Search for ^{136}Xe neutrinoless double beta decay with the Enriched Xenon Observatory (EXO)

24th Rencontres de Blois
Château de Blois, France

29-05-2012

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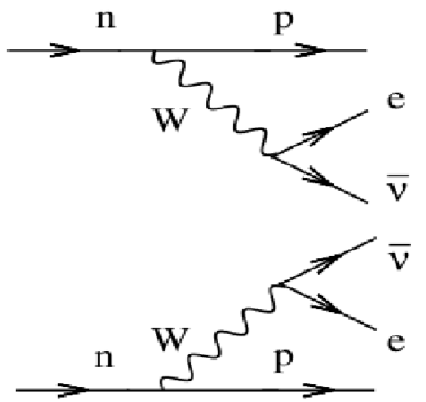
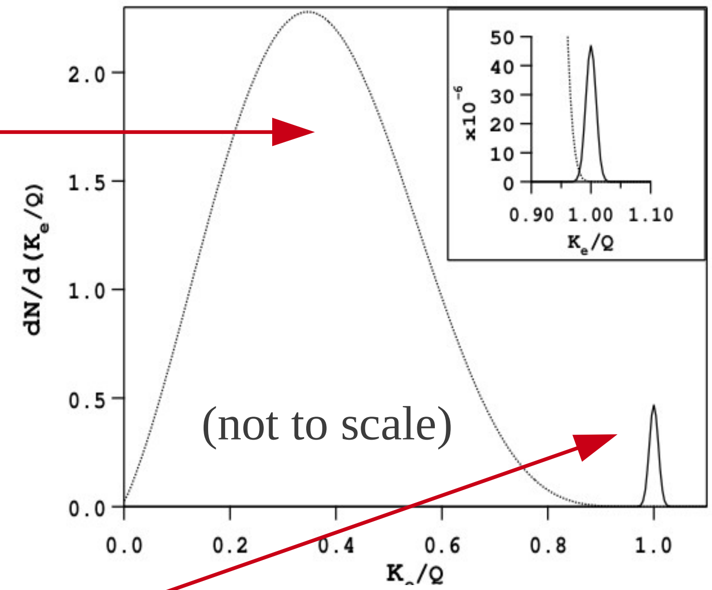
Double Beta Decay

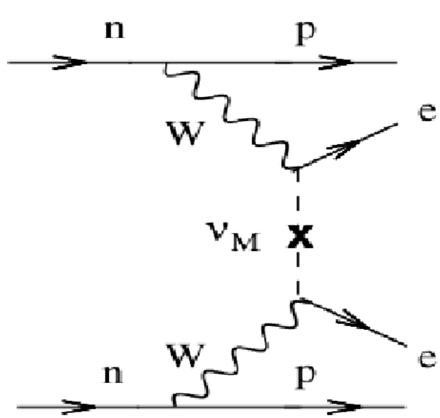
Two neutrino double beta decay



[P. Vogel, arXiv:hep-ph/0611243]



Neutrinoless double beta decay



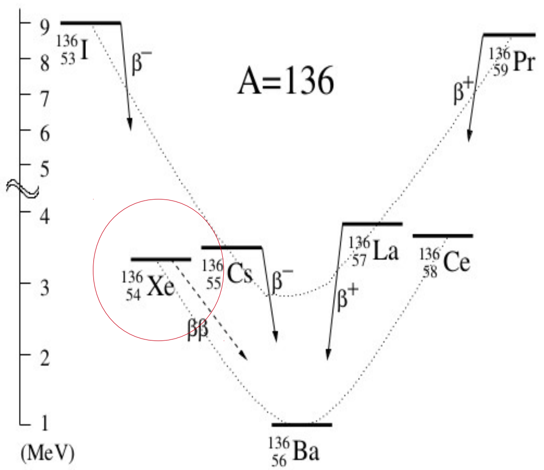
$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

$$\langle m_{\beta\beta}\rangle = |\Sigma_i |U_{ei}|^2 e^{i\alpha(i)} m_i|$$

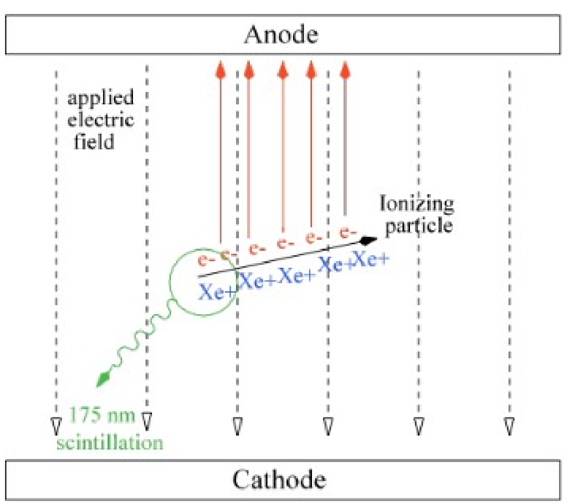
Observation of 0νββ:
- Majorana neutrino
- Neutrino mass scale
- Lepton number violation

The Enriched Xenon Observatory

Probing the $0\nu\beta\beta$ of ^{136}Xe

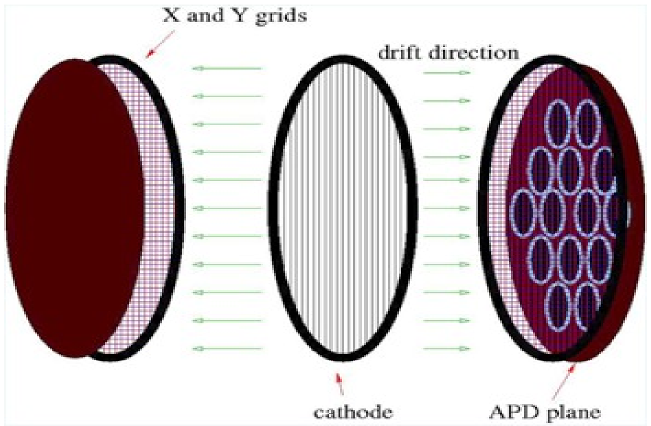


Simultaneous measurement of ionization and scintillation

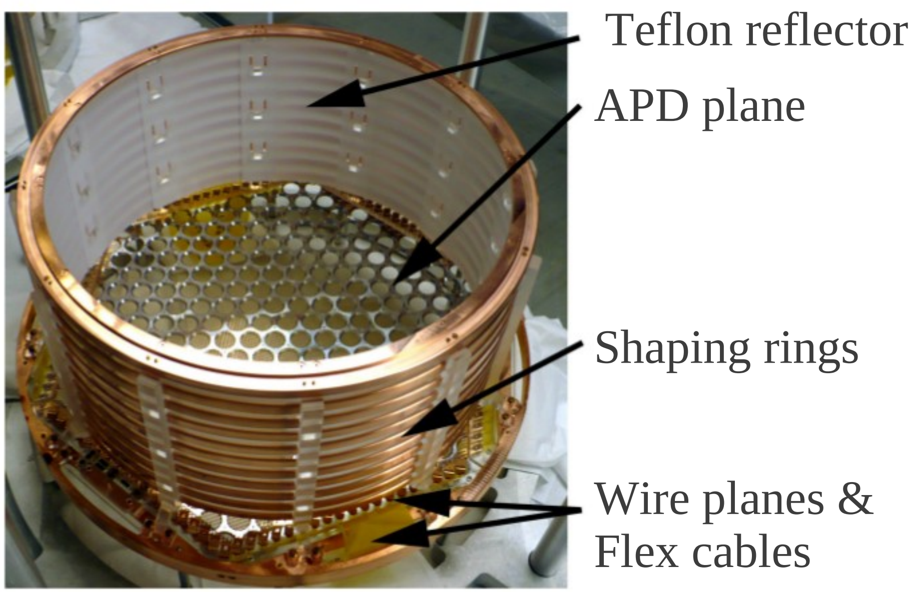


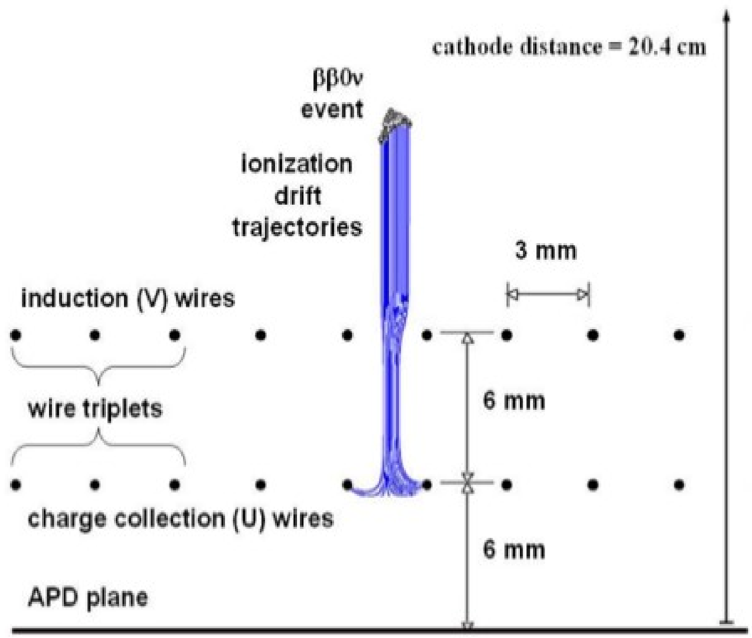
- Xenon is "reusable". Can be re-purified & recycled into new detector.
- High Q-value. $Q_{\beta\beta}$ = 2458 keV
- Monolithic detector. LXe is self shielding, surface contamination minimized.
- Minimal cosmogenic activation. No long lived radio isotopes of xenon.
- Energy resolution. Scintillation and ionization anti-correlated
- *Allows a novel coincidence technique.* Potential strong reduction of background by barium daughter tagging.

