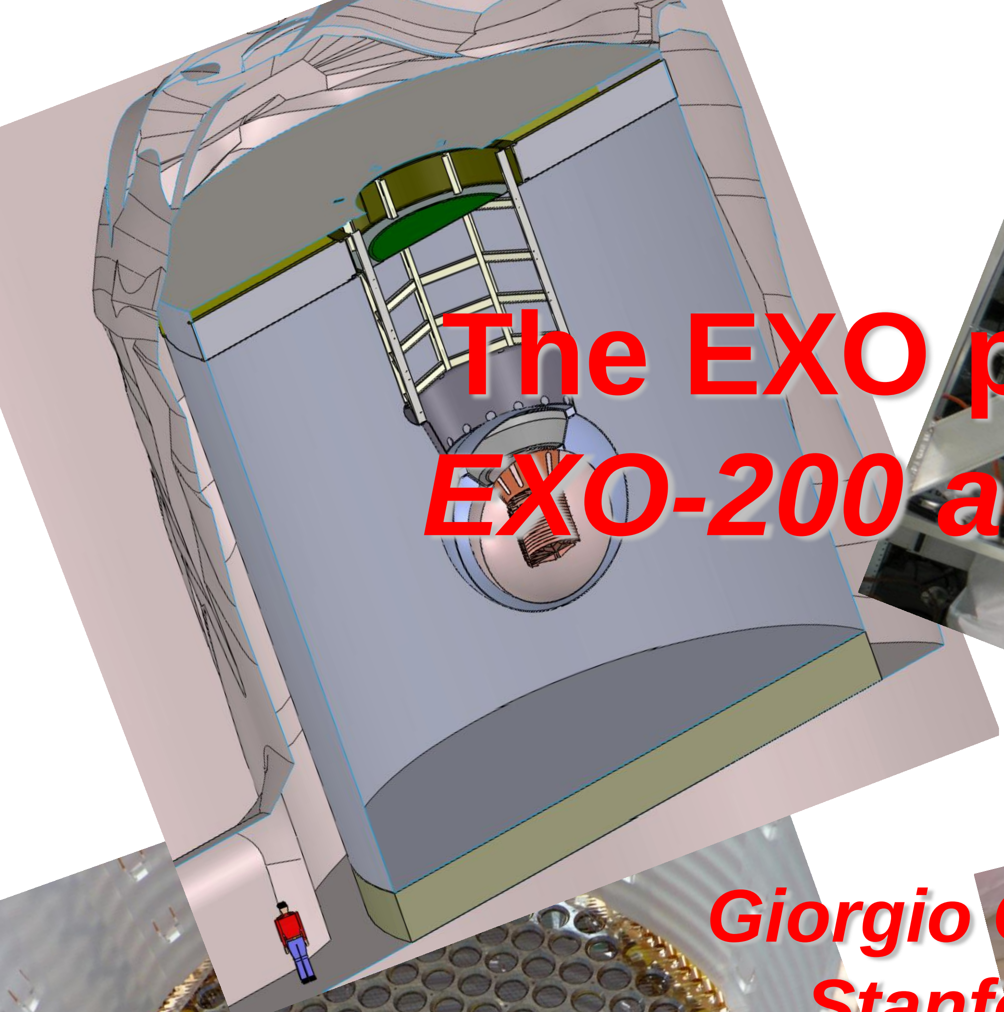
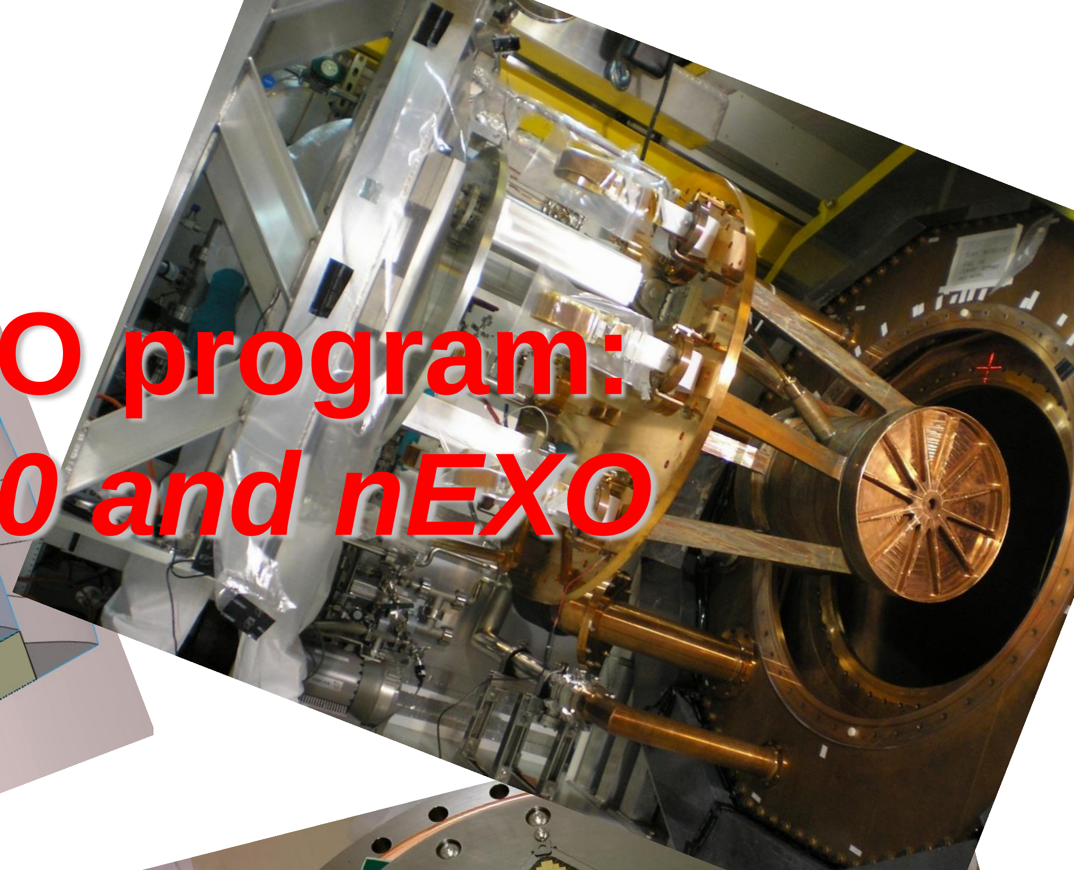
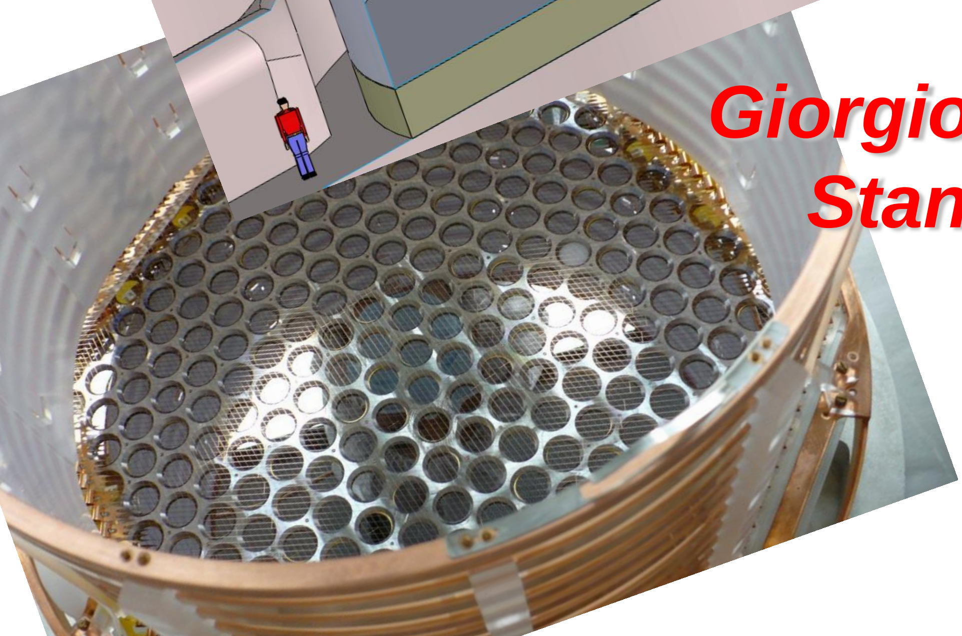
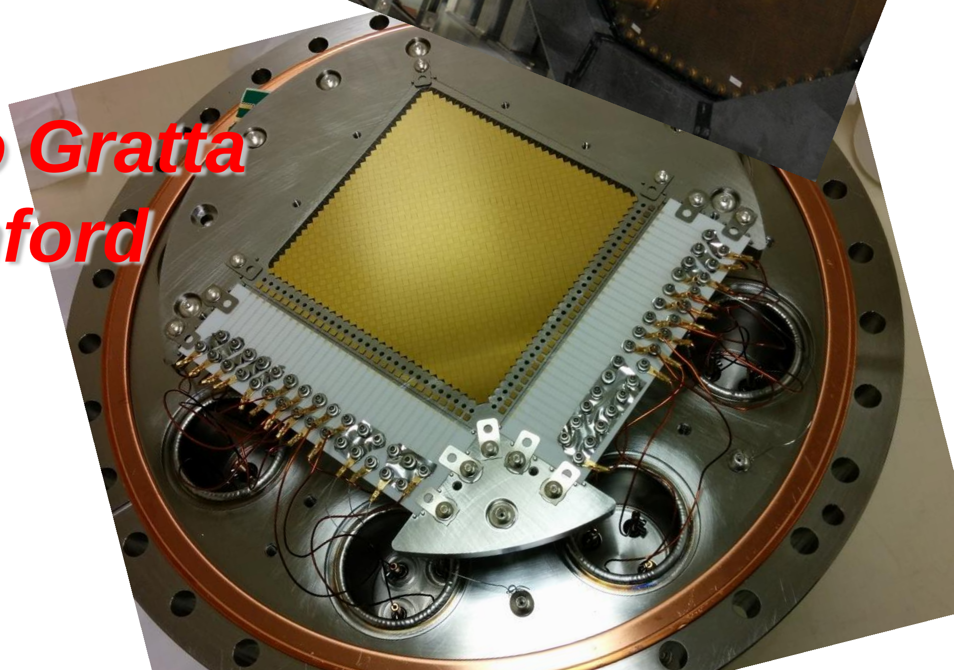



The EXO program:
EXO-200 and nEXO

Giorgio Gratta
Stanford

Four fundamental requirements for modern experiments:

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

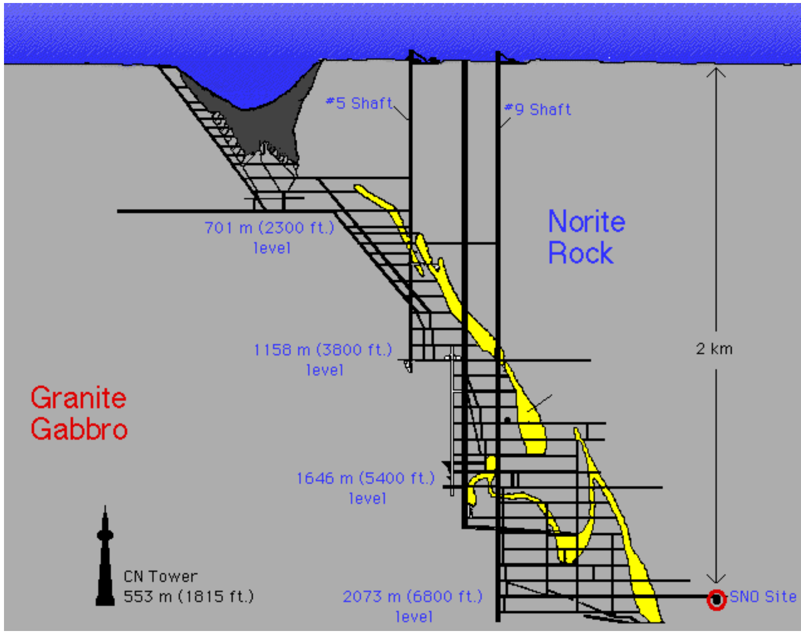
100kg – class experiment running or completed.

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:

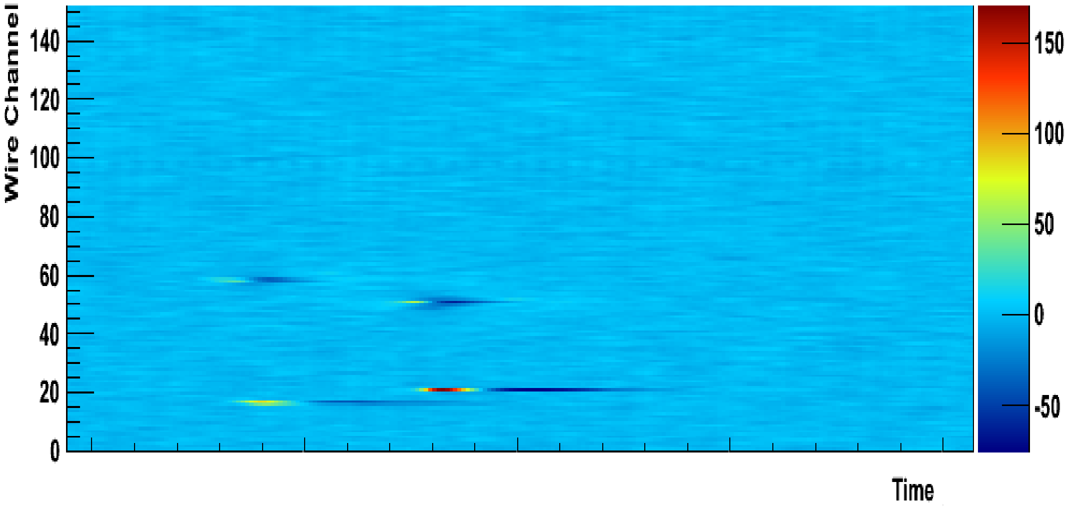
3) Ultra-low radioactive contamination for detector construction components

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!

