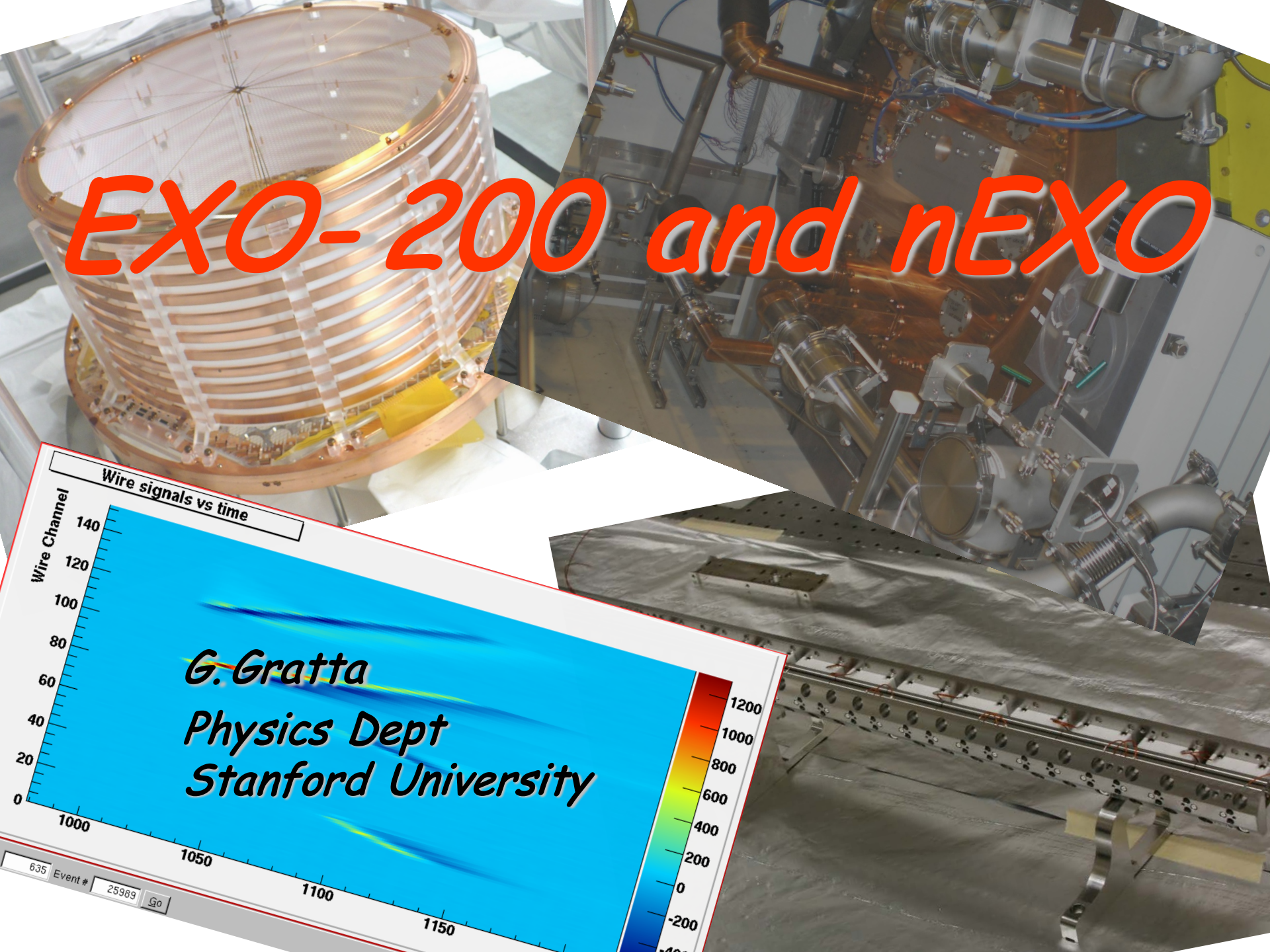
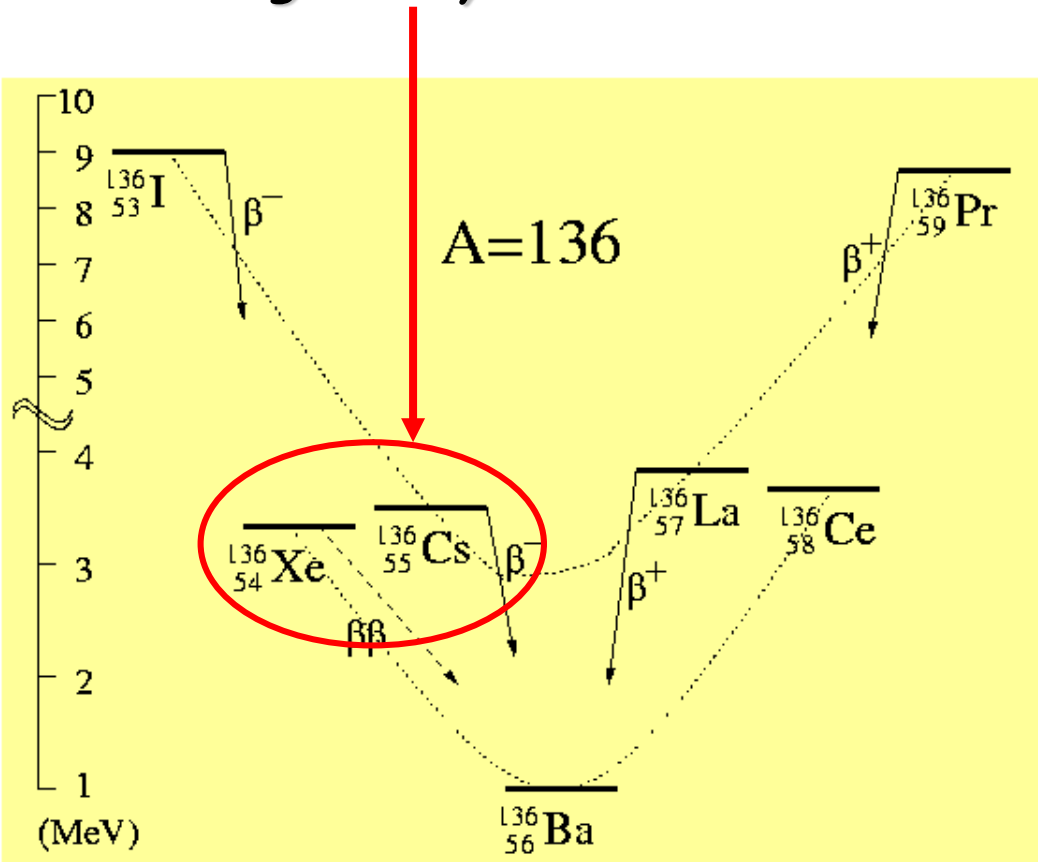
EXO-200 and nEXO



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

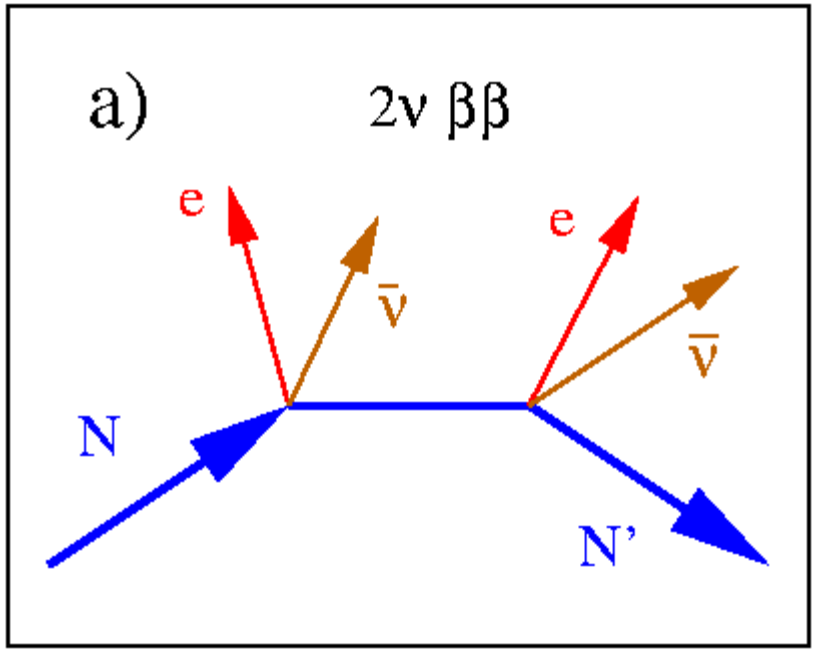
2ν mode:
a conventional
2nd order process
in nuclear physics

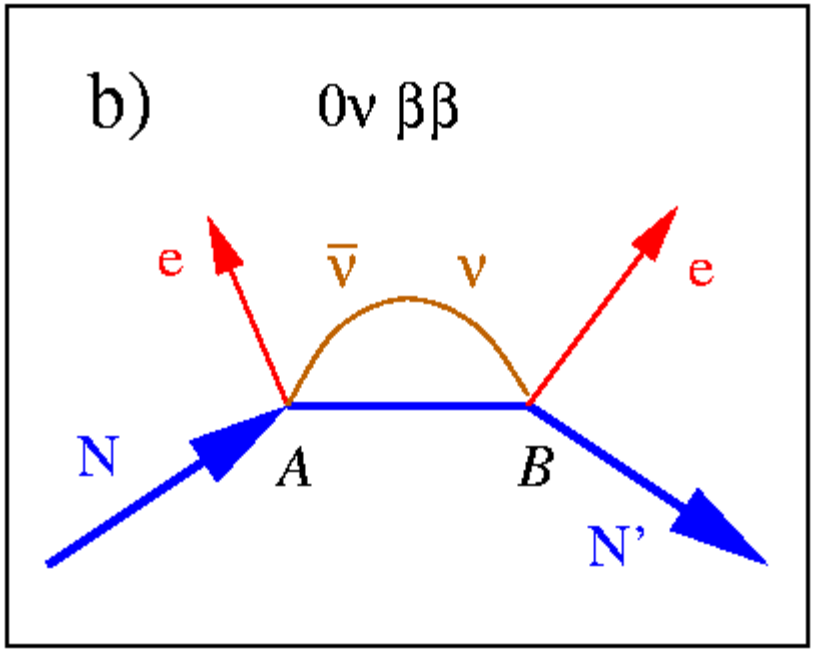
0ν mode: a hypothetical process can happen only if: $M_\nu \neq 0$

$\nu = \bar{\nu}$

$|\Delta L|=2$

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





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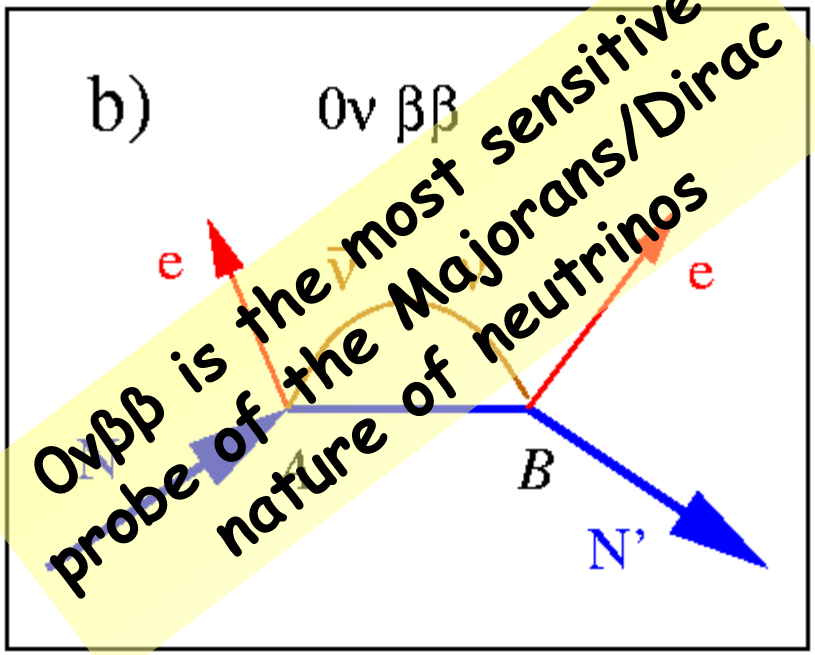
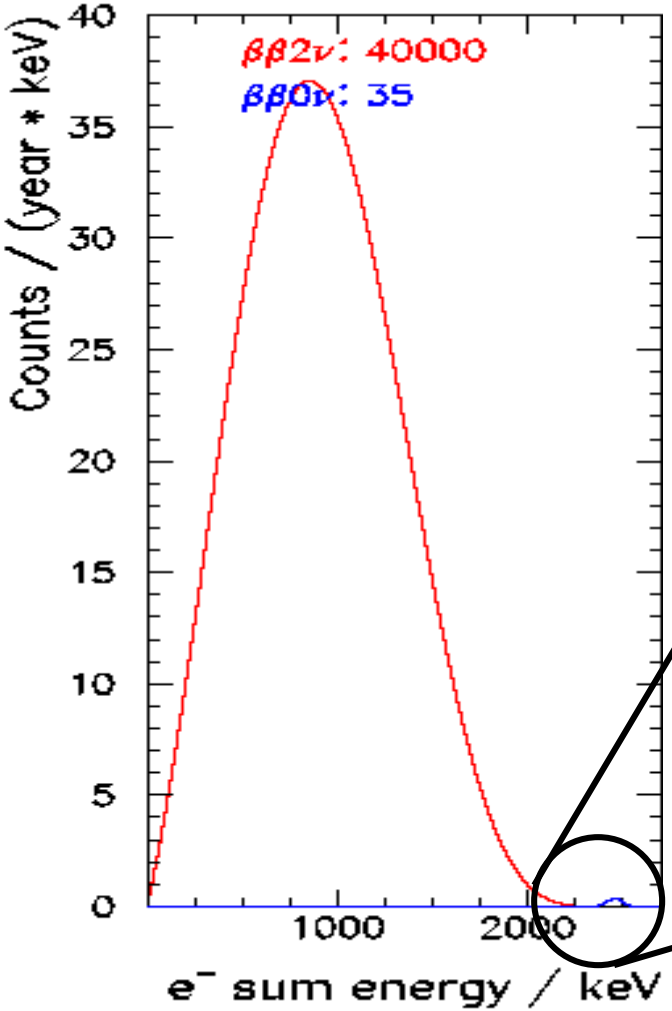
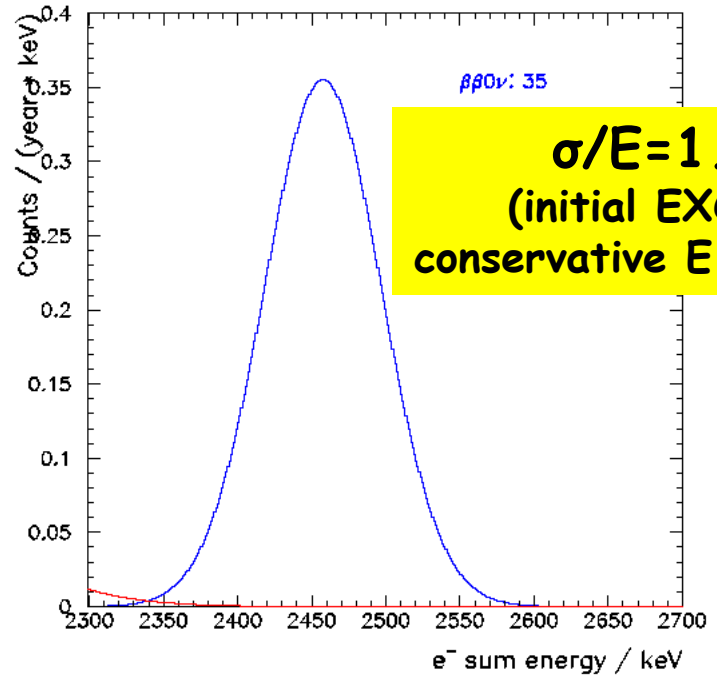


0νββ is the most sensitive probe of the Majorans/Dirac nature of neutrinos

Background due to the Standard Model 2νββ decay





σ/E=1.6%
(initial EXO-200 conservative E resolution)

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:

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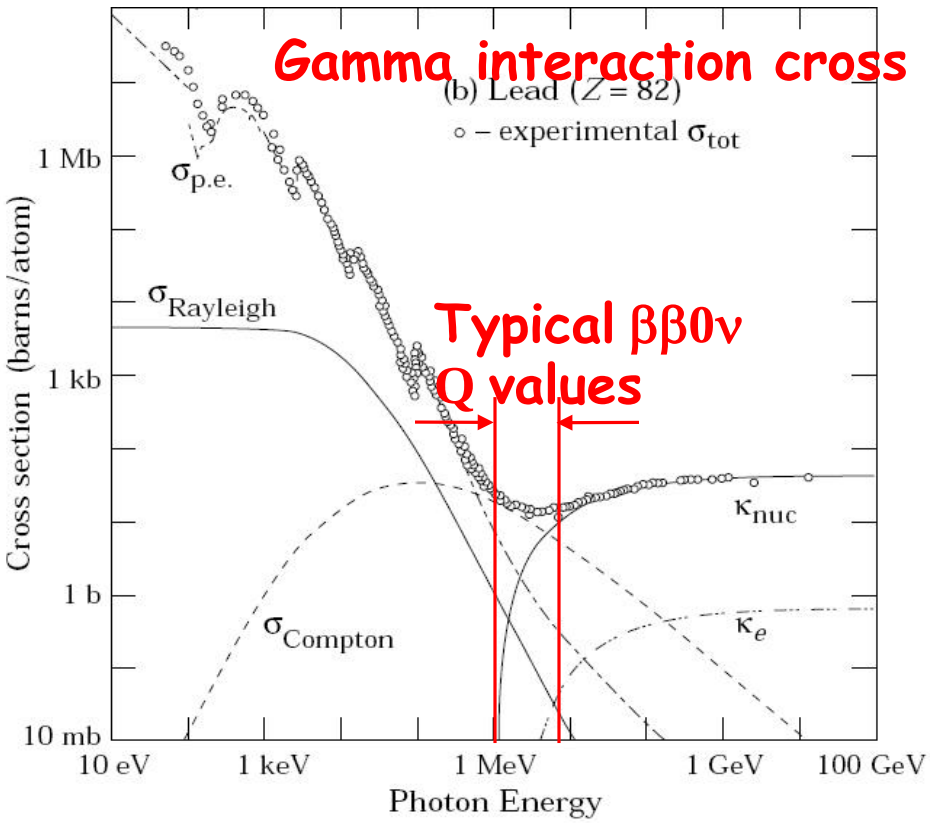
For no bkgnd $\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/\sqrt{Nt}$

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.



