

nEXO

NSAC Double-beta decay subcommittee

Washington DC Feb 24-25, 2014

The long term view:

- Working since 1999 on a staged approach to $0\nu\beta\beta$ decay
- “Stage 1”, i.e. EXO-200 has been taking data since May 2011, producing some of the most competitive results in the field
- EXO-200 detector performance was close to design from the very beginning of data taking
- EXO-200 is also a very successful prototype for a larger, “Stage 2” detector
- “Stage 2”, nEXO, is being designed as a 5 tonne LXe detector following closely the EXO-200 layout
- nEXO is also a very flexible and cost effective detector with a clear upgrade path and the built-in capability to address possible future science scenarios making the best use of the isotopically enriched isotope.

The EXO-200 Collaboration



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The EXO-200 Collaboration



113 collaborators (90% scientists and students, 10% engineers)
20 institutions
7 countries
3 continents

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 imaging 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 $\sim \Delta m$. For Xe 4.7 amu
- Only known case where final state identification appears to be not impossible
 - eliminate all non- $\beta\beta$ backgrounds, possibly only chance of getting to Normal Hierarchy
- ^{136}Xe can be replaced with $^{\text{Nat}}\text{I}\text{Xe}$ if a signal is observed!

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Material procurement

^{136}Xe enrichment easier and cheaper:

→ 90% enriched ^{136}Xe : ~10\$/g

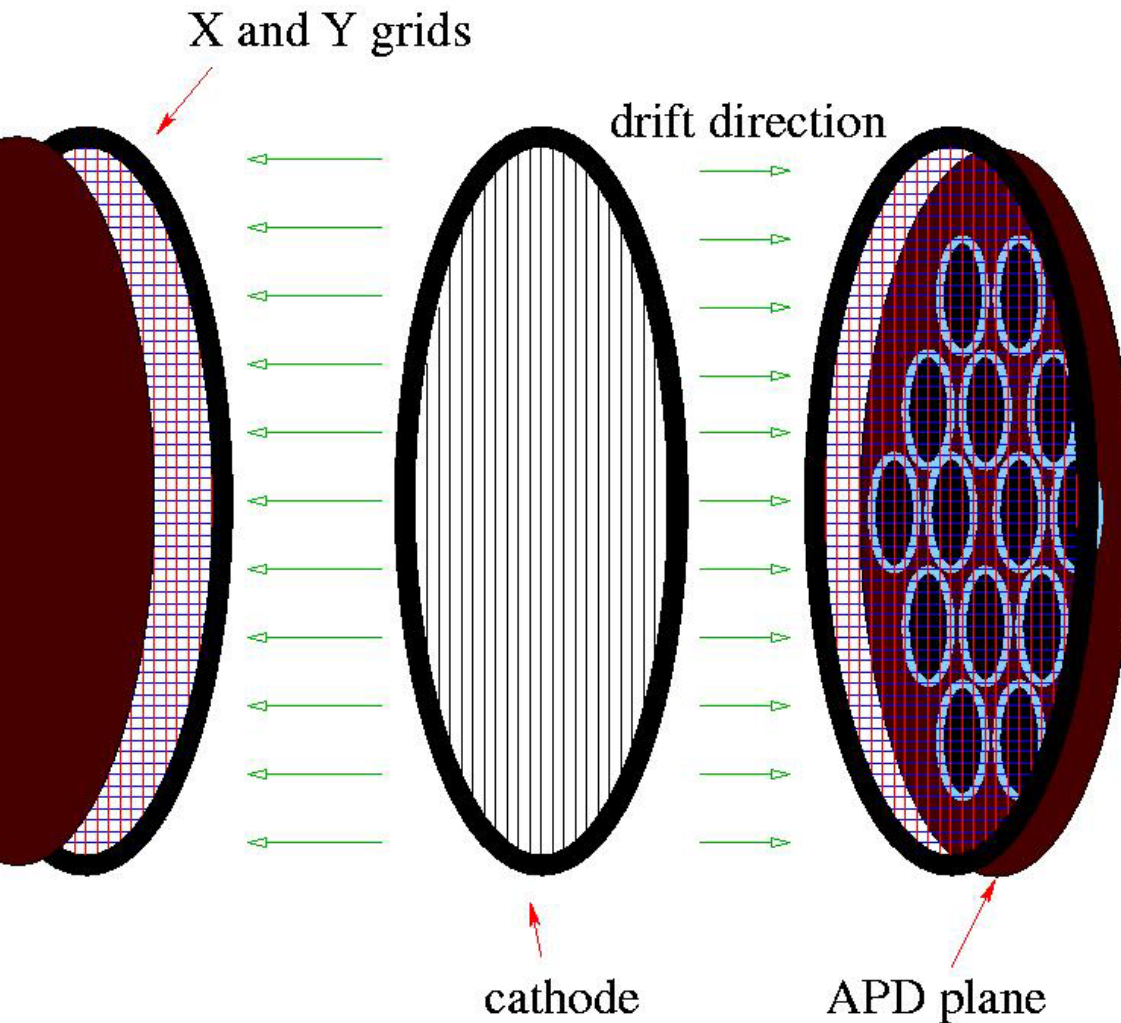
90% enriched ^{76}Ge : ~90\$/g (+xtal growth)

(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

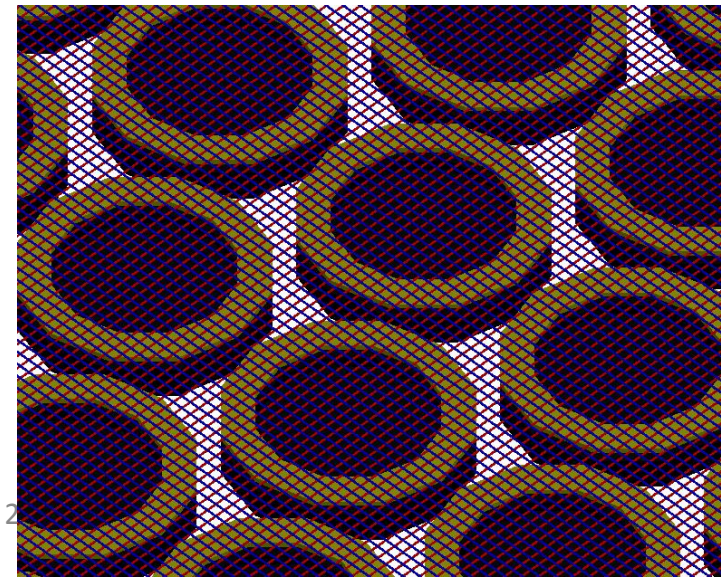
- *World $^{nat'l}\text{Xe}$ production is ~40 tonnes/yr (~4000kg ^{136}Xe), however large price fluctuations are not uncommon*
- *Coordination with DM experiments, space agencies and commercial customers is desirable*
- *A large order in a hurry is not a smart way to proceed*

EXO-200



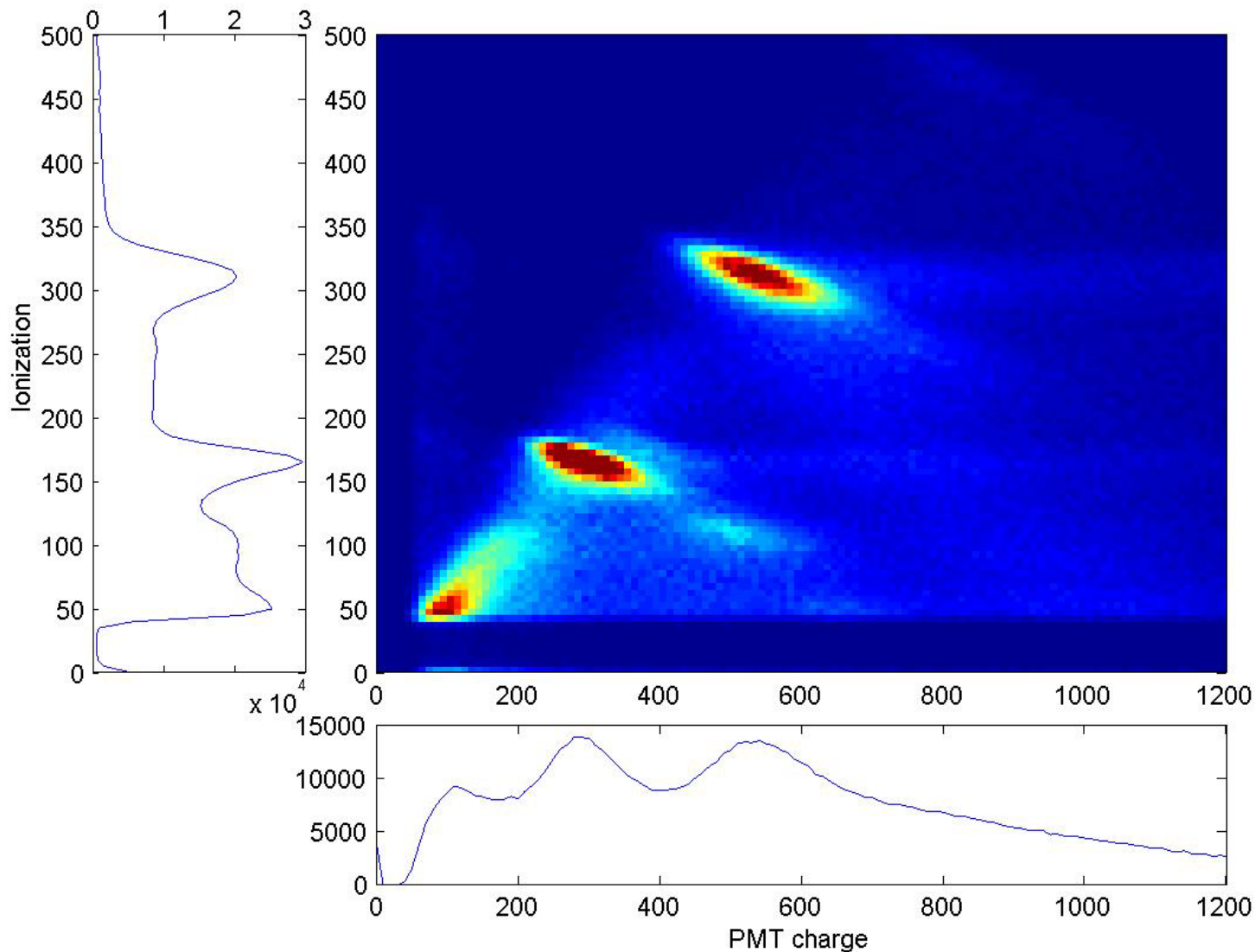
The principle:

**Simultaneous readout
of charge and
scintillation in a large
and homogeneous
Liquid Xe TPC**



EXO R&D showed the way to improved energy resolution in LXe:

Use (anti)correlations between ionization and scintillation signals



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

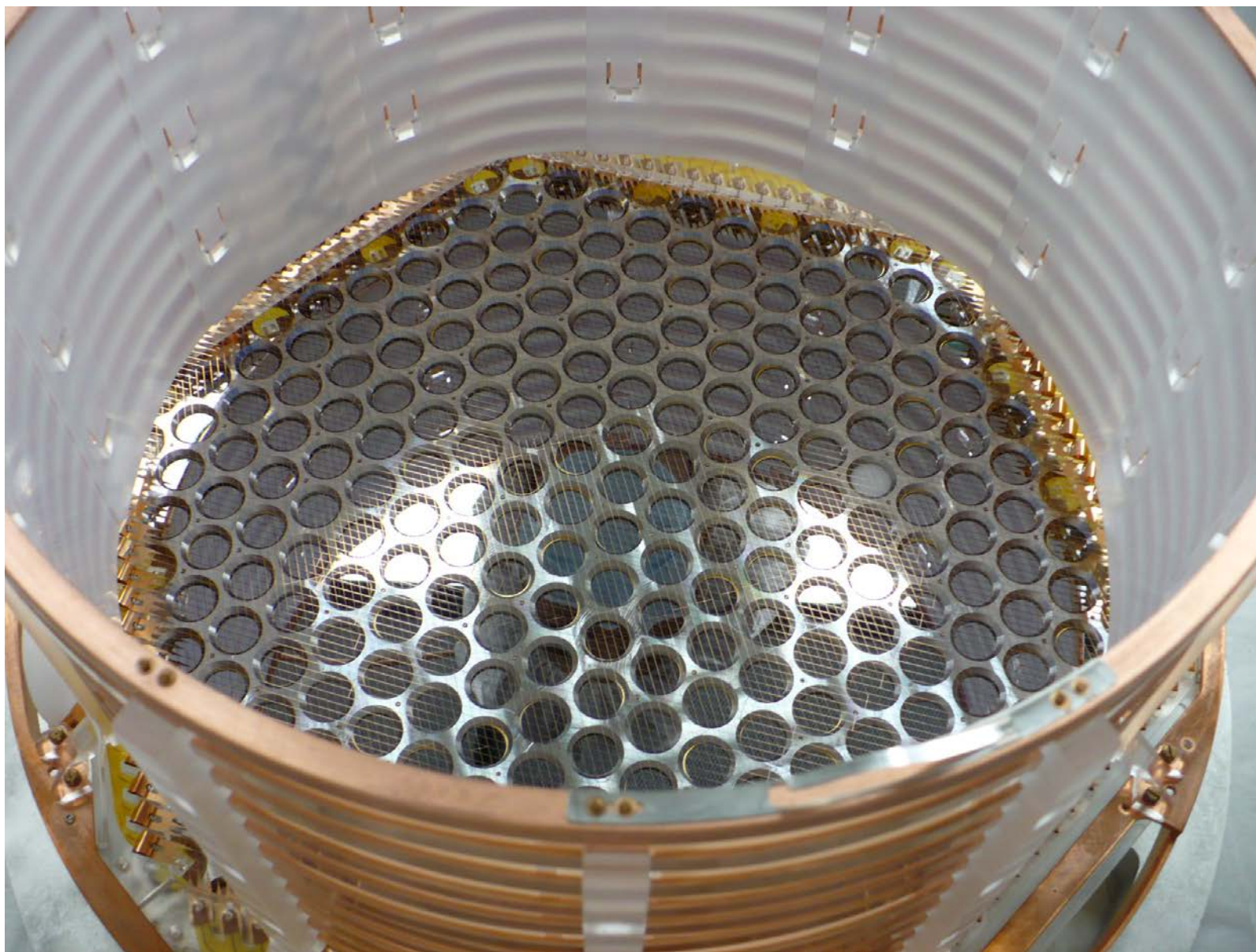


- very clean & light-weight
- QE~1 @175nm

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



M. Auger et al., JINST 7 (2012) P05010

Ultra-low activity Cu vessel



- Very light (~1.5 mm thin, ~15 kg) 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 in a CR-shielded clean building)

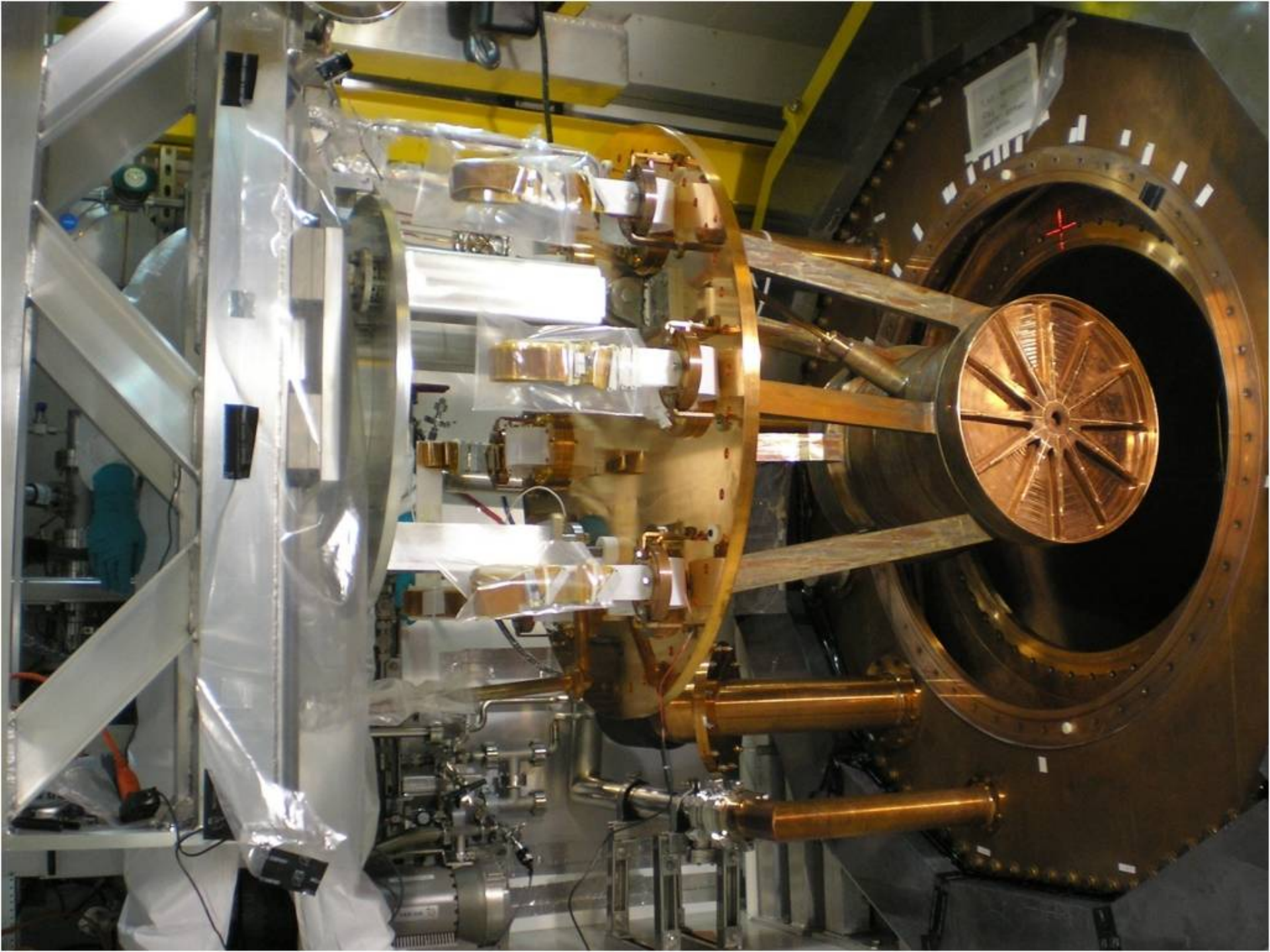
Massive effort on material radioactive qualification using:

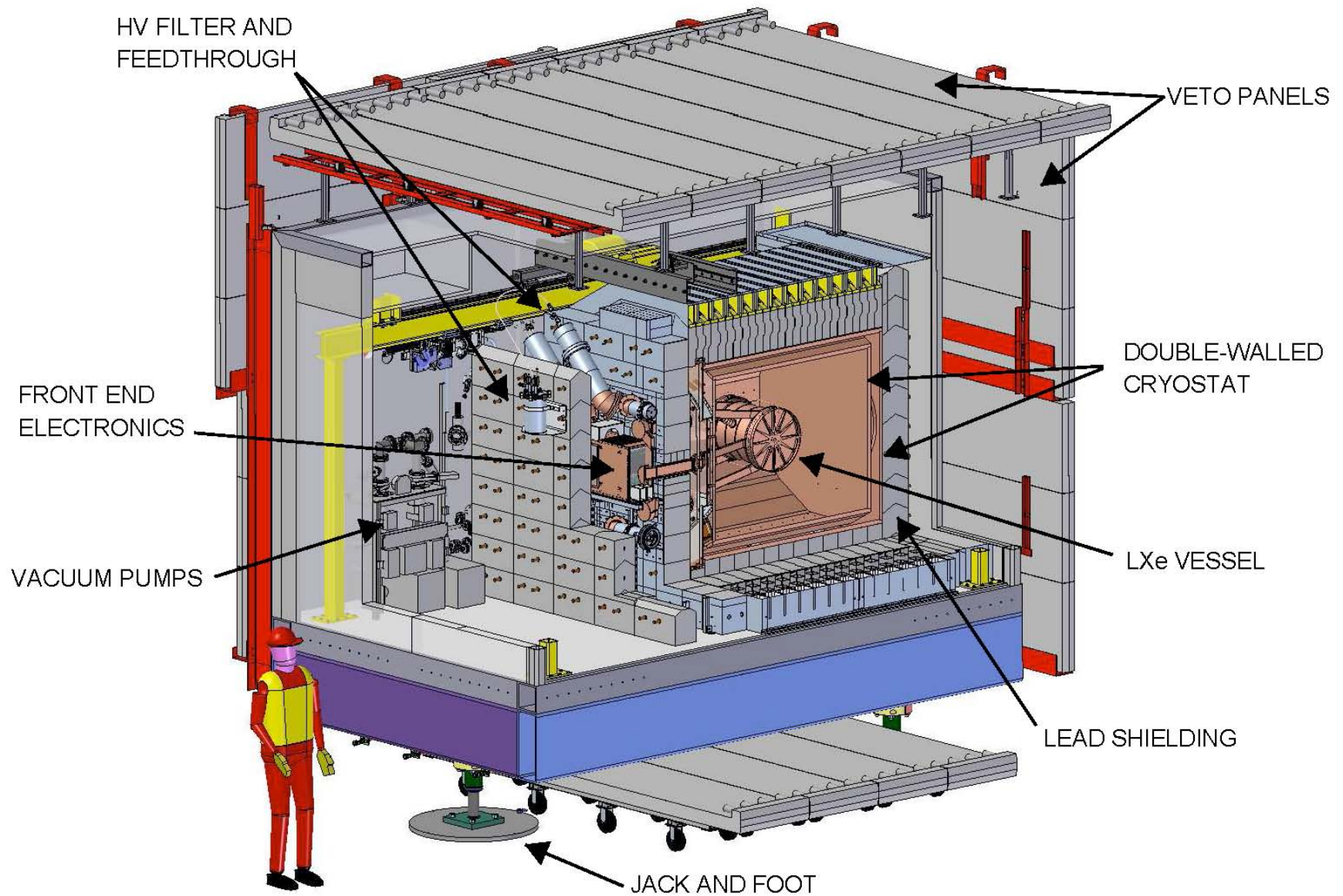
- NAA
- Low background γ -spectroscopy
- α -counting
- Radon counting
- High performance GD-MS and ICP-MS