The EXO-200 Time Projection Chamber (TPC)



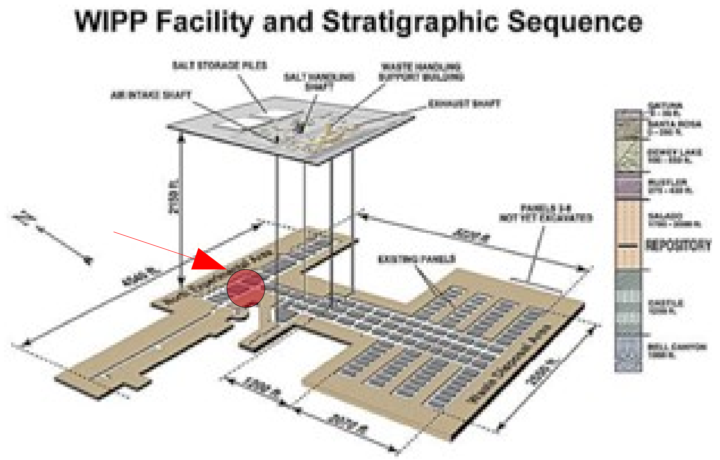
- Using ~110 kg of 80.6 % enriched Xe in the isotope 136
- Two TPC modules separated by a common cathode.
- LAAPD arrays for light measurement.
- Two planes of 38 collection wire triplets (U-wires).
- Two planes of 38 induction wire triplets (V-wires).
- Wire planes crossing at 60° for stereoscopic informations.

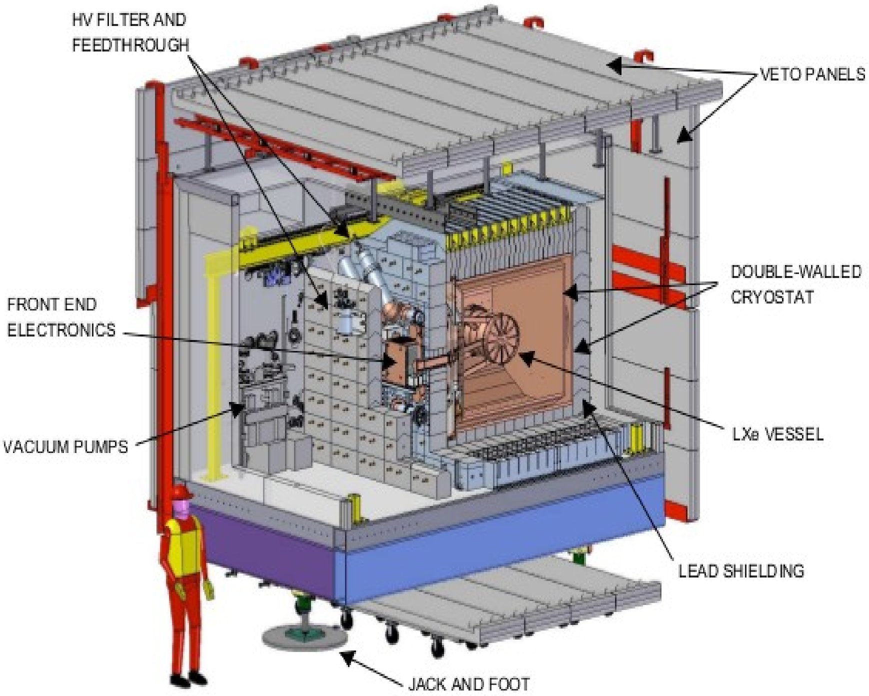




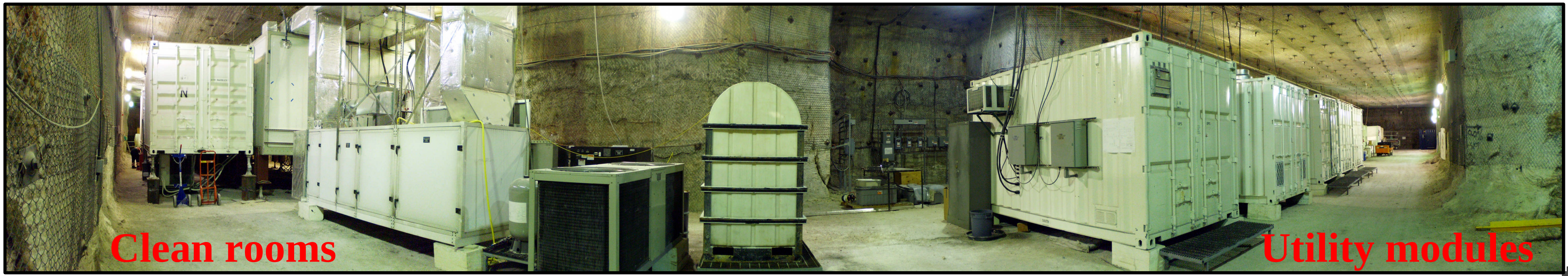
M. Auger et al. JINST 7 (2012) P05010.

The EXO setup at WIPP

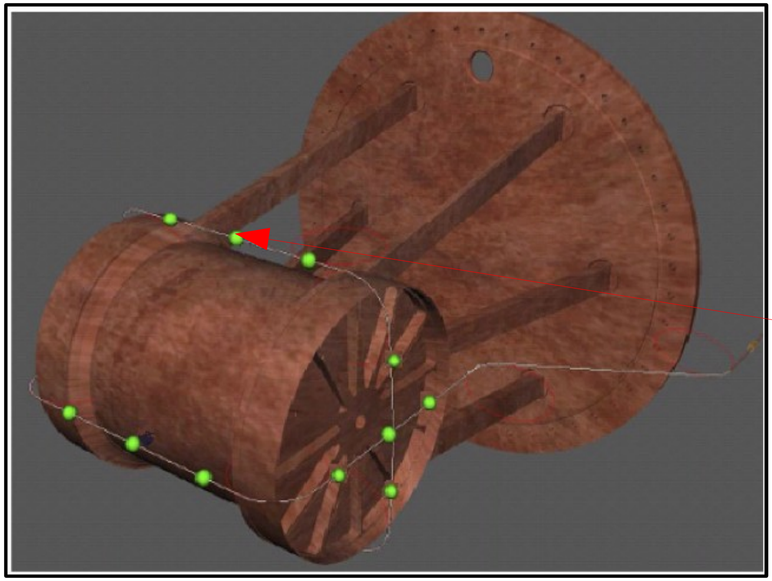


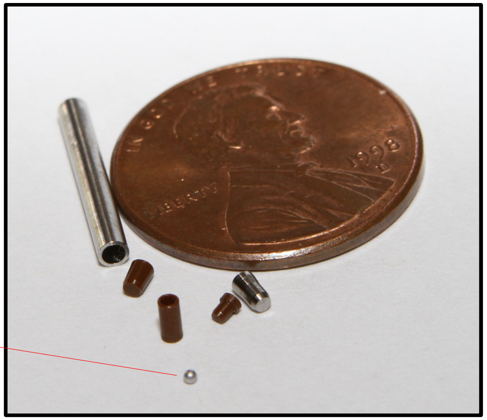


- Located at WIPP site (1600 m water equivalent depth)
- Low salt rock activity
- Installed in clean room



Source Calibration

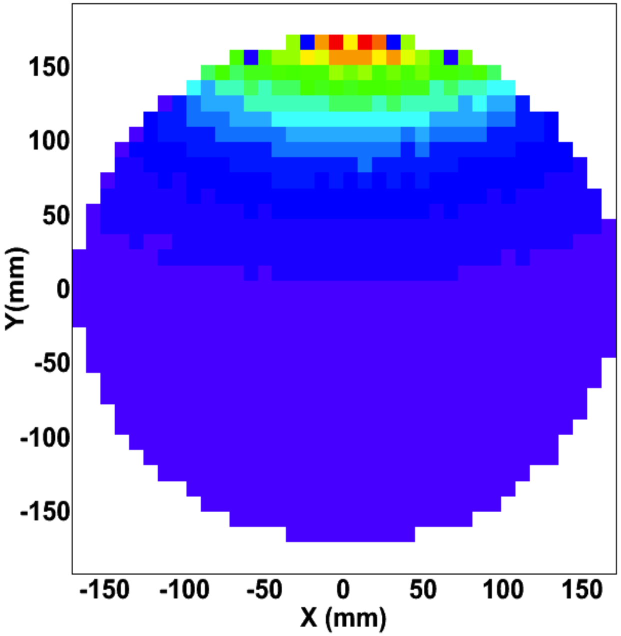




Custom miniaturized sources

Calibration system allows the positioning radioactive source just outside of the TPC

X-Y reconstructed distribution of events reflect the source position.



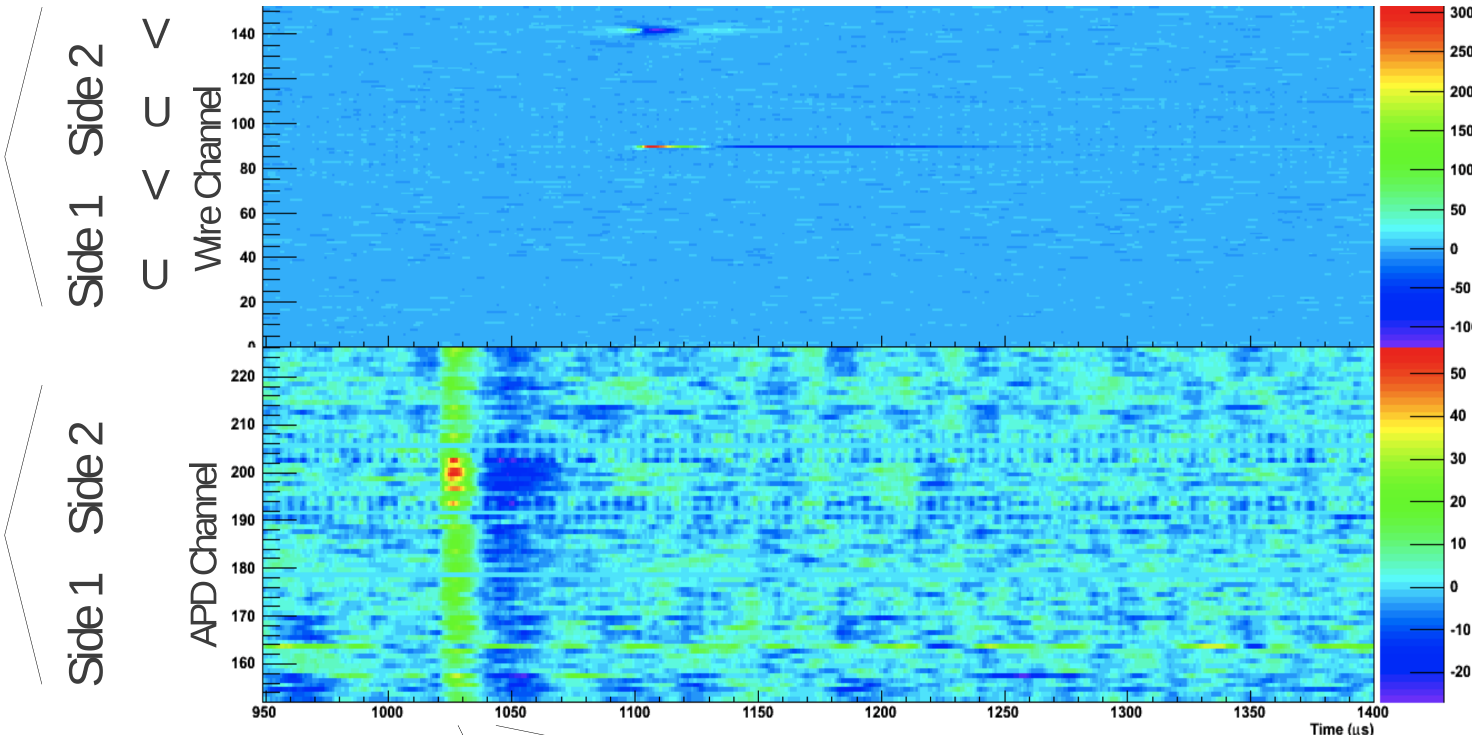
Event Display SS

Charge readout

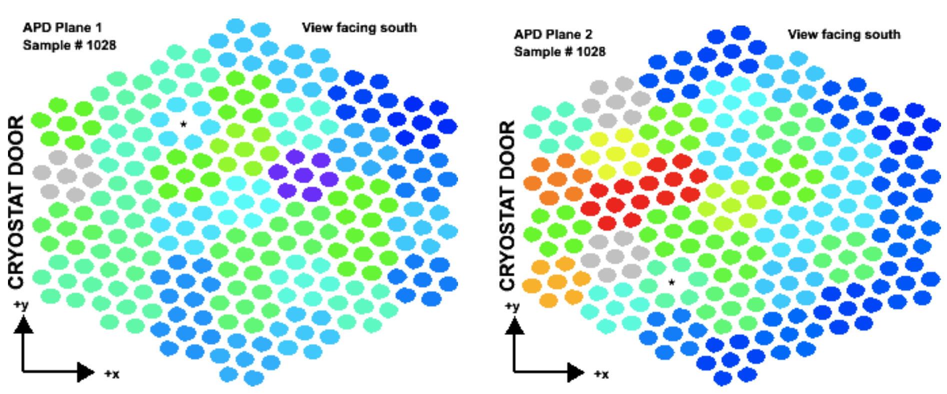
V: Induction

U: Collection

Light readout



one sample



A single-site energy deposition in EXO-200

Scintillation light is seen at both sides. The light is more diffuse on side 1 and more localized on side 2, where the event occurred.

The light signal always precedes both charge signals. The induction (V) signal precedes the collection (U) signal.

Event Display MS

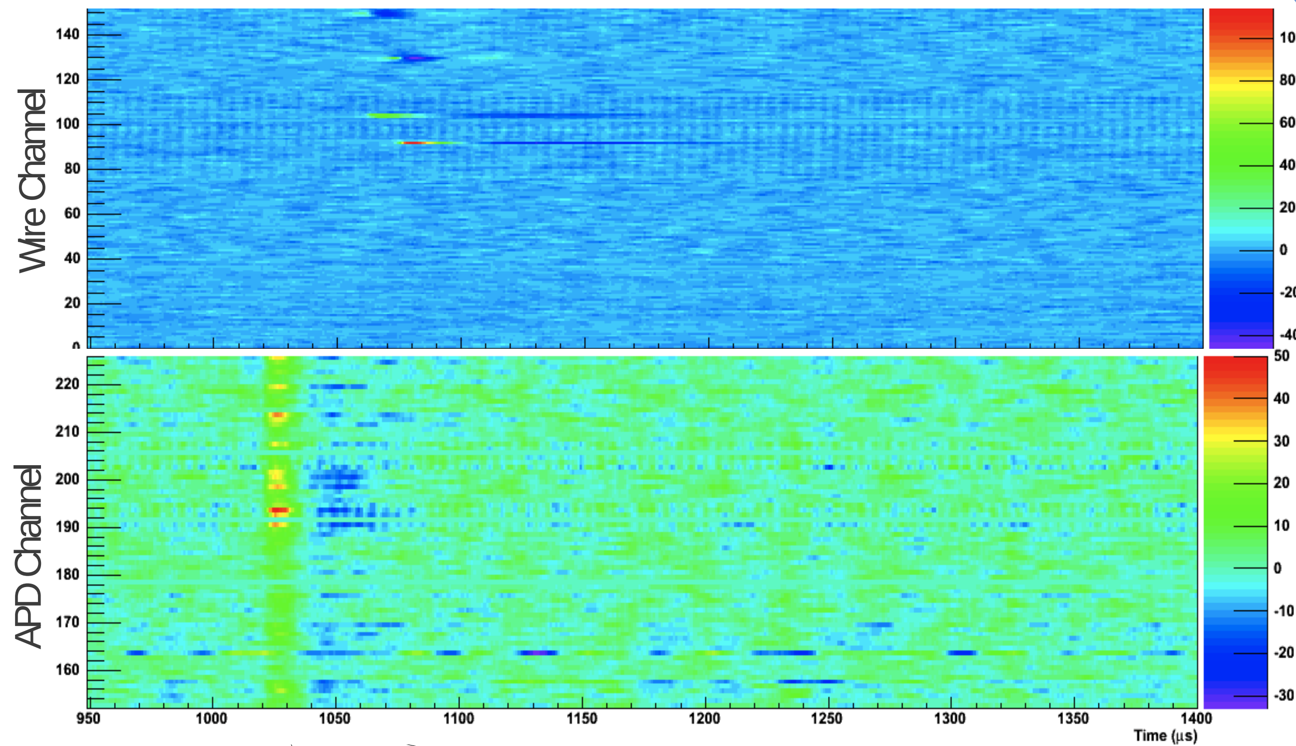
Charge readout

V: Induction

U: Collection

Side 2 V U

Side 1 V U

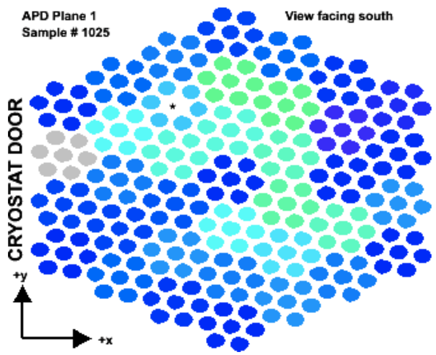


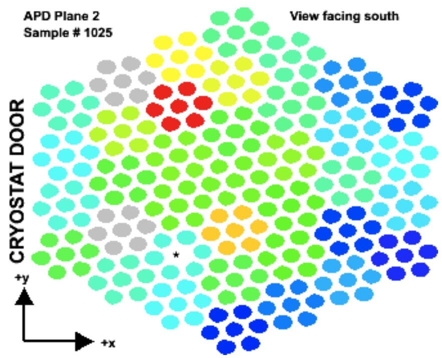
Light readout

Side 2

Side 1

one sample



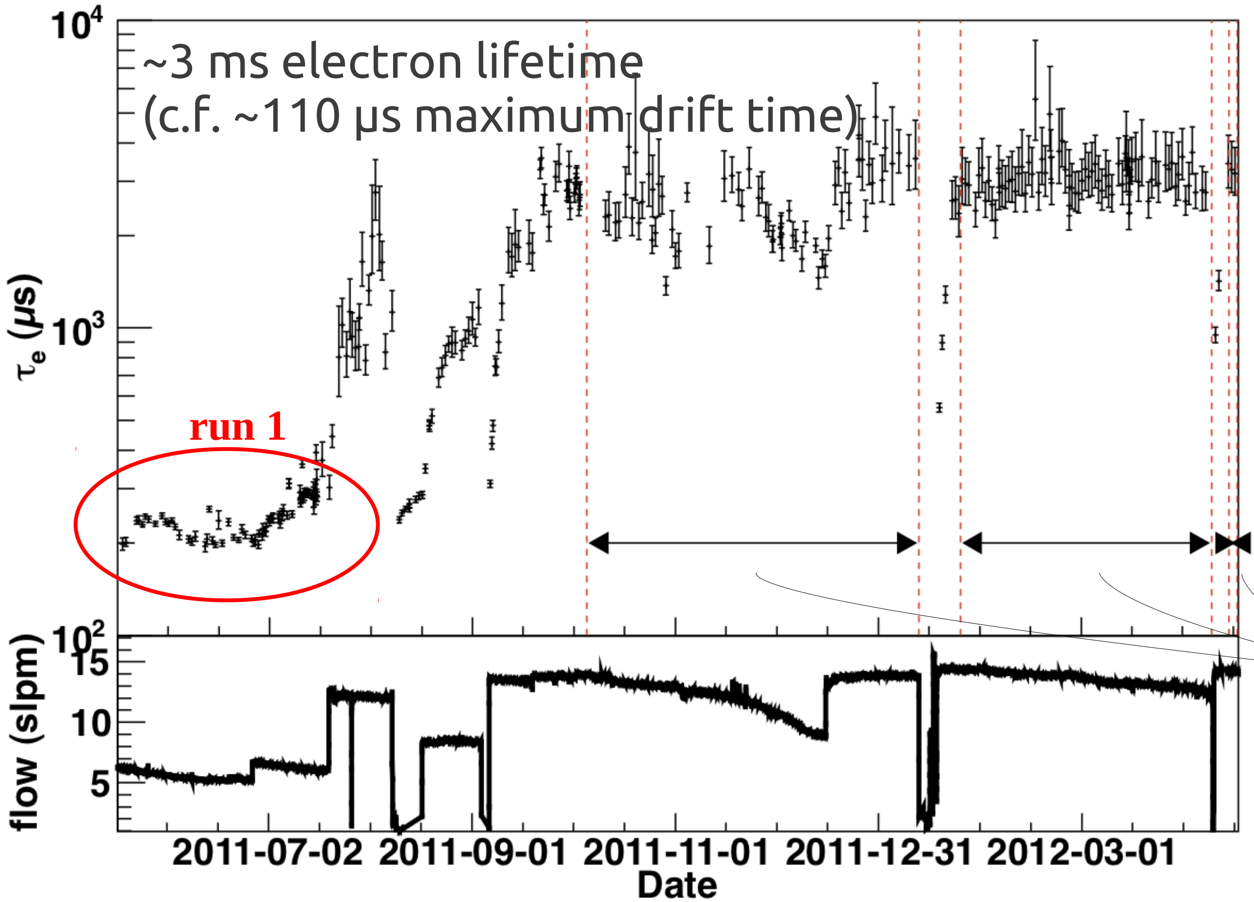


A two-site Compton scattering event

All scintillation light arrives at the same time, indicating that the two energy depositions are simultaneous.

