Recent results of EXO-200 and sensitivity of nEXO

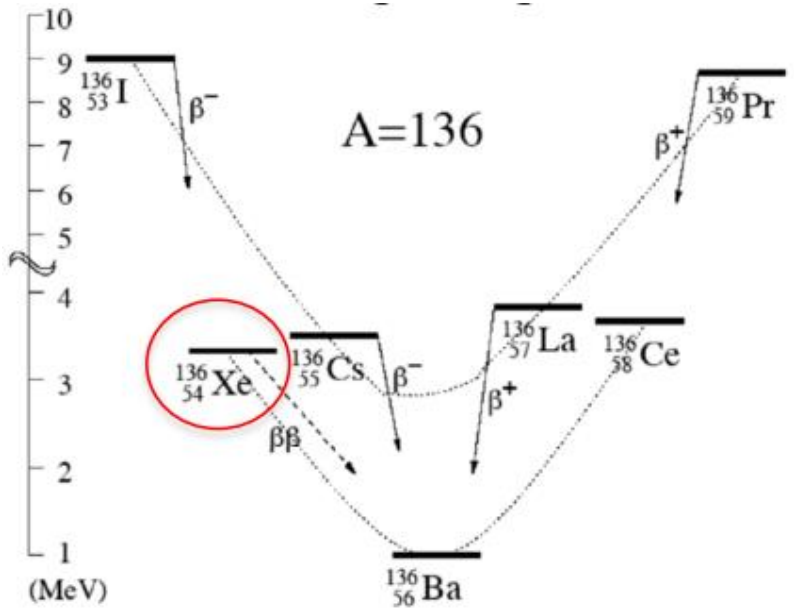
MATTHEW COON FOR THE EXO-200 COLLABORATION
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
DPF 2017, FERMILAB CHICAGO

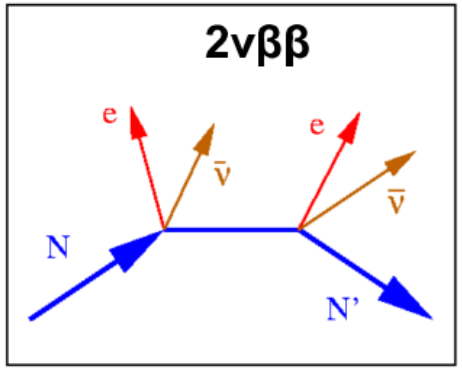
0νββ with ^{136}Xe:

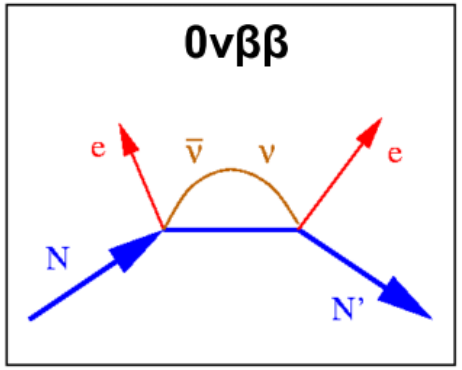
$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$, Q-value 2458 keV

- Double Beta decay is the most sensitive probe for the Majorana nature of the neutrino.

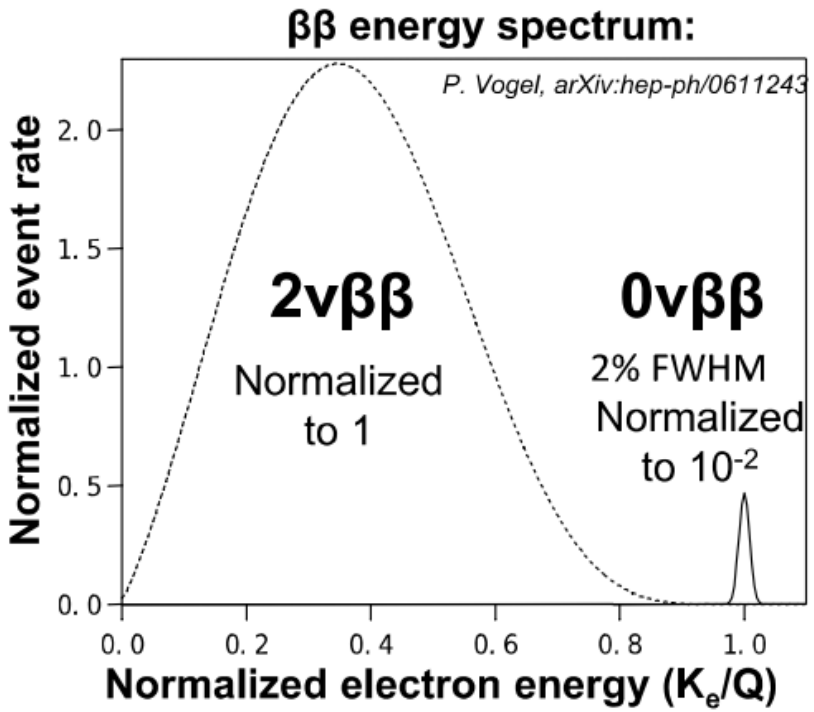
- Observation of the 0νββ would provide:
  - A lepton number violating process for physics beyond the standard model.
  - Imply the Majorana nature of the neutrino.
  - Constrain the absolute mass scale of the neutrino.







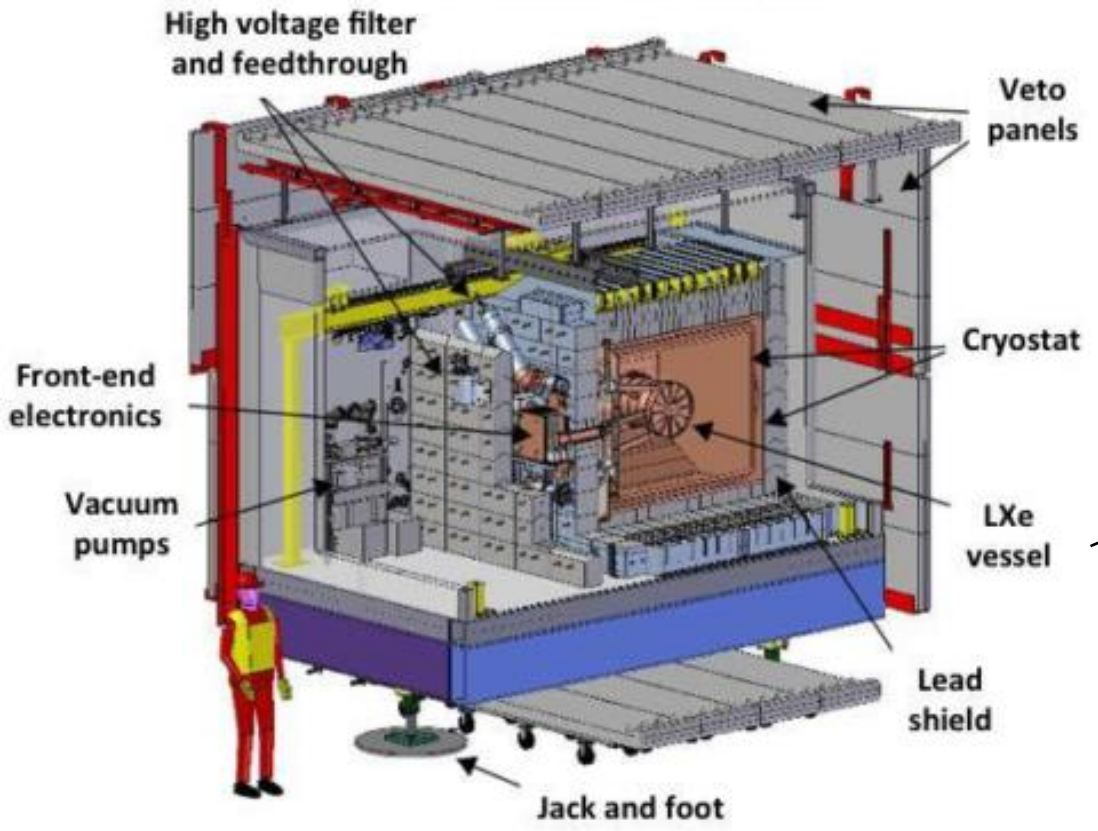
If neutrino is Majorana particle, decay can proceed without emitted neutrinos giving a peak at the Q-value.



