The EXO program:
EXO-200 and nEXO

Giorgio Gratta

Stanford

The general phenomenology of neutrinoless double-beta decay is not my topic today,

Yet I want to stress that we (double-beta decay community) have to work on educating (some of) our colleagues to avoid "motivational pitfalls" **(notwithstanding the prioritization from the long range planning exercise)**

The connection with neutrino masses is subtle and particularly insidious.

- **Finite masses, from oscillations, make 0νββ possible**
- **Beyond this, all one has to talk about is, at first order, the discovery of lepton number non-conservation and the discovery existence of Majorana fermions.**

This is the same type of bet that was made in increasing the energy from Tevatron to LHC! And should be enough…

The direct connection with Majorana masses is important because it identifies the energy scale of new physics but it also leads to arguments about

- **NH vs IH**
- **NME**
- **g_A**
- **…and even neutrino masses from cosmology**

The first 3 items have been recently addressed by

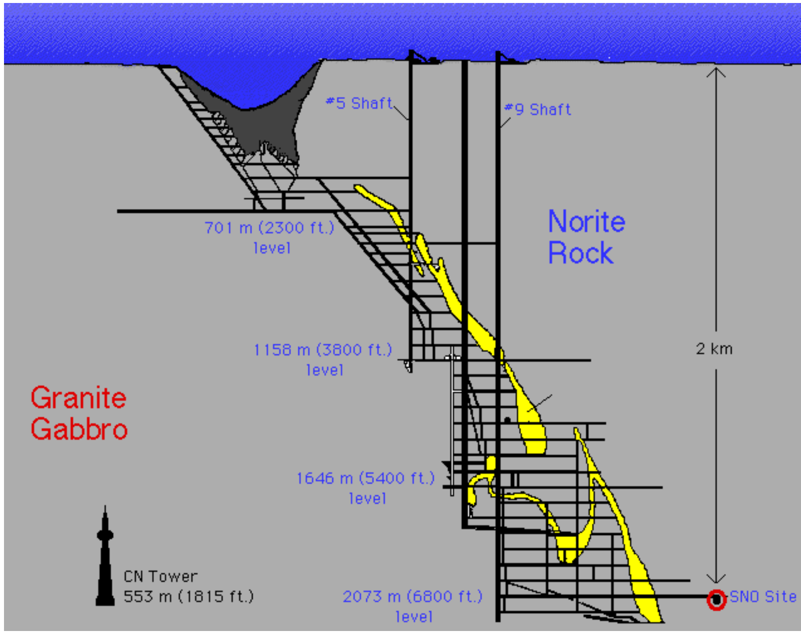
Agostini, Benato, Detwiler arXiv:1705.02996 and
Caldwell, Merle, Schulz, Totzauer, arXiv:1705.01945

yet, I hope our theorist friends will help formulating a crisp, simple and compelling message

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:

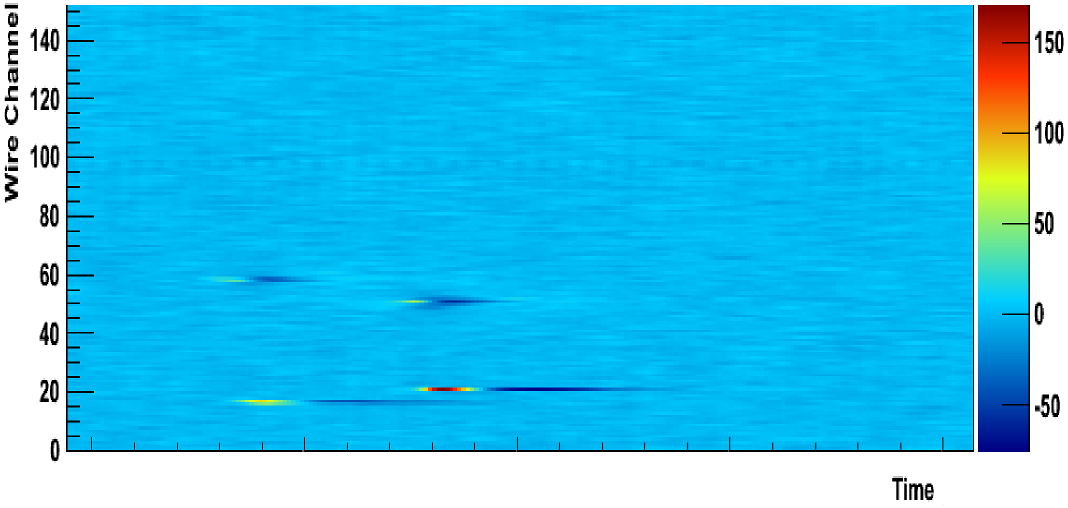
3) Ultra-low radioactive contamination for detector construction components

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!

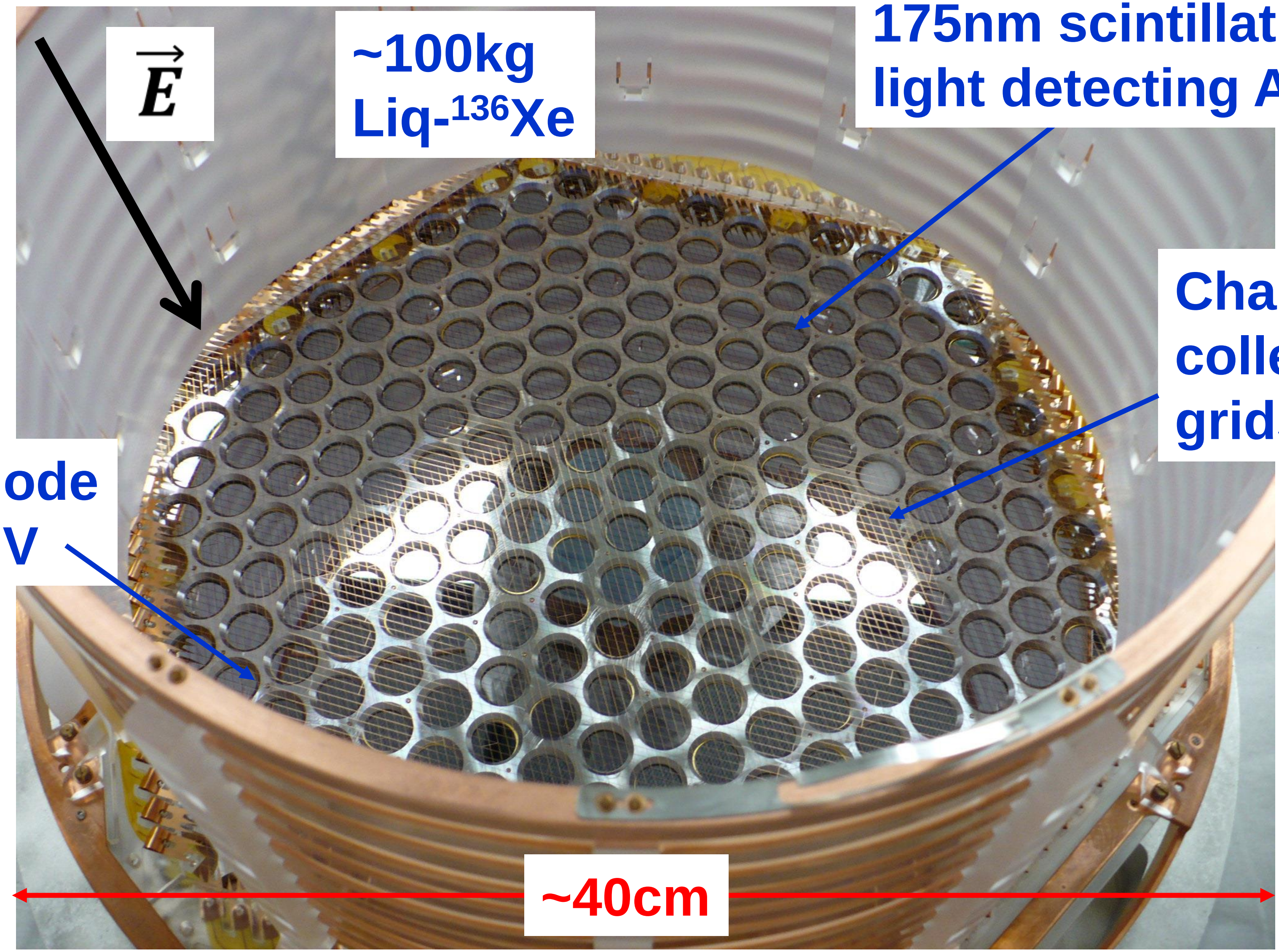
Powerful detectors use most of (possibly all) these parameters in combination, providing the best possible background rejection and simultaneously fitting for signal and background.

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

ཐིམ་ཕུ་ འབྲུག་ཡུལ་ (Thimphu, Bhutan) Feb 2015

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



~100kg Liq-^{136}Xe

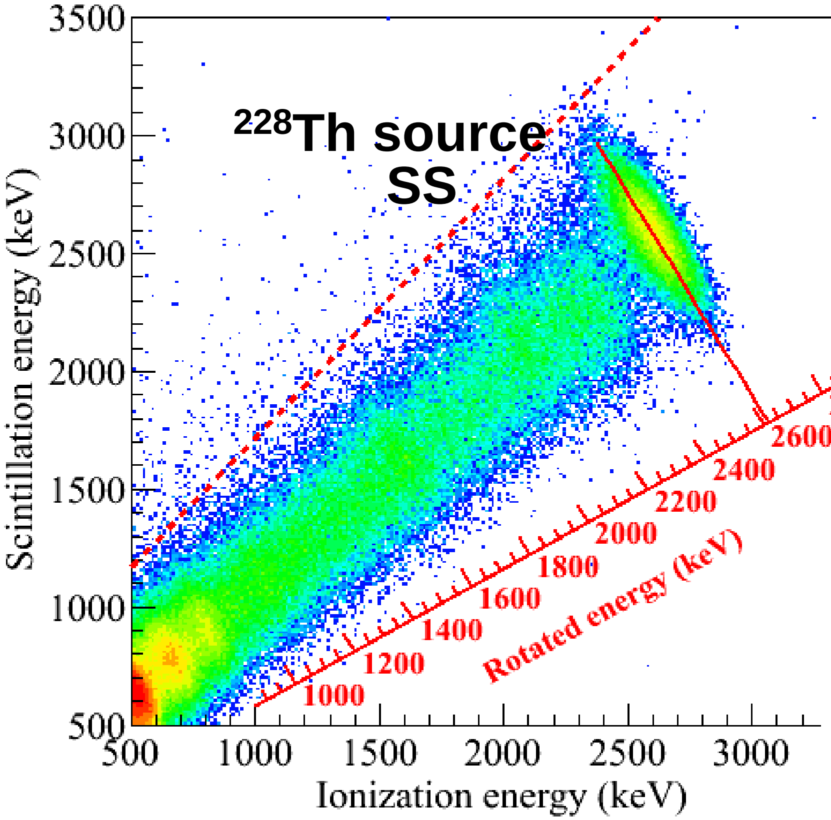
175nm scintillation light detecting APDs

