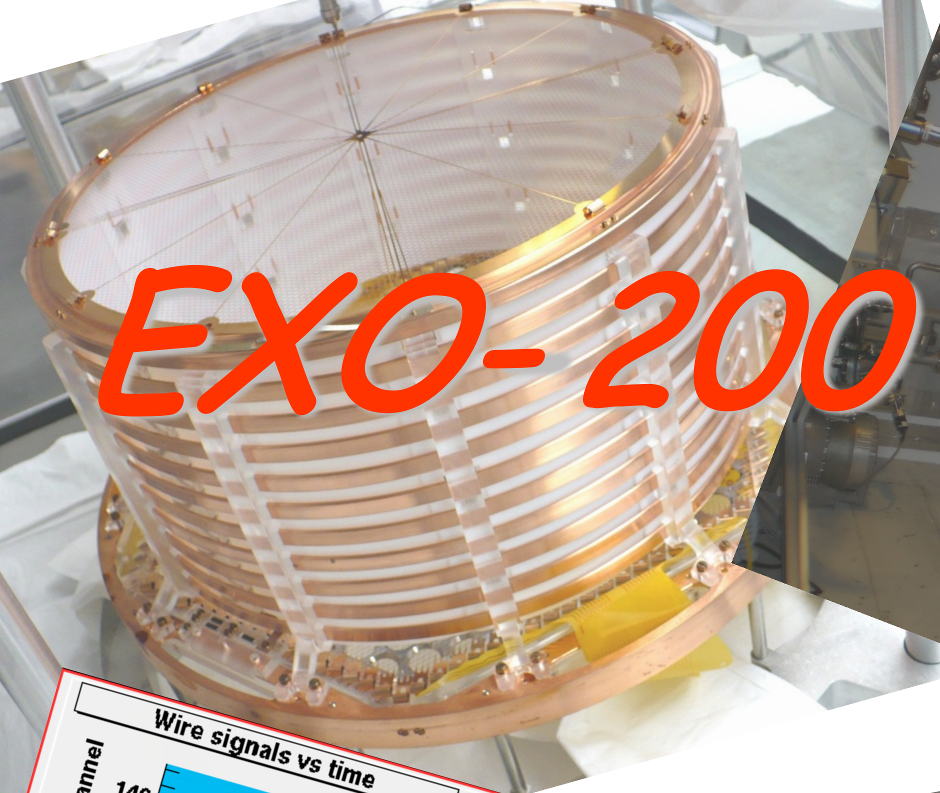
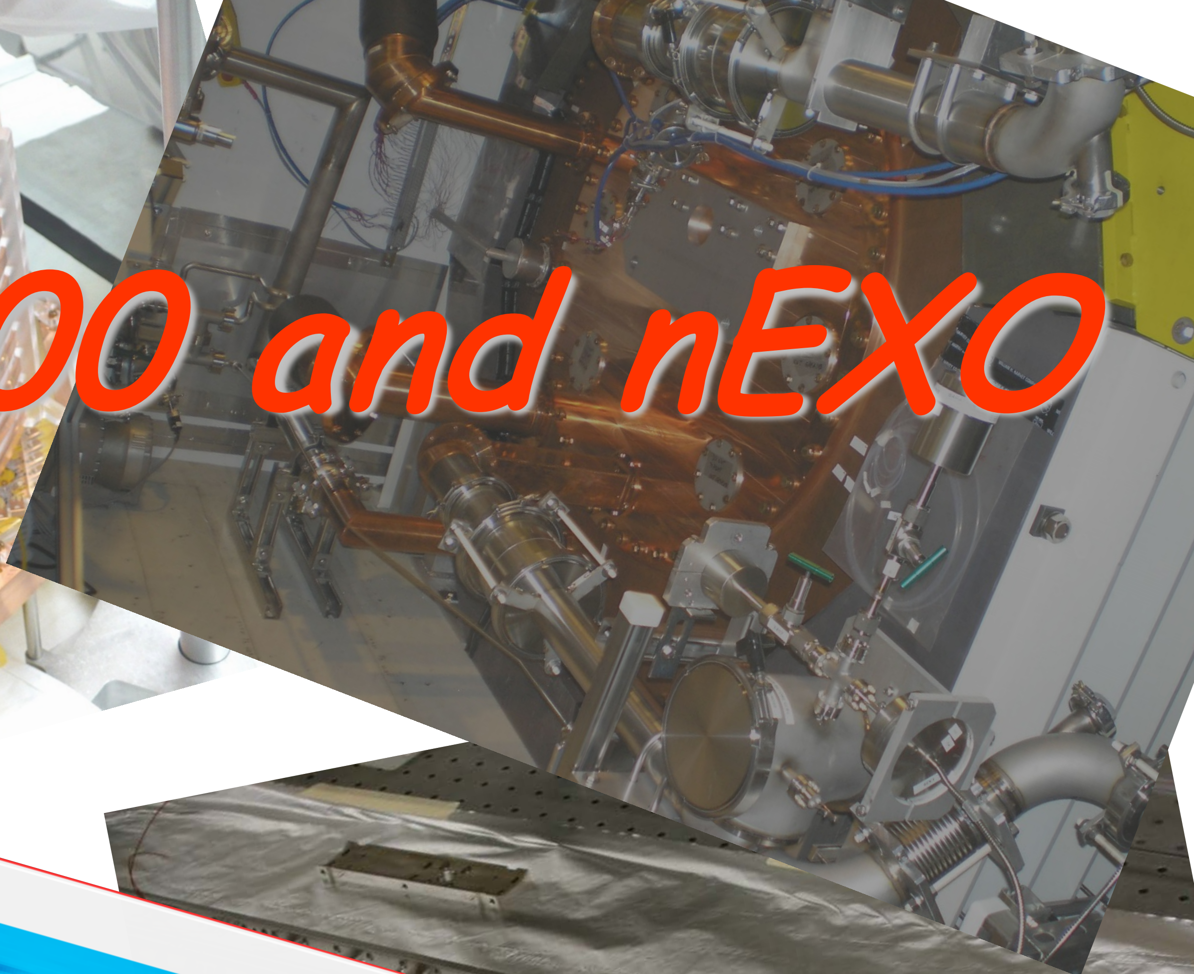
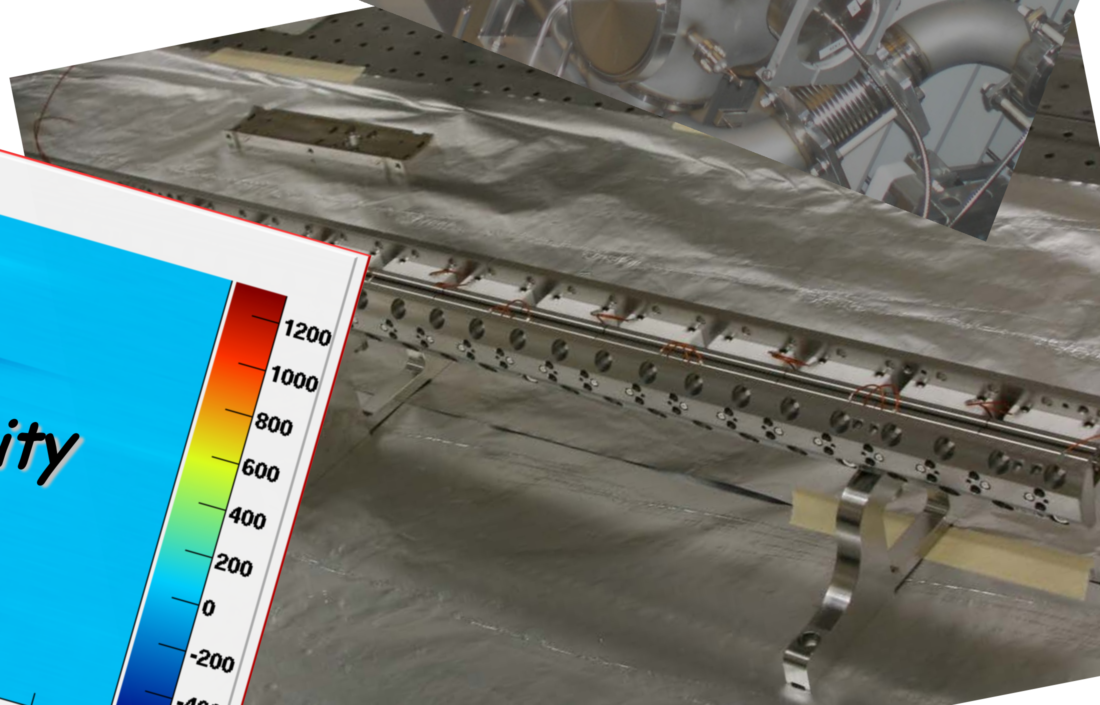
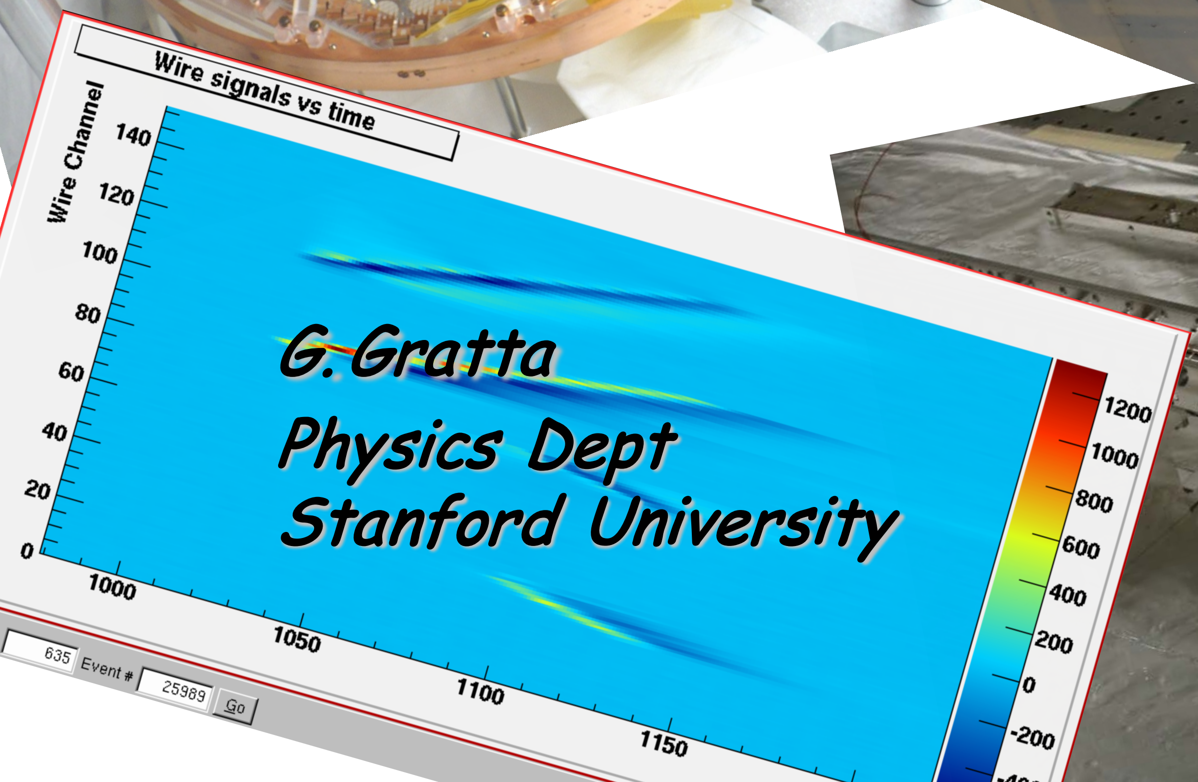
EXO-200 and nEXO







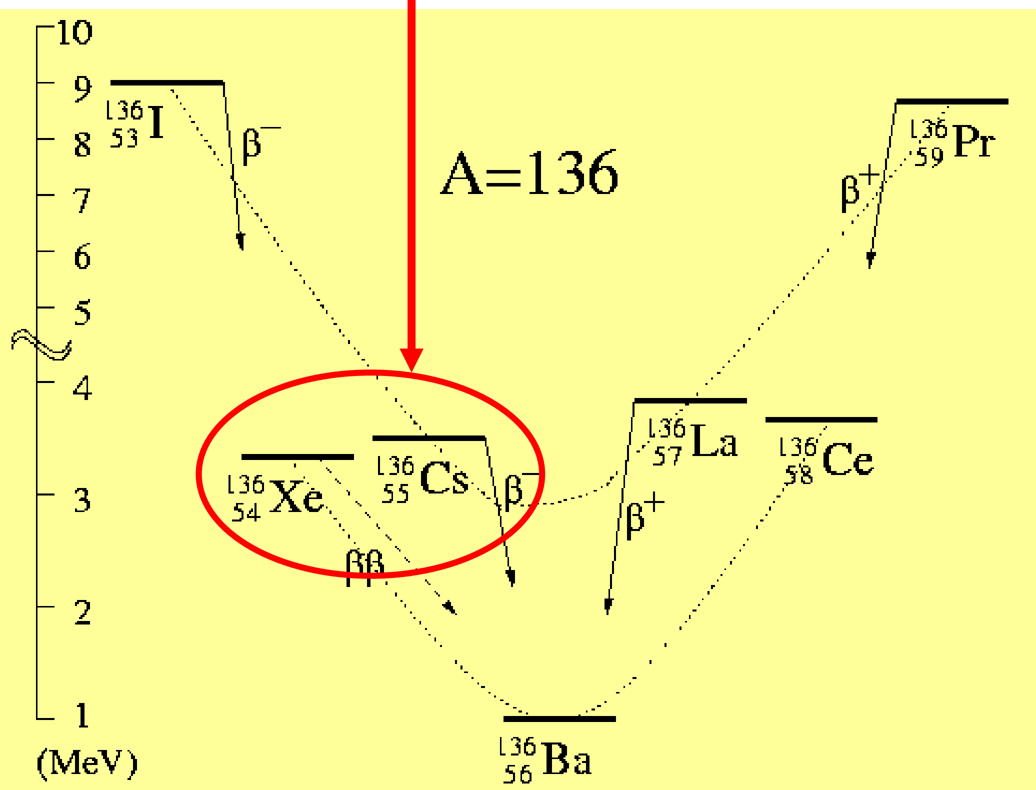


G. Gratta

Physics Dept
Stanford University

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
$^{136}Xe \rightarrow {}^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow {}^{150}Sm$	3.367	5.6

There are two varieties of ββ decay

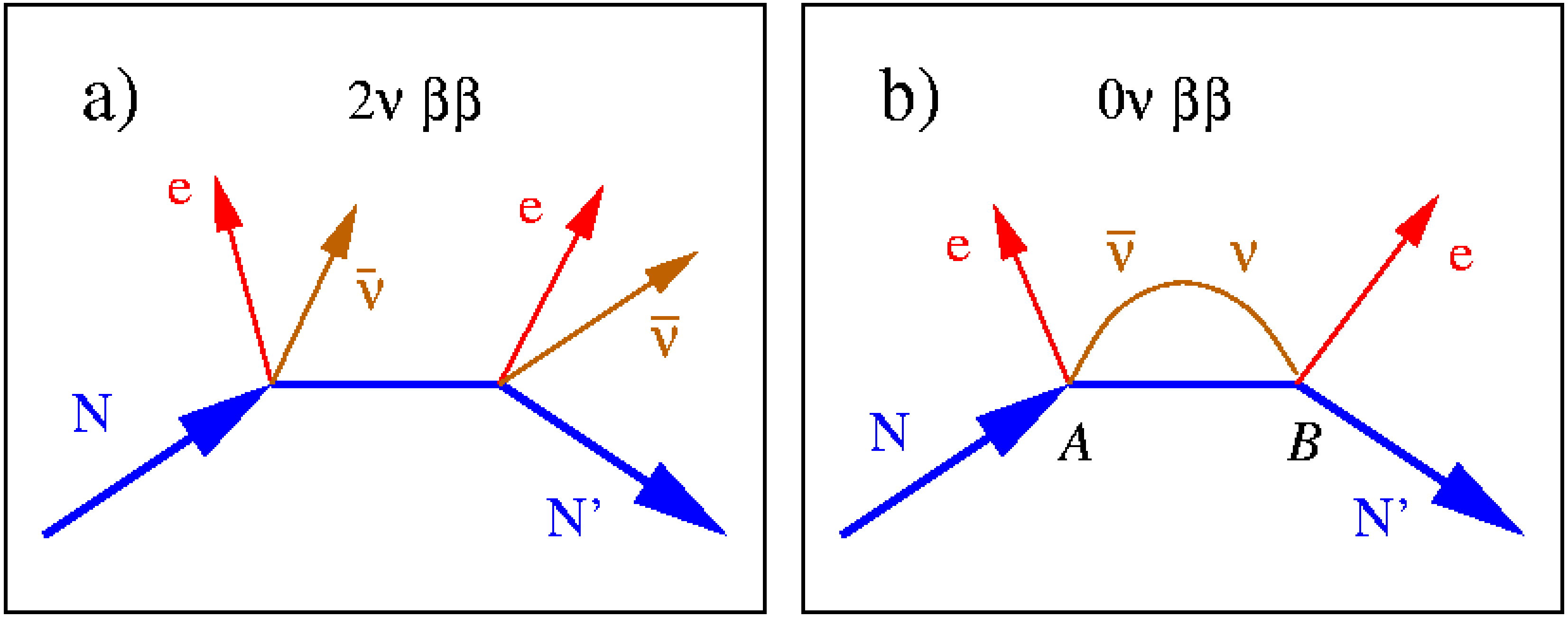
2ν mode:
a conventional
2^{nd} order process
in nuclear physics

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

$\nu = \bar{\nu}$

$|\Delta L|=2$

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



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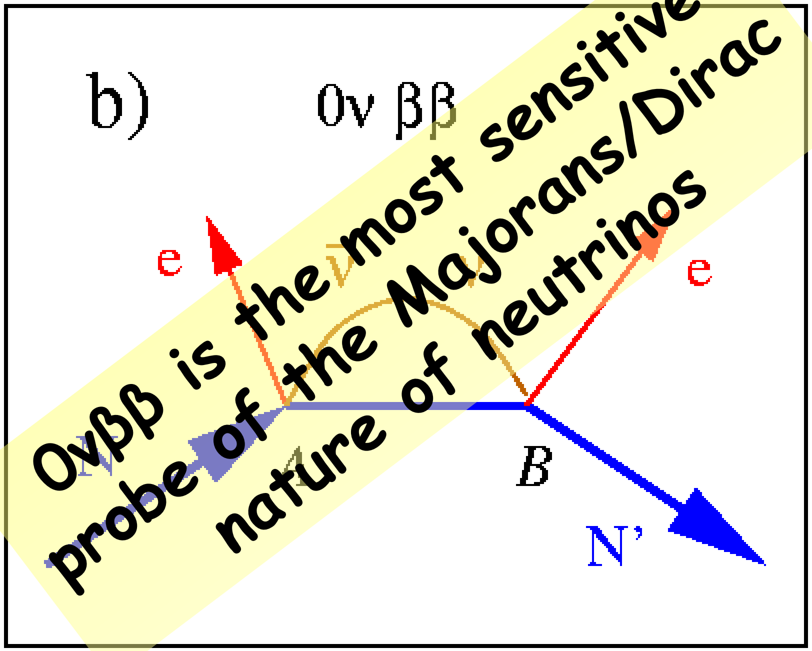
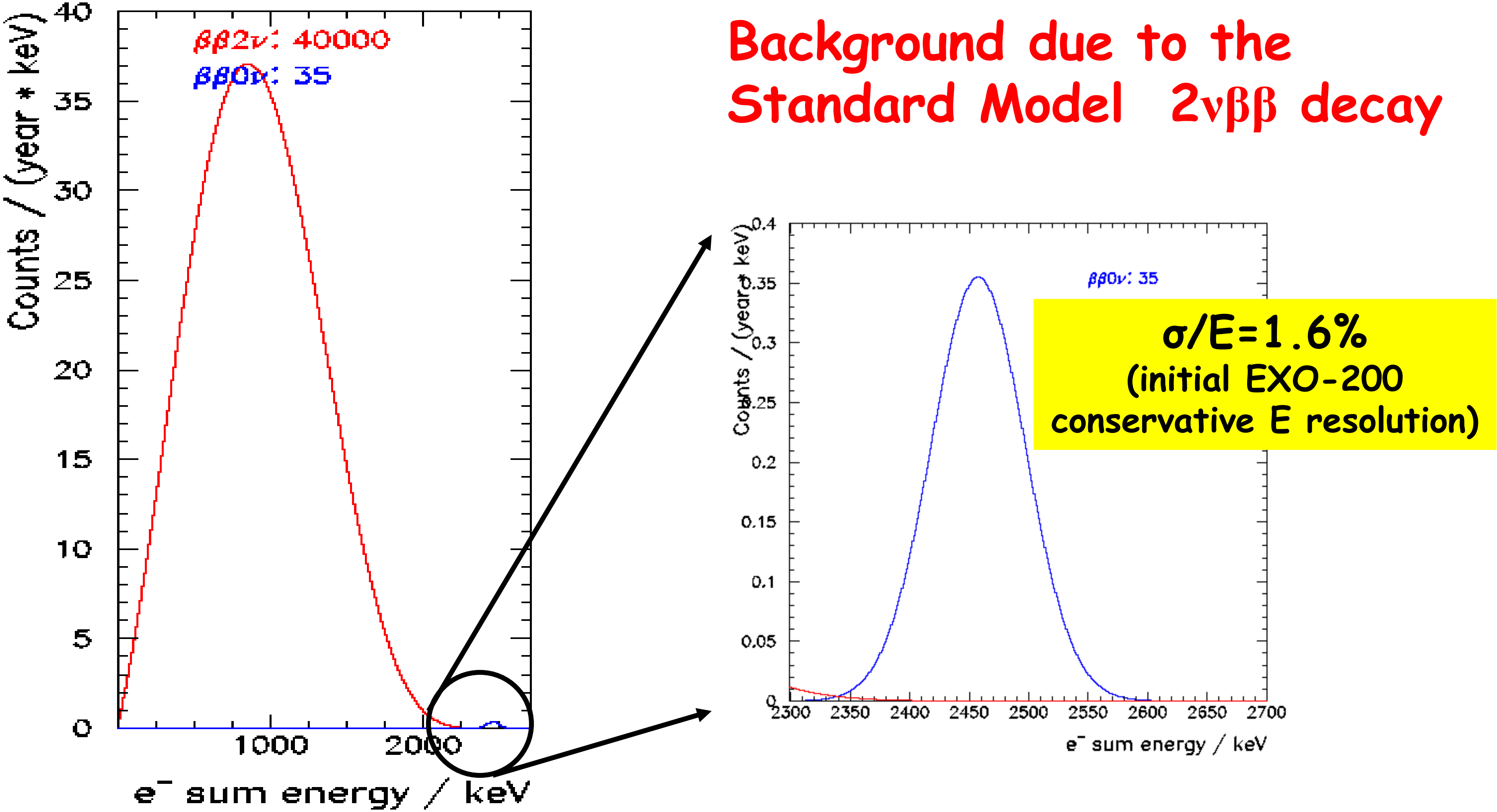


0νββ is the most sensitive probe of the Majorans/Dirac nature of neutrinos

Background due to the Standard Model 2νββ decay



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

Topology and particle ID are also important to recognize backgrounds

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 $\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/\sqrt{Nt}$

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
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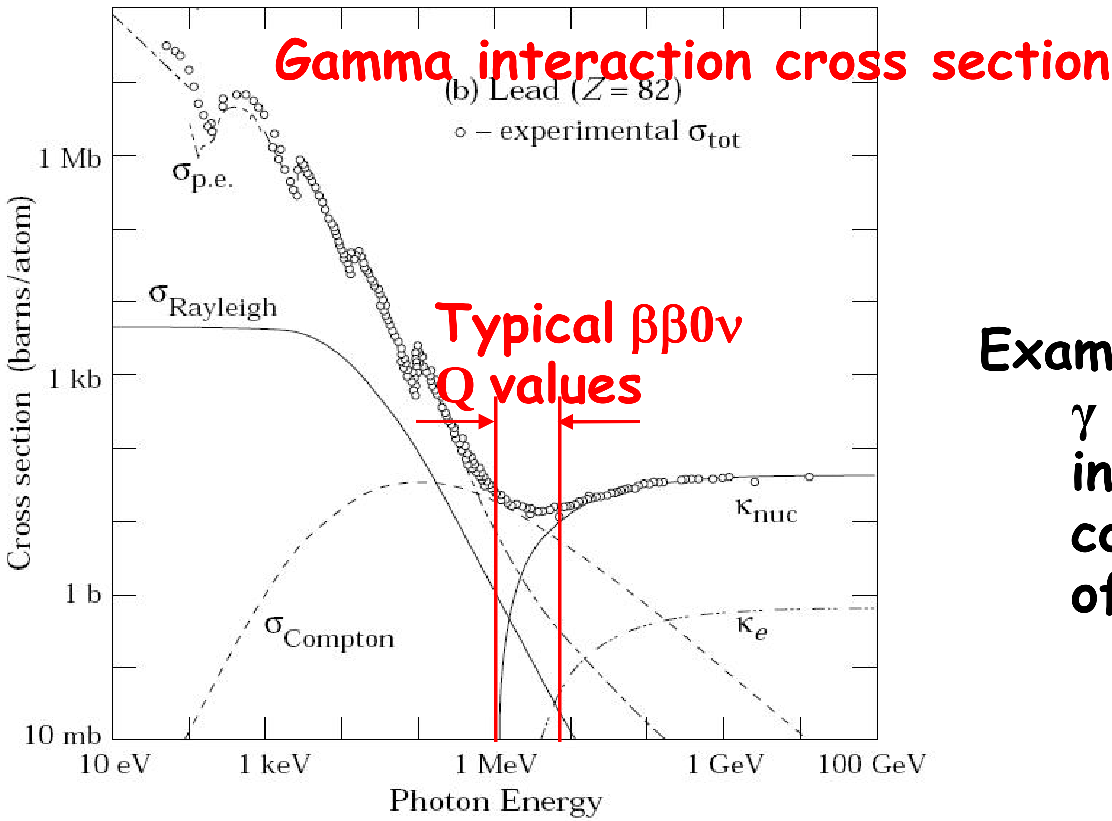
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

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

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



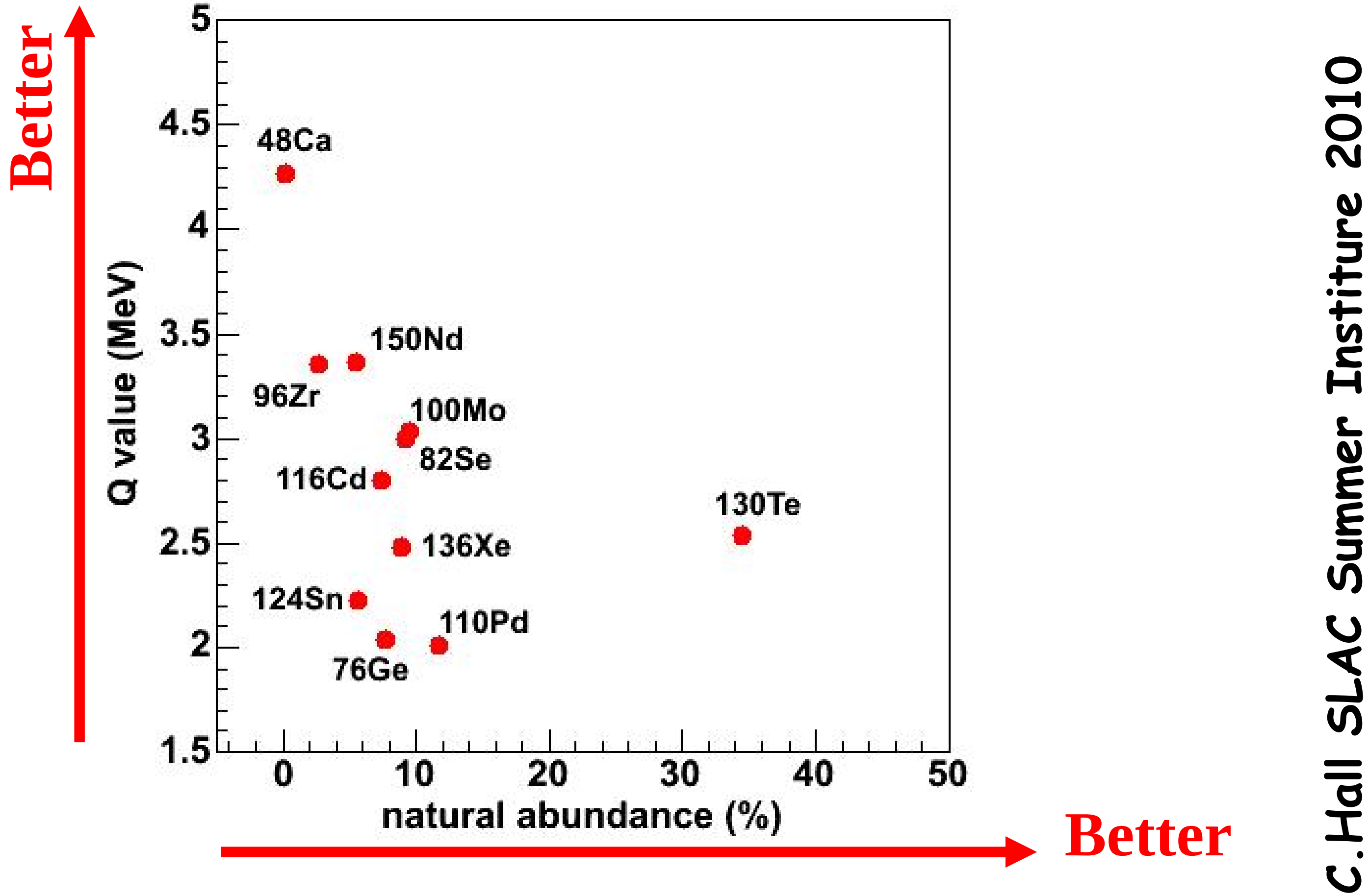
Example:

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

Shielding $\beta\beta$ decay detectors is much harder than shielding Dark Matter ones

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

How to "organize" an experiment: the source



- 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

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 (apparently quite small for ^{136}Xe)*
- *The elucidation of the mechanism producing the decay requires the analysis of more than one isotope*

The virtues of ^{136}Xe in a large TPC

- No need to grow crystals
- Can be re-purified during the experiment
- Noble gas: easy(er) to purify
- Can be easily transferred from one detector to another depending on results and available technology
- Good (although not best) energy resolution coupled with large homogeneous and imagining detector is very powerful
- No long lived Xe isotopes to activate
- ^{136}Xe enrichment easier and cheaper:
  - *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
  → eliminate all non-ββ backgrounds, possibly only chance of getting to Normal Hierarchy
- ^{136}Xe can be replaced with $^{Nat'l}$Xe if a signal is observed!

The EXO-200 Collaboration

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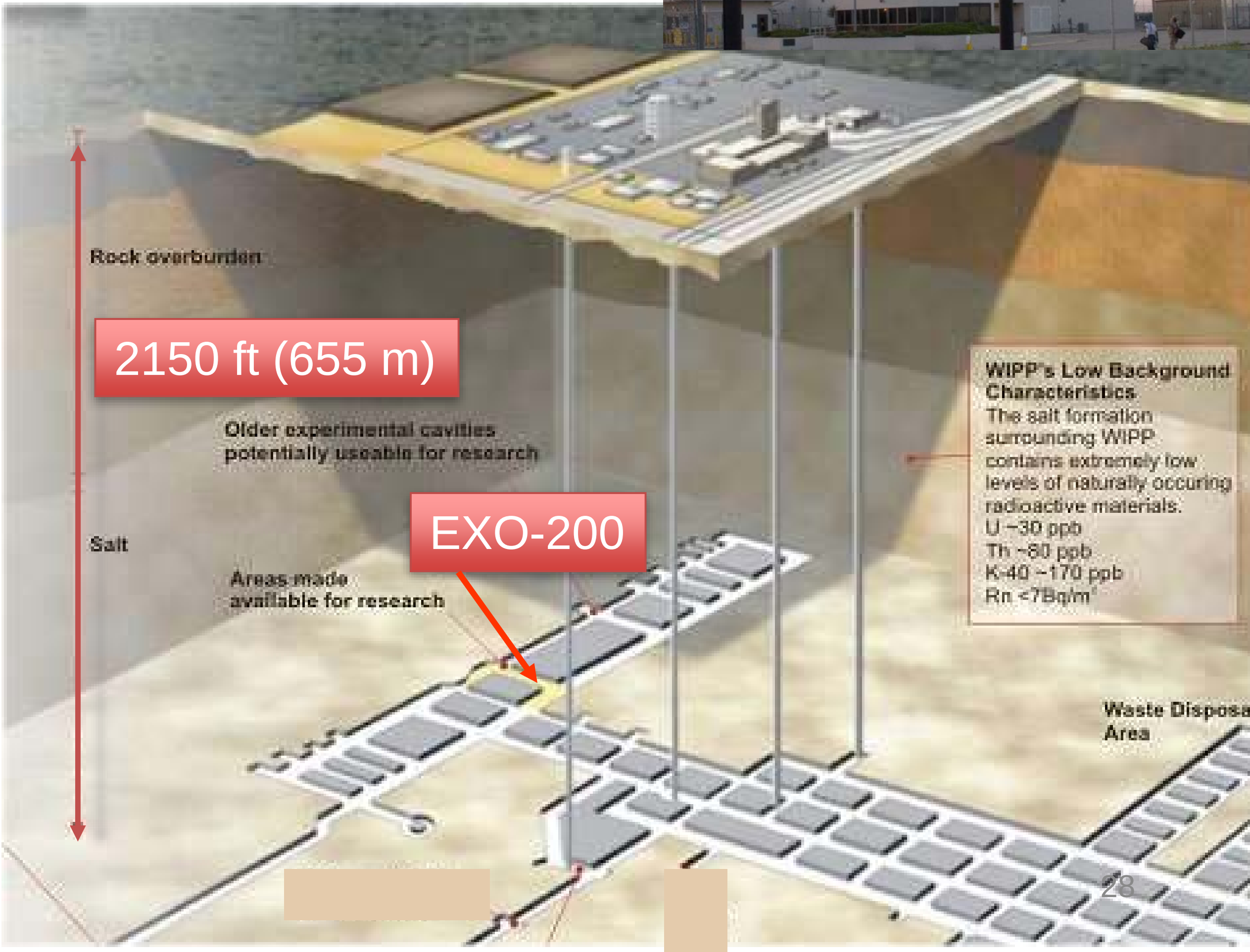
Stanford University, Stanford CA, USA - J. Bonatt, T. Brunner, J. Chaves, J. Davis, R. DeVoe, D. Fudenberg, G. Gratta, S.Kravitz, D. Moore, I. Ostrovskiy, A. Rivas, A. Schubert, D. Tosi, K. Twelker, M. Weber

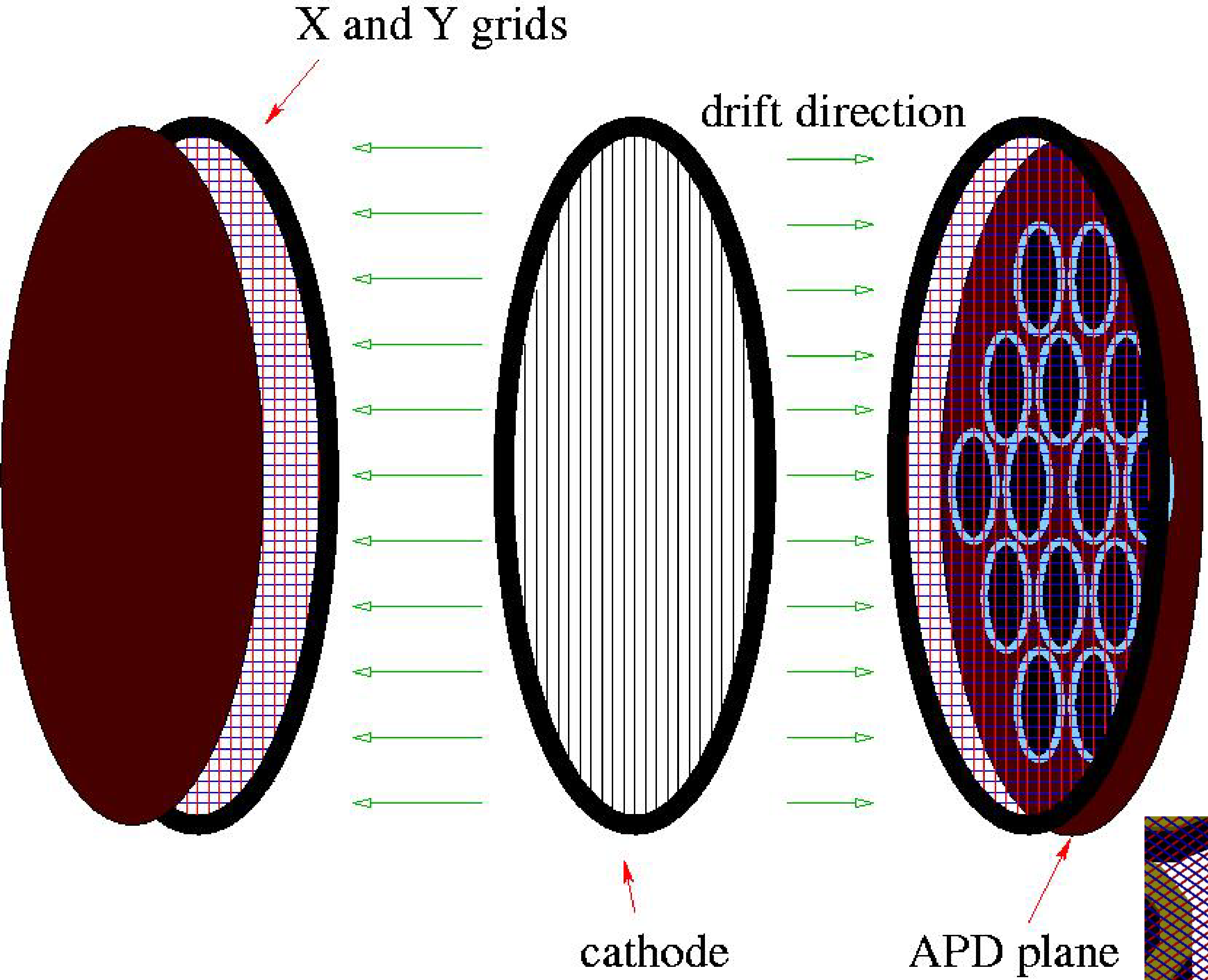
Technical University of Munich, Garching, Germany - W. Feldmeier, P. Fierlinger, M. Marino

TRIUMF, Vancouver BC, Canada – J. Dilling, R. Krucken, F. Retière, V. Strickland

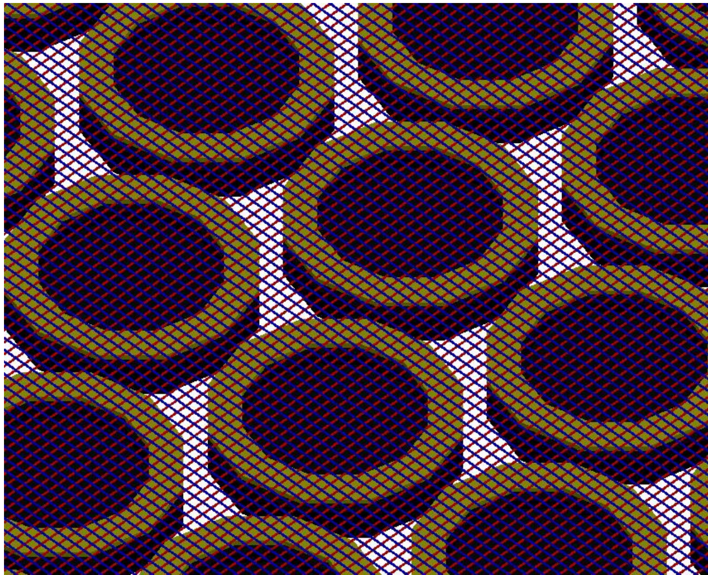
Underground location:
Waste Isolation Pilot Plant (WIPP) Carlsbad, NM

- ~1600 meter water equivalent flat overburden
- Relatively low levels of U and Th ($<$100 ppb in EXO-200 drift)
- Low levels of Rn (~20 Bq/m^3)
- Rather convenient access with large conveyance





EXO-200 does not have Ba tagging but it is compatible with Ba tagging



R. Neilson, *et* al. NIM A 608 (2009) 6875

APDs are ideal for our application:

- very clean & light-weight,
- very sensitive to VUV

QE > 1 at 175nm

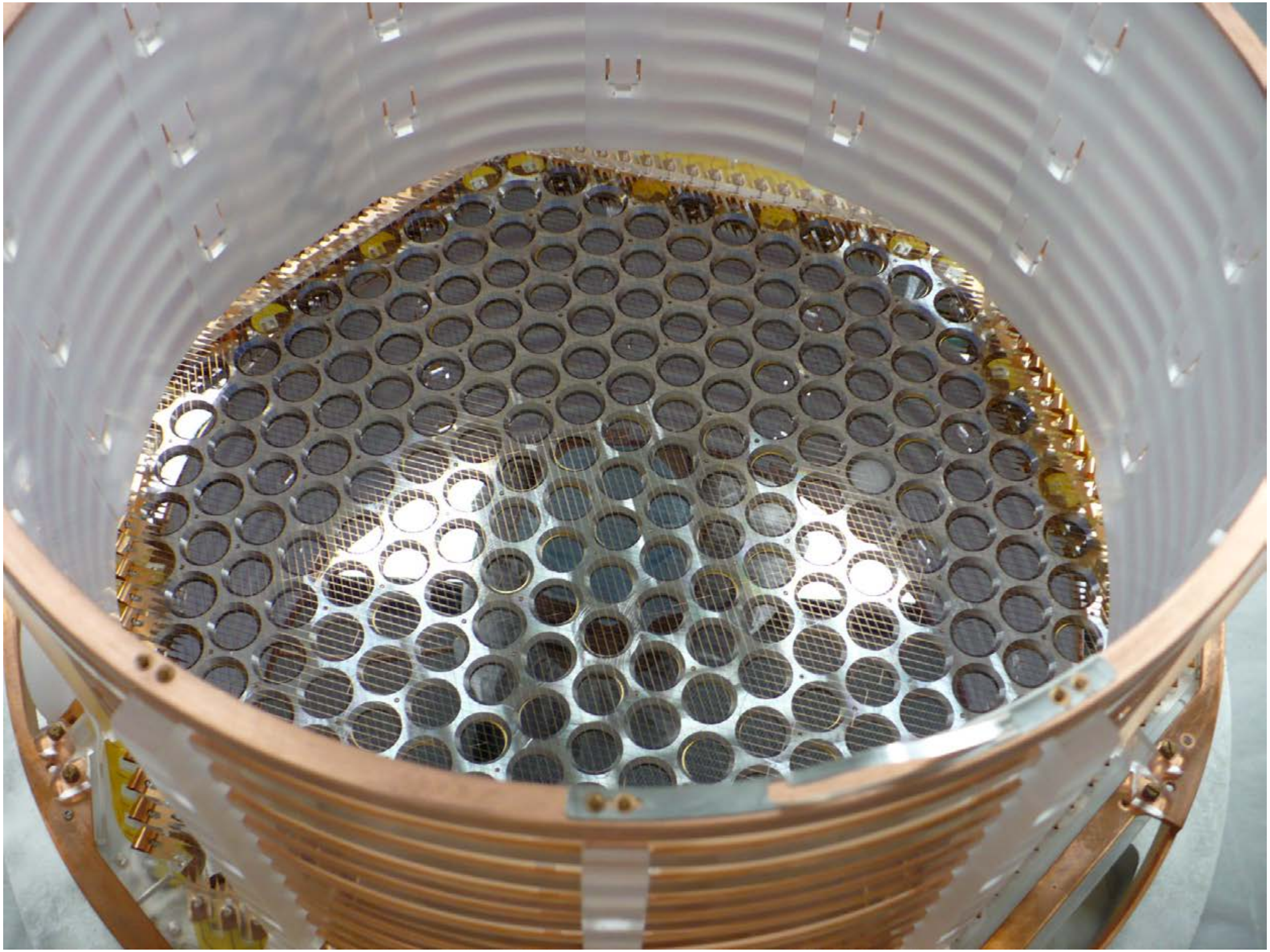
Gain set at 100-150

V~1500V

$\Delta V < \pm 0.5V$

$\Delta T < \pm 1K$ APD is the driver for temperature stability

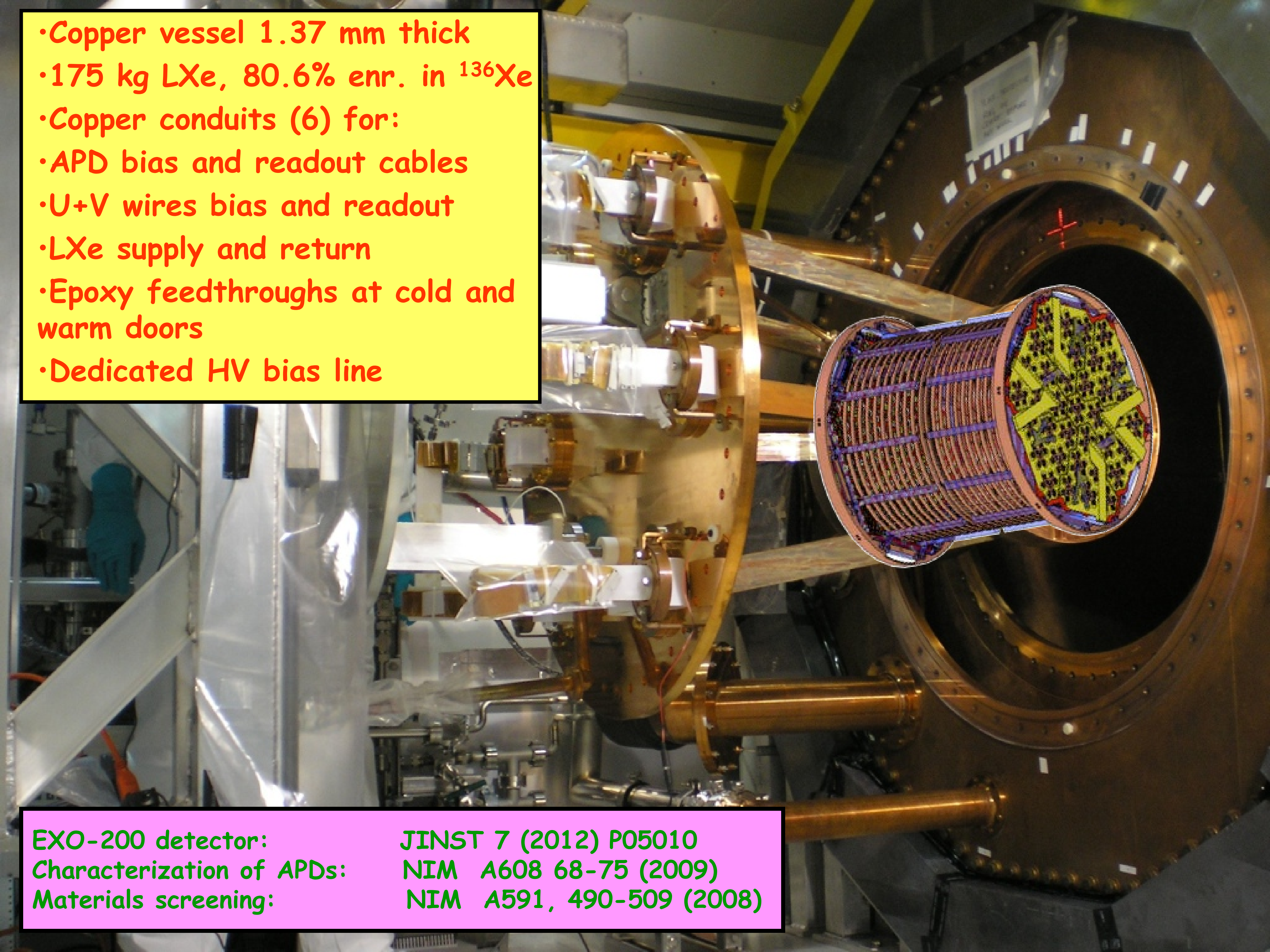
Leakage current OK cold



Ultra-low activity Cu vessel

- Very light (~1.5mm thin, ~15kg) to minimize materials

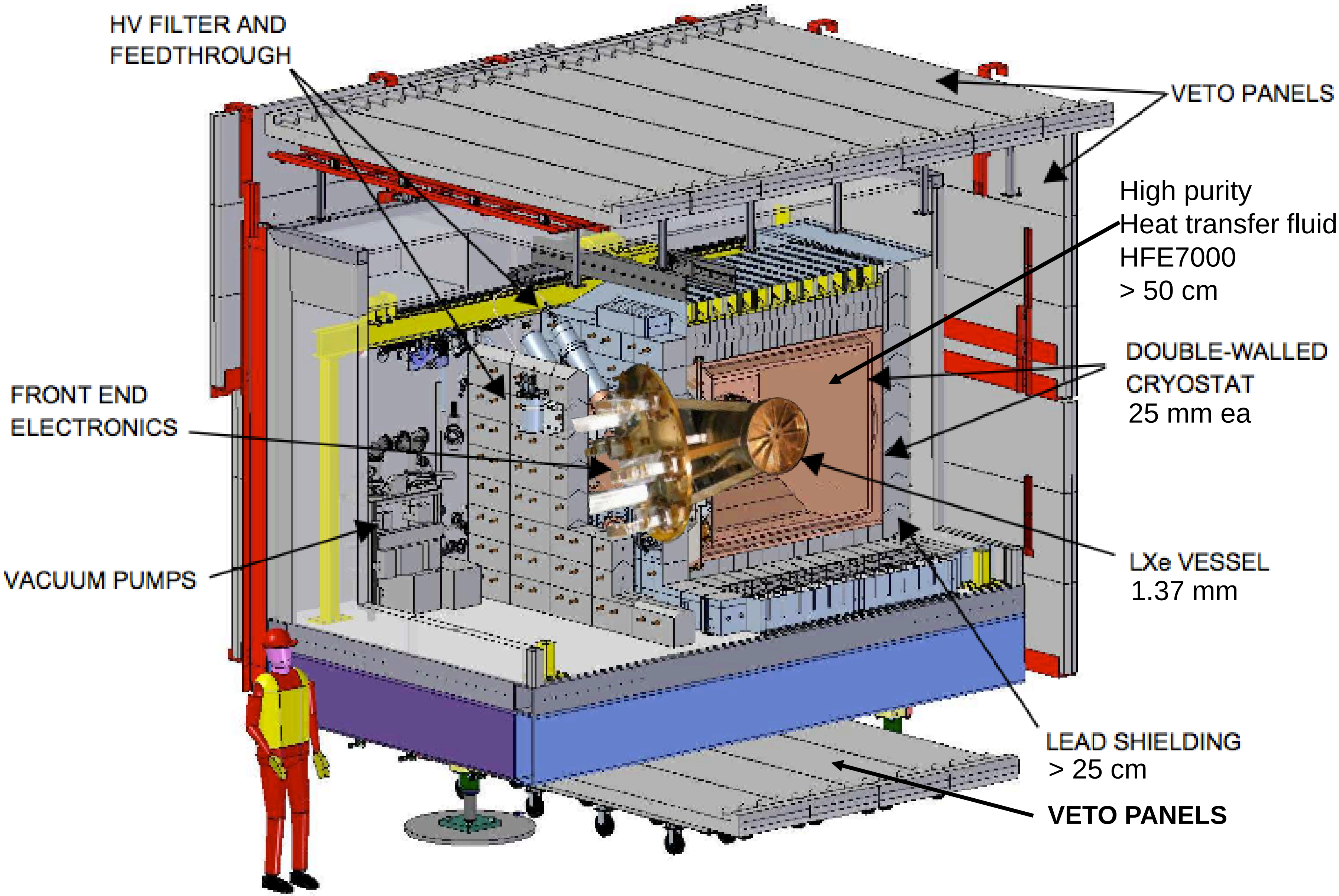
- Different parts e-beam welded together
- Field TIG weld(s) to seal the vessel after assembly (TIG technology tested for radioactivity)
- All machining done by in the CR-shielded HEPL building)



- 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



Massive effort on material radioactive qualification using:

- NAA
- Low background γ-spectroscopy
- α-counting
- Radon counting
- High performance GD-MS and ICP-MS

At present the database of characterized materials includes >300 entries

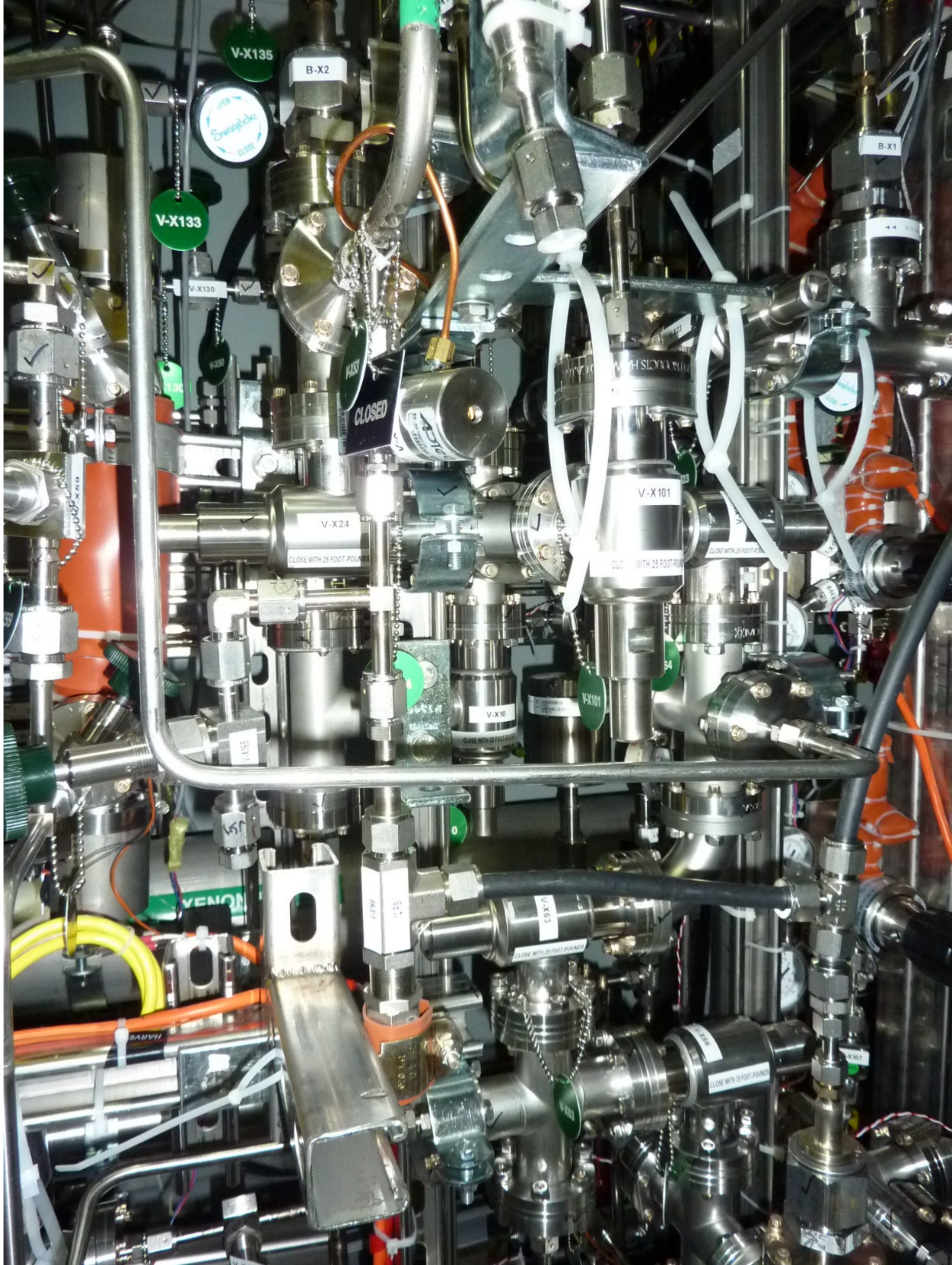
D.S. Leonard et al., Nucl. Ins. Meth. A 591, 490 (2008)

The impact of every screw within the Pb shielding is evaluated before acceptance

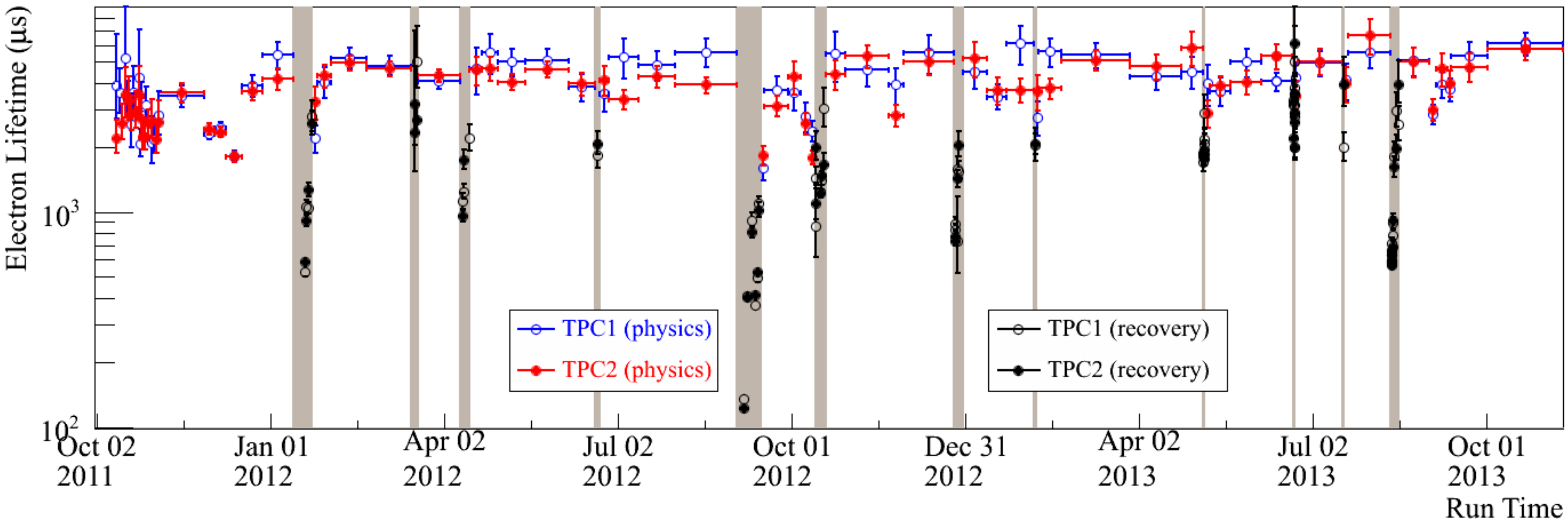
→ Goal: 40 cnts/2yr in the 0νββ ±2σ ROI in 140kg of LXe

A substantial system is required to

- protect the 1.5mm thin LXe container from pressure
- recirculate Xe in gas phase to purify it
- fill/empty the detector
- manage emergencies



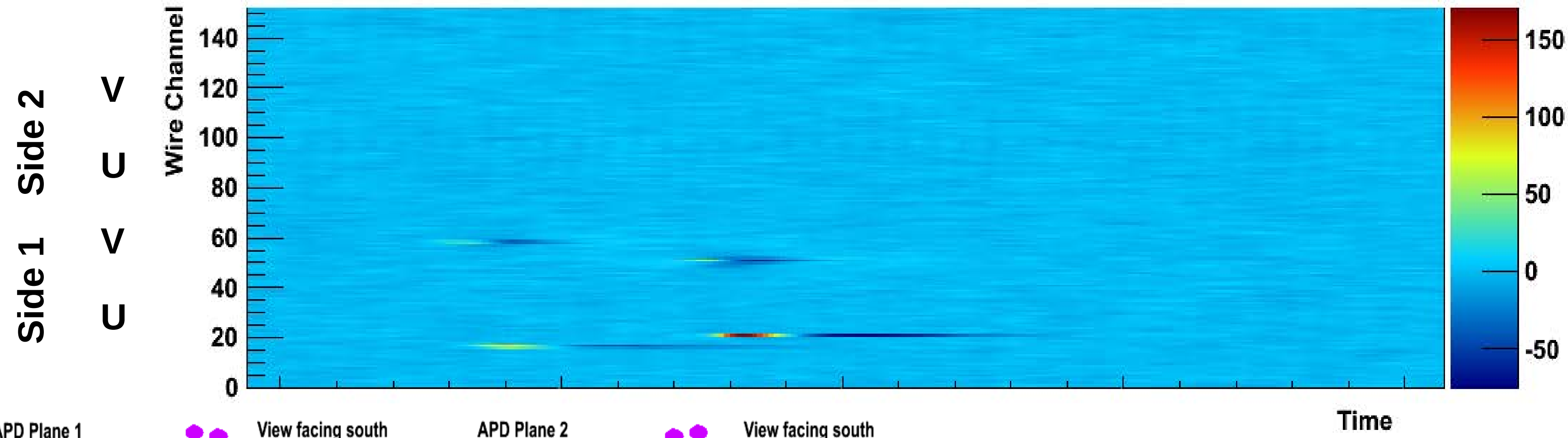
Xe purity is essential for good energy resolution

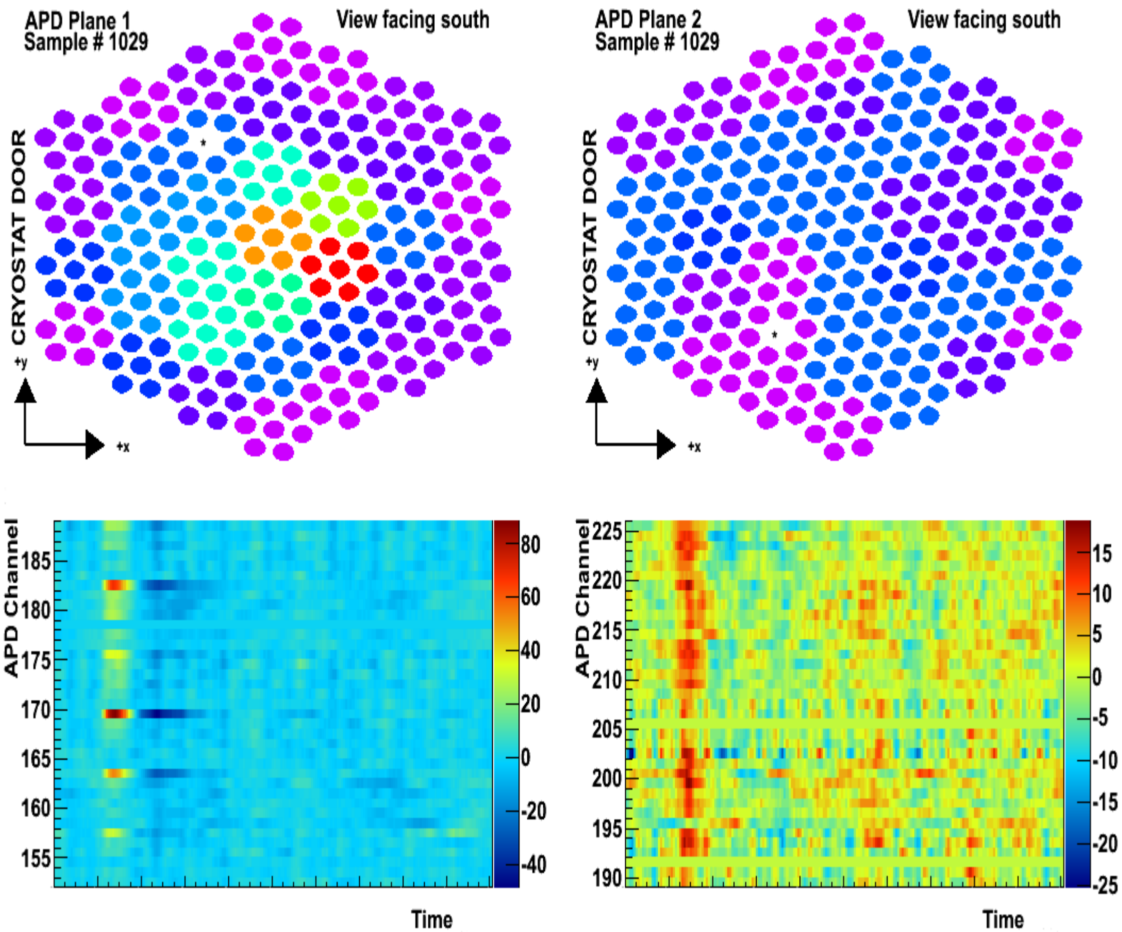


Xenon gas is forced through heated Zr getter by a custom ultraclean pump.

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*





A two-site Compton scattering event.

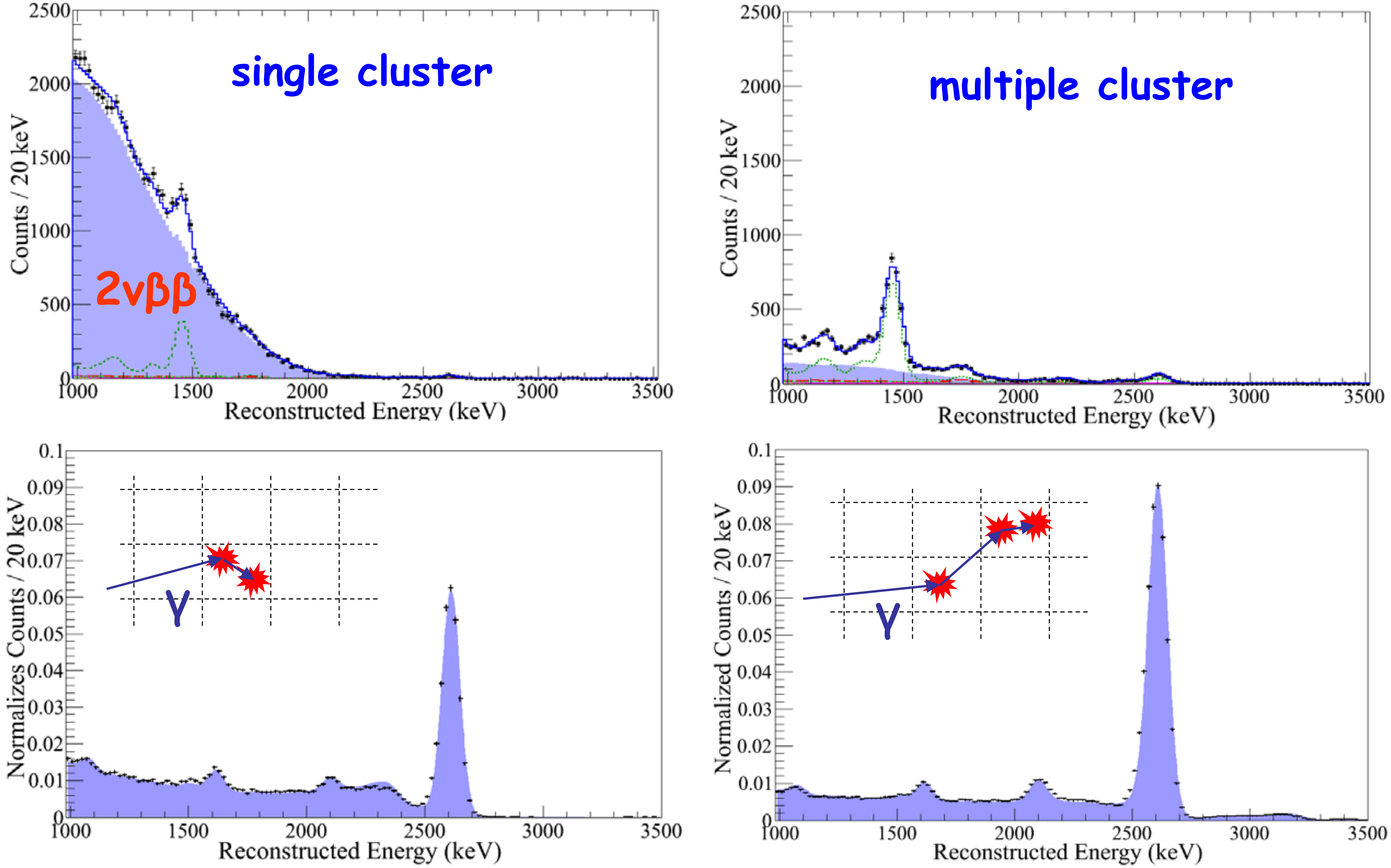
All scintillation light arrives at the same time, indicating that the two energy depositions are simultaneous.