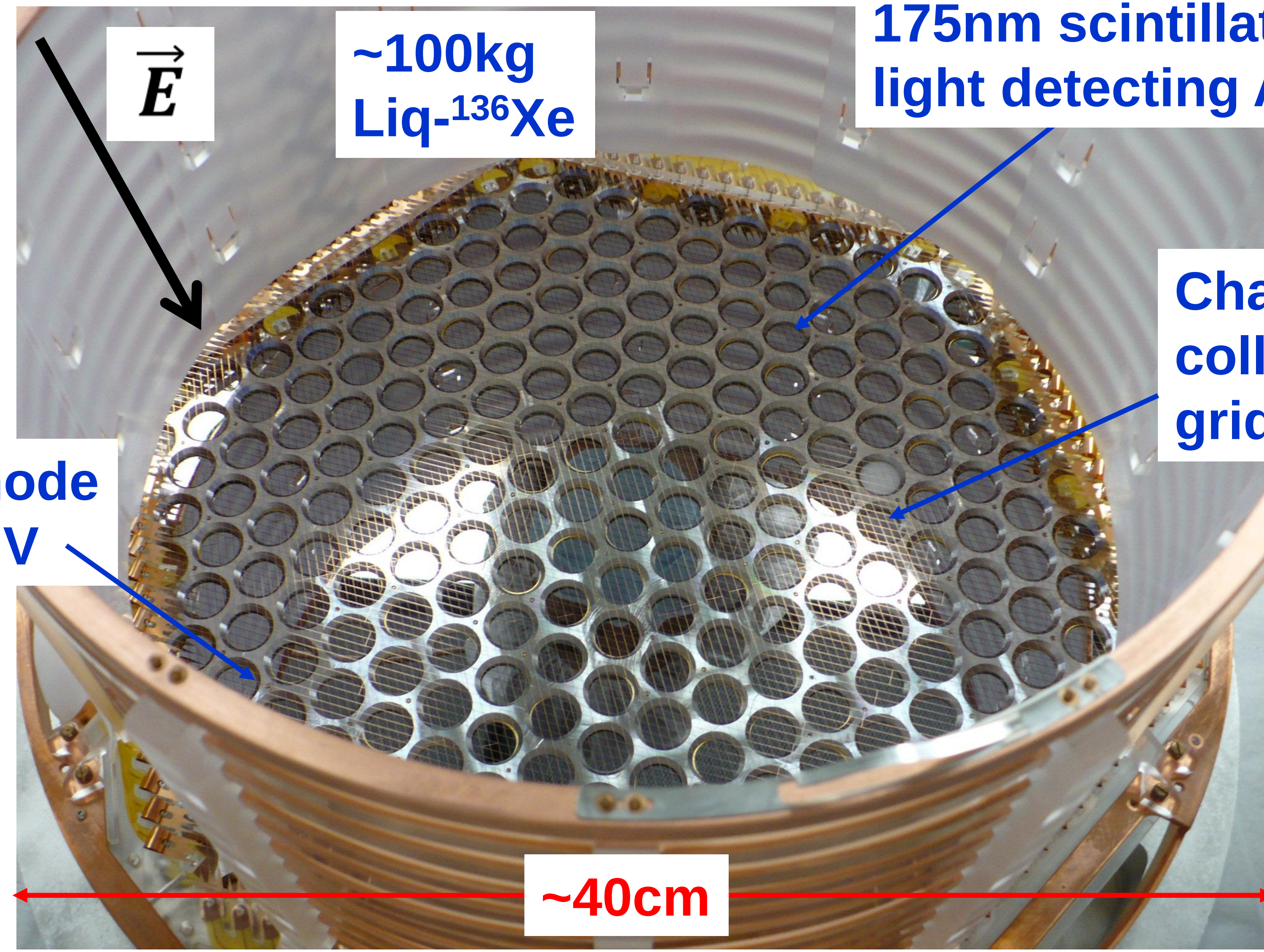
Powerful detectors use most of (possibly all) these parameters in combination, providing the best possible background rejection and simultaneously fitting for signal and background.

The EXO program

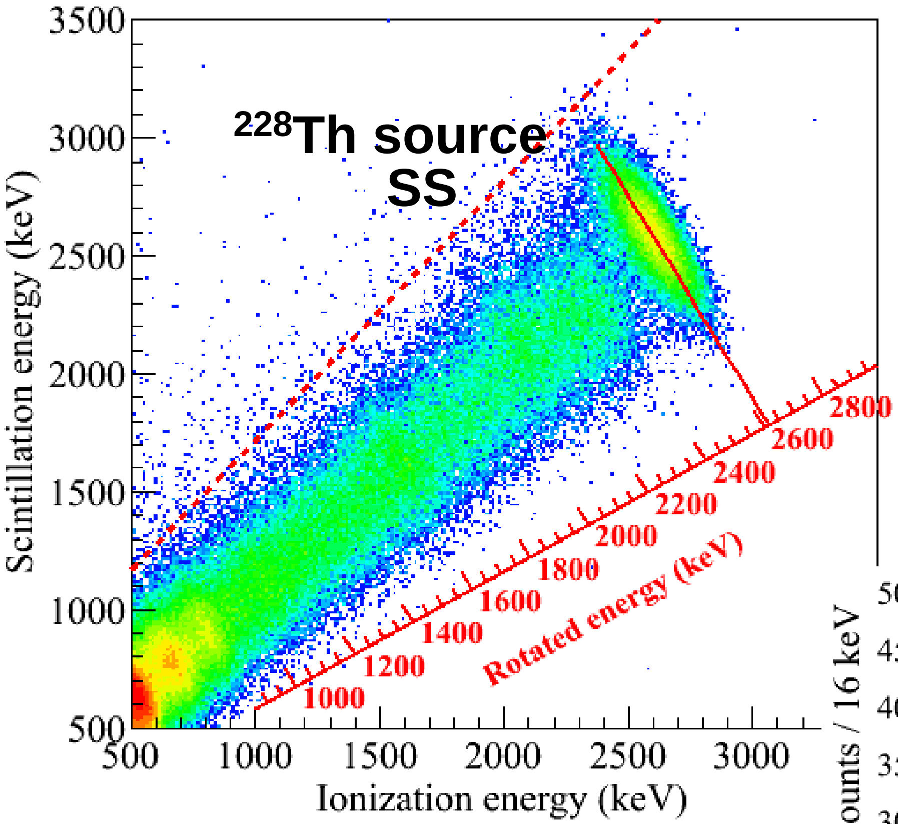
- Use ^{136}Xe in liquid phase
- Initial R&D on energy resolution using scintillation-ionization correlation
- Build EXO-200, first 100kg-class experiment to produce results. Run II in progress.
- Build a ton-scale detector (nEXO) able to cover the inverted hierarchy (for the standard mechanism)
- Explore the possibility of tagging the final state Ba atom to extend the sensitivity of a second phase nEXO detector

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

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



Combining Ionization and Scintillation

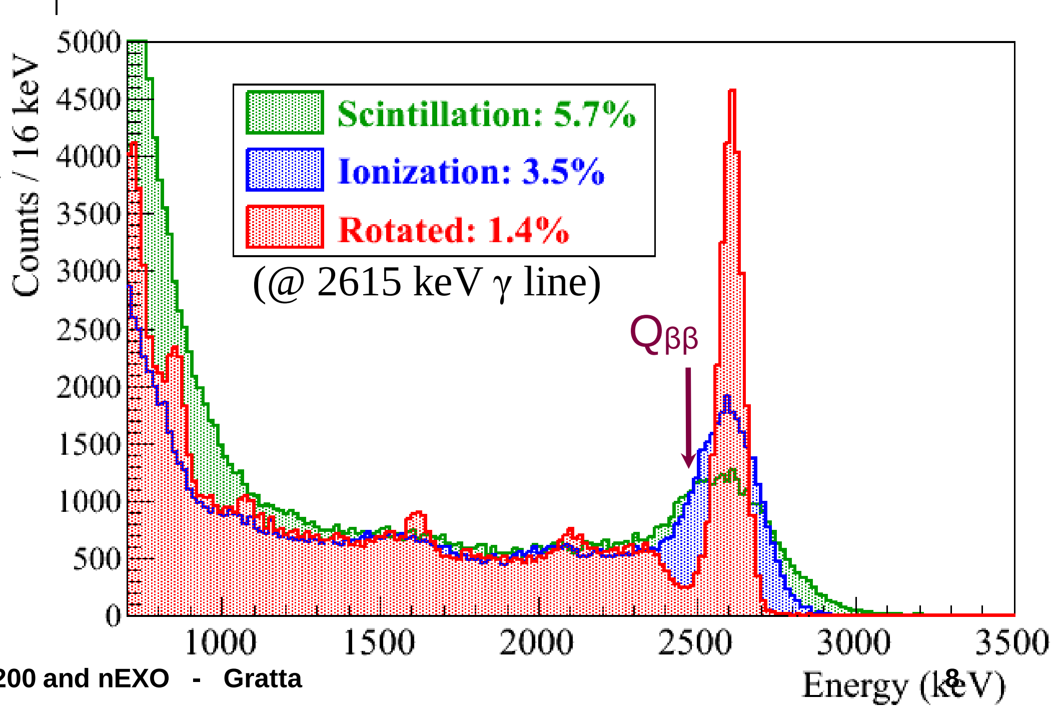


Anticorrelation between scintillation and ionization in LXe known since early EXO R&D

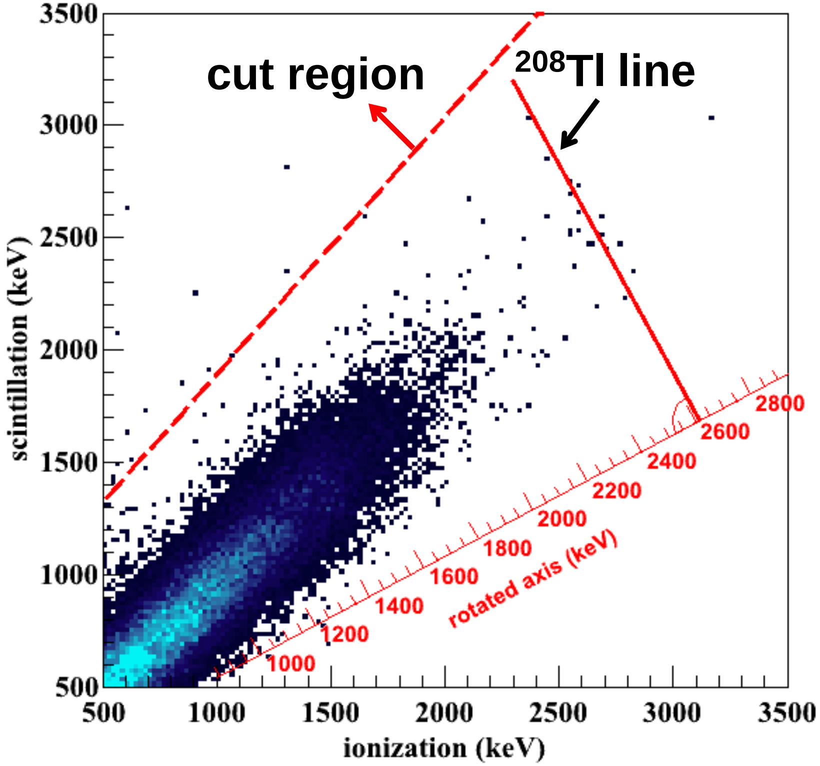
E.Conti et al.
Phys Rev B 68 (2003) 054201

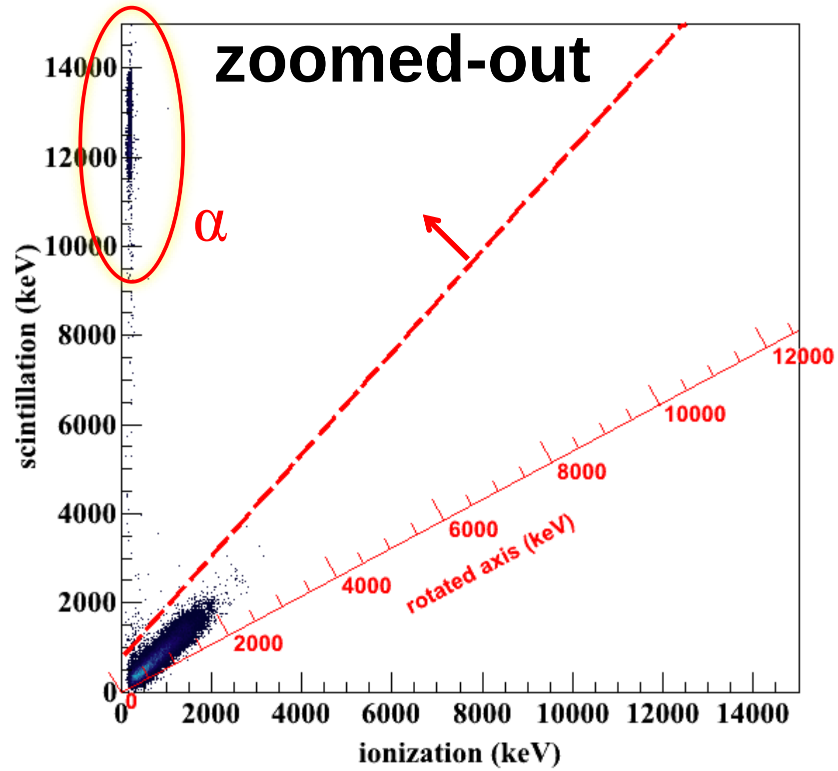
By now this is a common technique in LXe

