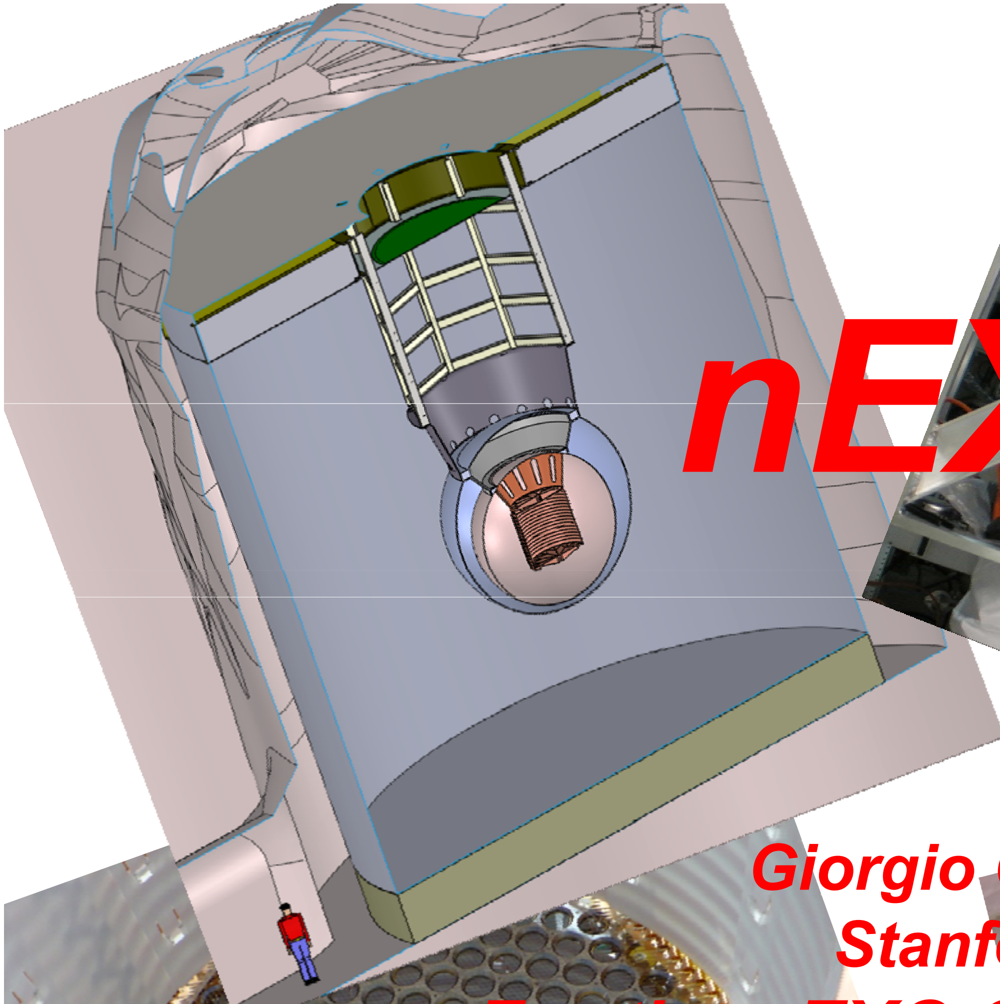
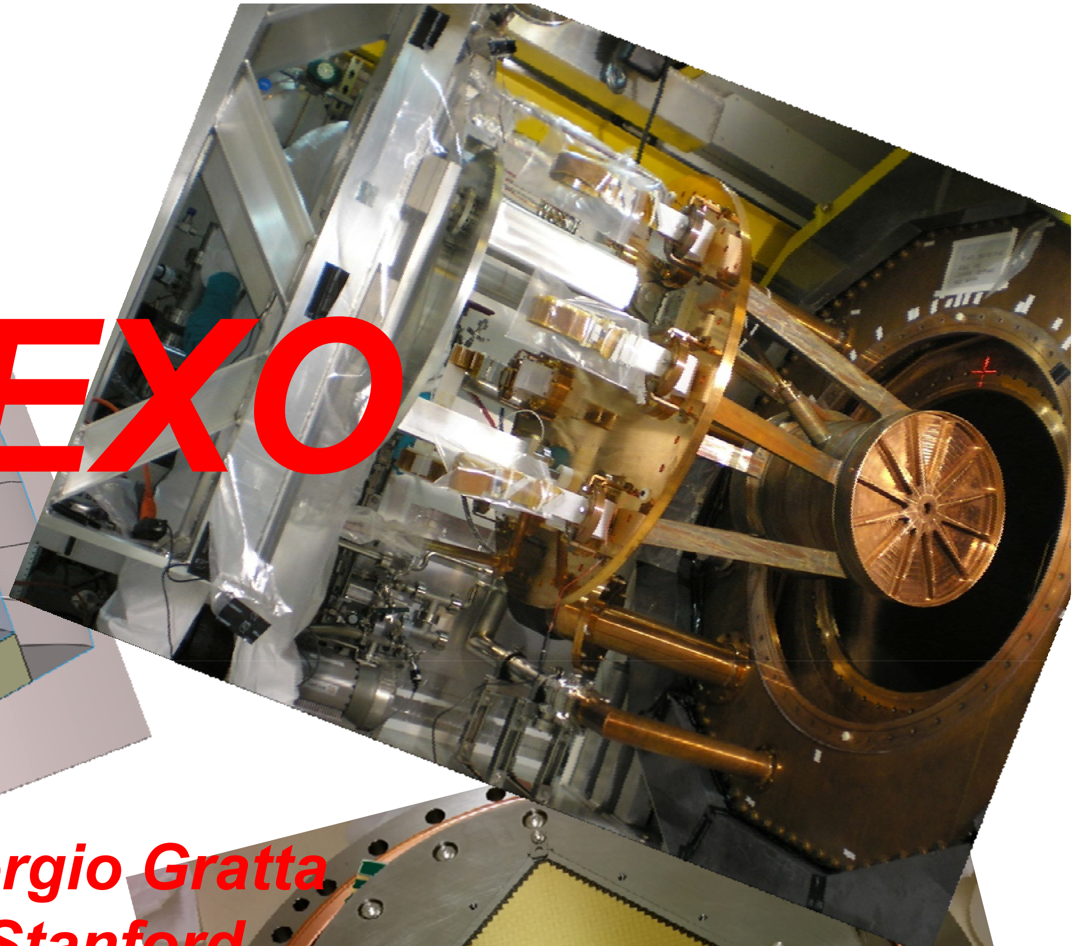
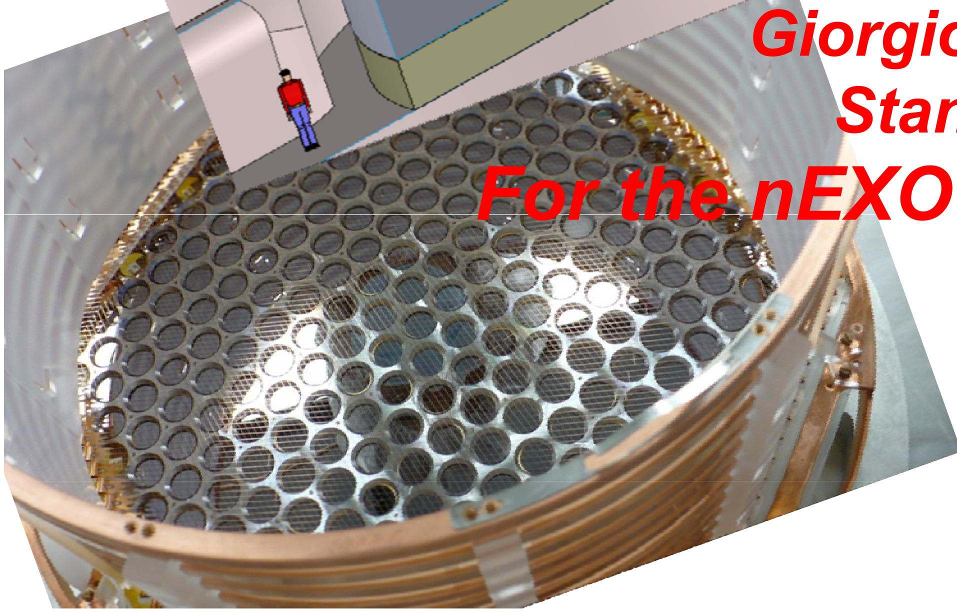
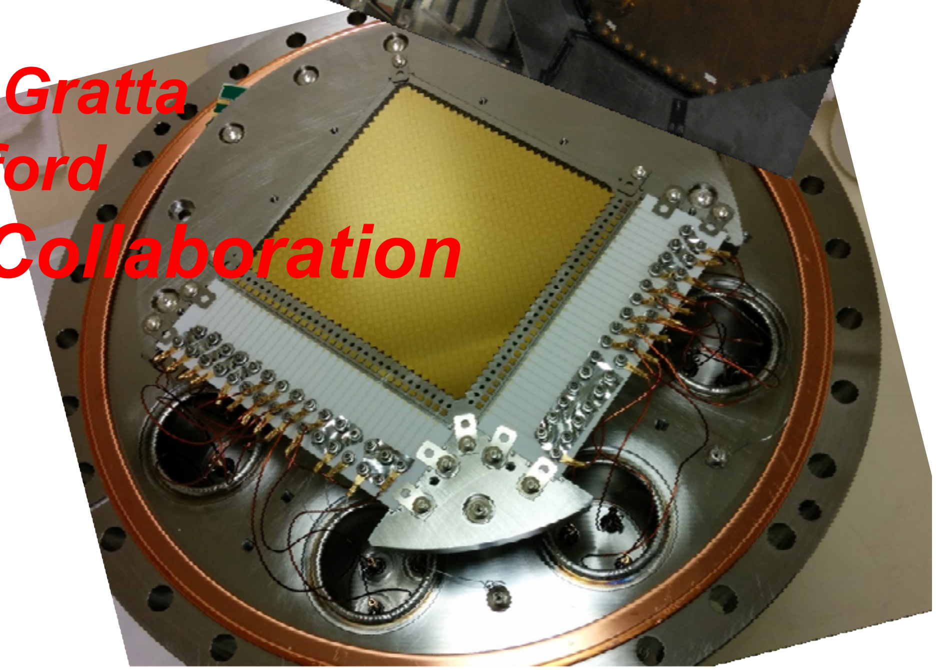
nEXO





Giorgio Gratta
Stanford
For the nEXO Collaboration





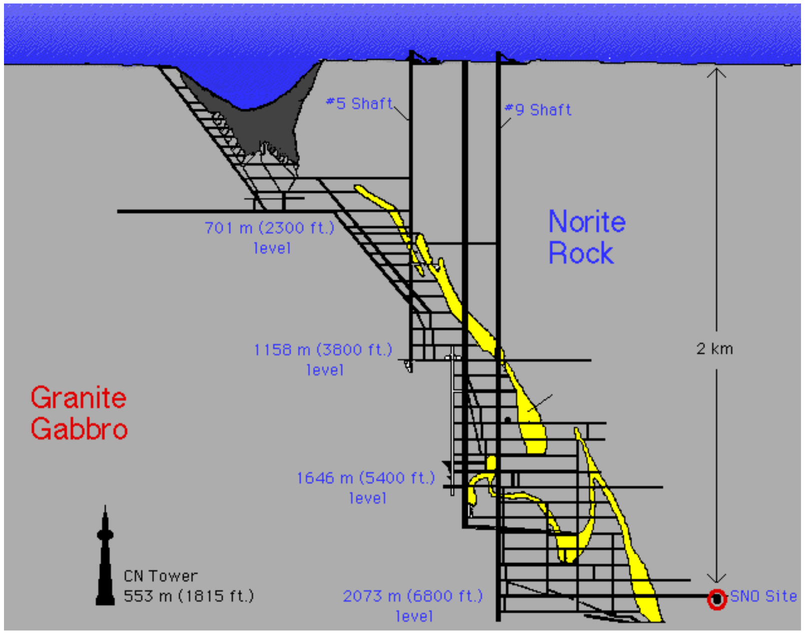
Four fundamental requirements for modern experiments:

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:

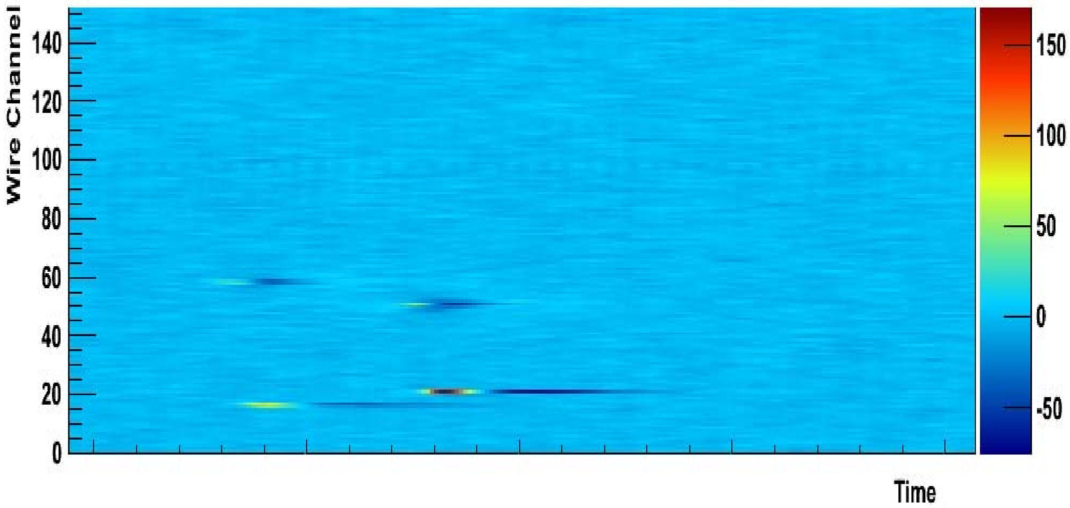
3) Ultra-low radioactive contamination for detector construction components

Some 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 be 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

