Results of the EXO-200 neutrinoless double-beta decay experiment

Michael Marino
Technische Universität München, Excellence Cluster 'Universe'
for the EXO collaboration

GDR Neutrino, Paris

22 May 2013

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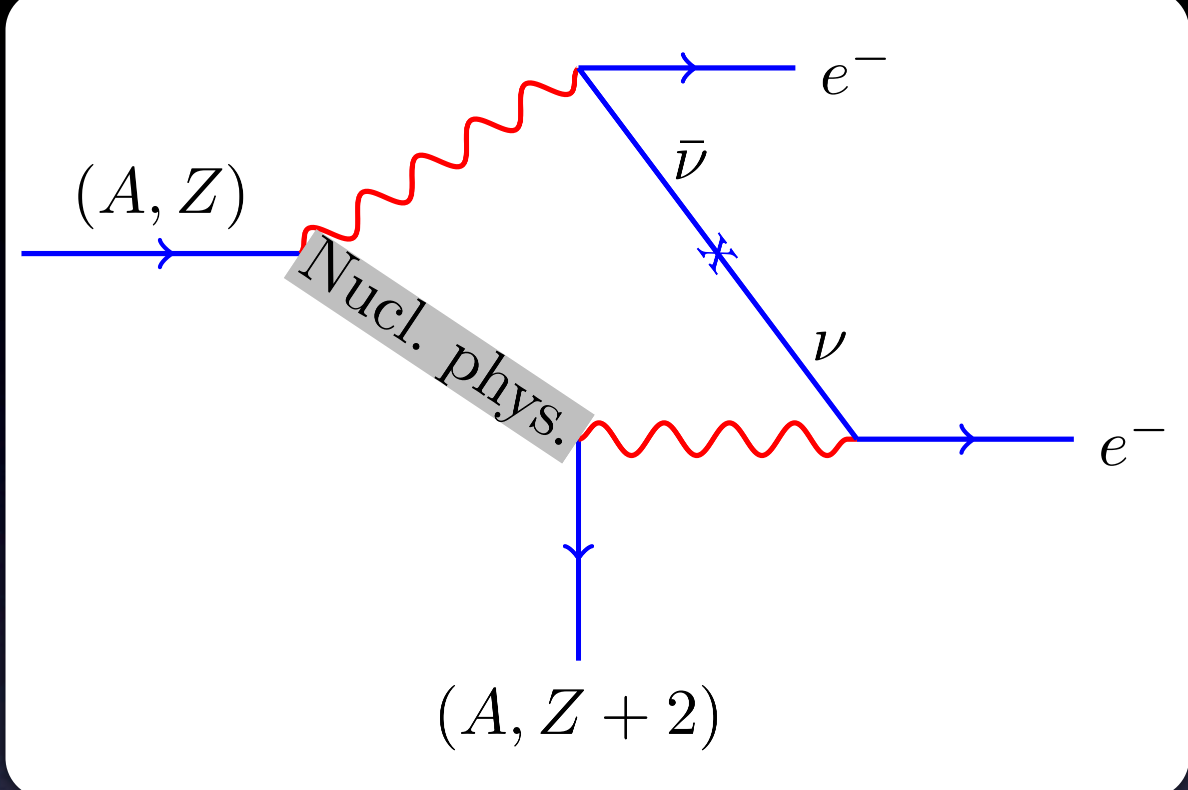
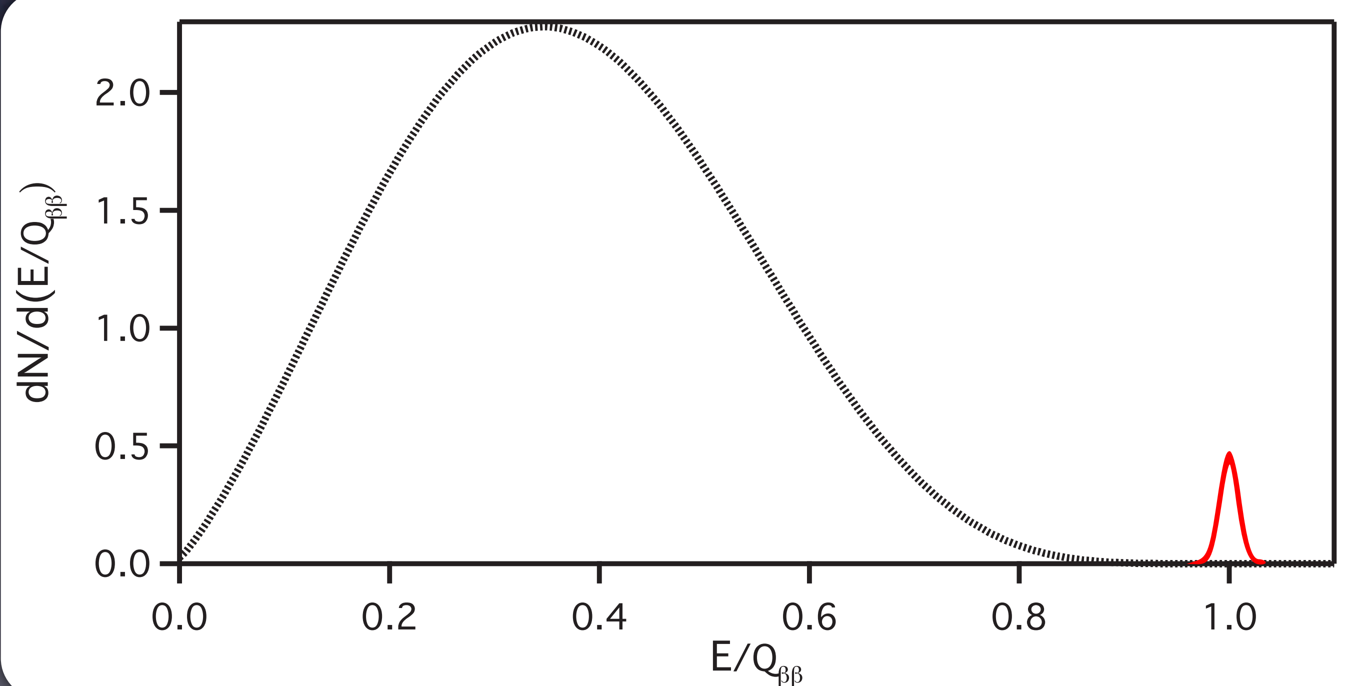
Neutrinoless Double-Beta Decay ($0\nu\beta\beta$)

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}|M^{0\nu}|^2\langle m_{\nu_{\beta\beta}}\rangle^2$$

$$\langle m_{\nu_{\beta\beta}}\rangle = \left|\sum m_i U^2_{ei}\right|$$



- If seen:
  - ν is a Majorana particle
  - Lepton-number violation (matter-antimatter asymmetry?)
  - ν-mass measurement



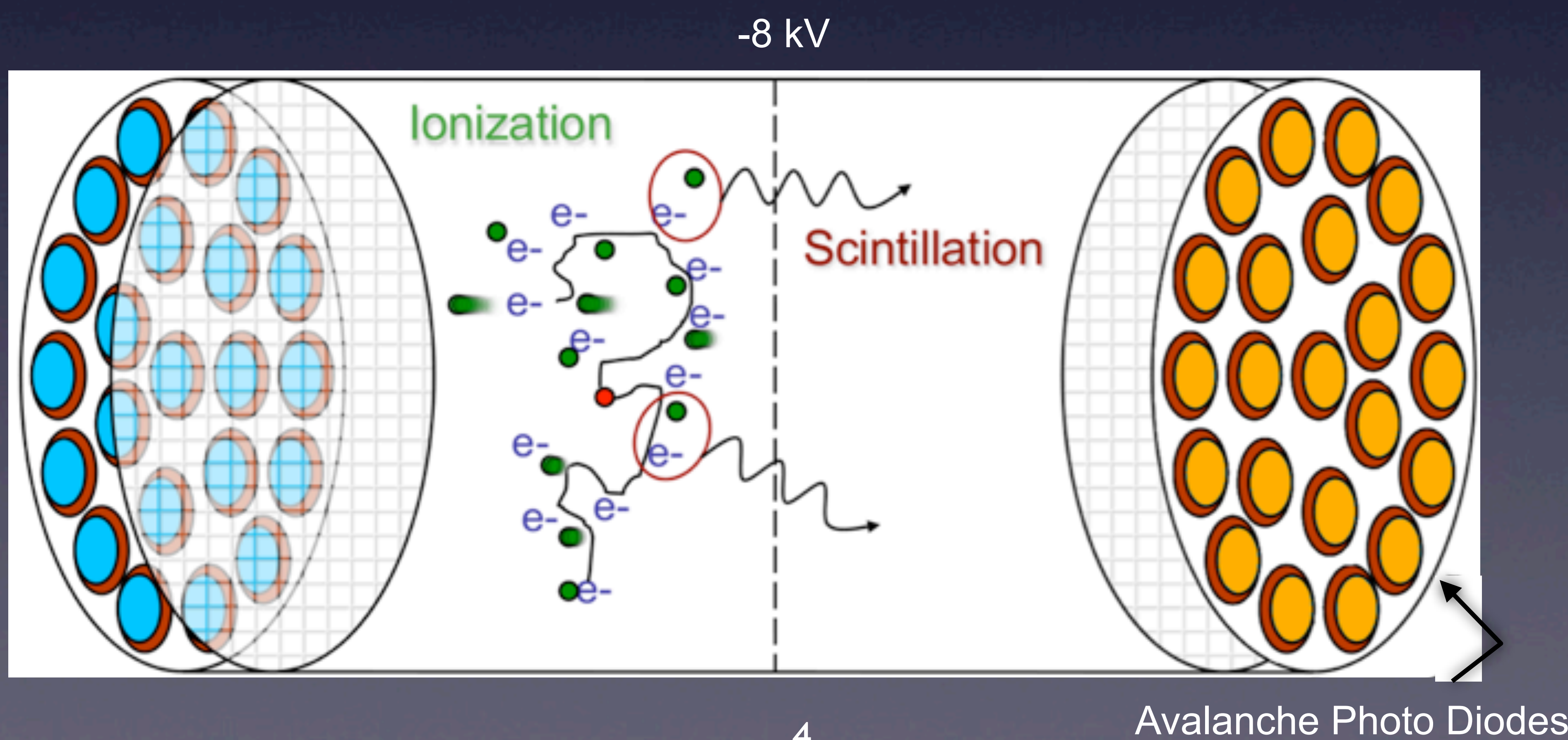
How do we find it?

A typical path:

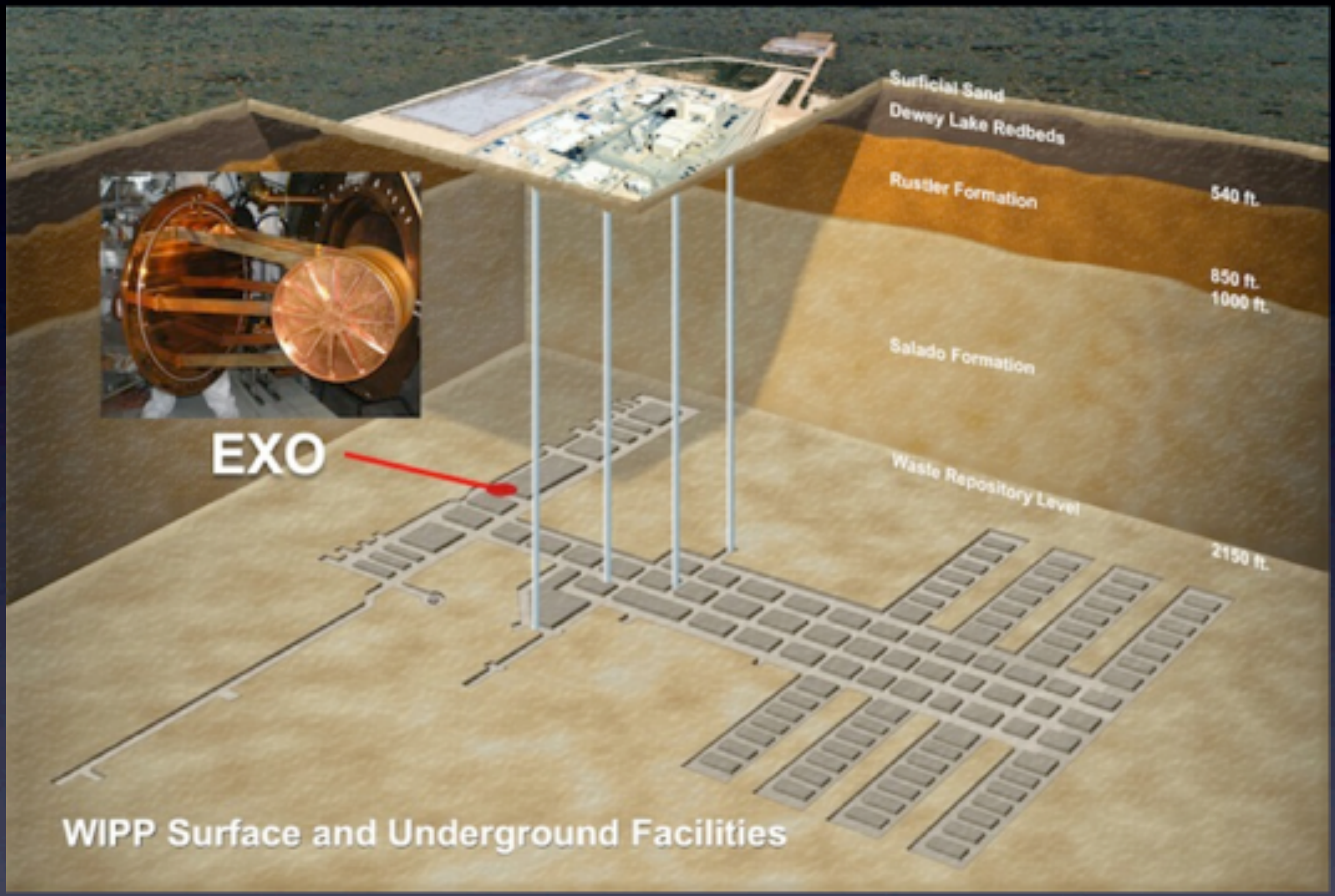
- Find an isotope (e.g. ^{136}Xe, ^{76}Ge, ^{130}Te)
- Make a detector out of it, Source = Detector
- Use ultra-low background material
- Wait (and measure).

EXO Enriched Xenon Observatory

- EXO-200: Liquid Xe Time Projection Chamber (TPC) currently running underground at WIPP (Waste Isolation Pilot Plant) in New Mexico, USA
- enriched ^{136}Xe (Q val: 2.48 MeV)



WIPP



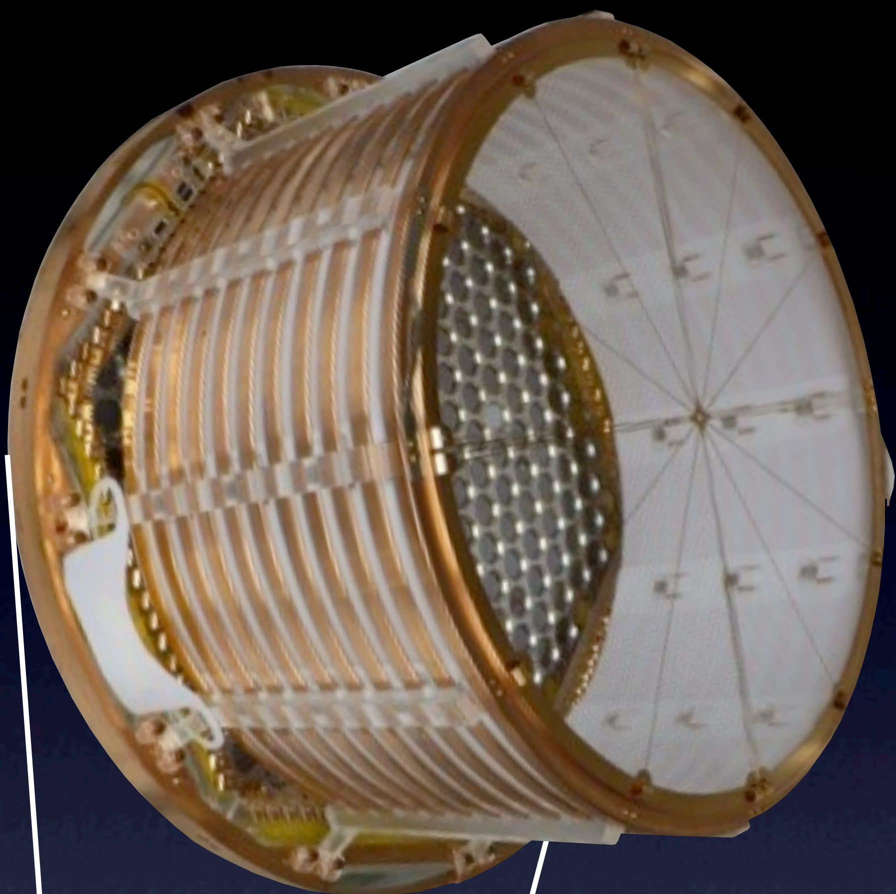
1585 meters water equivalent

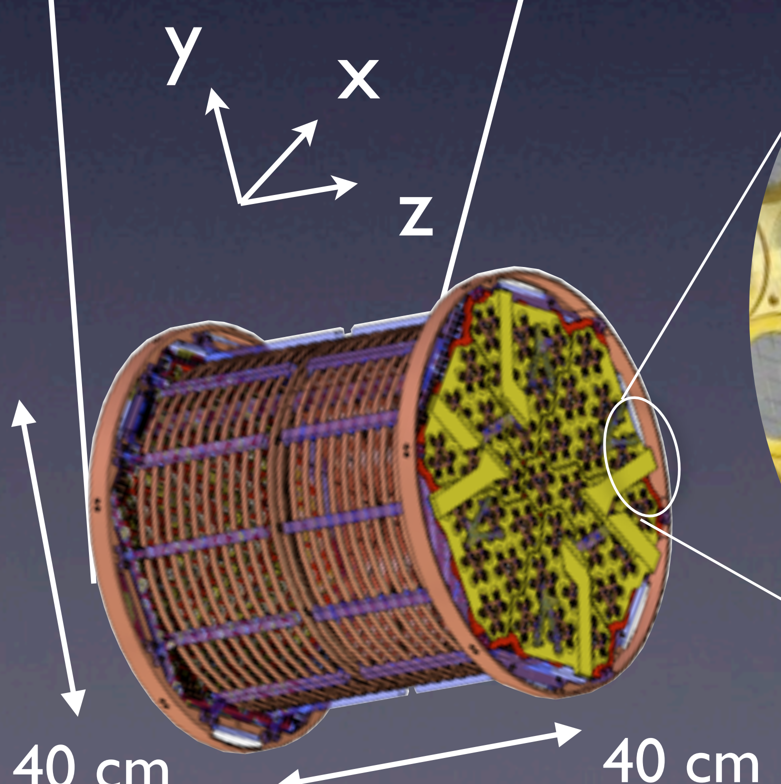
shielding from muons/cosmogenics

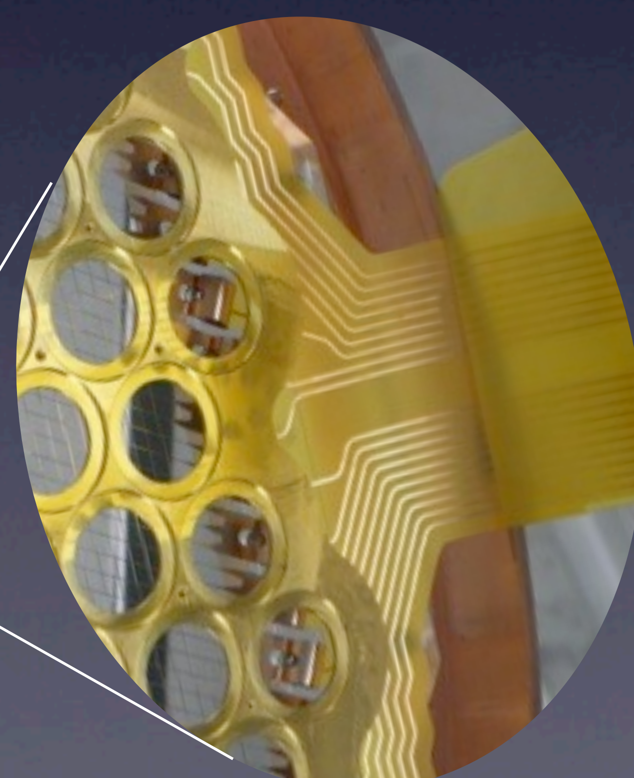
The EXO-200 TPC

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° (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

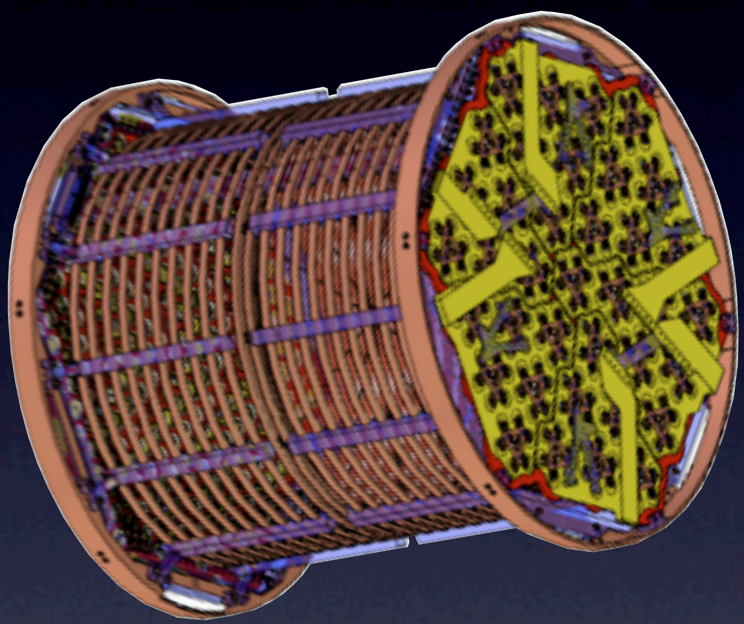




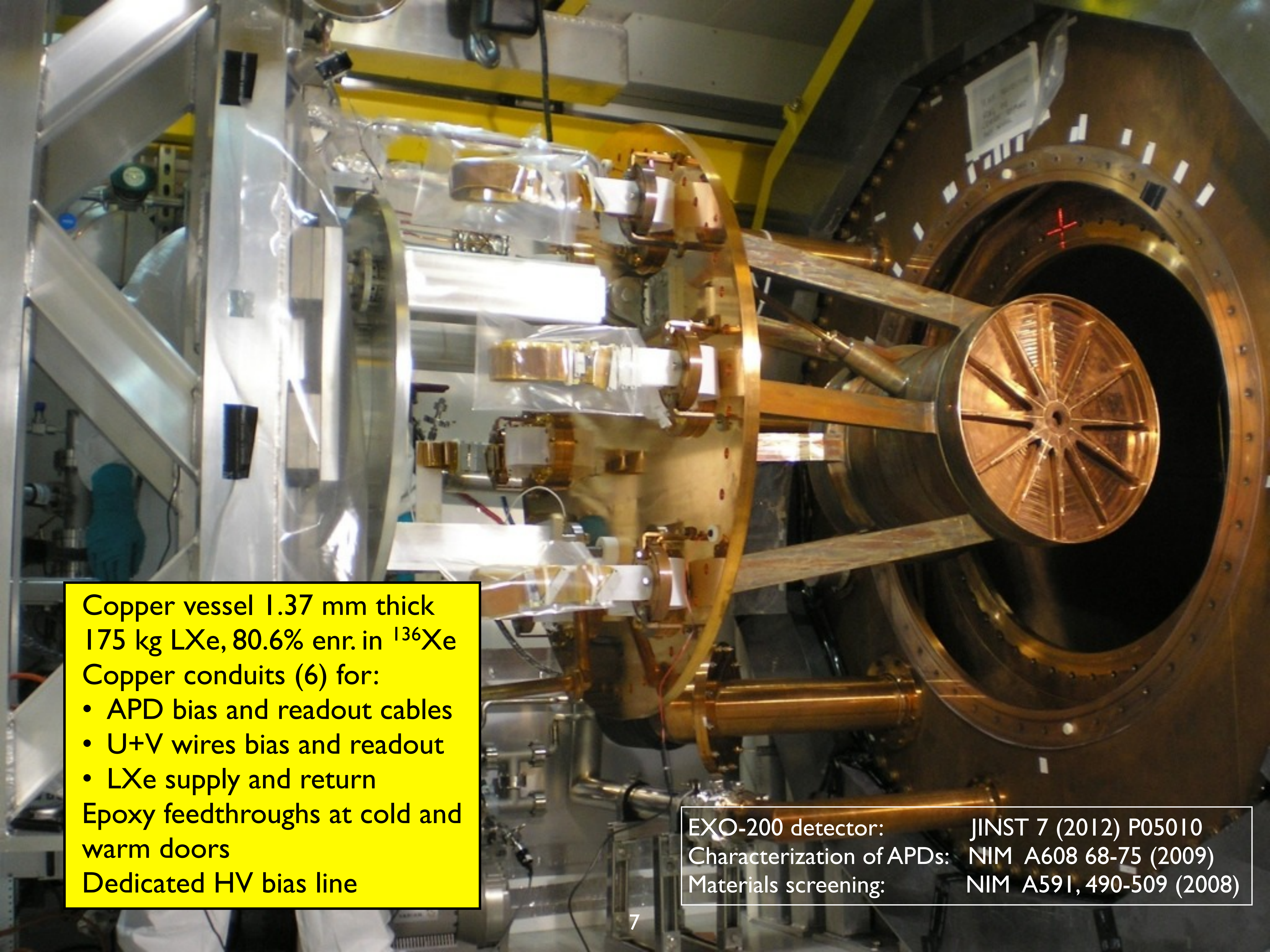


Comprehensive material screening program for internal components:

Goal: 40 cnts/2y in $0\nu\beta\beta$ $\pm 2\sigma$ ROI, 140 kg LXe



EXO-200 detector:	JINST 7 (2012) P05010
Characterization of APDs:	NIM A608 68-75 (2009)
Materials screening:	NIM A591, 490-509 (2008)



