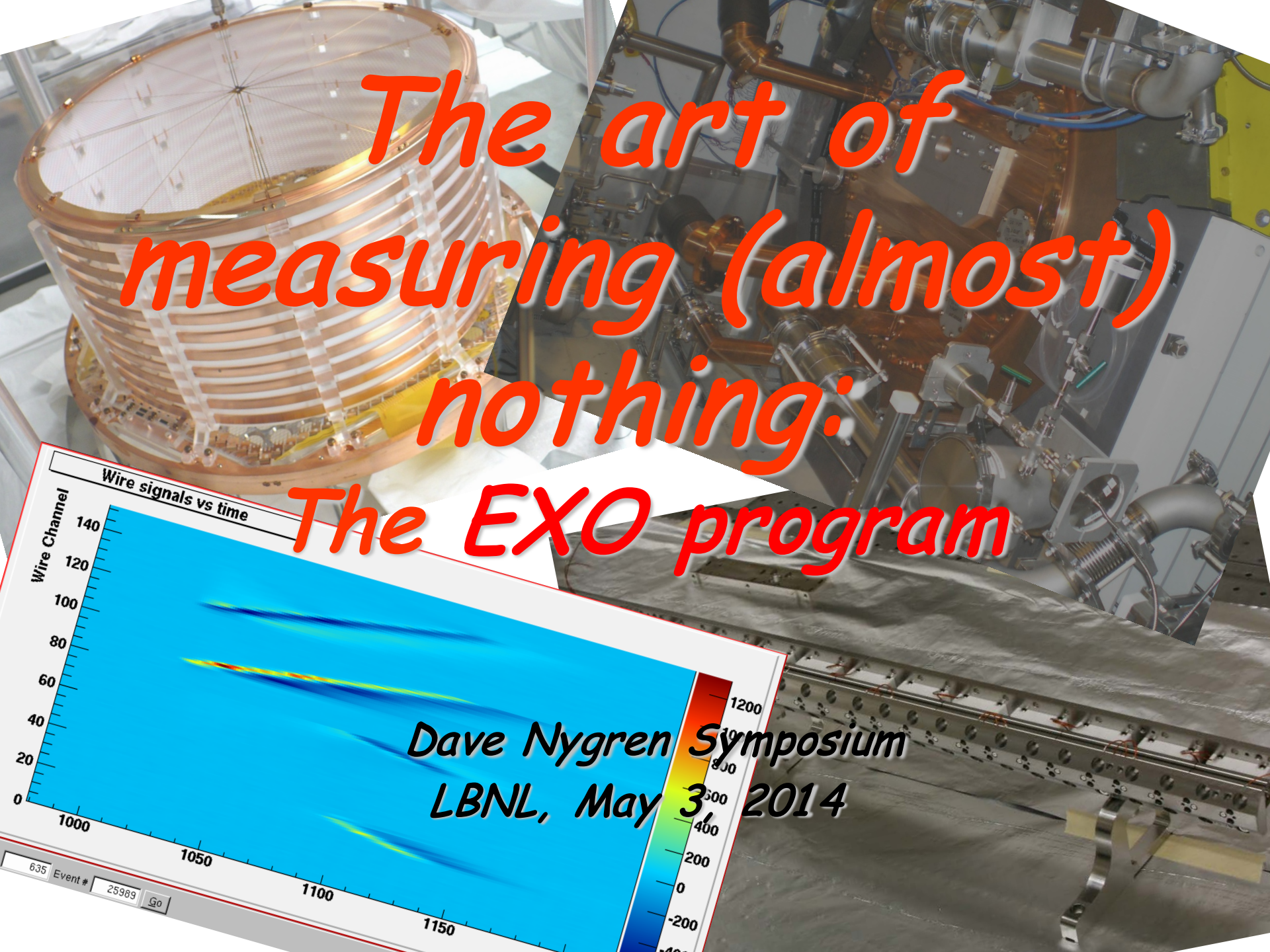
The art of measuring (almost) nothing: The EXO program



Dave Nygren Symposium
LBNL, May 3, 2014

Q: How can anyone possibly be interested in measuring almost nothing?

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A1: …there are plenty of dumb people in the world!

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A2: …measuring nothing evidently takes no effort and we like to enjoy life!

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~~A1: …there are plenty of dumb people in the world!~~

~~A2: …measuring nothing evidently takes no effort and we like to enjoy life!~~

A3: The "almost" is the most important word above!

Q: Is it difficult to measure almost nothing?

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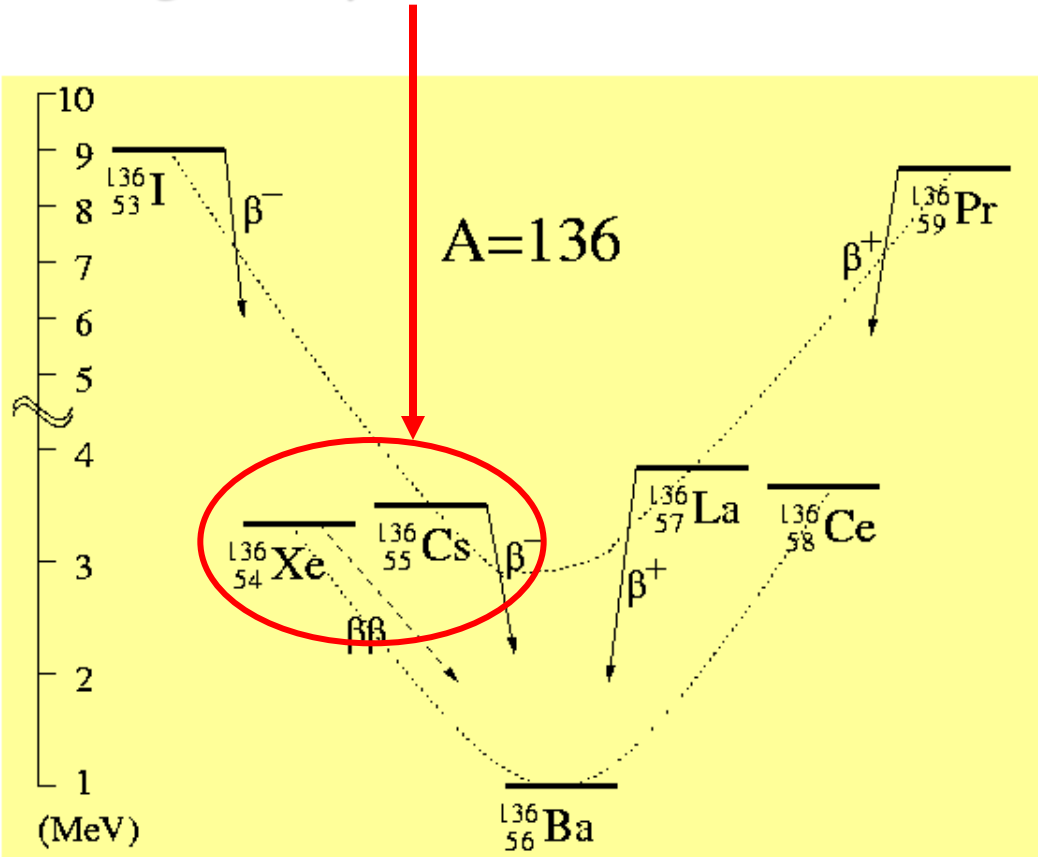
A: You bet is difficult!

Double-beta decay: a very rare nuclear 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

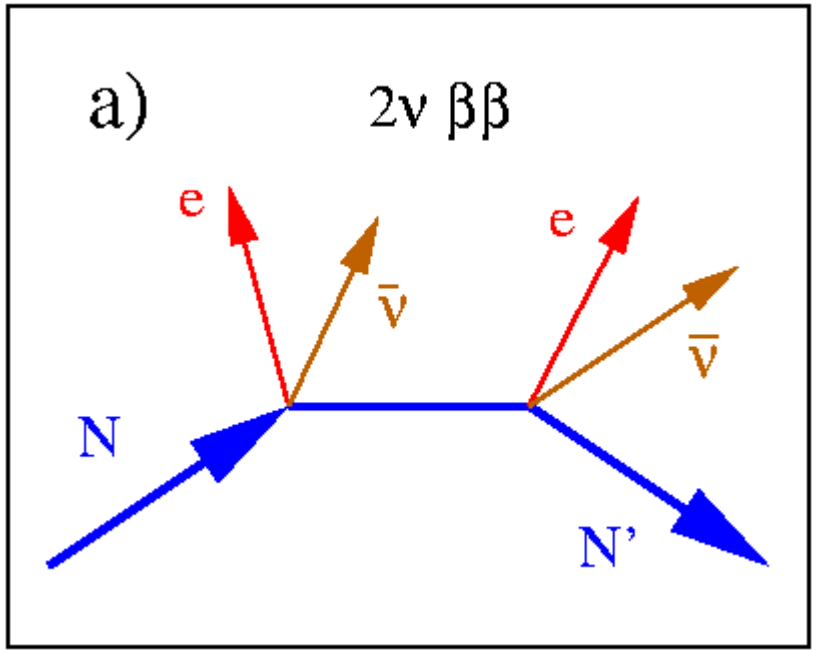
2ν mode:
a conventional
2nd order process
in nuclear physics

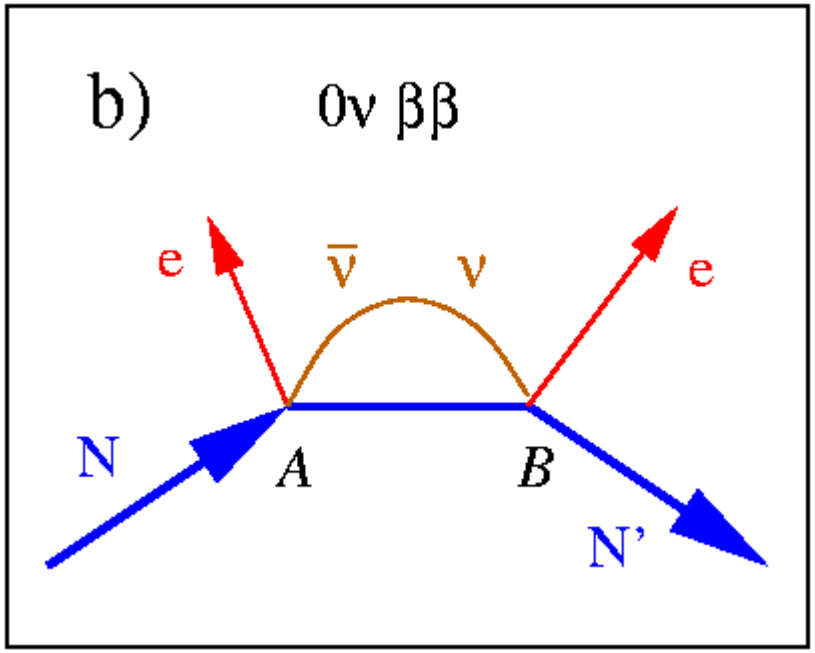
0ν mode: a hypothetical process can happen only if: $M_\nu \neq 0$

$\bar{\nu} = \nu$

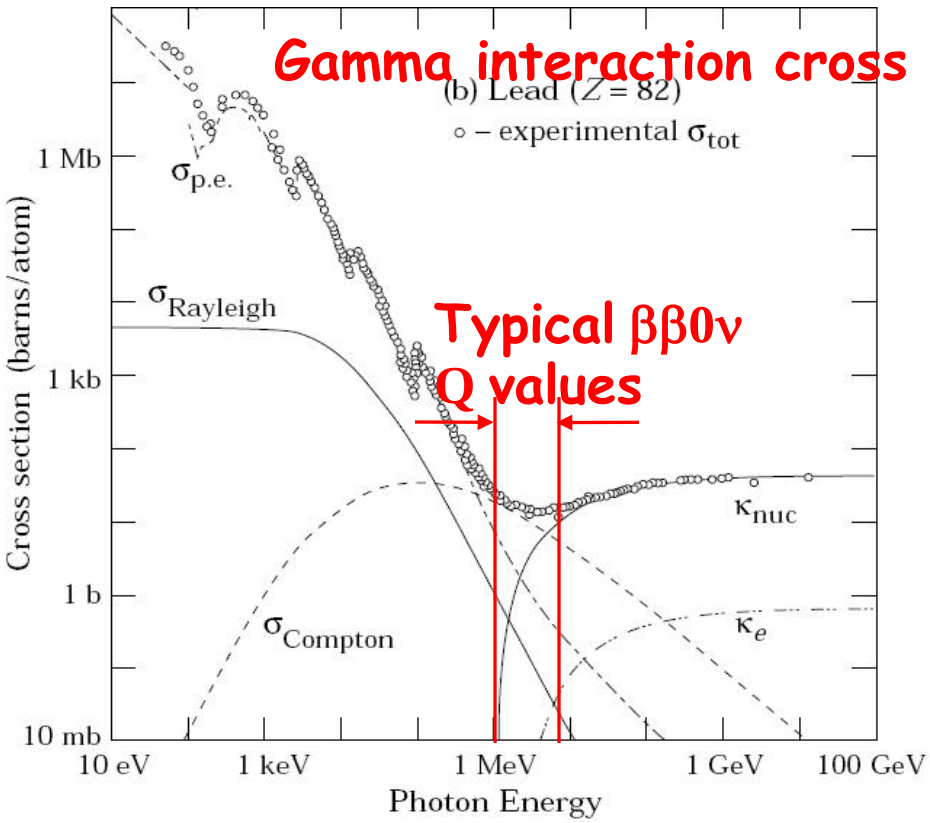
$|\Delta L|=2$

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





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

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*

…having said this, ^{136}Xe is clearly the best choice because…

- 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 ~ 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!

