Scalable search for Matter Creation©

nEXO

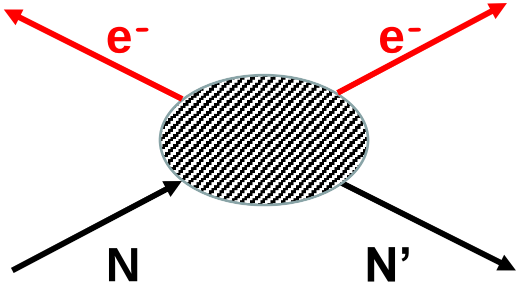
Giorgio Gratta

on behalf of the nEXO collaboration

“Black box” theorem*: “0νββ decay always implies new physics”

There is no scenario in which observing 0νββ decay would not be a great discovery

➔ Majorana neutrinos
➔ Lepton number violation
➔ Probe new mass mechanism up to the GUT scale
➔ Probe key ingredient in generating cosmic baryon asymmetry



Neutrino masses have to be non-zero for 0νββ to be possible.
➔ Because the distinction between Dirac and Majorana particles is only observable for particles of non-zero mass.

Strictly speaking, this is the ONLY connection with neutrino masses relevant to discover new physics.

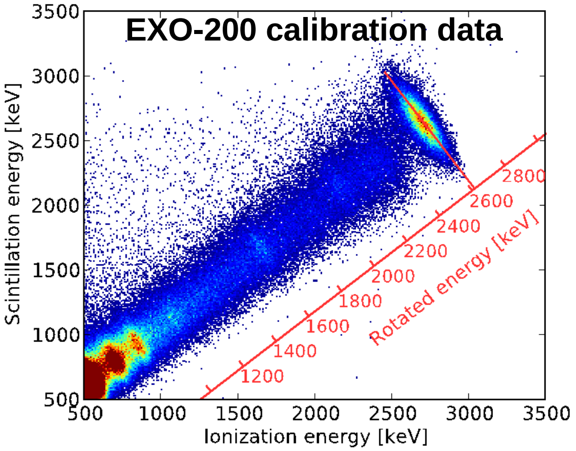
Hence it is appropriate to think of the sensitivity to new physics as scaling with $T_{1/2}$, irrespective of the neutrino mass scenarios. A $T_{1/2}$ sensitivity increase from ~10^{26} to ~10^{28} yr (~100x), should be compared, e.g., to the $\sqrt{s}$ increase from Tevatron to LHC (~20), although, admittedly, with a smaller array of channels for new physics.

* J. Schechter, and J. W. F. Valle, Phys. Rev. D25, 2951 (1982).

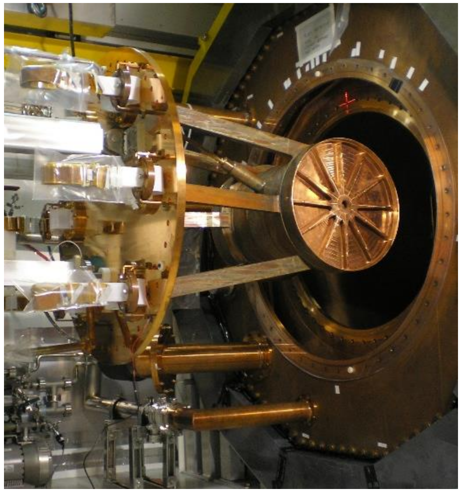
The EXO program

- 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.
  Phase II ended 30 Nov 2018



- Build the 5-tonne nEXO, reaching $T_{1/2}$~10^{28} yr and entirely covering the Inverted Hierarchy (with the caveats above)

- Develop a technique for tagging the final state Ba as a possibility to further upgrade nEXO and substantially exceed $T_{1/2}=10^{28}$ yr

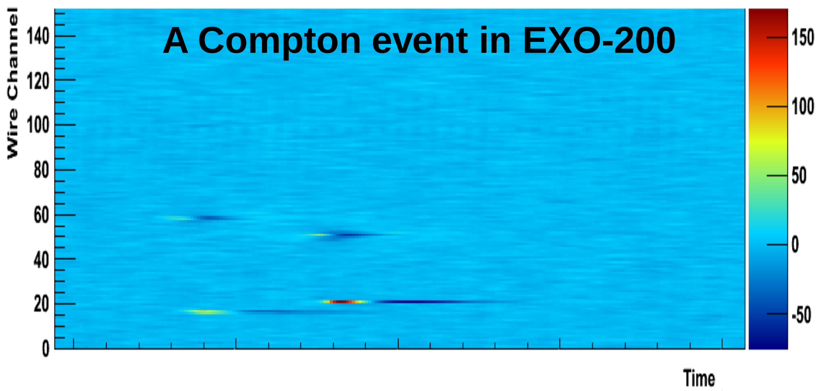
Particularly for large detectors, energy resolution is only one of the parameters used for background rejection:

- Energy measurement (for small detectors this is ~all there is).

- Event multiplicity (γ's Compton scatter depositing energy in more than one site).

- For large, monolithic detectors, depth is powerful discriminant against background.

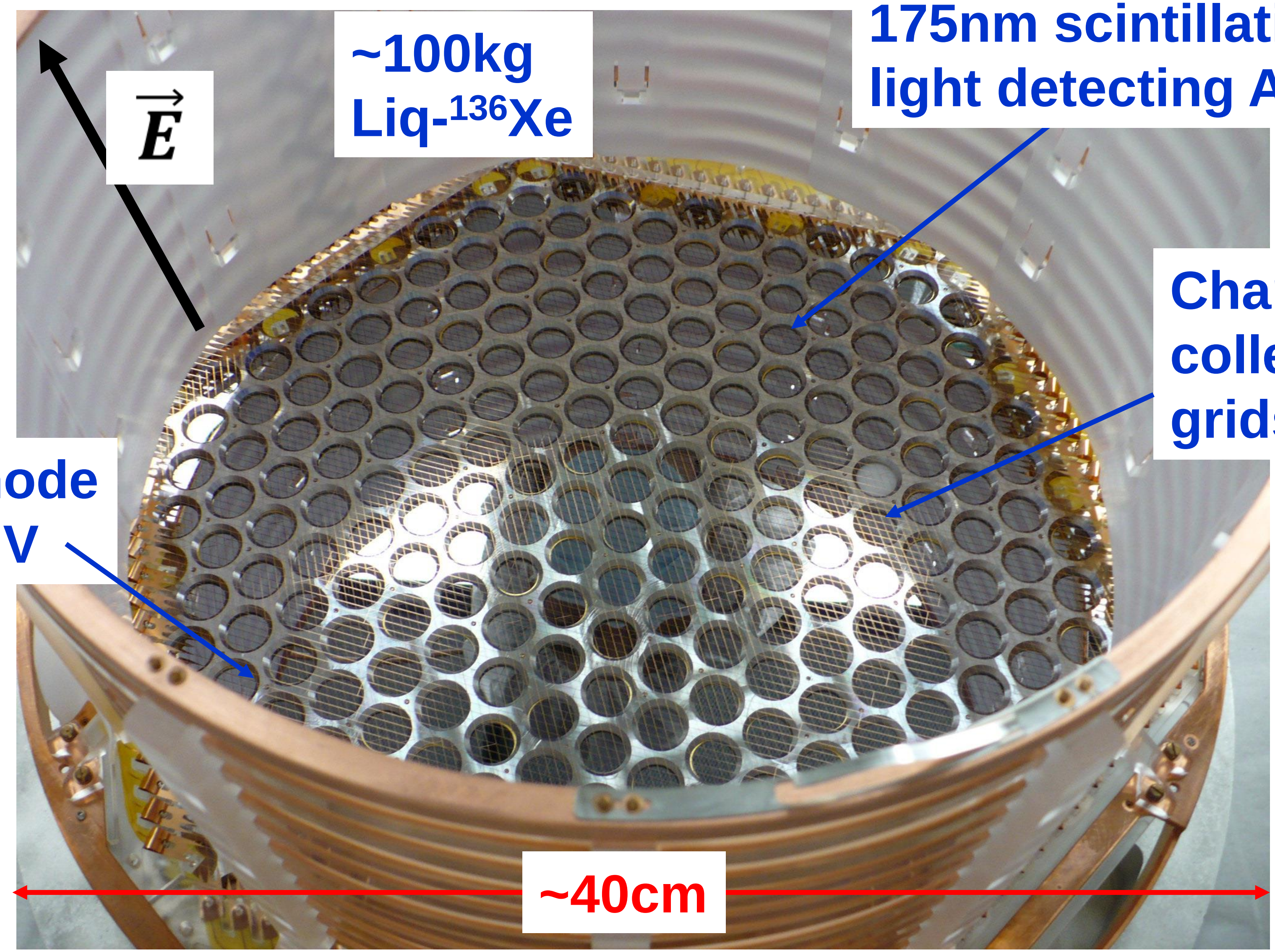
- α discrimination (from e^- / γ), possible in many detectors.



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.

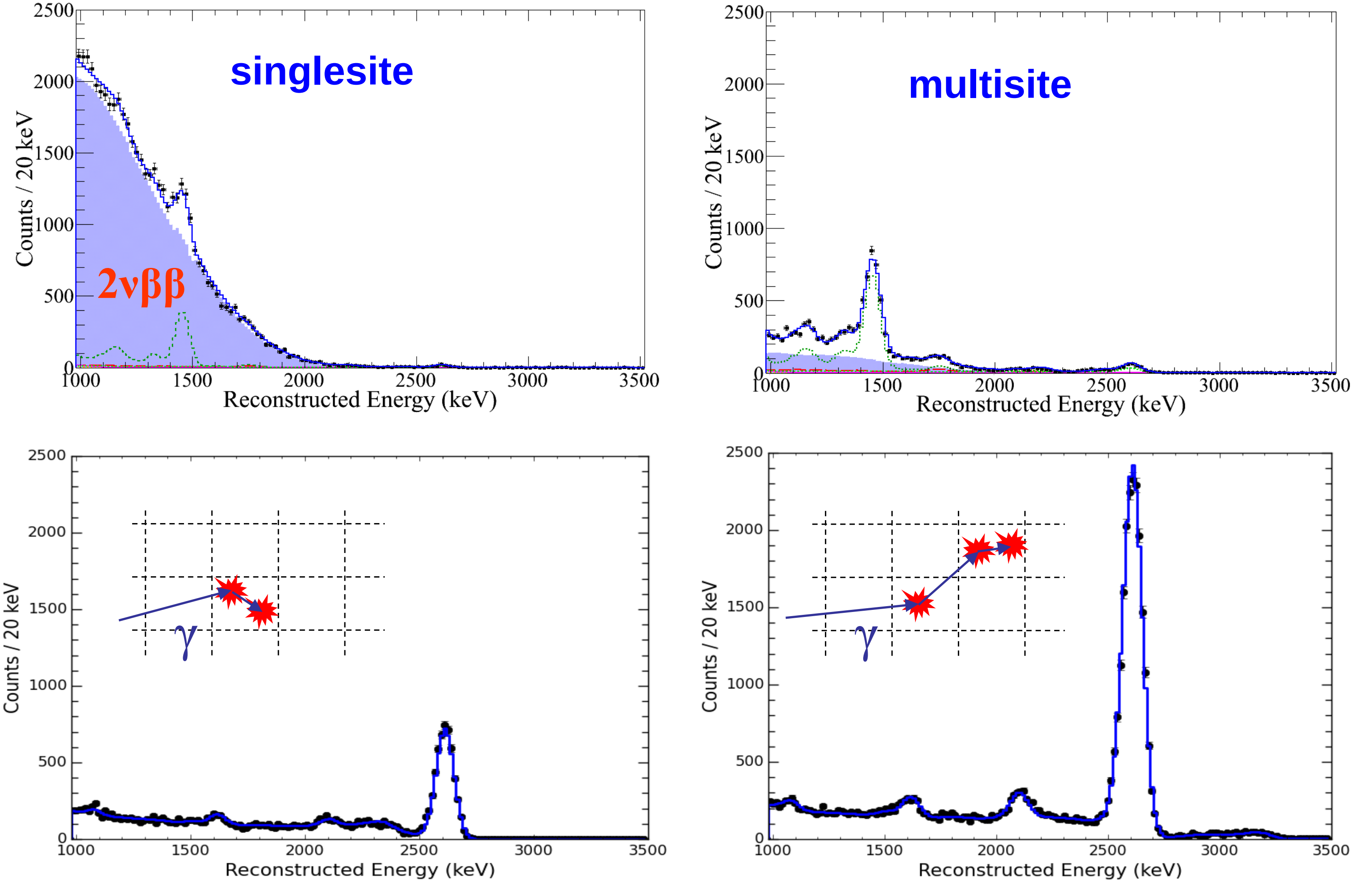
The EXO-200 liquid ^{136}Xe Time Projection Chamber



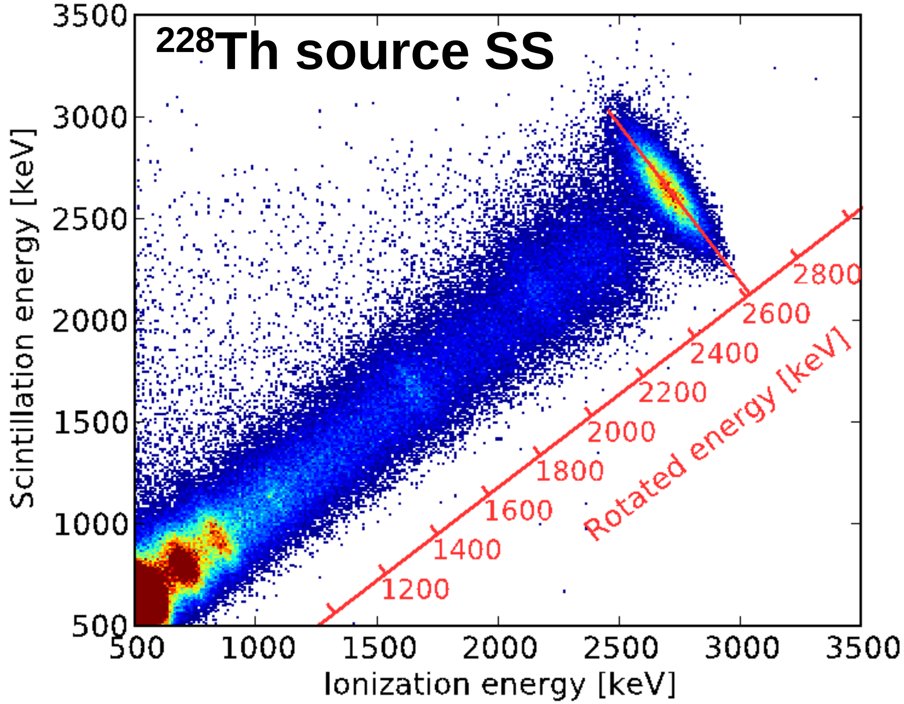
Using event multiplicity to recognize backgrounds

Low background data

^{228}Th calibration source



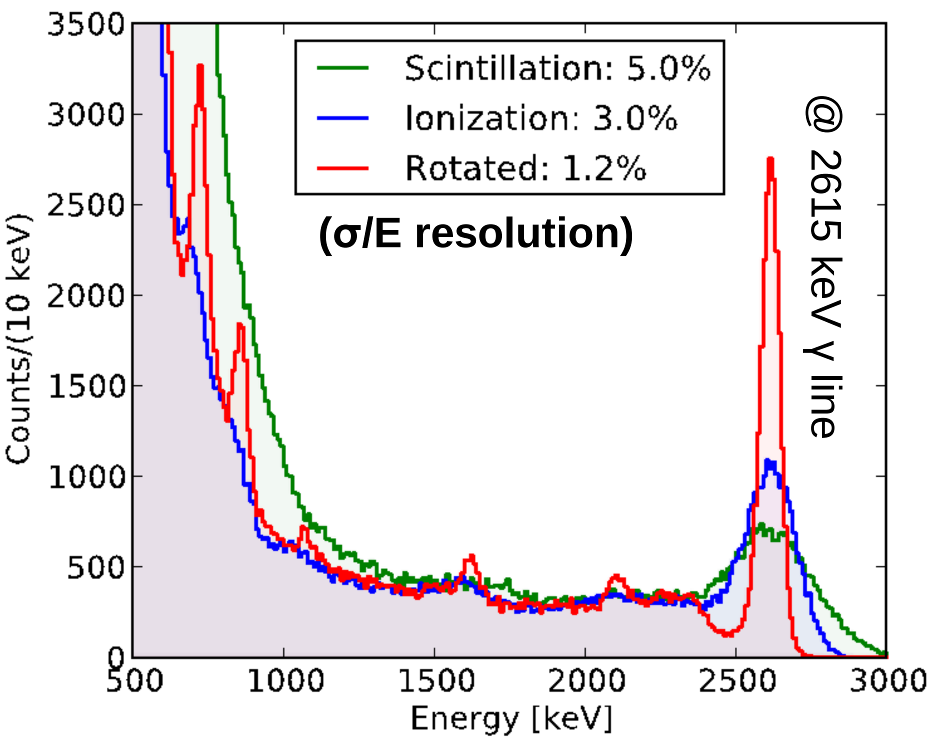
Combining Ionization and Scintillation



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

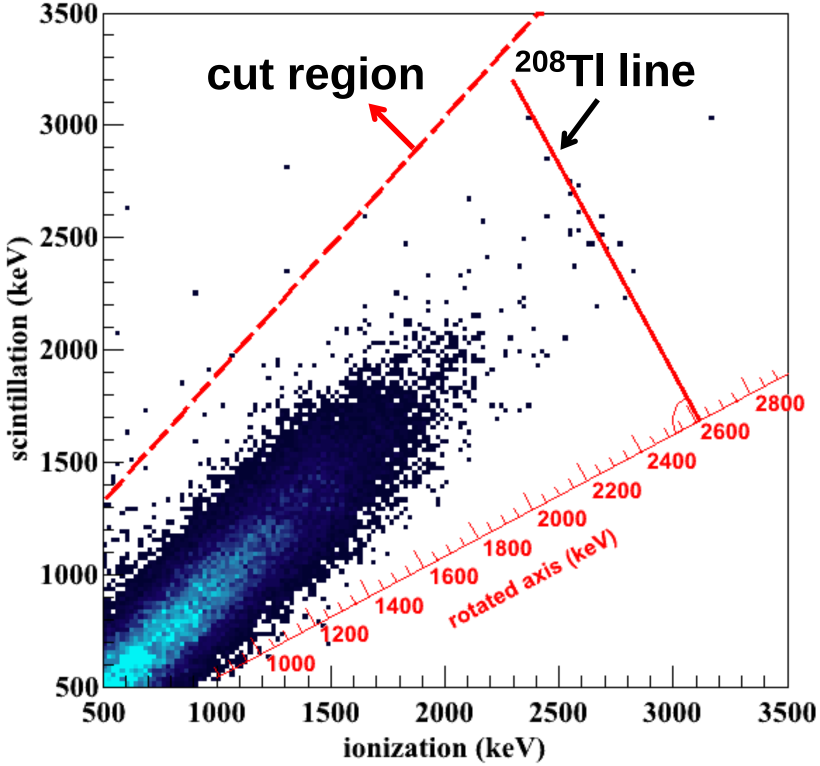
E.Conti et al.
Phys Rev B 68 (2003) 054201

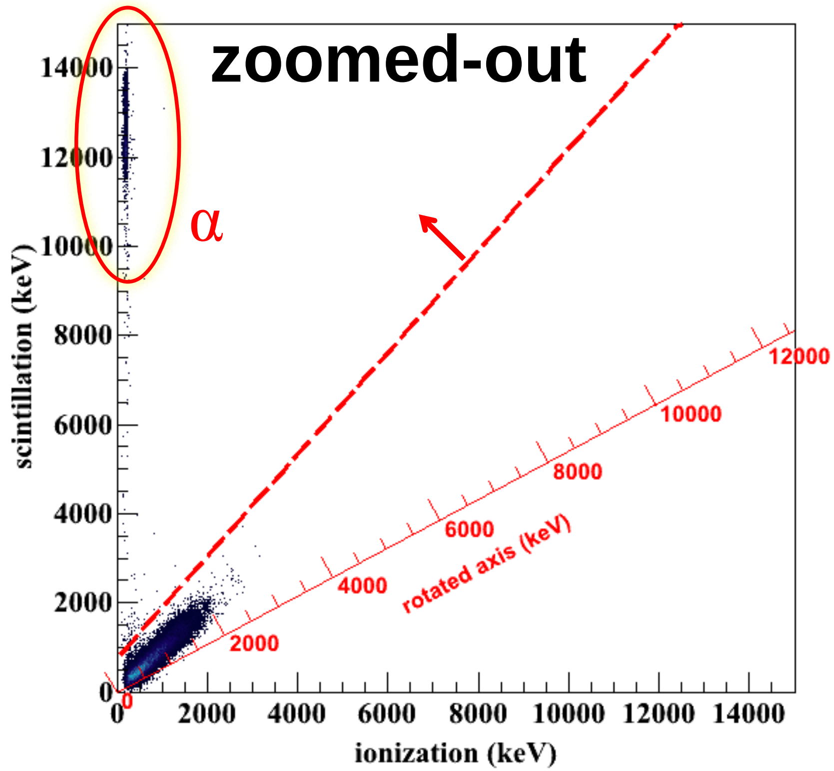
By now this is a common technique in LXe



Rotation angle chosen to optimize energy resolution at 2615 keV

Low Background 2D SS Spectrum

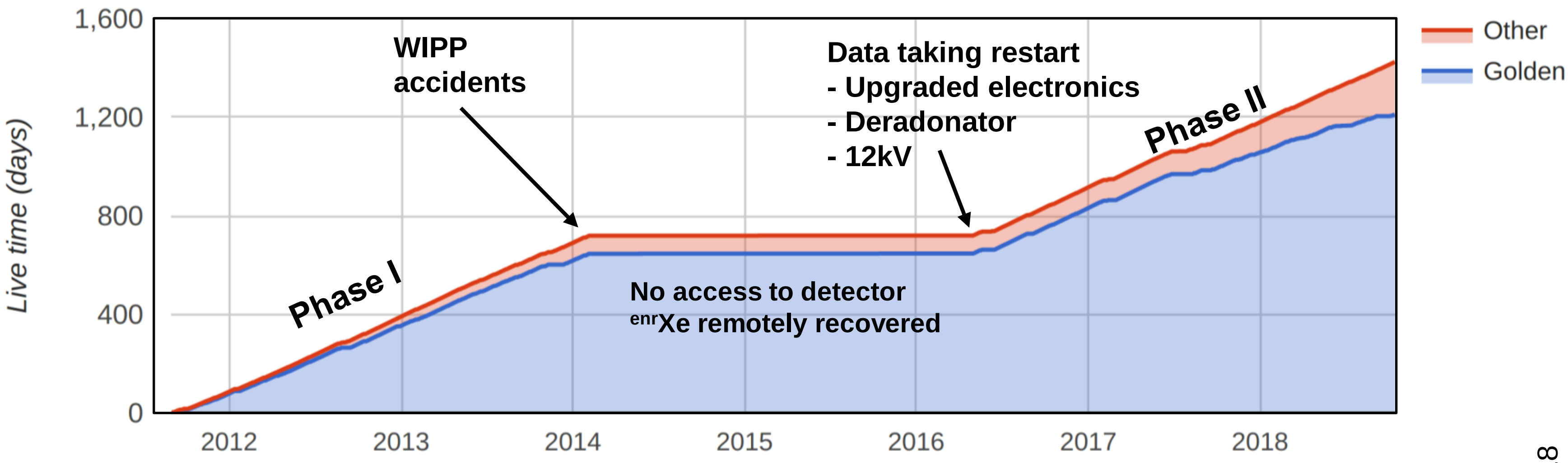




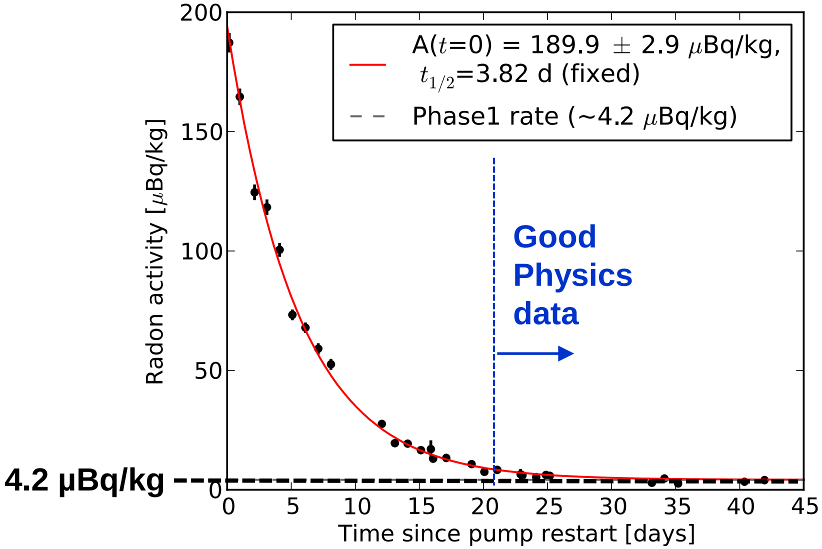
Events removed by diagonal cut:

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

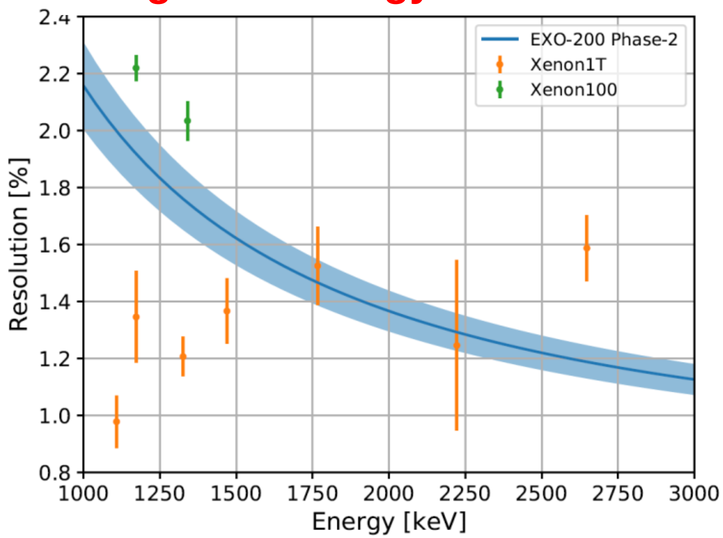
About 5 years of data on disk, Phase II just ended



Rn in LXe after restart



Singlesite energy resolution



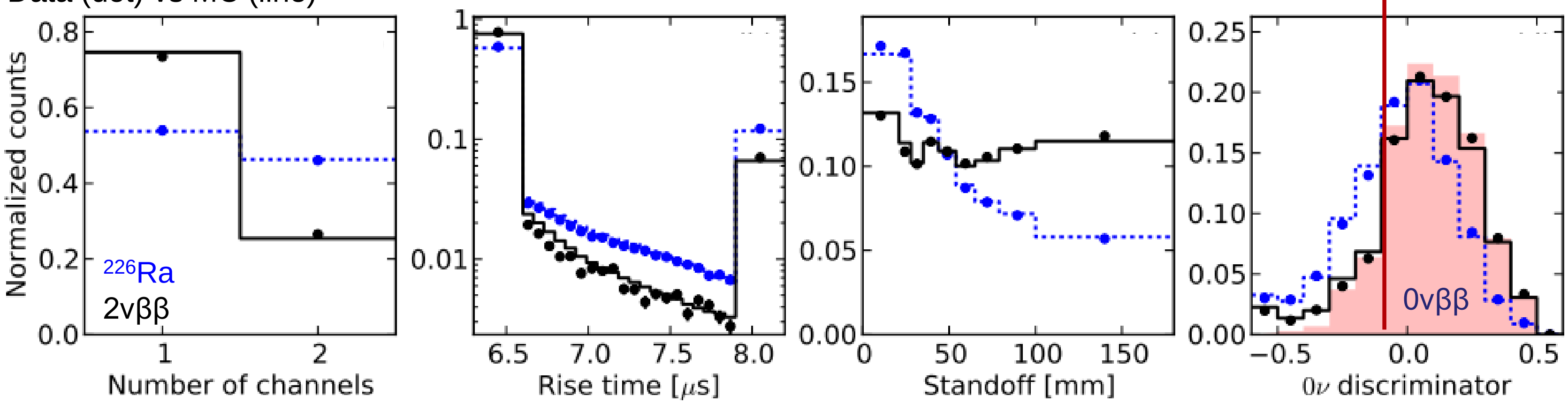
XENON data: K. Ni, UCLA Dark Matter 2018

Squeezing more discriminating power out of Singlesite events

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

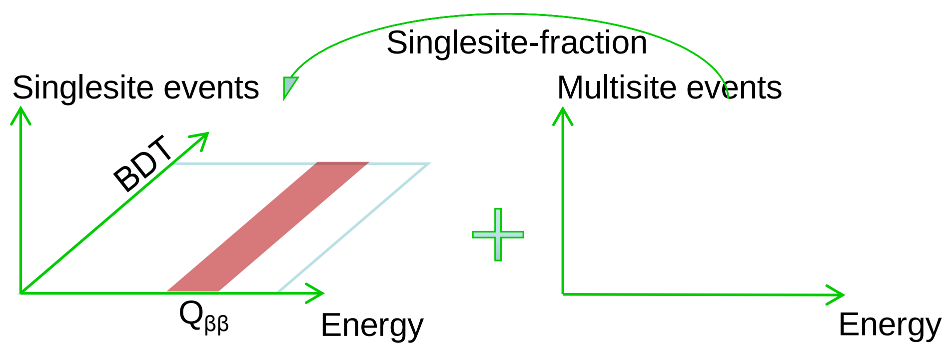
~35% γ-rejection
~90% signal efficiency

Data (dot) vs MC (line)



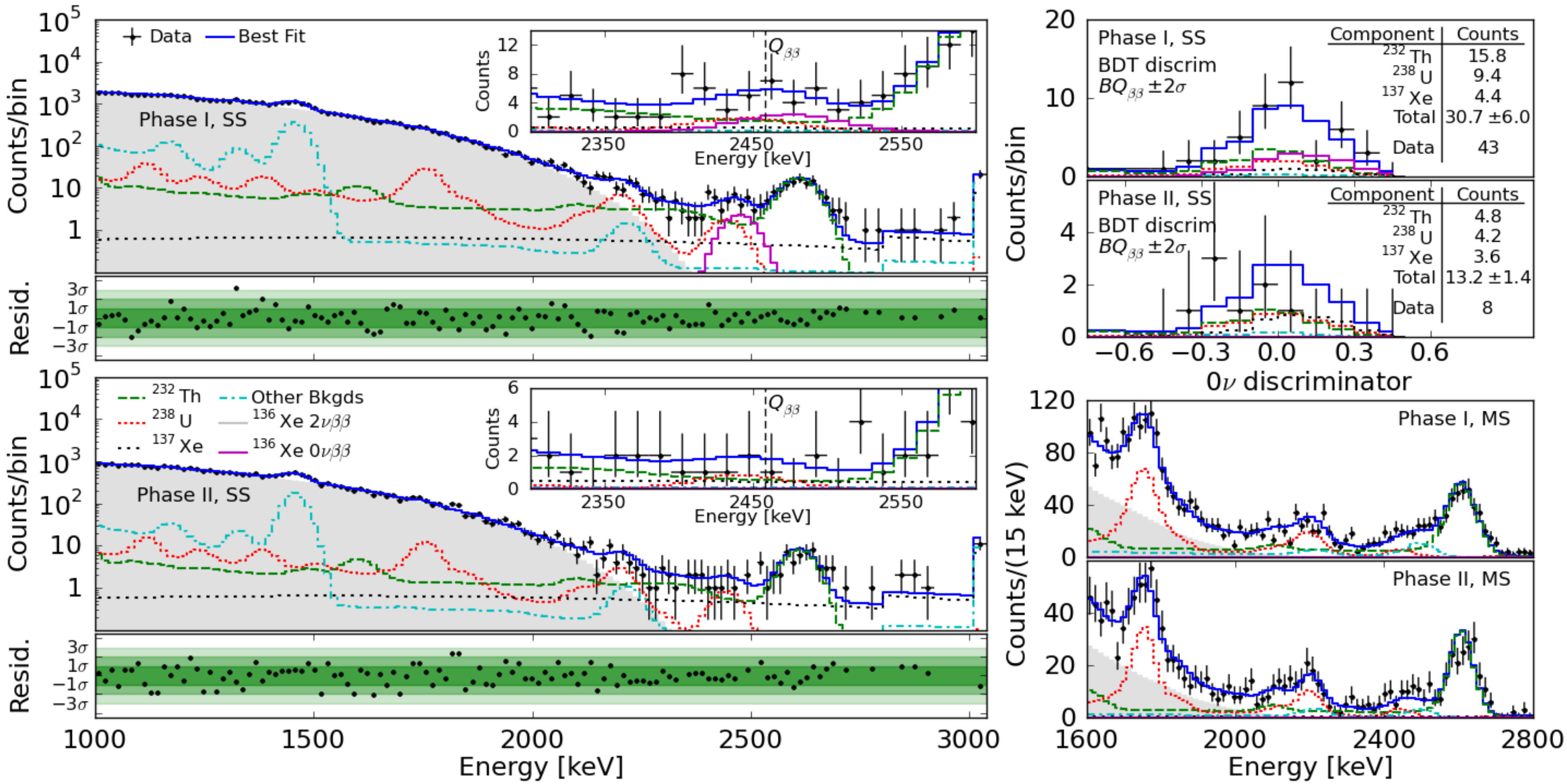
Fitting 0νββ discriminators

- **Energy**
- **Singlesite/multisite**
- ***BDT → ~15% sensitivity improvement***



Most Recent Results

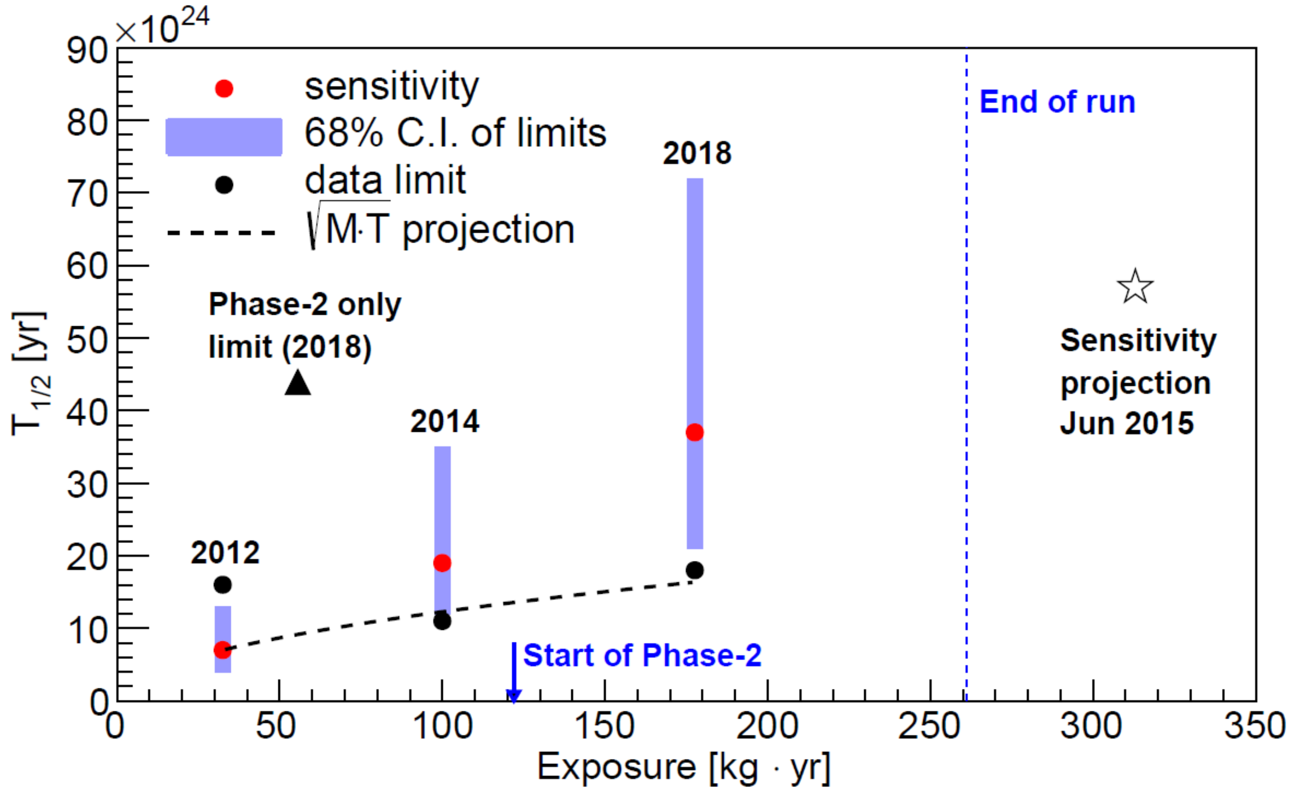
- Background model + data → maximum likelihood fit
- Combine Phase I + Phase II profiles



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

A brief history of EXO-200 0νββ results

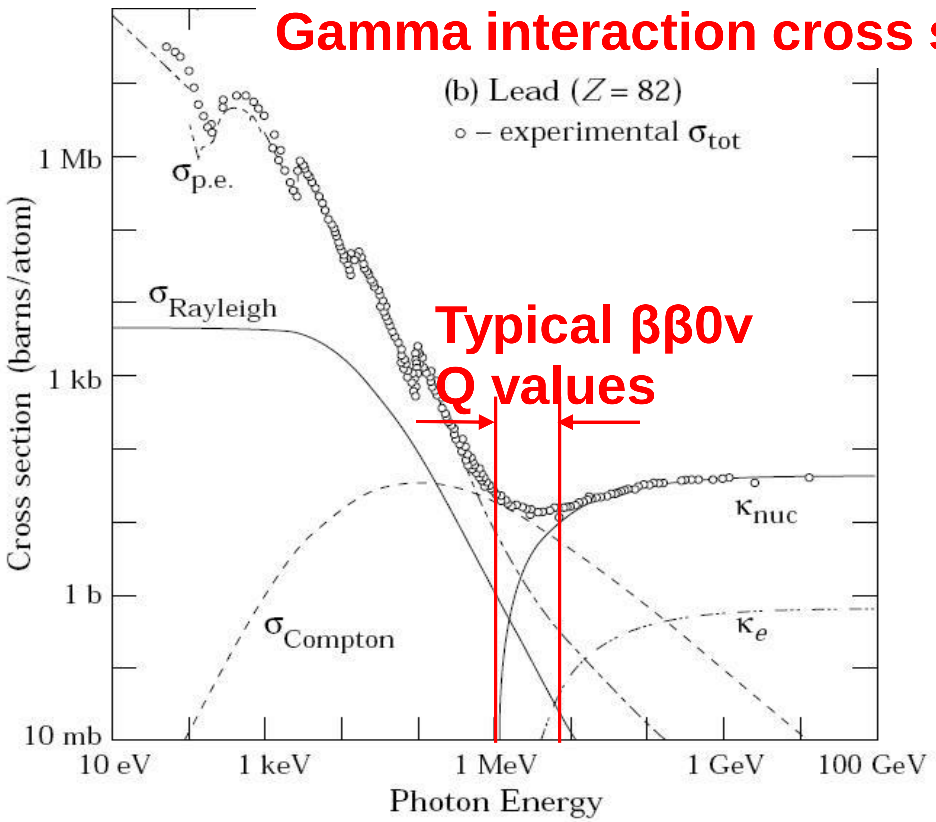
	Sensitivity (yr)	90% CL Limit (yr)	<$m_{\beta\beta}$> (meV)
PRL 109, 032505 (2012)	0.7×10^{25}	1.6×10^{25}	
Nature 510, 229 (2014)	1.9×10^{25}	1.1×10^{25}	
PRL 120 072701 (2018)	3.8×10^{25}	1.8×10^{25}	147-398



The sensitivity is the correct way to estimate the capability of an experiment, because it contains all the information that can be / is used.

If one wants to use the incomplete picture of a single parameter, then the "background index" is ~ (0.11±0.01) / (kg·yr·FWHM)

Shielding a detector from ~MeV γs is difficult!



Example:

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

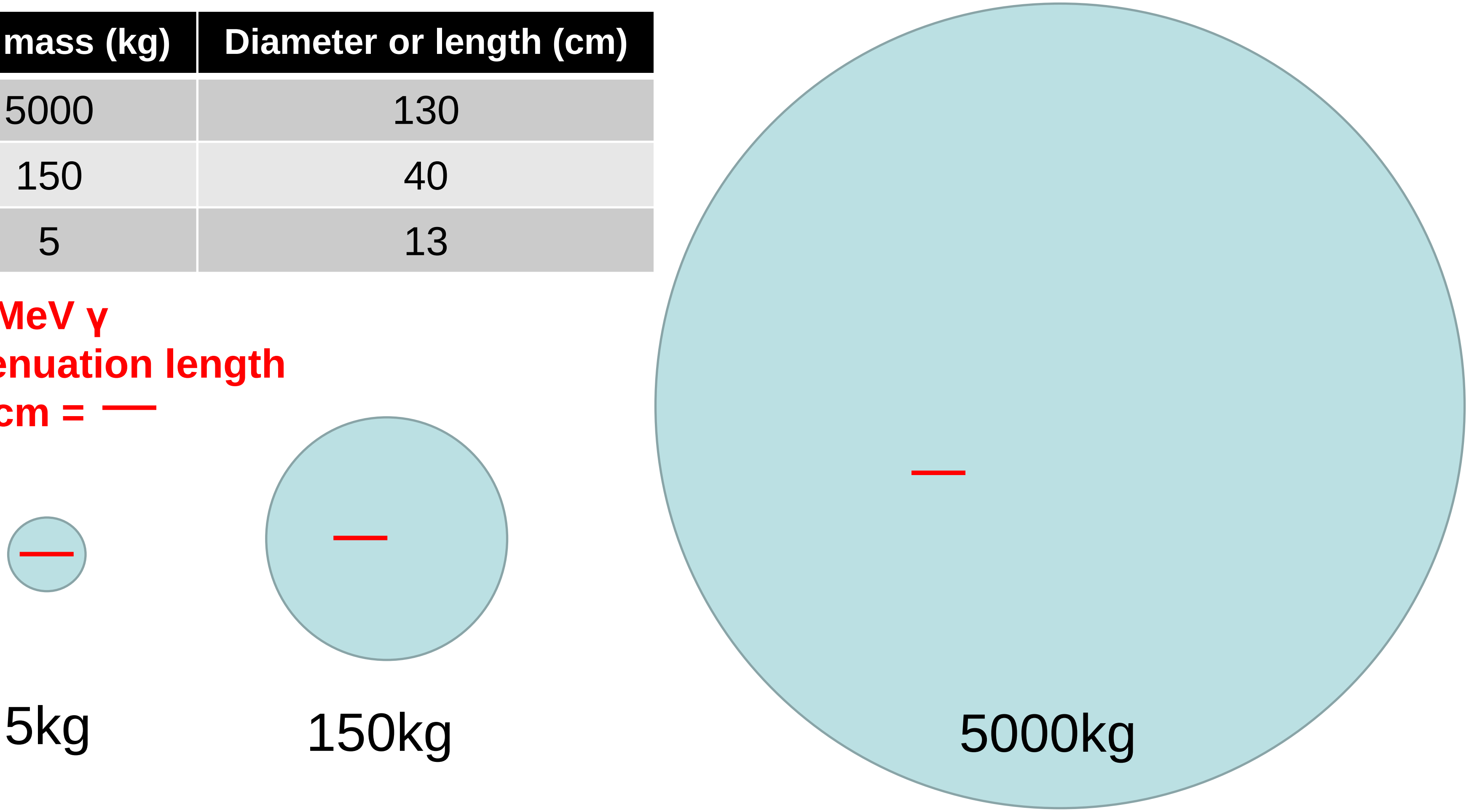
Shielding ββ decay detectors is much harder than shielding Dark Matter ones

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

Moving forward, monolithic is key

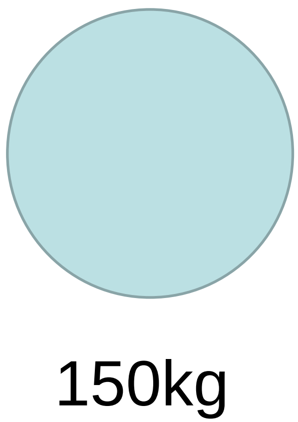
LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

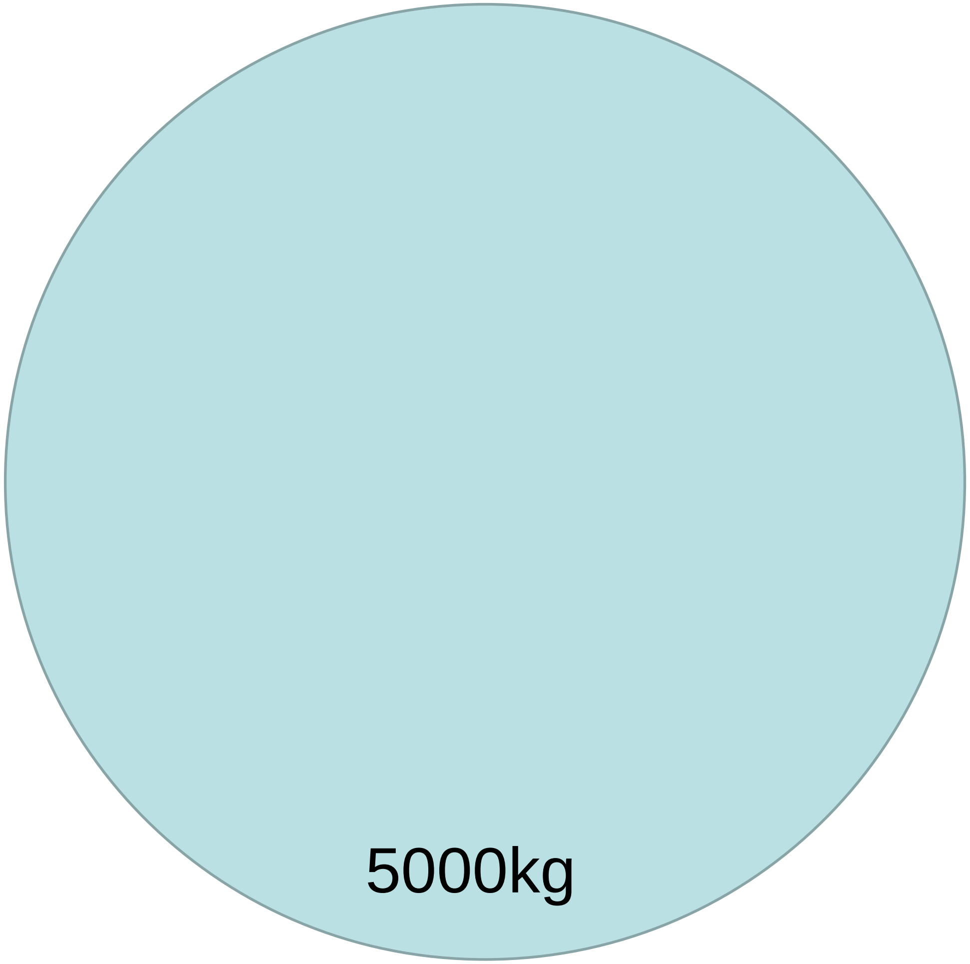
2.5MeV γ attenuation length 8.5cm = —



The current estimate of the nEXO sensitivity relies only on materials already tested for radioactivity and on hand (although not necessarily in sufficient amount)

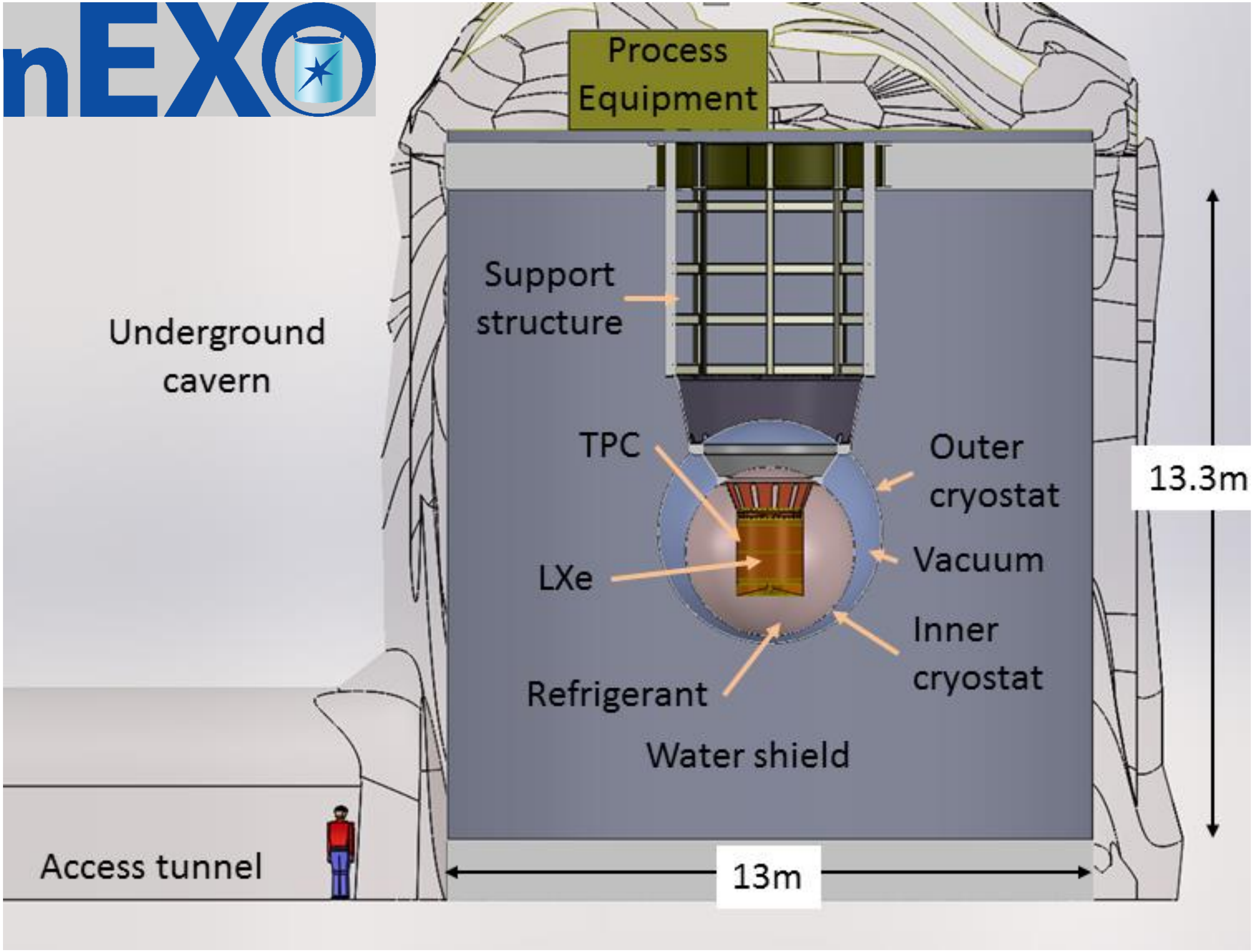
It is also important, to have the chance of making reliable and decisive discoveries, to increase the detector sensitivity (in this case its size) by a substantial amount.





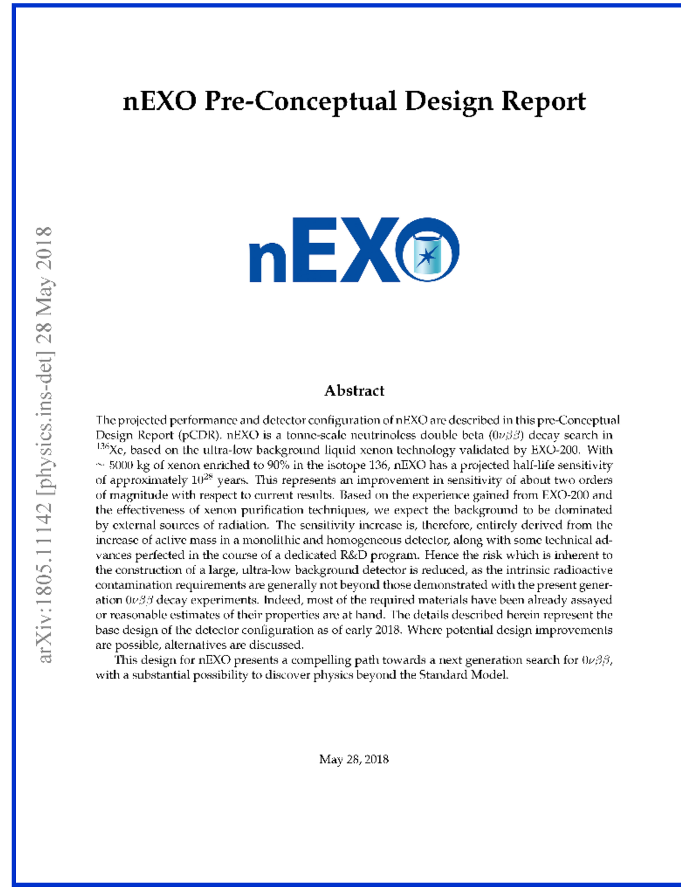
Small incremental sensitivity increases automatically imply that a true blind analysis is impossible.