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)
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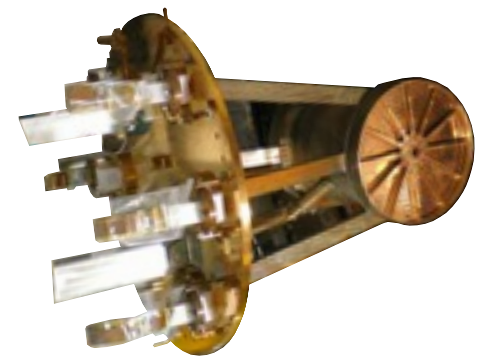
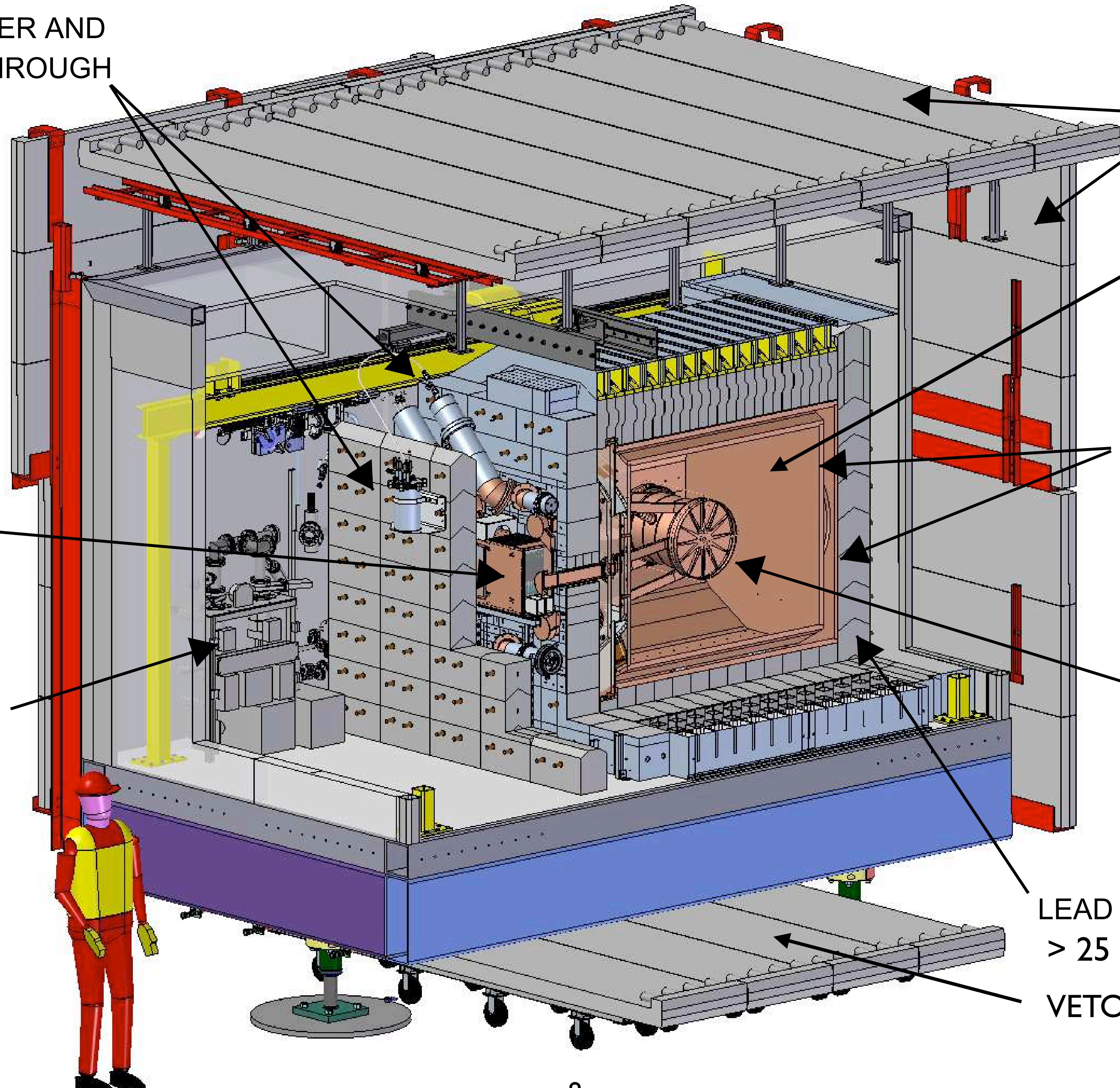
The EXO-200 Detector



The EXO-200 Detector



Muon veto

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

Data taking phases

	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	3.2 kg-yr	32.5 kg-yr
Publ.	PRL 107 (2011) 212501	PRL 109 (2012) 032505

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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

Data taking phases

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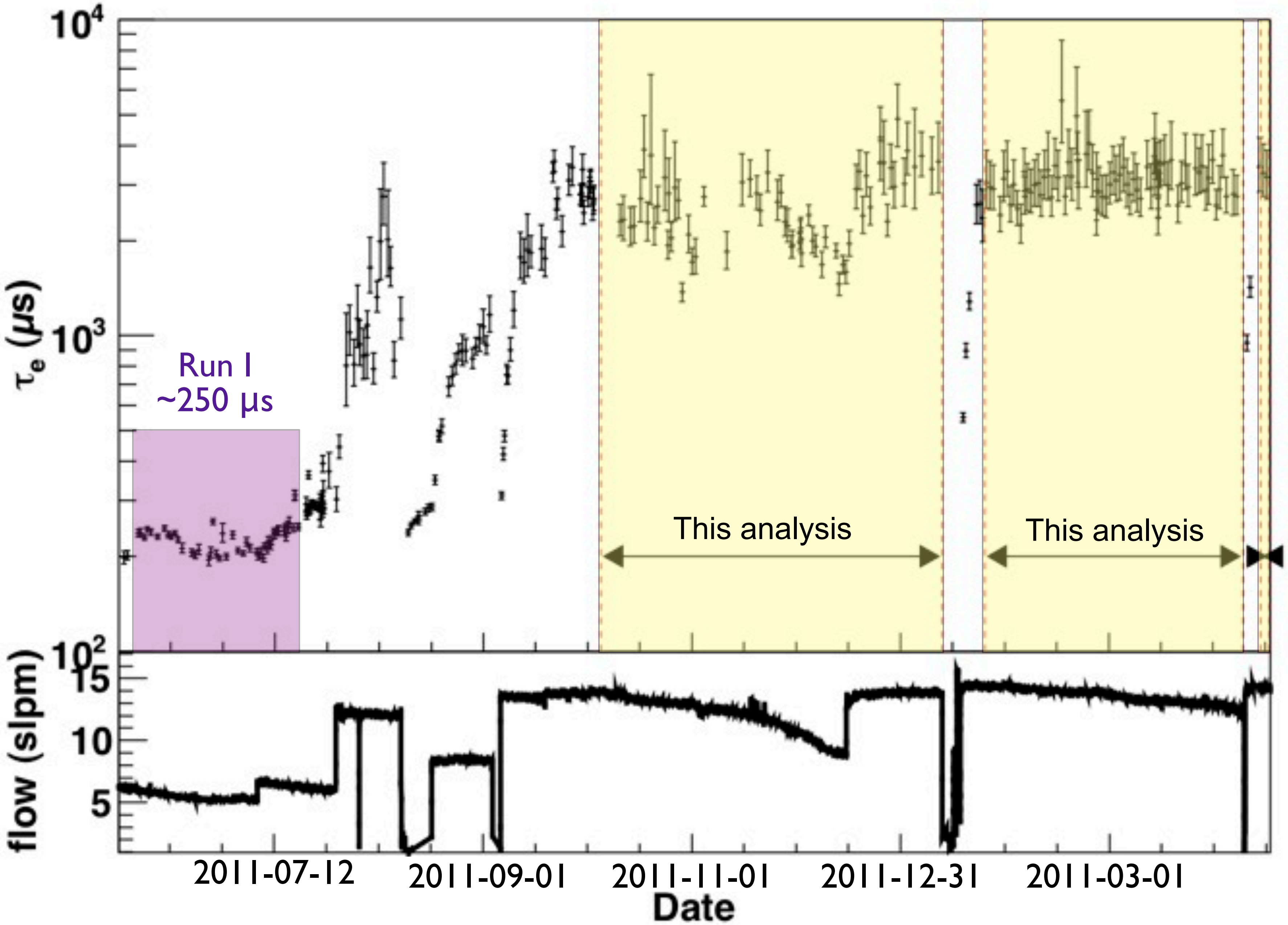
Sep 2011 – Hardware upgrades

- APD gain increase by factor 2
- improved U-wire shaping
- added outer lead shield
- Purity improvements

Data taking phases and Xenon Purity



Purity

Xenon gas is forced through heated Zr getter by custom ultra-clean pump.

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

At τ_e = 3 ms:

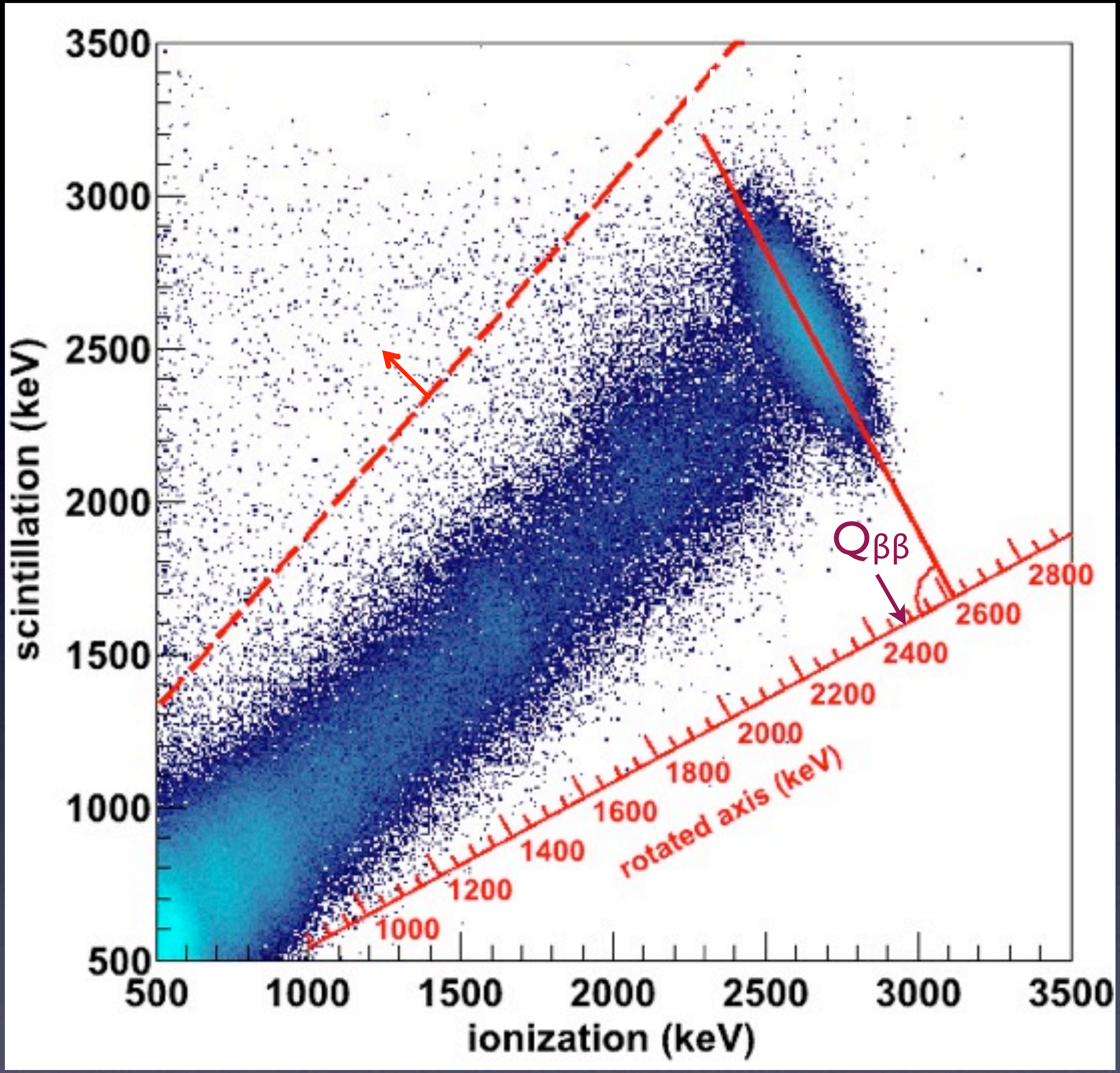
- max. drift time ~110 μs
- loss of charge is 3.6% at full drift length