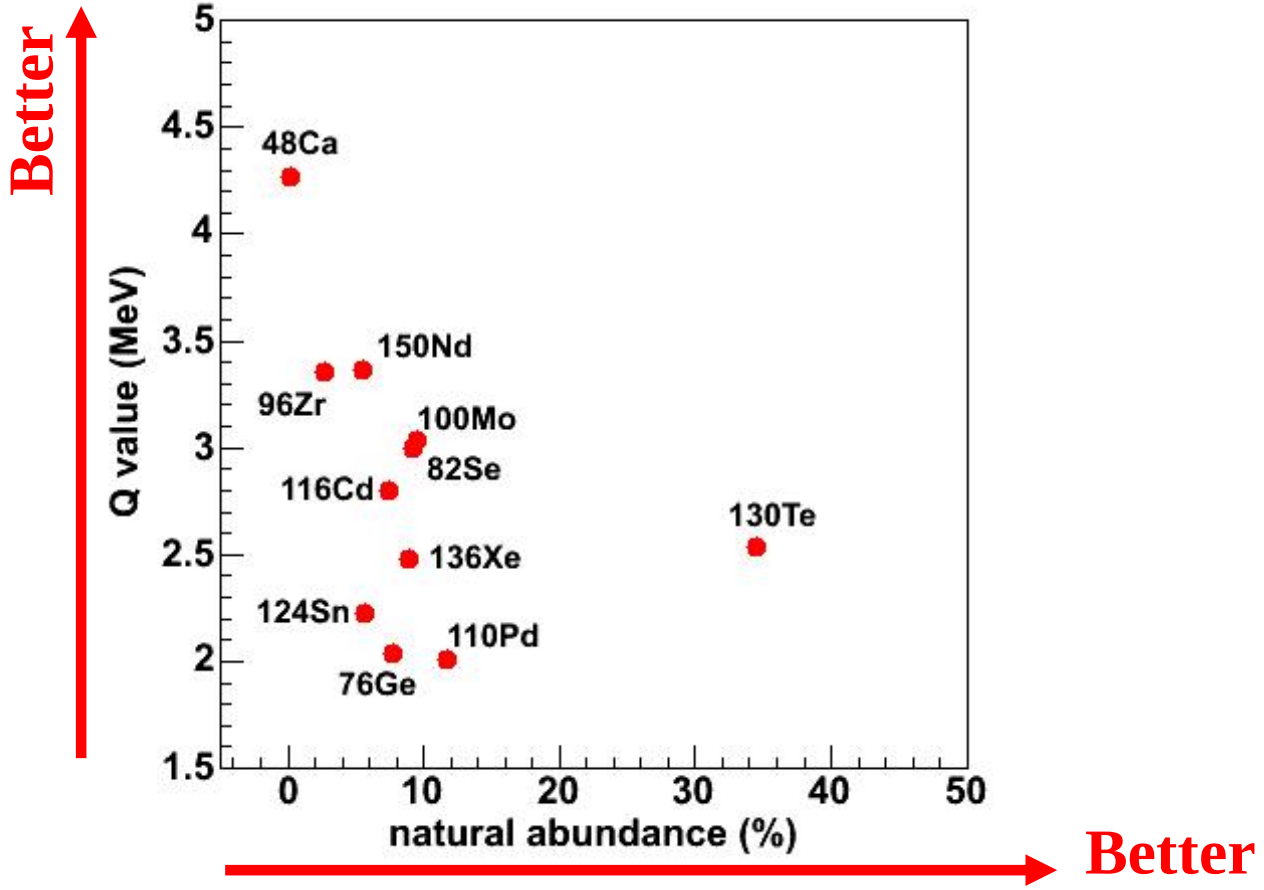
Example:

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

Shielding 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

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

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 0νββ 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

University of Alabama, Tuscaloosa AL, USA - D. Auty, T. Didberidze, M. Hughes, A. Piepke, R. Tsang

University of Bern, Switzerland - S. Delaquis, G. Giroux, R. Gornea, T. Tolba, J-L. Vuilleumier

California Institute of Technology, Pasadena CA, USA - P. Vogel

Carleton University, Ottawa ON, Canada - V. Basque, M. Dunford, K. Graham, C. Hargrove, R. Killick, T. Koffas, F. Leonard, C. Licciardi, M.P. Rozo, D. Sinclair

Colorado State University, Fort Collins CO, USA - C. Benitez-Medina, C. Chambers, A. Craycraft, W. Fairbank, Jr., T. Walton

Drexel University, Philadelphia PA, USA - M.J. Dolinski, M.J. Jewell, Y.H. Lin, E. Smith, Y.-R Yen

Duke University, Durham NC, USA - P.S. Barbeau

IHEP Beijing, People's Republic of China - G. Cao, X. Jiang, L. Wen, Y. Zhao

University of Illinois, Urbana-Champaign IL, USA - D. Beck, M. Coon, J. Ling, M. Tarka, J. Walton, L. Yang

Indiana University, Bloomington IN, USA - J. Albert, S. Daugherty, T. Johnson, L.J. Kaufman

University of California, Irvine, 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 University, Sudbury ON, Canada - B. Cleveland, A. Der Mesrobian-Kabakian, J. Farine, B. Mong, U. Wichoski

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

University of Massachusetts, Amherst MA, USA - T. Daniels, S. Johnston, K. Kumar, A. Pocar, D. Shy

University of Seoul, South Korea - D.S. Leonard

SLAC National Accelerator Laboratory, Menlo Park CA, USA - M. Breidenbach, R. Conley, A. Dragone, K. Fouts, R. Herbst, S. Herrin, A. Johnson, R. MacLellan, K. Nishimura, A. Odian, C.Y. Prescott, P.C. Rowson, J.J. Russell, K. Skarpaas, M. Swift, A. Waite, M. Wittgen

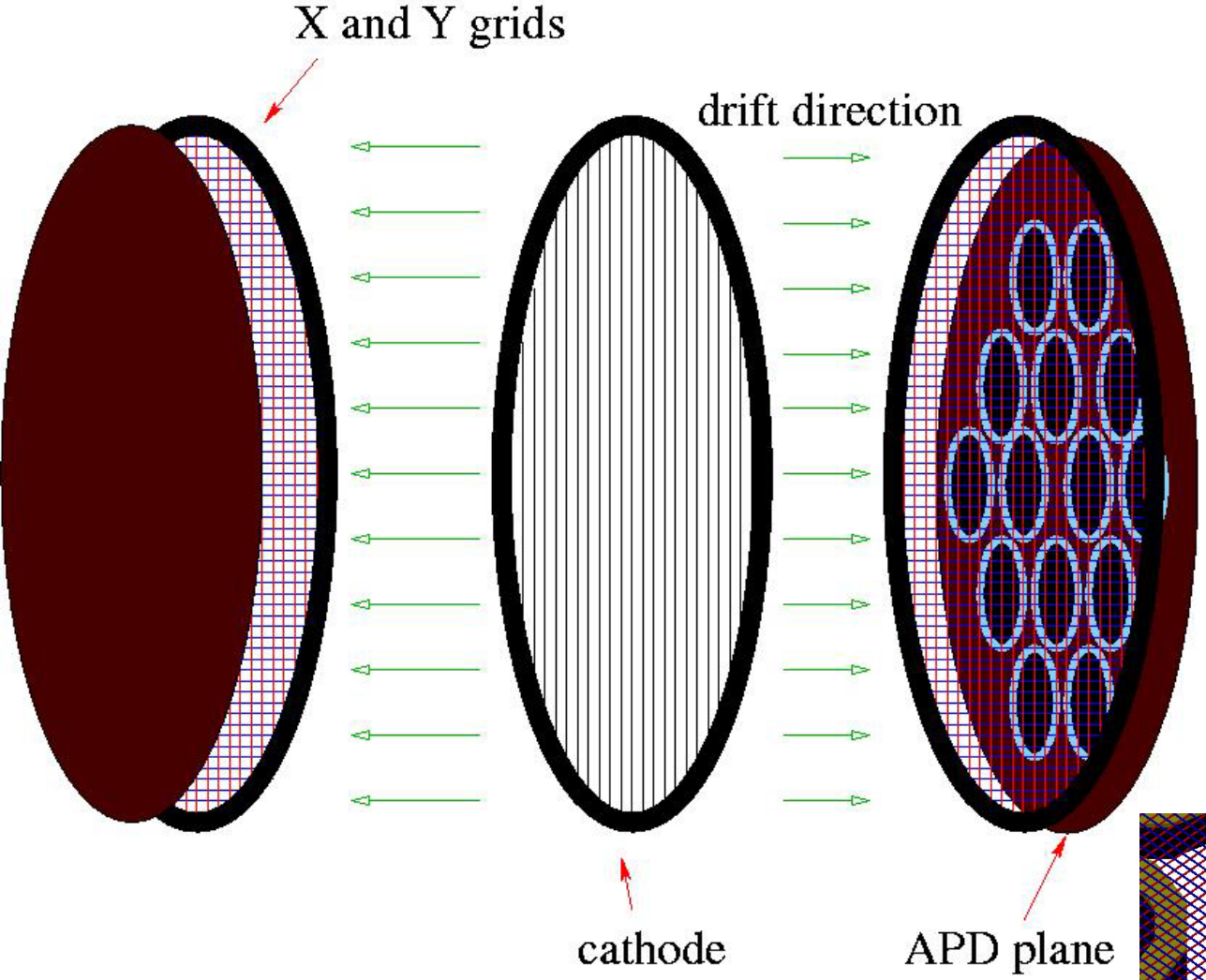
Stanford University, Stanford CA, USA - J. Bonatt, T. Brunner, J. Chaves, J. Davis, R. DeVoe, D. Fudenberg, G. Gratta, S.Kravitz, D. Moore, I. Ostrovskiy, A. Rivas, A. Schubert, D. Tosi, K. Twelker, M. Weber

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

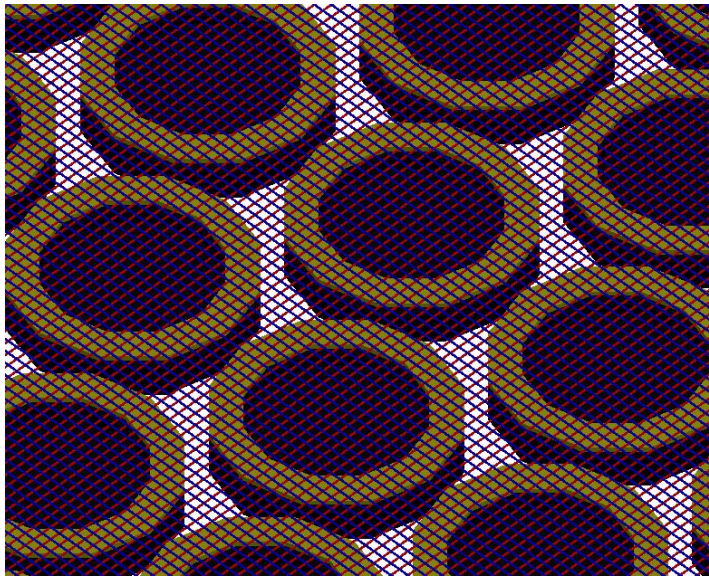
TRIUMF, Vancouver BC, Canada – J. Dilling, R. Krucken, F. Retière, V. Strickland

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

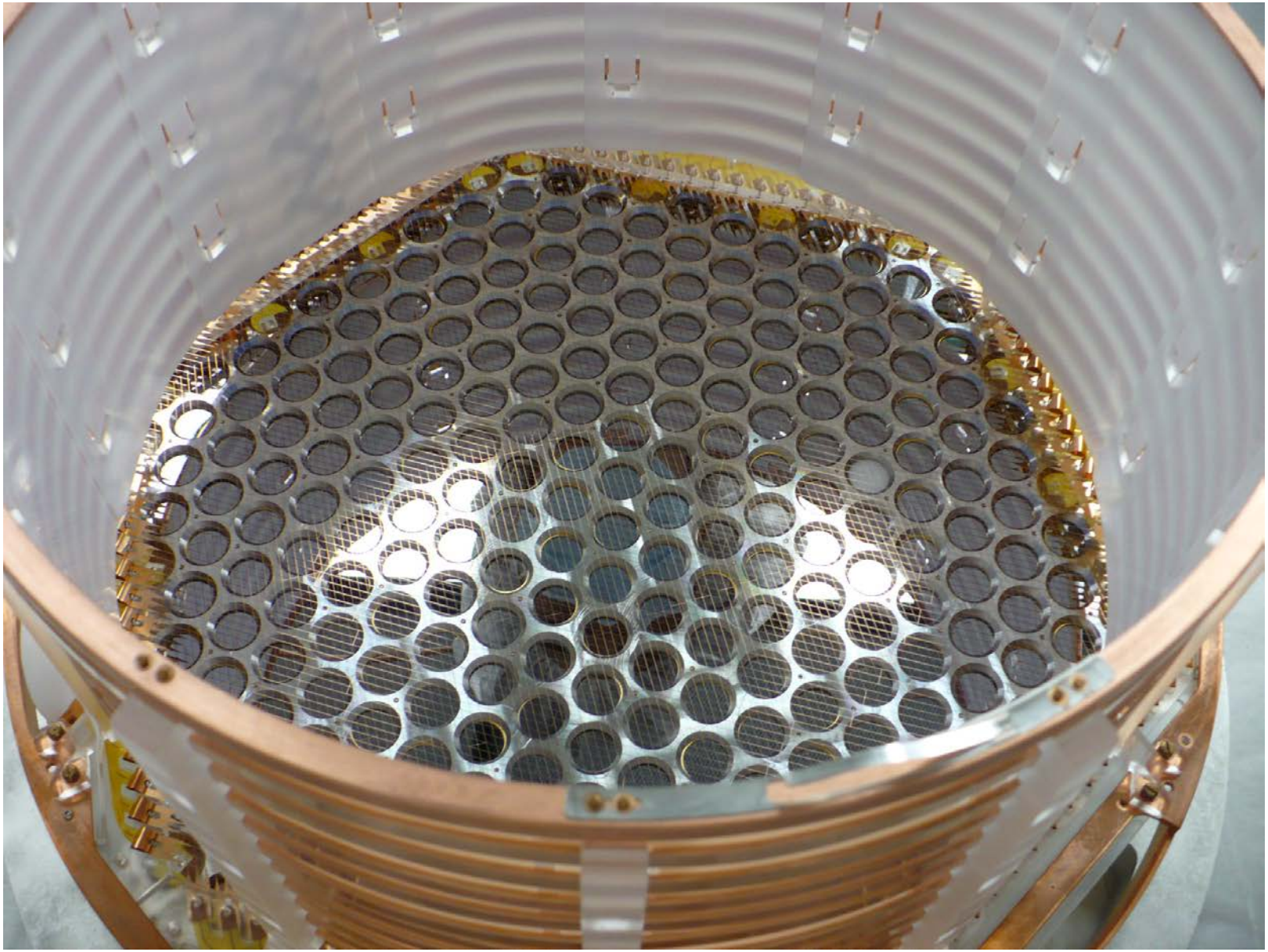


R. Neilson, et al. NIM A 608 (2009) 6875

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

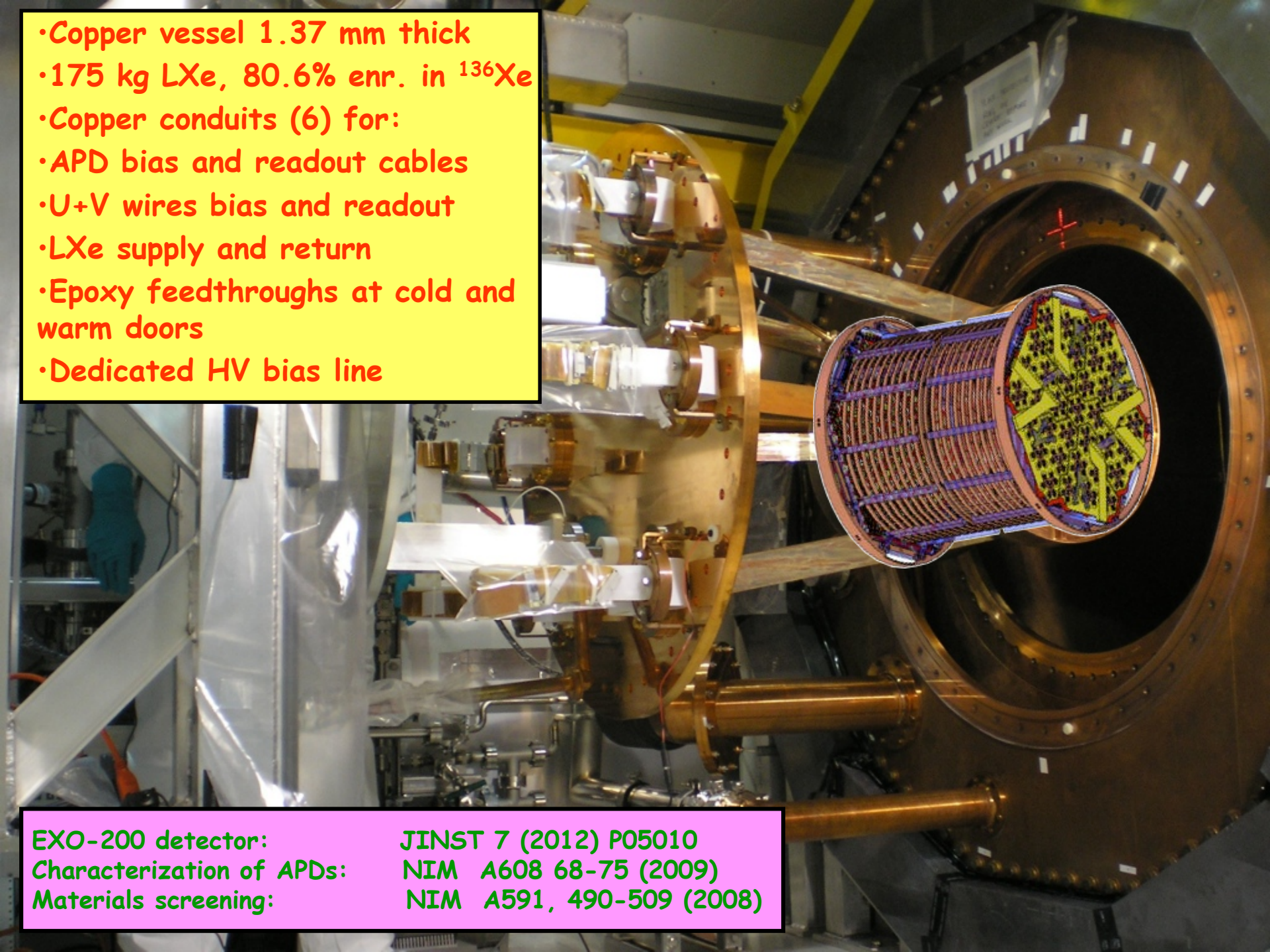


Ultra-low activity Cu vessel

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

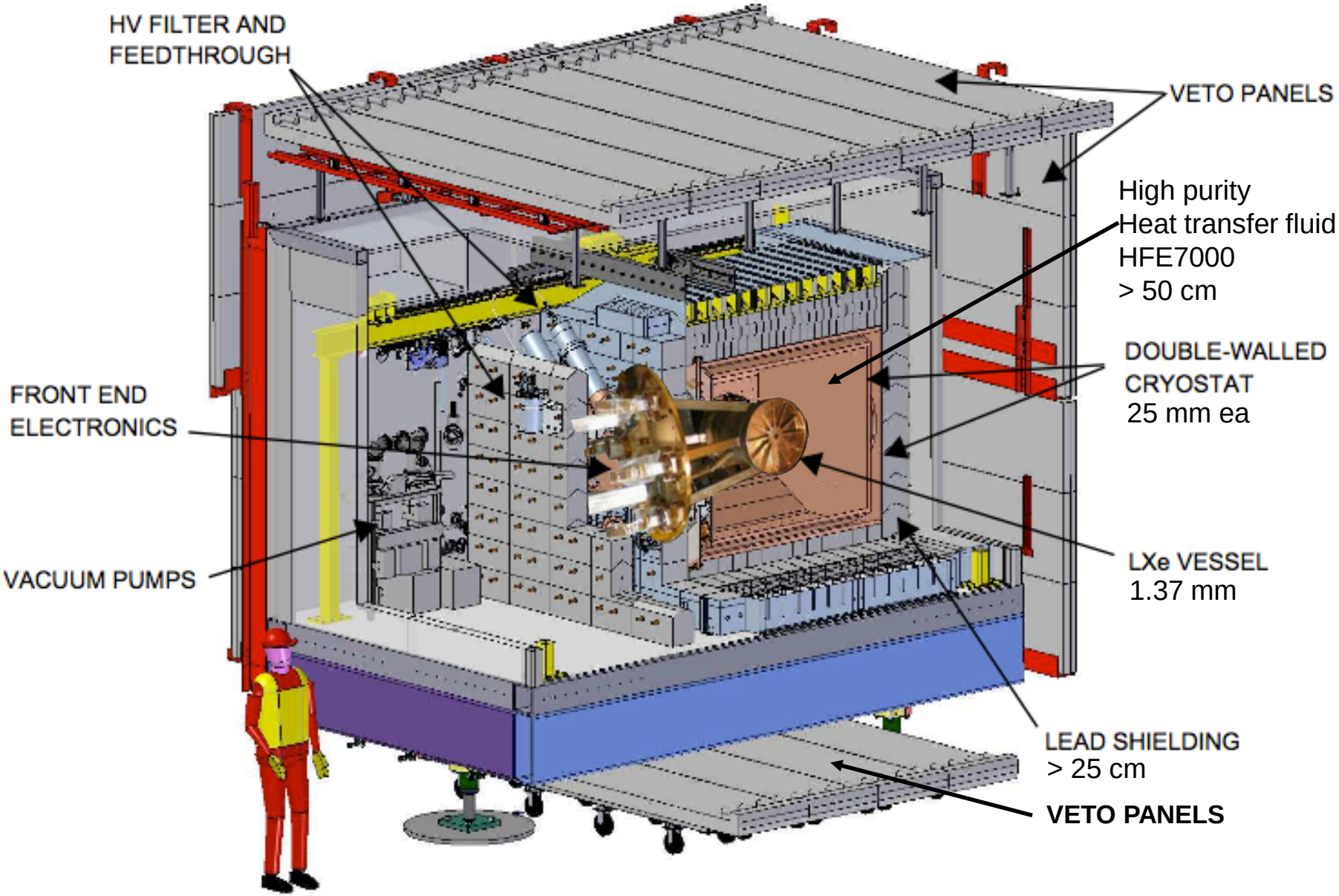
- Different parts e-beam welded together
- Field TIG weld(s) to seal the vessel after assembly (TIG technology tested for radioactivity)
- All machining done by in the CR-shielded HEPL building)

