Neutrinoless double beta decay search with EXO

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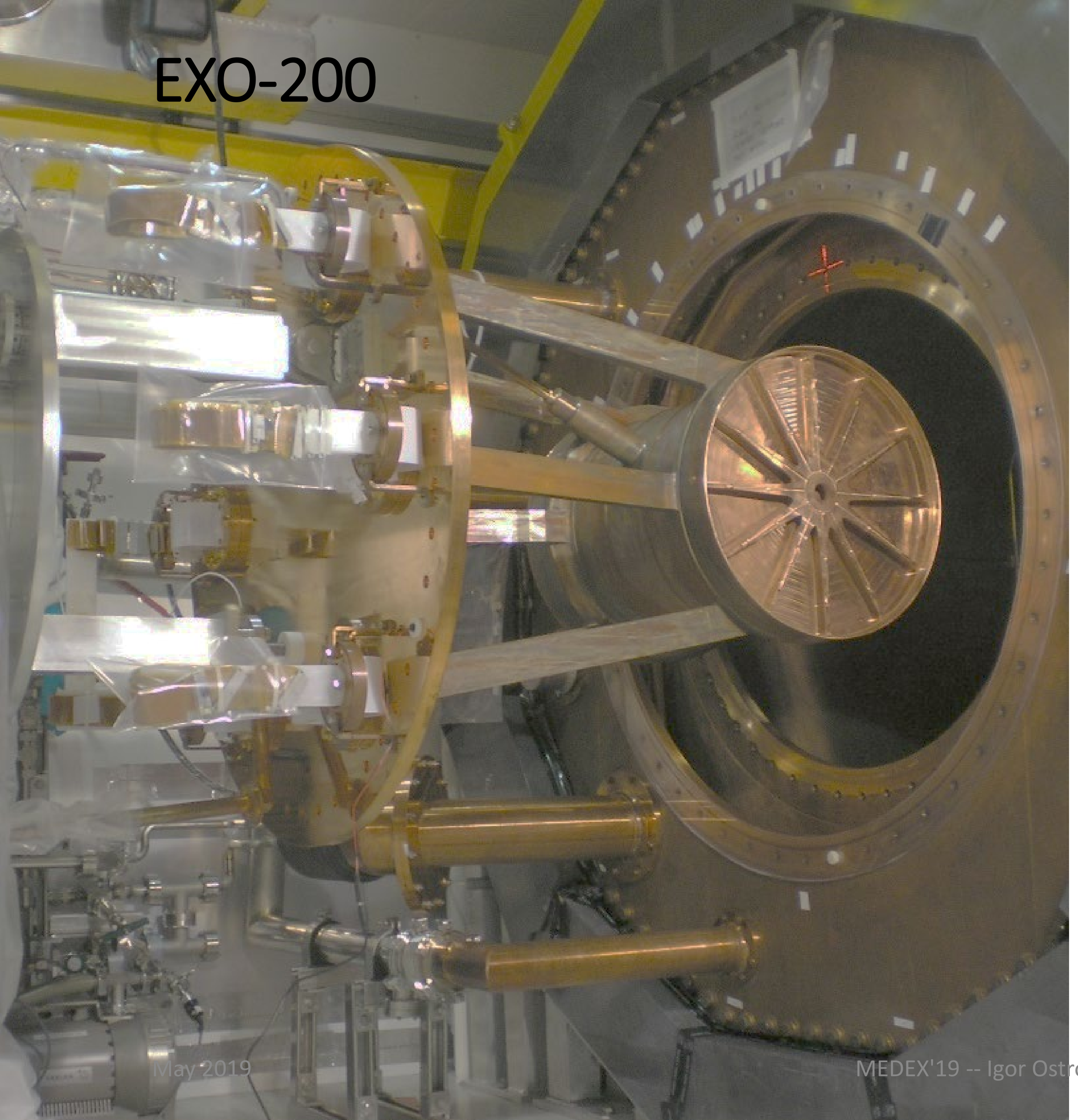
Introduction

- EXO-200
  - Results so far
  - End of Phase-II
  - New analysis approaches

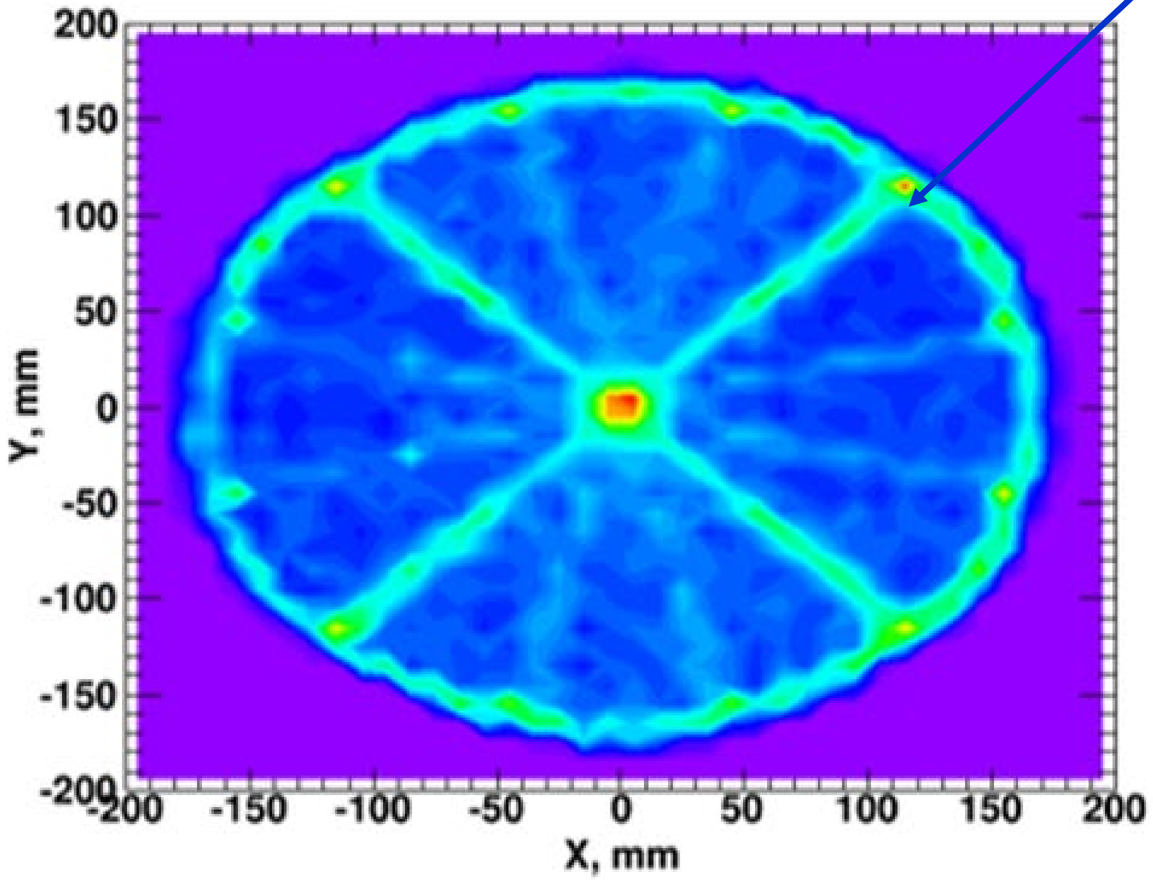
- nEXO
  - Bigger, cleaner
  - Sensitivity projections

EXO-200

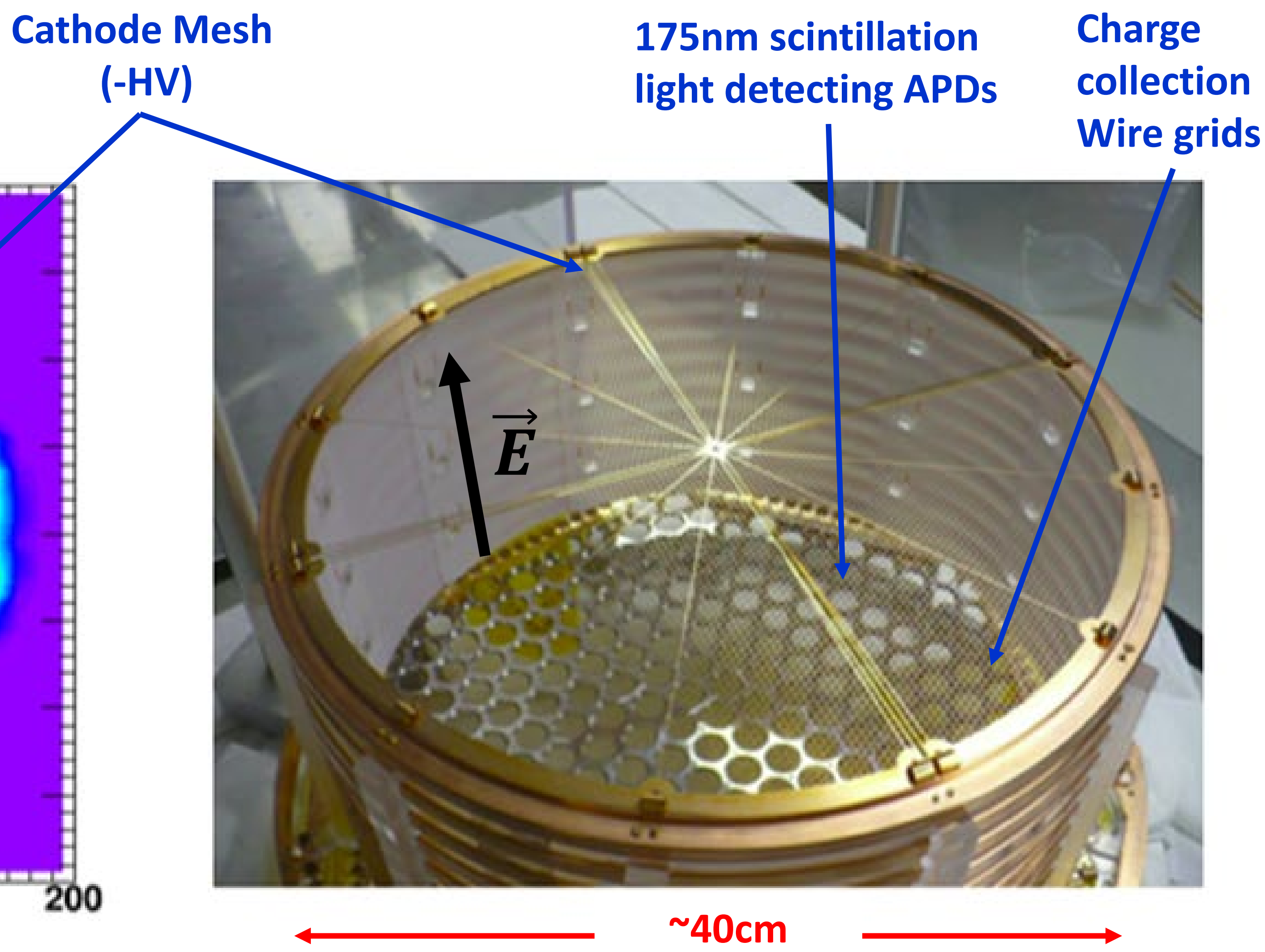


- Main goal is to search for neutrinoless double beta decay of ^{136}Xe
- ~200 kg of Xe enriched to 80.6% in ^{136}Xe
  - ~175 kg of liquid ^{enr}Xe inside a single-phase cylindrical Time Projection Chamber
  - ~90 kg current fiducial mass
- Located at 1585 m.w.e. in the Waste Isolation Plant near Carlsbad, NM
- Carefully selected radioactively clean materials, rigorous cleaning procedures

