Recent Results of EXO-200

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Neutrino masses: What we know from other experiments

Neutrino oscillations…

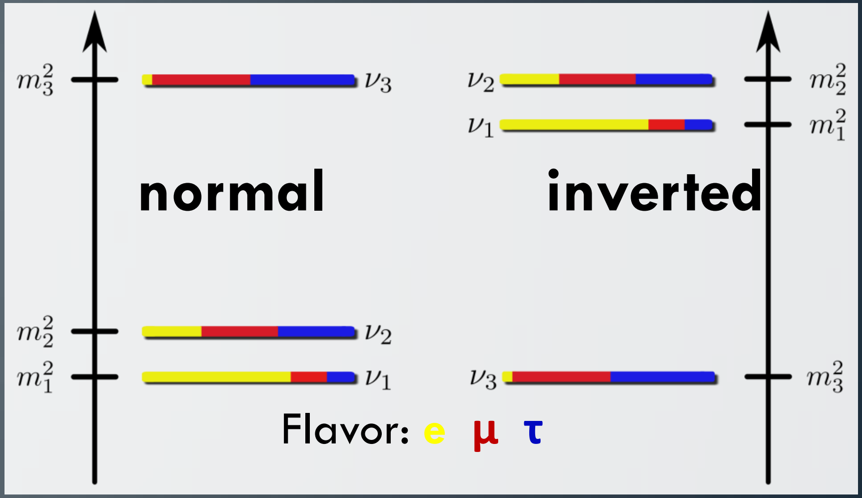
- Measure Δm_{ij}^2
- Have shown that ν have mass
- Have shown that flavor states ≠ mass eigenstates

Tritium decay…

- Measures $m_\beta := \sqrt{\sum_i |U_{ei}|^2 |m_i|^2}$
- $m_\beta < 2.1$ eV (95% CL)

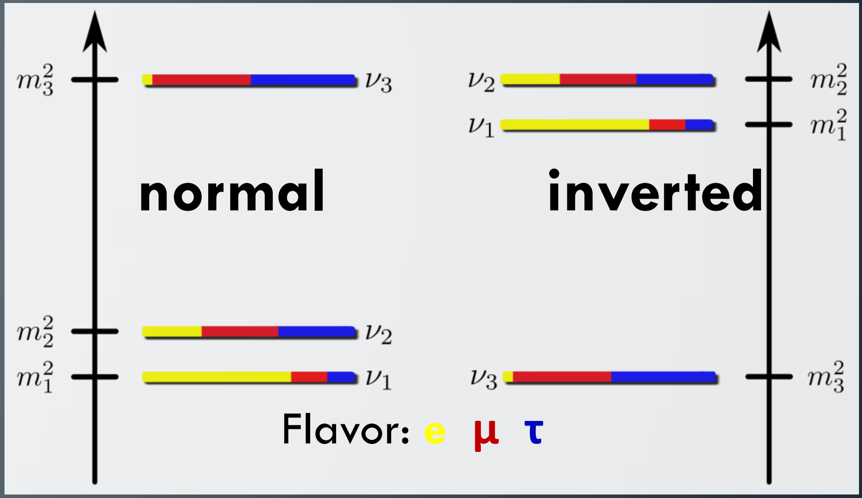
Cosmology…

- Constrains $\sum_i m_i$
- $\sum_i m_i < 0.5$ eV

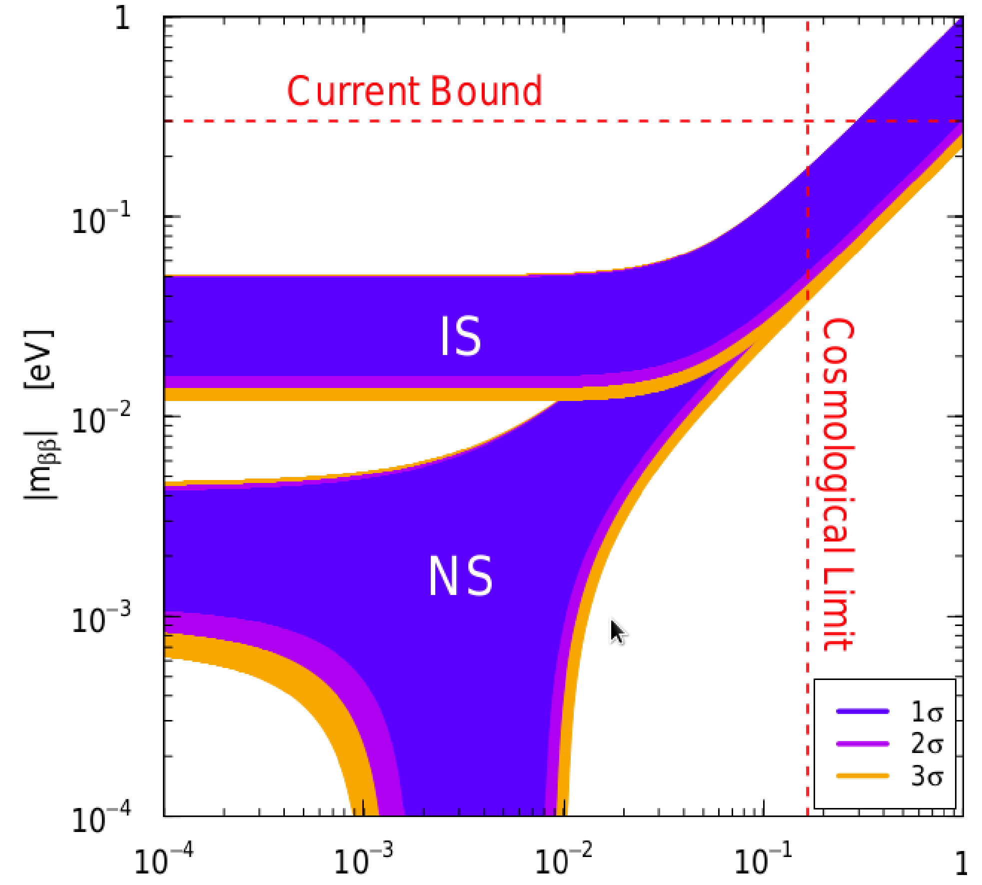


Neutrino masses: What Neutrinoless Double-β Decay (0νββ) can tell us

- Measures $|m_{\beta\beta}| := |\sum_i U_{ei}^2 m_i|$
- What is the absolute mass scale? $m_i = ?$
- Normal or inverted hierarchy? Quasi-degenerate mass spectrum?
- Dirac- or Majorana-ν?