In this case, the gamma ray occurred on side 2. The light hitting side 2 is more localized, while the light hitting side 1 is more diffuse across the plane.

Xenon Purity



Electron lifetime was determined by measuring the attenuation of the ionization signal as a function of drift time for the full-absorption peak of gamma ray sources

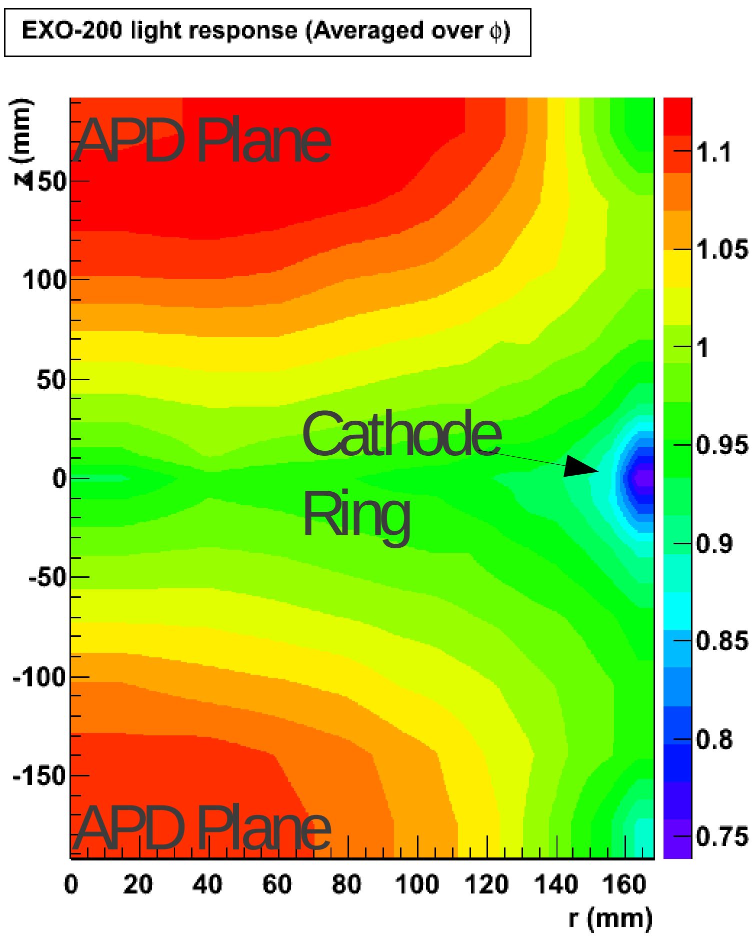
† Rev Sci Instrum. 2011 Oct;82(10):105114

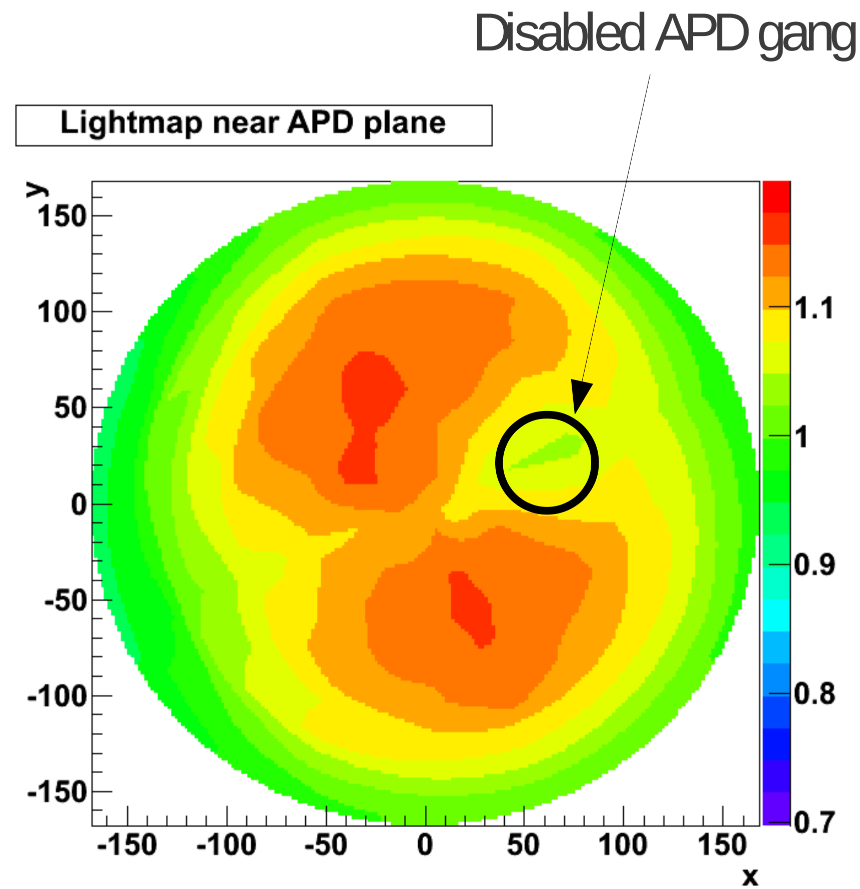
•Xenon gas is circulated through a heated zirconium getter using a custom-built ultraclean pump†.

•Occasional stops for maintenance, etc. resulted in temporary reductions in electron lifetime, followed by quick recovery.

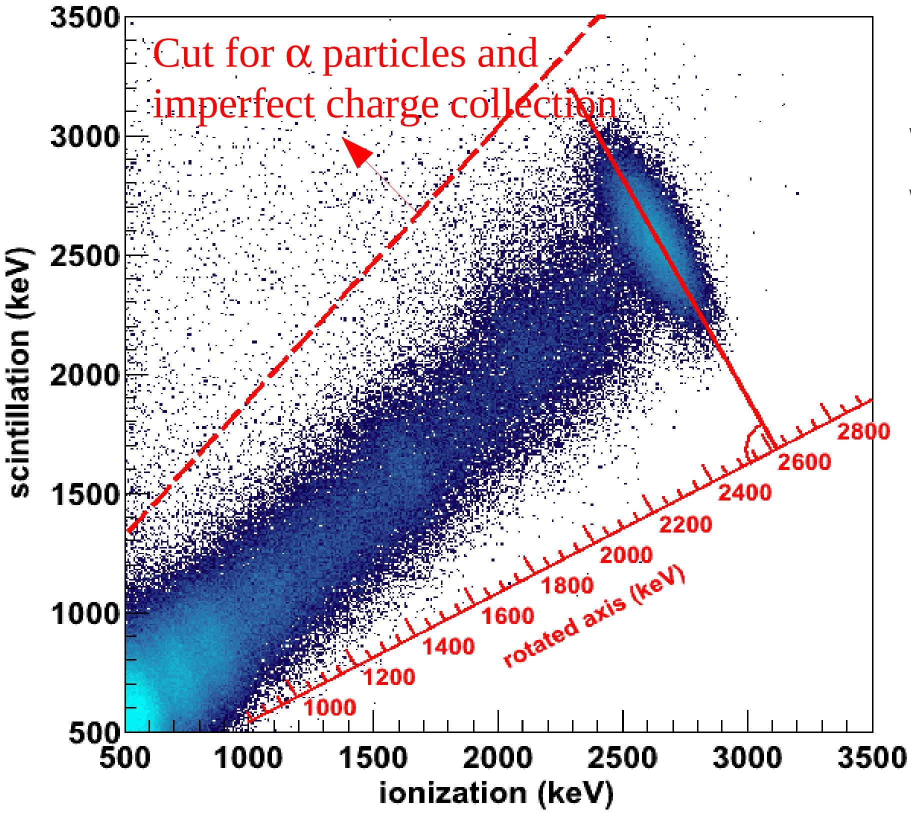
Correcting for Light Response

- Use full absorption peak of 2615 keV gamma from 208Tl to map light response in TPC
- Linearly interpolate between 1352 voxels





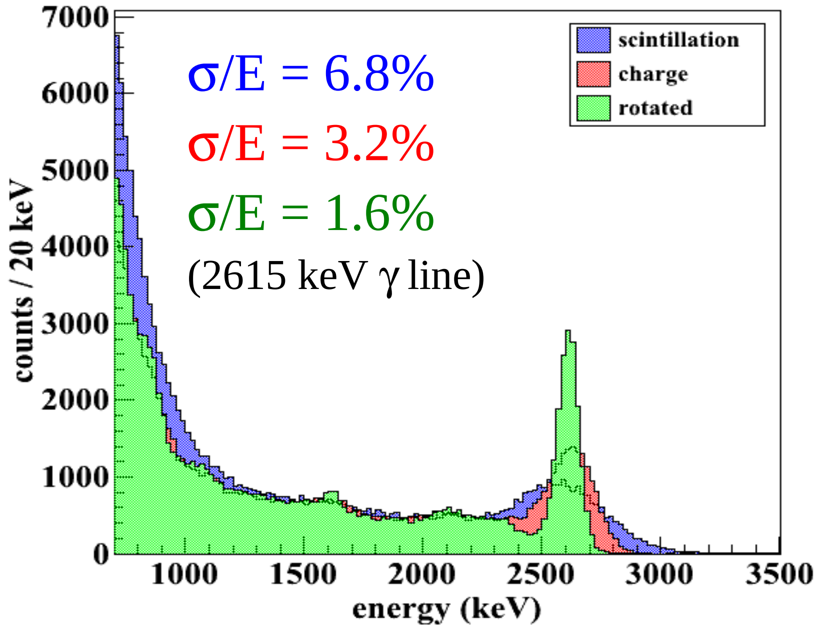
2D Anti-correlated spectra



Conservation of energy means increased scintillation is associated with decreased ionization (and vice-versa)†

