Double-beta decay:

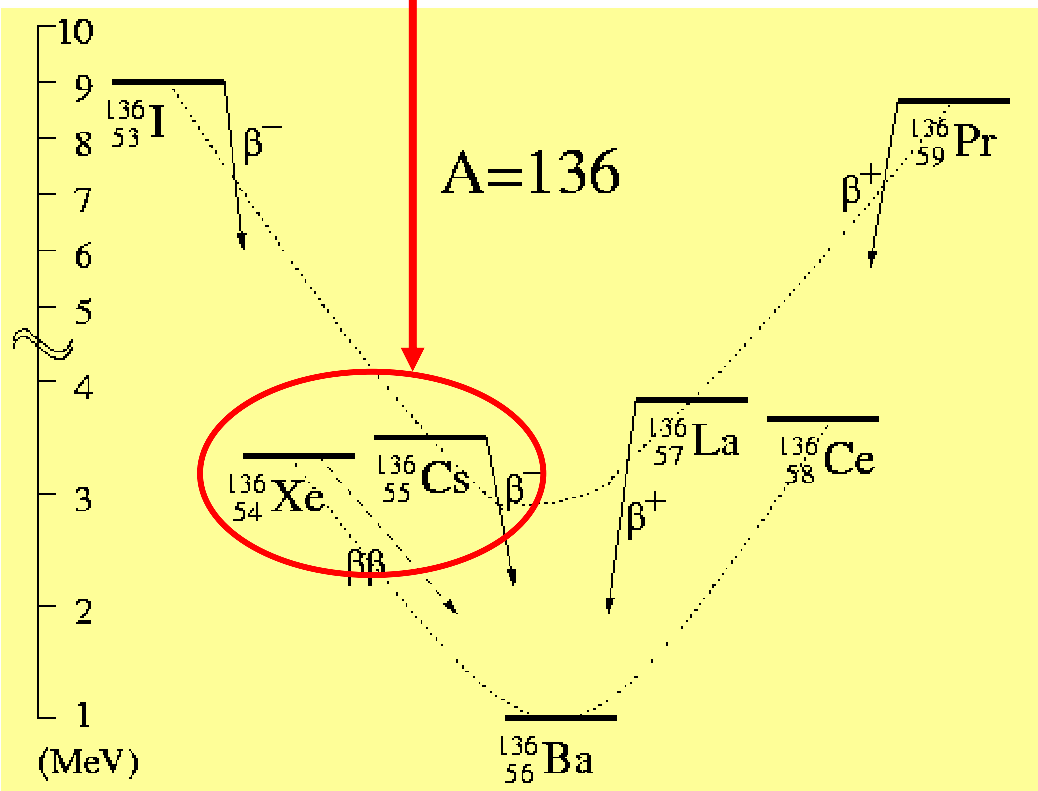
and new results from EXO-200

G.Gratta
Physics Dept
Stanford University

SPP 2012, Groningen, Jun 2012

Double-beta decay:

a second-order process only detectable if first order beta decay is energetically forbidden



Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.458	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

There are two varieties of ββ decay

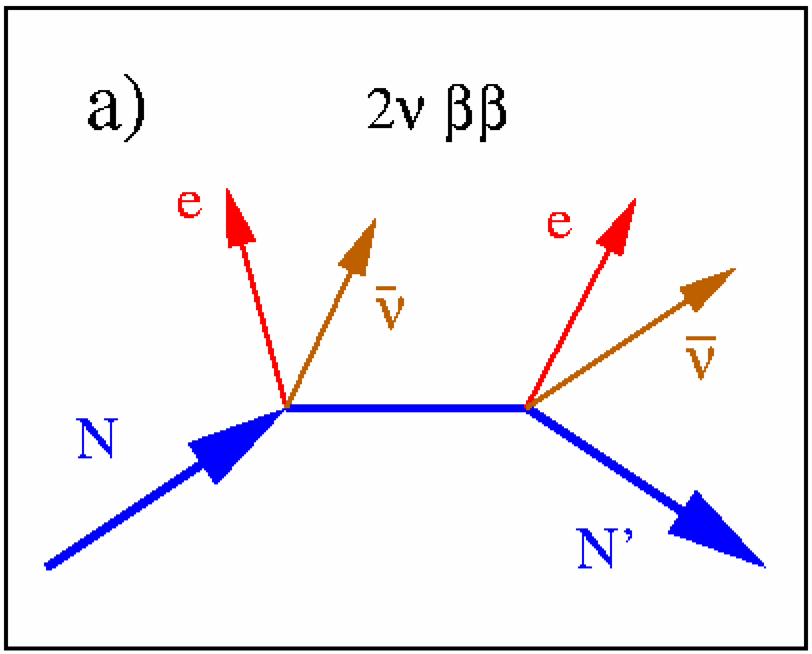
2ν mode:
a conventional
2nd order process
in nuclear physics

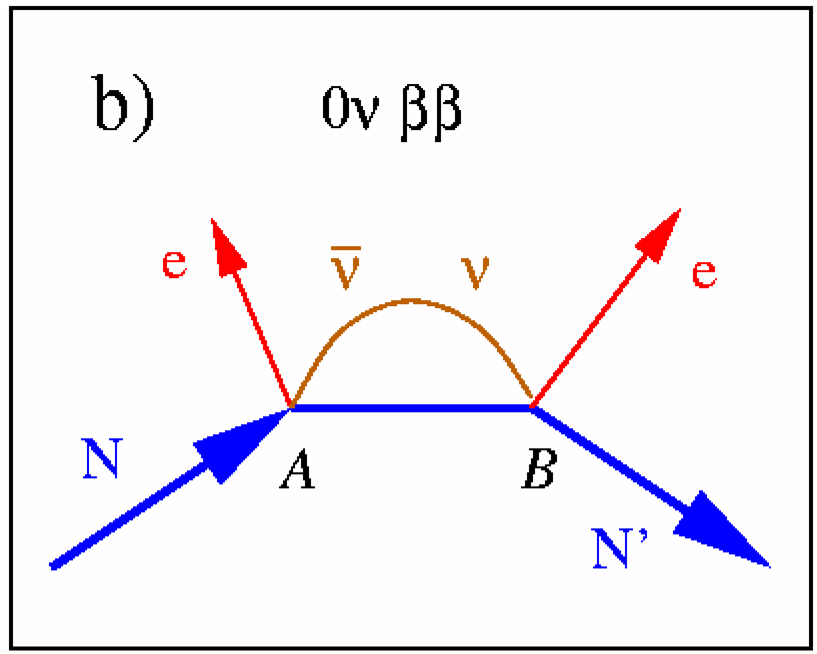
0ν mode: a hypothetical
process can happen
only if: $M_\nu \neq 0$

$\nu = \bar{\nu}$

$|\Delta L| = 2$

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





"Dirac" neutrinos

(some "redundant" information but the "good feeling" of things we know…)

$$\nu^D = \begin{pmatrix} \nu_L \\ \overline{\nu}_L \\ \nu_R \\ \overline{\nu}_R \end{pmatrix}$$

"Majorana" neutrinos

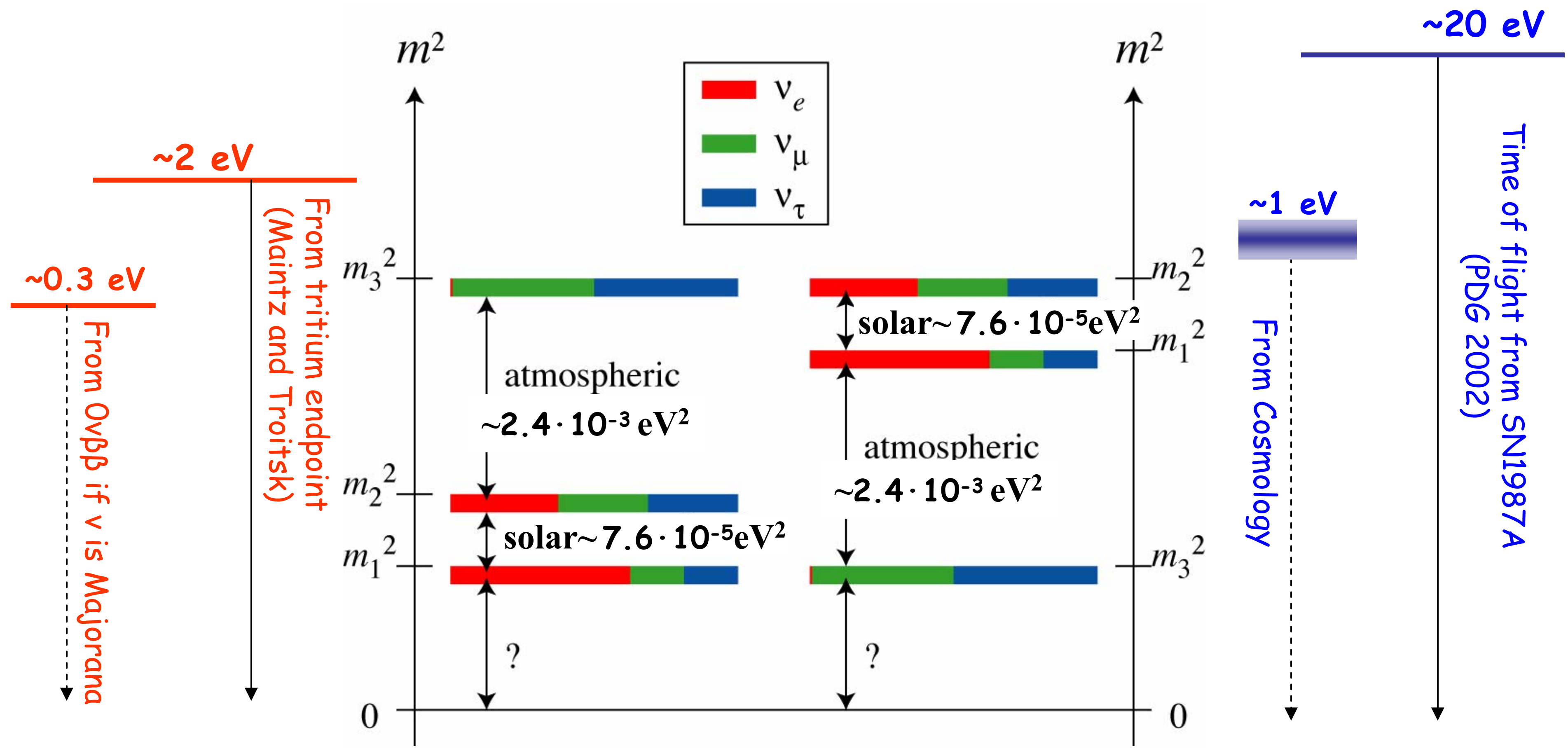
(more efficient description, no lepton number conservation, new paradigm…)

$$\nu^M = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

Which way Nature chose to proceed is an experimental question

→ **But the alternative is only meaningful/testable for massive particles… which we now know neutrinos are!**

Our knowledge of the ν mass pattern



The connection of ν masses with cosmological measurements is particularly interesting because it ties together very different fields.

We need both, the connection between the two is the interesting part!

In the last 10 years there has been a transition

1) From a few kg detectors to 100s or 1000s kg detectors
→ Think big: qualitative transition from cottage industry to large experiments

2) From "random shooting" to the knowledge that at least the inverted hierarchy will be tested

Discovering 0νββ decay:

→ Discovery of the neutrino mass scale
→ Discovery of Majorana particles
→ Discovery of Majorana masses
→ Discovery of lepton number violation

If $0\nu\beta\beta$ is due to light ν Majorana masses

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} \; G^{0\nu\beta\beta}(E_0, Z) \; \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1}$$

$M_F^{0\nu\beta\beta}$ and $M_{GT}^{0\nu\beta\beta}$ can be calculated within particular nuclear models

