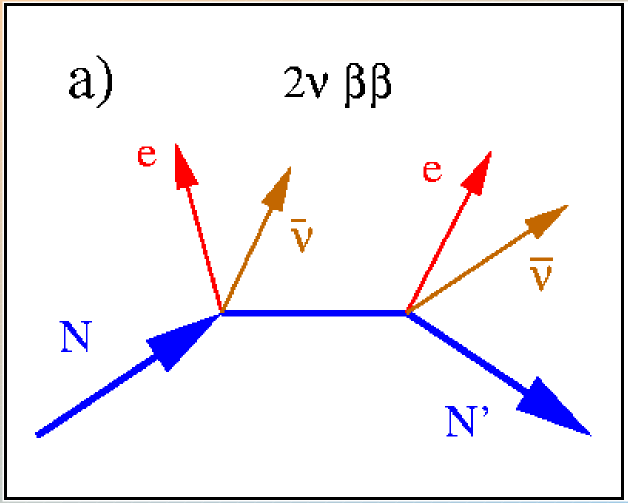
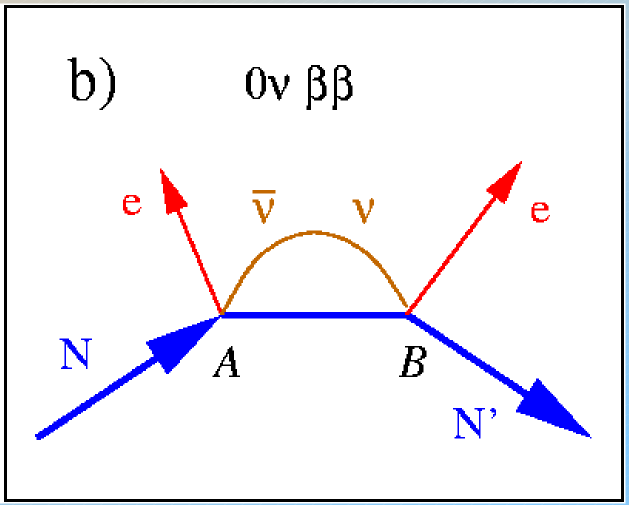
Recent results from EXO-200

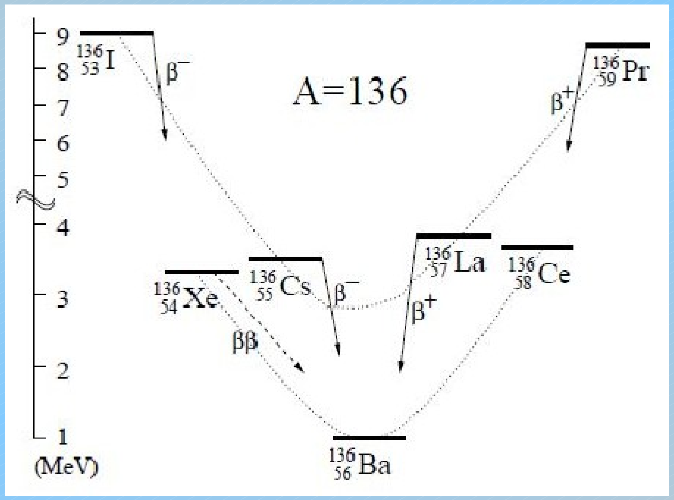
Vladimir Belov, ITEP & MEPhI
for the EXO collaboration

16th Lomonosov Conference, Moscow, 23 August 2013

Double beta decay





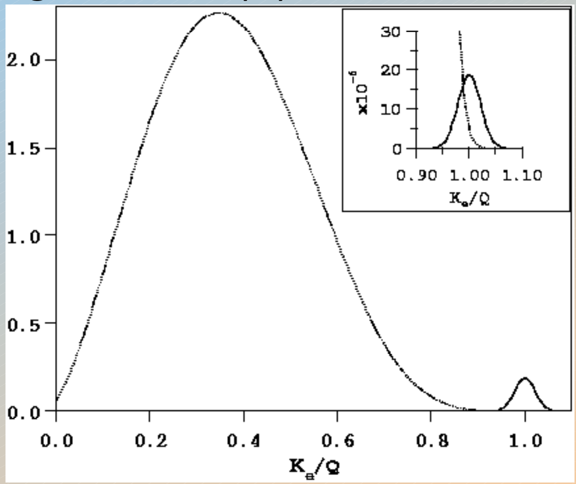


2ν mode:
a conventional
2nd order process
in Standard Model

0ν mode:
a hypothetical process
can happen only if:
$\langle m_\nu \rangle \neq 0$, $\nu = \bar{\nu}$

$|\Delta L|=2$, $|\Delta(B-L)|=2$

Simulated double beta decay spectrum
P.Vogel. arXiv:hep-ph/0611243



To reach high measurement sensitivity for 0ν mode one requires,

- High energy resolution
- Large Isotope mass
- Low background

Why xenon

Energy resolution is poorer than the crystalline devices (~ factor 10), but...

Monolithic detector. Xenon can form detection medium, allow self shielding, surface contamination minimized. Very good for large scale detectors.

Has high Q value. Located in a region relatively free from natural radioactivity.

Isotopic enrichment is easier. Xe is already a gas & ^{136}Xe is the heaviest isotope.

Xenon is "reusable". Can be purified & recycled into new detector (no crystal growth).

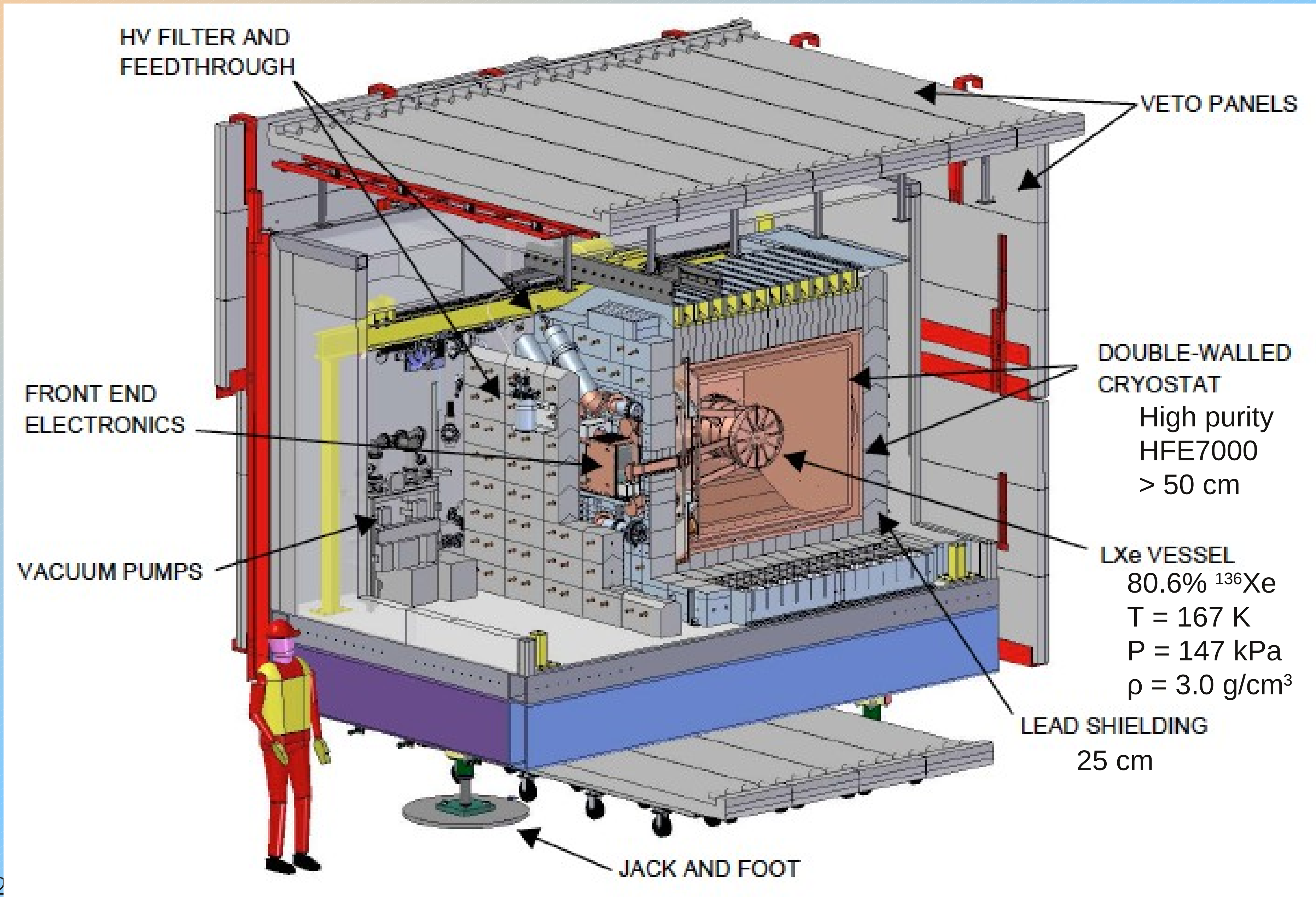
Minimal cosmogenic activation. No long lived radioactive isotopes of Xe.

Energy resolution in LXe can be improved. Scintillation light/ionization correlation.

Particle identification. Slightly limited, but can be used to tag alphas from Rn chain.

… admits a novel coincidence technique. Background reduction by Ba daughter tagging.

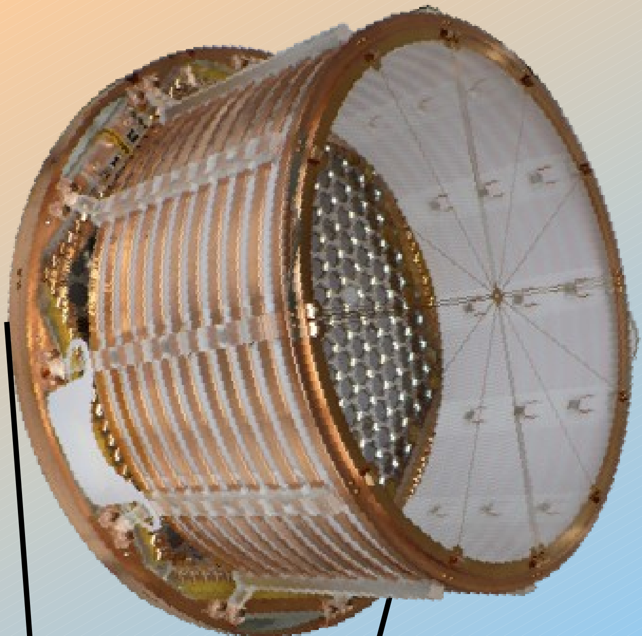
EXO-200 detector

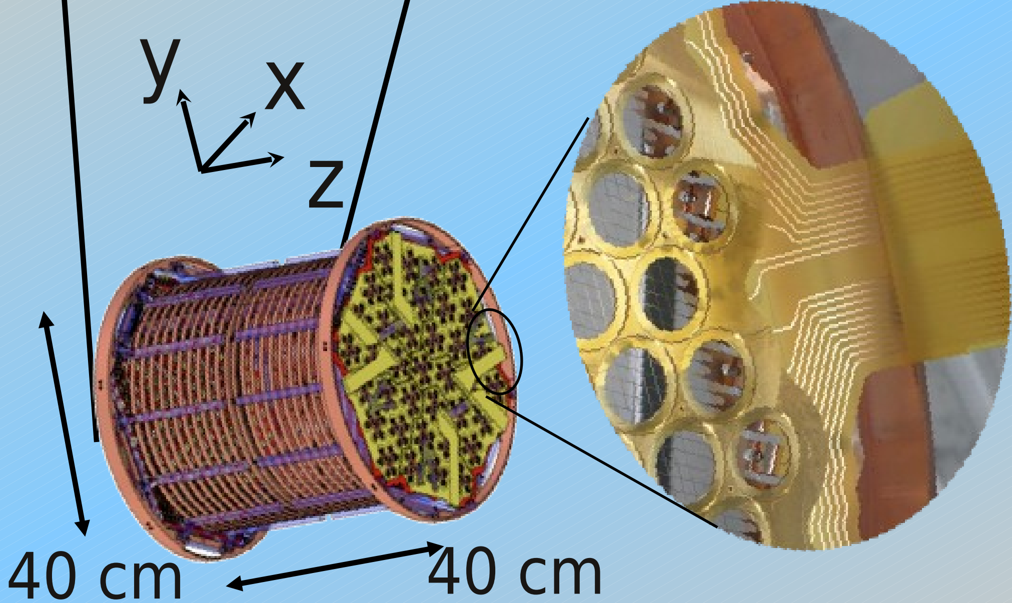


The EXO-200 TPC

Two almost identical halves reading ionization and 178 nm scintillation, each with:

