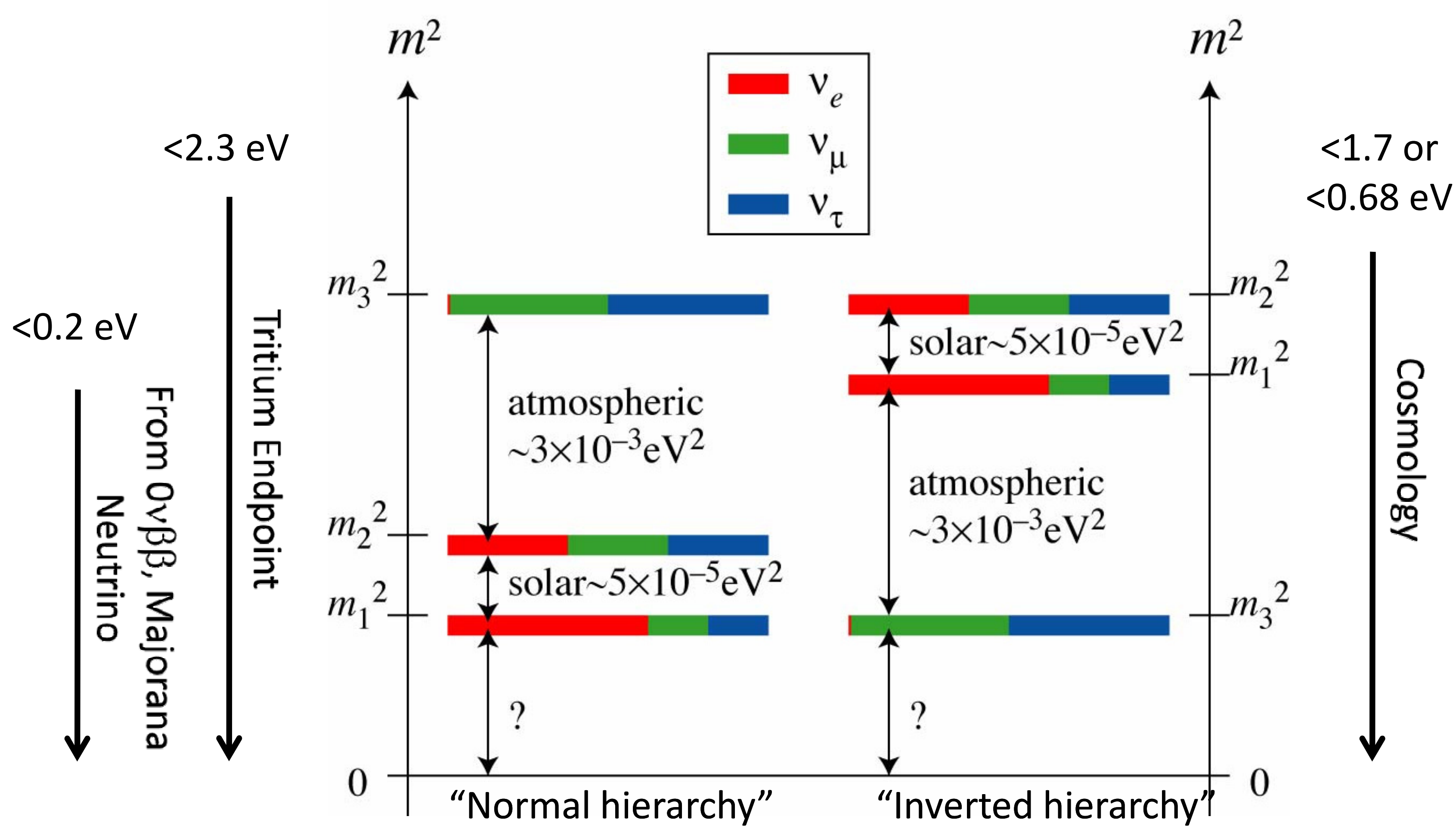
A search for neutrinoless double beta decay with EXO-200

Steve Herrin
On behalf of the EXO Collaboration
SLAC Experimental Seminar
2012-06-12

Outline

- Neutrinos and Double Beta Decay
- EXO-200 Detector
- Calibrations and corrections
- Background cuts
- Physics data and results

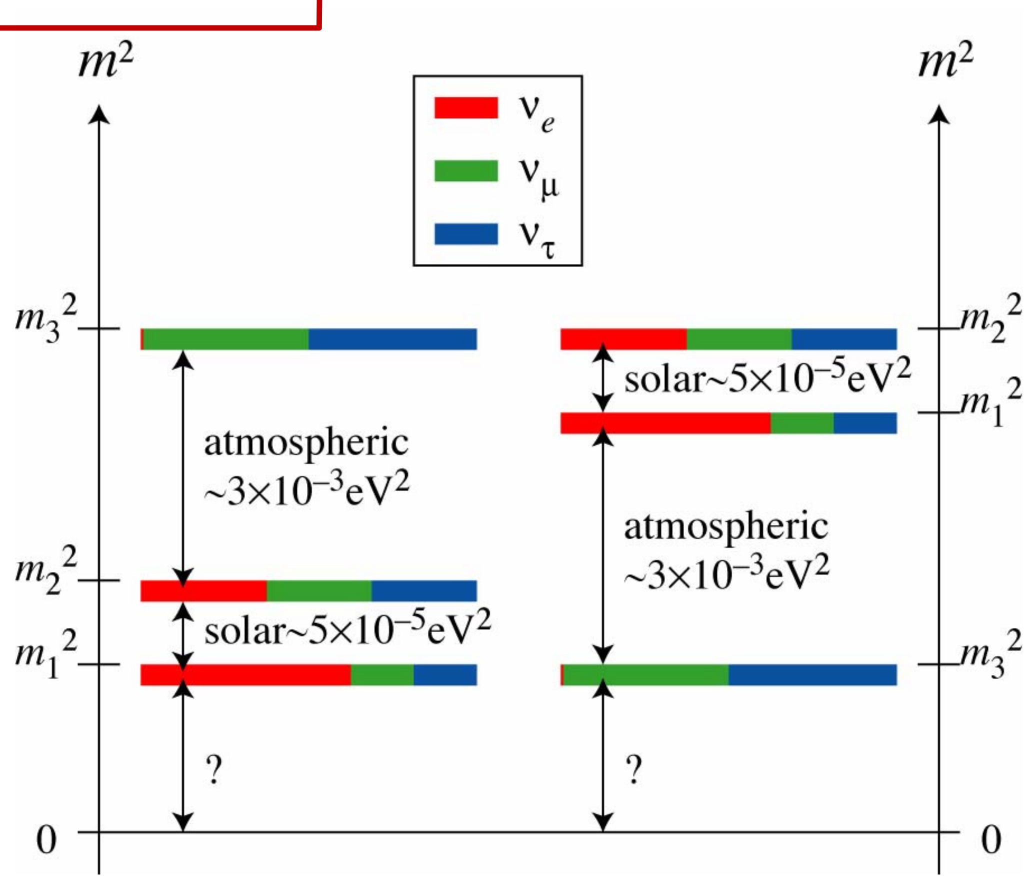
What we know about neutrinos



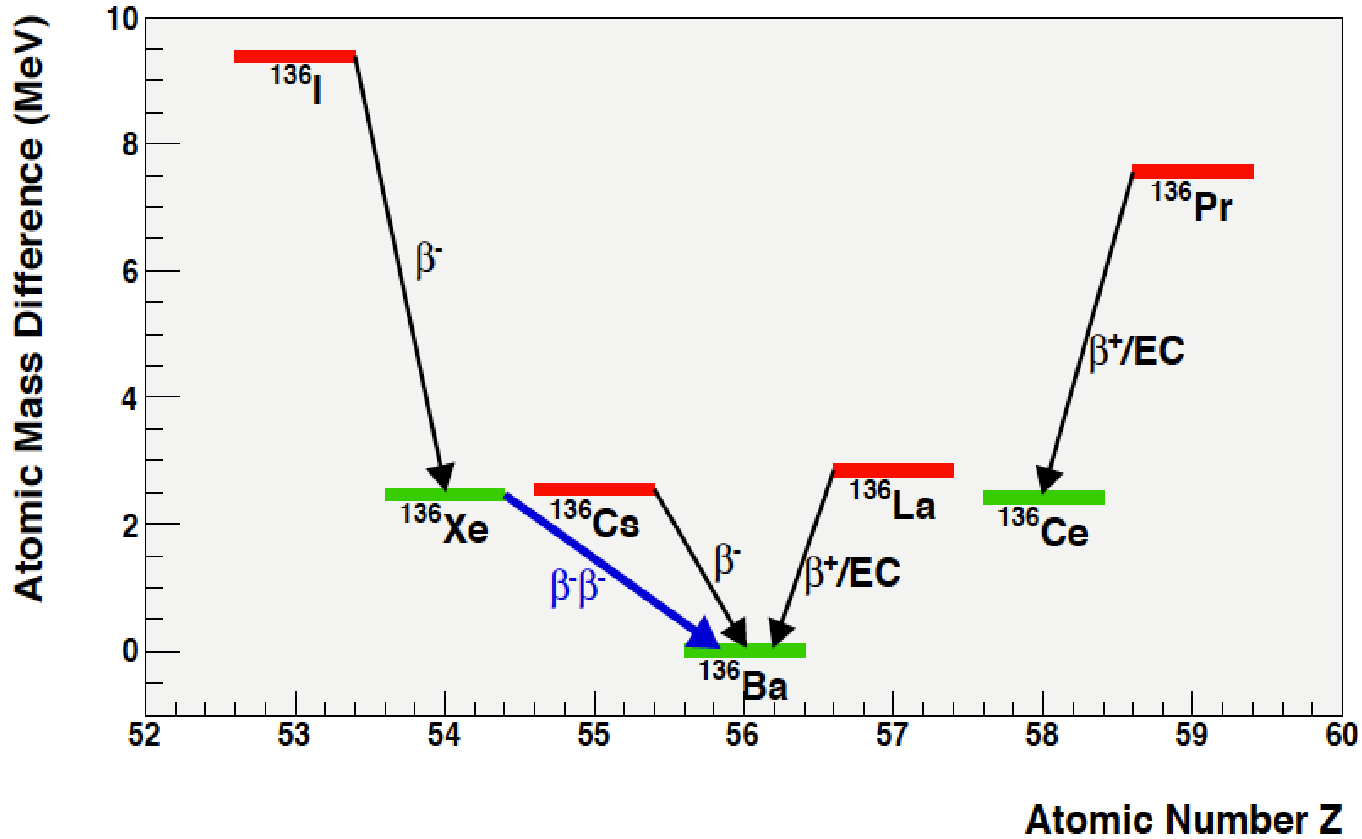
What we don't know

- Majorana nature
  - Is neutrino its own antiparticle?
- Absolute mass scale
- Mass hierarchy
  - Normal or inverted
- CP violating phase
- (Unknown unknowns)

Neutrinoless double beta decay can help answer these

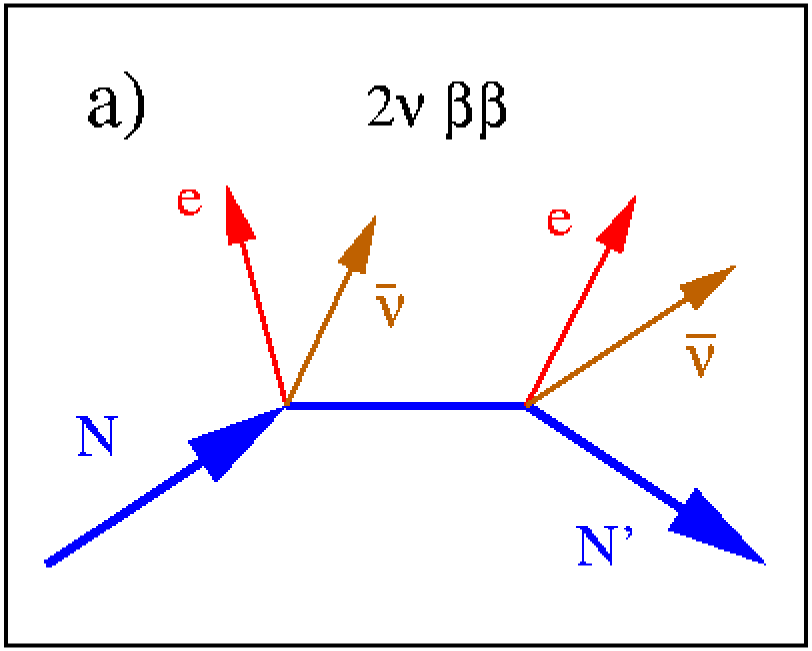


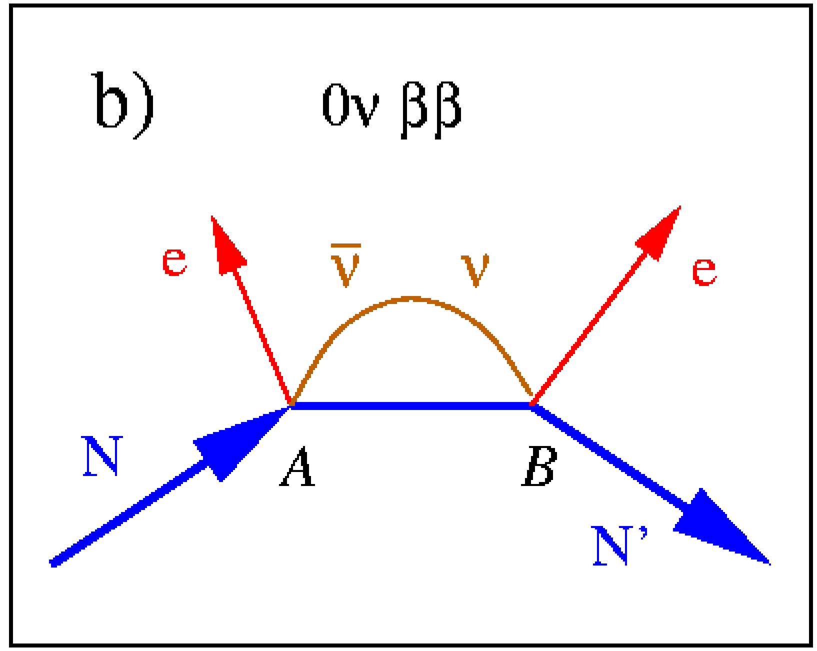
Double beta decay



If first-order beta decay is forbidden energetically or by spin, second-order double beta decay can be observed

Two modes of double beta decay



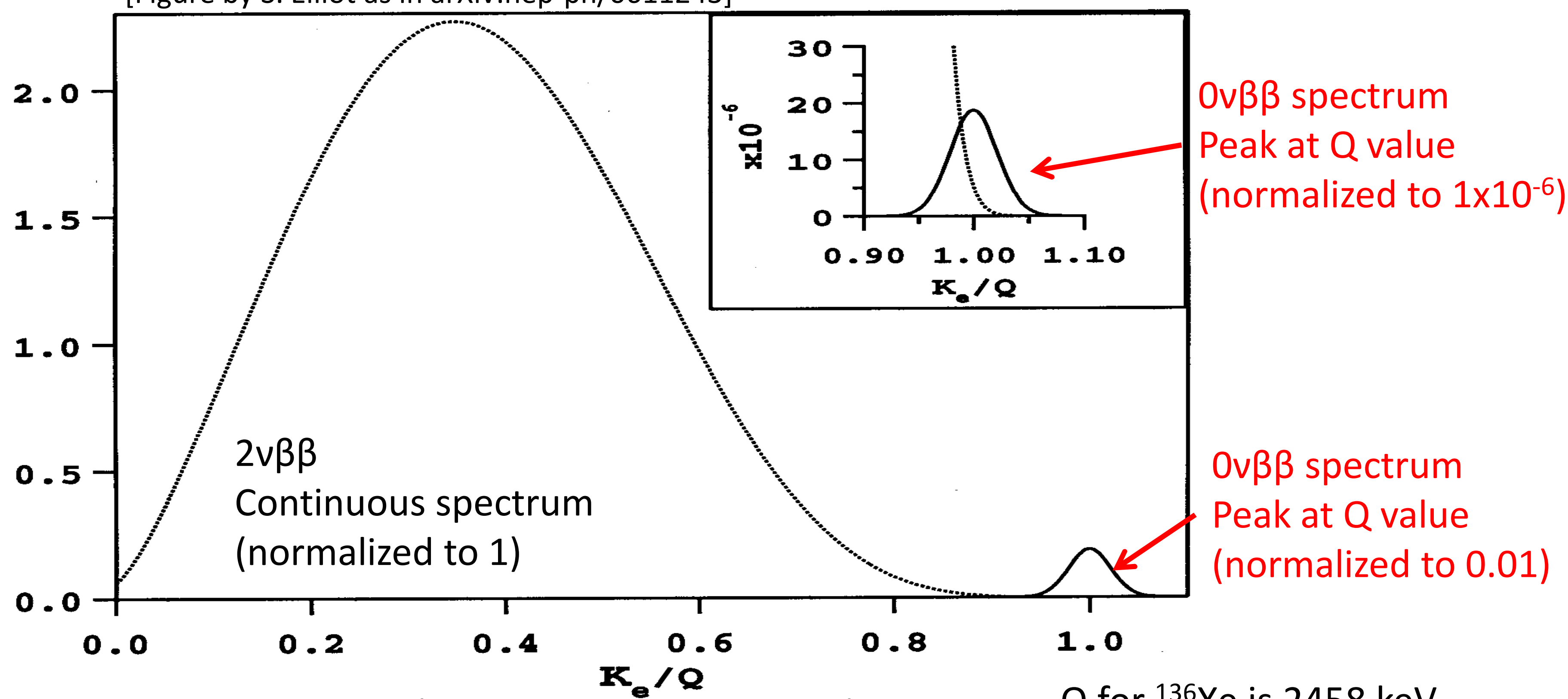


Two neutrino mode:
•Standard model process
•Second order

Neutrinoless mode:
•Hypothetical process
•Can only happen if:
  • neutrino has nonzero mass
  • neutrino is its own antiparticle
•Total lepton number violating

Double beta decay spectrum

[Figure by S. Elliot as in arXiv:hep-ph/0611243]



(summed electron energy)

Q for ^{136}Xe is 2458 keV

The two modes can be distinguished by their energy spectra in a detector with good energy resolution

Neutrinoless mode and mass

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} G_{0\nu\beta\beta}(E_0, Z) \left| M_{0\nu\beta\beta} \right|^2 \right)^{-1}$$

Effective Majorana mass

To be measured

Phase space factor
(known)

Matrix element
(can be calculated with
various models)

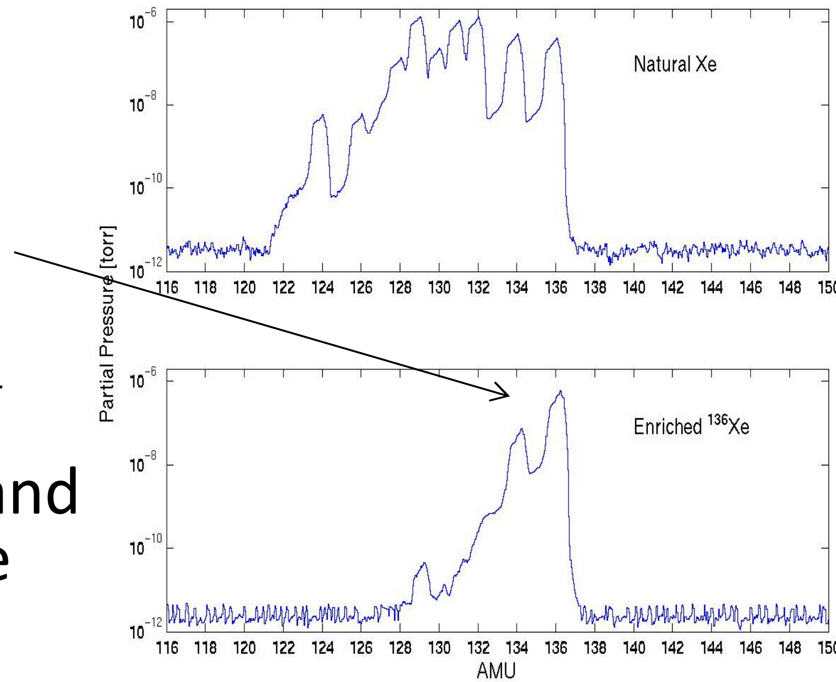
$$\langle m_\nu \rangle = \left| \sum_i U_{ei}^2 m_i \varepsilon_i \right|$$

Experimental sensitivity

$$S_{m_{\beta\beta}} \propto \left(\frac{A}{\varepsilon a}\right)^{1/2}\left(\frac{B\Gamma}{MT}\right)^{1/4}$$

ε is efficiency
a is isotopic abundance
A is atomic mass
M is source mass
T is time
B is background
Γ is resolution

- To maximize sensitivity
  - Xenon enriched to 80.6% in isotope 136
  - Large mass (98.5 kg fiducial)
  - Low background construction†
  - Makes use of both ionization and scintillation signals to optimize energy resolution‡



†[D.S. Leonard et al. Nucl. Instr. Meth. A 591 (2008) 490.]