Charge collection grids

Cathode -HV

~40cm

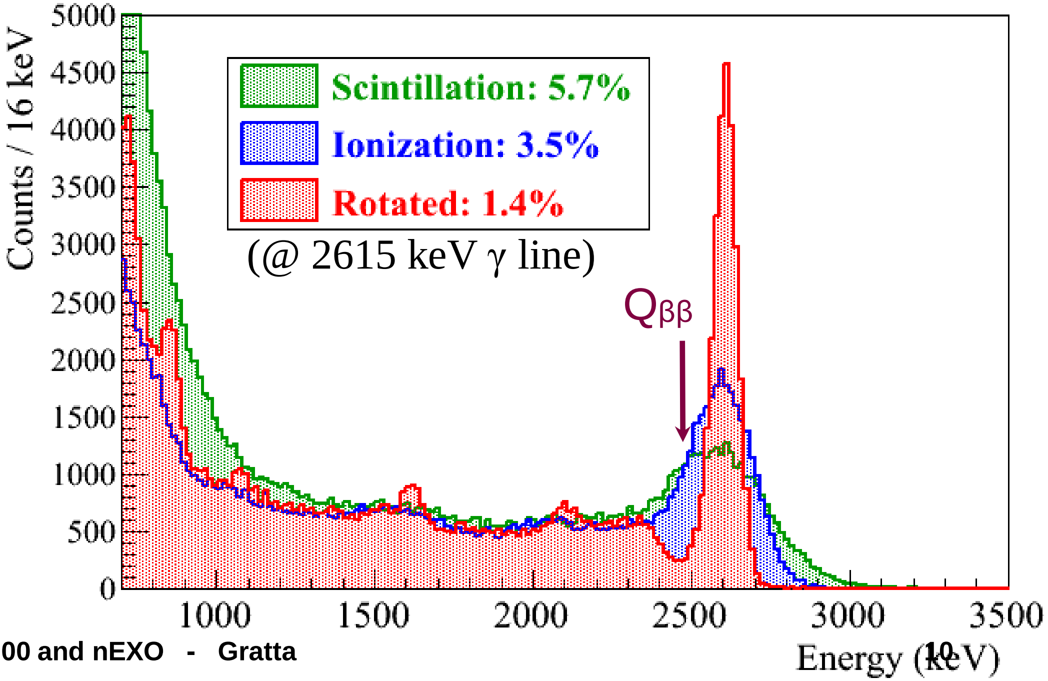
Combining Ionization and Scintillation



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

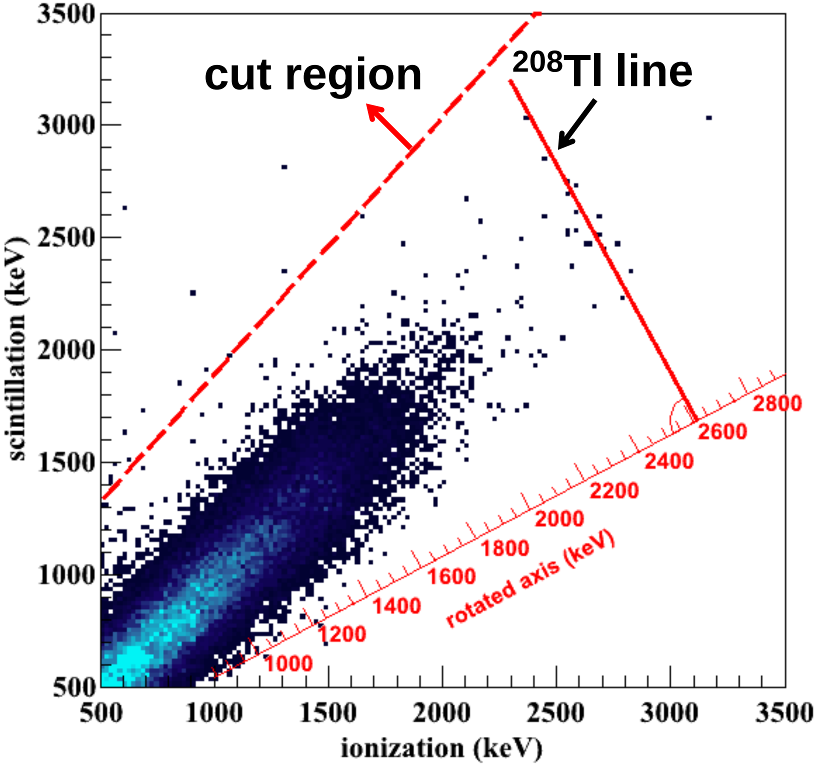


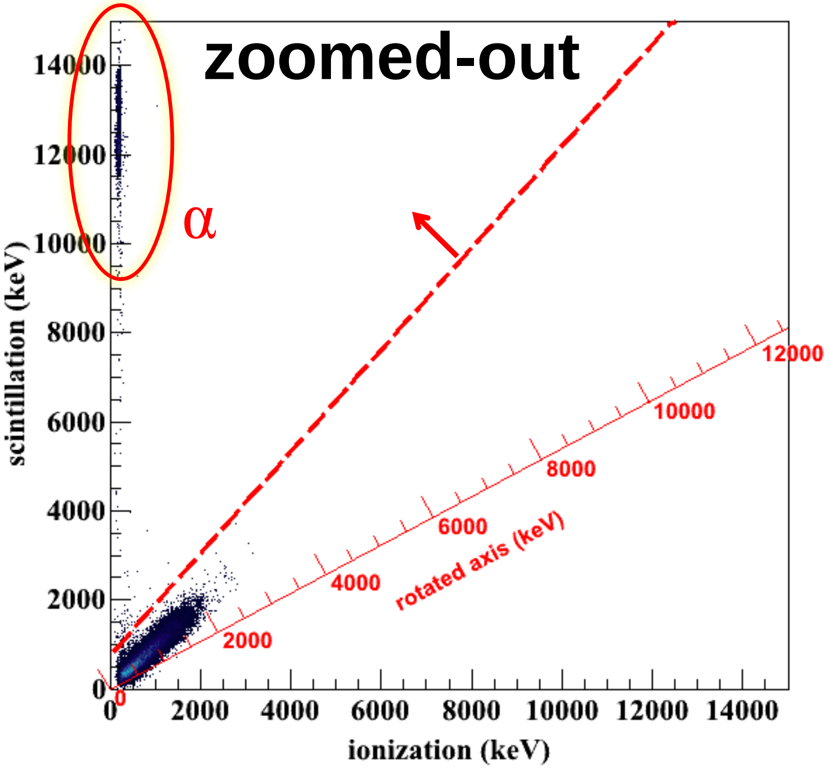
- 🟩 Scintillation: 5.7%
- 🟦 Ionization: 3.5%
- 🟥 Rotated: 1.4%

(@ 2615 keV γ line)

Rotation angle chosen to optimize energy resolution at 2615 keV

Low Background 2D SS Spectrum



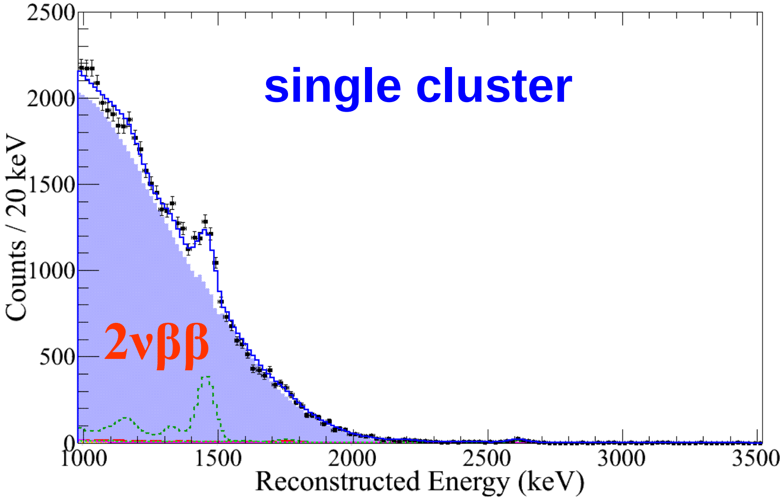


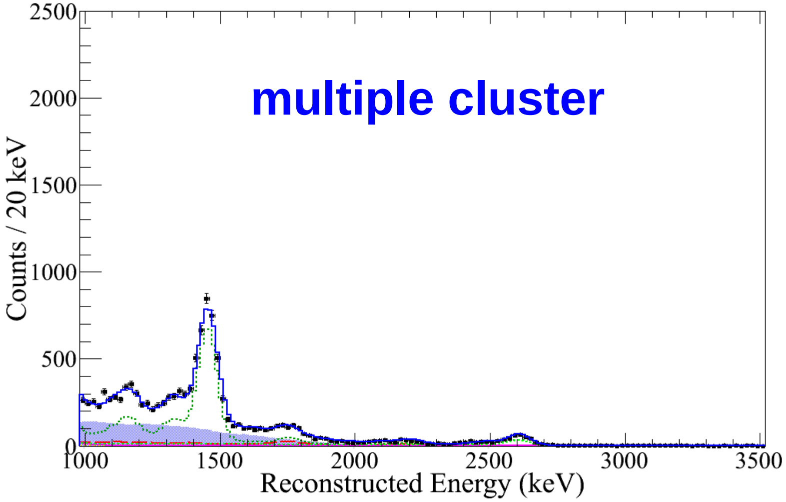
Events removed by diagonal cut:

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

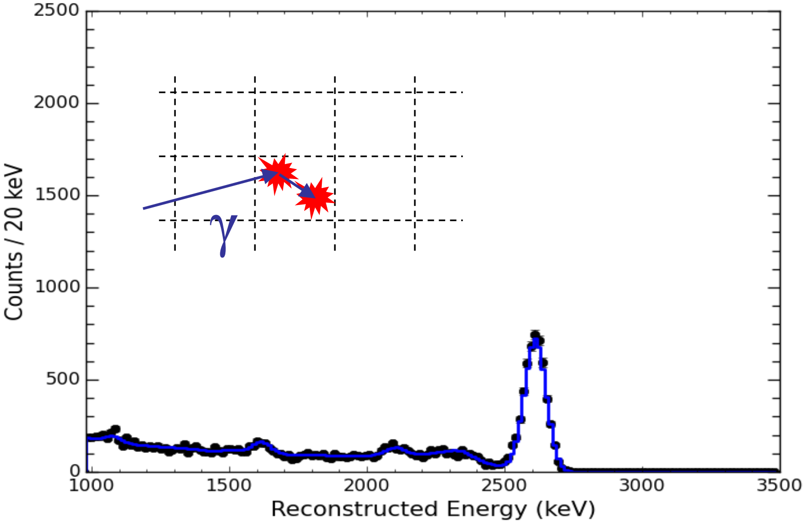
Using event multiplicity to recognize backgrounds

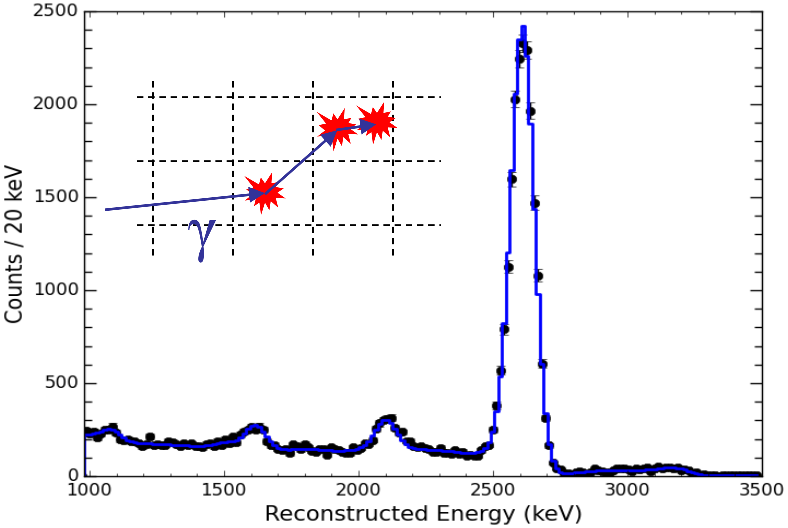
Low background data



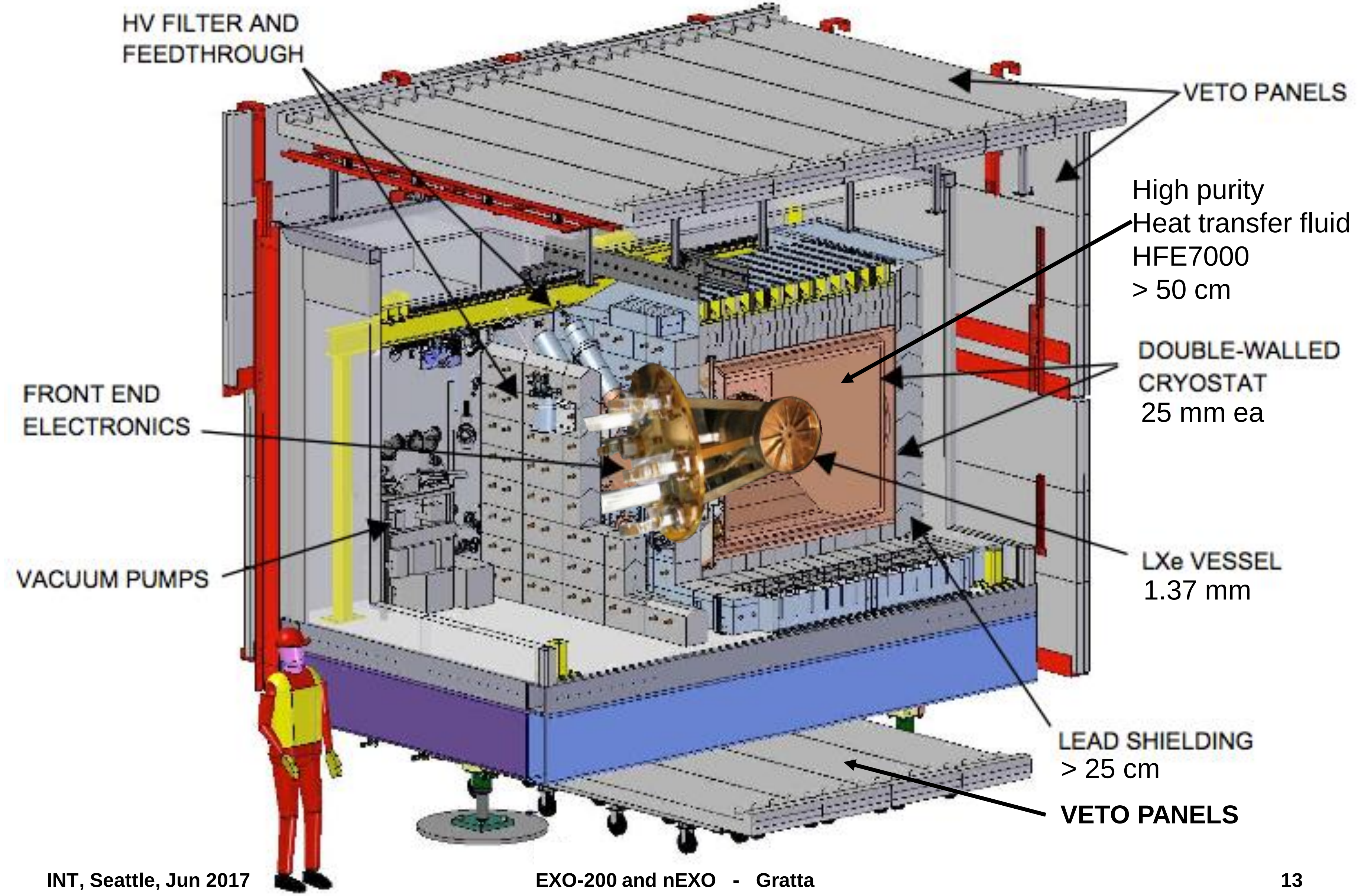


^{228}Th calibration source

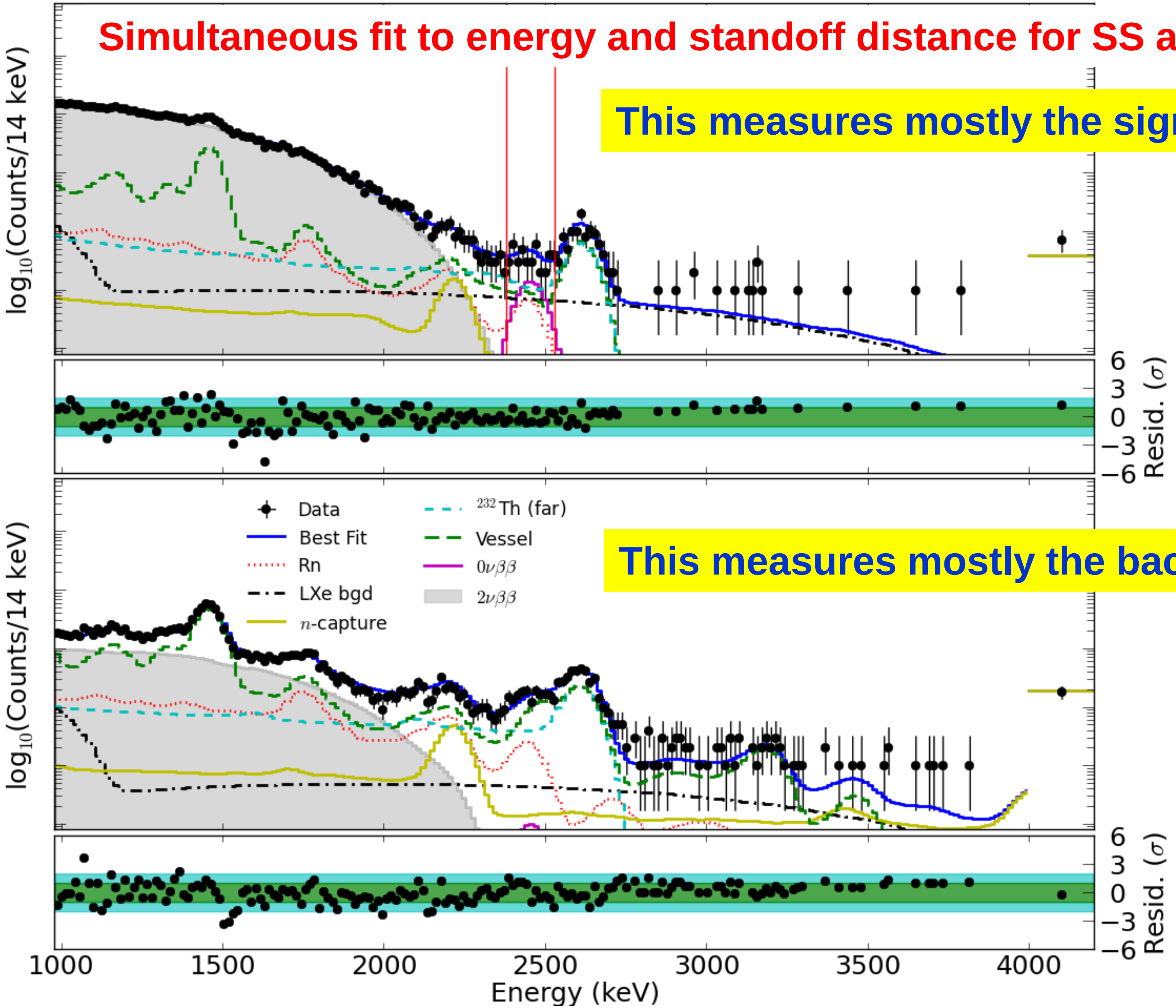




25cm-thick Pb shield, in a cleanroom, surrounded by a cosmic-ray veto, 655m underground



Simultaneous fit to energy and standoff distance for SS and MS



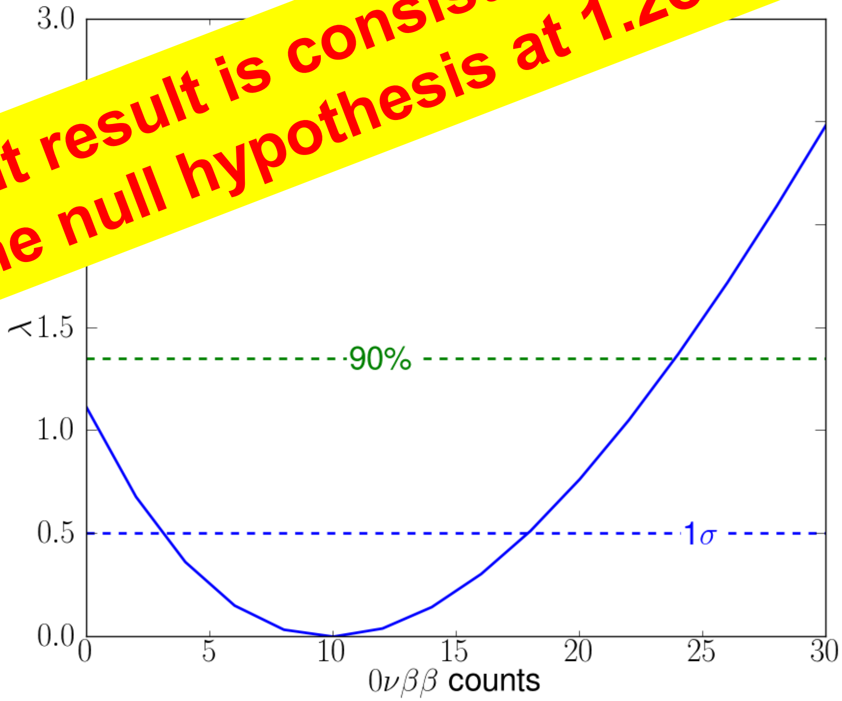
This measures mostly the signal

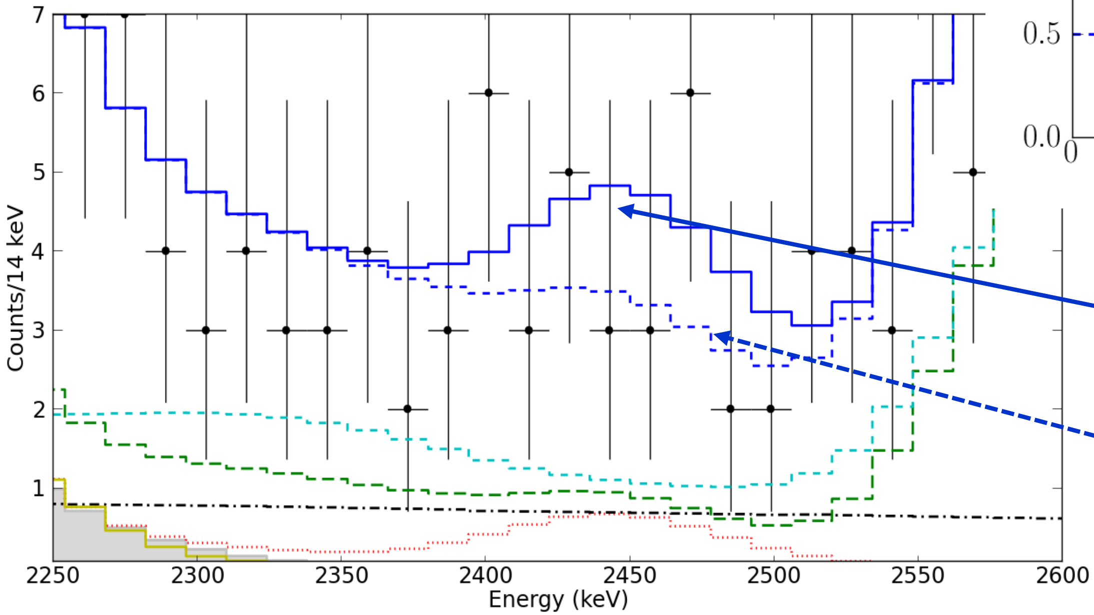
This measures mostly the background

0νββ decay and background fit:

Fit components	
Backgrounds	31.1
0νββ decay	9.9
Total	41.0

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



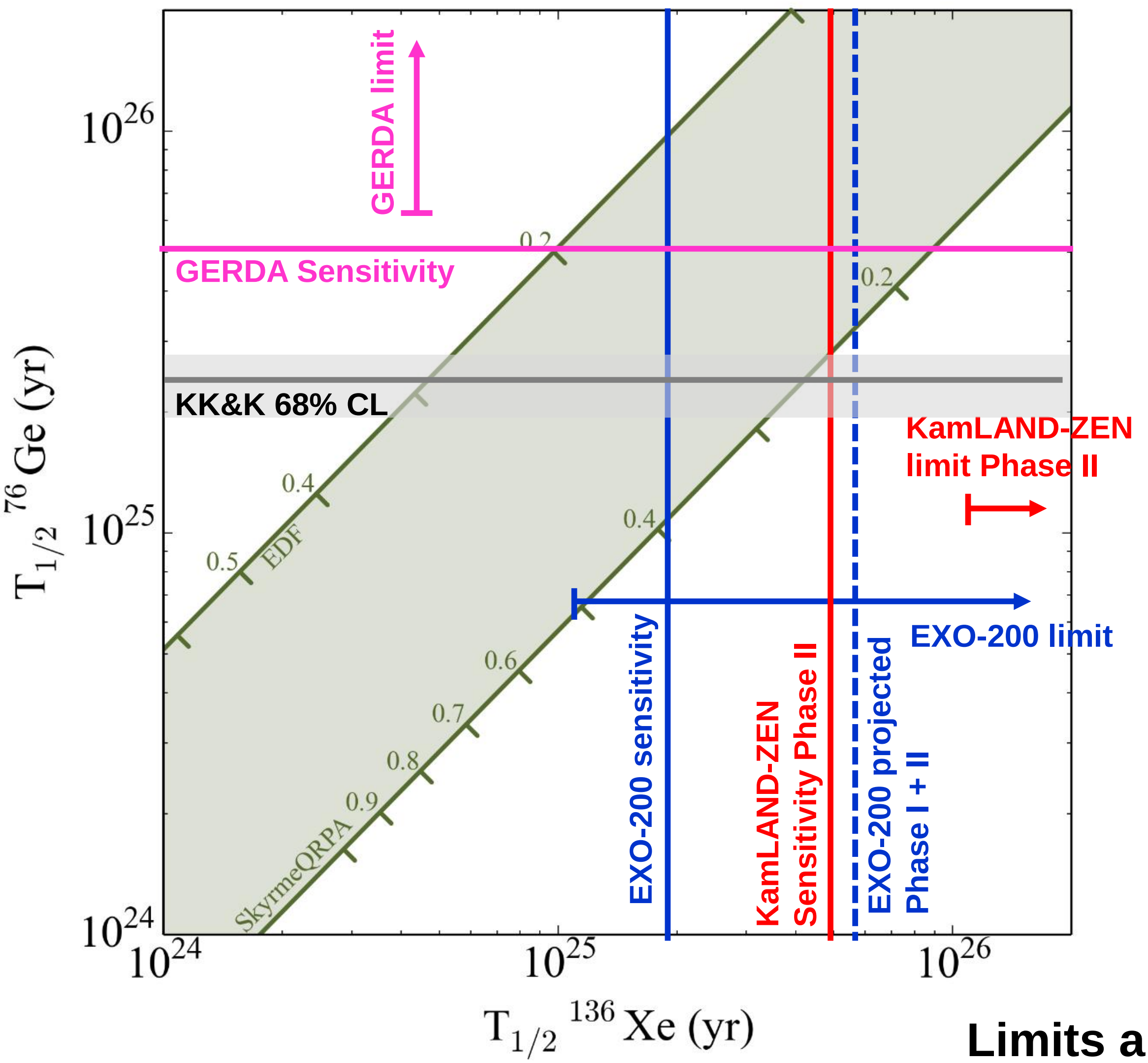


Fit with 0νββ decay

Fit without 0νββ decay

EXO-200: $T_{1/2} > 1.1 \times 10^{25}$ yr [$8.0 \times 10^{14}\ T_{universe}$] $\langle m_\nu \rangle < 190 - 450$ meV
Average sensitivity 1.9×10^{25} yr

J.B.Albert et al., Nature 510 (2014) 299



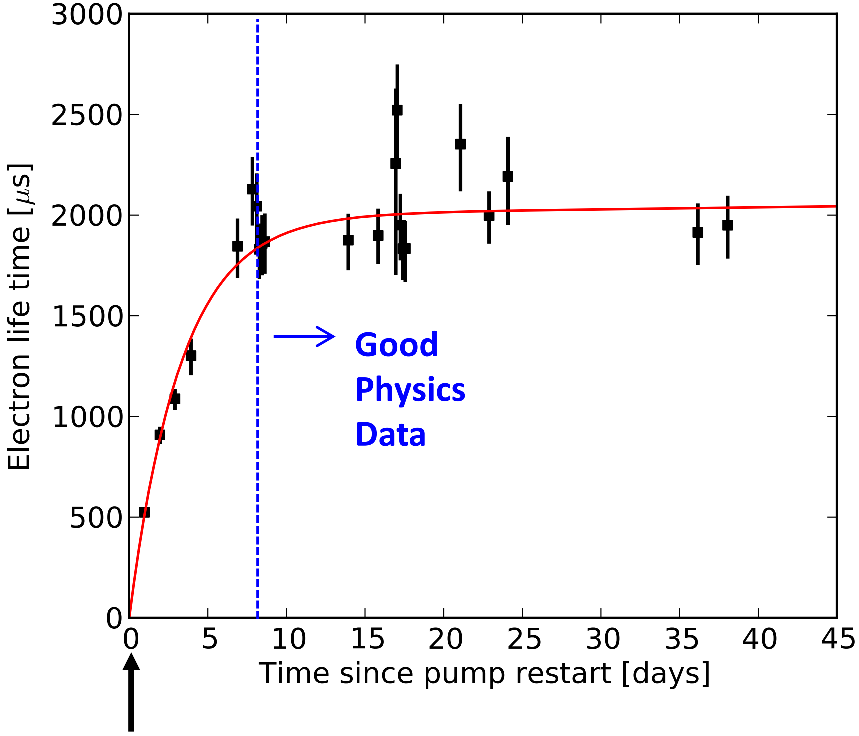
GERDA: M.Agostini et al., Nature 544 (2017) 47

