nEXO

The search for neutrino-less double beta decay using the nEXO experiment: Simulation needs and challenges

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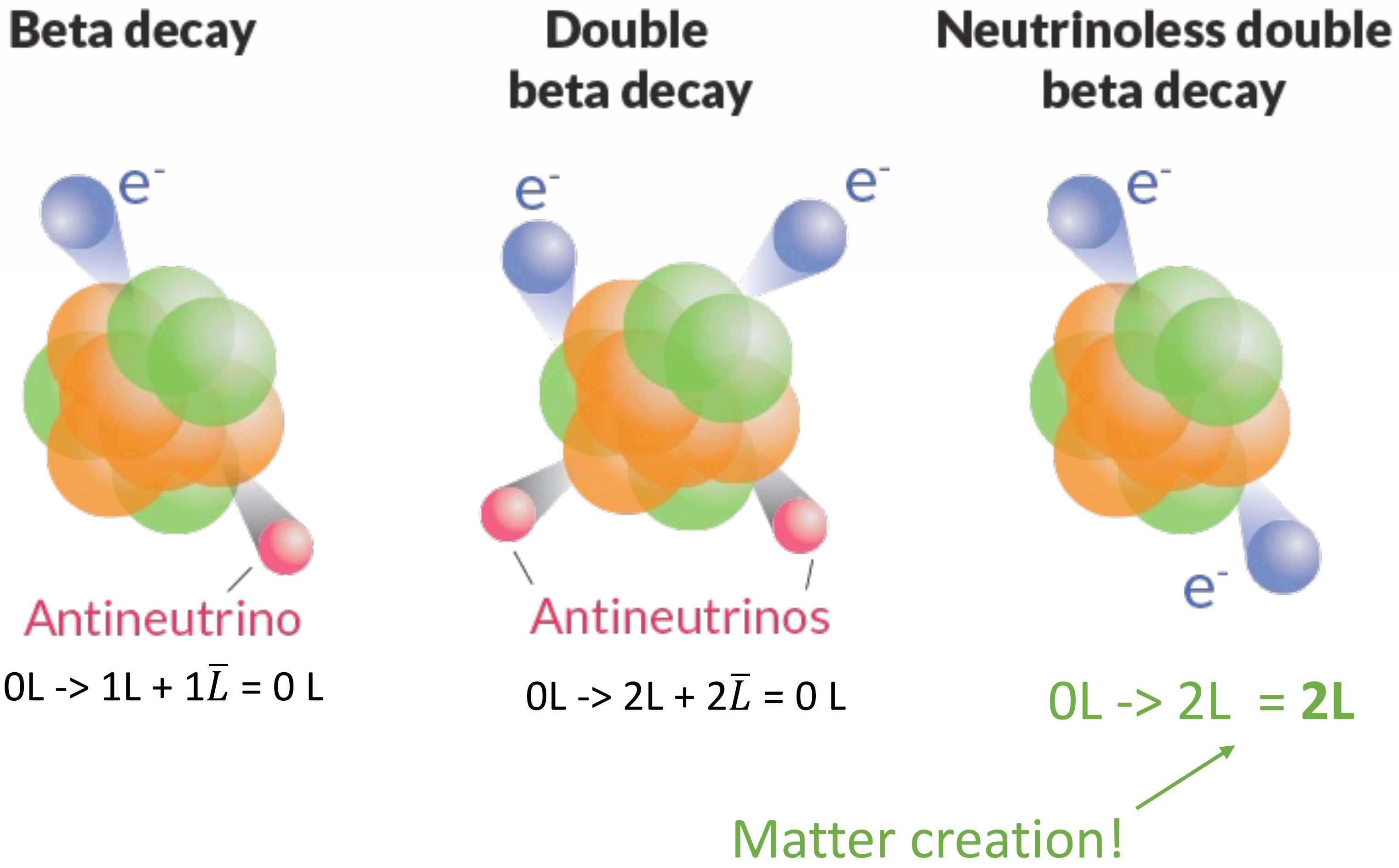
McGill

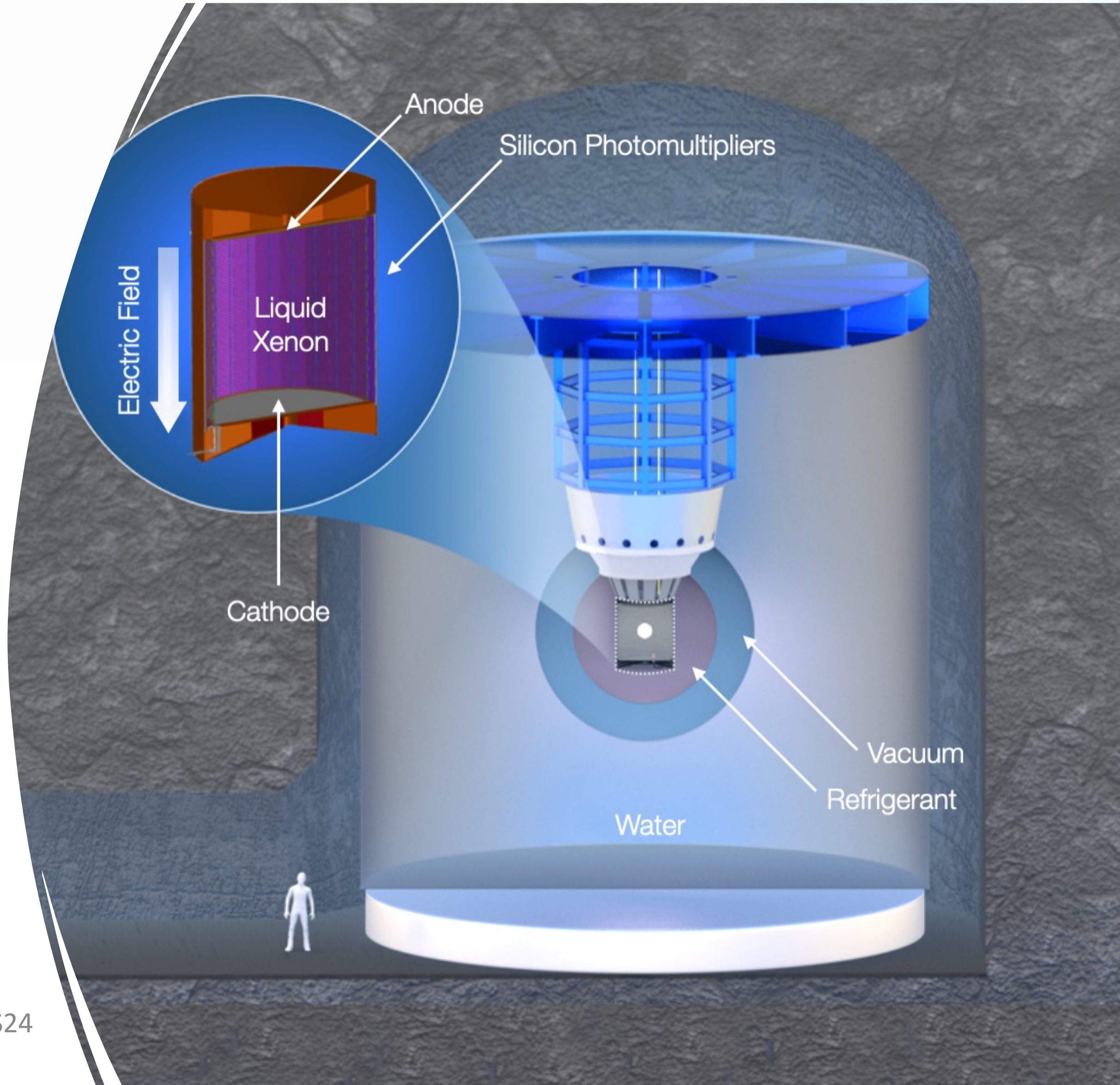
Neutrino-less Double Beta Decay

- Neutrino-less Double Beta Decay (0νββ) is a hypothetical **rare** form of nuclear decay
- Enabled by non-zero neutrino mass
- **Is a lepton number violating process**
  - Majorana Fermions are a new class of particles
- Provides insight into the fundamental nature of neutrinos and the origin of their mass



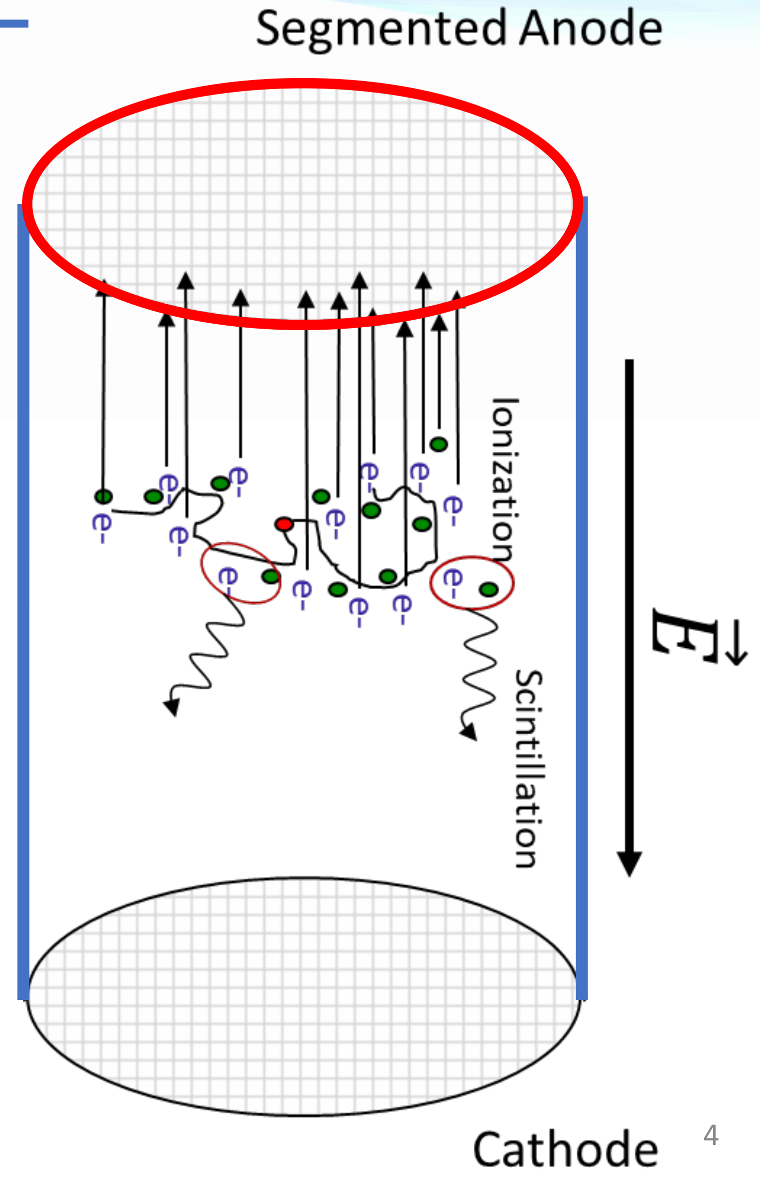
nEXO - Searching for 0vBB

- nEXO is a proposed 5-tonne single-phase liquid xenon time projection chamber (LXe TPC)
- LXe is **90% enriched in 2νββ isotope ^{136}Xe**
  - Q_{BB} ~2.46 MeV
- Extensive radio-assay program for background mitigation
  - **Ultra-low background technique based on success of EXO-200 program**
- nEXO projected sensitivity to 0νββ half-life is **1.35×10^{28} years at 90% CL** after 10 years [1]
  - Current experimental limits in ^{136}Xe: >2.6×10^{26} yrs (KamLAND-Zen)



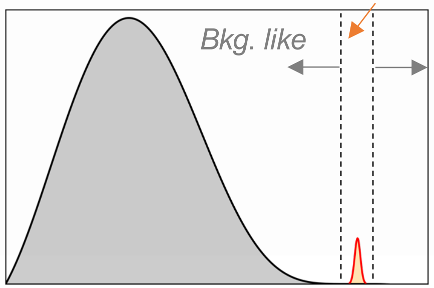
Detecting 0νββ

- Radiation in LXe produces ionization electrons + scintillation light
- TPC configuration is optimized to measure both charge and light signals
  - Drift charge to **Charge Collection Anode**
    - **~3800 Channels in 120x10cm tiles**
  - Collect light along barrel with **Silicon Photomultipliers (SiPMs)**
    - **24 “Staves” with 20 tiles of 16x6cm^2 Sub-arrays -> 7680 channels over 4.6m^2**
  - **Combine both for <1% energy resolution at Q_{BB}**
- 3D Position Reconstruction based on charge (XY) and charge delay time (Z)

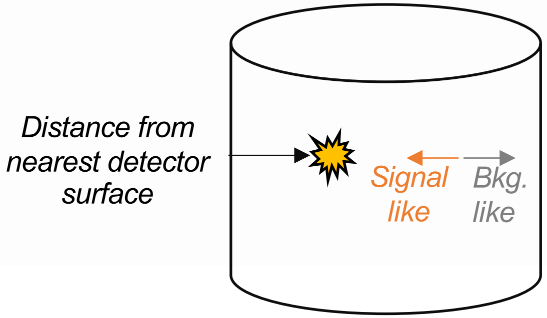


TPC Multiparameter Analysis

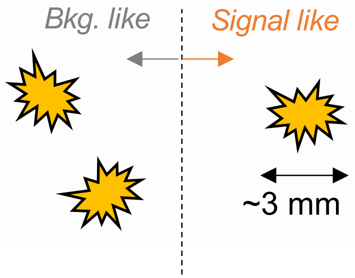
Energy:



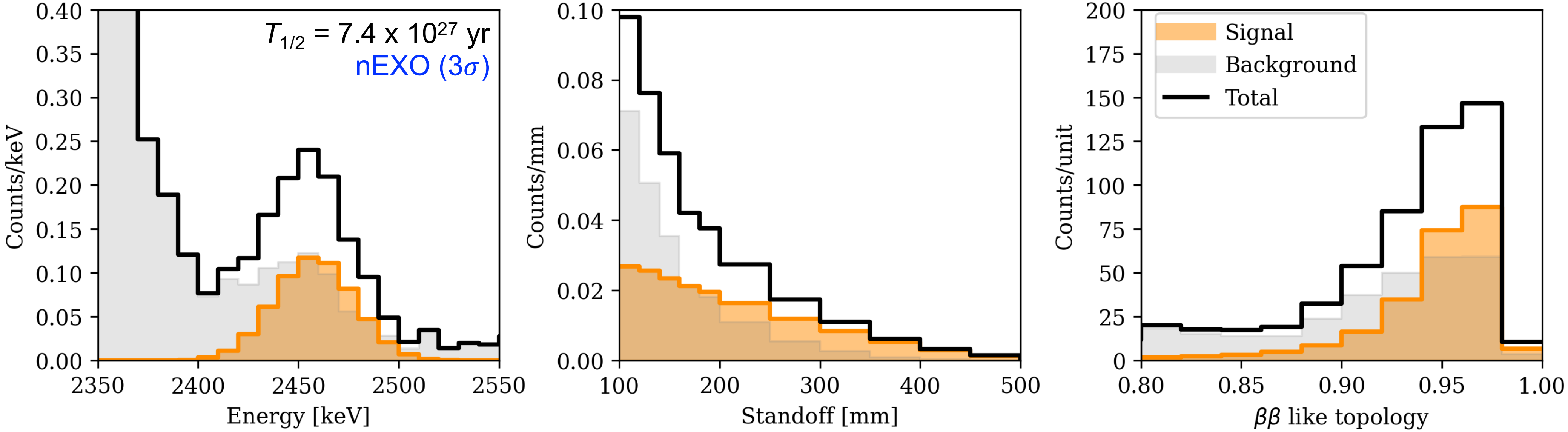
Standoff:



Topology:

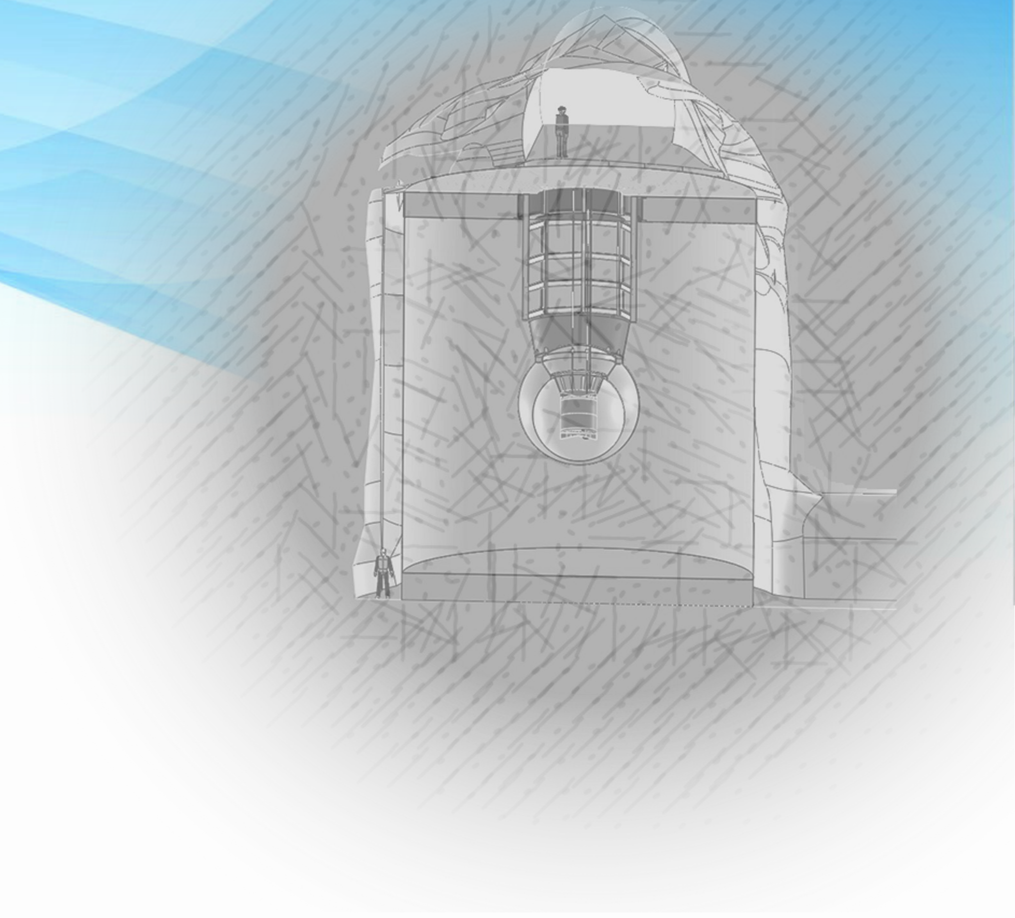


1D projections of simulated nEXO signal and backgrounds:



nEXO Simulations

Time to get technical



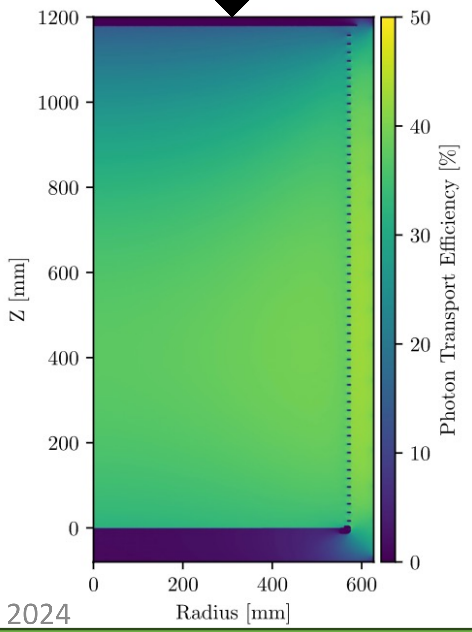
nEXO Simulations Framework

nEXO

Stand-alone GPU

Detailed Light Simulation

CHROMA
Light Simulation for nEXO



Light Map

Modular CPU using SNiPER

Primary Particle Transport

GEANT4
A SIMULATION TOOLKIT

LXe Energy Deposit Response

NEST

Ionization Electrons

Scintillation Photons

Light Map + Efficiency

Charge Simulation

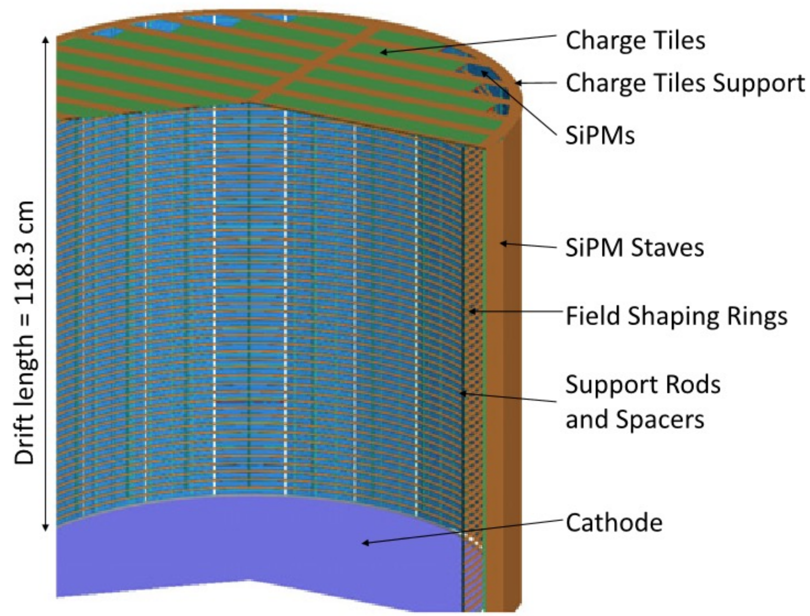
Diffusion + Transport + Attn.

Charge Waveform + Noise

Detector Response

GEANT4 for nEXO

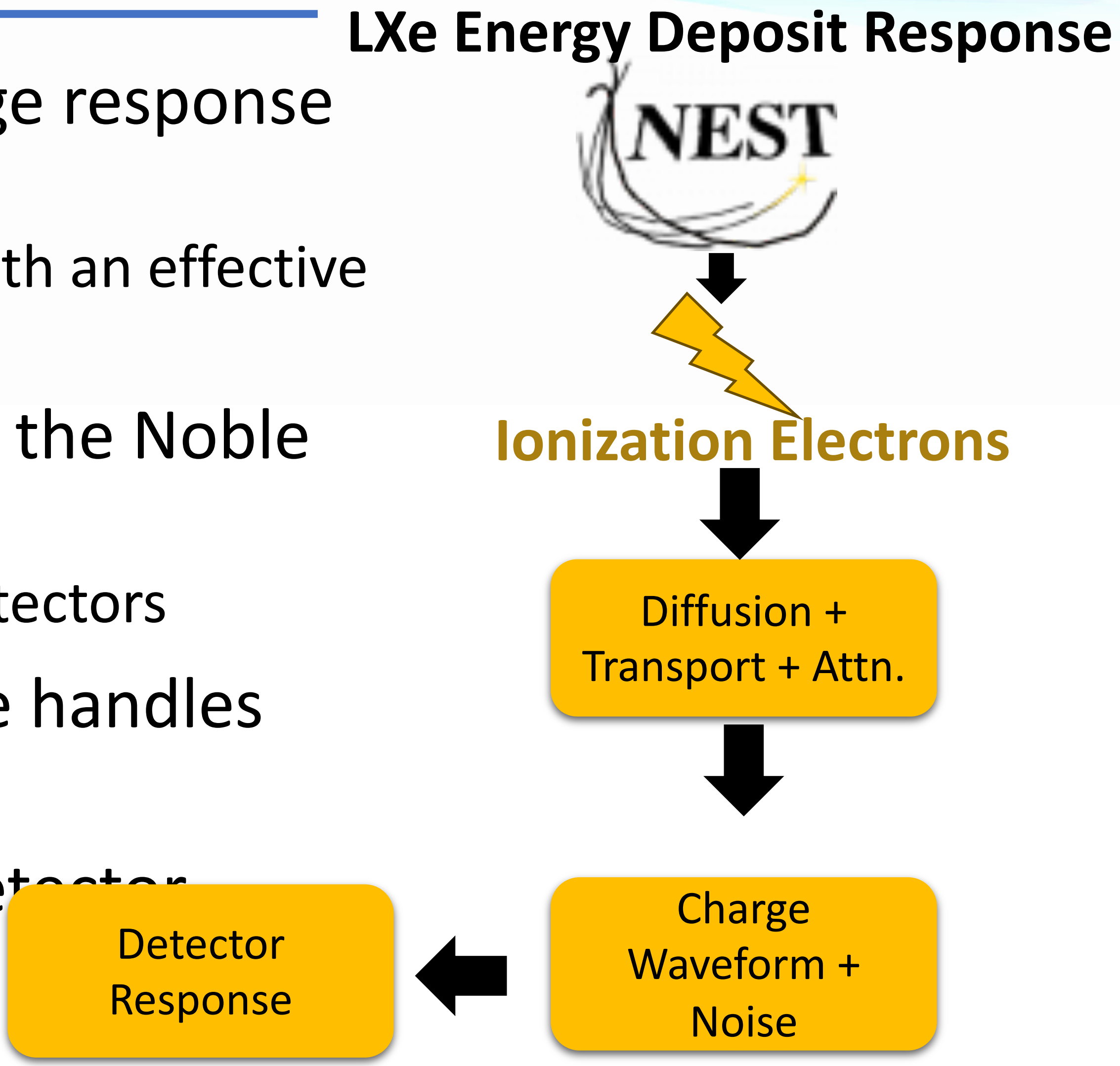
- We all know what GEANT4 is
- nEXO Runs GEANT4 in SNiPER Framework
  - Integrated modular analysis and secondary detector response simulations
- It’s essential to run full GEANT4 simulations for all background sources
  - Integrated online assay and radiopurity data-base used for cataloguing, version control and background contribution estimation
  - Check out our Radiopurity DB Paper [3] for more details!



See Li T, et al. *Parallelized JUNO simulation software based on SNiPER* [3],for more info on SNiPER

Charge Response Simulation

- nEXO has developed a detailed charge response simulation
  - Option to run fully detailed or “fast” with an effective model
- Ionization Electrons are produced by the Noble Element Scintillation Toolkit (NEST)
  - Microphysics MC for noble element detectors
- Standalone SNiPER Algorithm service handles charge simulation
- Reconstruction algorithm handles detector response and reconstruction



See Li Z, et al., *Simulation of charge readout with segmented tiles in nEXO* [4], for full details!