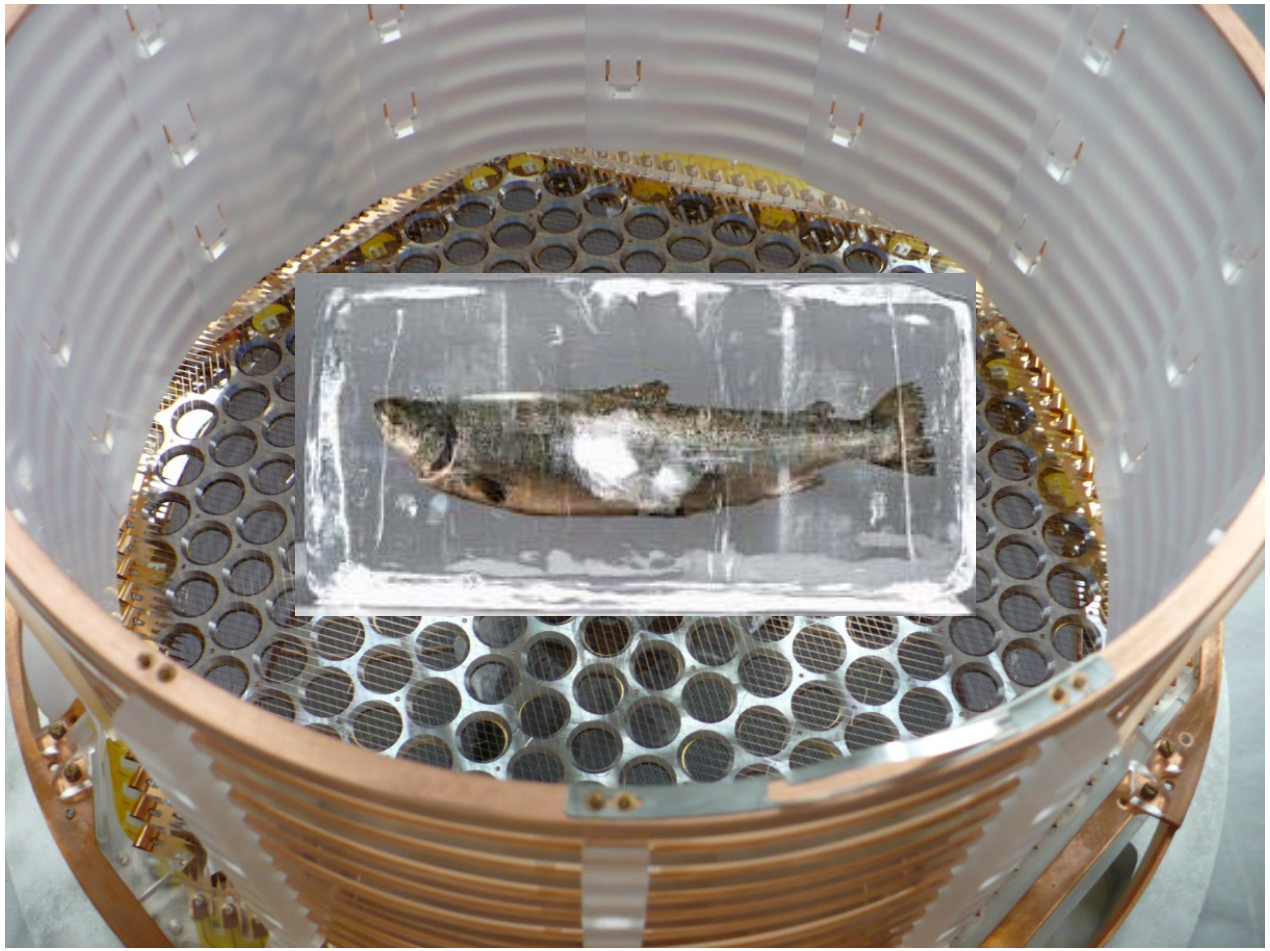
…having said this, ^{136}Xe is clearly the best choice because…

But many of these reasons can be summarized as:

➔ Because we can build a homogeneous TPC

But beyond this our ways part, Dave…

Our favorite TPC is in liquid phase: LXe



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

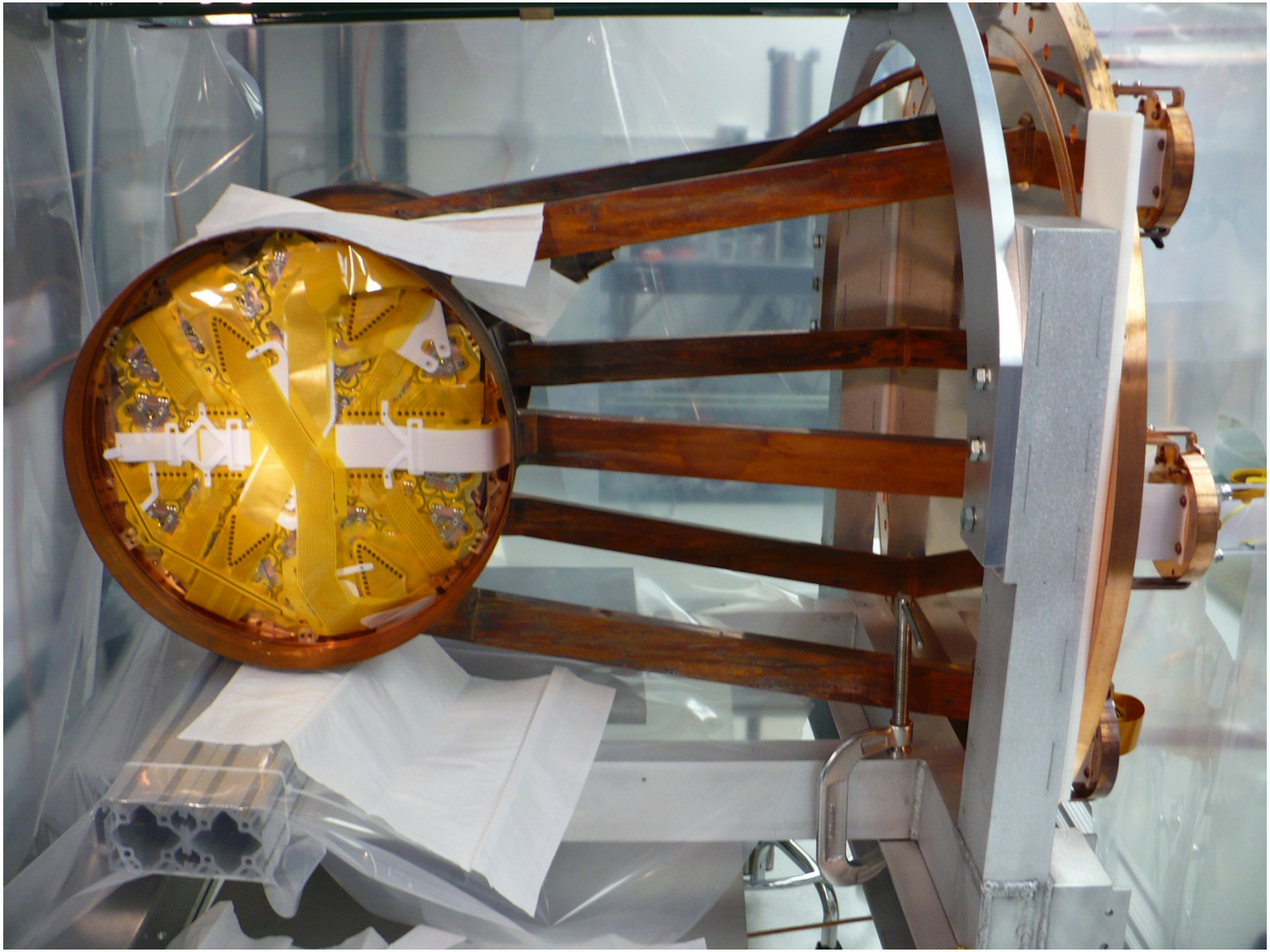
R. Neilson, et al. NIM A 608 (2009) 6875

APDs are ideal for our application:
- very clean & light-weight,
- very sensitive to VUV

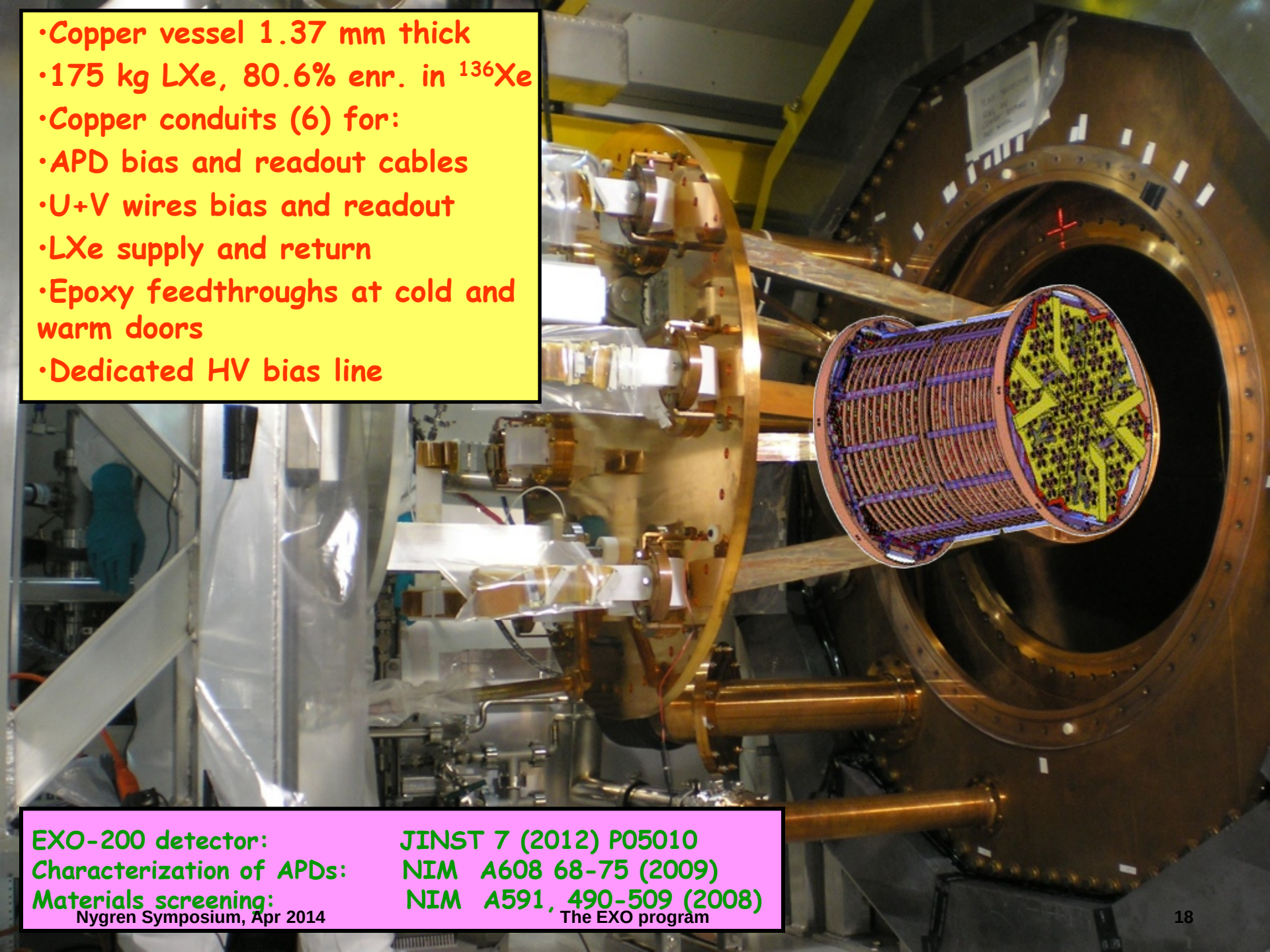
QE > 1 at 175nm

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

EXO-200 TPC Assembled

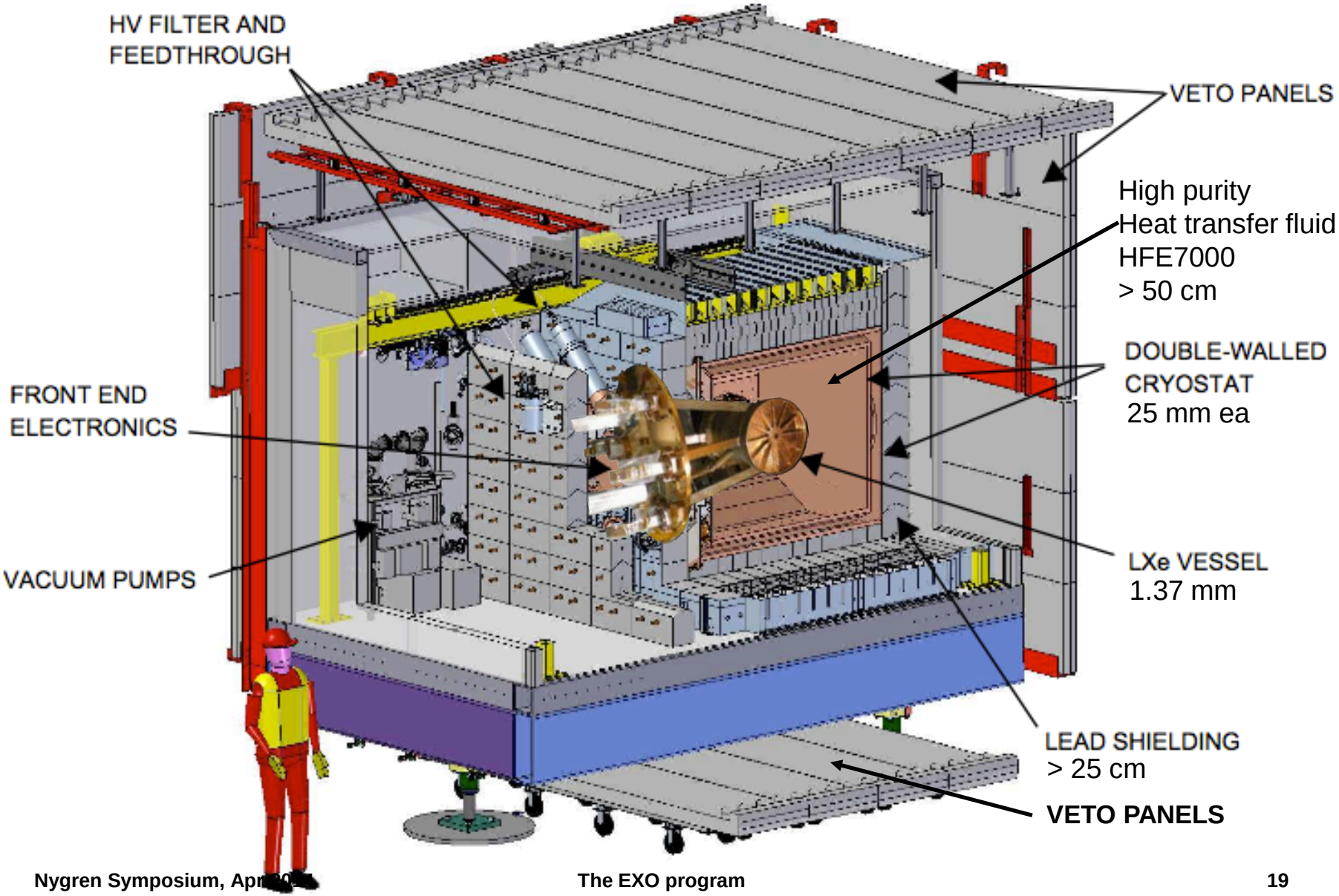


- Copper vessel 1.37 mm thick
- 175 kg LXe, 80.6% enr. in ^{136}Xe
- Copper conduits (6) for:
- APD bias and readout cables
- U+V wires bias and readout
- LXe supply and return
- Epoxy feedthroughs at cold and warm doors
- Dedicated HV bias line



