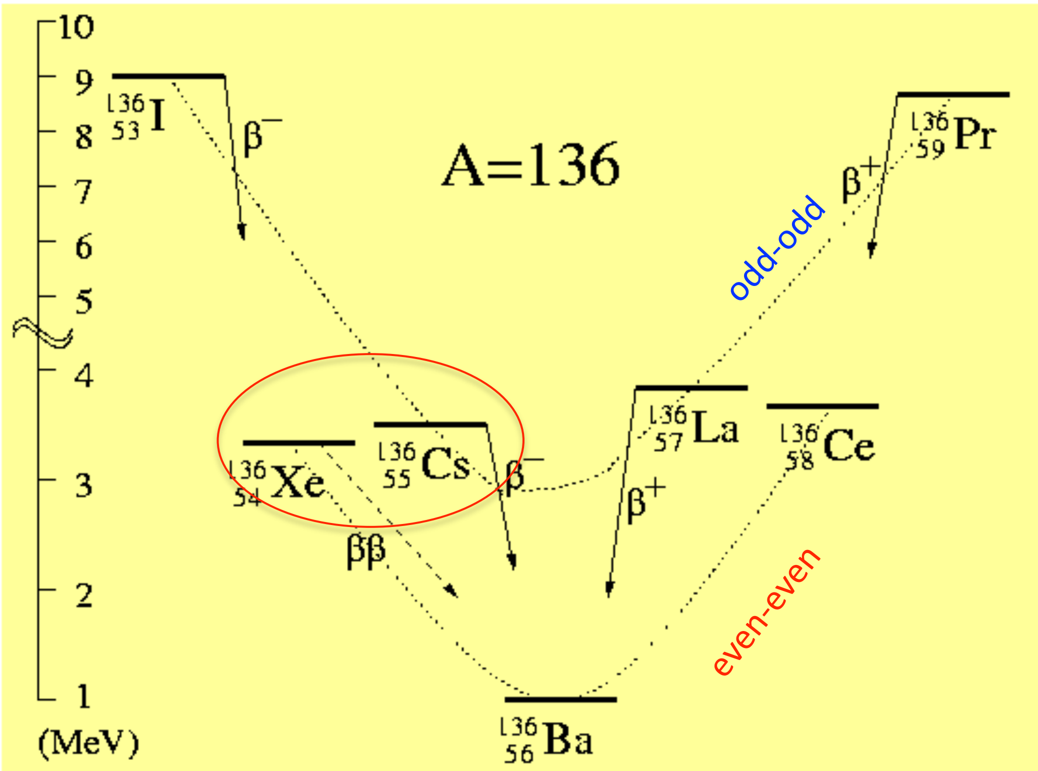
EXO-200 First $0\nu\beta\beta$ result

48th Rencontres de Moriond
David Auty for the EXO Collaboration
University of Alabama
5th March 2013

What is ββ decay



- A second order weak interaction where two neutrons turn into two protons
- Only allowed for nuclei where beta decay is energetically forbidden or highly suppressed due to a large angular momentum difference

2 ways for ββ to occur

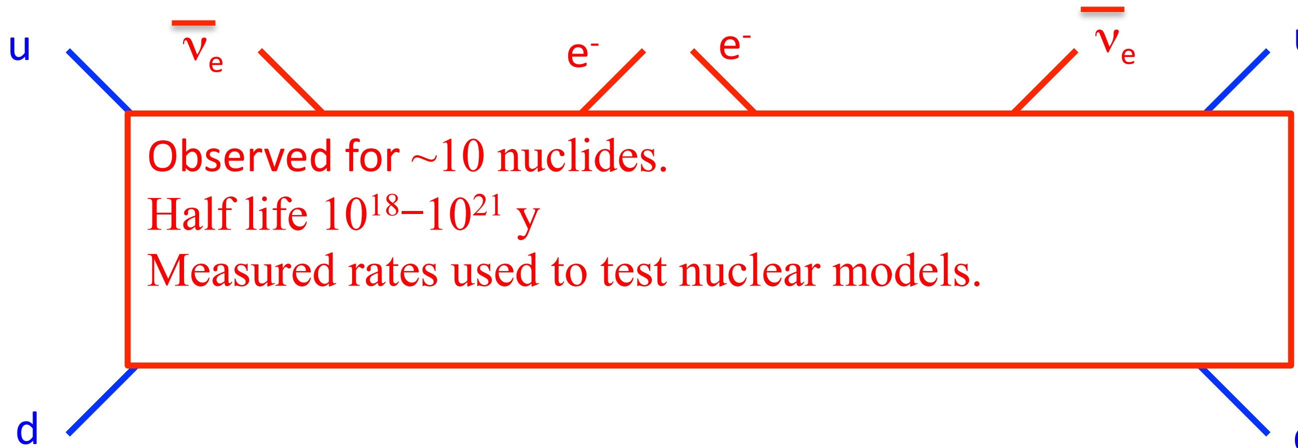
B	L
1/3	0

$\Delta B=0$

$\Delta L=0$

$\Delta(B-L)=0$

1/3	0



ββ2ν

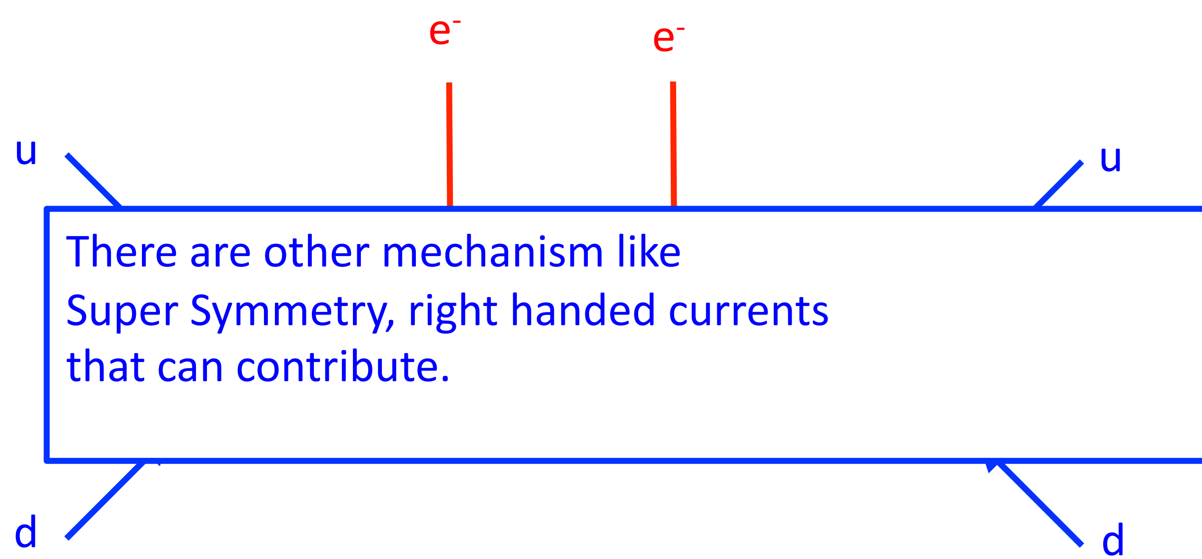
B	L
1/3	2

$\Delta B=0$

$\Delta L=2$

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

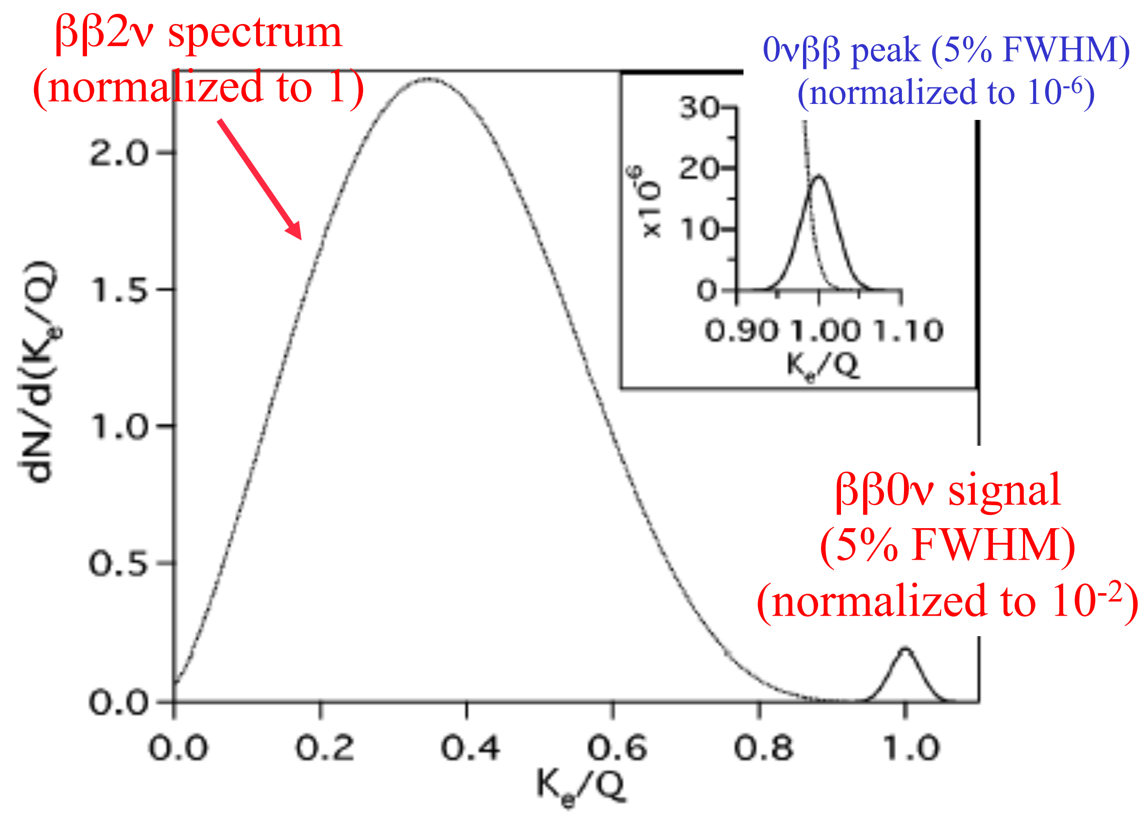
1/3	0



ββ0ν

B: Baryon Number
L: Lepton Number

How do we Measure the Rate?



Elliot, S. et al., Annu. Rev. Nucl. Part. Sci. 2002. 52:115–51

Summed electron energy in units of the kinematic endpoint (Q)

To maximize sensitivity:
- Large mass
- Low background
- High detection efficiency
- Good energy resolution

$$S_{1/2}^{0\nu} \propto \varepsilon \frac{a}{A} \left[\frac{MT}{B\Gamma} \right]^{1/2}$$

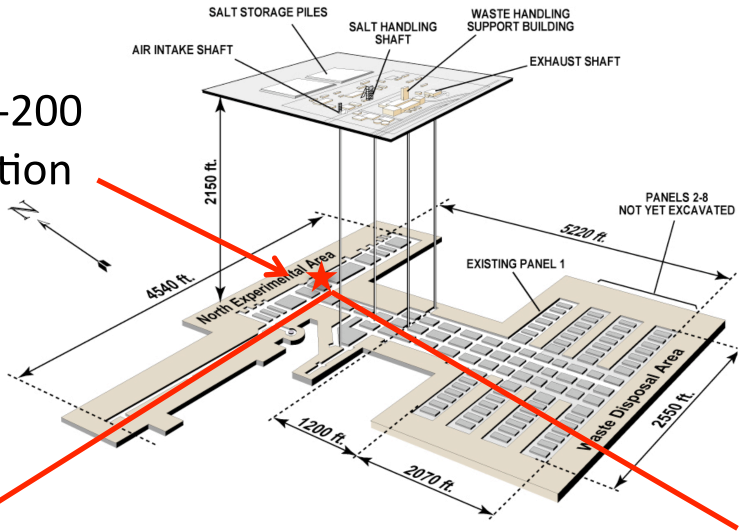
ε is efficiency
a is isotopic abundance
A is atomic mass
M is source mass
T is time
B is background
Γ is resolution

Why xenon-136

- It has a reasonable Q-value 2457.9±0.4keV
- Xenon can be continuously purified and recyclable (no crystal growth)
- Allows charge drift and scintillates
- Cost effective to enrich as Xe-136 is the heaviest long lived isotope
- No long lived Xe isotopes
- Potential to tag Ba-136 daughter nuclei
- Monolithic detector as liquid Xe is self shielding

EXO-200 installation site: WIPP

EXO-200 location



- EXO-200 installed at WIPP (Waste Isolation Pilot Plant), in Carlsbad, NM
- 1600 mwe flat overburden (2150 feet, 650 m)
- U.S. DOE salt mine for low-level radioactive waste storage
- Cleanroom installed on adjustable stands to compensate salt movements.
- Salt “rock” low activity relative to hard-rock mine

