Neutrinoless double-β decay with nEXO

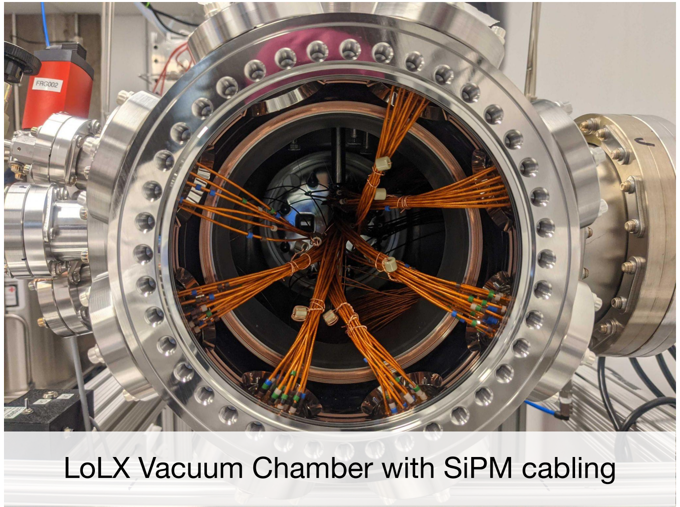
[Phys. Rev.C 97, 065503 (2018)]

[arXiv:2106.16243 (2021)]

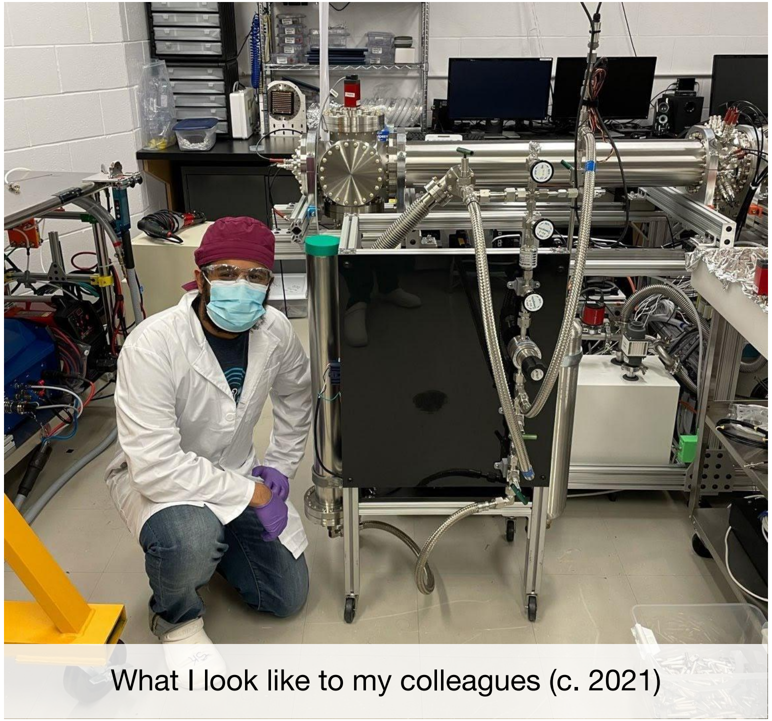
Soud Al Kharusi
SNOLAB User's Meeting
Aug 13th 2021

Who am I?

- 3rd year PhD student at McGill Univ.
  - Co-supervised by Thomas Brunner & Daryl Haggard
- Working on
  - nEXO Cosmogenics, Outer Detector, Supernova Neutrino Detection
  - Light-only Liquid Xenon experiment (LoLX)



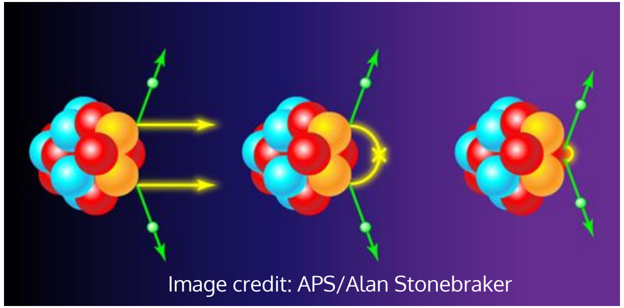
LoLX Vacuum Chamber with SiPM cabling

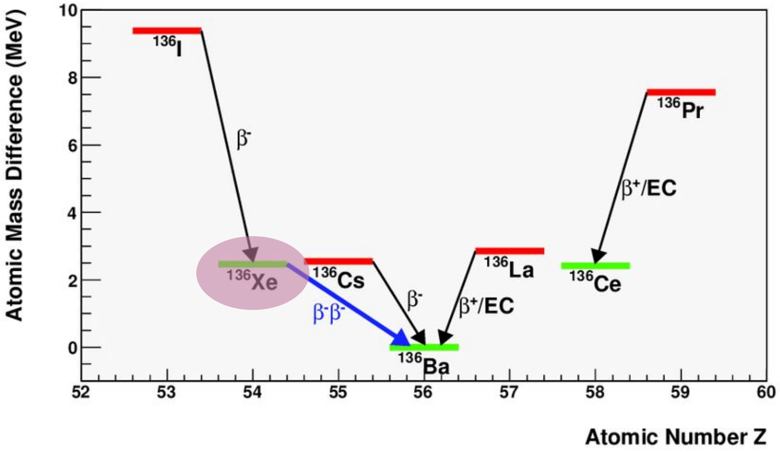


What I look like to my colleagues (c. 2021)

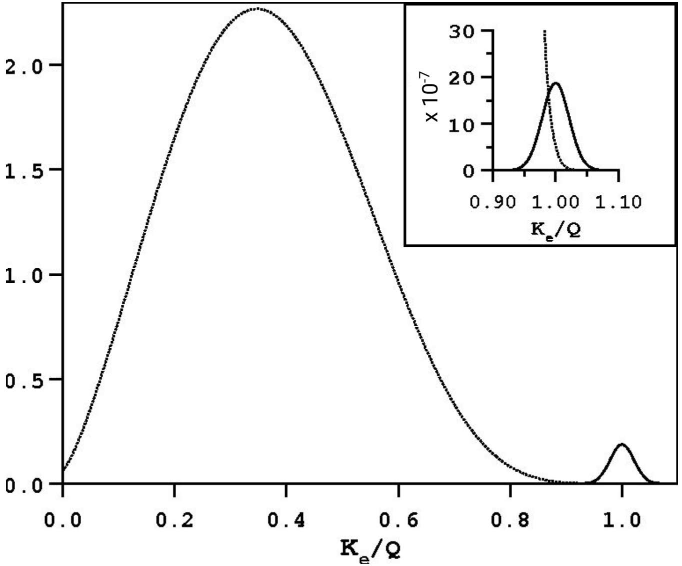
Introduction and Motivation: Why $0\nu\beta\beta$?