Ultraclean pump:
Rev Sci Instrum. 82(10):105114

Gas purity monitors:
NIM A659 (2011) 215-228

Xenon purity with mass spectroscopy:
NIM A675 (2012) 40-46

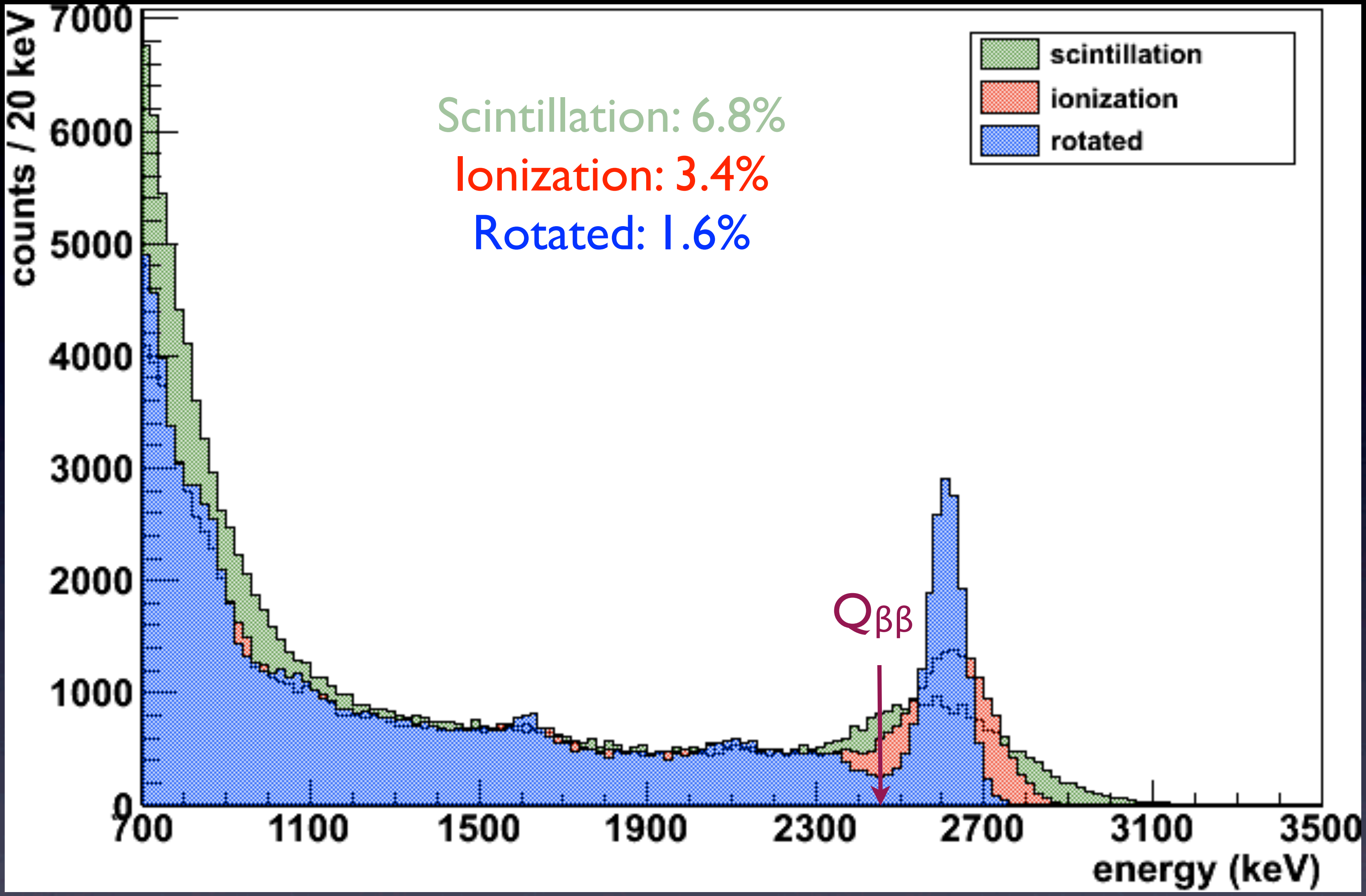
Combining Ionization and Scintillation



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

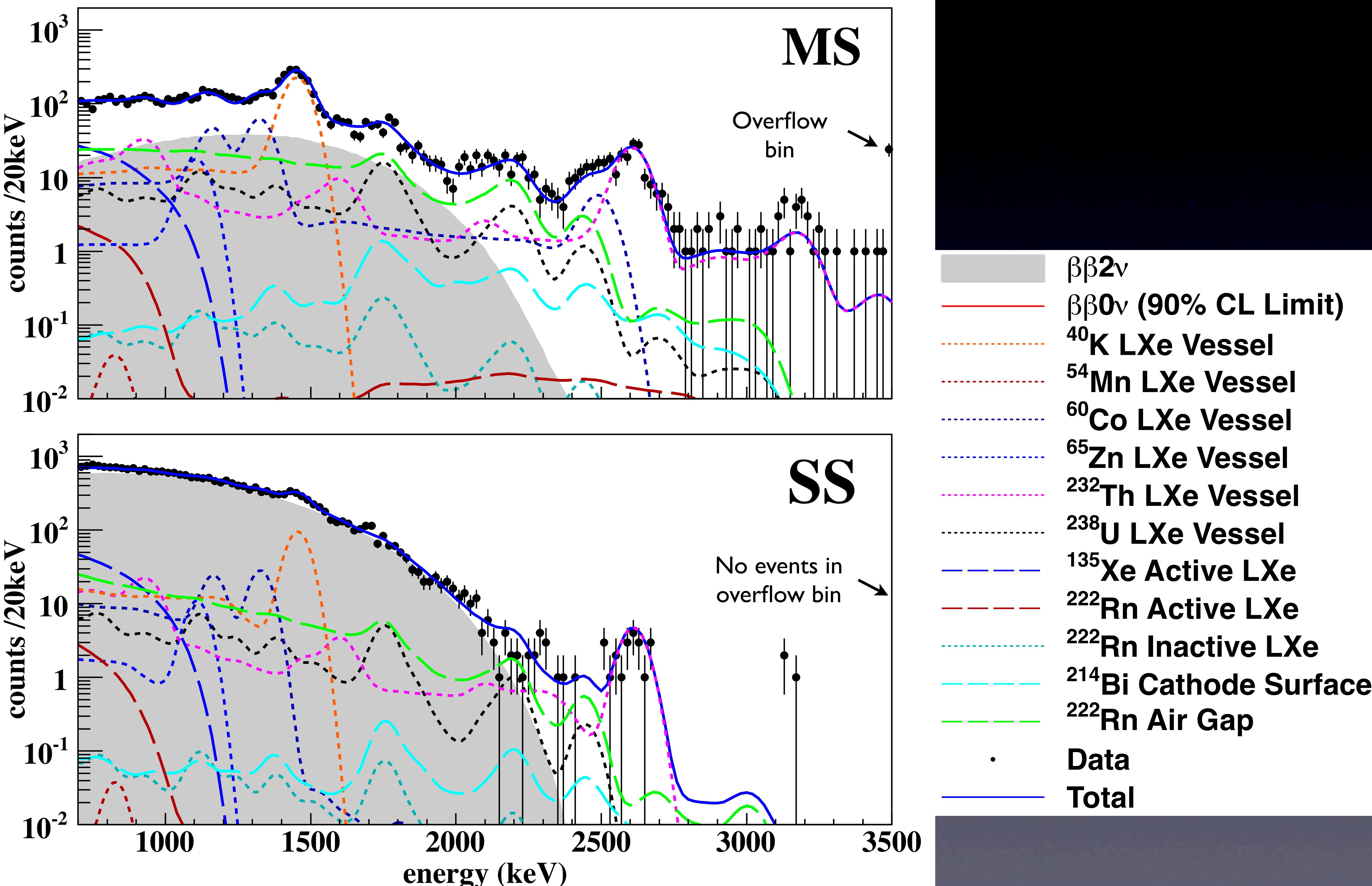
E. Conti et al. Phys. Rev. B 68 (2003) 054201

Combining Ionization and Scintillation



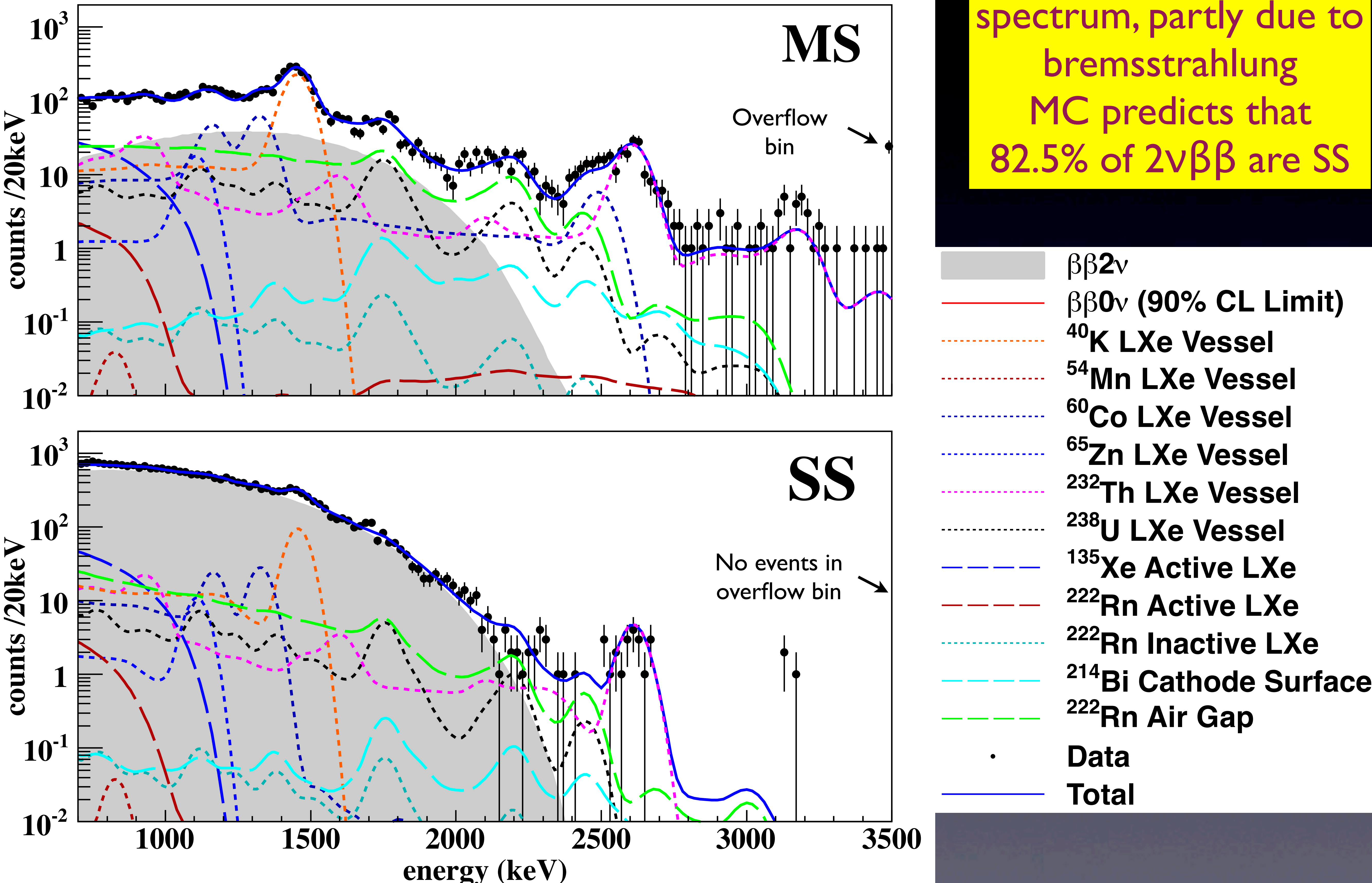
Use projection onto a rotated axis to determine event energy:

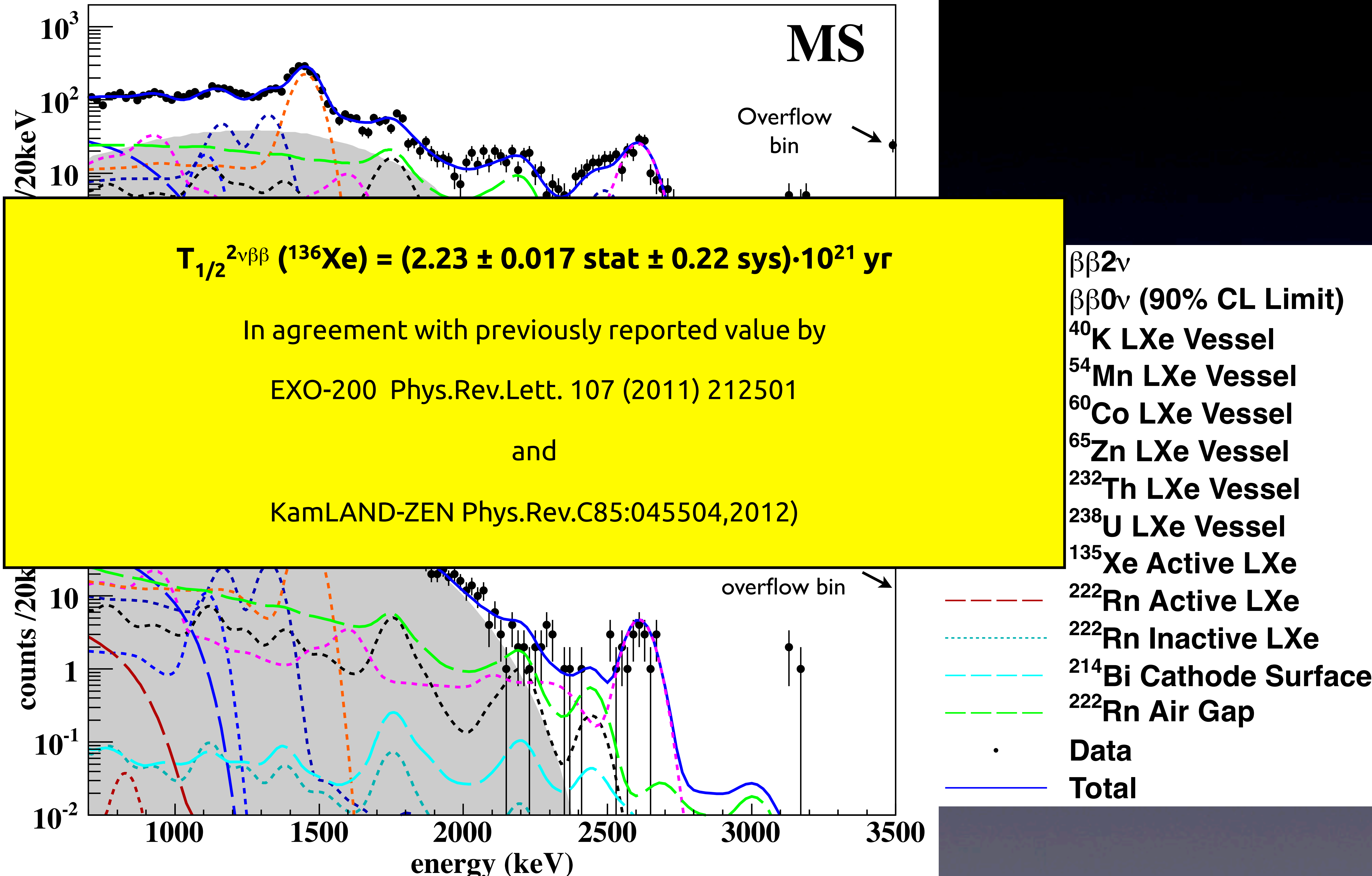
Rotation angle chosen to optimize energy resolution at 2615 keV