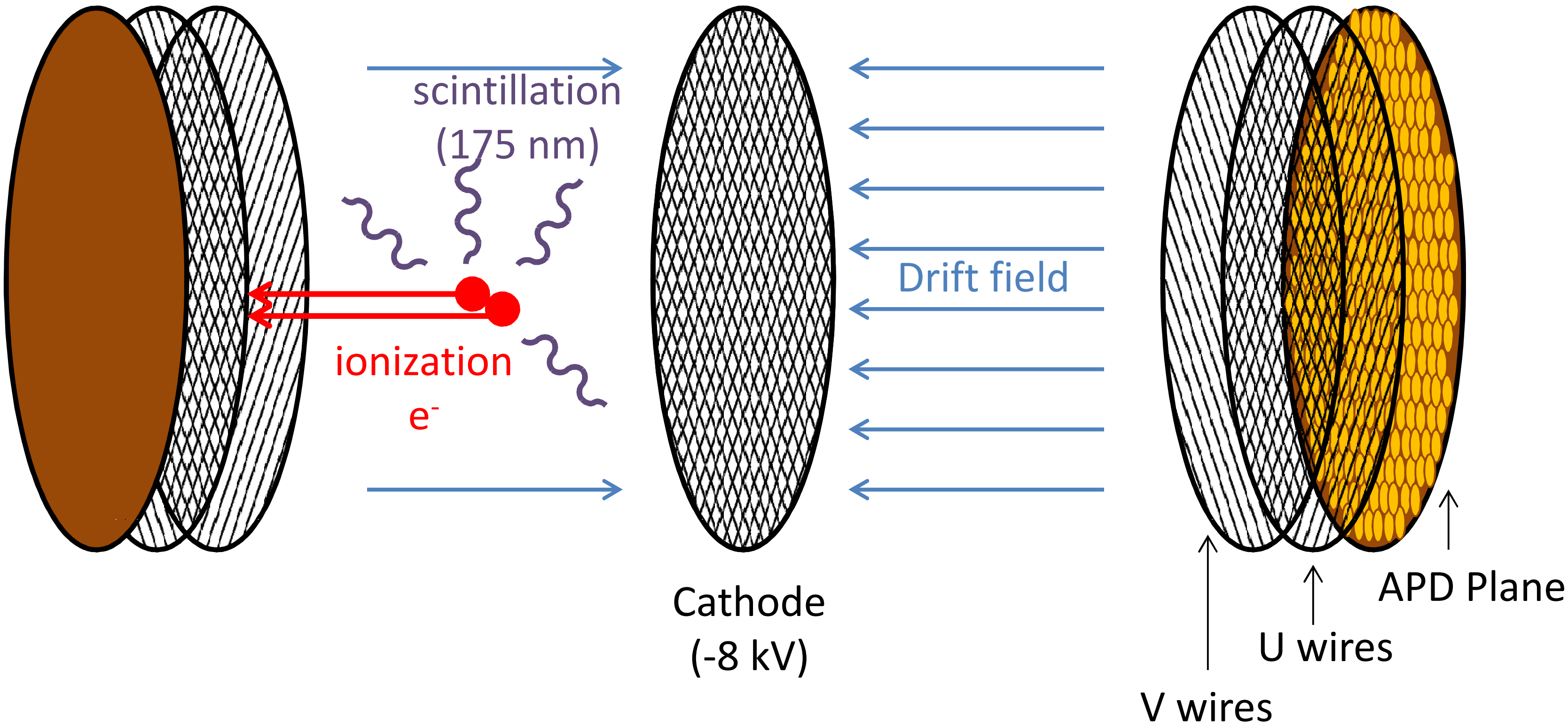
‡[E. Conti et al. Phys. Rev. B 68 (2003) 054201.]

Previous experimental limits

Isotope	$0\nu\beta\beta$ half life ($\times 10^{22}$ years)	Experiment
^{48}Ca	> 5.8	ELEGANT-VI
^{76}Ge	> 1900	Heidelberg-Moscow
^{76}Ge	2230^{+440}_{-310}	Subset of HM collaboration
^{82}Se	> 36	NEMO-3
^{96}Zr	> 0.92	NEMO-3
^{100}Mo	> 110	NEMO-3
^{116}Cd	> 17	Solotvino
^{130}Te	> 280	Cuoricino
^{136}Xe	*> 570*	*KamLAND-Zen*†
^{150}Nd	> 1.8	NEMO-3

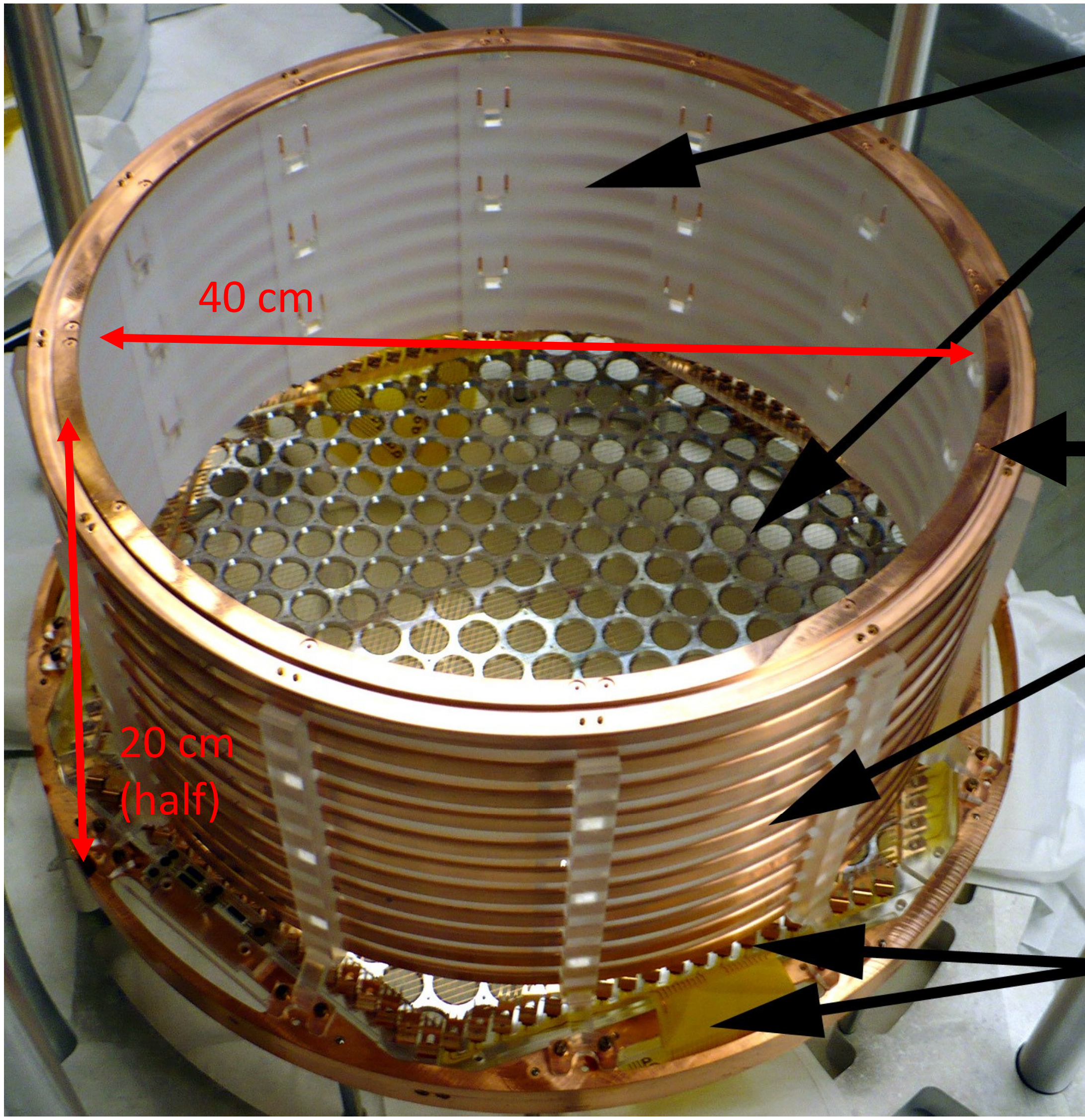
[F. Avignone, S. Elliot, J. Engel, arXiv:0708: 1033v2 (2007)]
†[KamLAND-Zen Collaboration, Phys.Rev.C 85 045504 (2012)]

EXO-200 TPC Concept



- The EXO-200 Time Projection Chamber (TPC) consists of 2 modules with a common cathode
- Large Area Avalanche Photodiodes (LAAPDS) (~200 per side) observe prompt scintillation for energy and longitudinal position (from drift time)
- Crossed wire grids observe charge signal
  - V wires (induction) (38 triplets per side) for transverse position
  - U wires (collection) (38 triplets per side) for transverse position and energy

EXO-200 TPC (half of it)



Teflon Reflectors
(increase light collection)

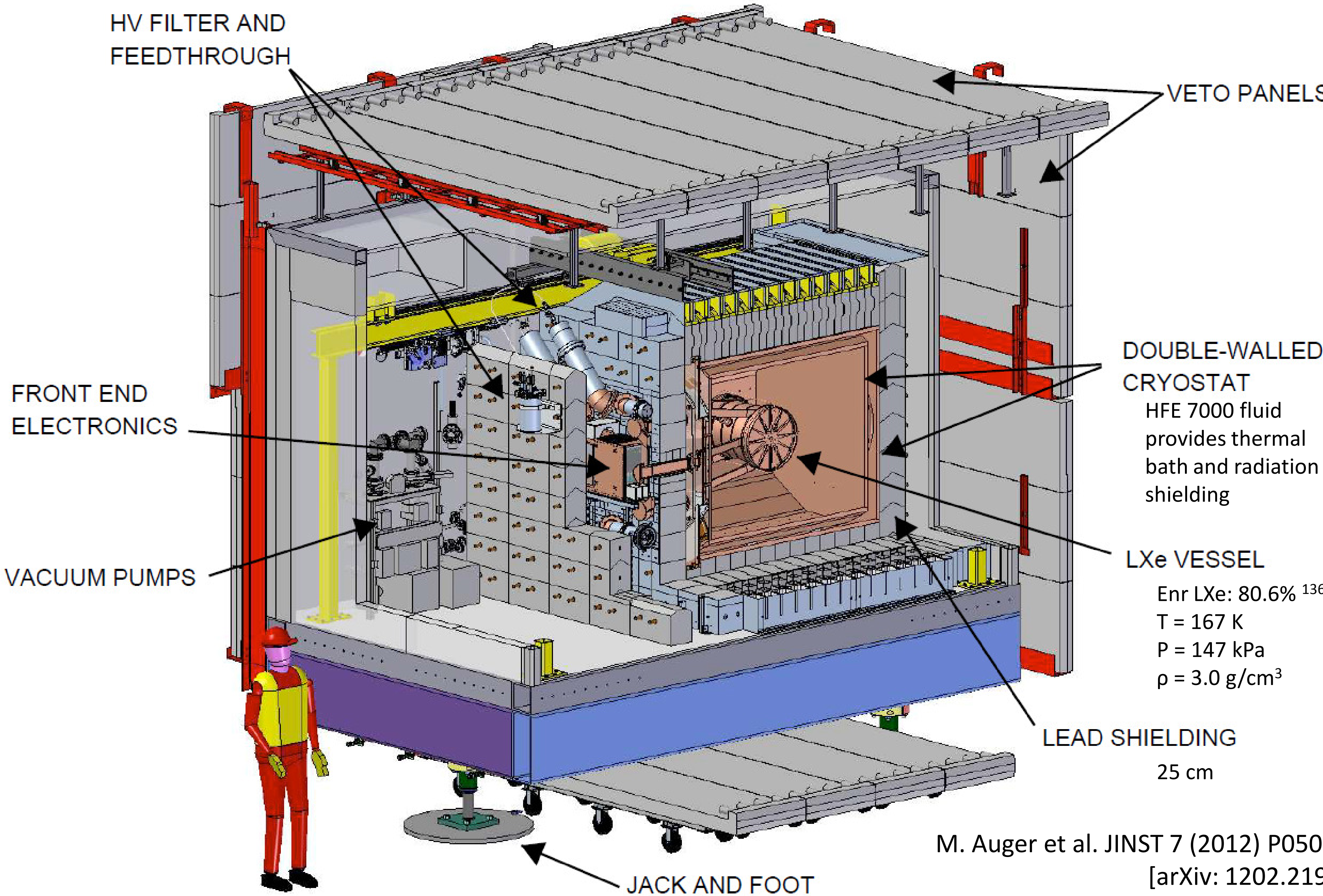
APD plane and wire planes
(wires are photo-etched)

Central HV plane
(photo-etched phosphor bronze)

Acrylic supports
and field shaping
rings

Kapton flex cables
(spring connections
eliminate solder joints
and glue)

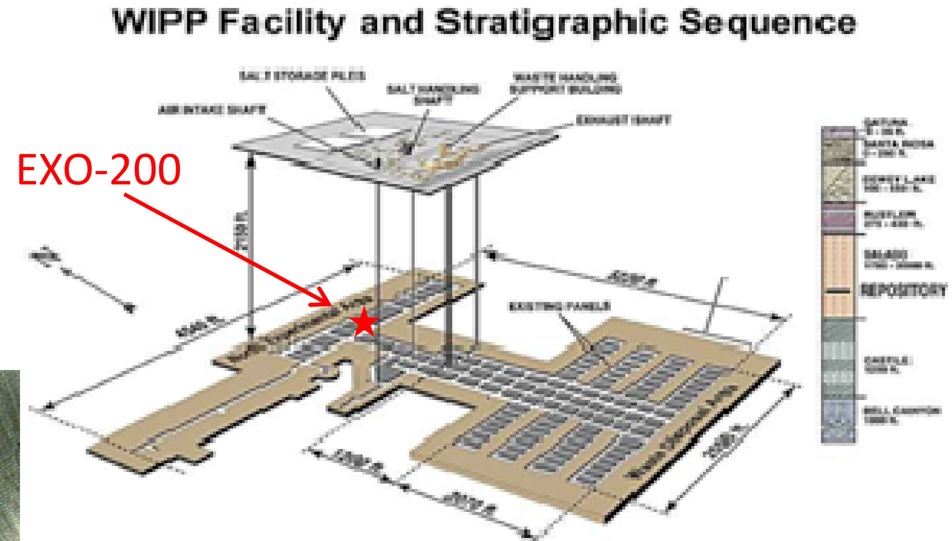
EXO-200 Installation



M. Auger et al. JINST 7 (2012) P05010
[arXiv: 1202.2192]

EXO-200 at WIPP

The US Department of Energy disposes of nuclear waste at the Waste Isolation Pilot Plant, located SE of Carlsbad, NM



2150 ft depth provides ~1600 m water equivalent shielding

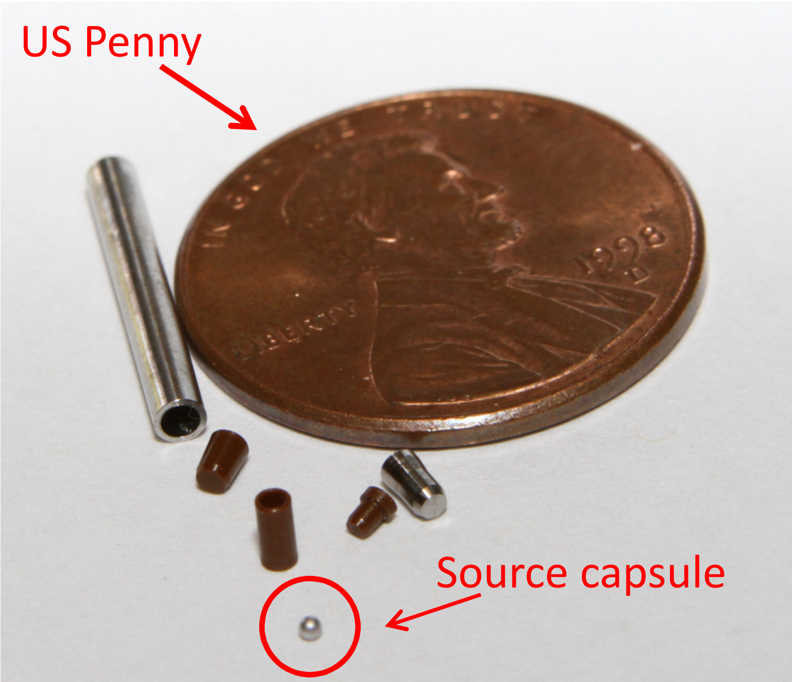
Salt walls are naturally low in uranium, thorium (< 100 ppb)

Radon in air < 10 Bq/m^3

EXO-200 History

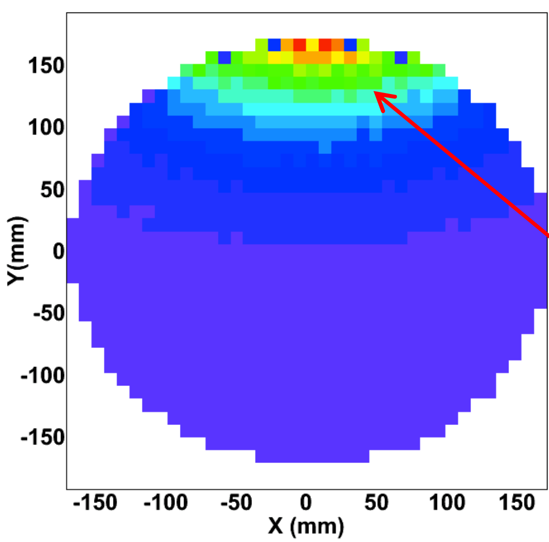
- Late 2010
  - Engineering run with natural Xe
- May 2011 – July 2011 “2νββ Run”
  - First run with enriched Xe
  - First measurement of 2νββ in ^{136}Xe
  - 5.4 kg yr exposure (4.4 kg isotope 136)
  - [Phys. Rev. Lett. 107, 212501 (2011)]
- August 2011 – September 2011
  - Install final lead shielding
  - Electronics and other upgrades
- October 2011 – March 2012 “Run 2”
  - Data taken for this analysis
  - 32.6 kg yr exposure (26.3 kg isotope 136)

