Search for neutrinoless double-beta decay with EXO

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Outline

- Introduction
  - Neutrino
  - Double beta decay
  - Enriched Xenon Observatory (EXO)

- EXO-200
  - Detector design
  - Data analysis
  - Physics results

- Next steps

Introduction: Neutrino

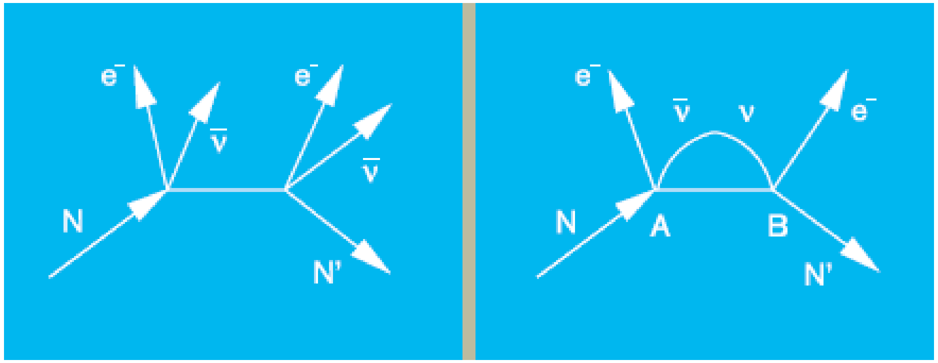
- From neutrino oscillation experiments we know that neutrino has a non-zero mass. We have measured relative mass-squared differences of different states
  - But what about absolute mass values?
  - How do different states align (normal, inverted hierarchy)?
  - What is the origin of mass term (Dirac, Majorana)?

Composition	Elementary particle
Statistics	Fermionic
Generation	First, second and third
Interactions	Weak interaction and gravitation
Symbol	ν_e, ν_μ, ν_τ, $\bar{\nu}_e$, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$
Antiparticle	Antineutrinos are possibly identical to the neutrino (see *Majorana fermion*).
Theorized	ν_e (Electron neutrino): Wolfgang Pauli (1930) ν_μ (Muon neutrino): Late 1940s ν_τ (Tau neutrino): Mid 1970s
Discovered	ν_e: Clyde Cowan, Frederick Reines (1956) ν_μ: Leon Lederman, Melvin Schwartz and Jack Steinberger (1962) ν_τ: DONUT collaboration (2000)
Types	3 – electron neutrino, muon neutrino and tau neutrino
Mass	Small, but non-zero. See the *mass* section.
Electric charge	0 e
Spin	$\frac{1}{2}$
Weak hypercharge	−1
B − *L*	−1
X	−3

From Wikipedia

Introduction: Double beta decay

- Two-neutrino mode is a Standard model process
  - though extremely rare, already observed for several isotopes



- Neutrino-less mode violates lepton number conservation
  - can only happen if neutrinos are **massive Majorana** particles
  - provides information about **absolute mass** scale
  - has never been observed*

* a controversial discovery claim exists by a sub-group of Heidelberg-Moscow collaboration [H.V. Klapdor-Kleingrothaus and I.V. Krivosheina Mod. Phys. Lett., A21 (2006) 1547]

Introduction: Experimental signature

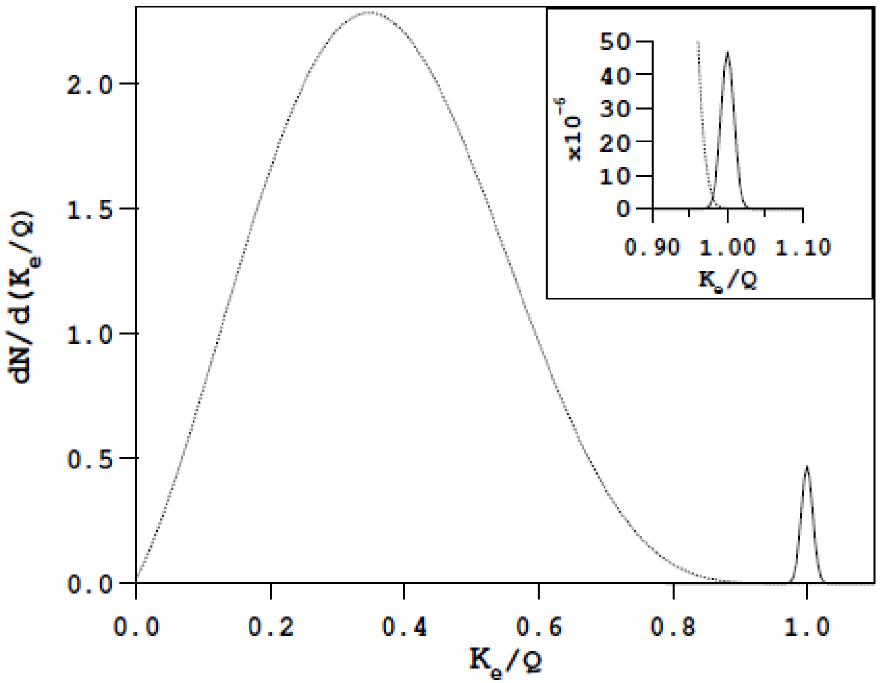


Illustration from P.Vogel, arXiv:hep-ph/0611243,
Assumes 2% resolution and 1e2 (1e6 in insert) ratio of 2nu/0nu

- In the two-neutrino mode electrons have to share energy with undetectable neutrinos
  - A calculable, but broad and featureless spectrum
- In the neutrinoless mode, a mono-energetic peak is expected at Q-value
  - Good energy resolution is essential
  - Large Q-value is preferred

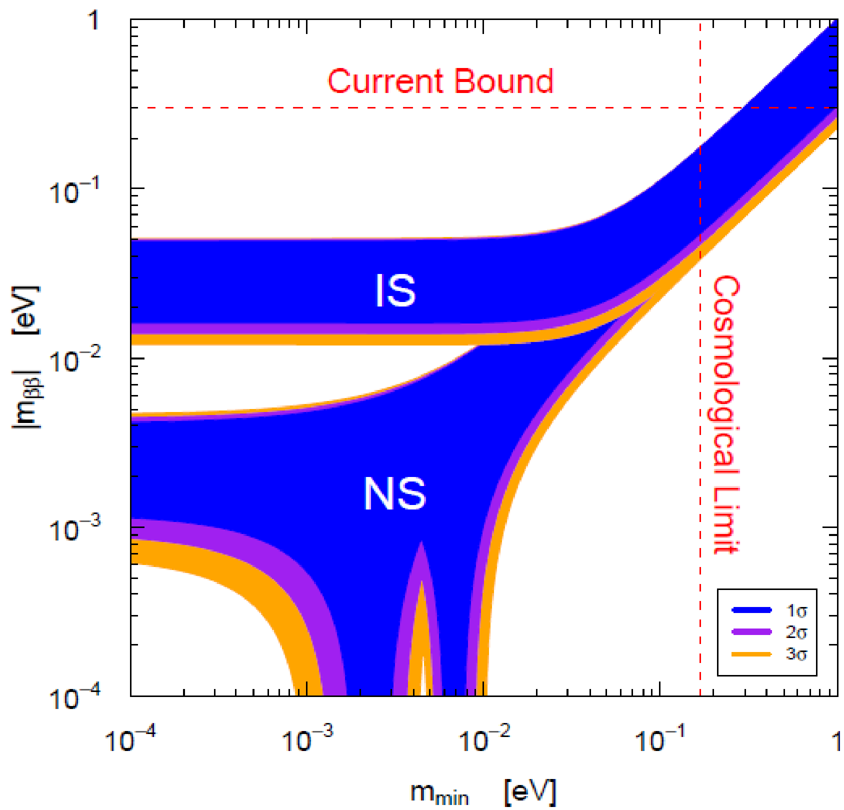
Introduction: From half-life to mass

- Observing a peak at Q value gives estimate of half-life (our job!)
- The half-life is then related to the **effective Majorana mass** through
  - Reliably calculable **phase-space factor**
  - Strongly model-dependent **matrix element**

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

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

Introduction: The two hierarchies



Bilenky, Giunti, arXiv:1203.5250

- Cosmology limits sum of neutrino masses to <~0.5 eV

  Hannestad, Prog.Part.Nucl.Phys, 65 (2010)185

- Heidelberg-Moscow limits effective Majorana mass to <~0.3 eV

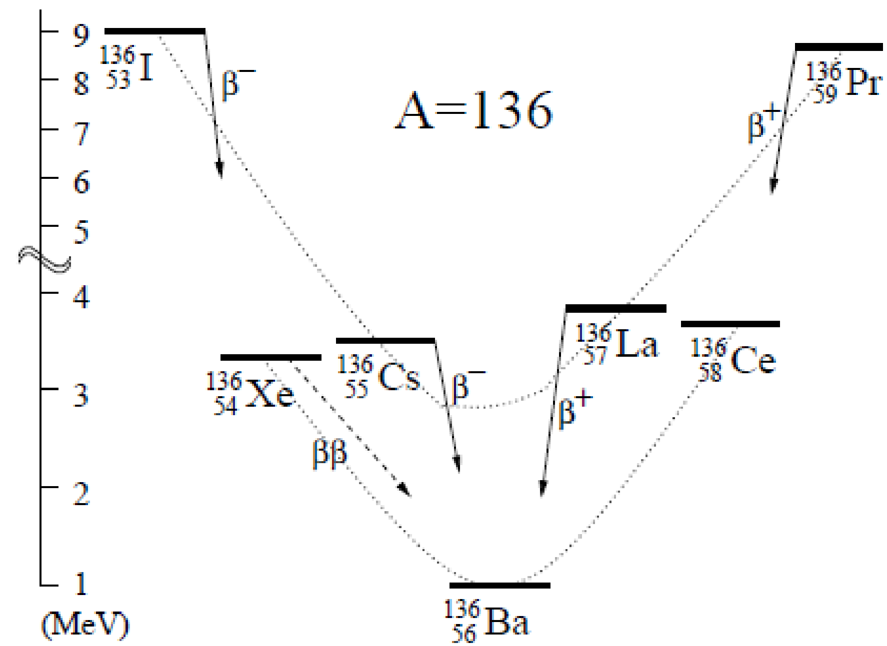
Introduction: Some pursued options

$\beta\beta$-decay	$G^{0\nu}$ $[10^{-14}\,\mathrm{y}^{-1}]$	Q [keV]	nat. abund. [%]	experiments
$^{48}Ca \rightarrow {}^{48}Ti$	6.3	4273.7	0.187	CANDLES
$^{76}Ge \rightarrow {}^{76}Se$	0.63	2039.1	7.8	GERDA, Majorana
$^{82}Se \rightarrow {}^{82}Kr$	2.7	2995.5	9.2	SuperNEMO, Lucifer
$^{100}Mo \rightarrow {}^{100}Ru$	4.4	3035.0	9.6	MOON, AMoRe
$^{116}Cd \rightarrow {}^{116}Sn$	4.6	2809	7.6	Cobra
$^{130}Te \rightarrow {}^{130}Xe$	4.1	2530.3	34.5	CUORE
$^{136}Xe \rightarrow {}^{136}Ba$	4.3	2461.9	8.9	EXO, KamLAND-Zen, NEXT, XMASS
$^{150}Nd \rightarrow {}^{150}Sm$	19.2	3367.3	5.6	SNO+, DCBA/MTD

Bilenky, Giunti, arXiv:1203.5250

Introduction: Enriched Xenon Laboratory

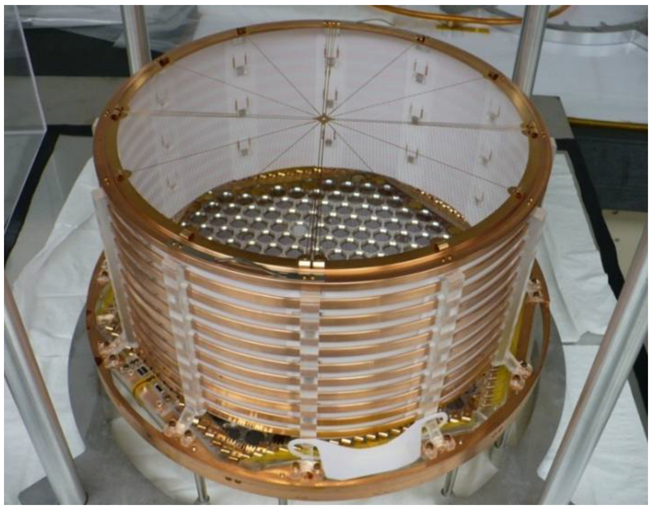
- A multistage program to search for neutrinoless double beta-decay of Xe-136
- Xenon is a good candidate for bb0n search
  - Can serve as both source and detector
  - Q-value larger than energy of gammas from most natural radionuclides
  - Relatively easy to enrich in Xe-136 isotope
  - No need to grow high-purity crystals, continuous purification is possible, more easily scalable
  - No long-lived cosmogenically activated isotopes
  - Final state (Ba-136 ion) can, in principle, be tagged, greatly reducing backgrounds