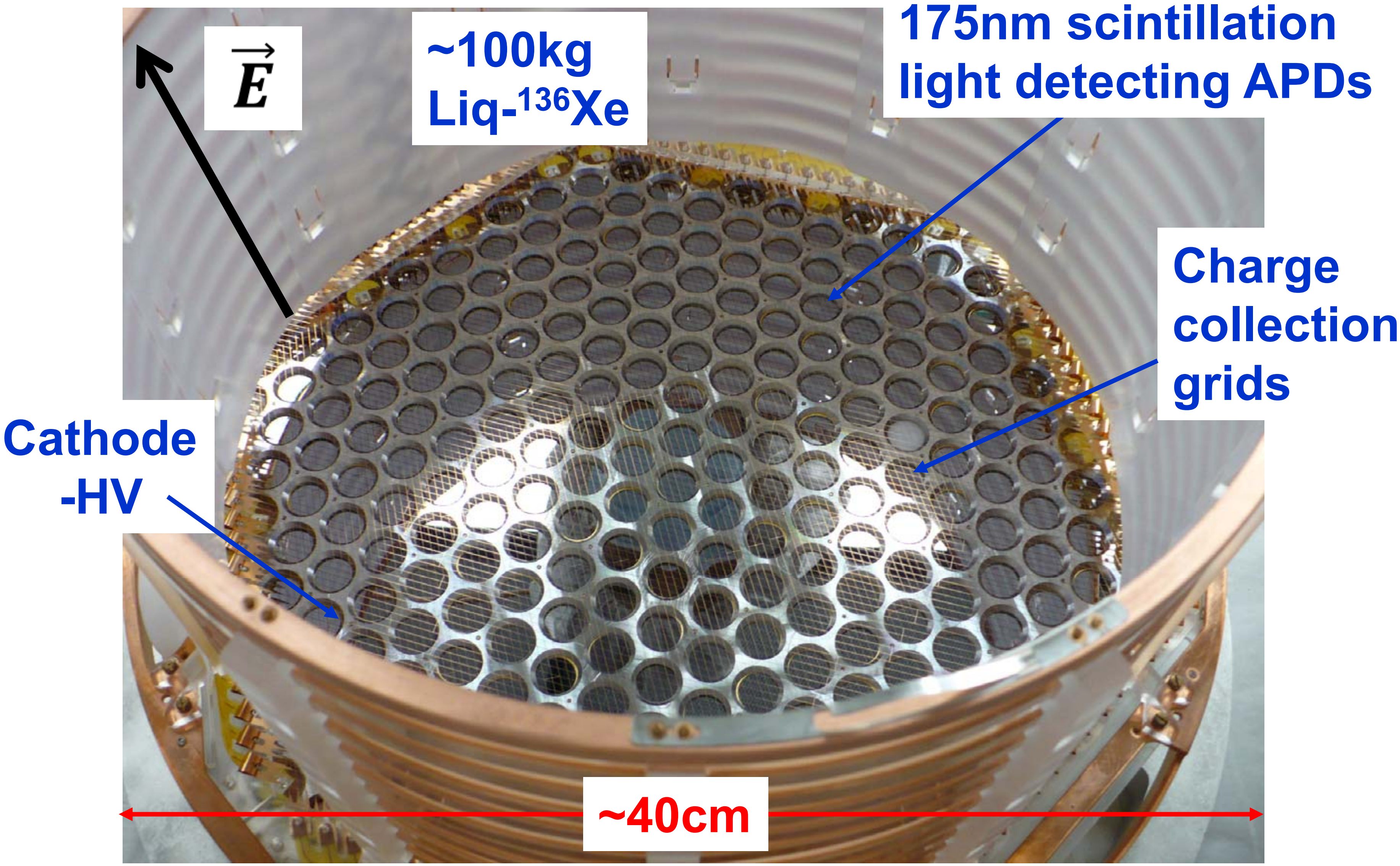
- Initial R&D on energy resolution using scintillation-ionization correlation

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

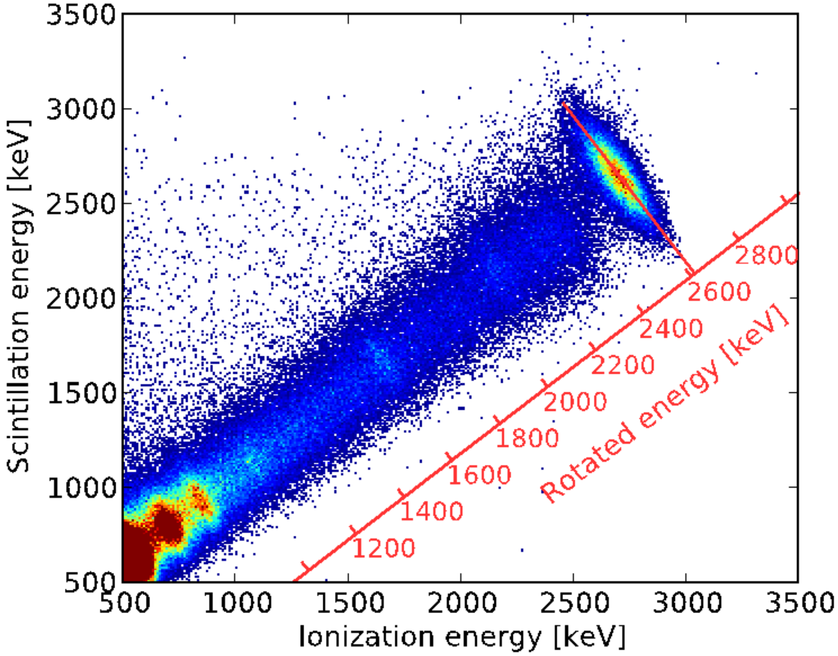
- Build a ton-scale detector (nEXO) with 100x the discovery reach and able to cover the inverted hierarchy (for the standard mechanism)

- 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



Combining Ionization and Scintillation

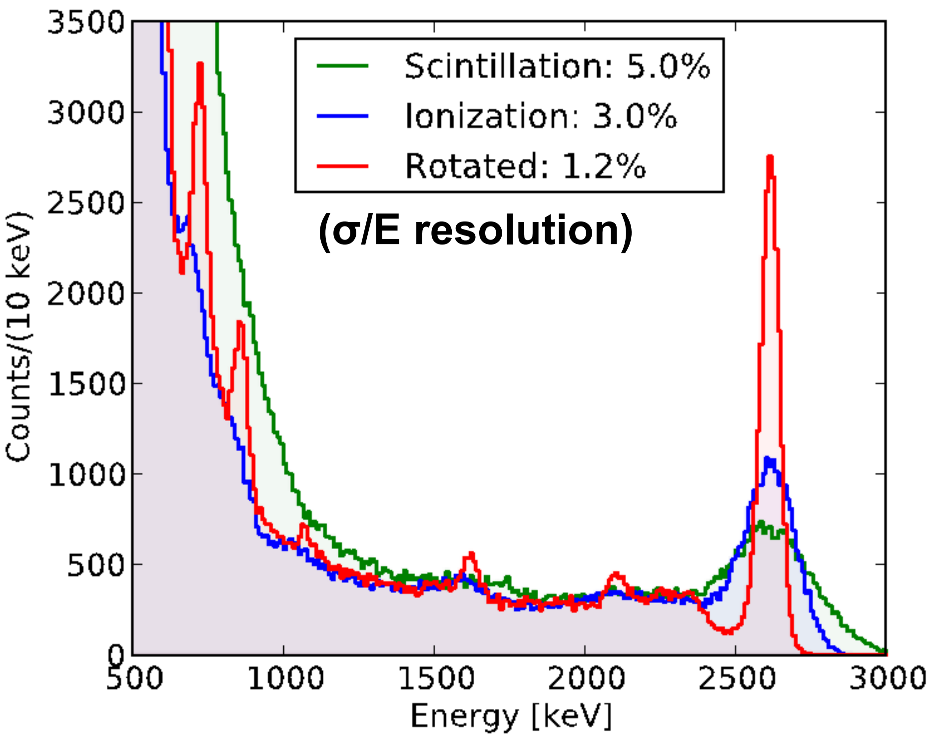


^{228}Th source SS

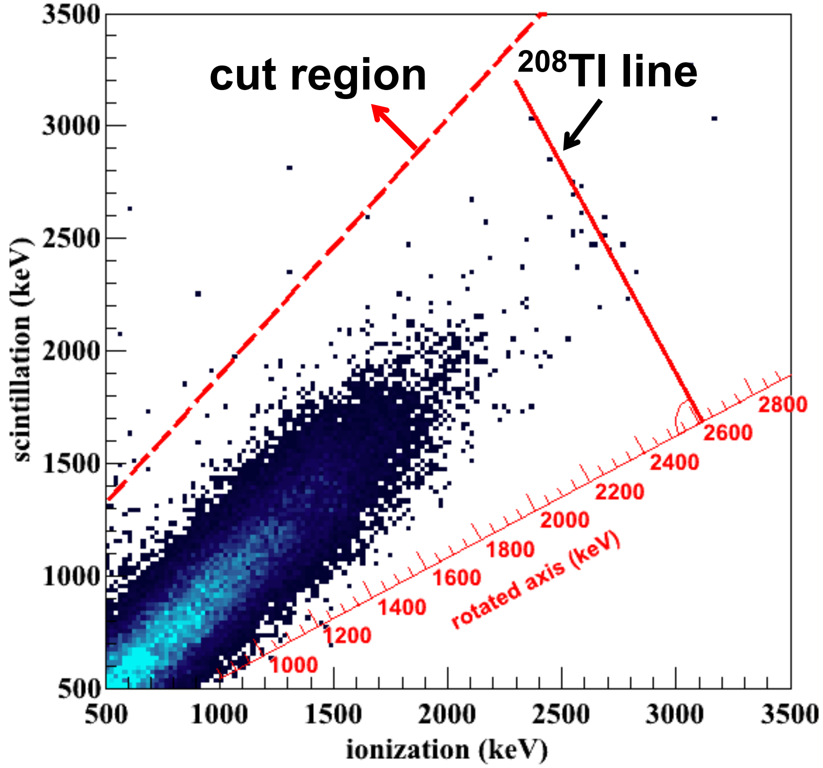
Anticorrelation between scintillation and ionization in LXe known since early EXO R&D

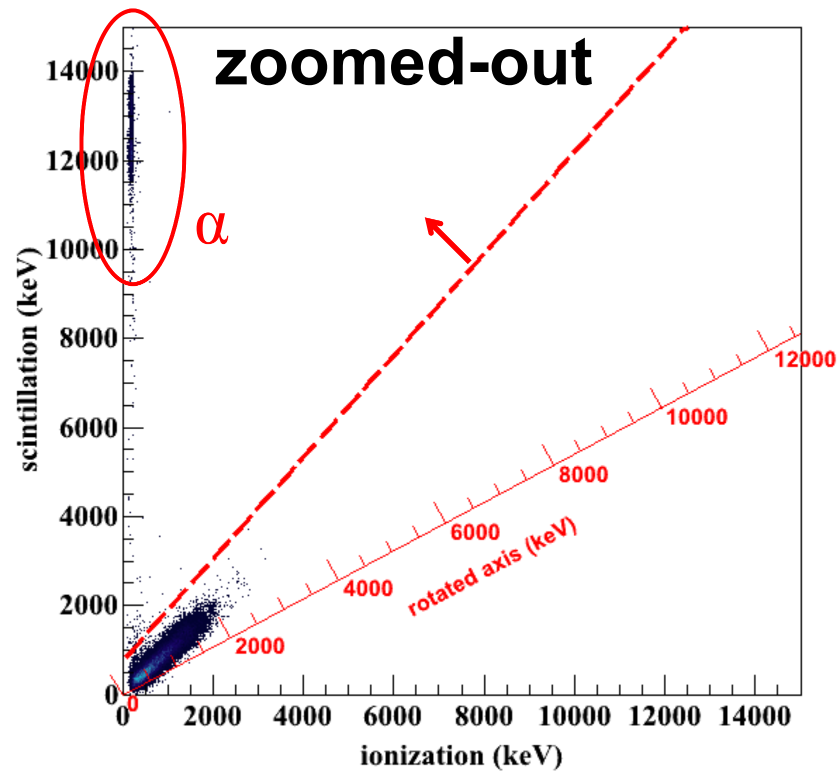
E.Conti et al.
Phys Rev B 68 (2003) 054201

By now this is a common technique in LXe



Low Background 2D SS Spectrum



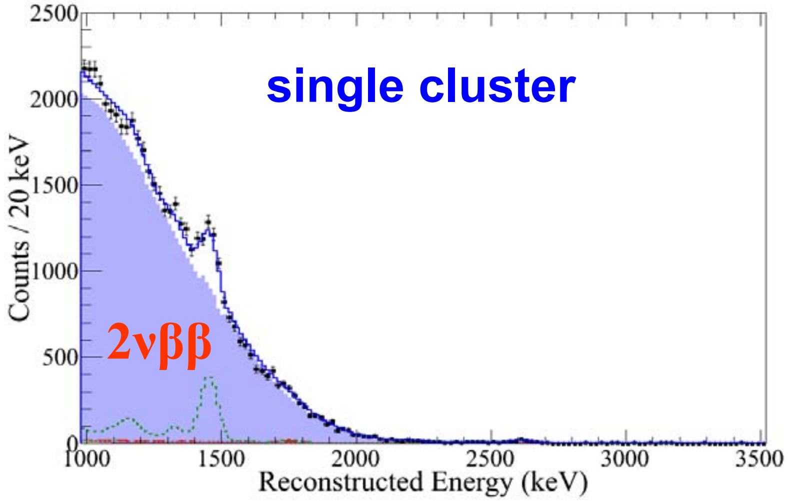


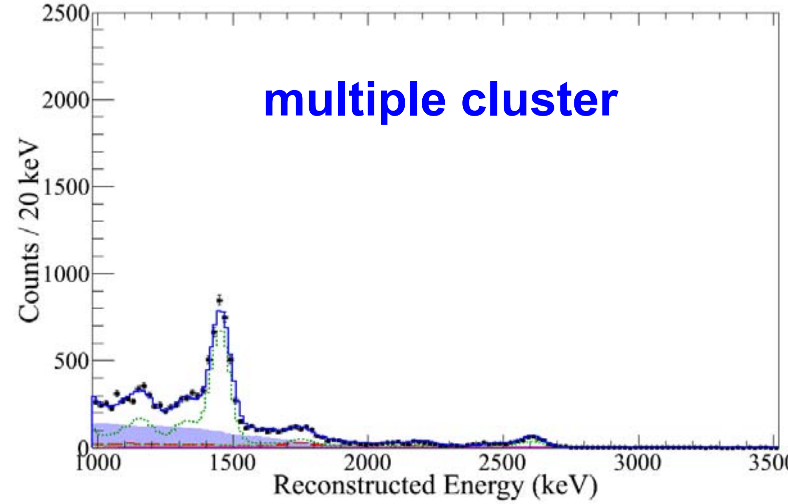
Events removed by diagonal cut:

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

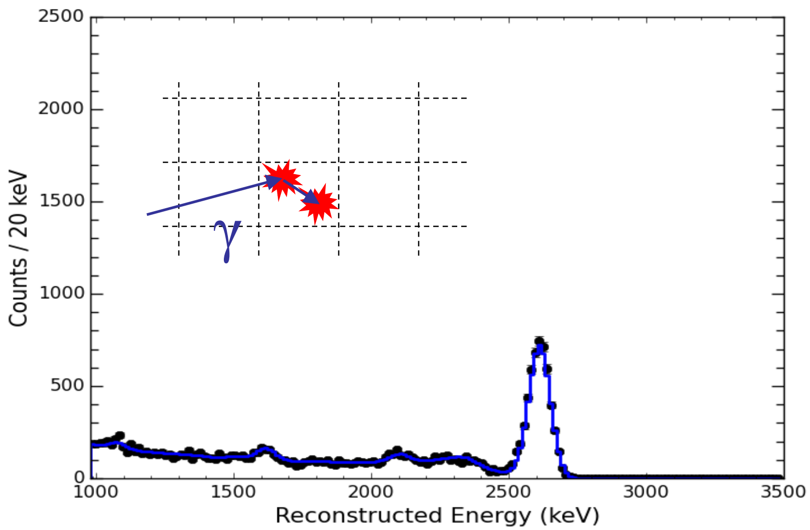
Using event multiplicity to characterize backgrounds

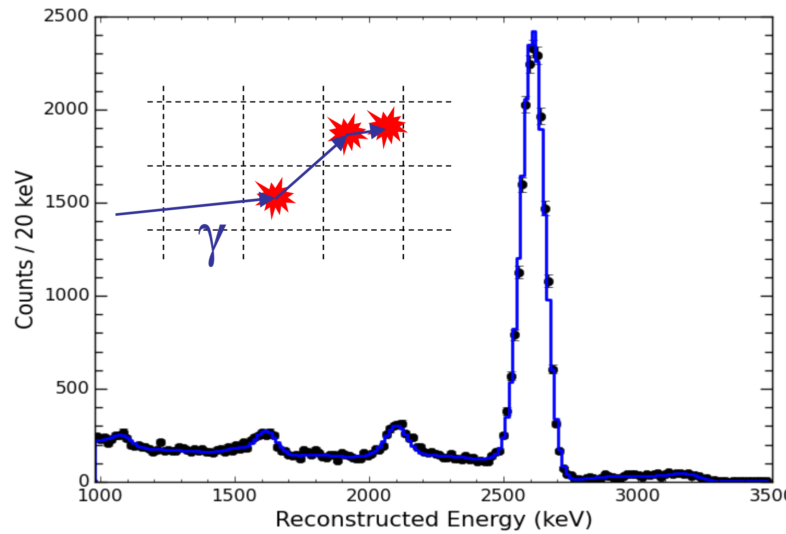
Low background data





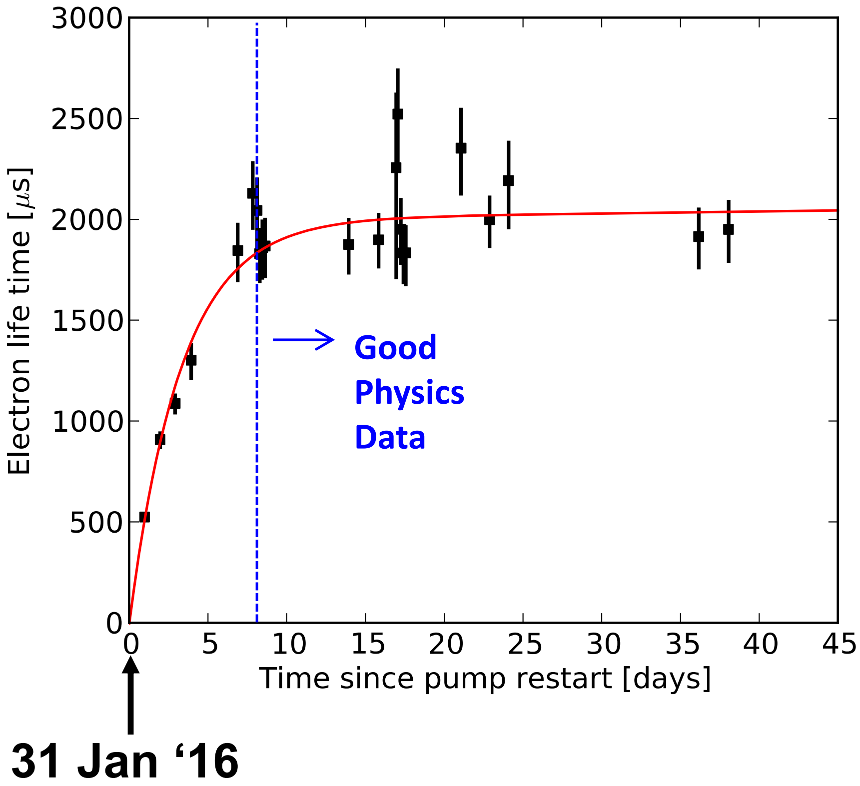
^{228}Th calibration source

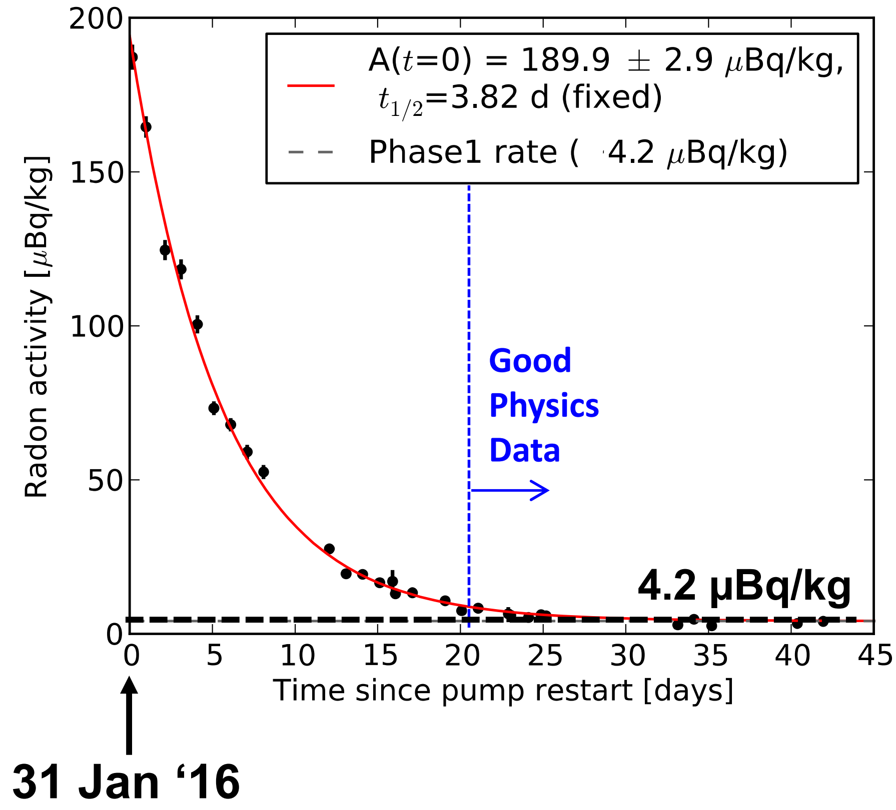




EXO-200 Phase-II Operation

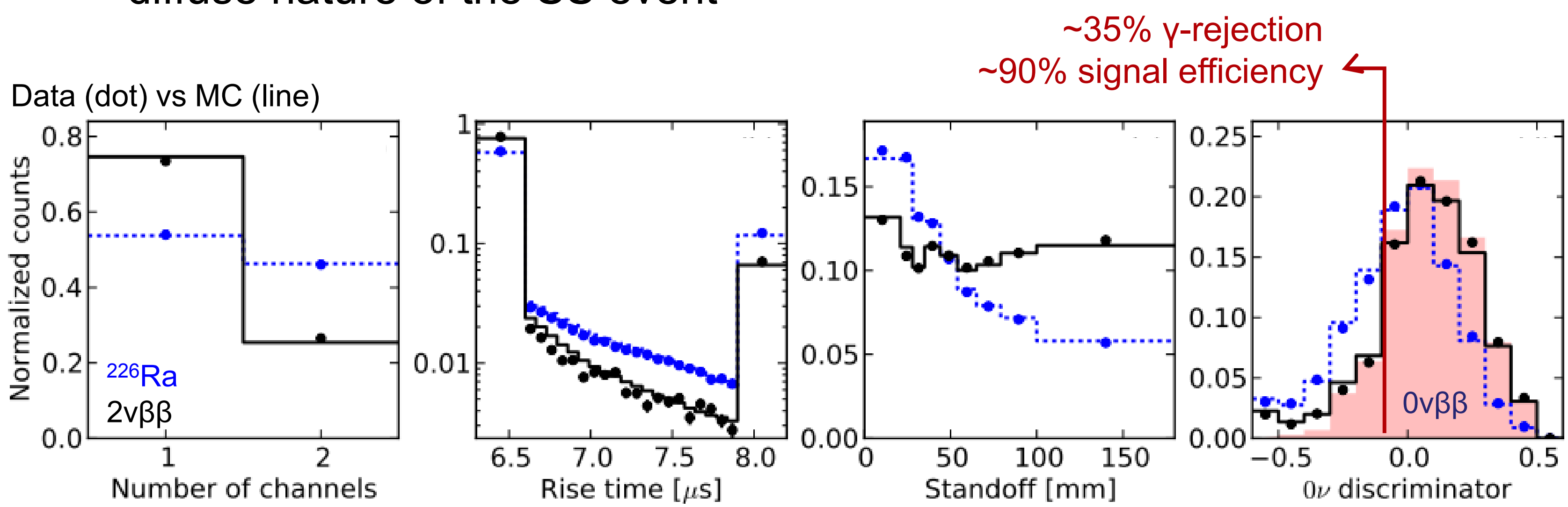
- **EXO-200 Phase-II operation begins on 31 Jan 2016, after enriched liquid xenon fill.**
- **Data shows that the detector reached excellent xenon purity and ultra-low internal Rn level shortly after restart.**





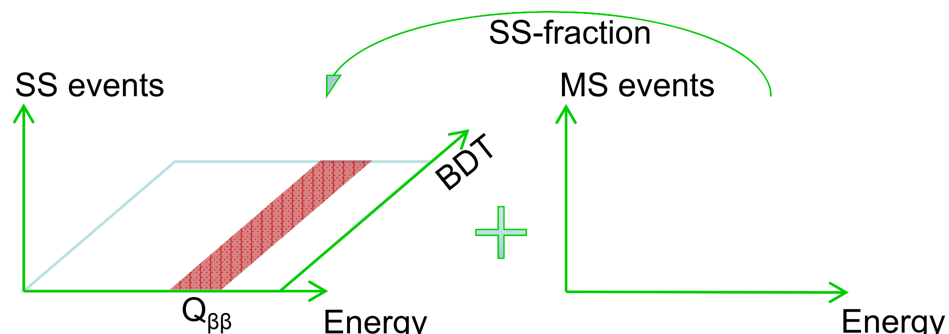
Squeeze more discriminating power from SS events

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



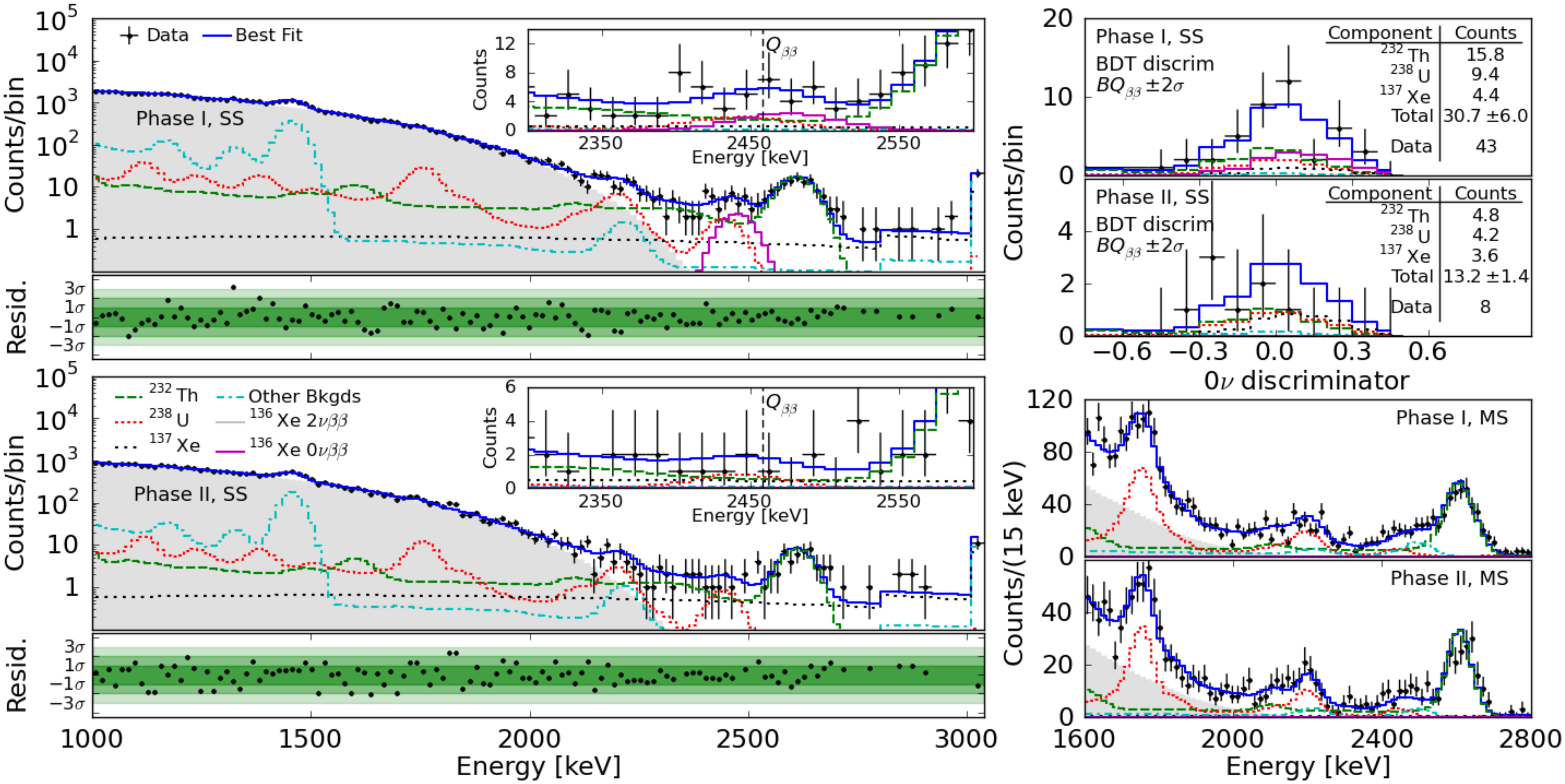
Fitting 0νββ discriminators

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



Most Recent Results

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



- 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)

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

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

(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)

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.”

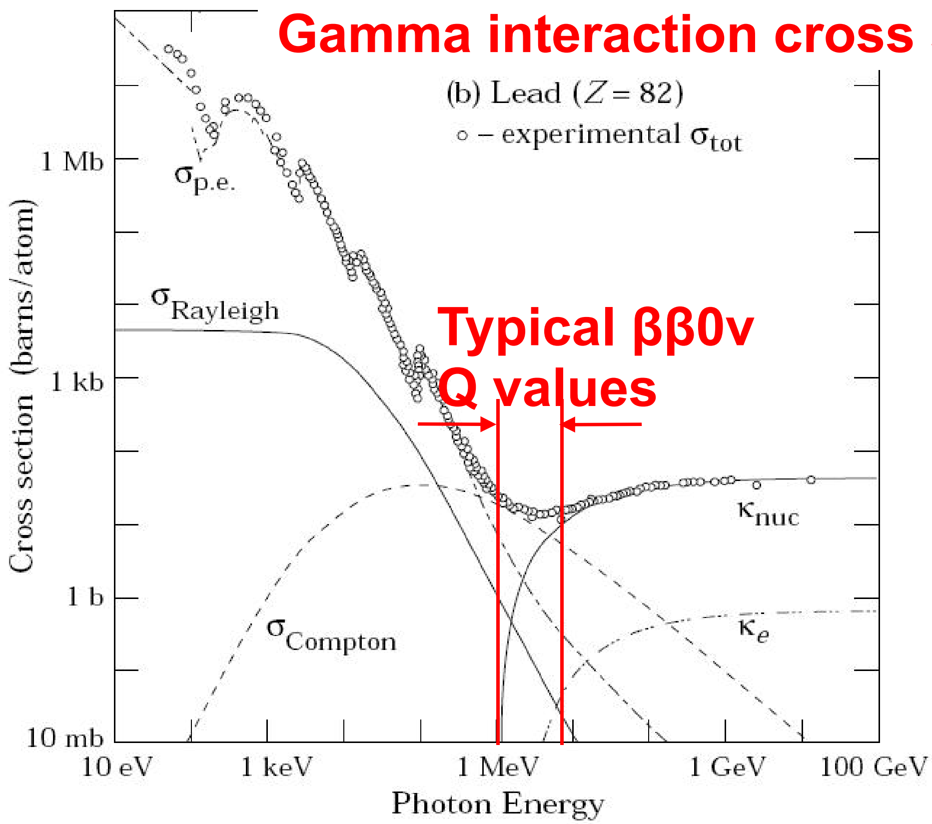
➔ **This is in full swing now**

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 the 0νββ decay discovery***
- ***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***
- ***The elucidation of the mechanism producing the decay requires the analysis of more than one isotope***

Shielding a detector from gammas is difficult!



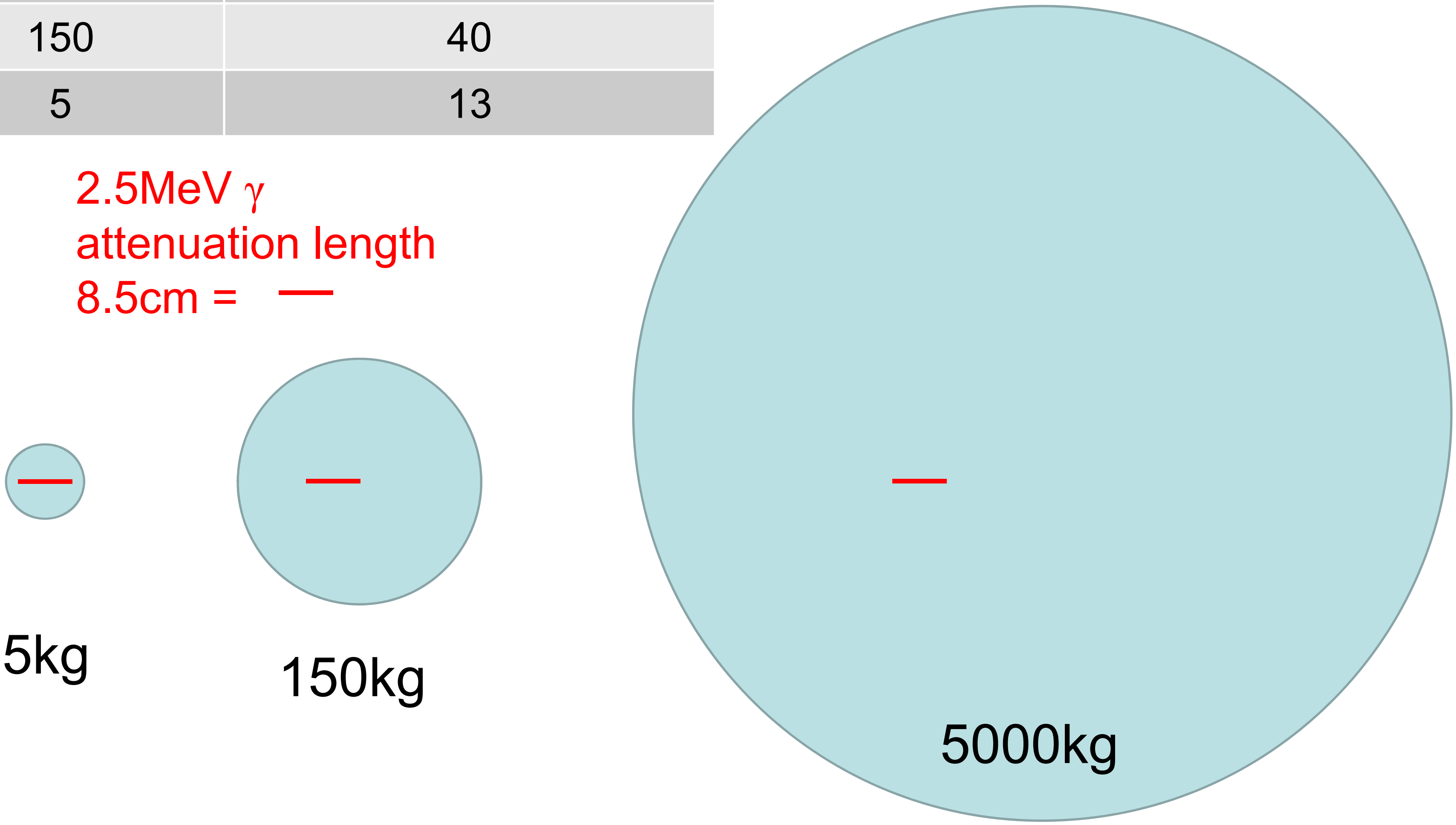
Example:
γ attenuation length @ Q-value comparable to the size of a germanium detector.

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

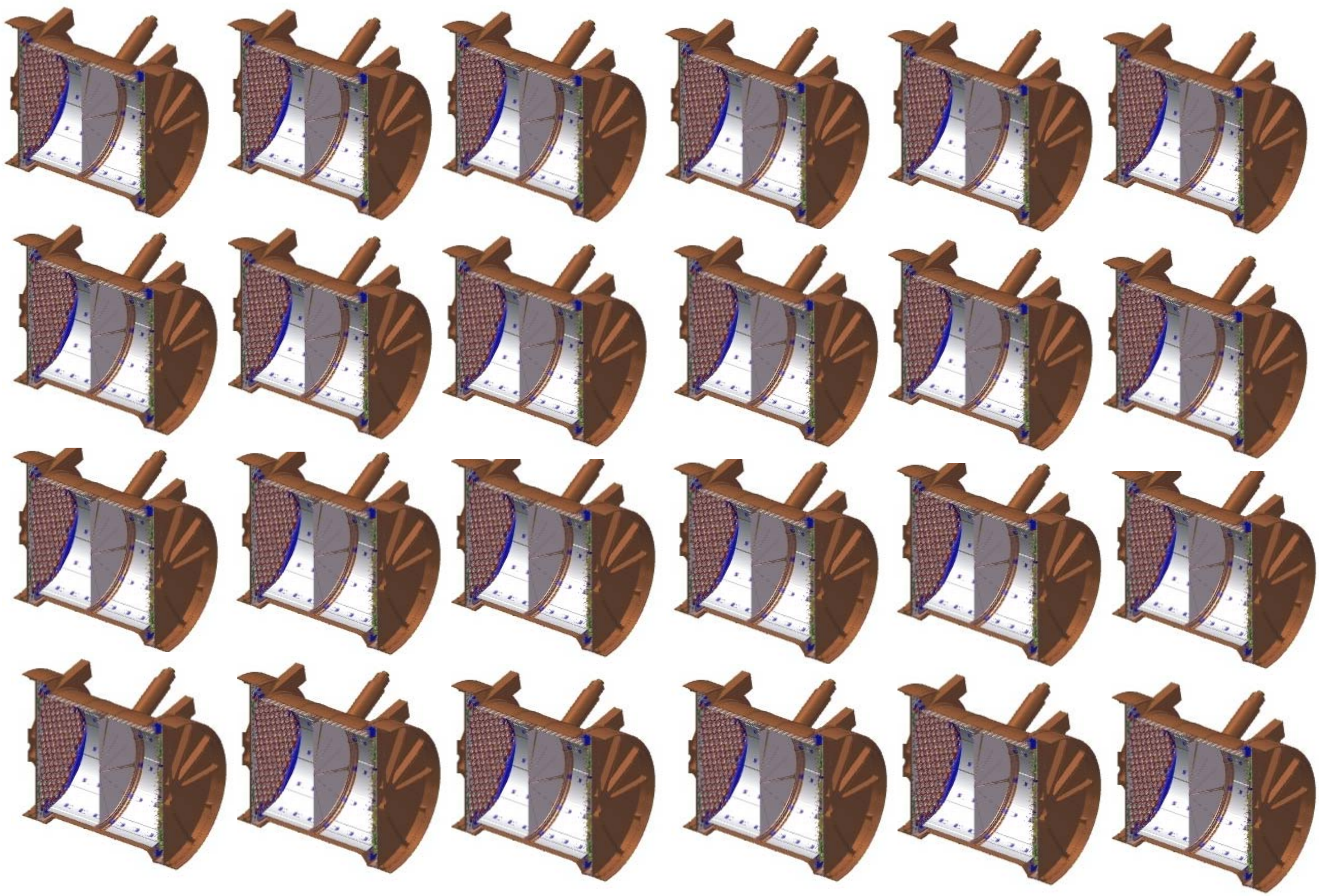
LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

2.5MeV γ
attenuation length
8.5cm =



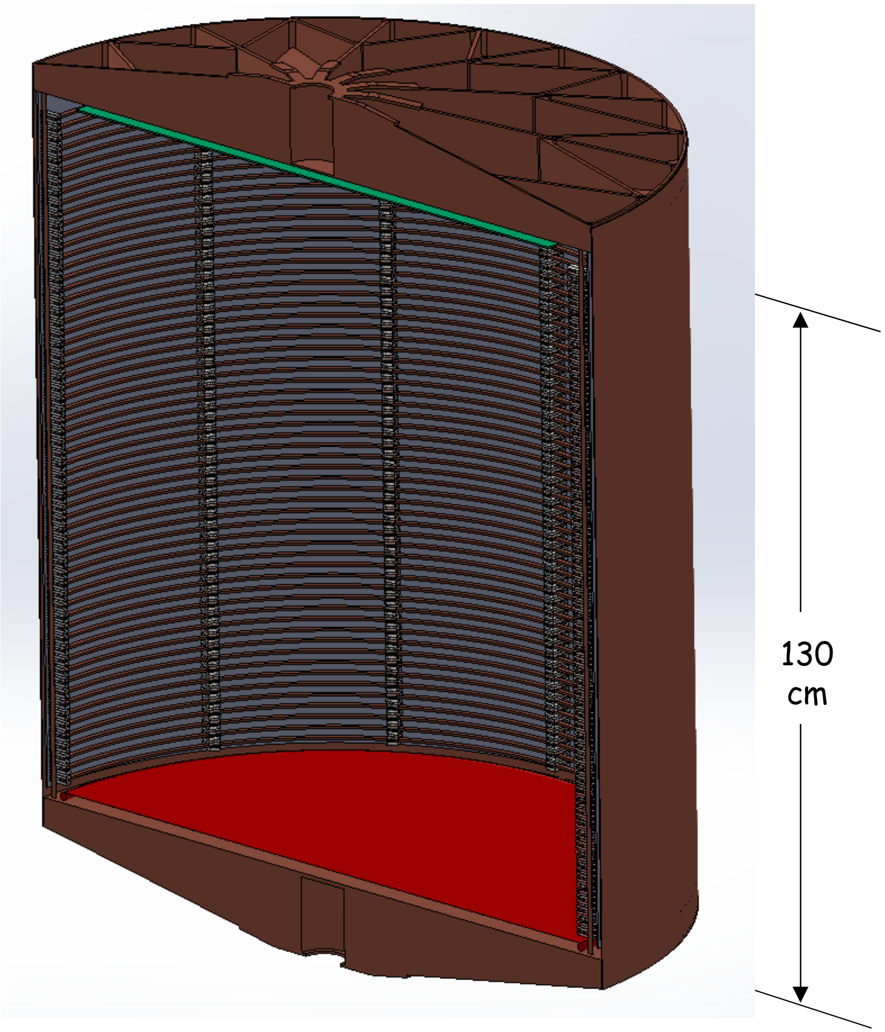
This works best for a monolithic detector

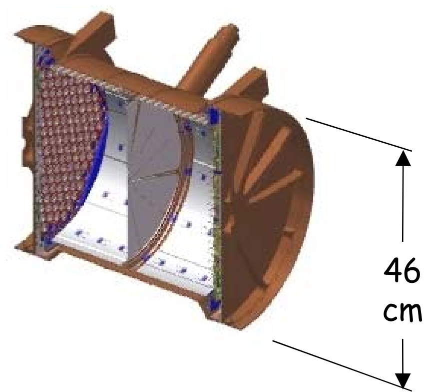
The wrong design for nEXO



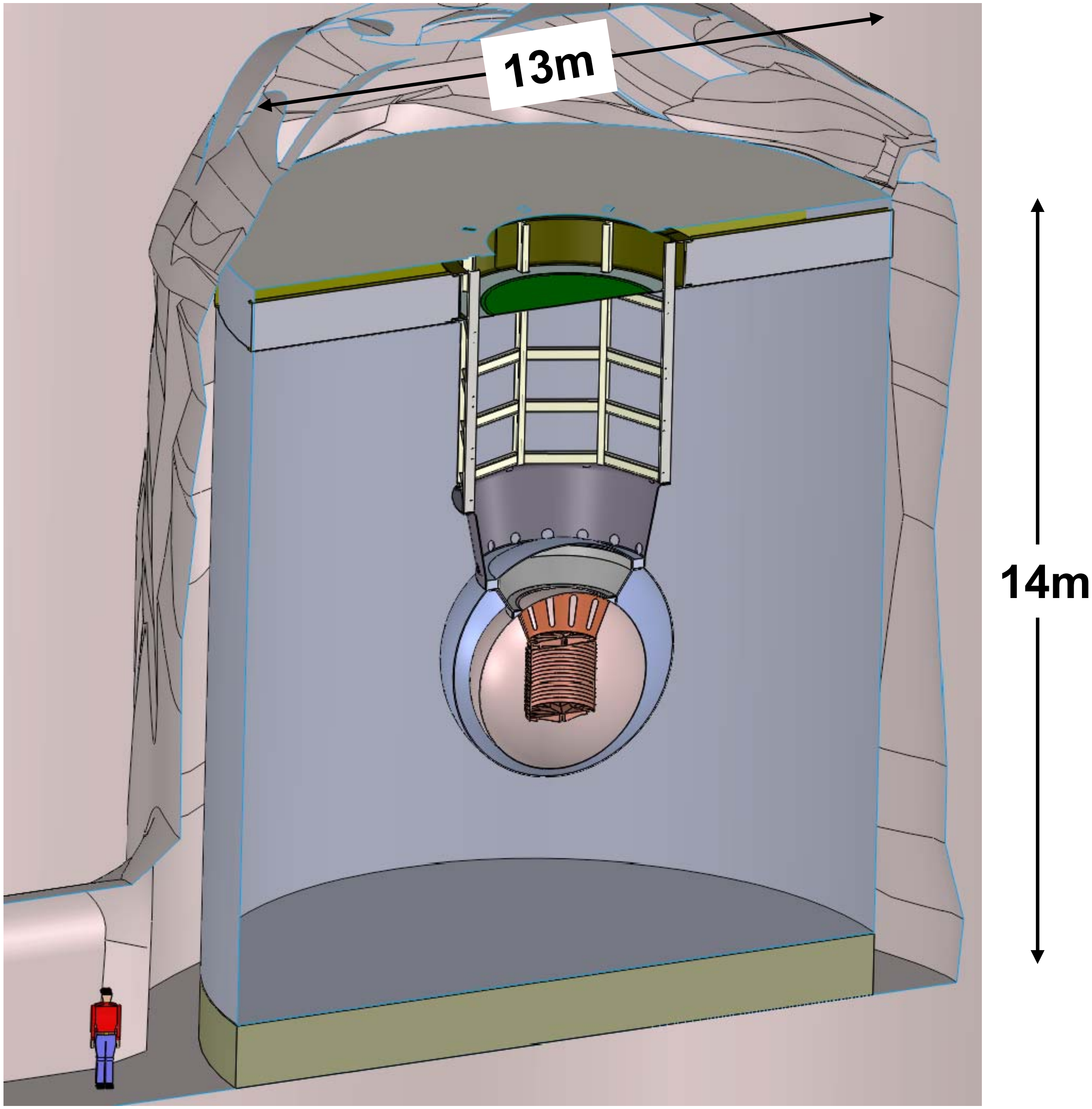
The nEXO detector

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





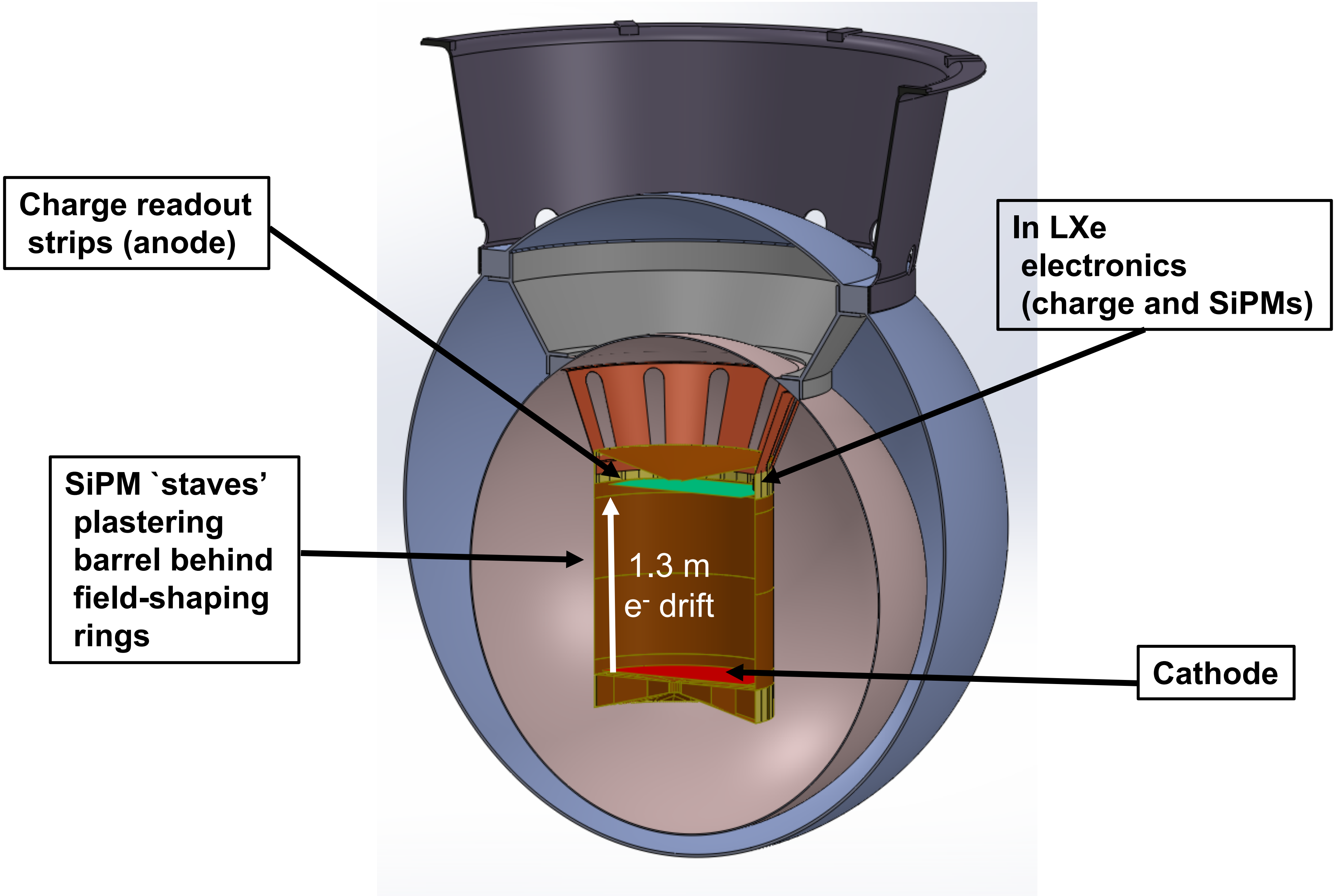
Preliminary artist view of nEXO in the SNOlab Cryopit

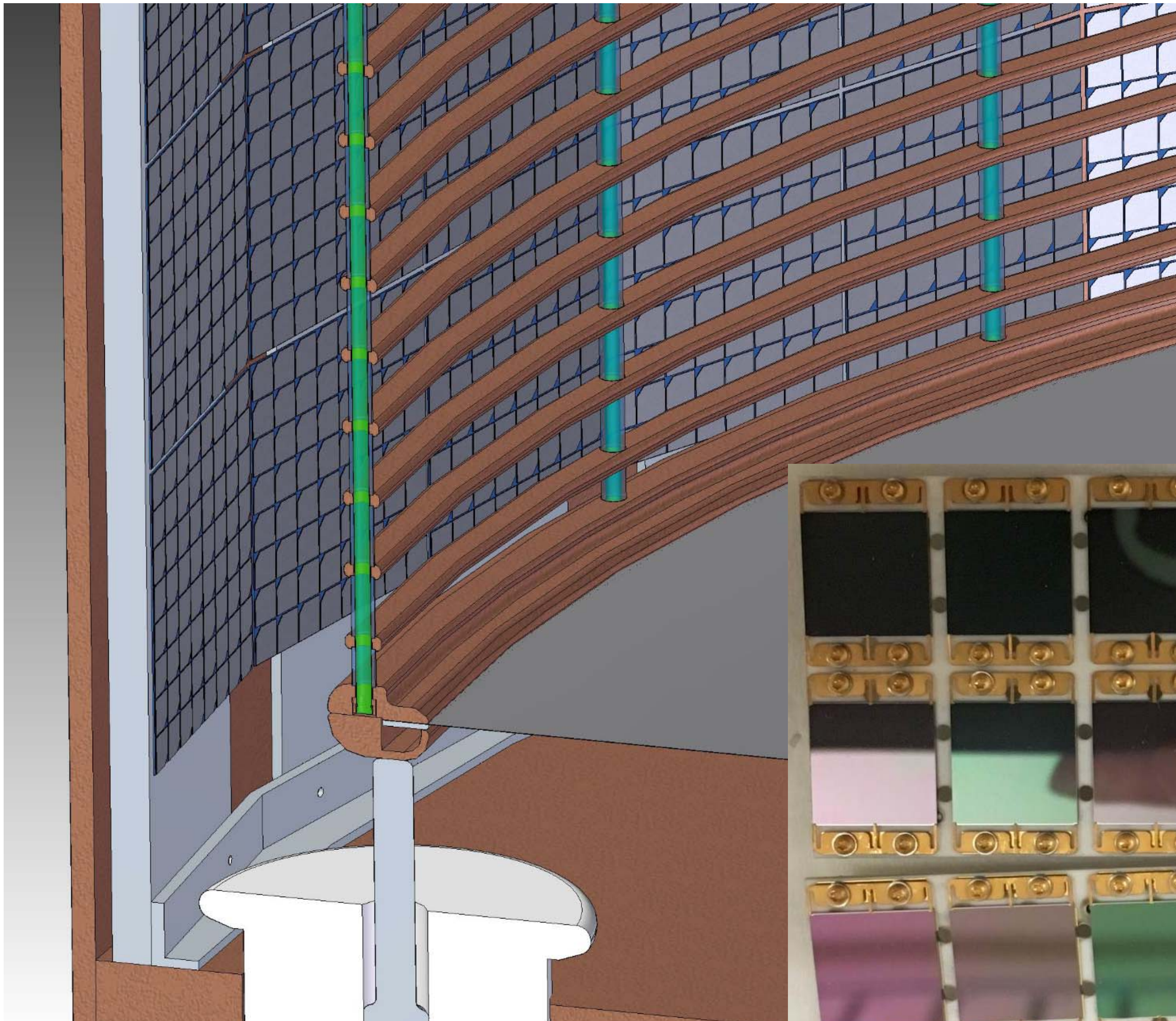


Optimization from the EXO-200 to the nEXO scale

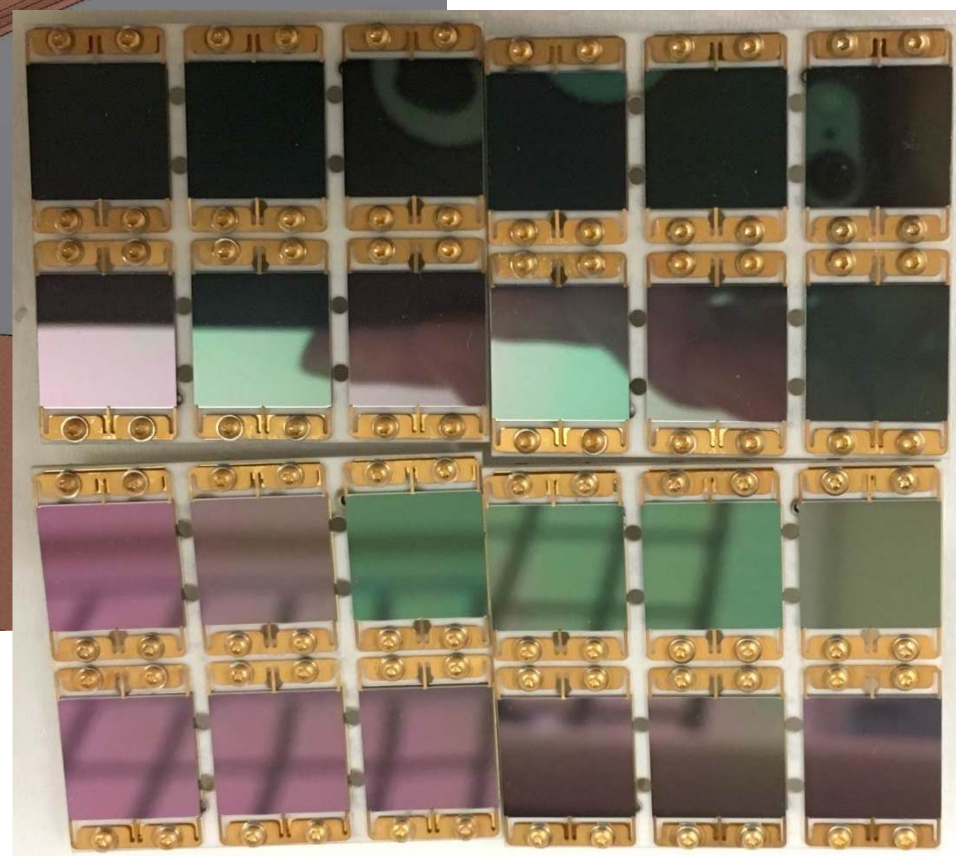
What	Why
~30x volume/mass	To give sensitivity to the inverted hierarchy
No cathode in the middle	Larger low background volume/no ^{214}Bi in the middle
6x HV for the same field	Larger detector and one drift cell
>3x electron lifetime	Larger detector and one drift cell
Better photodetector coverage	Energy resolution
SiPM instead of APDs	Higher gain, lower bias, lighter, E resolution
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

The nEXO baseline TPC





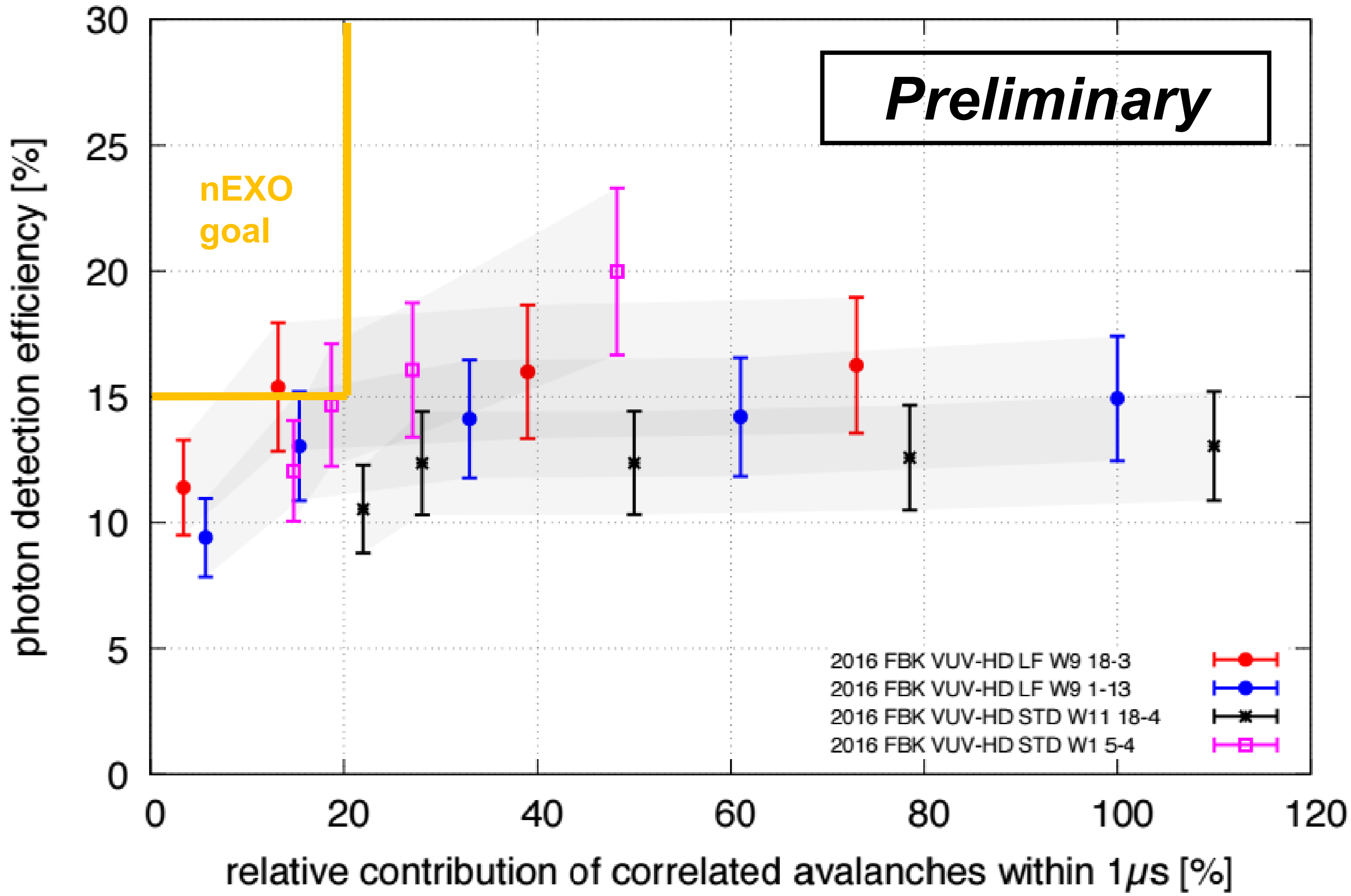
Need ~4m^2 of VUV-sensitive SiPMs



1cm

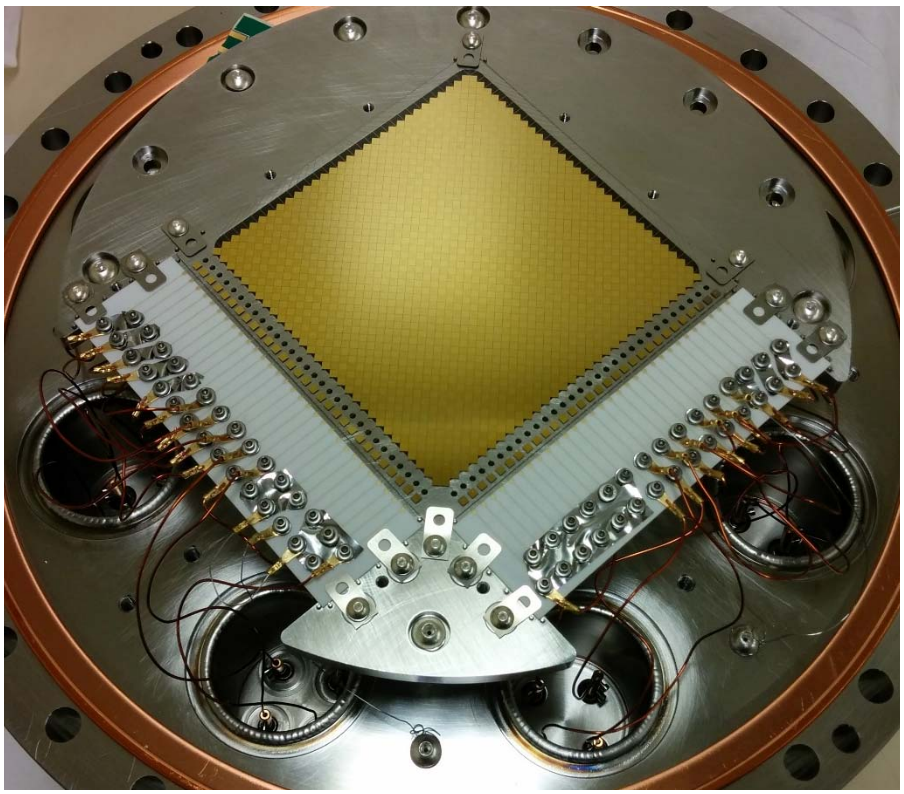
At least one type of 1cm² VUV devices now match our desired properties, with a bias requirement ~30V

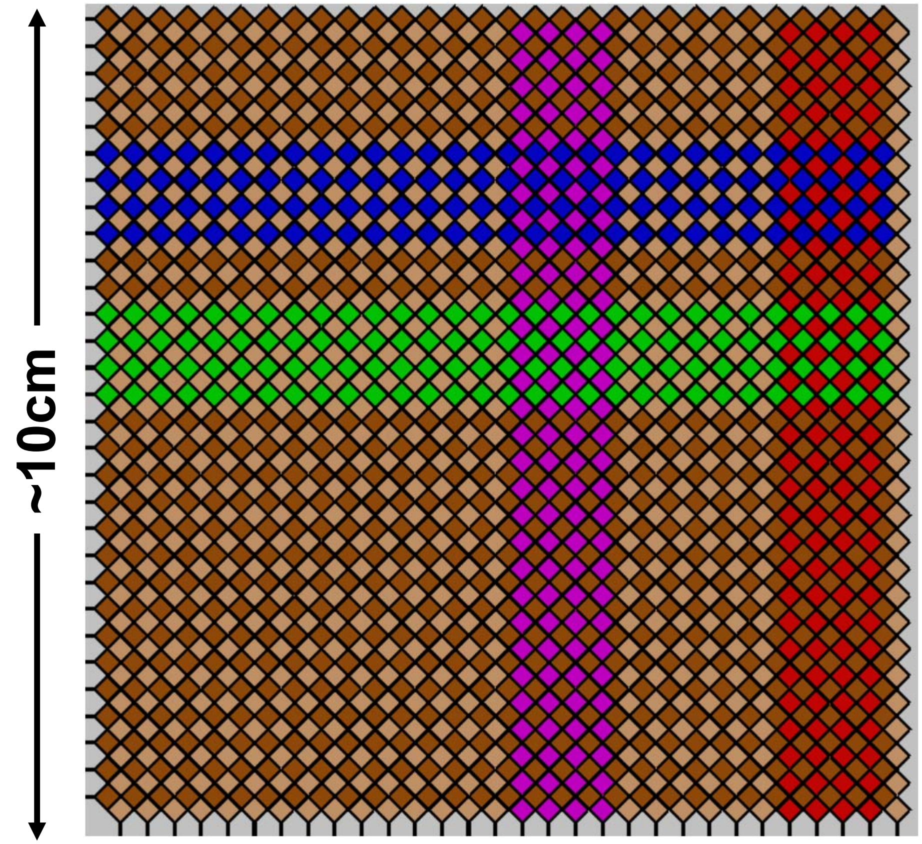
(as opposed to the 1500V of EXO-200 APDs)



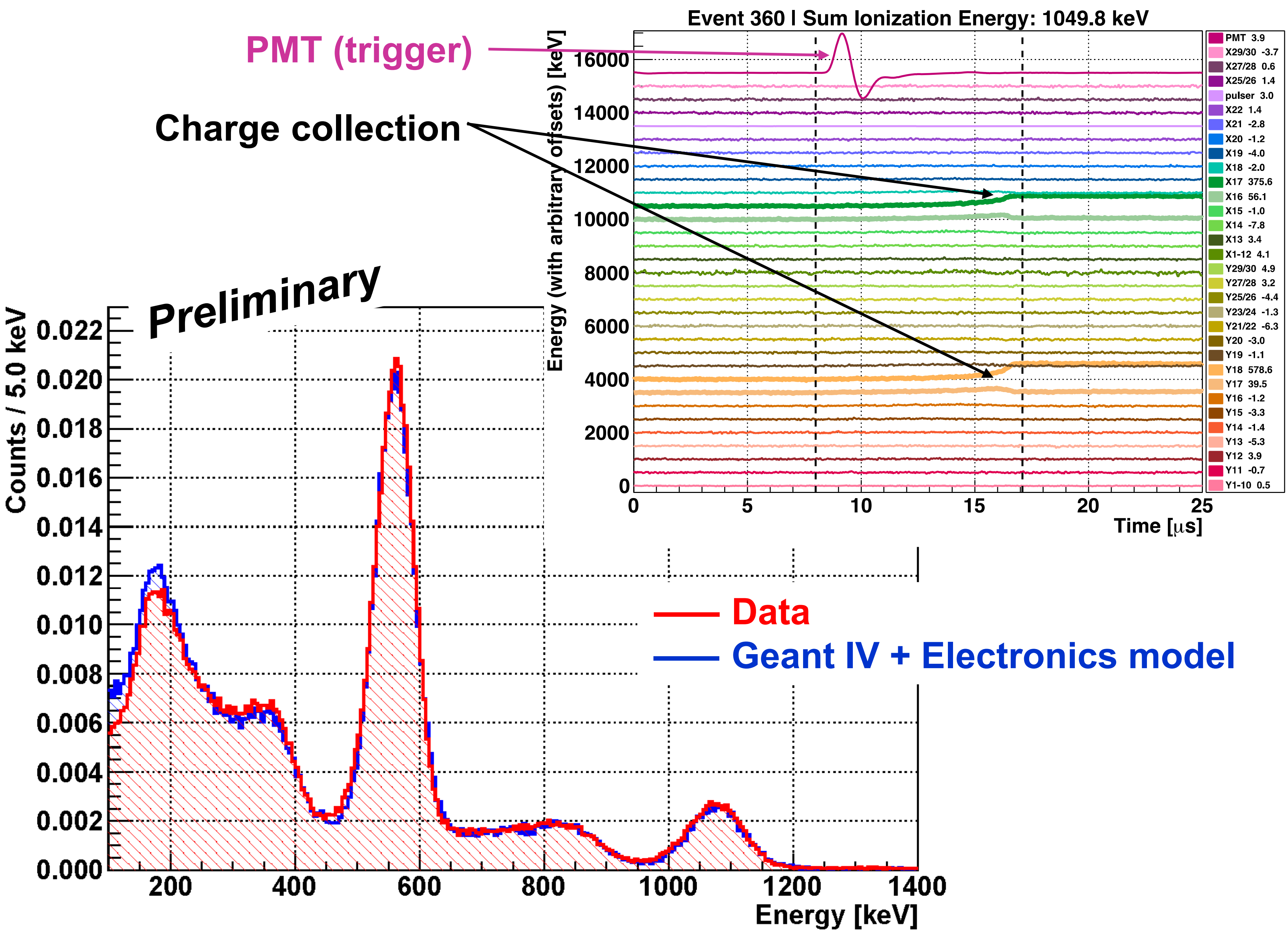
Charge will be collected on arrays of strips fabricated onto low background dielectric wafers (baseline is silica)

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



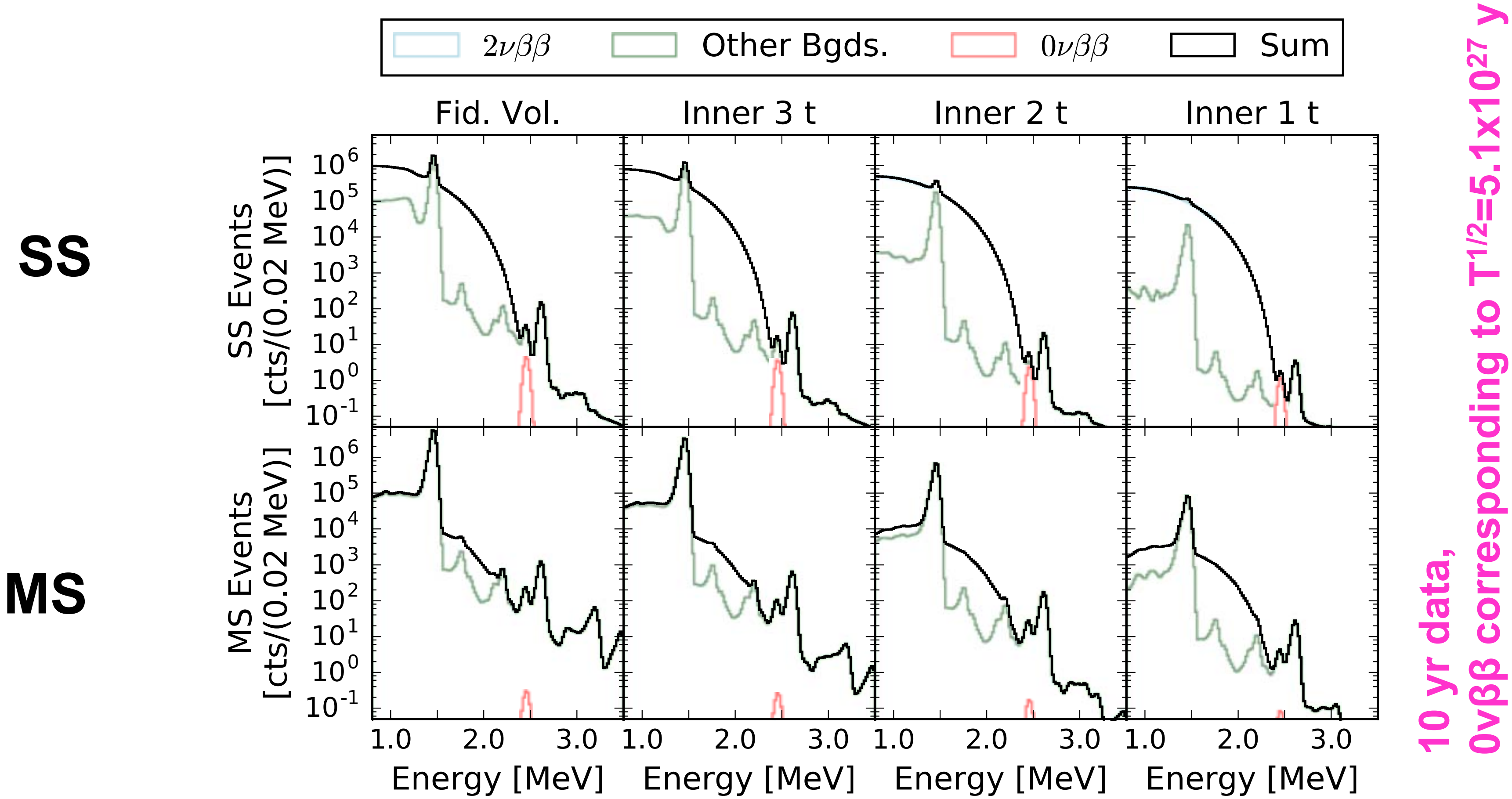


Max metallization cover with min capacitance


PMT (trigger)
Charge collection
Preliminary
Event 360 I Sum Ionization Energy: 1049.8 keV
Energy (with arbitrary offsets) [keV]
Time [μs]
Counts / 5.0 keV
Energy [keV]
Data
Geant IV + Electronics model