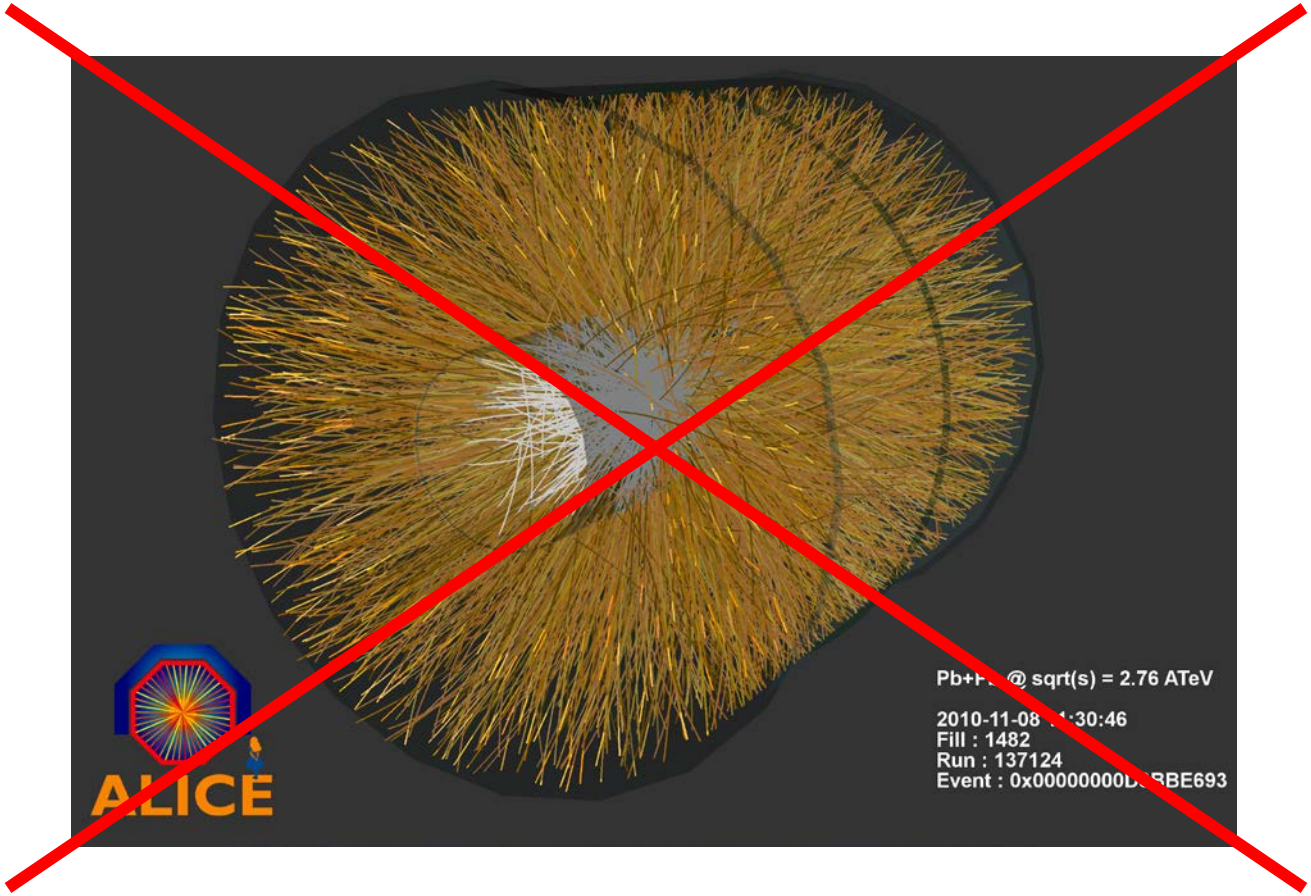
EXO-200 detector:	JINST 7 (2012) P05010
Characterization of APDs:	NIM A608 68-75 (2009)
Materials screening:	NIM A591, 490-509 (2008)

The EXO-200 Detector

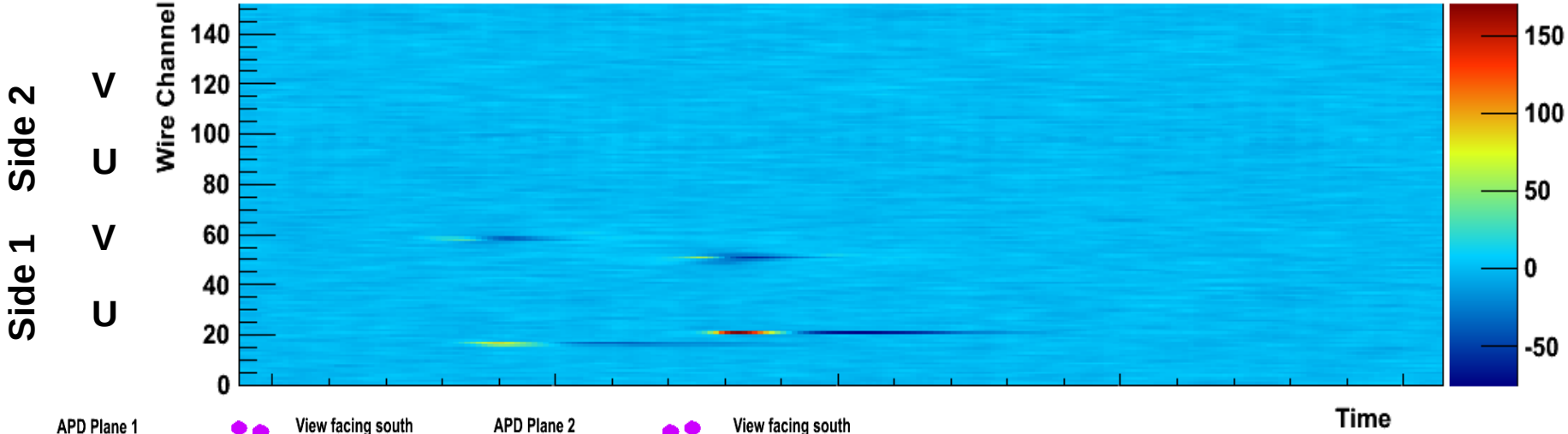


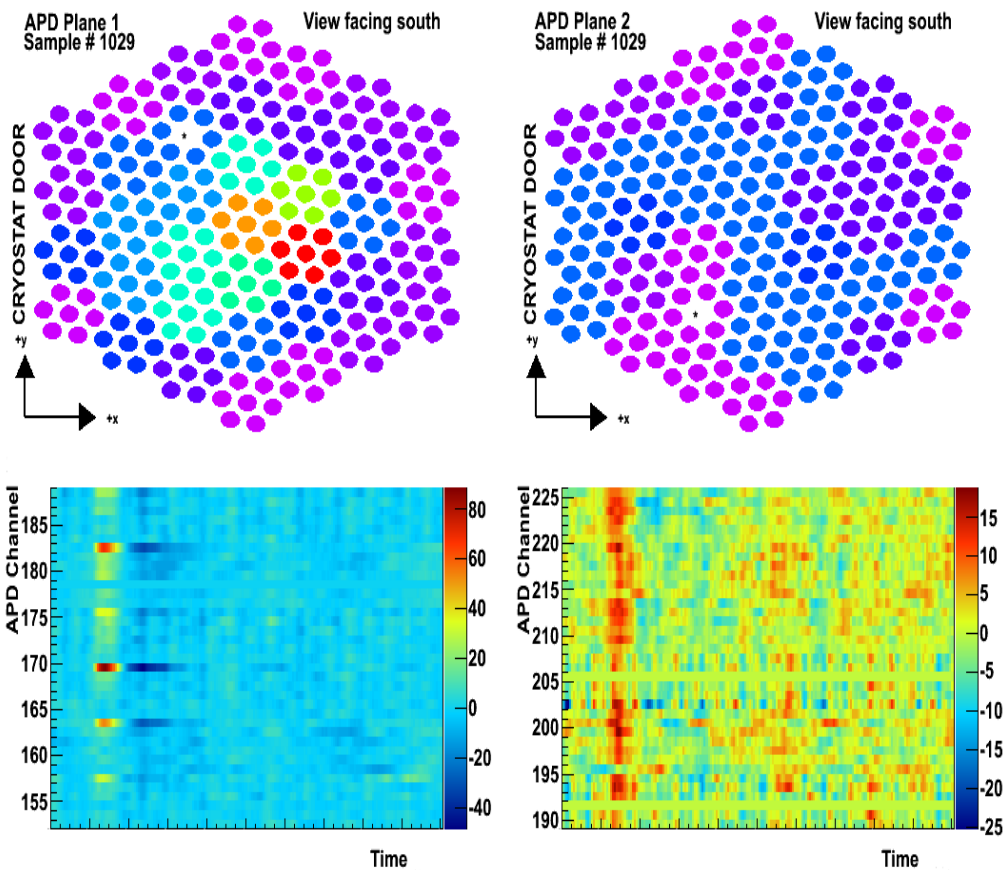
In this case there is

- No high rate
- No high occupancy
- No radiation damage



Events don't look like much…



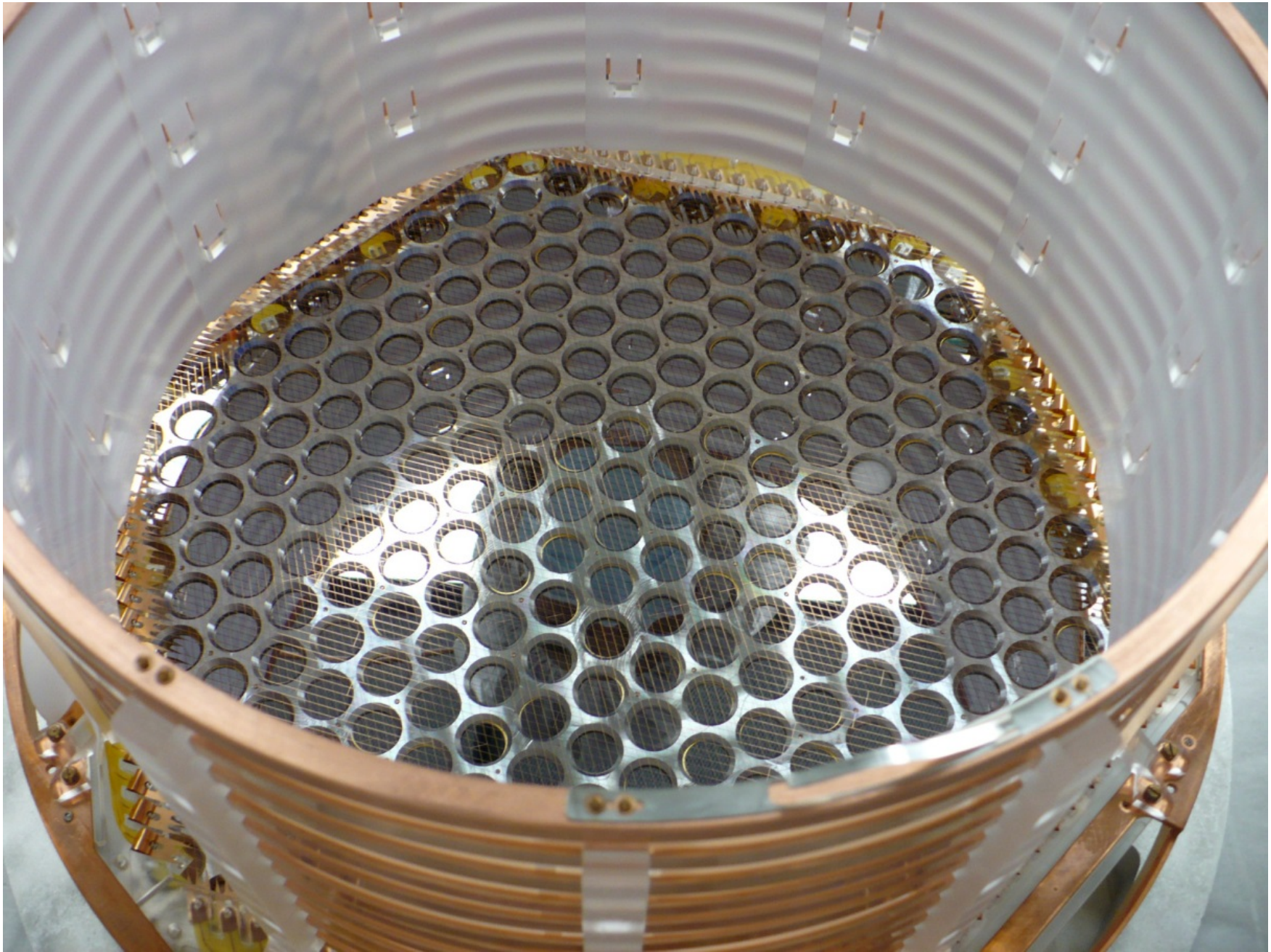


A two-site Compton scattering event.

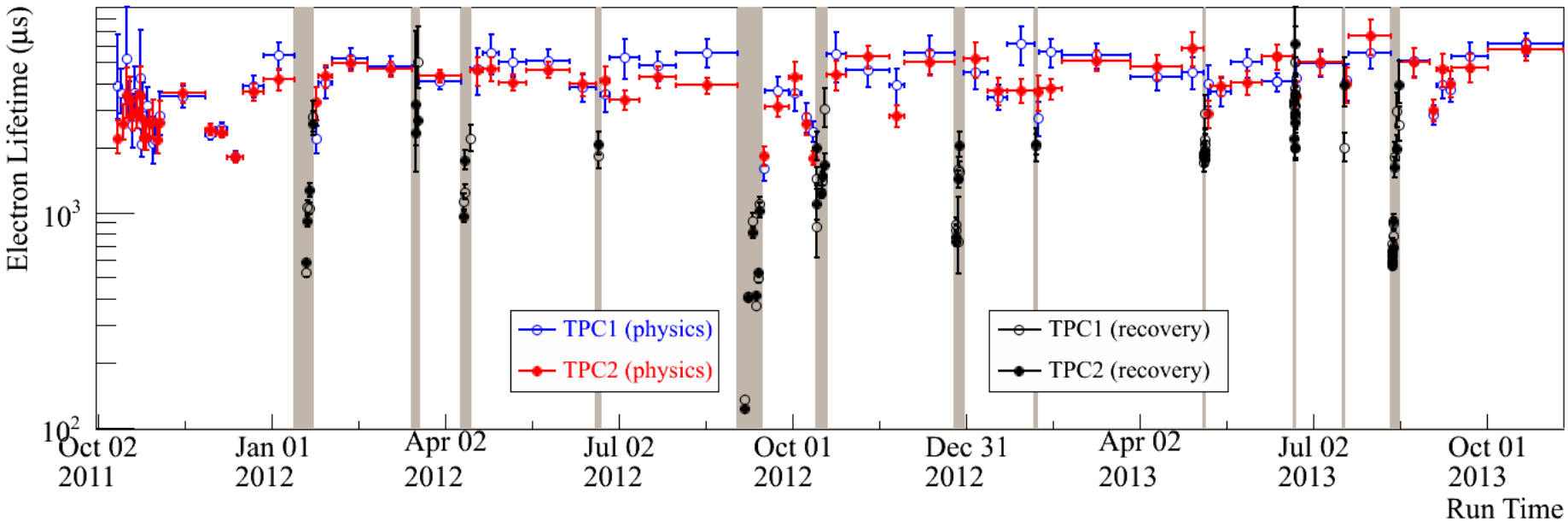
All scintillation light arrives at the same time, indicating that the two energy depositions are simultaneous.

