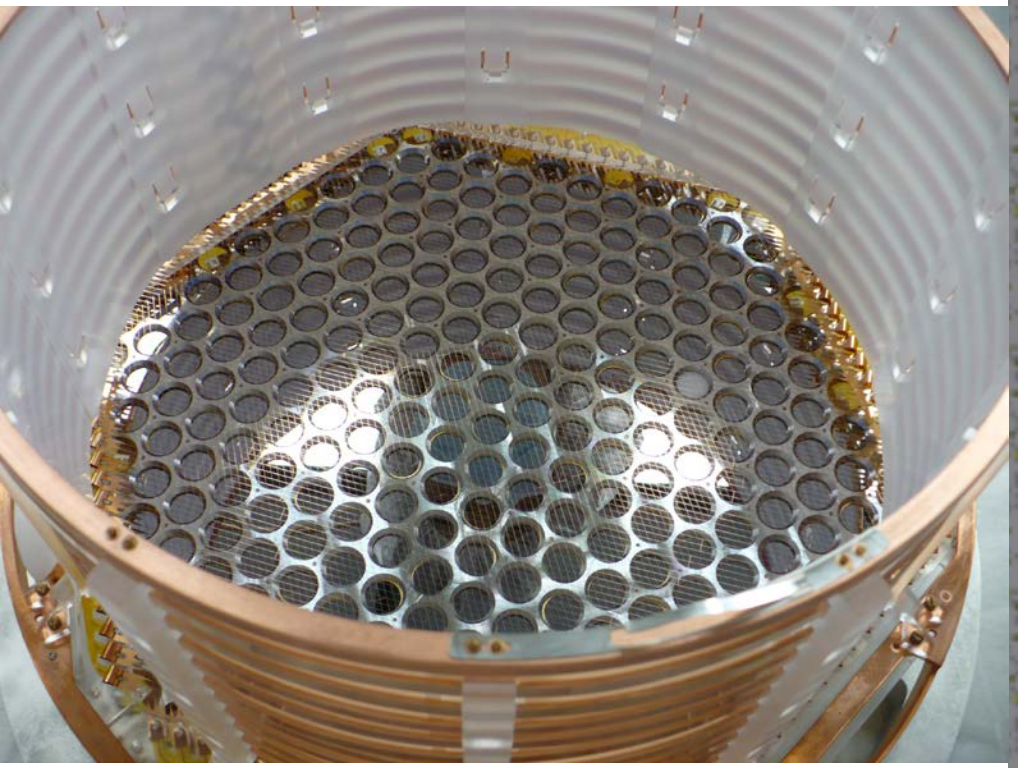
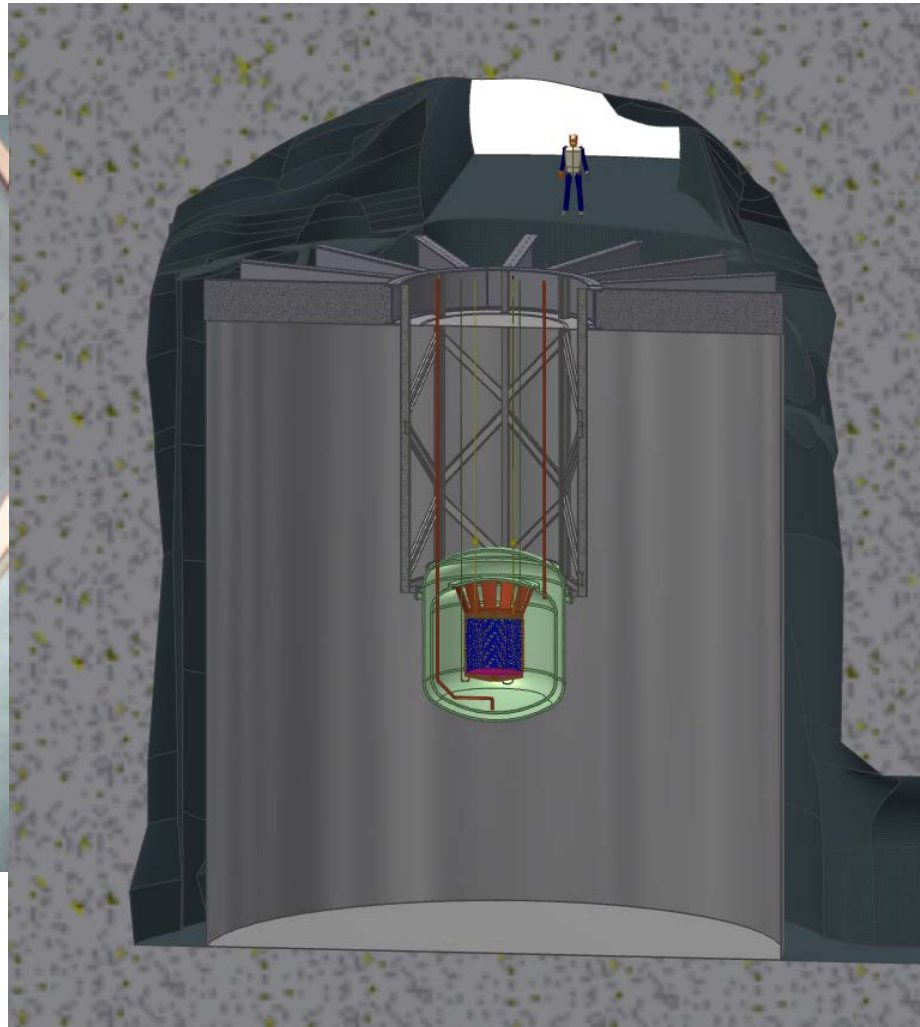
LXe TPCs for double-beta decay EXO-200, nEXO and beyond

Giorgio Gratta
Stanford University





In a nutshell…

EXO-200 was the first experiment designed to search for $0\nu\beta\beta$ decay using a homogeneous $L^{136}Xe$ TPC

EXO-200 was the first 100kg class detector to operate

EXO-200 Phase 1 took data from May 2011 to Feb 2014

- Discovery of $2\nu\beta\beta$ decay in ^{136}Xe
- Very competitive search for $0\nu\beta\beta$ decay

2.5 more year of running (EXO-200 Phase 2) will increase the $T^{1/2}_{0\nu\beta\beta}$ reach by ~3x

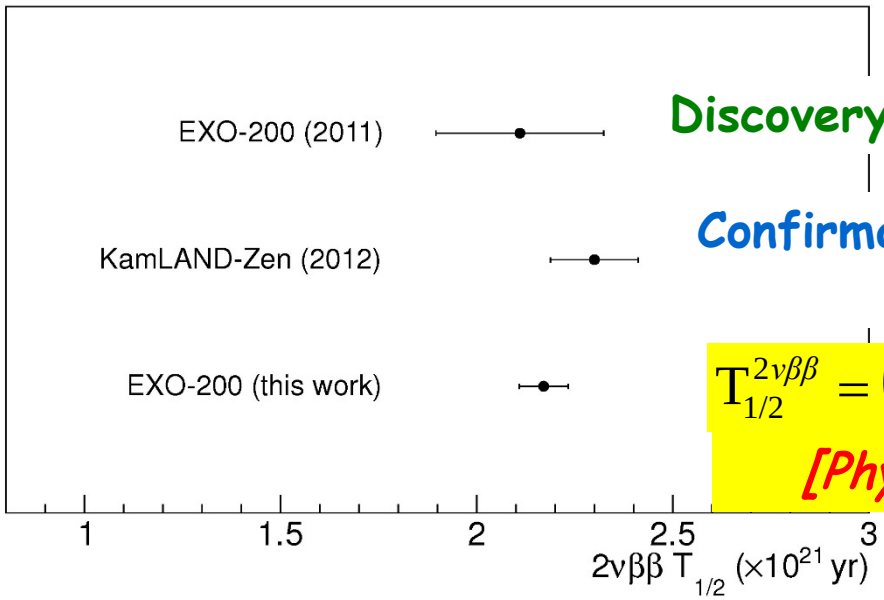
EXO-200 detector performance at or better than proposal

Detector optimization very different from that of LXe Dark Matter experiments

Scaling laws clearly favorable for this technique that with nEXO (5 ton) will reach its full potential

The use of ^{136}Xe in a ton-scale experiment potentially enables a very powerful program beyond nEXO (phase 1)

2νββ decay in EXO-200: the most accurate measurement and the rarest mode!



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

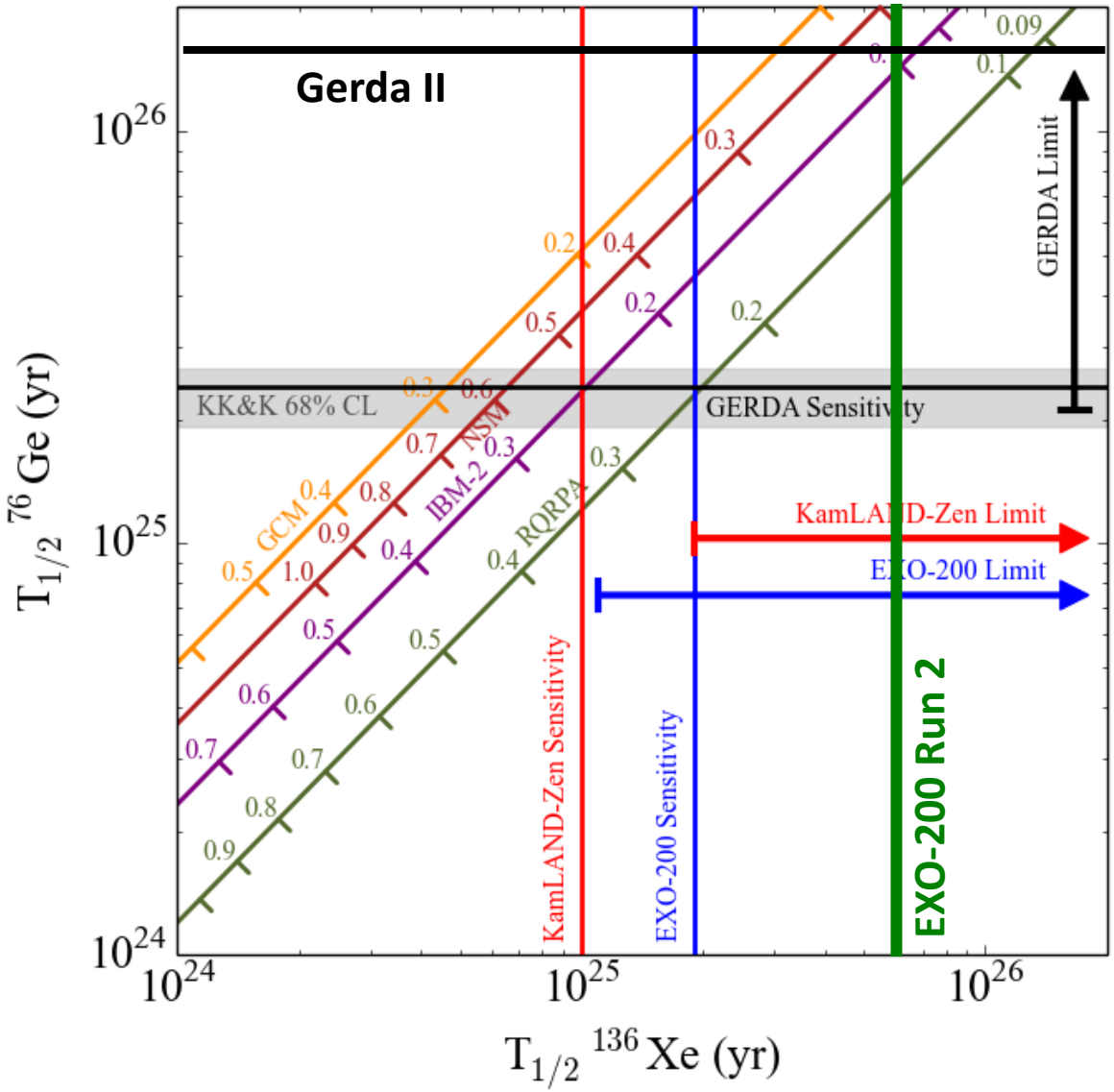
Confirmation by KamLAND-Zen *[PRC 85, 045504 (2012)]*

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

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

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)

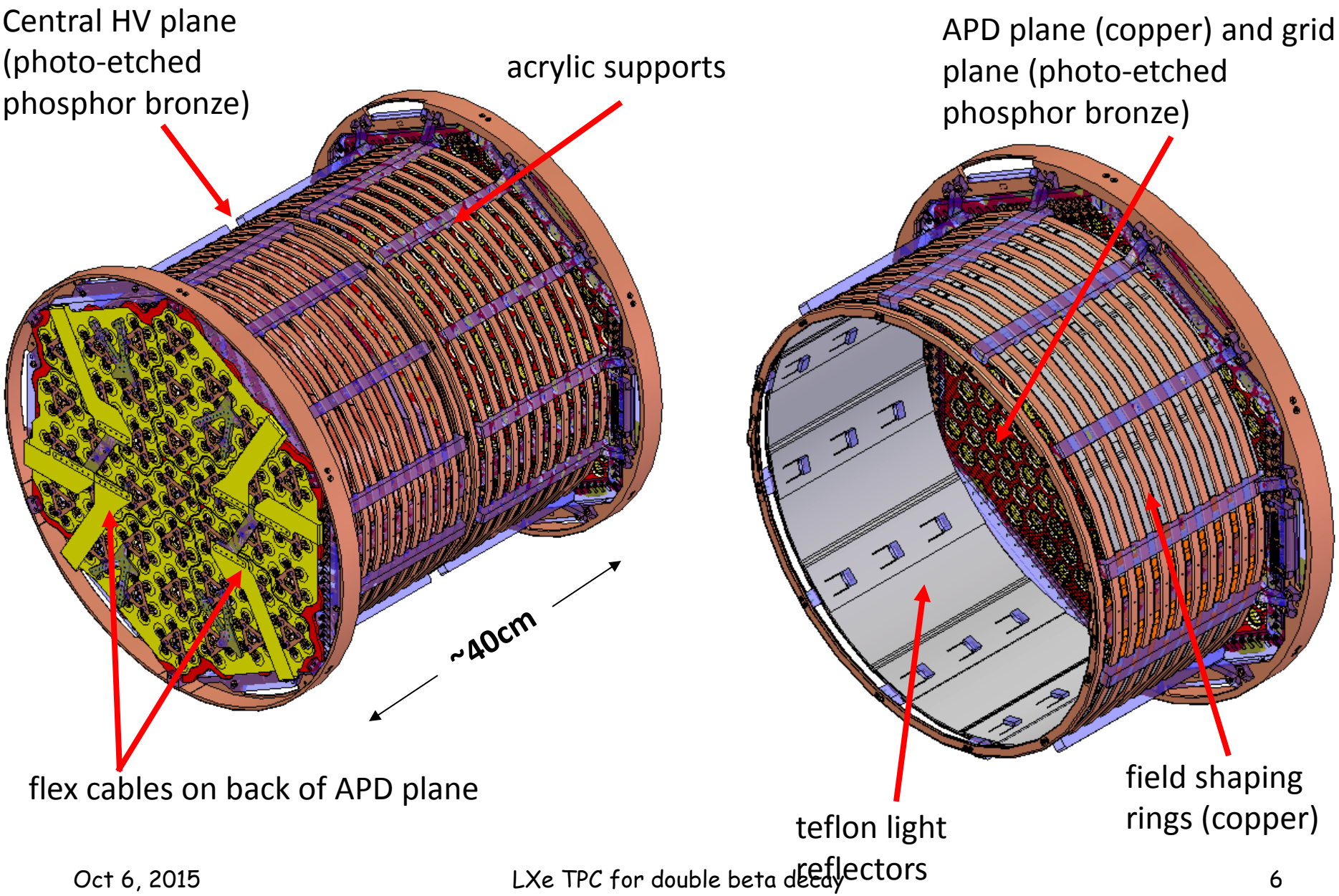
0νββ results and predictions (EXO-200)