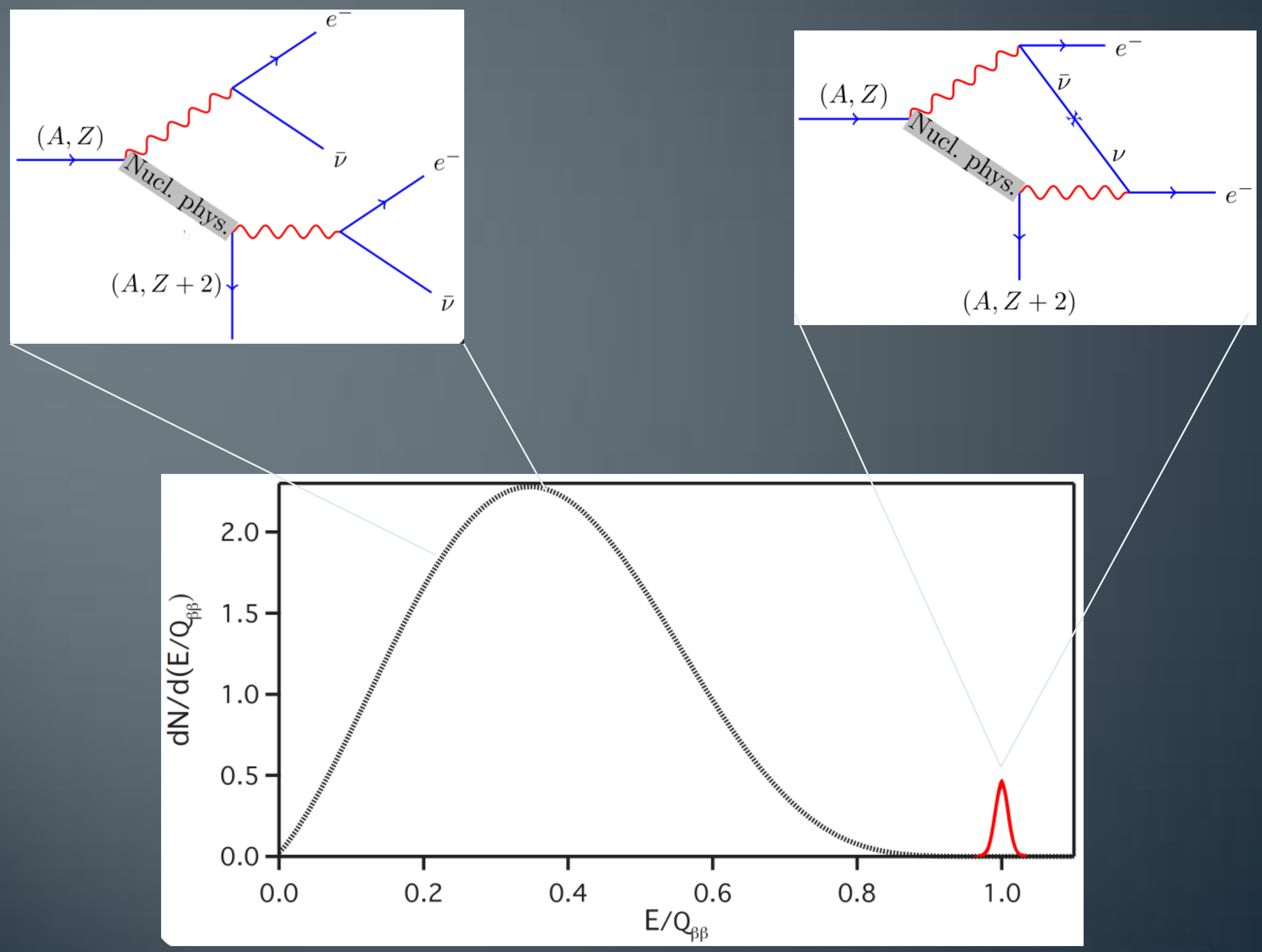


Neutrino mass hierarchy: Current status

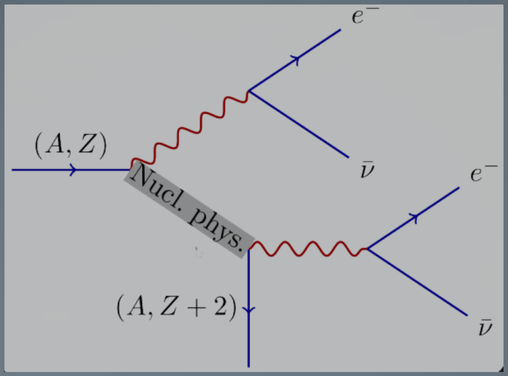


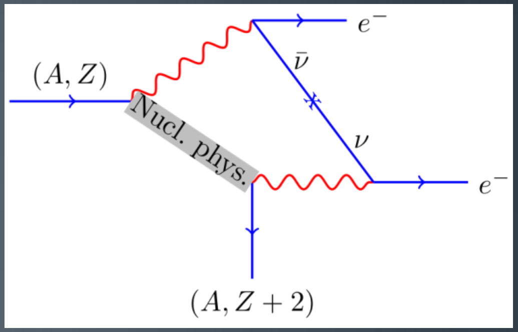
Plot: S. Bilenky et al

Neutrinoless Double-β Decay



Neutrinoless Double-β Decay

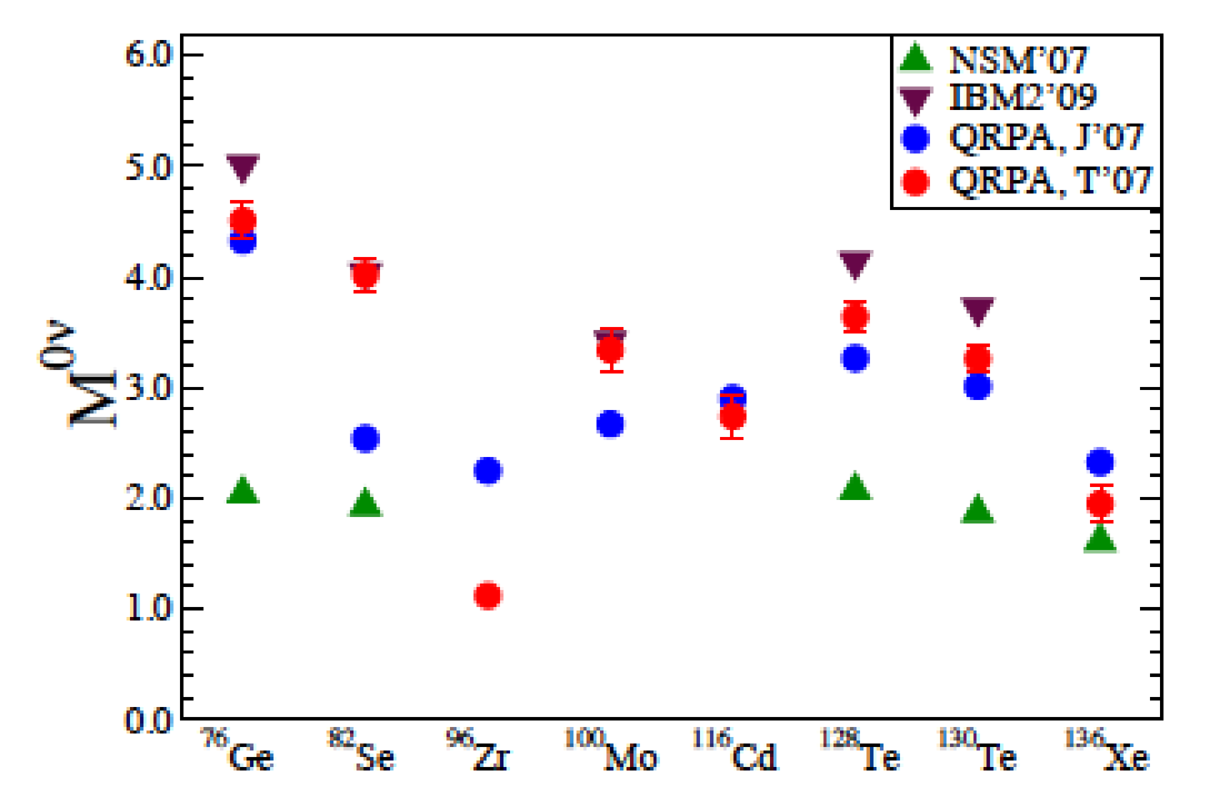




$$\boldsymbol{{T_{\frac{1}{2}}^{0\nu}}^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2\left|m_{\beta\beta}\right|^2}$$

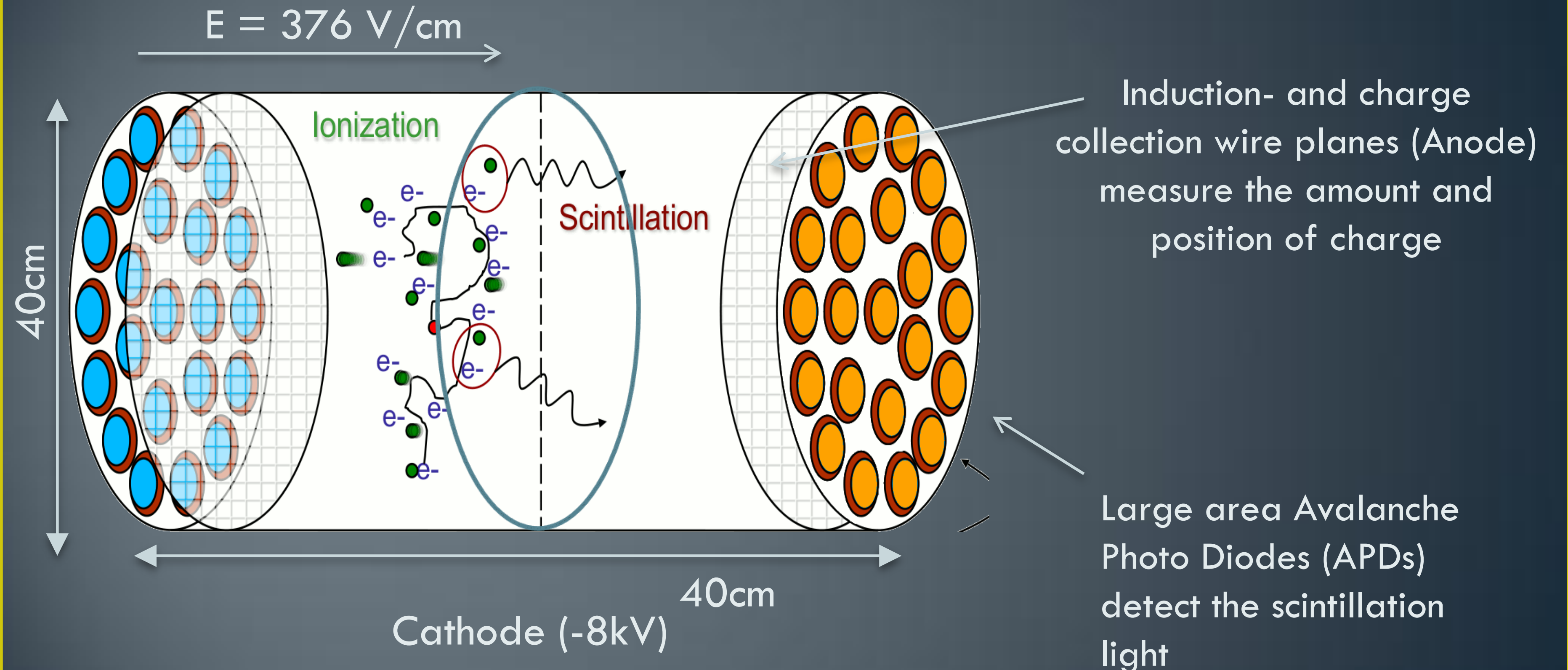
$$|m_{\beta\beta}| = \left|\sum_i U_{ei}^2 m_i\right|$$

Nuclear Matrix Elements (calculated)



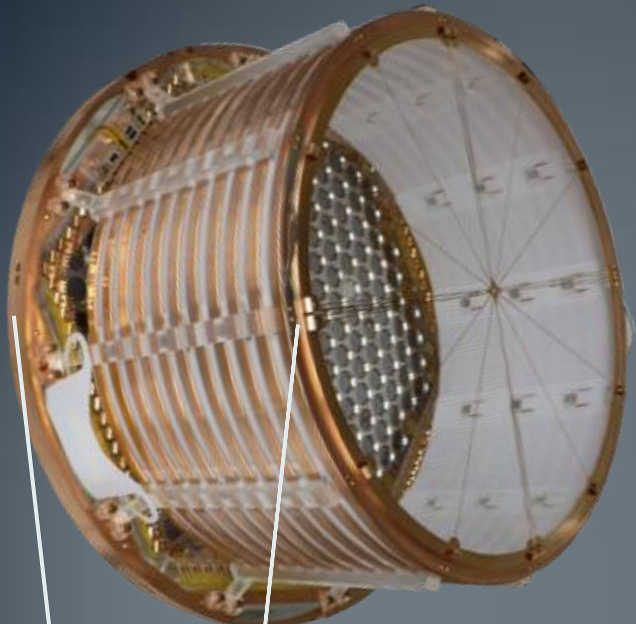
Plot: V. Rodin, arXiv:0910.5866

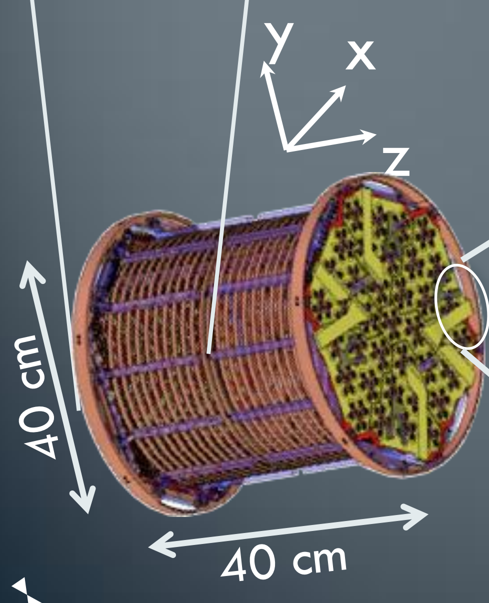
The Detector (Principle)