KLZ: A.Gando et al., Phys. Rev. Lett. 117 (2016) 082503

Limits are 90% CL

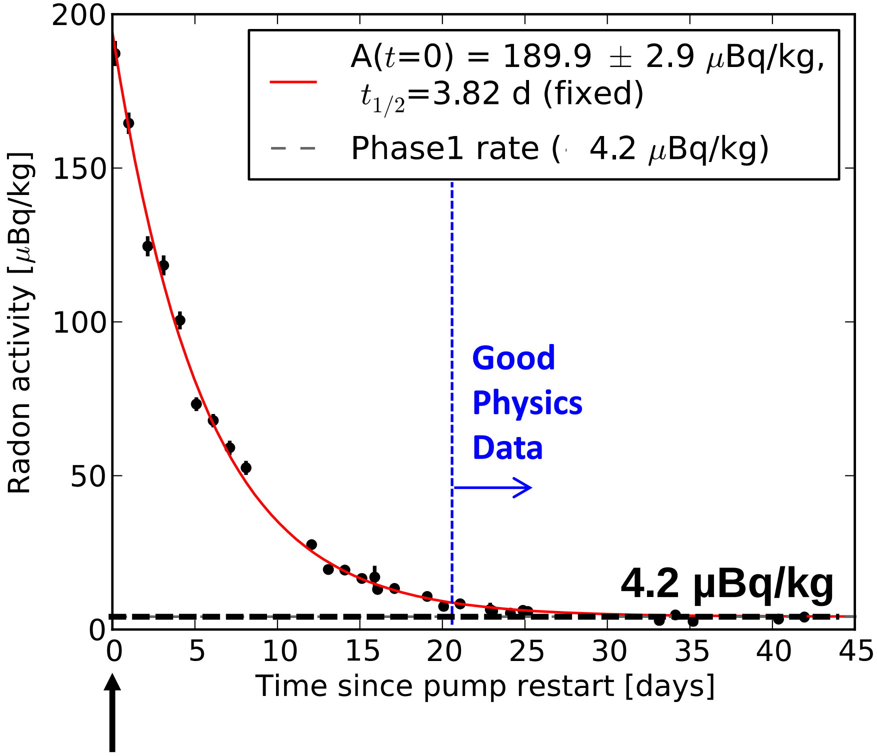
EXO-200 Phase-II Operation

- **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.**



Good Physics Data

31 Jan ‘16

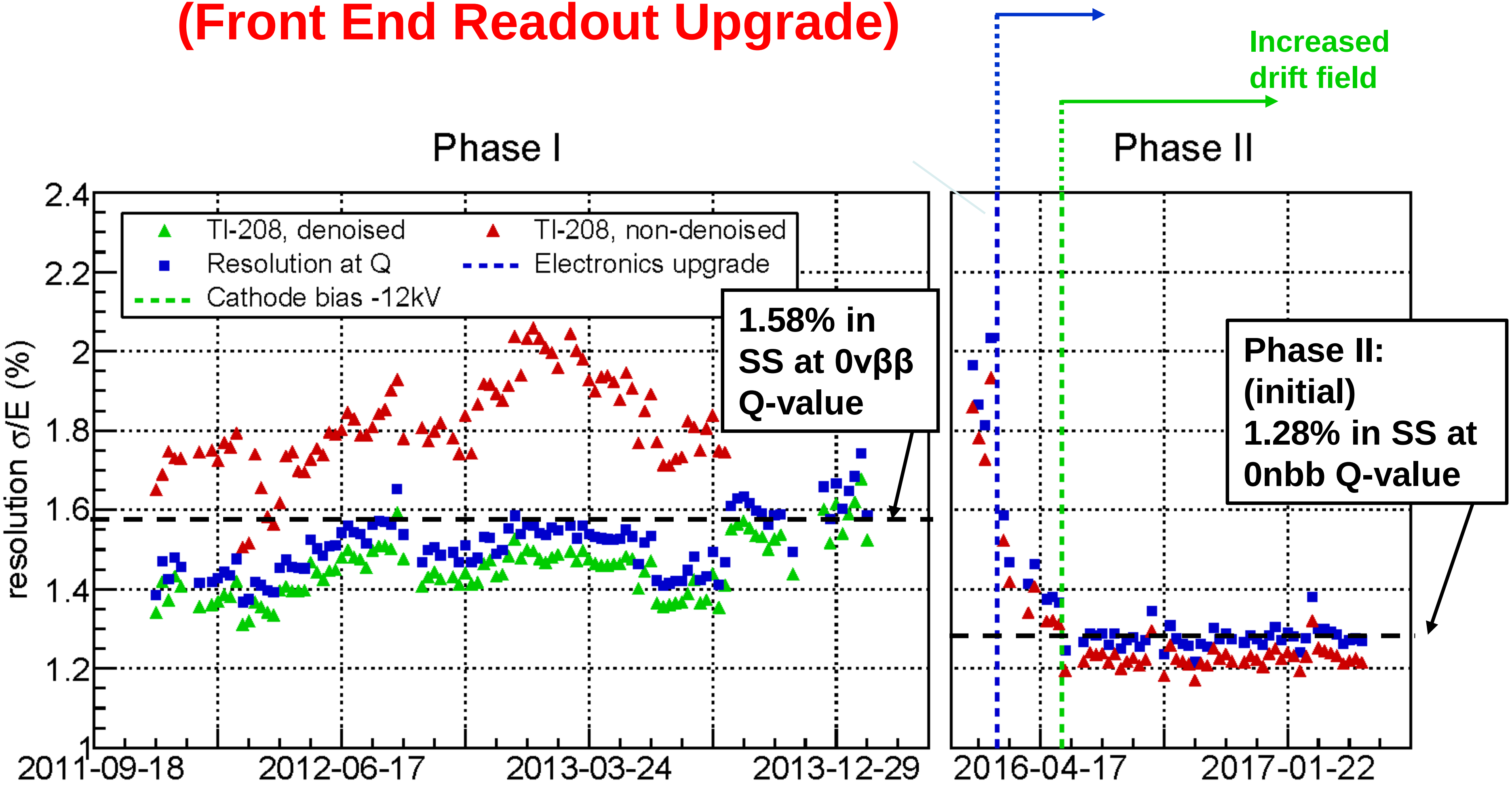


Good Physics Data

4.2 μBq/kg

31 Jan ‘16

EXO-200 Phase II Upgrade Performance (Front End Readout Upgrade)



Front end readout upgrade

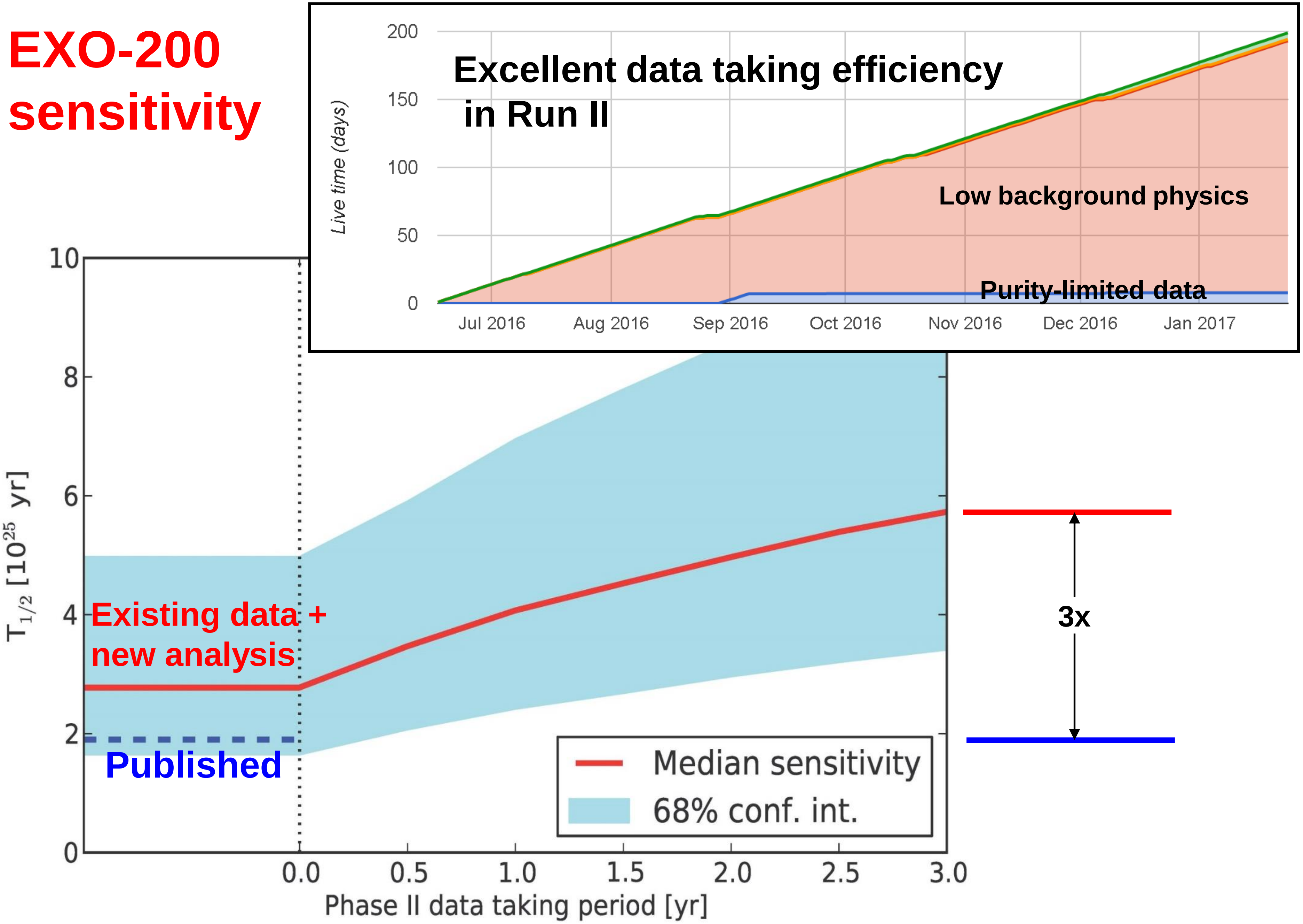
Increased drift field

1.58% in SS at 0νββ Q-value

Phase II: (initial) 1.28% in SS at 0nbb Q-value

Further improvements in detector energy resolution may be possible with better signal reconstruction and detector non-uniformity corrections.

EXO-200 sensitivity


Excellent data taking efficiency in Run II

Low background physics

Purity-limited data

Existing data + new analysis

Published

3x

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

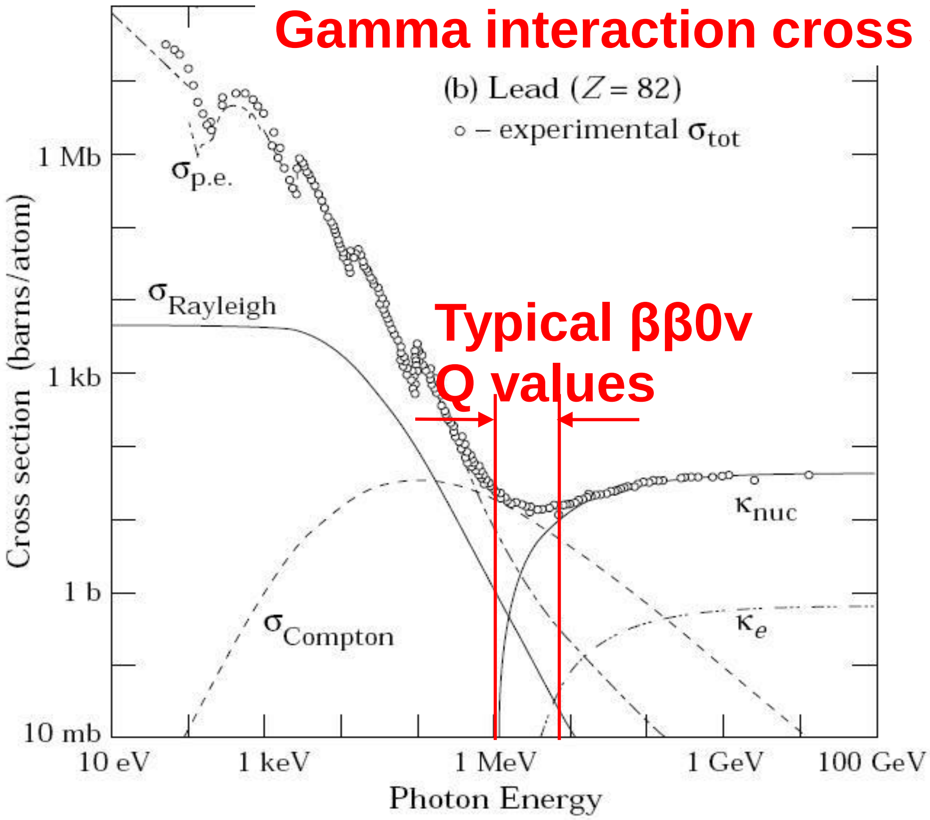
“We recommend vigorous detector and accelerator R&D in support of the neutrinoless double beta decay program and the EIC.”

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!