- 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

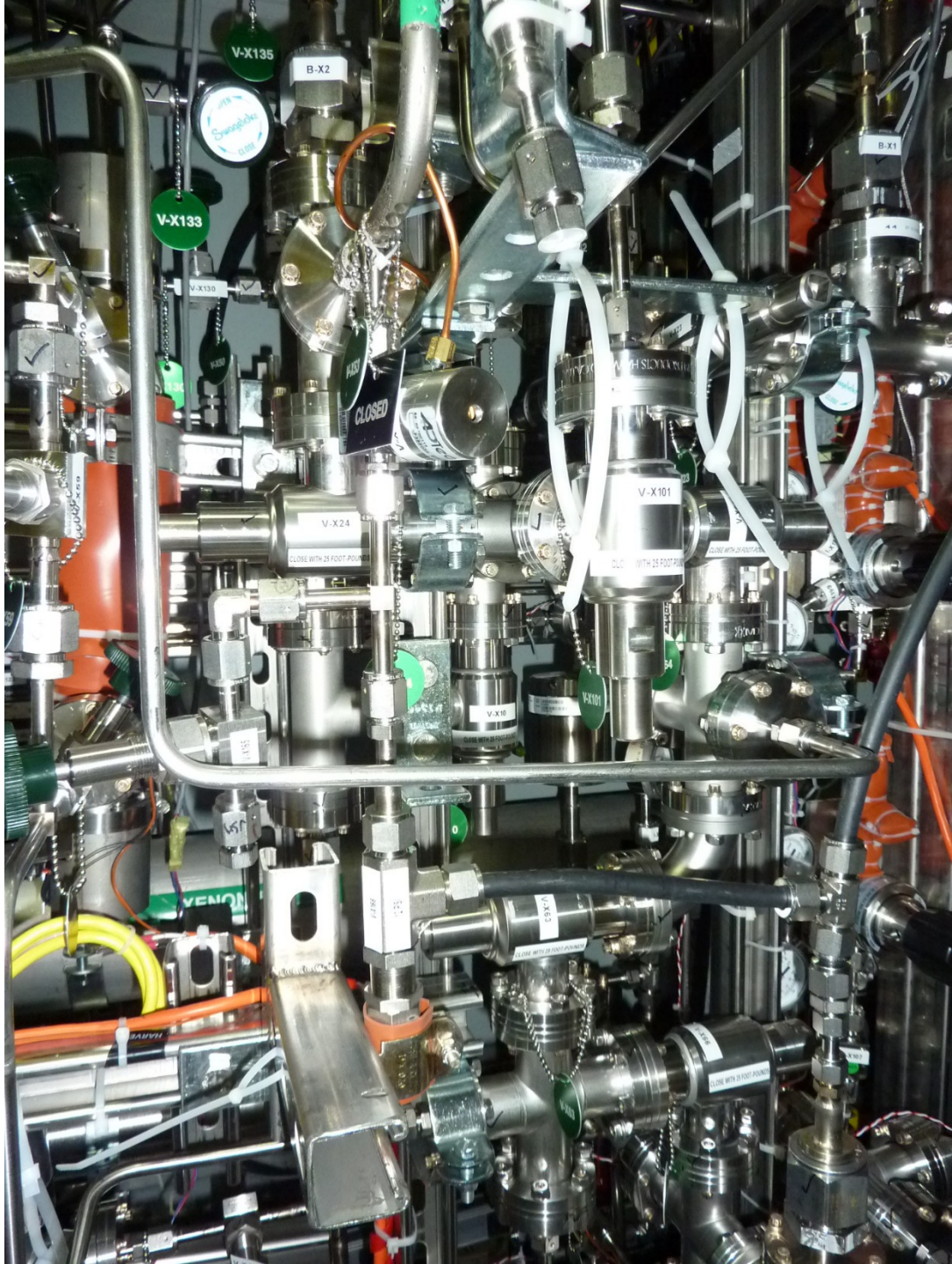
D.S. Leonard et al., Nucl. Ins. Meth. A 591, 490 (2008)

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

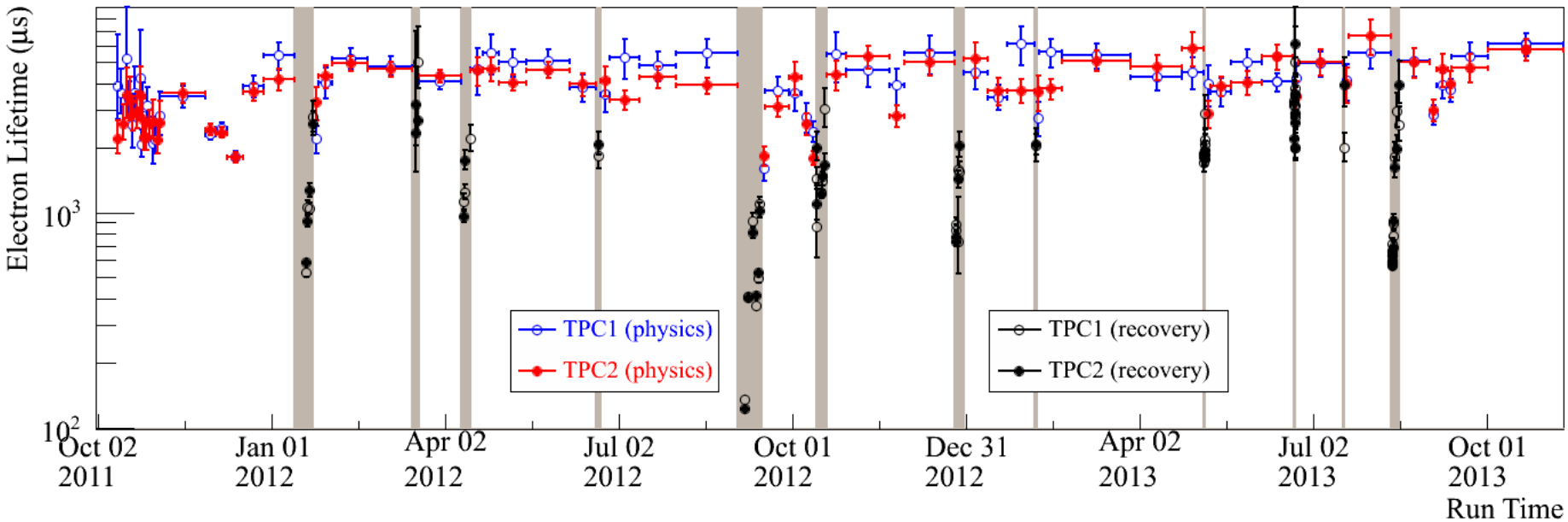
→ Goal: 40 cnts/2yr in the 0νββ ±2σ ROI in 140kg of LXe

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



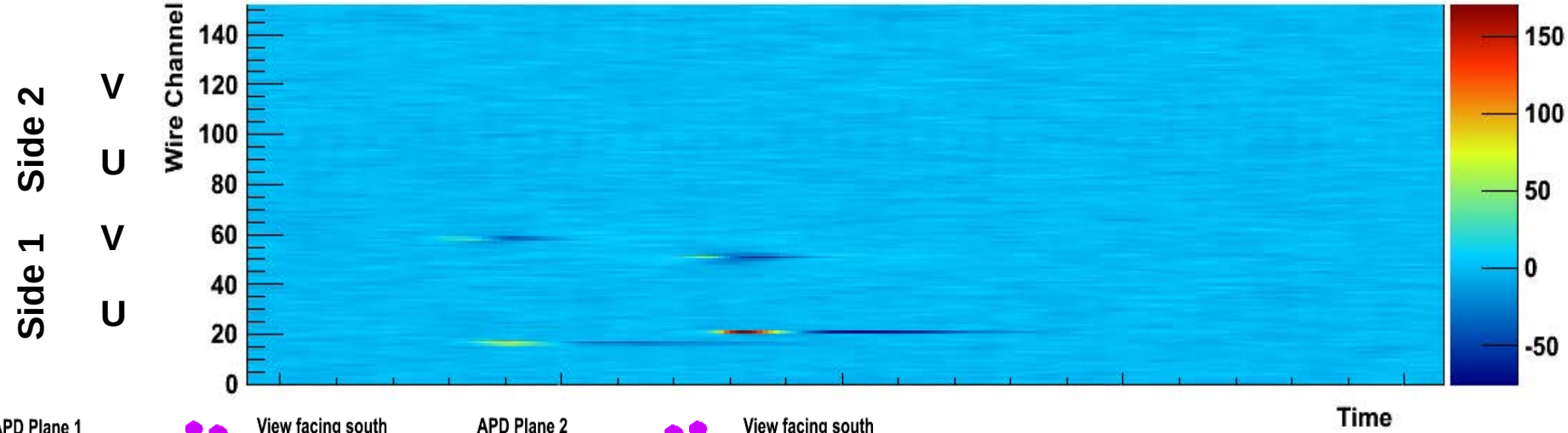
Xe purity is essential for good energy resolution

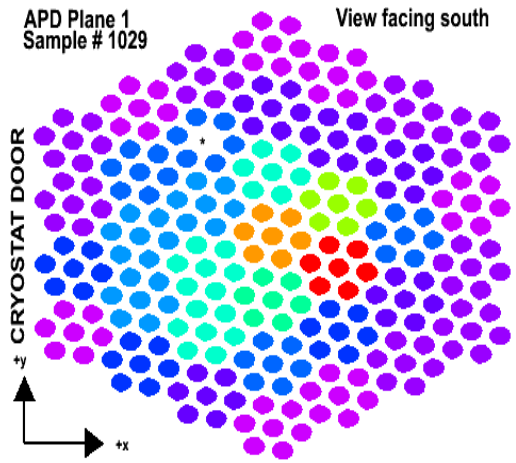


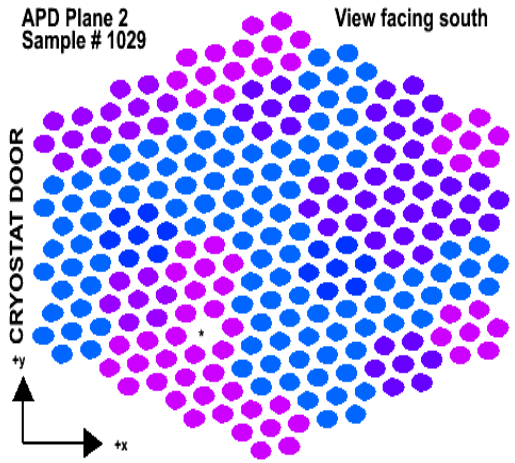
Xenon gas is forced through heated Zr getter by a custom ultraclean pump.

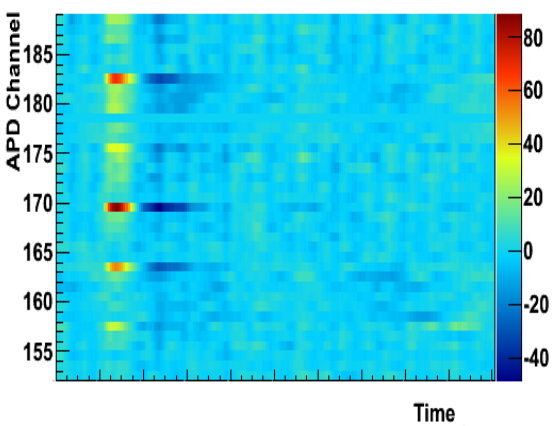
At τ_e = 3 ms:
- drift time <110 μs
- loss of charge: 3.6%
at full drift length

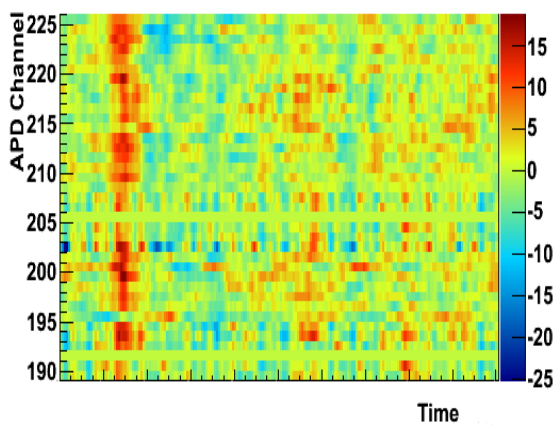
Ultraclean pump: *Rev Sci Instr. 82 (10) 105114*
Xenon purity with mass spec: *NIM A675 (2012) 40*
Gas purity monitors: *NIM A659 (2011) 215*











A two-site Compton scattering event.

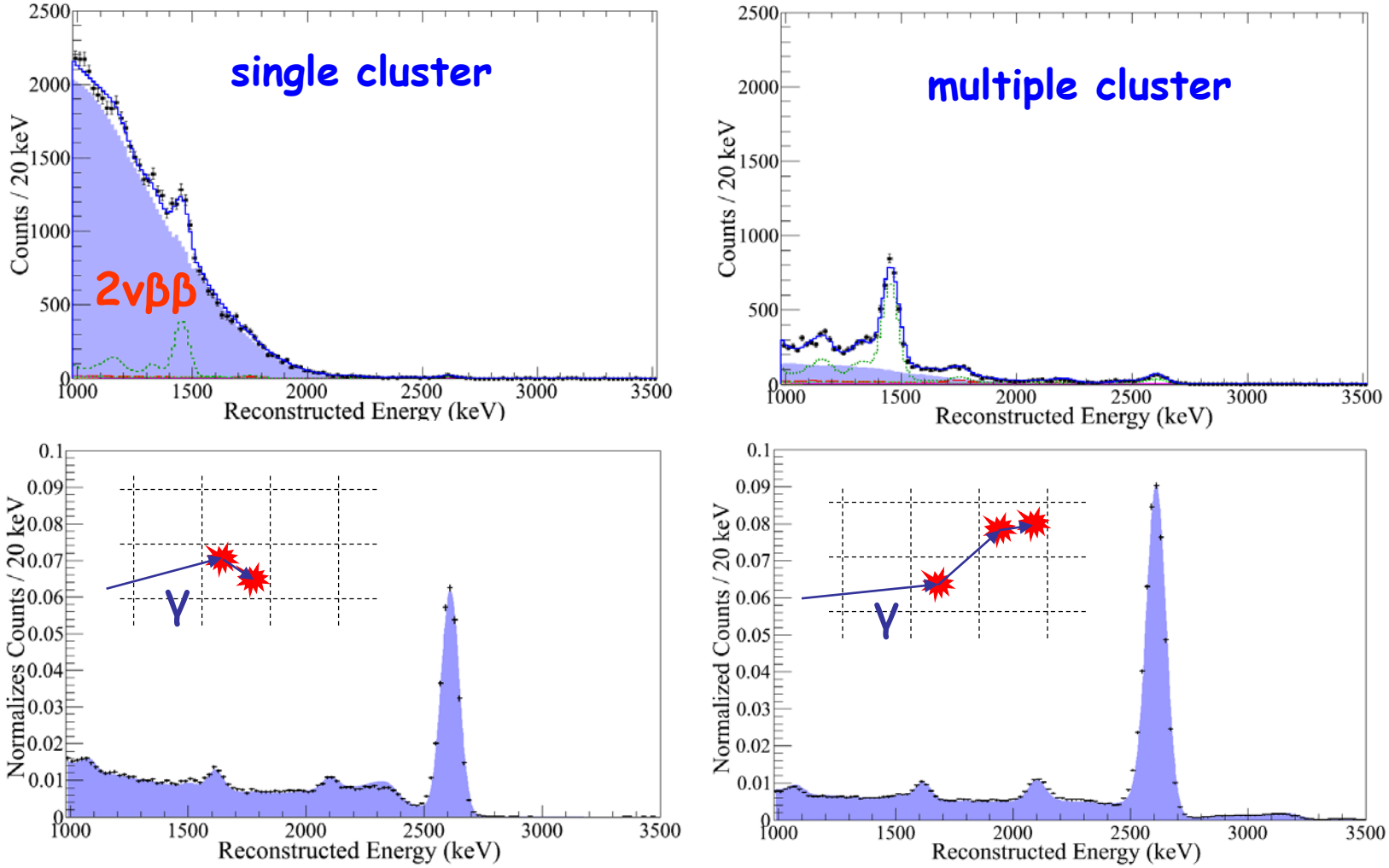
All scintillation light arrives at the same time, indicating that the two energy depositions are simultaneous.

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

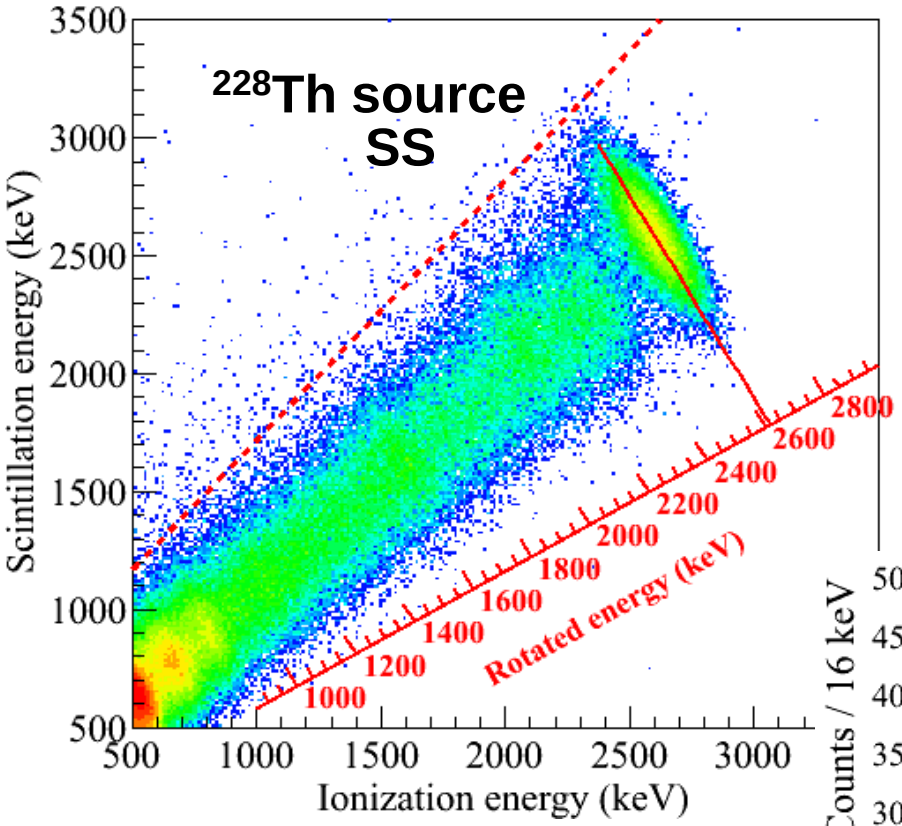
Tracking:
an essential tool to identify and suppress backgrounds

Low background data

^{228}Th calibration source



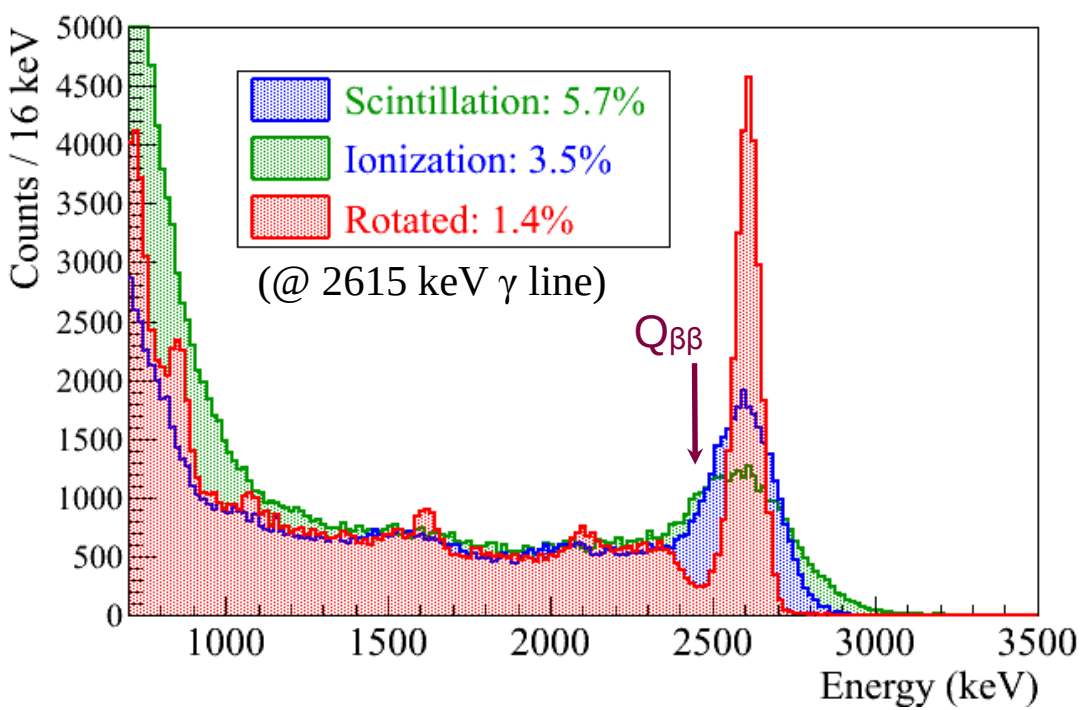
Combining Ionization and Scintillation



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

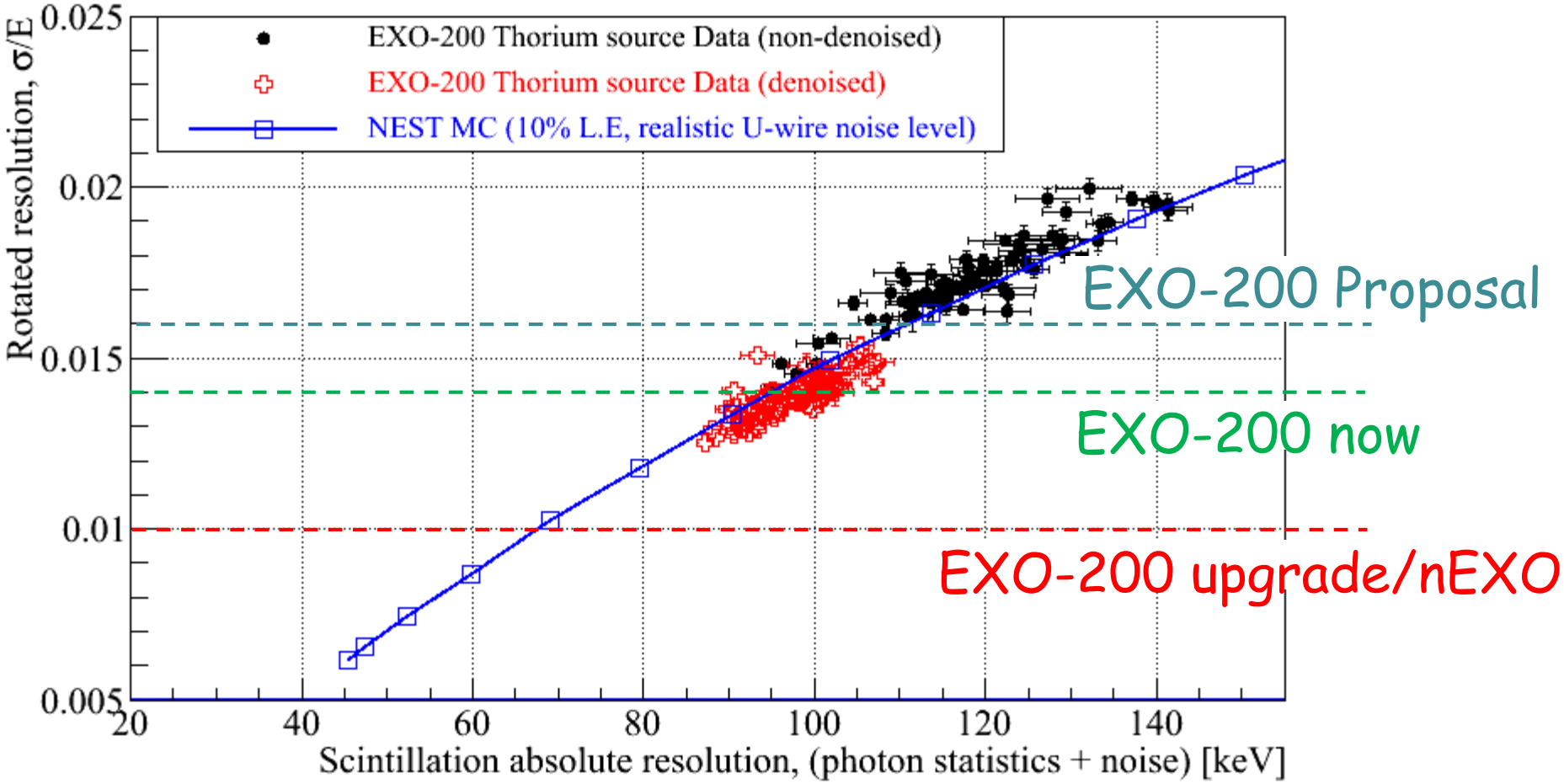
E.Conti et al. Phys Rev B 68 (2003) 054201