- 38 U triplet wire channels (charge)
- 38 V triplet wire channels, crossed at 60^{o} (induction)
- 234 large area avalanche photodiodes (APDs, light in groups of 7)
- Wire pitch 3 mm (9 mm per channel)
- Wire planes 6 mm apart and 6 mm from APD plane
- All signals digitized at 1 MS/s, ±1024S around trigger
- Drift field 376 V/cm

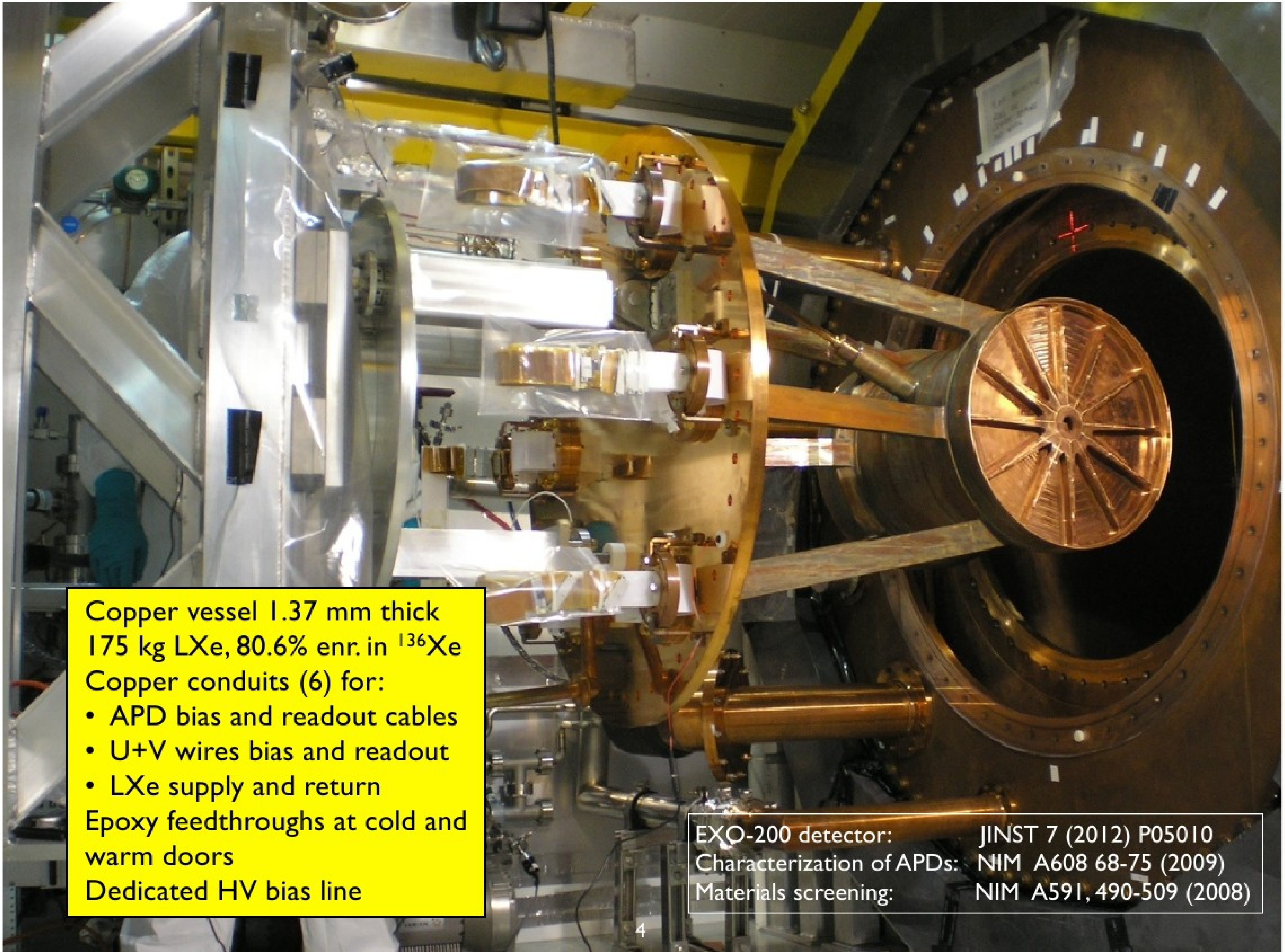




- Field shaping rings: copper
- Supports: acrylic
- Light reflectors/diffusers: Teflon
- APD support plane: copper; Au (Al) coated for contact (light reflection)
- Central cathode, U+V wires: photo-etched phosphor bronze
- Flex cables for bias/readout: copper on kapton, no glue

Comprehensive material screening program

Goal: 40 cnts/2y in 0νββ ±2σ ROI, 140 kg LXe



Copper vessel 1.37 mm thick
175 kg LXe, 80.6% enr. in ^{136}Xe
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:	JINST 7 (2012) P05010
Characterization of APDs:	NIM A608 68-75 (2009)
Materials screening:	NIM A591, 490-509 (2008)

Muon veto

50 mm thick plastic scintillator panels surrounding TPC on four sides.

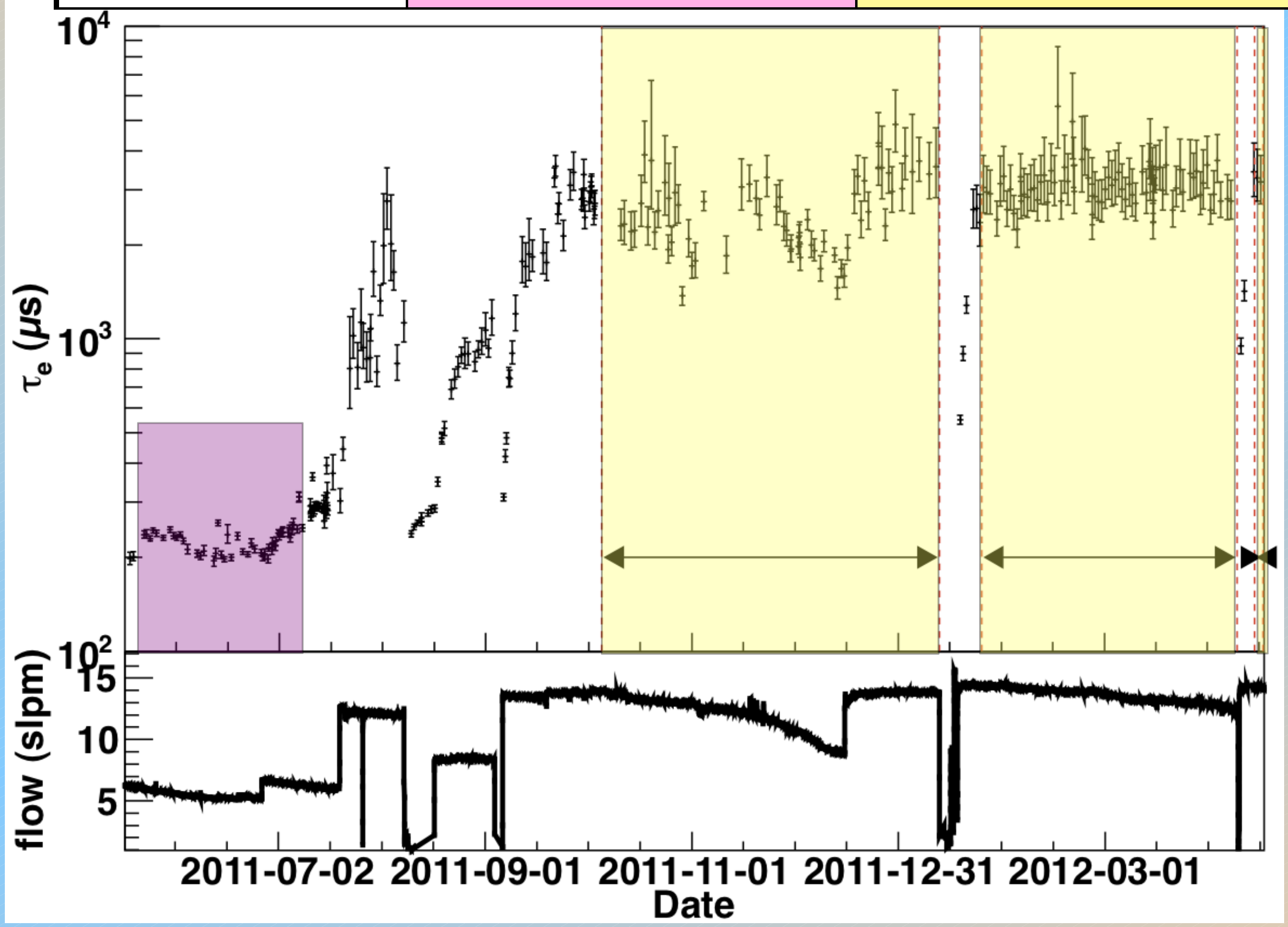
95.5 ± 0.6 % efficiency

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

Data taking phases and xenon purity

	Run I	Run 2a
Period	May 21, 11 – Jul 9, 11	Sep 22, 11 – Apr 15,12
Live Time	752.7 hr	2,896.6 hr
^{136}Xe exposure	3.7 kg-yr	32.5 kg-yr
Publication	PRL 107 (2011) 212501	arXiv:1205:5608



Sep 2011 – Hardware upgrades
- APD gain increase by factor 2
- improved U-wire shaping
- added outer lead shield

Purity

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

For this analysis, the recirculation rate was increased to 14 slpm, leading to long electron lifetimes in the TPC

At τ_e = 3 ms:
- max. drift time ~110 μs
- loss of charge is 3.6% at full drift length

Ultraclean pump:
Rev Sci Instrum. 82(10):105114
Xenon purity with mass spectroscopy:
NIM A675 (2012) 40-46
Gas purity monitors:
NIM A659 (2011) 215-228

Event reconstruction

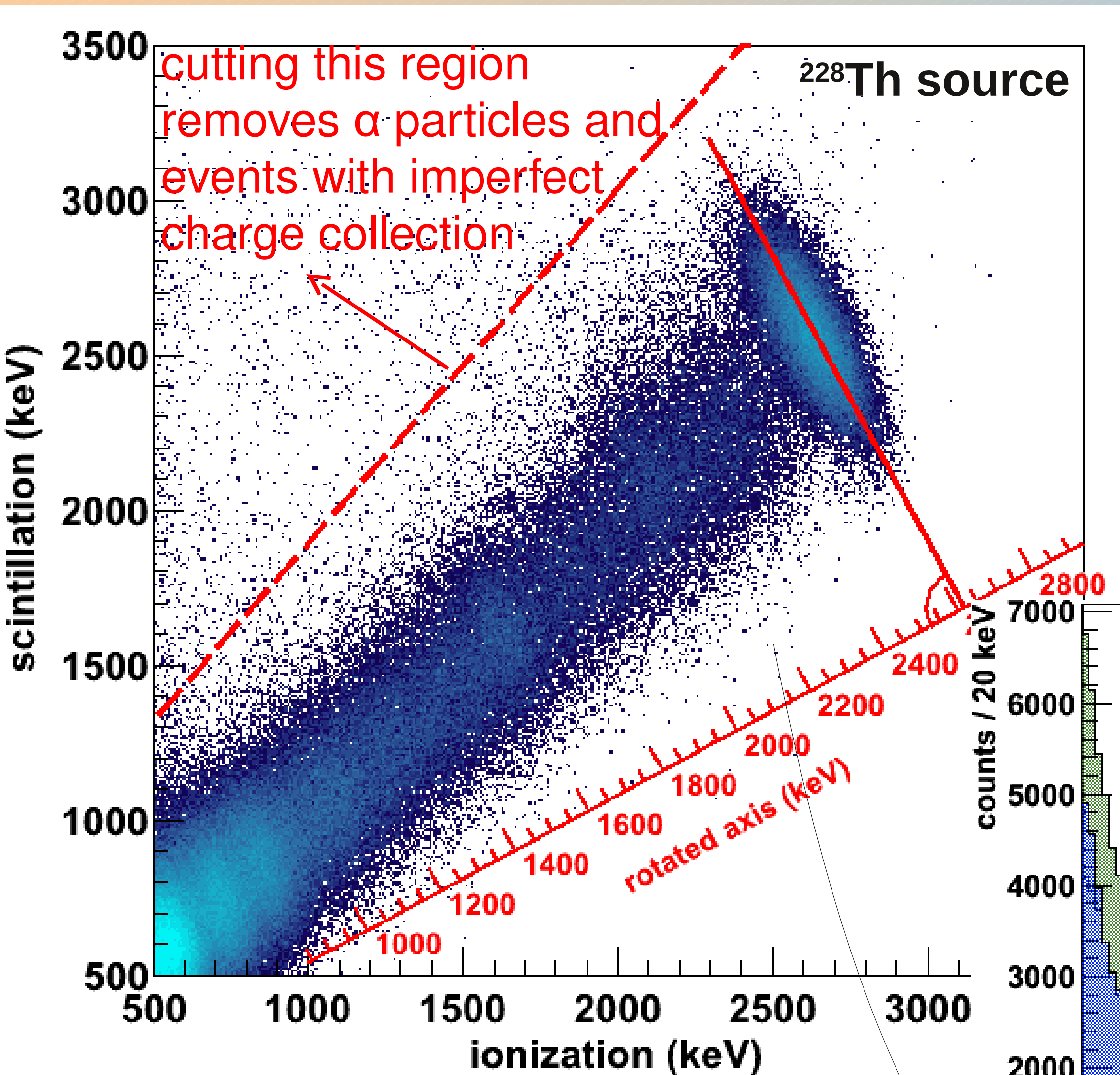
• Signal finding – matched filters applied on U,V and APDs waveforms
• Signal parameter estimation (t, E) for charge and light
• Cluster finding – assignment to Single Site (SS) or Multiple Site (MS): resolution 18mm in X and Y and 6 mm in Z