MS
Overflow bin
SS
No events in overflow bin
counts /20keV
energy (keV)
ββ2ν
ββ0ν (90% CL Limit)
^{40}K LXe Vessel
^{54}Mn LXe Vessel
^{60}Co LXe Vessel
^{65}Zn LXe Vessel
^{232}Th LXe Vessel
^{238}U LXe Vessel
^{135}Xe Active LXe
^{222}Rn Active LXe
^{222}Rn Inactive LXe
^{214}Bi Cathode Surface
^{222}Rn Air Gap
Data
Total

~22,000 $2\nu\beta\beta$ events !
Also populate MS spectrum, partly due to bremsstrahlung
MC predicts that 82.5% of $2\nu\beta\beta$ are SS





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

In agreement with previously reported value by

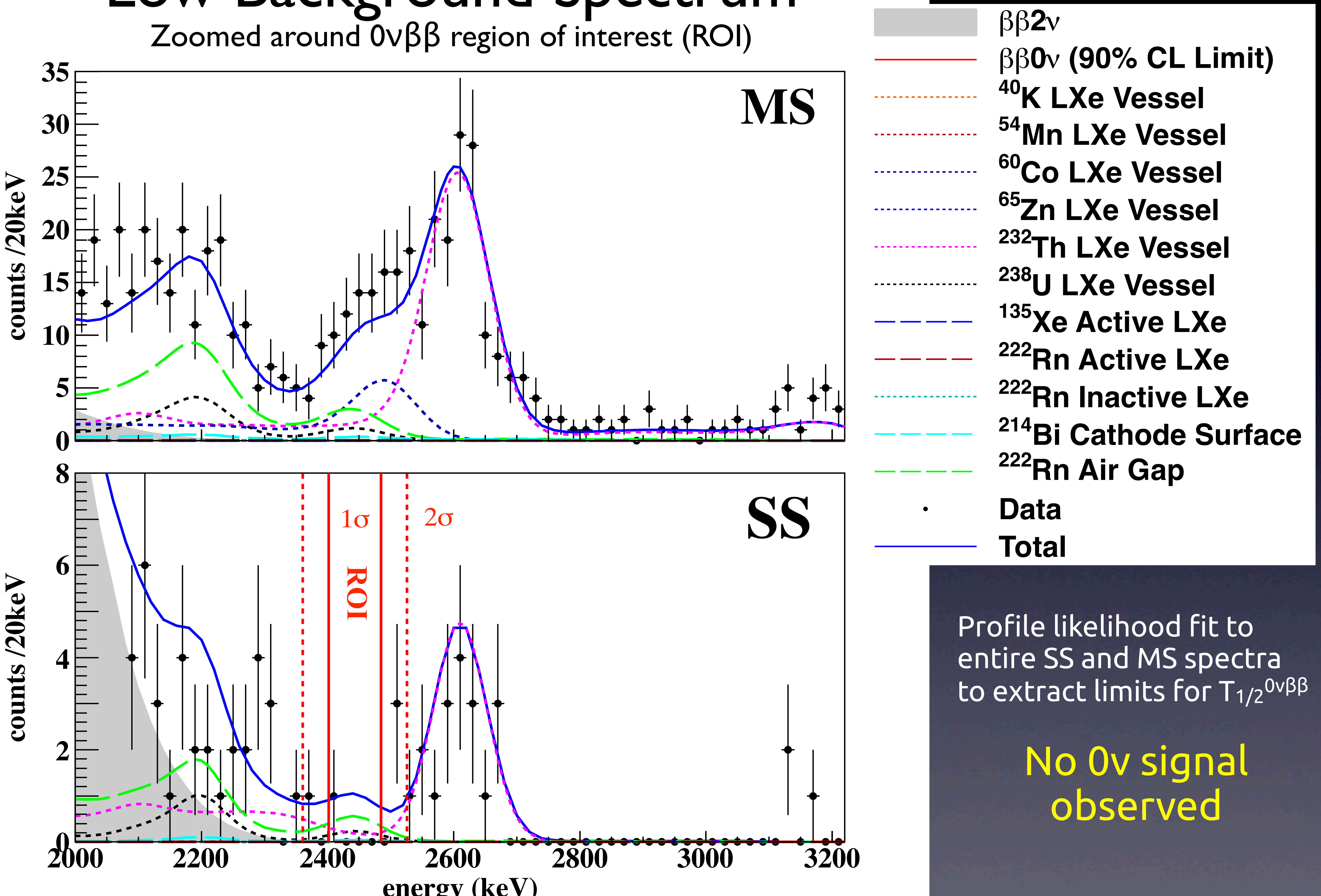
EXO-200 Phys.Rev.Lett. 107 (2011) 212501

and

KamLAND-ZEN Phys.Rev.C85:045504,2012)

Low Background Spectrum

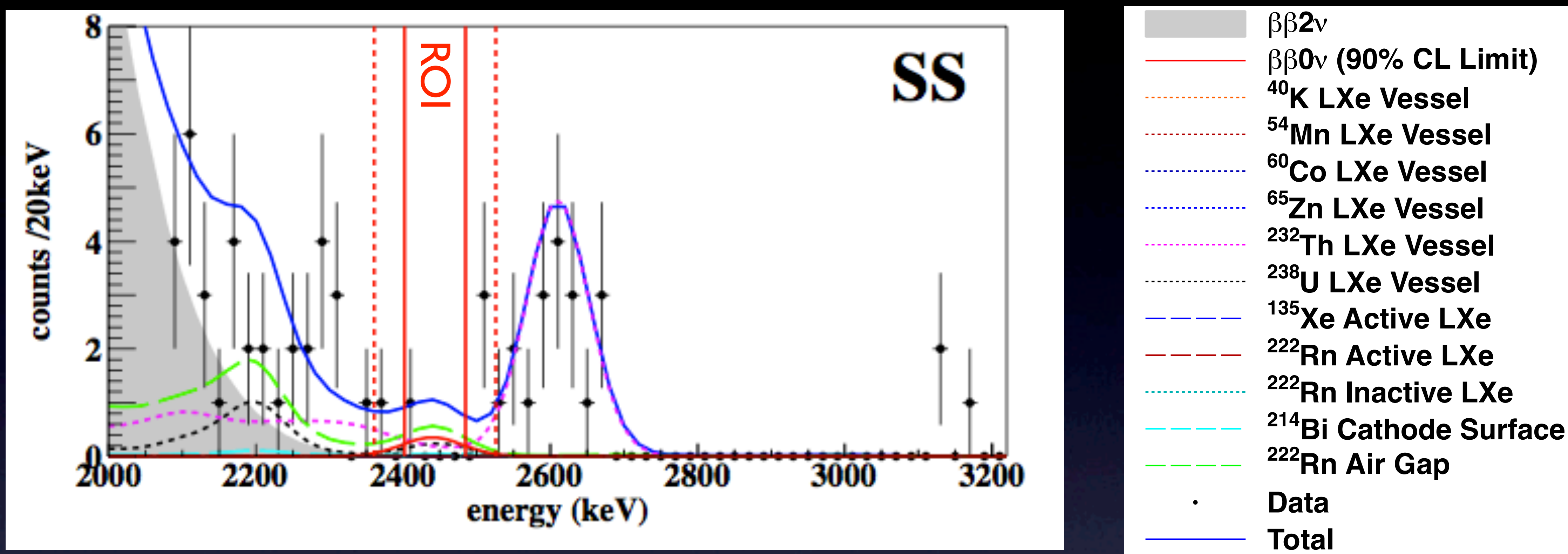
Zoomed around 0νββ region of interest (ROI)



Profile likelihood fit to entire SS and MS spectra to extract limits for $T_{1/2}^{0\nu\beta\beta}$

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 goal (beginning of talk):

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

Limits on $T_{1/2}^{0\nu\beta\beta}$ and $\langle m_{\beta\beta} \rangle$

Interpret as lepton number violating process with effective Marojana mass $\langle m_{\beta\beta} \rangle$:

$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu}\left|M_{nucl}\right|^2 \langle m_{\beta\beta} \rangle^2$$

From profile likelihood:

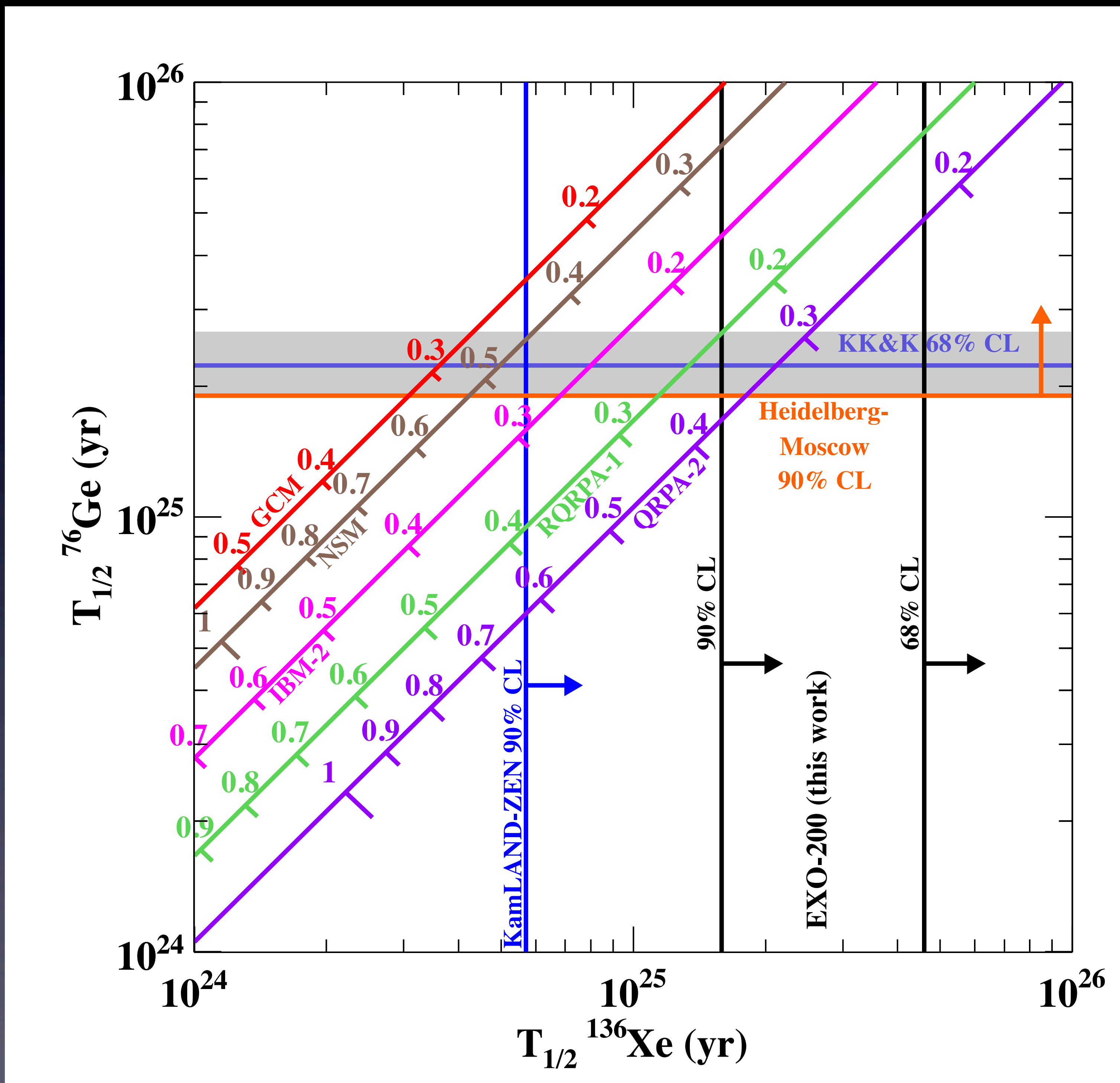
$T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25}$ yr

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

(90% C.L.)