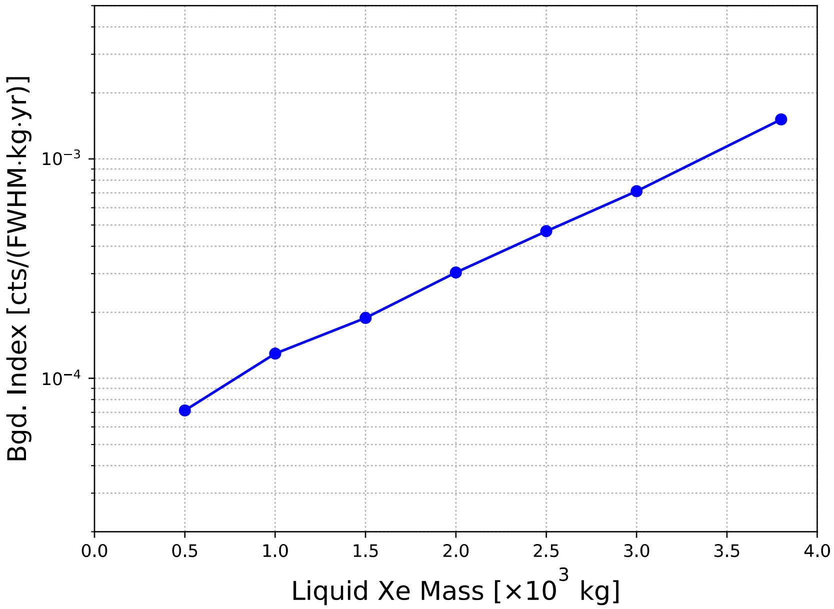
Particularly in the larger nEXO, background identification and rejection fully use a fit that considers simultaneously energy, multiplicity and event position.

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



Again, there is no single value for nEXO background index
➔ This is a feature!

But, if one insists in looking at this simple-minded figure then this should at least seen as a function of the sub-volume



In the inner 2000 kg, nEXO has ~ $3x10^{-4}$ cts/FWHM/kg/y

This is one of the lowest backgrounds for this kind of experiments

Note that this is achieved with all measured materials!

No extrapolation of material properties is needed!!
(the only "extrapolation" is the one that required GEANT 4 to know the physics of Compton scattering)

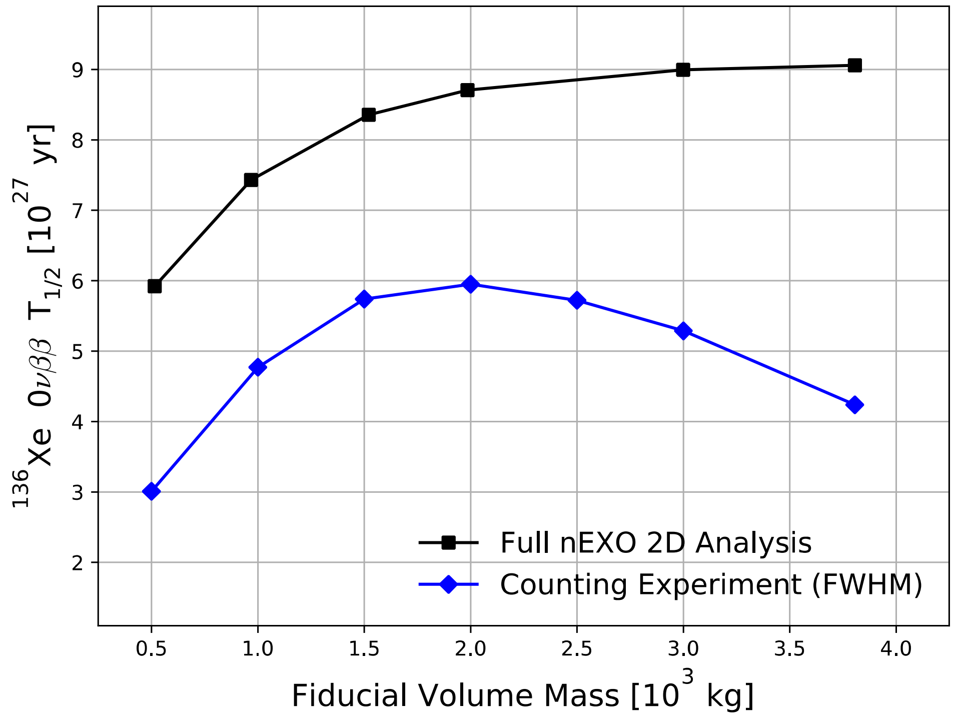
Note that the global-fit analysis *(BTW, not as advanced as the one in EXO-200)* optimally exploits all of the LXe volume:

- The shallower LXe measures more the background than the signal

- The deeper LXe measures more the signal than the background

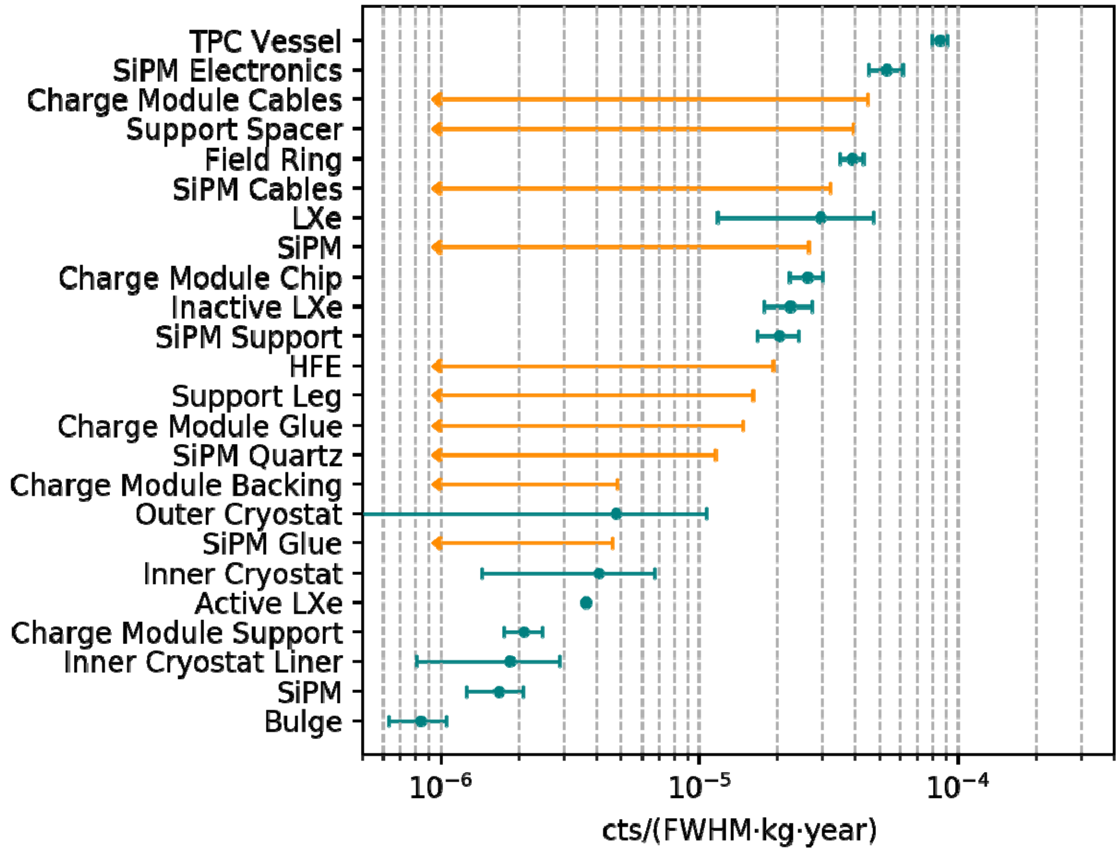
But all LXe measures both!!

Here such analysis is compared to a simple counting experiment



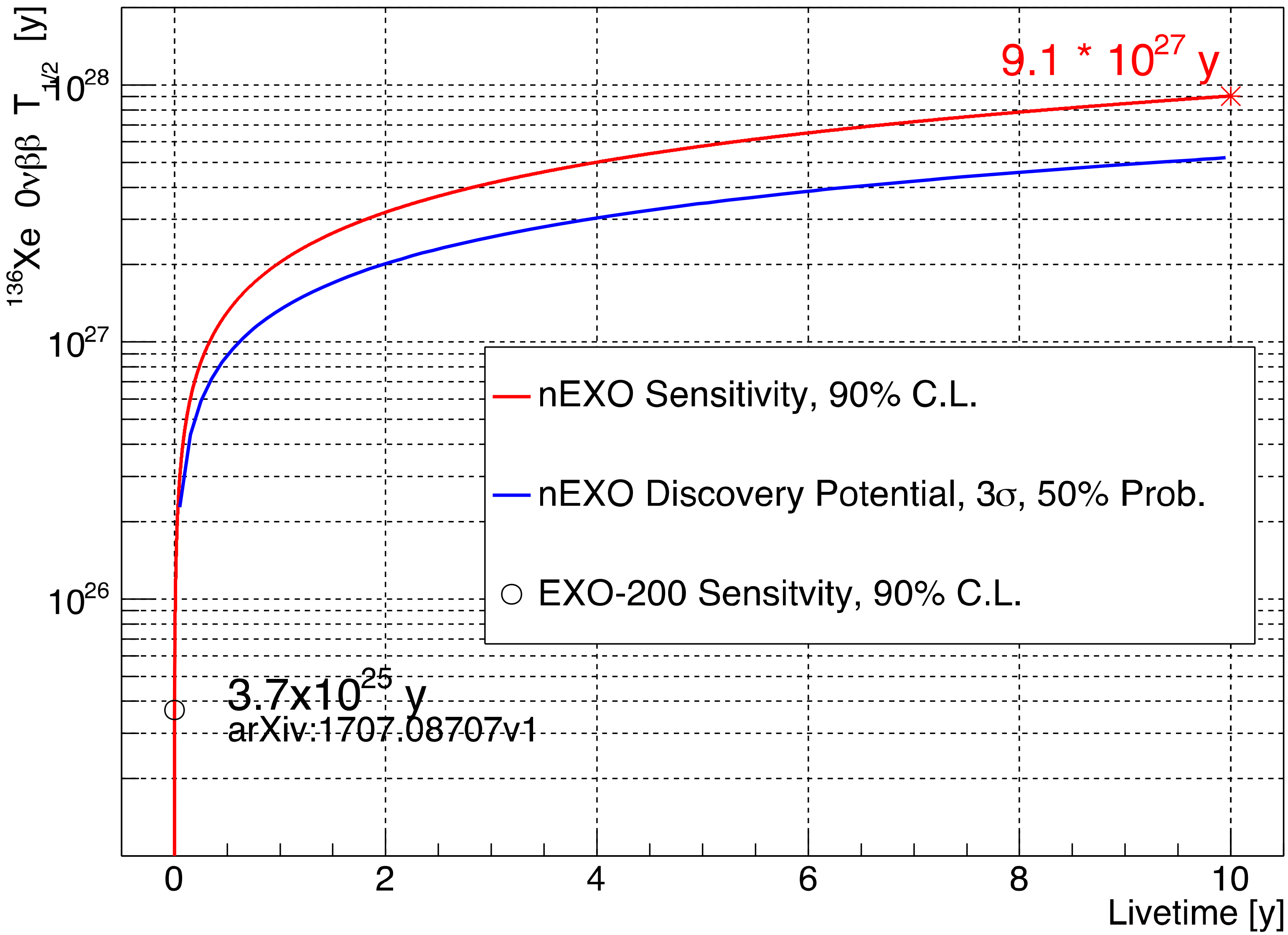
This justifies choice of 2000 kg as reference value since ~95% of the sensitivity is reached within 2000 kg

Background budget by component

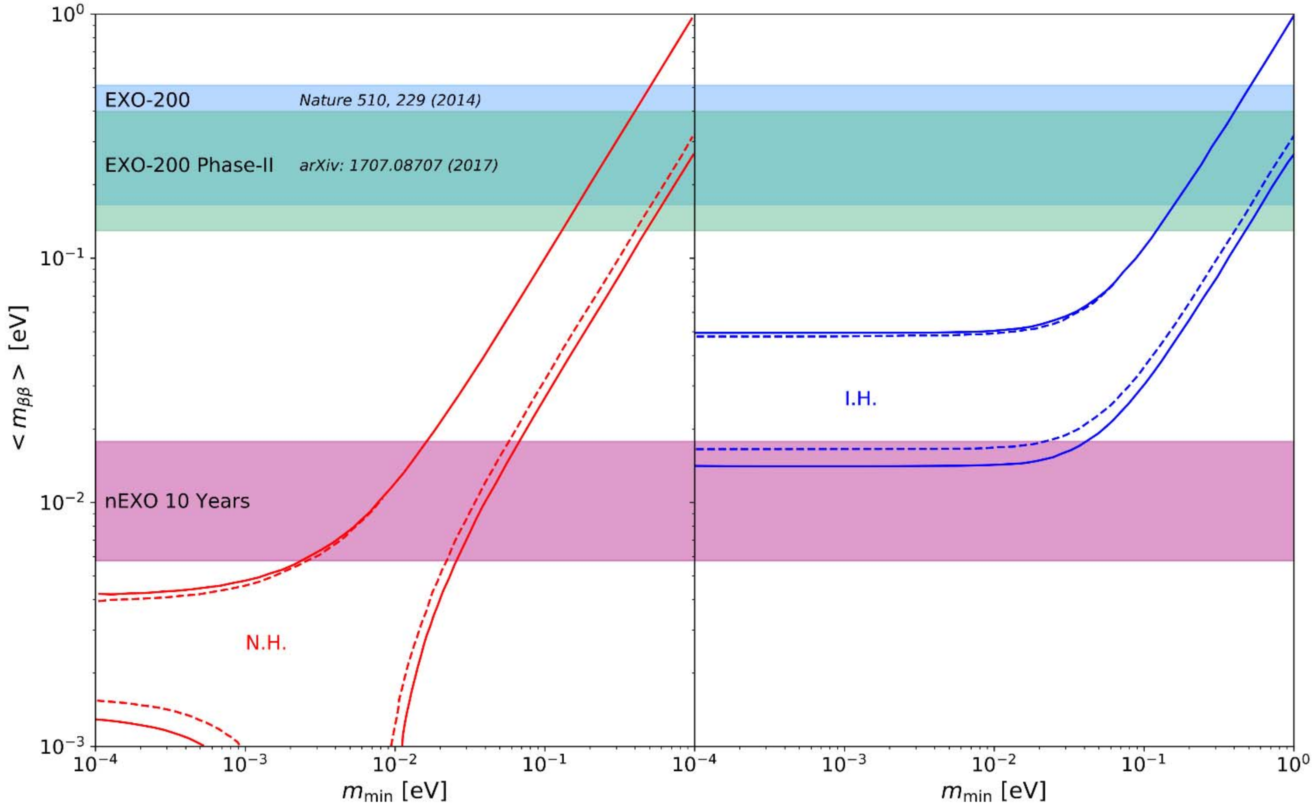


- **This same procedure predicted the EXO-200 background spot-on**
- **Internal materials dominate (as expected)**
- **Apart for the TPC vessel several items contribute in a similar way (this is part of the optimization)**
- **Several radioassay entries with only 90% CL limit (more measurements may improve the estimated background)**