Amplitudes corrected by channel for gain variation
Signal fitting functions use individual parameters for each channel
Optimized light correction using charge position
Charge corrected for inefficiency on small drift
Require events to be fully reconstructed in 3D

Reconstruction efficiency for $0\nu\beta\beta$ is 71% – estimated by MC and verified by comparing the $2\nu\beta\beta$ MC efficiency with low background data, over a broad range in energy

SS and MS spectra are fitted simultaneously with MC-generated probability density functions

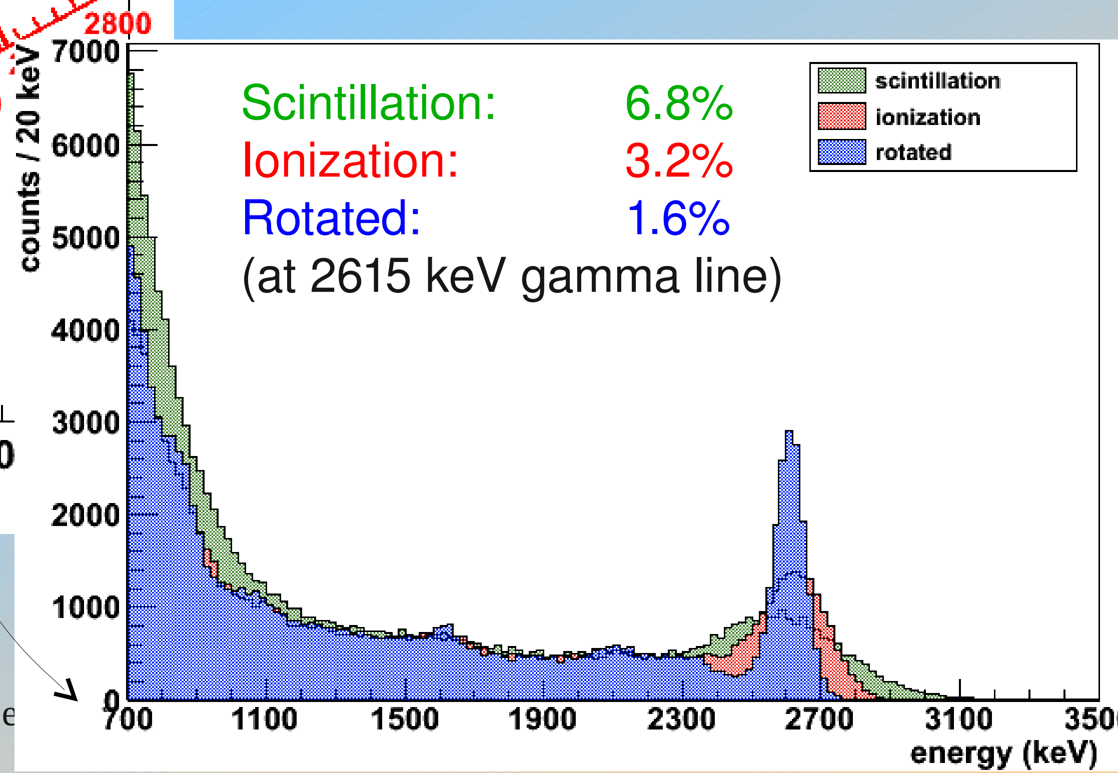
Combining ionization and scintillation



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

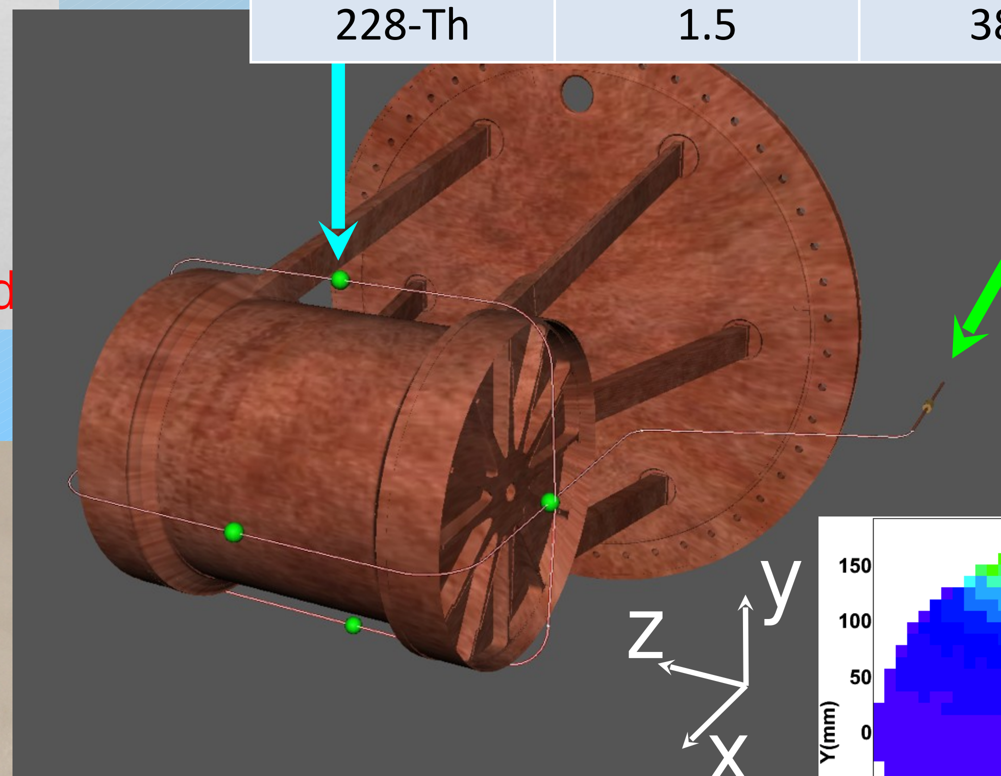
Use projection onto a rotated axis to determine event energy

