Measurement of SiPM External Crosstalk in a LXe Detector

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LXe detectors & SiPMs

- **Liquid Xenon (LXe)** is a scintillating material that produces ultraviolet light from radiation interactions
- **Silicon photomultipliers (SiPMs)** are solid-state single-photon counting sensors
- We use **SiPMs** to count photons from radiation in **LXe** to perform a proportional energy measurement

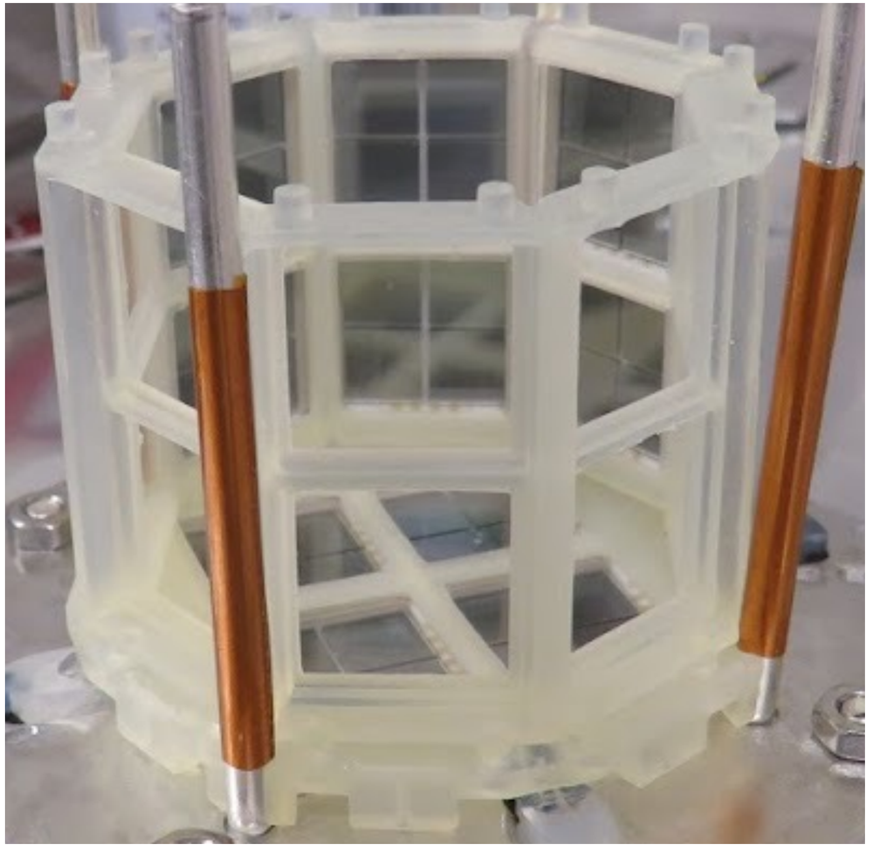


Fig: Hamamatsu VUV4 Packages in LoLX detector during installation

LoLX

- Light only Liquid Xenon (LoLX) is a modular small-scale LXe experiment
    - 📍 McGill University
- Two experimental phases to date:
    - **Phase-1 – This Talk**
    - Phase-2 (See Alex Li's Talk [M2-1-3:00])
- Phase-1 Employed 96 Hamamatsu SiPMs in an octagonal prism geometry
    - Equipped with a ^{90}Sr beta source needle

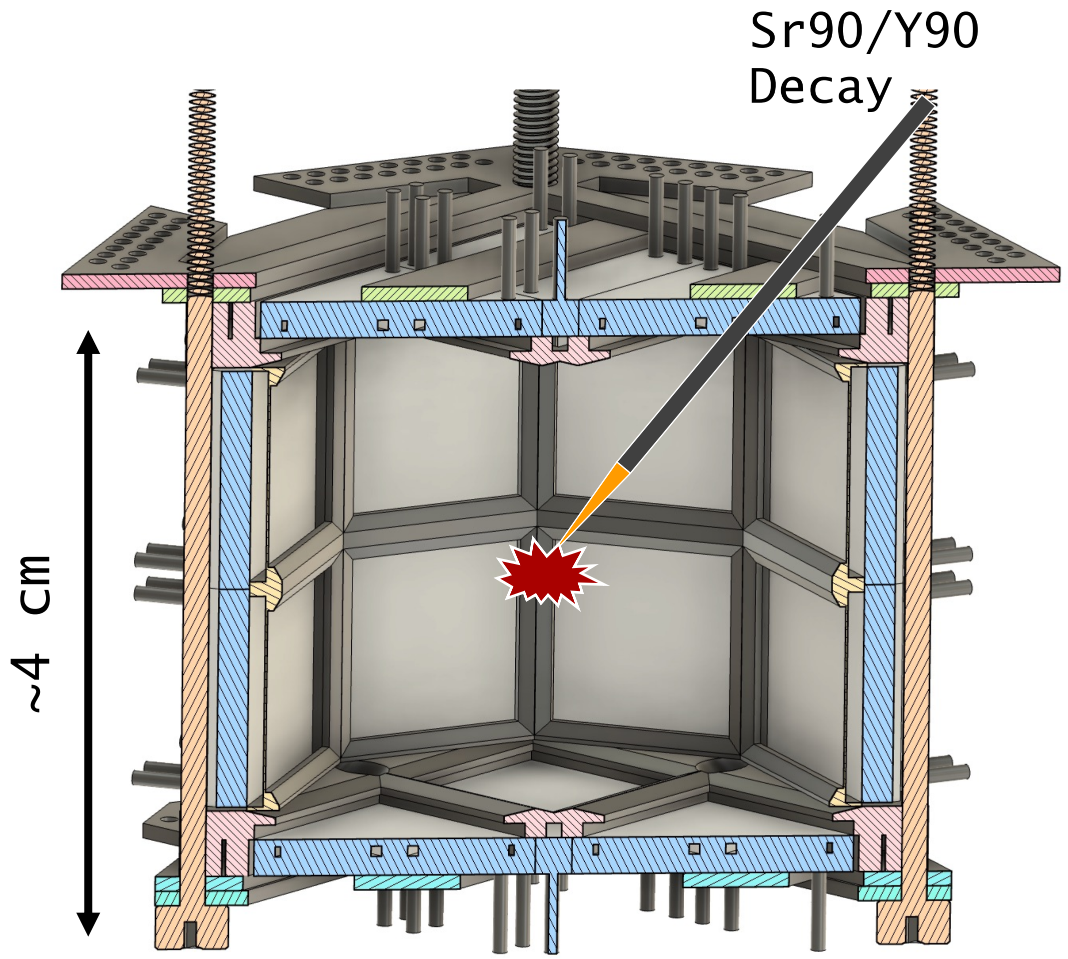


Fig: Cross-section of LoLX Phase-1 Detector

LoLX

- SiPMs are grouped in **packages of 4**
- 23/24 packages are covered by optical filters
  - 22x >220 nm longpass filters
  - 1x 175 nm bandpass filter
- Filters separate **LXe scintillation** from **SiPM External Crosstalk**

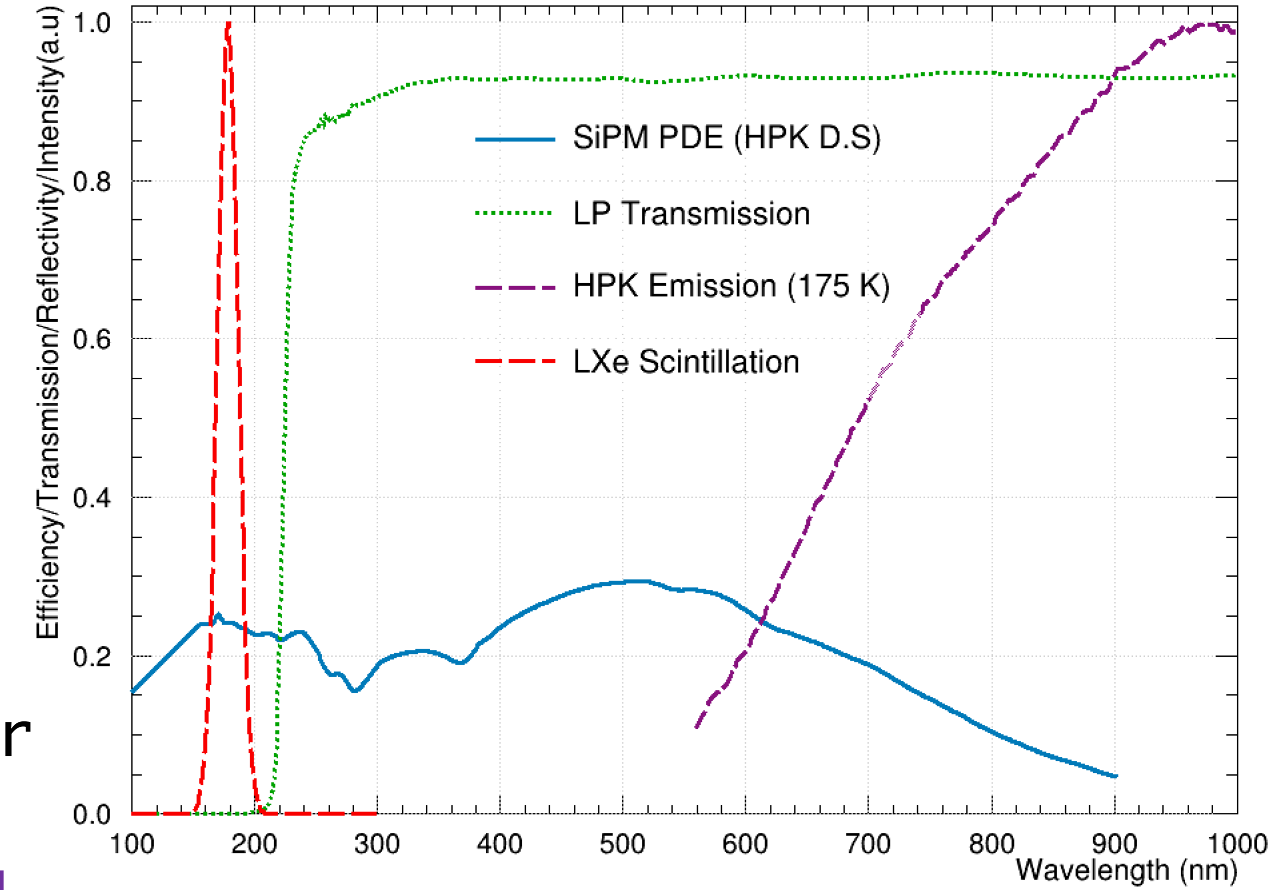
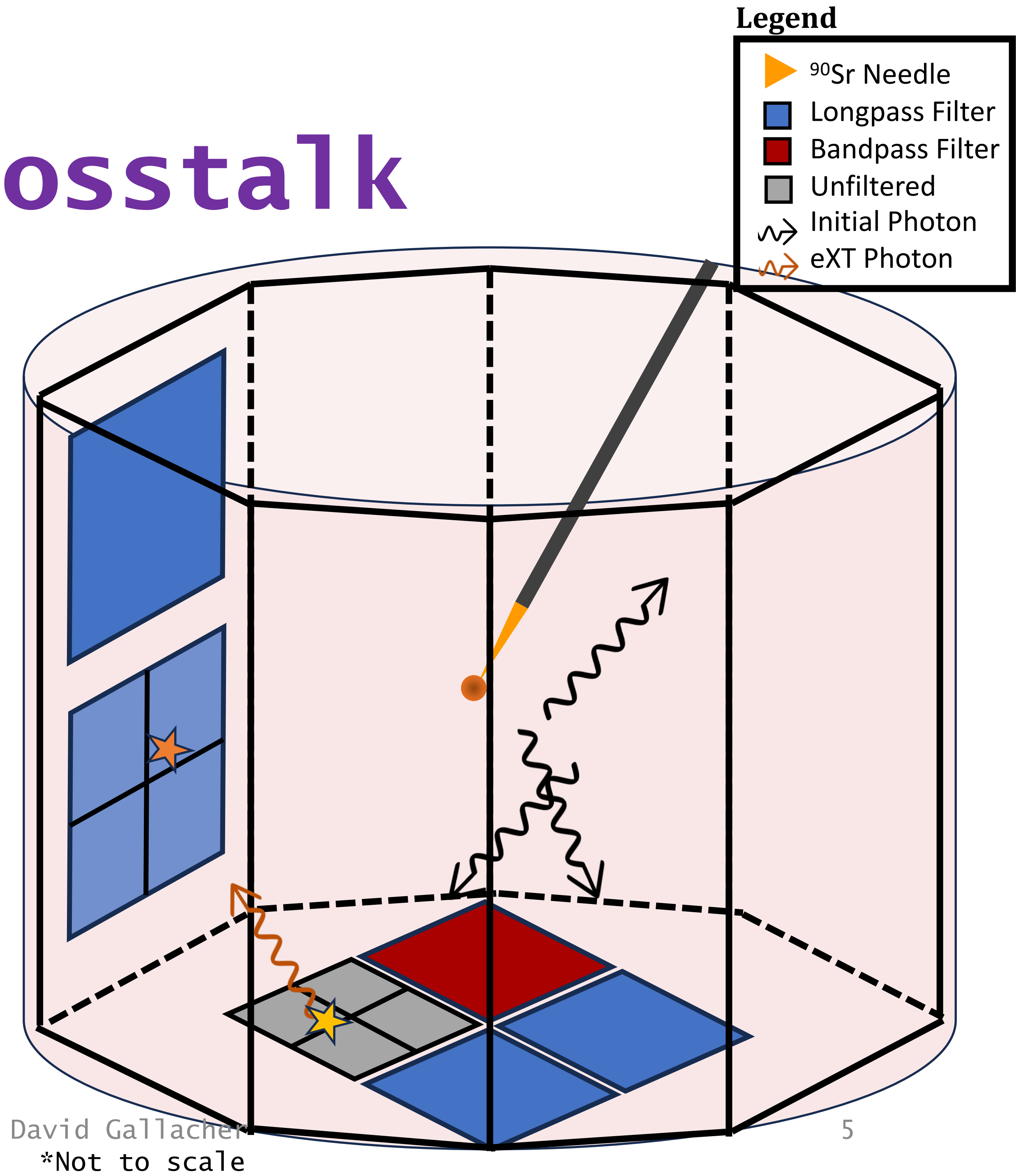


Fig: Overview of wavelength-dependent optical properties in LoLX

SiPM External Crosstalk

- During the SiPM detection process near-infrared (NIR) photons are produced
- These photons may escape the SiPM and be detected elsewhere
  - Known as SiPM External Crosstalk or ExCT
- This is a source of **correlated avalanches (CA)**
- Our goals:
  - Characterize **SiPM ExCT** in a LXe detector
  - Create a simulation model of ExCT to predict impact on future LXe detectors



What's the impact?

- Next generation rare event search experiments will use large quantities of SiPMs
  - **Neutrino-less double beta decay (nEXO)**
  - Dark Matter (ARGO/DS20K)
- Cylindrical geometries enhance ExCT impact
- Need to evaluate the impact of SiPM ExCT on **energy resolution**, threshold and position reconstruction

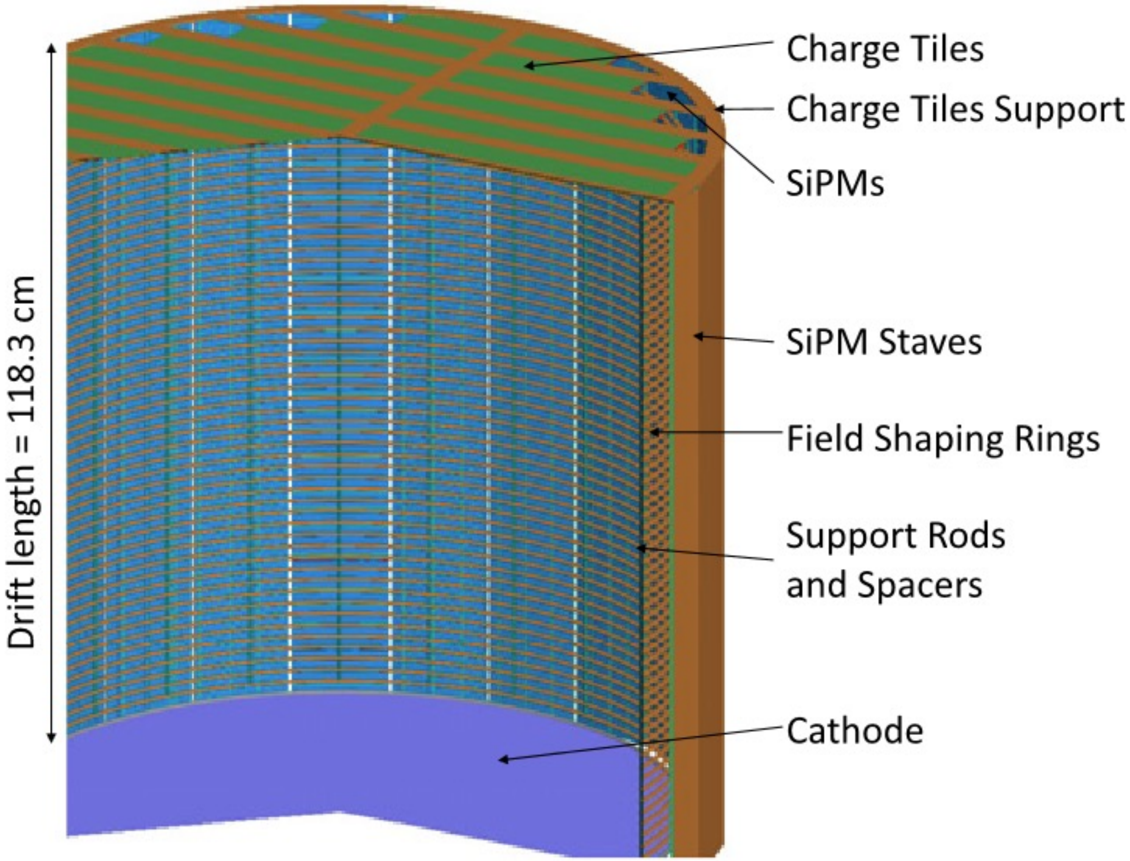
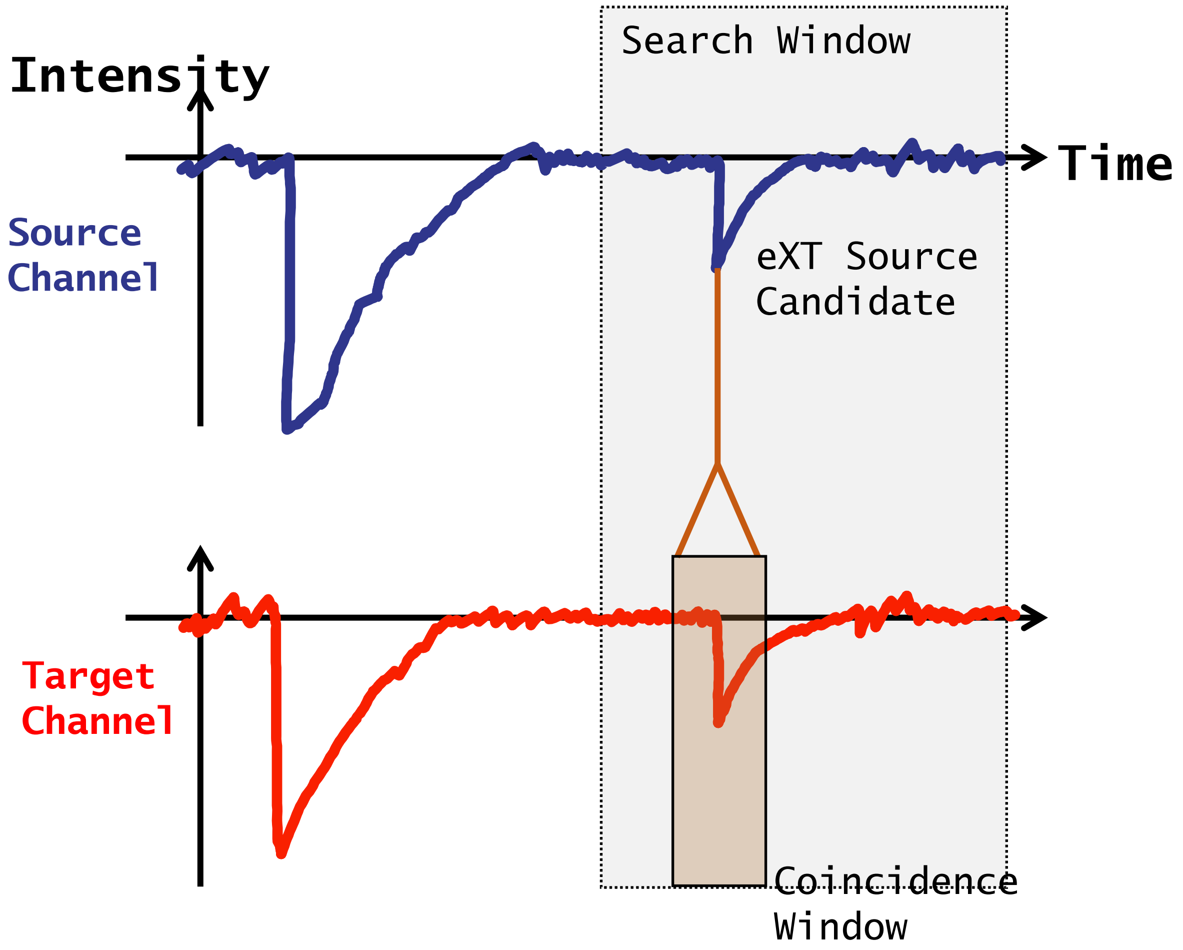


Fig: Rendering of nEXO TPC design, SiPM barrel faces inward with ~50k devices

Measuring SiPM ExCT with LoLX

- To measure SiPM ExCT we look at **time**
- Signature of ExCT is two pulses in time coincidence from two different channels
- We look **late** in the event window for **correlated delayed pulses**



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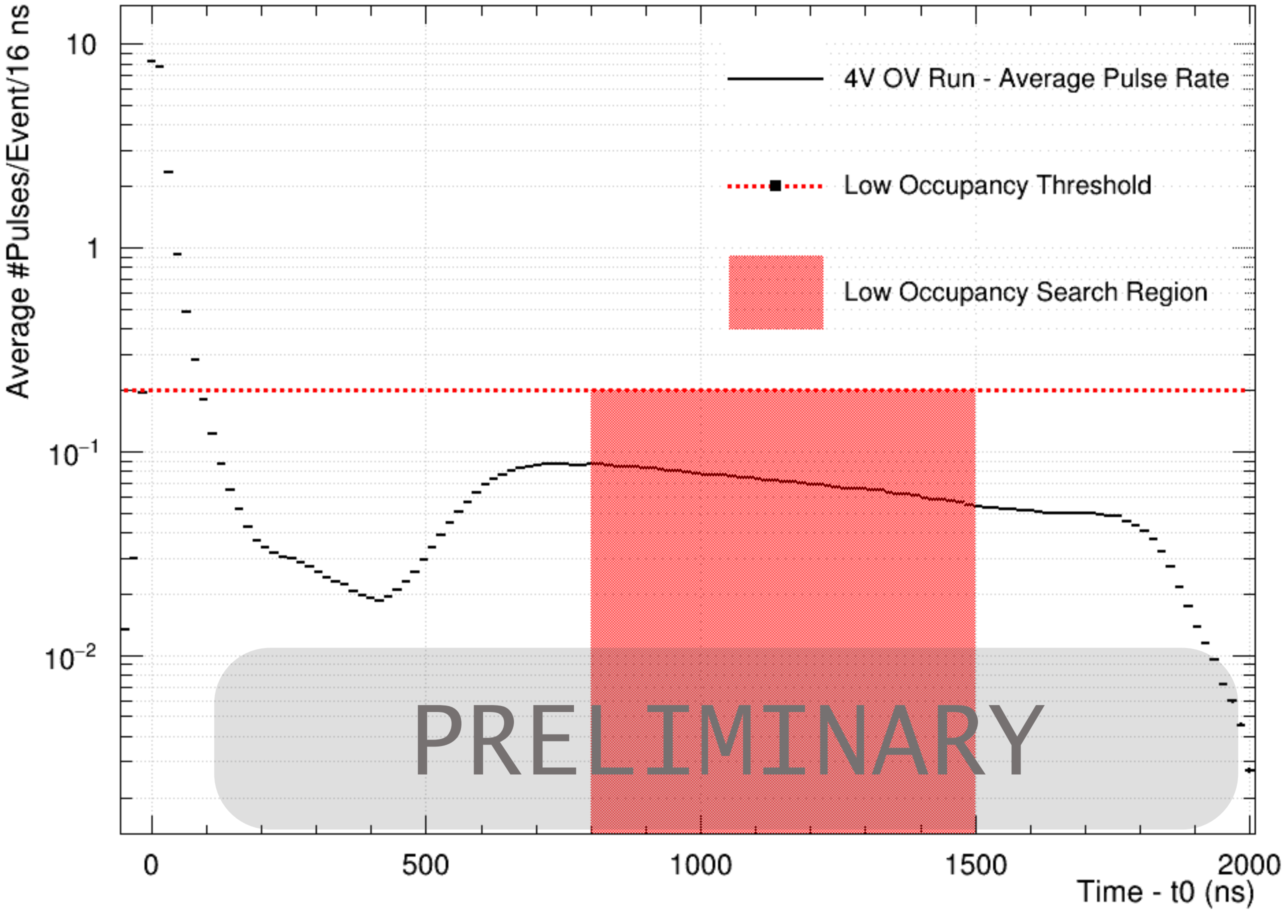


Fig: Occupancy for all channels in LoLX, search window is [800,1500 ns] post trigger

How do we see ExCT?

- By collecting pairs of pulses in the low-occupancy region we build a distribution in Δt
  - Pairs are between unfiltered “source” and longpass filtered “targets”
- Excess at $\Delta t = 0$ over combinatorial background is attributed to **SiPM ExCT**
- Repeat for each run and voltage (4 + 5V OV)

$$P_{corr,source} = \frac{N_{correlated} - N_{background}}{N_{source}}$$

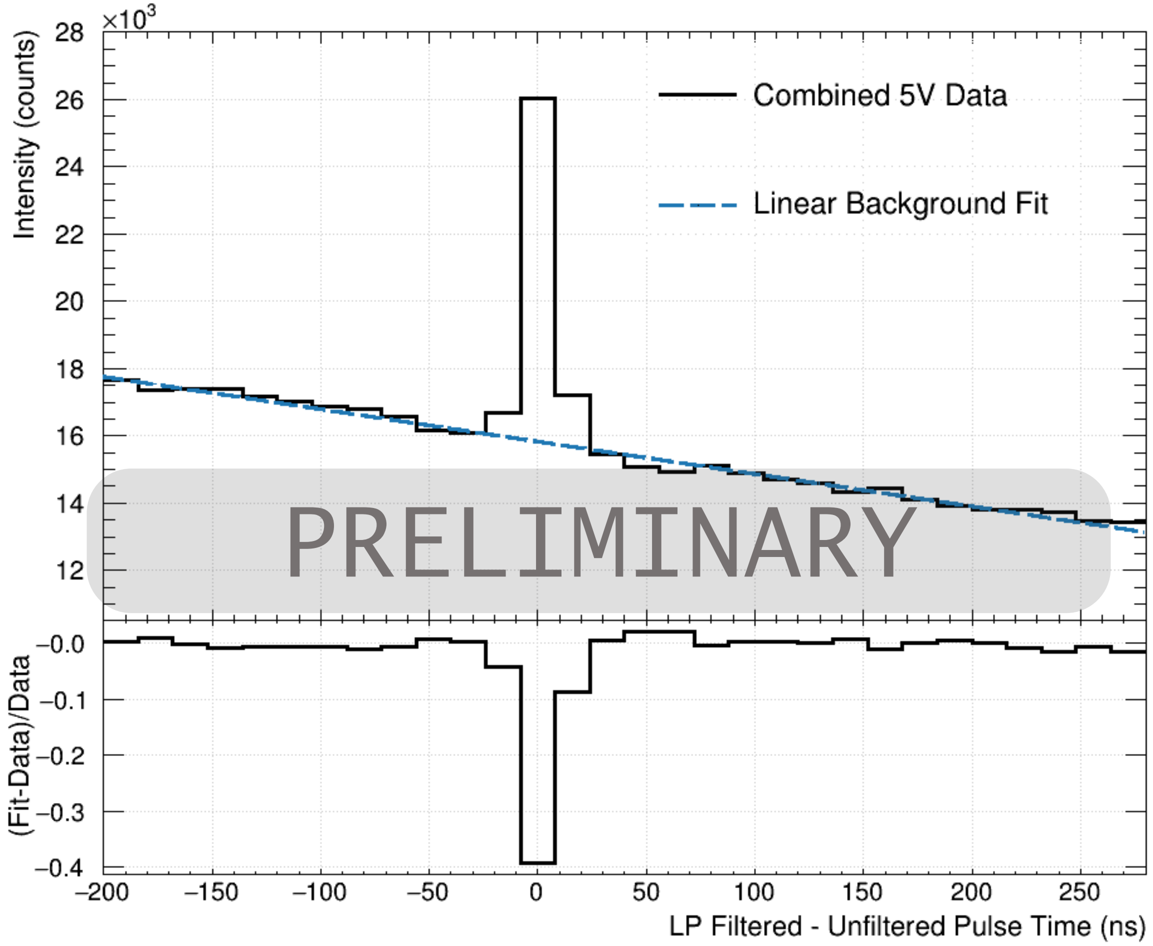


Fig: Fit to summed delta-time distribution for all 5V data summed

ExCT simulation model

- Simulations of SiPM ExCT carried out using custom GEANT4 physics extensions
- Similar implementation to fluorescence in GEANT4
  - For each "detected" photon, we trigger ExCT process and produce photons to track through detector
- Photons are produced "at source" (Within Silicon) with a "Mean emission intensity"
  - **~97% of photons produced in Si do not escape the SiPM**
  - Using input from TRIUMF measurements of ExCT and detailed SPAD simulations†
  - Randomly sample each photon property and determine if it escapes
- Distribution of escaping ExCT photons shown to the right

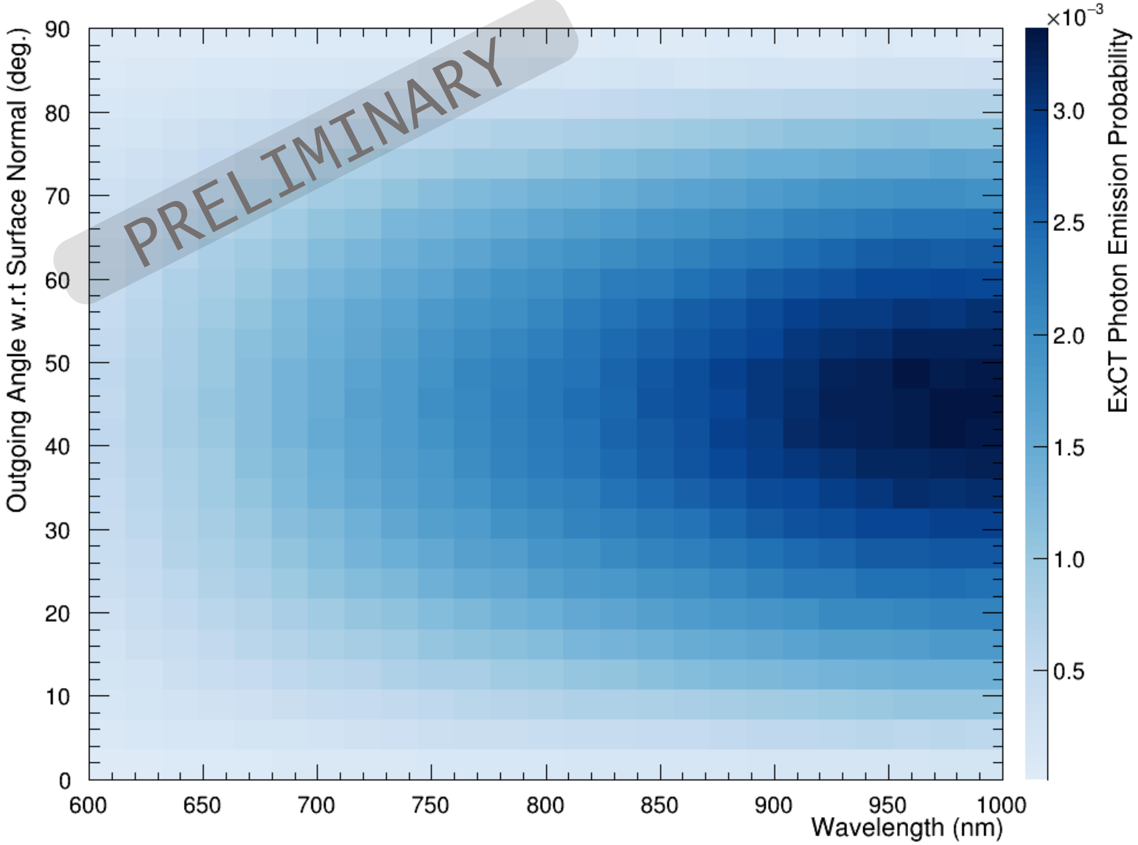
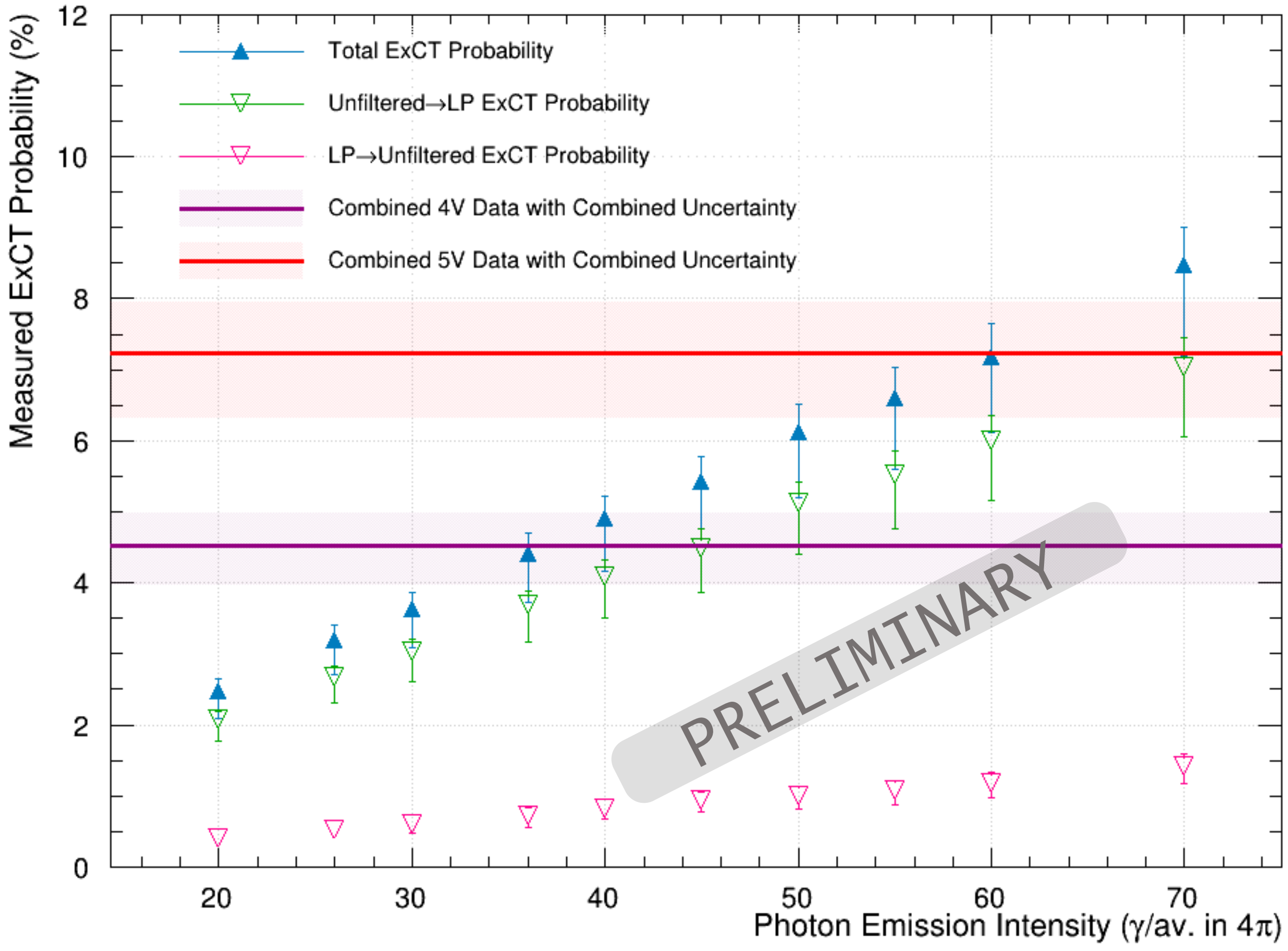


Fig: Distribution of simulated emitted ExCT photons, normalized to proportion of emitted photons in the outgoing hemisphere (2 π)

† K. Raymond et. al. 2024 (2402.09634)

What do we see?

- First sweep over simulated ExCT intensities
  - Mean # of Photons/Avalanche (#ph/av.)
- Compare the measured ExCT yield with simulation results
  - Interpolate simulation curve for #ph/av. **produced** at each voltage
- Determine #ph/av. **emitted** from simulations



What do we see?

PRELIMINARY

Overvoltage	ExCT Probability (%)	Emission within Si (γ/Av.)	Emission into LXe (γ/Av.)
4 V	4.52 ± 0.12 (stat.) $^{+0.43}_{-0.56}$ (sys.)	$37.1^{+7.9}_{-9.0}$	$1.02^{+0.22}_{-0.25}$
5 V	7.21 ± 0.19 (stat.) $^{+0.69}_{-0.89}$ (sys.)	$60.4^{+12.7}_{-15.1}$	$1.66^{+0.35}_{-0.42}$

- **Probabilities are for detecting ExCT from any unfiltered to any longpass filtered channel in LoLX**
- Emission reported as internal (before escaping) and external (transmitted into LXe)
- Systematic uncertainties dominate over statistical at ~10% from data and ~20% from simulations
- Ex-situ measurements reported values 39.2 +/- 9.3 ph/av. and 1.23 +/- 0.43 in LXe†

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Outlook and next steps

- SiPM ExCT measured directly in a LXe detector
- Developed a GEANT4 simulation method for characterizing
- Good agreement between simulation and data with nominal inputs
- Measurement of ExCT emission intensity are within uncertainty of ex-situ measurements†

- Manuscript for this work is nearing completion, keep an eye out soon!
- Building on the simulation method here, we will evaluate the impact of SiPM ExCT for nEXO
- Follow up measurements with faster timing and angular dependence planned in LoLX Phase-2

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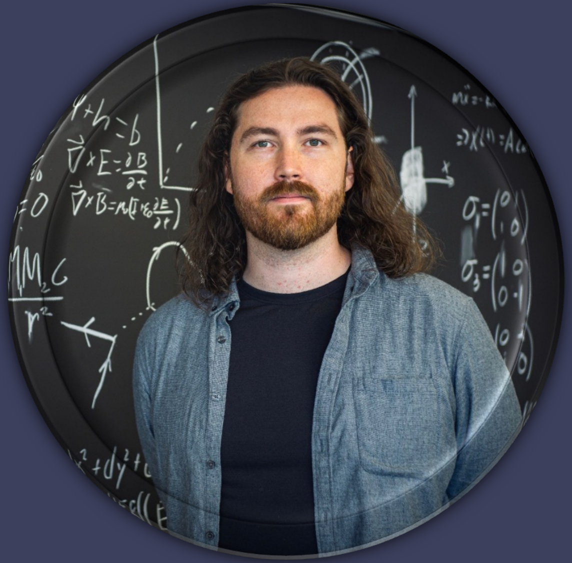
Thank you for your attention from the LoLX Collaboration!

Questions?

Please reach out to get in touch!



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Backup slides

Backup – Event and Pulse Selection

Excerpts from paper draft (in Review, preliminary)

For a given source channel, we search for ExCT source candidate pulses. These are identified as follows:

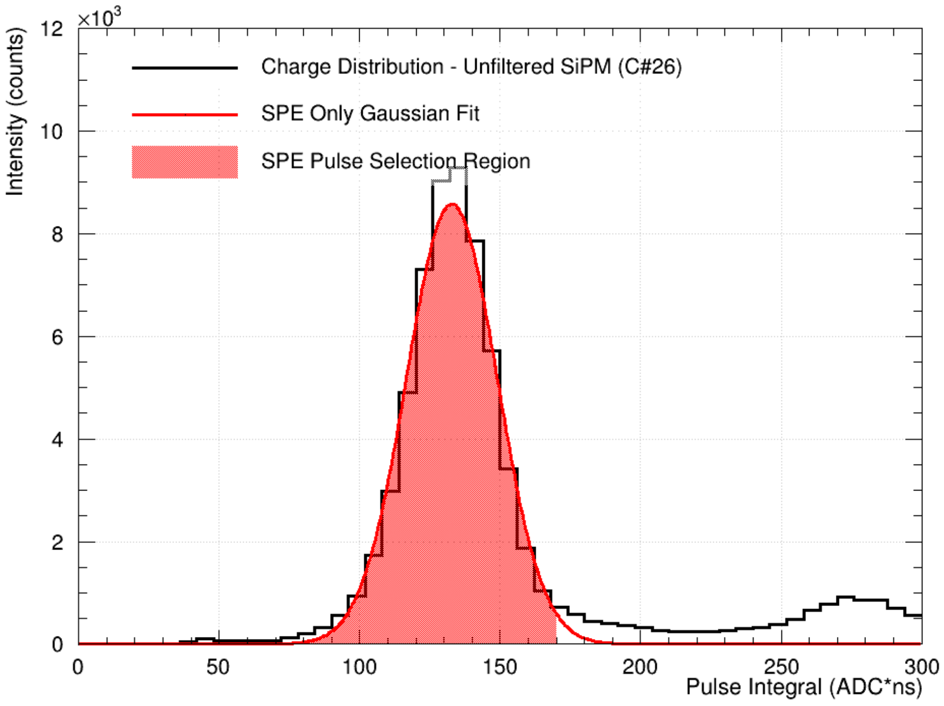
- Occurs within the search window, defined as the region of sufficiently low occupancy (chosen as <0.2 pulses in the window per waveform on average), see Figure 9 for reference.
- Candidate source pulses are SPE-like from charge-based estimation, to ensure approximately constant emission intensity amongst source pulses, SPE selection region is shown in Figure 6
- Candidate source pulses haves no additional subpeaks (no afterpulsing)

Data were taken with a >3 photon equivalent ADC threshold on any channel in the unfiltered SiPM quad. Events selected for analysis must pass a selection of data cleaning and analysis cuts:

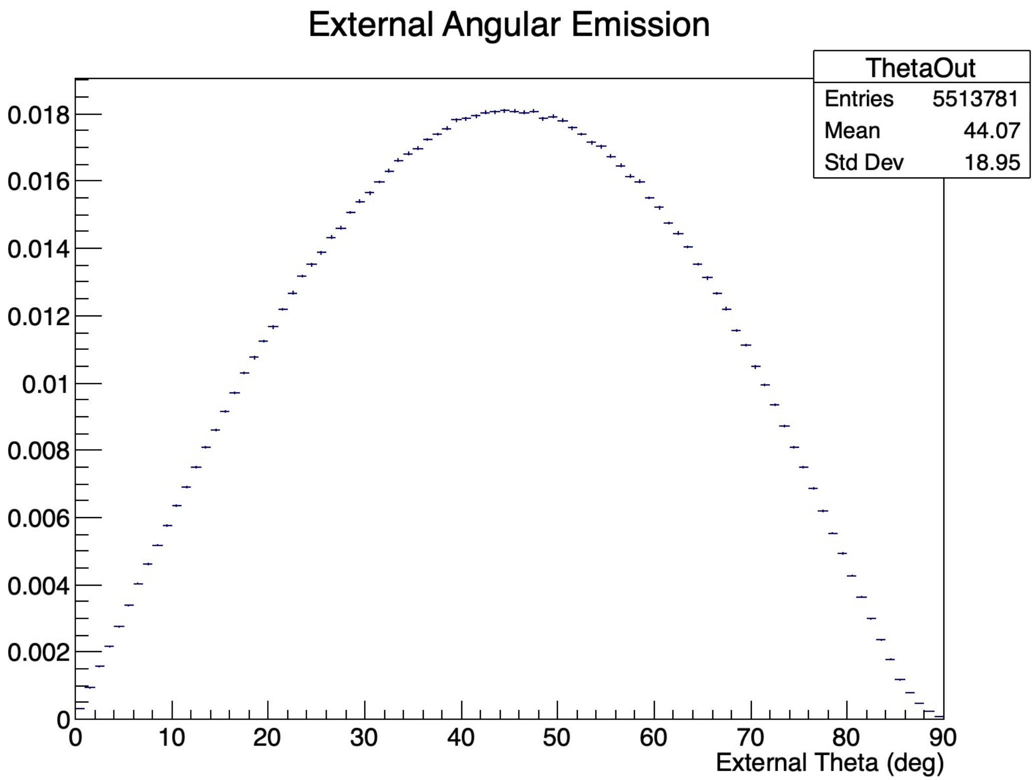
- No channels may clip the digitizer or saturate the devices dynamic range (Removes muon-like events with much higher light output than source events)
- Stable pre-trigger baselines (Removes events with saturation or digitizer clipping in the preceding event)
- Only one trigger candidate per event (Removes accidental pile-up)
- Well-defined start time for the event (No significant pre-trigger light from a pre-trigger pileup low-energy event)

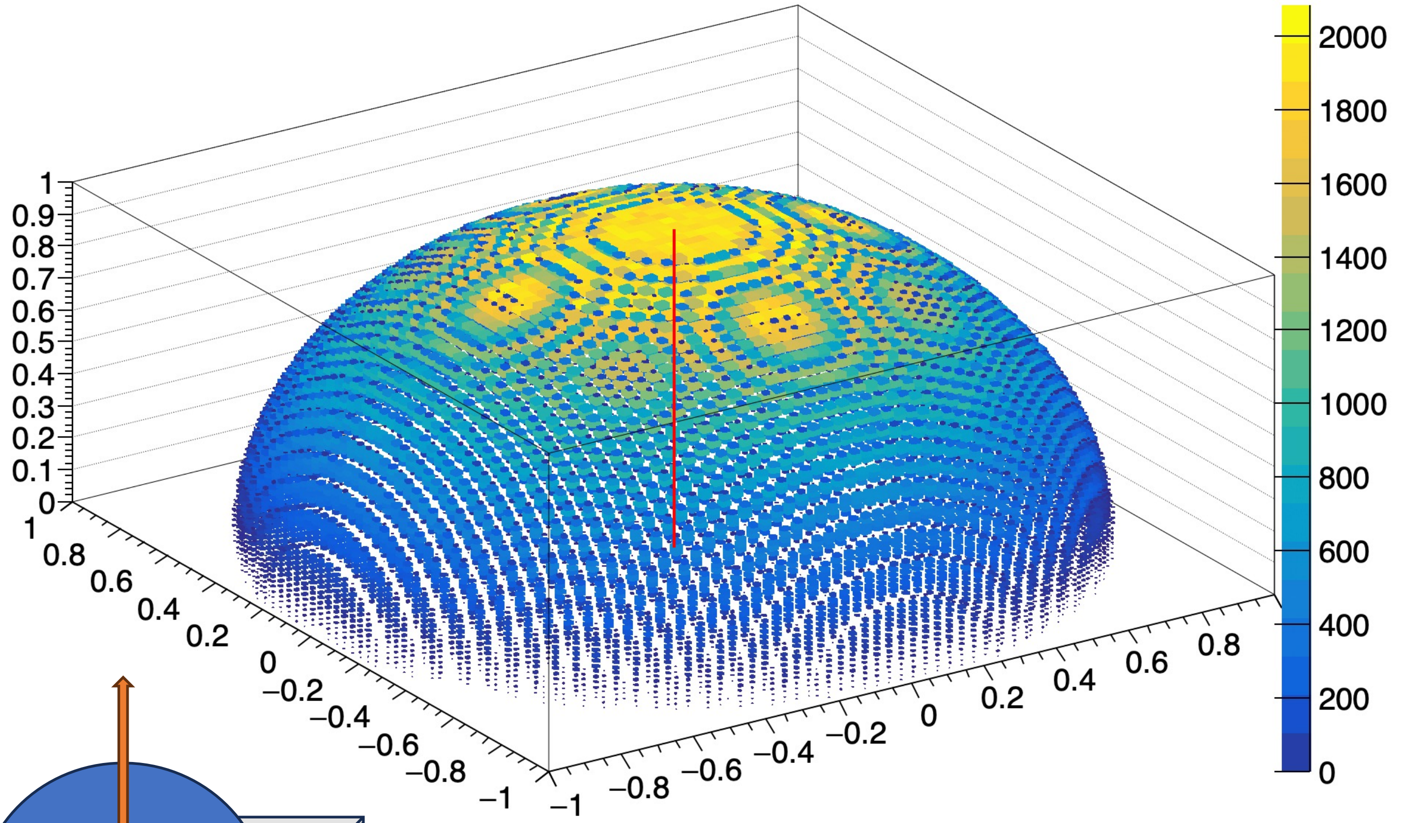
Backup – SPE Selection

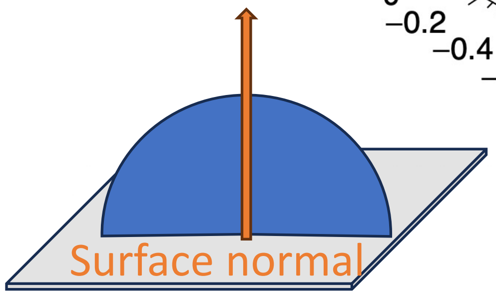
- Maximize our signal/background by using the Unfiltered SiPMs as the "Source" and 220 nm cutoff filtered channels as "Targets"
- To ensure nominal ExCT intensity, we select SPE pulses for source candidates
- SPE selection is done by gaussian fits to each channel with 90% acceptance region
- No after-pulsing permitted

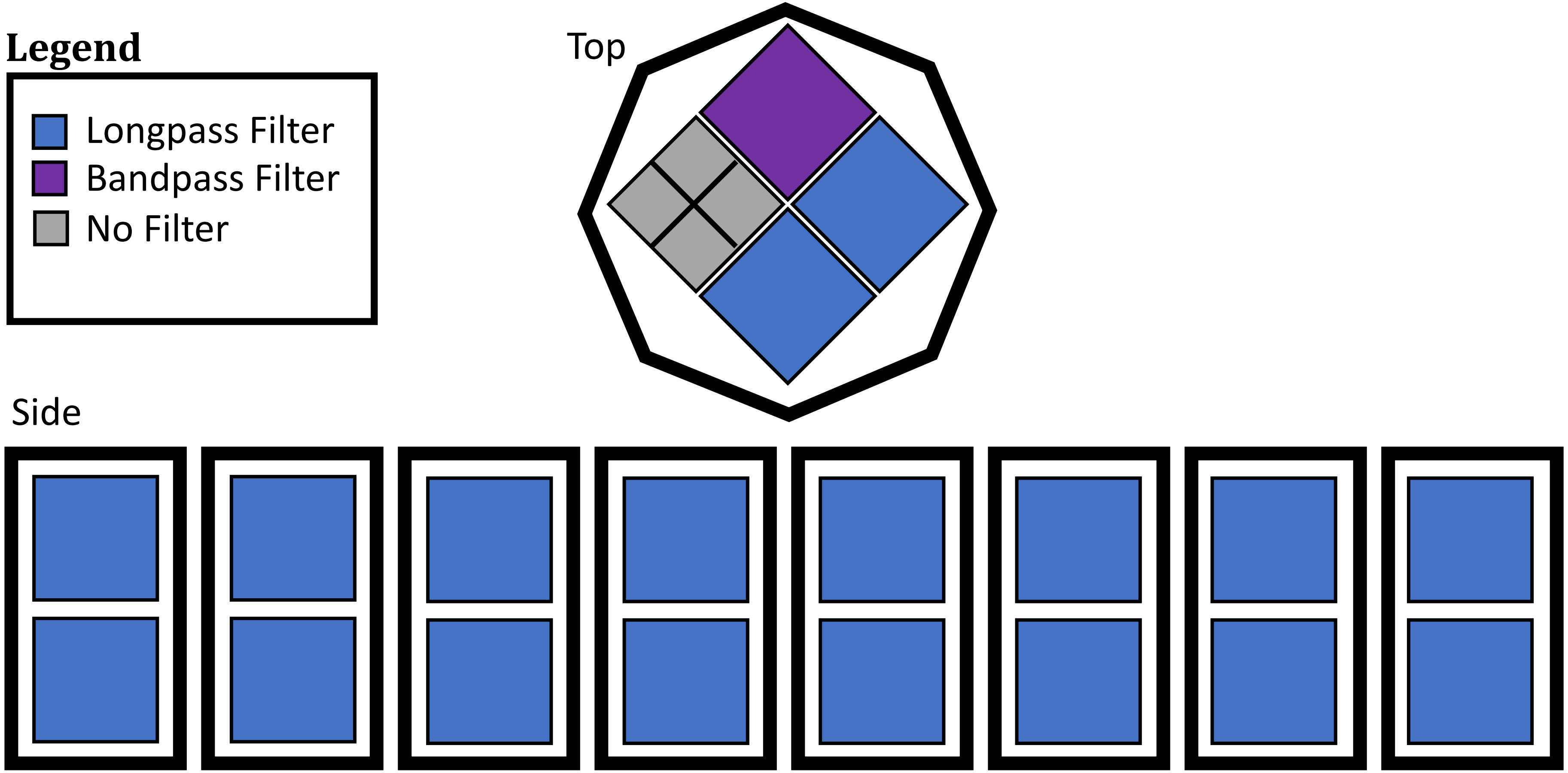


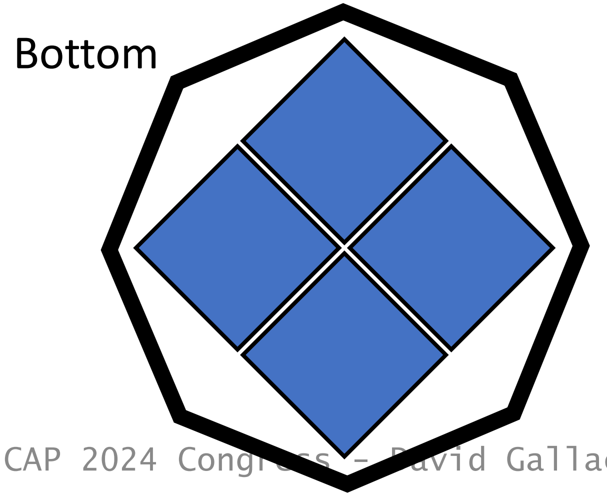
Backup – Simulation Details









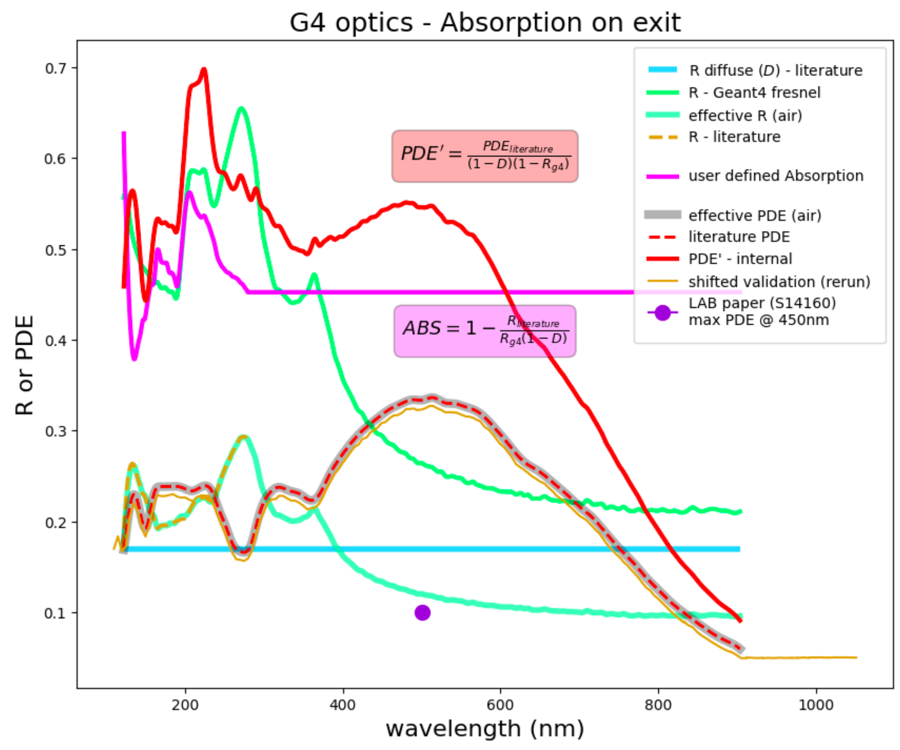


Backup – LoLX outline

Backup – Systematic Budget

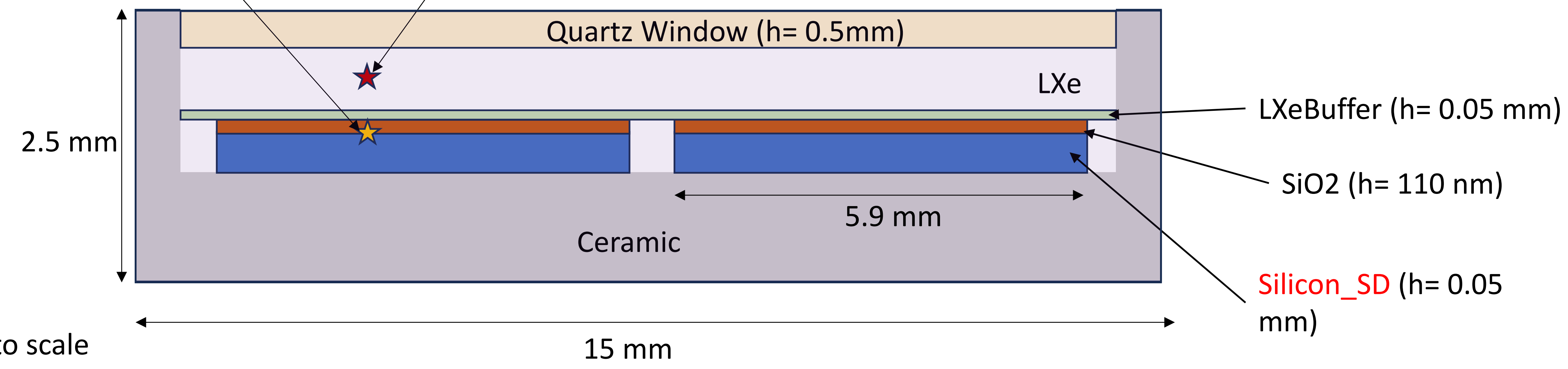
Systematic Name	Type	Variation	Relative Uncertainty (%)
NIR SiPM PDE	Simulation	$\pm$10% Relative	+7.9, -10.6
NIR LP Transmittance	Simulation	$\pm$10% Relative	+1.3, -6.1
Cage Reflectivity	Simulation	-25% Absolute	$\pm$17.2
SiPM OV Spread	Sim. + Data	5% Smear	Negligible
Pile-up Algorithm Threshold	Data	$\pm$ 1 photon equivalent	+7.9, -13.1
DiCT Backwards Correlation Contribution	Sim. + Data	Estimate	$\pm$ 1.6
Total Data Uncertainty			**+9.3, -12.1**
Total Simulation Uncertainty			**+19.0, -21.1**

lolxsim: VUV4Volume



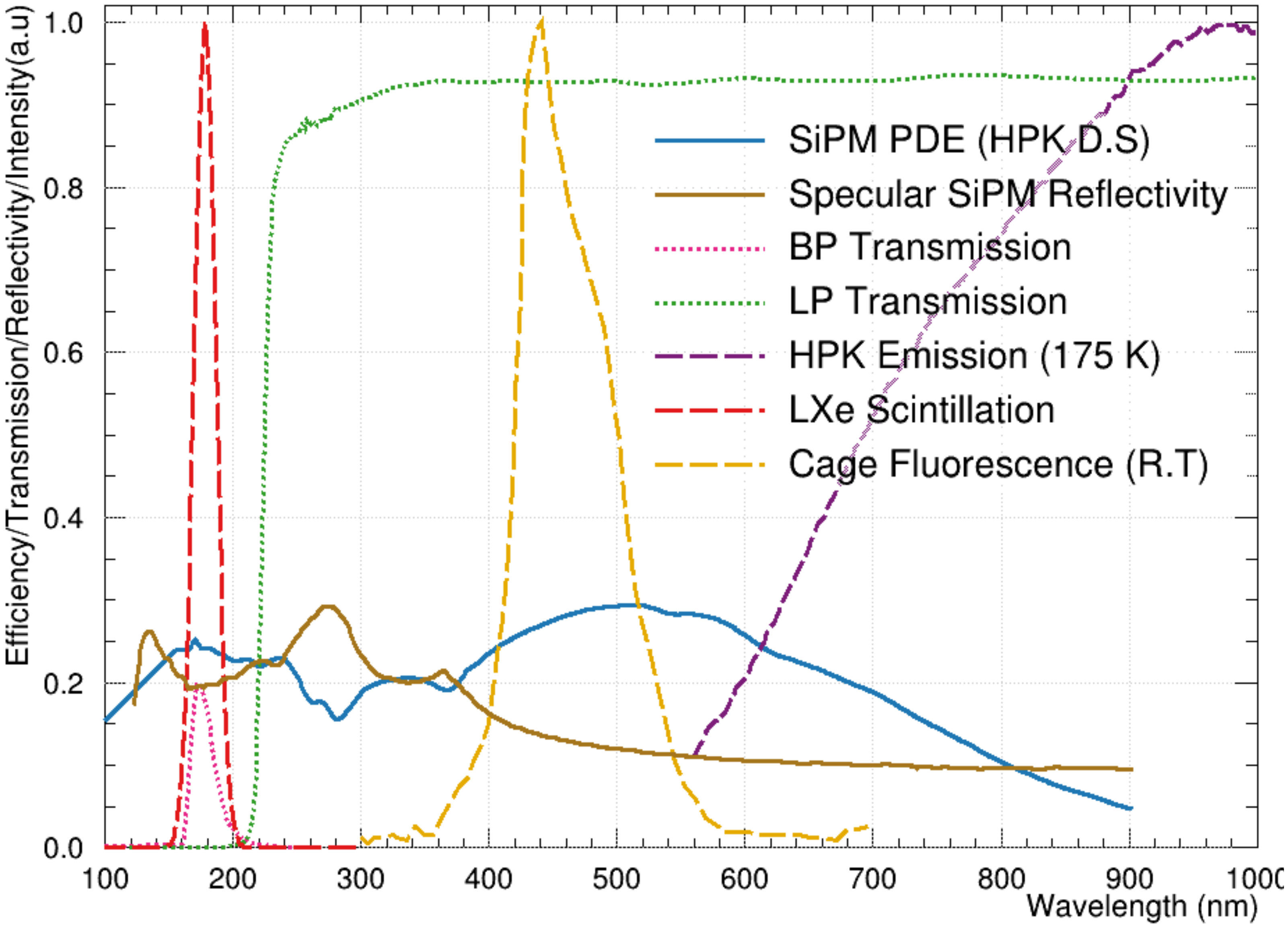
eXT photons generated in the gap to avoid doubling optics at boundaries(shift 0.2mm along surface normal)

Photons detected at Si boundary



*not to scale

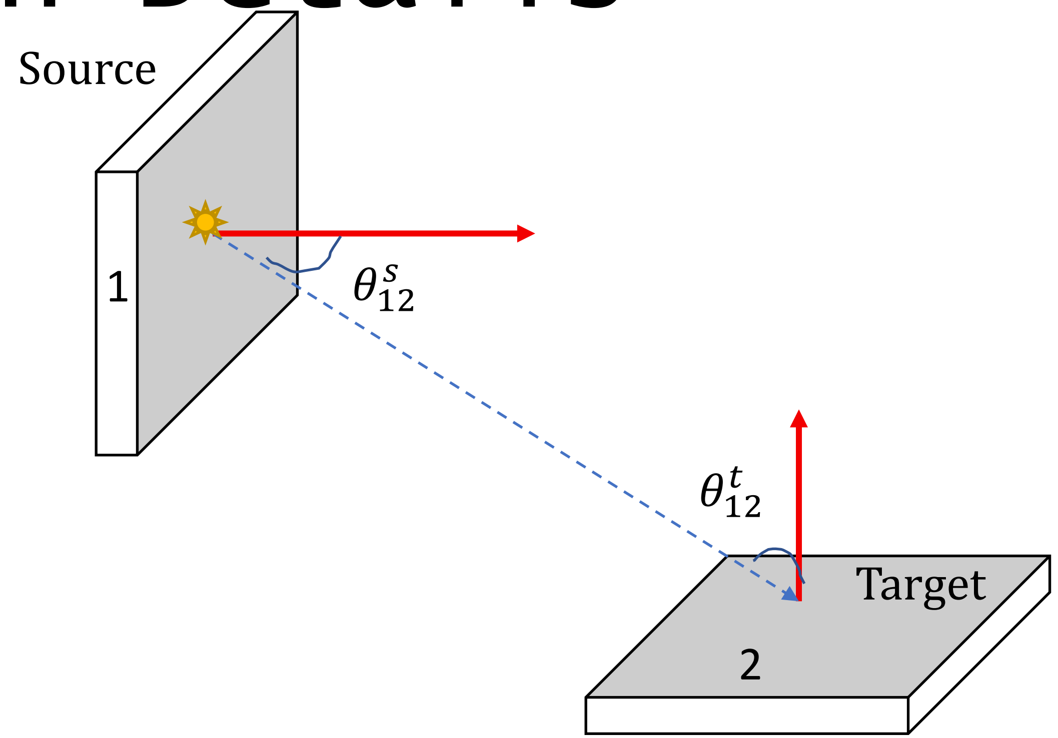
Backup



Efficiency/Transmission/Reflectivity/Intensity(a.u)
1.0
0.8
0.6
0.4
0.2
0.0
100
200
300
400
500
600
700
800
900
1000
Wavelength (nm)
SiPM PDE (HPK D.S)
Specular SiPM Reflectivity
BP Transmission
LP Transmission
HPK Emission (175 K)
LXe Scintillation
Cage Fluorescence (R.T)

Backup- Simulation Details

- In our data measurements we measure "total correlation probability"
- This includes "Direct" correlation
  - Source->Target
- Also includes "Backwards" correlation
  - Target->Source
- For simulations, we measure both independently
- Source->Target
  - Enable ExCT Simulation **ONLY** for source
- Target->Source
  - Enable ExCT Simulation for all **EXCEPT** source
- Sum of two contributions is the "Total Correlation Probability"
- From simulations we see roughly ~16% contribution of backwards correlation to total
  - Stable across many simulation configurations, driven by solid-angles and transport efficiency + emission angular distribution



$$Prob = \frac{Target\ eXT\ Detections}{Source\ Hits}$$

In simulation, we use the MC truth information, so estimates have no background