- What is double beta decay?
- Why the sudden rise in interest over the last ~20 years?
  - Neutrino mass / oscillations
- Lepton Number Violation / Matter Antimatter Asymmetry





Source: 10.1393/ncr/i2012-10074-9 / arXiv:1109.5515



Source: Elliott, S.. (2003). Corpus ID: 17996273

Real Motivation

- What is double beta decay?
- Why the sudden rise in interest over the last ~20 years?
  - Neutrino mass / oscillation
- Lepton Number Violation / Matter Antimatter Asymmetry

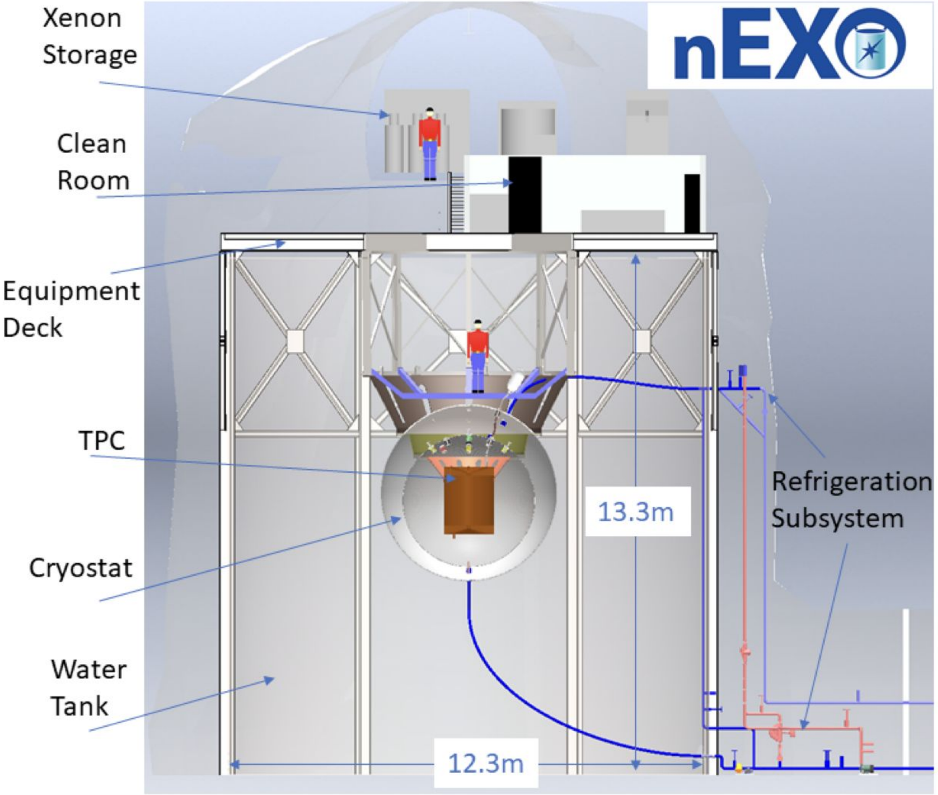
Particle physics community searching for BSM physics

Regardless of what mechanism $0\nu\beta\beta$ proceeds by, it always implies new physics

What is nEXO?

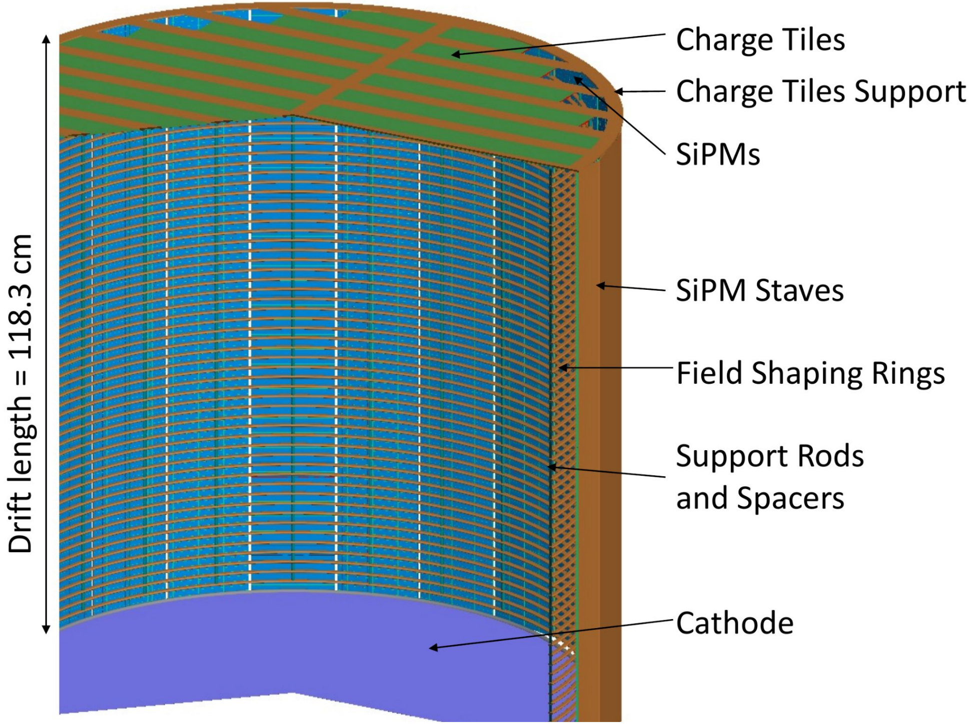
nEXO is a proposed $0\nu\beta\beta$ experiment

- 5-tonne single-phase liquid Xe TPC
- 90% enriched in the target isotope, ^{136}Xe
- Extensive radio-assay program (ultra low backgrounds validated by EXO-200 data)



Distinguishing Features

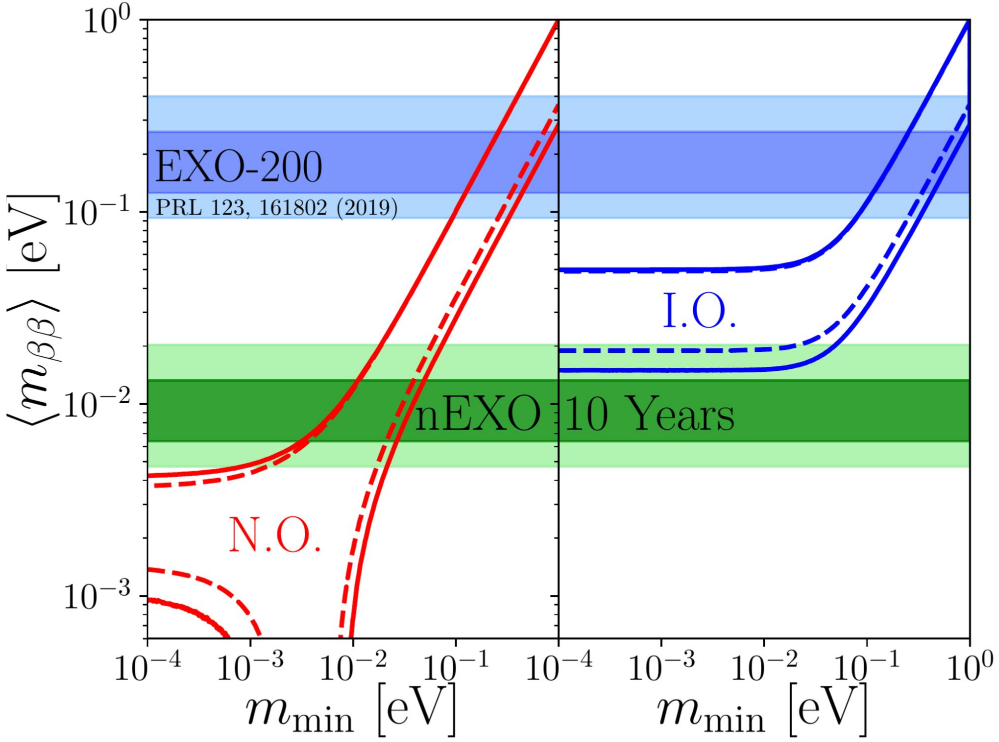
- Multi-parameter search
  - Single- and multi-site discrimination
  - Standoff distance to detector components
  - ~1% energy resolution at $Q_{\beta\beta}$
- Homogeneous detector medium
- Novel technology in light (SiPMs) and charge detection (custom-made charge tiles)
- Possibility for control run in case of discovery