Preliminary artist view of nEXO in the SNOLAB Cryopit



nEXO papers, describing the detector, the experiment's sensitivity and some results from the R&D

- "nEXO pCDR" arXiv:1805.11142 (May 2018)
- "Sensitivity and Discovery Potential of nEXO to $0\nu\beta\beta$ decay"
  Phys. Rev. C 97 (2018) 065503
  arXiv:1710.05075
- "Imaging individual Ba atoms in solid xenon for barium tagging in nEXO"
  arXiv:1806.10694 (Jun 2018)*
- "VUV-sensitive Silicon Photomultipliers for Xenon Scintillation Light Detection in nEXO"
  IEEE Trans. NS 65 (2018) 2823
- "Characterization of an Ionization Readout Tile for nEXO" J.Inst. 13 P01006 (2018)
- "Characterization of Silicon Photomultipliers for nEXO", IEEE Trans. NS 62, 1825 (2015)



arXiv:1805.11142 [physics.ins-det] 28 May 2018

nEXO Pre-Conceptual Design Report

Abstract

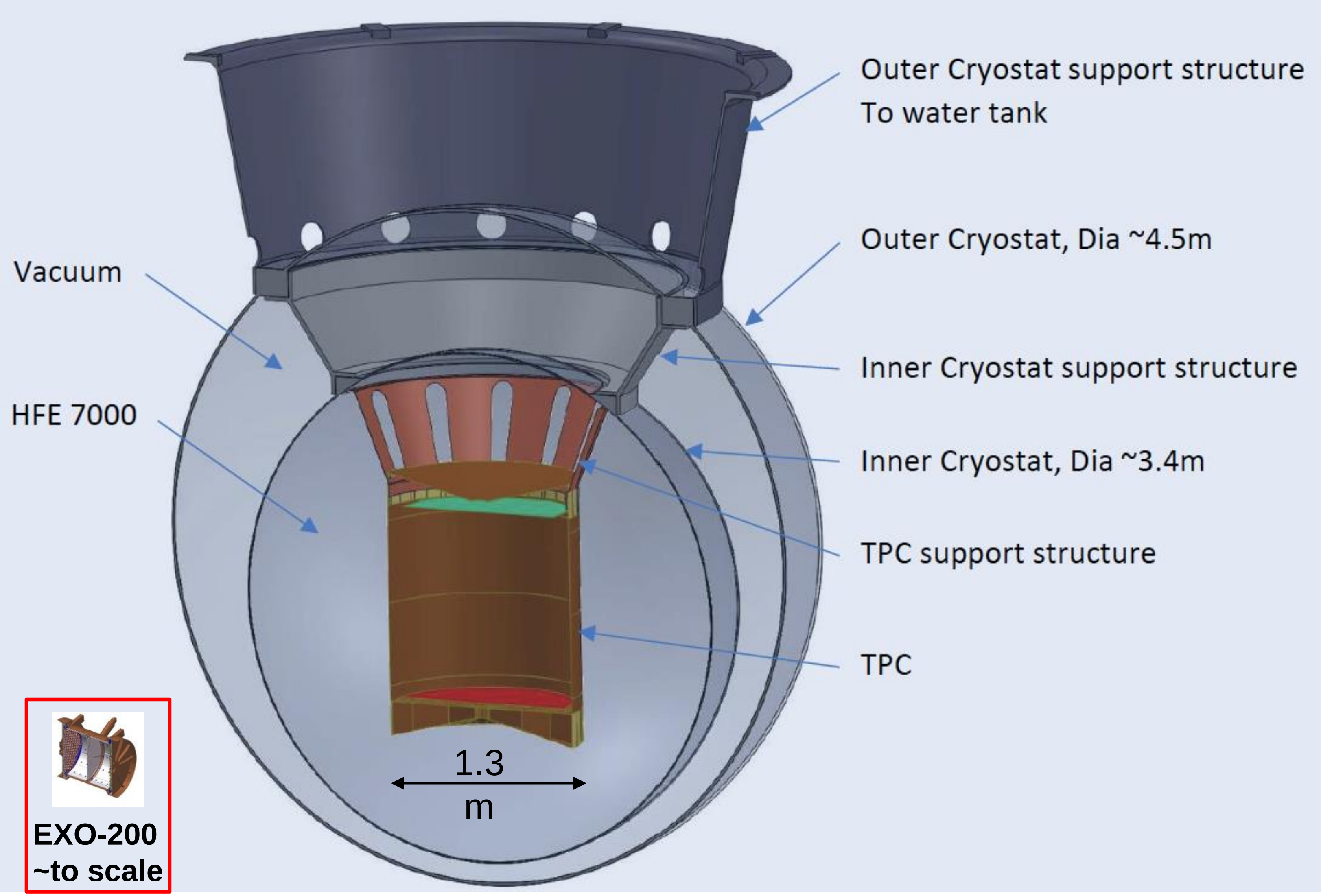
The projected performance and detector configuration of nEXO are described in this pre-Conceptual Design Report (pCDR). nEXO is a tonne-scale neutrinoless double beta ($0\nu\beta\beta$) decay search in ^{136}Xe, based on the ultra-low background liquid xenon technology validated by EXO-200. With ~ 5000 kg of xenon enriched to 90% in the isotope 136, nEXO has a projected half-life sensitivity of approximately 10^{28} years. This represents an improvement in sensitivity of about two orders of magnitude with respect to current results. Based on the experience gained from EXO-200 and the effectiveness of xenon purification techniques, we expect the background to be dominated by external sources of radiation. The sensitivity increase is, therefore, entirely derived from the increase of active mass in a monolithic and homogeneous detector, along with some technical advances perfected in the course of a dedicated R&D program. Hence the risk which is inherent to the construction of a large, ultra-low background detector is reduced, as the intrinsic radioactive contamination requirements are generally not beyond those demonstrated with the present generation $0\nu\beta\beta$ decay experiments. Indeed, most of the required materials have been already assayed or reasonable estimates of their properties are at hand. The details described herein represent the base design of the detector configuration as of early 2018. Where potential design improvements are possible, alternatives are discussed.

This design for nEXO presents a compelling path towards a next generation search for $0\nu\beta\beta$, with a substantial possibility to discover physics beyond the Standard Model.

May 28, 2018

* Not nEXO baseline, nevertheless very exciting

The nEXO TPC


Outer Cryostat support structure
To water tank
Outer Cryostat, Dia ~4.5m
Vacuum
Inner Cryostat support structure
HFE 7000
Inner Cryostat, Dia ~3.4m
TPC support structure
TPC
1.3
m
EXO-200
~to scale

Retain what possible from EXO-200, further improve where reasonable

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

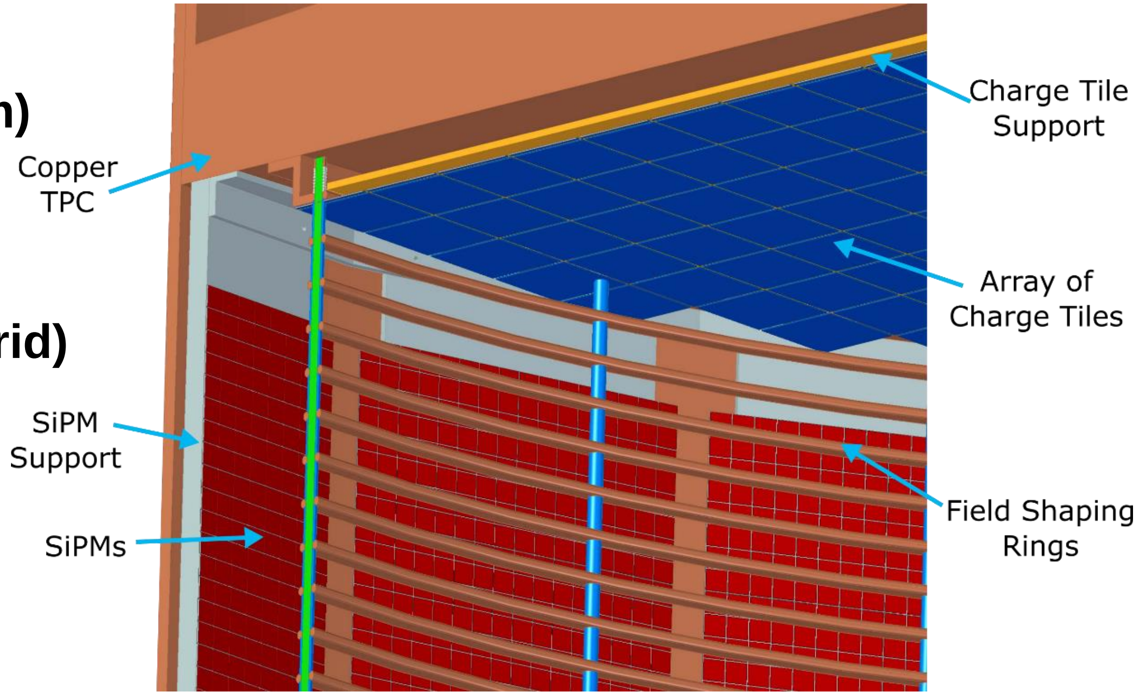
Charge readout

Prefer to stay away from free standing wires (EXO-200 option) because of length, temperature cycling, material for harp support and modularity.

Quartz (or sapphire) tiles are modular, reliable, eventually with built-in readout.

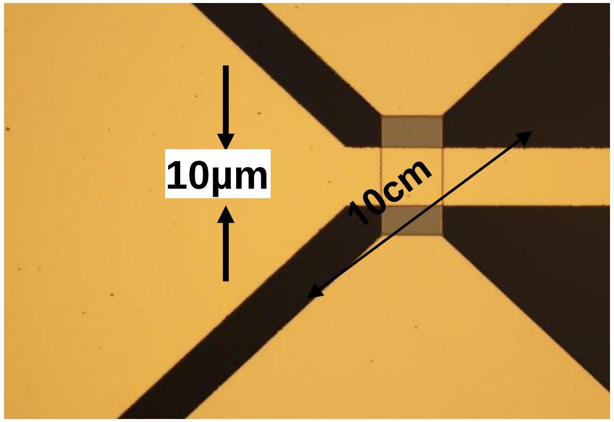
Critical parameters:

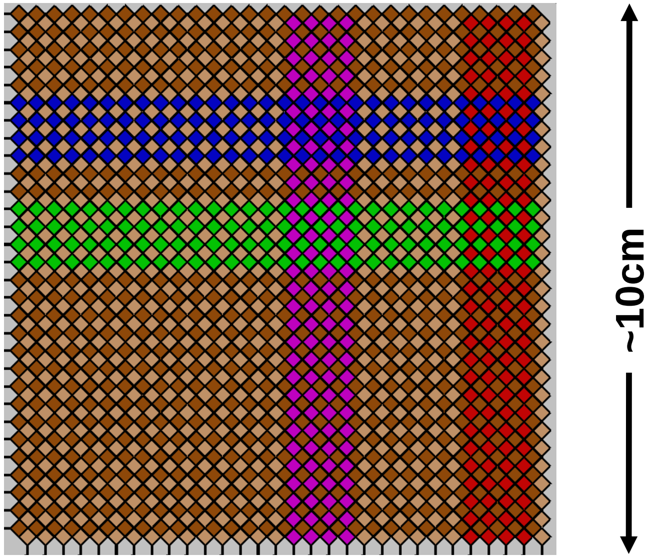
- **Pitch (TBD from 3mm to 6mm)**
- **Radioactivity**
- **Capacitance**
- **Readout from the rear**
- **Signal shape (no shielding grid)**



Charge-collection tiles

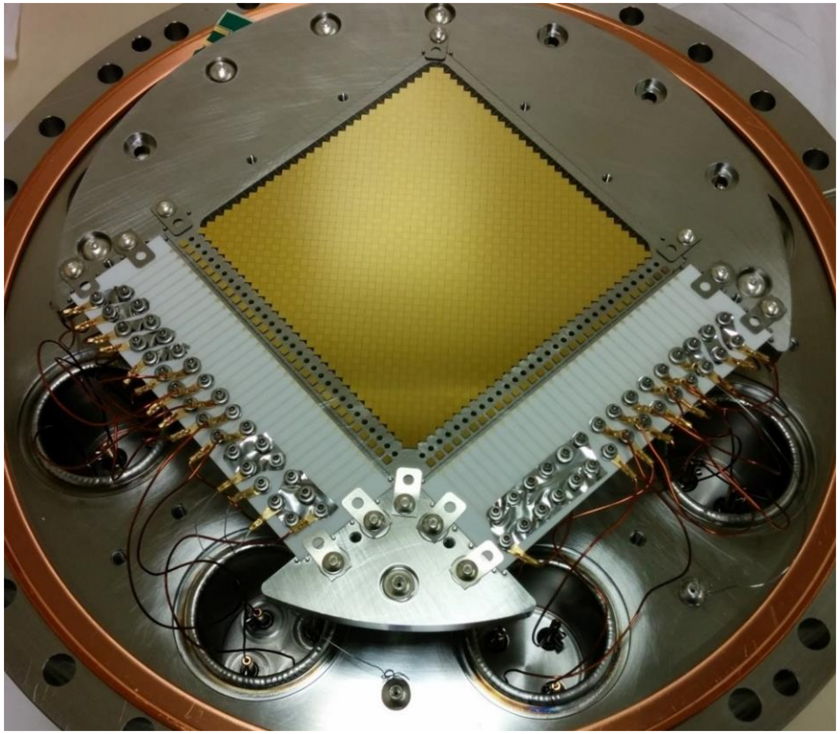
M.Jewell et al., "Characterization of an Ionization Readout Tile for nEXO", J.Inst. 13 (2018) P01006



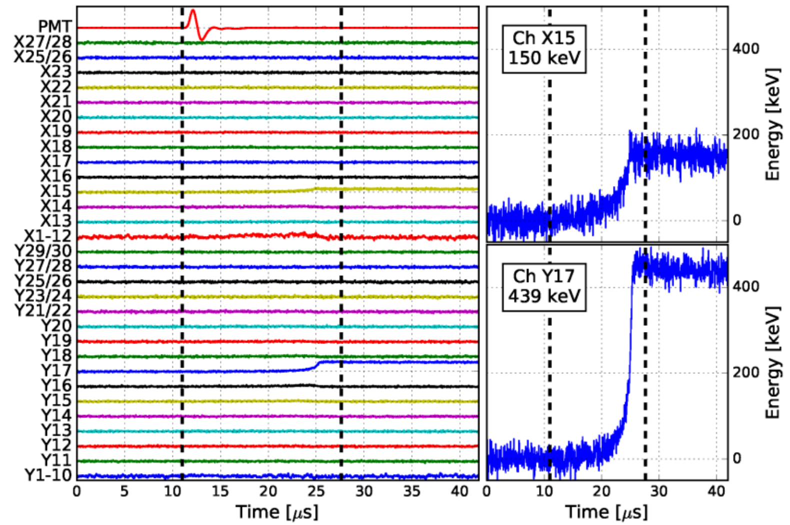


Max metallization cover with min capacitance:

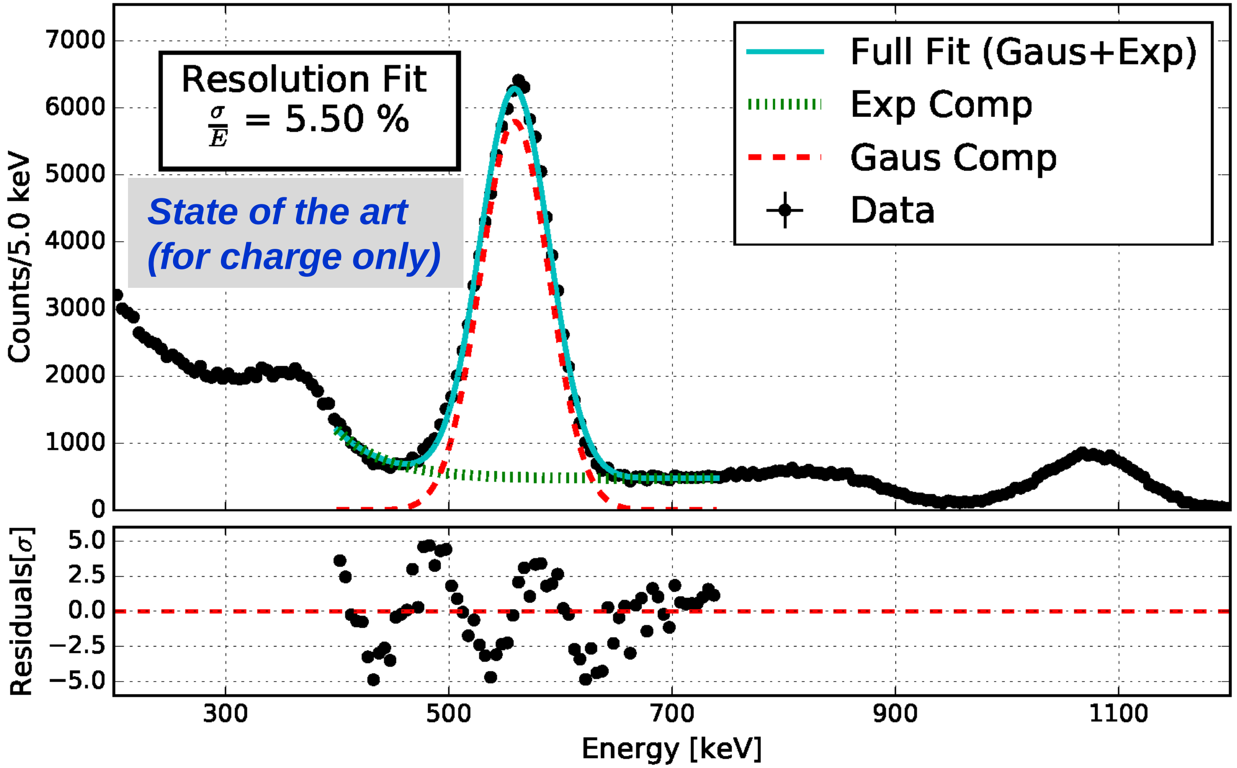
80 fF at crossings
0.86 pF between adjacent strips



Note that the signal shape is unisual because of the absence of Fritsch grid

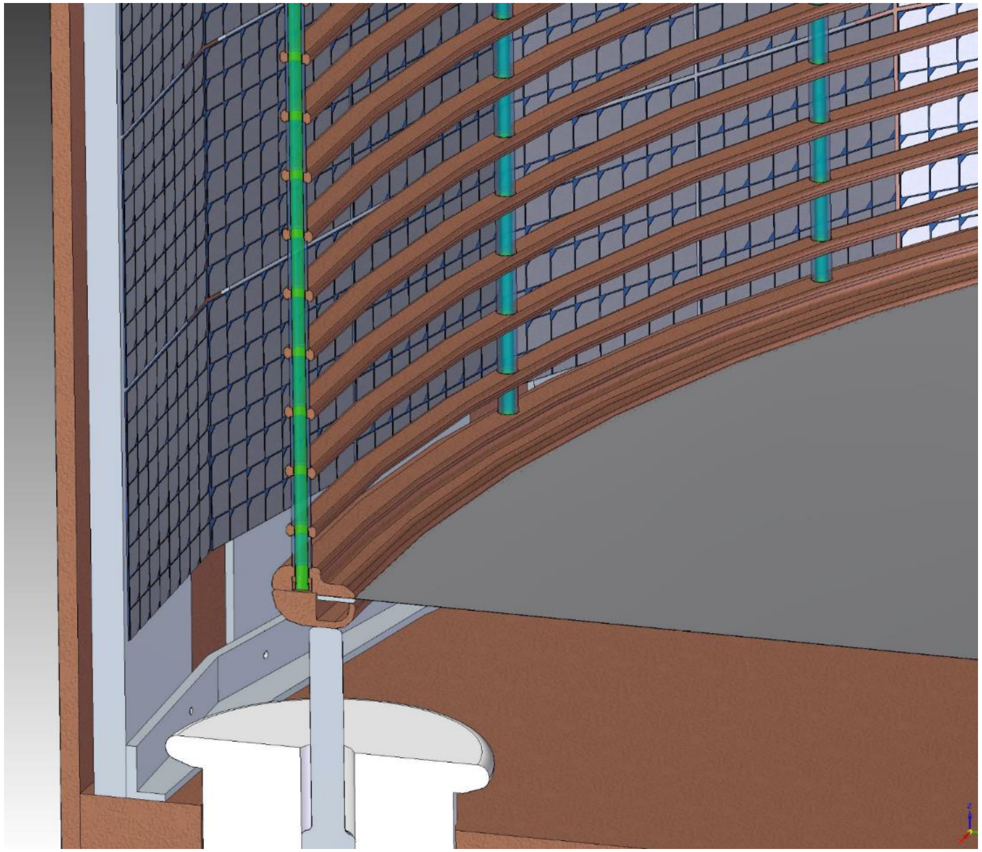


^{207}Bi, 570 keV, charge only

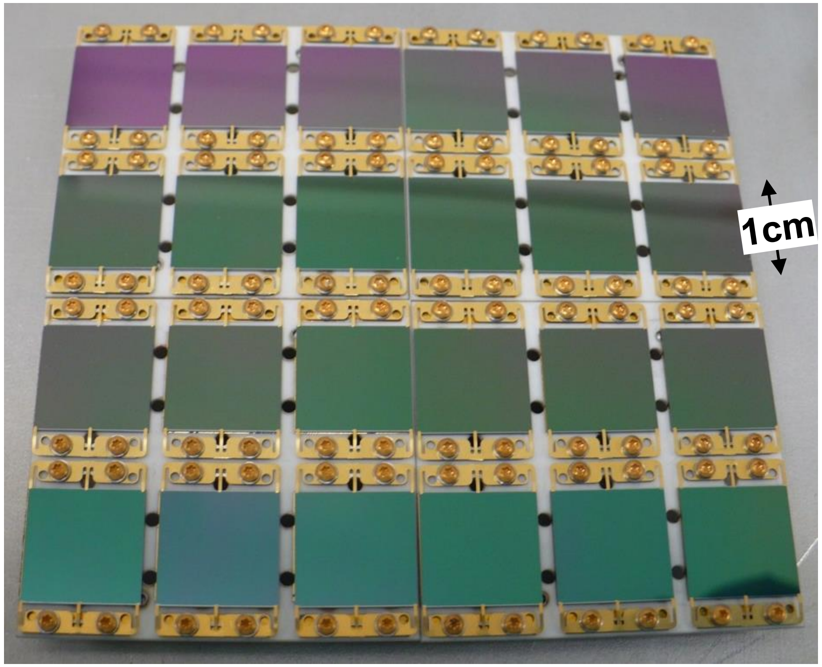


Photodetectors: 4.5m^2 of VUV-sensitive SiPMs

These are used as bare dies to minimize the radioactive contamination indide the detector.

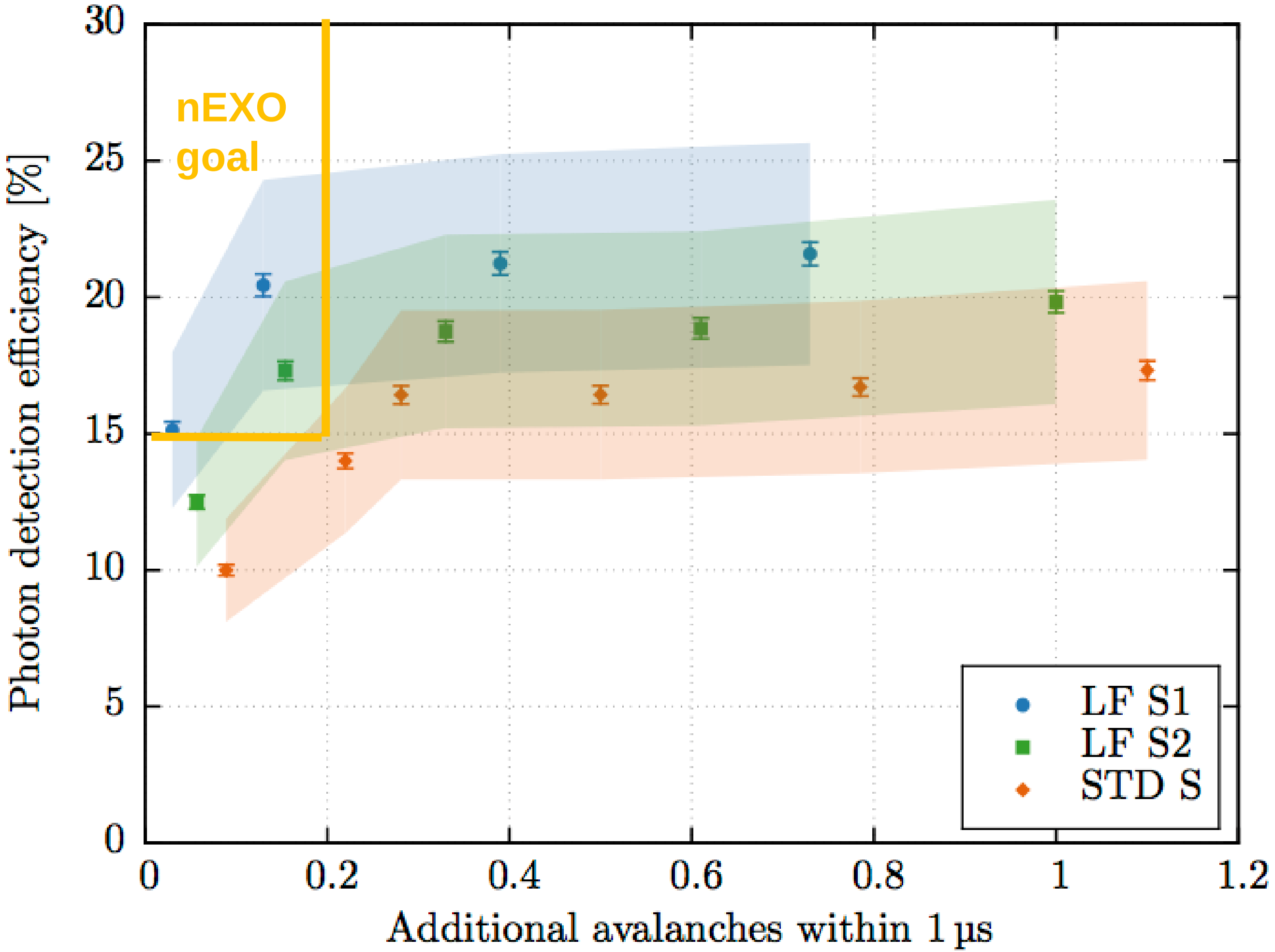


First sizeable arrays are now available (the dismountable hardware is temporary)



After the first round of R&D, some 1cm^2 VUV devices now match our desired properties, with a bias of ~30V

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



A.Jamil et al., IEEE Trans. NS 65 (2018) 2823

Radioactive contamination also well within requirements

nEXO sensitivity and discovery potential

J.B. Albert et al.,
"Sensitivity and Discovery Potential of nEXO to Neutrinoless Double Beta Decay",
Phys. Rev. C 97 (2018) 065503

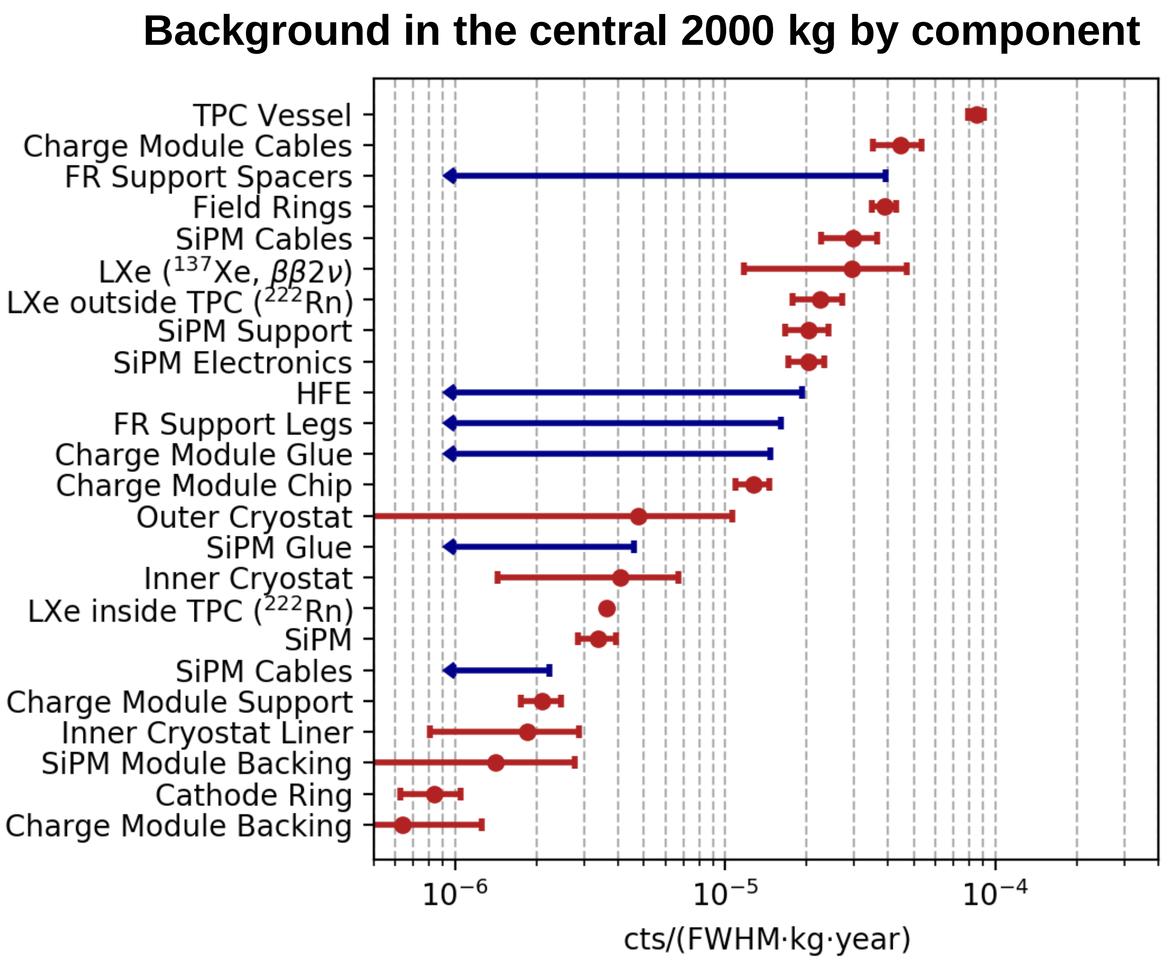
nEXO is unique among future experiments in that it does *not* require assuming new or better materials* in order to reach the design sensitivity

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)**

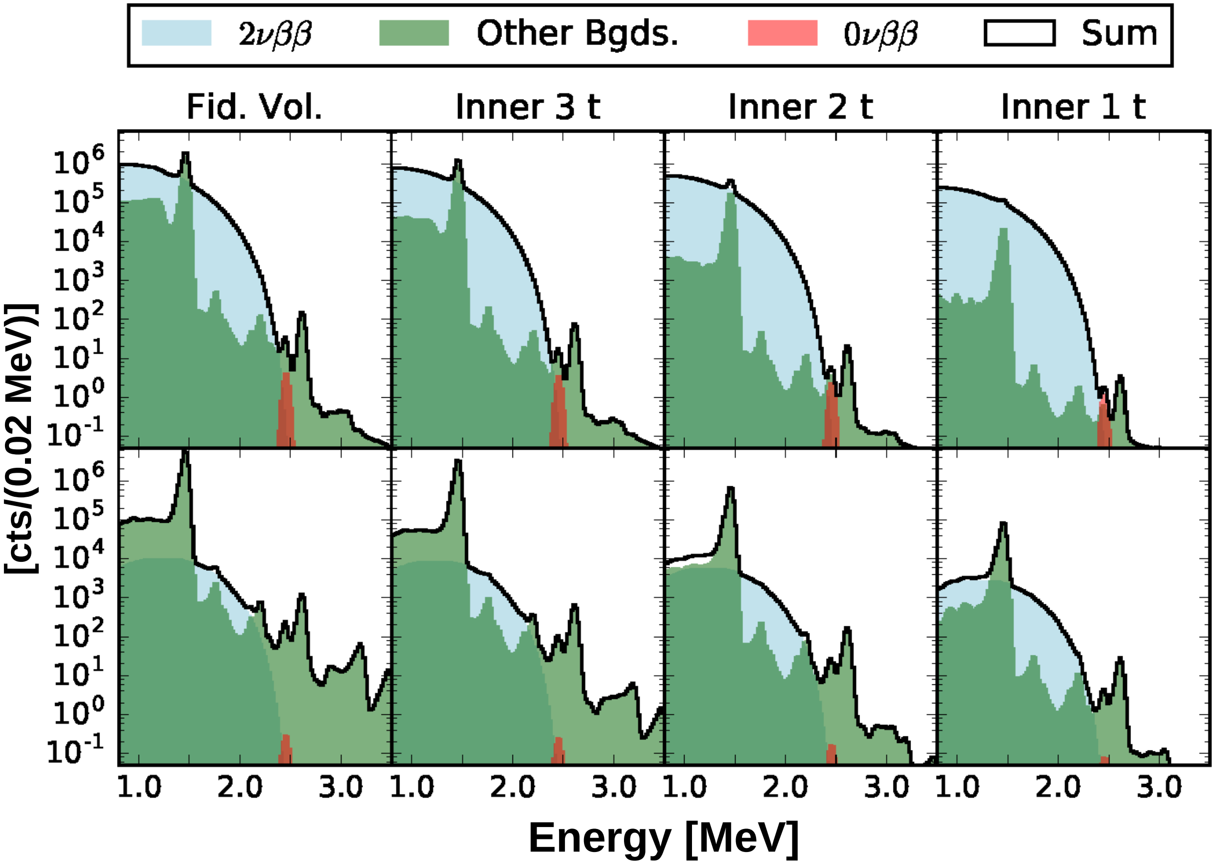
*** Except for the assumption that the electron lifetime will increase from ~3ms (EXO-200) to 10ms. This appears comfortable, having removed much of the plastics from the TPC.**

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 considering simultaneously energy, e-γ and α-β discrimination and event position.

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

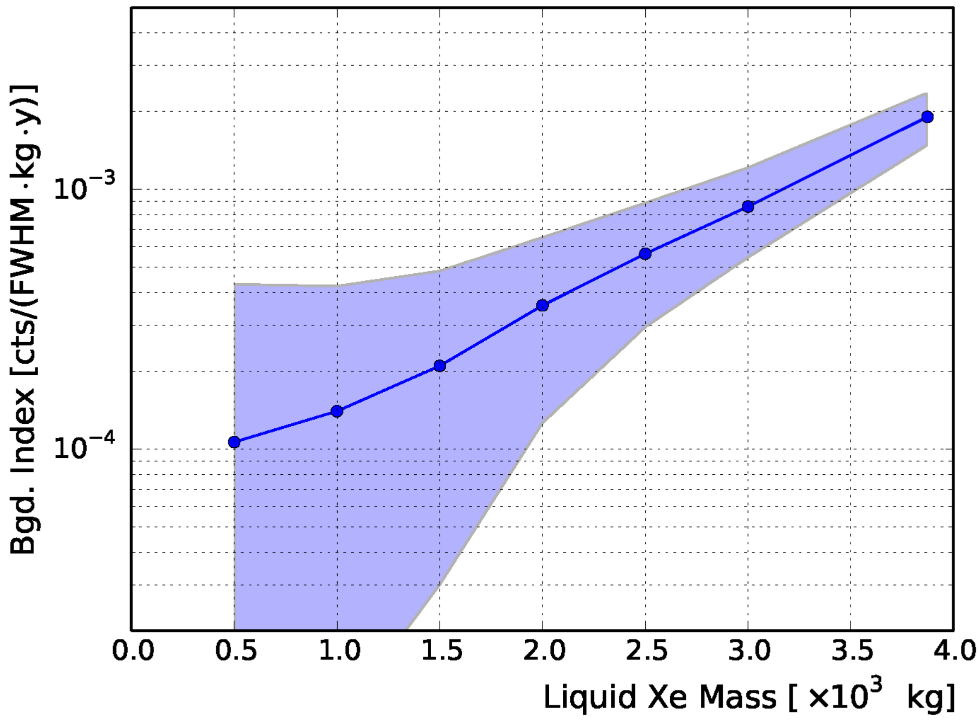


Corresponding to 10 yr data, with 0νββ $T^{1/2}=5.7\times10^{27}$ yr

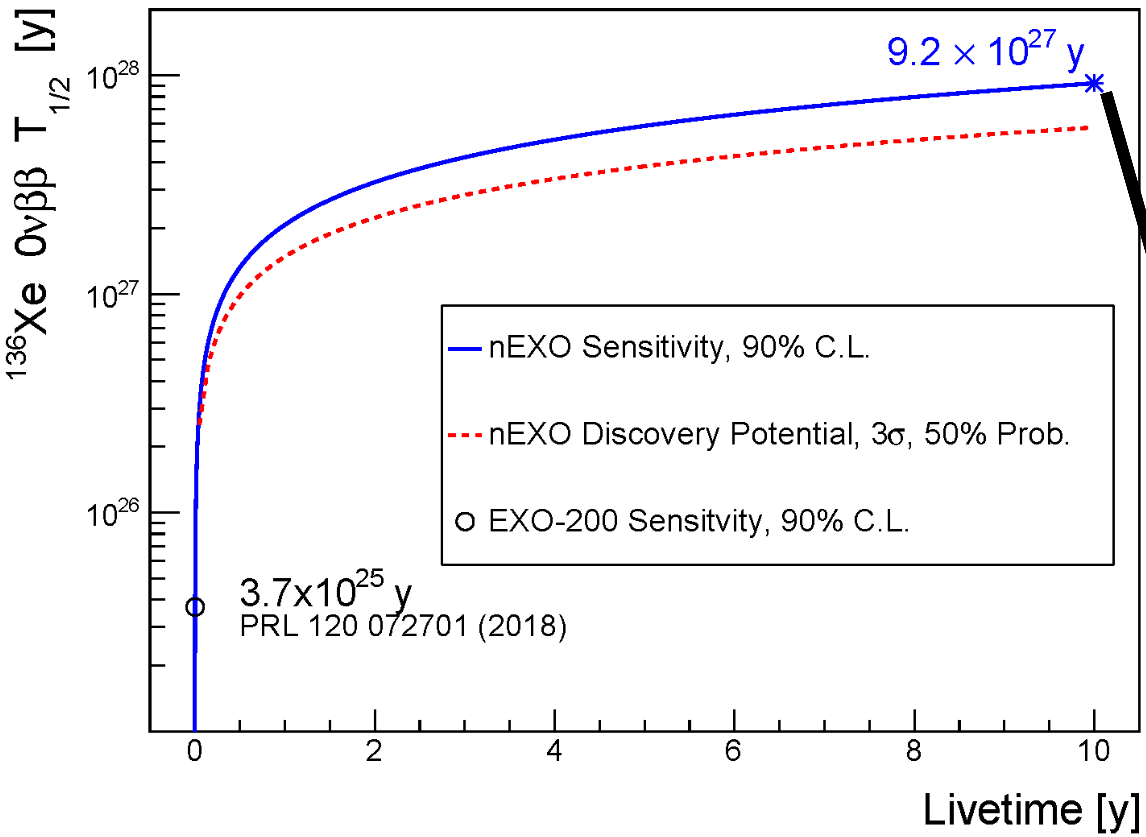
So, a simple “background index” is not the entire story.

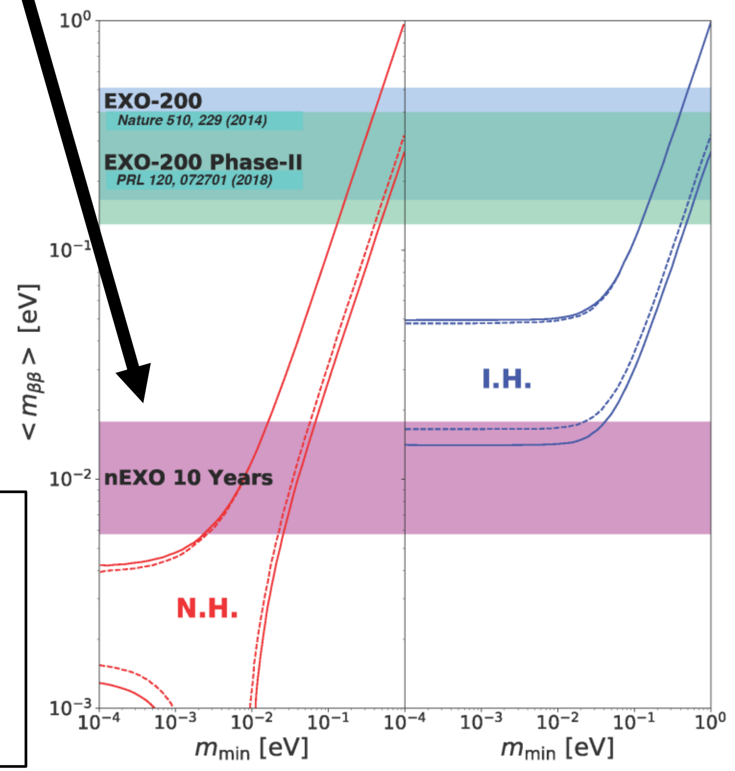
- *The innermost LXe mostly measures signal*
- *The outermost LXe mostly measures background*
- *The overall fit knows all this (and more) very well and uses all the information available to obtain the best sensitivity*