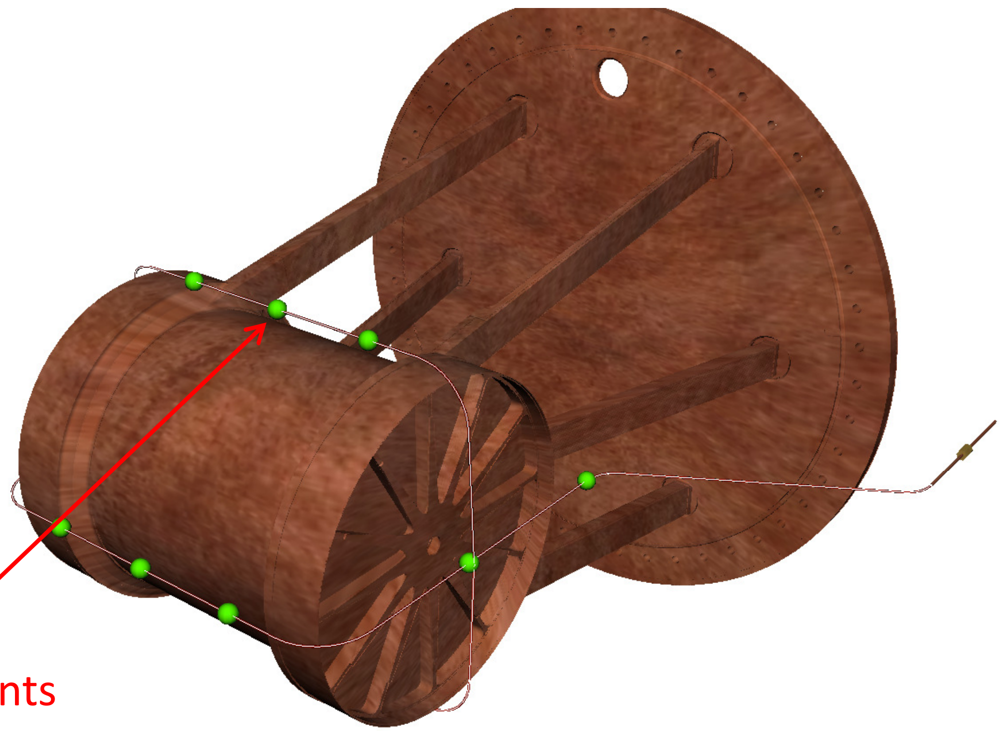
Calibration



A copper guide tube around the outside of the TPC allows radioactive sources to be deployed to predetermined locations around the TPC

We use ^{228}Th (2615 keV), ^{60}Co (1173 and 1333 keV), and ^{137}Cs (662 keV) gamma ray sources



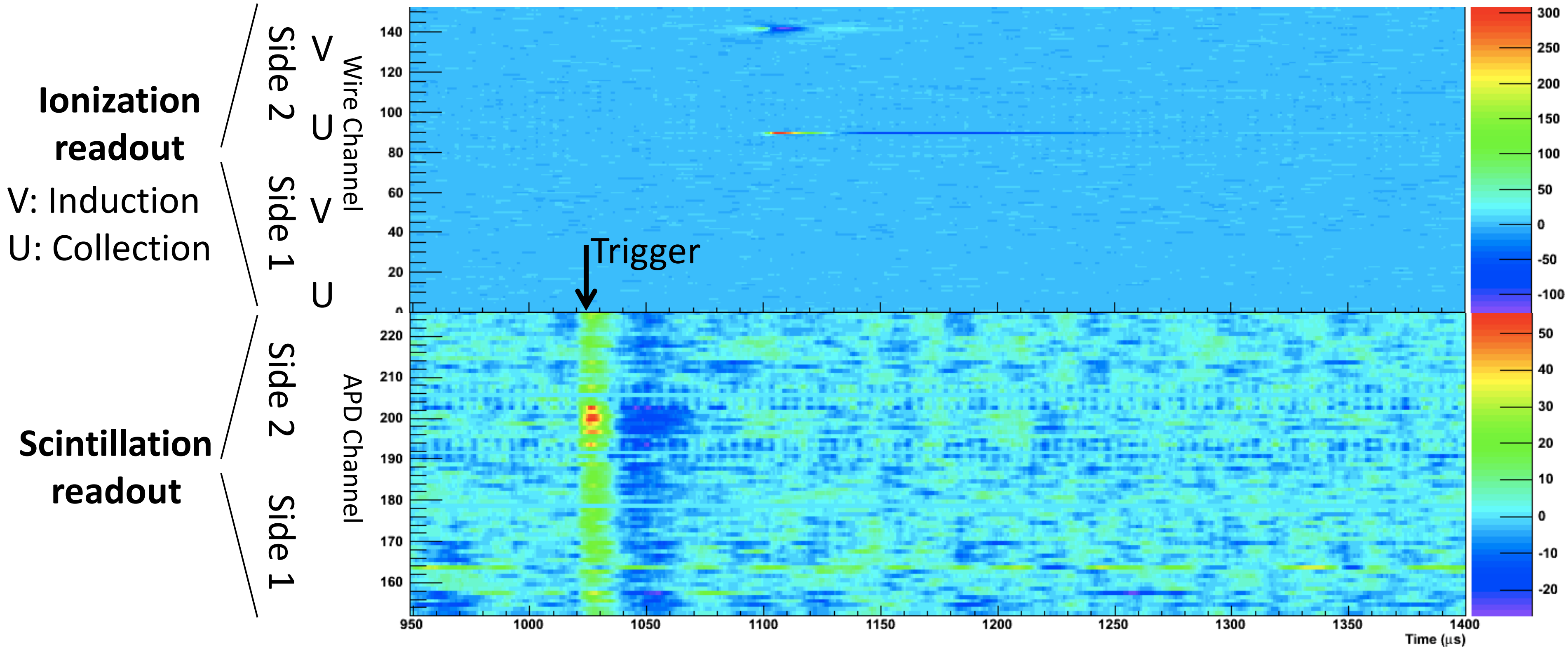


Excess of events near source location

Triggering

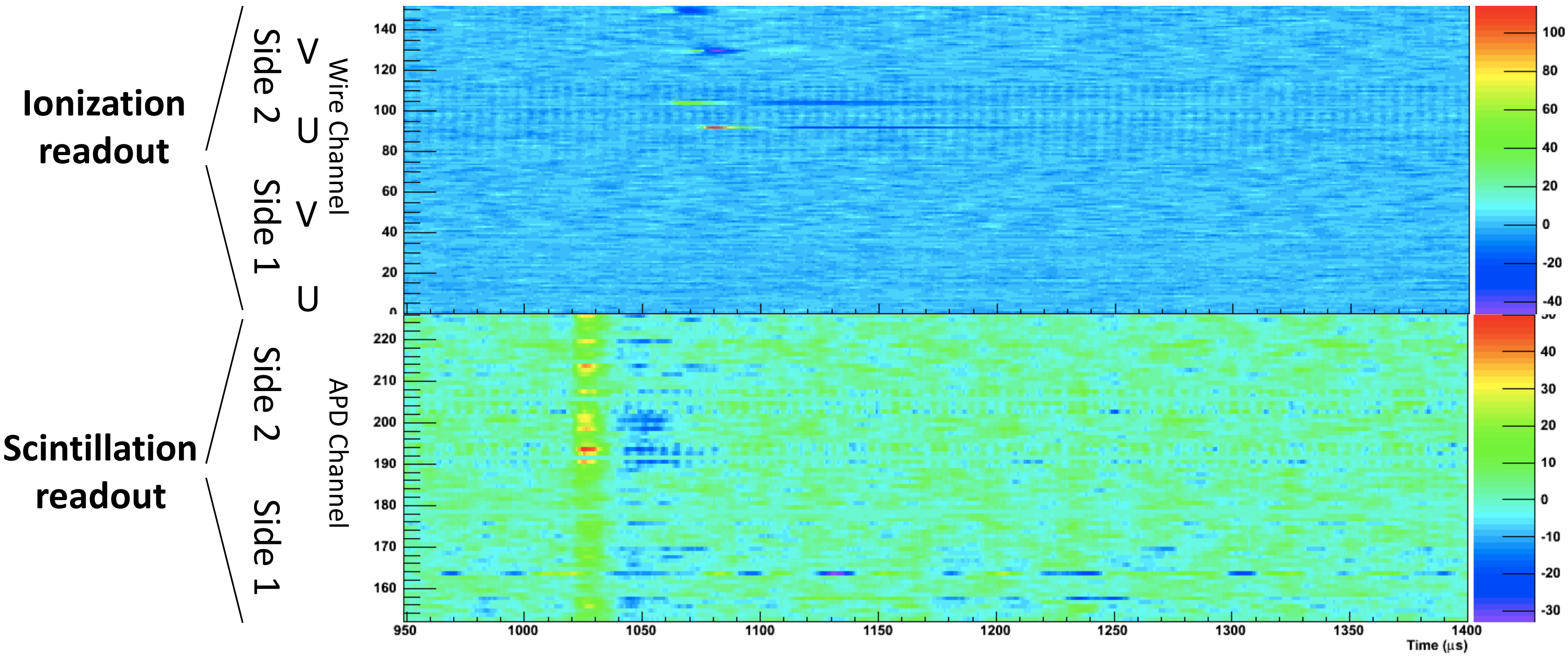
- For physics data:
  - Can trigger on
    - Sum APD signal
    - Individual APD signal
    - Sum collection wire signal
    - Individual collection wire signal
- A frame of ±1024 μs is saved around every trigger

A single-site event in EXO-200



- Scintillation signal
  - Observed in both sides (but more localized in side 2)
  - Precedes ionization signal
- Ionization signal
  - Observed on both wire planes in side 2

A two-site Compton scattering event

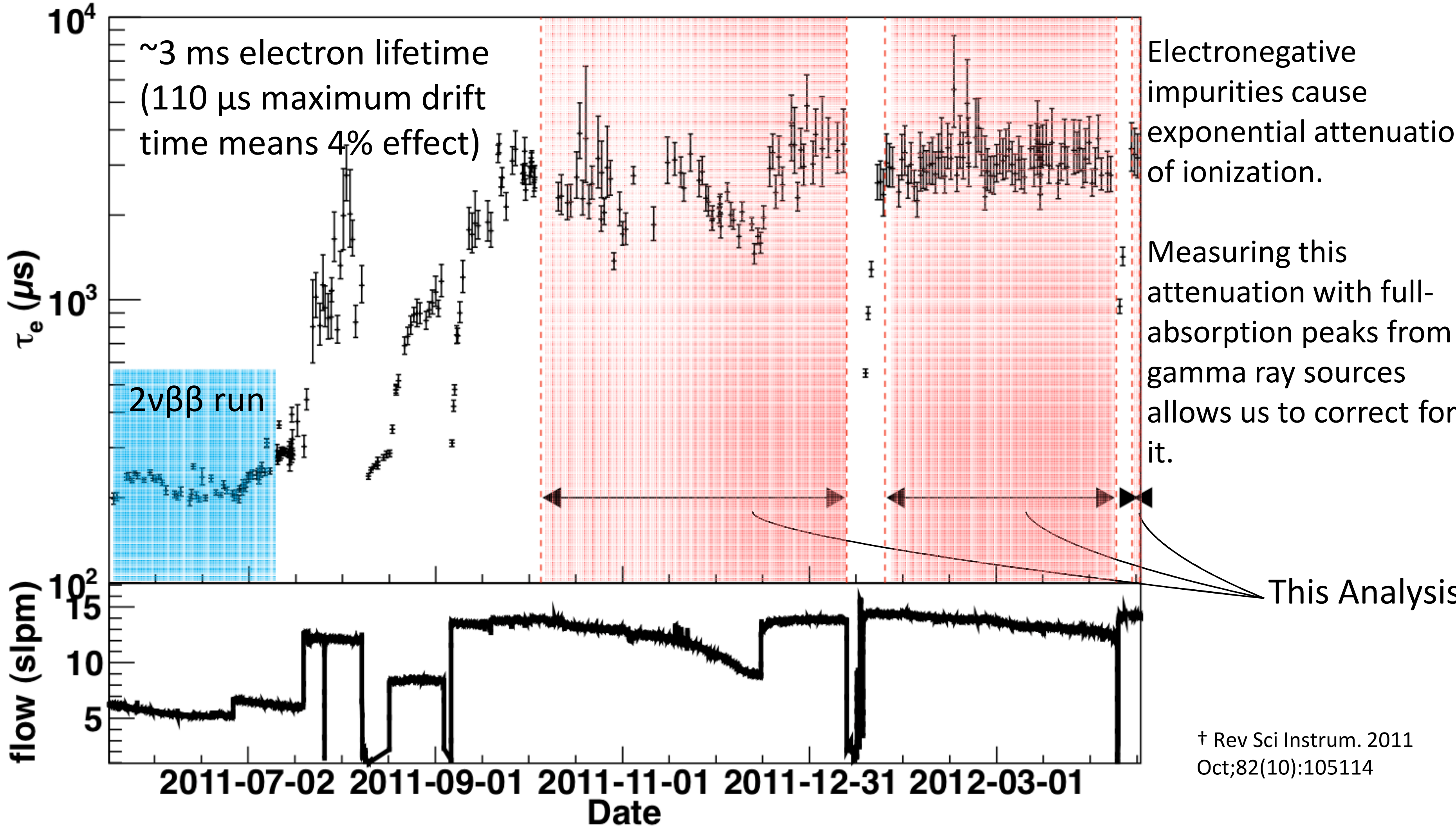


- All scintillation light arrives at a single time, indicating the two energy depositions were simultaneous
- Two separate ionization signals visible in side 2

Event reconstruction

- Stages are roughly:
  - Signal finding with matched filters on U, V, APD signals
  - Extract energies and times for found signals, applying channel-based corrections
  - Assign signals to clusters
    - Single Site (SS) or Multiple Site (MS)
    - Can distinguish clusters ~6 mm in z dimension, ~18 mm in u dimension
  - Apply position-based corrections
  - Apply calibrations
- Reconstruction efficiency for $0\nu\beta\beta$ is 71%. This is estimated with Monte Carlo simulations and verified by comparing the MC estimated efficiency for $2\nu\beta\beta$ with data over a broad energy range

Electron Lifetime Corrections



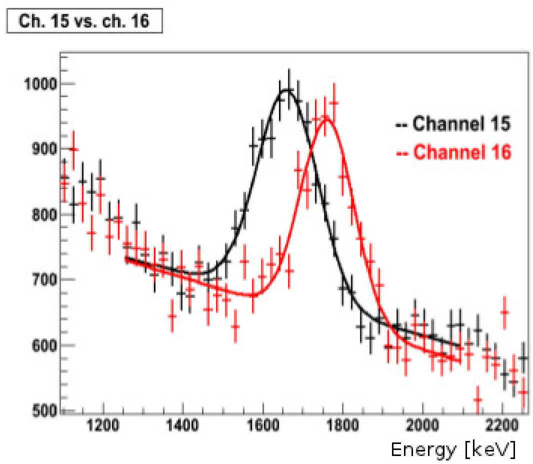
Electronegative impurities cause exponential attenuation of ionization.

Measuring this attenuation with full-absorption peaks from gamma ray sources allows us to correct for it.

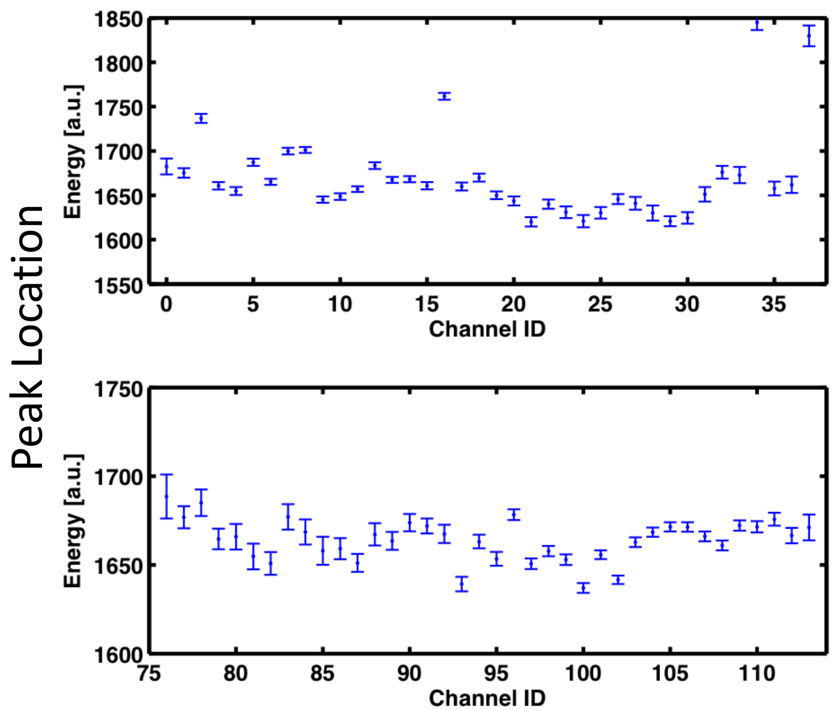
† Rev Sci Instrum. 2011 Oct;82(10):105114

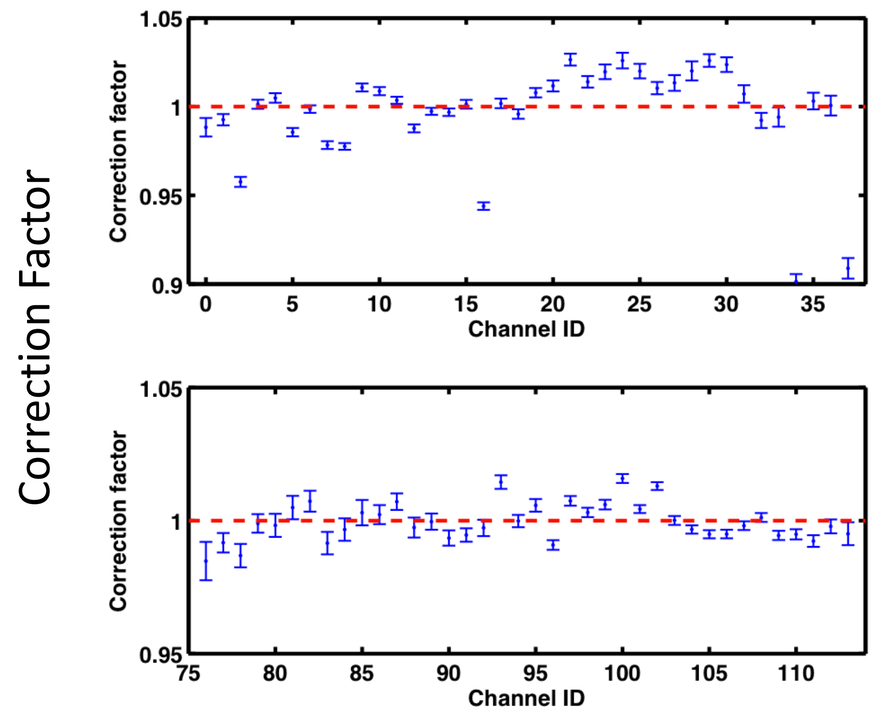
Xenon gas is circulated through a heated zirconium getter using a custom-built ultraclean pump†.
For this analysis, the recirculation rate was increased to 14 slpm, leading to long electron lifetimes in the TPC.

