Search for ^{136}Xe $0\nu\beta\beta$ with the Enriched Xenon Observatory (EXO)

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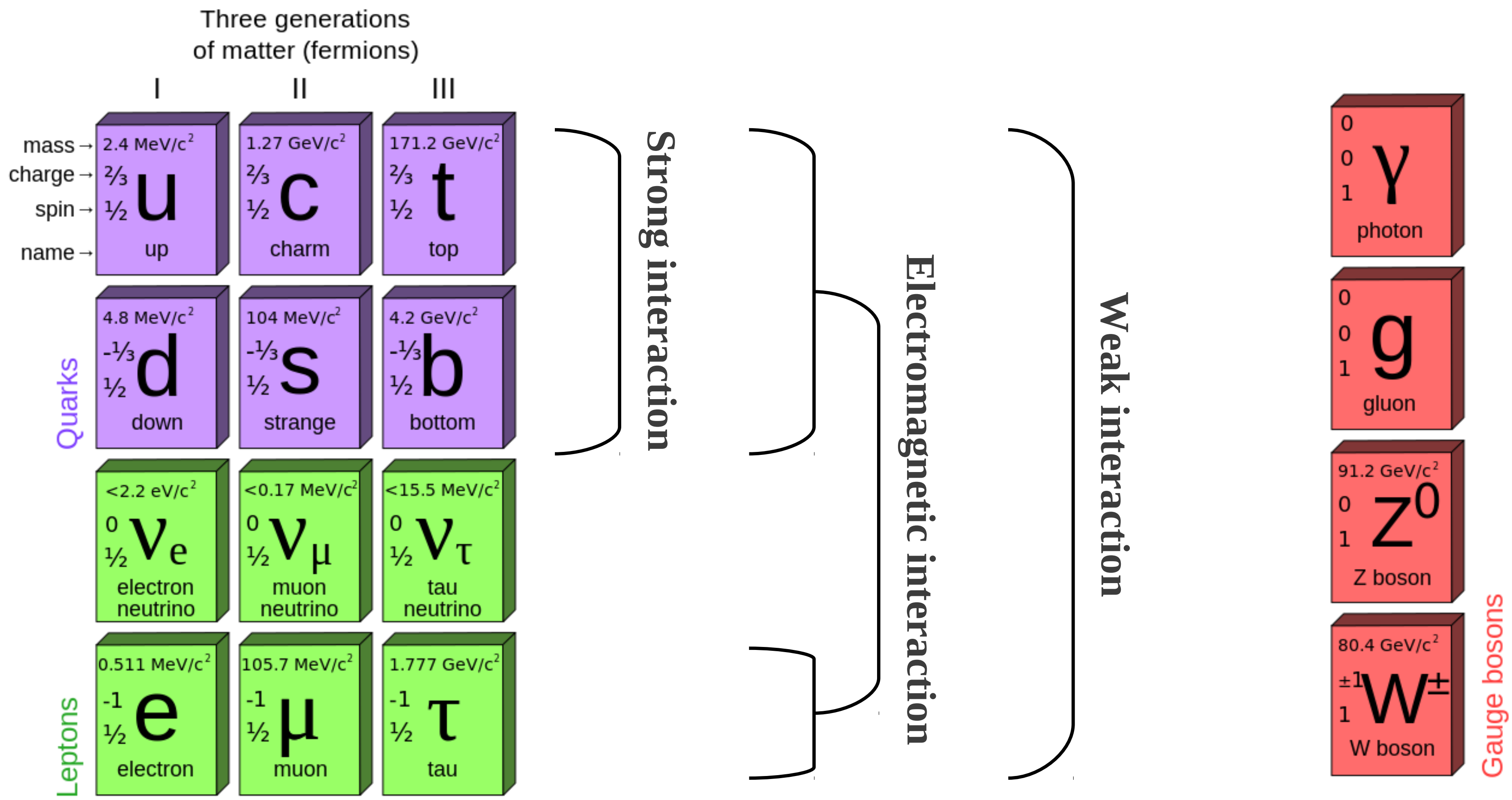
Guillaume Giroux
Laboratory for High Energy Physics
Albert Einstein Center for Fundamental Physics
University of Bern

Outline

- Theoretical motivations
- The EXO-200 detector
- Event reconstruction
- Search for $0\nu\beta\beta$
- Short and long term plans

Neutrinos in the Standard Model



Neutrinos in the standard model:

- Participate only through weak interaction
- Only left-handed (right-handed) neutrinos (anti-neutrinos) participate
- Neutrinos are massless
- Lepton flavor is conserved

Neutrino Oscillation

Atmopheric, solar, reactor and accelerator neutrino experiments: **neutrino flavor is not conserved**

Explanation: neutrino flavor eigenstates are distinct from their mass eigenstates:

$$\nu_l = \sum_{i=1}^{3} U_{li}\nu_i$$

where:

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

the PMNS mixing matrix.
(Pontecorvo-Maki-Nakagawa-Sakata)

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

3 mixing angle θ_{12}, θ_{23}, θ_{13} + 1 Dirac CP-violating phases δ + 2 Majorana CP-violating phase $\alpha 1$ and $\alpha 2$

The neutrino mass eigenstates don't propagate at the same speed: **the flavors oscillate.**

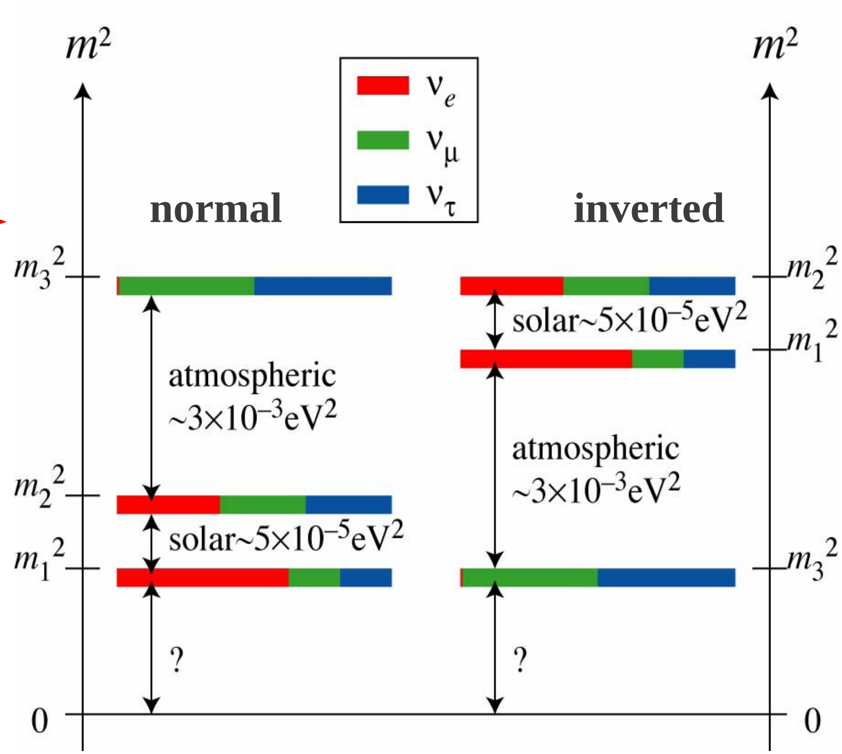
$$P(\nu_l \rightarrow \nu_{l'}) \neq 0$$

P is function of distance, energy, PMNS elements and Δm^2.

Neutrino oscillation experiments measured: θ_{12}, θ_{23}, θ_{13}, Δm^2_{12} and Δm^2_{23}

Remaining unknowns:

- Absolute mass scale
- Hierarchy (normal or inverted)
- Dirac/Majorana nature
- CP-violating phases



Constraints on the neutrino mass:

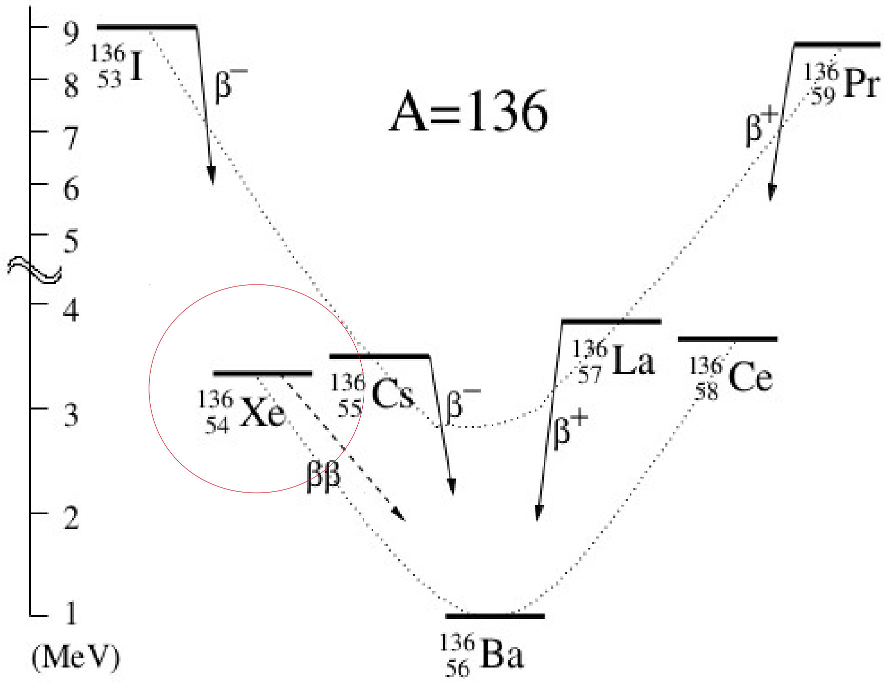
Heaviest neutrino mass: $m_h > 0.04$ eV

^{3}H beta-decay end-point: $m_{\nu_{ee}} = \sqrt{\sum_i |U_{ei}|^2 m_i^2} < 2.3$ eV (95% CL)

Cosmological observations: $\sum_i m_i < 0.5$ eV

Even-even nuclei are more bound than the odd-odd ones.

Atomic mass diagram

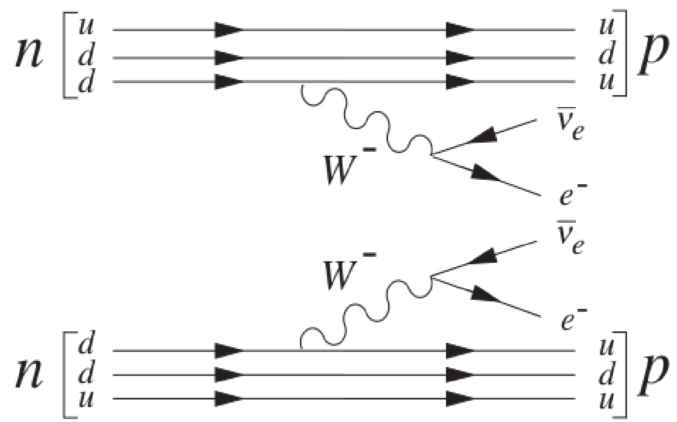


Energy conservation forbids normal beta decay of ^{136}Xe to ^{136}Cs.

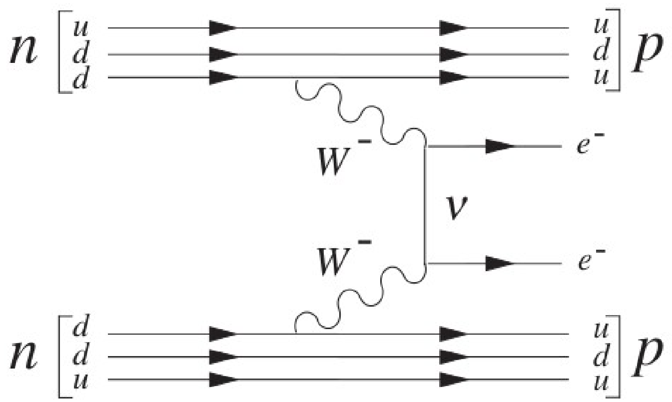
Second order **double beta decay** is allowed to ^{136}Ba.

Two modes of double beta decay

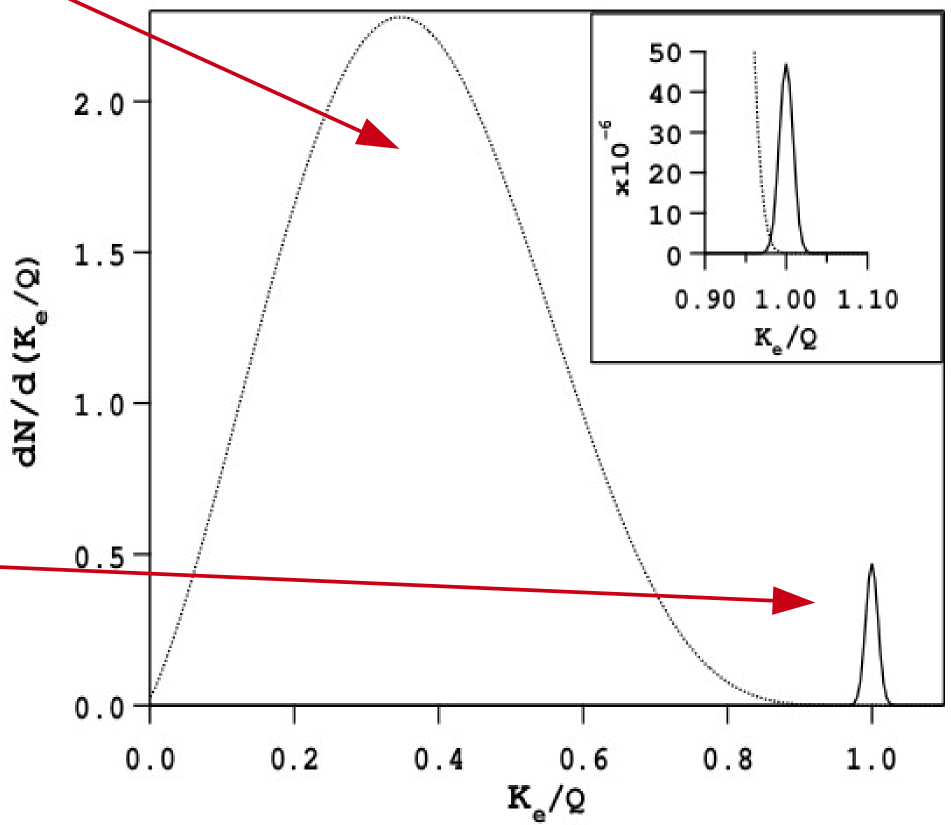
Two-neutrino double beta decay (2νββ)



Neutrino-less double beta decay (0νββ)

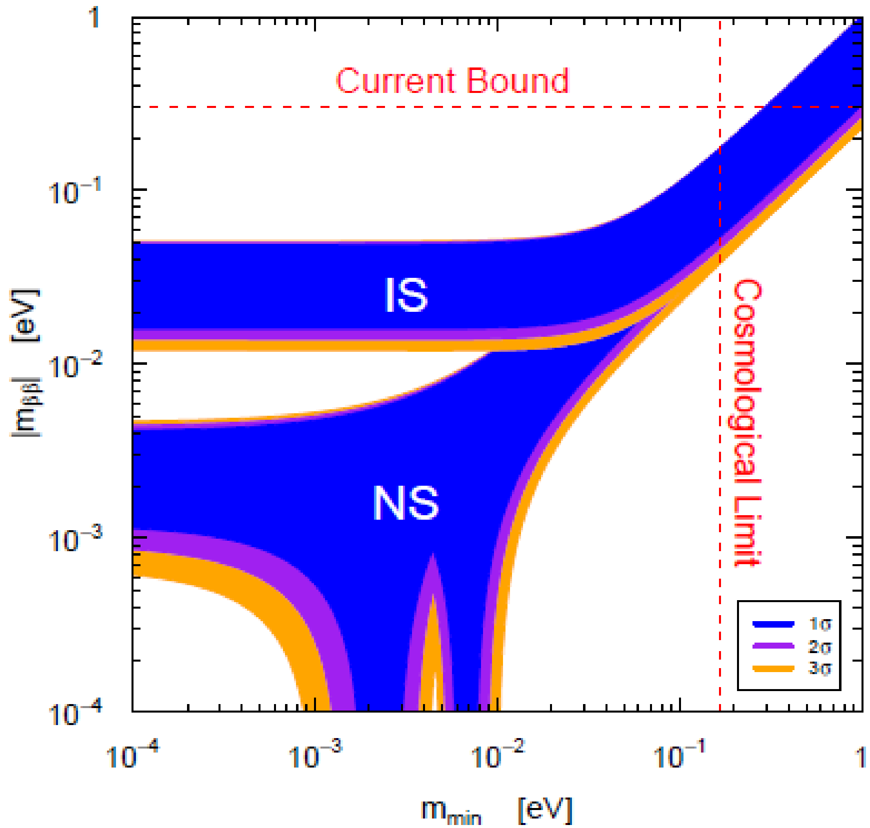


Summed electrons energy spectrum



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

Effective Majorana mass as a function of the lightest neutrino mass



$0\nu\beta\beta$ is allowed given:

- Neutrino masses ≠ 0
- Neutrinos are Majorana ($\nu = \bar{\nu}$)
- Lepton number violation

Decay half-life:

Phase space factor

Nuclear matrix element

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

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

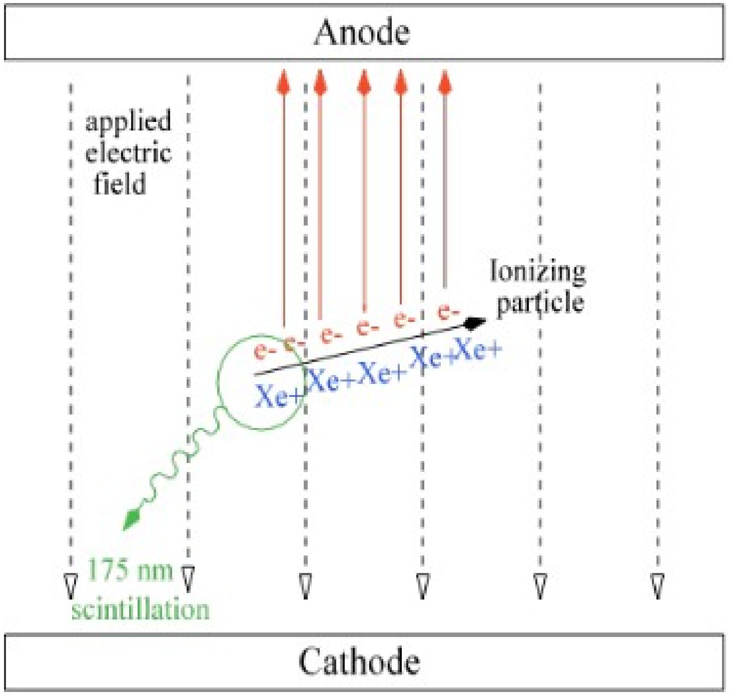
PMSN elements

Majorana phases

Neutrino mass of eigenstate *i*

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**
- ***Admits a novel coincidence technique.*** **Potential strong reduction of background by barium daughter tagging (not yet demonstrated.)**