Rotation angle chosen to optimize energy resolution at 2615 keV



Low Background 2D SS Spectrum

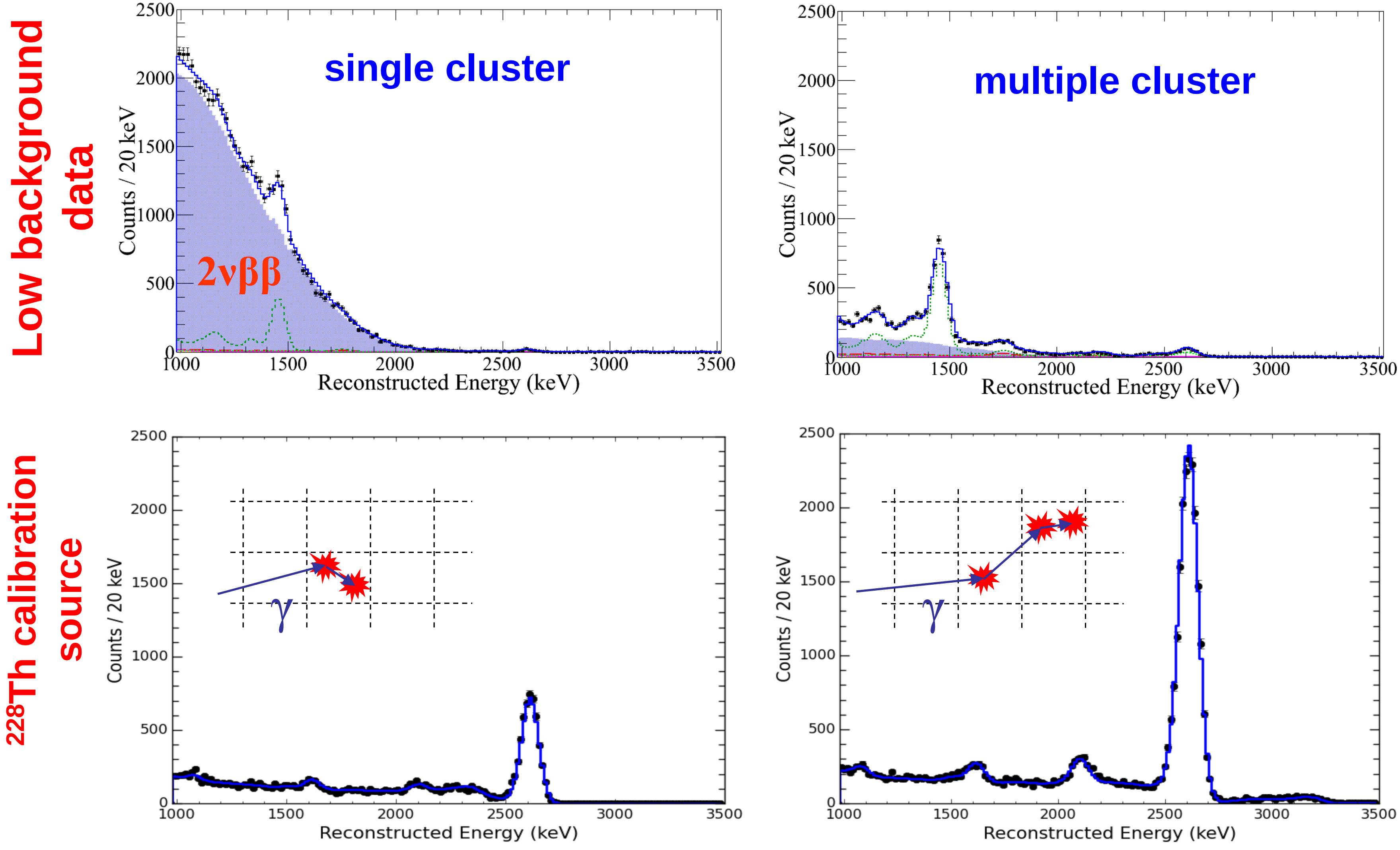




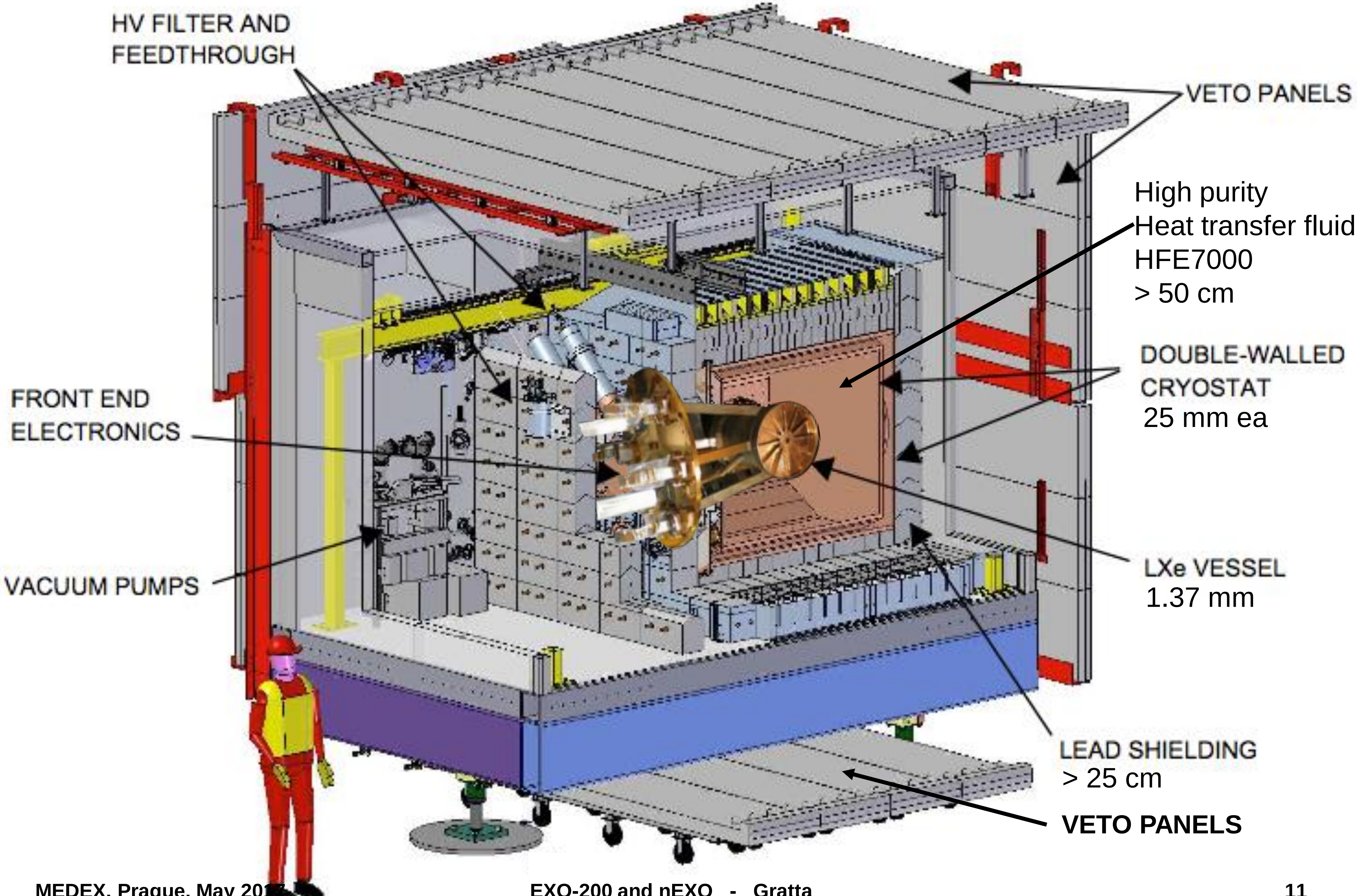
Events removed by diagonal cut:

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

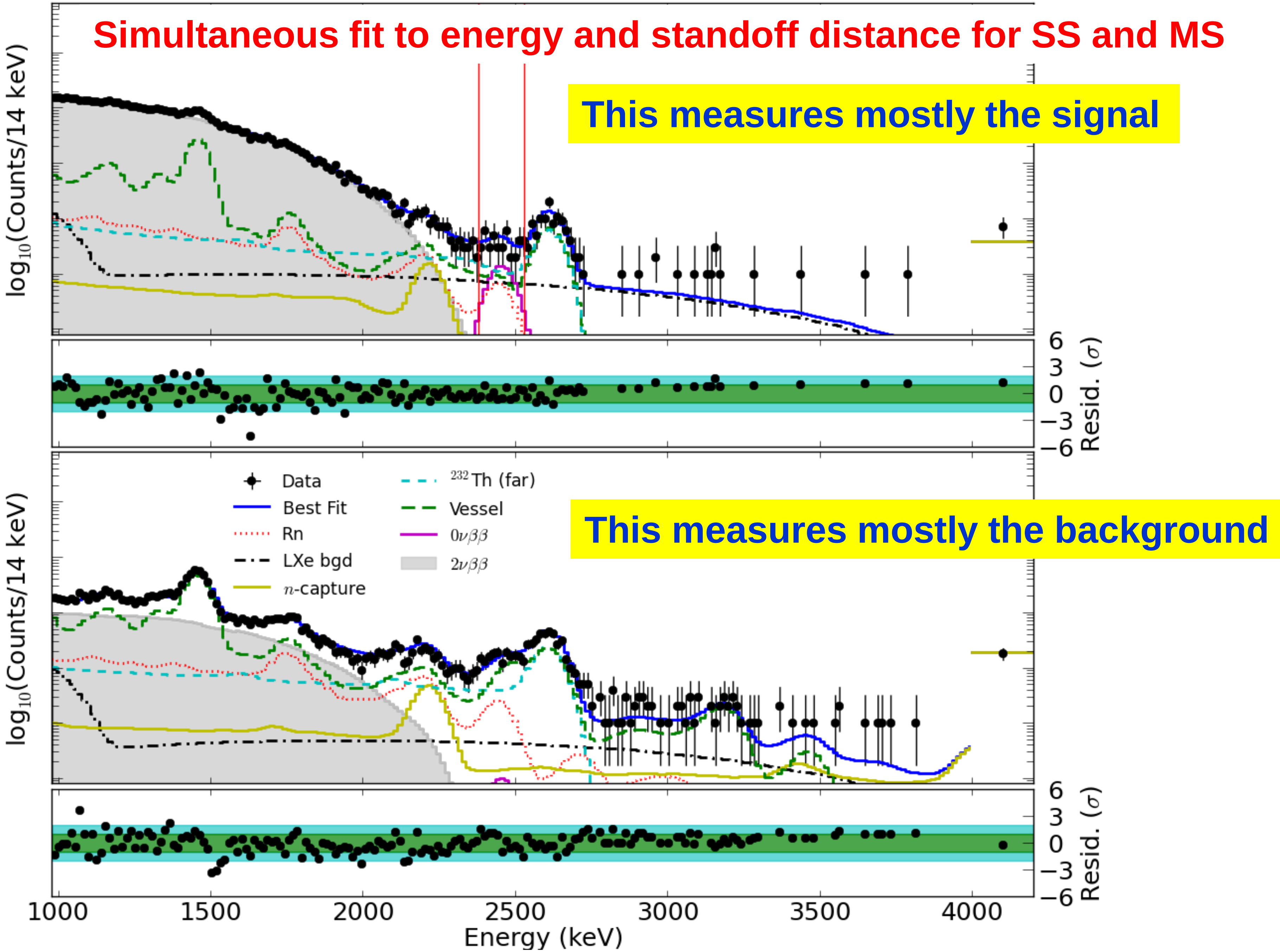
Using event multiplicity to recognize backgrounds



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



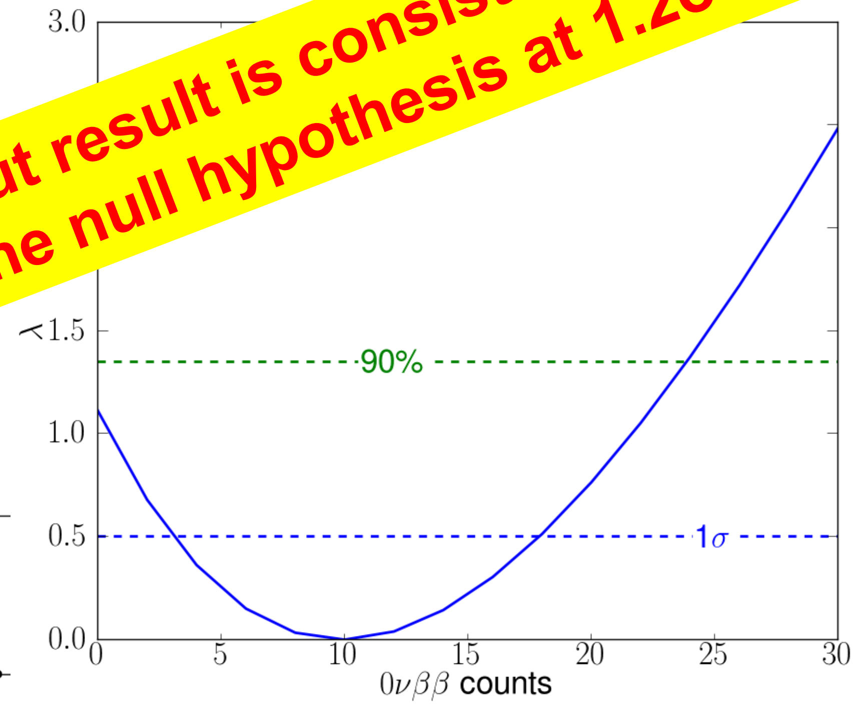
Simultaneous fit to energy and standoff distance for SS and MS

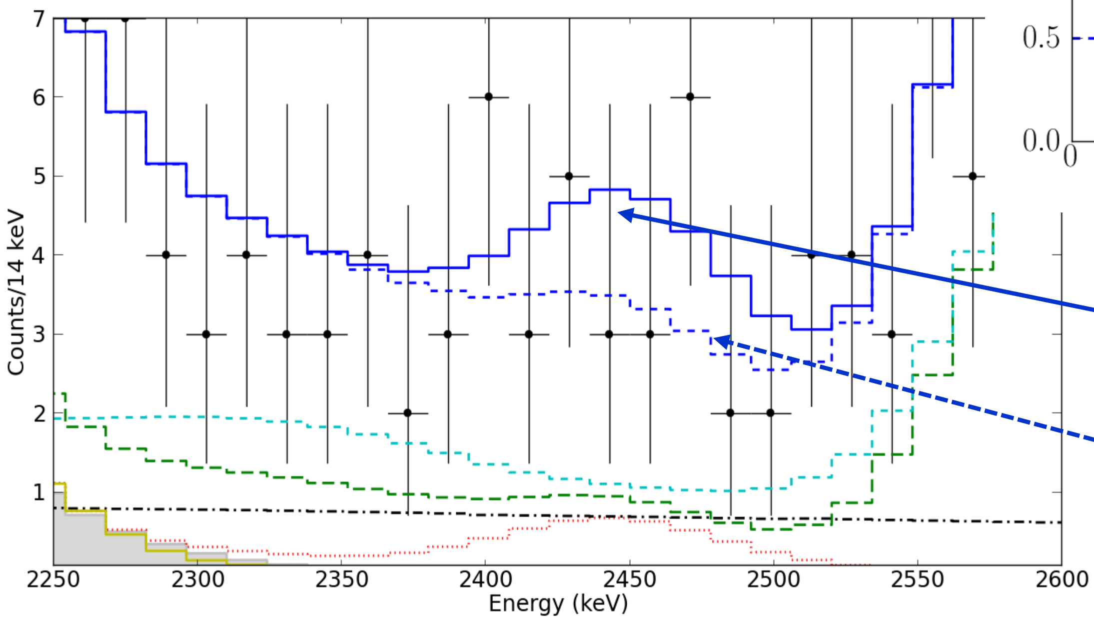


$0\nu\beta\beta$ decay and background fit:

Fit components	
Backgrounds	31.1
$0\nu\beta\beta$ decay	9.9
Total	41.0

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





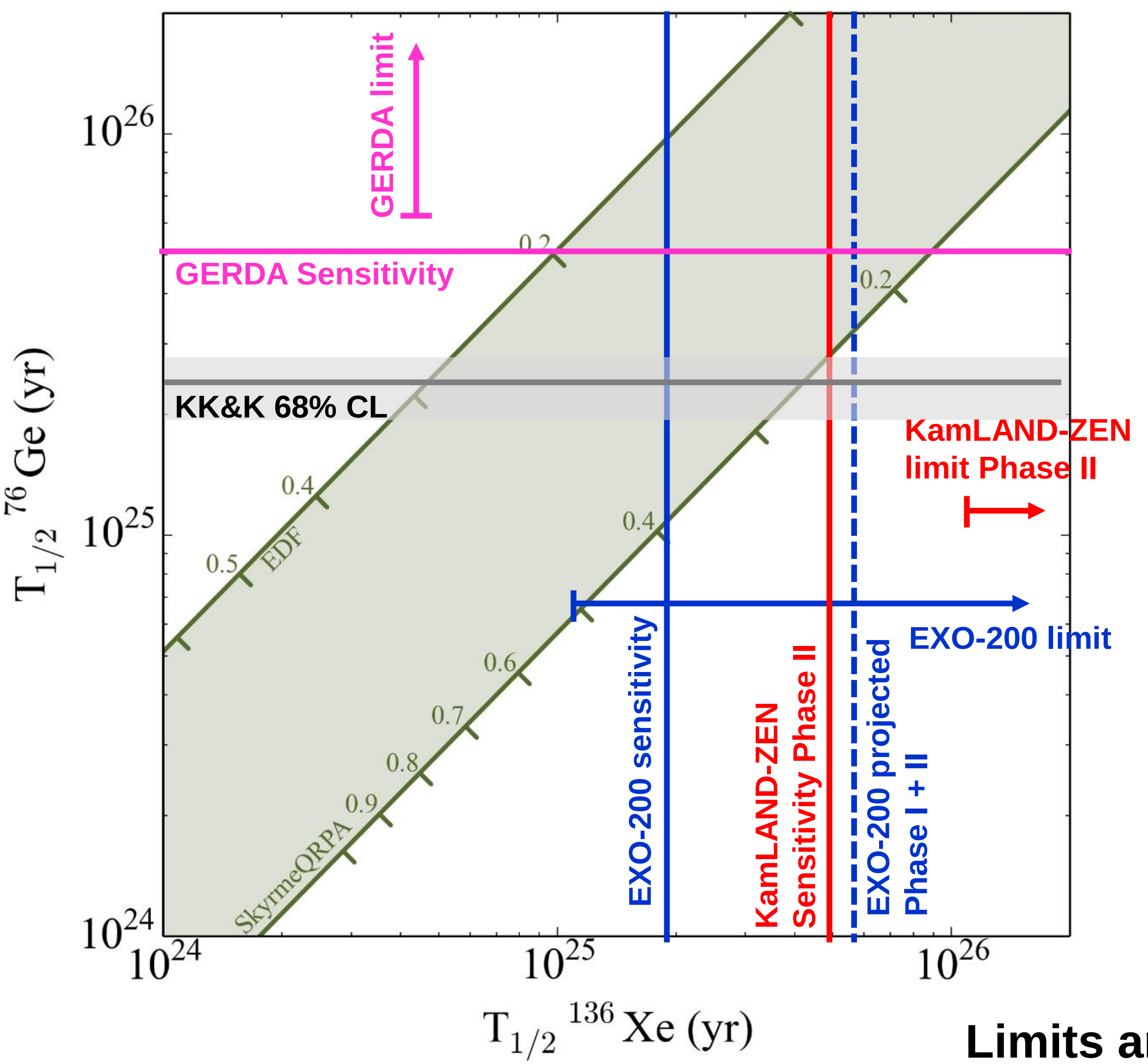
Fit with $0\nu\beta\beta$ decay

Fit without $0\nu\beta\beta$ decay

EXO-200: $T_{1/2}$ > 1.1 x 10^{25} yr [8.0 x 10^{14} $T_{universe}$] <m_ν> < 190 - 450 meV

Average sensitivity 1.9 x 10^{25} yr

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



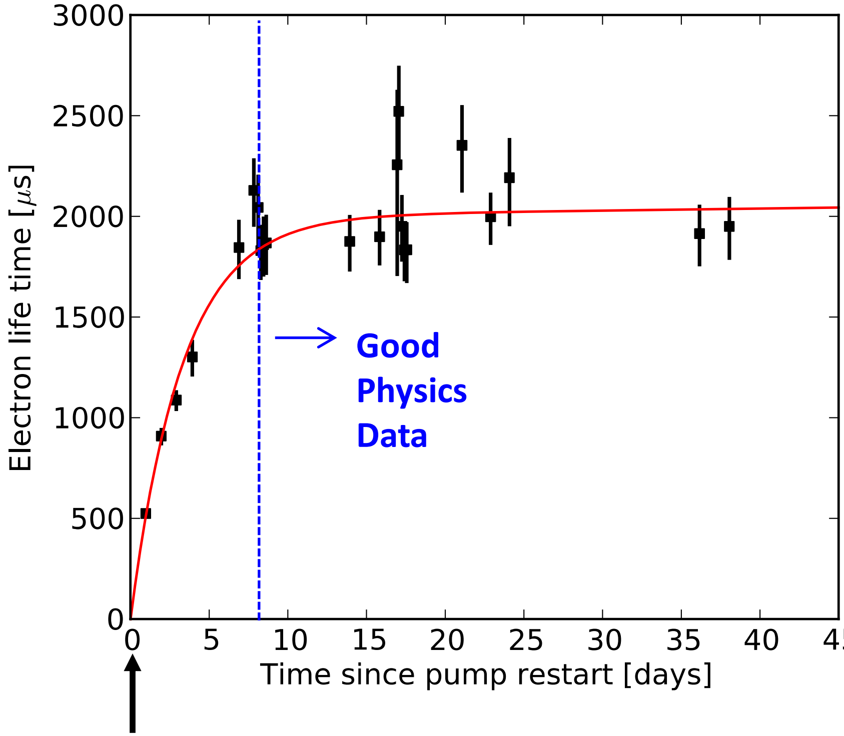
GERDA: M.Agostini et al., Nature 544 (2017) 47