Wire Gain Corrections

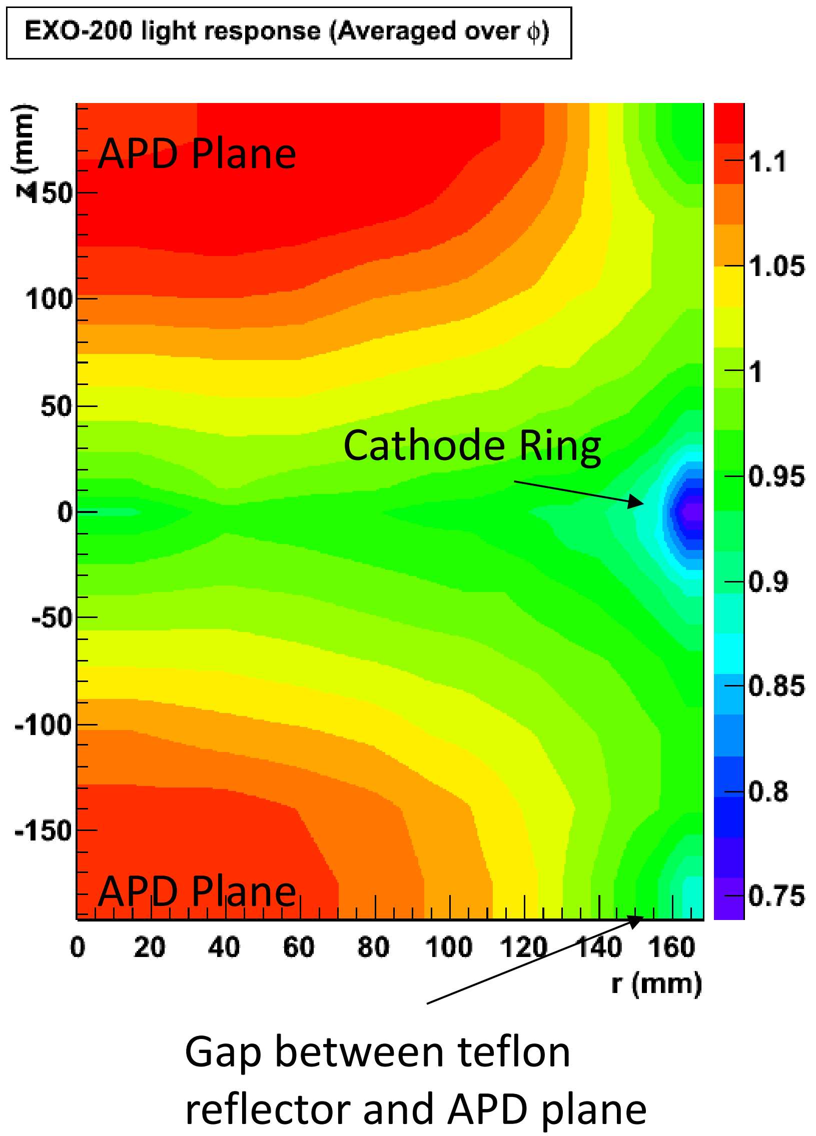


- Use 1593 keV pair production events from ^{228}Th to measure collection wire transfer functions and gains



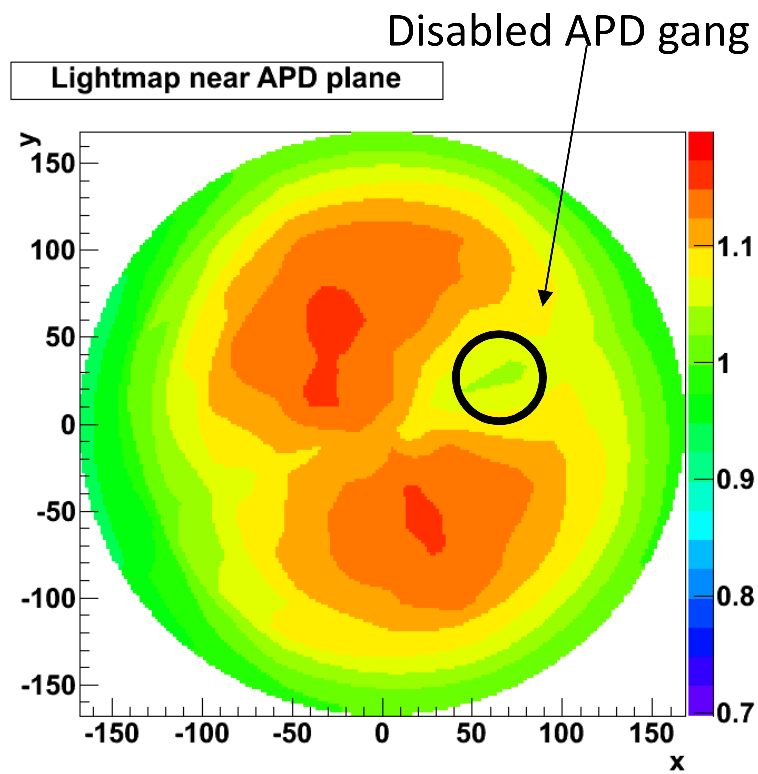


Light Response Correction

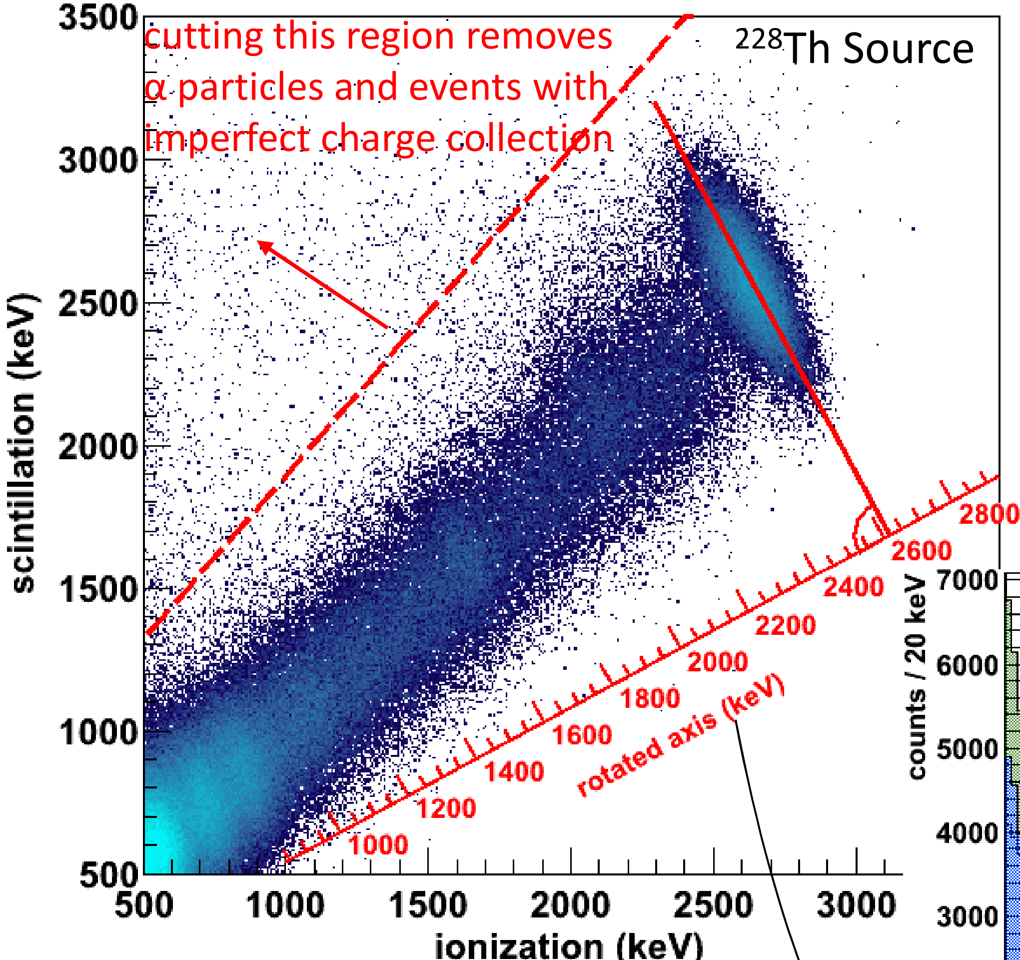


Use full absorption peak of 2615 keV gamma from ^{228}Th to map light response in TPC

Linearly interpolate between 1352 voxels

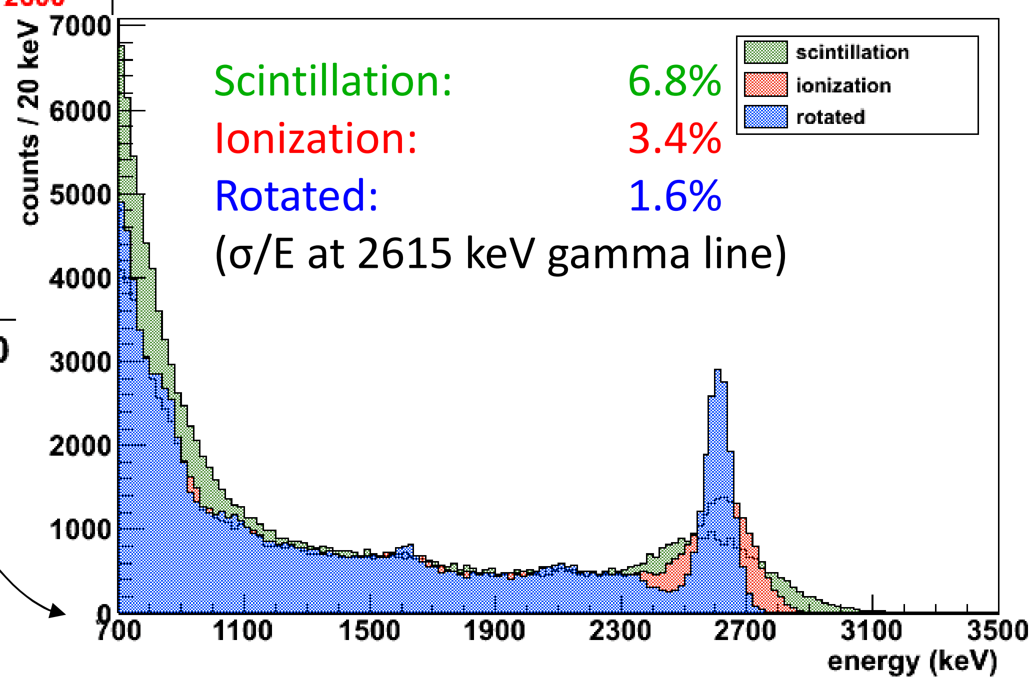


Combining Ionization and Scintillation



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



Use projection onto a rotated axis to determine event energy

Calibration Process

- Use 2615 keV gamma line to determine optimal angle independently for SS and MS events
- Combine scintillation and ionization using these angles for all gamma lines
- Fit to peak energies and apply calibration

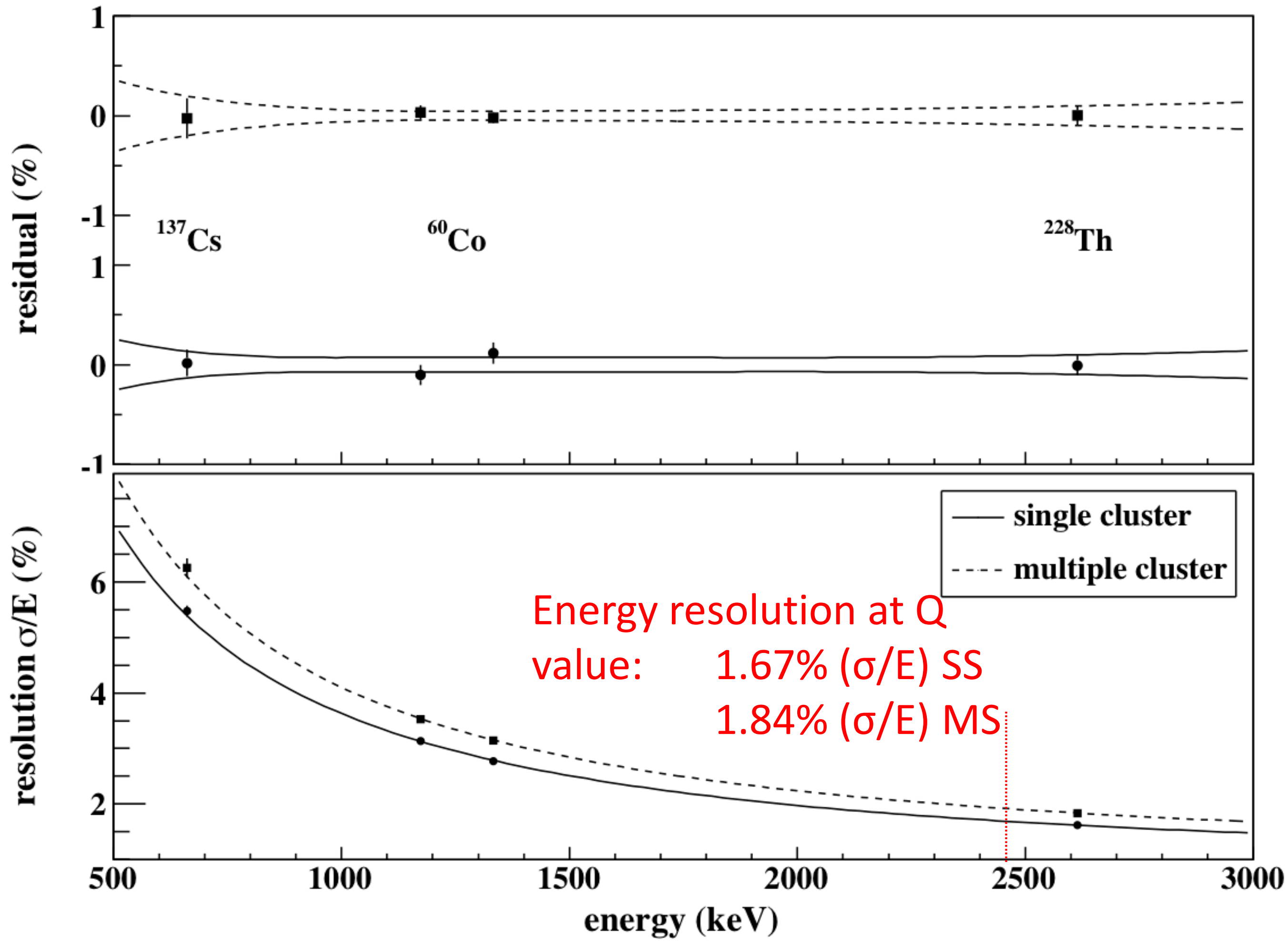
$$E_{true} = a + bE_{reconstructed} + cE_{reconstructed}^2$$

- Residuals given by $residual = \frac{E_{fit} - E_{true}}{E_{true}}$
- Parameterize resolution $\sigma_{tot}^2 = a\sigma_{noise}^2 + b\sigma_{stat}^2 + c\sigma_{drift}^2$

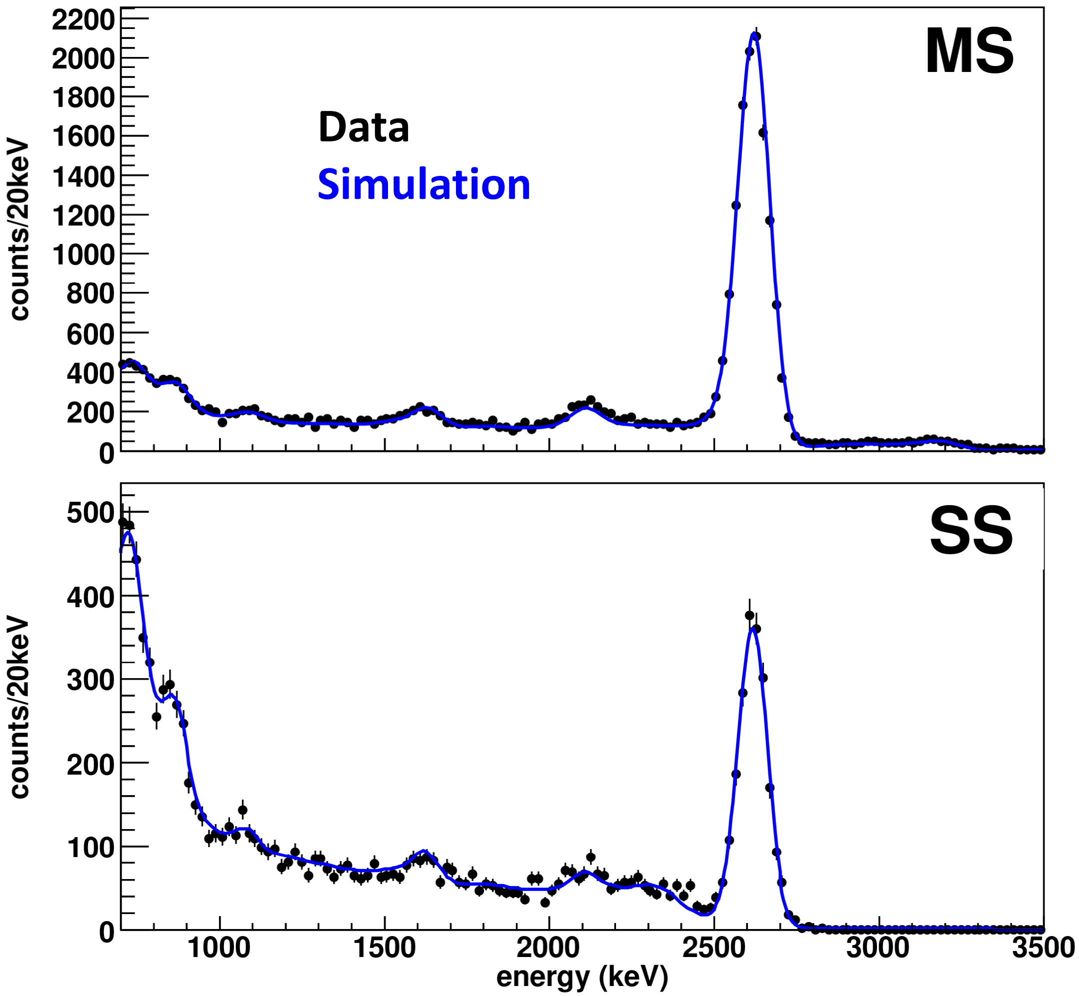
$$\sigma_{tot}^2 = (w\sigma_{elec})^2 + \left(\sqrt{w}\sqrt{F}\sqrt{E}\right)^2 + (kE)^2$$

Calibration

- After correction and applying a quadratic calibration, residuals are less than 0.1%