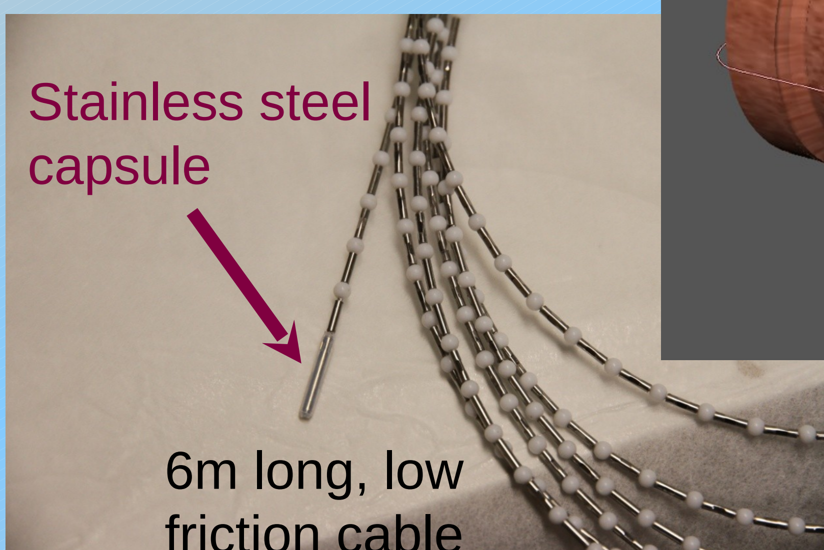


Rotation angle chosen to optimize energy resolution at 2615 keV

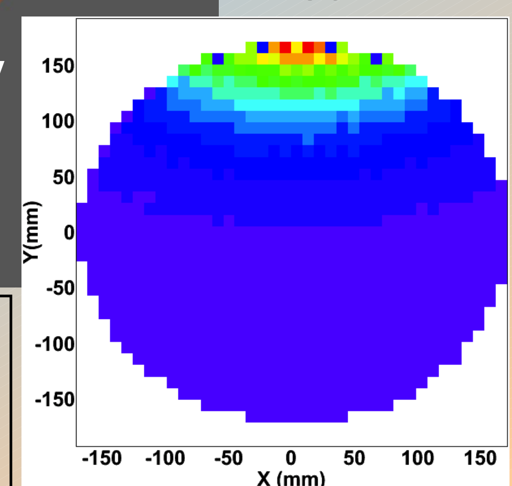
Calibrations

Source	Weak (kBq)	Strong (kBq)
60-Co	3.0	15.0
137-Cs	0.5	7.2
228-Th	1.5	38.0



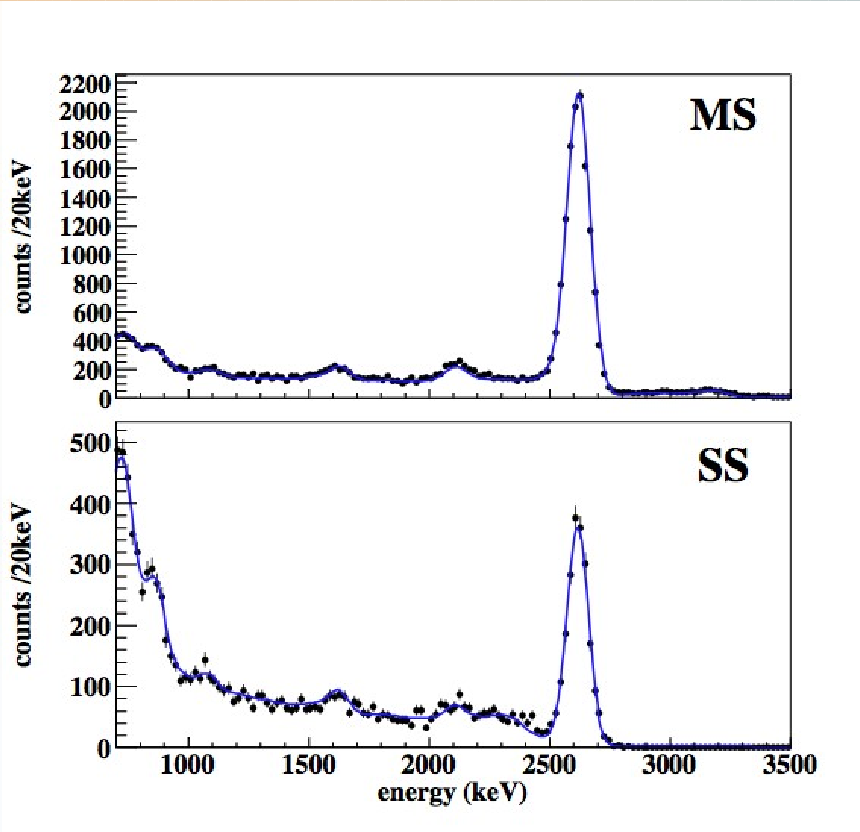


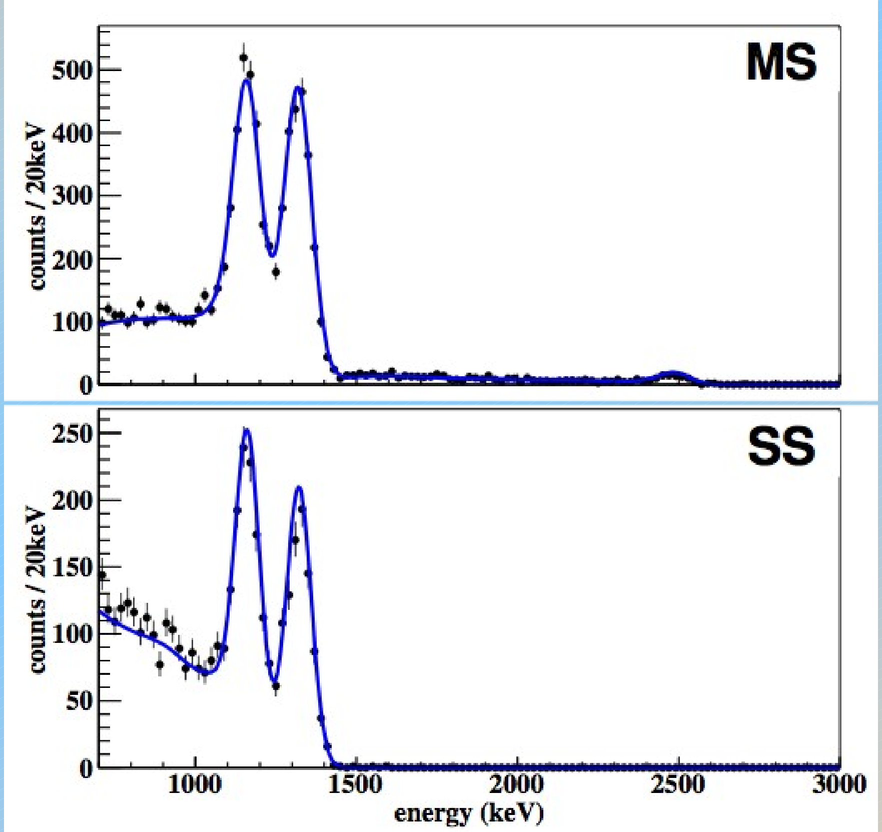
weak ^{228}Th



Provide 4 full energy deposition peaks in the energy range 662 keV – 2615 keV

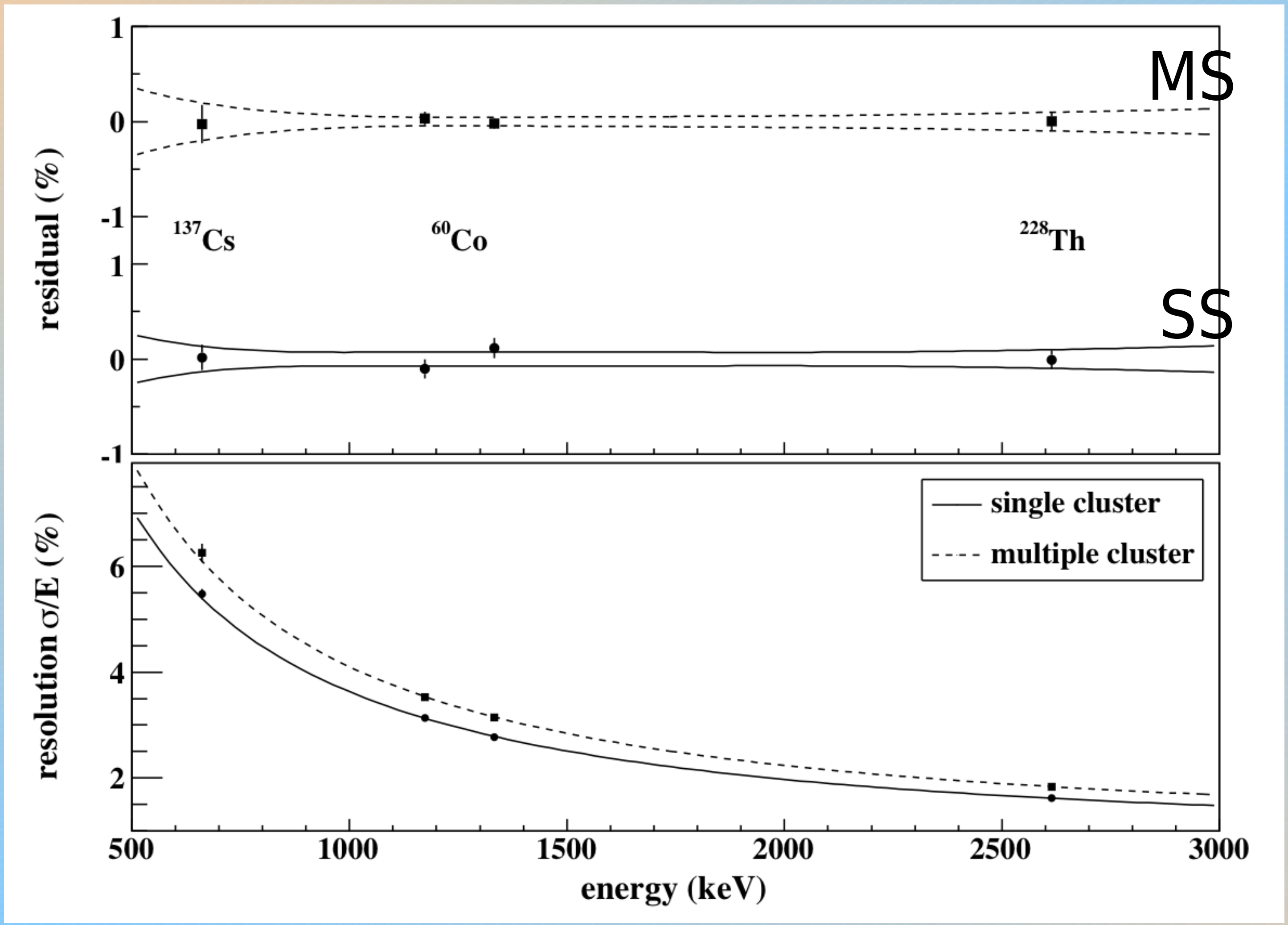
Calibrations source spectrum agreement





- Multi site (MS) and single site (SS) data (black points) are compared to model (blue curves)
- Single site fraction agrees to within 10%
- Can measure source activities better than 4%

Energy Calibration



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

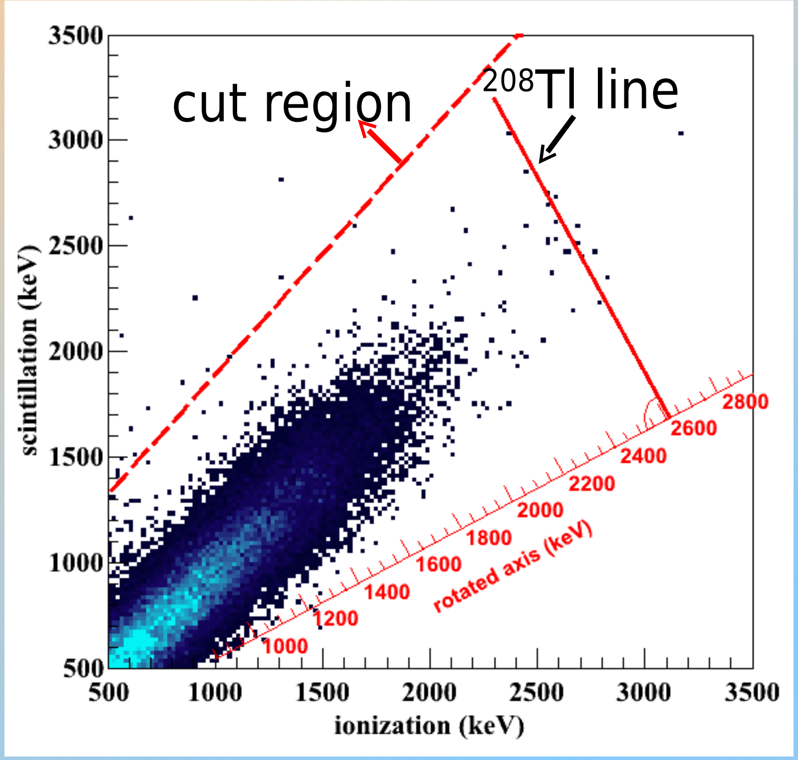
Energy resolution model:

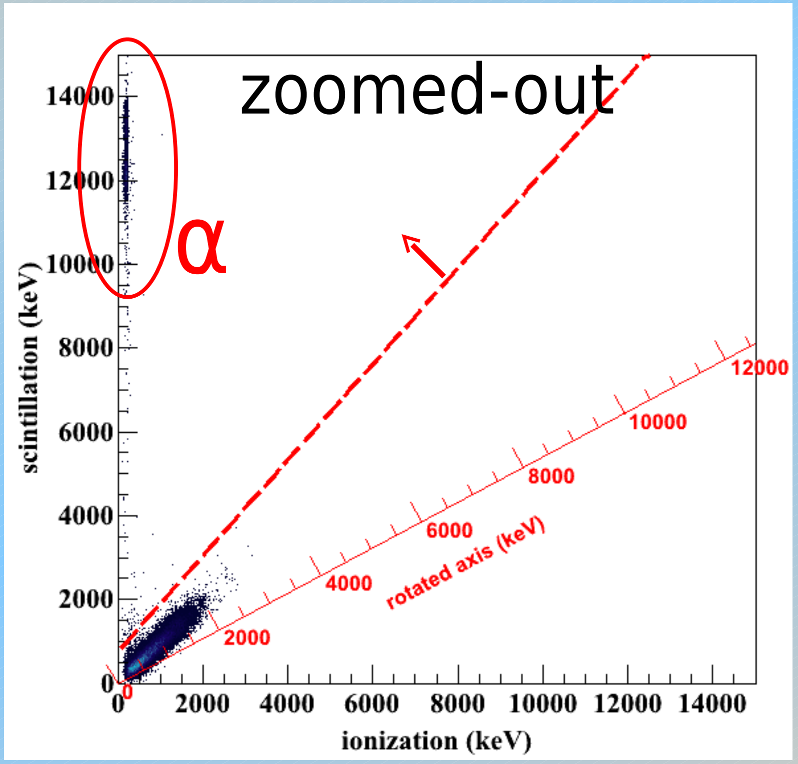
$$\sigma_{Tot}^2 = p_0^2 E + p_1^2 + p_2^2 E^2$$

Resolution dominated by constant (noise) term p_1

At $Q_{\beta\beta}$ (2458 keV):
σ/E = 1.84 % (SS)
σ/E = 1.93 % (MS)

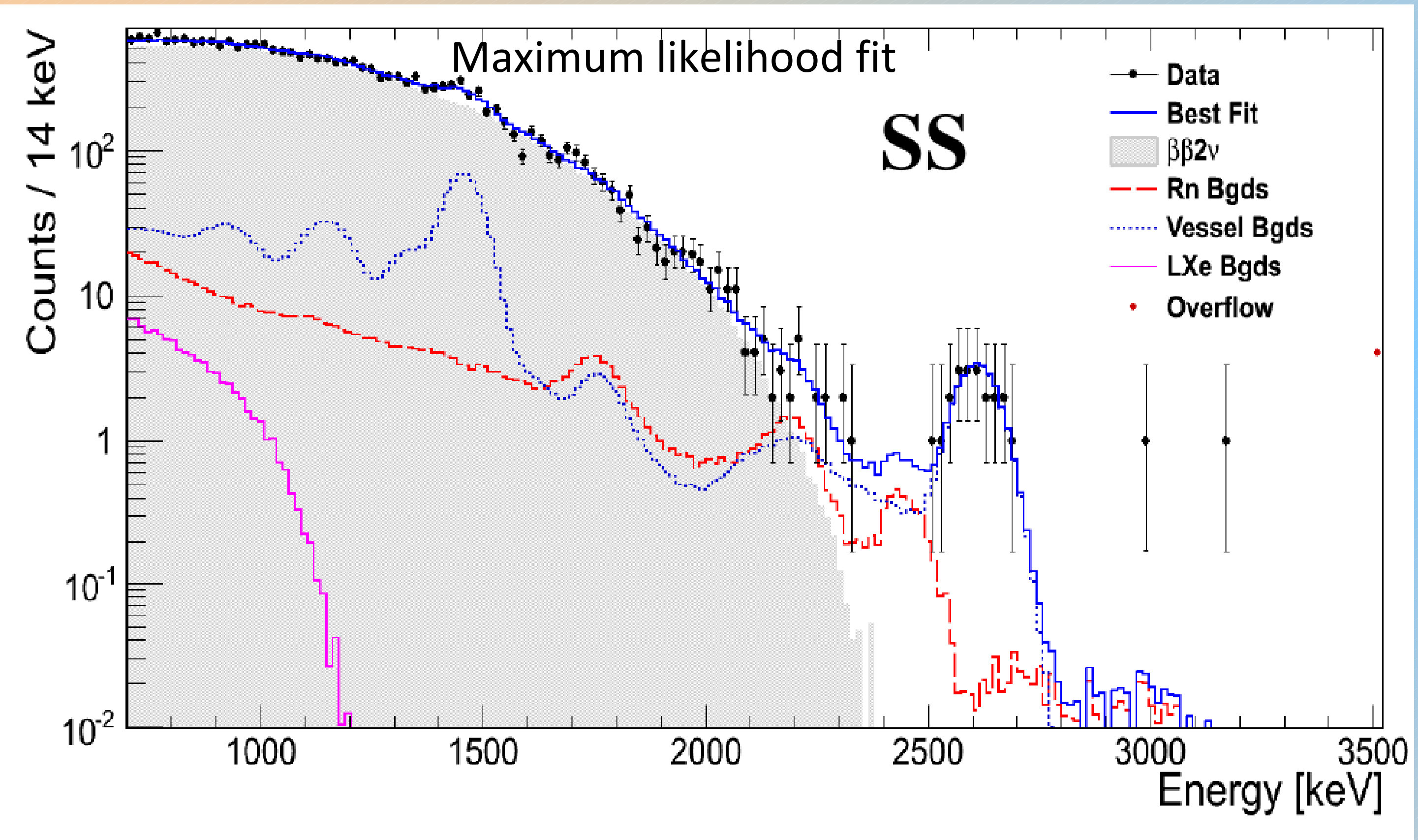
Data analysis cuts





- Veto, noise, etc. anticoincidences (5.6% total dead-time)
- «Diagonal» cut to remove alphas and events with bad charge collection
- Only events with 1 scintillation and 3 coordinates reconstructed
- 700 keV low energy cut
- Fiducial cut (15 mm from cathode, 10 mm from anodes and 30 mm from teflon reflector)
- 58% efficiency for 2nu estimated by MC

Updated results for 2β2ν



Trigger fully efficient above 700 keV

Low background run 2a
livetime: **127.6 days**
dead time: **5.6%**

Active mass:
82.75 kg LXe
(66.2 kg ^{136}LXe)

^{136}Xe exposure: **23.14 kg·yr**

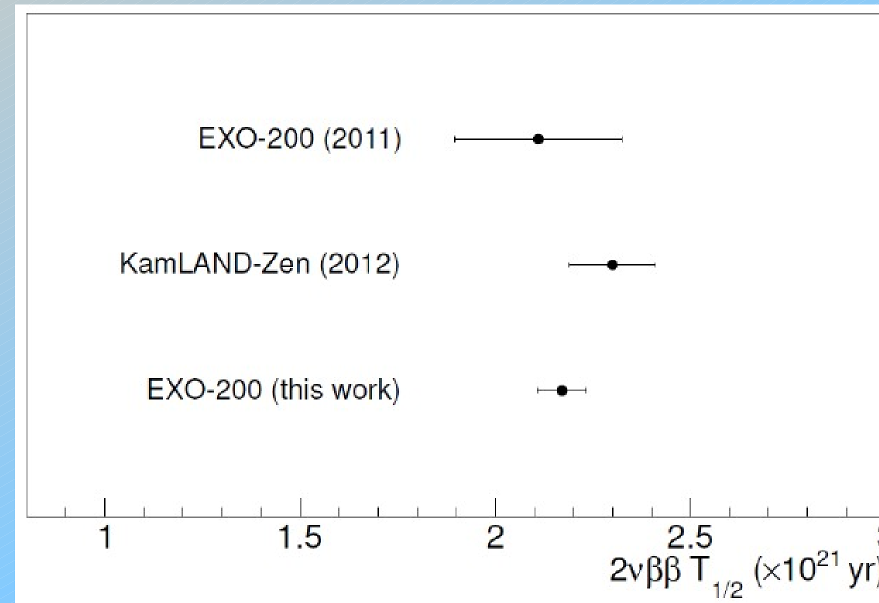
Various background PDFs fitted along with 2νββ and 0νββ PDFs

$T_{1/2}$ = (2.172 ± 0.017 stat ± 0.06 sys)·10^{21} yr

The most accurate $T_{1/2}$ of any 2νββ decay (arXiv:1306.6106)

KamLAND-Zen
$T_{1/2}$ = (2.38 ± 0.02 stat ± 0.14 sys)·10^{21} yr
A.Gando et al., Phys. Rev. C 85 (2012) 045504

Comparison of the results for $2\beta 2\nu$

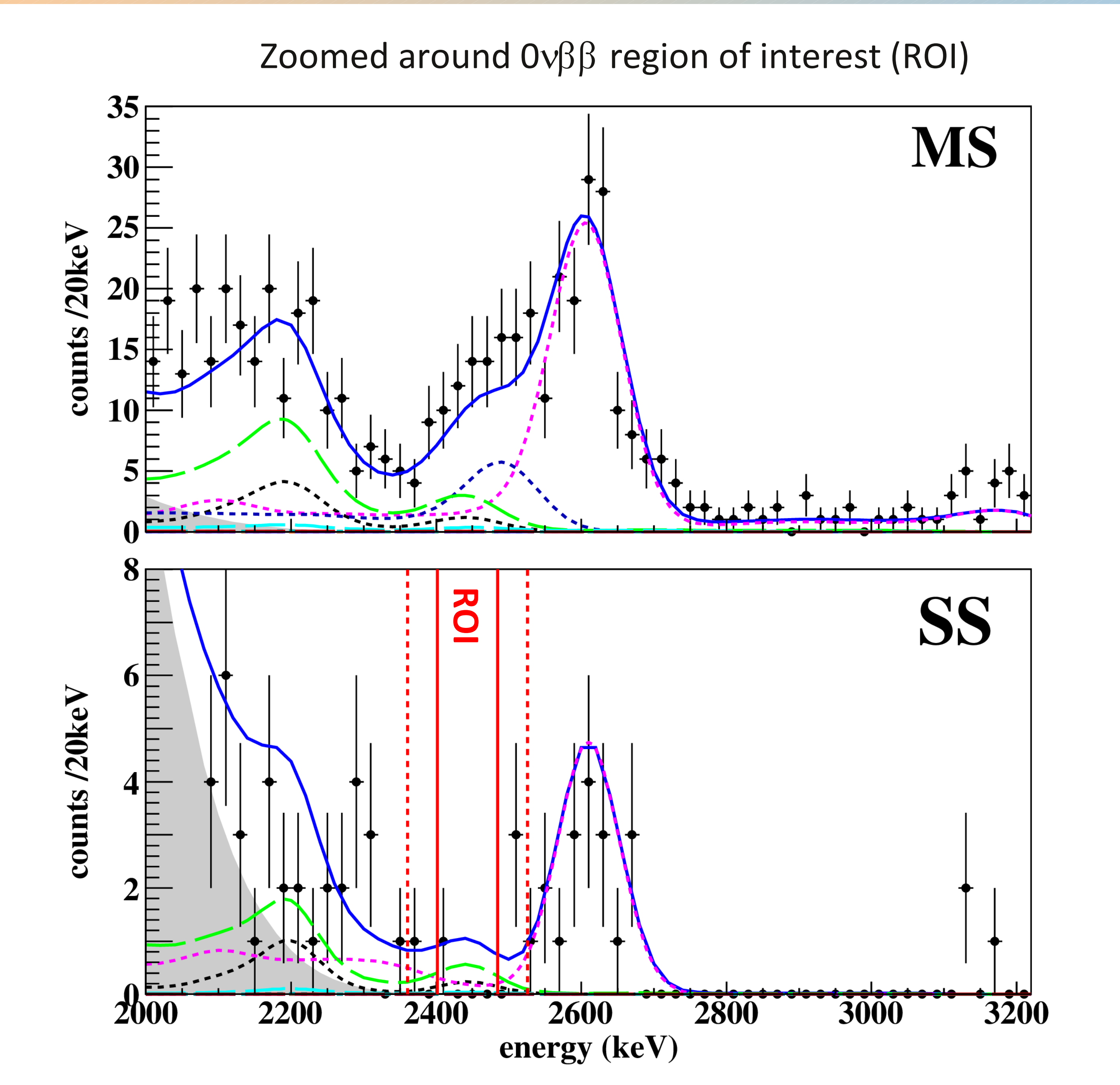


Comparison between
this result (improved Run 2a)
and EXO-200 (2011, Run 1)
and KamLAND-Zen (2012) results.

List of the most precise measurements of 2β. Only direct experiments shown.

Nuclide	$T_{1/2}^{2\nu\beta\beta} \pm$ stat $\pm$ sys [y]	rel. uncert. [%]	$G^{2\nu}$ [10^{-21} y^{-1}]	$M^{2\nu}$ [MeV^{-1}]	rel. uncert. [%]	Experiment (year)
^{136}Xe	$2.172 \pm 0.017 \pm 0.060 \cdot 10^{21}$	± 2.85	1433	0.0217	± 1.4	EXO-200 (this work)
^{76}Ge	$1.84^{+0.09+0.11}_{-0.08-0.06} \cdot 10^{21}$	$^{+7.7}_{-5.4}$	48.17	0.129	$^{+3.9}_{-2.8}$	GERDA (2013)
^{130}Te	$7.0 \pm 0.9 \pm 1.1 \cdot 10^{20}$	± 20.3	1529	0.0371	± 10.2	NEMO-3 (2011)
^{116}Cd	$2.8 \pm 0.1 \pm 0.3 \cdot 10^{19}$	± 11.3	2764	0.138	± 5.7	NEMO-3 (2010)
^{48}Ca	$4.4^{+0.5}_{-0.4} \pm 0.4 \cdot 10^{19}$	$^{+14.6}_{-12.9}$	15550	0.0464	$^{+7.3}_{-6.4}$	NEMO-3 (2010)
^{96}Zr	$2.35 \pm 0.14 \pm 0.16 \cdot 10^{19}$	± 9.1	6816	0.0959	± 4.5	NEMO-3 (2010)
^{150}Nd	$9.11^{+0.25}_{-0.22} \pm 0.63 \cdot 10^{18}$	$^{+7.4}_{-7.3}$	36430	0.0666	$^{+3.7}_{-3.7}$	NEMO-3 (2009)
^{100}Mo	$7.11 \pm 0.02 \pm 0.54 \cdot 10^{18}$	± 7.6	3308	0.250	± 3.8	NEMO-3 (2005)
^{82}Se	$9.6 \pm 0.3 \pm 1.0 \cdot 10^{19}$	± 10.9	1596	0.0980	± 5.4	NEMO-3 (2005)

Results for 2β0ν

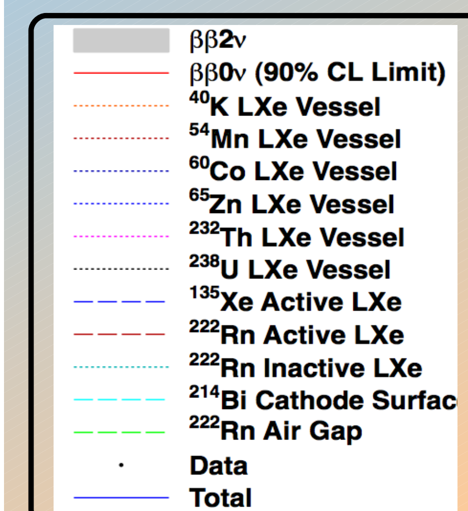


Low background run 2a
No signal observed

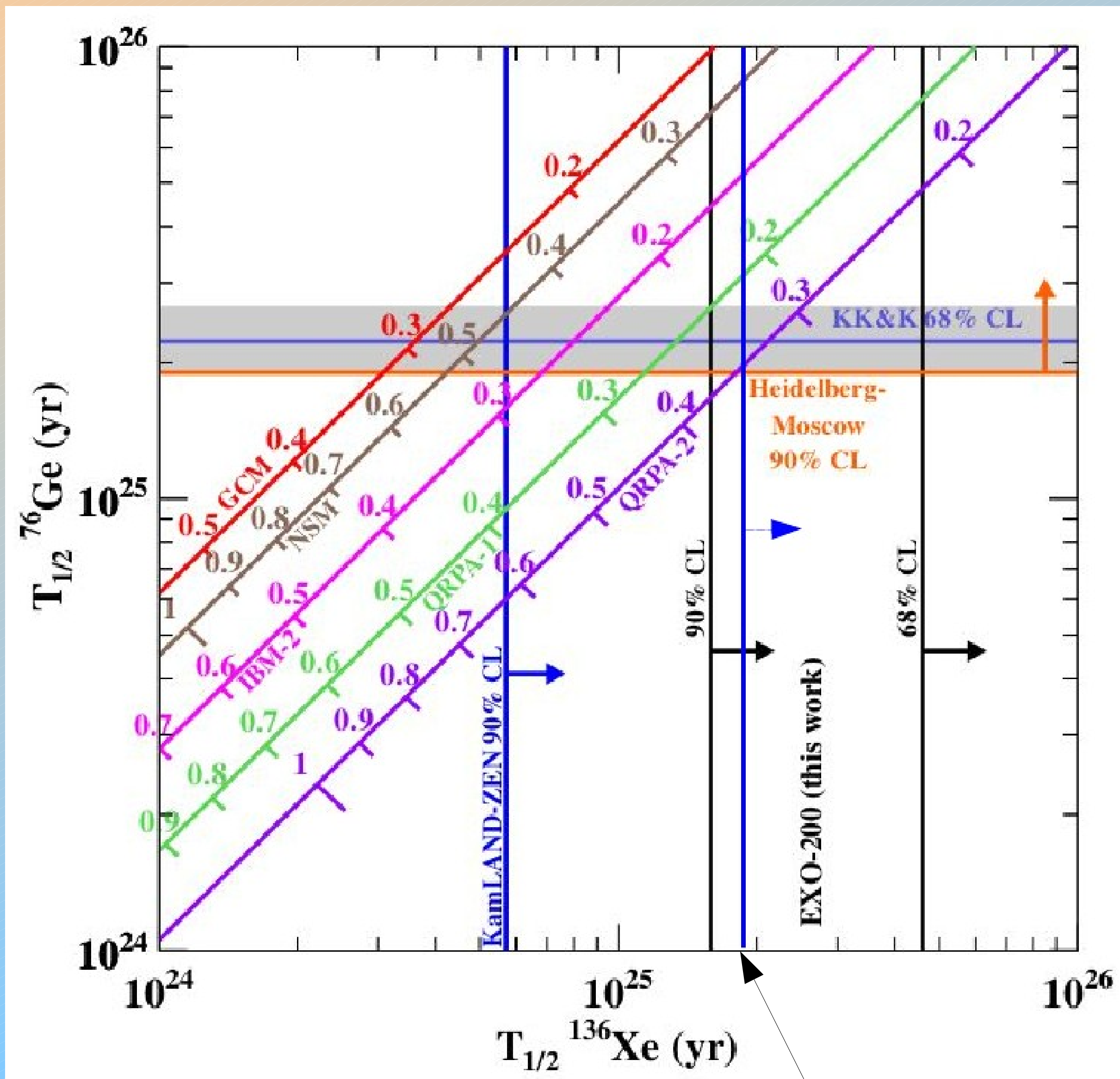
Background in ± 1 ROI:
$1.5 \cdot 10^{-3} \pm 0.1$ $kg^{-1}yr^{-1}keV^{-1}$
- perfectly low

$T_{1/2}^{0\nu\beta\beta}$ (^{136}Xe) > $1.6 \cdot 10^{25}$ yr
(90% C.L.)
Phys. Rev. Lett. V.109 I.3 (2012)

Majorana mass limit
<140-380 meV



Limits on 0νββ



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

⟨$m_{\beta\beta}$⟩ < 140-380 meV

(90% C.L.)