The scintillation light is Brighter and more localized on Side 1 where the scattering occurs

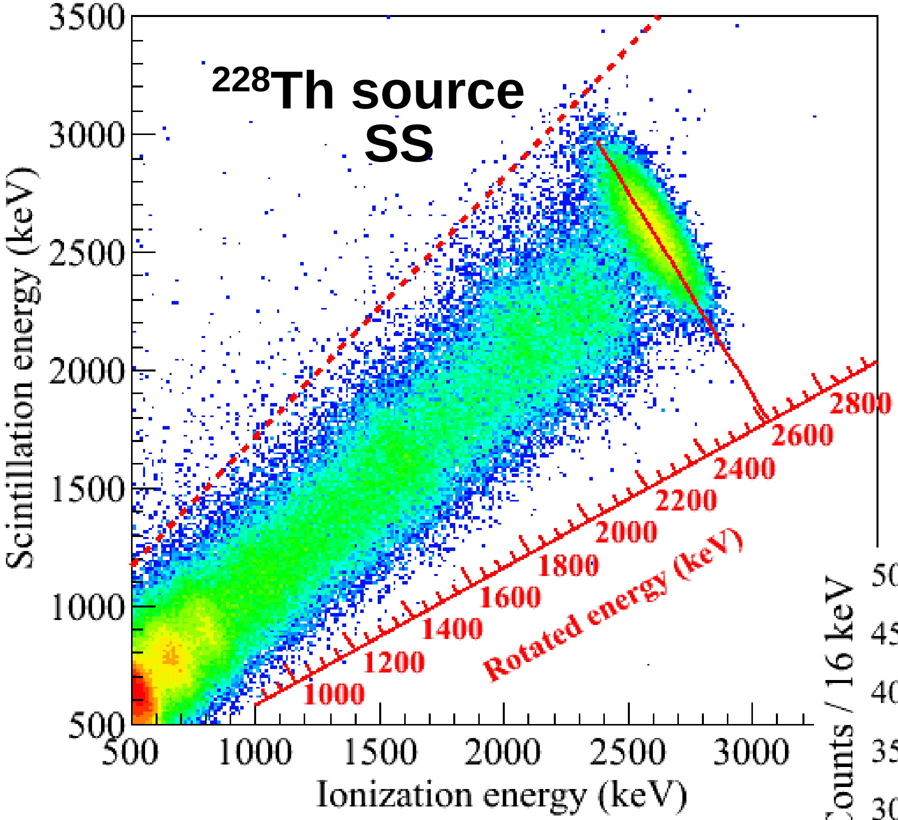
Tracking:
an essential tool to identify and suppress backgrounds

Low background data

^{228}Th calibration source



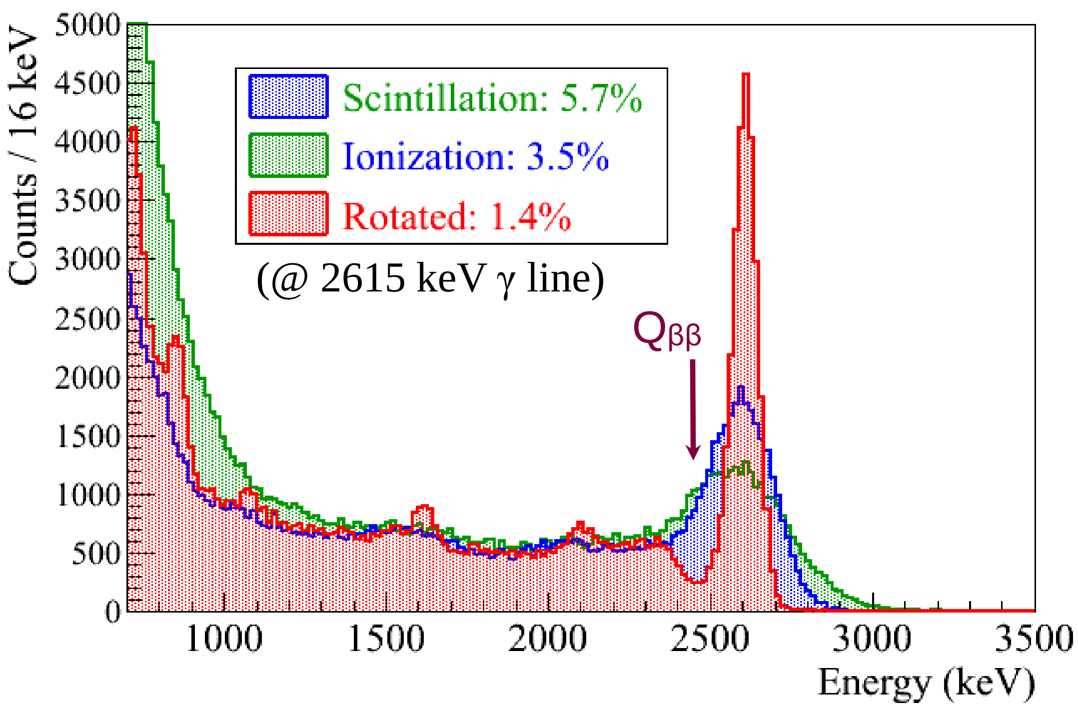
Combining Ionization and Scintillation



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

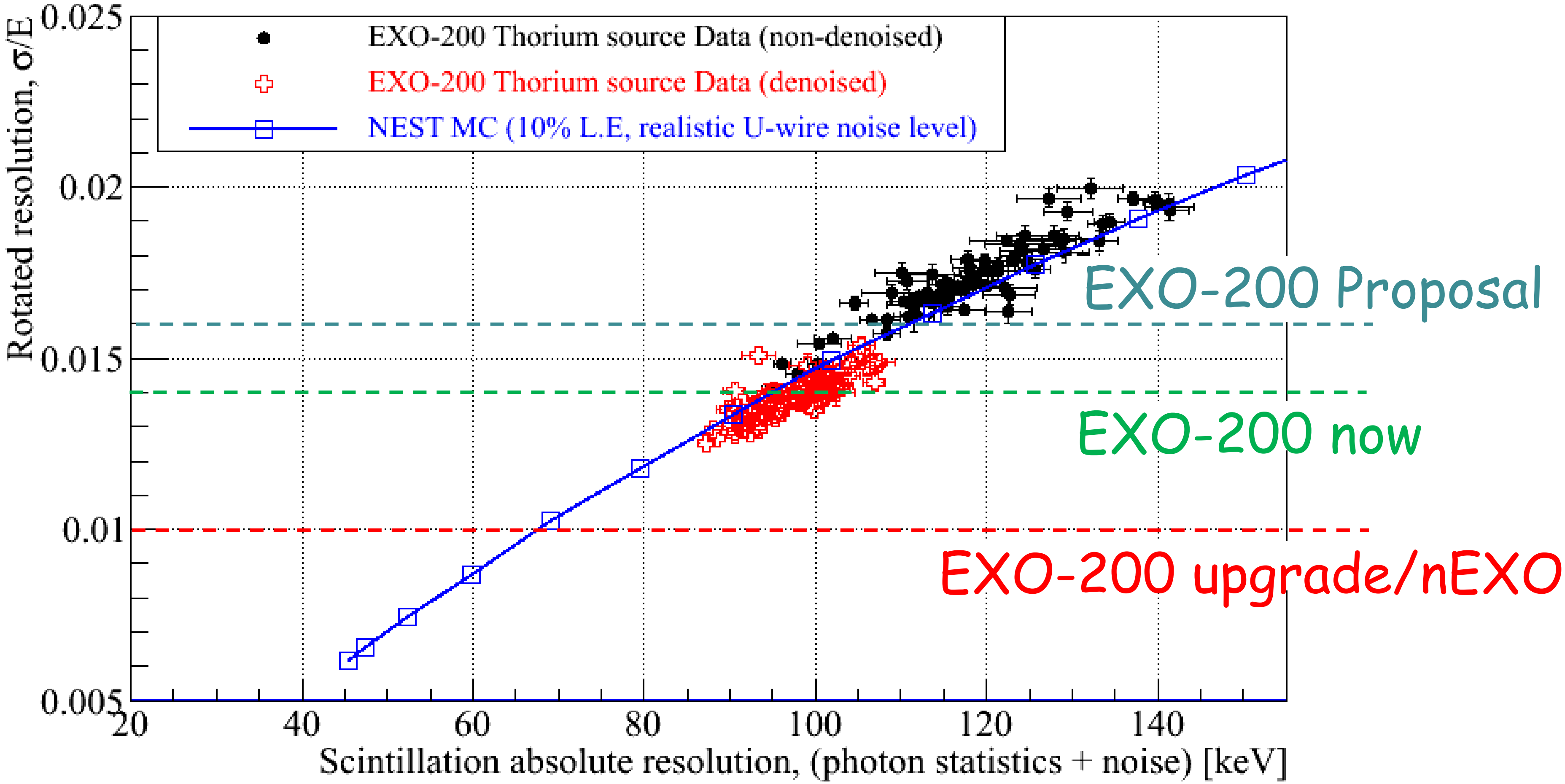
E.Conti et al. Phys Rev B 68 (2003) 054201

Note improvement due to LAAPD denoising

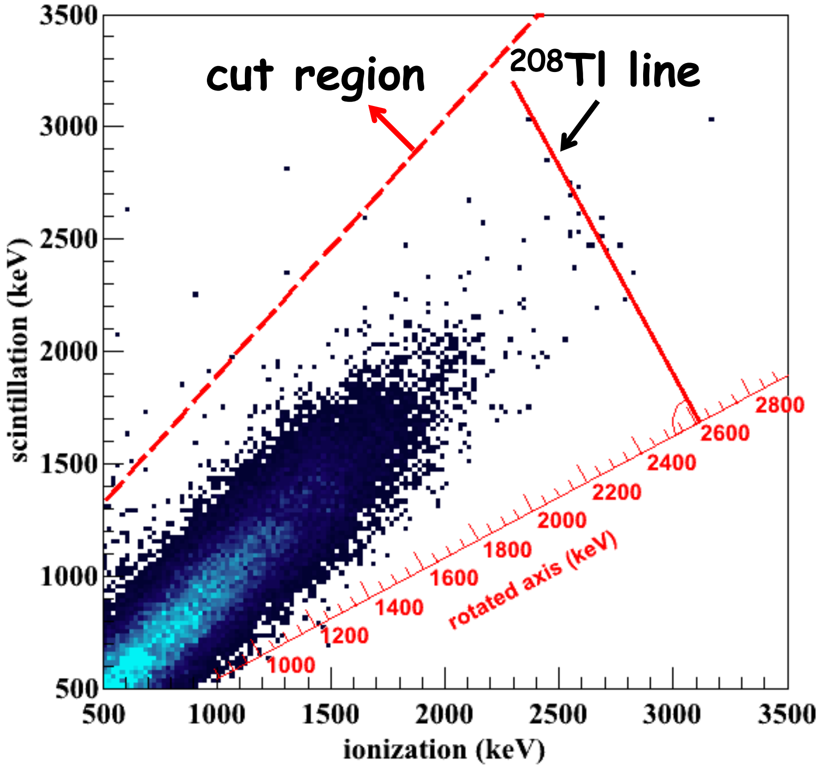


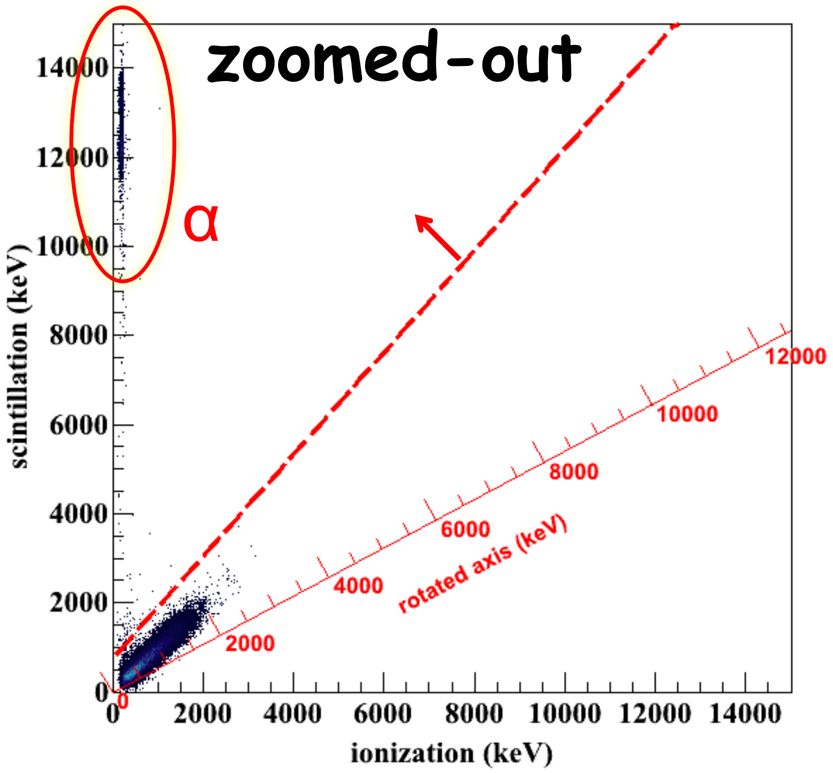
Rotation angle chosen to optimize energy resolution at 2615 keV

EXO-200 and nEXO resolutions



Low Background 2D SS Spectrum

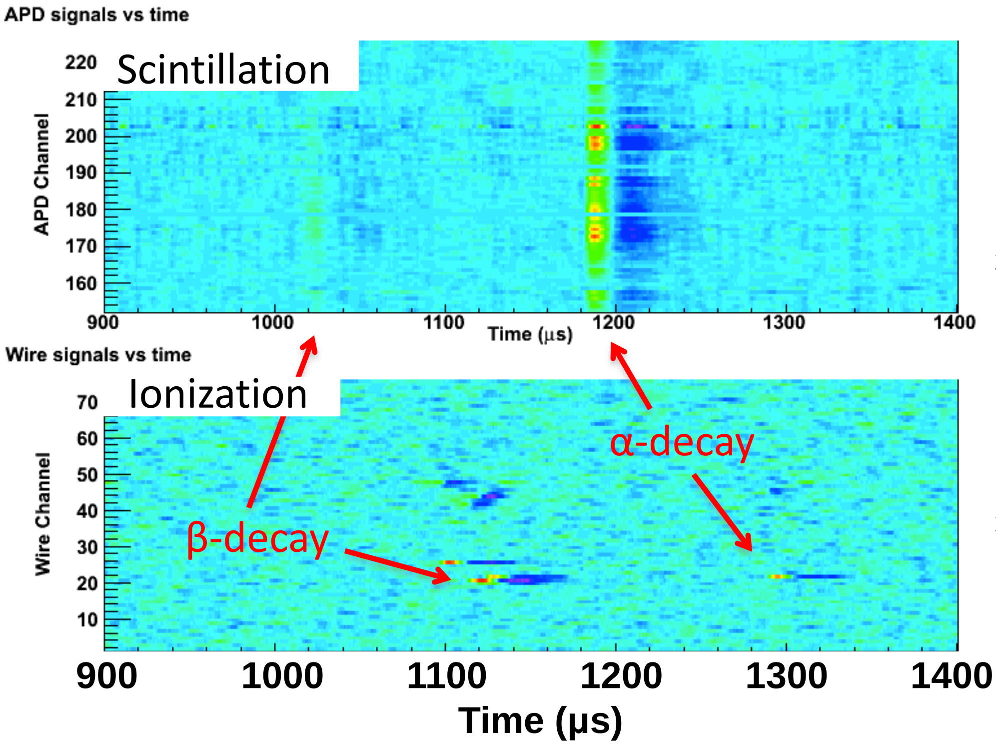




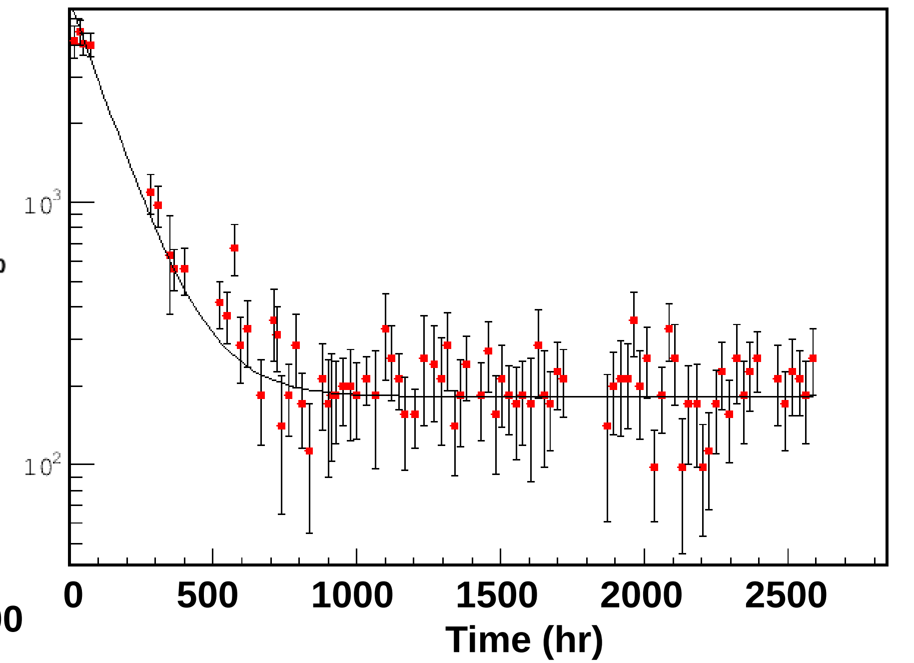
Events removed by diagonal cut:

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

Rn Content in Xenon



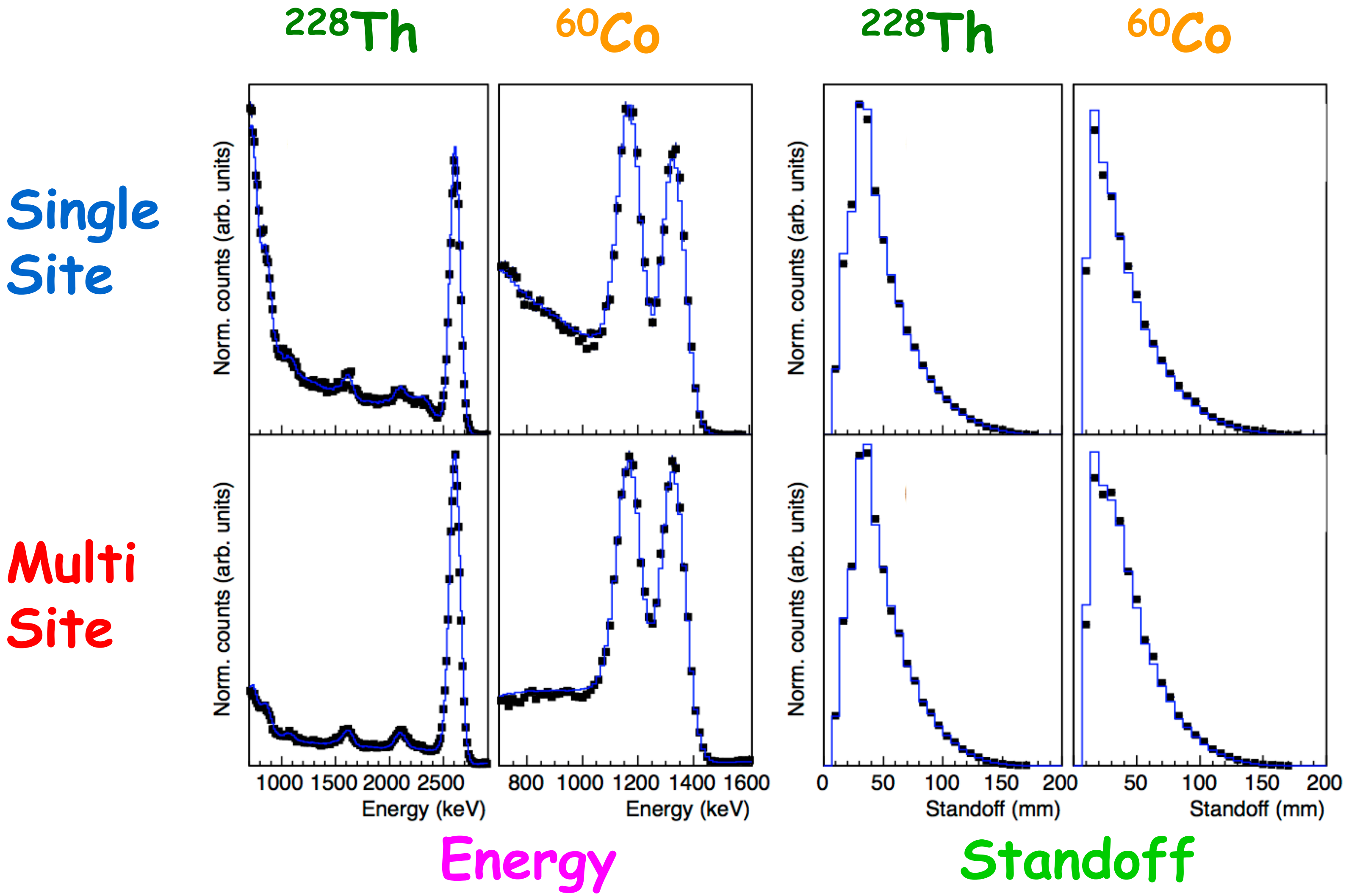
^{214}Bi – ^{214}Po correlations in the EXO-200 detector



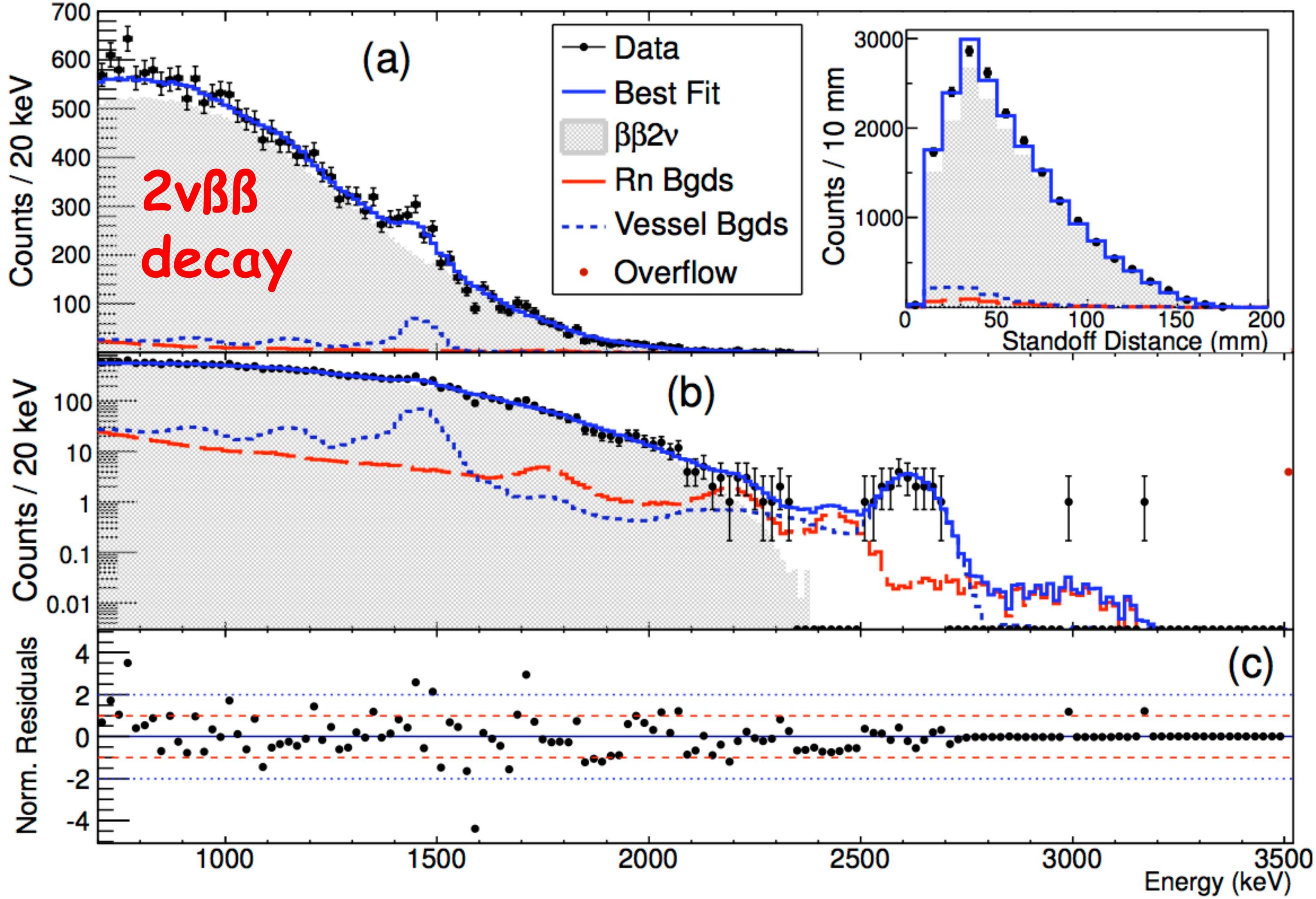
Total ^{222}Rn in LXe after initial fill

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

Energy and position spectra are reproduced by the Monte Carlo with high fidelity



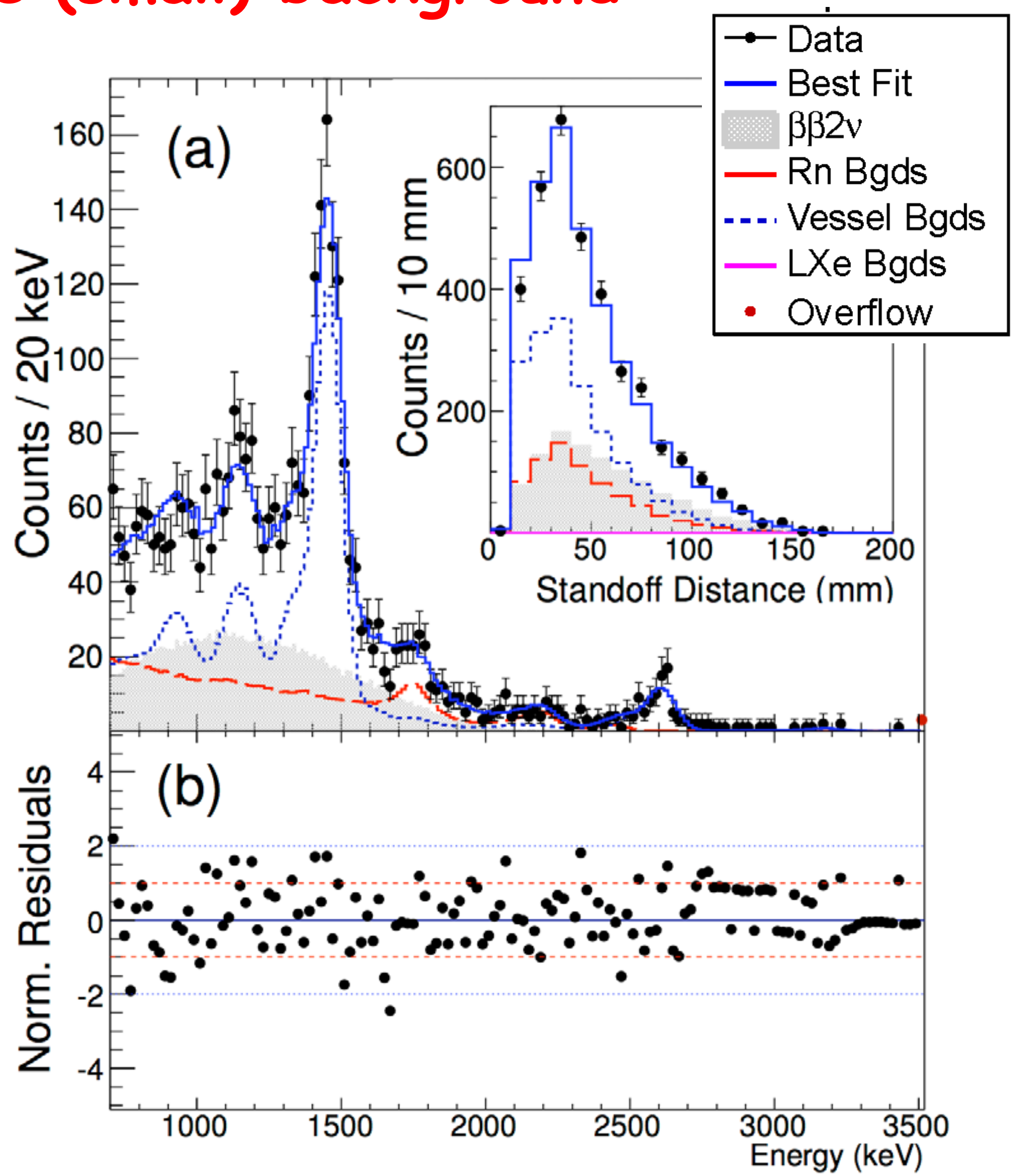
Low background single-site energy (and standoff) spectrum for 28.69 kg·yr (82.1 kg Xe, 127.6 d)



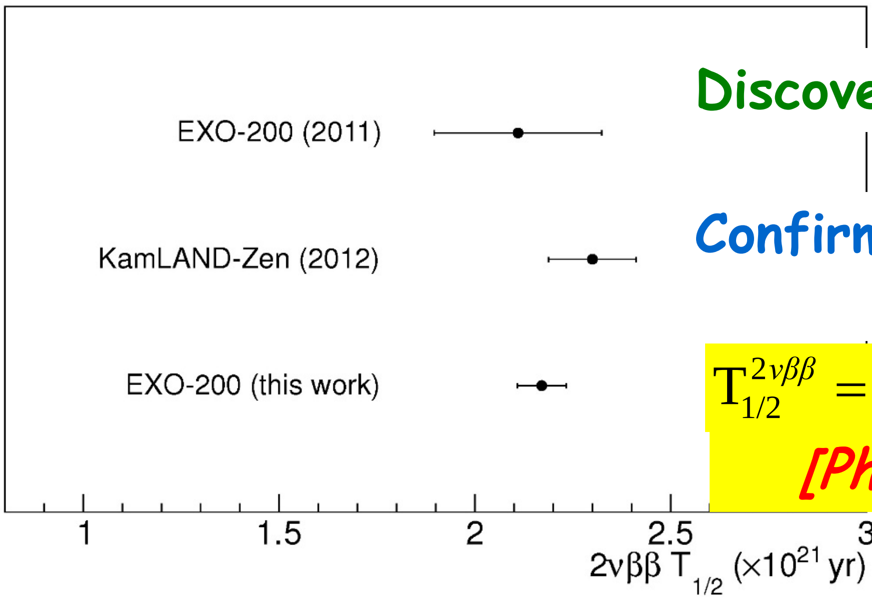
Signal-to-Background ratio 10 - 20

Multi-site spectrum directly measures the (small) background

Note that an unknown γ line at the ββ endpoint would produce a larger peak in the multi-site spectrum, providing a rejection



…since the start of EXO-200 data taking in Jun 2011…



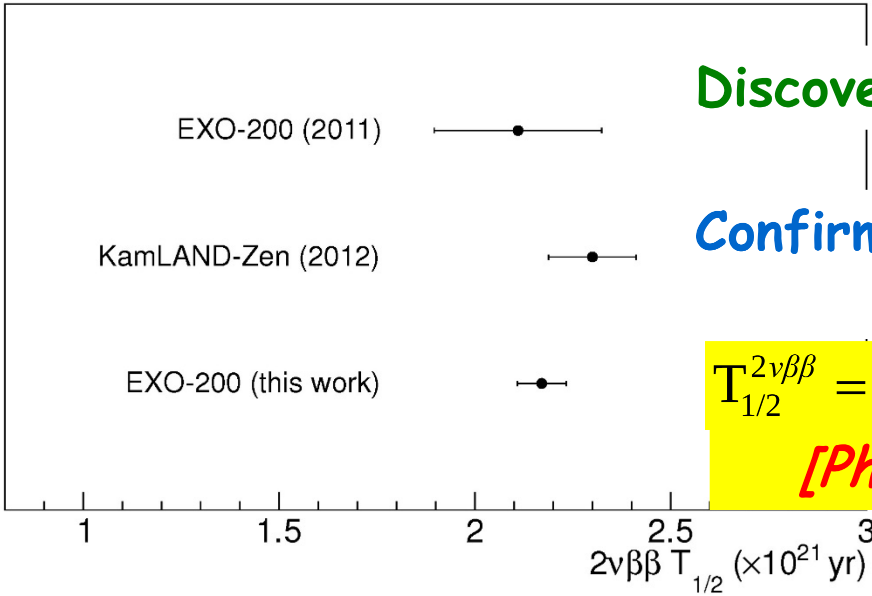
Discovery of 2ν mode *[PRL 107, 212501 (2011)]*

Confirmation by KamLAND-Zen *[PRC 85, 045504 (2012)]*

$$T_{1/2}^{2\nu\beta\beta} = \left(2.165 \pm 0.016^{\text{stat}} \pm 0.059^{\text{syst}}\right) \cdot 10^{21}\ \text{yr}$$

[Phys Rev C 89 (2014) 015502]

…since the start of EXO-200 data taking in Jun 2011…



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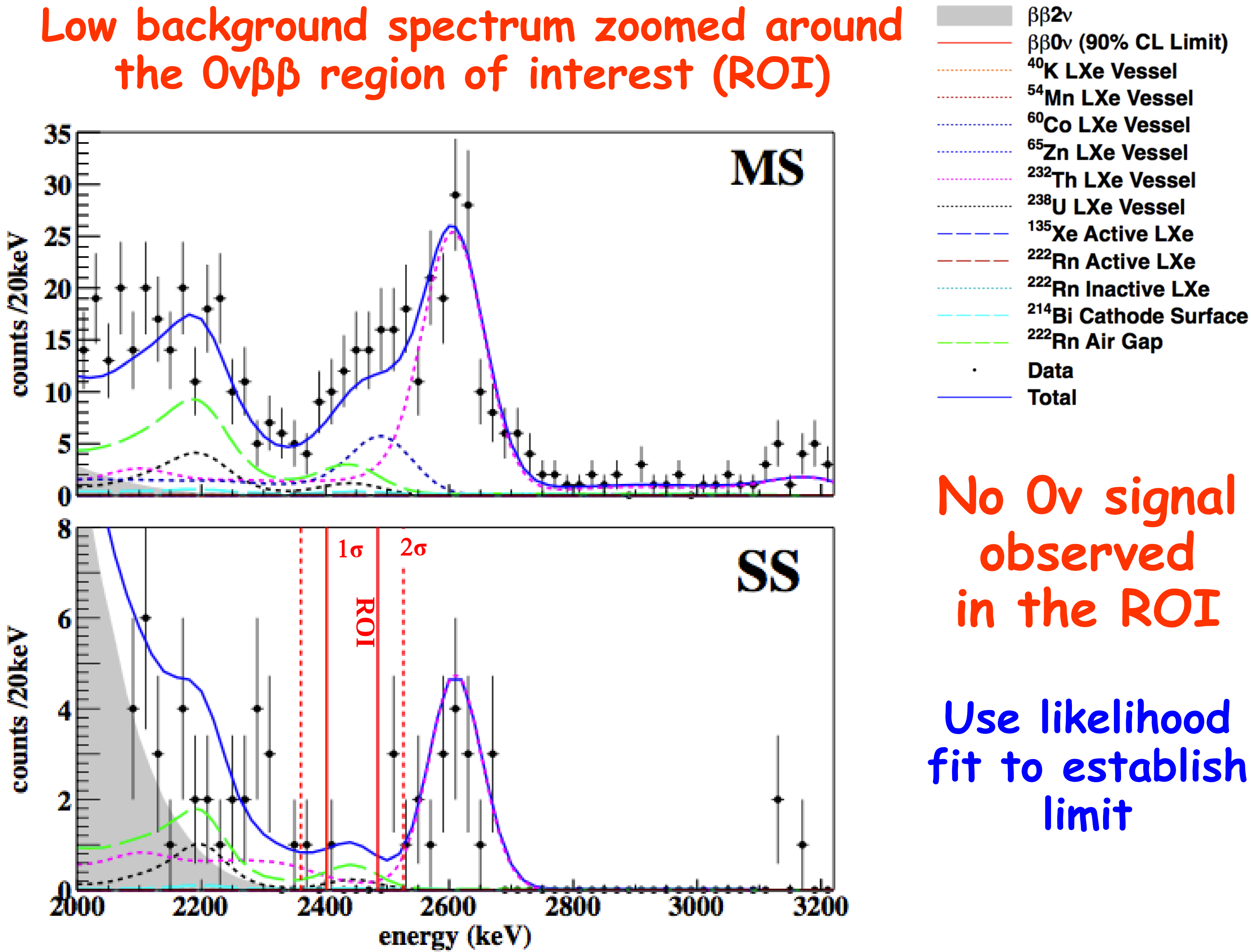
[Phys Rev C 89 (2014) 015502]

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	$2.165 \pm 0.016 \pm 0.059 \cdot 10^{21}$	± 2.83	1433	0.0218	± 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 [39] (2013)
^{130}Te	$7.0 \pm 0.9 \pm 1.1 \cdot 10^{20}$	± 20.3	1529	0.0371	± 10.2	NEMO-3 [40] (2011)
^{116}Cd	$2.8 \pm 0.1 \pm 0.3 \cdot 10^{19}$	± 11.3	2764	0.138	± 5.7	NEMO-3 [41] (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 [41] (2010)
^{96}Zr	$2.35 \pm 0.14 \pm 0.16 \cdot 10^{19}$	± 9.1	6816	0.0959	± 4.5	NEMO-3 [42](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 [43](2009)
^{100}Mo	$7.11 \pm 0.02 \pm 0.54 \cdot 10^{18}$	± 7.6	3308	0.250	± 3.8	NEMO-3 [44](2005)
^{82}Se	$9.6 \pm 0.3 \pm 1.0 \cdot 10^{19}$	± 10.9	1596	0.0980	± 5.4	NEMO-3 [44](2005)

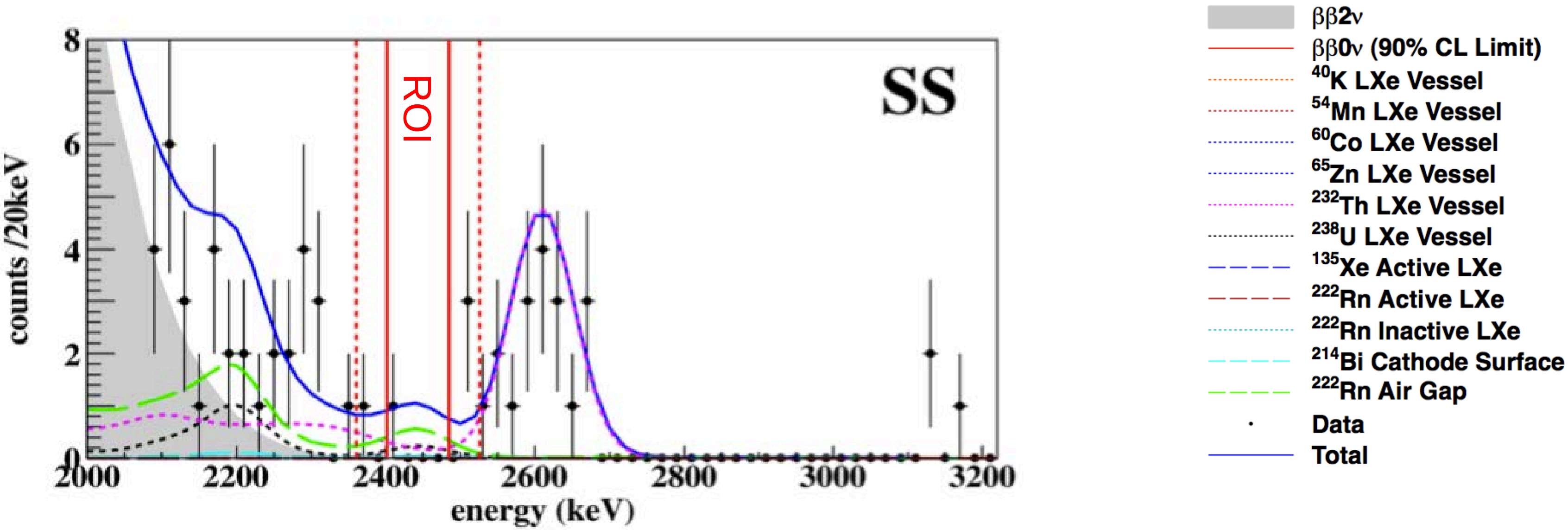
Low background spectrum zoomed around the 0νββ region of interest (ROI)



No 0ν signal observed in the ROI

Use likelihood fit to establish limit

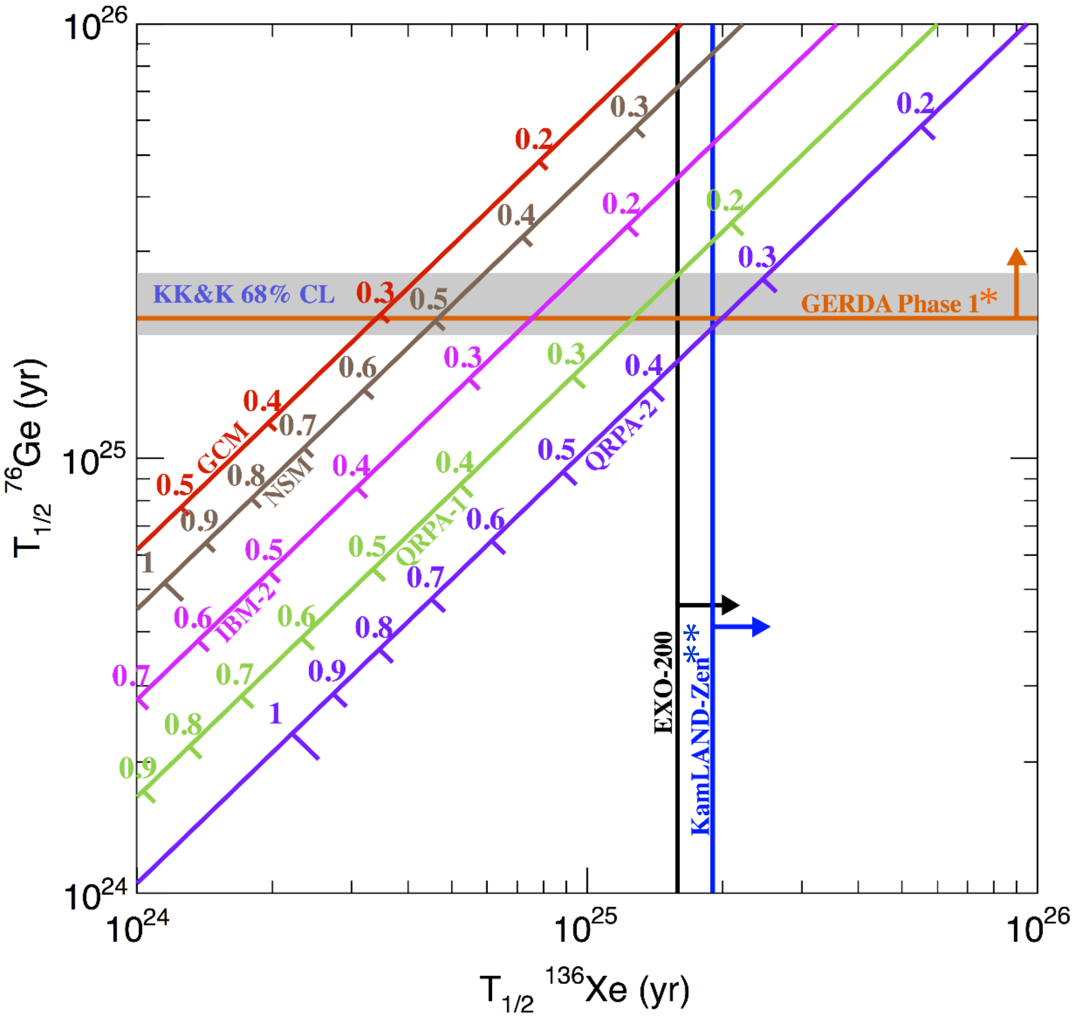
Background counts in ±1,2 σ   ROI



	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	

60 cnts/2yr in the 0νββ ±2σ ROI in 140kg of LXe

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

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

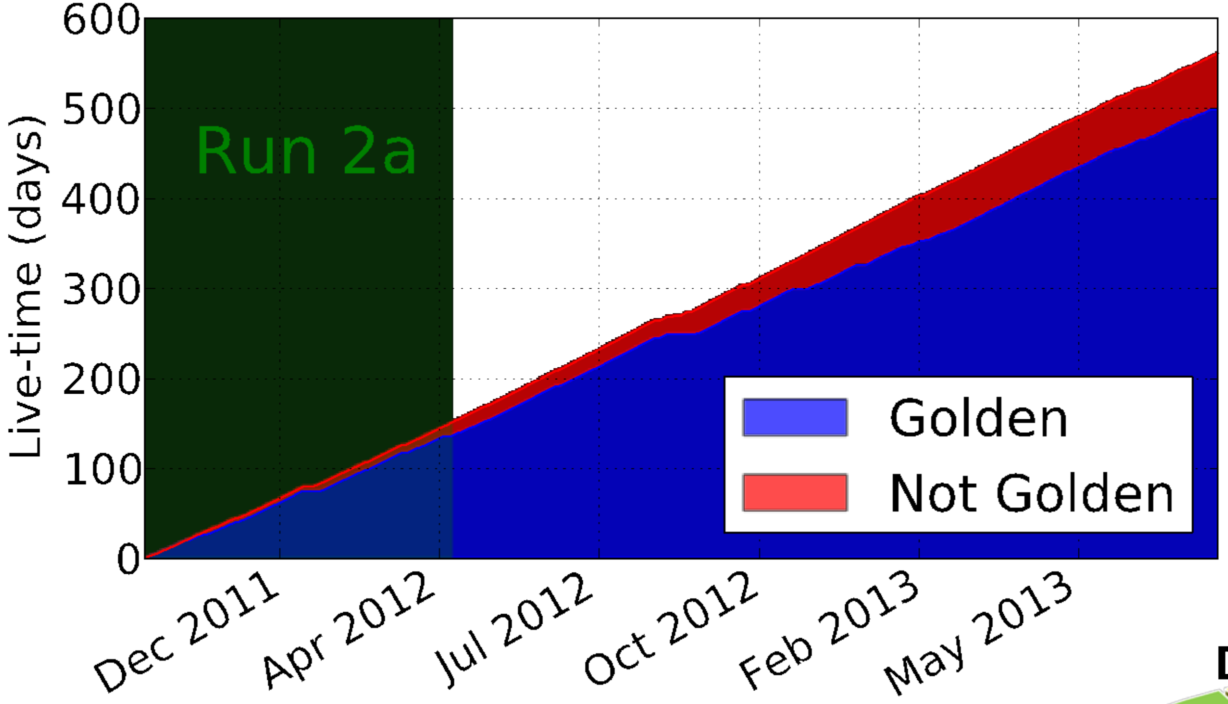
(90% C.L.)

Phys Rev Lett 109 (2012) 032505

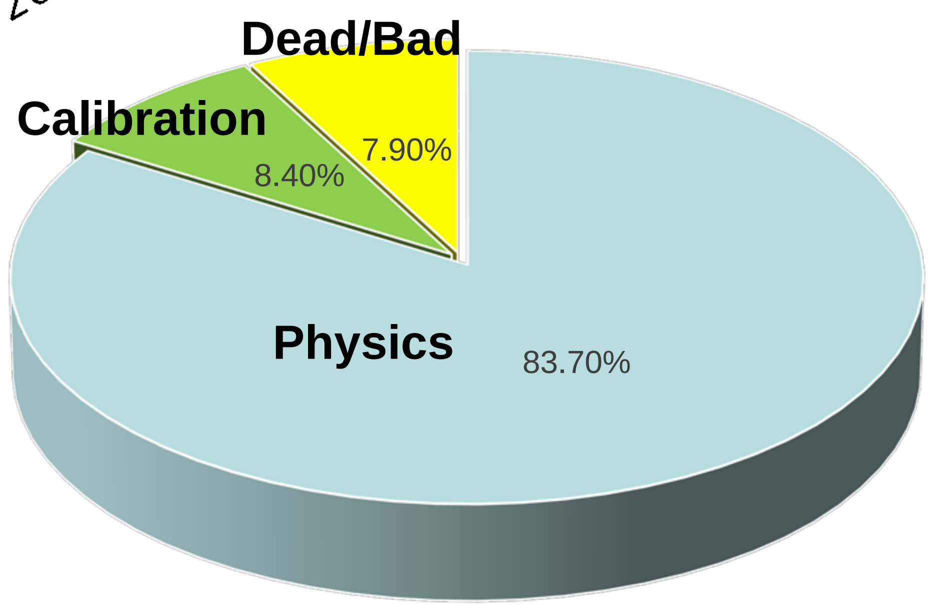
* M.Agostini et al. PRL 111 (2013) 122503

** A.Gando et al. PRL 110 (2013) 062502

Data accumulation (6 Oct 2011- 6 Aug 2013)



4x datadet on disk



As EXO-200 continues data taking a new collaboration

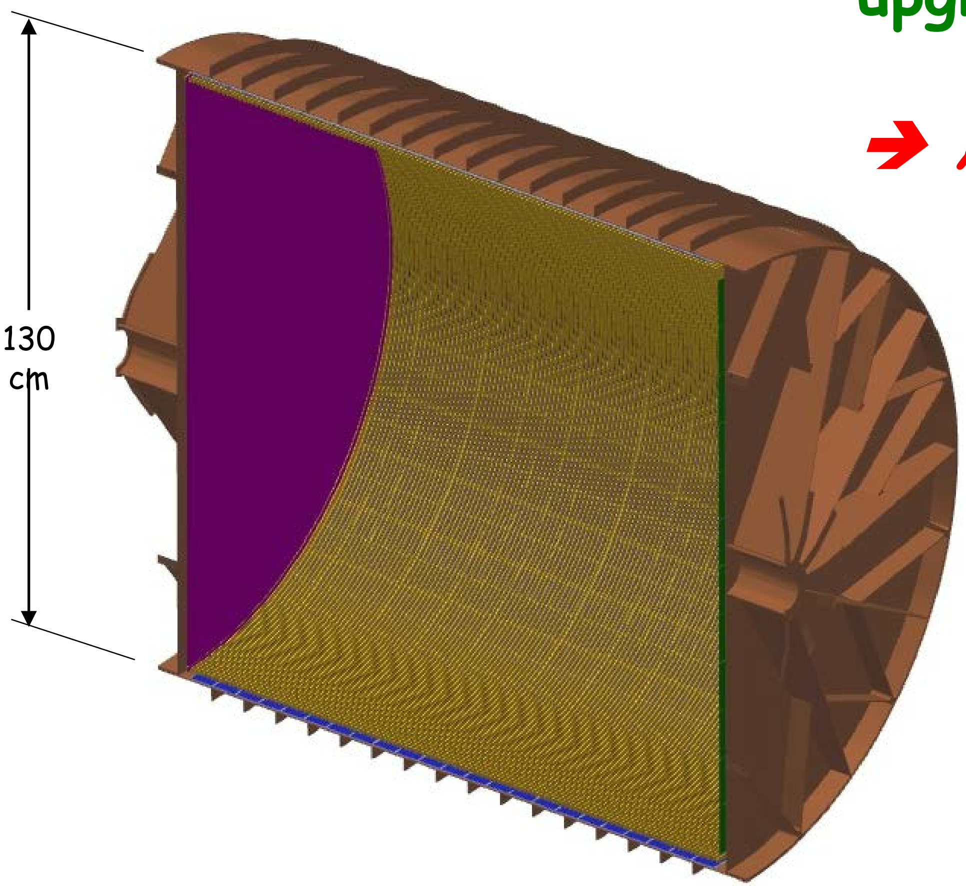
nEXO

is being formed

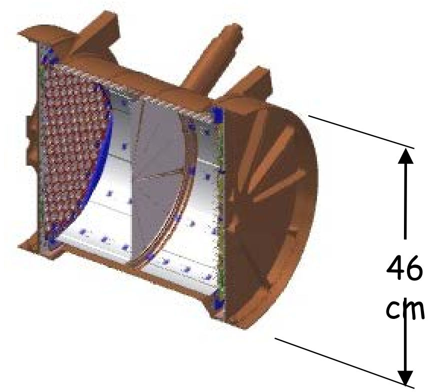
- *New groups have the opportunity to join as "charter members"*
- *Only conflict with ton-scale projects*
- *Larger collaboration organized to execute a larger and more formal project*

nEXO

- 5 tonnes of ^{enr}Xe: entirely cover inverted hierarchy
- LXe TPC "as similar to EXO-200 as possible"
- Provide access ports for a possible later upgrade to Ba tagging



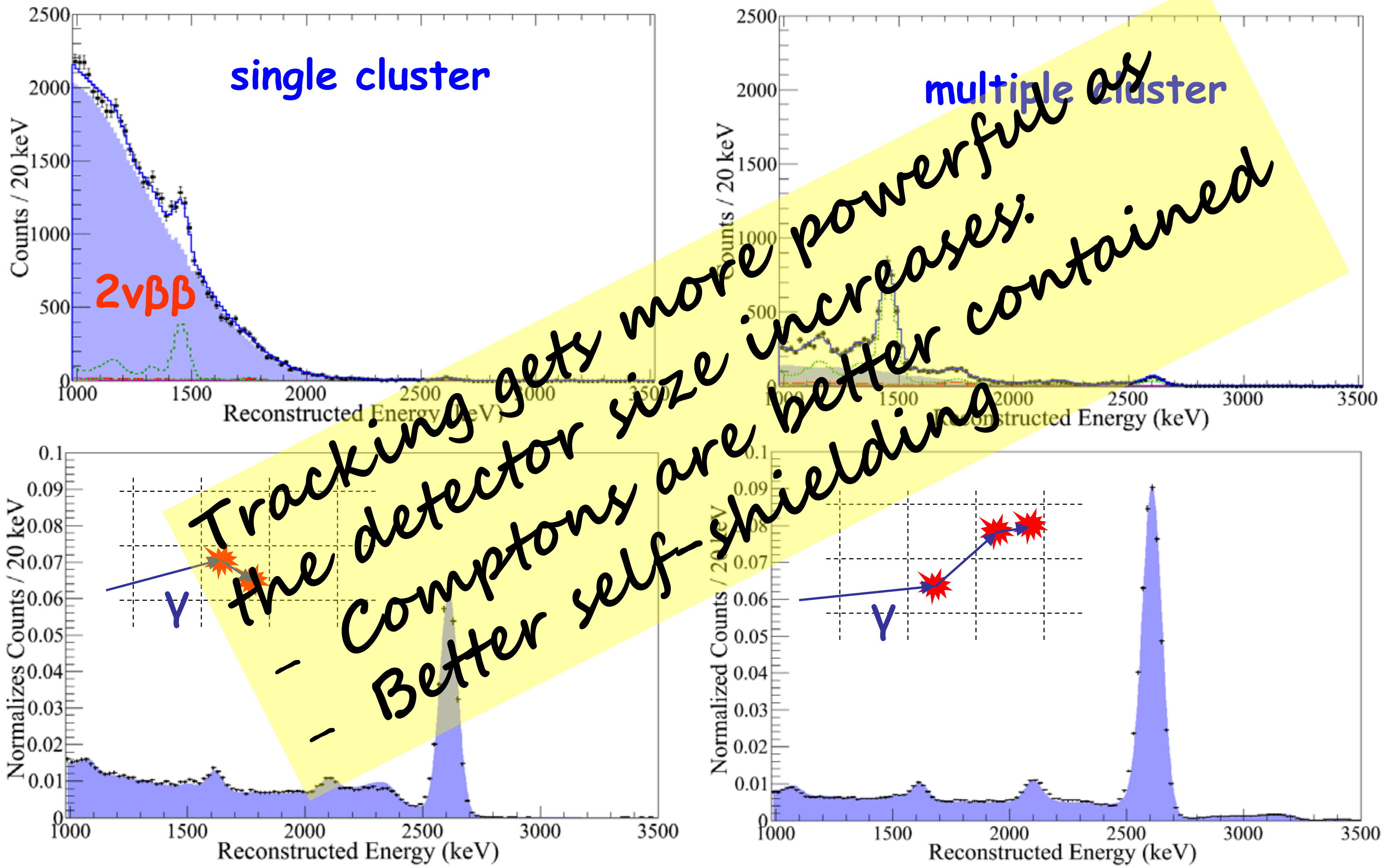
➔ *A unique combination of conservative and aggressive design with important upgrade paths as desirable for a large experiment*



Tracking:
an essential tool to identify and suppress backgrounds

Low background data

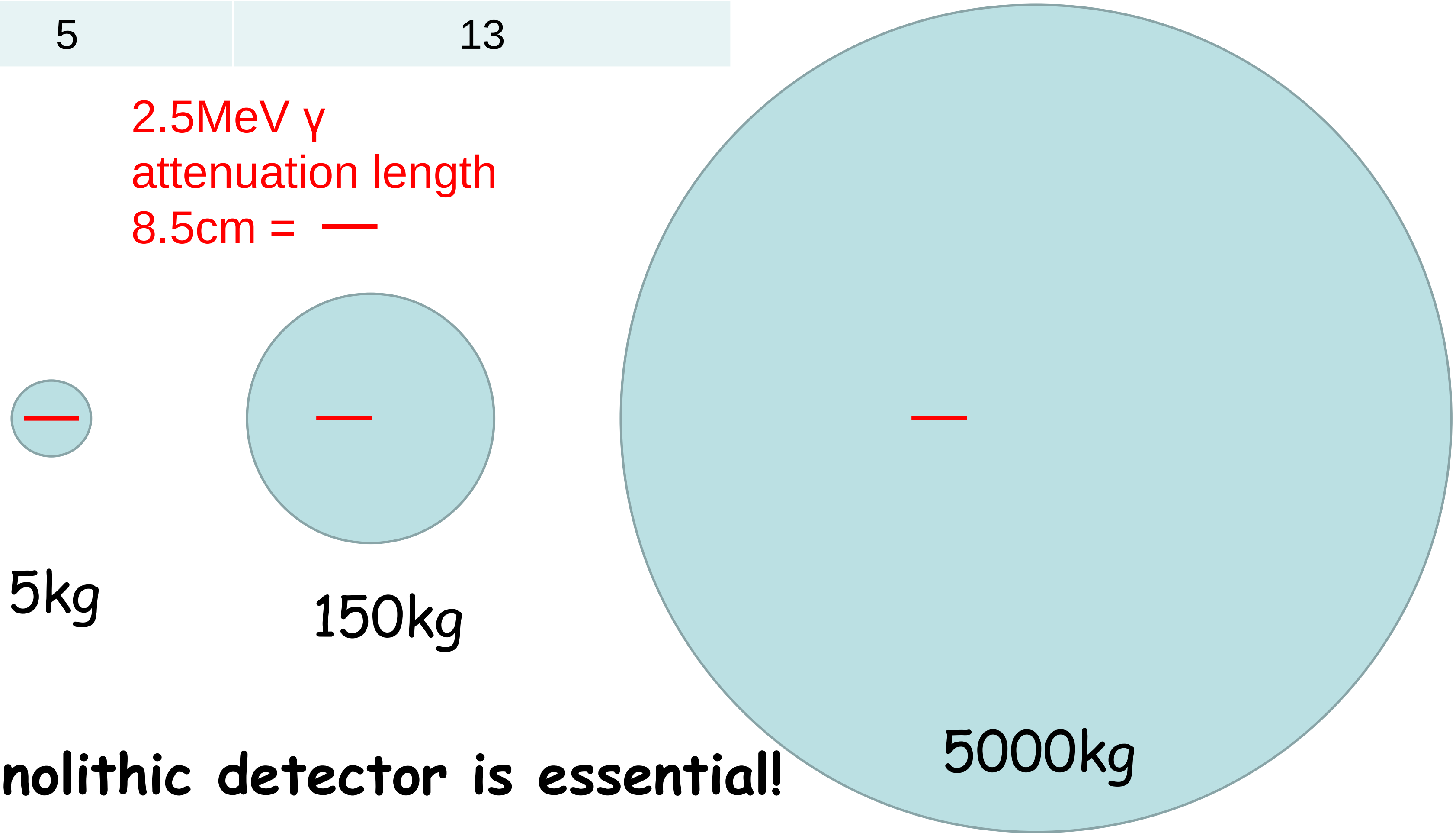
^{228}Th calibration source



Tracking gets more powerful as the detector size increases.
- Comptons are better contained
- Better self-shielding

LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

2.5MeV γ attenuation length 8.5cm = —



Monolithic detector is essential!

Material procurement

^{136}Xe enrichment easier and cheaper:

➔ **90% enriched ^{136}Xe: ~10$/g**

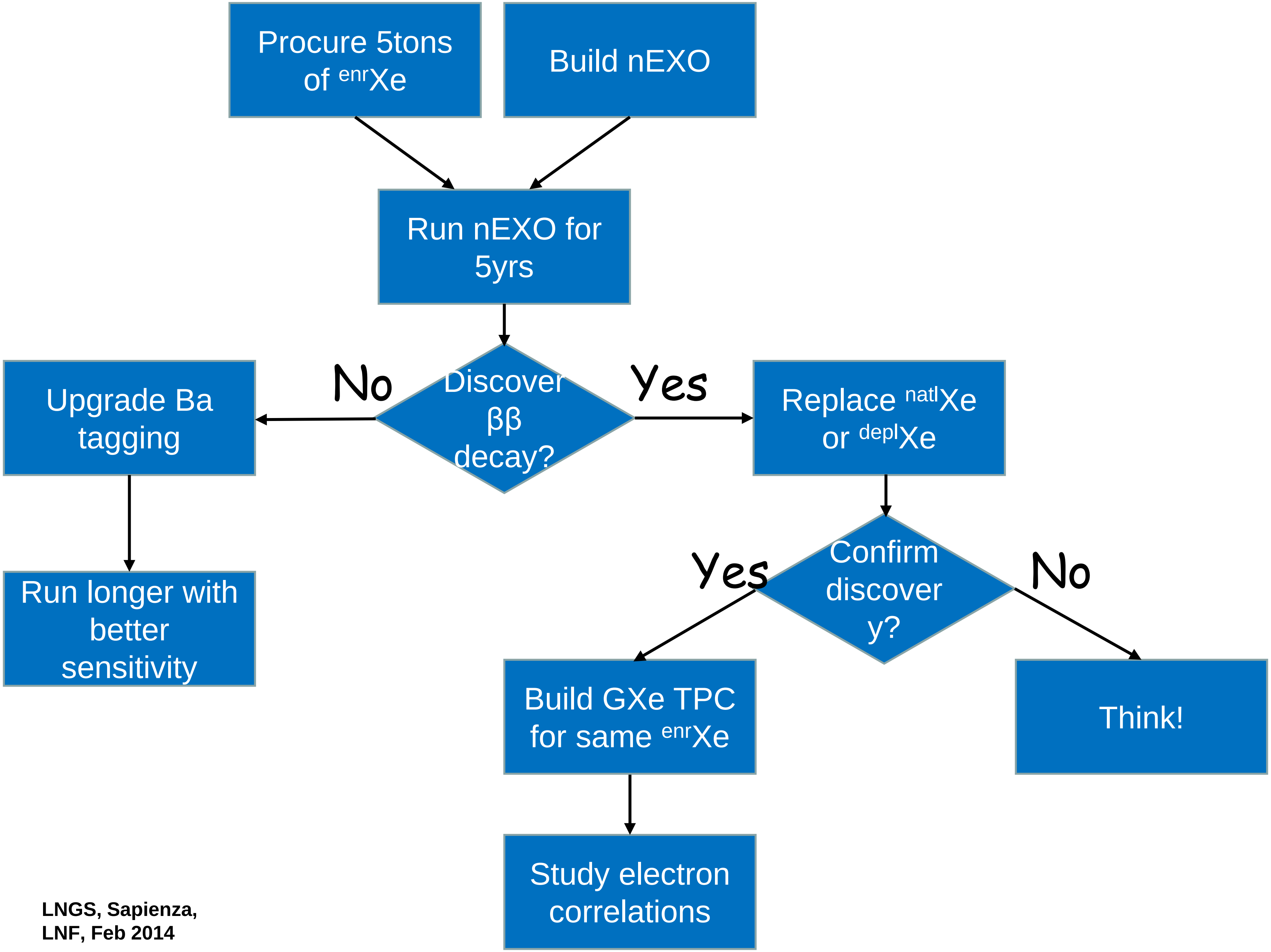
90% enriched ^{76}Ge: ~90$/g (+xtal growth)

(EXO-200 uses 80% enriched Xe. It now seems customary to do 90% and it appears that there is no major cost difference)

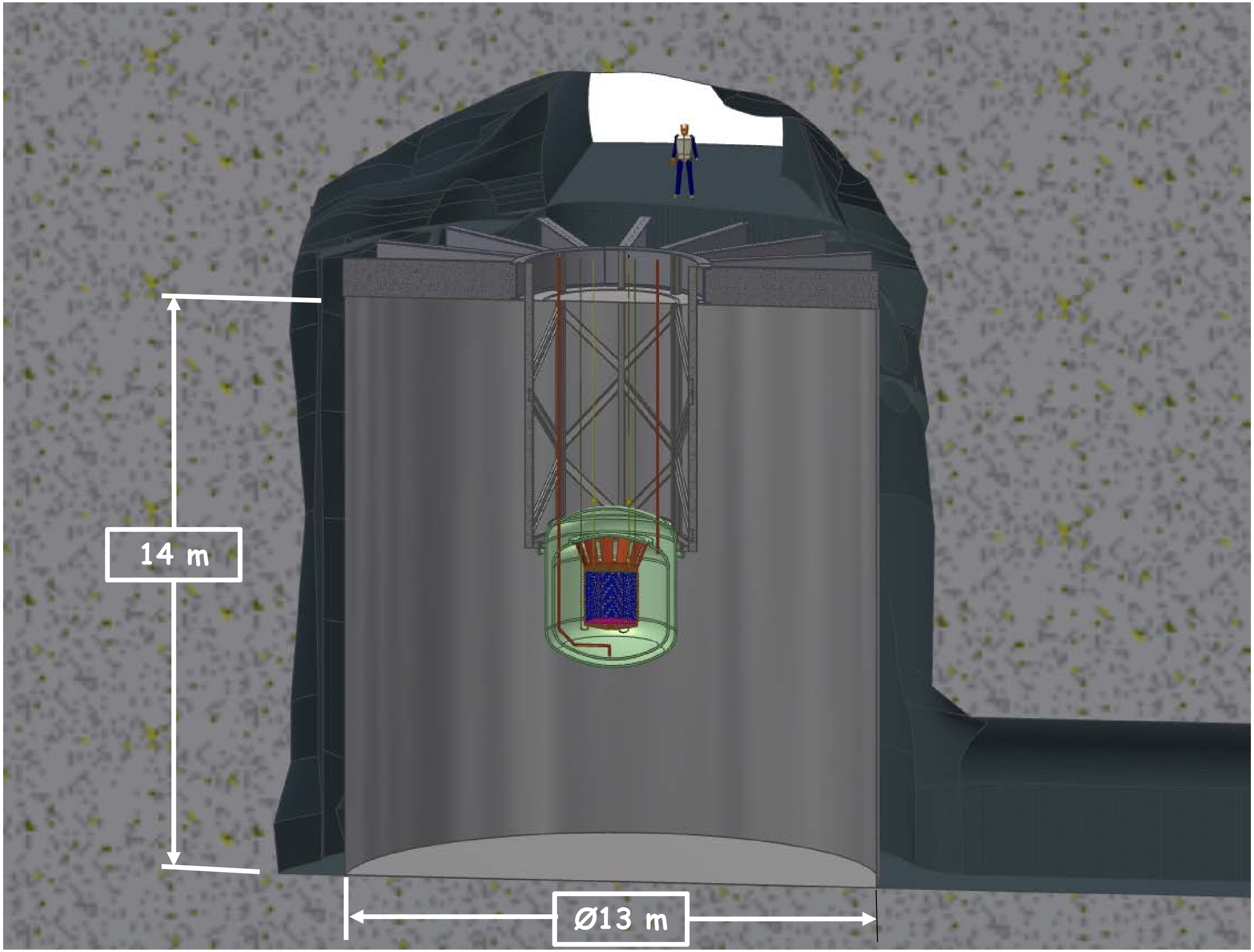
Exact centrifuge capacity in Russia is classified but our contacts indicate that 5000kg in 5 years is comfortable

- *World $^{nat'l}$Xe production is ~40 tonnes/yr (~4000kg ^{136}Xe), however large price fluctuations are not uncommon*
- *Coordination with DM experiments, space agencies and commercial customers is desirable*

Flexible program based on the initial nEXO investment



Preliminary artist view of nEXO in the SNOlab Cryopit



nEXO design:

Rule #1: Follow as closely as possible the design of EXO-200 since EXO-200 works so well

Rule #2: When in doubt, look at Rule #1

→ ***Limited R&D required:***
much of the detector can be/is being designed now.

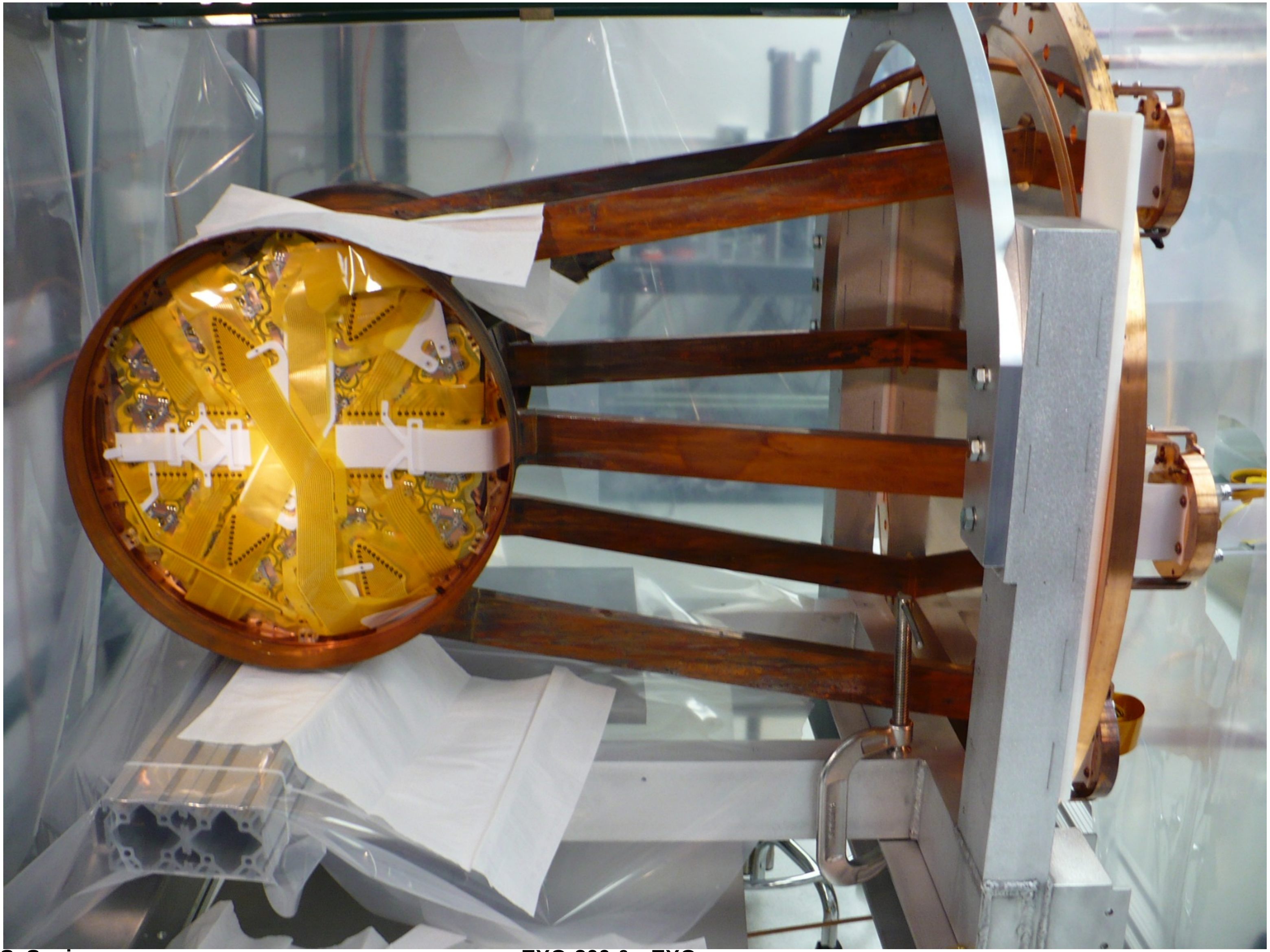
→ ***Low risk***

What we need to change (Cat):

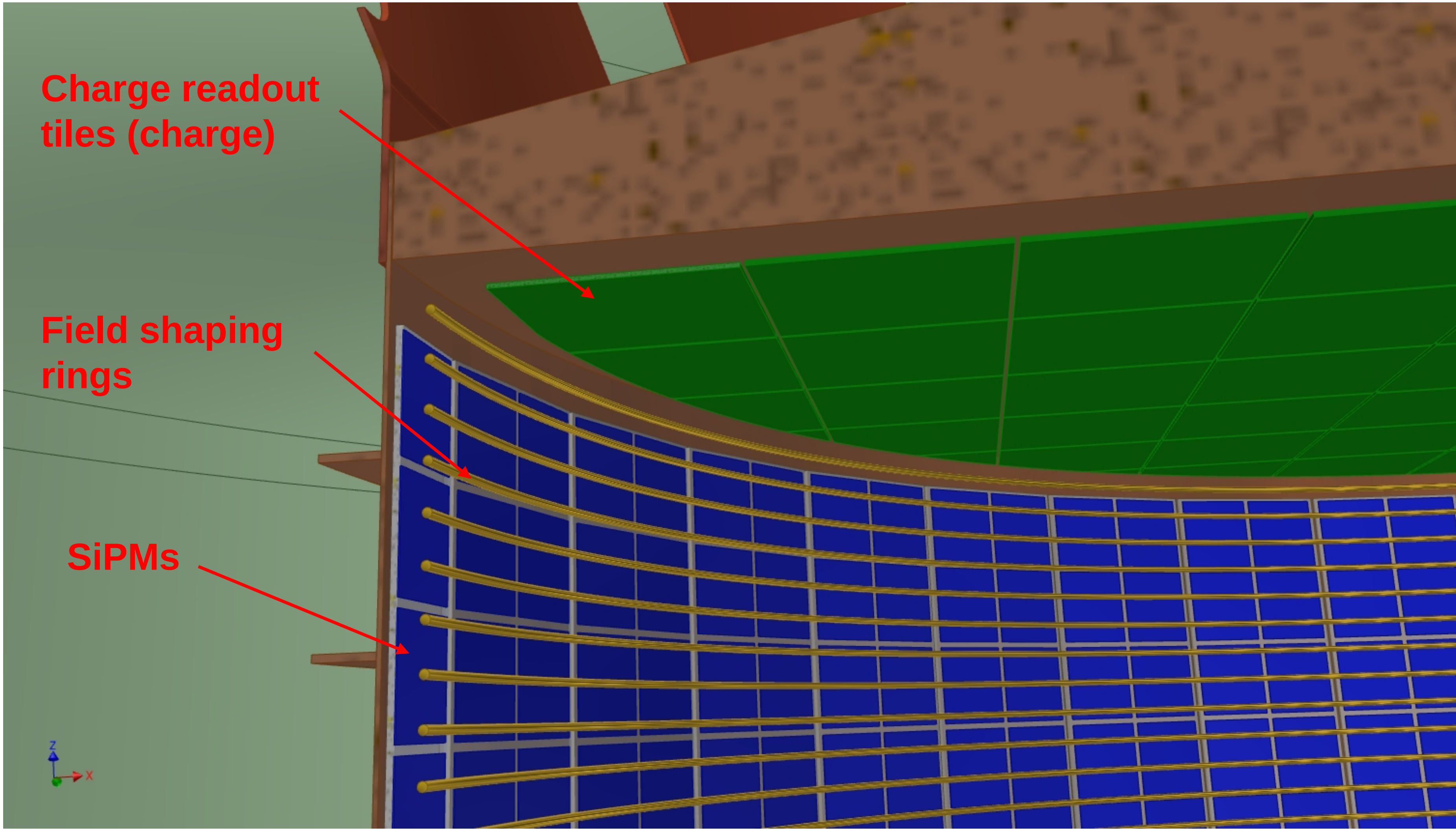
1. We know of a few things that were not quite right in EXO-200
2. Some items don't scale properly from 150kg to 5000kg

Item/concept	Reason to change	Cat	Risk
Water shield	More convenient for large size, very standard	2	Very low
Vertical detector axis	Horizontal for EXO-200 due to site constraint	1	None
Composite cryostat	Too large for conveyance at SNOlab, composite easier to build underground	2	Low
One drift space	Lowest background in the middle	1	Medium
Internal electronics	Lower outgassing, lower activity, better S/N	2	Low
SiPMs	Better S/N, Lower mass, More common, no HV	1, 2	Medium
No Teflon reflectors	Lower outgassing	1	None
Higher charge readout density	Better background rejection	1	Low
High Voltage Noise	EXO-200 (and other LXe detectors) can't reach full HV	1	Medium
Add LXe purity mtr	Longer drift, harder calibration	2	Low
Add prepurif Xe source	No purity loss from feeds, higher live time	1	None

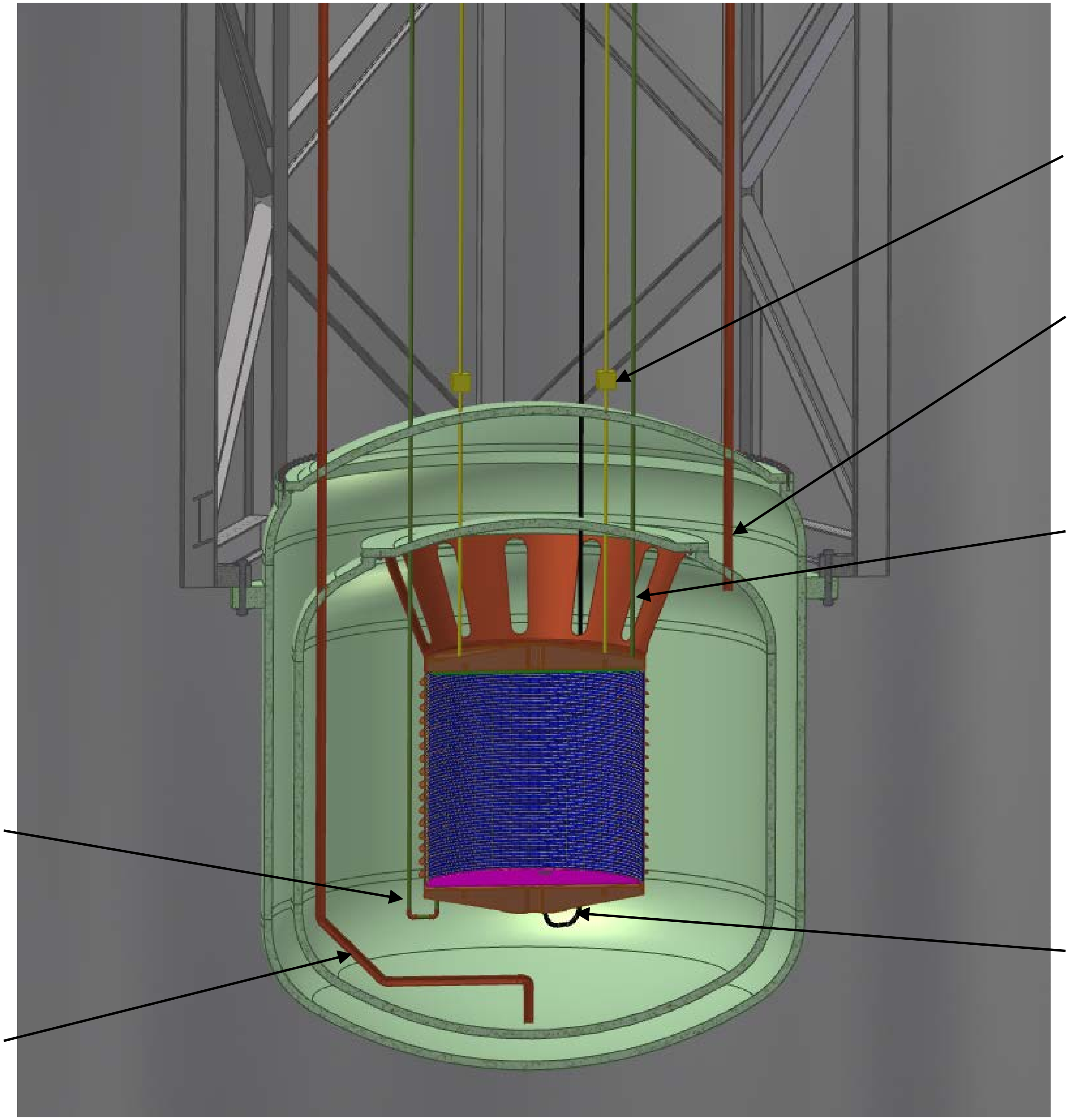
…it is remarkable that EXO-200 can achieve 5ms electron lifetime with a detector stuffed of (very clean and purged) plastics



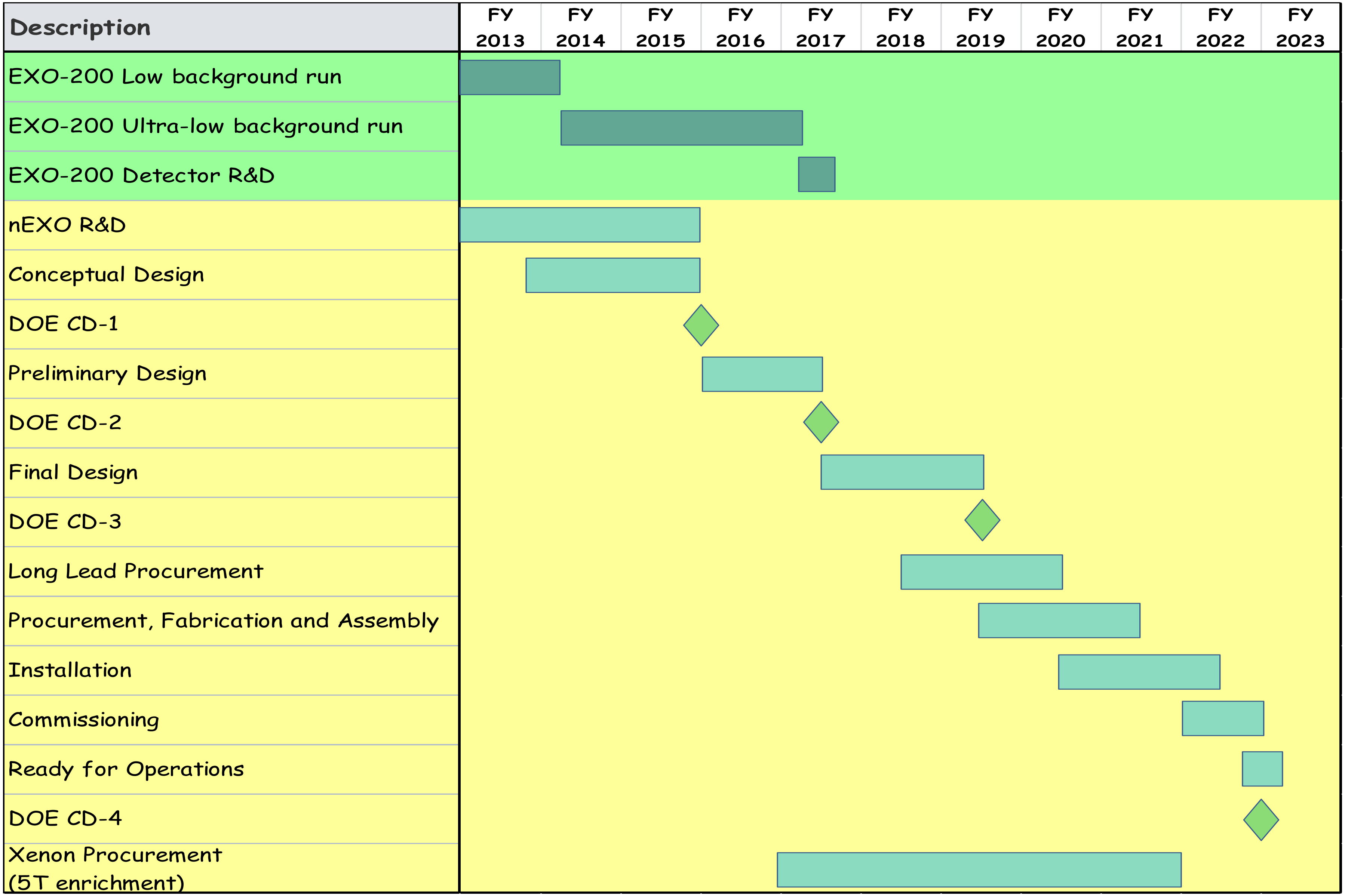
Close-up of the field shaping rings, anode readout tiles and SIPMs



Detail of the cryostat concept



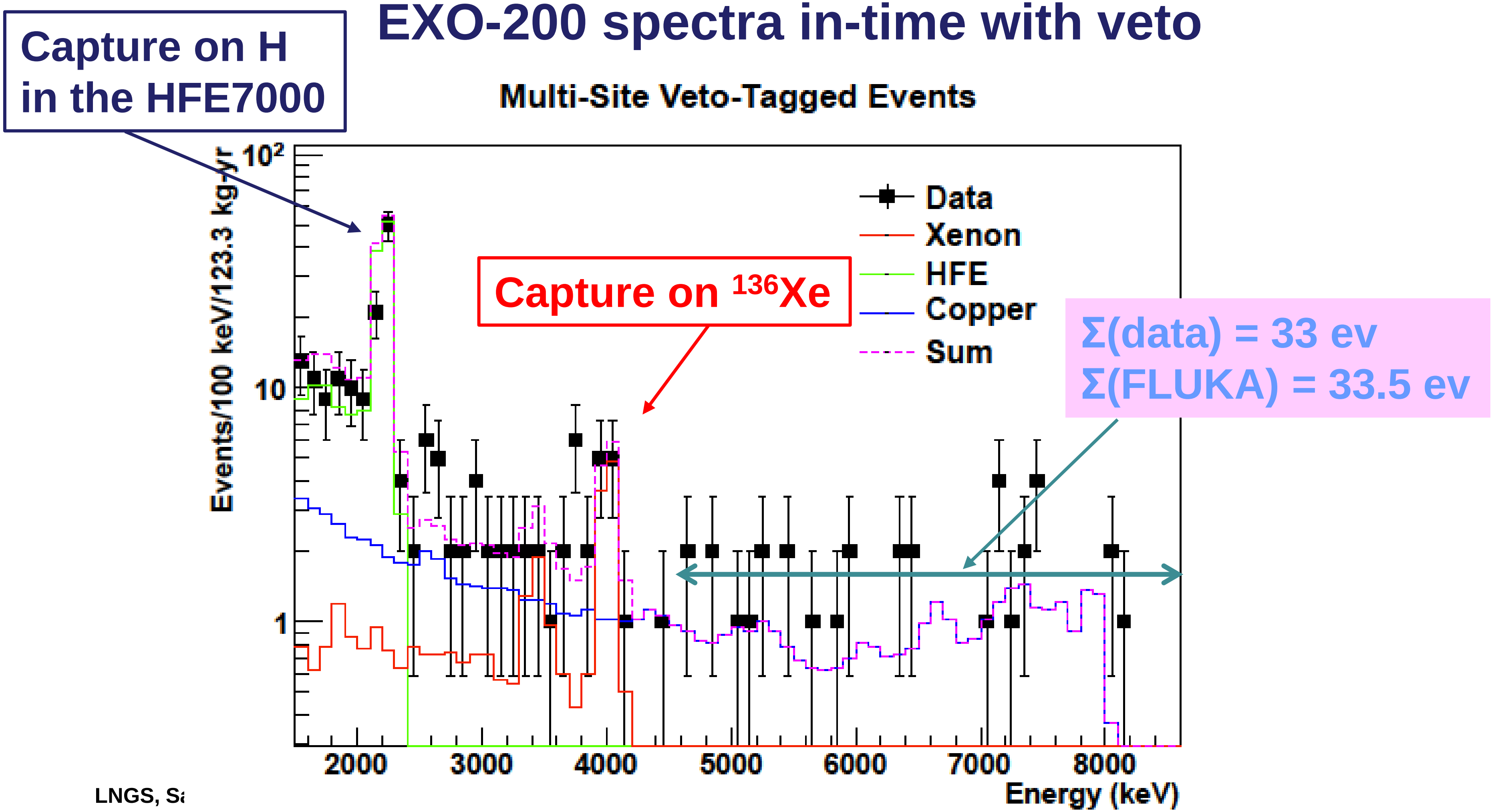
Notional time schedule for nEXO



Cosmogenic n backgrounds in nEXO simulated using FLUKA

…but, before relying on it, FLUKA's prediction can be verified with actual EXO-200 data!

EXO-200 spectra in-time with veto



Other n backgrounds

- **Prompt events following a muon**
- **Neutrons from rock radioactivity**

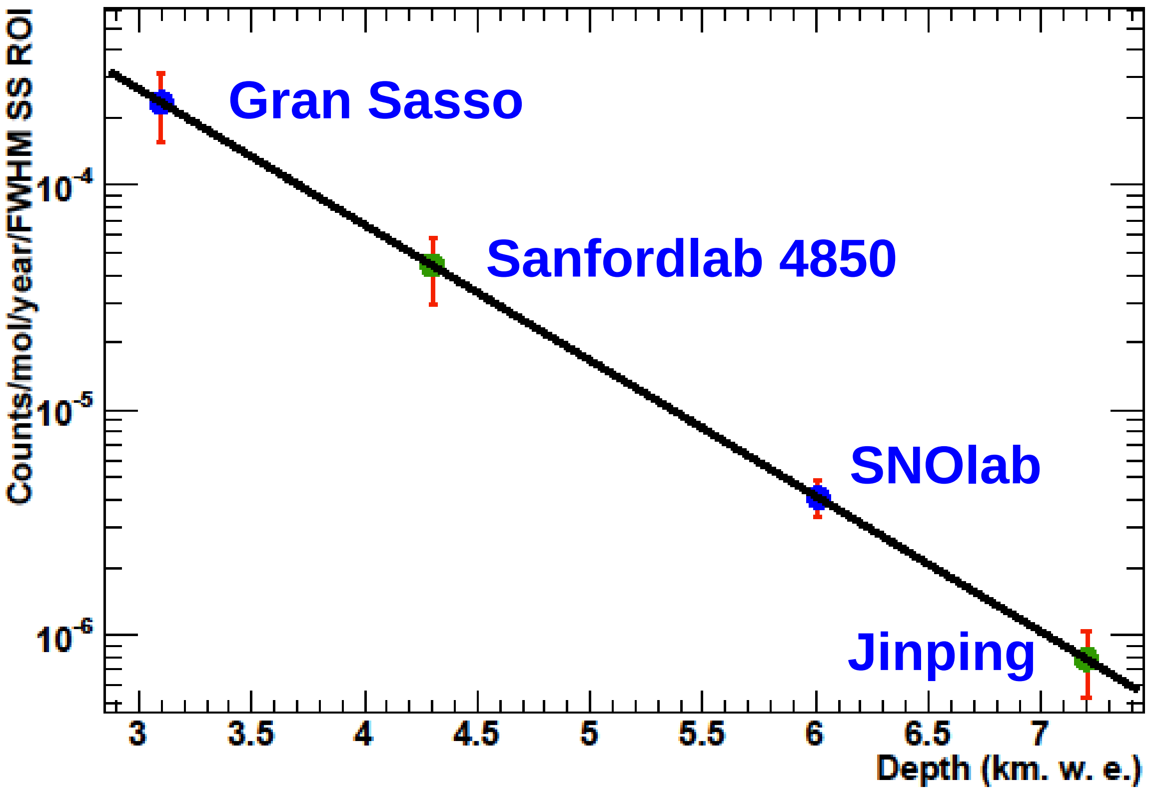
➔ very strongly suppressed by the large water shield and give a negligible contribution

…and ν induced backgrounds

Direct solar ν interaction	Rate all energies (ev/tonne/10yr)	Rate in ROI	
		(ev/tonne/10yr/ FWHM)	(ev/mol/yr/ FWHM)
N_e – e elastic scattering (^{8}B+reactors+Geo)	17.6	0.16	$3.1 \cdot 10^{-6}$
ν capture on ^{136}Xe (^{8}B ν)	20	0.16	$3.2 \cdot 10^{-6}$
ν-induced ^{136}Cs decay	50	0.03	$4 \cdot 10^{-7}$
Total	88	0.35	$6.7 \cdot 10^{-6}$

From this study can extract backgrounds as function of depth

Simulation done with muon spectrum and rate of LNGS



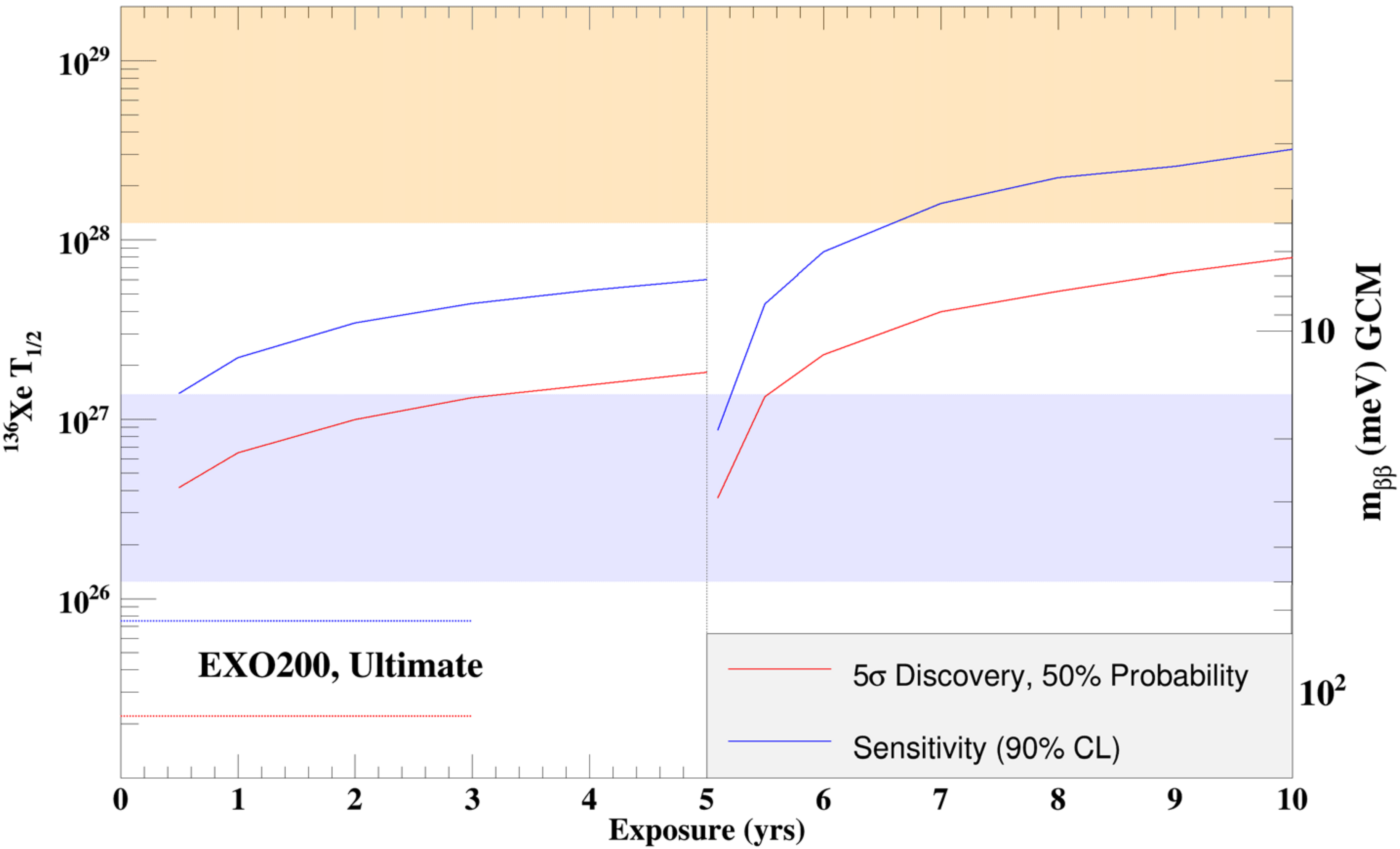
Conclusion:

- SNOlab and Jinping are comfortable
- SanfordLab at 4850 is probably ok
- Gran Sasso is marginal but may be ok, needs veto study

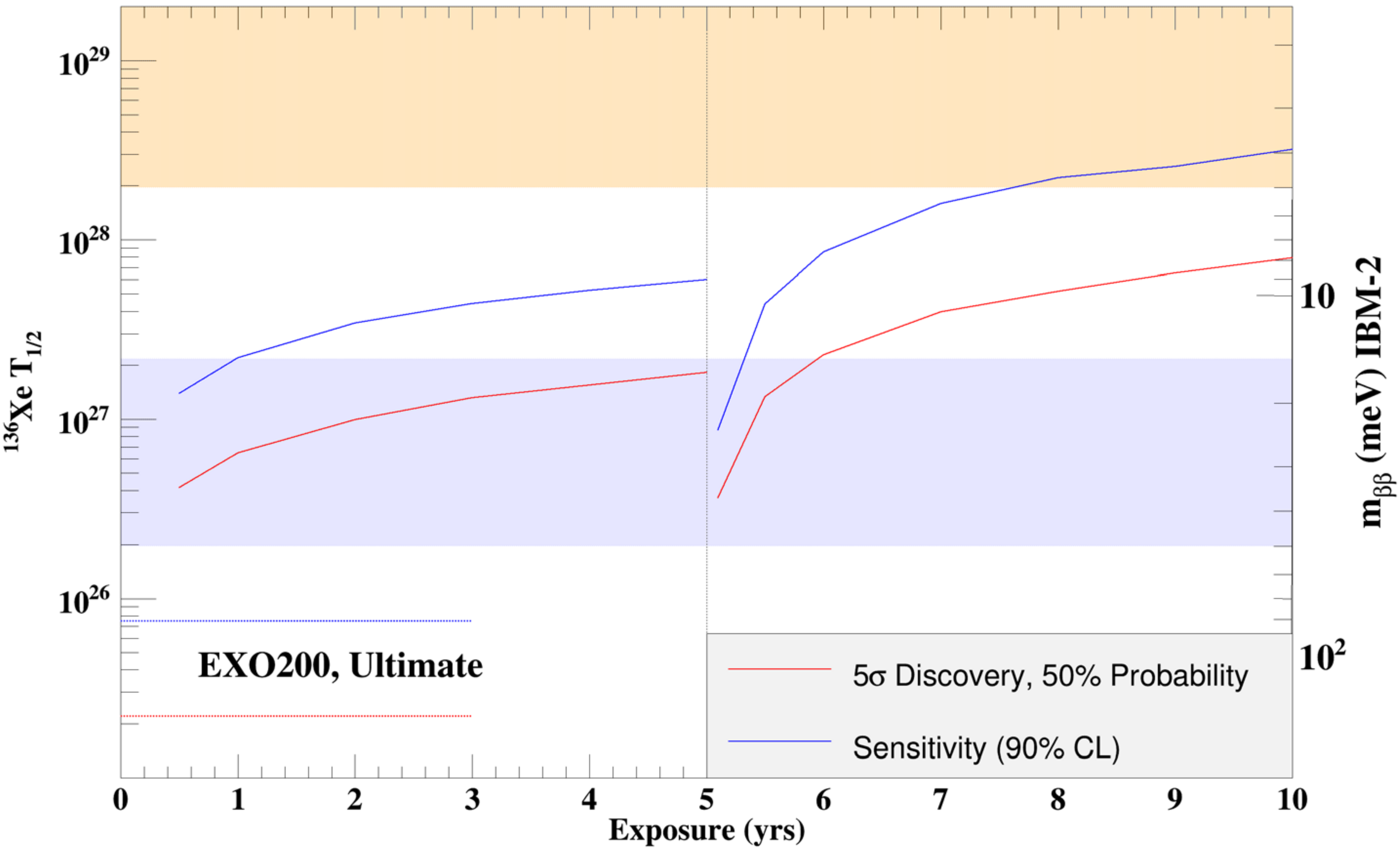
Summary of nEXO assumptions compared to EXO-200

Parameter	nEXO	EXO-200
Fiducial Mass (kg)	4780	98.5
Enrichment (%)	90	80
Data taking time (yr)	5	5
Energy resolution @$Q_{\beta\beta}$ (keV)	58	88 (58)
Background in ROI (ev/yr/mol_{136})	$6.1 \cdot 10^{-4}$	0.022 (0.0073)
Background in ROI inner 3000kg (ev/yr/mol_{136})	$1.6 \cdot 10^{-4}$	-

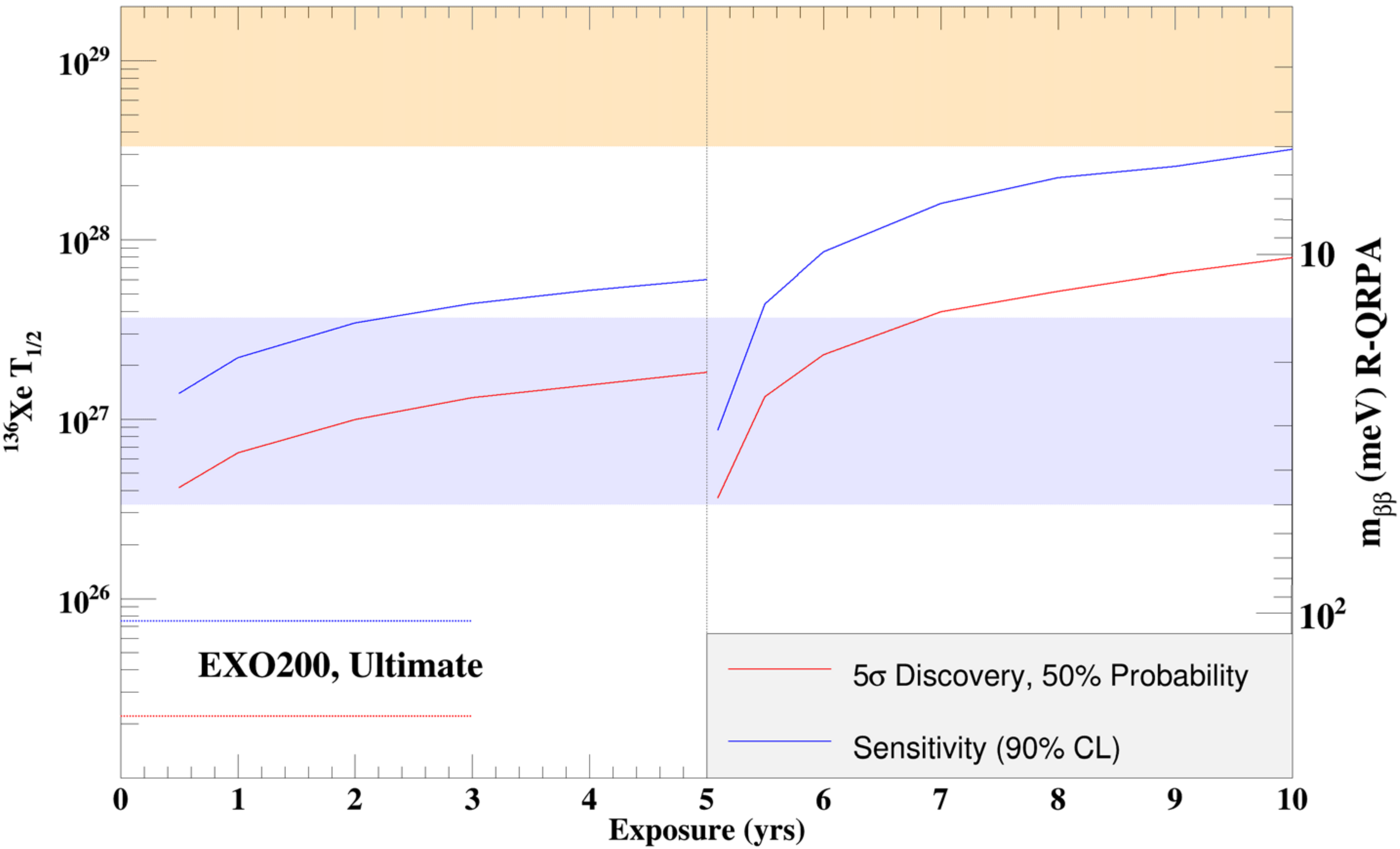
Sensitivity and discovery potential as a function of time



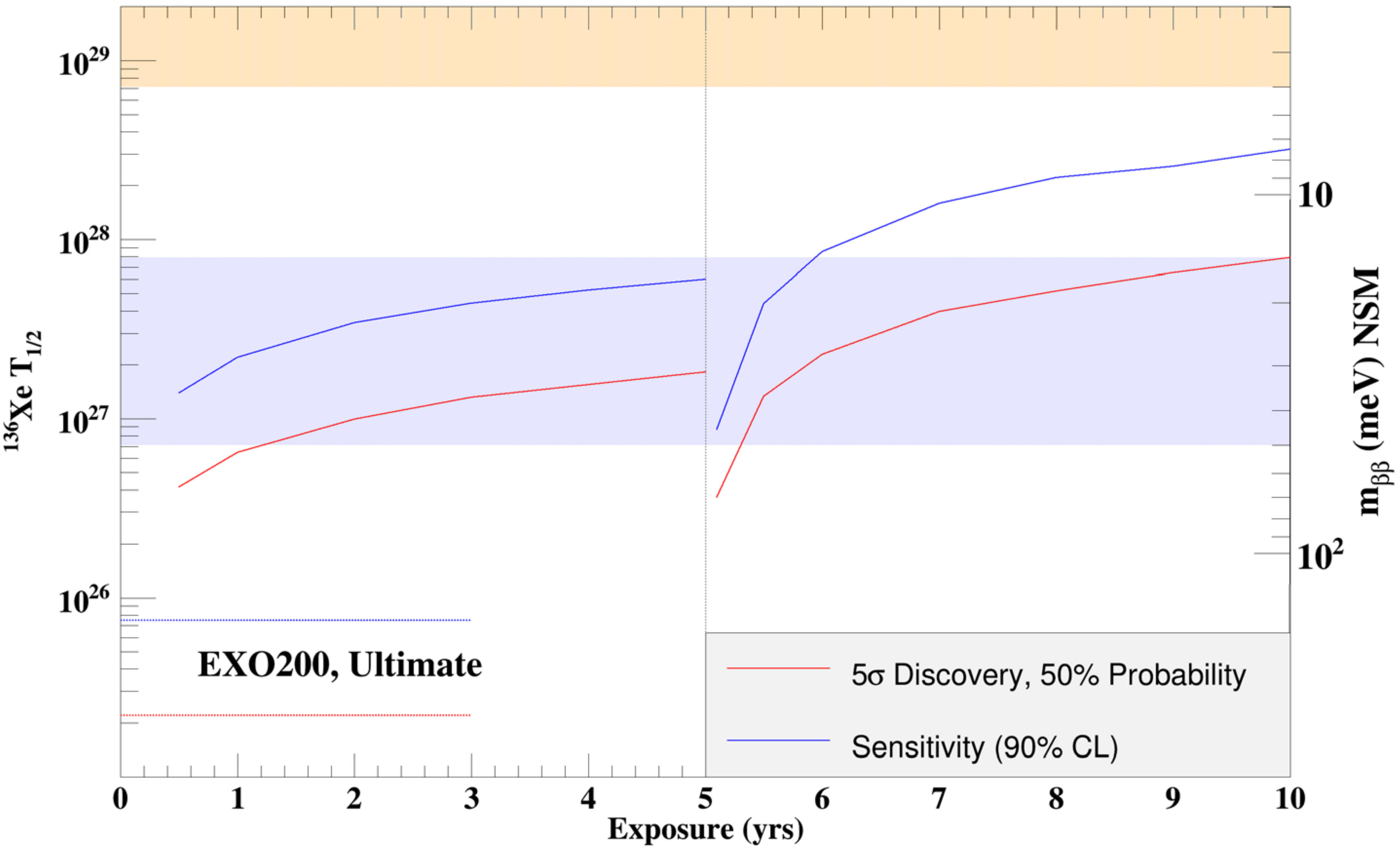
Sensitivity and discovery potential as a function of time



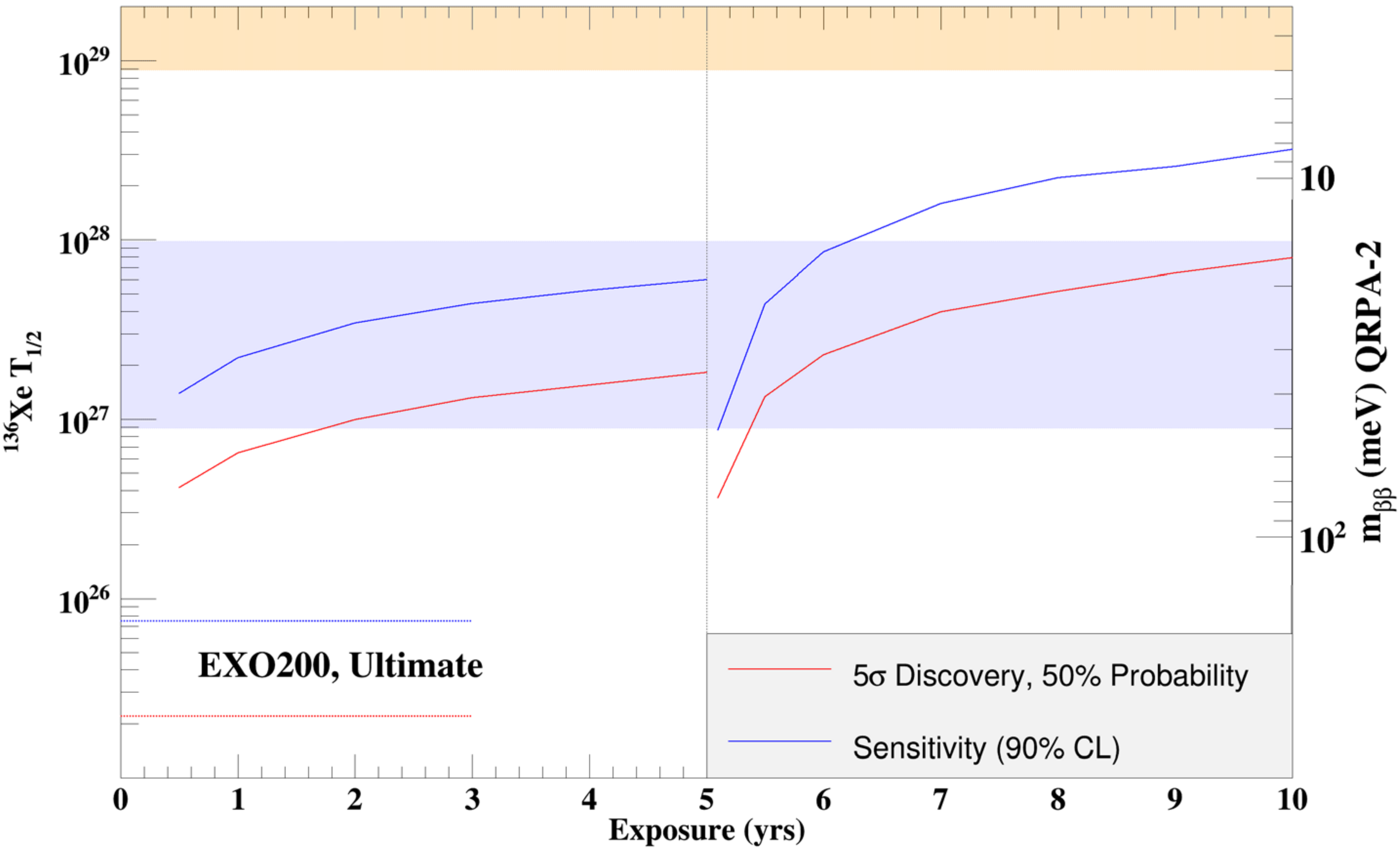
Sensitivity and discovery potential as a function of time

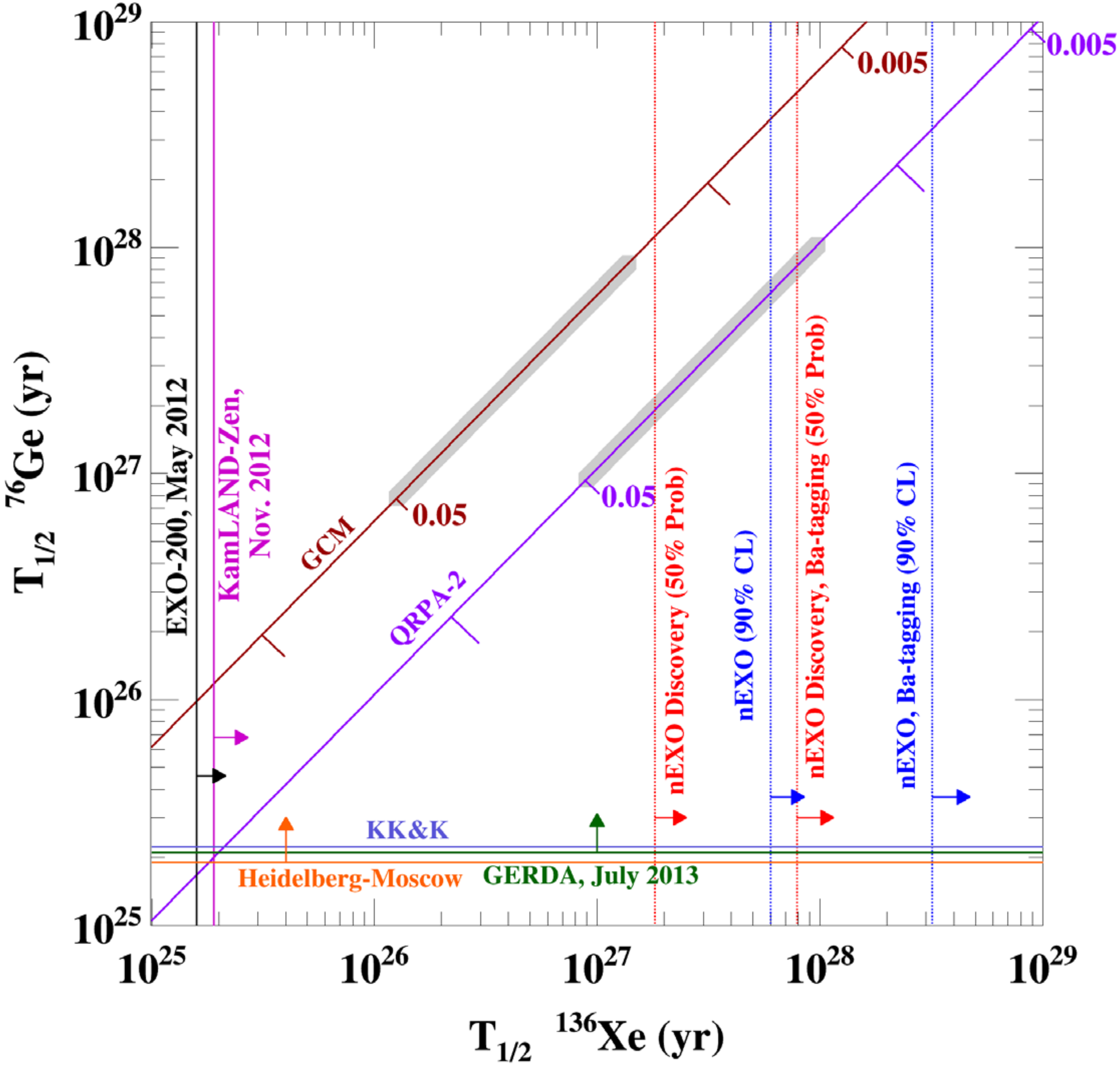


Sensitivity and discovery potential as a function of time



Sensitivity and discovery potential as a function of time





10^{29}
10^{28}
10^{27}
10^{26}
10^{25}
$T_{1/2}$ ^{76}Ge (yr)
$T_{1/2}$ ^{136}Xe (yr)
0.005
0.005
0.05
0.05
GCM
QRPA-2
EXO-200, May 2012
KamLAND-Zen, Nov. 2012
nEXO Discovery (50% Prob)
nEXO (90% CL)
nEXO Discovery, Ba-tagging (50% Prob)
nEXO, Ba-tagging (90% CL)
KK&K
Heidelberg-Moscow
GERDA, July 2013

Summary

- EXO-200 taking data since Jun 2011
- Discovered the 2νββ decay in ^{136}Xe;
  most accurate measurement to date
- Very competitive limit on the 0νββ decay
  with the first 4 month of data
- ~4x dataset on disk, better analysis
- Rn abatement system and upgraded
  electronics being prepared
- Working on the design of nEXO
- Next few years will be very exciting!