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

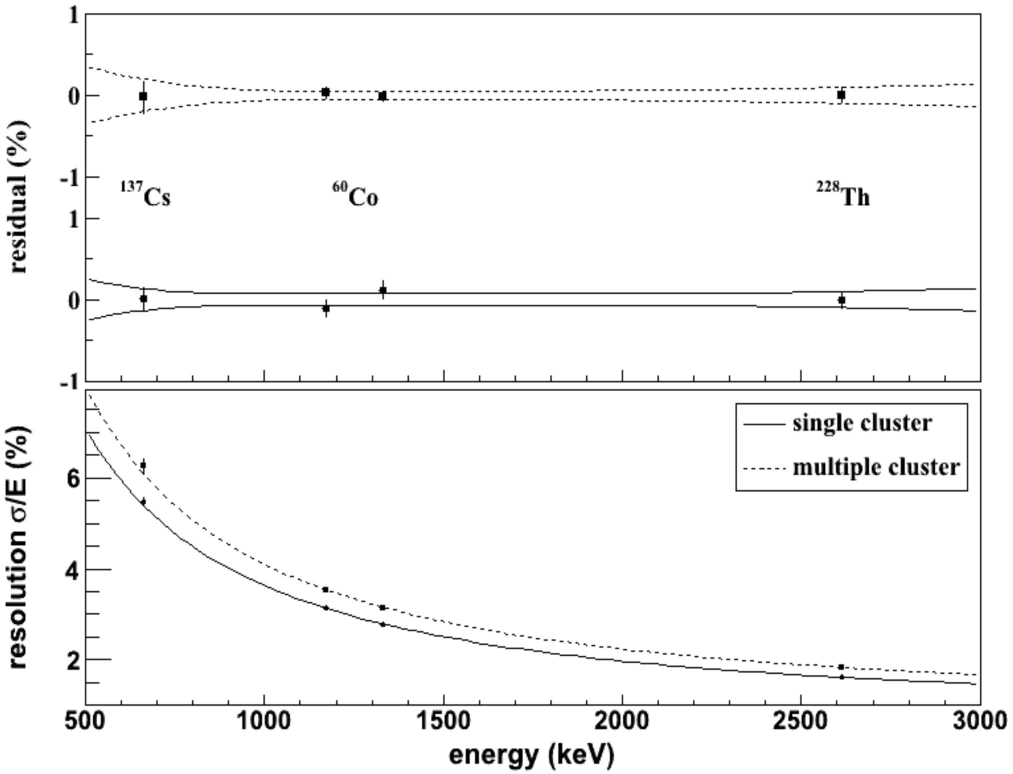
Projection onto a rotated axis



Blue: Projection on scintillation axis
Red: Projection on charge axis
Green: Projection on rotated axis

Energy Calibration

- EXO-200 has 3 types of sources
  - ^{137}Cs (3 kBq (weak), 15 kBq (strong))
  - ^{60}Co (0.5 kBq (weak),7.2 kBq (strong))
  - ^{228}Th (1.5 kBq (weak), 38 kBq (strong))
- In total they provide 4 full energy deposition peaks in the energy range of 662 keV – 2615 keV



Using quadratic model for energy calibration, single- and multi-site residual are < 0.1%

Energy resolution model:

$$\sigma^2_{Tot} = \sigma^2_{Stat} + \sigma^2_{Noise} + \sigma^2_{Drift}$$
$$\sigma^2_{Tot} = p_0^2 E + p_1^2 + p_2^2 E^2$$

Resolution dominated by constant (noise) term p_1

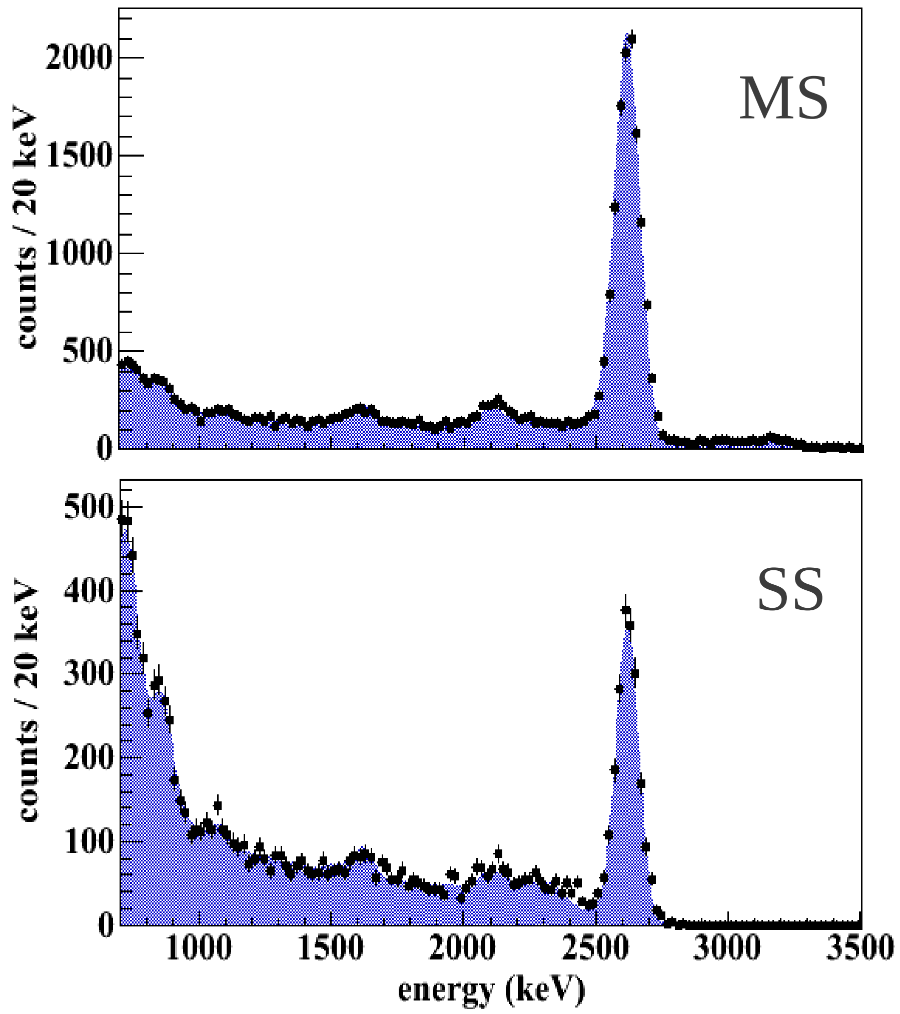
At $Q_{\beta\beta}$: σ/E = 1.67 % (SS)

σ/E = 1.84 % (MS)

Source Agreement with simulations

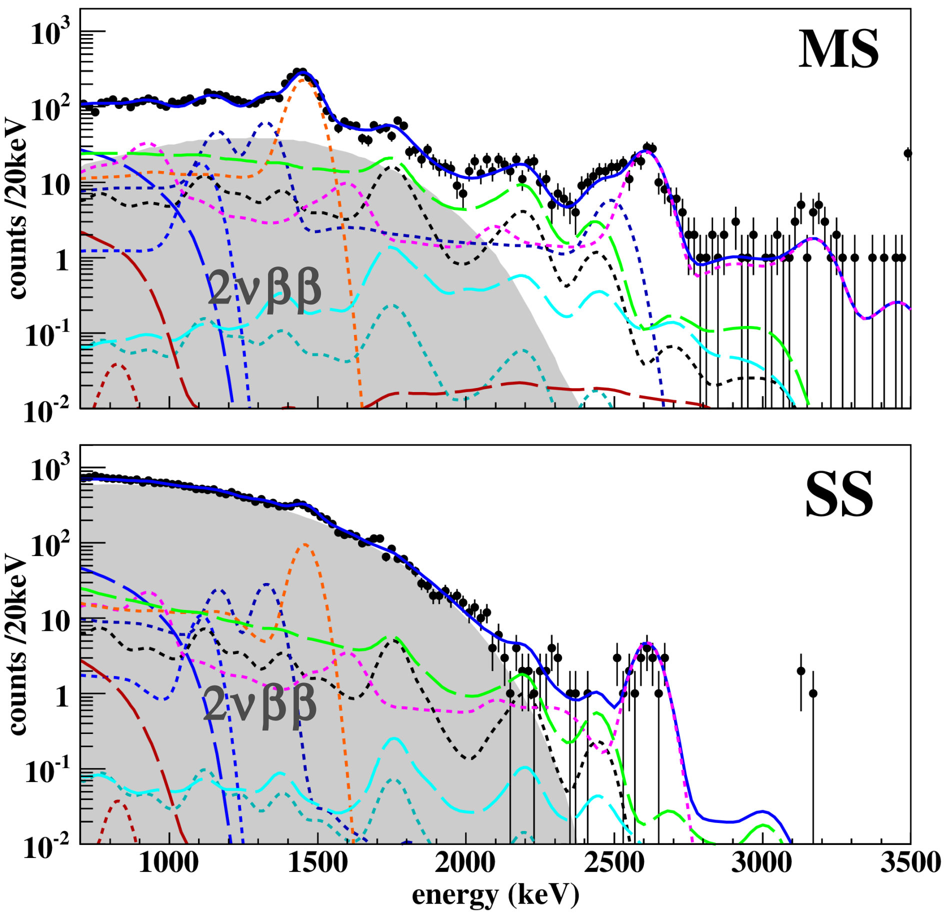
Comparison of source calibration data (black points) with our fit model from Geant 4 simulation (blue area) for multi site (MS) and single site (SS).

- Shapes agree very well
- Maximum rate discrepancy is 9.4%
- Maximum single site fraction discrepancy is 8.5%



Low Background Run

Maximum likelihood fit



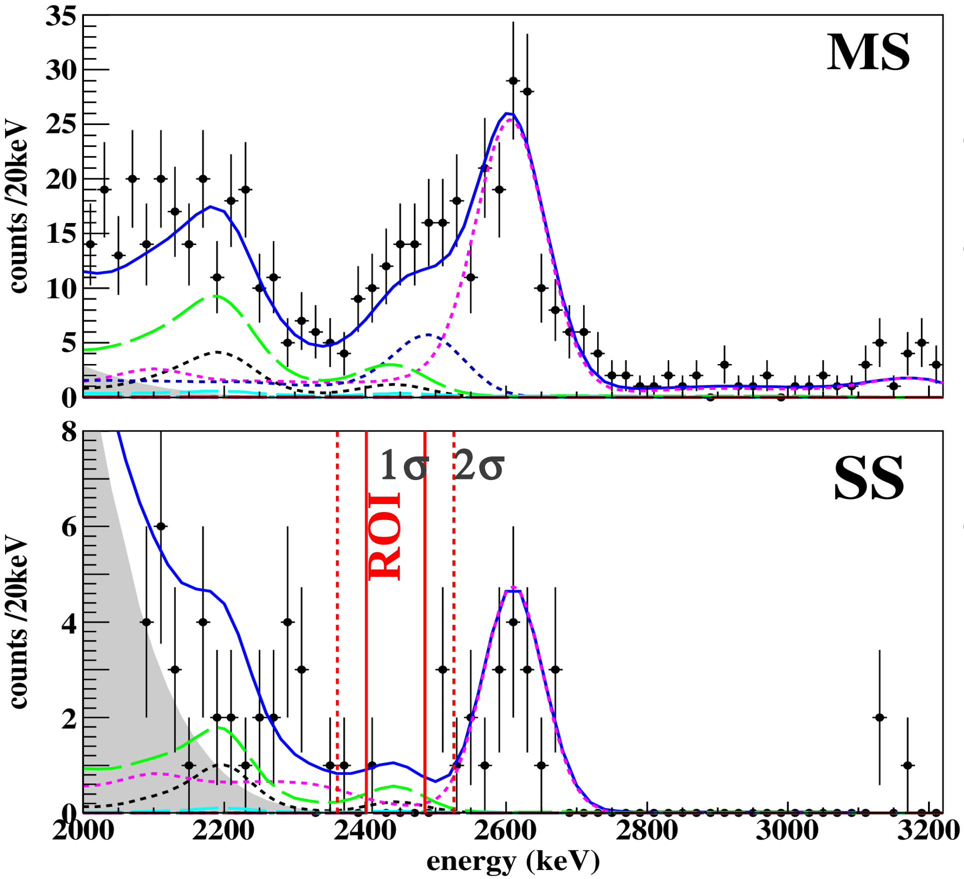
- Trigger fully efficient above 700 keV
- Low background run livetime: **120.7 days**
- Active mass: **98.5 kg LXe (79.4 kg ^{136}LXe)**
- Exposure: **32.5 kg·yr**
- Total dead time (vetos): 8.6%
- Various background PDFs fitted along with 2νββ and 0νββ PDFs