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, M. Weber, J-L. Vuilleumier

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

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

Colorado State University, Fort Collins CO, USA
S. Alton, C. Benitez-Medina, 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.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, Amherst MA, USA
T. Daniels, S. Johnson, K. Kumar, A. Pocar, D. Wright

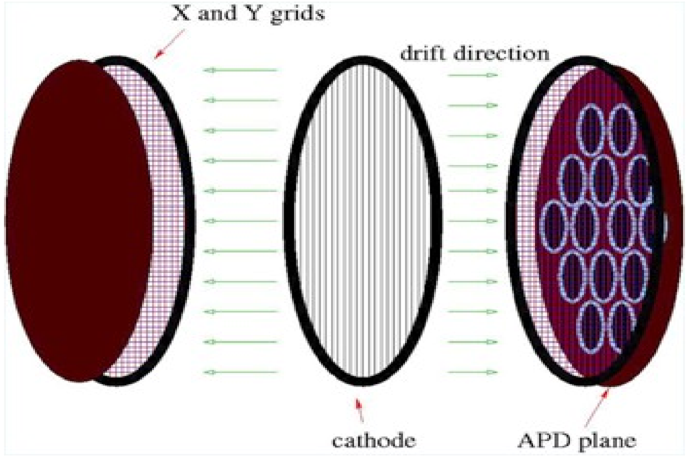
University of Seoul, Republic of Korea
D.Leonard

Stanford Linear Accelerator Center (SLAC), 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

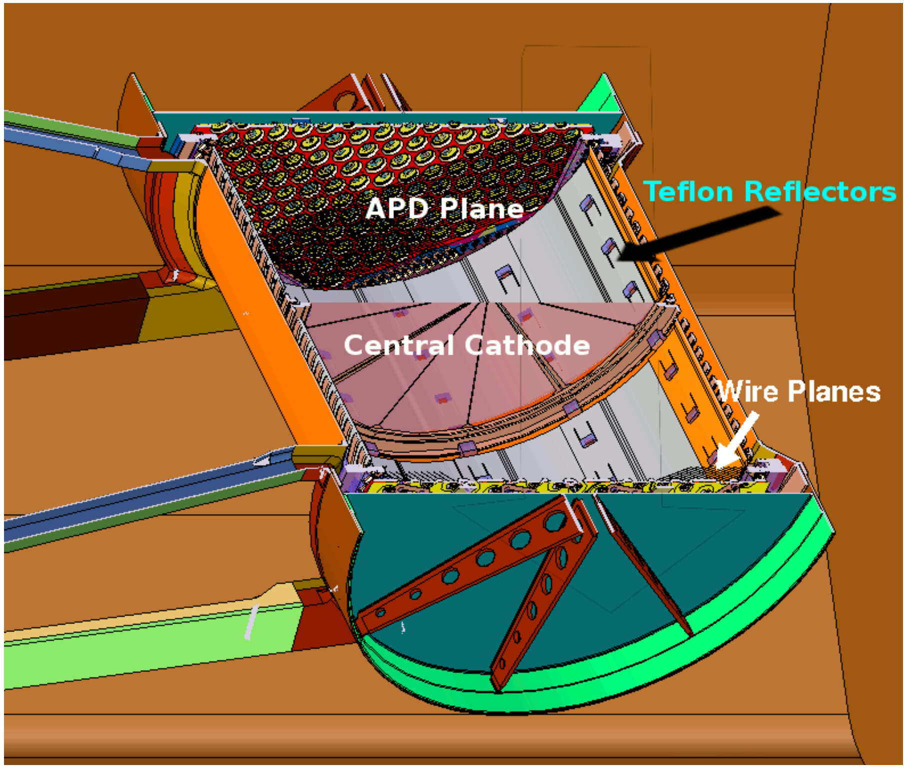
Stanford University, Stanford CA, USA
P. S. Barbeau, T. Brunner, J. Davis, R. DeVoe, M. J. Dolinski, G. Gratta, M. Montero-Diez, A.R. Müller, R. Neilson, I. Ostrovsky, K. O'Sullivan, A. Rivas, A. Sabourov, D. Tosi, K. Twelker

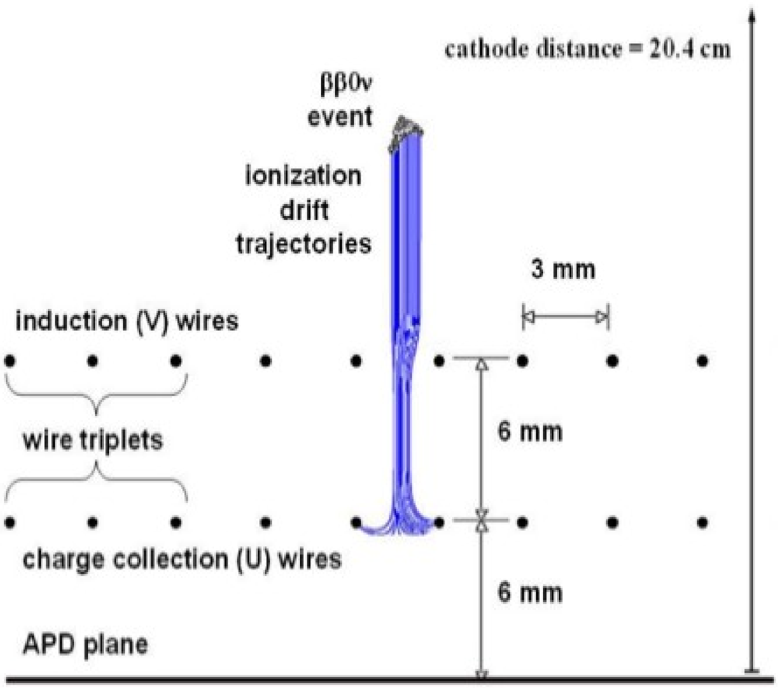
Technical University of Munich, Garching, Germany
W. Feldmeier, P.Fierlinger, M. Marino

The EXO-200 Time Projection Chamber (TPC)

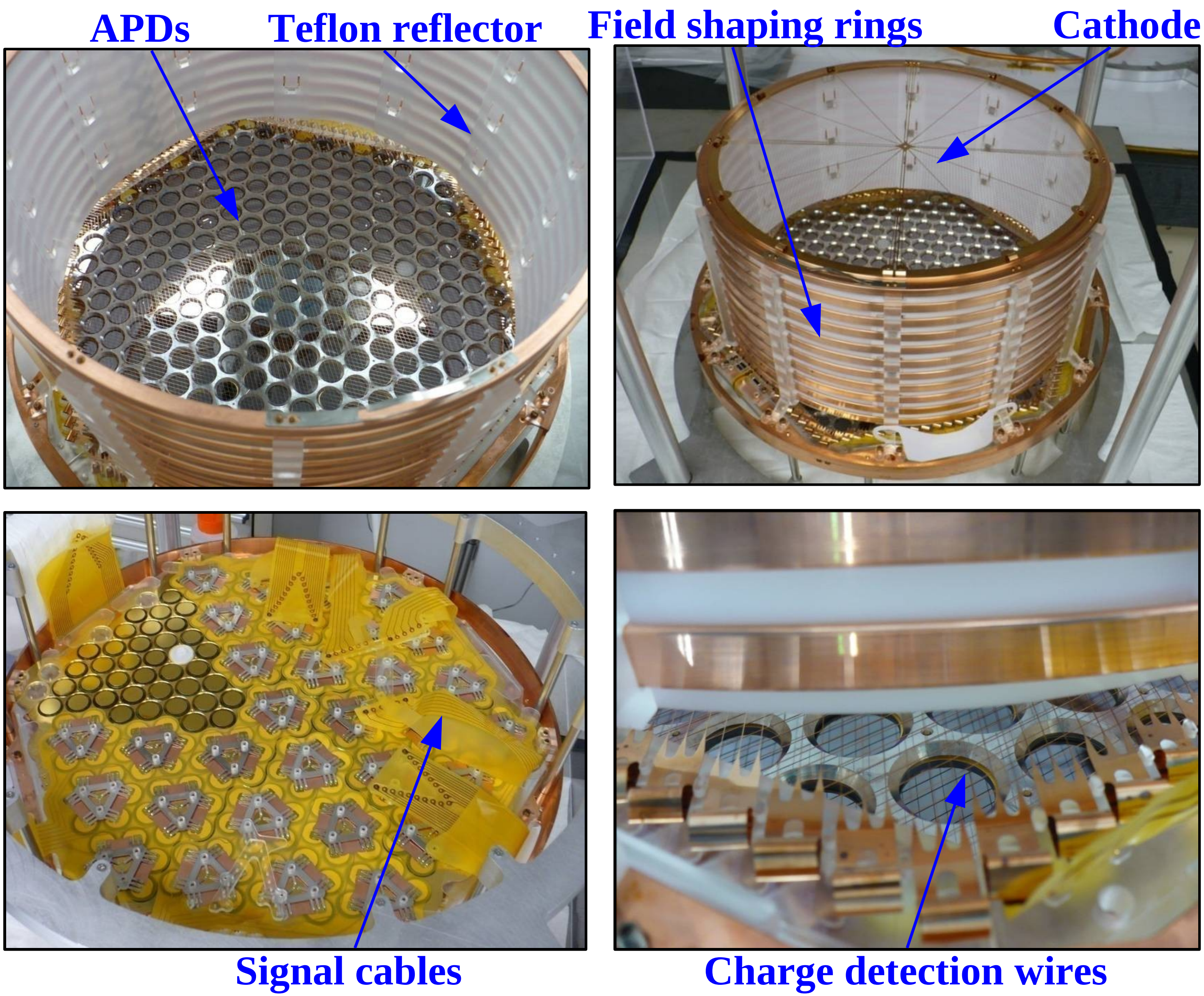


- Using ~110 kg of 80.6 % enriched Xe in the isotope 136
- Two TPC modules separated by a common cathode.
- LAAPD arrays for light measurement.
- Two planes of 38 collection wire triplets (U-wires).
- Two planes of 38 induction wire triplets (V-wires).
- Wire planes crossing at 60° for stereoscopic informations.

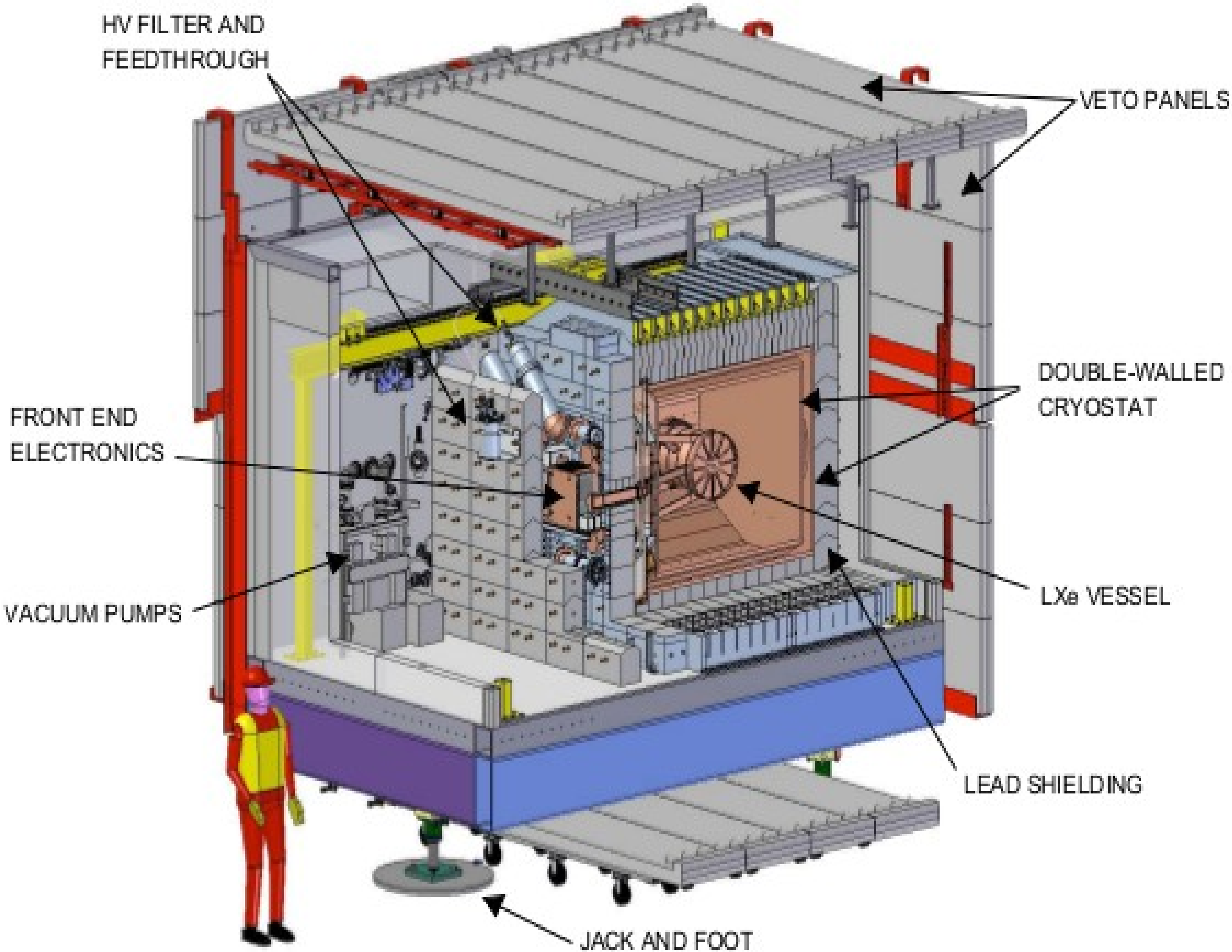




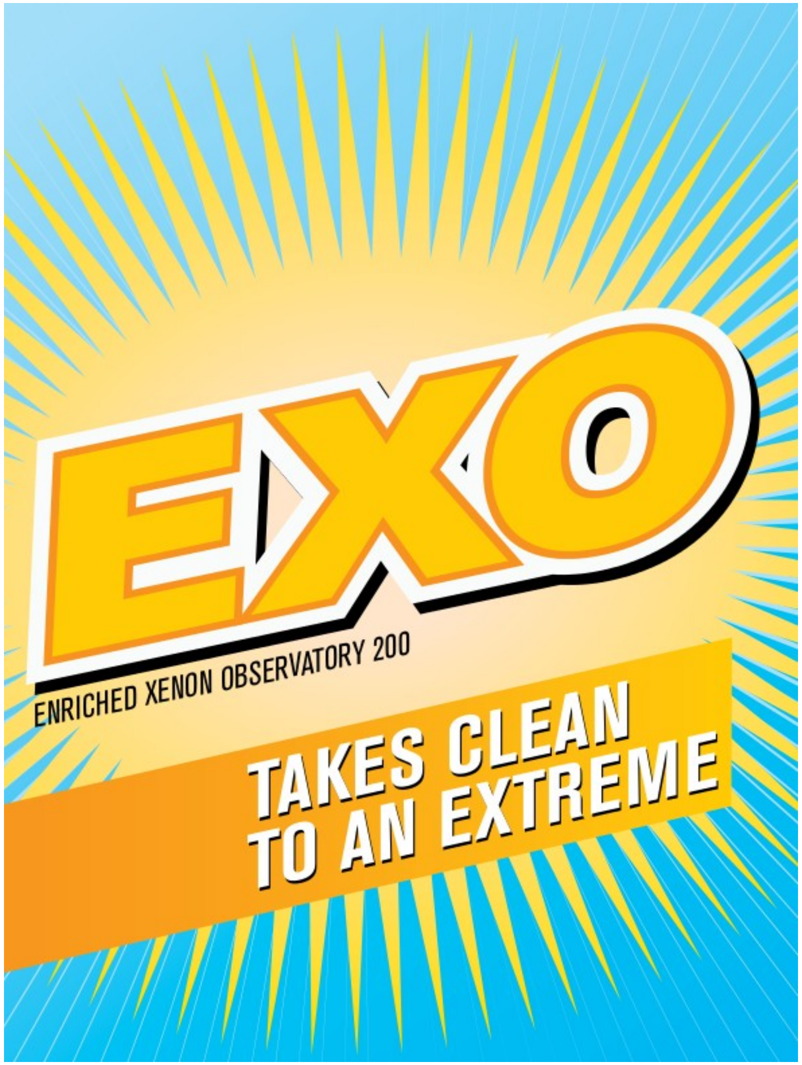
The EXO-200 Time Projection Chamber (TPC)



The EXO Detector



Material Background Control

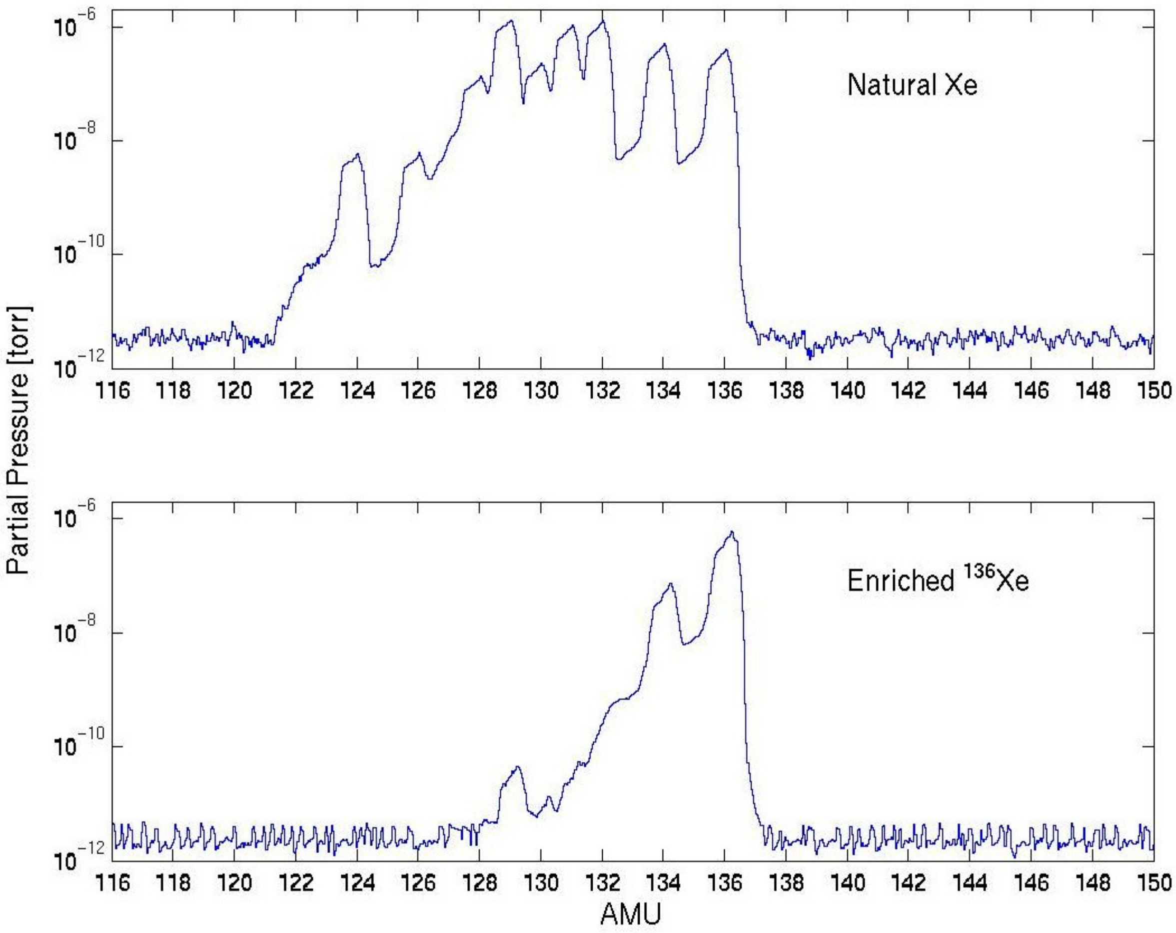


Symmetry Magazine (2010)

- Radioactive background screening of more than 400 materials †.
- Small number of materials selected.
- Conductors: copper, phosphor-bronze, silicon-bronze.
- Dielectrics: acrylic, polyimide substrate, PTFE.
- Material surface treatment.
- Cosmic rays activation control: TPC assembly in clean-room with concrete overburden,
- Prompt TPC delivery (terrestrial) to the WIPP site for storage.

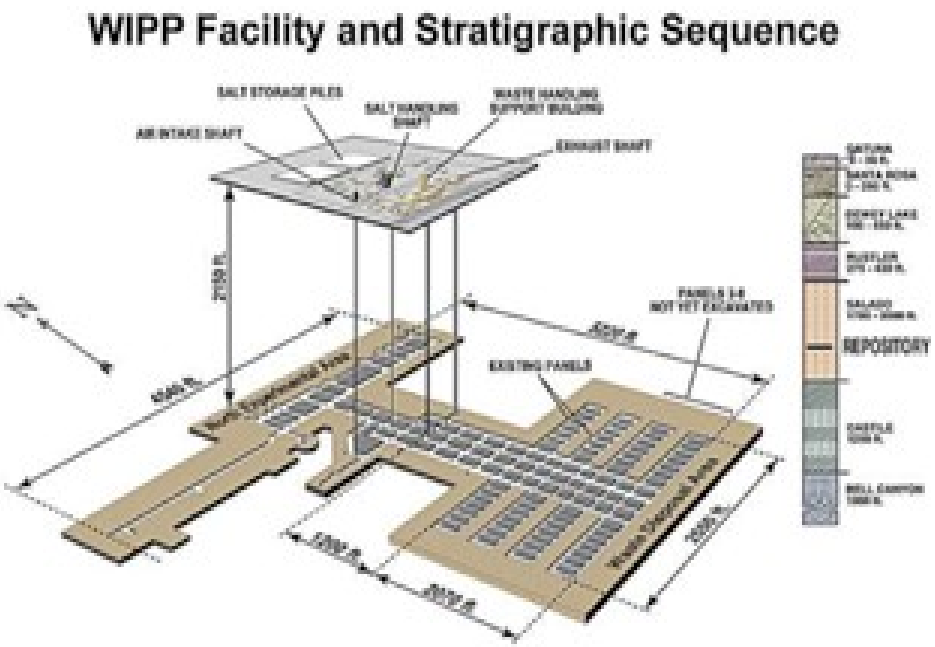
† D. S. Leonard et al. **Systematic study of trace radioactive impurities in candi-**
date construction materials for EXO-200. Nucl. Inst. Meth., page 490, 2008.

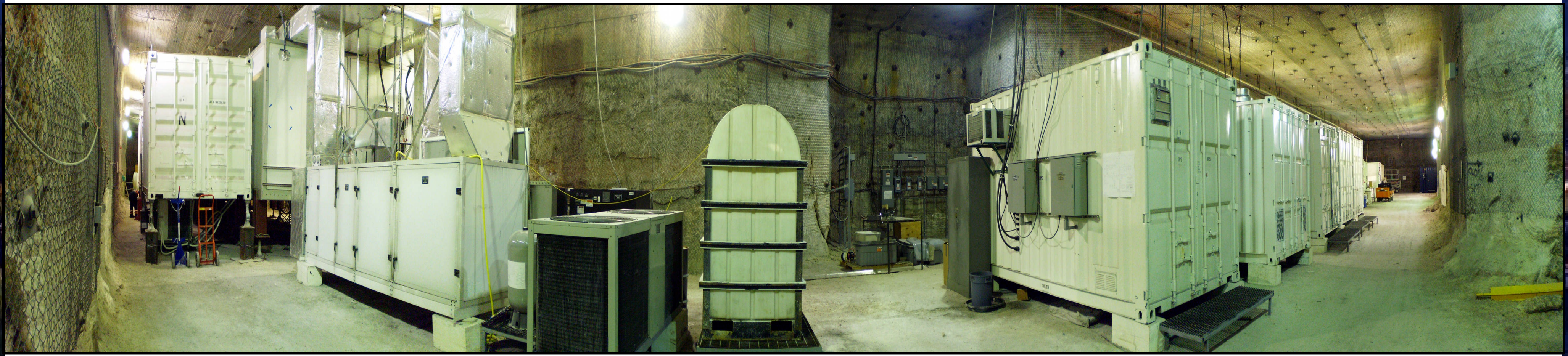
Mass spectra obtained by a residual gas analyzer (RGA)



- 200 kg of enriched Xenon: **161.2 kg of ^{136}Xe**
- Remaining isotope mostly ^{134}Xe
- Other isotopes in negligible concentration

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



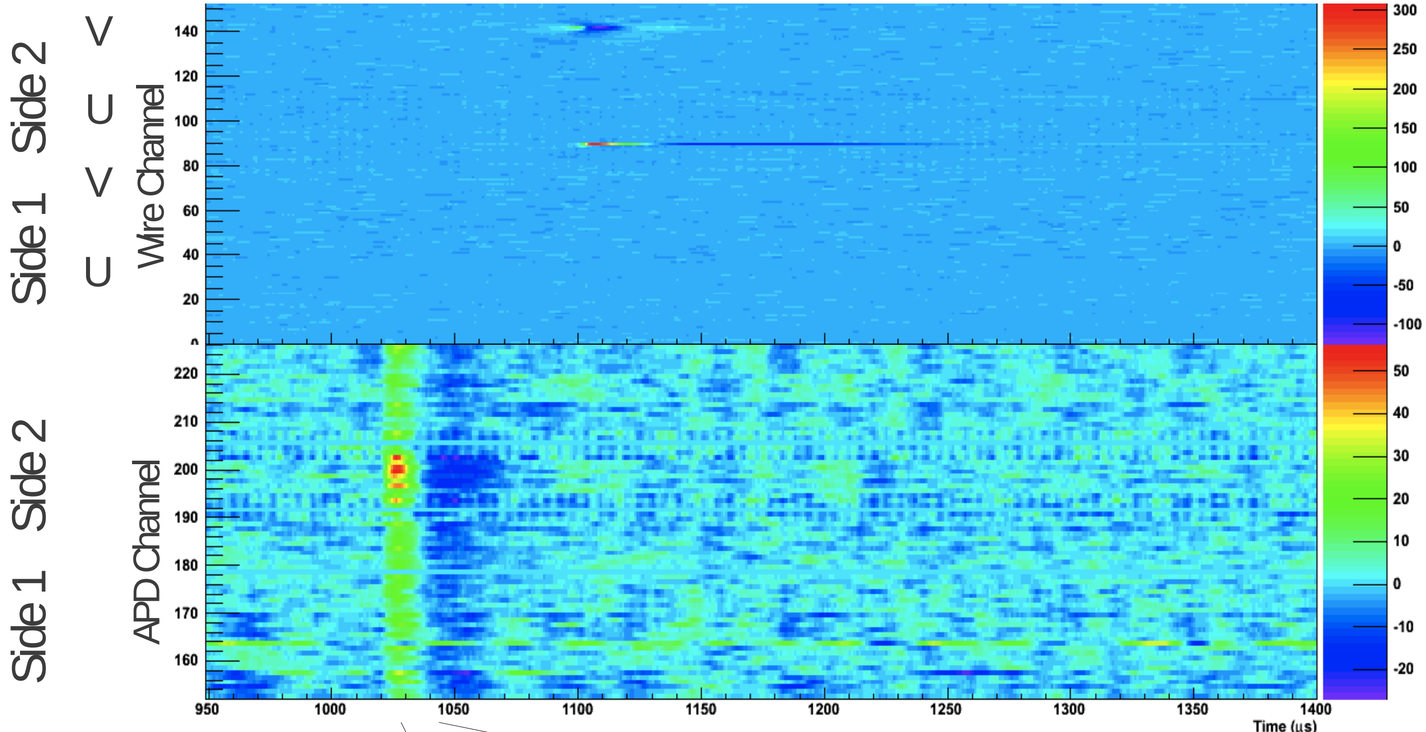


Charge readout

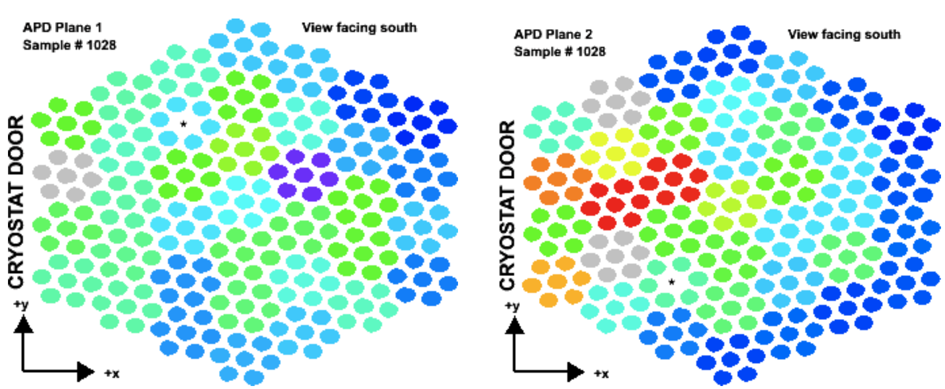
V: Induction

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.

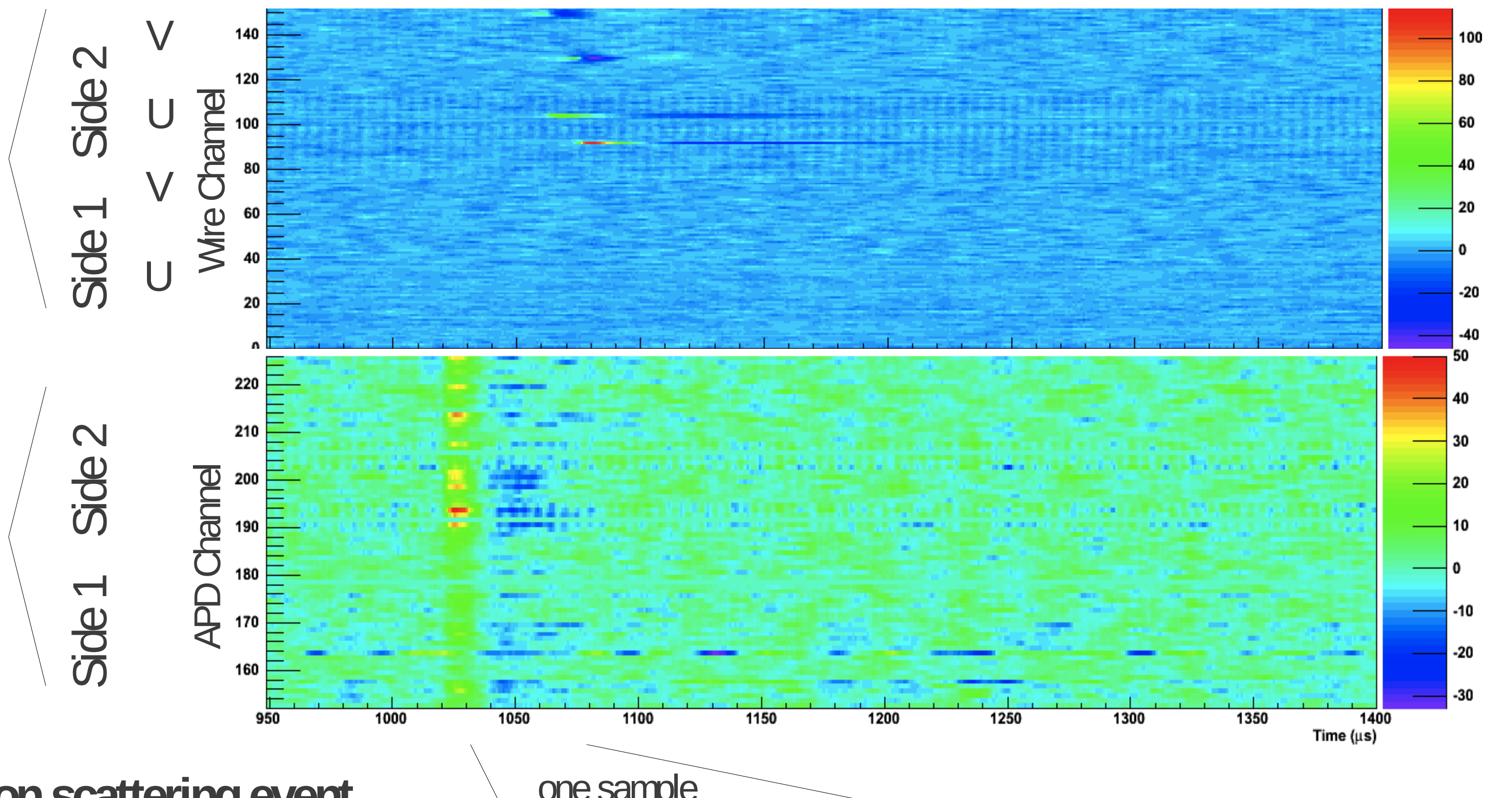
The light signal always precedes both charge signals. The induction (V) signal precedes the collection (U) signal.

Charge readout

V: Induction

U: Collection

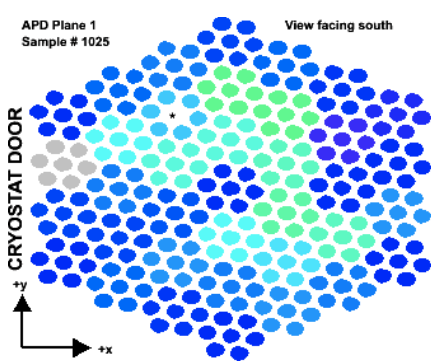
Light readout

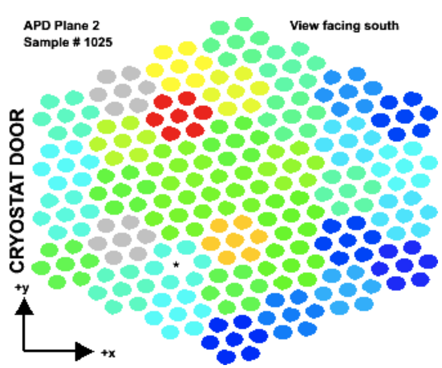


A two-site Compton scattering event

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.





Event Reconstruction - Outline

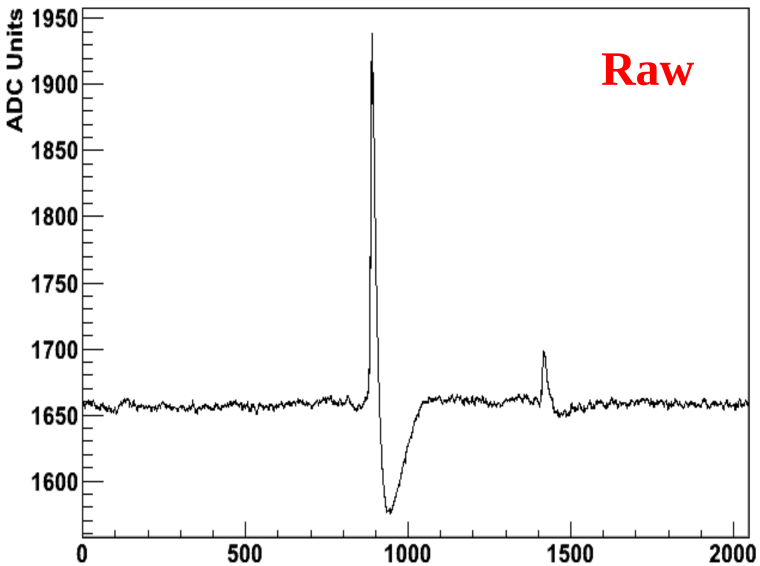
3 stages of event reconstruction

1. Signal Finding →
- Maximize efficiency
- Discriminate electronic noise
- **APDs, u-wires and v-wires**

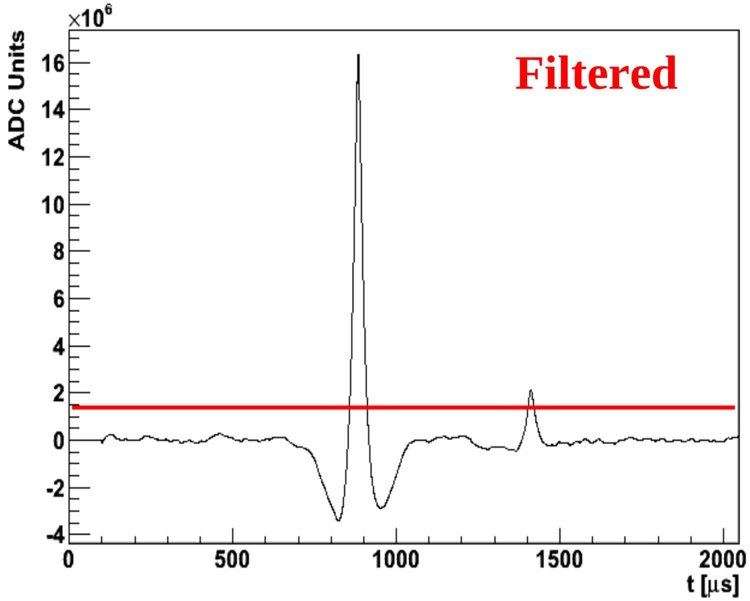
2. Parameter Extraction →
- Energy resolution
- Timing: z-spatial resolution

3. Event Clustering →
- Combine charge and light channels
- Spatial resolution
- Event topology: <u>background discrimination</u>

Signal finding with a matched filter: APDs and u-wires



Matched filter: convolution of a signal model on the raw waveform: high signal to noise efficiency



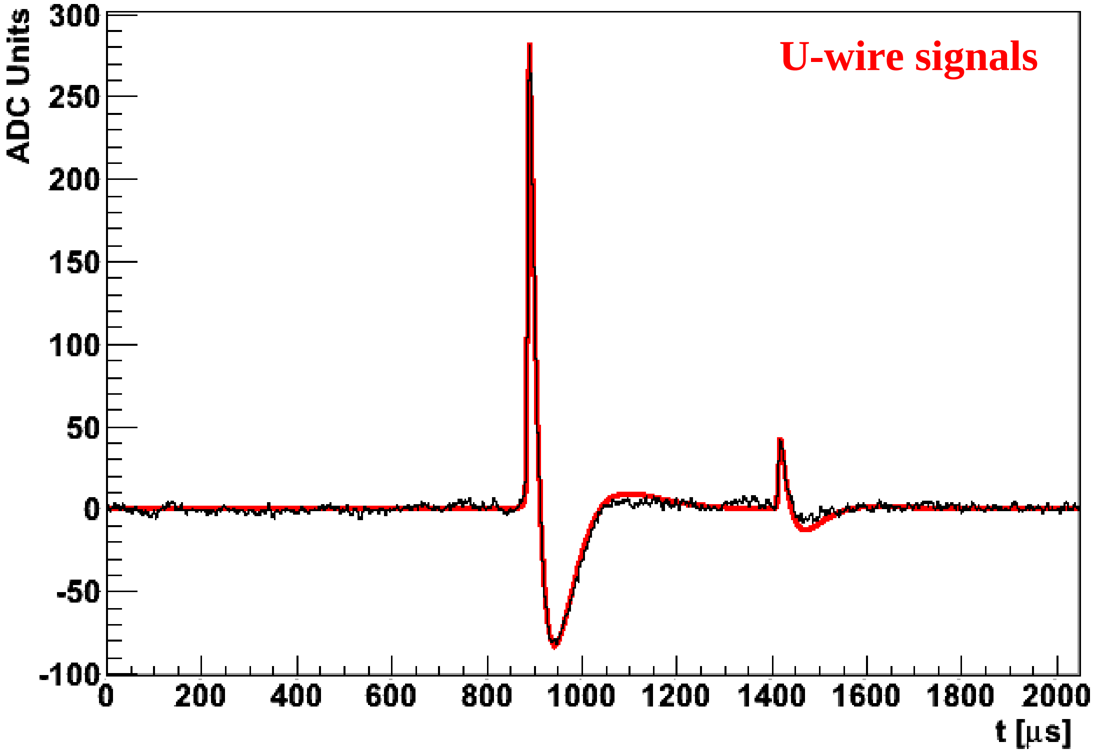
Filtered waveform: signals appear as peaks.

The threshold is calculated for each waveforms according to the noise level.

Event Reconstruction – Parameter Extraction

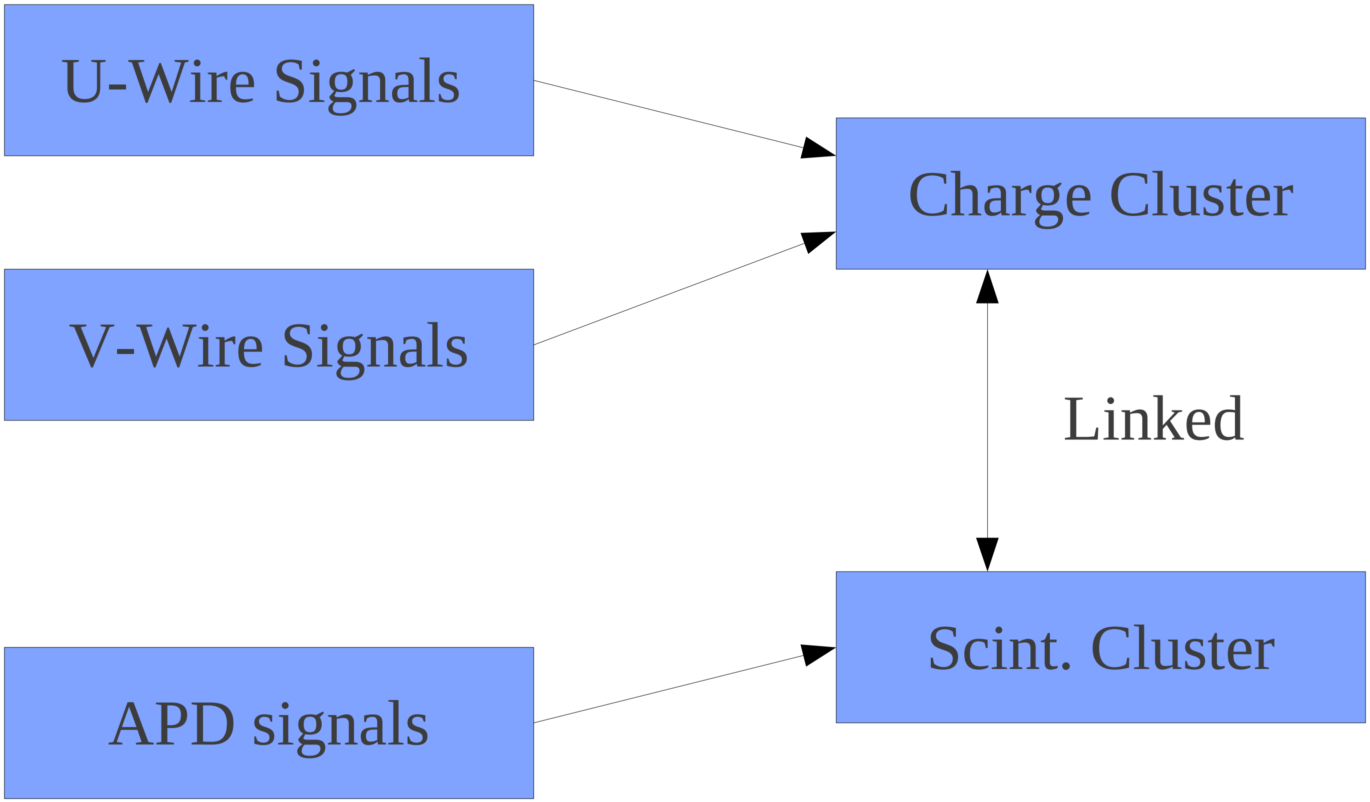
For each found signal (u-wires and APDs):

1. Signal model is fitted
2. Energy and t_0 extracted



Signals with bad fits are removed

Event Reconstruction – Event Clustering



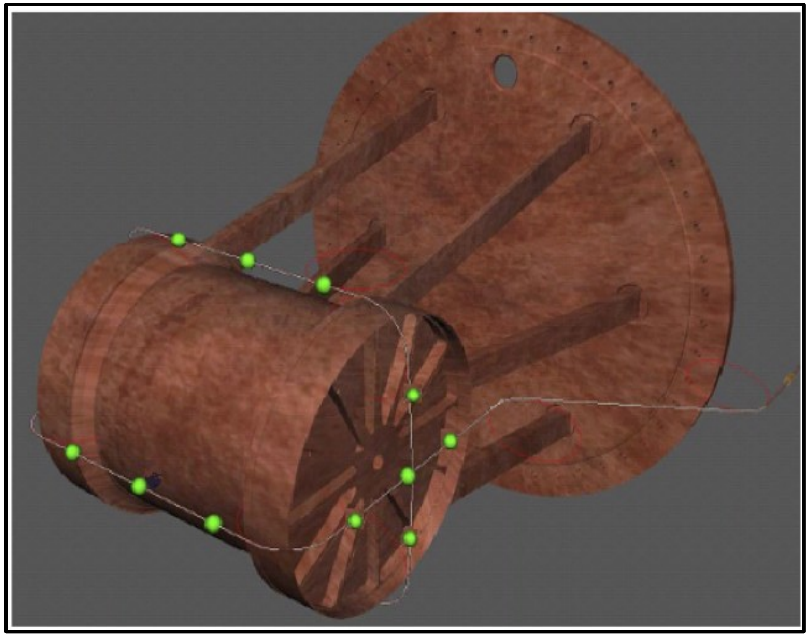
Charge and scintillation clusters:

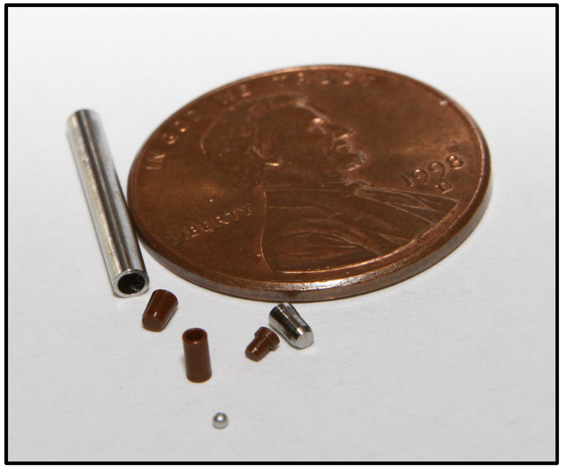
energy, channel multiplicity, coordinates, collection time, etc

Single-site event: scintillation cluster has a single charge cluster

Multi-site event: scintillation cluster has multiple charge clusters

Source Calibration

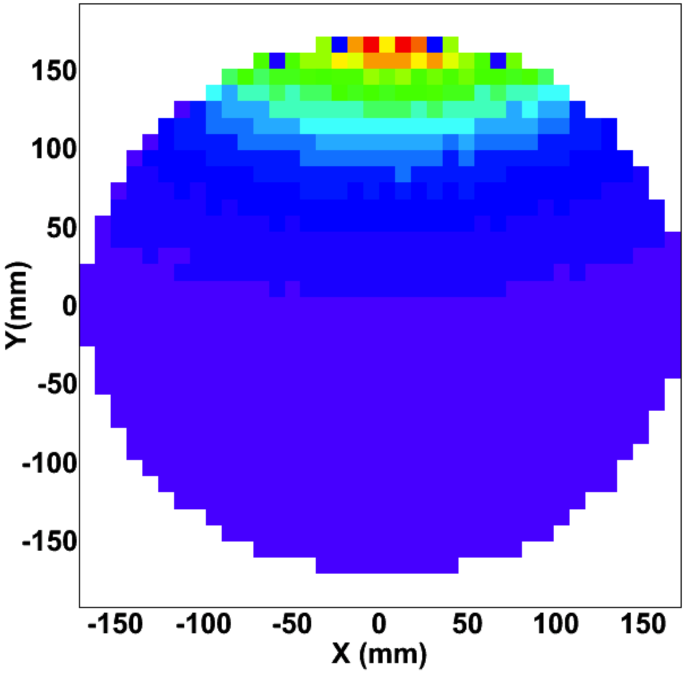




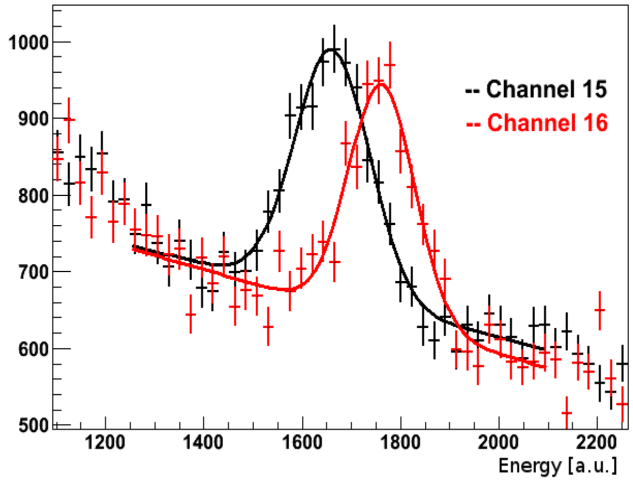
Custom miniaturized sources

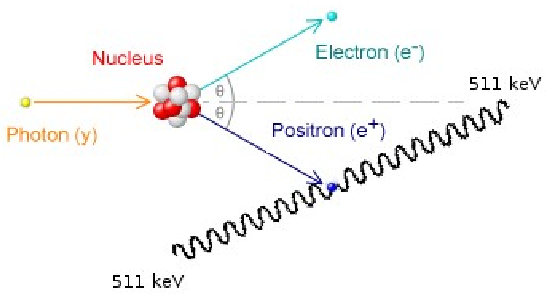
Calibration system allows the positioning radioactive source just outside of the TPC

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



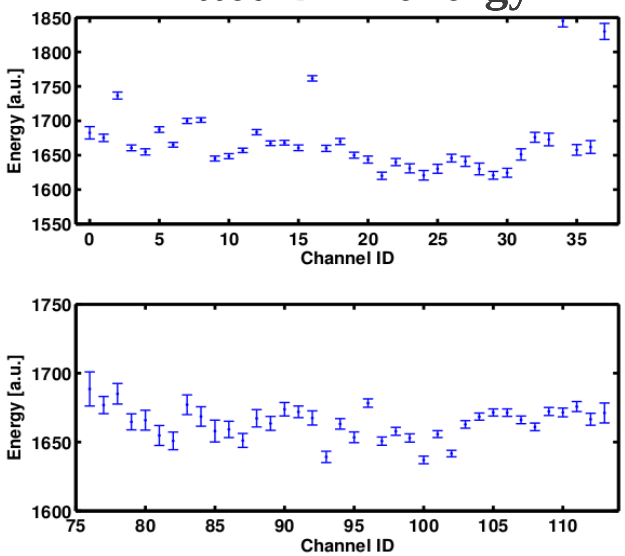
^{208}Tl fitted DEP energy to measure relative u-wire gains



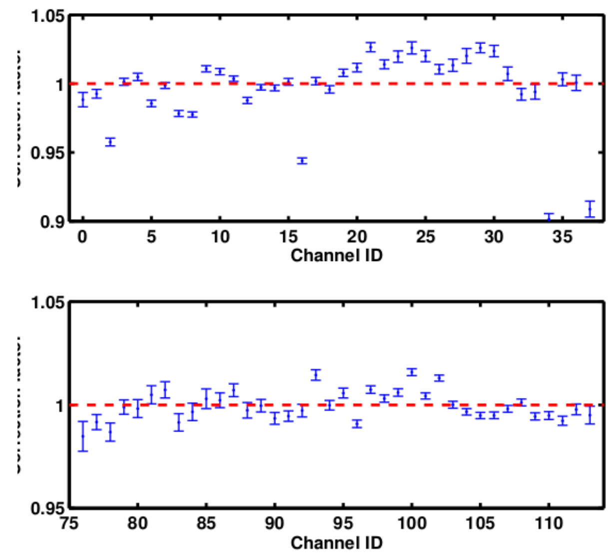


Gain corrections, along with higher Xe purity, **improved the charge resolution from 4.5% to 3.4% at 2615 keV.**