EXO-200 contradicts Klapdor-Kleingrothaus and Krivosheina claim for 0νββ discovery at the 90% for most matrix elements

A. Gando et al. 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.

KamLAND-Zen

PRL, 110, 062502 (2012)

Summary

EXO-200 is taking low background data, approved at least end of 2014

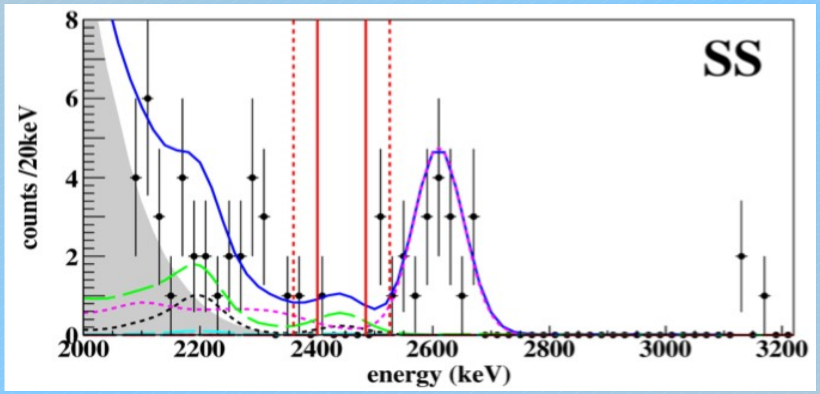
About 3 times larger dataset acquired

Detector working well, met our goals:

Energy resolution: 1.84% at $Q_{\beta\beta}$

Background: 1.5×10^{-3} $kg^{-1}keV^{-1}yr^{-1}$

1 (5) counts in 1σ (2σ) 0νββ ROI

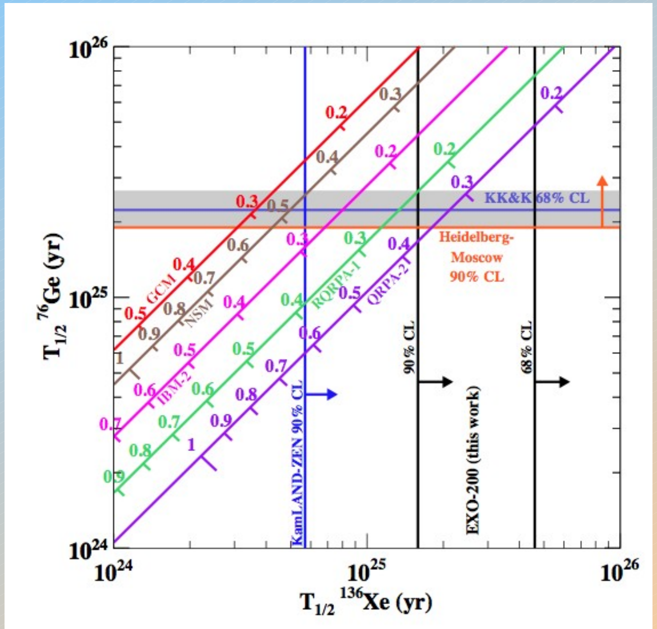


$T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25}$ yr

$\langle m_{\beta\beta} \rangle < 140\text{–}380$ meV

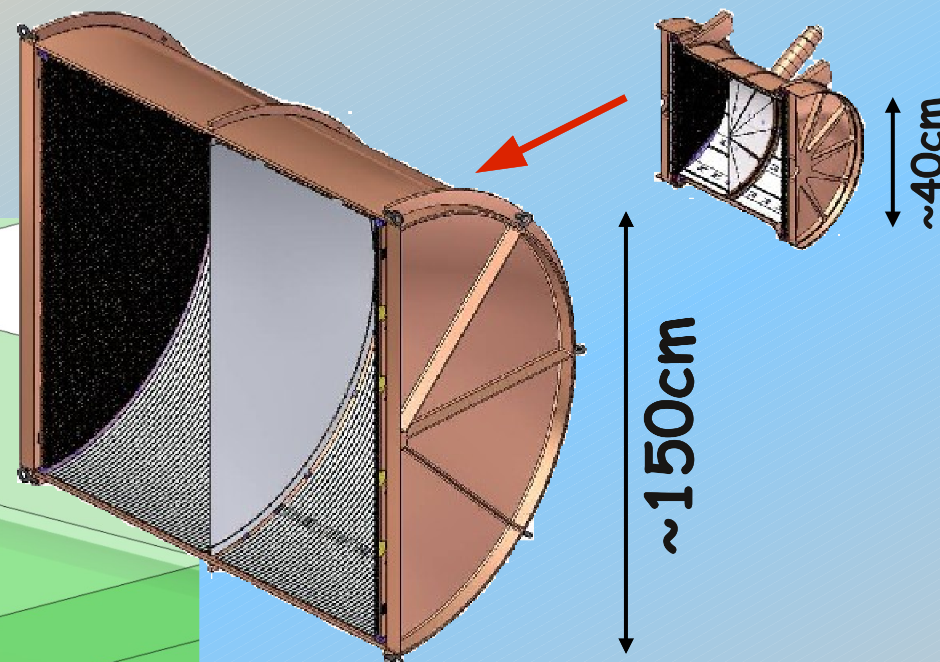
(90% C.L.)

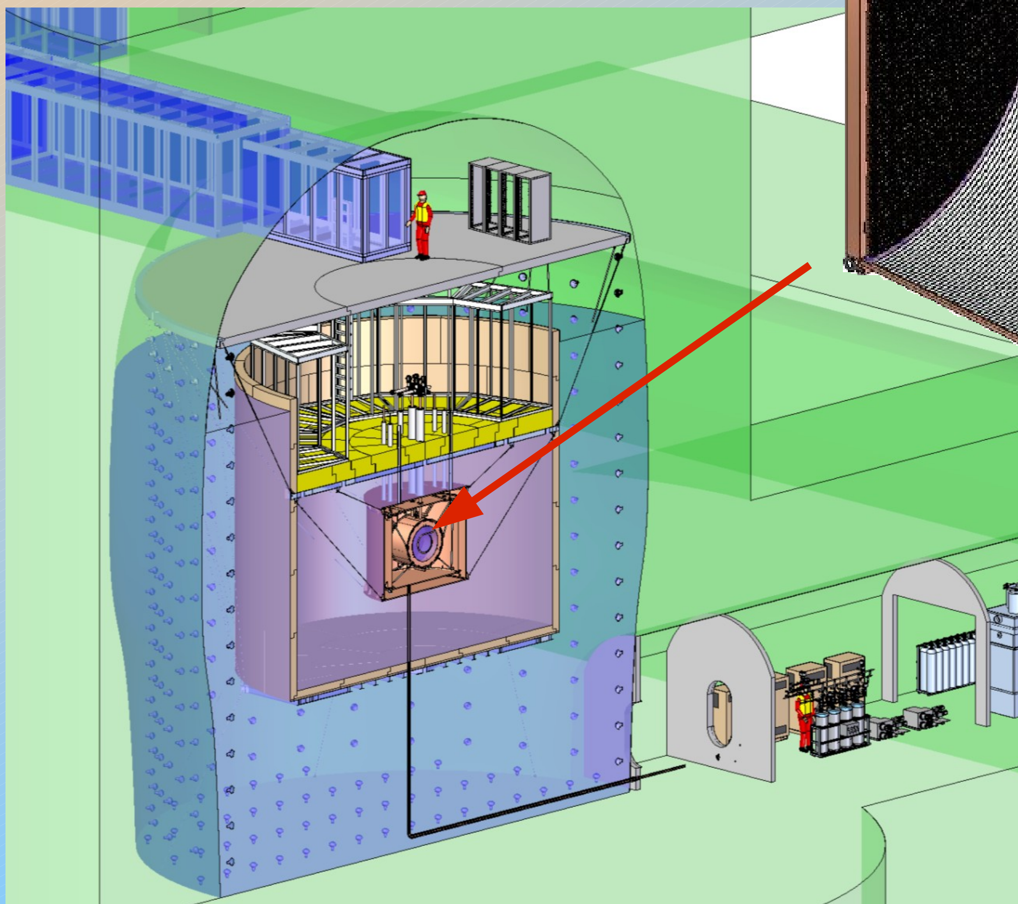
Phys. Rev. Lett. V.109 I.3 (2012)



R&D for the next generation (nEXO) started

nEXO at SNOLab

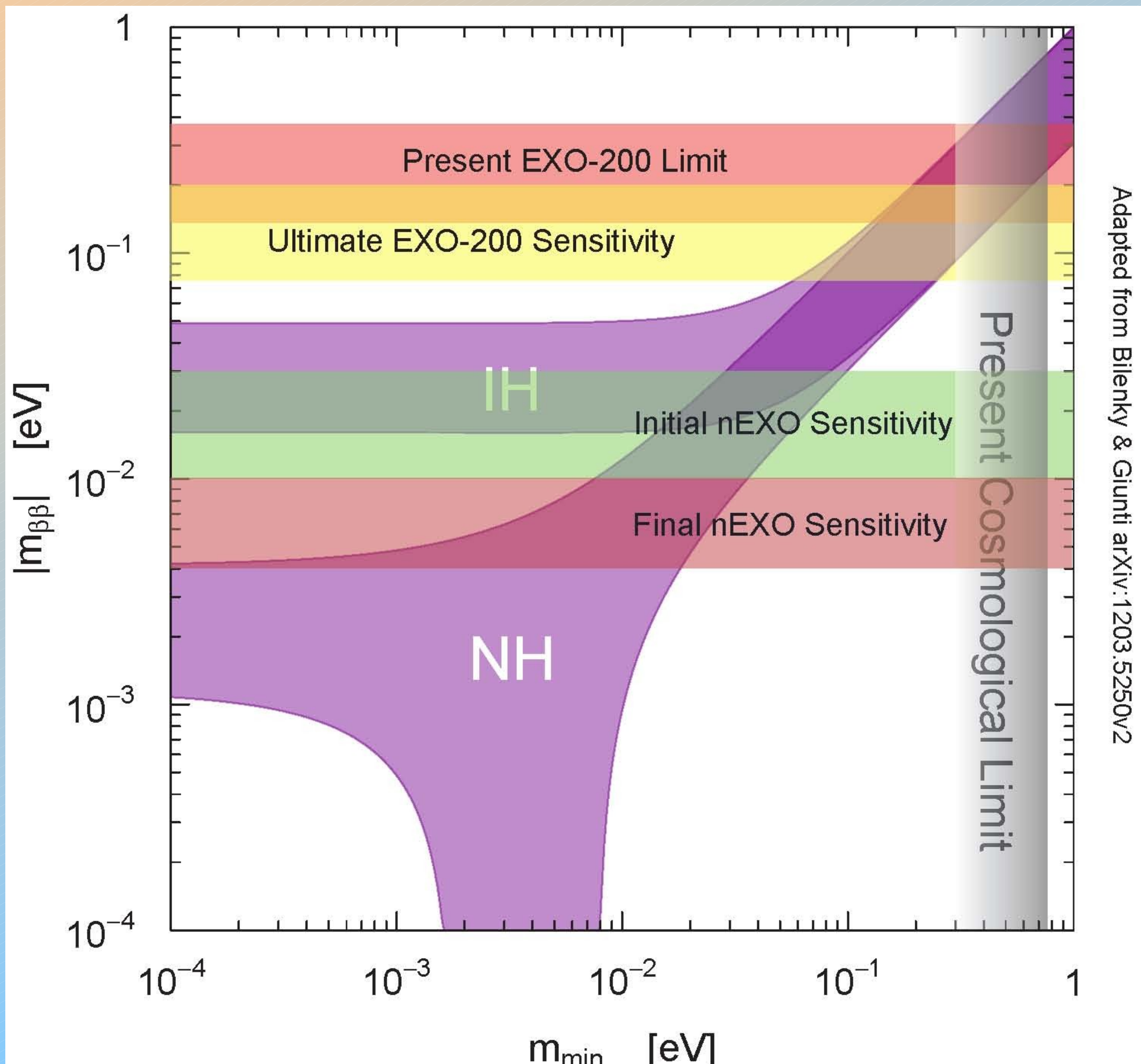




Conceptual design for SNOLab

- 5 tonne LXe TPC "as similar to EXO200 as possible"
- R&D for cold electronics, SiPM photodetectors, alternative charge collection shcheme
- Provide access ports for a possible later upgrade to Ba tagging

EXO-200 and nEXO projected sensitivities



Blue bands are 68%CL from oscillation experiments for "Inverted" and "Normal" Hierarchy

The EXO-200 "Present limit" is the 90%CL envelope of Limits (for different NMEs) from PRL 109 (2012) 032505

The EXO-200 "Ultimate" sensitivity: 90%CL for no signal in 4 yrs livetime with new analysis & Rn removal

The "Initial nEXO" band refers to a detector directly scaled from EXO-200, including its measured background and 10yr livetime.

The "Final nEXO" band refers to the same detector and no background other than 2ν

The EXO Collaboration

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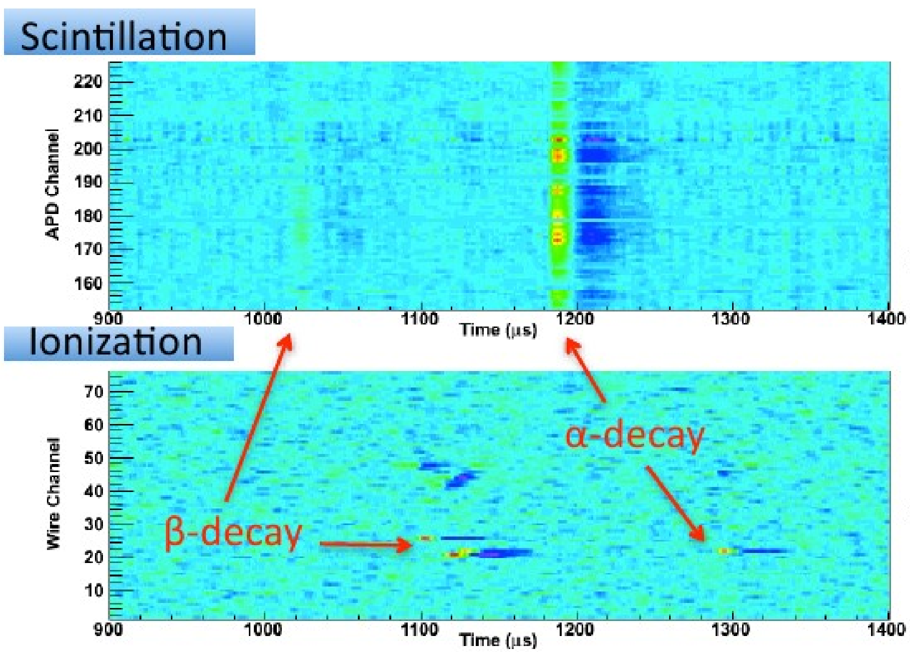
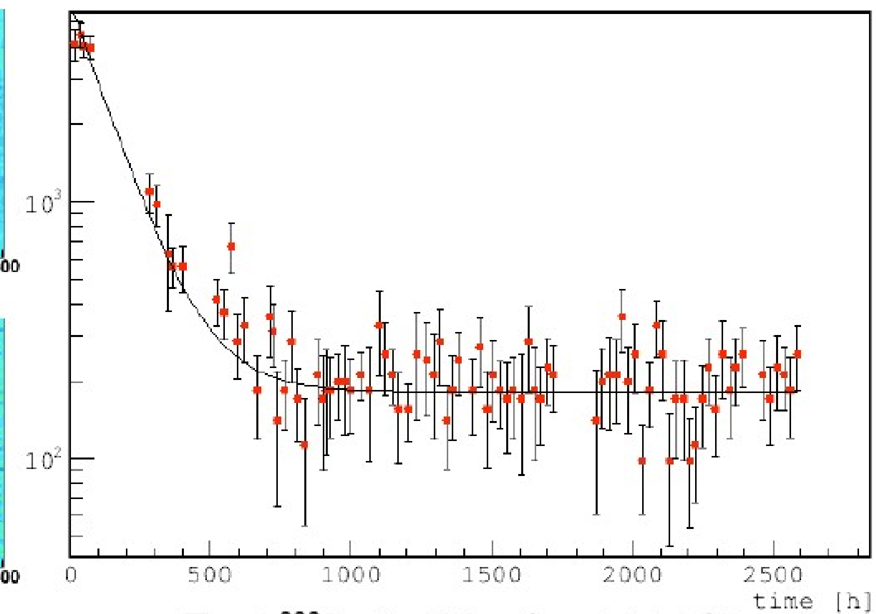
Technical University of Munich, Garching, Germany - W. Feldmeier, P. Fierlinger, M. Marino

Rn Content in Xenon



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



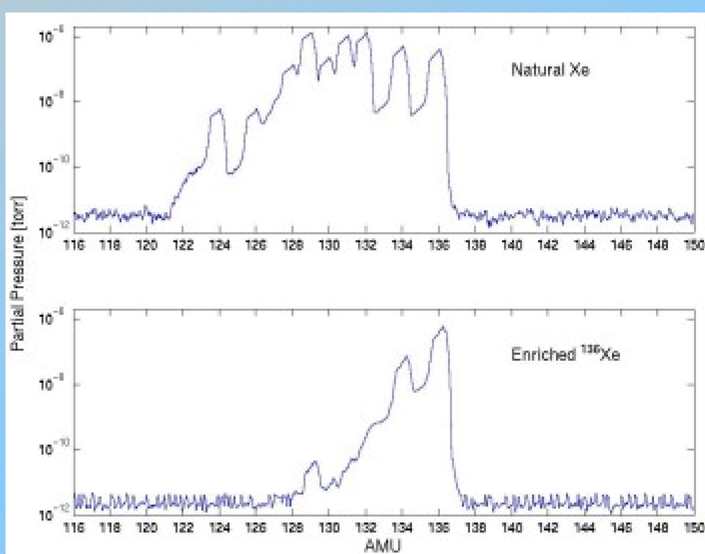
Total ^{222}Rn in LXe after initial fill

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.)

EXO-200: the first 200kg Double Beta Decay Experiment

Centrifuge facility in Russia

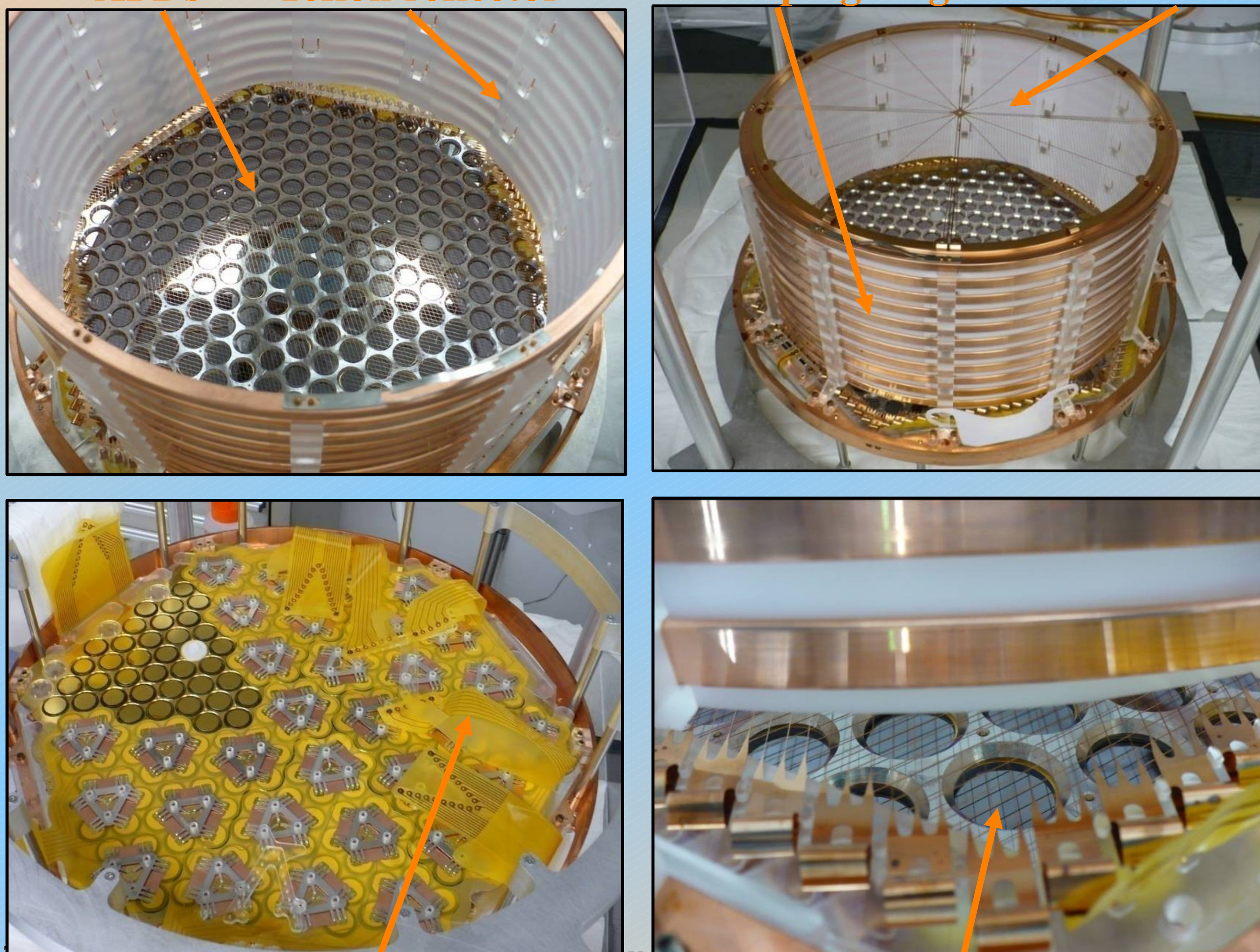


RGA mass scan of xenon samples

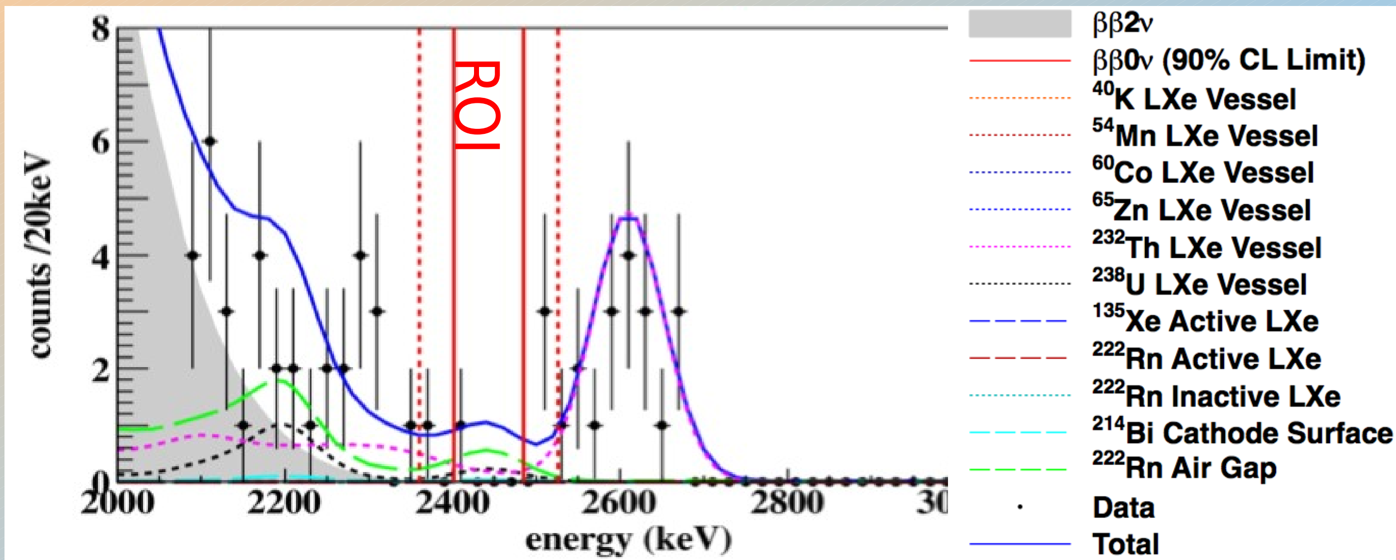
Enriched xenon storage bottles for EXO

EXO collaboration currently have 200 kg of xenon enriched to 80% = 160 kg of ^{136}Xe