$$\Phi_{\mu} \sim 1.5 \times 10^{5}\, yr^{-1} m^{-2} sr^{-1}$$

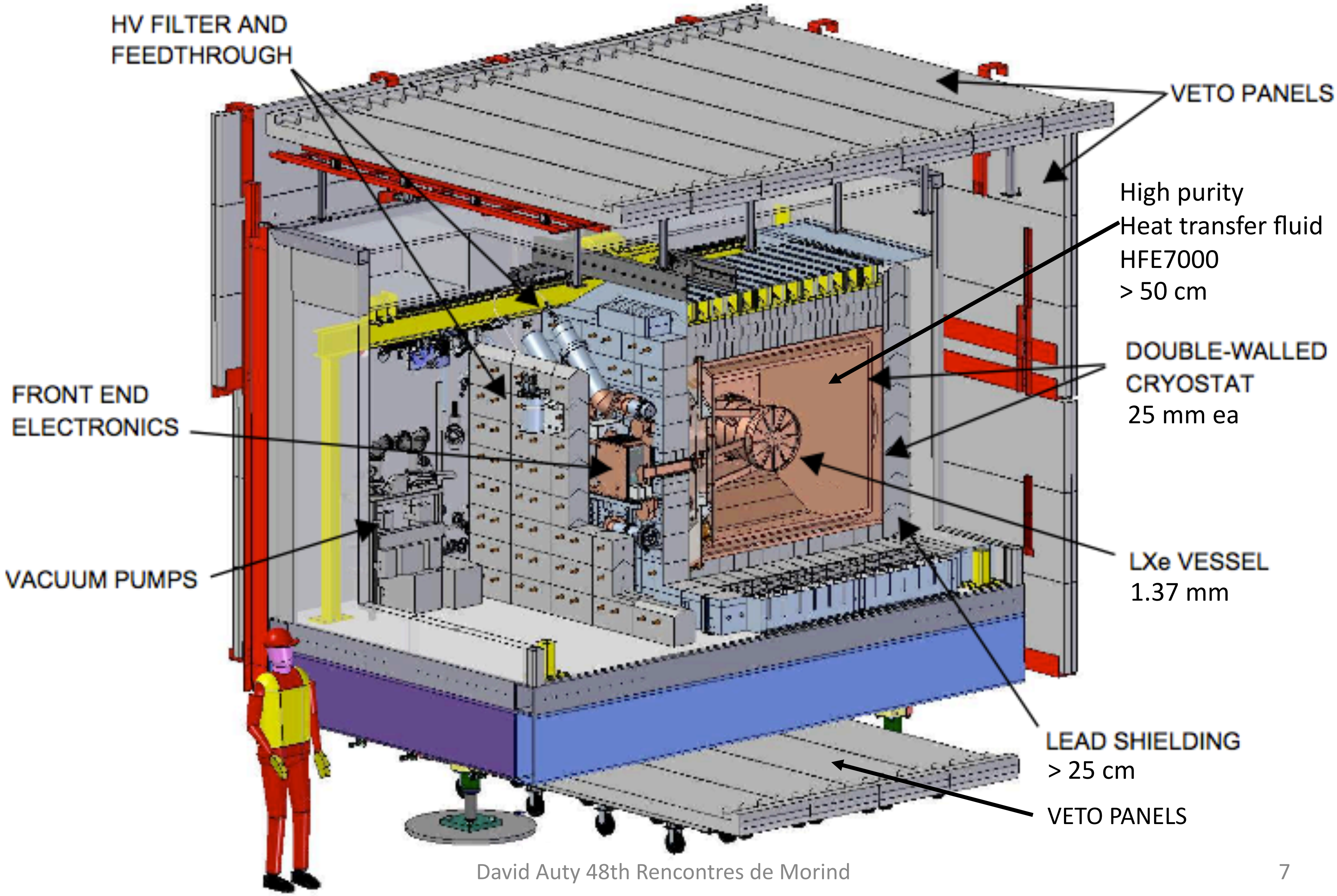
$$U \sim 0.048\, ppm$$

$$Th \sim 0.25\, ppm$$

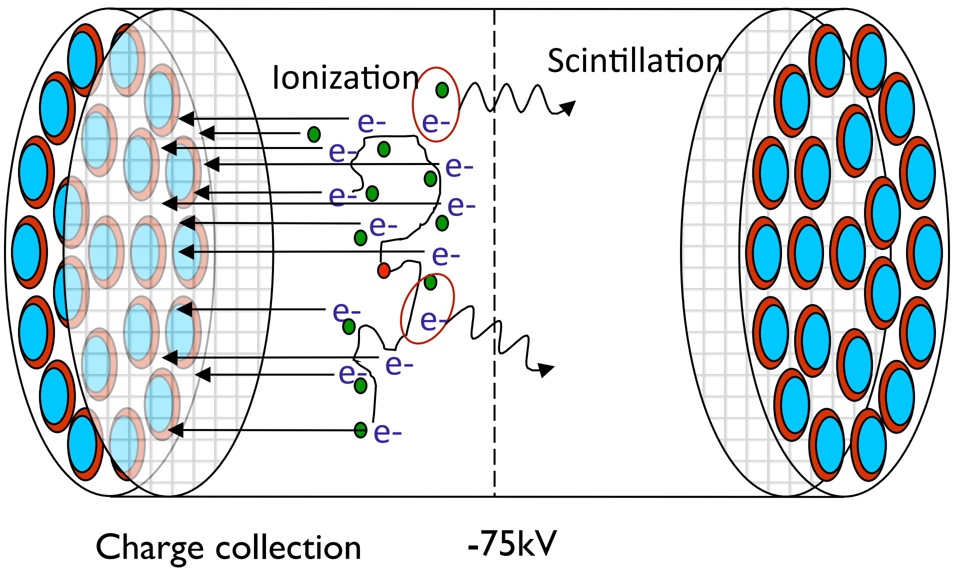
$$K \sim 480\, ppm$$

Esch et al., arxiv:astro-ph/0408486 (2004)

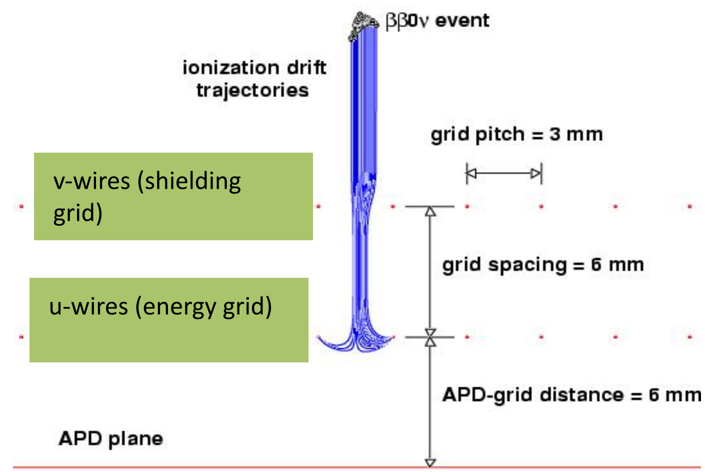
The EXO-200 Detector



EXO-200 Time Projection Chamber (TPC) Basics



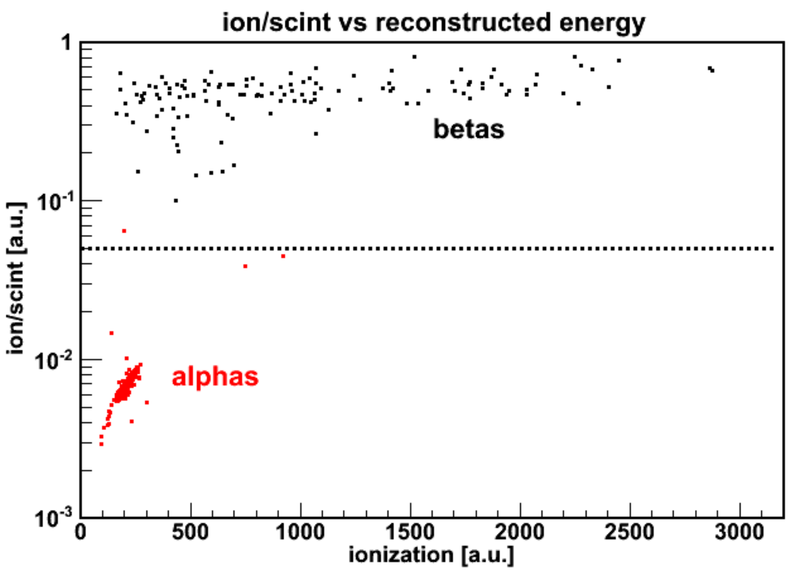
TPC Schematics



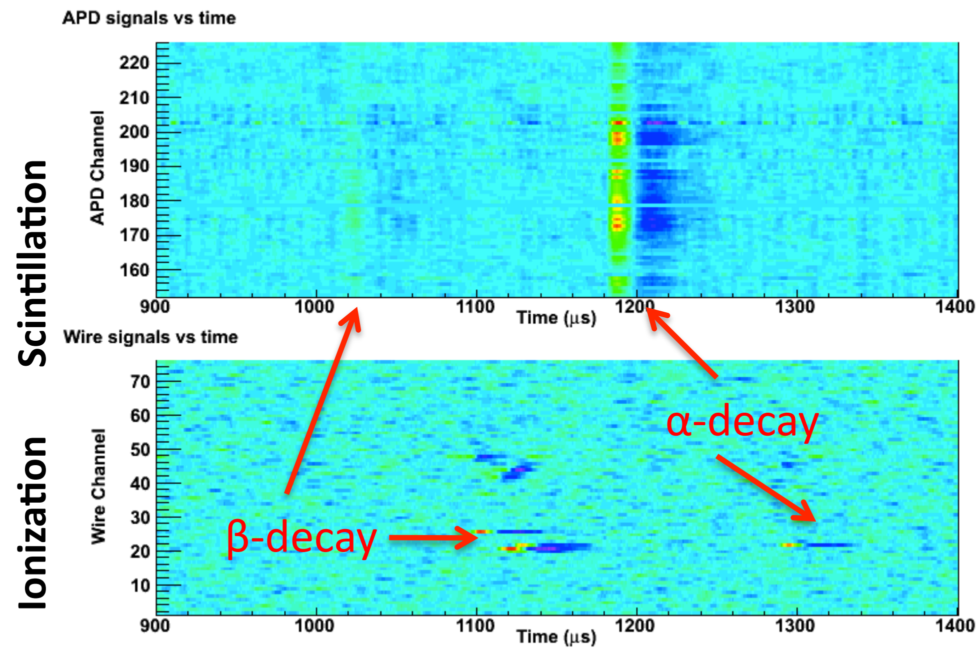
Simulation of Charge Drift

- Two TPC modules with common cathode in the middle.
- APD array observes prompt scintillation for drift time measurement.
    - From which the Z-position can be calculated
- V-position given by induction signal on shielding grid.
- U-position and energy given by charge collection grid.

Rn Content in Xenon



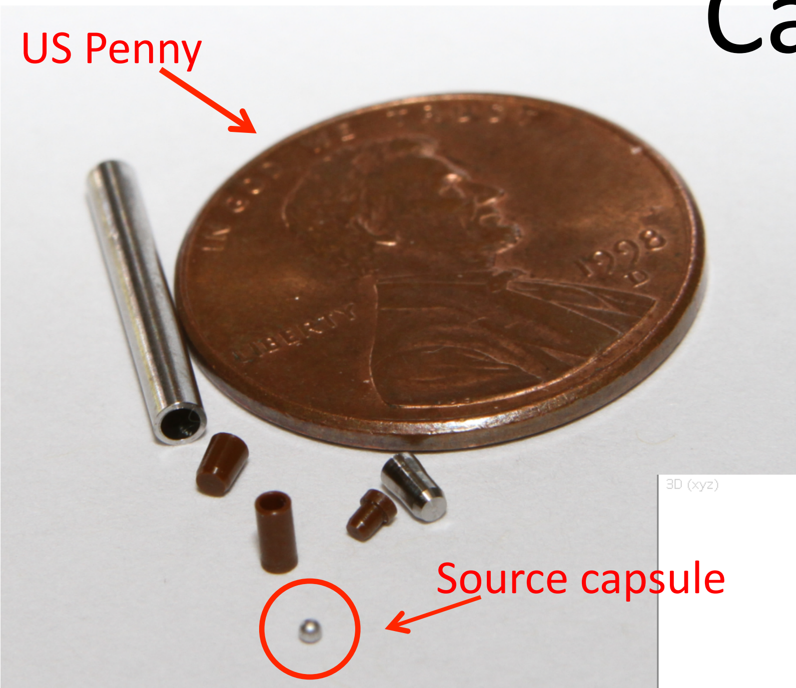
α: strong light signal, weak charge signal
β: weak light signal, strong charge signal



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

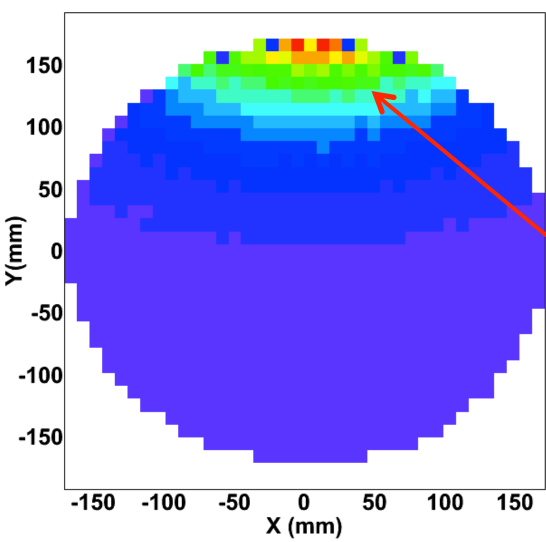
- Charge to Light ratio is a powerful tool for decimating between alpha and beta events.
- Using the Bi-Po (Rn daughter) coincidence technique, we can estimate the Rn content in our detector.

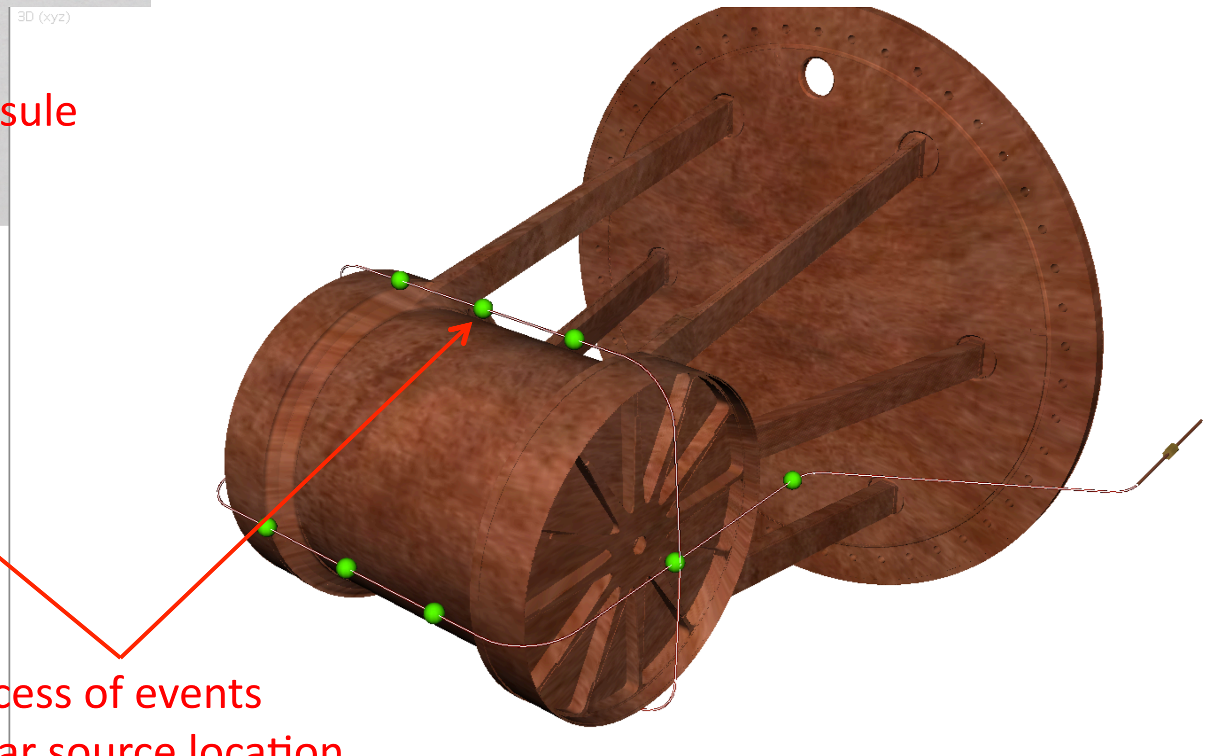
Calibration



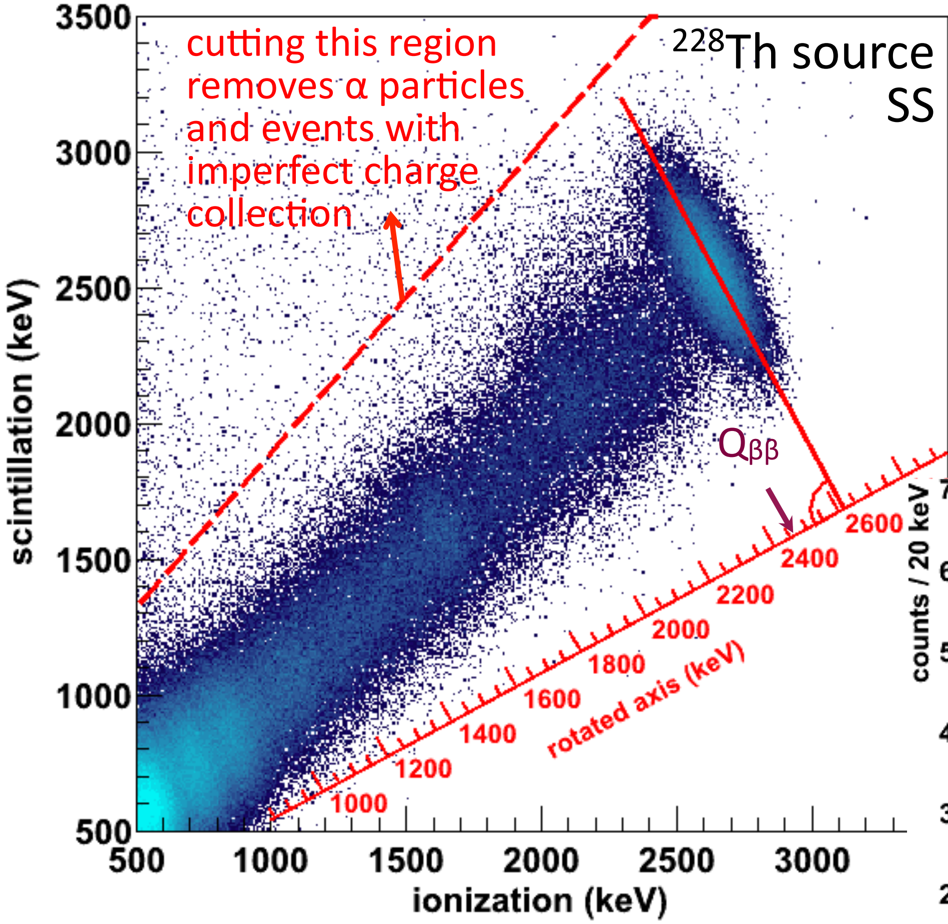
A copper guide tube around the outside of the TPC allows radioactive sources to be deployed to predetermined locations around the TPC