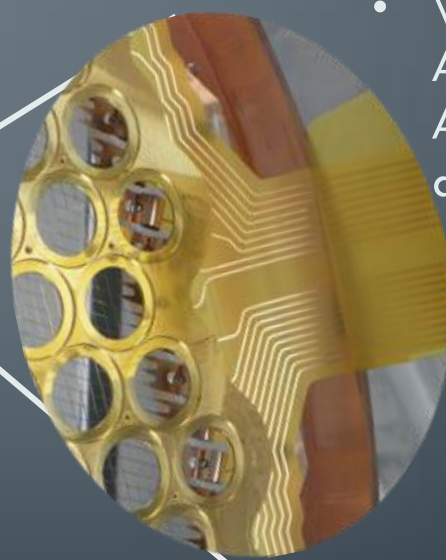


- Liquid ^{136}Xe as source- and detector material

The Detector







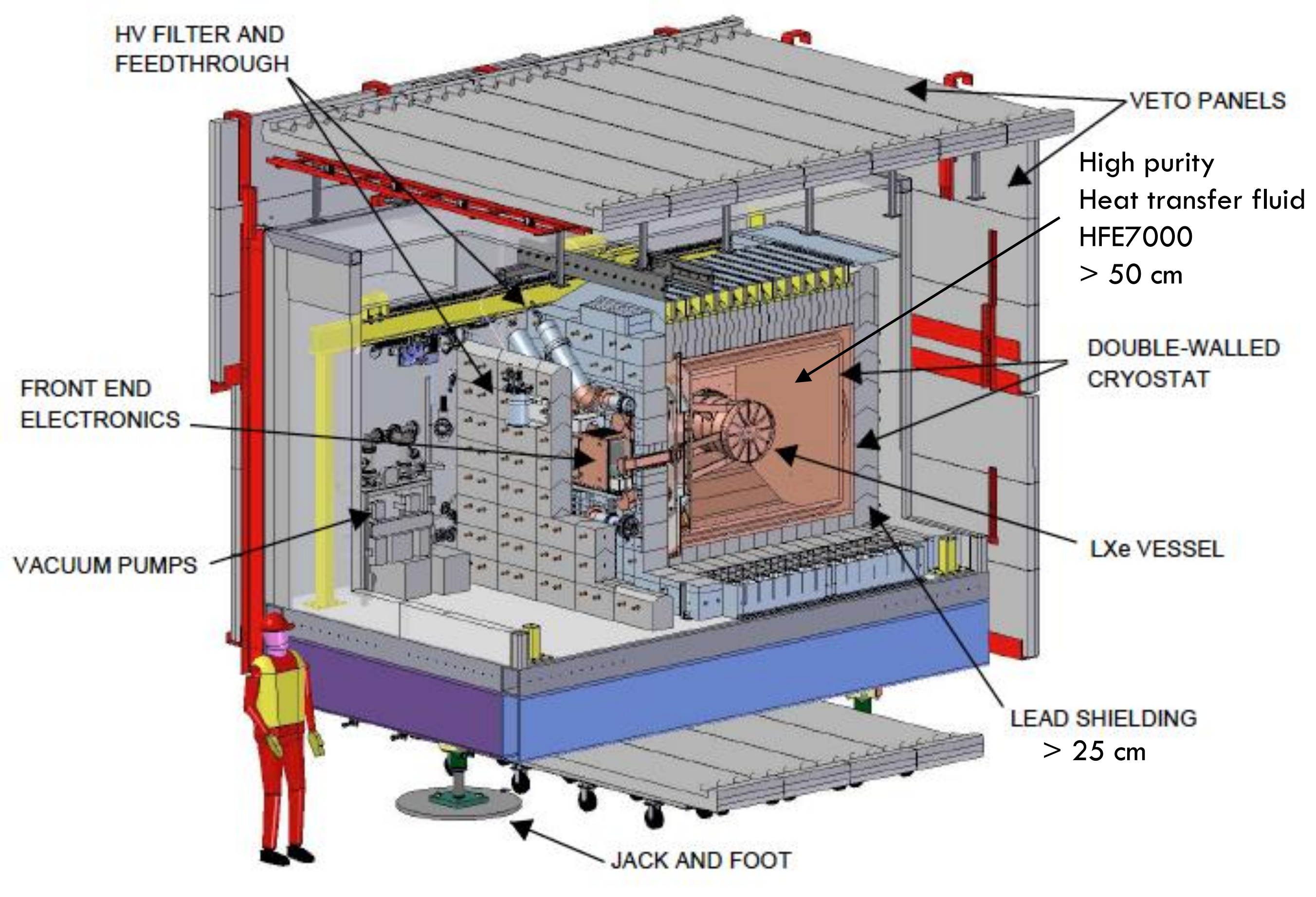
Two almost identical halves reading ionization and 178 nm scintillation, each with:

- 38 U triplet wire channels (charge deposition)
- 38 V triplet wire channels, crossed at 60° (induction)
- 234 APDs (7 per channel)
- Wire pitch 3 mm (9 mm per channel)
- Wire planes 6 mm apart and 6 mm from APD plane

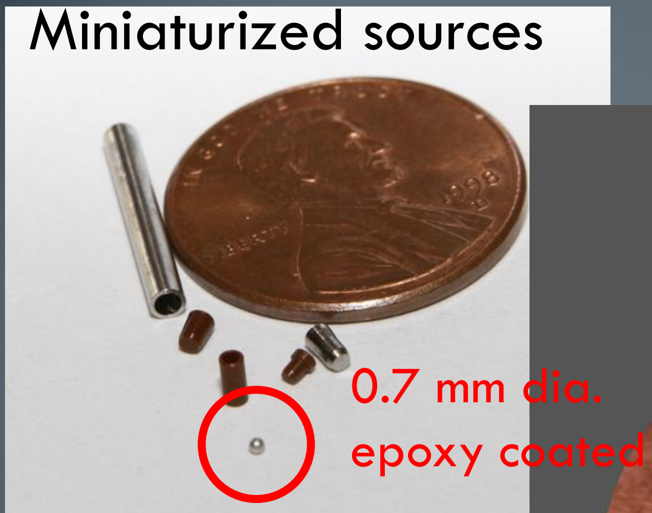
All signals digitized at 1 MS/s, ±1024S around trigger

The Detector (Surroundings)

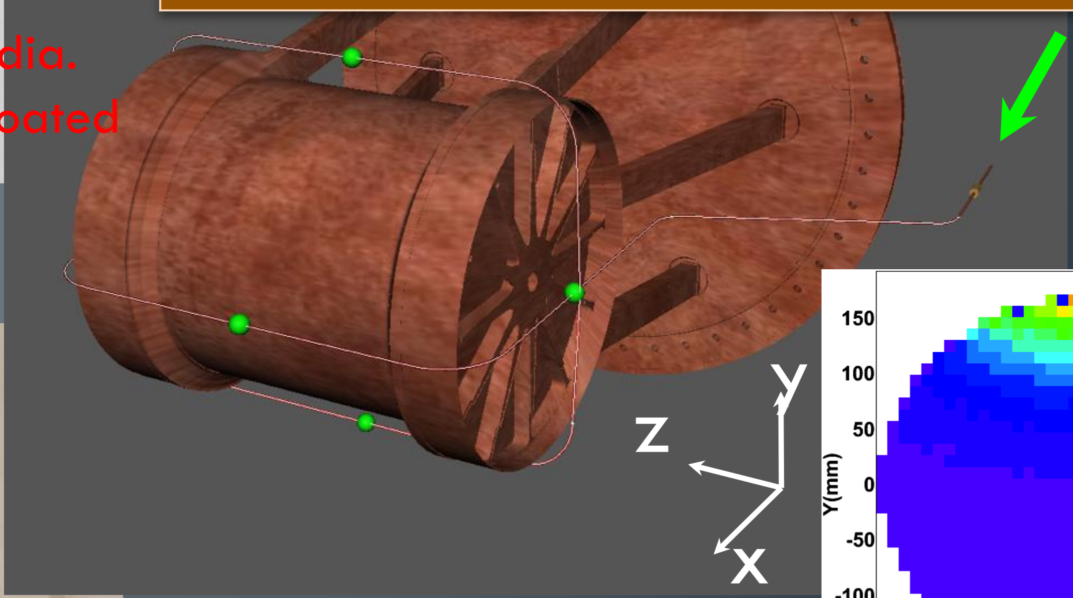
655m depth ≈ 1585 mwe

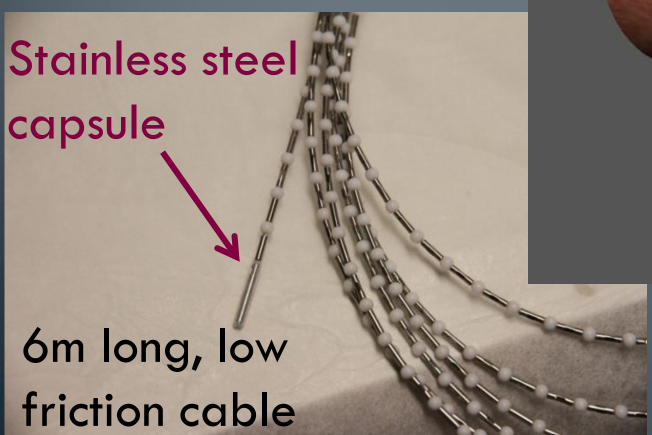


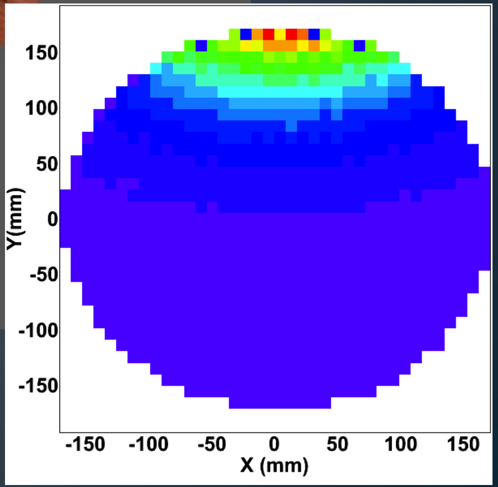
Calibration



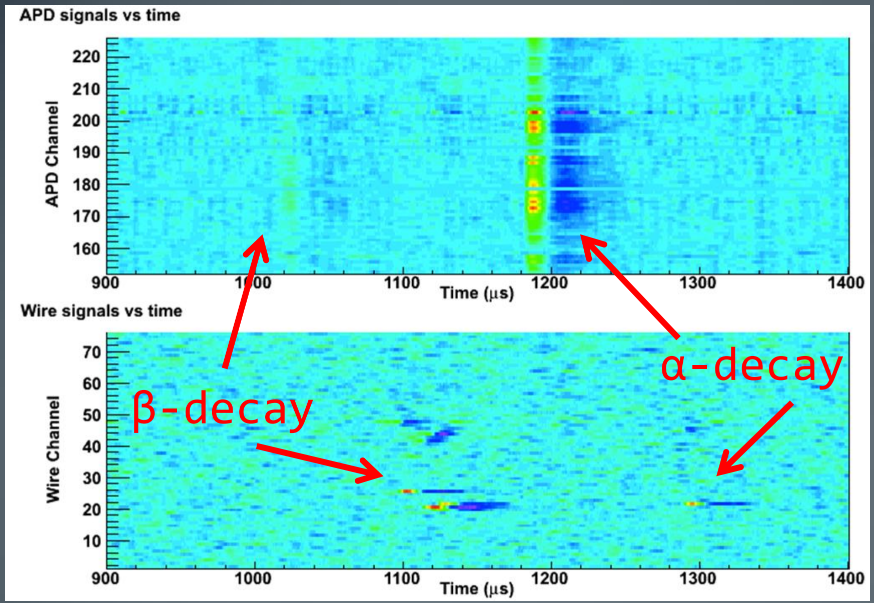
Source	Weak (kBq)	Strong (kBq)	Photopeak (keV)
60-Co	3.0	15.0	1173, 1333
137-Cs	0.5	7.2	660
228-Th	1.5	38.0	2615



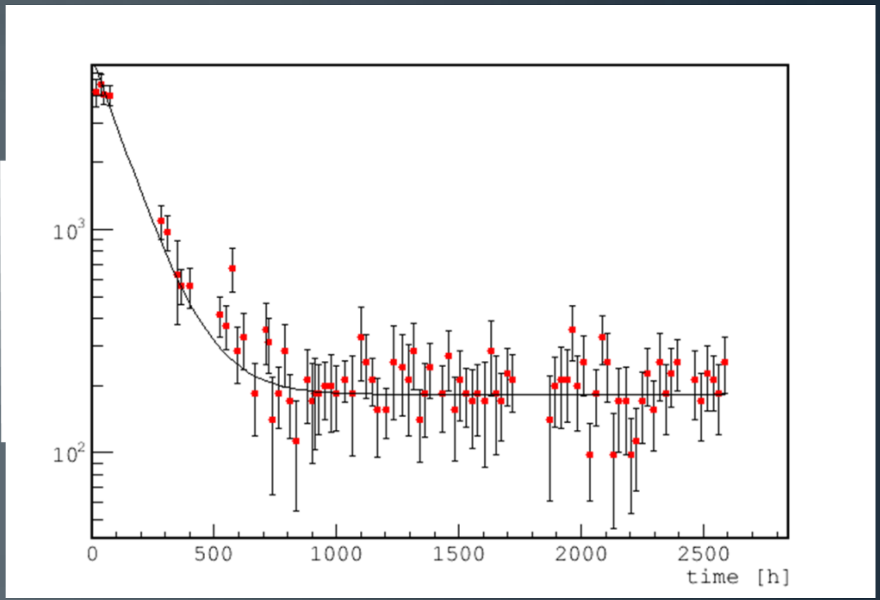




Radon content in Xenon



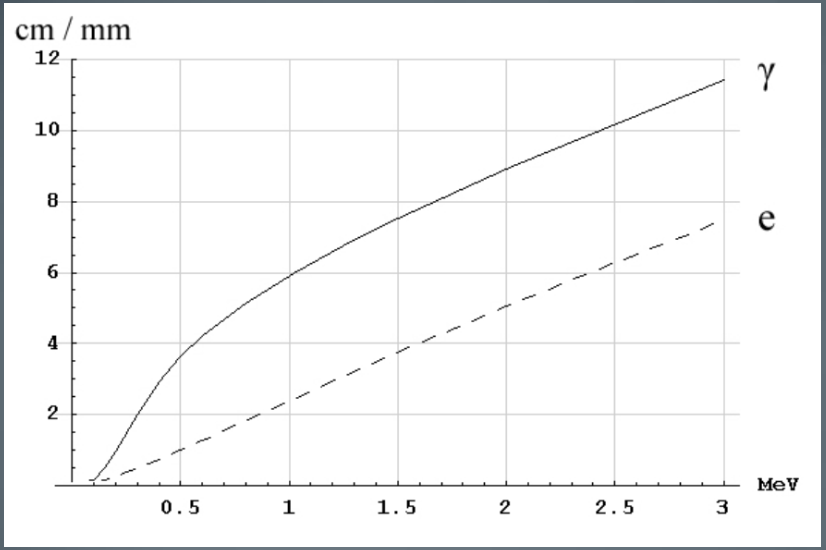
^{214}Bi – ^{214}Po coincidence



^{222}Rn content after initial fill

- Using the ^{214}Bi – ^{214}Po coincidence (both ^{222}Rn daughters) we can estimate the amount of ^{222}Rn in the Lxe
- Alphas create high ionization density due to their short range →high recombination rate → increased light/charge ratio
- Long-term study shows a constant source of ^{222}Rn dissolving in ^{enr}LXe: 360 ± 65 μBq (Fid. vol.)