$G^{0\nu\beta\beta}$ a known phasespace factor

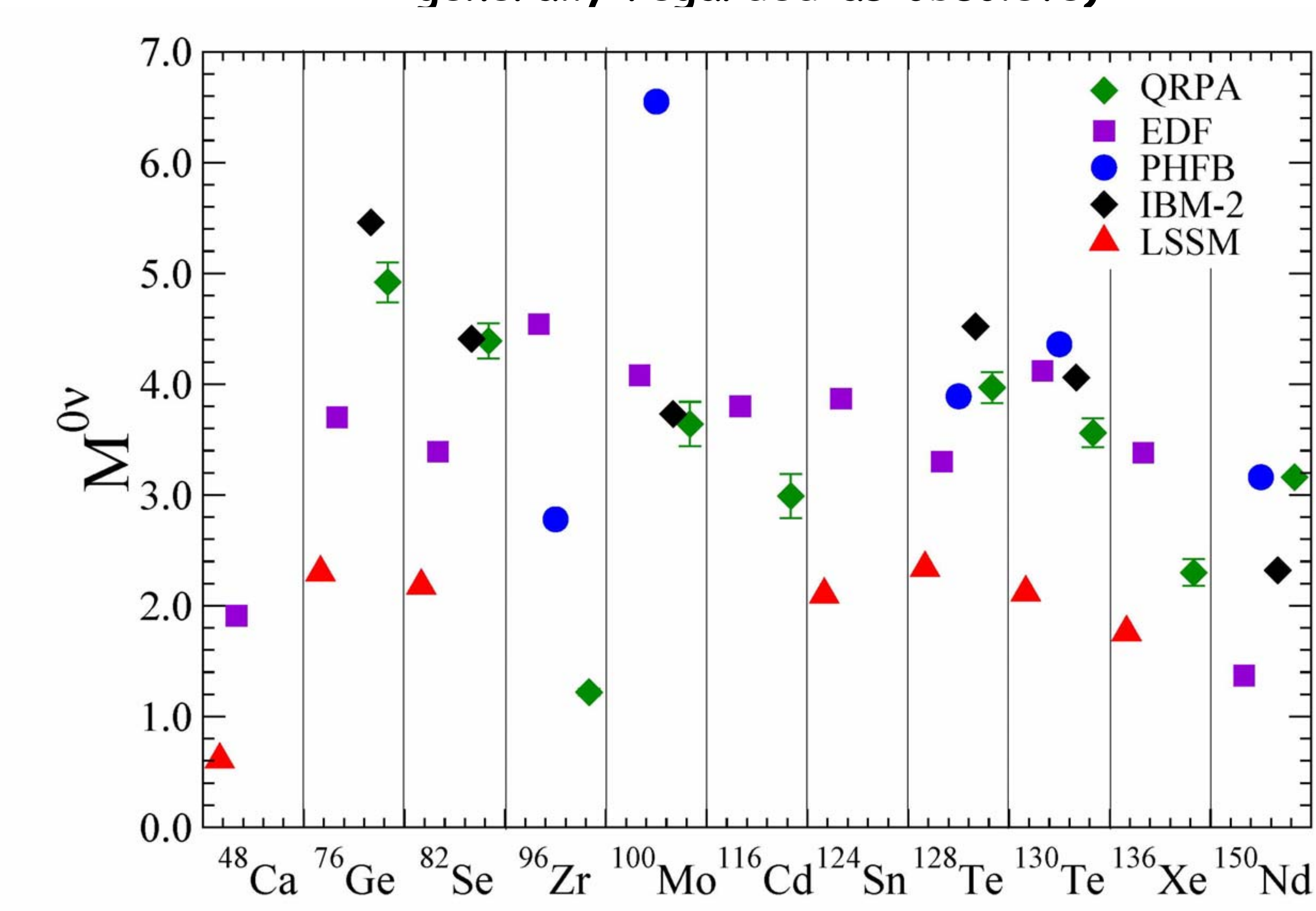
$T_{1/2}^{0\nu\beta\beta}$ is the quantity to be measured

$$\langle m_\nu \rangle = \sum_{i=1}^{3} \left| U_{e,i} \right|^2 m_i \; \varepsilon_i$$

effective Majorana ν mass
($\varepsilon_i = \pm 1$ if CP is conserved)

Calculations differ by about a factor of two

(but care is necessary in treating some of them generally regarded as obsolete)



S.M. Bilenky and C.Giunti arXiv:1203.5250v2

Note, however, that to discover Majorana neutrinos and lepton number violation the value of the nuclear matrix element is inessential!

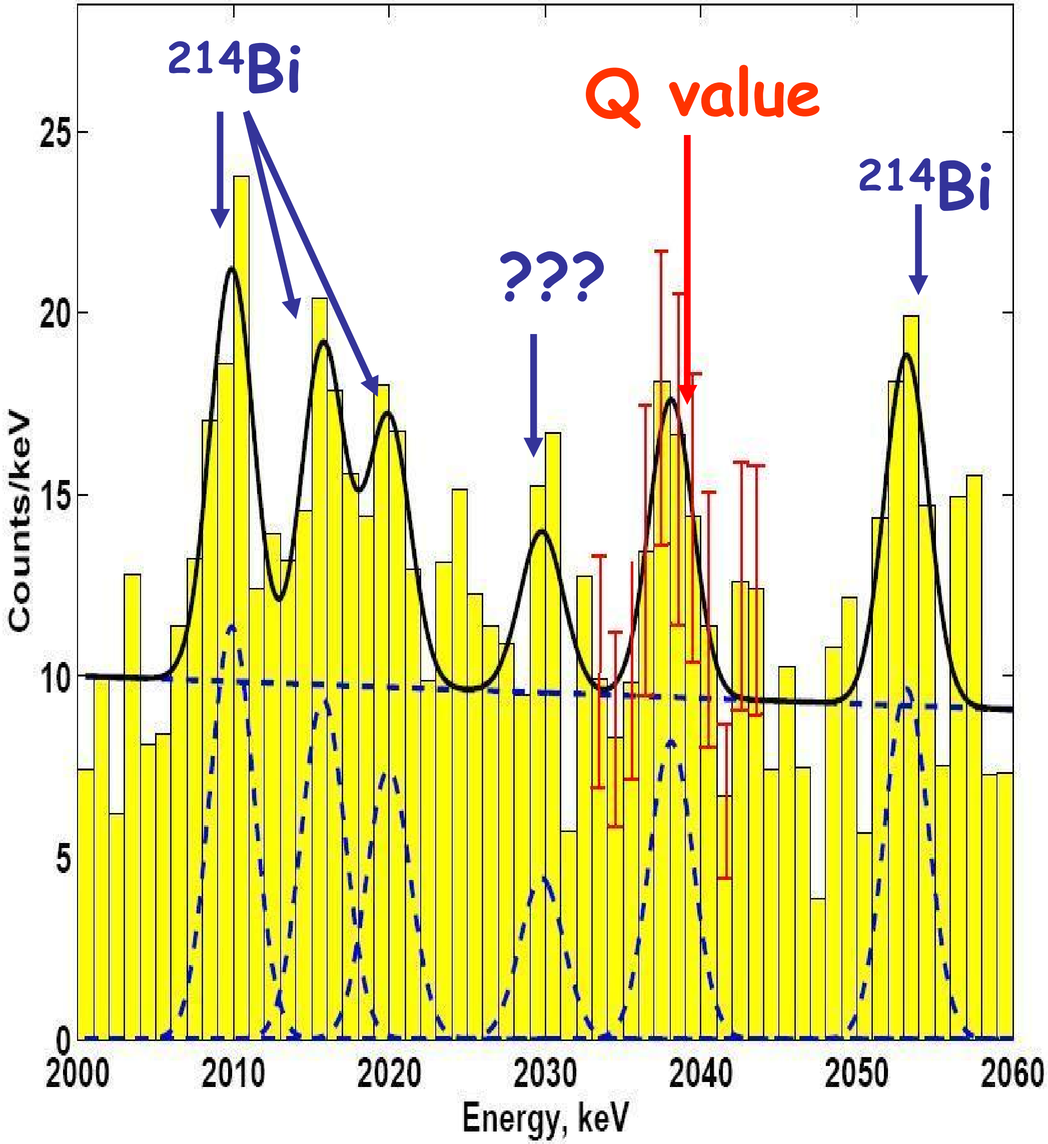
→ $0\nu\beta\beta$ decay always implies new physics

This is comforting for the ones of us spending their time building experiments!

Simplified List of Limits for ββ0ν decay

Candidate nucleus	Detector type	(kg yr)	Present $T_{1/2}^{0\nu\beta\beta}$ (yr)	<m> (eV)
^{48}Ca			$>5.8*10^{22}$ (90%CL)	
^{76}Ge	Ge diode	47.7	$>1.9*10^{25}$ (90%CL)	<0.35
^{82}Se			$>2.1*10^{23}$ (90%CL)	
^{96}Zr			$>9.2*10^{21}$ (90%CL)	
^{100}Mo	Foil.Geiger tubes		$>5.8*10^{23}$ (90%CL)	
^{116}Cd			$>1.7*10^{23}$ (90%CL)	
^{128}Te			$>1.1*10^{23}$ (90%CL)	
^{130}Te	TeO_2 cryo	~12	$>3*10^{24}$ (90%CL)	<0.19-0.68
^{136}Xe	~~Xe scint~~	~~~4.5~~	~~$>1.2*10^{24}$ (90%CL)~~	~~<1.1-2.9~~
	Xe TPC	32.3	$>1.6*10^{25}$ (90%CL)	<0.14-0.38
^{150}Nd			$>1.8*10^{22}$ (90%CL)	
^{160}Gd			$>1.3*10^{21}$ (90%CL)	

ββ0ν discovery claim



Fit model:
6 gaussians + linear bknd.

Fitted excess @ $Q_{\beta\beta}$
28.75 ± 6.86.

Claimed significance: 4.2 σ

$$T_{1/2} = 2.23^{+0.44}_{-0.31} \cdot 10^{24}\, yr$$

$$\langle m_\nu \rangle = 0.32 \pm 0.03\, eV$$

[H.V.Klapdor-Kleingrothaus and I.Krivosheina, Mod.Phys.Lett. A21 (2006) 1547]

However, this is a very controversial matter

See e.g. Strumia+Vissani Nucl Phys B726 (2005) 294

Need very large fiducial mass (tons) of isotopically separated material (except for ^{130}Te)

[using natural material typically means that 90% of the source produced background but not signal]

This is expensive and provides encouragement to use the material in the best possible way:

For no bkgnd $\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/\sqrt{Nt}$

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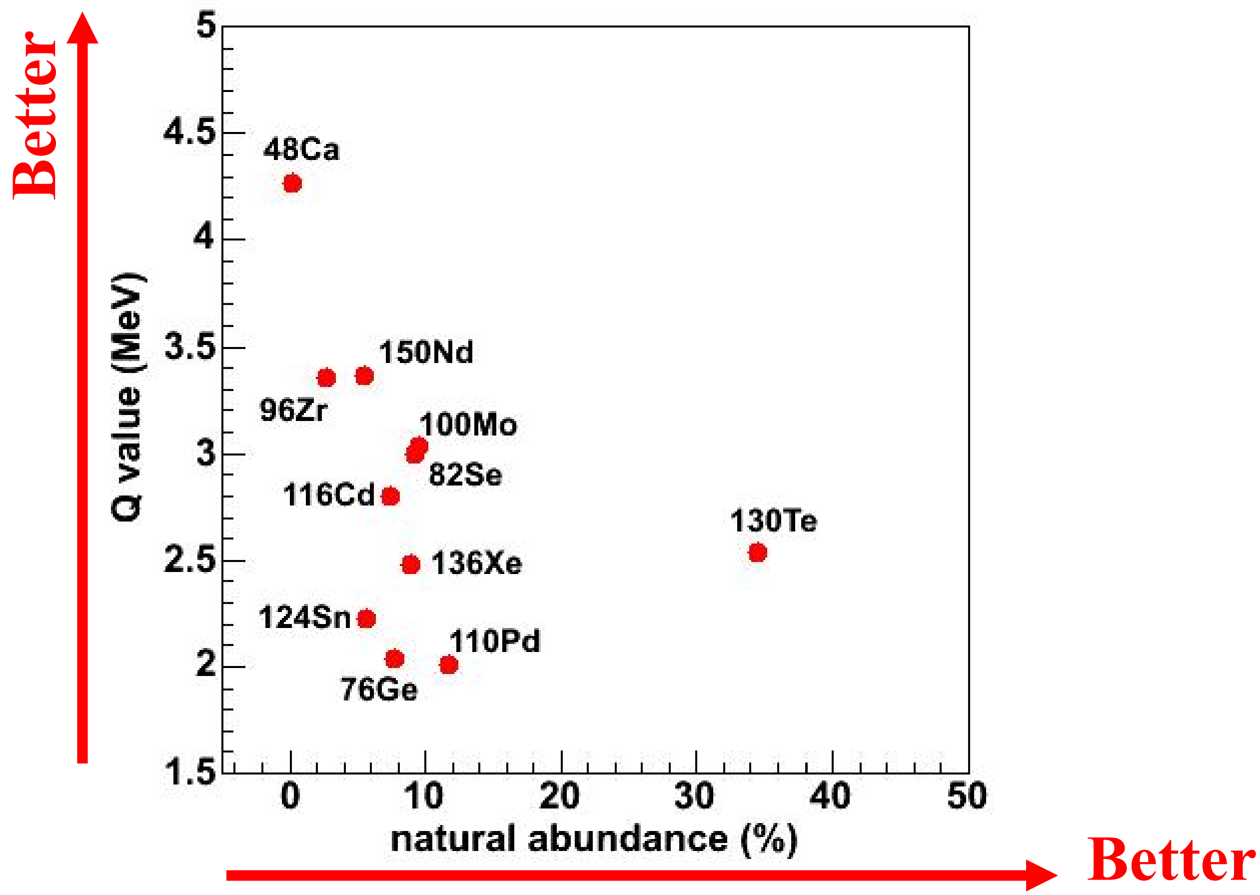
For statistical bkgnd subtraction $\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/(Nt)^{1/4}$

How to "organize" an experiment: the source



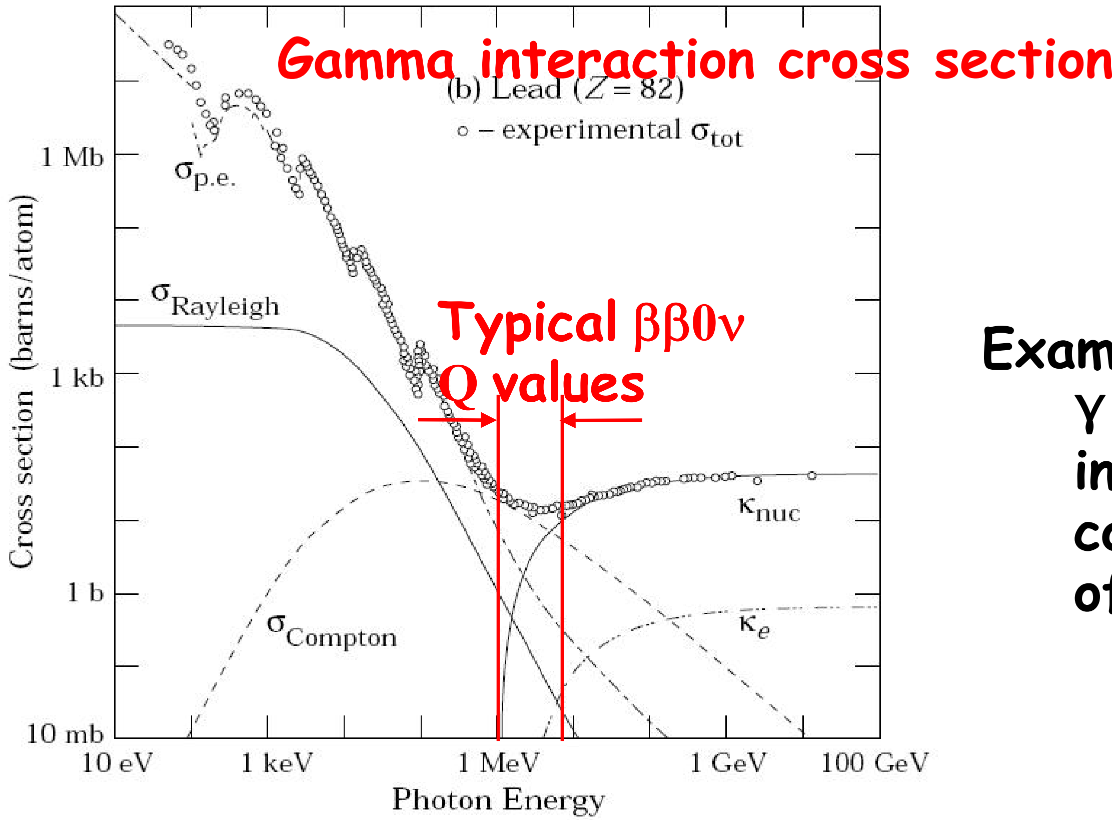
C.Hall SLAC Summer Institute 2010

- High Q value reduces backgrounds and increases the phase space & decay rate,
- Large abundance makes the experiment cheaper
- A number of isotopes have similar matrix element performance

How to "organize" an experiment: the technique

- Final state ID: 1) "Geochemical": search for an abnormal abundance of (A,Z+2) in a material containing (A,Z)
  2) "Radiochemical": store in a mine some material (A,Z) and after some time try to find (A,Z+2) in it
  + Very specific signature
  + Large live times (particularly for 1)
  + Large masses
  - Possible only for a few isotopes (in the case of 1)
  - No distinction between 0ν, 2ν or other modes
- "Real time": ionization or scintillation is detected in the decay
  a) "Homogeneous": source=detector
  b) "Heterogeneous": source≠detector
  + Energy/some tracking available (can distinguish modes)
  + In principle universal (b)
  - Many γ backgrounds can fake signature
  - Exposure is limited by human patience

Shielding a detector from gammas is difficult because the absorption cross section is small.

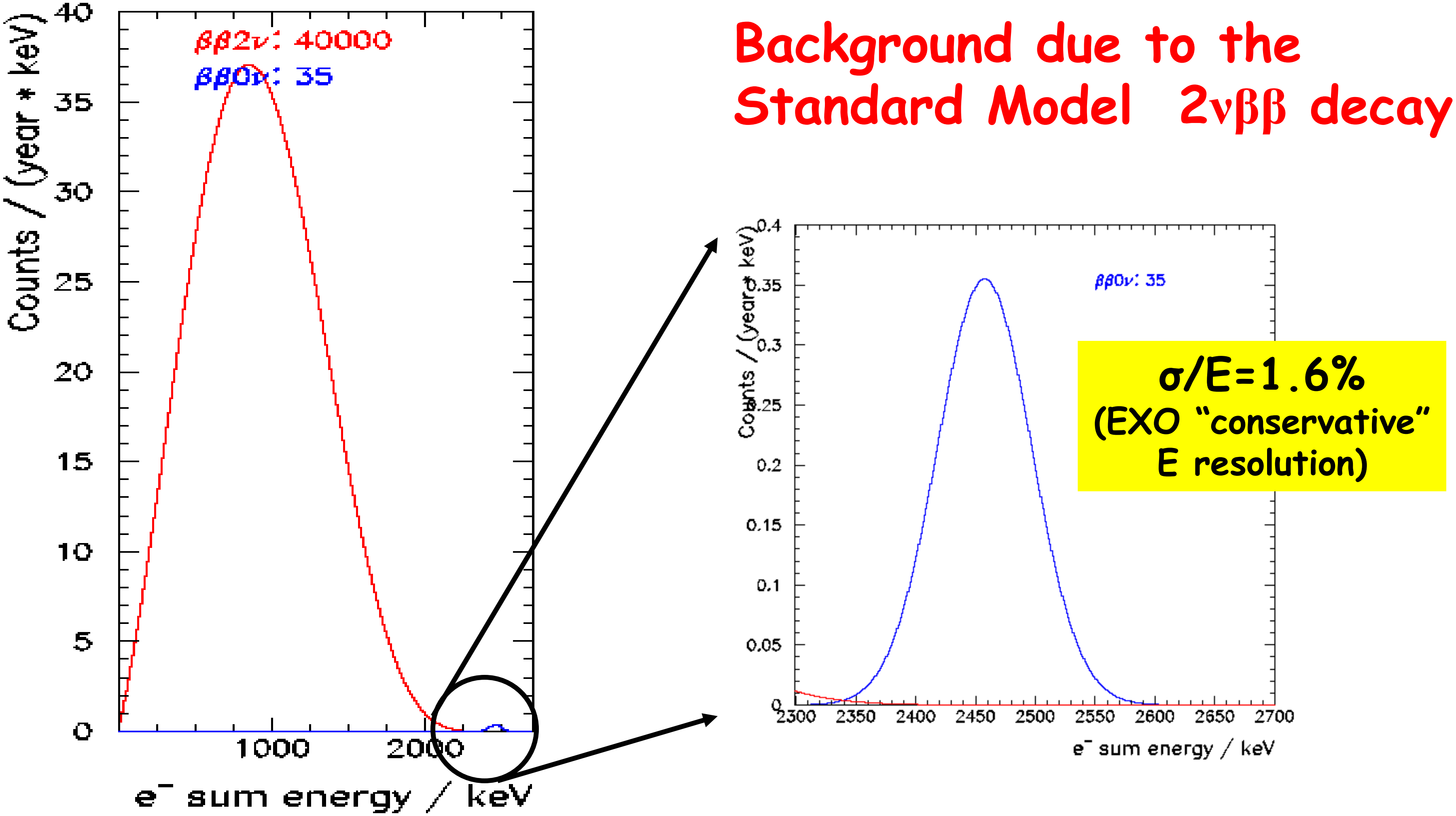


Example:

γ interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector.

Shielding ββ decay detectors is much harder than shielding Dark Matter ones

We are entering the "golden era" of ββ decay experiments as detector sizes exceed int lengths



Background due to the Standard Model $2\nu\beta\beta$ decay

The two can be separated in a detector with sufficiently good energy resolution

Topology and particle ID are also important to recognize backgrounds

Some experiments in preparation
(~approved or under construction, in addition a number of R&D efforts)

Isotope	Experiment	Main principle	Fid mass	Status	Lab
^{76}Ge	Majorana†	Eres,2site tag, Cu shield	30-60kg	Construction	SUSEL
	Gerda†	Eres,2site tag, LAr shield	34.3 kg	Data taking	G Sasso
	MaGe/GeMa	See above	~1ton	Planning	?
^{150}Nd	SNO+	Size/shielding	44 kg	Construction	SNOlab
^{82}Se	SuperNEMO‡	Tracking	100 kg	Planning	Canfranc Frejus
$^{130}Te^{*}$	CUORE	E Res.	204 kg	Construction	G Sasso
^{136}Xe	KamLAND-Zen	Size/shielding	400 kg	Data taking	Kamioka
^{136}Xe	EXO	Tracking/Eres	150 kg	Data taking	WIPP
		Ba tag, Track/Eres	1-10ton	Planning	SNOlab?

* No isotopic enrichment in baseline design
† Plan to merge efforts for ton-scale experiment
‡ Non-homogeneous detector

It is very important to understand that a healthy neutrinoless double-beta decay program requires more than one isotope. This is because:

- *There could be unknown gamma transitions and a line observed at the "end point" in one isotope does not necessarily imply that $0\nu\beta\beta$ decay was discovered*
- *Nuclear matrix elements are not very well known and any given isotope could come with unknown liabilities*
- *Different isotopes correspond to vastly different experimental techniques*
- *2 neutrino background is different for various isotopes*
- *The elucidation of the mechanism producing the decay requires the analysis of more than one isotope*

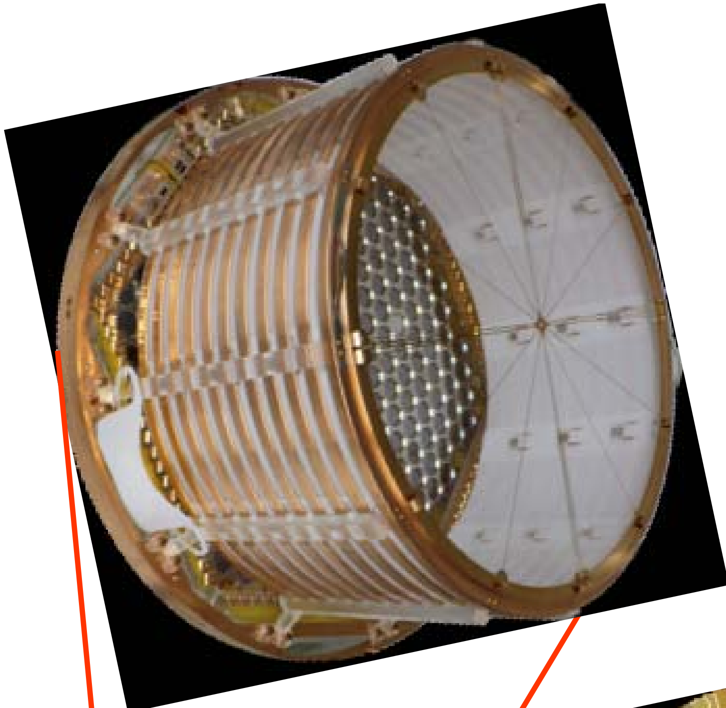
Xe is ideal for a large experiment

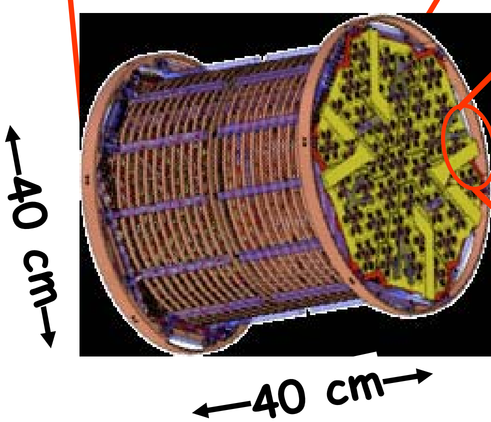
- No need to grow crystals
- Can be re-purified during the experiment
- No long lived Xe isotopes to activate
- Can be easily transferred from one detector to another if new technologies become available
- Noble gas: easy(er) to purify
- ^{136}Xe enrichment easier and safer:
  - noble gas (no chemistry involved)
  - centrifuge feed rate in gram/s, all mass useful
  - centrifuge efficiency ~ Δm. For Xe 4.7 amu
- Only known case where final state identification appears to be not impossible
  → elominate all non-ββ backgrounds
- ^{129}Xe is a hyperpolarizable nucleus, under study for NMR tomography… a joint enrichment program ?

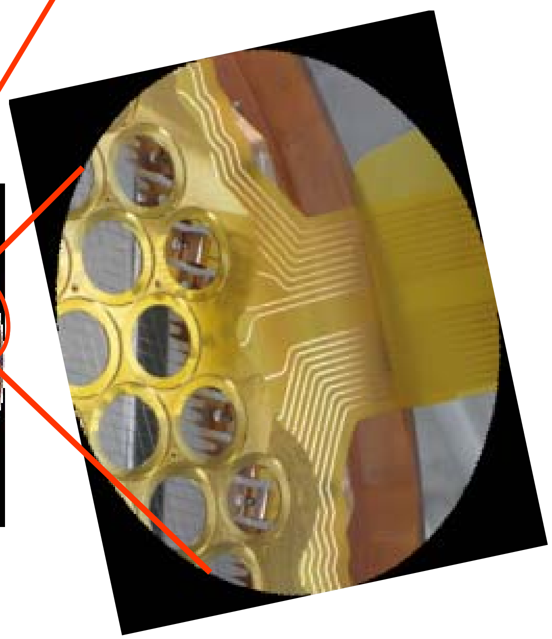
The EXO-200 TPC

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

- 38 U triplet wire channels (charge)
- 38 V triplet wire channels, at 60° (induction)
- 234 large Avalanche PhotoDiodes (in gangs of 7)
- Triplet pitch 9 mm
- Wire planes 6 mm apart and 6 mm from APDs
- Signals digitized at 1 MS/s, ±1024s around trigger
- Drift field 376 V/cm

