The nEXO Experiment

Searching for Neutrinoless Double Beta Decay in ^{136}Xe

G Adhikari et al. (nEXO Collaboration), 2022 J. Phys. G: Nucl. Part. Phys. 49 015104

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Feb. 22nd 2023

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Why Search for 0$\nu\beta\beta$?

- The discovery of neutrino mass from oscillation experiments provides **new pathways to mass generation** in the neutrino sector
    - Dirac vs Majorana masses
    - feeble couplings to Higgs field vs seesaw mechanisms
- Neutrinoless double beta decay (0$\nu\beta\beta$) **exploits the nucleus as a virtual environment to probe high energy physics** processes
- Implications for **matter-antimatter asymmetry problem**

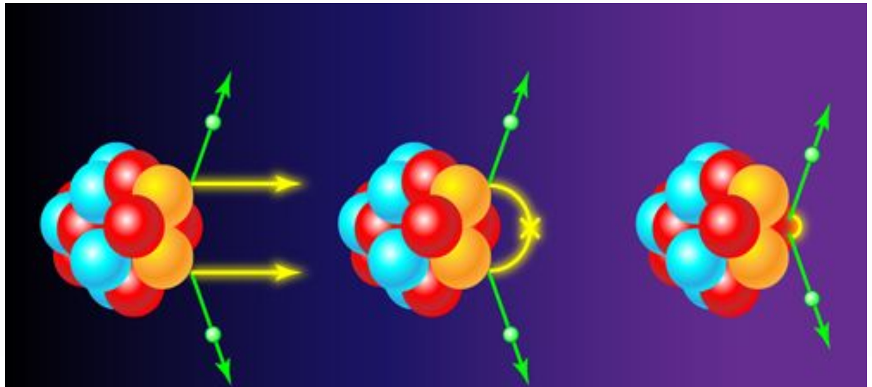

Image credit: APS/Alan Stonebraker

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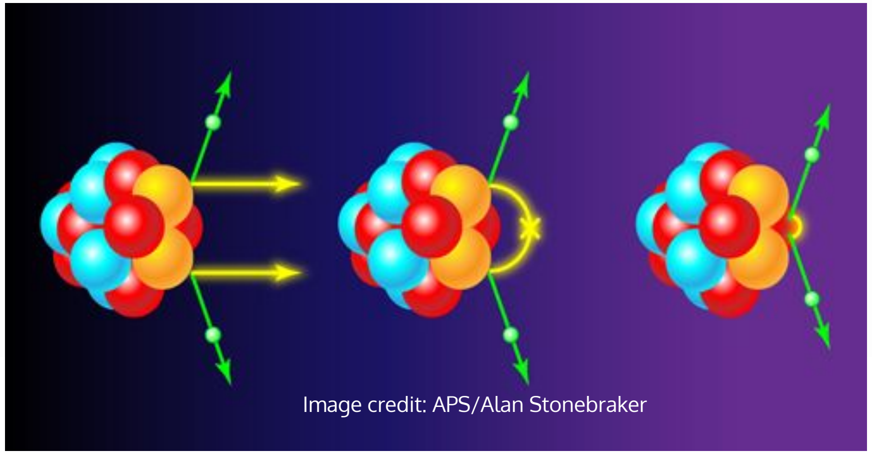

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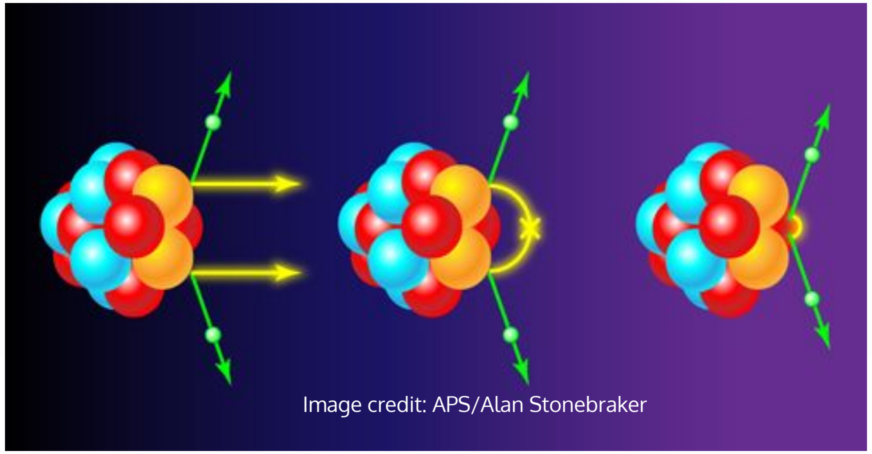
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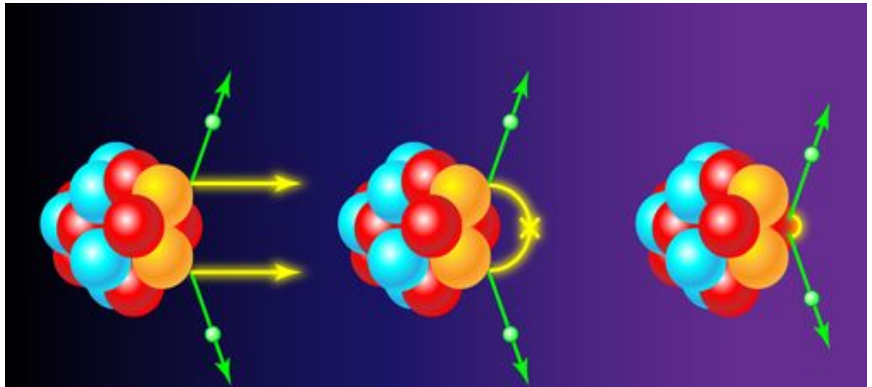
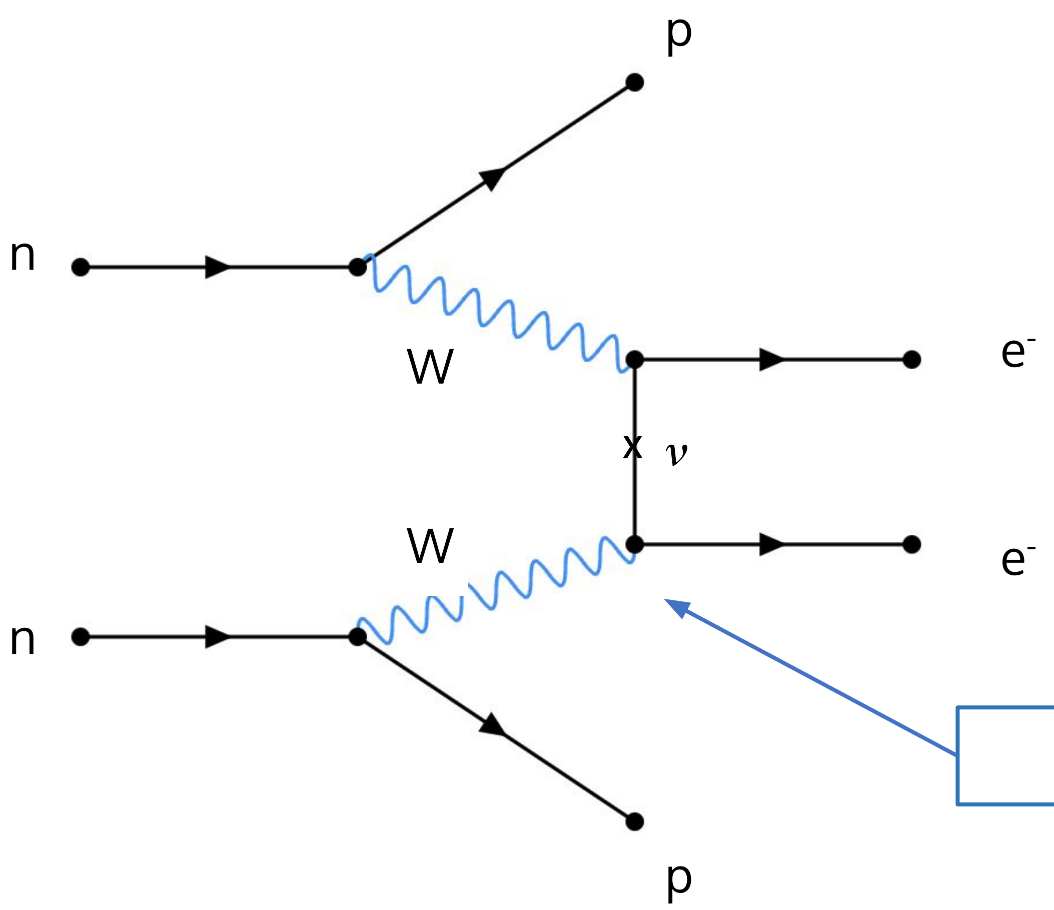


Image credit: APS/Alan Stonebraker

Searches for neutrinoless double beta decay (0$\nu\beta\beta$) are searches for Lepton Number Violation & Physics Beyond the Standard Model

How would $0\nu\beta\beta$ even work?



Light Majorana neutrino exchange?

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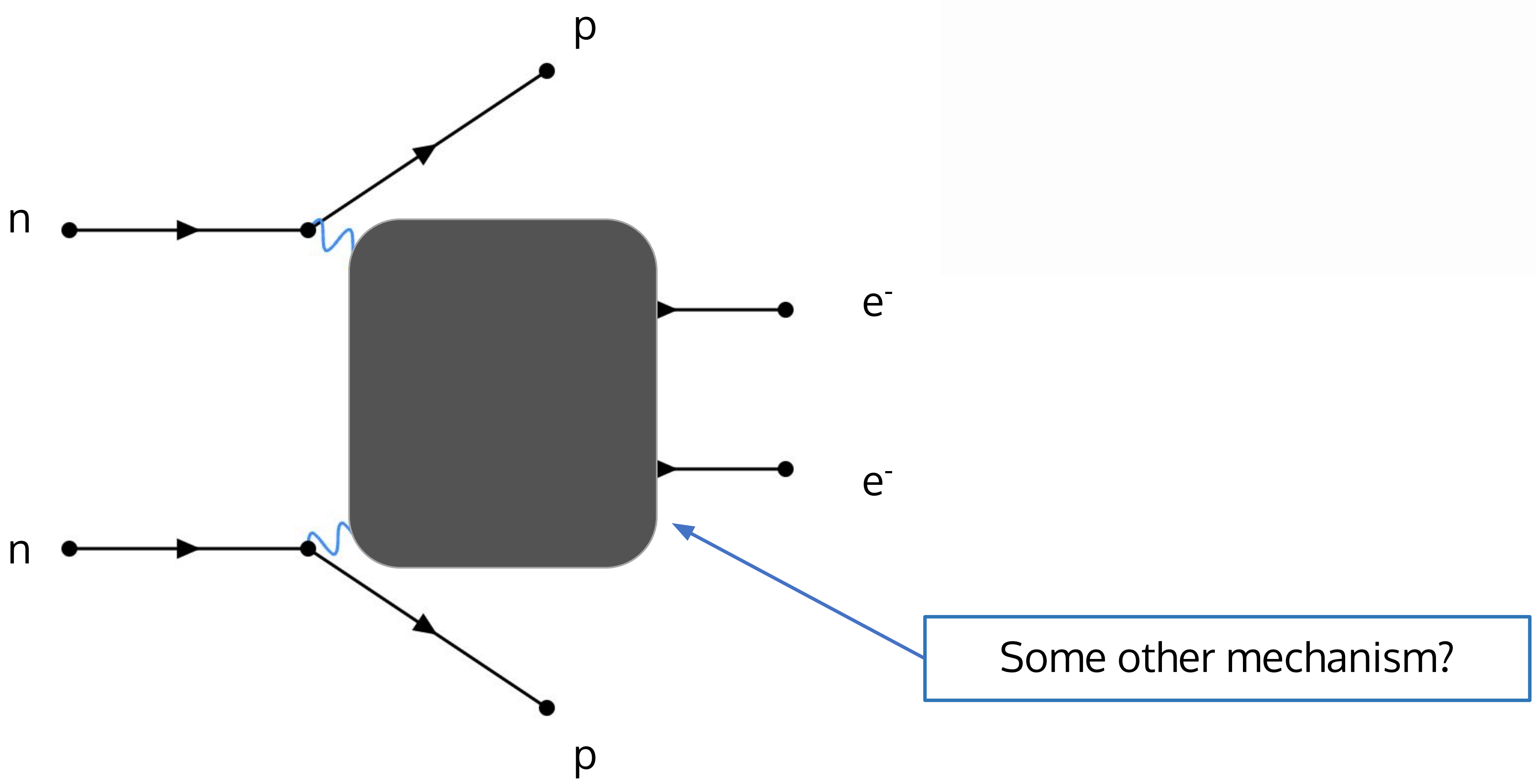

Searching for $0\nu\beta\beta$: The Real Motivation

Particle physics community searching for physics beyond the standard model

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

(Schechter, and Valle. Phys. Rev. D 25.11 (1982): 2951. "black box theorem")

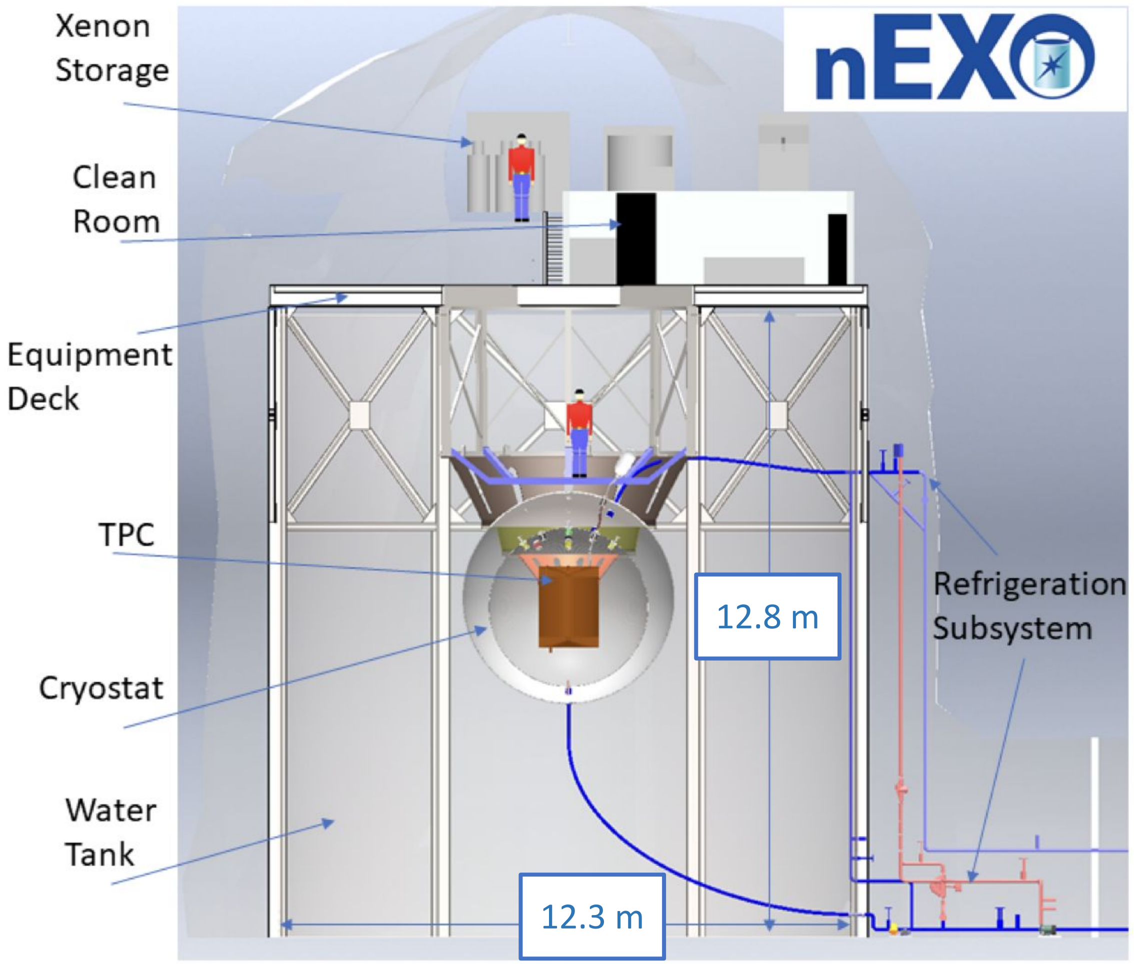
What is nEXO?

nEXO is a **proposed experiment searching for 0νββ**, following successes of EXO-200

currently in the conceptual design stage:

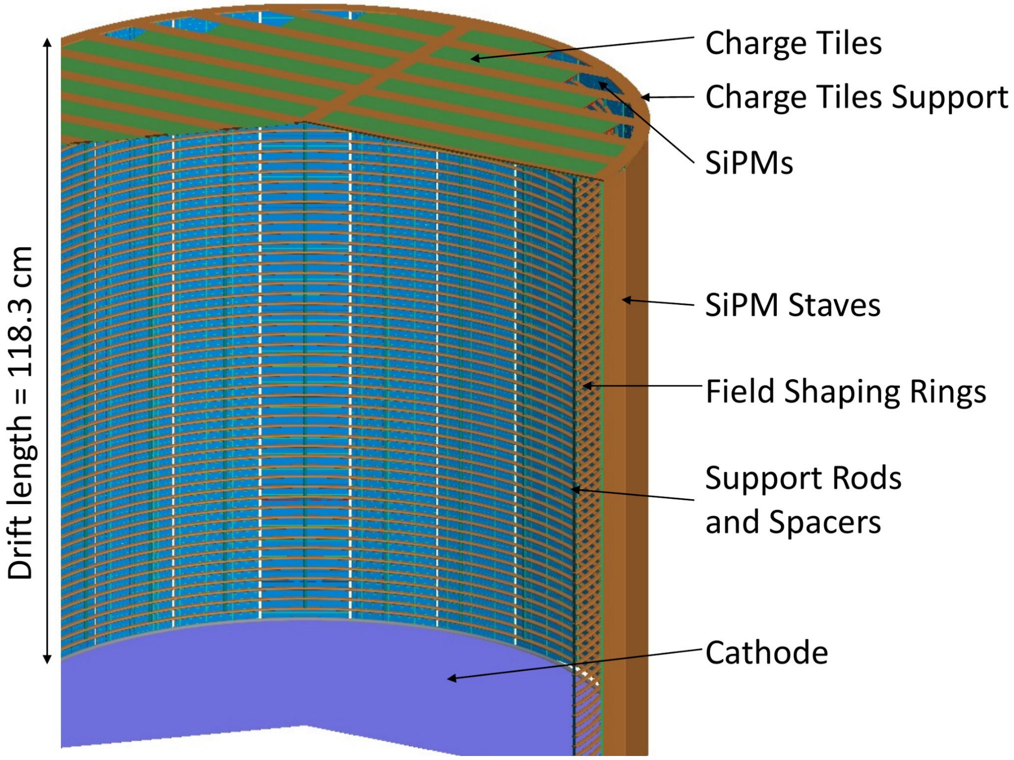
funding for the nEXO project from U.S. DoE has started to flow!

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



nEXO: Distinguishing Features

- Homogeneous, dense, liquid detector medium with high-Z nucleus
  - online purification
  - self-shielding of γ radiation
  - scalability
- Multiparameter Analysis
- Possibility to tag daughter nucleus
- Possibility for control run in case of discovery



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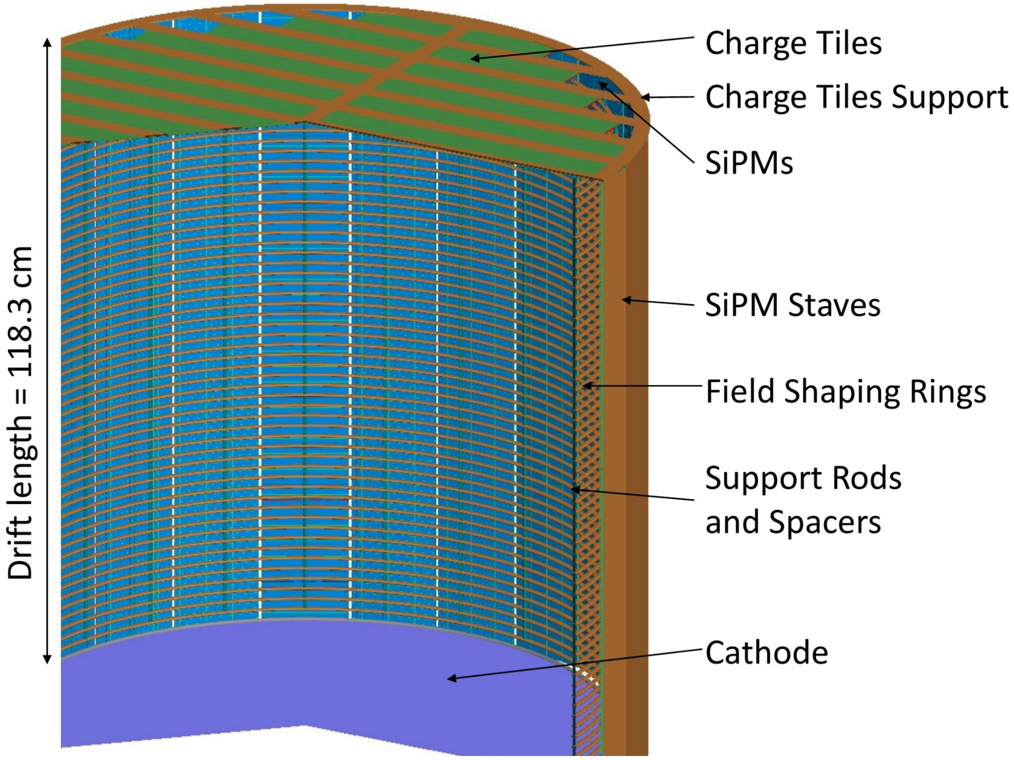

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  - Nature 569, no. 7755 (2019): 203-207
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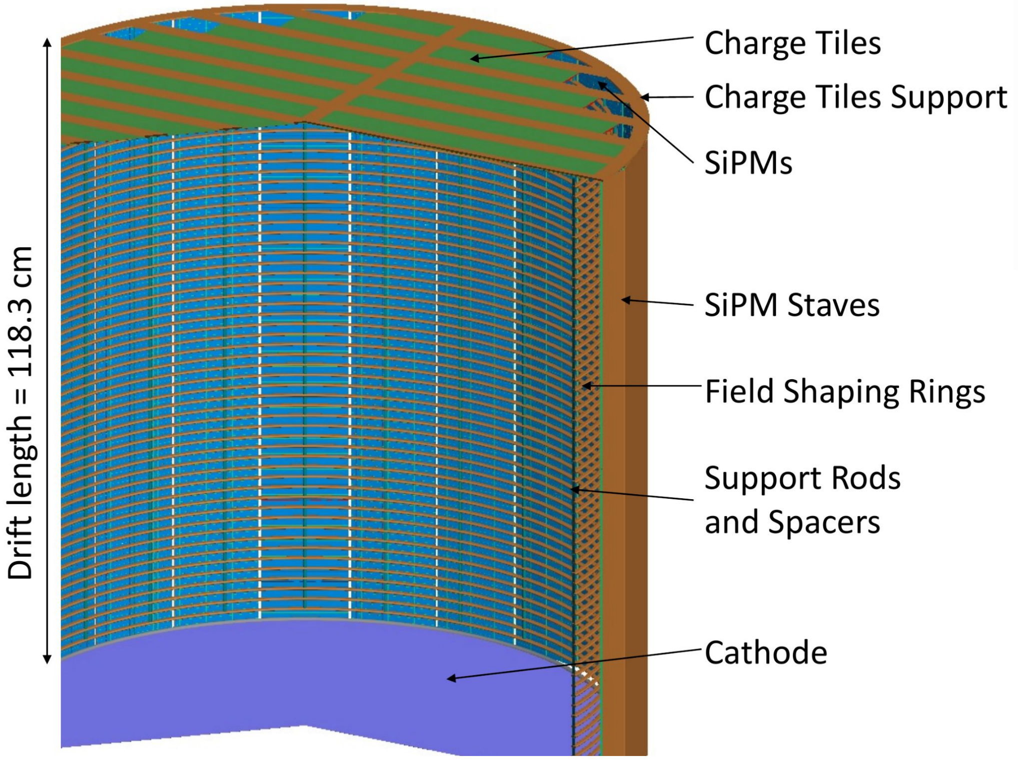

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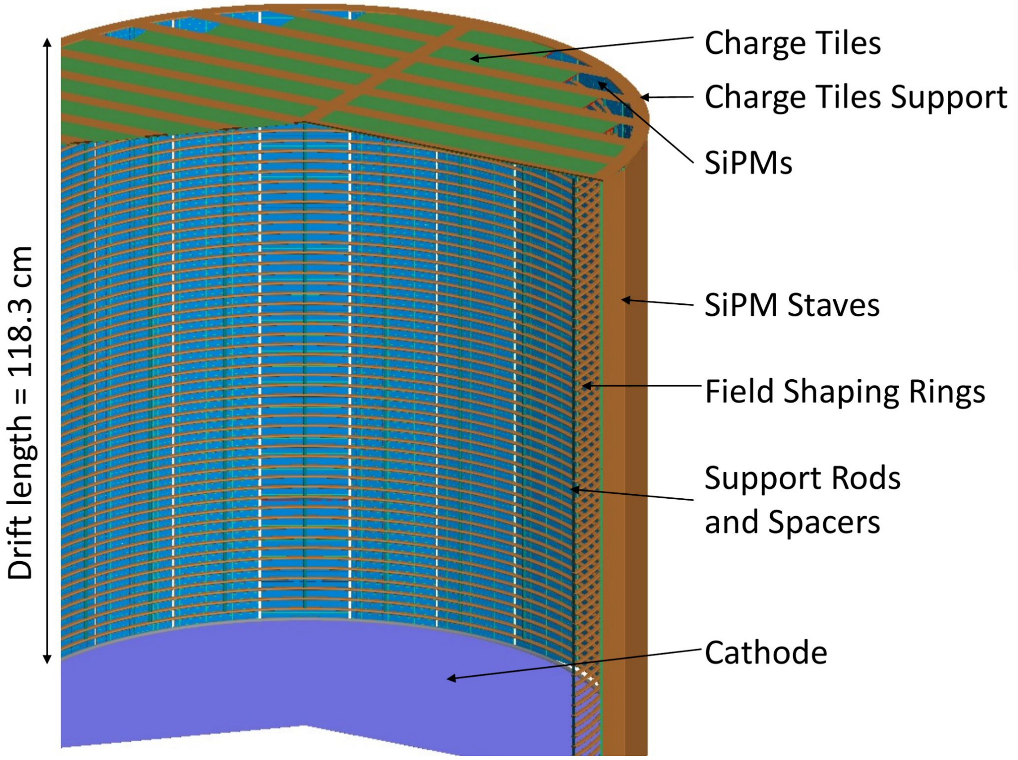
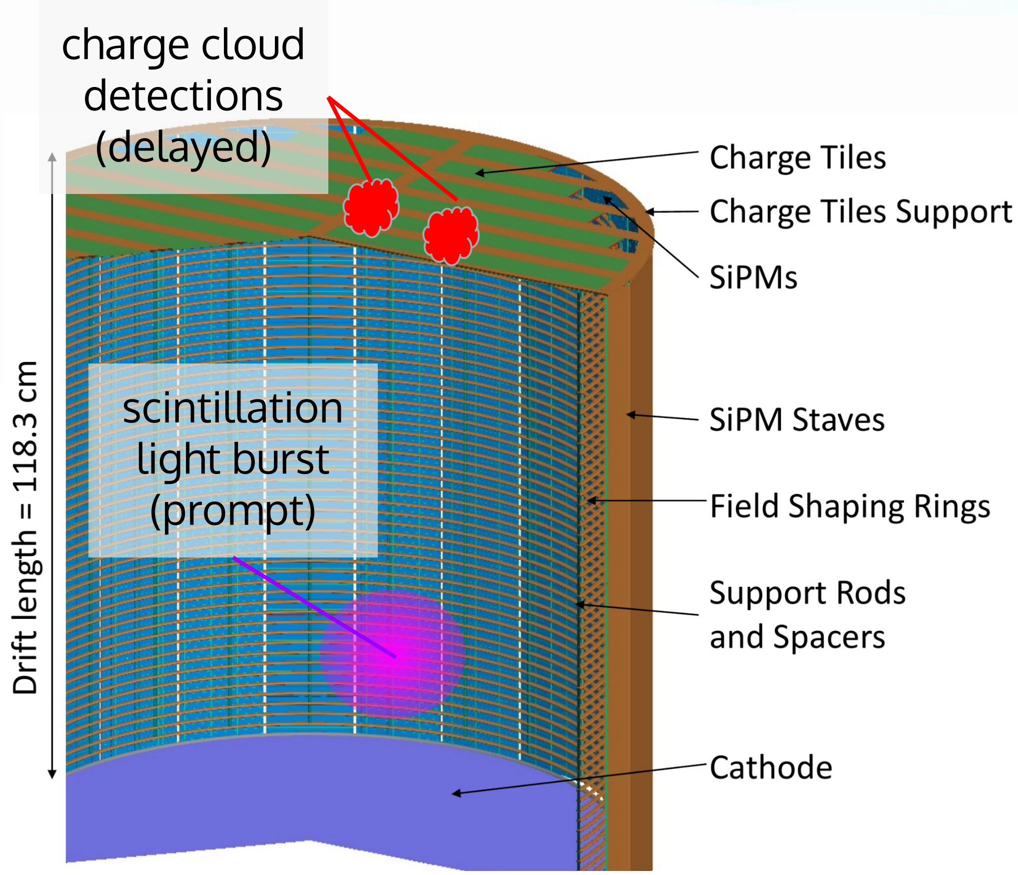
- Possibility for control run in case of discovery
  - use unenriched xenon & repeat the experiment!



How does nEXO work?

- Energy deposits in the LXe liberate electrons, ionize the surrounding liquid
  - excited dimers of Xe release ~175 nm scintillation light
  - ionization clouds drift to segmented anode in applied E-field
- Combination of light + charge readout gives us…



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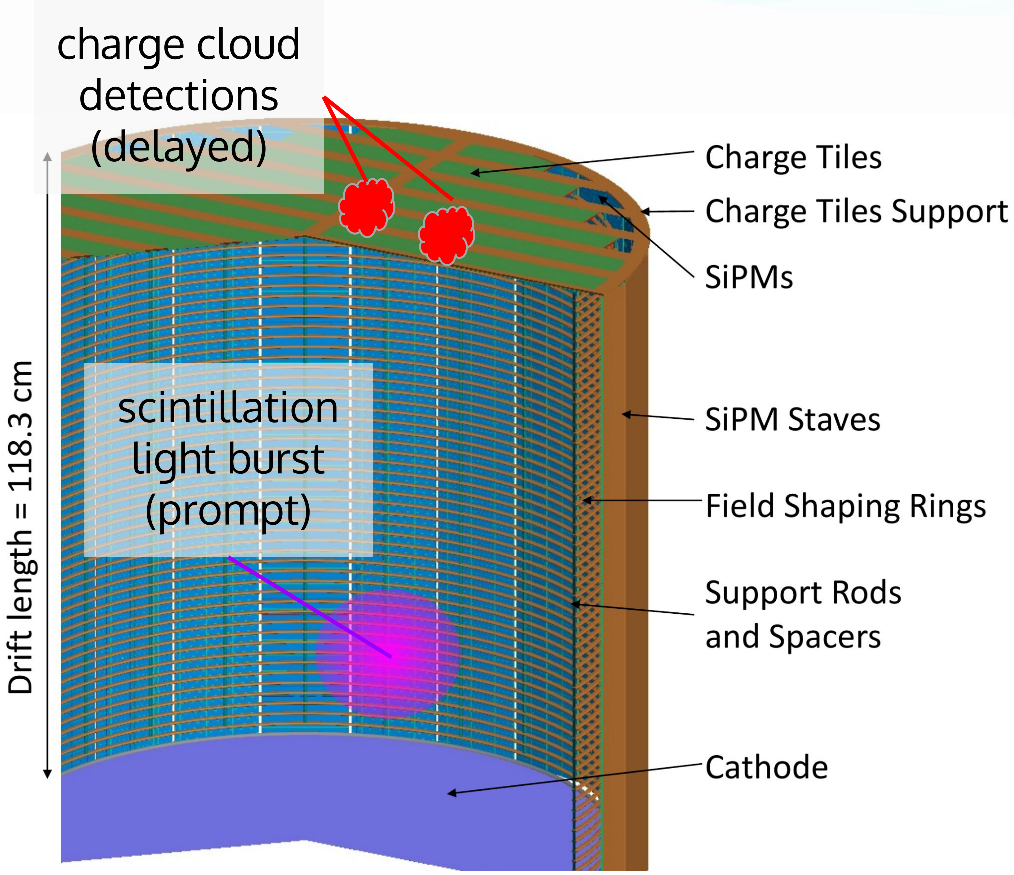
- Combination of light + charge readout gives us:
  - Better energy resolution
  - Better spatial positioning (localization)
  - Topological discriminator between α, β and γ events

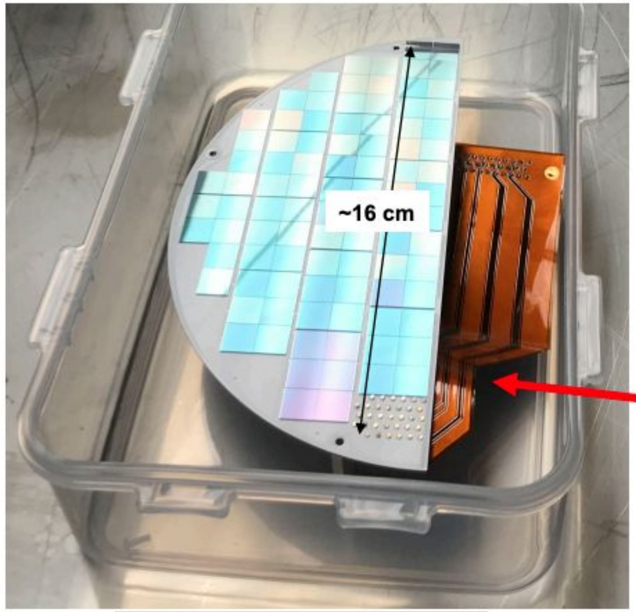


Hardware?
An Active R&D Program

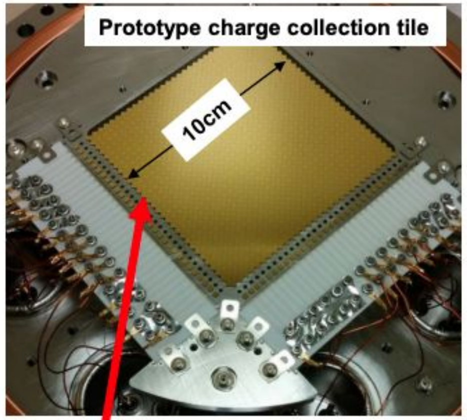
- Basic principles and backgrounds **validated and measured by EXO-200**

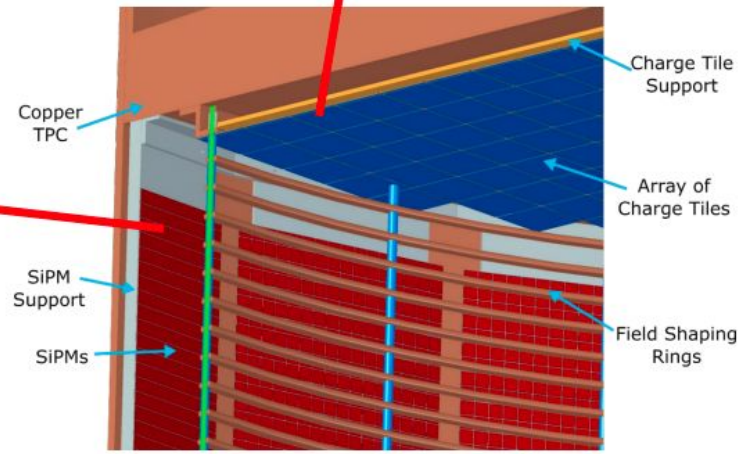
- **Technological upgrades** and further **background reductions** give nEXO a **>250x projected improvement over EXO-200 sensitivity** to $0\nu\beta\beta$ half-life with only **~25x increase in mass!**

At the core of the TPC are Light and Charge collection devices



Prototype VUV SiPM array (FBK)



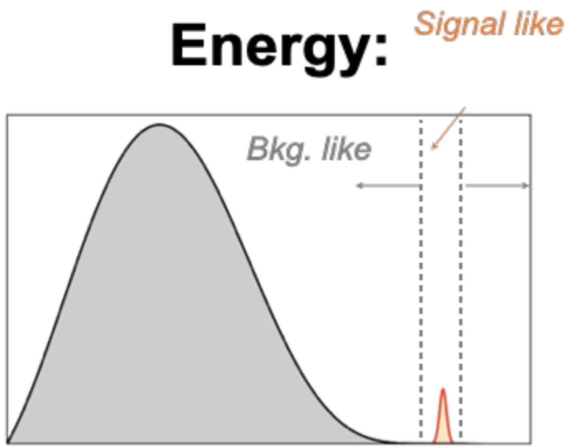


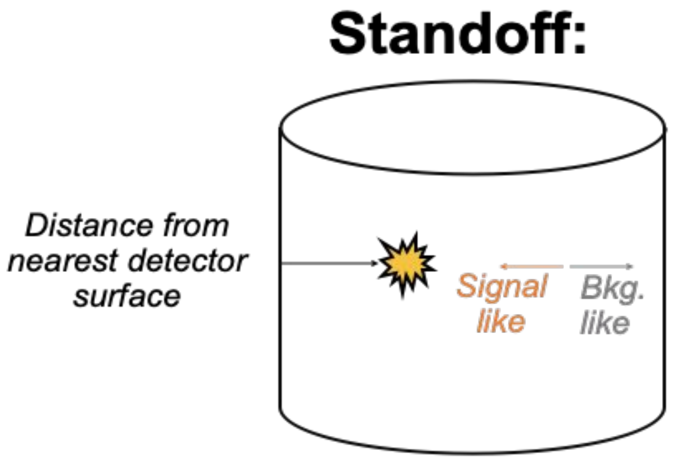
Multiparameter Analysis

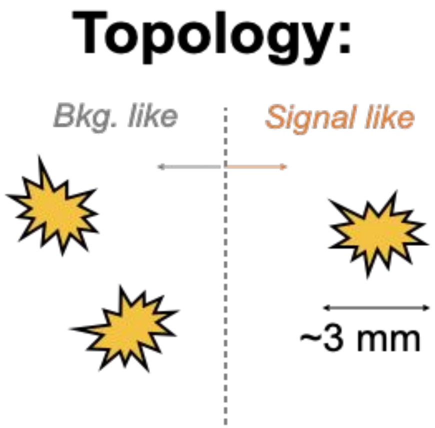
nEXO is not a counting experiment

Three high-level variables:

- ~1% **Energy** resolution at $Q_{\beta\beta}$
- **Standoff** distance to detector components (precise event localization, depth in xenon)
- **Topology** score (DNN): single- and multi-site discrimination (β-like vs γ-like event separation)



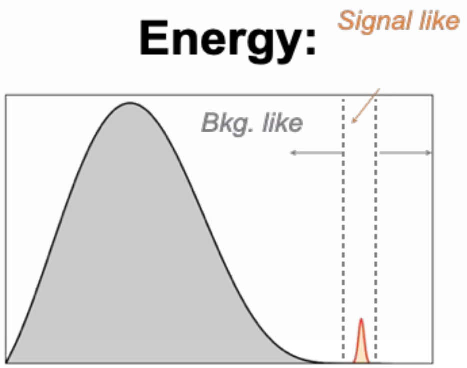




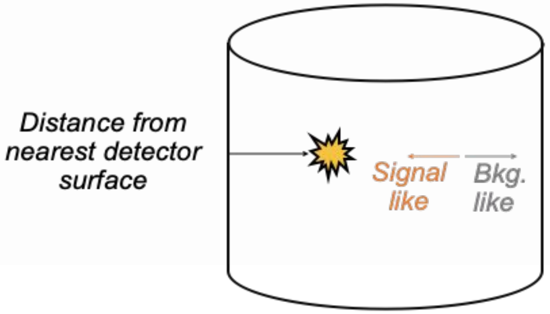
Multiparameter Analysis

A 3D Parameter Space

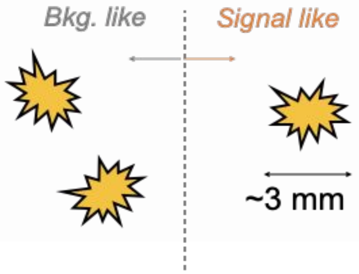
Energy:

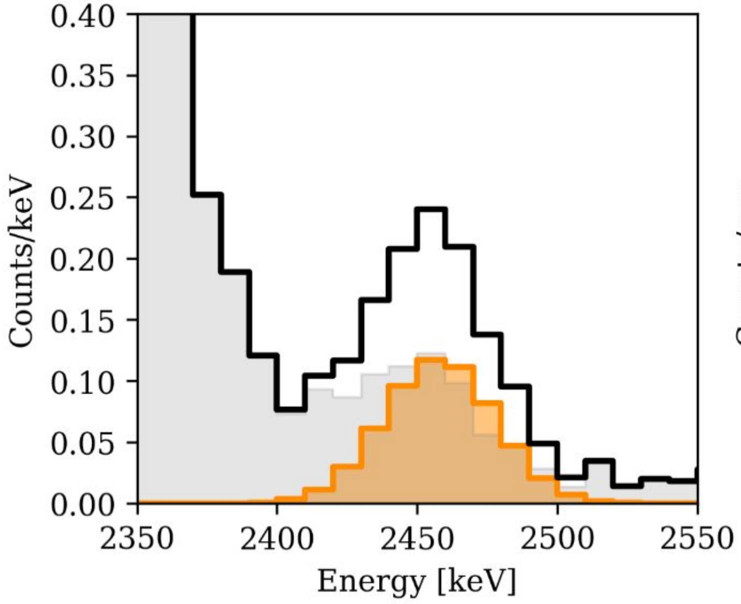


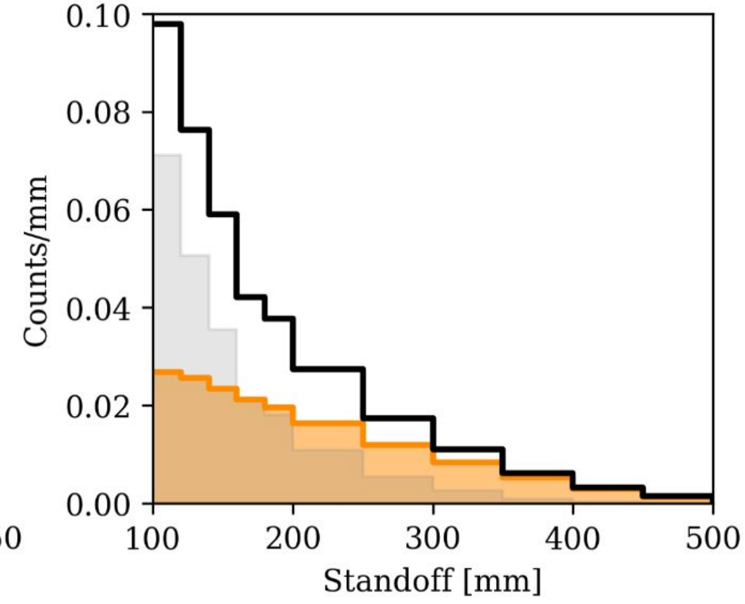
Standoff:

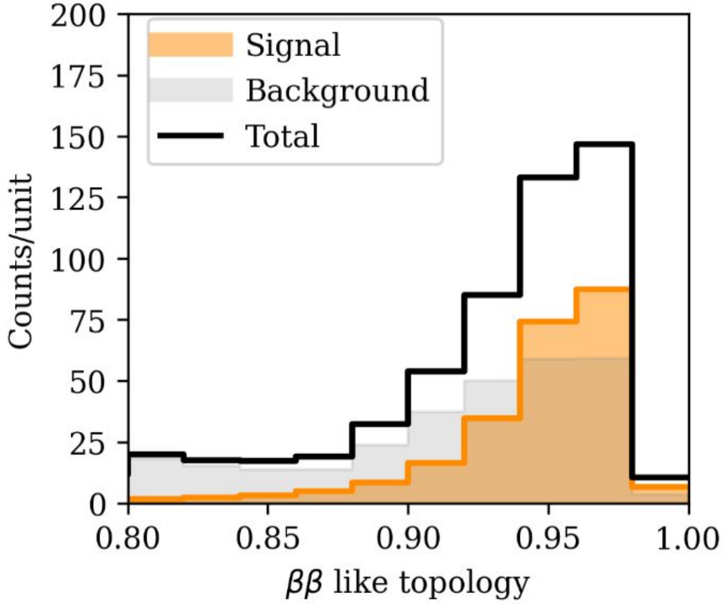


Topology:









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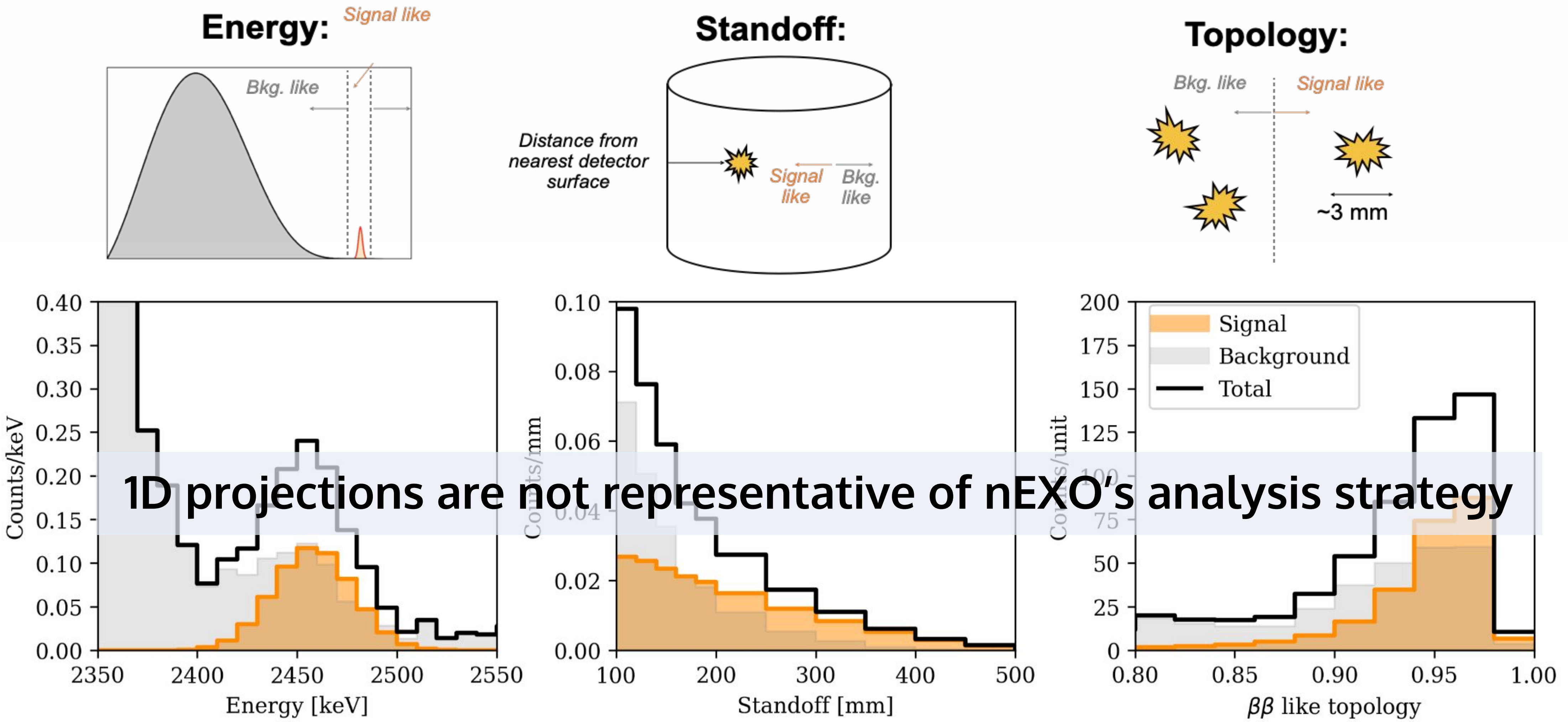
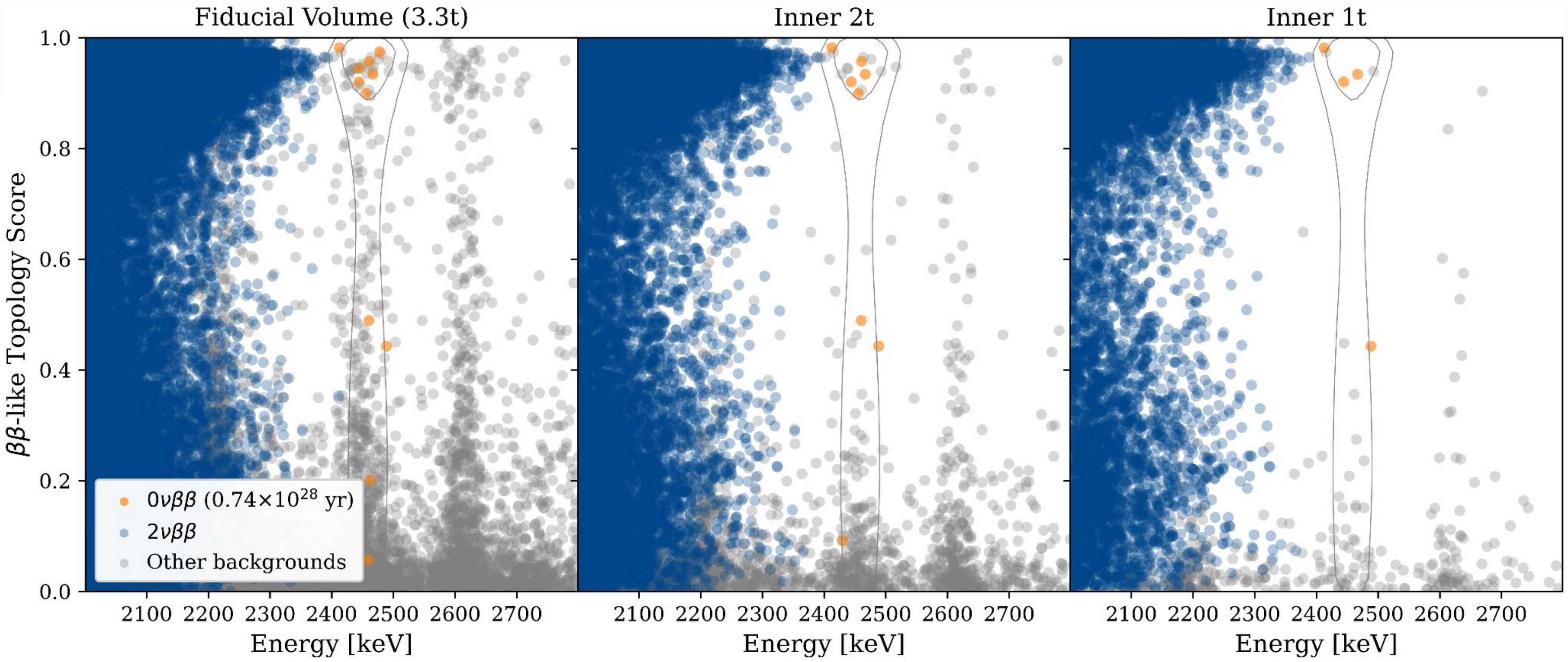


1D projections are not representative of nEXO's analysis strategy

Multiparameter Analysis

What will nEXO data look like?

- 1 and 2σ contours on signal ($0\nu\beta\beta$)
- Deeper in the LXe, backgrounds are quieter, signal dominates… but we **use all the LXe in analysis**!
- Below: realizations of nEXO 10 yr dataset at 0.74x10^{28} yr half life for $0\nu\beta\beta$ in ^{136}Xe (3σ discovery)



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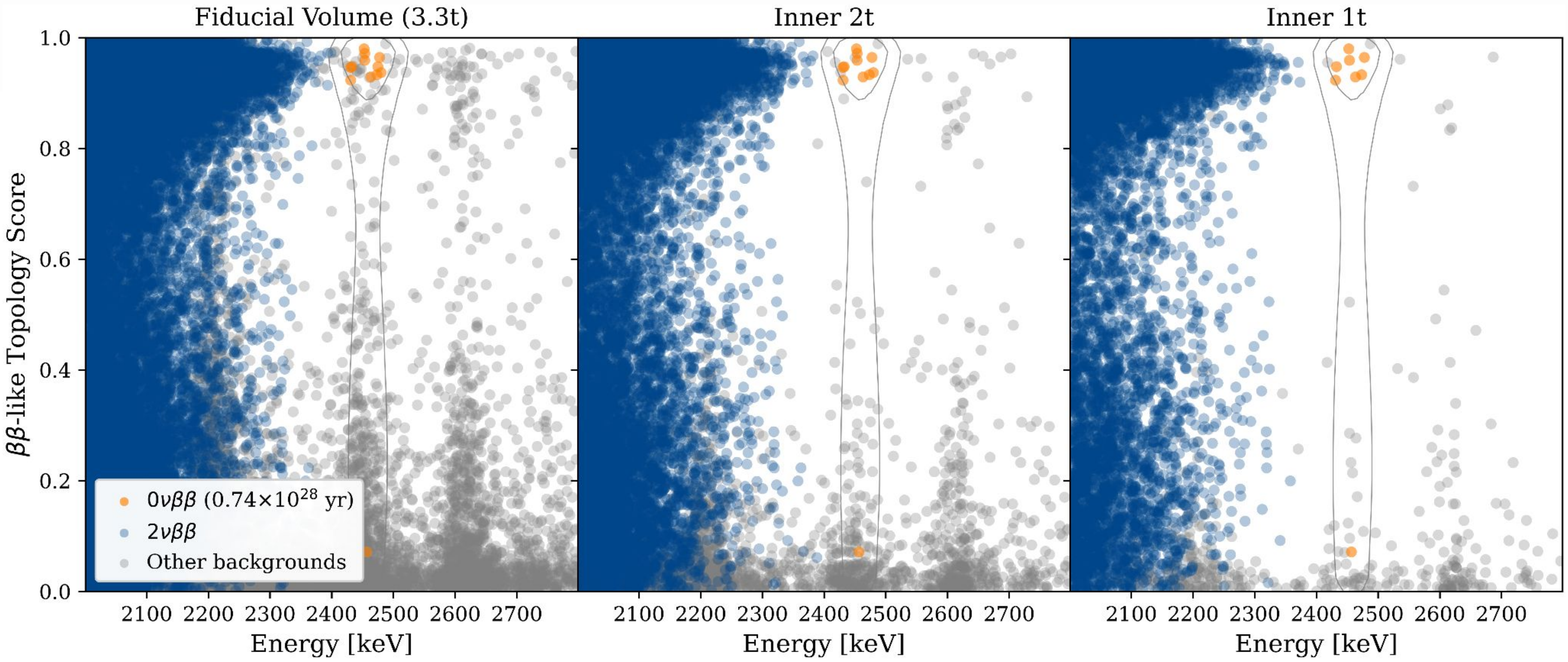

Multiparameter Analysis

3D profile likelihood fit: ultimate test of 0$\nu\beta\beta$ hypothesis

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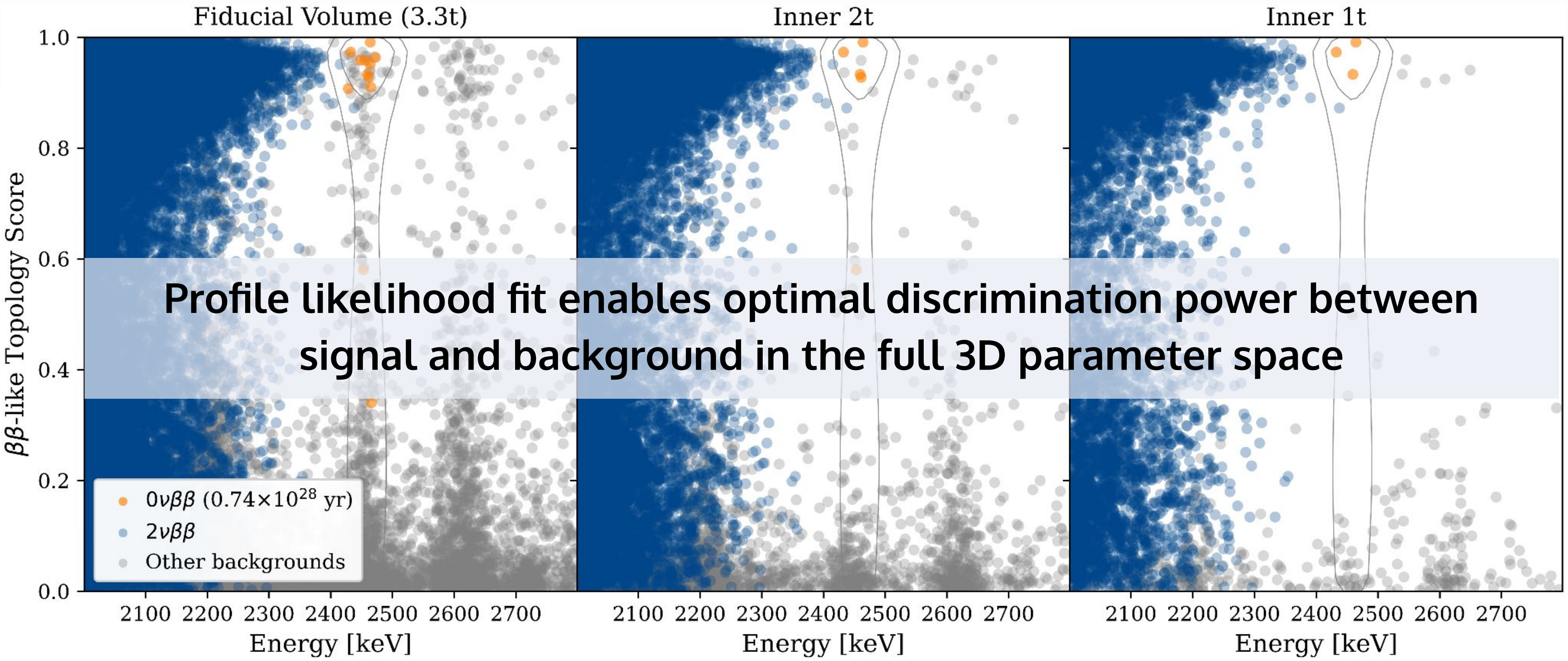
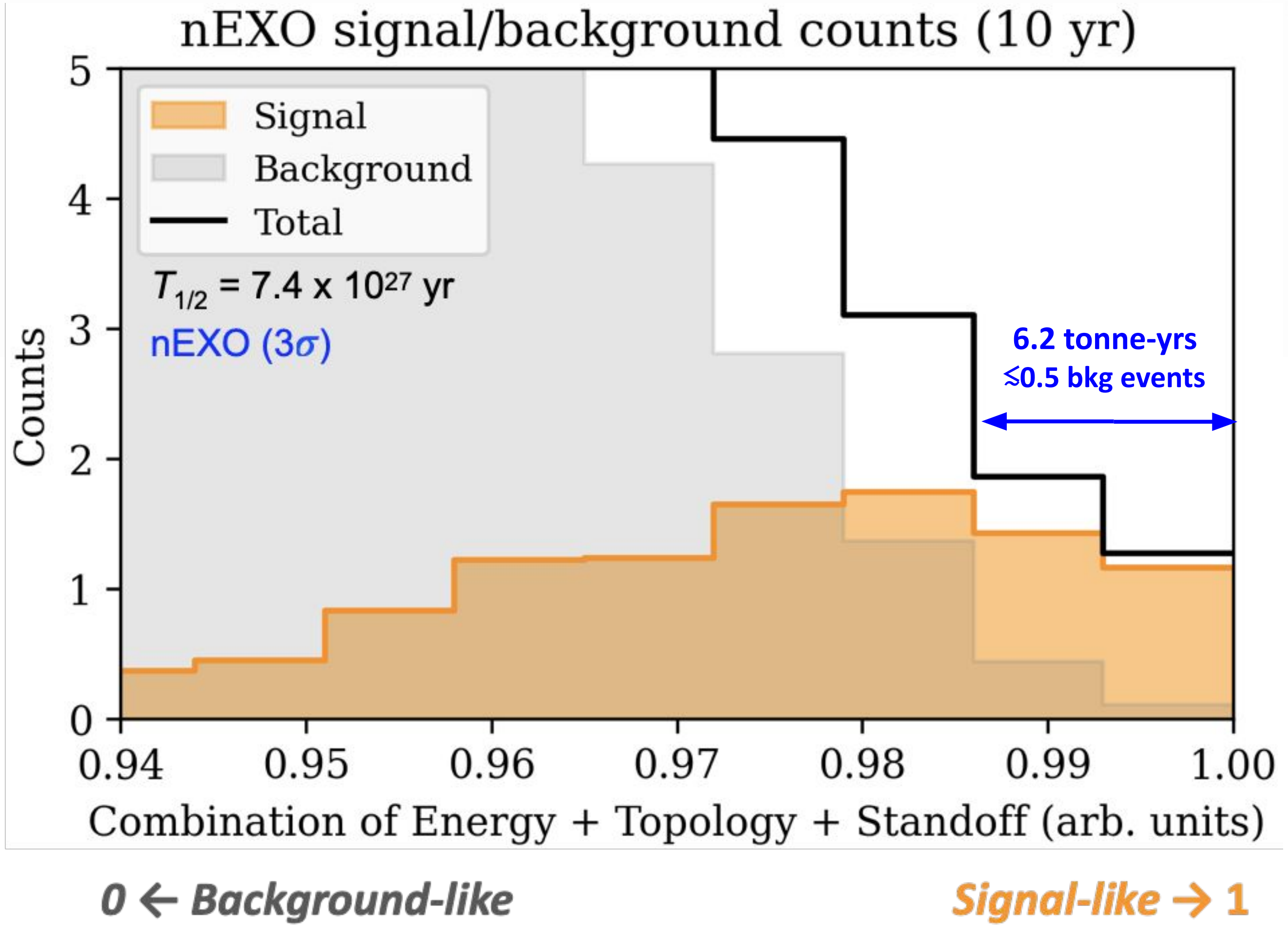


Profile likelihood fit enables optimal discrimination power between signal and background in the full 3D parameter space

Multiparameter Analysis

3D⟶ 1D visualization

- Arranging the 3D bins into 1D, ordered by signal-to-background ratio, helps **visualize the signal and background separation** in nEXO



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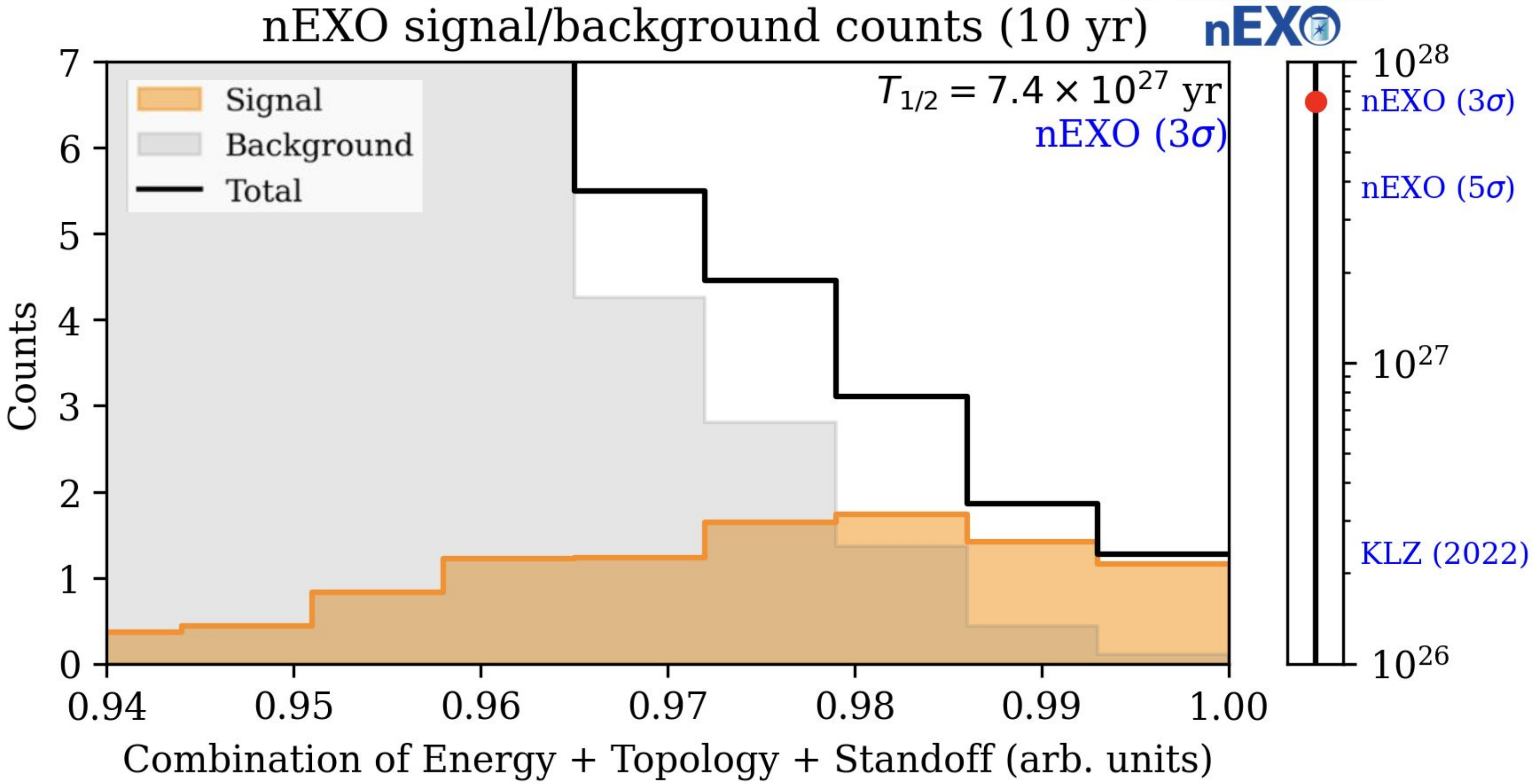

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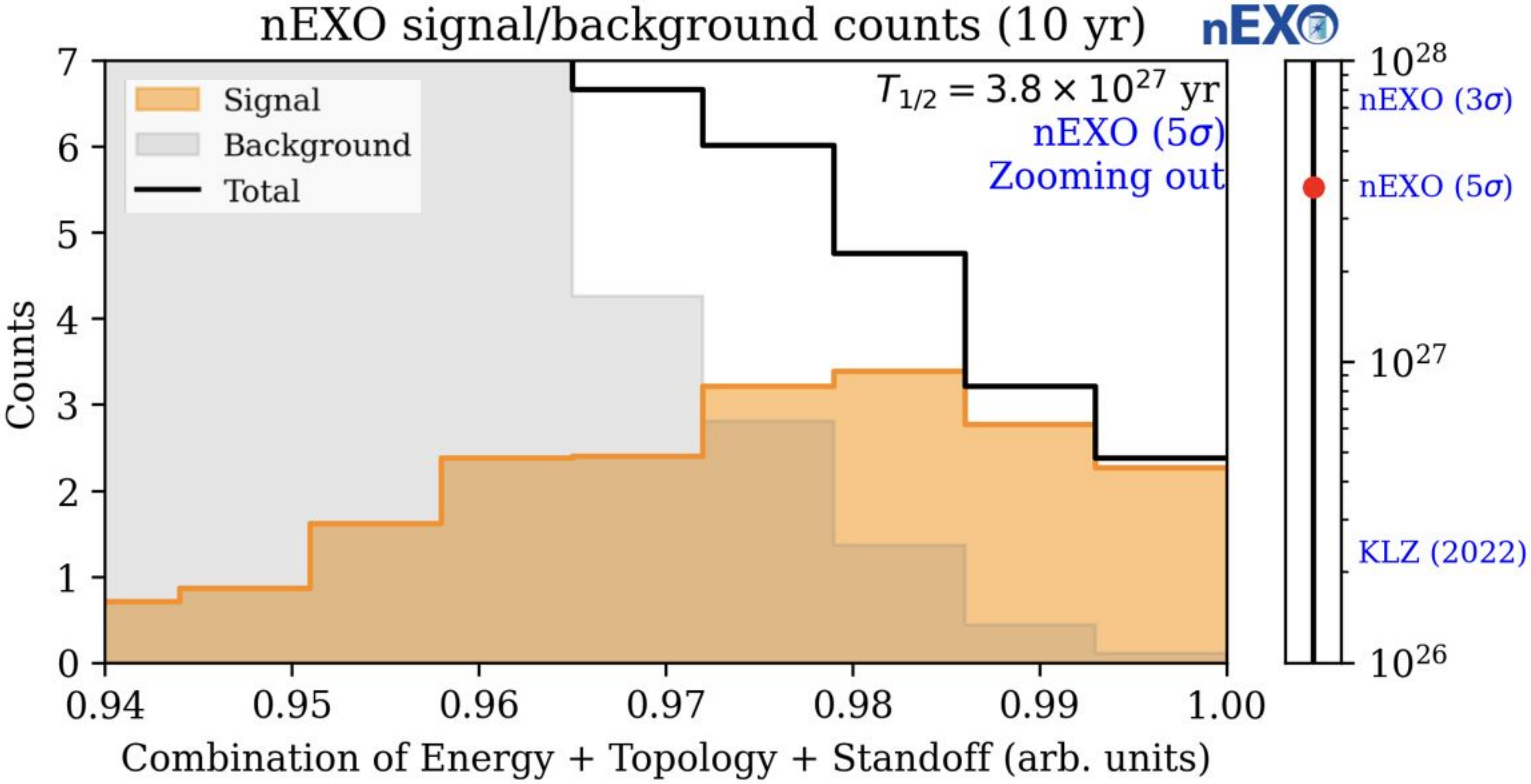

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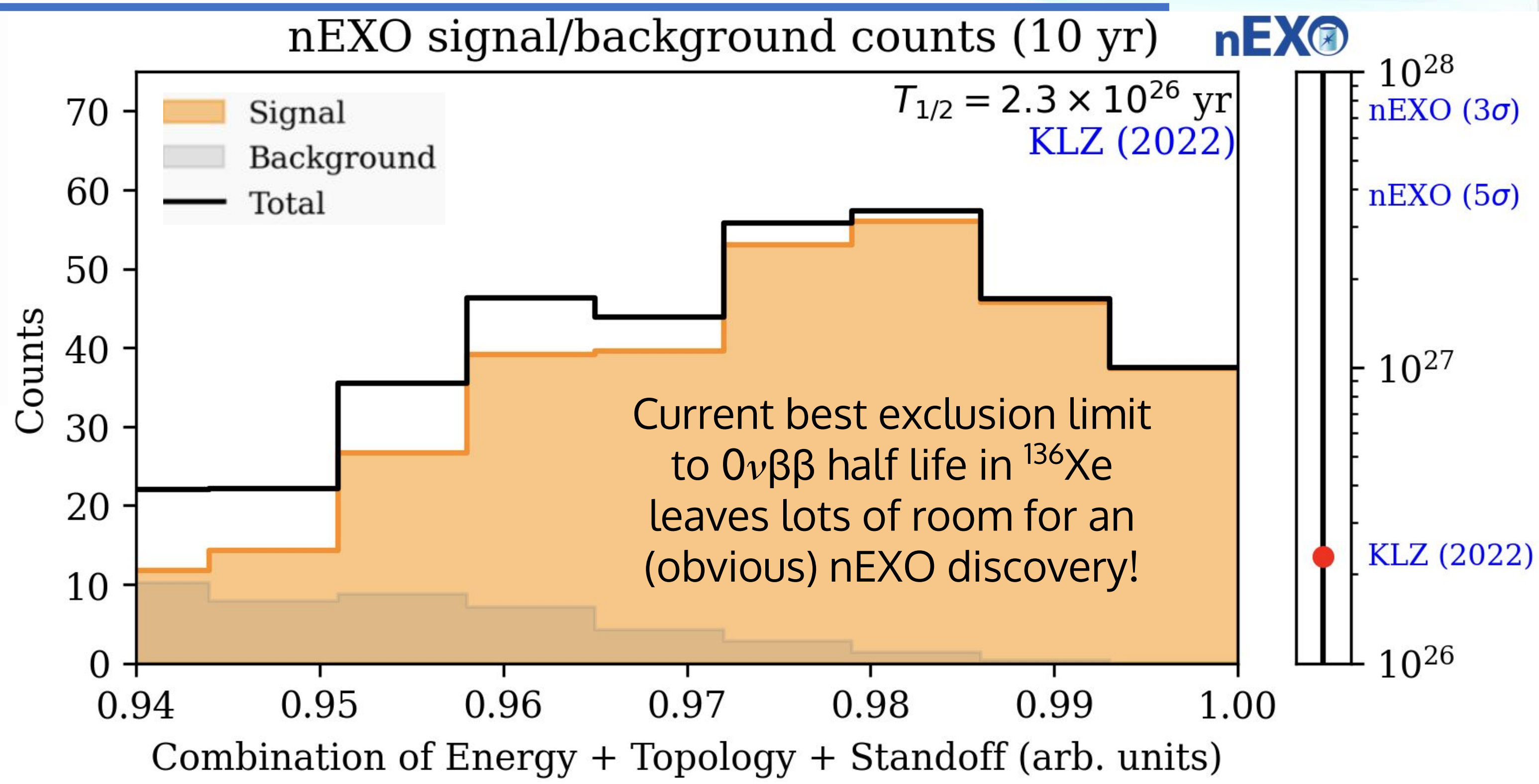
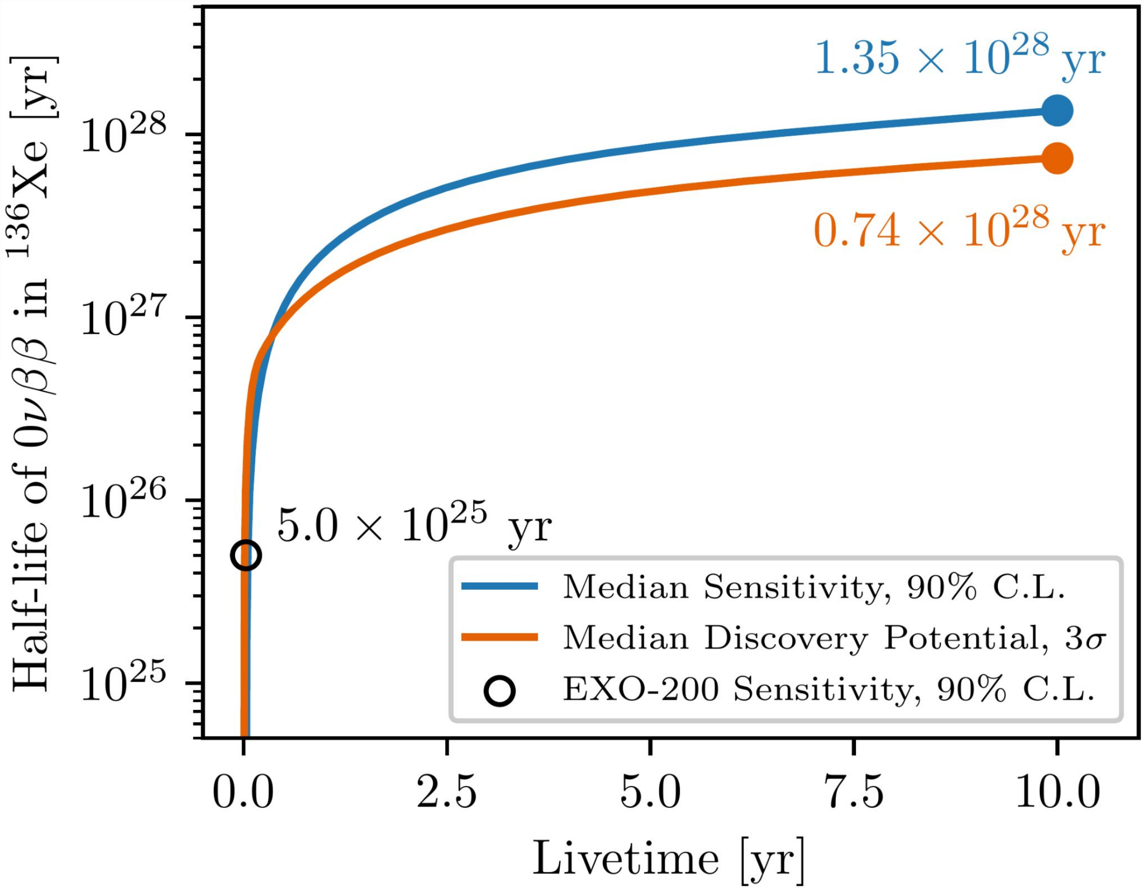


KLZ exclusion limit: https://doi.org/10.1103/PhysRevLett.130.051801

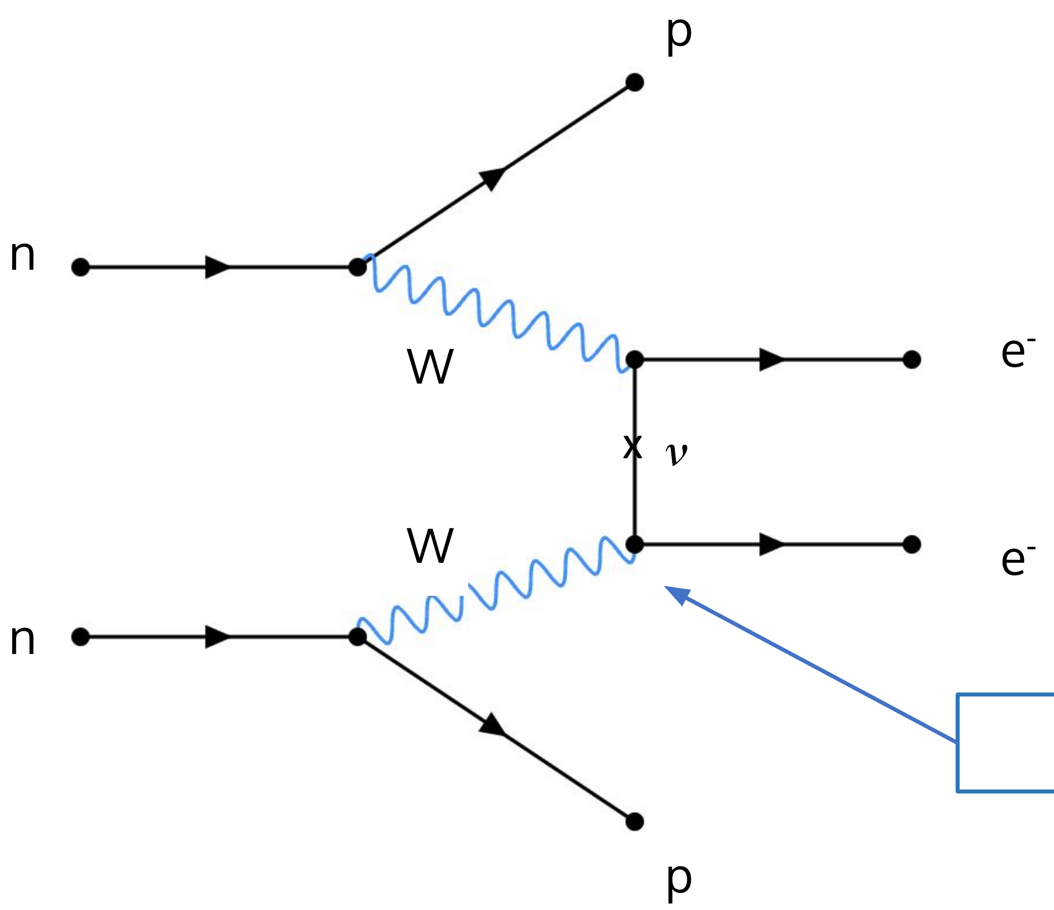
nEXO Sensitivity

Ultimate Goal of 1.35×10^{28} yr half life

- In 6.5 years of data, nEXO will reach a exclusion **sensitivity to $0\nu\beta\beta$ half life in xenon $>10^{28}$ years** (90% C.L.)
  - Age of the universe $\times 10^{18}$!



A Neutrino Mass Measurement?



Light Majorana neutrino exchange

nEXO Sensitivity

Neutrino Mass Measurement

- **Half lives of 0νββ correspond to an effective Majorana mass** of the electron neutrino **$<m_{\beta\beta}>$**
  - combination of 3 neutrino mass states
  - **Assumes dominant process for 0νββ is light-Majorana neutrino exchange**
- $<m_{\beta\beta}>$ is isotope-independent

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

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$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

- $\langle m_{\beta\beta} \rangle$ is isotope-independent
  - Depends on your choice nuclear matrix element (NME) when converting from a half life measurement to neutrino mass, **NME is least constrained theoretical parameter below**
  - Complex nuclear/particle physics could change $\langle m_{\beta\beta} \rangle \longrightarrow$ **we need to search for $0\nu\beta\beta$ in multiple isotopes**

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2} G^{0\nu} g_A^4 |M^{0\nu}|^2$$

Nuclear Matrix Element (NME)

Axial coupling, $g_A = 1.27$

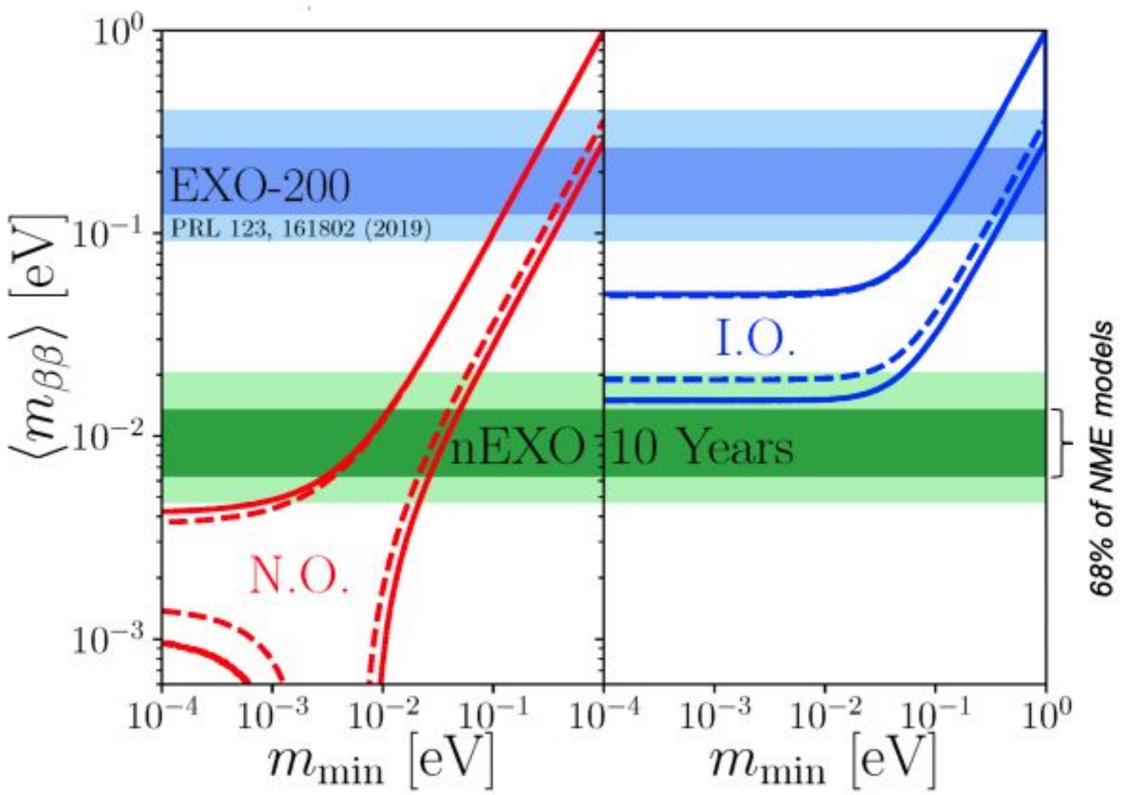
Phase space factor

J. Kotila and F. Iachello, Phys Rev C 85, 034316 (2012)

nEXO Sensitivity

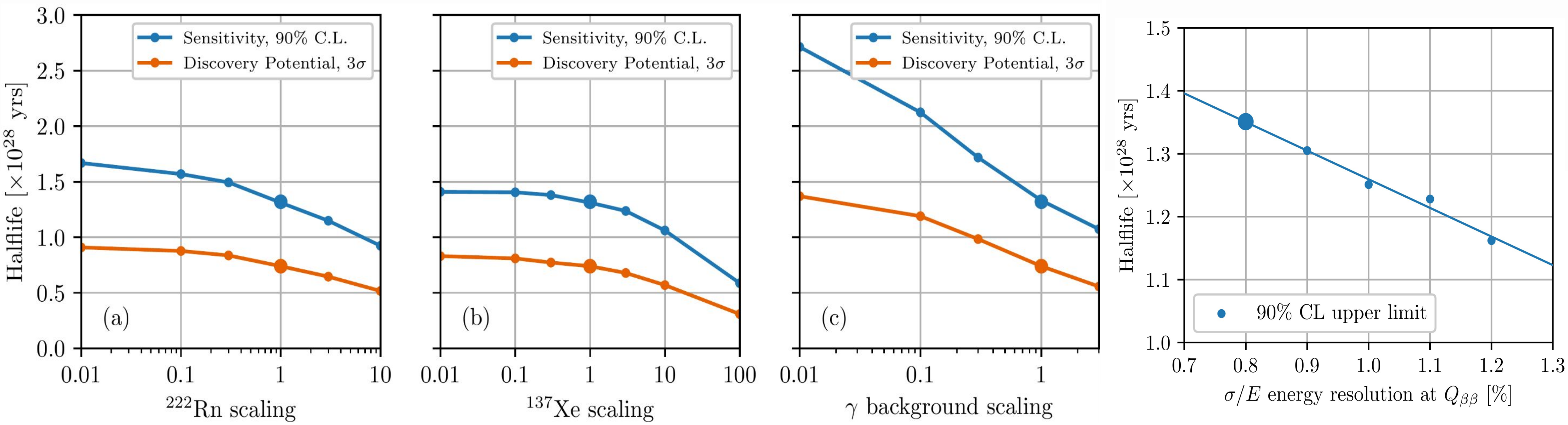
Neutrino Mass Measurement

- In 6.5 years, **nEXO will reach a sensitivity to 0νββ half life in xenon >10^{28} years**
  - Age of the universe x 10^{18} !
- **Effective Majorana mass of the neutrino ≲8 meV**; excludes inverted mass ordering parameter space



nEXO Sensitivity Robustness

- Well studied response to fluctuations in background model, energy resolution, ...



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

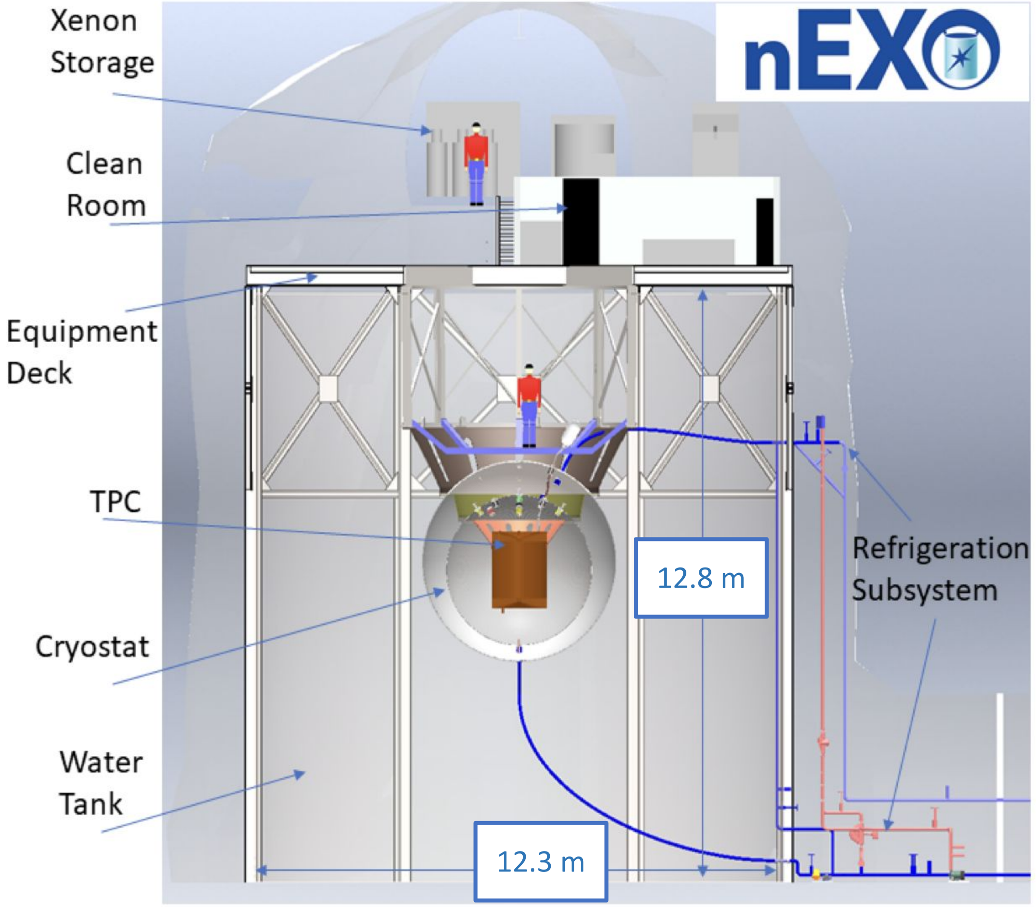
G Adhikari et al. (nEXO Collaboration), 2022 J. Phys. G: Nucl. Part. Phys. 49 015104

Summary

- nEXO is **searching for Lepton Number Violation via $0\nu\beta\beta$**

- nEXO utilizes a 5 tonne single-phase LXe TPC
  - LXe is **purifiable in-situ**
  - LXe is **self-shielding against γ backgrounds**
  - **Multiparameter analysis** provides **robustness to unknown backgrounds**, and background fluctuations
  - **Scalable** technology & **repeatable** experiment
  - Possibility for **"Ba-tagging" upgrade**

- nEXO's **sensitivity to $0\nu\beta\beta$ half life in ^{136}Xe is 1.35×10^{28} yr**
  - **$\lesssim$8 meV effective Majorana mass of the neutrino**



Thank you!

Ask me about nEXO Diversity Equity & Inclusion Activities:

- Mentorship program
- Climate surveys
- Outreach

Follow us!

@nEXOexperiment

soud.alkharusi@mail.mcgill.ca

https://www.physics.mcgill.ca/~soudal/

Thank you!

nEXO Publications:

2022:
- Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO
- Development of a 127Xe calibration source for nEXO

2021:
- nEXO: neutrinoless double beta decay search beyond 1028 year half-life sensitivity
- Reflectivity of VUV-sensitive silicon photomultipliers in liquid Xenon
- Event reconstruction in a liquid xenon Time Projection Chamber with an optically-open field cage

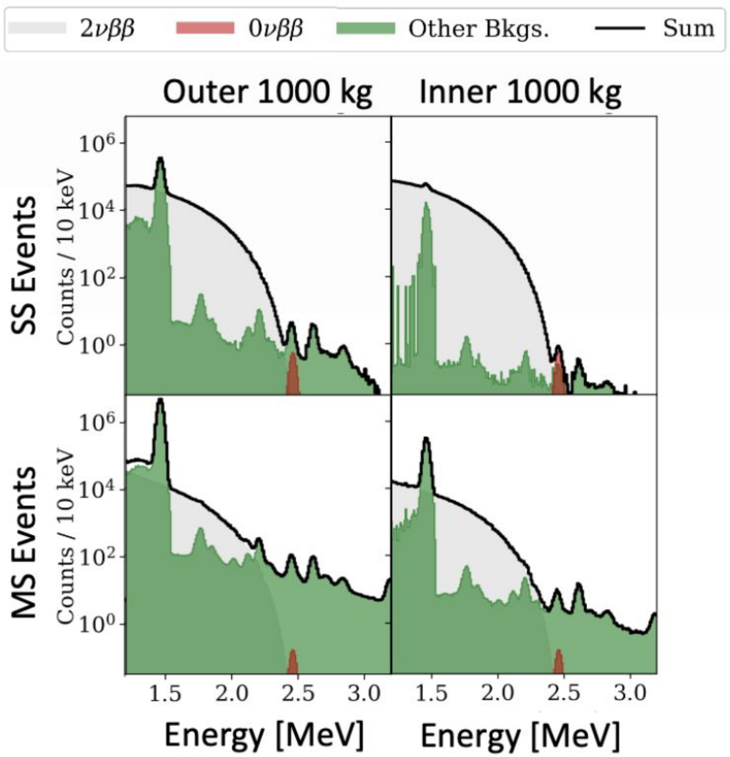
2020:
- Reflectance of Silicon Photomultipliers at Vacuum Ultraviolet Wavelengths
- Measurements of electron transport in liquid and gas Xenon using a laser-driven photocathode

2019:
- Characterization of the Hamamatsu VUV4 MPPCs for nEXO
- Simulation of charge readout with segmented tiles in nEXO

2018
- nEXO pre-conceptual design report

Unknown external background?

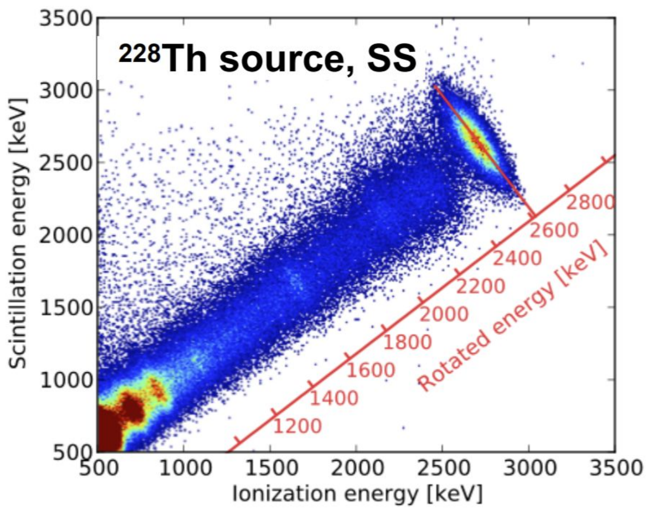
If an unknown decay were strong enough to produce as many SS events in the inner 3000 kg as a 3σ discovery at a half-life of 5.7×10^{27} yr, this decay would produce 271 counts in the MS outer volume, enough to rule out the expected background model at $p < 0.00001$.

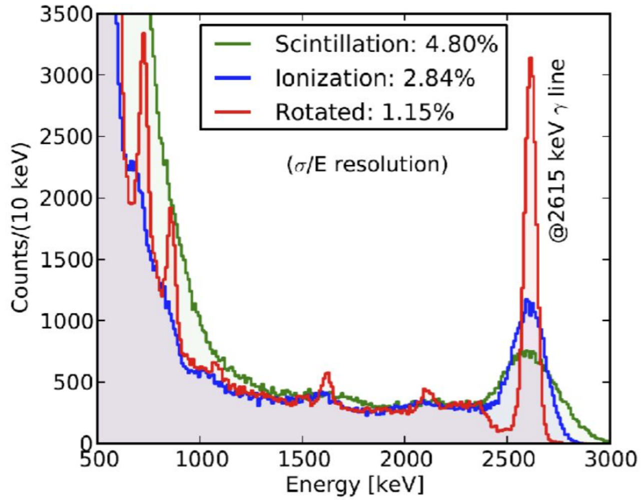


Phys. Rev.C 97, 065503 (2018)

Rotated energy scale

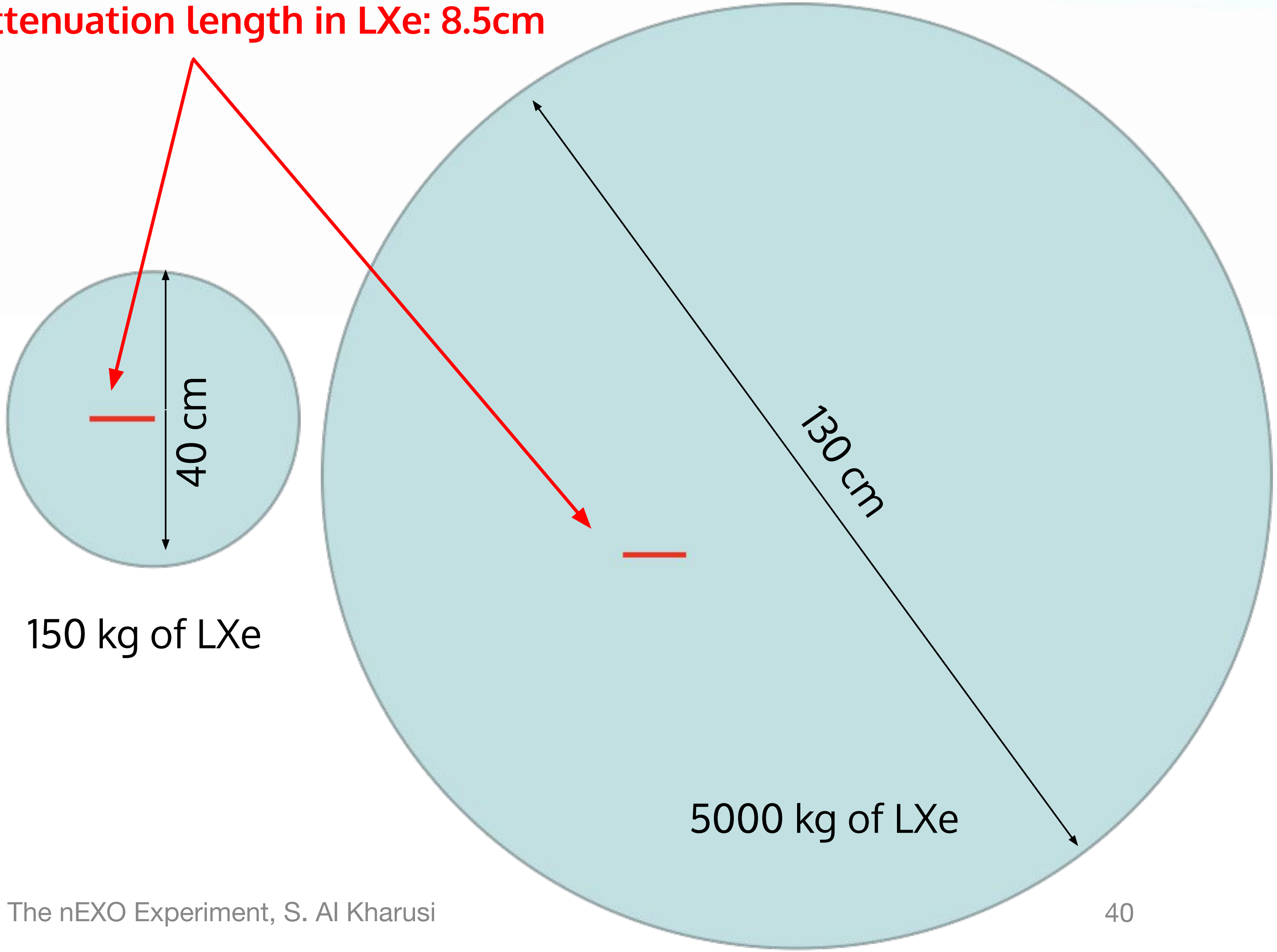
- LXe rotated energy (exploiting anticorrelation in charge and light) allows for optimization of energy resolution
  - Conti, E., et al. "Correlated fluctuations between luminescence and ionization in liquid xenon." Phys. Rev. B 68.5 (2003): 054201.
- 2022: LZ achieved <0.7% energy resolution in LXe!





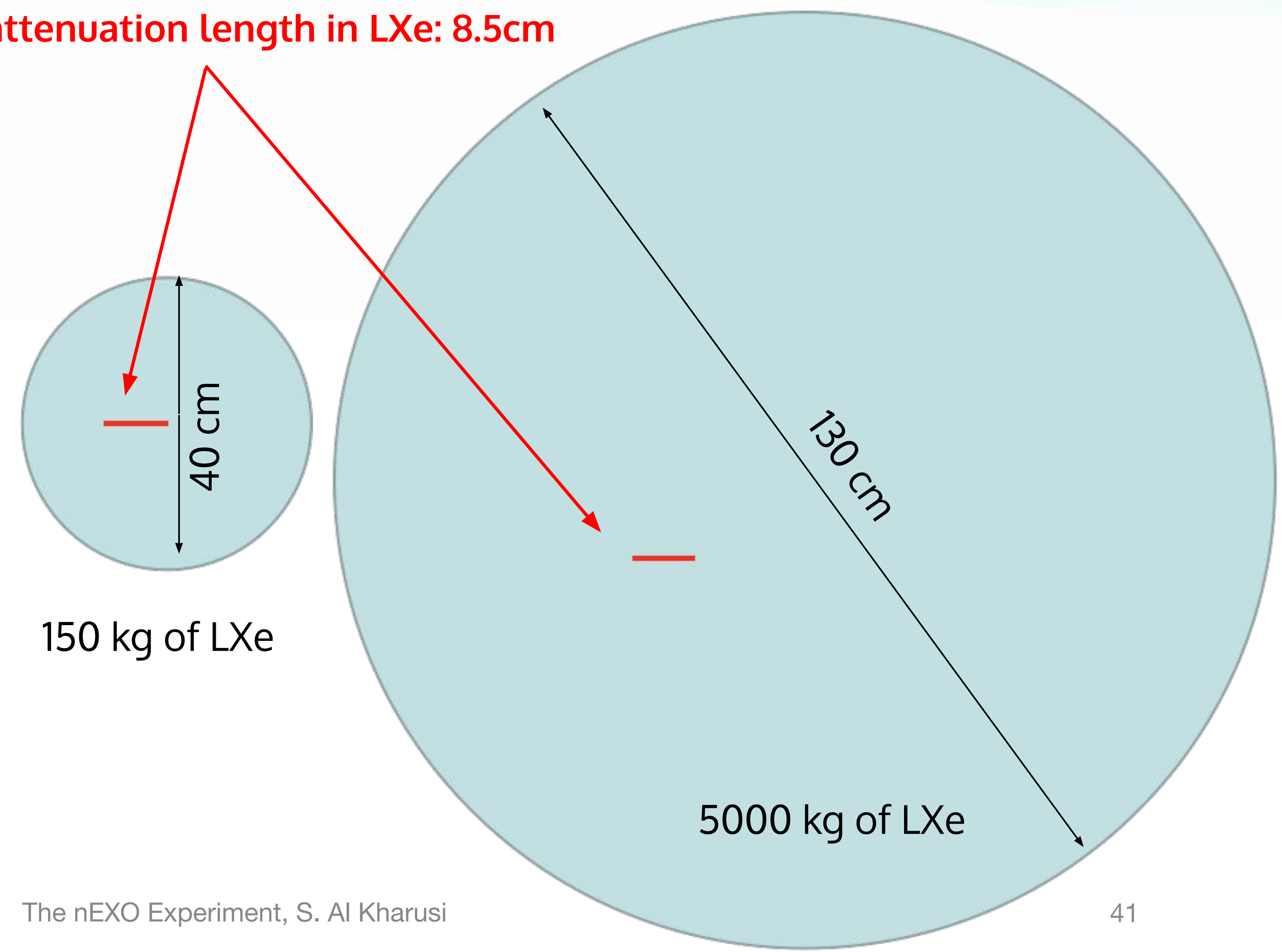
LXe TPC Scalability (1/2)

- LXe is self shielding: larger TPC means **better attenuation of gammas**, and even **better constraints on fluctuations to backgrounds.**
- **Any potential $0\nu\beta\beta$ signal** would have to **not be anomalous in all 3 high level distributions**: Energy, Standoff, and Topology.
  - Due to gamma attenuation lengths << detector scale, this improves with larger masses



LXe TPC Scalability (2/2)

- Going from 5 tonne to 100 tonne would require LXe TPCs of size scale = 1.3*(100/5)^(1/3) ~ 3.5 m
- We know how to make liquid noble TPCs even larger (see DUNE)

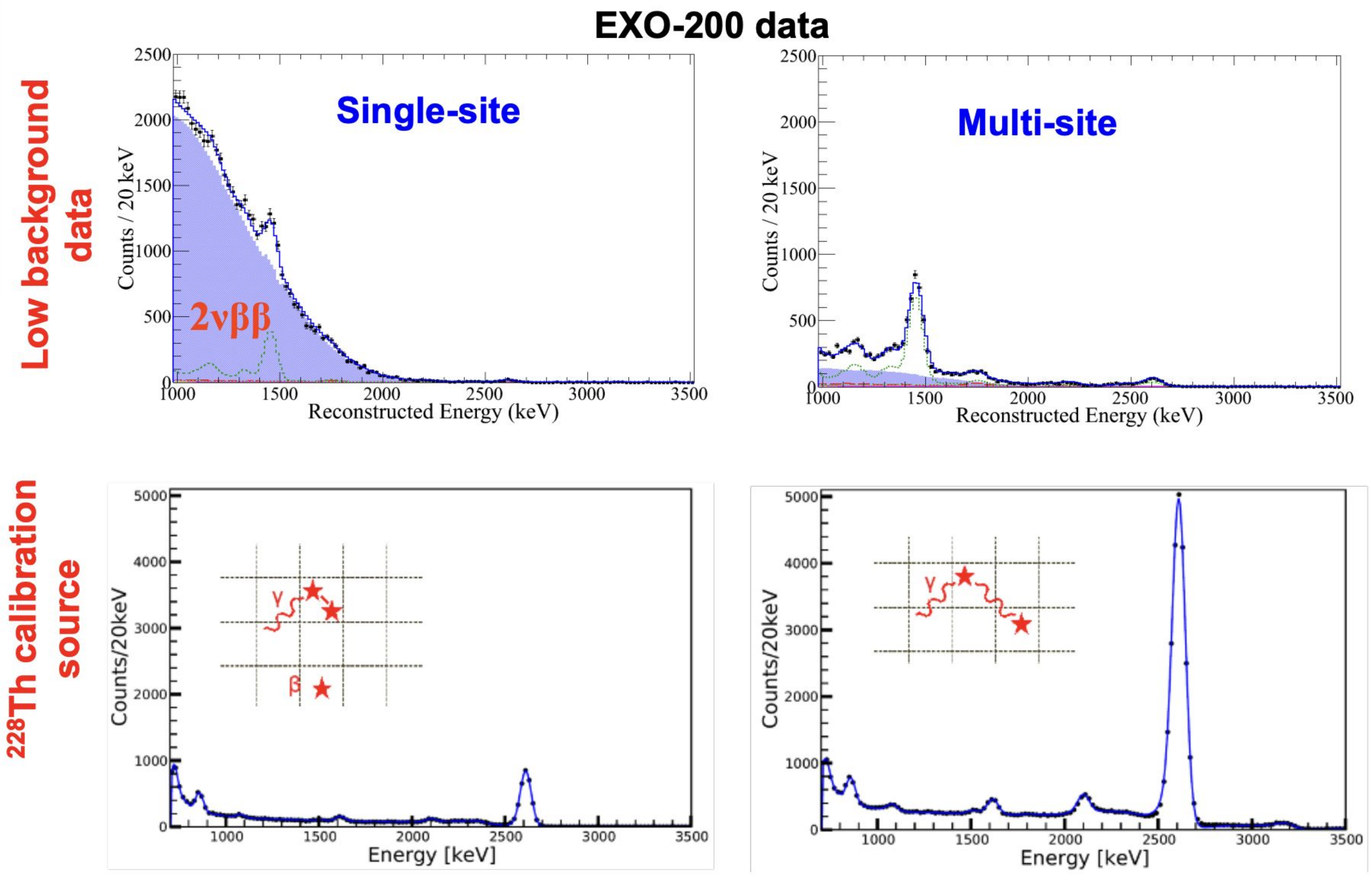


Beyond $0\nu\beta\beta$ discovery?

- **If $0\nu\beta\beta$ is discovered in any isotope**, we would want to explore **what mechanism is producing the decay**
  - We would do this by measuring the **energy and angular distributions** of the two emitted electrons in $0\nu\beta\beta$ events
    - Straightforward in an enriched gaseous xenon TPC
    - Design constraints set by half life measurements in an LXe TPC (e.g. nEXO)
- $0\nu\beta\beta$ decay mechanisms change the value of $\langle m_{\beta\beta} \rangle$, and probe couplings to BSM physics
- Discovering $0\nu\beta\beta$ and exploring it in multiple isotopes is key
  - Nuclear physics is hard, and extracting BSM physics couplings without multiple isotopes confirming $0\nu\beta\beta$, half lives, mechanisms etc... will be difficult

Multiparameter Analysis

EXO-200 Validation



Multiparameter Analysis

nEXO is **not a counting experiment**

- ~1% energy resolution at $Q_{\beta\beta}$
- Topology scoring: single- and multi-site discrimination (β-like vs γ-like event separation)
- standoff distance to detector components (precise event localization, depth in xenon)