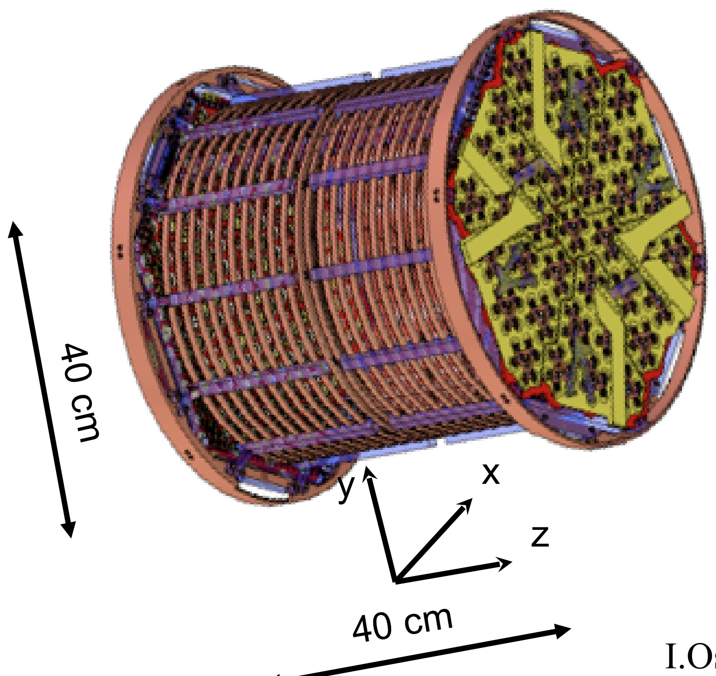


EXO-200

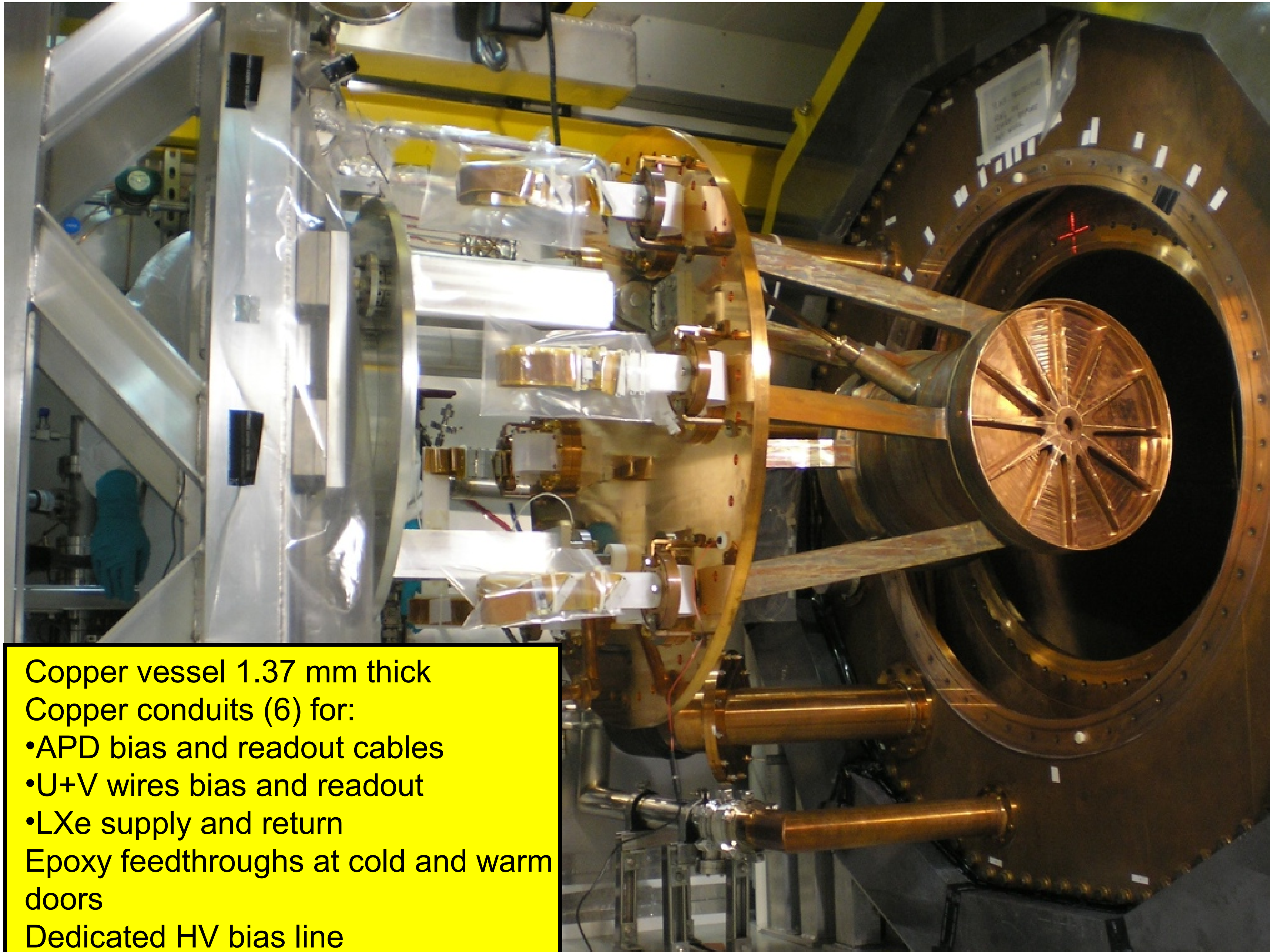
- First stage of the experiment
- 200 kg of Xe enriched to 80.6% Xe-136 total procured
  - 175 kg in liquid phase inside a cylindrical Time Projection Chamber
  - 98.5 kg current fiducial mass
- Located at 1585 m.w.e. in the Waste Isolation Plant near Carlsbad, NM
  - Muon rate reduced to the order of 10^{-7} Hz /cm^2 /sr
  - Salt has inherently lower levels of U/Th, compared to rock
- Carefully selected radioactively clean materials used in construction, rigorous cleaning procedures, the detector installation is inside class 1000 clean room
  - Goal of 40 counts/2yrs in 2-sigma 0nu energy window (assuming 140 kg LXe, 1.6% resolution)
  - M. Auger et al., JINST 7 (2012) P05010 and D.S. Leonard et al., NIM A 591 (2008) 490

EXO-200: TPC





- Common cathode + Two Anodes
  - 376 V/cm drift field
- Each half records both charge and scintillation information with
  - 38 U (charge collection) + 38 V (charge induction) triplet wire channels, crossed at 60 degrees
    - Wire pitch 3 mm (9 mm / channel)
    - Photo-etched Phosphor bronze
  - 234 large area avalanche photo-diodes, in groups of 7 (178 nm Xe light)
    - Copper support plane with Au (Al) plating for contact (reflection)
- Teflon reflectors
- Copper field shaping rings
- Acrylic supports
- Flexible bias/readout cables: copper on kapton, no glue

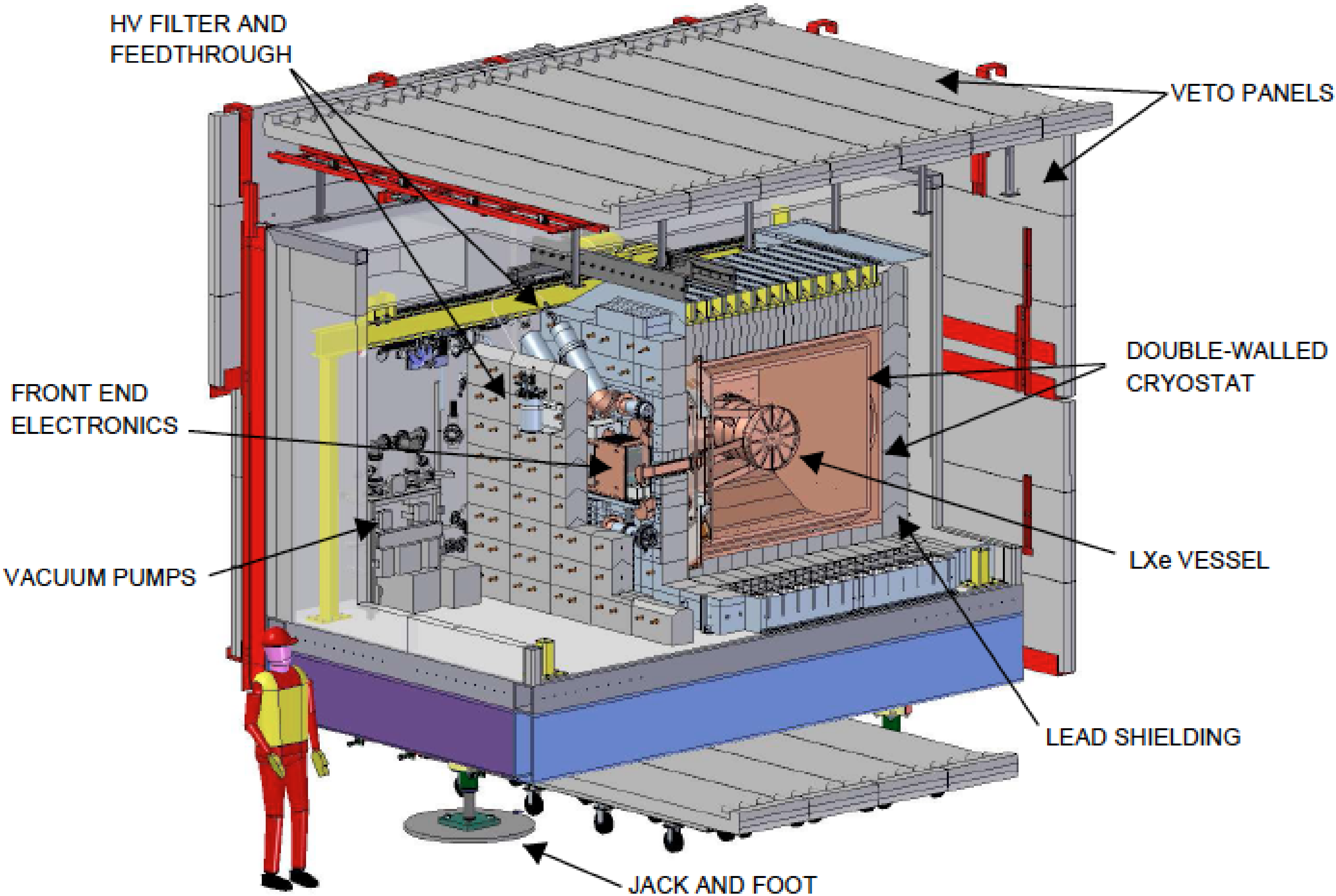


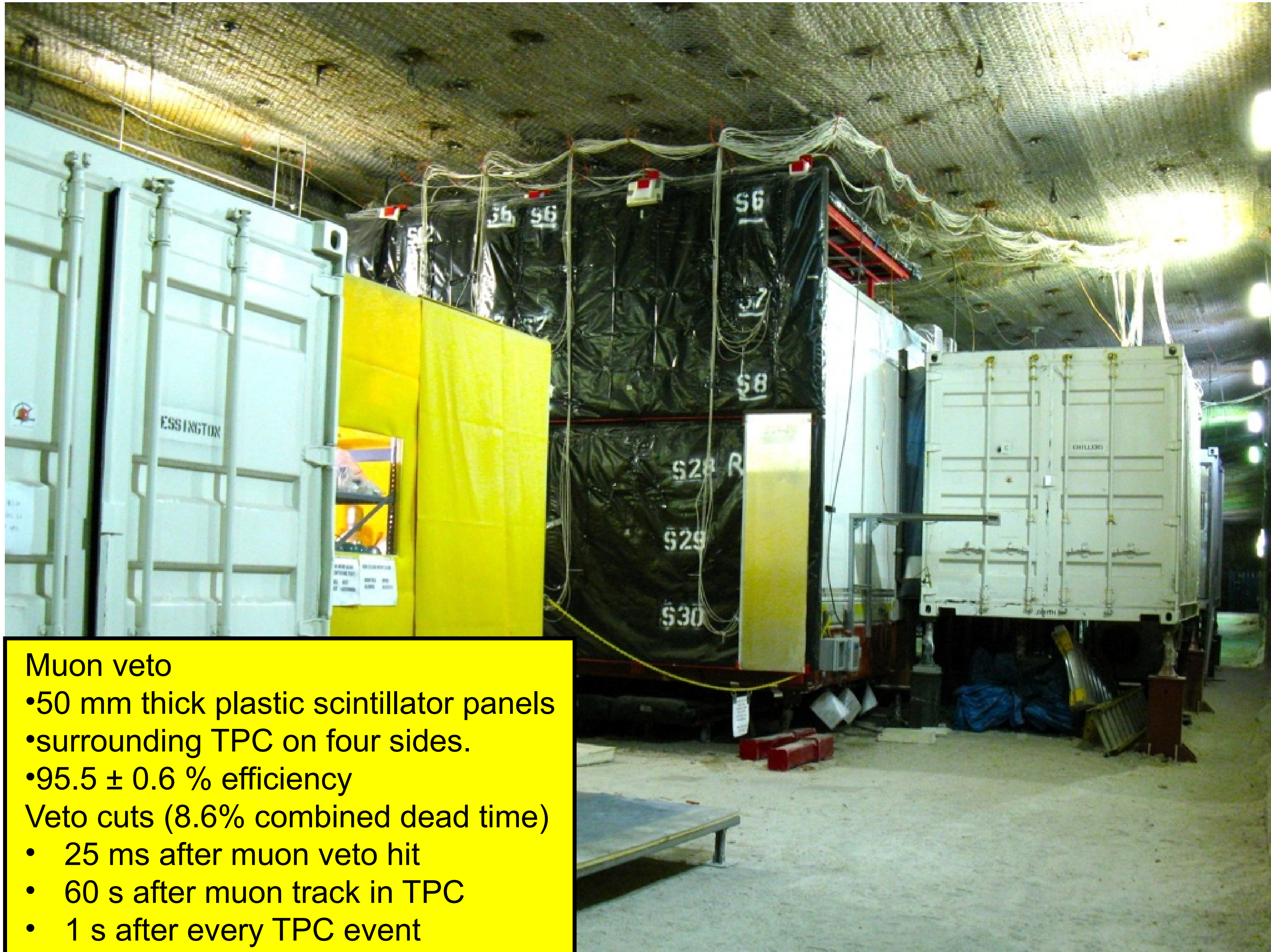
Copper vessel 1.37 mm thick
Copper conduits (6) for:

- APD bias and readout cables
- U+V wires bias and readout
- LXe supply and return

Epoxy feedthroughs at cold and warm doors
Dedicated HV bias line

EXO-200: Detector



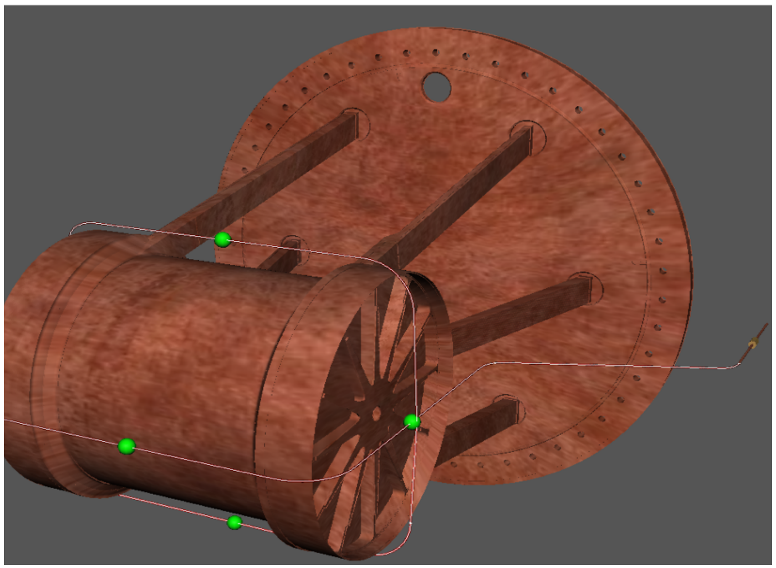


Muon veto
•50 mm thick plastic scintillator panels
•surrounding TPC on four sides.
•95.5 ± 0.6 % efficiency

Veto cuts (8.6% combined dead time)

- 25 ms after muon veto hit
- 60 s after muon track in TPC
- 1 s after every TPC event

EXO-200: Calibration system

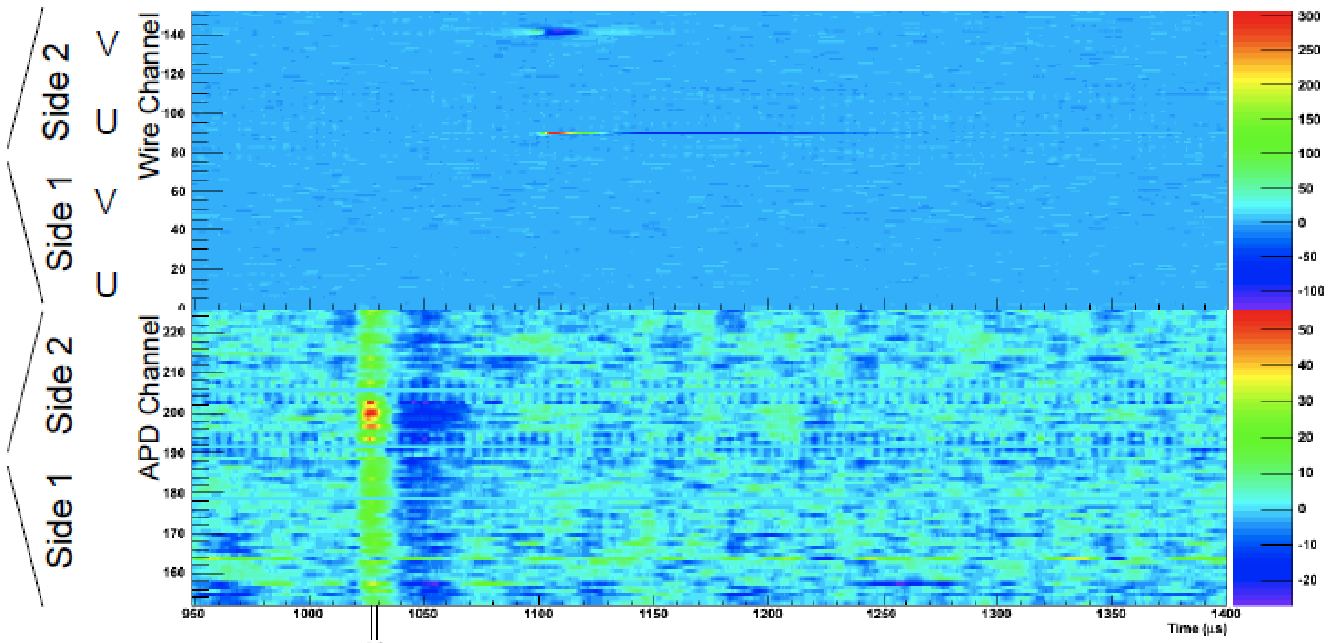


- A guide-tube to allow insertion of miniature radioactive calibration sources
- Several positions in cathode and anode planes and several sources to map out the detector response
  - Th-228
  - Co-60
  - Cs-137
- Frequent calibrations with most important Th-228 (2.6 MeV peak close to end-point energy) for purity, stability of energy scale, other corrections

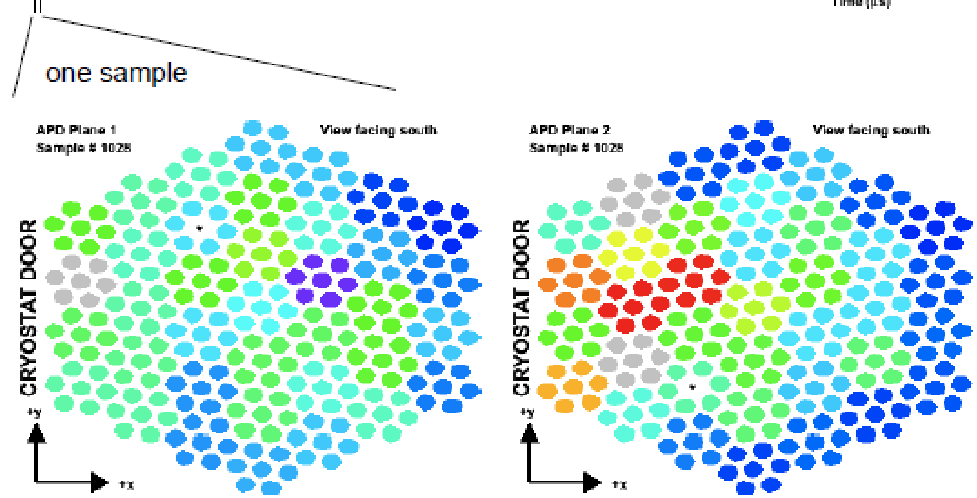
EXO-200: Data

Charge readout
V: Induction
U: Collection

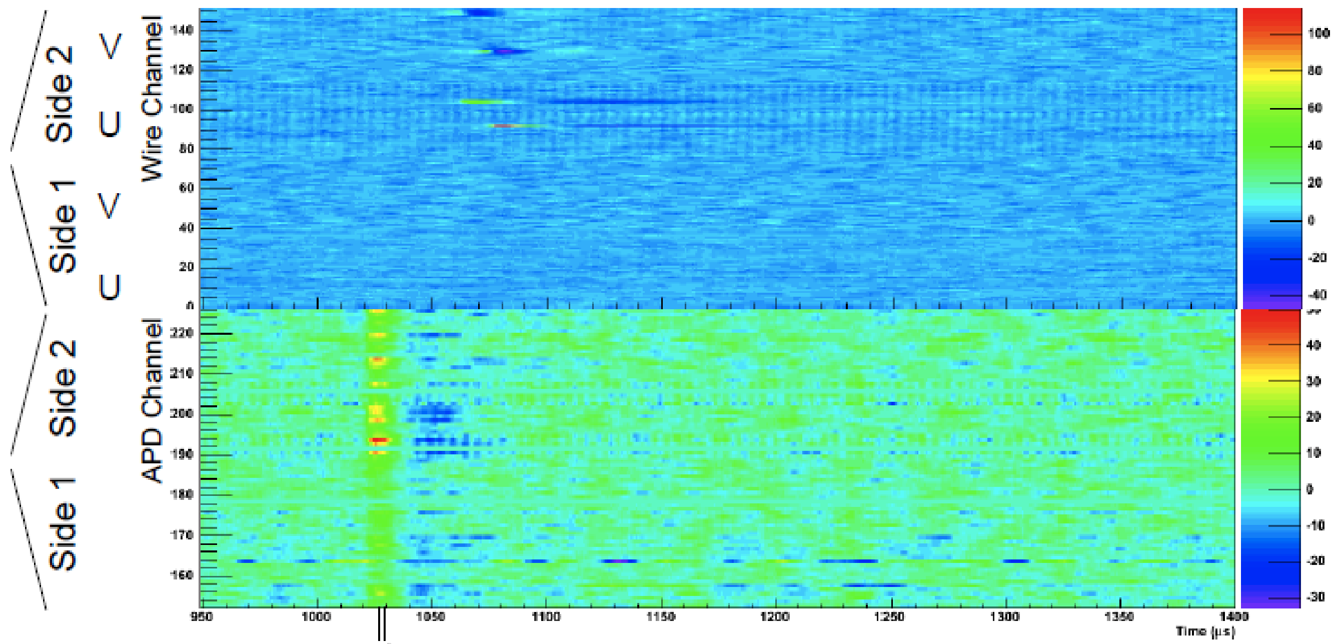
Light readout



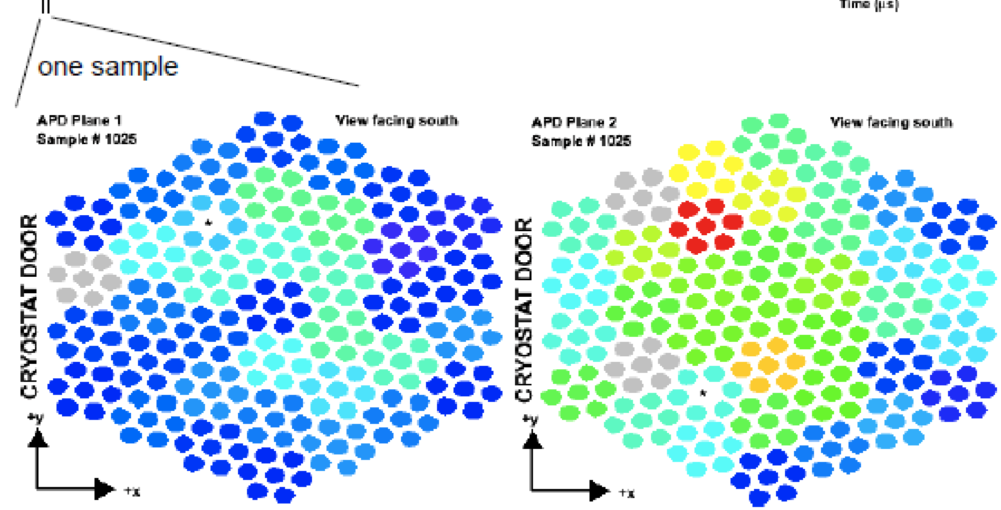
A single-site energy deposition in EXO-200



EXO-200: Data



A two-site Compton scattering event



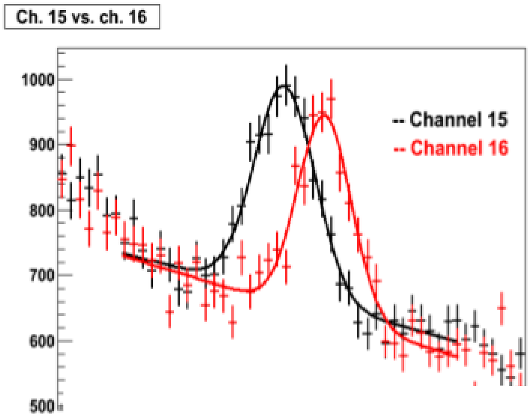
EXO-200: Milestones

- Late 2010
  - Engineering run with natural Xe
- May 2011 – July 2011 Run 1 “two-neutrino Run”
  - First run with enriched Xe
  - First successful measurement of two-neutrino double beta decay in Xe-136
  - 5.4 kg*yr exposure (4.4 kg Xe-136)
  - N. Ackerman et al., Phys. Rev. Lett. 107 (2011) 212501
- August 2011 – September 2011
  - Installation of final lead shielding
  - Electronics and other upgrades
- October 2011 – March 2012 “Run 2”
  - 32.6 kg*yr exposure (26.3 kg Xe-136)

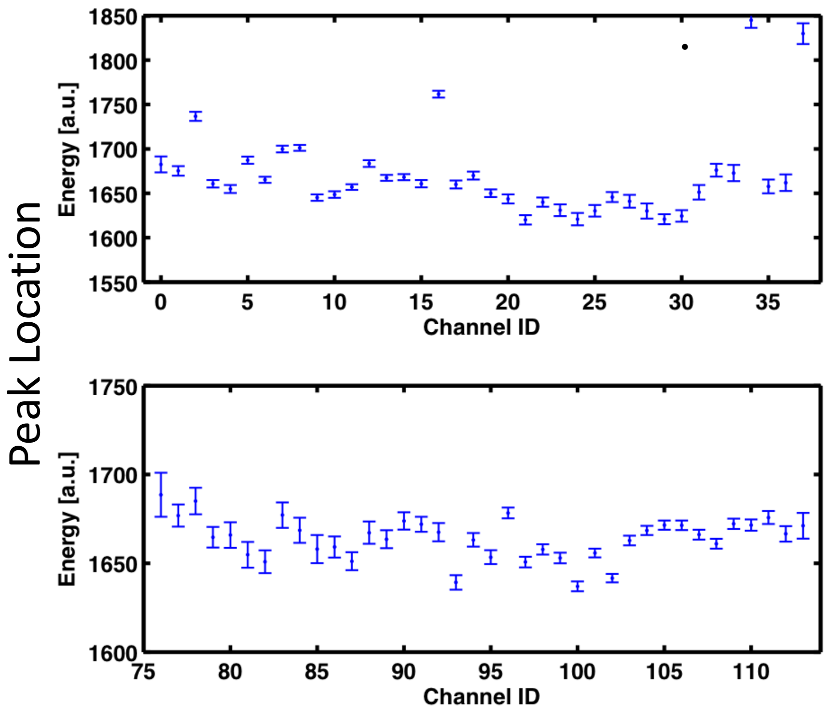
EXO-200: Event Reconstruction

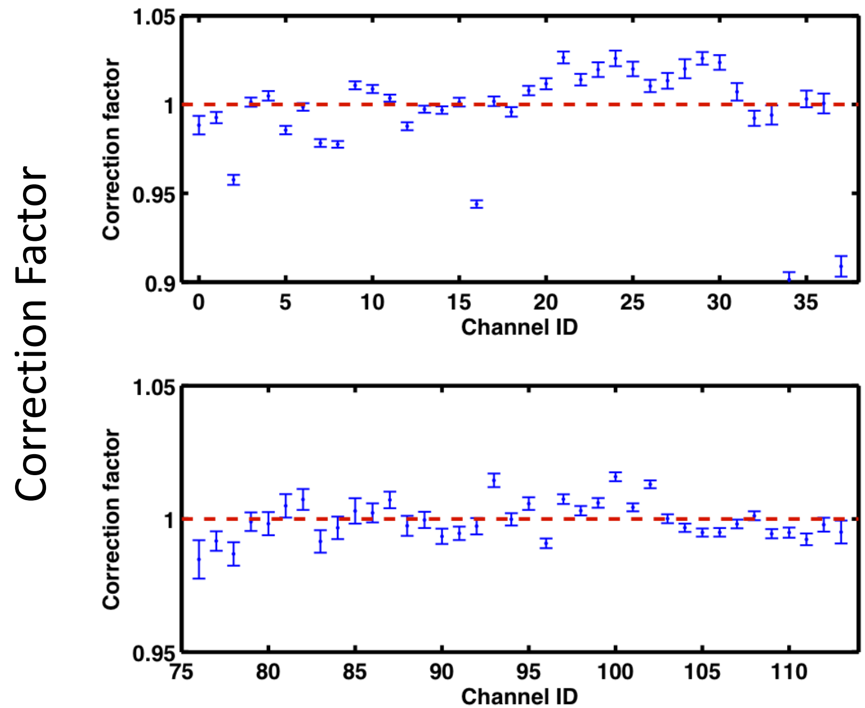
- Identify signals on individual U, V wires, summed APDs signals using matched filters
- Fit by waveform templates to determine time, amplitude in both charge and light channels
- Apply channel dependent correction for wire gain
- Combine U and V signals in one or more charge clusters (single- vs. multi-site events) based on time and U position, associate with nearest preceding scintillation signal
  - U and V coordinate, together with time since scintillation pulse, provide 3D coordinate of an event
  - Can distinguish clusters ~6 mm in z dimension, ~18 mm in u dimension
- Apply position dependent corrections
  - for light collection and APD gain inhomogeneity
  - for charge loss due to finite xenon purity
  - shielding grid inefficiency

EXO-200: wire gains

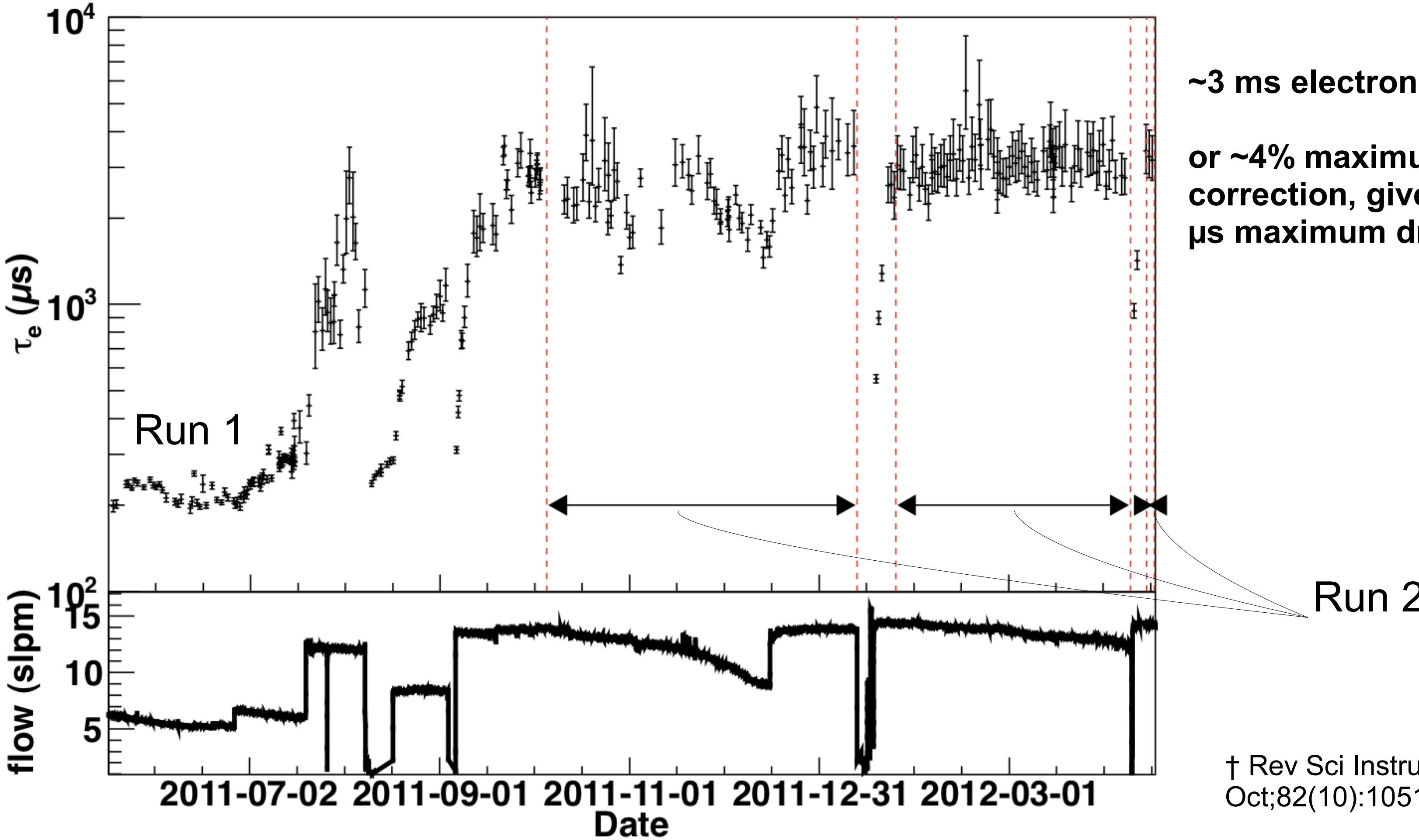


- Use 1593 keV pair production events from Th-228 to measure collection wire transfer functions and gains for each channel
- Improves resolution in the charge channel to 3.4%, from 4.5% (@2.6 MeV)