CHROMA – GPU Accelerated Photon Transport

- Using the Chroma Framework from https://github.com/BenLand100/chroma
  - Chroma has recent renewed support and is being developed under https://github.com/pennneutrinos/chroma
  - We will fast-forward to the stable development branch soon!
- Chroma + GPU libraries are kept in a singularity container
  - Works with NVIDIA GPUs
  - Compatible with HPC cluster GPUs
- Geometry is defined by STLs
  - No need for simplifying assumptions, export the whole detector CAD as STL files and configure optical properties in data tables

- GPU-based photon transport simulation
- Surface-based triangular mesh geometry
- Development in Python (core simulation in CUDA-C)
- Does:
  - Optical Photon Transport
  - Wavelength Shifting
  - Photon Detection

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- GPU-based photon transport simulation
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- Does:
  - Optical Phot…
  - Wave…

Up to 200x faster for optical photon tracking in Chroma vs GEANT4

CHROMA Integration

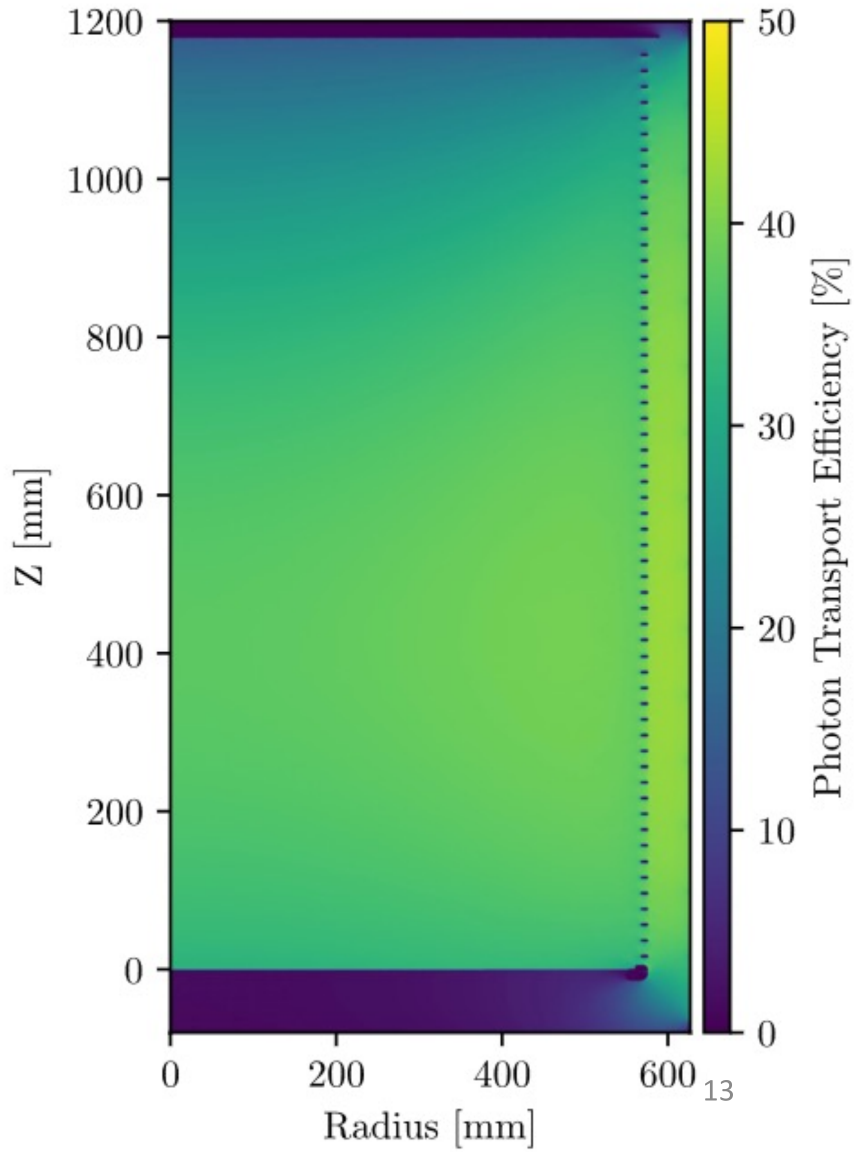
Currently CHROMA is used in two modes

1. Stand-alone high photon # simulation to produce accurate light-map as input for GEANT4 simulations
2. Detailed Light-only studies of light transport to for individual photons
   - Light-only studies used to understand requirements for key optical elements inside of nEXO
   - Exploration of background rejection techniques in light channel
   - Used to design and characterize response of water-Cherenkov detector for muon veto

- Current work is focusing on integrating GEANT4 output into Chroma indirectly using upROOT + nestpy for event-by-event analysis in detailed light simulation
- Investigating CHROMA integration into SNiPER with nEXO GEANT4
  - **Cons: Significant work required, need not demonstrated**
  - Pros: Fast accurate detailed light transport with only one-geometry to maintain, opens new possibilities for light-only analyses. Full correlations maintained!

Light Response Simulation

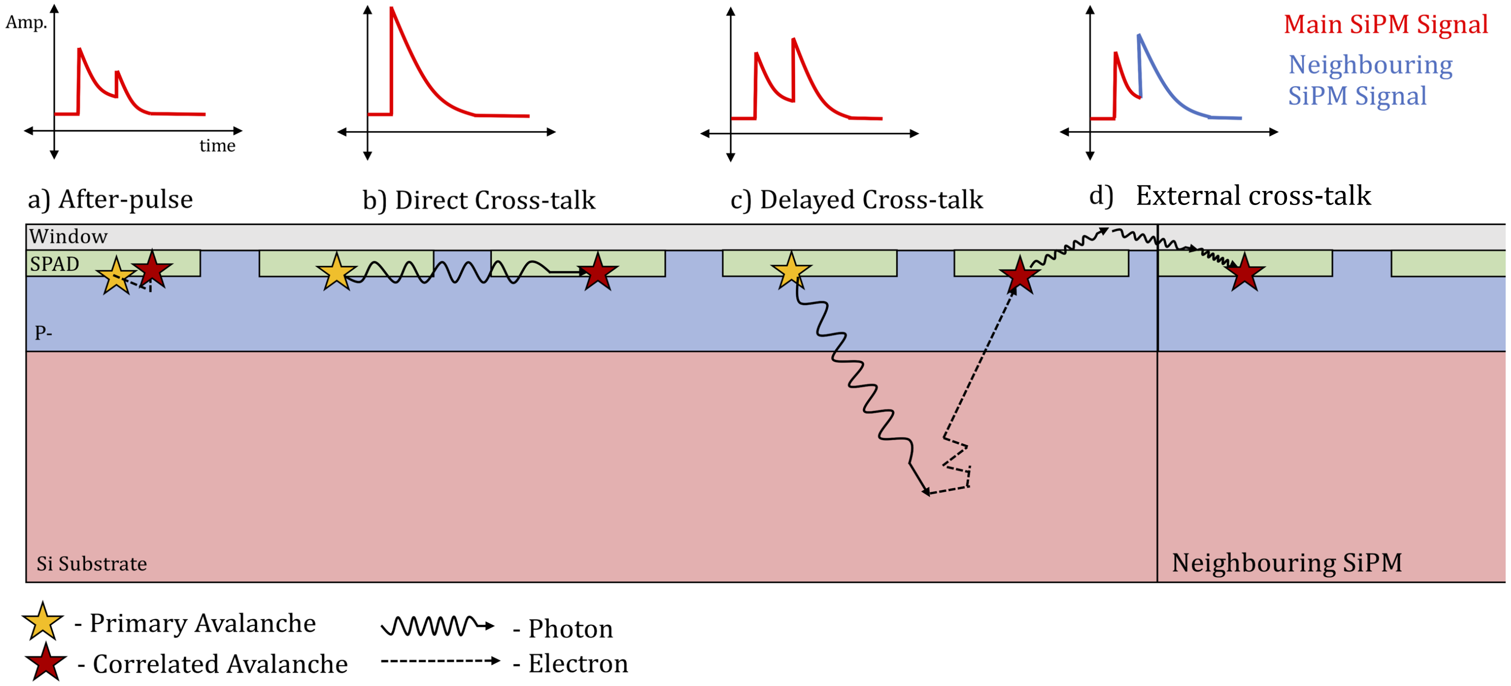
- Stand-alone high statistics (O(10^{12}) photons) GPU Simulation of light transport in CHROMA aka **Light Map**
- Light map used to determine photon transport efficiency (PTE) for each energy deposit location from GEANT4 simulation
- NEST calculates # of photons
- PTE and SiPM efficiency, correlated noise and fluctuations included to determine # of detected PE for each event

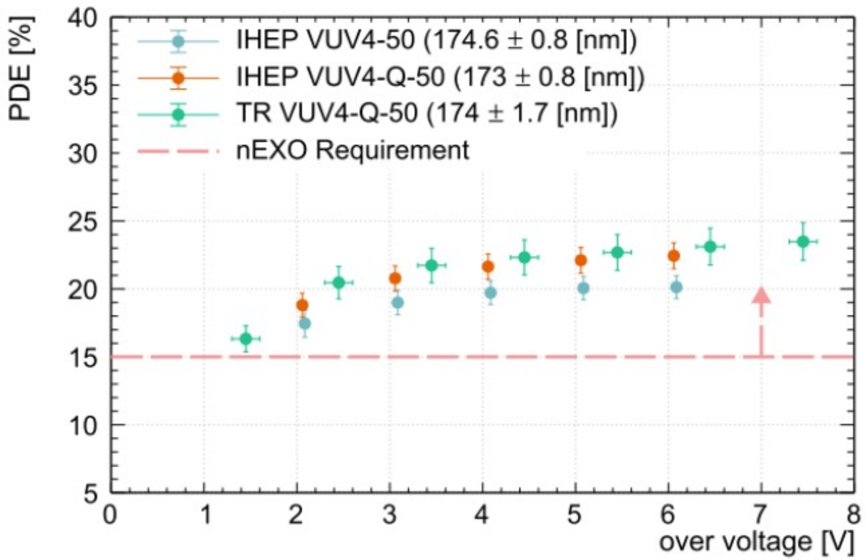


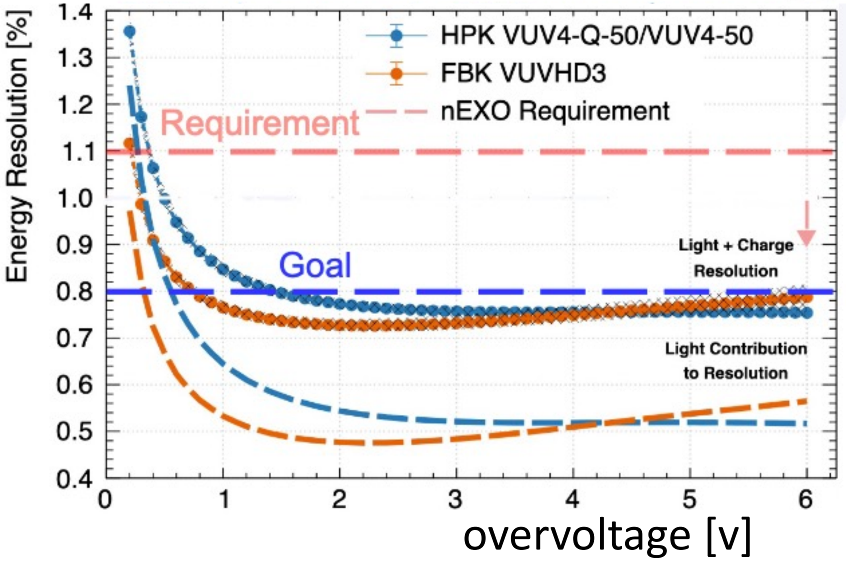
Modelling SiPM Response

For a complete simulation, we must accurately model SiPM correlated noise, PDE, and detector readout response!

A full SiPM response simulation library in development, in early stages currently







Figures from: Gallina G. et. al, *Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO* [5]

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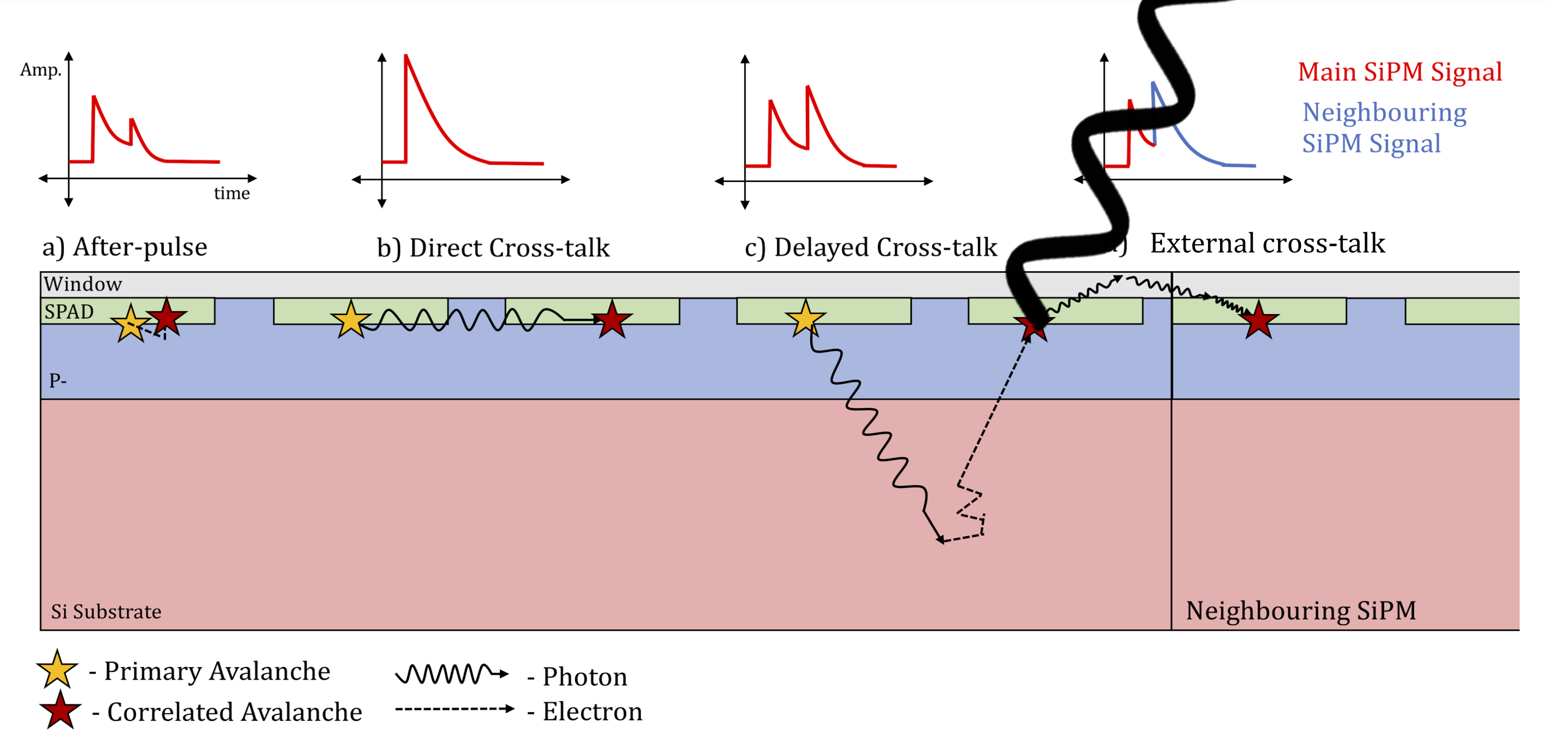