PRL 109 (2012) 032505

Limits on $T_{1/2}^{0\nu\beta\beta}$ and $\langle m_{\beta\beta} \rangle$



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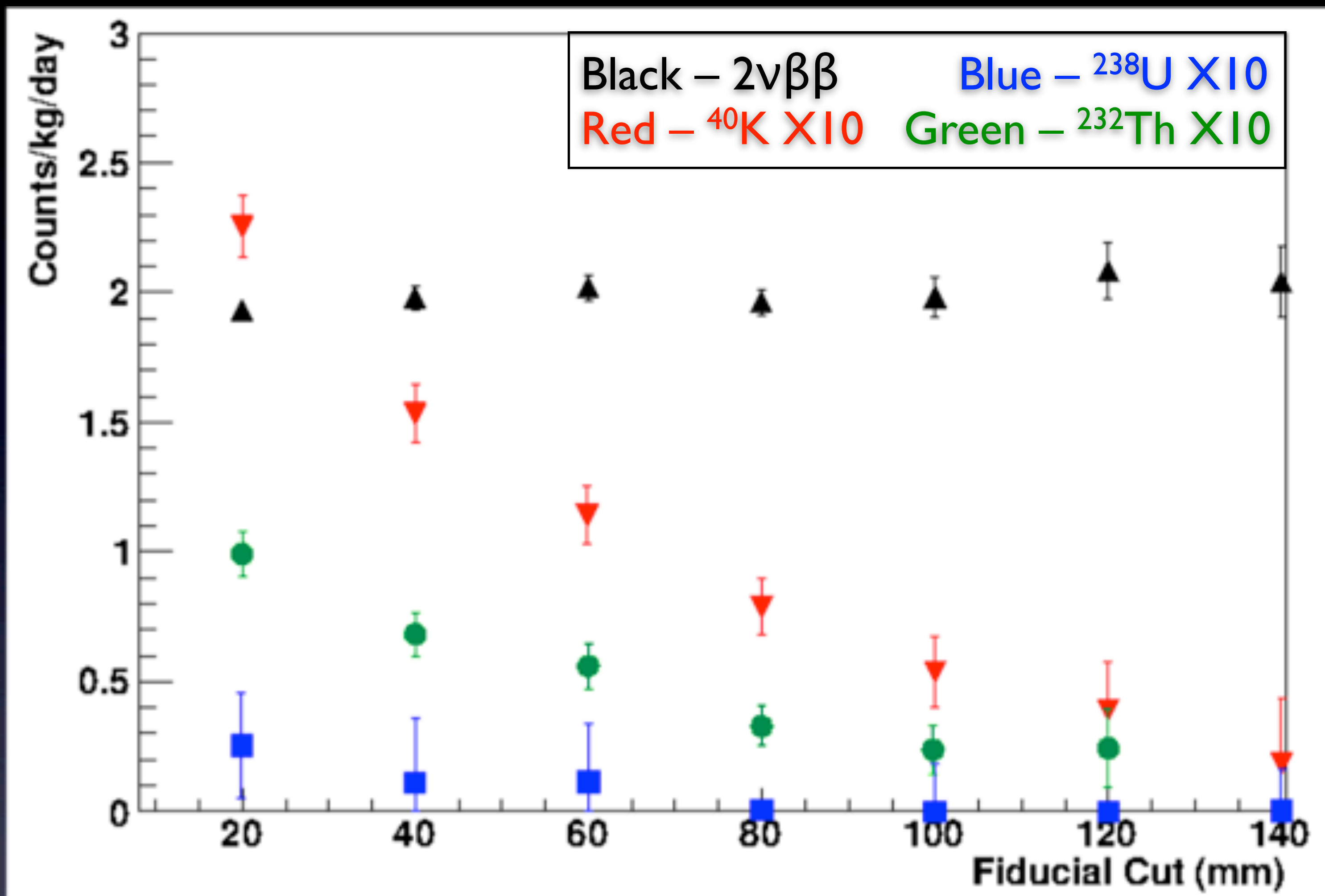
PRL 109 (2012) 032505

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.

Ongoing work



> 77 kg·yrs of exposure and counting

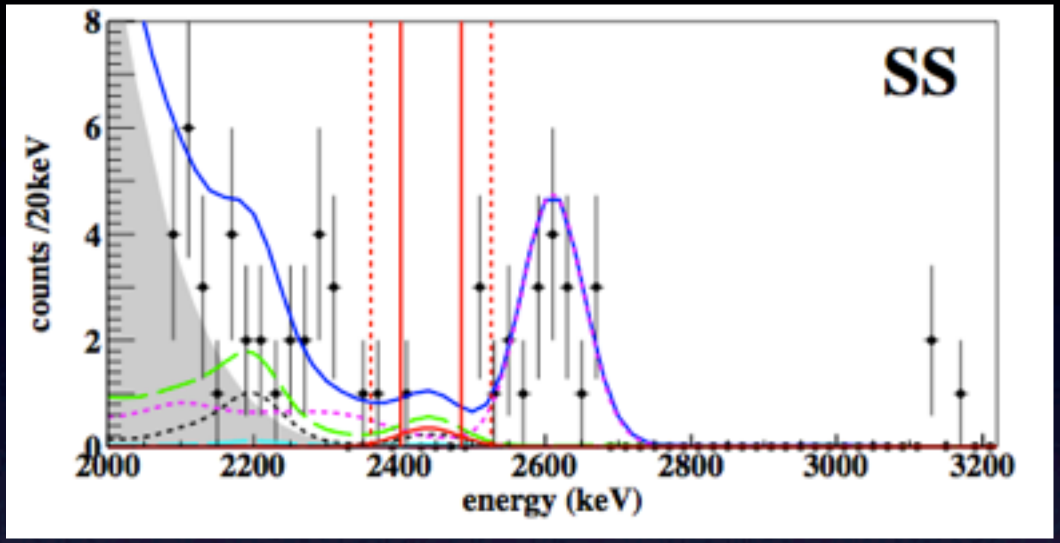
- Multidimensional fitting
- Improving single-site reconstruction efficiency for 0νββ (was 71% for this analysis)
- Improving multi-site discrimination (better clustering, investigating other selection criteria)
- Improving fiducial volume errors
- Investigate/address apparent Rn background

Summary

EXO-200 is taking low background data

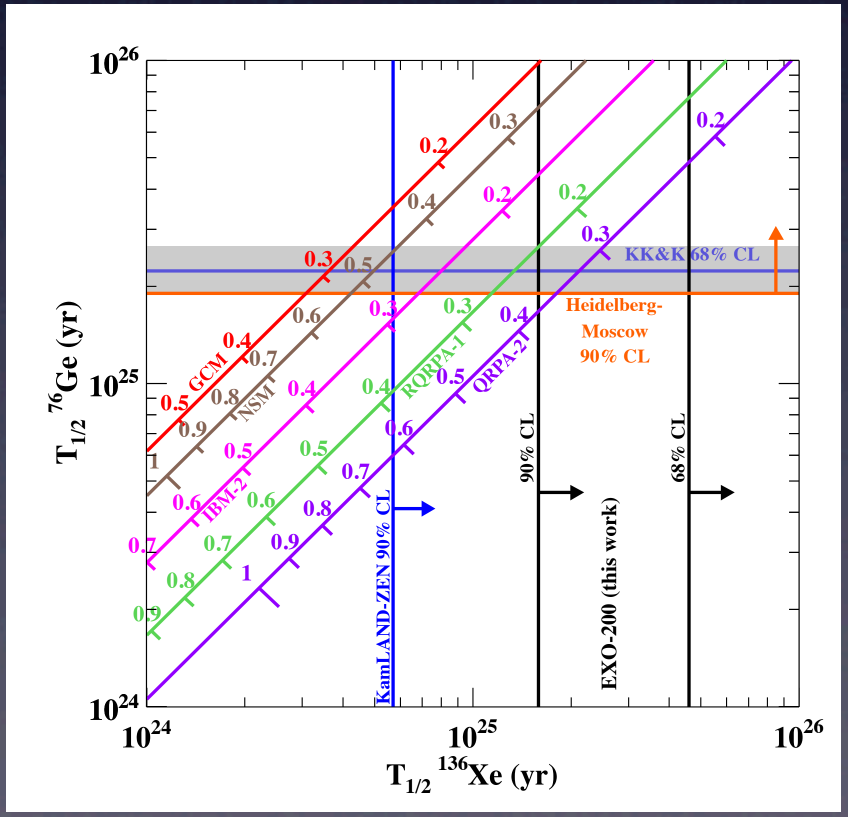
Detector working well, met our goals:

- 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



$T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25}$ yr
$\langle m_{\beta\beta} \rangle < 140$–$380$ meV
(90% C.L.)

PRL 109 (2012) 032505



Improvements on σ and b in progress

EXO-200 approved to run for 4 more years

The EXO collaboration

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Extra slides

Analysis summary

Low background run livetime: 120.7 days

Active mass: 98.5 kg LXe (79.4 kg 136LXe)