Gamma interaction cross section

Typical ββ0v Q values

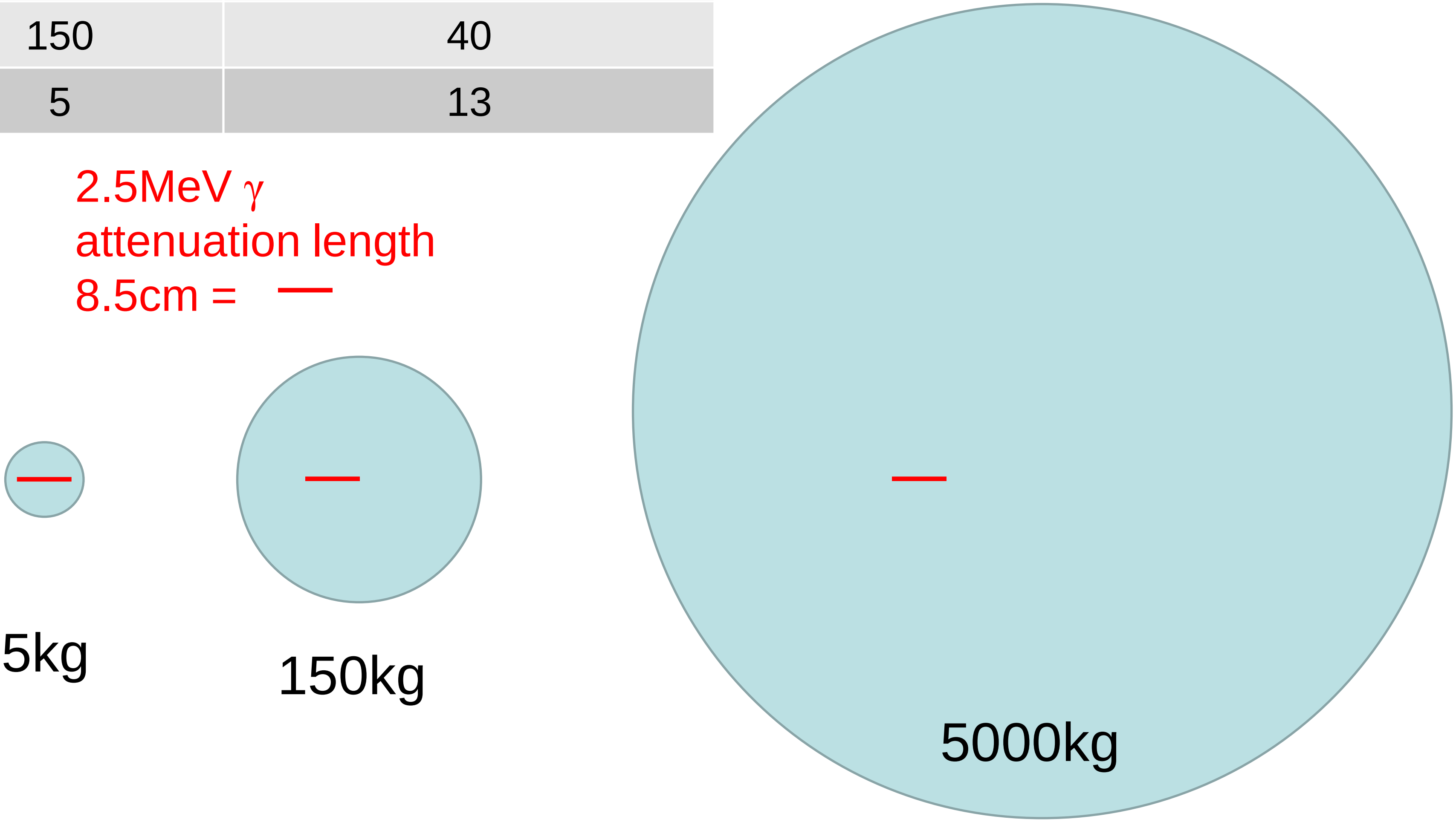
Example:

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

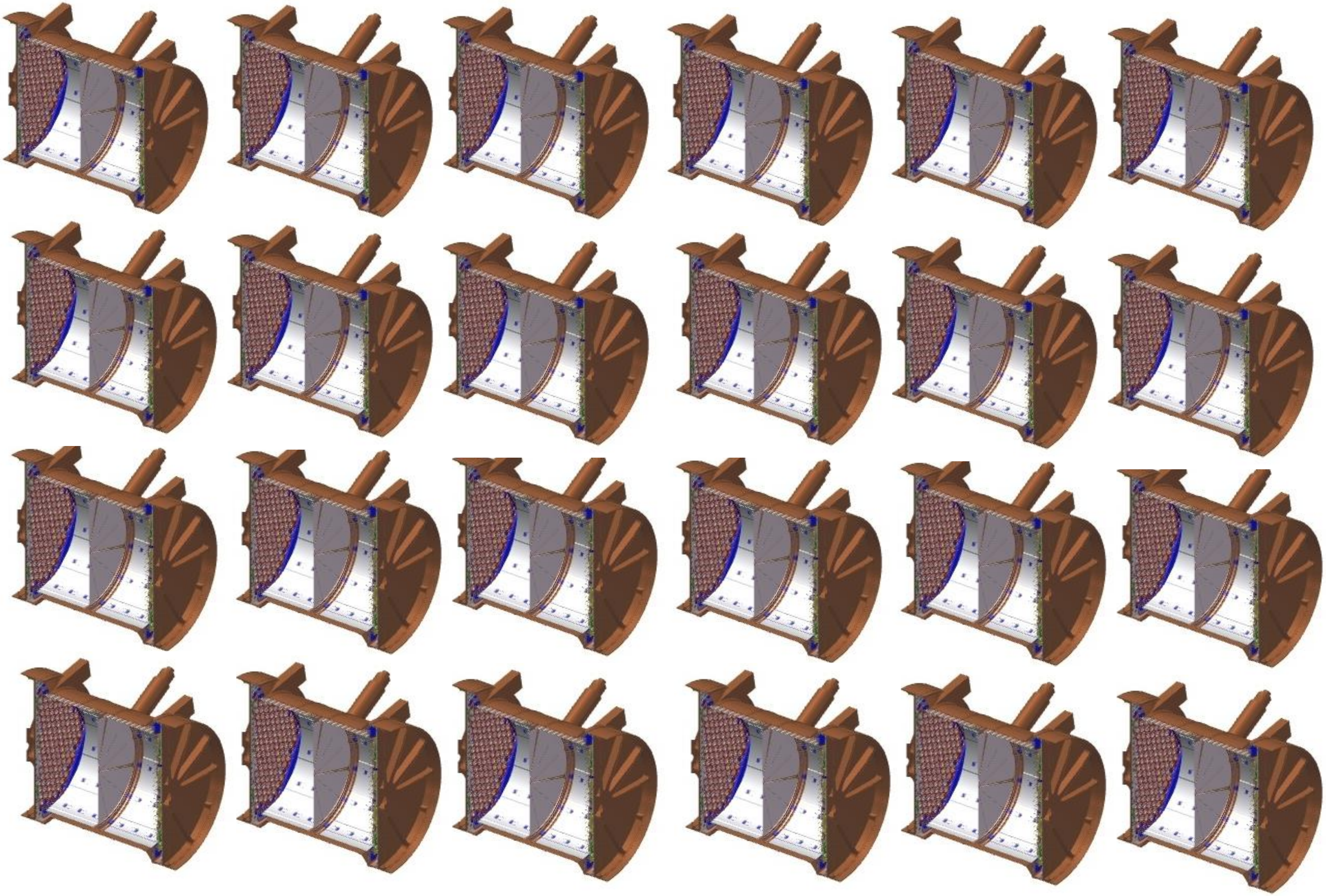
We are entering the "golden era" of ββ decay experiments as detector sizes exceed int lengths

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



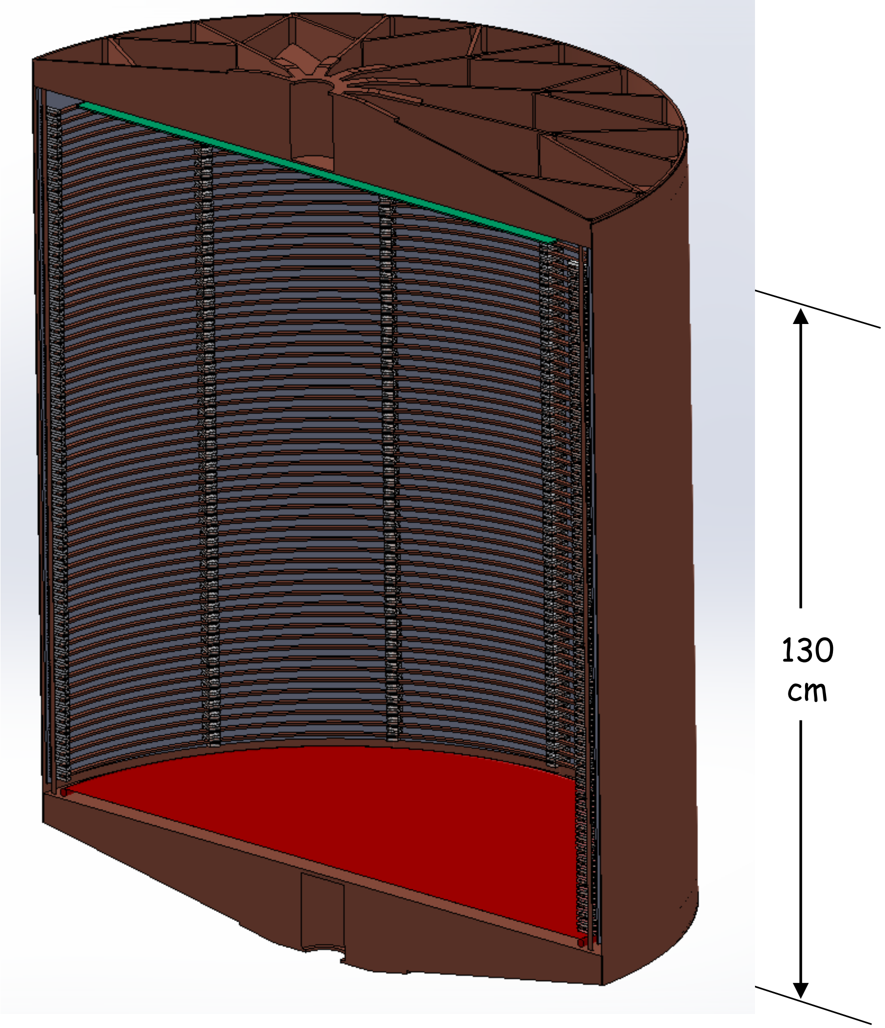
This works best for a monolithic detector

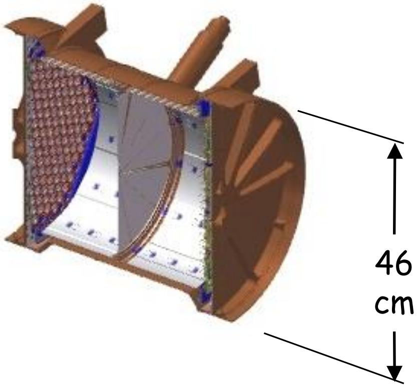
The wrong design for nEXO (requiring no R&D)