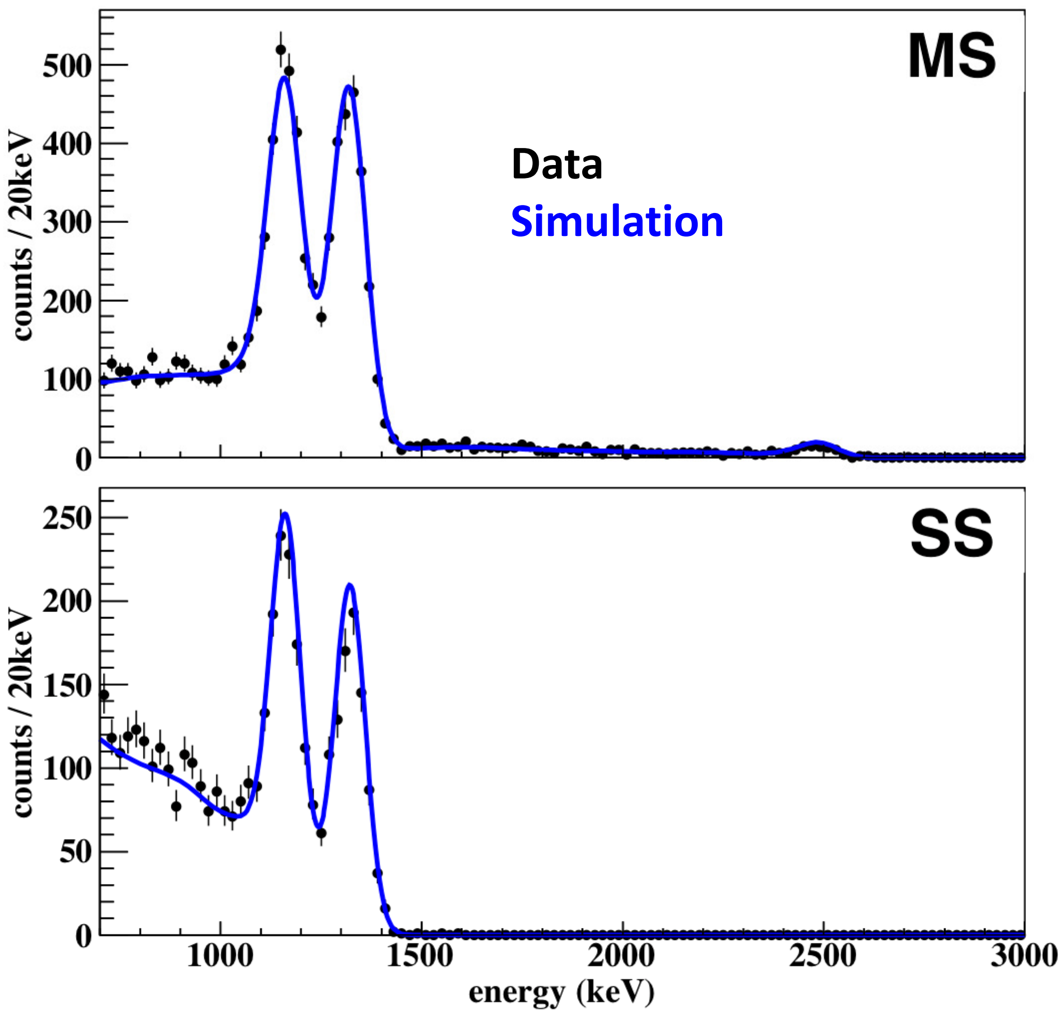


Spectral Shape Agreement – ^{228}Th



- Fraction of single site events agrees with simulation to within 8.5%
- Absolute source activity agrees to within 9.4%

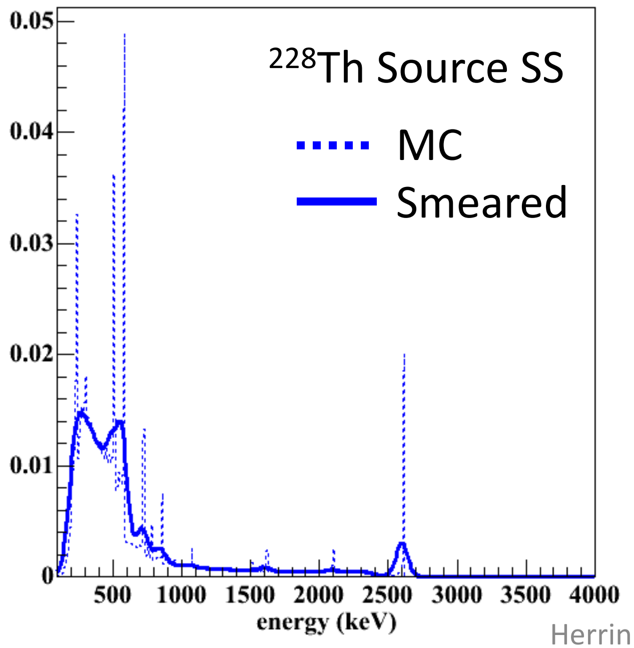
Spectral Shape Agreement – ^{60}Co

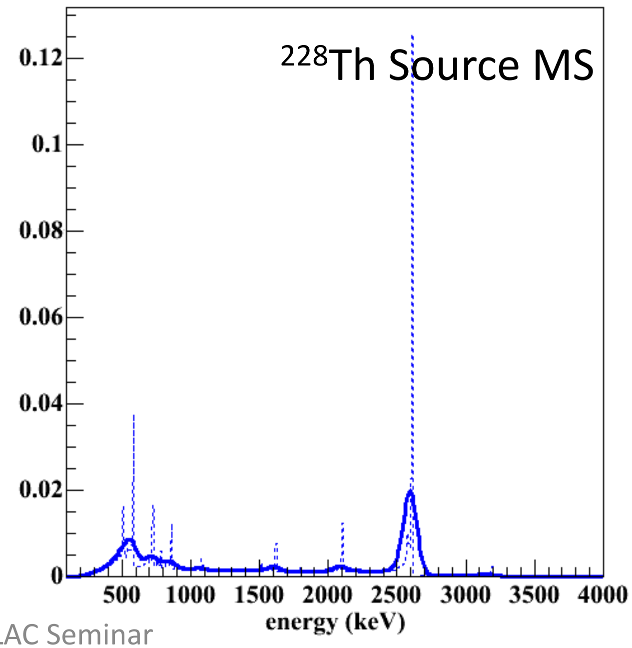


- Fraction of single site events agrees with simulation to within 8.5%
- Absolute source activity agrees to within 9.4%

Simulating spectra for PDFs

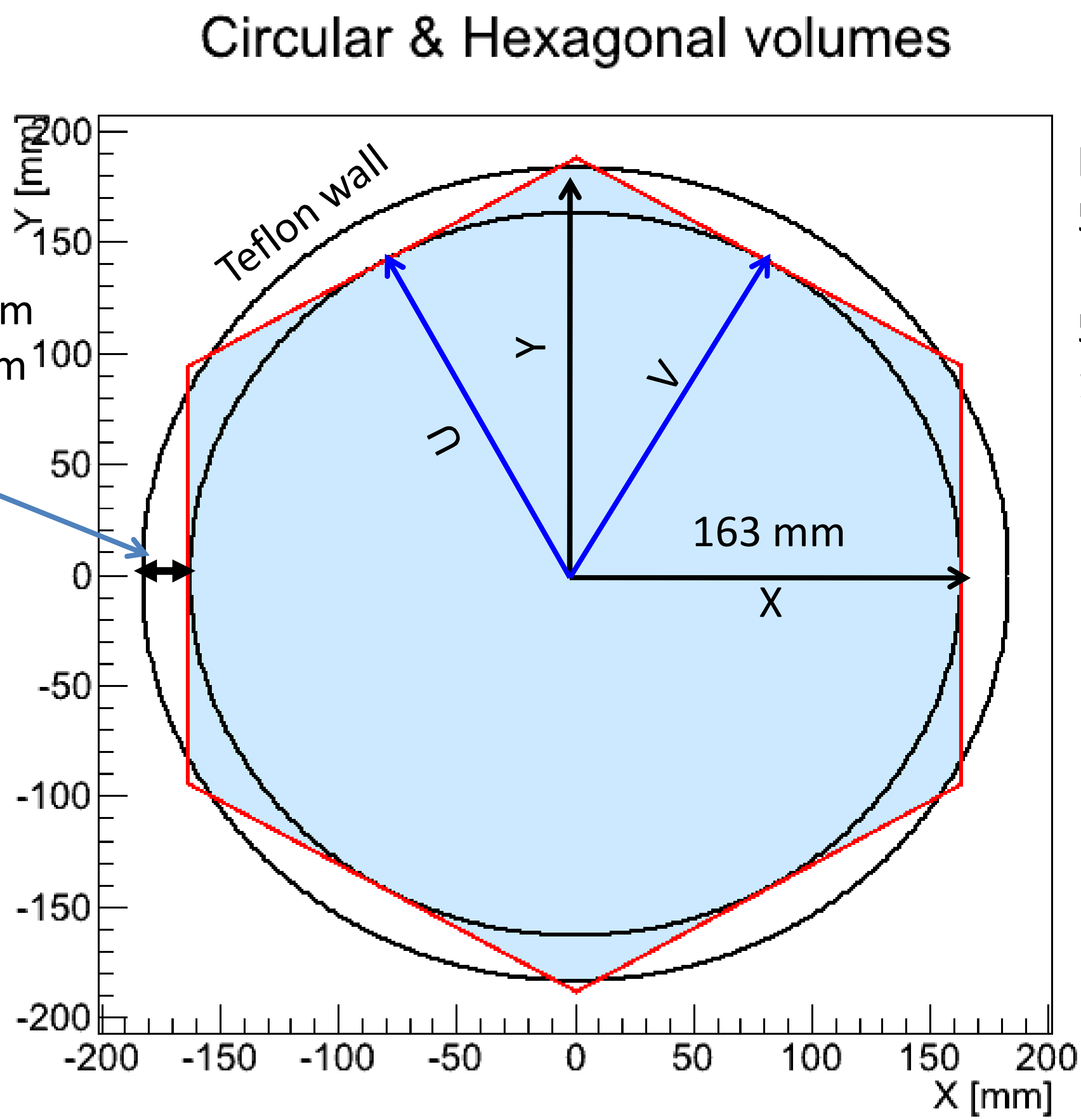
- Use a GEANT4 simulation of detector (and surroundings) to simulate
  - Signals (2νββ, 0νββ)
  - a variety of backgrounds (uranium, thorium, radon, etc.)
  - in various locations (TPC vessel, dissolved in liquid, outside of cryostat)
- Use the energy deposition information to form single-site and multi-site PDFs
- These are smeared according to the energy resolution, but not until the final stage of fitting





Fiducial Volume

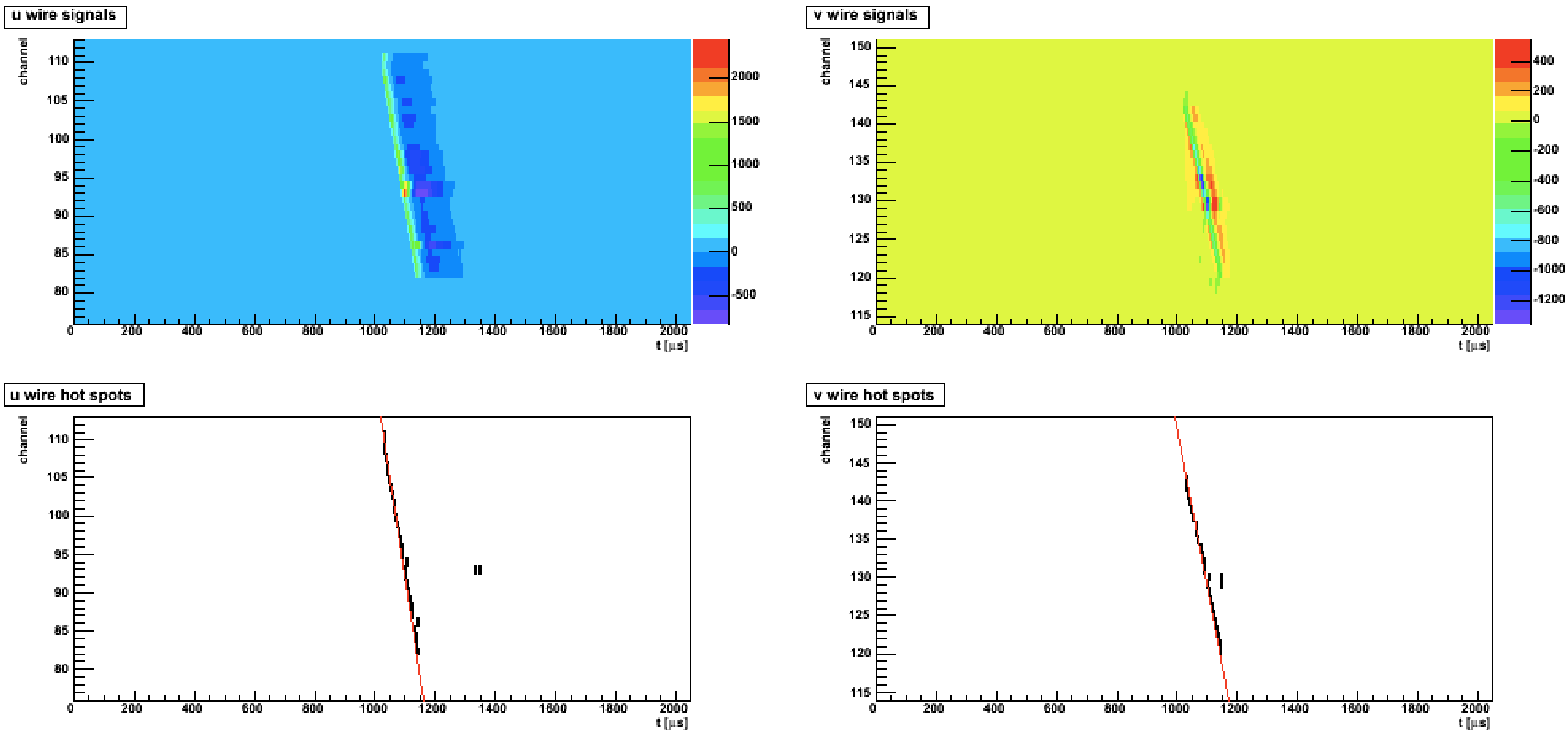
Standoff distance 20 mm Measured from Teflon wall to hexagon



In z dimension,
5 mm < |z| < 182 mm

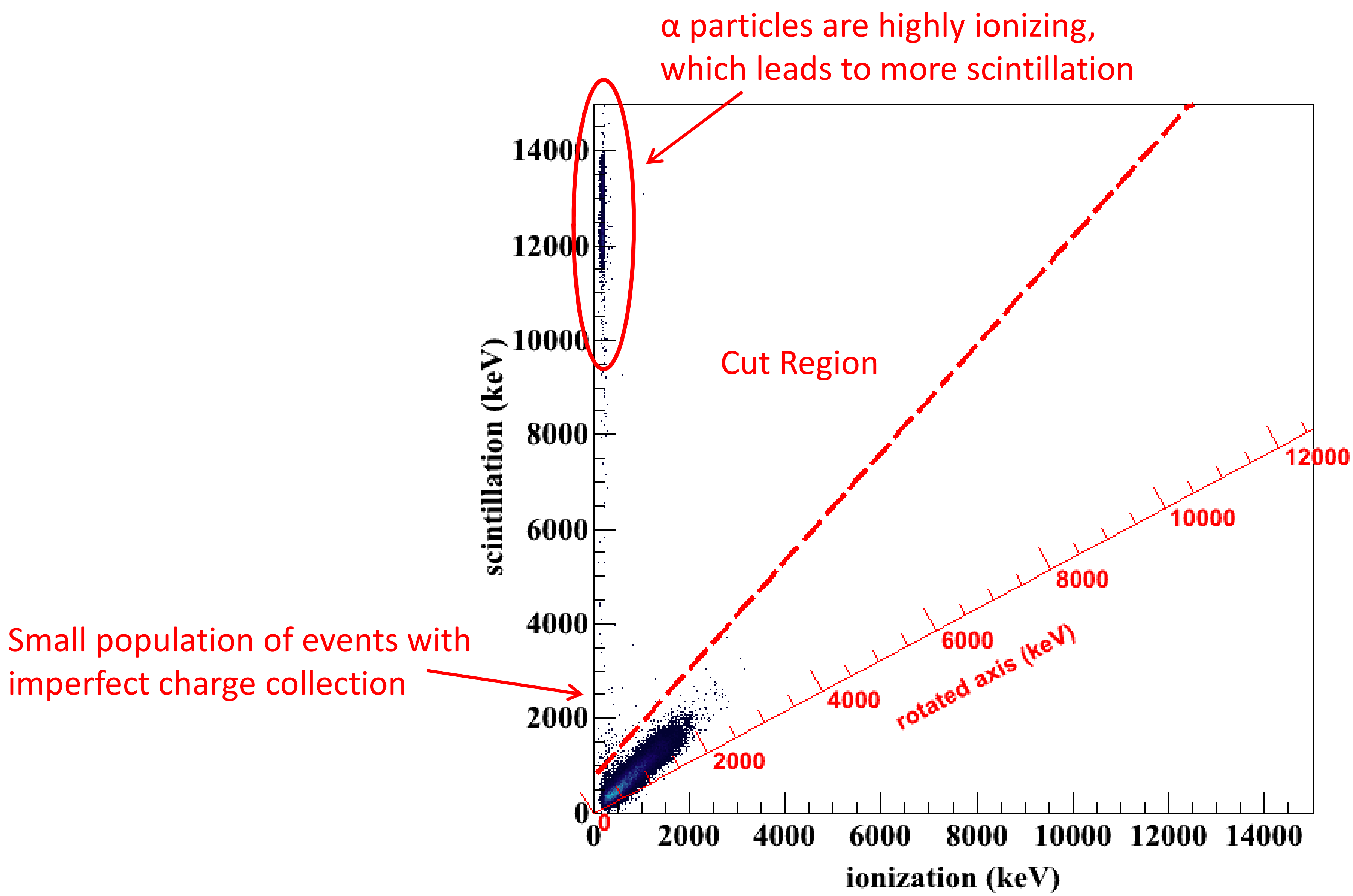
5 mm from cathode
10 mm from wire plane

Cosmic ray muons in the TPC

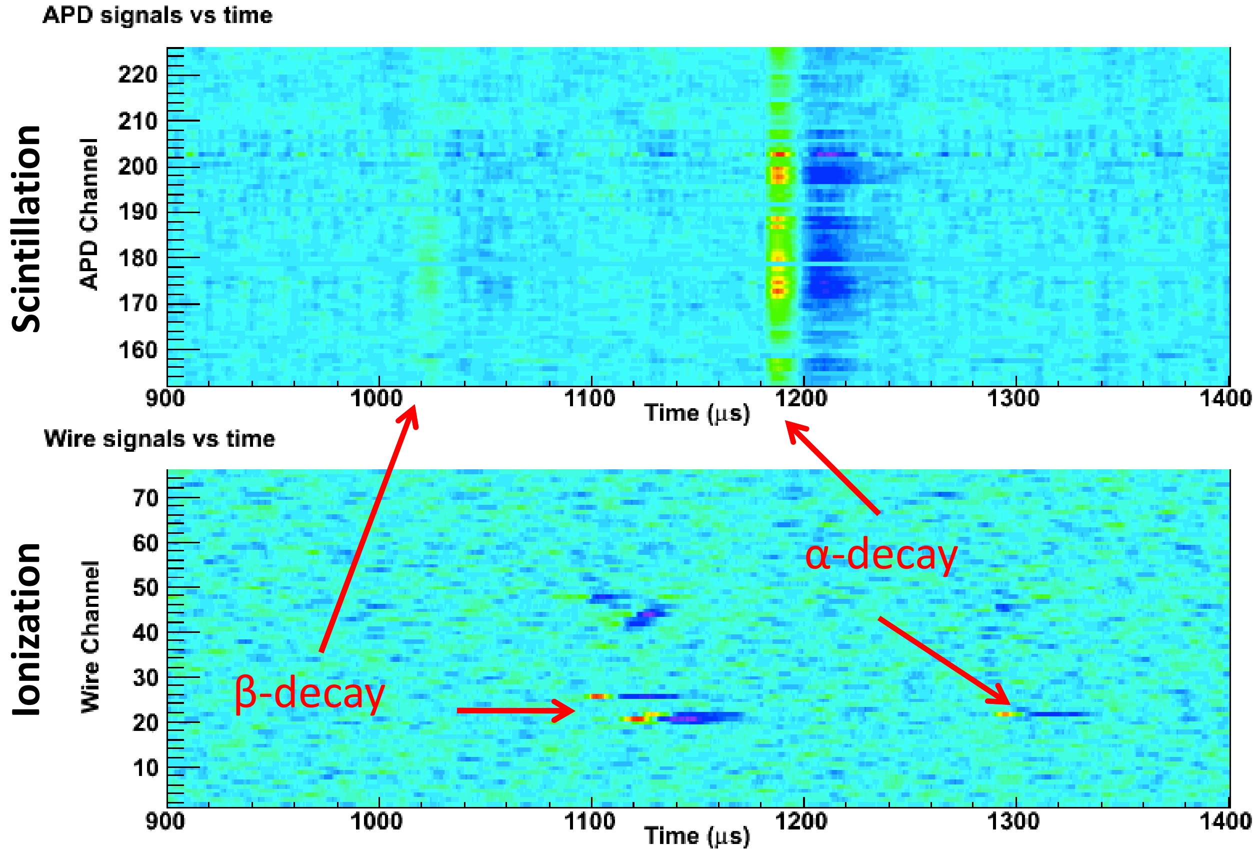


- Cosmic rays can create short-lived isotopes that have high energy gamma or beta decays
- Cosmic ray muons can be identified by the distinctive tracks they leave in the TPC
  - Cut all events within 60 s of a tagged muon in the TPC
- The muon veto panels that surround the clean rooms also have 96% efficiency at detecting muons that could pass through the TPC
  - Cut all events within 25 ms of a panel hit

Physics 2D data diagonal cut



Bismuth Polonium Coincidences

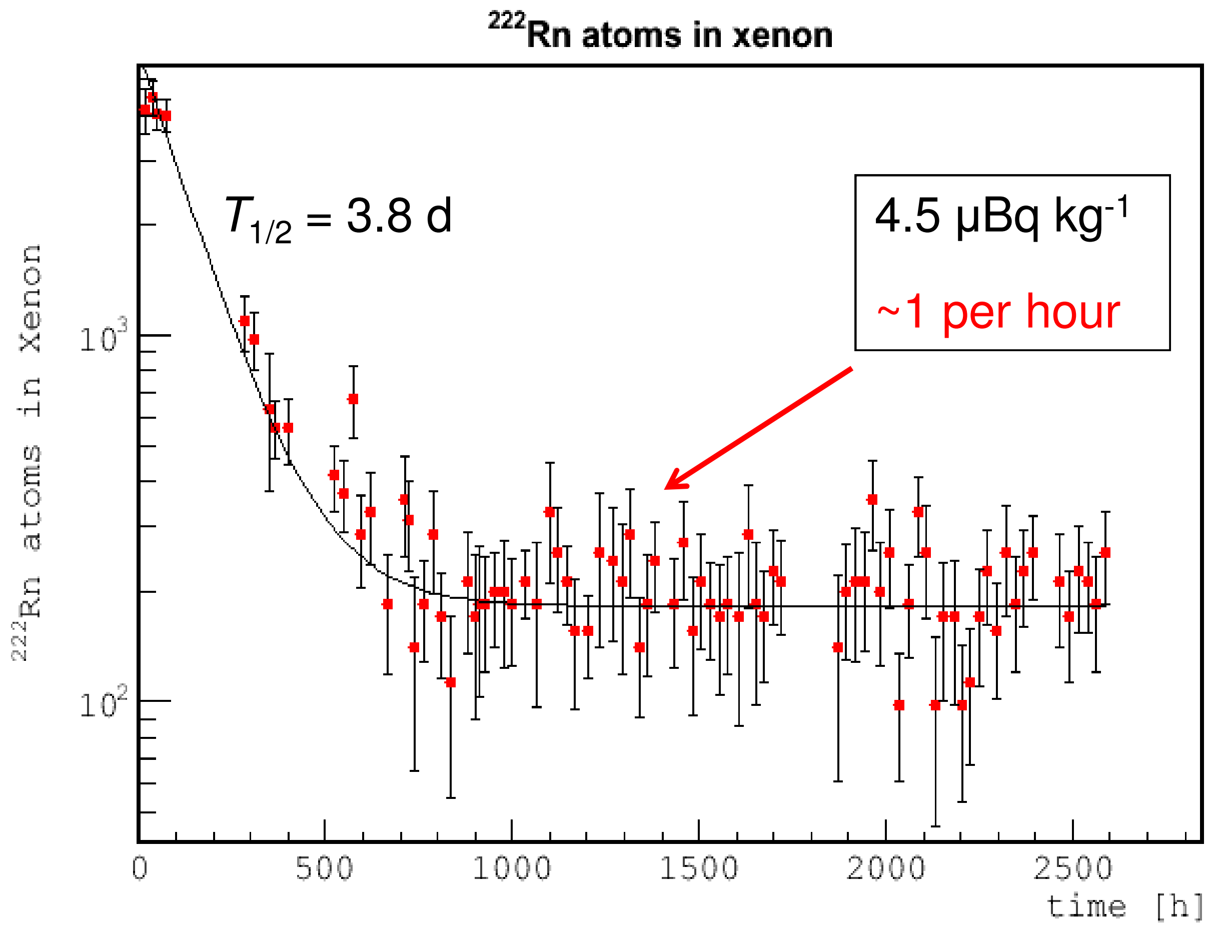


α: strong light signal, weak charge signal

β: weak light signal, strong charge signal

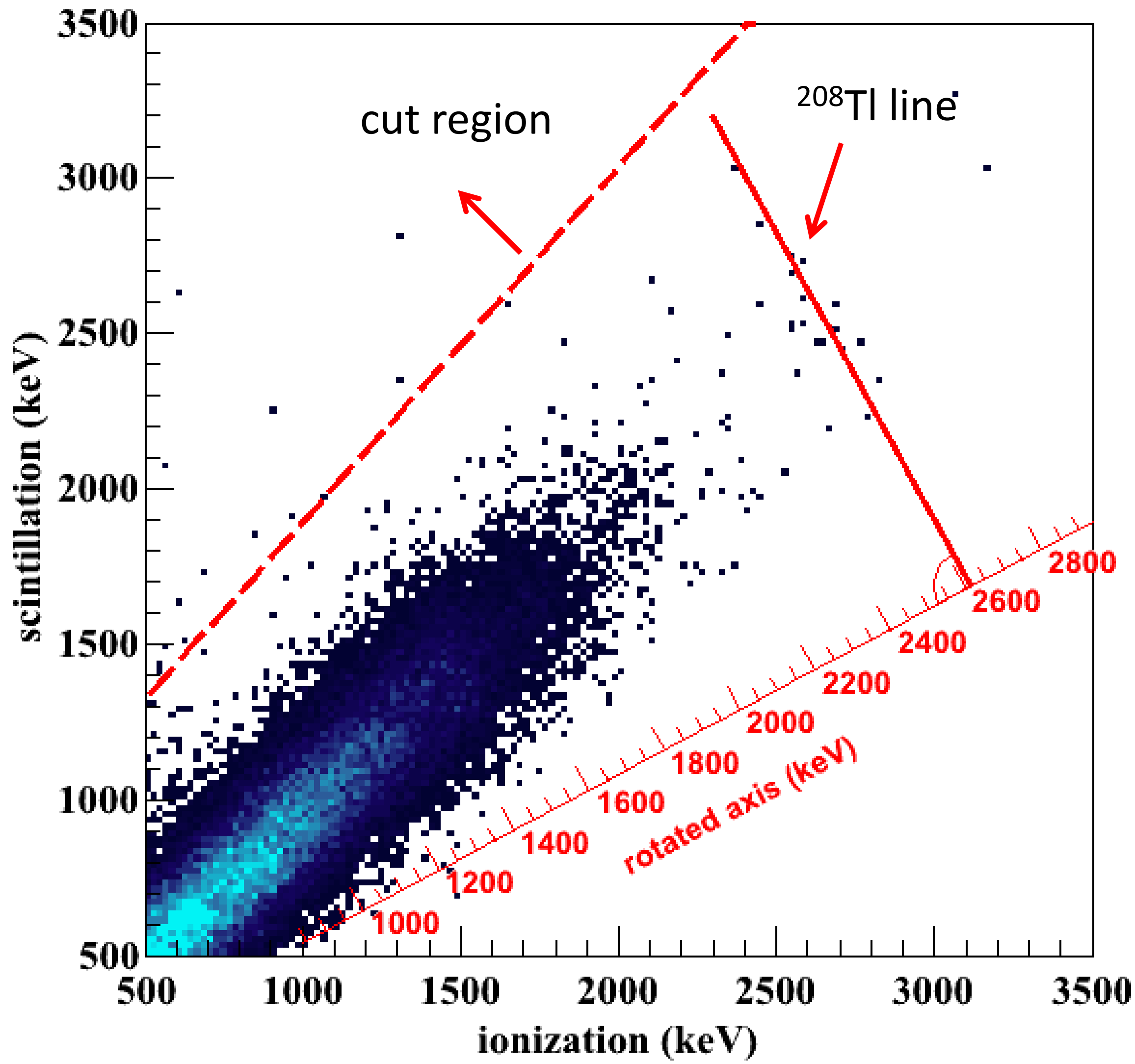
- ^{214}Bi decays are followed by ^{214}Po decays
- Cut any events that are within 1 s of another event (this also eliminates other potential coincident backgrounds)

Radon dissolved in the Xe



- ^{214}Bi rate is consistent with a steady state source of radon in the system (no radon trap installed)
  - 360 ± 65 μBq/kg in fiducial volume

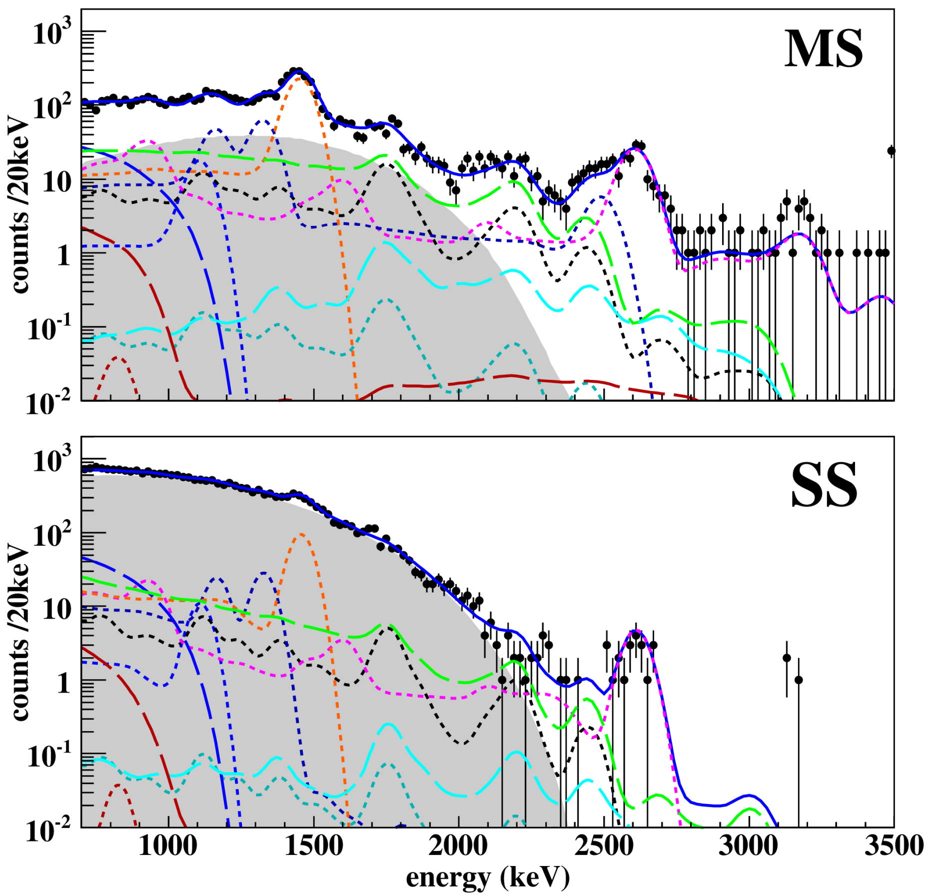
Physics data 2D spectrum



- After all cuts, this is our spectrum

Physics data rotated spectrum

Maximum Likelihood Fit

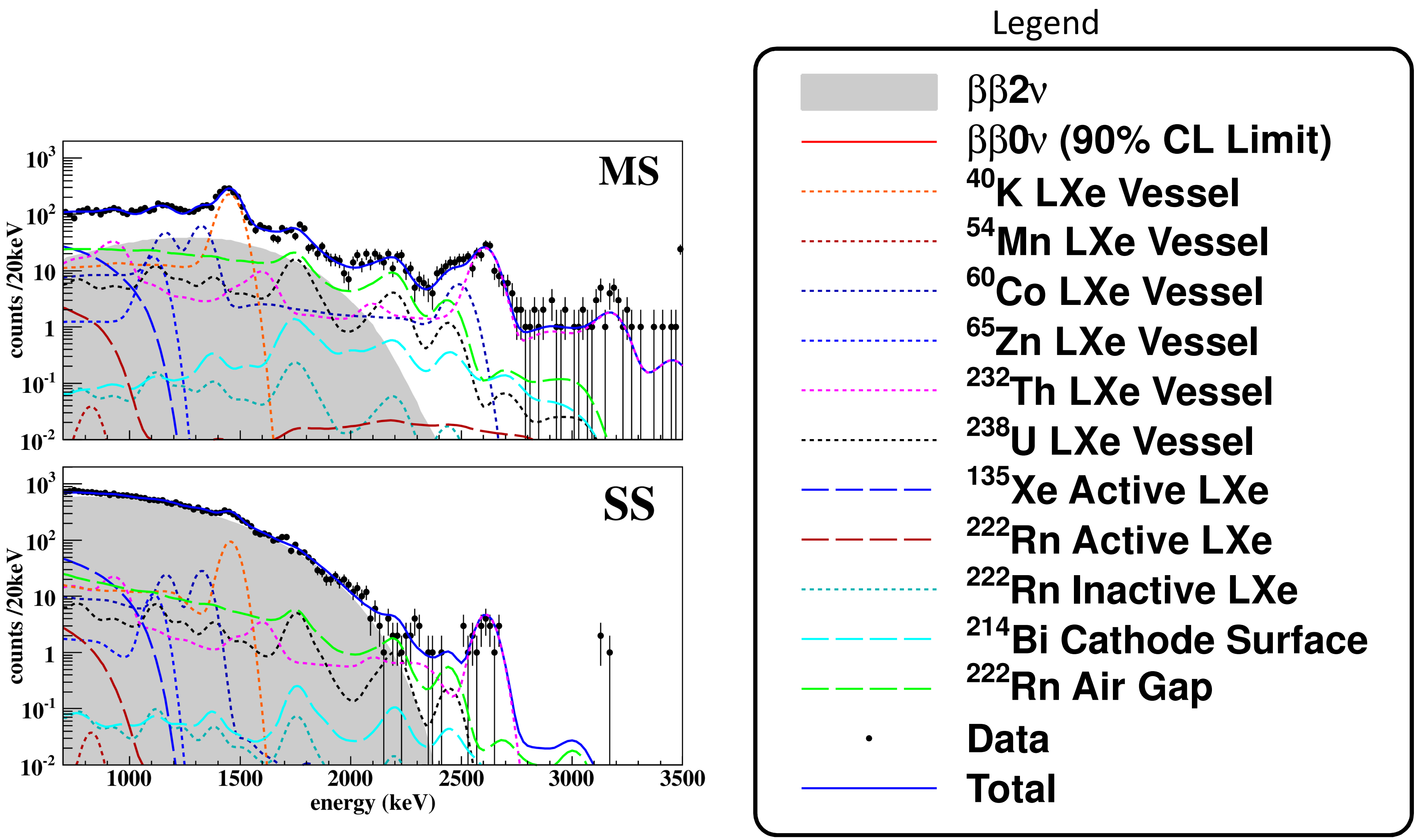


- Trigger fully efficient above 700 keV
- Low background live time: 120.7 days
  - Total dead time due to vetoes: 8.6%
- Active mass: 98.5 kg
  - ($79.4\ ^{136}Xe$)
- Exposure: 32.6 kg yr
  - ($26.3\ ^{136}Xe$)
- Simultaneous fit to signal and background for SS and MS events

$T_{1/2}^{2\nu\beta\beta}$ (^{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)

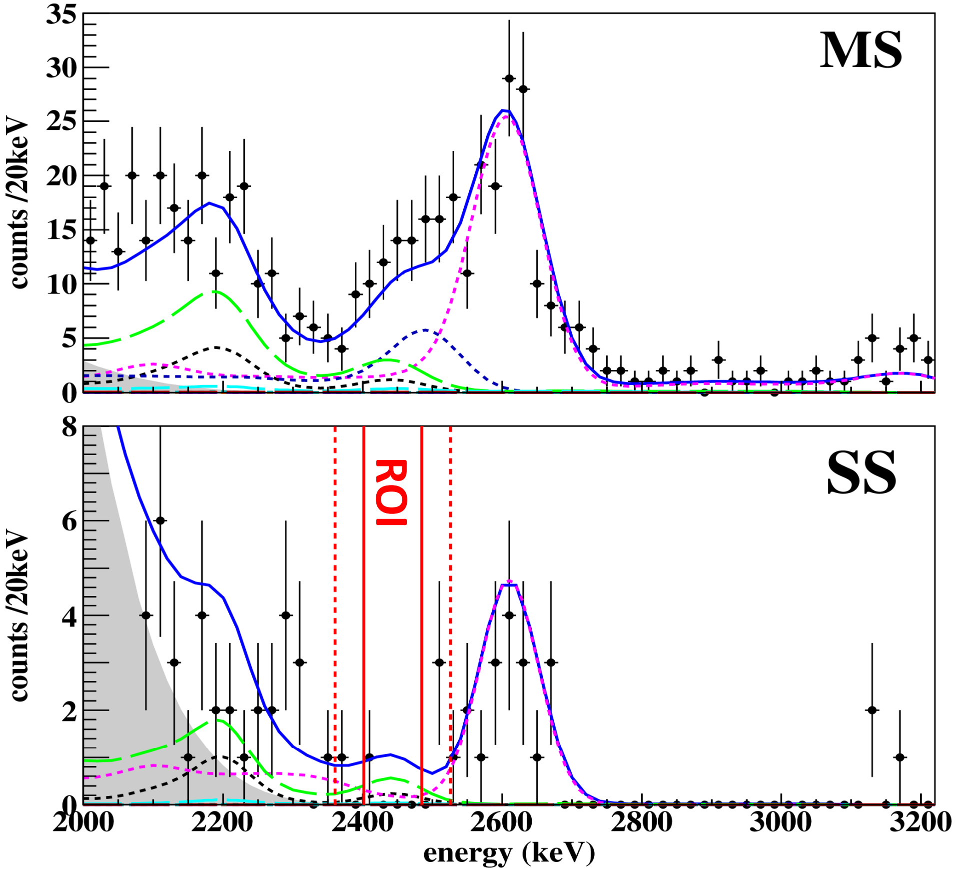
Physics data rotated spectrum



$T_{1/2}^{2\nu\beta\beta}$ (^{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 around Q value