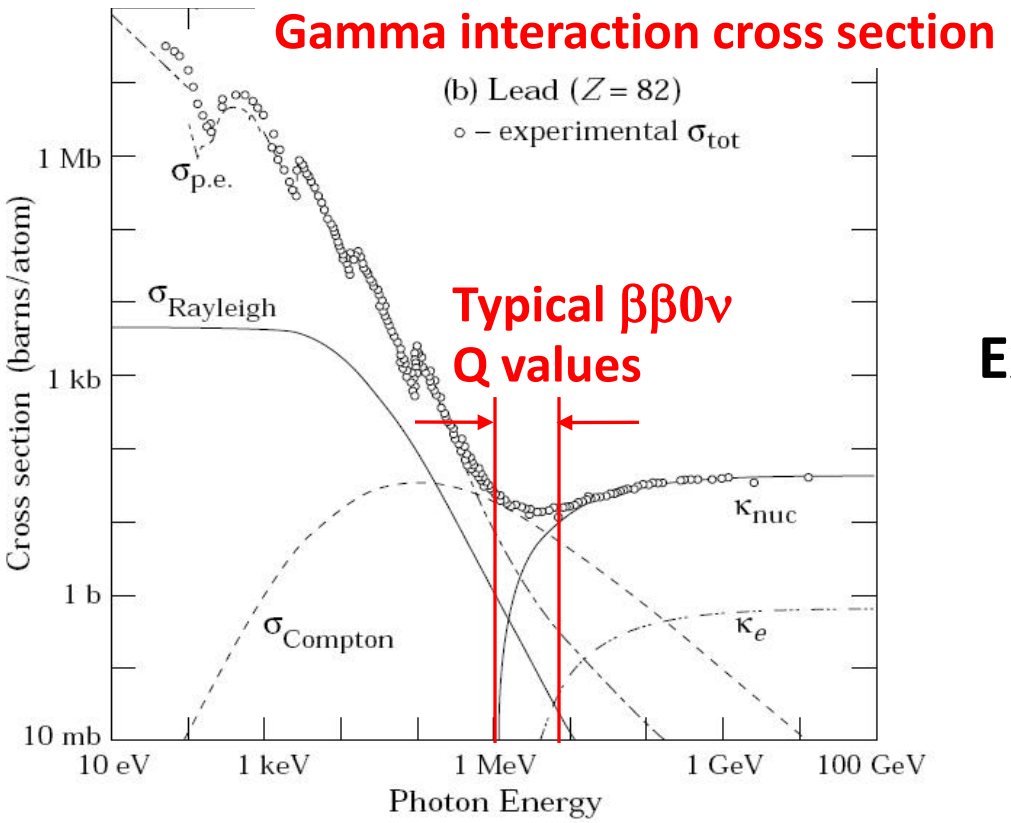
Basic detector design principles

- Nothing but LXe in the bulk of the detector
- Use enriched ^{136}Xe
- Efficiently hug the LXe to optimally use ^{enr}Xe
- Ultra low background everything
- Long electron lifetime in LXe (somehow in conflict with above)
- Readout both scintillation and ionization
  (with ultra-low background components)
  - Energy resolution
  - e/γ vs α discrimination
- Tracking, even if the 2νββ decay looks like a point in LXe
- Along with the usual hermetic and low background
  shielding and deep underground location

EXO-200 LXe TPC field cage & readout planes



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

Massive effort on material radioactive qualification using:

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

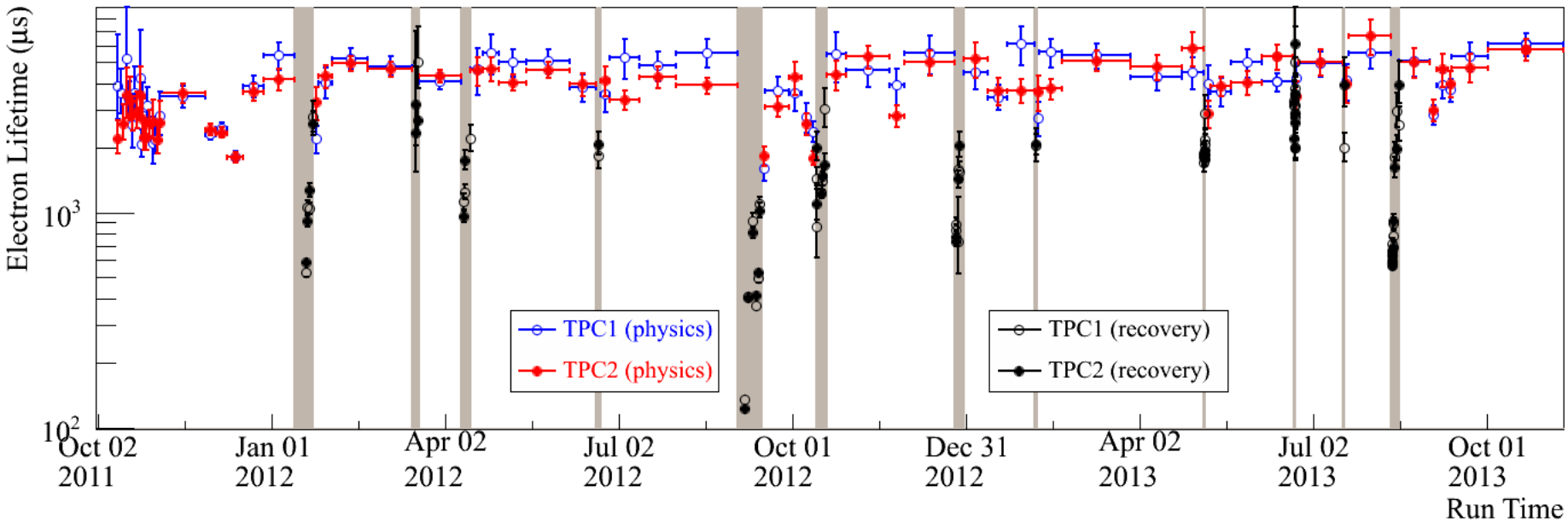
At present the database of characterized materials includes >300 entries

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

This imposes huge constraints on the design of the detector

Xe purity is essential for good energy resolution

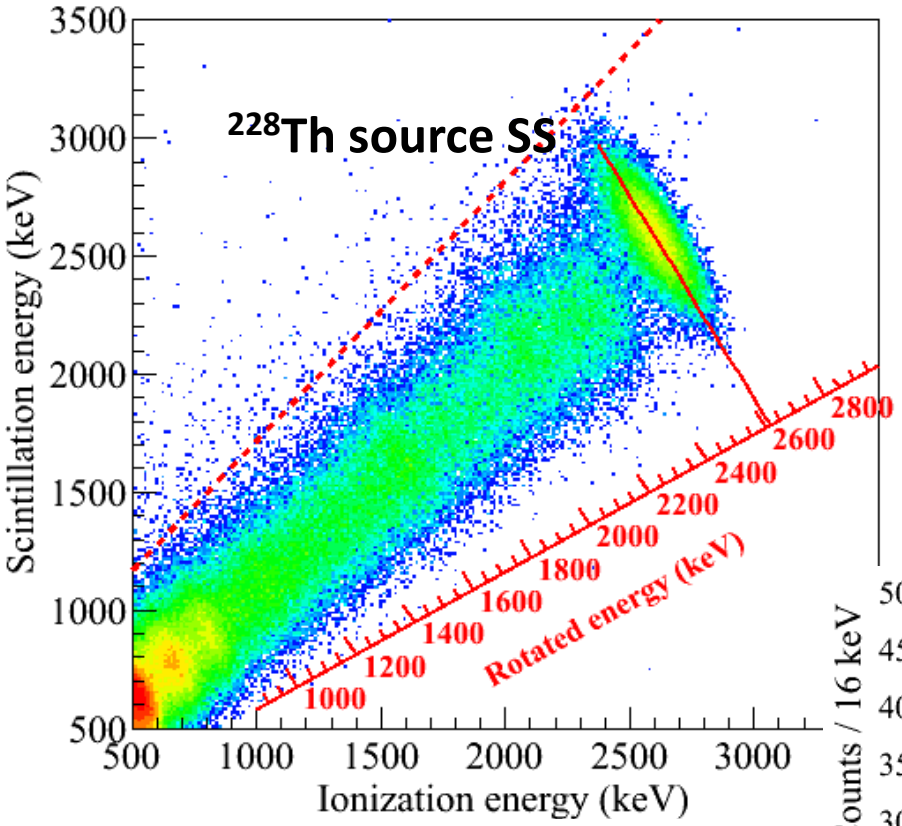


Xenon gas is forced through heated Zr getter by a custom ultraclean pump.

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***

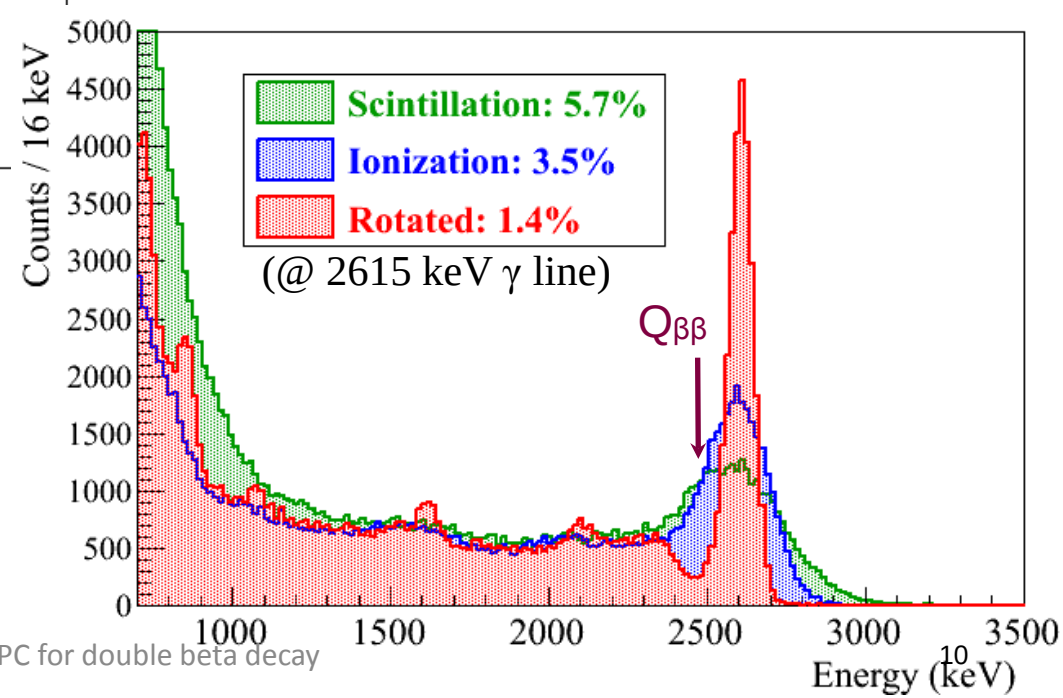
Combining Ionization and Scintillation in EXO-200



Anticorrelation between scintillation and ionization in LXe known since early EXO-200 R&D

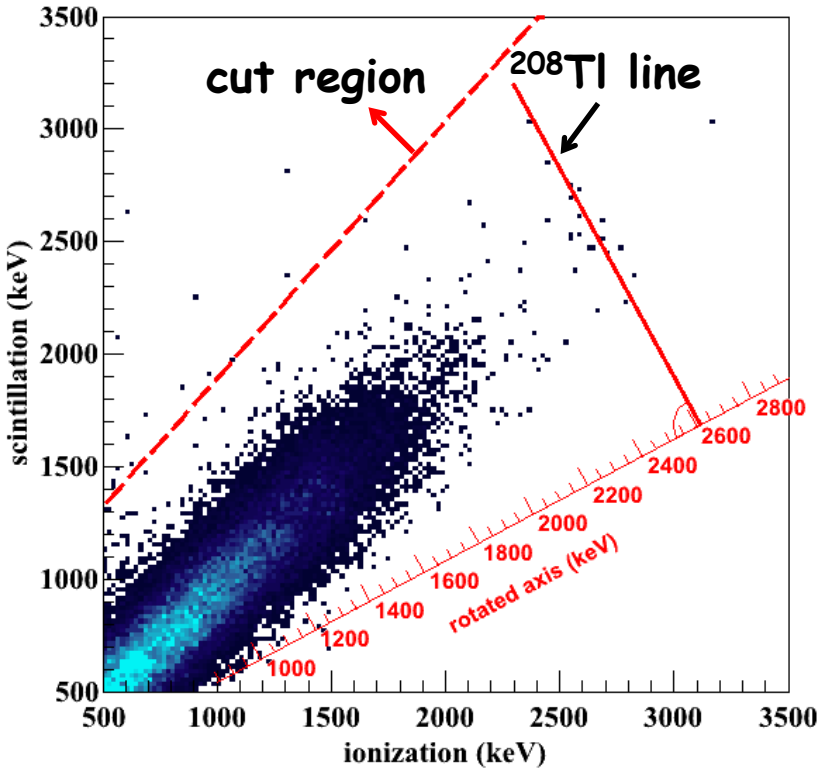
E.Conti et al. Phys Rev B 68 (2003) 054201

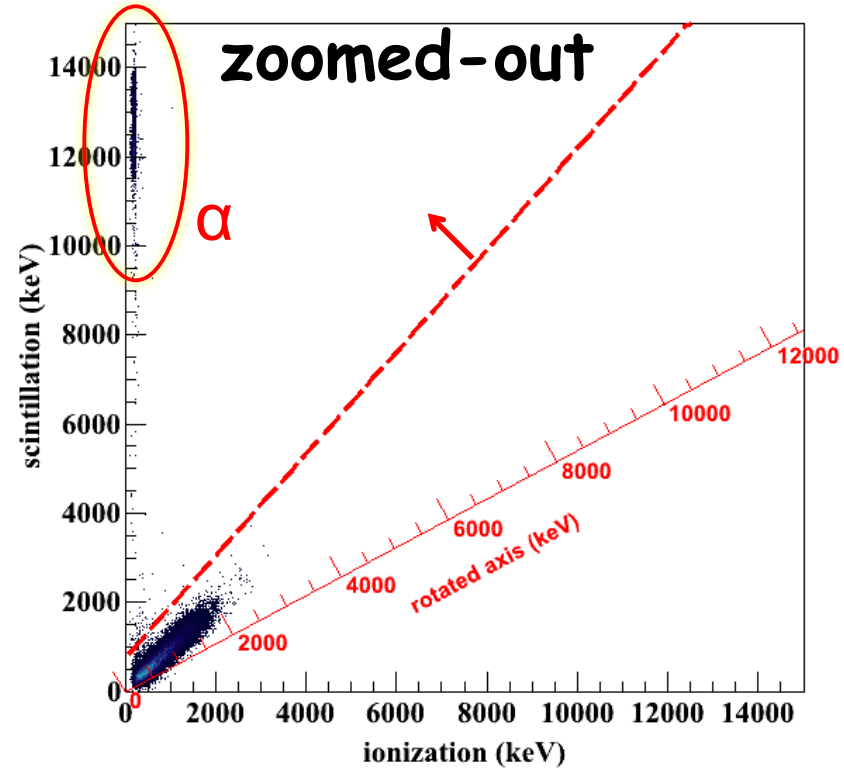
Design spec was 1.6% @2615keV



Rotation angle chosen to optimize energy resolution at 2615 keV

Low Background 2D SS Spectrum





Easy to tag and remove α's:

α : larger ionization density

→ more recombination

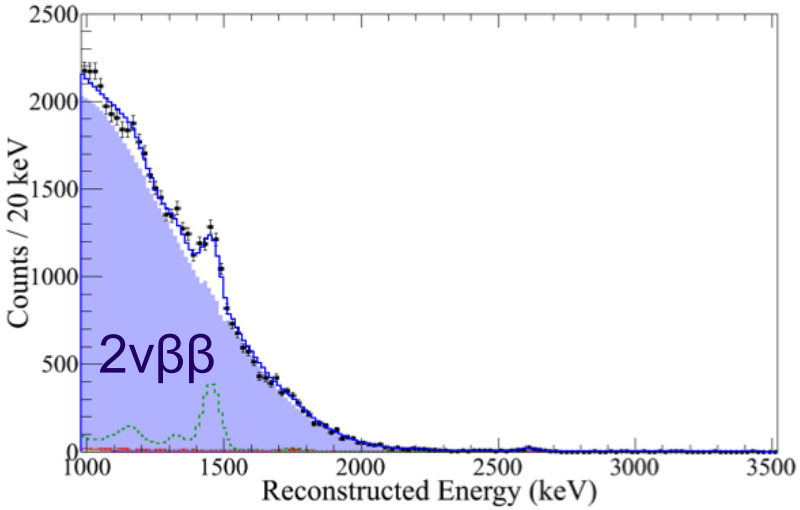
→ more scintillation light

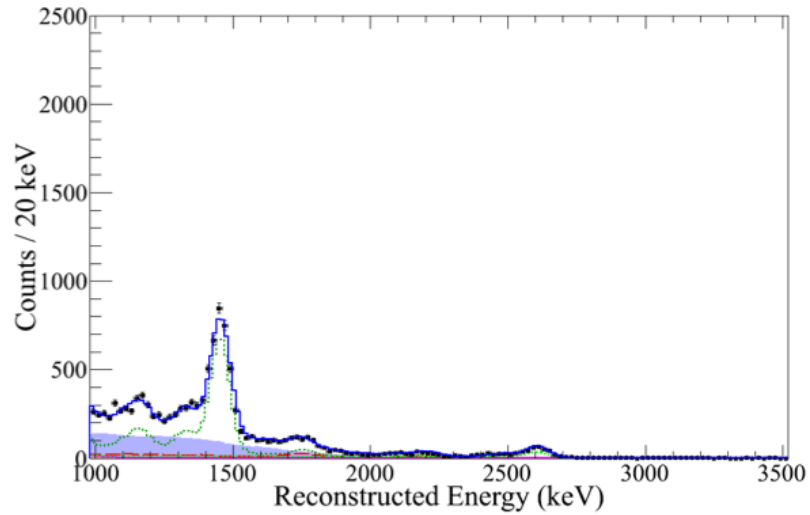
Event multiplicity and background discrimination

(example from EXO-200 real data)

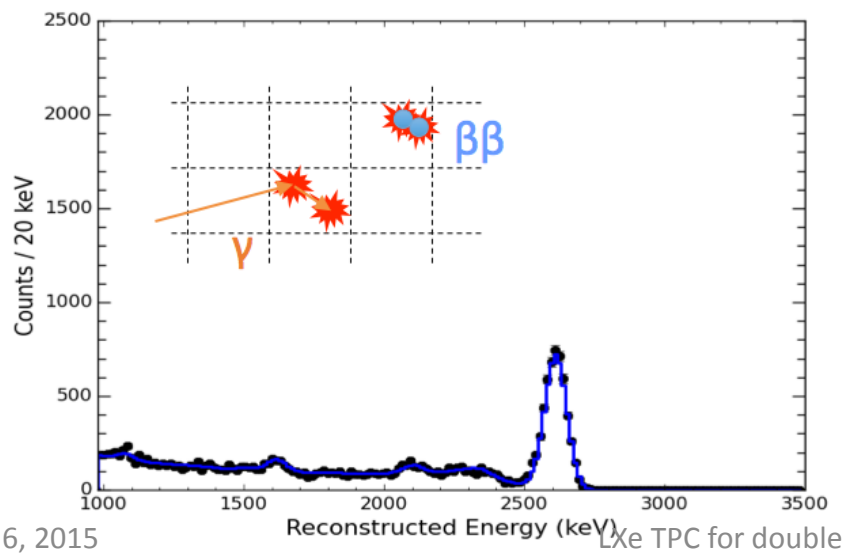
Single Site (SS) | **Multiple Site (MS)**

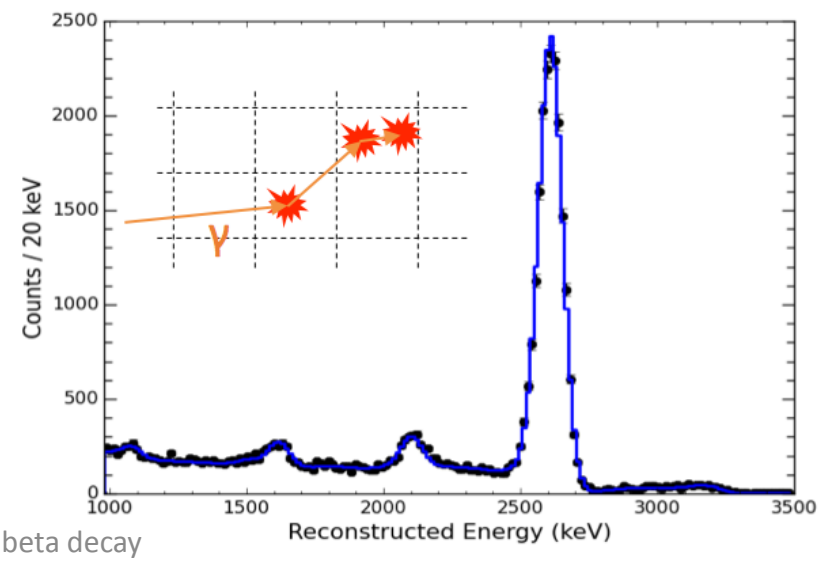
Low Background Data





^{228}Th Calibration Source





So, unlike many ββ decay experiments:

THIS IS NOT A PURE CALORIMETER

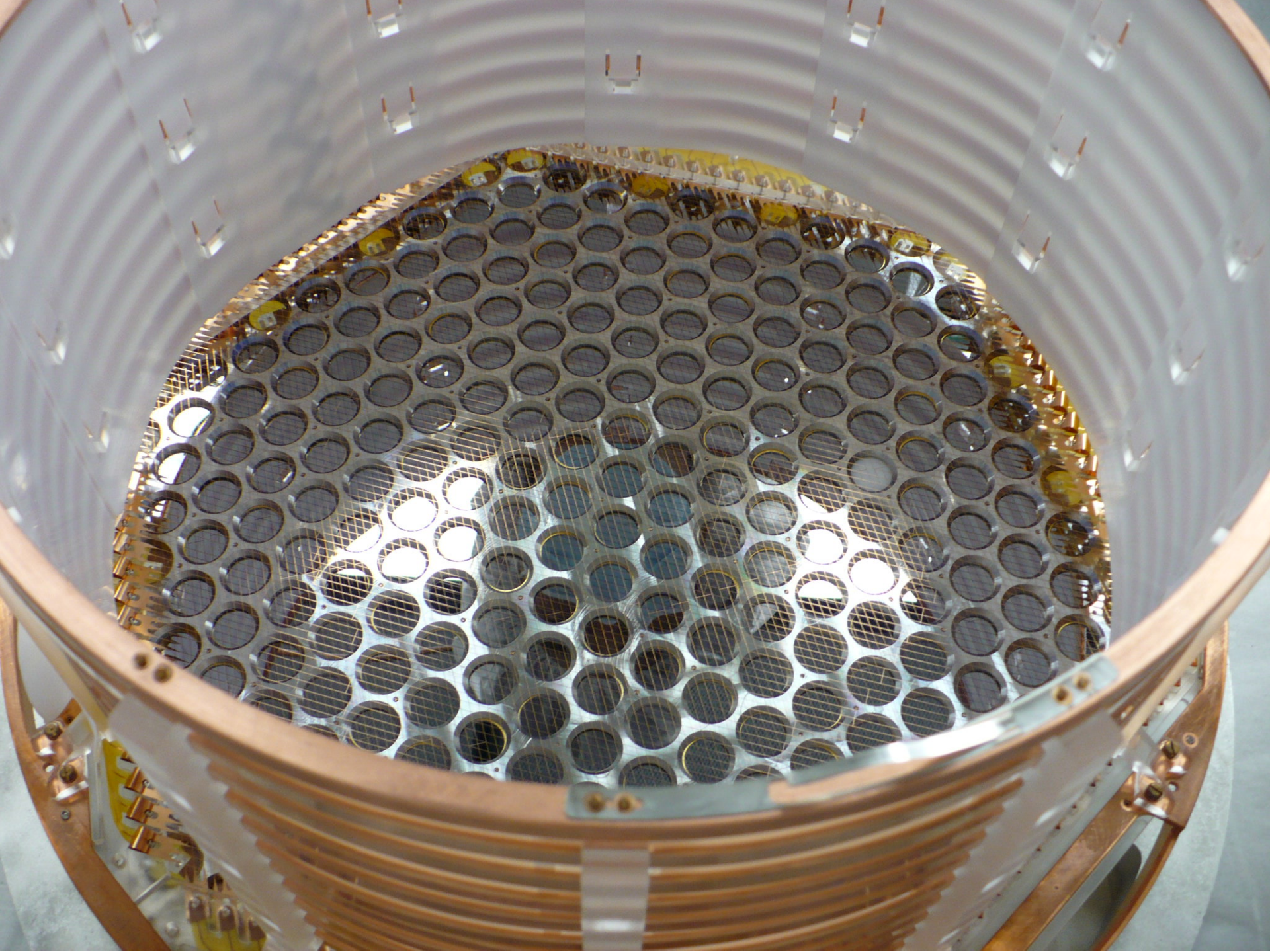
To think exclusively in terms of E resolution is misleading

The signal/background discrimination is based on four parameters:

1. **Energy measurement**
2. **Event multiplicity (SS/MS in EXO-200)**
3. **Distance from the TPC surface**
4. **Particle ID (α-electron)**

These two only work optimally for homogeneous detectors

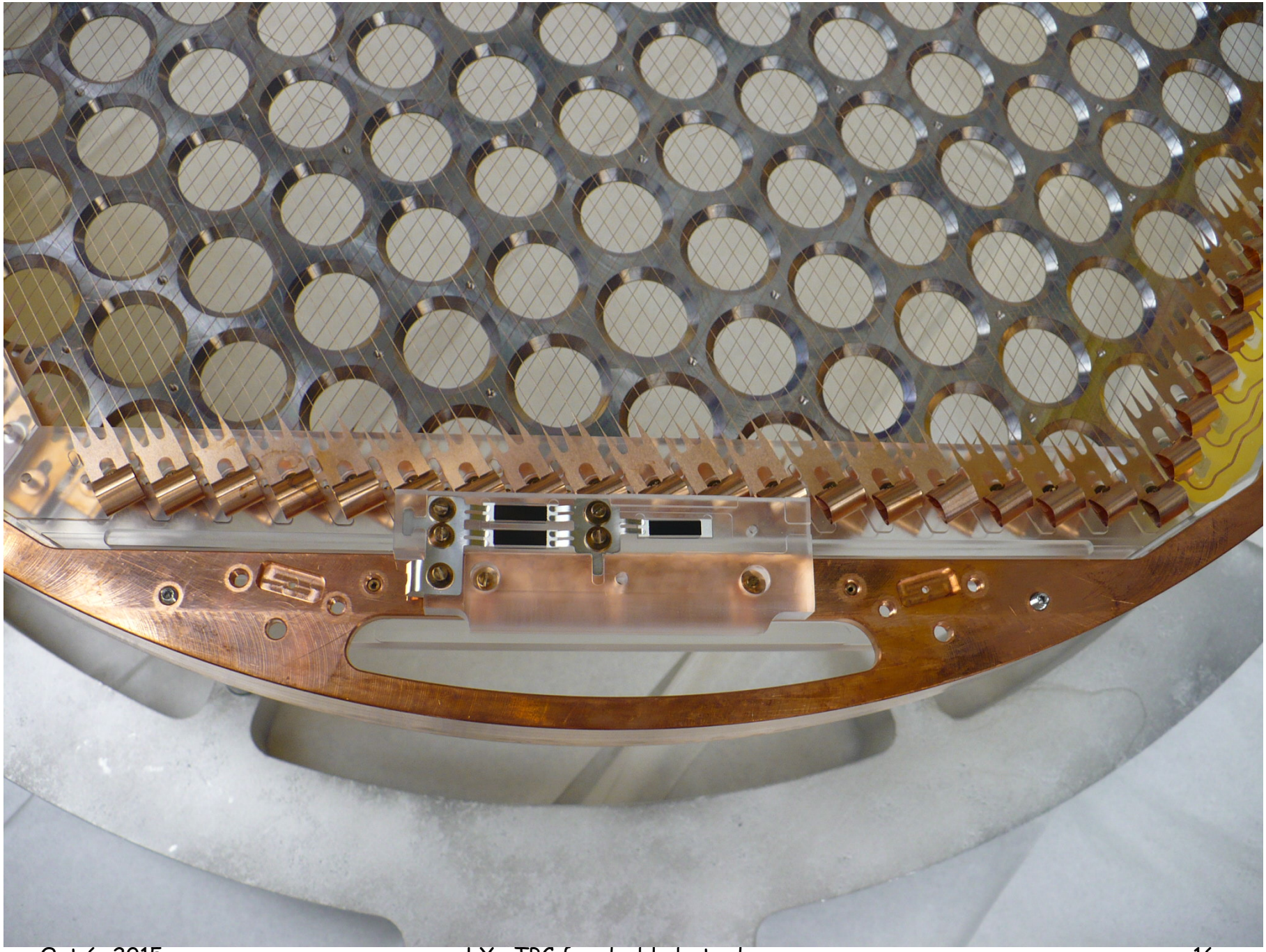
There is no rational reason to prefer the use of an "Energy ROI" over a "topology ROI" or a "topology ⊗ energy ROI". In fact, more independent axes provide a more powerful constraint on the signal.



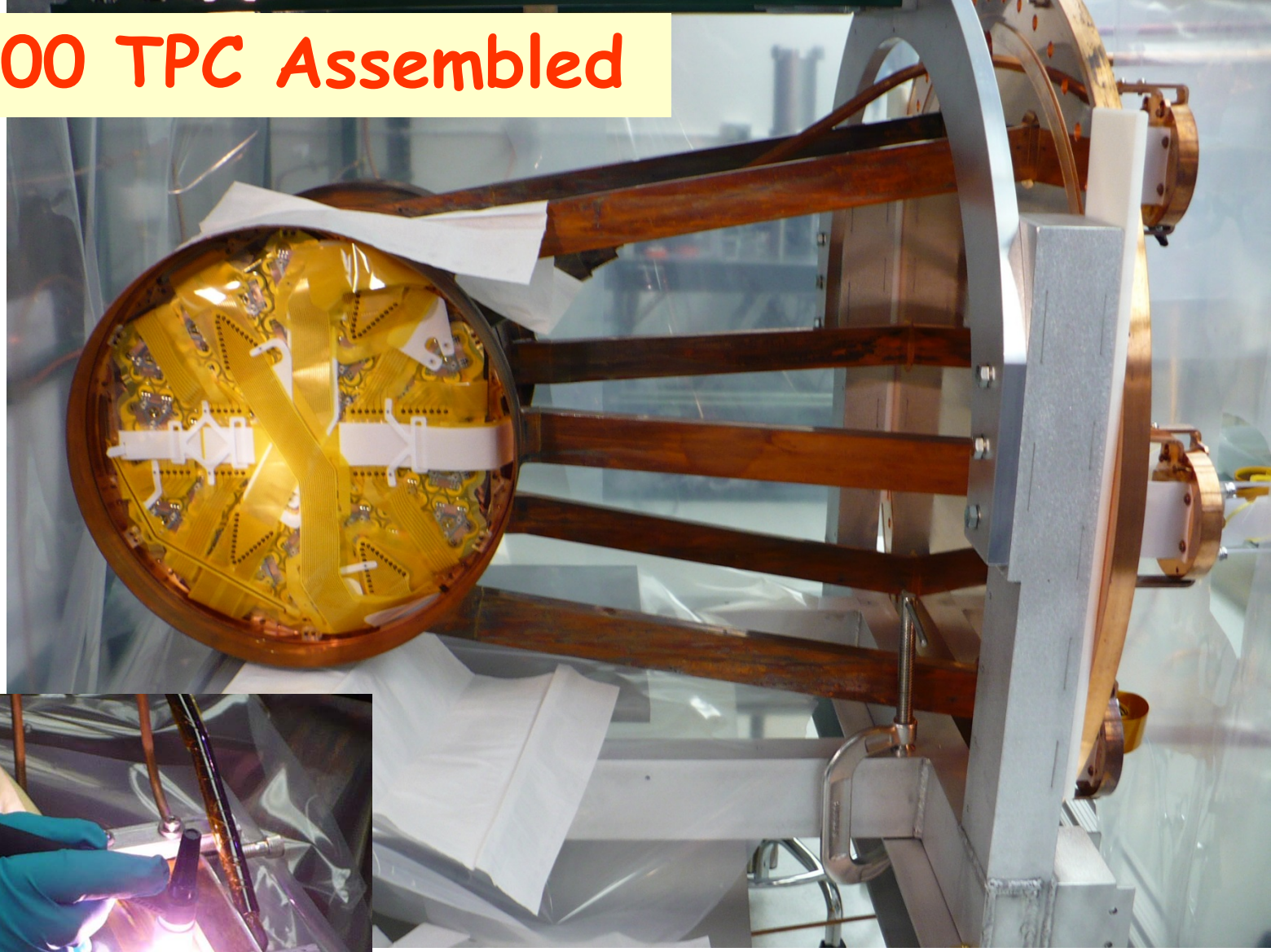
Ultra-low activity Cu vessel

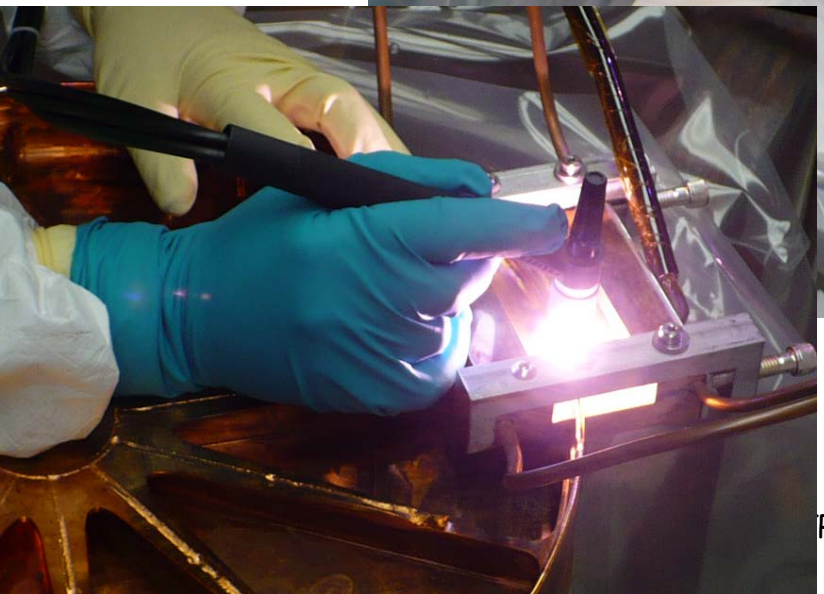
- Very light (~1.5mm thin, ~15kg) to minimize materials

- 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)



EXO-200 TPC Assembled





…and welded shut

Cryogenics/fluidics

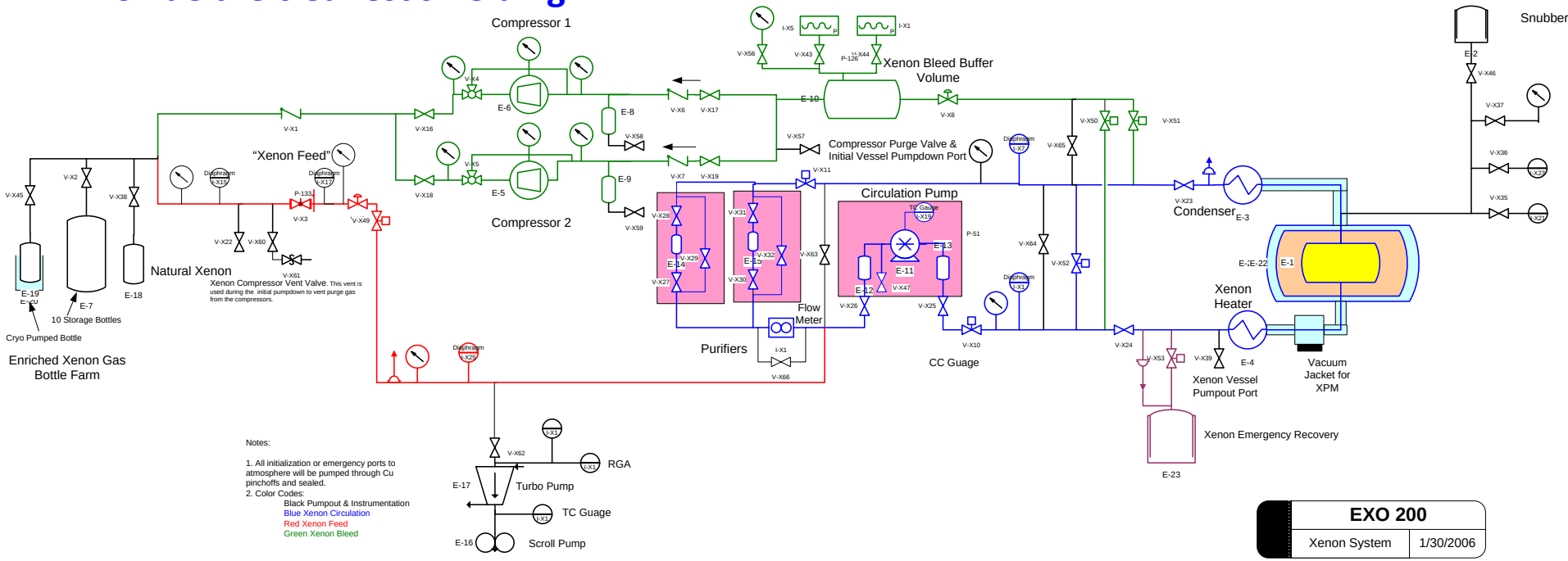
HFE7000 fluid is used to

- **Maintain uniform and constant temperature with a very flimsy TPC vessel**
- **Transfer pressures from the flimsy TPC vessel to the cryostat**

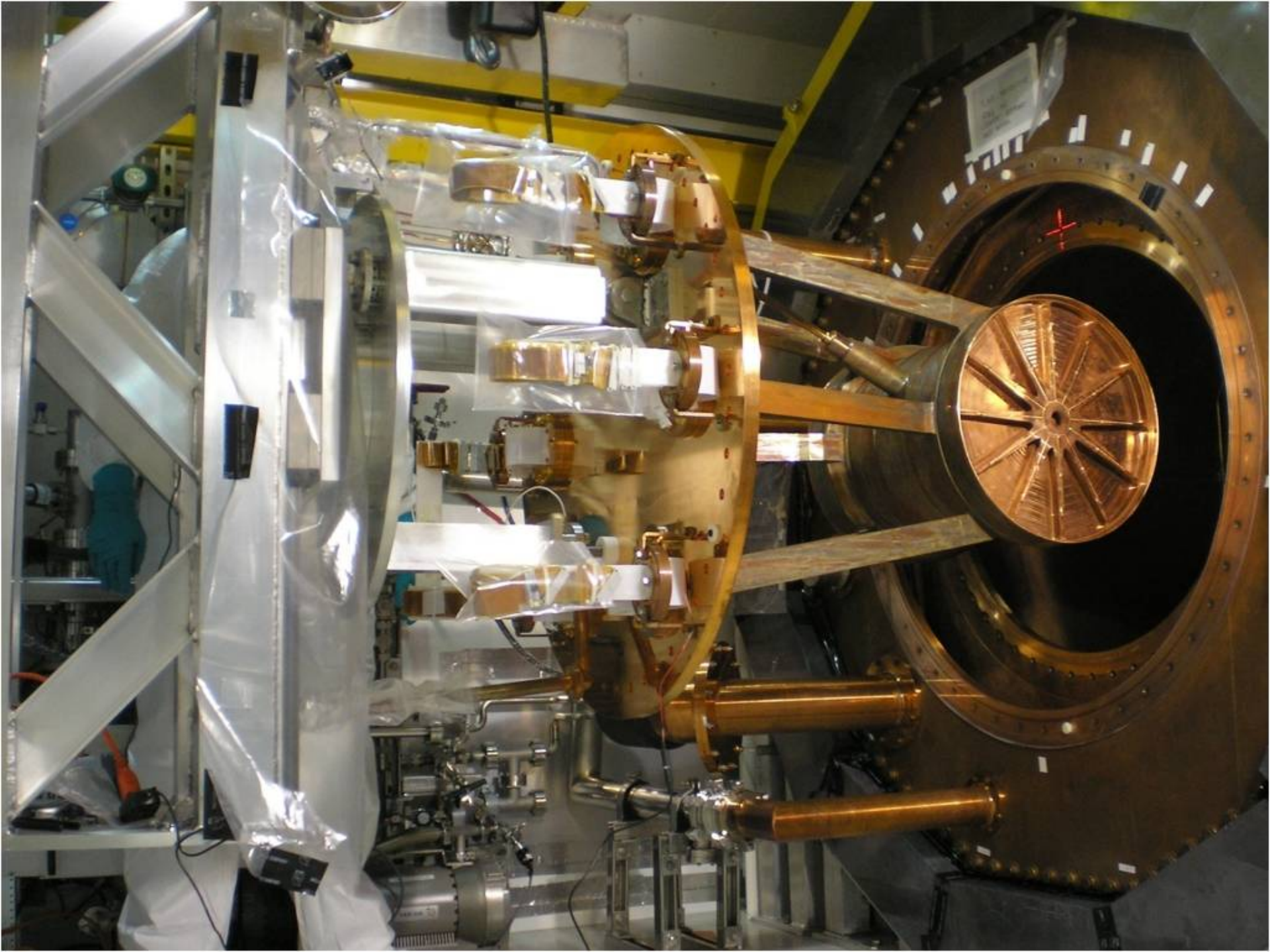
  Must maintain ΔP = ±0.3 bar across the thin copper vessel

  ➔ **in reality deadband is +60torr/-0torr**

  ➔ **in reality we violated the ΔP = ±0.3 bar by a large factor after the WIPP accidents**
- **Provide the cleanest shielding**



This also applied to pumping/flushing/filling the detector and during power outages



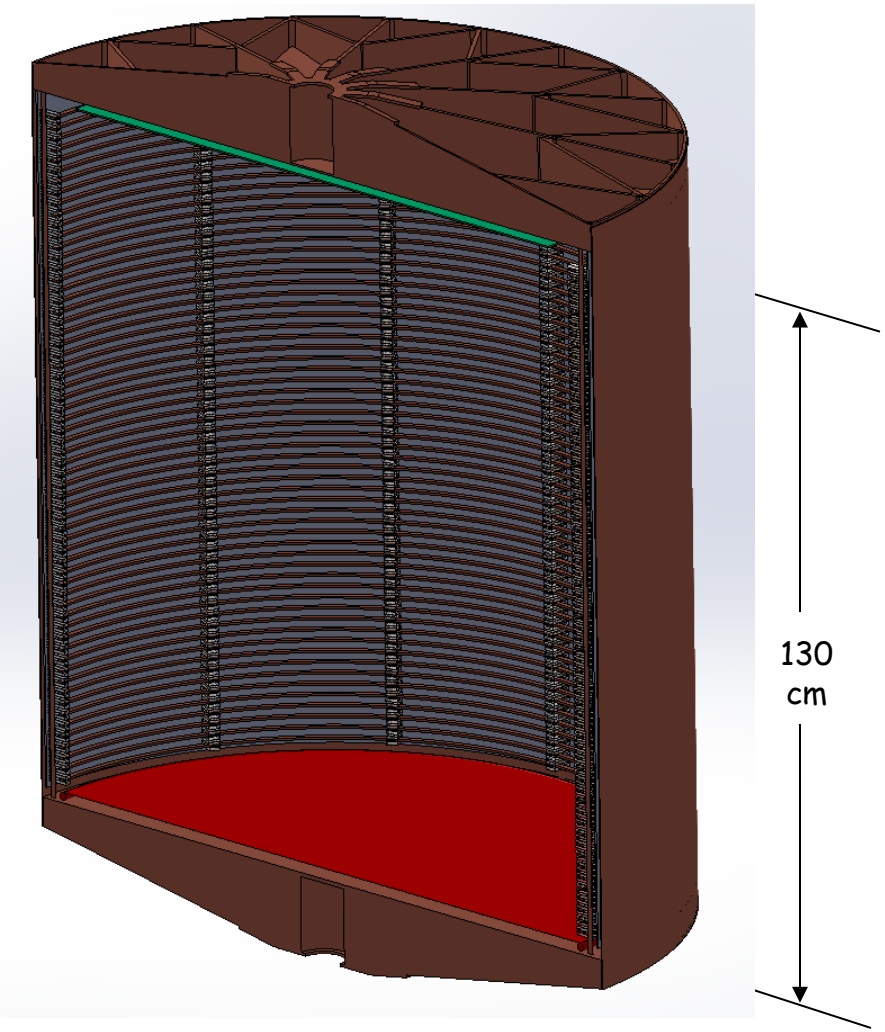
EXO-200 backgrounds were predicted very accurately

- J.B. Albert, et al. "Investigation of radioactivity-induced backgrounds" PRC 92, 015503 (2015).
- M. Auger, et al. "The EXO-200 detector…" J. Inst 7 (2012) P05010.

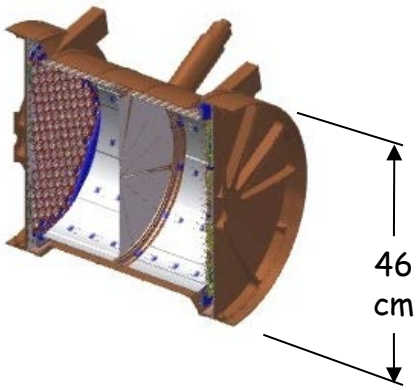
Events in ±2σ around Q	Radioactive bkgd prediction during construction	Radioactive bkgd prediction using present Monte Carlo	^{137}Xe bkgd	Background from 0ν analysis fit
90%CL Upper	48	22	7	31.1 ± 1.8 ± 3.3 (39 events observed)
90%CL Lower	9.4	3.3		

This is essential in scaling up to nEXO as the only tool required to estimate the sensitivity is Geant's ability to simulated Compton scattering

The nEXO detector



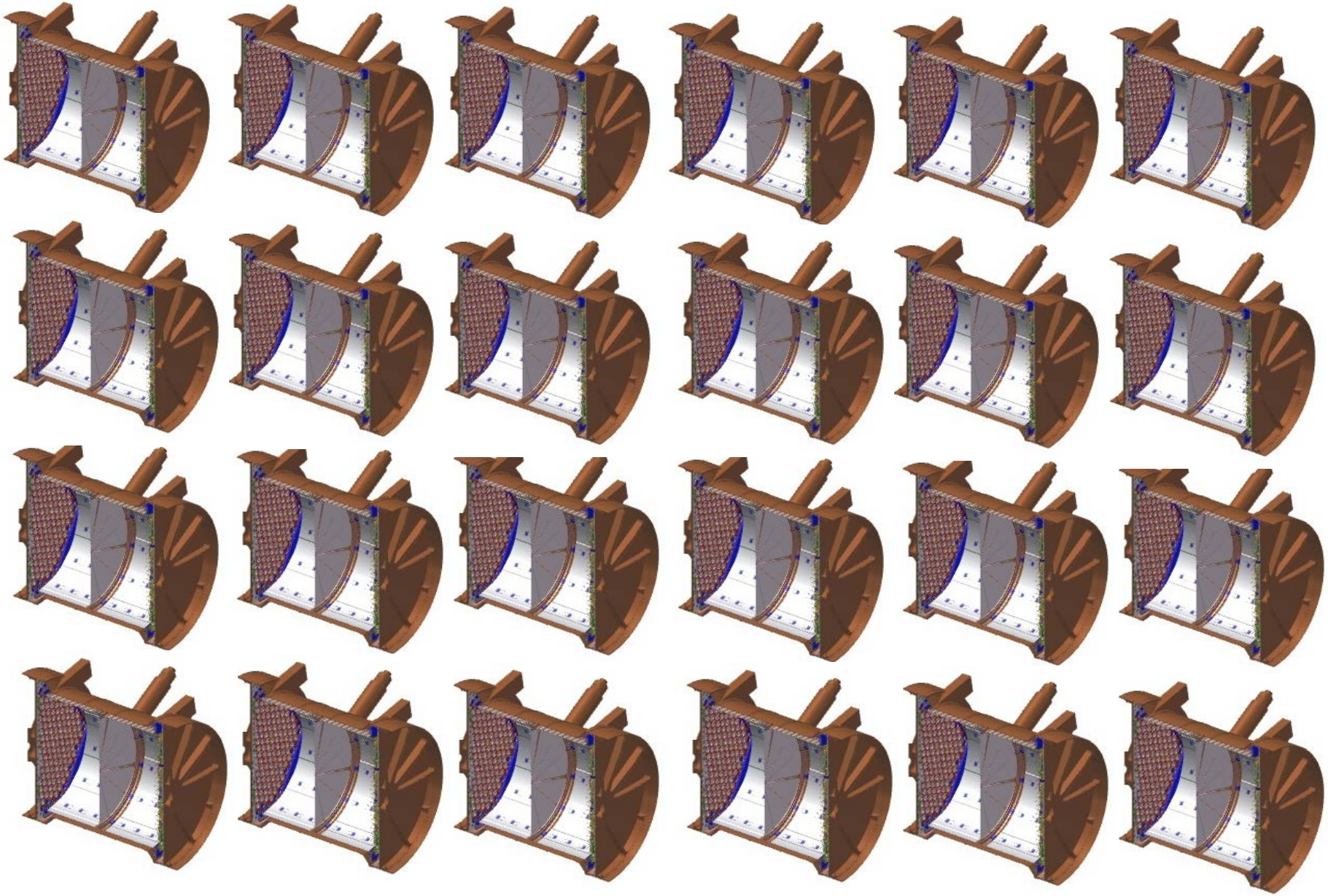
5 ton enriched LXe



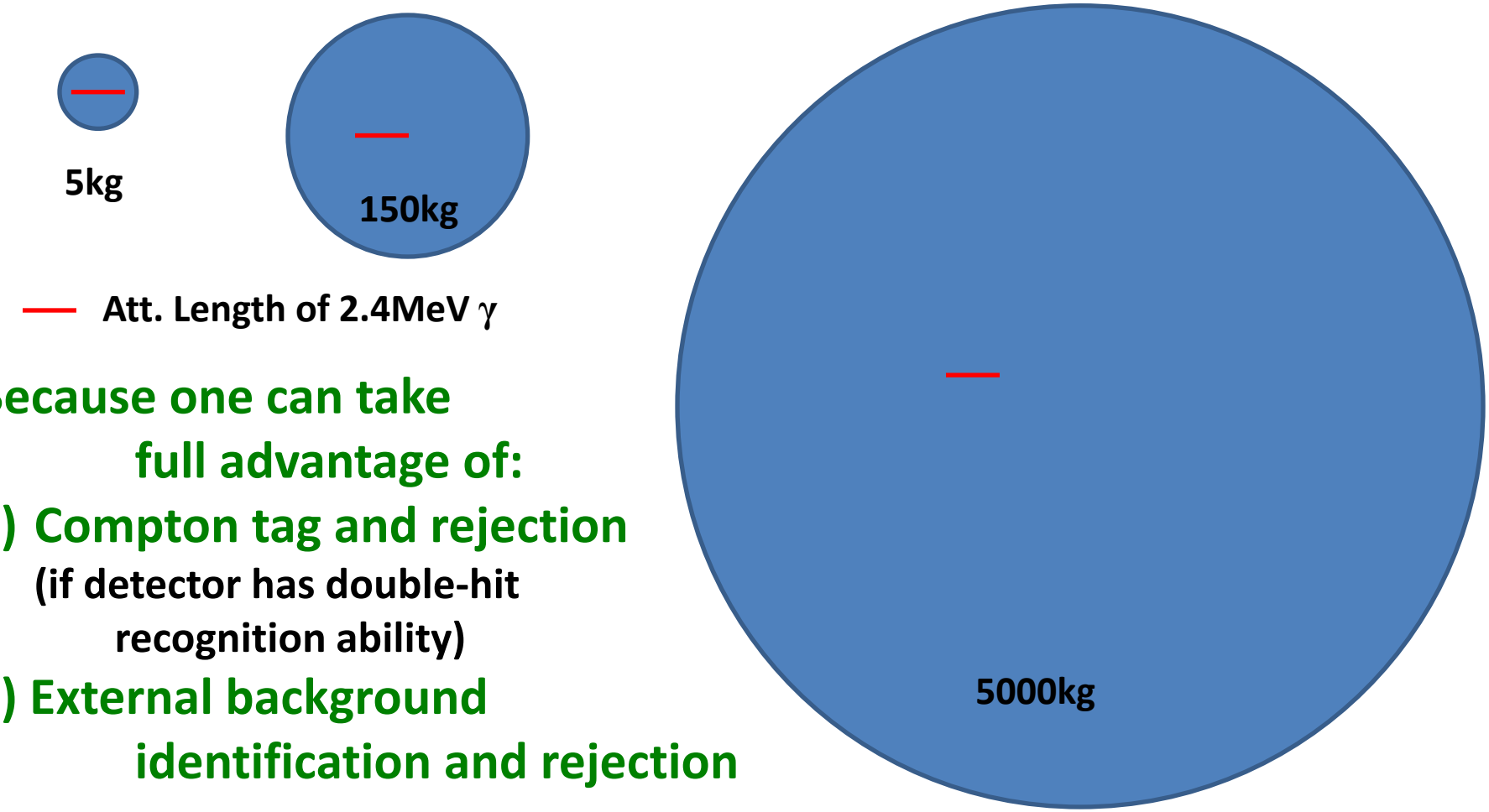
Designing nEXO:

A large,
homogeneous,
optimized detector

…and this is not the optimized detector!



Homogeneity is an essential feature of nEXO



Because one can take full advantage of:

1) Compton tag and rejection
(if detector has double-hit recognition ability)

2) External background identification and rejection

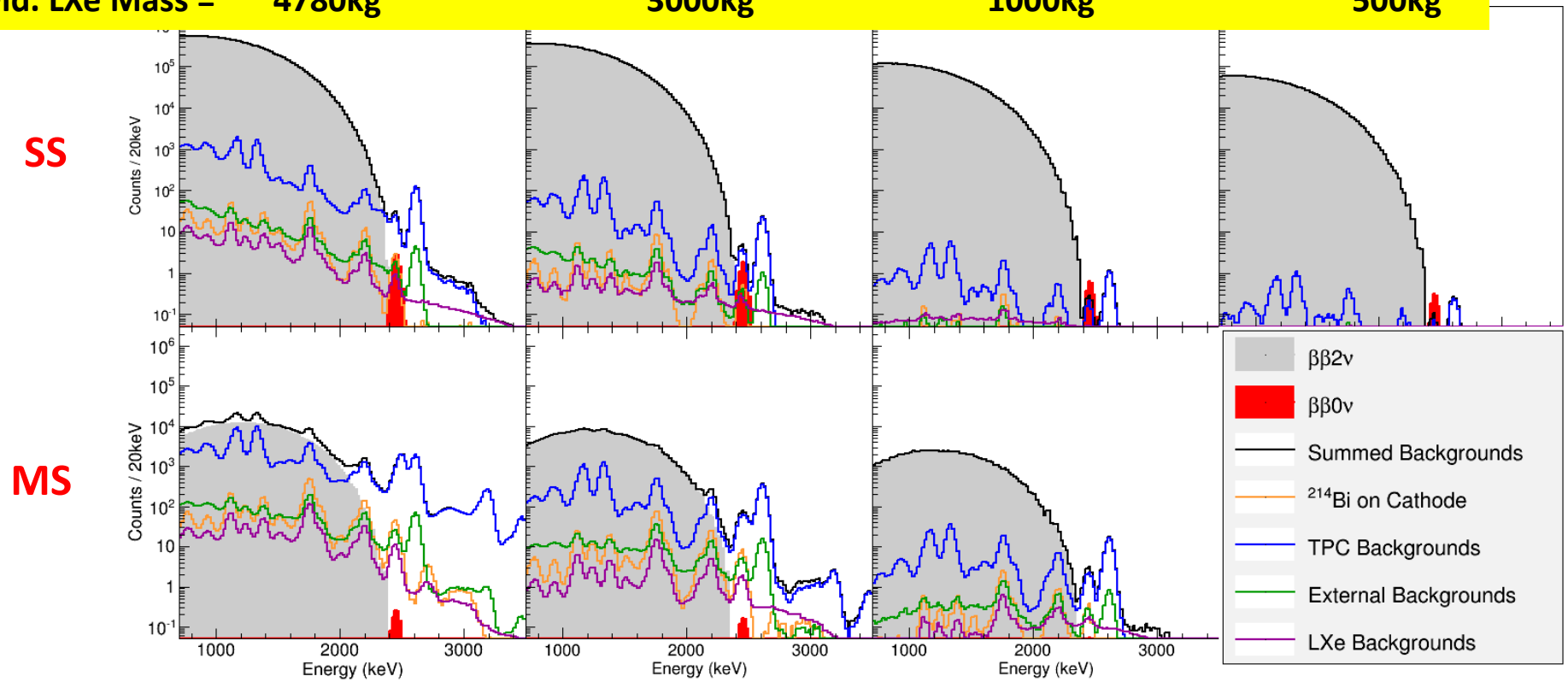
The larger the detector the more useful this is.

➔ Ton scale is where these features become dominant.

The role of the standoff distance in background identification and suppression

Example: nEXO, 5 yr data, 0νββ @ $T_{1/2}$=6.6x10^{27} yr, projected backgrounds from subsets of the total volume

Fid. LXe Mass = 4780kg 3000kg 1000kg 500kg



The fit gets to see all this information and use it in the optimal way

Correlation matrix from the fit

The largest correlation term for 0νββ is with the ^{238}U chain because of the ^{214}Bi line.

Yet, this is a relatively small (anti)correlation that allows the 0νββ signal to be well identified.

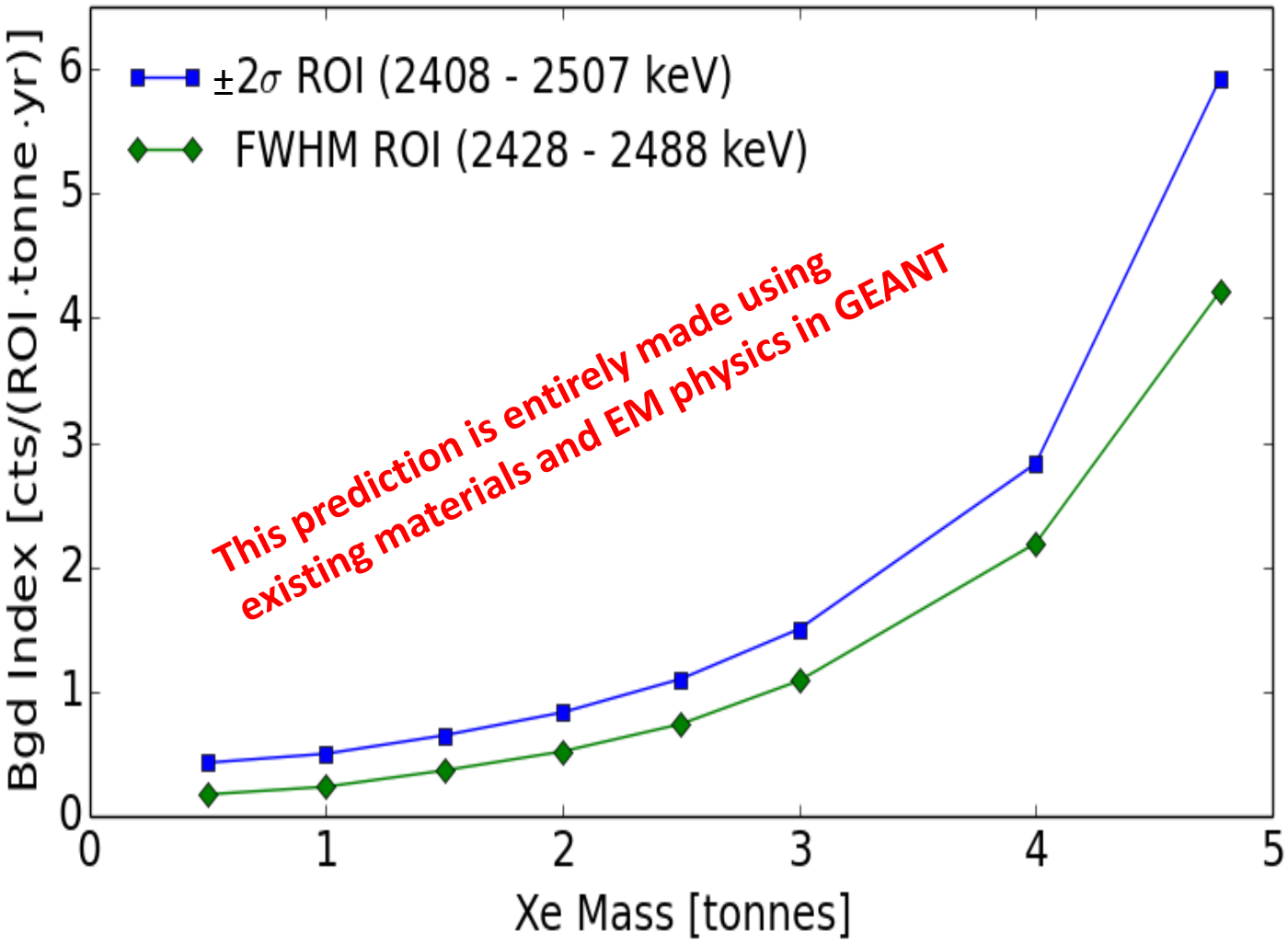
	APD+field rings	Cathode ^{214}Bi	TPC ^{232}Th	TPC ^{238}U	LXe ^{222}Rn	LXe ^{137}Xe	TPC ^{60}Co	0νββ	2νββ
APD+field rings	1	-0.25	-0.05	0.24			-0.78	-0.01	
Cathode ^{214}Bi	-0.25	1	0.28	-0.95			0.36	0.03	0.07
TPC ^{232}Th	-0.05	0.28	1	-0.31		-0.03	-0.07	0.01	-0.01
TPC ^{238}U	0.24	-0.95	-0.31	1	-0.05		-0.38	-0.10	-0.09
LXe ^{222}Rn				-0.05	1	-0.05			
LXe ^{137}Xe			-0.03		-0.05	1		-0.07	
TPC ^{60}Co	-0.78	0.36	-0.07	-0.38			1	0.02	-0.06
0νββ	-0.01	0.03	0.01	-0.10		-0.07	0.02	1	0.04
2νββ		0.07	-0.01	-0.09			-0.06	0.04	1

Entries <0.01 are suppressed and constraints are not listed for clarity/simplicity.

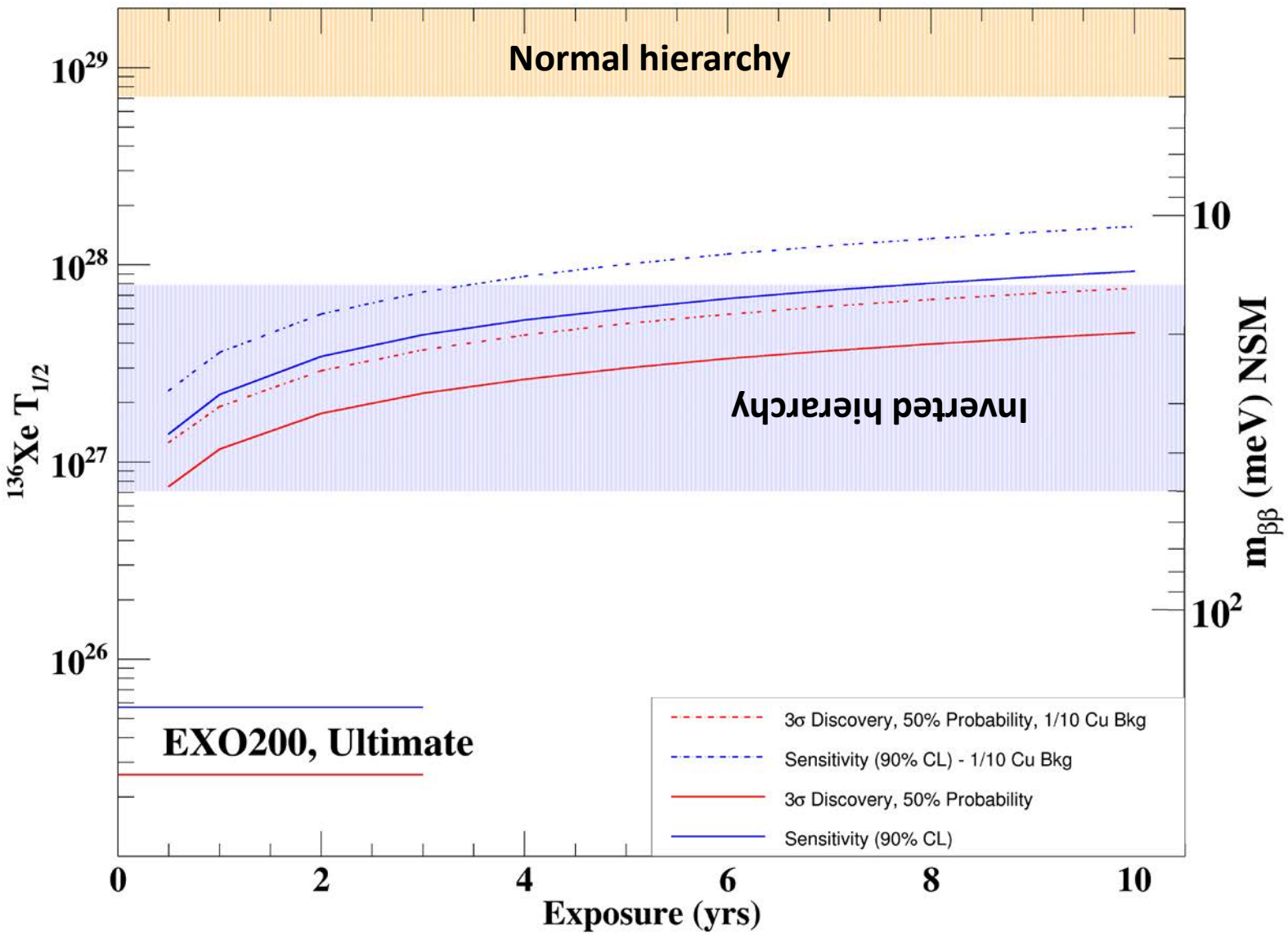
Note that an unknown gamma line would likely be identified by the same fit procedure.

Background Index [in counts/(ROI·tonne·yr)] versus fiducial volume is shown for two choices of the ROI: ±2·σ and FWHM.

Note that in nEXO the Background Index is not a single number

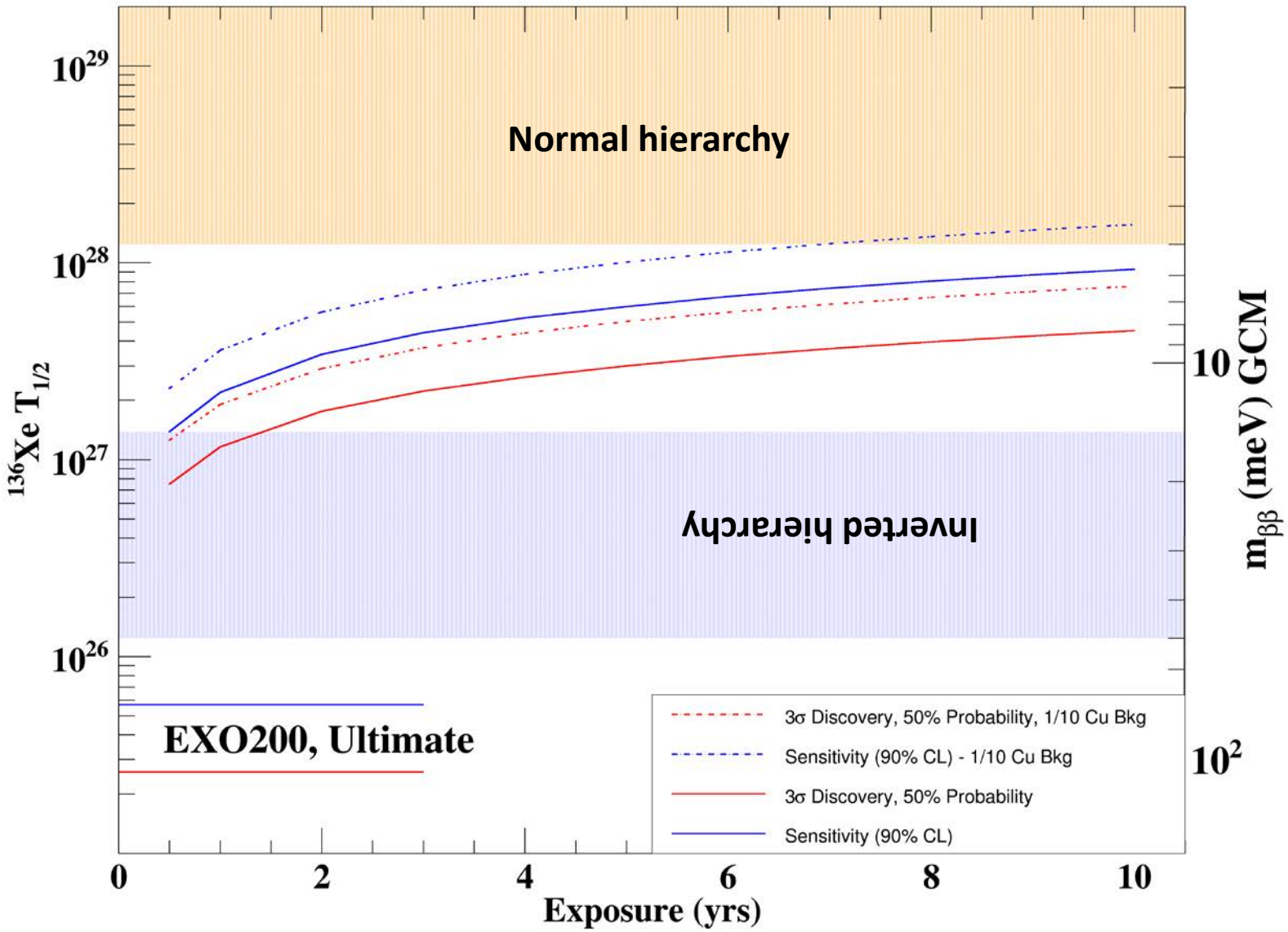


Sensitivity as a function of time for the worst-case NME (Shell Model)



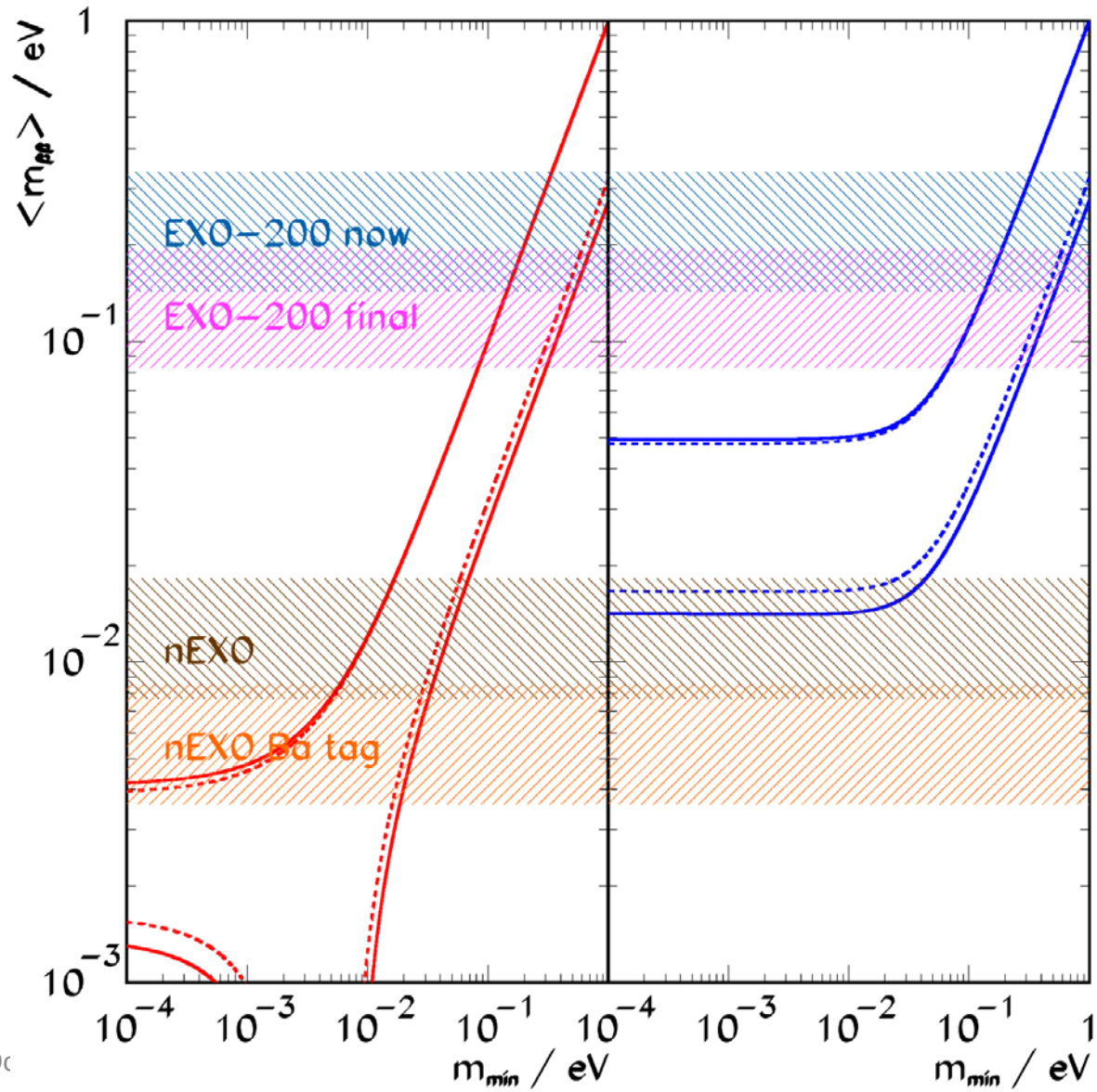
NSM: Menendez, Poves, Caurier, Nowacki, Nucl.Phys. A 818 (2009) 139

Sensitivity as a function of time for the best-case NME (GCM)



GCM: Rodriguez, Martinez-Pinedo, Phys. Rev. Lett. 105 (2010) 252503

A “static” version of the sensitivity plots, for 5 year run



NH and IH bands are also 90%CL

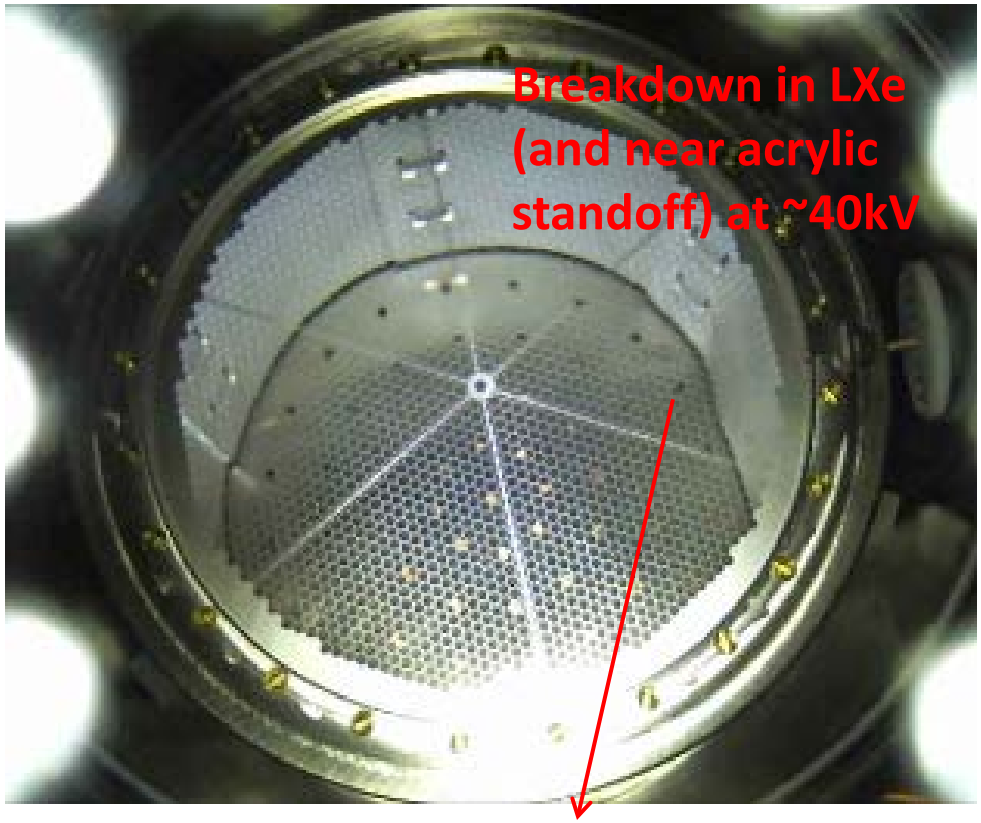
Forero et al., PRD 90 (2014) 093006
Forero et al., Private Comm.

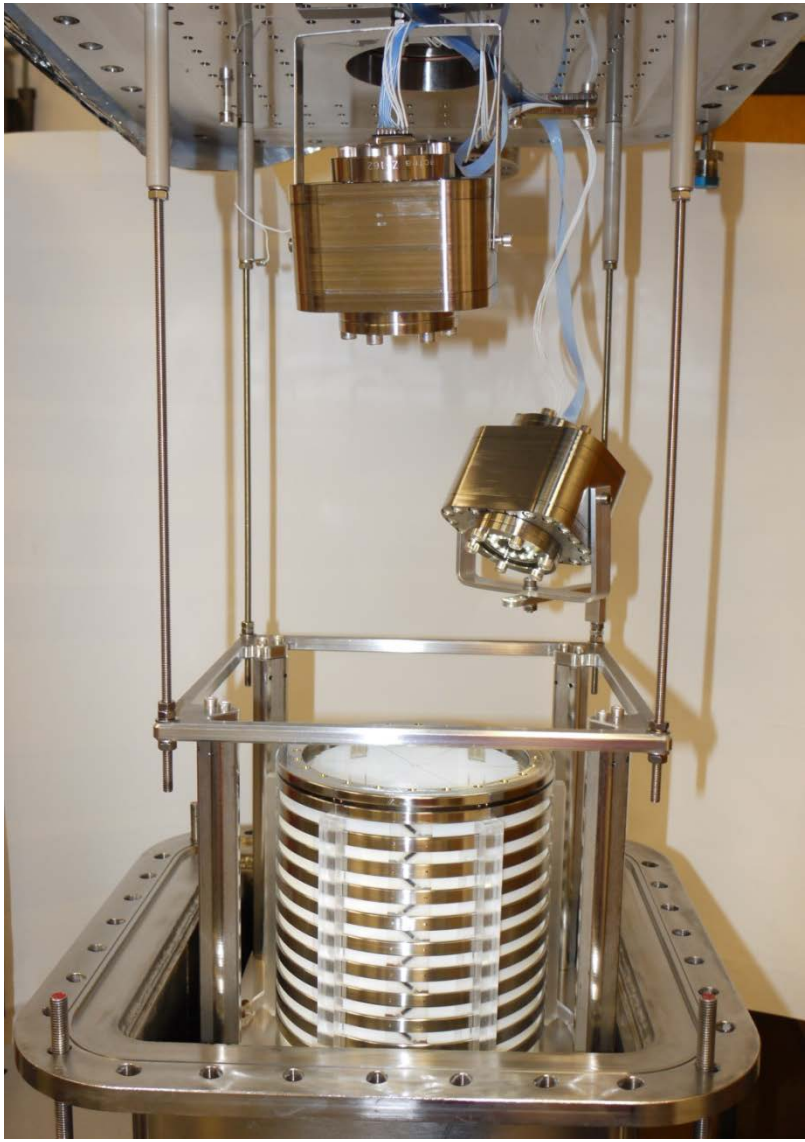
Optimization from the EXO-200 to the nEXO scale

What	Why
~30x volume/mass	To give sensitivity to the inverted hierarchy
No cathode in the middle	Larger low background volume/no ^{214}Bi in the middle
6x HV for the same field	Larger detector and one drift cell
>3x electron lifetime	Larger detector and one drift cell
Better photodetector coverage	Energy resolution, lower scintillation threshold
SiPM instead of APDs	Higher gain, lower bias, lighter, E resolution, lower scintillation threshold
In LXe electronics	Lower noise, more stable, fewer cables/feedthroughs, E resolution, lower threshold for Compton ID
Lower outgassing components	Longer electron lifetime
Different calibration methods	Very “deep” detector (by design)
Deeper site	Less cosmogenic activation
Larger vessels	5 ton detector and more shielding

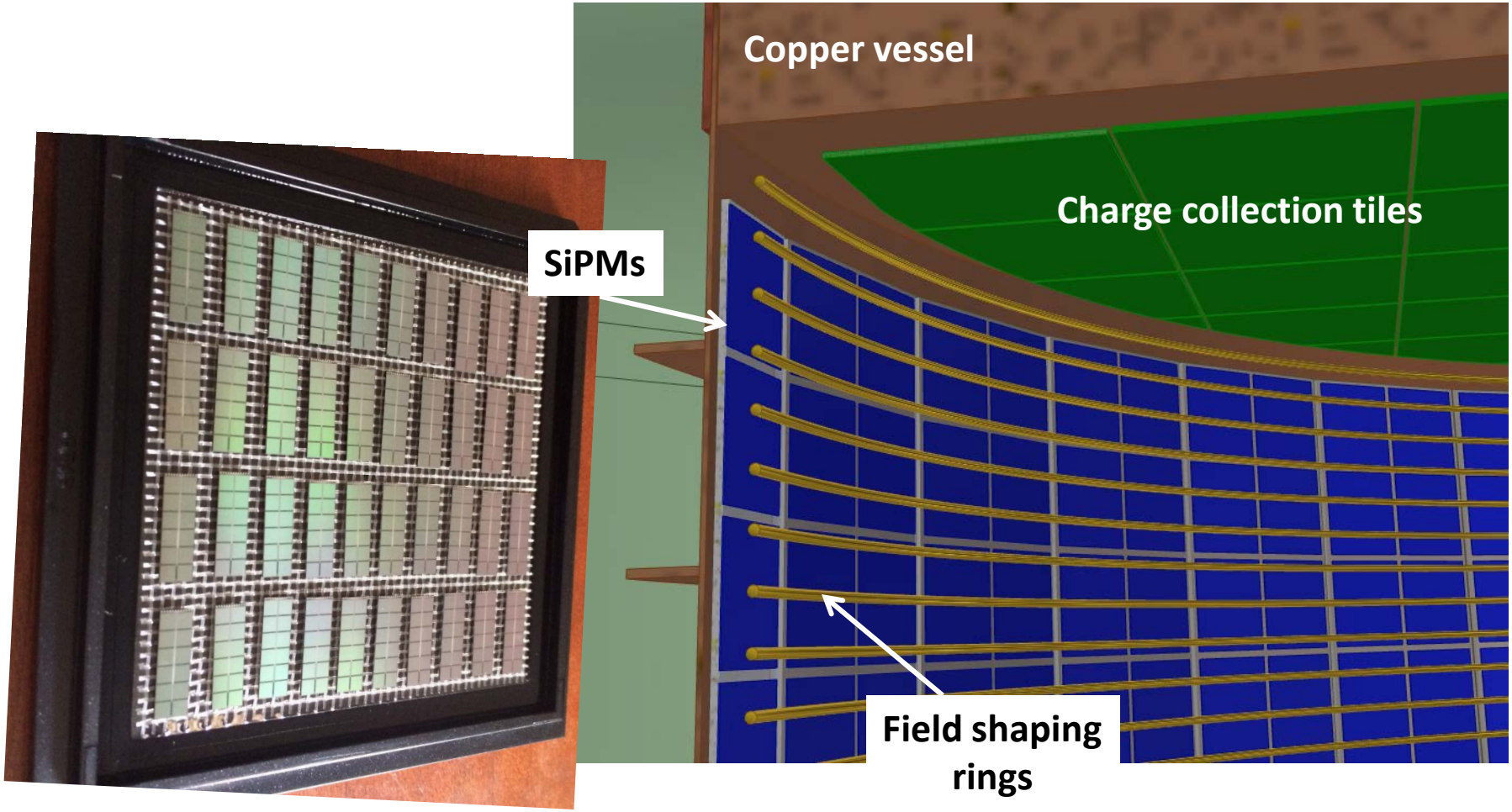
High Voltage R&D: need 50kV

Phase 2: Assemble "miniEXO-200" with spare parts (dielectrics) and run in a ~100kg LXe cell in Bern (moving to Carleton)





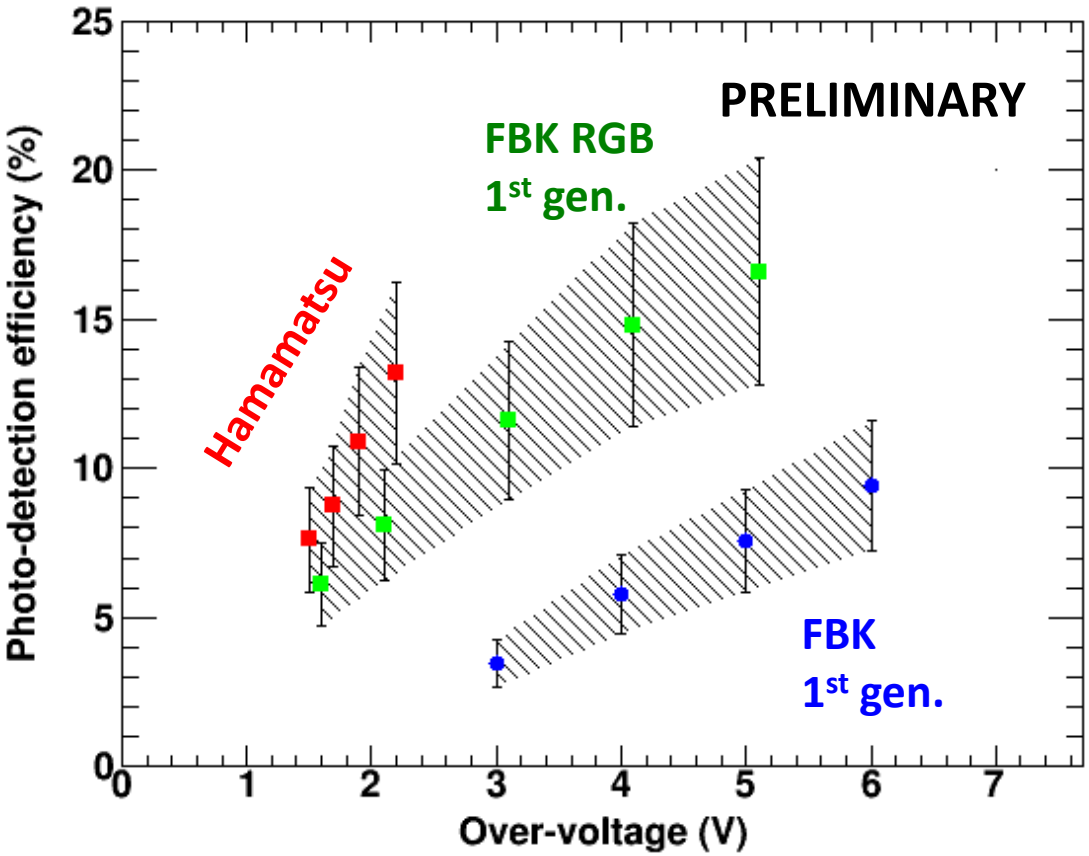
Photodetector: 4m^2 of VUV sensitive, base SiPMs



Photodetector

Hamamatsu produces devices with QE= ~12% @ 175nm but until now they have refused to sell them un-encapsulated (hence they are too radioactive)

First nEXO-specific run at FBK (Italy) provided ~10% QE ***[I.Ostrovskiy et al. IEEE TNS 62 (2015) 1825.]***
New "RGB" devices reach 15% QE with 7.7x7.7mm^2.



A new run at FBK will use a new technology (NUV-HD) with the promise to reach QE>15% @170nm, lower dark noise and crosstalk with 1x1cm^2 devices.

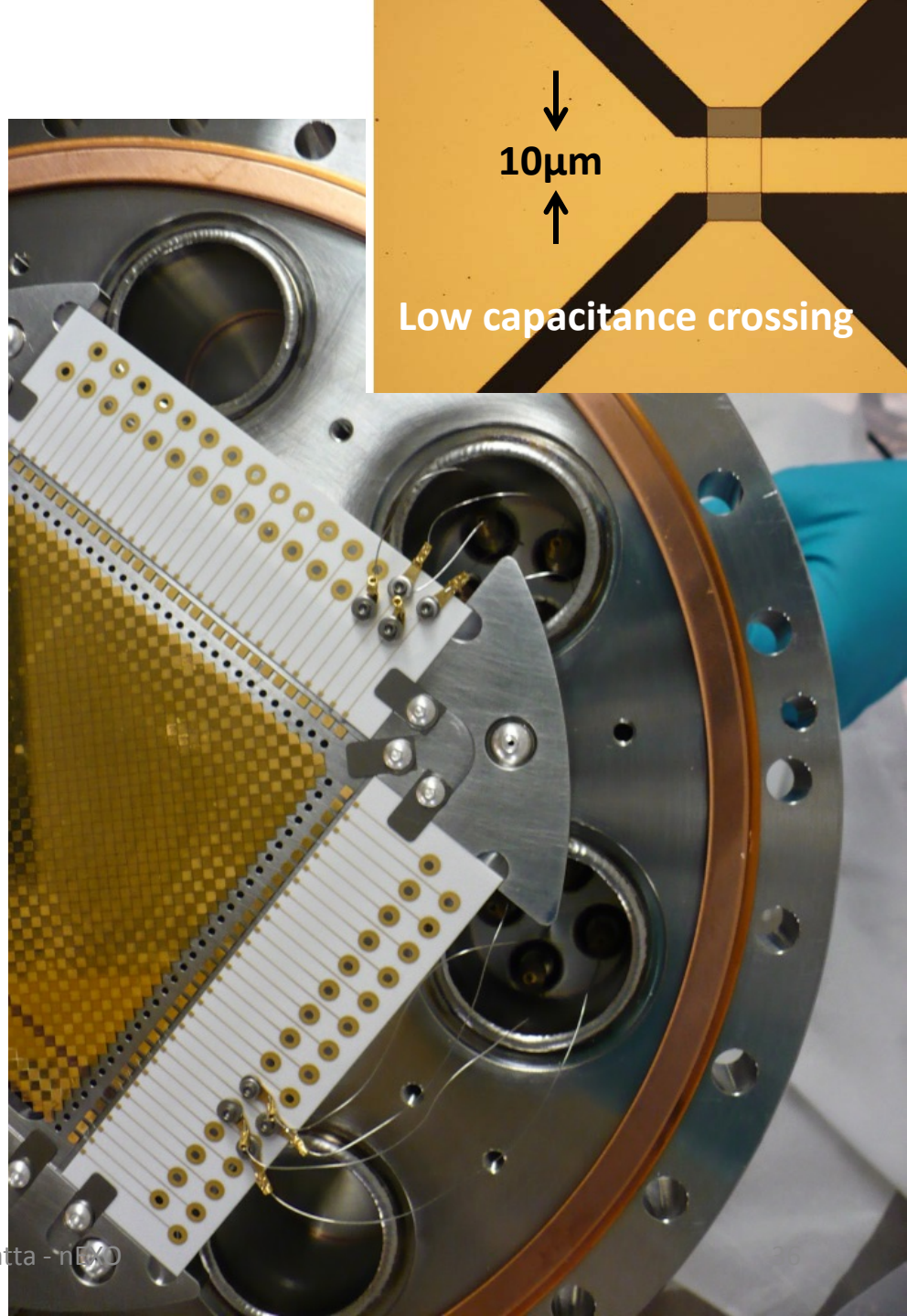
FBK devices are almost low activity enough (a Th anomaly needs to be investigated with the new run (Alabama))

Charge readout tiles

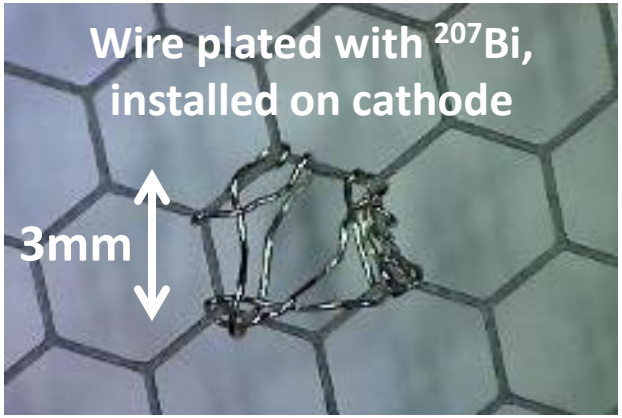
3mm pitch, crossed strip, full coverage, quartz- or sapphire-supported charge collection/readout tile. Produced by IHEP; functional testing in LXe in the US.