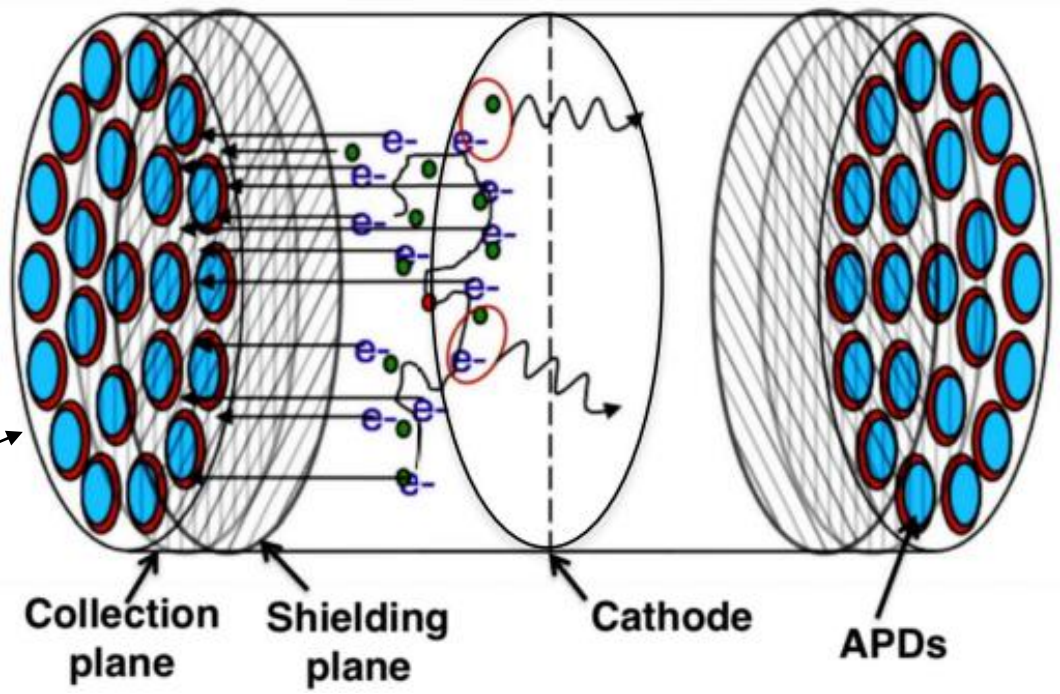
EXO-200 Detector:

- Radiopure TPC filled with LXe enriched to 80.6%
- Simultaneous measurements of both light and charge:
  - light collection with large avalanche photo-diode (APD) planes.
  - charge collection with 2 wire grids (induction and collection on each wire grid set).
- HV is applied between the cathode in the middle of the TPC and anodes placed at each opposing end of the TPC.
- Monolithic detector provides great background rejection capabilities.

Detector schematic:



Full 3D reconstruction of events



EXO-200 operations:

EXO-200 is located at the Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM approx. 2,150 ft. underground.

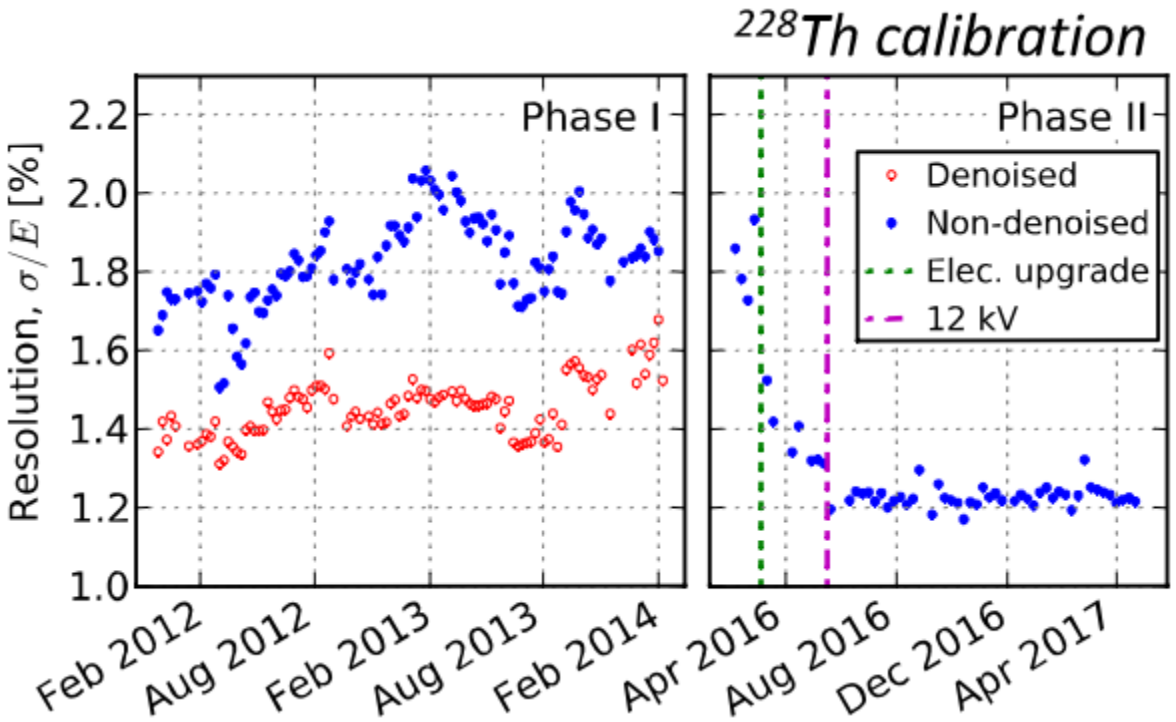
Phase-I

- Sep 2011 to Feb 2014
  - Total live time 596.7 days
- Selected physics results
  - Most precise 2νββ measure
    - *Phys. Rev. C* ***89****, 015502 (2013)*
  - Stringent 0νββ searches
    - *Nature* ***510****, 229 (2014)*
    - Sensitivity $T_{1/2}^{0\nu\beta\beta} > 1.9\times10^{25}$ yr (90%CL)

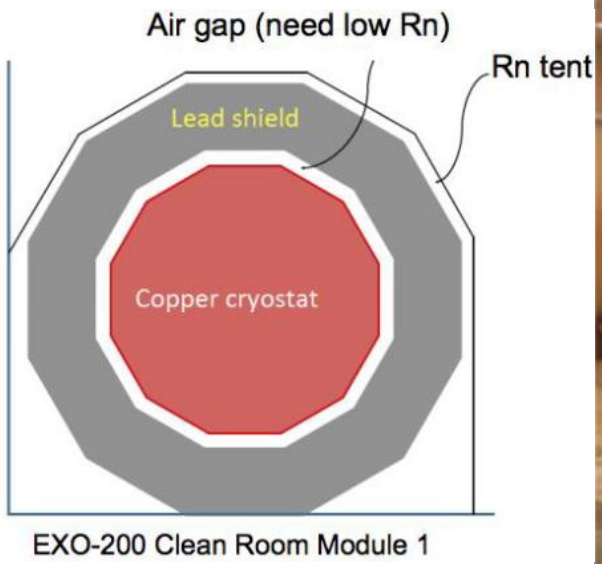
Phase-II

- Access regained in 2015 after stop imposed by WIPP accidents
- Jan to May 2016
  - Hardware upgrades
- HV raised by 50% in May 2016
  - Live time 271.8 days
- Physics results: this talk!

Detector upgrades for Phase II:



- Front-end readout electronics replaced, reducing APD readout noise.
- HV raised by 50% from -8kV -> -12kV.
- Energy Resolution:
  - Phase I: σ/E(Q) = 1.38%
  - Phase II: σ/E(Q) = 1.23%



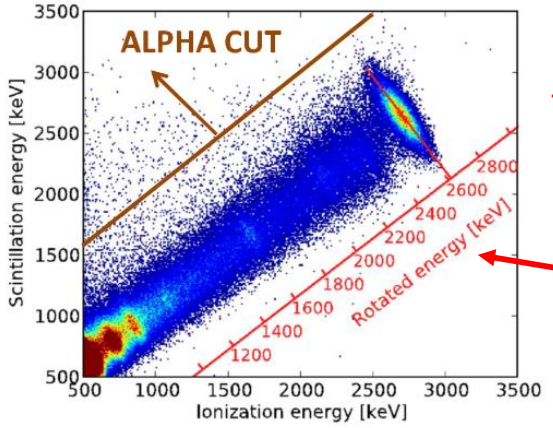
- System to suppress radon from the air gap. (Not removing radon from LXe!)
- Direct air sampling shows radon reduction by factor greater than 10.

Detector Performance:

Energy Resolution:

Use anticorrelation between scintillation and ionization energy.

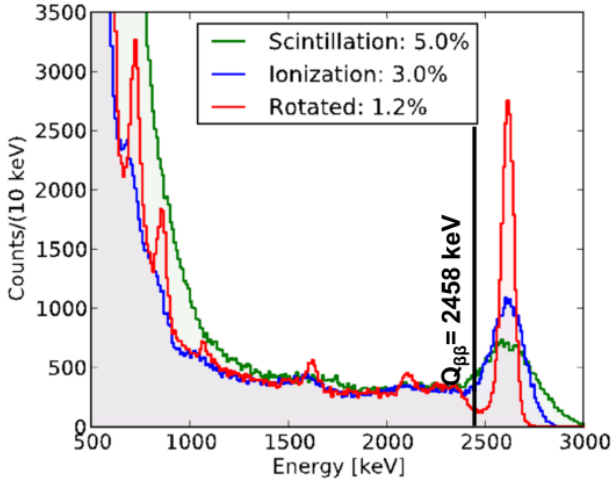
Scintillation vs. ionization, ^{228}Th calibration:



Use rotated energy axis to optimize resolution in the energy region of interest.