EXO-200: Xenon purity



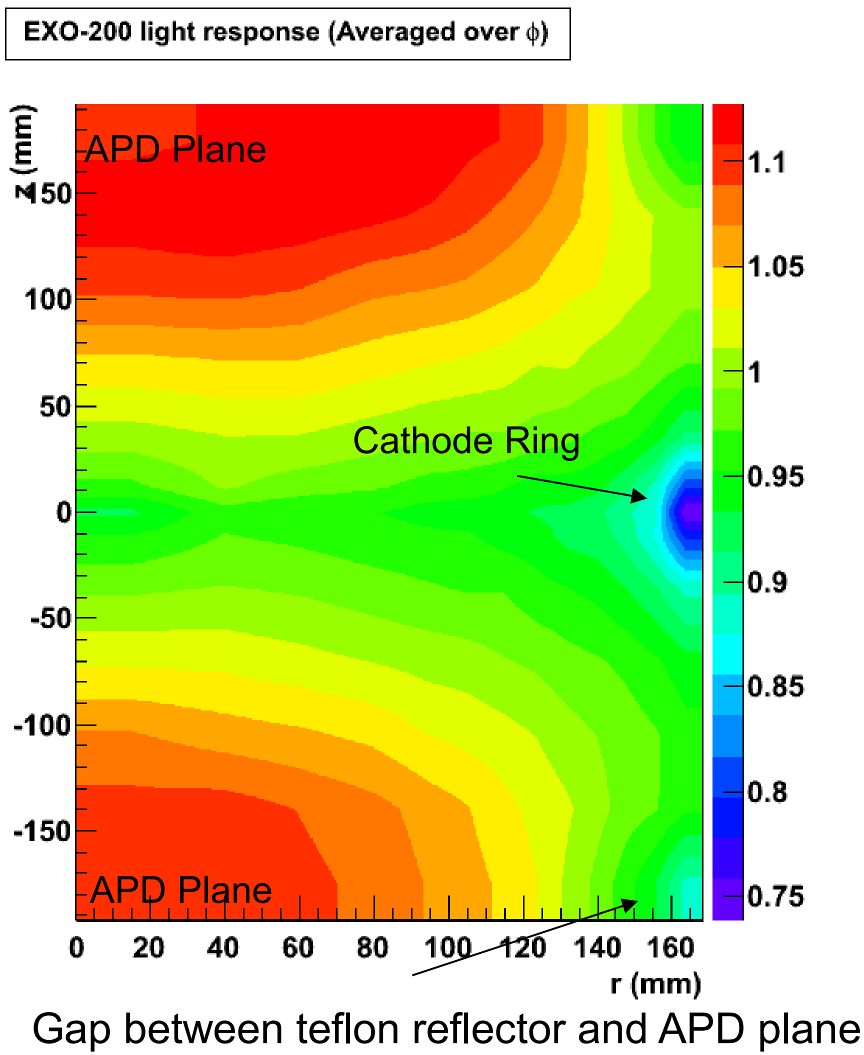
~3 ms electron lifetime

or ~4% maximum correction, given ~110 μs maximum drift time

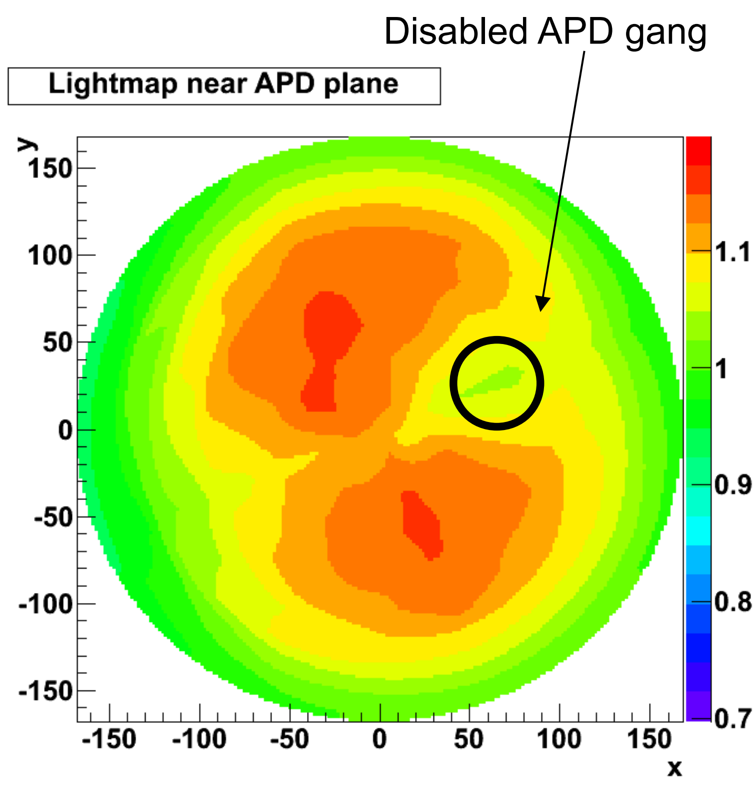
† Rev Sci Instrum. 2011 Oct;82(10):105114

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

EXO-200: light correction

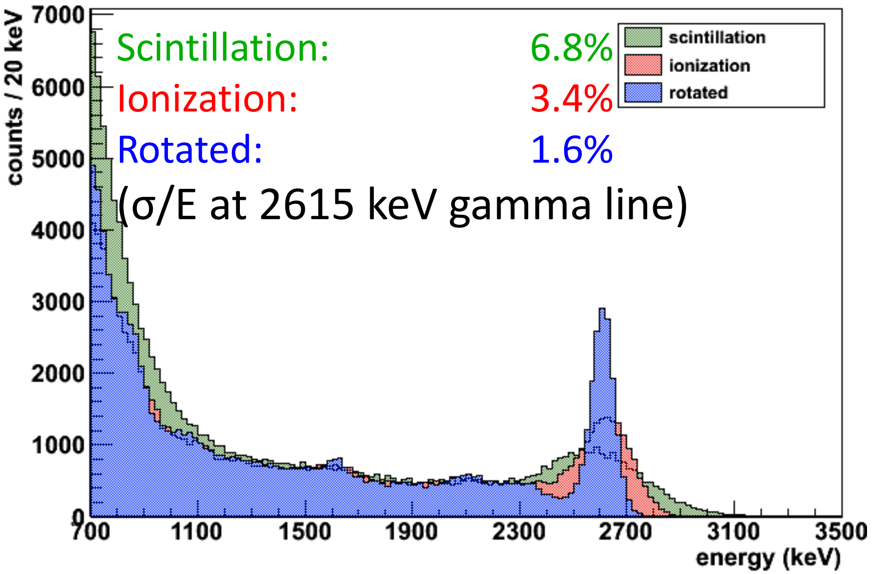


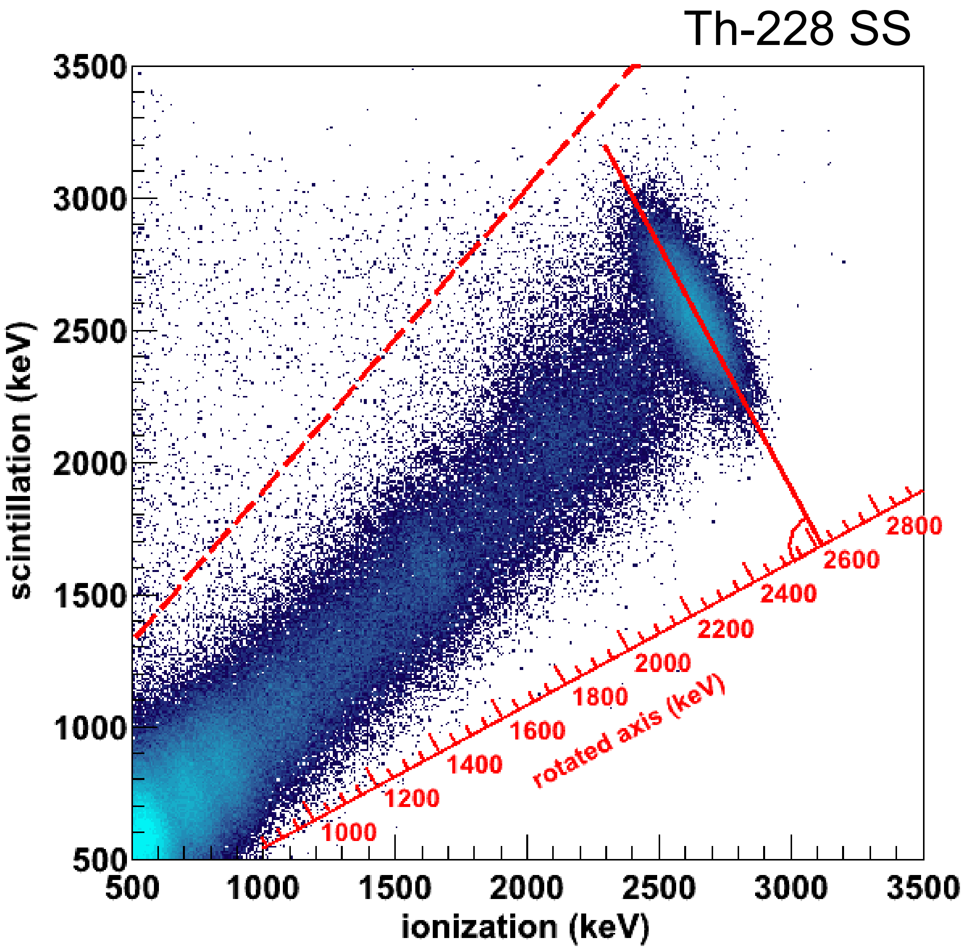
- Use full absorption peak of 2615 keV gamma from Th-228 to map light response in TPC
- Linearly interpolate between 1352 voxels



EXO-200: Anti-correlation

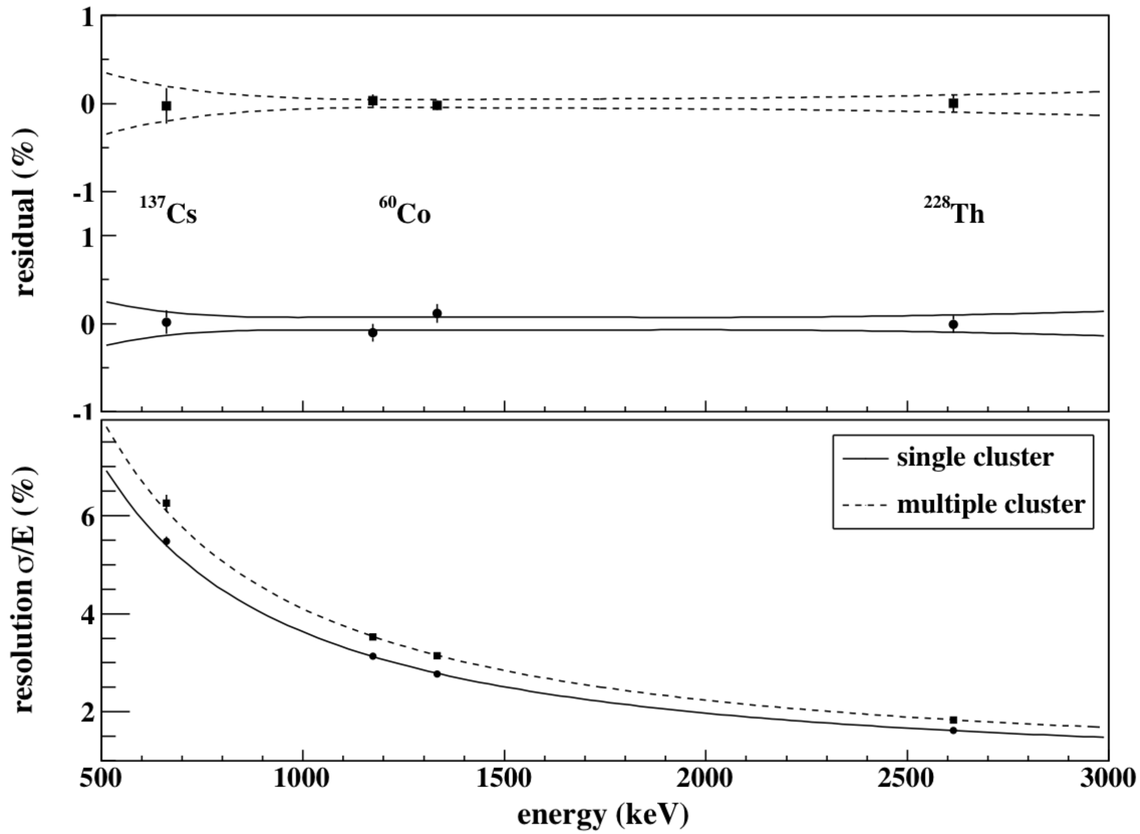
- Good energy resolution is essential for successful 0nu search
- It is known that charge and light production in liquid Xe are anti-correlated
  - E. Conti et al. Phys.Rev.B 68 (2003) 054201





- **Use the combination of charge, light channels that optimizes resolution as an energy estimator**

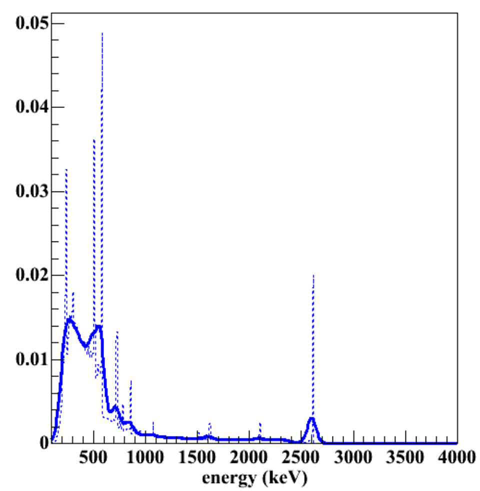
EXO-200: Energy/resolution calibration

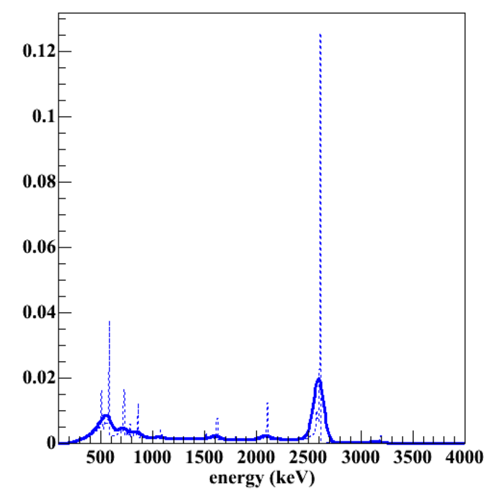


- Energy calibration residuals are less than 0.1% with quadratic calibration
- Energy resolution in the rotated space is 1.67% (1.84%) for single (multi) site events

EXO-200: Generating prediction for signal/backgrounds

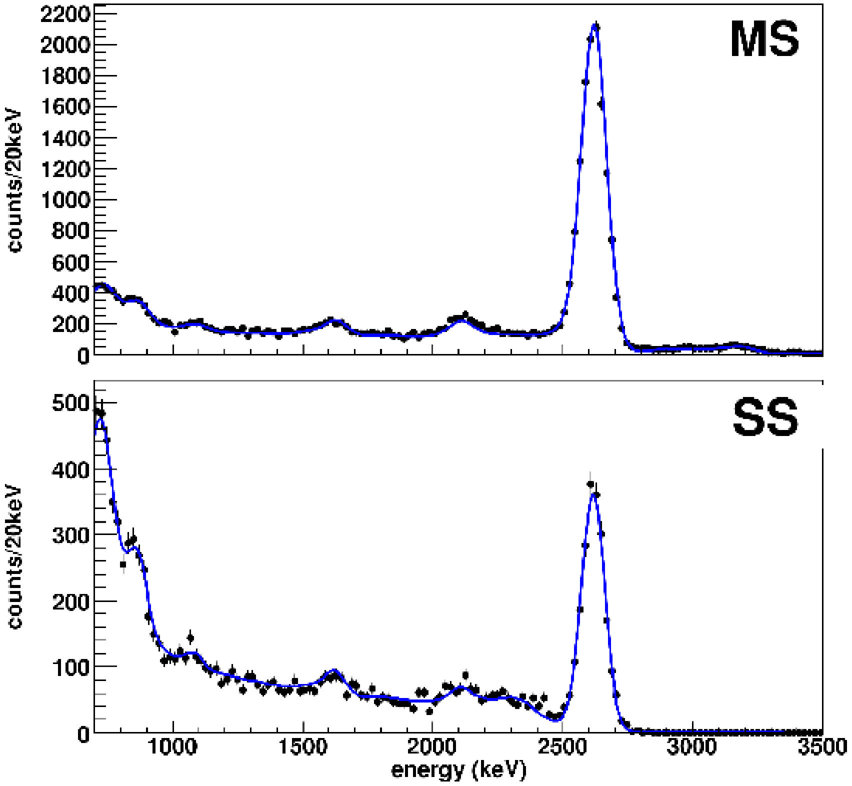
- We will fit the data by probability density functions (PDFs) describing shape of the signal and various expected background components
- We employ a combination of MC and data driven approaches
  - Use Geant4 to simulate true energy depositions given source/position
  - Pass through digitization / reconstruction algorithms to perform single- vs. multi-site assignment
  - Perform a Gaussian convolution of the true MC energy with energy-dependent resolution function, measured from the data