$T_{1/2}^{2\nu\beta\beta}$ (^{136}Xe) = (2.23 ± 0.017 stat ± 0.22 sys)·10^{21} yr

(In agreement with previously reported value by EXO-200 and KamLAND-ZEN collaborations)

Low Background Run

Zoomed around 0νββ region of interest (ROI)



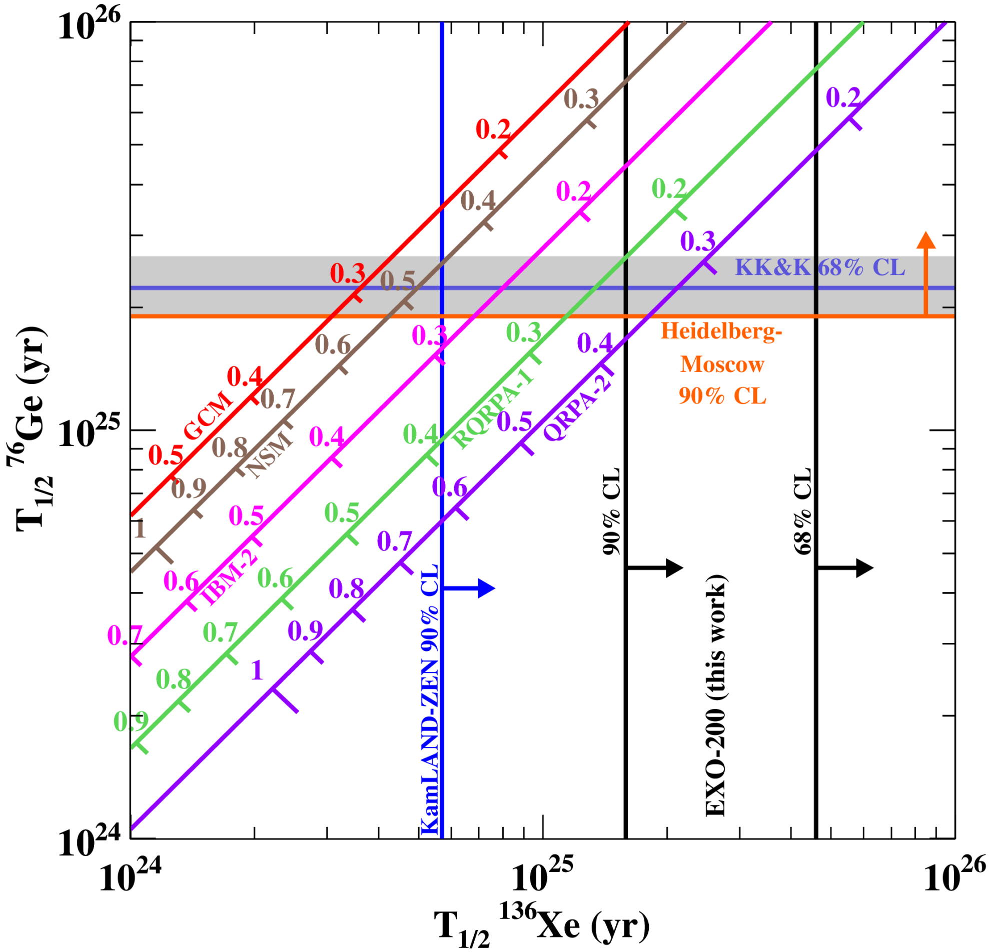
- No signal observed
- Background in ROI:

  $(1.5 \pm 0.1) \cdot 10^{-3}\ kg^{-1} yr^{-1} keV^{-1}$ in ± 1σ ROI

- **Profile likelihood study to extract limits for $T_{1/2}^{0\nu\beta\beta}$**

$T_{1/2}^{0\nu\beta\beta}$ (^{136}Xe) > $1.6 \cdot 10^{25}$ yr (90% C.L.) [arXiv:1205.5608]

Limits on $T_{1/2}^{0\nu\beta\beta}$



90% C.L. limit compared with Recent ^{136}Xe constraints (KamLAND-ZEN)* >2.5 factor improvement.

*A. Gando et al. Phys. Rev. C 85 (2012) 045504.

EXO-200 contradicts Klapdor† claim at the 90% C.L. for most matrix element calculations.

† H.V. Klapdor-Kleingrothaus and I.V. Krivosheina, Mod. Phys. Lett., A21 (2006) 1547.

$T_{1/2}^{0\nu\beta\beta}$ (^{136}Xe) > $1.6\cdot10^{25}$ yr (90% C.L.) [arXiv:1205.5608]

Summary

- EXO-200 achieved $\sigma/E = 1.67\ \%$ @ $Q_{\beta\beta}$
- No signal observed in 32.5 kg·yr exposure
- Background in ROI as low as ~$1.5\cdot10^{-3}\ kg^{-1}yr^{-1}keV^{-1}$
- **$T_{1/2}^{2\nu\beta\beta}$ (^{136}Xe) = (2.23 ± 0.017 stat ± 0.22 sys)·10^{21} yr**
- **$T_{1/2}^{0\nu\beta\beta}$ (^{136}Xe) > $1.6\cdot10^{25}$ yr (90% C.L.)** ← [arXiv:1205.5608]

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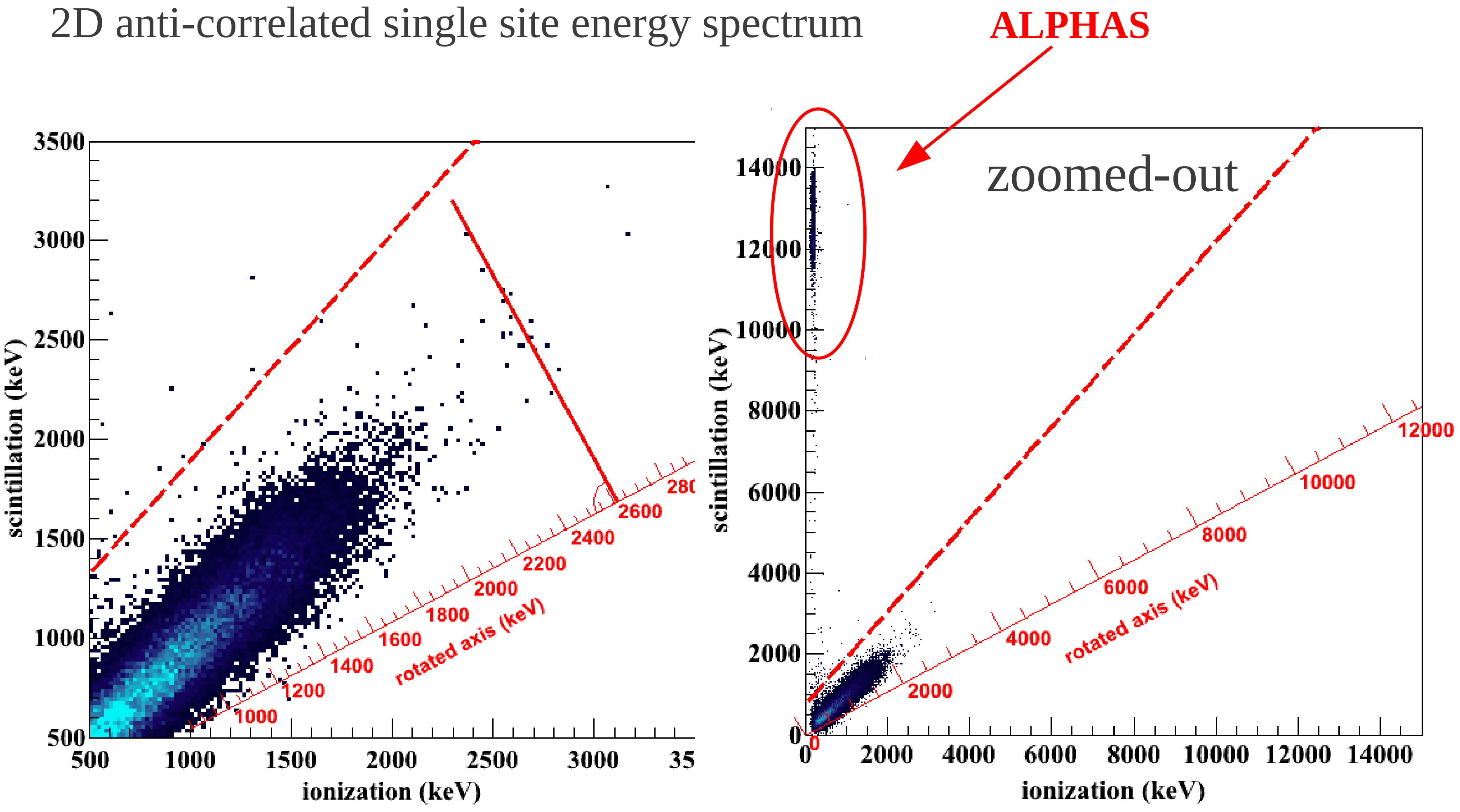
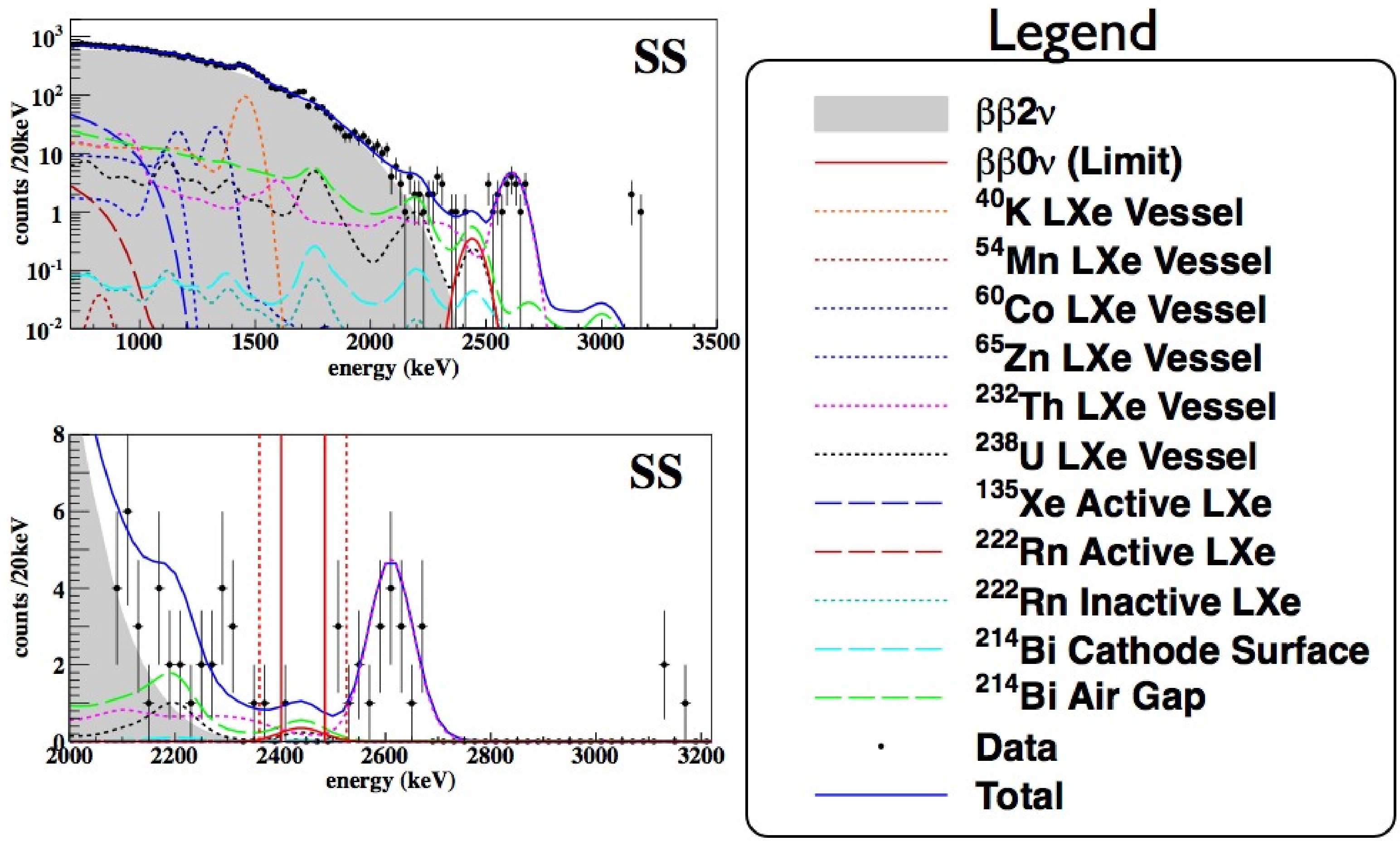
EXTRA SLIDES

