Sensitivity of the nEXO neutrinoless double beta decay experiment

(Based on arXiv:2106.16243)

Brian Lenardo

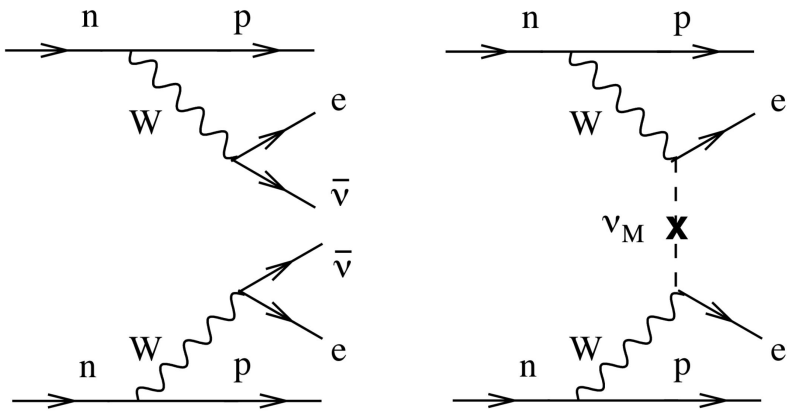
Light Detection In Noble Elements (LIDINE)

September 14, 2021

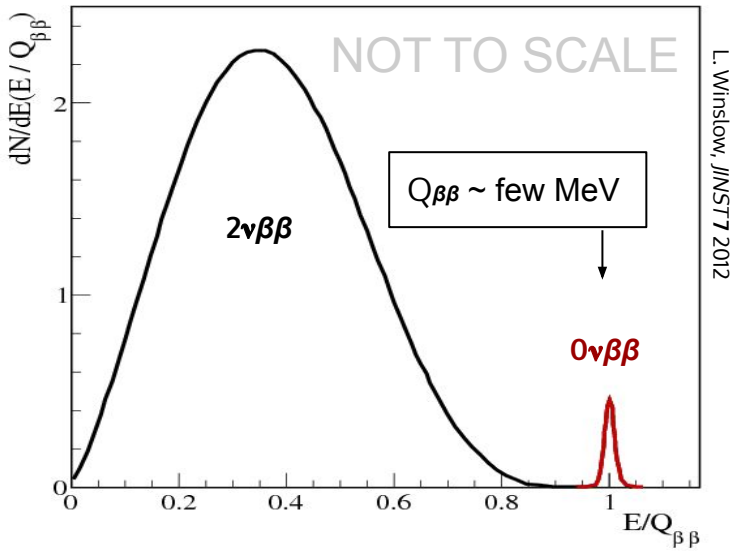
Searching for new physics via 0νββ

0νββ 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)

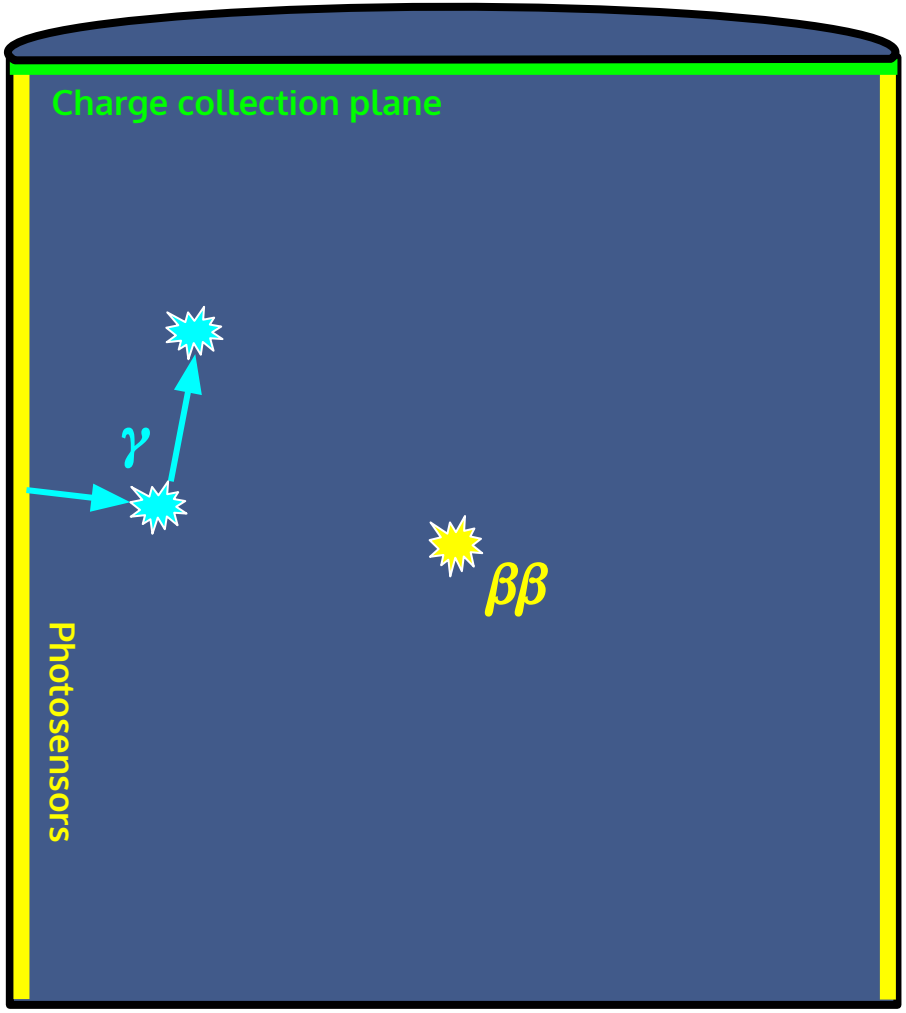


Current $T_{1/2}$ limits: >10^{26} years!

Requirements for next-gen 0νββ experiments:

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

Searching for 0νββ in a liquid Xe TPC



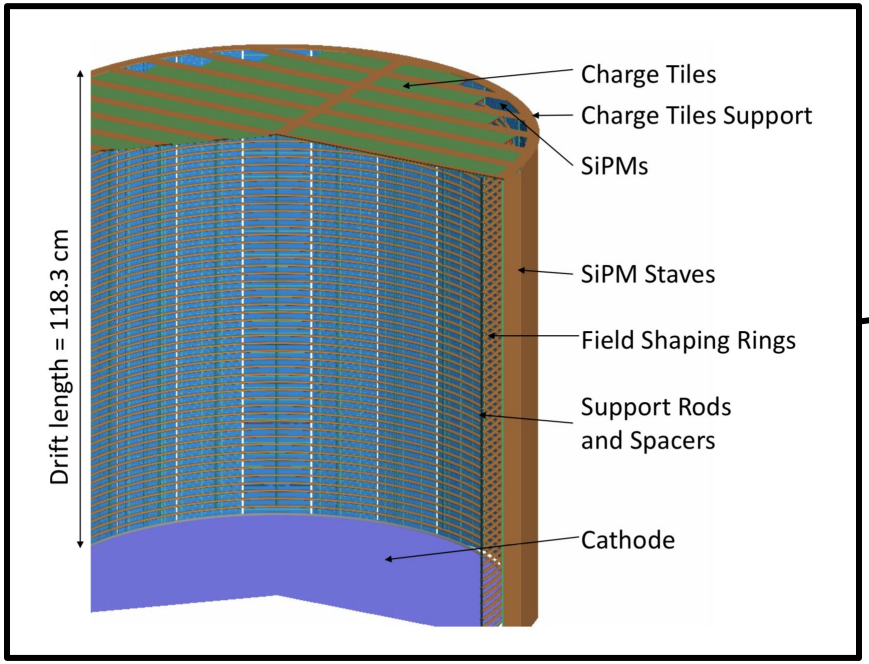
Addressing the challenges in 0νββ searches:

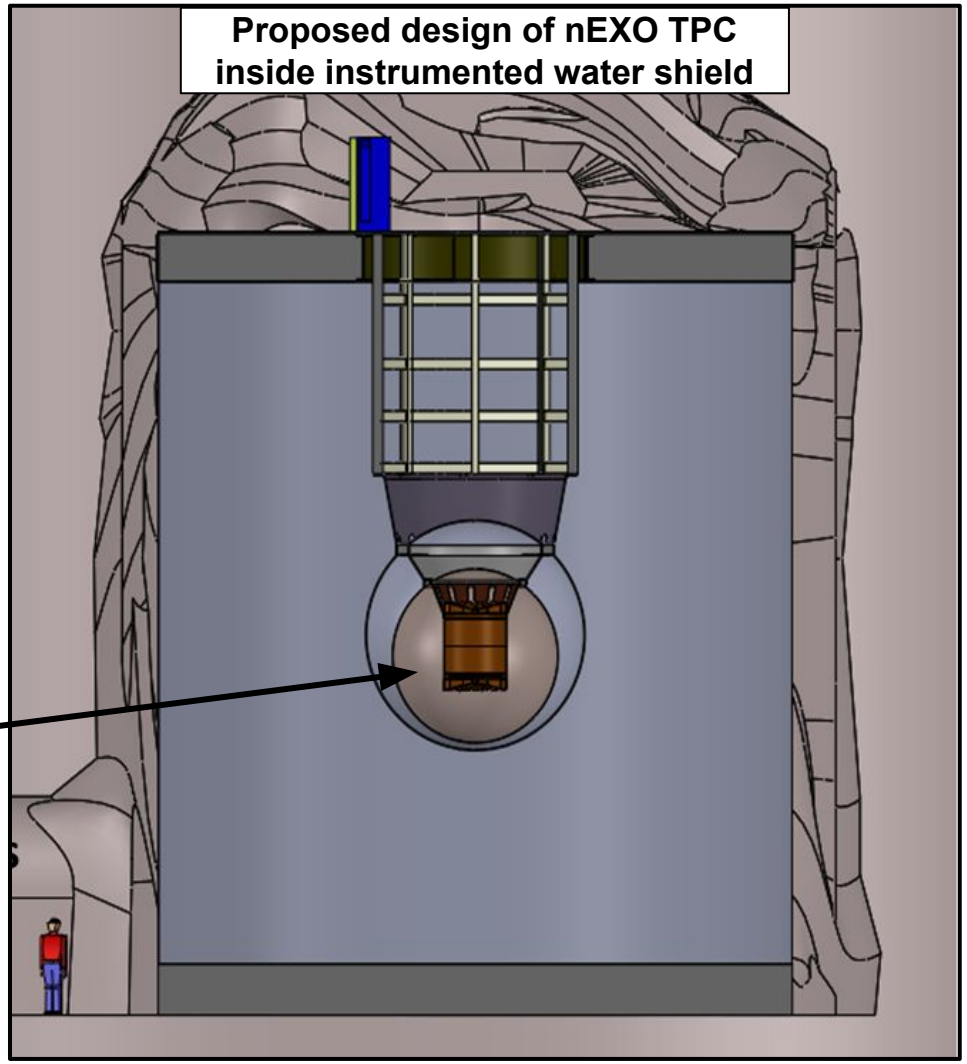
- **Large samples of ββ isotope (^{136}Xe)**
  - Ton-scale LXe TPCs are already operating
  - Enrichment is straightforward
- **Low, well-characterized backgrounds in MeV range (low radioactivity)**
  - Very low intrinsic backgrounds in Xe
  - Strong self-shielding
- **Good energy resolution**
  - Combining charge and light can reach <1%
- **Signal/background discrimination**
  - Powerful position reconstruction and multi-site rejection

The next-gen Enriched Xenon Observatory (nEXO)

Search for 0νββ decay of ^{136}Xe ($Q_{\beta\beta}$ = 2.457 MeV)

- Single-phase liquid xenon TPC
- Five tonne target volume, 90% enriched in ^{136}Xe
- ~2000m overburden
  - To be located in the SNOLAB cryopit
- Active water Cherenkov veto





Projecting the sensitivity of nEXO

Procedure:

1. Build a background model
2. Simulate the detector response
3. Analyze (simulated) data and perform statistical analysis

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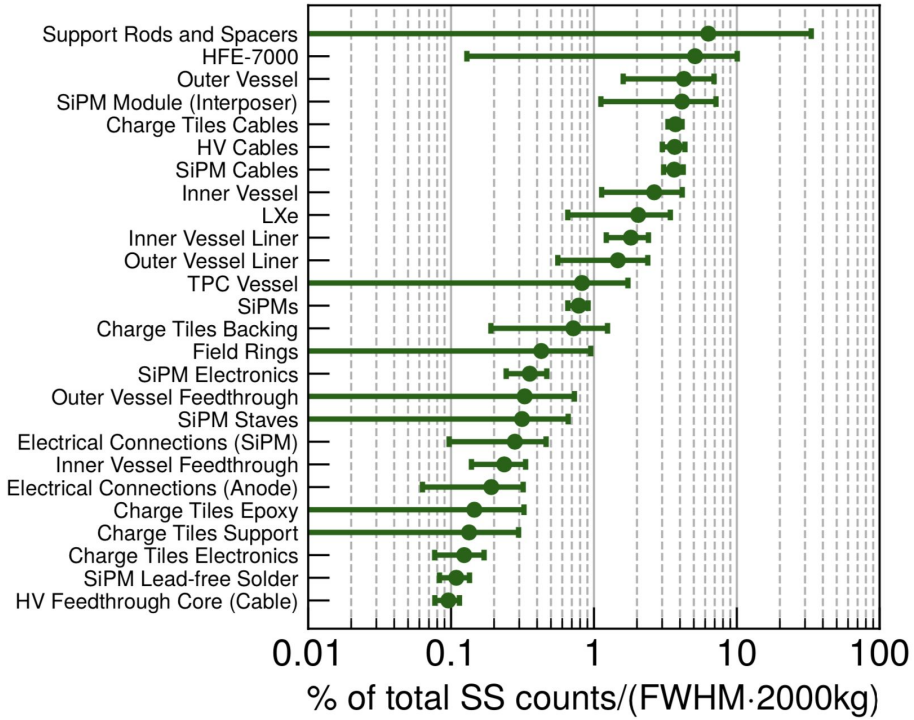
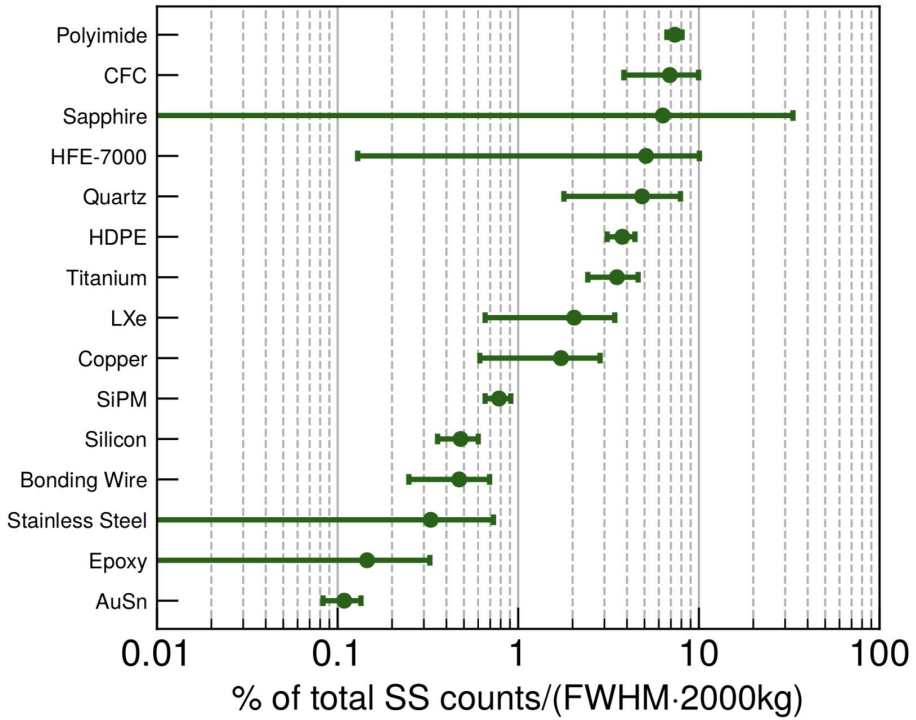
1. Building a background model: materials

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

Every material in existing design has been screened for radiopurity

→ nEXO's material background assumptions are data-driven





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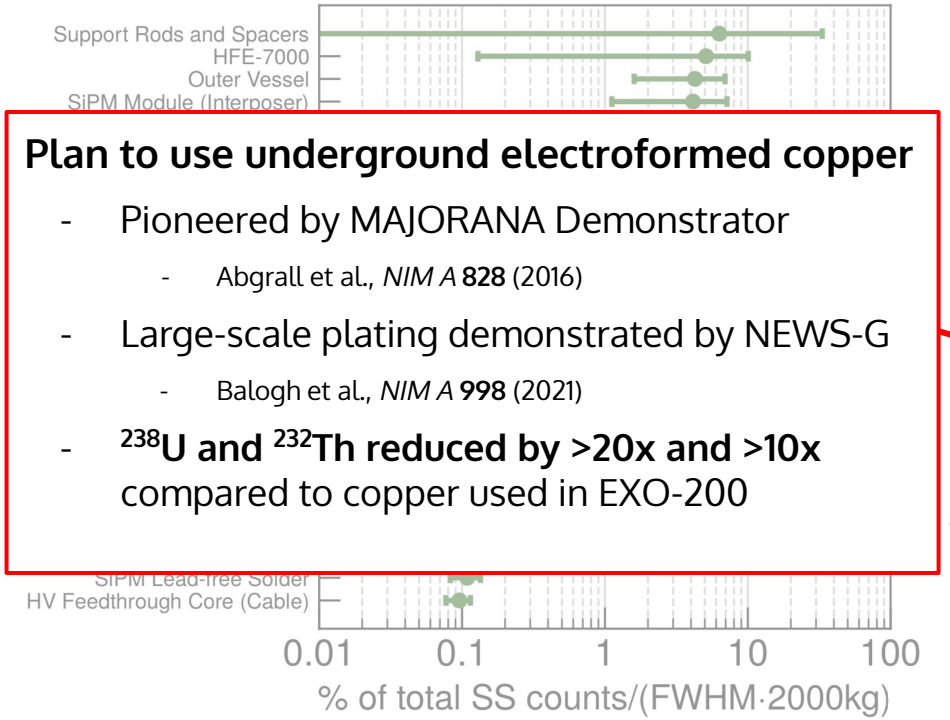
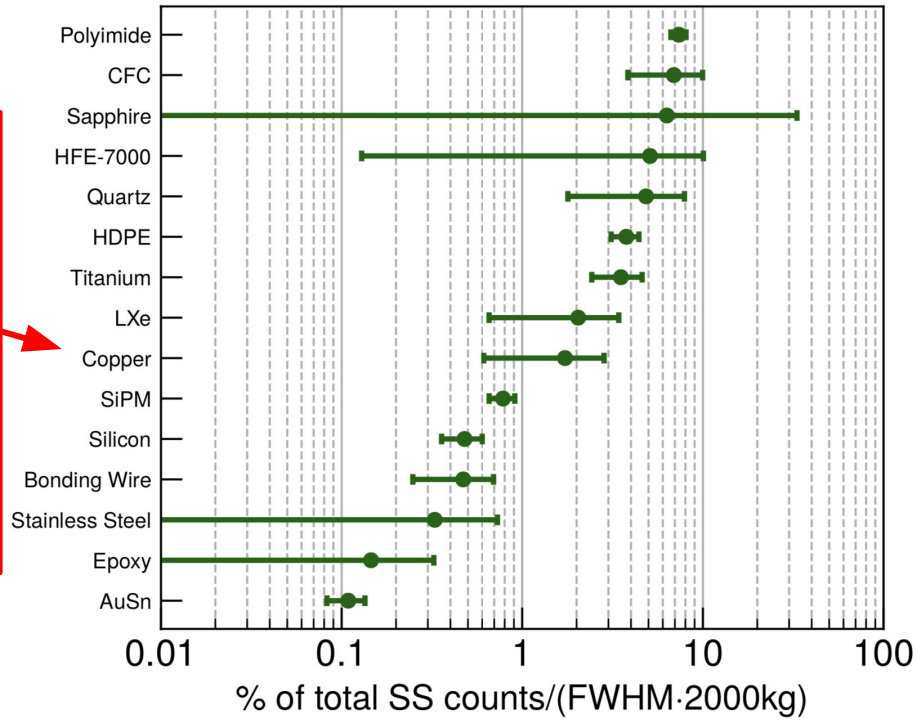
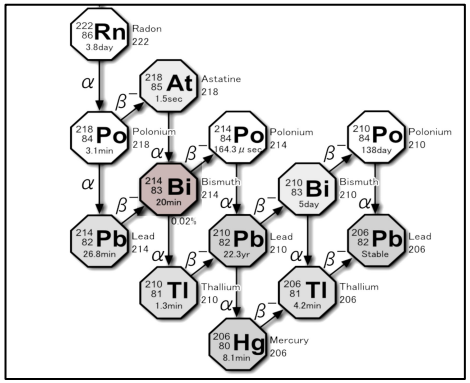


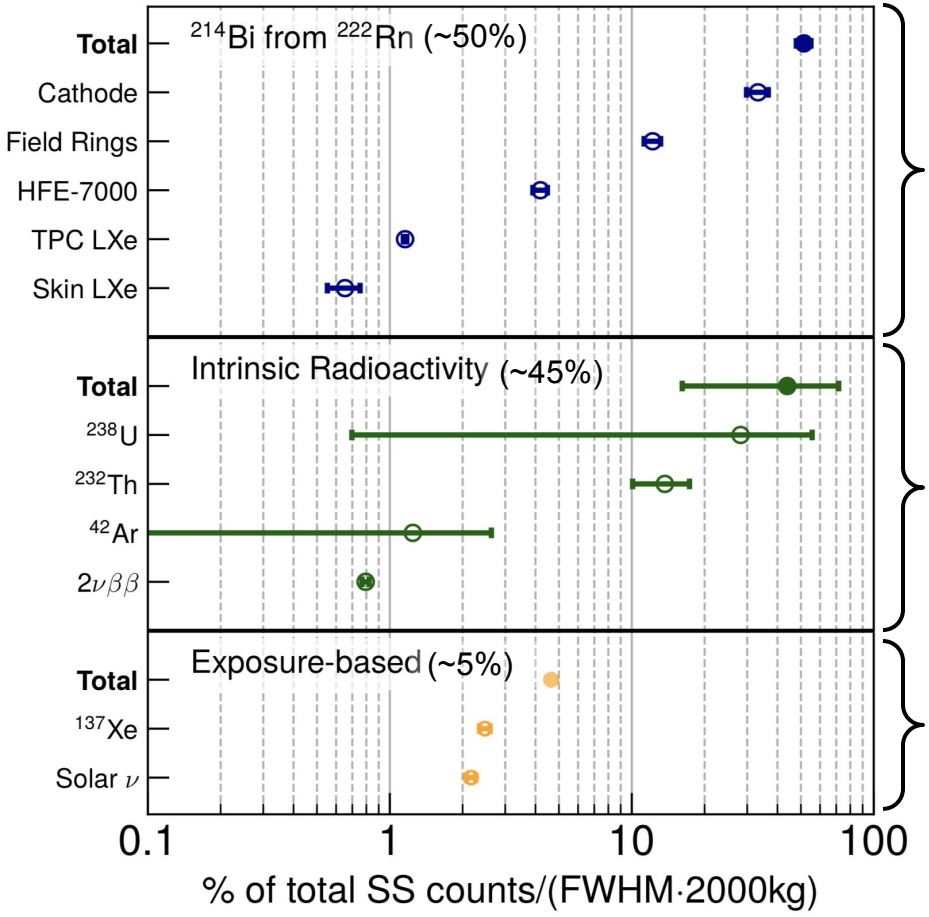
Plan to use underground electroformed copper

- Pioneered by MAJORANA Demonstrator
  - Abgrall et al., *NIM A* **828** (2016)
- Large-scale plating demonstrated by NEWS-G
  - Balogh et al., *NIM A* **998** (2021)
- **^{238}U and ^{232}Th reduced by >20x and >10x** compared to copper used in EXO-200



1. Building full background model





Primary bkg from ^{222}Rn emanated into the Xe system

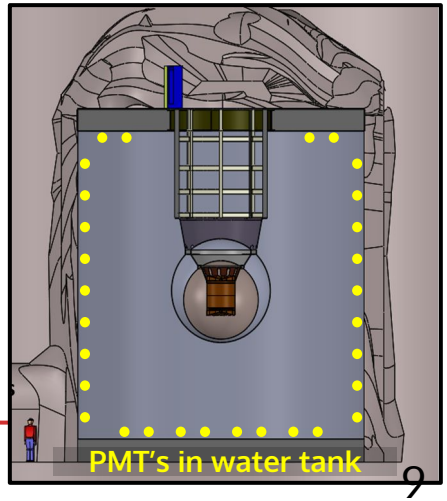
- Assume steady-state population of 600 atoms of ^{222}Rn in the xenon (extrapolation from EXO-200)
- Primary issue is daughters attached to detector surfaces

Detector materials

- Previous slide

Backgrounds unaffected by detector construction

- We conservatively assume **70% rejection of ^{137}Xe bkg** via active muon veto, based on simulations



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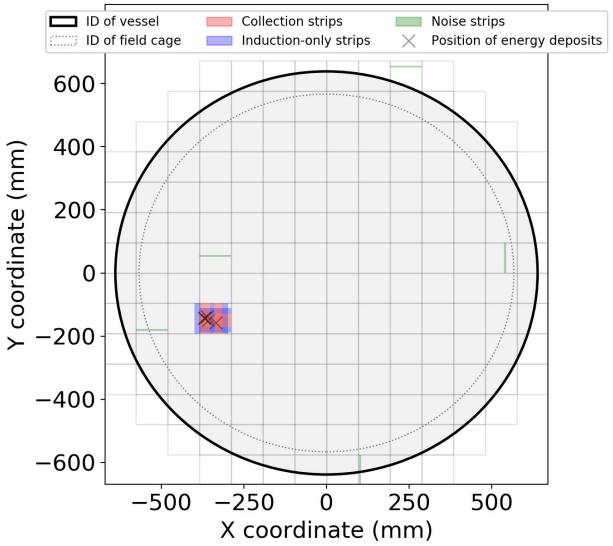
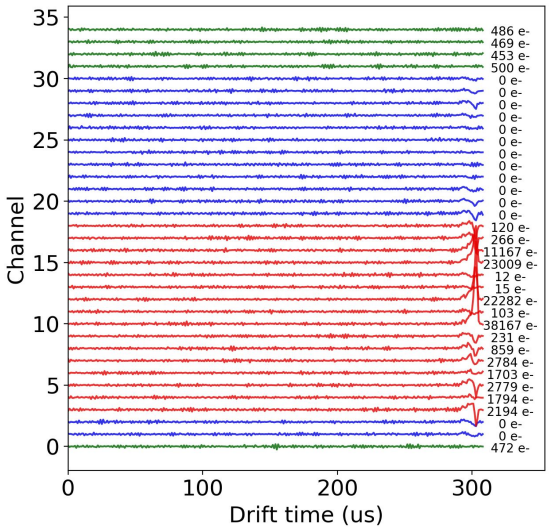
Recent work on readout simulations

Charge readout modeled at the waveform level

- 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)

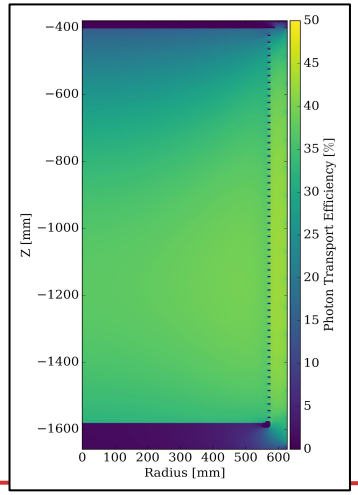
Charge reconstruction of 0nuBB event with a bremsstrahlung

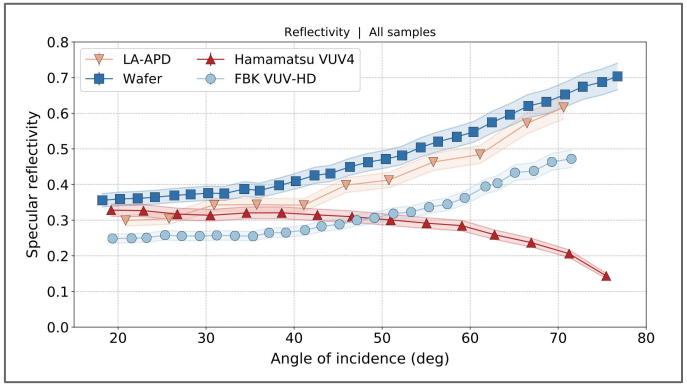




Light collection modeling improved with new data and software

- 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) *JINST* **16** (2021)





M. Wagenpfeil, *JINST* (2021) arXiv:2104.07997

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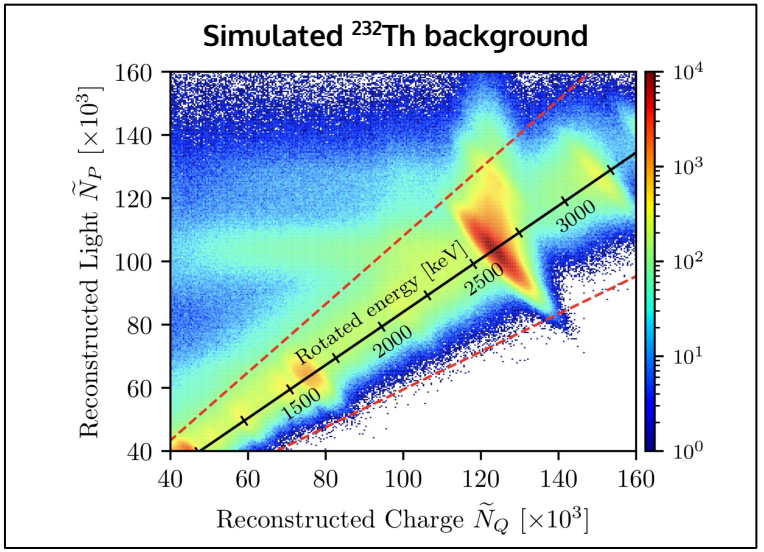
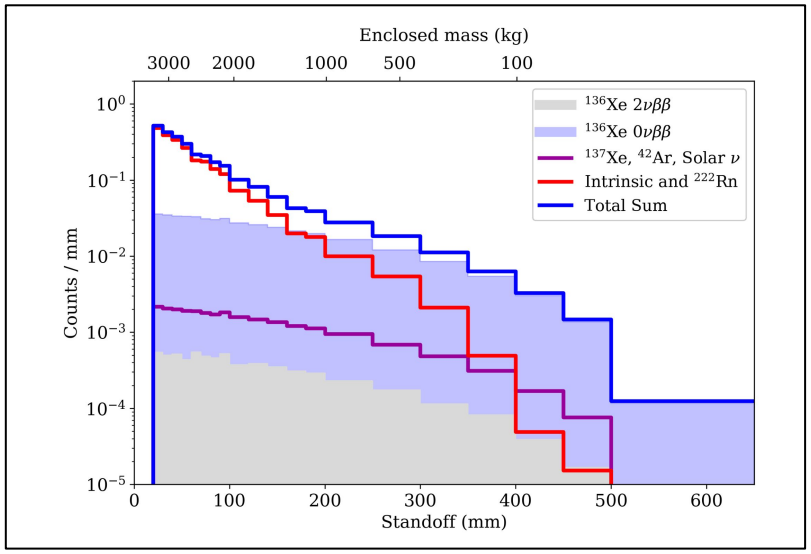
Data analysis in 3D

Event energy:

- Sum of reconstructed light and charge



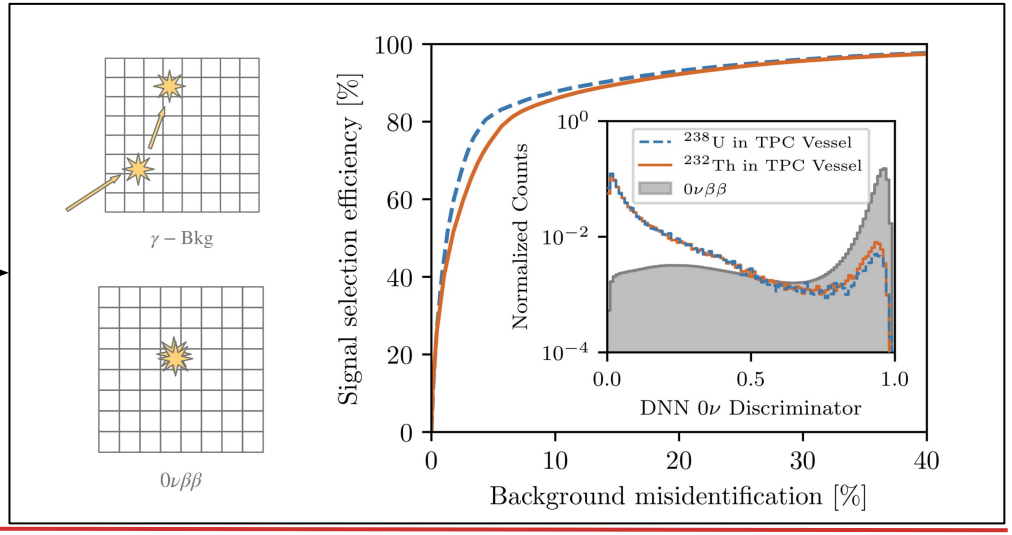


Standoff distance:

- Defined as minimum distance between an event vertex and a detector surface

Deep neural network (DNN):

- Utilize imaging capabilities of TPC to separate **single-site** (signal-like) from **multi-site** (background-like)



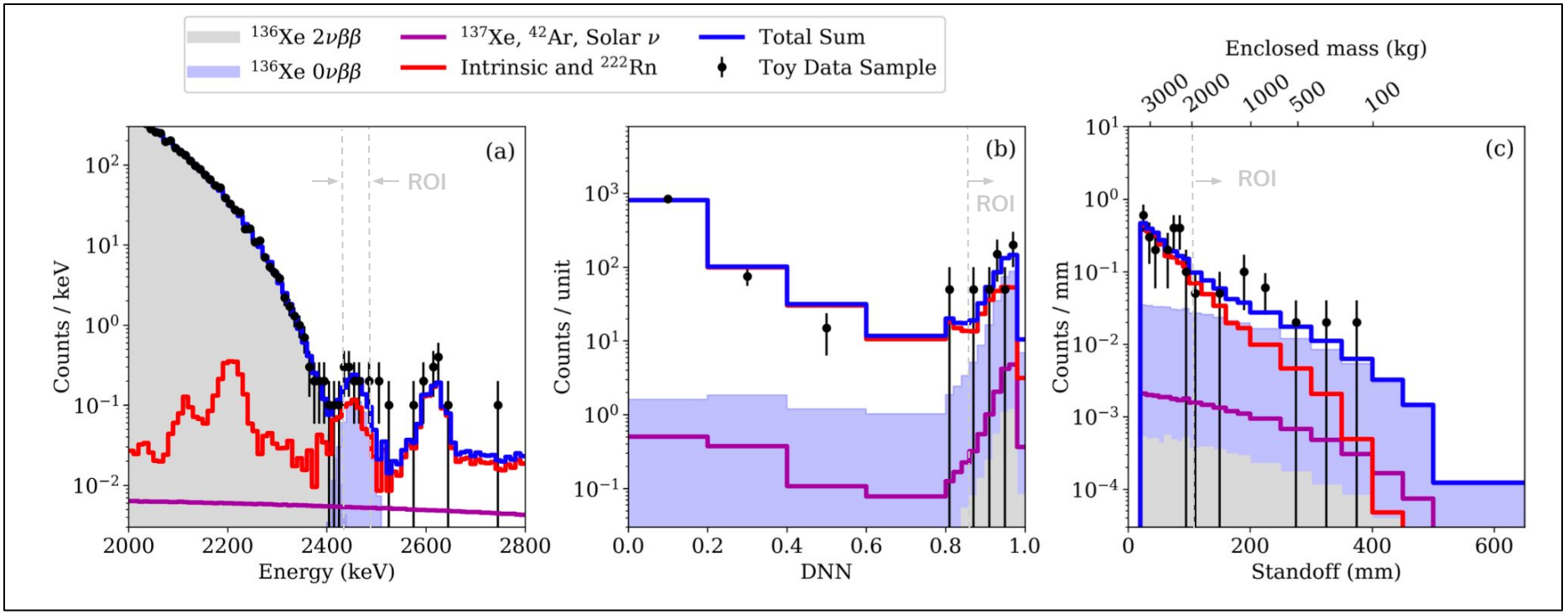
nEXO's data inside the "ROI"

Illustration of a simulated dataset with a 3σ discovery ($T_{1/2}$ = 0.74 x 10^{28} yrs)

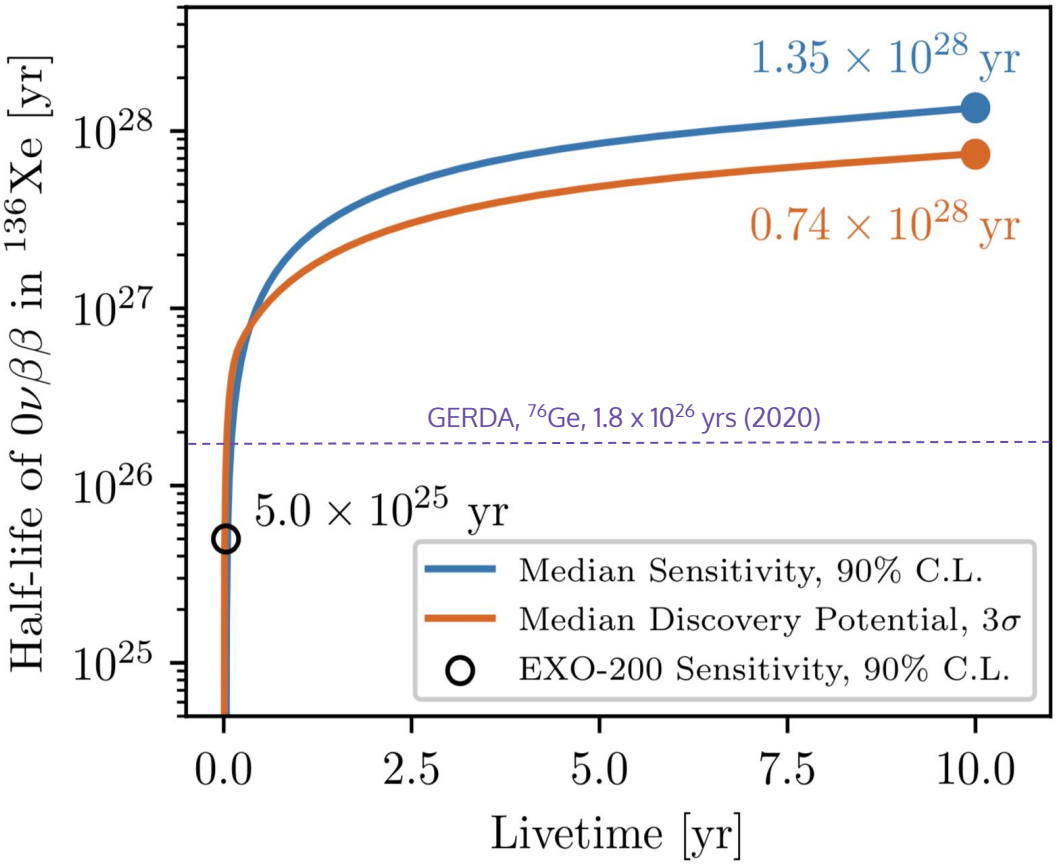
Three-dimensional analysis allows robust discovery of a signal

nEXO's ROI is defined as:

- Energy within 0$\nu\beta\beta$ FWHM
- Innermost 2 tonnes of liquid Xe (cut on standoff)
- DNN > 0.85 ("single-site" events)



Sensitivity and discovery potential for 0νββ



Three-dimensional profile likelihood ratio analysis

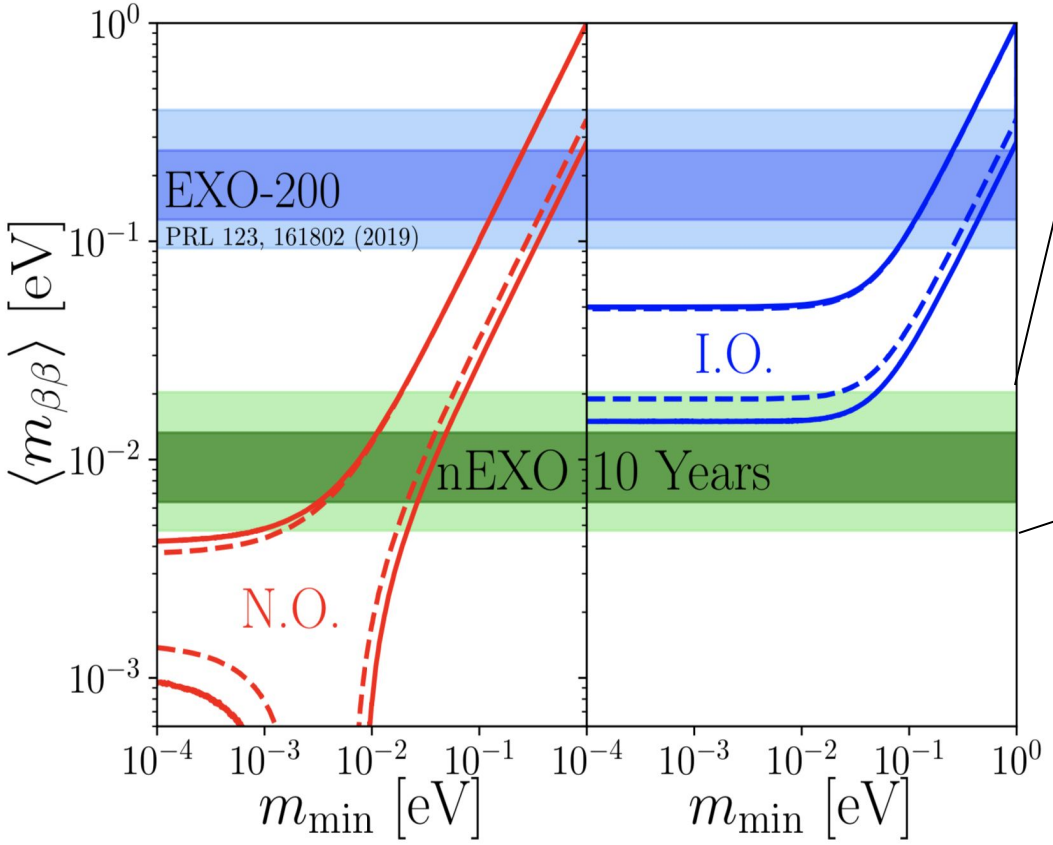
- Optimizes discrimination between signal and background
- Robust against previously unknown gamma backgrounds

Sensitivities reported are median values over 5,000 toy experiments

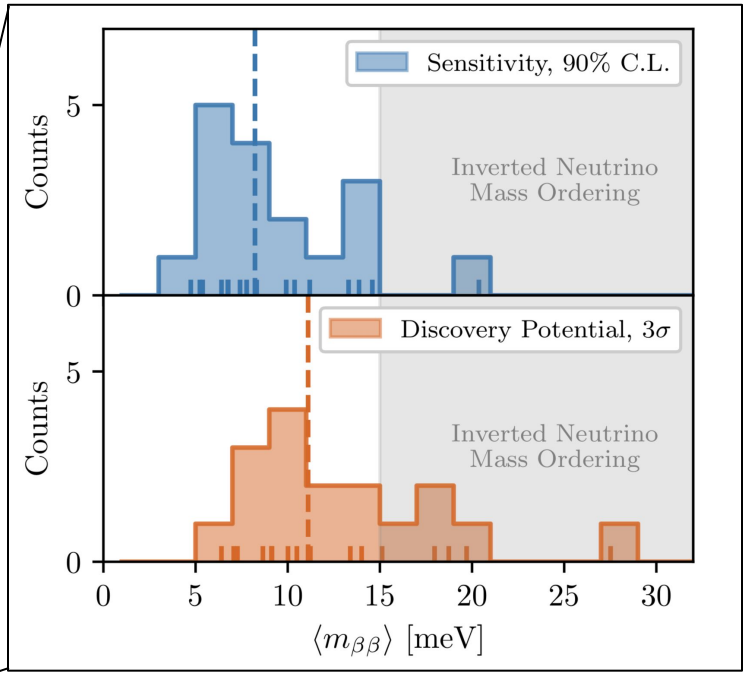
- Can *exclude* 0νββ halflife of **1.35 x 10^{28} yrs at 90% CL**
- Can *discover* 0νββ halflife of **0.74 x 10^{28} yrs at 3σ significance**

Sensitivity to new physics

$$\left[T^{0\nu}_{1/2}\right]^{-1} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}\, G^{0\nu}\, \mathcal{M}^{0\nu}$$



Distribution over different matrix element calculations



Sensitivity to Majorana neutrino mass:

$$m_{\beta\beta} \approx 4.7 - 20.3 \text{ meV}$$

Completely explores the inverted mass ordering in almost all cases

Conclusions

nEXO will employ a five-tonne liquid xenon time projection chamber to search for neutrinoless double beta decay

- Leverages well-established capabilities of xenon TPCs

Projected sensitivity of $T_{1/2} > 1.35 \times 10^{28}$ yrs at 90% CL, nearly two orders of magnitude beyond current limits

- Sensitivity to Majorana neutrino masses of $m_{\beta\beta} = 4.7 - 20.3$ meV
  - Matrix elements are dominant systematic uncertainty
- Projections use high-fidelity simulation and data-driven modeling of detector performance

For further details, see arXiv:2106.16243

Other nEXO talks at LIDINE!

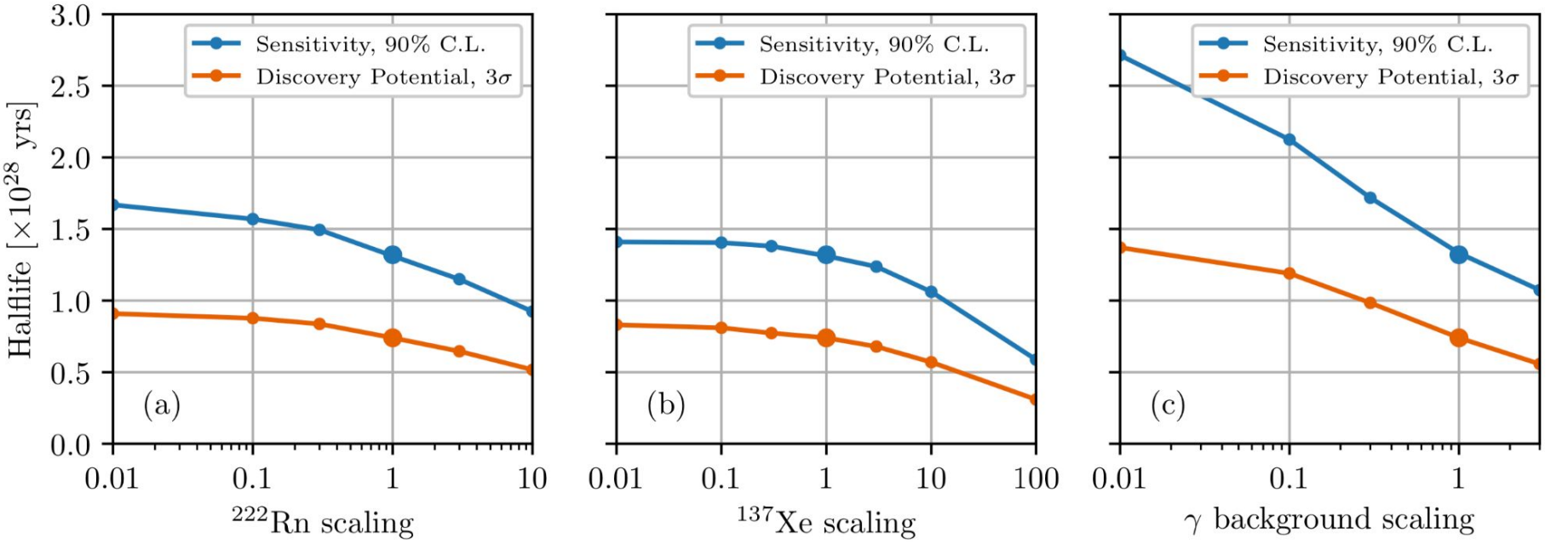
- J. Dalmasson, 12:25pm PT today
- C. Hardy, 2:15pm PT Wednesday
- E. Angelico, 11:00am PT Thursday
- A. Jamil, 10:30am PT Friday

Thank you!


Mike Heffner
Seth Thibado
nEXO
Collaboration Meeting Dec 2020

Backup

Dependence of sensitivity on backgrounds



Depends on ^{222}Rn control

- Dust/materials control is critical
- Online removal under investigation (distillation demonstrated by XENON)

Depends on cosmogenic muons

- Veto efficiency (70%) supported by detailed simulations, paper soon
- Overburden at SNOLAB (assumed site) is near optimal

Depends on materials

- ^{222}Rn-related backgrounds are included here
- Significant improvements expected if Ba-tagging is possible in future