The EXO program:
EXO-200 and nEXO

Giorgio Gratta
Stanford

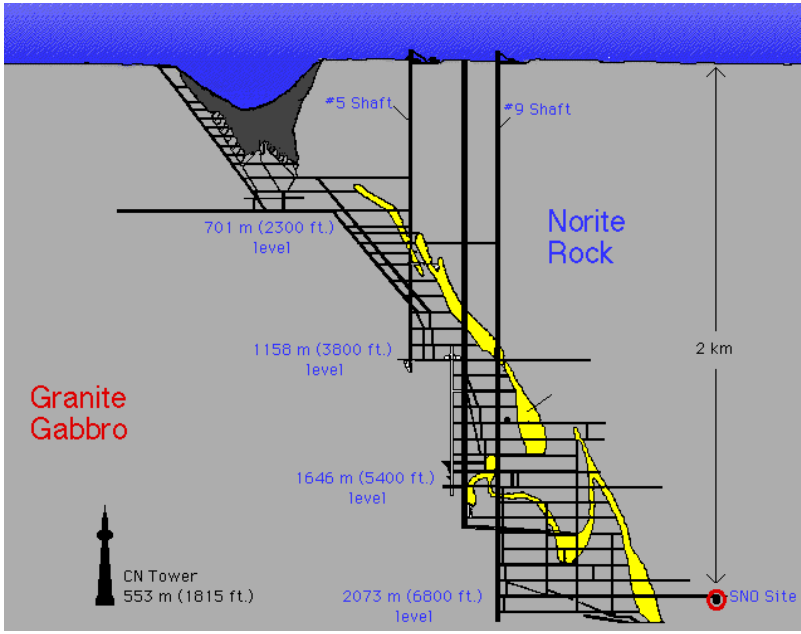
Four fundamental requirements for modern experiments:

1) Isotopic enrichment of the source material (that is generally also the detector)

100kg – class experiment running or completed.
Ton – class experiments under planning.

2) Underground location to shield cosmic-ray induced background

Several underground labs around the world,
next round of experiments 1-2 km deep.



Four fundamental requirements for modern experiments:

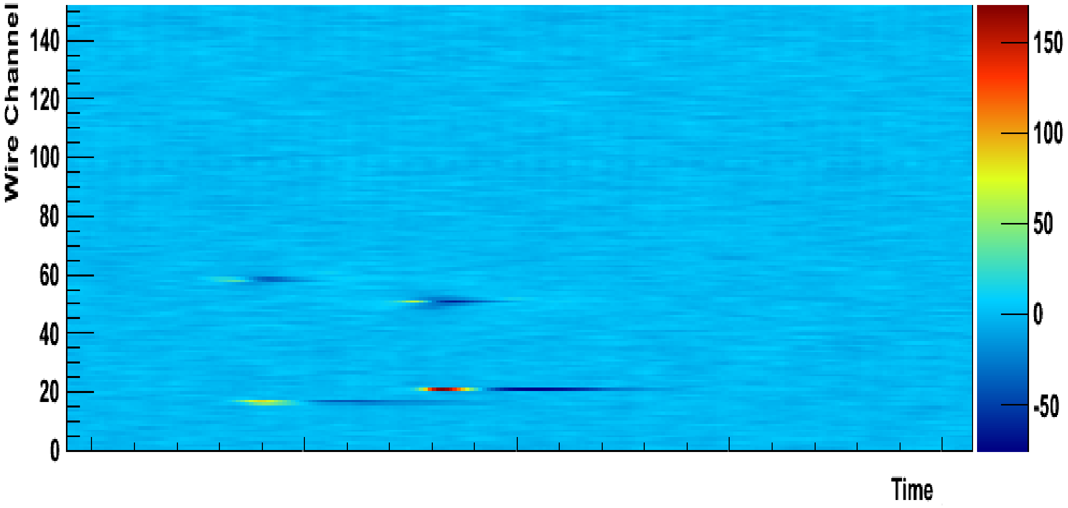
3) Ultra-low radioactive contamination for detector construction components

Materials used ≈<10^{-15} in U, Th
(U, Th in the earth crust ~ppm)

4) New techniques to discriminate signal from background

Non trivial for E~1MeV

But this gets easier in larger detectors.



The last point deserves more discussion, particularly as the size of detectors grows…

The signal/background discrimination can/should based on four parameters/measurements:

1. **Energy measurement (for small detectors this is ~all there is).**
2. **Event multiplicity (γ's Compton scatter depositing energy in more than one site in large detectors).**
3. **Depth in the detector (or distance from the walls) is (for large monolithic detectors) a powerful parameter for discriminating between signal and (external) backgrounds.**
4. **α discrimination (from e^- / γ), possible in many detectors.**

It is a real triumph of recent experiments that we now have discrimination tools in this challenging few MeV regime!

Powerful detectors use most of (possibly all) these parameters in combination, providing the best possible background rejection and simultaneously fitting for signal and background.

The EXO program

- Use ^{136}Xe in liquid phase

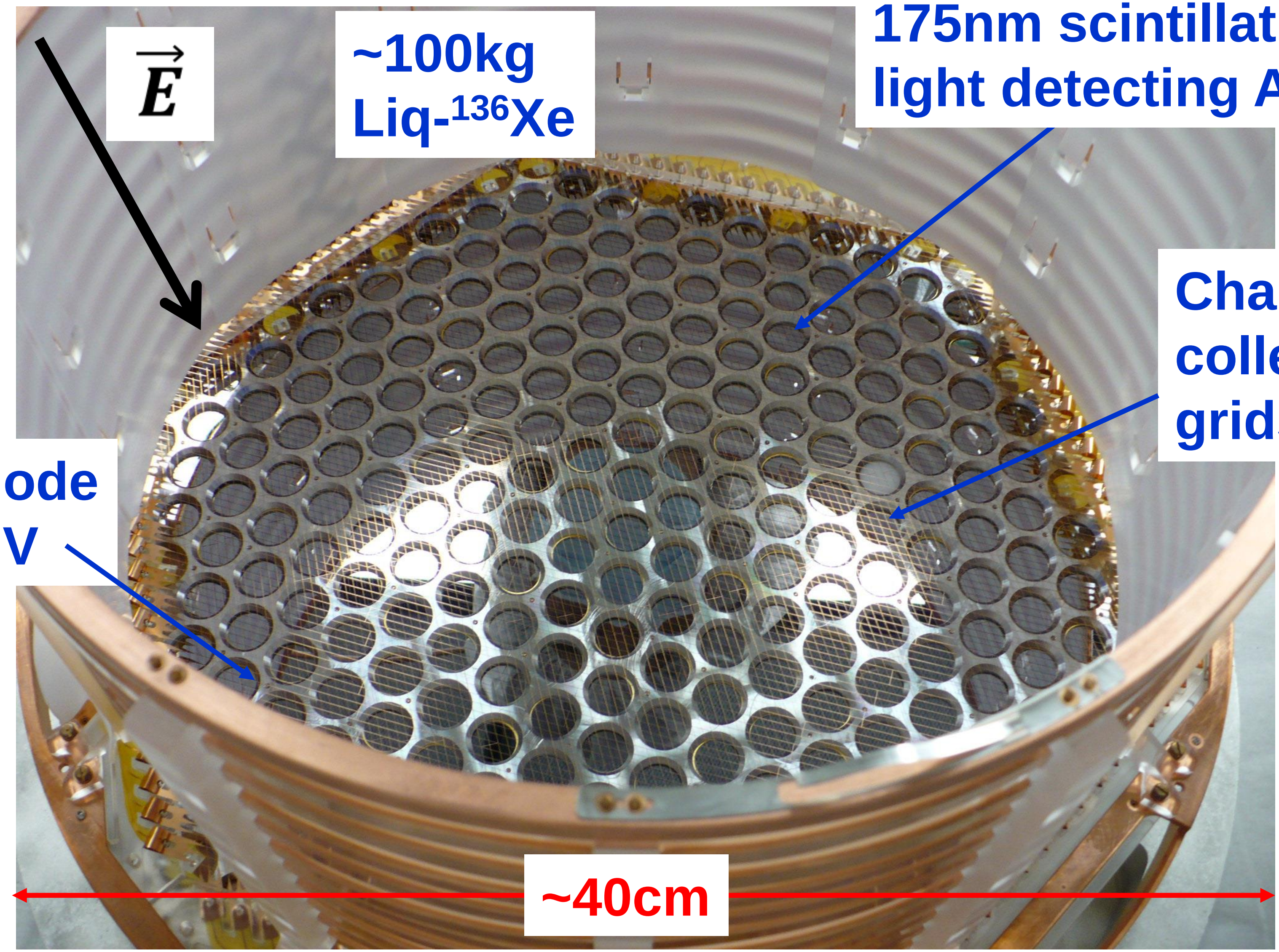
- Initial R&D on energy resolution using scintillation-ionization correlation

- Build EXO-200, first 100kg-class experiment to produce results. Run II in progress.

- Build a ton-scale detector (nEXO) able to cover the inverted hierarchy (for the standard mechanism)

- Explore the possibility of tagging the final state Ba atom to extend the sensitivity of a second phase nEXO detector

The EXO-200 liquid ^{136}Xe Time Projection Chamber



$\vec{E}$

~100kg Liq-^{136}Xe

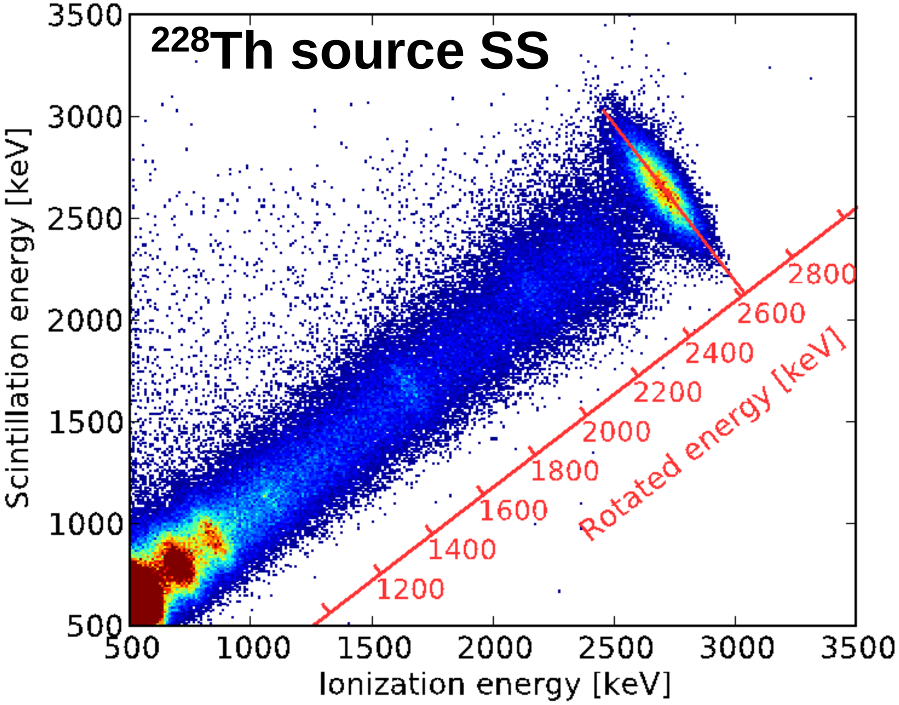
175nm scintillation light detecting APDs

Charge collection grids

Cathode -HV

~40cm

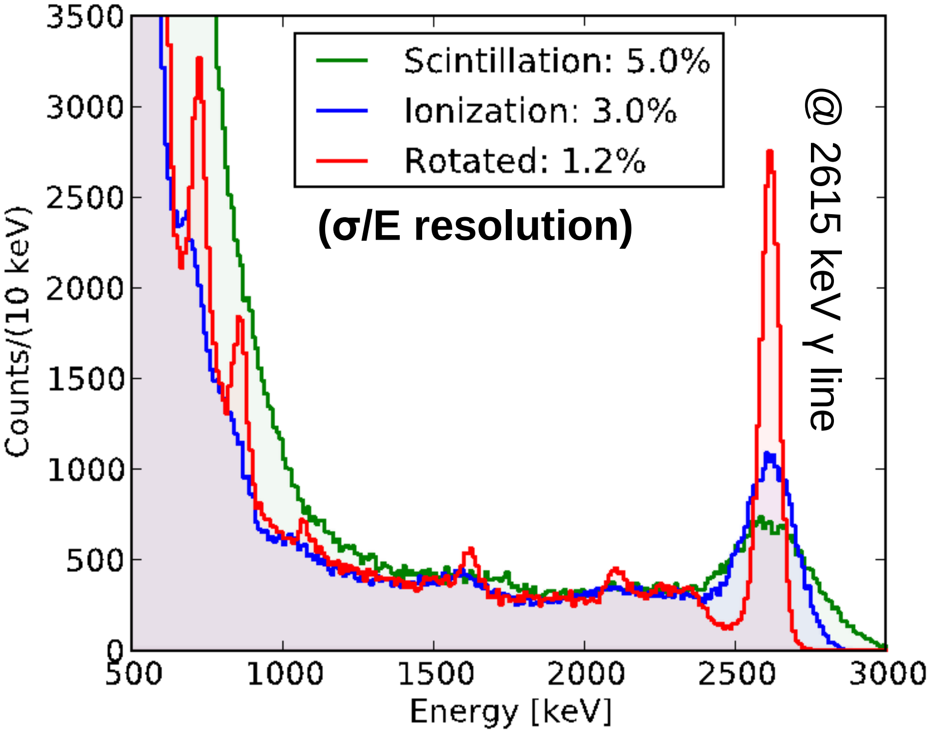
Combining Ionization and Scintillation



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

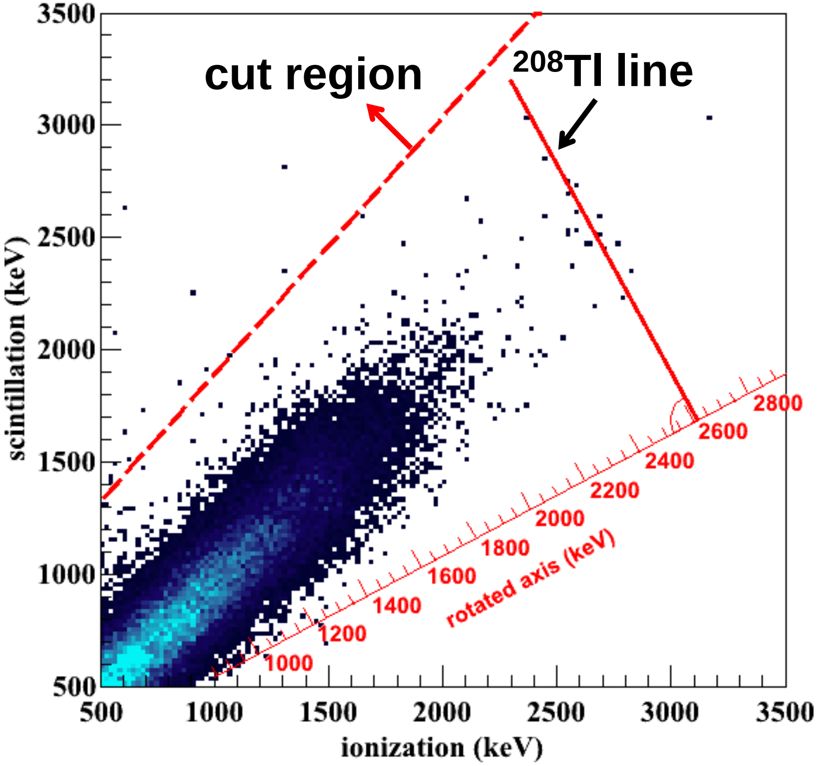
E.Conti et al.
Phys Rev B 68 (2003) 054201