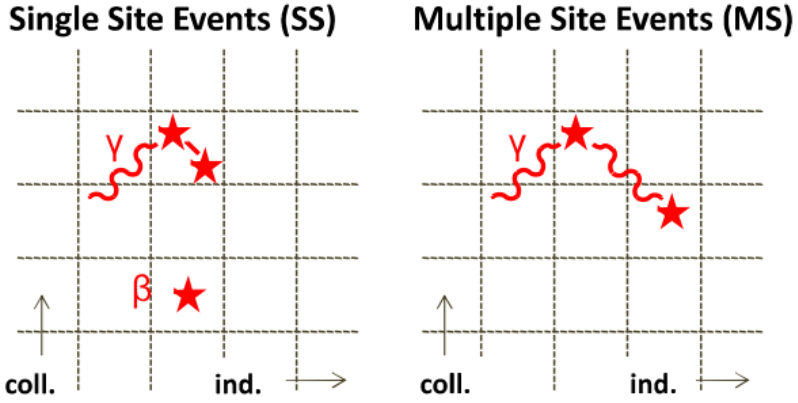
Use light/charge ratio to cut α's from β/γ events

Reconstructed energy, ^{228}Th calibration:



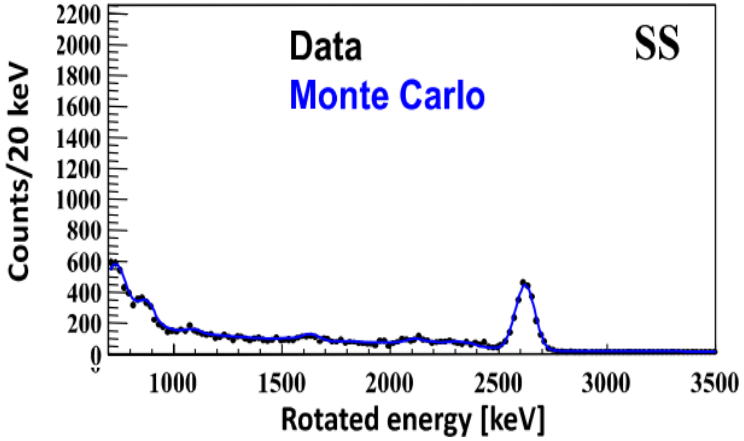
Position Discrimination:

Using induction and collection wire grids, categorize single-site (SS) and multi-site (MS) events giving discrimination between γ-like events and β-like events.

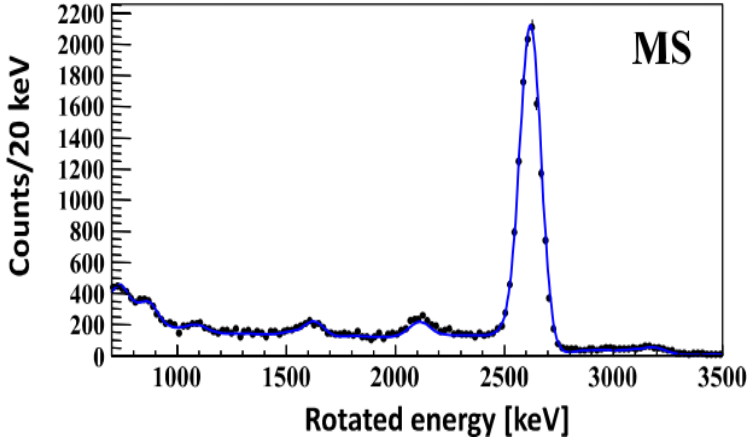


- SS fraction approx. 20% in energy ROI.
- Calculate "standoff" distance (SD) for each event where β-like events should be more evenly distributed throughout TPC.

Energy spectrum, ^{228}Th calibration data, SS:



Energy spectrum, ^{228}Th calibration data, MS:

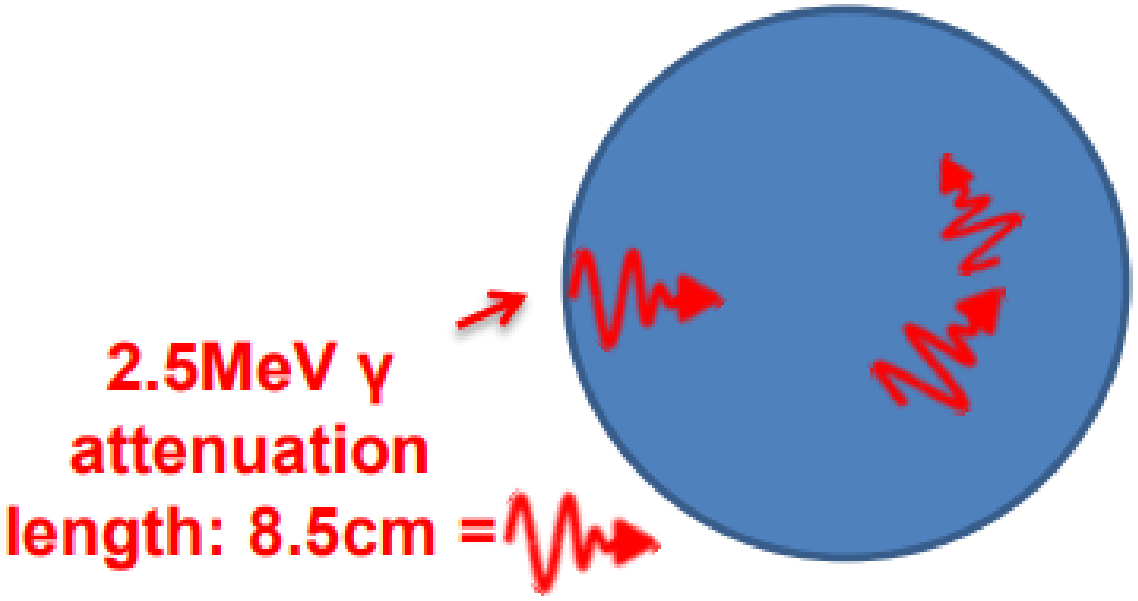


Detector Performance:

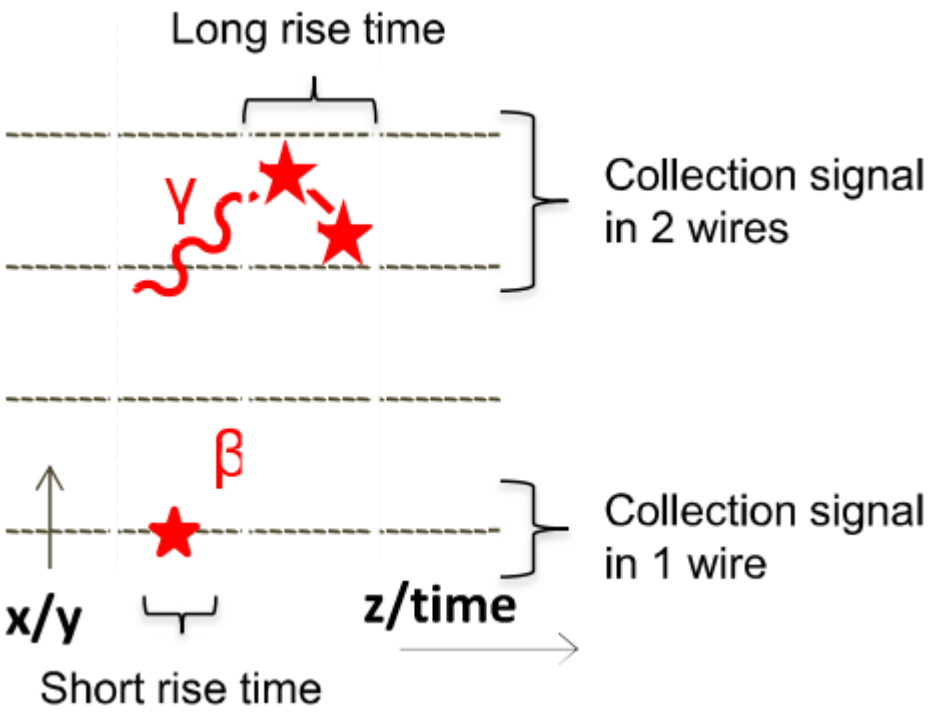
Spatial distribution of standoff distance:

- Calculate standoff distance of each event.
- LXe self shielding provides independent measurement of γ backgrounds.
- Looking at the distribution of standoff distances for each event, β events will be more uniformly distributed throughout the TPC. (additional discrimination between β/γ)

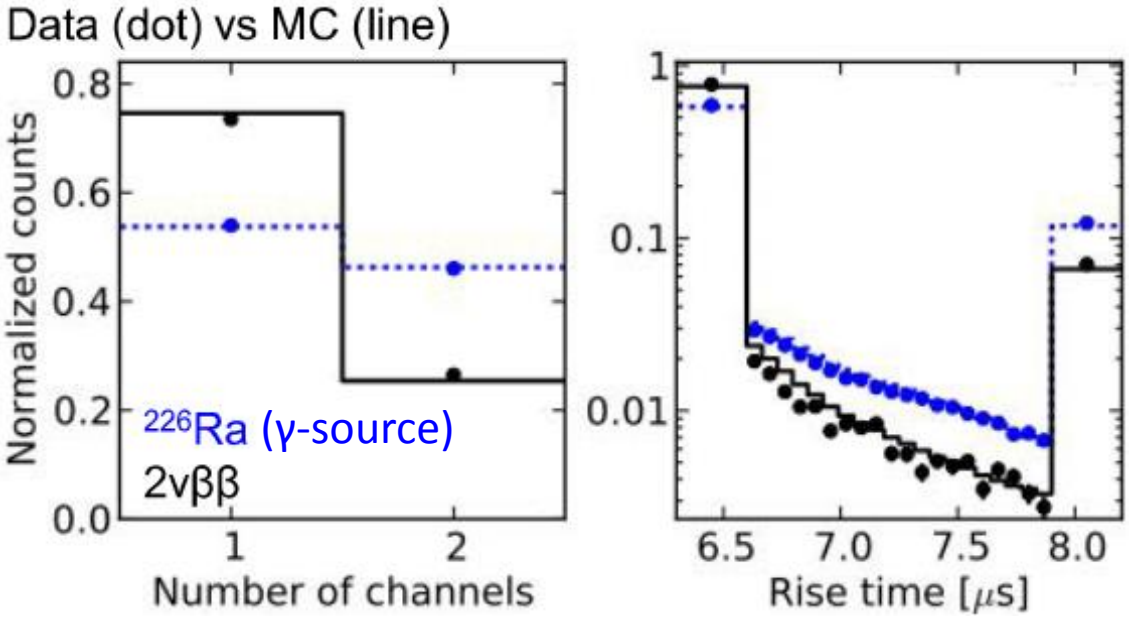
LXe self-shielding:



Further discrimination between γ's and β's:



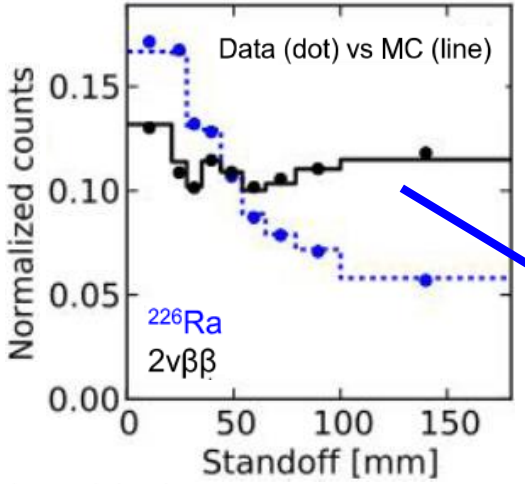
- Allow further γ-like rejection in SS events by looking at cluster size.



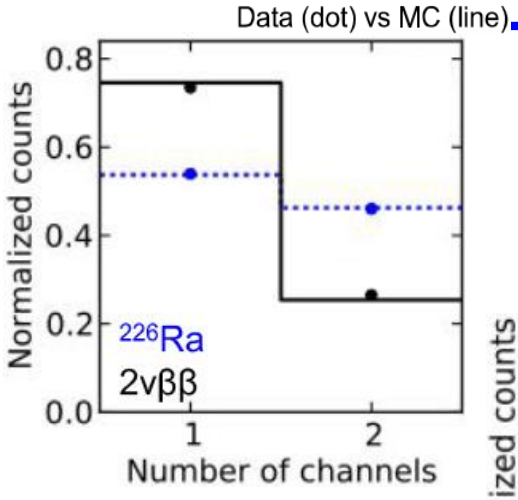
Discriminators for fit:

- Energy
- SS/MS

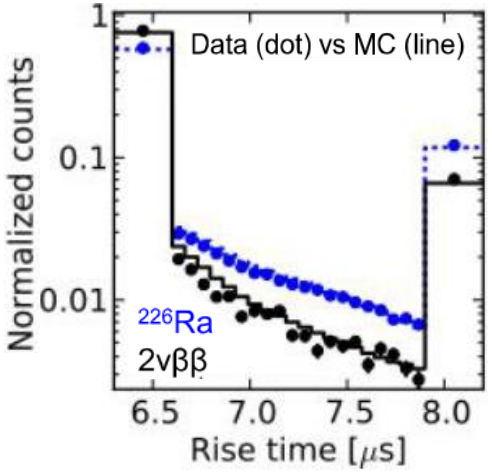
- Standoff Distance



- Number of channels in SS.



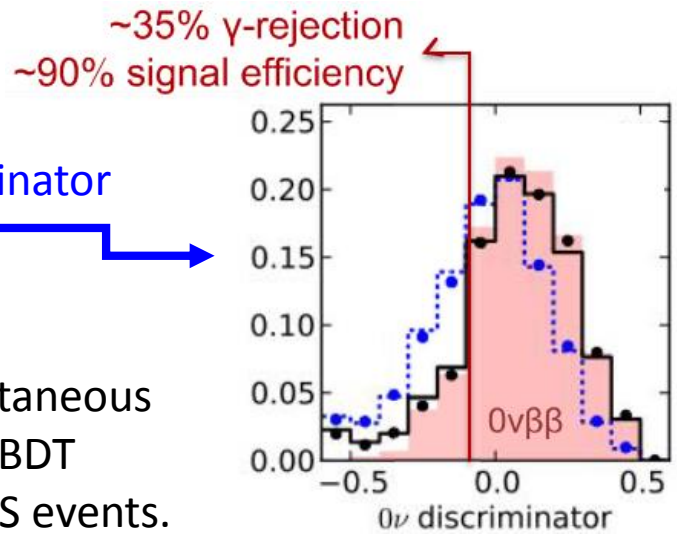
- Signal rise times in SS.



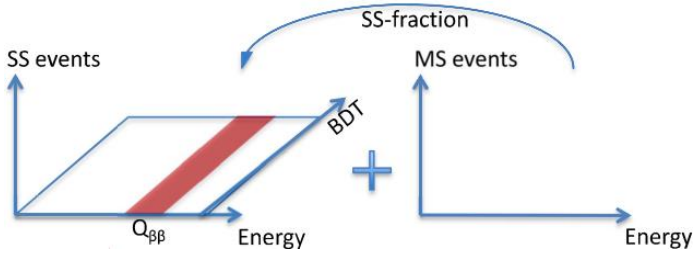
- Combine SD, Number of collection channels, and Rise time into one variable using Boosted decision tree (BDT) machine learning.

- BDT gives approx. 15% sensitivity improvement.

BDT Discriminator



- Final fit will be simultaneous ML with energy and BDT variable trained on SS events.

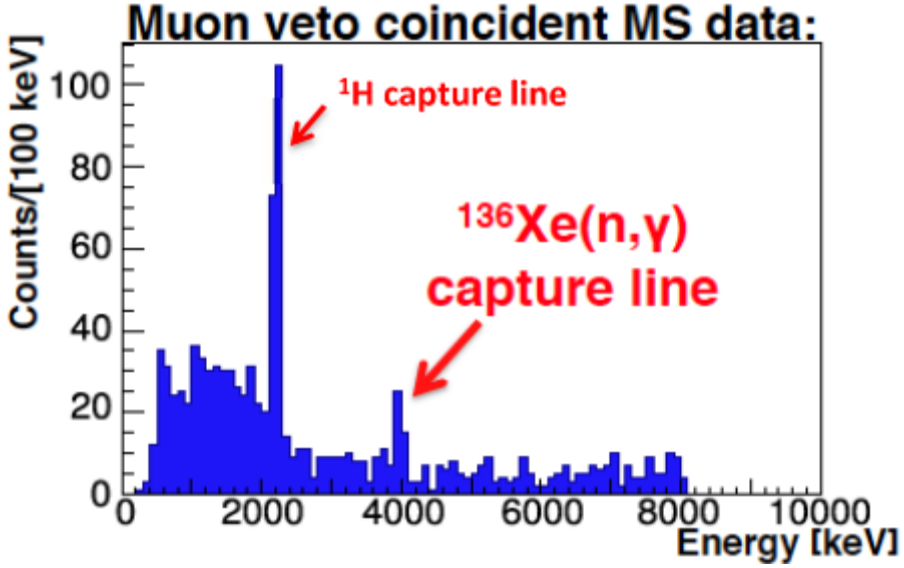


Neutron capture and β-decay of ^{137}Xe:

Muons entering the TPC can create neutron showers, yielding neutron capture via ^{136}Xe + n -> ^{137}Xe, which then β-decays.

- Can suppress ^{137}Xe β-decay using veto panel and de-excitation γ's information.

