The nEXO Neutrinoless Double Beta Decay Experiment

Brian Mong - SLAC

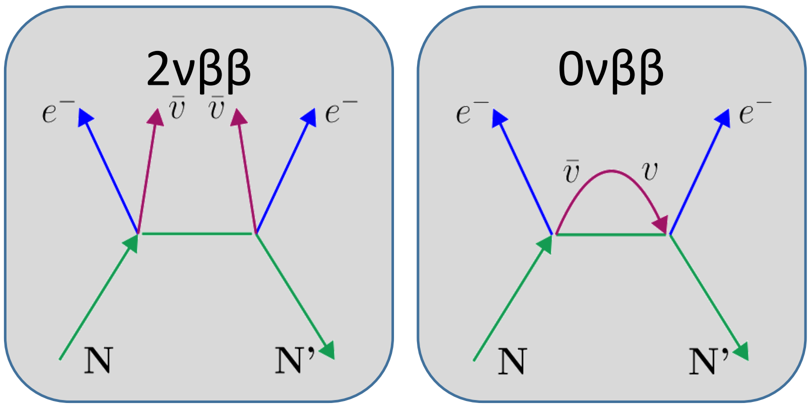
nEXO Collaboration

SLAC NATIONAL ACCELERATOR LABORATORY

nEXO

Double beta decay motivation

(in one slide)



Measured

Known

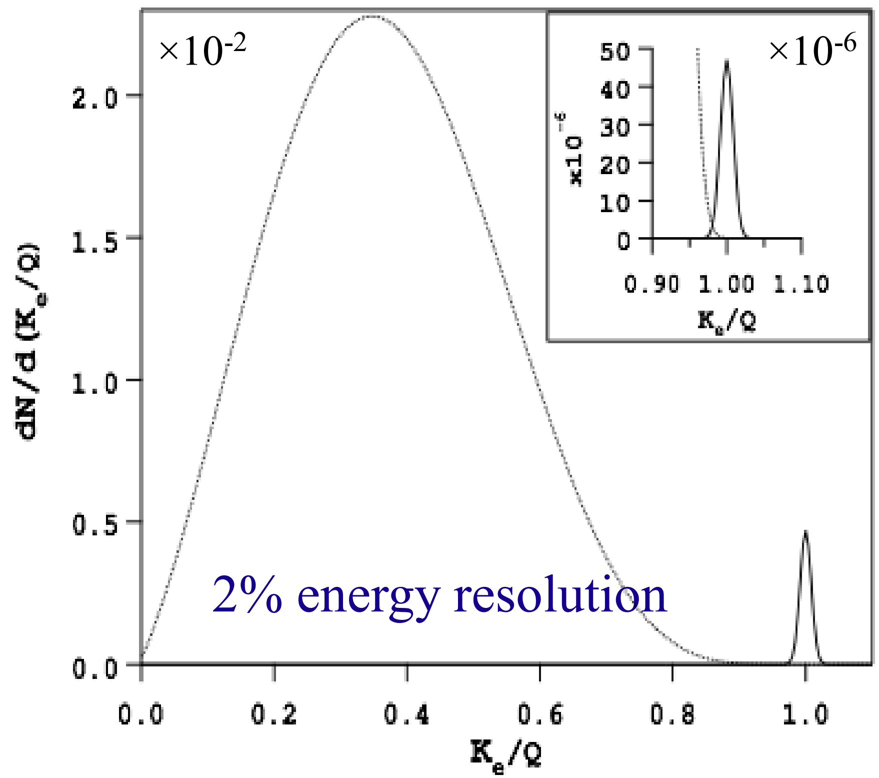
Calculated (theory)

$$\langle m_\nu \rangle = \left(T_{1/2}^{0\nu\beta\beta} G^{0\nu\beta\beta}(E_0, Z) \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1/2}$$

$$\langle m_\nu \rangle = \sum_{i=1}^{3} \left| U_{\alpha i} \right|^2 m_i$$

$$mass \mu \frac{1}{\sqrt{T_{1/2}^{0nbb}}}$$

[P. Vogel, arXiv:hep-ph/0611243]

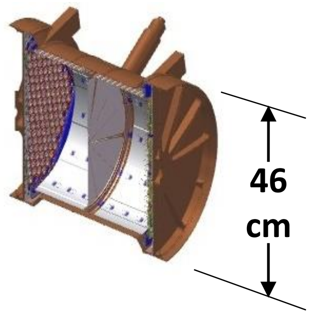


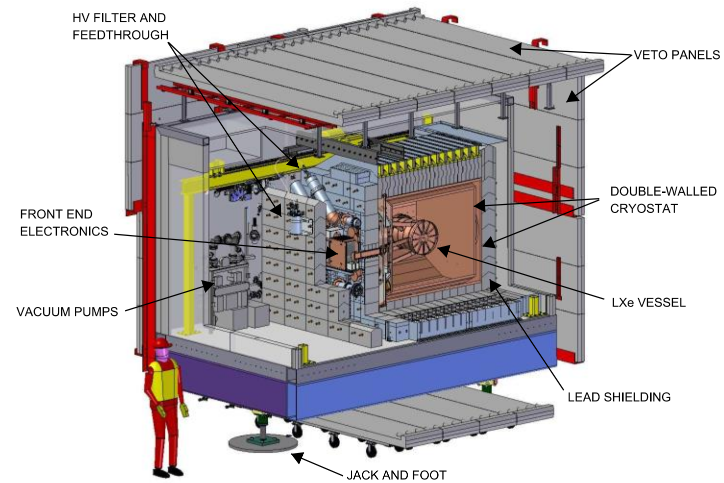
Observation means discovery of:

- Majorana fermion
- Neutrino mass scale
- Lepton number violation (SM)

EXO-200 and nEXO

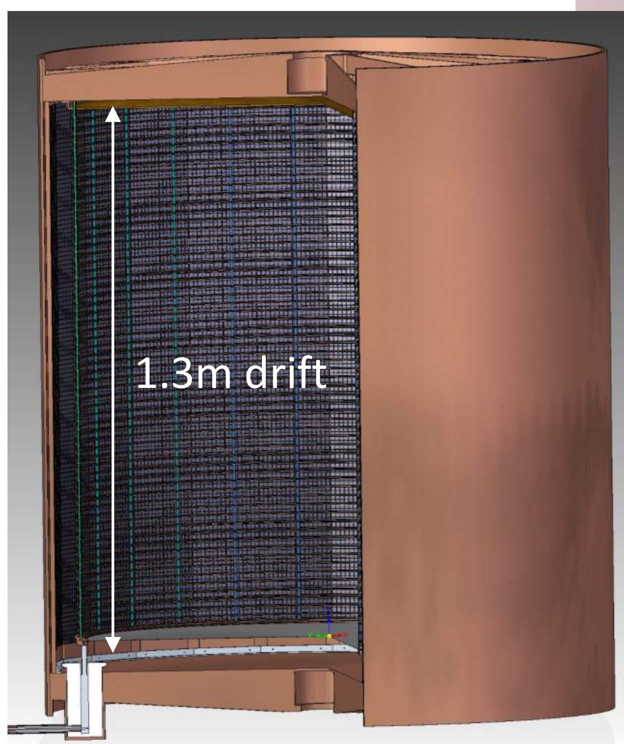
EXO200:
- ~175 kg LXe
- Final Sensitivity: $T_{1/2}$ 5E25yr

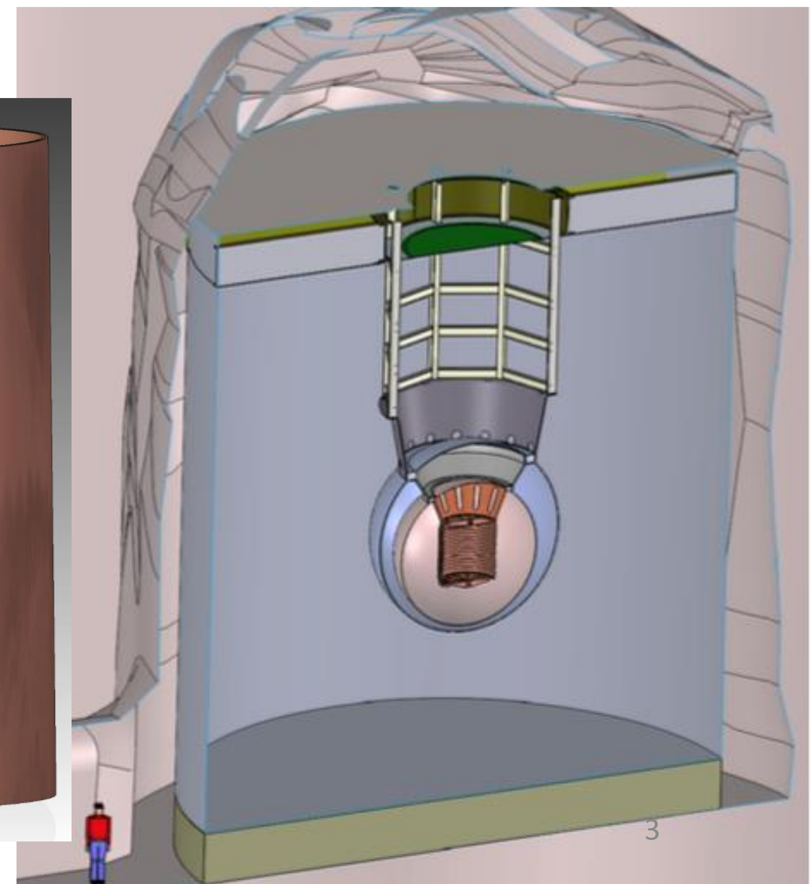




(roughly to scale)