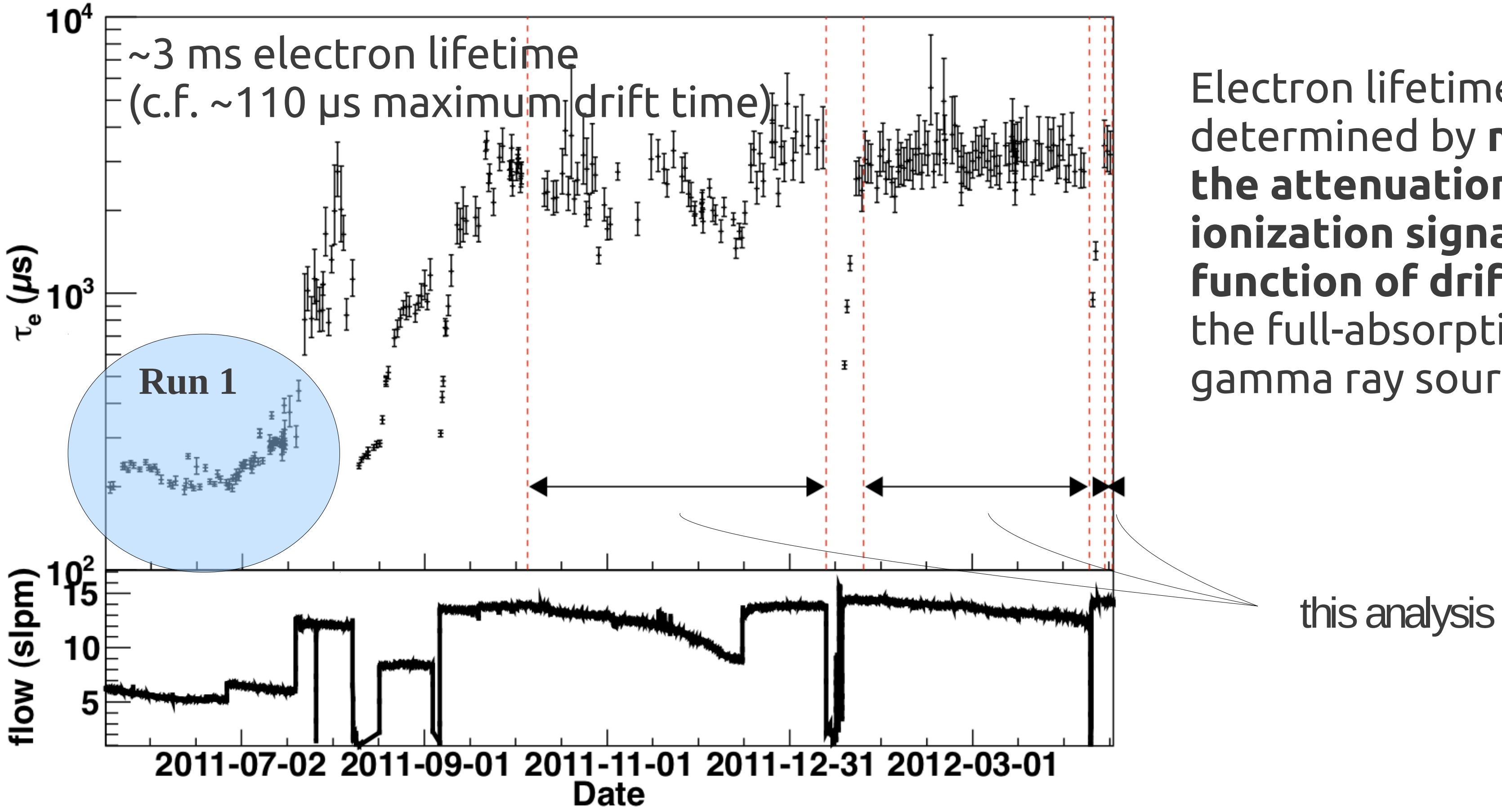
Fitted DEP energy



Correction factors



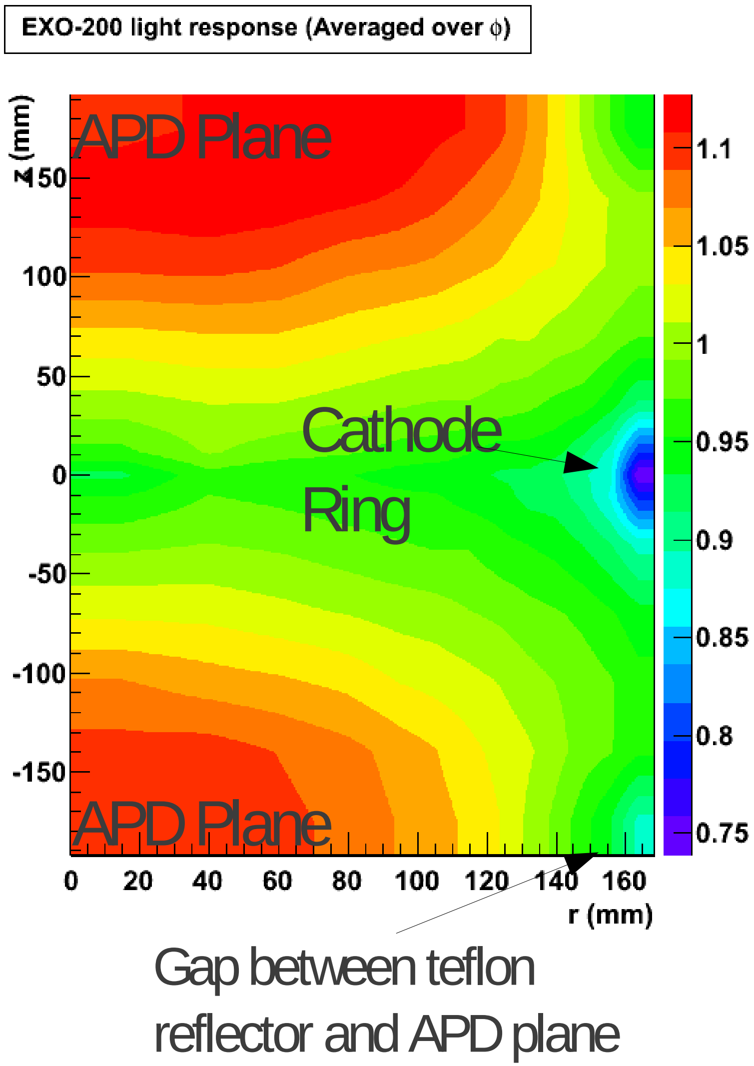
Xenon Purity



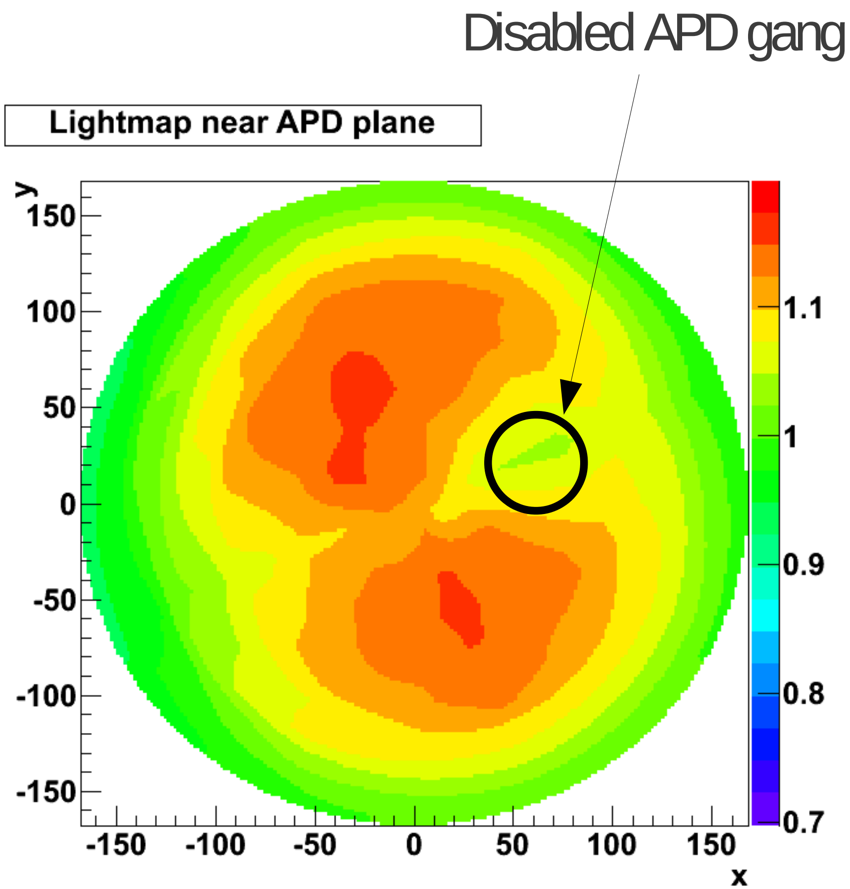
Electron lifetime was determined by **measuring the attenuation of the ionization signal as a function of drift time** for the full-absorption peak of gamma ray sources

Xenon gas is circulated through a heated zirconium getter using a custom-built ultraclean pump[†] † Rev Sci Instrum. 2011 Oct;82(10):105114

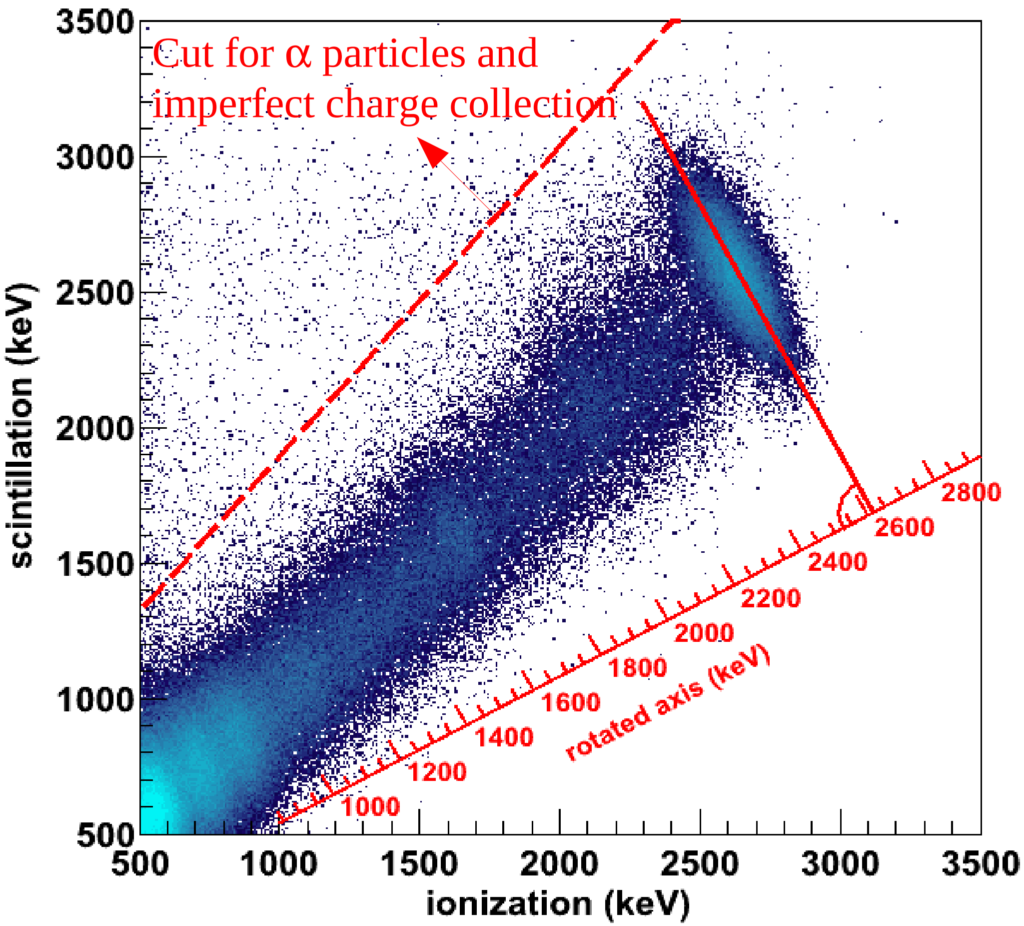
Correcting for Light Response



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



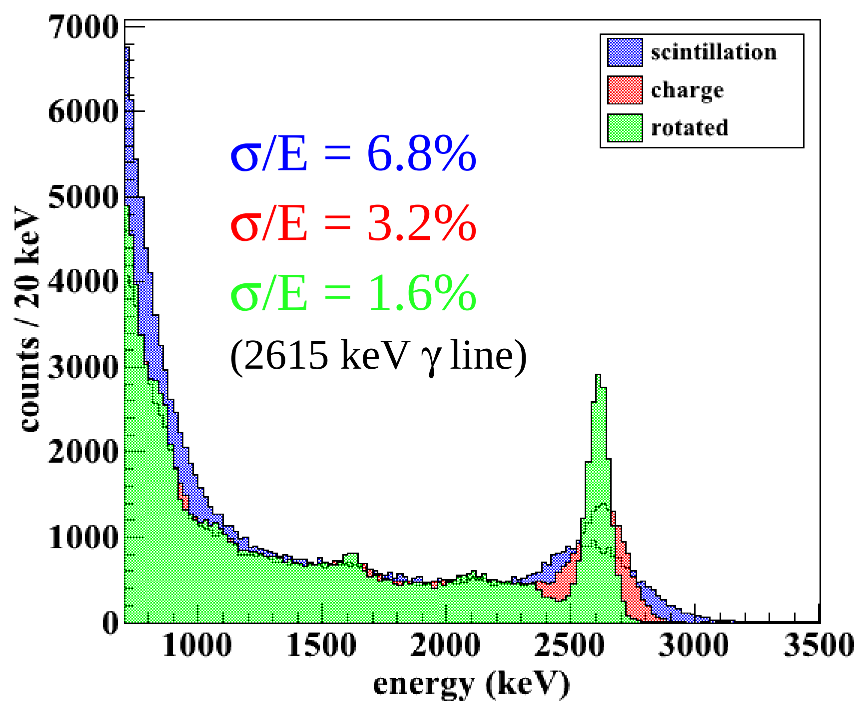
2D Anti-correlated spectra



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



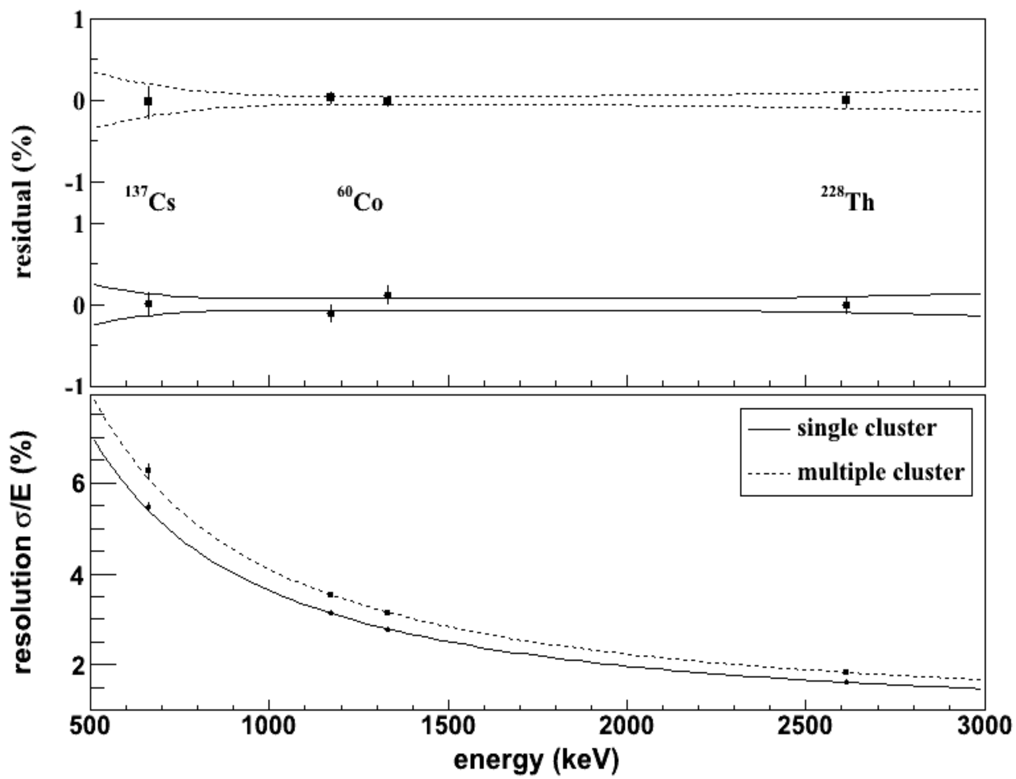
Blue: Projection on scintillation axis

Red: Projection on charge axis

Green: Projection on rotated axis

Energy Calibration

- EXO-200 has 3 types of sources
  - o ^{137}Cs (3 kBq (weak), 15 kBq (strong))
  - o ^{60}Co (0.5 kBq (weak),7.2 kBq (strong))
  - o ^{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:

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

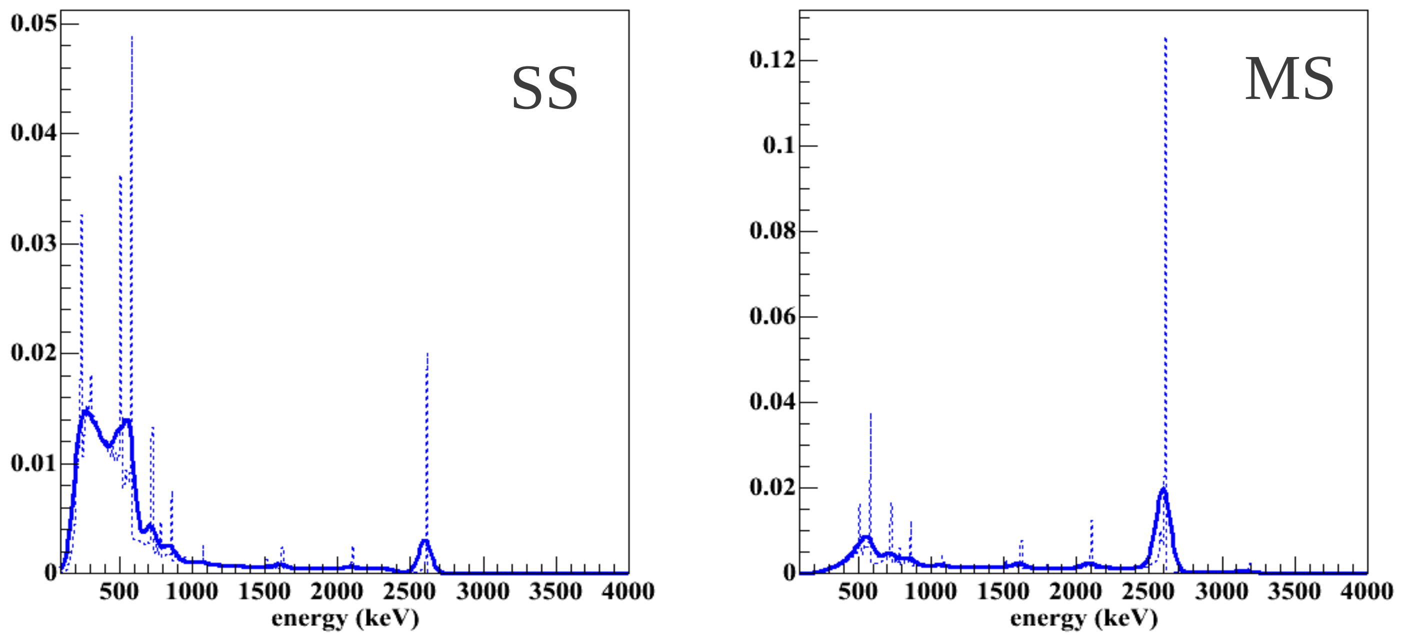
Resolution dominated by constant (noise) term p_1

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

$\sigma/E = 1.84\ \%$ (MS)

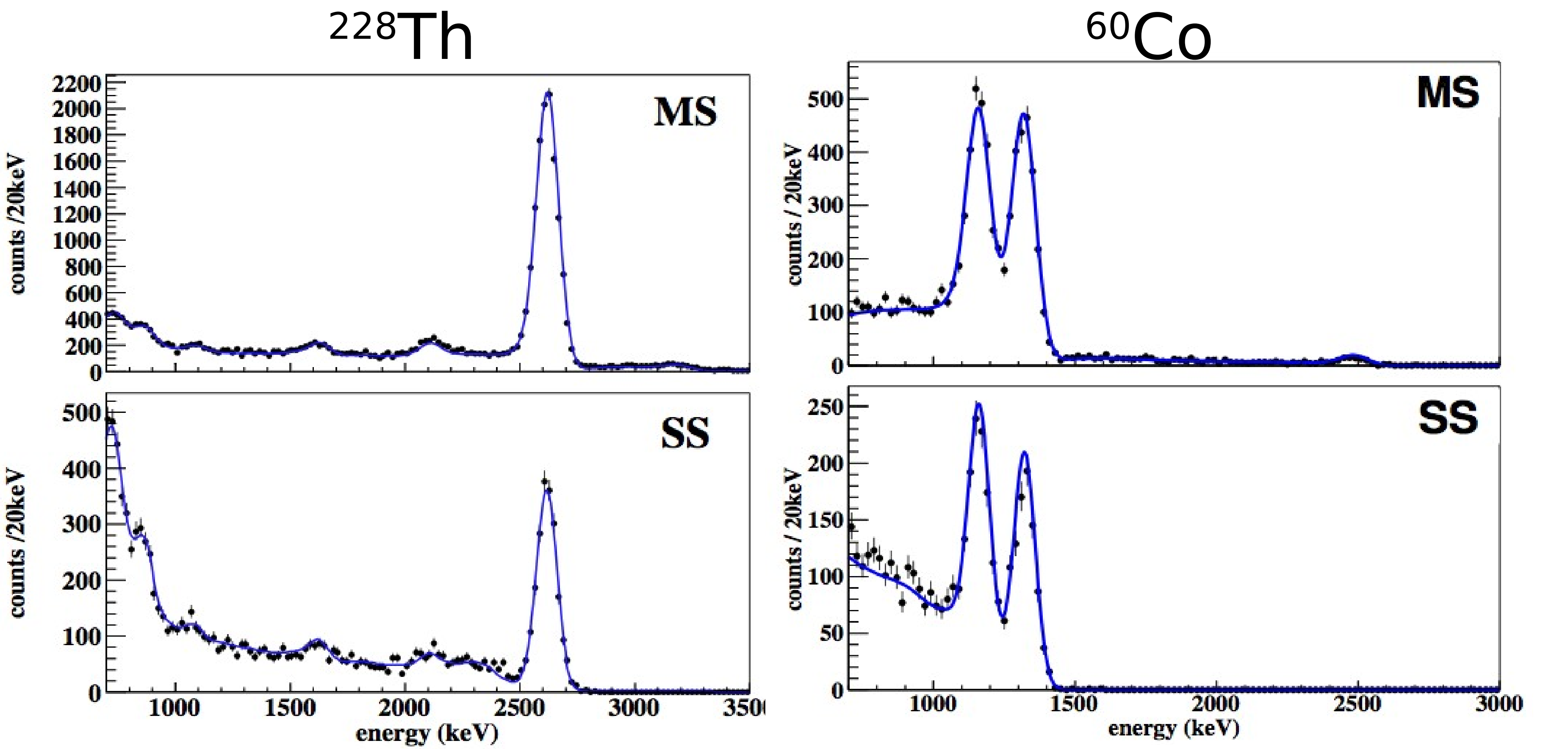
PDF generation with **Geant4** Monte-Carlo simulation

