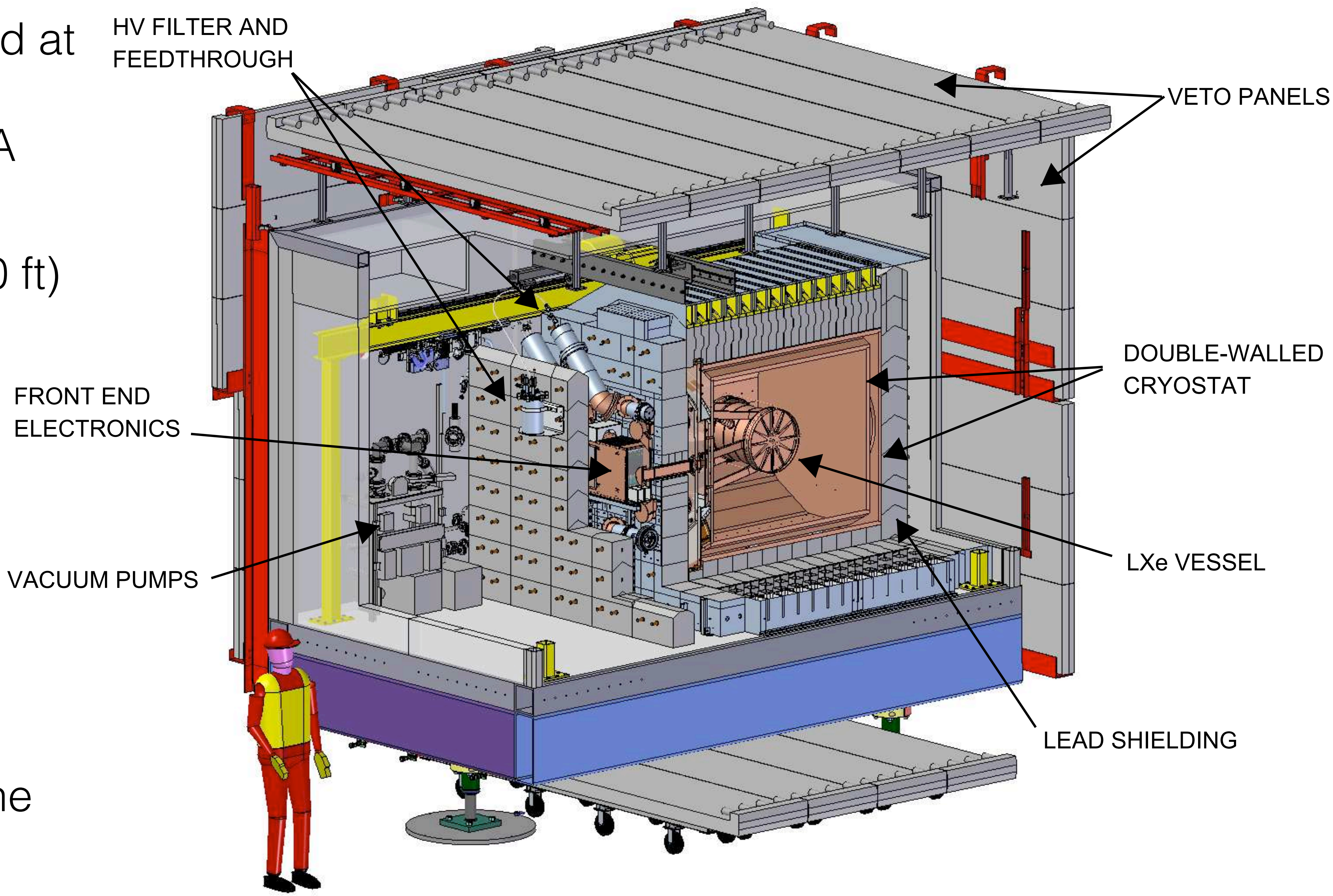
- Easy to enrich: 8.9% natural abundance of 136-Xe
- Xenon can be purified continuously
- High Q-value: 2458 keV
- Minimal cosmogenic activation: no long-lived radioisotopes
- Self shielding



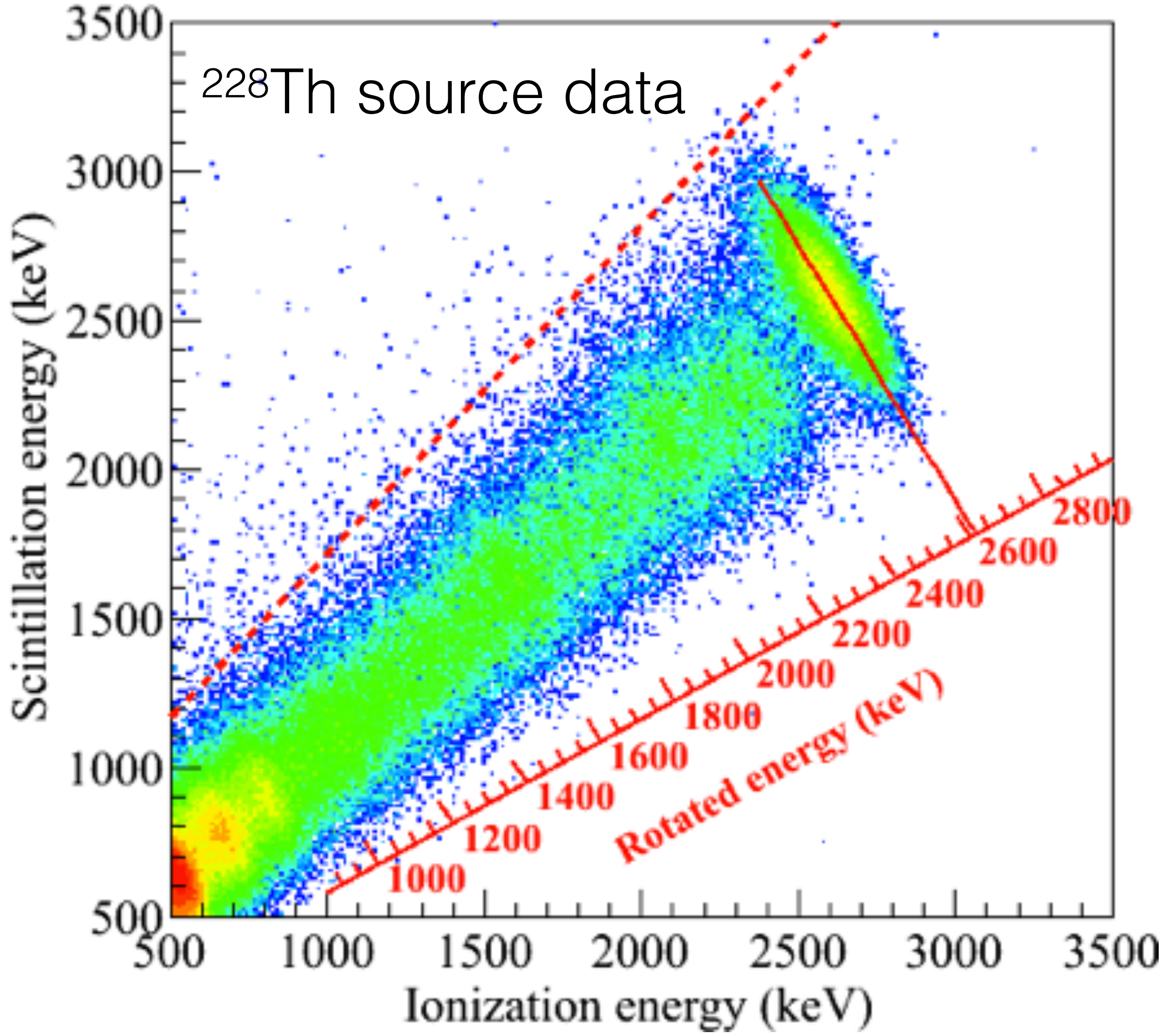


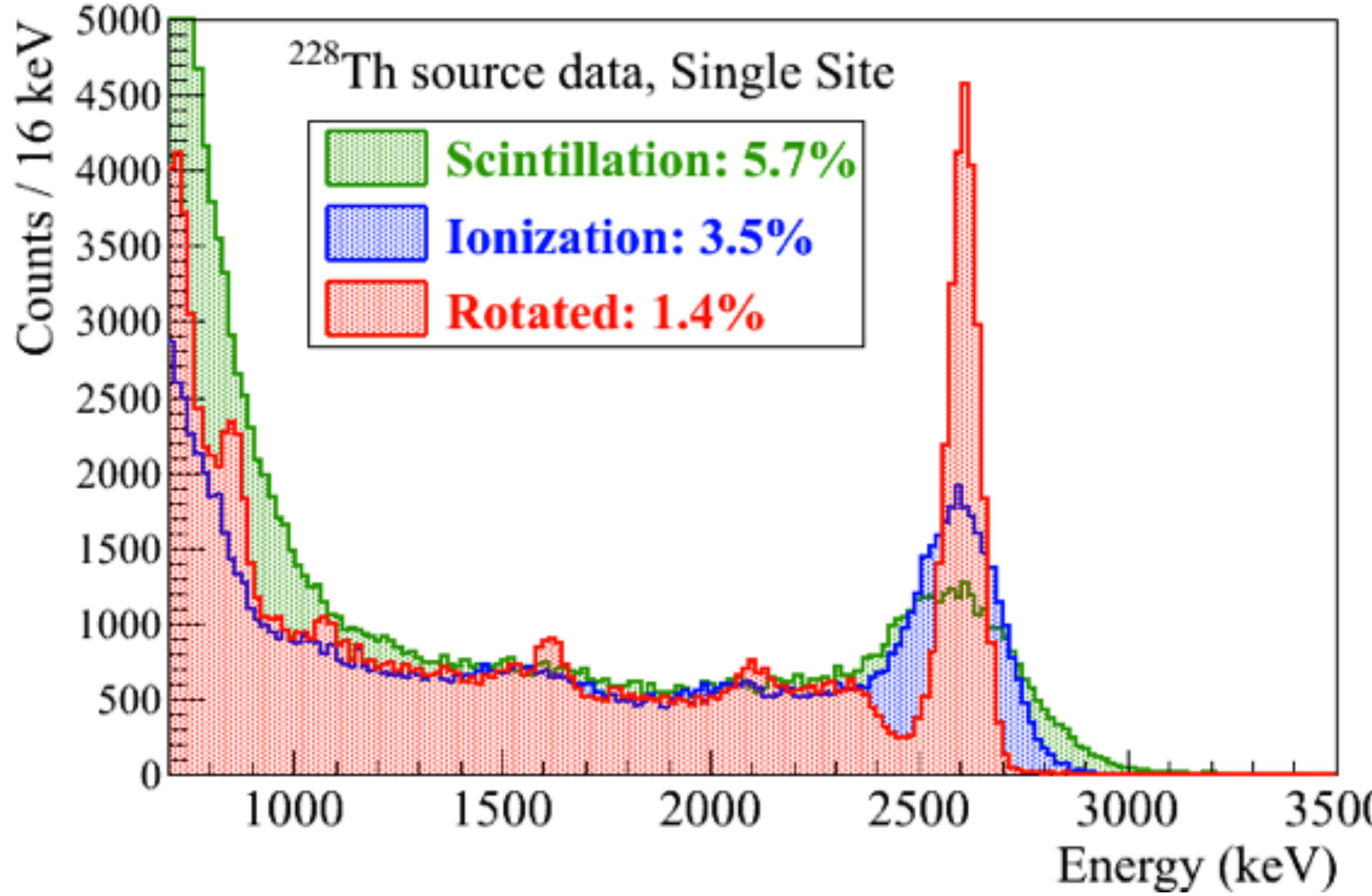
The EXO-200 detector

- EXO-200 is installed at WIPP, a mine in Carlsbad, NM, USA
- Depth: 655m (2150 ft) 1600 m.w.e.
- Salt mine is low in uranium, thorium activity
- Several layers of passive and active shielding protect the detector