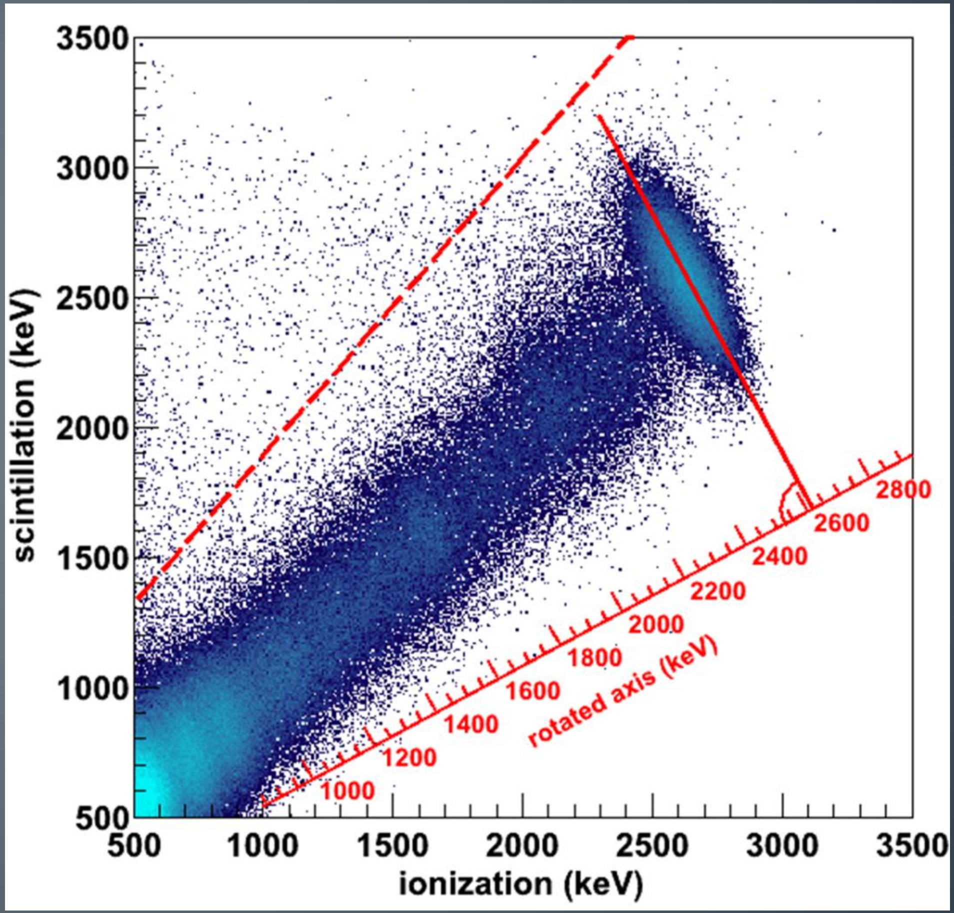
Backgrounds and event topology



- Plot shows mean free path of γ and stopping distance of e
- Y-axis scale in mm for e and cm for γ
- Detector resolution on the order of ~1 mm

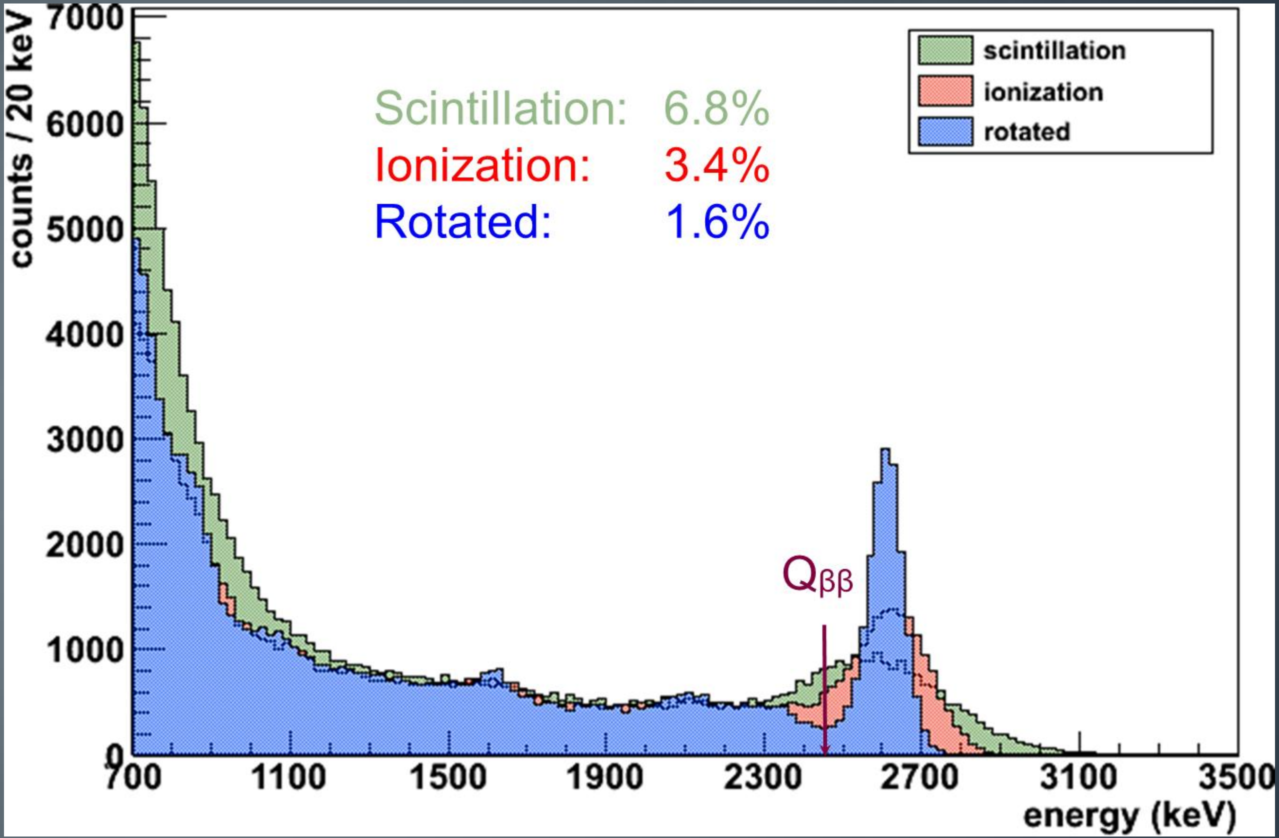
- γ usually scatter to multiple sites, while
- e have continuous energy loss within < 1mm → single site event
- Single site and multiple site spectra

Combining ionization and scintillation energy



Properties of Xe cause increased ionization to be associated with decreased scintillation E. Conti et al. Phys. Rev. B 68 (2003) 054201

Combining ionization and scintillation energy



Use projection onto rotated axis to determine event energy:
„Rotation“ angle determined via optimization of energy resolution at ^{228}Th photopeak (2615 keV)