Exposure: 32.5 kg·yr

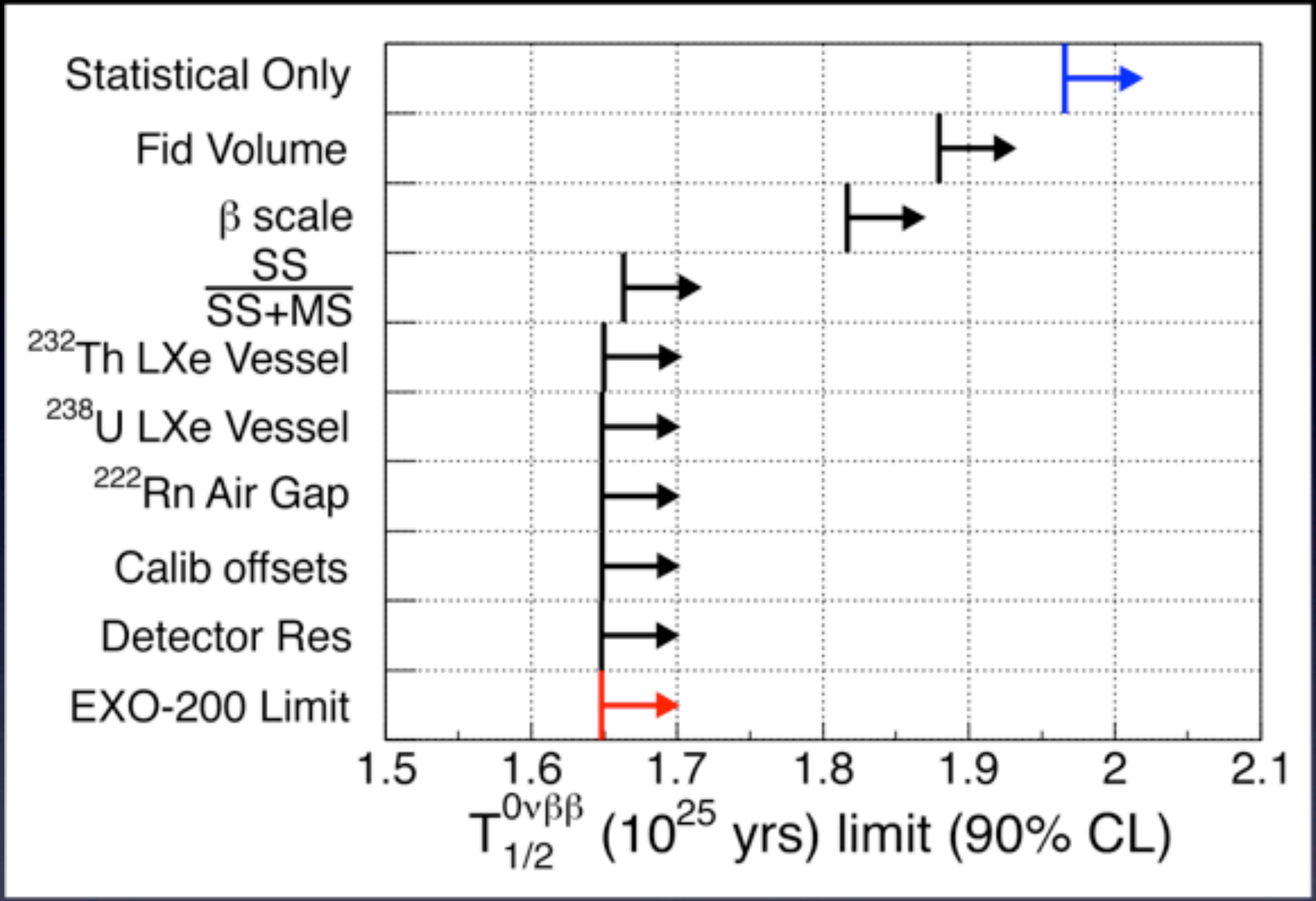
Total dead time from vetos: 8.6%

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

Extracting Physics

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

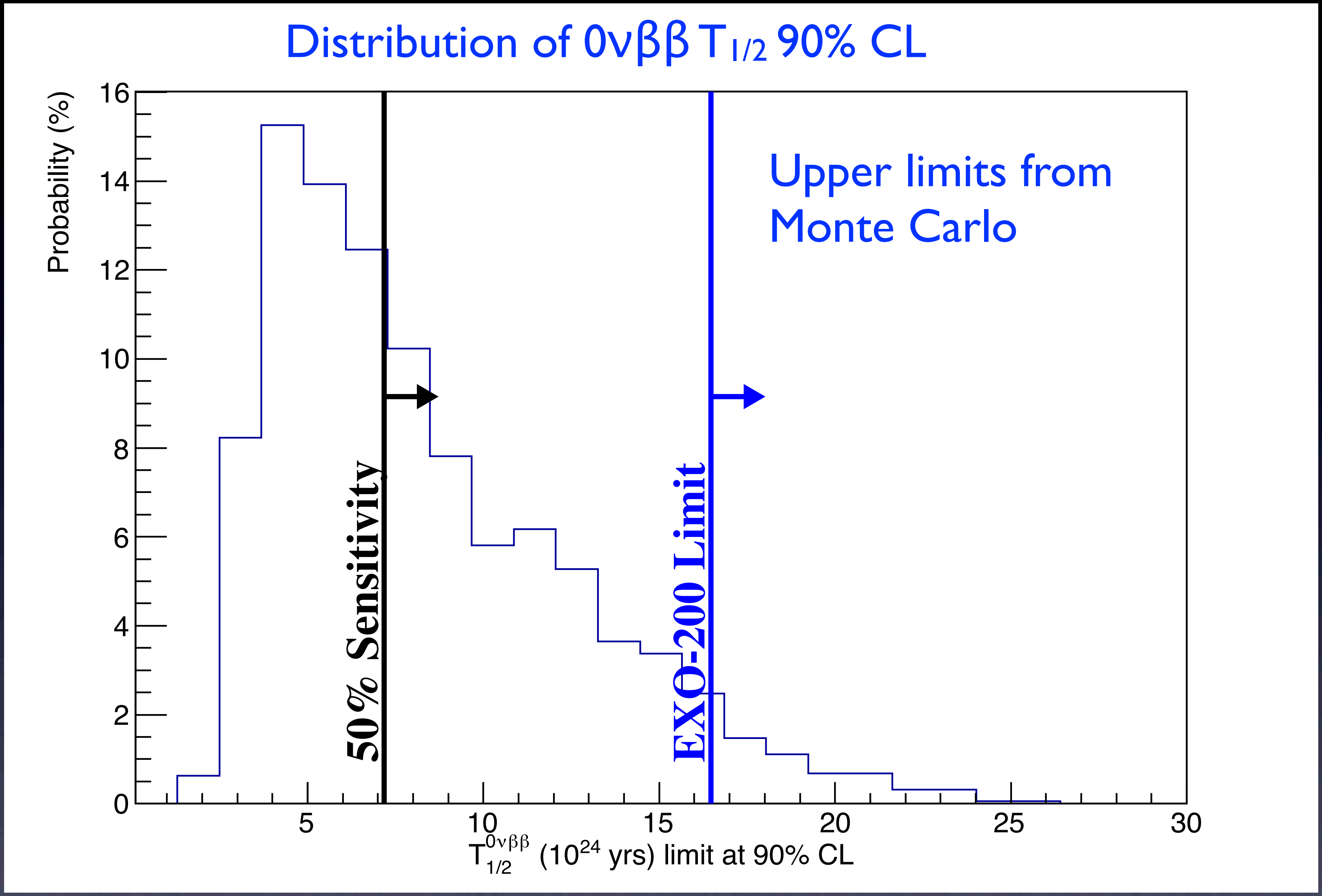
Systematics



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

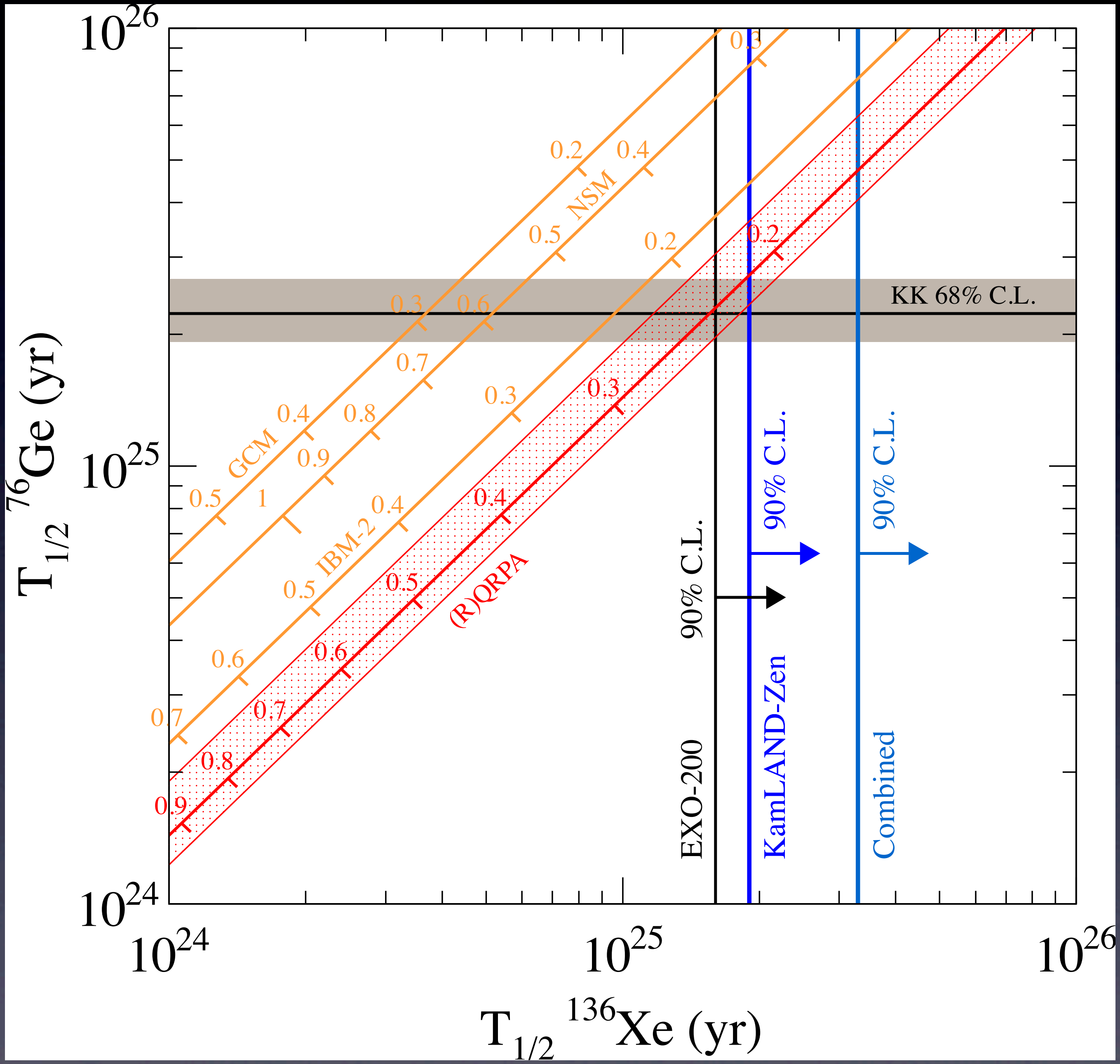


From estimated background, expect to quote a 90% CL upper limit on $T_{1/2}$:

$\geq$ 1.6 x 10^{25} yr   6.5% of the time

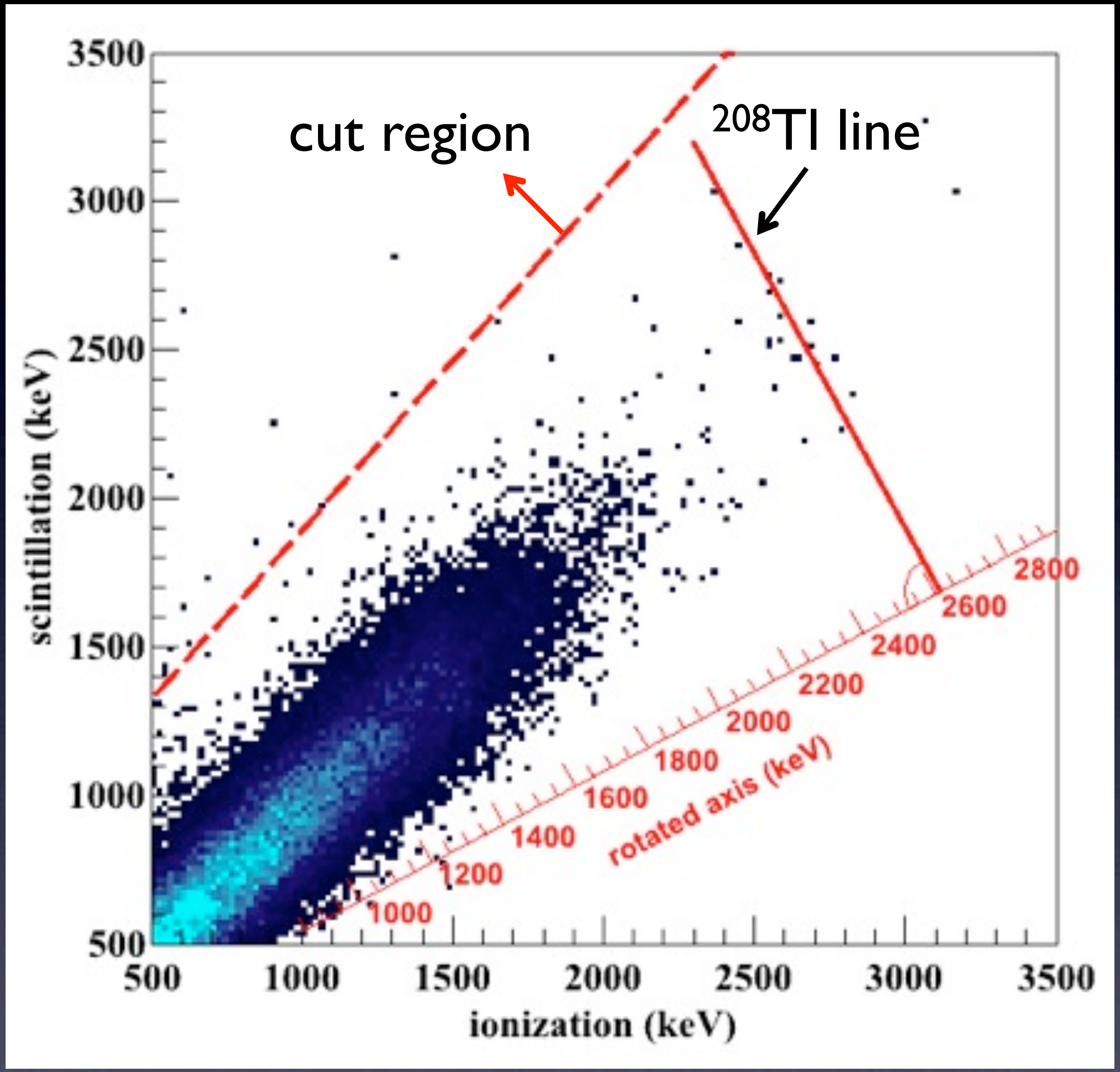
$\geq$ 7   x 10^{24} yr 50%   of the time

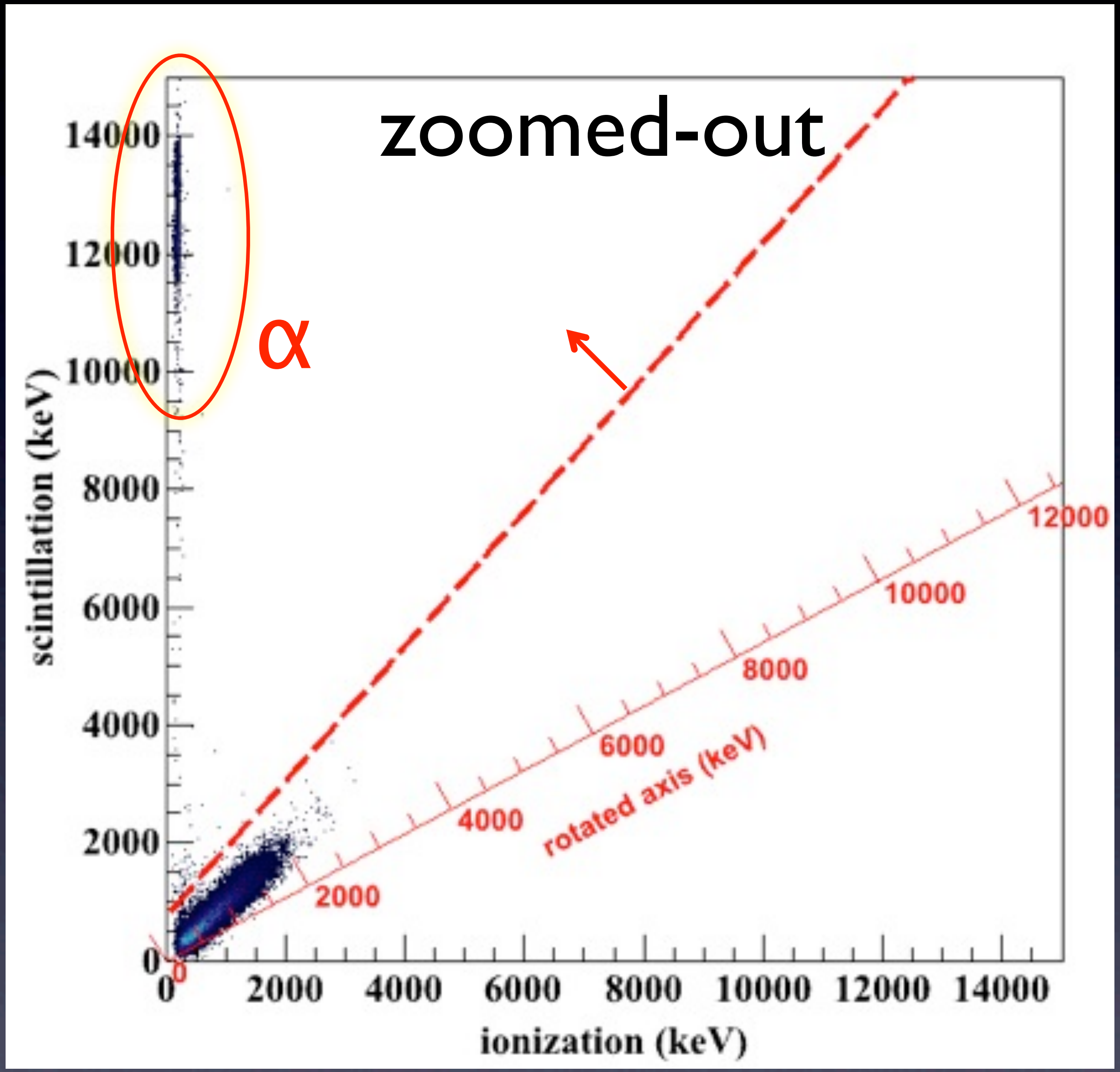
Comparison with recent Kamland-ZEN results



arXiv:1211.3863, 16 Nov 2012

Low Background 2D SS Spectrum

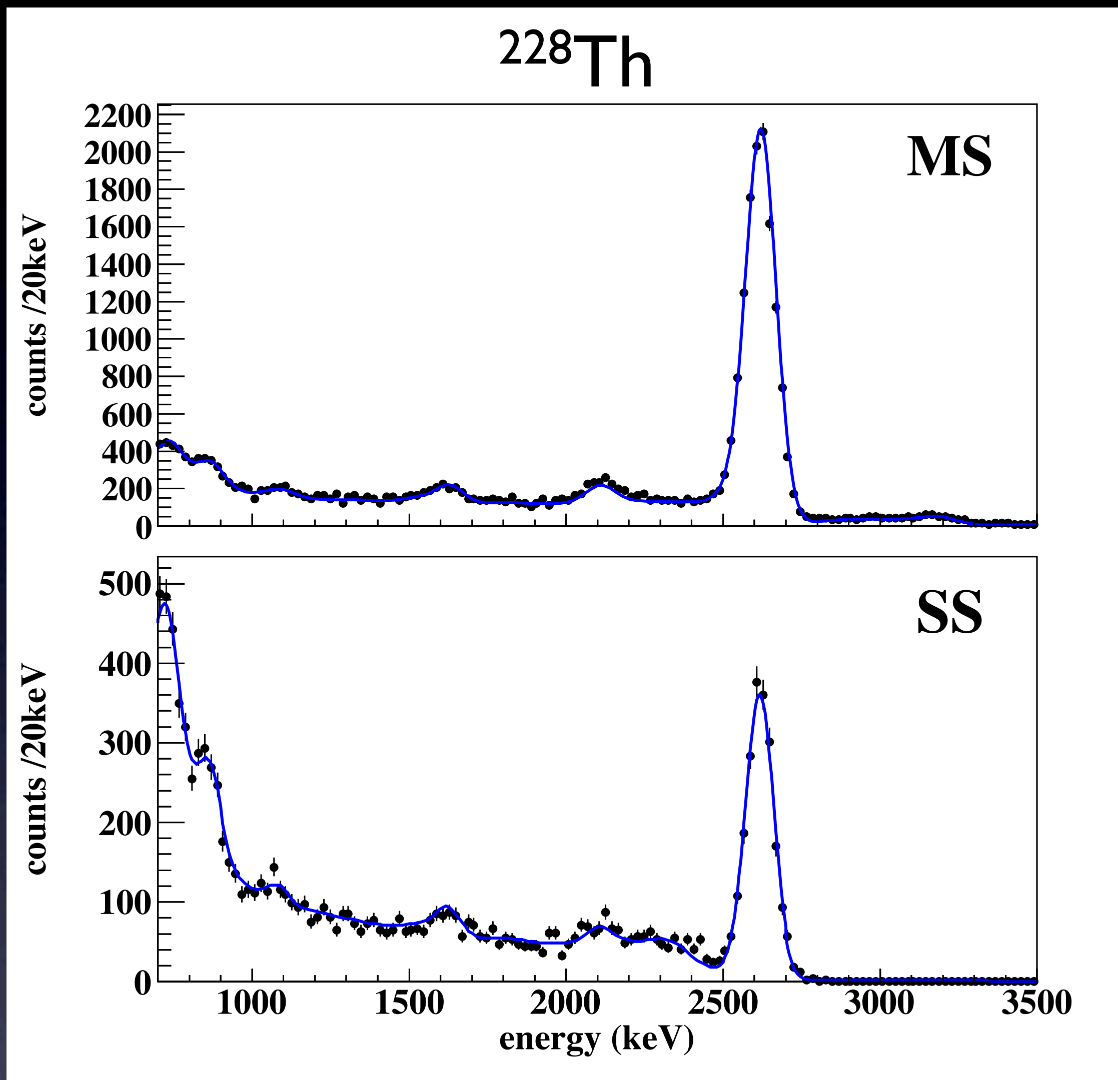


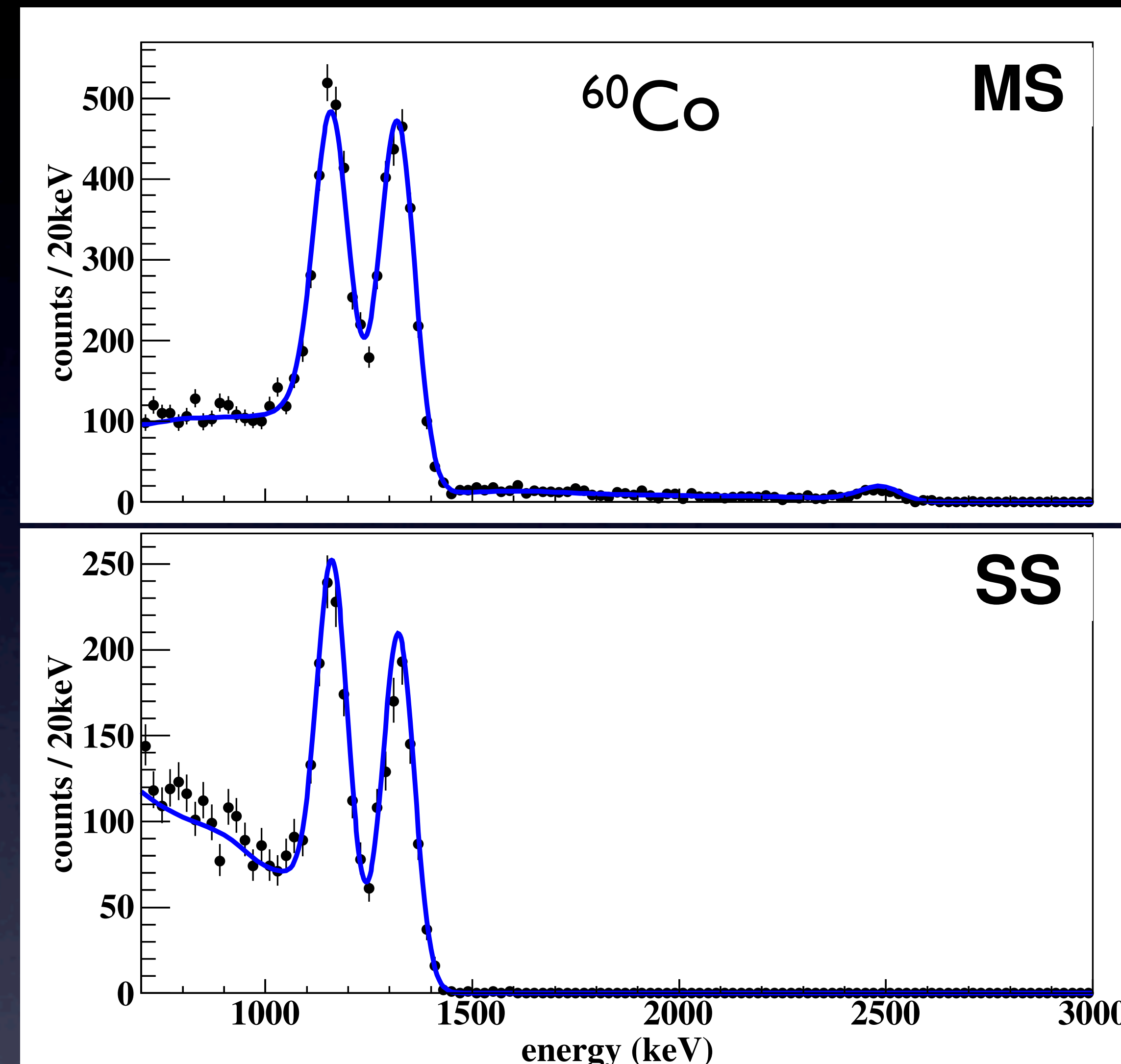


Events removed by diagonal cut:

- 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

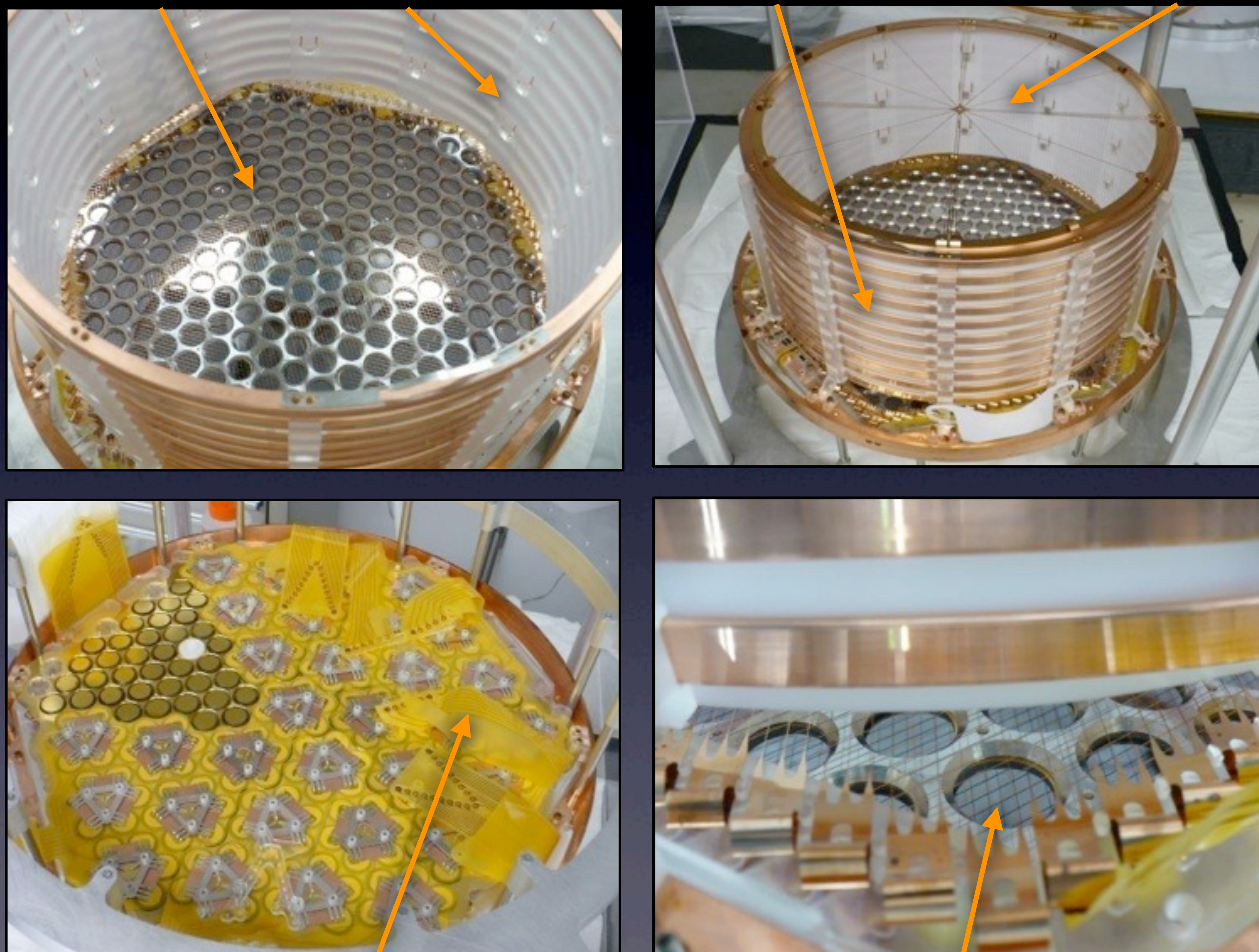
Source Data/MC Agreement





- Multi site (MS) and single site (SS) data (black points) are compared to model (blue curve) (MC + measured resolution function)
- Single site fraction agrees to within 8.5%
- Source activities measured to within 9.4%

The EXO-200 Time Projection Chamber (TPC)



EXO Sensitivity to ⟨$m_{\beta\beta}$⟩