nEXO Projected Sensitivity

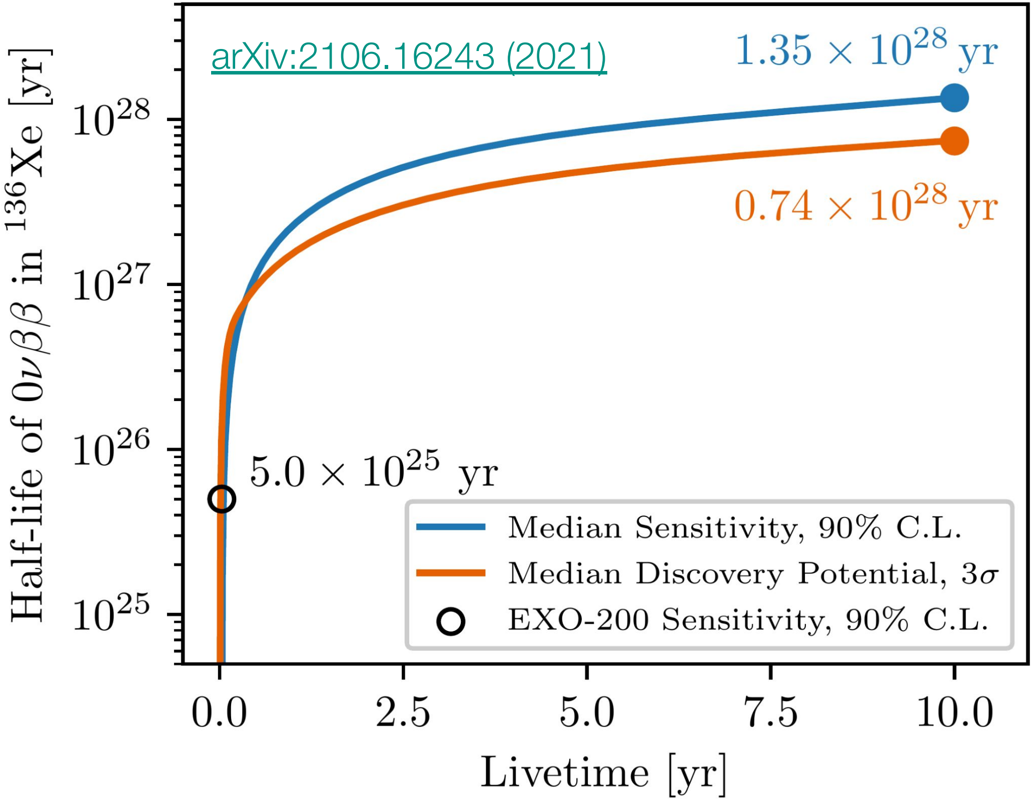
arXiv:2106.16243 (2021)

- Covers entire I.O. parameter space
- Significant fraction of N.O. space excluded after 10 years



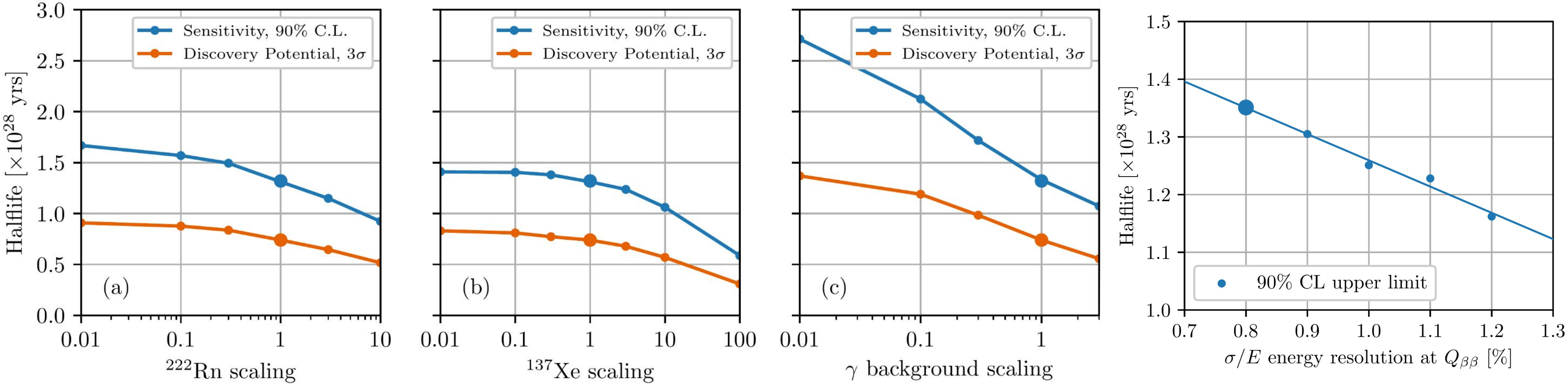
nEXO Projected Sensitivity

- >250x improvement over EXO-200 sensitivity to $0\nu\beta\beta$ half-life
  - With only ~25x increase in mass!



nEXO Sensitivity

Well studied response to fluctuations in background model, energy resolution, … arXiv:2106.16243 (2021)



Confidence in the sensitivity estimate arises from a detailed conservative model with measured input parameters

nEXO Sensitivity

Well studied response to fluctuations in background model, energy resolution, …

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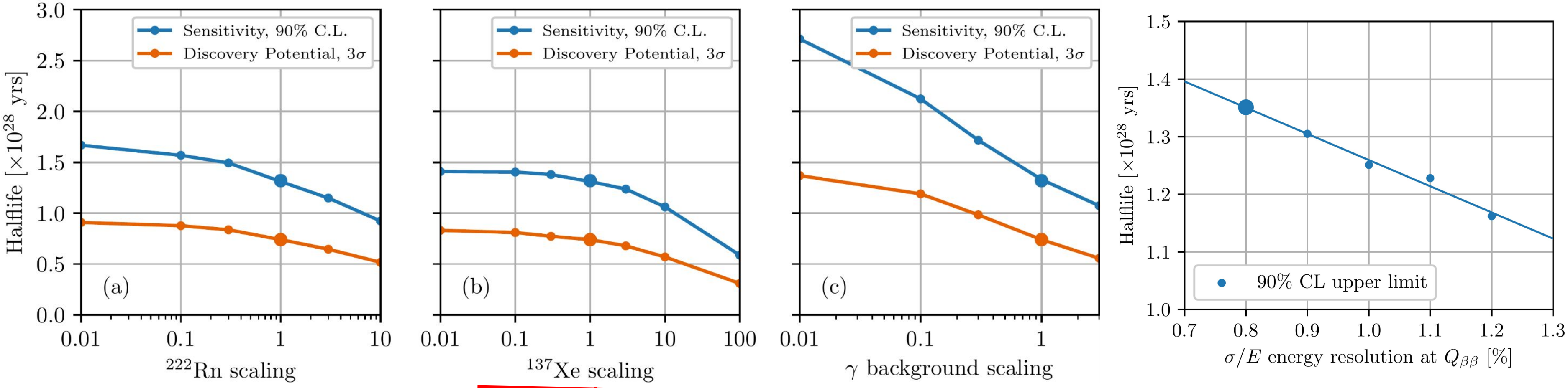
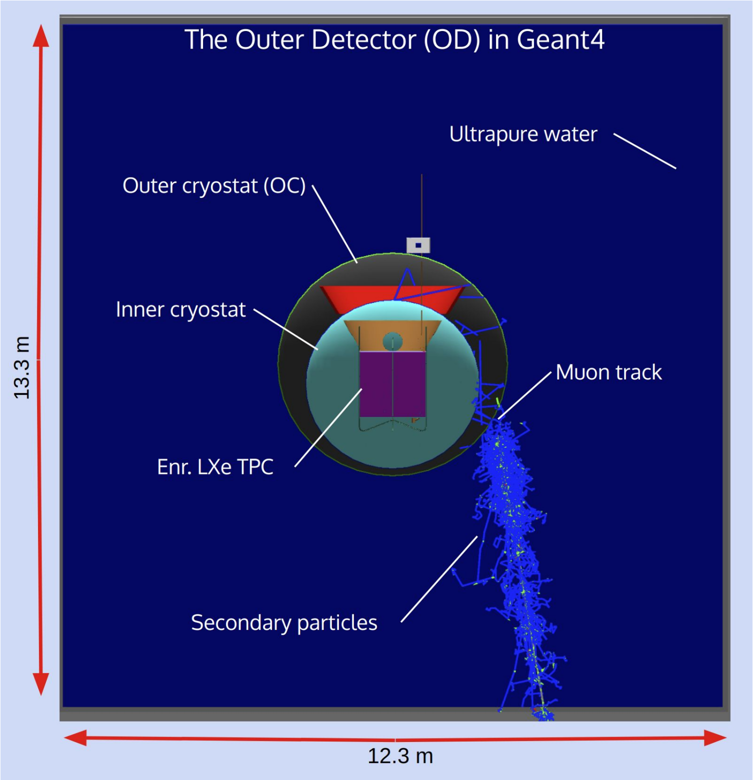


dominant cosmogenic background

nEXO requires an instrumented water tank

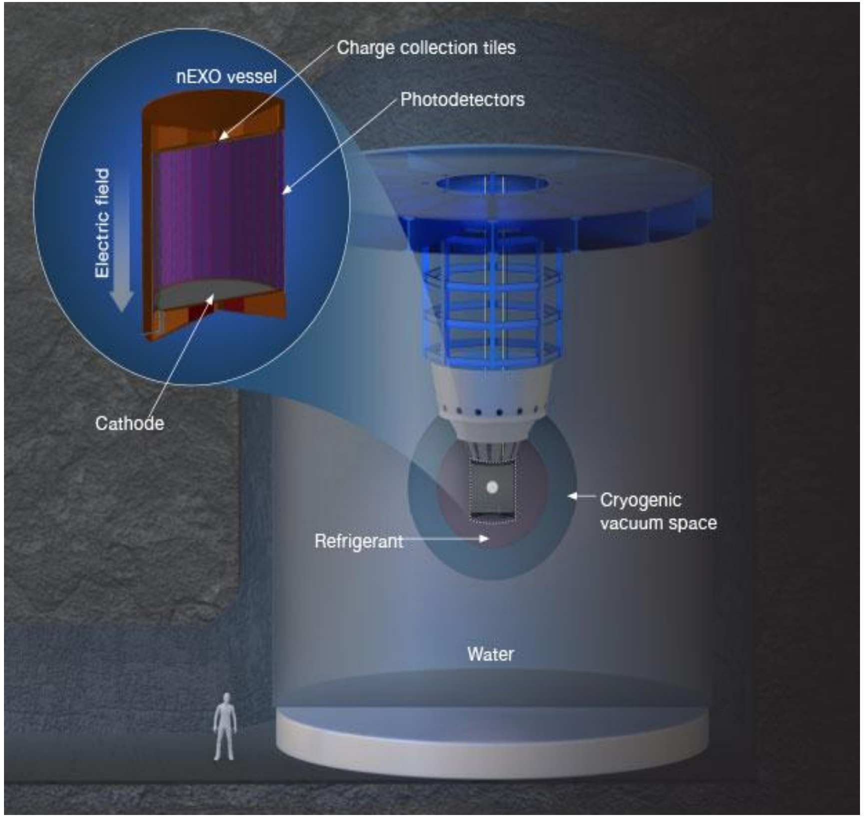
In the case of $0\nu\beta\beta$ discovery, need to justify absence of cosmogenic backgrounds in dataset



Geant4 model of nEXO

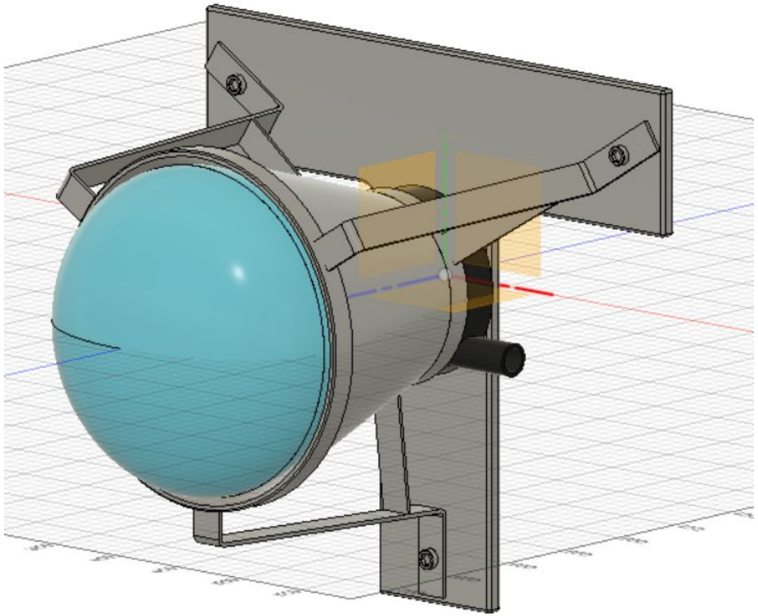
nEXO Outer Detector: Overview

- Water **shields from external gammas, neutrons** coming from the surrounding rock



nEXO Outer Detector: Overview

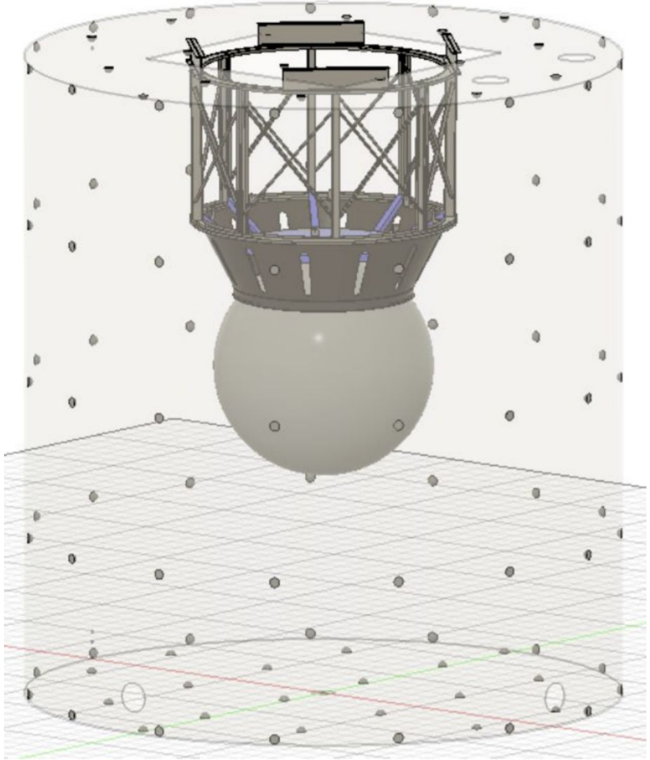
- Water **shields from external gammas, neutrons** coming from the surrounding rock
- PMTs **tag muons via their Cherenkov emission in water**
    - Hamamatsu R5912 8″ PMTs from Daya Bay



(Figure/Model from L. Retty)

nEXO Outer Detector: Overview

- Water **shields from external gammas, neutrons** coming from the surrounding rock
- PMTs **tag muons via their Cherenkov emission in water**
  - Hamamatsu R5912 8″ PMTs from Daya Bay
- Coincidence of muon Cherenkov signal with TPC low-energy neutron-capture gammas allows for **strong cosmogenic background rejection (>70%) with minimal losses in livetime**



CAD model of nEXO Outer Detector

Geant4 ⟶ Chroma

- Geant4 tracking of optical photons from high energy muons is **computationally expensive**
- Chroma is a **GPU-based program** with the ability to ray-trace 100s of times faster than any CPU program

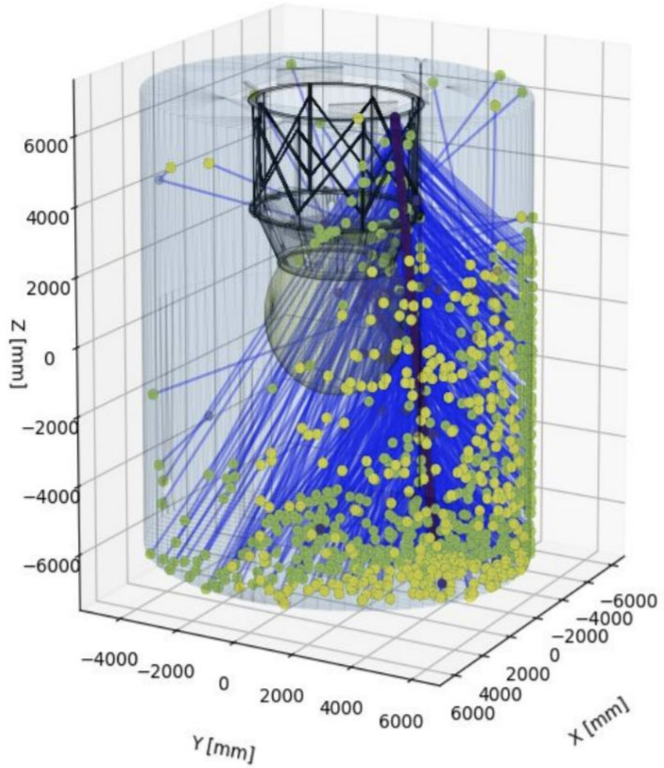
We developed a cosmogenic muon simulation in Chroma that includes proper Cherenkov photon propagation to allow **fast-turnaround of optical trade studies with high statistics runs**

Geant4 ⟶ Chroma

What do I mean by "fast-turnaround of trade studies with high statistics runs"?

- How many PMTs do we need?
  - What is the optimal PMT distribution?
- What should our trigger condition be?
- Do we need reflective foil on all surfaces or just some?
- What requirements do we set for the optical properties of the water?
- At what level can we track muons?
- …

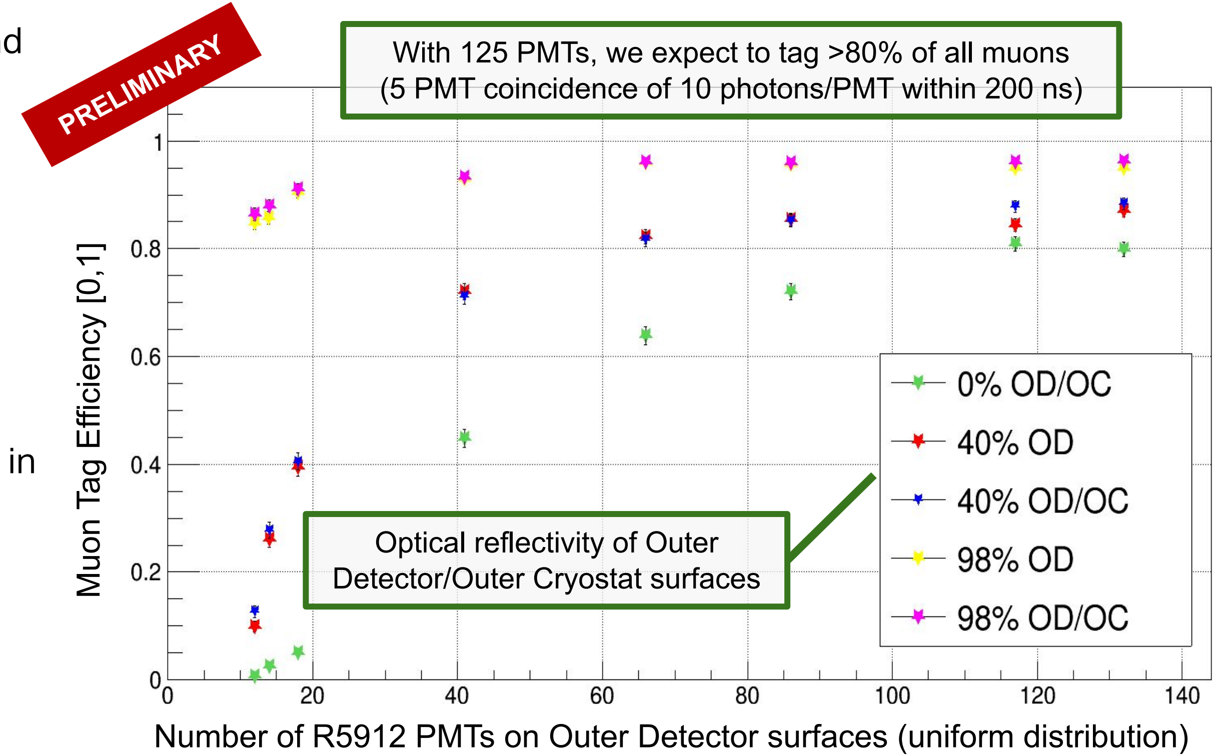
Answering the above questions leads to an improved design of the Outer Detector and a comprehensive muon tag.



Sample of photons from a muon track in Chroma (plot by E. Klemets)

Where are we now?

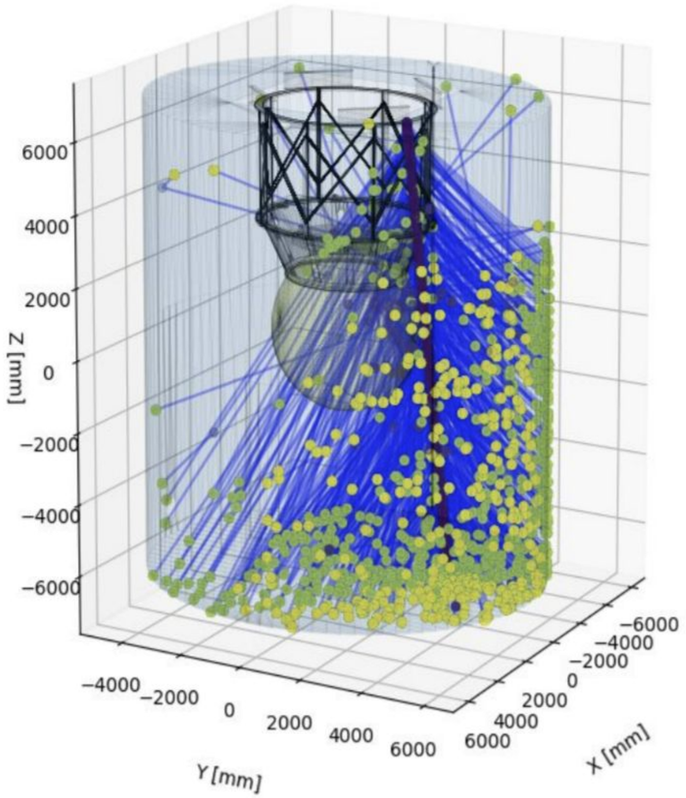
- Realistic CAD models completed and imported into simulation
- Muon Cherenkov production and optics have been developed in the nEXO Chroma simulation
- Preliminary studies previously done in Geant4 are being validated with Chroma



Preliminary Geant4 results of muon tag efficiency
(Work of R. Hill)

Conclusion

- nEXO is a future $0\nu\beta\beta$ search in ^{136}Xe
- Outer Detector design and simulations are handled by Canadian groups in close cooperation with SNOLAB
- Chroma simulation of muon Cherenkov emission and PMTs has developed
    - Currently validated against preliminary Geant4 studies
    - Will be used to tackle detailed design choices regarding the Outer Detector



Acknowledgements

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Thomas Brunner, Erica Caden, Caio Licciardi, Allen Odian, Ubi Wichoski, David Hawkins, Lisa Kaufman, Raymond H.M. Tsang, Samuele Sangiorgio

and the greater nEXO Collaboration

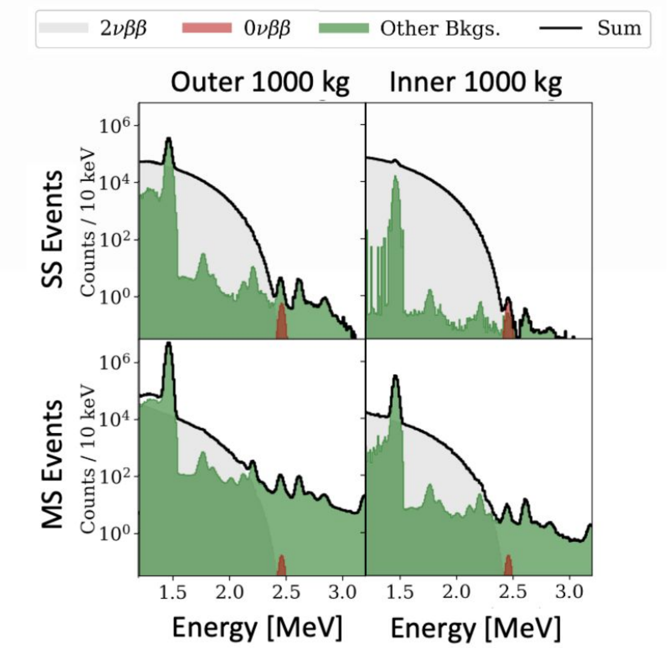
A Worldwide Effort

nEXO

Backup Slides

Fun facts

If an unknown decay were strong enough to produce as many SS events in the inner 3000 kg as a 3σ discovery at a half-life of 5.7×10^{27} yr, this decay would produce 271 counts in the MS outer volume, enough to rule out the expected background model at $p < 0.00001$.

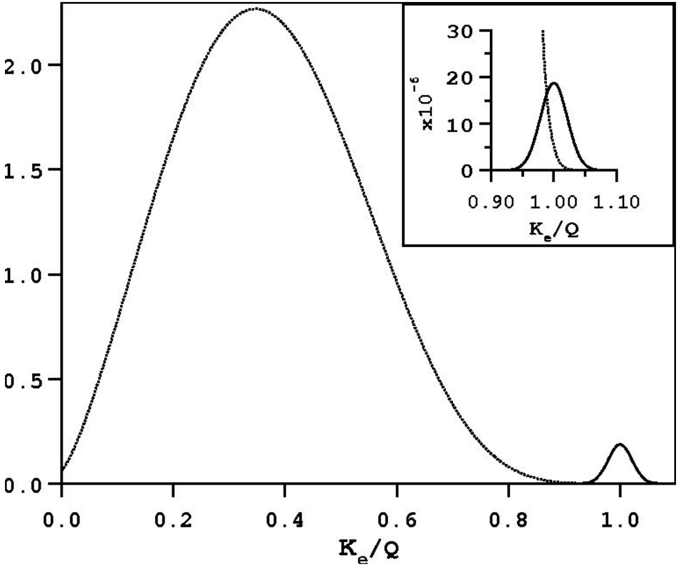


[Phys. Rev.C 97, 065503 (2018)]

What are nEXO's main event discriminators?

Three main discriminators, nEXO is **not just a counting experiment**:

1. Event energy: σ/E ~ 1% at 2.458 MeV -> use charge-light anticorrelation to optimize this.



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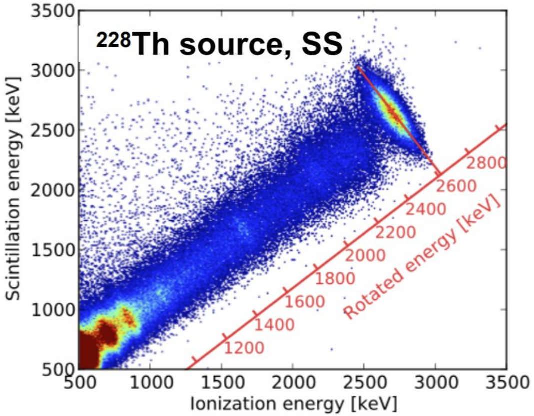
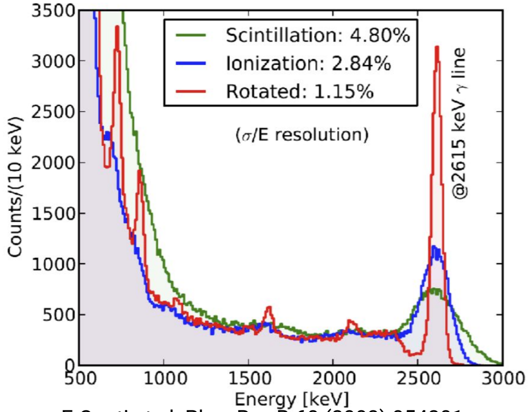


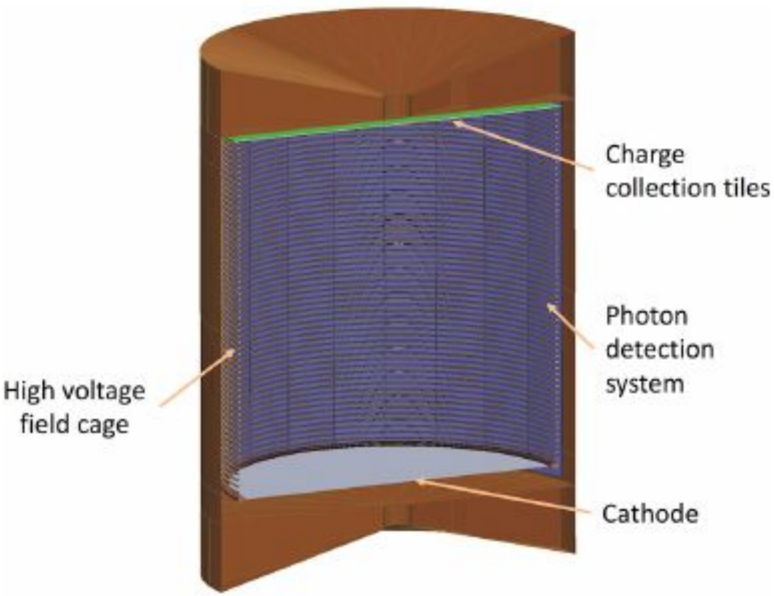


E.Conti et al. Phys Rev B 68 (2003) 054201

What are nEXO's main event discriminators?

Three main discriminators, nEXO is **not just a counting experiment**:

2. Event topology: how many charge clusters do we read on the anode? Single, or many? -> Use a DNN on charge channel data.



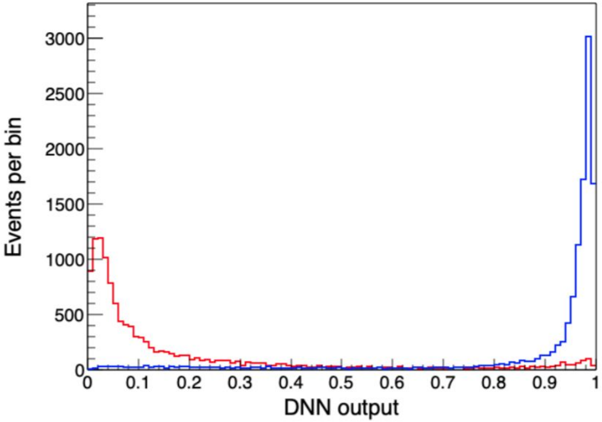
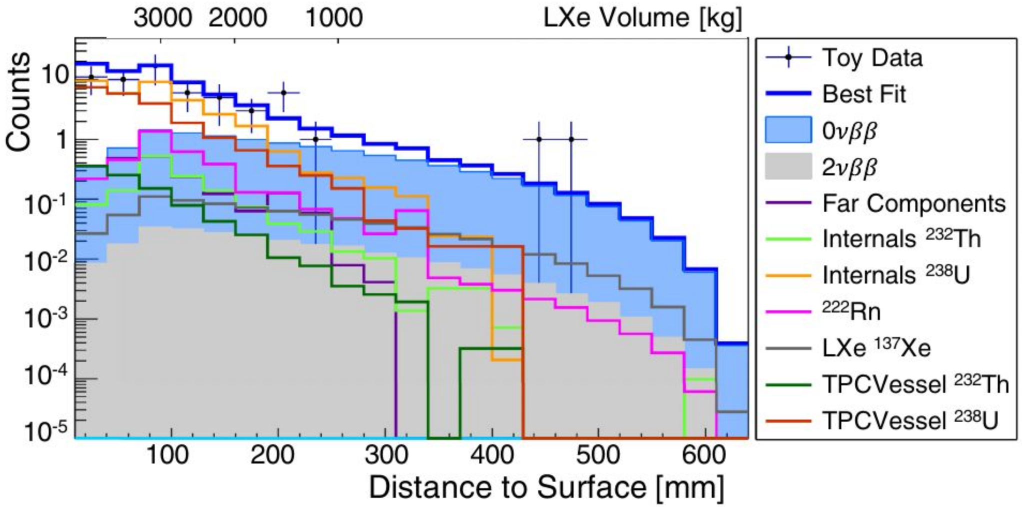


Image source: Li, Z., et al. "Simulation of charge readout with segmented tiles in nEXO." *JINST* 14.09 (2019): P09020.

What are nEXO's main event discriminators?

Three main discriminators, nEXO is **not just a counting experiment**:

3. Event location: did the event happen in the inner 1t, 2t, of liquid xenon or near the TPC vessel? -> attenuation length of ~MeV gammas in LXe (~8 cm) < TPC scale (65 cm radius & half-height) .

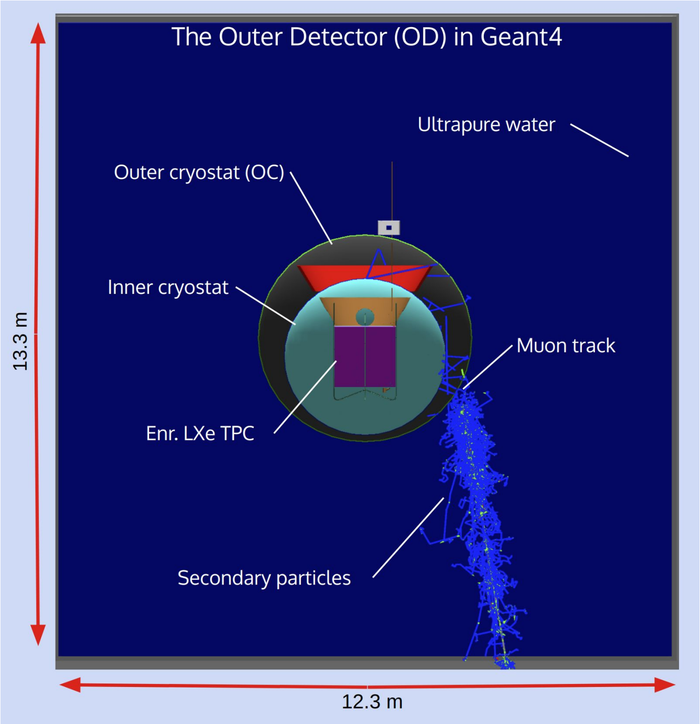


Backgrounds to nEXO

Cosmogenically activated Radionuclides

Two parts:

1. Things can be activate above ground (during transportation, storage, machining)
   a. Co-56/Co-60 activation (copper TPC)
   b. Cs-137 from above ground activation will be purified out
2. Underground cosmogenic activation:
   a. From EXO-200, we know what isotopes are produced per muon (mostly the same detector materials for nEXO)
   b. Other than Xe-137, all other isotopes have a background rate 1% relative this Xe-137 value (low activation rates)



Neutrino-induced backgrounds

- Mostly from the Sun
- Neutrino-electron elastic scattering
  - Cross section is small, but expect ~0.02 SS events/(FWHM yr) in inner 2t
  - Backgrounds below this level are considered negligible

$$(\nu + e^- \rightarrow \nu + e^-)$$

- Xe-136 neutrino capture *v + Xe -> e- + Cs-136*
  - e- + Cs-136 has many gammas (strong multi-site features)
  - Cs-136 -> Ba-136 (13.6 day half life, multi-site rejection expected)

$$\nu + {}^{136}\mathrm{Xe} \rightarrow e^- + {}^{136}\mathrm{Cs}$$

- Neutral current channel (nuclear excitation of Xe-136)
  - No known nuclear level with energy near Q-value

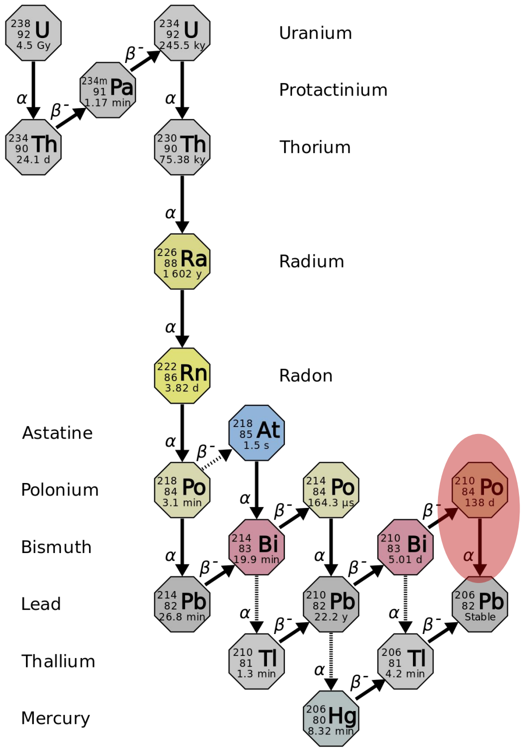
All neutrino backgrounds are considered negligible

Radionuclides from (α, n) reactions

- Po-210, daughter of Rn-222 is α-unstable
- These α particles can interact with low-Z detector materials and produce neutrons
- Neutrons can capture on materials and produce background (e.g. Xe-136)

This is controlled by limiting material exposure to regular air (which has Rn-222 in it). This is a concern for the HFE (cryofluid).

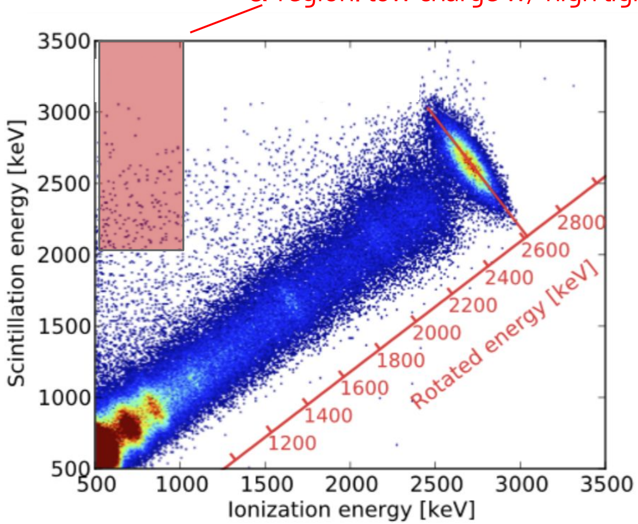
Uranium series



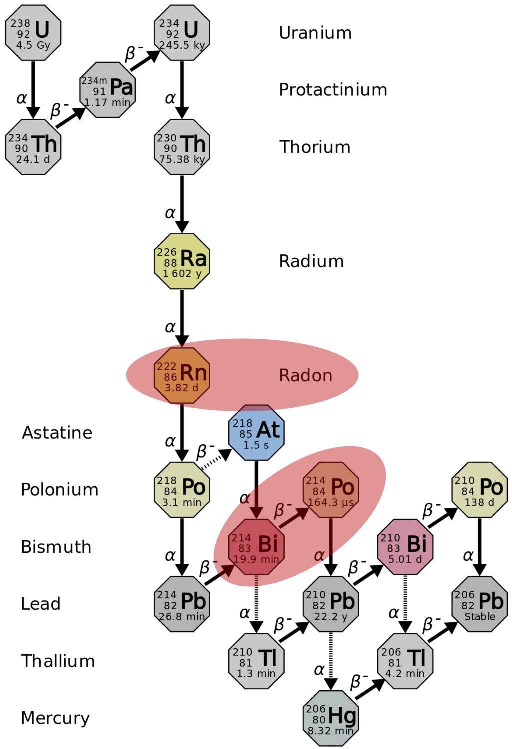
Rn-222

- Main concern is the daughter isotope Bi-214
  - Gamma line only 10 keV below $Q_{\beta\beta}$
- Must control processes that can allow Rn into the LXe
- Estimate of number of Rn atoms can be done by searching for Bi-Po coincidence events

α region: low charge w/ high light

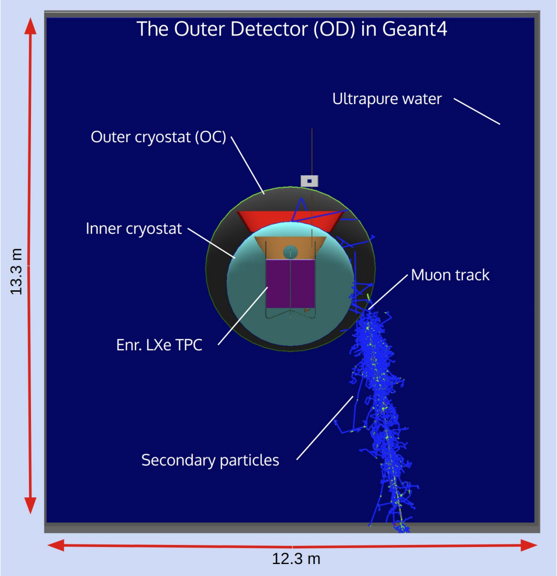


Uranium series



Detector Simulations

- Geant4: the swiss army knife of particle tracking and Monte Carlo
  - nEXO selects radionuclides of interest from background model
  - Let Geant4 propagate and track the particle + secondaries
- Detector response done in custom code which parameterized the energy response (with help of NEST), SS/MS ability
- Long electron lifetime (>10 ms) due to lack of electronegative impurities in the xenon allows for low degradation in σ_E/E during drift.



What happened to supernovae?

The high-rate gamma background from rock Tl-208 (2.6 MeV) at SNOLAB overwhelms the low energy signal region, which removes the ability to do:

1. Detect low energy pre-SN neutrinos
2. Measure neutrino spectra well (anti-nue mainly)
3. Reconstruct position in the OD well (low PMT density does not help)

Our (relatively) small water tank will have too few statistics to:

1. Investigate neutrino flux evolution
2. Point to the SN via triangulation or reconstructing individual events, *unless the event is rather close at ~3 kpc*

In summary, we ***can produce a supernova alert*** *and extract some physics for only very close SN events*

The TPC will be interesting for only very close SN events due to small mass/cross sections + low stats.

Most interesting channel (CEvNS) difficult to measure with nEXO baseline design (low energy nuclear recoils)