LoLX

Advancements in SiPM Characterization and Optical Simulations for Noble-Liquid Detectors in Nuclear Physics

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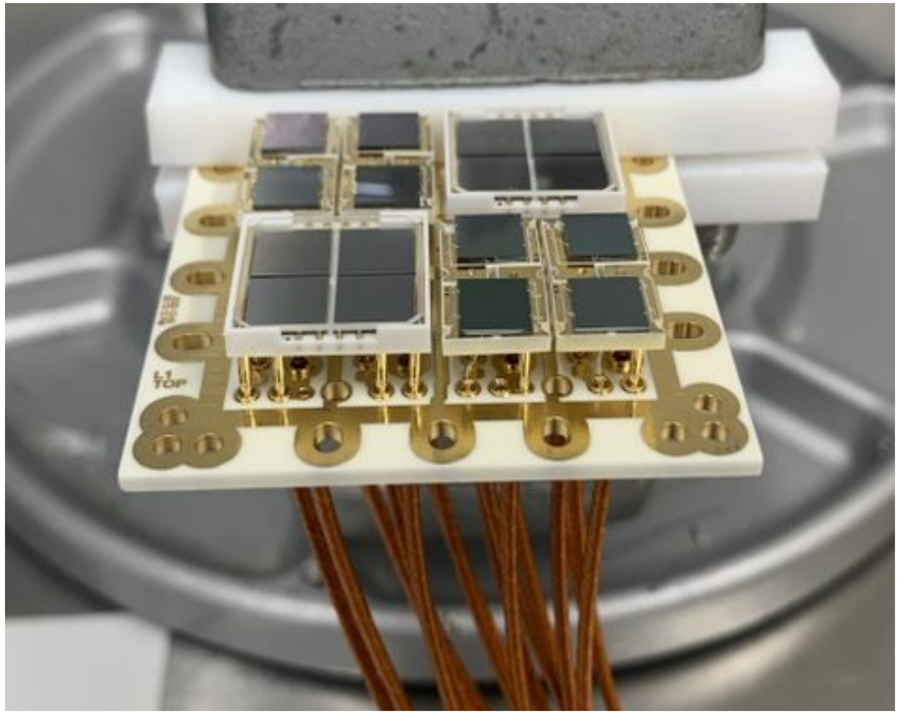
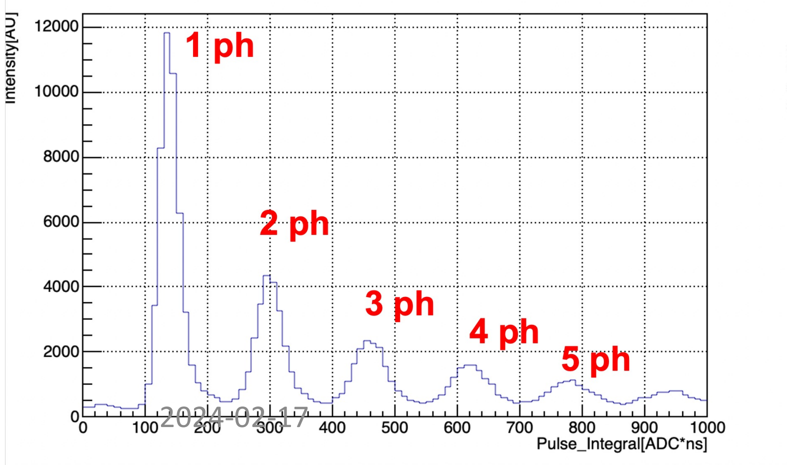
McGill

Silicon Photomultipliers

LoLX

- Silicon Photomultipliers (SiPMs)
  - Solid state **single-photon** sensitive light detectors
  - Composed of Silicon, can be made radiopure
  - Excellent photon counting resolution (See below)





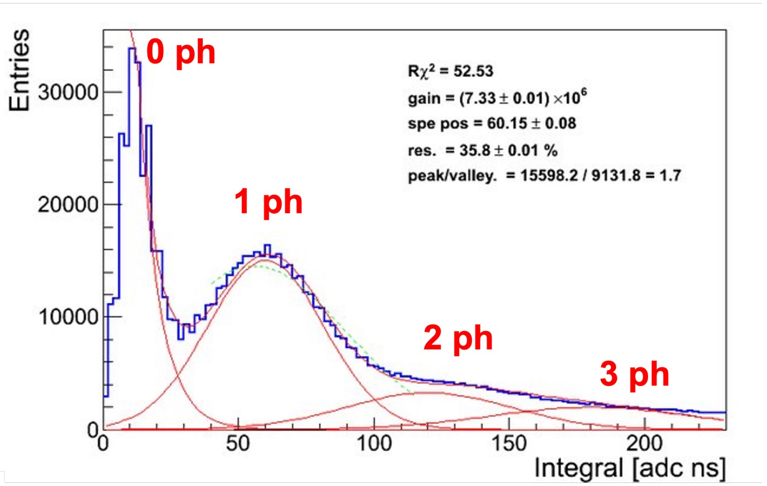


Fig. 1: (Top) PCB Tile with 16 VUV-sensitive SiPMs from LoLX (8x Hamamatsu VUV4, 8x FBK HD3), (Left) Typical SPE distributions for SiPM (left) and PMT (right, from [DOI]), highlighting the excellent resolution of SiPMs

A next generation observatory for 0vBB

- Ton scale next generation 0vBB search experiment
  - 5T Liquid xenon (LXe) TPC filled, enriched to 90% in ^{136}Xe
  - Planned for the SNOLAB Cryopit
- TPC configuration gives anti-correlated light and charge
  - Particle identification for background discrimination
- Need < 1 % Energy resolution at ^{136}Xe Q_{BB} (~2.45 MeV)
- **~50k vacuum ultra-violet(VUV) sensitive Silicon photo-multipliers (SiPMs) for scintillation light detection**

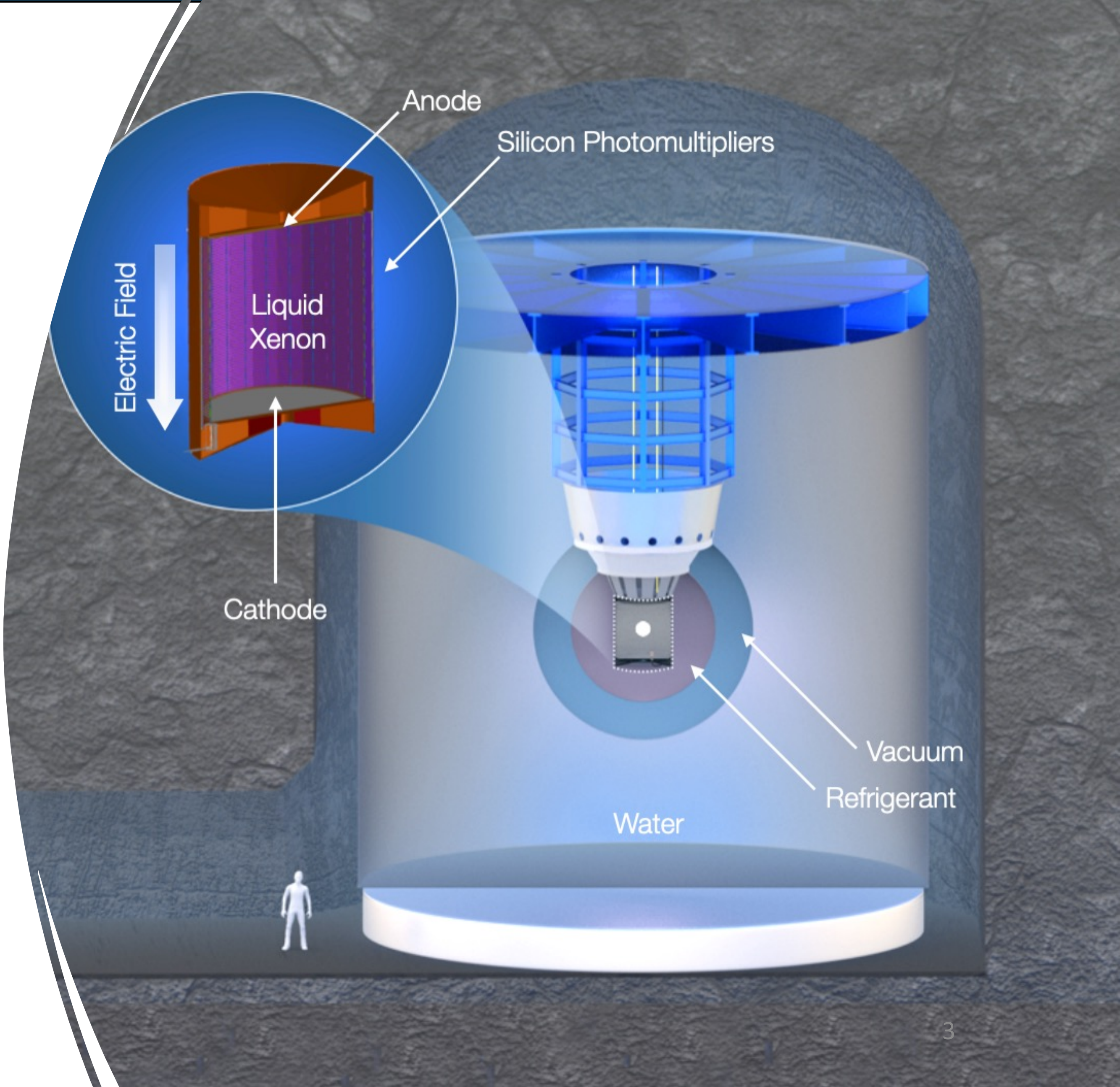


Fig. 2: Illustration of nEXO

Light Only Liquid Xenon - LoLX

- 0vBB sensitivity and nEXO detector response estimations **critically depend** on simulations
- For high fidelity simulations we need validation against data
- Light only Liquid Xenon (LoLX) detector helps fill this gap
  - Perform measurements of SiPM performance in LXe, including long-term stability, PDE and external crosstalk characterization and more
  - Validate and improve simulations of photon production, transport and SiPM response for nEXO

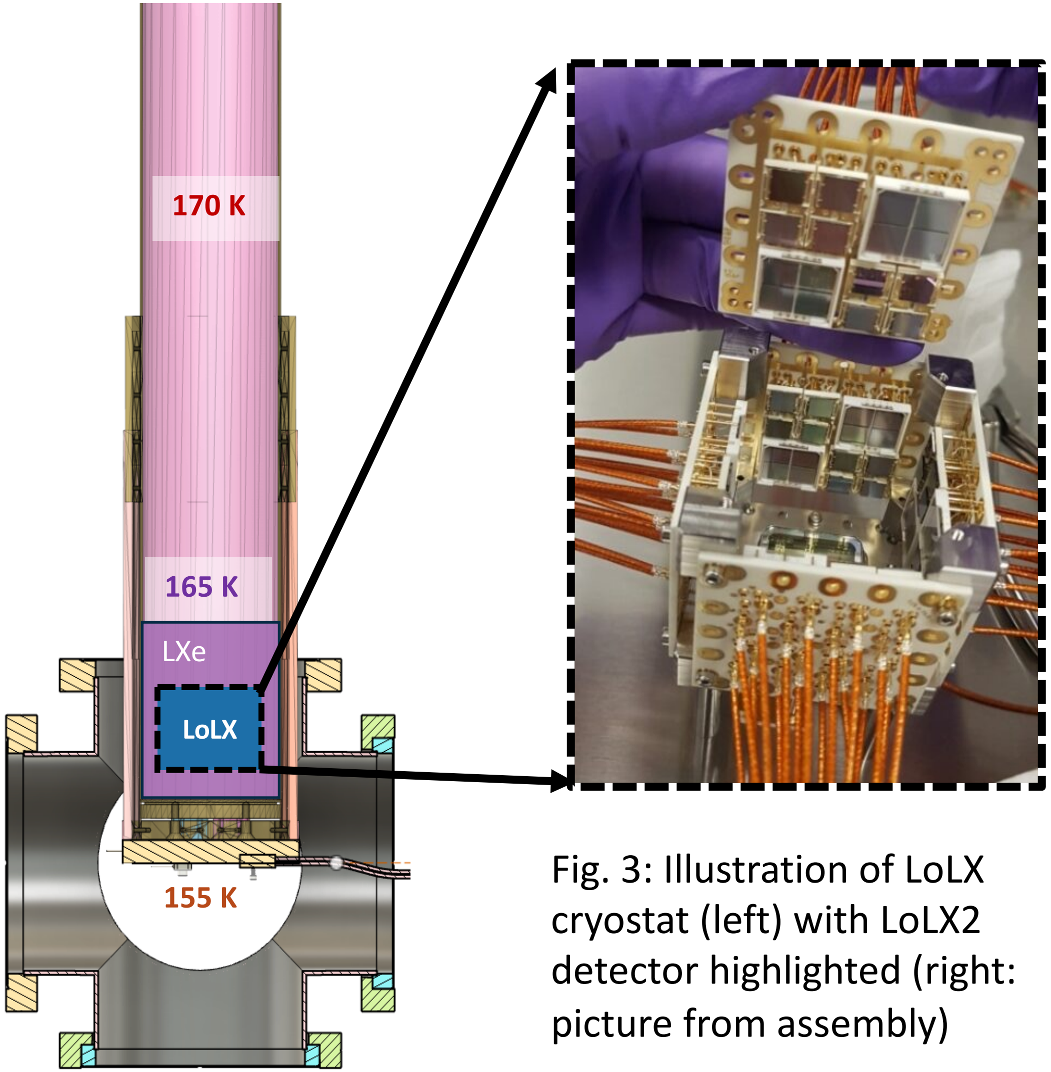


Fig. 3: Illustration of LoLX cryostat (left) with LoLX2 detector highlighted (right: picture from assembly)