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

The "minimalistic" TPC



Xe purity is essential for good energy resolution



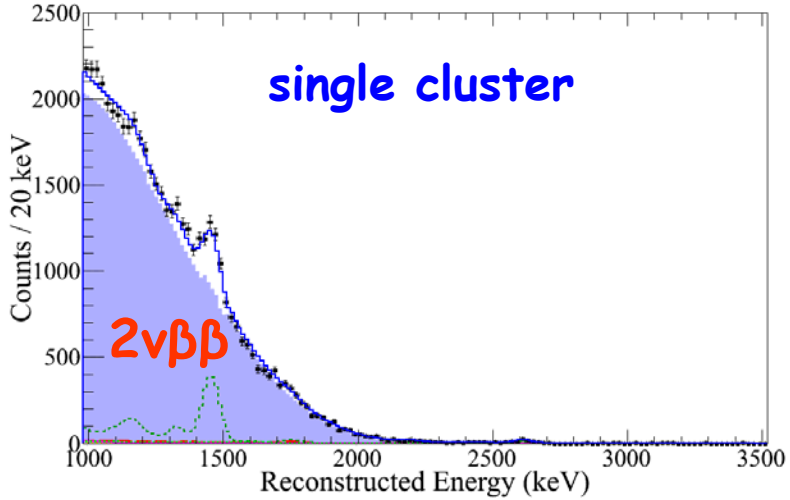
Xenon gas is forced through heated Zr getter by a custom ultraclean pump.

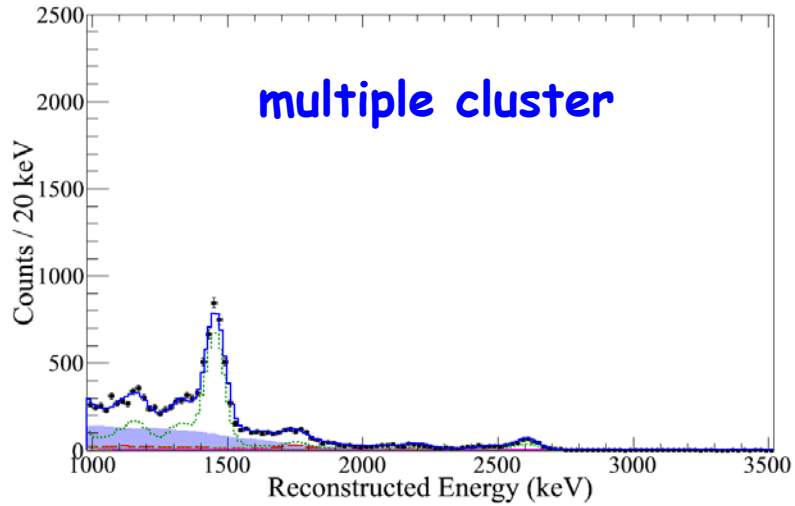
At τ_e = 3 ms:
- drift time <110 μs
- loss of charge: 3.6% at full drift length

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

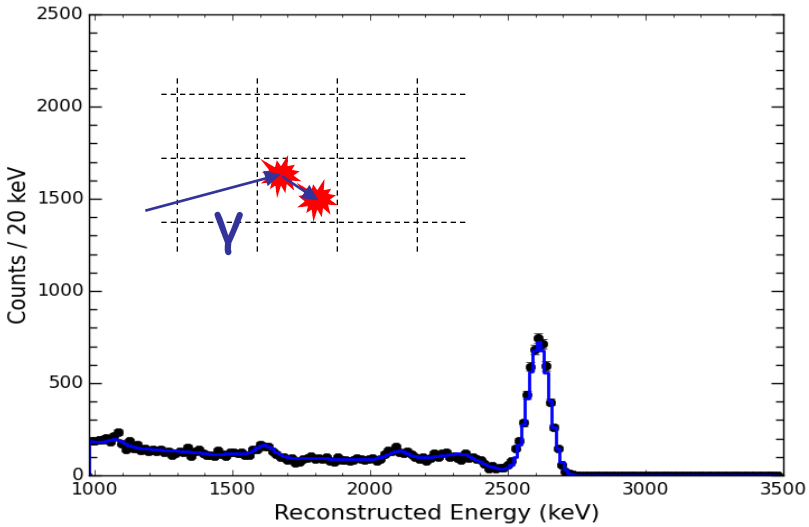
Tracking:
an essential tool to identify and suppress backgrounds

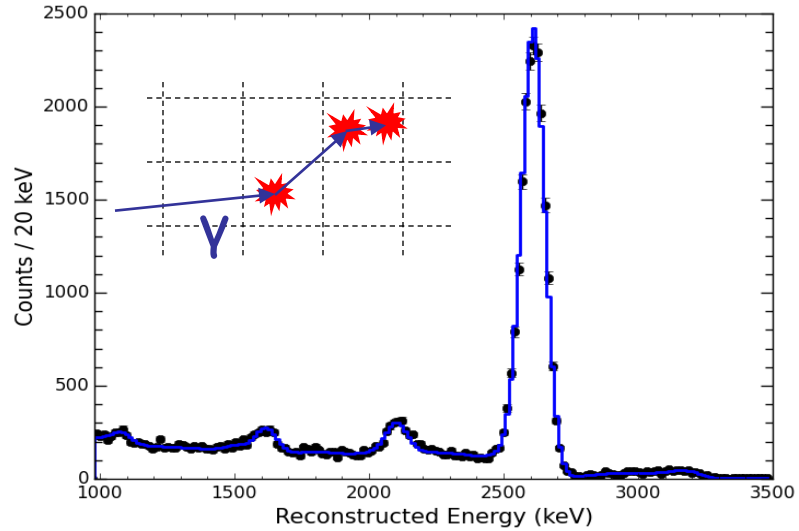
Low background data



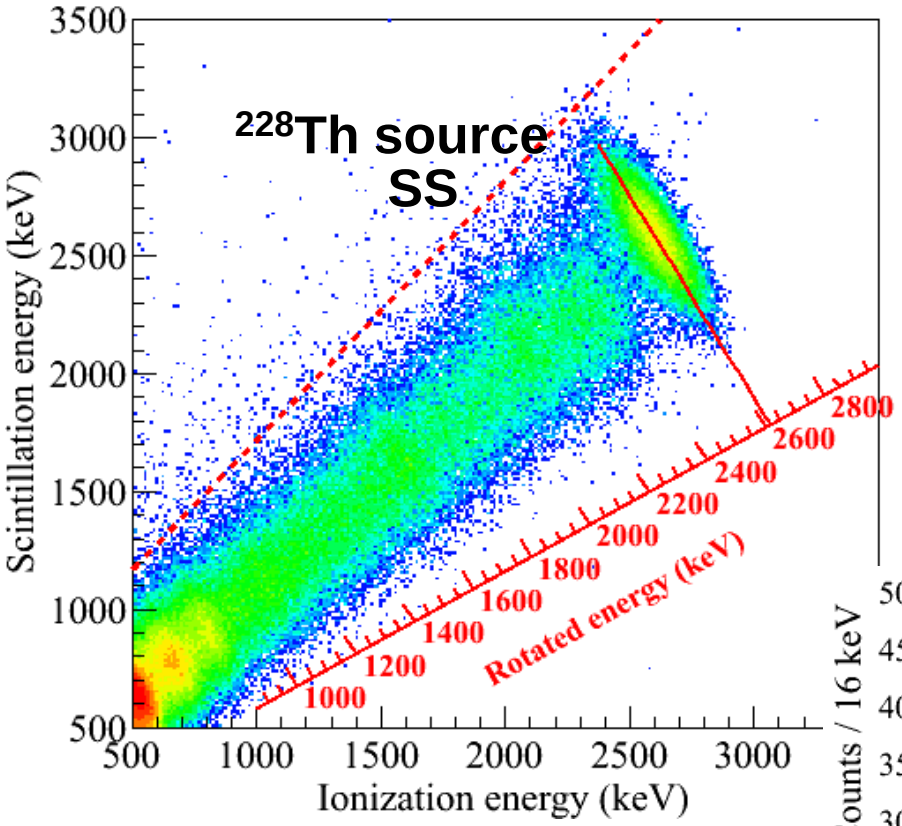


^{228}Th calibration source





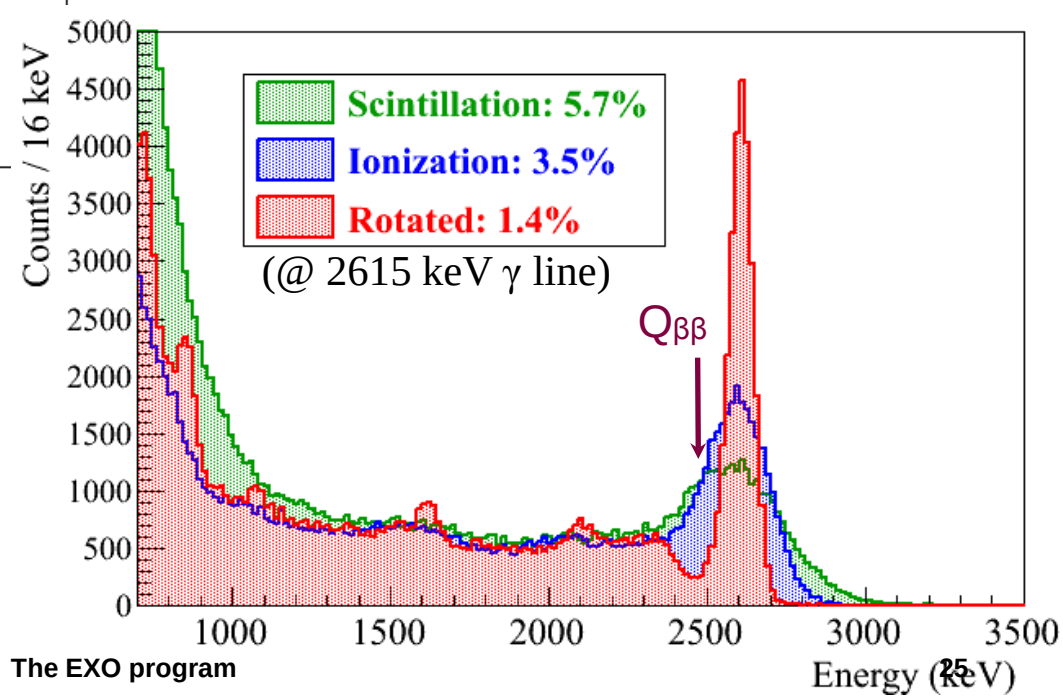
Combining Ionization and Scintillation



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

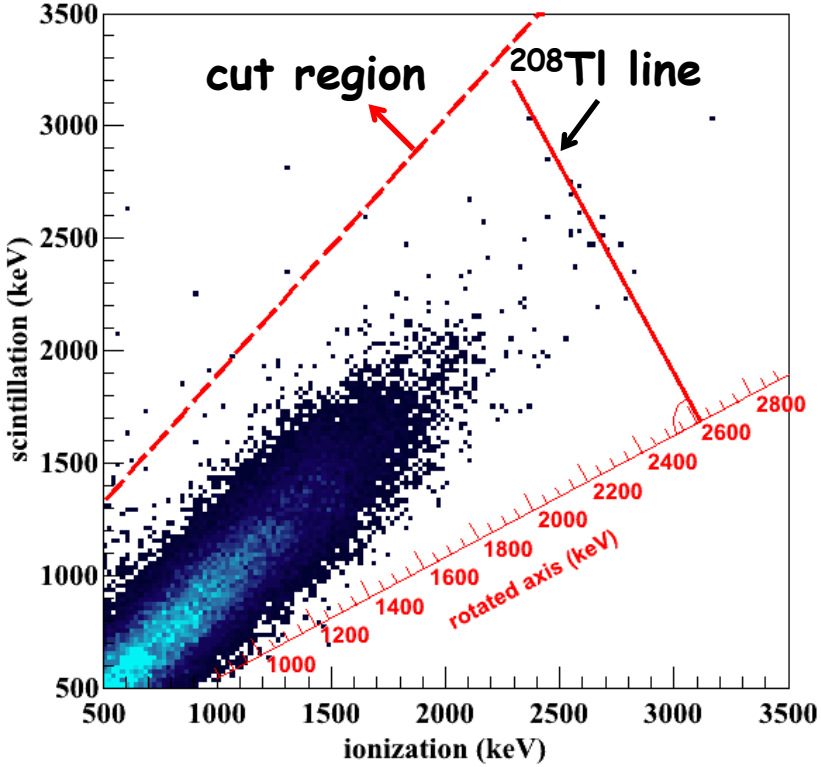
E.Conti et al. Phys Rev B 68 (2003) 054201