Note improvement due to LAAPD denoising

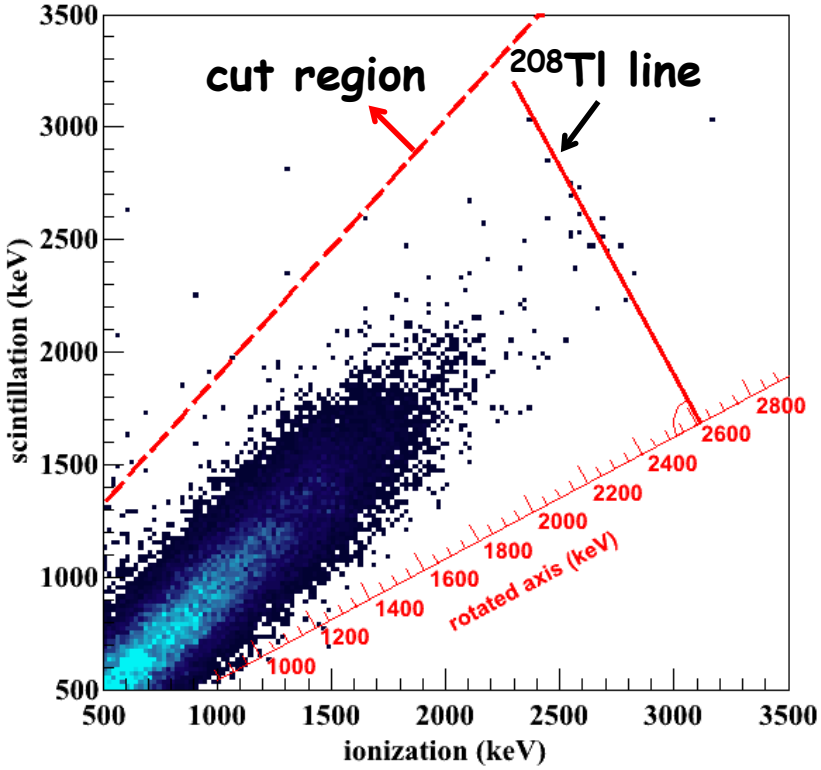


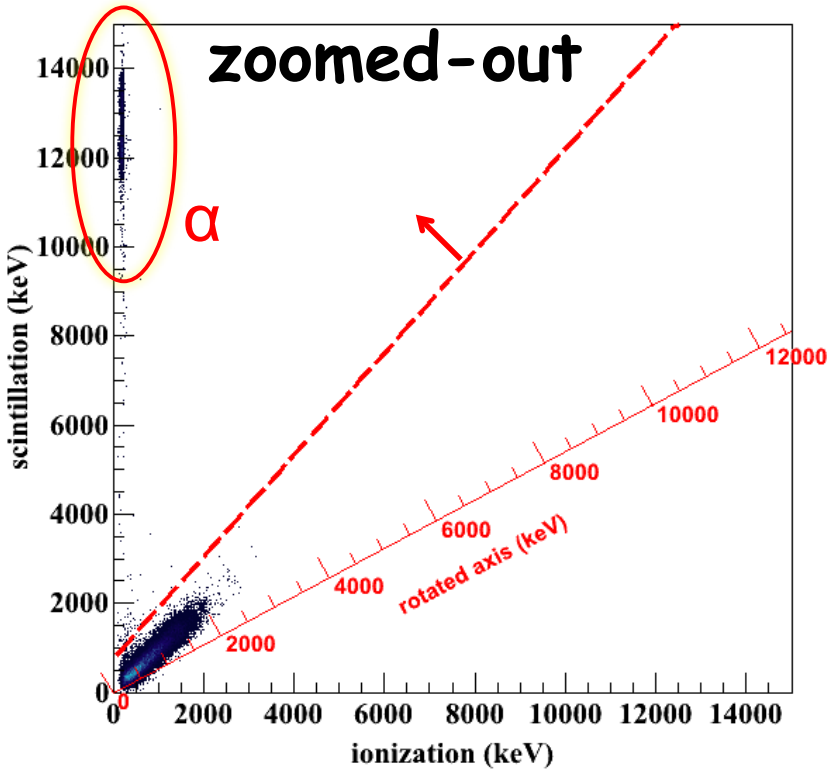
Rotation angle chosen to optimize energy resolution at 2615 keV

EXO-200 and nEXO resolutions



Low Background 2D SS Spectrum

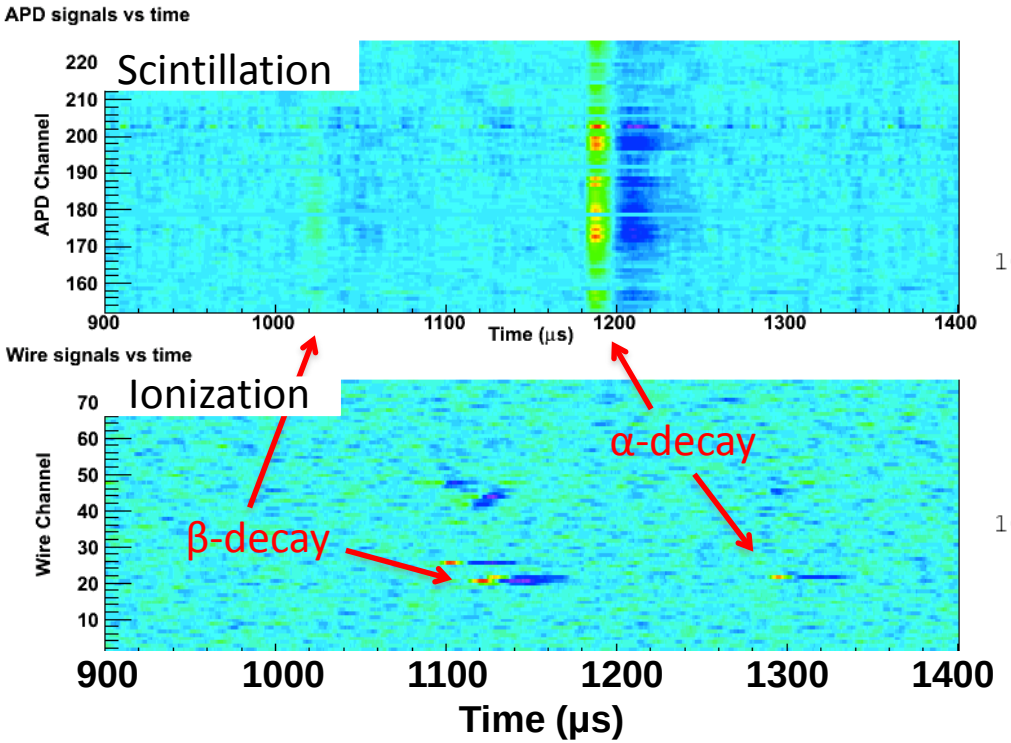




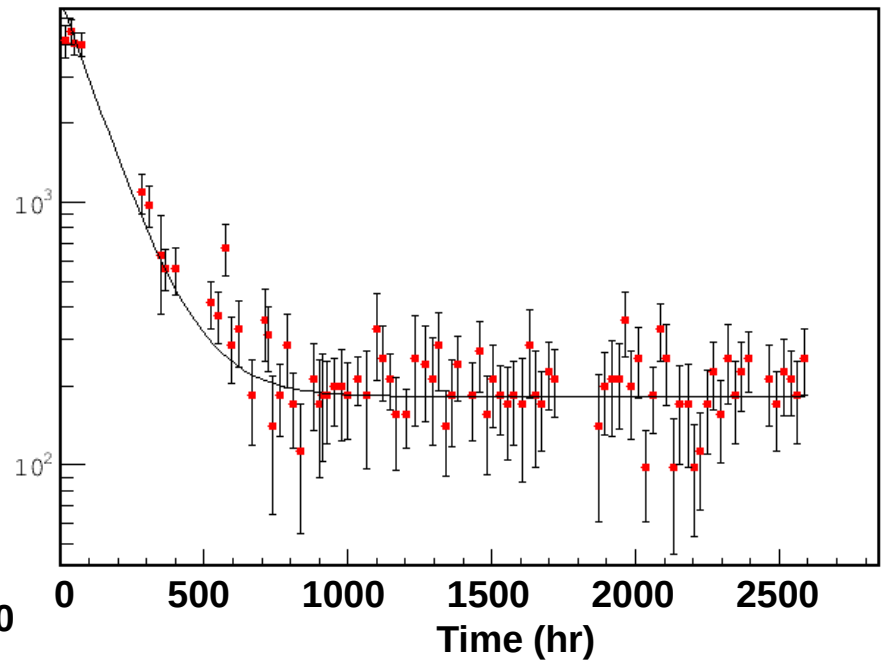
Events removed by diagonal cut:

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

Rn Content in Xenon



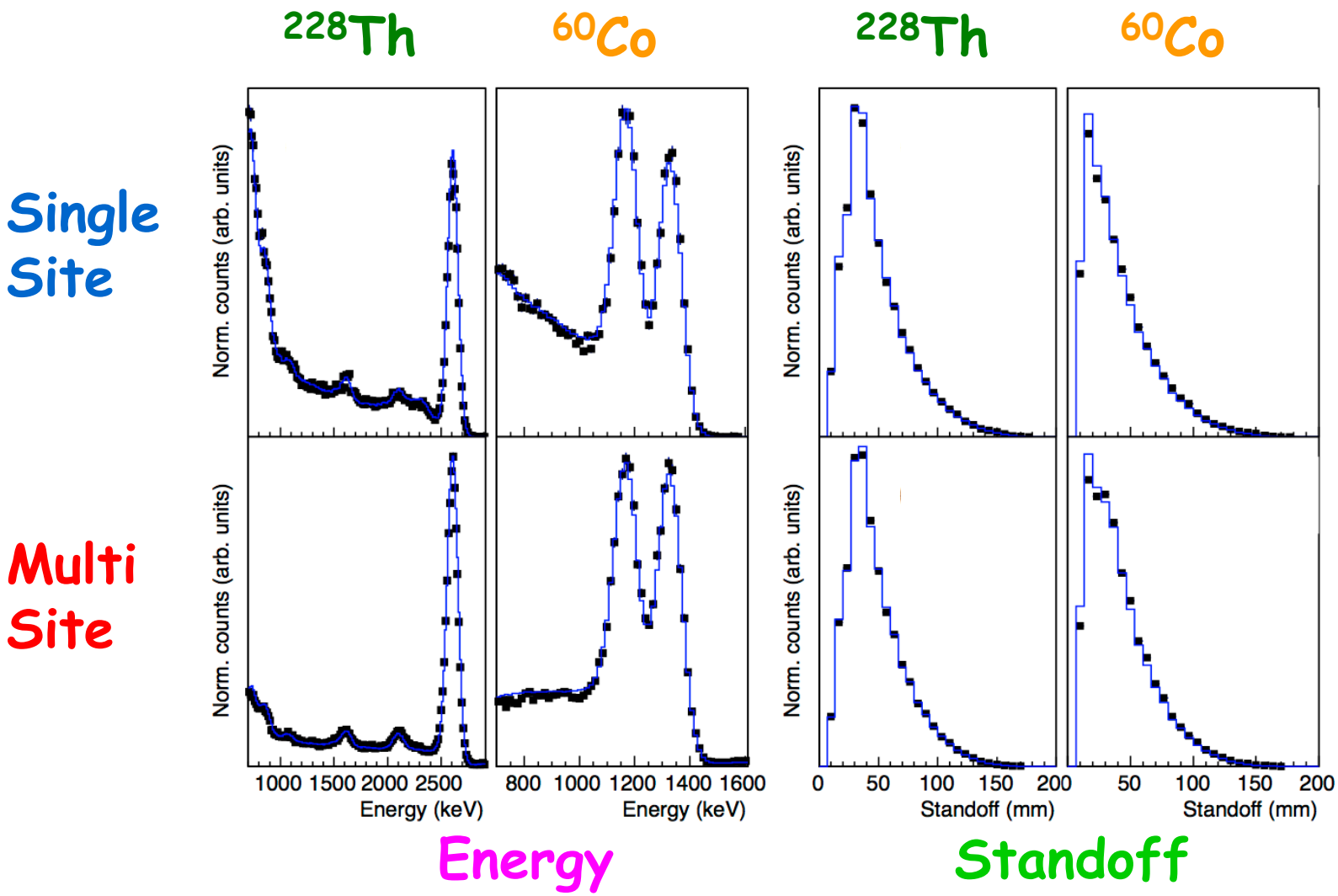
^{214}Bi – ^{214}Po correlations in the EXO-200 detector



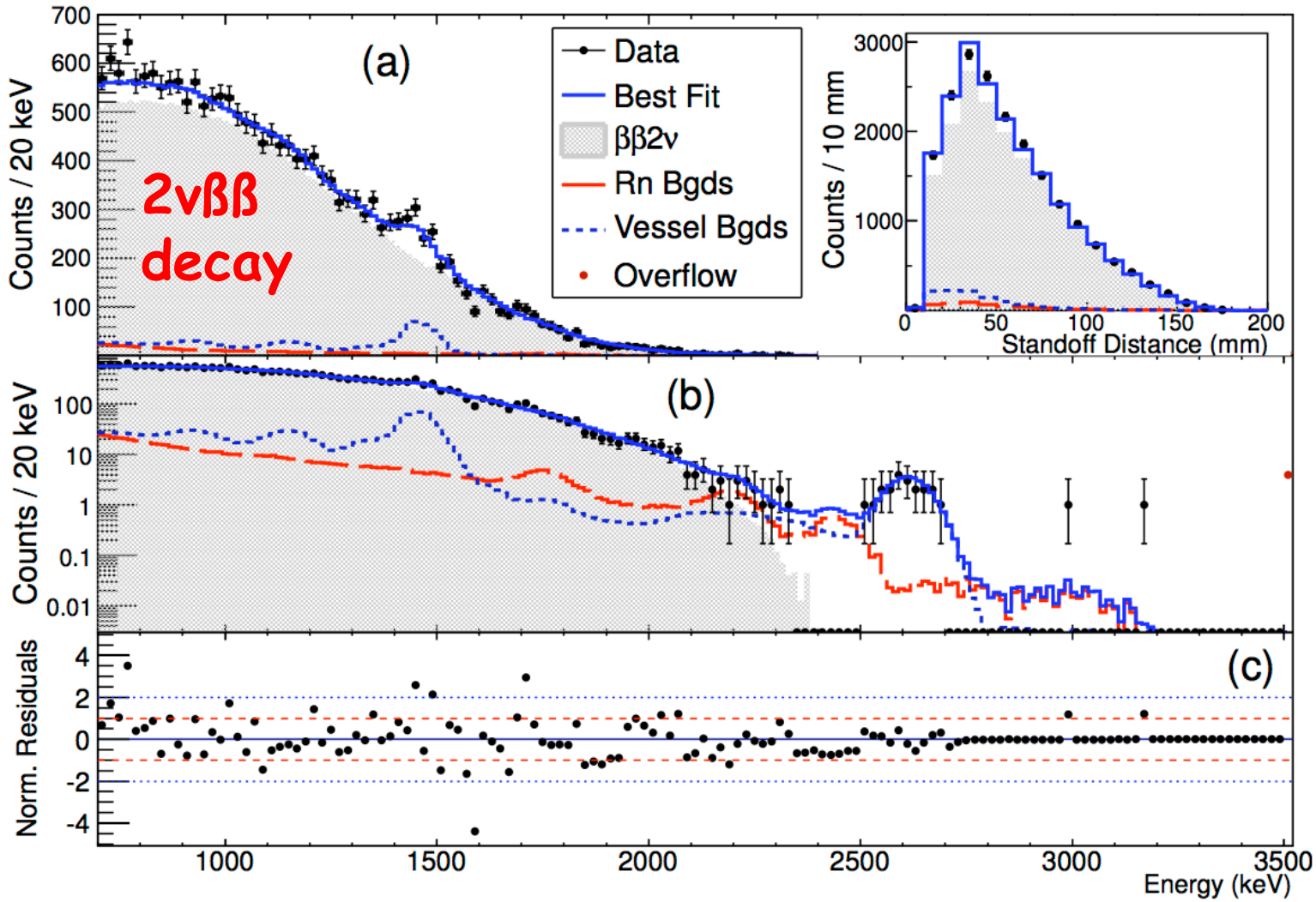
Total ^{222}Rn in LXe after initial fill

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



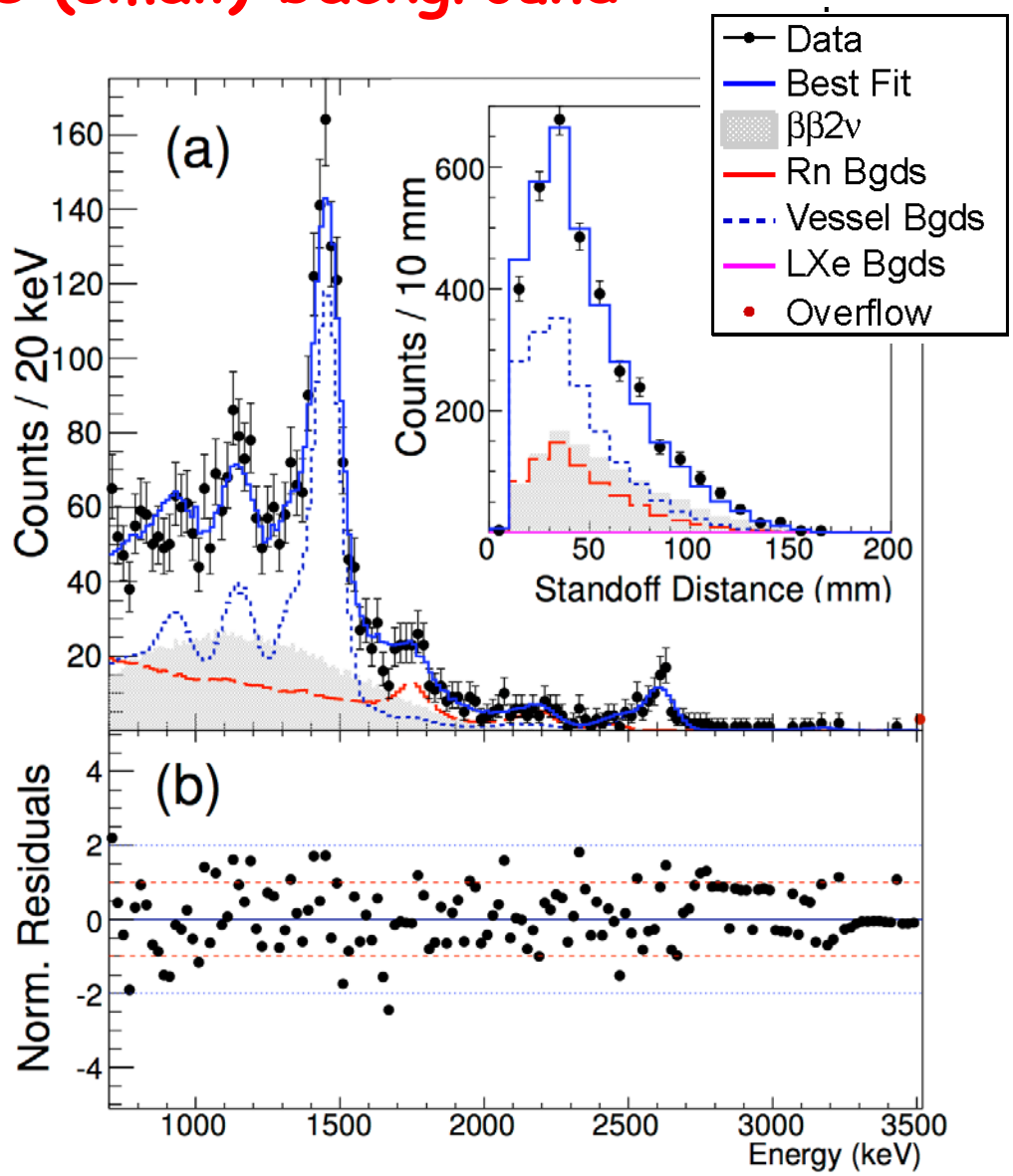
Low background single-site energy (and standoff) spectrum for 28.69 kg·yr (82.1 kg Xe, 127.6 d)