**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 was evaluated
before acceptance**



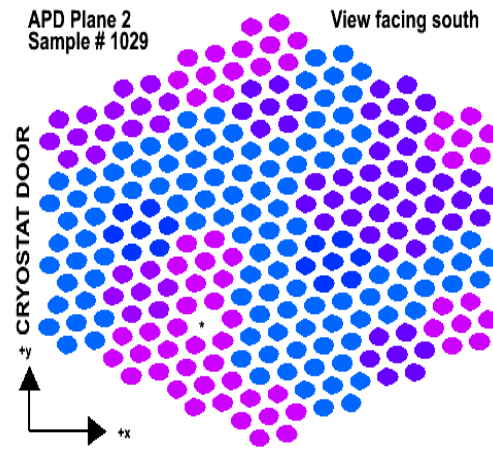
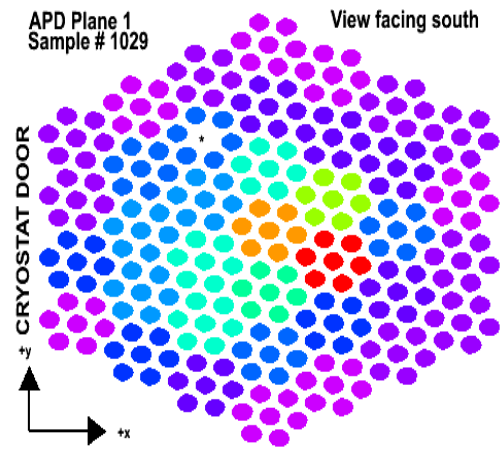
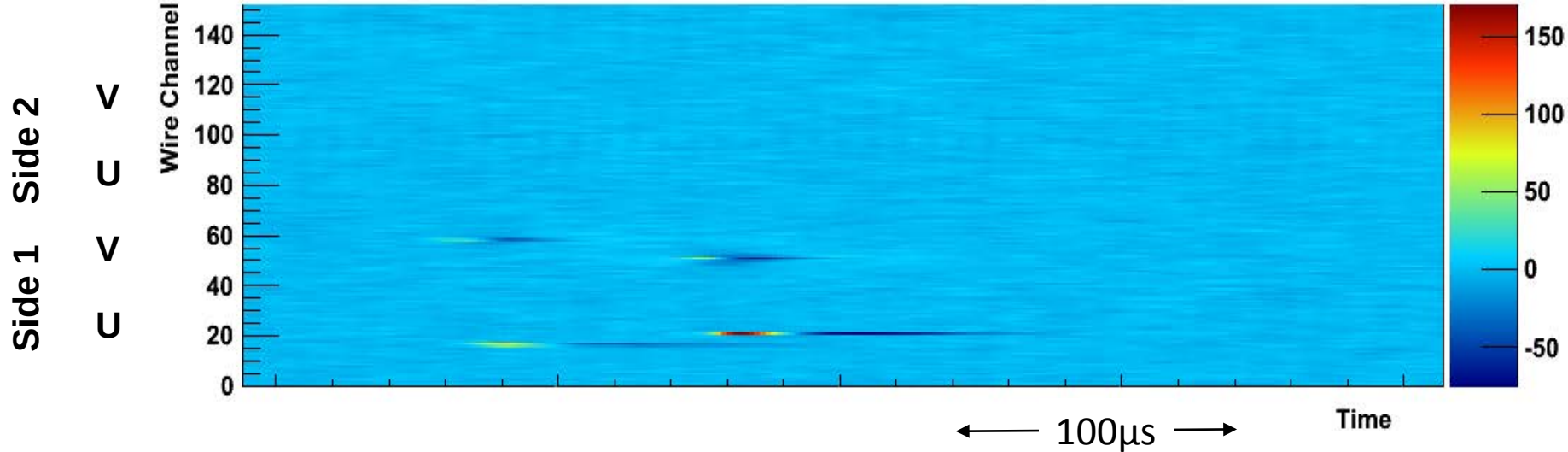


Underground location: Waste Isolation Pilot Plant (WIPP) Carlsbad, NM

- ~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/m³)
- Rather convenient access with large conveyance



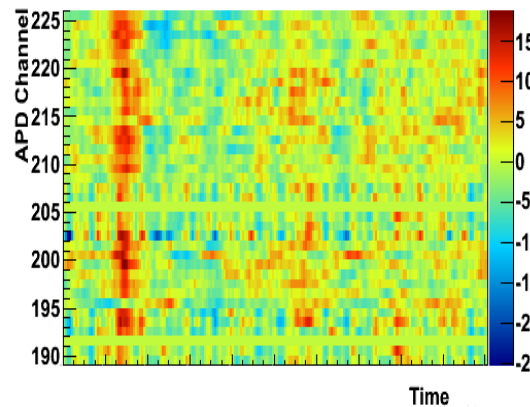
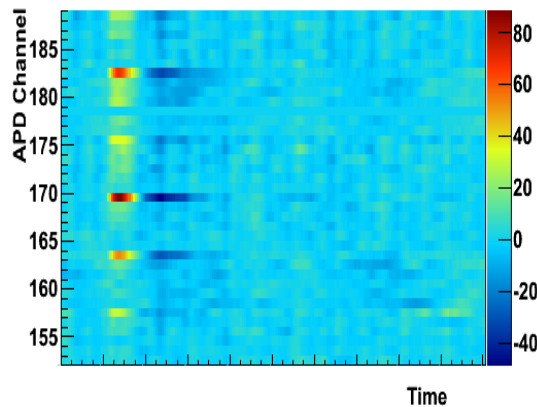




A two-site Compton scattering event.

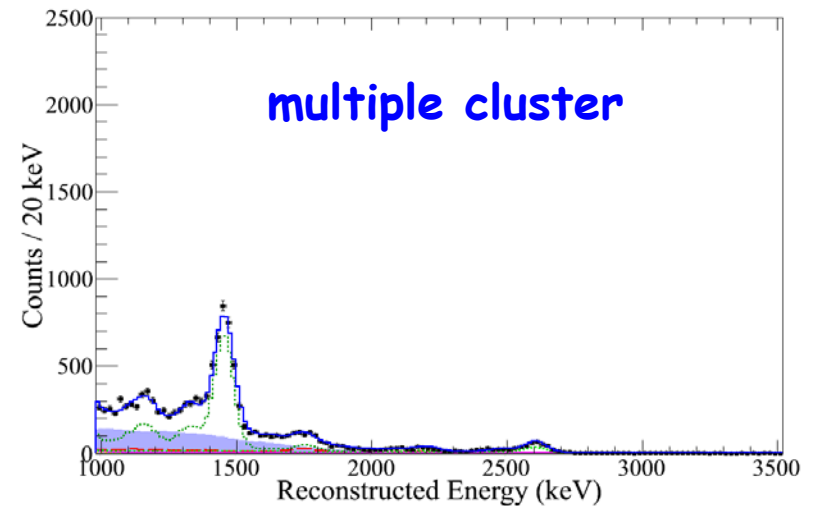
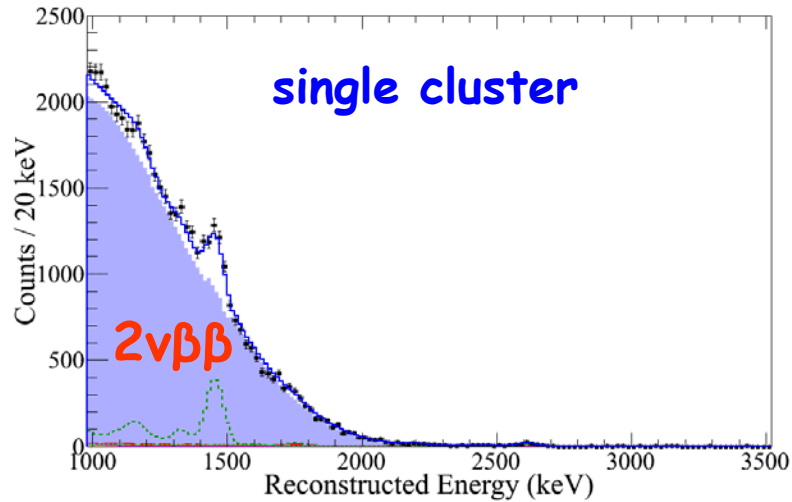
All scintillation light arrives at the same time, indicating that the two energy depositions are simultaneous.

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

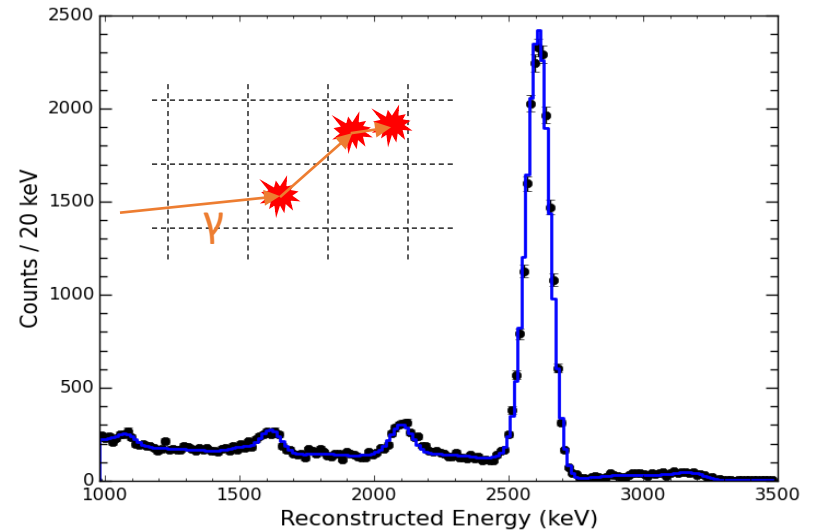
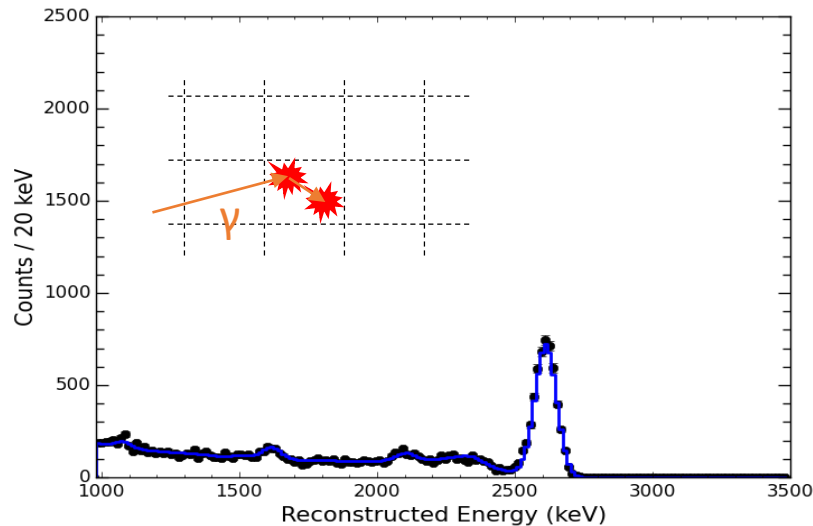


Tracking: an essential tool to identify and suppress backgrounds

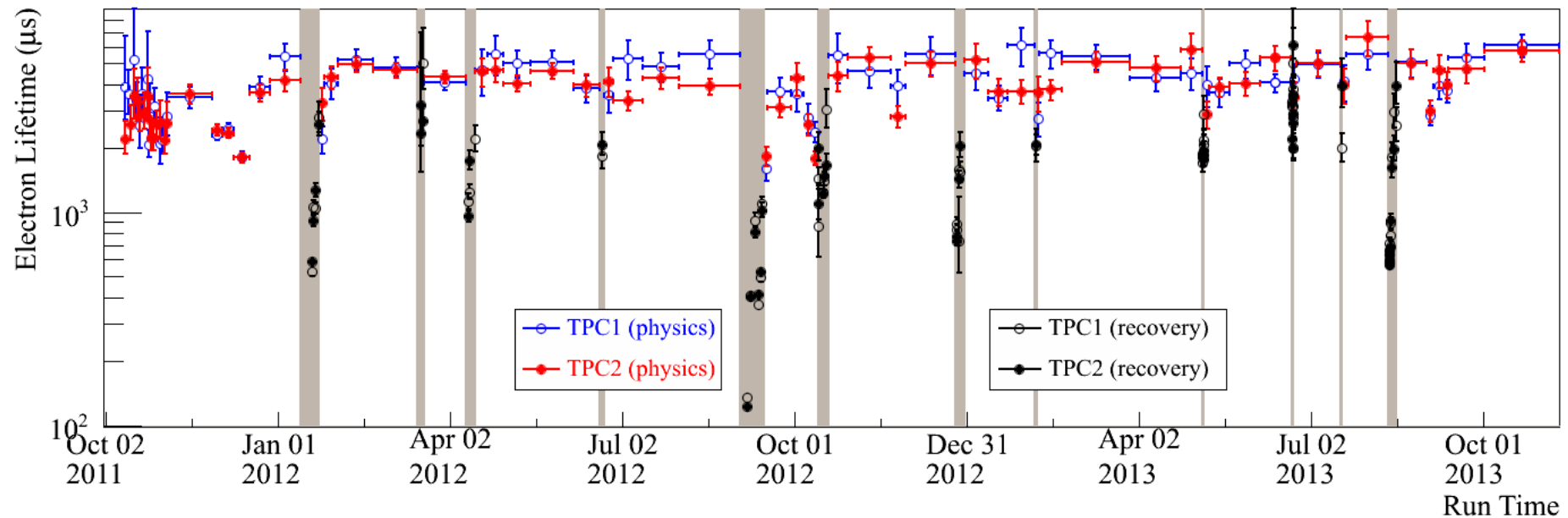
Low background
data



^{228}Th calibration
source



Xe purity is essential for good energy resolution



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

At $\tau_e = 3$ ms:
- drift time $< 110 \mu\text{s}$
- loss of charge: 3.6%
at full drift length

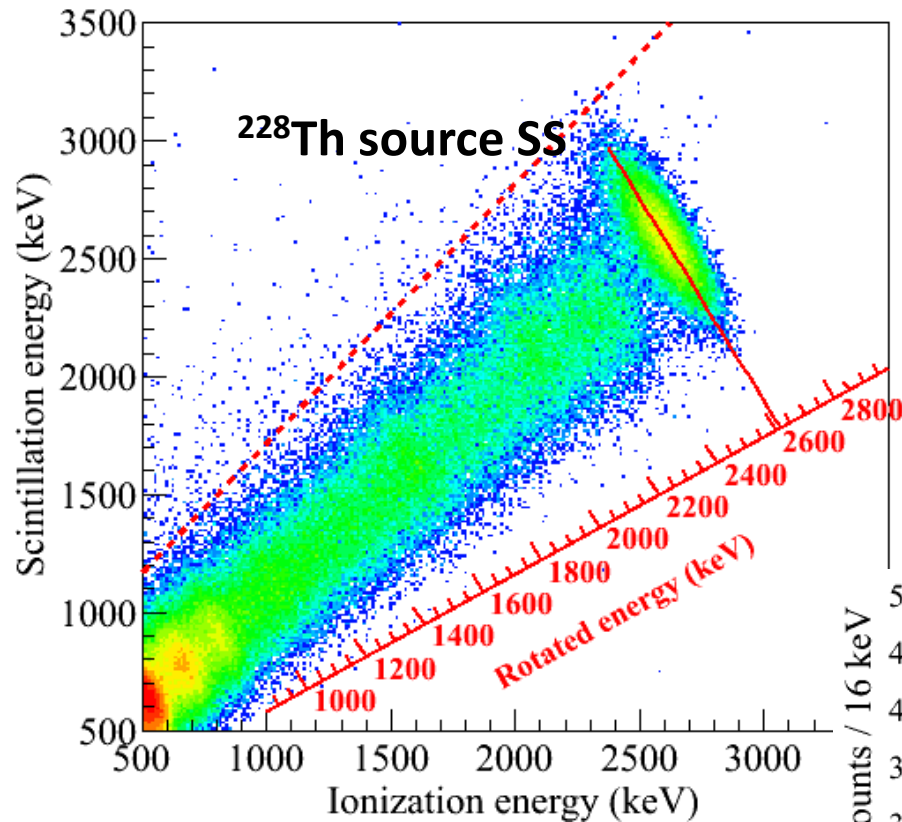
Ultraclean pump: *Rev Sci Instr.* 82 (10) 105114
Xenon purity with mass spec: *NIM A*675 (2012) 40
Gas purity monitors: *NIM A*659 (2011) 215

Combining Ionization and Scintillation

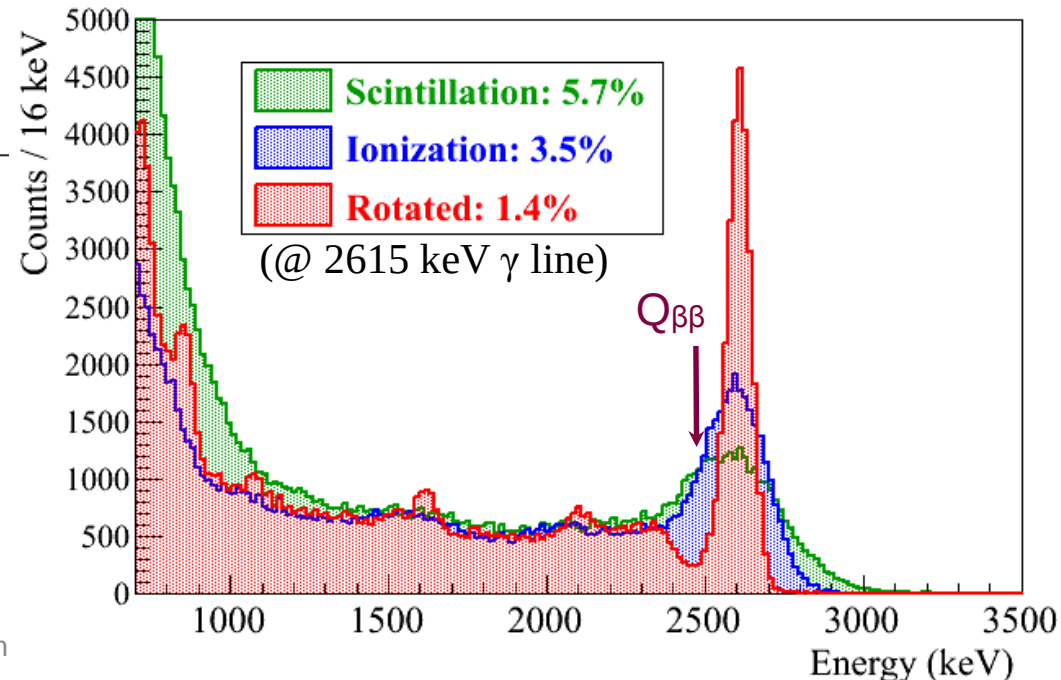
Anticorrelation between
scintillation and ionization
in LXe known since early EXO R&D