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

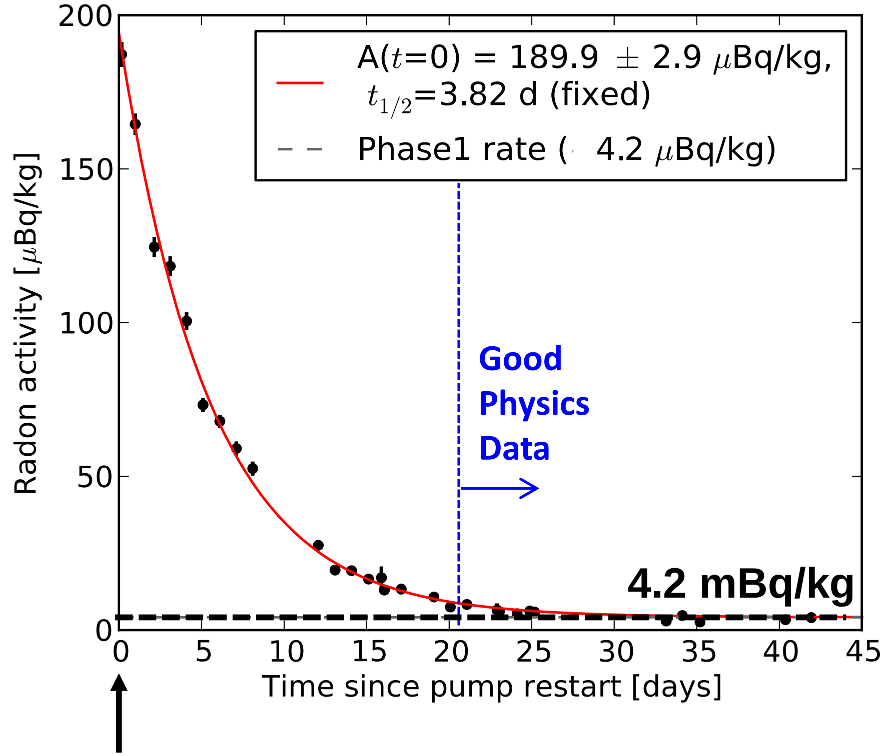
Limits are 90% CL

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.**

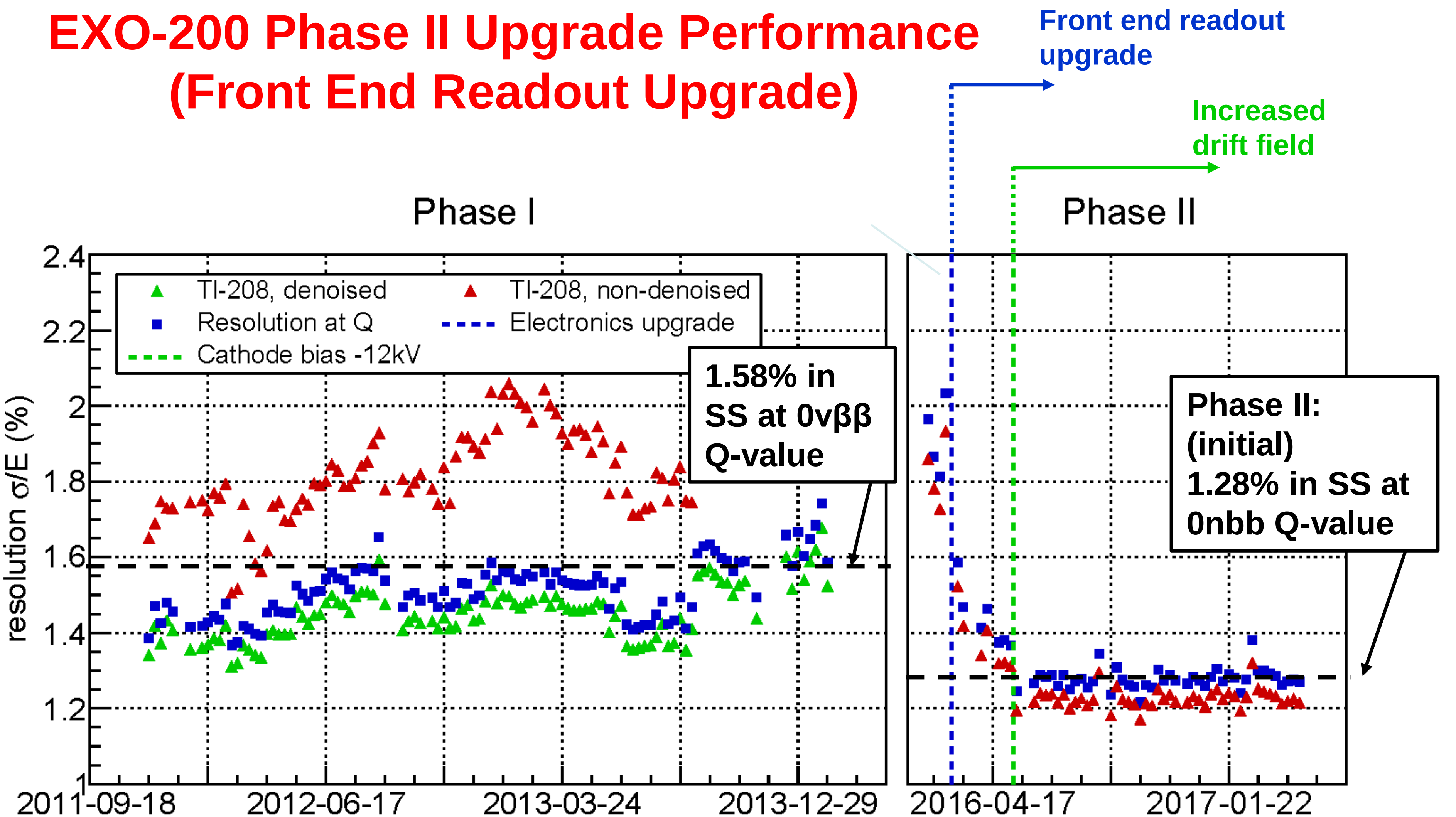


31 Jan '16



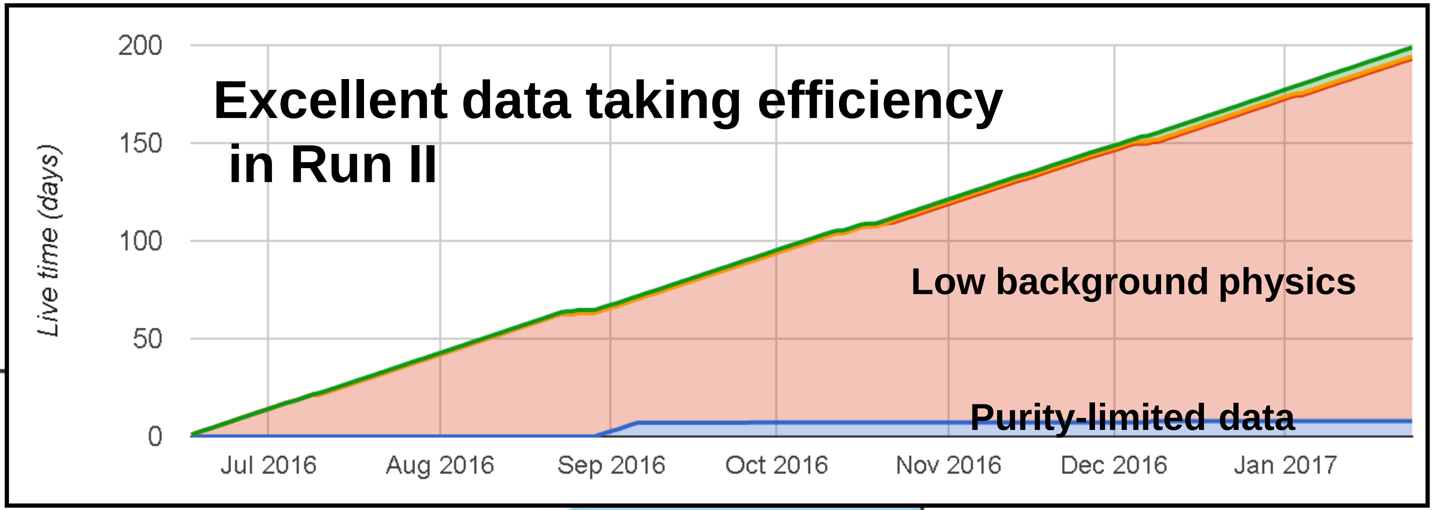
31 Jan '16

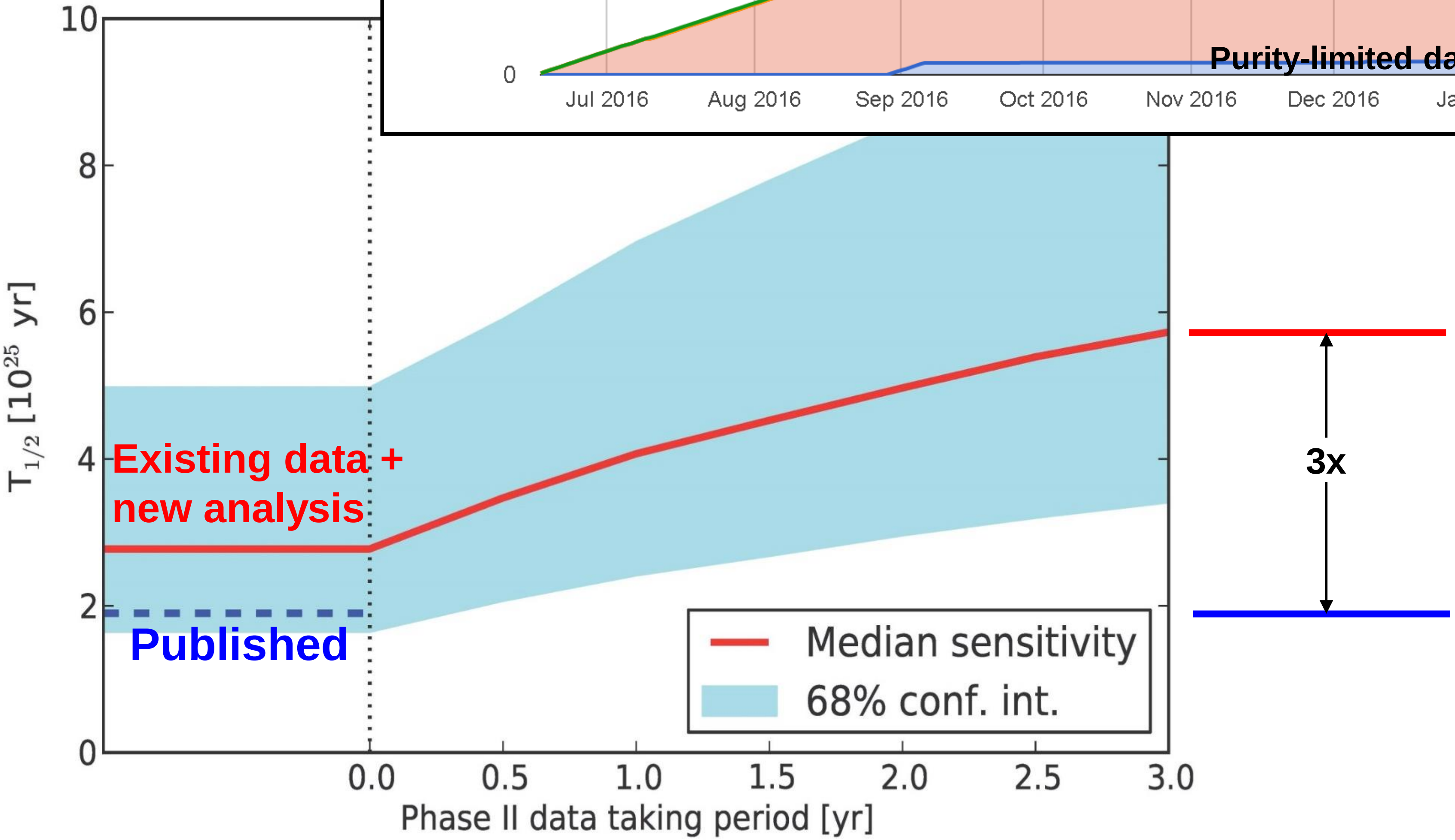
EXO-200 Phase II Upgrade Performance (Front End Readout Upgrade)

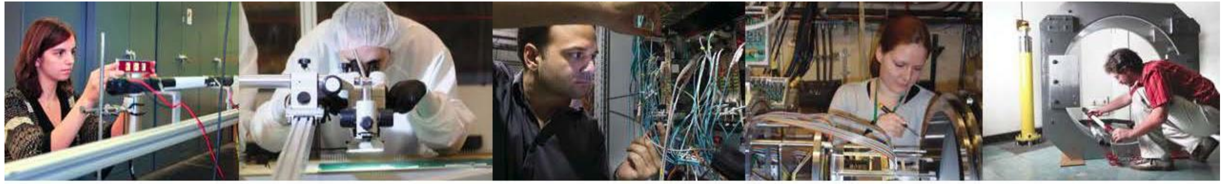


Further improvements in detector energy resolution may be possible with better signal reconstruction and detector non-uniformity corrections.

EXO-200 sensitivity







The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

"RECOMMENDATION II

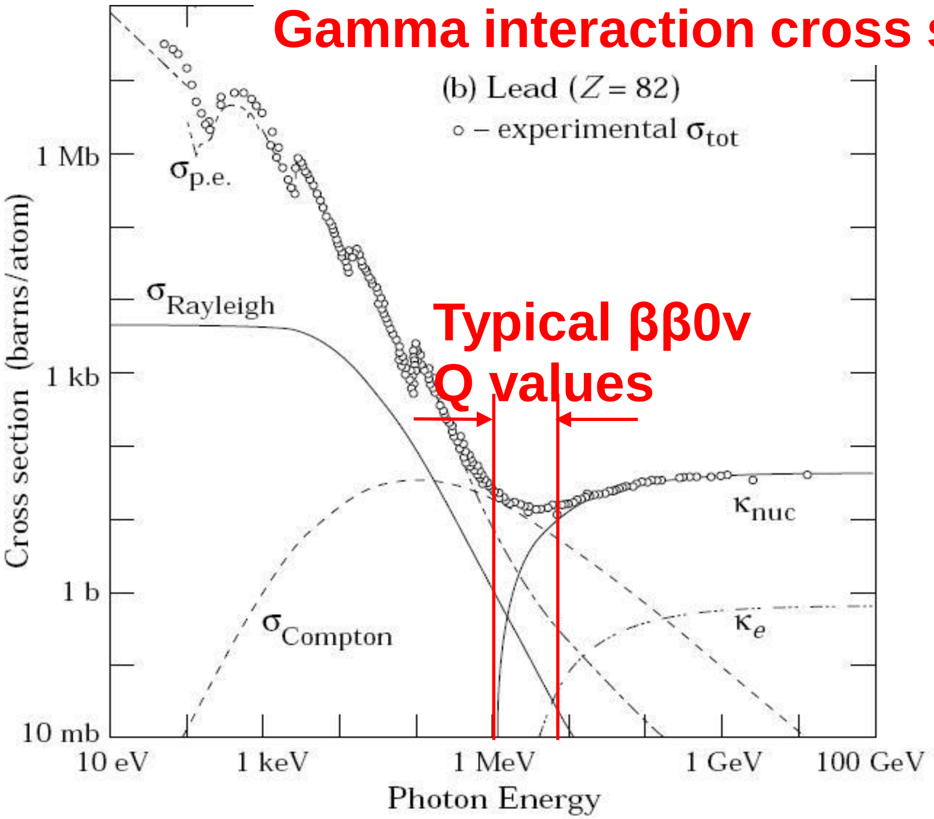
The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding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



Example:

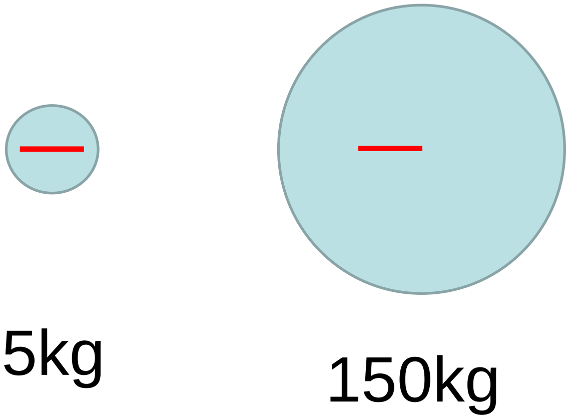
γ interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector.

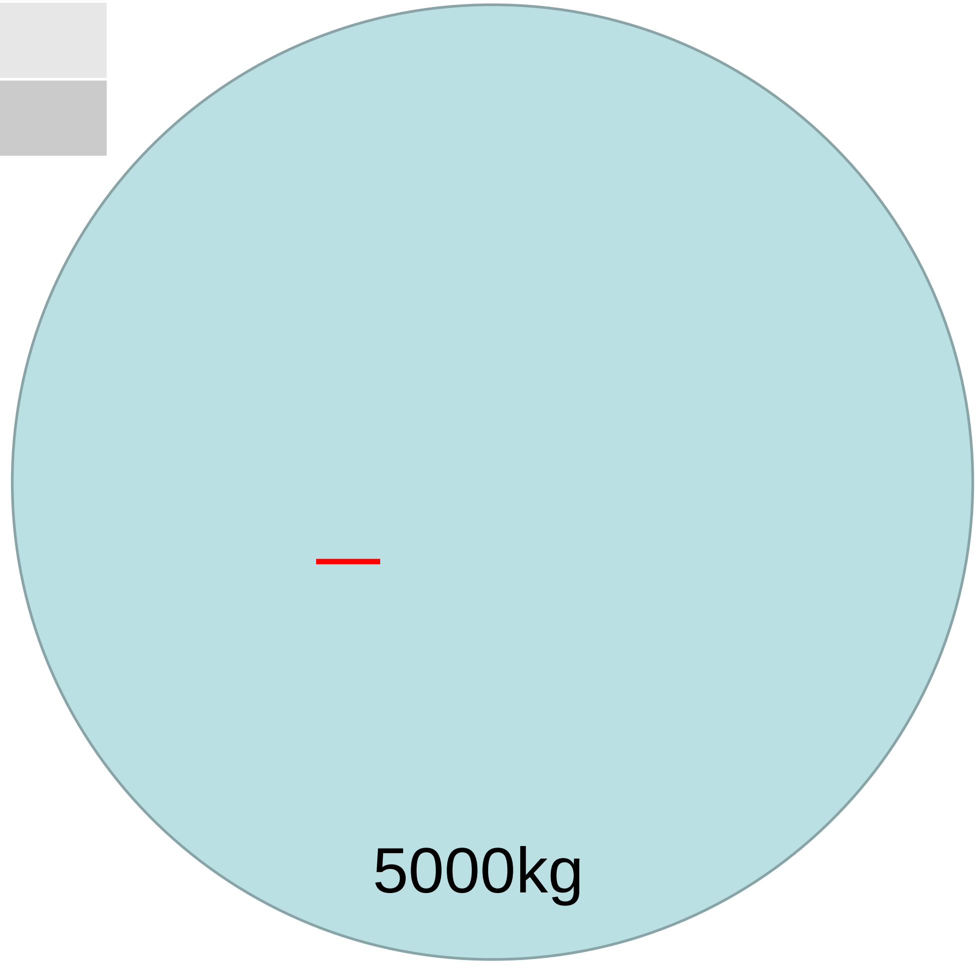
Shielding ββ decay detectors is much harder than shielding Dark Matter ones

