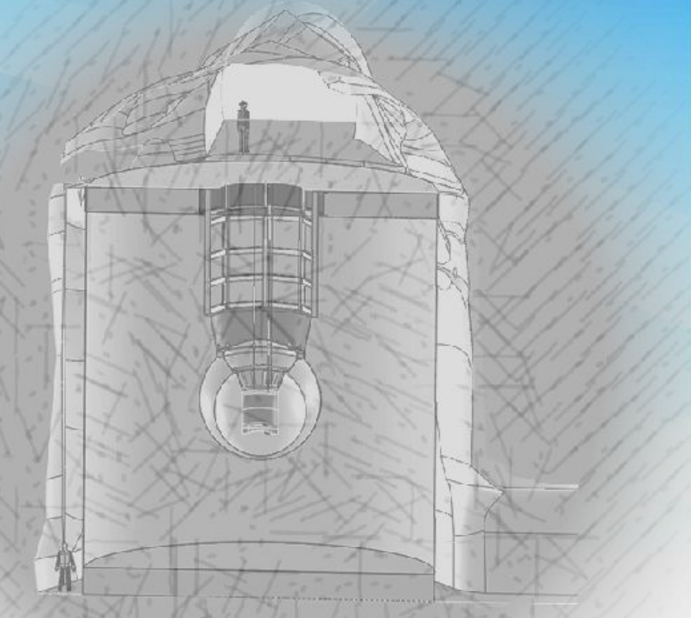

Mitigating Cosmogenic Backgrounds in nEXO

Ray Tracing Muon Cherenkov Light with Chroma

Soud Al Kharusi, McGill University

Winter Nuclear and Particle Physics Conference

Feb. 18th 2023

soud.alkharusi@mail.mcgill.ca

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

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**

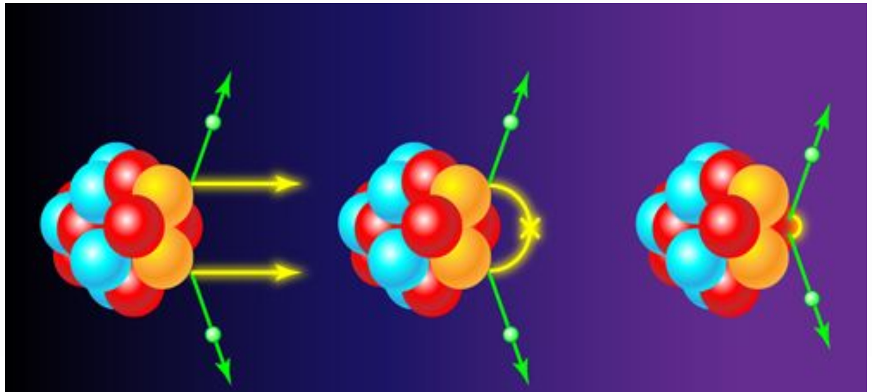
Image credit: APS/Alan Stonebraker

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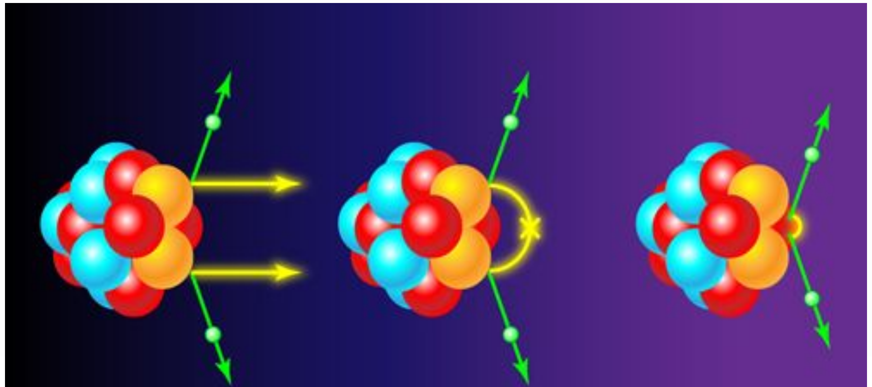
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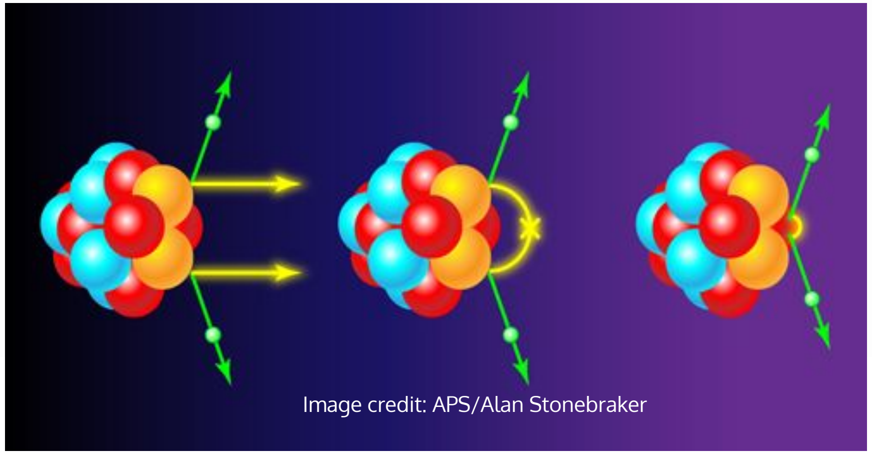

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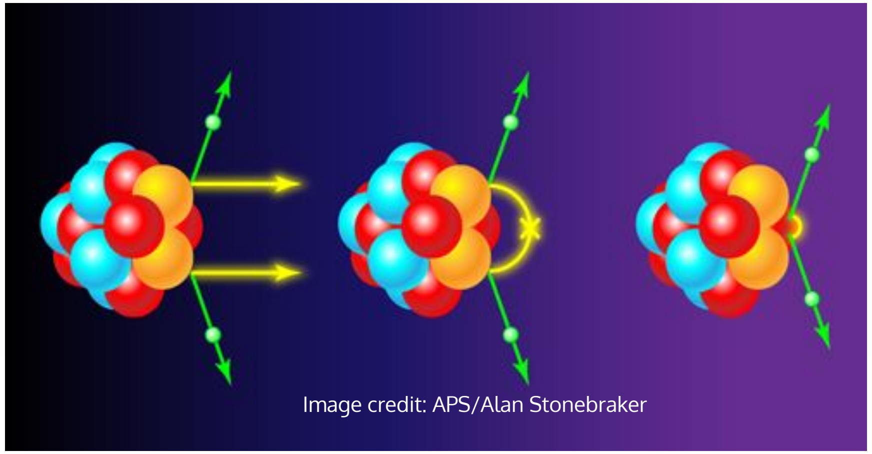
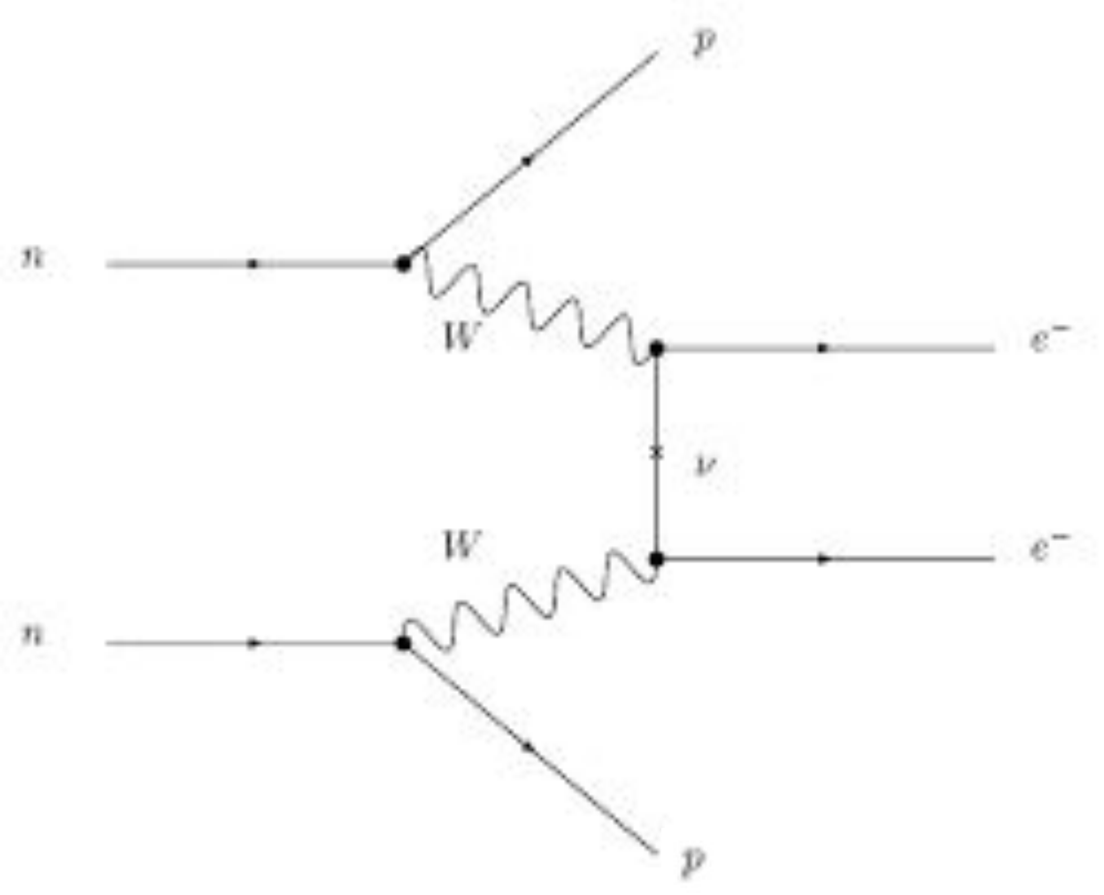


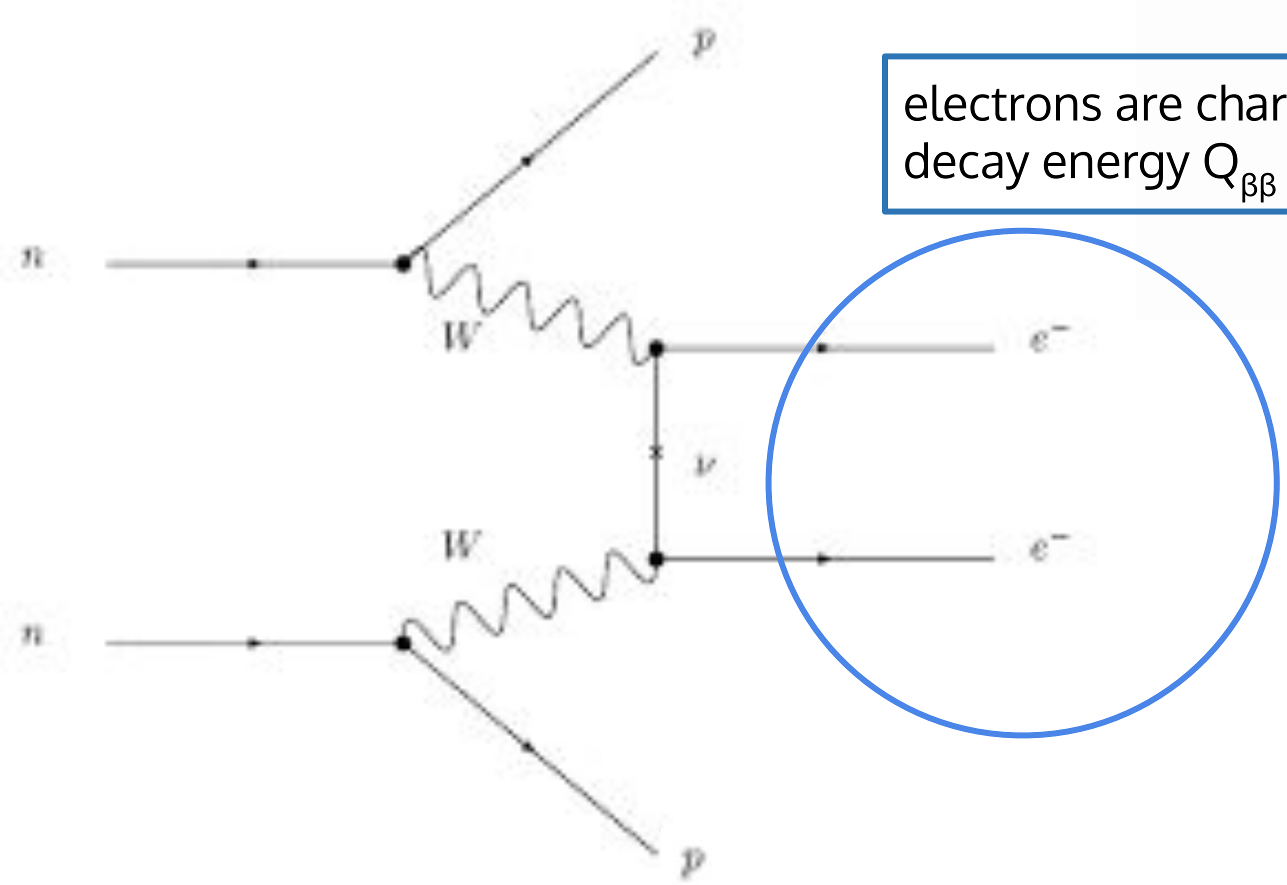
Searches for neutrinoless double beta decay (0$\nu\beta\beta$) are searches for lepton number violation & Physics Beyond the Standard Model