Signal-to-Background ratio 10 - 20

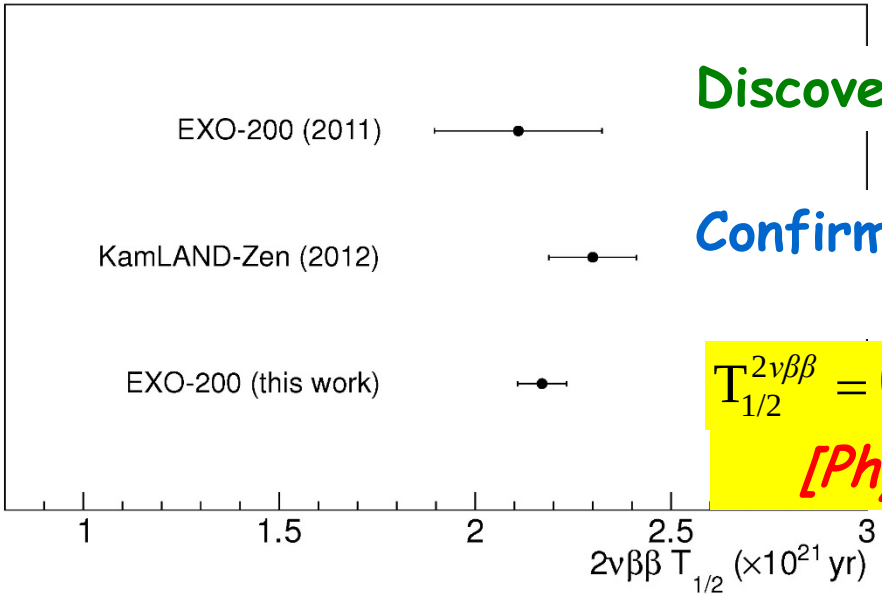
Multi-site spectrum directly measures the (small) background

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



EXO-200 & nEXO

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



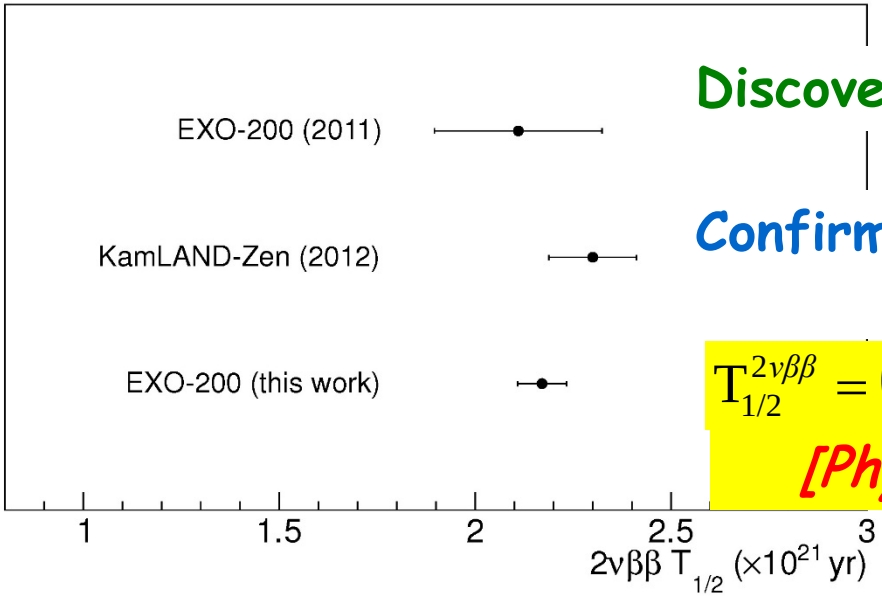
Discovery of 2ν mode *[PRL 107, 212501 (2011)]*

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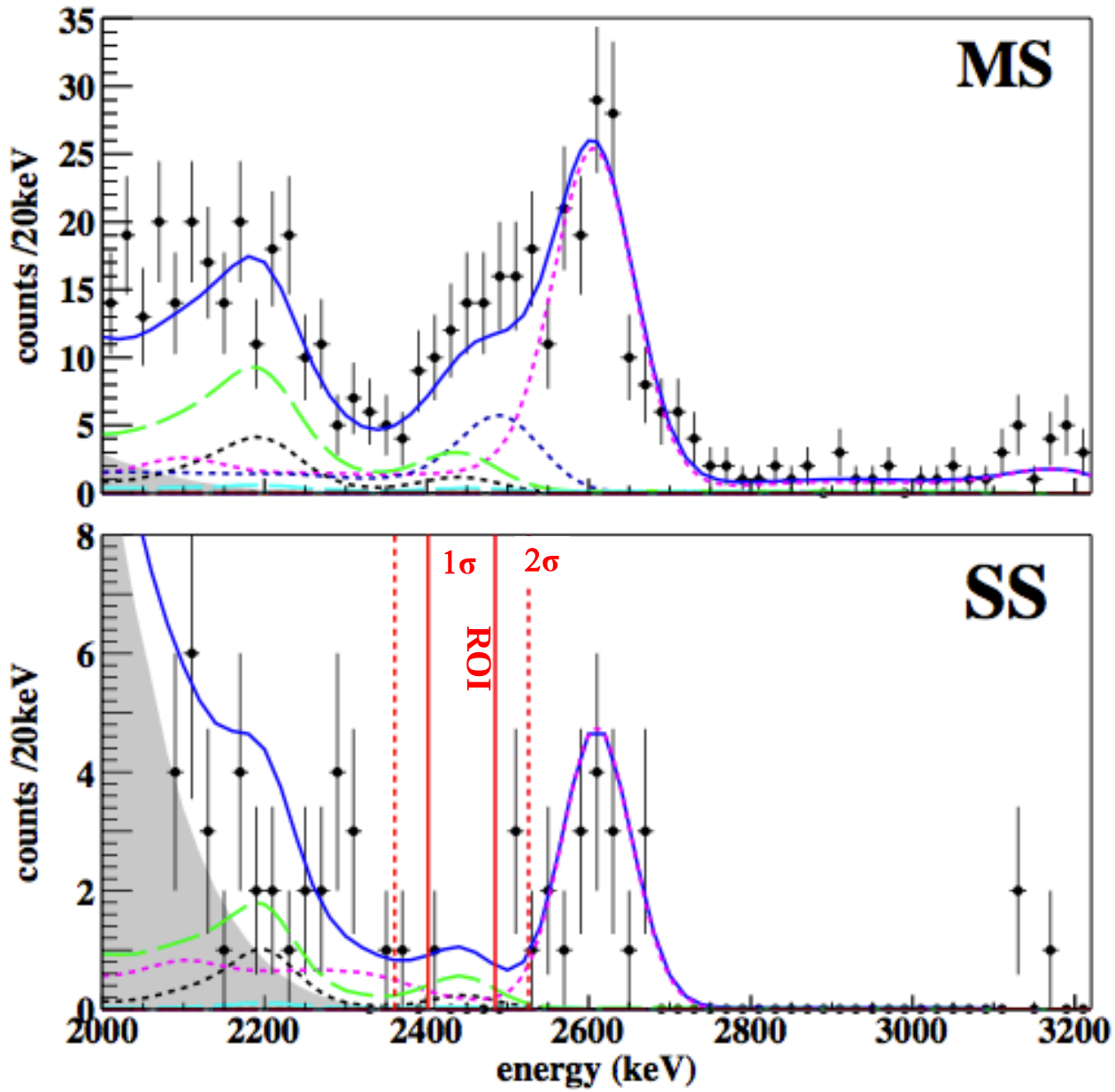
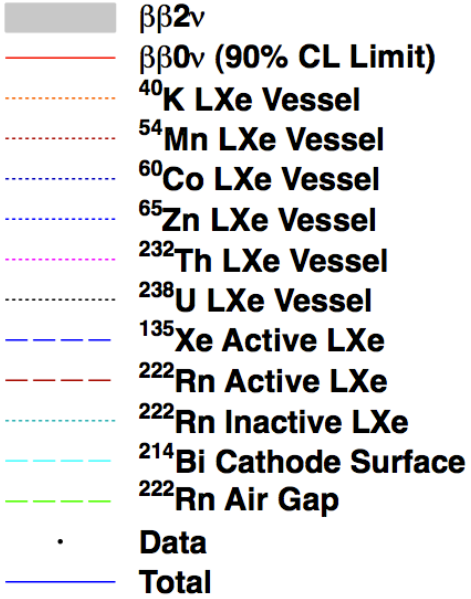
$$T_{1/2}^{2\nu\beta\beta} = \left(2.165 \pm 0.016^{\text{stat}} \pm 0.059^{\text{syst}}\right) \cdot 10^{21}\ \text{yr}$$

[Phys Rev C 89 (2014) 015502]

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)

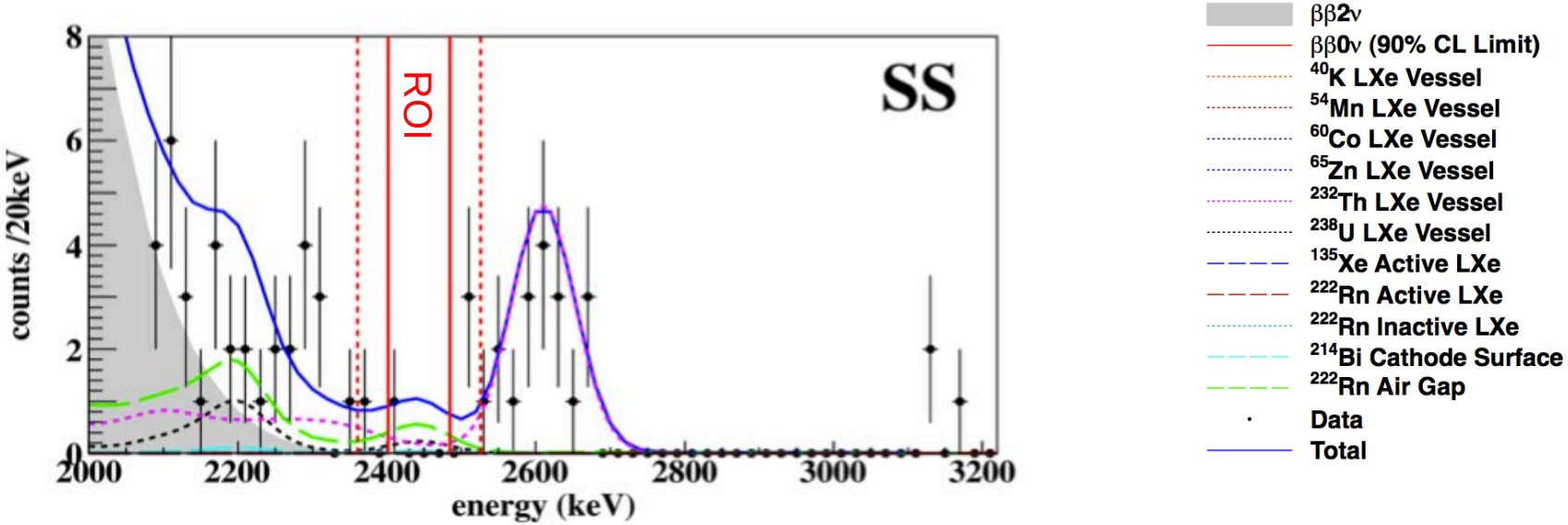




No 0ν signal observed in the ROI

Use likelihood fit to establish limit

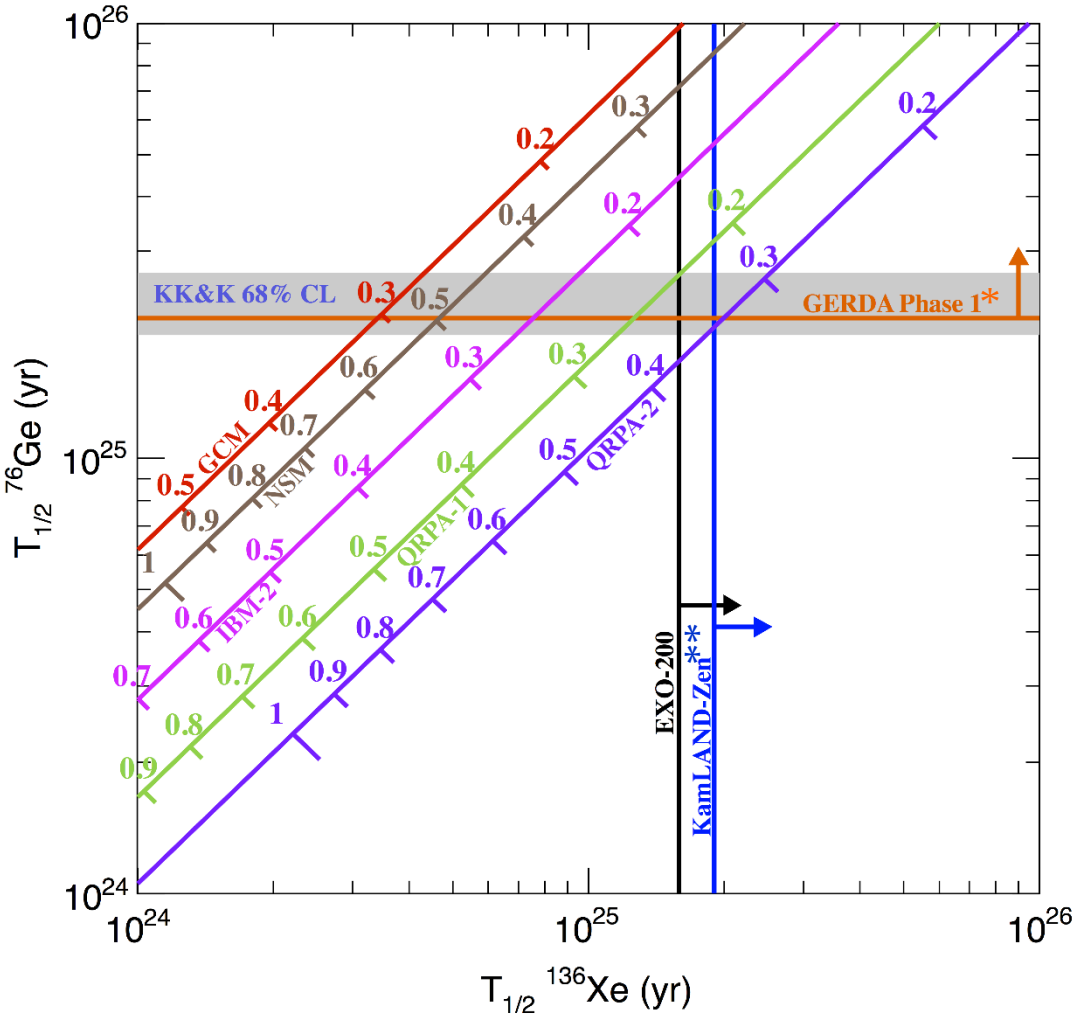
Background counts in ±1,2 σ ROI



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

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

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

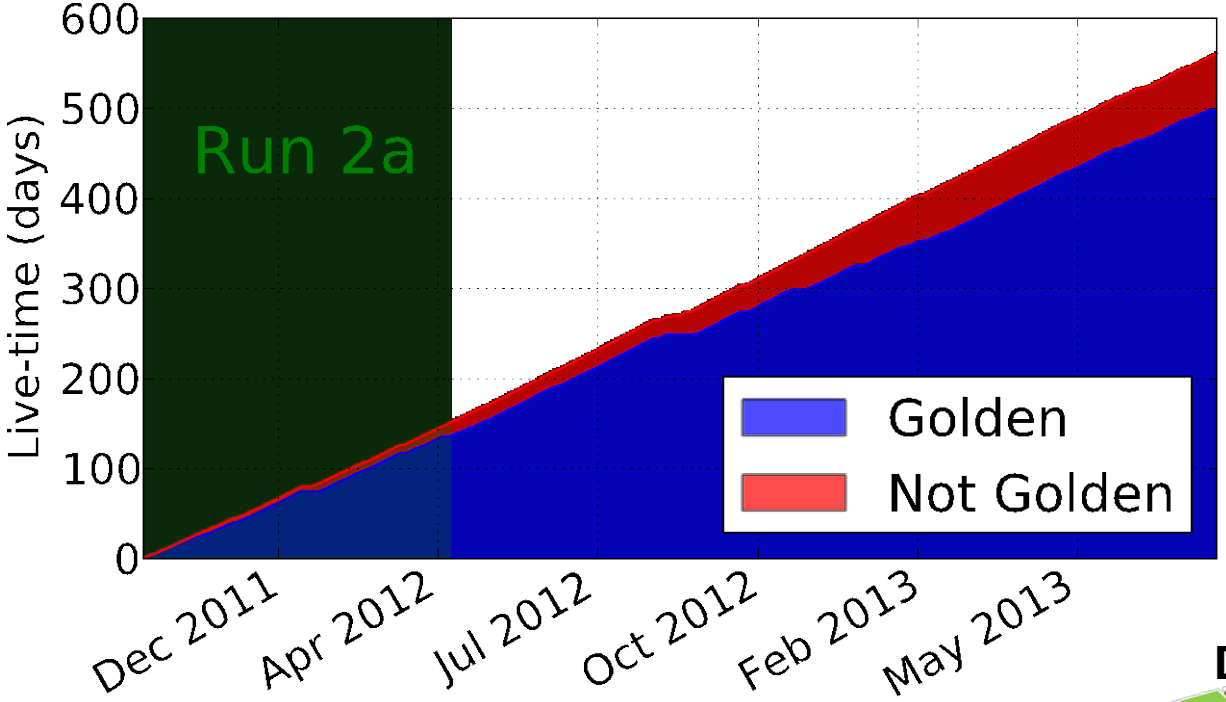
(90% C.L.)