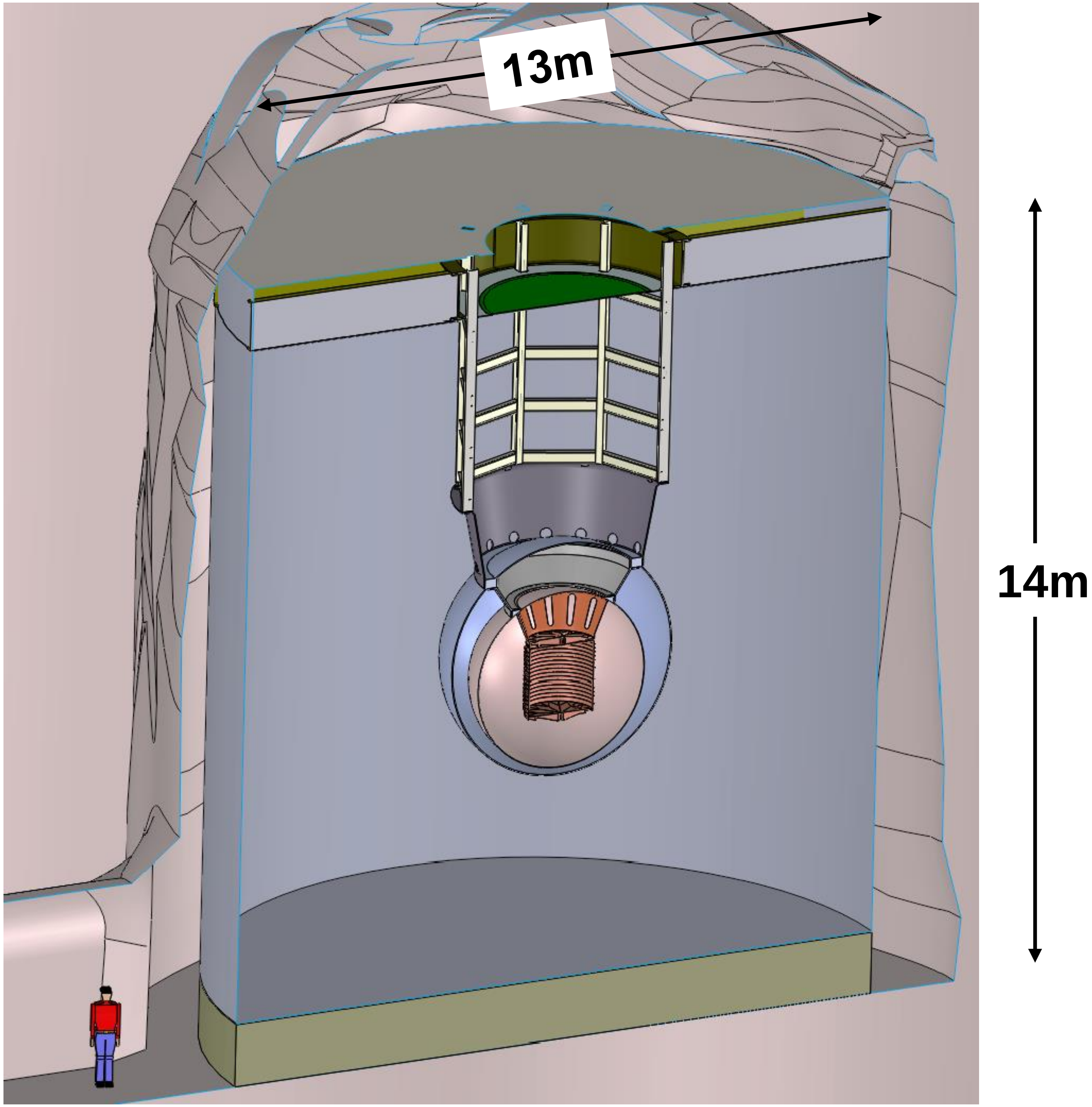
The nEXO detector

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





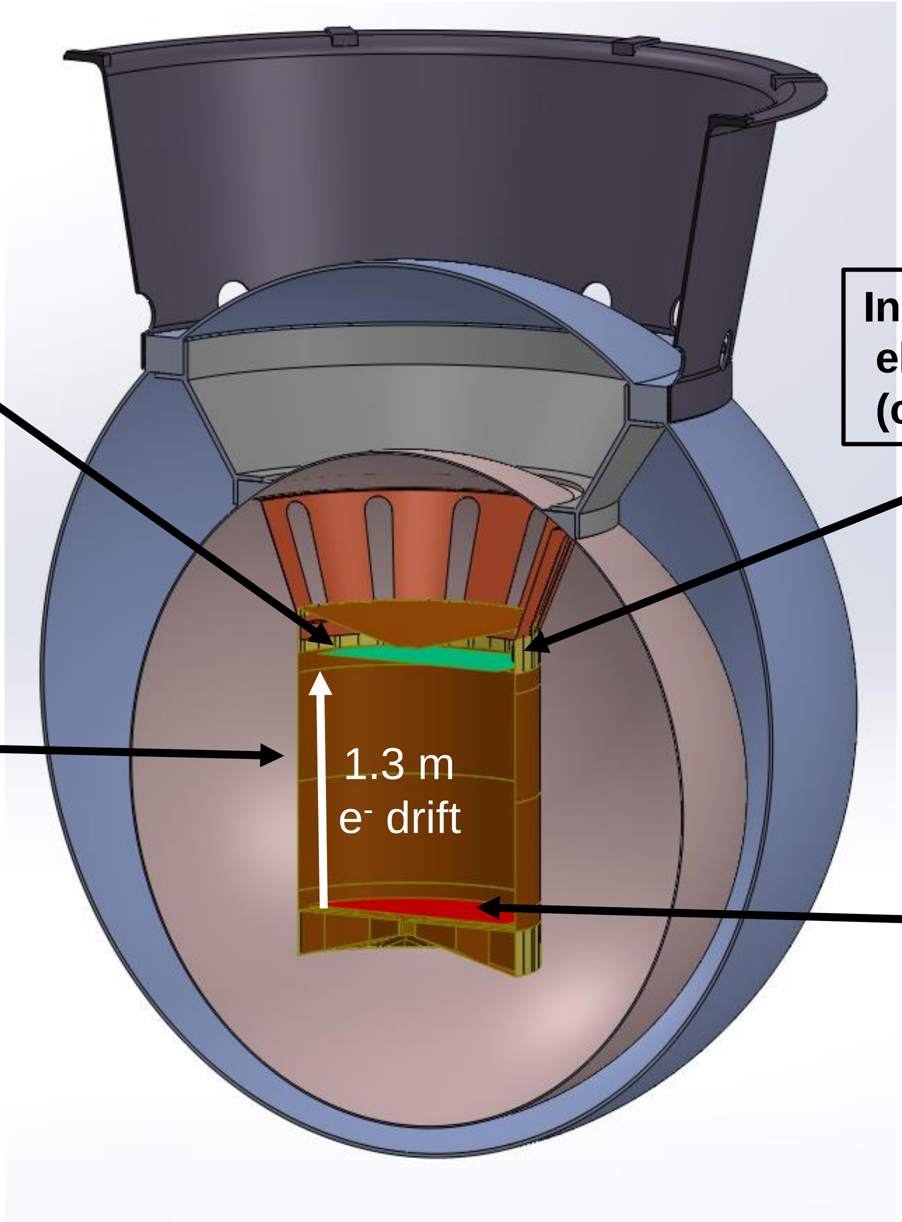
Preliminary artist view of nEXO in the SNOlab Cryopit



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



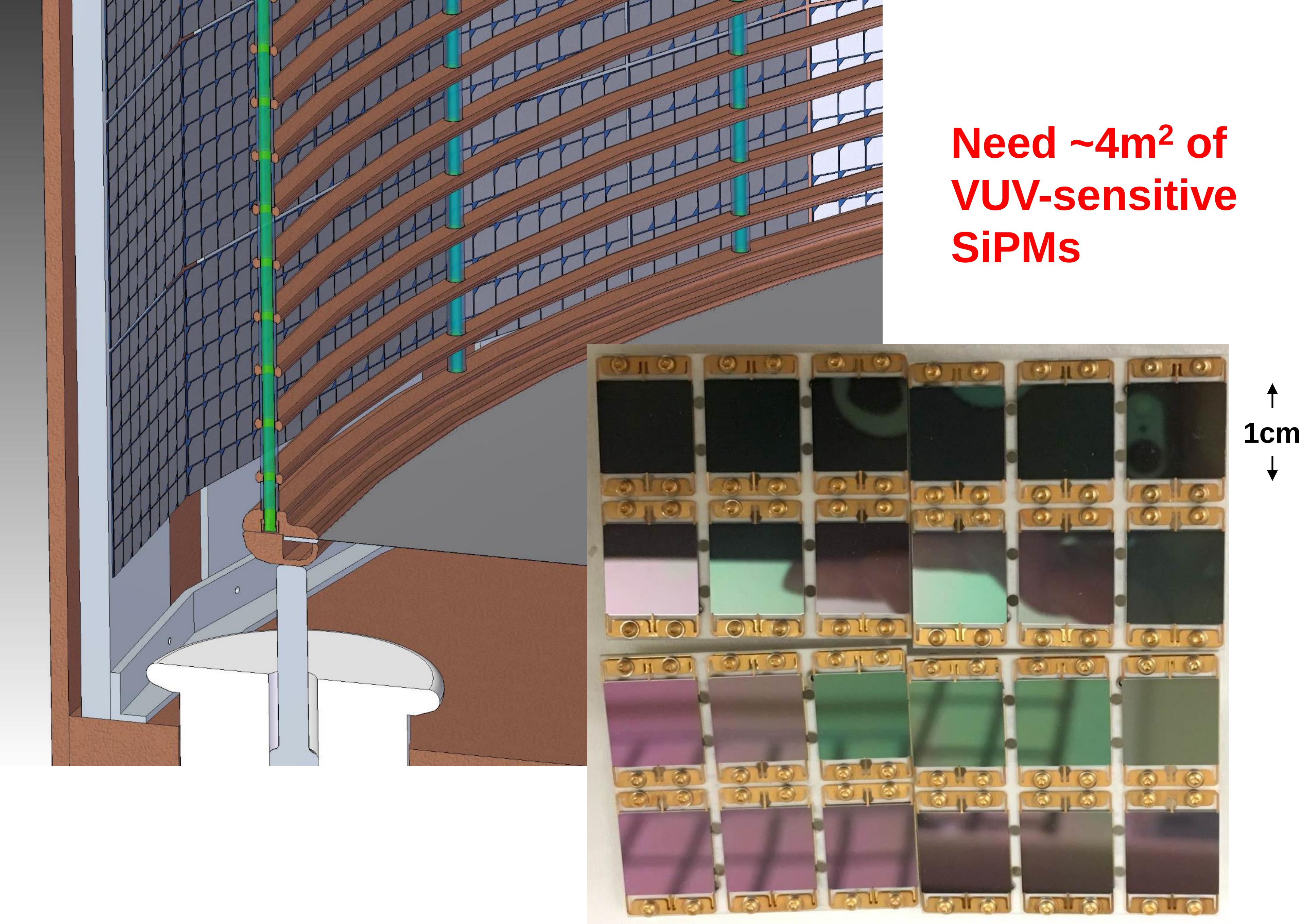
Charge readout strips (anode)

In LXe electronics (charge and SiPMs)

SiPM `staves' plastering barrel behind field-shaping rings

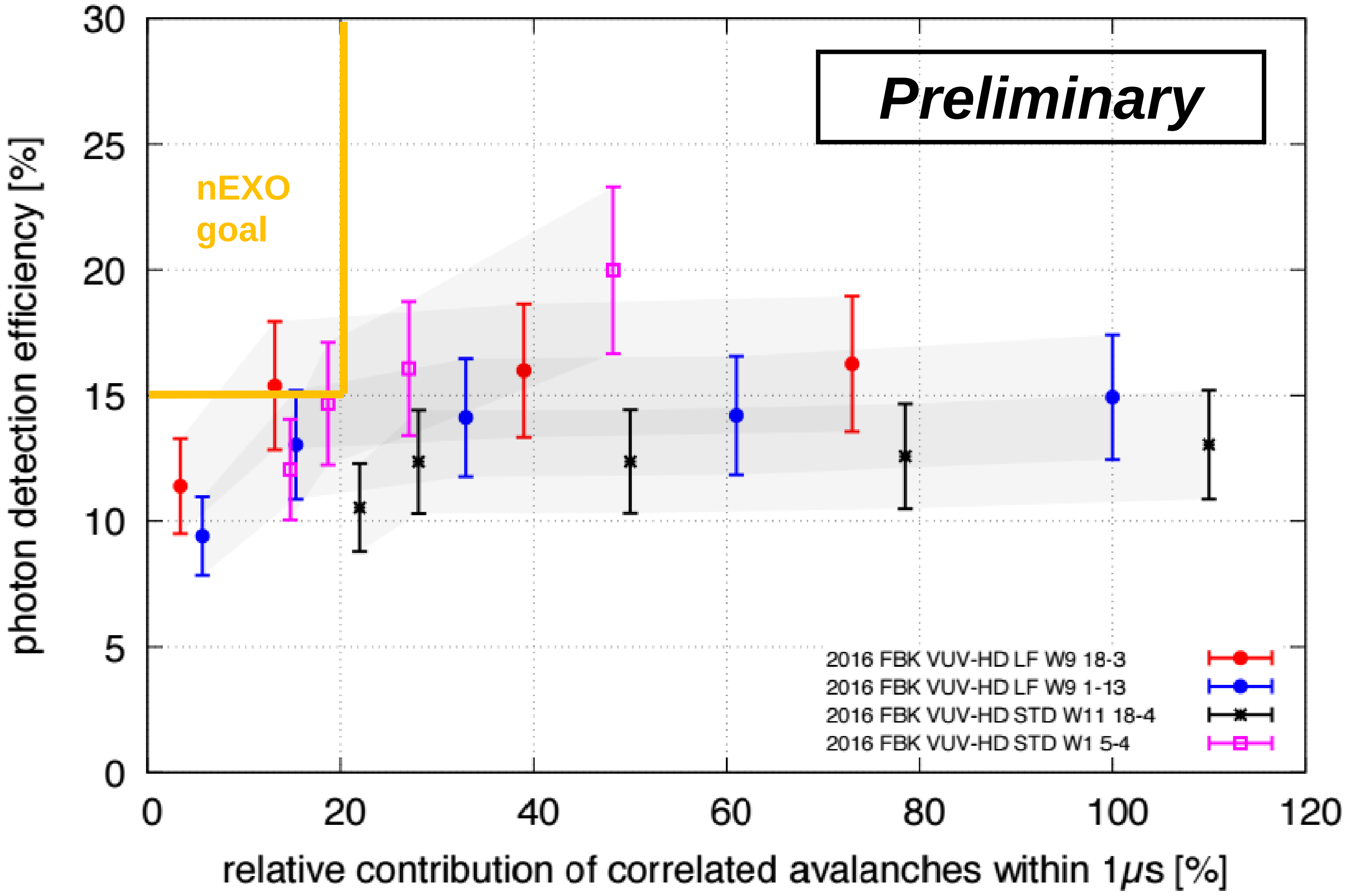
Cathode

Need ~4m^2 of VUV-sensitive SiPMs



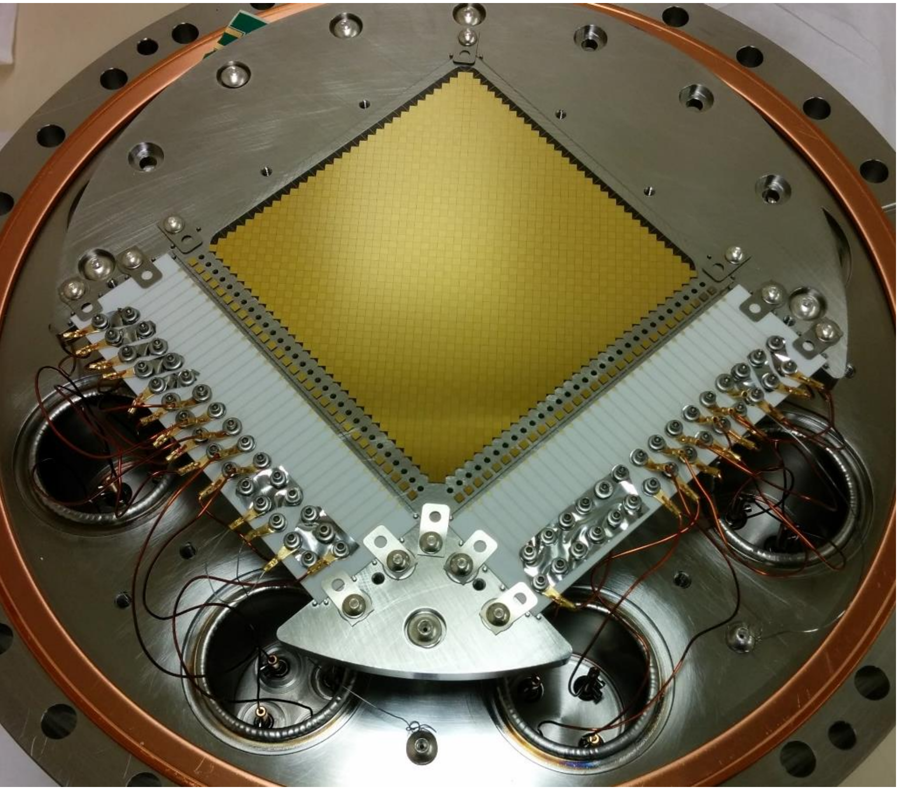
At least one type of 1cm^2 VUV devices now match our desired properties, with a bias requirement ~30V

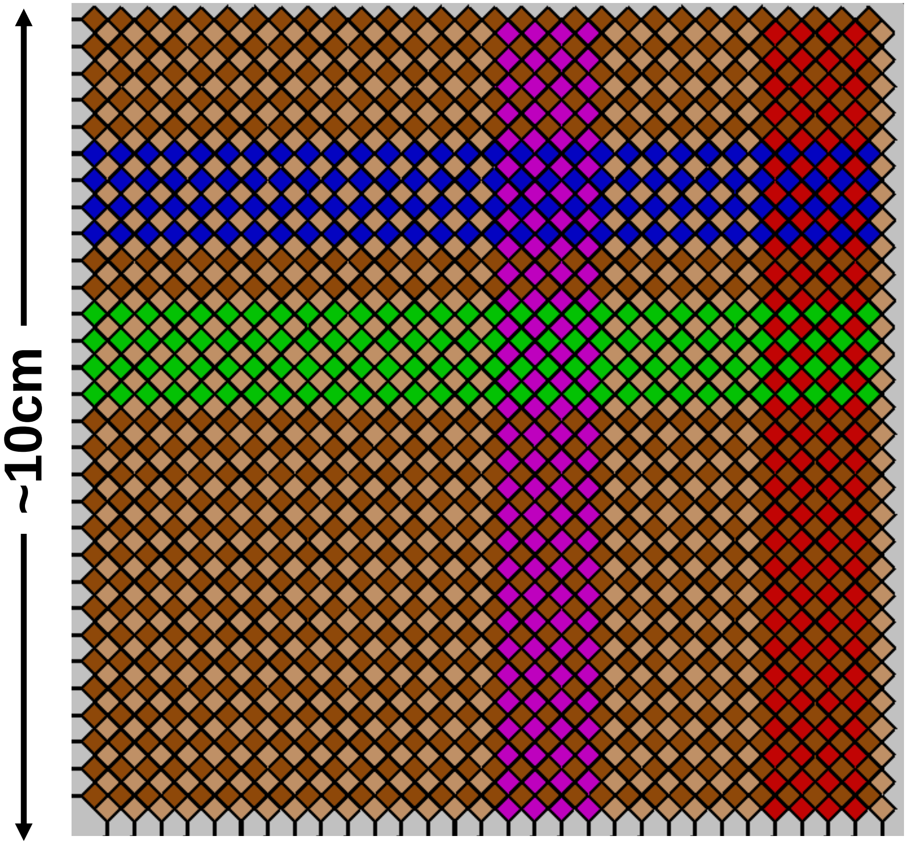
(as opposed to the 1500V of EXO-200 APDs)



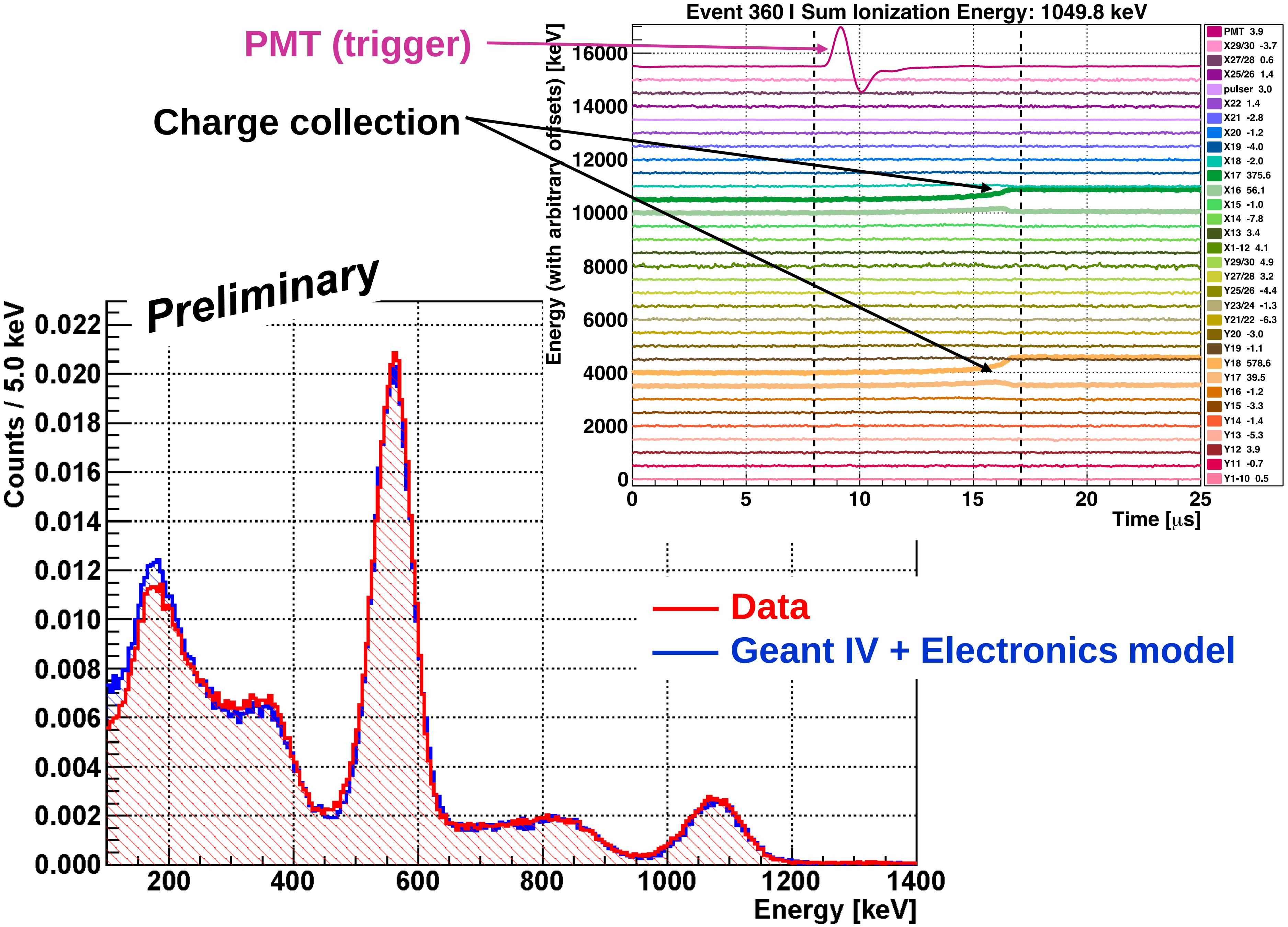
Charge will be collected on arrays of strips fabricated onto low background dielectric wafers (baseline is silica)

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





Max metallization cover with min capacitance

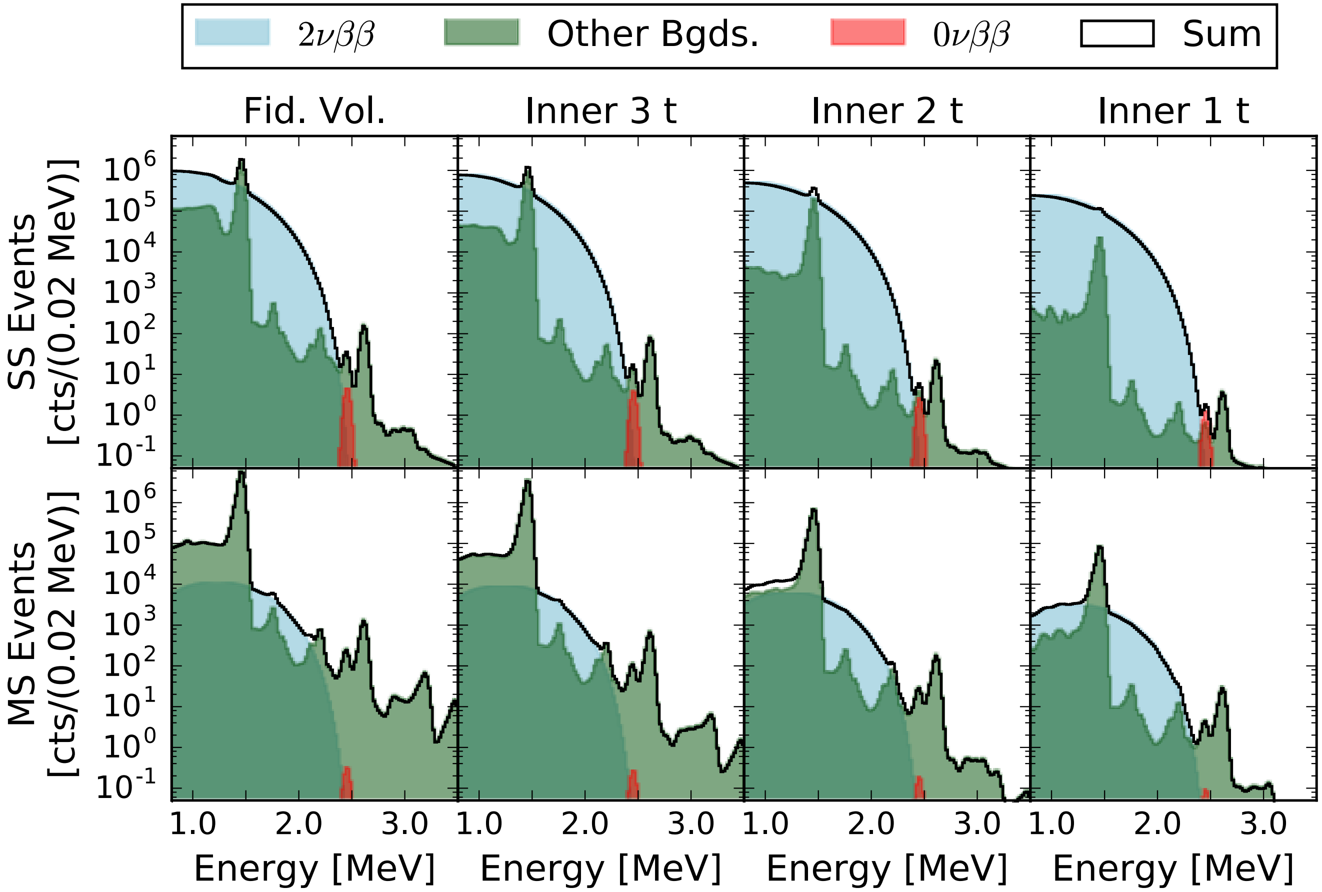

PMT (trigger)
Charge collection
Preliminary
Event 360 | Sum Ionization Energy: 1049.8 keV
Energy (with arbitrary offsets) [keV]
0
2000
4000
6000
8000
10000
12000
14000
16000
Time [μs]
0
5
10
15
20
25
PMT 3.9
X29/30 -3.7
X27/28 0.6
X25/26 1.4
pulser 3.0
X22 1.4
X21 -2.8
X20 -1.2
X19 -4.0
X18 -2.0
X17 375.6
X16 56.1
X15 -1.0
X14 -7.8
X13 3.4
X1-12 4.1
Y29/30 4.9
Y27/28 3.2
Y25/26 -4.4
Y23/24 -1.3
Y21/22 -6.3
Y20 -3.0
Y19 -1.1
Y18 578.6
Y17 39.5
Y16 -1.2
Y15 -3.3
Y14 -1.4
Y13 -5.3
Y12 3.9
Y11 -0.7
Y1-10 0.5
Counts / 5.0 keV
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0.016
0.018
0.020
0.022
Energy [keV]
200
400
600
800
1000
1200
1400
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!***

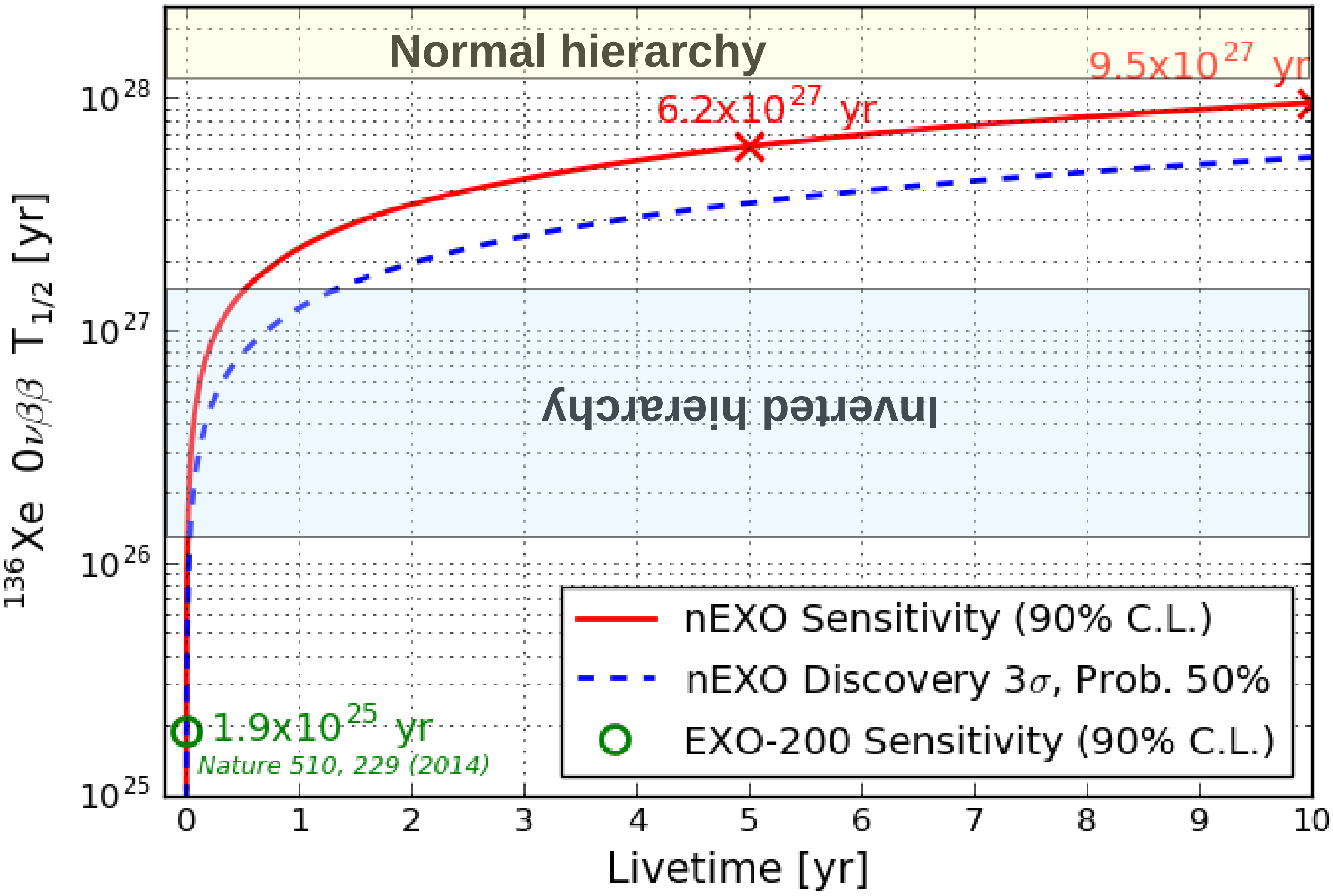
SS

MS



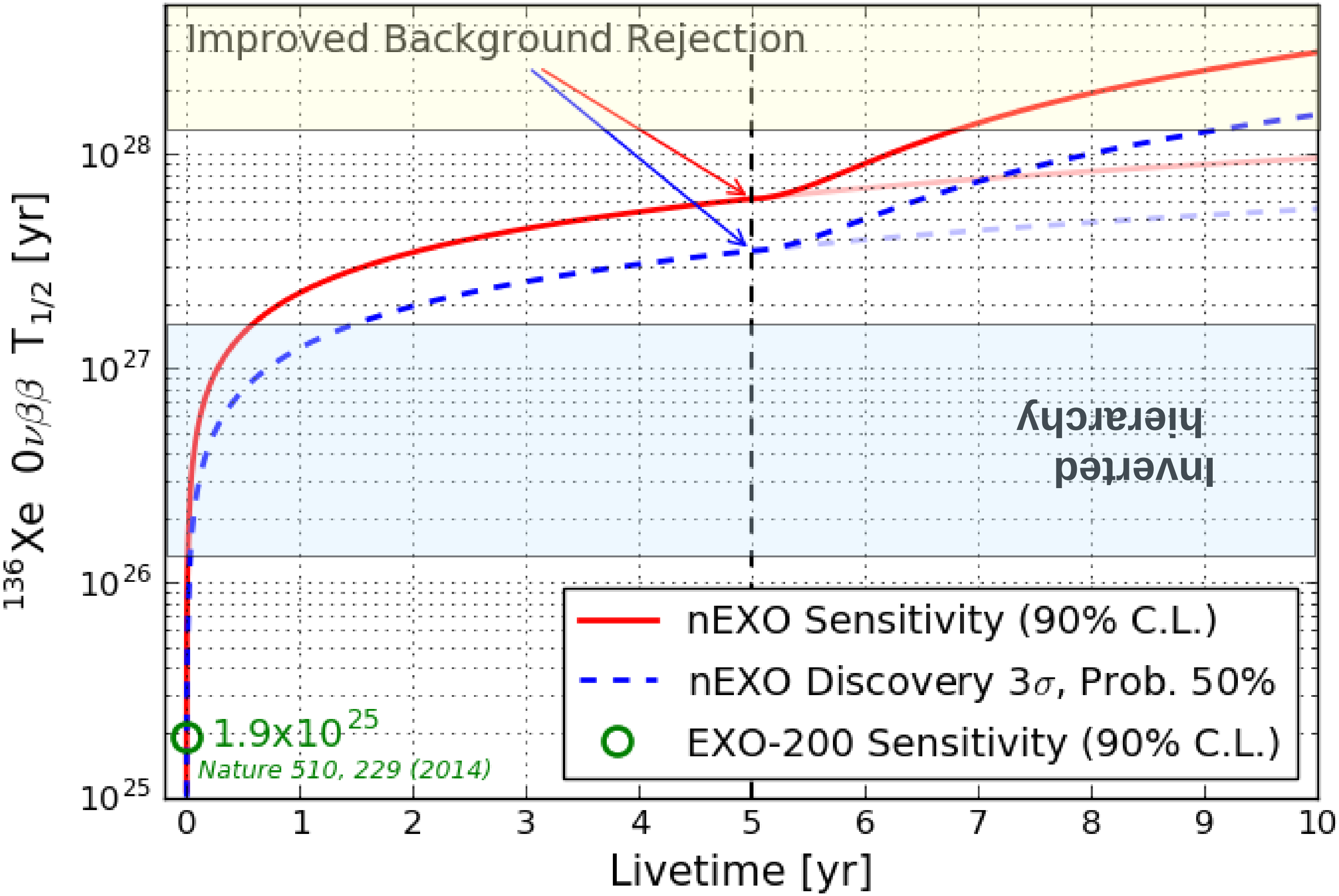
10 yr data,
$0\nu\beta\beta$ corresponding to $T^{1/2}=5.5\times10^{27}$ yr

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



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

This can be further improved, after a detector upgrade, if Ba tagging can be demonstrated (R&D in progress)



Normal hierarchy

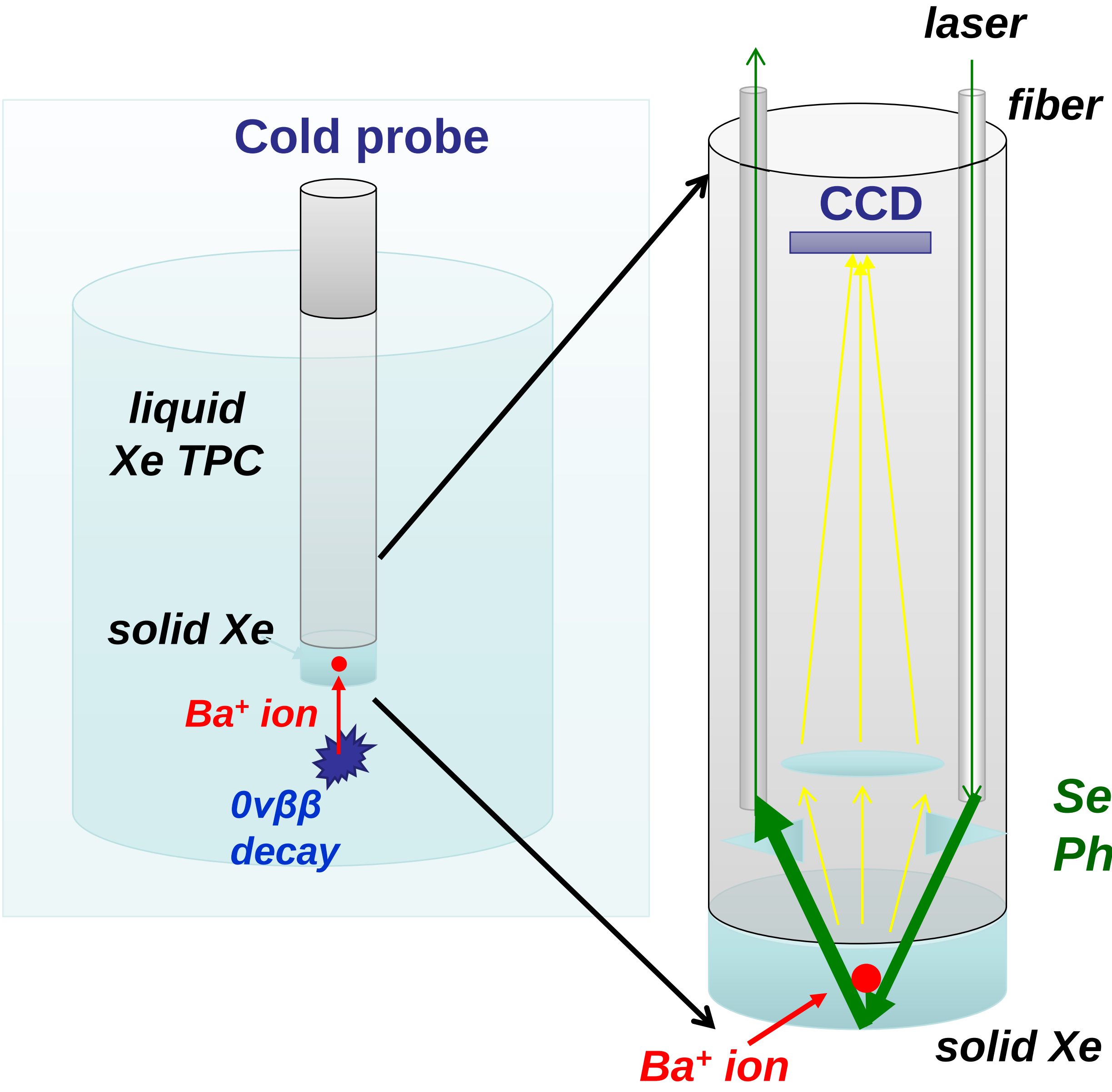
Early ββ decay experiments were based on the identification of trace amounts of element B in a sample of element A (after a geological or anyway long time).

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.

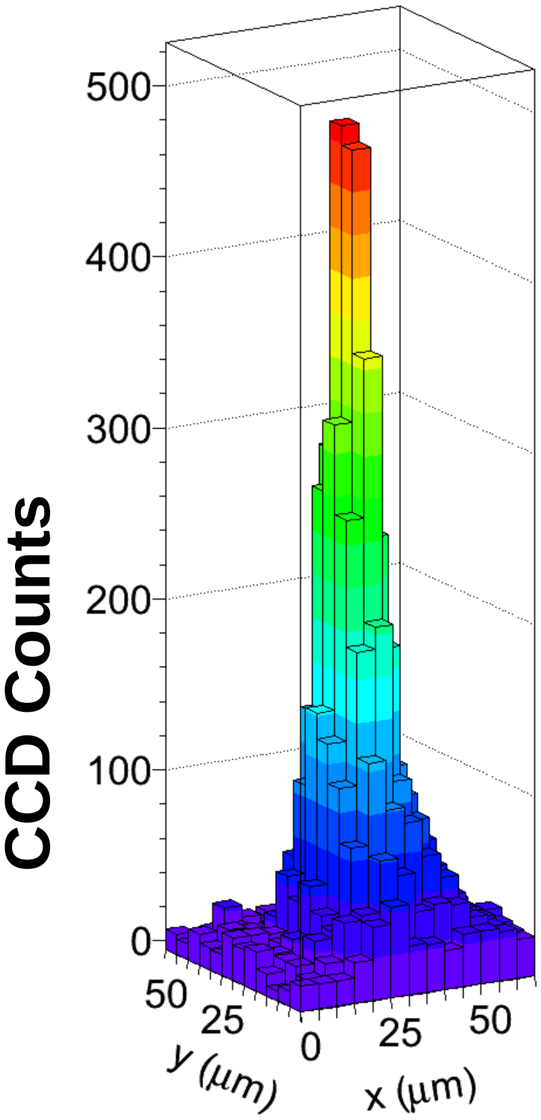
Ba tagging in situ with solid Xe probe

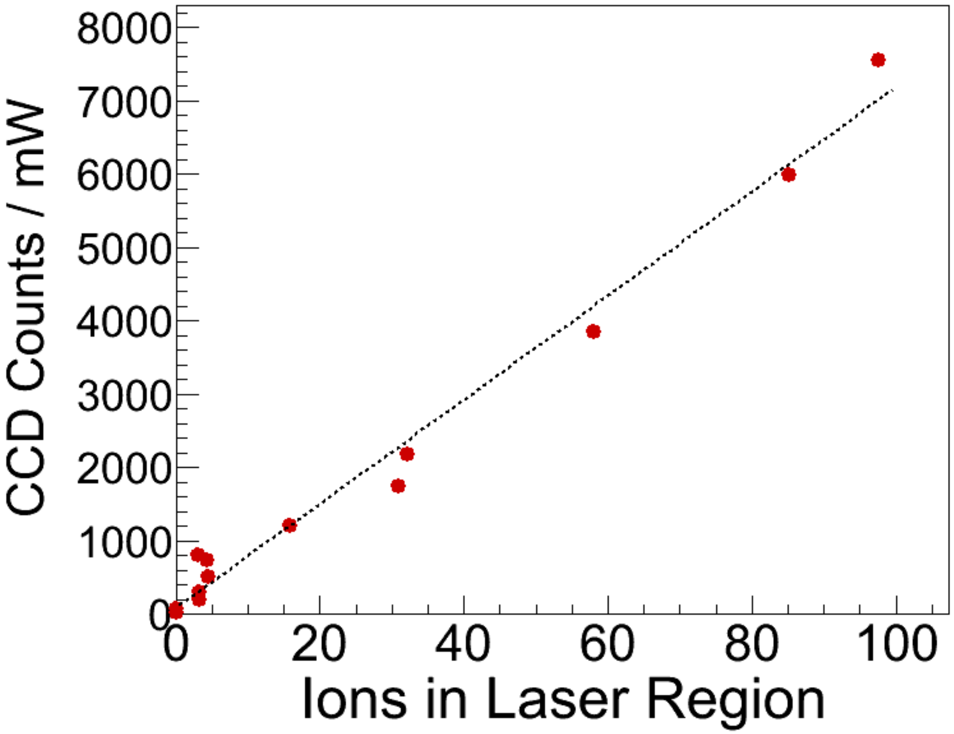


Setup and initial results in
Phys Rev A 91 (2015) 022505

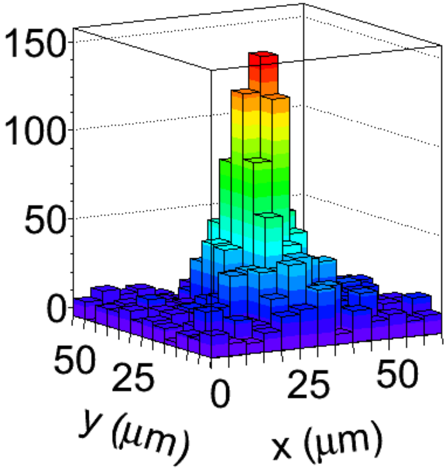
Background-free detection of a few Ba atoms has beed demonstrated

≤ 58-atom

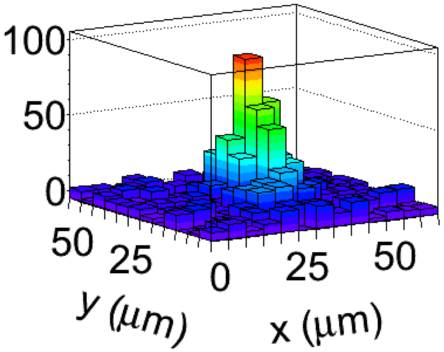




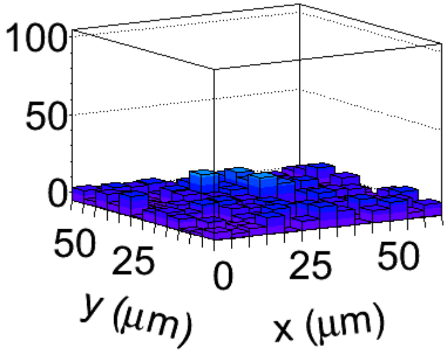
≤ 15-atom



≤ 4-atom



0-atom



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, first round of results soon
- 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 ~3×10^{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