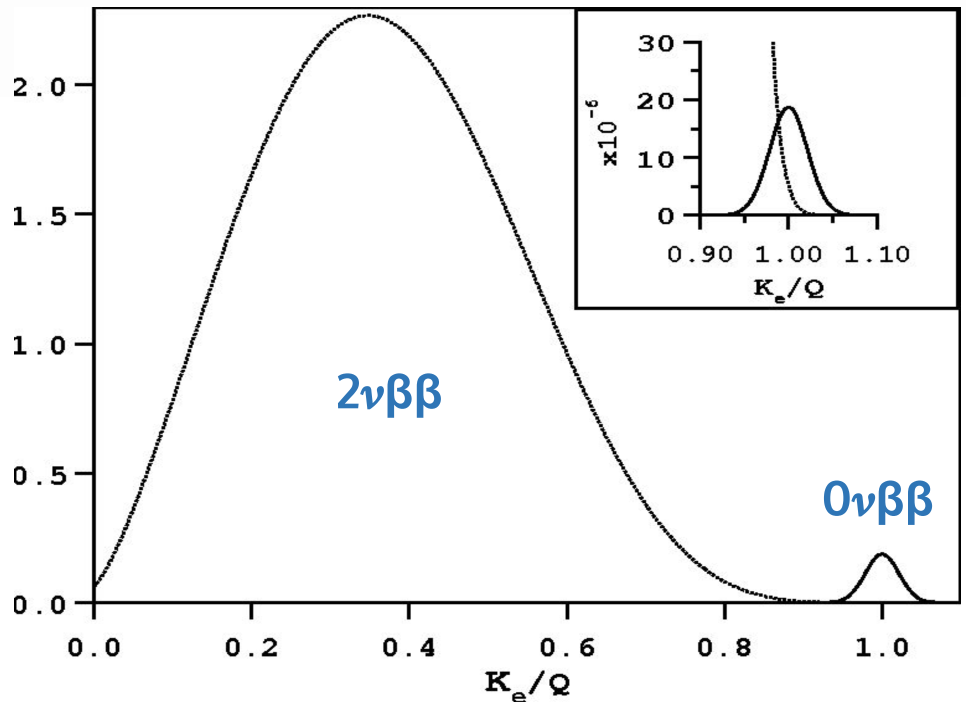
$0\nu\beta\beta$ vs $2\nu\beta\beta$



$0\nu\beta\beta$ vs $2\nu\beta\beta$

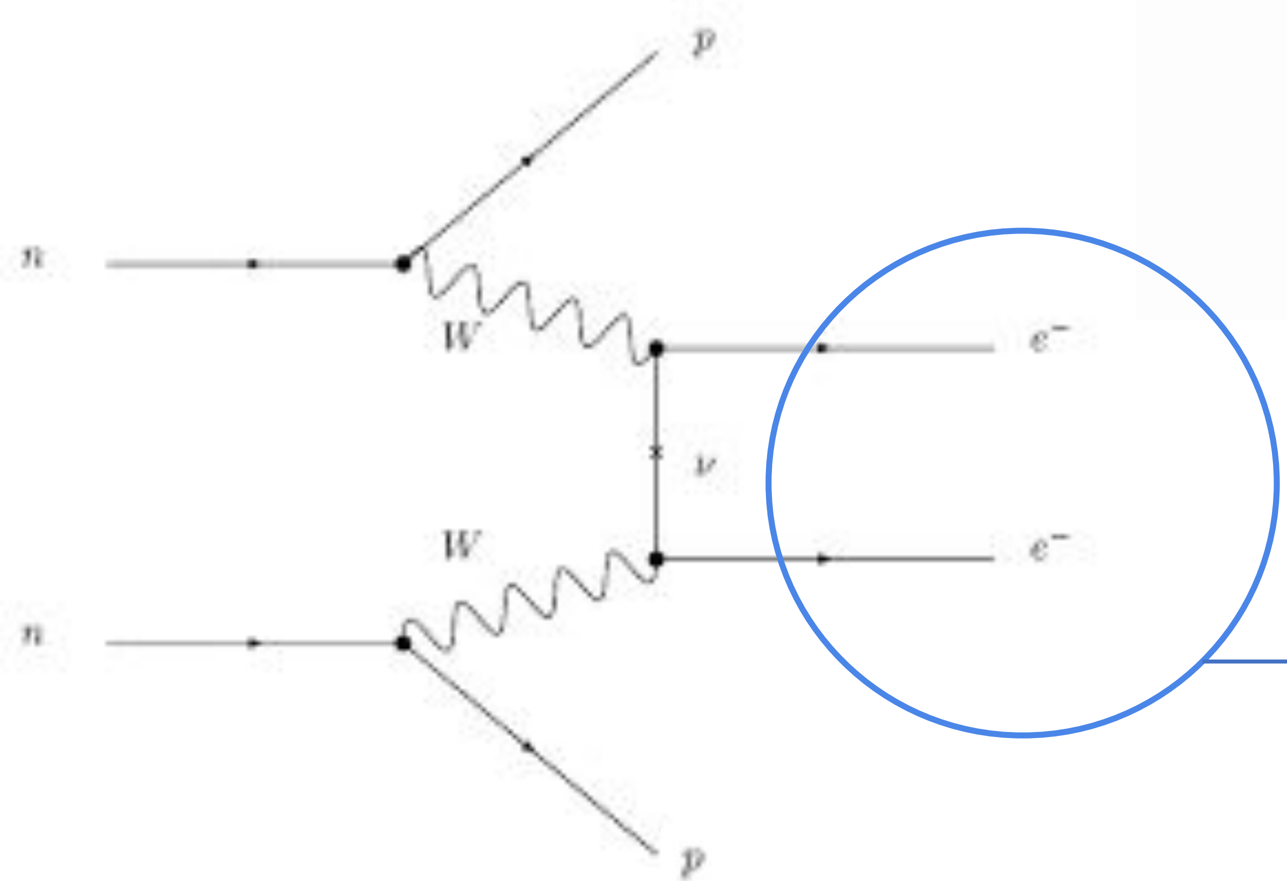
electrons are charged! We can measure the full decay energy $Q_{\beta\beta}$ (ignore the tiny nuclear recoil)

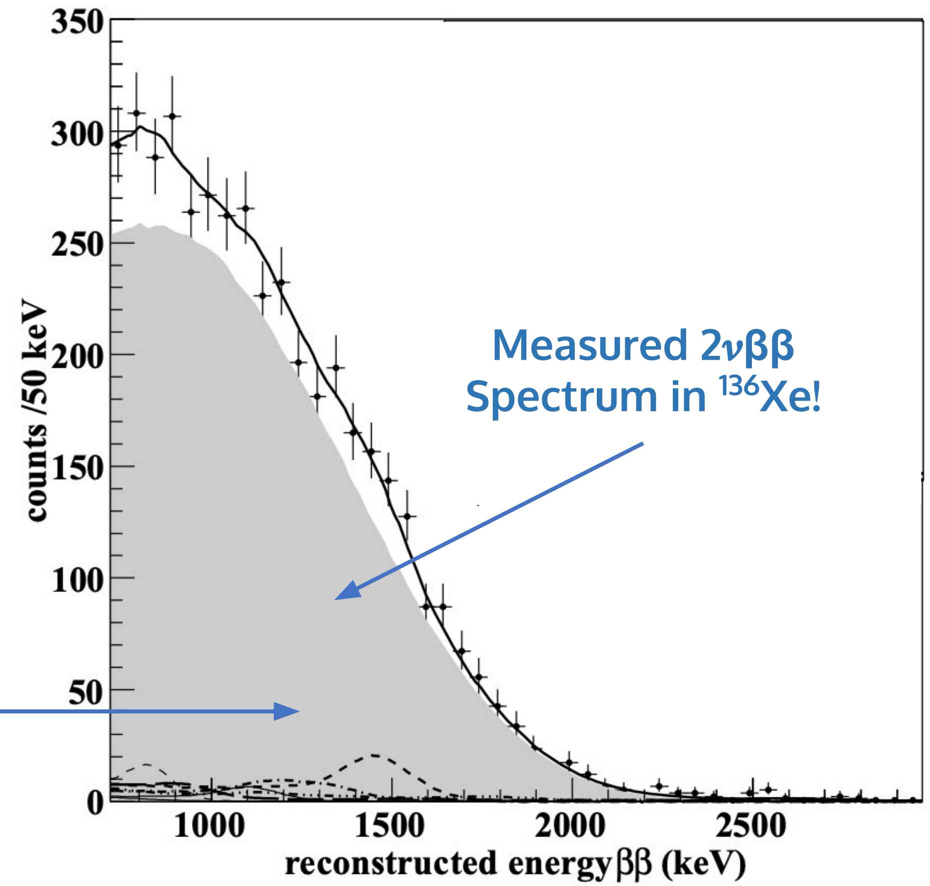




Source: Elliott, S.. (2003). Corpus ID: 17996273

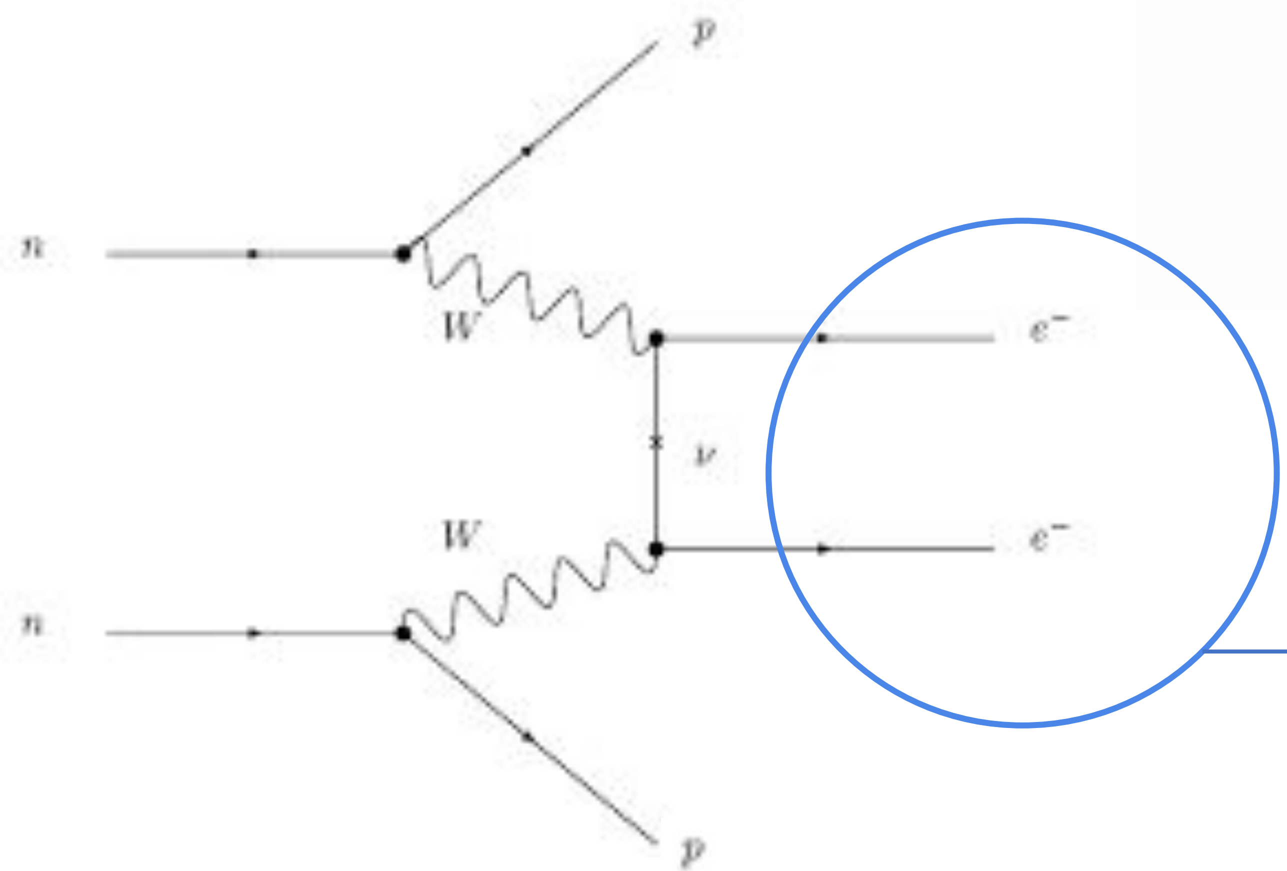
0νββ vs 2νββ

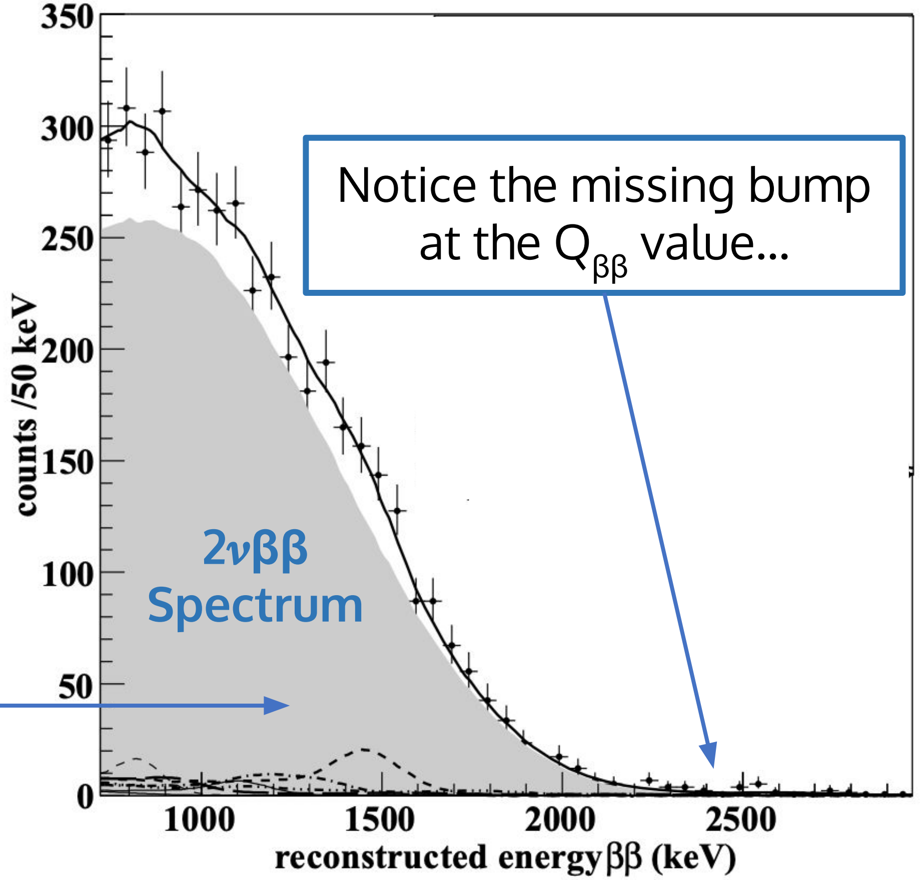




Adapted from: Ackerman, N., et al. "Observation of two-neutrino double-beta decay in Xe-136 with the EXO-200 Detector." *Phys Rev Lett* 107.21 (2011): 212501.

$0\nu\beta\beta$ vs $2\nu\beta\beta$





Notice the missing bump at the $Q_{\beta\beta}$ value...

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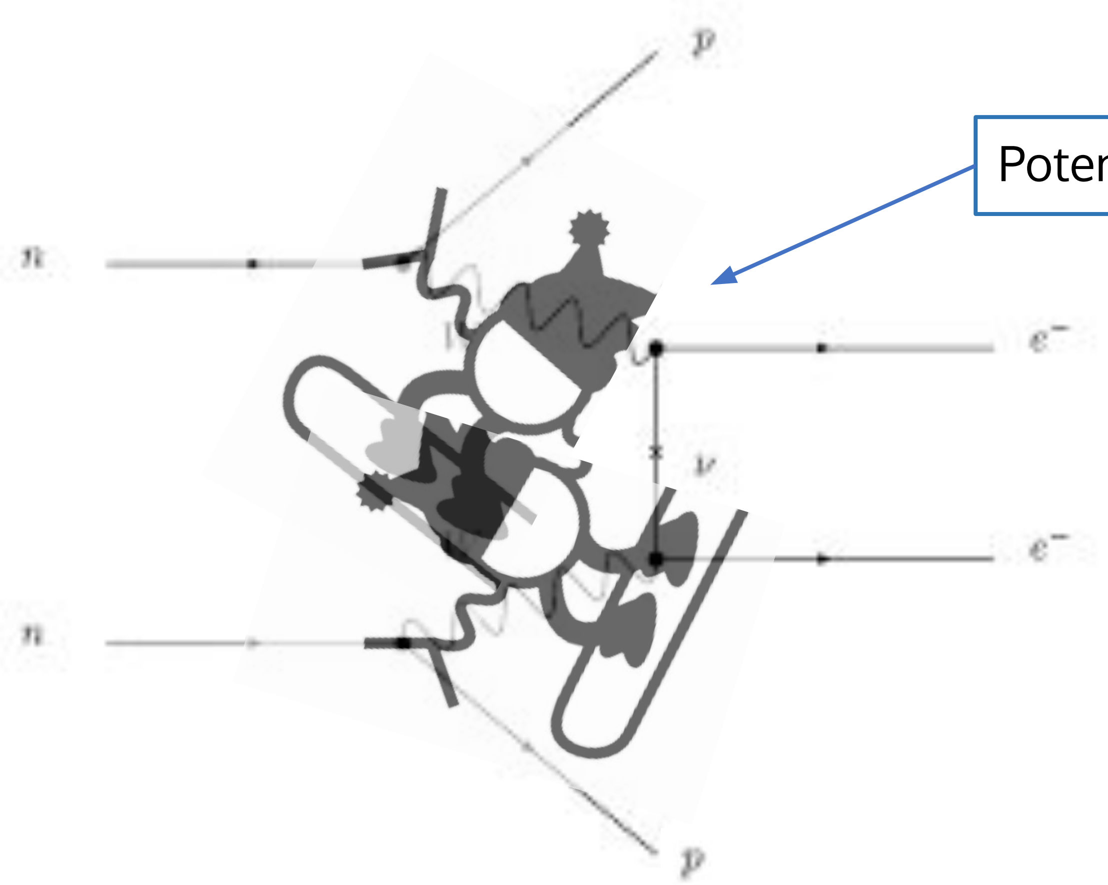
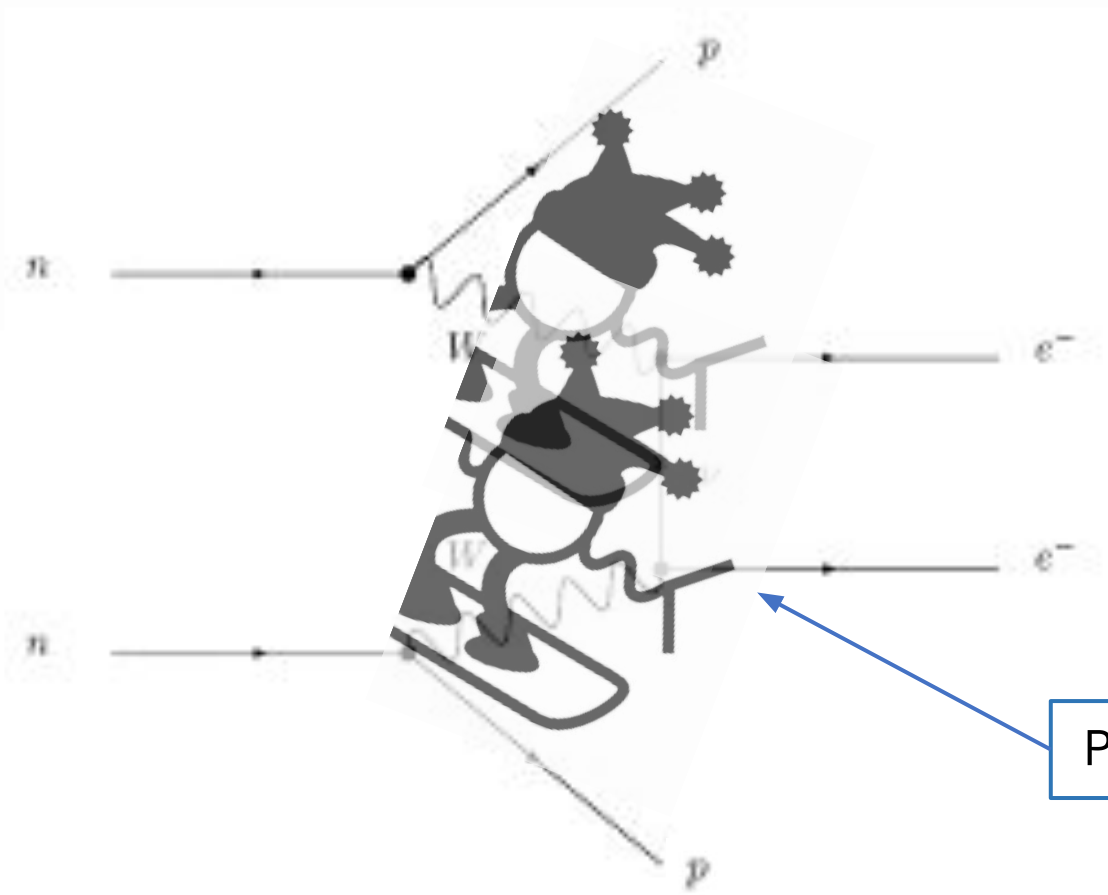
How would 0νββ even work?



Potential 0νββ mechanism #1

How would 0νββ even work?



Potential 0νββ mechanism #2

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

Particle physics community searching for physics beyond the standard model

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

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

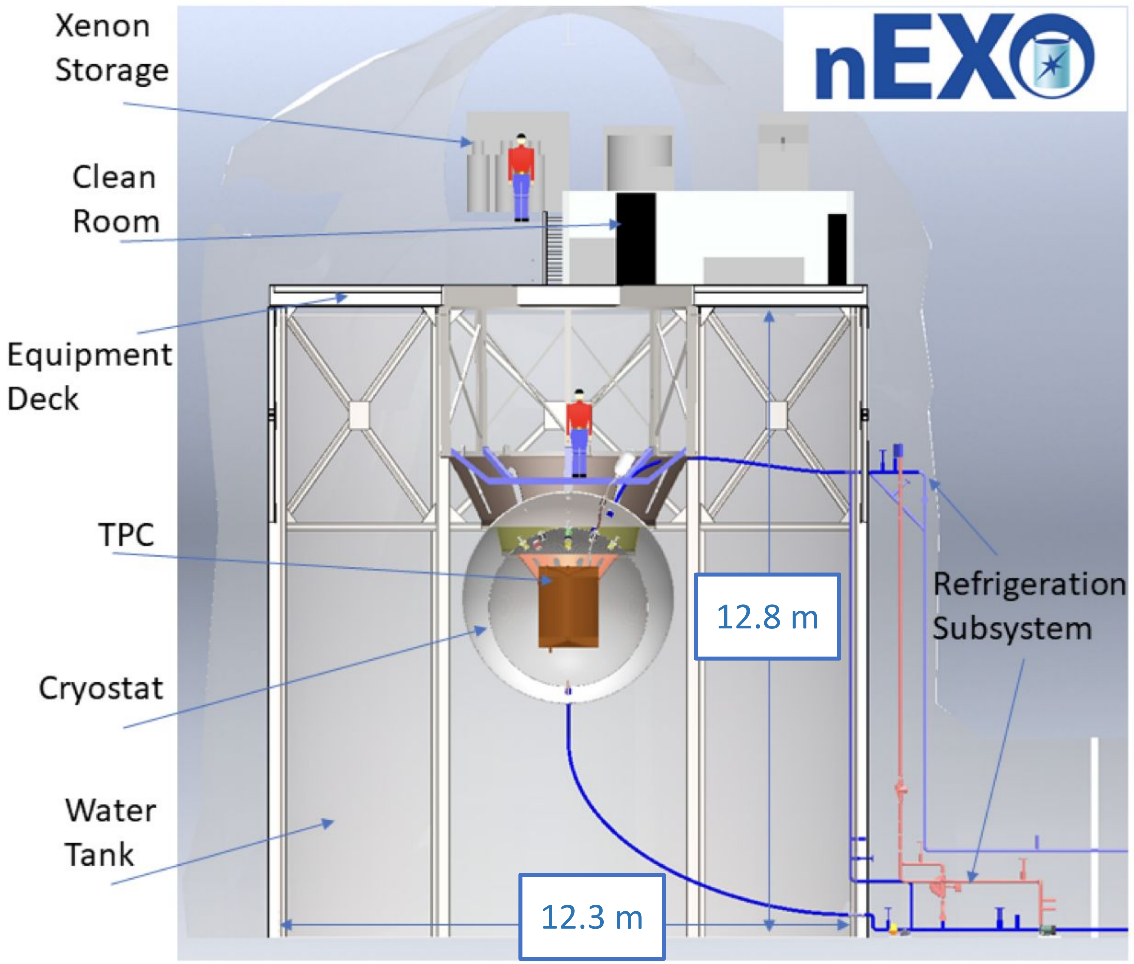
What is nEXO?

nEXO is a **proposed experiment searching for 0νββ**

currently in the conceptual design stage:

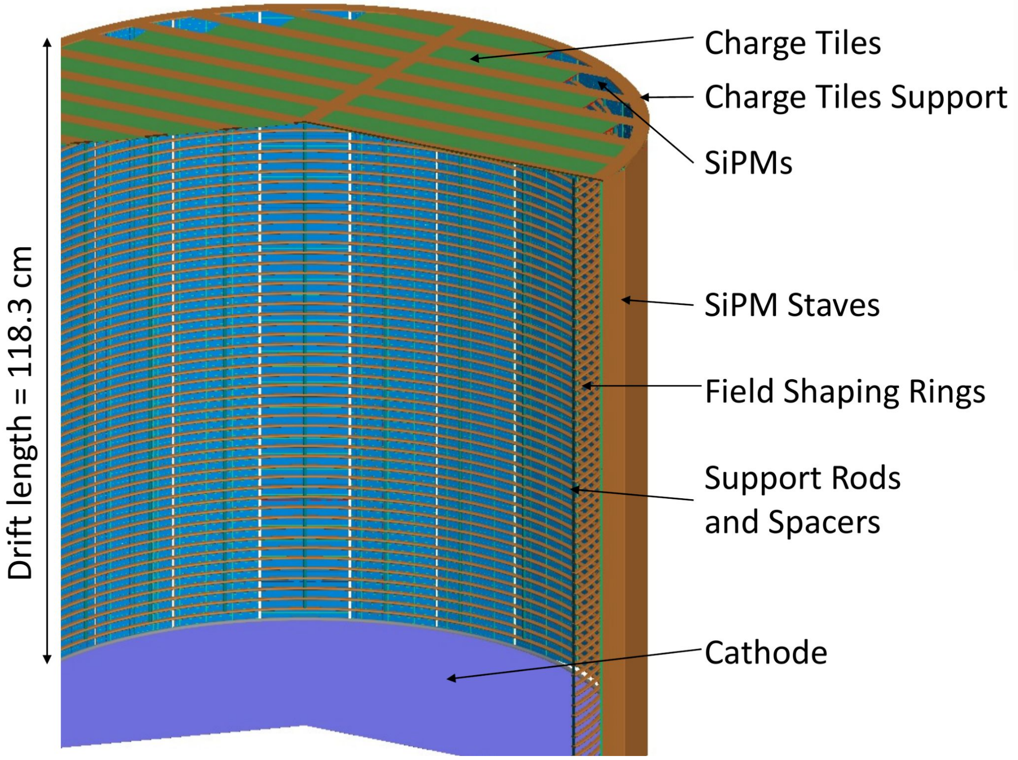
funding for the nEXO project from U.S. DOE has started to flow!

- 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 for control run in case of discovery



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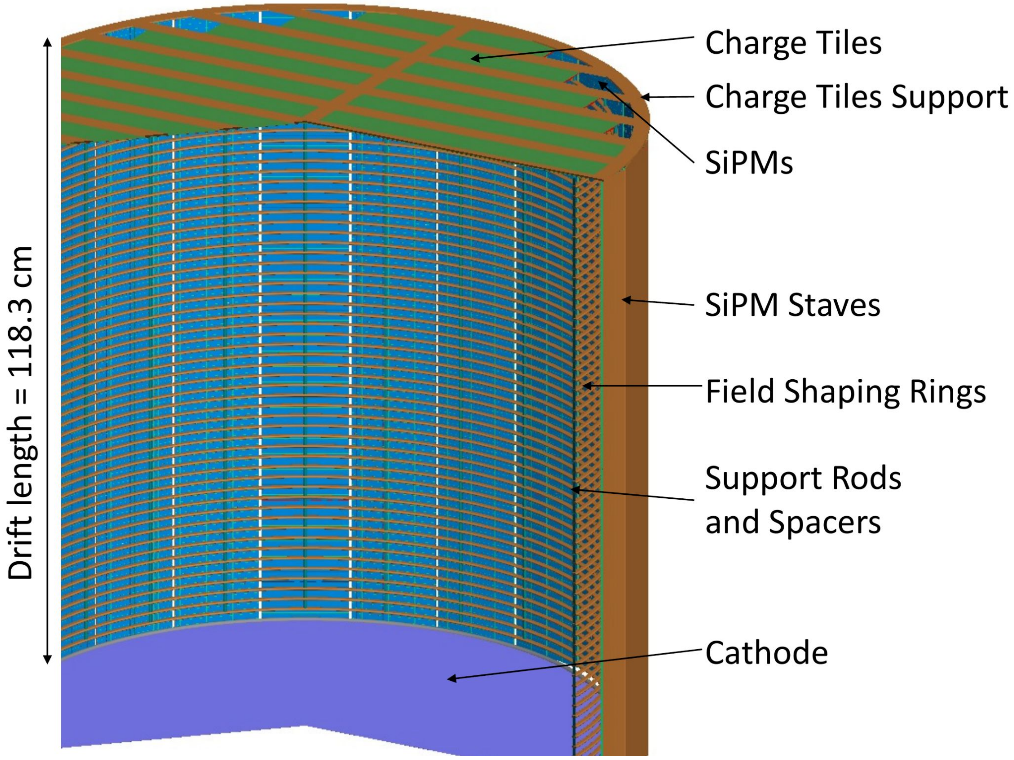

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  - Less sensitive to background fluctuations
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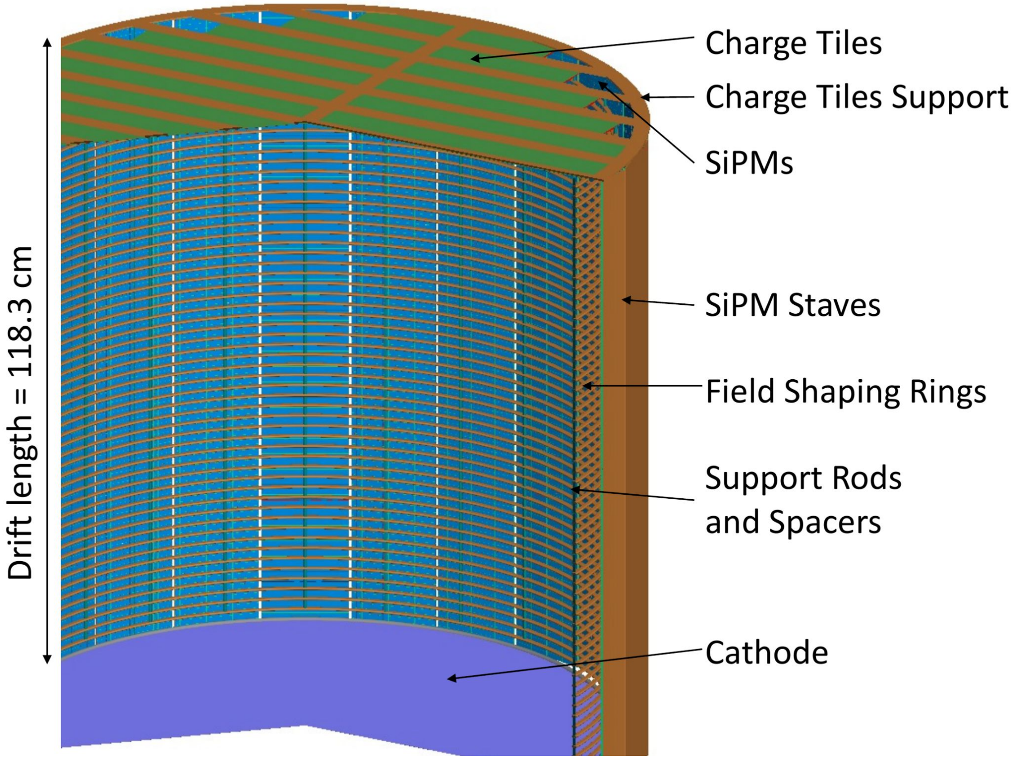
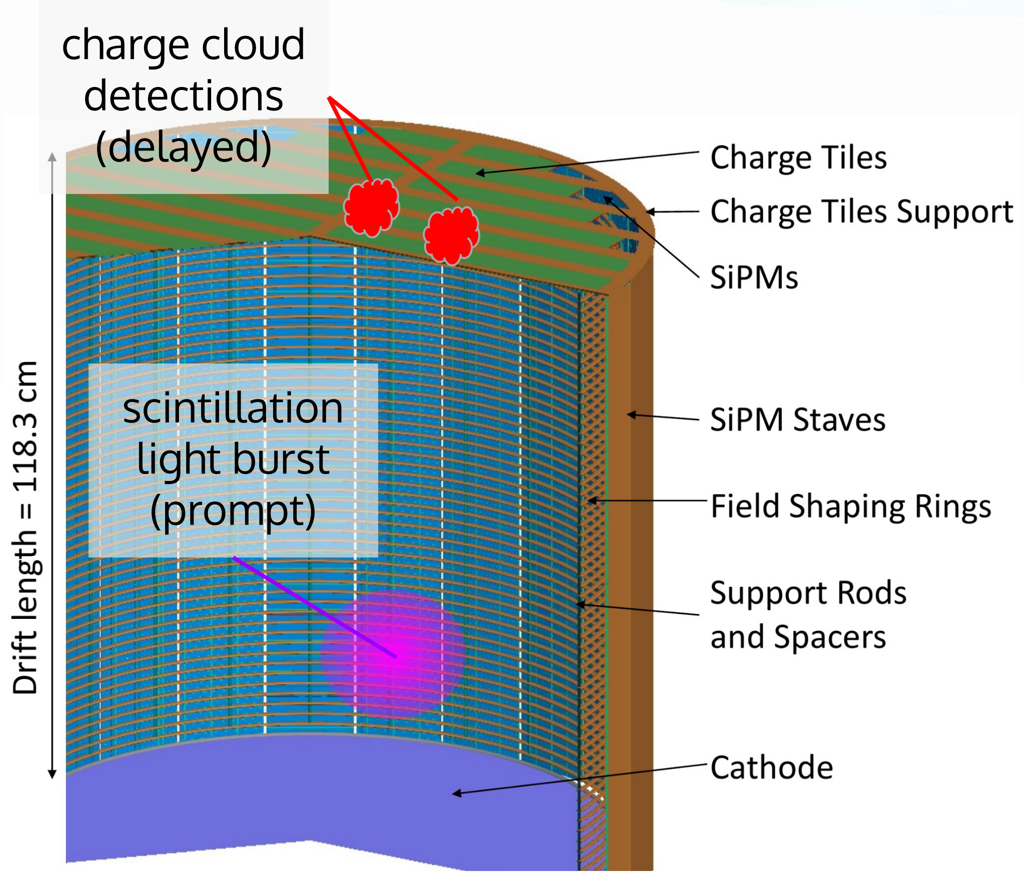
- Possibility for control run in case of discovery
  - use unenriched xenon & repeat the experiment!



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 in a 400 V/cm E-field drift to the anode
- Combination of light + charge readout gives us…
- Novel sensing and readout technology



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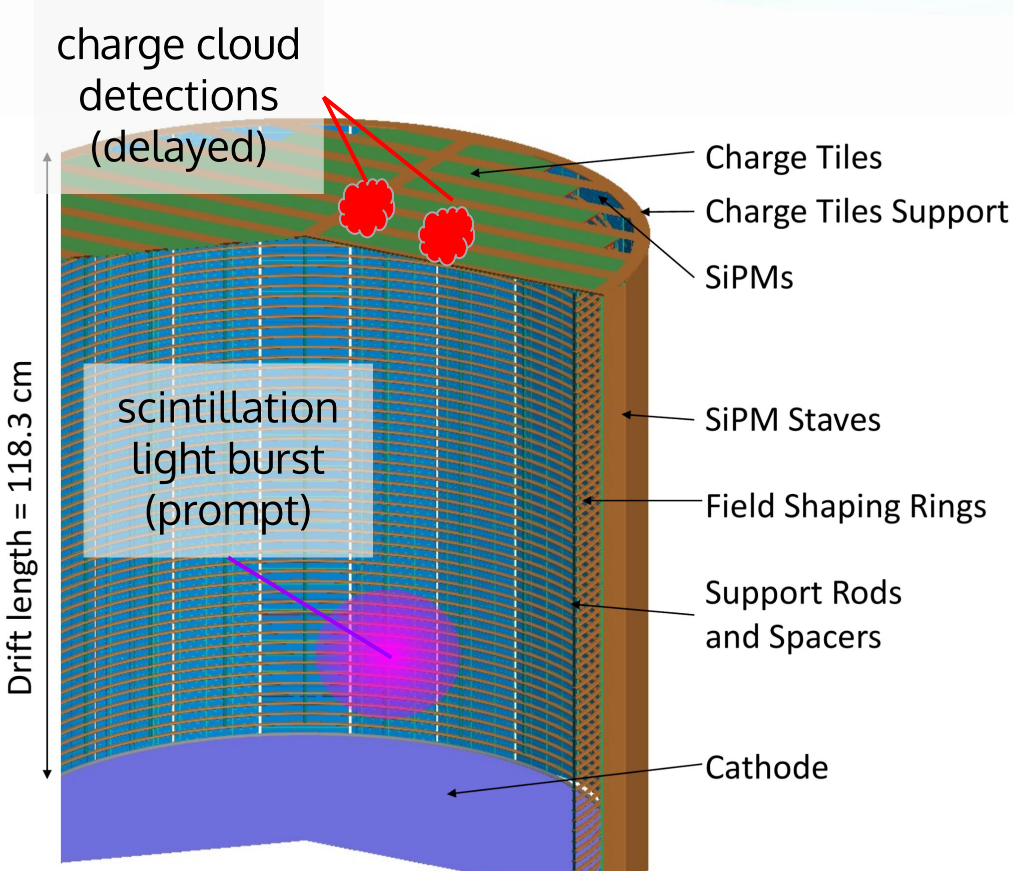

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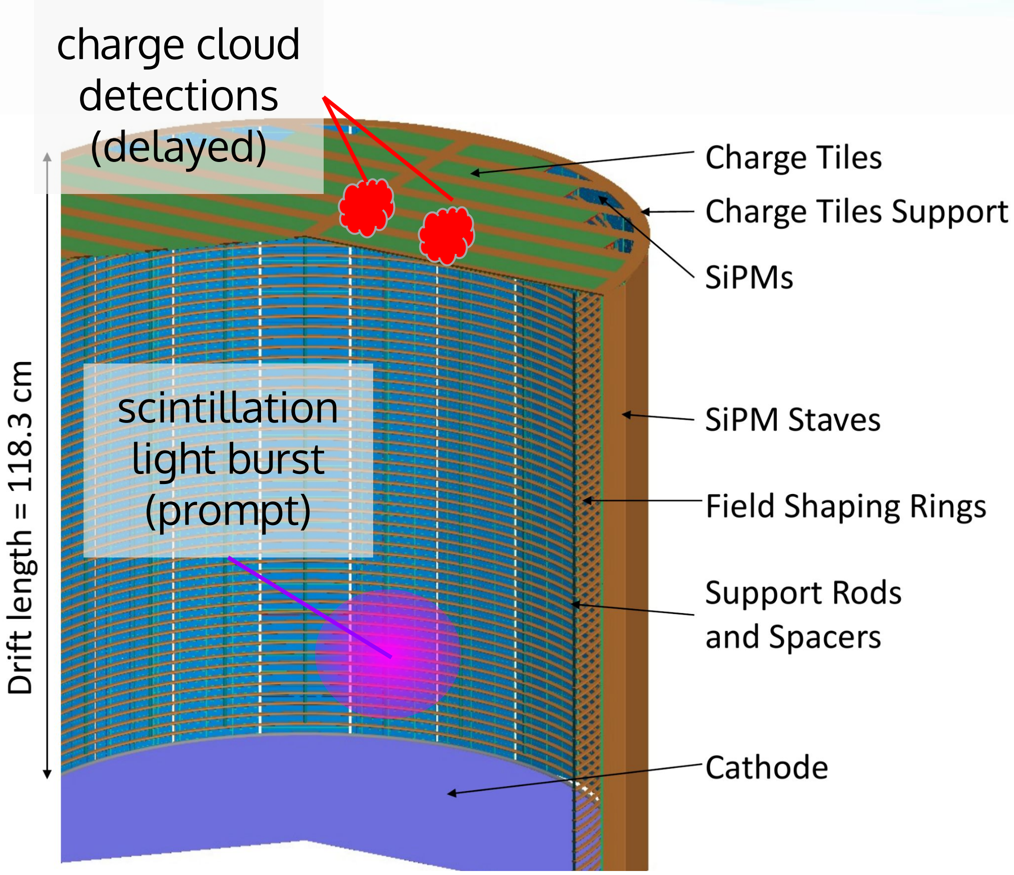
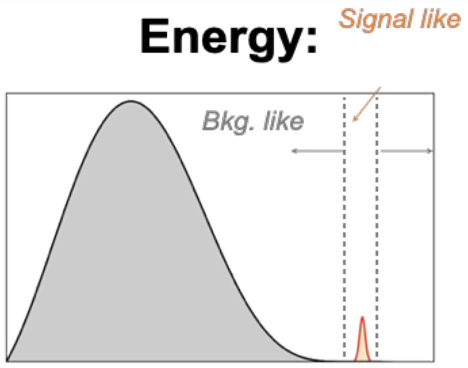
  - scintillation light is readout with silicon photomultipliers (SiPMs) $\longrightarrow$ see next talk by B. Chana!
  - drifted charge is collected using custom-made segmented tiles

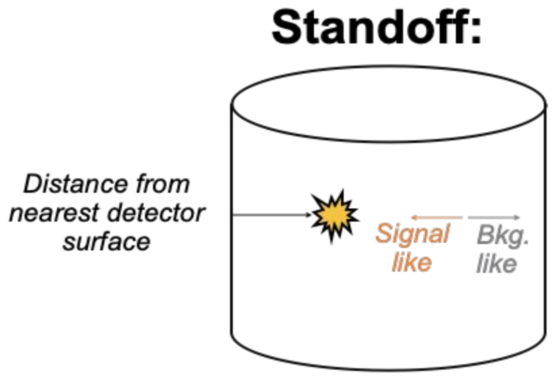


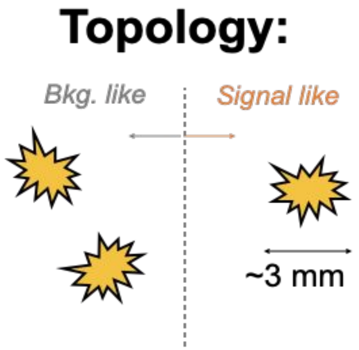
Multiparameter Analysis

A 3D Profile-likelihood Fit

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







Eliminates γ backgrounds

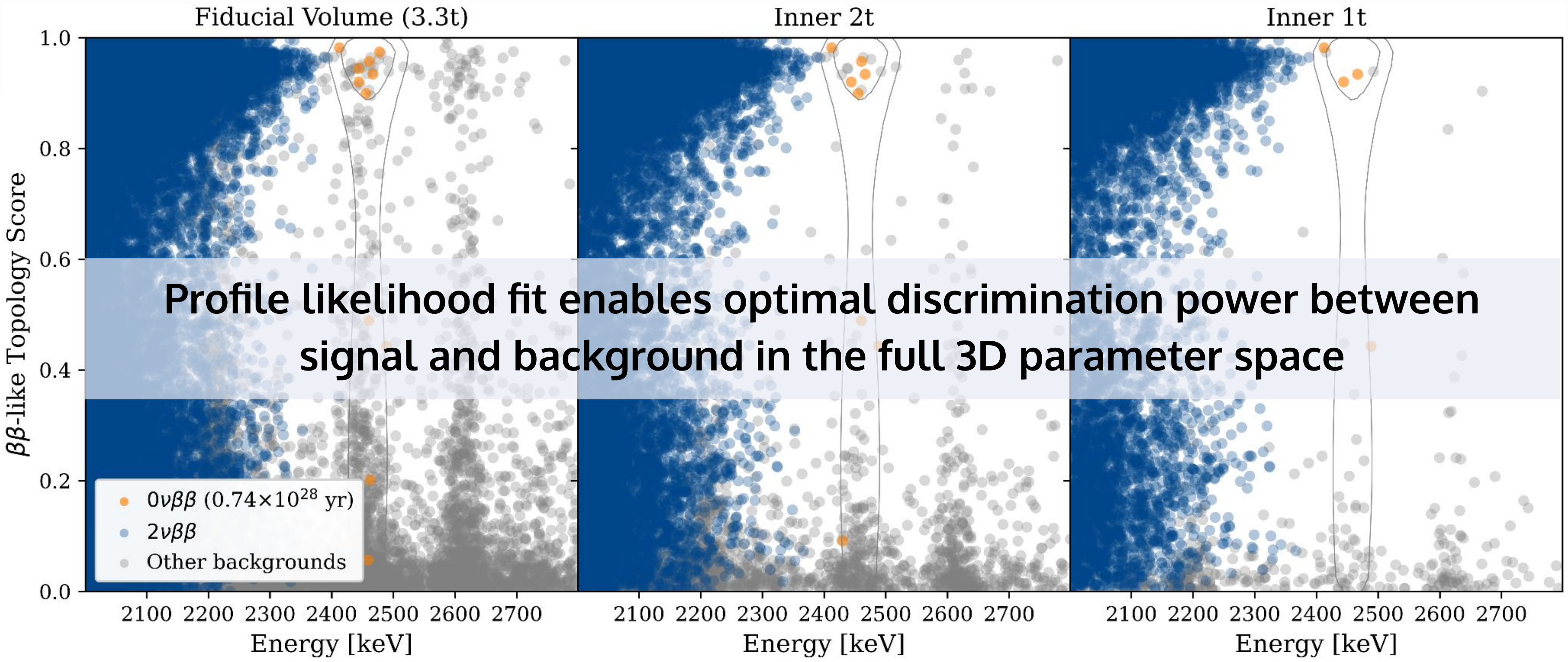
Eliminates external backgrounds

Eliminates most backgrounds

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 0.74×10^{28} yr half life for $0\nu\beta\beta$ in ^{136}Xe (3σ discovery)



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

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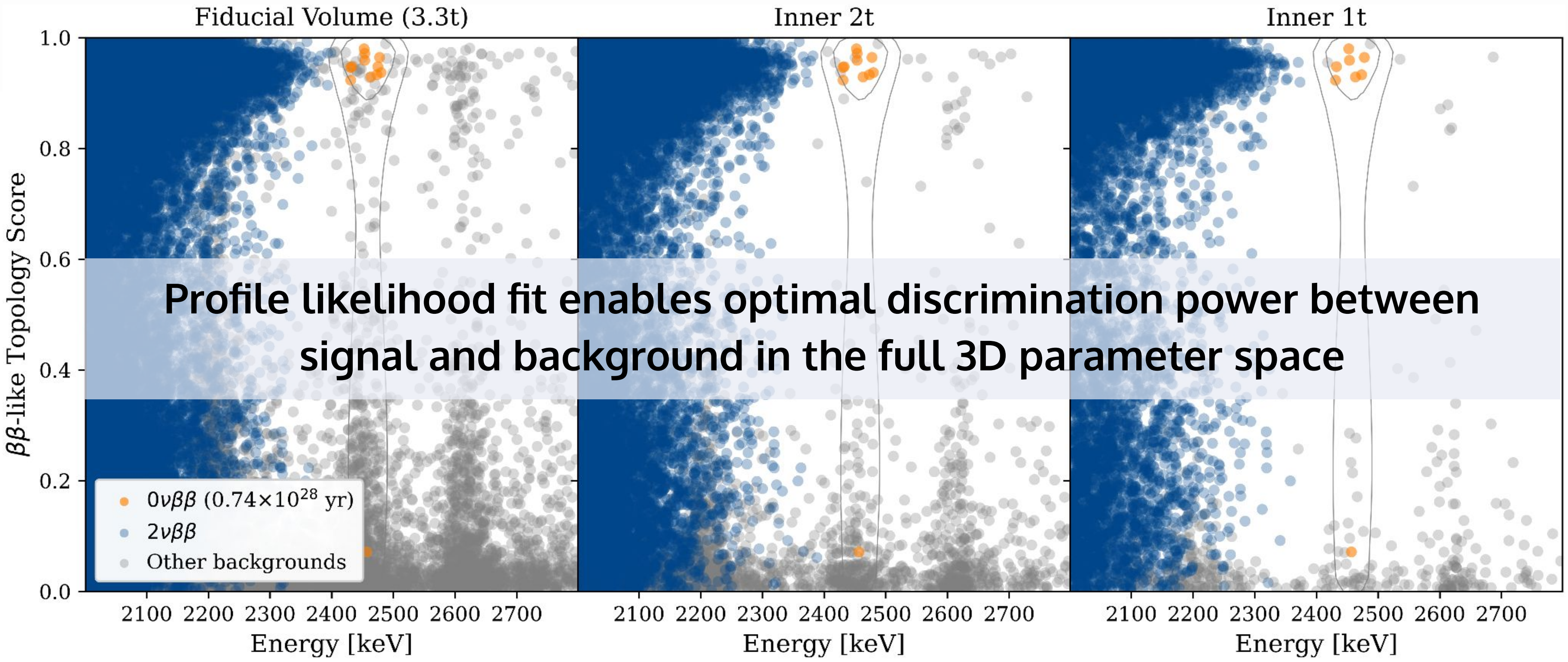

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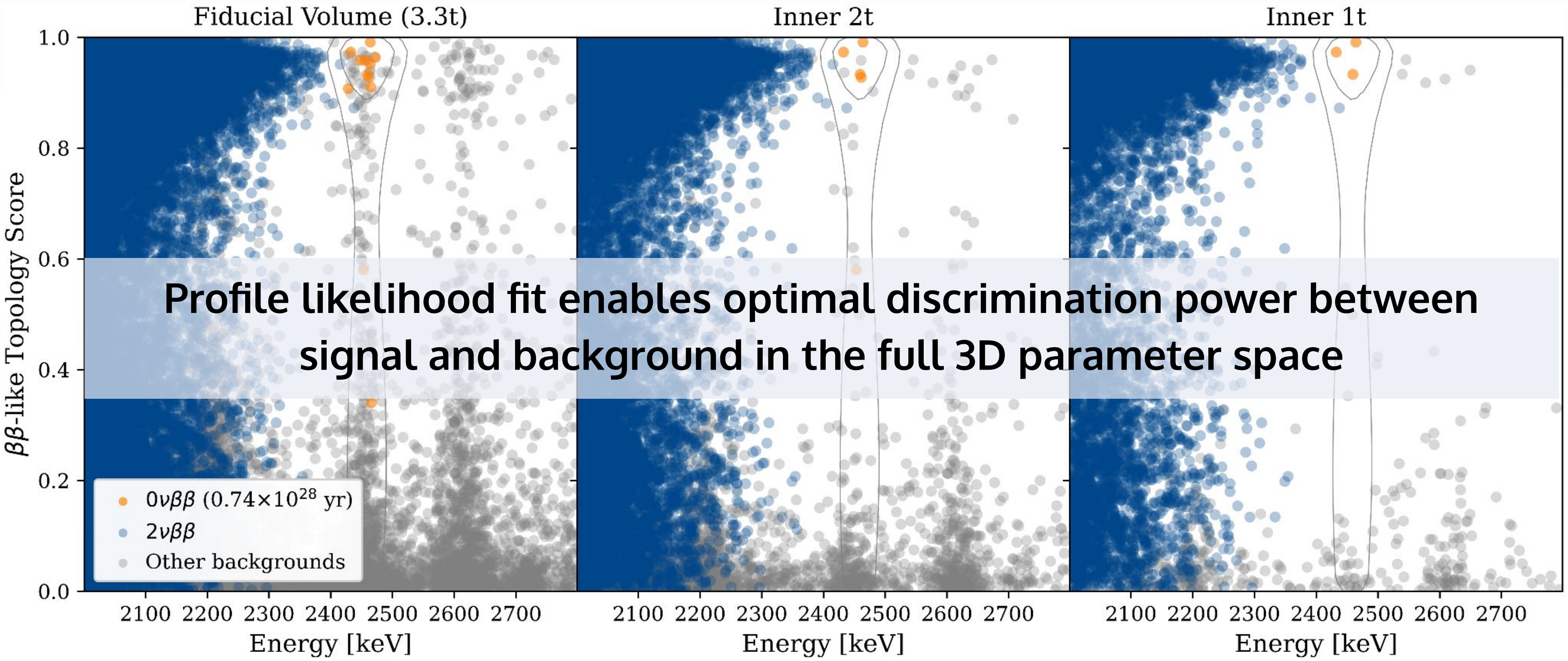
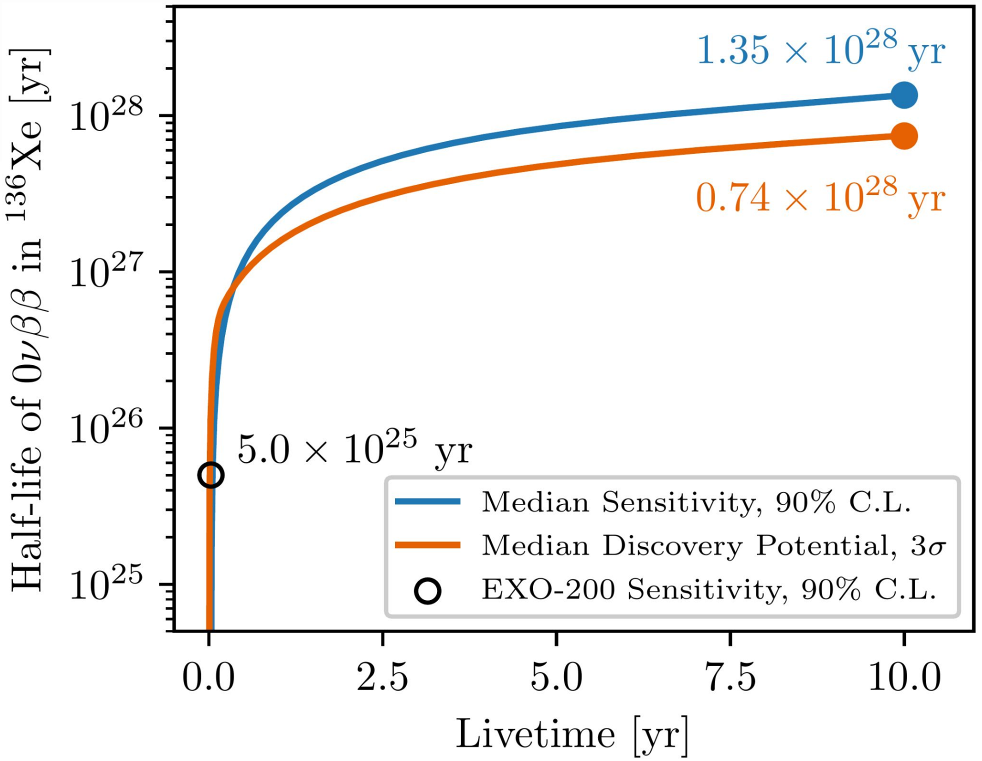


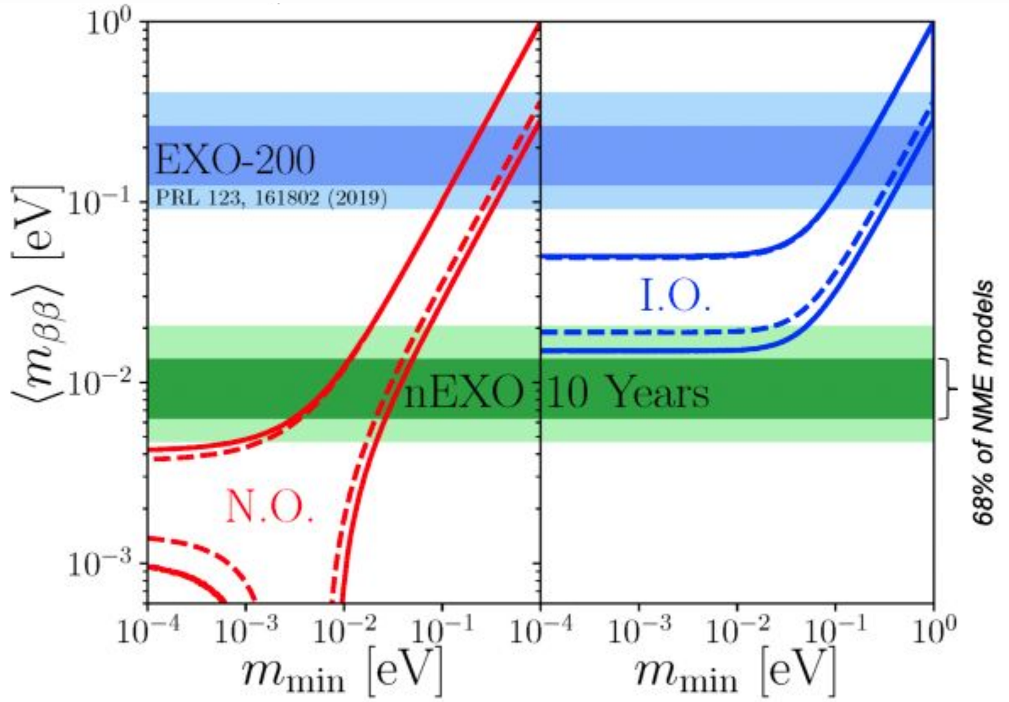
Profile likelihood fit enables optimal discrimination power between signal and background in the full 3D parameter space

Multiparameter Analysis

nEXO's Ultimate Sensitivity to $0\nu\beta\beta$ and $\langle m_{\beta\beta}\rangle$

- In 10 years of data: **sensitivity to $0\nu\beta\beta$ half life is 1.35×10^{28} yr** (90% C.L. exclusion limit)
  - **Effective Majorana mass of the neutrino ≲8 meV**; excludes inverted mass ordering parameter space





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

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What about homogenous β-backgrounds?

Where do they come from?

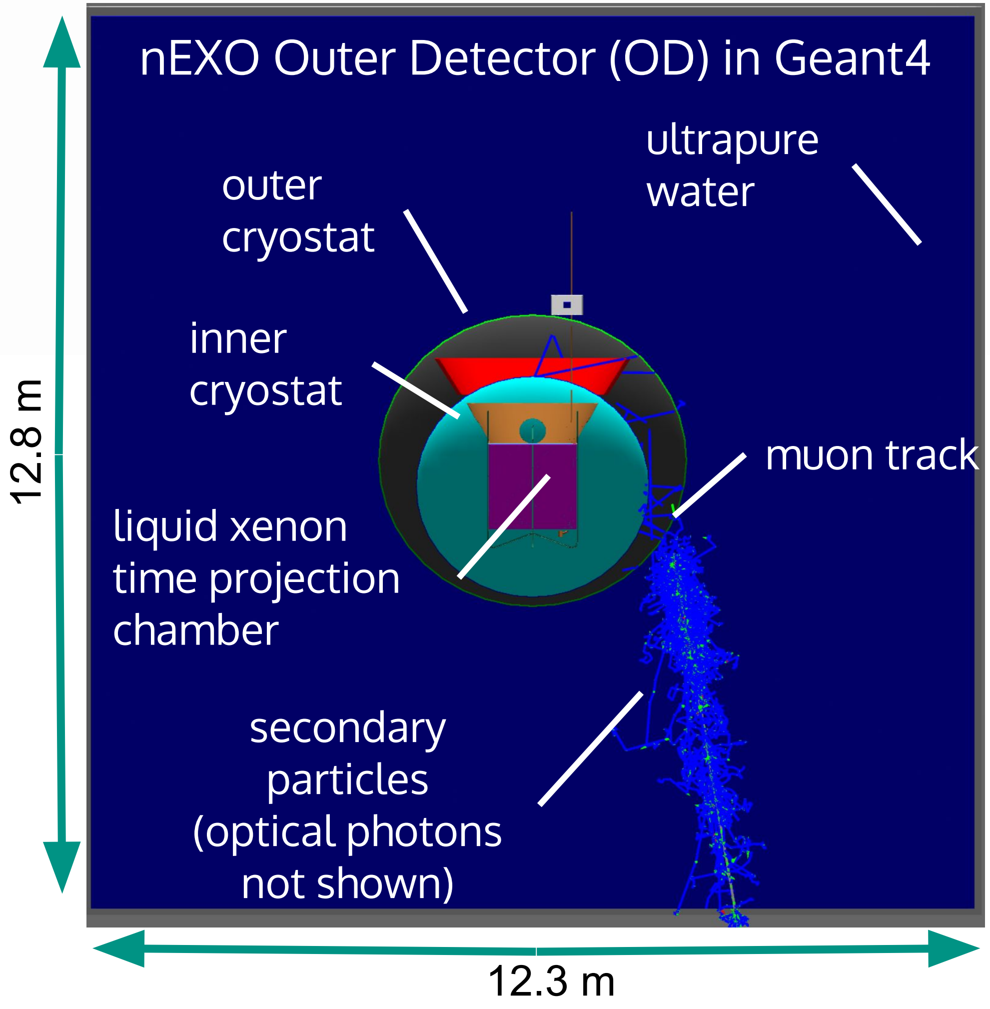
Eliminates γ backgrounds

Eliminates external backgrounds

Eliminates most backgrounds

Cosmogenic Backgrounds

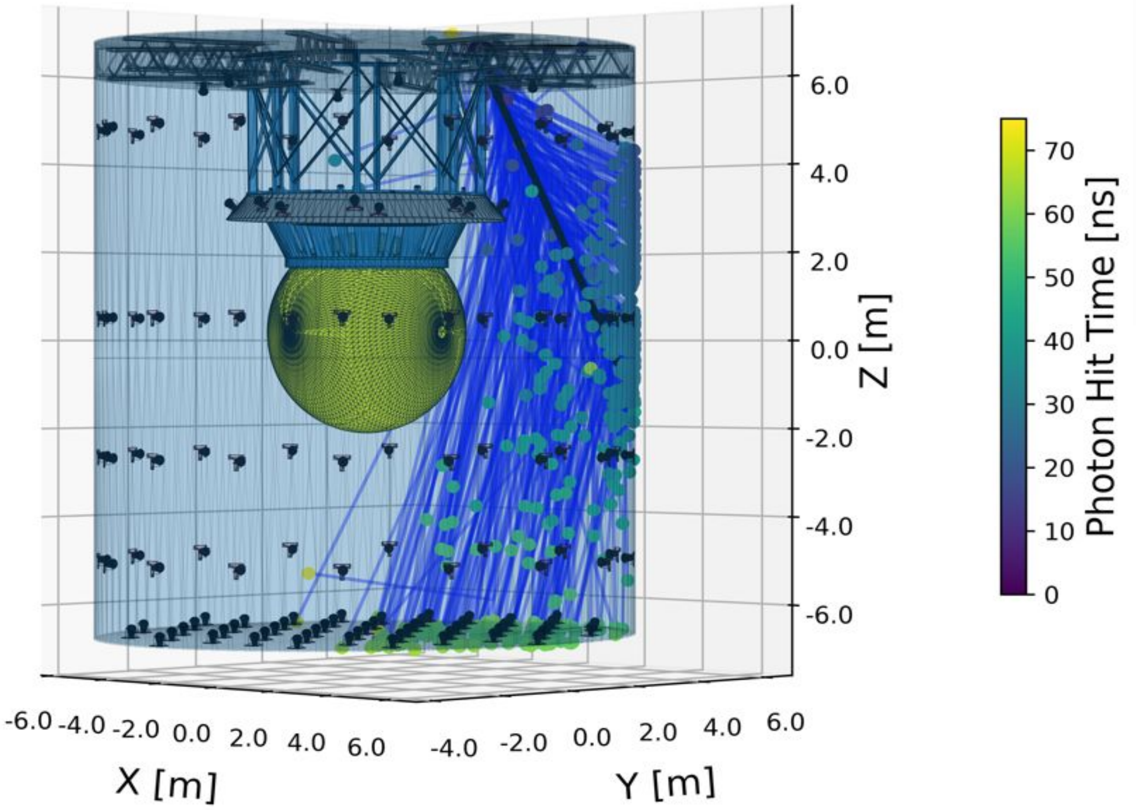
- nEXO is **anticipated to be placed 2 km underground** at SNOLAB
  - 2 km of rock above shields nEXO from vast majority muons
- Residual muons are high energy E_μ ~ 350 GeV
  - High energy **μ disintegrate nuclei in the rock**, releasing many neutrons
  - **Neutrons capture on and activate nuclei in the detector**, distributing them ~uniformly in the TPC
- **Activation products can β-decay some time later** and mimic a $0\nu\beta\beta$ signal, e.g. ^{137}Xe



Cosmogenic Mitigation Strategy

nEXO Muon Veto System

- **Tag muons by their Cherenkov emission** as they traverse through a large water tank
  - Precise **muon timing allows a ~10 ms TPC veto** to remove any prompt muon-related deposits

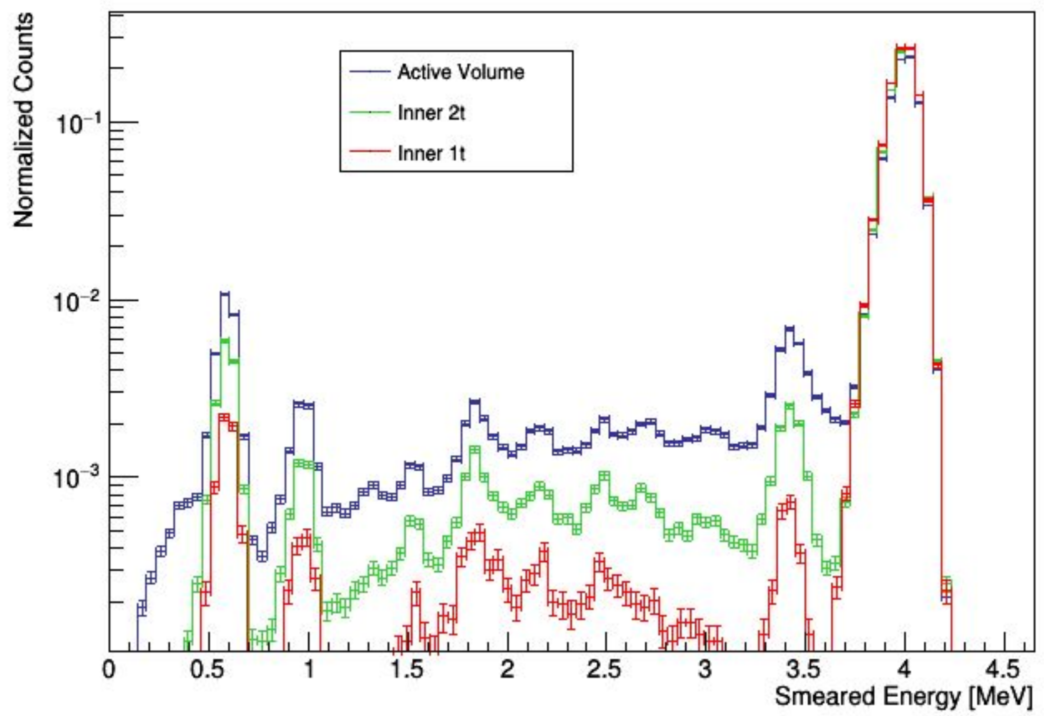


Cosmogenic Mitigation Strategy

Tagging Neutron Captures

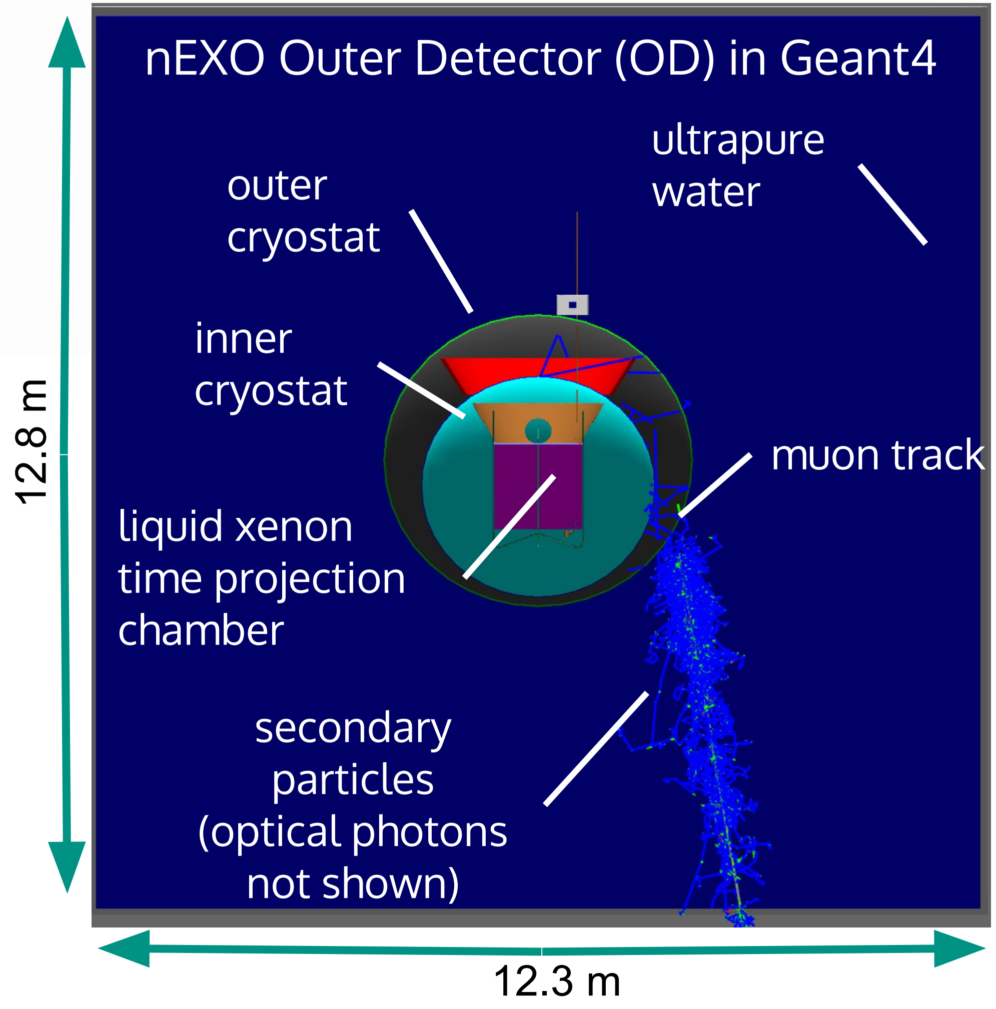
- **Tag muons by their Cherenkov emission** as they traverse through a large water tank
  - Precise **muon timing allows a ~10 ms TPC veto** to remove any prompt muon-related deposits
- **Tag capture gamma cascades** in the TPC, e.g. $Xe^{136}(n,\gamma)$ ^{137}Xe, for a longer veto to **remove cosmogenically activated backgrounds**
  - Nice! Make use of the dense LXe and high-Z nucleus...

^{136}Xe (n, γ) ^{137}Xe spectrum



Geant4 and Physics…

- **Geant4 is a CPU-based Monte Carlo** particle tracking software
- Allows for detailed physics analyses of activation in the TPC, and **ray tracing of optical physics in water (relatively slow)**



Chroma & GPU-based Programming

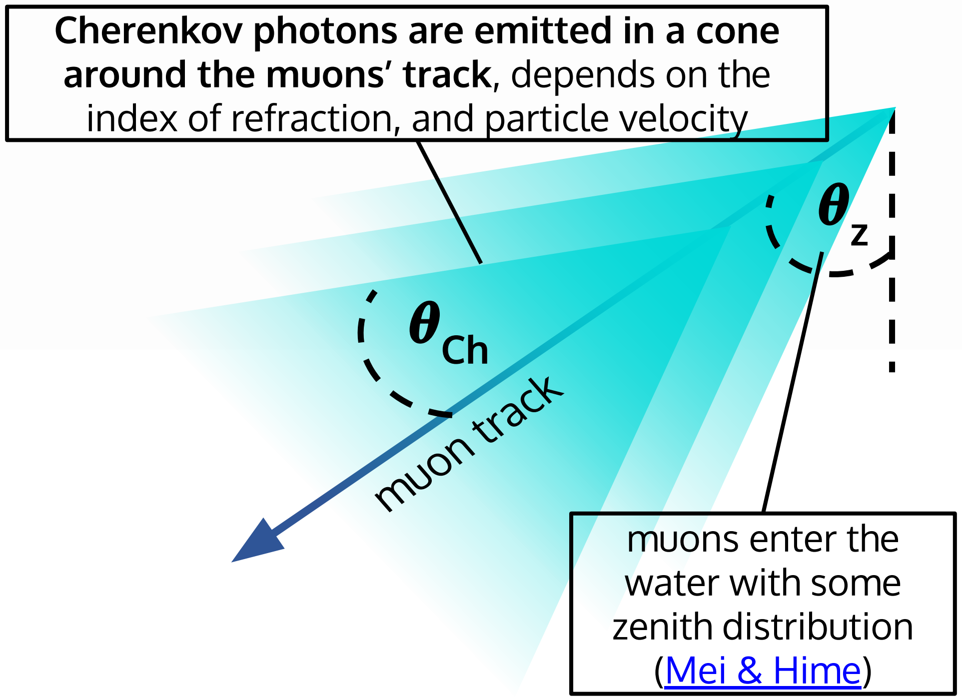
- Chroma is an open-source **GPU-based ray tracing** software
  - CAD files importable directly in geometry, *.STL* formats
  - YAML-definable optical properties
  - custom light sources can be implemented
- Parallelized ray tracing and propagation of light
  - ~100x computational speed increase relative to Geant4

Chroma & GPU-based Programming

- We have **programmed muon Cherenkov physics into Chroma** as a custom light source