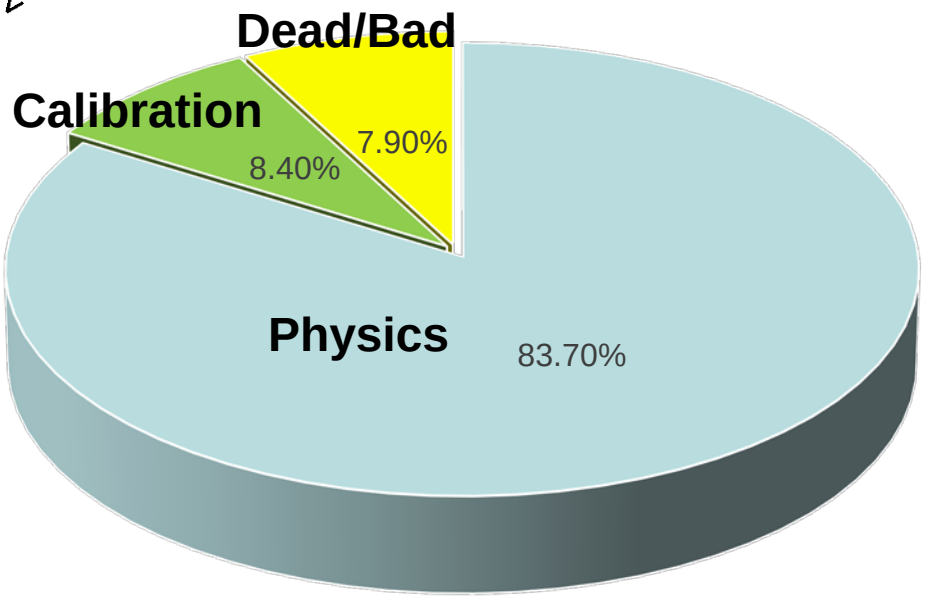
Phys Rev Lett 109 (2012) 032505

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

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

Data accumulation (6 Oct 2011- 6 Aug 2013)





~3x dataset on disk

As EXO-200 continues data taking a new collaboration

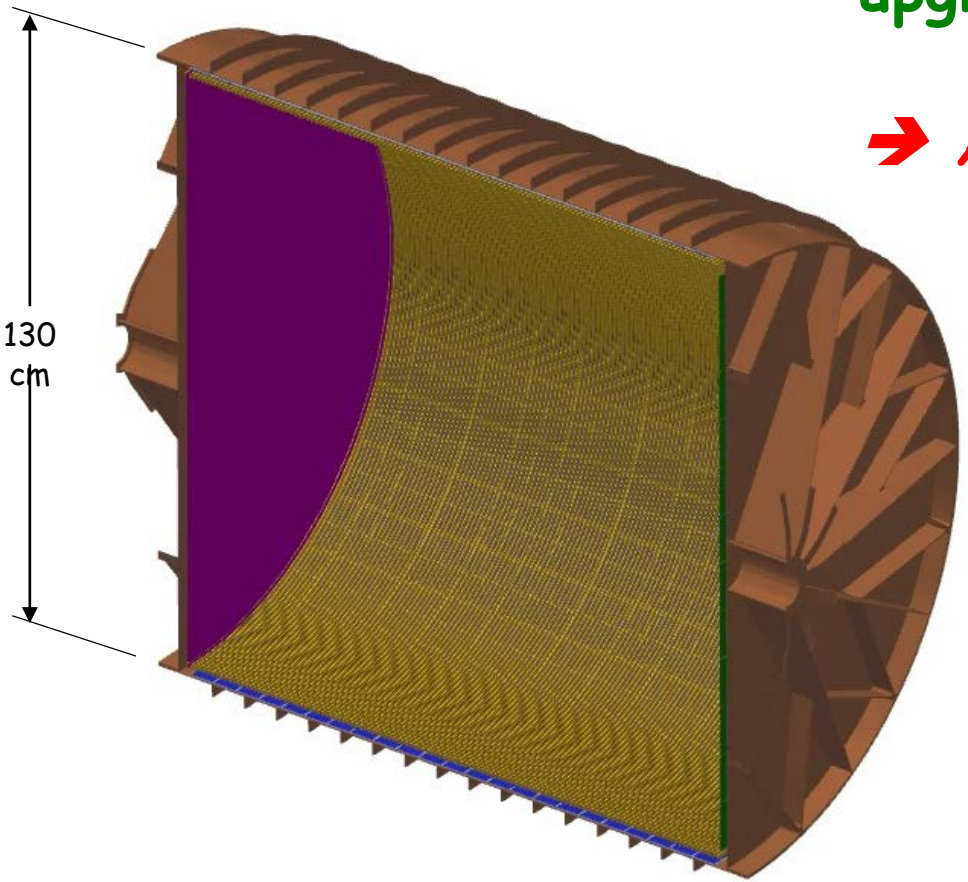
nEXO

is being formed

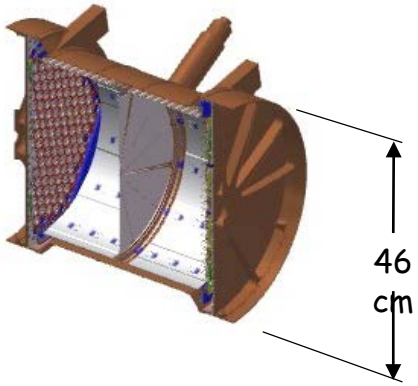
- *New groups have the opportunity to join as "charter members"*
- *Only conflict with ton-scale projects*
- *Larger collaboration organized to execute a larger and more formal project*

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



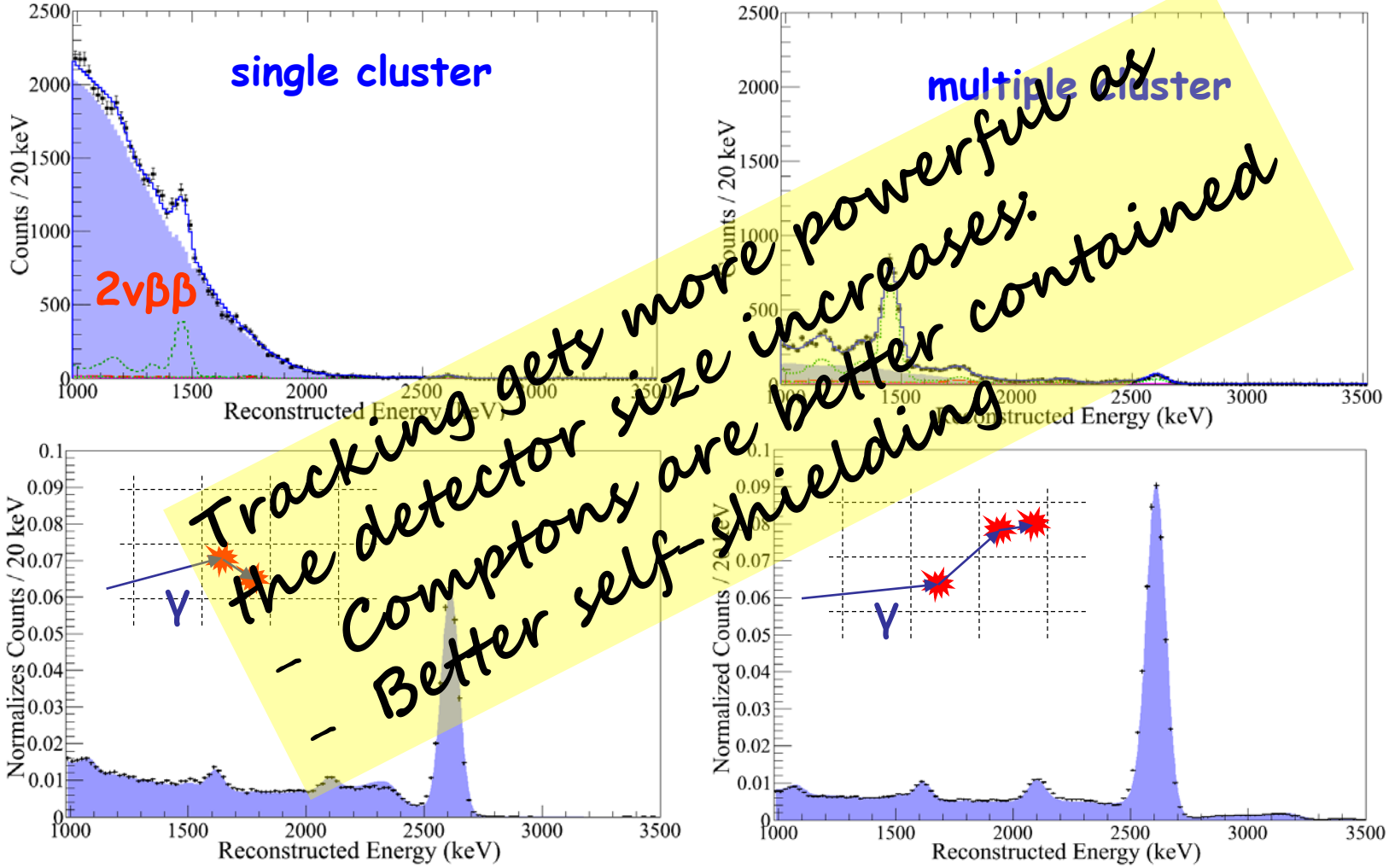
➔ *A unique combination of conservative and aggressive design with important upgrade paths as desirable for a large experiment*



Tracking:
an essential tool to identify and suppress backgrounds

Low background data

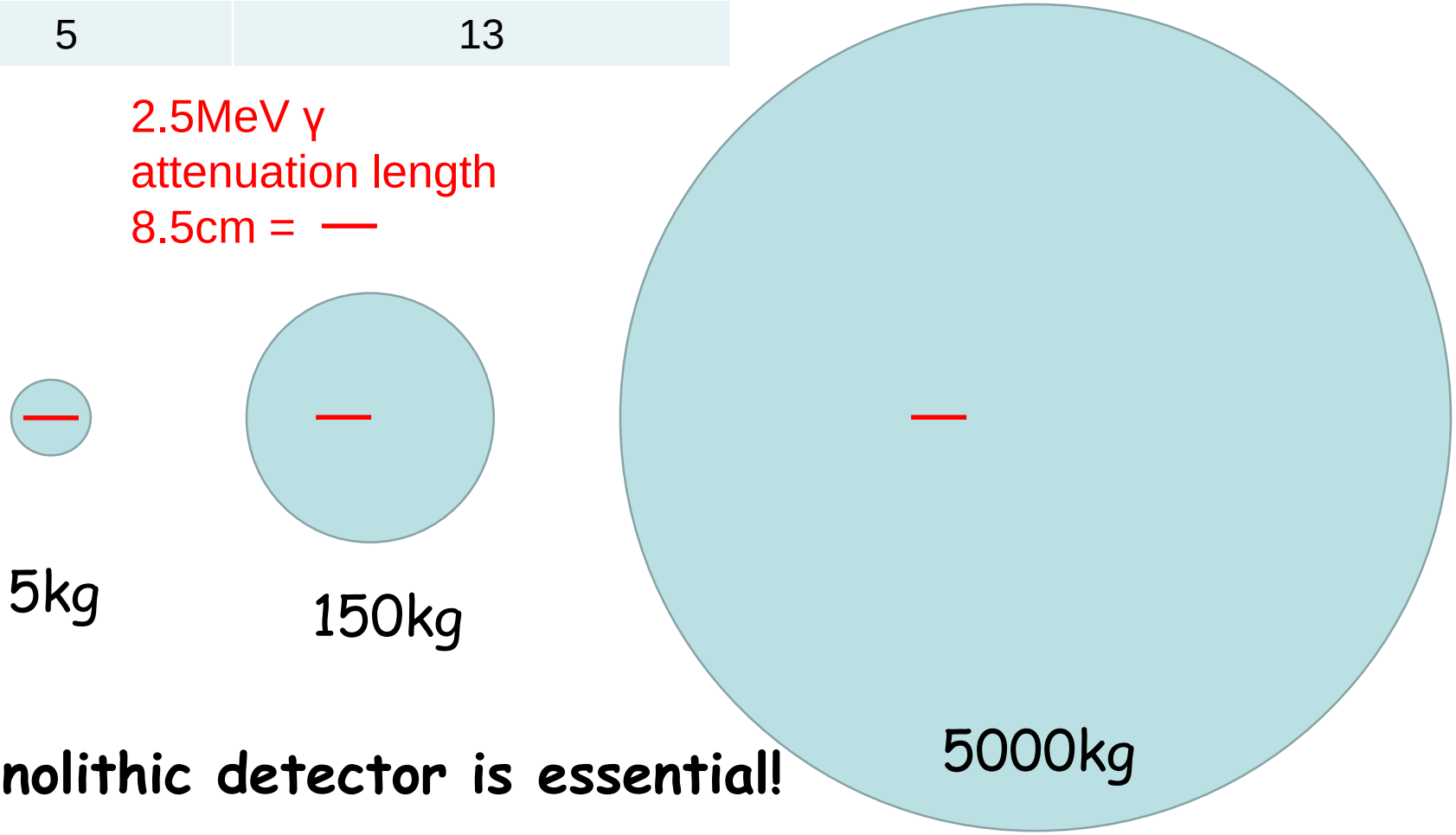
^{228}Th calibration source



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

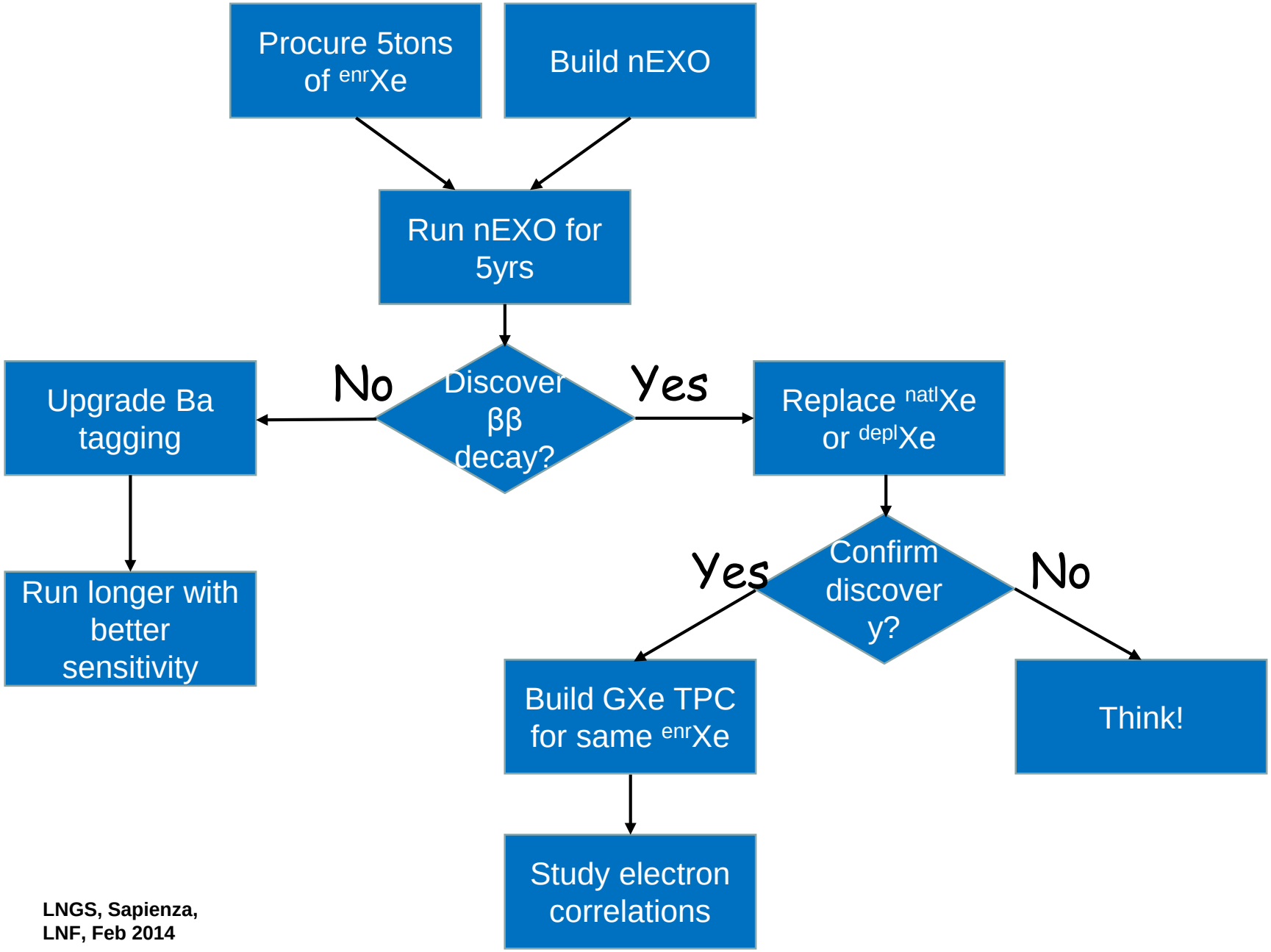
90% enriched ^{76}Ge: ~90$/g (+xtal growth)

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

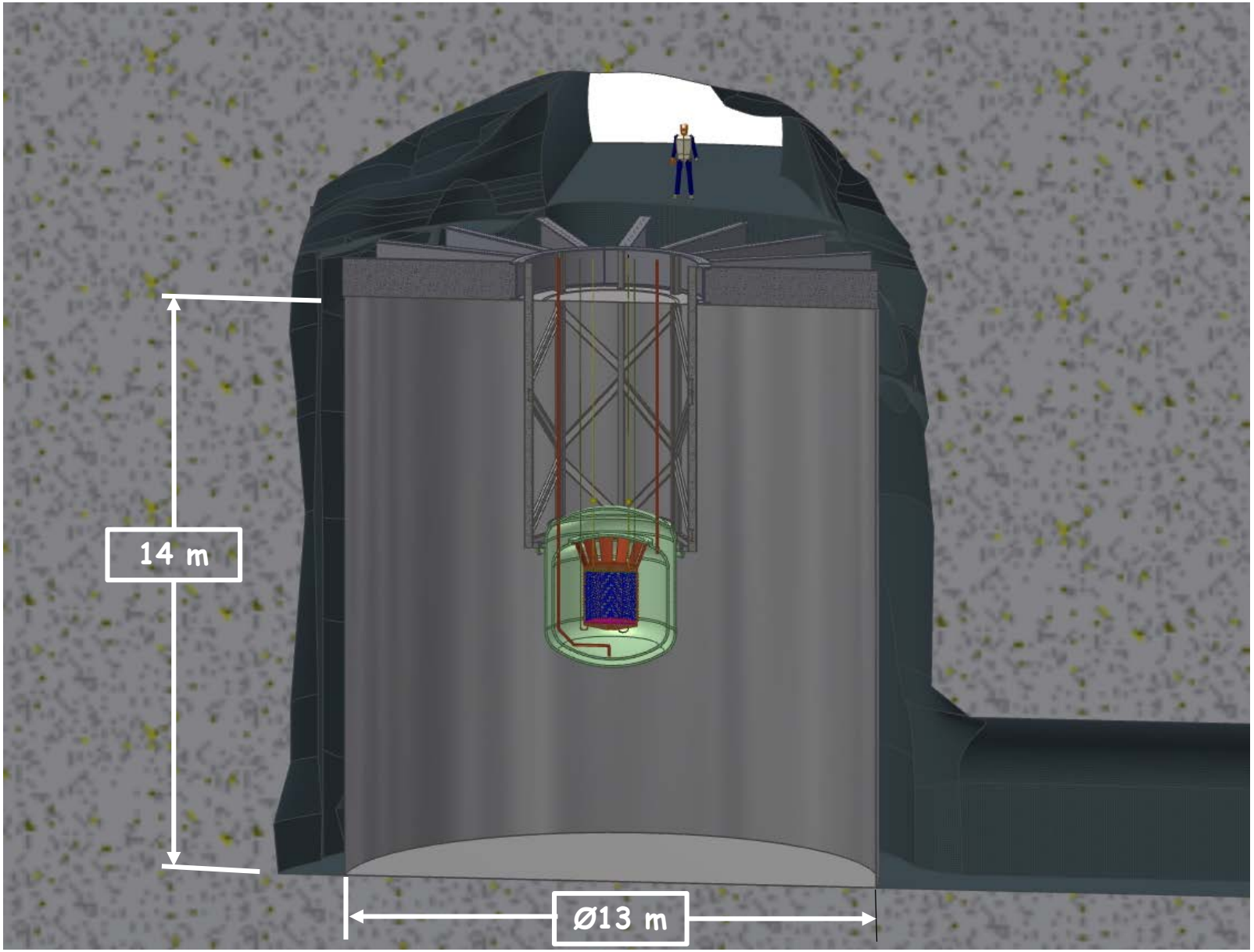
Exact centrifuge capacity in Russia is classified but our contacts indicate that 5000kg in 5 years is comfortable

- *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.