EXO-200

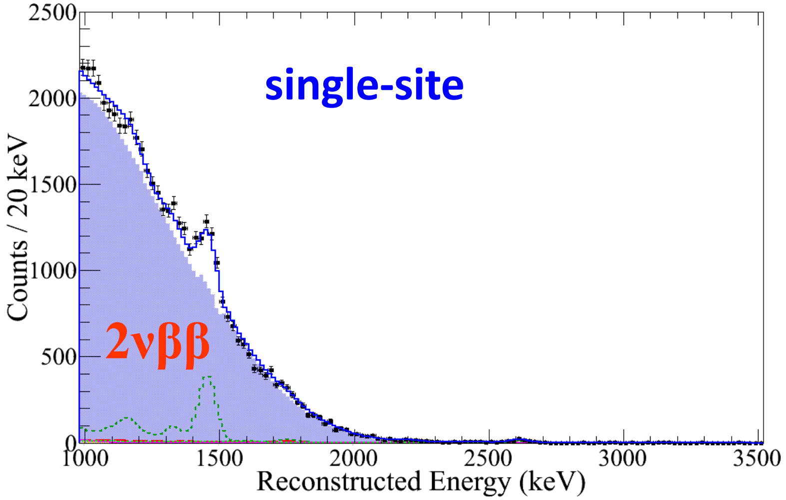


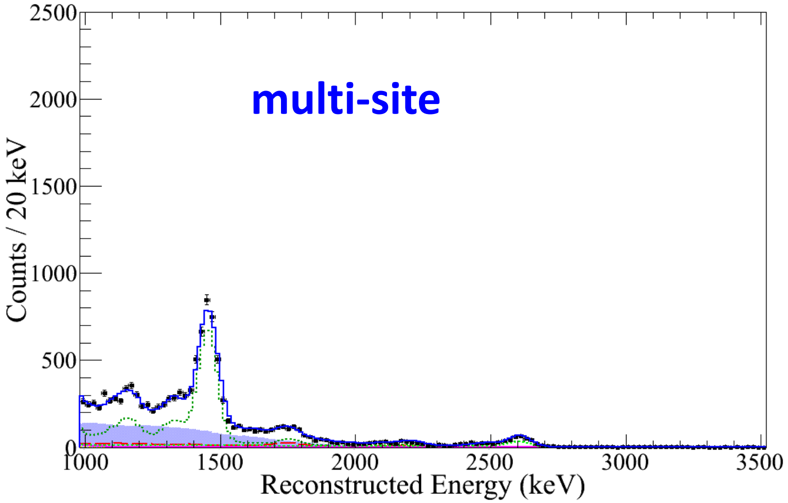
Negatively biased cathode attracts Radon decay daughters, which stick to it and decay further. Reconstructing the X,Y positions of such decays in EXO-200 reveals many features of the cathode mesh



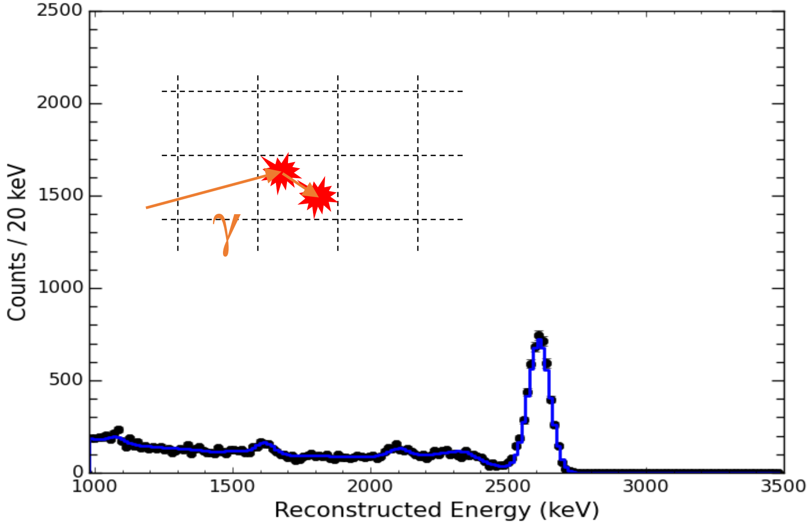
Event multiplicity

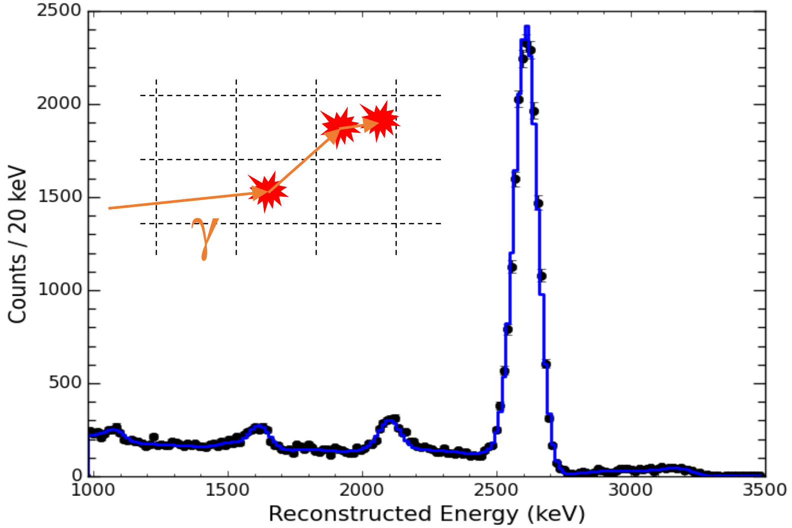
Low background data



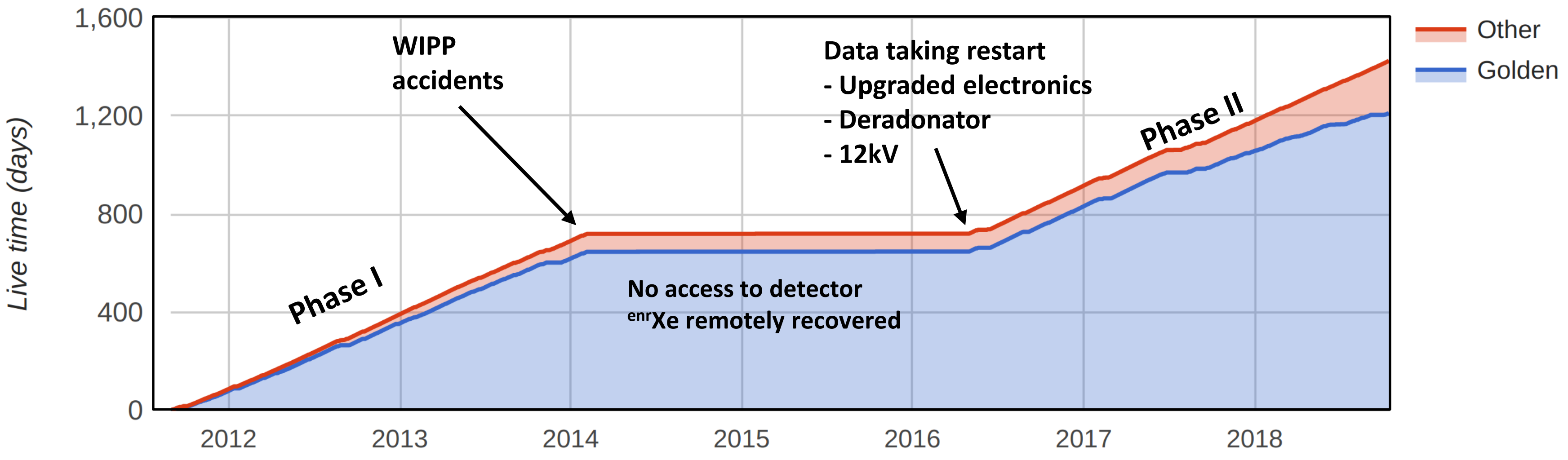


^{228}Th calibration source

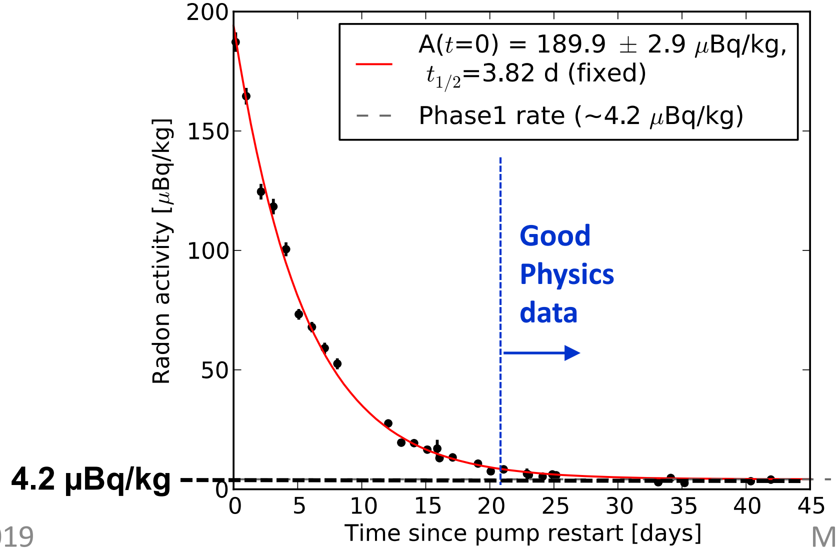




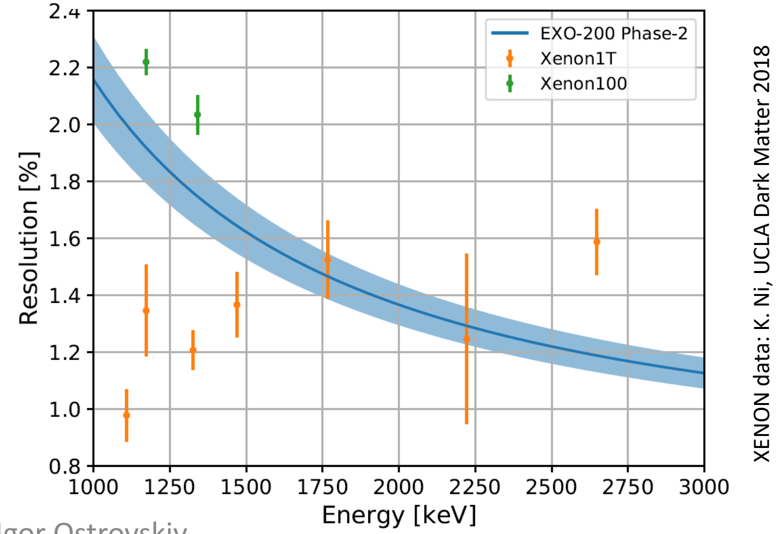
The experiment ended in 12/18, with ~3 ys of golden data on disk