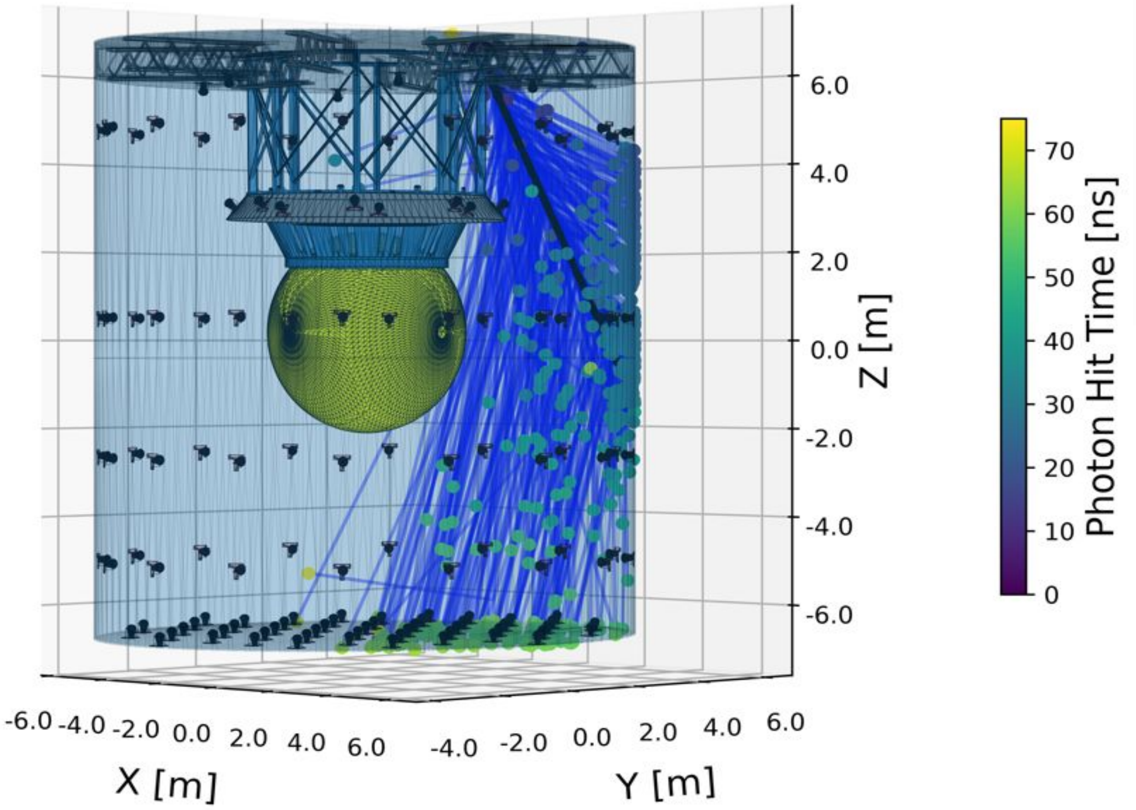
$$\frac{\partial^2 E}{\partial x\,\partial \omega} = \frac{q^2}{4\pi}\mu(\omega)\omega\left(1 - \frac{c^2}{v^2 n^2(\omega)}\right)$$

Frank Tamm formula: defines the Cherenkov photons' frequency spectrum and photon emission/unit length



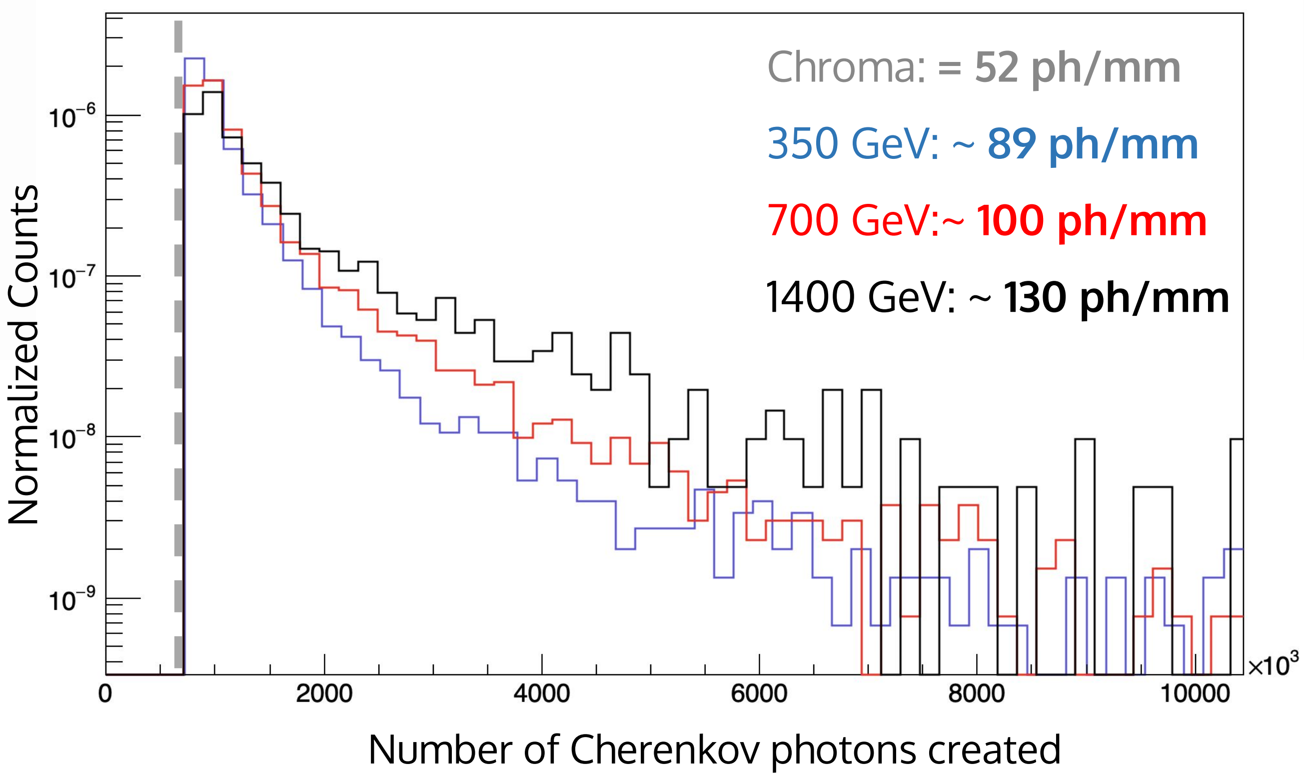
Chroma & GPU-based Programming

- **Parameterized underground muon distributions** allow for rapid turnaround of PMT placement, optical property studies…



Light Yields as a Function of Energy

- Mean overall photon yield increases with muon energy
  - 350 GeV : 1.14x10^6 ~ **89 ph/mm**
  - 700 GeV : 1.3x10^6 ~ **100 ph/mm**
  - 1400 GeV : 1.65x10^6 ~ **130 ph/mm**
- Chroma result is consistently lower regardless of muon energy
  - Fixed at ~ **52 ph/mm** with no spread
  - Does not include muon shower physics, secondary charged particles ($e^{\pm}$, $\pi^{\pm}$, p^{+}...)



Distribution of photons produced from μ^- passing vertically down through the full nEXO Outer Detector (shower physics on, Geant4 v10.5 Shielding physics list + Cherenkov). Chroma result is overlaid in dashed line.

EM & Hadronic Shower Production

- Spallation neutrons tend to come with large hadronic showers
- Hadronic showers extend ~1 m laterally from the muon track
  - EM showers spread ~0.1 m laterally

PHYSICAL REVIEW D **91**, 105005 (2015)

Spallation backgrounds in Super-Kamiokande are made in muon-induced showers

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[1]*Center for Cosmology and AstroParticle Physics (CCAPP), Ohio State University, Columbus, Ohio 43210, USA*
[2]*Department of Physics, Ohio State University, Columbus, Ohio 43210, USA*
[3]*Department of Astronomy, Ohio State University, Columbus, Ohio 43210, USA*
(Received 16 March 2015; published 5 May 2015)

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.91.105005

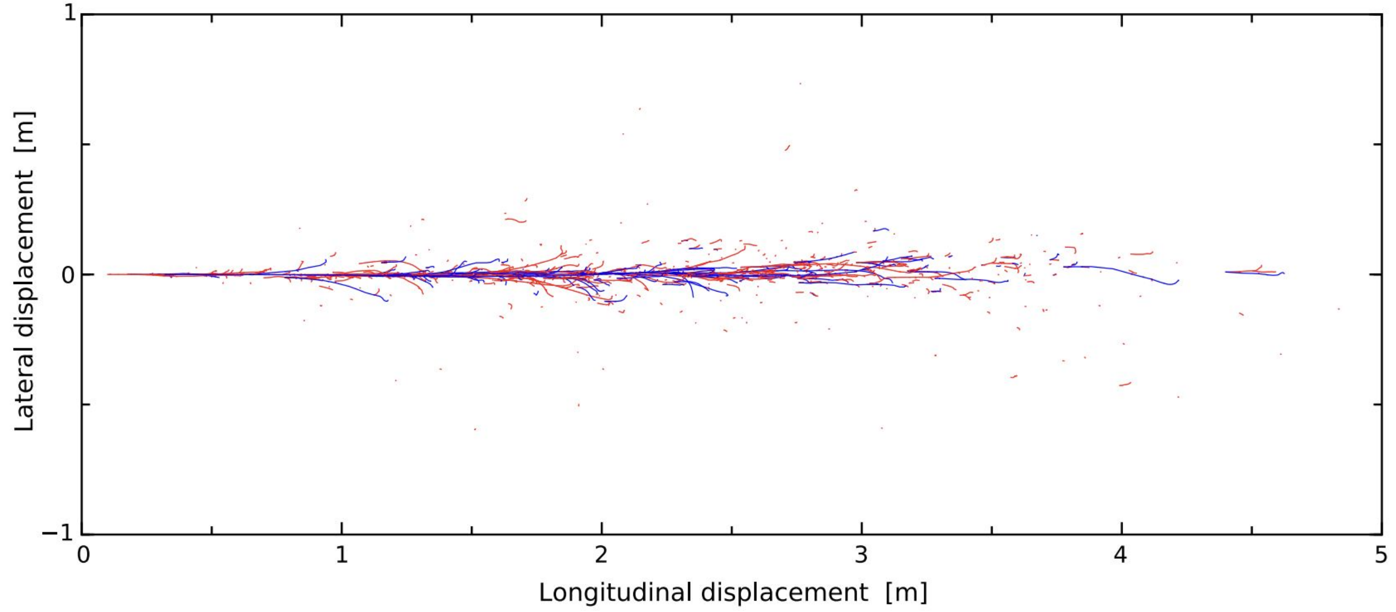


FIG. 1 (color online). An electromagnetic shower in water initiated by a 10 GeV electron. The red lines are electrons, and the blue lines are positrons. The x and y axis ranges are chosen to not distort the relative lateral and longitudinal scales.

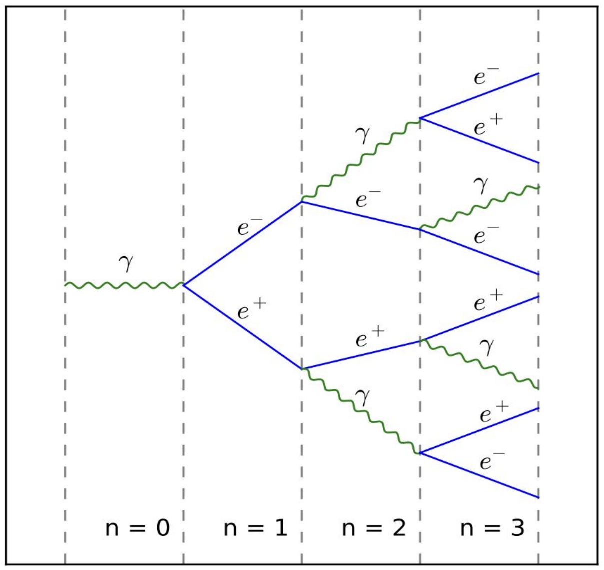
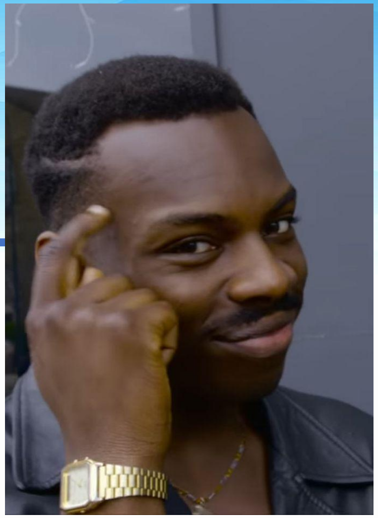


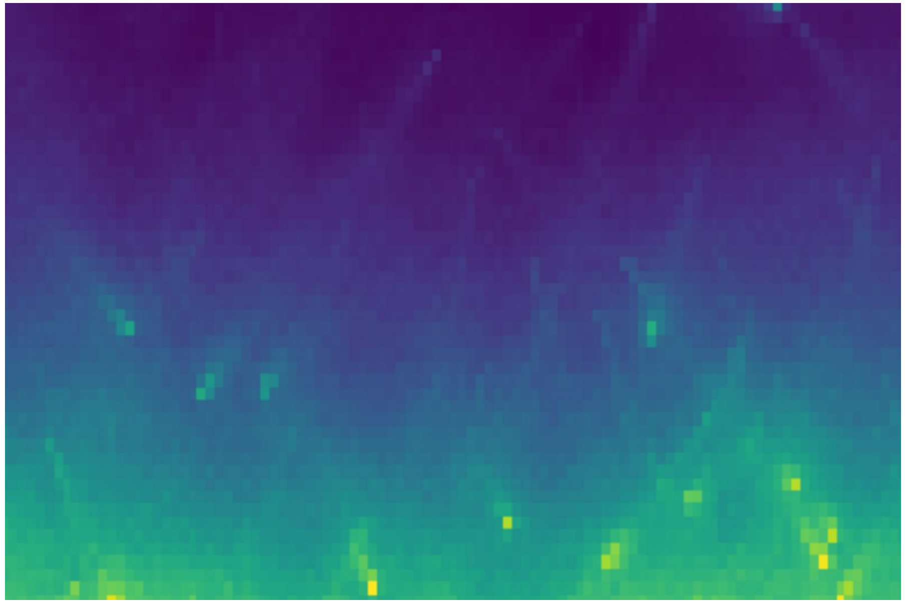
FIG. 2 (color online). Schematic diagram of Heitler's model for electromagnetic showers in the growing phase, which continues until the particle energies are below E_c.

Food for thought



- **Can we parameterize the shower physics sufficiently well**
  - so that we can obtain similar photon production distributions in Geant4, Chroma, and other GPU-based softwares?
  - retain speed advantages from the GPU parallelization?
  - what about the “blurriness” of the resulting Cherenkov ring(s)?

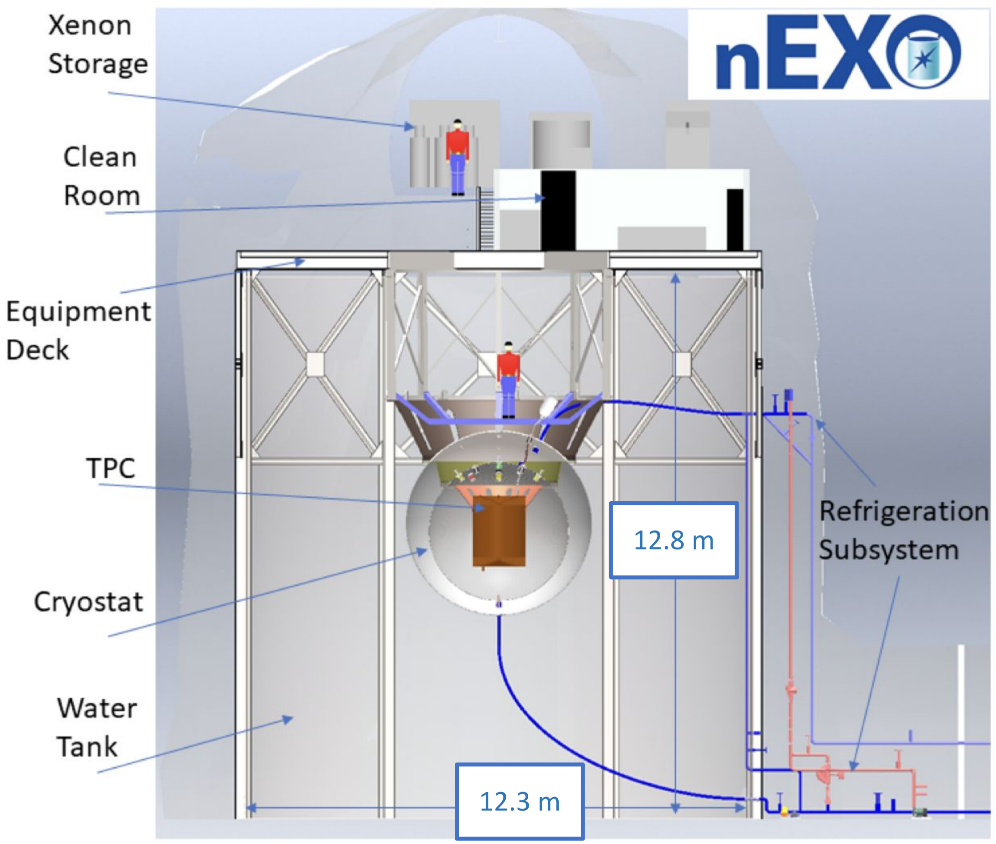
Should these muon showers and other light amplification processes be added into standalone GPU-based programs (Chroma), or should we be pushing GPU capability in Geant4 (G4Opticks)?



Chroma overlay of several muons’ photon hit patterns on nEXO Outer Detector cylindrical wall

Summary

- nEXO is **searching for Lepton Number Violation via 0νββ**
- Tagging muons in the **Outer Detector via their water Cherenkov emission** and **neutron activation in the TPC via their (n, γ) emission mitigates cosmogenic backgrounds**
- We **developed muon Cherenkov physics in Chroma** to hasten our studies on PMT placement & muon veto efficiency
- Results indicate that **Chroma is under-producing photons** (as expected) due to lack of secondary charged particles



Thank you!

nEXO

A lot of Chroma/Muon work done by:
L. Retty, R. Ross, E. Klemets, A. Jamil

Ask me about nEXO DEI Activities:
- Mentorship program
- Climate surveys
- Outreach

Follow us!
@nEXOexperiment

soud.alkharusi@mail.mcgill.ca

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

Supervisors: T. Brunner, D. Haggard

CINP ICPN

SNOLAB

INNOVATION
Canada Foundation for Innovation
Fondation canadienne pour l'innovation

Thank you!

nEXO

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

nEXO Sensitivity

Neutrino Mass Measurement, $\langle m_{\beta\beta} \rangle$

- Half lives of $0\nu\beta\beta$ correspond to an effective Majorana mass of the neutrino $\langle m_{\beta\beta} \rangle$
  - combination of 3 neutrino mass states
  - Assumes dominant $0\nu\beta\beta$ mechanism is light-Majorana neutrino exchange (minimal model)
- $\langle m_{\beta\beta} \rangle$ is isotope-independent, but depends on your choice nuclear matrix element (NME, $M^{0\nu}$) when converting from a half life measurement to neutrino mass
  - $M^{0\nu}$ is the least constrained parameter in the conversion formula below

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

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

Nuclear Matrix Element

Axial coupling, $g_A = 1.27$

Phase space factor

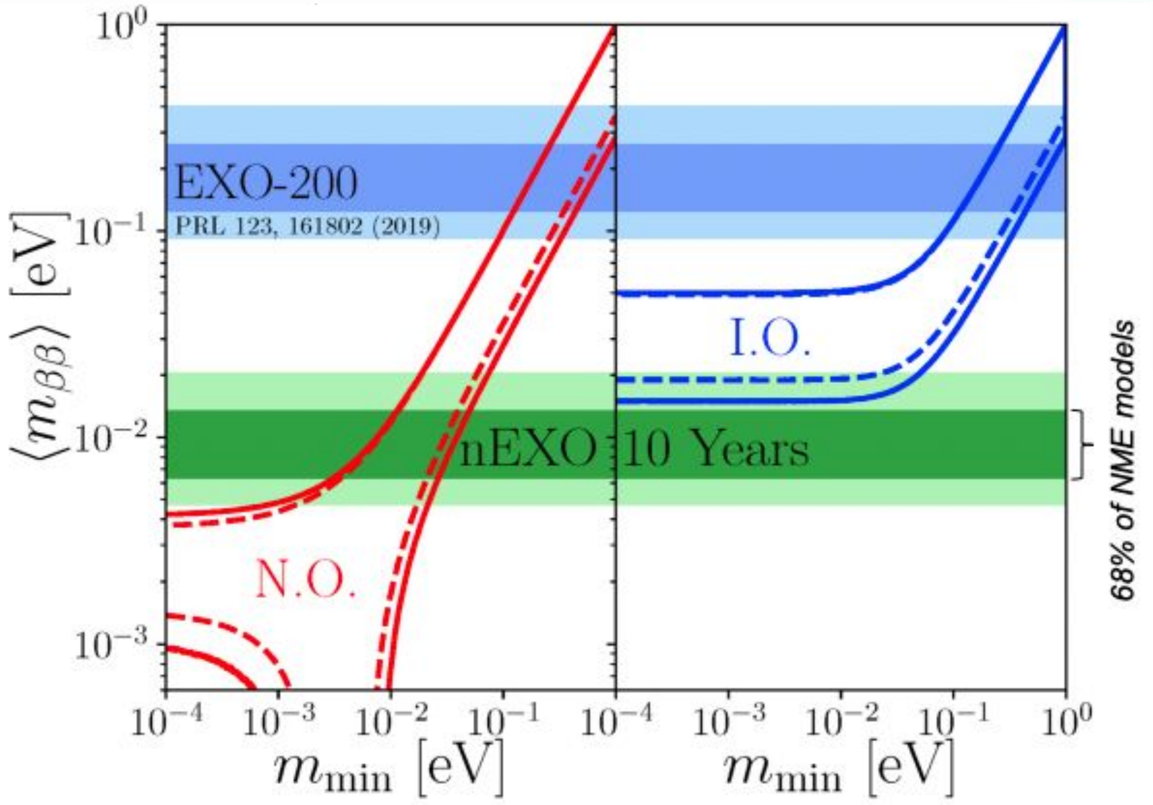
J. Kotila and F. Iachello, Phys Rev C 85, 034316 (2012)

nEXO Sensitivity

Neutrino Mass Measurement

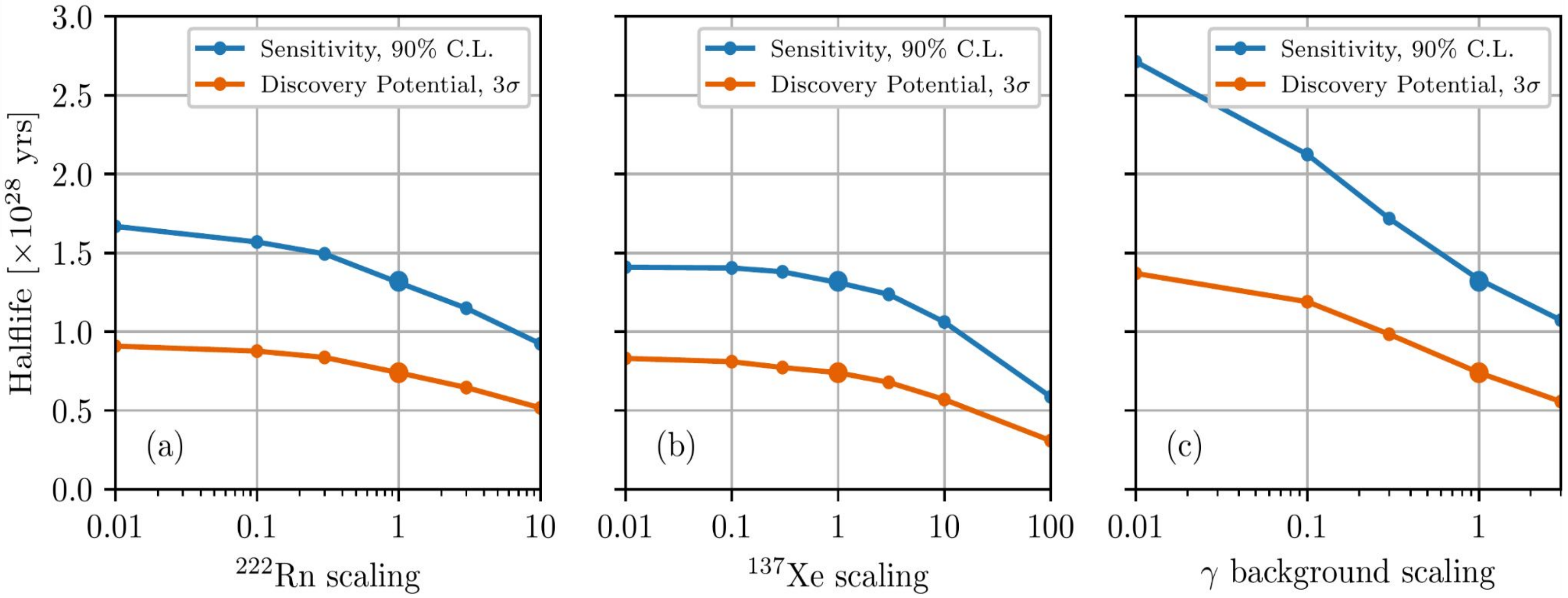
In the event that no $0\nu\beta\beta$ signal is seen in nEXO:

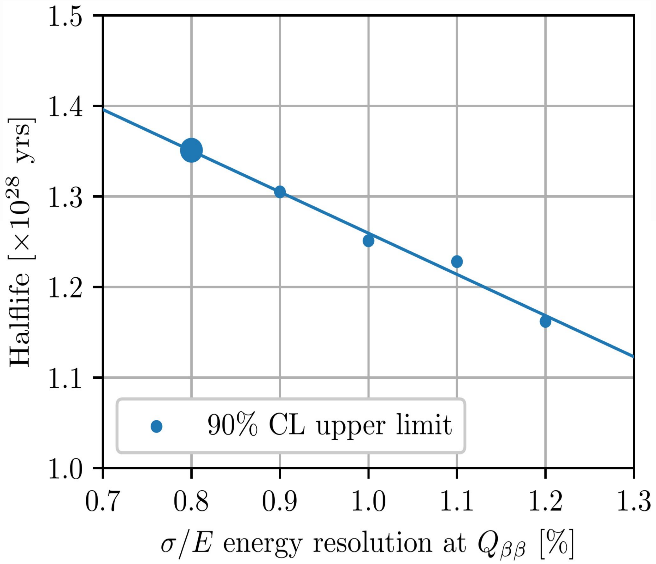
- Half life of $0\nu\beta\beta$ in ^{136}Xe must be **above 1.35 x 10^{28} yr** (90% C.L.)
- **Effective Majorana mass** of neutrinos **$\langle m_{\beta\beta} \rangle$** must be **below ~8 meV** (median NME)
    - Neutrino masses are **much more likely to have normal ordering** (if Majorana)



nEXO Sensitivity Robustness

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

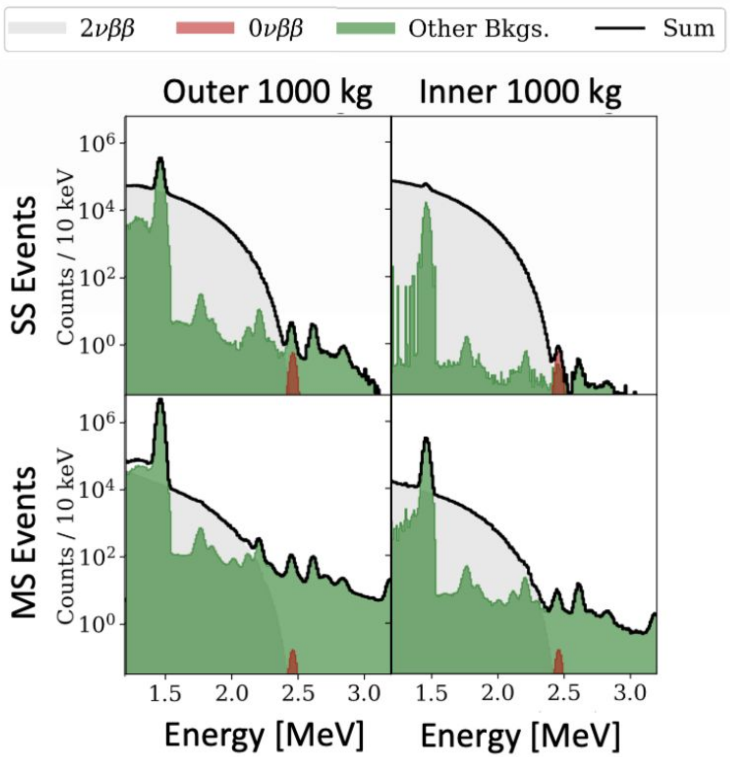




Confidence in the sensitivity estimate arises from a detailed conservative model with measured input parameters

Backup: unknown external background

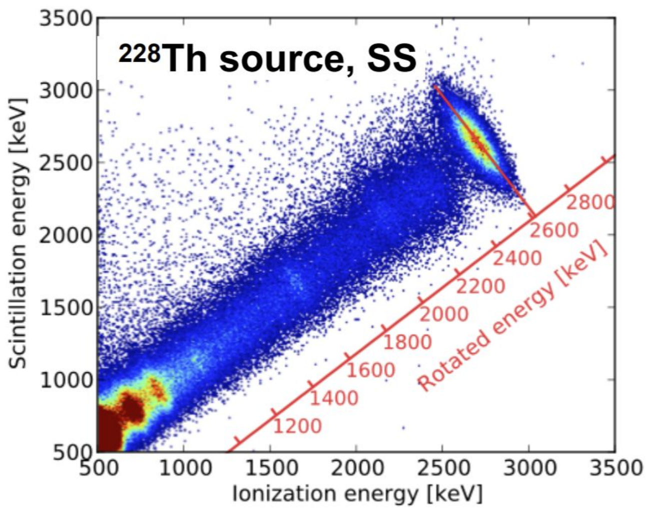
If an unknown decay were strong enough to produce as many SS events in the inner 3000 kg as a 3σ discovery at a half-life of 5.7×10^{27} yr, this decay would produce 271 counts in the MS outer volume, enough to rule out the expected background model at $p < 0.00001$.



Phys. Rev.C 97, 065503 (2018)

Backup: 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.](#)