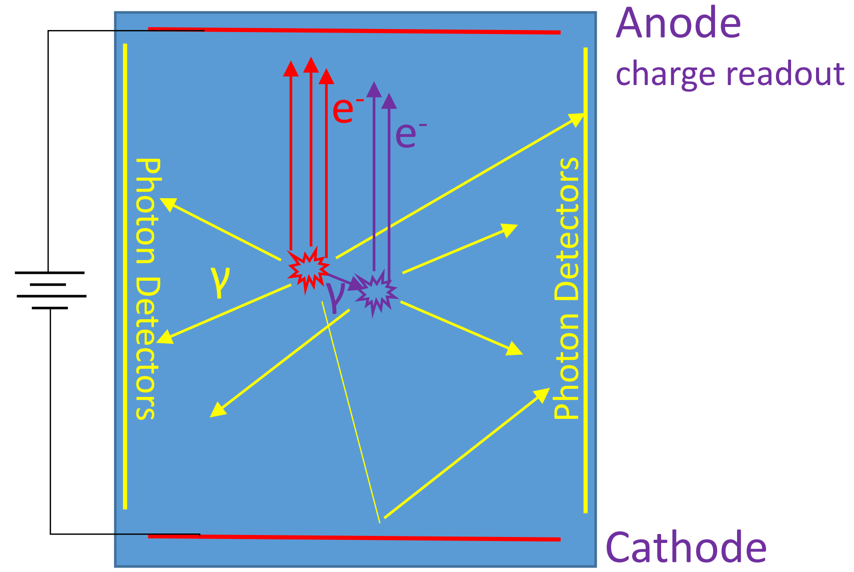
nEXO
- ~5000 kg LXe
- Sensitivity goal: $T_{1/2}$ 1E28yr @90% C.L.

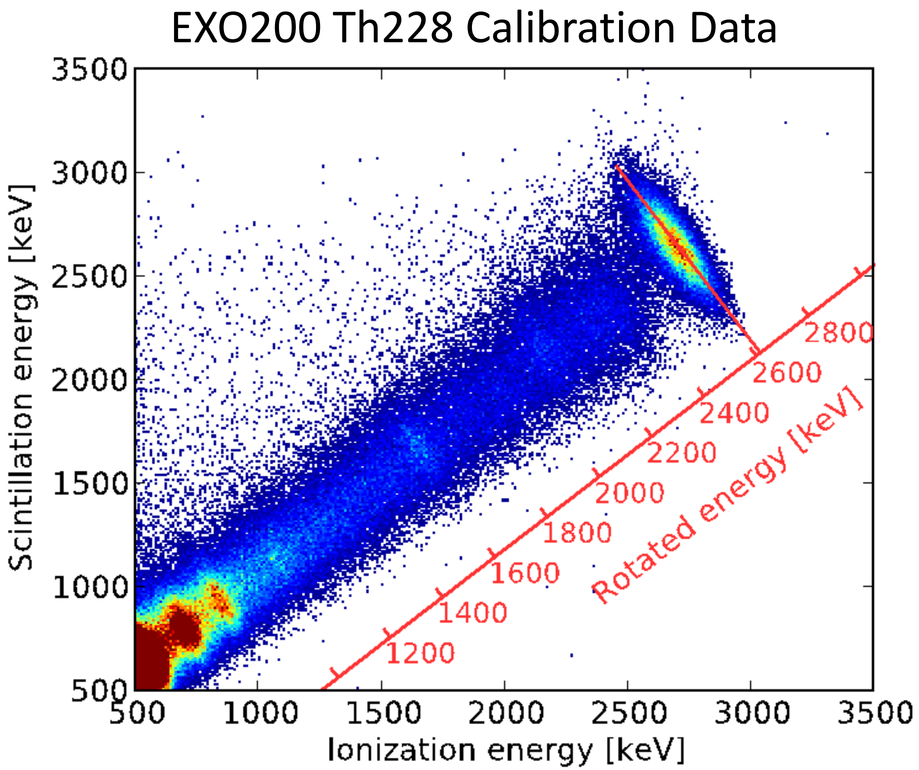


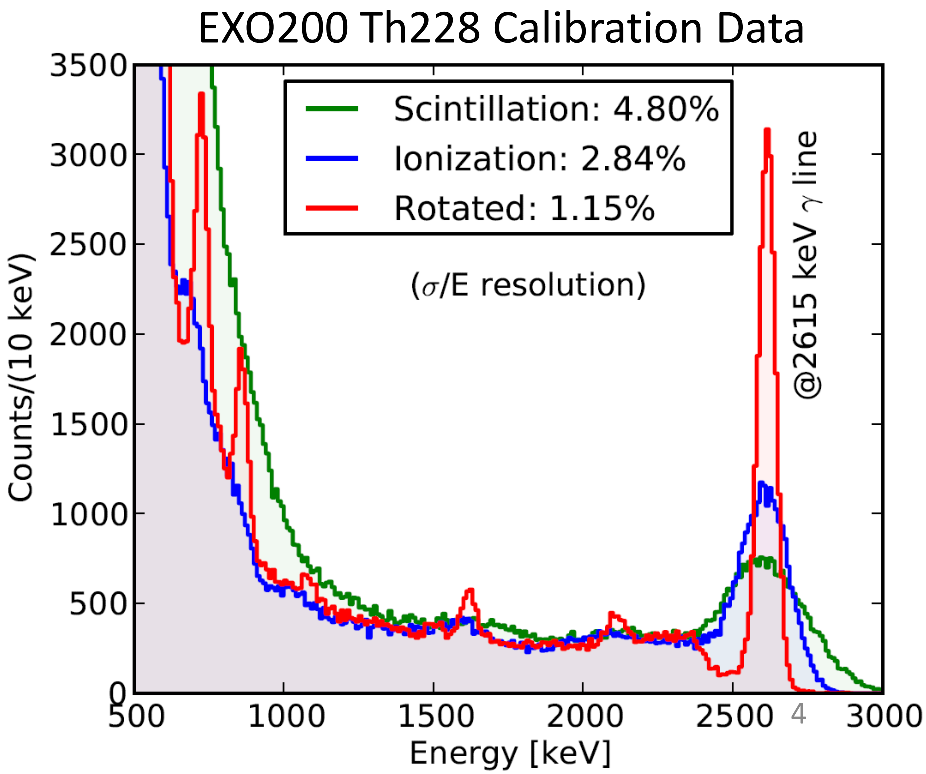


LXe TPC

- Readout prompt light and drifted charge
- Combine both signals with correct anticorrelation coefficient to get best energy estimate
- Charge/Light ratio allow β/α discrimination
- Determine multiplicity with charge clustering (β/γ discrimination)

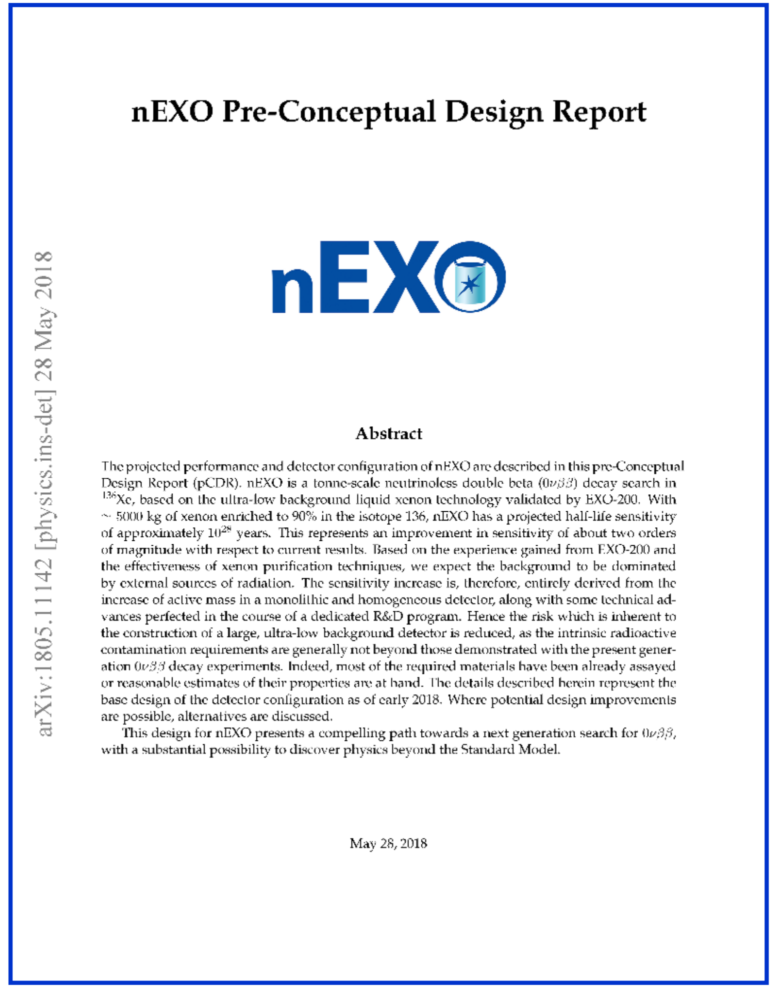






nEXO papers describing the detector, sensitivity, and R&D

- "Simulation of charge readout with segmented tiles in nEXO" arXiv:1907.07512 (July 2019)
- "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.
- "Characterization of the Hamamatsu VUV4 MPPCs for nEXO" arXiv:1903.03663, to appear in Nucl Inst Meth A
- "Study of Silicon Photomultiplier Performance in External Electric Fields" JINST 13 (2018) T09006
- "VUV-sensitive Silicon Photomultipliers for Xe 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)
- "Imaging individual Ba atoms in solid xenon for barium tagging in nEXO" Nature 569 (2019) 203 (Not nEXO baseline)


nEXO Pre-Conceptual Design Report

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

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 $\sim$ 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.

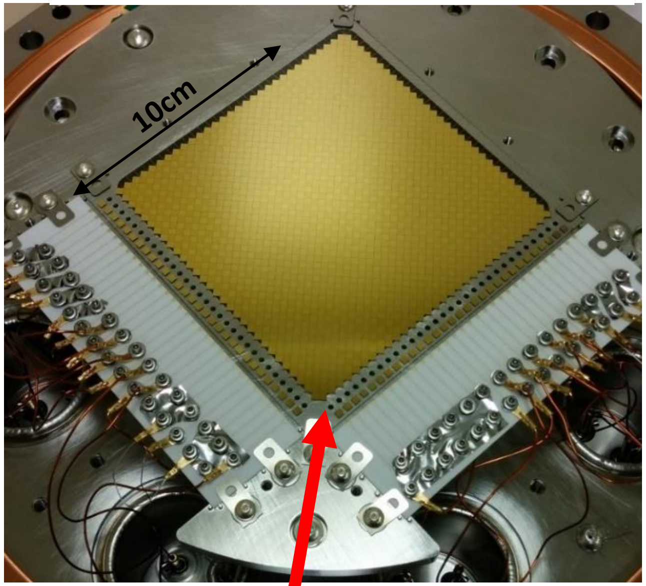
May 28, 2018

Main technical changes on the EXO-200 theme

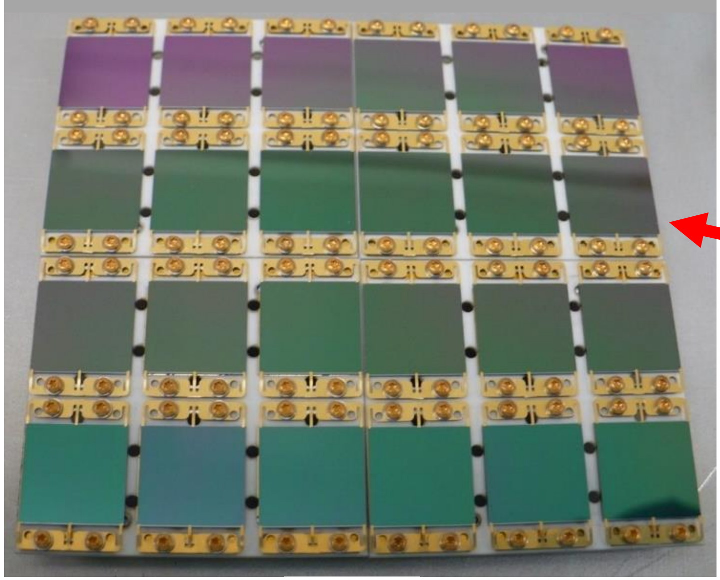
- One drift region
- Silica substrate charge collection tiles
- VUV SiPMs (~4.5m^2)
- ASIC electronics in LXe
- Minimize plastics in the TPC (>10ms purity)

Goal 1% energy resolution @$Q_{\beta\beta}$

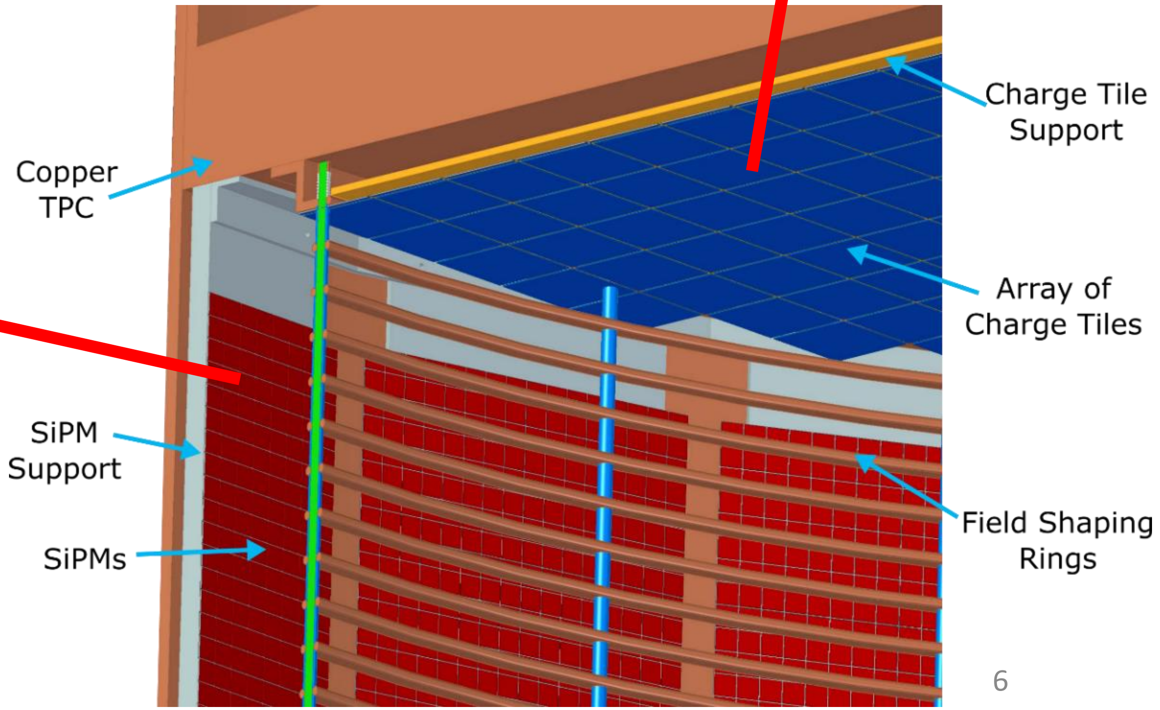
Prototype charge collection tile



Prototype VUV SiPM array (FBK)

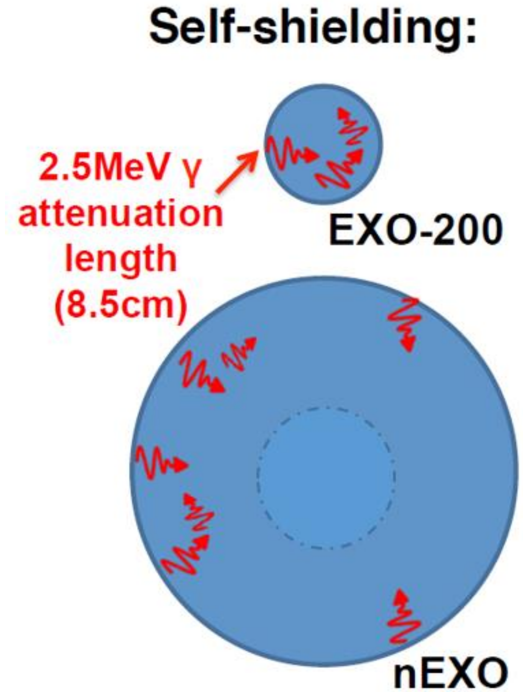


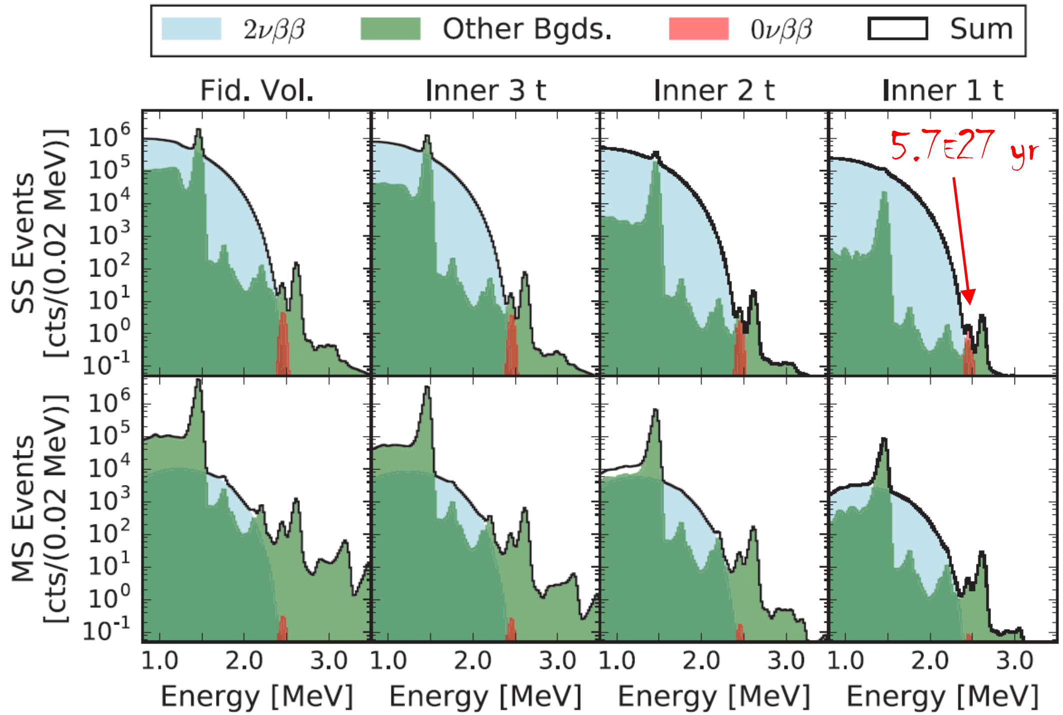
~6cm

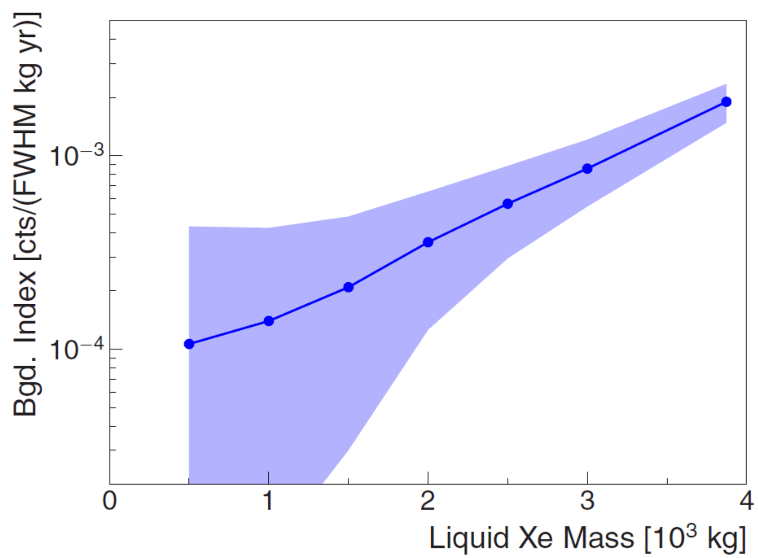


The power of a monolithic detector

- Outer region measures background
- Inner region is shielded and nearly background free
- Fit exploits distributions of backgrounds and signals





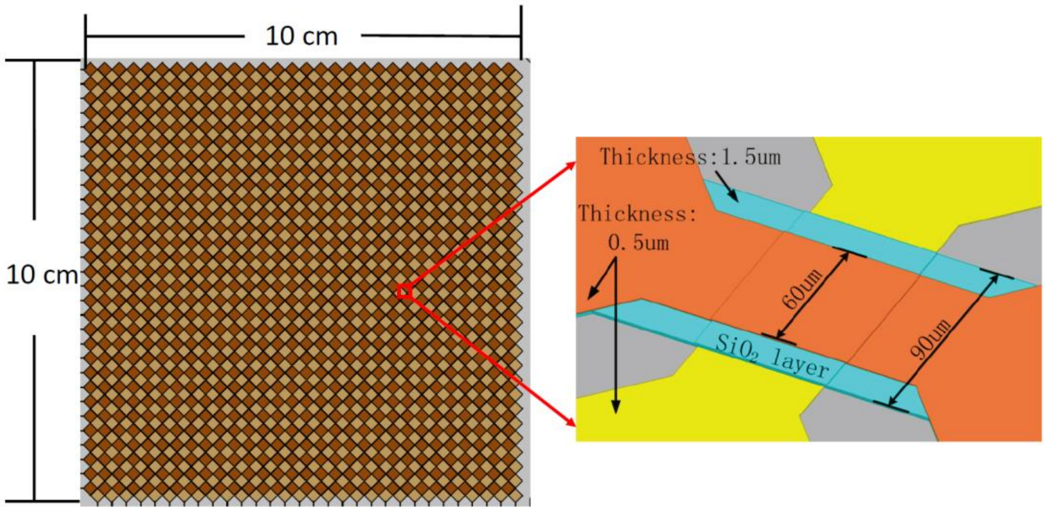


PHYSICAL REVIEW C **97**, 065503 (2018)

Charge collection tiles

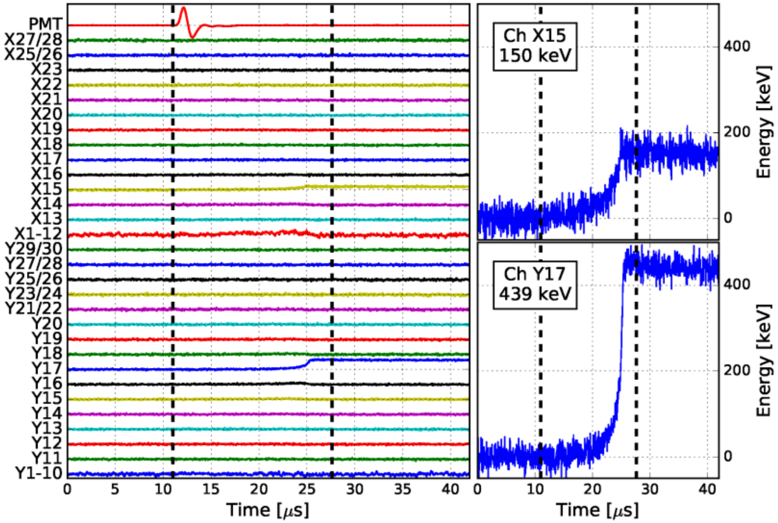
Max metallization cover with min capacitance:

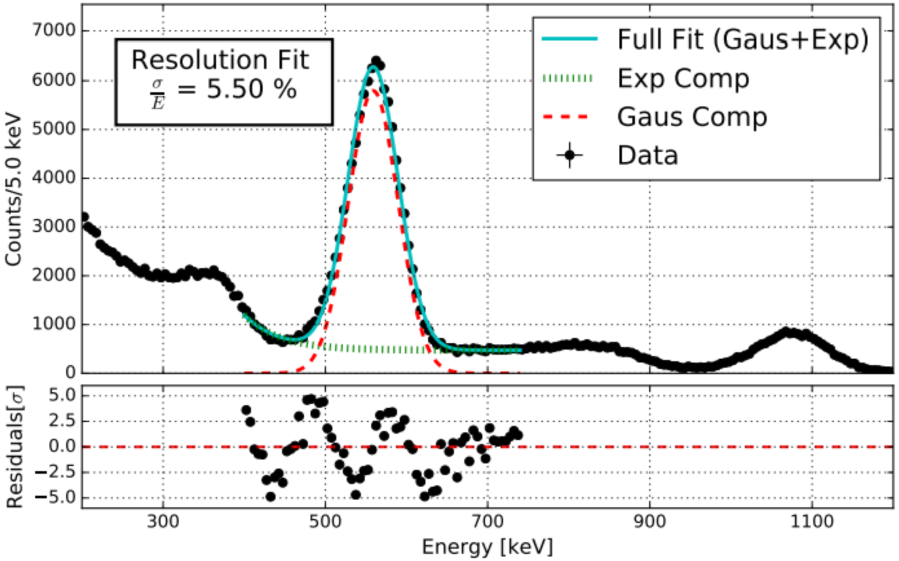
- 80 fF at crossings
- 0.86 pF between adjacent strips



Pulse shape is unusual, because of the absence of a shielding grid.

However, excellent charge only energy resolutions has been achieved.

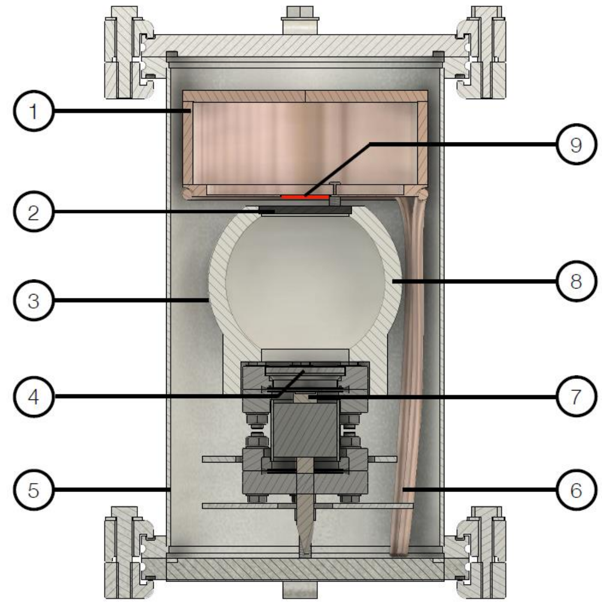




With 1/sqrt(E) scaling that's 2.6% at $Q_{\beta\beta}$ and 1kV/cm field

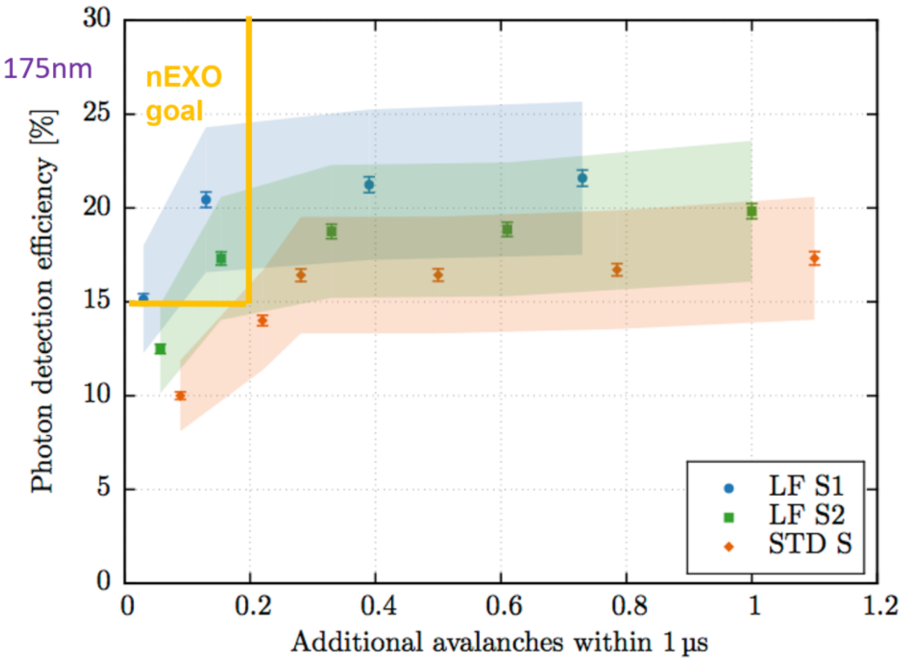
SiPM VUV devices

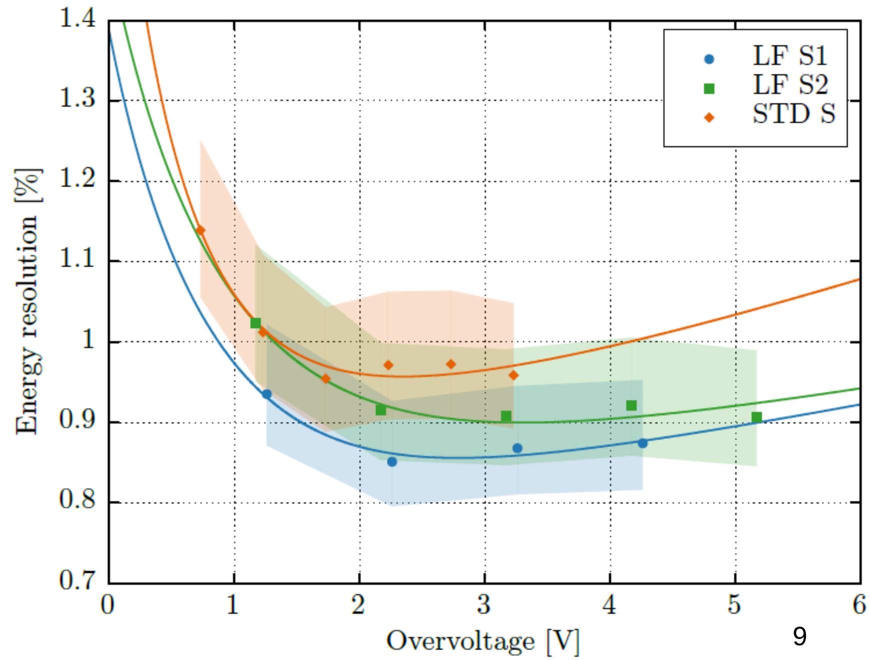
After the first round of R&D, some 1cm² VUV devices now match our desired properties, with a bias of ~30V



nEXO Scintillation Light Detection Goals:

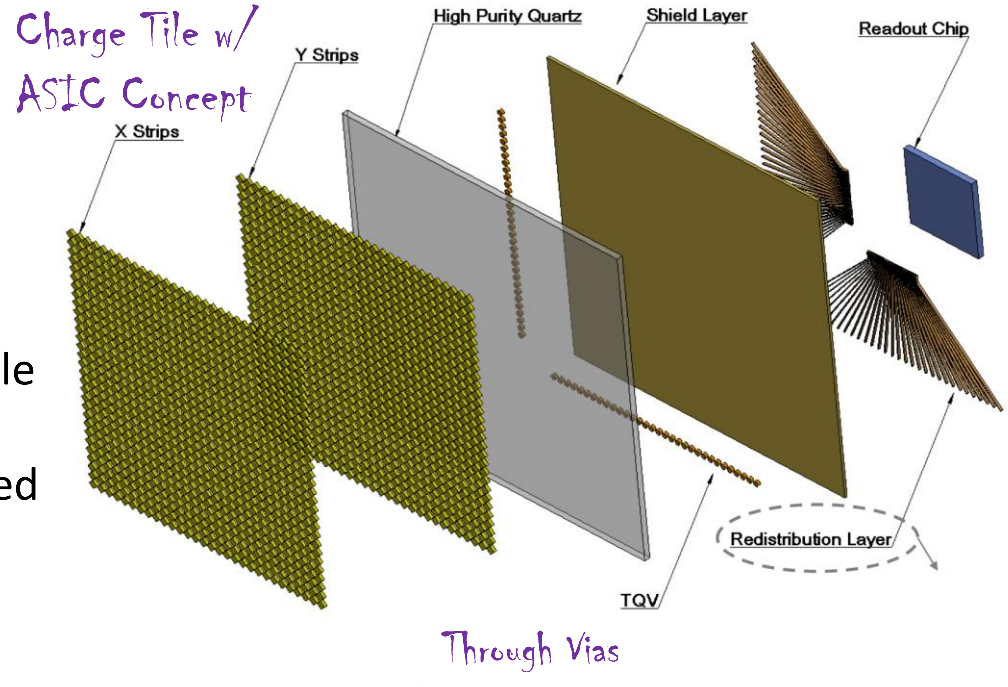
- 20% Photon Transport Efficiency (not a prop of SiPM)
- 15% Photon Detection Efficiency
- <20% additional avalanches within 1us

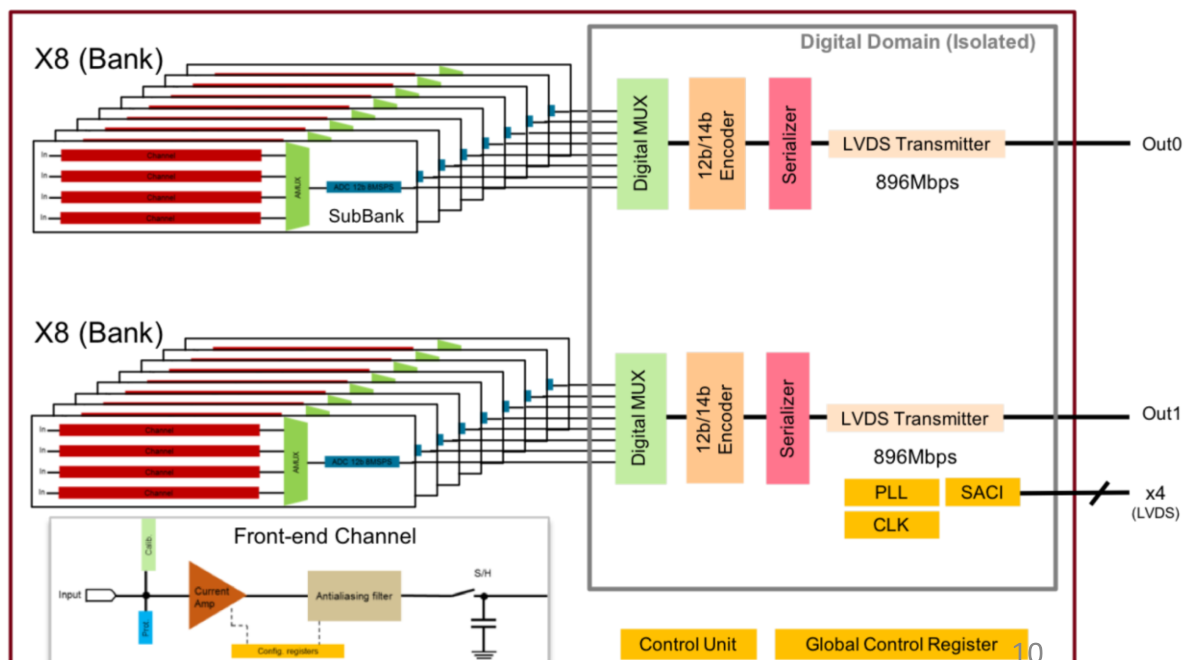




ASICs in LXe

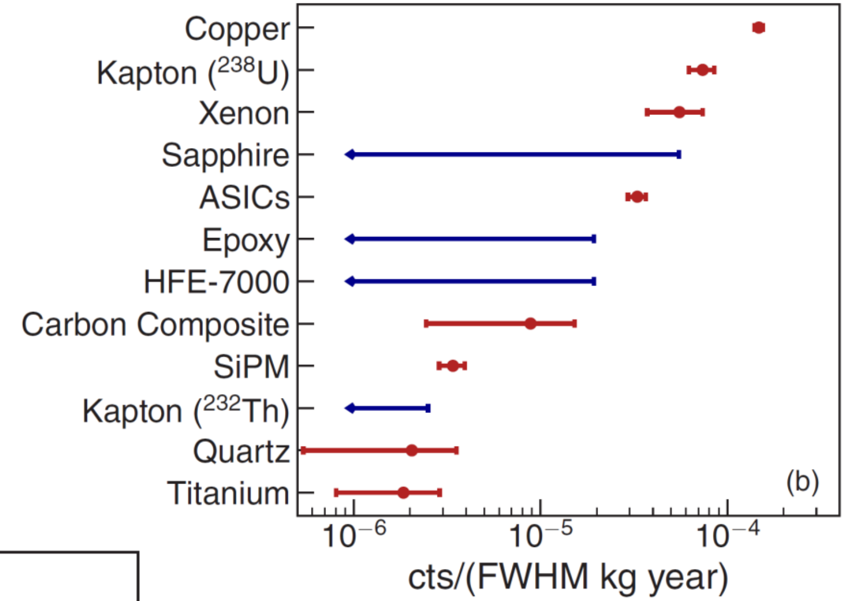
- Cryogenic ASIC for nEXO (and DUNE)
- Shapes and digitizes 64 channels
- Goal: <200e- noise
- Analog input has in-situ programmable shaper and gain on each channel
- First batch of ASICs being characterized now, including cryogenic tests

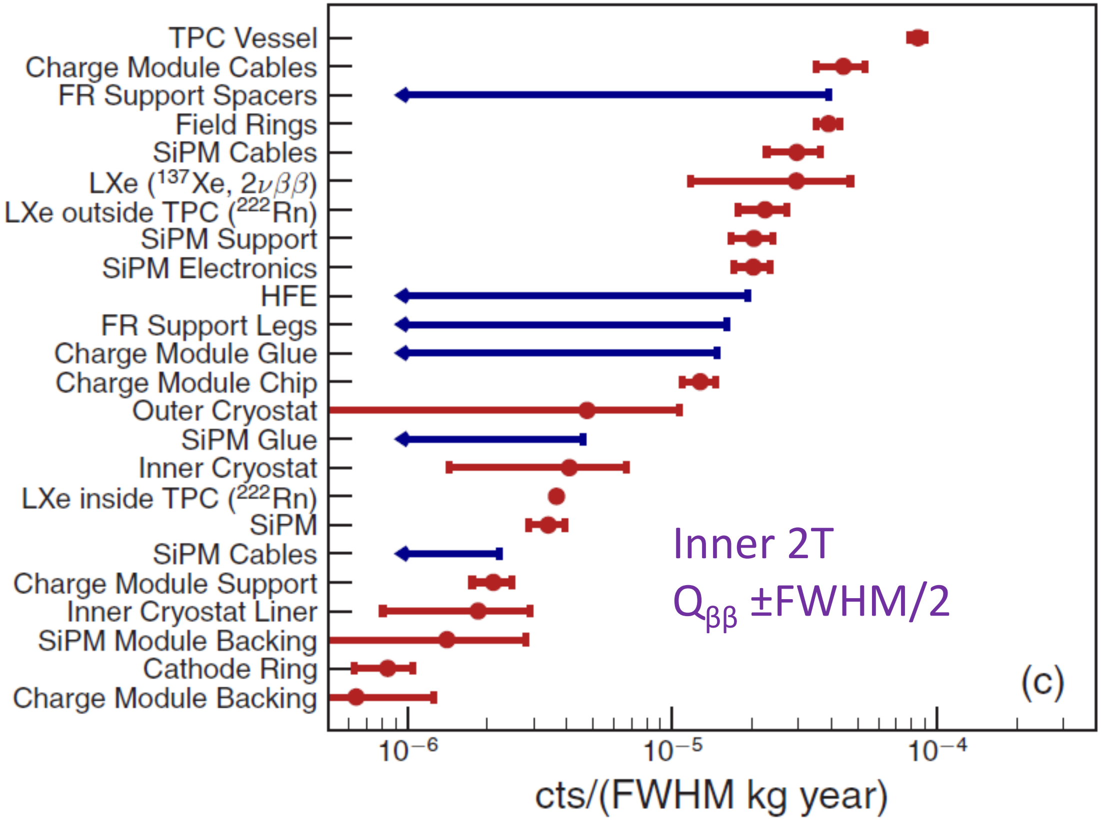




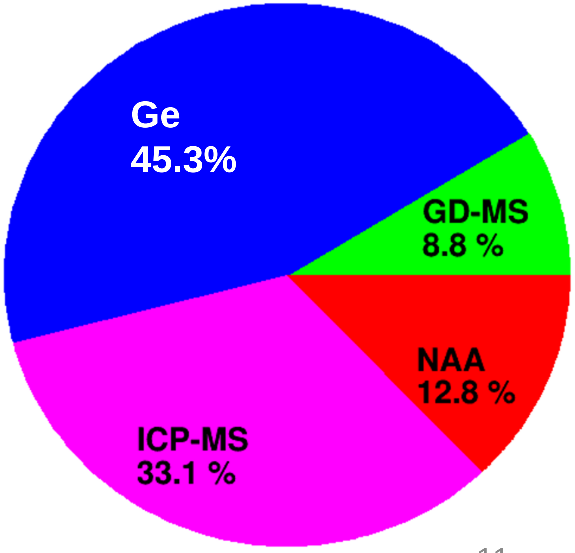
State of Backgrounds

- Actual materials available and assayed
  - some from EXO-200, some new
- nEXO geometry simulated in Geant4 to determine energy depositions
- Reconstruction algorithms based on EXO200 and R&D (and continue to improve)

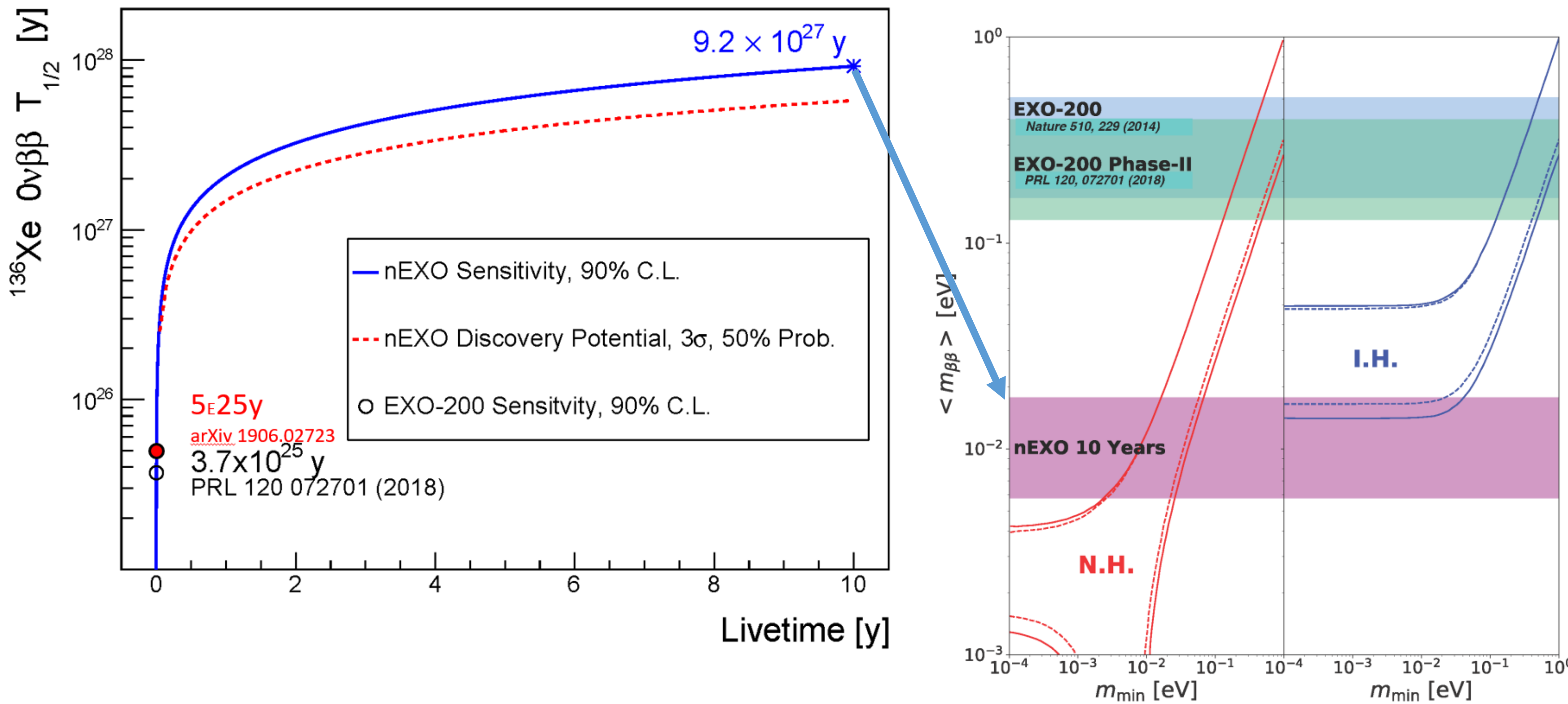




Assay Techniques Used



nEXO Sensitivity Projections

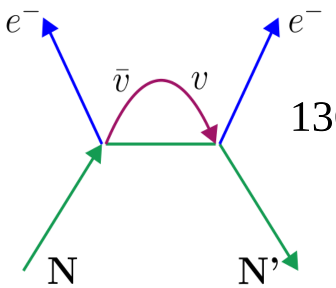


- $g_A = g_A^{free}$=-1.2723
- Band is the envelope of NME:

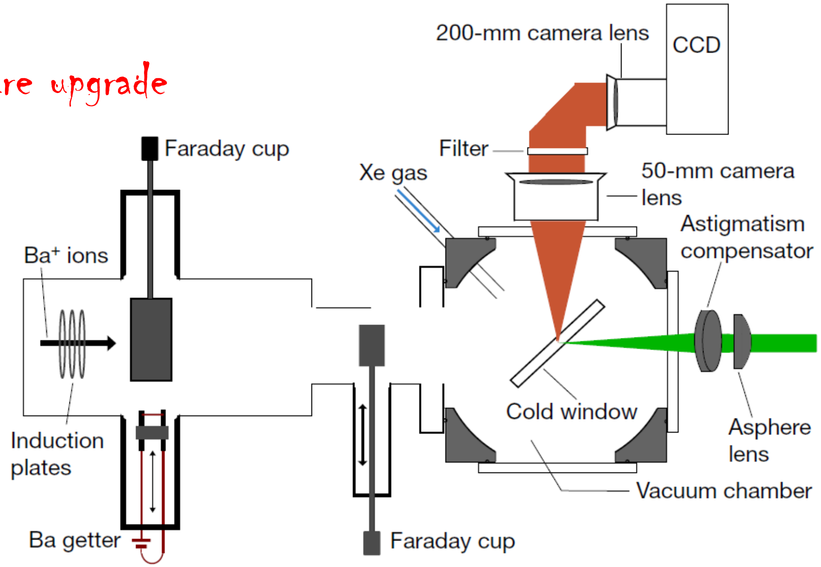
EDF: T.R. Rodríguez and G. Martínez-Pinedo, PRL 105, 252503 (2010)
ISM: J. Menendez et al., Nucl Phys A 818, 139 (2009)
IBM-2: J. Barea, J. Kotila, and F. Iachello, PRC 91, 034304 (2015)
QRPA: F. Šimkovic et al., PRC 87 045501 (2013)
SkyrmeQRPA: M.T. Mustonen and J. Engel PRC 87 064302 (2013)

nEXO Barium Tagging

not nEXO baseline, but possibly a future upgrade



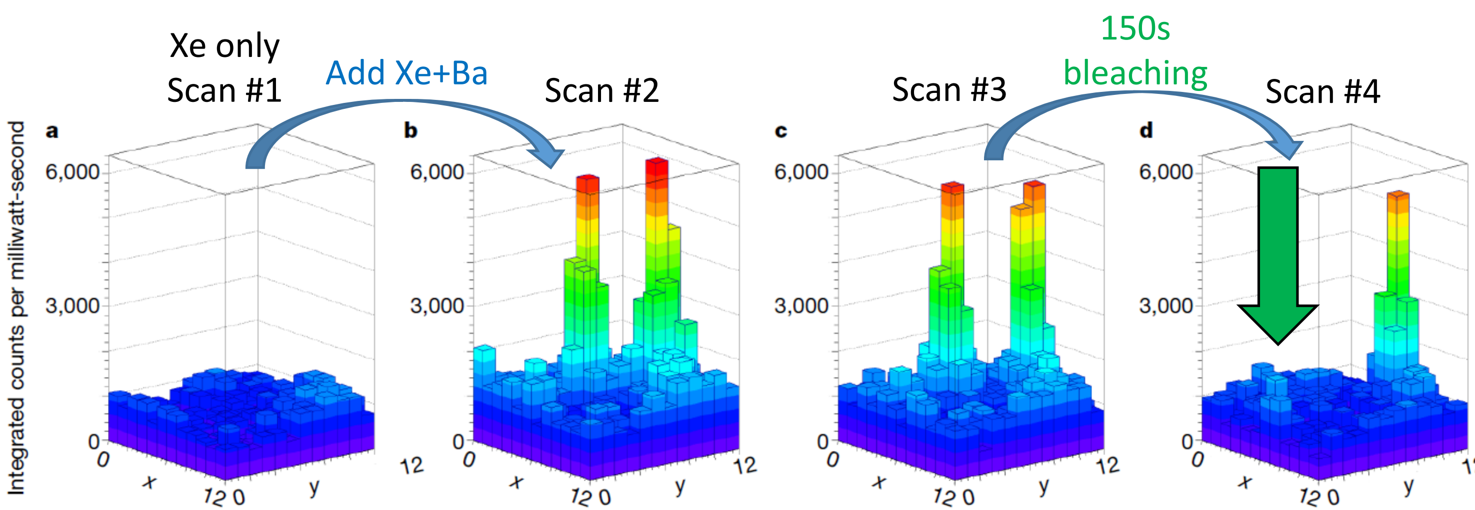
$$^{136}Xe \rightarrow ^{136}Ba^{++} + 2e^-$$



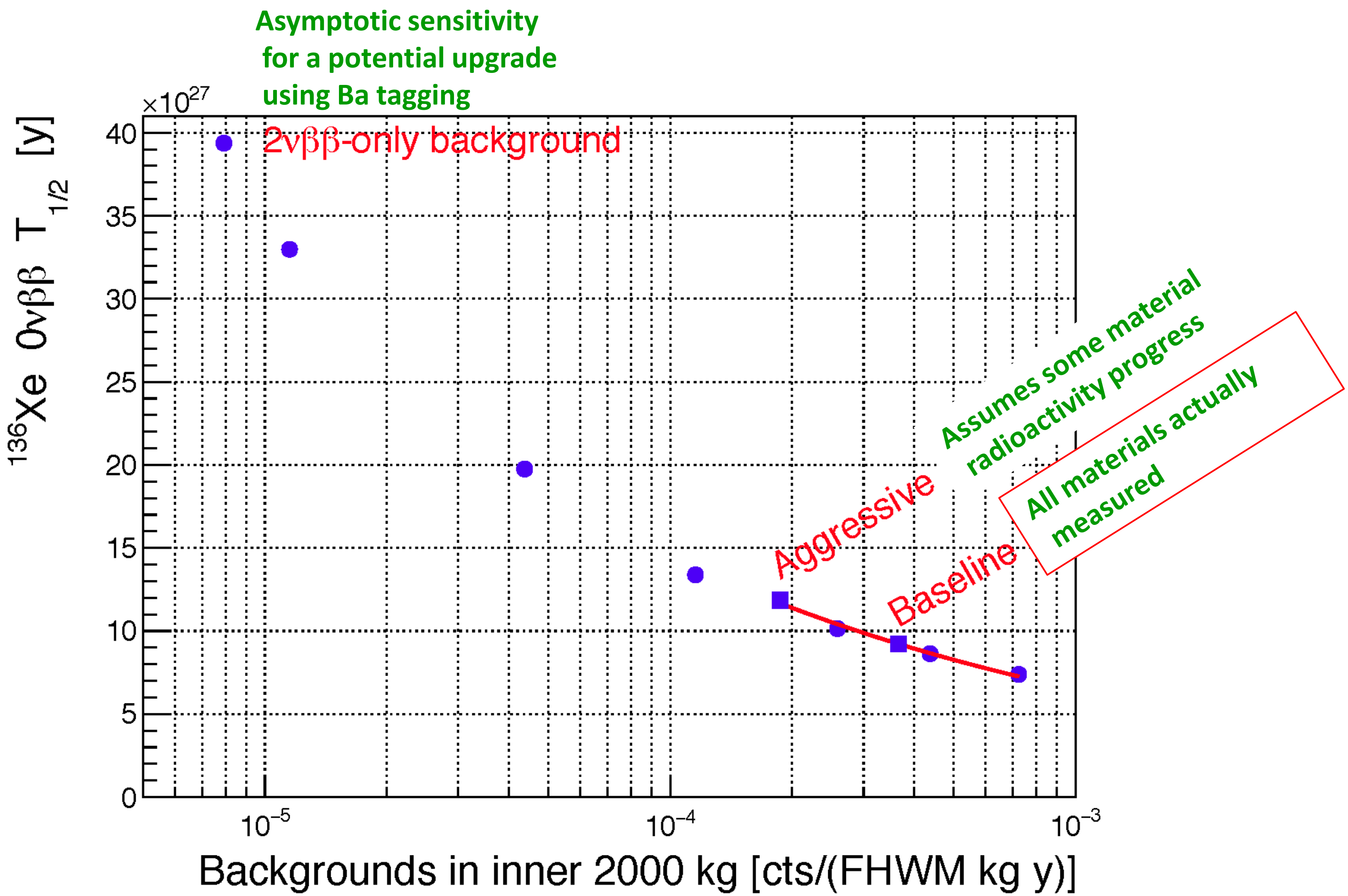
Removes backgrounds other than 2νββ

Demonstrated single Ba atom detection in SXe!

Grabbing from detector and detecting on a probe somewhere still work in progress



Sensitivity vs backgrounds



nEXO

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, D Sinclair, B. Veenstra, J Watkins

Colorado School of Mines, Golden CO, USA --- K. Leach, C. Natzke

Colorado State University, Fort Collins CO, USA --- C Chambers, A Craycraft, D Fairbank, W Fairbank Jr, A Iverson, J Todd

Drexel University, Philadelphia PA, USA --- MJ Dolinski, P Gautam, E Hansen, YH Lin, E Smith, Y-R Yen

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, P Lv, Z Ning, X Sun, T Tolba, W Wei, L Wen, W Wu, 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, J Echevers, S Li, L Yang

Indiana University, Bloomington IN, USA --- JB Albert, SJ Daugherty, G Visser

Laurentian University, Sudbury ON, Canada — B Cleveland, A Der Mesrobian-Kabakian, J Farine, C Licciardi, A Robinson, U Wichoski

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 --- S Al Kharusi, T Brunner, L Darroch, T McElroy, K Murray, T Totev,

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

Rensselaer Polytechnic Institute, Troy NY, USA — E Brown, K Odgers

Université de Sherbrooke, Sherbrooke QC, Canada --- 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 --- S Delaquis, A Dragone, G Haller, LJ Kaufman, B Mong, A Odian, M Oriunno, PC Rowson, K Skarpaas

University of South Dakota, Vermillion SD, USA --- T Bhatta, A Larson, R MacLellan

Stanford University, Stanford CA, USA --- J Dalmasson, R DeVoe, G Gratta, M Jewell, S Kravitz, B.Lenardo, G Li, M Weber, S Wu

Stony Brook University, SUNY, Stony Brook NY, USA --- K Kumar, O Njoya

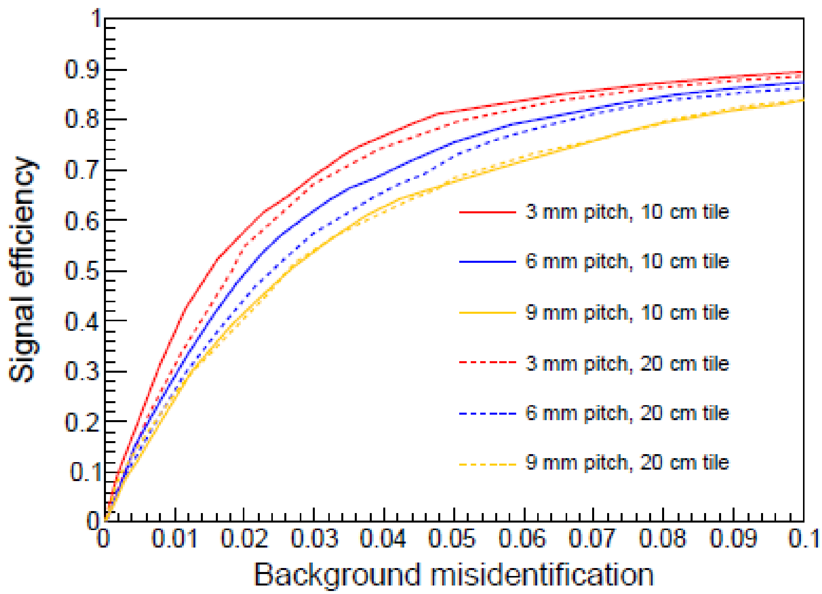
Technical University of Munich, Garching, Germany --- P Fierlinger

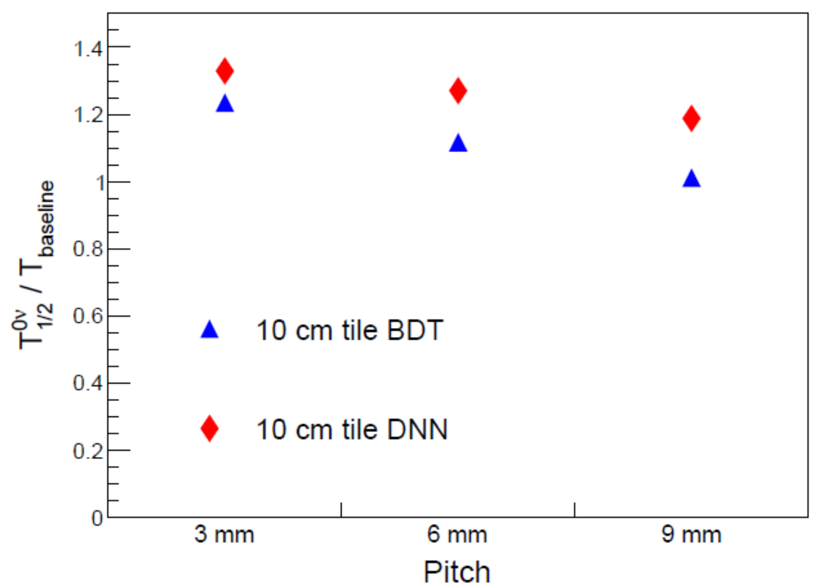
TRIUMF, Vancouver BC, Canada --- J Dilling, P Gumplinger, R Krücken, Y Lan, F Retière, V Strickland

Yale University, New Haven CT, USA — A Jamil, Z Li, D Moore, Q Xia

Charge collection tile studies

- Studying pitch effect on sensitivity
- Also, using new DNN/BDT reconstruction shows improved sensitivity over traditional reconstruction





"Simulation of charge readout with segmented tiles in nEXO" arXiv:1907.07512 (July 2019)

Sensitivity paper BG fit