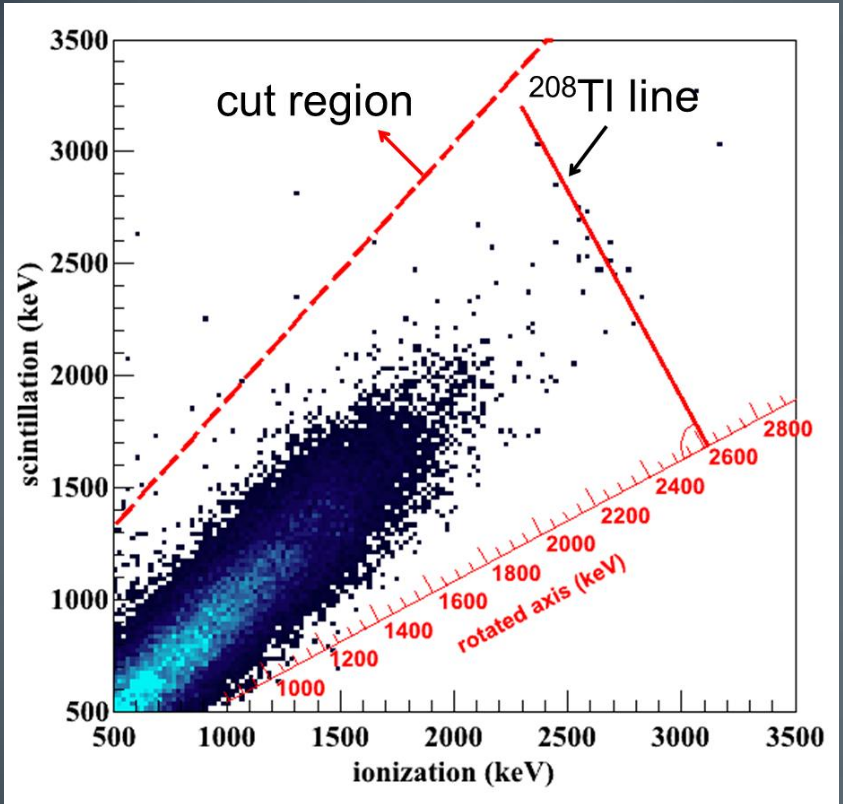
Recent analysis overview

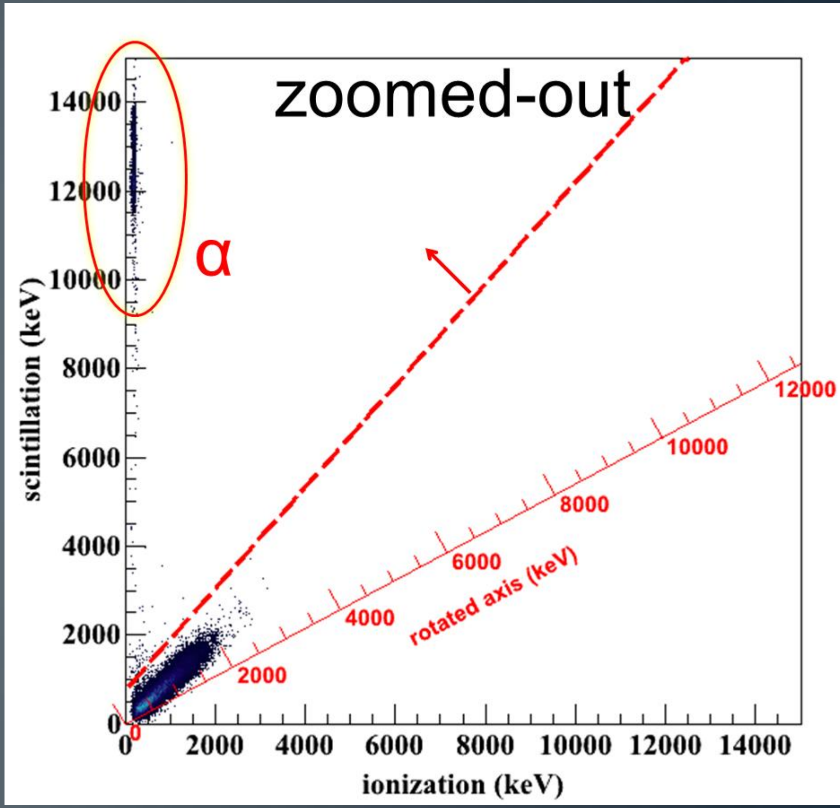
- Measurement period: Sep 22 2011 – Apr 15 2012
- Low background run livetime: 120.7 days
- Active mass: 98.5 kg LXe (79.4 kg ^{136}LXe)
- Exposure: 32.5 kg.yr
- Total dead time from vetos: 8.6%
- Events required to be fully reconstructed in 3D (U-, V-position, APD signal found
  - Reconstruction efficiency (SS) for ββ0ν: 71%
- Energy resolution at Q value: 1.67%
  - Dominated by constant noise term (electronics noise)

Applied cuts

- Muon veto:
  - 25 ms after muon veto panel hit (0.58% dead time)
  - 60 s after muon track identified in TPC (5.0 % dead time)
- Time coincidence cut:
  - Removes any two events that occur within 1s (3.3% dead time)
  - Removes β-α decay coincidences due to ^{214}Bi ^{214}Po (^{222}Rn daughters)
- Energy spectrum „diagonal“ cut
  - Removes events with incomplete charge collection (detector edges)
  - Removes α-events
- Fiducial volume cut
  - Removes events which have clusters outside fiducial volume

Low background spectrum



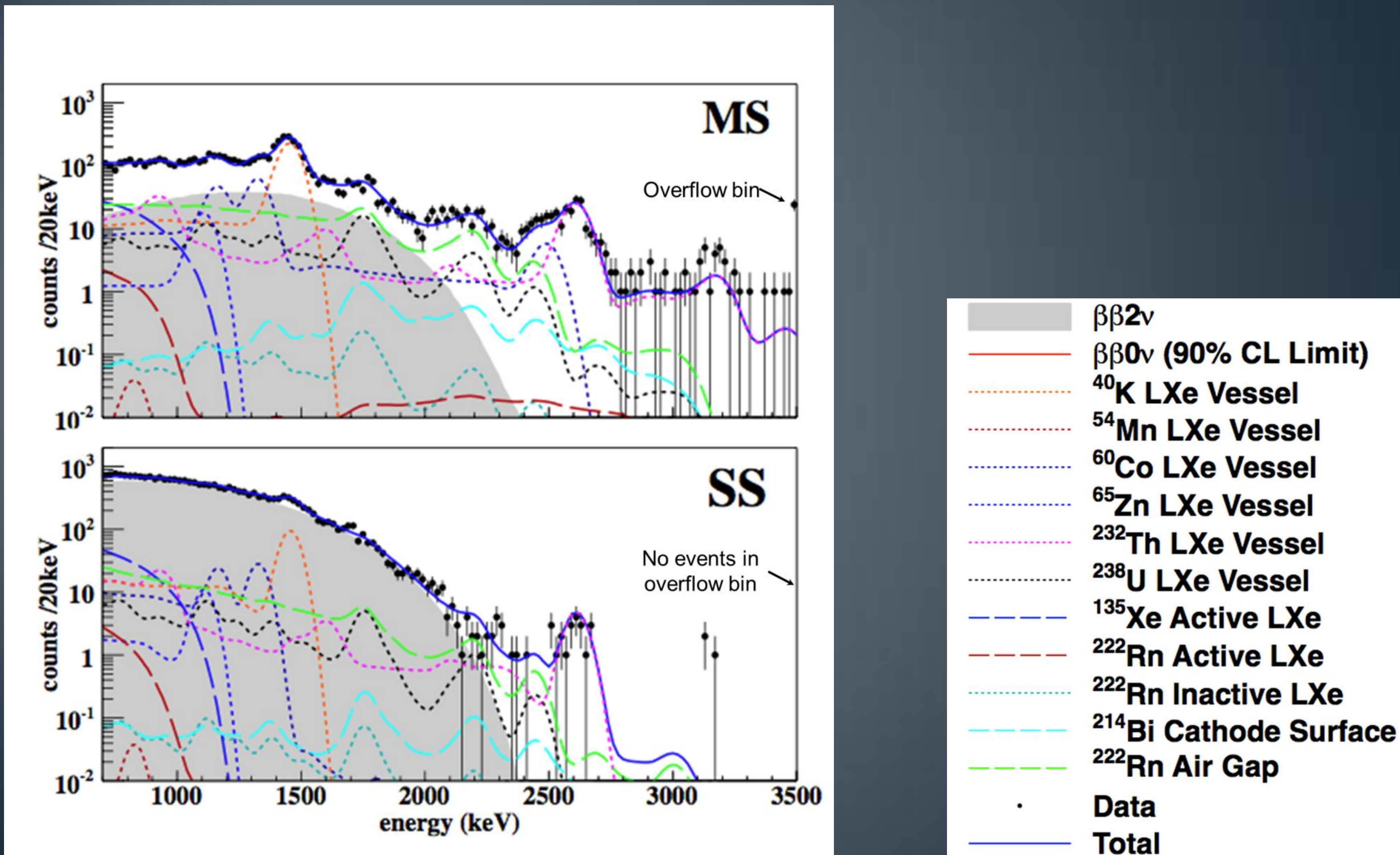


- Alphas create high ionization density due to their short range →high recombination rate → increased light/charge ratio

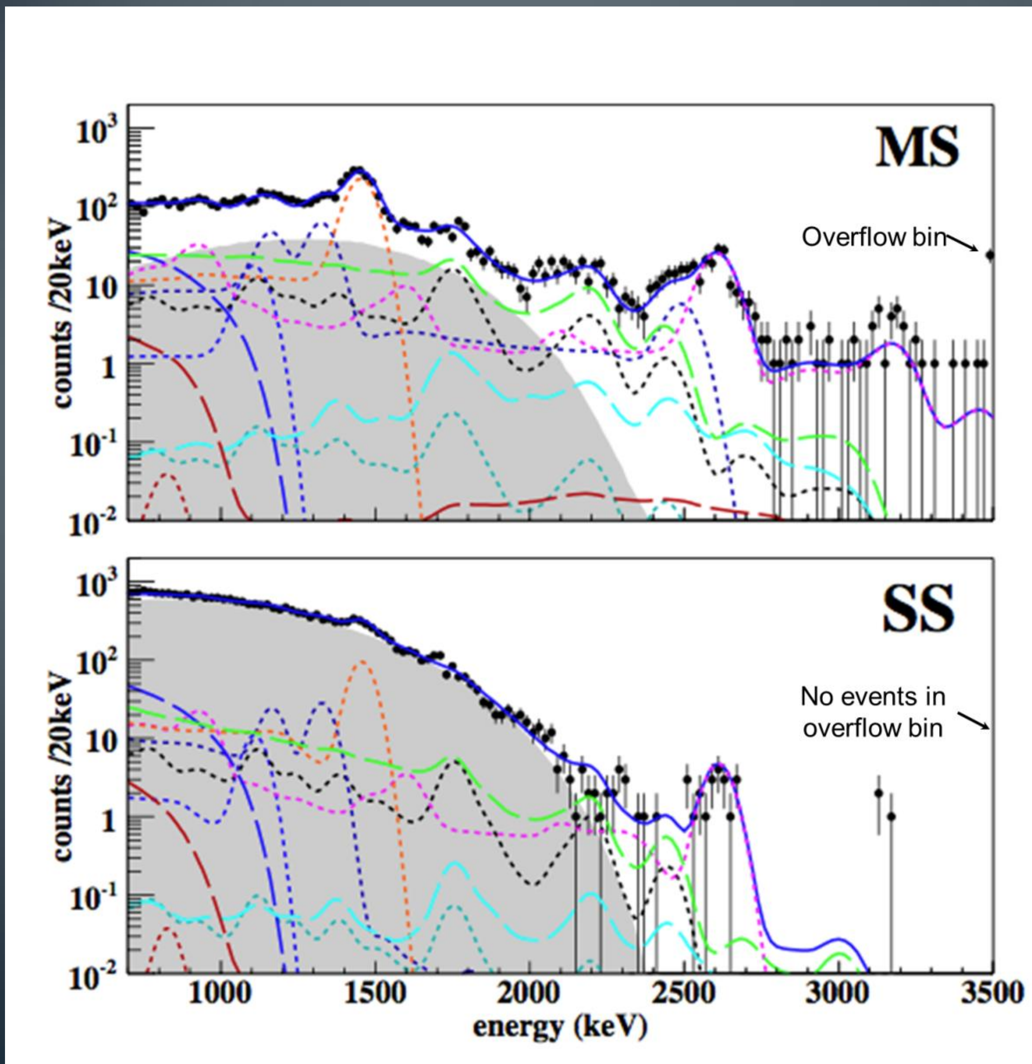
Fit to low background spectra

- Signal ($0\nu\beta\beta$, $2\nu\beta\beta$) and background PDFs generated by MC
- Convolved with (parameterized) resolution function
- Combined to perform Maximum Likelihood fit on data (simultaneously across MS and SS event populations)
- Systematics (MS/SS ratios, resolution, calibration, etc.) constrained by measurements