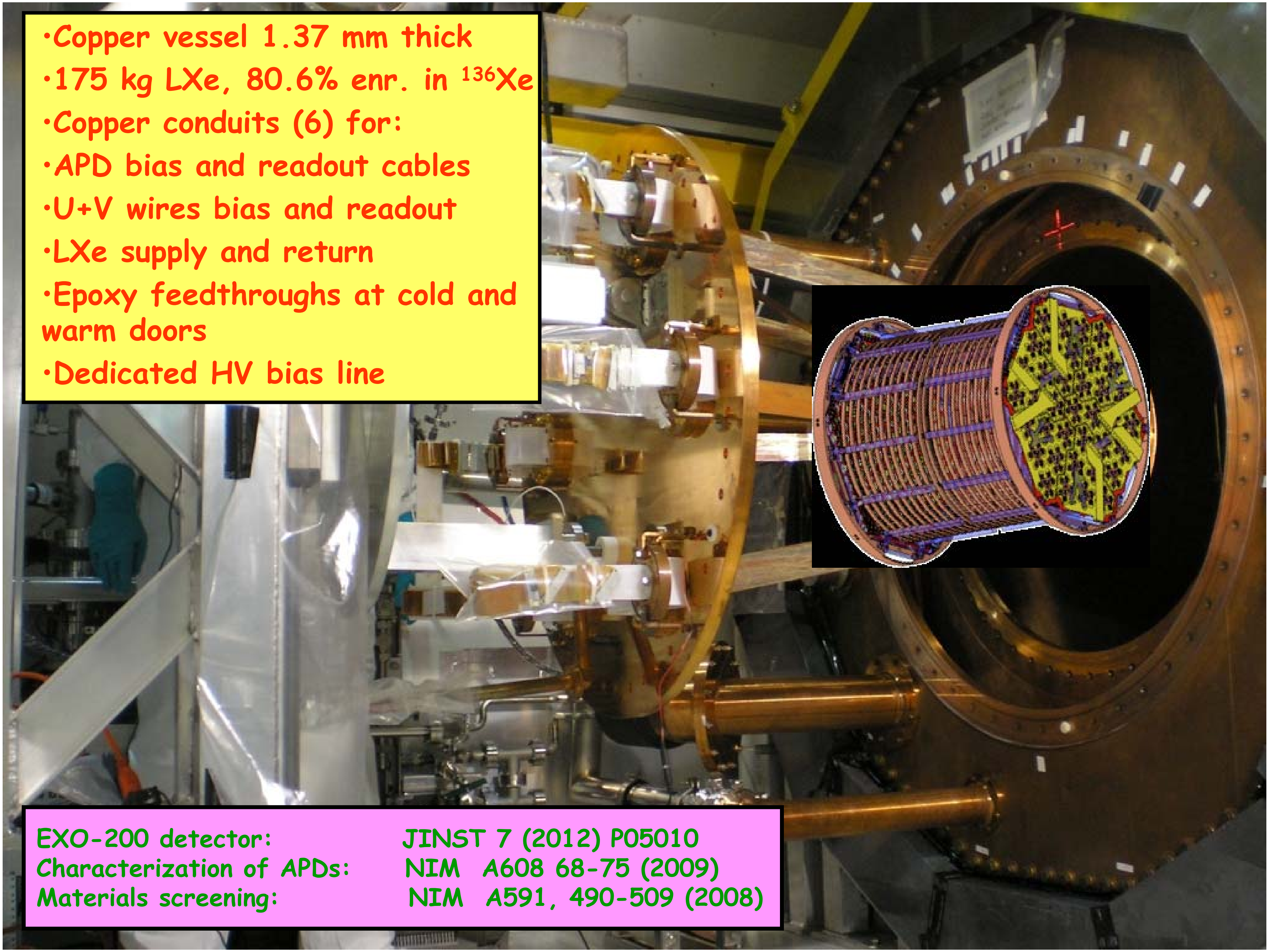






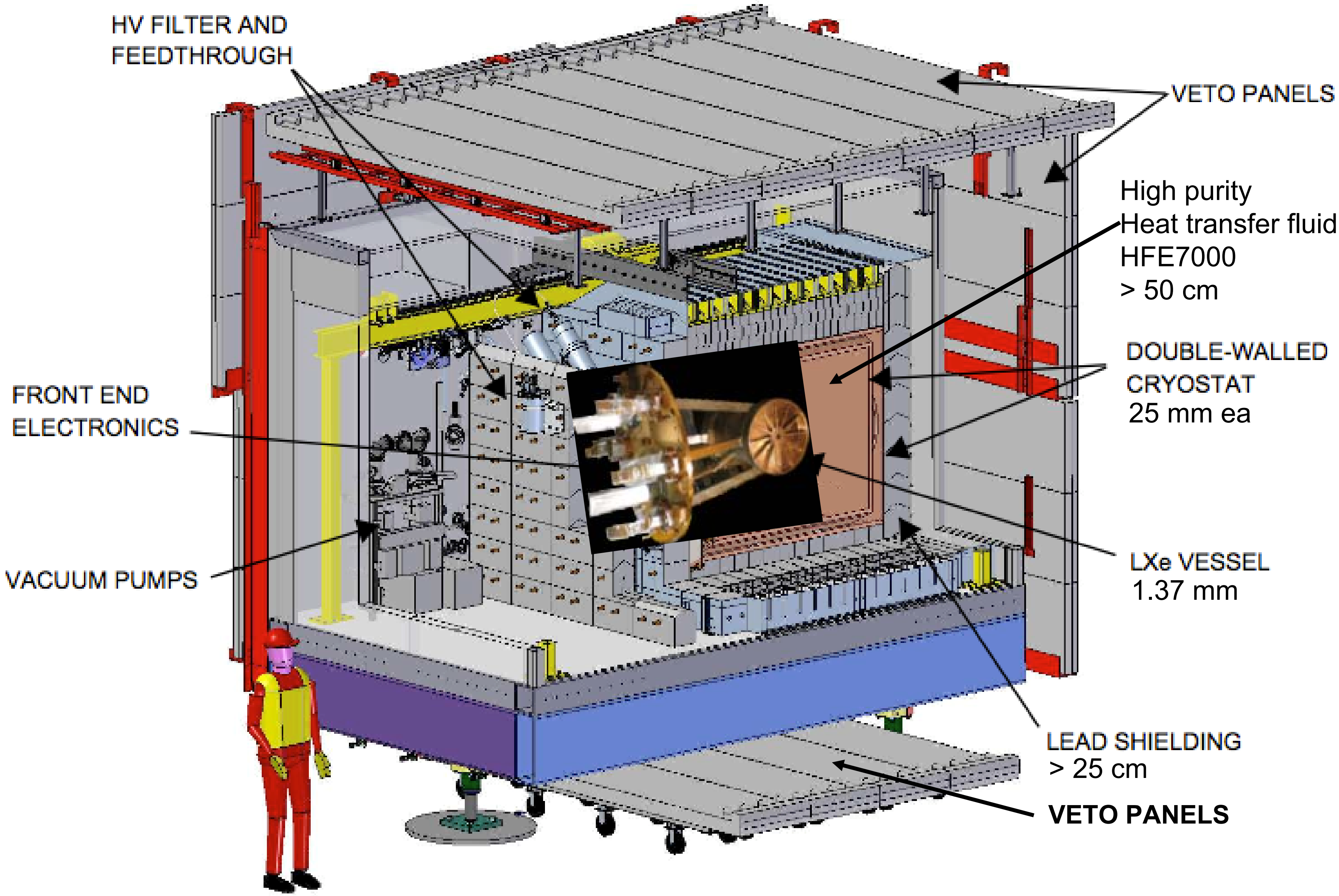
- Field shaping rings: copper
- Supports: acrylic
- Light reflectors/diffusers: Teflon
- APD support plane: copper; Au (Al) coated for contact (light reflection)
- Central cathode, U+V wires: photo-etched phosphor bronze
- Flex cables for bias/readout: copper on kapton, no glue
- Vast material screening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

→ Goal: 40 cnts/2y in $0\nu\beta\beta$ ±2σ ROI, 140 kg LXe



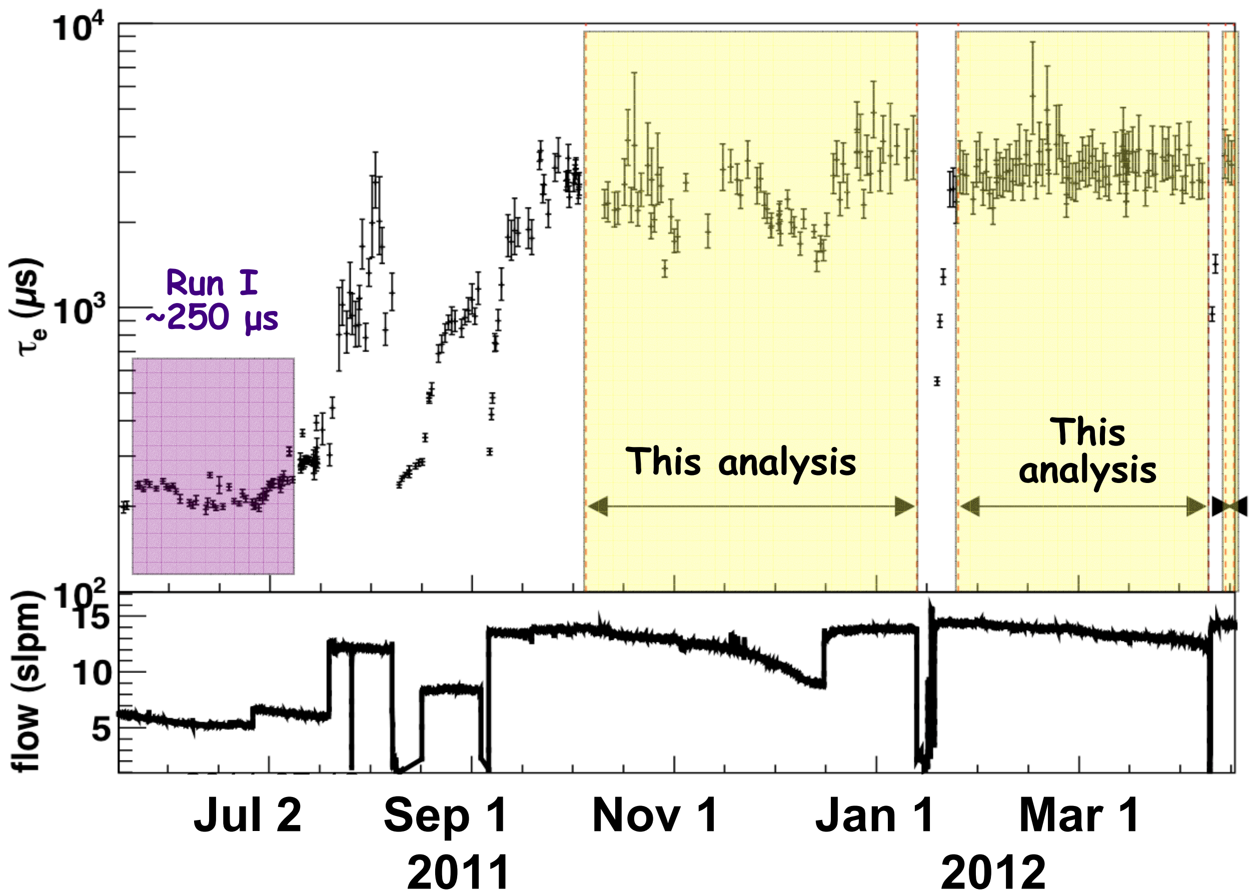
•Copper vessel 1.37 mm thick
•175 kg LXe, 80.6% enr. in ^{136}Xe
•Copper conduits (6) for:
•APD bias and readout cables
•U+V wires bias and readout
•LXe supply and return
•Epoxy feedthroughs at cold and warm doors
•Dedicated HV bias line
EXO-200 detector: JINST 7 (2012) P05010
Characterization of APDs: NIM A608 68-75 (2009)
Materials screening: NIM A591, 490-509 (2008)

The EXO-200 Detector



Data taking phases and Xenon Purity

	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	arXiv:1205:5608 (May 2012)



Xenon gas is forced through heated Zr getter by a custom ultraclean pump.

Electron lifetime τ_e:
→ measure ionization signal attenuation as a function of drift time for the full-absorption peak of γ ray sources

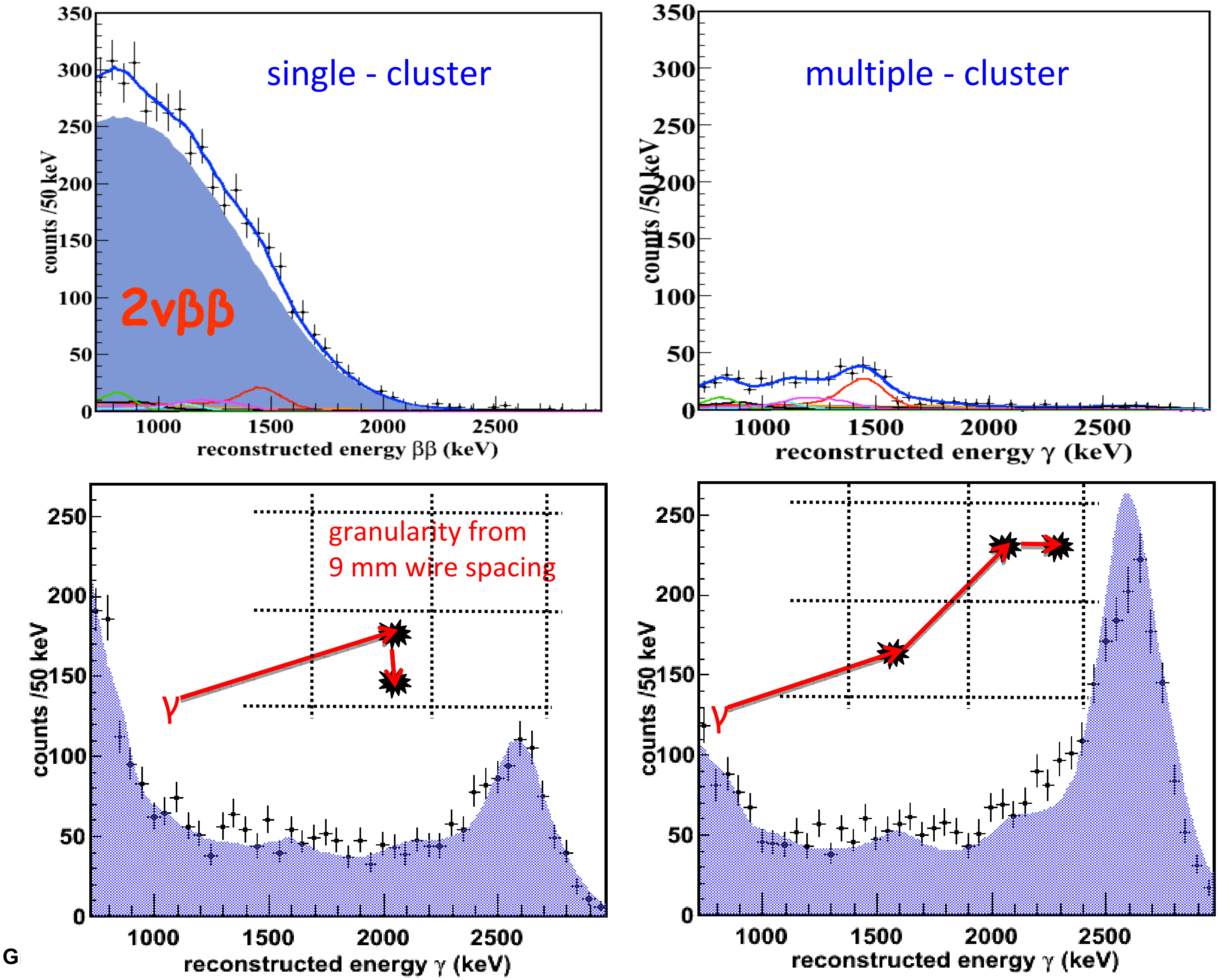
At τ_e = 3 ms:
- drift time <110 μs
- loss of charge: 3.6% at full drift length

Ultraclean pump:
Rev Sci Instr. 82 (10) 105114
Xenon purity with mass spec:
NIM A675 (2012) 40
Gas purity monitors:
NIM A659 (2011) 215

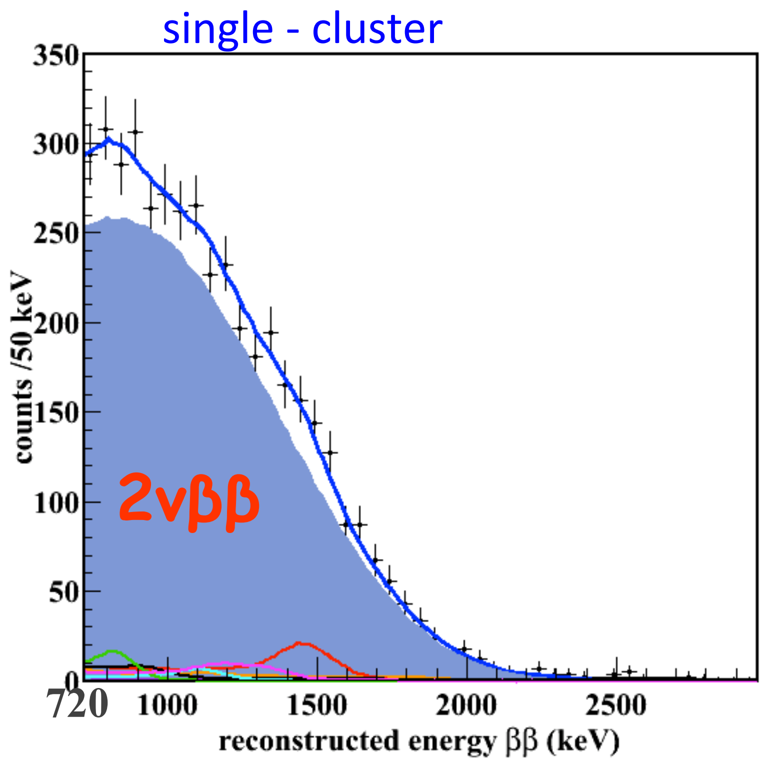
Pattern recognition can be a very powerful tool against background

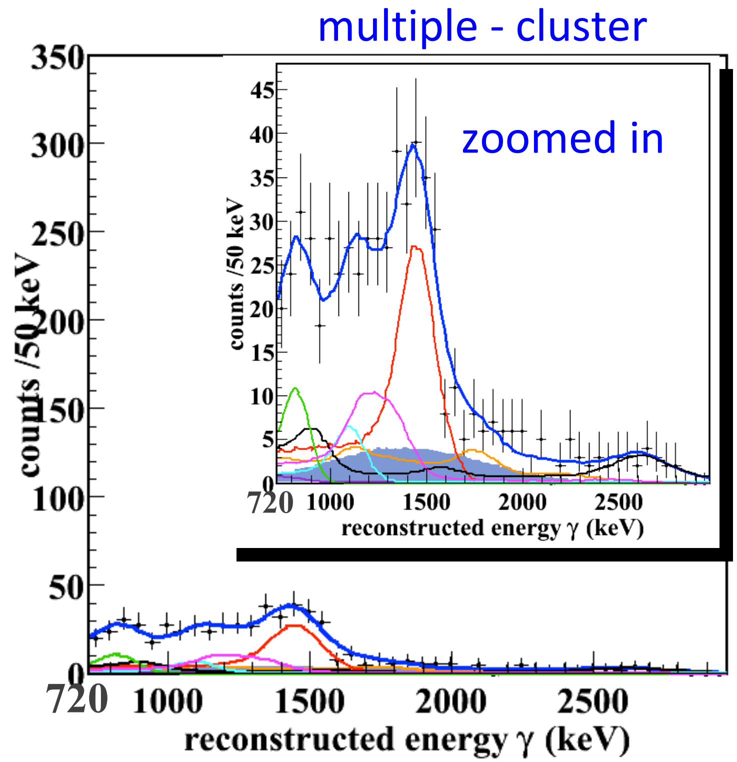
Low background data

^{228}Th calibration source



First observation of the 2νββ decay in ^{136}Xe

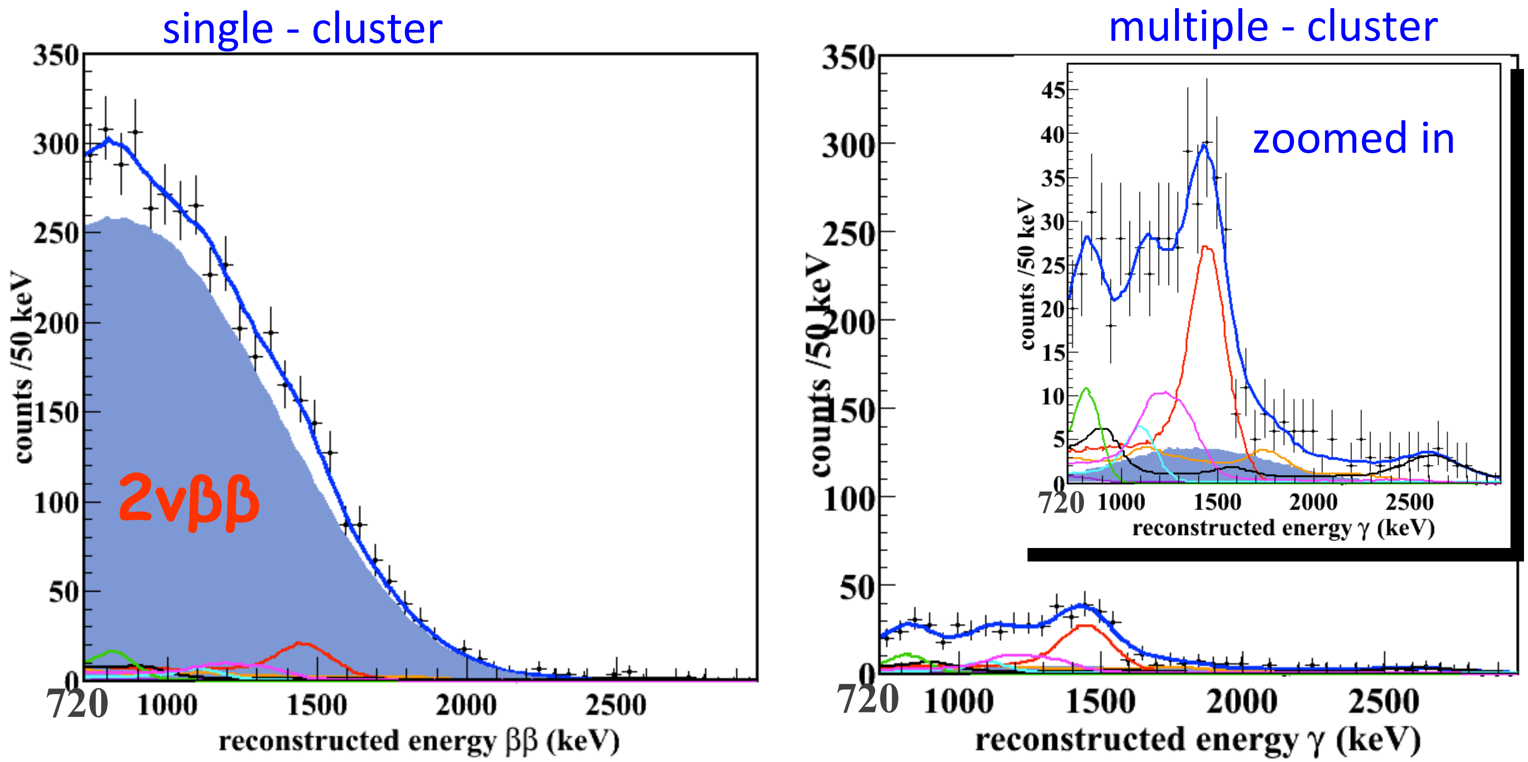




$T_{1/2}$ = (2.11 ± 0.04 stat ± 0.21 sys) · 10^{21} yr

[Ackerman et al Phys Rev Lett 107 (2001) 212501]

First observation of the 2νββ decay in ^{136}Xe



$T_{1/2}$ = (2.11 ± 0.04 stat ± 0.21 sys) · 10^{21} yr

[Ackerman et al Phys Rev Lett 107 (2001) 212501]

In significant disagreement with previous limits:

$T_{1/2}$ > 1.0·10^{22} yr (90% C.L.) (R. Bernabei *et al.* Phys. Lett. B 546 (2002) 23)

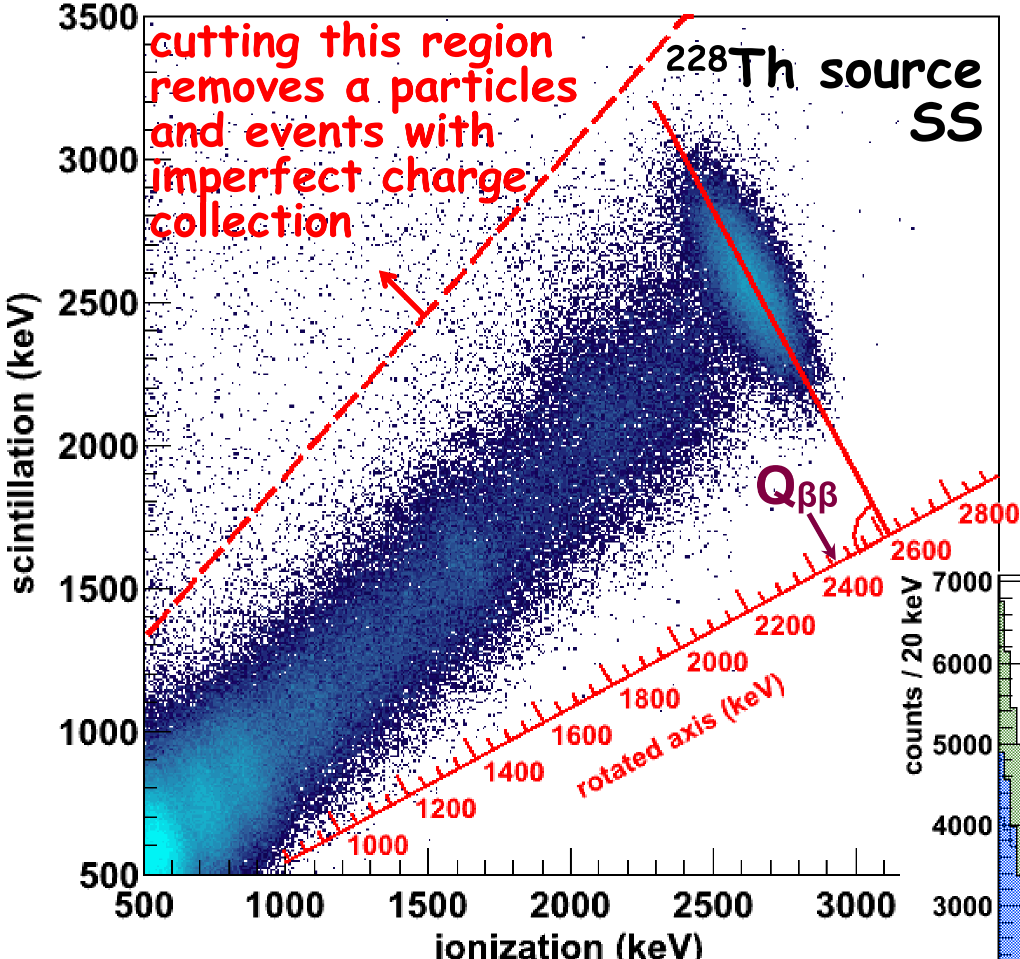
$T_{1/2}$ > 8.5·10^{21} yr (90% C.L.) (Yu. M. Gavriljuk *et al.*, Phys. Atom. Nucl. 69 (2006) 2129)

Later confirmed by KamLAND-ZEN

$T_{1/2}$=(2.38 ± 0.02stat ± 0.14sys)·10^{21} yr

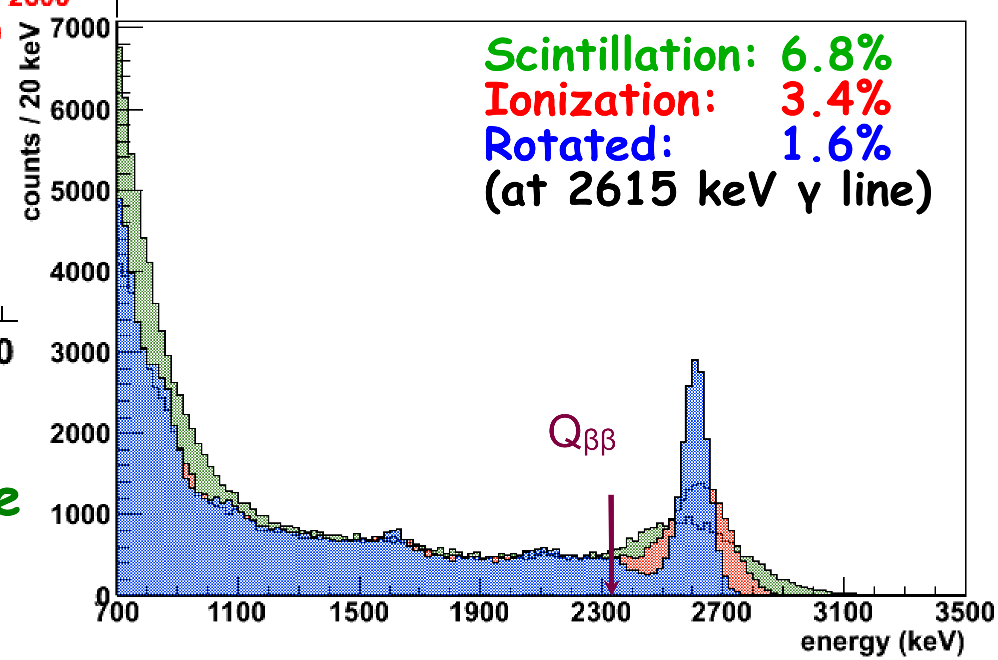
[A.Gando et al. Phys Rev C 85 (2012) 045504]

Combining Ionization and Scintillation



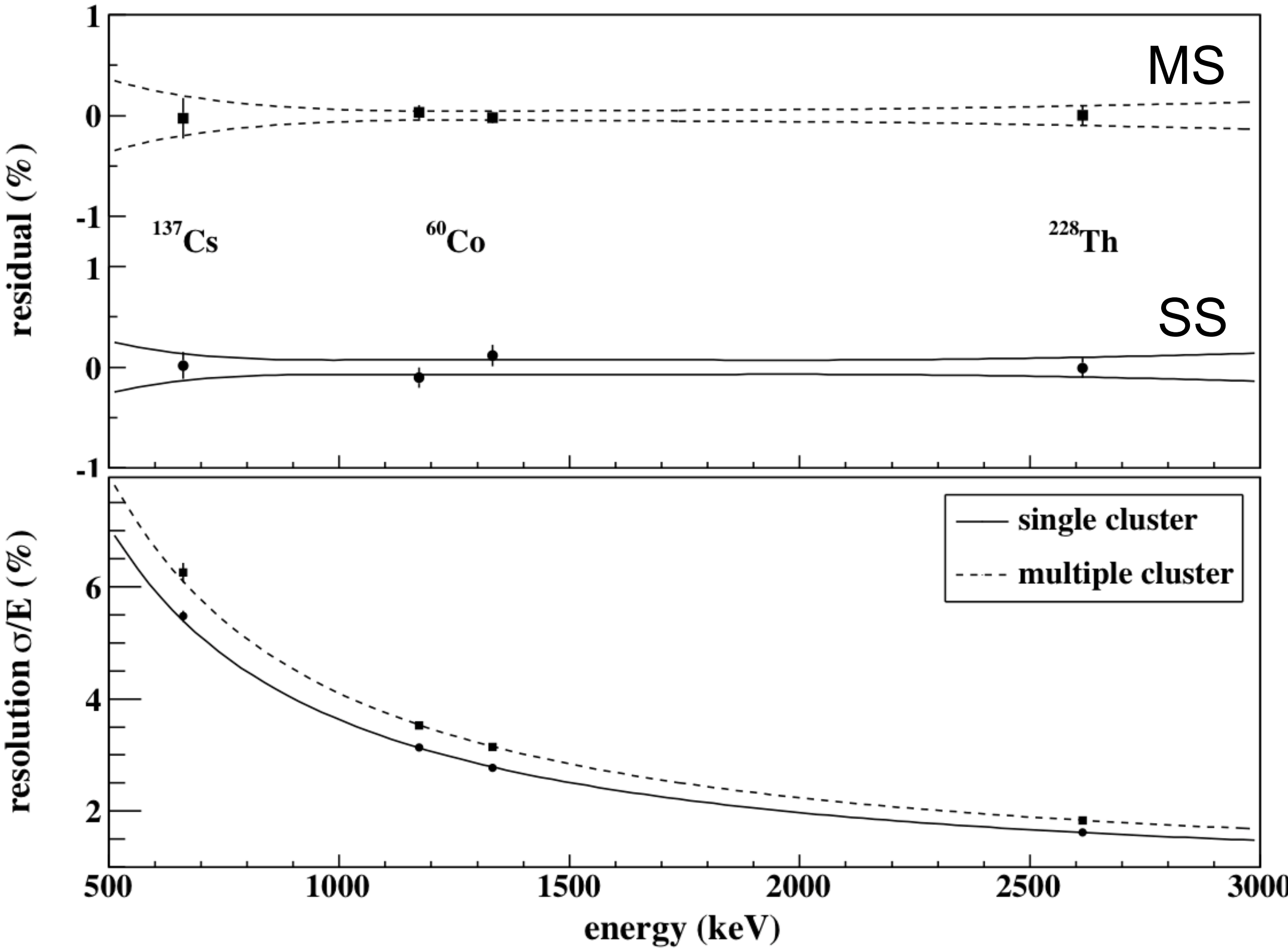
Anticorrelation between scintillation and ionization in LXe known since EXO R&D

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



Rotation angle chosen to optimize energy resolution at 2615 keV

Energy Calibration



Energy resolution model:

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

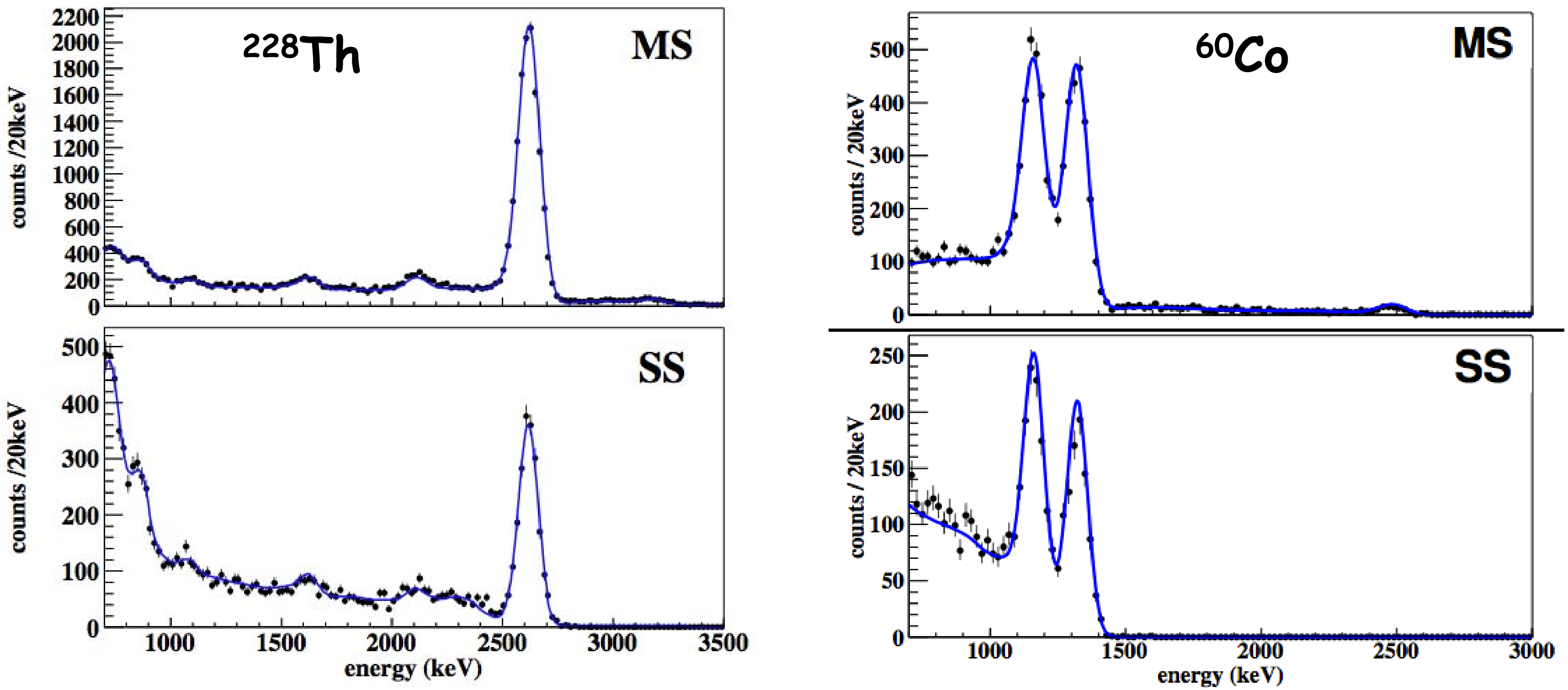
Residuals <0.1%

Resolution dominated by constant (noise) term p_1

At $Q_{\beta\beta}$ (2458 keV):

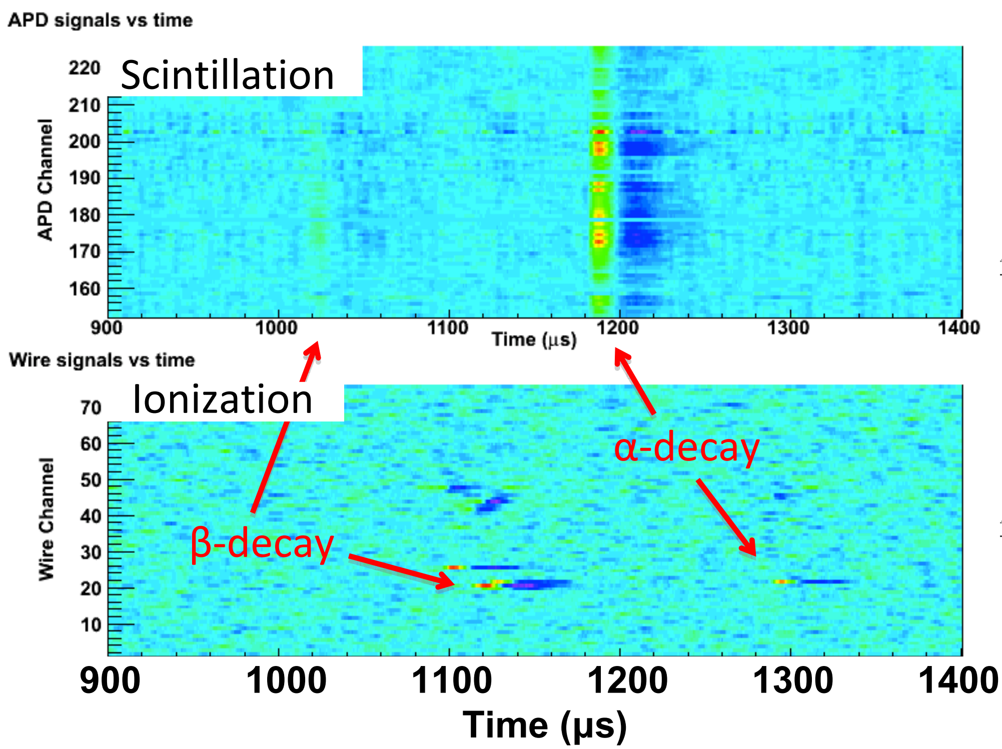
σ/E = 1.67 % (SS)
σ/E = 1.84 % (MS)

Source Data/MC Agreement

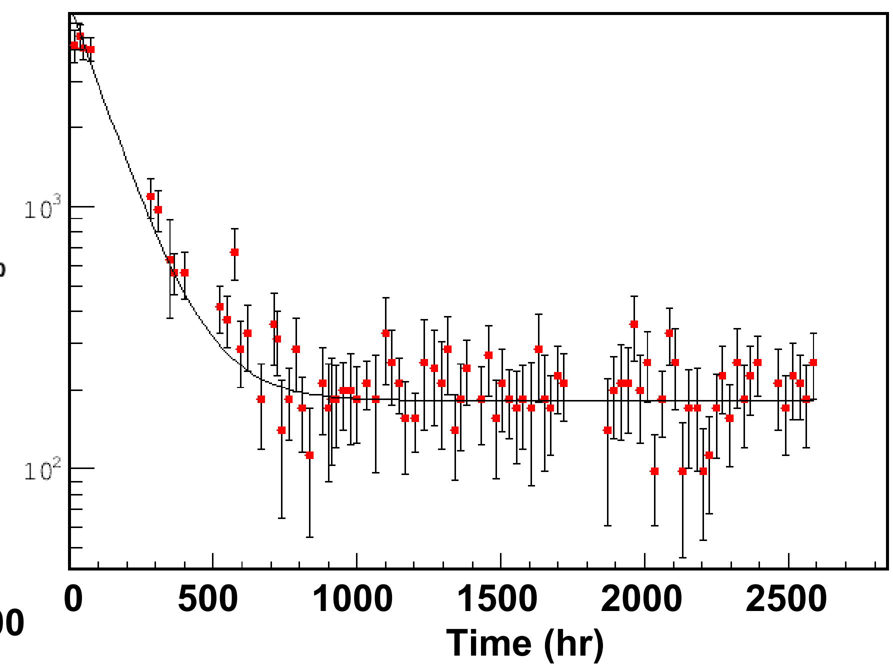


- Single site fraction agrees to within 8.5%
- Source activities measured to within 9.4%

Rn Content in Xenon



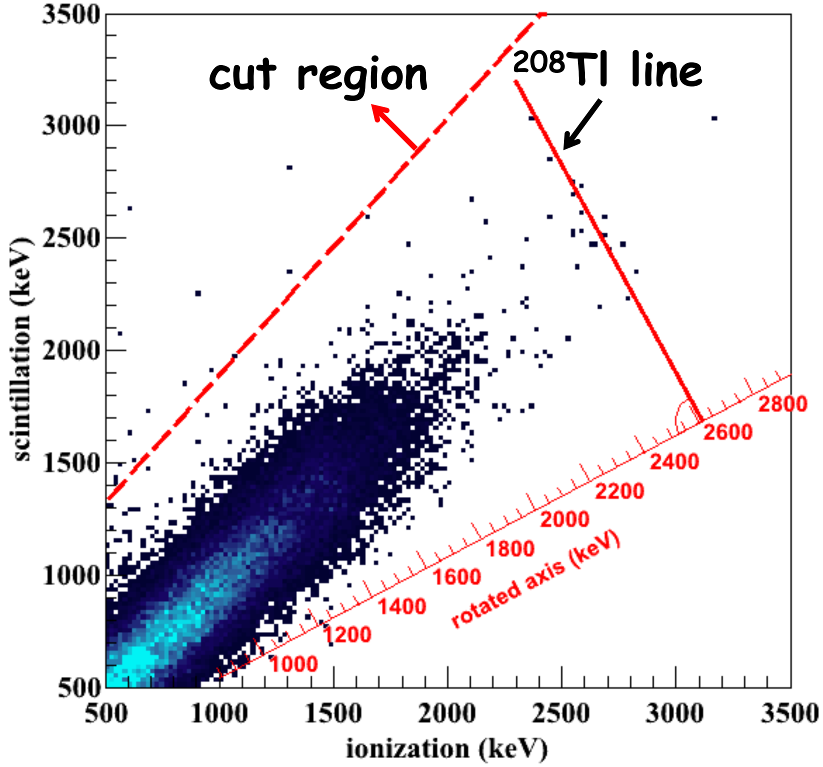
^{214}Bi – ^{214}Po correlations in the EXO-200 detector

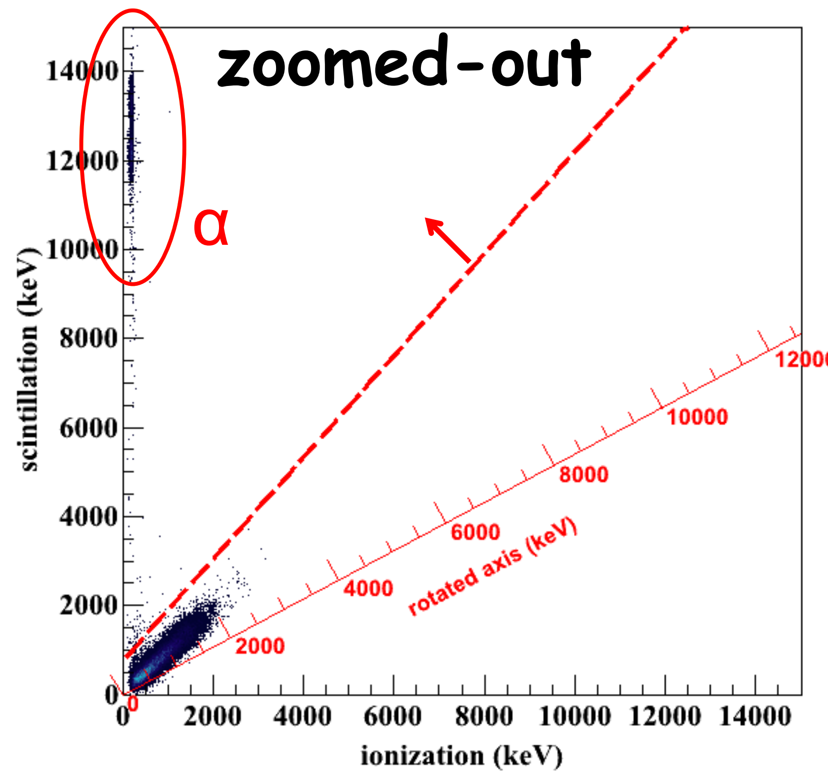


Total ^{222}Rn in LXe after initial fill

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

Low Background 2D SS Spectrum

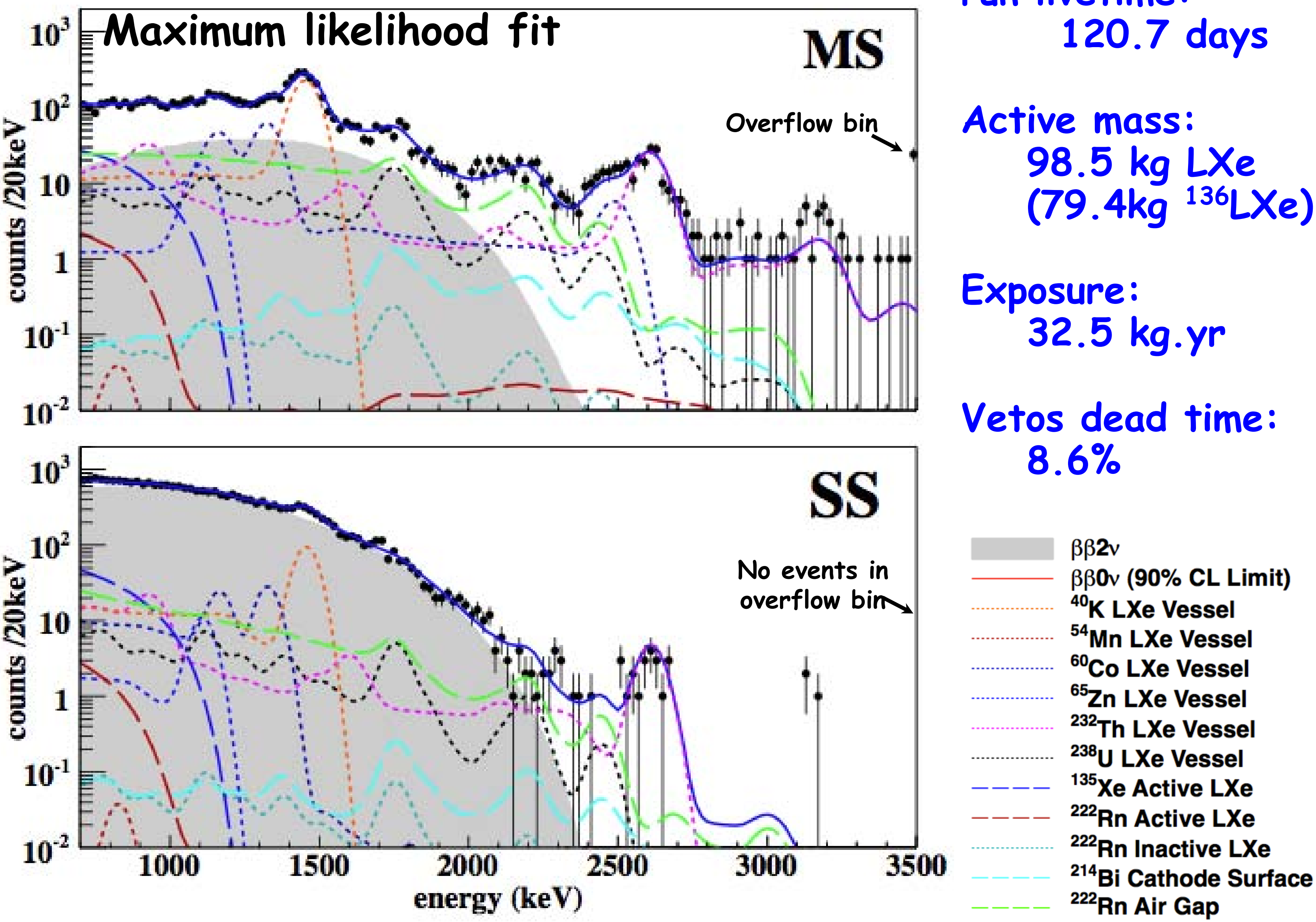




Events removed by diagonal cut:

- α (larger ionization density → more recombination → more scintillation light)
- events near detector edge → not all charge is collected

Low Background Spectrum

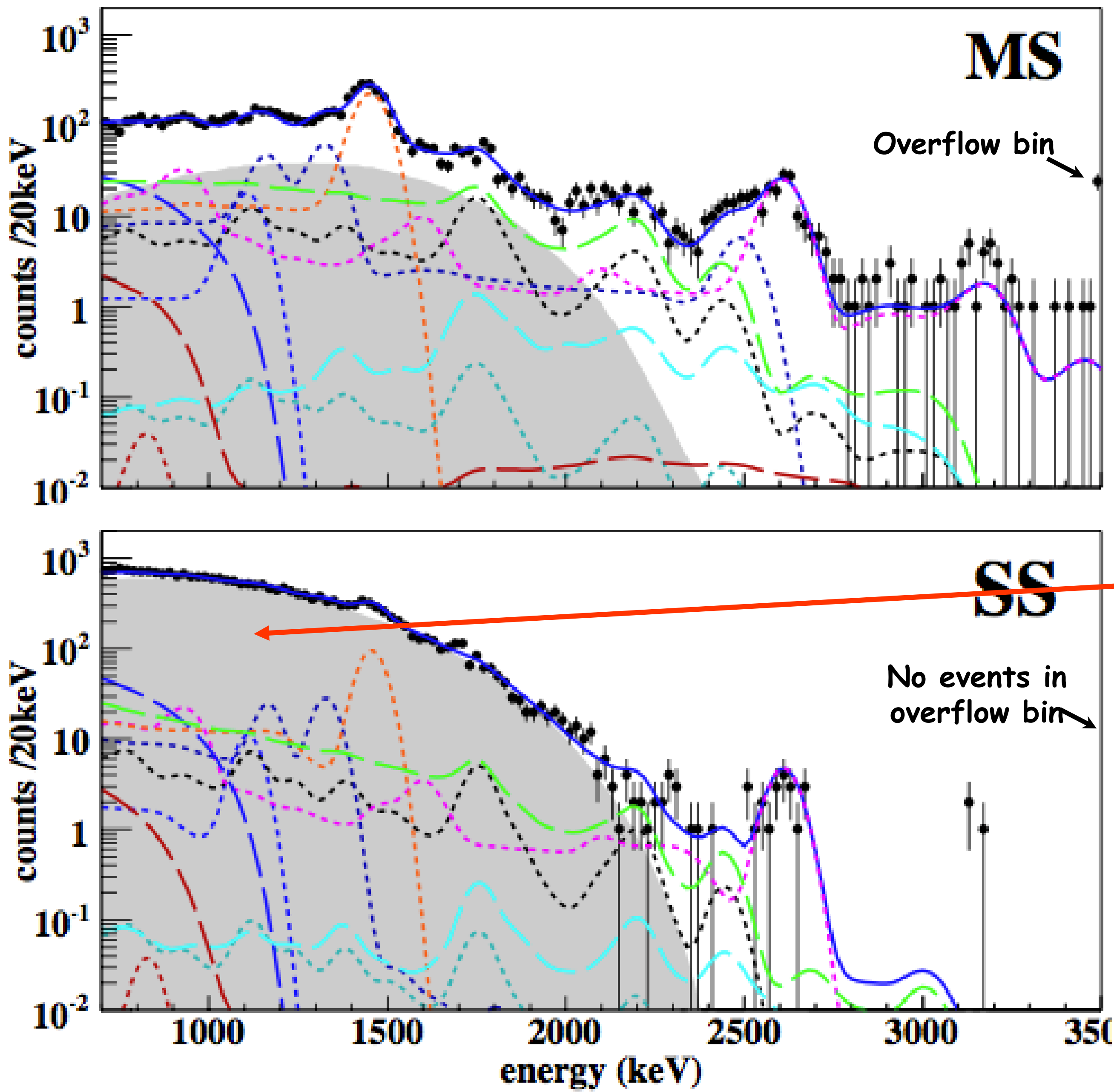


Low background run livetime:
120.7 days

Active mass:
98.5 kg LXe
(79.4kg ^{136}LXe)

Exposure:
32.5 kg.yr

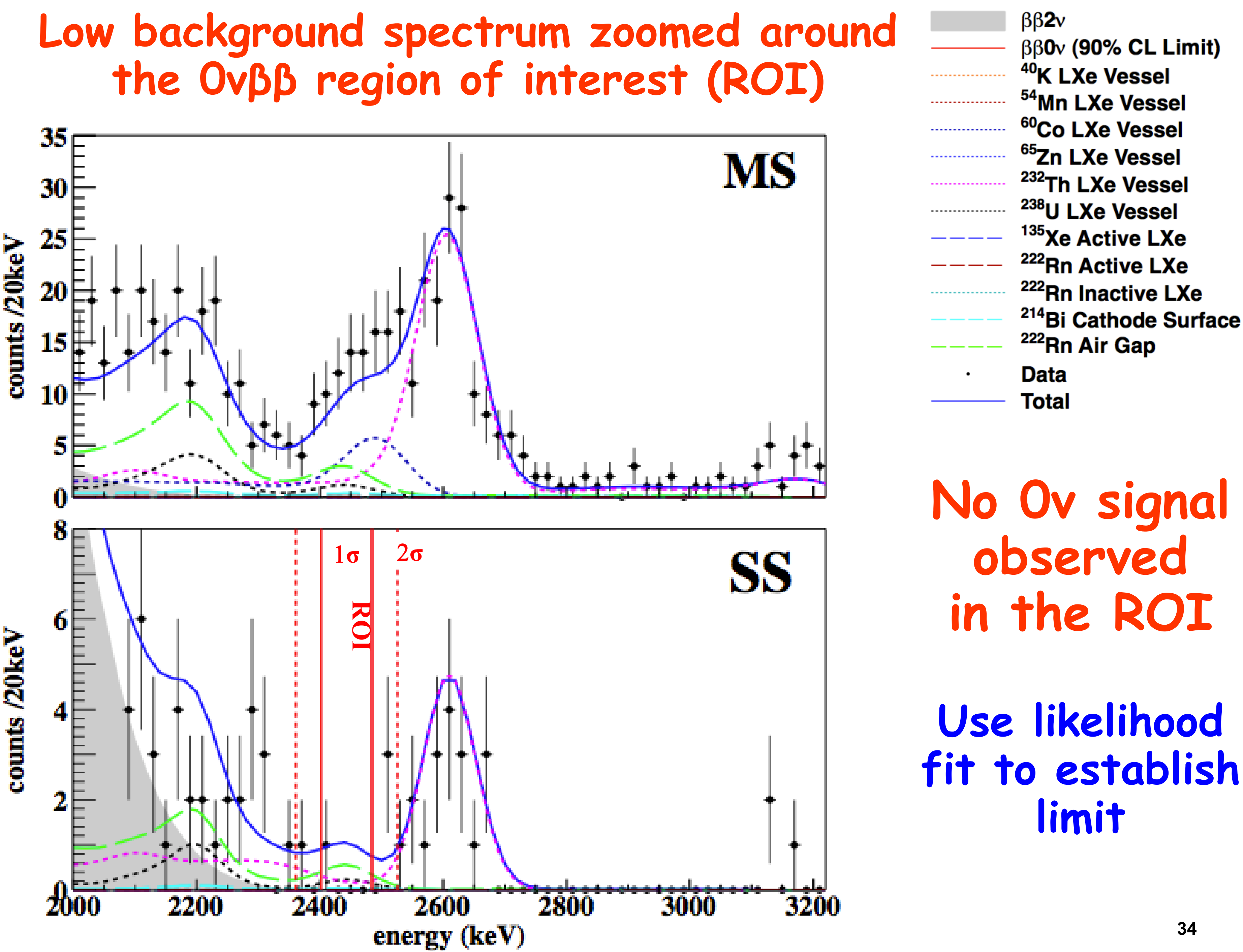
Vetos dead time:
8.6%



~22,000 2νββ events !

This is a mode that until Aug 2011 we did not know existed!

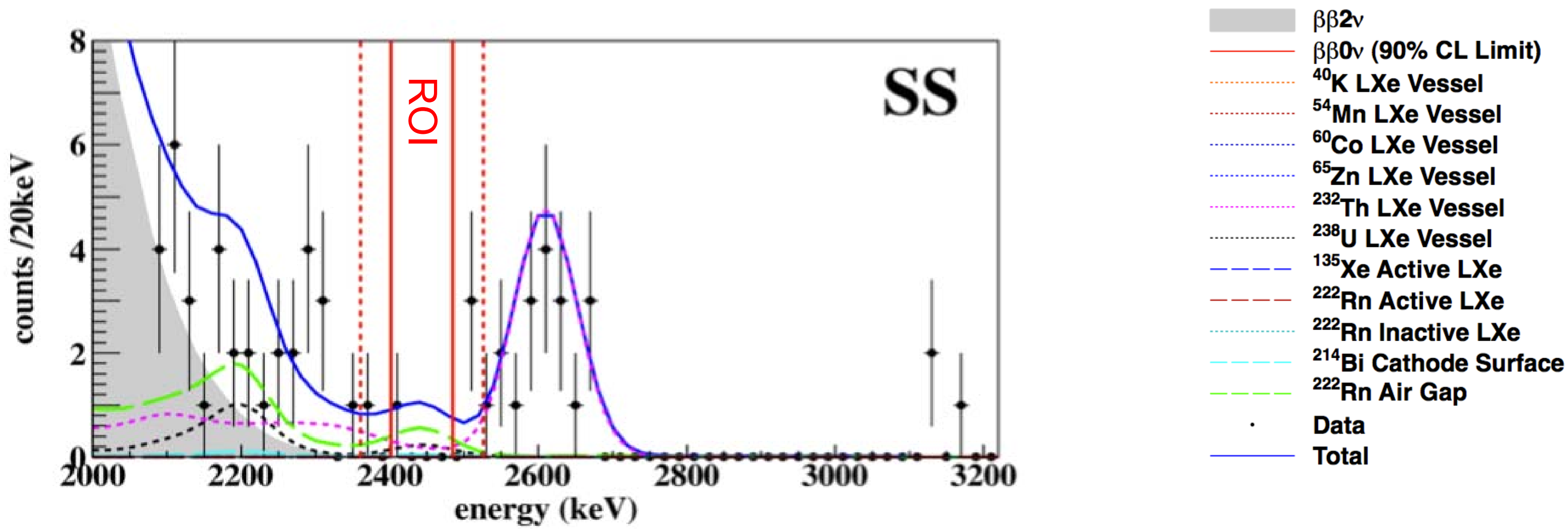
Low background spectrum zoomed around the 0νββ region of interest (ROI)



No 0ν signal observed in the ROI

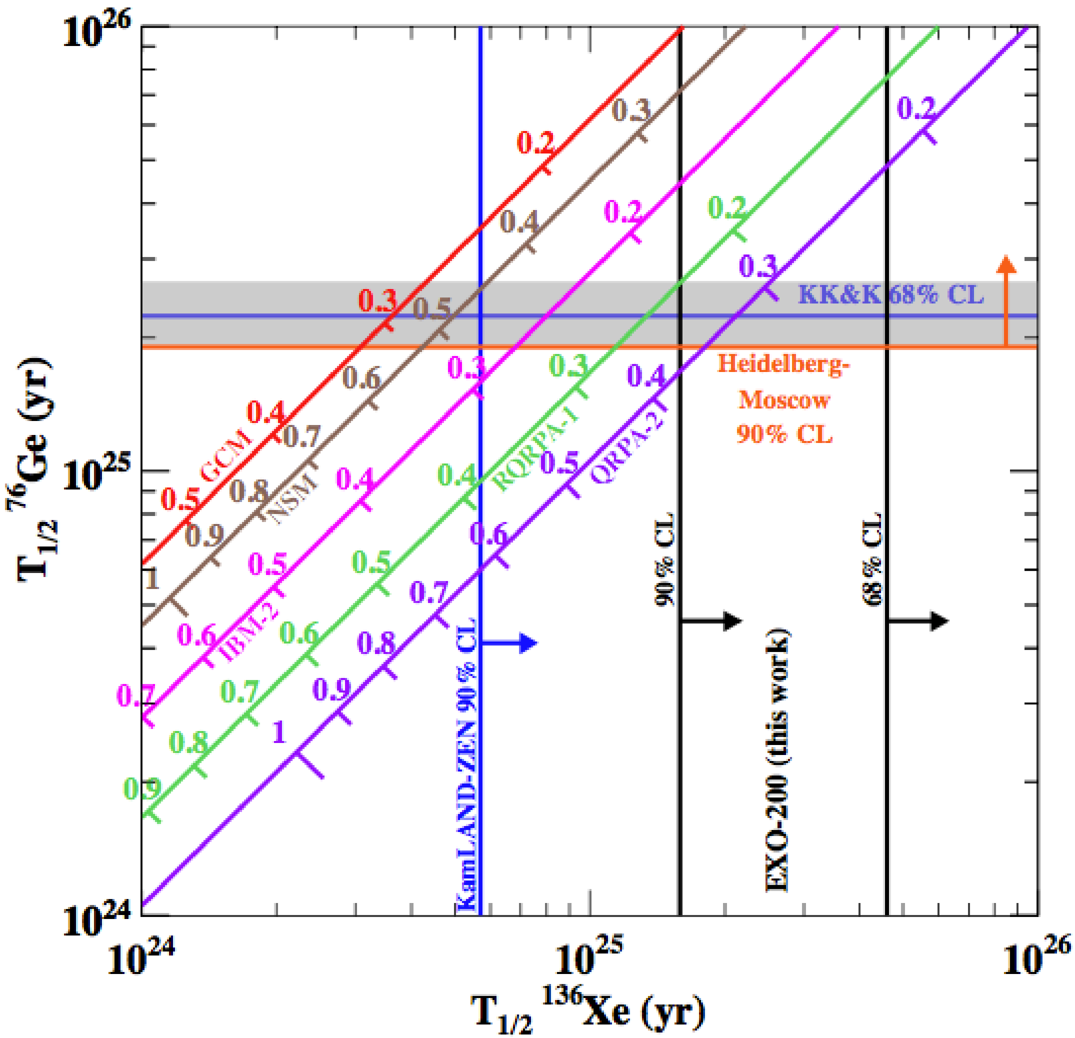
Use likelihood fit to establish limit

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

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



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.)

arXiv:1205.5608
(subm. to PRL)

Summary

- Several new experiments started taking data in the last year
- As usual, new experiments are much more powerful than the previous generation
- Expect rapid progress for the next few years
- Stay tuned for more results!

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, J-L. Vuilleumier, M. Weber

CALTECH, Pasadena CA, USA
P. Vogel

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

Colorado State U., Fort Collins CO, USA
S. Alton, C. Benitez-Medina, C. Chambers, Adam Craycraft, S. Cook, W. Fairbank, Jr., K. Hall, N. Kaufold, T. Walton

University of Illinois, UC, USA
D. Beck, J. Walton, L. Yang

Indiana University, Bloomington IN, USA
T. Johnson, L.J. Kaufman

University of California, 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 U, Sudbury ON, Canada
E. Beauchamp, D. Chauhan, B. Cleveland, J. Farine, B. Mong, U. Wichoski

U of Maryland, College Park MD, USA
C. Davis, A. Dobi, C. Hall, S. Slutsky, Y-R. Yen

U of Massachusetts, Amherst MA, USA
T. Daniels, S. Johnston, K. Kumar, A. Pocar, J.D. Wright

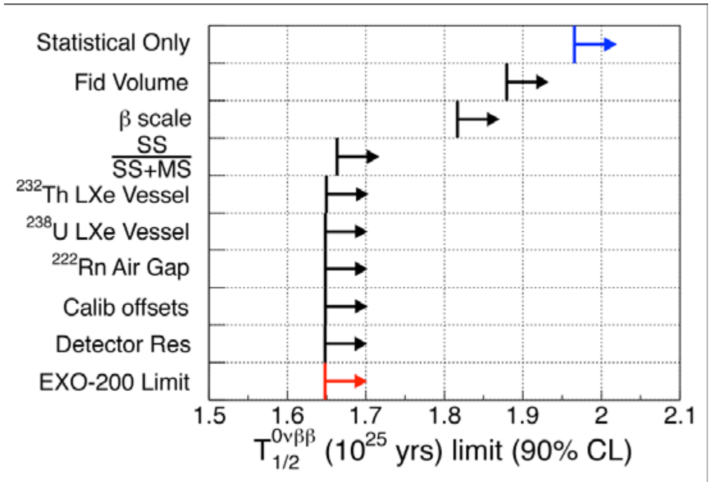
University of Seoul, South Korea D. Leonard

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-Díez, A.R. Müller, R. Neilson, I. Ostrovskiy, K. O'Sullivan, A. Rivas, A. Sabourov, D. Tosi, K. Twelker

TUM, Garching, Germany
W. Feldmeier, P. Fierlinger, M. Marino

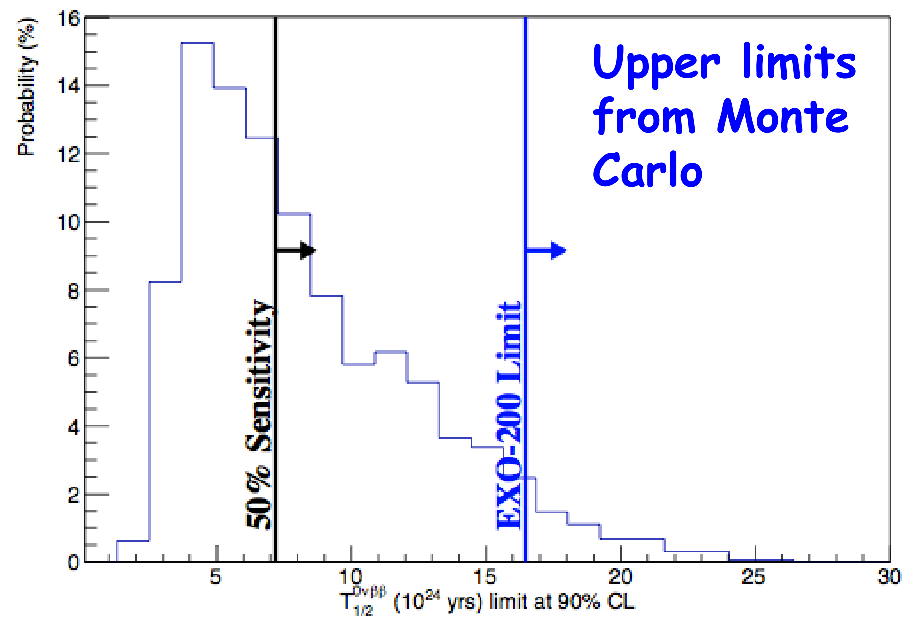
Systematics and sensitivity



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

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

Distribution of 0νββ $T_{1/2}$ 90% CL



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