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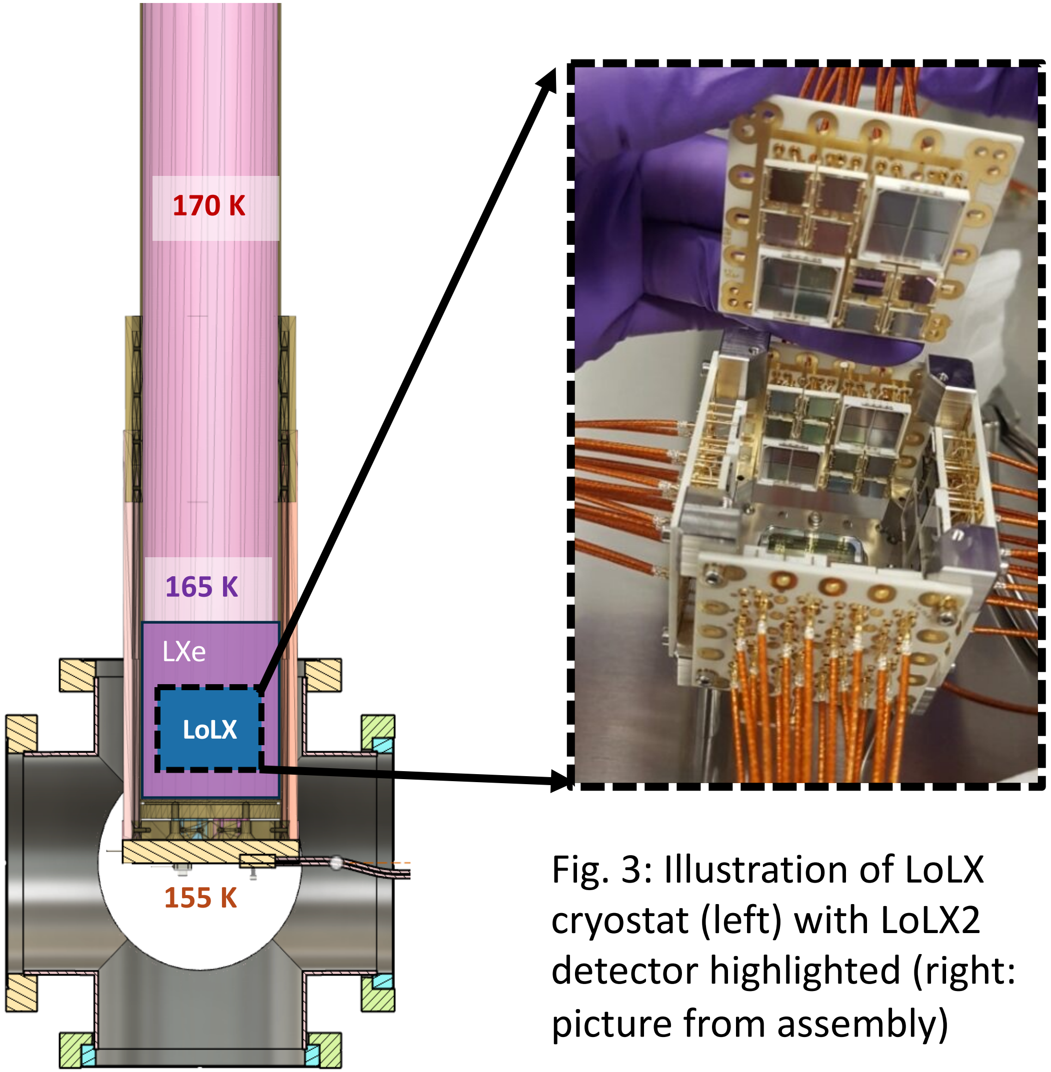

Fig. 3: Illustration of LoLX cryostat (left) with LoLX2 detector highlighted (right: picture from assembly)

Optical Simulations for Noble Liquid Detectors

GEANT4
A SIMULATION TOOLKIT

- CPU-based transport
- Solid-based tree structured geometry
- Development in C++
- Does:
  - Particle tracking and creation
  - Particle transport (Including optical photons)
  - Custom track/event user actions for high level integrated analysis
  - Sensitive detectors with custom detection schemes

Light Simulation for nEXO

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

GEANT4
A SIMULATION TOOLKIT

- CPU-based transport
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  - Sensitive detectors with custom detection schemes

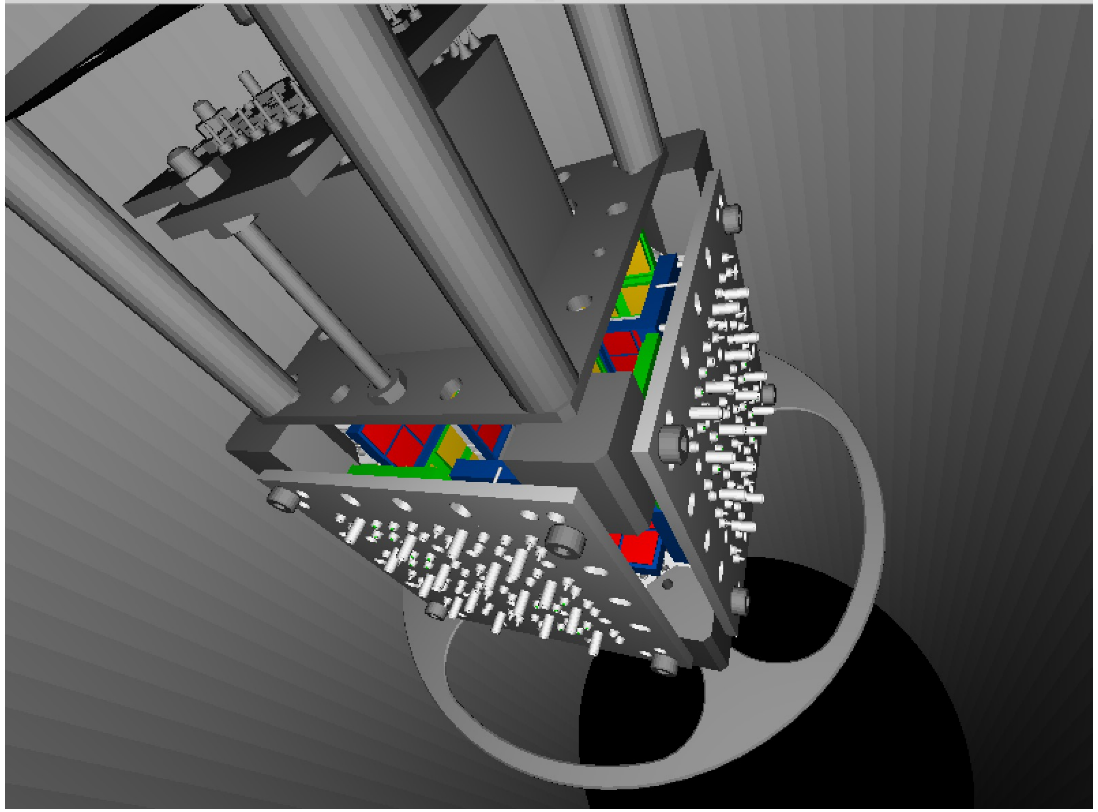
CHROMA
Light Simulation for nEXO

- GPU-based transport
- Surface-based triangular mesh geometry
- Development in Python (c… simulation in CUDA…
- Does:
  - Op… …rt
  - …
  - Pl… …etection

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

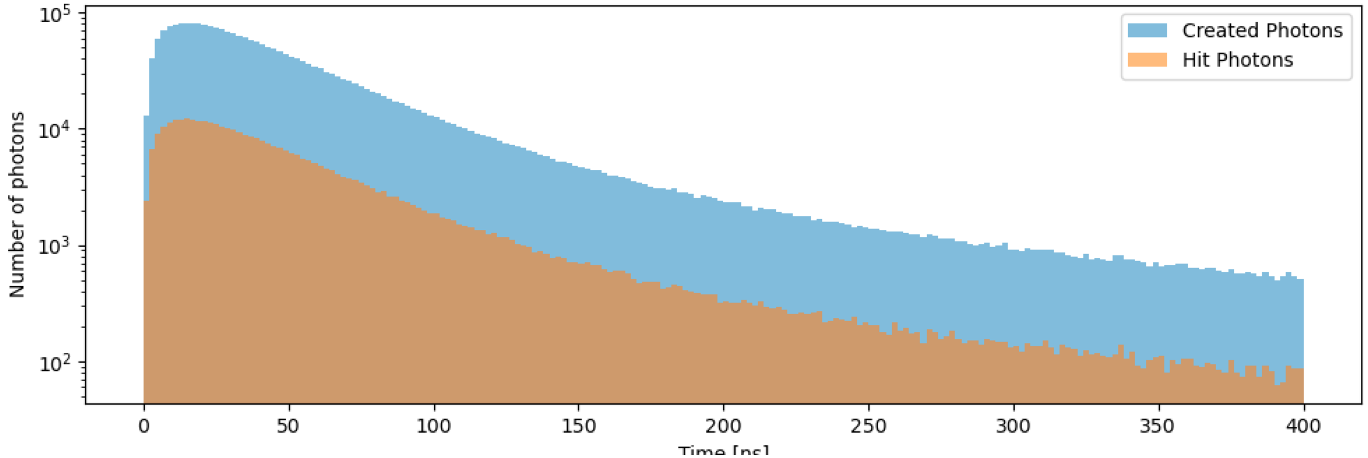
Chroma-Simulation

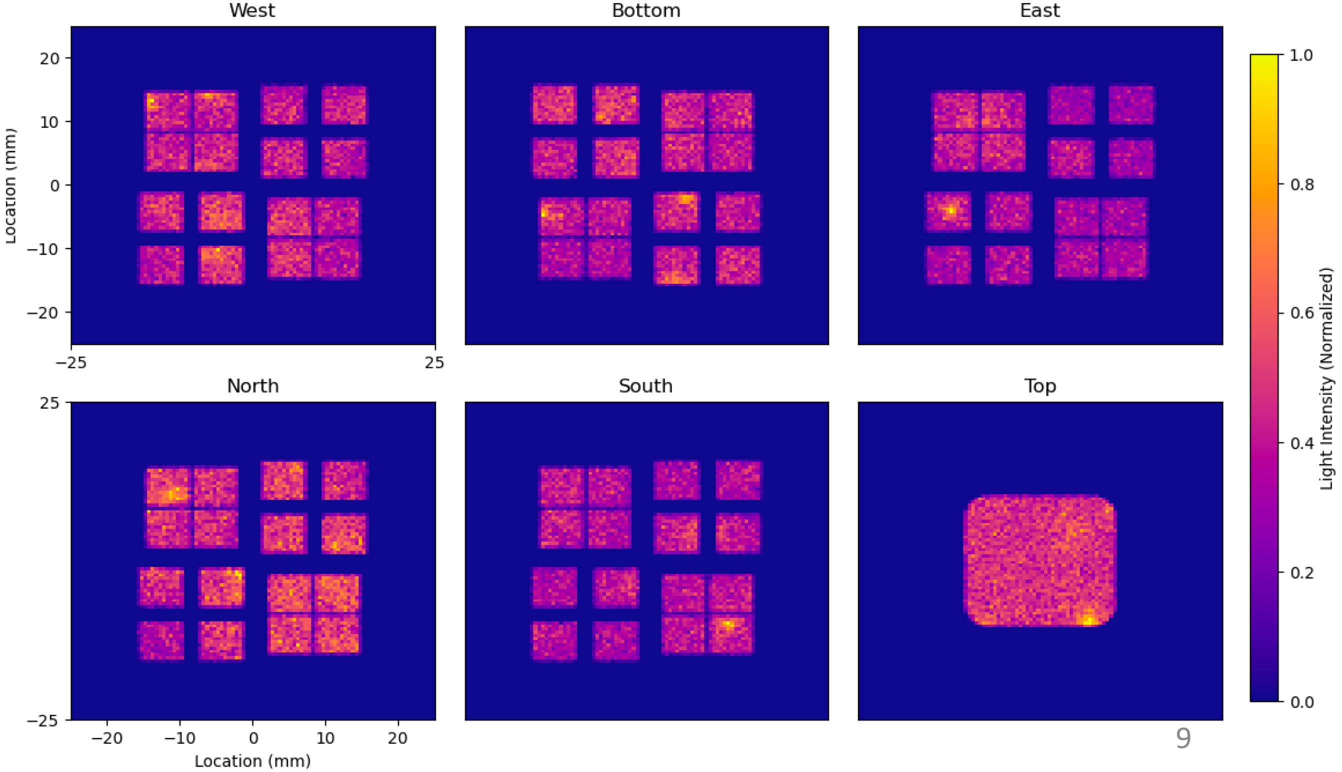
- Using the Chroma Framework from https://github.com/BenLand100/chroma
- Chroma-Simulation developed by nEXO is a full simulation implemented in the Chroma framework
- Chroma + GPU libraries are kept in a singularity container
  - Works with NVIDIA GPUs
  - Compatible with DRAC cluster GPUs
- Geometry is defined by STLs
  - Export your detector CAD as individual STLs, optical properties are defined in Yaml files and applied to STL components
- Easy to define custom position and photon sources, with a quick turn-around simulation pipe-line for rapid prototyping



Chroma-Simulation + NEST

- NEST is integrated with Chroma-simulation through python bindings: nestpy
- NEST calculates scintillation and charge yields, with toy MC outputs for simulation integration
- Energy deposits in LXe are converted into LXe scintillation photons for simulation using the NEST model
  - Dependence on: Particle type, energy deposited, electric field



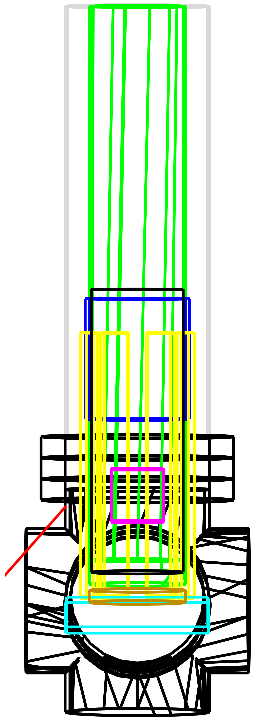


Two-part GEANT4 Integration

GEANT4 Integration for LoLX Simulations happens in two stages:

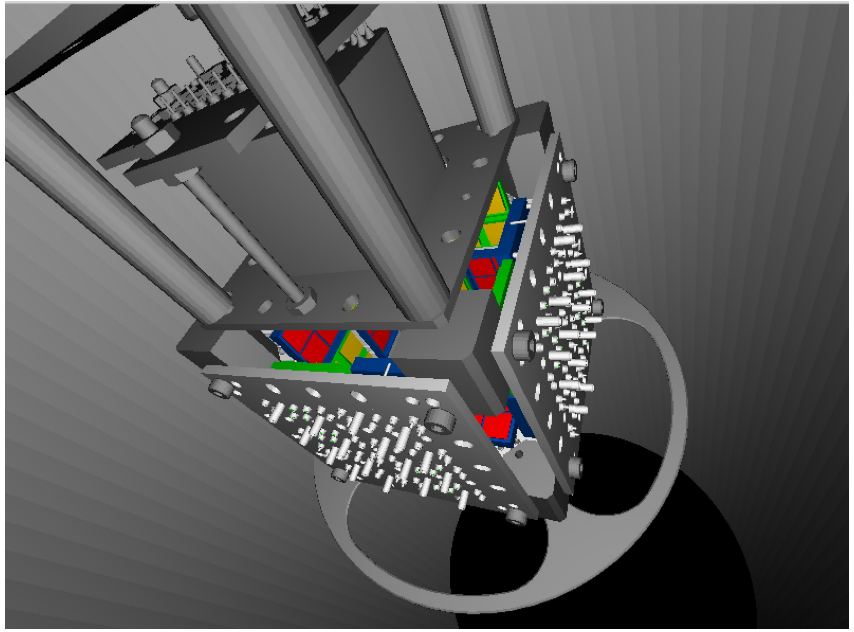
1. Full model of cryostat and shielding in GEANT4 with LXe sensitive detector inside, steps in LXe are recorded and saved to .root file
2. ROOT file is read using UpROOT into Chroma-simulation and each step is read for energy deposits (Scintillation) and for Cherenkov tracks

1. Simulate sources in GEANT4 with simple geometry (Optics off)



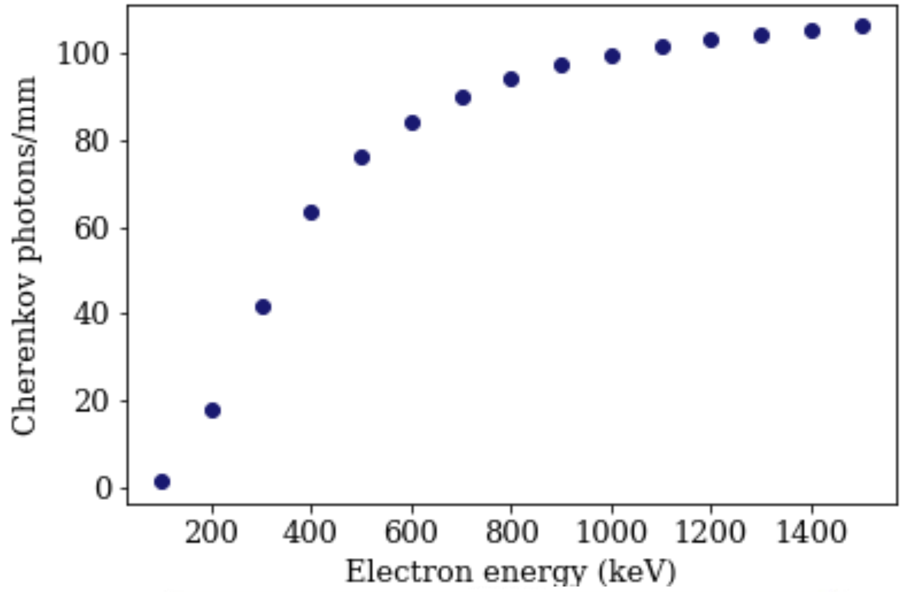
2. Load track information into Chroma-simulation using UpROOT

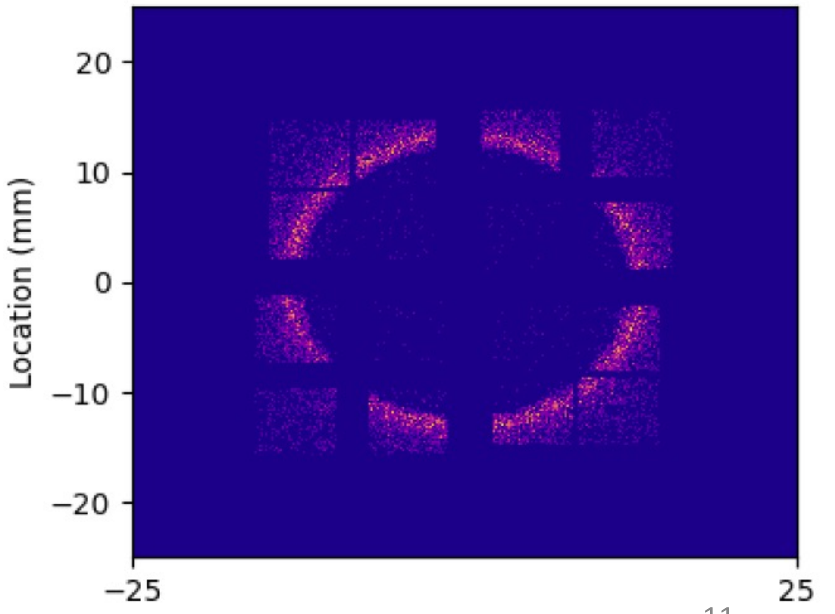
3. Build detector in Chroma from STLs, create photons from ROOT using nestpy



Cherenkov Light Generation

- We implemented a pythonic version of G4Cerenkov directly into our Chroma-simulation framework
- Benchmarked against G4Cerenkov and validated
- Can be used as a standalone light generator (For MIPs for example)
- Or used in concert with GEANT integration to add Cherenkov to applicable particle tracks
- Examples on the right show betas in LXe

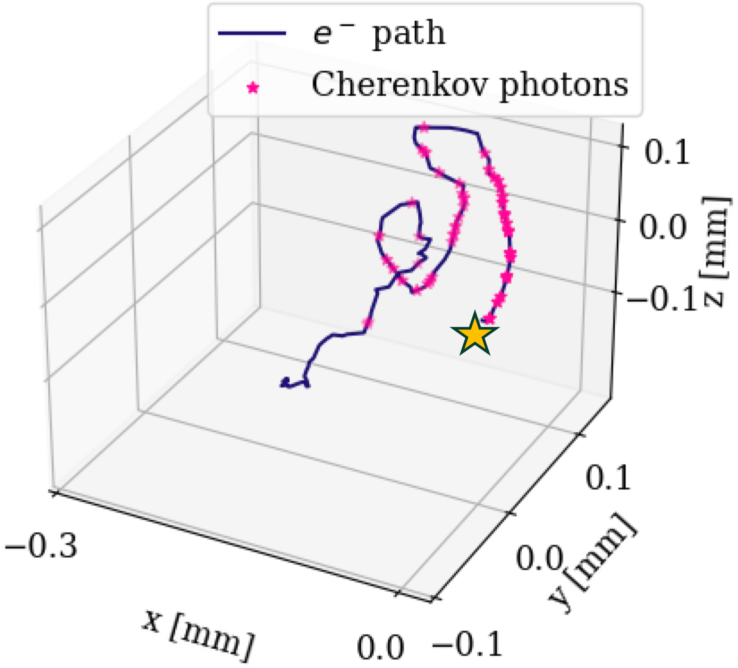


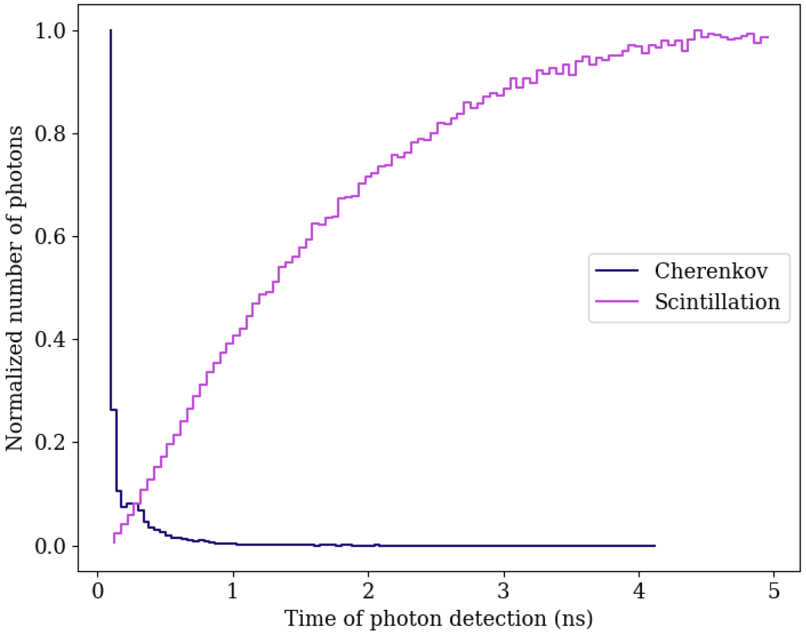


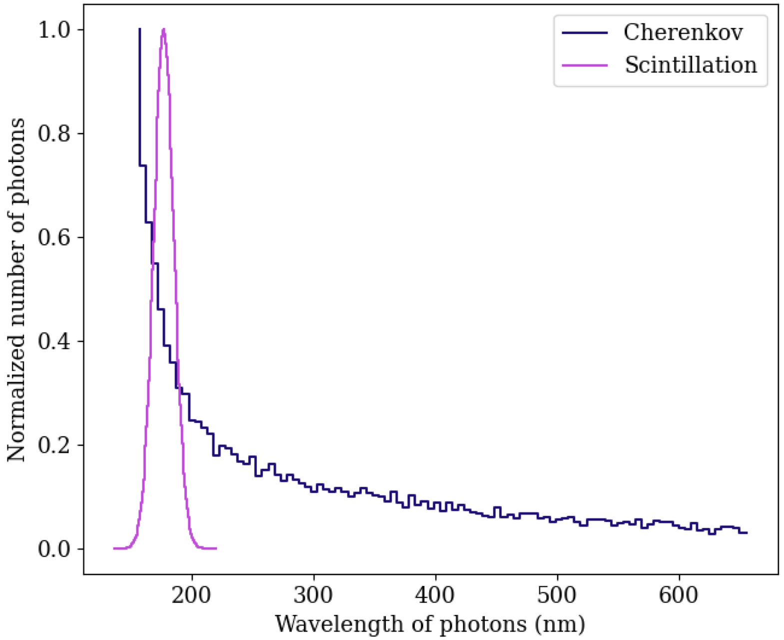
Figures from Sandhya Rottoo (McGill Ugrad)

Cherenkov Light Generation + ROOT

By combining our GEANT4 + NEST and Cherenkov implementation we simulate realistic Cherenkov + scintillation emission from low-energy beta tracks (R&D for LXe TOF-PET)







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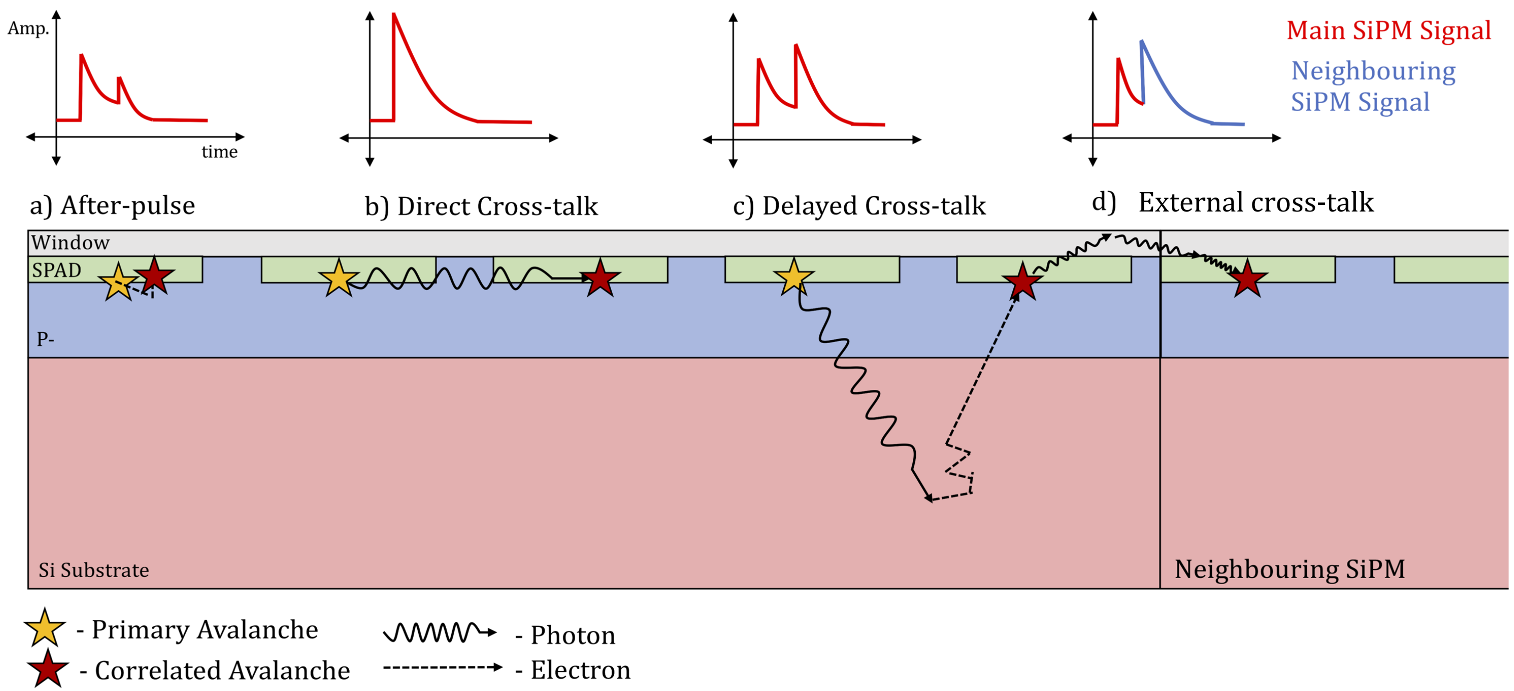
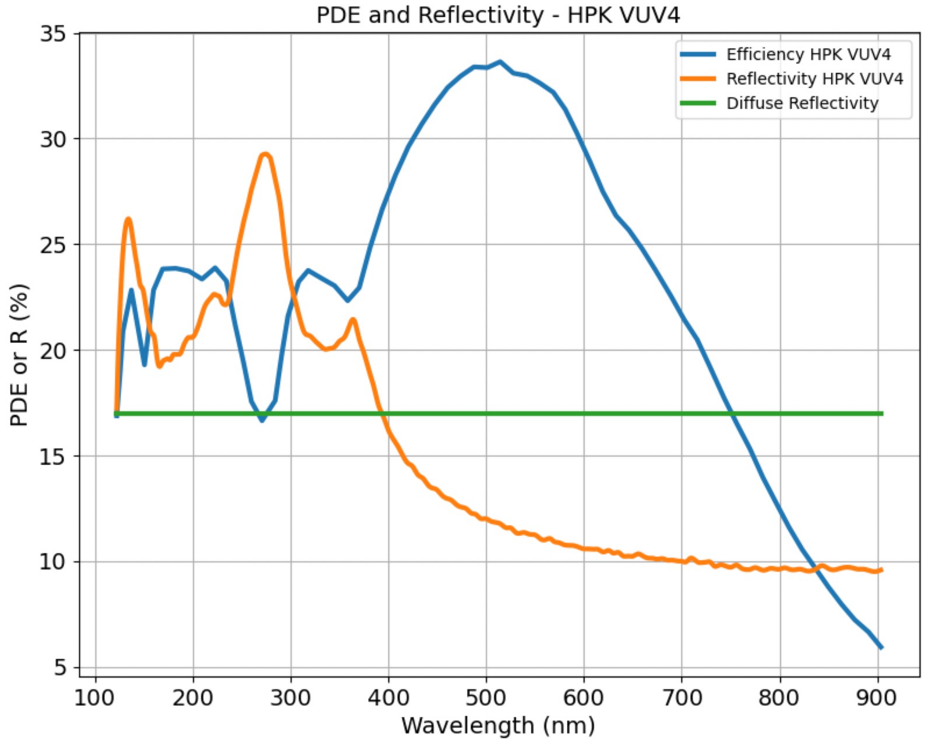
Modelling SiPM Response

For a complete simulation, we must model SiPM correlated noise and PDE accurately

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

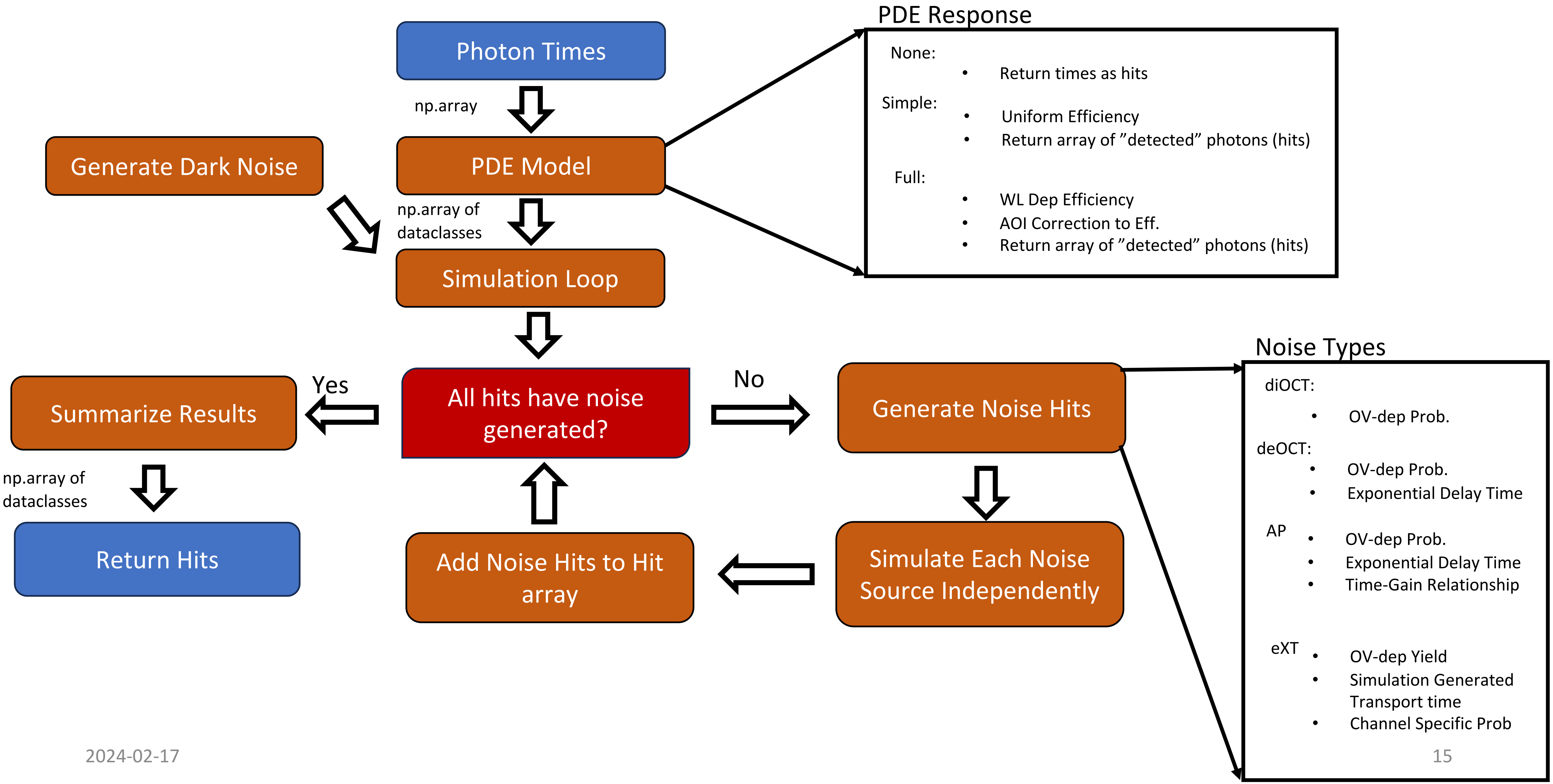




SiPM Response Model

- Goals:
  - Easily configurable and customizable response (Yaml Inputs)
  - Integration directly into GEANT4 analysis pipeline for nEXO
  - Integration directly into nEXO & LoLX 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 angle dep.) and Simplified PDE models
  - Toy MC for all correlated and uncorrelated noise – Parameters read in through data files
    - OV dependent
    - Includes timing and gain dependence
  - External crosstalk response model
    - Based on LoLX and TRIUMF measurements and model
    - Requires full detector simulations for input (Chroma)

SiPM Response Model



Outlook

LoLX

- LoLX has a critical role to play in characterizing SiPMs and benchmarking simulations for nEXO
- We've developed performative and robust LXe detector simulations that are easily configurable for an R&D experiment
- Work is beginning on a full SiPM response model, benchmarked against ex-situ and in-situ measurements of SiPM performance
- Open to collaboration on developing an open-source flexible and robust general simulation toolkit for noble liquid detectors based on the Chroma GPU Framework
- Reach out to David.Gallacher@mail.mcgill.ca or head to davidgallacherphysics.com to find my contact info if interested in collaborating!

Thank you!

Questions?

SiPM Response Model Preliminary Results

Num Hits = 14370452, Primary = 11638259, Noise = 2732193, Fraction = 0.190126
Mean of Total PE = 28740.904, res = 1.713 %
Mean of Primary PE = 23276.518, res = 1.552 %

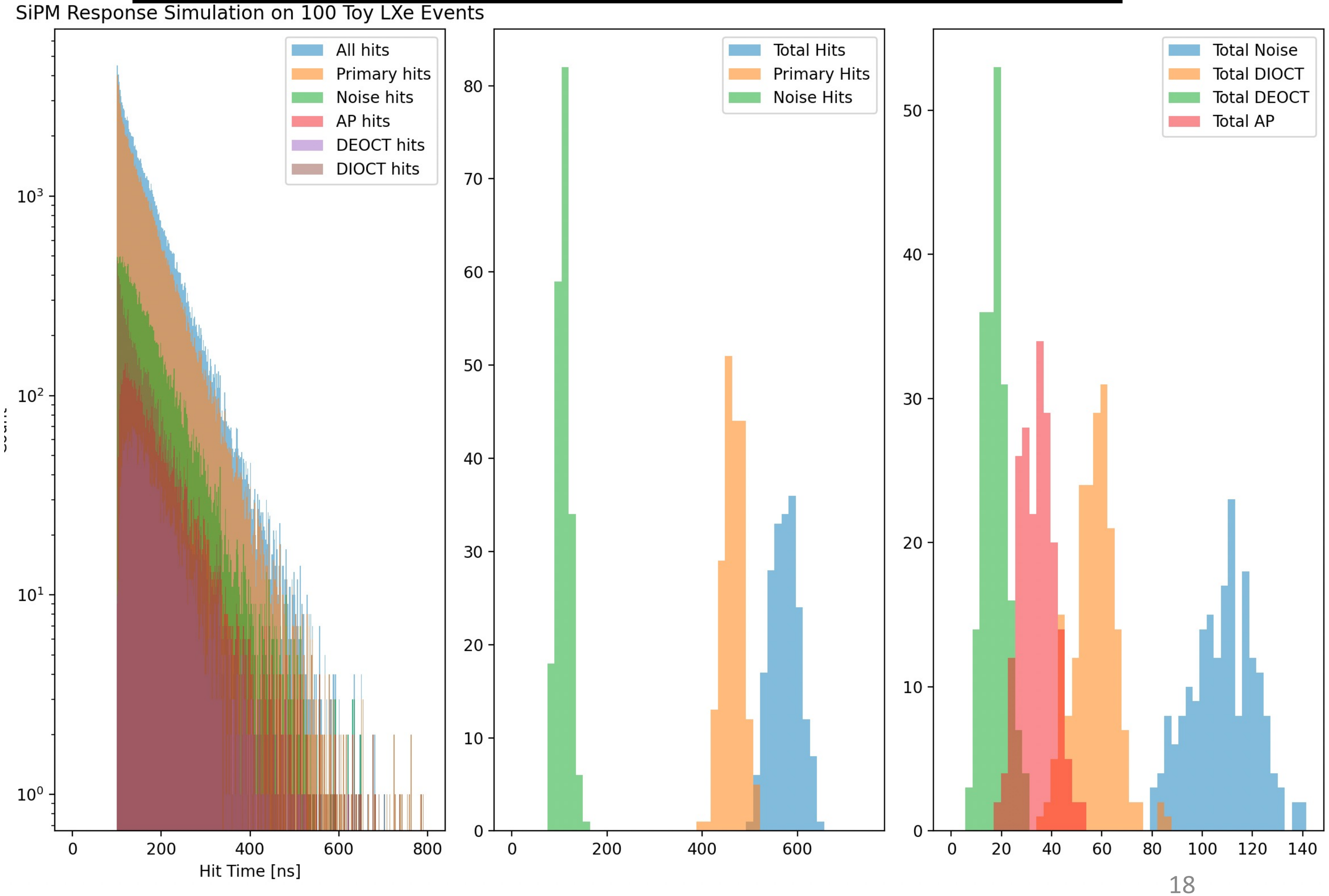
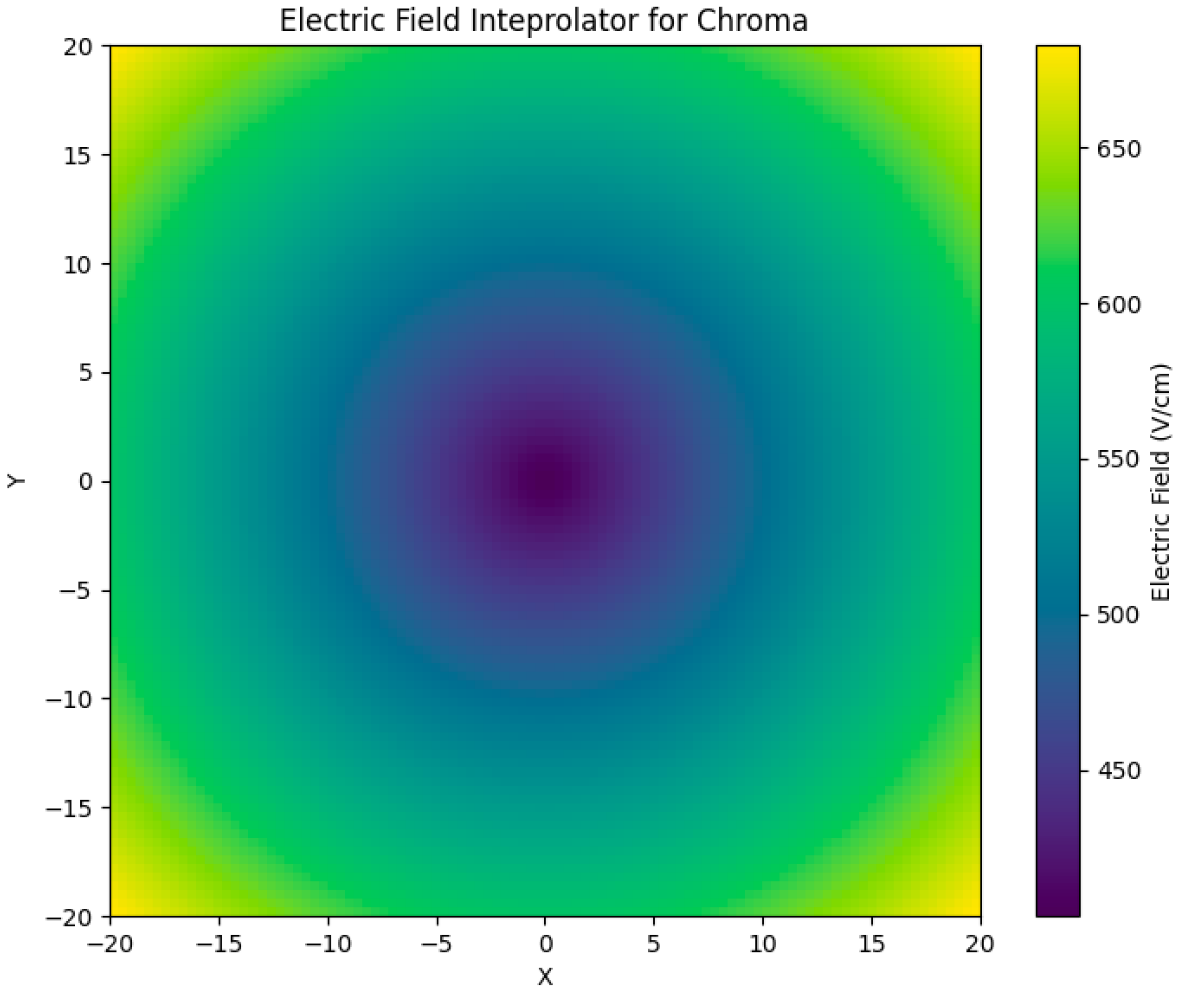
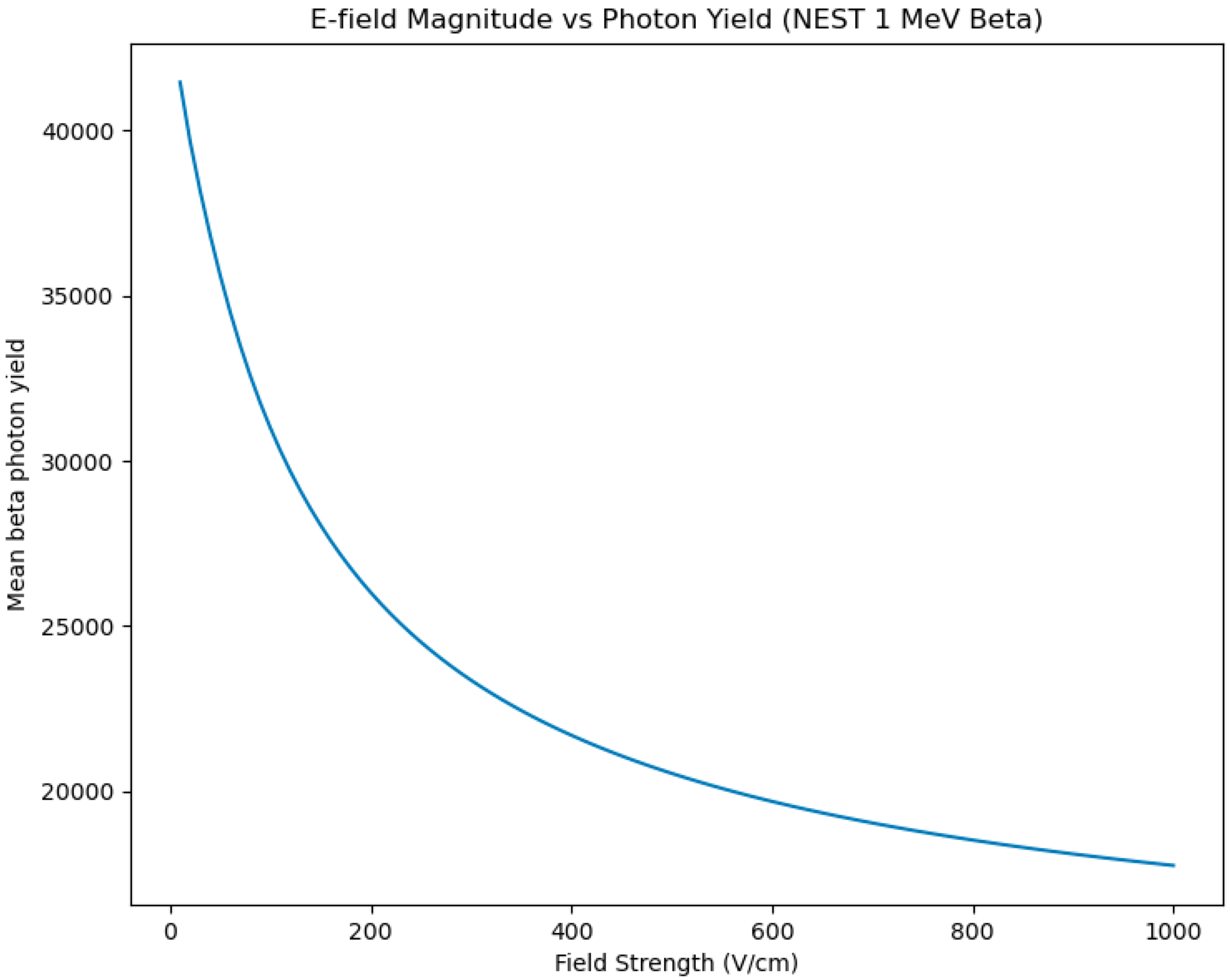


Fig: Preliminary test results of SiPM response simulation, simulating response and contribution of SiPM correlated noise to energy estimation with place-holder noise values

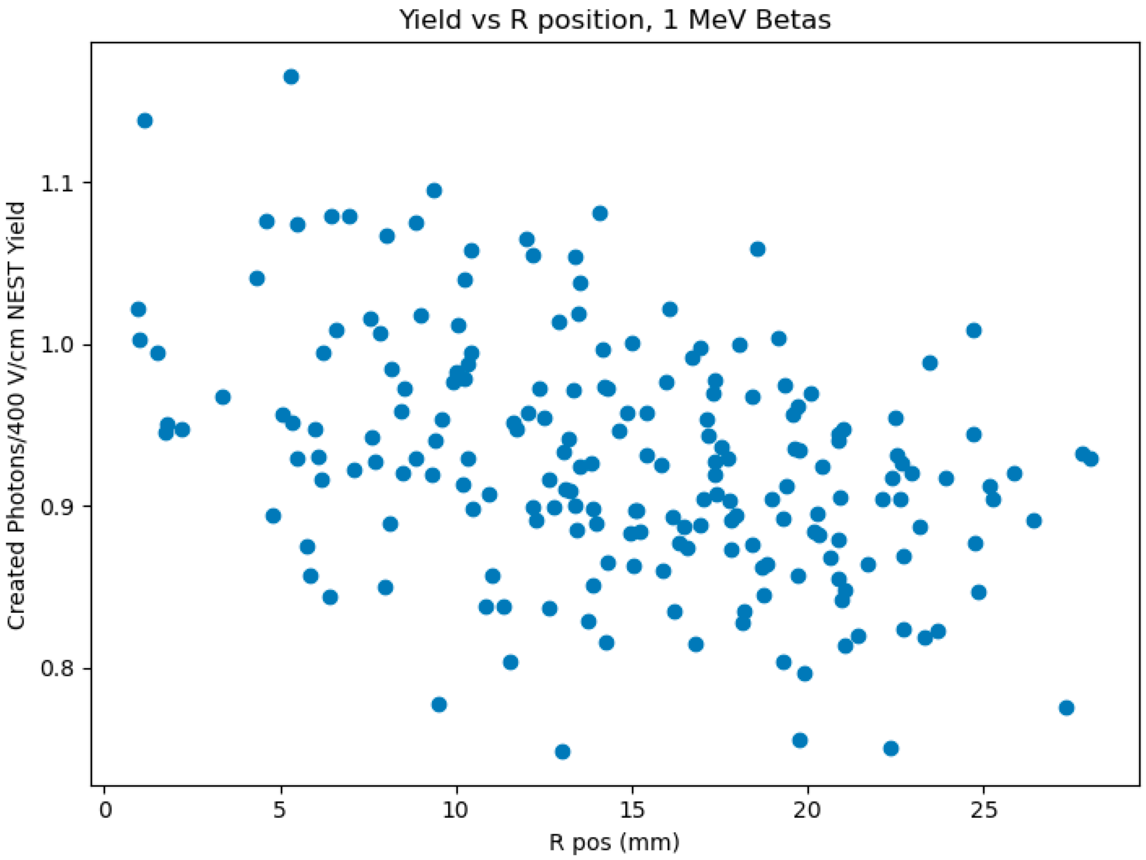
Backup – NEST + Field interpolator

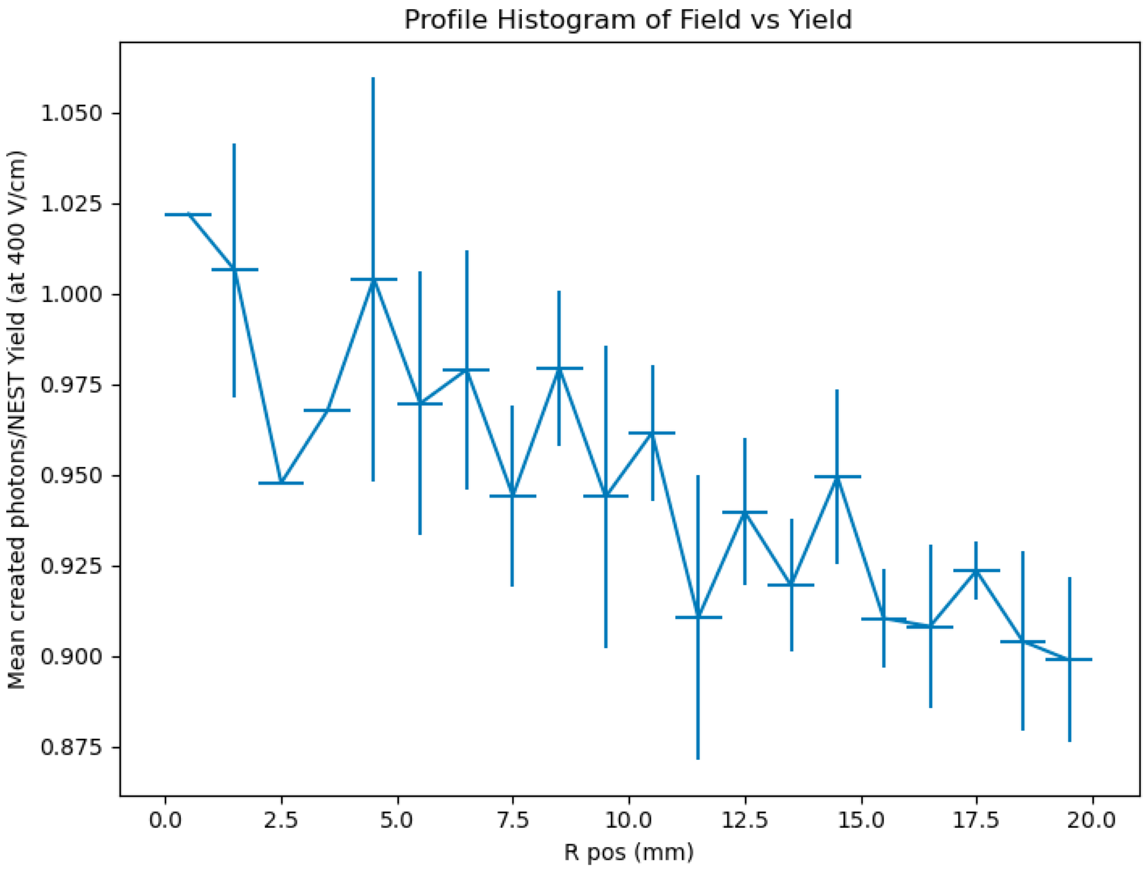




Backup – NEST Field interpolation tests

LoLX



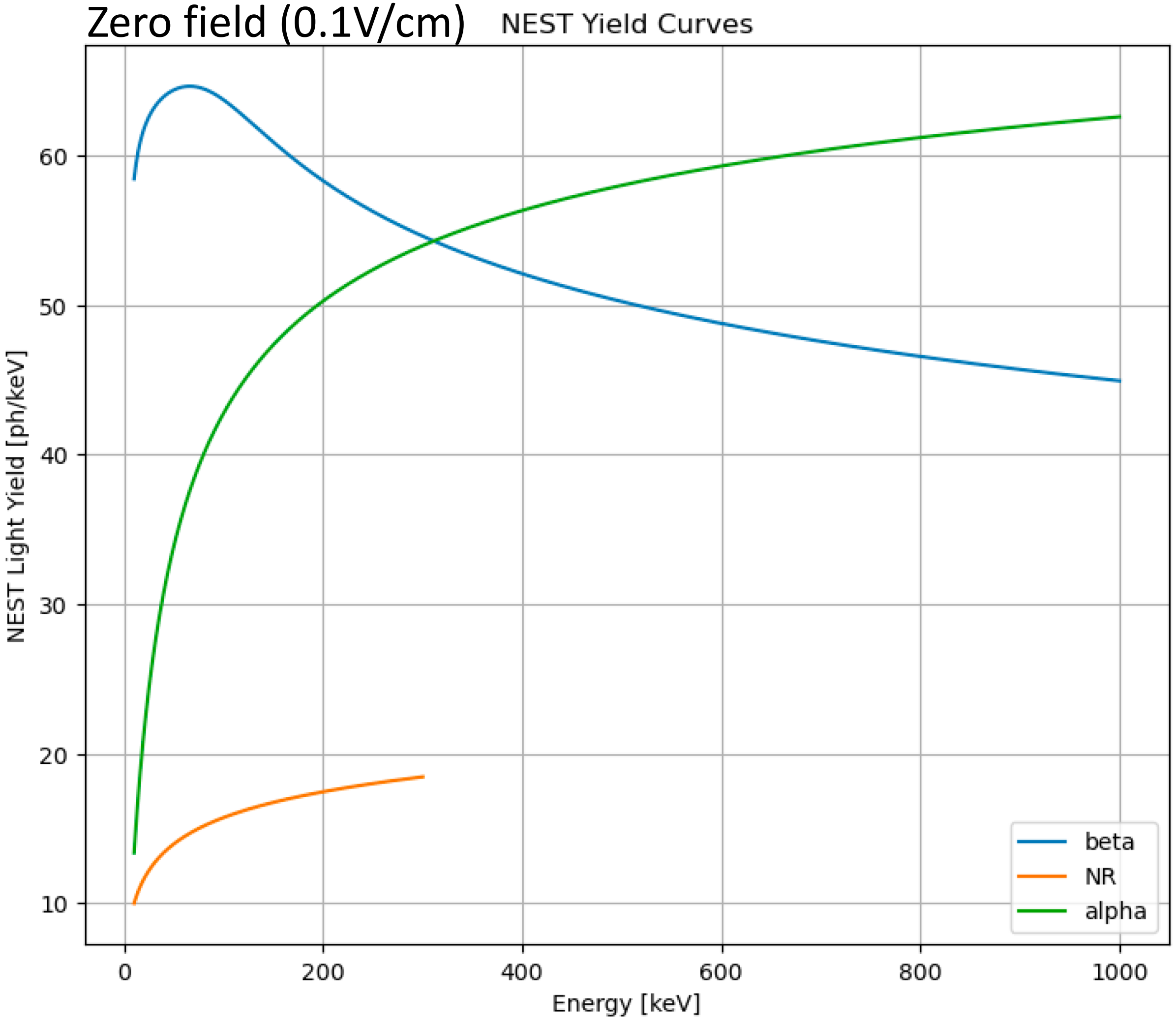


Using LoLX to test, with radial field, (see previous slide), 200 events randomly chosen within LoLX, normalized to 400 V/cm the value at the centre

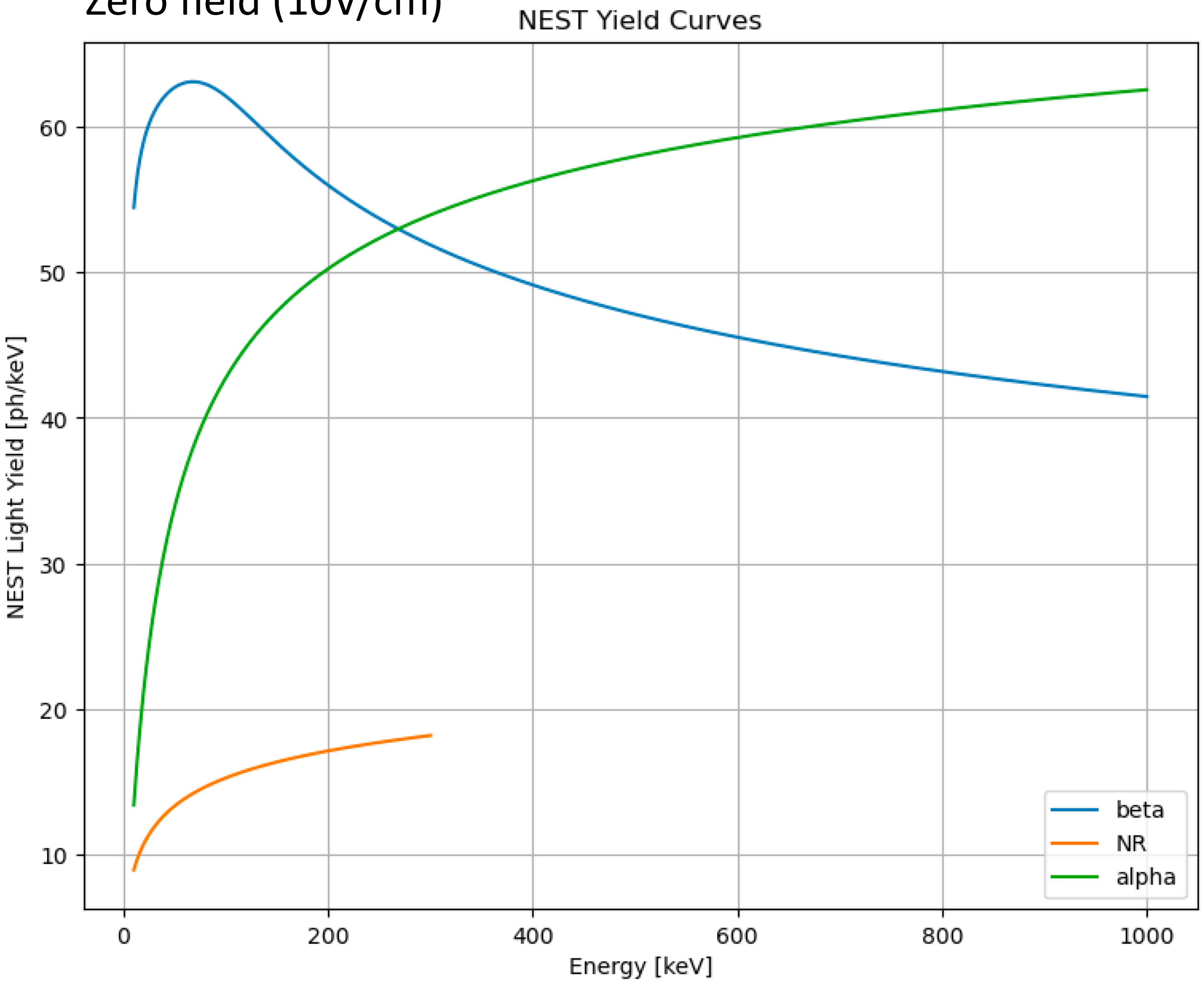
Profile histogram of radial position vs relative yields for 1 MeV betas in LoLX using radial test field (Expected drop to ~0.88, based on truth values)

NEST Yields – Energy and particle

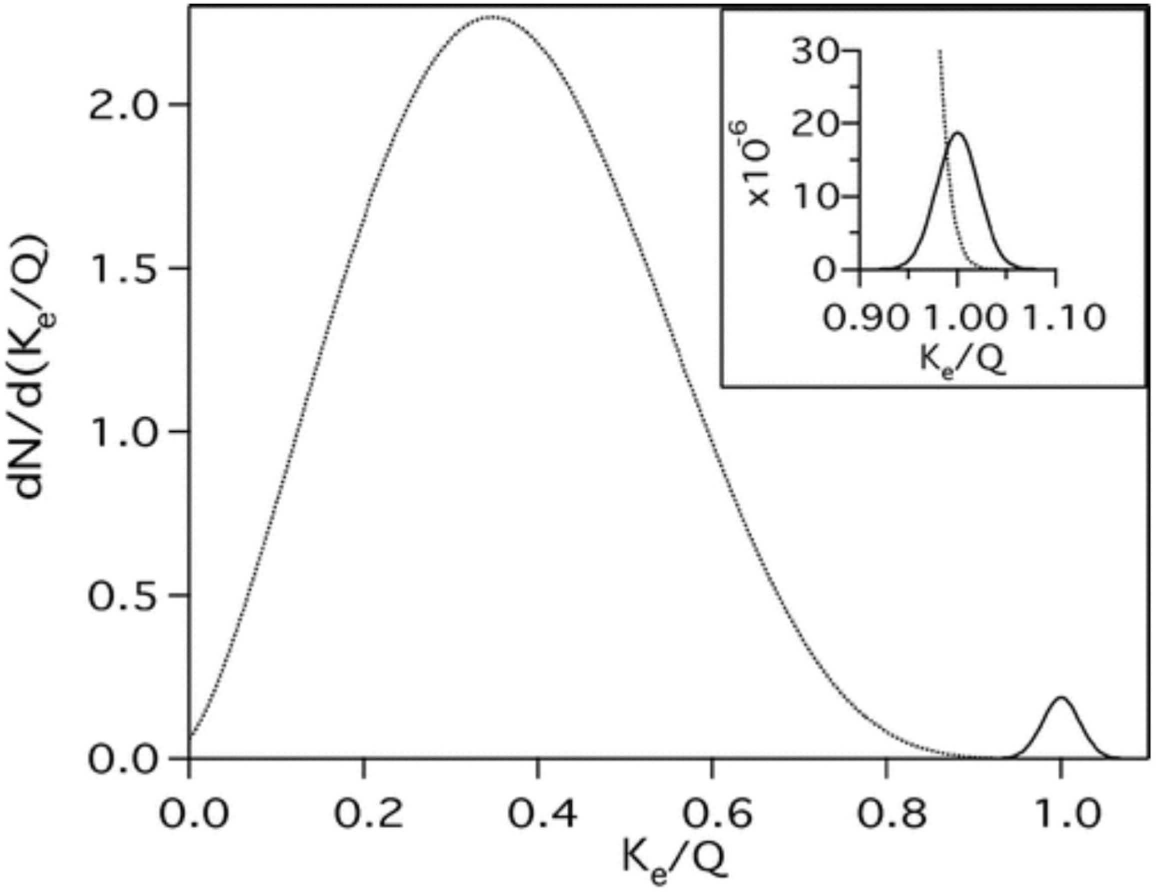
Zero field (0.1V/cm)

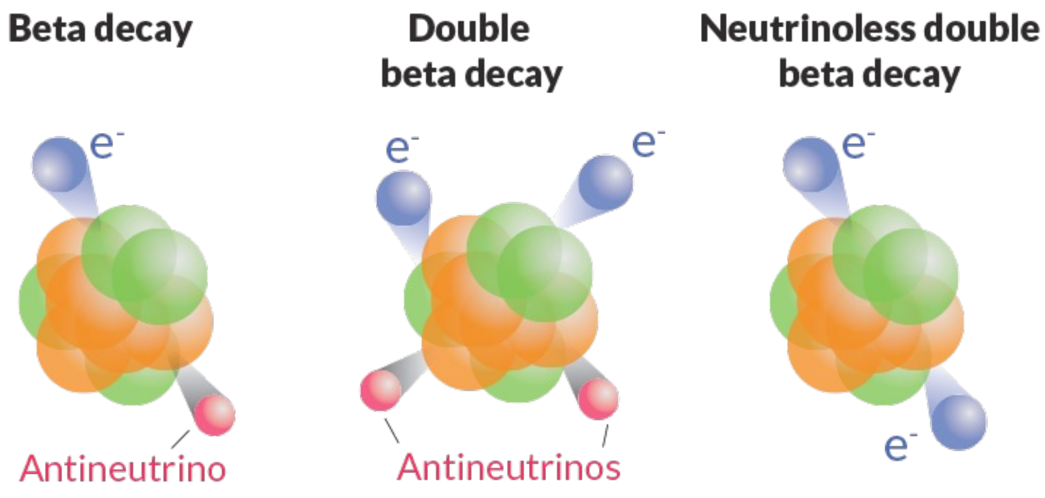


Zero field (10V/cm)

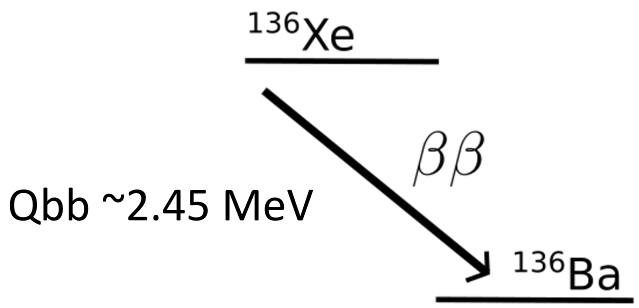


Backup -0vBB

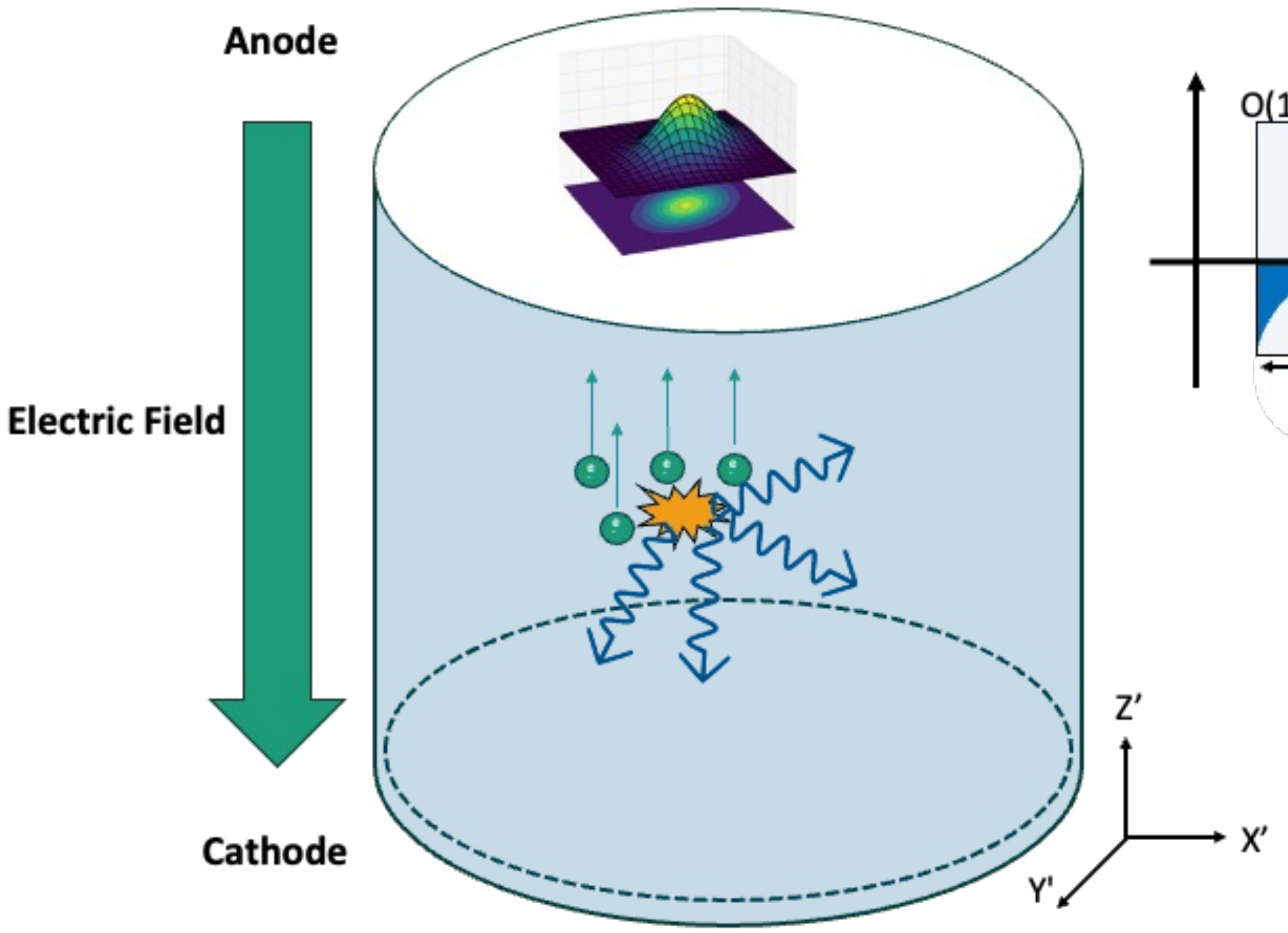




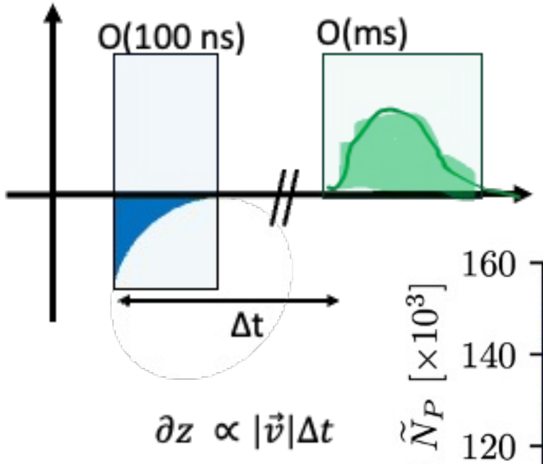
Provides a direct probe into the fundamentals of neutrino interactions



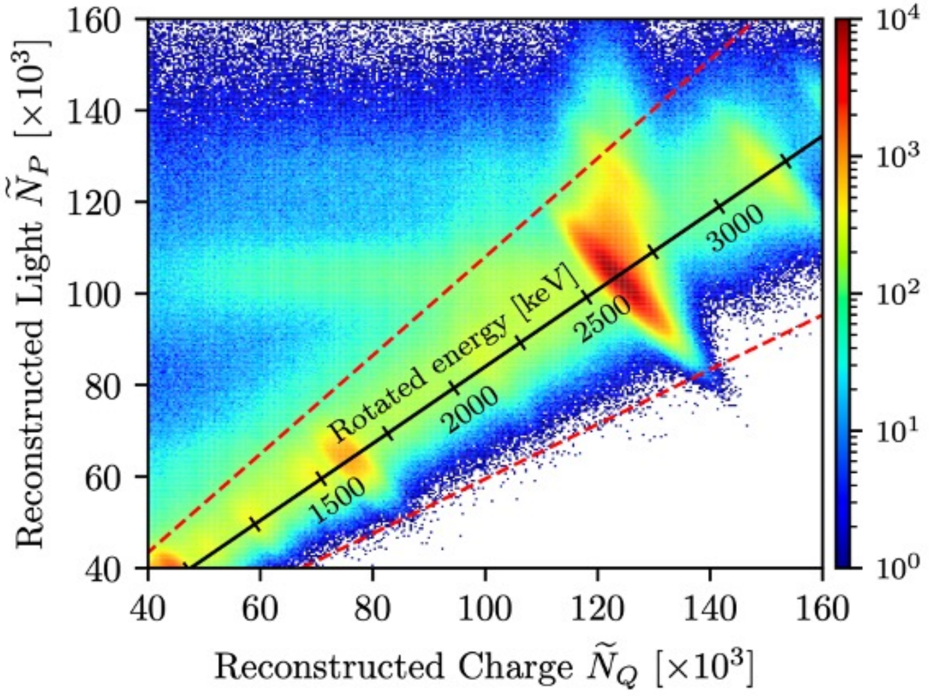
LXe TPC



Anode
Electric Field
Cathode
Z'
X'
Y'

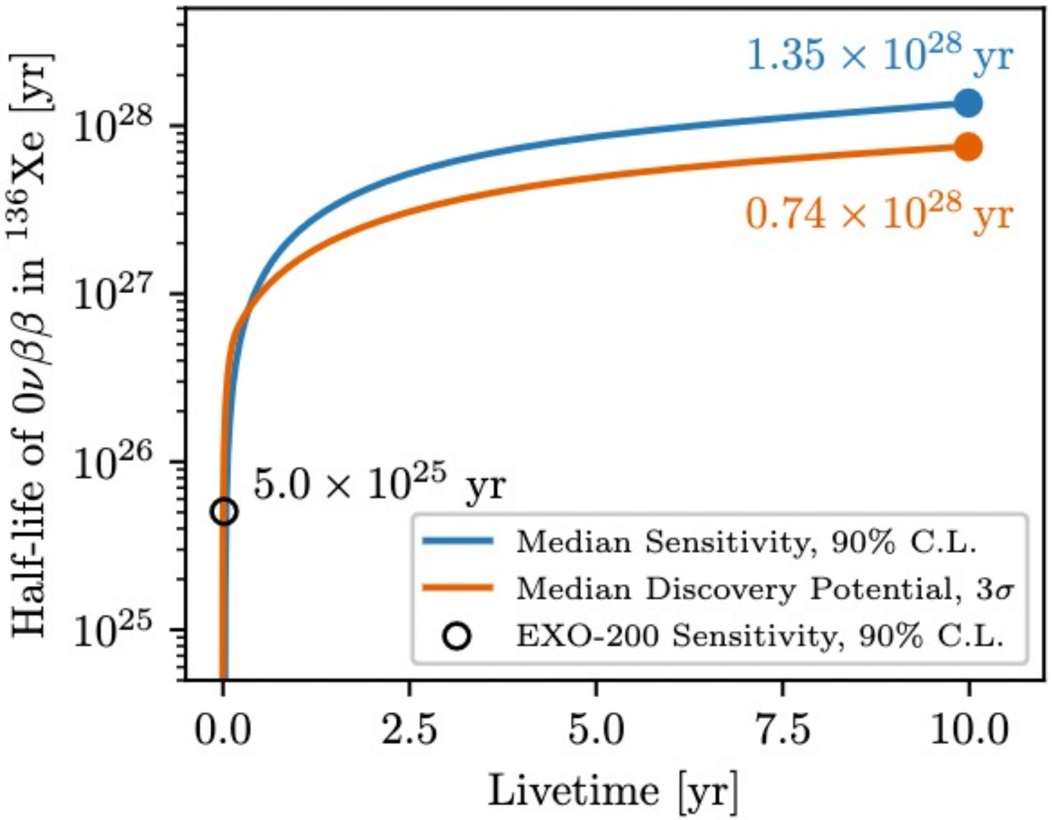


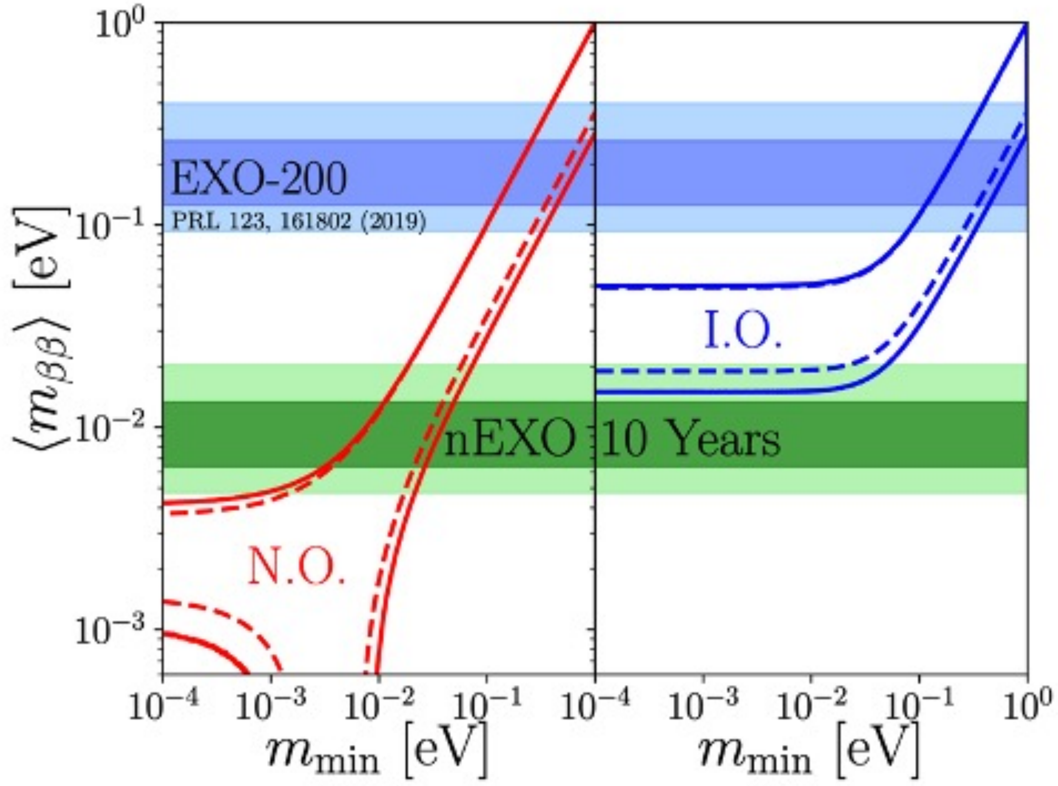
O(100 ns)
O(ms)
Δt
$\partial z \propto |\vec{v}|\Delta t$



Reconstructed Light $\tilde{N}_P$ [$\times 10^3$]
Reconstructed Charge $\tilde{N}_Q$ [$\times 10^3$]
Rotated energy [keV]
1500
2000
2500
3000
40
60
80
100
120
140
160
10^0
10^1
10^2
10^3
10^4

0vBB Sensitivity





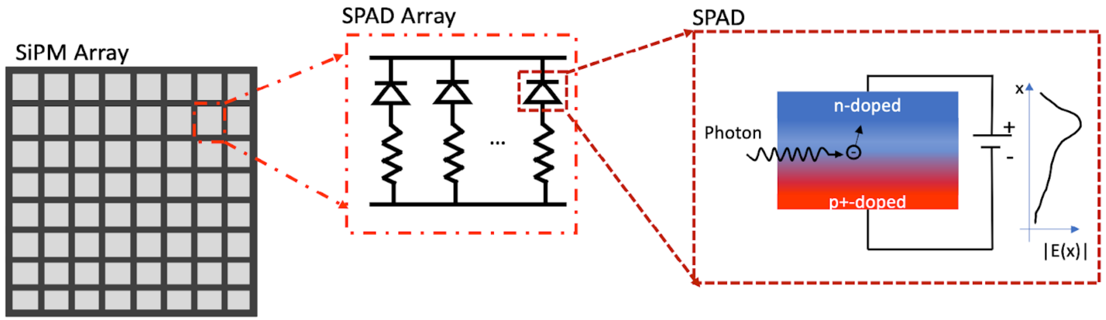


FIGURE 2.10: Illustration of SPADs modelled as a P-N junction within a SiPM array with each channel corresponding to an individual SiPM. Each SiPM is then composed of many such SPADs. Photons ionize atoms in the SPADs depletion region, creating an avalanche of charge that is then readout.

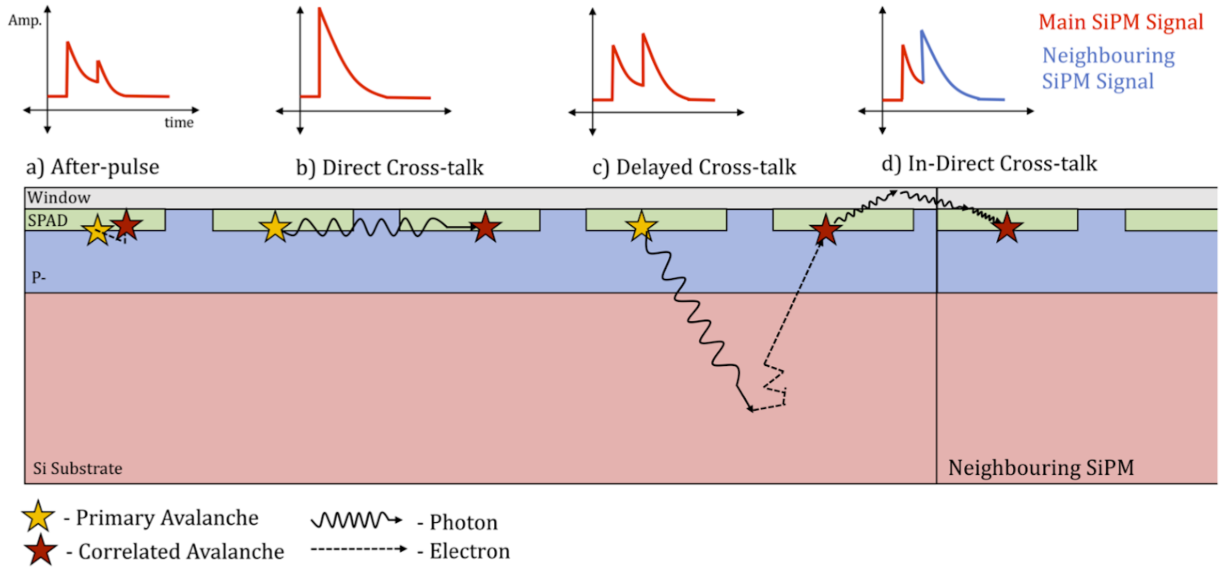


FIGURE 2.11: Illustration for different classes of correlated noise with expected measured pulse-shapes above. a) After-pulsing (AP), b) Direct Cross-talk (Di-CT), c) Delayed Cross-talk (De-CT), and d) In-direct Cross-talk (InDi-CT). Reproduced from [42].