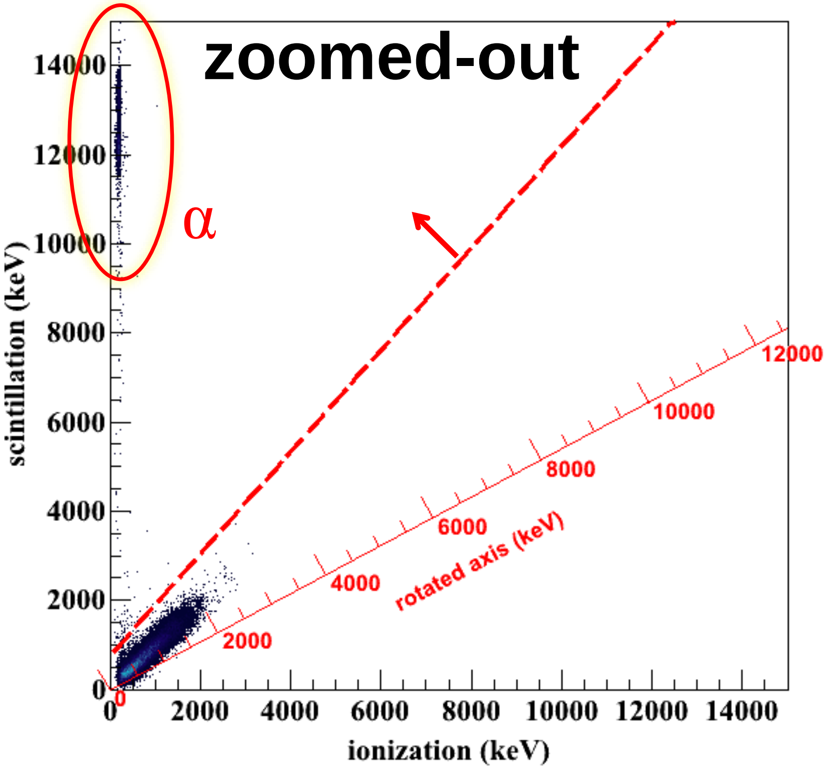
By now this is
a common technique in LXe



Rotation angle chosen to optimize energy resolution at 2615 keV

Low Background 2D SS Spectrum



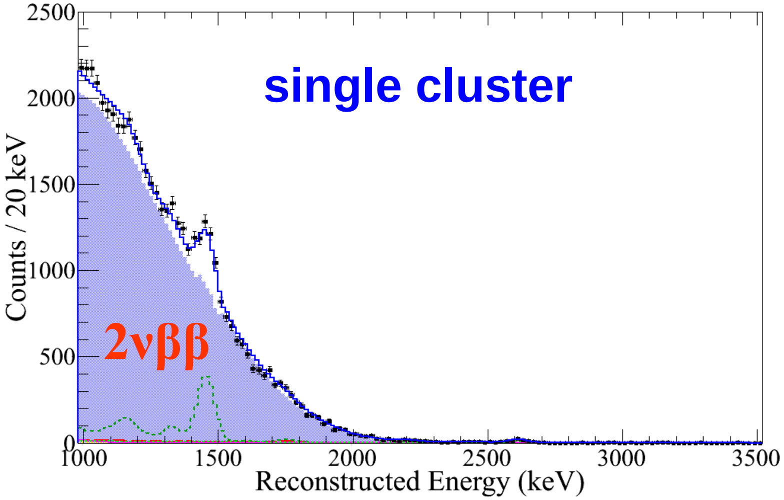


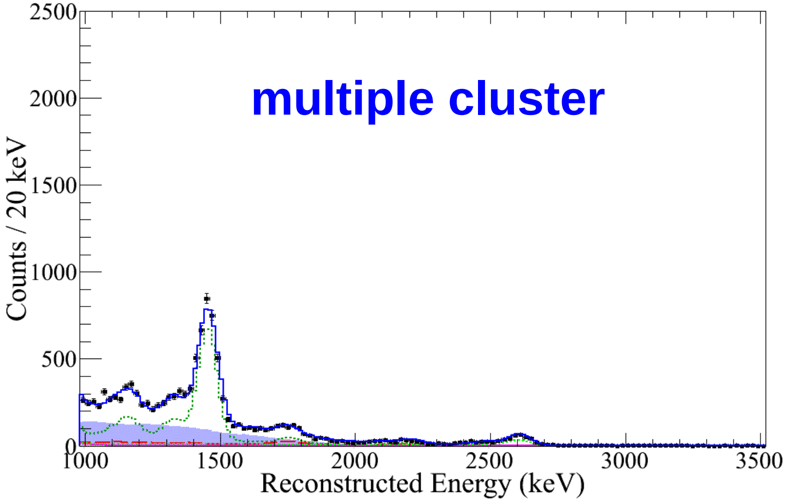
Events removed by diagonal cut:

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

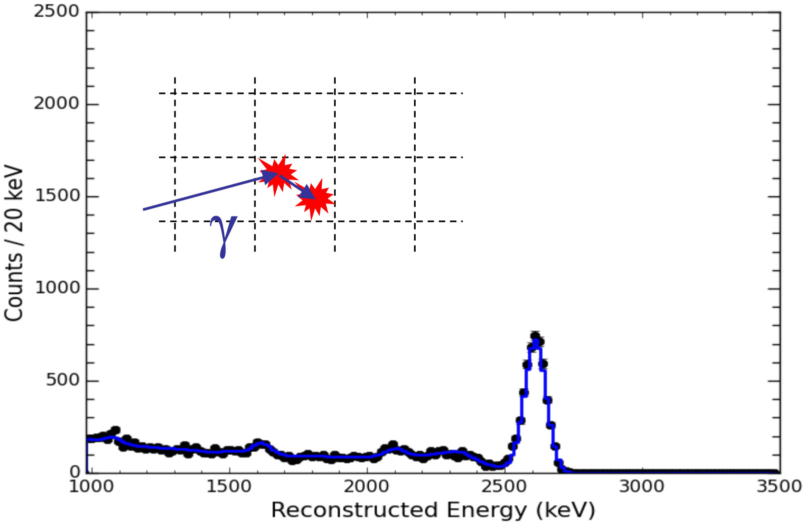
Using event multiplicity to recognize backgrounds

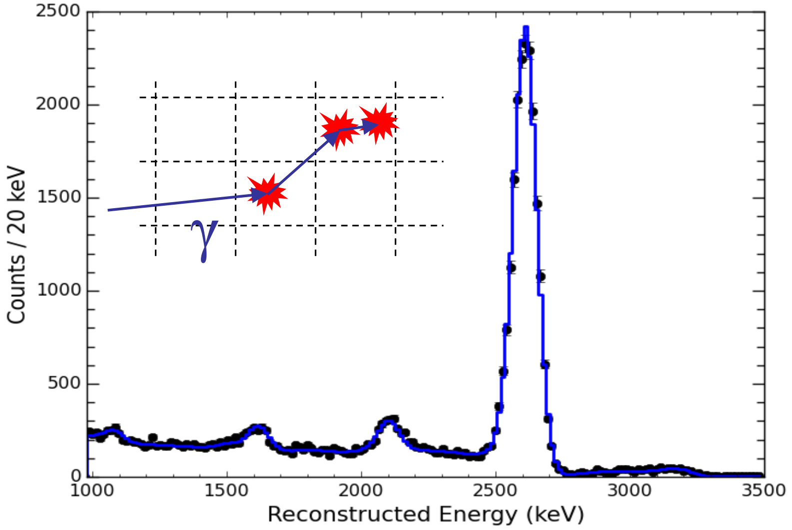
Low background data





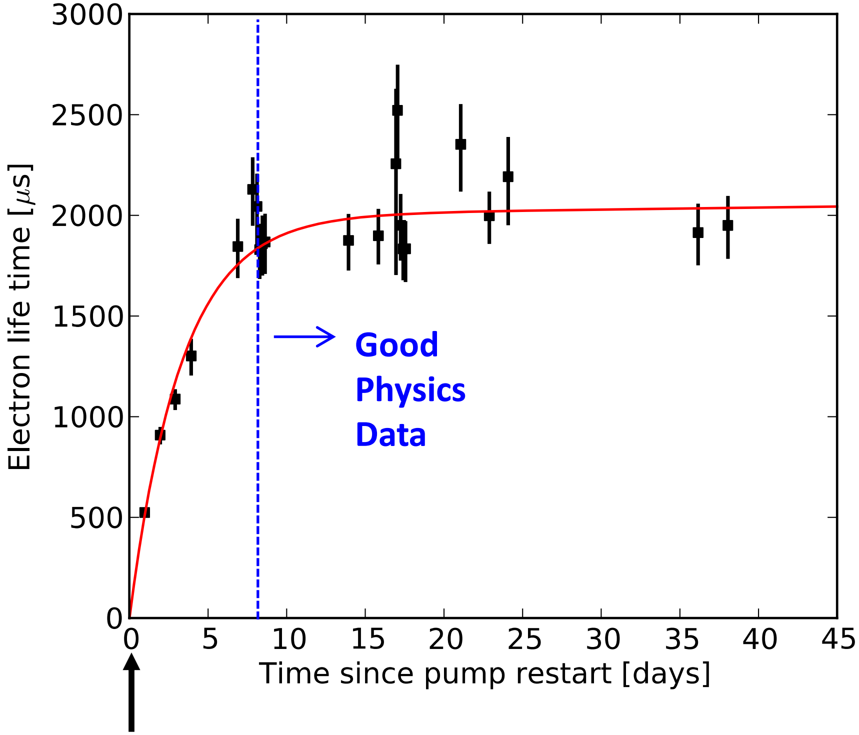
^{228}Th calibration source



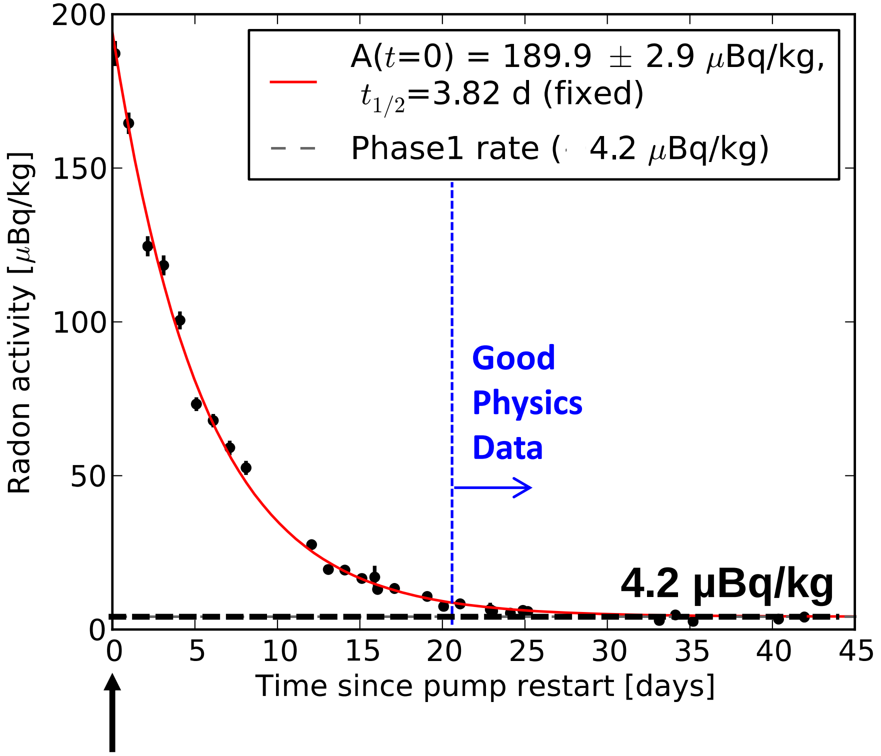


EXO-200 Phase-II Operation

- EXO-200 Phase-II operation begins on 31 Jan 2016, after enriched liquid xenon fill.
- Data shows that the detector reached excellent xenon purity and ultra-low internal Rn level shortly after restart.



31 Jan '16

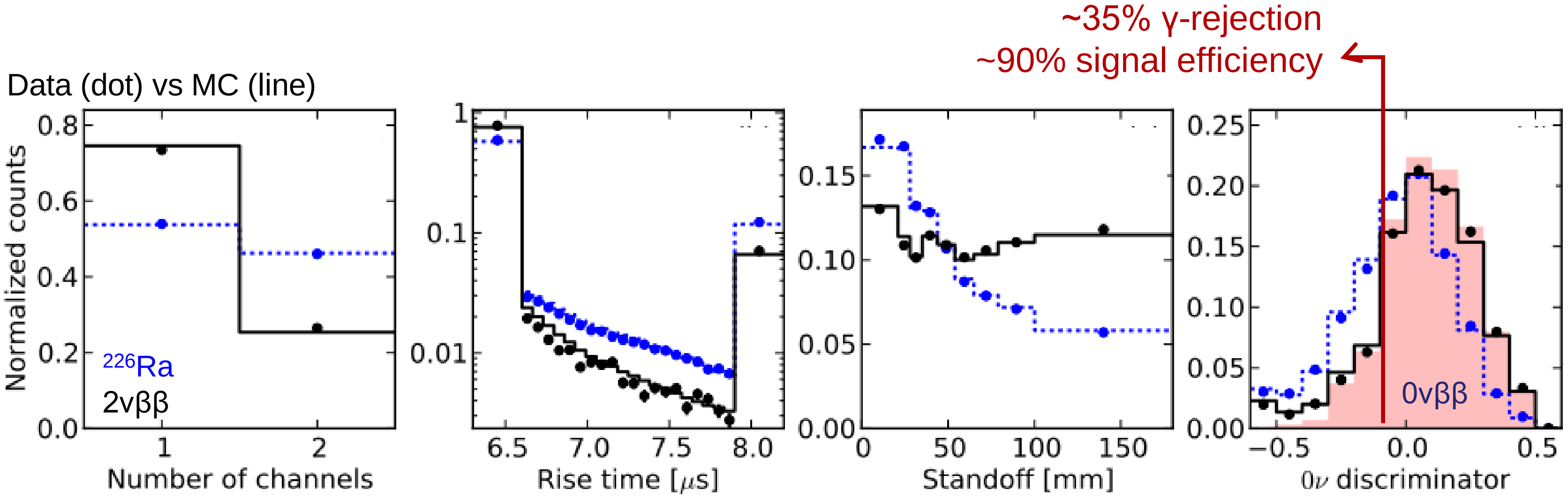


31 Jan '16

Squeezing more discriminating power out of SS events

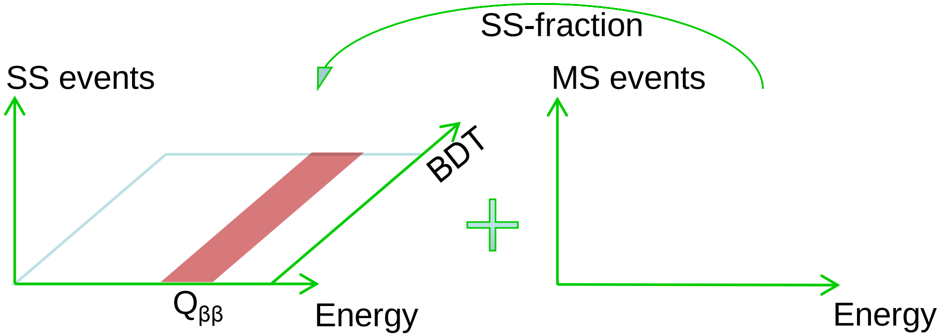
- ➔ **Use a boosted decision tree (BDT) fed more information about the diffuse nature of the SS event**