The EXO-200 TPC



Background counts in ±1,2 σ ROI



	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 ($kg^{-1}yr^{-1}keV^{-1}$)	$1.5 \cdot 10^{-3} \pm 0.1$		$1.4 \cdot 10^{-3} \pm 0.1$	

EXO-200 goal (slide 3):

40 cnts/2y in ±2σ ROI,
140 kg LXe

In this data 120 days, 98.5 kg, this would be: 4.6

Expected from the fit: 7.5

Observed: 5

Background within expectation

KamLand-ZEN

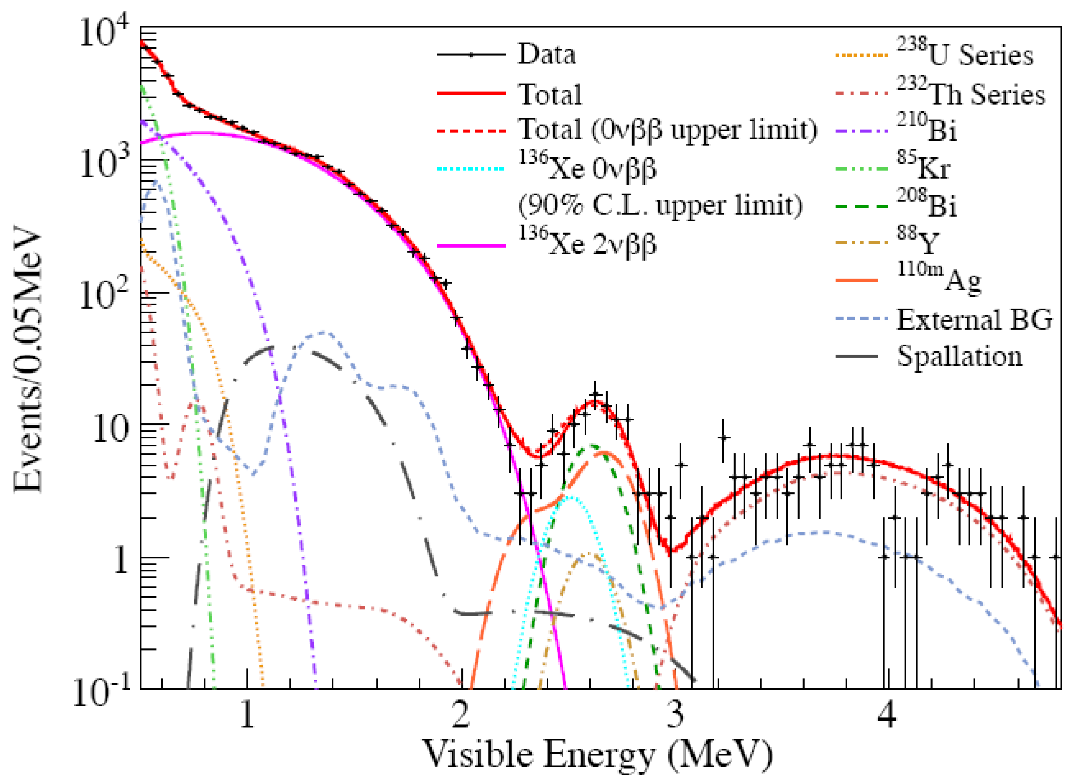


FIG. 4: Energy spectrum of selected $\beta\beta$ decay candidates together with the best-fit backgrounds and $2\nu\beta\beta$ decays, and the 90% C.L. upper limit for $0\nu\beta\beta$ decays.

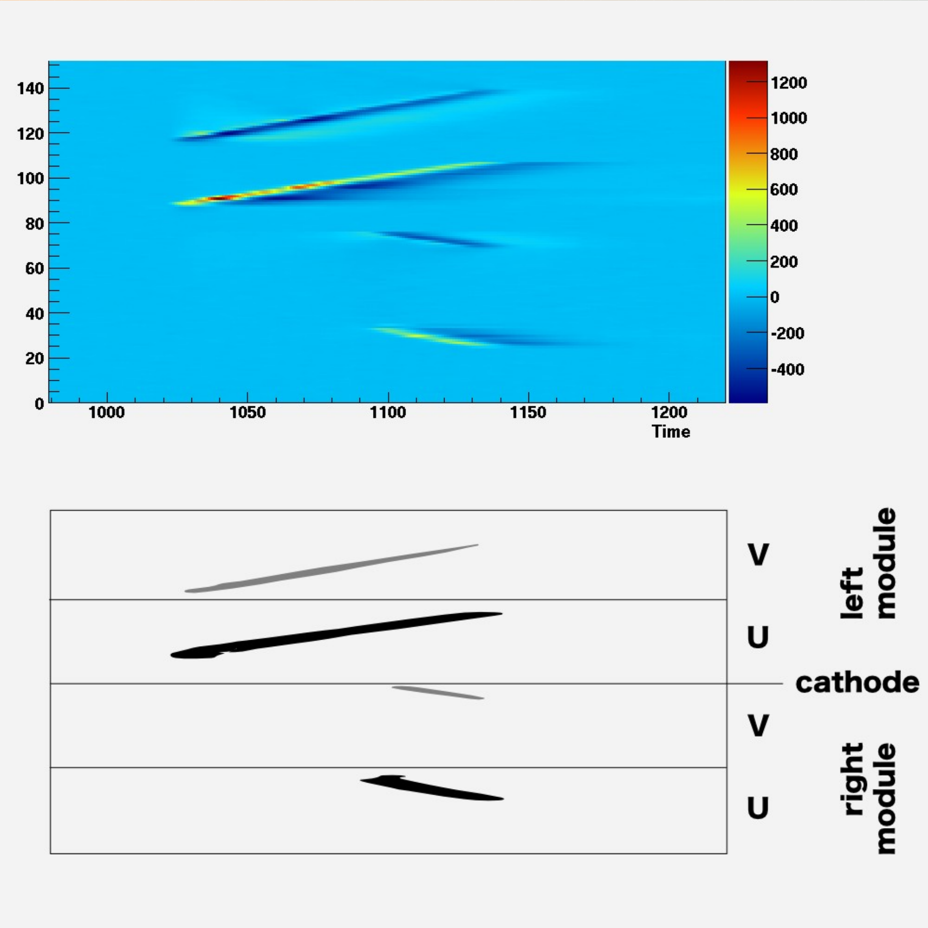
112.3 days 38.6kg-yr

T2ν1/2 = 2.30±0.02(stat)±0.12(syst) $\times 10^{21}$ years arXiv:1205.6372

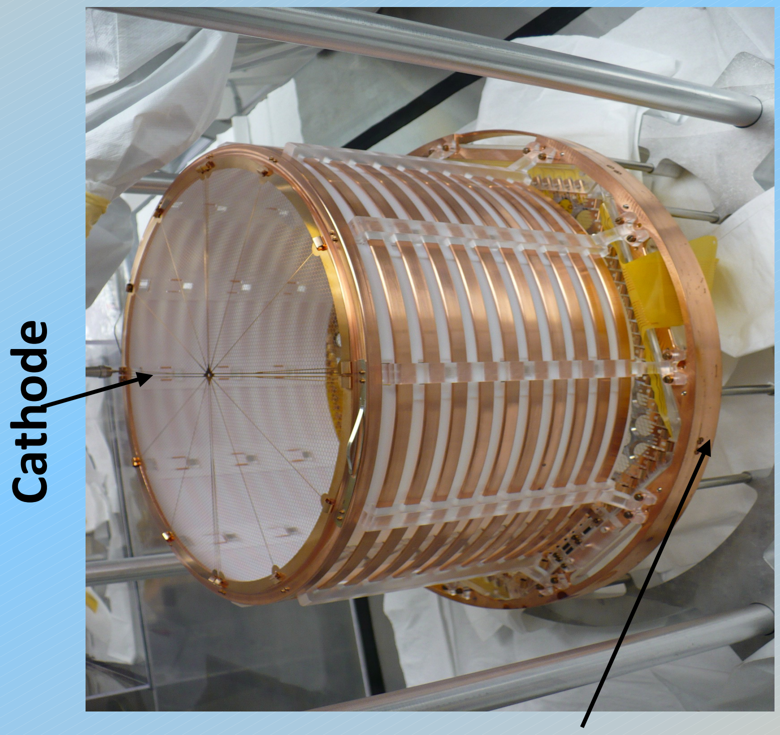
T0ν1/2 > 6.2$\times 10^{24}$ years (KL-Zen 112days)

〈 mββ 〉 < 0.26~0.54 eV @90% C.L.

Muon track in EXO-200



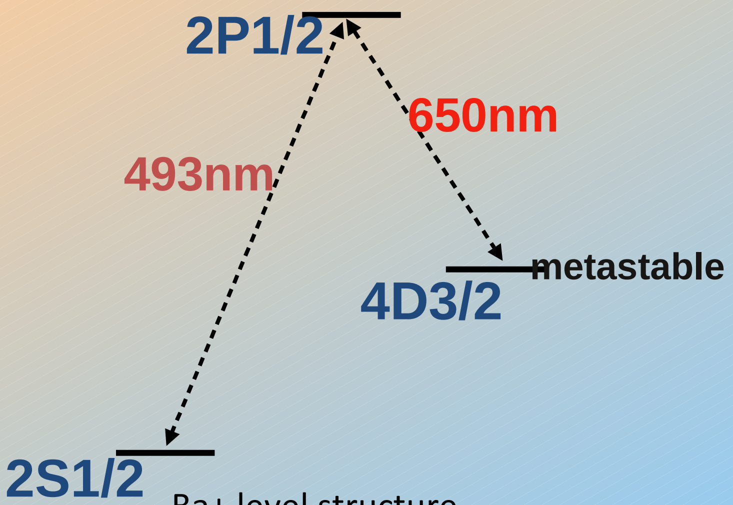
One of the two TPC modules



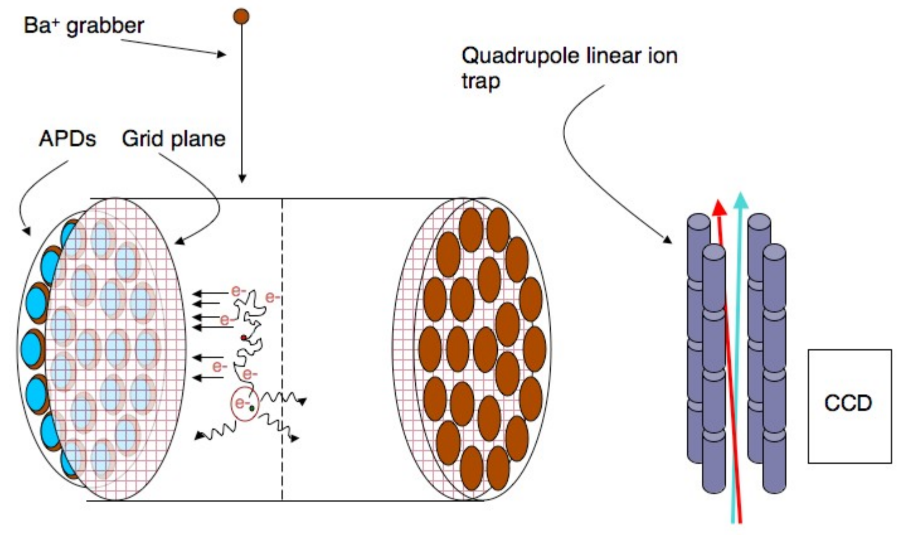
A track from a cosmic-ray muon in EXO-200. The horizontal axis represents time (uncalibrated for now) while the vertical is the wire position (see sketch). V wires see inductive signals while U wires collects the charge.

The muon in the present event traverses the cathode grid, leaving a long track in one TPC module and a shorter one in the other.

Barium Tagging R&D Summary



Ba+ level structure



One proposed barium tagging scheme

Method	**Summary**
RIS probe	Desorb and resonantly ionize Ba from probe tip, then identify with laser spectroscopy in ion trap
Hot probe	Release neutral by heating and ionize with hot surface, then identify with laser spectroscopy in ion trap
Solid Xe probe	Storage and spectroscopy of Ba+ in Xe ice
Direct tag in liquid	Laser identification of Ba+ in liquid Xe
Gas Xe extraction	Guide ions from high pressure (10 bar) Xe to low pressure trapping region, then identify with laser spectroscopy