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

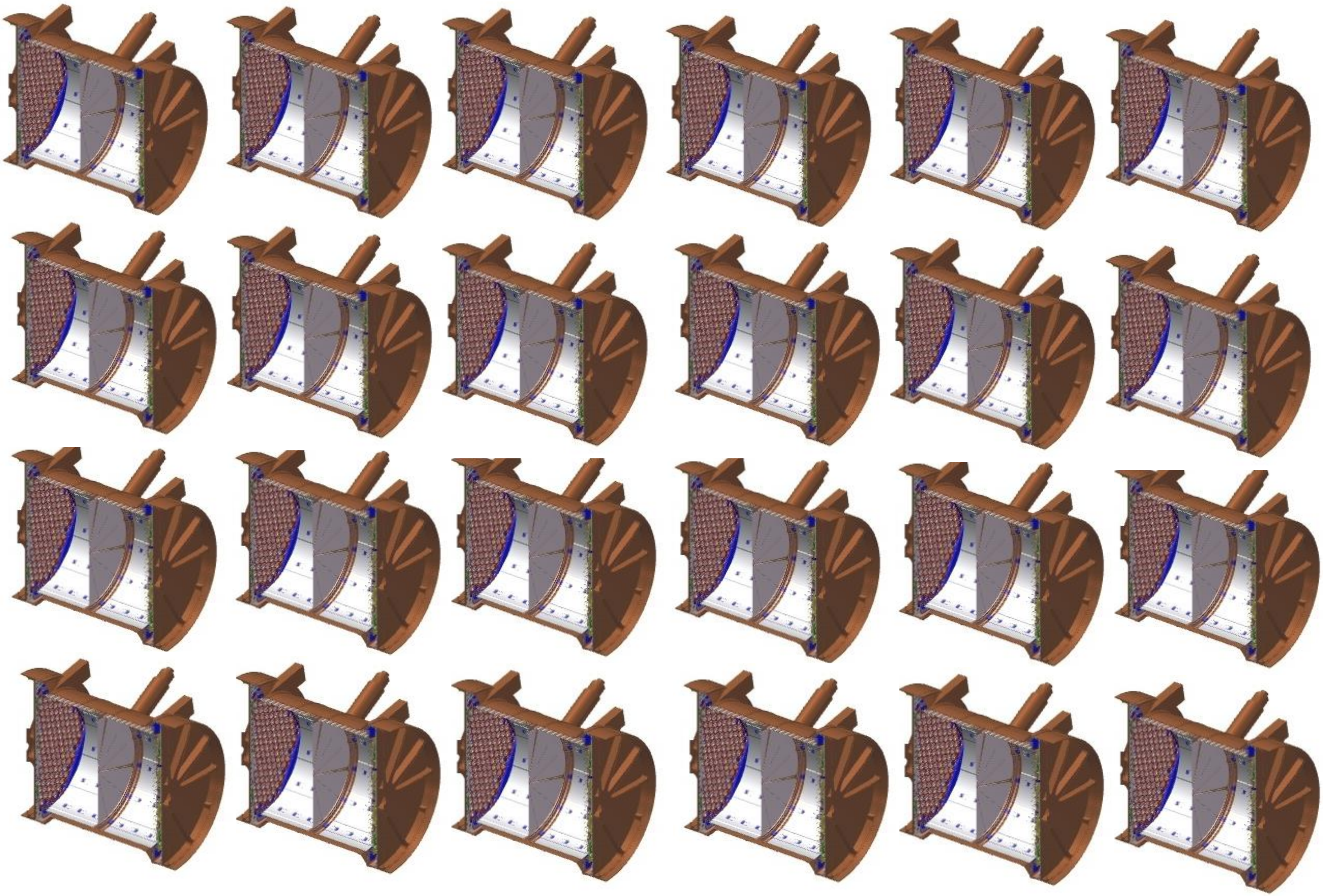
2.5MeV γ
attenuation length
8.5cm = —





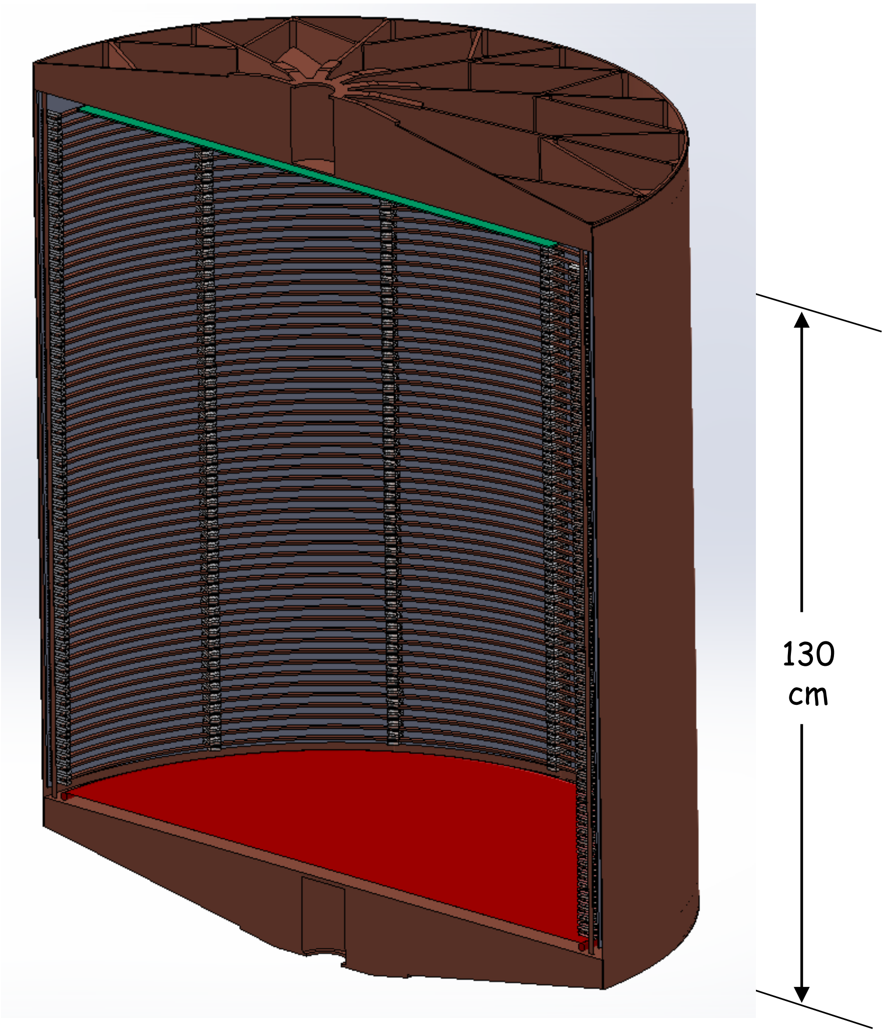
This works best for a monolithic detector

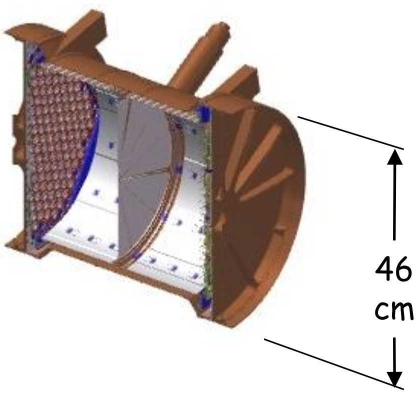
The wrong design for nEXO (requiring no R&D)



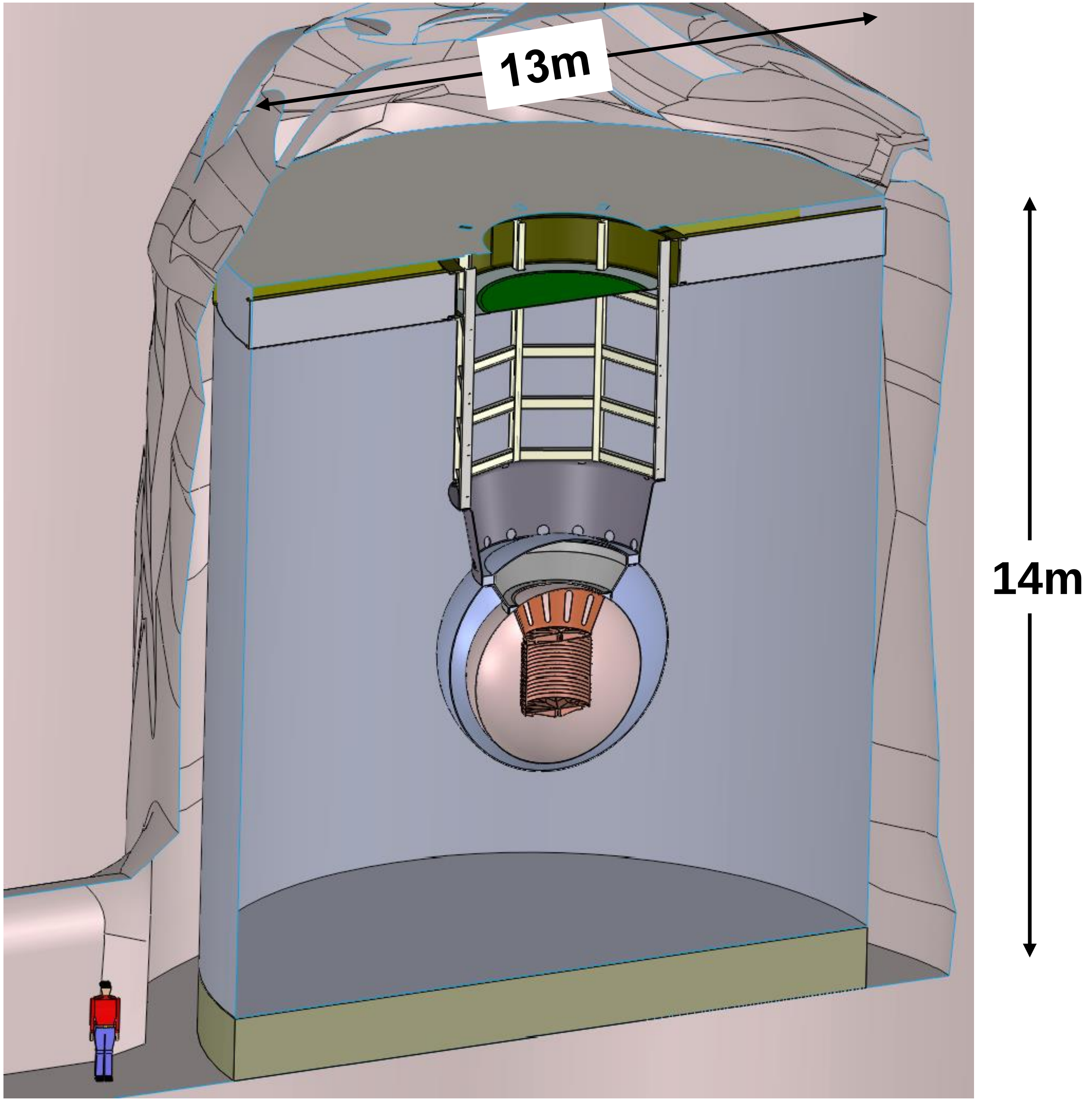
The nEXO detector

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





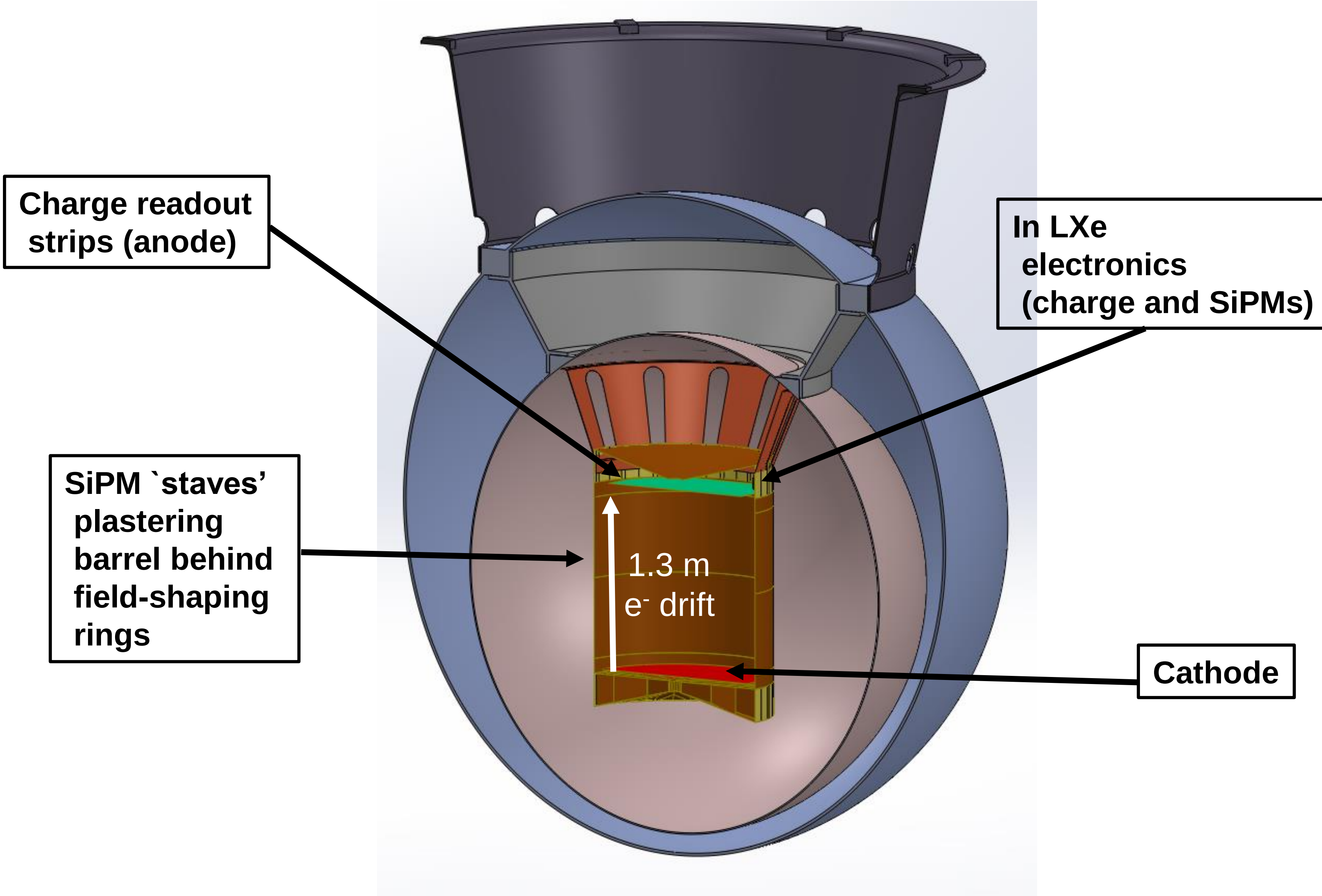
Preliminary artist view of nEXO in the SNOlab Cryopit

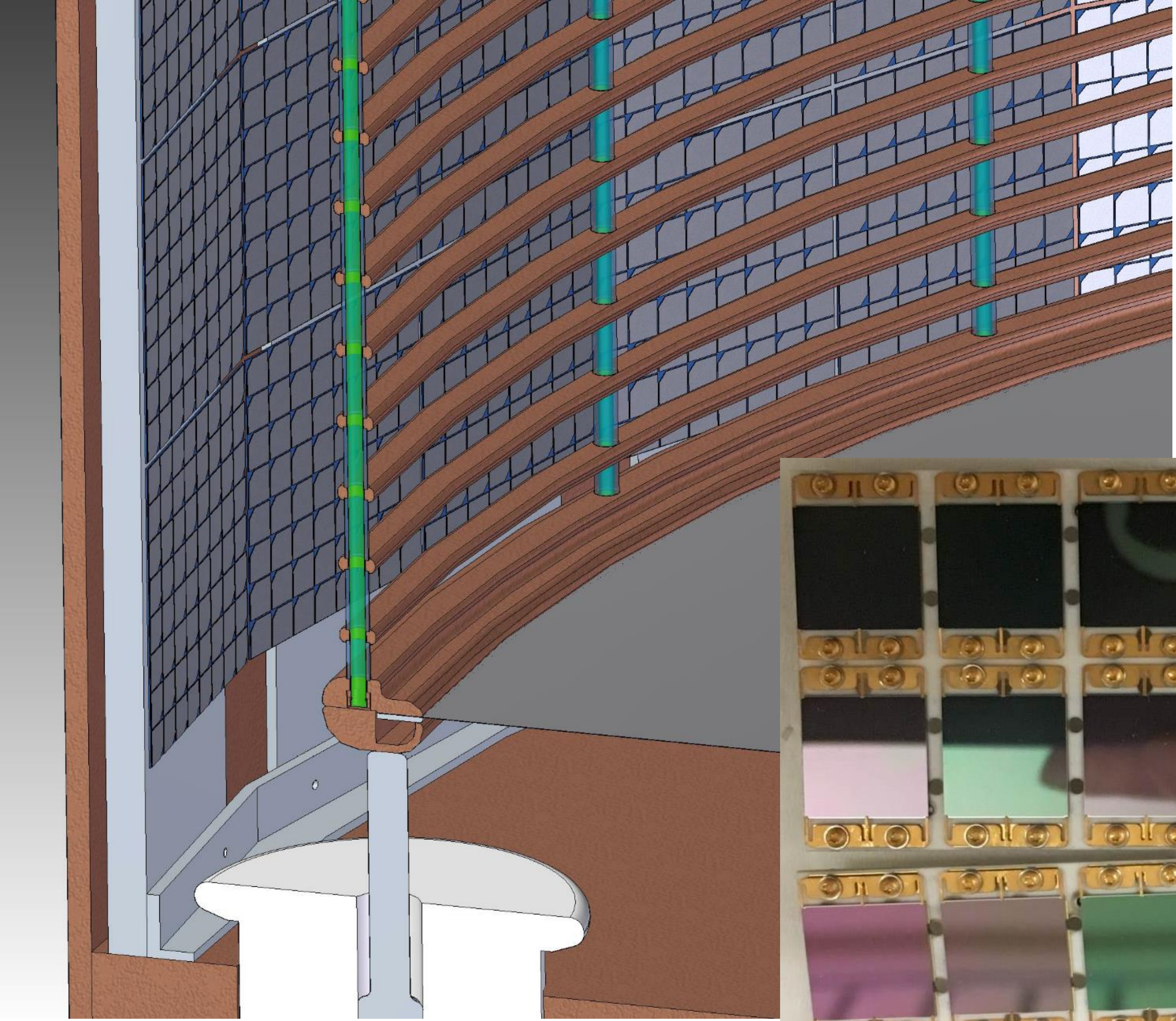


Optimization from the EXO-200 to the nEXO scale

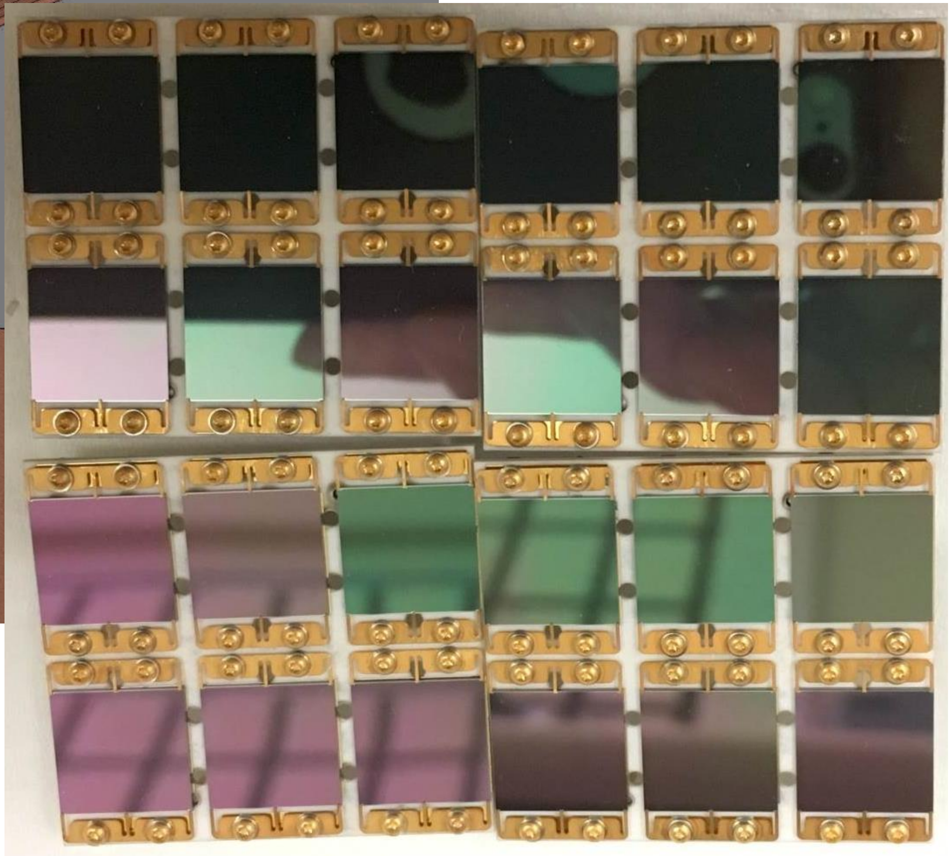
What	Why
~30x volume/mass	To give sensitivity to the inverted hierarchy
No cathode in the middle	Larger low background volume/no ^{214}Bi in the middle
6x HV for the same field	Larger detector and one drift cell
>3x electron lifetime	Larger detector and one drift cell
Better photodetector coverage	Energy 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



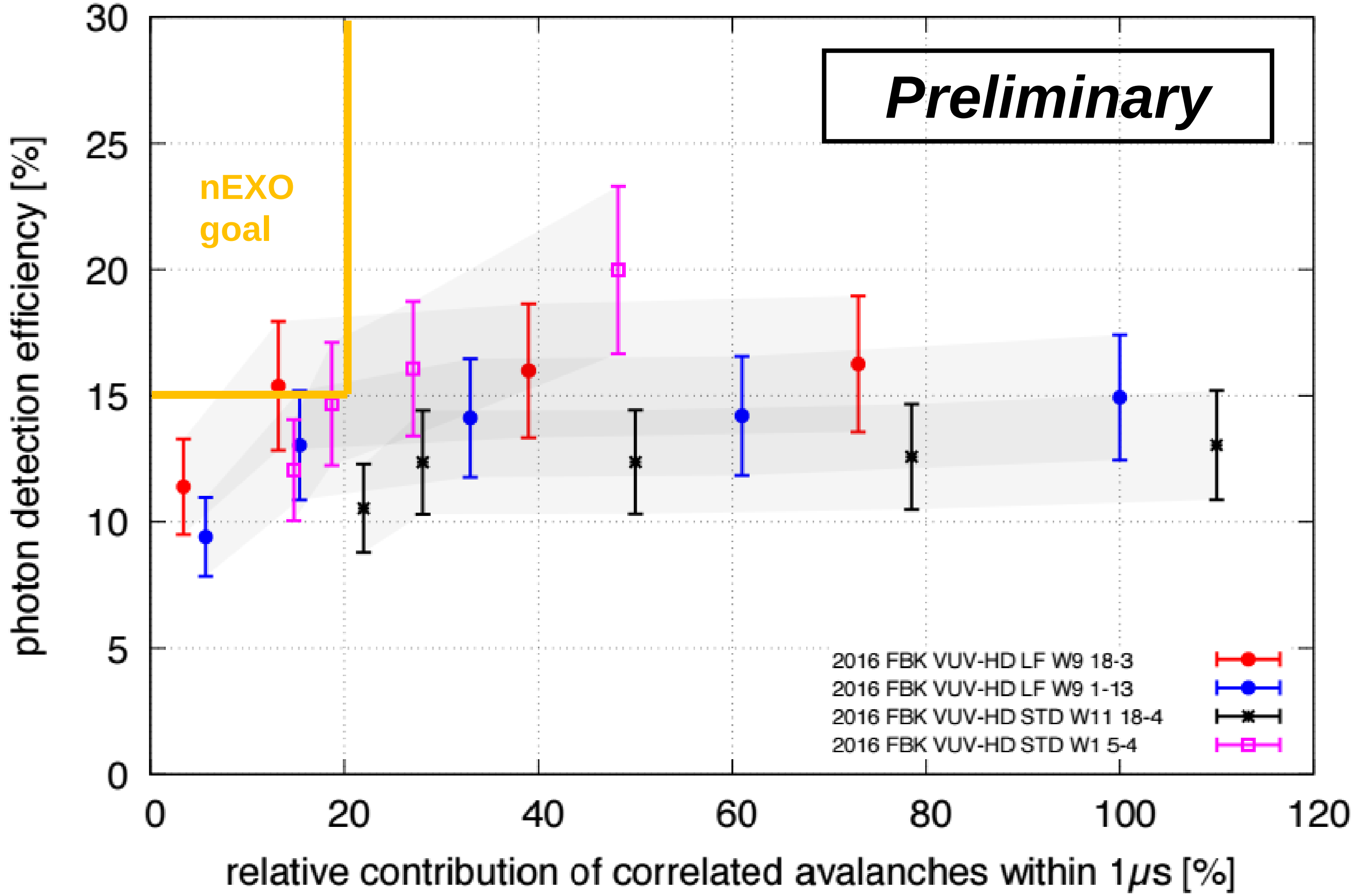


Need ~4m² of VUV-sensitive SiPMs



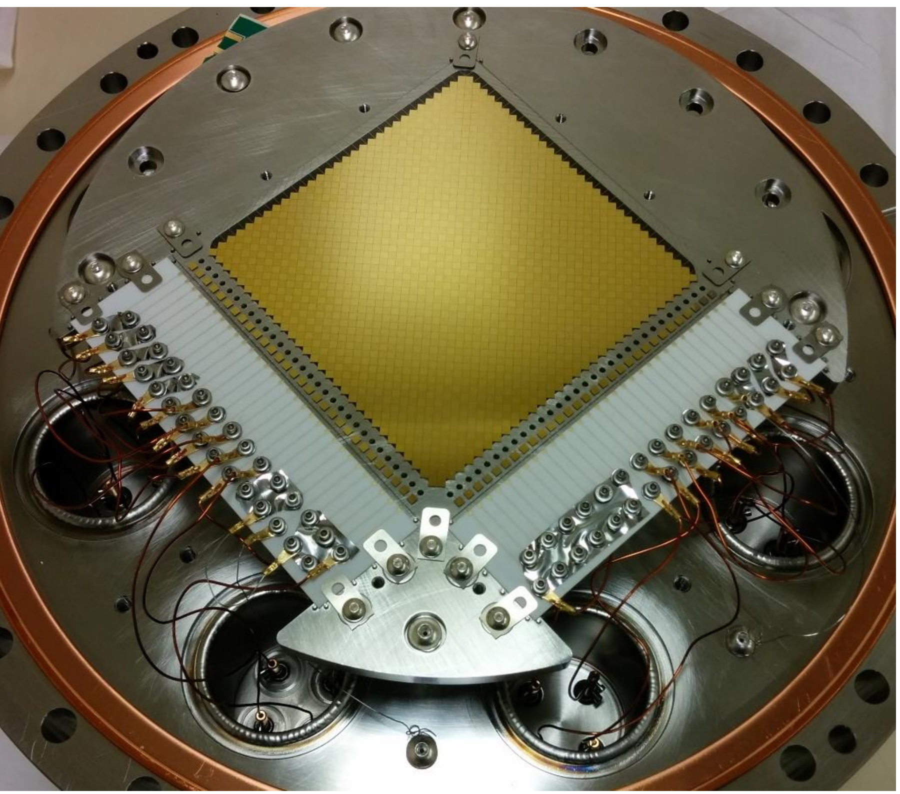
At least one type of 1cm² VUV devices now match our desired properties, with a bias requirement ~30V

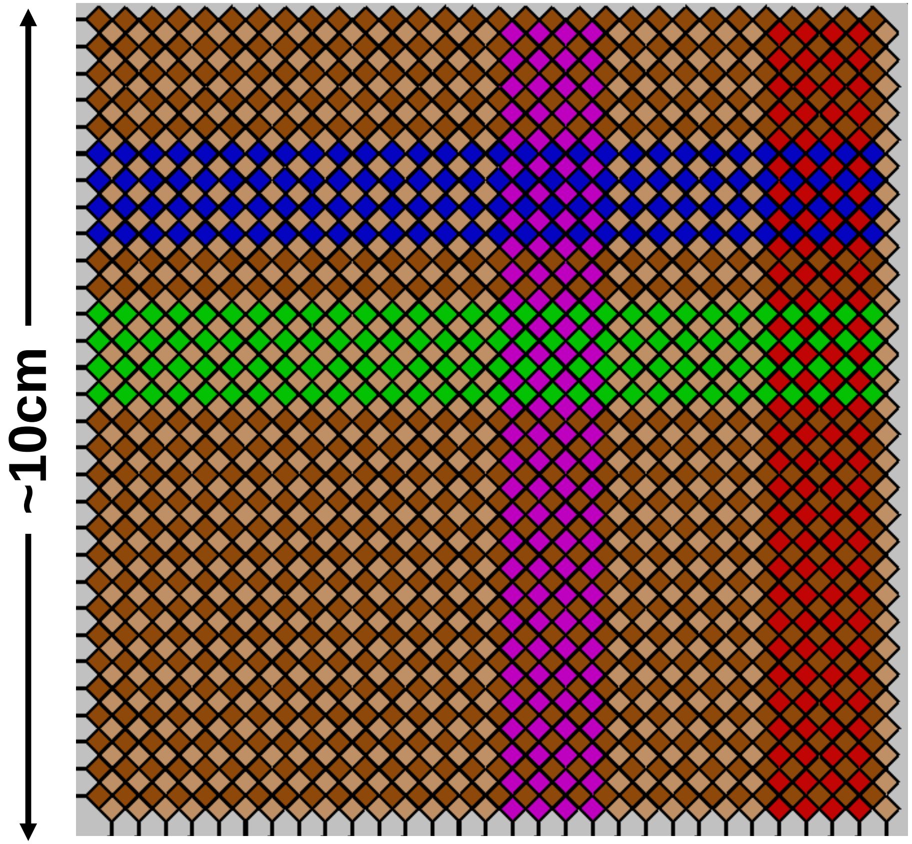
(as opposed to the 1500V of EXO-200 APDs)



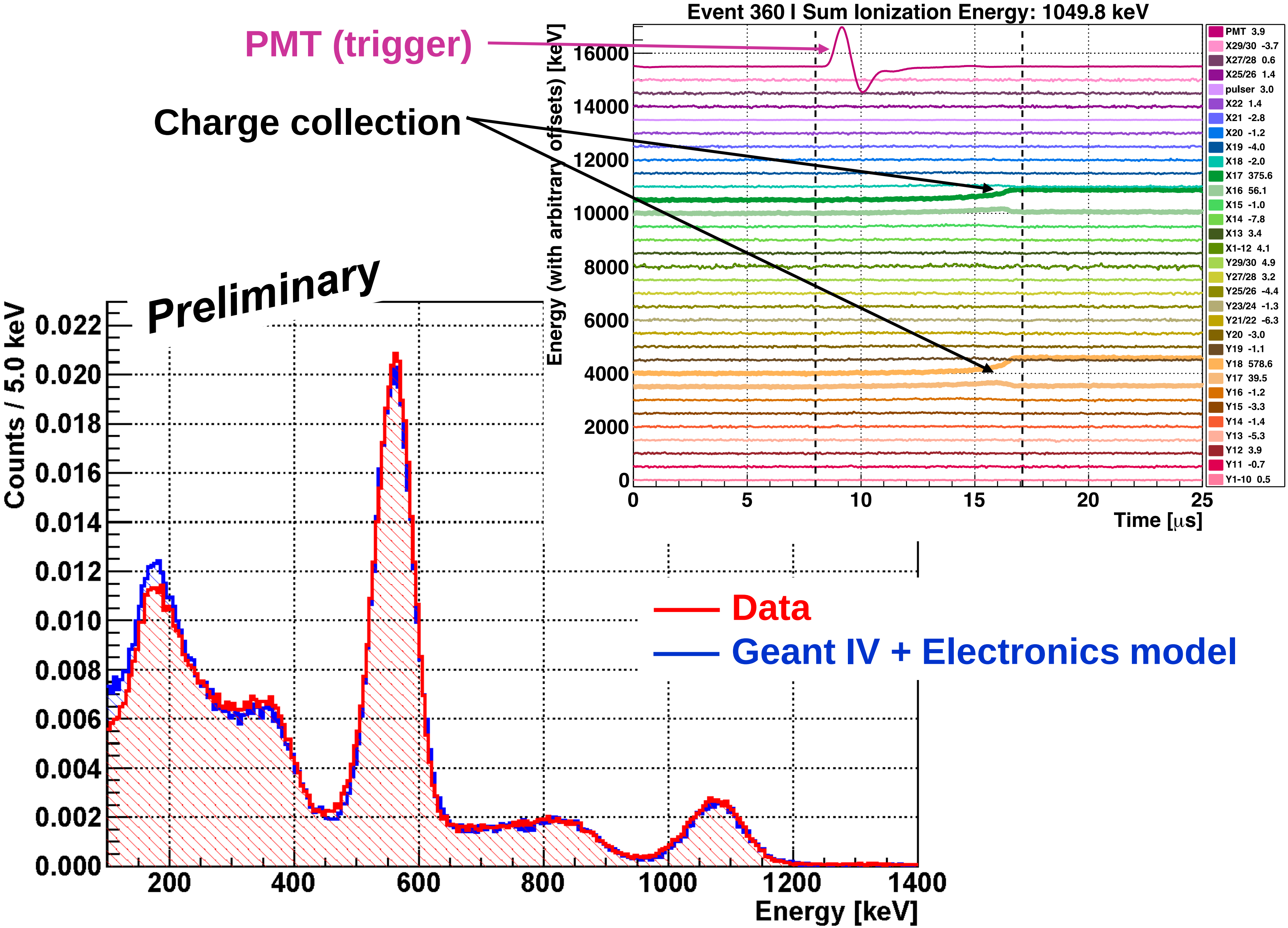
Charge will be collected on arrays of strips fabricated onto low background dielectric wafers (baseline is silica)

- 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

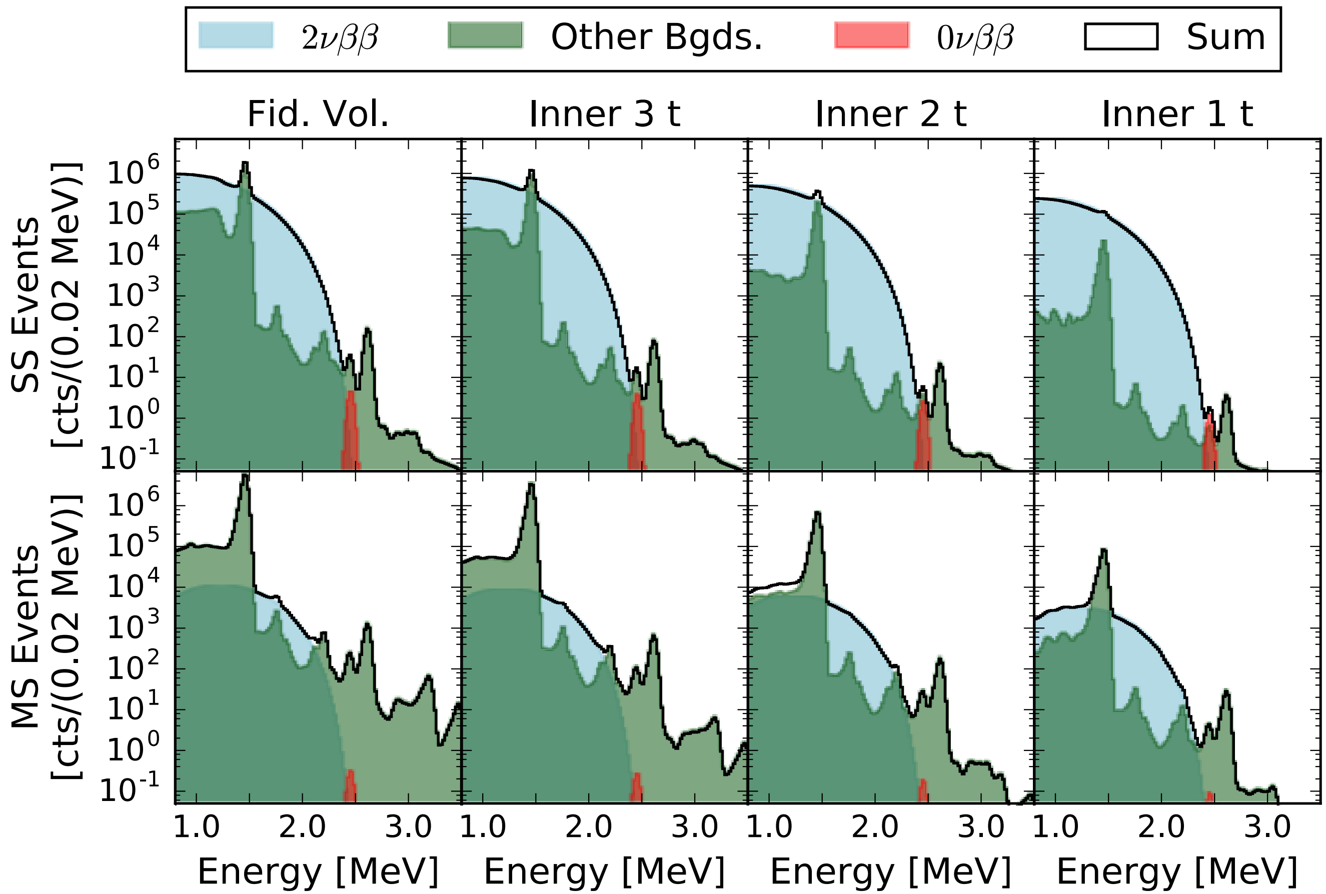

PMT (trigger)
Charge collection
Preliminary
Event 360 I Sum Ionization Energy: 1049.8 keV
Energy (with arbitrary offsets) [keV]
Time [μs]
PMT 3.9
X29/30 -3.7
X27/28 0.6
X25/26 1.4
pulser 3.0
X22 1.4
X21 -2.8
X20 -1.2
X19 -4.0
X18 -2.0
X17 375.6
X16 56.1
X15 -1.0
X14 -7.8
X13 3.4
X1-12 4.1
Y29/30 4.9
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
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!***

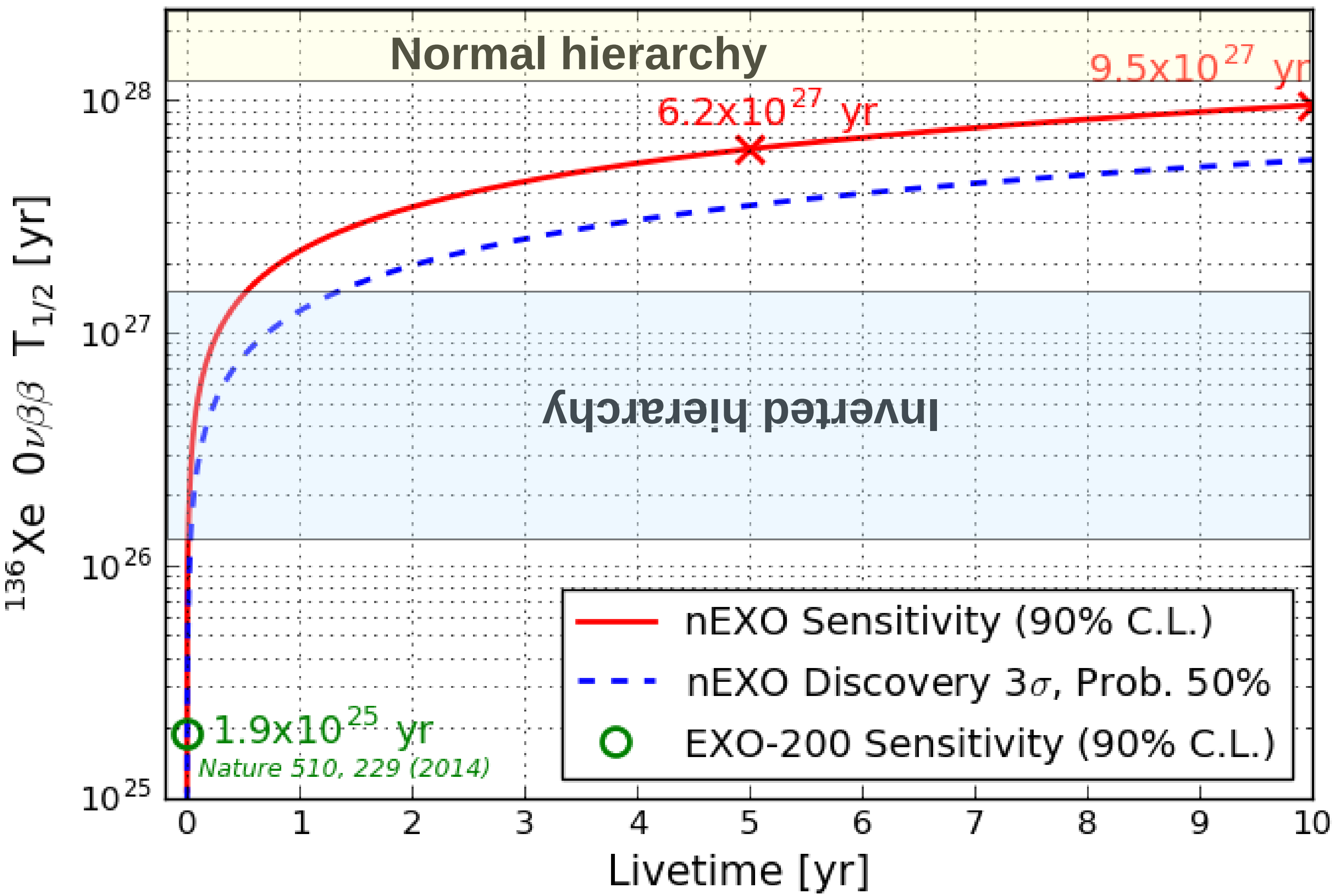
SS

MS



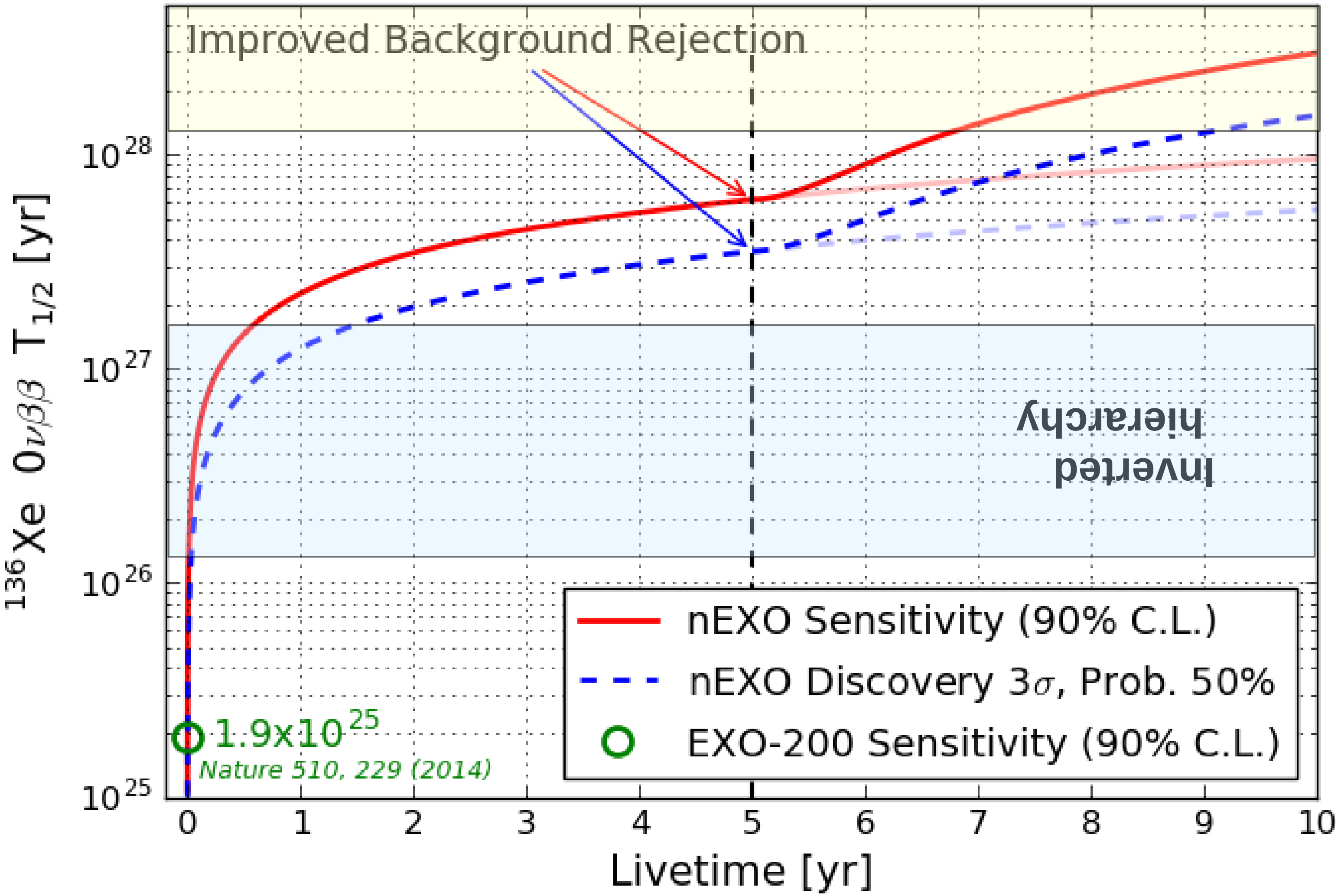
10 yr data, $0\nu\beta\beta$ corresponding to $T^{1/2}=5.5\times10^{27}$ yr

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

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 ~$3x10^{28}$ yr

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G Ortega, C Overman, R Saldanha, R Tsang
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