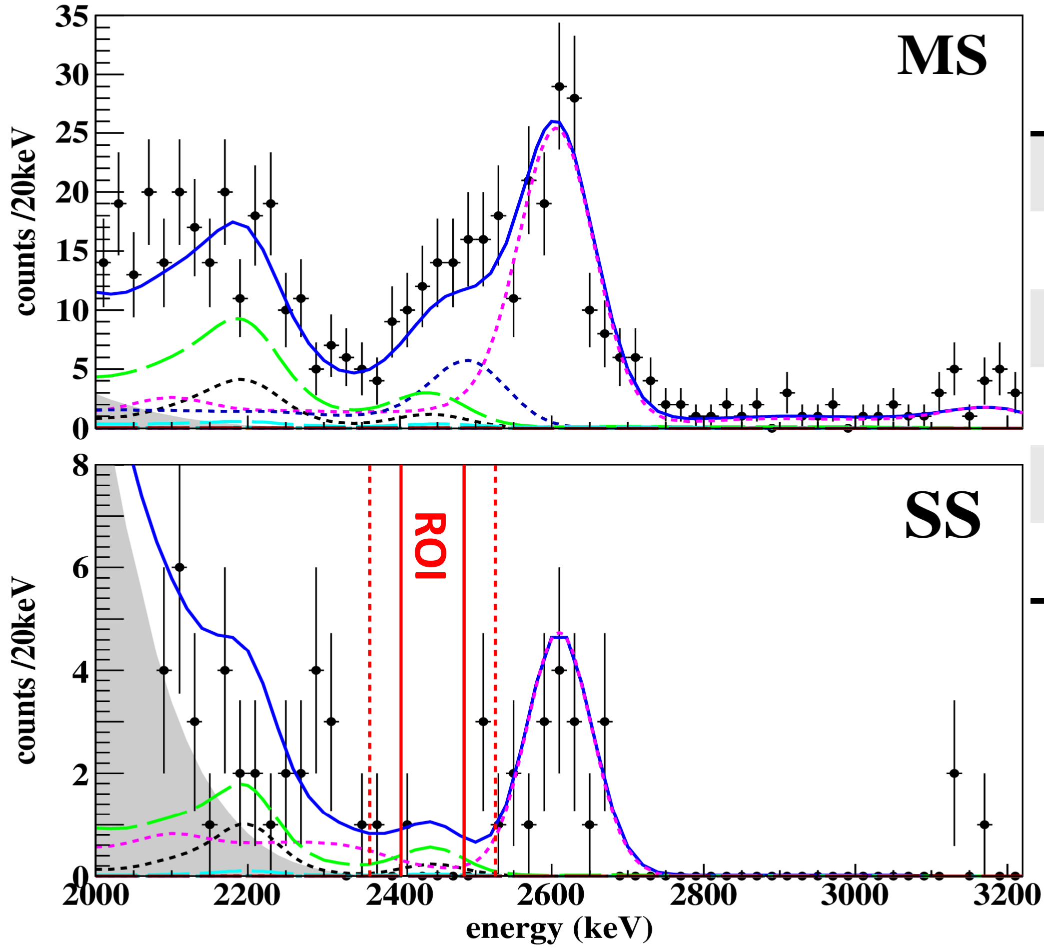


- No signal observed
- Background in ± 1σ ROI (from fit):
  $1.5 \cdot 10^{-3} \pm 0.1\ kg^{-1}yr^{-1}keV^{-1}$
- Profile likelihood study to extract limits for $T_{1/2}^{0\nu\beta\beta}$

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

Backgrounds in ± 1σ ROI

Zoomed around 0νββ region of interest (ROI)

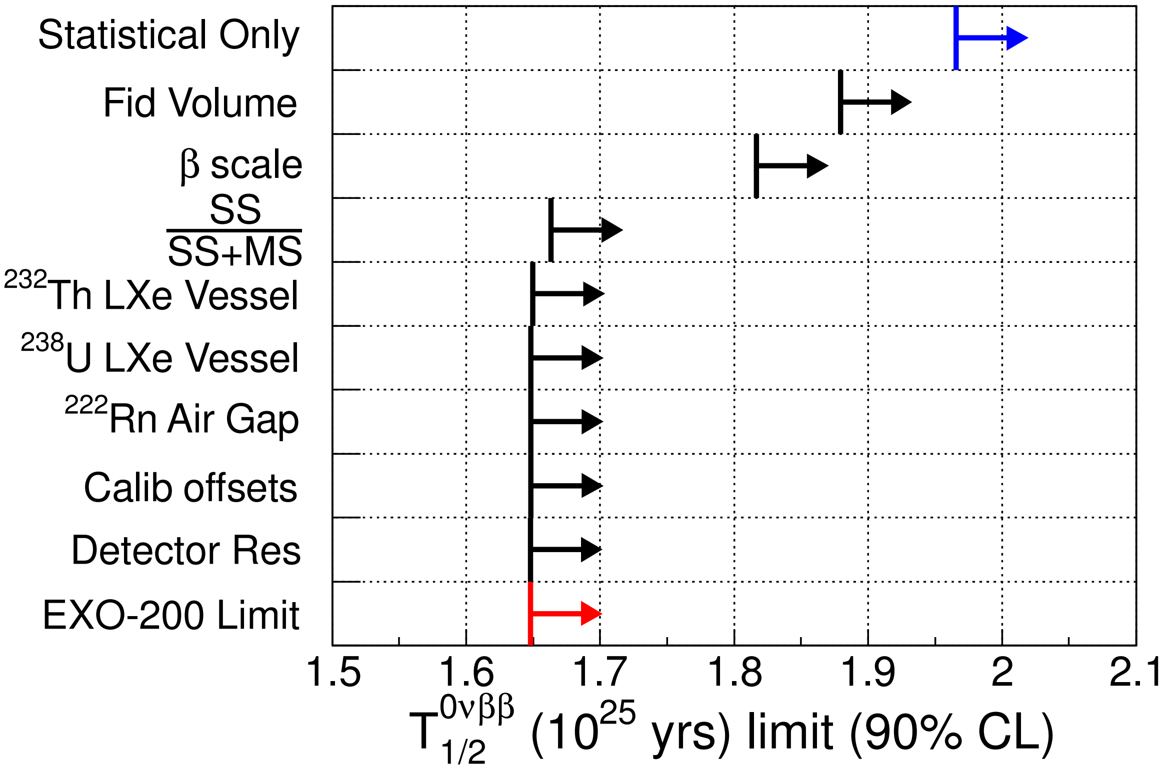


Observe 1 count
expect from fit:

^{222}Rn in cryostat—Pb gap	1.9	±0.2
^{238}U in LXe Vessel	0.9	±0.2
^{232}Th in LXe Vessel	0.9	±0.1
^{214}Bi on Cathode	0.2	±0.01
All Others	~0.2	
Total	4.1	±0.3

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

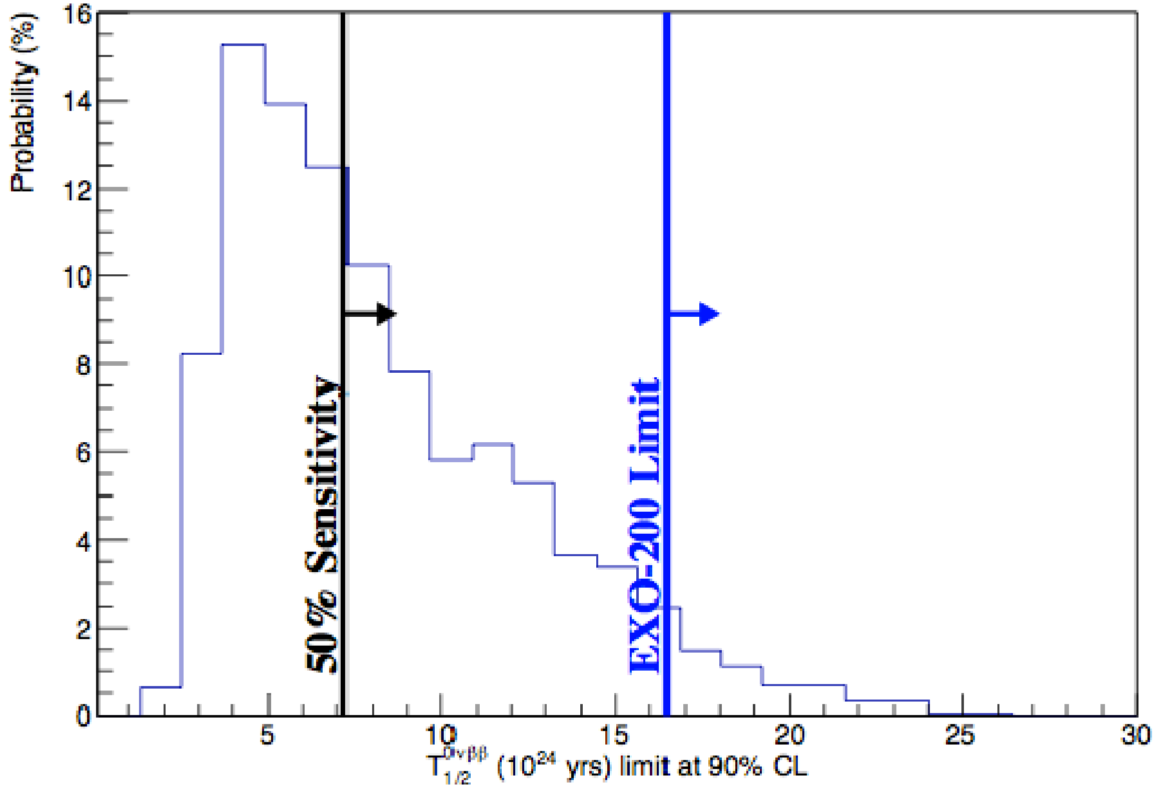
Systematic Error Breakdown



Term	%
Fid Volume	12.34
β scale	9.32
$\frac{SS}{SS+MS}$	0.93
^{232}Th LXe Vessel	0.11
^{238}U LXe Vessel	0.04
^{222}Rn Air Gap	0.04
Calib offsets	0.04
Detector Res	0.00

- Bars show the expected 90% confidence limit if we assume perfect knowledge of parameters that contribute to systematic errors

Sensitivity



Distribution of $0\nu\beta\beta$ $T_{1/2}$ 90% CL upper limits from Monte Carlo simulations

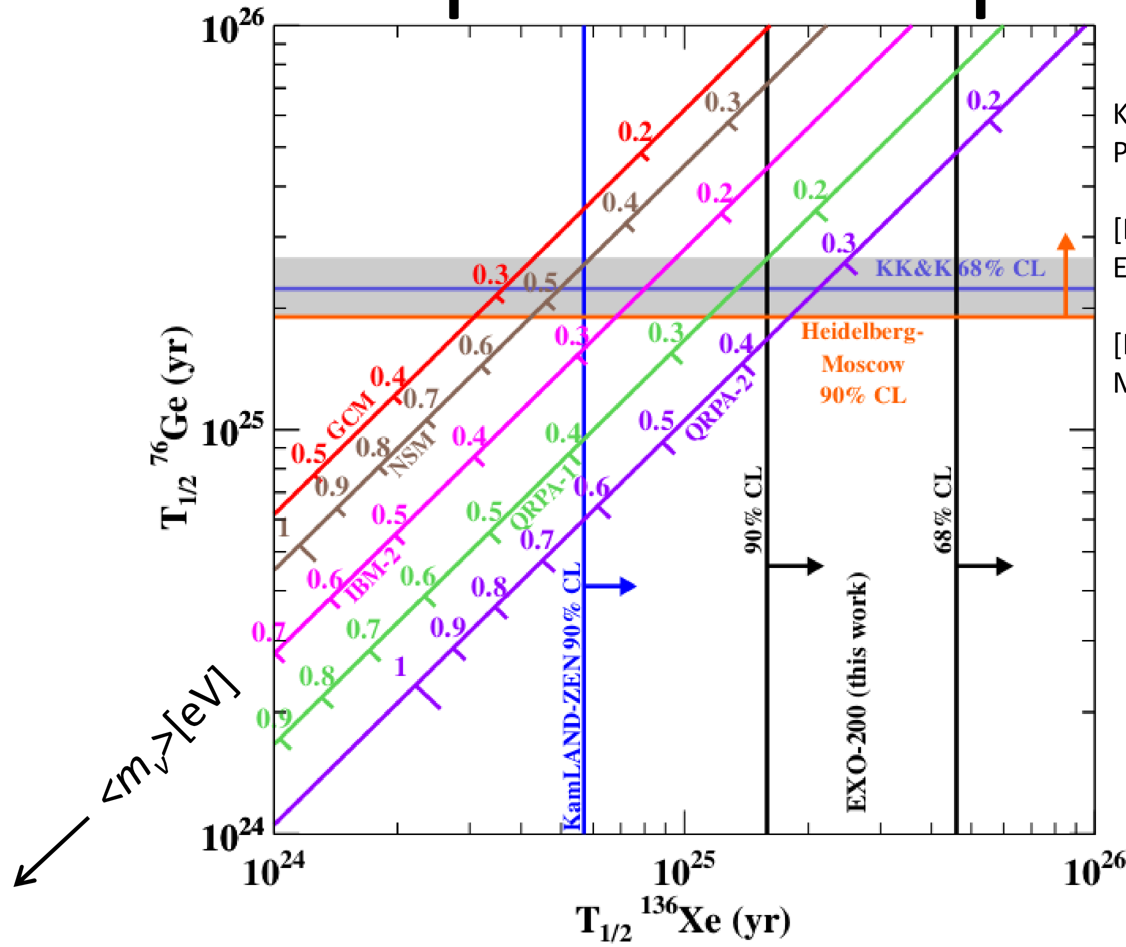
- Given our estimated background, we expect a 90% CL on $T_{1/2}$ of 1.6×10^{25} years or better 6.5% of the time.
- We would quote a 90% CL upper limit of 7×10^{24} years or better 50% of the time

New experimental limit

Isotope	0νββ half life (x10^{22} years)	Experiment
^{48}Ca	> 5.8	ELEGANT-VI
^{76}Ge	> 1900	Heidelberg-Moscow
^{76}Ge	2230^{+440}_{-310}	Subset of HM collaboration
^{82}Se	> 36	NEMO-3
^{96}Zr	> 0.92	NEMO-3
^{100}Mo	> 110	NEMO-3
^{116}Cd	> 17	Solotvino
^{130}Te	> 280	Cuoricino
^{136}Xe	*> 570*	*KamLAND-Zen†*
→ *^{136}Xe*	*> 1600*	*EXO-200‡* ←
^{150}Nd	> 1.8	NEMO-3

[F. Avignone, S. Elliot, J. Engel, arXiv:0708: 1033v2 (2007)]
†[KamLAND-Zen Collaboration, Phys.Rev.C 85 045504 (2012)]
‡[arXiv:1205.5608]

Graphical Comparison



KamLAND-Zen Collaboration
Phys. Rev. C 85 (2012) 045504]

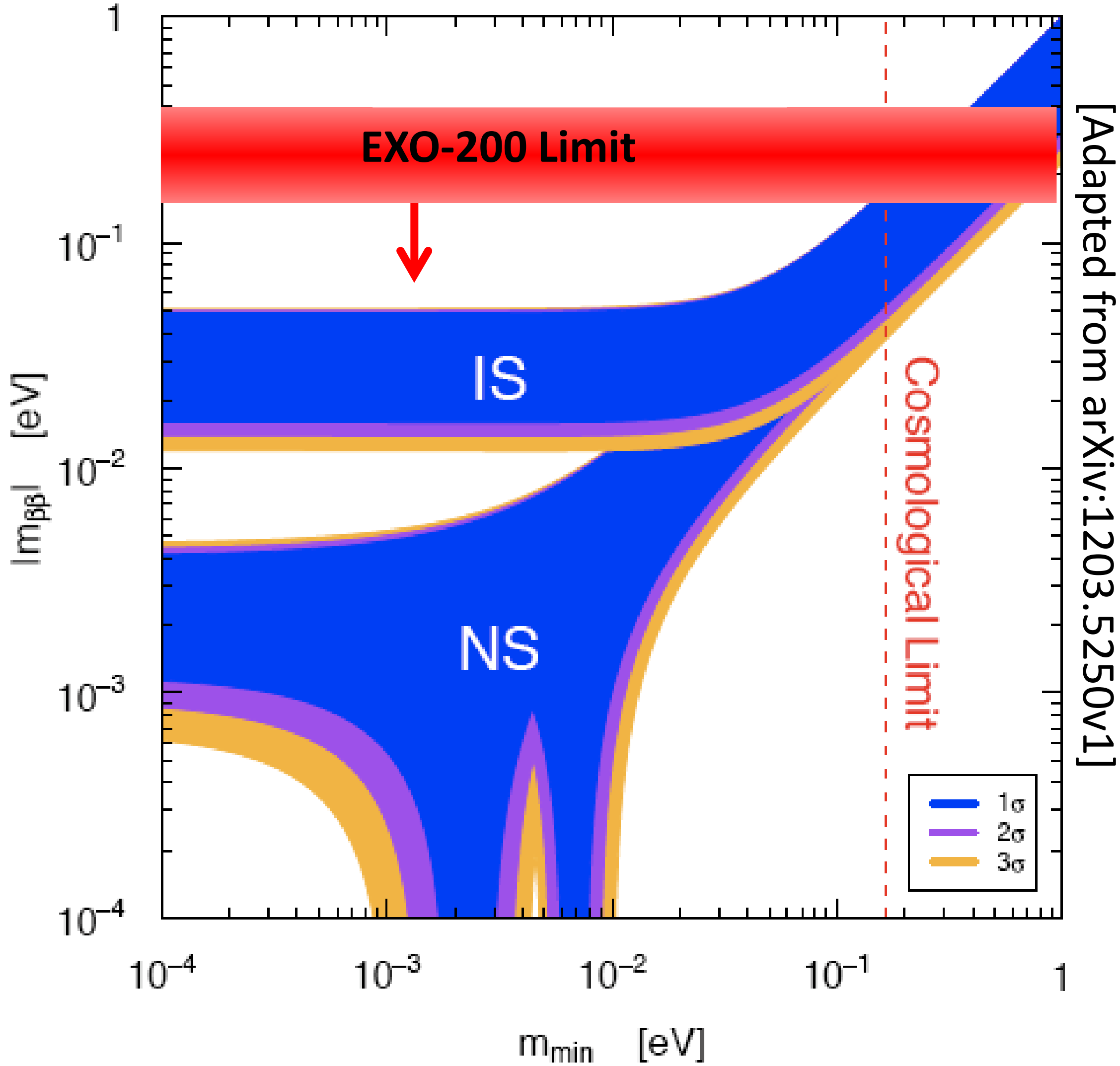
[H.V. Klapdor-Kleingrothaus et al.
Eur. Phys. J. A12 (2001) 147]

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

<m_ν> < 140—380 meV

- The EXO-200 90% CL is a factor of 2.5 improvement over the KamLAND-Zen limit
- EXO-200 CL contradicts the claim of discovery in ^{76}Ge by a subset of the Heidelberg-Moscow collaboration for most (all) nuclear models at the 90% (68%) confidence level