Low Background Spectra

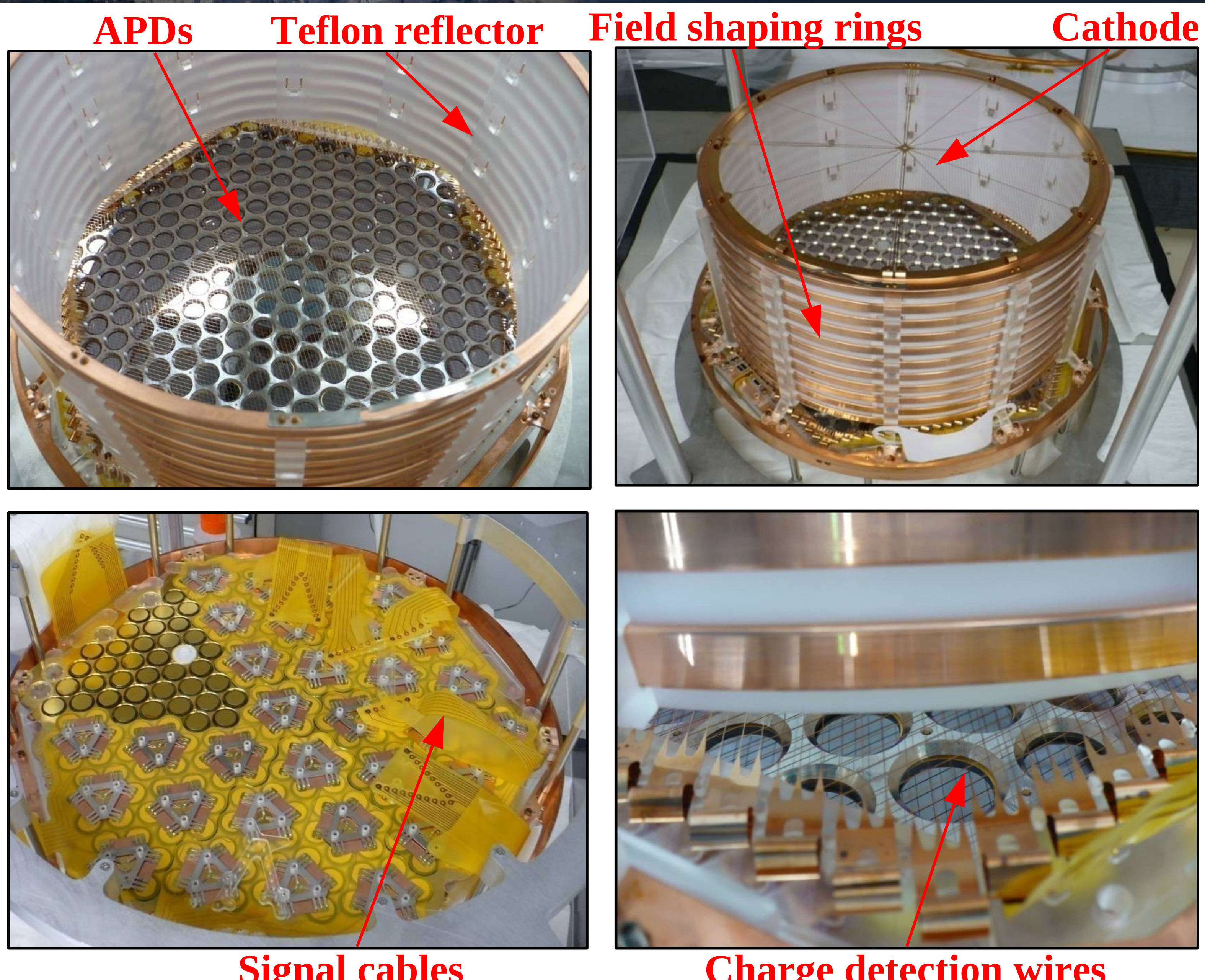
2D anti-correlated single site energy spectrum