EXO-200: Source agreement

- To validate our ability to accurately describe data using PDFs, we use calibration sources to quantify
  - Shape agreement
    - Deemed compatible by χ^2, KS tests
  - Rate agreement
    - 9.4% maximum deviation from measured source activities (used as systematic)
  - Single-site fraction agreement
    - 8.5% maximum deviation with source data (used as systematic)



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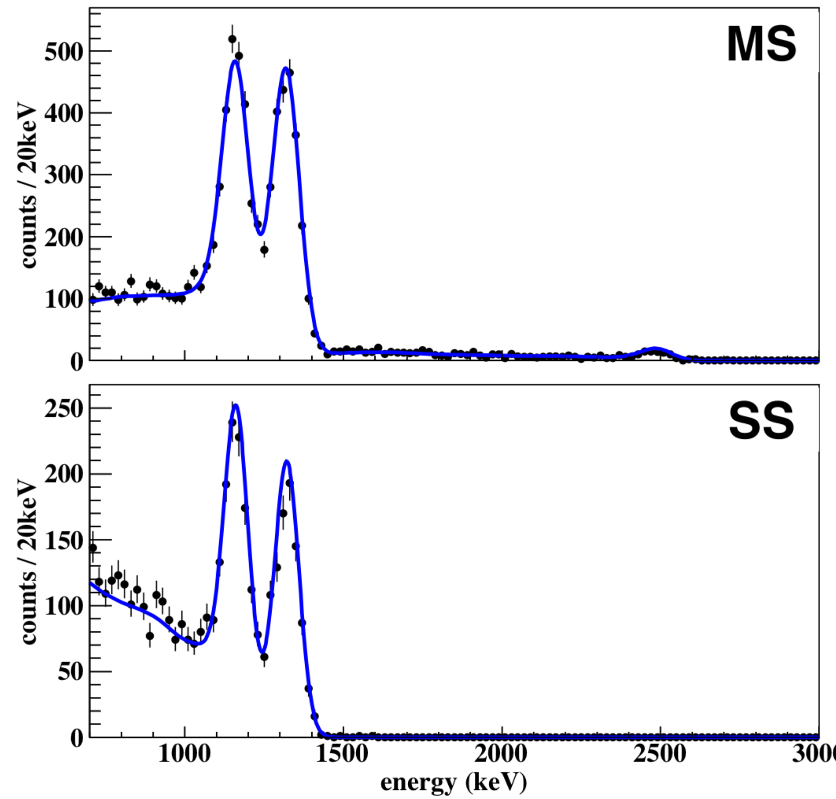
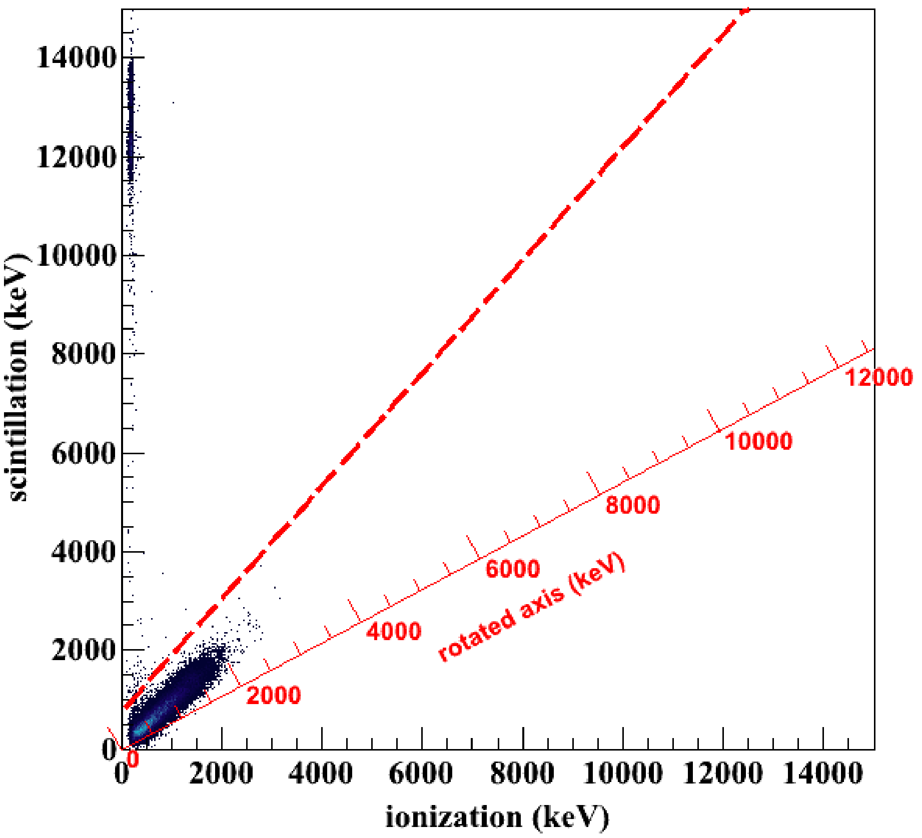


EXO-200: Final data analysis cuts

- Veto cuts (8.6% total dead-time)
  - 60 s after muon track in TPC to avoid muon-induced activity
  - 25 ms after muon veto hit (possible shoulder-clippers)
  - 1 s after every TPC events to exclude coincidences, e.g. Bi-Po
- “Diagonal” cut to remove events with large light/charge ratio (alphas and events with imperfect charge collection)
- Keep events with all 3 coordinates reconstructed
- 700 keV low energy cut (trigger fully efficient)
- Fiducial cut
  - 5 mm from cathode, 10 mm from anodes, 2 cm standoff from Teflon reflector
- 71% total efficiency for 0nu
  - Estimated by MC and verified by comparing 2nu to the data over broad range of energies



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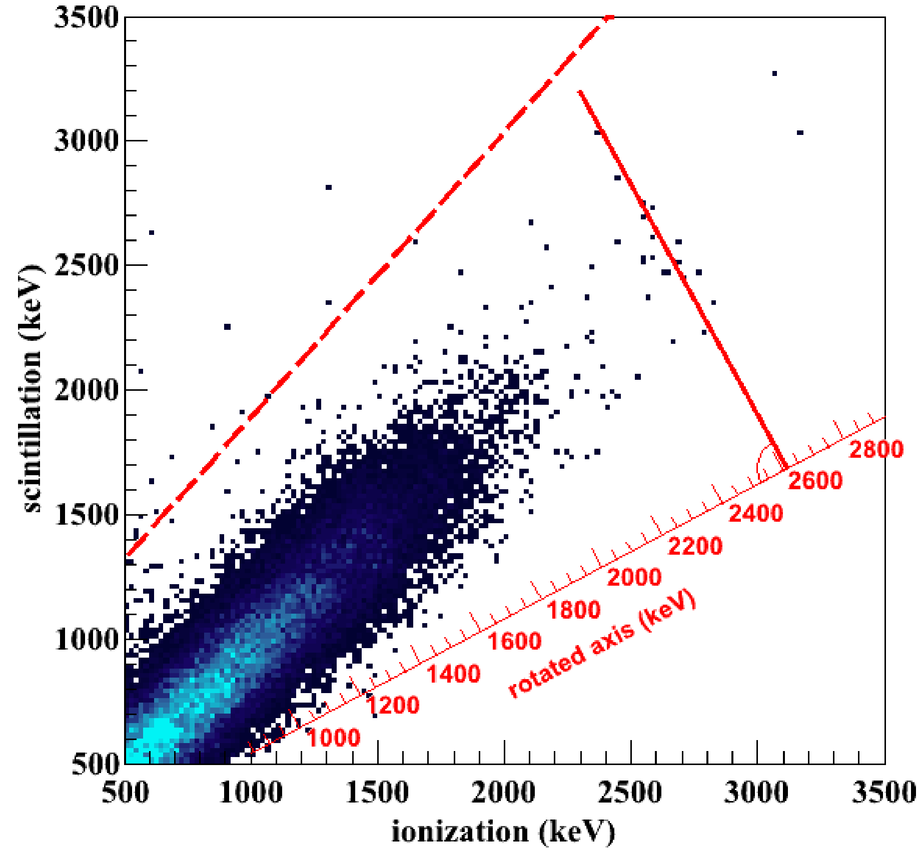
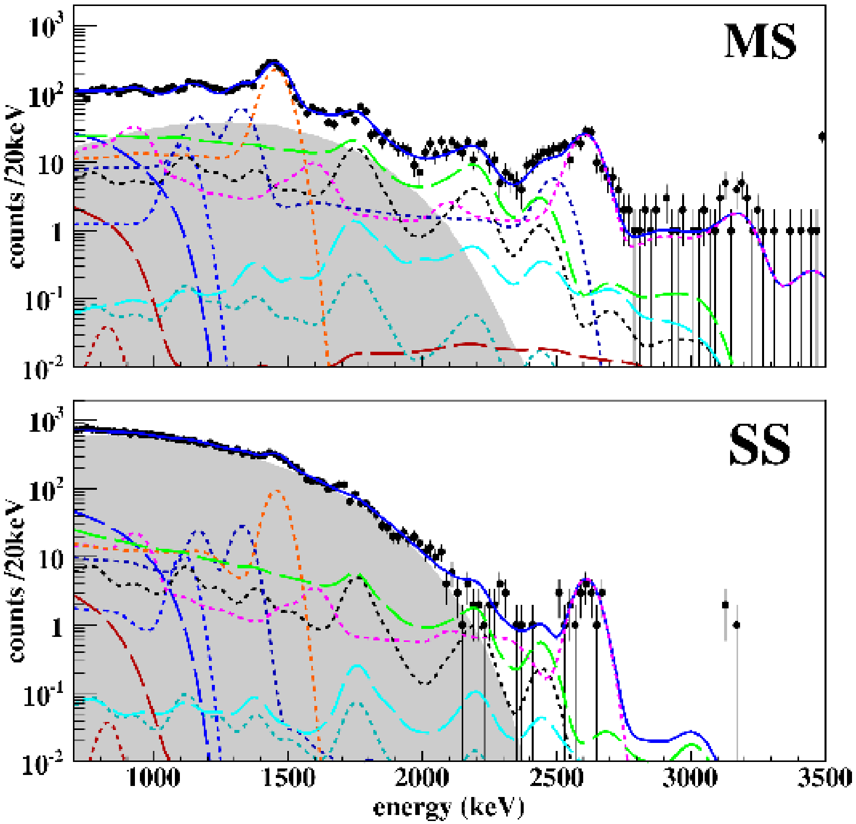
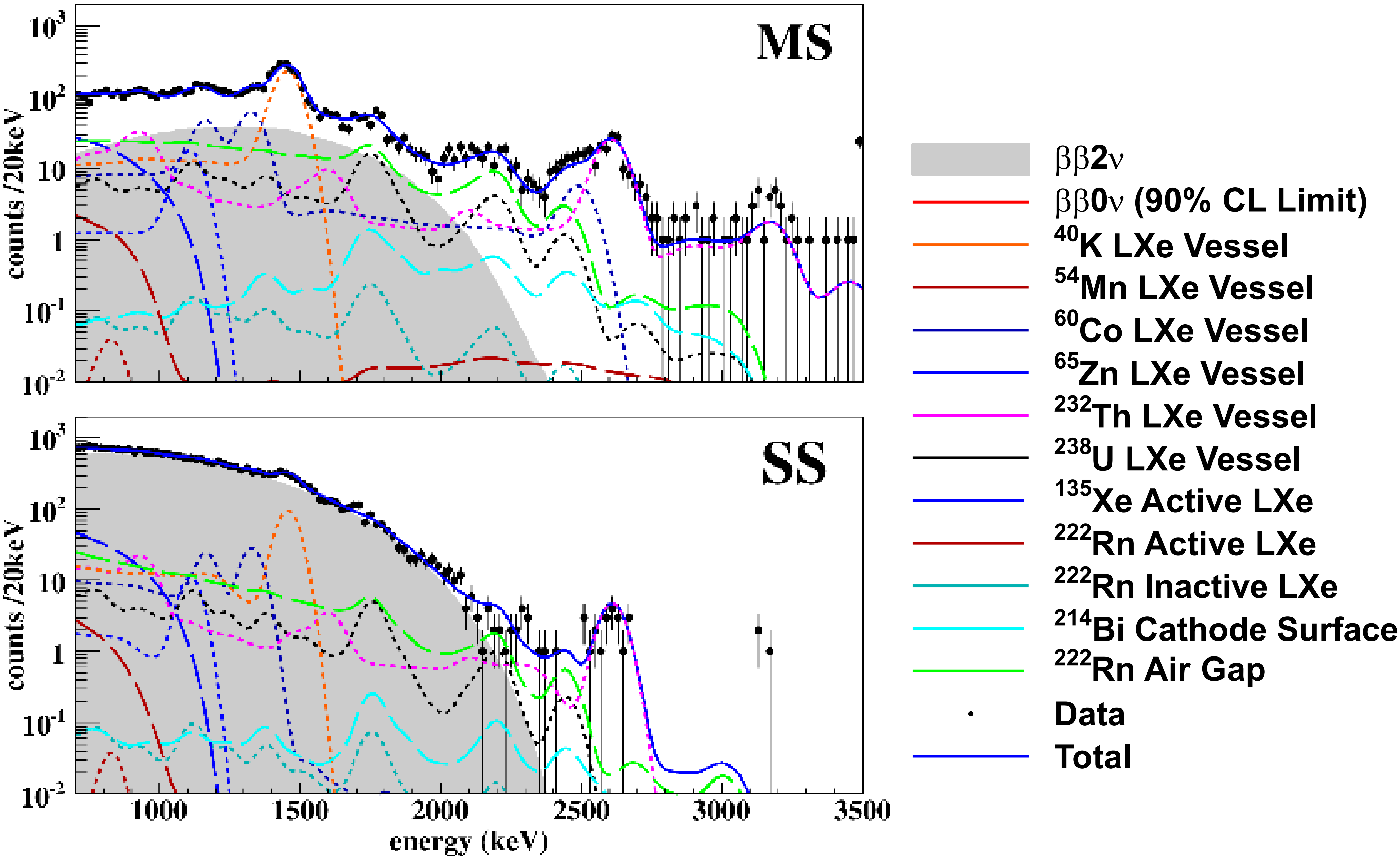


EXO-200: 0nu analysis final fit



- Binned maximum likelihood fit to 0nu, 2nu, and various backgrounds PDFs
- Simultaneous fit to SS and MS spectra
  - SS fractions float with 8.5% constraint
- Rn in LXe and in air gap between cryostat/led wall float with constraints by dedicated studies
- Calibration offset/resolution parameters float, constrained by corresponding error/matrix
- Slightly different energy scales for betas/gammas used, as preferred by dedicated profile likelihood tests

  - Live-time: **120.7 days**
  - Active mass: **98.5 kg** (79.4 Xe-136)
  - Exposure: **32.5 kg*yr**