More graphical context



- EXO-200 will explore deeper into the degenerate hierarchy with continued operation

Future Plans and Improvements

Better APD gain calibration through laser pulser

Other energy resolution improvements

$$S_{m_{\beta\beta}} \propto \left(\frac{A}{\varepsilon a}\right)^{1/2} \left(\frac{B\Gamma}{MT}\right)^{1/4}$$

Radon purge for air gap between lead wall and cryostat
(this is half of our background in the ROI)

Further background reduction through improved multiplicity assignment

This analysis uses ~7 months of data
So continue running

Conclusions

- EXO-200 has completed its first low background run in search of 0νββ
- Energy resolution σ/E = 1.67% at $Q_{\beta\beta}$
- Low background rate

$$b = (1.5 \pm 0.1) \cdot 10^{-3} kg^{-1} yr^{-1} keV^{-1}$$

- Confirmed measurement of 2νββ

$$T_{1/2}^{2\nu\beta\beta} = 2.23 \times 10^{21} \pm 0.017(\text{stat.}) \pm 0.22(\text{sys.})$$

- Lower limit on 0νββ

$$T_{1/2}^{0\nu\beta\beta}\Big|_{90\%CL} > 1.6 \times 10^{25}\, yr$$

- And upper limit on Majorana mass

$$\langle m_\nu \rangle\Big|_{90\%CL} < 140 - 380\text{meV}$$

The EXO Collaboration

University of Alabama, Tuscaloosa AL, USA - D. Auty, M. Hughes, R. MacLellan, A. Piepke, K. Pushkin, M. Volk

University of Bern, Switzerland - M. Auger, S. Delaquis, D. Franco, G. Giroux, R. Gornea, T. Tolba, J-L. Vuilleumier, M. Weber

California Institute of Technology, Pasadena CA, USA - P. Vogel

Carleton University, Ottawa ON, Canada - A. Coppens, M. Dunford, K. Graham, C. Hägemann, C. Hargrove, F. Leonard, C. Oullet, E. Rollin, D. Sinclair, V. Strickland

Colorado State University, Fort Collins CO, USA - S. Alton, C. Benitez-Medina, C. Chambers, Adam Craycraft, S. Cook, W. Fairbank, Jr., K. Hall, N. Kaufold, T. Walton

University of Illinois, Urbana-Champaign IL, USA - D. Beck, J. Walton, L. Yang

Indiana University, Bloomington IN, USA - T. Johnson, L.J. Kaufman

University of California, Irvine, Irvine CA, USA - M. Moe

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

Laurentian University, Sudbury ON, Canada - E. Beauchamp, D. Chauhan, B. Cleveland, J. Farine, B. Mong, U. Wichoski

University of Maryland, College Park MD, USA - C. Davis, A. Dobi, C. Hall, S. Slutsky, Y-R. Yen

University of Massachusetts, Amherst MA, USA - T. Daniels, S. Johnston, K. Kumar, A. Pocar, J.D. Wright

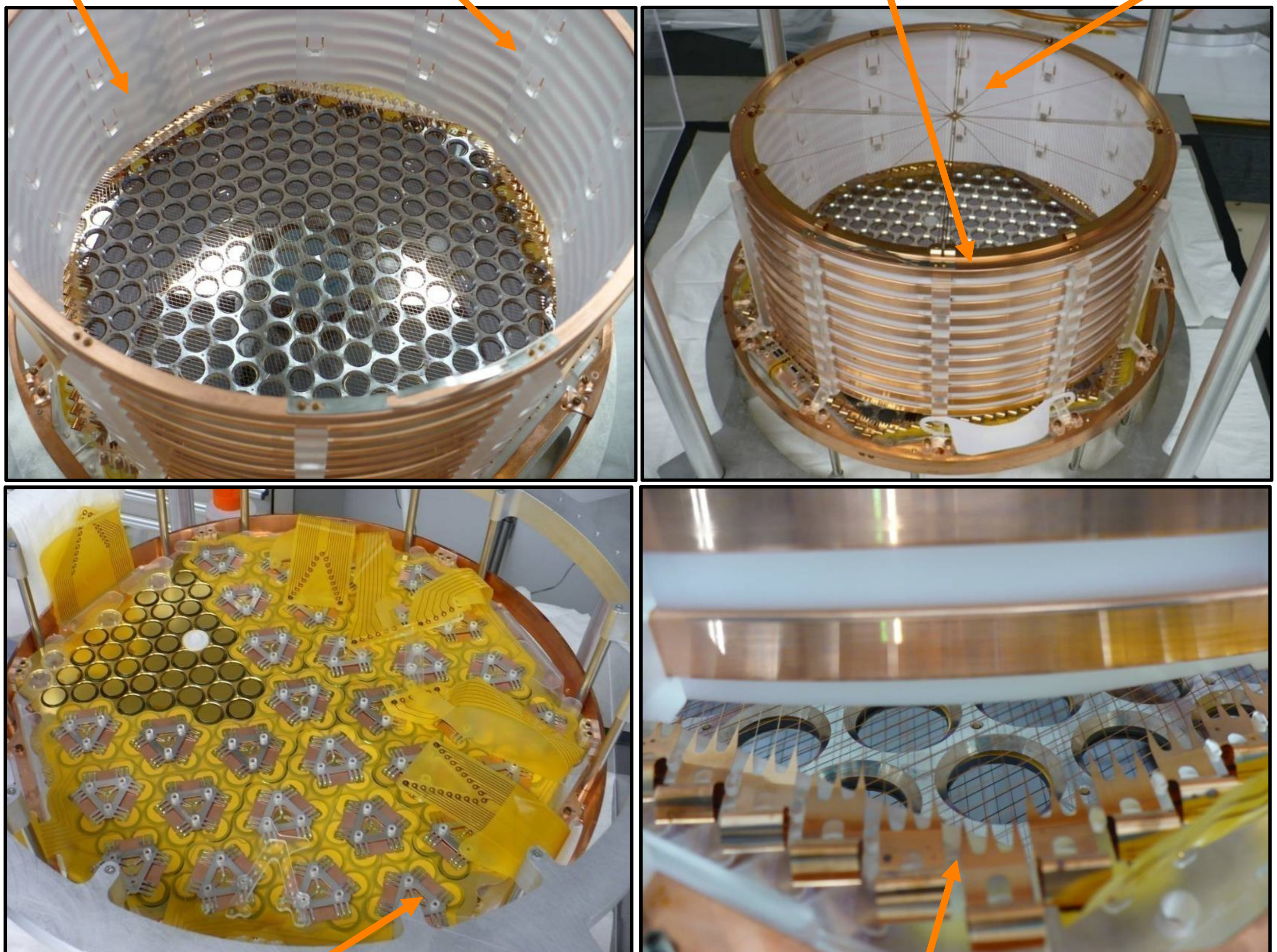
University of Seoul, South Korea - D. Leonard

SLAC National Accelerator Laboratory, Menlo Park CA, USA - M. Breidenbach, R. Conley, R. Herbst, S. Herrin, J. Hodgson, A. Johnson, D. Mackay, A. Odian, C.Y. Prescott, P.C. Rowson, J.J. Russell, K. Skarpaas, M. Swift, A. Waite, M. Wittgen, J. Wodin

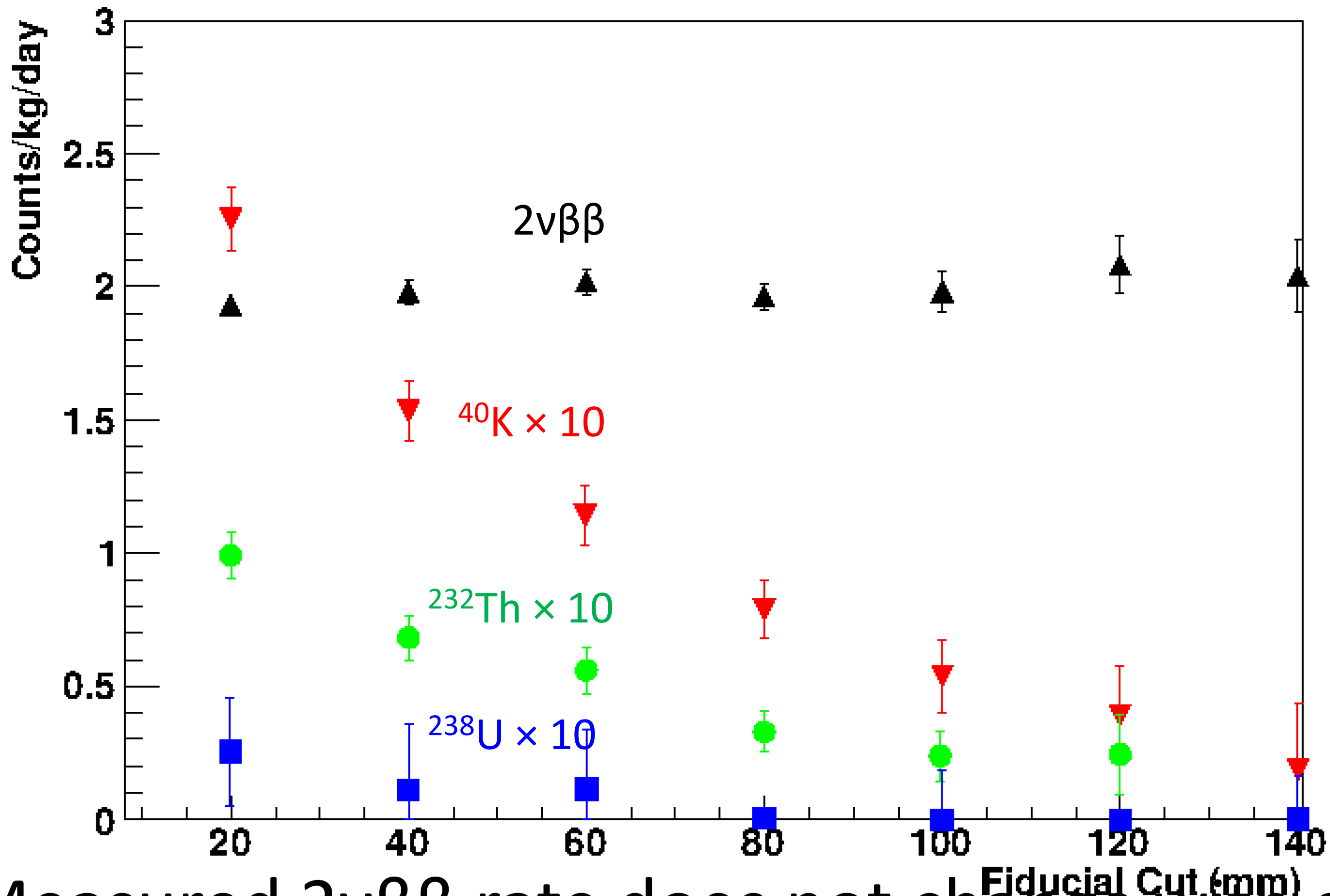
Stanford University, Stanford CA, USA - P.S. Barbeau, T. Brunner, J. Davis, R. DeVoe, M.J. Dolinski, G. Gratta, M. Montero-Díez, A.R. Müller, R. Neilson, I. Ostrovskiy, K. O'Sullivan, A. Rivas, A. Sabourov, D. Tosi, K. Twelker

Technical University of Munich, Garching, Germany - W. Feldmeier, P. Fierlinger, M. Marino

Backup: Detector Photos

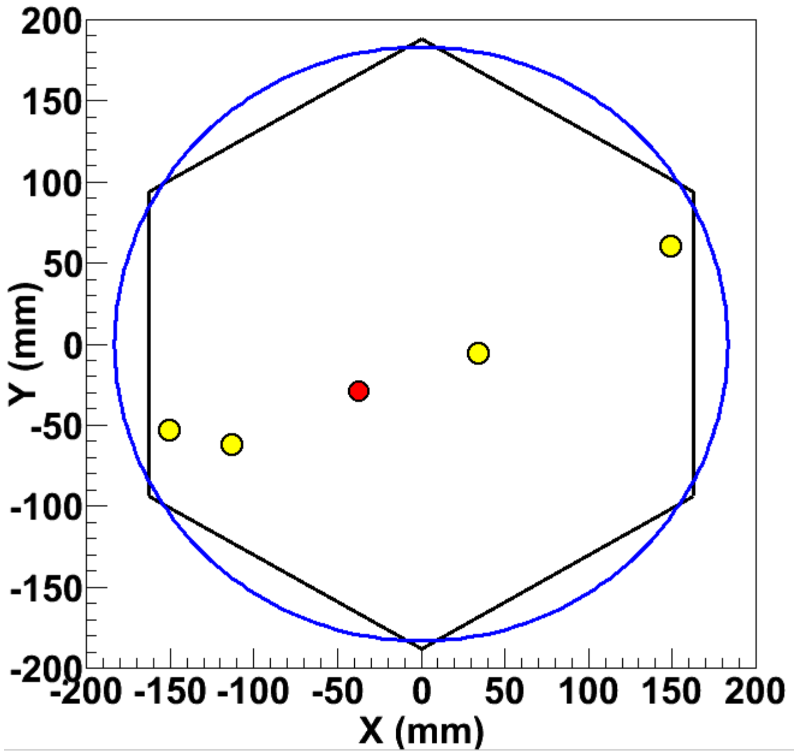


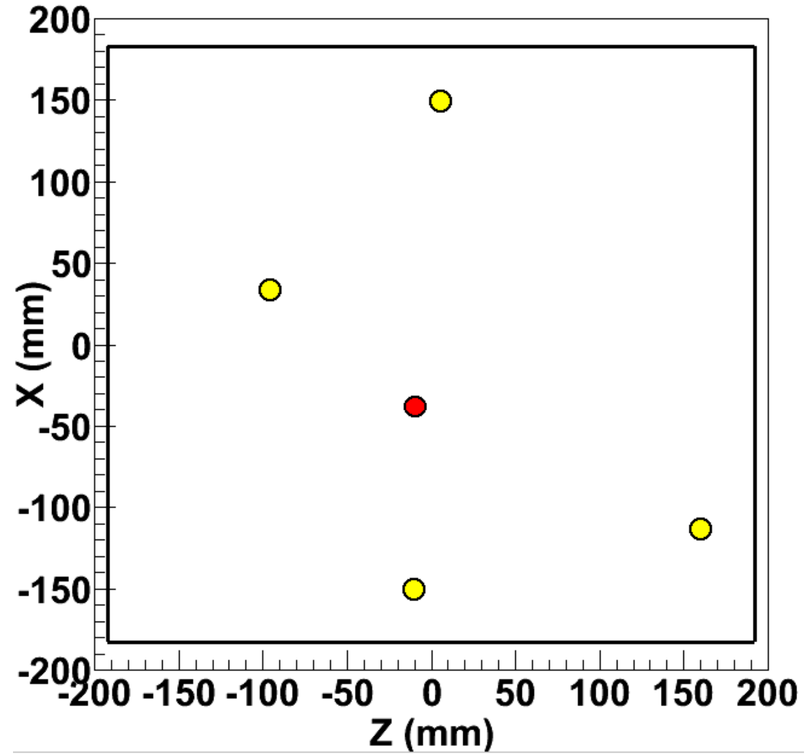
Backup: Rates vs Fiducial Cuts



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

Backup: Spatial Distribution

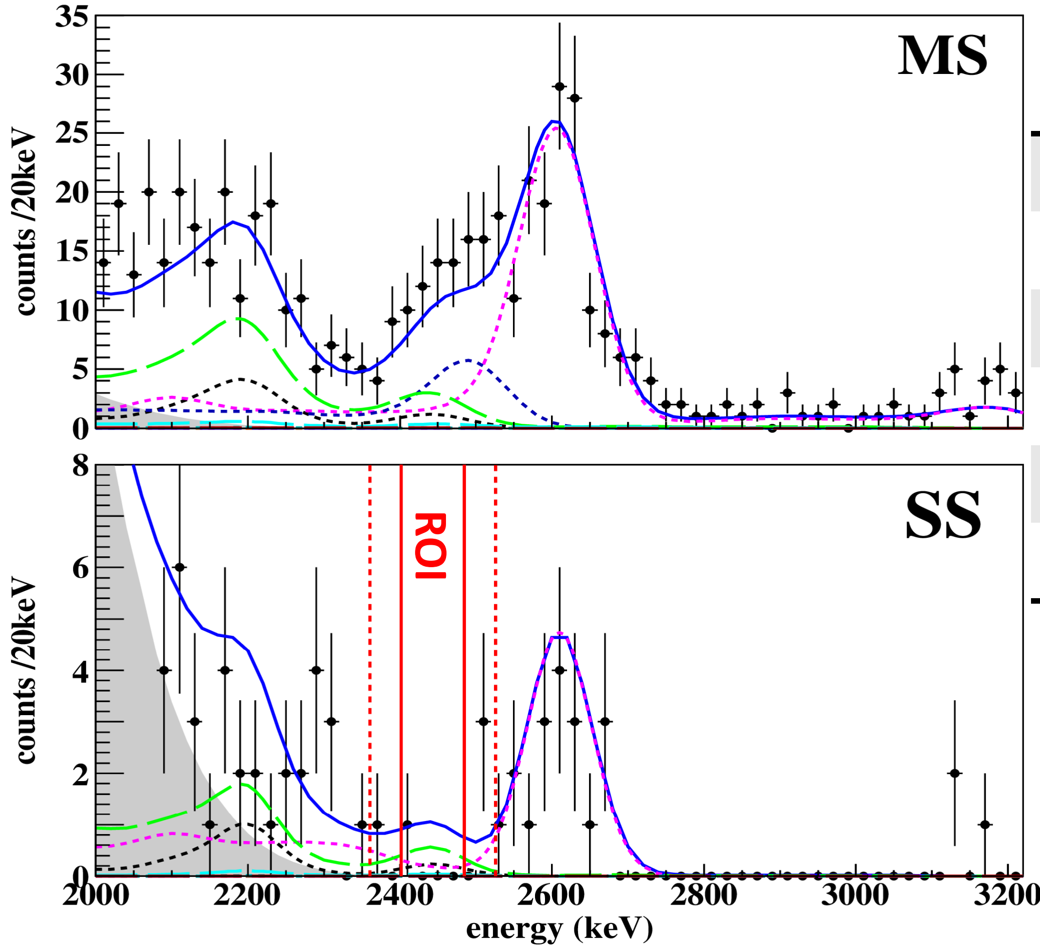




- Events within ± 1 σ
- Events within ± (1—2)σ

Backup: Backgrounds in ± 2σ ROI

Zoomed around 0νββ region of interest (ROI)



Observe 5 counts
expect from fit:

^{222}Rn in cryostat air-gap	2.9	±0.3
^{238}U in LXe Vessel	1.3	±0.3
^{232}Th in LXe Vessel	2.9	±0.3
^{214}Bi on Cathode	0.3	±0.02
All Others	~0.2	
Total	7.5	±0.5

$1.4 \cdot 10^{-3} \pm 0.1$ kg^{-1}yr^{-1}keV^{-1} in ± 2σ ROI

Backup: 2νββ Measurement

- 31 live days with 63 kg active mass
- Ionization only
- Signal:background = 10:1
- [PRL 107 (2011) 212501]

$$T_{1/2}^{2\nu\beta\beta} = 2.11\times10^{21} \pm 0.04(\text{stat.}) \pm 0.21(\text{sys.})$$