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} (kg yr FWHM)$^{-1}$



Sensitivity as a function of time for the baseline design

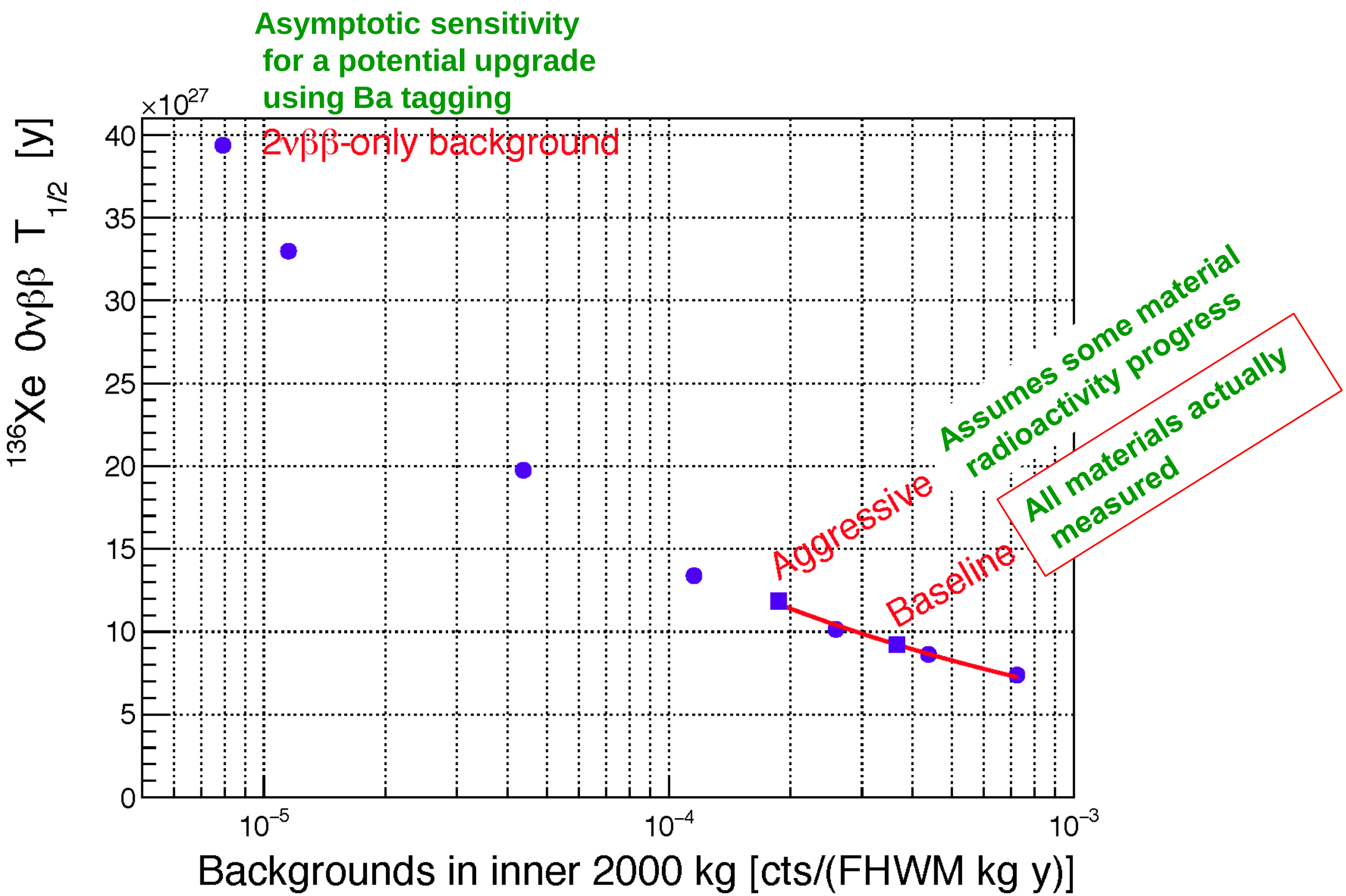




- $g_A = g_A^{free} = -1.2723$
- Band is the envelope of NME:

EDF: T.R. Rodríguez and G. Martínez-Pinedo, PRL 105, 252503 (2010)
ISM: J. Menendez et al., Nucl Phys A 818, 139 (2009)
IBM-2: J. Barea, J. Kotila, and F. Iachello, PRC 91, 034304 (2015)
QRPA: F. Šimkovic et al., PRC 87 045501 (2013)
SkyrmeQRPA: M.T. Mustonen and J. Engel PRC 87 064302 (2013)

How does the sensitivity scale with background assumptions?

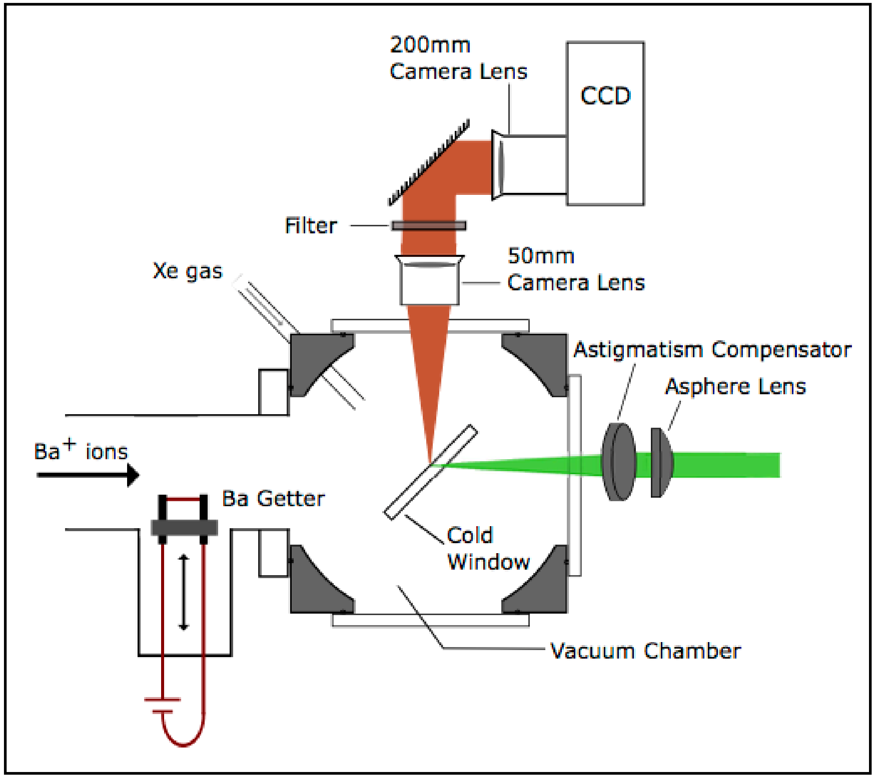


^{136}Xe presents the possibility to confirm a ββ decay even by retrieving and tagging spectroscopically the Ba atom in the final state.

This is not necessary for nEXO to reach its design sensitivity and, indeed, is not part of the design presented in the CDR.

Should be seen as a possible path for a future upgrade.

The R&D in this area has two stages:
- Demonstrate the physical principles → Done
- Demonstrate a plausible engineering solution



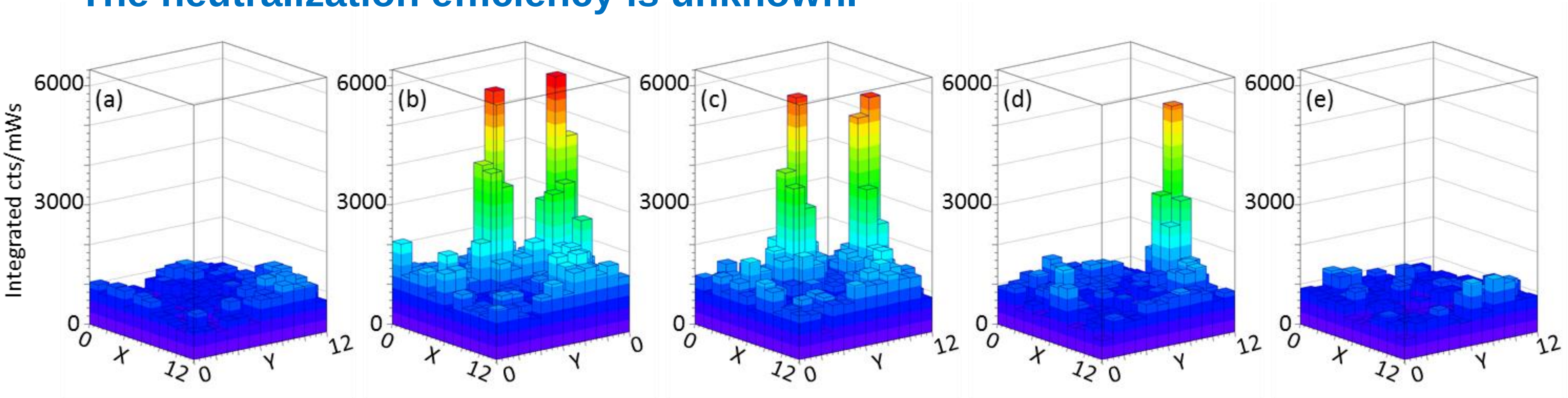
- Embed the Ba atom in a frozen Xe layer (other materials are always to dirty for the purpose)
- Image the individual atoms using fluorescence

This process if tricky to do, in part because it is hard to reliably produce single atoms.

Of course this will not be an issue in a real experiment, where the system will be exercised using the abundant 2νββ decay

Finally the physics of this appears to work well:

Deposit a few Ba atoms and repeatedly raster scan the substrate with the laser.
Note that Ba^+ is deposited but the detection is Ba.
The neutralization efficiency is unknown.



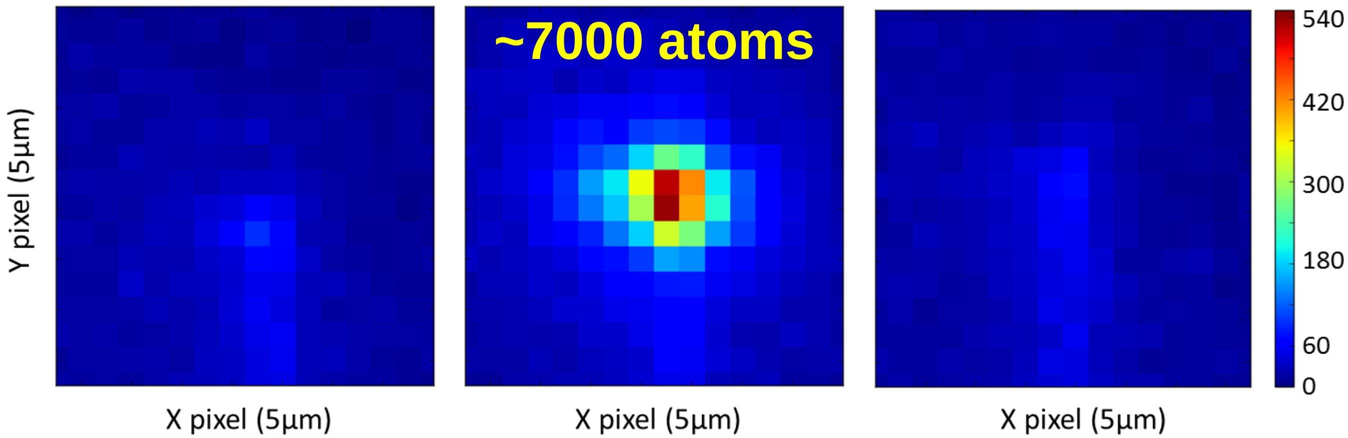
Before Ba deposition	Two atoms at different sites	Raster again Still there	Insist, one atom is gone	Eventually back to nothing

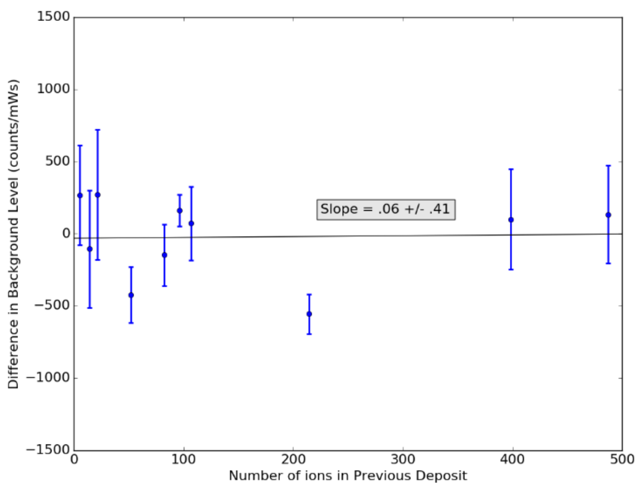
Note low background!

Note quantization!

C.Chambers et al., arXiv:1806.10694 (Jun 2018)

Full signal erasure, after burning off and reforming the solid Xe substrate





The quality of the erasure is independent on the amount of Ba (remember that 1 atom is ~6000 cts/mWs)

C.Chambers et al., arXiv:1806.10694 (Jun 2018)

Of course, this is just a “scientific” demonstration. Plenty of engineering will be required to turn this result into a practical upgrade path for nEXO.

Conclusions

- **EXO-200 was the first 100kg-class experiment to run and demonstrated the power of a large and homogeneous LXe TPC.**
- **This is clearly the way to go for tonne-scale detectors, as the power of the technique will further improve with increasing size.**
- **nEXO is becoming the flagship experiment in North America and is rapidly proceeding towards a construction project.**
- **The baseline 5-ton detector will drastically advance the field, entirely covering the inverted hierarchy and with substantial sensitivity to the normal one.**
- **New and exciting results from the Ba tagging effort (not part of the nEXO baseline) suggest that there may be a path for a future upgrade beyond nEXO.**
- **The collaboration is eager to grow, particularly in Europe, where we have a relatively modest footprint.**

nEXO

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