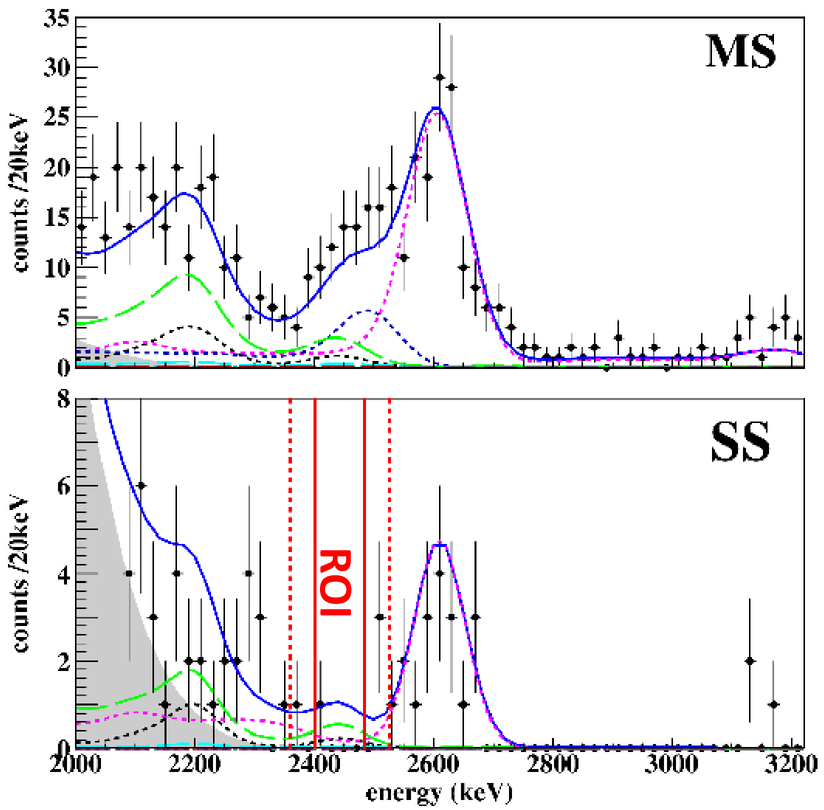


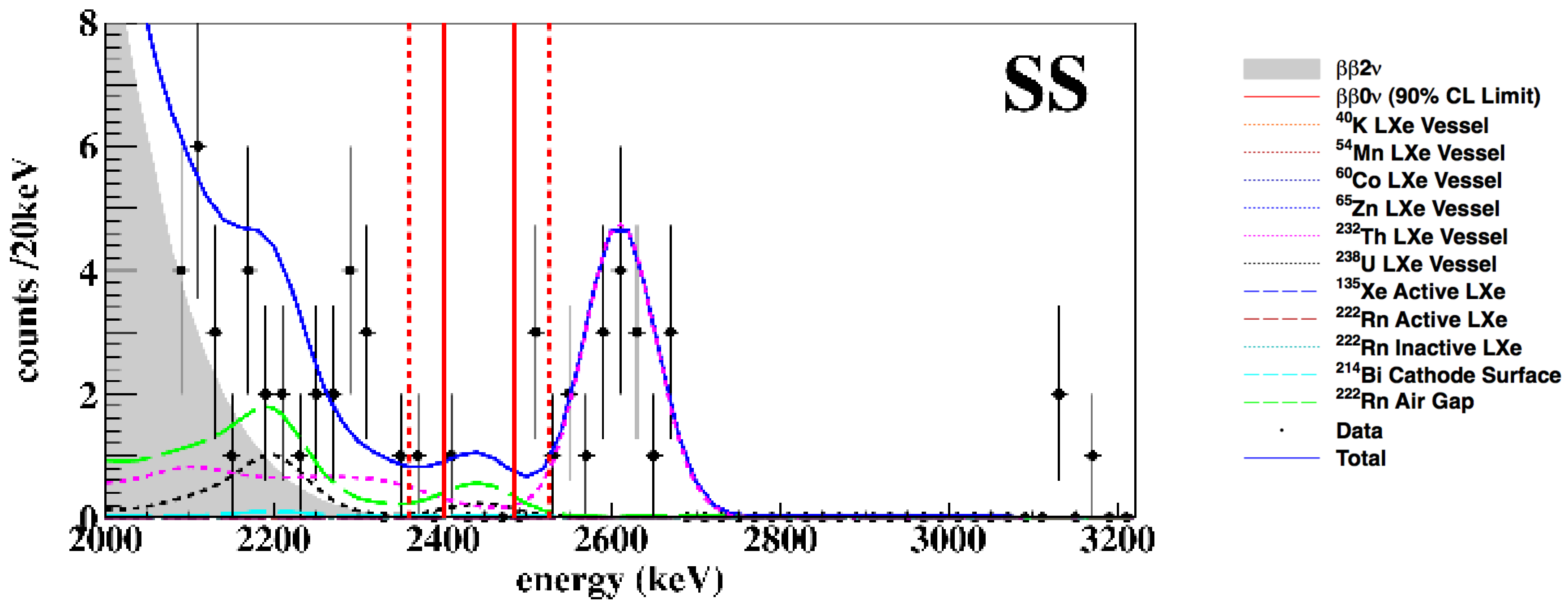
$T_{1/2}$ $2\nu\beta\beta$ (136Xe) = (2.23 ± 0.017 stat ± 0.22 sys)$\cdot 10^{21}$ yr

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

EXO-200: Region of interest

- No signal found
- Background from the fit in 1 sigma ROI:
  - **$1.5 \cdot 10^{-3} \pm 0.1$ /kg /yr /keV**
- Upper limit with profile likelihood method
  - **$T_{1/2}$ $0\nu\beta\beta > 1.6 \cdot 10^{25}$ yr @90% C.L**
  - **$\langle m_{\beta\beta} \rangle$ < 140-380 meV**





Best-fit background estimates
in 1 sigma ROI:

222Rn in cryostat air-gap	1.9	±0.2
238U in LXe Vessel	0.9	±0.2
232Th in LXe Vessel	0.9	±0.1
214Bi on Cathode	0.2	±0.01
All Others	~0.2	
Total	4.1	±0.3

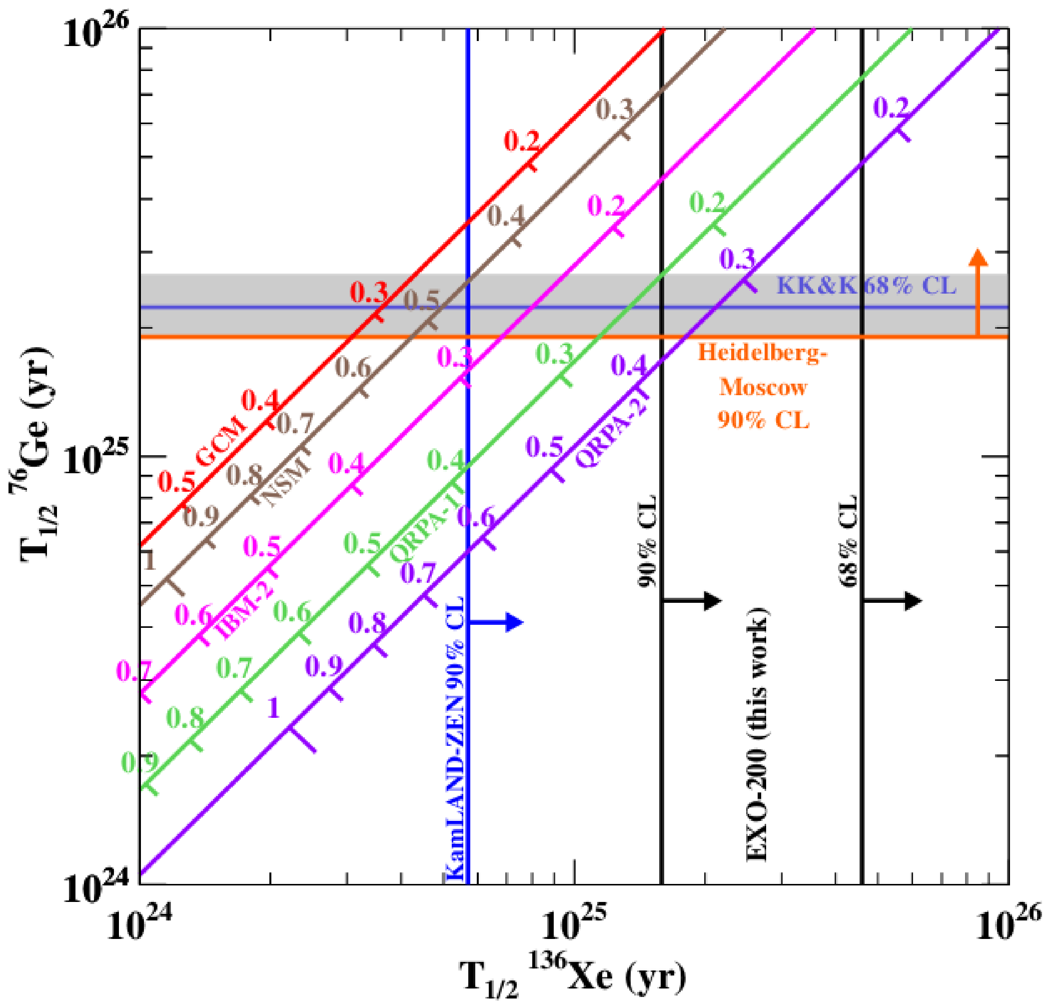
Observed:

1 count in 1 sigma ROI
(0.0015 /kg /yr /keV)

5 counts in 2 sigma ROI
(0.0014 /kg /yr /keV)

consistent

Design goal: 40 /2yrs /140kg /2sigma,
Or ~4.6 counts for this dataset



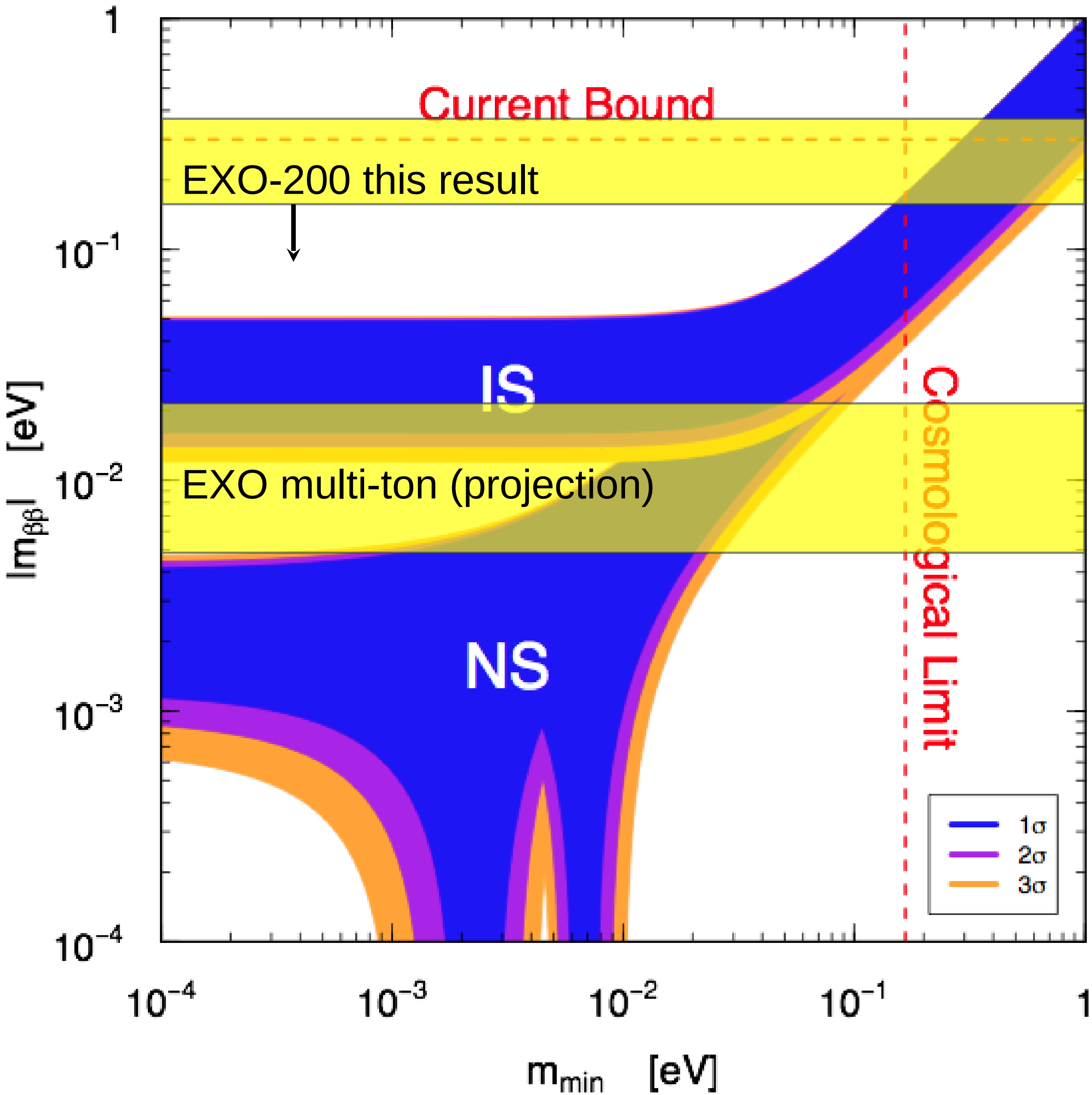
90% C.L. limit compared with Recent Xe-136 constraints (KamLAND-ZEN) >2.5 factor improvement.

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

What's next?

- Basically, doubled the dataset
- Will continue to run with EXO-200 for few more years
- Further improvements in the works
    - New radon purge in the air gap between lead shield and cryostat
    - Possible further improvements to resolution, reconstruction efficiency
    - Incorporate position-dependency in PDFs – additional handle on backgrounds

- R&D for the next generation of EXO (nEXO) has started
    - A multi-ton TPC
    - Initially, without Ba-tagging



I.Ostrovskiy, UC Davis, January 2013

The EXO Collaboration

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Drexel University, Philadelphia PA, USA - M.J. Dolinski

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IHEP Beijing, People's Republic of China - G. Cao, X. Jiang, L. Wen, Y. Zhao

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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

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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, M. Lodato, C. Mackeen, K. Malone, A. Pocar, J.D. Wright

University of Seoul, South Korea - D. Leonard

SLAC National Accelerator Laboratory, Menlo Park CA, USA - M. Breidenbach, R. Conley, K. Fouts, R. Herbst, S. Herrin, J. Hodgson, A. Johnson, R. MacLellan, 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, J. Bonatt, T. Brunner, J. Chaves, J. Davis, R. DeVoe, D. Fudenberg, G. Gratta, S.Kravitz, M. Montero-Díez, D. Moore, 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

Comparison with KamLAND-ZEN latest result (arXiv:1211.3863)