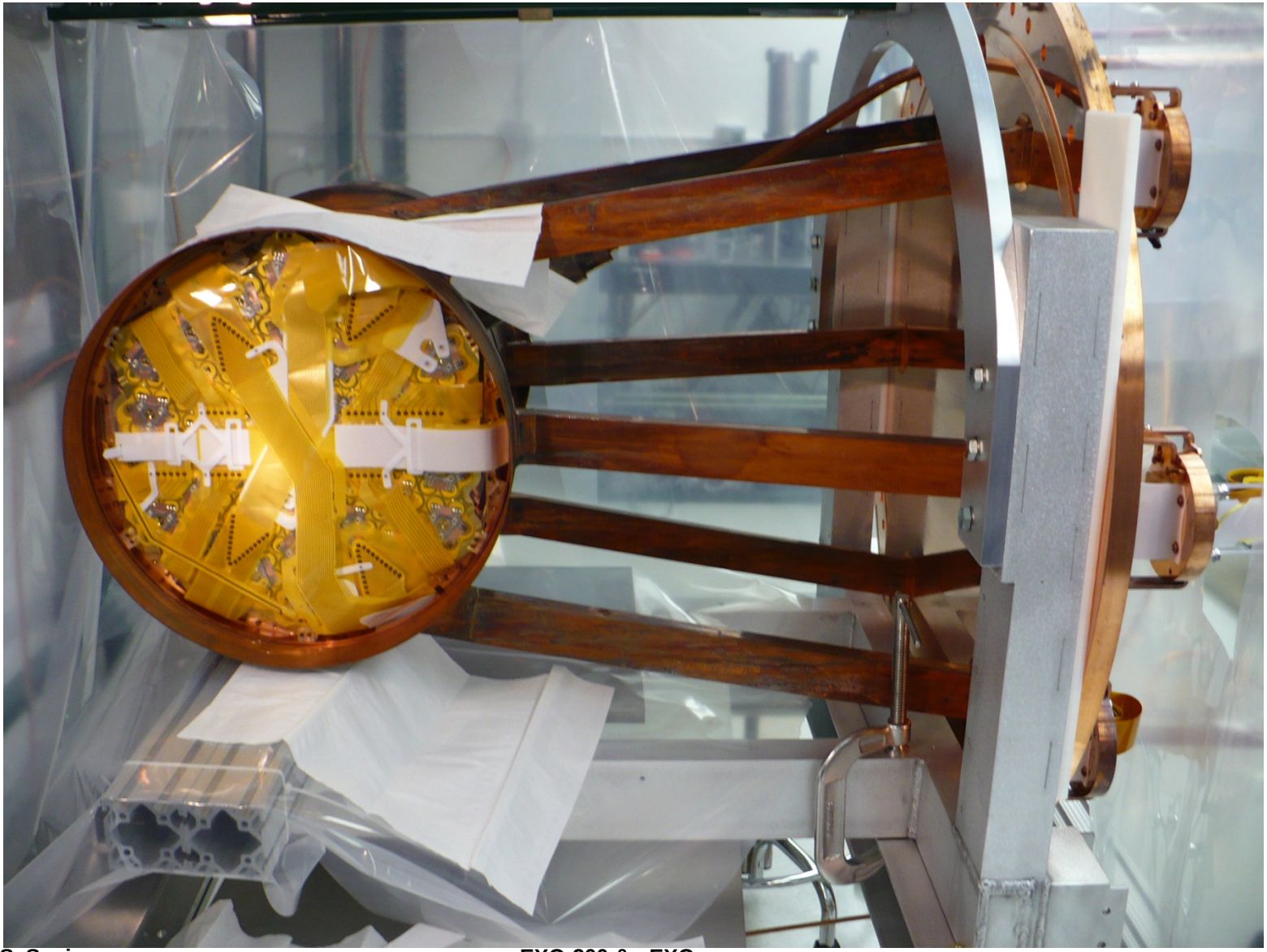
→ *Low risk*

What we need to change (Cat):

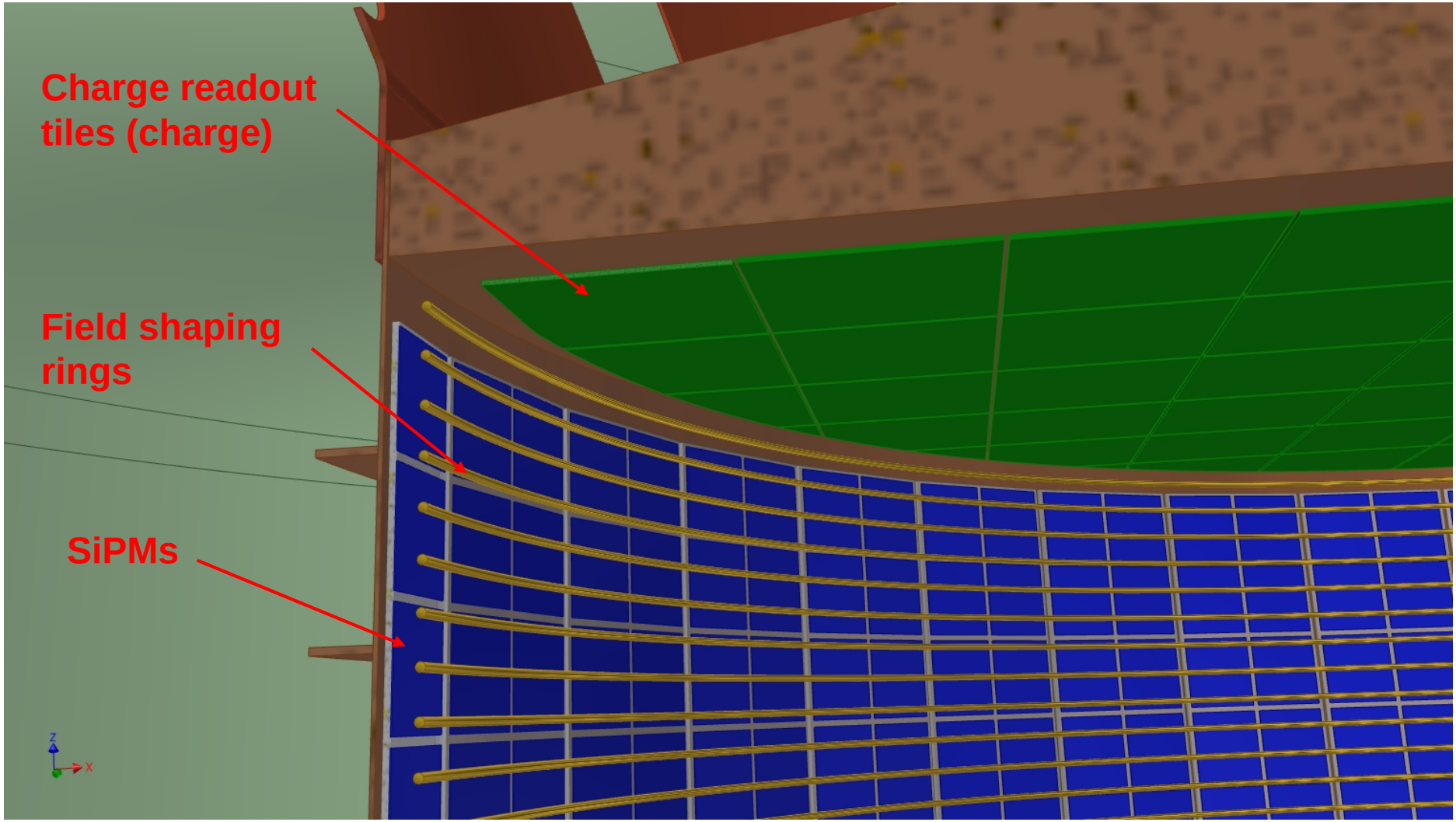
1. We know of a few things that were not quite right in EXO-200
2. Some items don't scale properly from 150kg to 5000kg

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

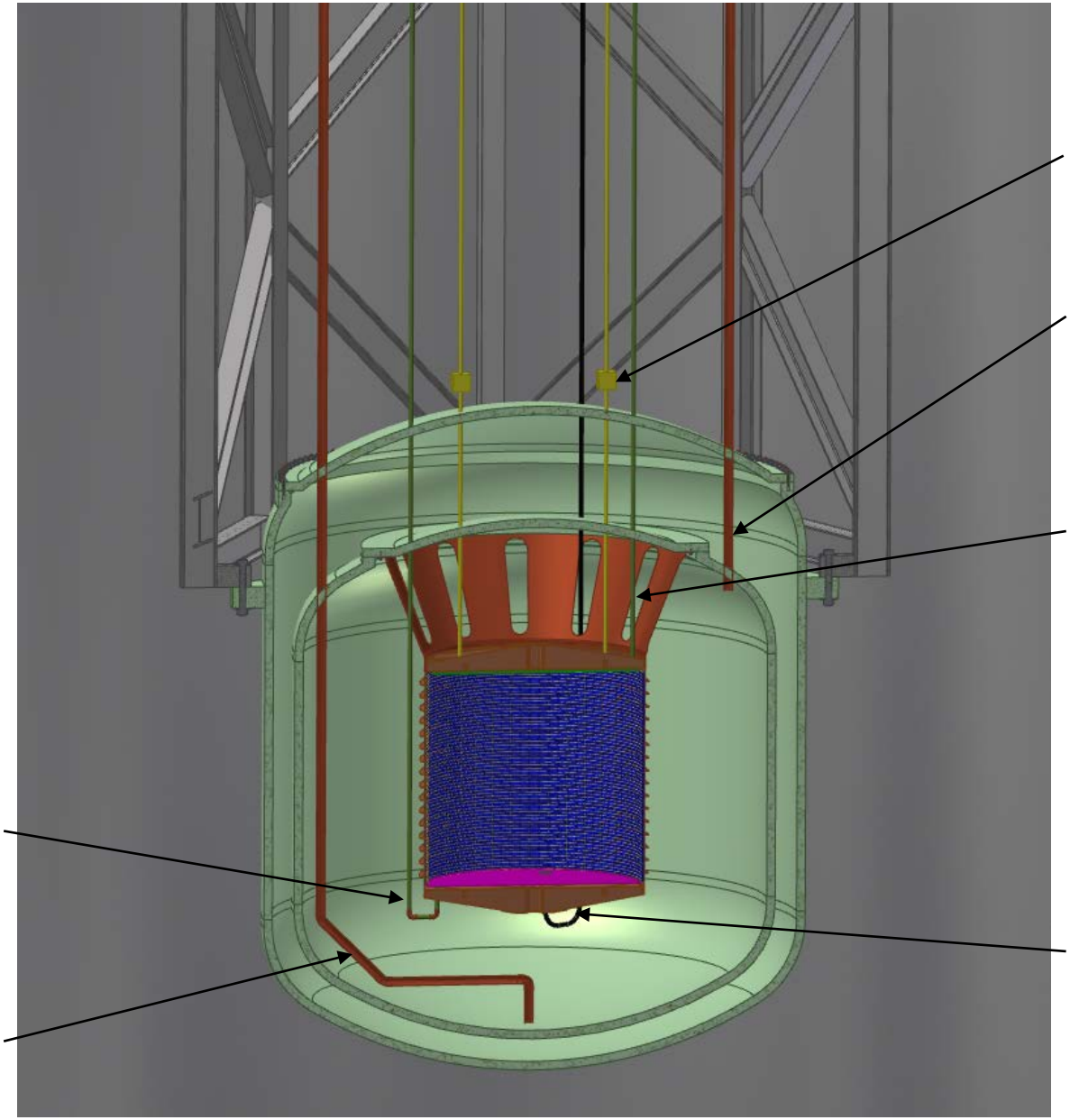
…it is remarkable that EXO-200 can achieve 5ms electron lifetime with a detector stuffed of (very clean and purged) plastics



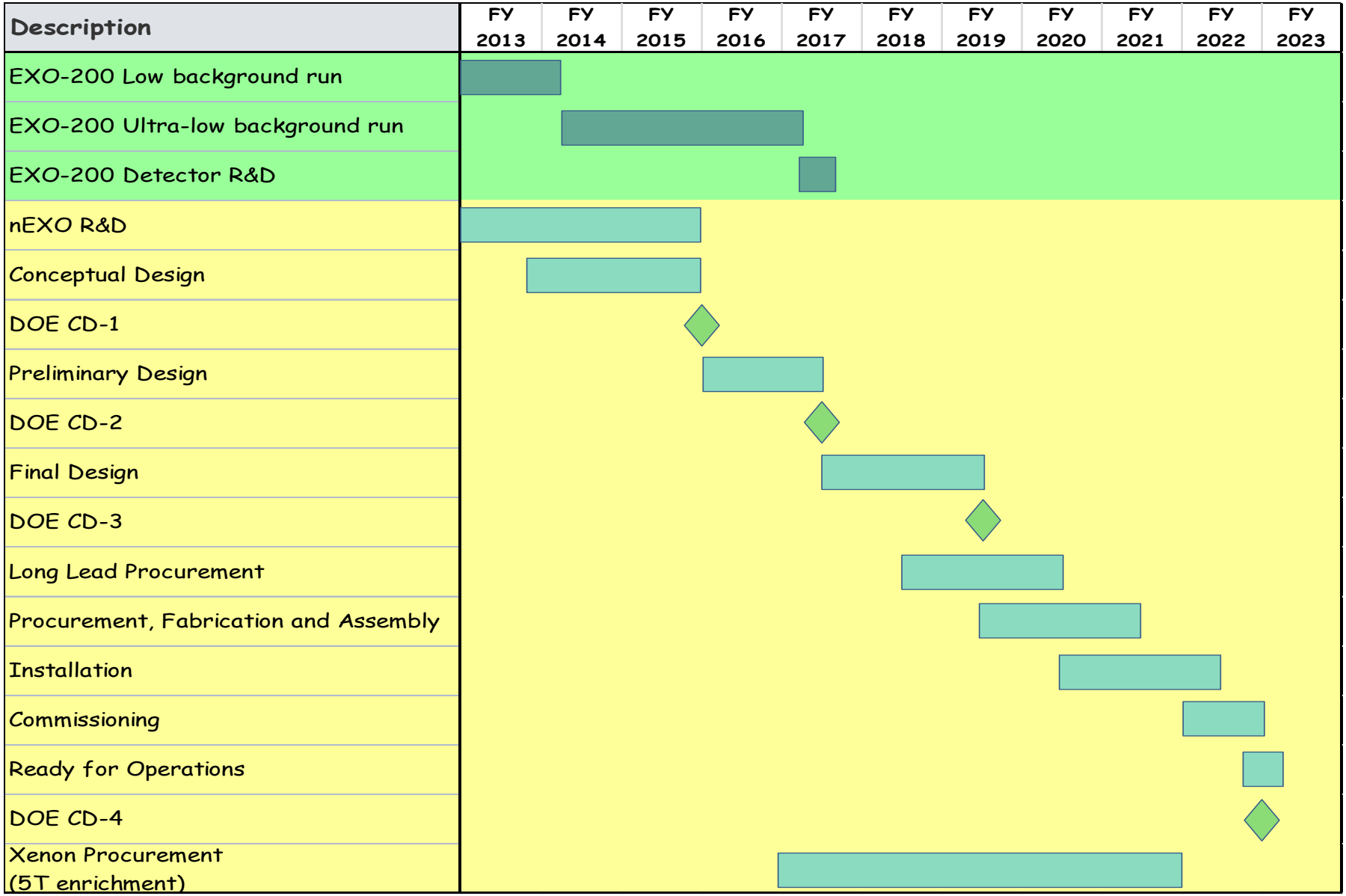
Close-up of the field shaping rings, anode readout tiles and SIPMs



Detail of the cryostat concept



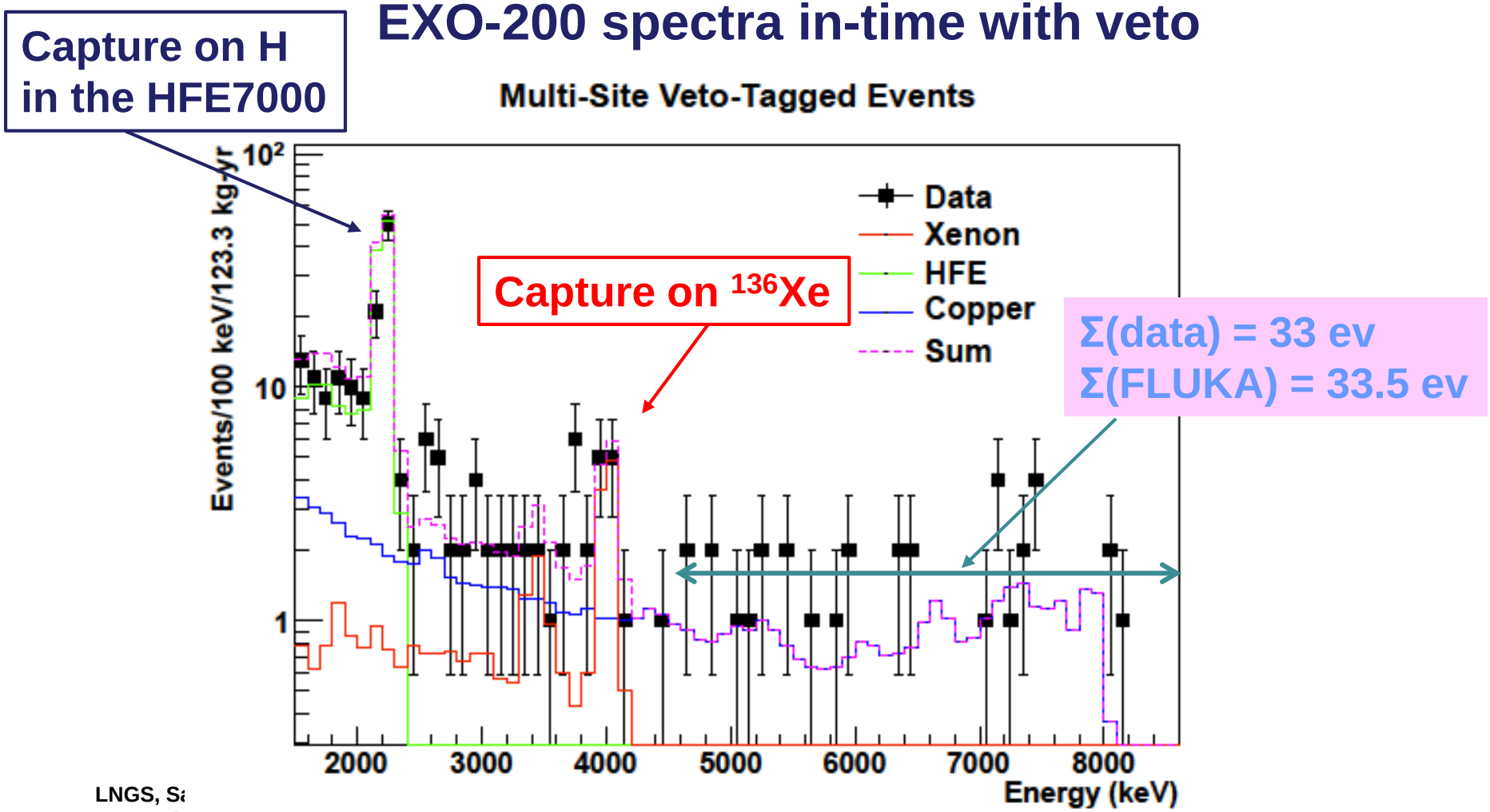
Notional time schedule for nEXO



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**

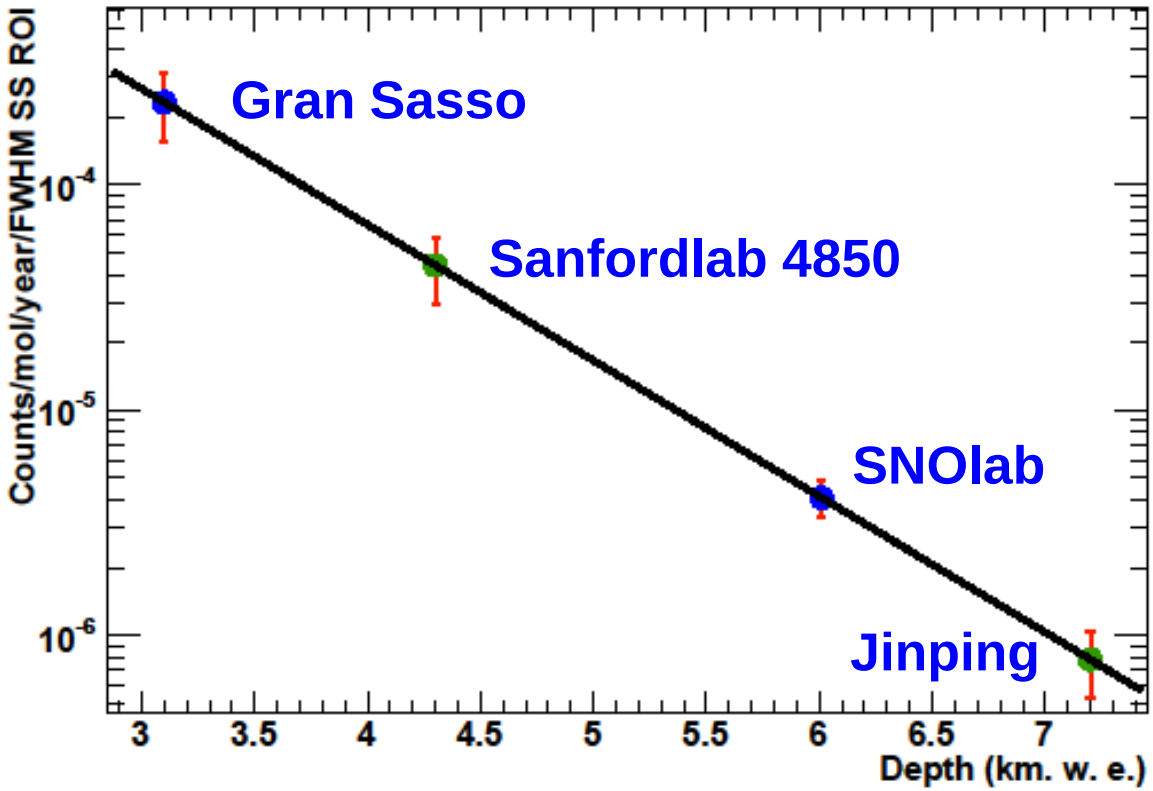
➔ very strongly suppressed by the large water shield and give a negligible contribution