Sensitivity as a function of time



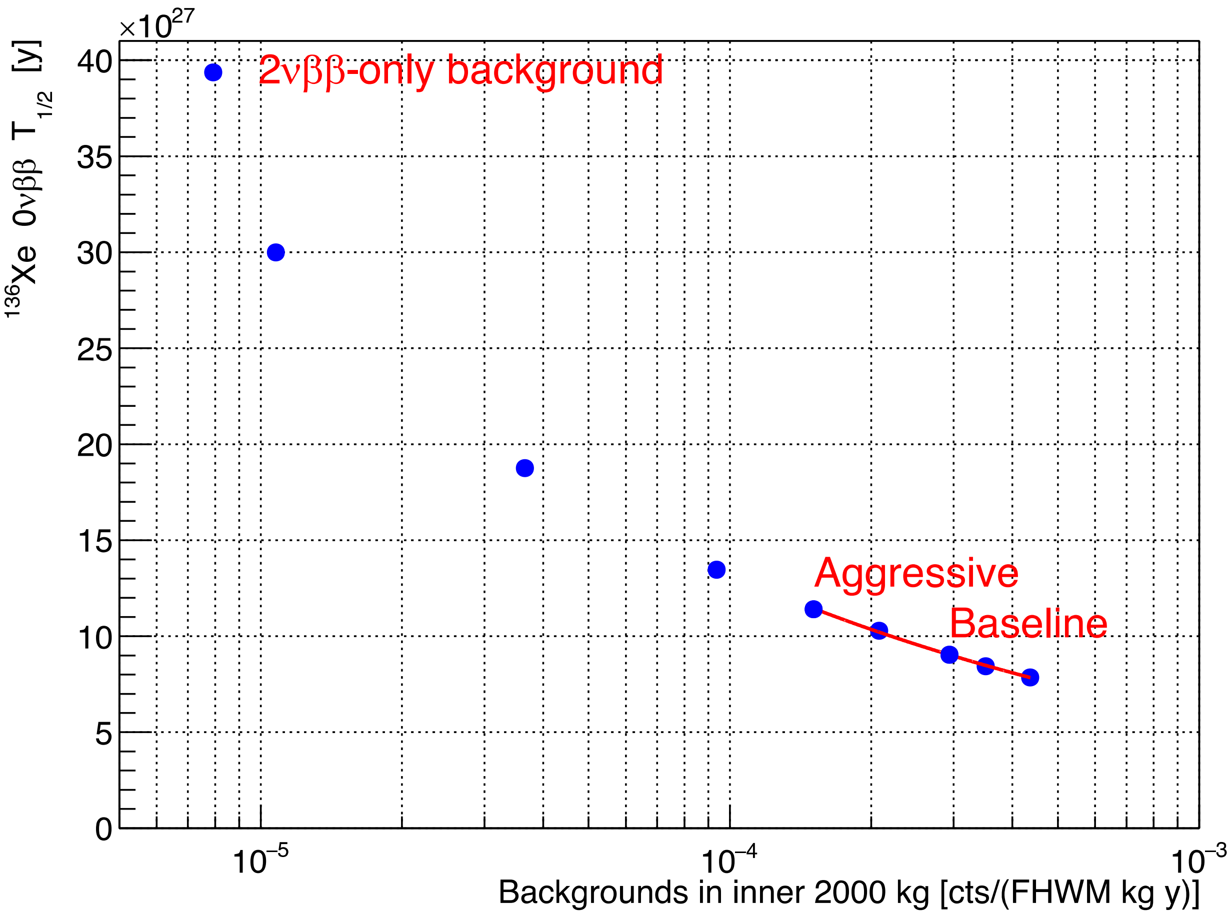
nEXO Sensitivity to Neutrino Mass assuming the standard mechanism and un-quenched g_A



- **Allowed neutrino mass bands:**
  90% CL, Forero et al., PRD 90 (2014) and Forero et al., private comm.
- **nEXO based on 10yr Sensitivity of 9.1 x 10^{27} y**

Calculation	NME value	<mbb> (meV)	Ref
Skyrme-QRPA	1.55	17.48	PRC.87.064302.2013
QRPA-Tu	2.18	12.43	PRC.91.034304.2015
RQRPA	2.54	10.67	PRC.91.024316.2015
NREDF	4.77	5.68	PRC.91.024316.2015
REDF	4.32	6.27	PRC.91.024316.2015
ISM	2.32	11.68	NPA.818.139.2009
IBM-2	3.05	8.88	PRC.91.034304.2015

Since, alas, we have not started building nEXO yet a materials improvement program is under way, so the sensitivity is likely to be better than shown in the previous slide.



Here all materials are scaled down together to the total value in abscissa

Eventually, only the 2νββ decay is left, representing the case of Ba tagging

Power-law fit near baseline gives

$$T \propto \frac{1}{B^{0.35}}$$

Early ββ decay experiments were based on the identification of trace amounts of element B in a sample of element A (after a geological or anyway long time).

Can we imagine doing this in nEXO, but

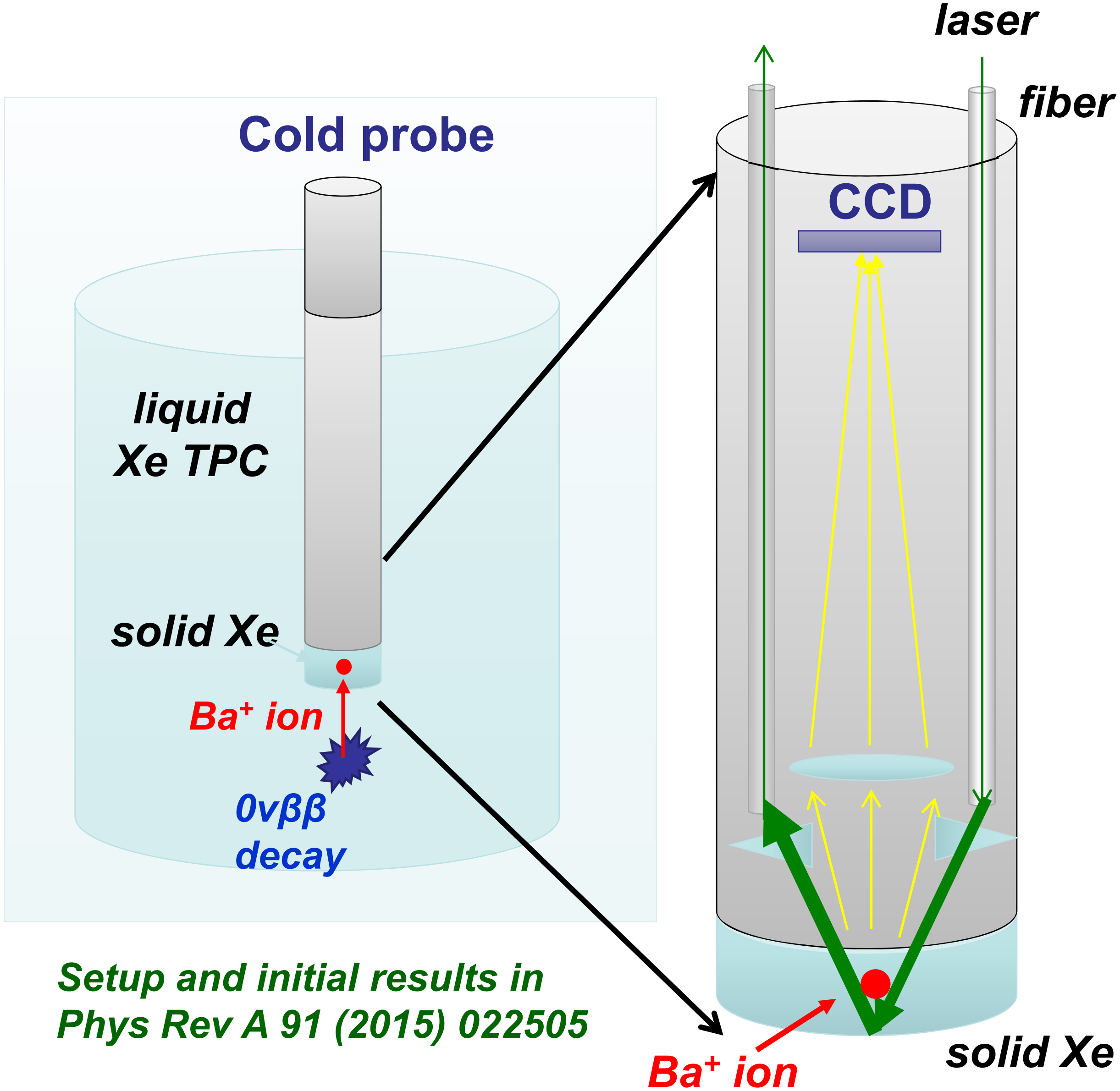
real time and for individual atoms

so that the "chemical tag" can be associated to the other parameters of the decay, in particular the energy to discern the 0ν from the 2ν background.

The final state atom in the ββ decay of ^{136}Xe is ^{136}Ba.

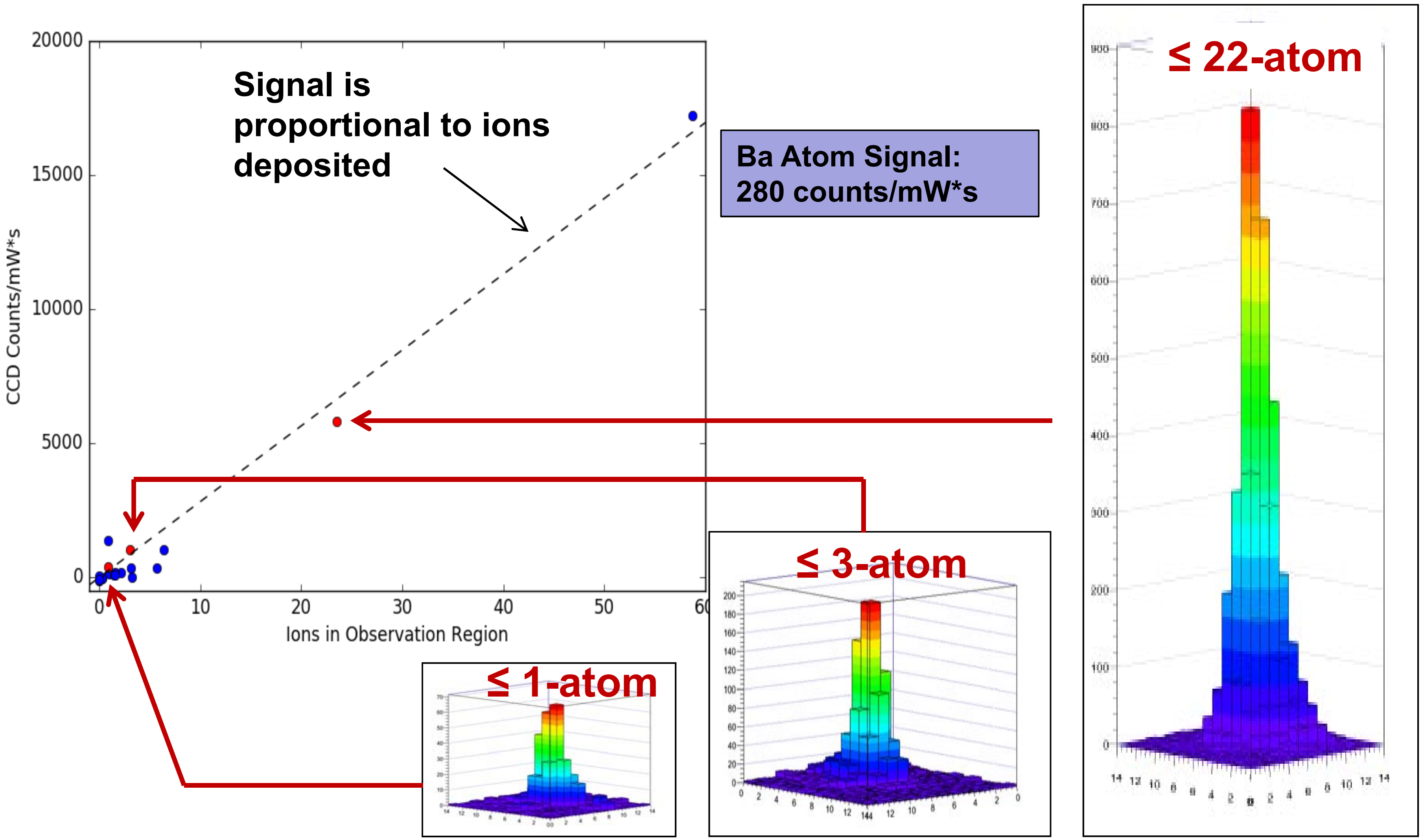
A substantial R&D program to develop spectroscopic techniques to achieve this is in progress.

…speaking of which…
Ba tagging R&D is making steady progress



Setup and initial results in
Phys Rev A 91 (2015) 022505

Images of Ba atoms in solid Xe on a sapphire plate



Number of atoms in the image is based on the number of ions deposited. The neutralization fraction is unknown, but the number of atoms is less than the measured number of ions.

Conclusions

- **$0\nu\beta\beta$ searches are discovery physics,**
  with connections to many areas of modern physics
- **Results from 100 kg yr searches are here,**
  with no discovery yet
- **Looking at more than one isotope is important**
- ***We are ready to build ton-scale experiments with***
  negligible background
- **(in the US) the (NP) community has selected this**
  effort as the top priority for the next large project
- **The 10meV region is within reach!**

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, E Hansen, 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, 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, Y Ito, 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,
LJ Kaufman, 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, S Wu
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 — Z Li, D Moore, Q Xia