~35% γ-rejection
~90% signal efficiency



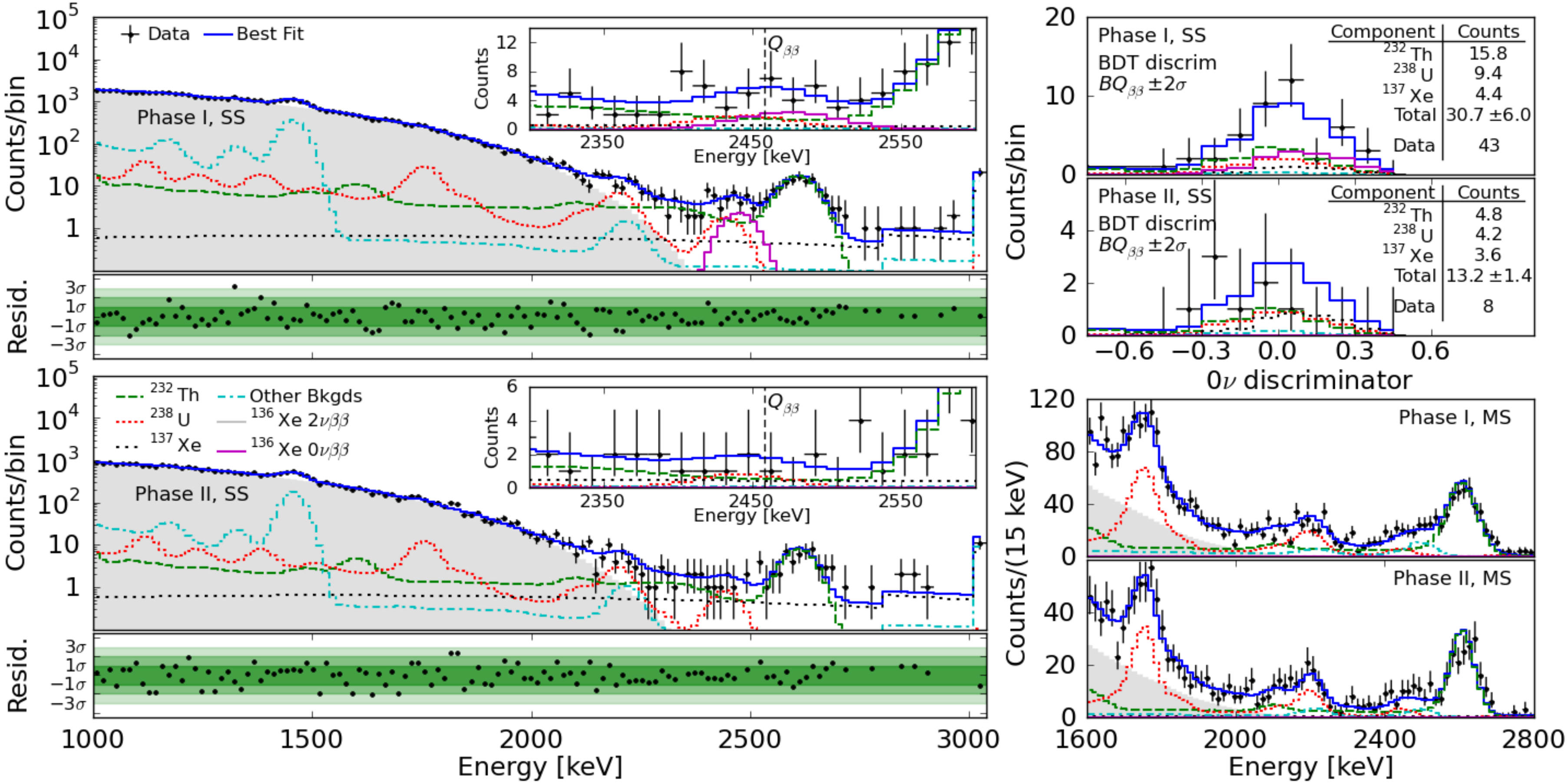
Fitting 0νββ discriminators

- **Energy**
- **SS/MS**
- ***BDT → ~15% sensitivity improvement***



Most Recent Results

- Background model + data → maximum likelihood fit
- Combine Phase I + Phase II profiles



Phase I, SS

Component	Counts
^{232}Th	15.8
^{238}U	9.4
^{137}Xe	4.4
Total	30.7 ±6.0
Data	43

Phase II, SS

Component	Counts
^{232}Th	4.8
^{238}U	4.2
^{137}Xe	3.6
Total	13.2 ±1.4
Data	8

- No statistically significant excess: combined p-value ~1.5σ

Combined analysis:

Total exposure = 177.6 kg·yr

Contributions to BQ±2σ	Phase I (cts)	Phase II (cts)
^{232}Th	15.8	4.8
^{238}U	9.4	4.2
^{137}Xe	4.4	3.6
Total	**30.7±6.0**	**13.2±1.4**
Data	***43***	***8***

Sensitivity of 3.7×10^{25} yr (90% CL)

$$T_{1/2}^{0\nu\beta\beta} > 1.8 \times 10^{25}\ \mathrm{yr}$$

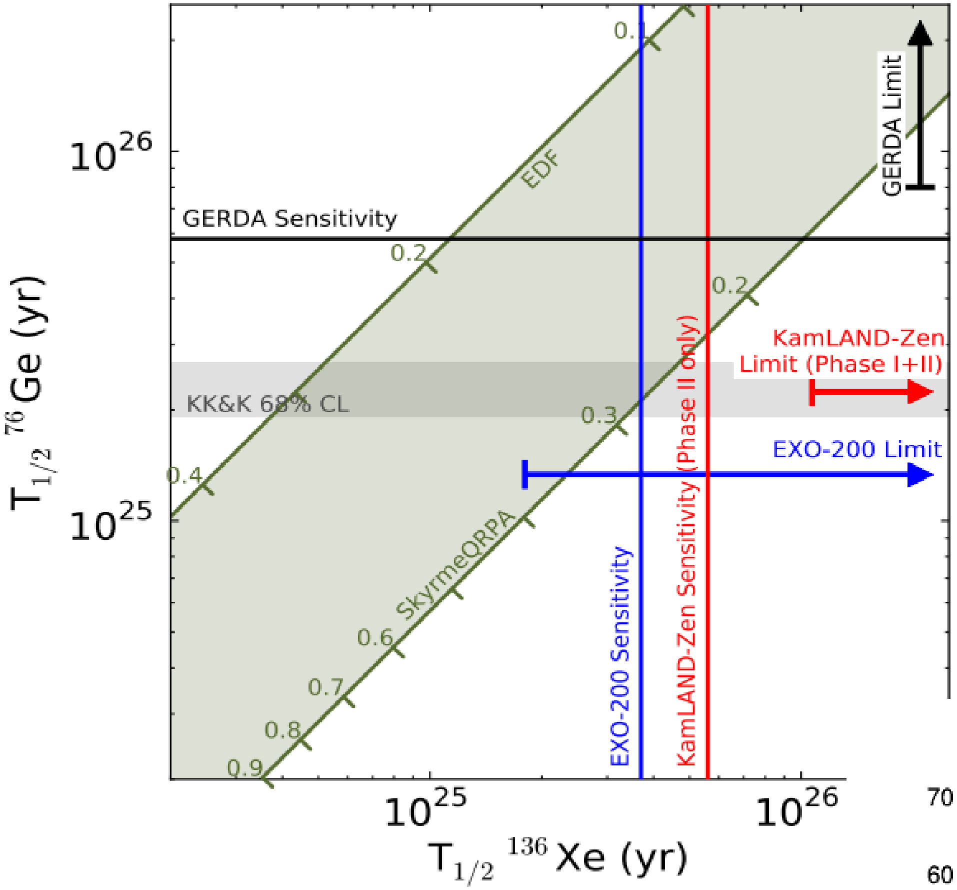
$$\langle m_{\beta\beta} \rangle < 147 - 398\ \mathrm{meV}$$

(90% C.L.)

arXiv: 1707.08707

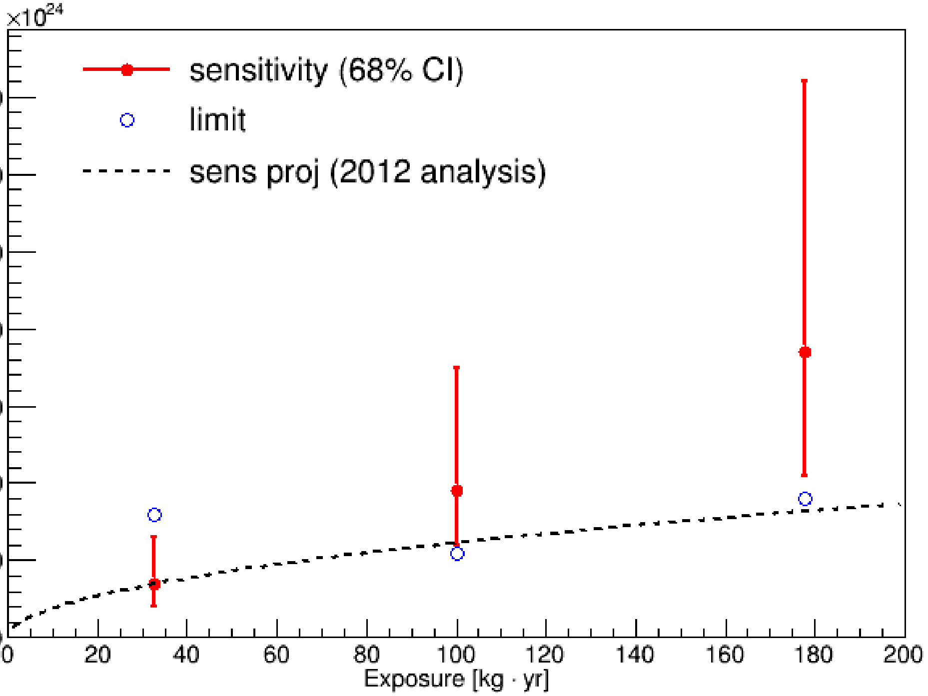
The sensitivity is really the correct way to estimate the worth of a measurement/experiment, because it contains all the information that can be/is used.

If one wants to use the incomplete picture of a single parameter notion then the "background index" is ~ $(1.5\pm0.2)\times10^{-3}$ / (kg·yr·keV)



A brief history of EXO-200 (results)

	sensitivity	limit
PRL 109, 032505 (2012)	**0.7×10^{25}**	**1.6×10^{25}**
Nature 510, 229 (2014)	**1.9×10^{25}**	**1.1×10^{25}**
arXiv: 1707.08707 (2017)	**3.8×10^{25}**	**1.8×10^{25}**



The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

“RECOMMENDATION II

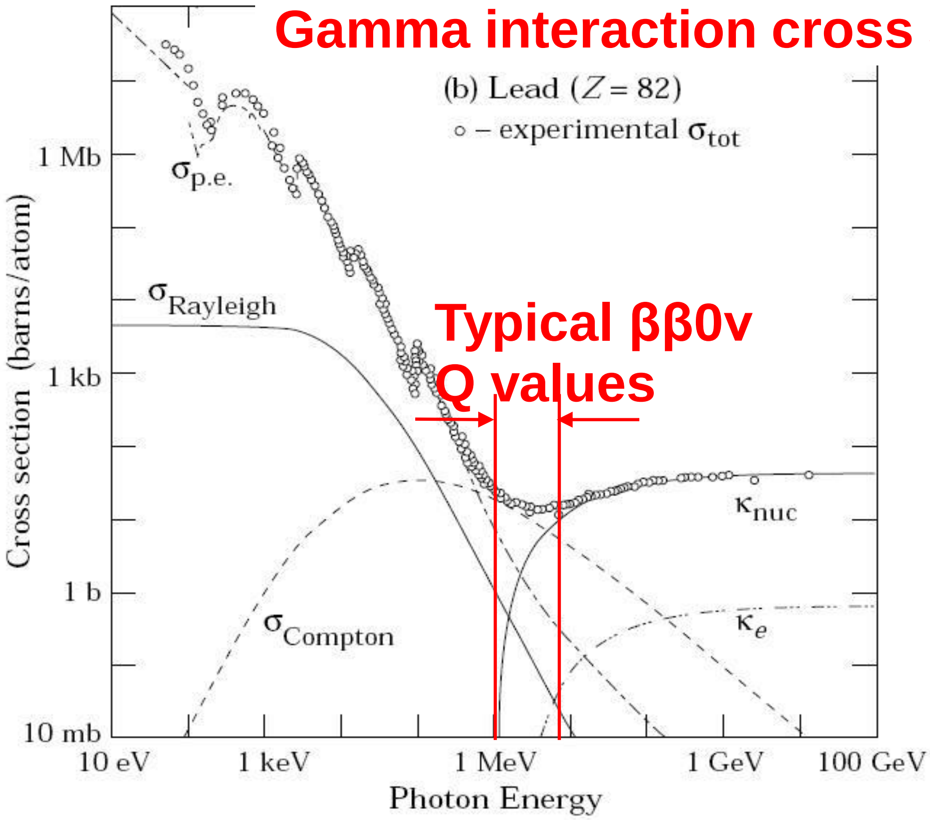
The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.”

Initiative B

“We recommend vigorous detector and accelerator R&D in support of the neutrinoless double beta decay program and the EIC.”

Shielding a detector from gammas is difficult!



Gamma interaction cross section

Typical ββ0ν Q values

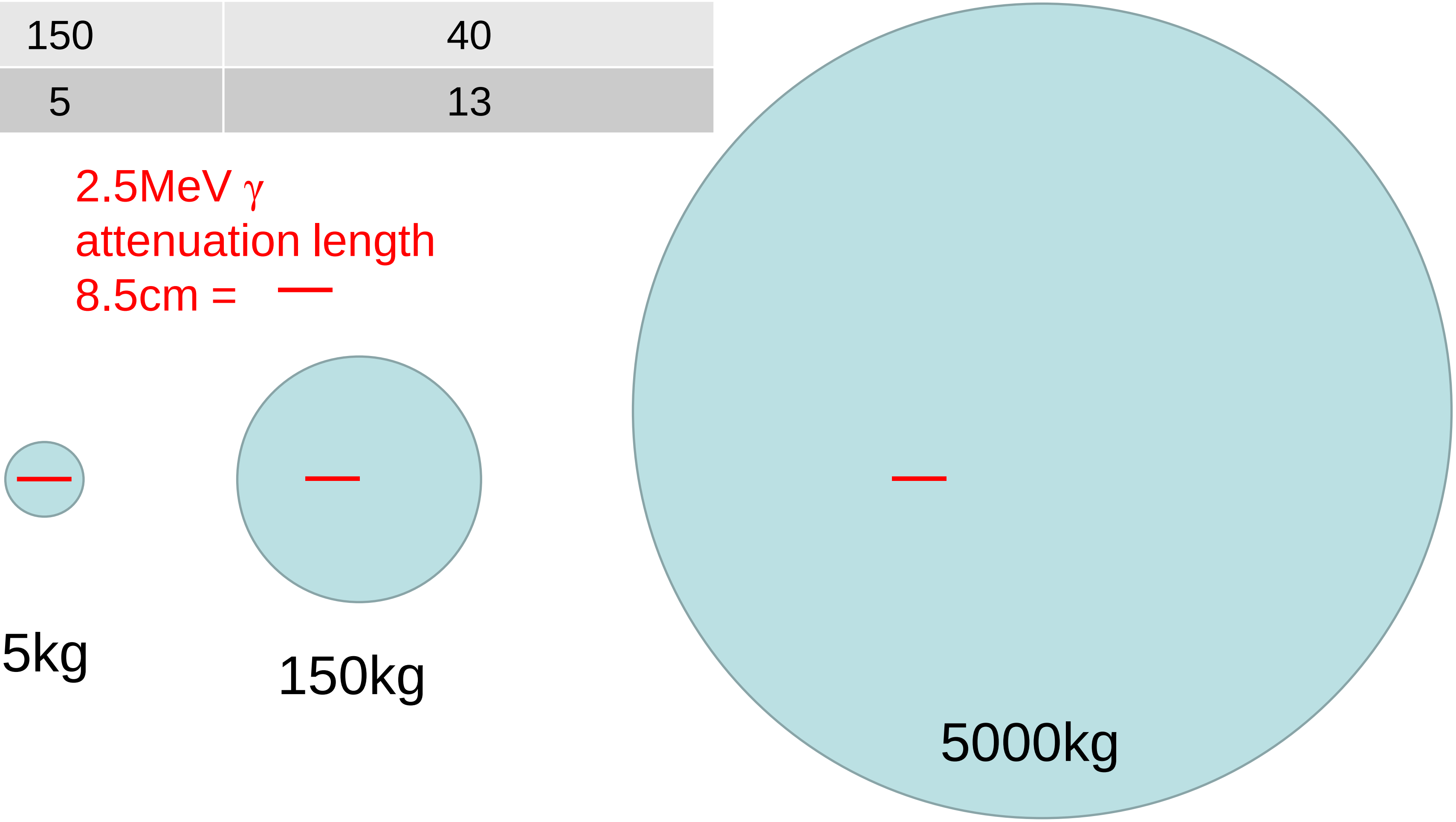
Example:
γ interaction length
in Ge is 4.6 cm,
comparable to the size
of a germanium detector.

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

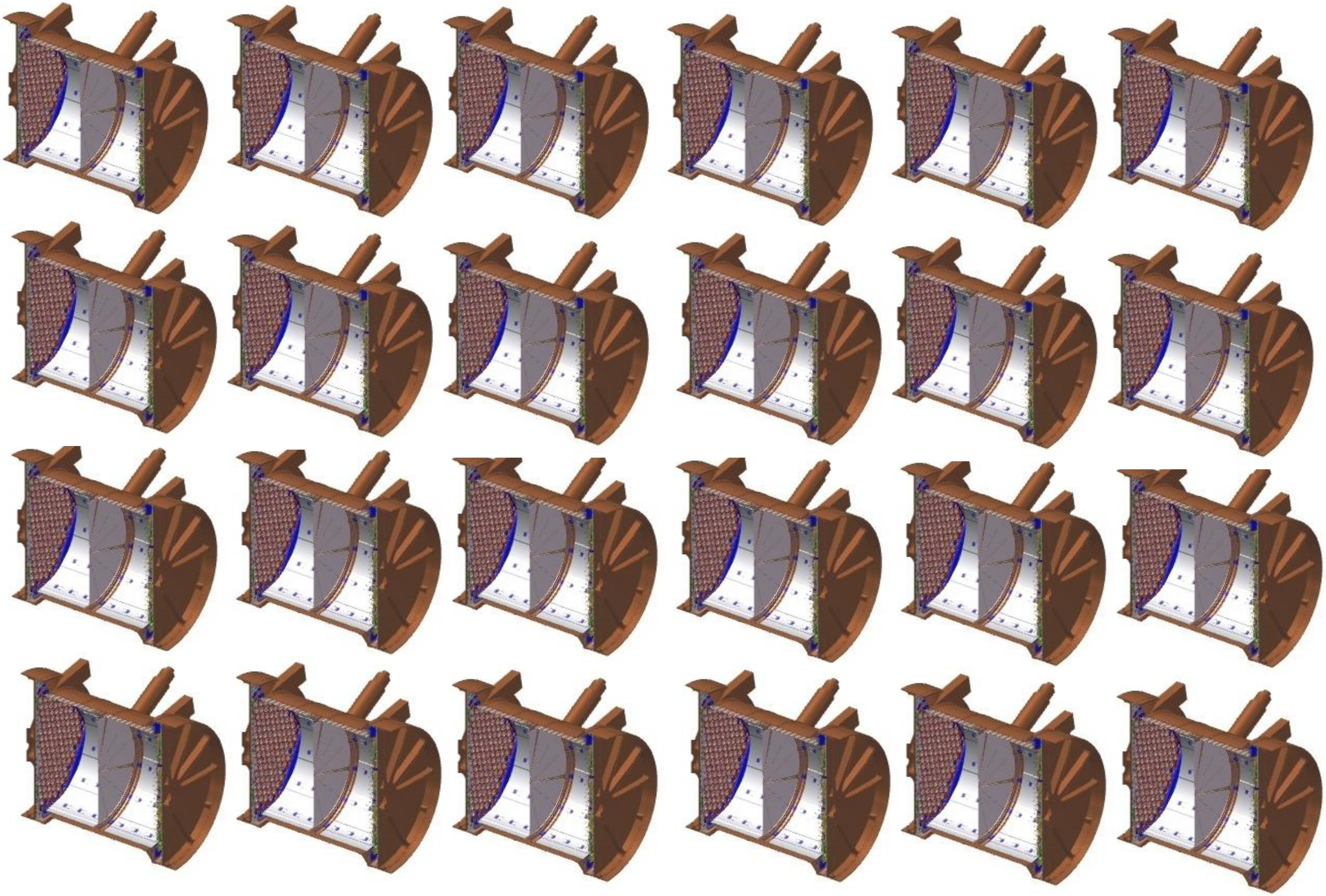
LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

2.5MeV γ
attenuation length
8.5cm = —



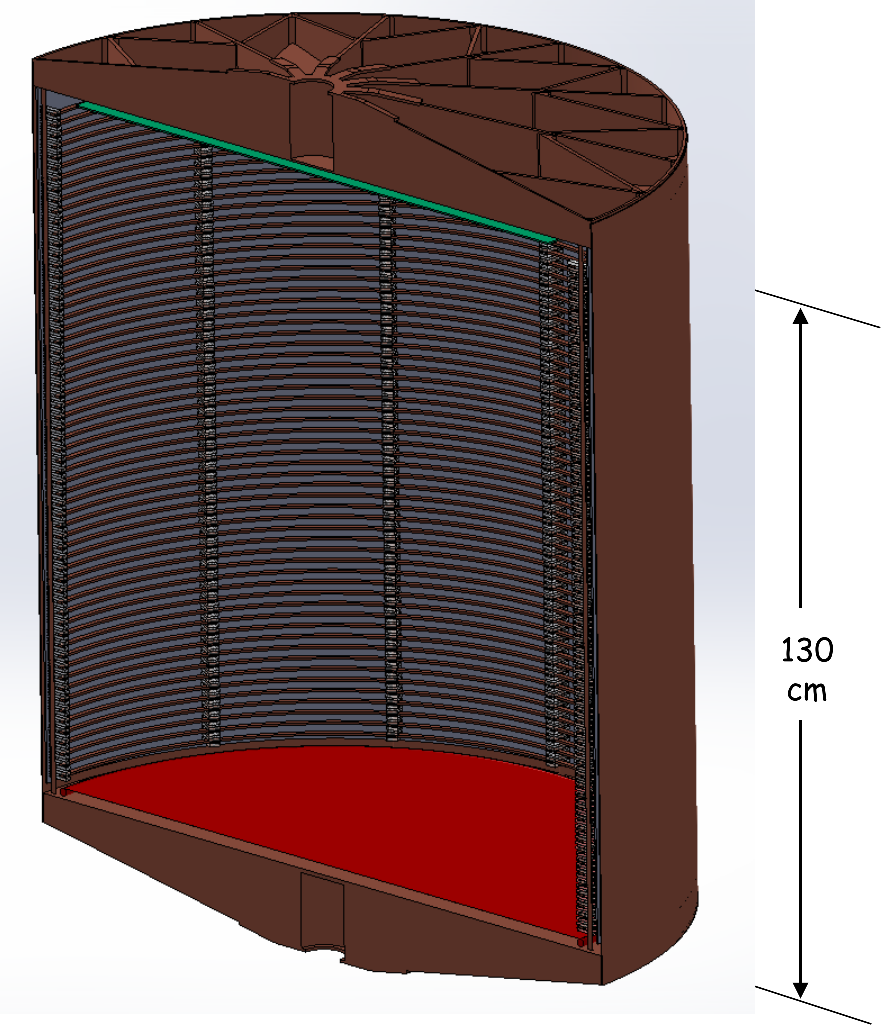
This works best for a monolithic detector

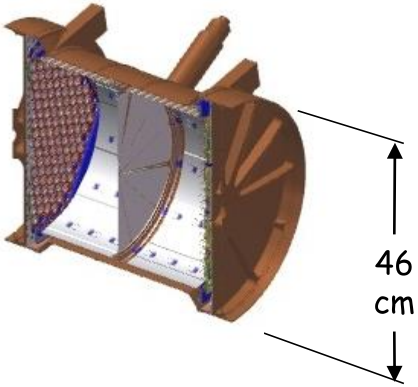
The most conservative (and wrong) design for nEXO



