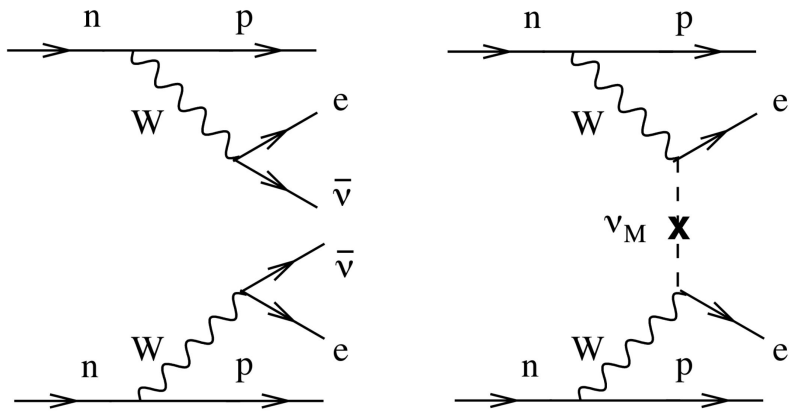
The nEXO neutrinoless double beta decay experiment

Brian Lenardo
Stanford University
Neutrino Telescopes 2021
Venezia, IT (in spirit!)

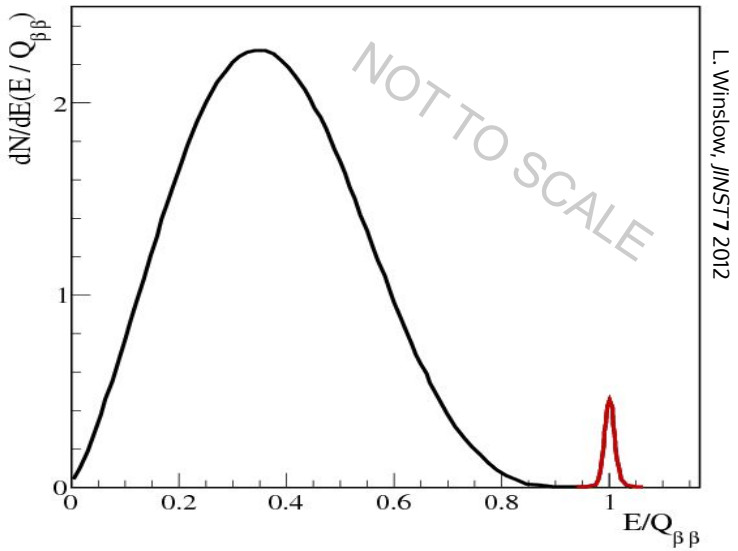
Extending the reach of 0ν$\beta\beta$ searches

0ν$\beta\beta$ decay is a sensitive probe of physics beyond the standard model

- Lepton number violation
- Majorana nature of neutrino
- May explain neutrino mass scale (see-saw mechanism), matter/antimatter asymmetry (leptogenesis)



Avignone, Elliott, & Engel
Rev. Mod. Phys. **80** (2008)

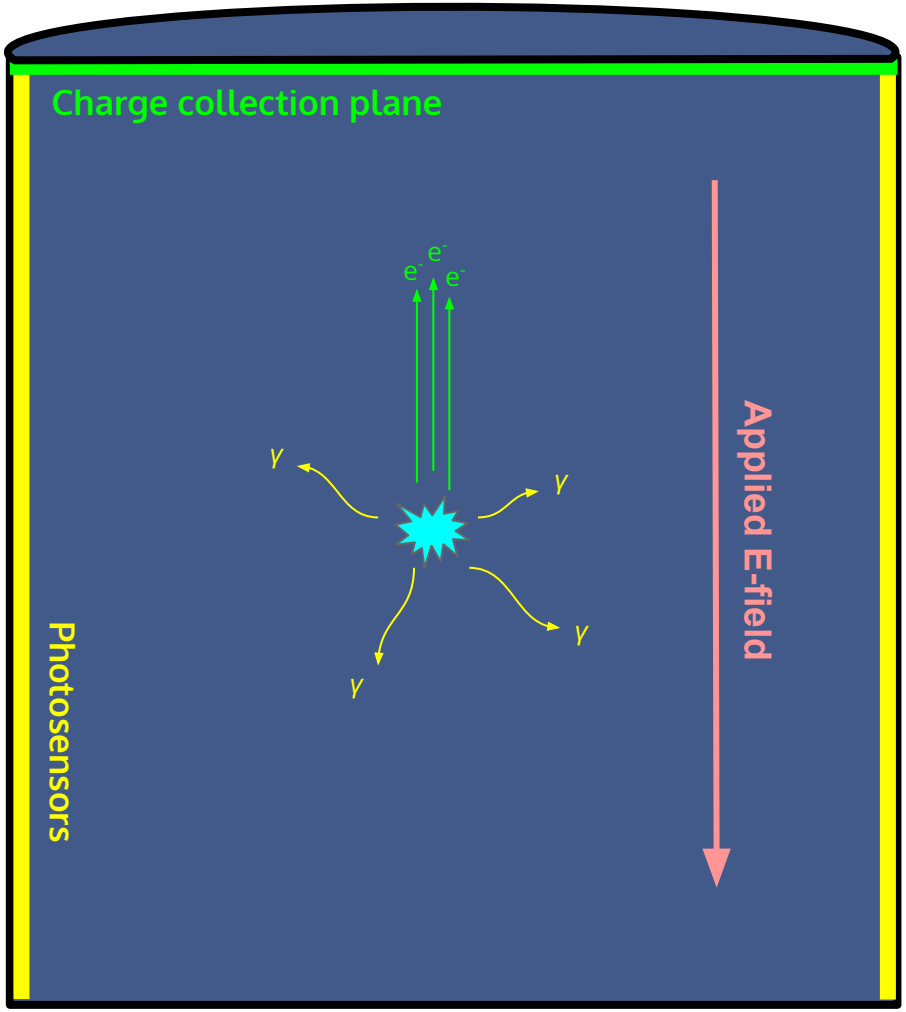


Current $T_{1/2}$ limits: >10^{26} years!

Requirements for a next-gen 0ν$\beta\beta$ experiment

- A LOT of the isotope of interest (>10^{27} atoms)
- Low backgrounds in MeV range (low radioactivity)
- Signal/background discrimination
- Good energy resolution

Liquid xenon time projection chambers (TPCs)

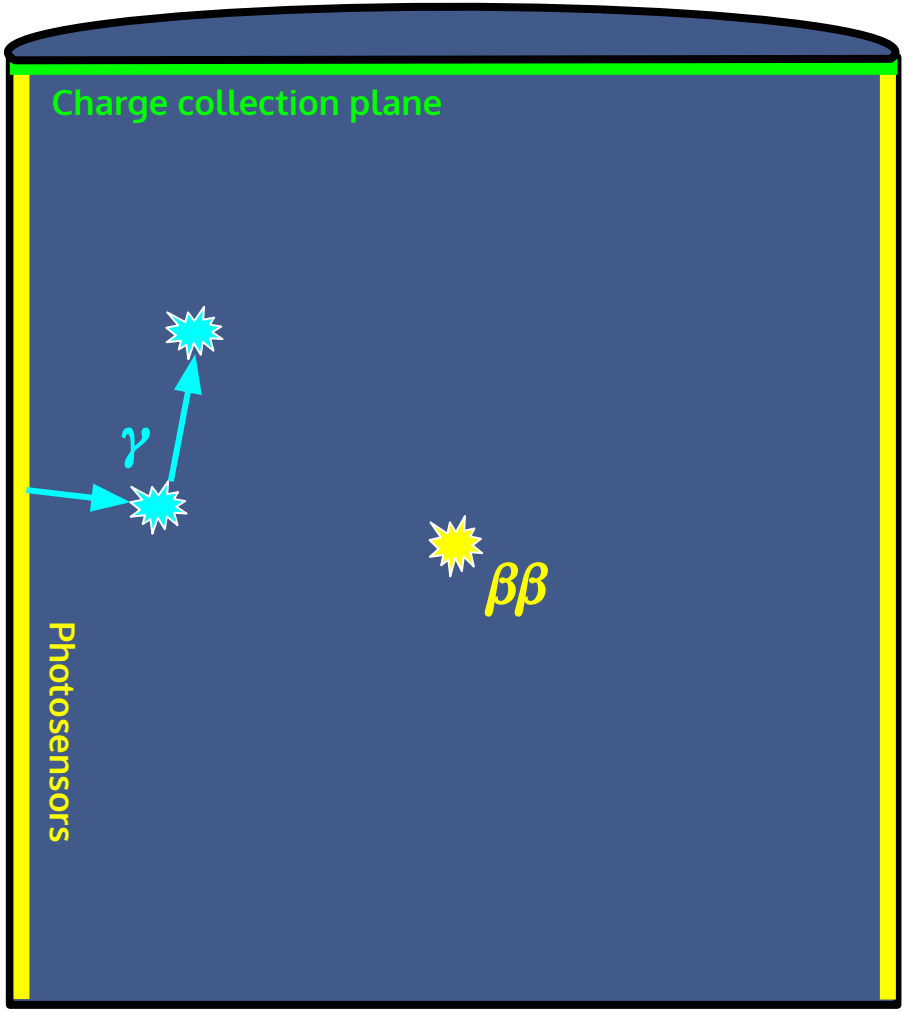


Dual-channel measurement
Scintillation light + ionized charge

3-D position reconstruction for each energy deposition

Can fill with ^{136}Xe, a $0\nu\beta\beta$ candidate
Detector medium = sample

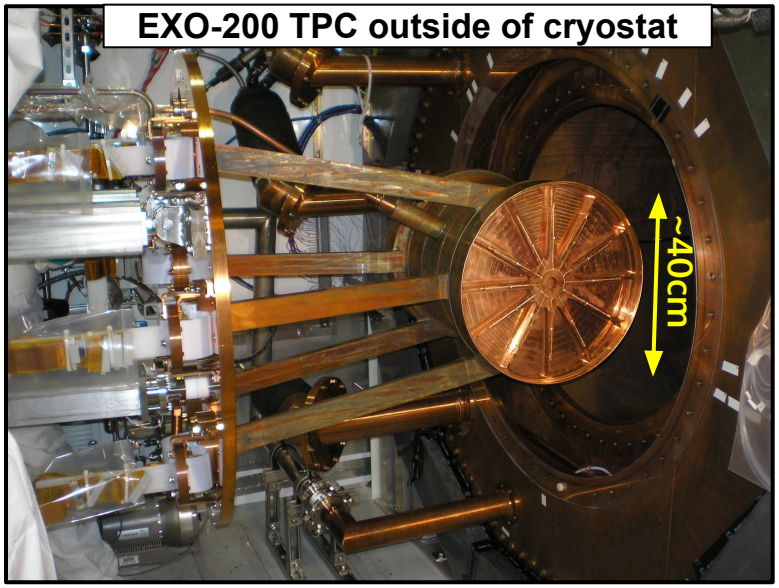
Liquid xenon time projection chambers

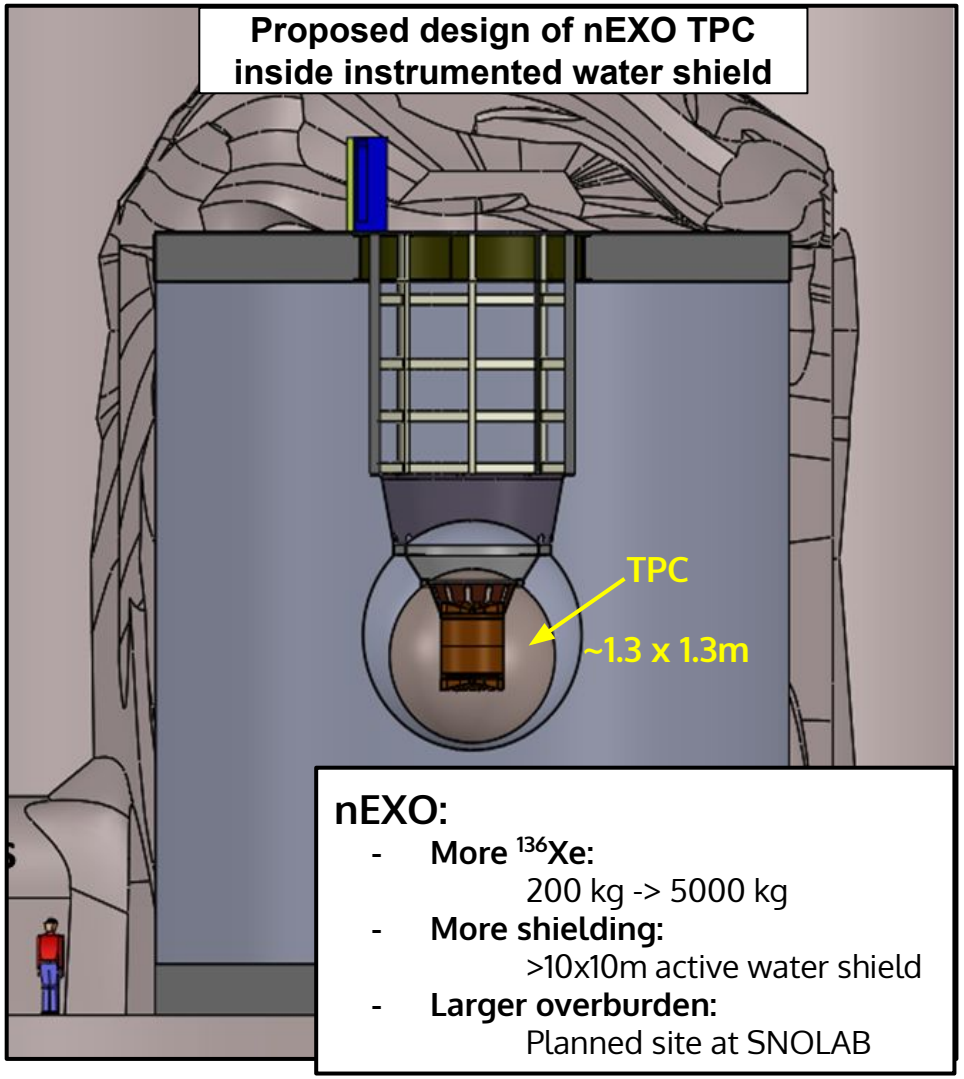


Addressing the challenges in 0νββ searches

- **A LOT of the ββ isotope (^{136}Xe)**
  - Ton-scale LXe TPCs are already operating (XENON1T)
  - Xe, while rare, is straightforward to enrich
- **Low, well-characterized backgrounds in MeV range (low radioactivity)**
  - Very low intrinsic backgrounds
  - Excellent self-shielding reduces external radioactivity
  - Powerful position reconstruction and multi-site rejection to characterize and reject BG
- **Good energy resolution**
  - Combining charge and light can reach <1% (demonstrated by XENON1T)

Scaling up from EXO-200 to nEXO





EXO-200: 2011 - 2018

- First 100kg-class 0νββ search
- Discovered 2νββ in ^{136}Xe
- $T_{1/2} > 3.5 \times 10^{25}$ yr for 0νββ in ^{136}Xe (*PRL* **123,** 2019)
- Multiple leading limits on other decay modes of ^{136}Xe and ^{134}Xe
- Pioneered ultra-low-background LXe TPC technology

nEXO:

- **More ^{136}Xe:**
  200 kg -> 5000 kg
- **More shielding:**
  >10x10m active water shield
- **Larger overburden:**
  Planned site at SNOLAB

The nEXO collaboration

University of Alabama, Tuscaloosa AL, USA
M Hughes, O Nusair, 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, S Rescia, T Tsang
University of California, Irvine, Irvine CA, USA
M Moe
California Institute of Technology, Pasadena CA, USA
P Vogel
Carleton University, Ottawa ON, Canada
I Badhrees, R Gornea, C Jessiman, T Koffas, B. Veenstra, M Elbeltagi, S Viel, D Goeldi, B Chana
Colorado State University, Fort Collins CO, USA
C Chambers, A Craycraft, D Fairbank, W Fairbank Jr, A Iverson, J Todd
Indiana University, Bloomington IN, USA
JB Albert, SJ Daugherty, G Visser
Drexel University, Philadelphia PA, USA
MJ Dolinski, P Gautam, E Hansen, YH Lin, E Smith, Y-R Yen

ITEP Moscow, Russia
V Belov, A Burenkov, A Karelin, A Kobyakin, A Kuchenkov, V Stekhanov, O Zeldovich
Laurentian University, Sudbury ON, Canada
B Cleveland, A Der Mesrobian-Kabakian, J Farine, C Licciardi, A Robinson, U Wichoski, E Caden
Lawrence Livermore National Laboratory, Livermore CA, USA
J Brodsky, M Heffner, A House, S Sangiorgio, T. Stiegler
University of Massachusetts, Amherst MA, USA
S Feyzbakhsh, D Kodroff, A Pocar, M Tarka
McGill University, Montreal QC, Canada
T Brunner, K Murray, T Totev, L Darroch, S Al Kharusi, T McElroy
University of North Carolina, Wilmington, USA
T Daniels
Oak Ridge National Laboratory, Oak Ridge TN, USA
L Fabris, RJ Newby
`Pacific Northwest National Laboratory, Richland, WA, USA
I Arnquist, EW Hoppe, JL Orrell, G Ortega, C Overman, R Saldanha, R Tsang, ML De Vacri
University of South Dakota, Vermillion SD, USA
T Bhatta, A Larson, R MacLellan

University of Illinois
L Yang, J Echevers
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
Duke University, Durham NC, USA
PS Barbeau, J Runge
Friedrich-Alexander-University Erlangen, Nuremberg, Germany
G Anton, J Hoessl, 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
Rensselaer Polytechnic Institute, Troy NY, USA
E Brown, K Odgers, A Fucarino

SLAC National Accelerator Laboratory, Menlo Park CA, USA
S Delaquis, A Dragone, G Haller, LJ Kaufman, B Mong, A Odian, M Oriunno, PC Rowson, K Skarpaas
Stanford University, Stanford CA, USA
J Dalmasson, R DeVoe, D Fudenberg, G Gratta, M Jewell, S Kravitz, G Li, M Patel, A Schubert, M Weber, S Wu, B Lenardo
Stony Brook University, SUNY, Stony Brook NY, USA
K Kumar, O Njoya
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
A Jamil, Z Li, D Moore, Q Xia
Colorado School of Mines, Golden, CO
K.G. Leach, C.R. Natzke

nEXO's TPC design updates

Monolithic detector volume

- >3 ton (~10^{28} atoms) fiducial volume
- Powerful self-shielding
- Measure backgrounds directly in the same detector

Advanced scintillation readout

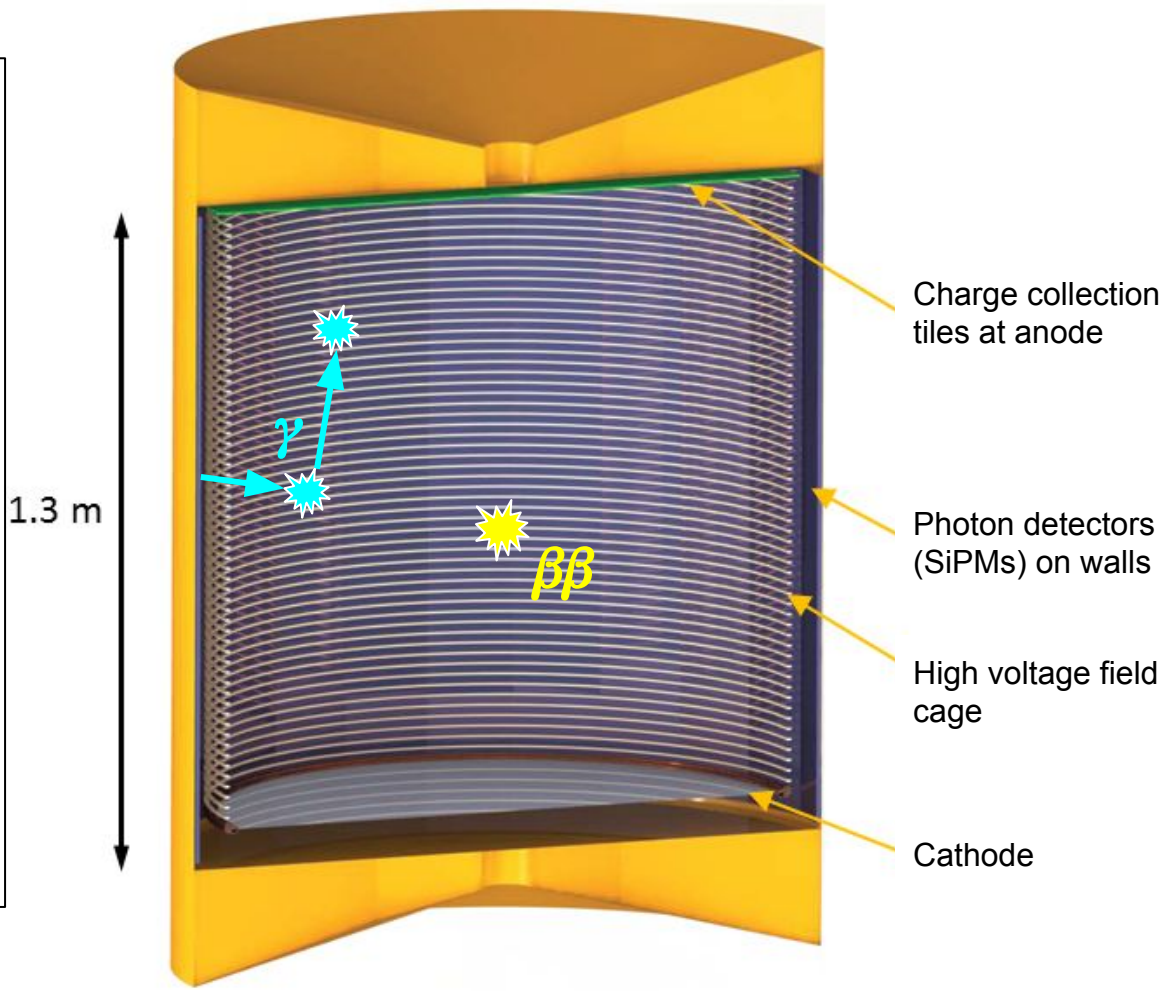
- VUV-sensitive SiPMs

Custom tiled charge readout

- Lower radioactivity, modular construction compared to wires

In-liquid-xenon, cold electronics

- Low-background ASICs for both light and charge readout



Charge readout

Gold strips on quartz substrate

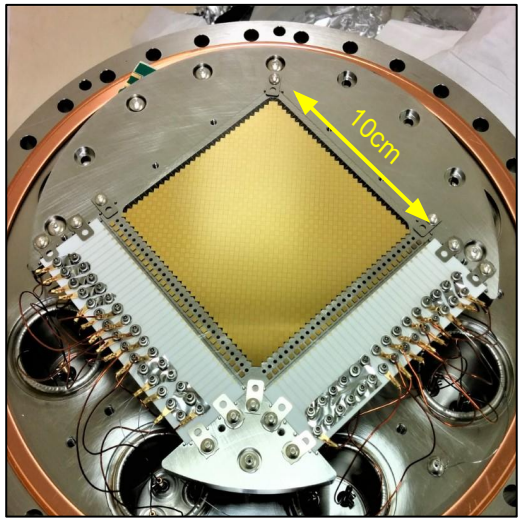
- 6mm pitch
- 3mm prototype tested: Jewell et al. *JINST* **13** (2018)

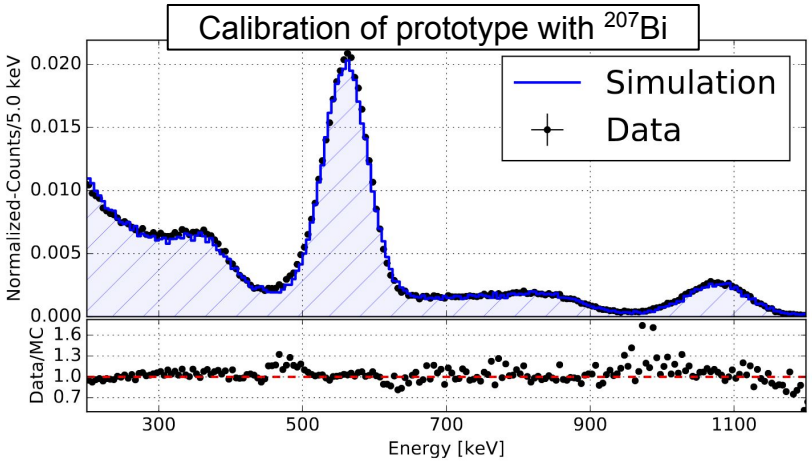
In-LXe cold electronics

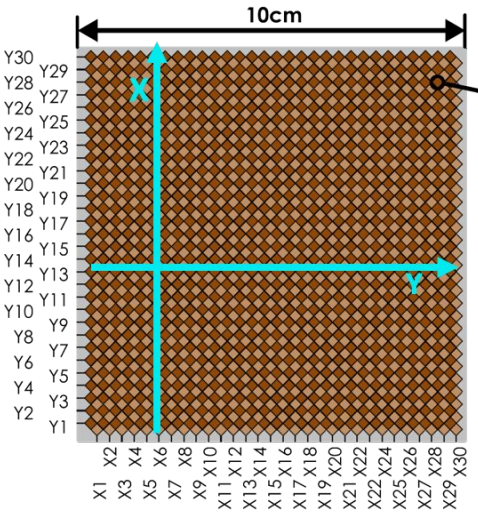
- Lower noise, smaller cable capacitance
- Stringent radioactivity & power requirements
- Custom ASICs under development

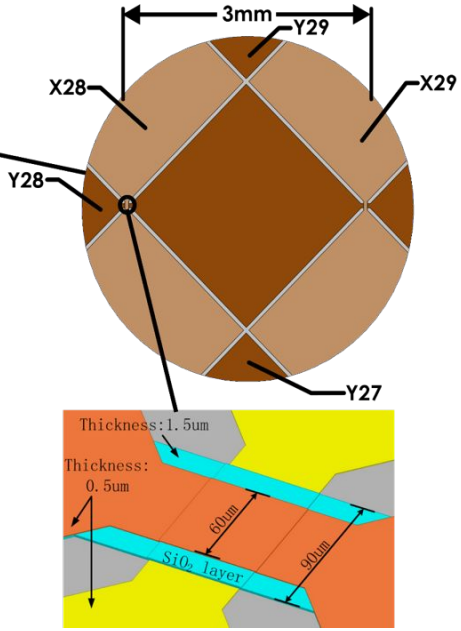
Advanced reconstruction techniques under study

Li et al., *JINST* **14** (2019)





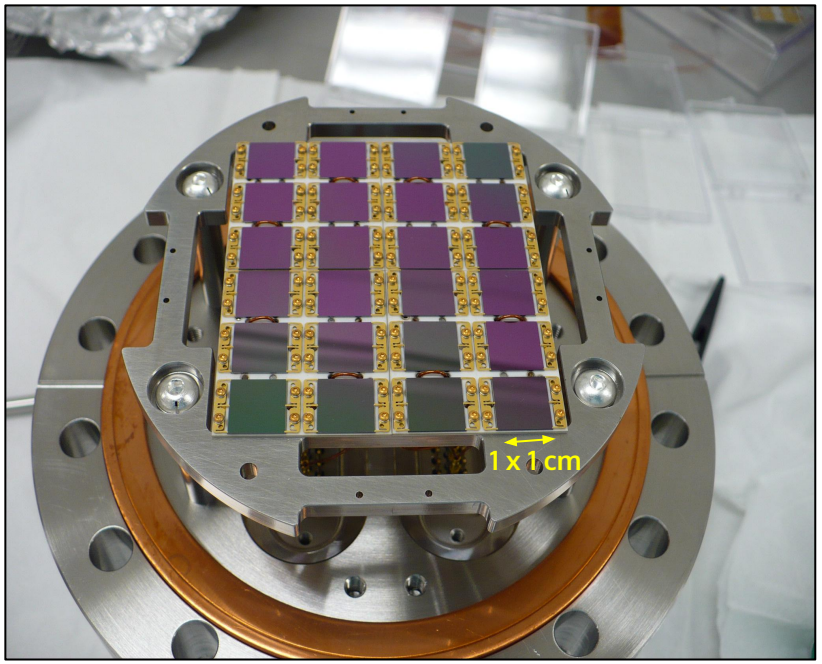




Scintillation readout

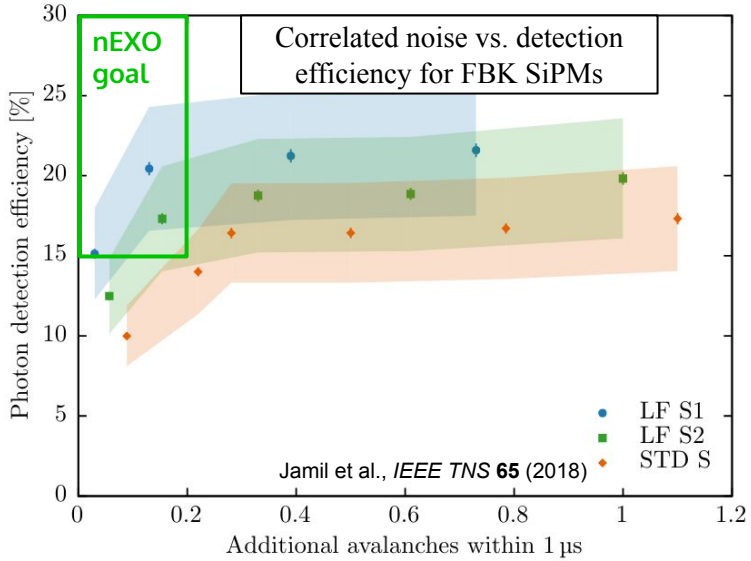
nEXO will use VUV-sensitive SiPMs for scintillation readout

- Lower noise than APDs in EXO200
- Better radiopurity than PMTs



Relatively new technology -- extensive R&D and characterization ongoing within collaboration

- Photon detection efficiency, noise properties
  - Ostrovskiy et al., *IEEE TNS* **62** (2015) arXiv:1502.07837
  - Jamil et al., *IEEE TNS* **65** (2018) arXiv:1806.02220
  - Gallina et al., *NIM A* **940** (2019) arXiv:1903.03663
- Development of in-LXe ASIC readout

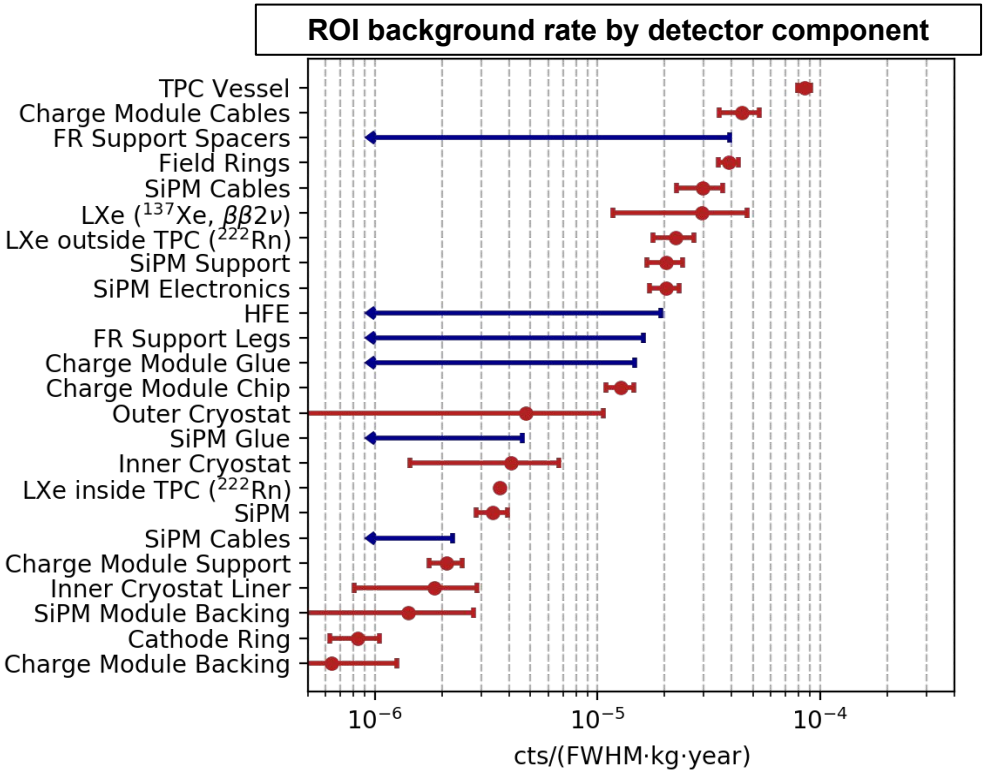


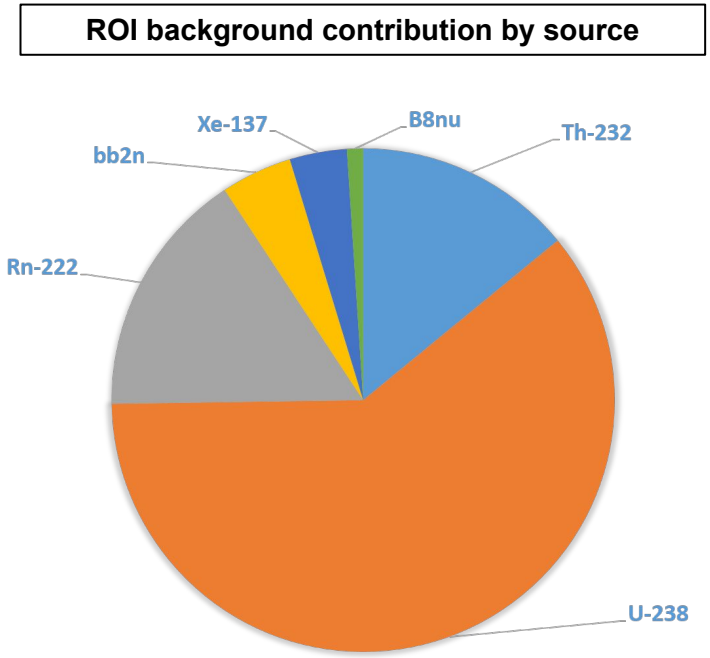
Estimating radioactive backgrounds

Extensive materials screening campaign, following success of EXO-200 (e.g. D. Leonard, *NIMA* **591** (2008))

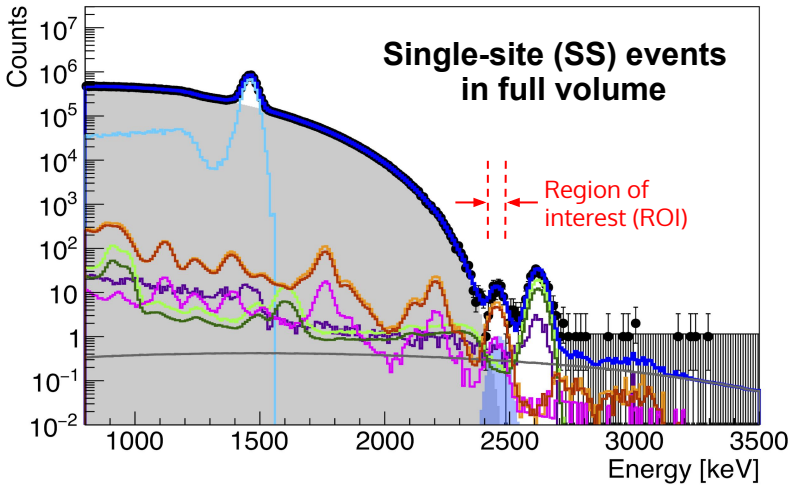
Essentially every material in existing design has been screened for radiopurity

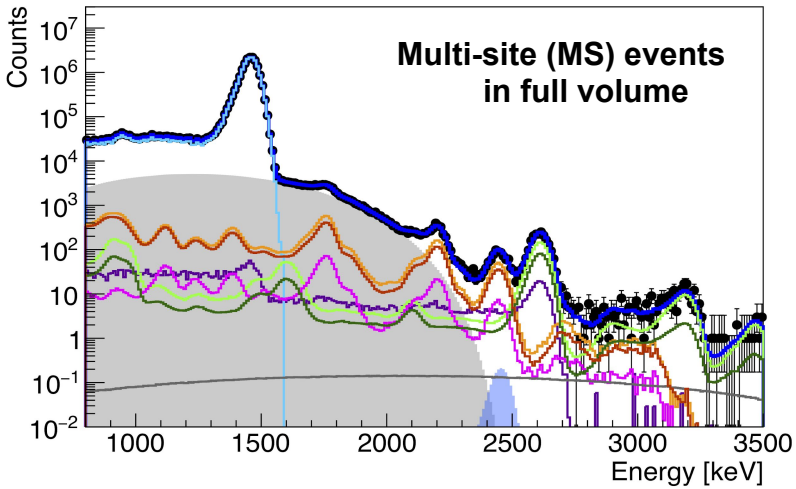
→ nEXO background model is conservative and data-driven