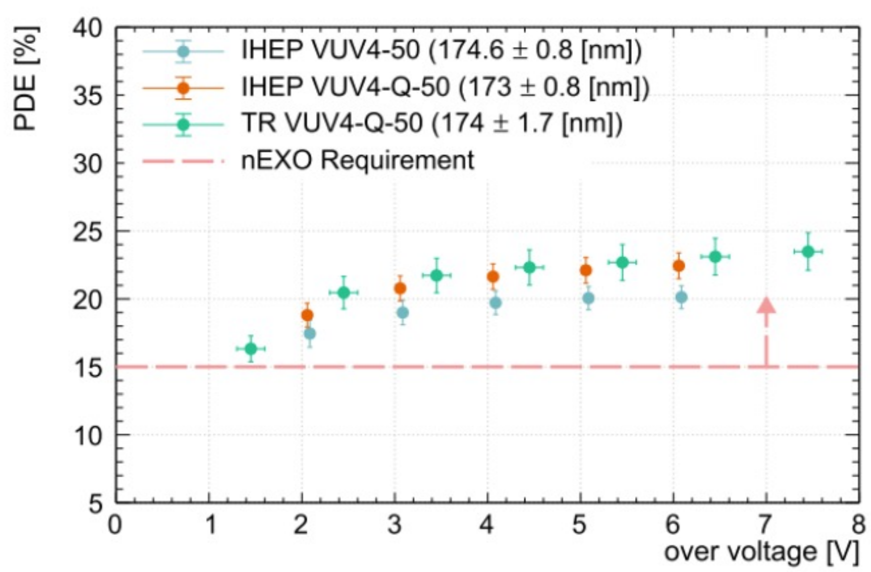

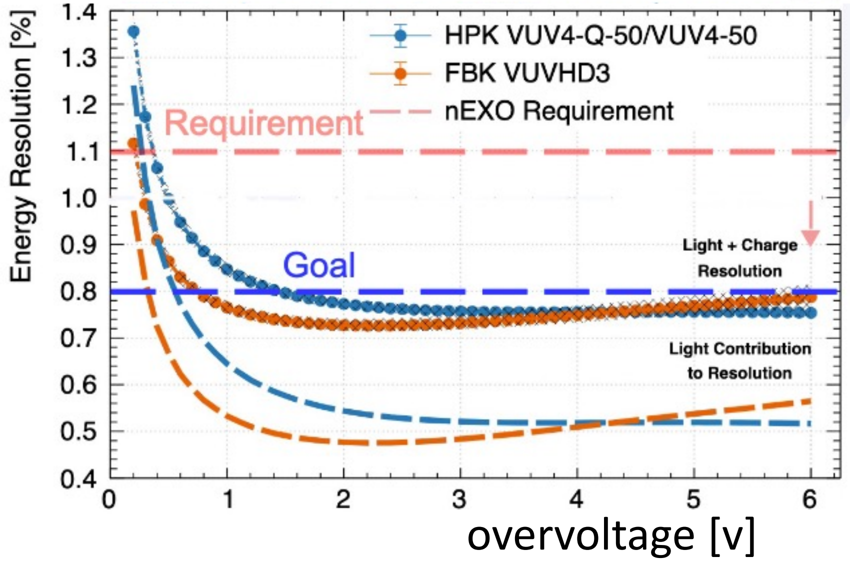

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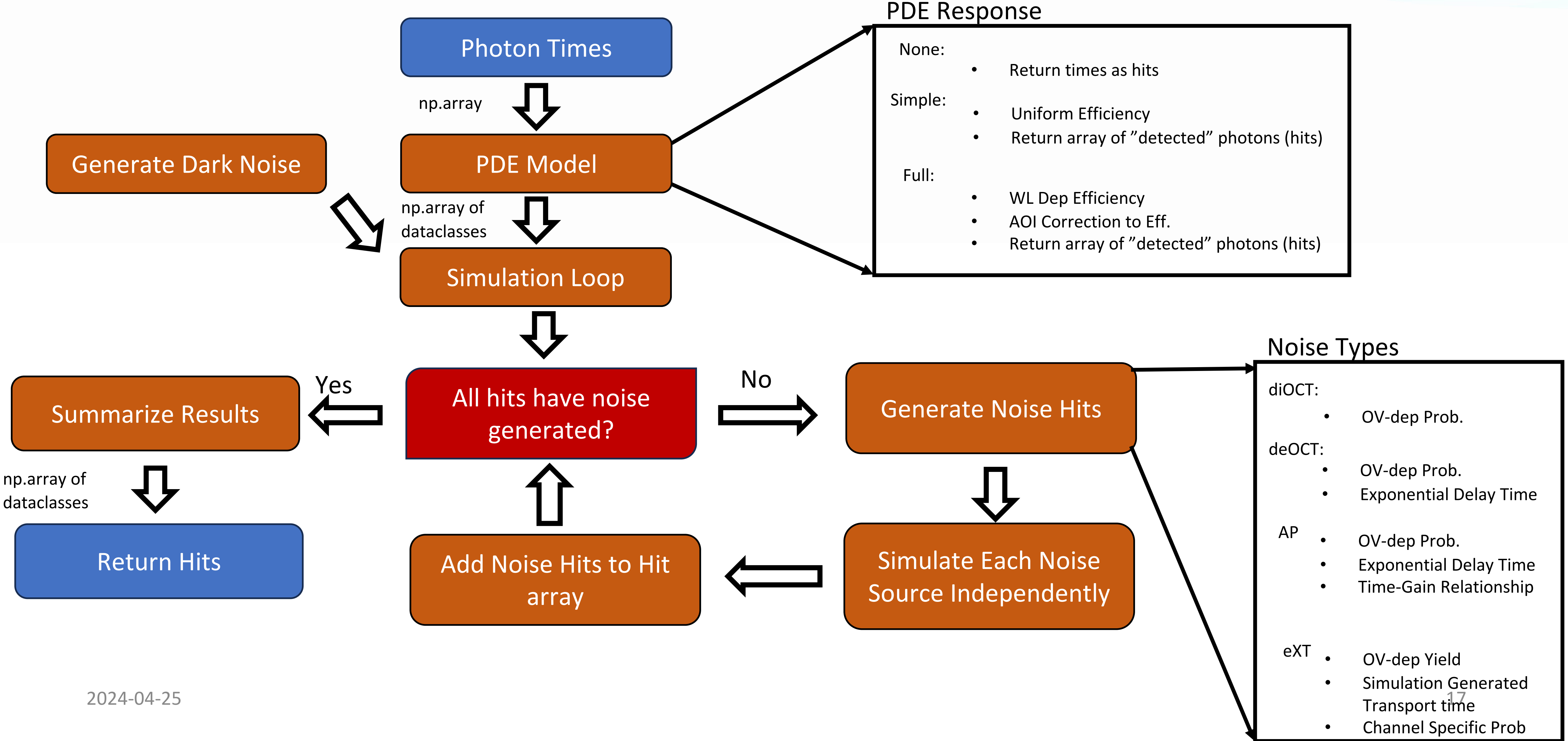
SiPM Response Model

- Goals:
  - Easily configurable and customizable response (Yaml Inputs)
  - Integration directly into SNiPER analysis pipeline for nEXO
  - Integration directly into Chroma simulation
  - Stand-alone capabilities for testing and noise studies
- Assumption:
  - Designed for “Photon counting” applications, assumption of low-occupancy (no saturation model for now)
- Includes:
  - Full (WL and θ dep.) and Simplified photon detection efficiency (PDE) models
  - Toy MC for all correlated and uncorrelated noise – Parameters read in through data files
    - OV dependent
    - Includes timing and gain dependence
    - Values from detailed characterization work in [5]
  - **External crosstalk response model**
    - Based on validated simulations and measurements from nEXO R&D groups
    - Requires full detector simulations for input (Chroma)

SiPM Response Model



Outlook and Future Plans

- nEXO is a next generation 0νββ search experiment, sensitive to half-lives beyond 10^{28} years
- nEXO has a robust simulation frame-work for background mitigation, building on the demonstrated success of the EXO-200 program
- Detailed charge and light simulations are in-place using modern frameworks to compliment GEANT4 simulations
  - Work is in progress on the last stages of the full light response simulation
- Exploring new optimizations for light simulations with GPU integration for photon transport
- Exciting future ahead for 0νββ searches!

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KEK
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Thank you!

References

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3. Lin, T., Zou, J. H., Li, W. D., Deng, Z. Y., Cao, G. F., Huang, X. T., & You, Z. Y. (2018). Parallelized JUNO simulation software based on SNiPER. *Journal of Physics: Conference Series*, *1085*, 032048. doi:10.1088/1742-6596/1085/3/032048
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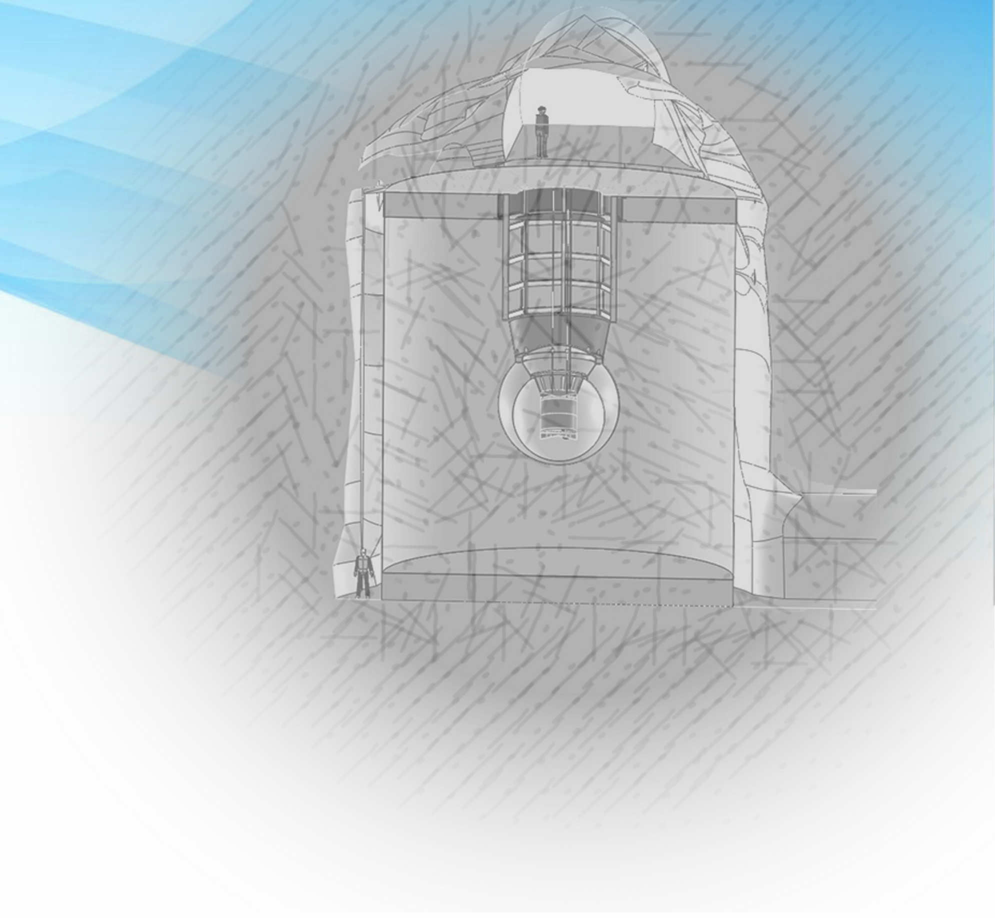
Backup



TPC: Rotated Energy

- Light and charge are anti-correlated in a LXe TPC
- A linear combination of light and charge for ER events gives "Rotated Energy"
- Discriminates alphas due to different charge/light ratios

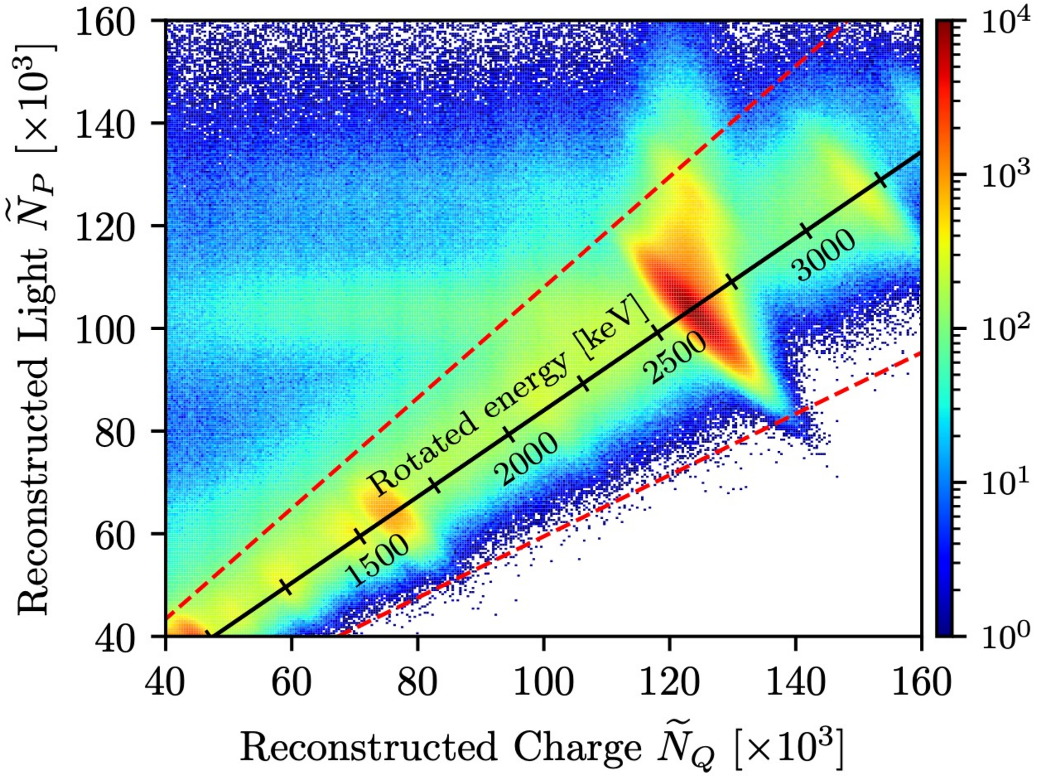
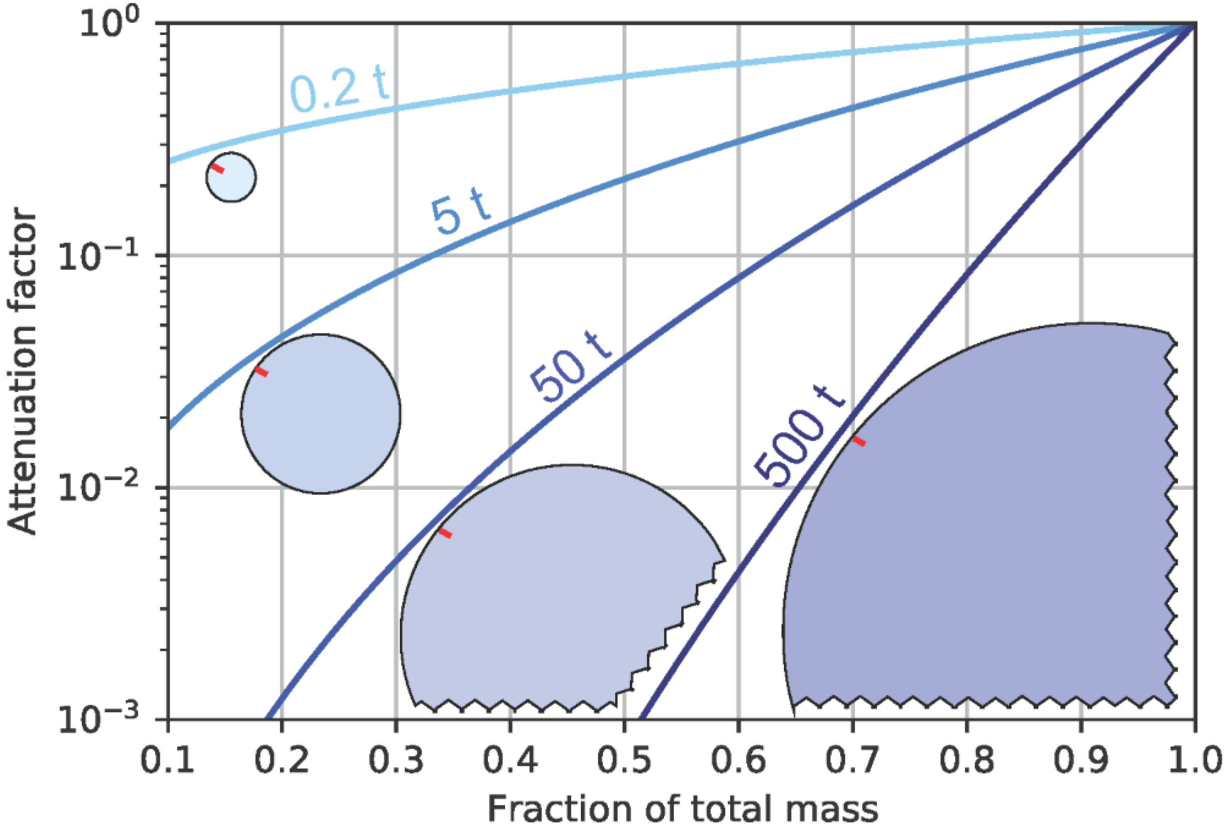


Figure 5. Reconstructed light and charge signals of all events in the FV from simulated ^{232}Th decays in the TPC vessel. The dashed lines indicate the location of the diagonal cut, described in the text. The rotated axis indicates the scale of the rotated energy.