Combining ionization and scintillation signals





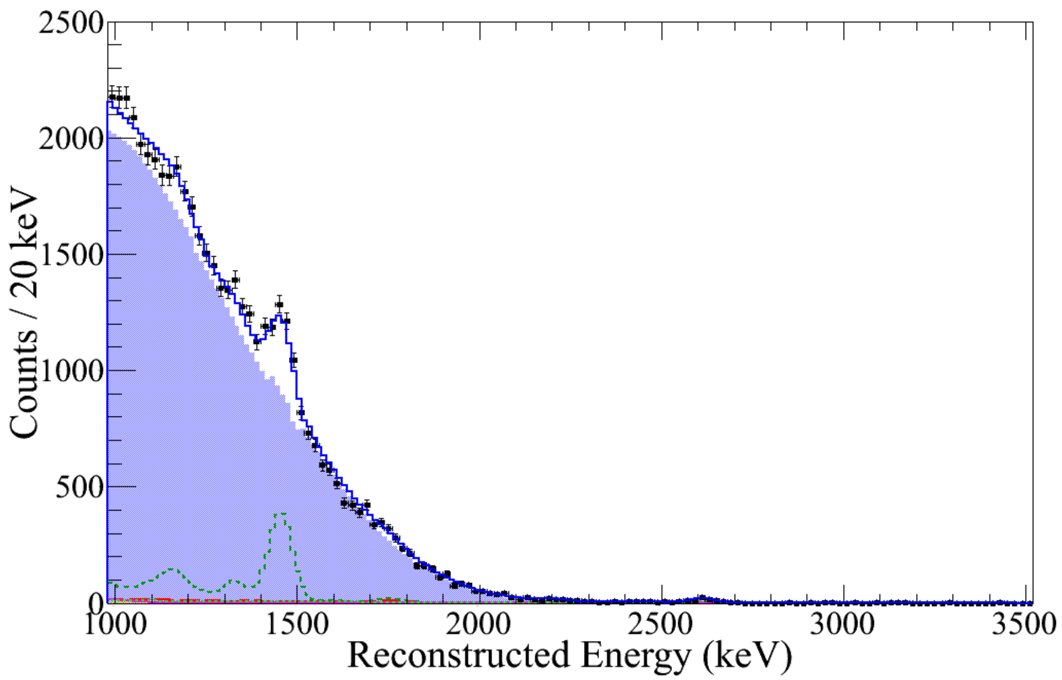
Anticorrelation between scintillation and ionization improves energy resolution

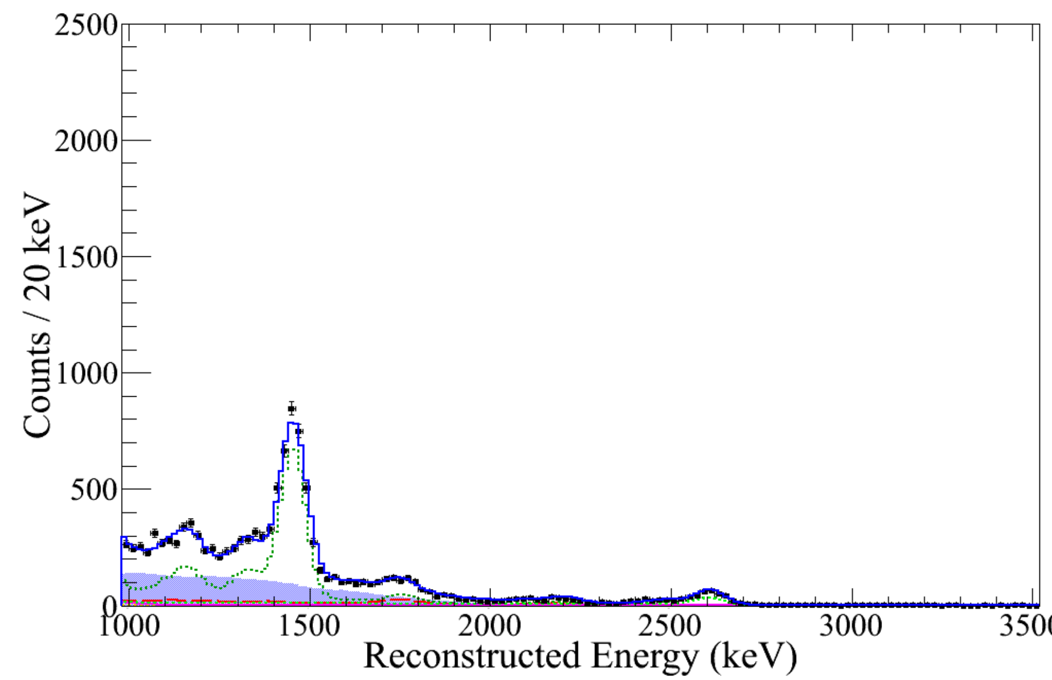
Rotation angle is chosen to optimize energy resolution at 2615 keV

Event discrimination

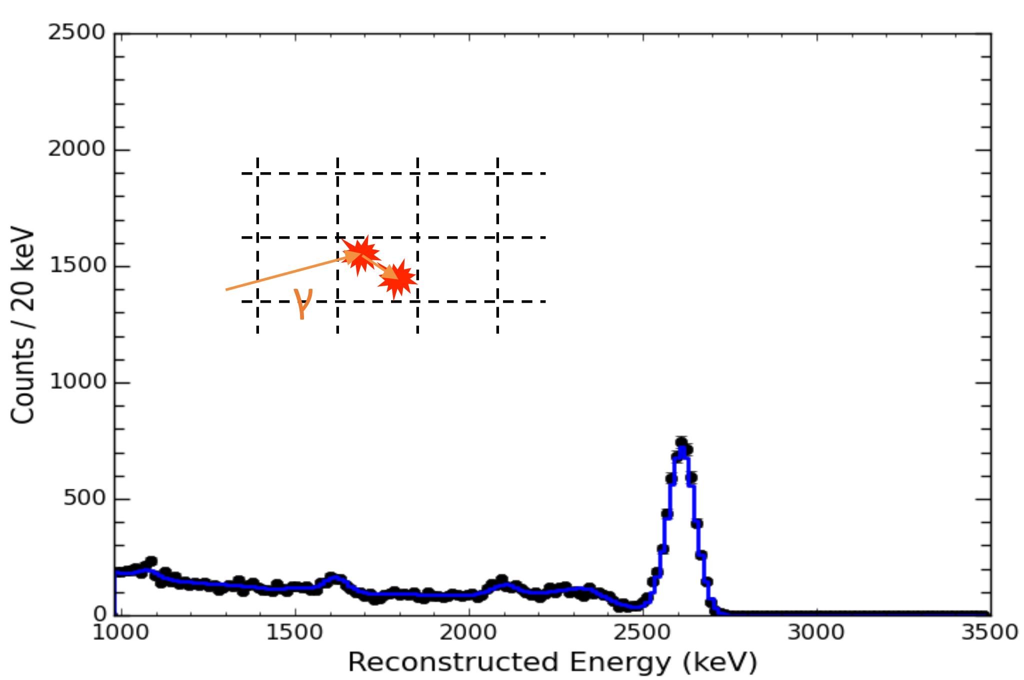
single-site events: 1 charge cluster | **multi-site events: >1 charge cluster**