JCAP ***1604***, *029 (2016)*



- Veto same half of the TPC as the γ for approx. 5 half-lives (19.1 min).
- Exposure loss approx. 3%.
- Approx. 25% rejection, Phase-I: 7 -> 4.4 counts.

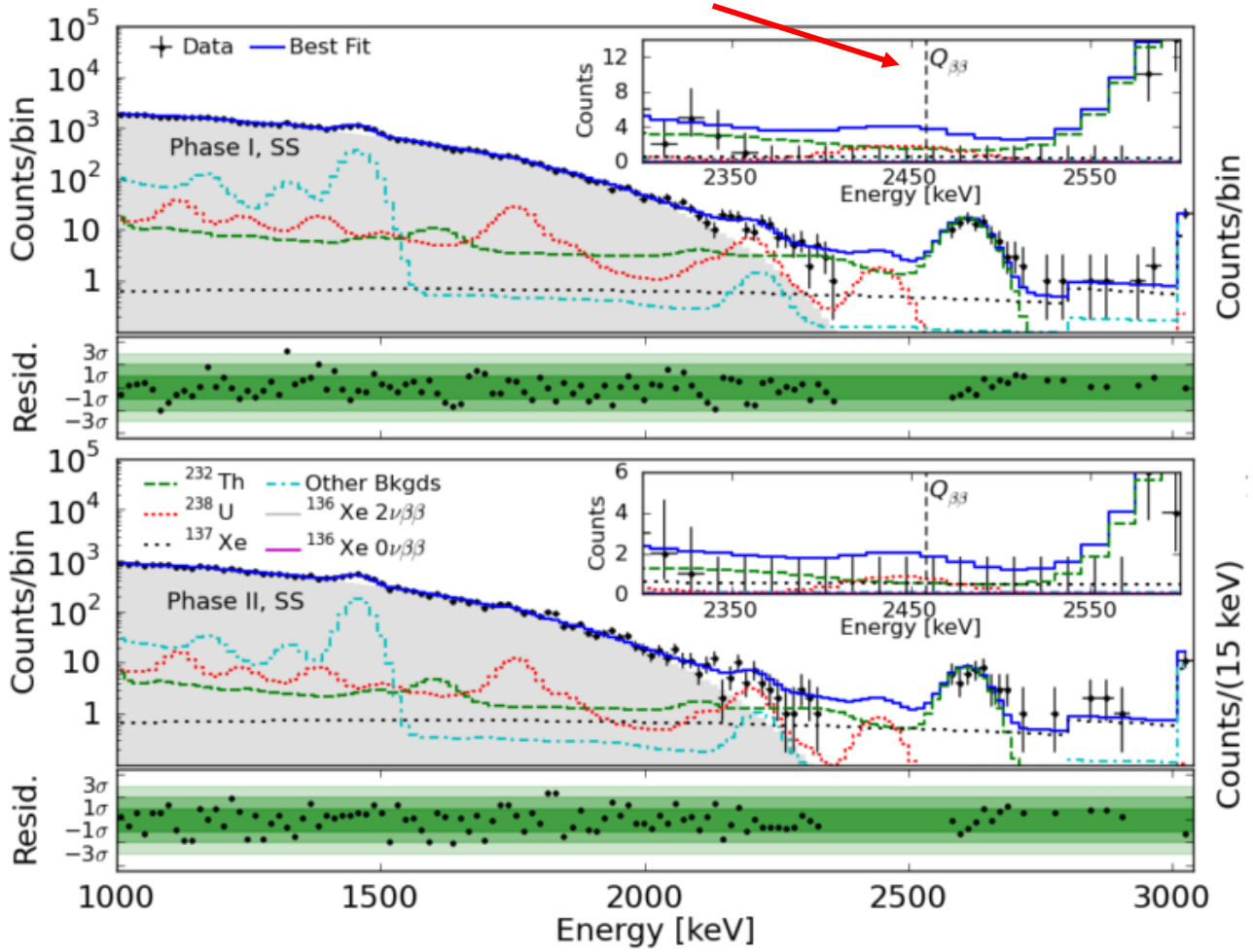
Nature ***510***, *229 (2014)*

Backgrounds in Q ± 2σ:	
Th chain	16.0
U chain	8.1
Xe-137	7.0
Total	31.1 ± 3.8

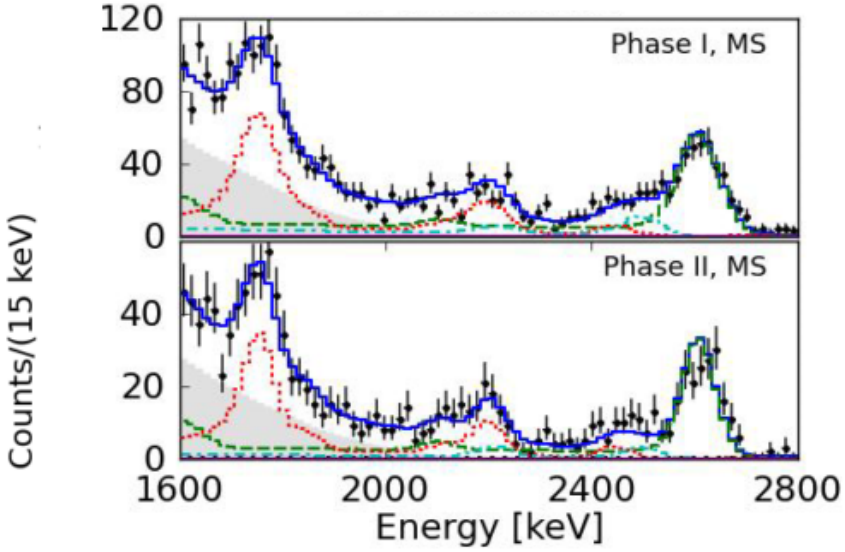
Blinded:

- Blind analysis.
- Background model + fit → ML fit.
- Combined phase-I and phase-II profiles. (Total exposure of 177.6 kg yr)

Blinded energy ROI



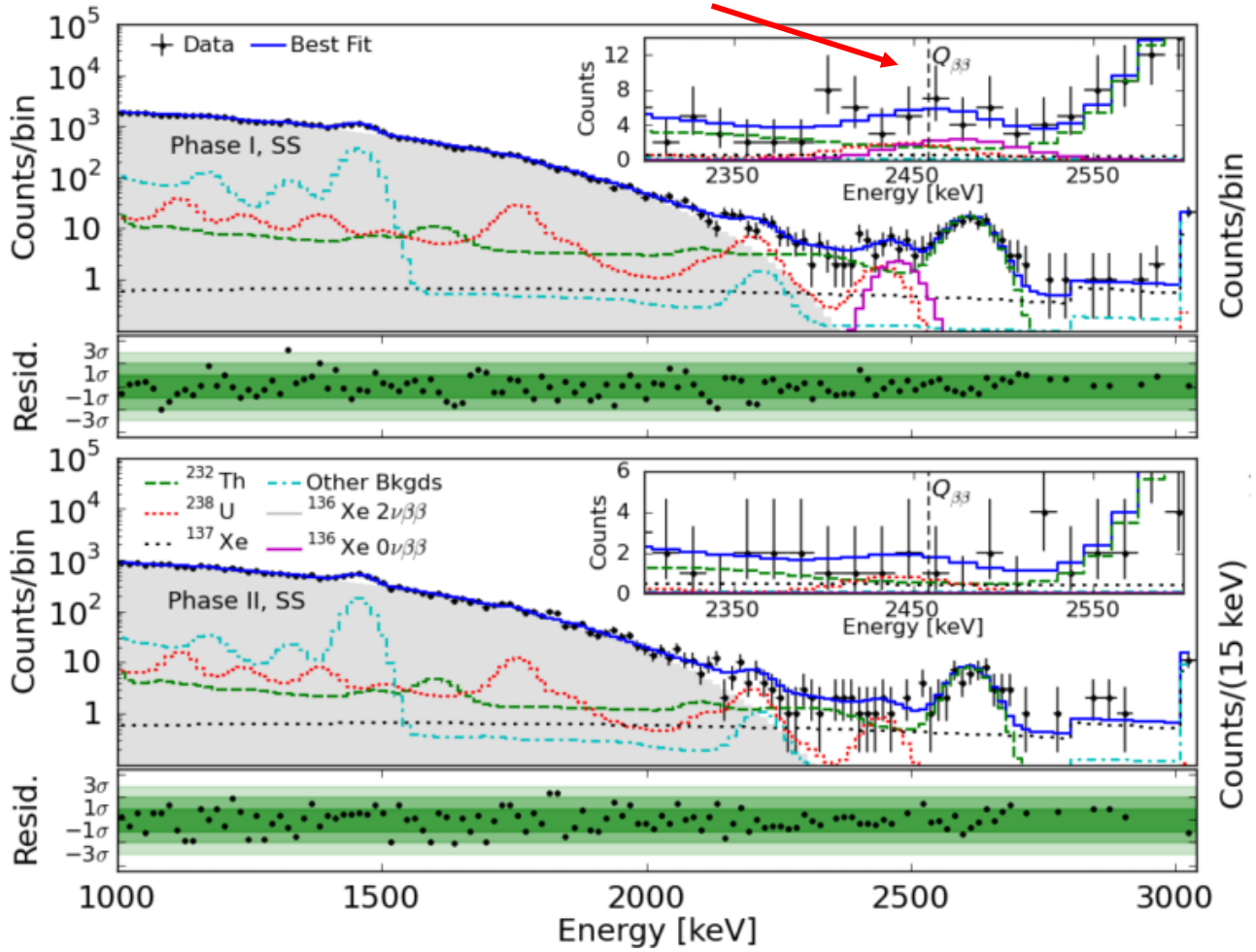
Systematics	Phase I (%)	Phase II (%)
Detection efficiency	82.4 ± 3.0	80.8 ± 2.9
Shape differences	±6.2	±6.2
SS fraction	±5.0	±8.8



Un-blinded:

- Blind analysis.
- Background model + fit → ML fit.
- Combined phase-I and phase-II profiles. (Total exposure of 177.6 kg yr)

Un-blinded energy ROI



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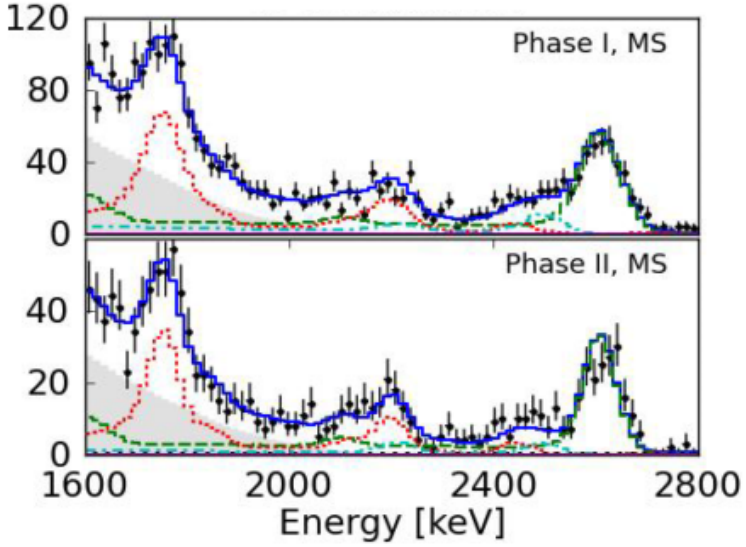


- No statistical excess in energy ROI.
- Combined p-value of approx. 1.5σ.

Results:

- Results show no statistical excess of events in the energy ROI with 177.6 kg yr exposure.
- 0νββ sensitivity improved by a factor of 2.

Sensitivity of 3.7×10^{25} yr (90% CL)

$$T_{1/2}^{0\nu\beta\beta} > 1.8 \times 10^{25} \text{ yr}$$

$$\langle m_{\beta\beta} \rangle < 147 - 398 \text{ meV}$$

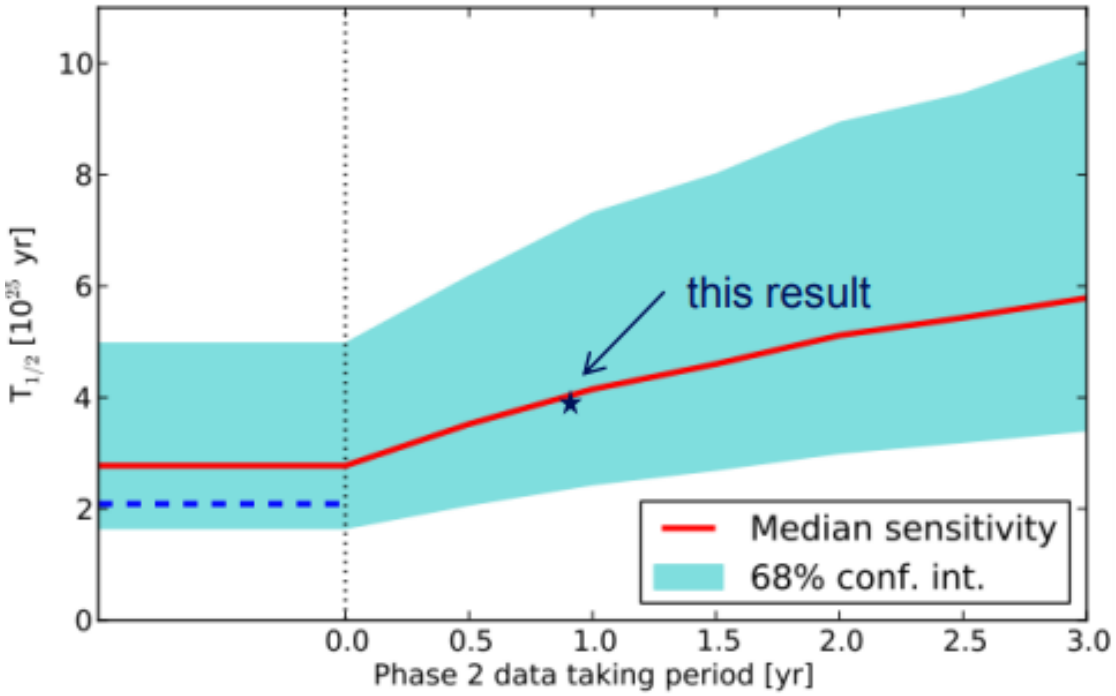
(90% C.L.)

arXiv: 1707.08707

- Independent analysis of phase-I and phase-II.

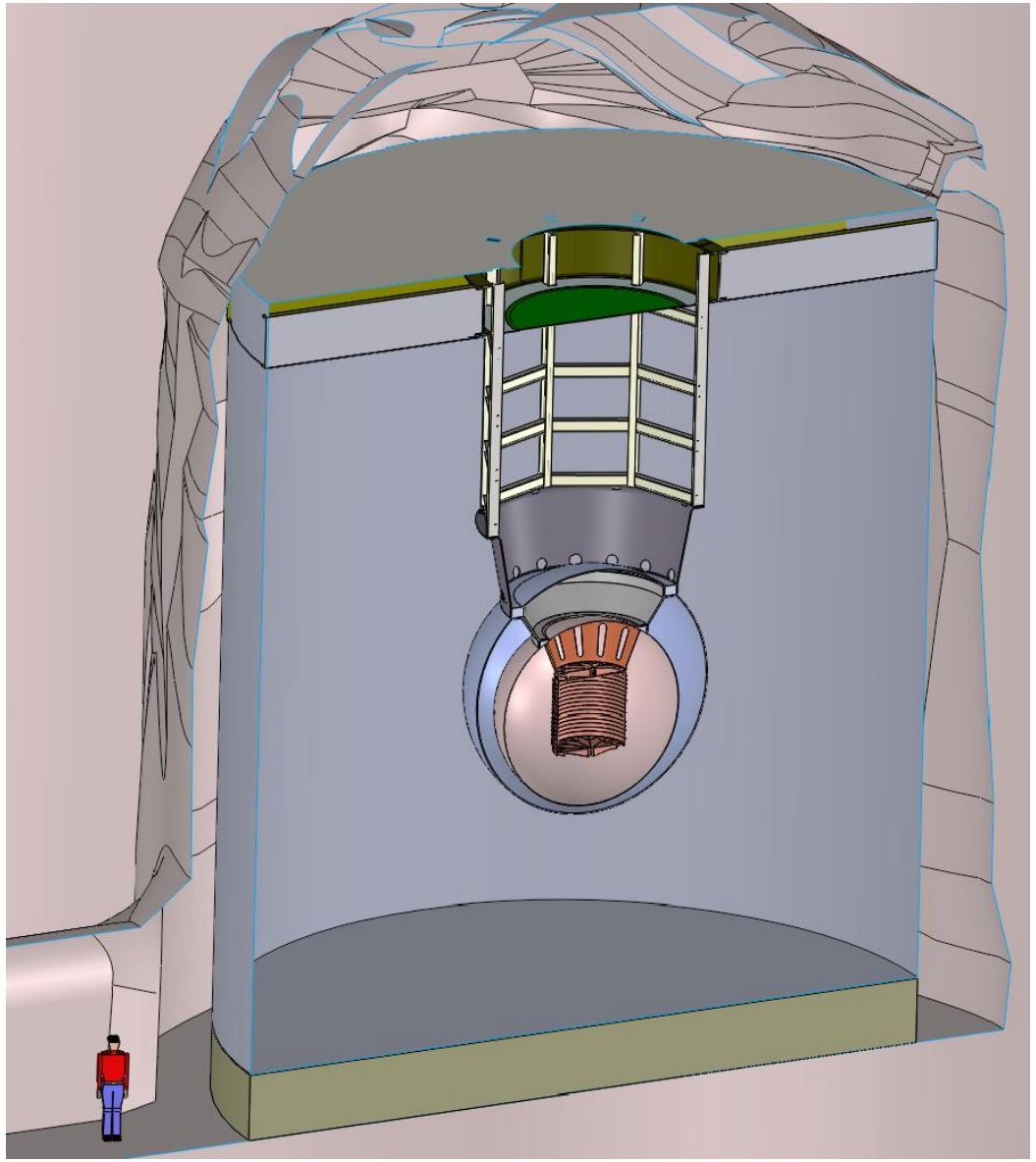
	Livetime	Exposure	Limit (90% CL)
Phase I	596.7 d	122.0 kg.yr	$T_{1/2}^{0\nu\beta\beta} > 1.0 \times 10^{25}$ yr
Phase II	271.8 d	55.6 kg.yr	$T_{1/2}^{0\nu\beta\beta} > 4.4 \times 10^{25}$ yr

- EXO-200 scheduled for another 1.5 year of data collecting.
- Continued data collection will improve the 0νββ sensitivity.

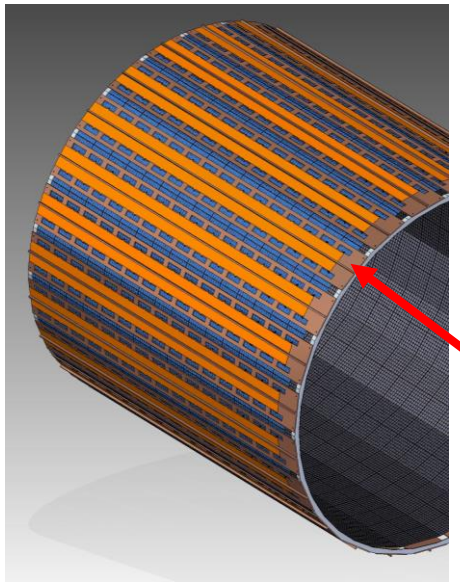


nEXO at SNOLAB:

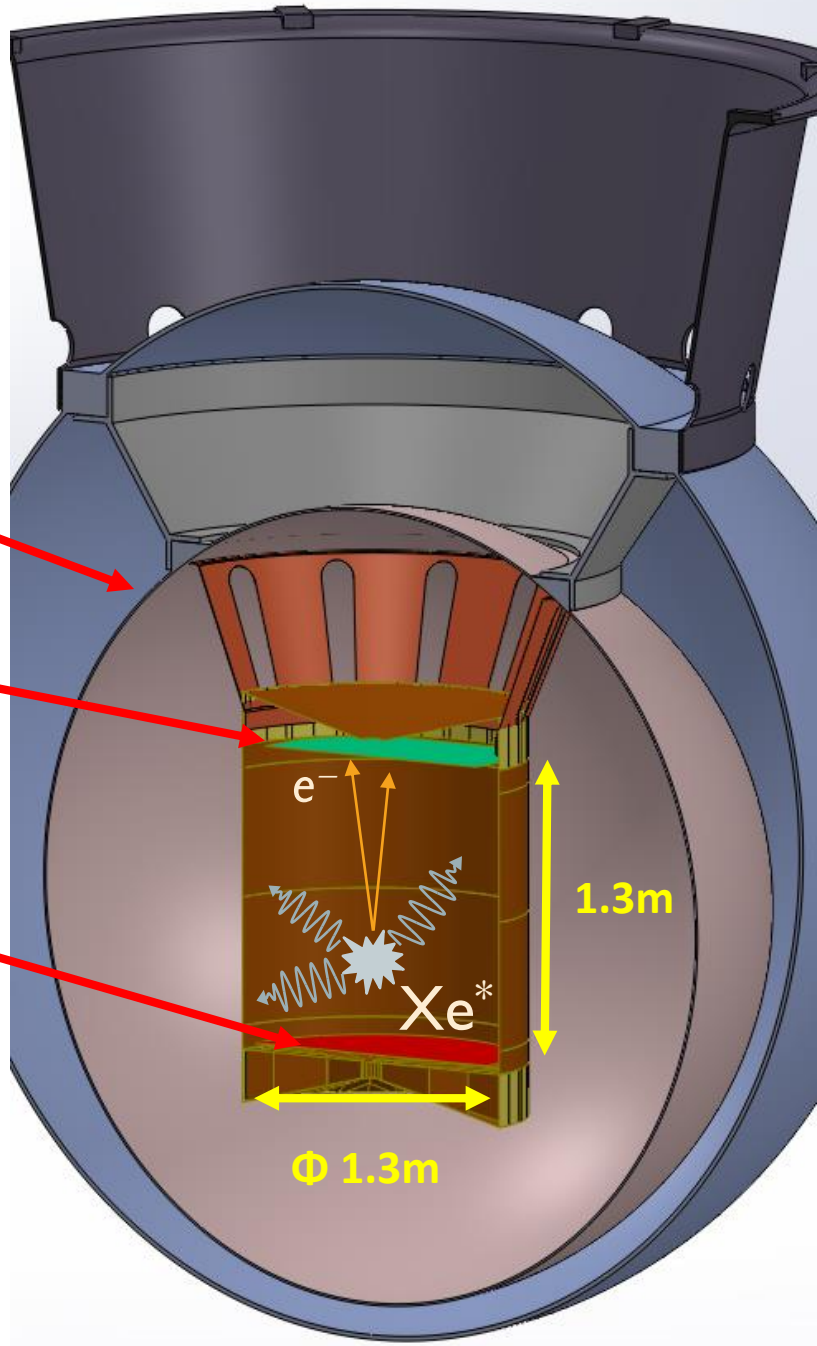
- nEXO is a proposed 5000 kg (5 t) next generation LXe TPC.
- EXO-200 has validated this approach showing good energy resolution with anticorrelation between scintillation light and ionization charge.
- EXO-200 has demonstrated the power of large homogeneous detector giving promise to the detector performance goals of nEXO.
- If tagging of the barium daughter nucleus from ββ-decay can be achieved, a virtually background free event measurement can be made.



Baseline design for nEXO:

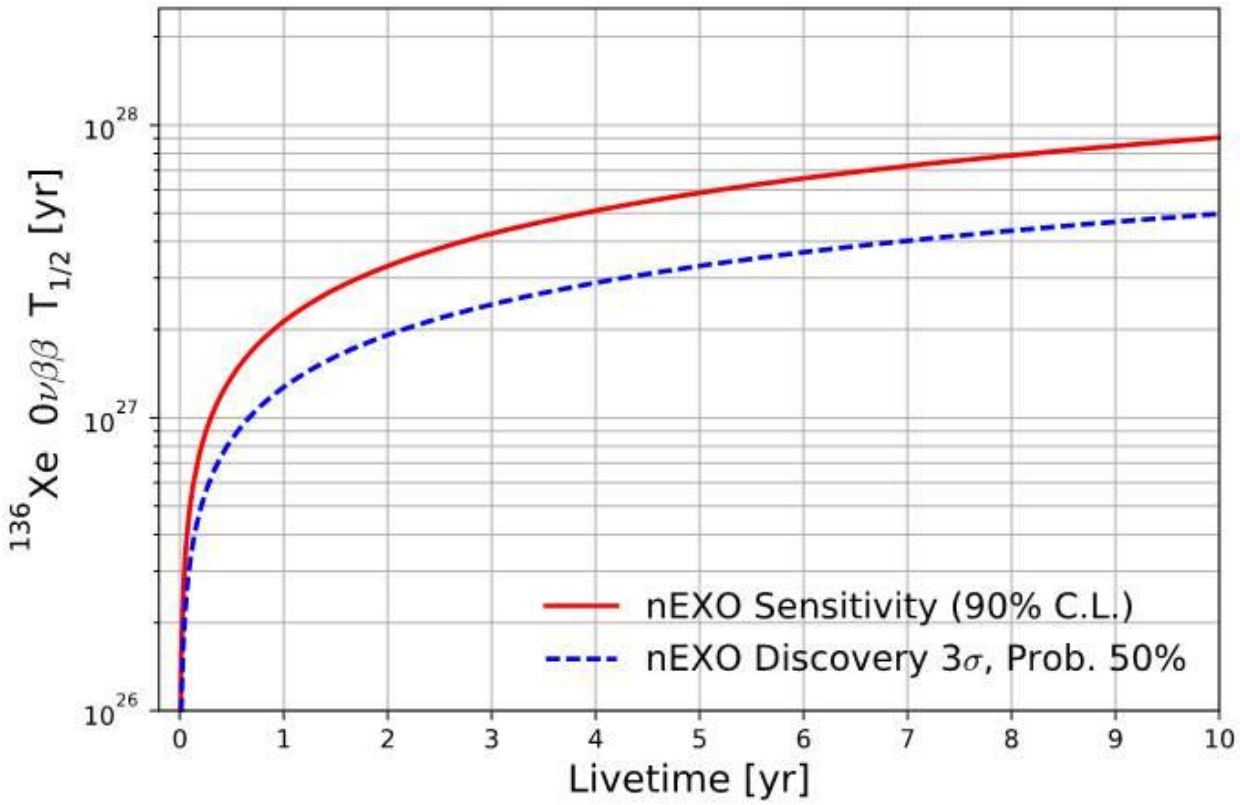


- Cold (in LXe) front end electronics.
- Spherical carbon fiber cryostat (lighter than copper).
- Charge readout pads (anode).
- 4 m^2 SiPM (high gain) staves lining the inside of the barrel.
- Reflective cathode.
- Large single drift volume. (1.3m)

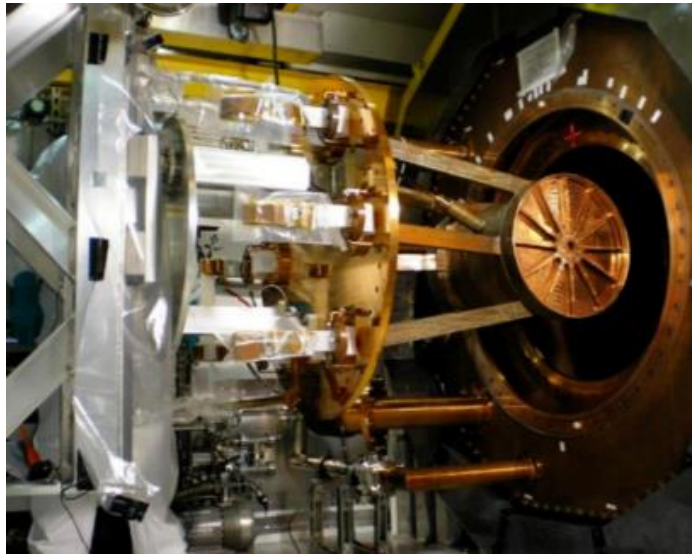


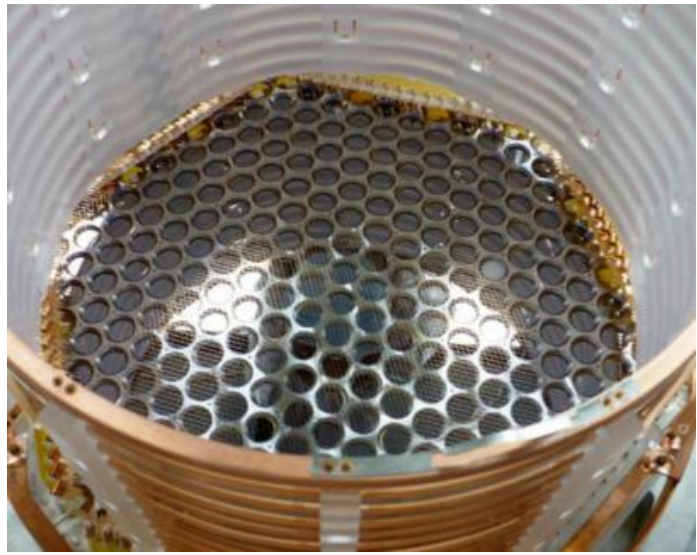
nEXO projected sensitivity and discovery potential:

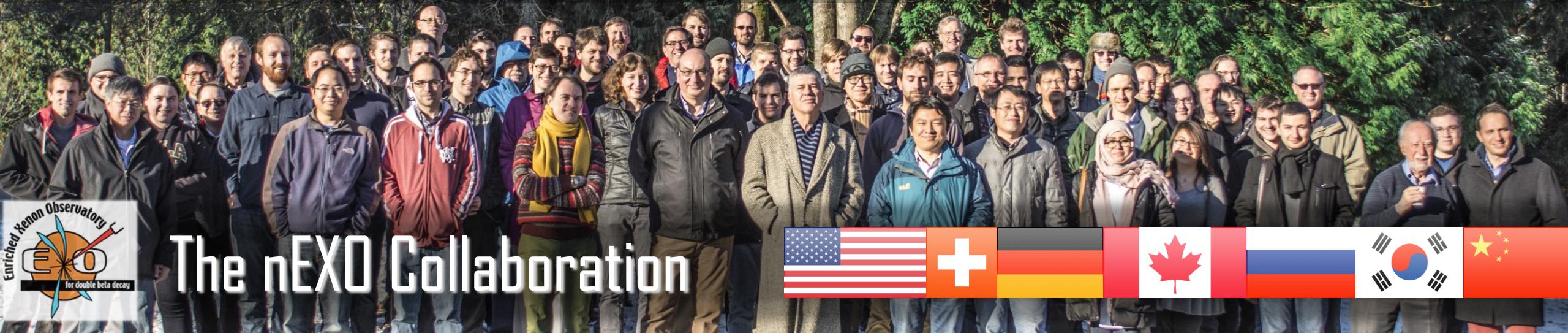
- Assumes baseline design of:
  - Existing materials (radiopure).
  - Energy resolution of 1%. (EXO-200 1.2%).
  - Improvement of SS/MS discrimination by factor of 2.



University of Alabama, Tuscaloosa AL, USA — M Hughes, I Ostrovskiy, A Piepke, AK Soma, V Veeraraghavan
University of Bern, Switzerland — J-L Vuilleumier
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, W Cree, R Gornea, K Graham, T Koffas, C Licciardi, D Sinclair
Colorado State University, Fort Collins CO, USA — C Chambers, A Craycraft, W Fairbank Jr, D Harris, A Iverson, J Todd, T Walton
Drexel University, Philadelphia PA, USA — MJ Dolinski, EV Hansen, YH Lin, Y-R Yen
Duke University, Durham NC, USA — PS Barbeau
Indiana University, Bloomington IN, USA — JB Albert, S Daugherty
Laurentian University, Sudbury ON, Canada — B Cleveland, A Der Mesrobian-Kabakian, J Farine, A Robinson, U Wichoski
University of Maryland, College Park MD, USA — C Hall
University of Massachusetts, Amherst MA, USA — S Feyzbakhsh, S Johnston, A Pocar
McGill University, Montreal QC, Canada — T Brunner, Y Ito, K Murray
The EXO-200 Collaboration
SLAC National Accelerator Laboratory, Menlo Park CA, USA — M Breidenbach, R Conley, T Daniels, J Davis,
S Delaquis, A Johnson, LJ Kaufman, B Mong, A Odian, CY Prescott, PC Rowson, JJ Russell, K Skarpaas, A Waite, M Wittgen
University of South Dakota, Vermillion SD, USA — J Daughhetee, R MacLellan
Friedrich-Alexander-University Erlangen, Nuremberg, Germany
G Anton, R Bayerlein, J Hoessl, P Hufschmidt, A Jamil, T Michel, M Wagenpfeil, G Wrede, T Ziegler
IBS Center for Underground Physics, Daejeon, South Korea — DS Leonard
IHEP Beijing, People's Republic of China — G Cao, W Cen, T Tolba, L Wen, J Zhao
ITEP Moscow, Russia — V Belov, A Burenkov, M Danilov, A Dolgolenko, A Karelin, A Kuchenkov, V Stekhanov, O Zeldovich
University of Illinois, Urbana-Champaign IL, USA — D Beck, M Coon, S Li, L Yang
Stanford University, Stanford CA, USA — R DeVoe, D Fudenberg, G Gratta, M Jewell, S Kravitz, G Li, A Schubert, M Weber, S Wu
Stony Brook University, SUNY, Stony Brook, NY, USA — K Kumar, O Njoya, M Tarka
Technical University of Munich, Garching, Germany — W Feldmeier, P Fierlinger, M Marino
TRIUMF, Vancouver BC, Canada — J Dilling, R Krücken, Y Lan, F Retière, V Strickland
Yale University, New Haven CT, USA — Z Li, D Moore, Q Xia





The nEXO Collaboration

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M Chiu, G Giacomini, V Radeka, E Raguzin, T Rao, S Rescia, T Tsang
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B Cleveland, A Der Mesrobian-Kabakian, J Farine, A Robinson, U Wichoski
Lawrence Livermore National Laboratory, Livermore CA, USA
O Alford, J Brodsky, M Heffner, A House, S Sangiorgio
University of Massachusetts, Amherst MA, USA
S Feyzbakhsh, S Johnston, CM Lewis, A Pocar
McGill University, Montreal QC, Canada — T Brunner, Y Ito, K Murray
Oak Ridge National Laboratory, Oak Ridge TN, USA — L Fabris, RJ Newby, K Ziock
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 — 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
J Dalmasson, T Daniels, S Delaquis, A Dragone, G Haller,
LJ Kaufman, A Odian, M Oriunno, B Mong, PC Rowson, K Skarpaas
University of South Dakota, Vermillion SD, USA — J Daughhetee, R MacLellan
Stanford University, Stanford CA, USA
R DeVoe, D Fudenberg, G Gratta, M Jewell, S Kravitz, G Li, A Schubert, M Weber, S Wui
Stony Brook University, SUNY, Stony Brook NY, USA — K Kumar, O Njoya, M Tarka
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 — Z Li, D Moore, Q Xia