...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



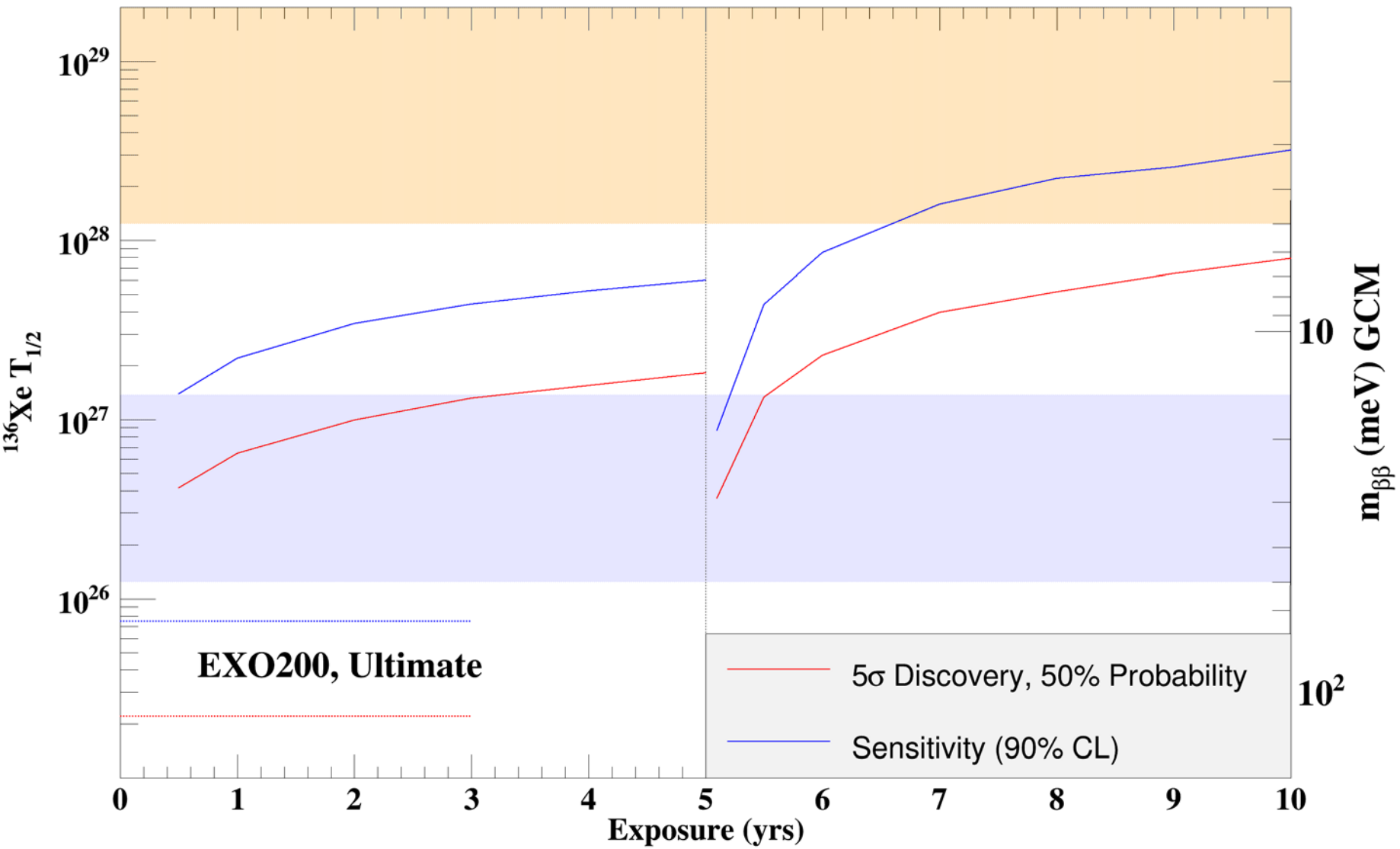
Conclusion:

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

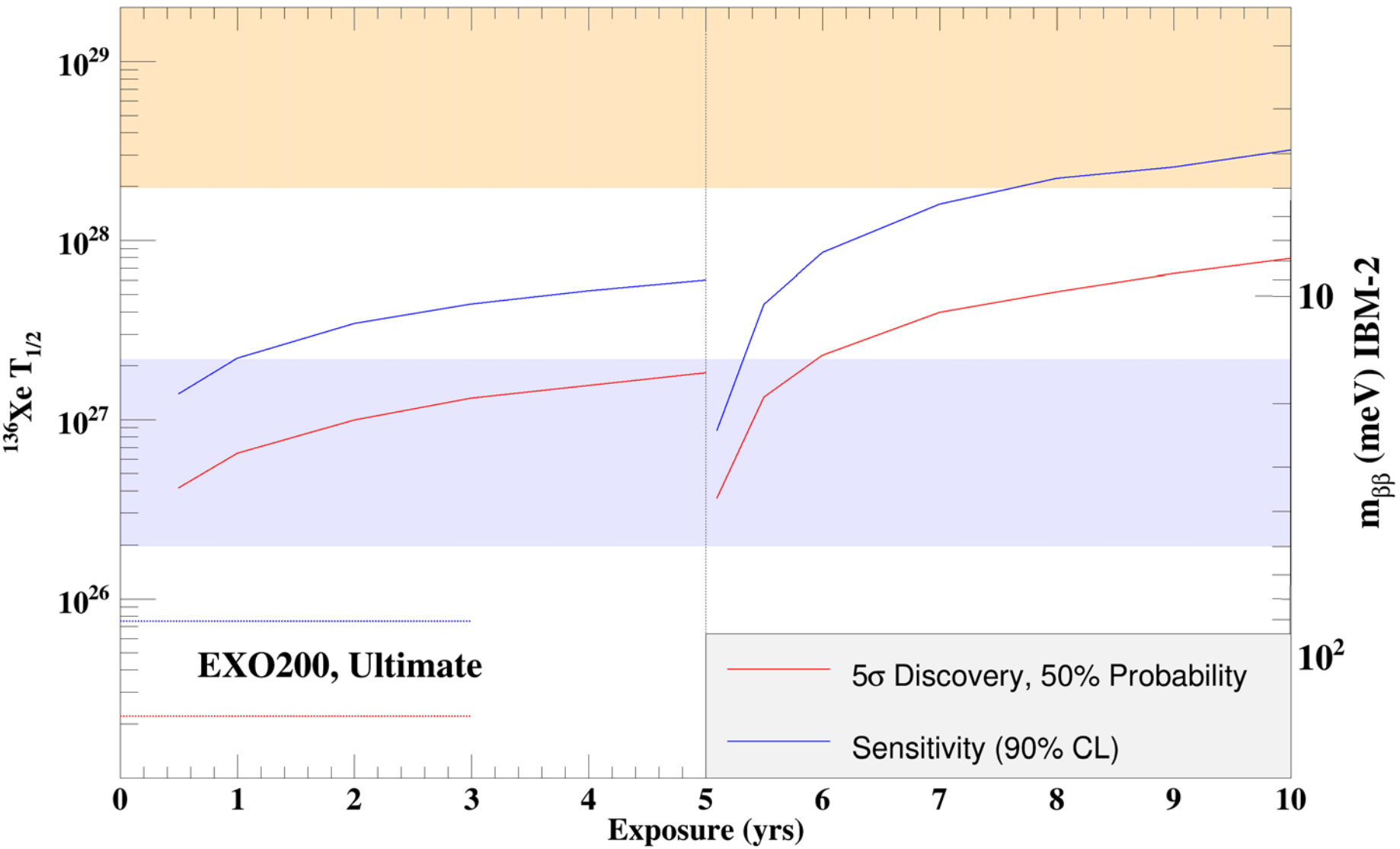
Summary of nEXO assumptions compared to EXO-200

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})	$1.6 \cdot 10^{-4}$	-

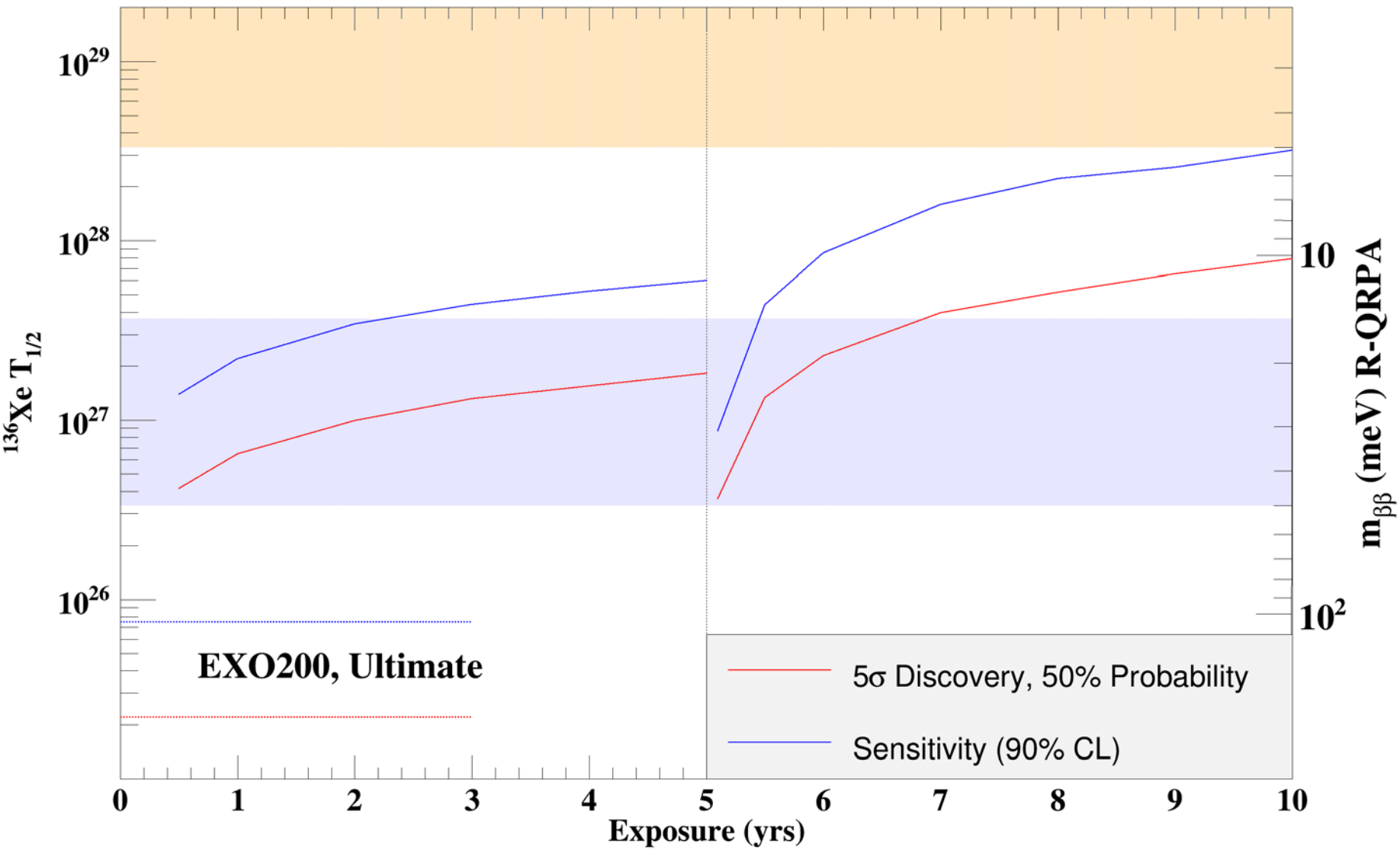
Sensitivity and discovery potential as a function of time



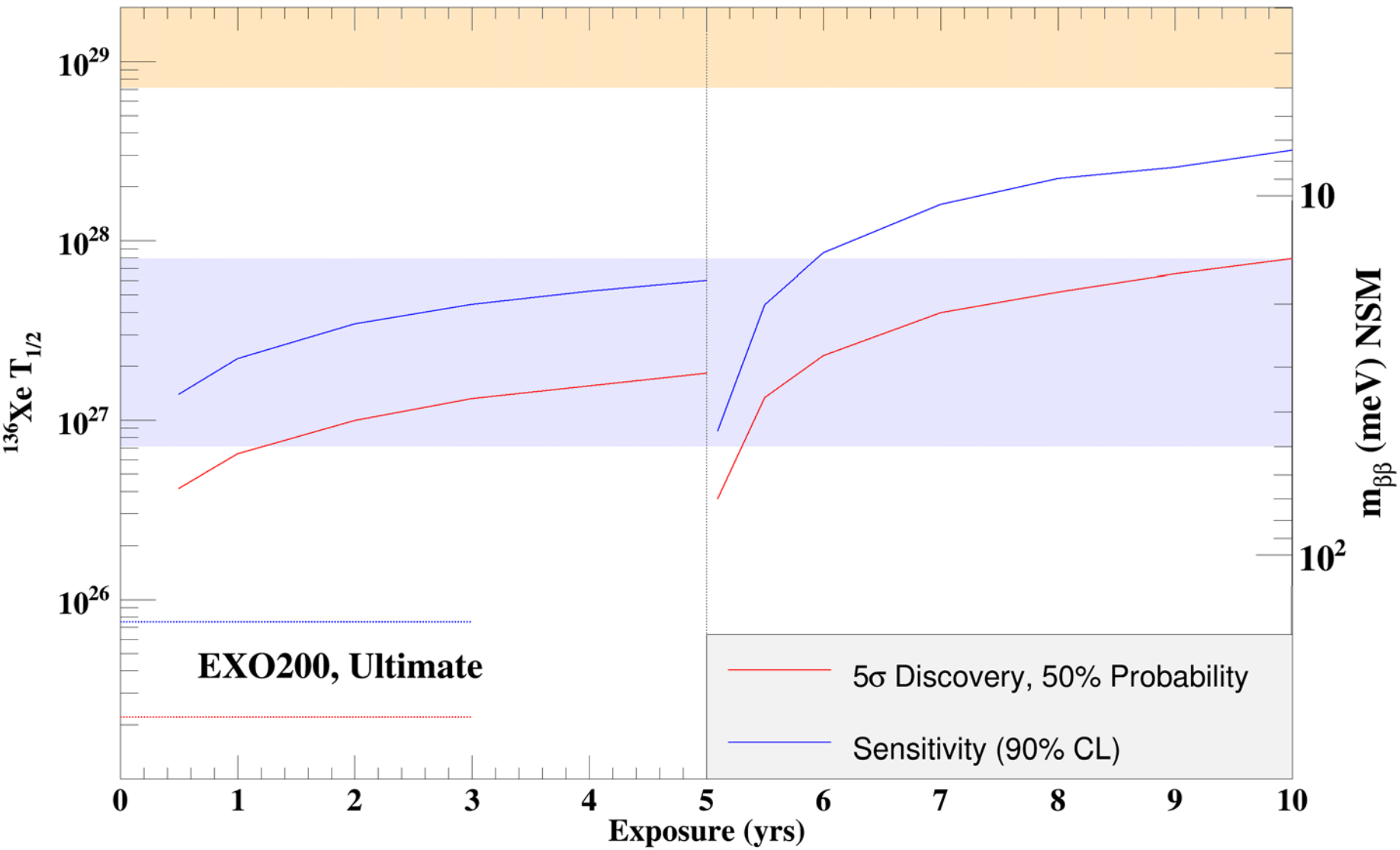
Sensitivity and discovery potential as a function of time



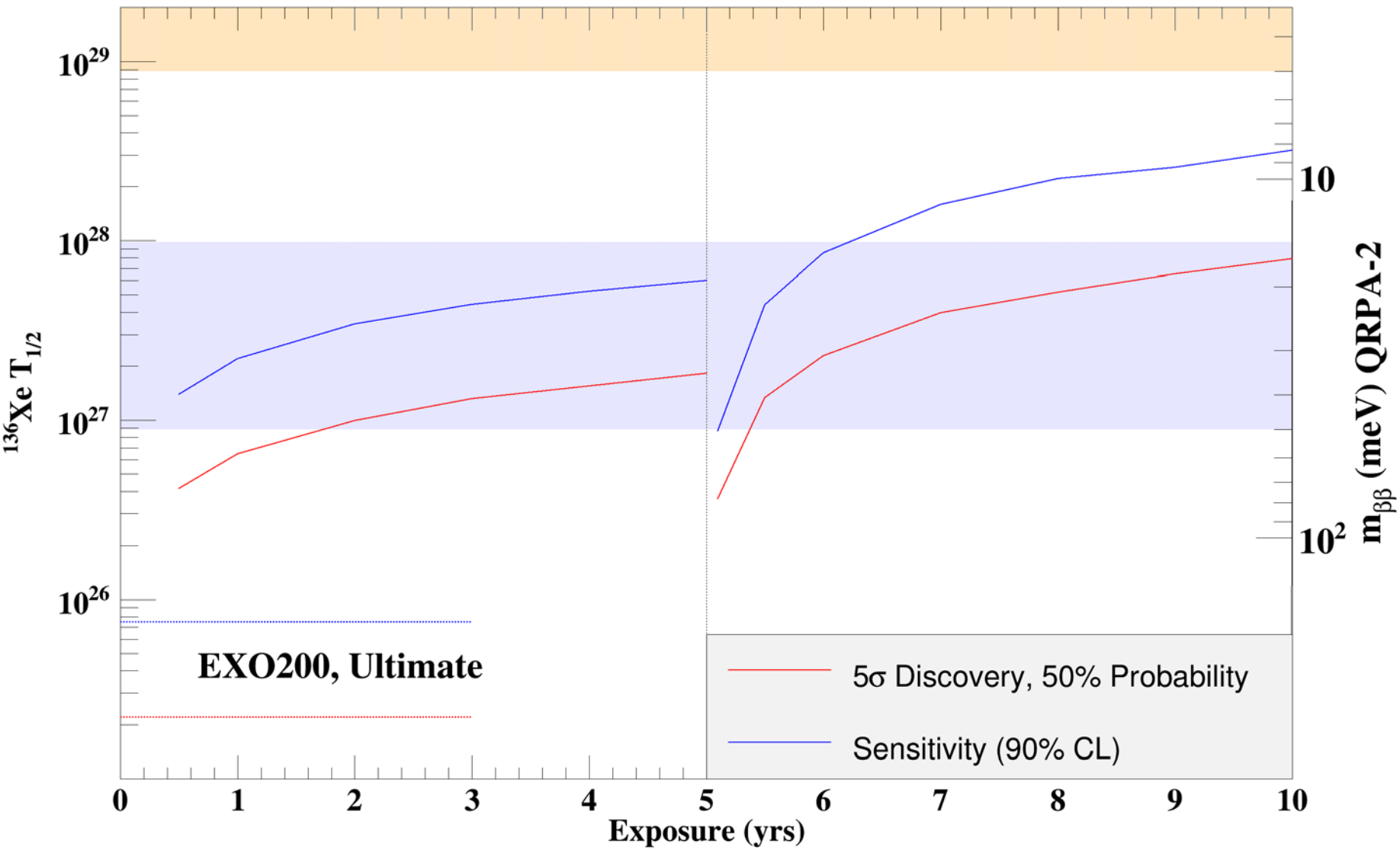
Sensitivity and discovery potential as a function of time

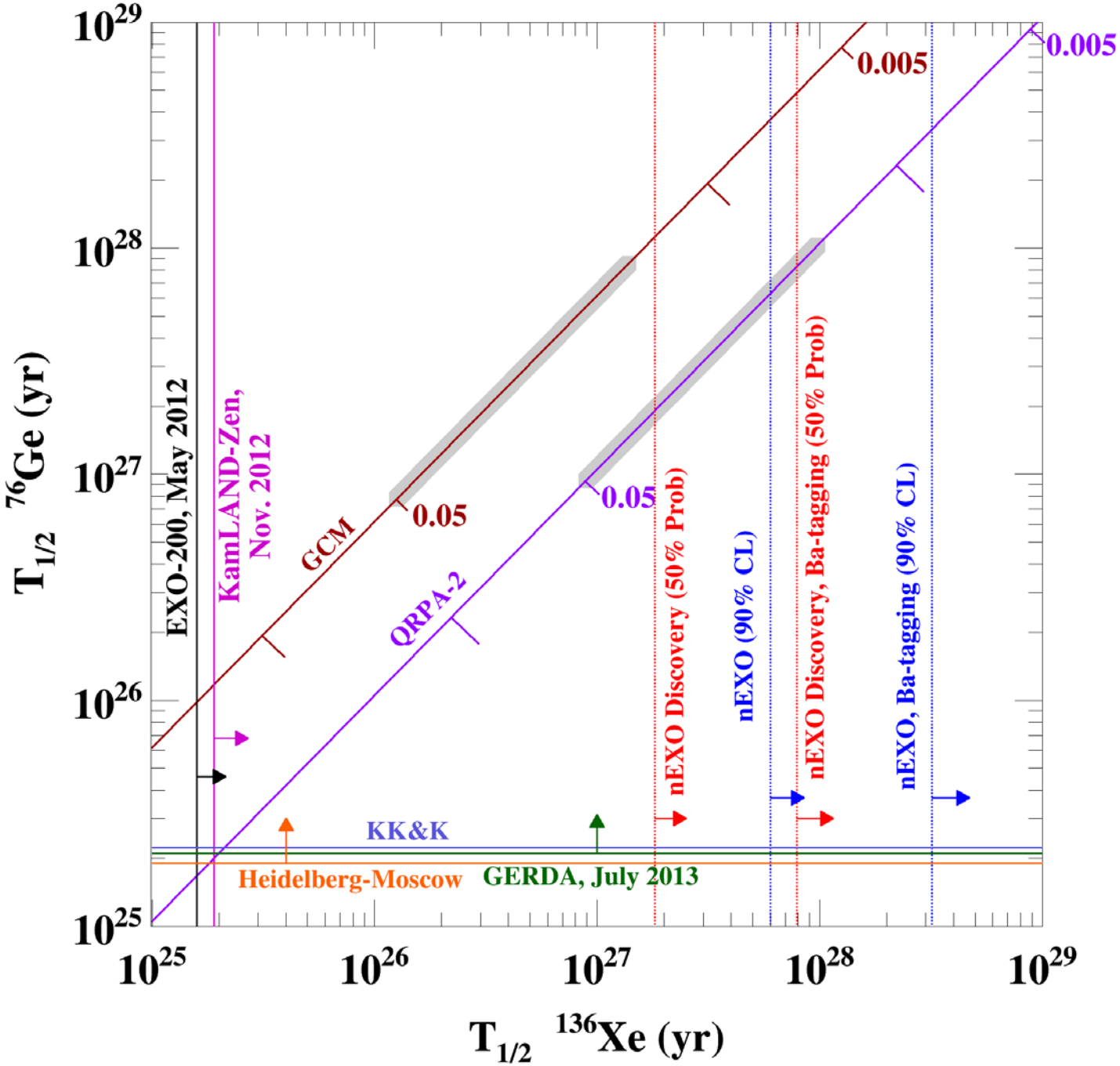


Sensitivity and discovery potential as a function of time



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)
10^{25}
10^{26}
10^{27}
10^{28}
10^{29}
$T_{1/2}$ ^{136}Xe (yr)
EXO-200, May 2012
KamLAND-Zen, Nov. 2012
GCM
0.05
0.005
QRPA-2
0.05
0.005
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
- ~3x 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!