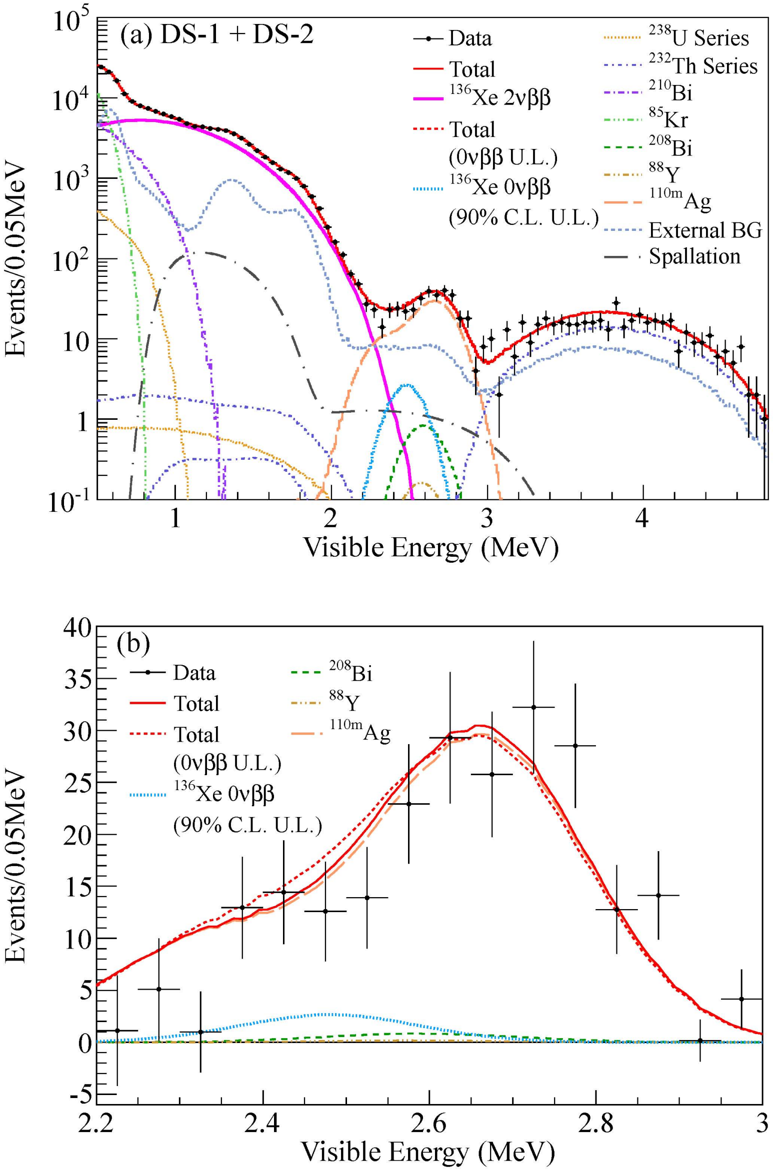
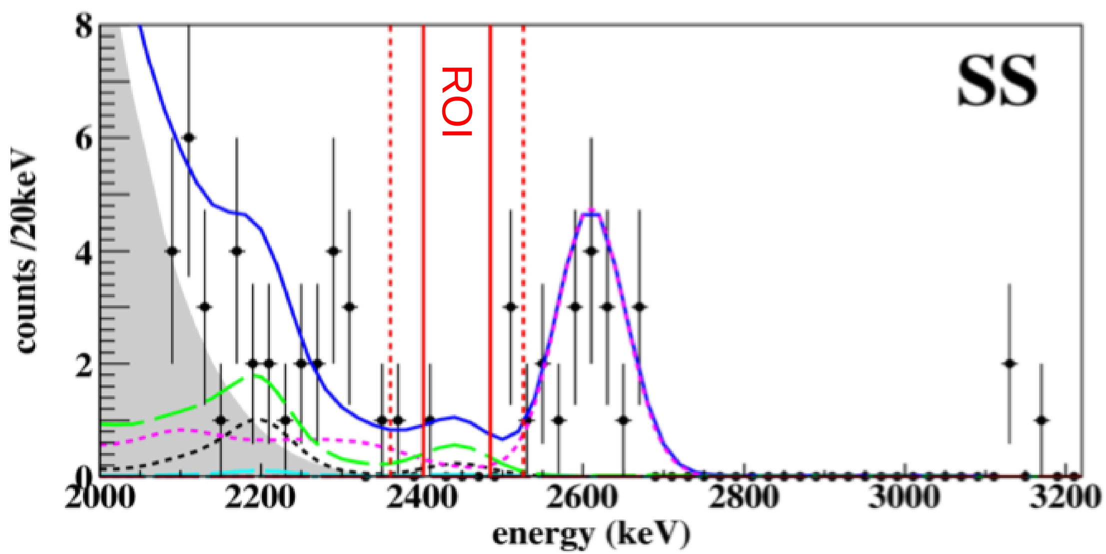


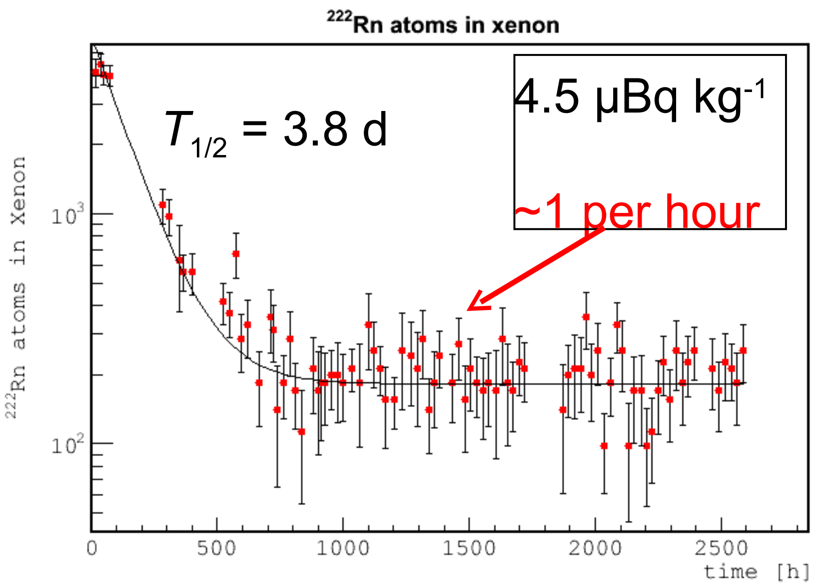
FIG. 1: (a ... nts together
with the b ... e 90% C.L.
upper lim ... m DS-1 and
DS-2; the ... up of (a) for
$2.2 < E$ ... nd contribu-
tions.

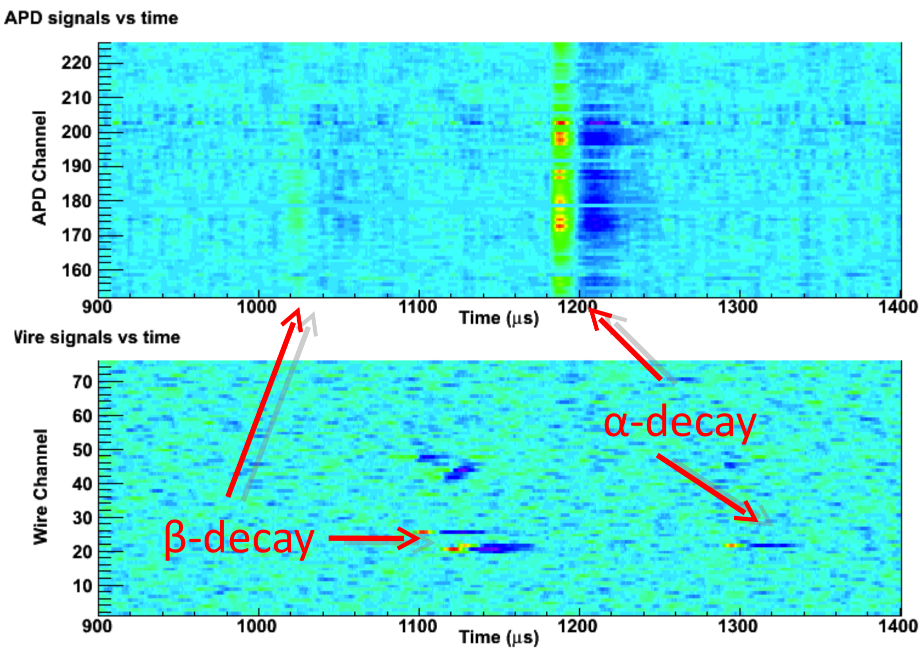
KamLAND-ZEN spectrum



EXO-200 spectrum
(PRL 109 (2012) 032505)

Rn in liquid Xe



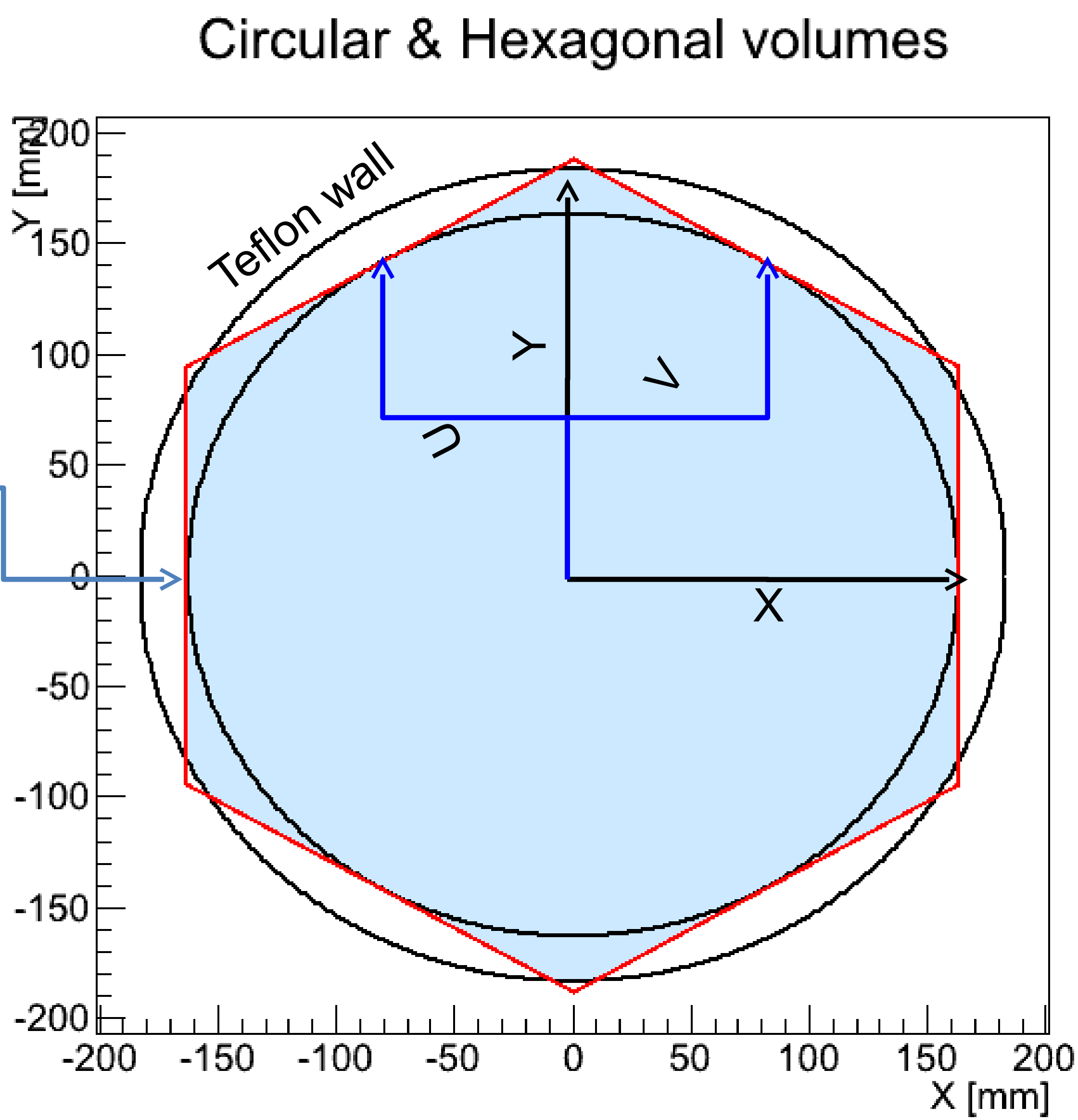


Bi-214 – Po-214 coincidence in EXO-200

Bi-214 rate is consistent with a steady state source of radon in the system (no radon trap installed)

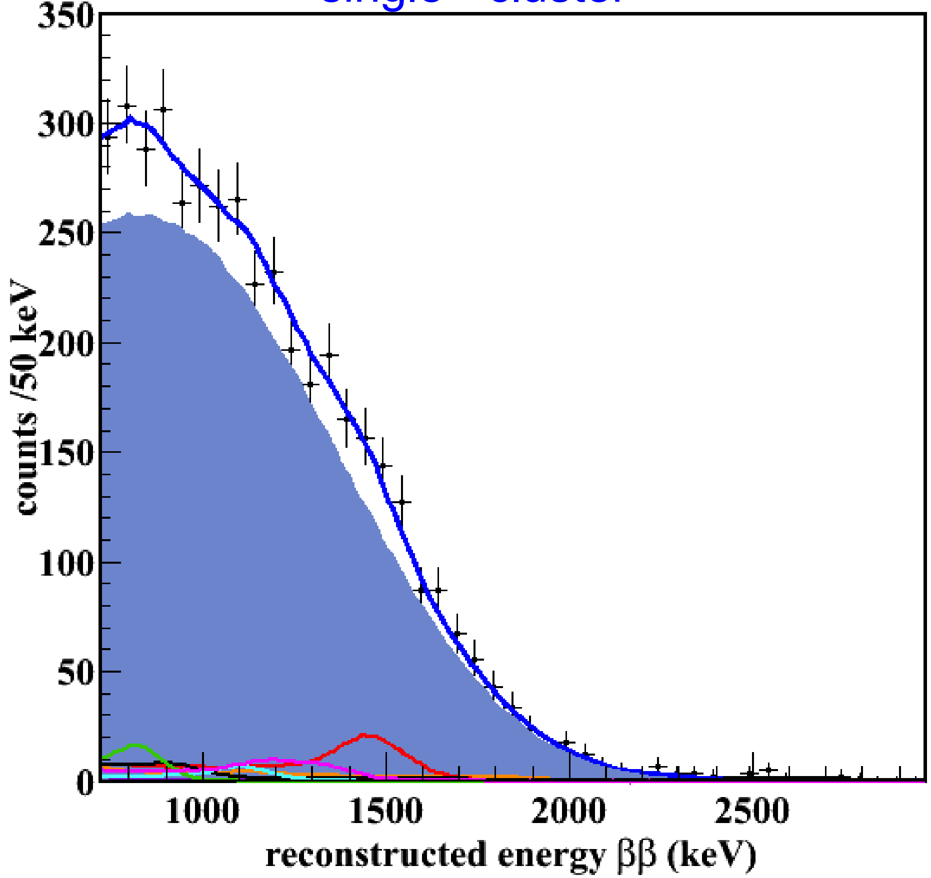
360 ± 65 μBq/kg in fiducial volume

Standoff distance measured from Teflon wall to hexagon

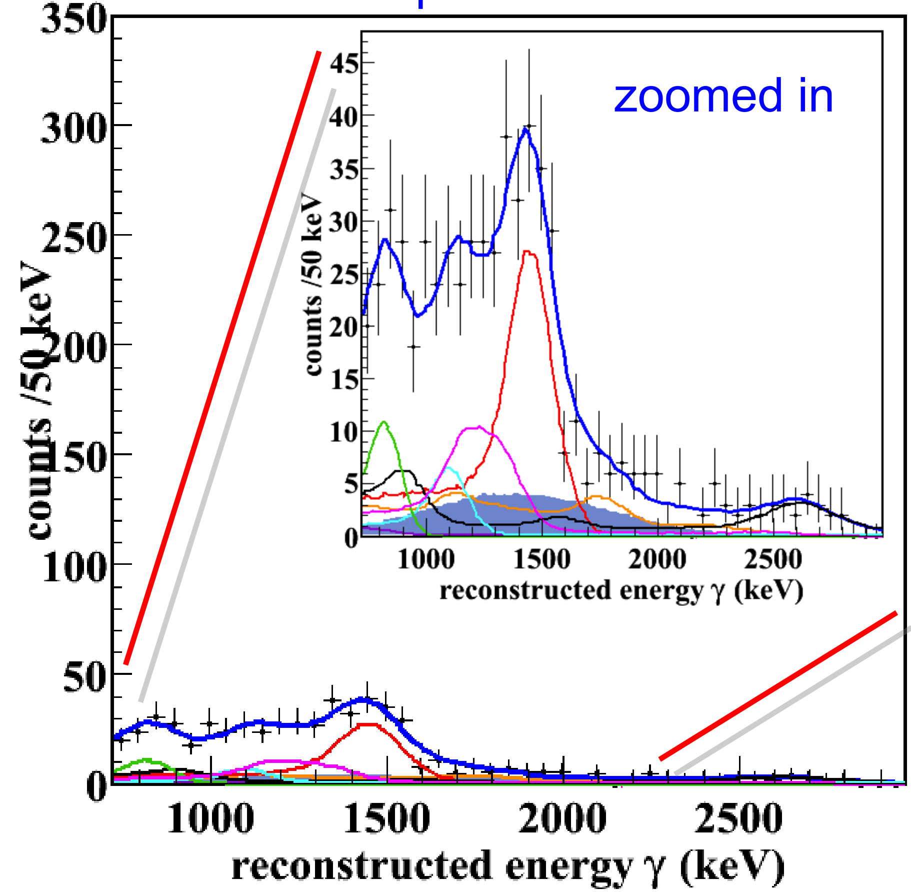


Run 1 result

single - cluster



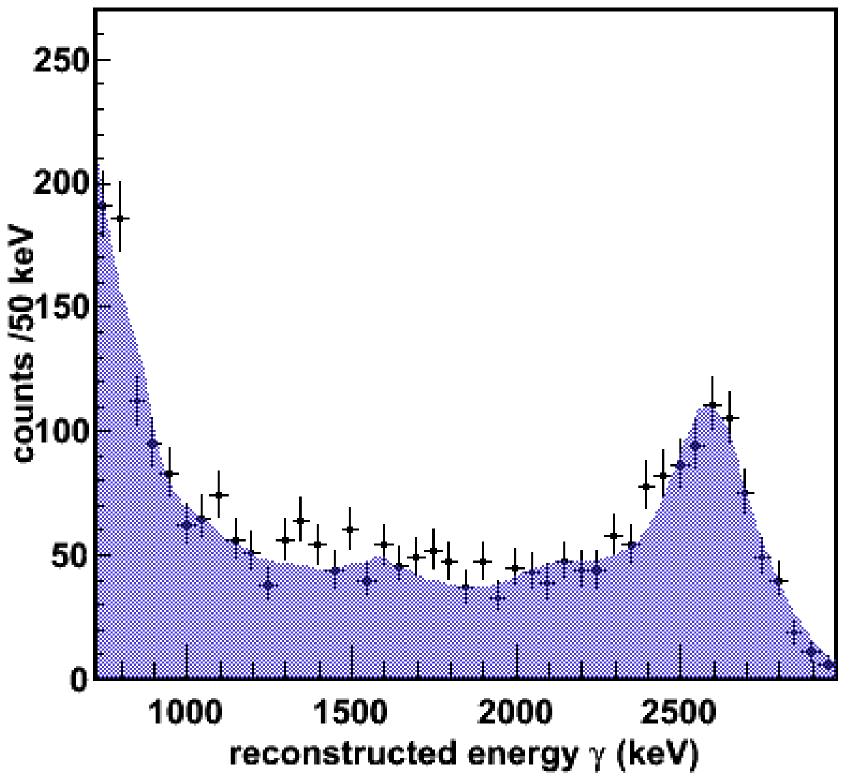
multiple- cluster

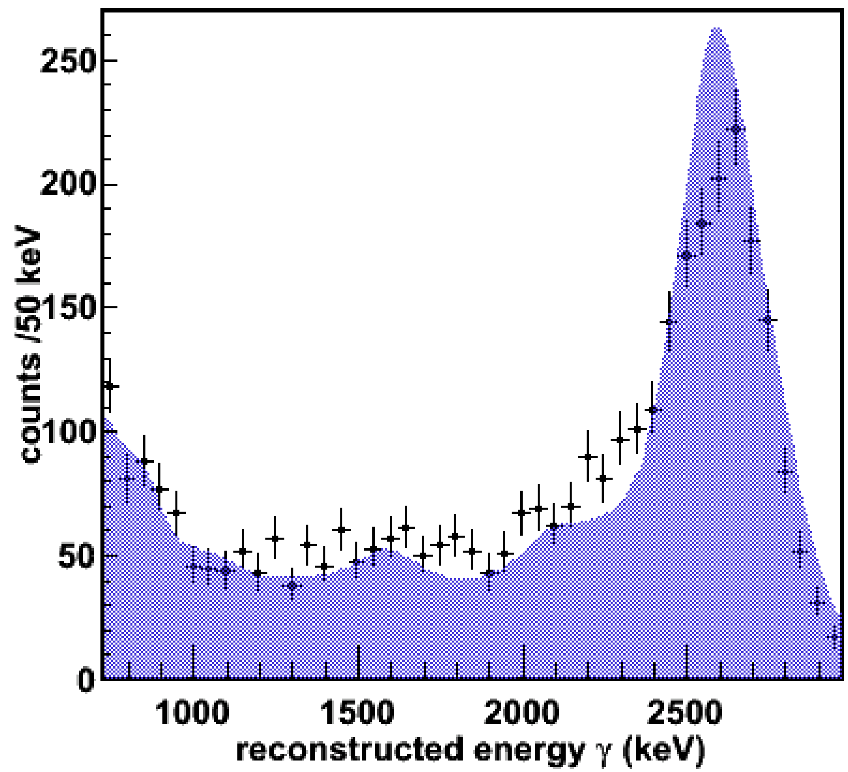


- 31 live-days of data
- 63 kg active mass
- Signal / Background ratio 10:1

$T_{1/2}$ = 2.11·10^{21} yr (± 0.04 stat) yr (± 0.21 sys)

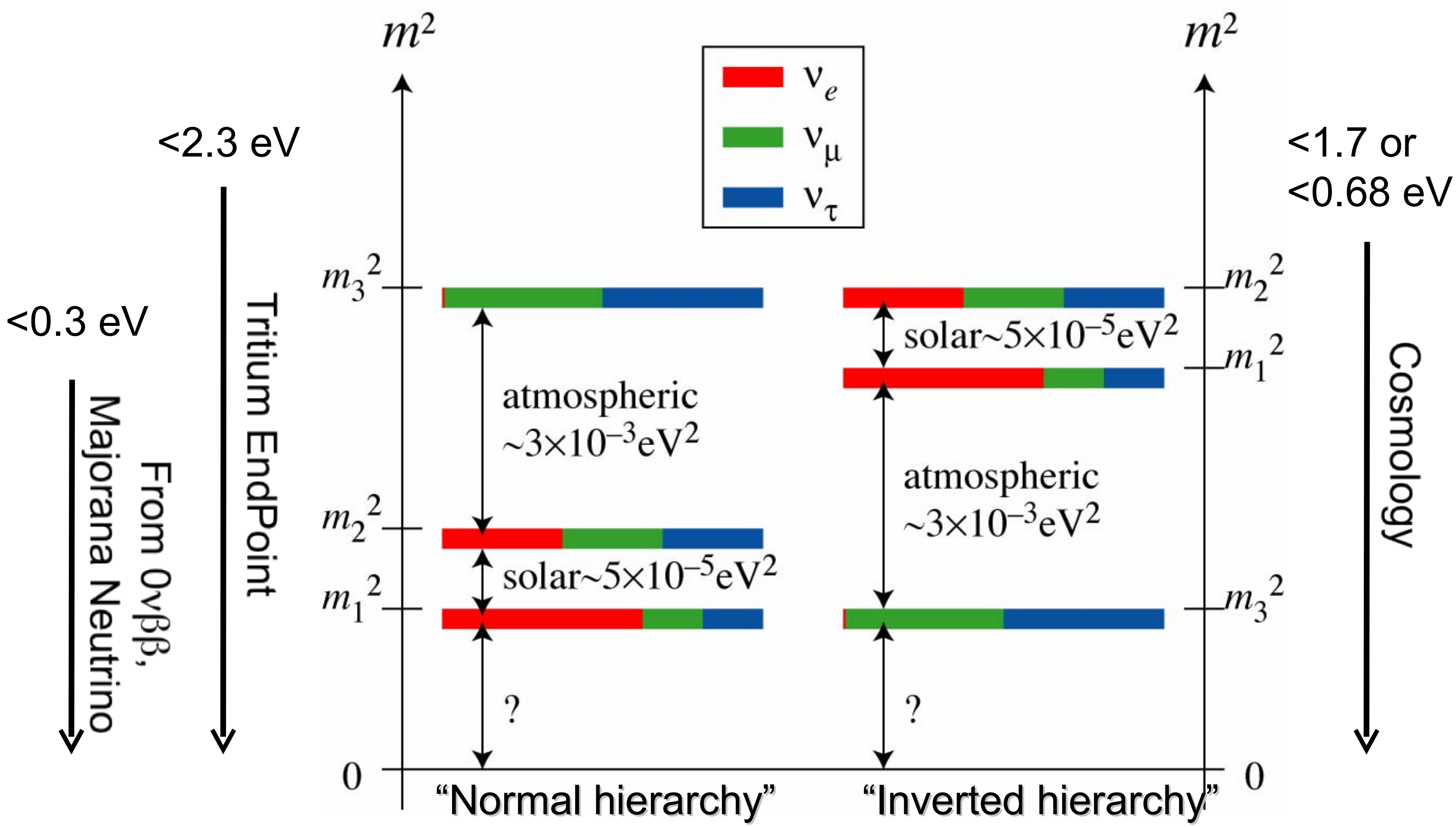
N. Ackerman et al., Phys. Rev. Lett. 107 (2011) 212501





Run 1 source agreement

Introduction: Neutrino mass scale



References for nuclear matrix elements:

RQRPA (Renormalized Quasiparticle Random Phase Approximation): from Table II, column 6, Simkovic *et al.,* Phys. Rev.C**79,** 055501 (2009). For 150Nd D.L. Fang, ArXiv:1009.5260

NSM (Nuclear Shell Model): J. Menendez *et al.,* Nucl. Phys.**A818**, 139 (2009).

IBM-2 (Interacting Boson Model -2): J. Barea and F. Iachell, Phys. Rev. C**79**, 044301 (2009) and private communication.

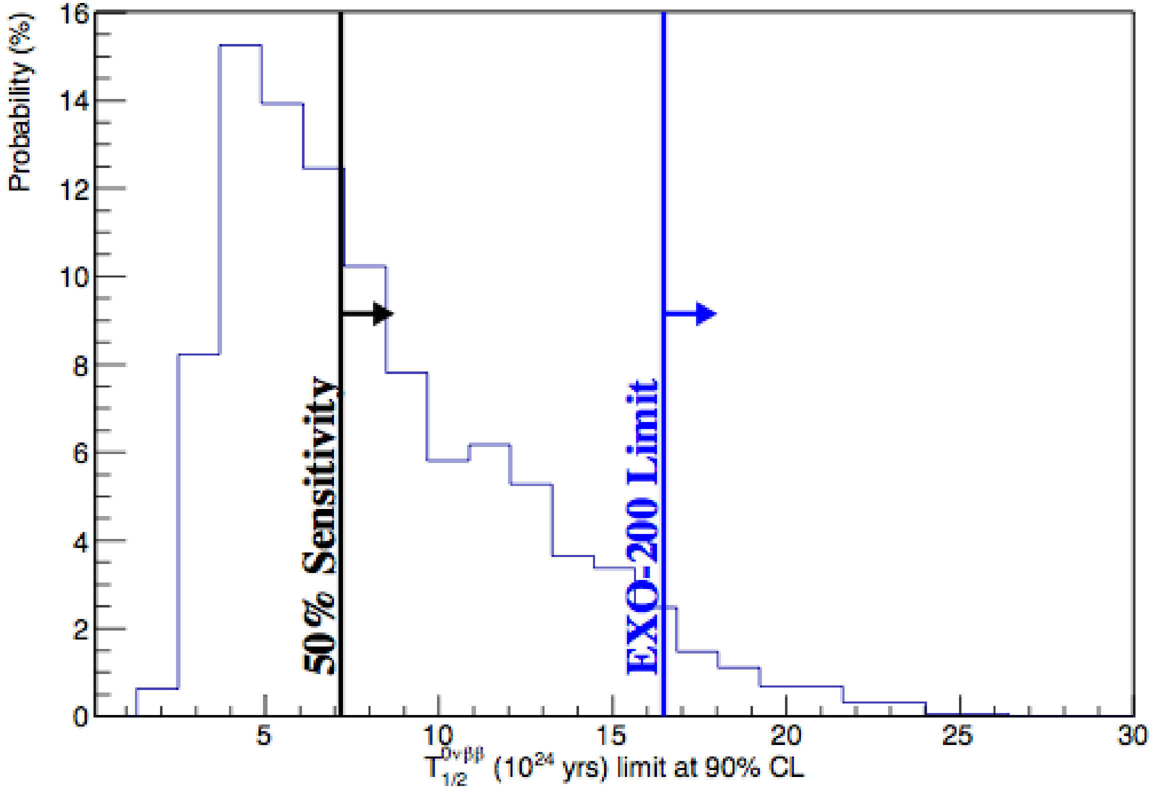
PHFB (Projected Hartree-Fock Bogoljubov): K. Chatuverdi *et al.,* Phys. Rev. C**78**, 054302 (2008).

EDF (Energy Density Functional): T. R. Rodriguez and G. Martinez-Pinedo, ArXiv:1008.5260

Phase space factors for the $0\nu\beta\beta$ decay from F. Boehm and P. Vogel, Vogel, 9/2010 Physics of Massive Neutrinos, Table 6.1

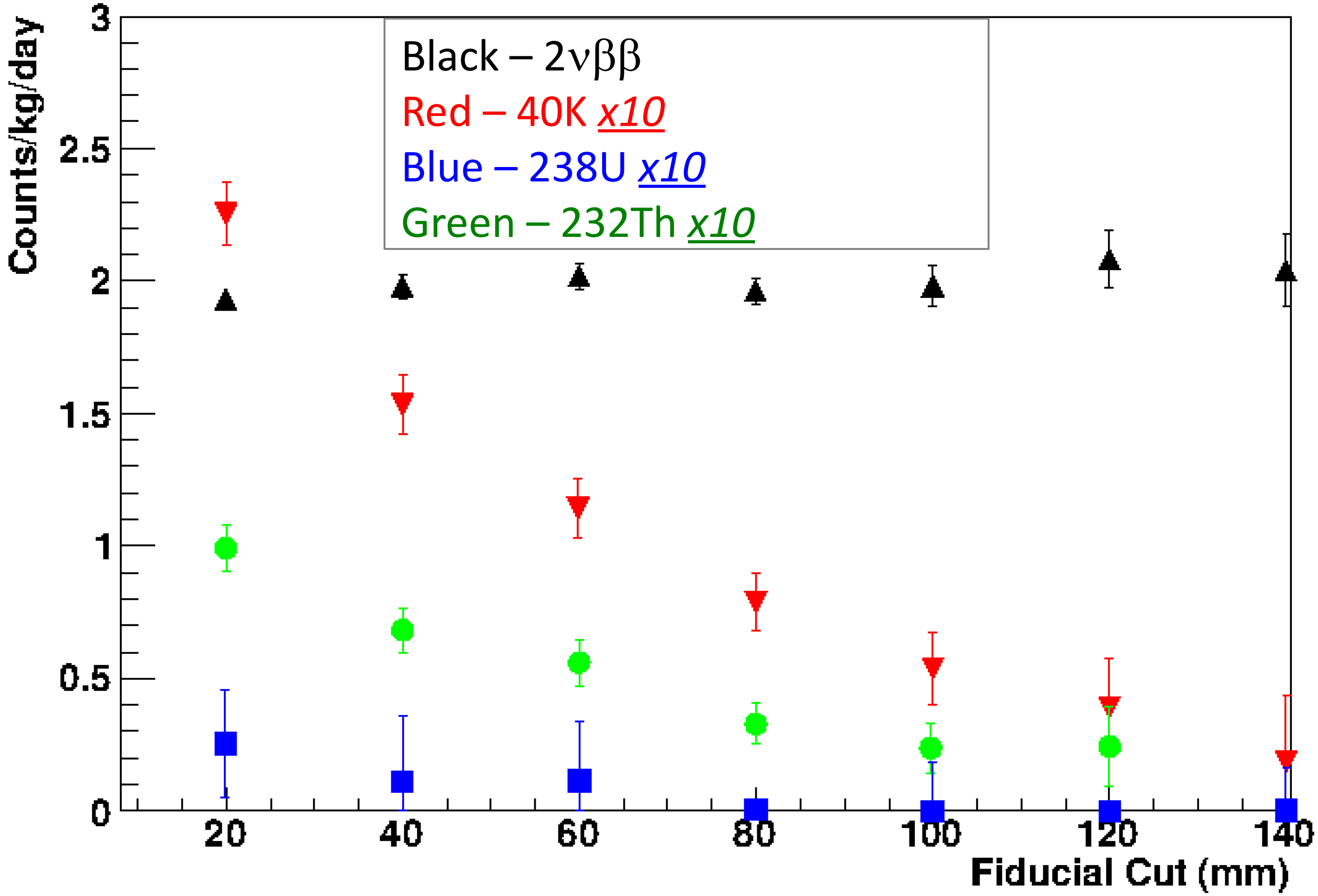
(slide from L.Kaufman, Physics in Collision 2012)

Sensitivity



Distribution of 0νββ T1/2 90% CL upper limits from Monte Carlo simulations

- Given our estimated background, we expect a 90% CL on T1/2 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



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