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

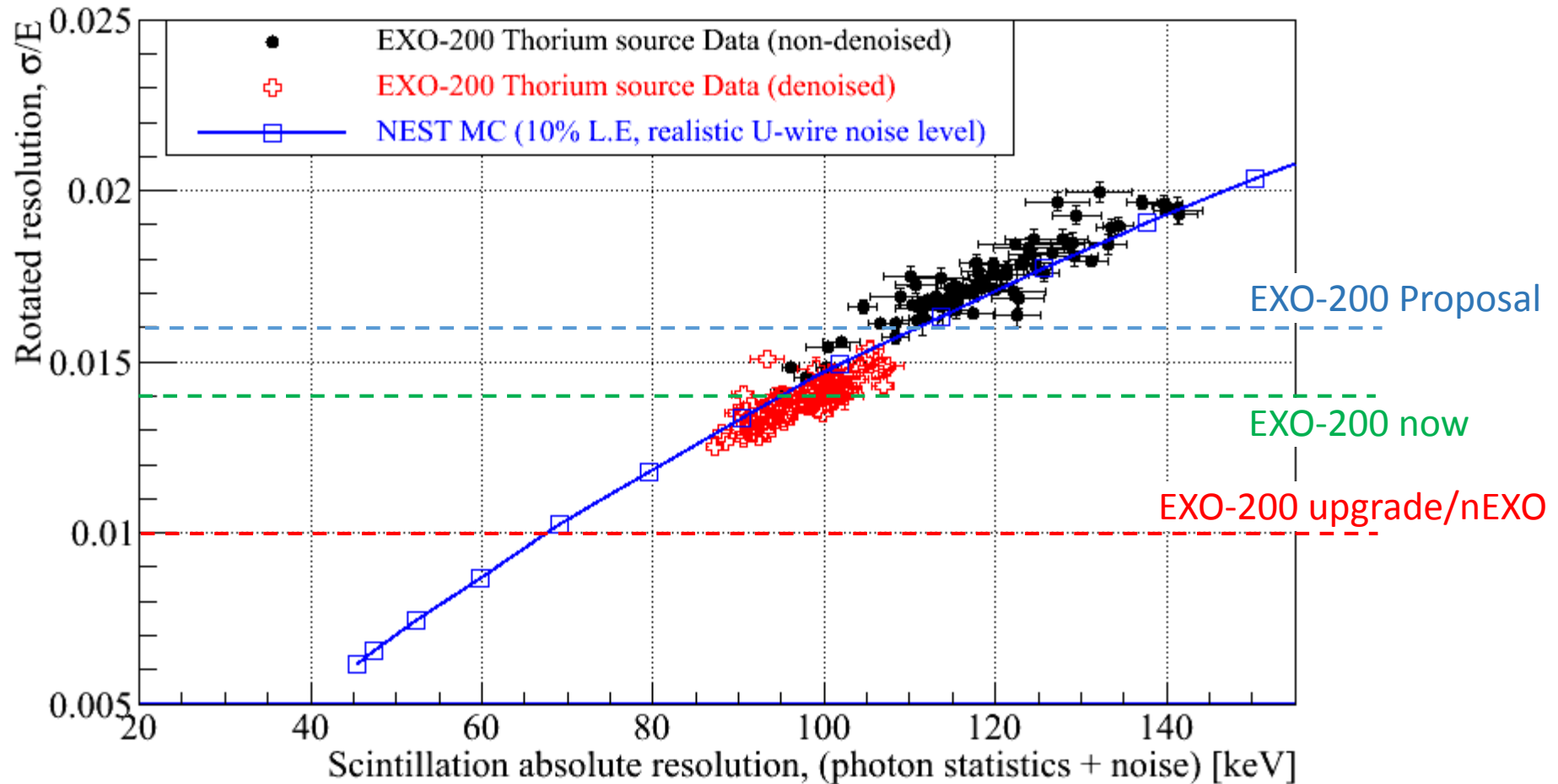
Note improvement due to
LAAPD denoising



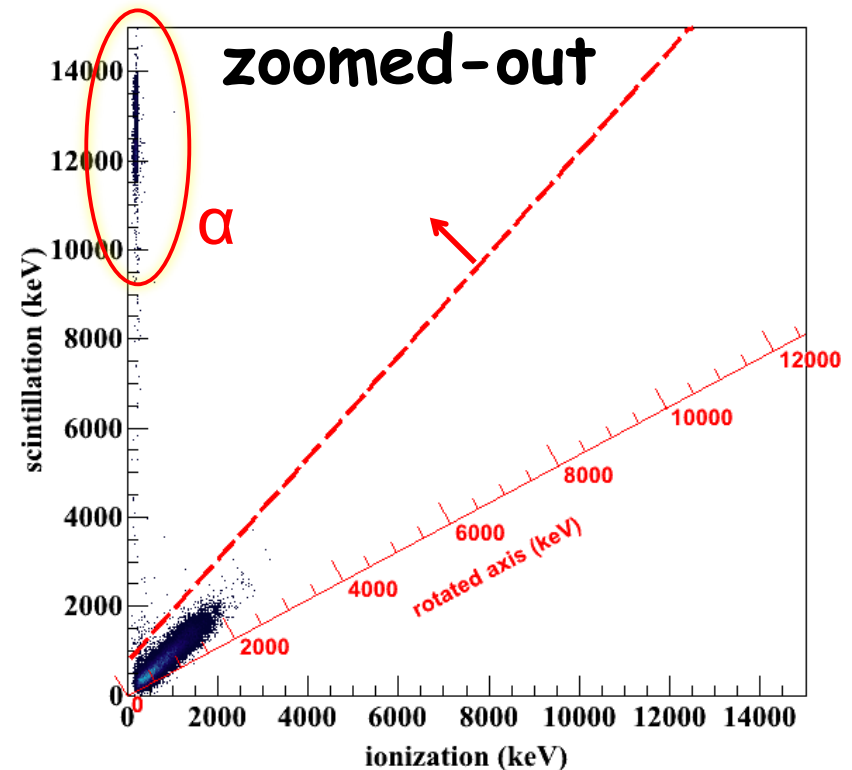
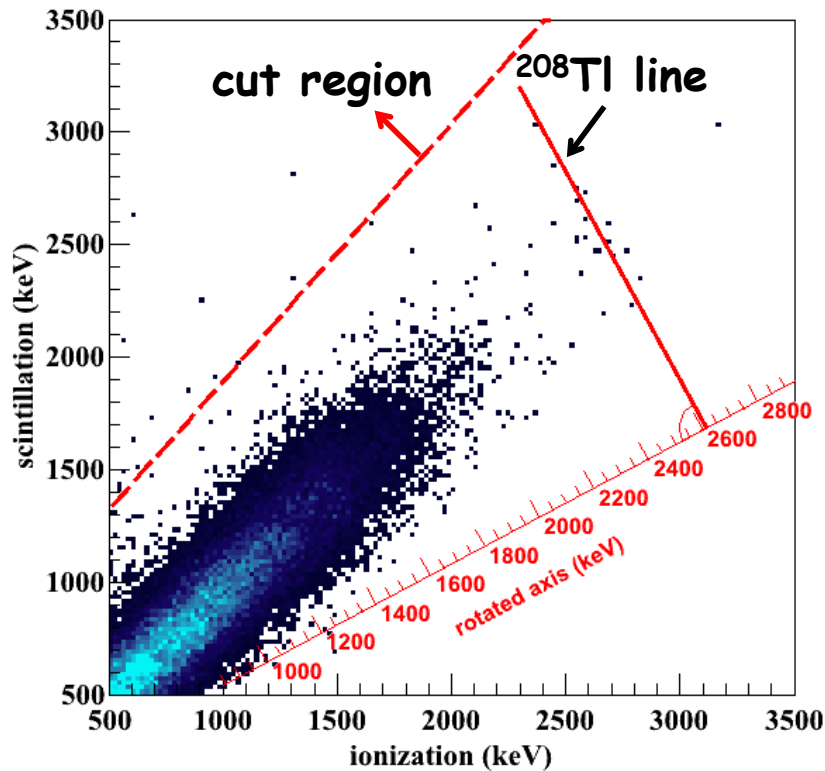
Rotation angle chosen to
optimize energy resolution
at 2615 keV



EXO-200 and nEXO resolutions



Rn in the detector is readily identified

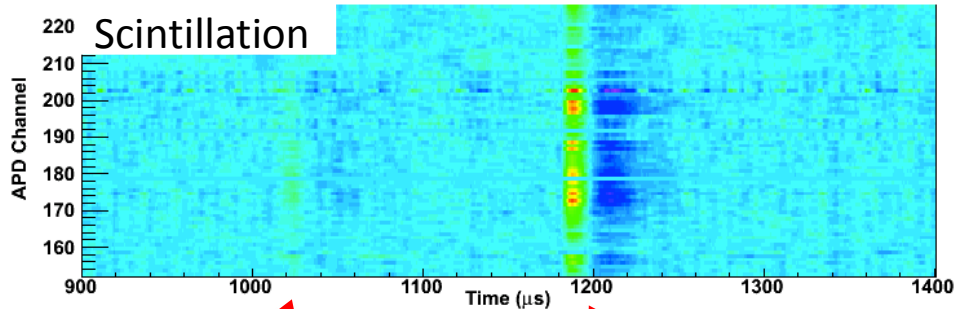


Events removed by diagonal cut:

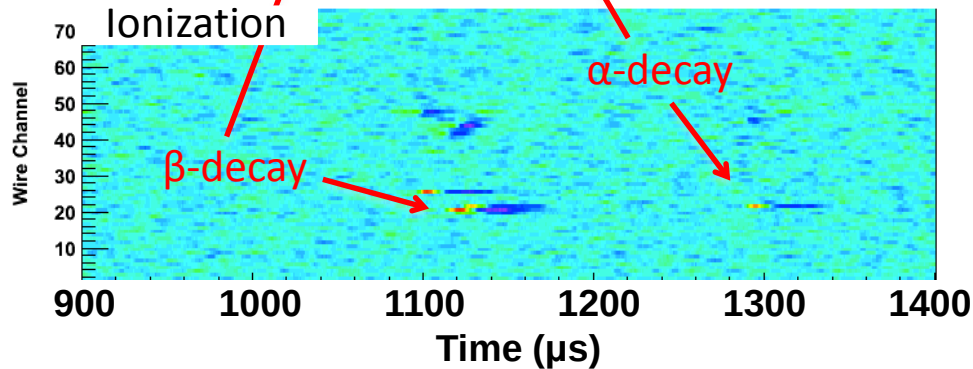
- α (larger ionization density $\rightarrow$ more recombination $\rightarrow$ more scintillation light)
- events near detector edge $\rightarrow$ not all charge is collected

Rn Content in Xenon

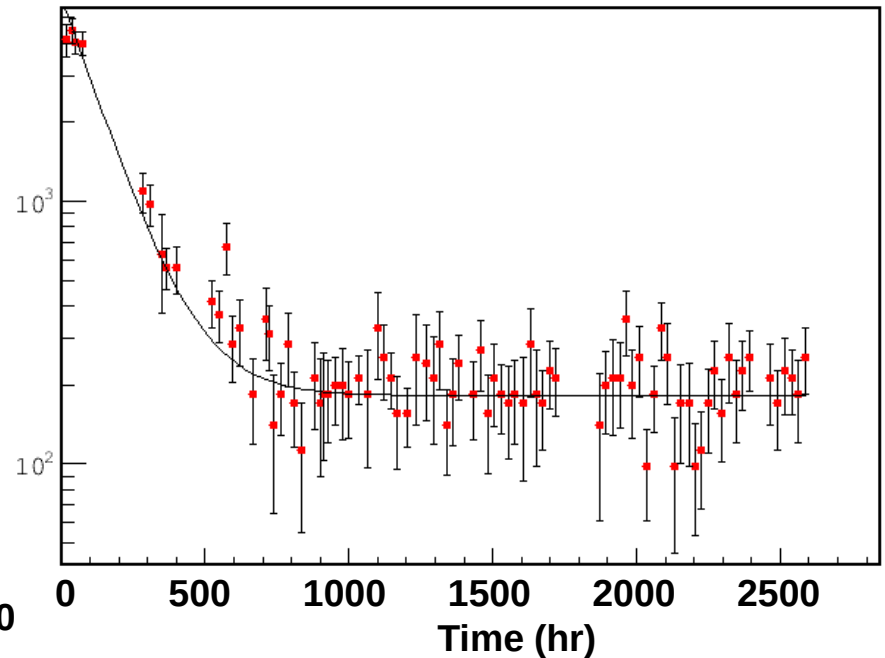
APD signals vs time



Wire signals vs time



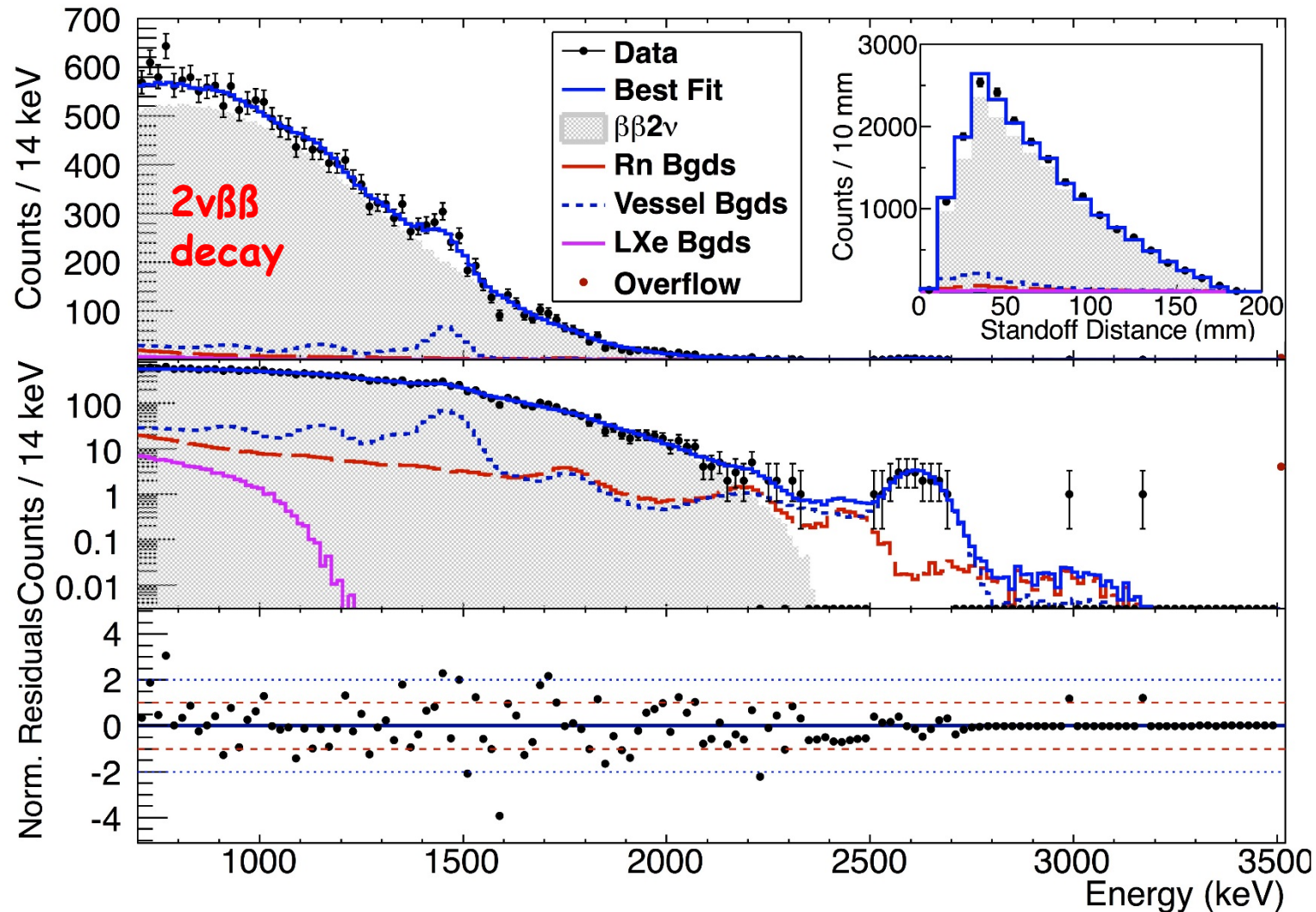
$^{214}\text{Bi} - ^{214}\text{Po}$ correlations
in the EXO-200 detector



Long term study shows a constant source of
 ^{222}Rn dissolving in $^{\text{enr}}\text{LXe}$: $360 \pm 65 \mu\text{Bq}$ (Fid. vol.)

or 200 atoms of ^{222}Rn in our Xenon!

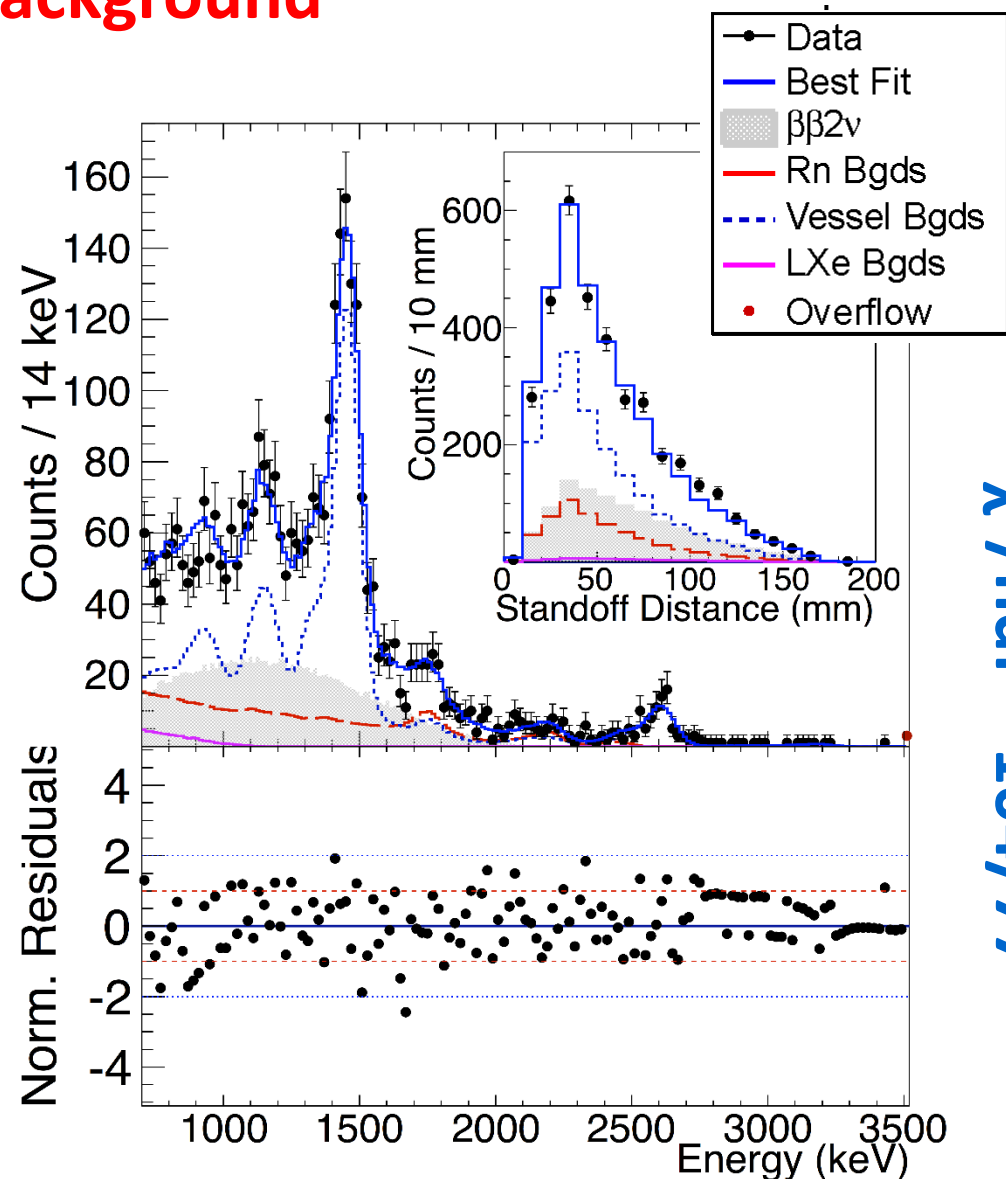
Low background single-site energy (and standoff) spectrum for 28.69 kg·yr (82.1 kg Xe, 127.6 d)



$\chi^2/\text{ndf} = 83 / 75$
Signal-to-Background ratio 10 - 20

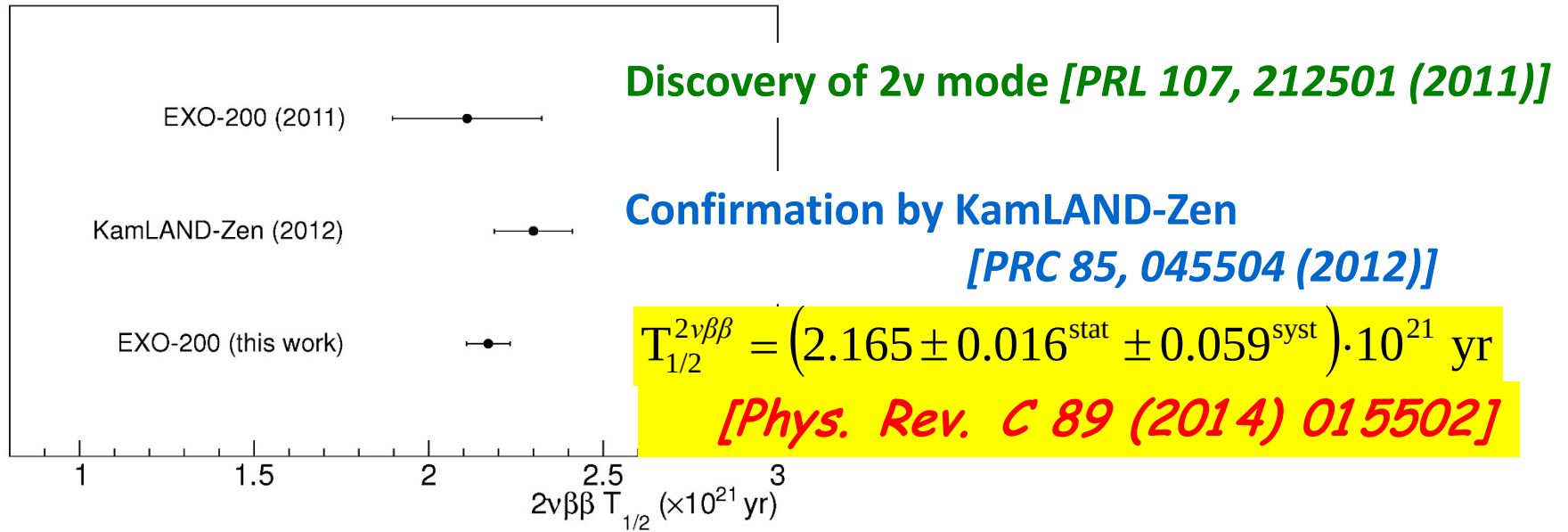
Multi-site spectrum directly measures the (small) background

Note that the presence of an unknown γ line at the $\beta\beta$ endpoint can be constrained, within statistics, by the study of the multi-site spectrum

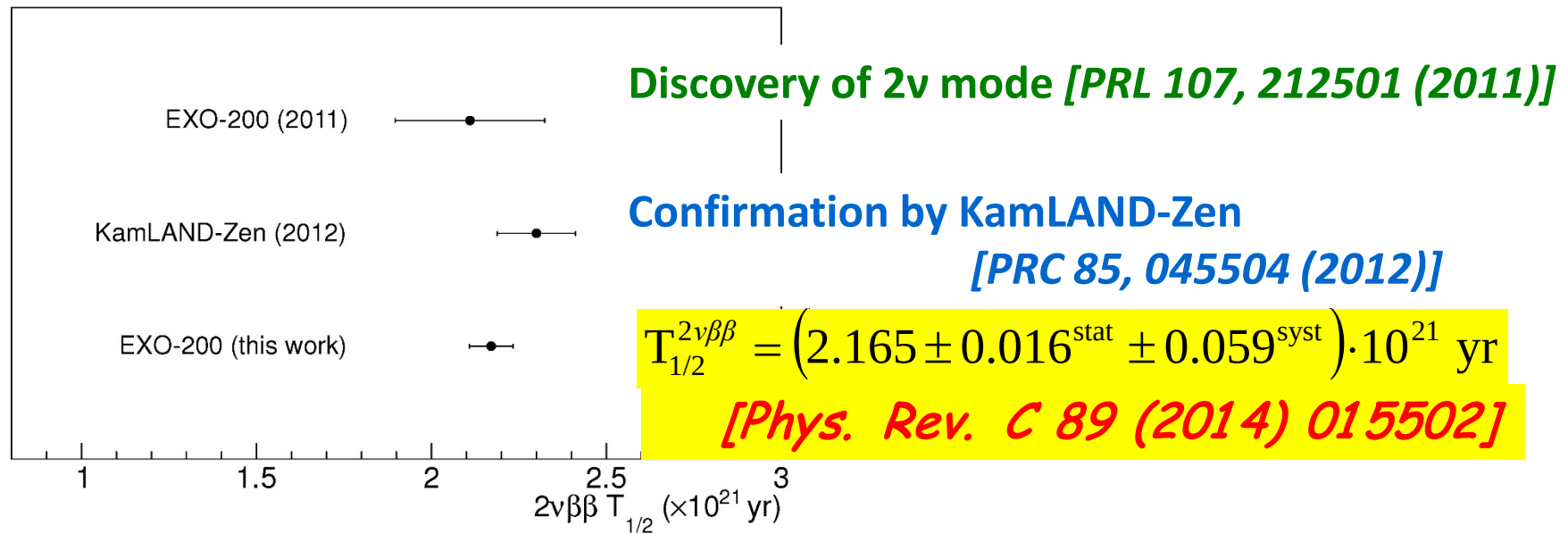


$\chi^2/\text{ndf} = 104/77$

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

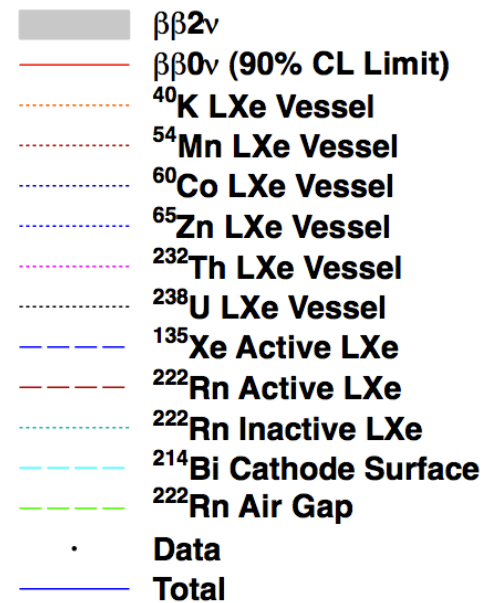
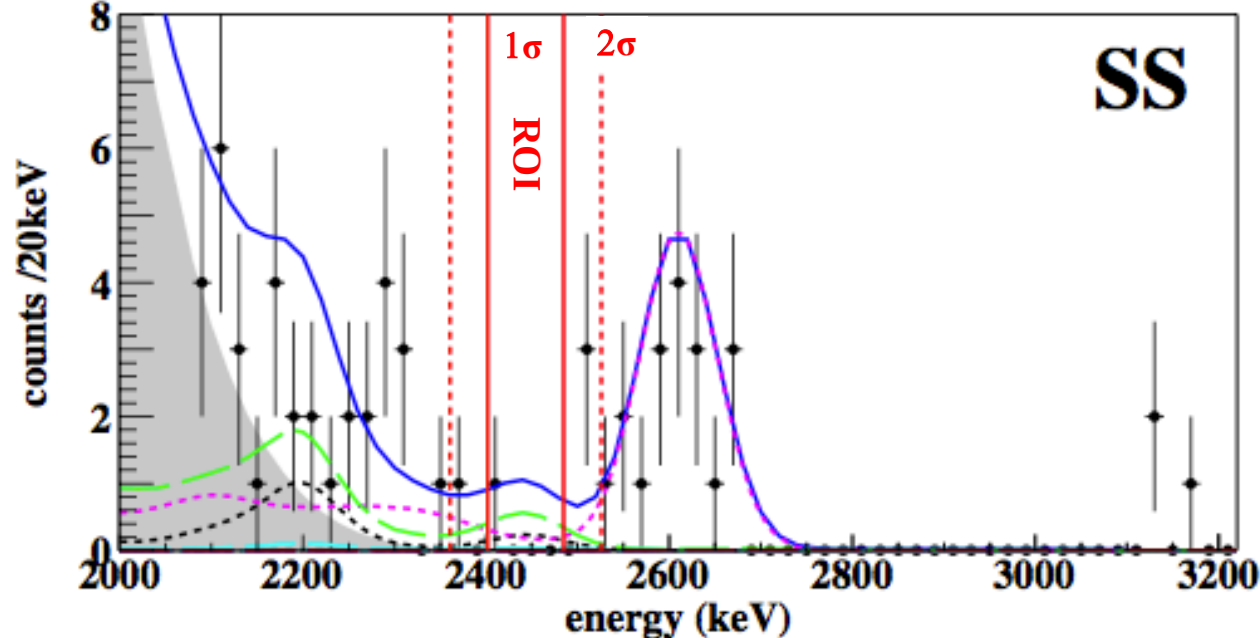
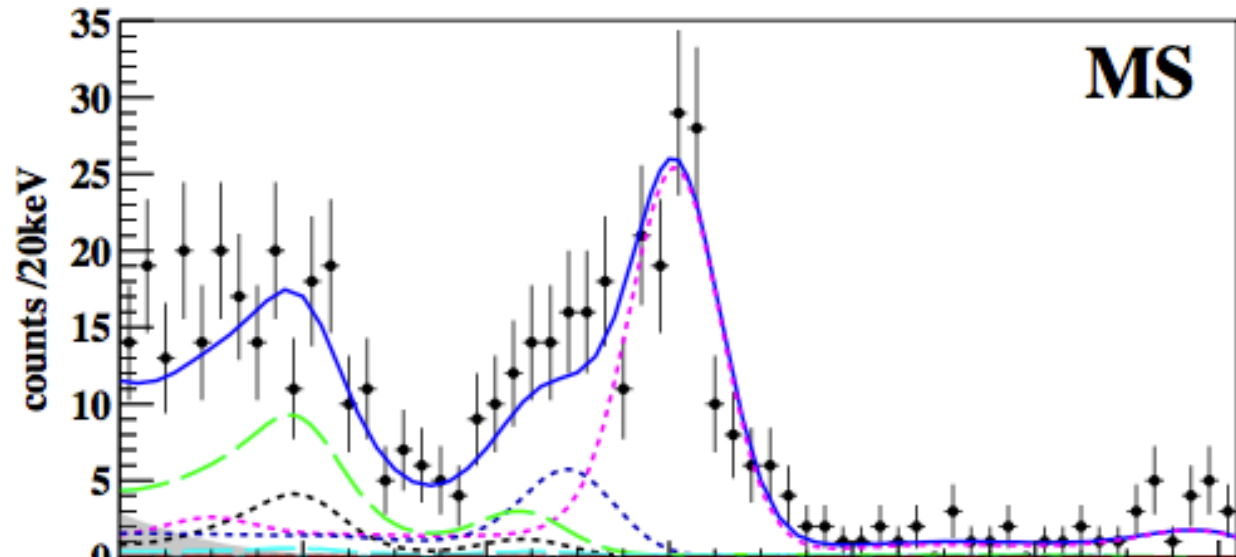


...since the start of EXO-200 data taking in Jun 2011...



Nuclide	$T_{1/2}^{2\nu\beta\beta} \pm \text{stat} \pm \text{sys}$ [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 $0\nu\beta\beta$ region of interest (ROI)



No 0ν signal
observed
in the ROI

Use likelihood fit
to establish limit

Profile likelihood analysis takes into account the peak shape of $0\nu\beta\beta$ signal. More sensitive than window analysis

Obtain $T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25} \text{ yr } @90\%CL$

The corresponding Majorana mass limit (for a broad range of NMEs) is:

$$\langle m \rangle_{\beta\beta} < 140 - 380 \text{ meV}$$

➔ *Phys Rev Lett 109 (2012) 032505*

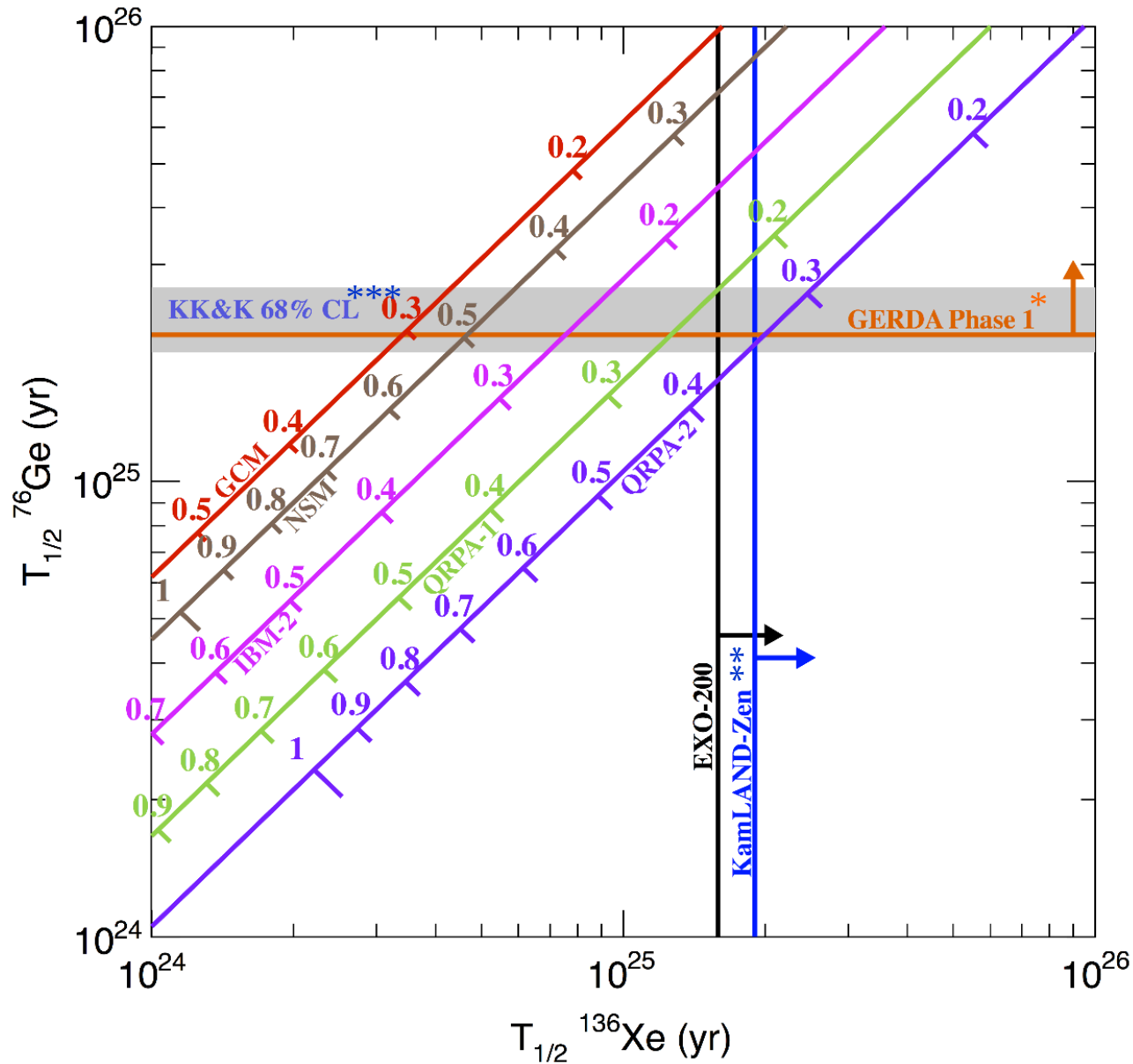
^{130}Te (Cuoricino): $T^{1/2} > 3 \cdot 10^{24} \text{ yr}$, $m < 190 - 660 \text{ meV}$ [Arnaboldi et al. PRC 78 (2008) 035502]

^{76}Ge (GERDA): $T^{1/2} > 2.1 \cdot 10^{25} \text{ yr}$, $m < 205-606 \text{ meV}$ [Agostini et al. PRL 110 (2013) 312]

^{100}Mo (NEMO-3): $T^{1/2} > 2.1 \cdot 10^{25} \text{ yr}$, $m < 470-1070 \text{ meV}$ [Barabash et al., PAN 74 (2011)312]

^{136}Xe (KL-ZEN): $T^{1/2} > 2.1 \cdot 10^{25} \text{ yr}$, $m < 143-376 \text{ meV}$ [Gando et al., PRL 110 (2013) 062502]

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



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

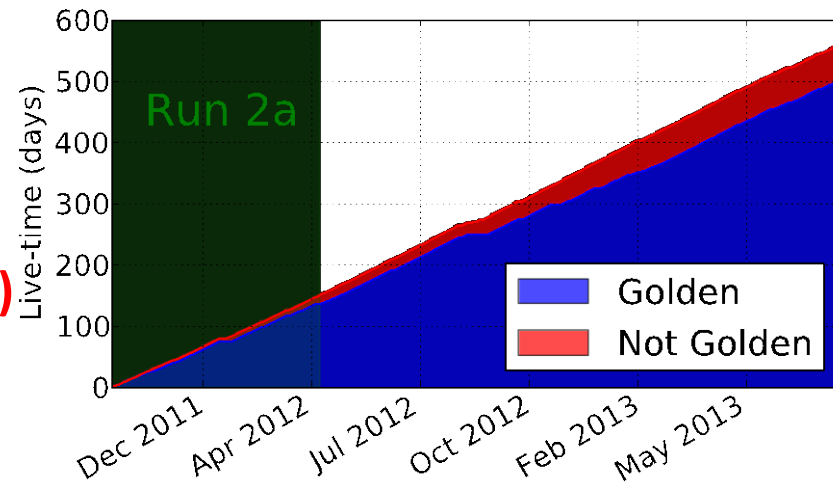
** A. Gando et al. PRL 110 (2013) 062502

*** H.V. Klapdor-Kleingrothaus et al. Eur. Phys. J. A12 (2001) 147

The future of EXO-200

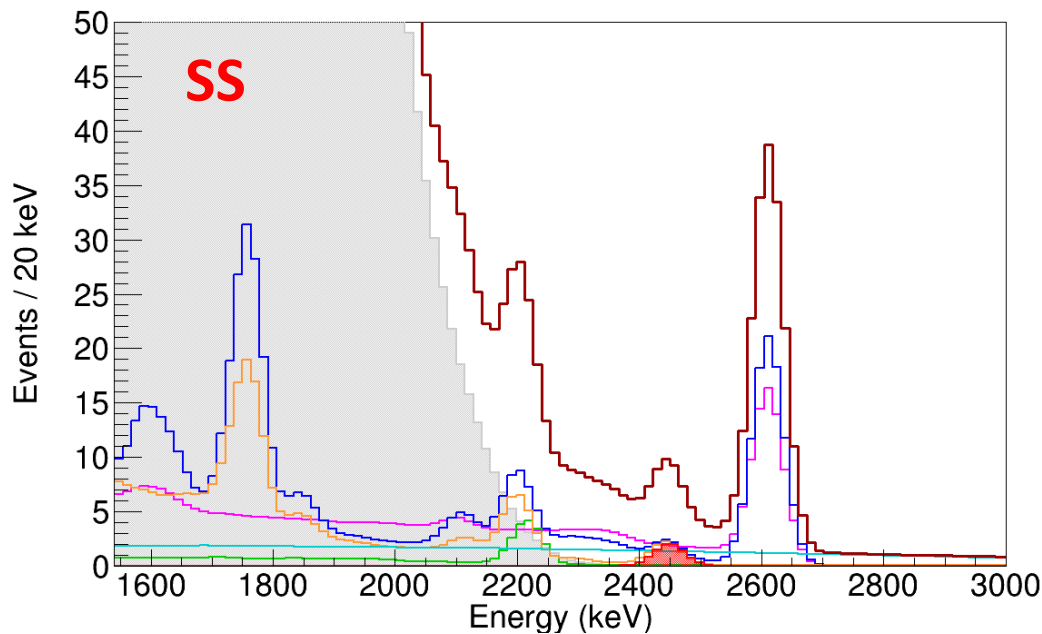
Analysis improvements:

- Improve e-reconstruction eff. (71% to 90%)
→ 2v analysis already reached 87.4%
- Reduce fiducial volume uncertainty
→ 2v analysis already @ 1.7% (66.2kg)
- Add standoff distance to fits
→ Done in 2v analysis
- More sophisticated topology classifier(s)
- Improve energy resolution → 37.6keV @ $Q_{\beta\beta}$
($\sigma/E=1.53\%$) already obtained