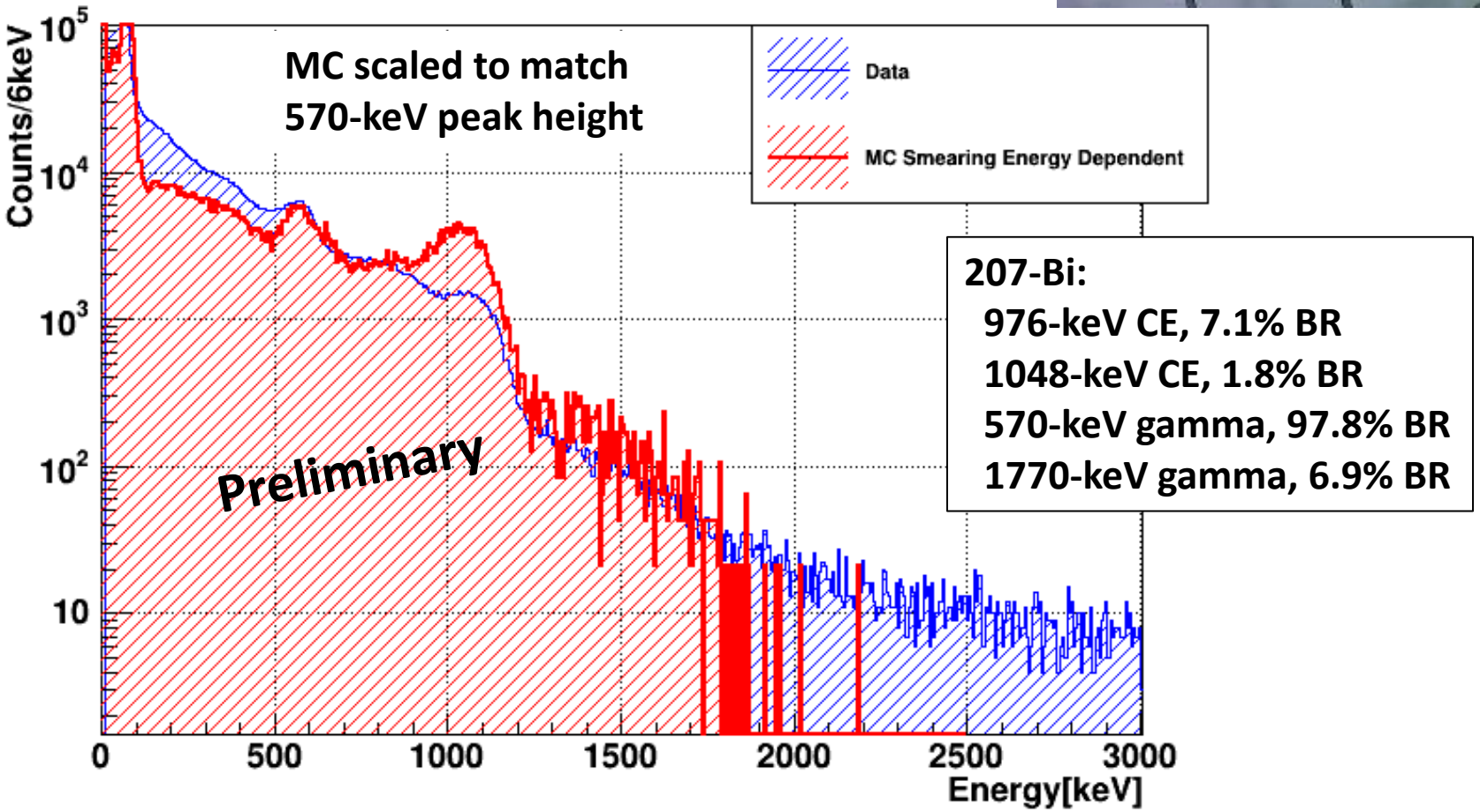
The prototype to the right uses a quartz substrate.

External readout is coupled with ceramic interface boards for the test. In “real life” the readout chip will be mounted directly onto the tile.

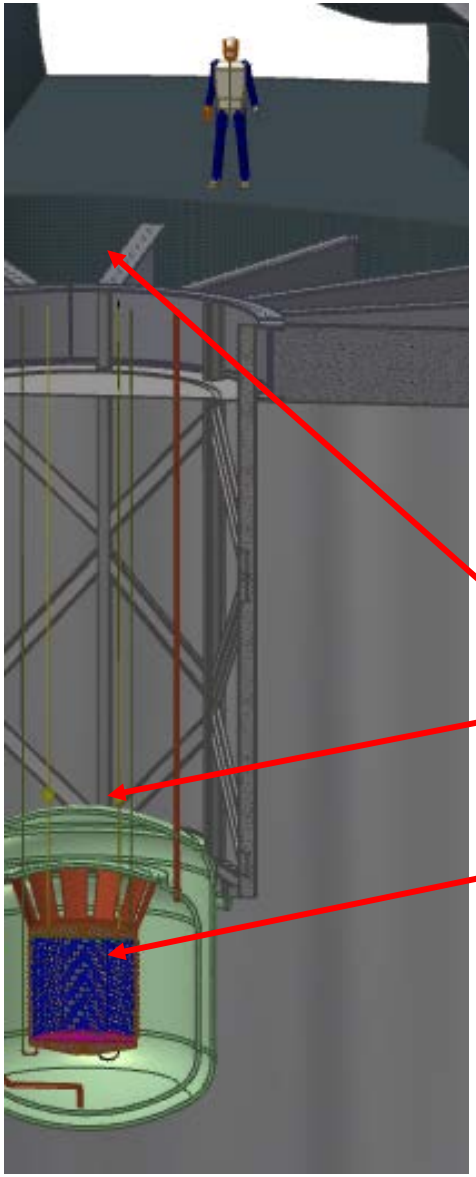


Very first run, comparing one channel with a very crude MC. The system basically works. Of course much more work is needed!





Comparison for noise and threshold between front-end locations for the Charge Channel



Location	Cable length (m)	Total cap (pF)	Intrinsic RMS Noise (e)	RMS contribution to charge energy resolution	Charge cluster threshold (keV)
In lab (warm)	8	800	3200	2.5%	600 keV
At cryostat (warm/cold)	2	200	800	0.6%	150 keV
Inside TPC (cold)	~0	<40	<200	0.2%	40 keV

Assumes simple tile charge collection system with interleaved strips and EXO-200 style cables for the remote location cases.

Radiopurity

We have proactively invested in several new facilities and have already been successful in specific and important areas.

- **Low background Ge counting: SNOlab (underground), Alabama (surface), Alabama & Duke developing new underground capability at KURF**
- **Neutron activation analysis: Alabama**
- **ICPMS: IHEP Beijing, IBS Korea**
- **GDMS: NRC Canada**
- **Radon emanation: Laurentian U. Canada**

➔ Already improved analytical sensitivity for U and Th in Cu by 3-fold (~1ppt)

Much work in progress to enhance capabilities and sensitivities for various specific issues/materials.

Material procurement

^{136}Xe enrichment easier and cheaper:

➔ **90% enriched ^{136}Xe: ~10$/g**

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

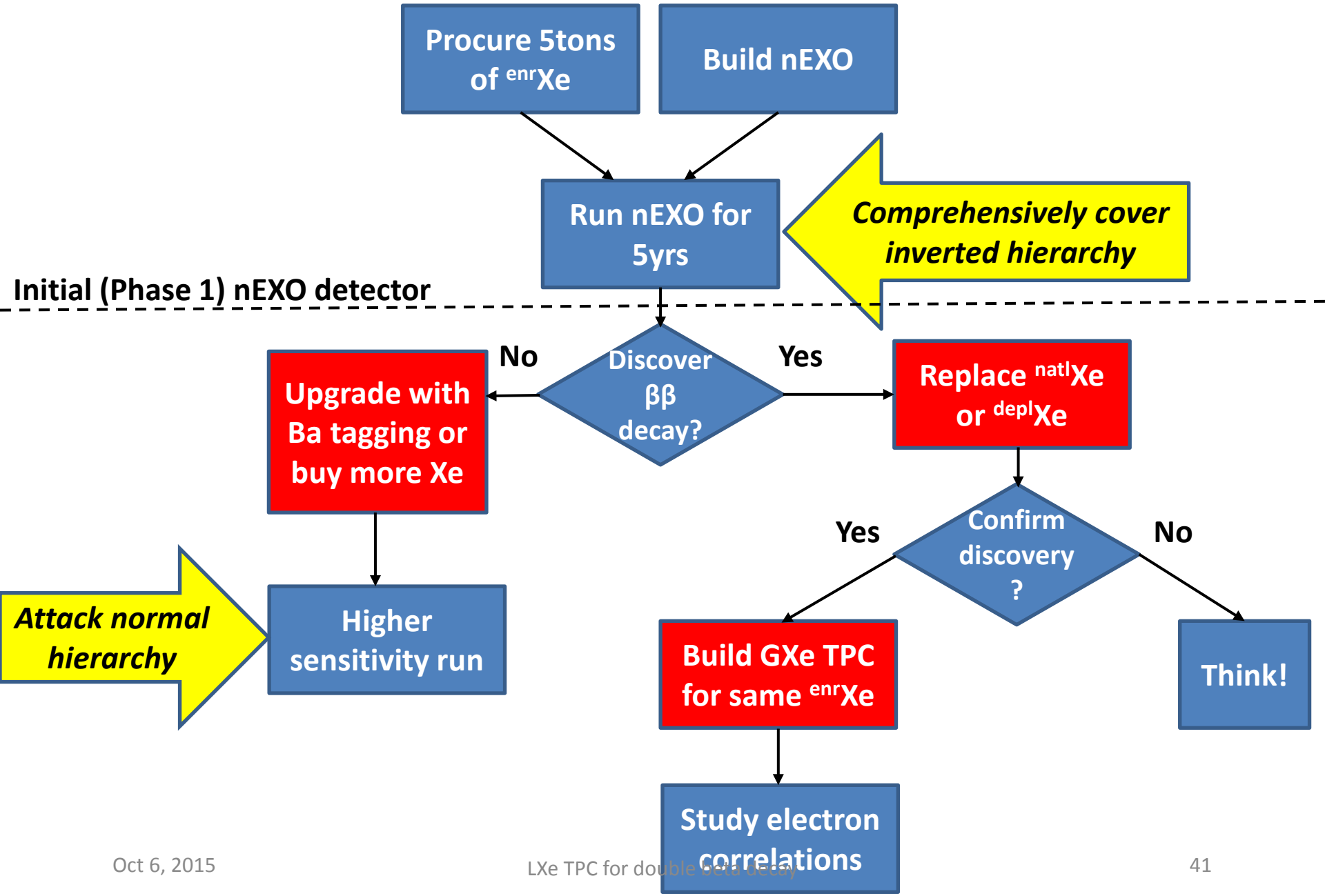
(EXO-200 uses 80% enriched Xe. It now seems customary to do 90% and it appears that there is no major cost difference)

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

Almost a ton of Xe enriched in the isotope 136 has been produced in the world in the last 10 years. So this information is quite reliable.

Flexible program based on the initial nEXO investment



The nEXO Collaboration

University of Alabama, Tuscaloosa AL, USA — T Didberidze, M Hughes, A Piepke, R Tsang

University of Bern, Switzerland — S Delaquis, R Gornea[†], J-L Vuilleumier

[†]Now at Carleton University

Brookhaven National Laboratory, Upton NY, USA — M Chiu, G De Geronimo, S Li, V Radeka, T Rao, G Smith, T Tsang, B Yu

California Institute of Technology, Pasadena CA, USA — P Vogel

Carleton University, Ottawa ON, Canada — Y Baribeau, V Basque, M Bowcock, M Dunford, M Facina, R Gornea, K Graham, P Gravelle, R Killick, T Koffas, C Licciardi, E Mane, K McFarlane, R Schnarr, D Sinclair

Colorado State University, Fort Collins CO, USA — C Chambers, A Craycraft, W Fairbank, Jr, T Walton

Drexel University, Philadelphia PA, USA — MJ Dolinski, YH Lin, E Smith, T Winick, Y-R Yen

Duke University, Durham NC, USA — PS Barbeau, G Swift

University of Erlangen-Nuremberg, Erlangen, Germany — G Anton, R Bayerlein, J Hoessl, P Hufschmidt, A Jamil, T Michel, T Ziegler

IBS Center for Underground Physics, Daejeon, South Korea — DS Leonard

IHEP Beijing, People's Republic of China — G Cao, W Cen, X Jiang, H Li, Z Ning, X Sun, T Tolba, W Wei, L Wen, W Wu, J Zhao

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

Indiana University, Bloomington IN, USA — JB Albert, S Daugherty, TN Johnson, LJ Kaufman, T O'Conner, G Visser, J Zettlemoyer

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

Lawrence Livermore National Laboratory, Livermore, CA, USA — O Alford, J Brodsky, M Heffner, G Holtmeier, A House, M Johnson, S Sangiorgio

University of Massachusetts, Amherst MA, USA — J Dalmasson, S Feyzbakhsh, S Johnston, A Pocar

McGill University, Montreal, Canada — T Brunner

Oak Ridge National Laboratory, Oak Ridge TN, USA — L Fabris, D Hornback, RJ Newby, K Ziock

Rensselaer Polytechnic Institute, Troy NY, USA — E Brown

SLAC National Accelerator Laboratory, Menlo Park CA, USA — T Daniels, K Fouts, G Haller, R Herbst, M Kwiatkowski, K Nishimura, A Odian, M Oriunno, PC Rowson, K Skarpaas

University of South Dakota, Vermillion SD, USA — R MacLellan

Stanford University, Stanford CA, USA — R DeVoe, D Fudenberg, G Gratta, M Jewell, S Kravitz, D Moore, I Ostrovskiy, A Schubert, K Twelker, M Weber

Stony Brook University, SUNY, Stony Brook, NY, USA — K Kumar, O Njoya, M Tarka

Technical University of Munich, Garching, Germany — P Fierlinger, M Marino

TRIUMF, Vancouver BC, Canada — J Dilling, P Gumplinger, R Krücken, F Retière, V Strickland