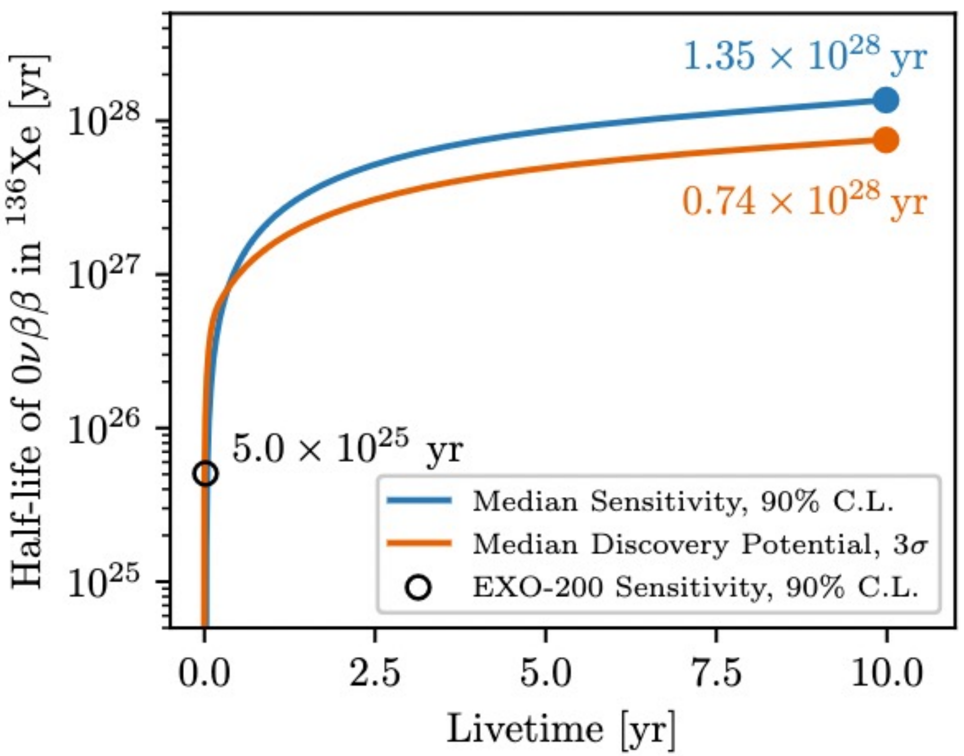
Beneficial Features of a LXe TPC

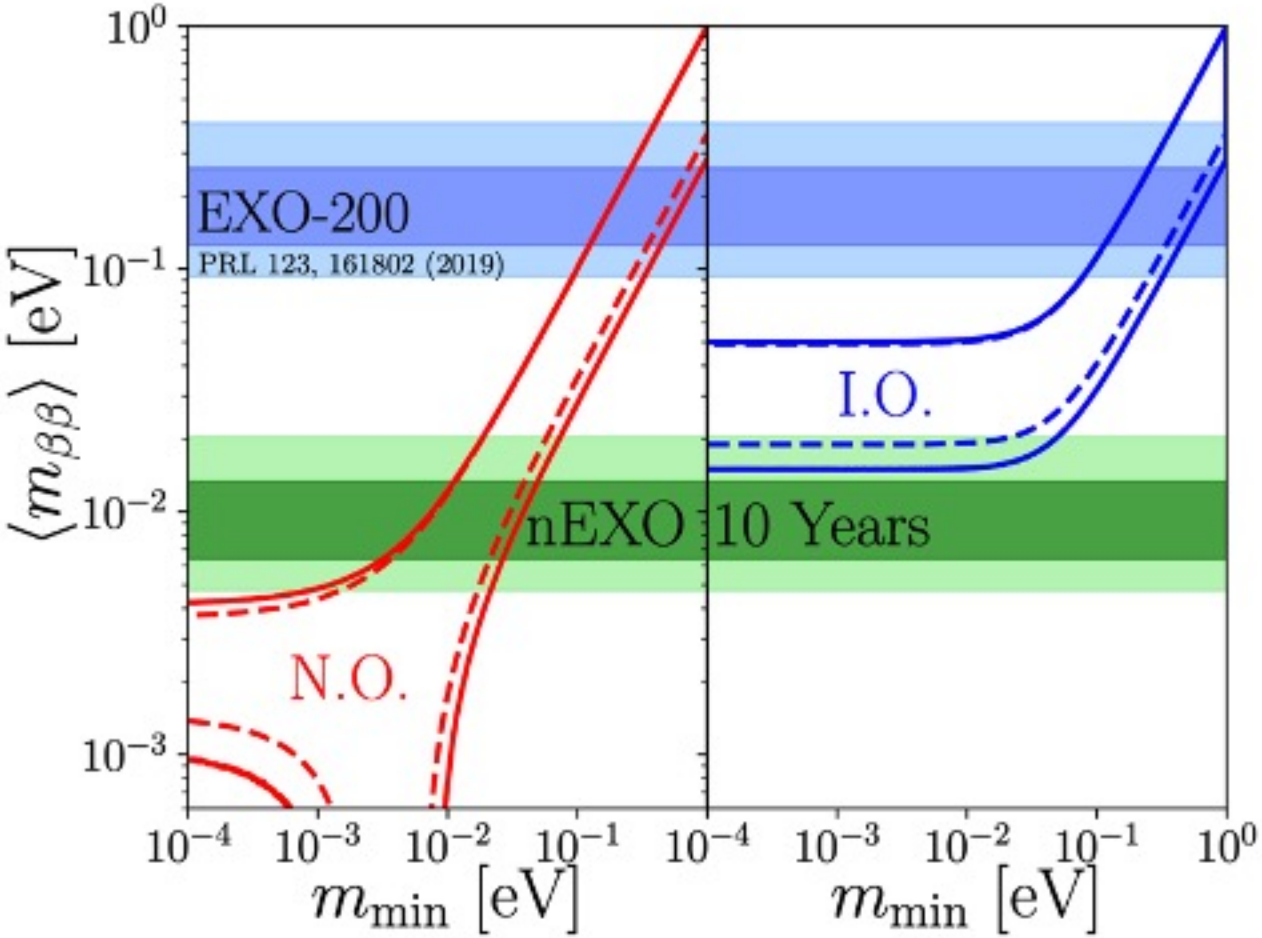
- Large scale monolithic homogenous detector
  - Scalability
  - Online purification
  - Self-shielding from dominant background – **External γ's**
- 3D position reconstruction
- Multiparameter analysis
- Ability to capture and tag daughter isotope
  - Rejects all non-ββ backgrounds
- Option to perform a control run



With 5 t of LXe, centre of nEXO is at least ~7 attenuation lengths from the external detector components

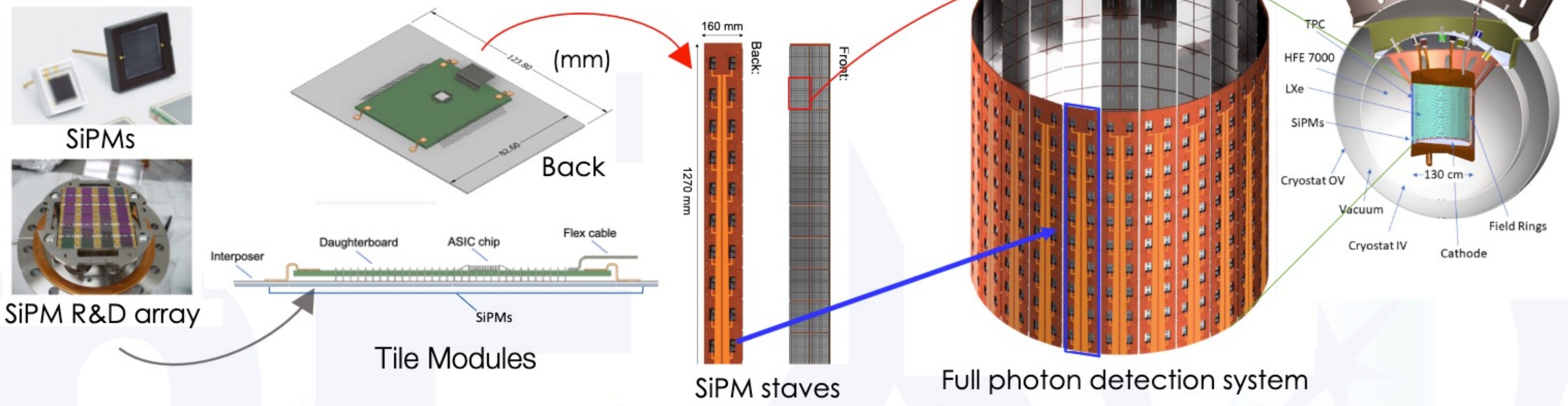
nEXO Sensitivity





Borrowed from Sierra Wilde APS Talk

nEXO's Photodetector



Silicon Photo-Multipliers (SiPMs)

Individual SiPMs

Grouped in 6 cm^2 sub-arrays → readout channels

Tile Modules

16 sub-arrays to tile w/ smaller daughterboard & integrated ASIC

20 tile modules arrayed to form stave

Staves

24 staves surround barrel, behind field shaping rings

Electroformed copper

Geometry

Square cylinder

Decreases the number of reflections before hitting a photodetector

Photocoverage

4.6 m^2

7,680 channels

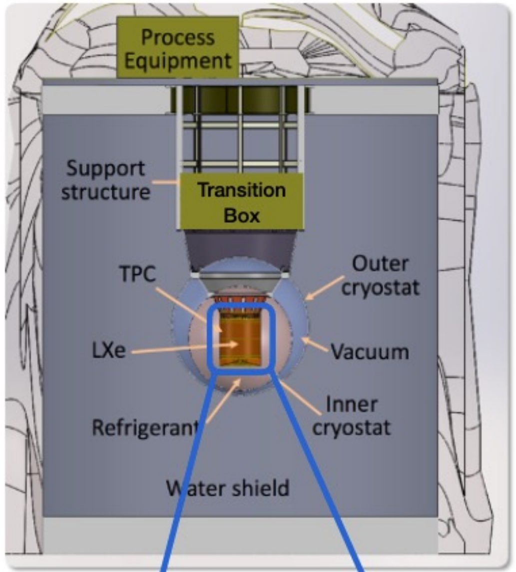
⬇

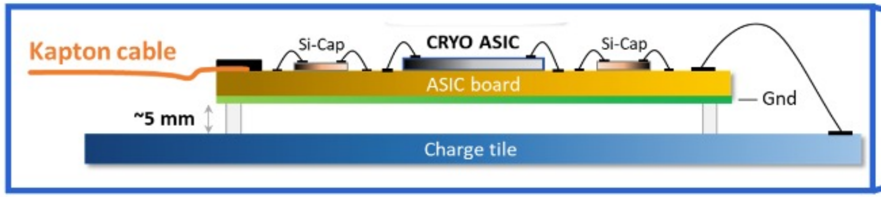
makes imaging of events possible

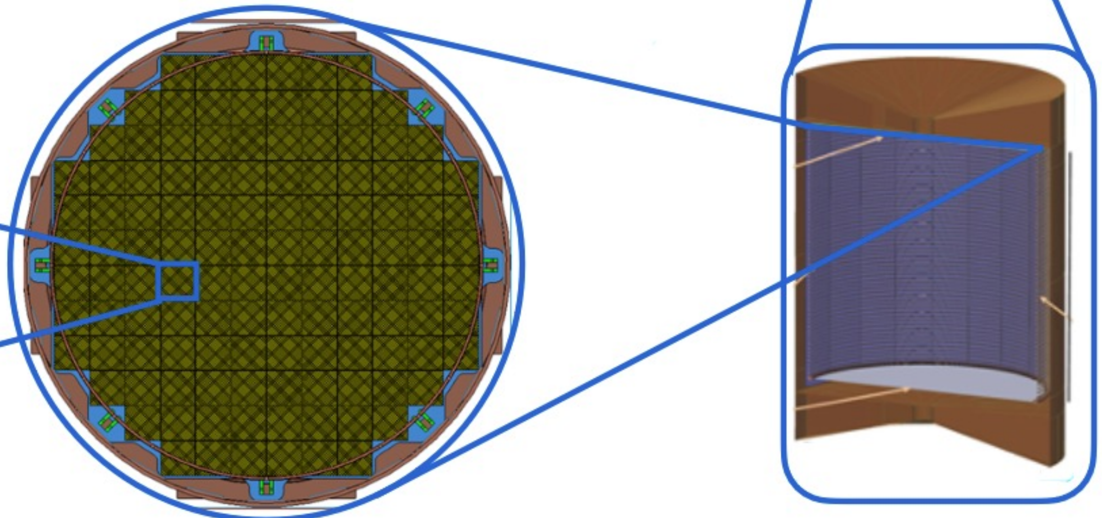
Borrowed from Glenn Richardson APS Talk

nEXO's Charge Readout System

- At the top of the TPC is the anode plane where the ionization electrons are collected and detected
- The anode plane will consist of 120 charge collection tiles
  - Each tile will have 32 channels for ~4,000 distinct charge channels in nEXO







1D Projection: Pseudo-Background Free

- Likelihood fit allows optimal weighting between signal and background combining energy, topology, and standoff over full 3D parameter space
- Arranging the 3D bins into 1D, ordered by signal-to-background ratio, to help visualize the signal and background separation in nEXO

Combine energy, topology, and standoff (preserving correlations)