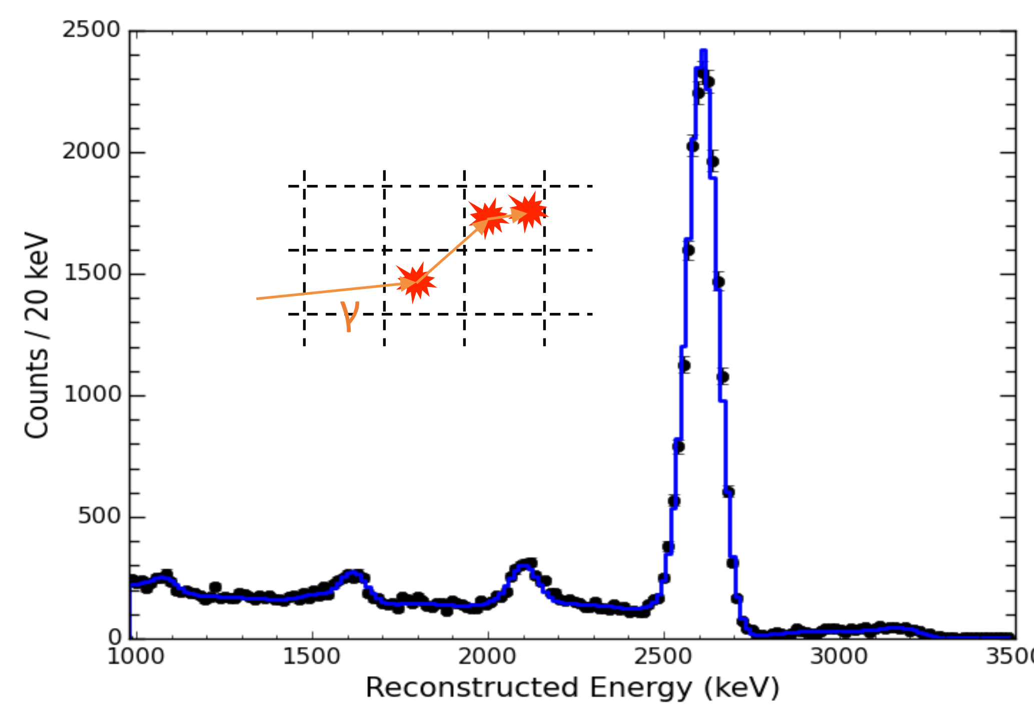
Low-background data





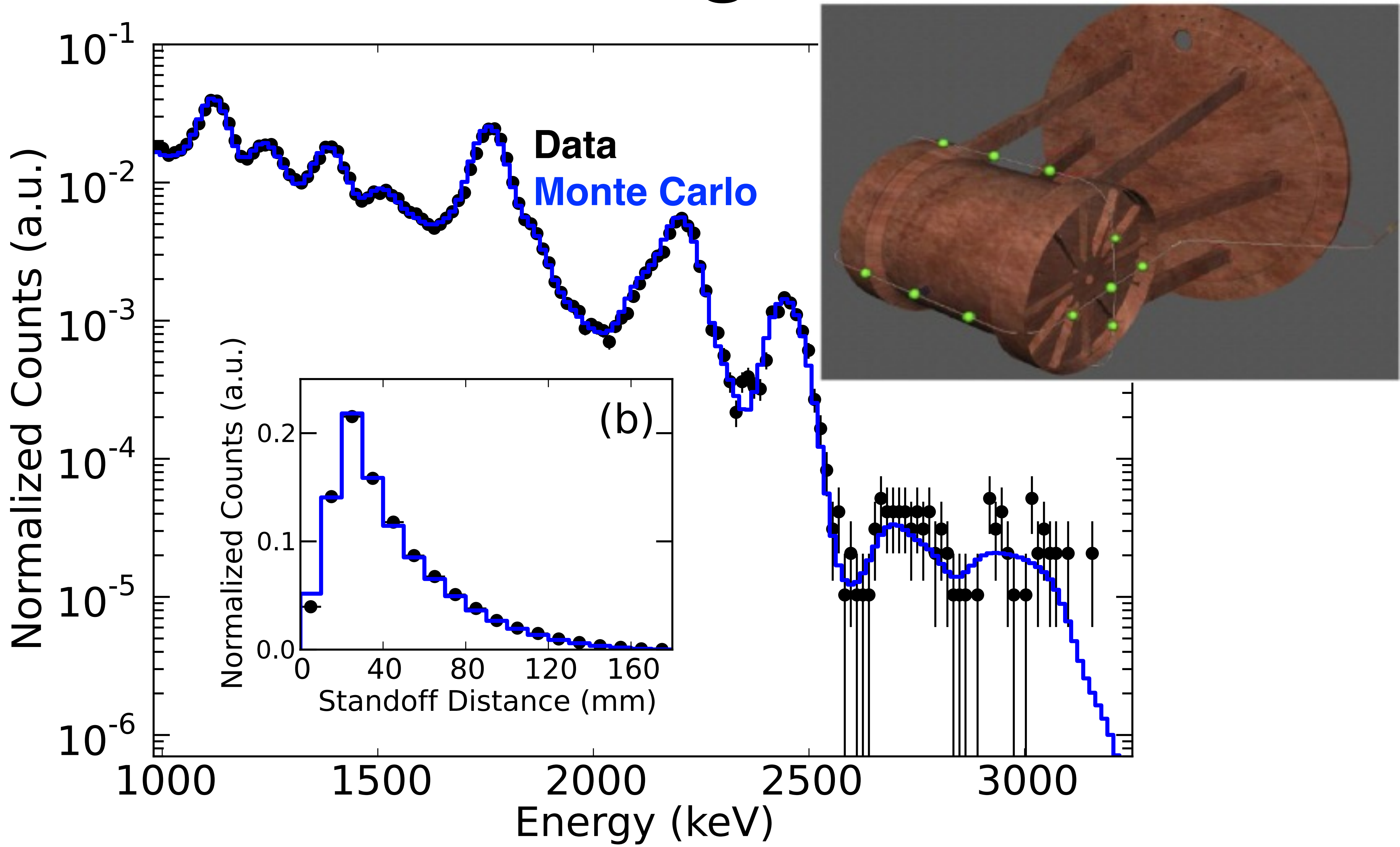
^{228}Th calibration source





0νββ: 90% single-site
gammas: 30% single-site

^{226}Ra source agreement



Response of our detector to sources and background simulated with Geant4-based Monte Carlo

Other calibration sources: ^{60}Co, ^{137}Cs, ^{228}Th

Sources used for energy calibration and systematic studies

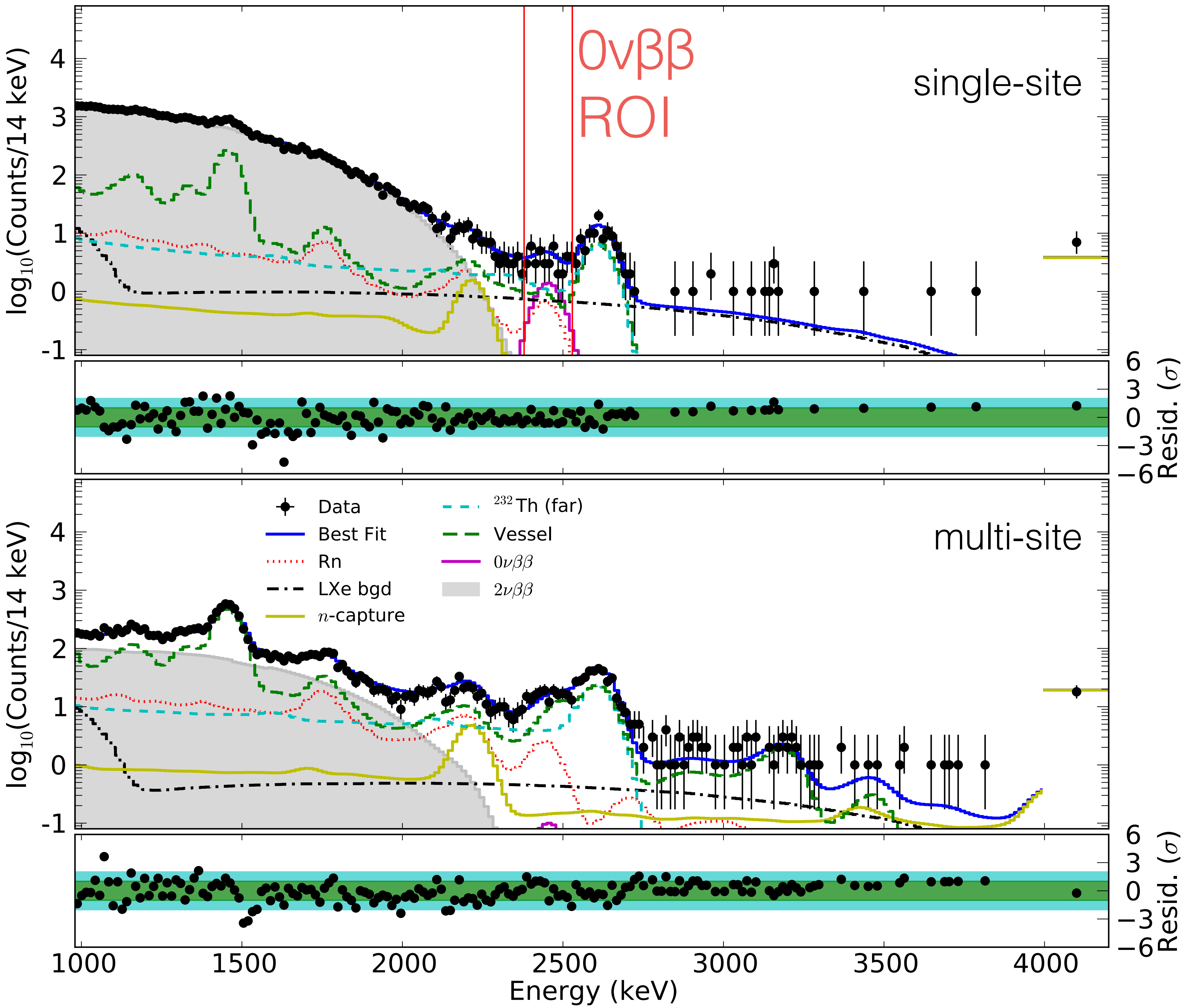
Final Fit

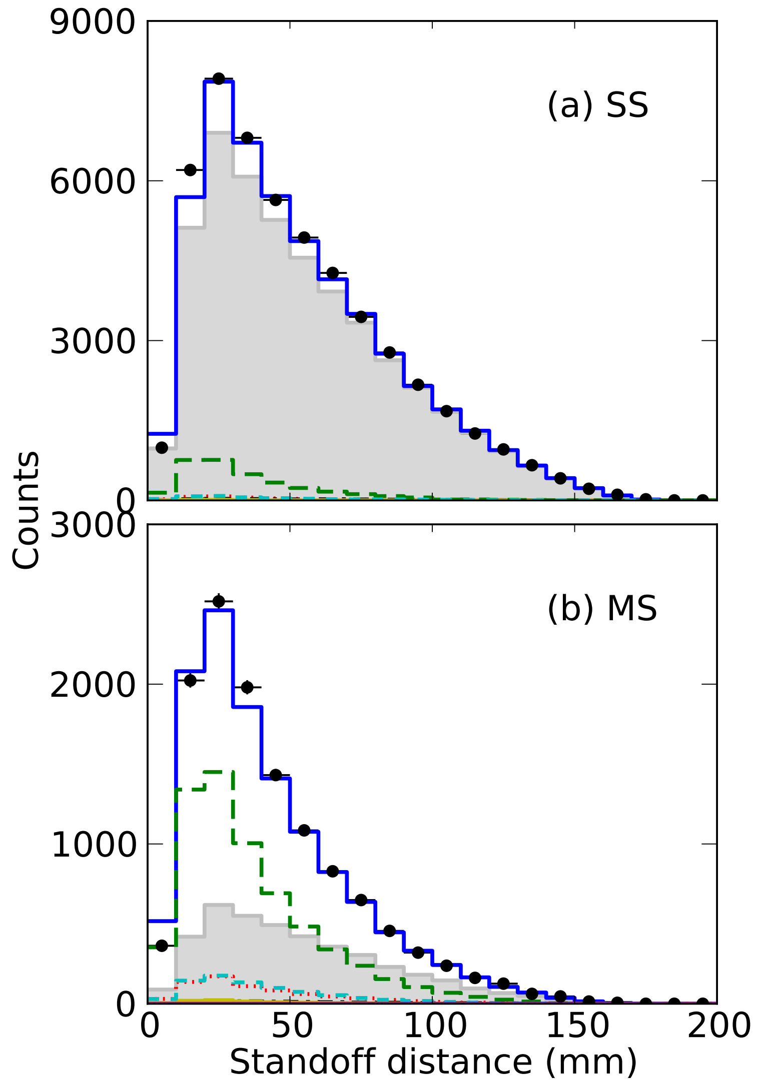
October 2011-
September 2013

Energy range:
980 to 9800 keV

448 days of lifetime

99.8 kg-years of
exposure of xenon-136





LLWI, 20 Feb 2015

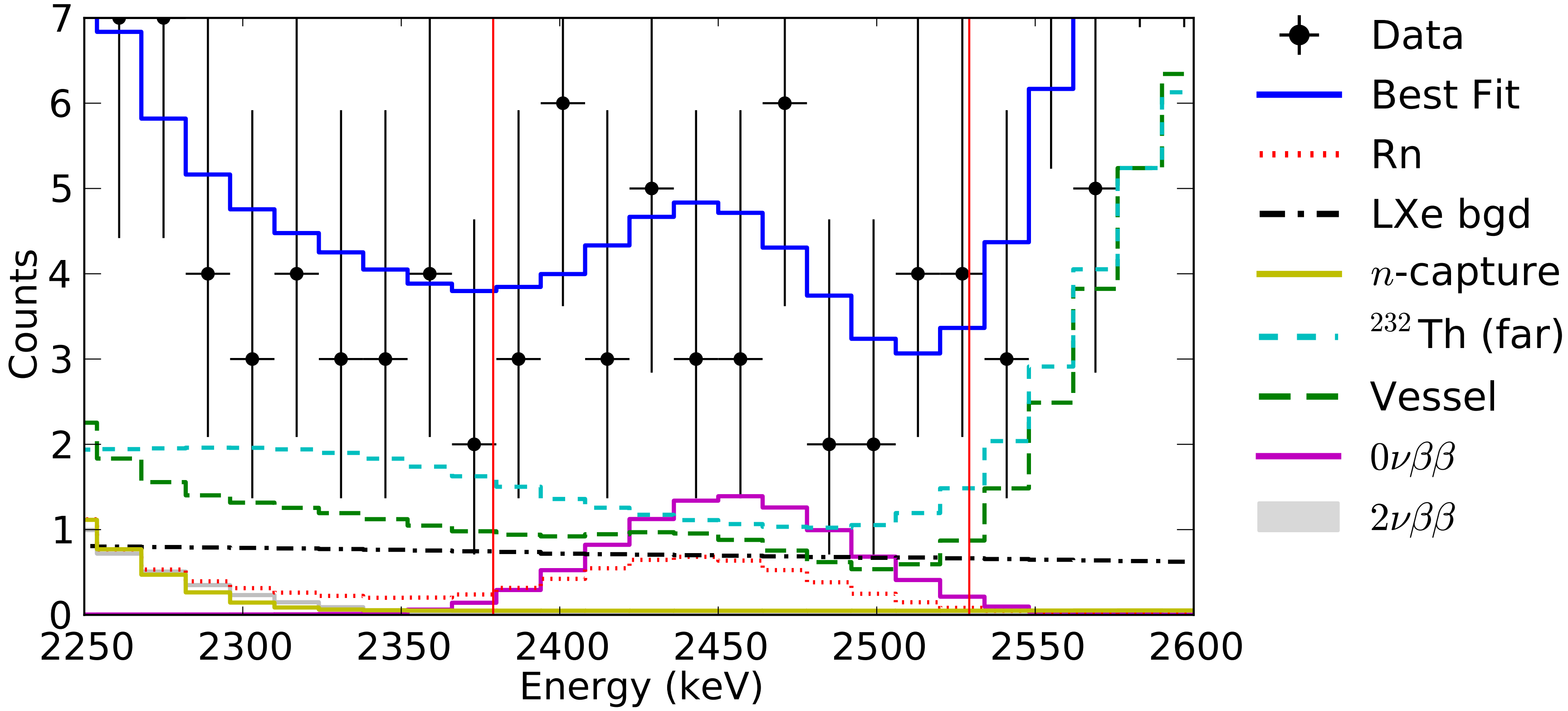
Final result

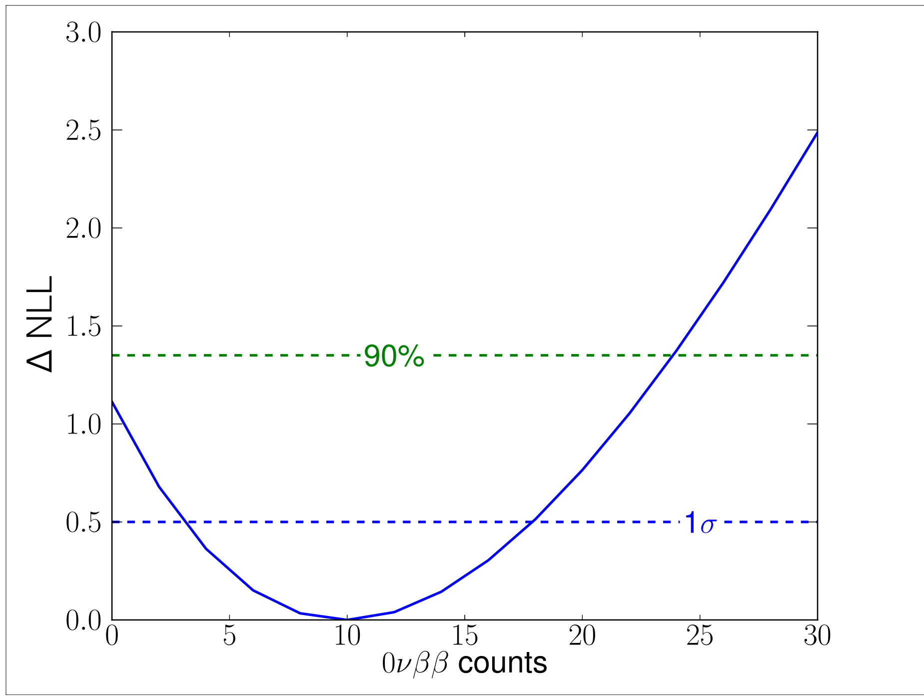
$T_{1/2}^{0\nu\beta\beta}$ > 1.1·10^{25} yr

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

(90% C.L.)

Nature ***510****, 229 (2014), arXiv:1402.6956*





Final result

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

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

(90% C.L.)

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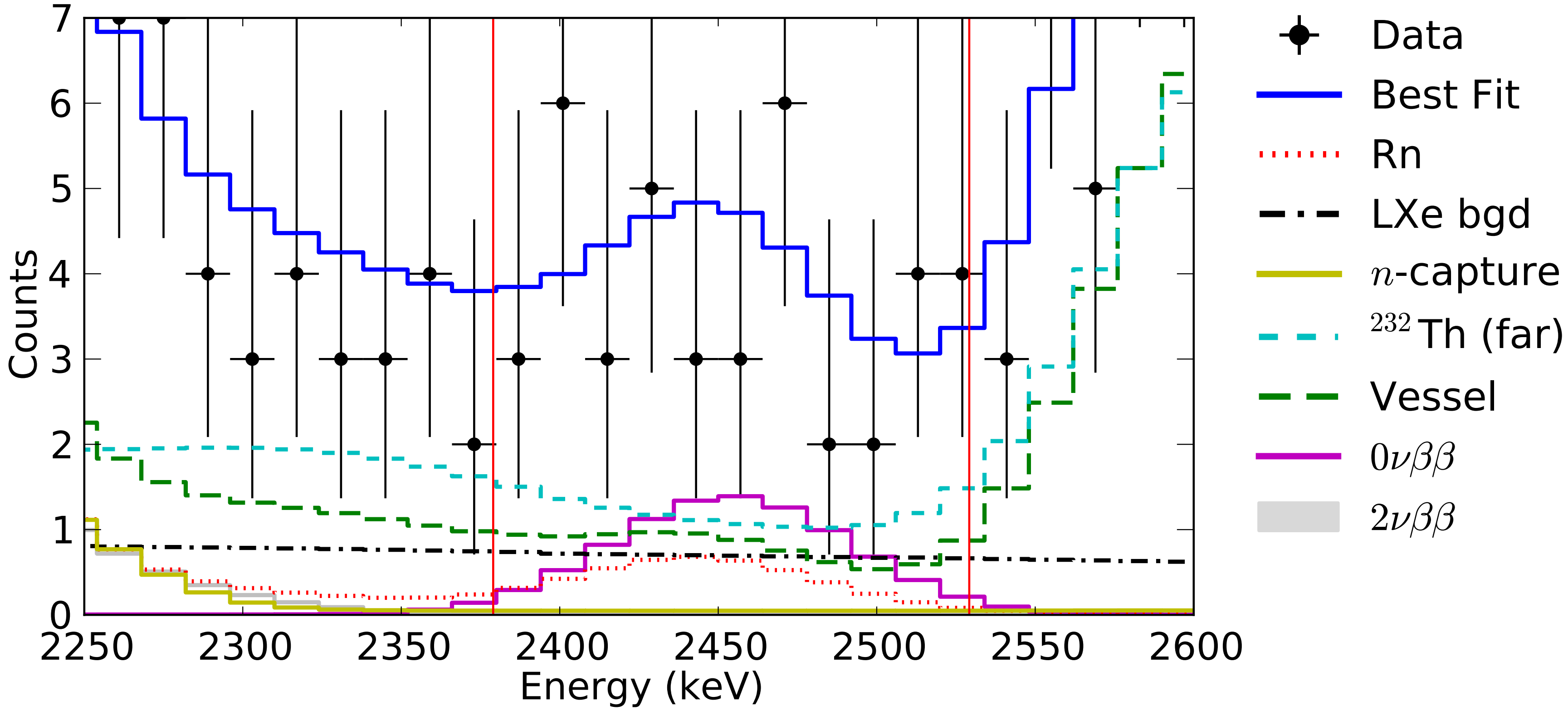


Backgrounds in ± 2σ ROI	
Th-232 chain	16.0
U-238 chain	8.1
Xe-137	7.0
Total	**31.1 ± 3.8**

Final result

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

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

(90% C.L.)

Nature ***510****, 229 (2014), arXiv:1402.6956*

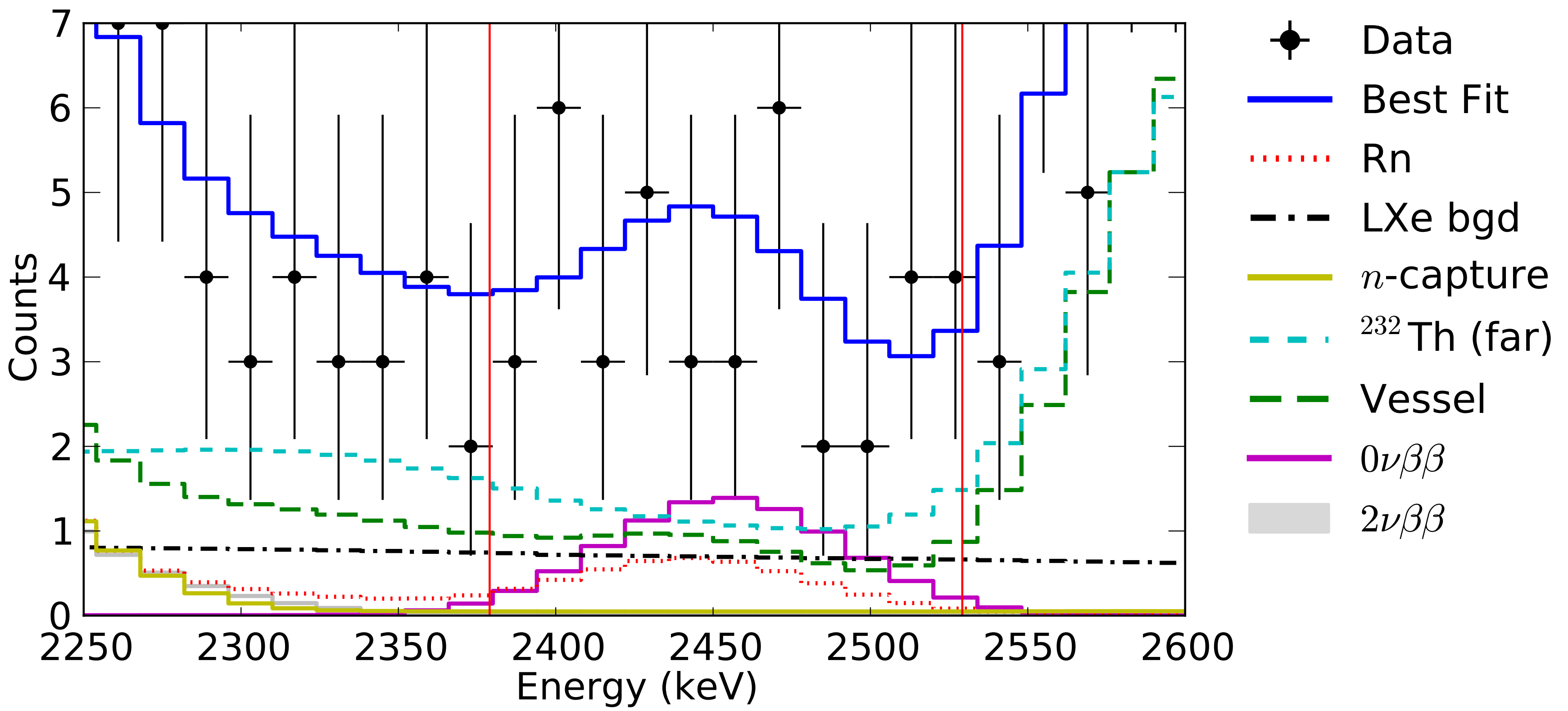
KamLAND-Zen

$T_{1/2}^{0\nu\beta\beta} > 2.6 \cdot 10^{25}$ yr

$\langle m_{\beta\beta} \rangle < 140 - 280$ meV

(90% C.L.)

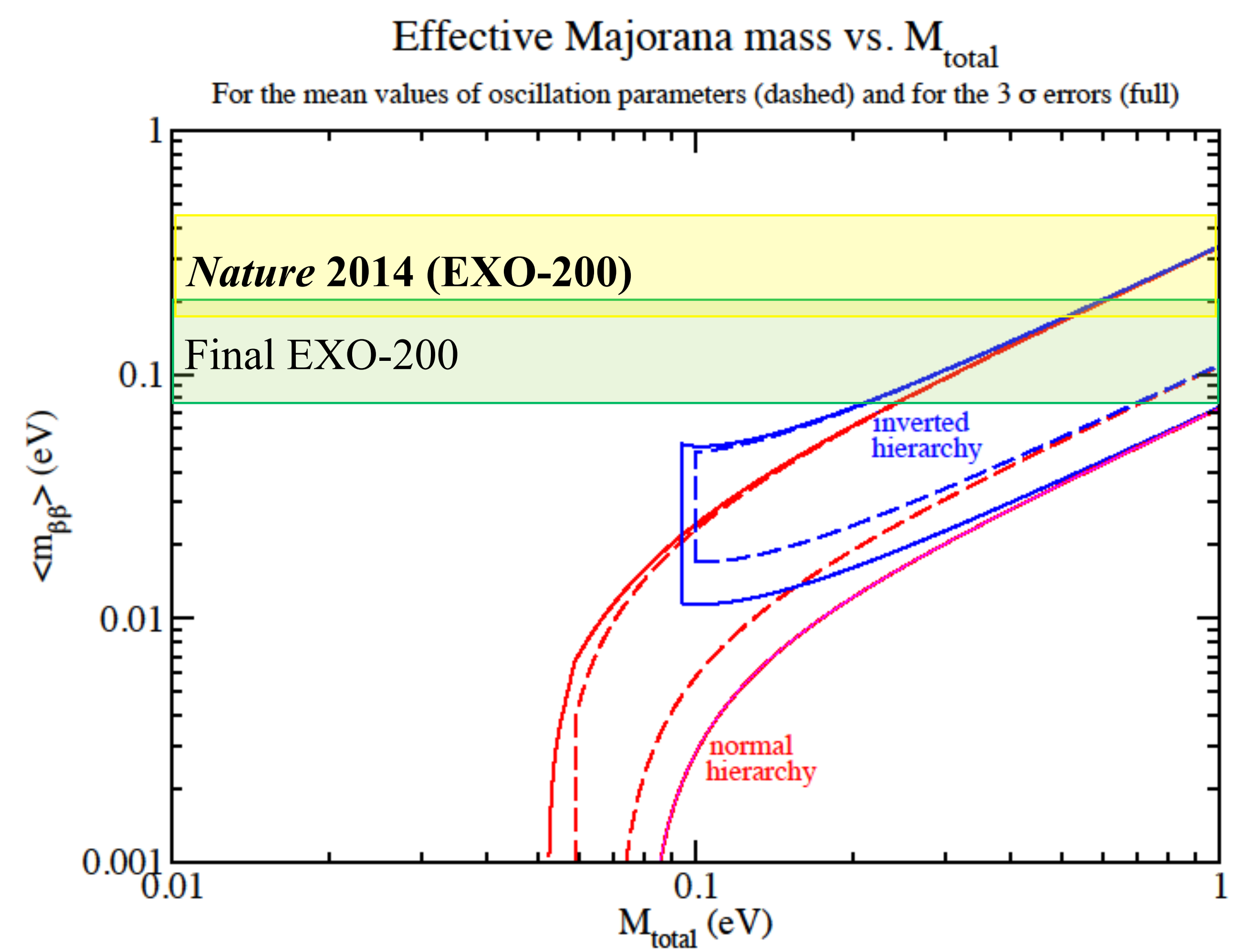
arXiv:1409.0077

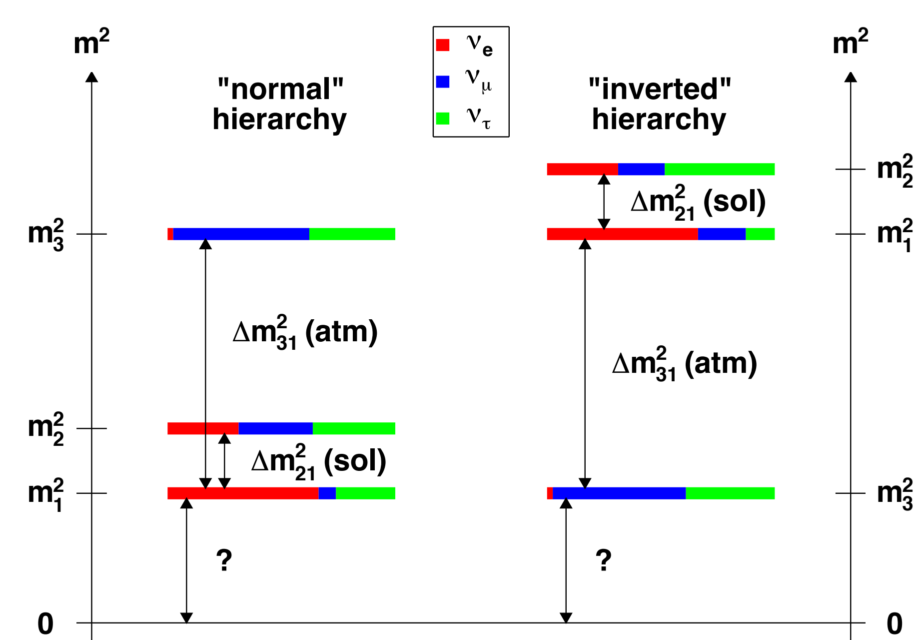


Backgrounds in ± 2σ ROI	
Th-232 chain	16.0
U-238 chain	8.1
Xe-137	7.0
Total	**31.1 ± 3.8**

Next generation 0νββ experiments

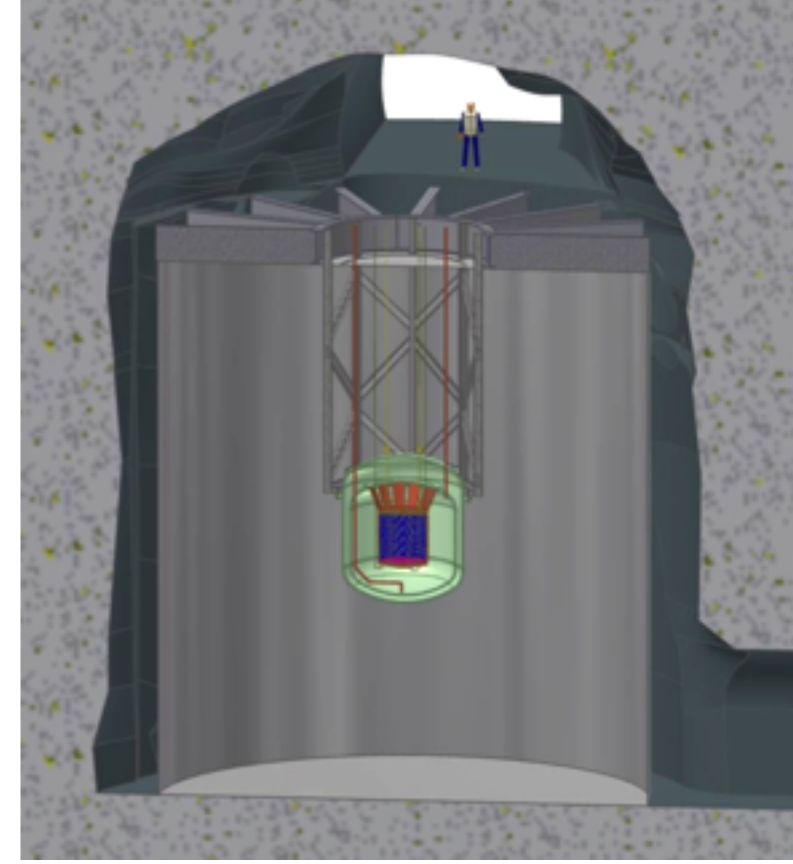
- The current generation of experiments have not observed 0νββ
- Next-generation experiments aim to search the inverted hierarchy of neutrino mass
- This will require more exposure and reduced backgrounds



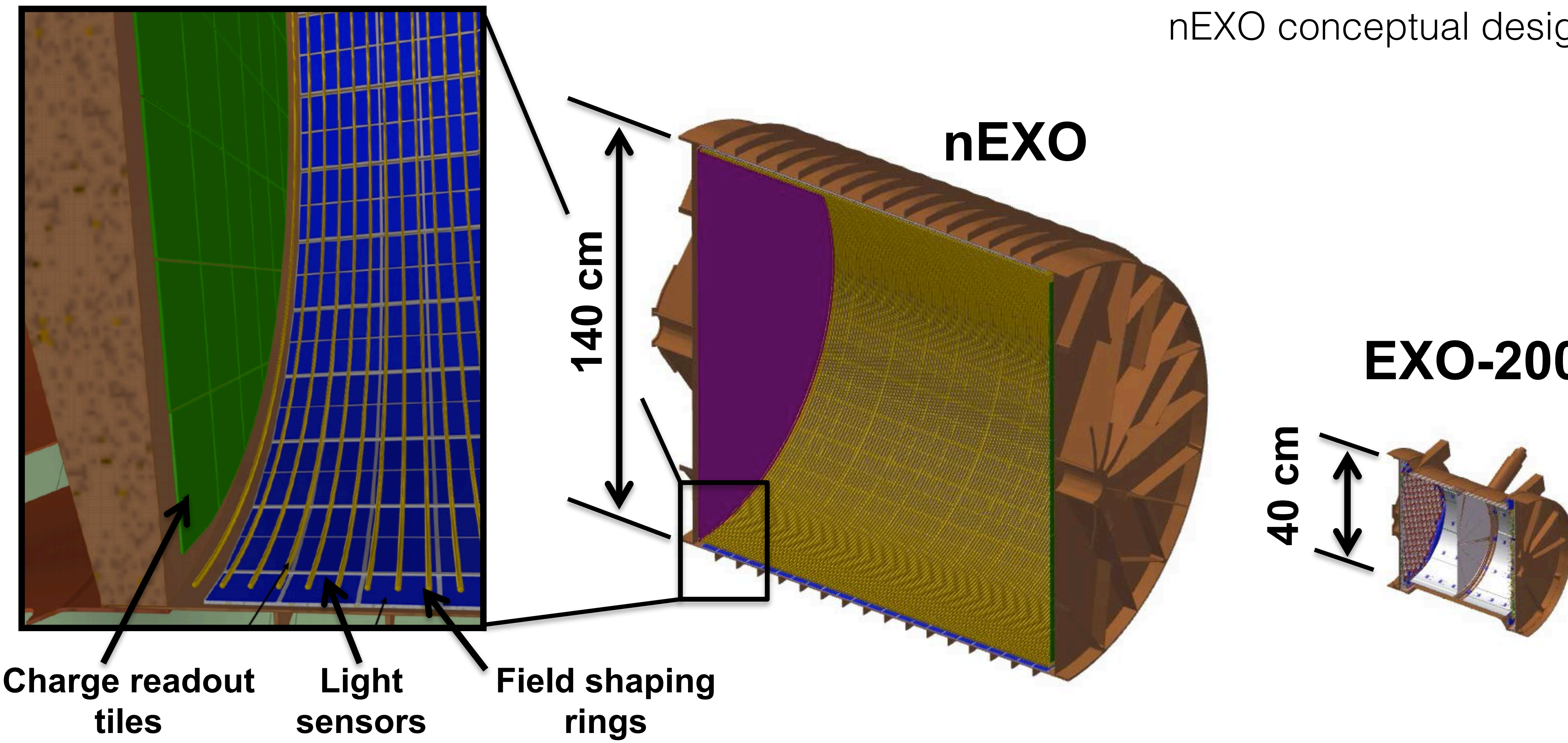


The nEXO detector

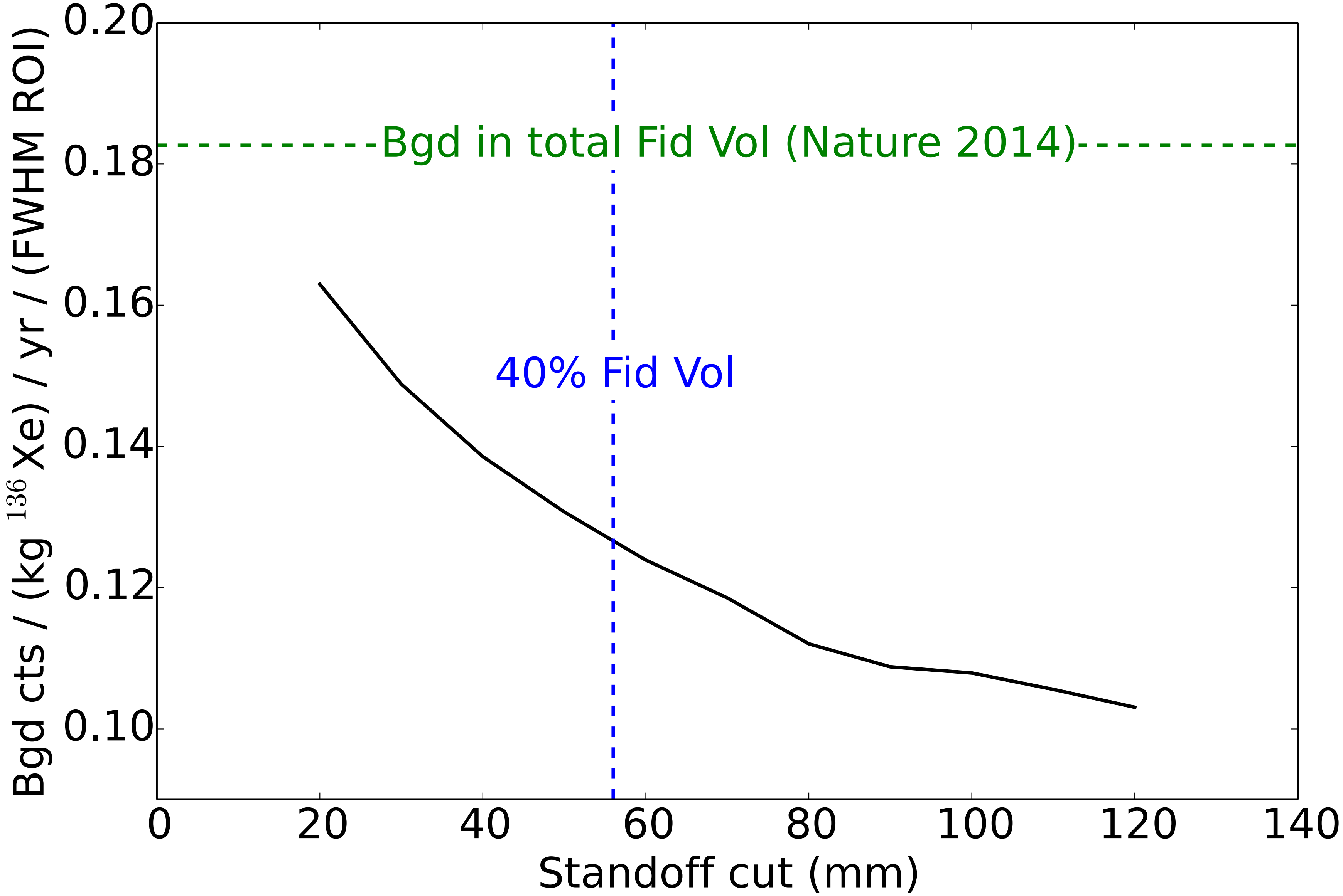
- A large monolithic LXe detector can build on the technology demonstrated by EXO-200
- Single-sided TPC: 1.3-m diameter, 5-ton LXe



nEXO conceptual design



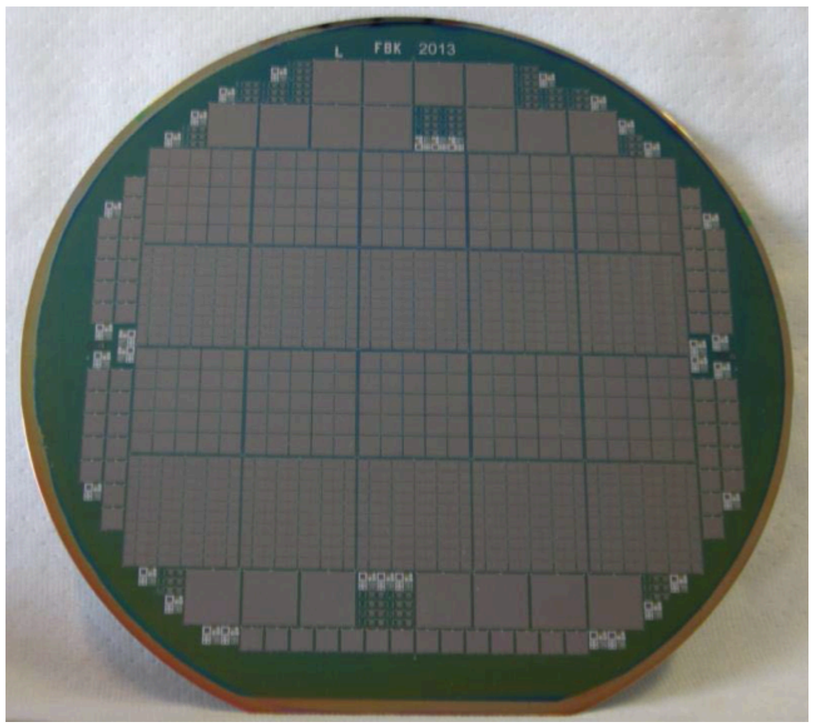
EXO-200 backgrounds decrease with depth into the detector



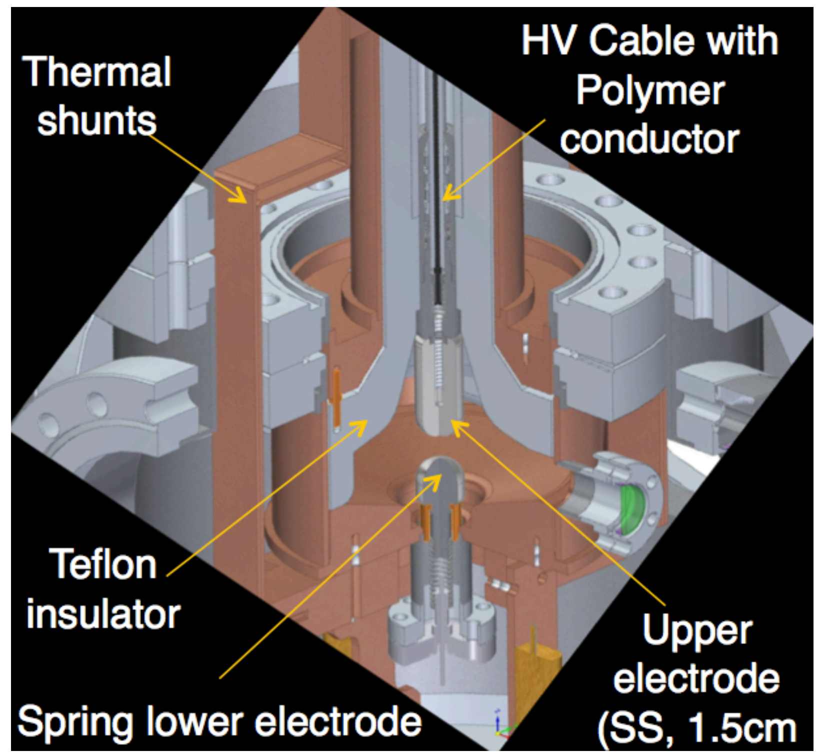
Attenuation length of 2.5-MeV gamma: 8.5 cm

EXO-200: 30% background reduction in inner 40% fiducial volume (reduction limited by size of TPC)

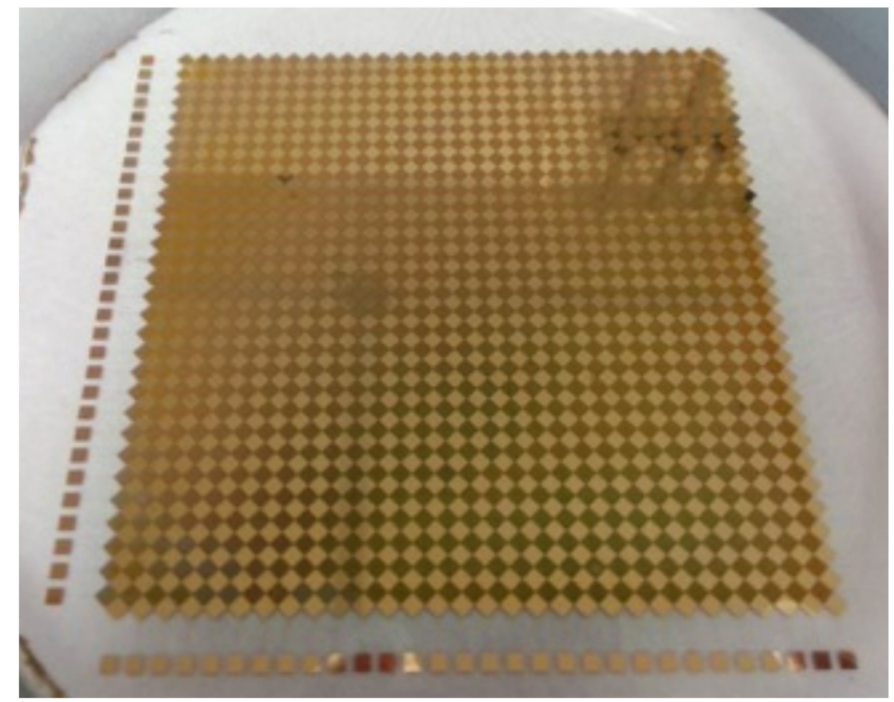
nEXO R&D efforts



Studies of alternate light-collection technology: SiPMs



Investigation of HV breakdown in liquid xenon

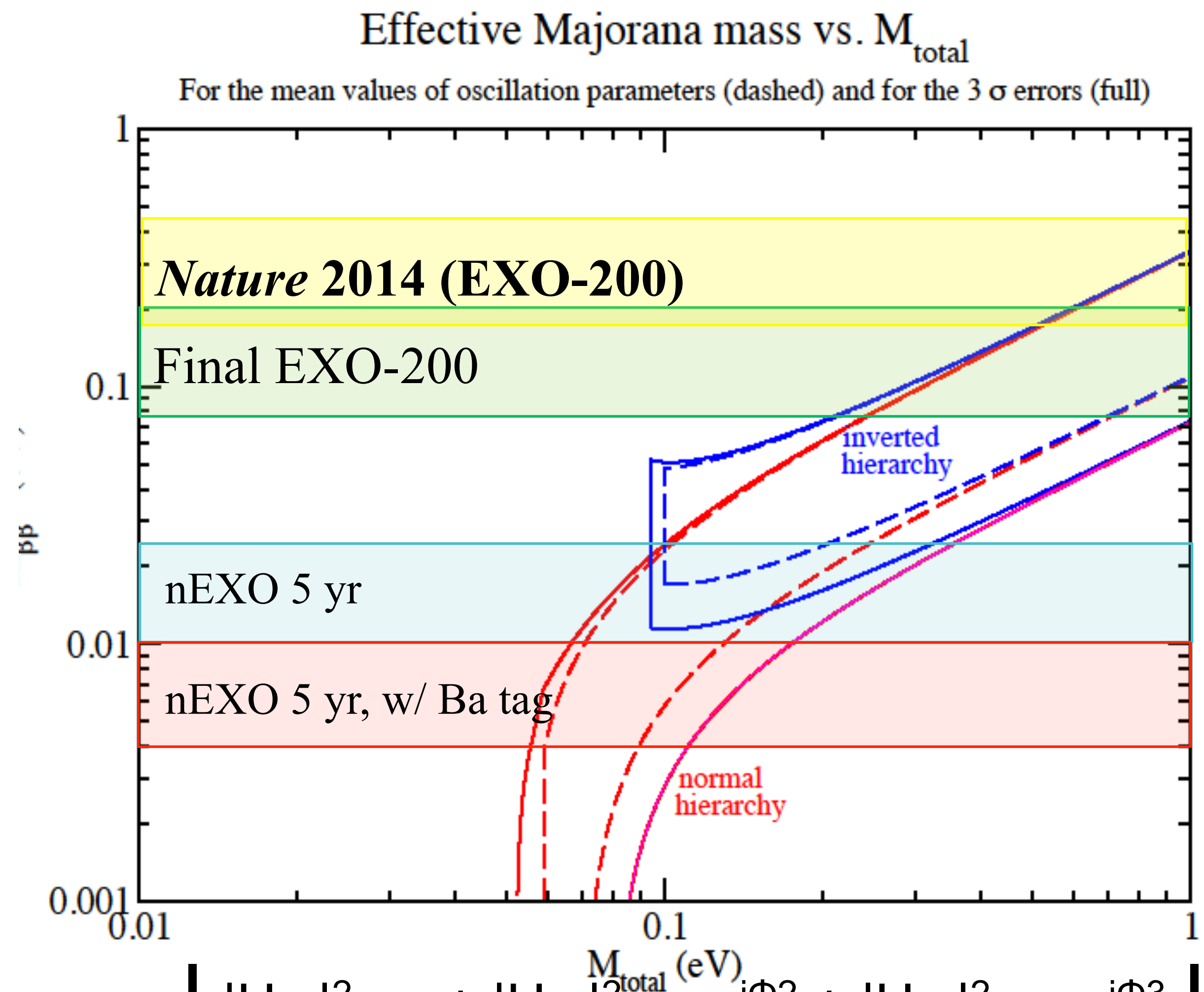


Tests of radiopure methods for charge collection: quartz tiles

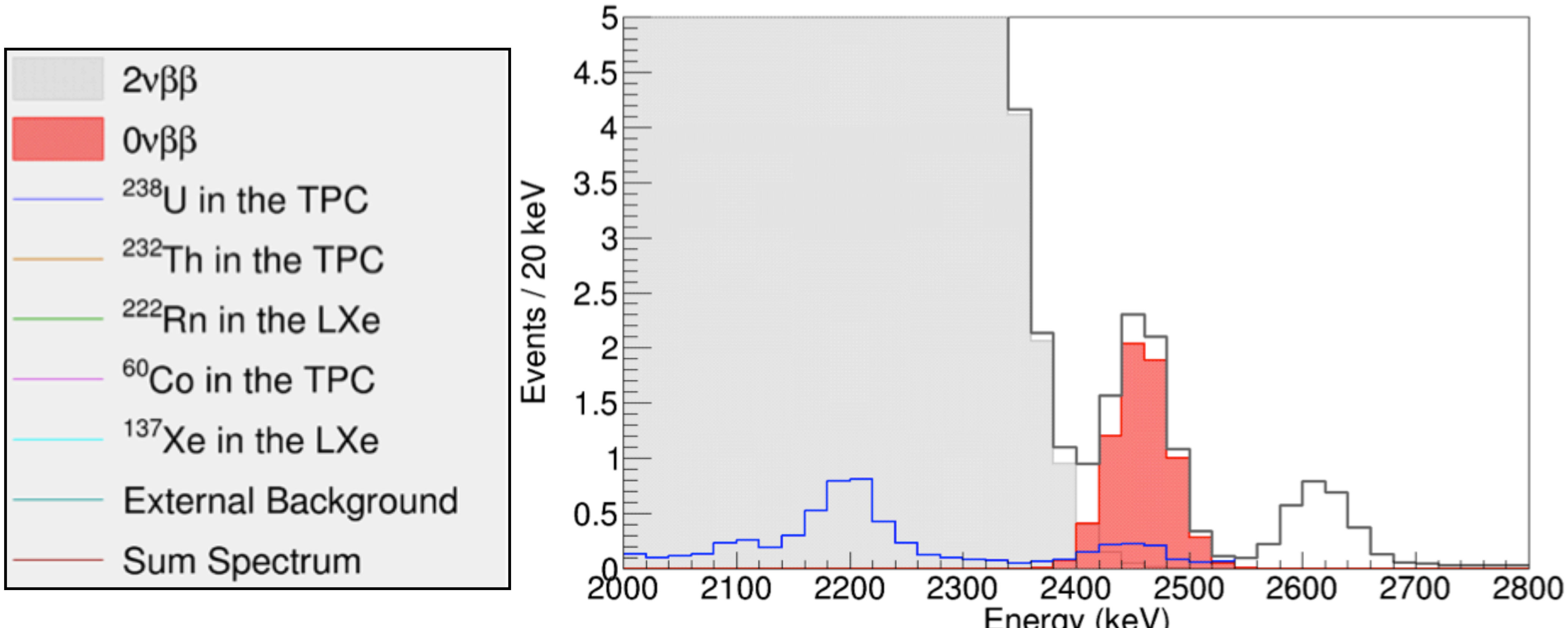
Other ongoing R&D includes simulations of detector response, electrical fields, barium tagging

The nEXO detector

- Projected performance at SNOLAB
- Improved energy resolution (1%)
- Self shielding
- 3mm wire pitch: improved SS/MS discrimination



eff. mass: $m_{0\nu\beta\beta} = \left| |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{i\Phi 2} + |U_{e3}|^2 m_3 e^{i\Phi 3} \right|$



Summary

- EXO-200 is a liquid xenon TPC searching for neutrinoless double-beta decay of xenon-136
    - Recent result:

$T_{1/2}^{0\nu\beta\beta} > 1.1\cdot10^{25}$ yr

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

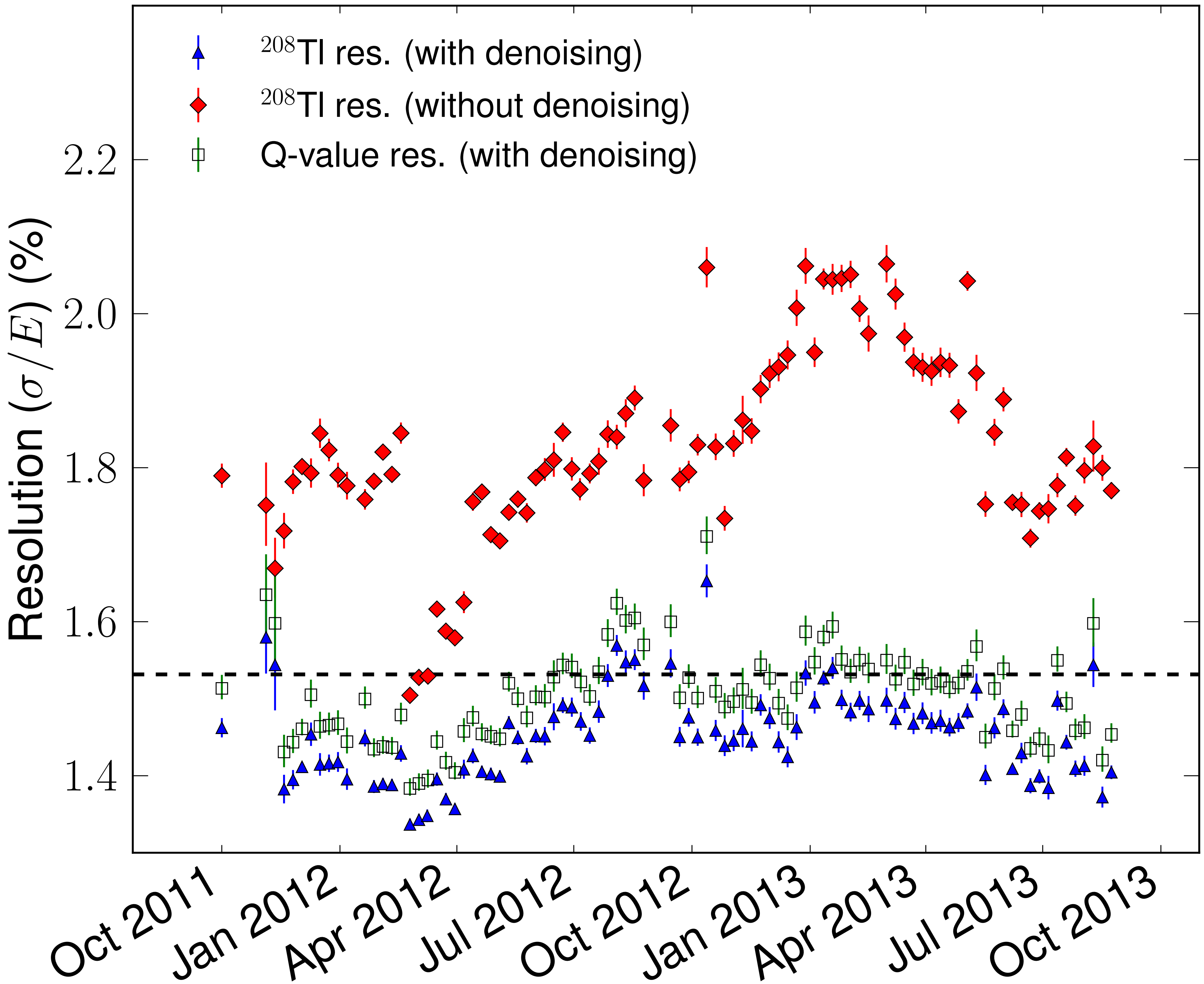
(90% C.L.)

*Nature **510**, 229 (2014), arXiv:1402.6956*

- nEXO is a planned 5-ton liquid xenon detector
    - Projected sensitivity to most of the inverted hierarchy after 5 years of exposure

supplemental slides

Scintillation signal denoising



nEXO backgrounds

nEXO backgrounds assume measured activities for all detector materials

Have compared to EXO-200 data to confirm validity of these assumptions

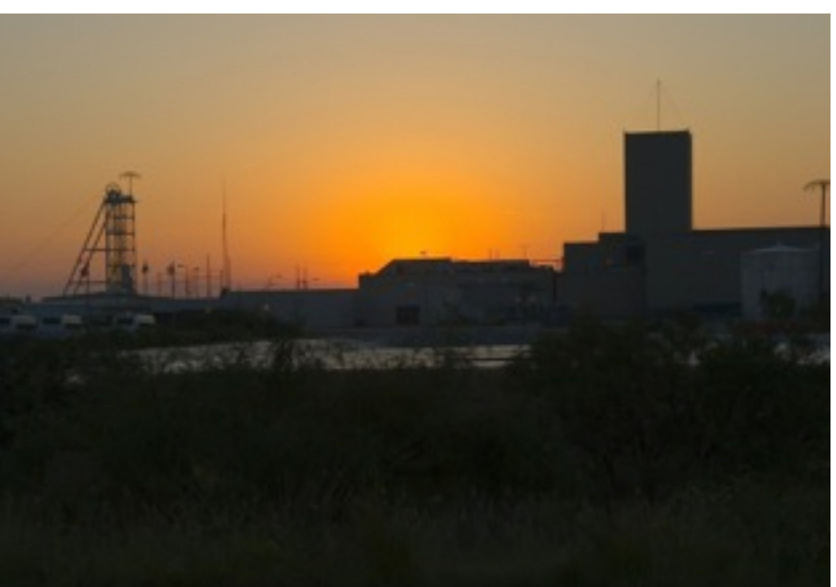
Measured background rate from EXO-200 is $\boldsymbol{B_{EXO\text{-}200}}$ **= 151 ± 19 ROI^{-1} ton^{-1} yr^{-1}**,
(ROI = $Q_{\beta\beta}$ ± 0.5·FWHM)
Agrees with predicted nEXO rate in outer 16.2 cm for same assumptions

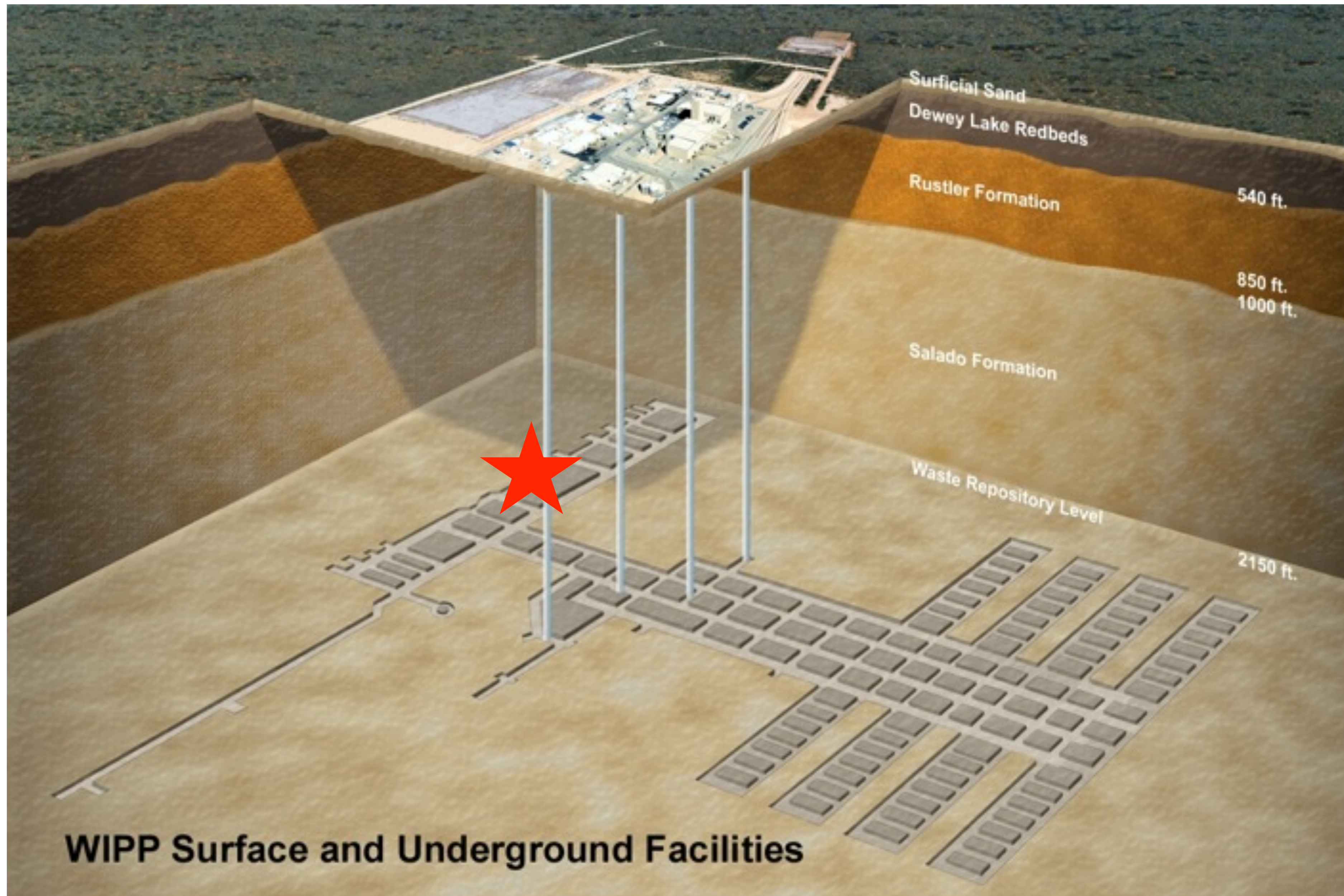
The following improvements over EXO-200 are assumed:
- Improved energy resolution ($\sigma/Q_{\beta\beta} = 0.01$)
- Improved SS/MS discrimination (3mm channel pitch)
- Improved Cu activity from more sensitive radio assay
- Reduced ^{137}Xe rate at SNOLAB
- Reduced ^{222}Rn density, longer time window in ^{214}Bi-^{214}Po coincidence cut
- Kapton cabling removed (using cold electronics instead)

Total nEXO background prediction in outer 16.2 cm: $\boldsymbol{B_{nEXO}}$ **= 3.7 ROI^{-1} ton^{-1} yr^{-1}**

Improvements give reduction of ~40x in background in background index relative to EXO-200

The Waste Isolation Pilot Plant (WIPP)





depth of 2150 ft (655m), ~1600 m.w.e.

Systematic errors

- Signal 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**

- 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**

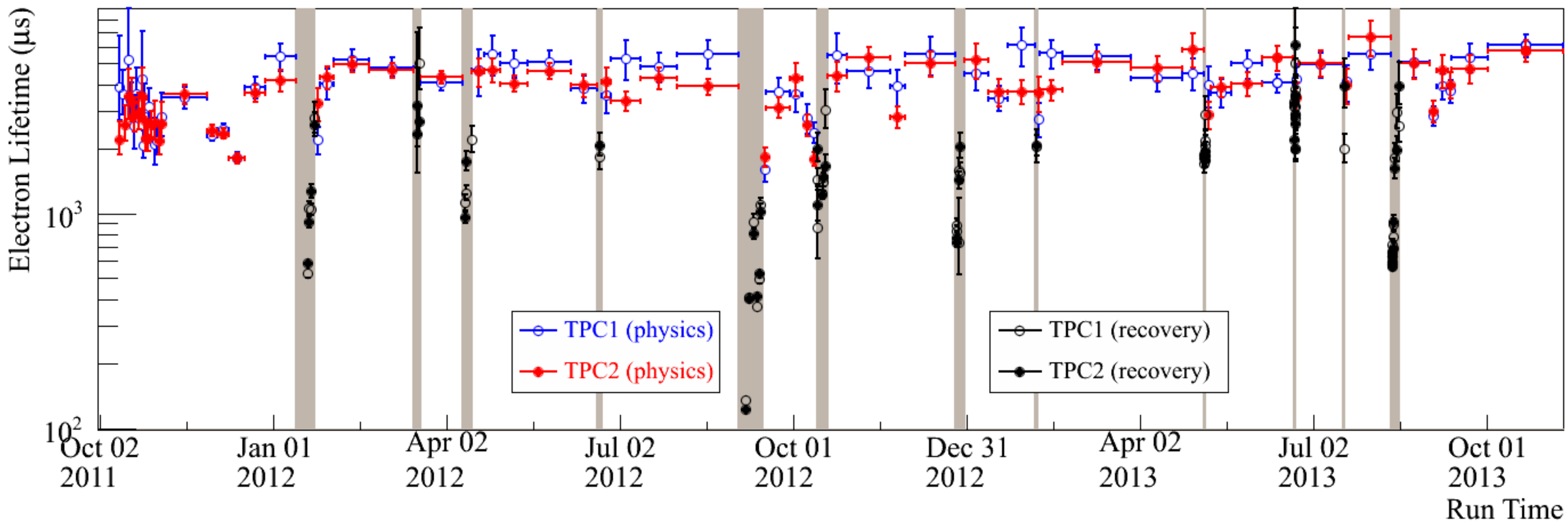
- Location of 0νββ ROI:

  Deviations between β and γ energy scale: $E_\beta = B^*E_\gamma$ $\Longrightarrow$ $\mathbf{B = 0.999 \pm 0.002}$

- Single-site fraction error:

  Maximum deviation between data and simulation, averaged over all calibration sources: **(Data – MC)/Data = 9.6%**

Xenon purity is essential for good energy resolution

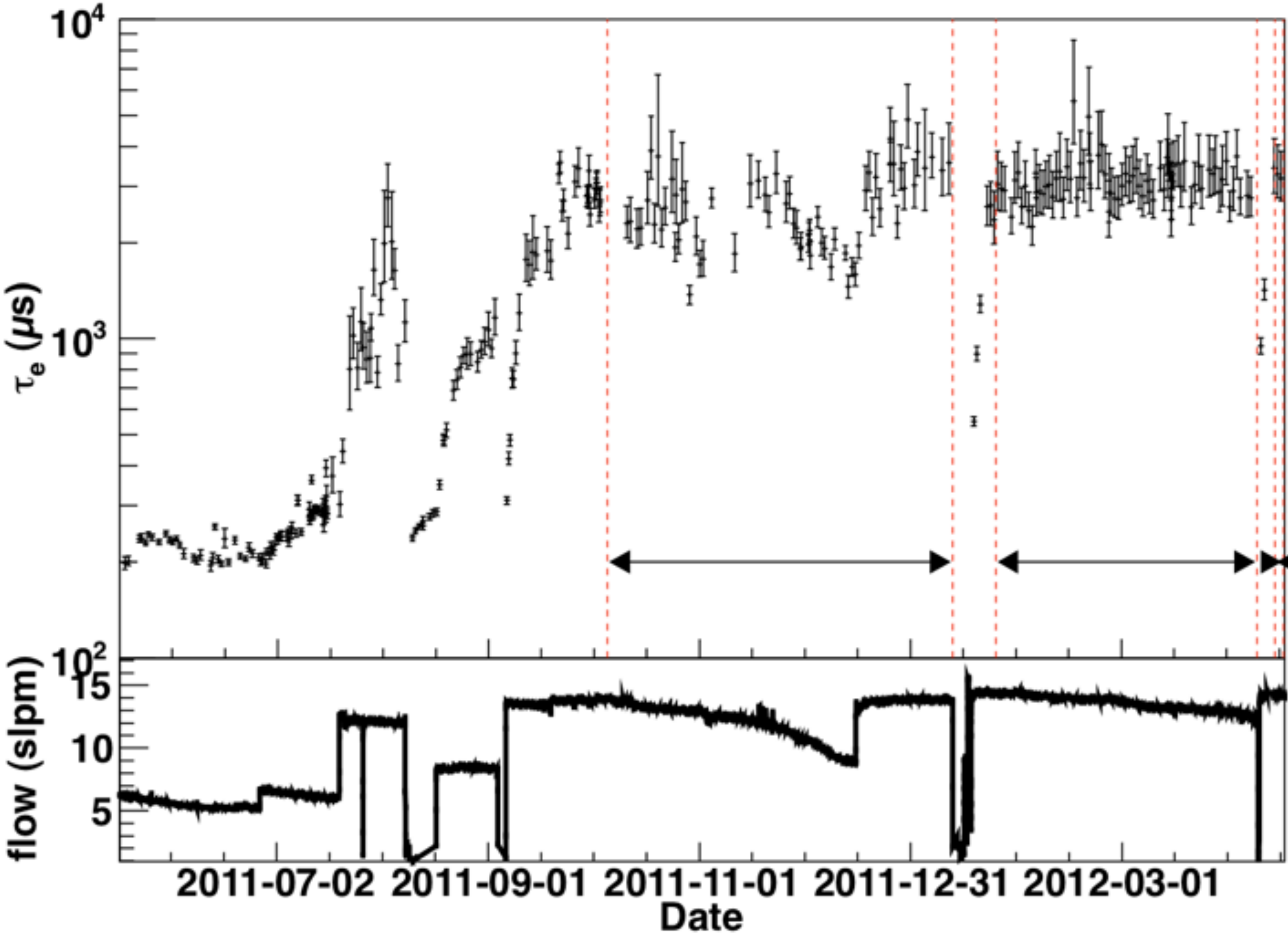


Xenon gas is forced through heated Zr getter by a custom ultraclean pump.

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

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

Electron lifetime depends on continuous purification



EXO-200 uses an ultra-clean magnetically driven xenon pump
Rev Sci Instr. 82 (10) 105114