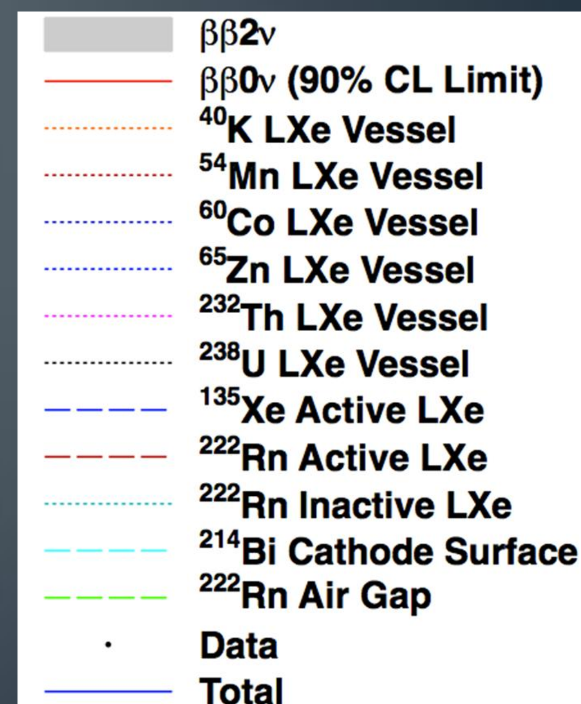
Low background fit



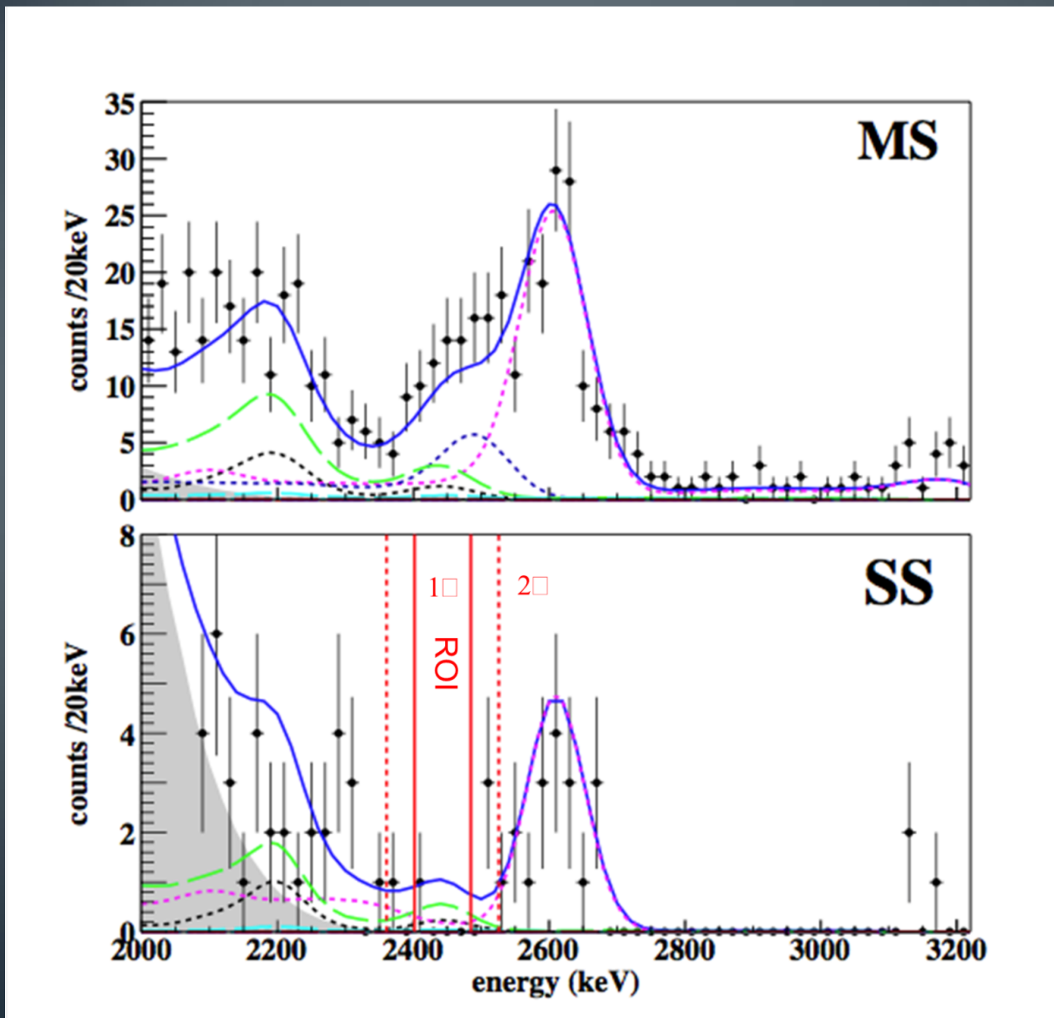
Low background fit



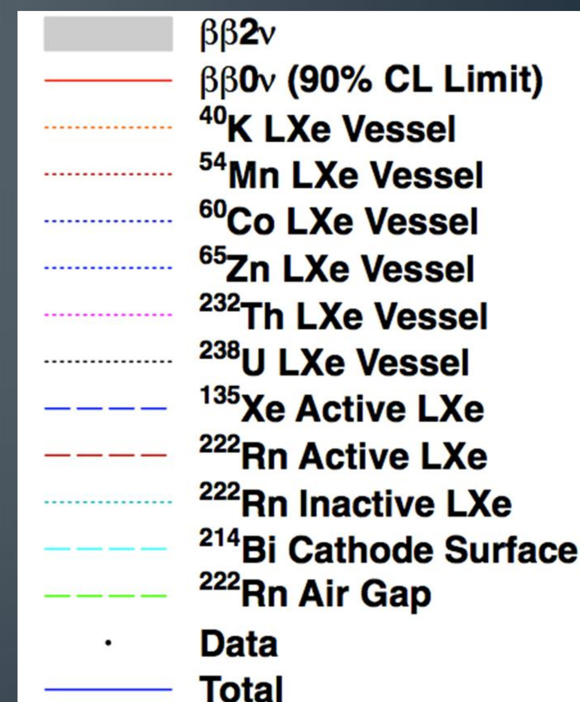
- ~22,000 2νββ events !
- Also populate MS spectrum, partly due to bremsstrahlung
- MC predicts that 82.5% of 2νββ are SS



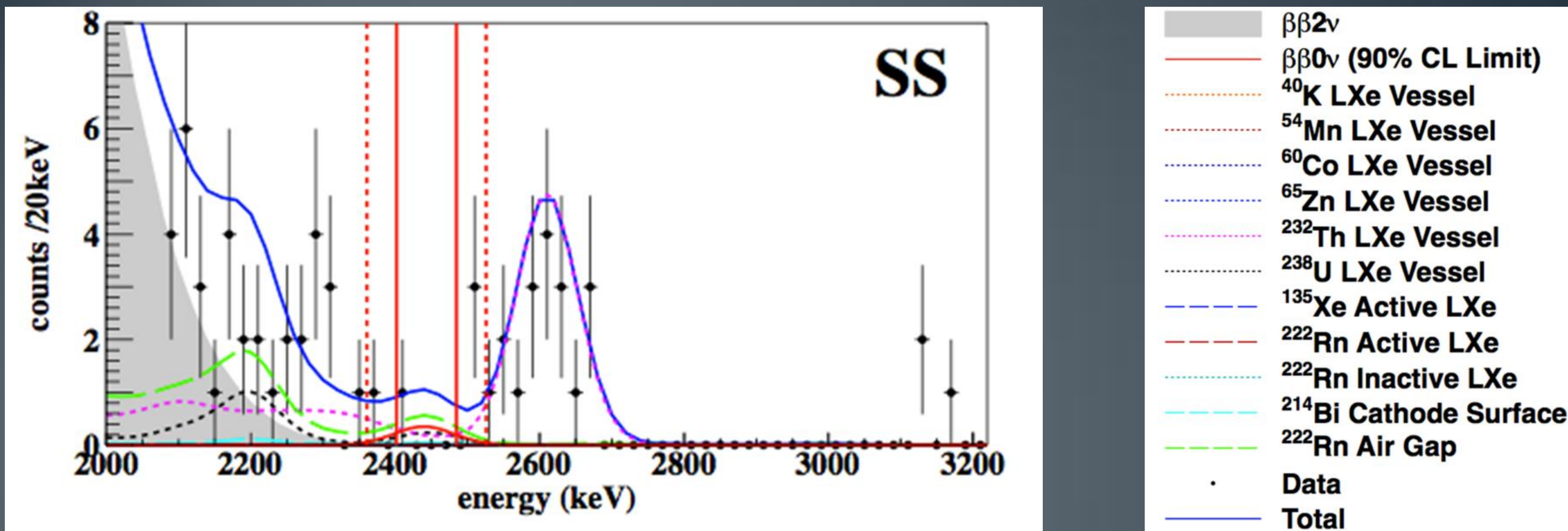
Low background fit (zoomed)



- No 0ν-signal observed



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 background goal:
  40 cnts/2y in ±2σ ROI, 140 kg LXe
- In this data, 120 days, 98.5 kg, this would be: 4.6 cnts
- Expected from the fit: 7.5
- Observed: 5
- Background within expectation

Limits on $T^{0\nu}_{1/2}$ and $|m_{\beta\beta}|$

$$T_{\frac{1}{2}}^{0\nu^{-1}} = G^{0\nu}\left|M^{0\nu}\right|^2\left|m_{\beta\beta}\right|^2$$

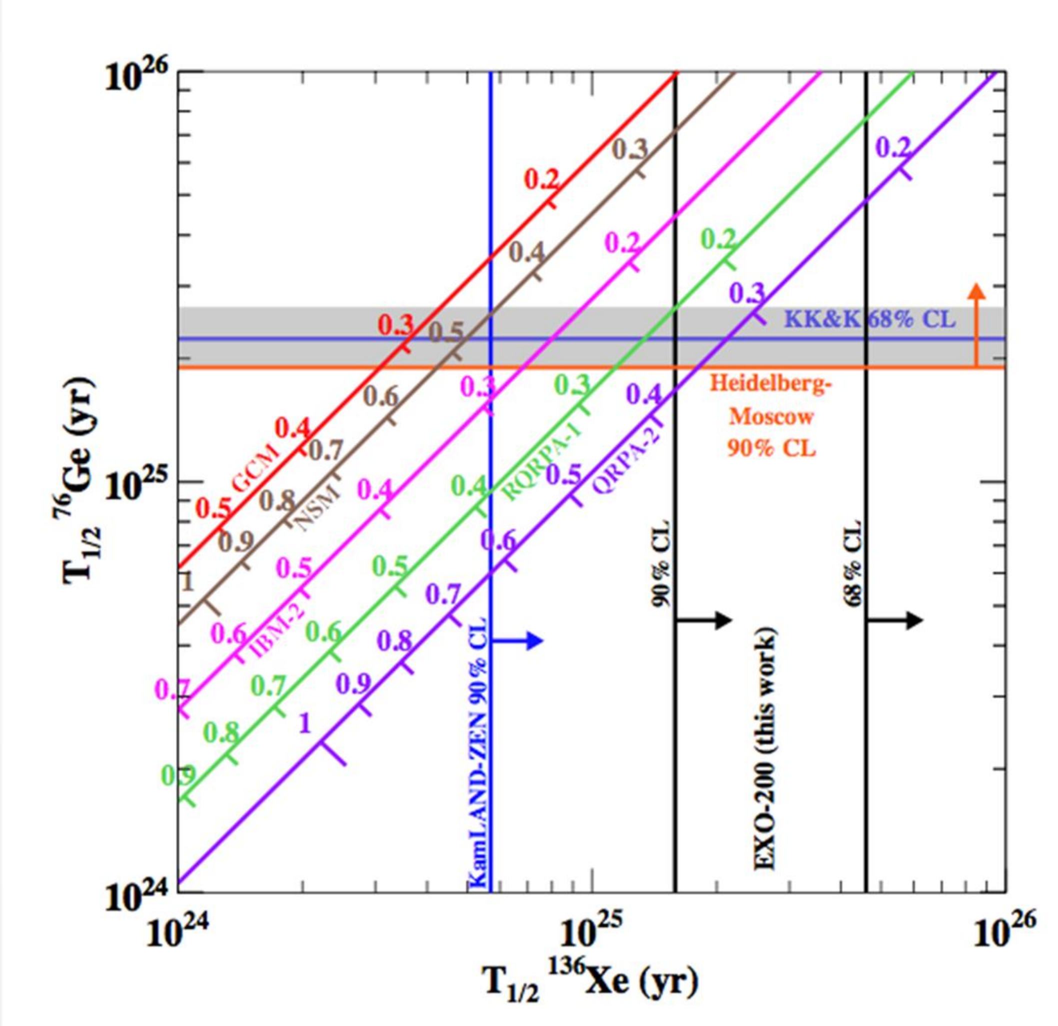
From Profile Likelihood (90% CL):

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

$$\left|m_{\beta\beta}\right| < 140 - 380\ \mathrm{meV}$$

arXiv:1205.5608 – Subm. to PRL

Limits on $T^{0\nu}_{1/2}$ and $|m_{\beta\beta}|$



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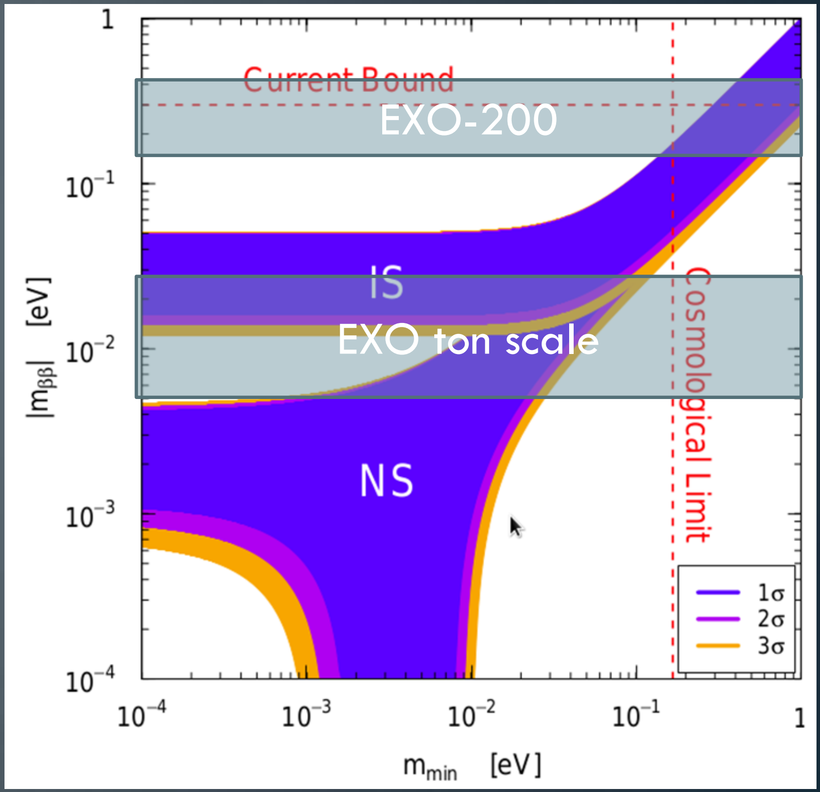
A. Gando et al. Phys. Rev. C 85 (2012) 045504
H.V. Klapdor-Kleingrothaus et.al. Eur. Phys. J. A12 (2001) 147
H.V. Klapdor-Kleingrothaus and I.V. Krivosheina, Mod. Phys. Lett., A21 (2006) 1547.

Summary

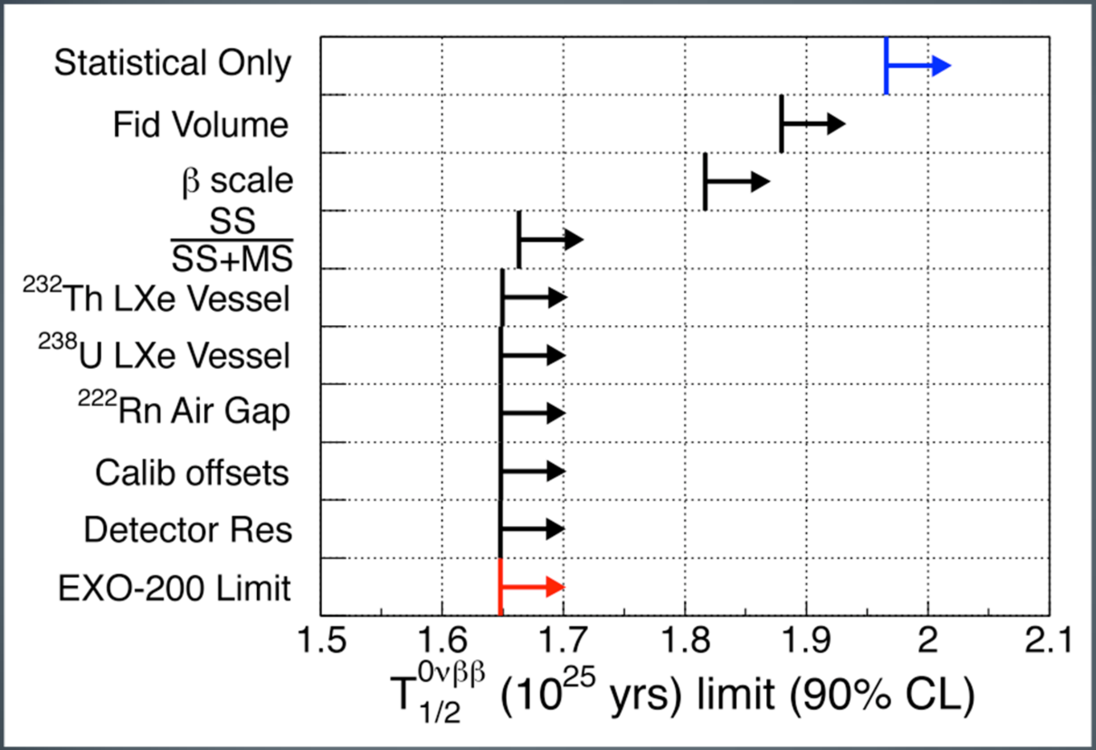
- EXO-200 is taking low background data
- Detector working well, we met our goals:
  - Energy resolution: 1.67% at $Q\beta\beta$
  - Background: 1.5×10^{-3} kg^{-1} keV^{-1} yr^{-1}
    1 (5) counts in 1σ (2σ) $0\nu\beta\beta$ ROI
- $T^{0\nu}_{1/2} > 1.6{*}10^{25}$ yr



- Improvements on σ and b in progress
- EXO-200 approved to run for 4 more years

Backup Slides

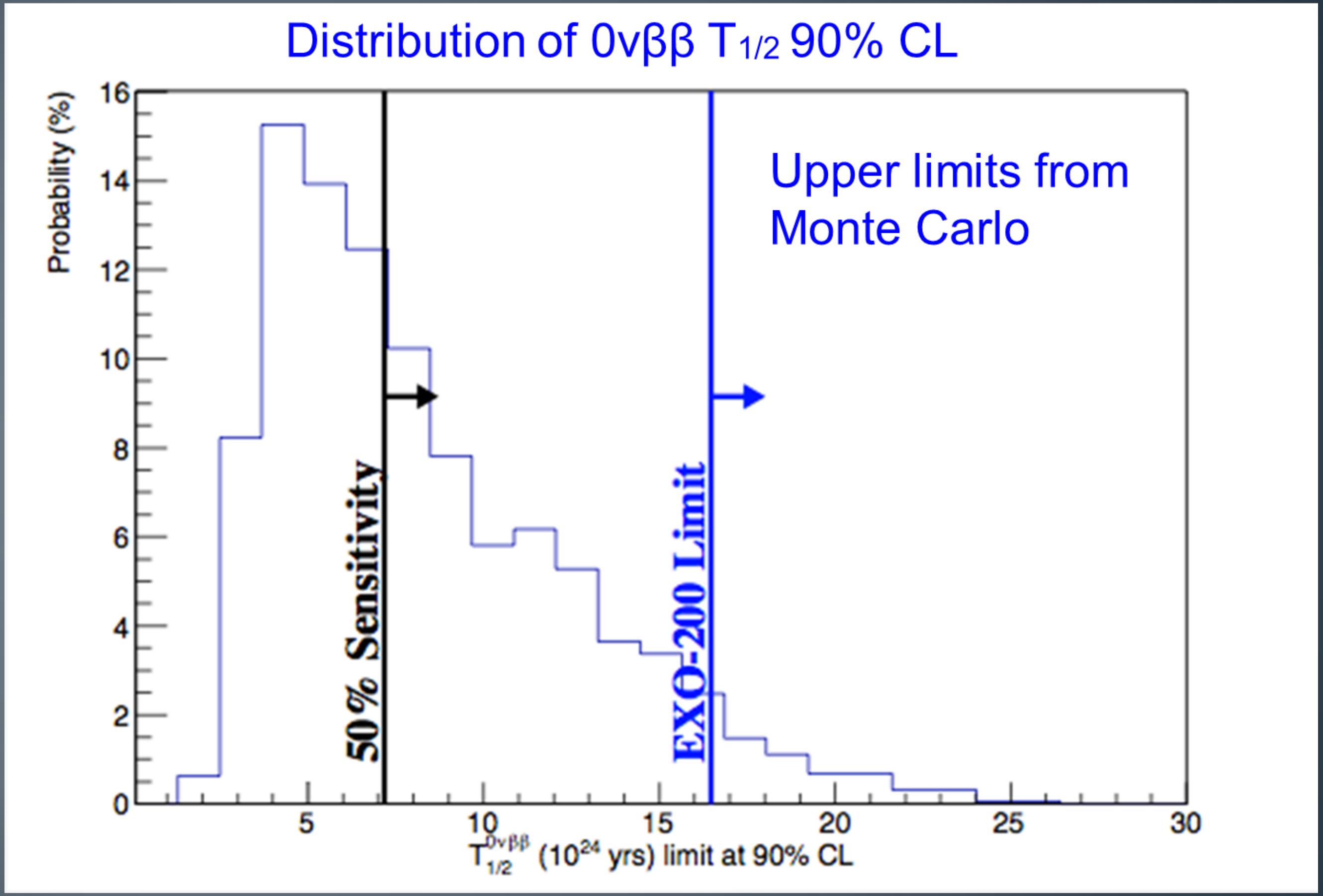
Systematics



Term	%
Fiducial Volume	12.34
β scale	9.32
SS / (SS + MS)	0.93
^{232}Th LXe Vessel	0.11
^{238}U LXe Vessel	0.04
^{222}Rn Air Gap	0.04
Calibration offsets	0.04

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

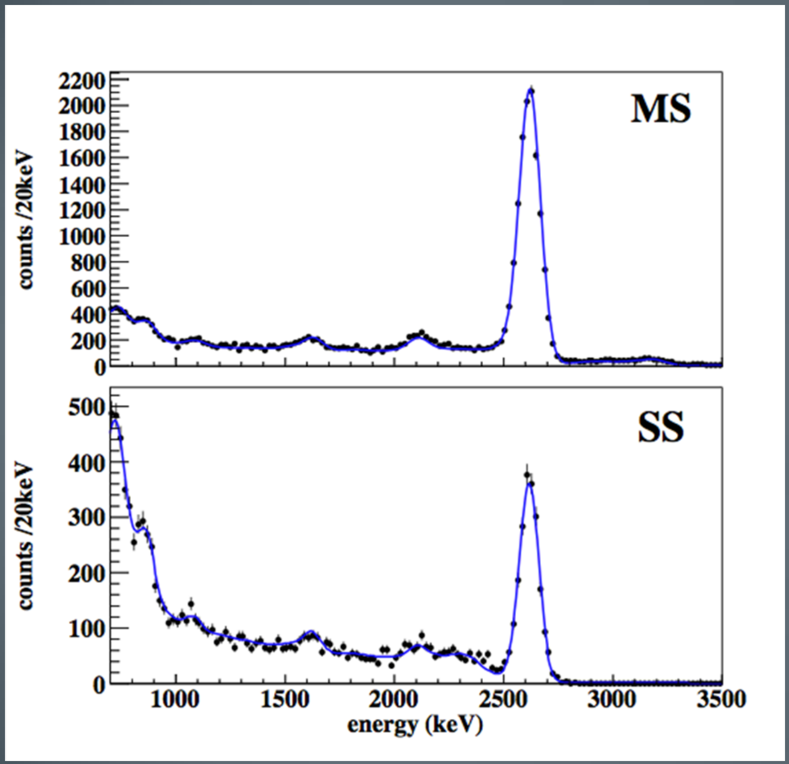
Sensitivity

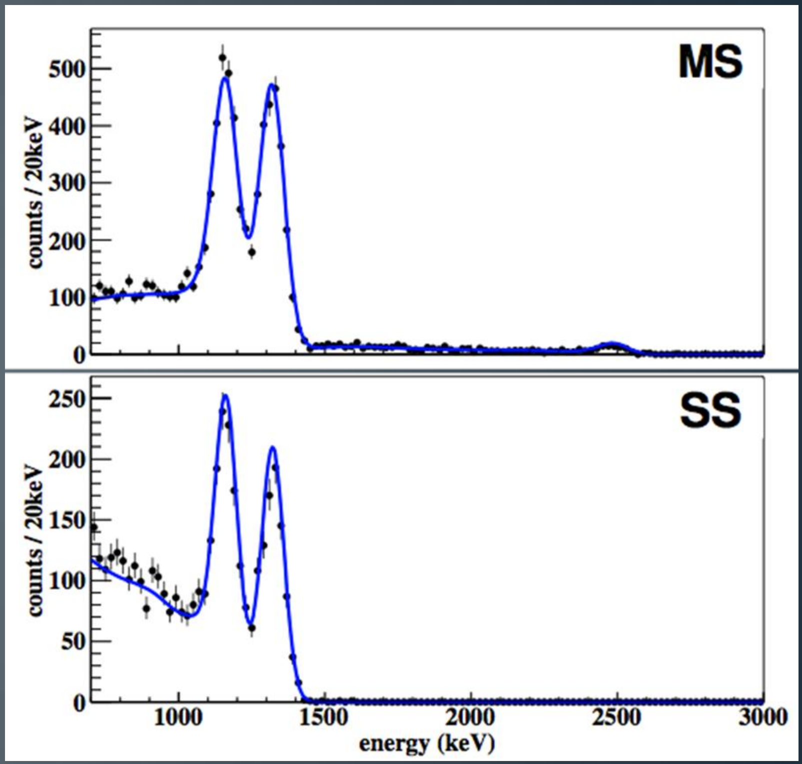


From estimated background, expect to quote a 90% CL upper limit on $T_{1/2}$:

- $\geq 1.6 \times 10^{25}$ yr   6.5% of the time
- $\geq 7 \times 10^{24}$ yr   50%   of the time

Calibration source data/MC agreement



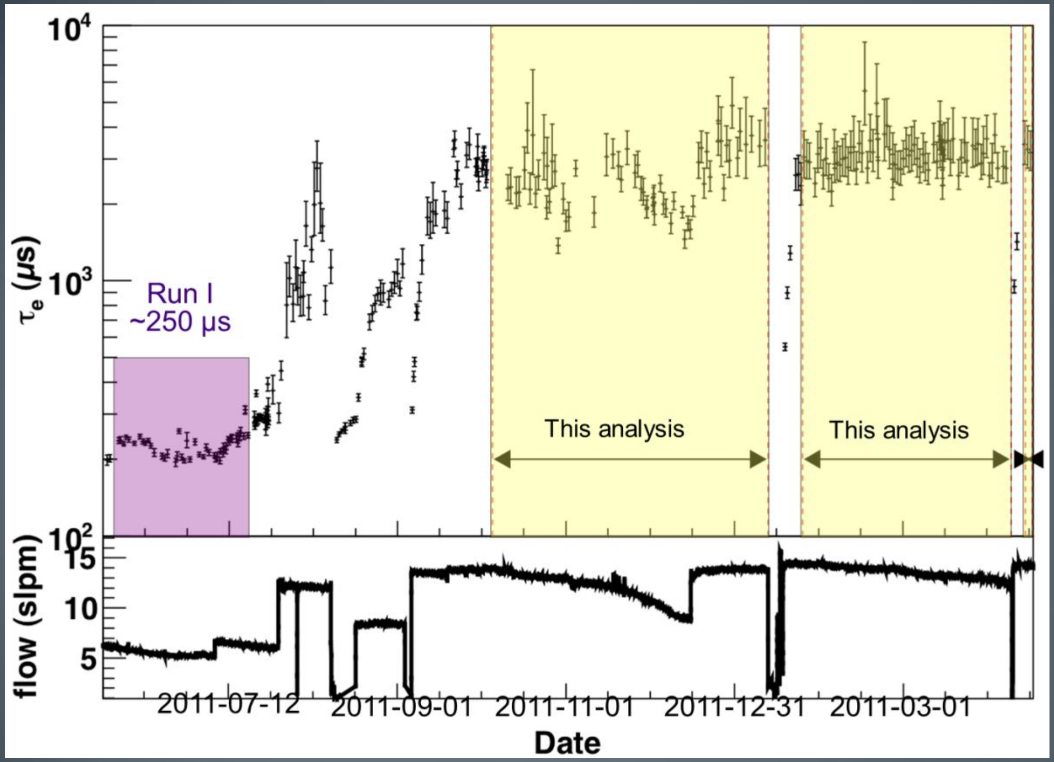


- Black dots: Data
- Blue line: MC

- SS/MS fraction agreement within 8.5%
- Overall rate agreement within 9.4%

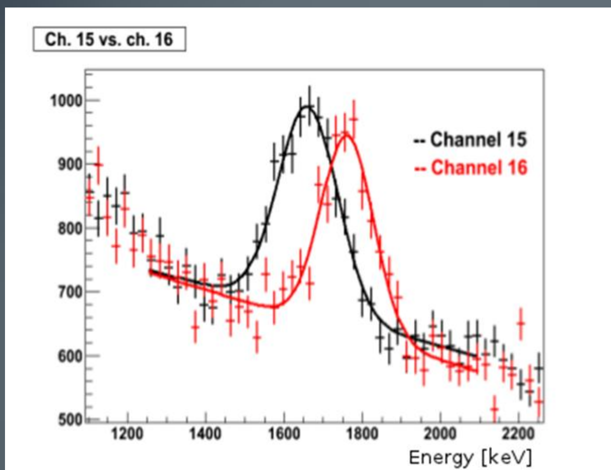
Corrections applied to data

Electronegative impurity correction

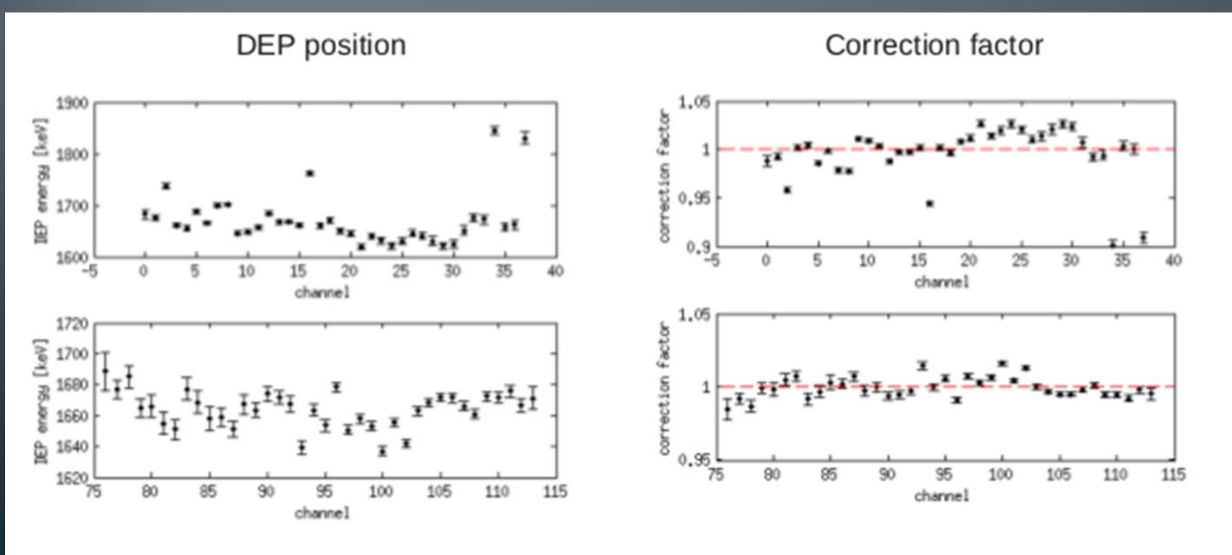


- e losses via catching by electronegative impurities
- Loss rate related to drift time: $\exp(-\frac{t_{drift}}{\tau_e})$
- Xe is purified by continuously recirculating through gas purifier
- Purity (= electron lifetime) clearly correlated to pump speed

Wire gain corrections

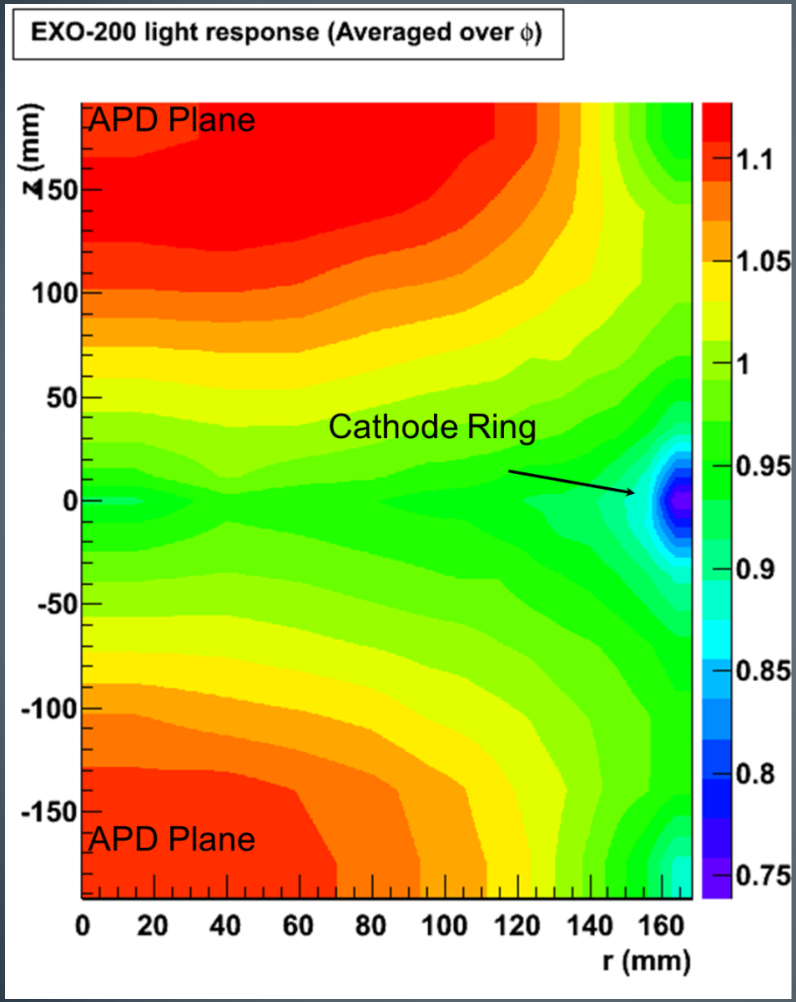


- Gains of wire channels measured with charge calibrations
- This is further corrected using the pair production peak (1593 keV) from ^{228}Th 2615 keV γ depositions.
- Have also individually measured the electronic transfer function of each channel, which are used to reconstruction the charge signals



- With all this and the excellent purity, the charge resolution improved from 4.5% to 3.4% at 2615 keV

Light yield correction



- Use full absorption peak of 2615 keV γ from ^{208}Tl (^{228}Th source) to map light response in TPC

Disabled APD gang