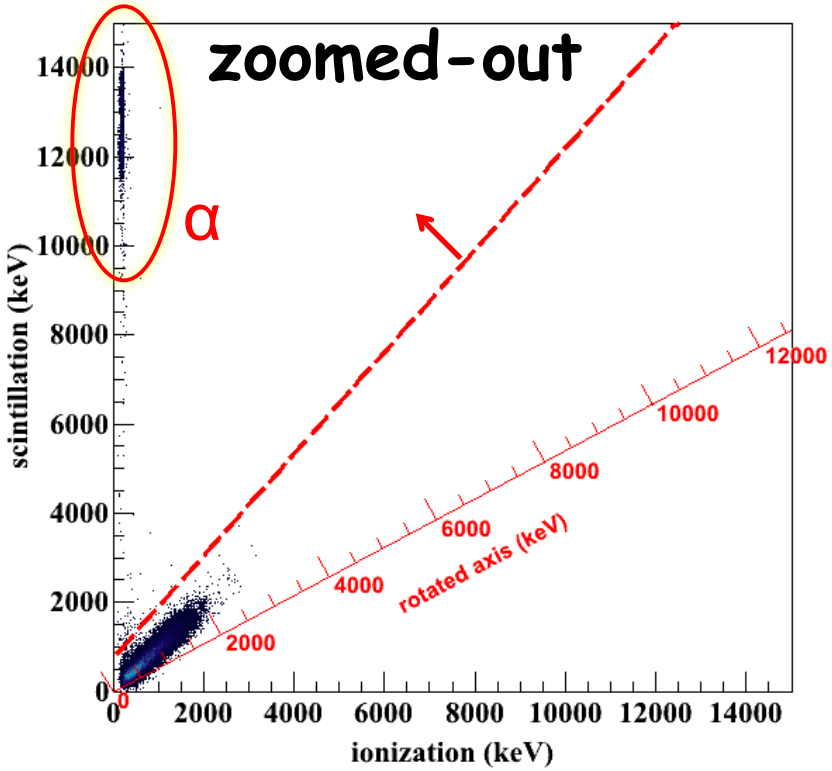
Note improvement due to LAAPD denoising



Rotation angle chosen to optimize energy resolution at 2615 keV

Low Background 2D SS Spectrum:
A different type of Particle ID

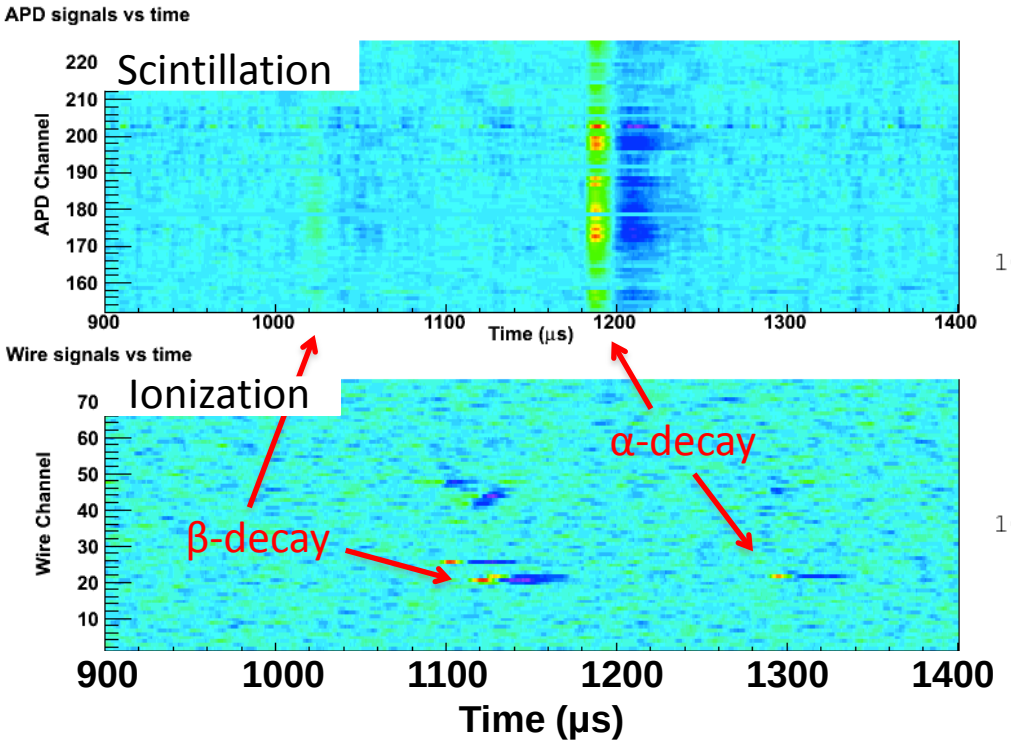




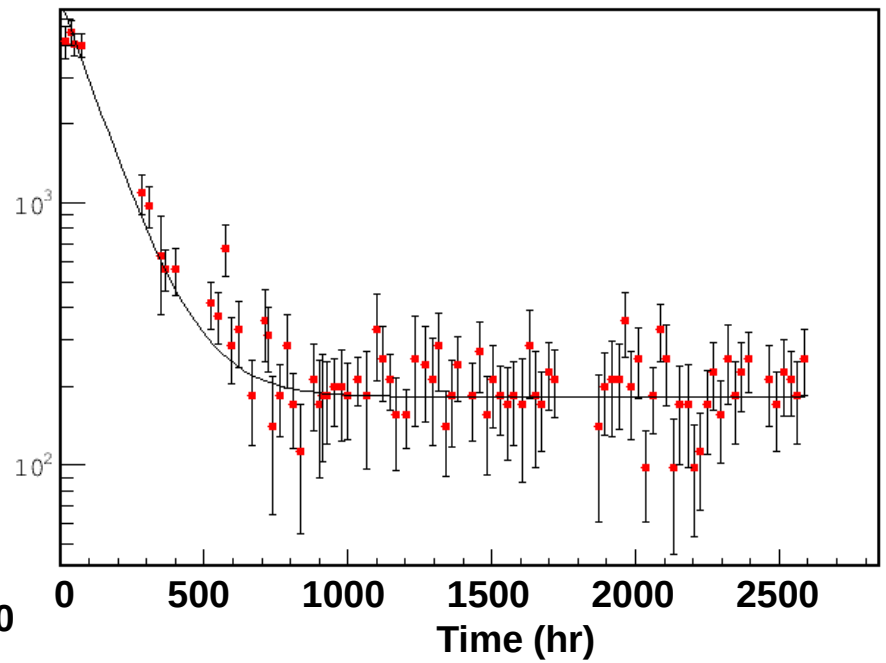
Events removed by diagonal cut:

- 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

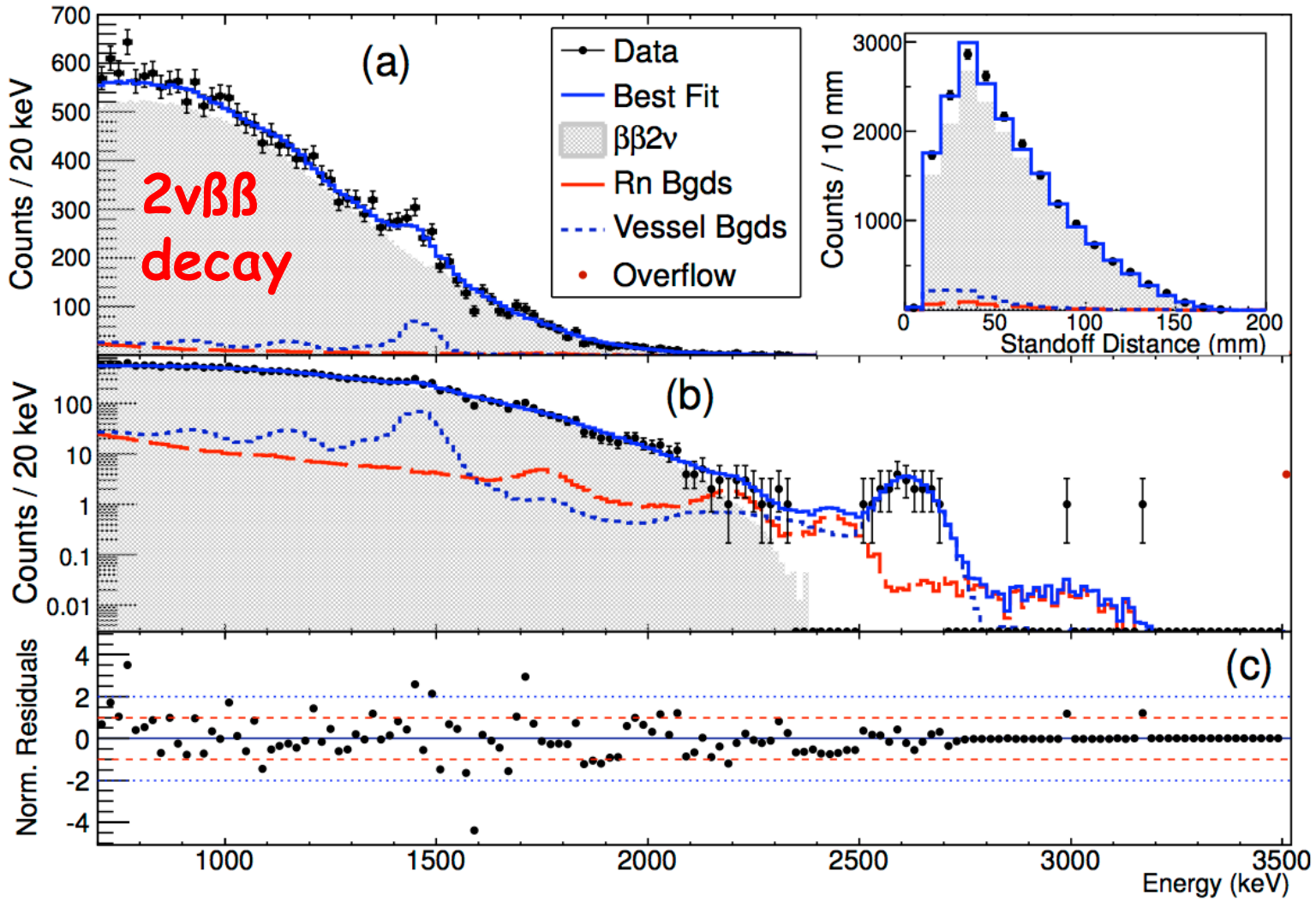


Total ^{222}Rn in LXe after initial fill

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

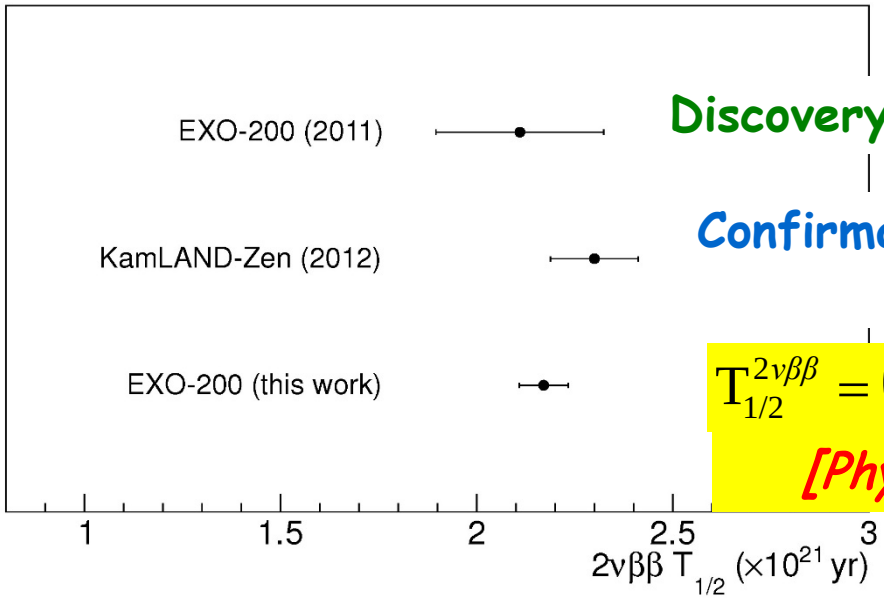
or 200 atoms of ^{222}Rn in our Xenon!

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



Signal-to-Background ratio 10 - 20

…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]

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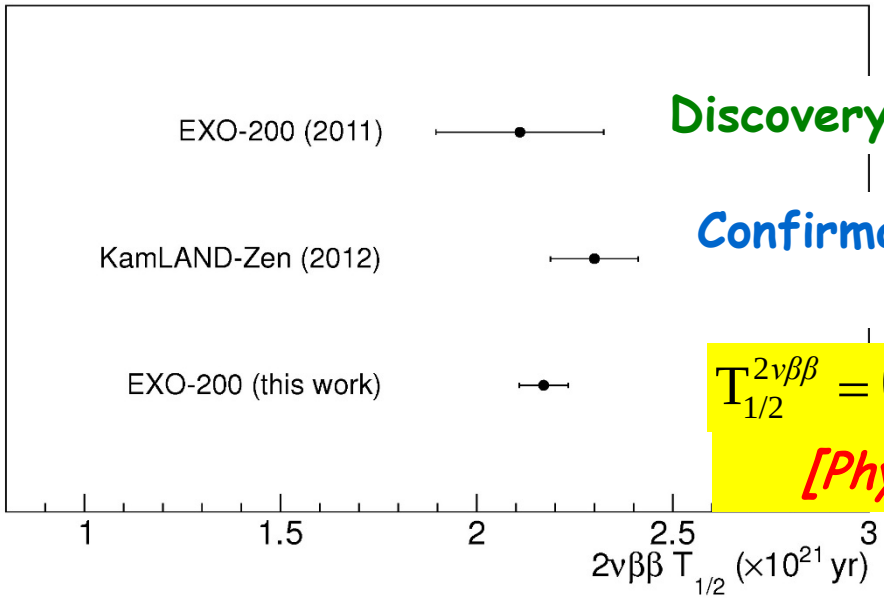

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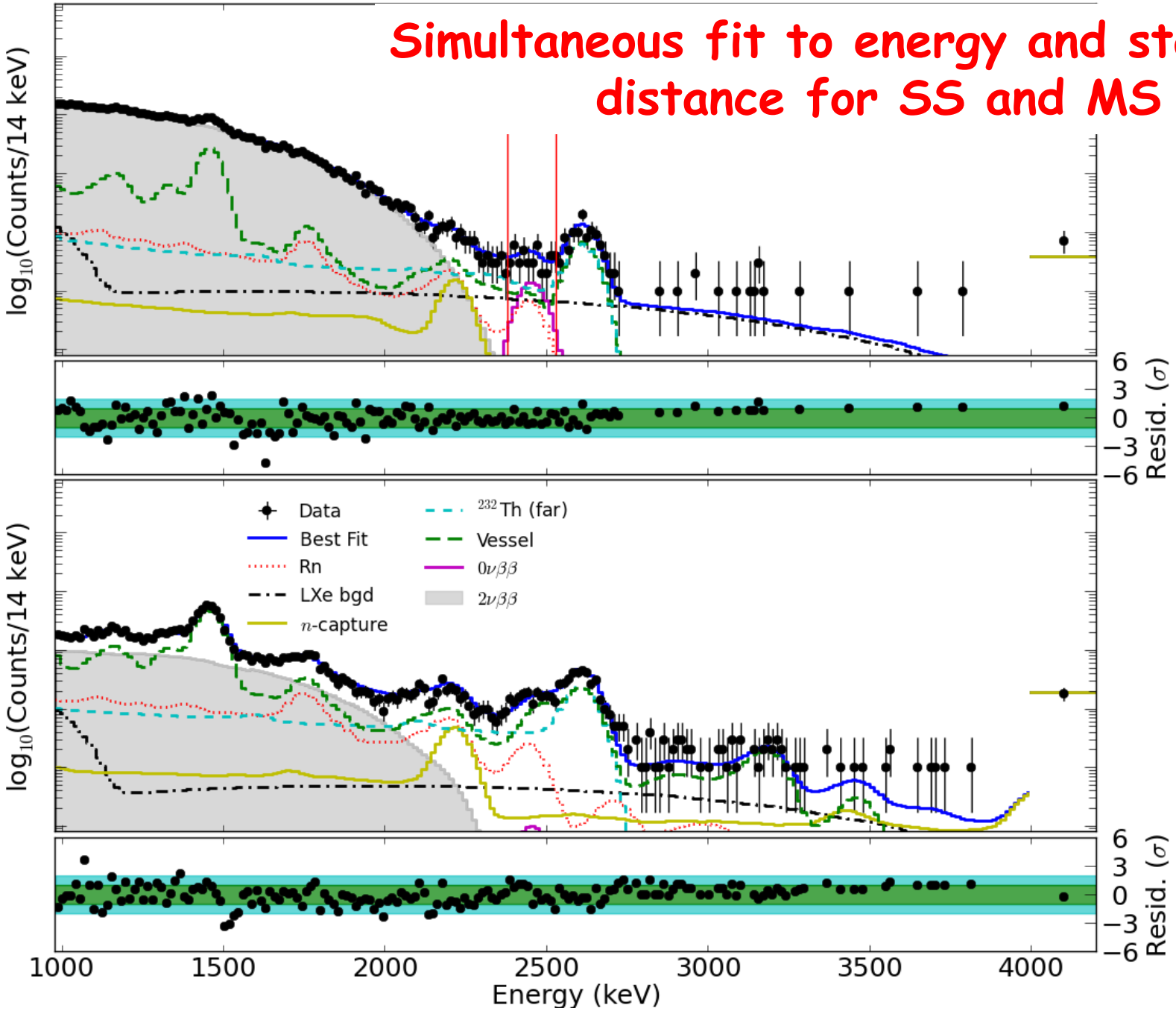
[Phys. Rev. C 89 (2014) 015502]

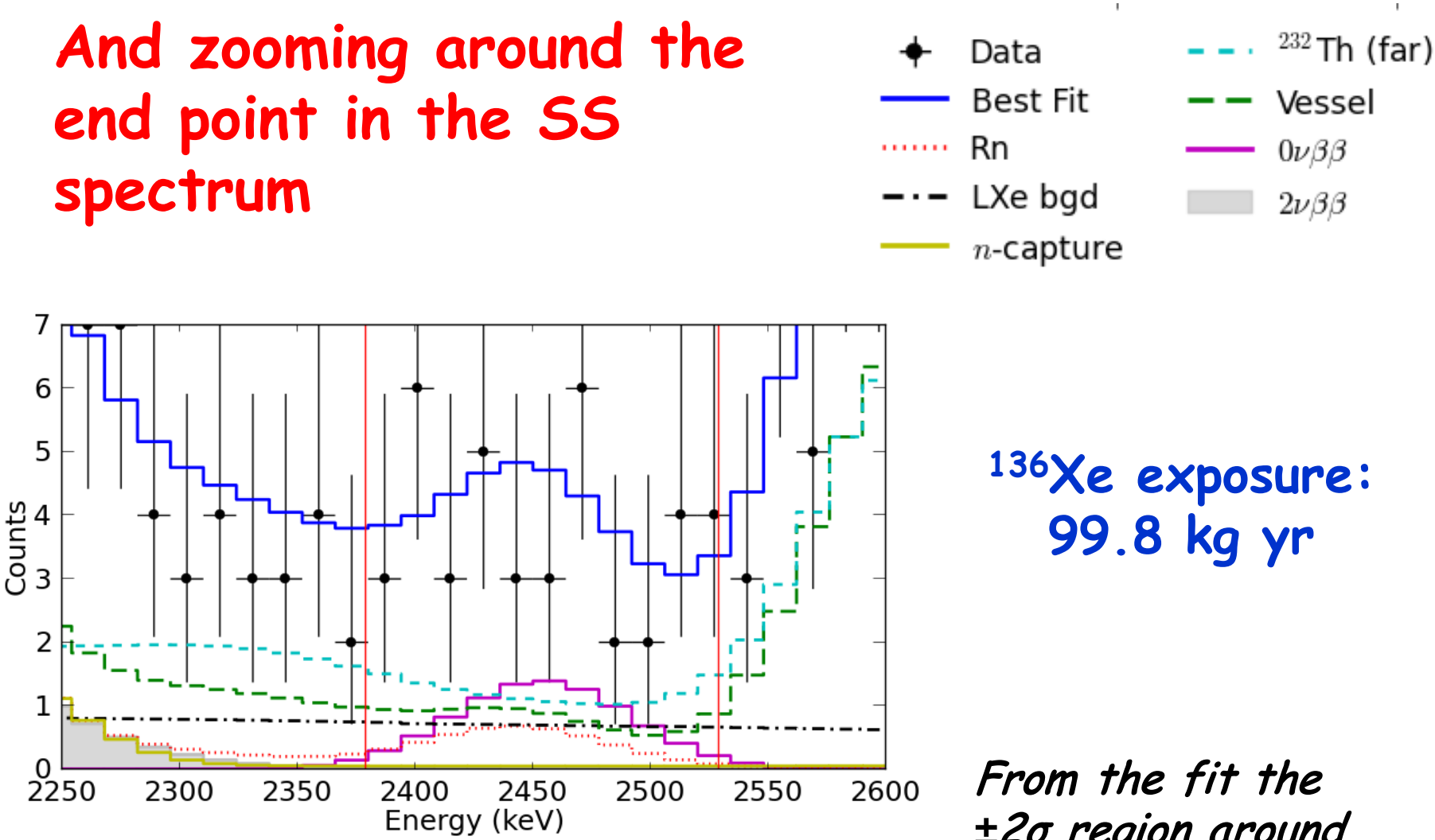
Nuclide	$T_{1/2}^{2\nu\beta\beta} \pm$ stat $\pm$ sys [y]	rel. uncert. [%]	$G^{2\nu}$ [10^{-21} y^{-1}]	$M^{2\nu}$ [MeV^{-1}]	rel. uncert. [%]	Experiment (year)
^{136}Xe	$2.165 \pm 0.016 \pm 0.059 \cdot 10^{21}$	± 2.83	1433	0.0218	± 1.4	EXO-200 (this work)
^{76}Ge	$1.84^{+0.09+0.11}_{-0.08-0.06} \cdot 10^{21}$	$^{+7.7}_{-5.4}$	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	[illegible]	NEMO-3 [41] (2010)
^{48}Ca	$4.4^{+0.5}_{-0.4} \pm 0.4 \cdot 10^{19}$	$^{+14.6}_{-12.9}$	15550	0.0444	$^{+7.3}_{-6.4}$	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	$9.11^{+0.25}_{-0.22} \pm 0.63 \cdot 10^{18}$	[illegible]	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)

We can do this because we have a homogeneous TPC!

Simultaneous fit to energy and standoff distance for SS and MS



And zooming around the end point in the SS spectrum



^{136}Xe exposure: 99.8 kg yr

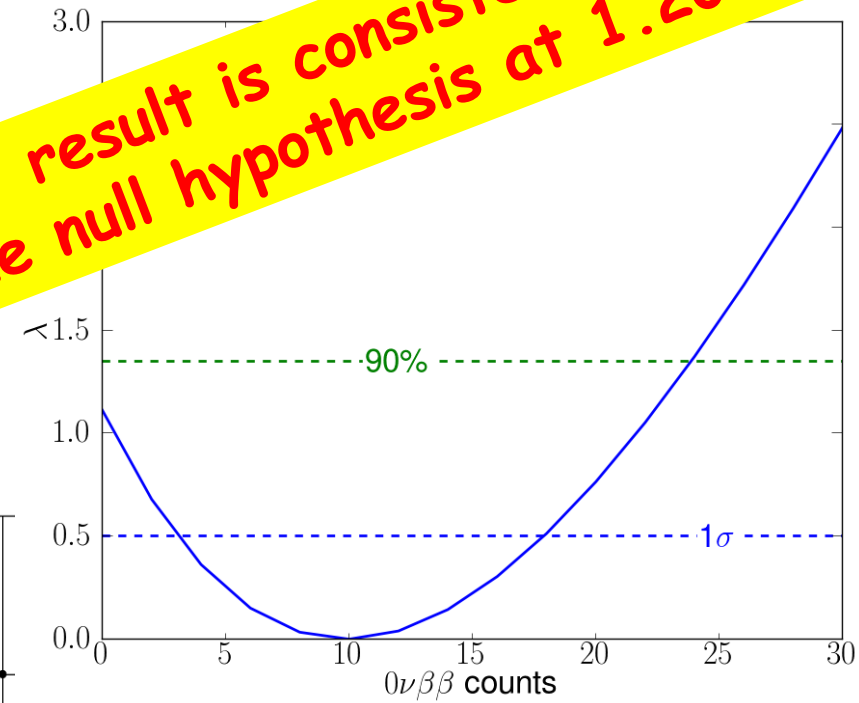
From the fit the ±2σ region around the end point includes the backgrounds:

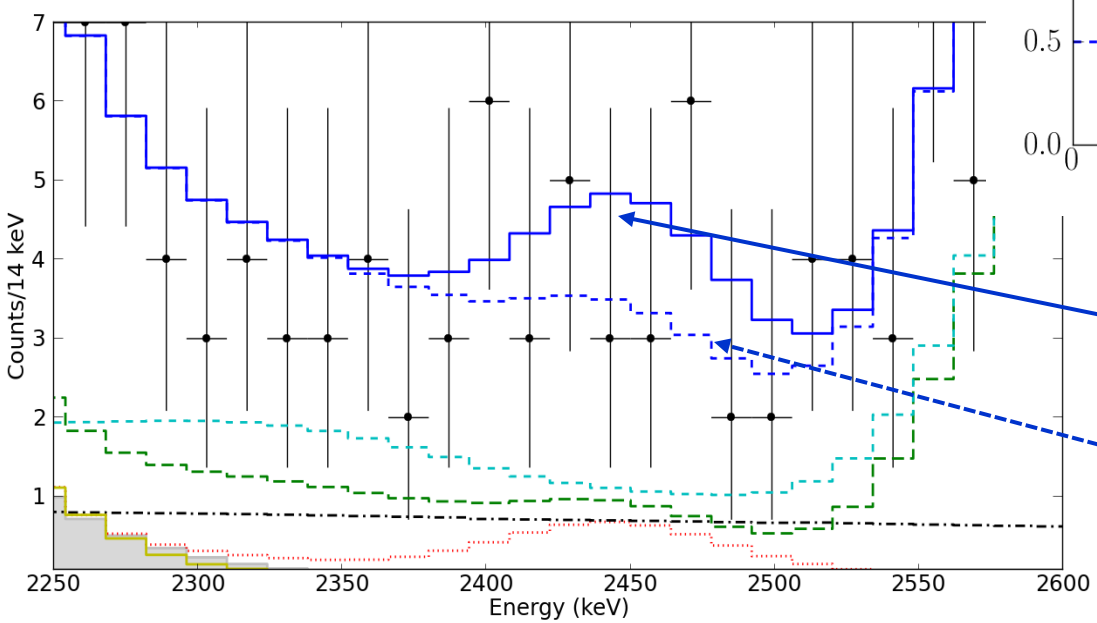
^{232}Th	**16.0**		
^{238}U	8.1		
^{137}Xe	7.0		
Total	31.1±1.8(stat)±3.3(syst)	$(1.7\pm0.2)\cdot10^{-3}$ keV^{-1} kg^{-1} yr^{-1}	~60 cnts/(2yr ±2σ ROI 140kg)

…and also a component from the 0νββ decay

Fit components	
Backgrounds	31.1
0νββ decay	9.9
Total	41.0

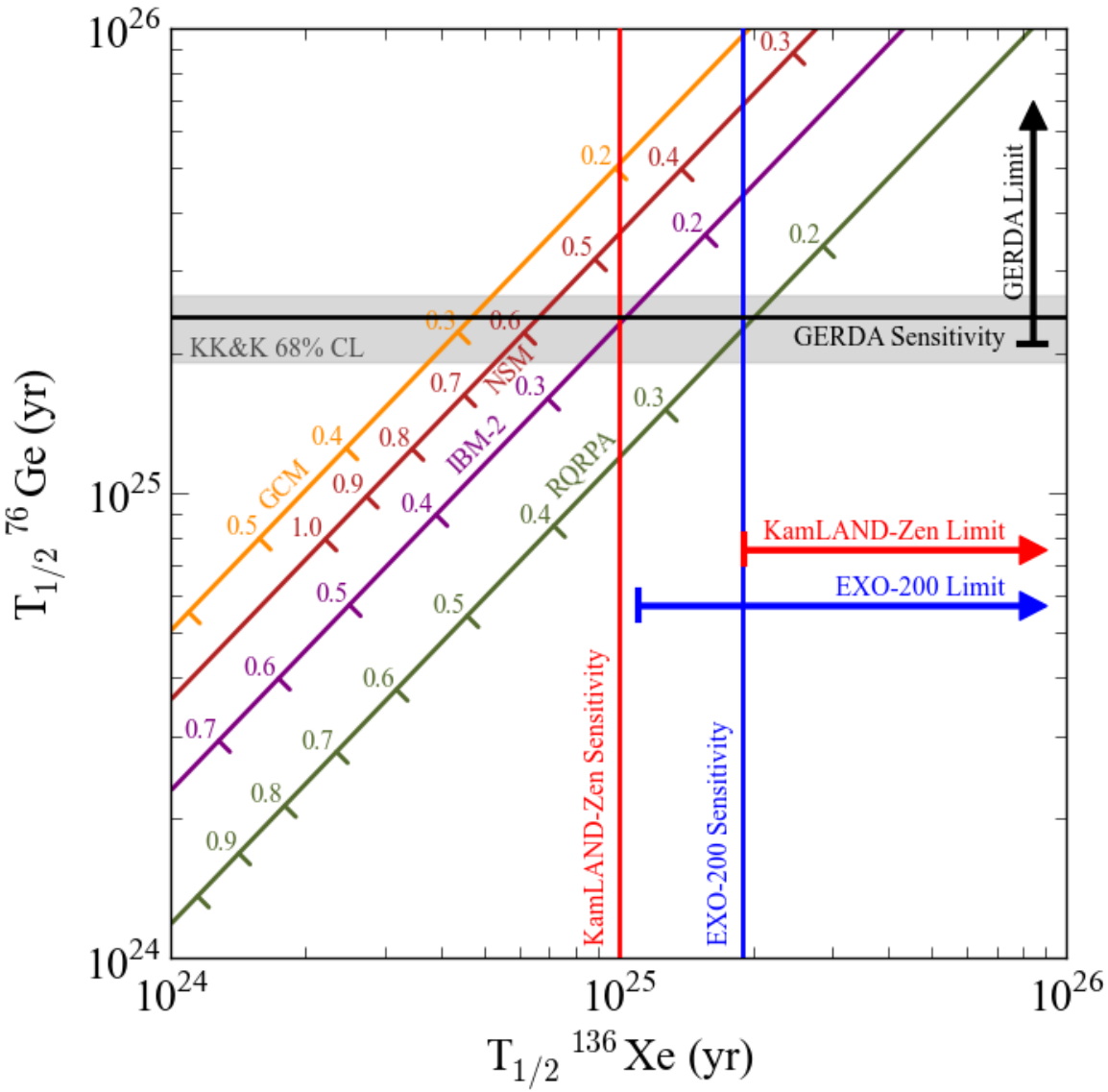
But result is consistent with the null hypothesis at 1.2σ level





Fit with 0νββ decay

Fit without 0νββ decay



$T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25}$ yr (90%CL)

$\langle m_\nu \rangle$ < 190 – 450 meV

Average $T_{1/2}^{0\nu\beta\beta}$ sensitivity:

$1.9 \cdot 10^{25}$ yr

J.B.Albert et al. (EXO-200)
arXiv:1402.6956 (27 Feb 2014)

A. Gando et al. (KamLAND-ZEN)
PRL 110 (2013) 062502

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

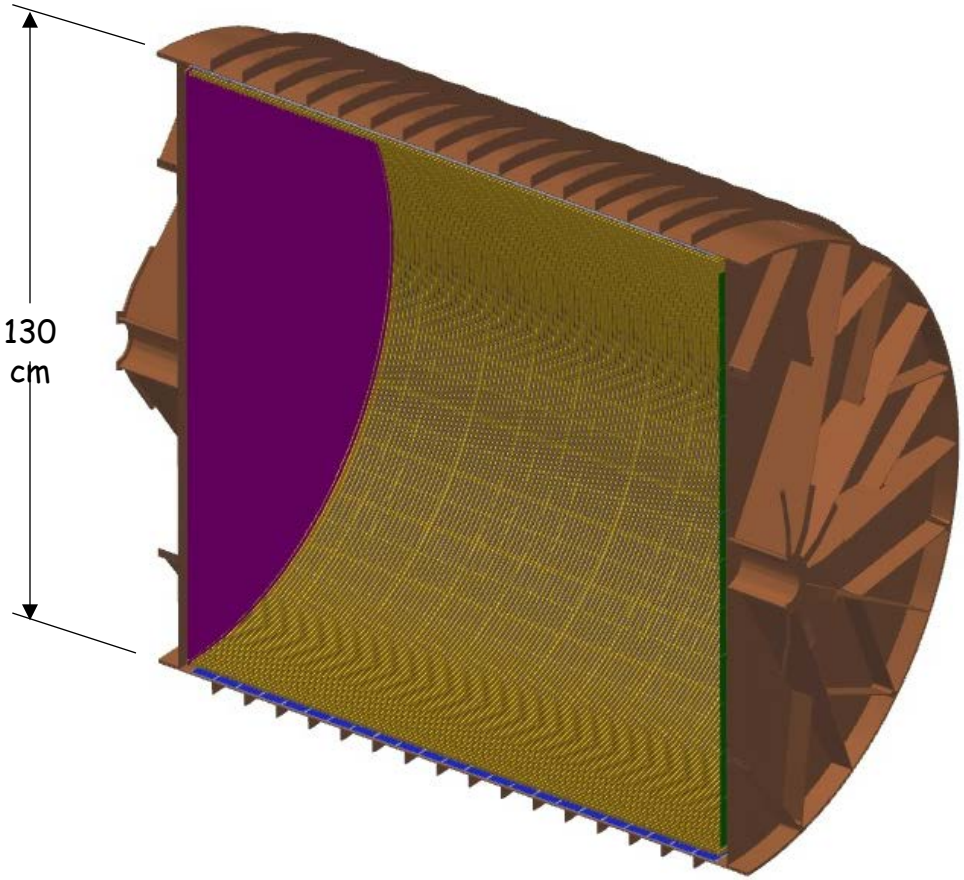
As EXO-200 continues data taking a new collaboration

nEXO

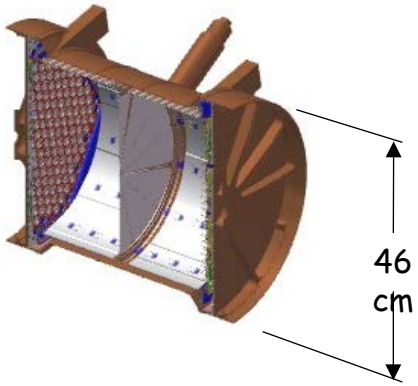
is pursuing the next phase of the search

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



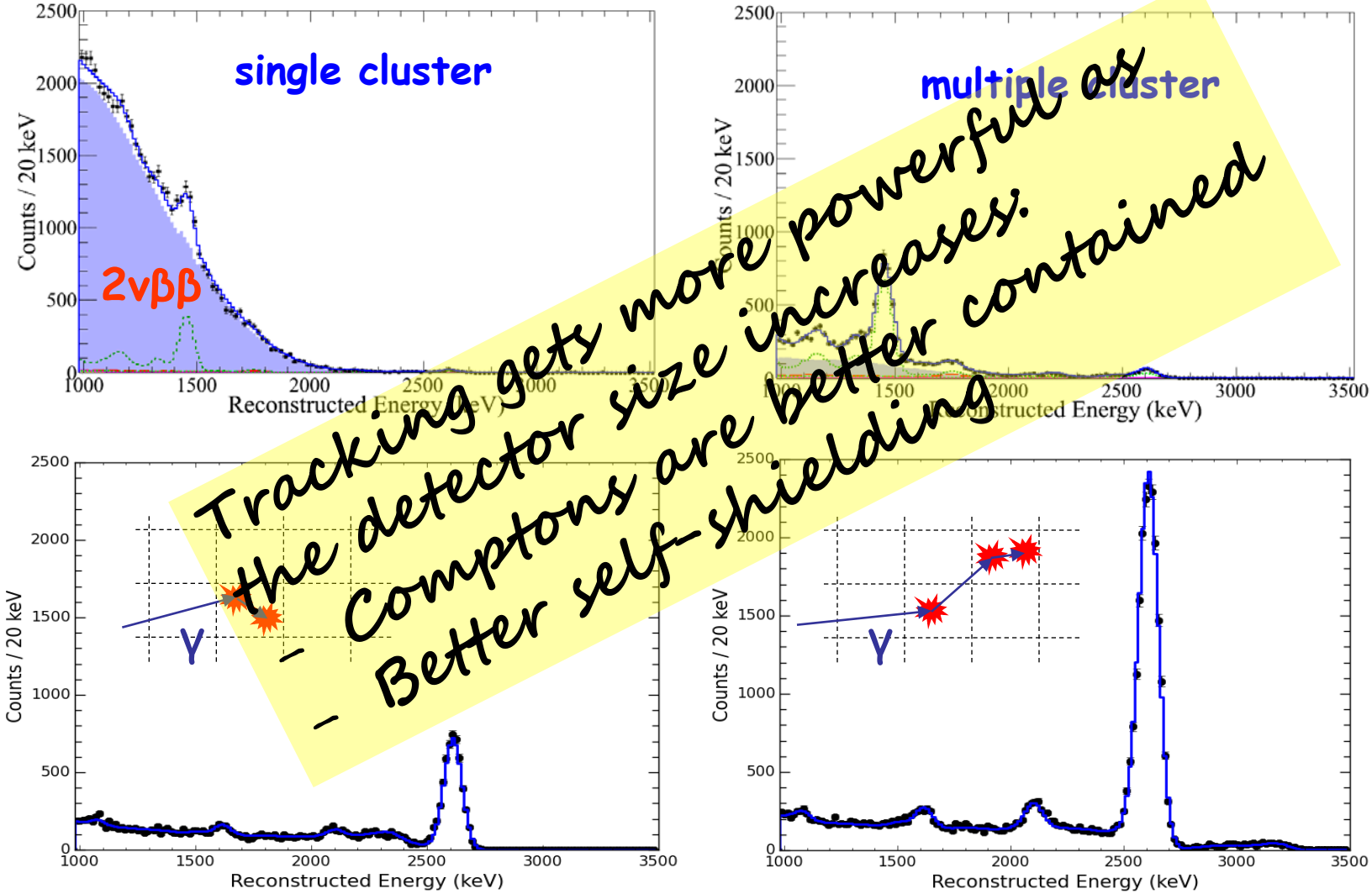
➔ *A unique combination of conservative and aggressive design with important upgrade paths as desirable for a large experiment*



Tracking:
an essential tool to identify and suppress backgrounds

Low background data

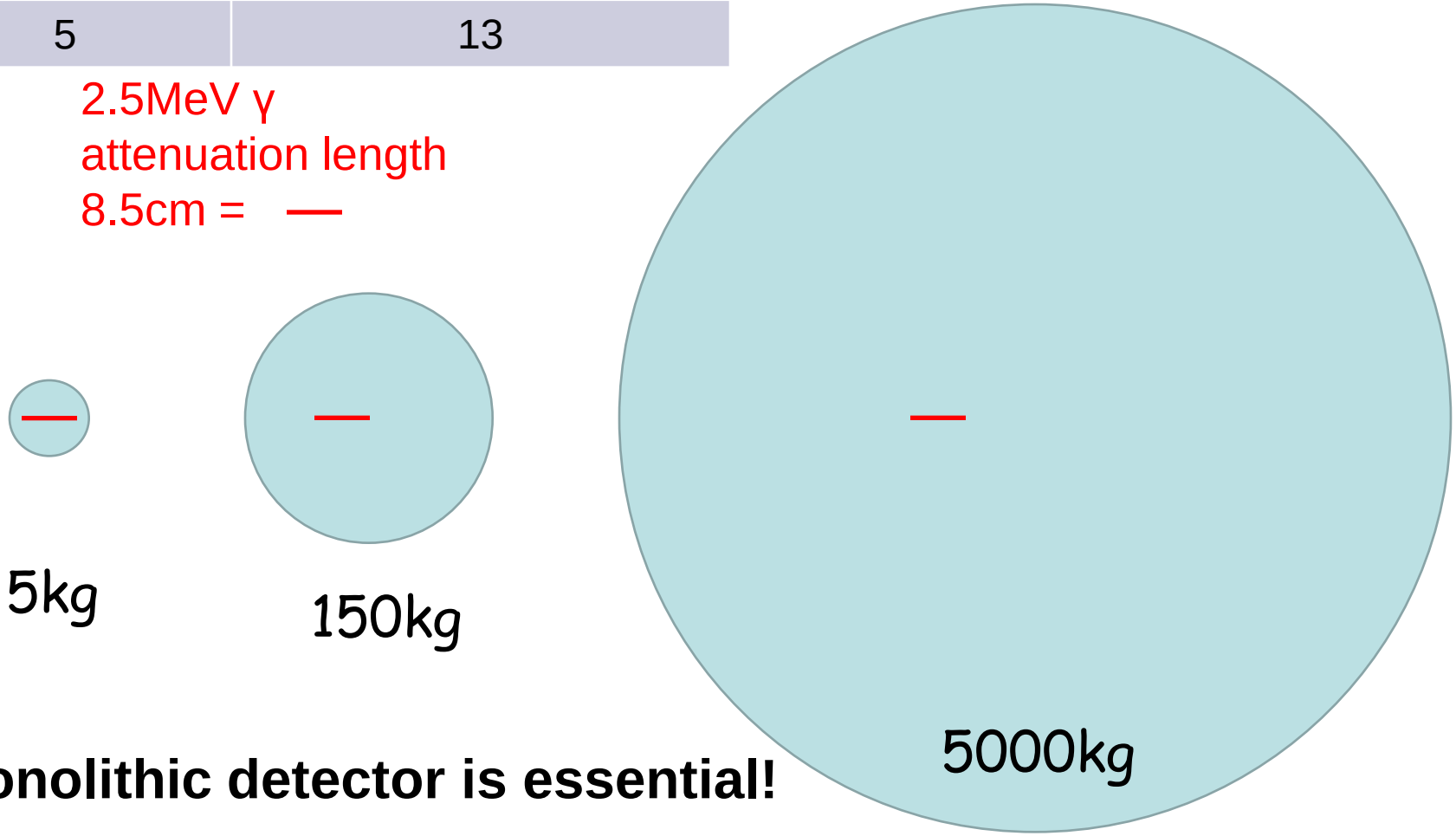
^{228}Th calibration source



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

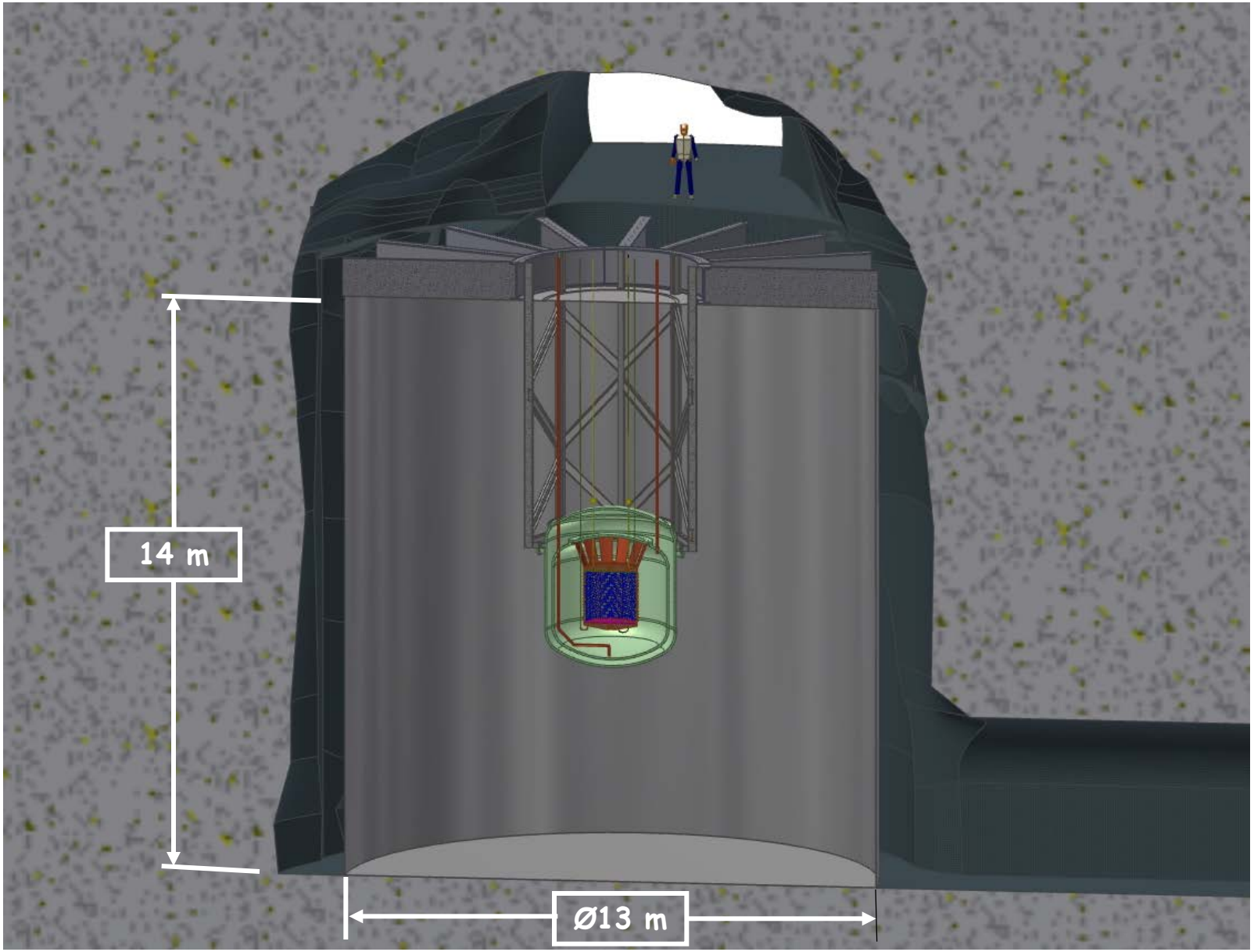
LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

2.5MeV γ
attenuation length
8.5cm =

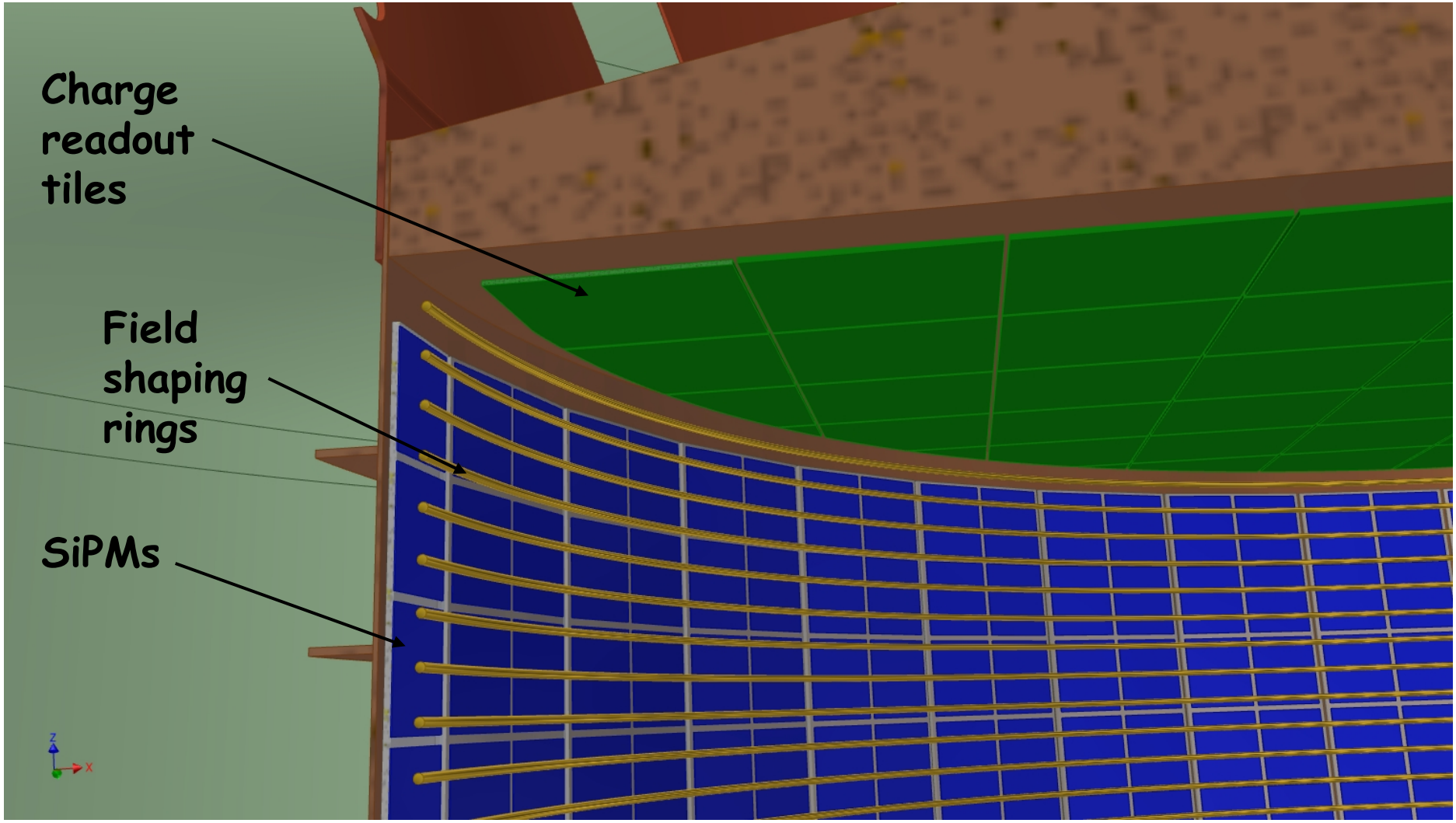


Monolithic detector is essential!

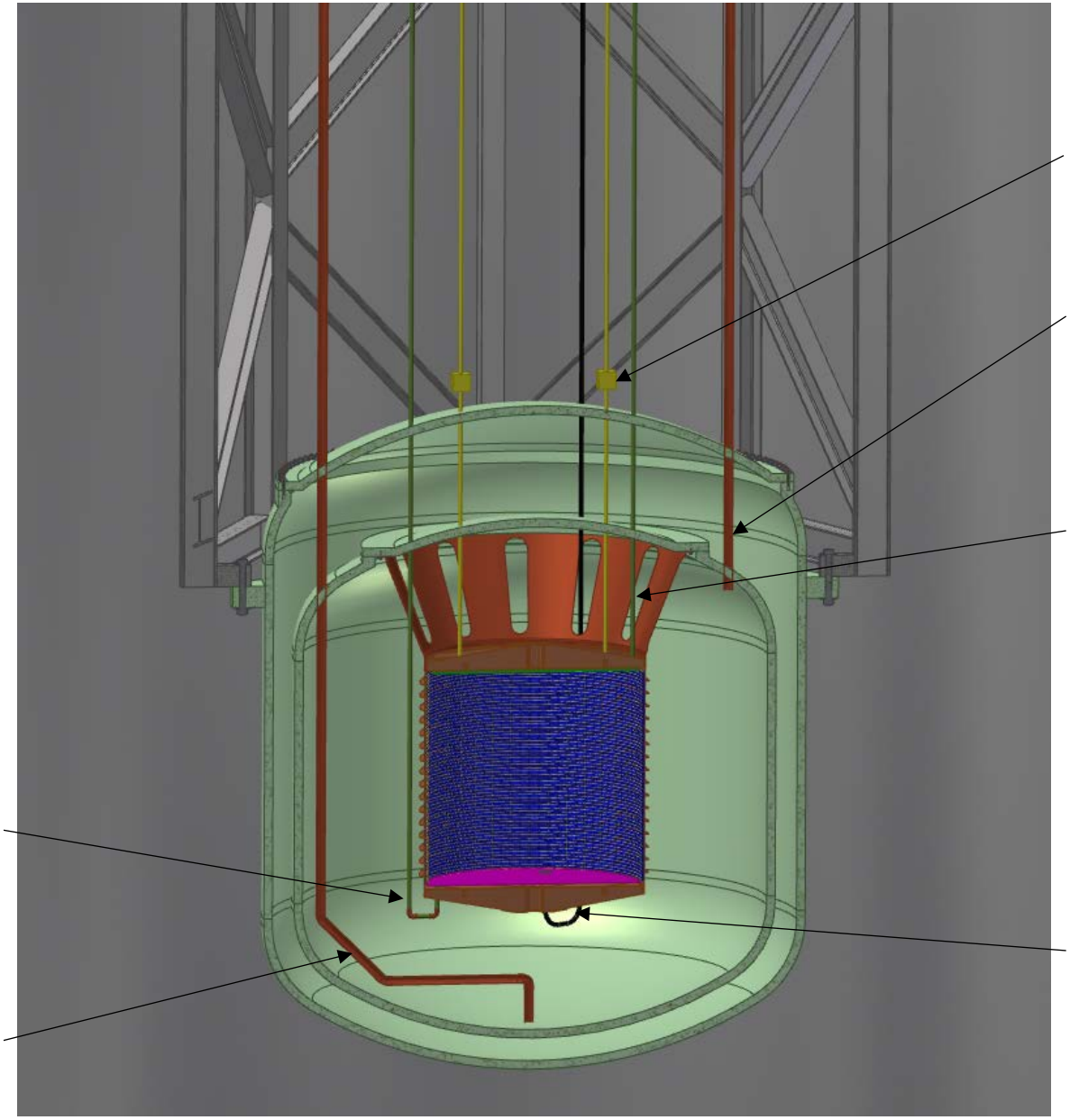
Preliminary artist view of nEXO in the SNOlab Cryopit



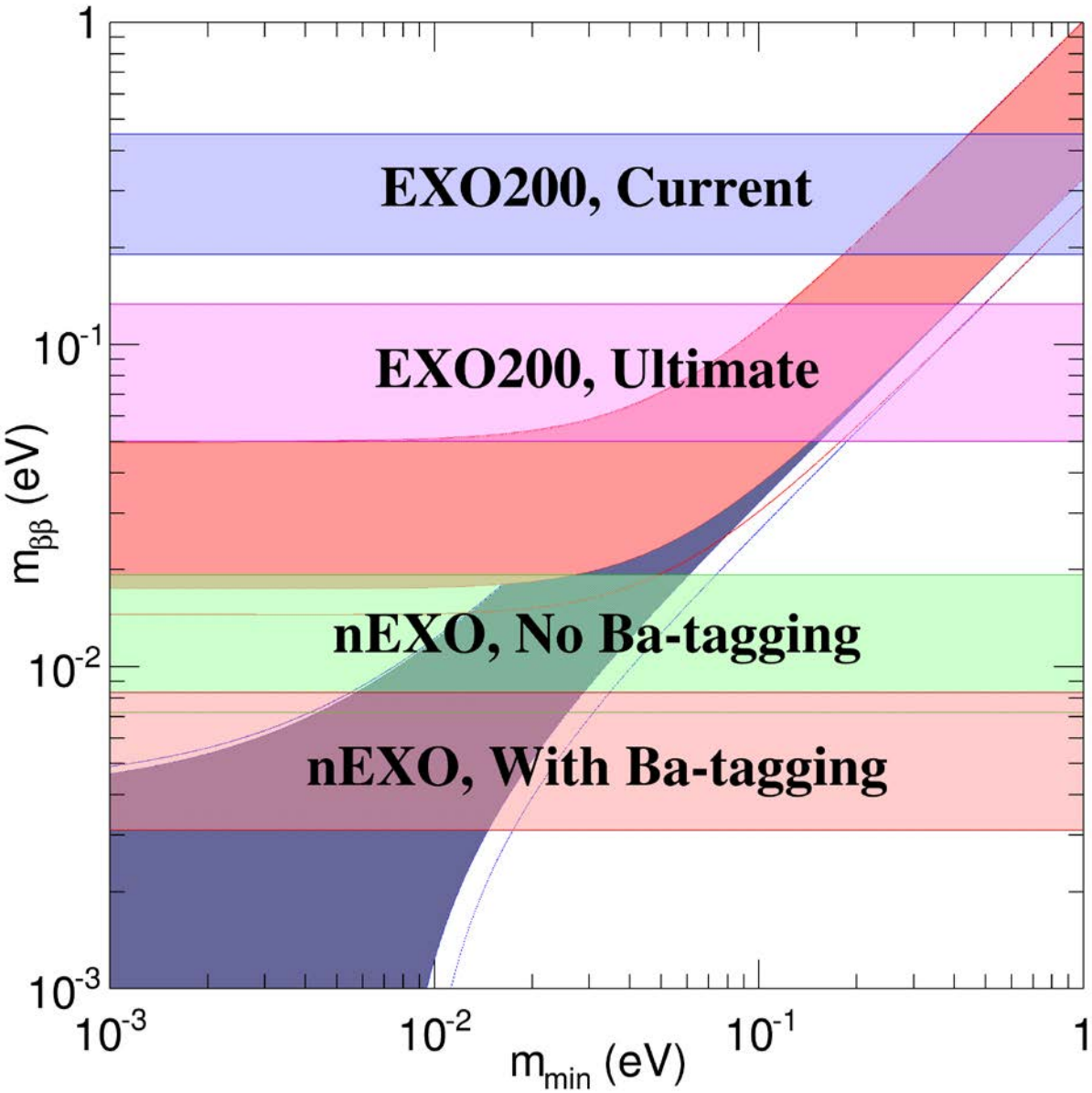
Close-up of the field shaping rings, anode readout tiles and SIPMs



Detail of the cryostat concept



Projected nEXO sensitivity



Summary

- The TPC, using LXe as medium has also become a leading tool in the search for ββ decay
- EXO-200 discovered the 2νββ decay in ^{136}Xe:
  - the rarest 2ν decay and now also
  - the most accurately measured
- EXO-200 0νββ sensitivity is now $1.9 \cdot 10^{25}$ yr
  ➔ 10^{15} x the age of the Universe!
- No signal observed, Majorana masses <~0.3eV
- A much larger and more powerful LXe TPC will get us to the next stage of this quest!
- Thanks Dave!

And thanks to the many people who made this a success!

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