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





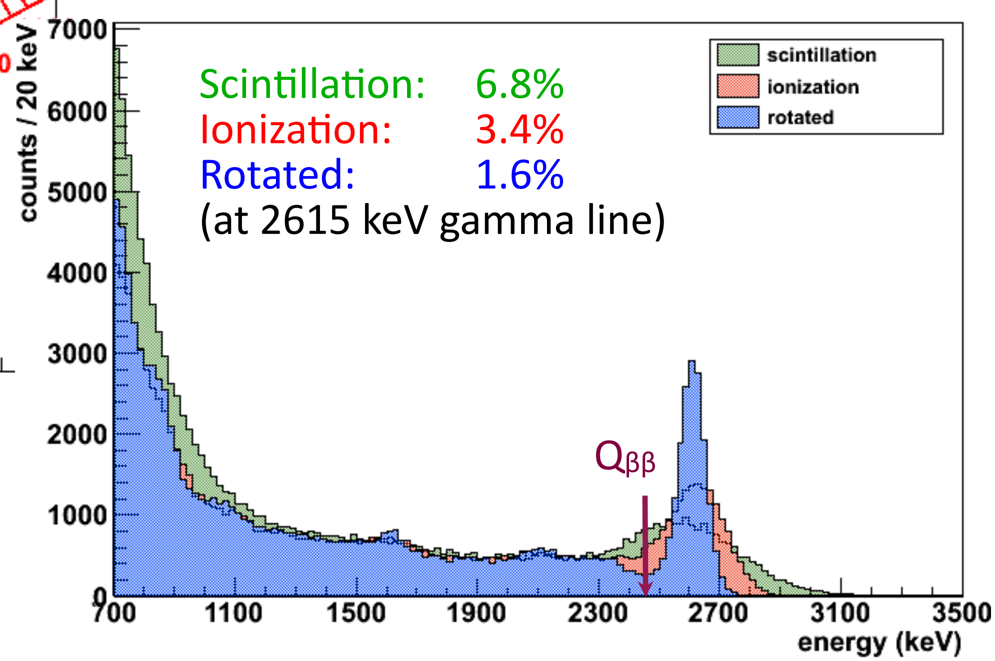
Combining Ionization and Scintillation



Properties of xenon cause increased scintillation to be associated with decreased ionization (and vice-versa)

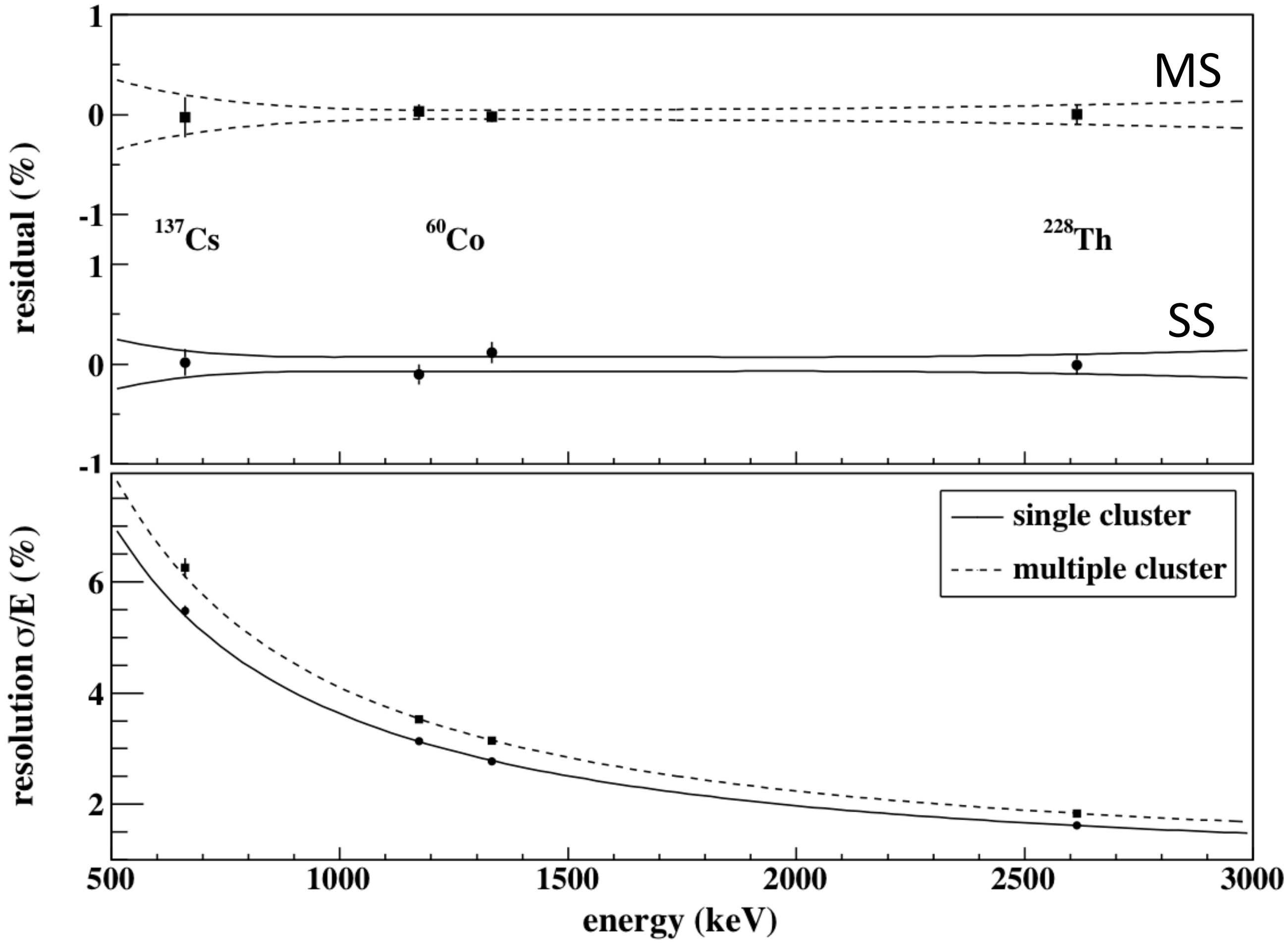
E. Conti et al. Phys. Rev. B 68 (2003) 054201

Use projection onto a rotated axis to determine event energy



Rotation angle chosen to optimize energy resolution at 2615 keV

Energy Calibrations



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

Energy resolution model:

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

Resolution dominated by constant (noise) term p_1

At $Q_{\beta\beta}$ (2458 keV):
σ/E = 1.67 % (SS)
σ/E = 1.84 % (MS)

EXO-200 Low-Background Run I Results

	Run I	Run 2 (this analysis)
Period	May 21, 11 – Jul 9, 11	Sep 22, 11 – Apr 15,12
Live Time	752.7 hr	2,896.6 hr
Exposure (^{136}Xe)	4.4 kg-yr	26.3 kg-yr
Publ.	PRL 107 (2011) 212501	PRL 109 (2012) 032505

Run I Results:

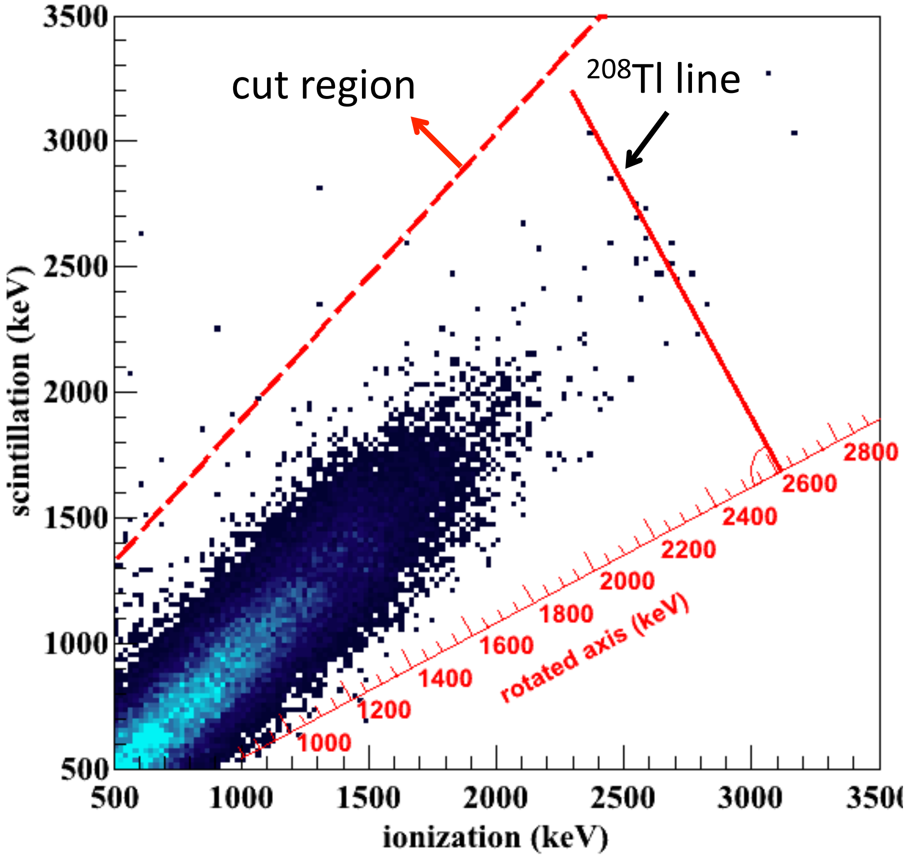
$\mathbf{T_{1/2}^{2\nu\beta\beta}\ (^{136}Xe) = (2.11 \pm 0.04\ stat \pm 0.21\ sys)\cdot 10^{21}\ yr}$

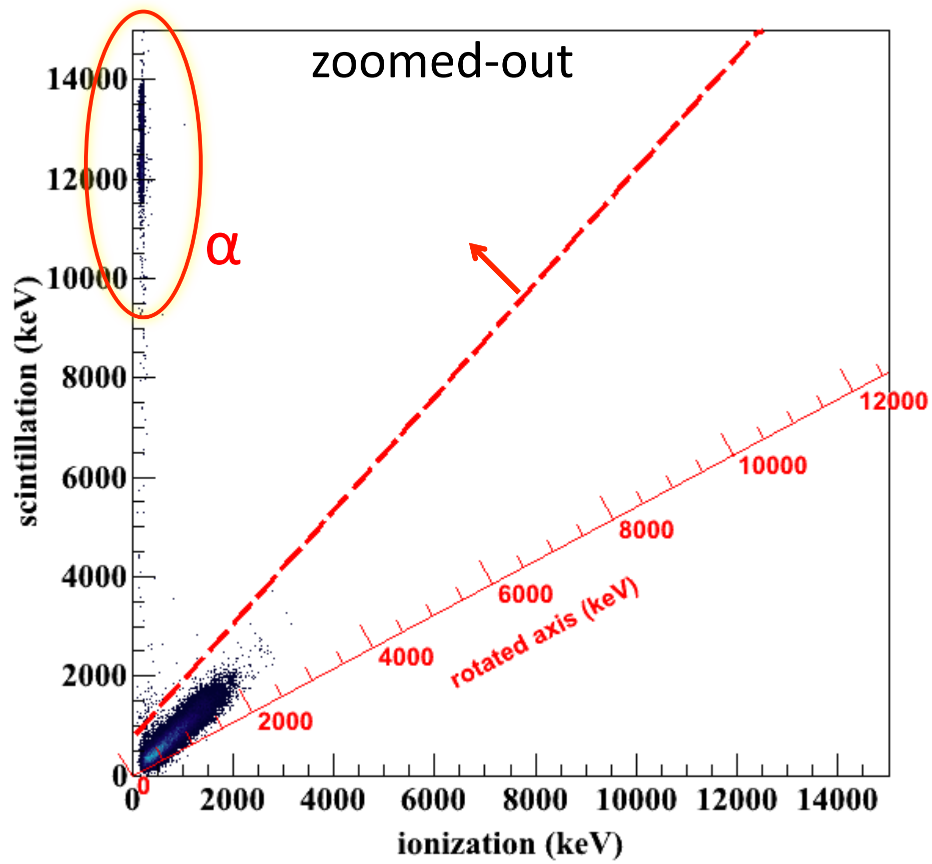
In disagreement with previously reported limits by
R. Bernabei et al. Phys. Lett. B 546 (2002) 23, and
Yu. M. Gavriljuk et al. , Phys. Atom Nucl. 69 (2006)

This was also a measurement of a nuclear matrix element
of 0.019 MeV^{-1}, the smallest measured among the $2\nu\beta\beta$ emitters

Result Confirmed by KamLAND-ZEN, Phys.Rev.C85:045504,2012

Low Background 2D SS Spectrum

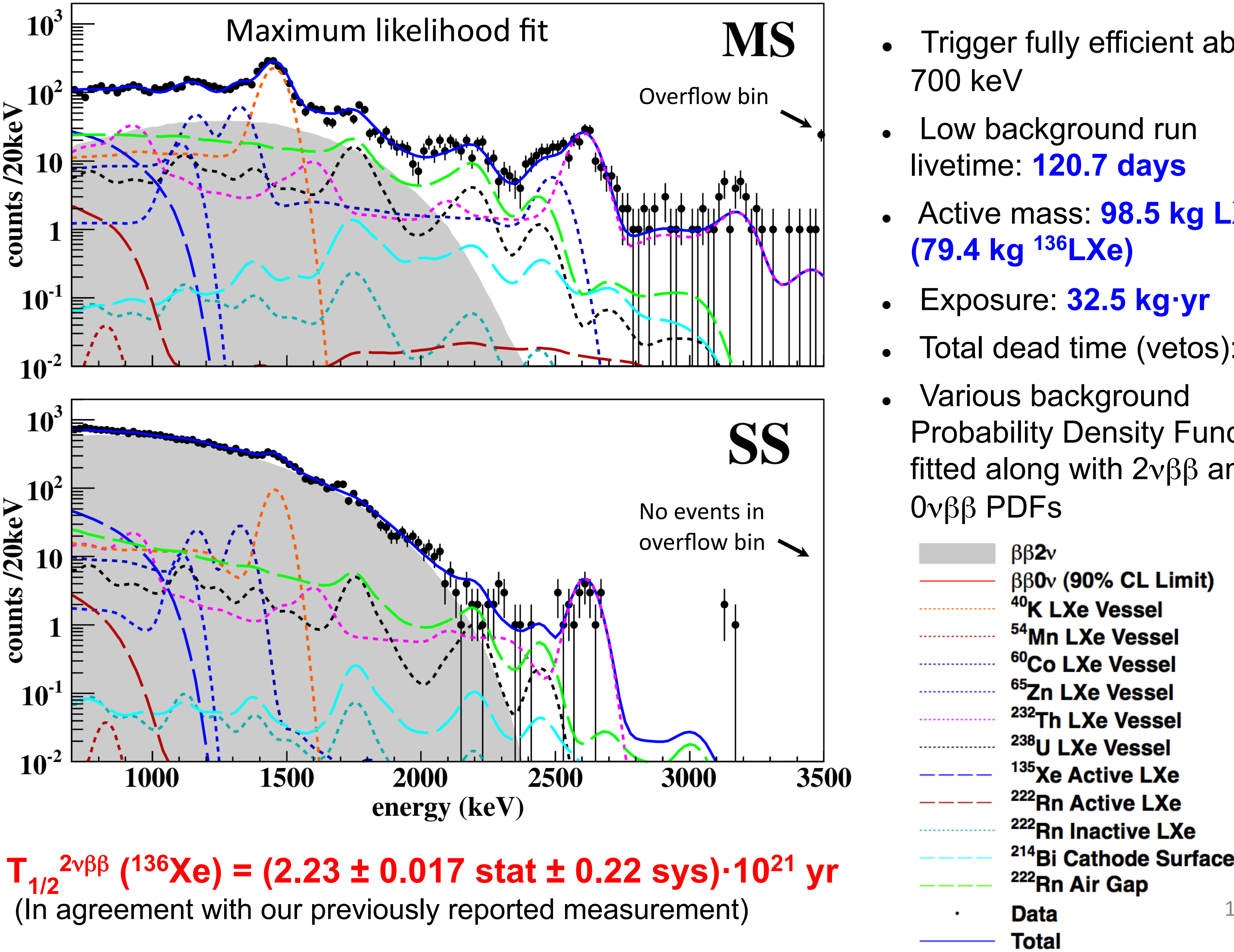




Events removed by diagonal cut:

- alpha events (they leave large ionization density, which leads to more recombination, which means more scintillation light)
- events near edge of detector, where not all the charge ends up on the collection wires

Low Background Spectrum



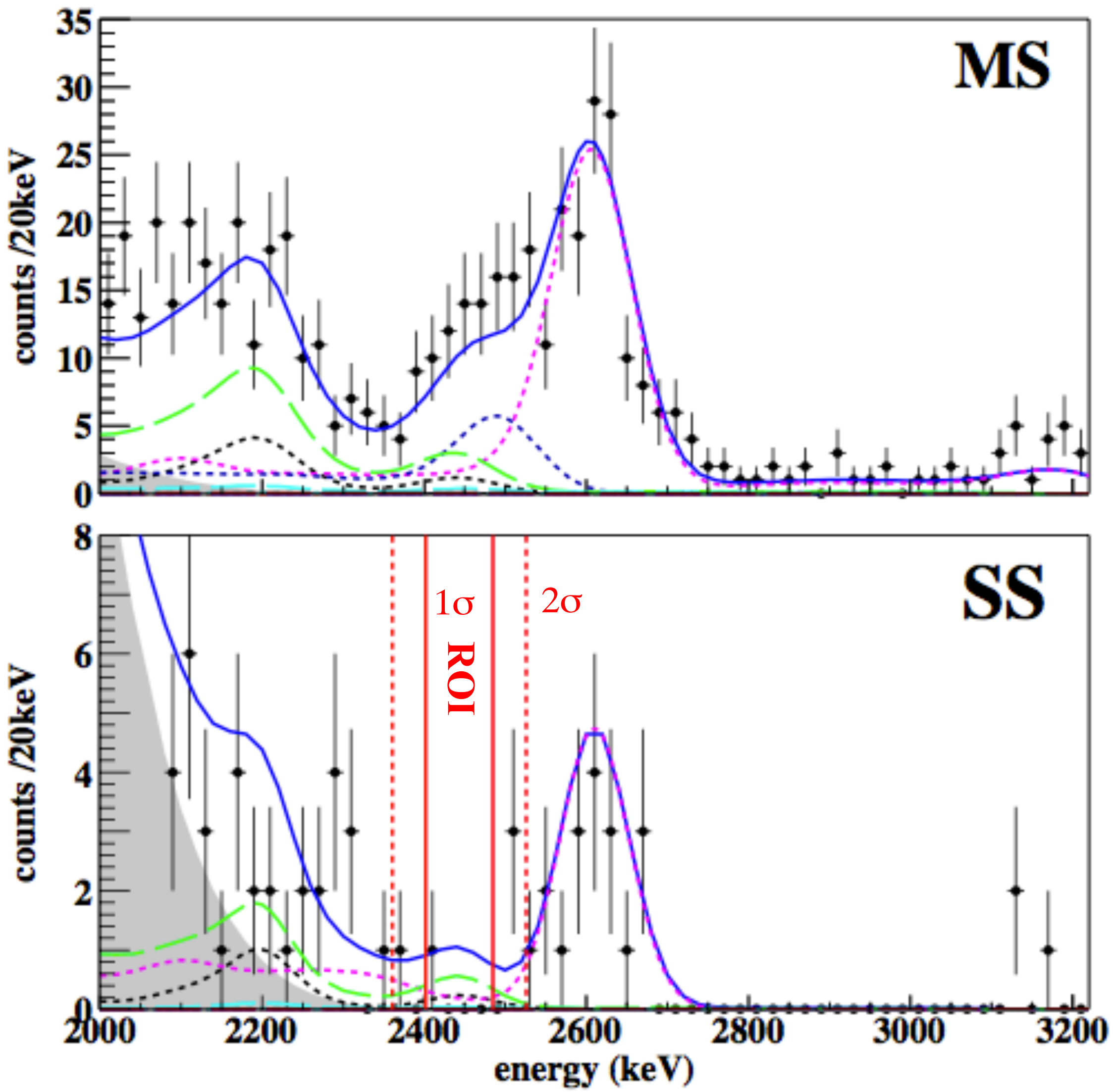
- Trigger fully efficient above 700 keV
- Low background run livetime: **120.7 days**
- Active mass: **98.5 kg LXe (79.4 kg ^{136}LXe)**
- Exposure: **32.5 kg·yr**
- Total dead time (vetos): 8.6%
- Various background Probability Density Functions fitted along with 2νββ and 0νββ PDFs

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

(In agreement with our previously reported measurement)

Low Background Spectrum

Zoomed around 0νββ region of interest (ROI)

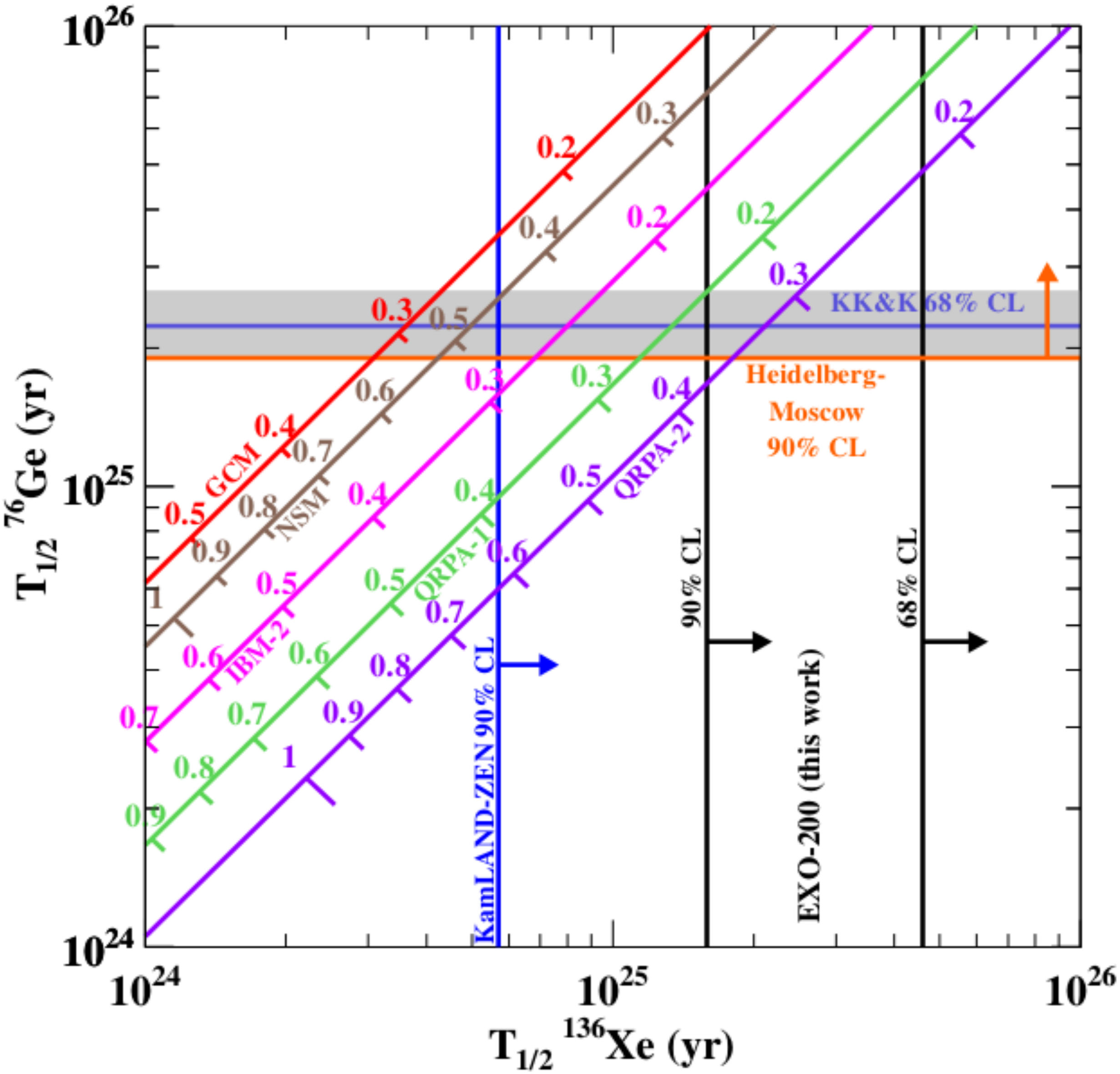


- Profile likelihood fit to entire SS and MS spectra to extract limits for $T_{1/2}^{0\nu\beta\beta}$
- Expected background in the 1σ region of interest $(1.5\pm0.1)\cdot10^{-3}kg^{-1}y^{-1}keV^{-1}$
- $\sigma_{Q\beta\beta}$ is 1.67% (41keV)
- Expected 3-4 events in the 1σ ROI
- Observed 1 event in this ROI

- Data consistent with no ββ0ν signal observed

$T_{1/2}^{0\nu\beta\beta}$ (^{136}Xe) > $1.6\cdot10^{25}$ yr (90% C.L.) [PRL 109 (2012) 032505]

Limits on $T_{½}^{0\nu\beta\beta}$ and $\langle m_{\beta\beta} \rangle$



90% C.L. limit compared with Recent ^{136}Xe constraints.

From profile likelihood

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

$\langle m_{\beta\beta} \rangle < 140 - 380$ mV

(90% C.L.)

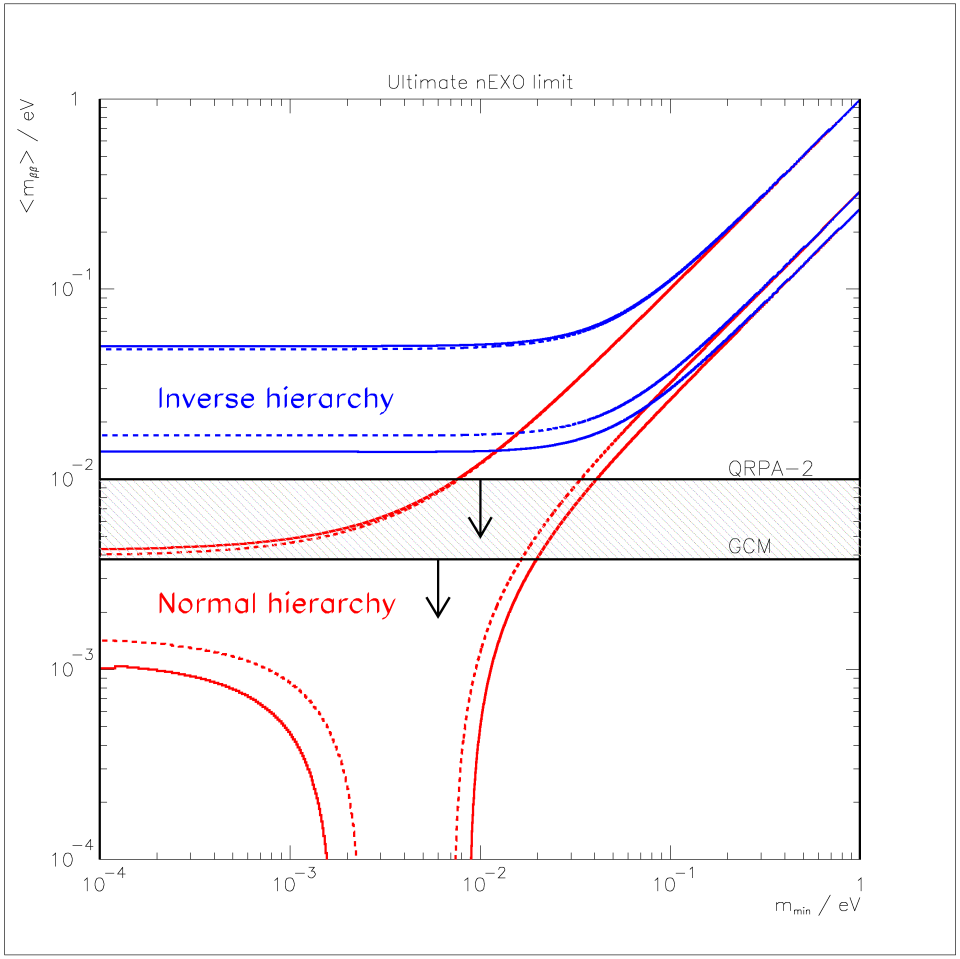
Tension with discovery claim in Ge.

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]

nEXO

- Next Enriched Xenon Observatory
- will be a tonne scale detector
  - ~5 tonne Xe expriment
  - initially without Ba tagging
    - but remaining an option in the future
- Assume
  - 4 tonnes active ^{enr}Xe (80% or higher)
  - 1.4% (σ) energy resolution
  - oberved EXO-200 backgrounds minous the Rn in the shield
  - $\beta\beta$-scales like the volume, the background like the surface are
    - assumes equal materials and thickness

EXO-200 and nEXO projected sensitivities



Neutrino parameters: Forero et al. 1205.4018v4, 95%CL.

The horizontal bands represent the envelopes of the 90% CL limits expected (or obtained For the top-most) assuming various NME calculations and assuming that no signal as detected

The EXO-200 "Present limit" is from PRL 109 (2012) 032505

The EXO-200 "Ultimate" sensitivity: 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

Summary

- $0\nu\beta\beta$ decay can shed light on the nature of the neutrino
  - Neutrinos are Majorana
  - that B-L is not a conserved symmetry
  - If found can find the neutrino mass scale
- EXO-200 has been operating for almost 2 years and discovered $2\nu\beta\beta$ decay in Xe-136 and set a limit on $0\nu\beta\beta$ decay that is in tension with the Ge result
  - First $T_{1/2}^{2\nu\beta\beta}$ $(2.11 \pm 0.04 \text{ stat} \pm 0.21 \text{ sys})\cdot 10^{21}$ yr [PRL 107 (2011) 212501]
  - First $T_{1/2}^{0\nu\beta\beta} > 1.6\cdot 10^{25}$ yr [PRL 109 (2012) 032505]
    - Updated $T_{1/2}^{2\nu\beta\beta}$ $(2.23 \pm 0.017 \text{ stat} \pm 0.22 \text{ sys})\cdot 10^{21}$
- New results this year with improved pattern recognition, reduced background, double the statistics…
- Designing nEXO

The EXO Collaboration

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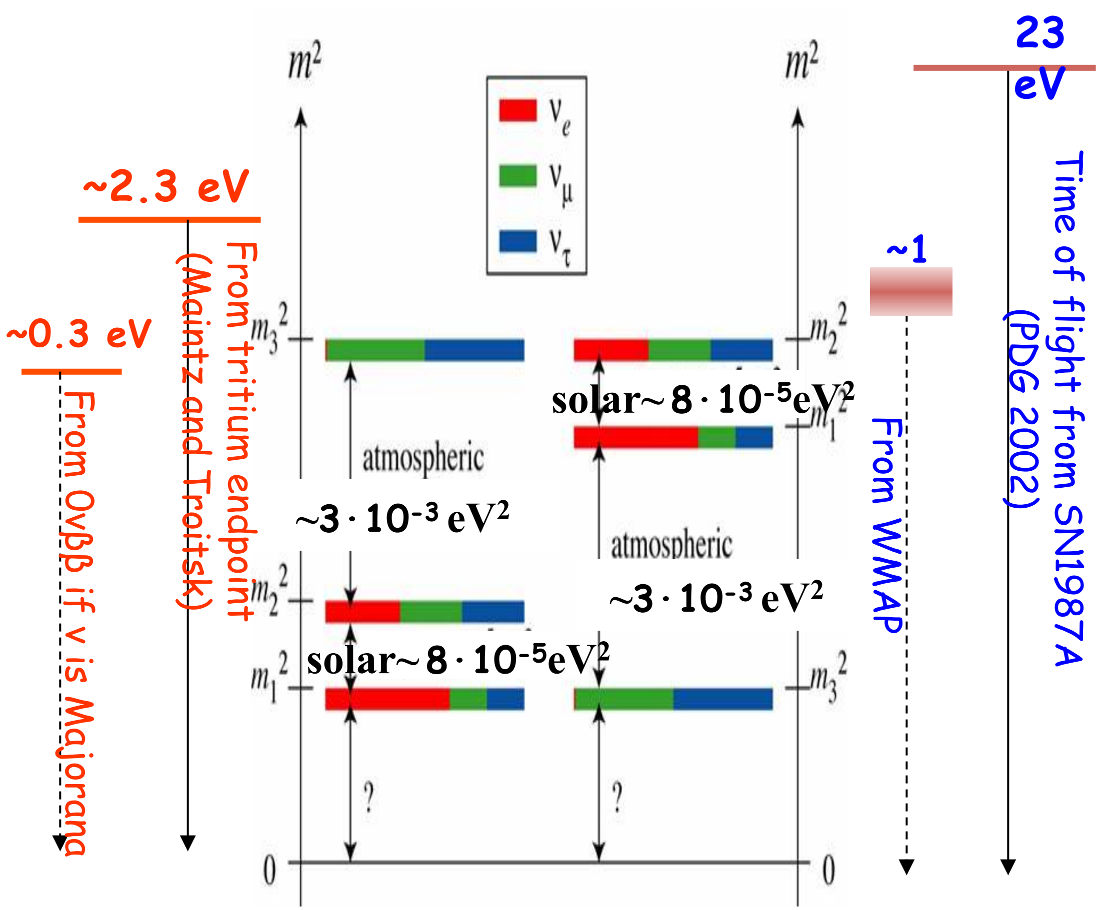
Our knowledge of the ν mass pattern



we know

- Neutrinos have mass
- Their masses are not the same
- Some of the mixing and parameters of the flavour states

We don't know

- The absolute masses of the eigen states
- Whether the neutrino is Dirac or Majorana
- Mass hierarchy
- CP violation phase

What do we know about neutrino mass assuming three flavors?

From experiments using solar ν and reactor $\bar{\nu}$:

$$\Delta m^2_{21} = \Delta m^2_{sol} = \left(7.58^{+0.22}_{-0.26}\right) \cdot 10^{-5}\ eV^2$$

$$\sin^2(\theta_{12}) = \sin^2(\theta_{sol}) = 0.306^{+0.018}_{-0.015}$$

From experiments using atmospheric and accelerator ν:

$$\Delta m^2_{32} = \Delta m^2_{atm} = \pm\left(2.35^{+0.12}_{-0.09}\right) \cdot 10^{-3}\ eV^2$$

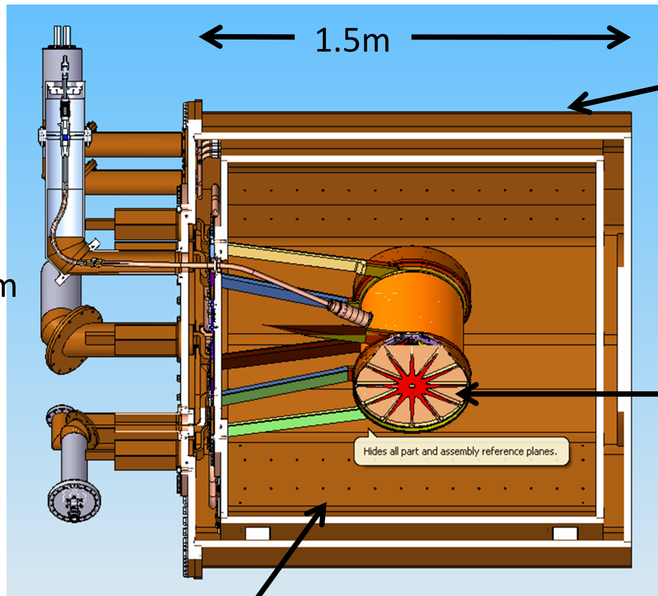
$$\sin^2(\theta_{23}) = \sin^2(\theta_{atm}) > 0.42^{-0.08}_{-0.03}$$

From experiments using reactor $\bar{\nu}$:

$$\sin^2(\theta_{13}) = 0.0251 \pm 0.0034$$

J.Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012)

EXO-200 TPC and cryostat



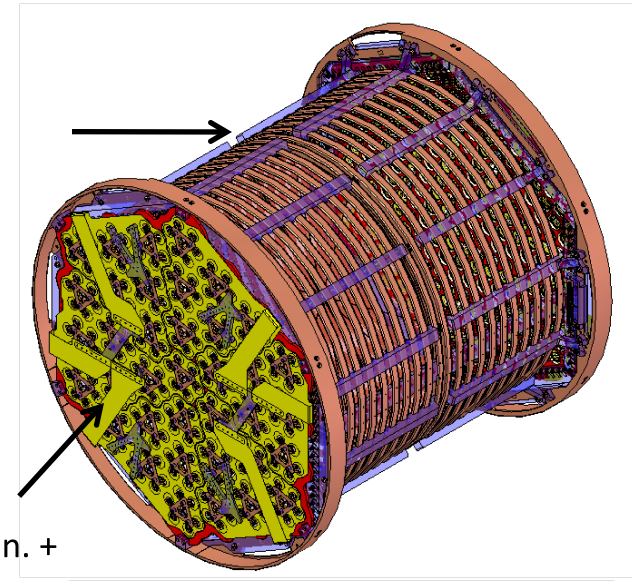
1.5m

Outer cryostat

TPC

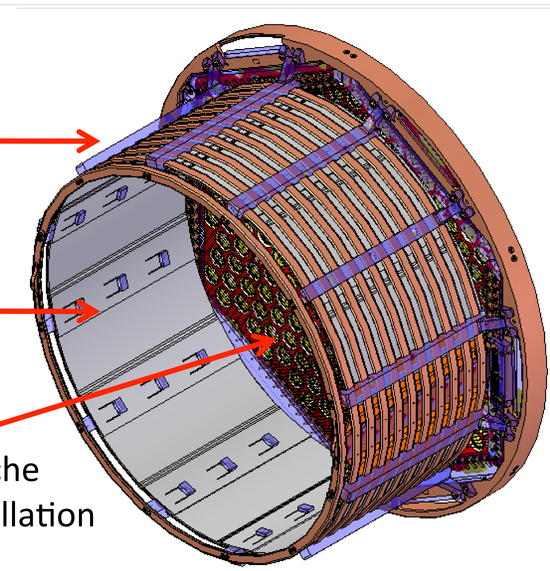
Inner cryostat filled with 50 cm HFE7000 cooling/shielding fluid (~ 1.8 g/cm^3 at 170 K)

Central HV plane (photoetched phosphor bronze)



Custom kapton signal cables (ion. + scint. readout)

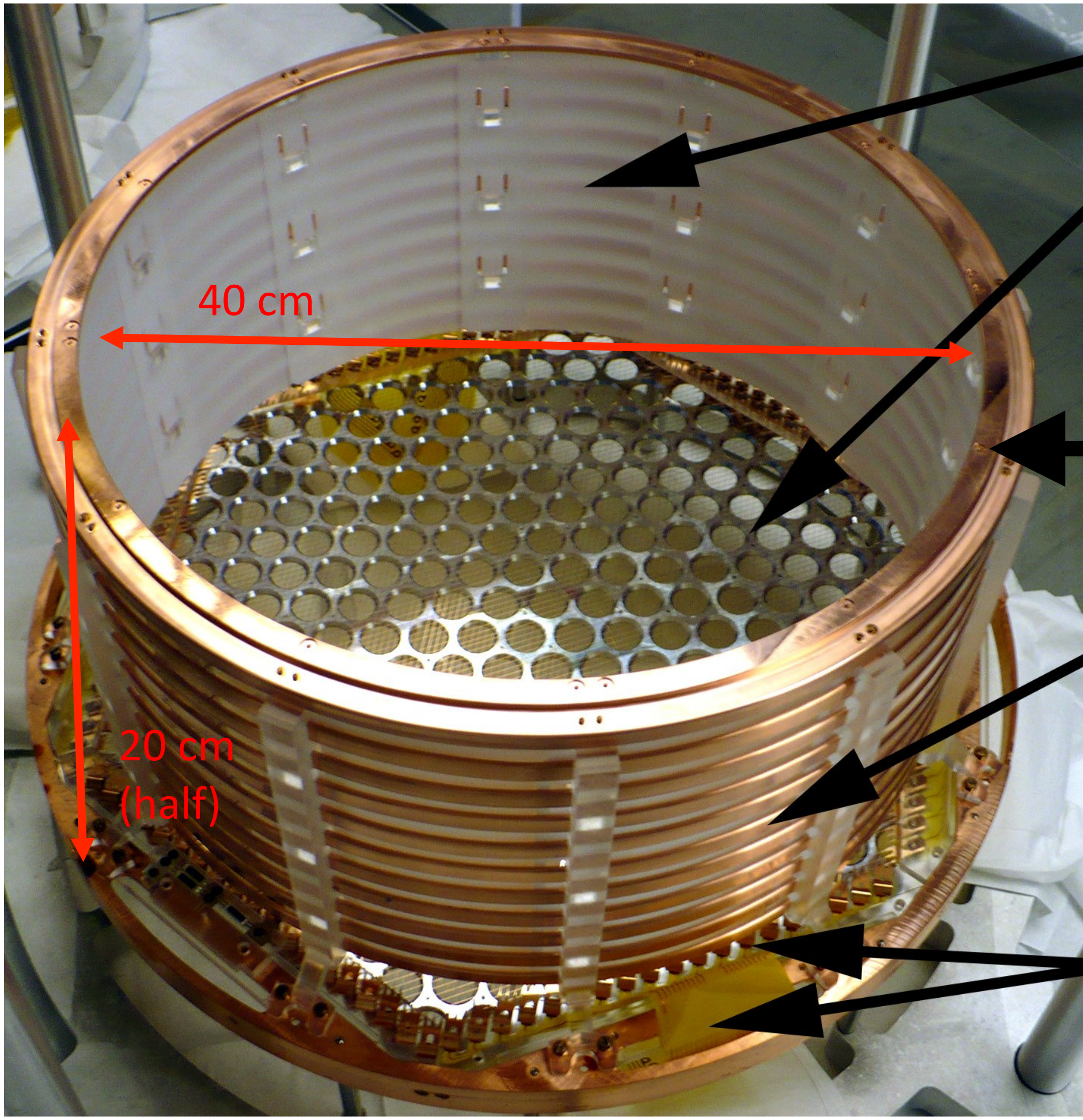
Acrylic supports and field shaping rings



Teflon light reflector

APD plane (avalanche photodiodes, scintillation detection)

EXO-200 TPC (half of it)



Teflon Reflectors
(increase light collection)

APD plane and wire planes
(38 U triplet wire
38 V triplet wire crossed at 60˚
234 large area APDs in groups of 7)

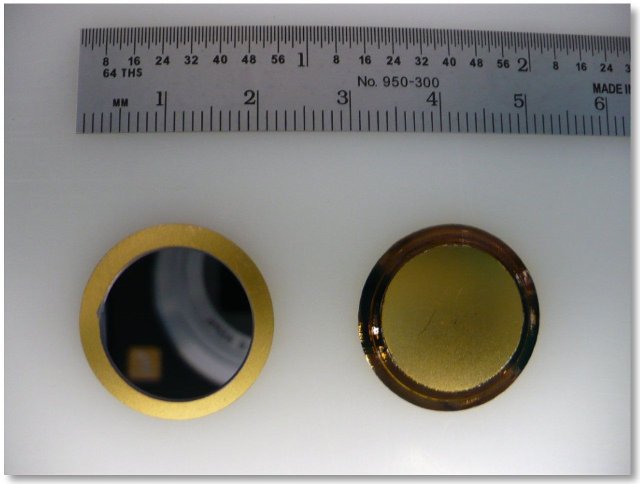
Central HV plane
(photo-etched phosphor bronze
Drift field 376 Vcm^{-1})

Acrylic supports
and field shaping
rings

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

EXO-200 LAAPD specs

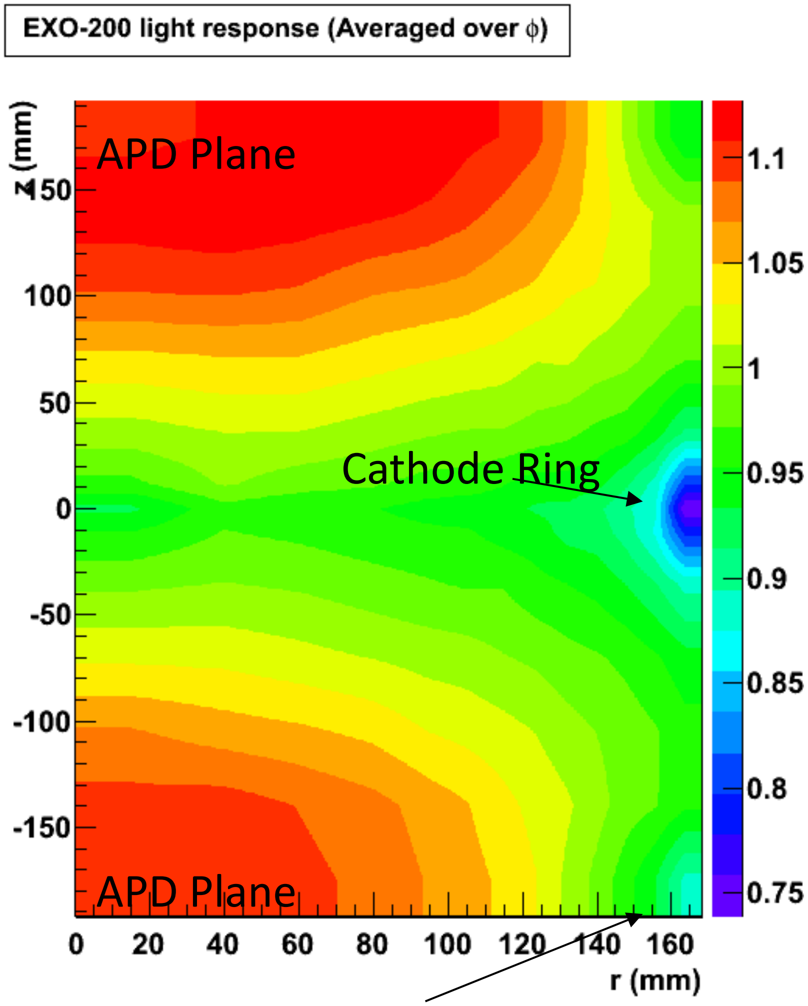
- Mass ~ 0.5 g/LAAPD
- Low radioactivity construction (used bare, no window, no ceramic, EXO-supplied chemicals & metals)[a]
- QE > 1 at 175 nm (NIST)
- Gain set at 100-150
- V ~ 1500V
- $\Delta V < \pm 0.5V$
- $\Delta T < \pm 1K$ APD is the driver for temperature stability
- Leakage current cold < 1μA
- Capacitance ~ 200 pF at 1400 V
- ϕ16 mm active area per LAAPD



Neilson, R. et al., NIM A 608, 1 (2009)

[a] D. S. Leonard, et al., Nucl. Instr. and Meth. A 591 (2008) 490-509

Correcting for light response

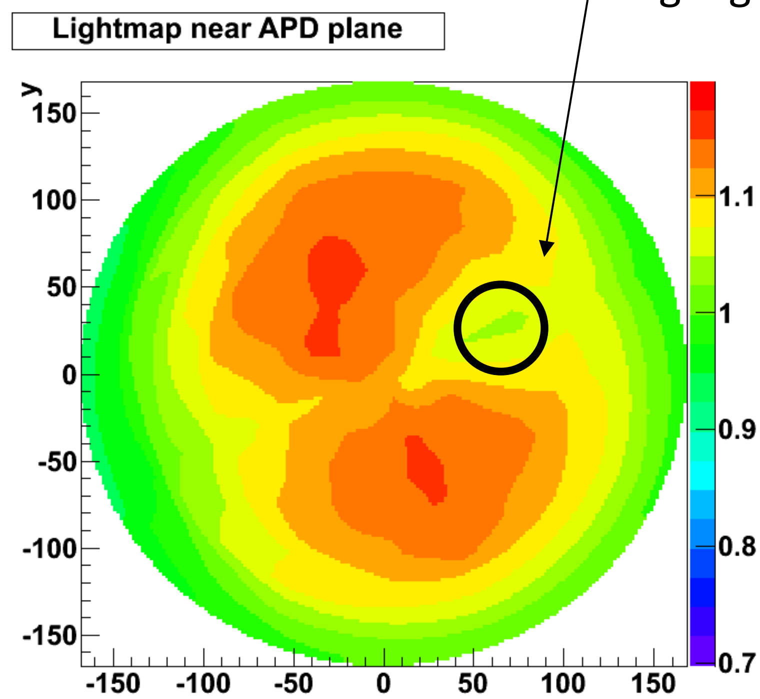


Gap between teflon reflector and APD plane

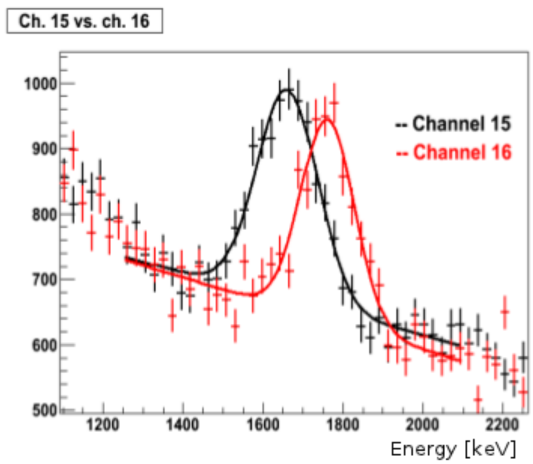
Use full absorption peak of 2615 keV gamma from 208Tl to map light response in TPC

Linearly interpolate between 1352 voxels

Disabled APD gang



Wire Gains

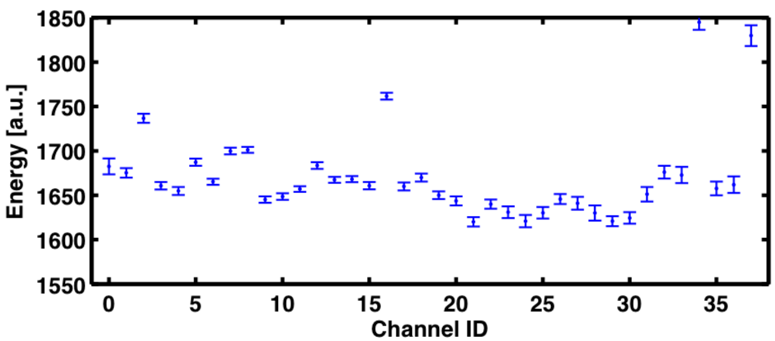


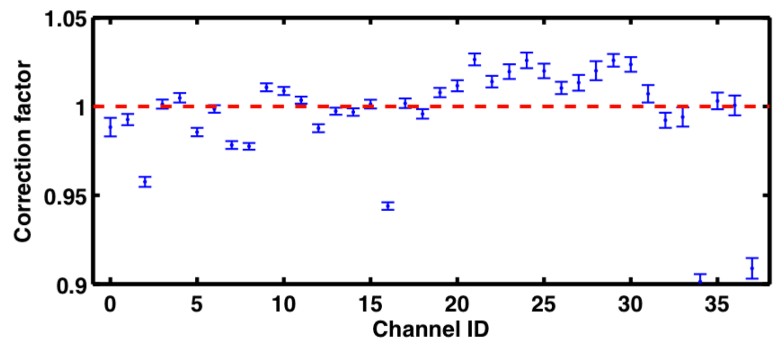
• gains of wire channels measured with charge calibrations

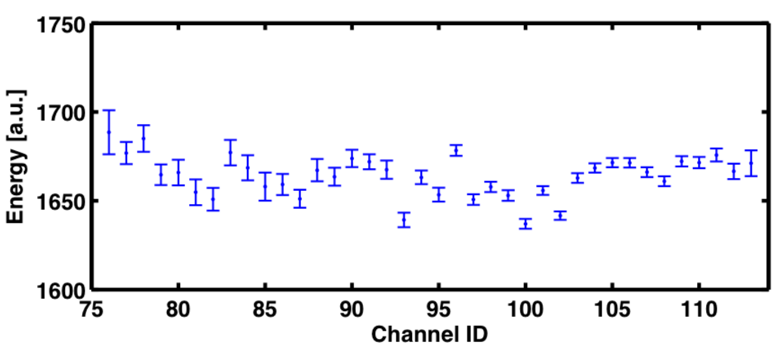
• This is further corrected using the pair production peak (1593 keV) from ^{232}Th 2615 keV gamma depositions.

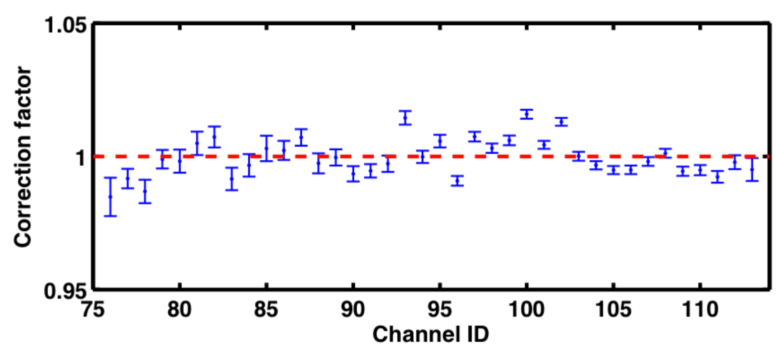
• Have also individually measured the electronic transfer function of each channel, which are used to reconstruction the charge signals

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

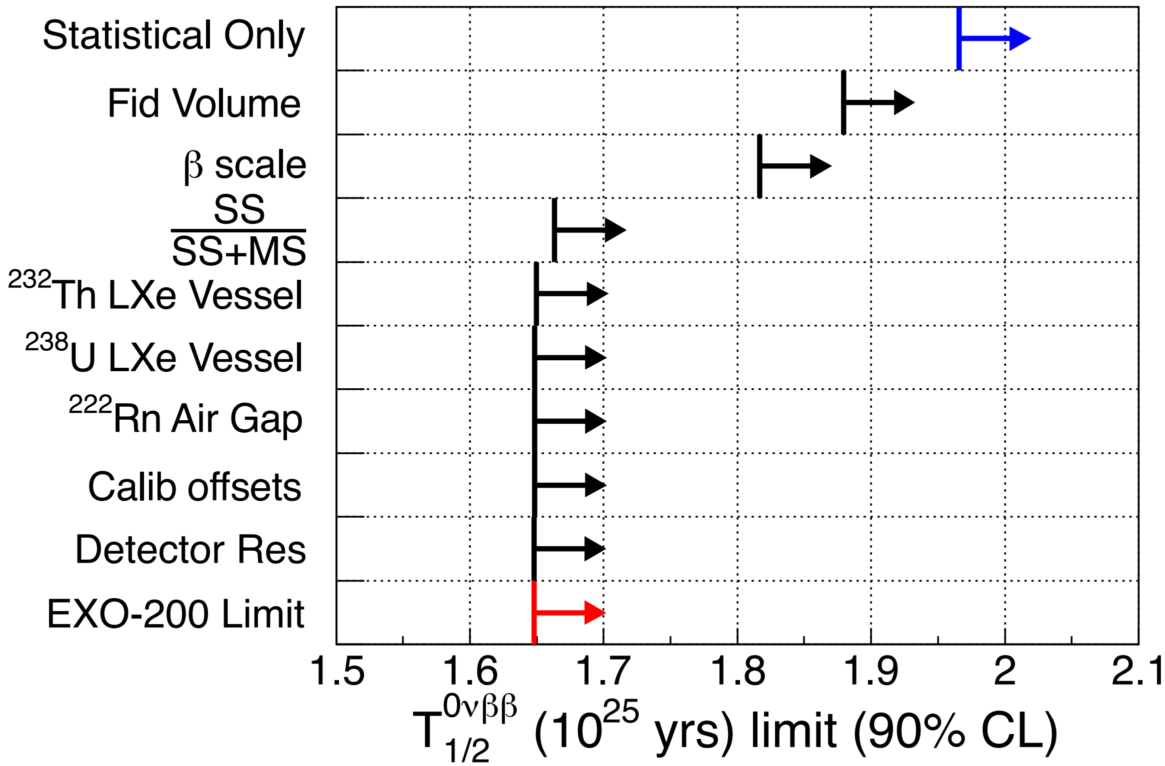








Systematic Error Breakdown



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

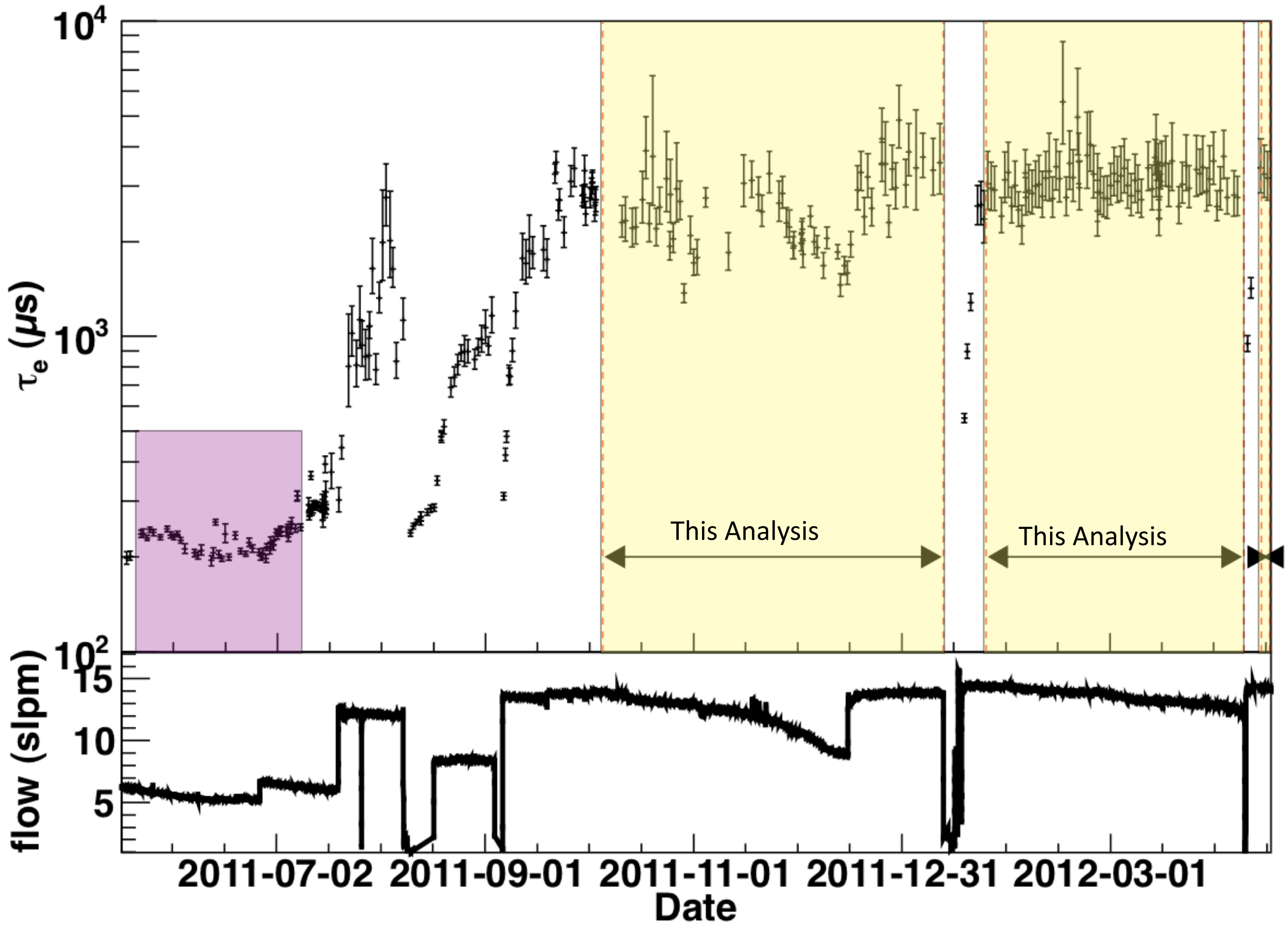
- Bars show the expected 90% confidence limit if we assume perfect knowledge of parameters that contribute to systematic errors

EXO-200 material screening

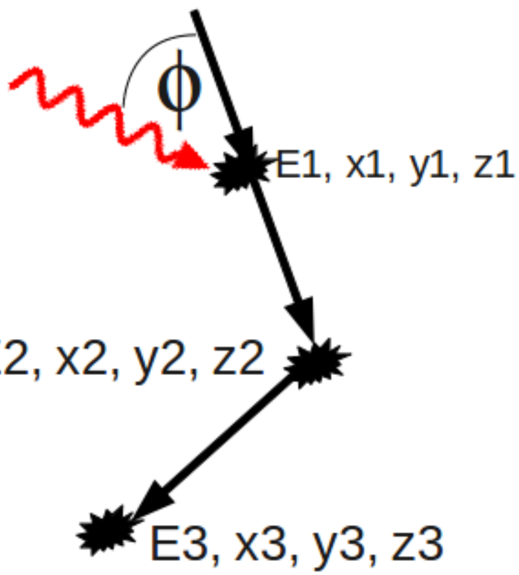
- Stringent requirements on K/Th/U concentrations on materials inside cryostat
- Large-scale materials testing, published in *Nucl. Instr. and Meth. A 591 (2008) 490–509*
- In particular:

Component	K 10^{-9} g/g	Th 10^{-12} g/g	U 10^{-12} g/g	^{210}Po Bq/kg
3M Novec HFE-7000, 1-methoxyheptafluoropropane	<1.08	<7.3	<6.2	
Lead shielding	<7	<1	<1	17-20
Copper	<55	<2.4	<2.9	
Acrylic	<2.3	<14	<24	
TPC grid wires	<90	47 +/- 2	320 +/- 2	

Xenon Purity



- Continuously recalculate Xe through SAES high temperature purifiers using a custom designed magnetic piston pump. [Neilson et al. (2011) arXiv:1104.5041v1].
- Average electron lifetime for $0\nu\beta\beta$ data set was ~ 3 ms with maximum drift time of 110 us.

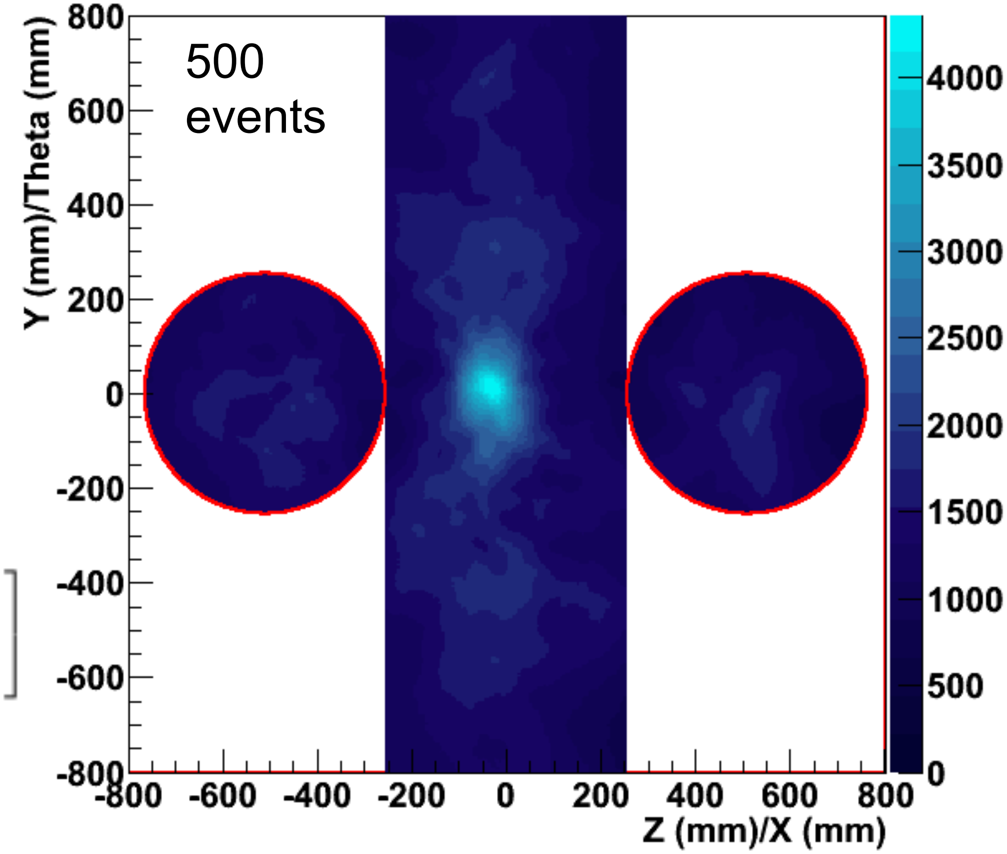


Can point to source using a Compton telescope technique

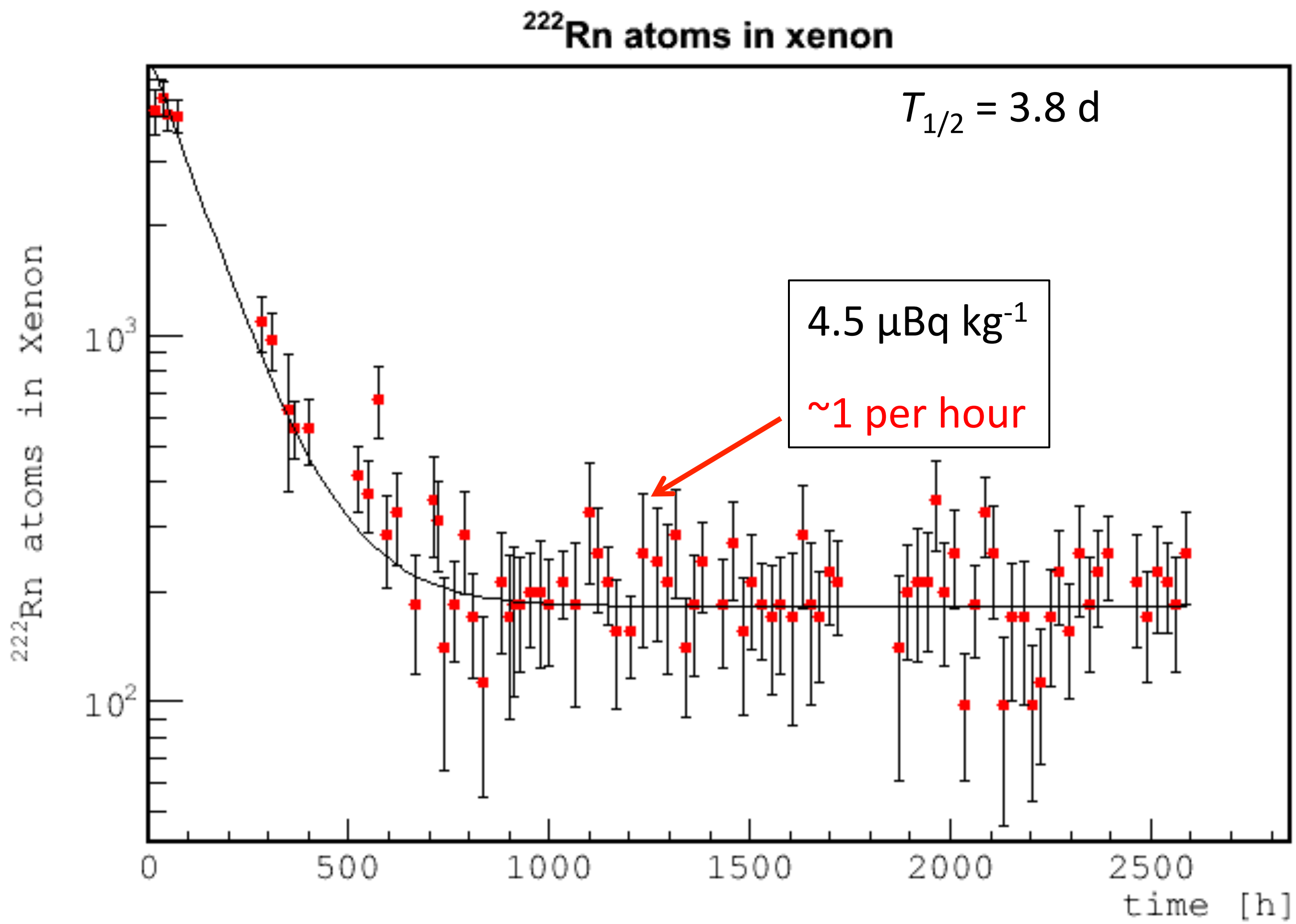
- Detector measures E, x, y, z for each site
- Use scattering formula

$$\phi = arccos\left[1 - m_e c^2 \cdot \left(\frac{1}{E_\gamma - E_1} - \frac{1}{E_1}\right)\right]$$

- From each site a cone is drawn and adding up these cones produces the image to the right

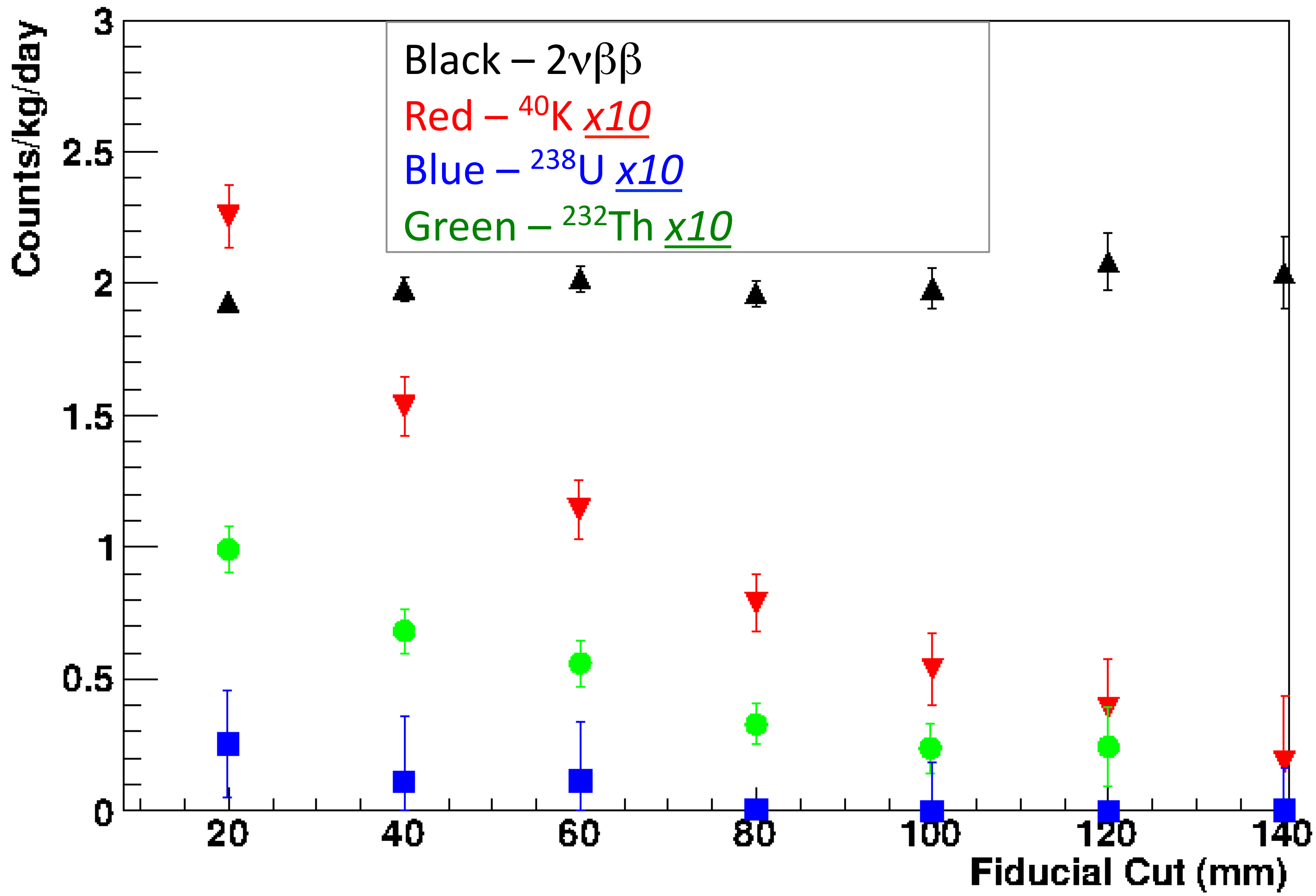


Rn Content in Xenon



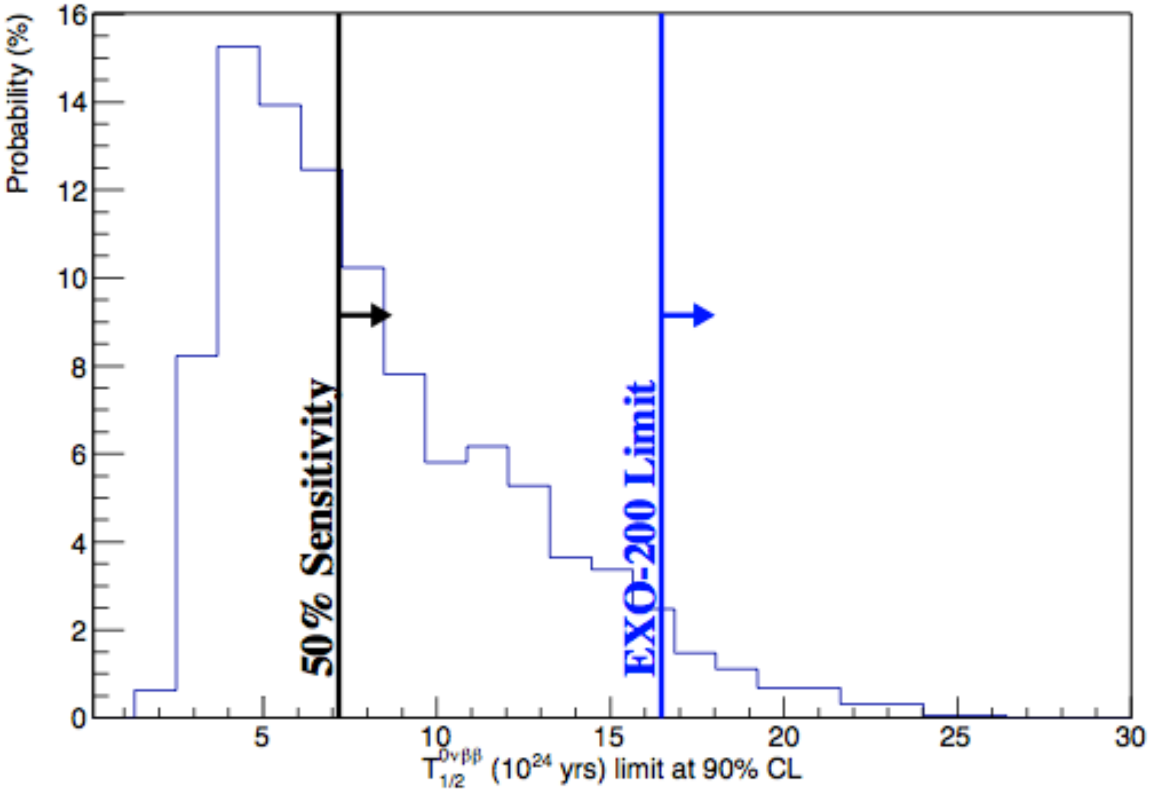
The Bi-214 is consistent with measurement from alpha-spectroscopy, and the expected Rn background.

Event Rates Versus Fiducial Cut



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

Sensitivity



Distribution of 0νββ $T_{1/2}$ 90% CL upper limits from Monte Carlo

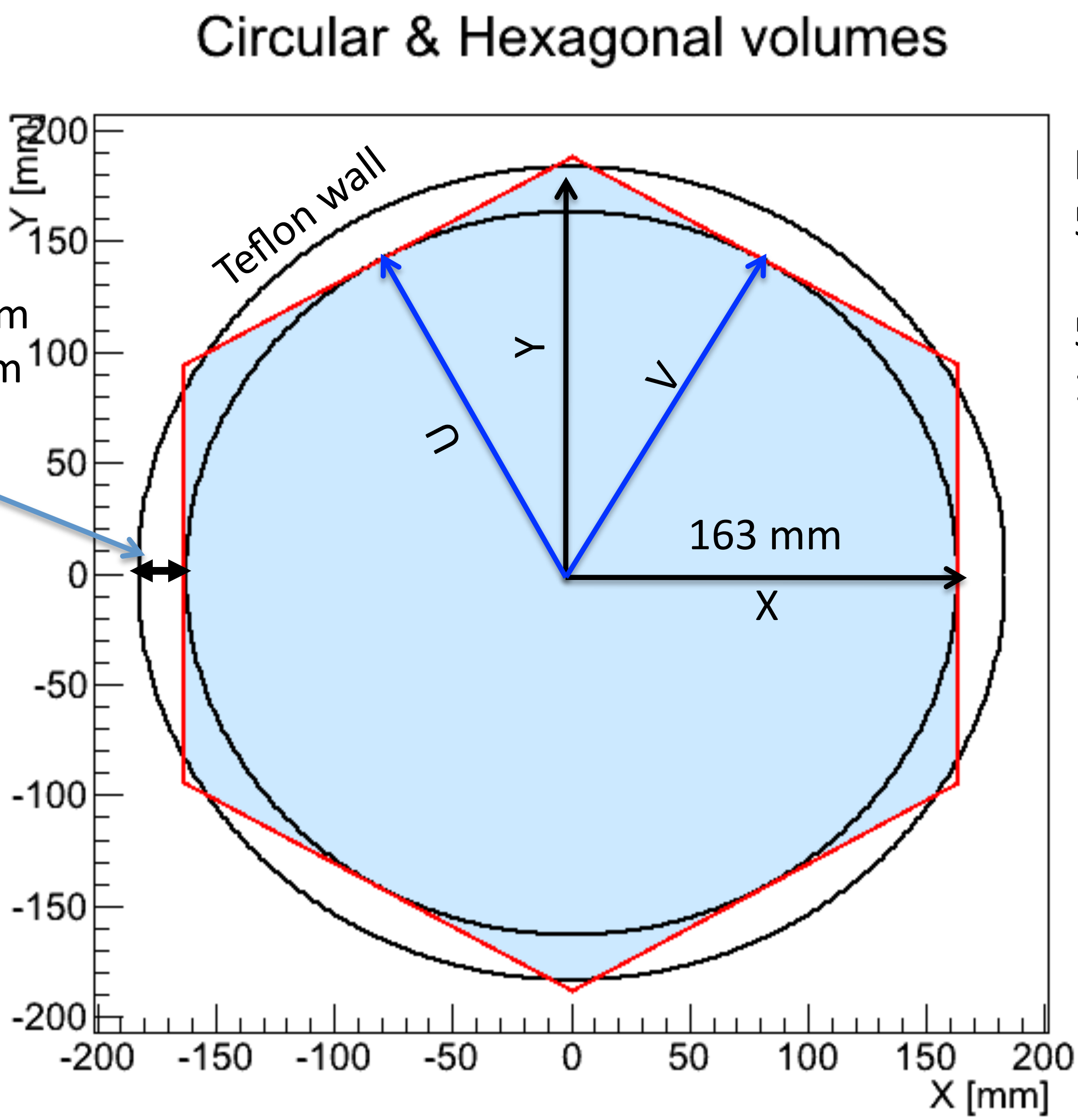
Given our estimated background, we expect to quote a 90% CL upper limit on $T_{1/2}$ of 1.6 x 10^{25} years or better, 6.5% of the time.
We would quote a 90% CL upper limit of 7 x 10^{24} years or better, 50% of the time.

Cuts

- Events must have a charge cluster and a scintillation cluster
- Not occur 1μs before a veto panel trigger or 25ms after
- Not occur within 1 second of any other event
- Not occur 1μs before or 60s after a TPC event tagged as a muon

Fiducial Volume

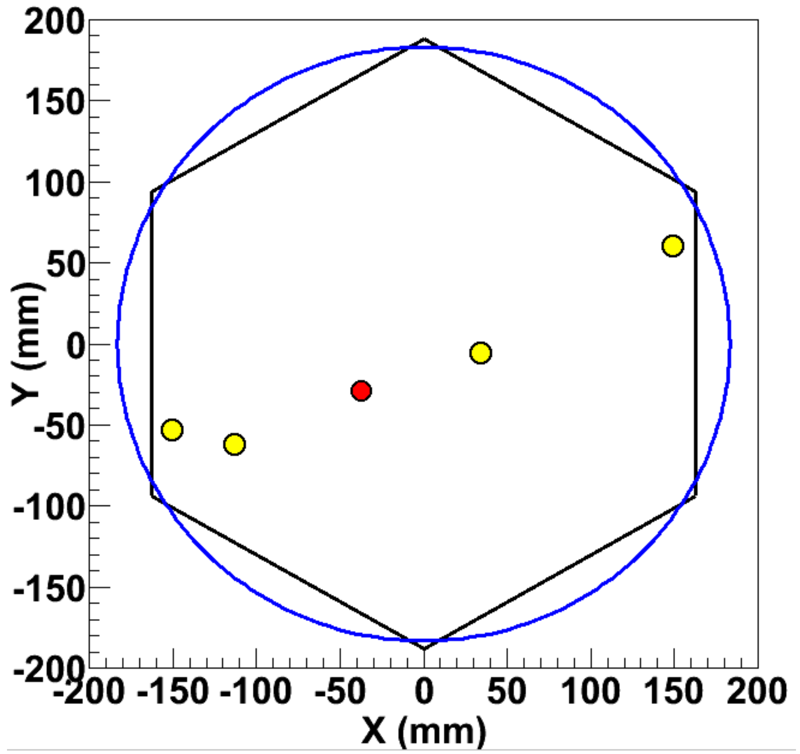
Standoff distance 20 mm Measured from Teflon wall to hexagon

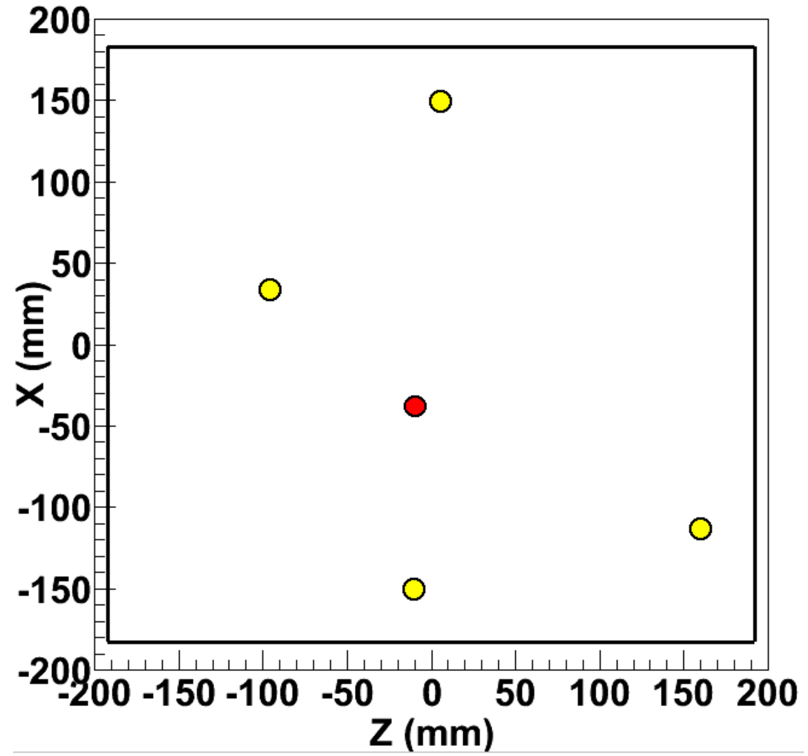


In z dimension,
5 mm < |z| < 182 mm

5 mm from cathode
10 mm from wire plane

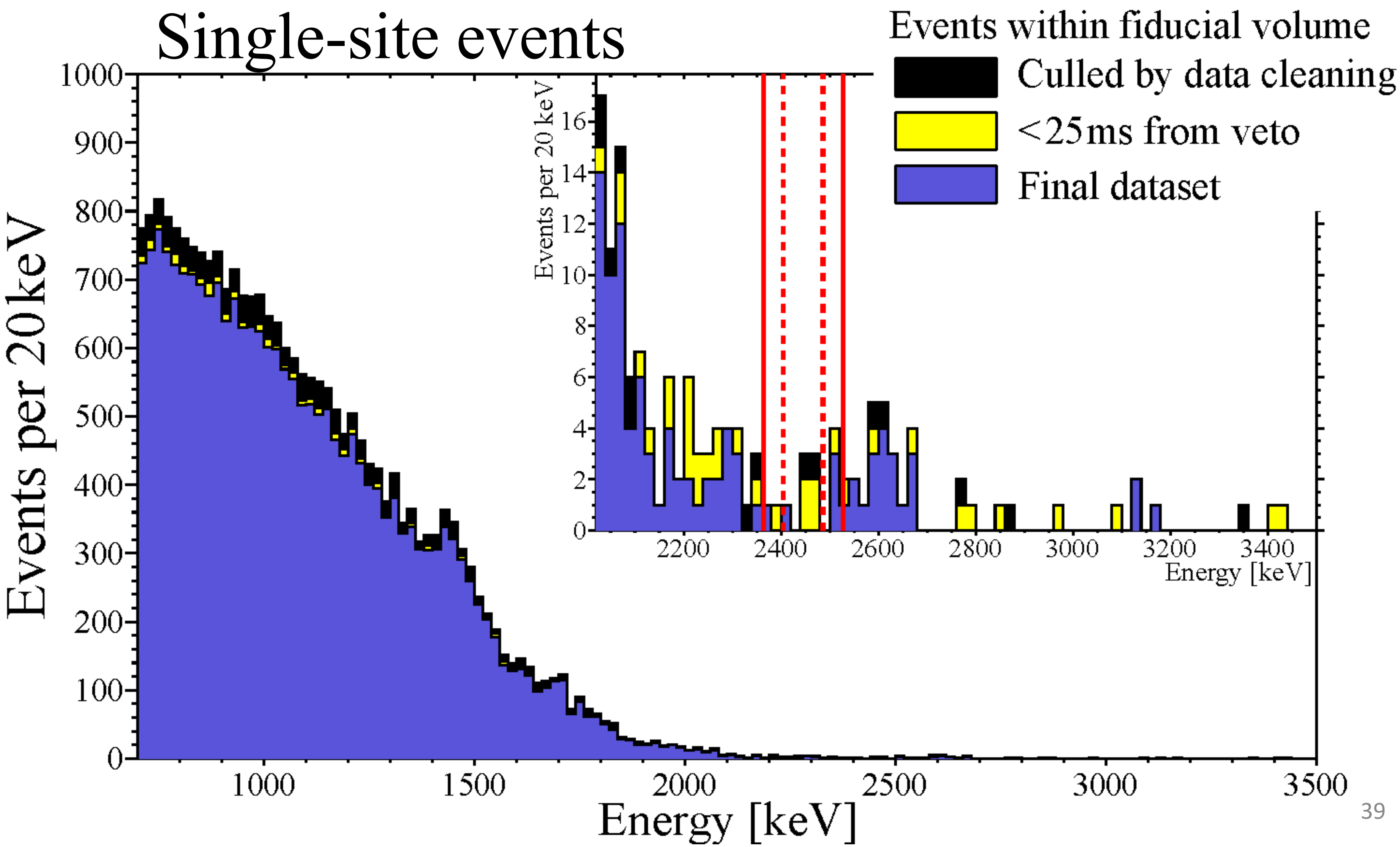
Backup: Spatial Distribution



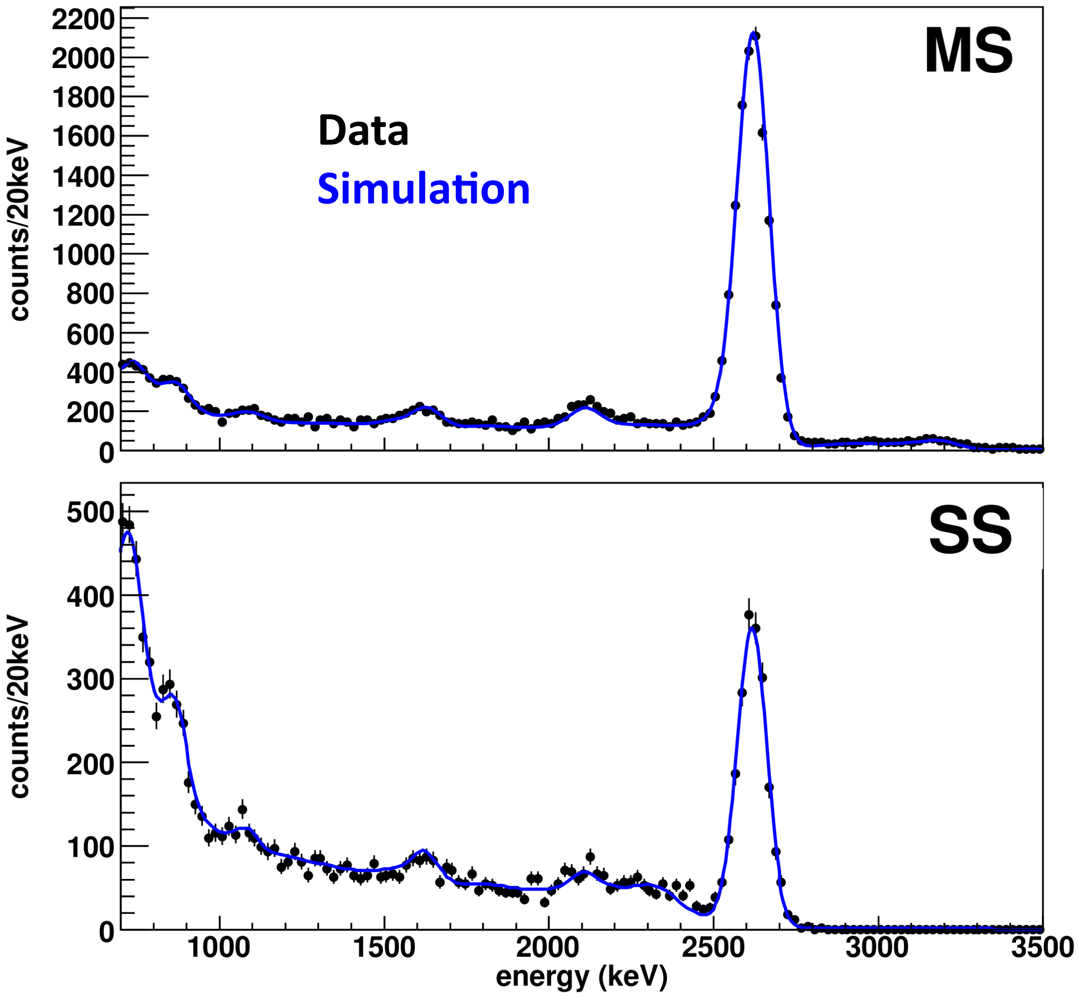


- Events within ± 1 σ
- Events within ± (1—2)σ

Cosmic-ray veto system impact

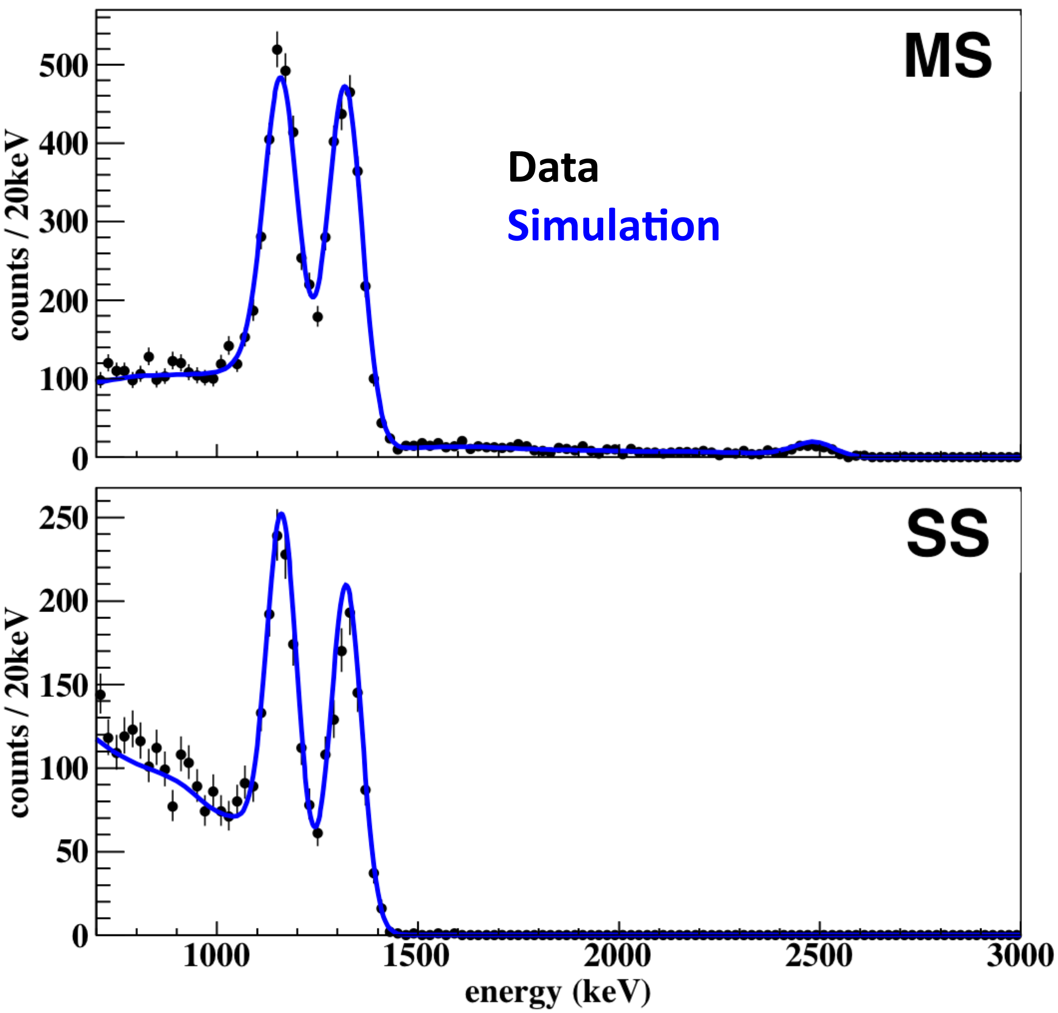


Spectral Shape Agreement – ^{228}Th



- 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%