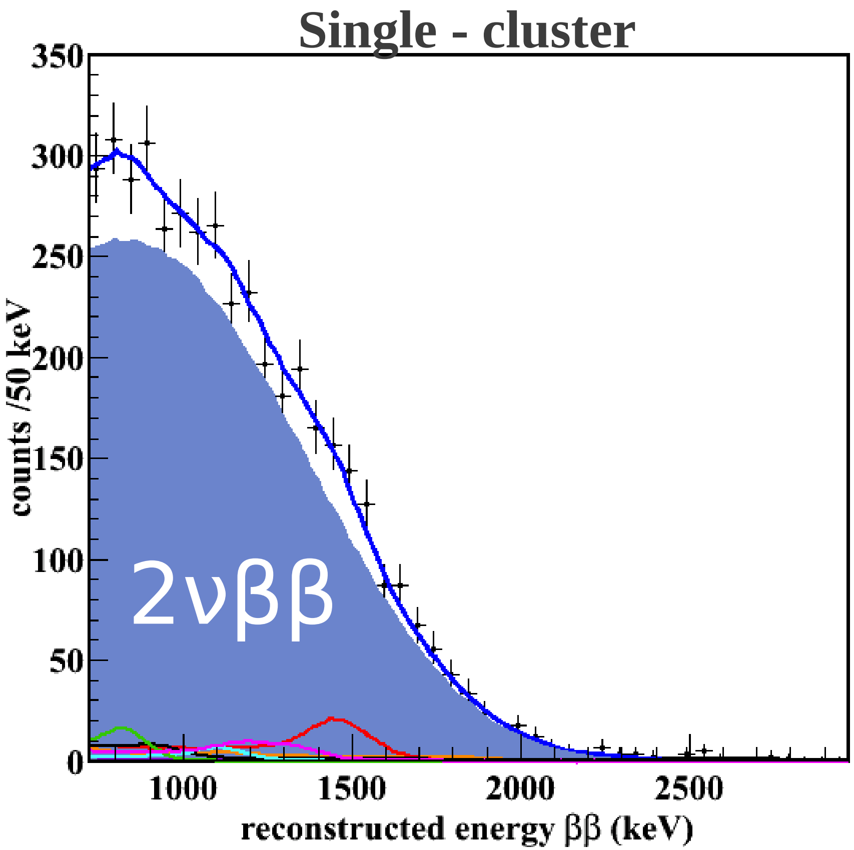
0νββ limit

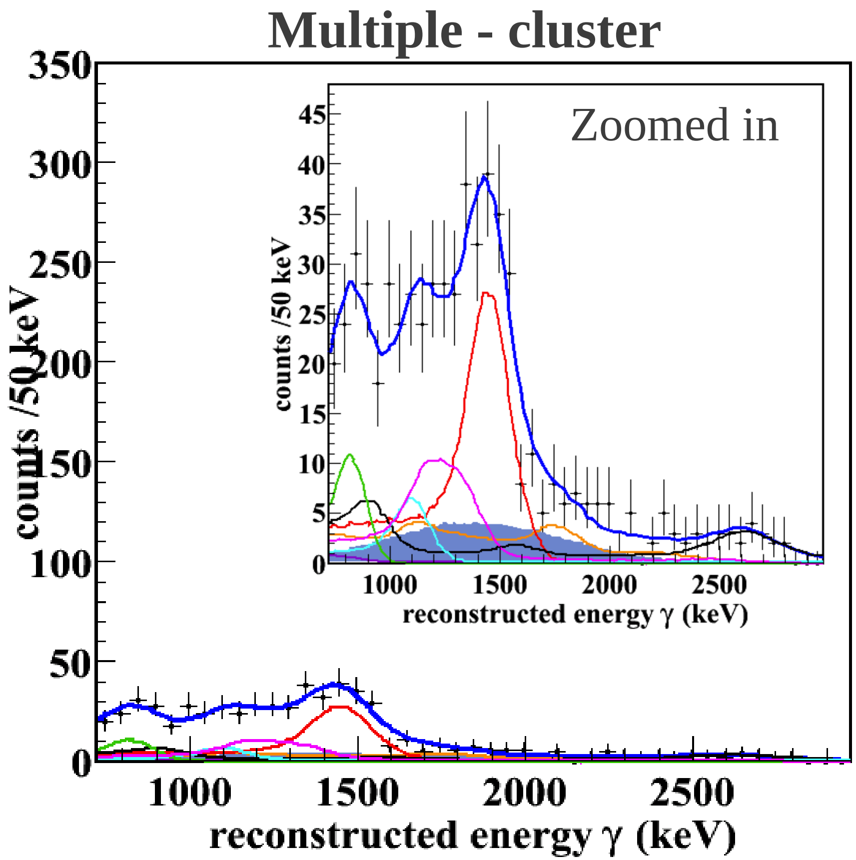

SS
counts /20keV
10^3
10^2
10
1
10^{-1}
10^{-2}
1000 1500 2000 2500 3000 3500
energy (keV)
SS
counts /20keV
8 6 4 2 0
2000 2200 2400 2600 2800 3000 3200
energy (keV)
Legend
ββ2ν
ββ0ν (Limit)
^{40}K LXe Vessel
^{54}Mn LXe Vessel
^{60}Co LXe Vessel
^{65}Zn LXe Vessel
^{232}Th LXe Vessel
^{238}U LXe Vessel
^{135}Xe Active LXe
^{222}Rn Active LXe
^{222}Rn Inactive LXe
^{214}Bi Cathode Surface
^{214}Bi Air Gap
Data
Total

The EXO-200 Time Projection Chamber (TPC)



2011 EXO-200 2νββ Measurement

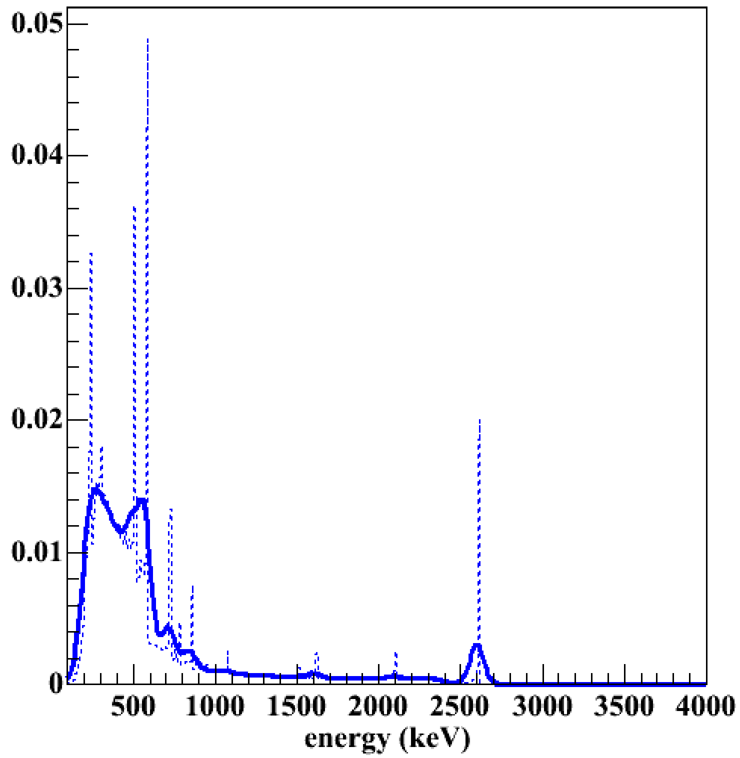


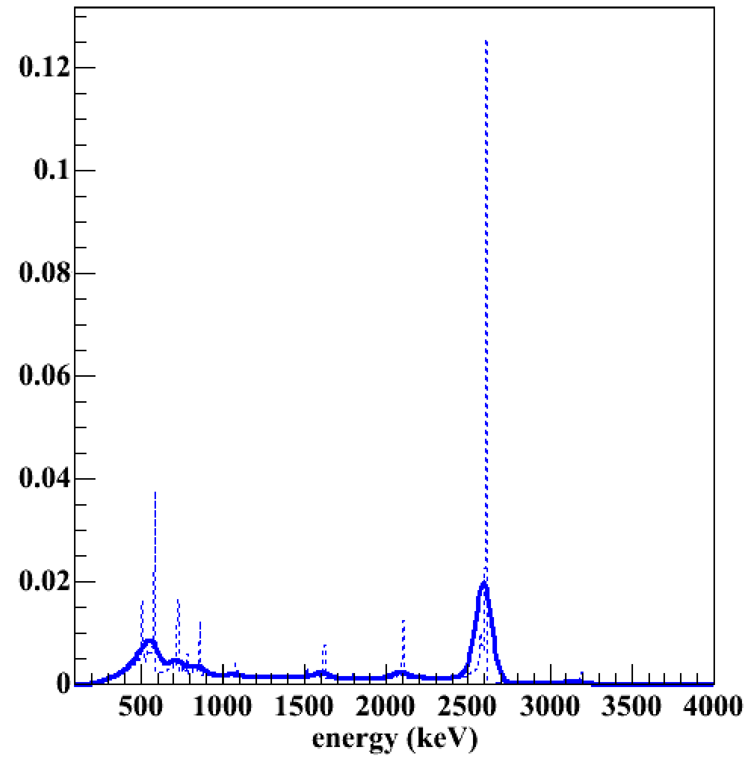


- 31 live-days of data
- 63 kg active mass
- Signal/background ratio 10:1 (as good as 40:1 for some extreme fiducial volume cuts

$T_{1/2} = 2.11 \cdot 10^{21}$ yr (± 0.04 stat) (± 0.21 syst) **[arXiv:1108.4193]**

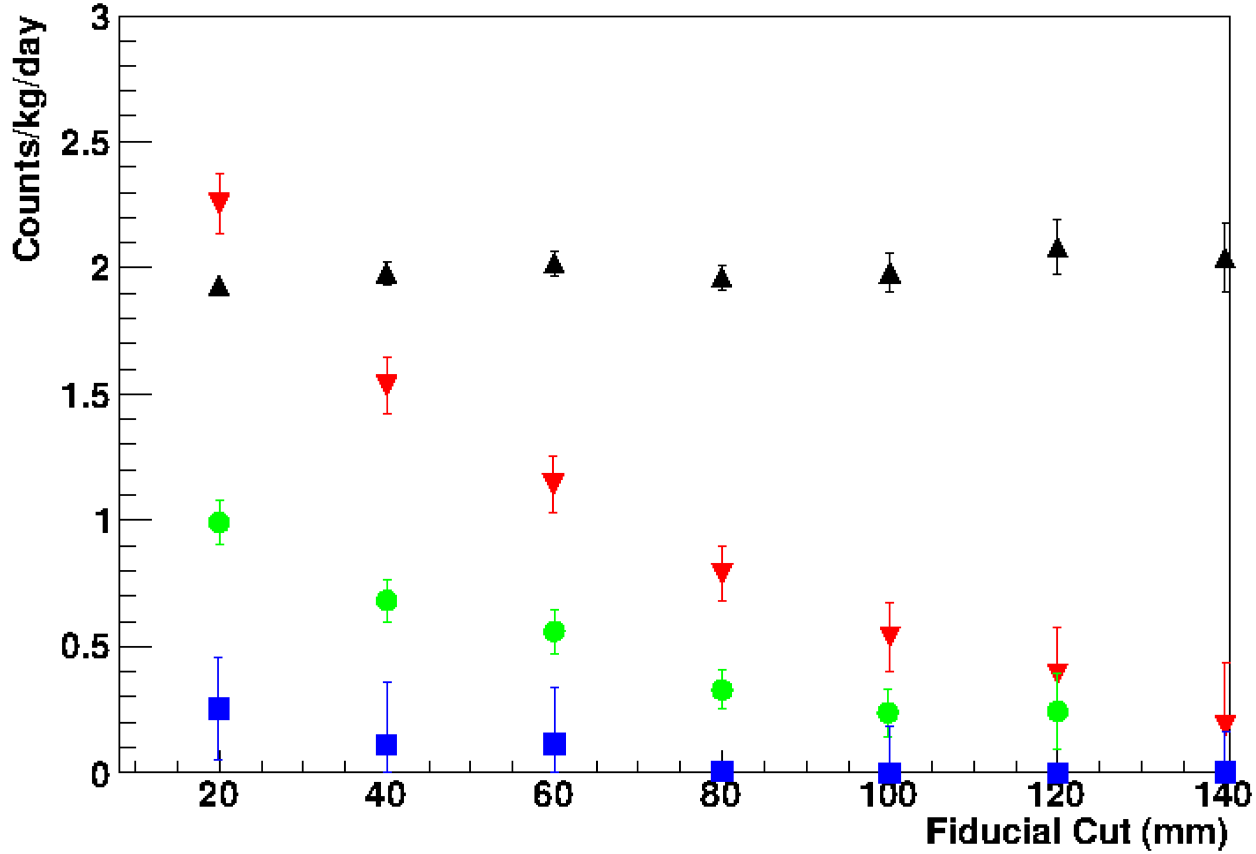
Simulated spectra generation





- Dotted line is Geant4 simulated energy deposition from ^{228}Th source.
- Solid line is energy spectra resulting from the convolution of the MC energy deposition with the energy resolution model.

Event Rates vs Fiducial Cut



Black – 2νββ
Red – ^{40}K X10
Blue – ^{238}U X10
Green – ^{232}Th X10

- Measured 2νββ rate does not change with choice of fiducial volume
- Rates of background gammas are less deep inside the detector