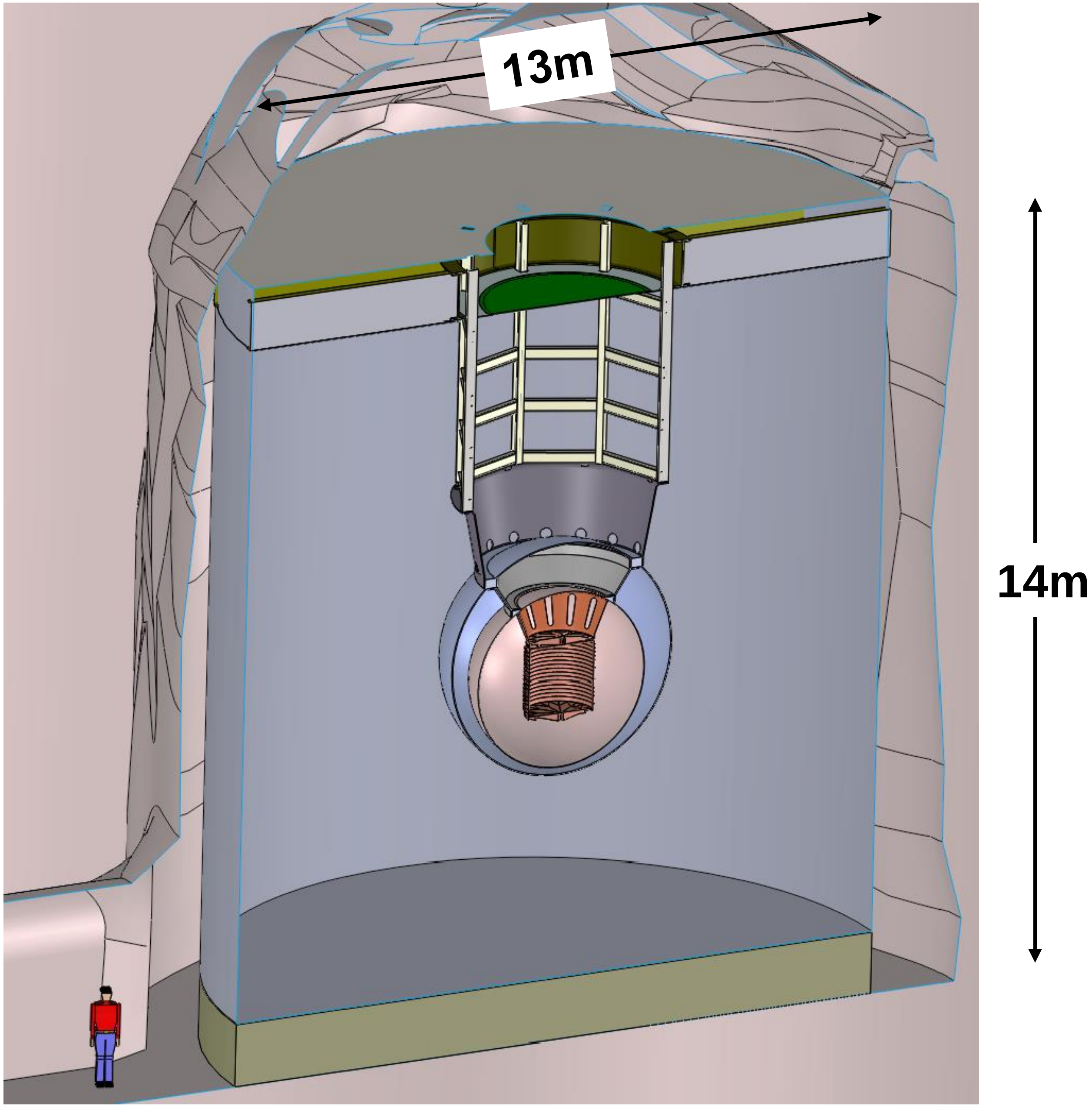
The nEXO detector

A 5000 kg enriched LXe TPC,
***directly extrapolated from* EXO-200**

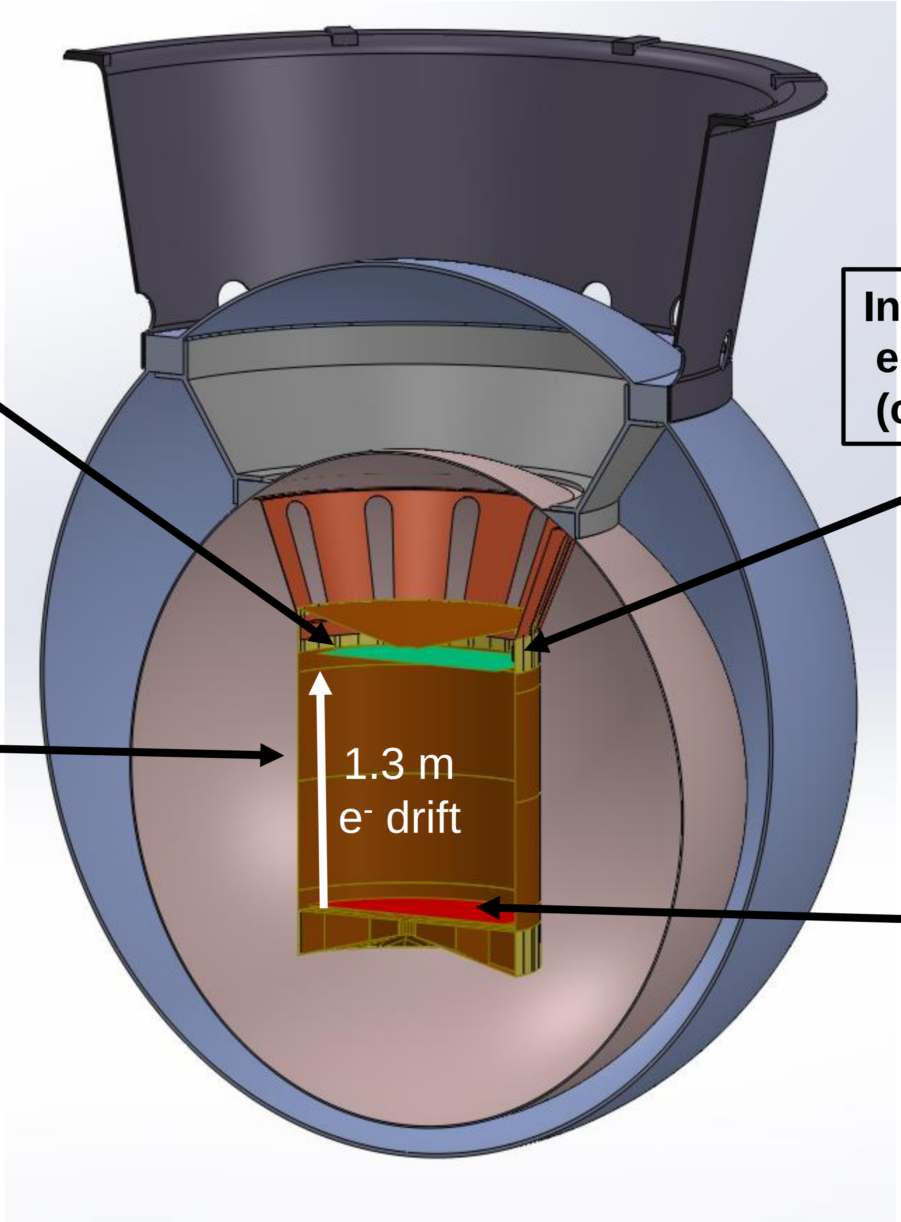




Preliminary artist view of nEXO in the SNOlab Cryopit



The nEXO baseline TPC

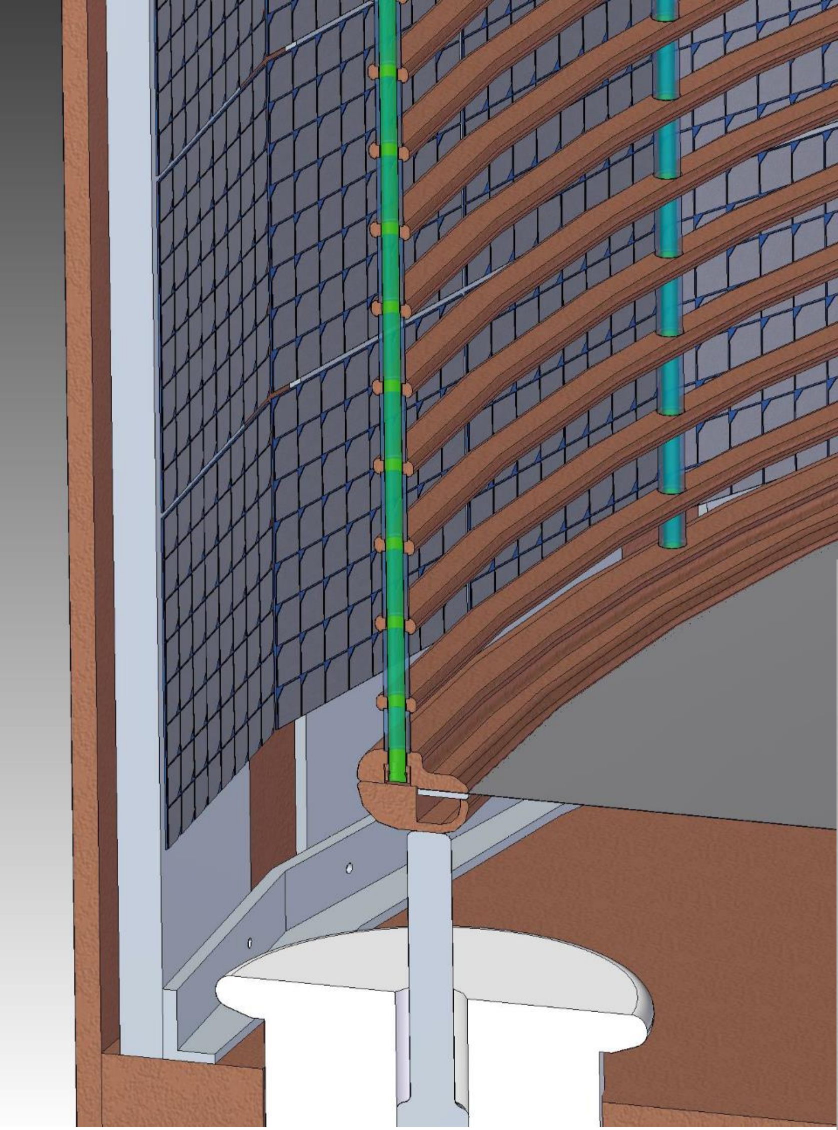


Charge readout strips (anode)

In LXe electronics (charge and SiPMs)

SiPM `staves' plastering barrel behind field-shaping rings

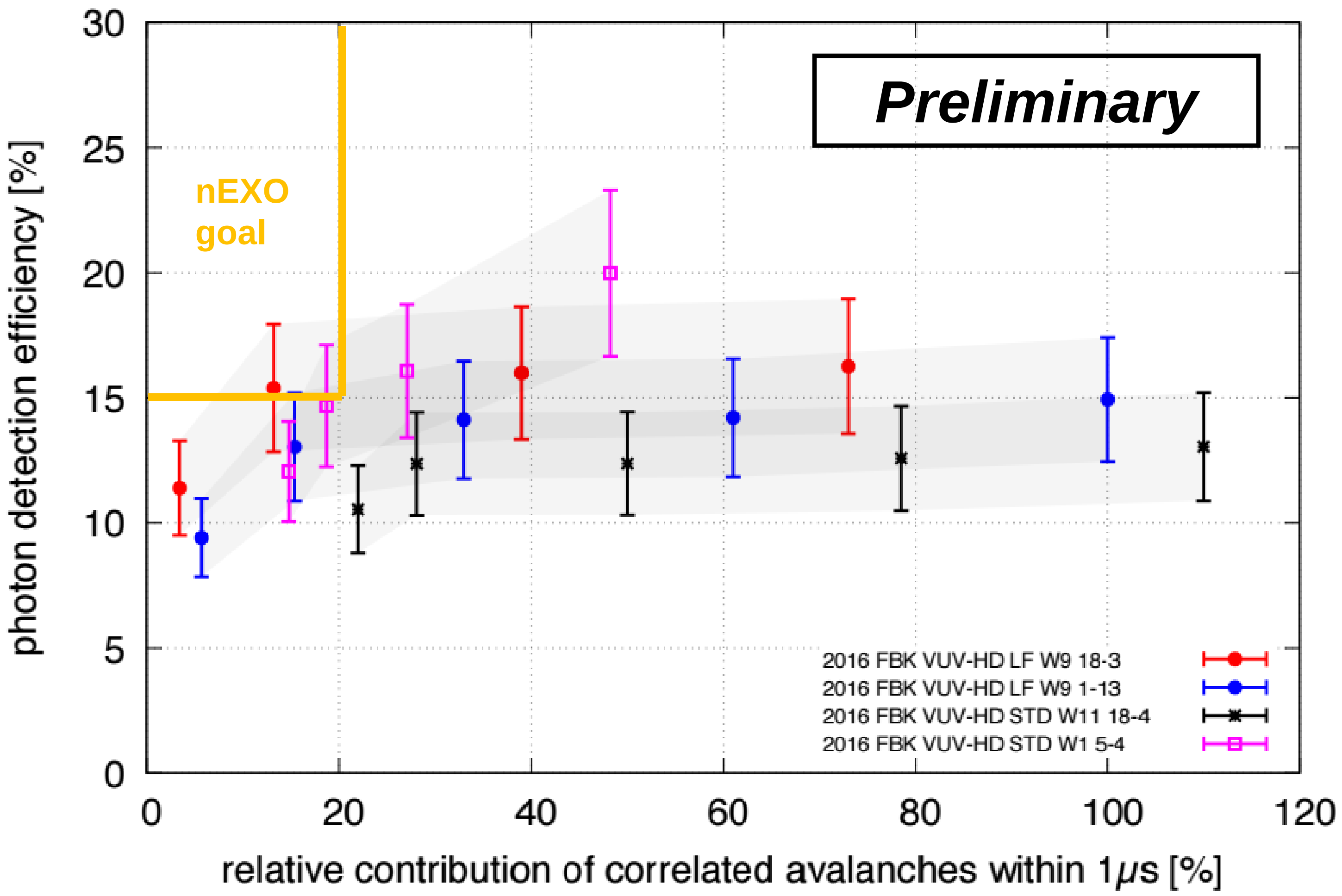
Cathode



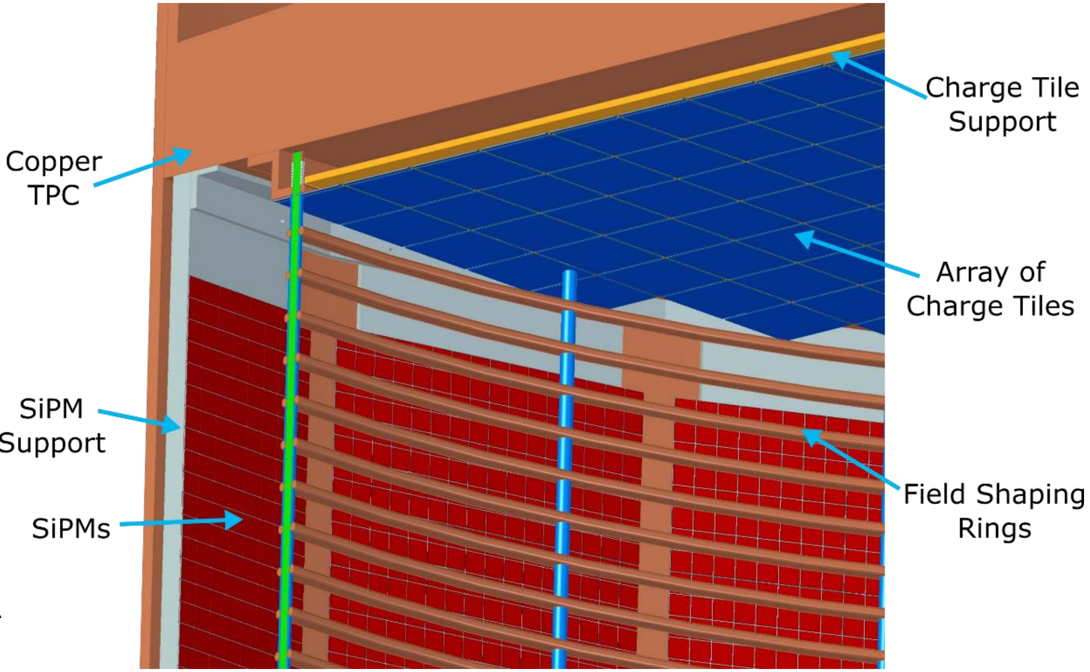
Need ~4m^2 of VUV-sensitive SiPMs

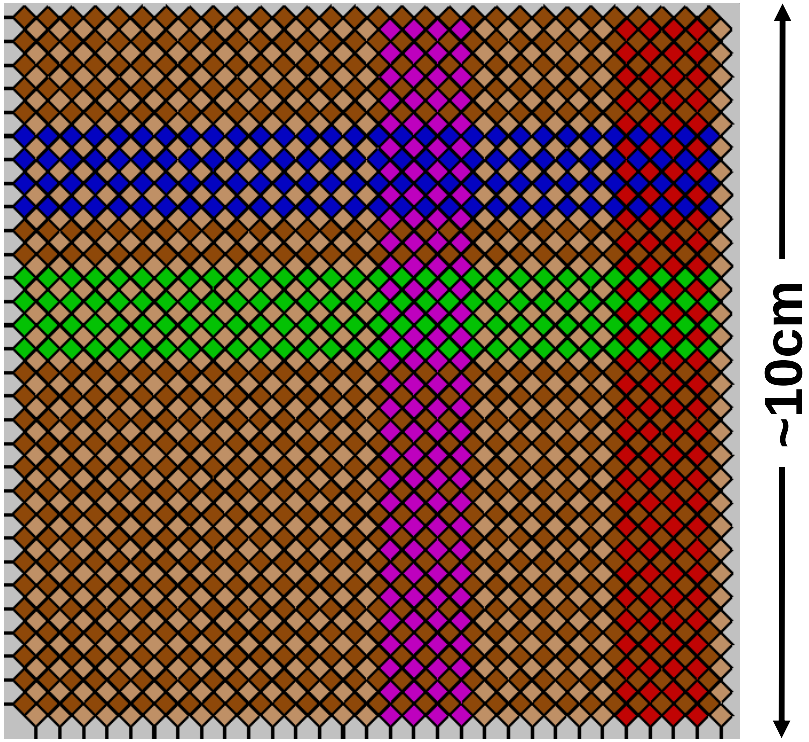
At least one type of 1cm^2 VUV devices now match our desired properties, with a bias requirement ~30V

(as opposed to the 1500V of EXO-200 APDs)



Charge will be collected on arrays of strips fabricated onto low background dielectric wafers (baseline is silica)

