EXO-200 and nEXO

Searching for $0\nu\beta\beta$ in ^{136}Xe

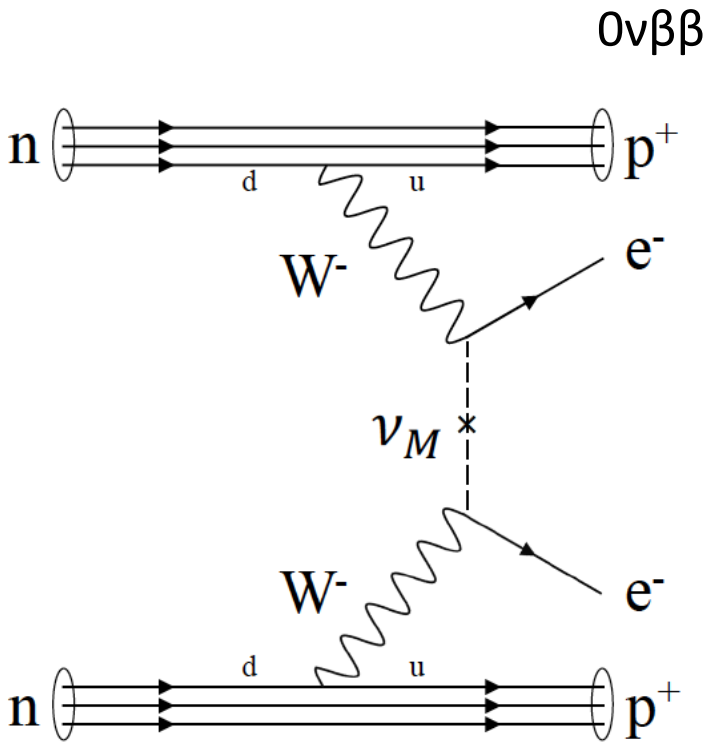
Thomas Brunner
On behalf of the nEXO Canada Team

IPP Town Hall
July 15, 2020

Motivation for 0νββ search

Observation of 0νββ would have far reaching impact on our understanding of the nature of matter and the evolution of the Universe:

- Irrefutable evidence for violation of Lepton number conservation.
- Discovery of a new type of fundamental particle, i.e. Majorana neutrino.
- Possible connection to new mass generating mechanism (seesaw mechanism)
- A possible explanation for the matter-antimatter asymmetry of the Universe



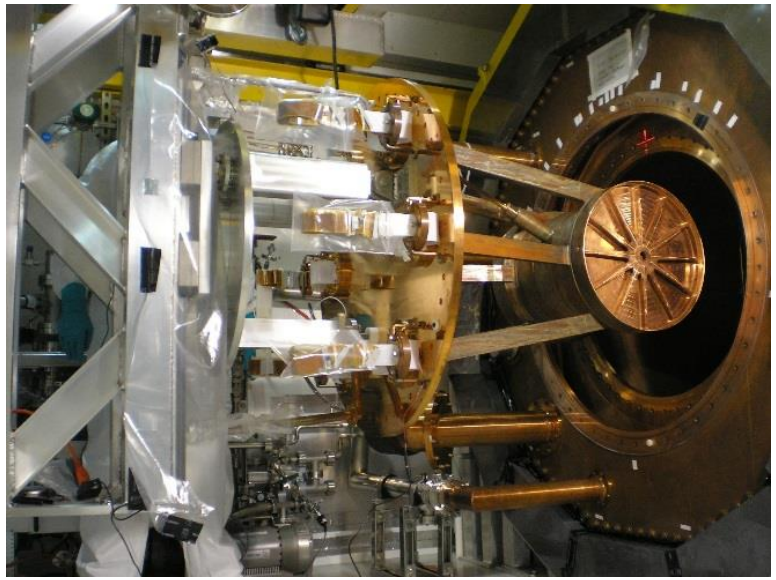
Searching for 0νββ in ^{136}Xe

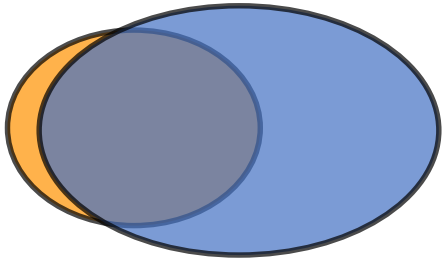
EXO-200:

- EXO-200 first 100-kg class ββ experiment
- First experiment to observe 2νββ in Xe-136
- 200kg liquid-Xe TPC with ~80% Xe-136
- Located at the WIPP mine in NM, USA
- Decommissioned in Dec. 2018
- 0νββ searches published in 1 Nature and 3 PRLs
- Analyze data from end-of-run calibration campaign
  → data will inform the detailed design of nEXO

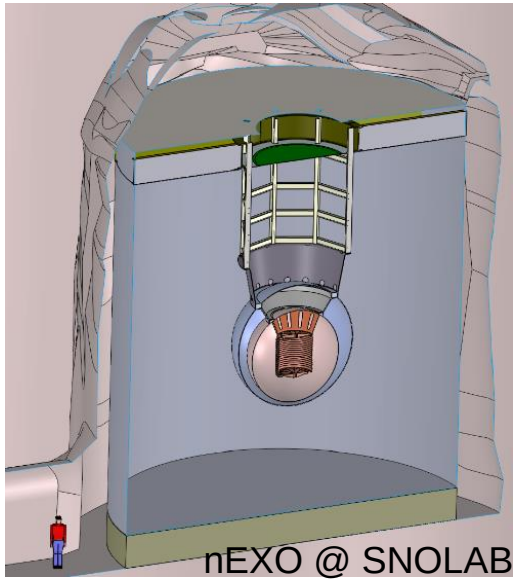
nEXO:

- proposed 5-tonne liquid Xe TPC
- Enriched in Xe-136 at ~90%
- SNOLAB cryopit preferred location by collaboration
- Design of nEXO well advanced
- Funding decision in the US expected soon
- CFI Innovation Fund requested in support of construction



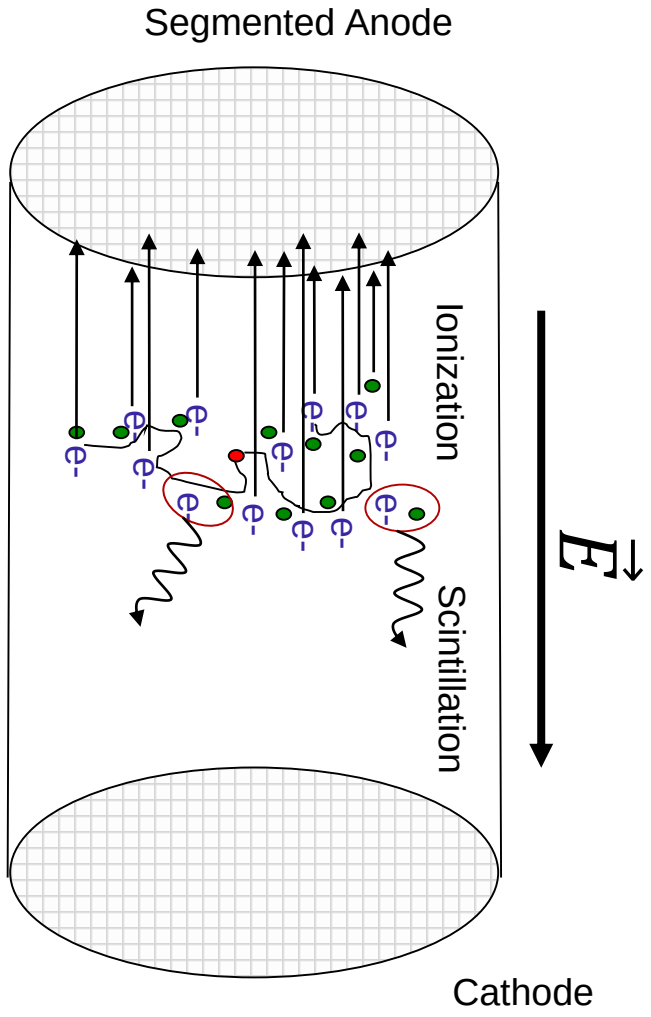


Most members of EXO-200 continued in nEXO but nEXO has grown significantly.



nEXO @ SNOLAB

0νββ search with liquid Xe TPC

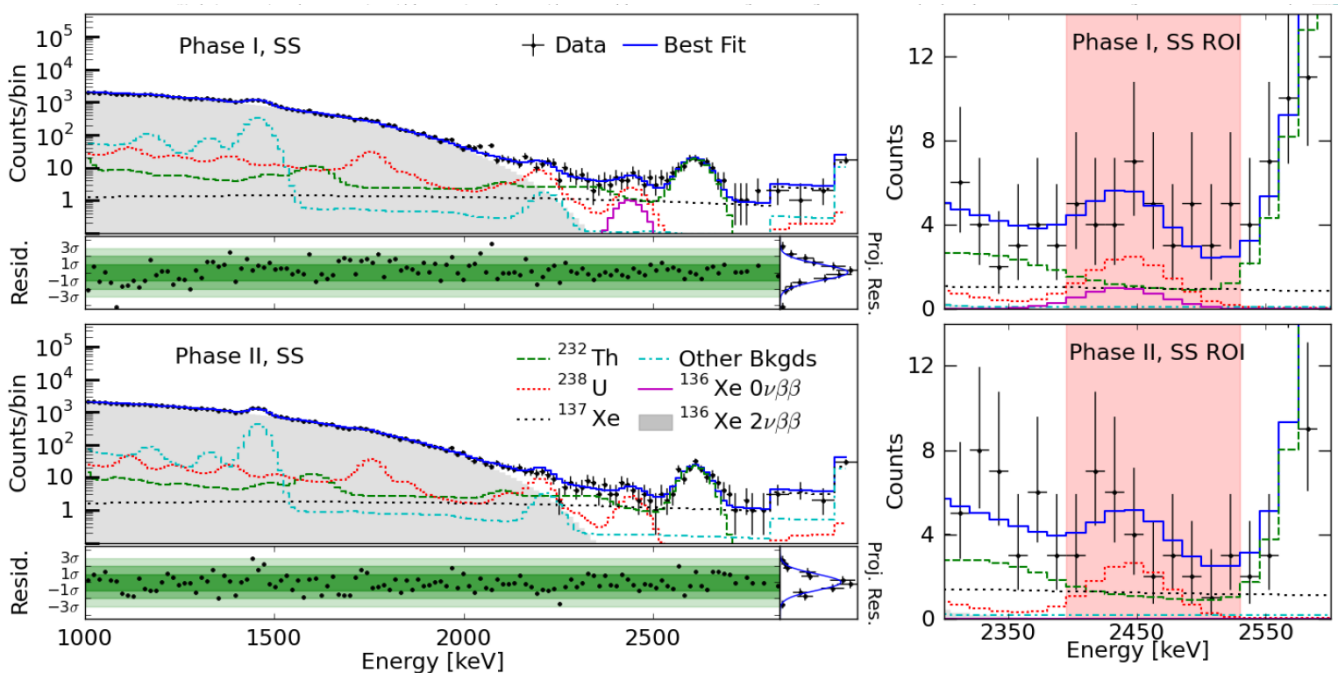


Liquid-Xe Time Projection Chamber (TPC)

- Xe is used both as the source and detection medium.
- Monolithic detector structure, excellent background rejection capabilities.
- Cryogenic electronics in LXe (at ~168 K).
- Detection of scintillation light and secondary charges.
  - 2D read out of secondary charges at segmented anode.
  - 3D event reconstruction using also scintillation light:
    1. Energy reconstruction
    2. Position reconstruction
    3. Event Multiplicity

Latest EXO-200 Results

No statistical significant signal observed



EXO-200 has achieved 1.15 ± 0.02% energy resolution at the Q-value.

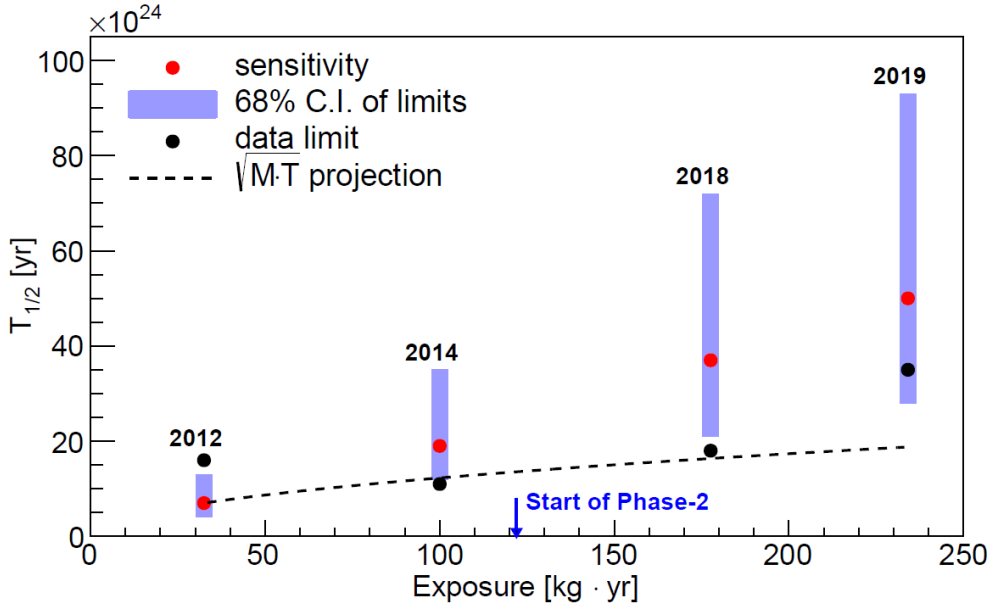
Phase I+II: 234.1 kg·yr ^{136}Xe exposure

Limit $T_{1/2}^{0\nu\beta\beta} > 3.5 \times 10^{25}$ yr (90% C.L.)

$\langle m_{\beta\beta} \rangle <$ (93 – 286) meV

Sensitivity 5.0×10^{25} yr

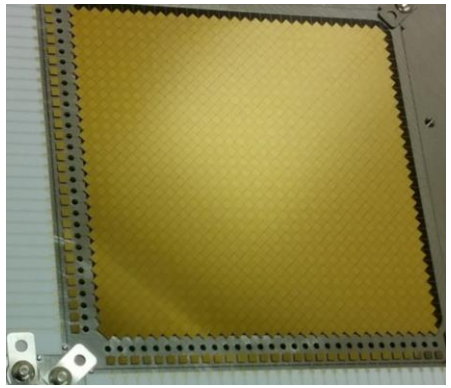
EXO-200 $0\nu\beta\beta$ search results



Linear increase in sensitivity with exposure due to detector upgrades and improved analysis techniques.

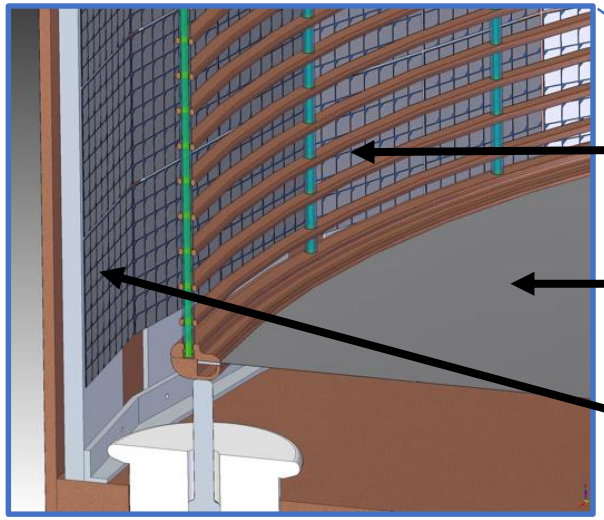
2012: Phys. Rev. Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229-234
2018: Phys. Rev. Lett. 120, 072701 (2018)
2019: Phys. Rev. Lett. 123, 161802 (2019)

The nEXO detector

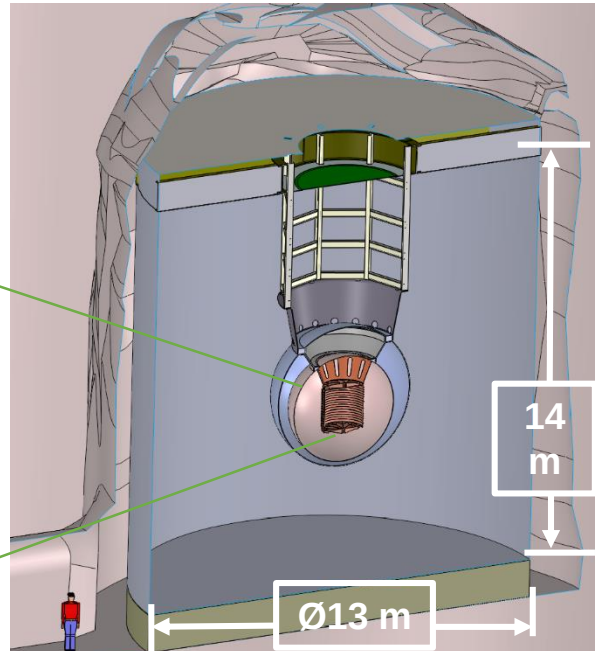


Picture: 10 x 10 cm^2 tile prototype
JINST 13, P01006 (2018)
Tile simulation:
JINST 14, P09020 (2019).

- Next-generation neutrinoless double beta decay detector
- 5 t liquid xenon TPC similar to EXO-200
- SiPM for 175nm scintillation light detection, 4.5m^2 SiPM array in LXe
- Tiles for charge read out
- In-cold electronics inside TPC in liquid Xe
- 3D event reconstruction
- Combine charge and light readout. Goal → σ/E of 1% at Q-value.



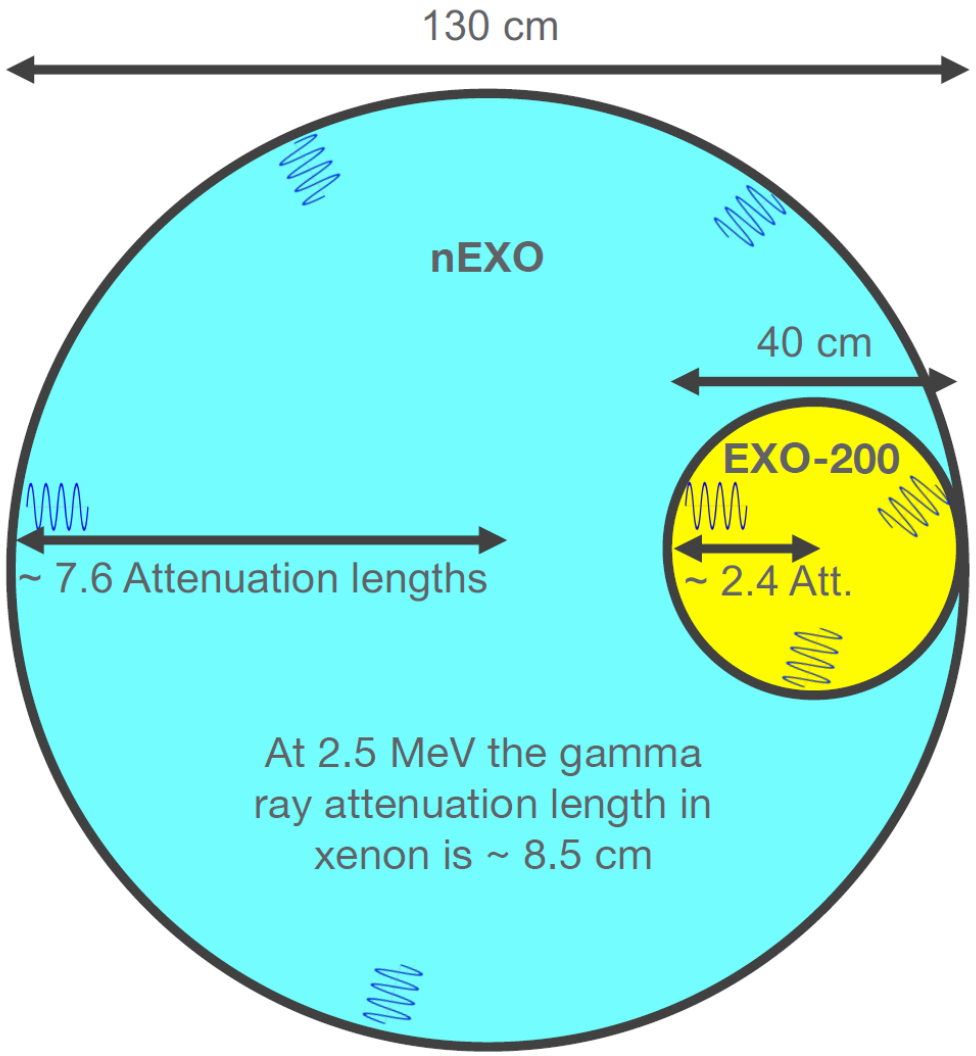
nEXO TPC



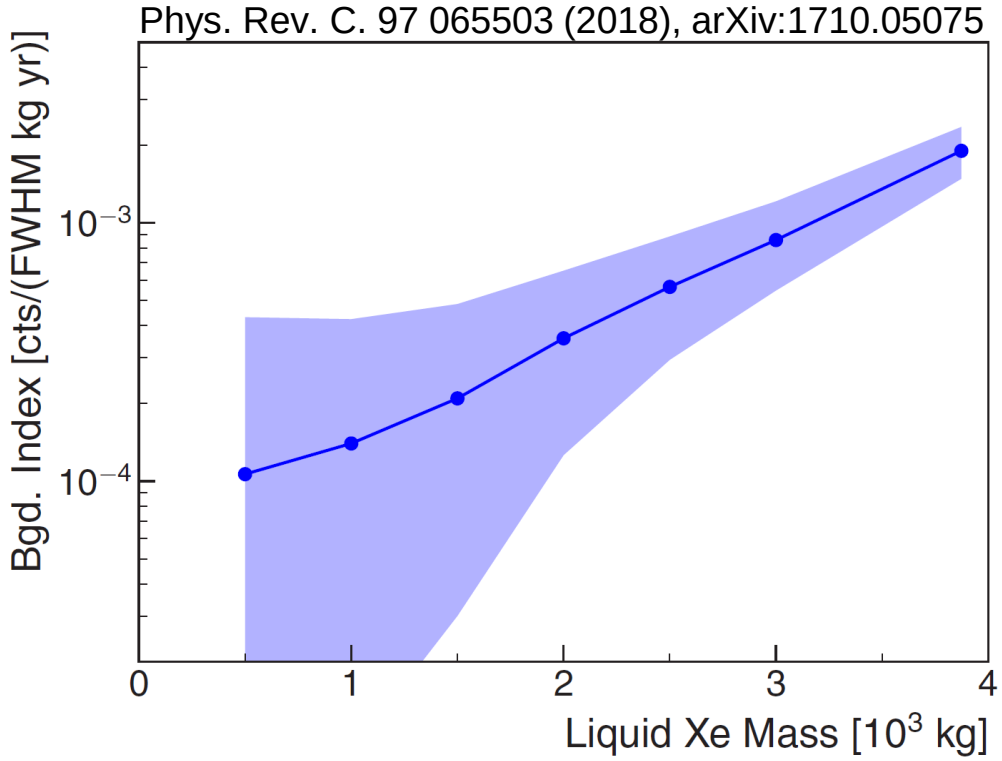
nEXO at the SNOLAB Cryopit

nEXO pre-CDR, arXiv:1805.11142

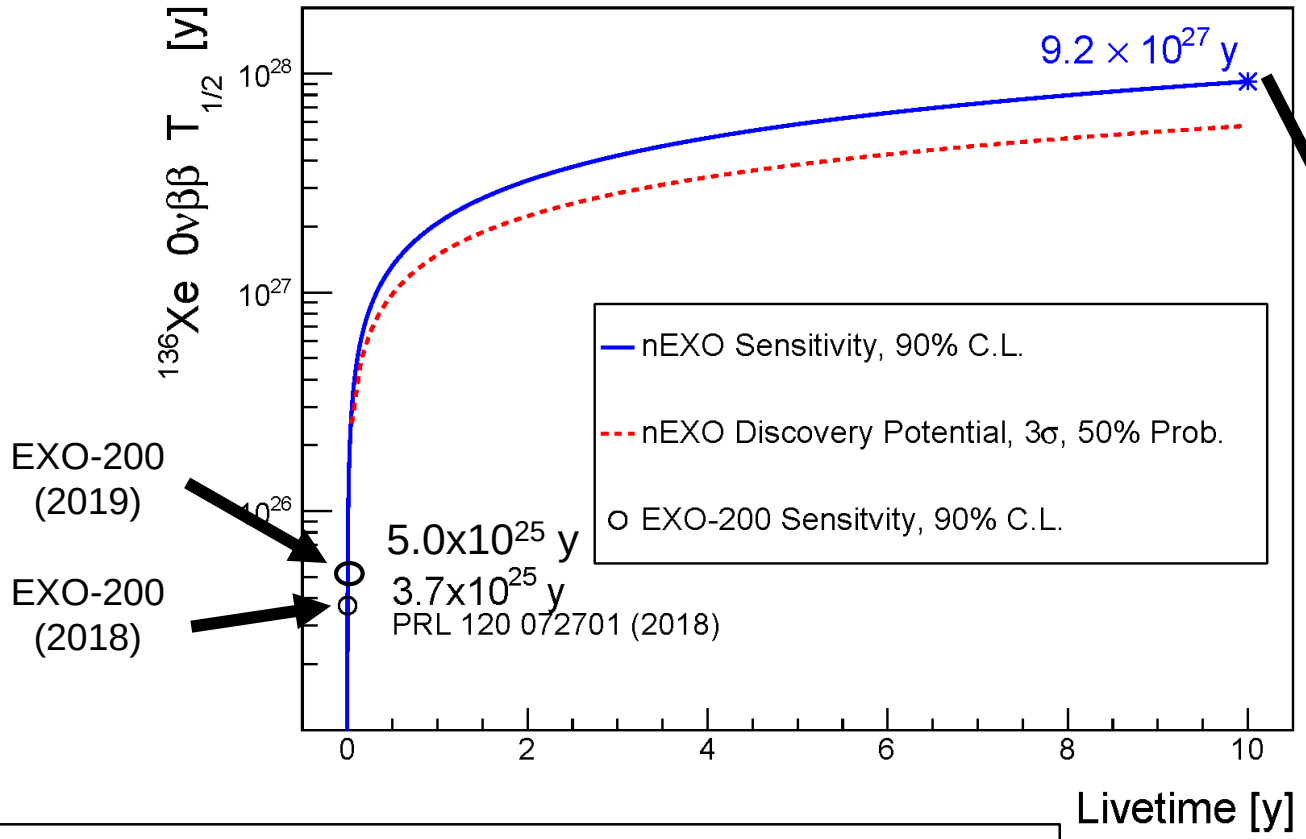
Self-shielding in LXe Detector



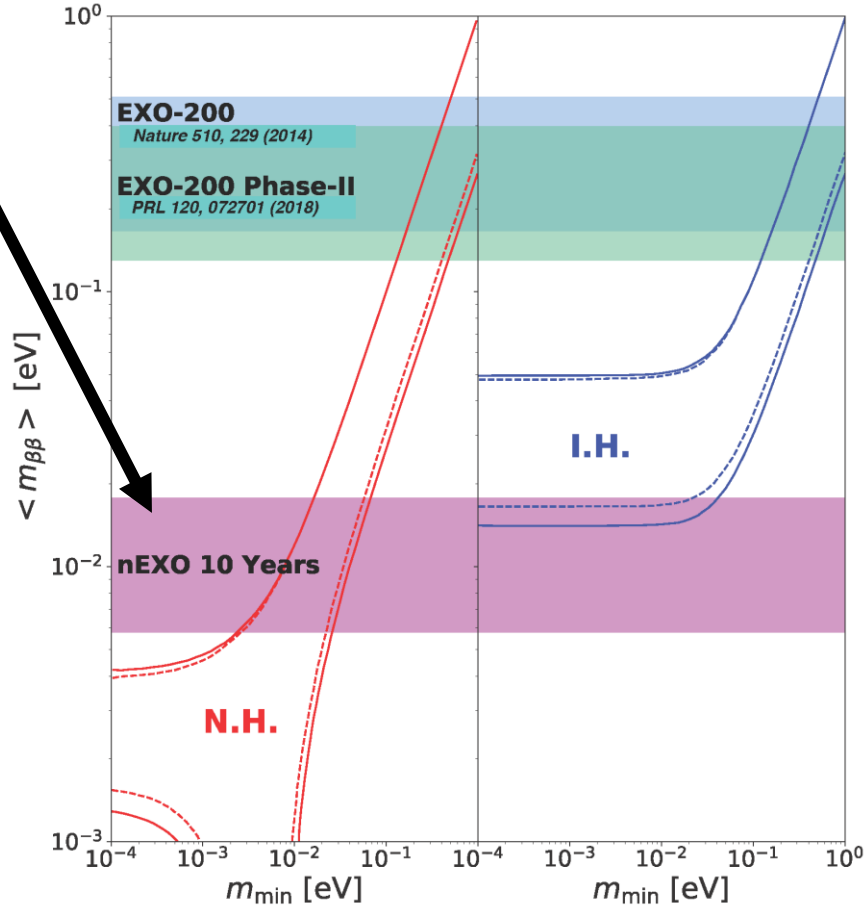
The large, monolithic volume of nEXO and high density of liquid xenon (2.9 g/cm3) is extremely beneficial to the attenuation of gamma rays coming from externa materials. High detection probability for scattered, multi-side gammas.



Projected nEXO Sensitivity



Projected sensitivity based on **actual** background level **measurements**!



Phys. Rev. C. 97 065503 (2018)

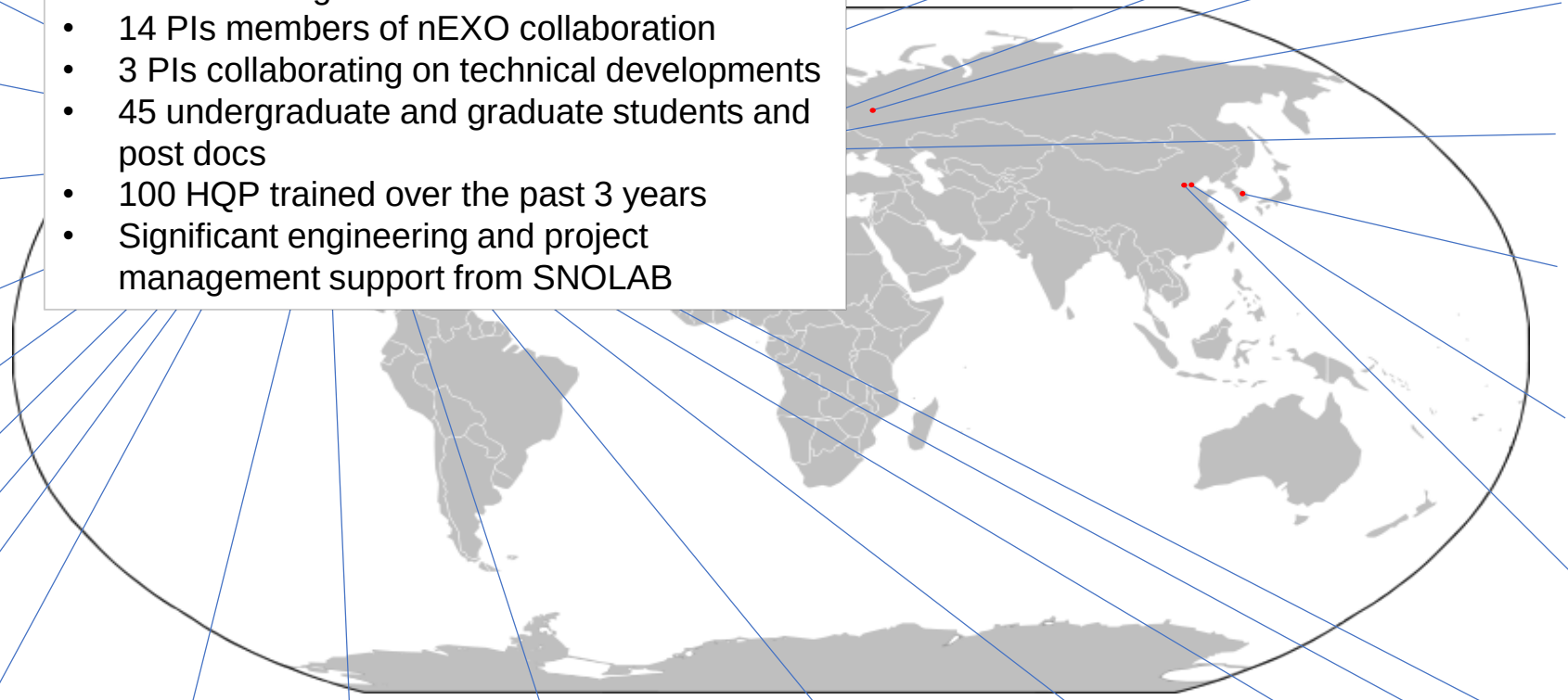
$g_A = g_A^{free} = -1.2723$
Band is the envelope of NME:

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

>150 scientists
31 institutions in 7 countries

Laurentian University / Université Laurentienne
Carleton University
McGill
Université de Sherbrooke
UMass Amherst
Yale University
Brookhaven National Laboratory
FAU Friedrich-Alexander Universität Erlangen-Nürnberg
ИТЭФ
The University of British Columbia
TRIUMF
Technical University of Munich
Pacific Northwest National Laboratory
u b Universität Bern
Lawrence Livermore National Laboratory
ibs Institute for Basic Science
SLAC National Accelerator Laboratory
IHEP
Stanford University
IMECAS
Caltech
Rensselaer
University of California Irvine
UC San Diego
Colorado School of Mines
Colorado State University
The University of Alabama
Oak Ridge National Laboratory
University of Kentucky
UNCW University of North Carolina Wilmington
Drexel University



Canadian contingent within nEXO

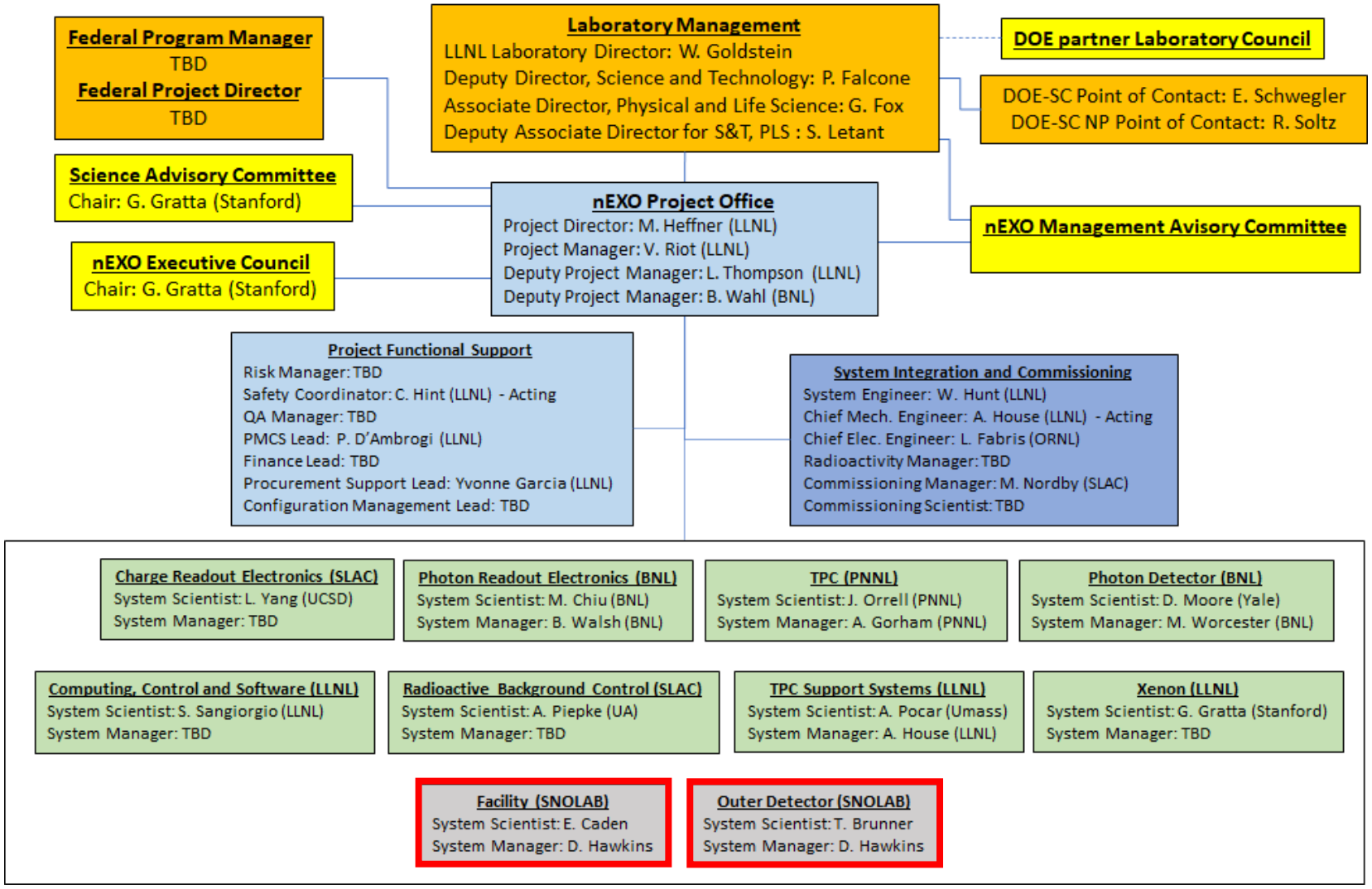
- 14 PIs members of nEXO collaboration
- 3 PIs collaborating on technical developments
- 45 undergraduate and graduate students and post docs
- 100 HQP trained over the past 3 years
- Significant engineering and project management support from SNOLAB

Diversity within nEXO Canada

- We commit to providing a welcoming and positive atmosphere where every collaboration member feels valued and supported to reach their fullest potential.
- It is important to us to increase the diversity within our group.
- Working on surveying the diversity of our group members in Canada.

- nEXO collaboration board approved a code of conduct in early 2019.
- The nEXO collaboration has a standing EDI committee.
- The nEXO collaboration elected two ombudspeople.

The nEXO Project



Canadian PIs take on leading roles in nEXO project:

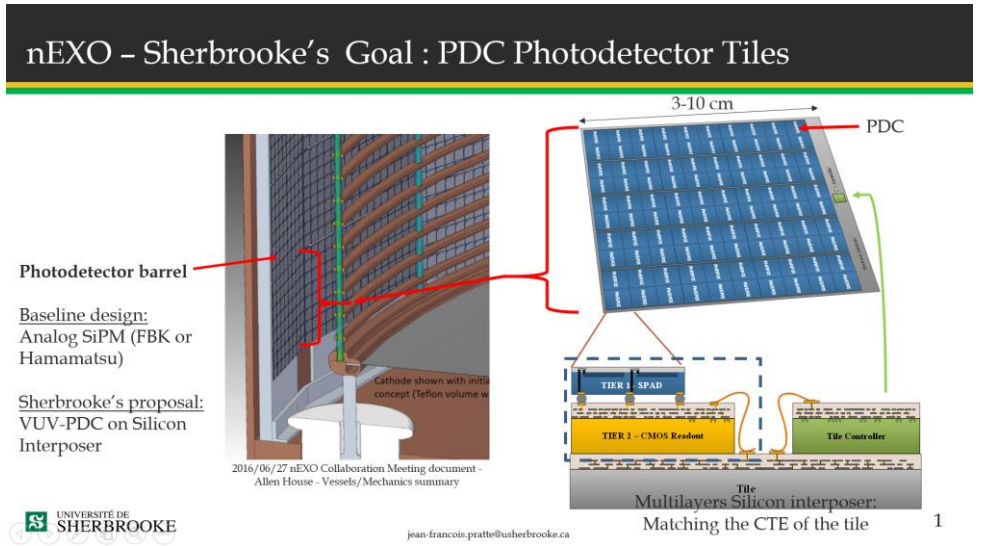
- Photon sensor infrastructure
- External calibration sources
- Outer detector (water shield and muon veto)
- SNOLAB facility
- Rn Emanation
- LXe HV tests
- Radioactive background control
- Simulation

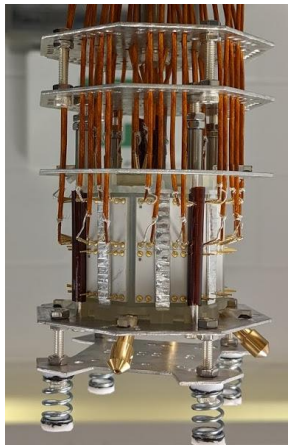
Timeline until 2036

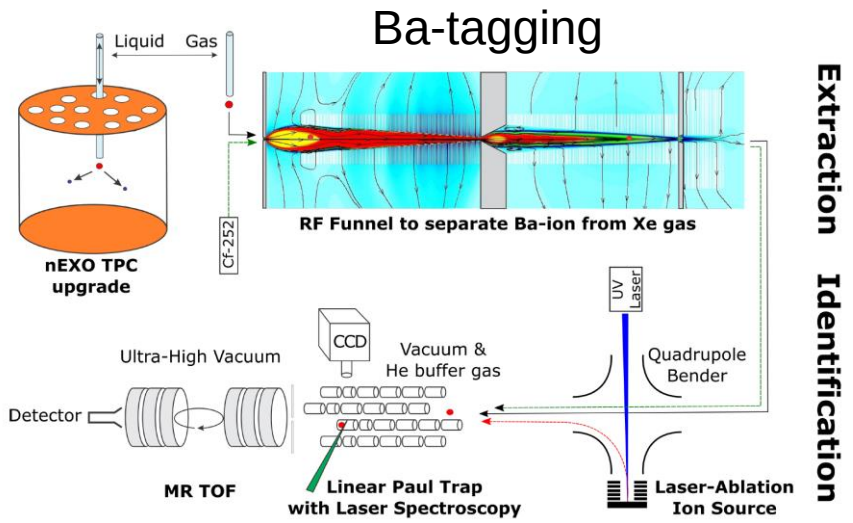
- **2018: US DOE-NP announced Critical Decision 0** – Mission Need (CD-0) for a tonne-scale 0νββ experiment.
- No time line available but we expect a decision by US DOE-NP on location and technology within the next months.
- We believe nEXO is a strong contender and SNOLAB is the location preferred by the collaboration.
- SNOLAB committed the Cryopit to a next-generation 0νββ experiment, which could be nEXO.
- Both **SNOLAB** and **TRIUMF** have **approved Gate 0** in their project governance, demonstrating the alignment of the project with their respective strategic plans.
- Construction of nEXO will start late 2021 or early 2022 depending on DOE timeline (Cryopit prep starting mid-2022).
- nEXO operation anticipated to start 2026 or early 2027 depending on start of construction.
- Data taking planned for 10 years lifetime (until ~2037).

R&D beyond nEXO baseline

- Canadian groups are leading technology R&D efforts for potential upgrade of nEXO.
- Goal of reaching zero-background with nEXO-upgrade:
  - Advanced photon detection (see talk by F. Retiere)
  - Investigation of light emission and propagation in liquid Xe with the Light-only LXe (LoLX) project.
  - Elimination of all non-ββ backgrounds with Ba-tagging





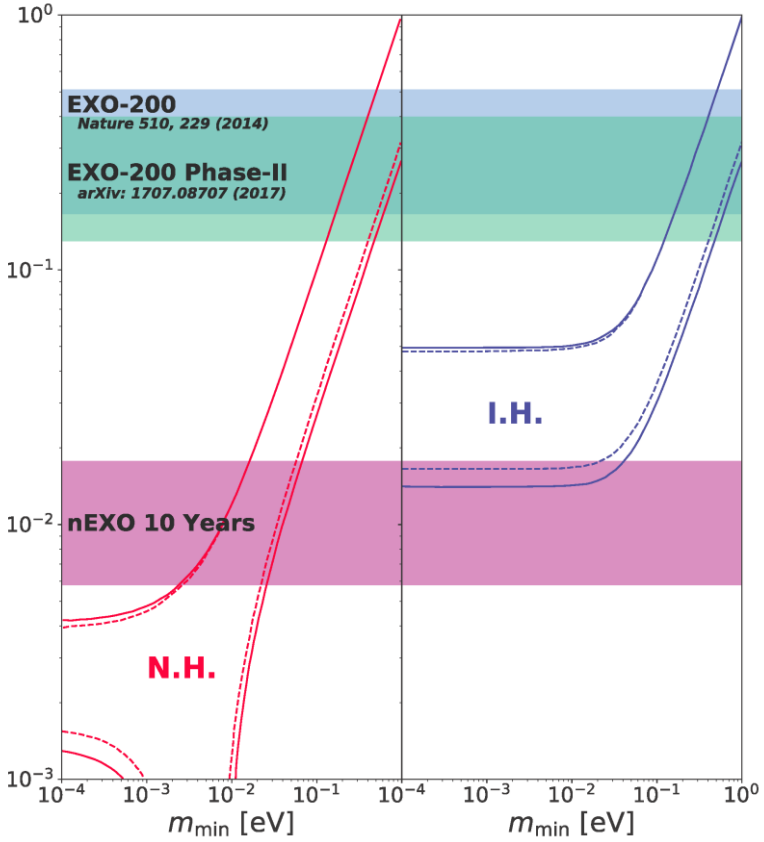


$0\nu\beta\beta$ search with EXO

- $0\nu\beta\beta$ most promising approach to search for Majorana neutrinos and Lepton number non-conservation in weak interactions.

Multi-phase program with LXe TPC:

- **EXO-200** – at WIPP mine:
  - Current limit on $0\nu\beta\beta$: 3.5 x 10^{25} years (EXO-200)
  - Sensitivity: $\langle m\beta\beta \rangle$ < (93 – 286) meV
- **nEXO** - R&D underway:
  - 5T xenon enriched at ~90%
  - Projected Sensitivity: 5-20 meV
  - Improved techniques for background suppression and possibly Ba tagging as future upgrade to nEXO
- Strong Canadian contribution to EXO-200 and nEXO



→ Development of nEXO is well advanced

University of Alabama, Tuscaloosa AL, USA
M Hughes, P Nakarmi, O Nusair, I Ostrovskiy, A Piepke, AK Soma, V Veeraraghavan
University of Bern, Switzerland — J-L Vuilleumier
University of British Columbia, Vancouver BC, Canada — G Gallina, R Krücken, Y Lan
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, B Chana, D Goeldi, R Gornea, T Koffas, C Vivo-Vilches
Colorado School of Mines, Golden CO, USA — K Leach, C Natzke
Colorado State University, Fort Collins CO, USA
A Craycraft, D Fairbank, W Fairbank, A Iverson, J Todd, T Wager
Drexel University, Philadelphia PA, USA — MJ Dolinski, P Gautam, EV Hansen, M Richman, P Weigel
Friedrich-Alexander-University Erlangen, Nuremberg, Germany
G Anton, J Hößl, T Michel, S Schmidt, M Wagenpfeil, W G Wrede, T Ziegler
IBS Center for Underground Physics, Daejeon, South Korea — DS Leonard
Lawrence Livermore National Laboratory, Livermore CA, USA
JP Brodsky, M Heffner, A House, S Sangiorgio, T Stiegler
University of Massachusetts, Amherst MA, USA
J Bolster, S Feyzbakhsh, KS Kumar, O Njoya, A Pocar, M Tarka, S Thibado
McGill University, Montreal QC, Canada
S Al Kharusi, T Brunner, D Chen, L Darroch, Y Ito, K Murray, T Nguyen, 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
IJ Arnquist, ML di Vacri, EW Hoppe, JL Orrell, GS Ortega, CT Overman, R Saldanha, R Tsang
Rensselaer Polytechnic Institute, Troy NY, USA — E Brown, A Fucarino, K Odgers, A Tidball
Université de Sherbrooke, QC, Canada — SA Charlebois, D Danovitch, H Dautet, R Fontaine, F Nolet, S Parent, J-F Pratte, T Rossignol, N Roy, G St-Hilaire, J Sylvestre, F Vachon
SLAC National Accelerator Laboratory, Menlo Park CA, USA — R Conley, A Dragone, G Haller, J Hasi,
LJ Kaufman, C Kenney, B Mong, A Odian, M Oriunno, A Pena Perez, PC Rowson, J Segal, K Skarpaas VIII
University of South Dakota, Vermillion SD, USA — T Bhatta, A Larson, R MacLellan

IHEP Beijing, People's Republic of China
GF Cao, WR Cen, YY Ding, XS Jiang, P Lv, Z Ning, XL Sun, T Tolba, W Wei, LJ Wen, WH Wu, J Zhao
ITEP Moscow, Russia — V Belov, A Karelin, 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 — SJ Daugherty, LJ Kaufman, G Visser
Laurentian University, Sudbury ON, Canada — E Caden, B Cleveland,
A Der Mesrobian-Kabakian, J Farine, C Licciardi, A Robinson, M Walent, U Wichoski
Stanford University, Stanford CA, USA
R DeVoe, G Gratta, M Jewell, S Kravitz, BG Lenardo, G Li, M Patel, M Weber
Stony Brook University, SUNY, Stony Brook NY, USA — KS Kumar
TRIUMF, Vancouver BC, Canada — J Dilling, G Gallina, R Krücken Y Lan, F Retière, M Ward
Yale University, New Haven CT, USA — A Jamil, Z Li, DC Moore, Q Xia

Canadian support for nEXO

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

nEXO R&D Supported by:
SAP Project
RTI
Carleton MRS
Universite de Montreal MRS

Backup

EXO-200 publications to date ($0\nu\beta\beta$ & exotic searches)

S. Al Kharusi, et al. “Measurement of the Spectral Shape of the β-Decay of ^{137}Xe to the Ground State of ^{137}Cs in EXO-200 and Comparison with Theory” PRL 124 (2020) 232502

G.Anton, et al. “Measurement of the scintillation and ionization response of liquid xenon at MeV energies in the EXO-200 experiment” PRC 101 (2020) 065501

G. Anton et al. “Search for Neutrinoless Double-Beta Decay with the Complete EXO-200 Dataset” PRL 123 (2019) 161802

S. Delaquis et al. "Deep Neural Networks for Energy and Position Reconstruction in EXO-200" JINST 13 (2018) P08023

J.B. Albert et al. "Search for nucleon decays with EXO-200" PRD 97 (2018) 072007

J.B. Albert et al. "Search for $0\nu\beta\beta$ Decay with the Upgraded EXO-200 Detector" PRL 120 (2018) 072701

D.S. Leonard et al. "Trace radioactive impurities in final construction materials for EXO-200” NIMA 871 (2017) 169

J.B. Albert et al. "Searches for Double Beta Decay of ^{134}Xe with EXO-200” PRD 96 (2017) 092001

J.B. Albert et al. "Measurement of the Drift Velocity and Transverse Diffusion of Electrons in Liquid Xenon with the EXO-200 Detector" PRC 95 (2017) 025502

C.G. Davis et al. "An Optimal Energy Estimator to Reduce Correlated Noise for the EXO-200 Light Readout” JINST 11 (2016) P07015

J.B. Albert et al. "Cosmogenic Backgrounds to $0\nu\beta\beta$ in EXO-200” J. Cosmol. Astropart. Phys. 4 (2016) 029

J.B. Albert et al. "First Search for Lorentz and CPT Violation in ββ Decay with EXO-200” PRD 93 (2016) 072001

J.B. Albert et al. "Search for $2\nu\beta\beta$ decay of ^{136}Xe to the 0_1^+ excited state of ^{136}Ba with EXO-200” PRC 93 (2016) 035501

J.B. Albert et al. "Measurements of the ion fraction and mobility of α and β decay products in LXe using EXO-200” PRC 92 (2015) 045504.

J.B. Albert et al. "Investigation of radioactivity-induced backgrounds in EXO-200” PRC 92 (2015) 015503

J.B. Albert, et al. "Search for Majoron-emitting modes of ββ decay of ^{136}Xe with EXO-200” PRD 90 (2014) 092004

J.B. Albert, et al. "Search for Majorana neutrinos with the first two years of EXO-200 data” Nature 510 (2014) 229

J.B. Albert, et al. "An improved measurement of the $2\nu\beta\beta$ half-life of ^{136}Xe with EXO-200” PRC 89 (2014) 015502

M. Auger, et al. "Search for Neutrinoless ββ Decay in ^{136}Xe with EXO-200” PRL 109 (2012) 032505

M. Auger, et al. "The EXO-200 detector, part I: Detector design and construction” J. Inst 7 (2012) P05010

A. Dobi, et al. "Xenon purity analysis for EXO-200 via mass spectrometry” NIM A 675 (2012) 40

N. Ackerman, et al. "Observation of Two-Neutrino ββ Decay in Xe-136 with EXO-200” PRL 107 (2011) 212501

A. Dobi, et al. "A Xenon Gas Purity Monitor for EXO" NIM A 659 (2011) 215

F. LePort, et al. "A magnetically-driven piston pump for ultra-clean applications" Rev. Sci. Inst. 82 (2011) 105114

R. Neilson, et al. "Characterization of large area APDs for the EXO-200 detector" NIM A 608 (2009) 6875

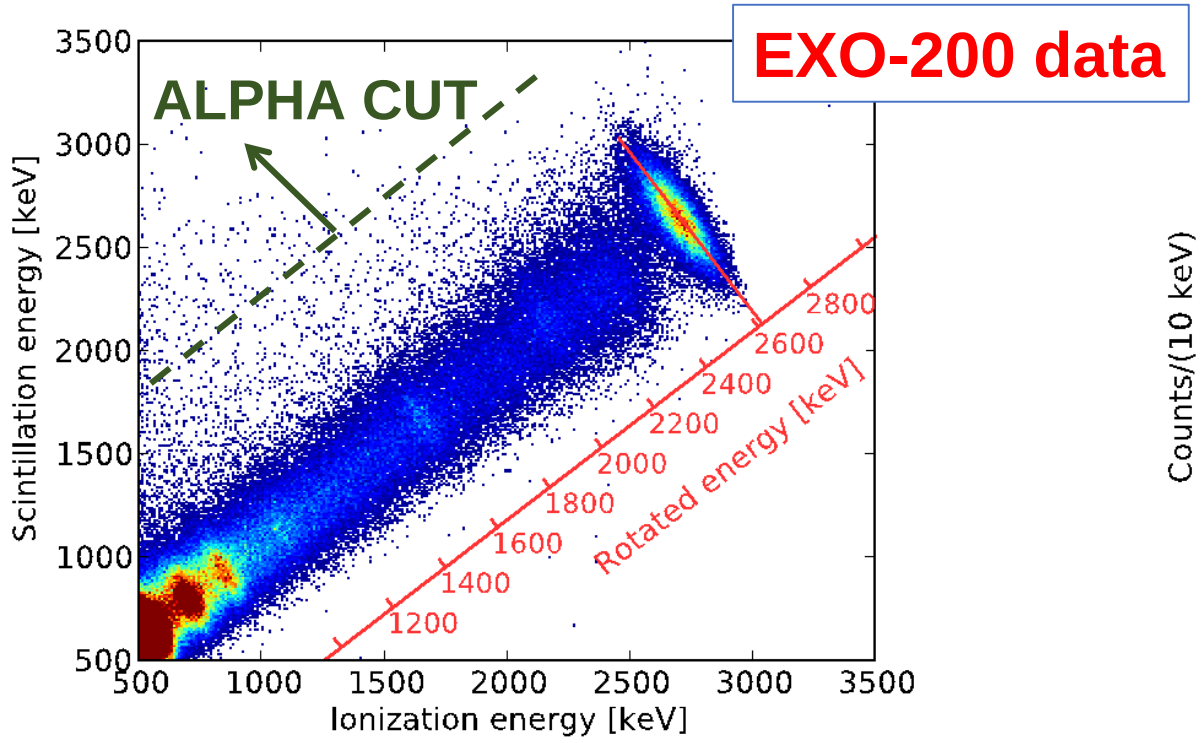
D. Leonard, et al. "Systematic study of trace radioactive impurities in candidate construction materials for EXO-200" Nucl. Ins. Meth. A 591 (2008) 490

nEXO publications (since 2018)

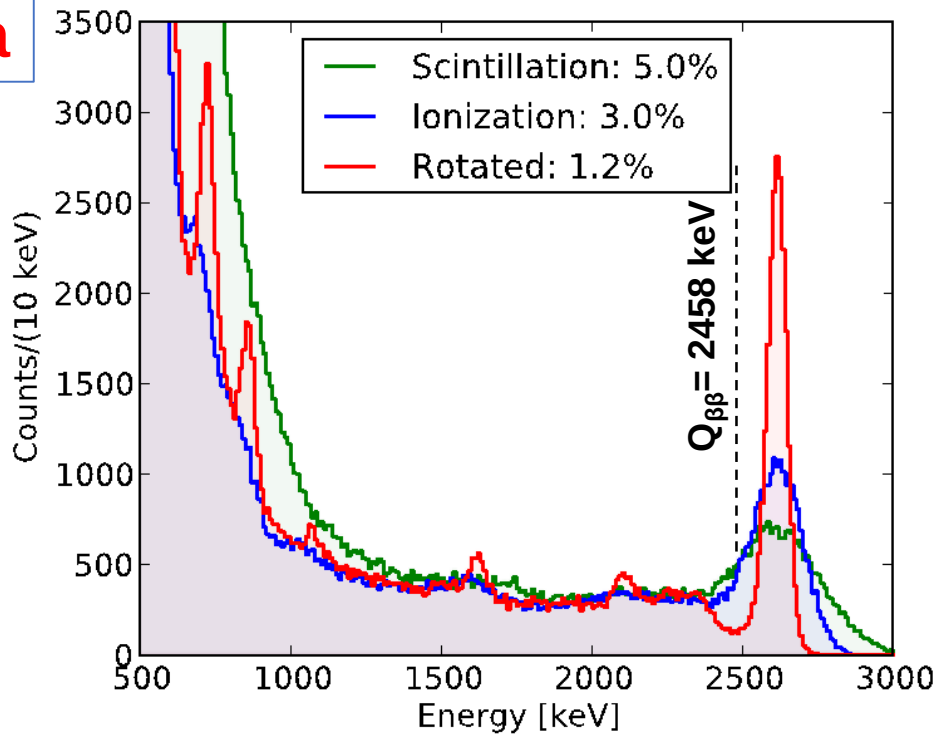
- **Characterization of the Hamamatsu VUV4 MPPCs for nEXO**, G. Gallina, et al. (nEXO), NIMA 940, 371 (2019)
- **Simulation of charge readout with segmented tiles in nEXO,** Z. Li, et al., (nEXO), JINST 14, P09020 (2019)
- **Measurements of electron transport in liquid and gas Xenon using a laser-driven photocathode,** O. Njoya, et al., (nEXO), NIM A 972, 163965 (2020)
- **Reflectance of Silicon Photomultipliers at Vacuum Ultraviolet Wavelengths,** P. Lv, et al., (nEXO), Submitted to IEEE Sensors Journal arXiv:1912.01841.
- **Reflectivity and PDE of VUV4 Hamamatsu SiPMs in Liquid Xenon,** P. Nakarmi, et al., (nEXO), JINST 15, P01019 (2020)
- **Study of Silicon Photomultiplier Performance in External Electric Fields, X.L. Sun,** et al., (nEXO), JINST 13, T09006 (2018) (arXiv:1807.03007) (nEXO Collaboration)
- **VUV-sensitive Silicon Photomultipliers for Xenon Scintillation Light Detection in nEXO,** IEEE Transactions on Nuclear Science 1 (2018) (arXiv:1806.02220)(nEXO Collaboration)
- **nEXO Pre-Conceptual Design Report,** arXiv:1805.11142v2 (nEXO Collaboration)
- **Characterization of an Ionization Readout Tile for nEXO,** JINST 13, P01006 (2018) (arXiv: arXiv:1710.05109v1)(nEXO Collaboration)
- **Sensitivity and Discovery Potential of nEXO to Neutrinoless Double Beta Decay,** Physical Review C 97, 065503 (2018) (arXiv: arXiv:1710.05075v1)(nEXO Collaboration)
- **Imaging individual Ba atoms in solid xenon for barium tagging in nEXO,** Nature 569, 203 (2019) (arXiv:1806.10694)(nEXO Collaboration)

Energy measurement

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



Reconstructed energy, ^{228}Th calibration:

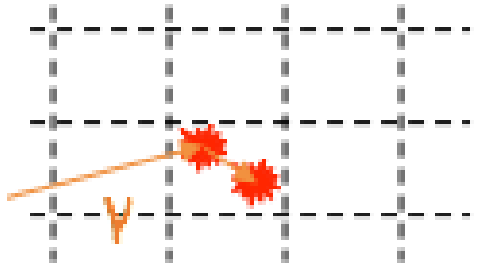


- Anticorrelation between scintillation and ionization in LXe known since early EXO R&D and now standard in LXe detectors [E.Conti et al. Phys Rev B 68 (2003) 054201]
- Rotation angle determined weekly using ^{228}Th source data, defined as angle which gives best rotated resolution
- EXO-200 has achieved ~ 1.15% (arxiv:1906.02723) energy resolution at the double-beta decay Q value in Phase II

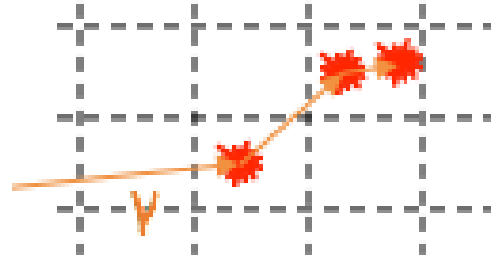
Position and multiplicity

Allows for background measurement and reduction

Events with **> 1** charge cluster: multi-site events (MS)
Events with **1** charge cluster: single-site events (SS)

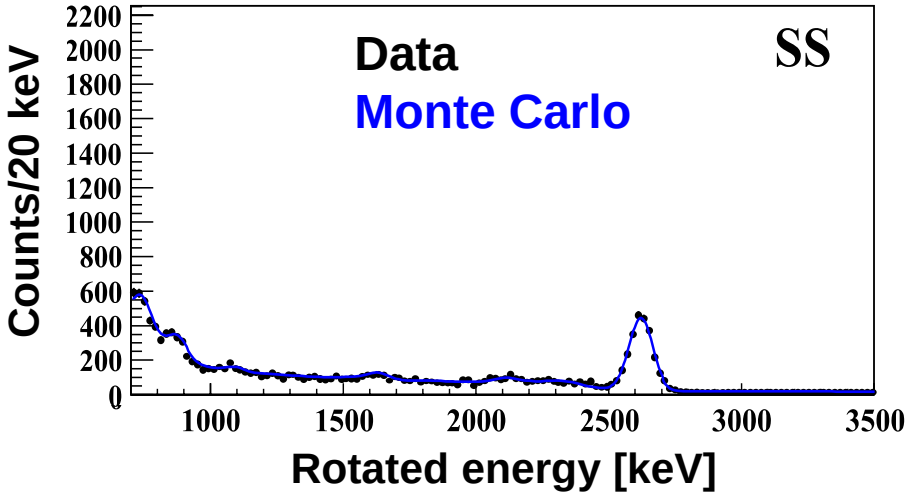


$0\nu\beta\beta$: ~90% SS
γ-rays: ~15% SS at $0\nu\beta\beta$ Q-value

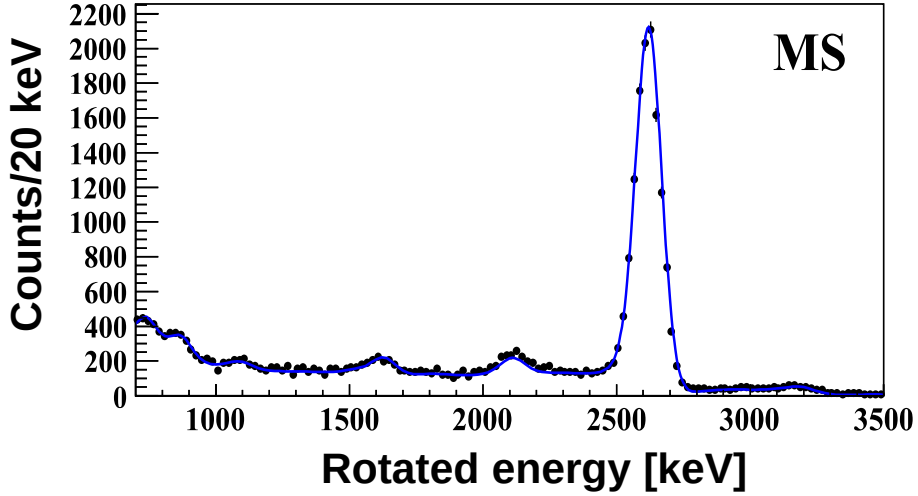


EXO-200 data

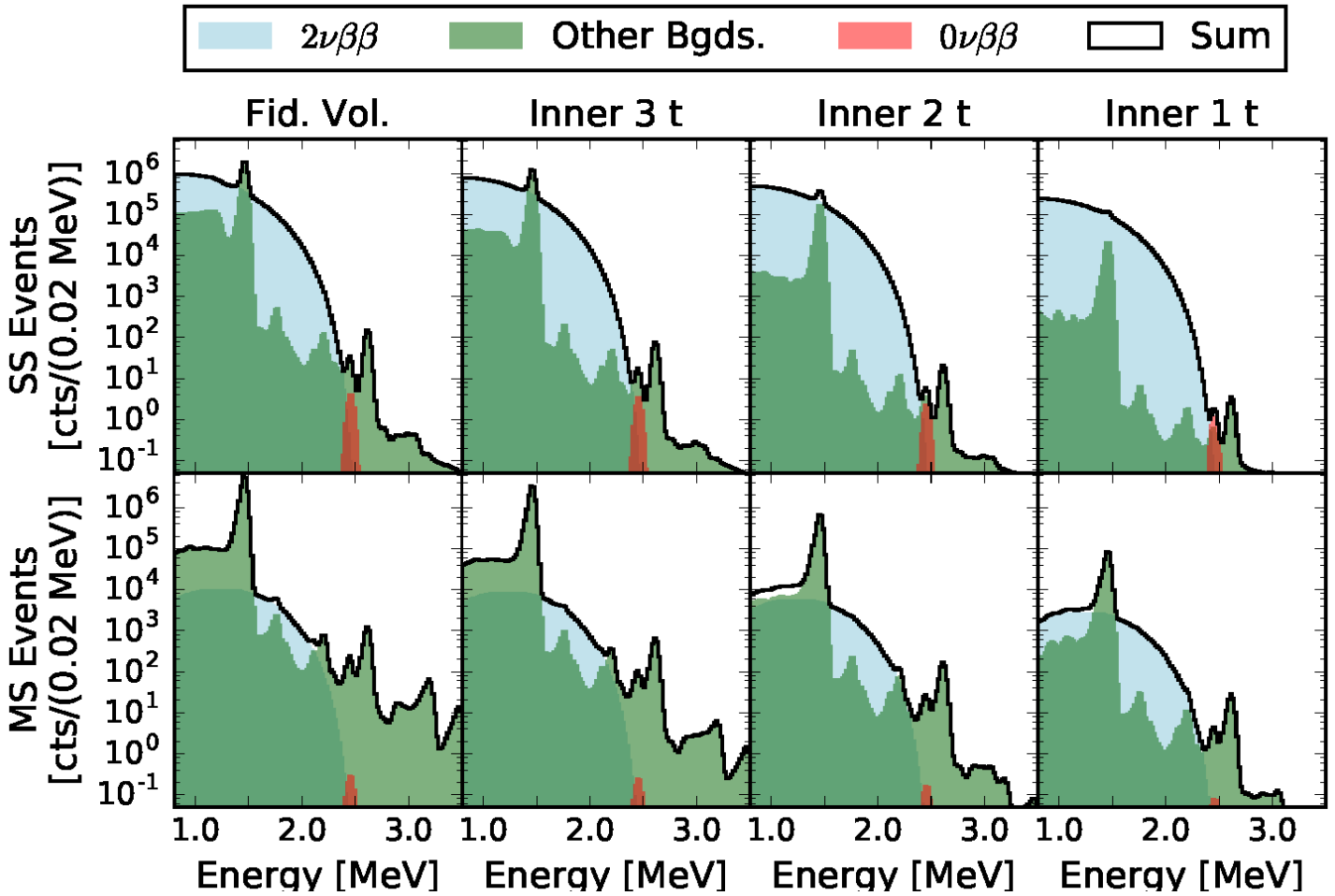
^{228}Th calibration data, SS:

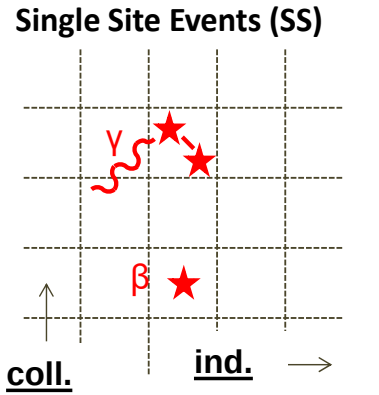


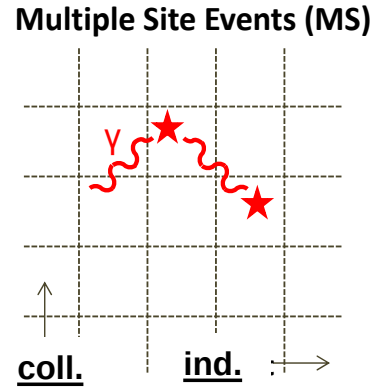
^{228}Th calibration data, MS:



nEXO discovery potential







Projected nEXO 10 year 3σ discovery potential at $T_{1/2}$=5.7x10^{27} yr

J.B. Albert et al., "Sensitivity and Discovery Potential of nEXO to Neutrinoless Double Beta Decay'', Phys. Rev. C. 97 065503 (2018), arXiv:1710.05075.

Interface between nEXO and SNOLAB

- **Several meetings between nEXO and SNOLAB:**
  - **SNOLAB (R.F.) participated in CFI kick-off meeting at McGill May 2018.**
  - **Meeting of nEXO Canada members at SNOLAB in August 2018.**
  - **Meeting of nEXO project management with SNOLAB October 2018.**
  - **Outer Detector mini workshop at McGill with participation from SNOLAB engineering team and nEXO Level 2 managers and nEXO project team in February 2019.**
  - **nEXO Project leaders visited SNOLAB in December 2019.**

- **Active and productive communication between nEXO and SNOLAB:**
  - **David Hawkins and Erica Caden are points of contact at SNOLAB.**
  - **David Hawkins and Erica Caden are System Manager and System Scientist, respectively, within nEXO Project.**

Currently, SNOLAB's engineering office dedicates roughly 20 hrs/week for the items mentioned in the previous slide.

SNOLAB is also providing project management support.

The Canadian Team

Carleton	Laurentian	McGill	Sherbrooke	TRIUMF/UBC
Razvan Gornea (0.8)	Erica Caden (0.3)	Thomas Brunner (0.9)	Serge Charlebois (0.75)	Jens Dilling (0.2)
Thomas Koffas (0.1)	Bruce Cleveland (0.2)	Daryl Haggard* (0.1)	Jean Francois Pratte (0.75)	Reiner Kruecken (0.2)
Simon Viel (0.3)	Jacques Farine (0.9)		Marc-André Tétrault* (0.7)	Fabrice Retiere (0.7)
David Sinclair**	Caio Licciardi (0.7)			Ania Kwiatkowski* (0.2)
	Ubi Wichoski (0.4)			

* D.H. and A.K. are collaborating on specific developments but are not a member of the nEXO collaboration.
** D.S. is member of EXO-200 only.

- The Canadian EXO spokes-team:

  Jacques Farine (Laurentian University) and

  Thomas Brunner (McGill University).
- Dr. Daryl Haggard (McGill) is collaborating with the team on astro-particle physics searches with the Outer Detector.
- Dr. Ania Kwiatkowski (TRIUMF) is collaborating on Ba-tagging developments.
- Marc-André Tétrault (Sherbrooke) is collaborating on investigating light properties in liquid Xe.