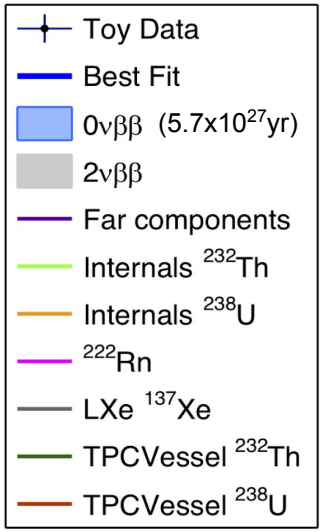


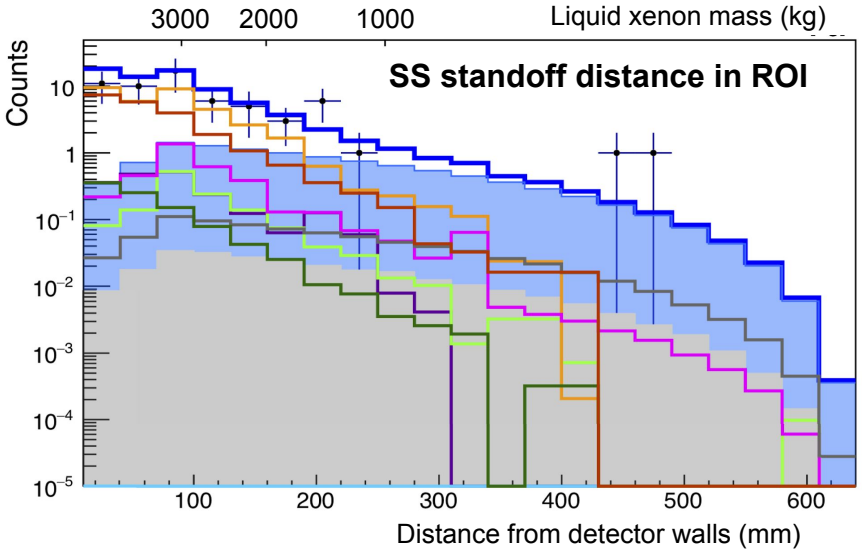


Expected performance - Geant4 simulation

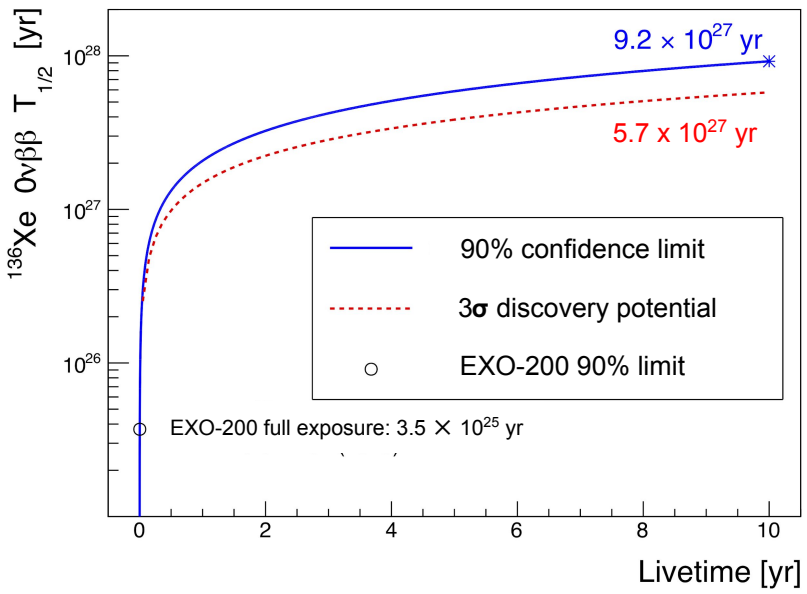


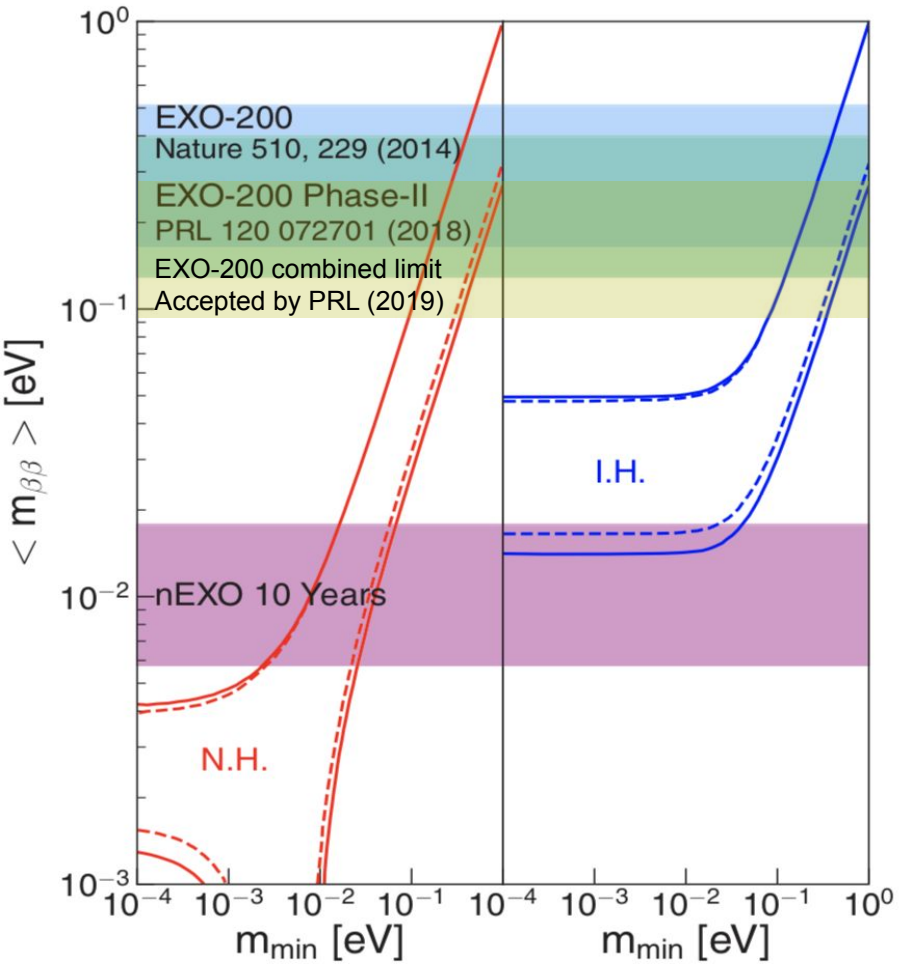






Projected physics reach ca. 2018





Projected sensitivity: $T_{1/2}$ > 9.2e27 yr @ 90% CL

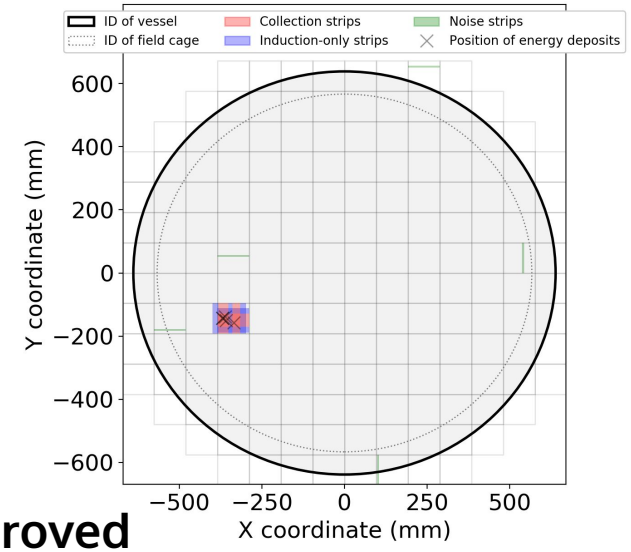
- J. Albert et al., *PRC* **97**, 2018

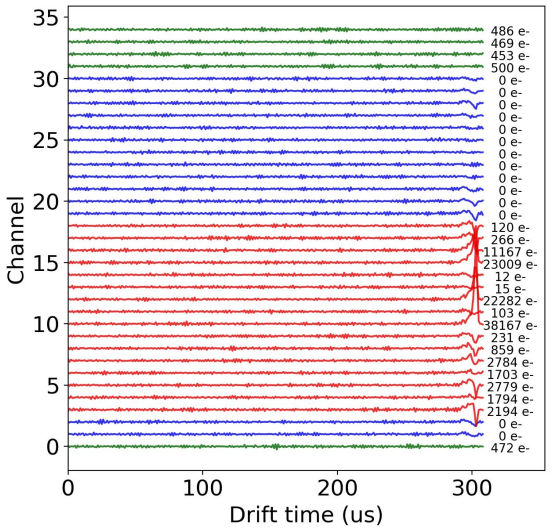
Recent improvements in readout simulations

Charge readout modeled end-to-end

- Full noise simulation of ASIC readout and charge propagation through TPC
- Induction and noise signals generated to mimic real data
  - Z. Li et al. (NEXO) *JINST* **14** (2019)
- **Machine learning classifier likely to improve signal/bkg discrimination**

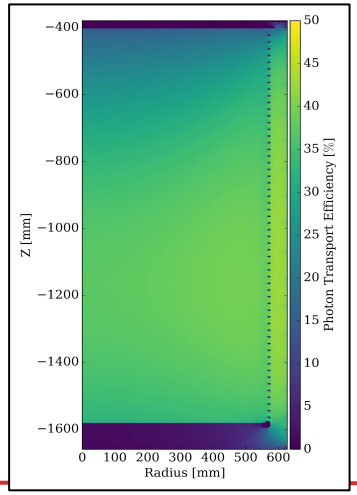
Charge reconstruction of 0nuBB event with a bremsstrahlung

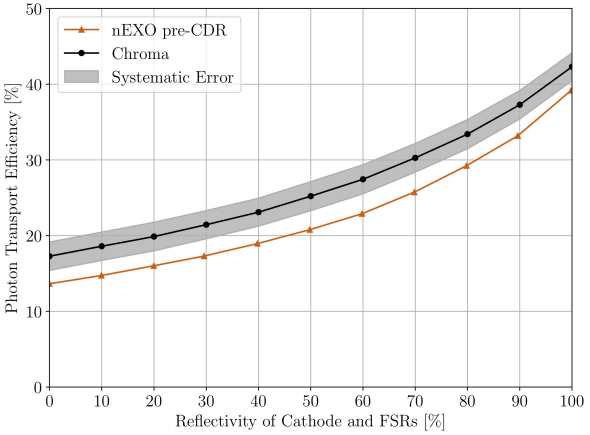




Light collection modeling improved with new data and software

- High-stats, fine-grained simulation using GPU-based Chroma software
- New measurements of SiPM optical properties and performance
  - P. Nakarmi et al. (NEXO) *JINST* **15** (2020)
  - G. Gallina et al. (NEXO) *NIMA* **940** (2019)
  - A. Jamil et al. (NEXO) *IEEE TNS* **65** (2018)
  - P. Lv et al. (NEXO) *IEEE TNS* **67** (2020)
  - M. Wagenpfeil et al. (NEXO) *In preparation*
- **Improvements in projected light collection based on new data**

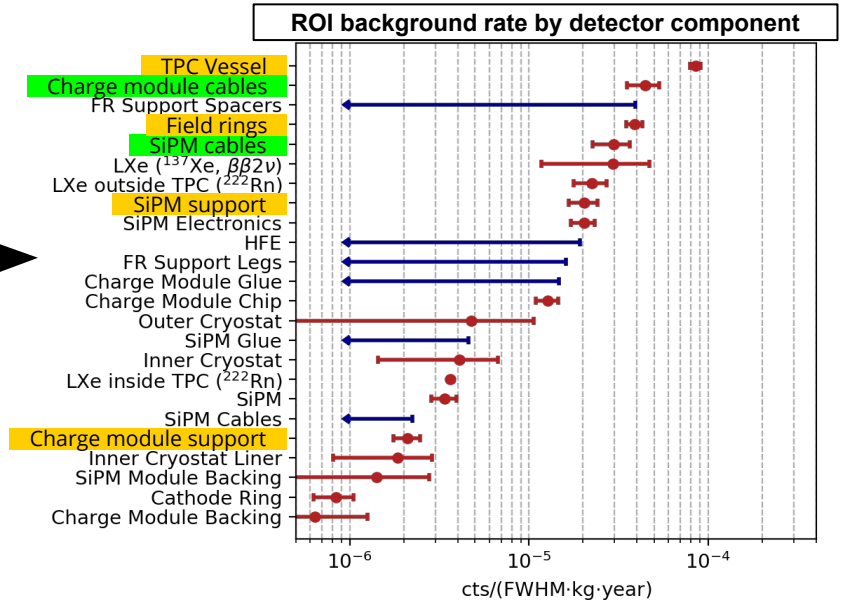


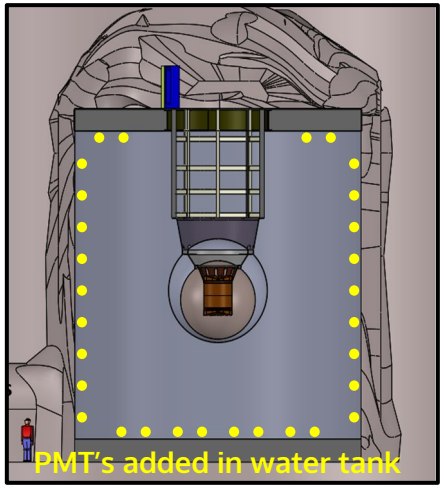


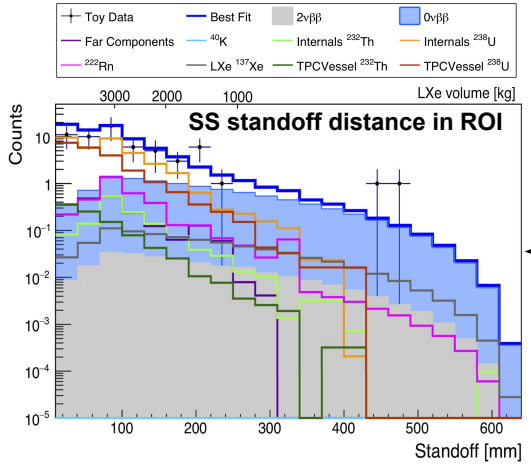
Avenues for further background reduction

Improved construction materials

- Underground electroformed copper (pioneered by MJD) could reduce **copper radioactivity** by x20 and x4 for ^{238}U and ^{232}Th respectively
- **Better polyimide cables** identified, with x3 (x5) reduction in ^{232}Th (^{238}U) activity
- **Reduces several big contributors to gamma-ray backgrounds**







Active cosmogenic veto

- Recycled Daya Bay PMTs could instrument water shield
- Muon tagging via Cherenkov light detection
- **Reduces ^{137}Xe β-decay bkg; largest in innermost LXe**

Conclusions

nEXO will use a monolithic liquid xenon TPC to search for neutrinoless double beta decay in ^{136}Xe:

- Projected sensitivity approaching 10^{28} years
- Data-driven design; backgrounds are estimated using measured activities and experience from the successful EXO-200 experiment

Ongoing R&D:

- Materials for better radiopurity
- Cosmogenic veto for reduction of ^{137}Xe backgrounds
- Testing and optimization the light/charge readout schemes
- Continued development of cold, low-background electronics
- Development of calibration methods and plans
- Improving event reconstruction for higher sensitivity
- In-line distillation for removal of ^{222}Rn