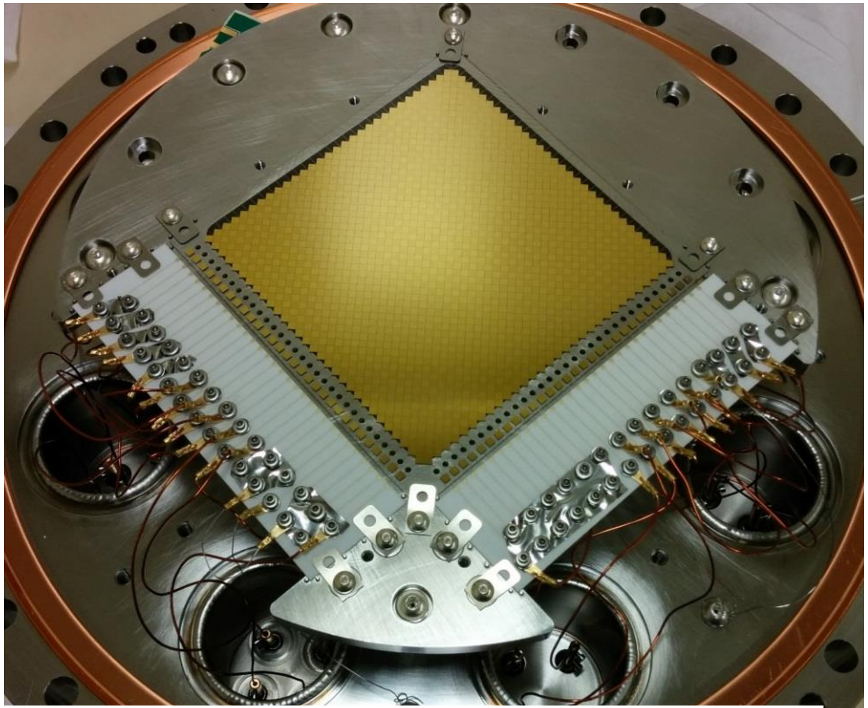


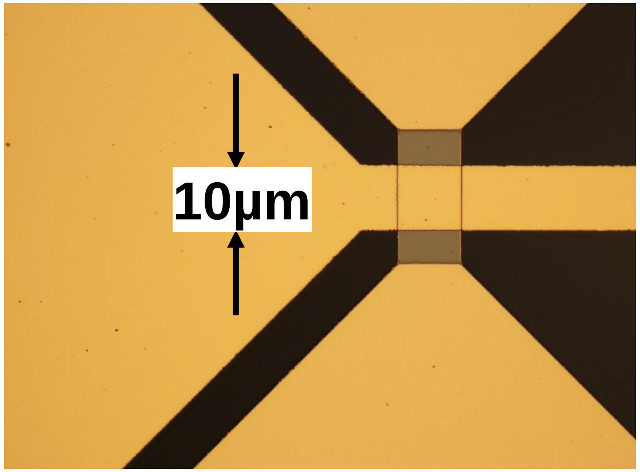


- Self-supporting/no tension
- Built-on electronics (on back)
- Far fewer cables
- Ultimately more reliable, lower noise, lower activity

Test of prototypes in LXe ongoing

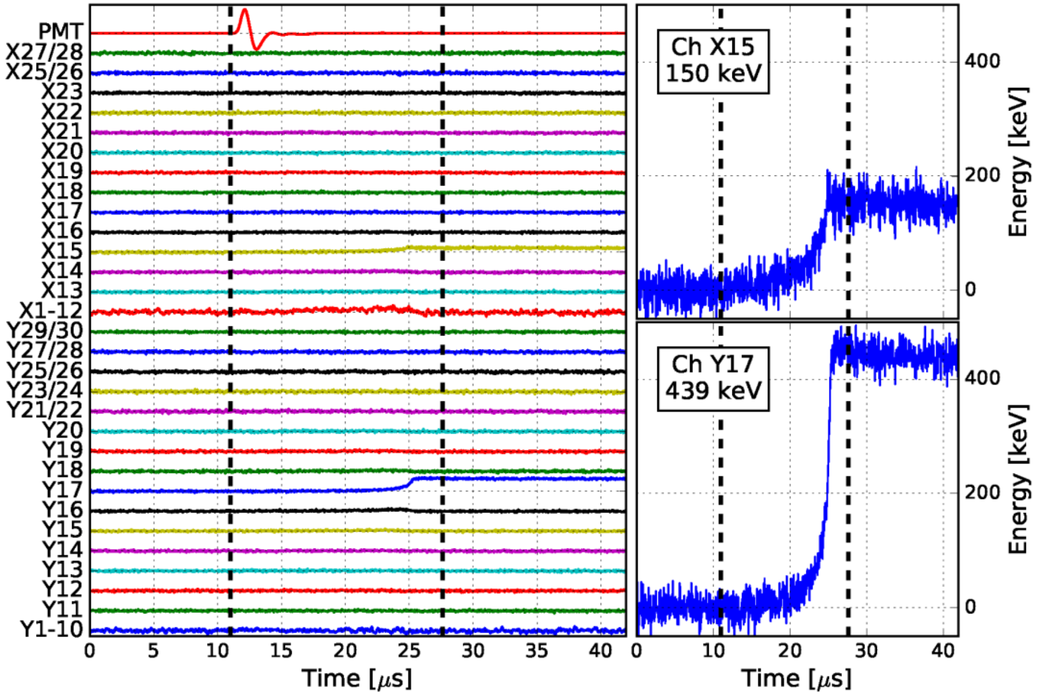
M.Jewell et al., “Characterization of an Ionization Readout Tile for nEXO”, *arXiv:1710.05109, 16 Oct 2017.*



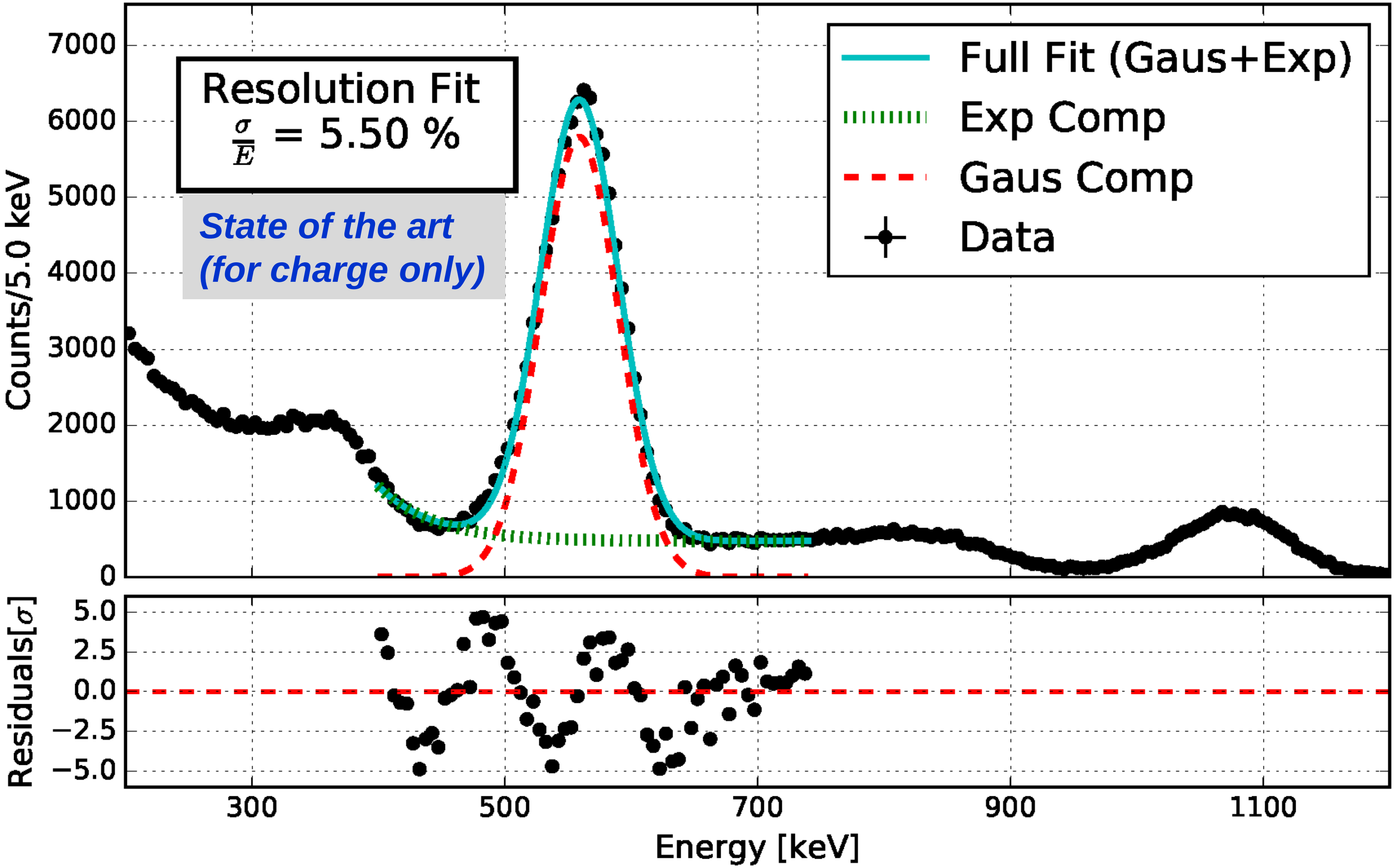


Max metallization cover with min capacitance:

80 fF at crossings
0.86 pF between adjacent strips



^{207}Bi, 570 keV, charge only



State of the art
(for charge only)

Soon we will have LXe data with tiles (charge) and SiPMs (scintillation) readout simultaneously

nEXO sensitivity and discovery potential

J.B. Albert et al.,
"Sensitivity and Discovery Potential of nEXO to Neutrinoless Double Beta Decay",
arXiv:1710.05075, 16 Oct 2017.

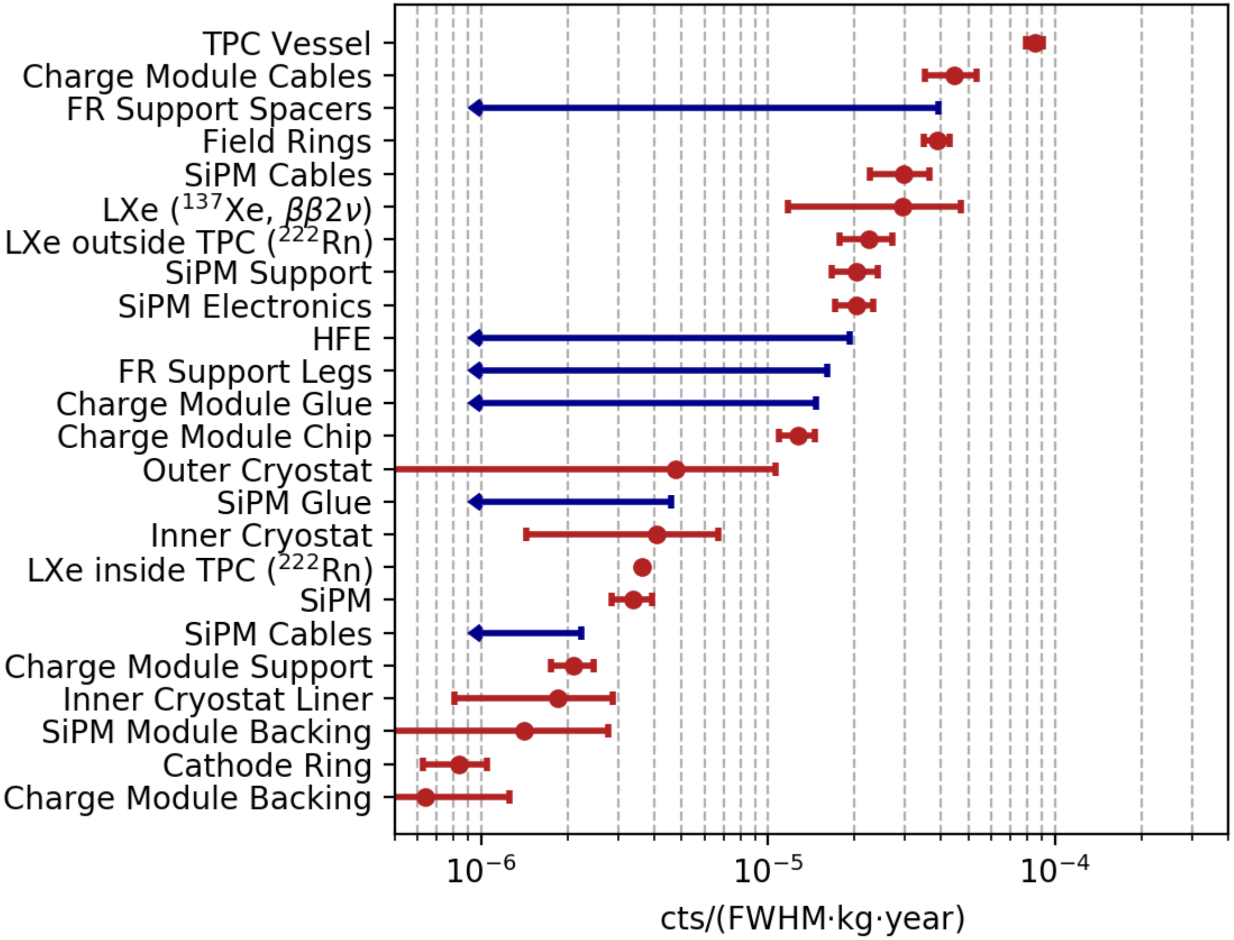
nEXO is unique among future experiments in that it does *not* require assuming new or better materials* in order to reach the design sensitivity

What goes in the model is

- **the geometry,**
- **the radioactivity measured on existing materials (some from EXO-200 some "freshly" measured)**
- **physics well known to GEANT (like Compton scattering)**

*** Except for the assumption that the electron lifetime will increase from ~3ms (EXO-200) to 10ms. This appears comfortable, having removed much of the plastics from the TPC.**

While our material screening techniques have improved since EXO-200 construction days, for some materials we still have only upper limits

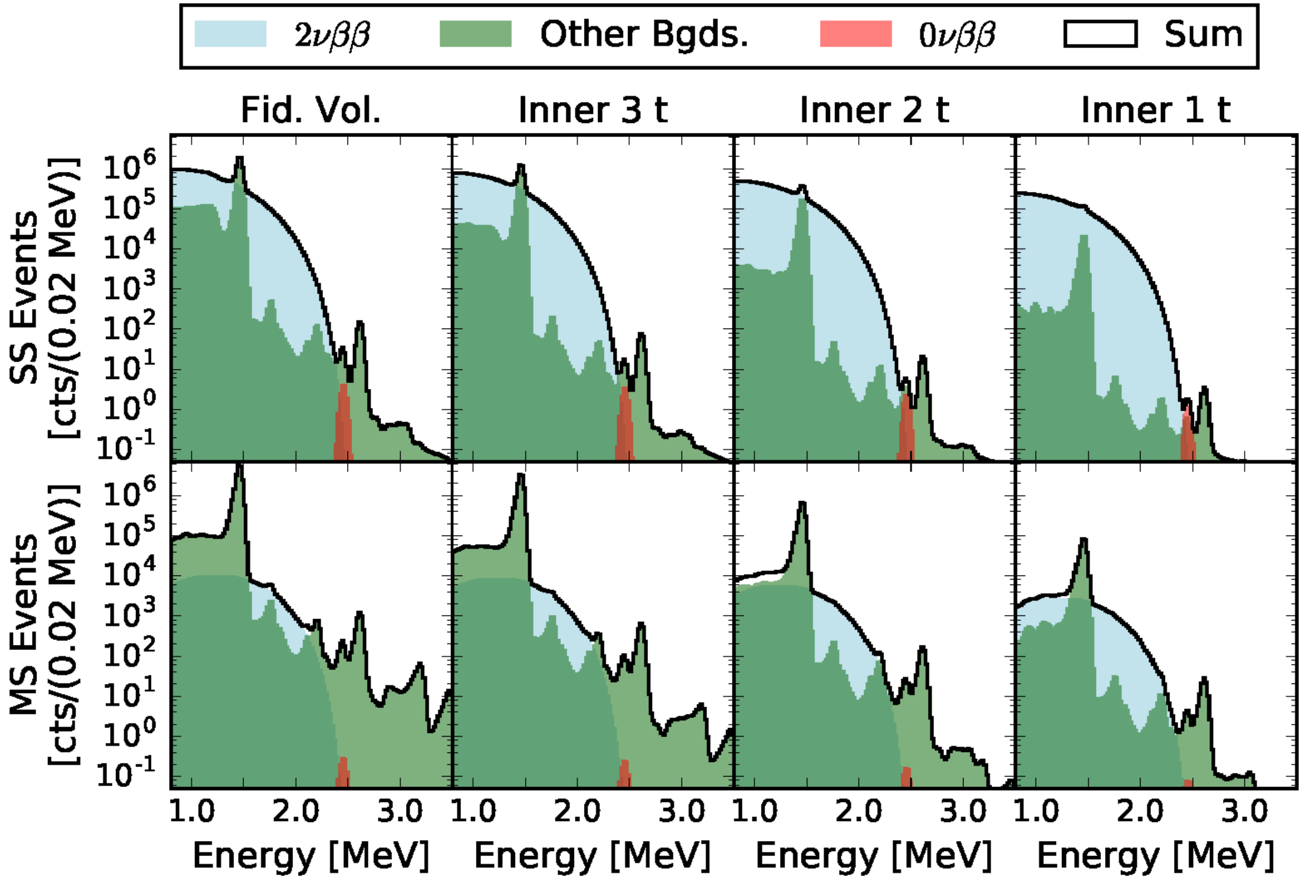


Particularly in the larger nEXO, background identification and rejection fully use a fit that considers simultaneously energy, multiplicity and event position.

➔ The power of the homogeneous detector, this is not just a calorimetric measurement!

SS

MS

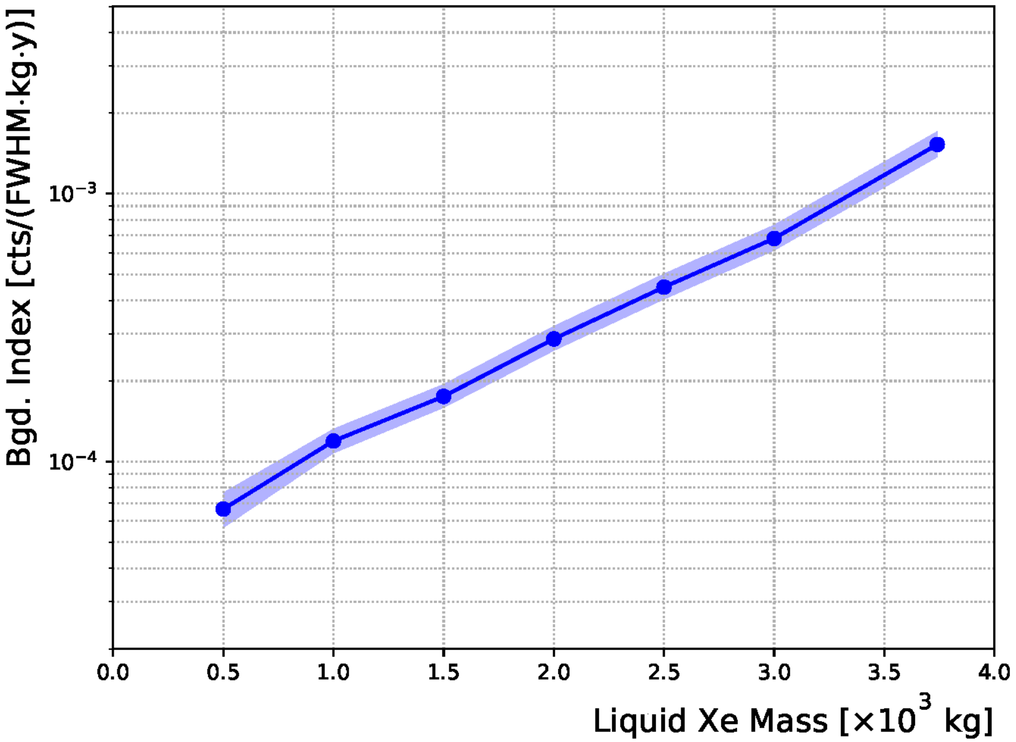


10 yr data, $0\nu\beta\beta$ corresponding to $T^{1/2}=5.7\times10^{27}$ yr

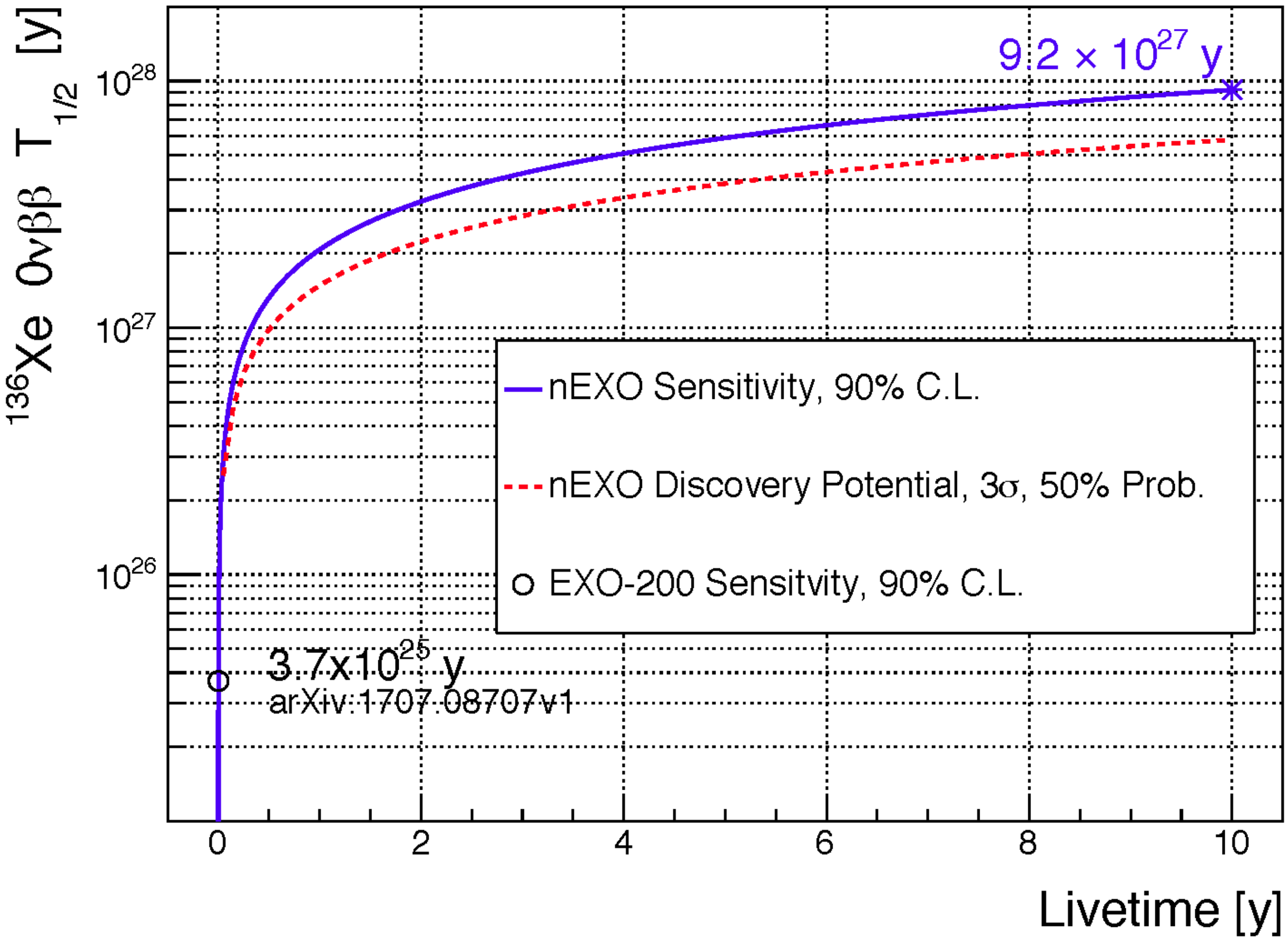
So, a simple “background index” is not the entire story.

- *The innermost LXe mostly measures signal*
- *The outermost LXe mostly measures background*
- *The overall fit know all this (and more) very well and uses all the information available to obtain the best sensitivity*

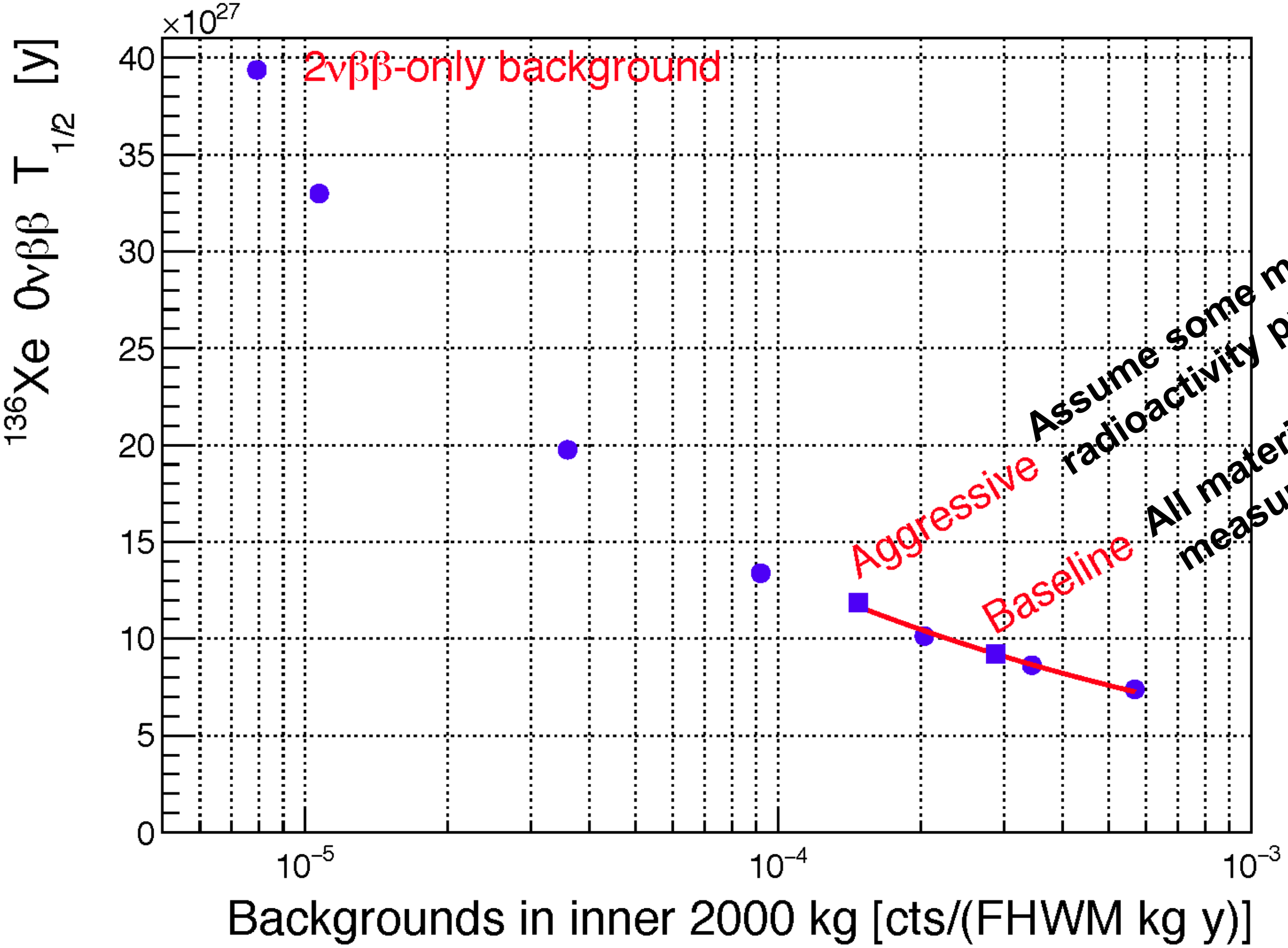
Nevertheless, for the aficionados of “background index”, here it is, as a function of depth in the TPC. For the inner 3000 kg this is better than 10^{-3} (FWHM kg yr)$^{-1}$



Sensitivity as a function of time for the baseline design



How does the sensitivity scale with background assumptions?

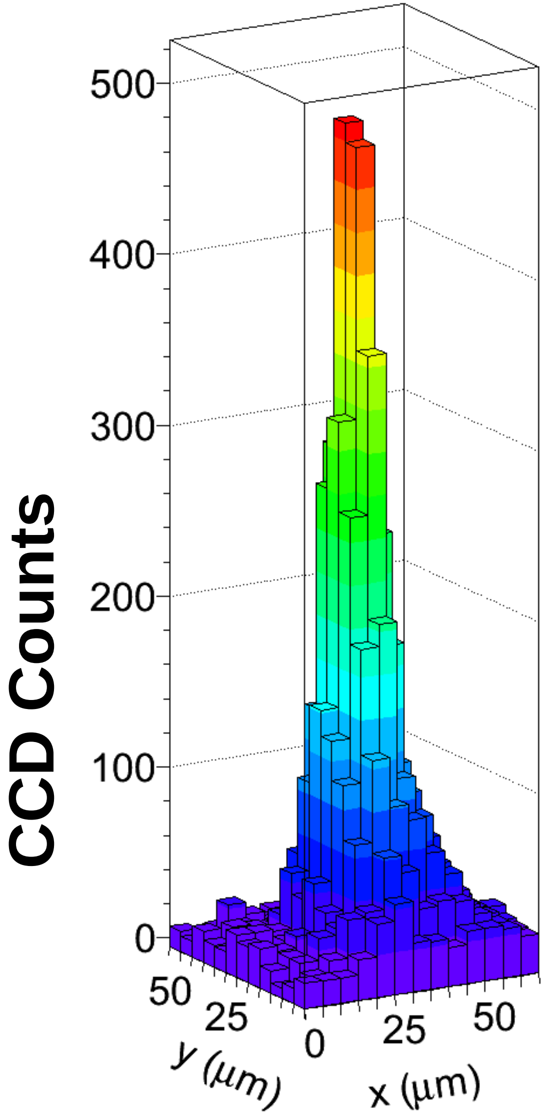


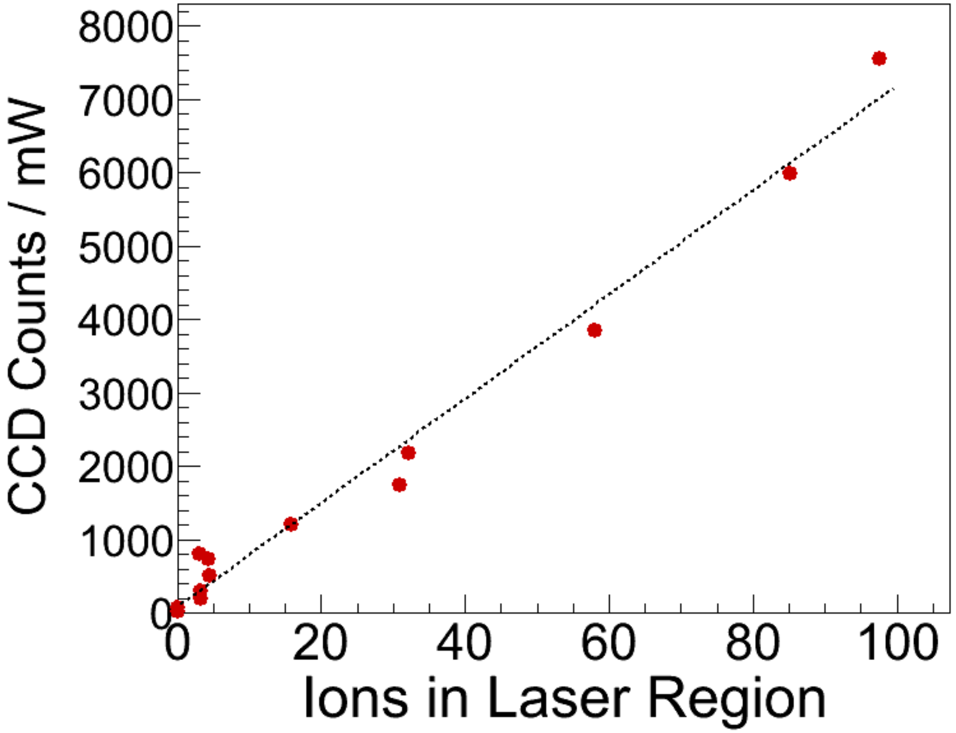
Assume some material radioactivity progress