Simulated 228Th source calibration



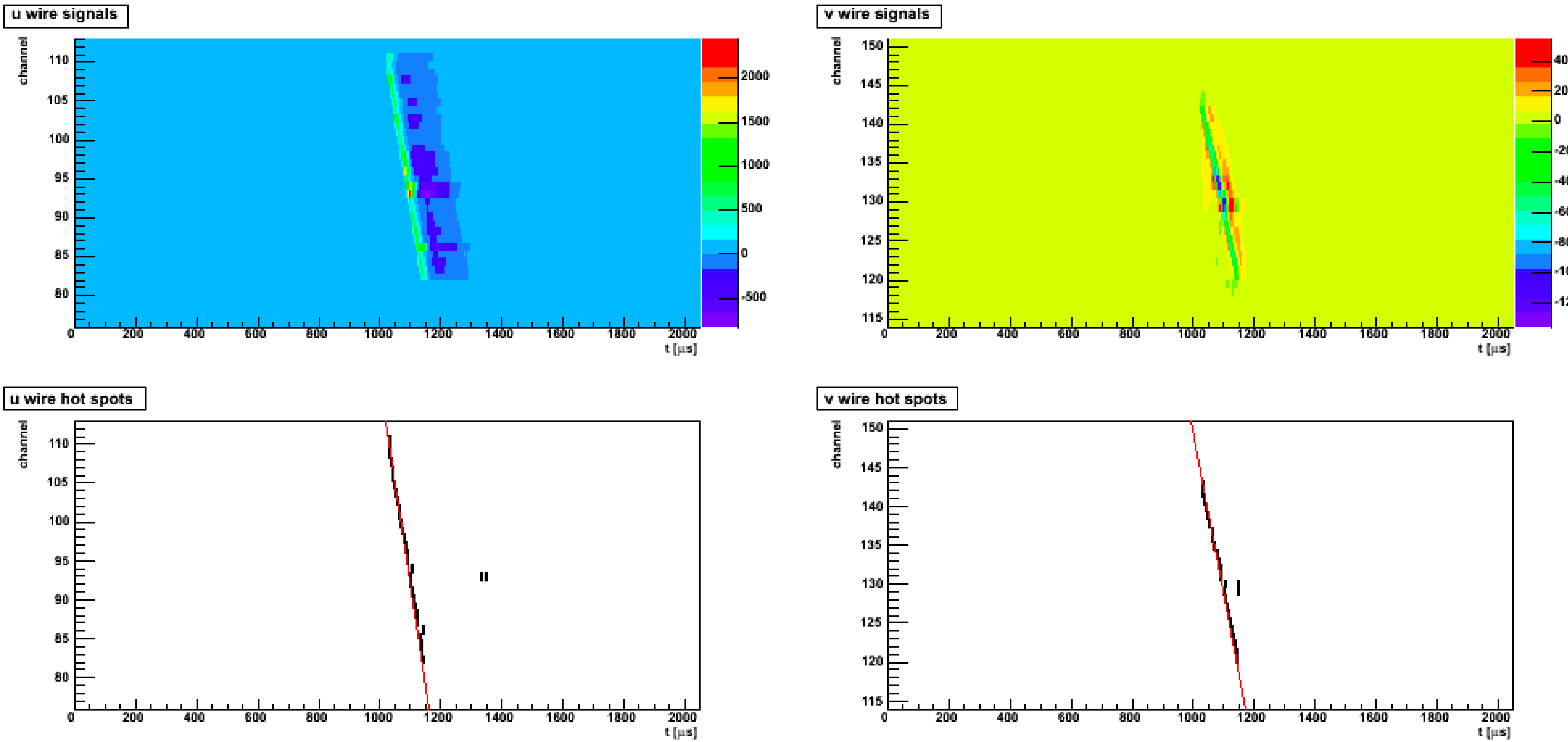
- Digitization simulation provides charge cluster multiplicity and positioning
- Energy spectrum uses the MC true charge deposition (dotted line)
- Energy spectrum convoluted the energy resolution model (solid line)

Comparison of **source calibration run** with the **Geant4 PDF**



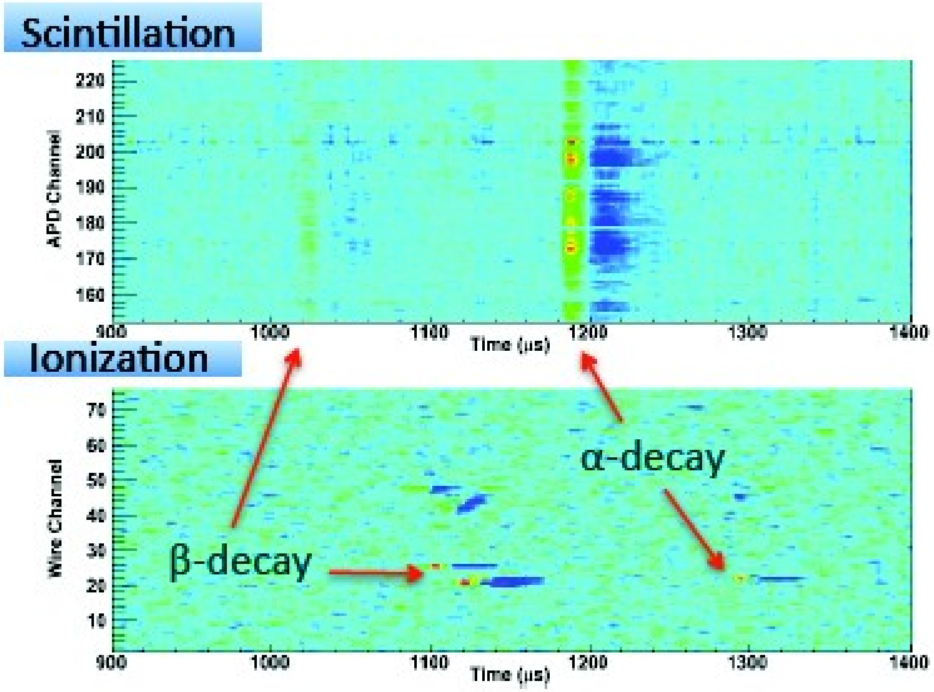
- Excellent agreement in **shape**
- Maximum **rate** discrepancy is 9.4% (fiducial volume uncertainty)
- Maximum **single site fraction** discrepancy is 8.5%

Cosmic Muons in the TPC

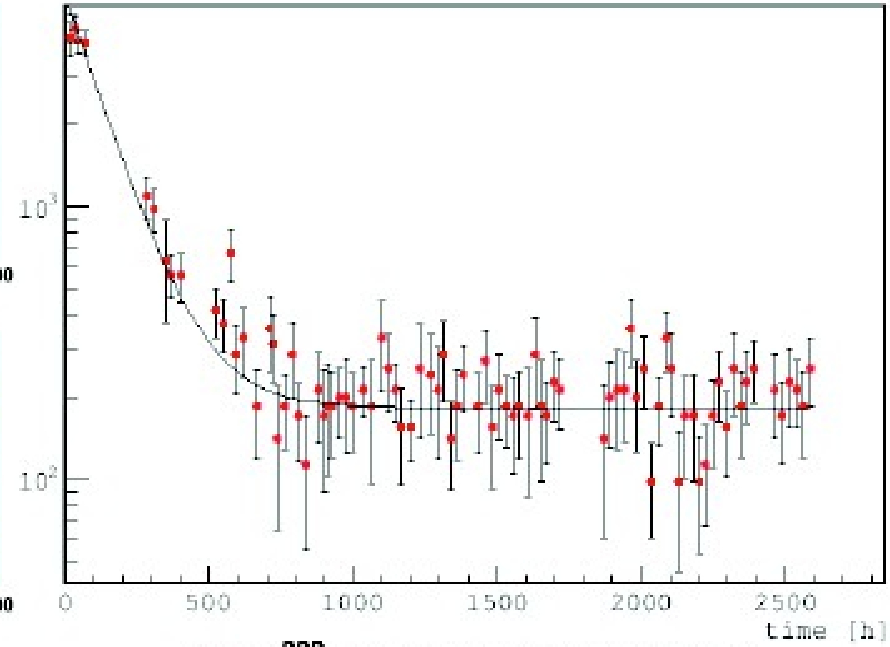


- Cosmic rays can create short-lived isotopes that have high energy gamma or beta decays
- Cosmic ray muons can be identified by the distinctive tracks they leave in the TPC
  - Cut all events within 60 s of a tagged muon in the TPC
- The muon veto panels that surround the clean rooms also have 96% efficiency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

Rn Content in Xenon



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

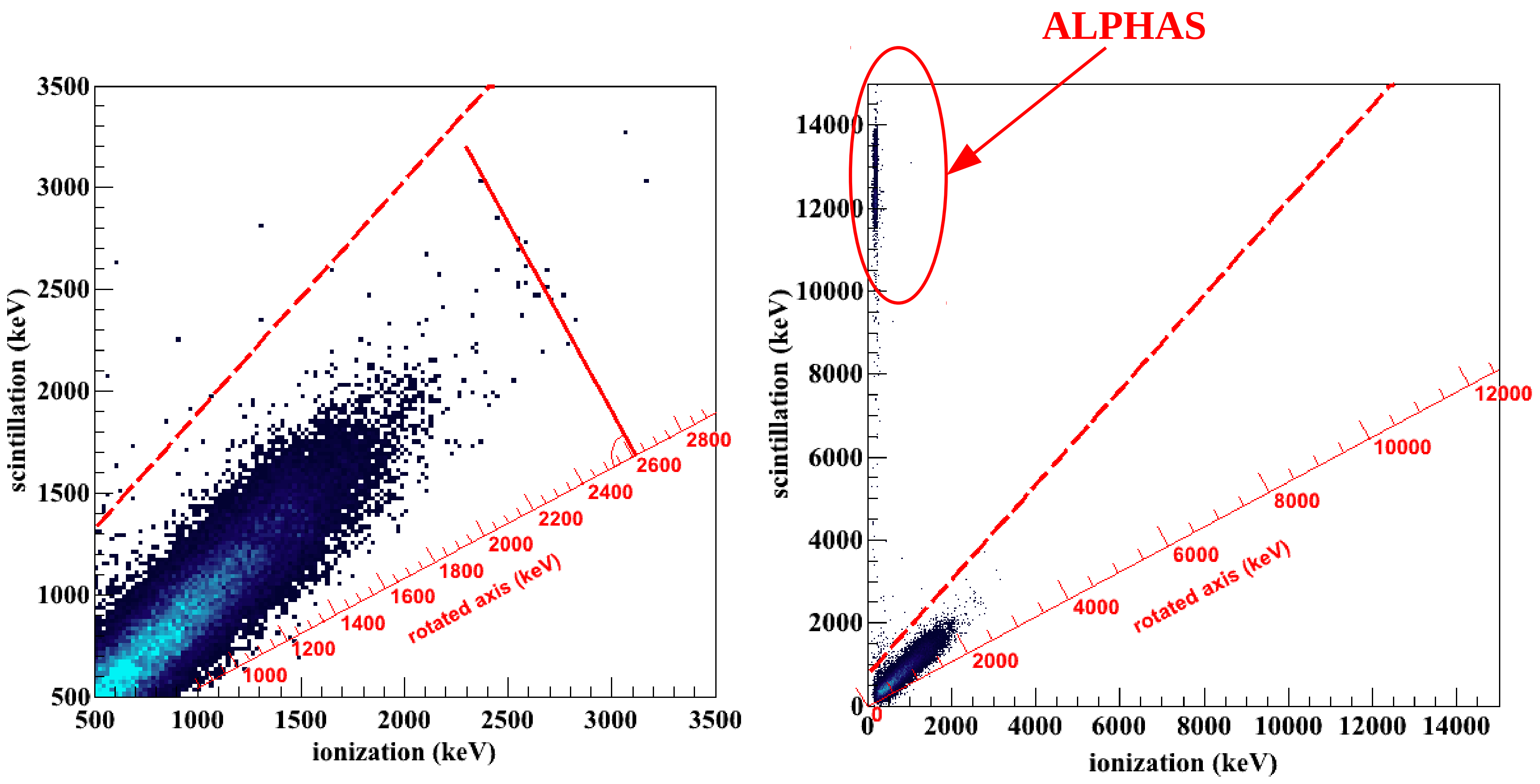


Total ^{222}Rn in LXe after initial fill

Using the Bi-Po (Rn daughter) coincidence technique, we can estimate the Rn content in our detector. The ^{214}Bi decay rate is consistent with measurements from alpha-spectroscopy.

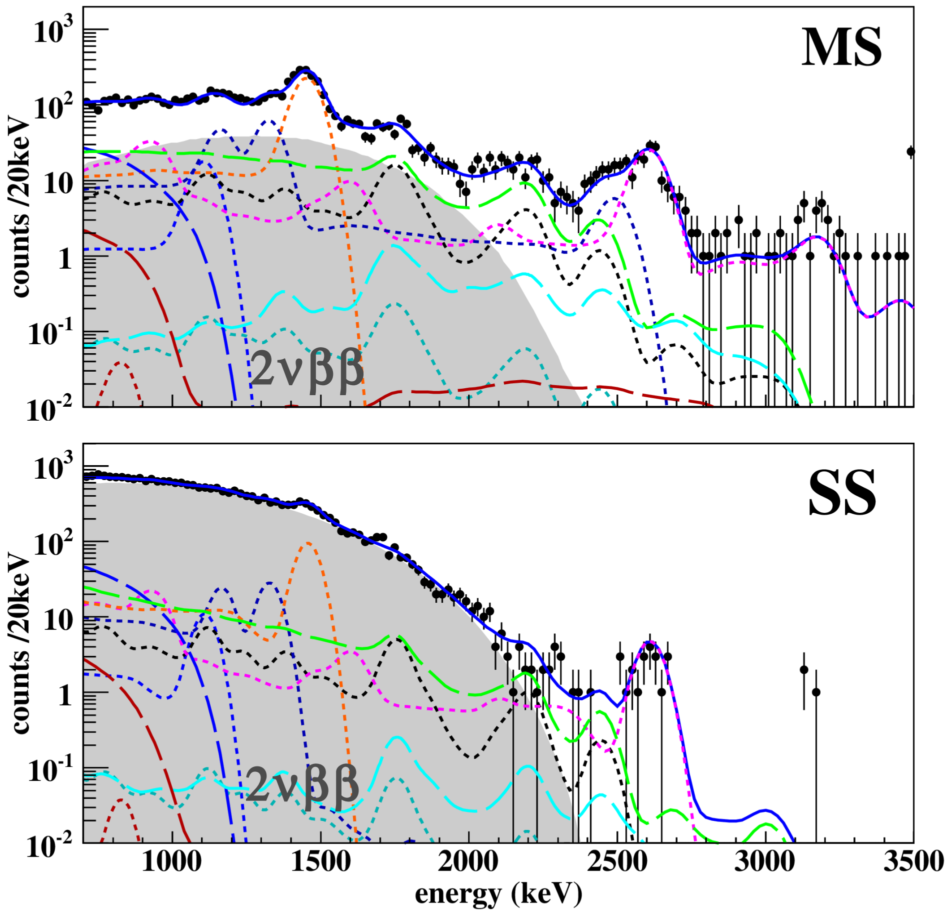
Long-term study shows a constant source of ^{222}Rn dissolving in ^{enr}LXe: 360 ± 65 µBq (Fid. vol.)

Low Background Spectra



Low Background Run

Maximum likelihood fit

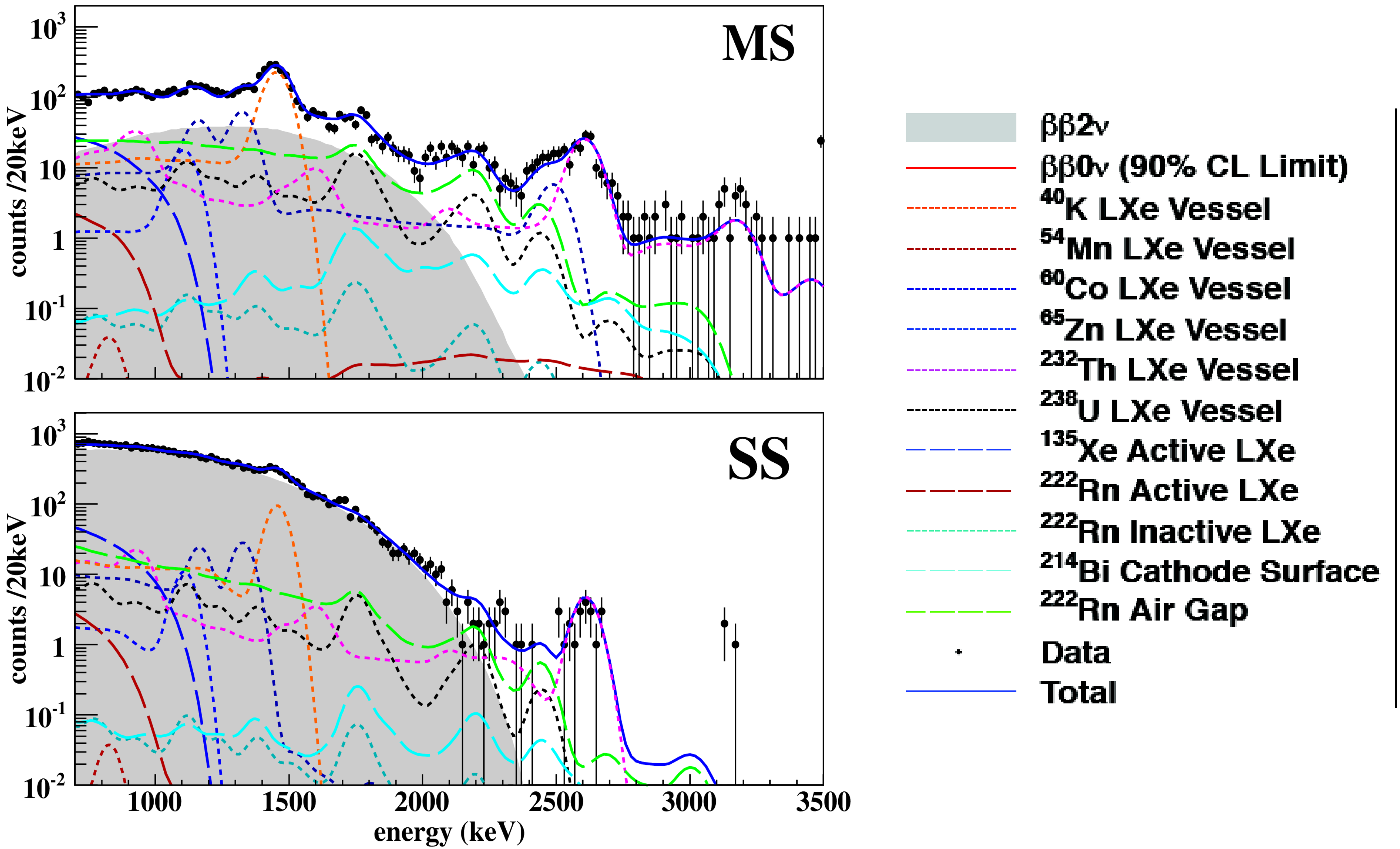


- Trigger fully efficient above 700 keV
- Low background run livetime: **120.7 days**
- Active mass: **98.5 kg LXe (79.4 kg ^{136}LXe)**
- Exposure: **32.5 kg·yr**
- Total dead time (vetos): 8.6%
- Various background PDFs fitted along with 2νββ and 0νββ PDFs

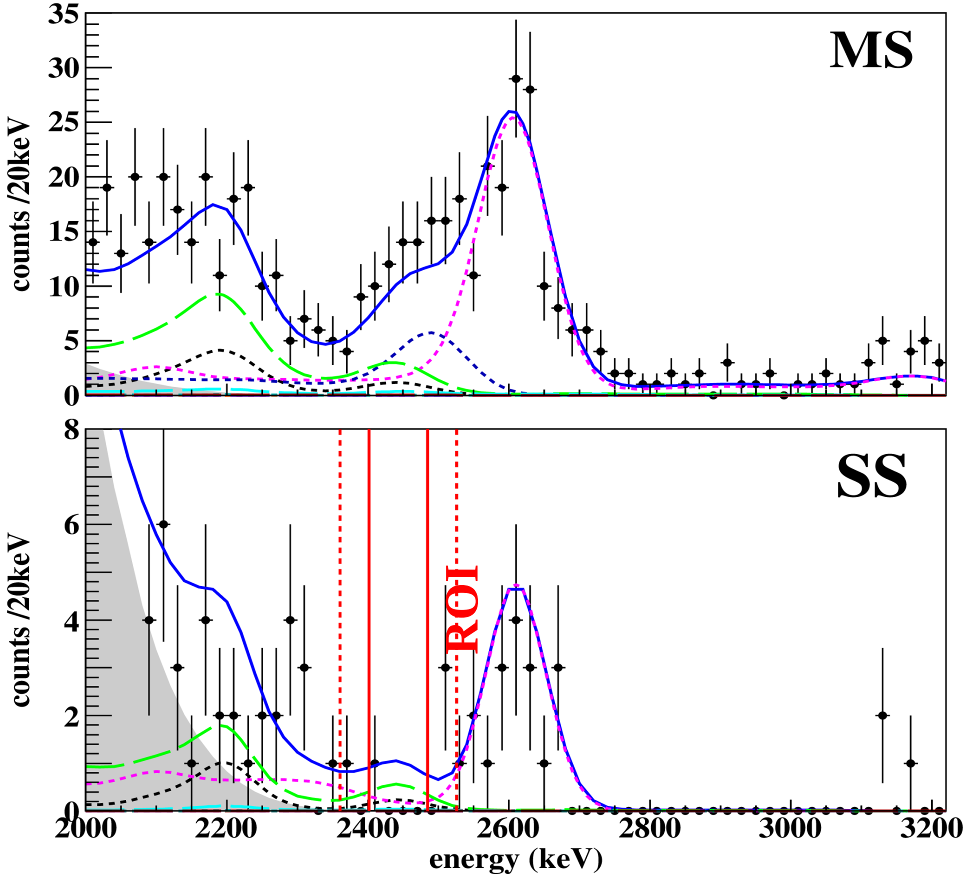
$T_{1/2}^{2\nu\beta\beta}$ (^{136}Xe) = (2.23 ± 0.017 stat ± 0.22 sys)·10^{21} yr

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

Low background Run



Zoomed around 0νββ region of interest (ROI)



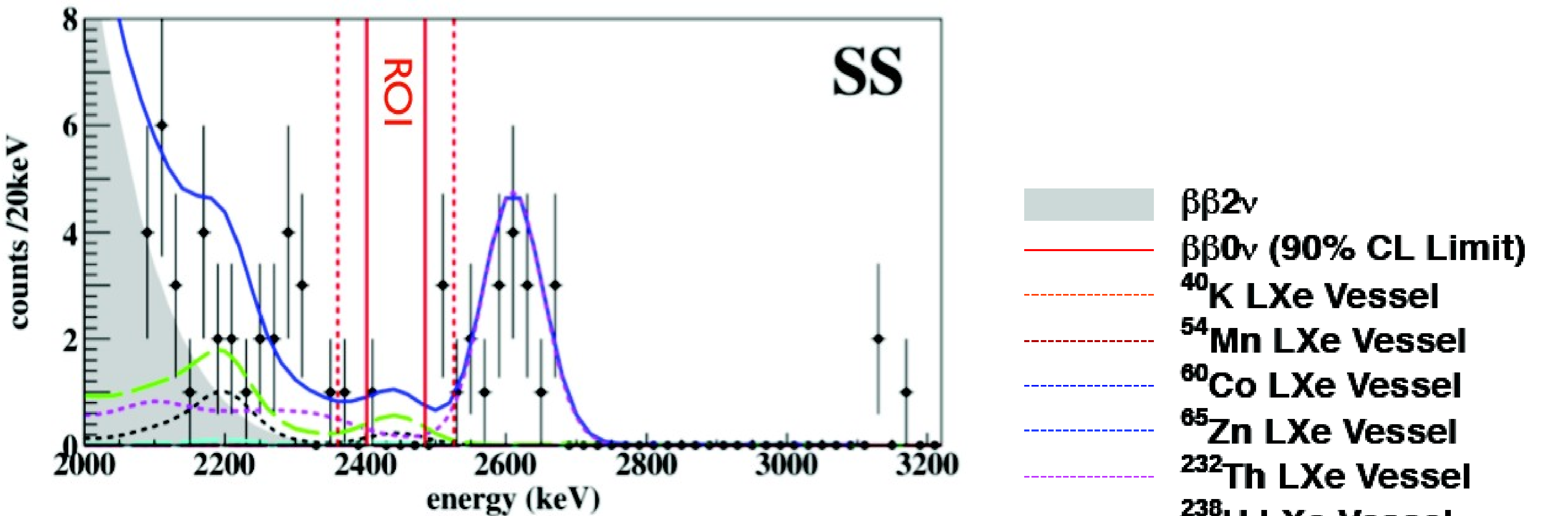
- No signal observed
- Background in ROI:

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

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

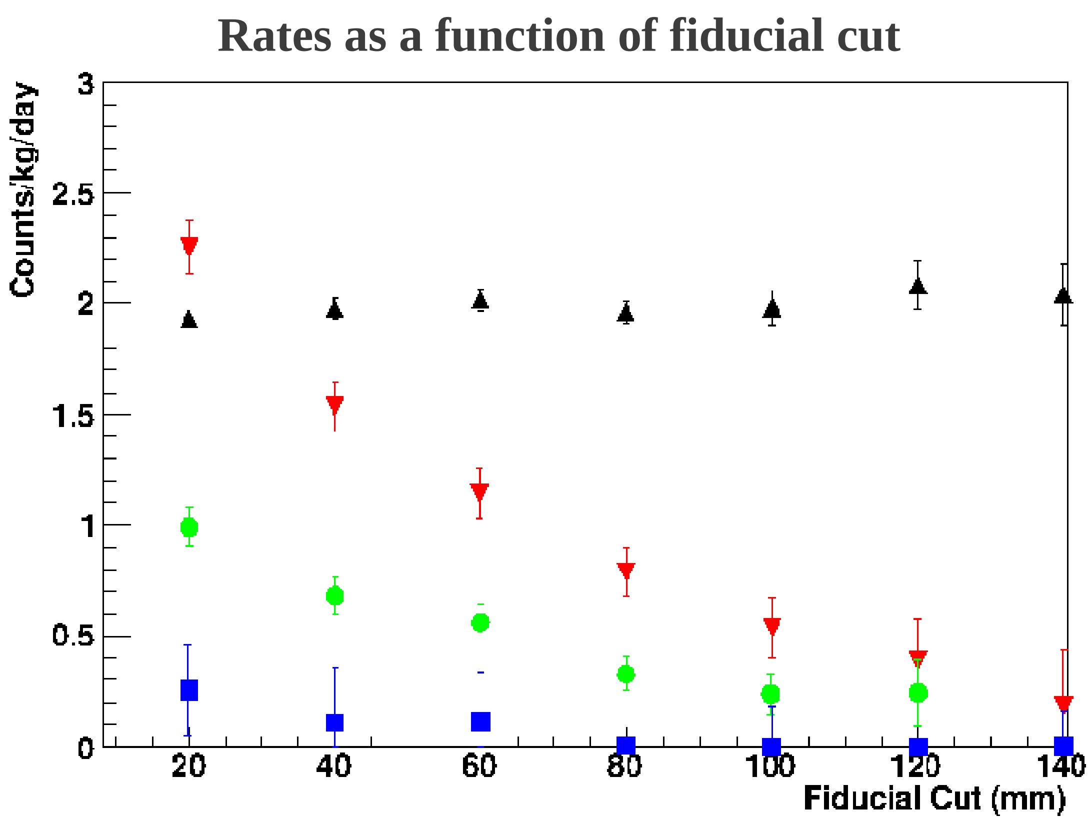
$T_{1/2}^{0\nu\beta\beta}$ (^{136}Xe) > $1.6{\cdot}10^{25}$ yr (90% C.L.)

M. Auger *et al.* Phys. Rev. Lett. 109, 032505 (2012)

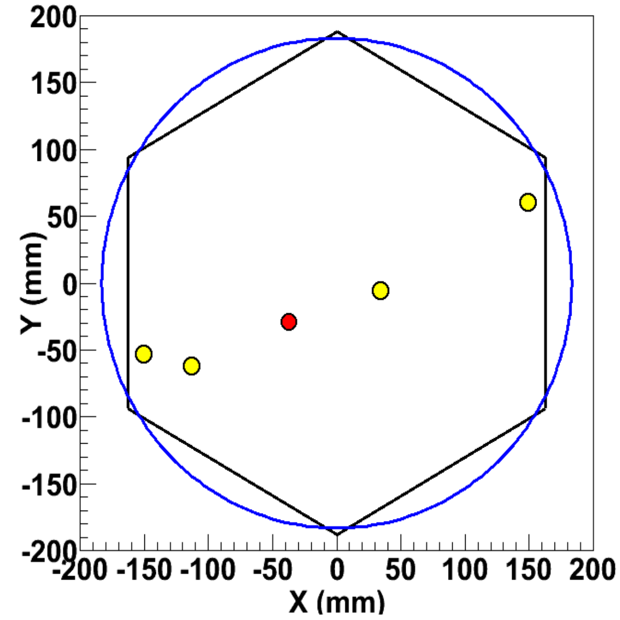


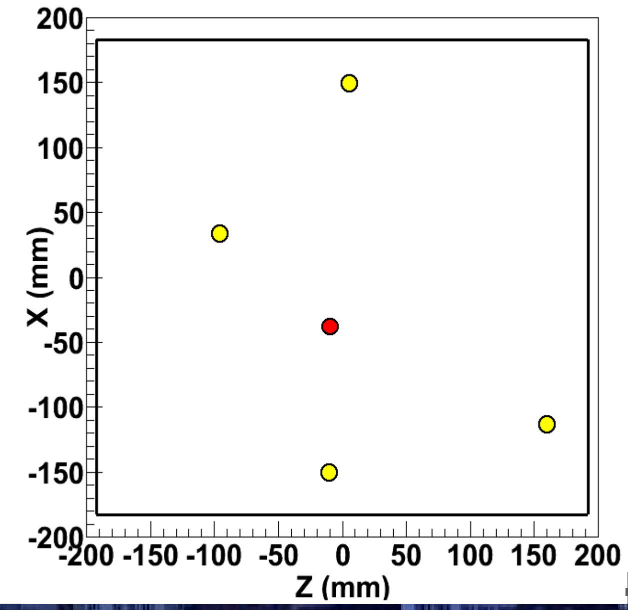
	Expected events from fit			
	±1 σ		±2 σ	
^{222}Rn in cryostat air-gap	1.9	±0.2	2.9	±0.3
^{238}U in LXe Vessel	0.9	±0.2	1.3	±0.3
^{232}Th in LXe Vessel	0.9	±0.1	2.9	±0.3
^{214}Bi on Cathode	0.2	±0.01	0.3	±0.02
All Others	~0.2		~0.2	
Total	4.1	±0.3	7.5	±0.5
Observed	1		5	
Background index b ($kg^{-1}yr^{-1}keV^{-1}$)	$1.5 \cdot 10^{-3} \pm 0.1$		$1.4 \cdot 10^{-3} \pm 0.1$	

1 (5) events from 1σ (2σ) ROI



Black – $2\nu\beta\beta$
Red – ^{40}K X10
Blue – ^{238}U X10
Green – ^{232}Th X10





CUTS:

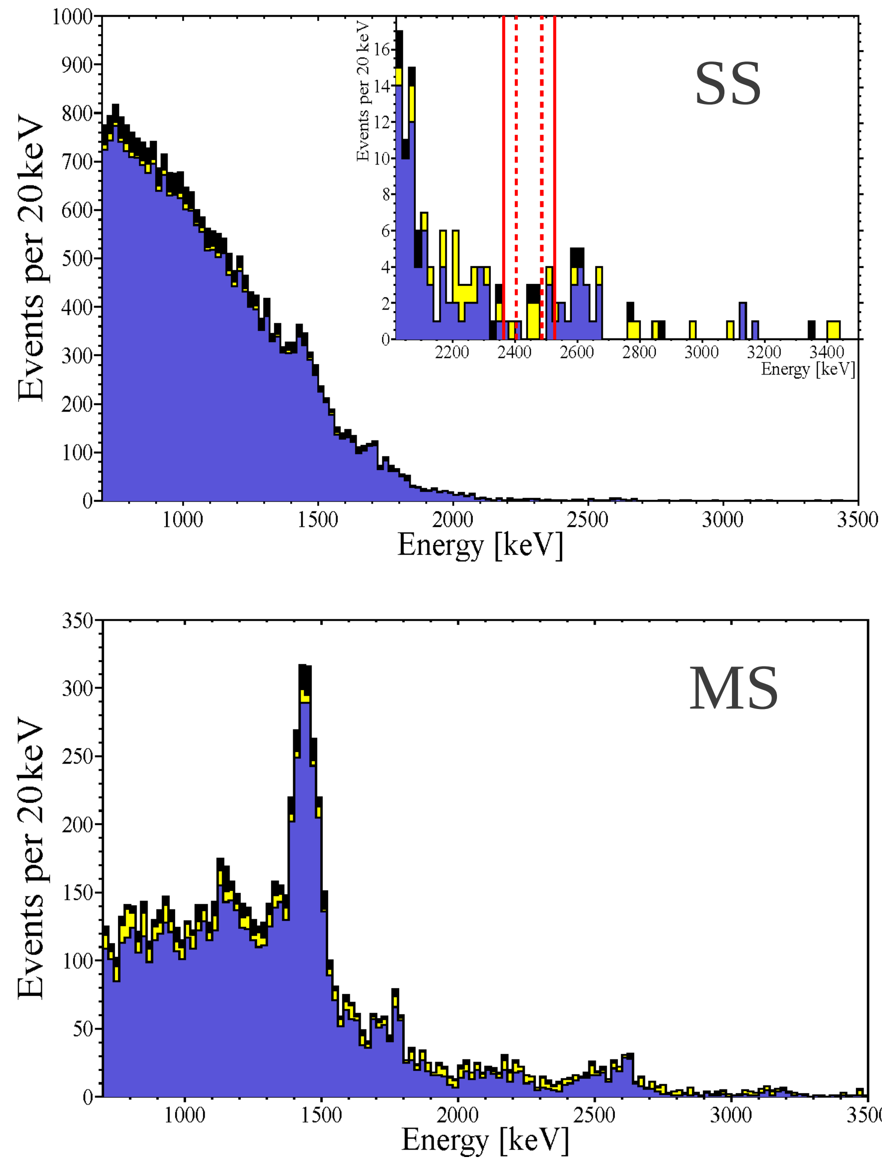
- Events less than 25 ms after a veto hit

- Events less than 60 s after a muon track

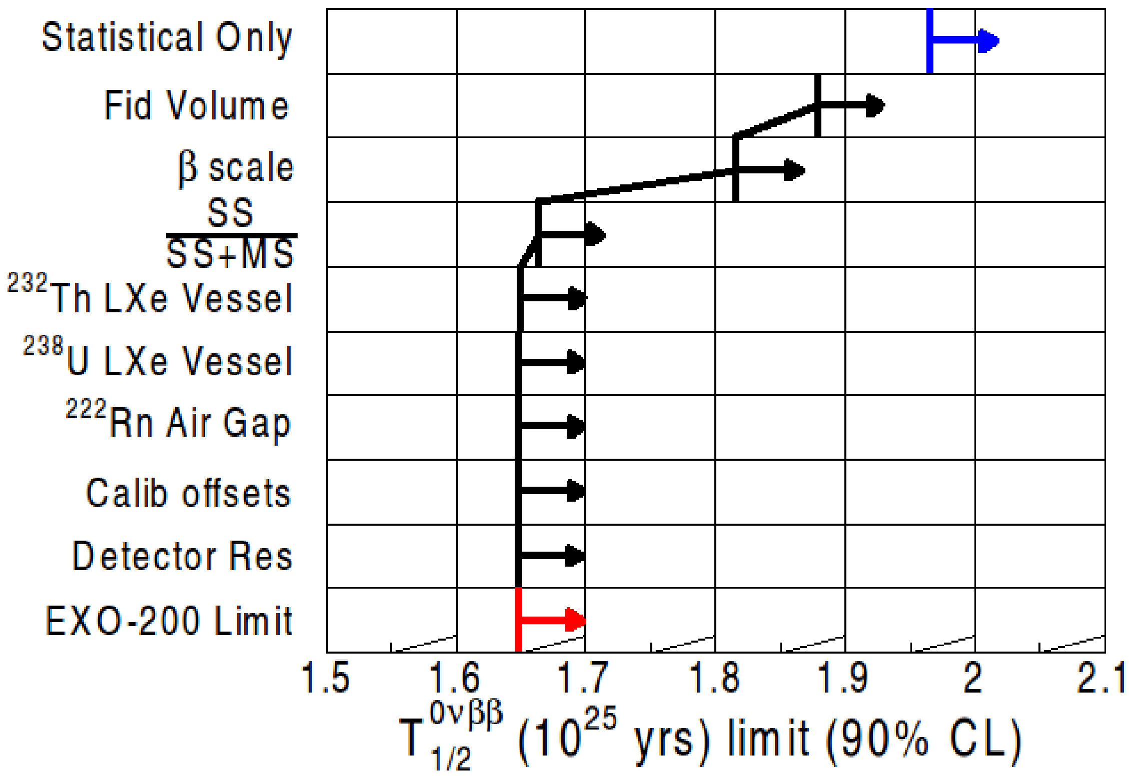
- 2 events occurring within 1 s

- More than 1 event in the acquisition frame

Total dead time: 8.6 %



Events within fiducial volume
- Culled by data cleaning
- <25ms from veto
- Final dataset

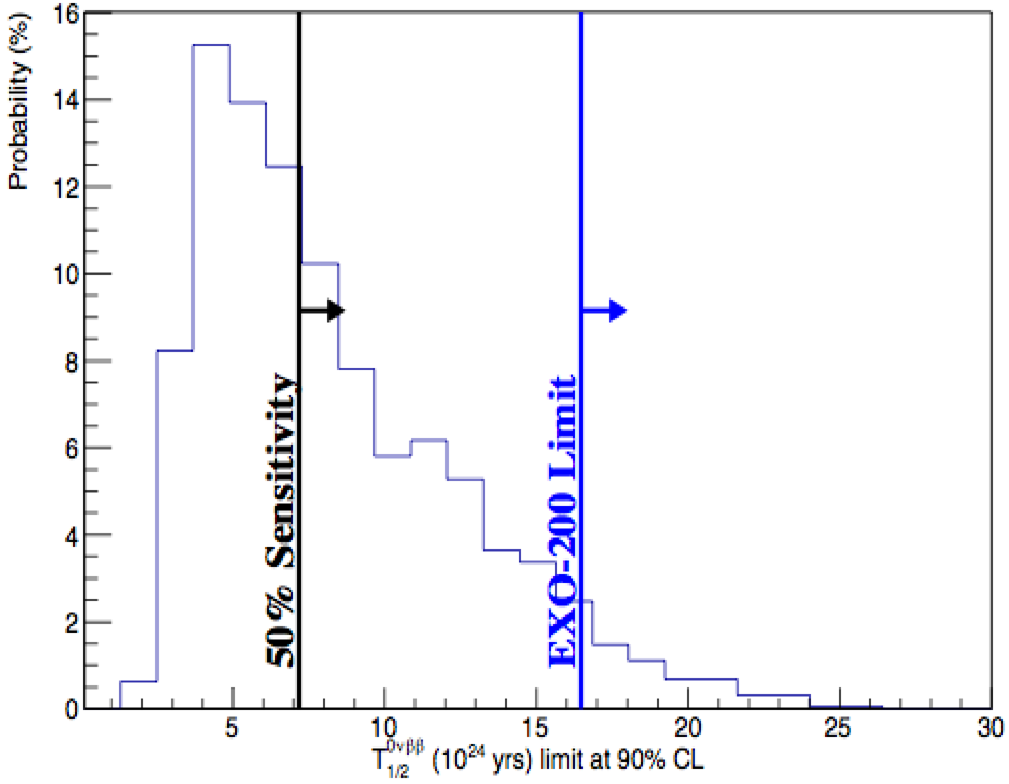


Term	%
Fid Volume	12.34
β scale	9.32
$\frac{SS}{SS+MS}$	0.93
^{232}Th LXe Vessel	0.11
^{238}U LXe Vessel	0.04
^{222}Rn Air Gap	0.04
Calib offsets	0.04
Detector Res	0.00

Error breakout: expected 90% CL limit given absolute knowledge (0 error) of a given parameter or set of parameters.

Low-Background Run - Sensitivity

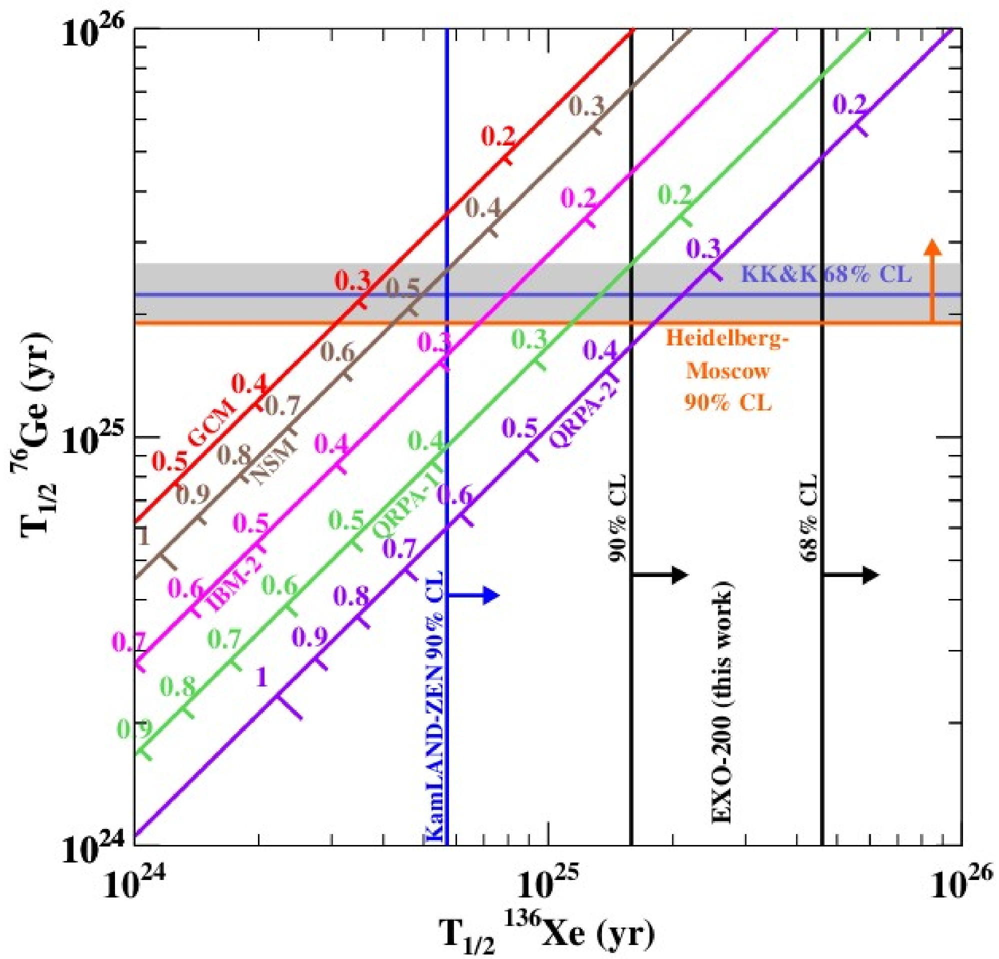
Distribution of 0νββ $T_{1/2}$ limits from Monte-Carlo (with null result)



We expect to quote a limit of **$7 \cdot 10^{24}$ yrs** or better **50%** of the time (sensitivity)

We expect to quote a limit of **$1.6 \cdot 10^{25}$ yrs** or better **6.5%** of the time

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.

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

$\langle m_{\beta\beta} \rangle < (140 – 380)$ meV (90% C.L.)

M. Auger *et al.* Phys. Rev. Lett. 109, 032505 (2012)

$0\nu\beta\beta$ run with 32.5 kg·yr exposure:

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

$T_{1/2}^{2\nu\beta\beta}$ (^{136}Xe) = (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)

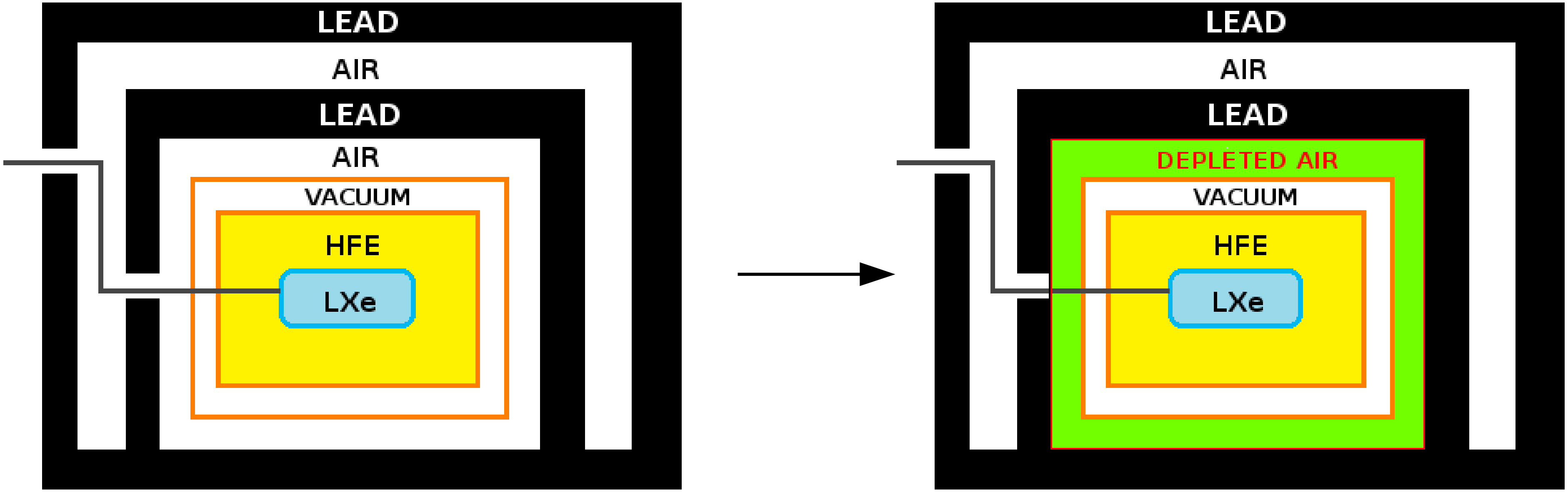
$T_{1/2}^{0\nu\beta\beta}$ (^{136}Xe) > $1.6 \cdot 10^{25}$ yr (90% C.L.)

$\langle m_{\beta\beta} \rangle$ < (140 – 380) meV (90% C.L.)

M. Auger *et al.* Phys. Rev. Lett. 109, 032505 (2012)

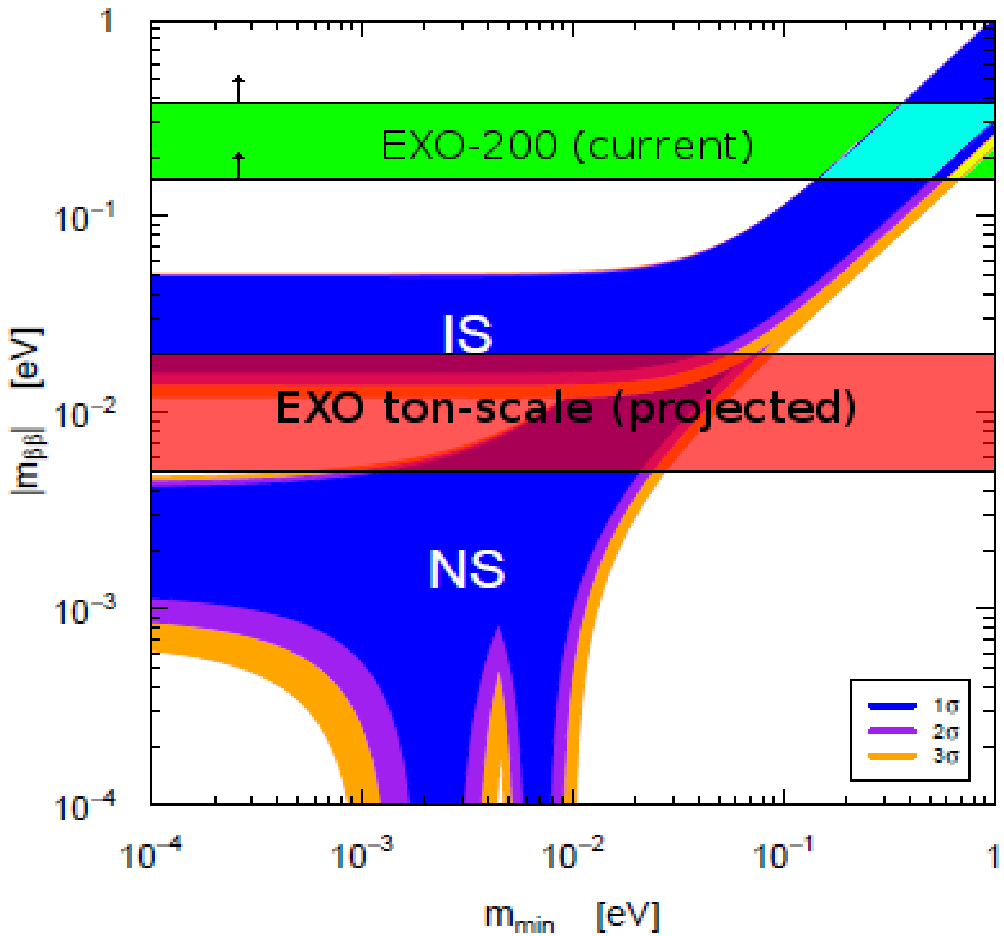
Future Work - Radon Tent Upgrade

- Fit results indicate **radon** in the **“air-gap”** is the dominant background.
- Plans to **upgrade** already implemented **“radon tent”.**
- Consolidate radon tent air-tightness and increase **depleted air** flow.



Short term future plans:

- Event reconstruction upgrades (**site multiplicity**)
- Radon tent work
- Induction signal study (**energy resolution + efficiency)**
- Exposure increasing



Longer term future plans:

Discussions for a ton-scale EXO detector (**nEXO**) have started.

nEXO would be designed to accept a barium-tagging apparatus when ready: <u>drastic background reduction.</u>

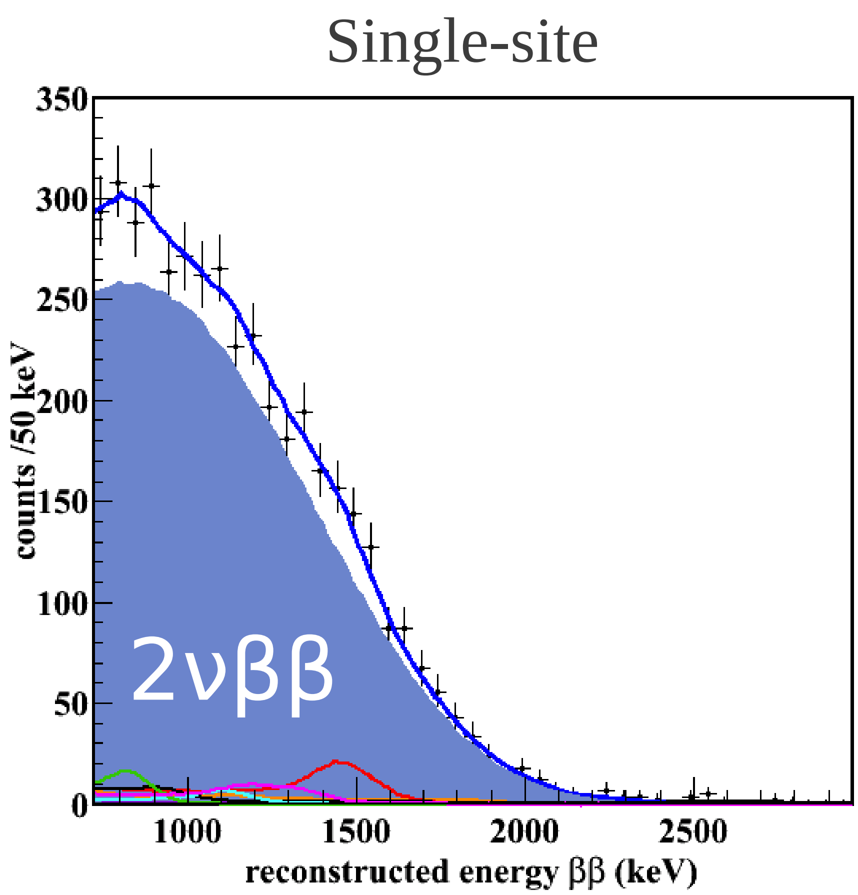
Thank you for your attention.

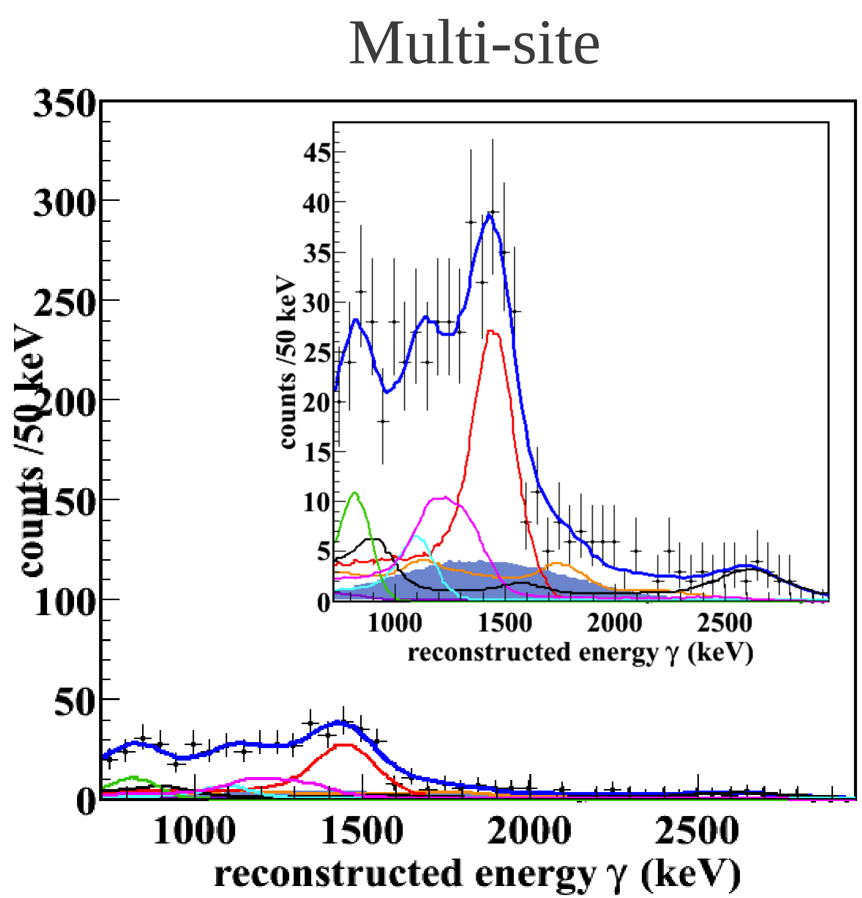
Enriched Xenon Observatory
for double beta decay

LABORATORIUM FÜR HOCHENERGIEPHYSIK
LHEP
UNIVERSITÄT BERN

EXTRA SLIDES

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]**