Rn in LXe after restart

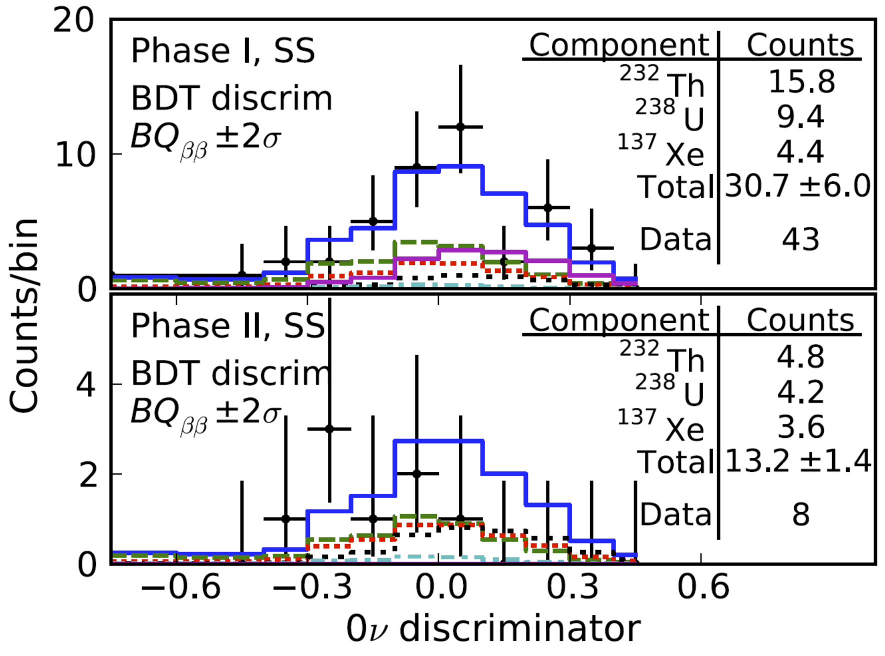


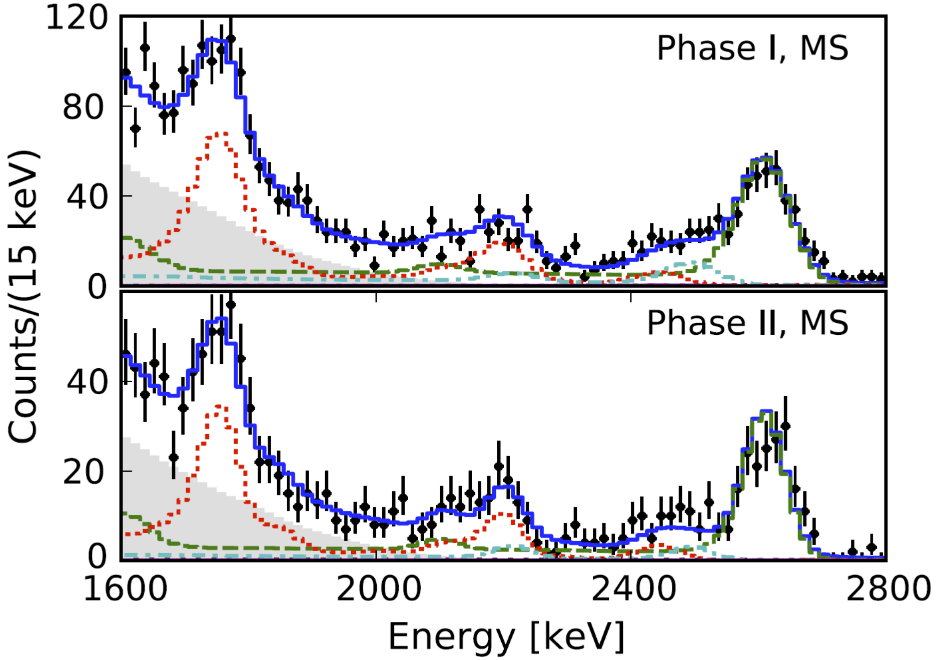
Singlesite energy resolution



Last published result (~3/4 of full data)

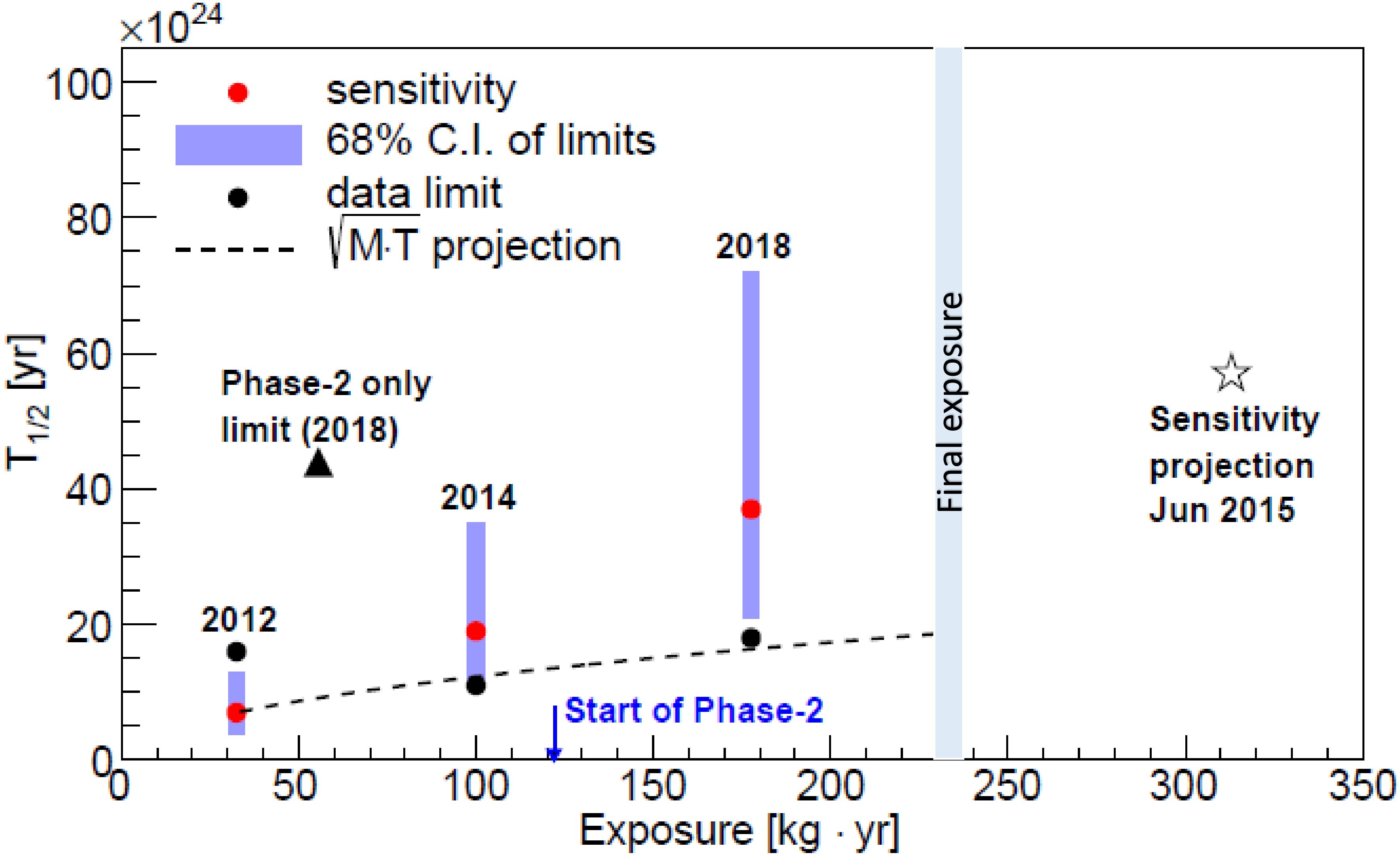
- Combined Dataset Before and After Shutdown/Upgrades
  - Total exposure of 177.6 kg·yr ^{136}Xe
- No statistically significant 0νββ signal
  - **$T_{1/2}$ > 1.8 · 10^{25} yr , 90% C.L.**
  - <$m_{\beta\beta}$> < (147- 398) meV, assuming no g_A quenching
  - **Median sensitivity 3.7 · 10^{25} yr**
  - Background index 1.5±0.2 · 10^{-3} / (kg·yr·keV), normalized to ^{enr}Xe mass





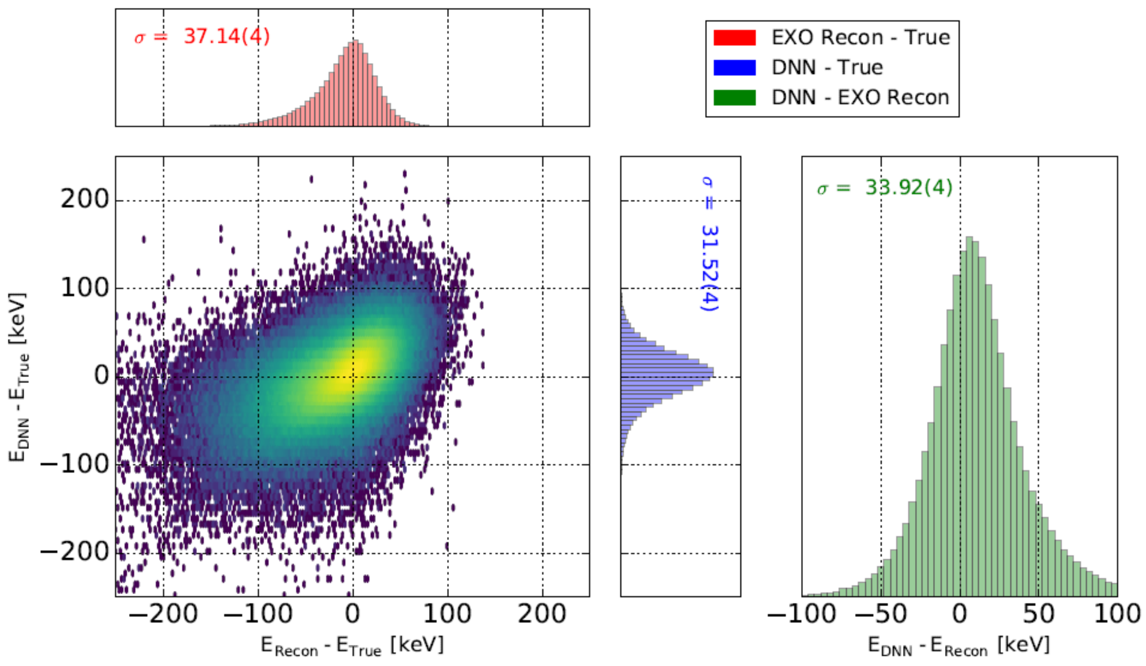
10.1103/PhysRevLett.120.072701

Summary of previous 0ν results and sensitivity projection



Legacy

- EXO-200's final 0νββ result is upcoming
- EXO-200 was one of the leading 0ν experiments of this generation (few 10s to few 100s kg)
- Its dataset will remain to be useful for some time, in particular as a testbed of new analysis approaches



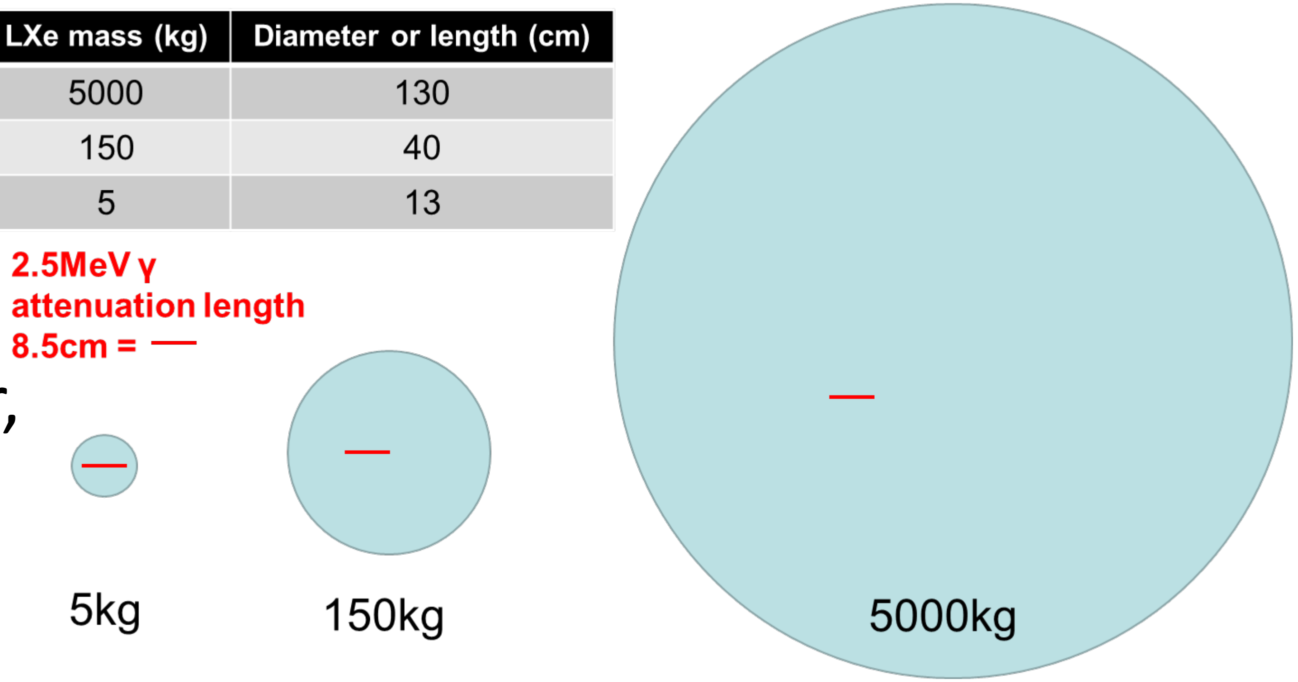
Residuals of the energy from the conventional reconstruction, E_{Recon}, and from the neural network, E_{DNN}, with respect to the true MC energy E_{True}

From "Deep neural networks for energy and position reconstruction in EXO-200", http://dx.doi.org/10.1088/1748-0221/13/08/P08023

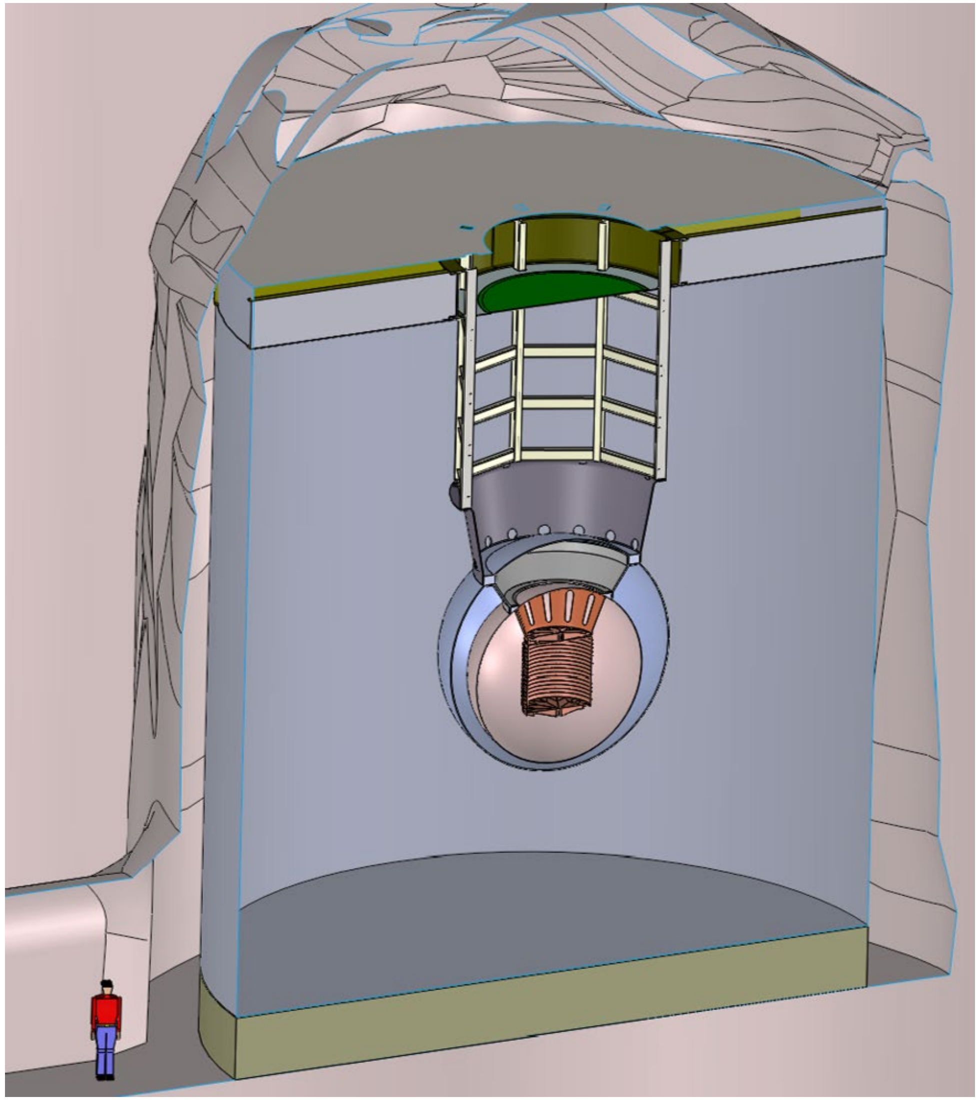
Future

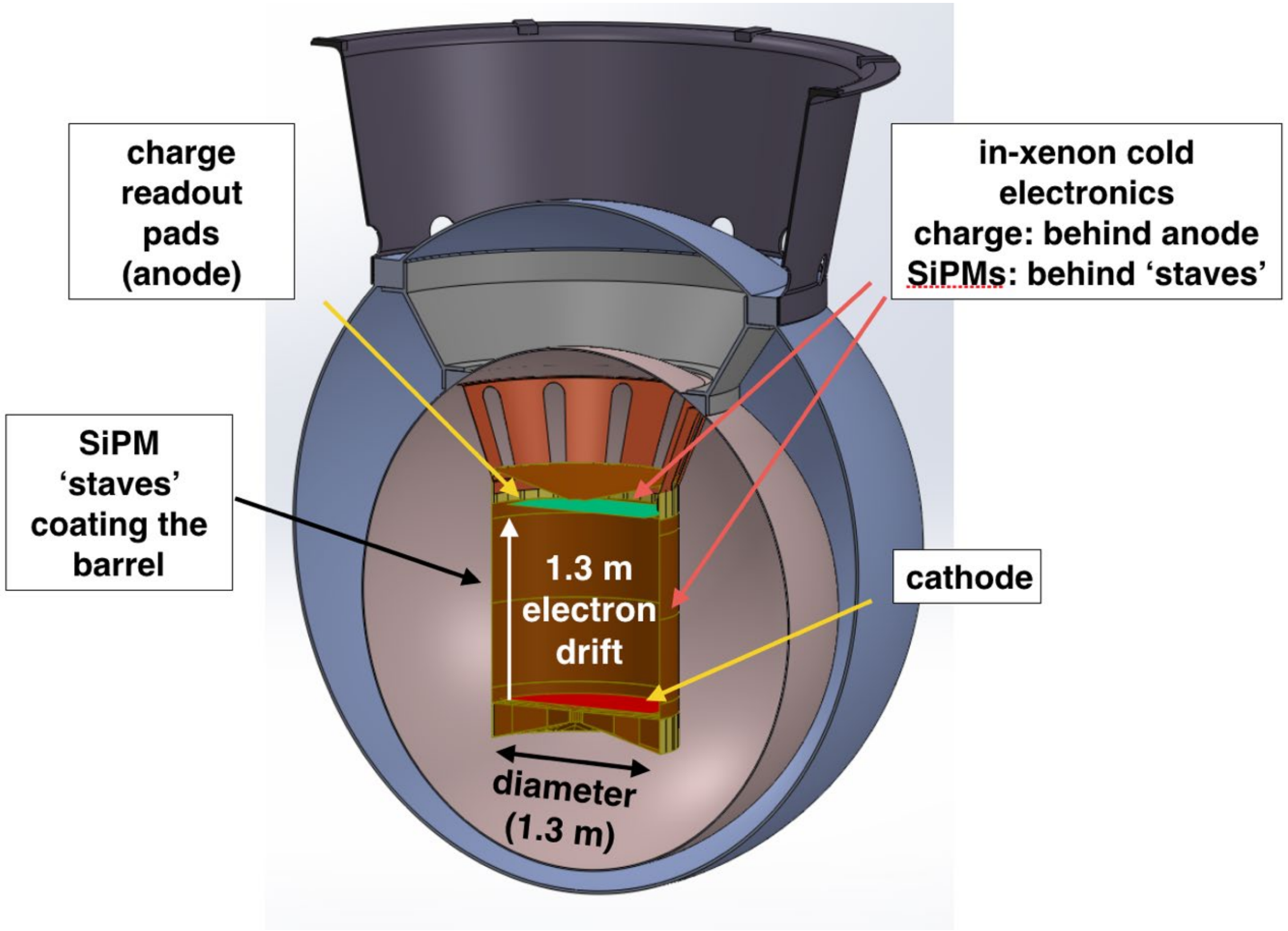
- Search for $0\nu\beta\beta$ of ^{136}Xe using a single-phase LXe TPC may not have the best energy resolution or γ/β discrimination
- But scaling to large mass is easier, and with it comes better self-shielding
- nEXO plans to use 5 tons of ^{enr}Xe

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



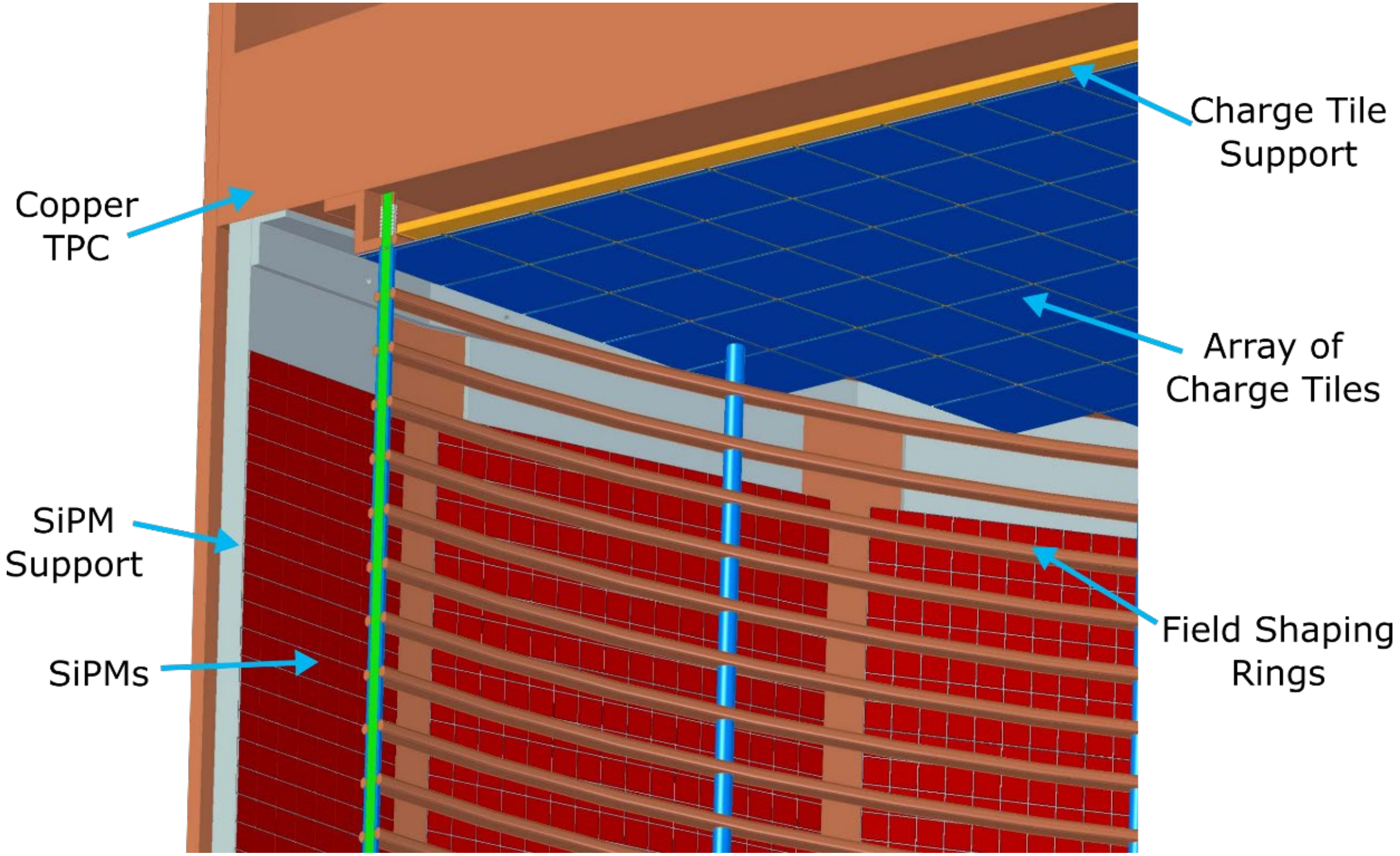
nEXO conceptual design





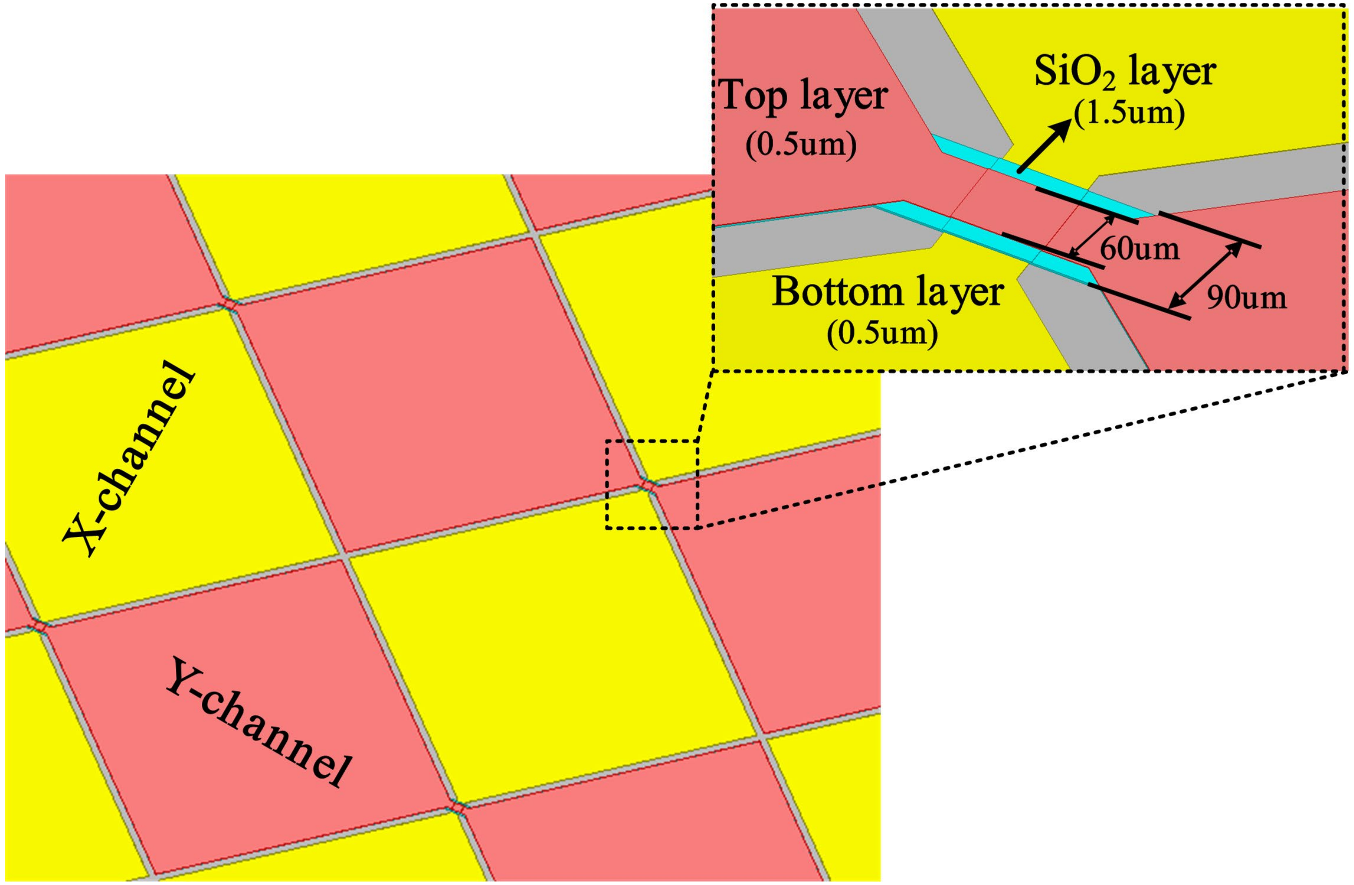
nEXO plans for SiPMs, instead of APDs; expects better E resolution

- APD noise limits resolution in EXO-200
- nEXO plans to use SiPMs
  - Directly VUV sensitive
  - Low mass, low radioactivity
  - 4.5 m^2 area covered

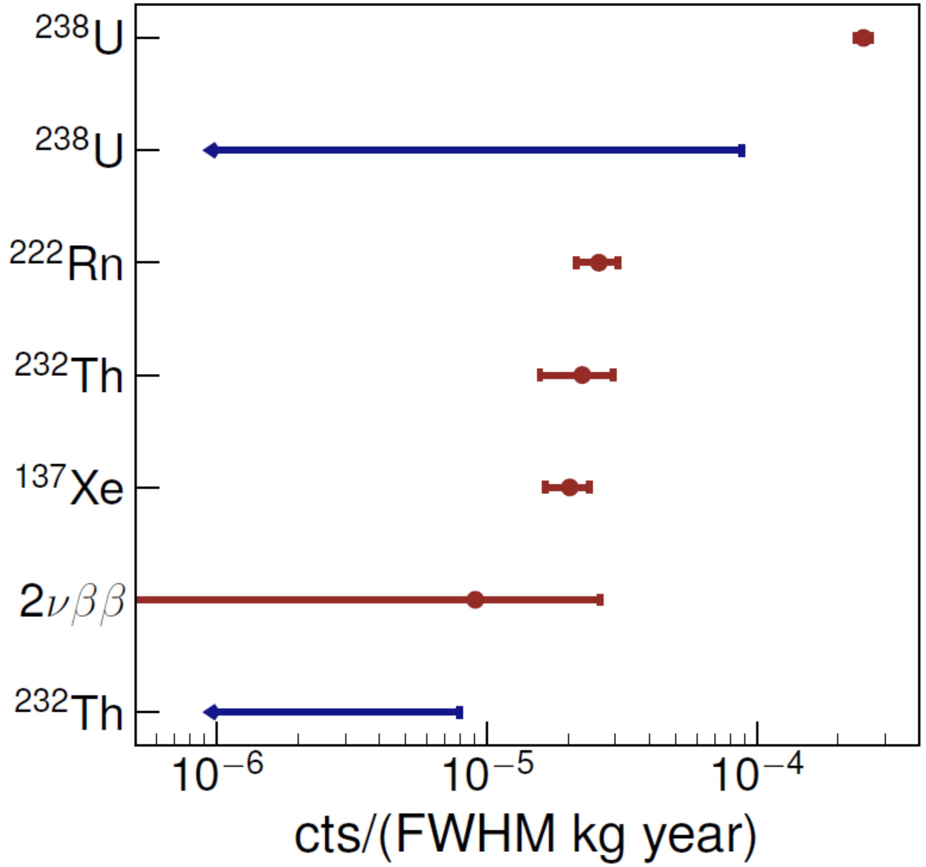


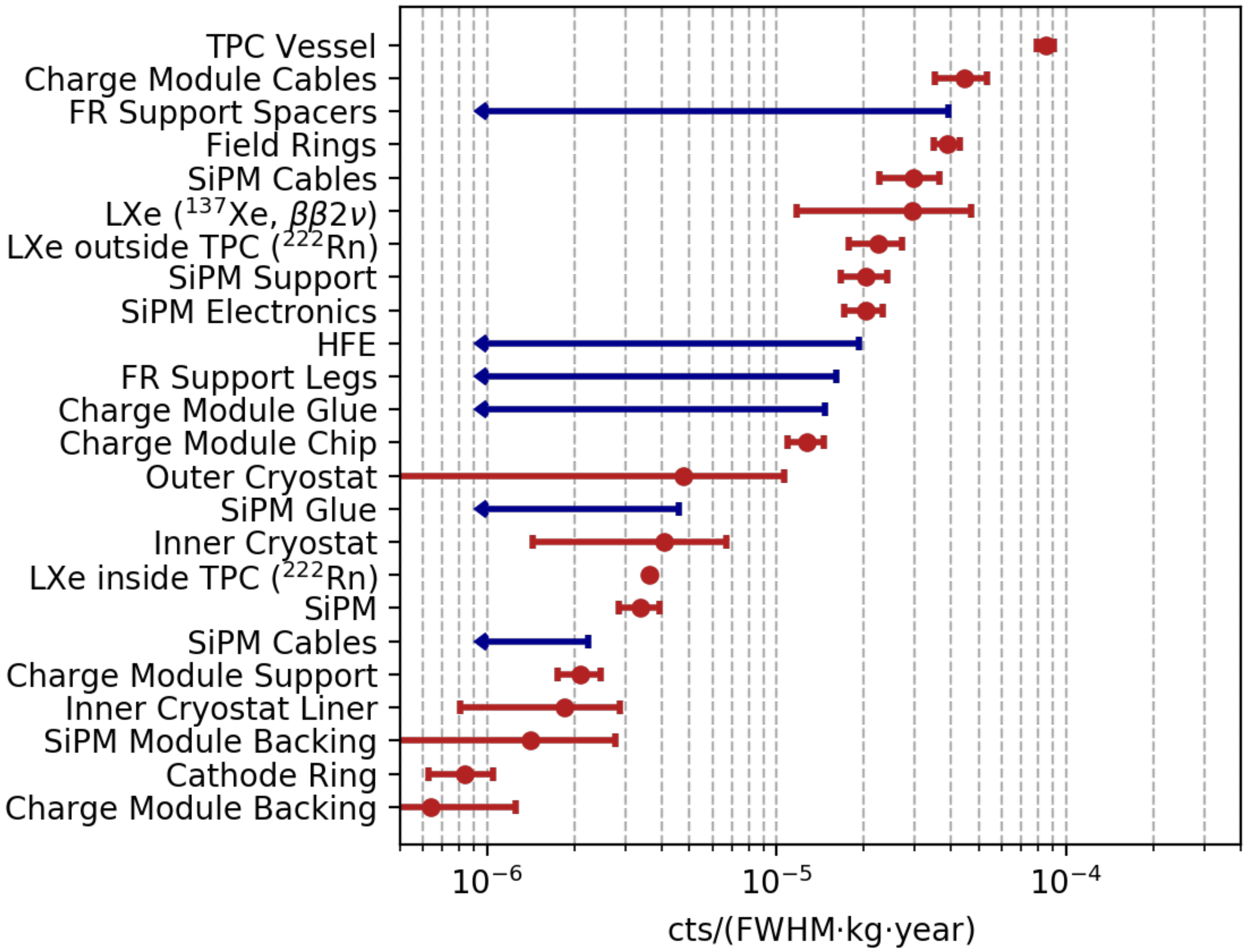
nEXO plans for charge readout tiles, instead of wires

- Tiles are modular, which makes them more reliable than long tensioned wires in a big detector
- Quartz (or sapphire) substrate with eventual built-in readout from the back
- γ/β topology discrimination is expected to be better than in EXO-200, due to finer "pitch" (3-6 mm, TBD)
  - But no Frisch grid, so need to be careful with signal reconstruction



Projected Backgrounds in nEXO, inner 2 tons

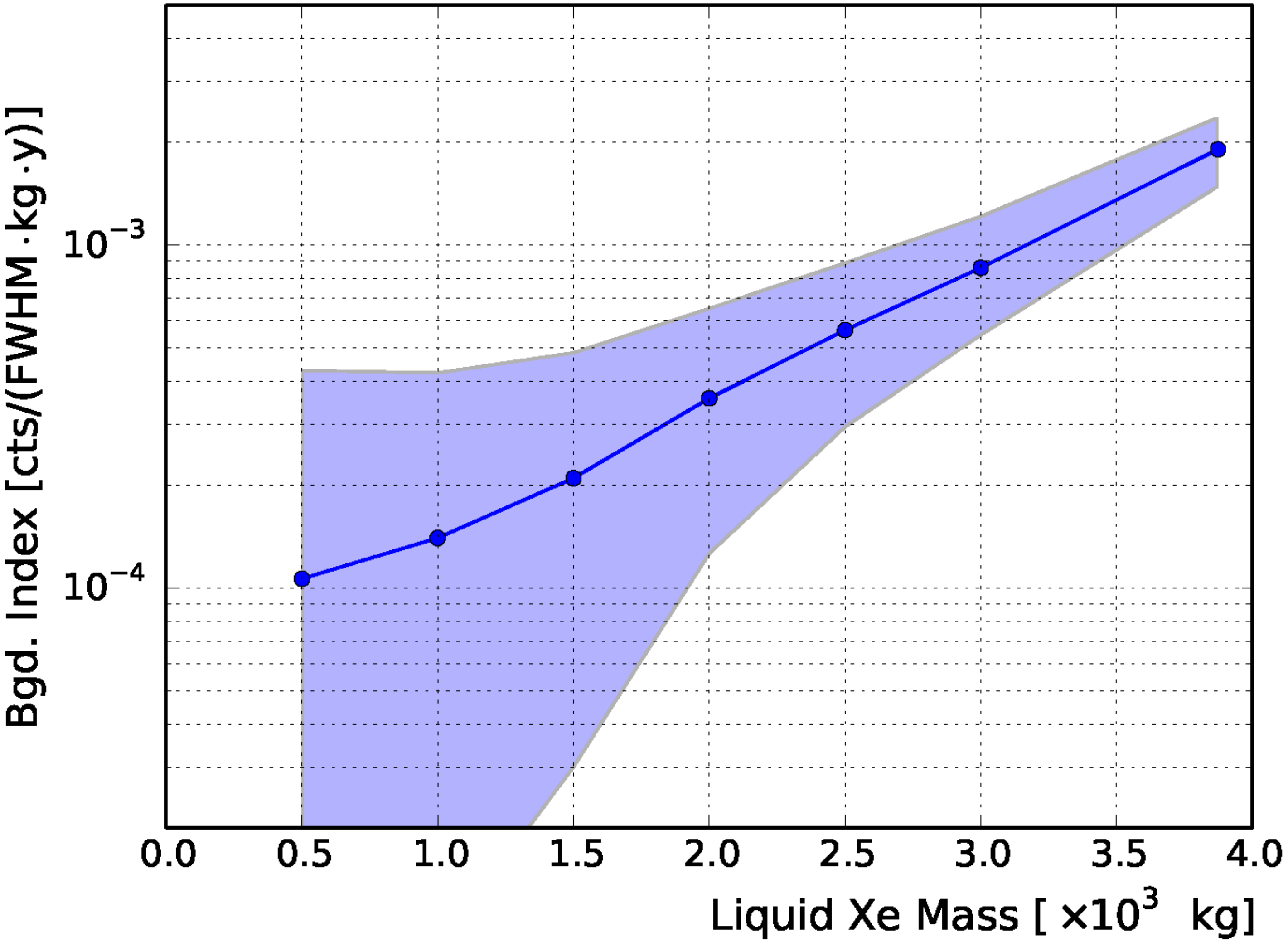




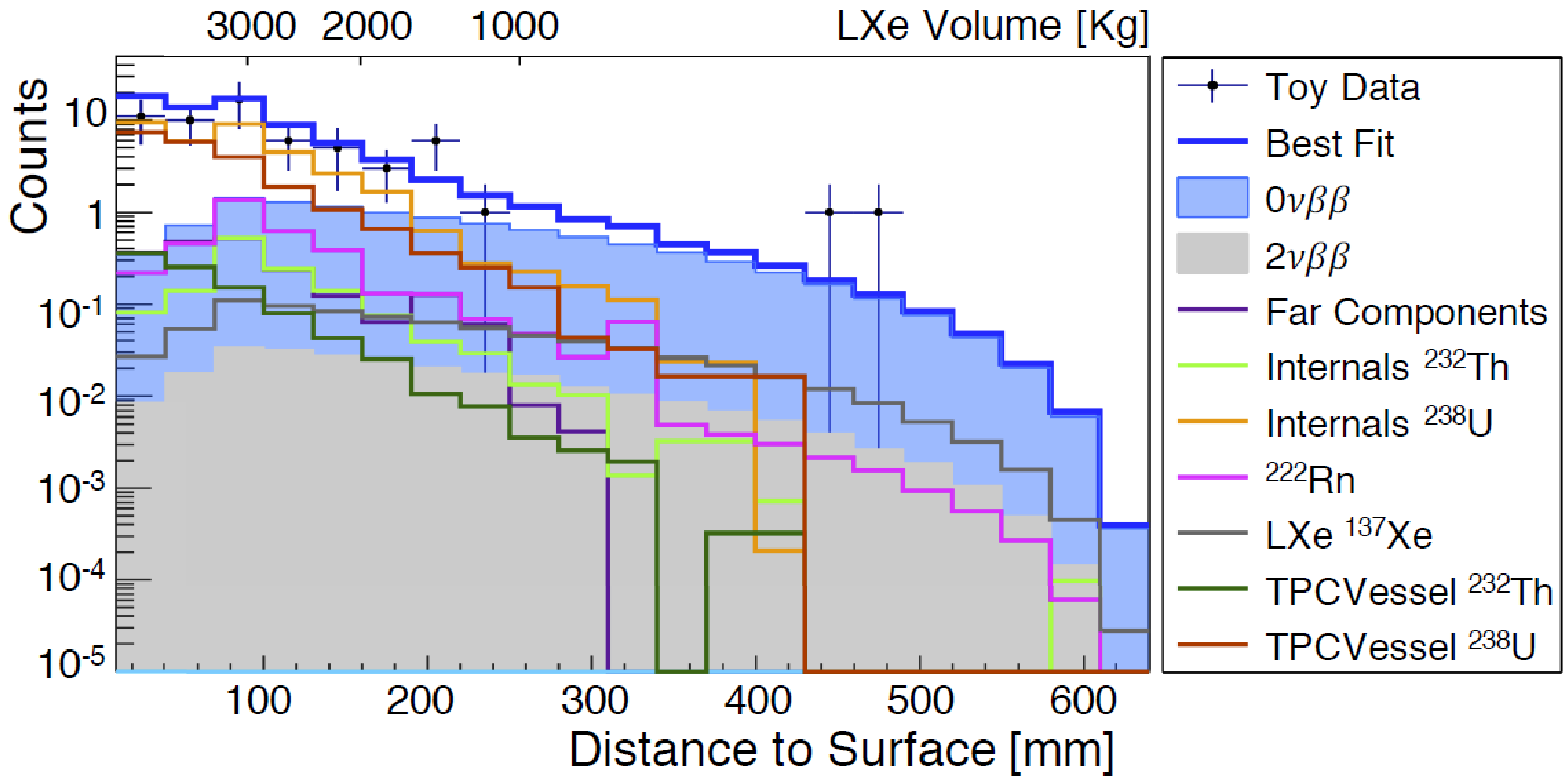
By nuclide

By component

Projected Background Index in nEXO, as a function of fiducial mass



Using event location to constrain backgrounds

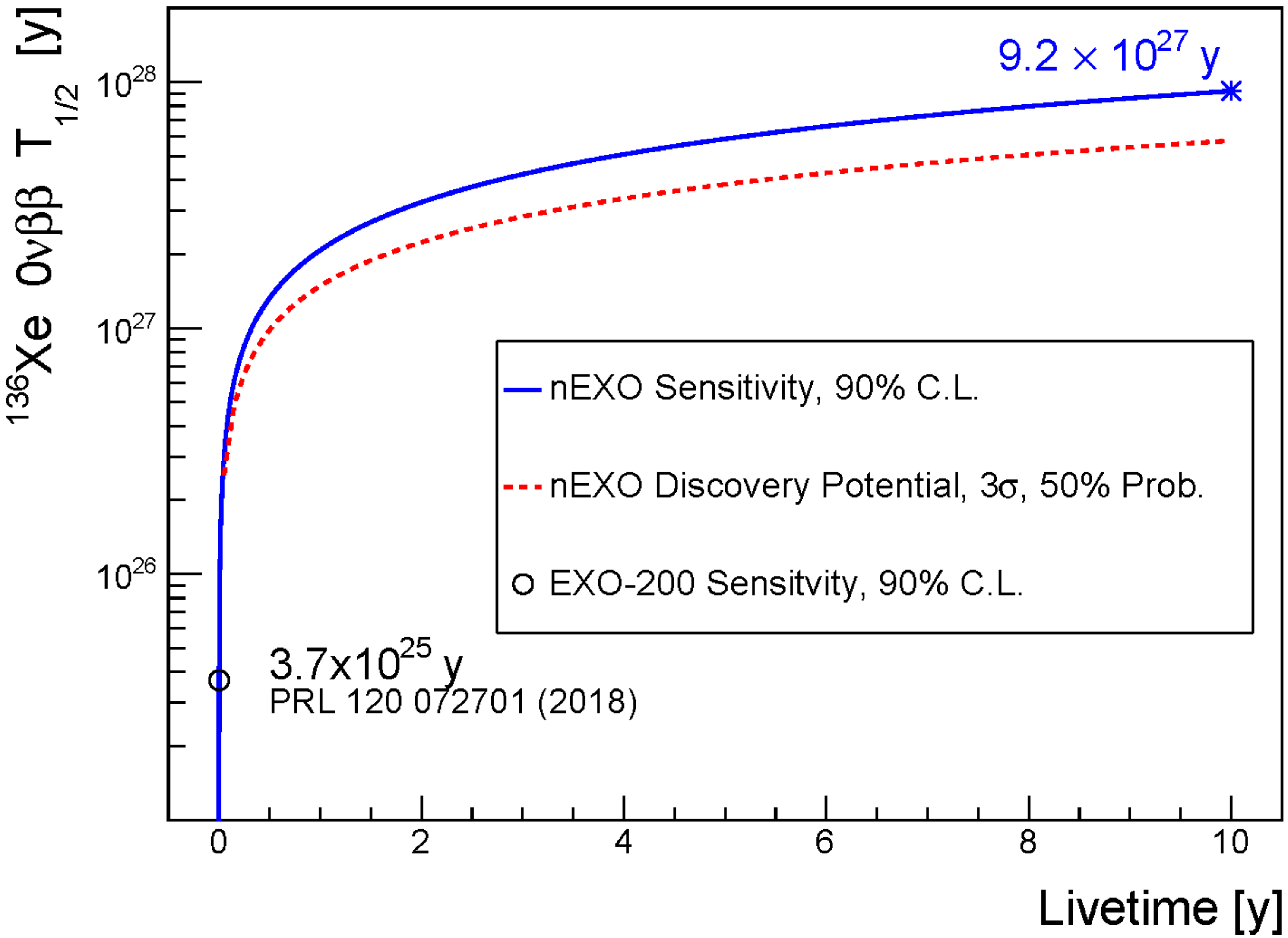


Toy MC fit assuming 10 years of data and 0νββ signal with $5 \cdot 10^{27}$ yr half-life

Single-site events in the ROI

- Instead of removing events outside the cleanest inner 2 tons, use the outermost region to measure and constrain backgrounds with a simultaneous energy and position fit

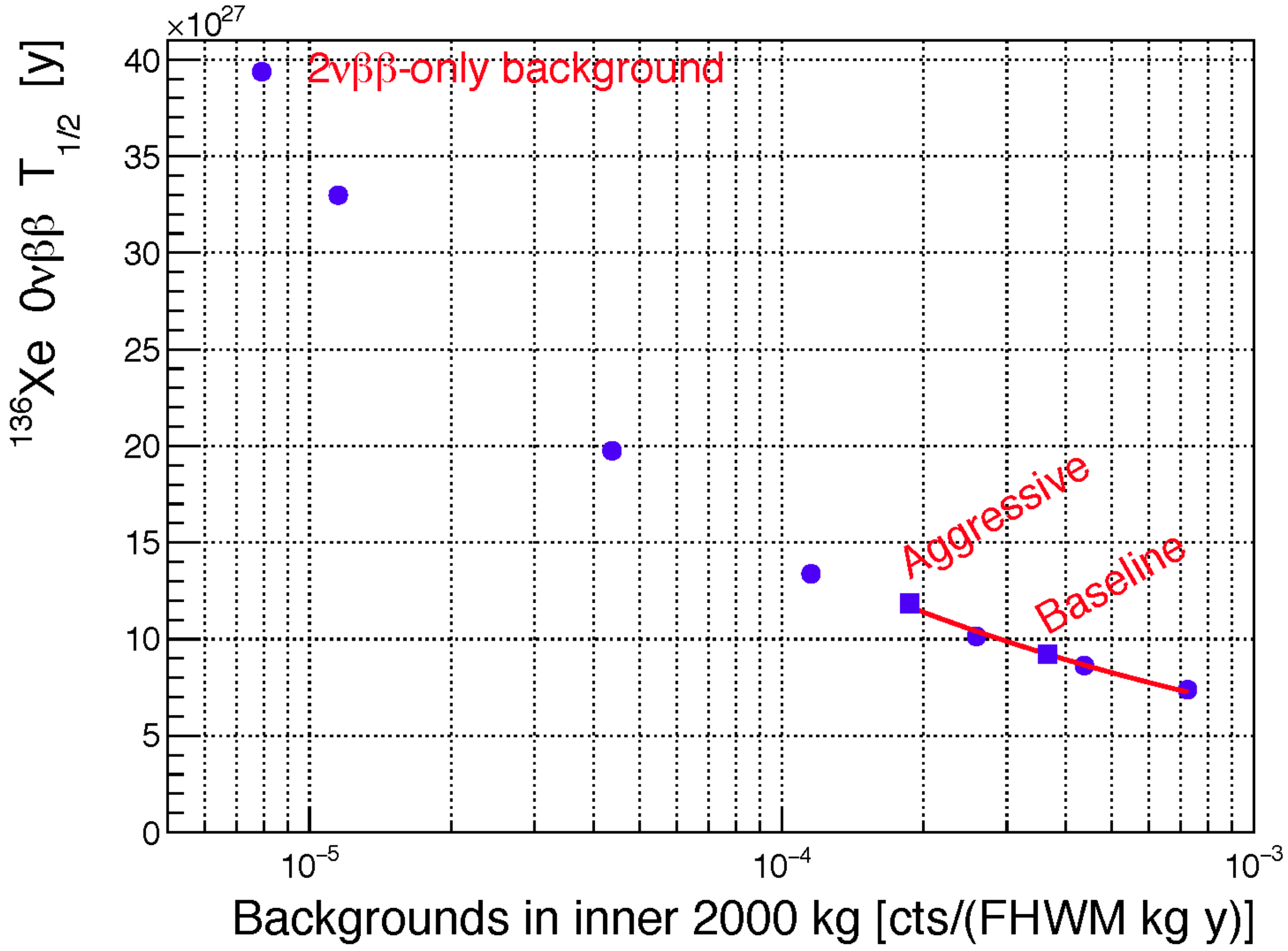
Sensitivity projections using baseline design