All materials actually measured (previous slide)

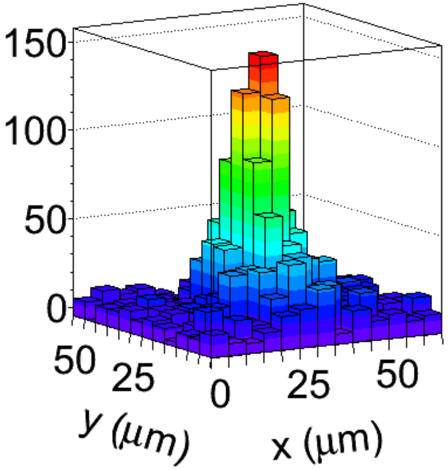
Background-free detection of a few Ba atoms has beed demonstrated

≤ 58-atom

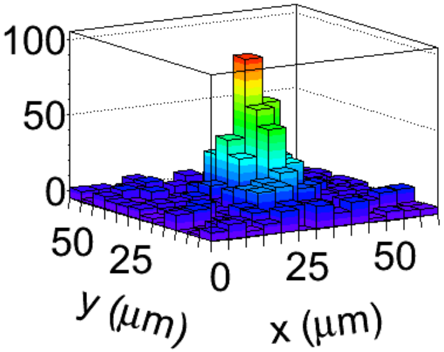




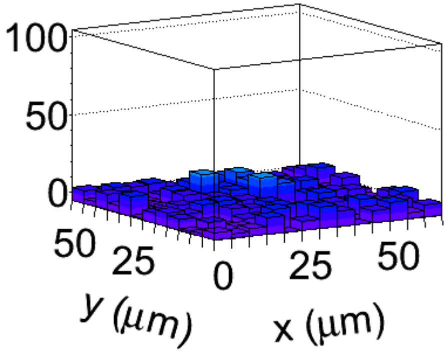
≤ 15-atom



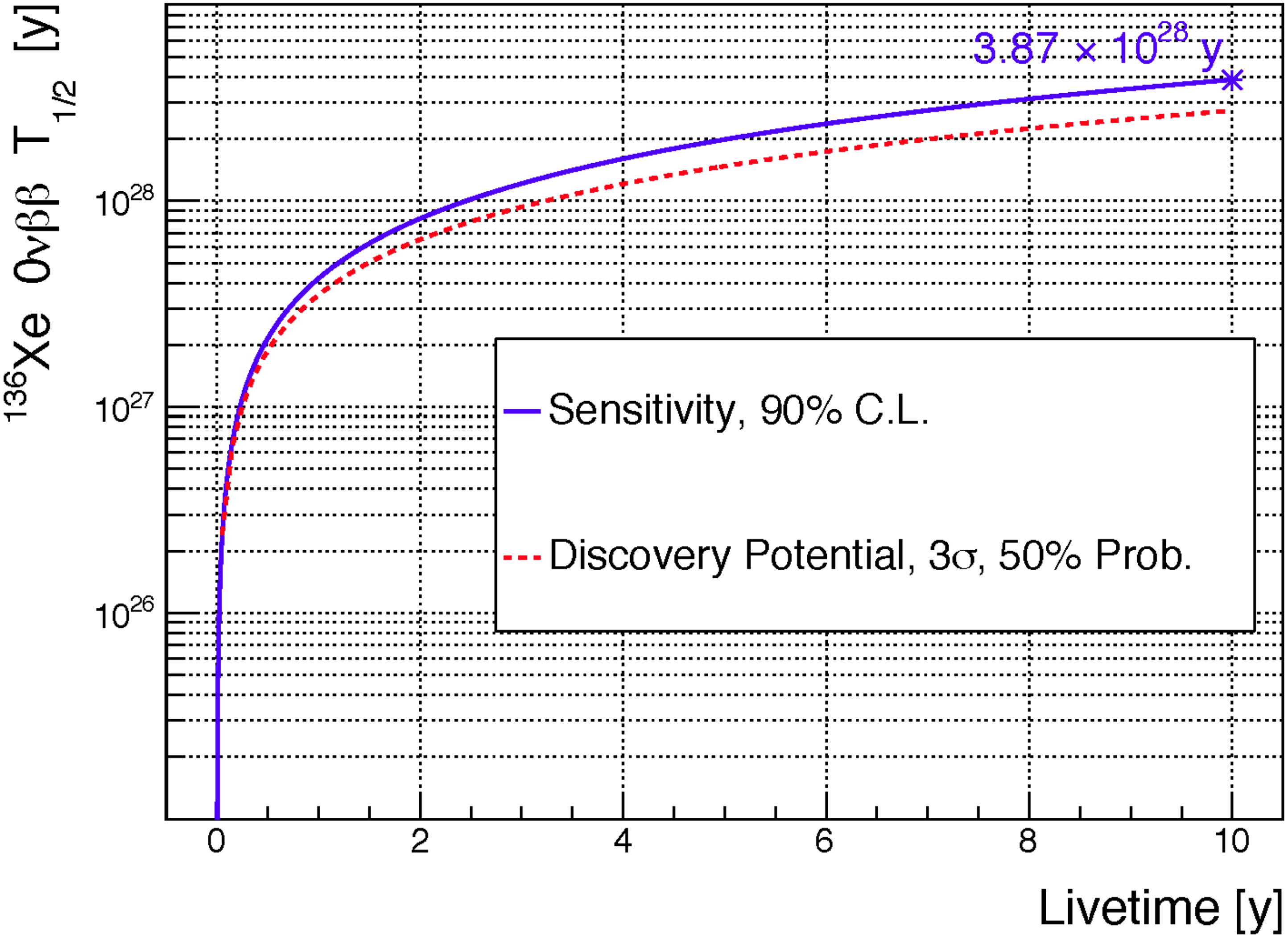
≤ 4-atom



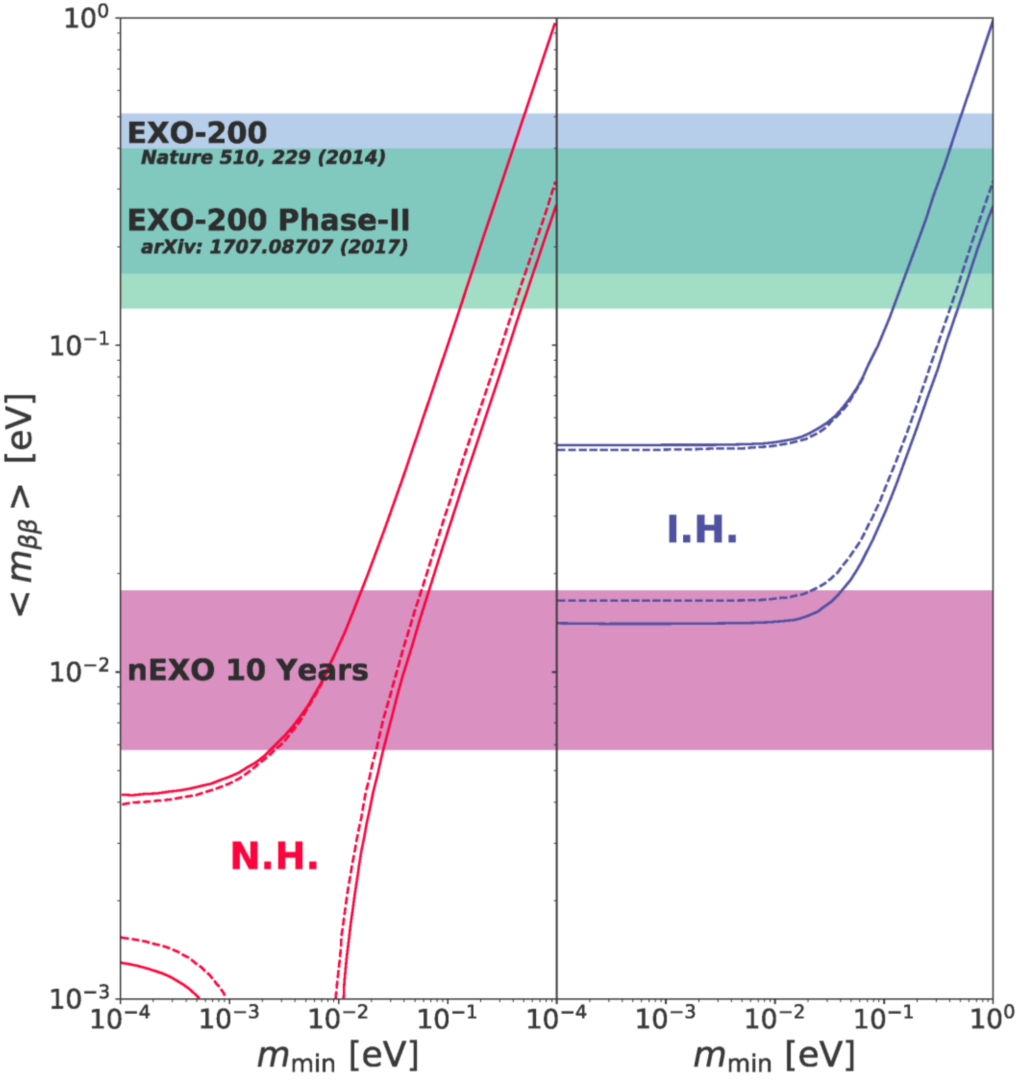
0-atom



The Ba tagging technique, that is not yet demonstrated, may provide an upgrade path, with ultimate sensitivity ~4x10^{28} yr



Back to the baseline design: Majorana mass sensitivity



NME used	
IBM-2	J. Barea et al, Phys. Rev. C91, 034304 (2015)
Skyrme-QRPA	M.T. Mustonen & J. Engel, Phys. Rev. C87, 064302 (2013)
QRPA	F. Šimkovic et al, Phys. Rev. C87, 045501 (2013)
RQRPA-UCOM	A.Faessler et al, J. Phys. G39, 124006 (2012)
NREDF	N. Lopez-Vaquero et al. Phys.Rev.Lett. 111, 142501 (2013)
REDF	J. M. Yao et al, Phys. Rev. C91, 024316 (2015)
ISM	J. Menéndez et al, Nucl. Phys. A818, 139 (2009)

Assume $g_A = 1.27$

Conclusions

- **EXO-200 was the first 100kg-class experiment to run and demonstrated the power of a large and homogeneous LXe TPC**
- **Run II is in progress, new results just reported**
- **This is clearly the way to go, as the power of the technique will further improve going to the ton scale**
- **Substantial R&D is in progress to fine-tune the design of nEXO, a 5-ton detector that will drastically advance the field, entirely covering the inverted hierarchy and with substantial sensitivity to the normal one**
- **There is also an upgrade path, using Ba tagging, that promises a background-free measurement all the way to ~4×10^{28} yr**

The nEXO Collaboration

University of Alabama, Tuscaloosa AL, USA
M Hughes, I Ostrovskiy, A Piepke, AK Soma, V Veeraraghavan
University of Bern, Switzerland — J-L Vuilleumier
Brookhaven National Laboratory, Upton NY, USA
M Chiu, G Giacomini, V Radeka, E Raguzin, T Rao, S Rescia, T Tsang
California Institute of Technology, Pasadena CA, USA — P Vogel
Carleton University, Ottawa ON, Canada — I Badhrees,
M Bowcock, W Cree, R Gornea, K Graham, T Koffas, C Licciardi, D Sinclair
Colorado State University, Fort Collins CO, USA — C Chambers,
A Craycraft, W Fairbank Jr, D Harris, A Iverson, J Todd, T Walton
Drexel University, Philadelphia PA, USA
MJ Dolinski, YH Lin, E Smith, Y-R Yen
Duke University, Durham NC, USA — PS Barbeau
University of Erlangen-Nuremberg, Erlangen, Germany
G Anton, R Bayerlein, J Hoessl,
P Hufschmidt, A Jamil, T Michel, M Wagenpfeil, T Ziegler
IBS Center for Underground Physics, Daejeon, South Korea
DS Leonard
IHEP Beijing, People's Republic of China — G Cao, W Cen, Y Ding,
X Jiang, Z Ning, X Sun, T Tolba, W Wei, L Wen, W Wu, X Zhang, J Zhao
IME Beijing, People's Republic of China — L Cao, X Jing, Q Wang
ITEP Moscow, Russia — V Belov, A Burenkov, A Karelin,
A Kobyakin, A Kuchenkov, V Stekhanov, O Zeldovich
University of Illinois, Urbana-Champaign IL, USA
D Beck, M Coon, S Li, L Yang
Indiana University, Bloomington IN, USA
JB Albert, S Daugherty, LJ Kaufman, G Visser
University of California, Irvine, Irvine CA, USA — M Moe
Laurentian University,Sudbury ON,Canada
B Cleveland, A Der Mesrobian-Kabakian, J Farine, A Robinson, U Wichoski
Lawrence Livermore National Laboratory, Livermore CA, USA
O Alford, J Brodsky, M Heffner, A House, S Sangiorgio

University of Massachusetts, Amherst MA, USA
S Feyzbakhsh, S Johnston, CM Lewis, A Pocar
McGill University, Montreal QC, Canada — T Brunner , K Murray
Oak Ridge National Laboratory, Oak Ridge TN, USA
L Fabris, RJ Newby, K Ziock
Pacific Northwest National Laboratory, Richland, WA, USA
I Arnquist, EW Hoppe, JL Orrell,
G Ortega, C Overman, R Saldanha, R Tsang
Rensselaer Polytechnic Institute, Troy NY, USA — E Brown, K Odgers
Université de Sherbrooke
F Bourque, S Charlebois , M Côté, D Danovitch, H Dautet,
R Fontaine, F Nolet, S Parent, JF Pratte, T Rossignol, J Sylvestre, F Vachon
SLAC National Accelerator Laboratory, Menlo Park CA, USA
J Dalmasson, T Daniels, S Delaquis, A Dragone,
G Haller, A Odian, M Oriunno, B Mong, PC Rowson, K Skarpaas
University of South Dakota, Vermillion SD, USA
J Daughhetee, R MacLellan
Stanford University, Stanford CA, USA — R DeVoe, D Fudenberg,
G Gratta, M Jewell, S Kravitz, G Li, A Schubert, 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, Y Lan, F Retière, V Strickland
Yale University, New Haven CT, USA — D Moore