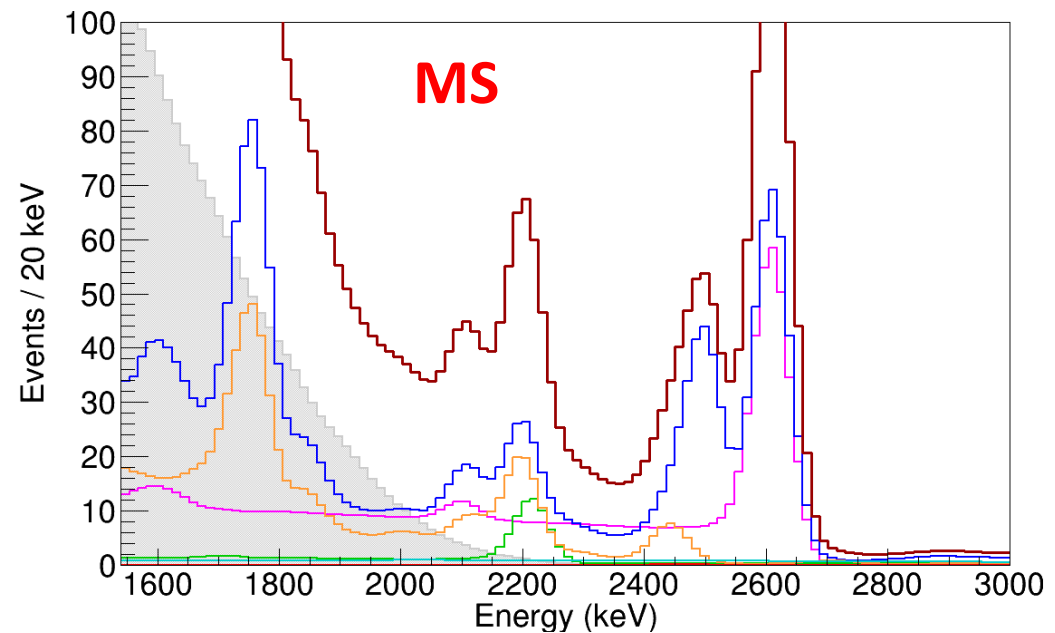
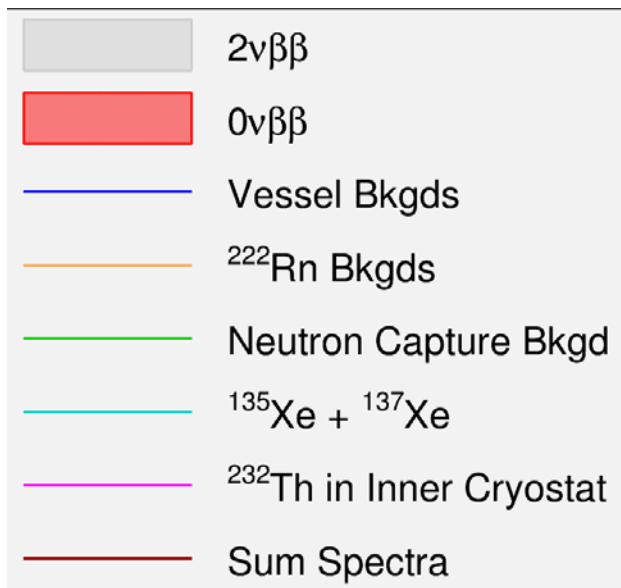


Expect 3 more years of data with better hardware (WIPP permitting...)

- Deradonator → lower background
- Lower electronics noise → better resolution
→ better clustering/background suppression



How does the projected
EXO-200 energy spectrum
look like in 5yrs of data,
corresponding to $T_{1/2}$
lower limit of $(1.2 \cdot 10^{26} \text{ yr})$?



Minor correction to the document submitted, page 2

	EXO-200 Currently Achieved	EXO-200 Final stage
Energy resolution at endpoint (FWHM in keV)	88	58
Event selection efficiency (in fiducial volume)	87%	87%
Background within FWHM of endpoint (events/yr/mole-isotope)	$2.2 \cdot 10^{-2}$	$7.3 \cdot 10^{-3}$
NLDBD lifetime limit (90% CL)	$1.6 \cdot 10^{25}$ yr (0.56 cal. years)	$1.2 \cdot 10^{26}$ yr (5 cal. years)
NLDBD lifetime (for 5 sig discov.)	-	$3.5 \cdot 10^{25}$ yr (5 cal years)

Sorry, the number we gave were for 0.8-34 months live, consistent with the currently expected run time



As EXO-200 continues data taking a new collaboration

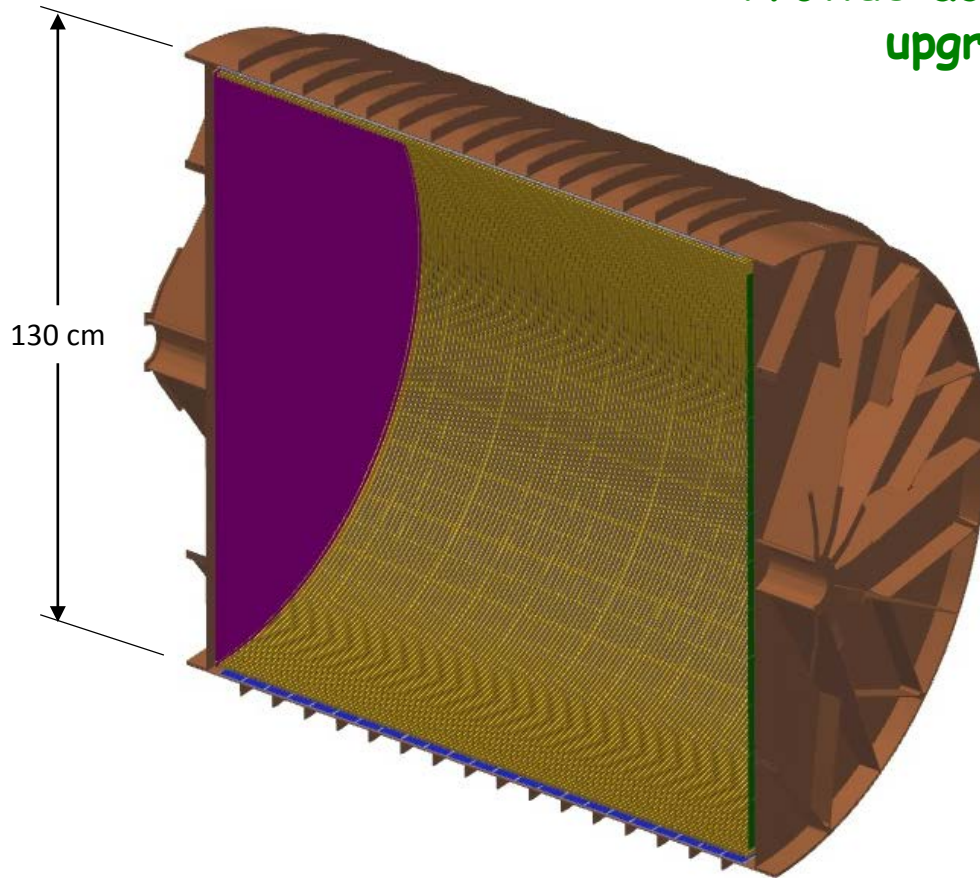
nEXO

is being formed

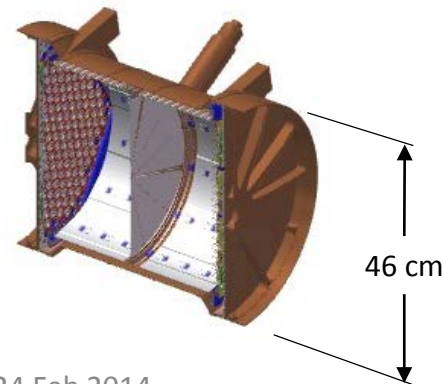
- ***New groups have the opportunity to join as “charter members”***
- ***Only conflict with ton-scale projects***
- ***Larger collaboration organized to execute a larger and more formal project***

nEXO

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

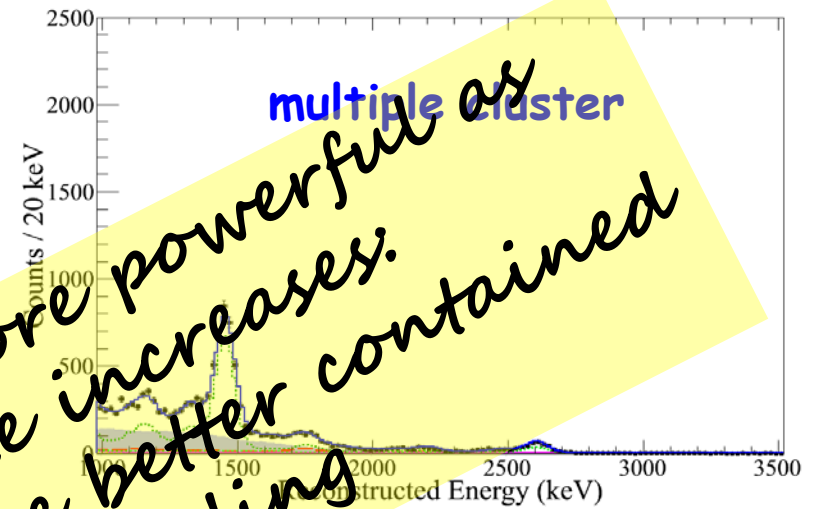
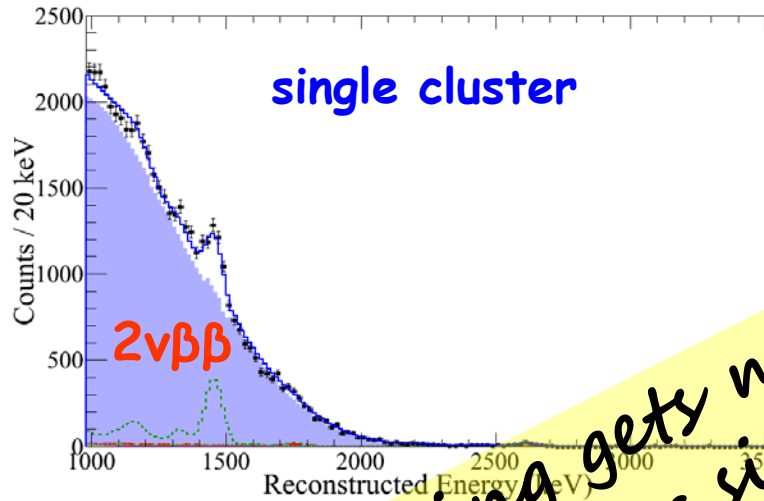


→ A unique combination of conservative and aggressive design with important upgrade paths as desirable for a large experiment



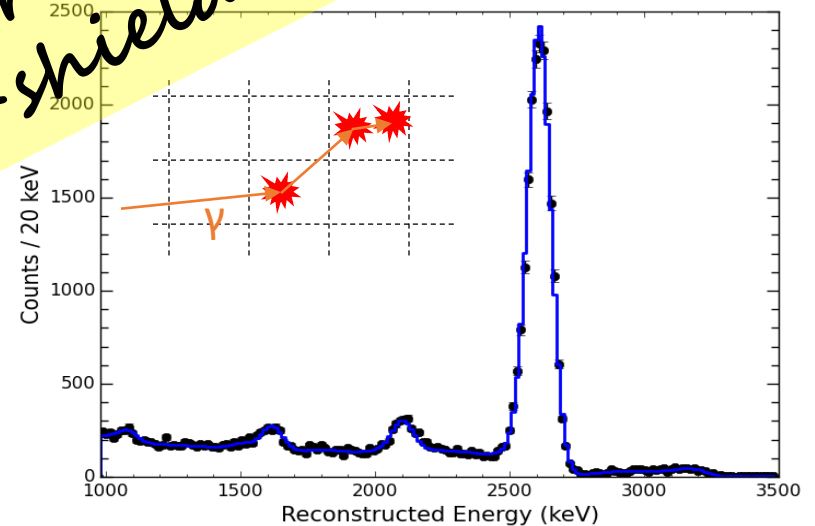
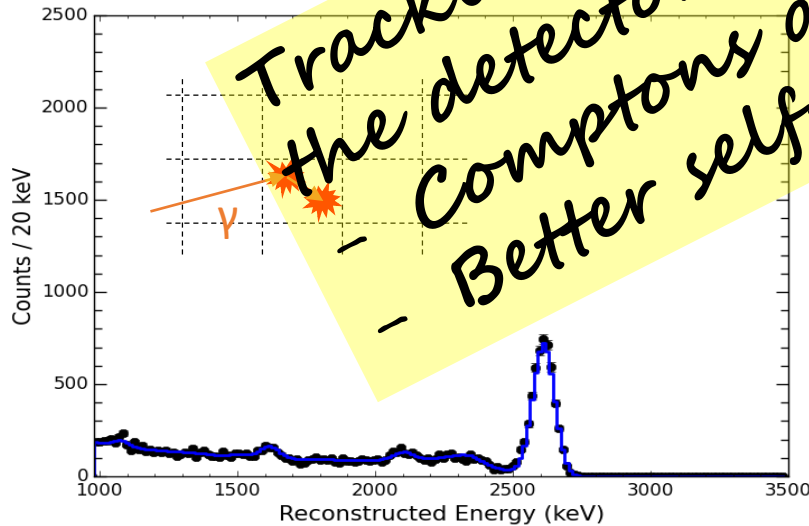
Tracking: an essential tool to identify and suppress backgrounds

Low background
data



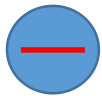
Tracking gets more powerful as the detector size increases.
Comptons are better contained
Better self-shielding

^{228}Th calibration
source

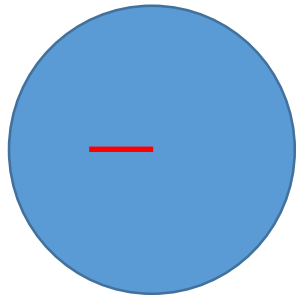


LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

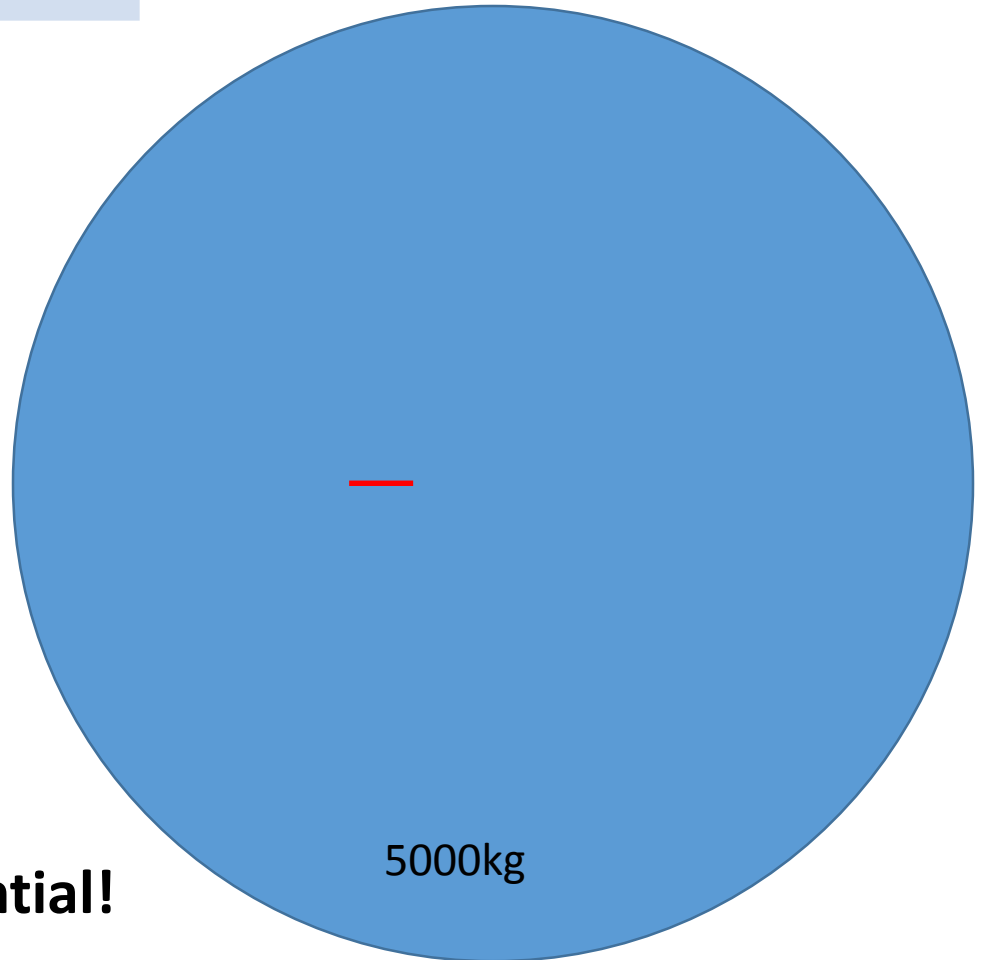
2.5MeV γ
attenuation length
8.5cm = —



5kg



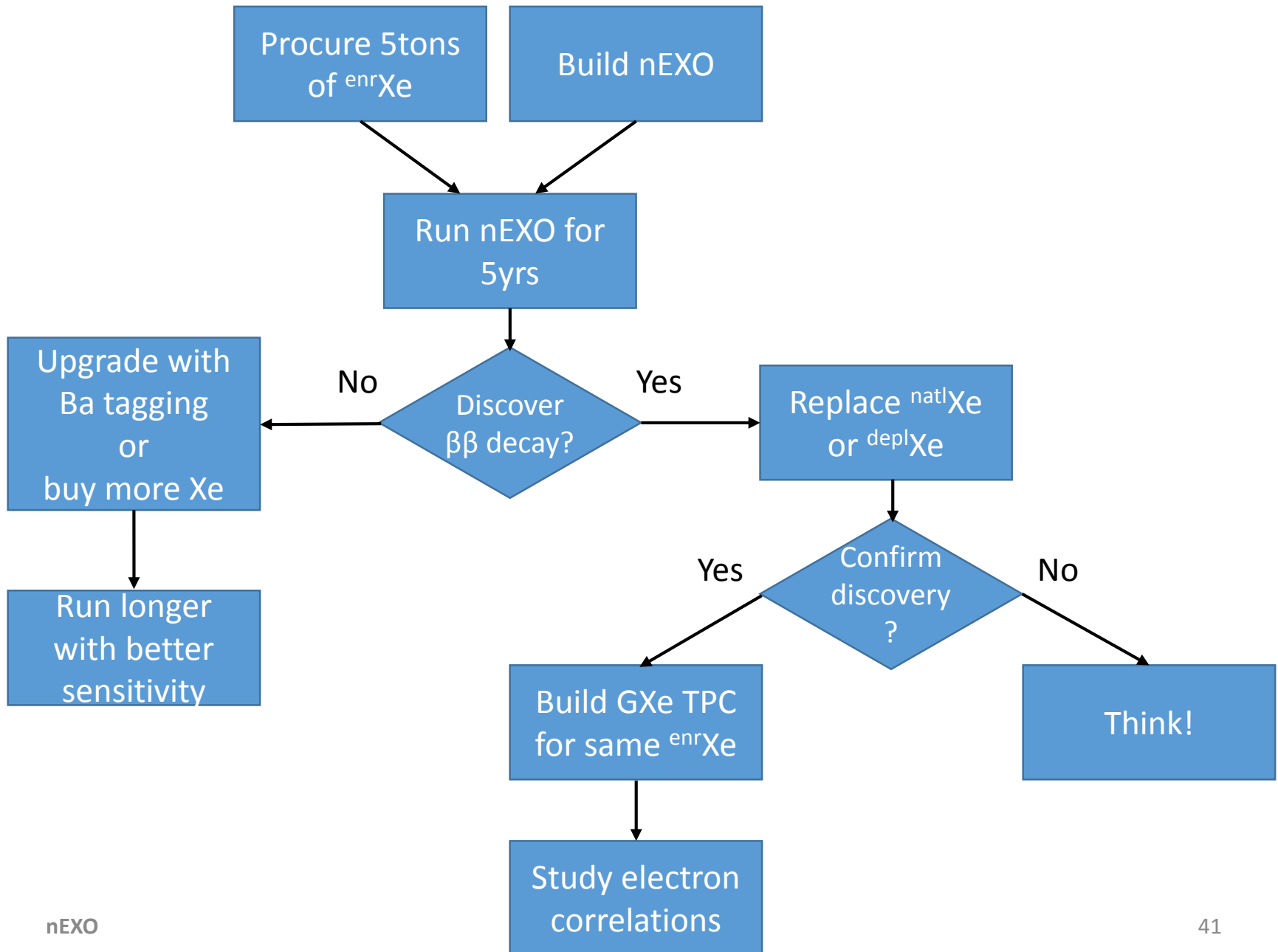
150kg



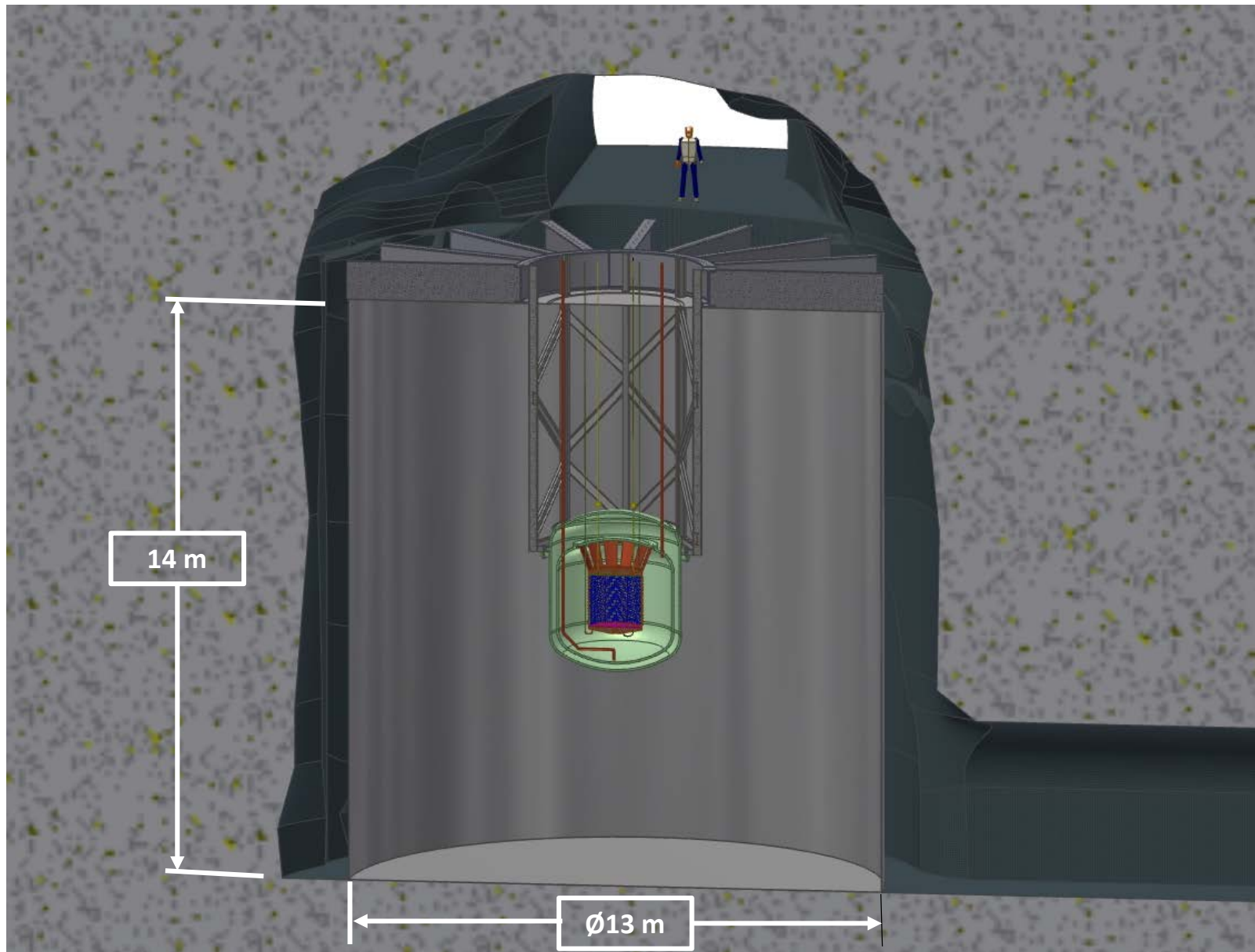
5000kg

Monolithic detector is essential!

Flexible program based on the initial nEXO investment



Preliminary artist view of nEXO in the SNOlab Cryopit



nEXO design:

**Follow as closely as possible the design of EXO-200
since EXO-200 works so well**

Only depart from this rules for good reasons:

- 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*

**→ *Limited R&D required, low risk:
much of the detector is being designed now***

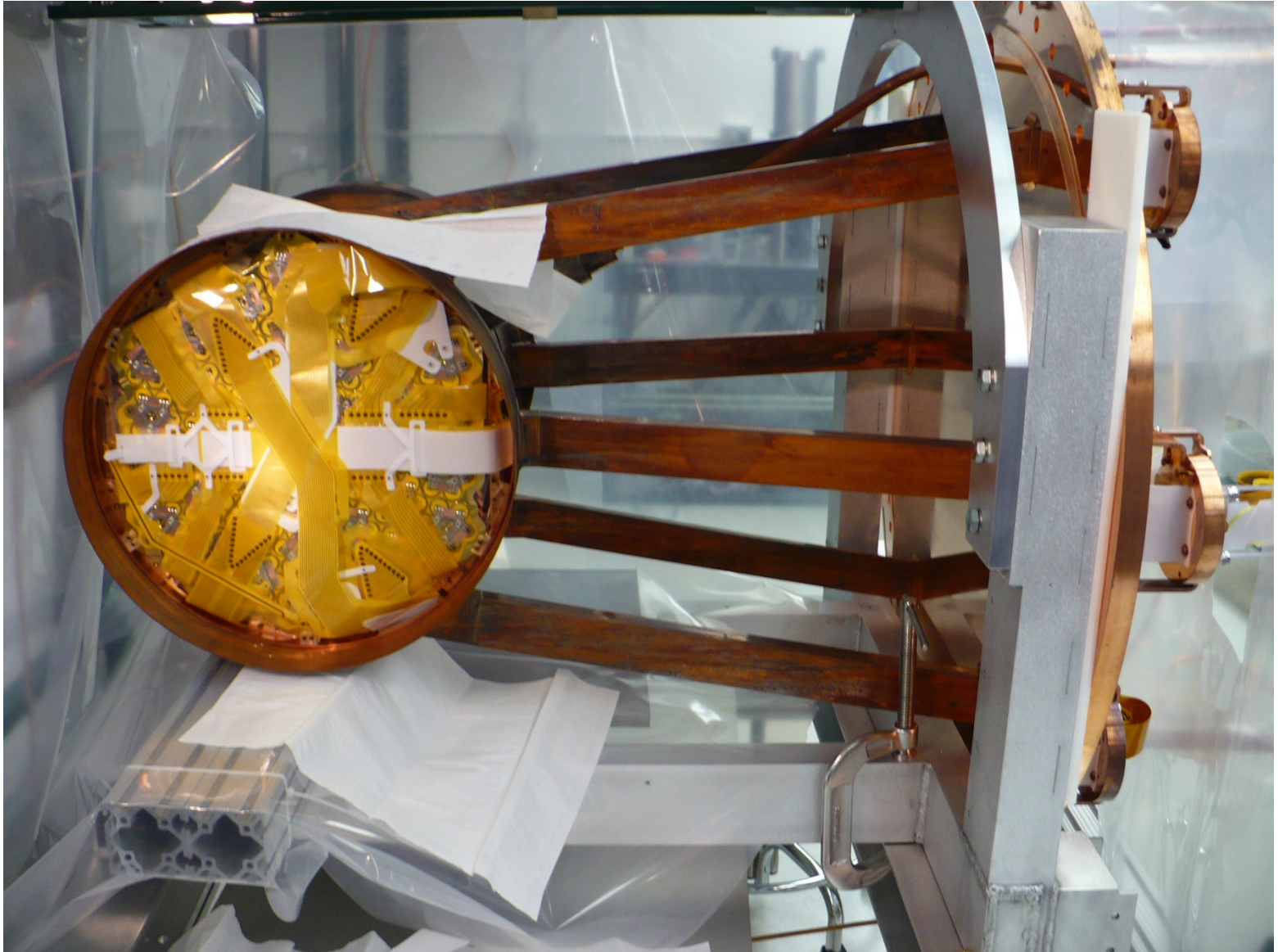
**Ba tagging R&D proceeding as an option, not required
for the experiment to be competitive and successful**

R&D in progress

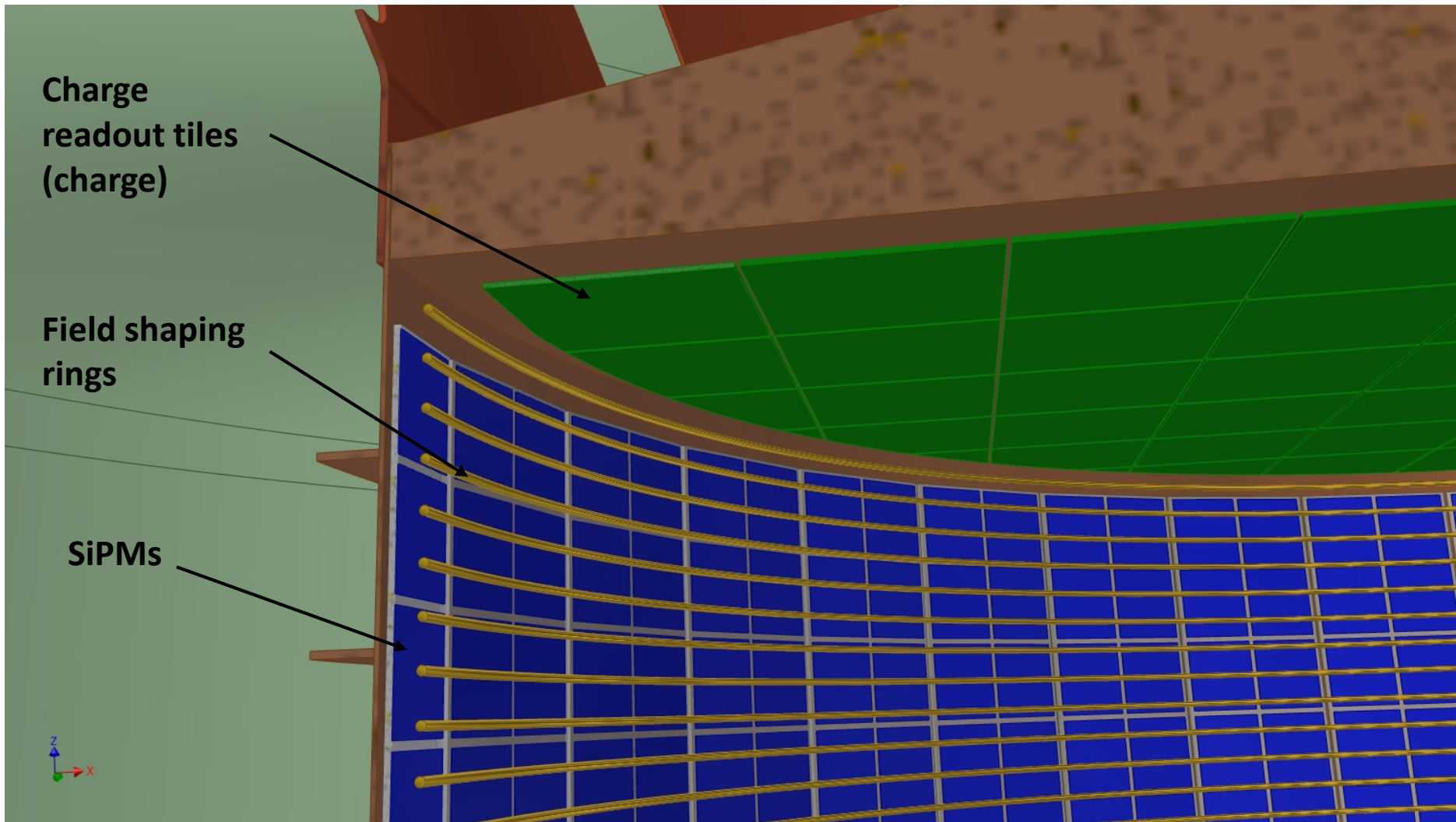
Item/concept	Reason to change	Cat	Risk
Water shield	More convenient for large size, very standard	2	None
Vertical detector axis	Horizontal for EXO-200 due to site constraint	1	None
Composite cryostat	Too large for conveyance at SNOlab, composite easier to build underground, lighter	2	Low
One drift space	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 dets) 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

None of these items precludes starting CD1

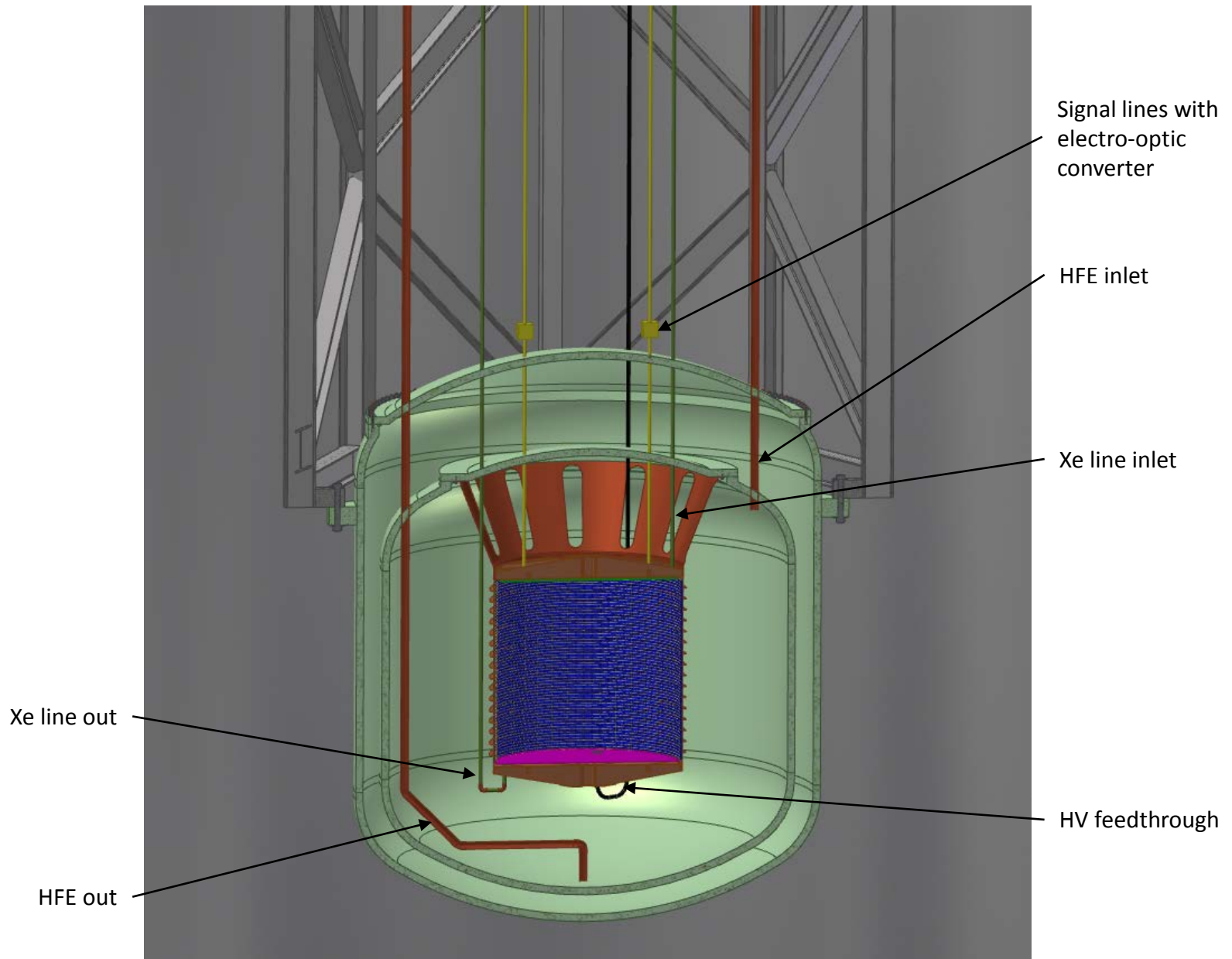
...it is remarkable that EXO-200 can achieve 5ms electron lifetime with a detector stuffed of (very clean and purged) plastics



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



Detail of the cryostat concept



Predicted γ backgrounds for 4780kg nEXO using GEANT 4 simulation with input from EXO-200 and initial nEXO material testing

Component Name	Magnitude (events/mol ₁₃₆ /FWHM/yr)	
	No Ba-tagging	With Ba-tagging
Outer Cryostat	1.0E-06	Negligible
Inner Cryostat	6.9E-06	
HFE7000	8.7E-05	
TPC Co60	6.3E-09	
TPC U238	3.8E-04	
TPC Th232	4.9E-05	
LXe Rn222	6.9E-05	
LXe Xe137	5.2E-06	
bb2n	8.9E-06	8.9E-06

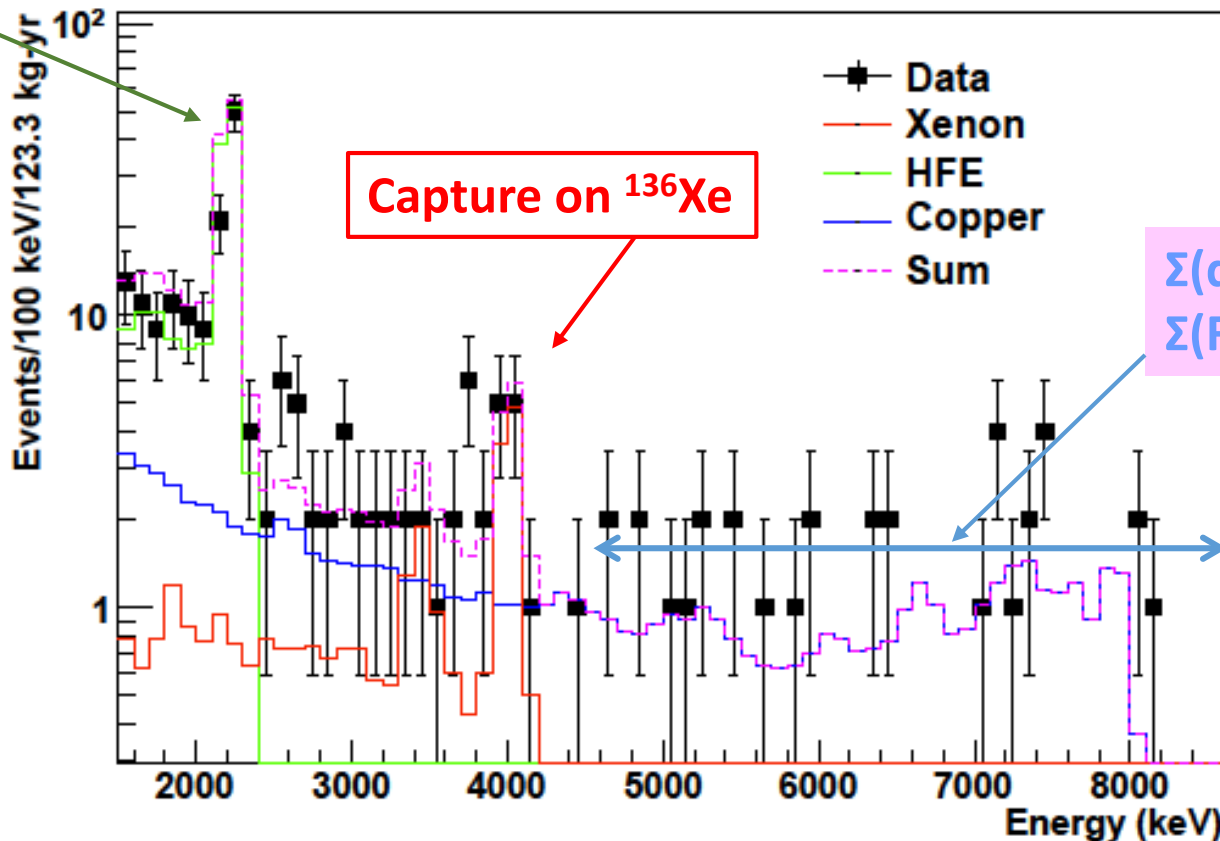
Cosmogenic n backgrounds in nEXO simulated using FLUKA

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

EXO-200 spectra in-time with veto

Multi-Site Veto-Tagged Events

Capture on H
in the HFE7000



Other n backgrounds

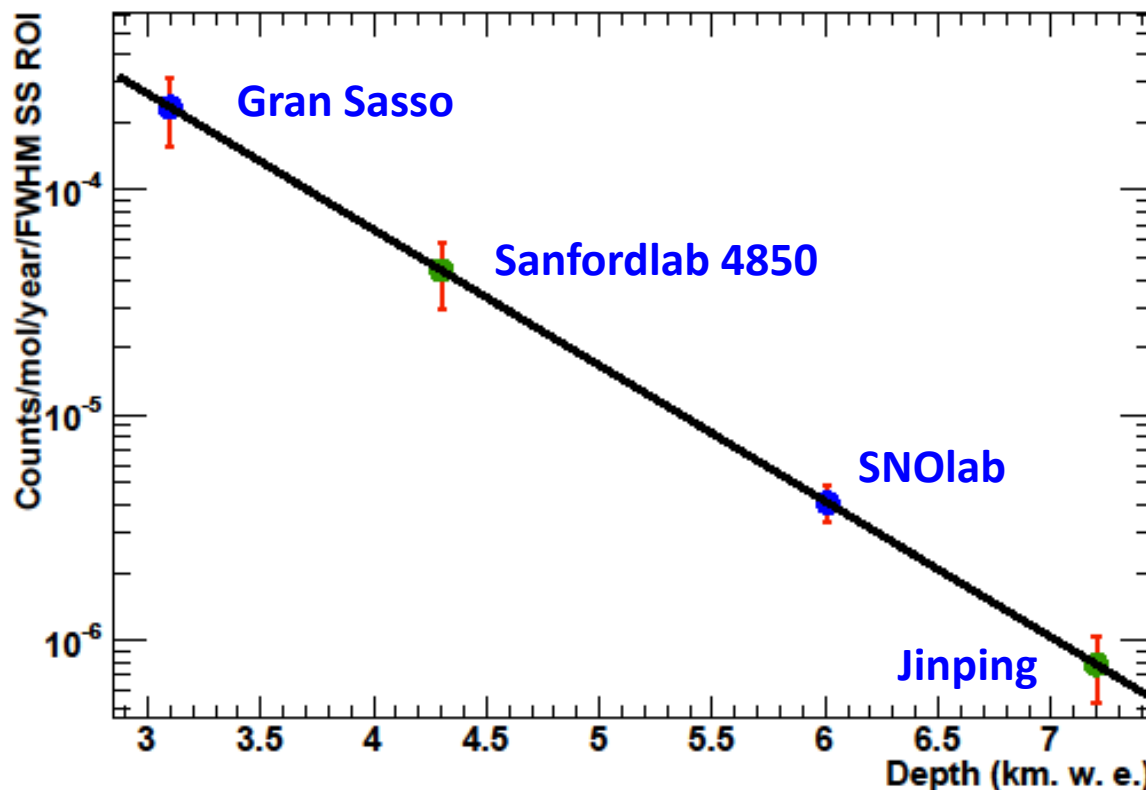
- Prompt events following a muon
- Neutrons from rock radioactivity
→ very strongly suppressed by the large water shield and give a negligible contribution

...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 (^8B +reactors+Geo)	17.6	0.16	$3.1 \cdot 10^{-6}$
ν capture on ^{136}Xe (^8B 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

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

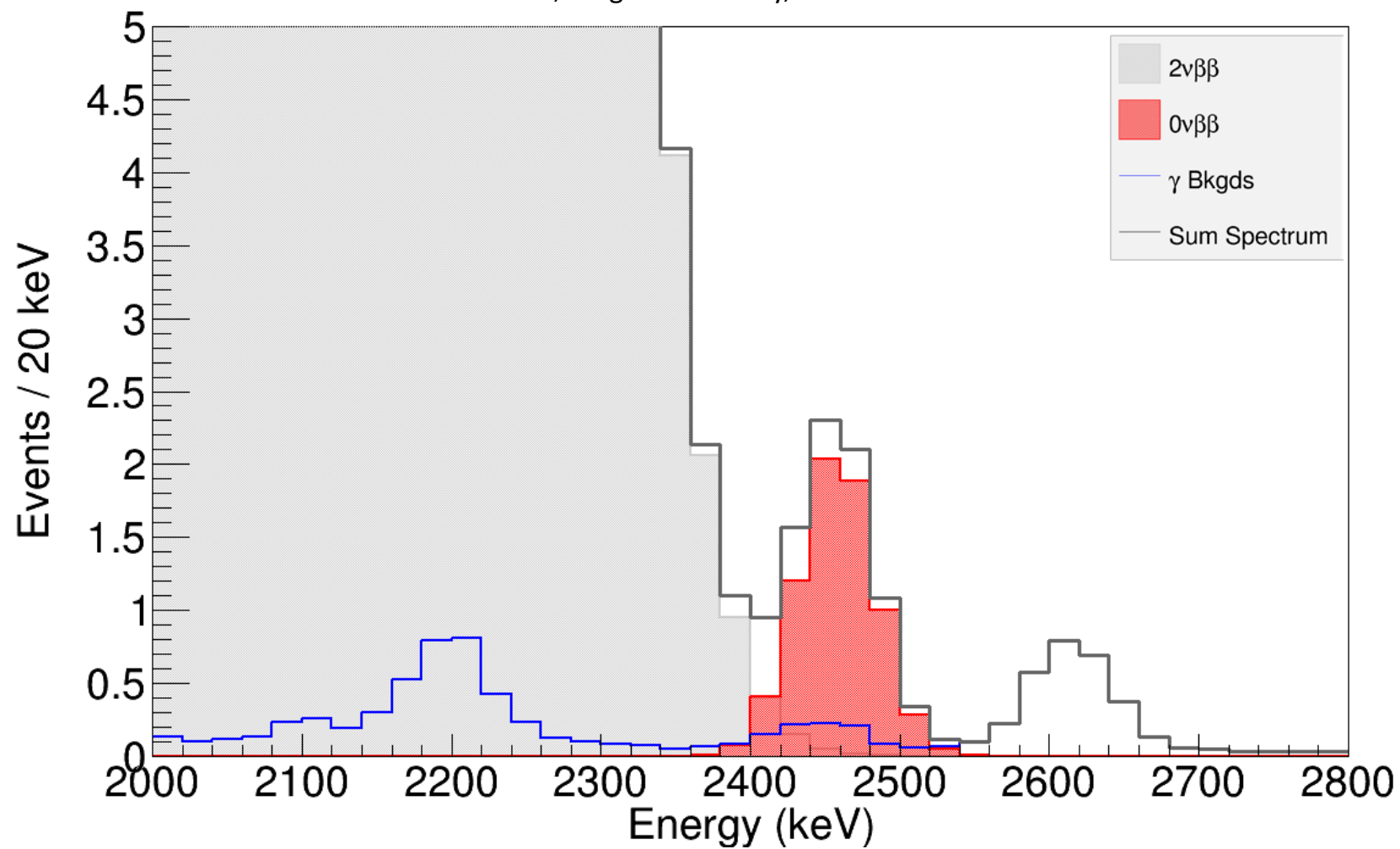
Sensitivity and discovery – energy spectra plots

The fit that provides the final discovery or lower limit on the half-life uses the standoff distance in the optimal way, something that is difficult to effectively show “at a glance”.

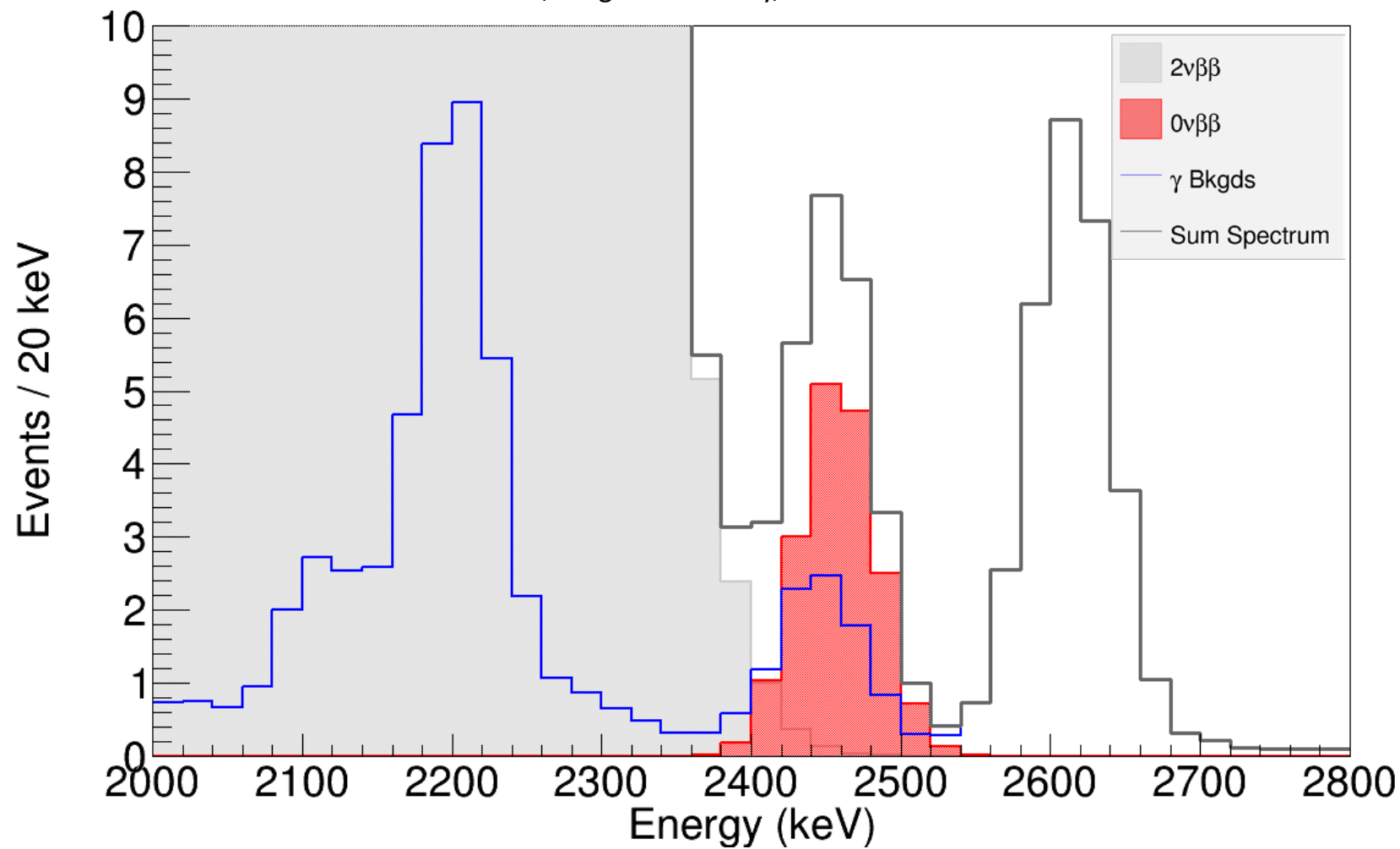
To help understanding how this works we are showing here the spectra (first for the discovery case and then for the 90% CL limit) for three different volumes carved inside the full 4.78 tonne (these are: central 1 tonne, central 2.5 tonne and full 4.78 tonne). Of course the deeper into the detector the less background. The fit knows this and in fact also takes advantage of the property of the background to decrease.

For clarity we are only showing one histogram for the total background

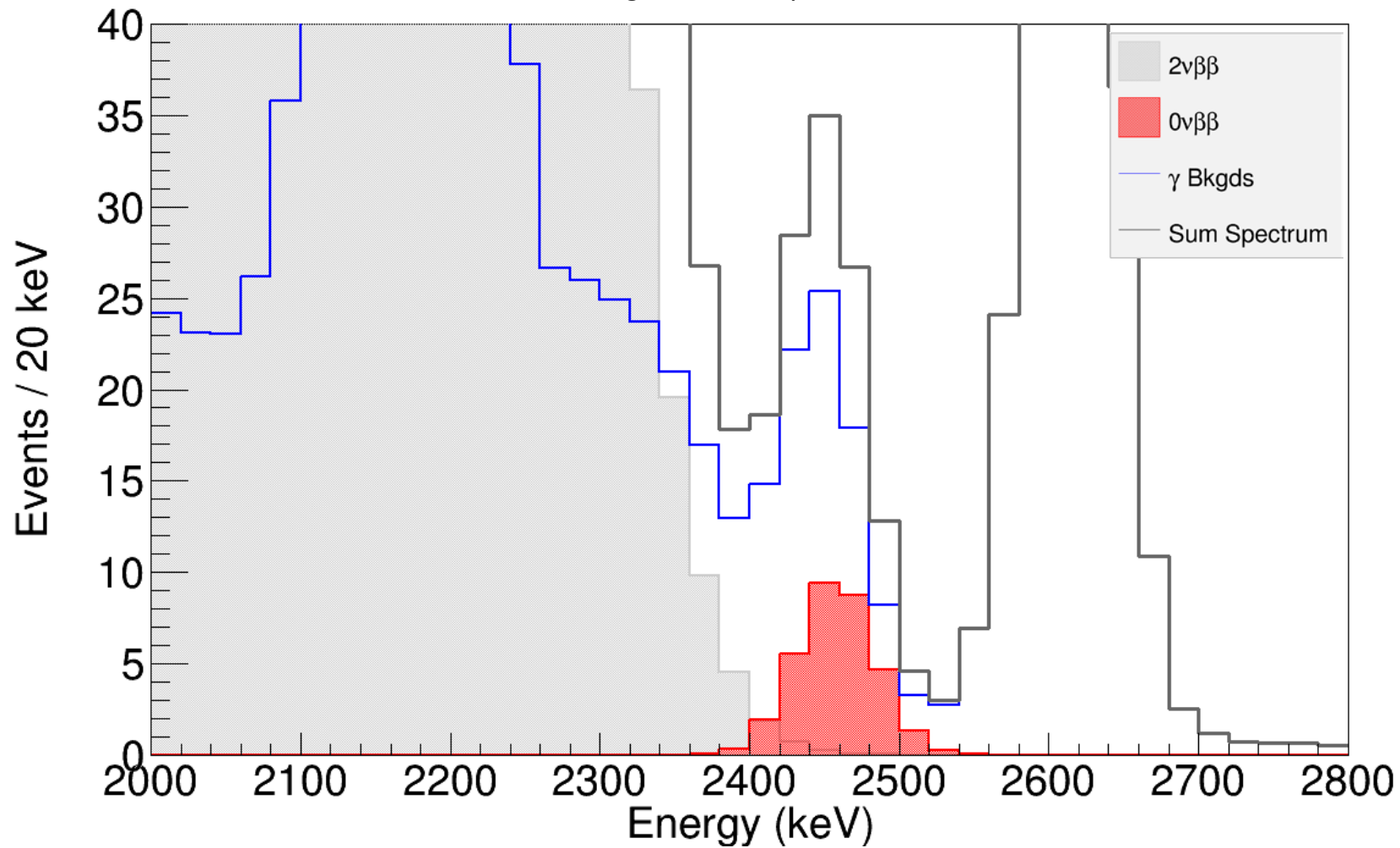
SS, 5 sigma discovery, central 1tonne



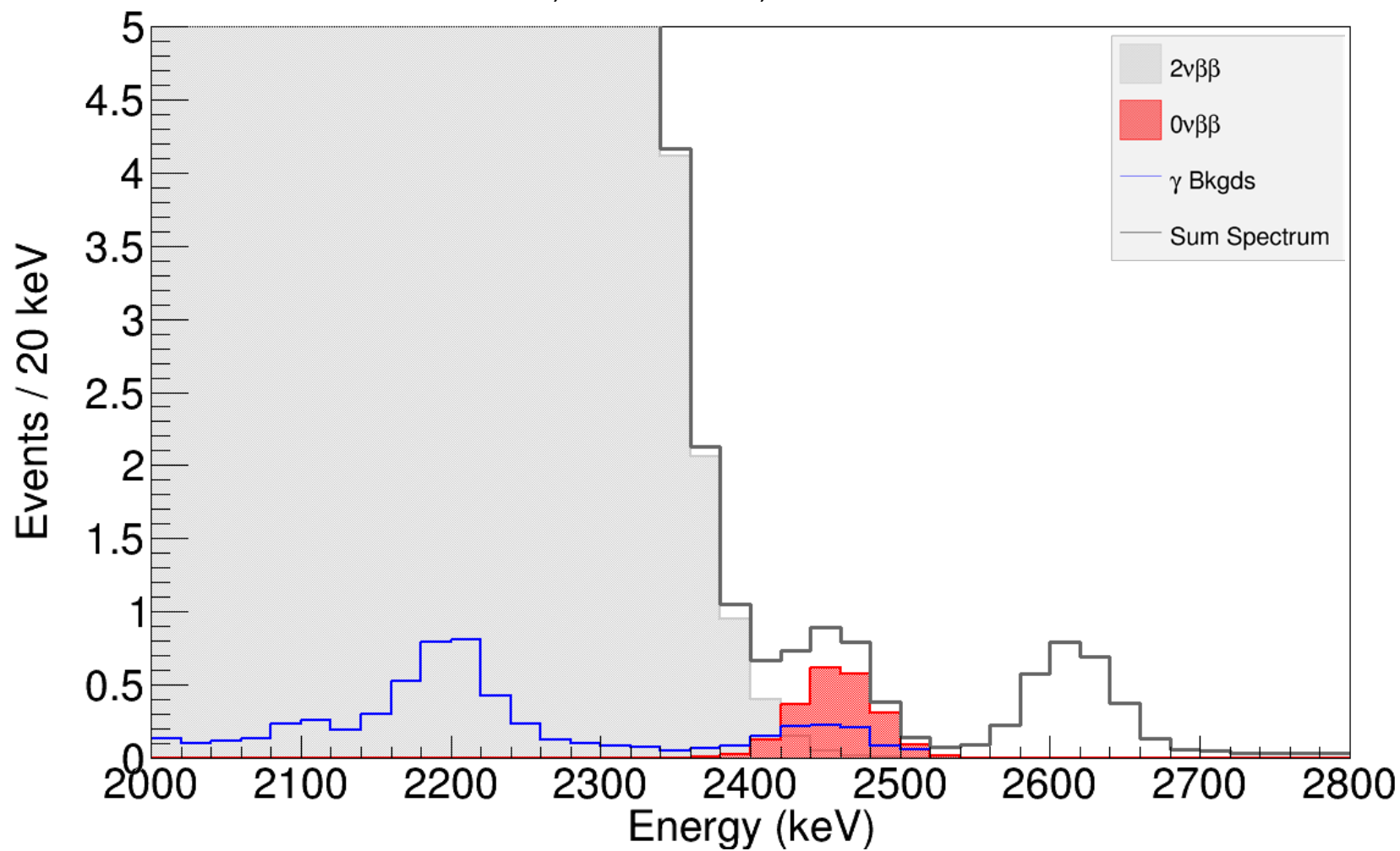
SS, 5 sigma discovery, central 2.5tonne



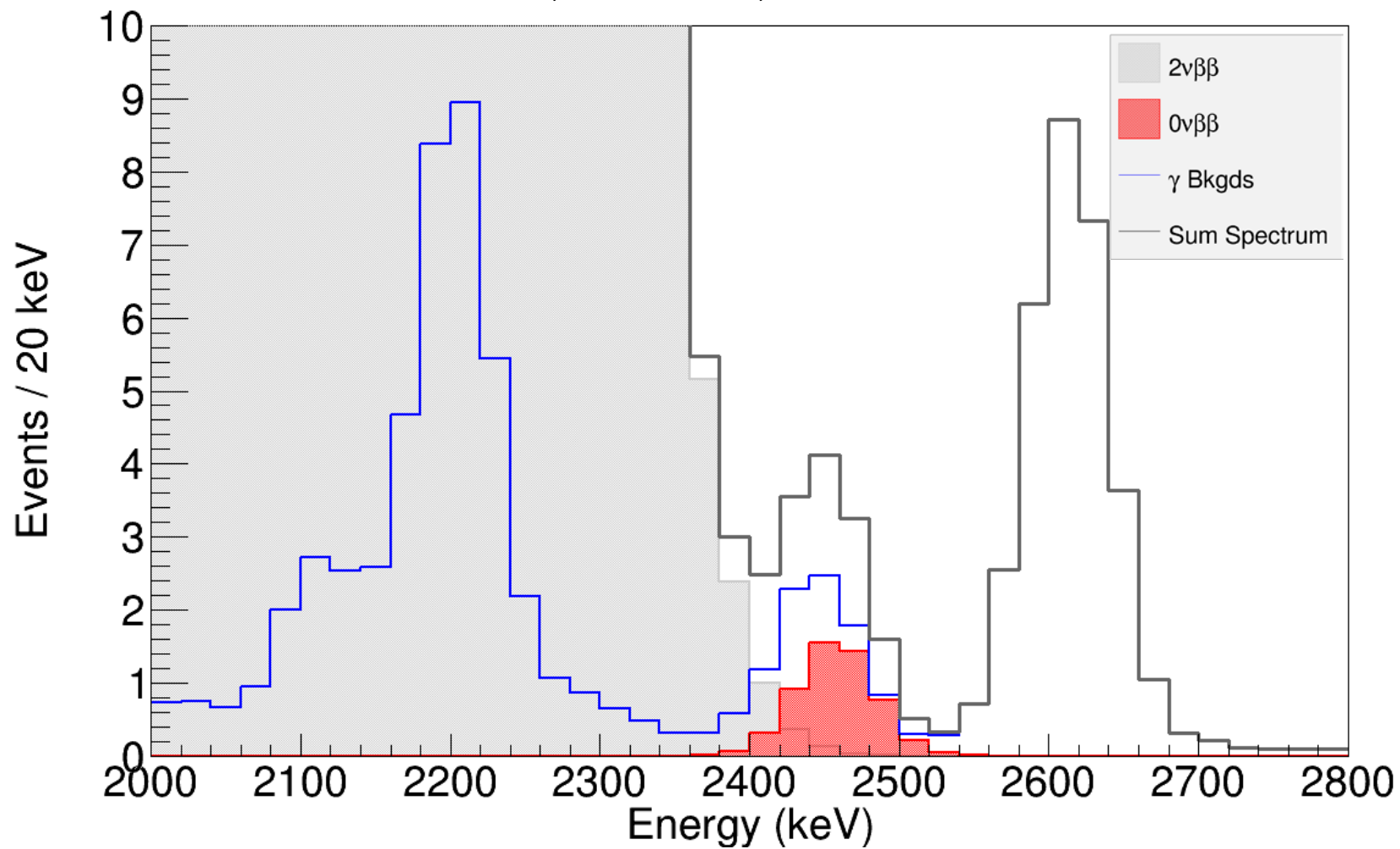
SS, 5 sigma discovery, full 4.78 tonne



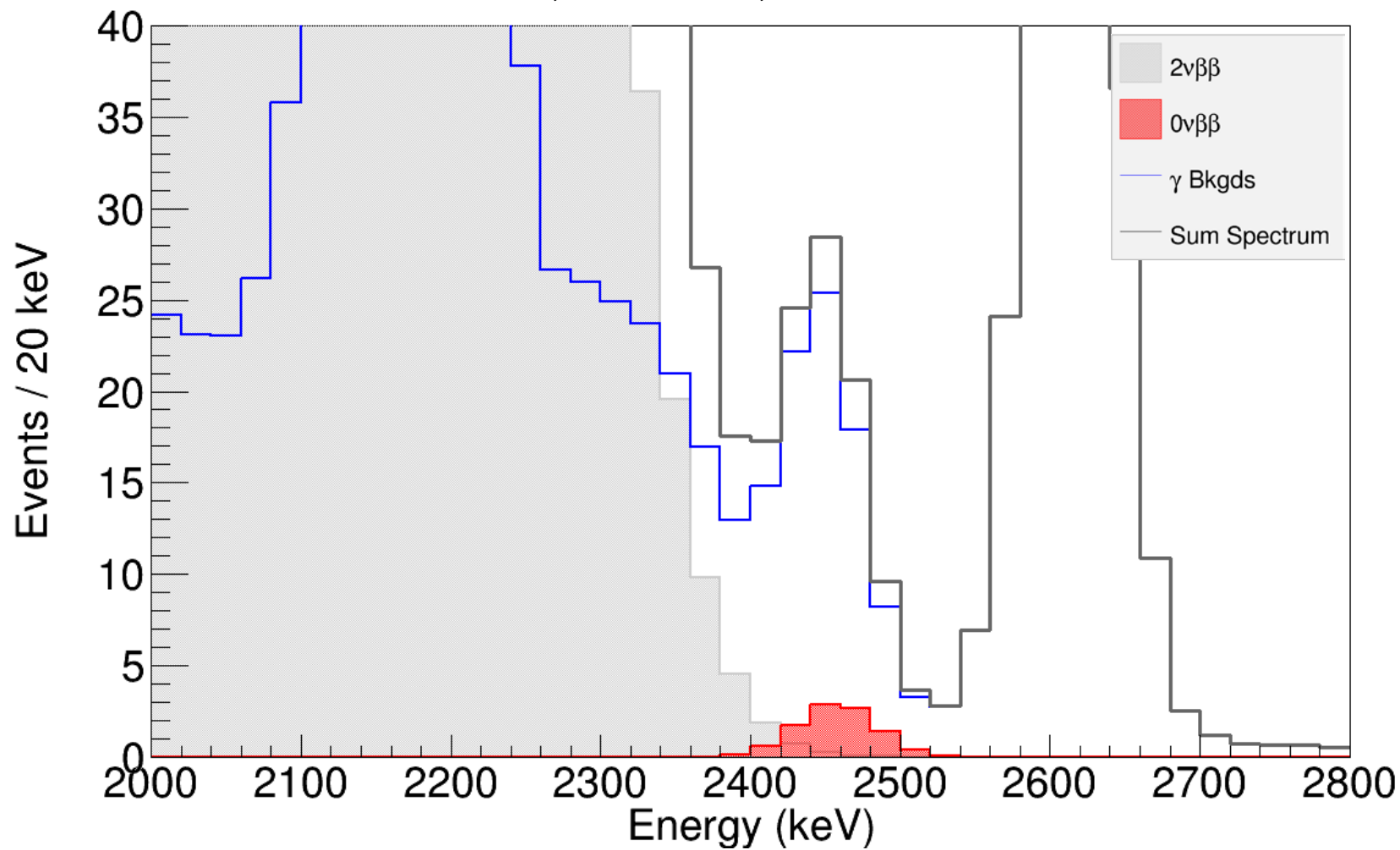
SS, 90% lower limit, central 1tonne



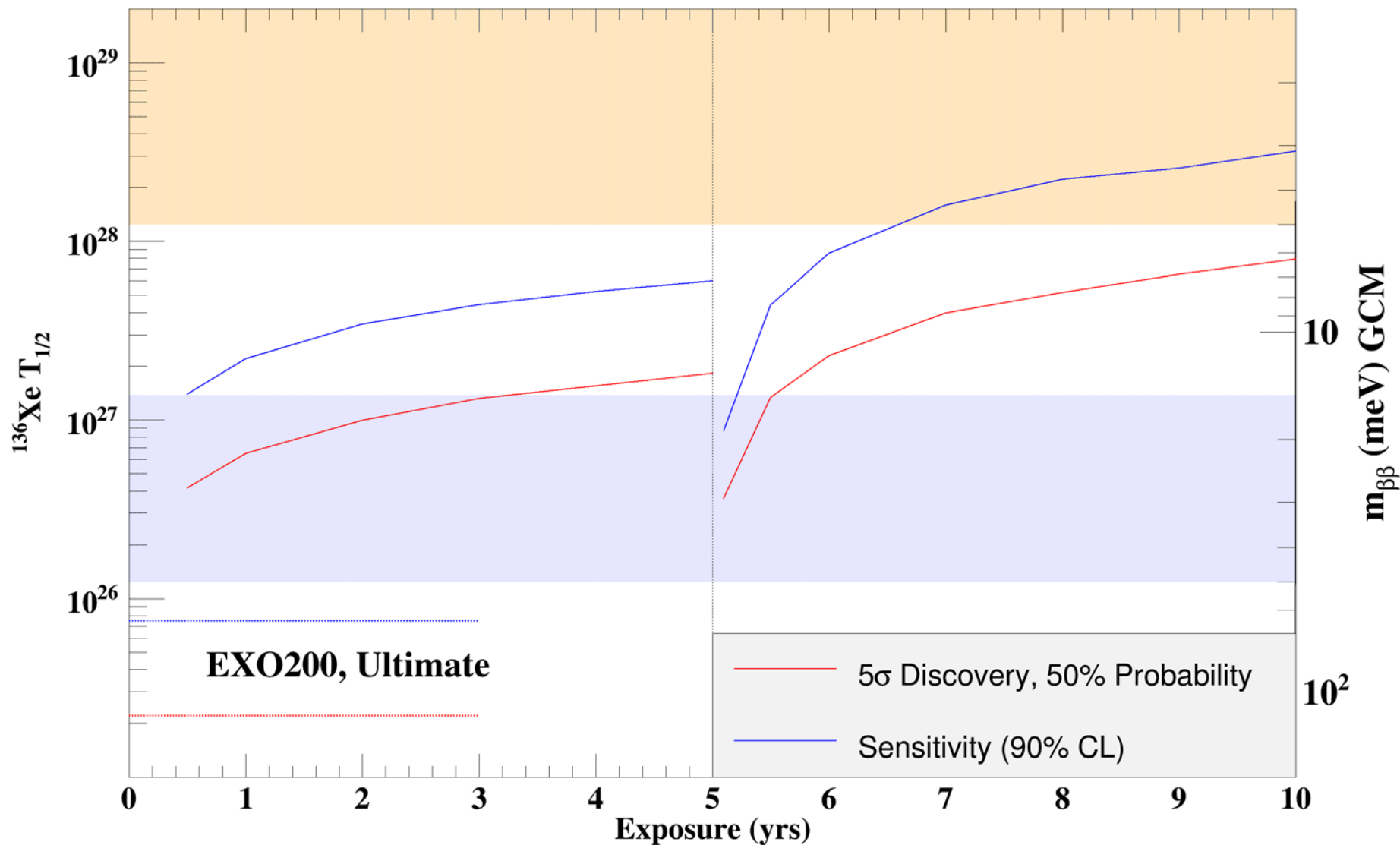
SS, 90% lower limit, central 2.5 tonne



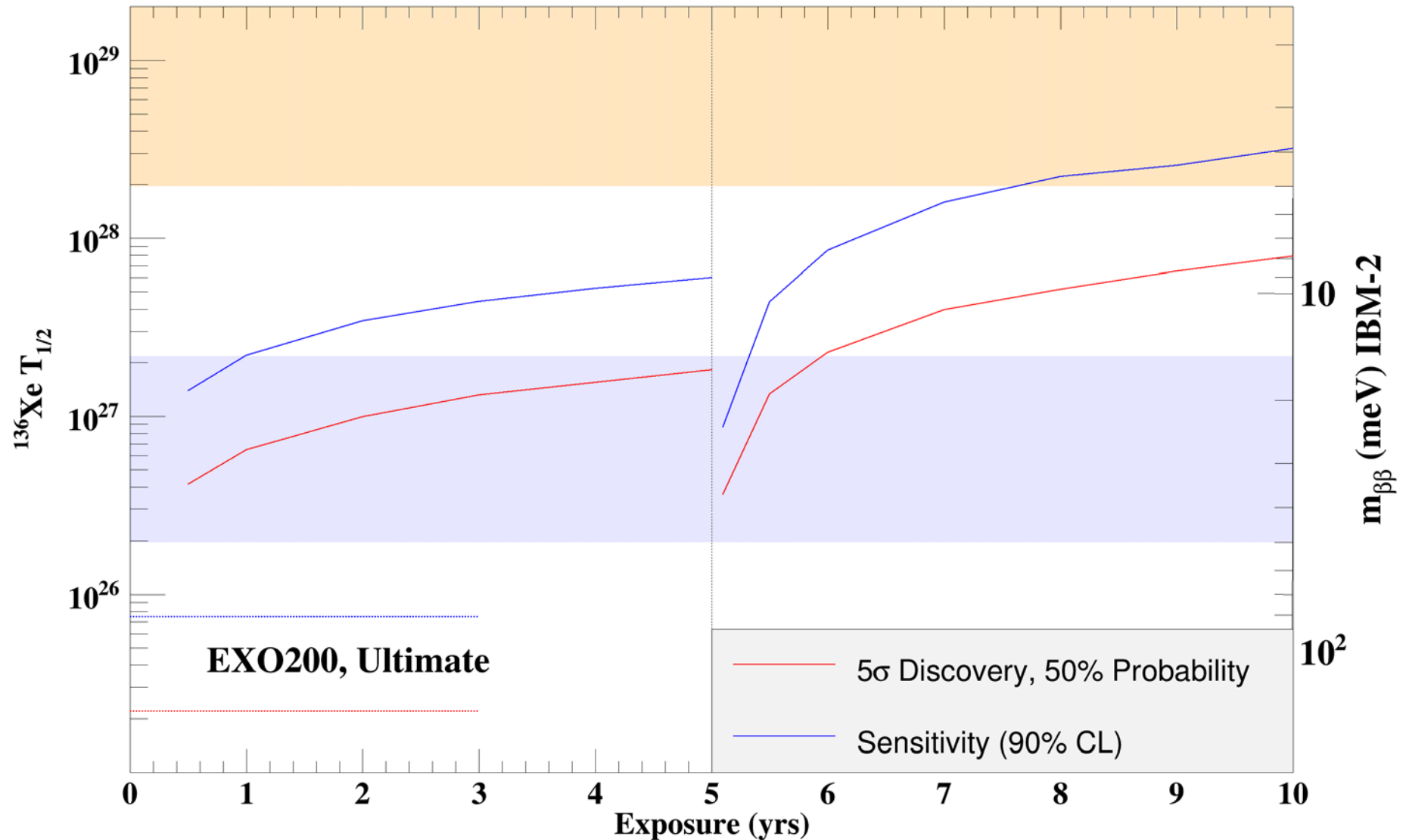
SS, 90% lower limit, central 4.78 tonne



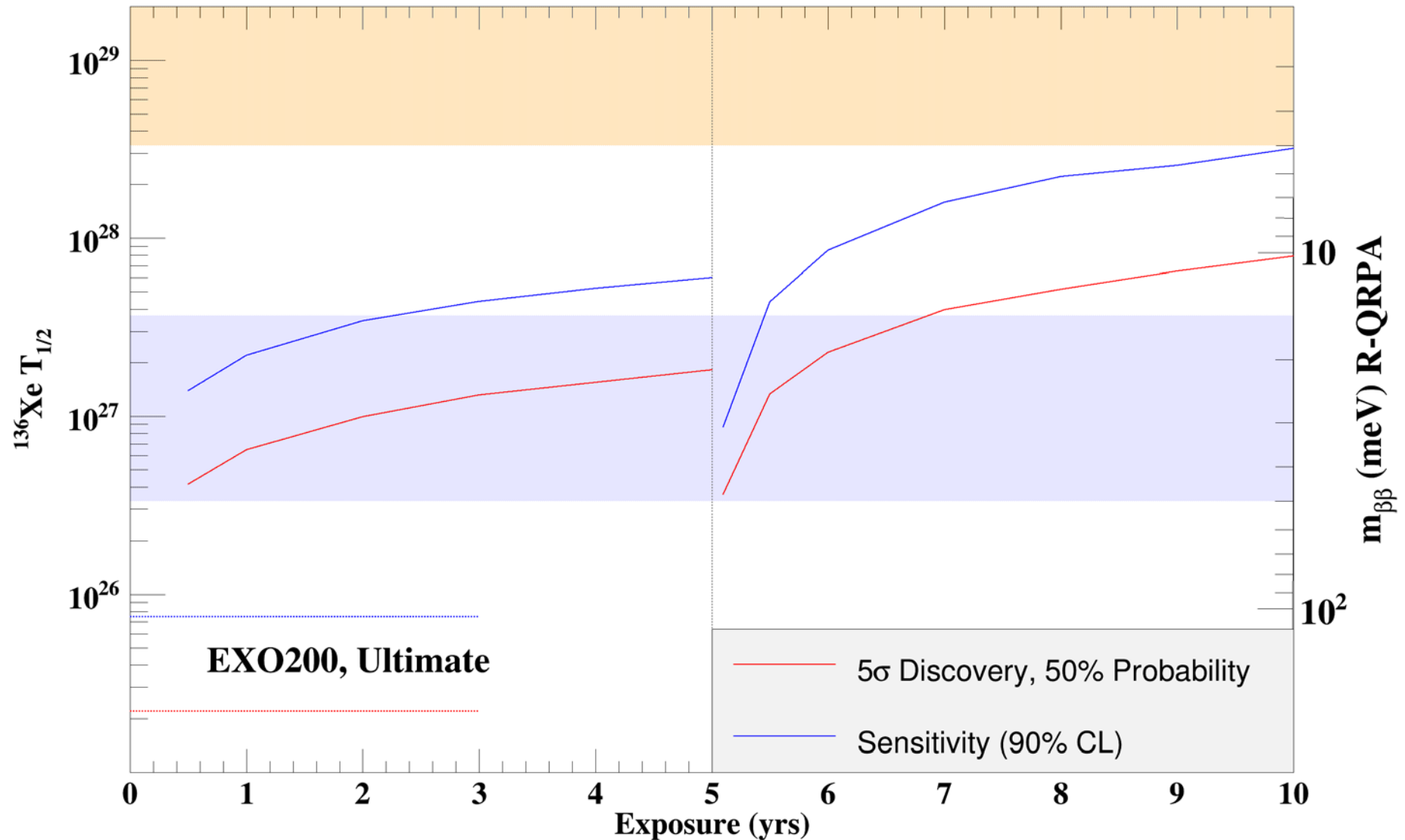
Sensitivity and discovery potential as a function of time



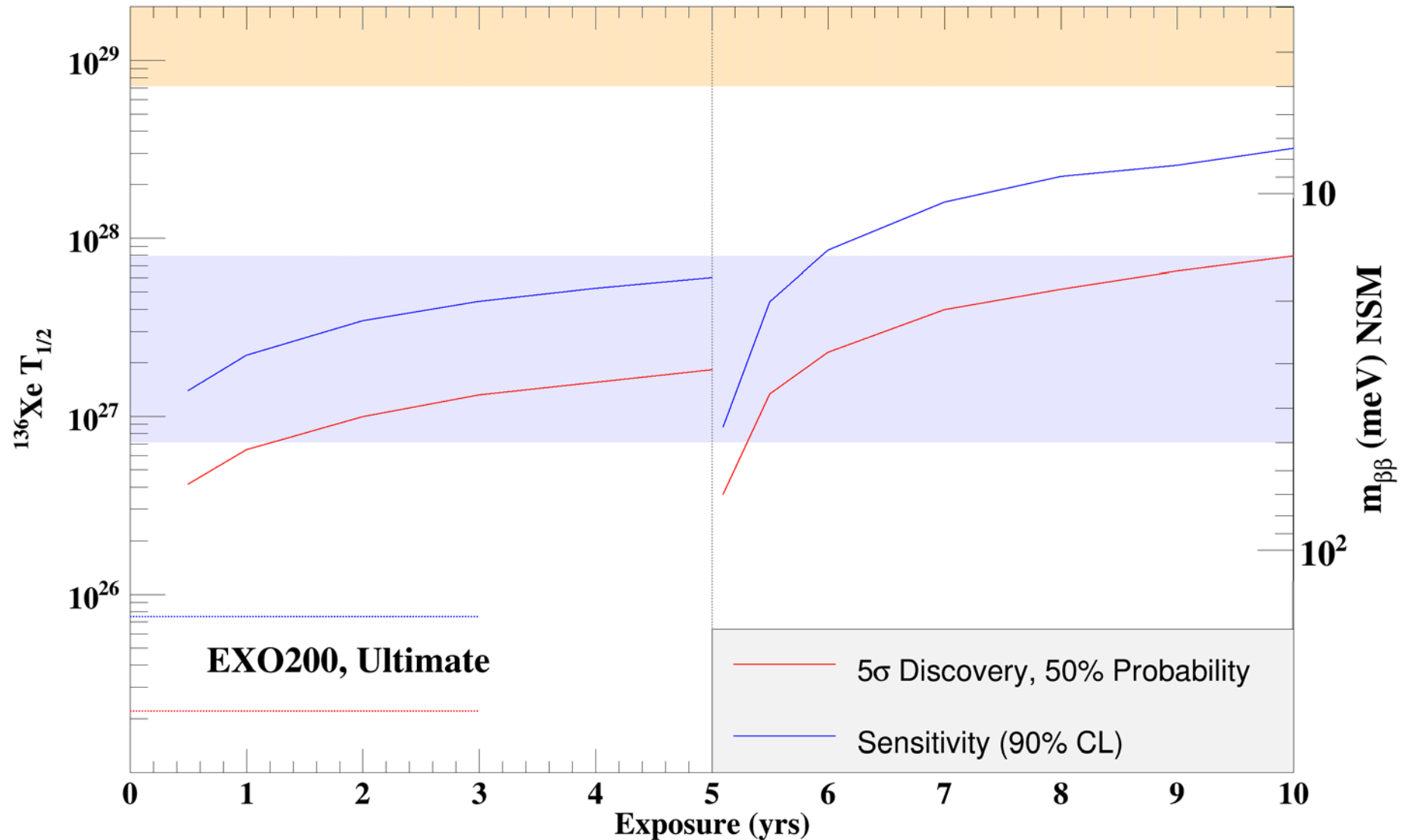
Sensitivity and discovery potential as a function of time



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