Sensitivity projections as a function of background

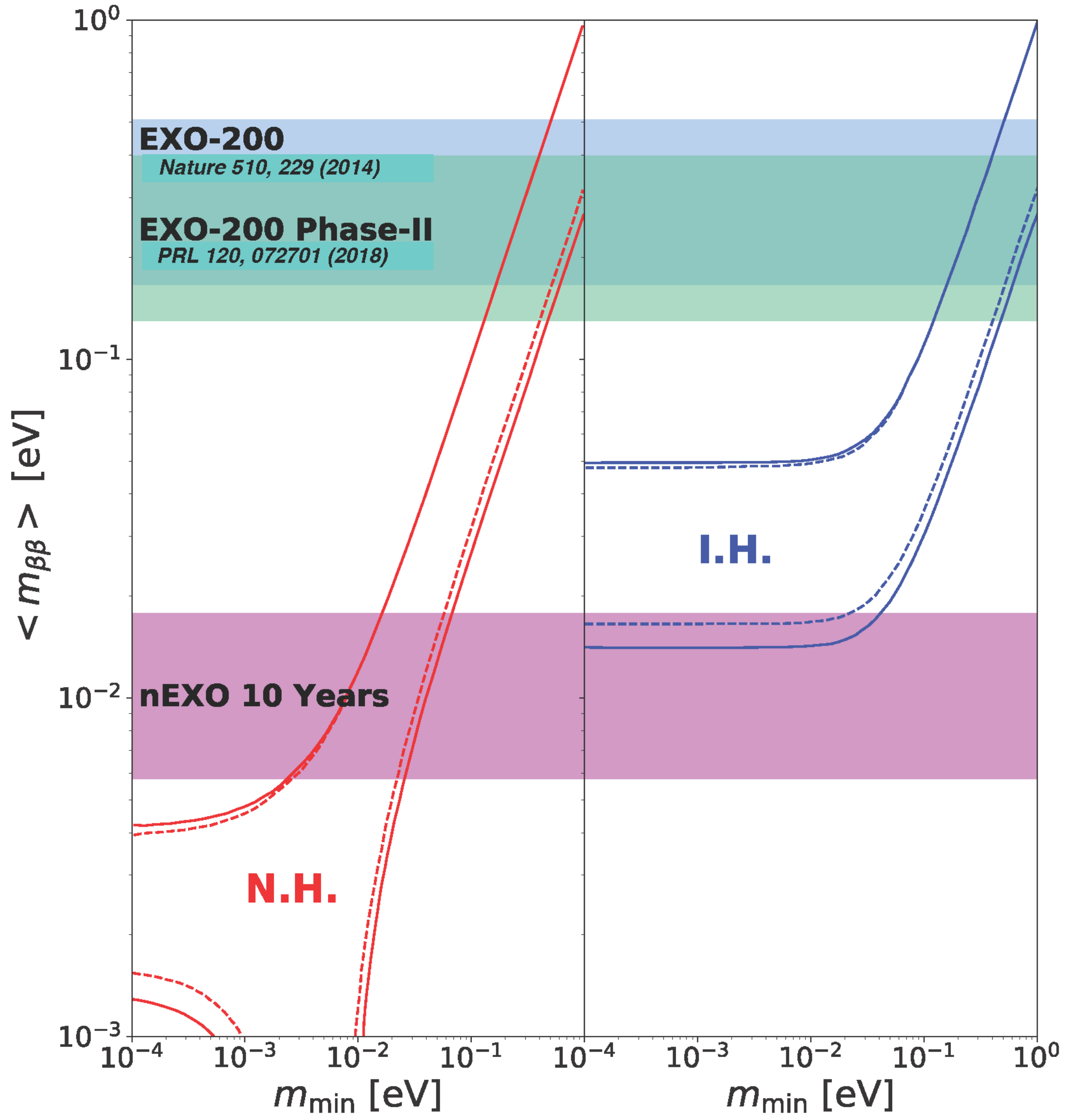
- Baseline – radioactivity for all materials "as measured"
- Aggressive – assumes some additional potential improvements
- 2νββ-only assumes "Ba-tagging" technology (not in the baseline design)

- Sensitivity scales with background as $T_{1/2}^{0\nu\beta\beta} \sim {}^{1}/_{B^{0.35}}$
  - Better than ${}^{1}/_{\sqrt{B}}$, due to 2D fit



We need to know the effective g_A

- Discovery of the 0νββ decay automatically implies new physics, and pushing the half-life limit by two orders of magnitude would be good
- But, at least for the simplest mechanism – light Majorana exchange – our chances to see something are much smaller than we hope if the g_A is strongly quenched



Assuming no g_A quenching. 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)

If you want to know more:

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 $\simeq$ 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
Minor revisions, Aug 12, 2018

Sensitivity and Discovery Potential of nEXO to Neutrinoless Double Beta Decay

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(Dated: October 17, 2017)

Summary

- EXO-200 is a successful current generation $0\nu\beta\beta$ search that has just recently completed operation. Final result is upcoming.
  - Its dataset will remain to be useful as a testbed of new analysis approaches and potentially for more exotic physics searches.

- nEXO is a planned next generation experiment with a projected ^{136}Xe half-life sensitivity of close to 10^{28} yr
  - Assuming no g_A quenching, it could cover the inverted hierarchy region

Sensitivity projections

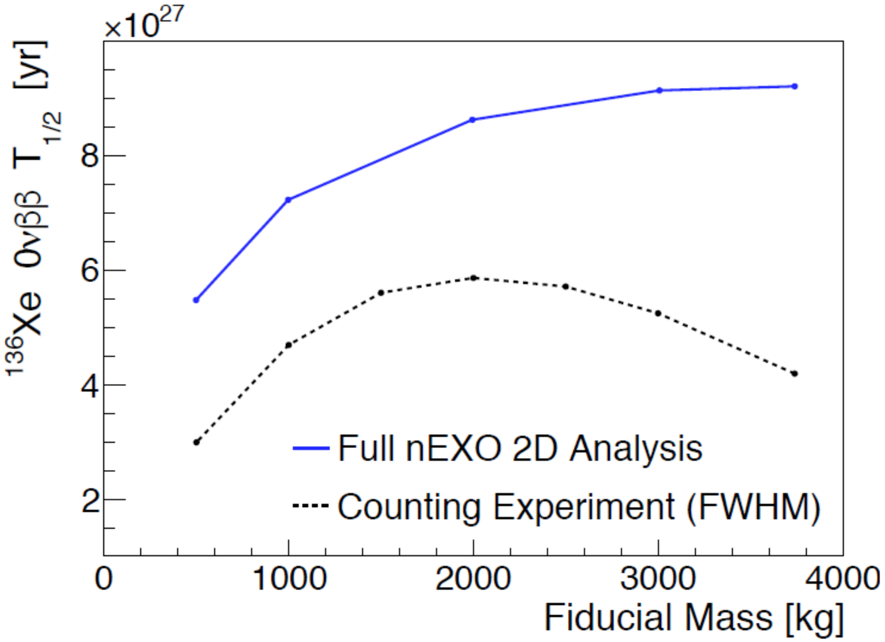


FIG. 11. nEXO exclusion sensitivity at 90% C.L. as a function of fiducial LXe volume. The blue points (upper curve) are obtained from the full 2D fit of energy vs distance to surface, while the black points (lower curve) are the result of a pure counting experiment of events with energy in $Q_{\beta\beta}\pm$FWHM/2. Both analyses are performed using the method of Ref. [42].

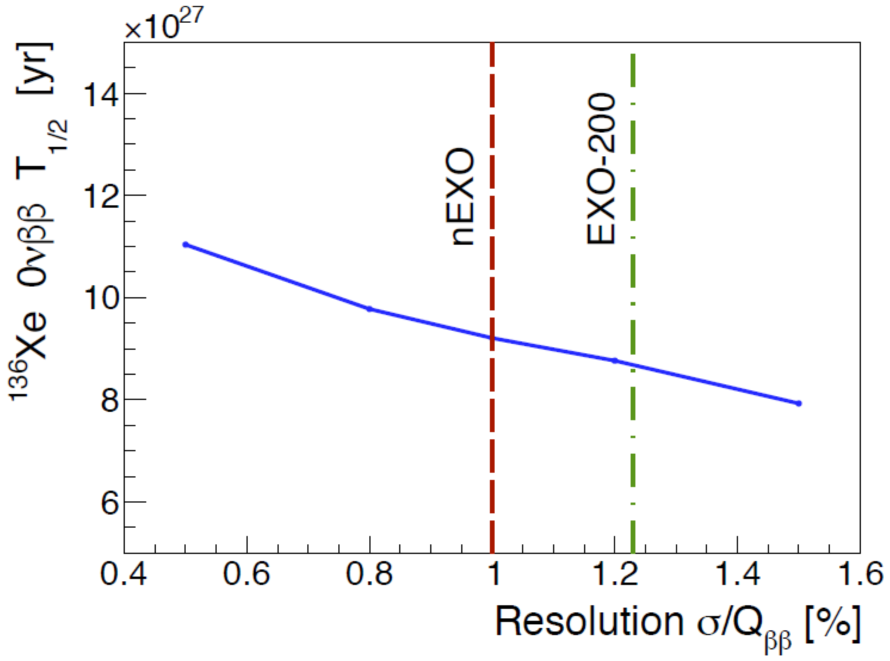
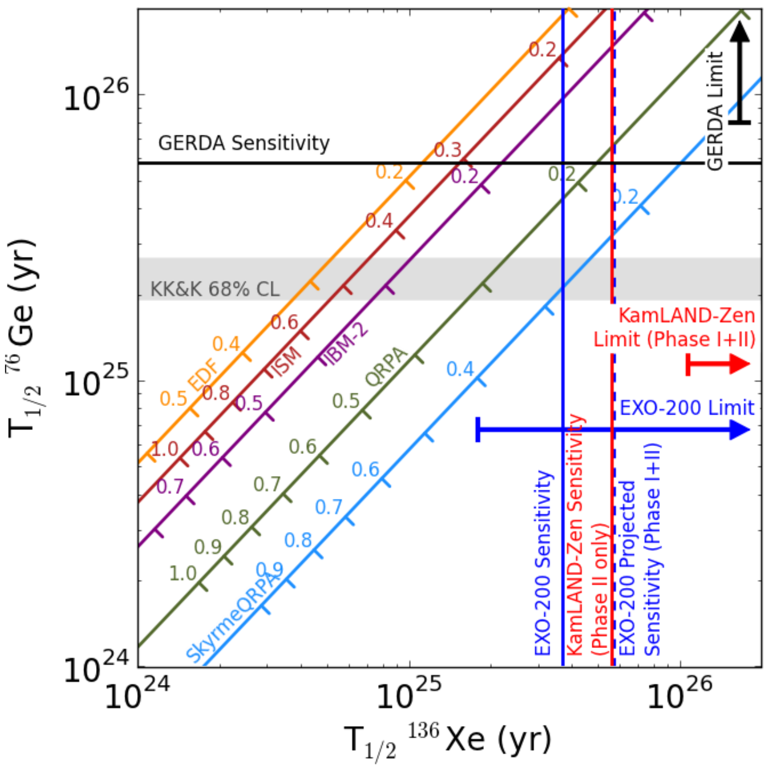


FIG. 12. nEXO median exclusion sensitivity at 90% C.L. computed for different assumptions of the experiment's energy resolution.

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

“Current” limits, ^{76}Ge vs. ^{136}Xe:



“Current” limits, ^{130}Te vs. ^{136}Xe: