Liquid TPCs (single phase)

David Moore, Yale University
(my personal opinions only)

$0\nu\beta\beta$ in Xe workshop, McGill

November 14, 2025

Wright Laboratory

Yale

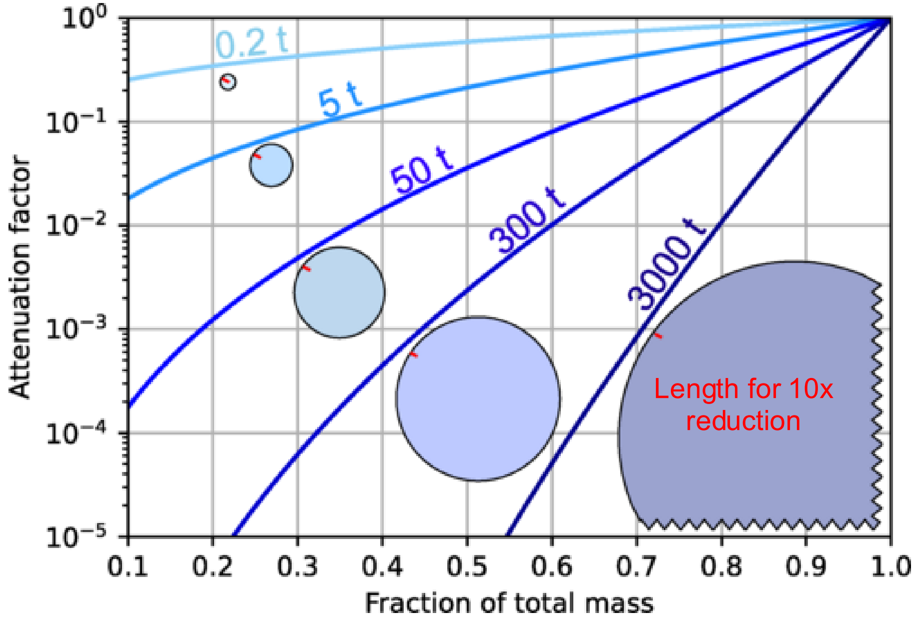
Single phase liquid TPCs (overview)

Single phase liquid Xe TPCs (key features/challenges):

1. Like other liquid/solid phase Xe detectors, high density ($\rho \approx 3$ g/cm^3):
    - Minimizes detector size at given target mass
    - Significantly larger self-shielding of external backgrounds than high-pressure gas TPCs
        - Favors homogeneous volume, without central cathode (ensure Rn daughters are external bkgs)
        - In large detectors, allows tagging/veto of ^{137}Xe production through tagging of ~4 MeV gamma cascade
    - Large detectors demonstrated in both LXe dark matter and LAr neutrino communities

Mass:	Approx. linear dimension:
100 kg	~30 cm
5 t	~1 m
1000 t	~7 m

Attenuation of external backgrounds vs size:



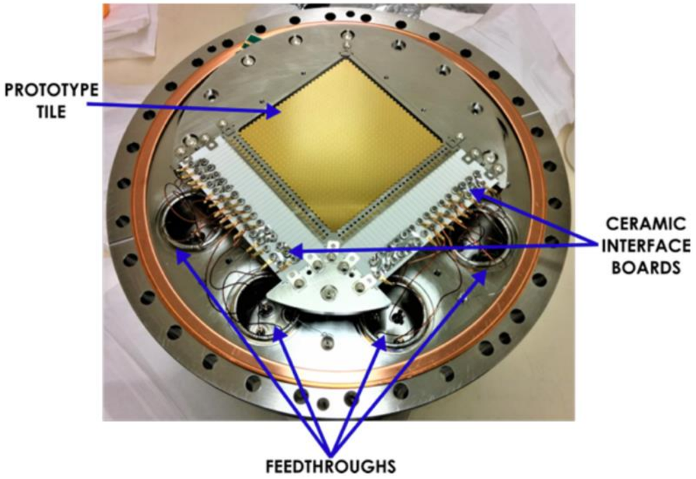
Avasthi et al., Phys. Rev. D 104, 112007 (2021), arXiv:2110.01537

Single phase liquid TPCs (overview)

Single phase liquid Xe TPCs (key features/challenges):

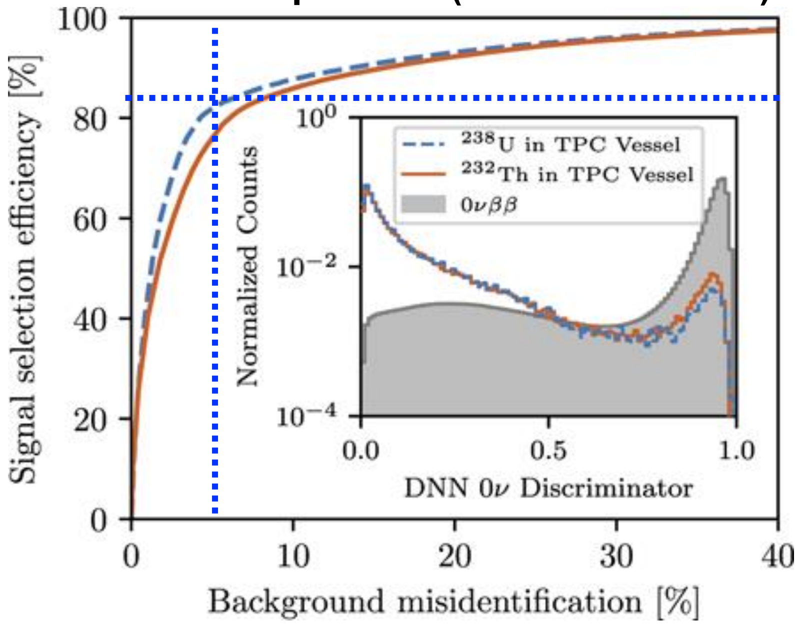
2. Direct readout of charge without amplification:
   - High LXe density gives ~3-4 mm $\beta\beta$ tracks:
     - σ_z~1-2 mm, $\sigma_{x,y}\sim 3$-4 mm scale spatial resolution to separate $\beta\beta$ from ~95% of Compton scatters
     - No possibility for single β vs $\beta\beta$ separation (as in HP gas)
     - Direct readout on pad electrodes/wires demonstrated at this resolution
   - No amplification of charge signal :
     - Low noise electronics ($\sigma \sim 200\ e$ for ~5 mm scale pad) are needed to reach <1% energy resolution
     - Required noise (nearly) achieved for cold electronics in LAr ASICs and LXe prototypes
     - No need to control liquid level, extraction field, no loss of electrons due to incomplete extraction efficiency
       - Poorer resolution demonstrated to date than dual phase($\sigma_E\ /E$~1.2% EXO-200 vs ~0.6-0.8% for LZ/XENON1T at 2.6 MeV)
     - Much worse energy threshold than dual phase (few 100 keV)

nEXO prototype charge readout tile:



M. Jewell et al., JINST 13 P01006 (2018), arXiv:1710.05109

SS/MS separation (nEXO simulation):



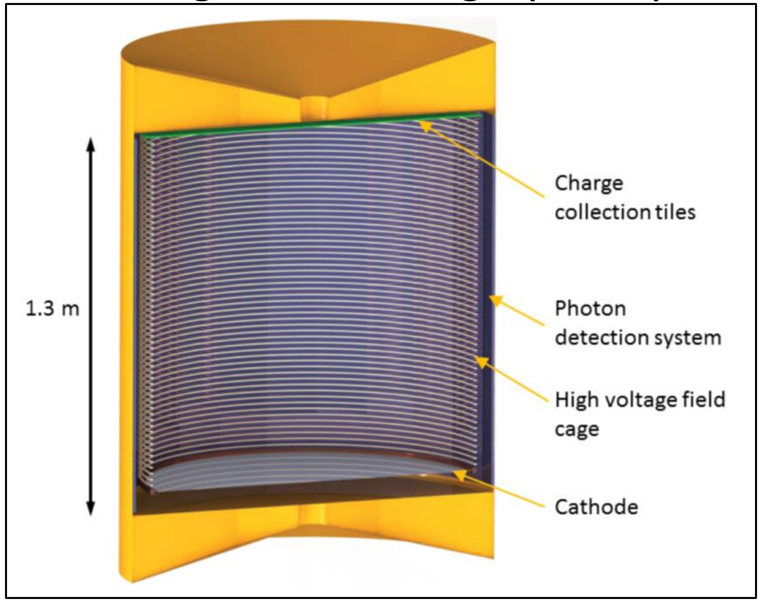
J. Phys. G: Nucl. Part. Phys. 49 015104 (2022), arXiv:2106.16243

Single phase liquid TPCs

Single phase liquid Xe TPCs (key features/challenges):

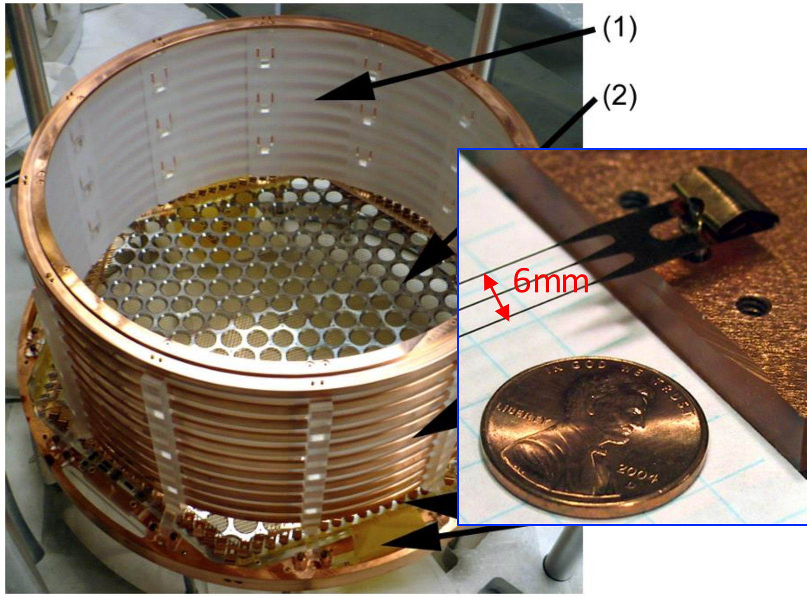
3. Engineering considerations (not comprehensive):
   - Compared to dual phase TPCs can avoid wire planes entirely if desired (e.g. nEXO design)
     - For direct charge readout, lack of shielding grid leads to complex signal shapes (induction)
     - Conventional design with wire planes/reflectors also possible (e.g. EXO-200)
   - High voltage only needs to be delivered to the cathode
     - Detector sensitivity is optimized for 200-400 V/cm (assuming ~5-10% light collection)
       - Energy resolution/topological discrimination improves with field
       - Requirements on electron lifetime/purity minimized (>5 ms)
       - Lose ~10-20% expected sensitivity at 100 V/cm, more rapidly below that
   - Extremely large single-phase LAr TPCs are being designed
     - Single phase detectors can possibly benefit with this engineering (e.g. cold electronics)

Wire grid free design (nEXO):



nEXO pre-Conceptual Design report, arXiv:1805.11142

Wire grids + reflector (EXO-200):

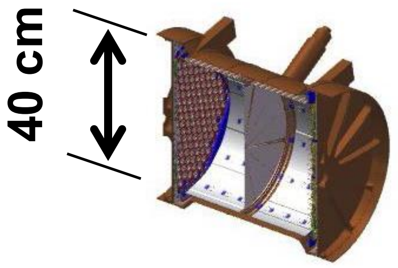


EXO-200, JINST 7 (2012) P05010, arXiv:1202.2192

LXe single phase TPCs (history/status)

- Initial ~150 kg detector (EXO-200) ran from 2011-2018, reaching 0.5 x 10^{26} yr sensitivity
- Conceptual design for 5000 kg detector (nEXO) developed to a high level of maturity by nEXO collaboration (just prior to DOE CD-1), with sensitivity estimated to be 1.35 x 10^{28} yr

EXO-200



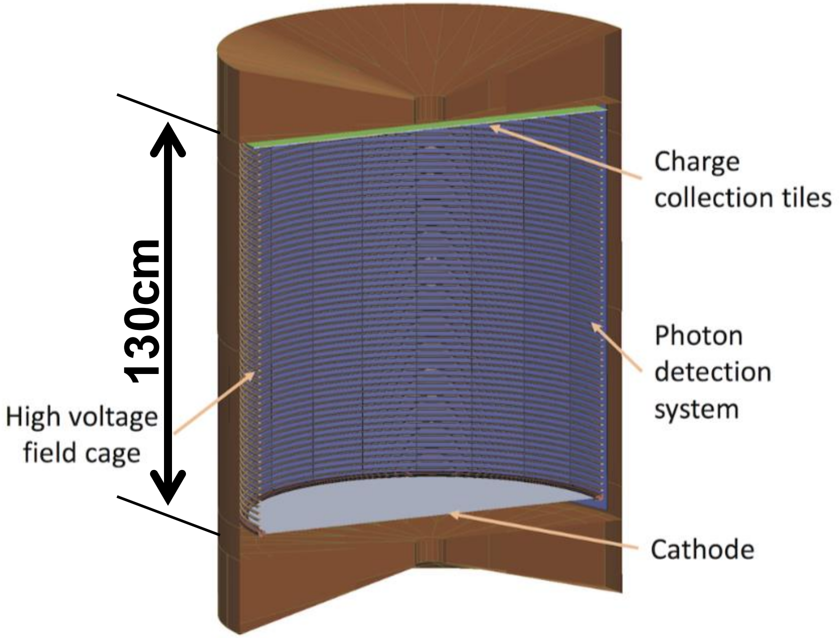
~150 kg ^{136}Xe

2011 - 2018

$T_{1/2}$ = 0.5 x 10^{26} yr

PRL 123, 161802 (2019), arXiv:1906.02723

nEXO

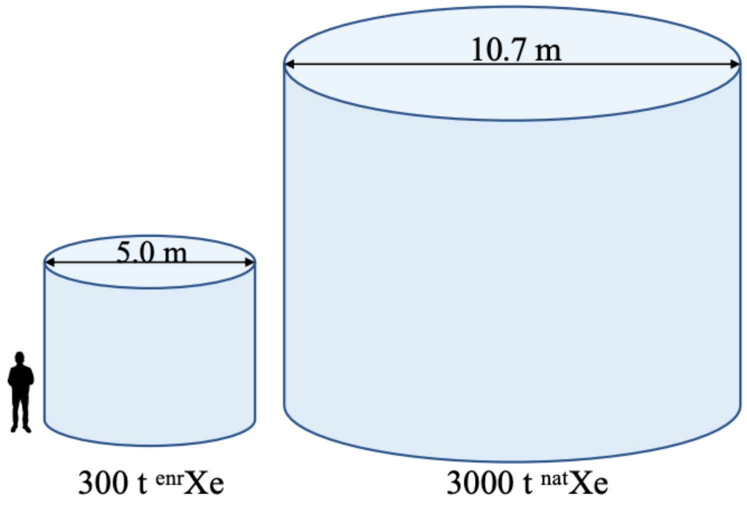


~5000 kg ^{136}Xe

$T_{1/2}$ = 1.35 x 10^{28} yr (projected)

J. Phys. G: Nucl. Part. Phys. 49 015104 (2022), arXiv:2106.16243

Future kton scale detector (?)



~300 t ^{136}Xe

$T_{1/2}$ ~ 10^{30} yr (?)

PRD 104, 112007 (2021), arXiv:2110.01537

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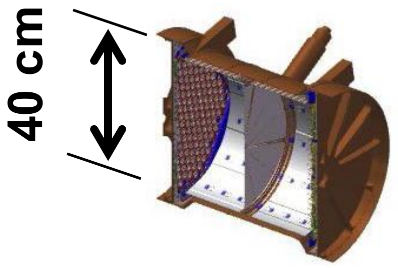
EXO-200



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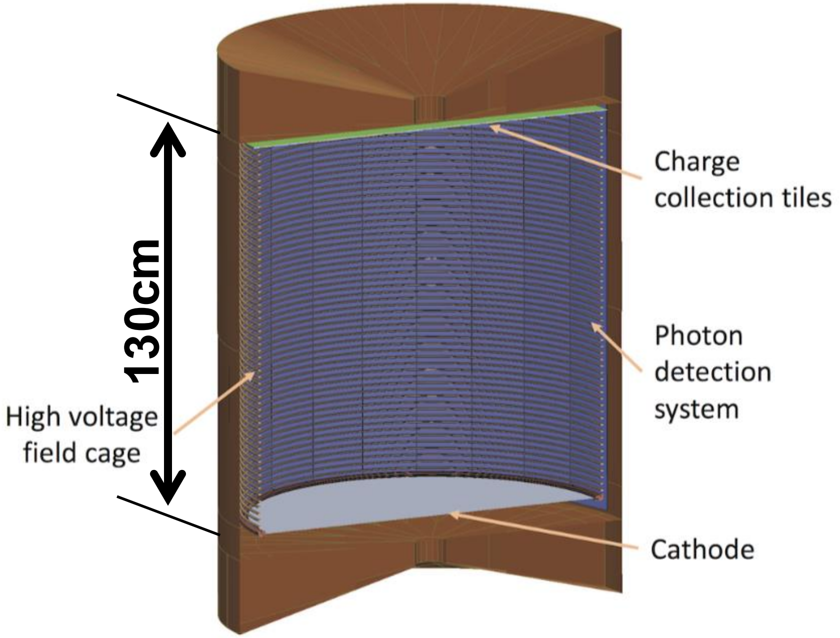

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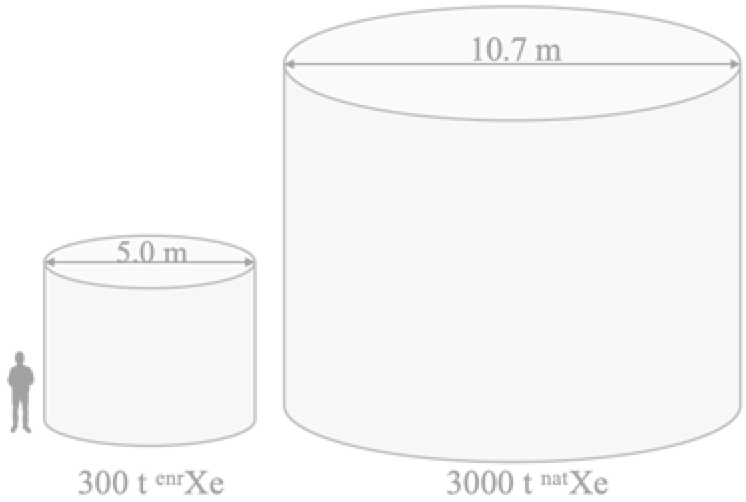


~300 t ^{136}Xe

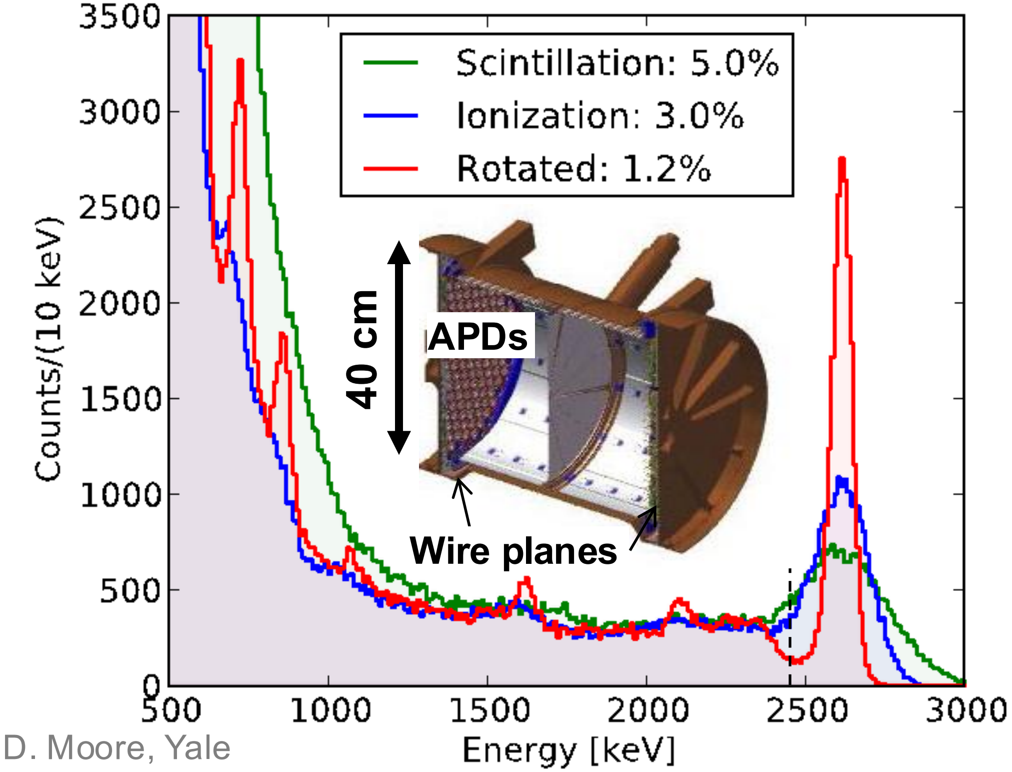
$T_{1/2}$ ~ 10^{30} yr (?)

PRD 104, 112007 (2021), arXiv:2110.01537

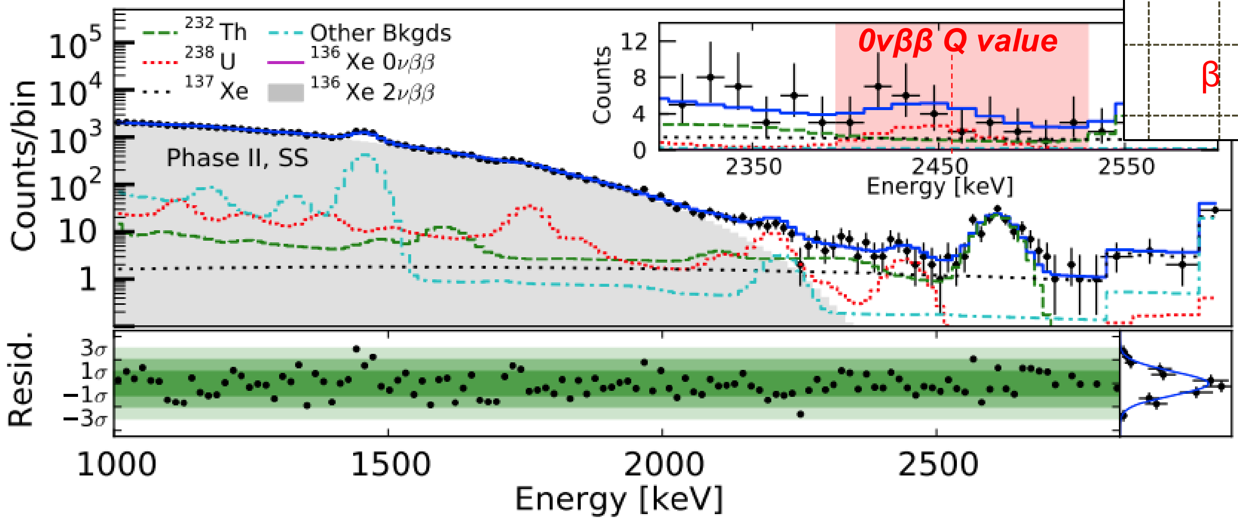
EXO-200

- Single phase LXe TPC (~150 kg, enriched to 80% ^{136}Xe), ran from 2011-2018
  - First discovery of $2\nu\beta\beta$ in ^{136}Xe
  - Final limits on $0\nu\beta\beta$ > 3.5 x 10^{25} yr
  - Demonstrated key aspects of LXe single-phase technology (bkg. prediction from material assays, σ_E/E = 1.2%, topological discrimination, …)

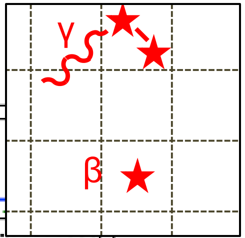
Reconstructed energy, ^{228}Th calibration:



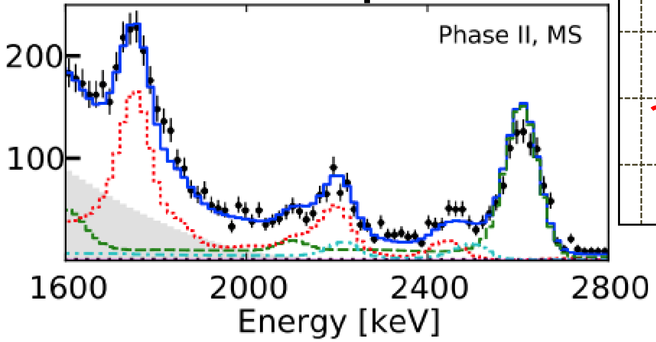
"Single-site" spectrum:



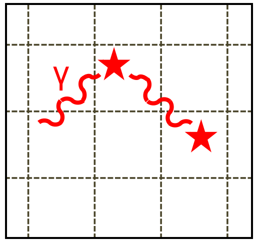
Signal-like:



"Multi-site" spectrum:



Background-like:



Results from complete exposure (234 kg yr):

$T_{1/2}^{0\nu\beta\beta}$ > 3.5 ·10^{25} yr (Phase 1+2)

median sensitivity = 5.0 ·10^{25} yr

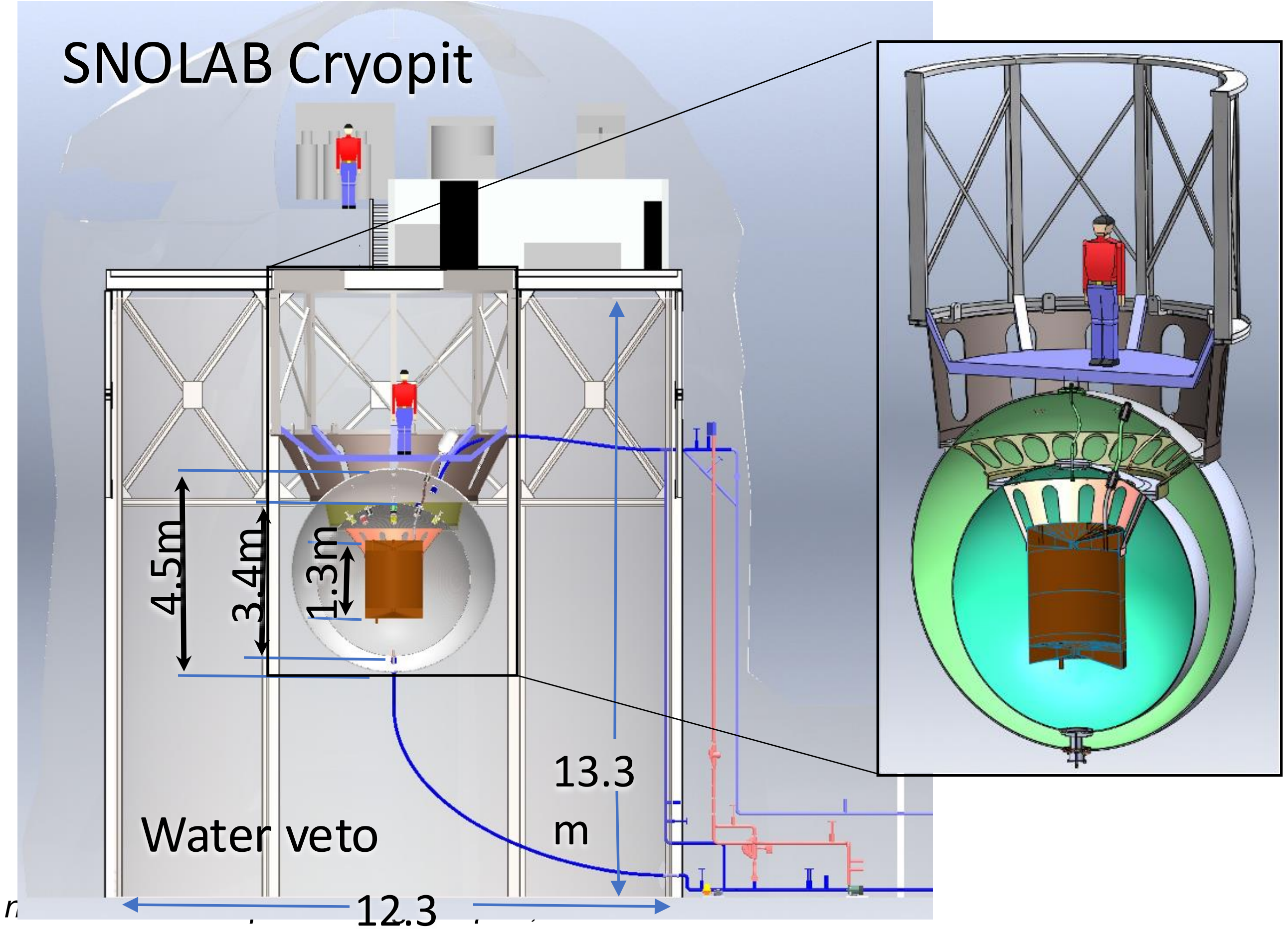
⟨$m_{\beta\beta}$⟩ < 93 - 286 meV

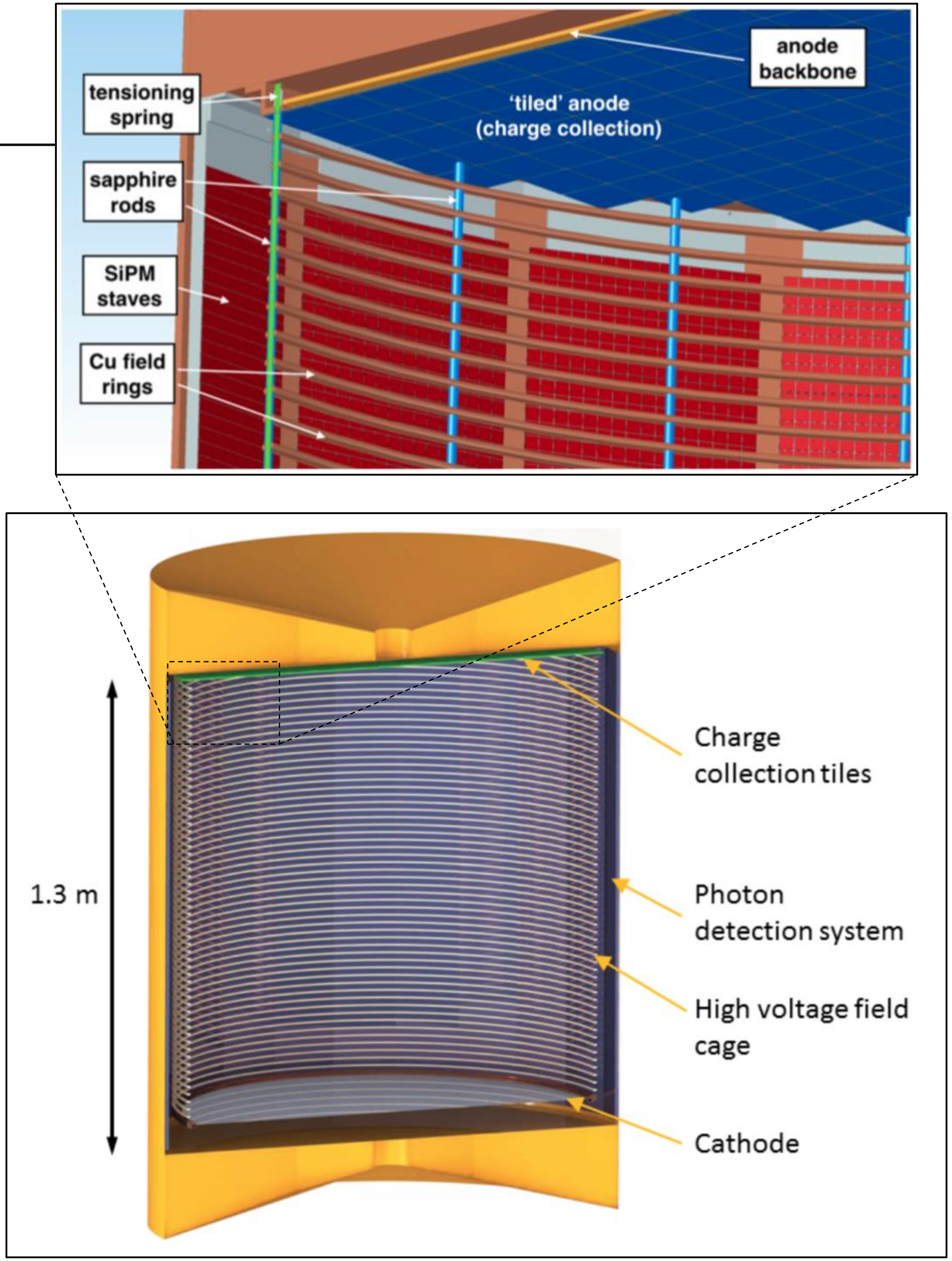
PRL 123, 161802 (2019), arXiv:1906.02723
PRL 120, 072701 (2018), arXiv:1707.08707
Nature 510, 229 (2014), arXiv:1402.6956

nEXO concept @ SNOLAB

- nEXO provides a multi-ton scale extension of the single-phase LXe TPC technology demonstrated in EXO-200
  - Detailed conceptual engineering design at SNOLAB

Conceptual design in SNOLAB Cryopit:

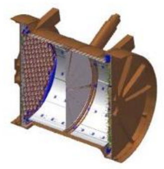




Tonne scale single-phase detector

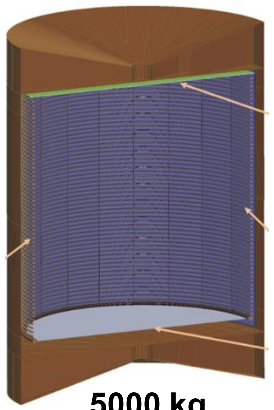
- By scaling liquid TPC to ~1.3 m linear dimensions, central region reaches extremely low background levels
  - Combining energy, standoff, topology -> effective 6.2 tonne yr exposure with estimated background of 0.5 events in most sensitive region
  - Sensitivity estimates based on bottom-up materials budget and radioassays of candidate components, reaches $T_{1/2}$ sensitivity $>10^{28}$ yr
- nEXO conceptual design reviewed at high level of detail (just before CD-1) through DOE process in US

EXO-200



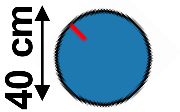
150 kg

nEXO

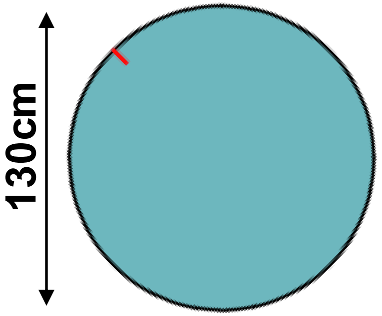


5000 kg

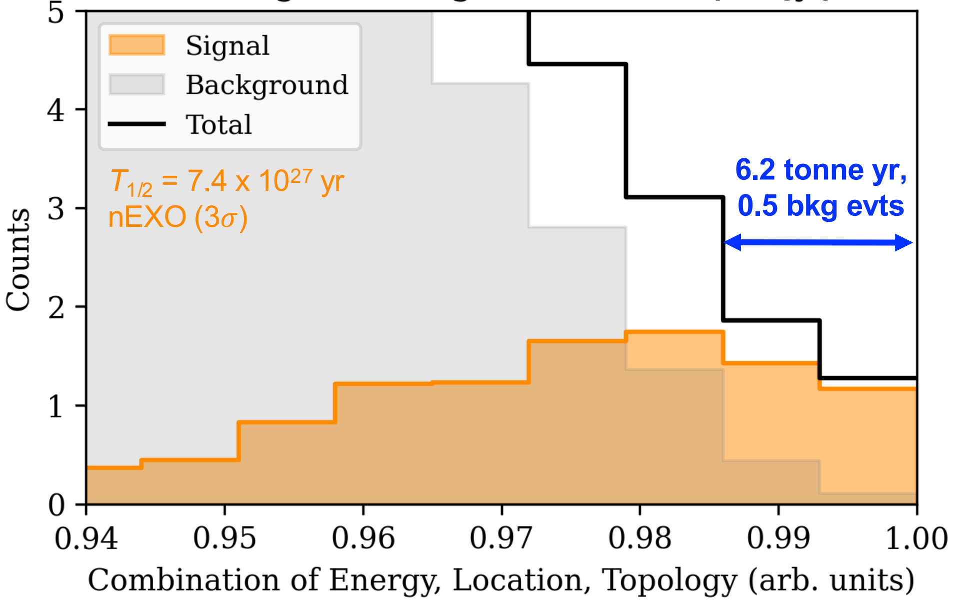
Detector cross-section:



2.5 MeV γ attenuation length = 8.5 cm

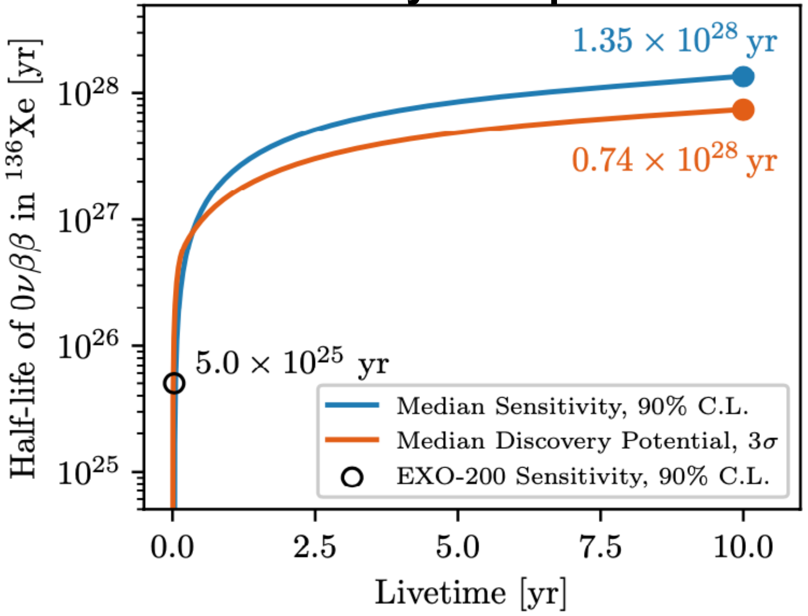


nEXO simulated spectrum (10 yr):



0 ← Background-like ***Signal-like → 1***

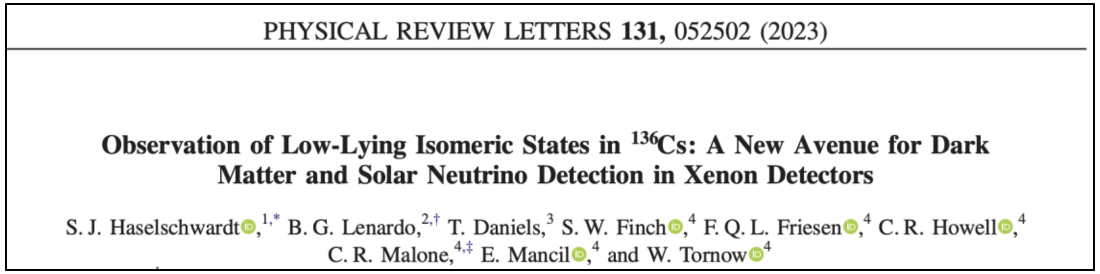
Sensitivity vs exposure:



J. Phys. G: Nucl. Part. Phys. 49 015104 (2022), arXiv:2106.16243

Other physics with single phase detector

- Single phase detector can reach sub-% resolution at 2.5 MeV, but can't reach thresholds needed to simultaneously do low energy physics (in particular WIMP dark matter)
- However, the same ^{136}Xe needed for world-class $0\nu\beta\beta$ decay experiments (gas, single, or dual phase) is likely to enable these detectors to do significant solar ν physics
  - Charged-current ν interactions can be tagged through de-excitation of long-lived (~100 ns) states of ^{136}Cs, possibly with extremely low backgrounds

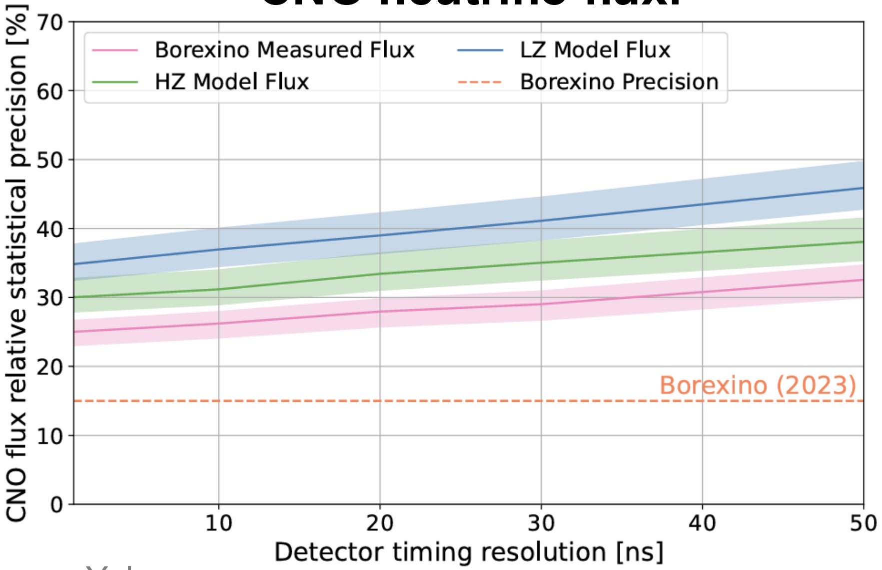

PHYSICAL REVIEW LETTERS **131,** 052502 (2023)

Observation of Low-Lying Isomeric States in ^{136}Cs: A New Avenue for Dark Matter and Solar Neutrino Detection in Xenon Detectors

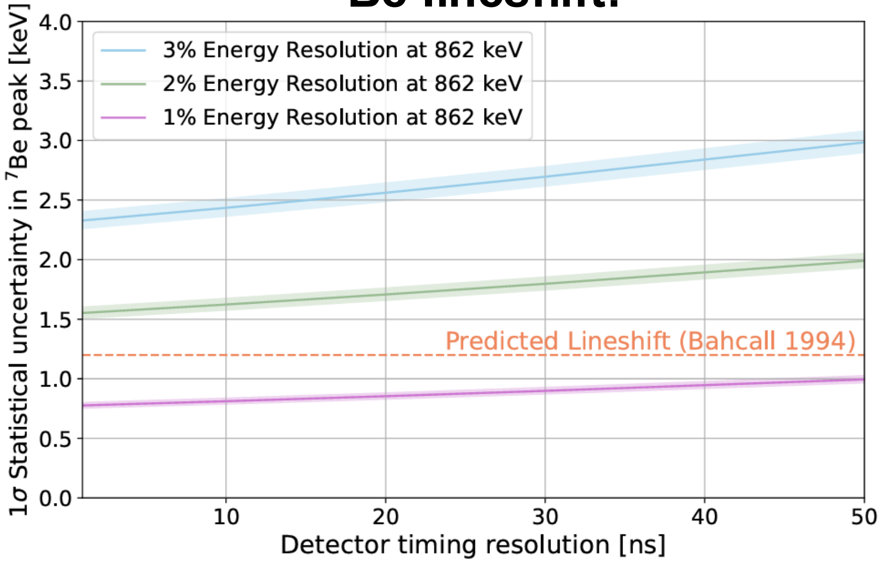
S. J. Haselschwardt,[1,*] B. G. Lenardo,[2,†] T. Daniels,[3] S. W. Finch,[4] F. Q. L. Friesen,[4] C. R. Howell,[4] C. R. Malone,[4,‡] E. Mancil,[4] and W. Tornow[4]

- Recent sensitivity evaluation for 5 tonne nEXO-like detector:

CNO neutrino flux:



^{7}Be lineshift:



See more details at:

G. Richardson et al. (nEXO), PRD 112, 103010 (2025), arXiv:2506.22586

Challenges/opportunities (my personal take):

- Significant investment in developing a fairly advanced conceptual design for a 5 tonne single-phase Xe TPC from DOE NP through the nEXO project
  - The technical aspects, cost, schedule, etc were reviewed at a high level of detail over many years, reaching readiness for CD-1 review (many aspects of the project at higher level of maturity)
  - Sensitivity estimates are mature and based on material assay/estimation procedure validated in ~150 kg scale single-phase detector
    - Challenges around funding in the US, transfer of knowledge from previous project team
    - Opportunity for this relatively mature concept to impact an international project sited at SNOLAB

- General technical challenges for single phase technology:
  - Background control and assays:
    - Even with significant attenuation of external backgrounds, extremely low background materials required to reach $>10^{28}$ year sensitivity
    - Control of radon/tagging of radon daughters on detector surfaces (Bi-Po, where Po is missed)
  - Low noise electronics for charge readout without amplification (custom cryogenic ASICs)
    - Opportunity to leverage parallel development for single phase LAr detectors
  - High voltage to maintain sufficiently high field needed to reach sub-percent resolution and topological rejection

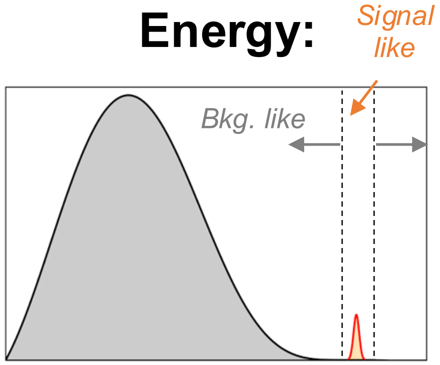
Challenges/opportunities (my personal take):

- While the technical challenges/opportunities are interesting, my personal take is that the real opportunity here is not technical
  - In my opinion, it is much more important for this community to coalesce around a single technology for the next steps
  - “Facts on the ground” are likely more important for going forward than technical comparisons of technologies, given all technologies have significant reach in principle
  - Xenon detectors have a huge opportunity to go not only to 10^{28} year sensitivity in the coming ~decade, but a plausible path to 10^{29} yrs and potentially beyond
    - This is a huge science opportunity I think we can’t miss as a community by not coming together around a project to make this happen

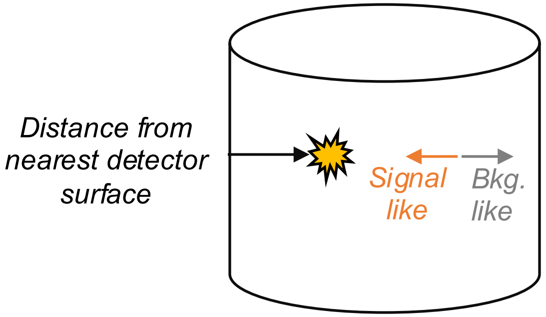
nEXO Signal and Background

- nEXO measures multiple parameters for each event to be able to robustly identify a $0\nu\beta\beta$ signal
- As a fully homogeneous detector, it precisely measures backgrounds in situ
  - No internal materials (other than Xe), making nEXO uniquely robust against unknown backgrounds

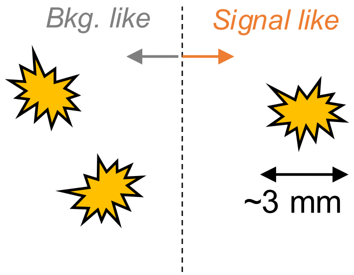
Energy:



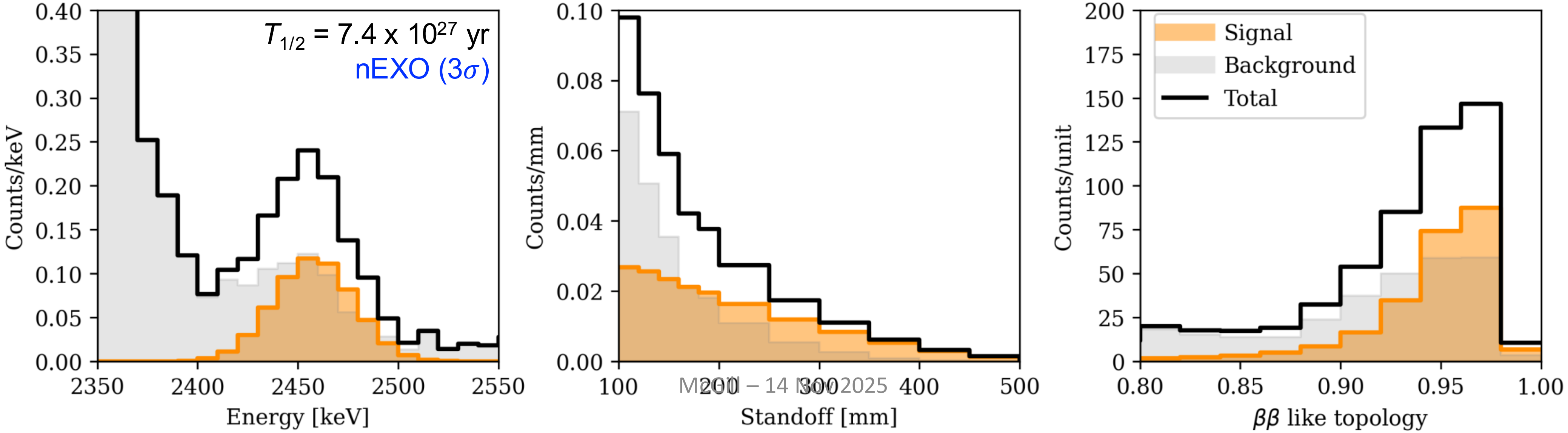
Standoff:



Topology:



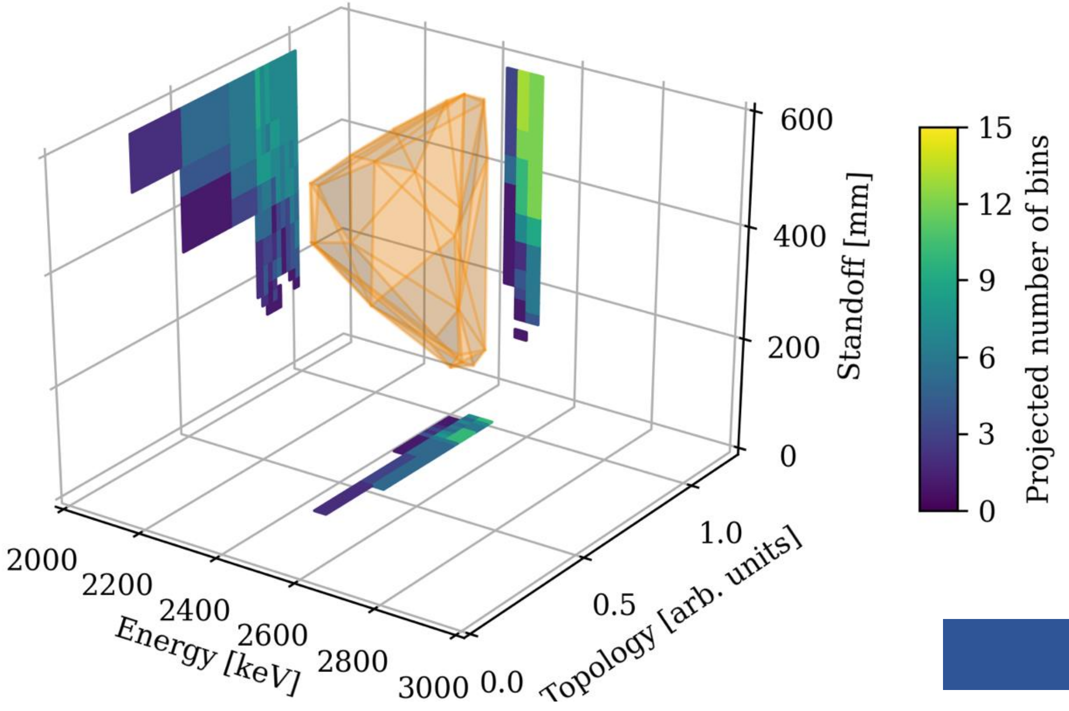
1D projections of simulated nEXO signal and backgrounds:



nEXO Signal and Background

- Likelihood fit allows optimal weighting between signal and background combining energy, topology, and standoff over full 3D parameter space
  - A simpler 1D combination can help visualize the signal and background separation in nEXO

3D ultra-low background region of interest:



Combine energy, topology, and standoff (preserving correlations)

Optimal 1D combination of all parameters: