



Optical Properties of Materials under Liquid Xenon VUV Scintillation Light



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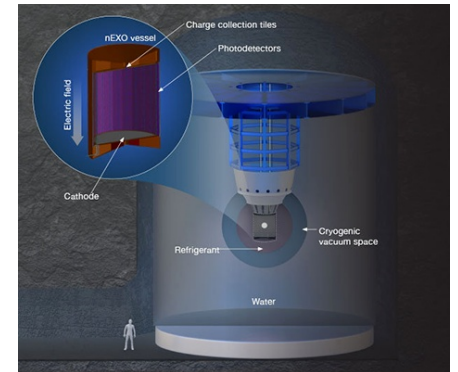
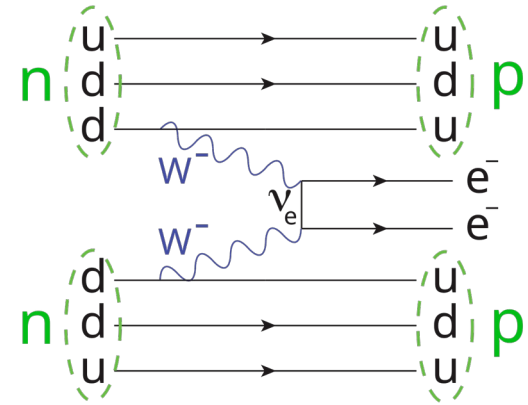
CPAD, Seattle

October 21st, 2026

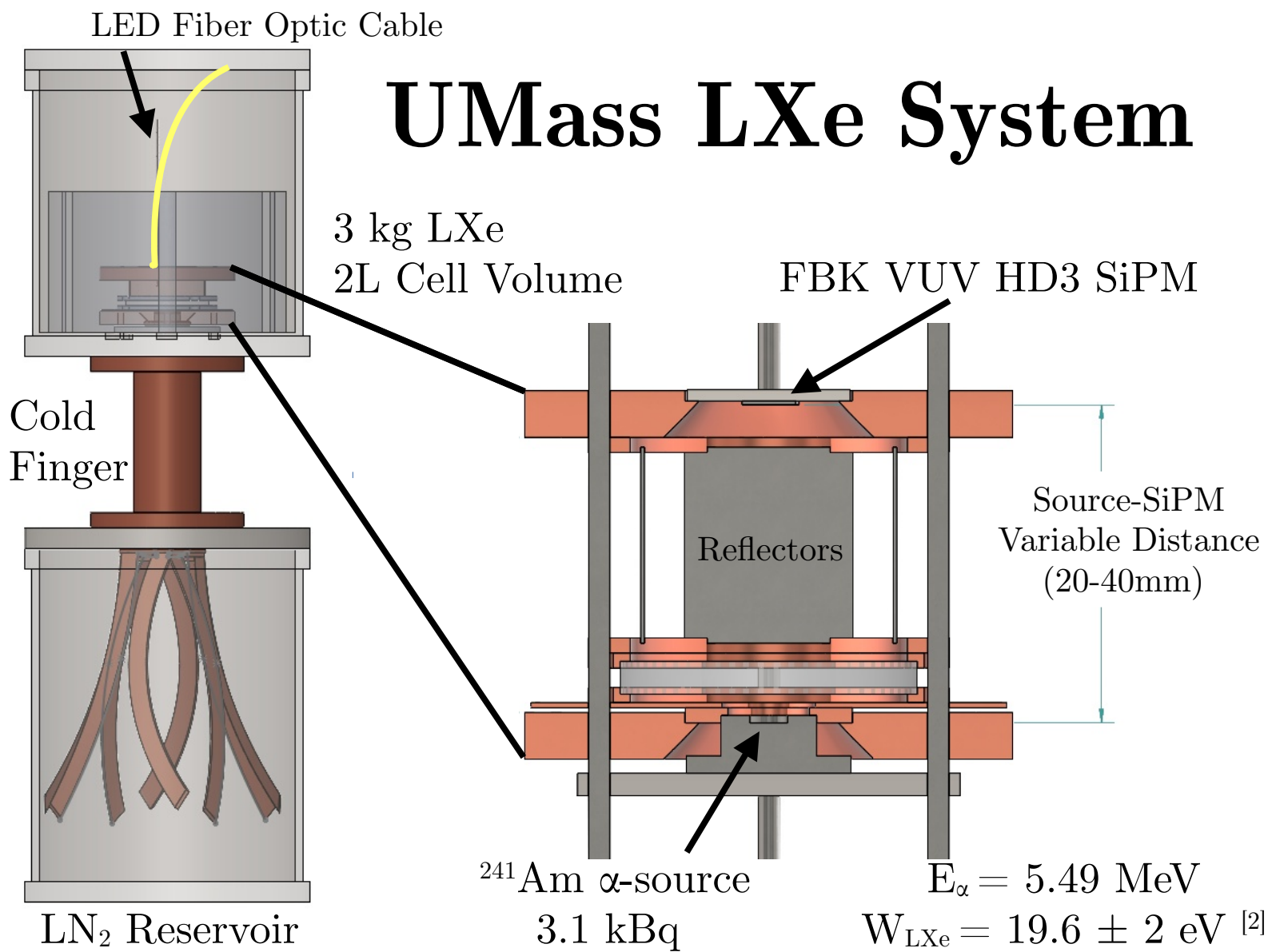
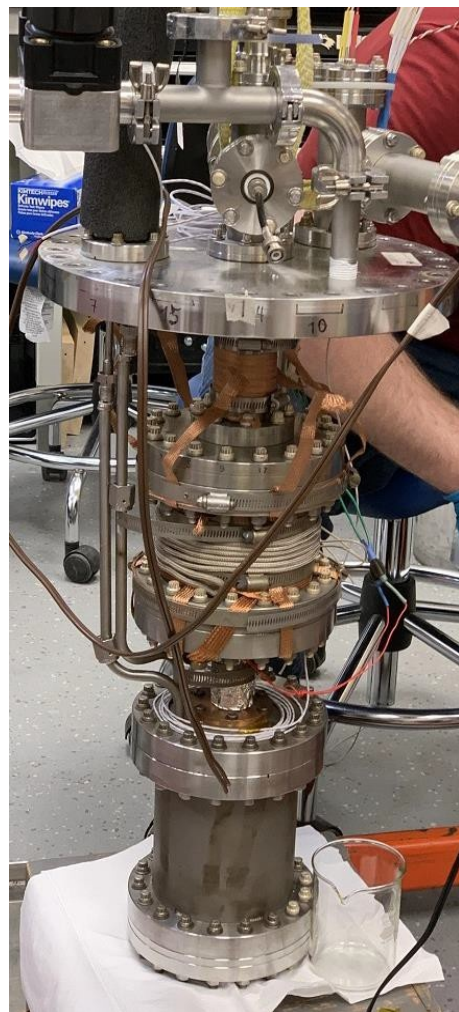


Need to Understand VUV Transmission and Detection to Build Next-Gen LXe Detectors

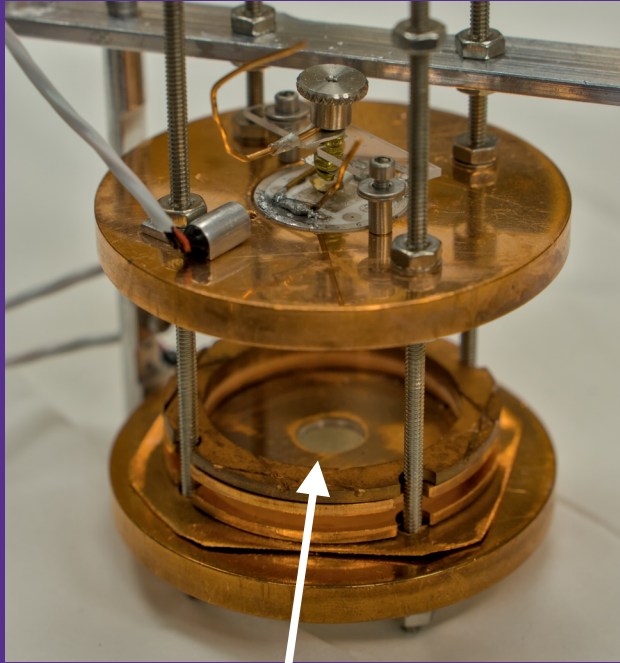
- Understand nature of neutrino mass
 - Search for neutrinoless double beta decay^[1]
- Explain the origins of dark matter
 - Search for WIMP nuclear recoil
- Need to collect LXe scintillation light for event reconstruction and event energy measurement



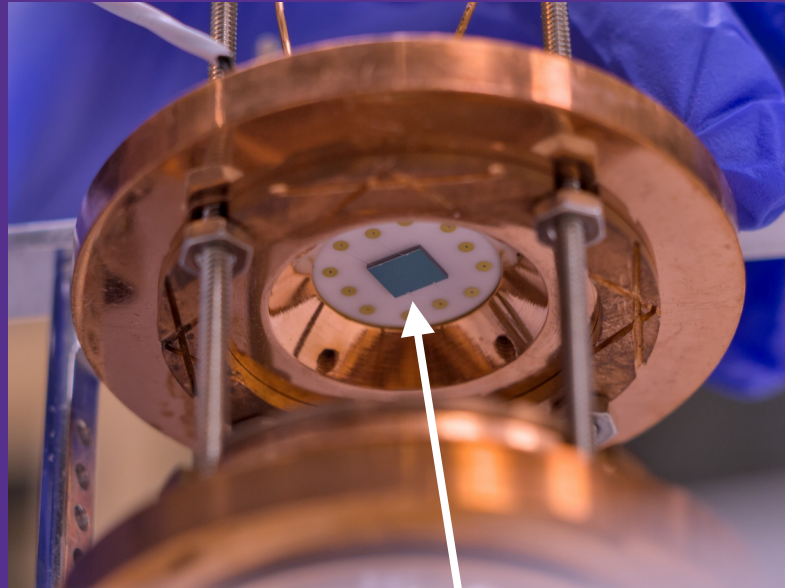
UMass LXe System



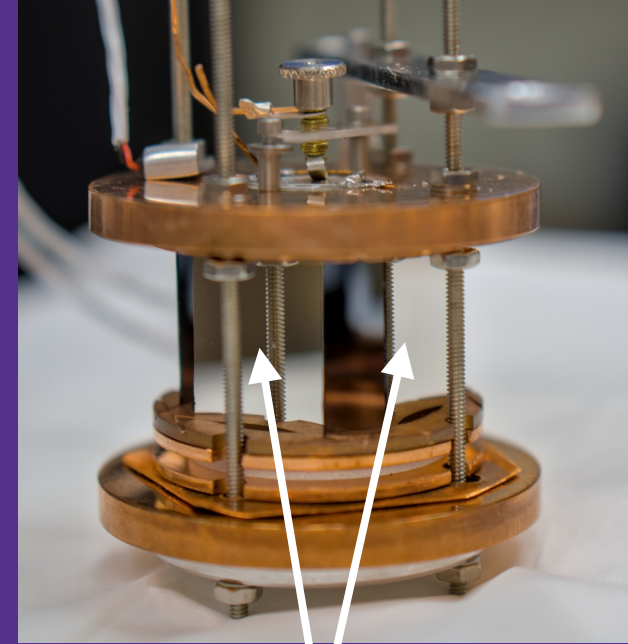
UMass LXe Optical System



^{241}Am α -source



FBK VUV SiPM

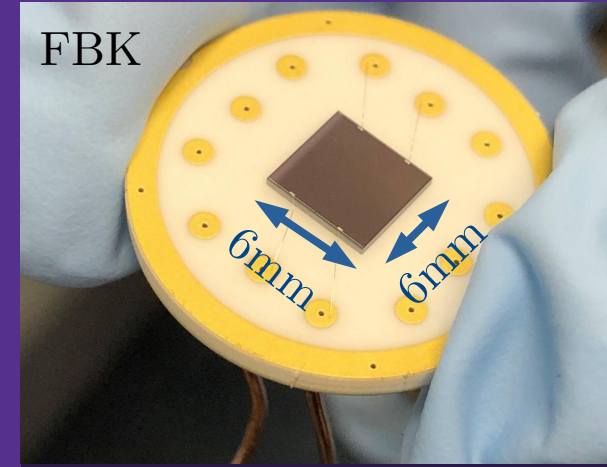


Amorphous Silicon
Reflectors (4-8 $\times$)

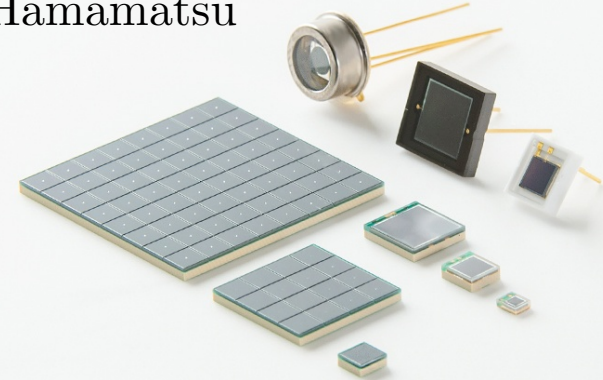
Silicon PhotoMultiplier

- Photon counting devices
- Array of 100-10,000 Single Photon Avalanche Diodes (SPADs)
- Photoelectric effect of PN junction produces electron from incident photon
 - Applied electric field accelerates electron, if above a characteristic **breakdown voltage** impact ionization causes a self sustaining electron avalanche
 - **Overvoltage:** Bias applied above the breakdown voltage
 - **Gain:** Charge carriers produced per initial photoelectron (10^5 - 10^7)
- Fondazione Bruno Kessler (FBK) designed SiPMs optimized for vacuum ultra-violet (VUV) wavelength light in cryogenic conditions for nEXO^[3]

(SiPM)



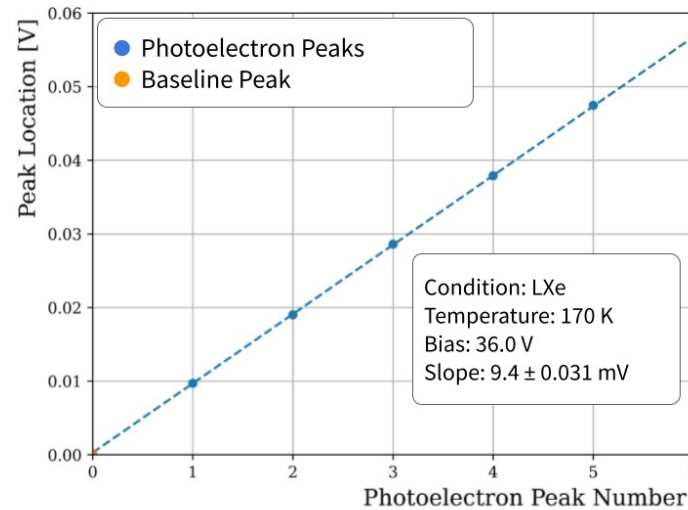
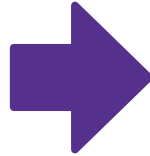
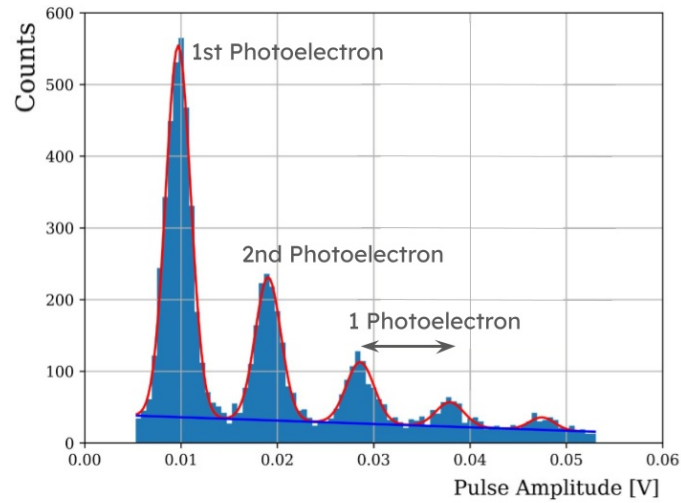
Hamamatsu



Studying the Same FBK VUV SiPM Continuously since 2021

History of FBK HD3 VUV SiPM (SN: VUVHD LF LOW-AP W13)	
November 2021	SiPM installed, first IV curves performed
March – November 2022	Characterization campaign in Gaseous Nitrogen
March – August 2023	Liquefactions in Liquid Xenon, Si 8 short configuration
June 2024	SiPM exposed to 370K over night
July 2024	SiPM readout wire redesigned
May – September 2025	Characterization campaign in Gaseous Nitrogen
July 2026	Fixed SiPM electrical connection
September 2026	Liquefactions in Liquid Xenon, Si 4 tall configuration

Characterize SiPM by Measuring Single Photo-Electrons



**Repeat
For 8-10
Voltages**

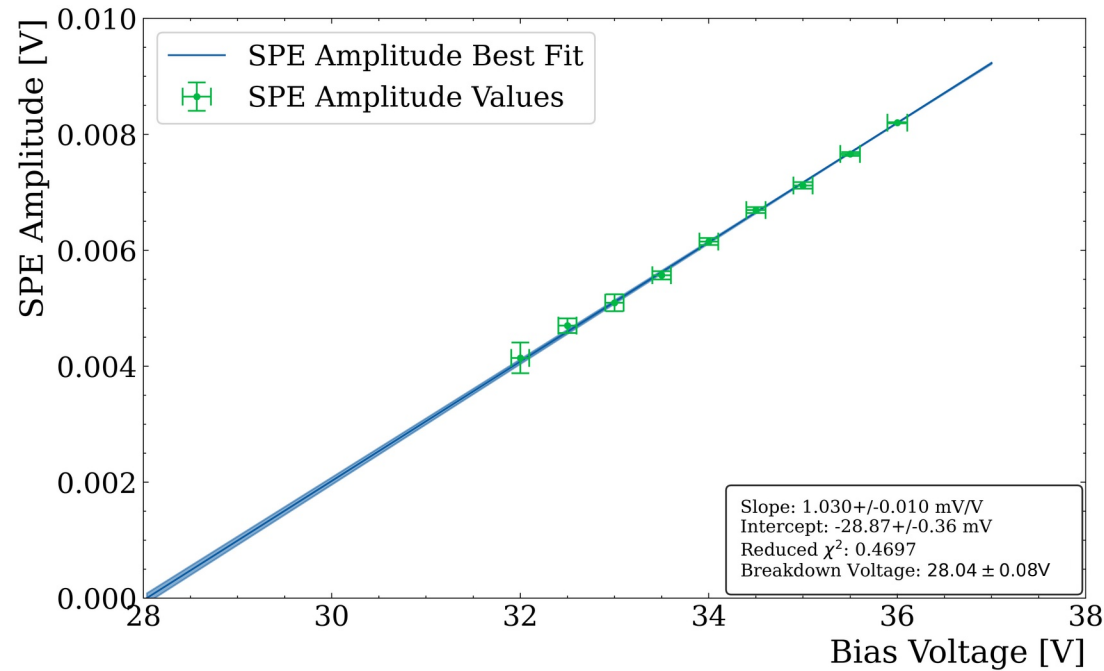
SiPM pulses (Q_i) are converted to voltage:

- Cremat CR-Z-SiPM charge sensitive pre-amplifier,
- Cremat CR-S-1us shaping amplifier,
- Z-TEC ZT4421 digitizer

Single PhotoElectron (SPE) Amplitude: Voltage.
of single photoelectron signal (A_{SPE}),

- The average distance between photoelectron peaks.
- Convert SiPM signal (γ_i) to number of SPAD avalanches.

SPE Amplitude is collected for 8-10 bias voltages and is then fit with a line and extrapolated



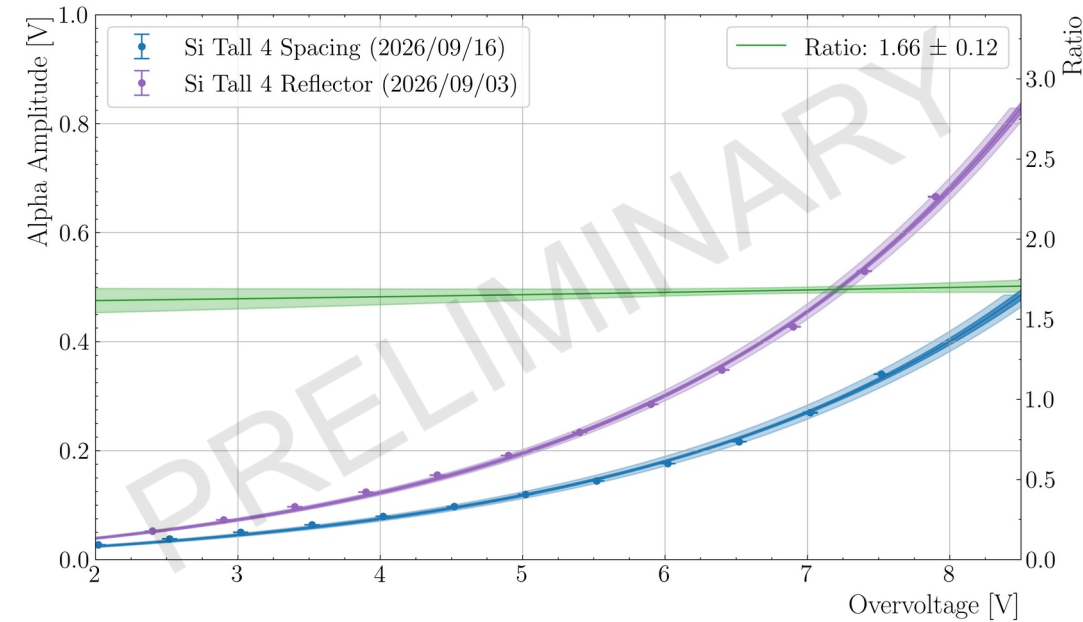
**Bias Voltage Where SPE Amplitude
is Zero is the Breakdown Voltage**

Need to Know Reflectance to Predict Detector Performance

- **Reflectance:** amount of incident light re-emitted from surface
 - Need to know for different surfaces in nEXO reflect VUV light,
 - And how to model the **specular nature** of reflection to simulate detector efficiency.
- Simulate increase in transmission of Xe scintillation light to SiPM with and without reflector
- Find reflectance and specular nature which causes model to match experimental results

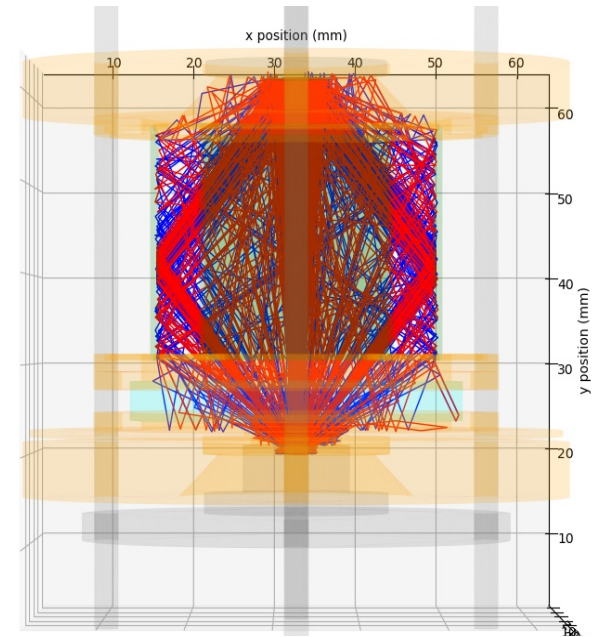
Xenon Scintillation Light Measurement

Measure increase in Xe scintillation light detection with reflector (γ_{aSi}) compared to without (γ_{aSi})



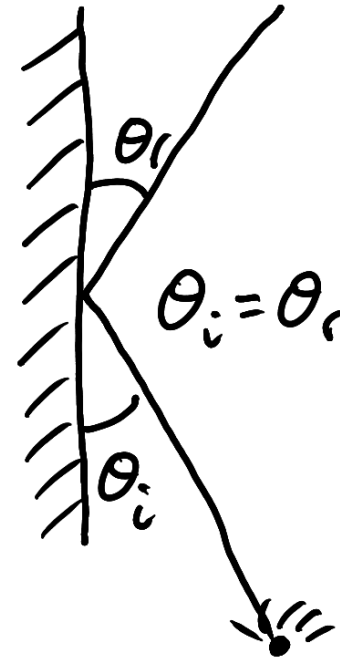
Simulate Photon Propagation with Chroma

- GPU accelerated ray-tracing Monte Carlo optical simulation^[4]
 - Given initial photon states, from alpha-induced point-like Xe scintillation
 - Propagate photons through geometry
- Input CAD geometry (triangle mesh) with:
 - Material's refraction index and surface roughness (specular fraction/width)
 - Liquid xenon's refraction index, absorption length, scattering length
- Simulate Xe cell to calculate **Photon Transmission Efficiency** (PTE):
 - Percent of photons that terminal at SiPM
- CAD model of Xe cell with and without reflector
 - The increase in photons with the reflector compared to without is the **reflector enhancement**: $\text{PTE}_{\text{aSi}}(\text{R}, \text{S}) / \text{PTE}_{\text{none}}$

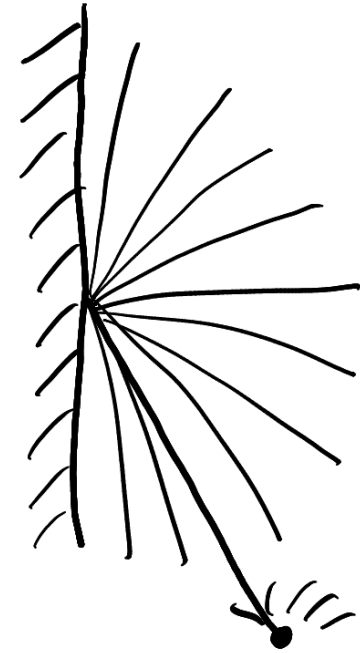


Specular-Diffusive Model

Specular



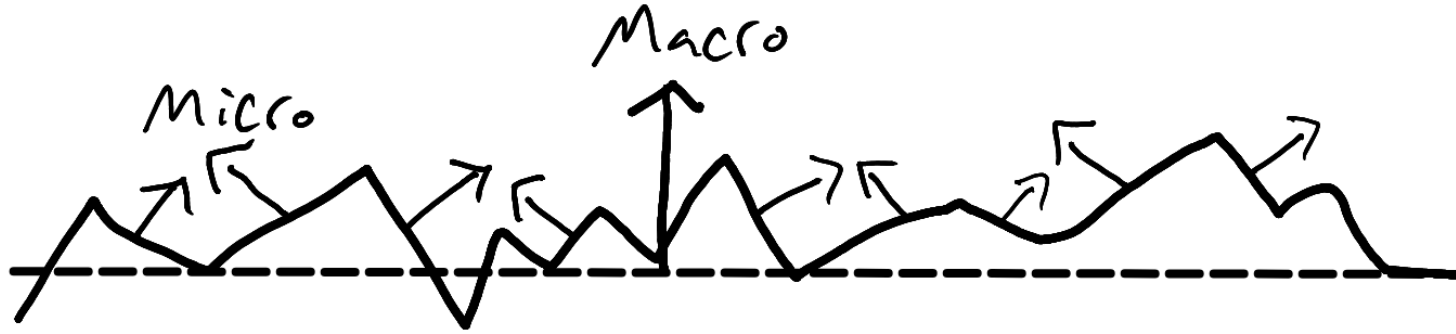
Diffusive



Binary model: perfectly specular, or uniformly diffusive.

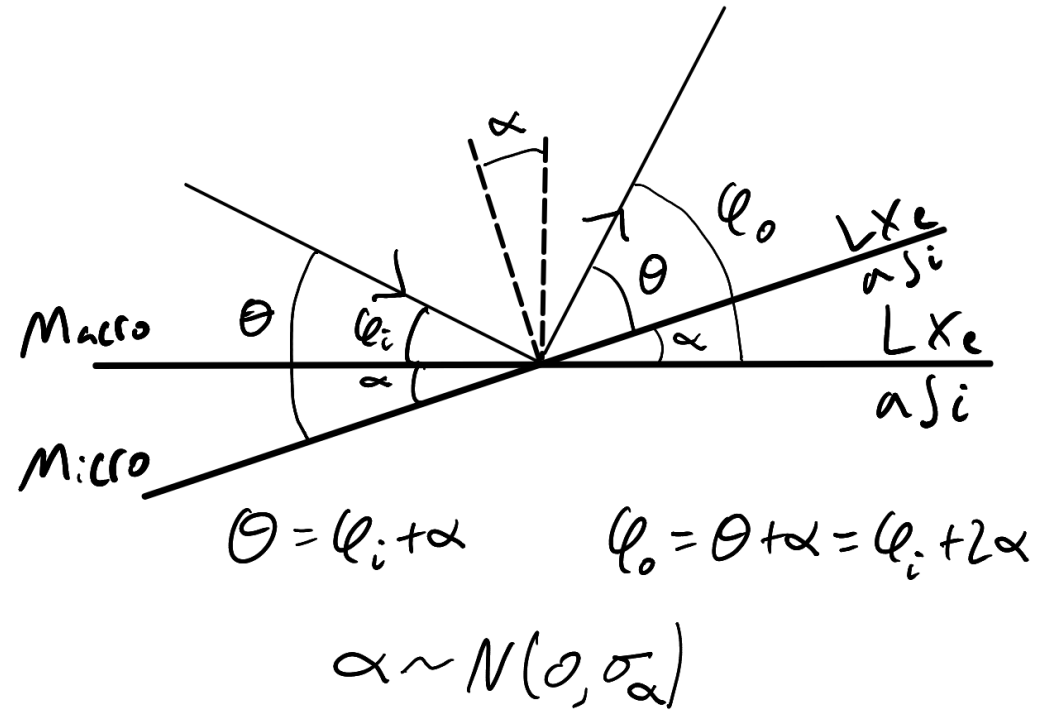
Percent determined by specular fraction

Microfacet model of surface roughness



- Microsurface normals' deviate from macrosurface normal
- Angle of deviation sampled from normal distribution

Specular-Lobe Model



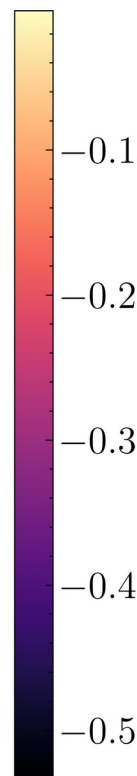
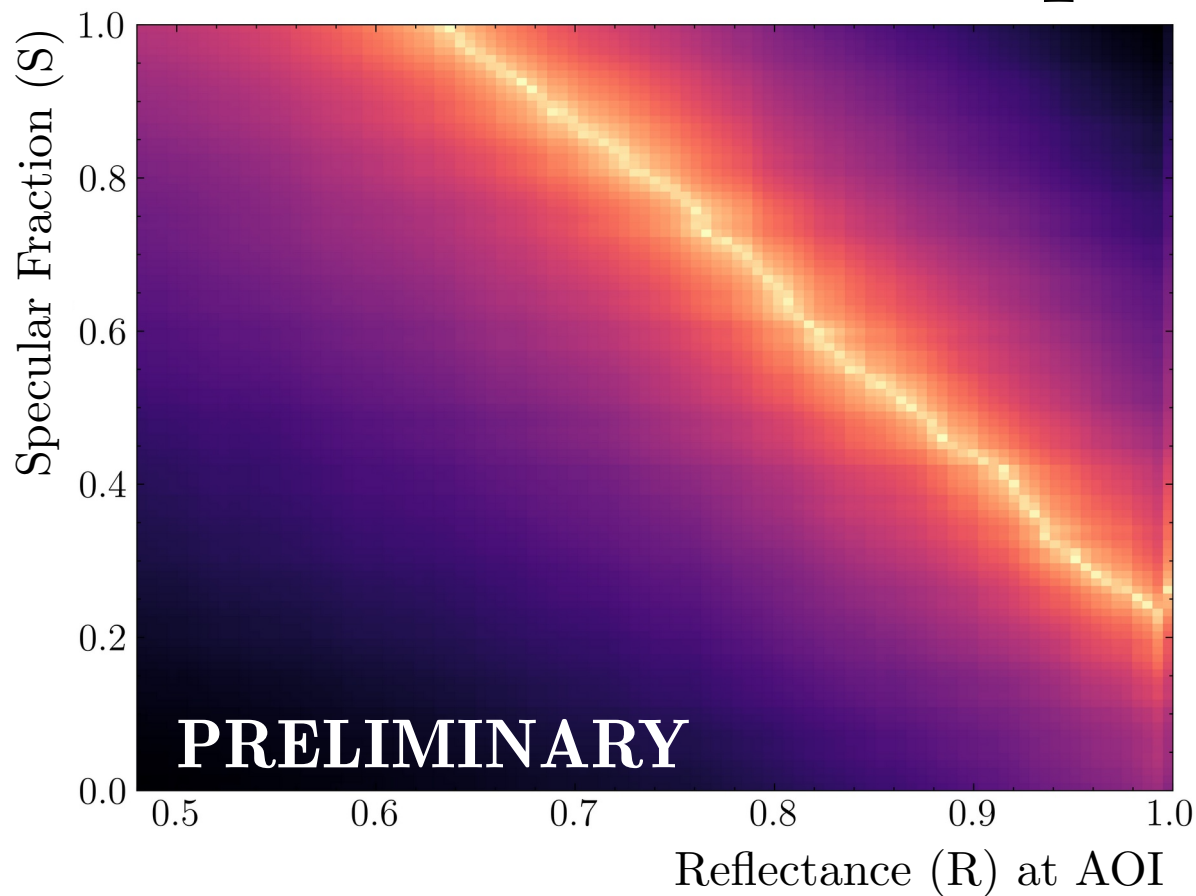
Replace specular-diffusive fraction with
specular-lobe width

Compare Reflector Enhancement Between Simulation and Experiment

Match **reflector enhancement** from experiment to
simulated reflector enhancement with material's
reflectance and specular nature

$$\frac{\text{PTE}_{\text{aSi}}(R, S)}{\text{PTE}_{\text{none}}} = \frac{\gamma_{\text{aSi}}}{\gamma_{\text{none}}}$$

One geometry gives a line of best fit reflectance and specular fraction

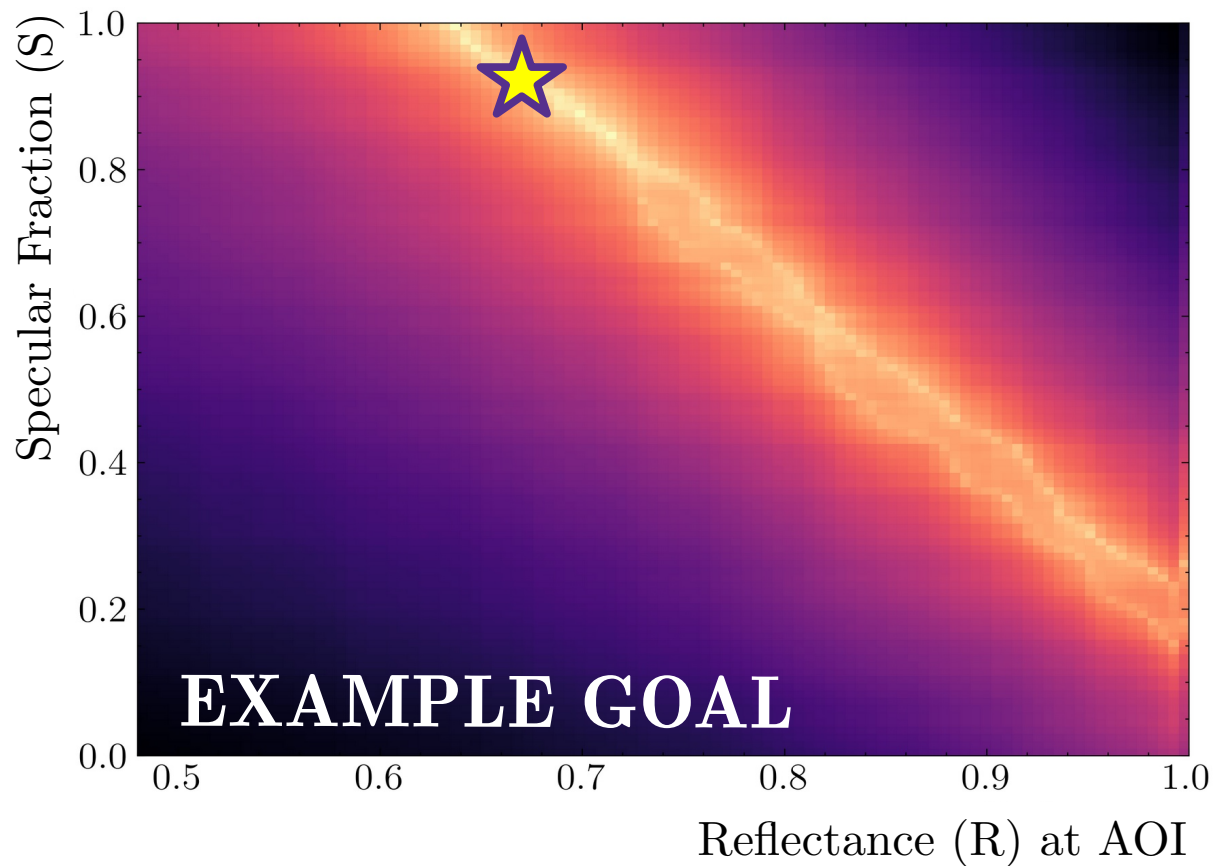


Score Function:

$$-\sqrt{\frac{\text{PTE}_{\text{aSi}}(R, S)}{\text{PTE}_{\text{no reflector}}}} - \frac{\gamma_{\text{aSi}}}{\gamma_{\text{no reflector}}}$$

(arbitrary scale)

Point of intersection gives measured reflectance and specular nature

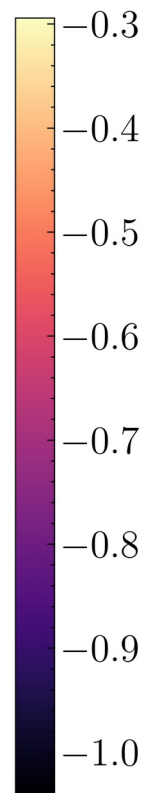
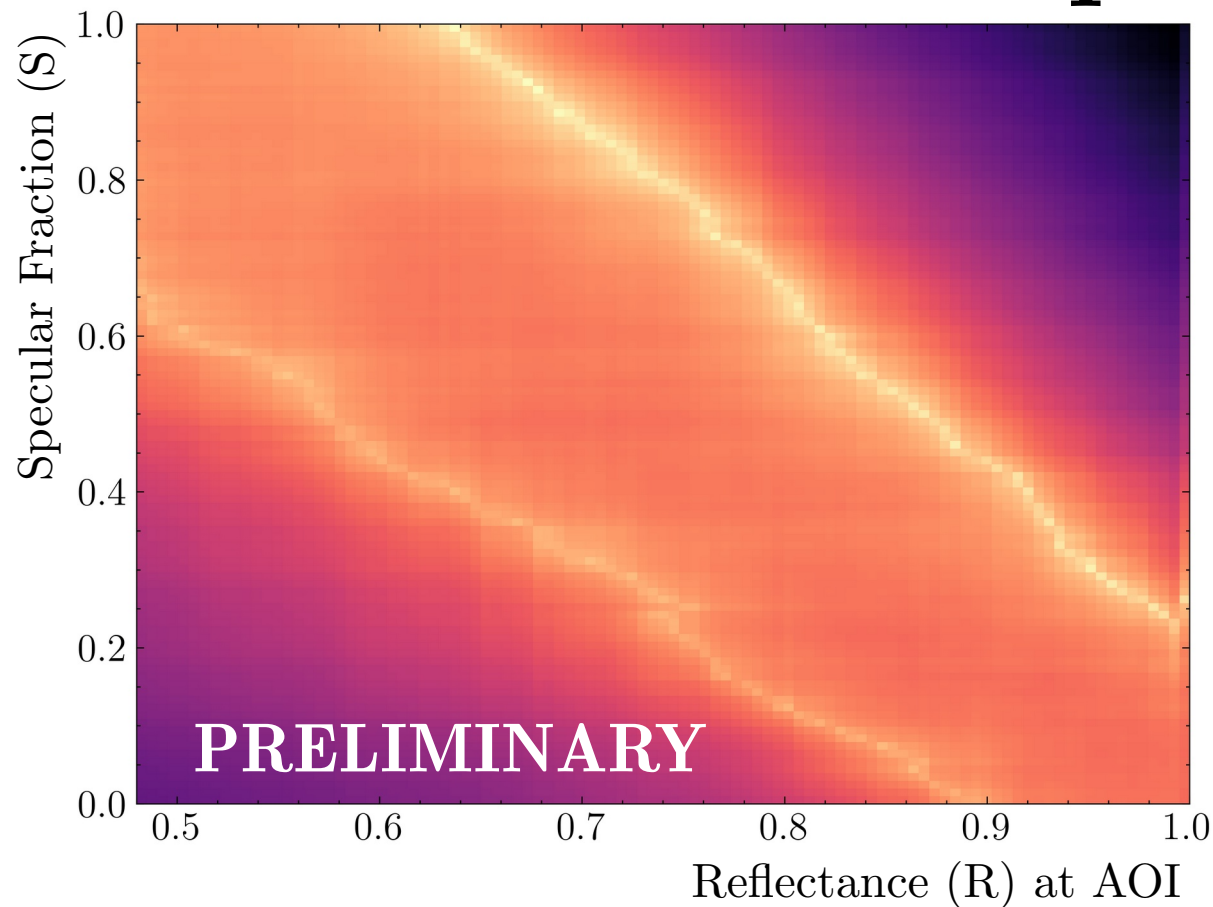


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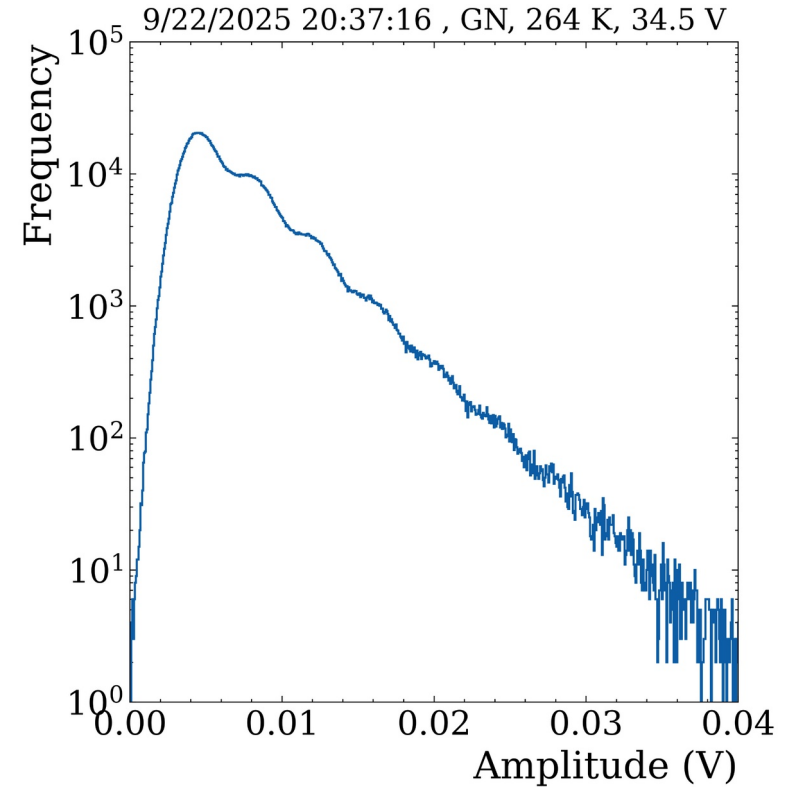
(arbitrary scale)

SiPM Correlated Avalanches

Characterization of SiPM

Correlated Avalanches

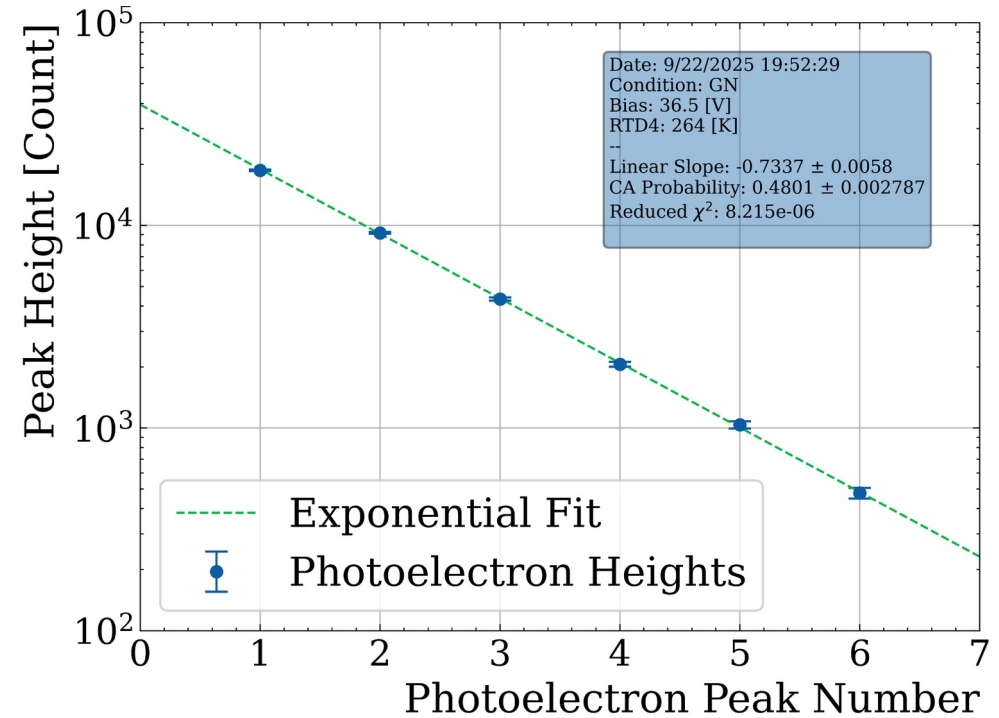
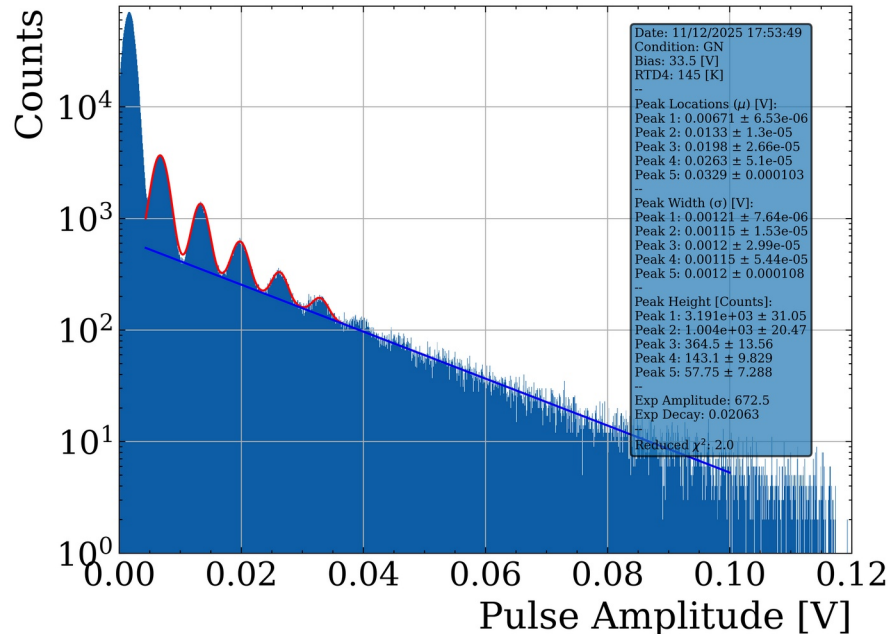
- **Correlated Avalanches (CA):** SiPM signal caused by electron avalanche process, not incident photon
- Traditionally, CA is measured from the average amplitude of all the SPE pulses
 - Highly dependent on the included range of pulse peaks.
 - If first PE peak overlaps with the noise pedestal then many of the single PE amplitudes will be excluded,
 - Artificially raising the estimation of CA.
 - Low statistics artificially cuts off high PE peaks, lowering CA.



$$CA = \frac{1}{N} \sum_{i=0}^N \frac{A_i}{A_{SPE}} - 1$$

CA from Photo-Electron Peak Heights

Use multi-Gaussian best fit instead of all pulses with noise

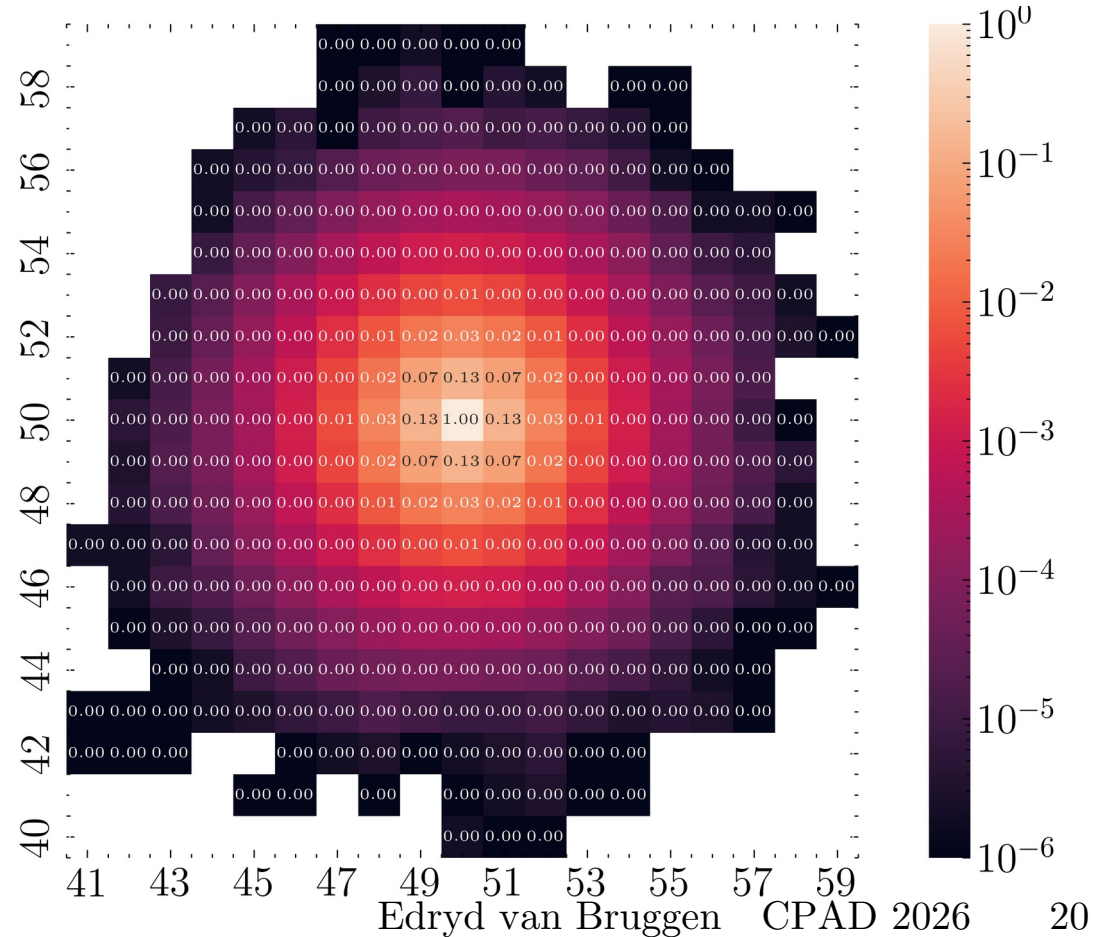


Ratio of photo-electron peak heights is the probability of an avalanche to cause CA

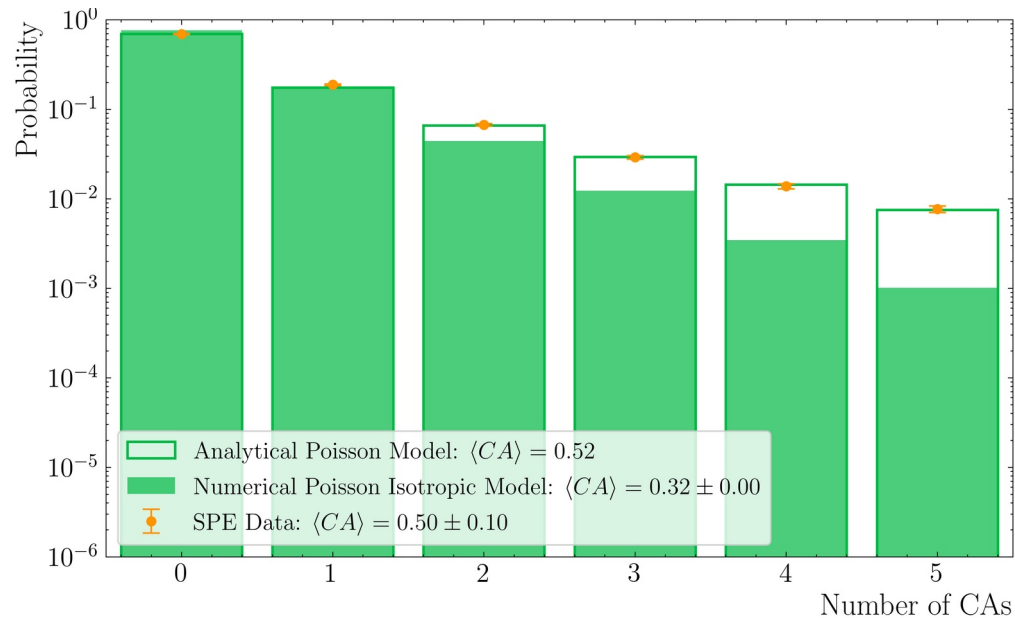
Convert probability of CA to average number of CA

SPAD-level Simulation to Understand CA propagation

- SiPM is modeled as finite grid of SPAD microcells
 - Each can contain 0 or 1 avalanche
- Initialize SiPM with 1 primary avalanche
 - Randomly distributed across SiPM
- Each new avalanche has a probability of causing CA
 - Sample Poissonian to determine number of CA per avalanche
 - Recursively applied to each new avalanche



Use Numerical Simulation to See Effect of SPAD Saturation



- Data matches analytical model better than simulation
 - Overestimating the effects of local saturation
 - Or not taking into account additional effects (afterpulsing? Non-uniform SPADS?)

Conclusion

- Measure increase in Xe scintillation light with reflector, and compare to increase in simulation to find model of reflectance and specular nature
- Photo-electron peak heights can be used to measure probability of CA

Next Steps

- Understand systematics to make reflectance measurement
 - Incorporate specular-lobe model into Chroma
 - Repeat measurement for Al-MgF₂
- Measure number of CA from photo-electron peak heights

Thank You!



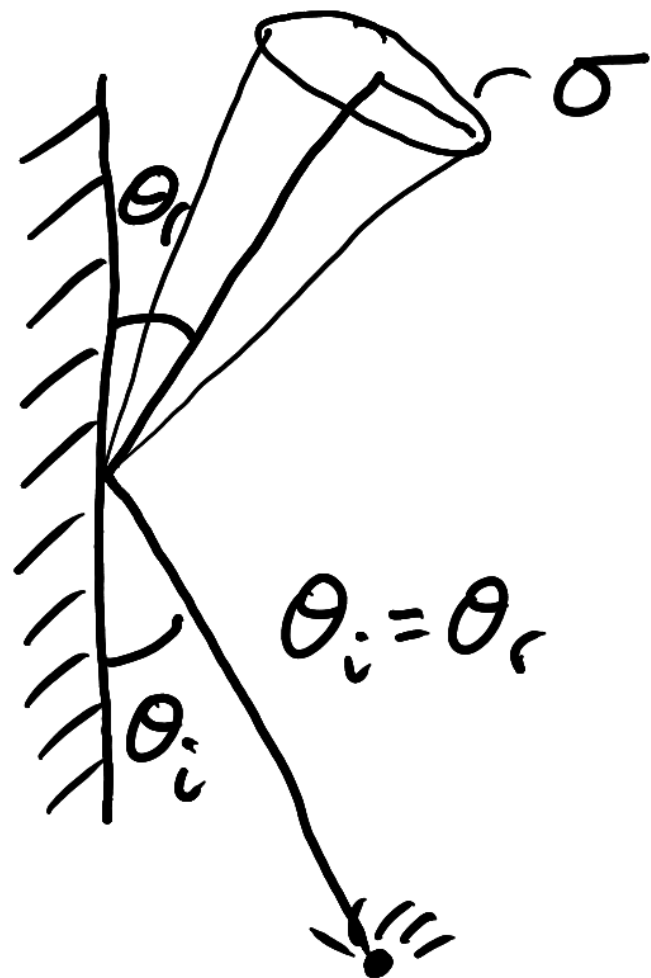
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evanbruggen@umass.edu

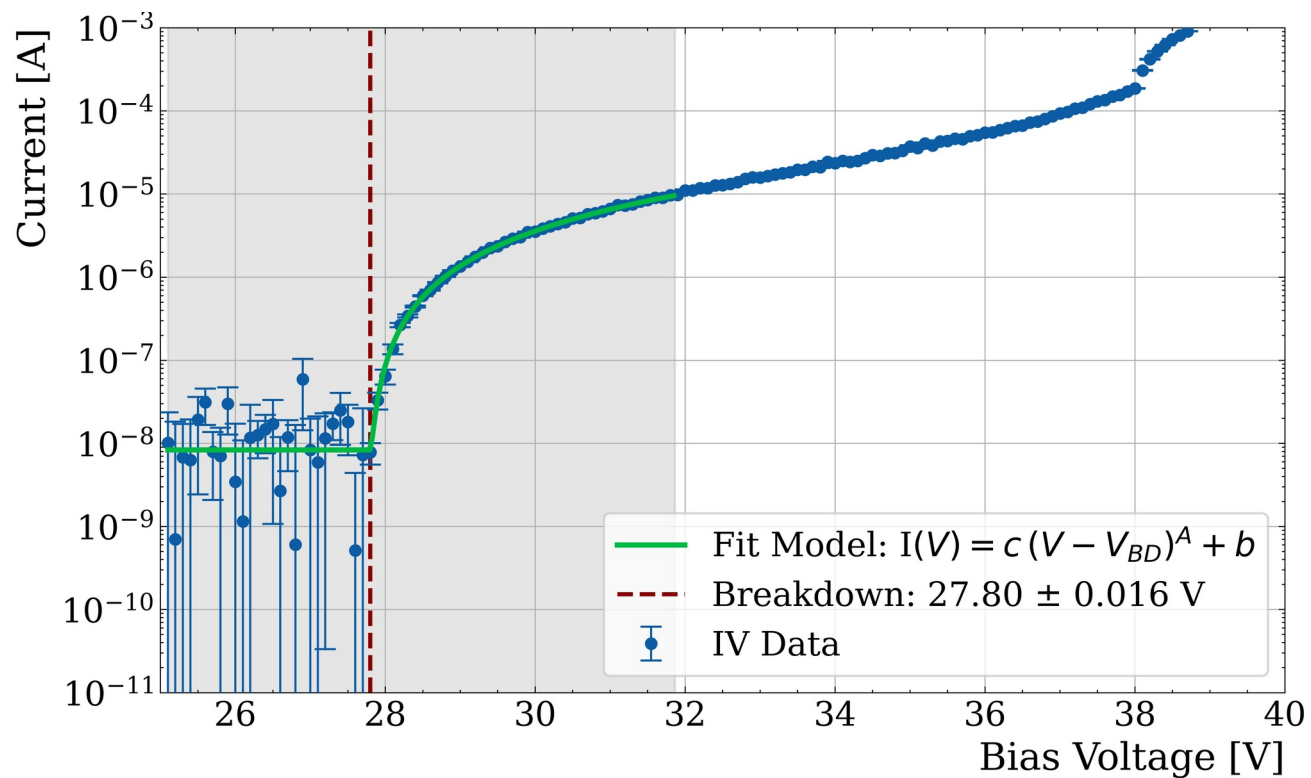
References

- [1] nEXO Collaboration. NEXO: Neutrinoless double beta decay search beyond 10^{28} year half-life sensitivity. J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022)
- [2] A. Baldini, C. Bemporada, F. Cei, et al. Liquid Xe scintillation calorimetry and Xe optical properties. IEEE Transactions on Dielectrics and Electrical Insulation, 13(3), 547-555. Article 1657967 (2003)
- [3] G. Gallina, Y. Guan, F. Retiere, et al. Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO. Eur. Phys. J. C 82, 1125 (2022)
- [4] S. Seibert, A. LaTorre. Fast Optical Monte Carlo Simulation With Surface-Based Geometries Using Chroma. (2011)

Extra Slides



IV Curves



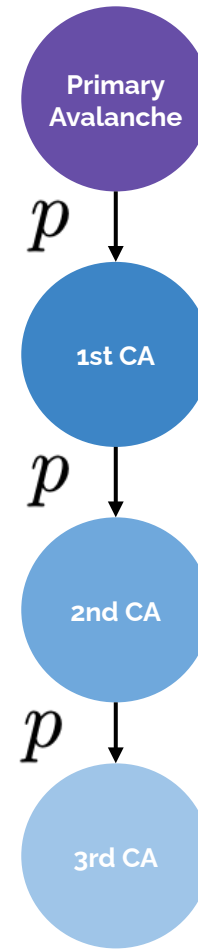
Geometric Model

Analytical

$$P(k) = p^{k-1} (1 - p)$$

Numerical

- Sample probability of CA, create new avalanche if passed
- **If avalanche already exists in cell, don't create new one**
- Repeat recursively until no more new avalanches



Poissonian Model

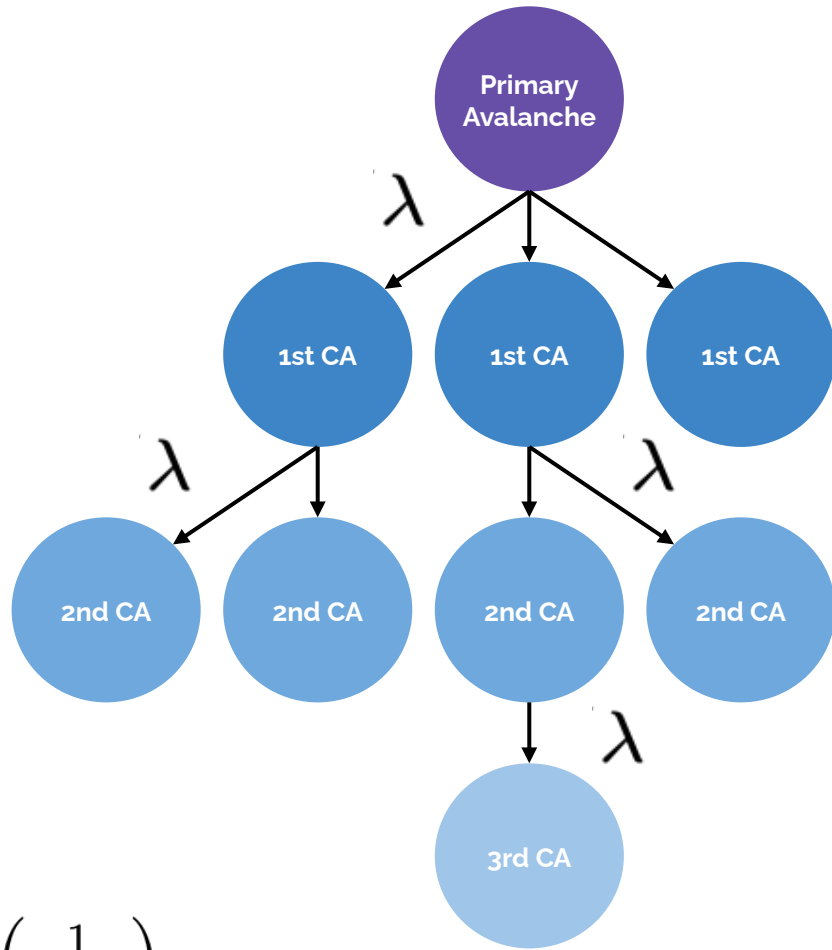
Analytical

$$P(\lambda, k) = \frac{(\lambda k)^{k-1} e^{-\lambda k}}{k!}$$

Numerical

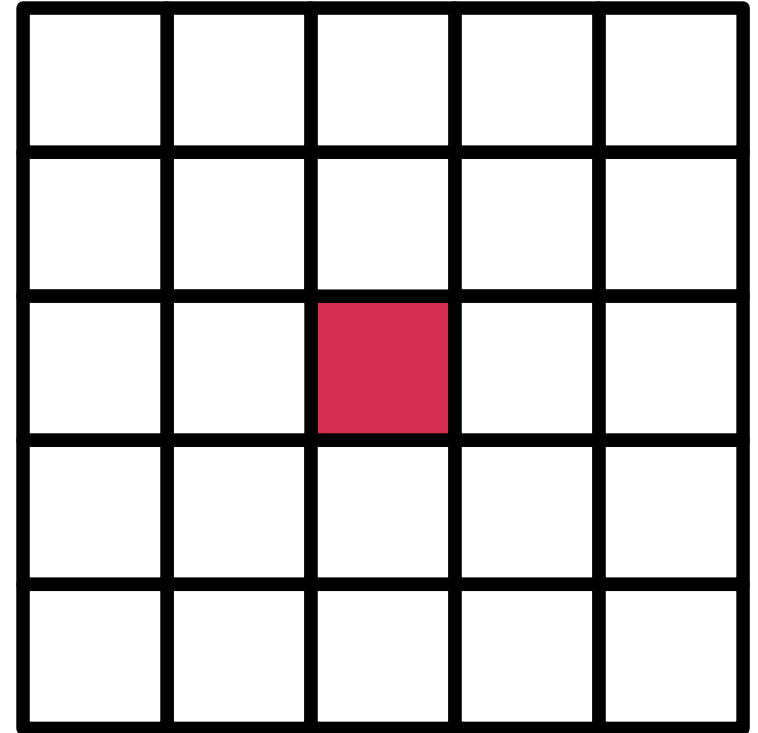
- Sample Poissonian distribution and create that many number of CAs
- **If avalanche already exists in cell, don't create new one**
- Repeat recursively until no more new avalanches

$$P(\lambda, 0) = 1 - p = e^{-\lambda} \Rightarrow \lambda = \log\left(\frac{1}{1-p}\right)$$



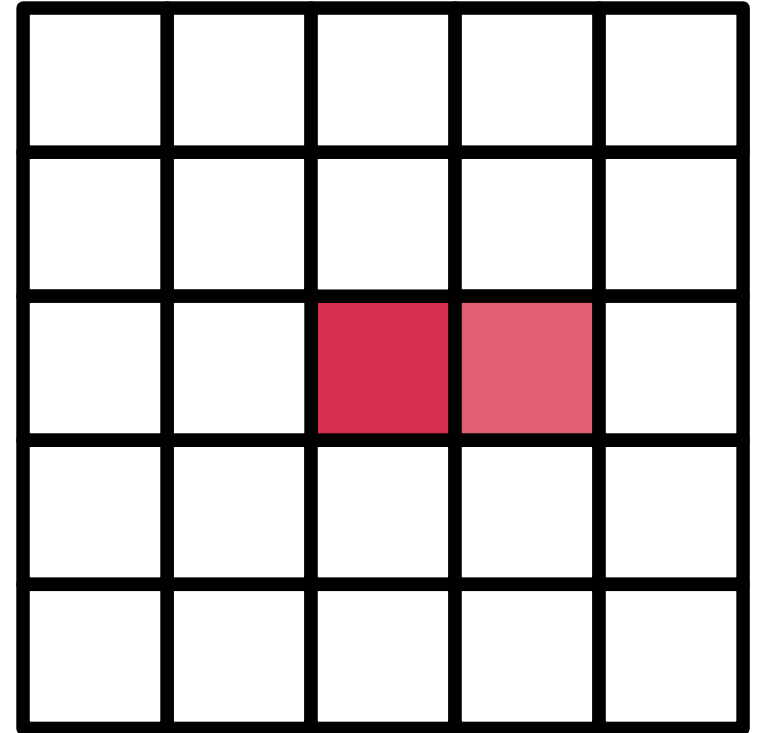
SiPM Simulation

- Initialize SiPM with primary avalanche(s)
- Simulate correlated avalanches
 - Internal crosstalk
 - Afterpulsing
- Model and understand CA saturation
- Improve understanding of CA propagation and calculation of total number of CA



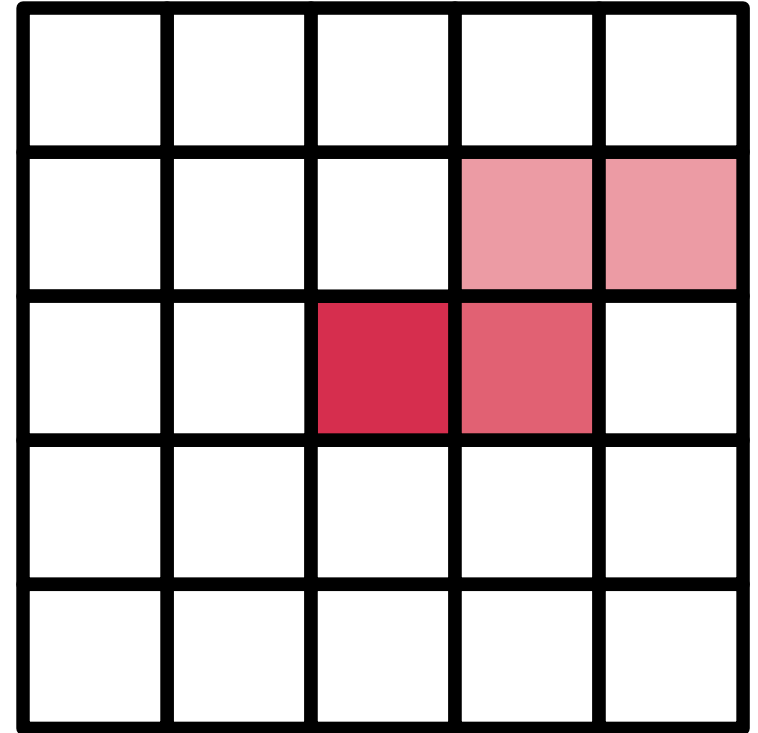
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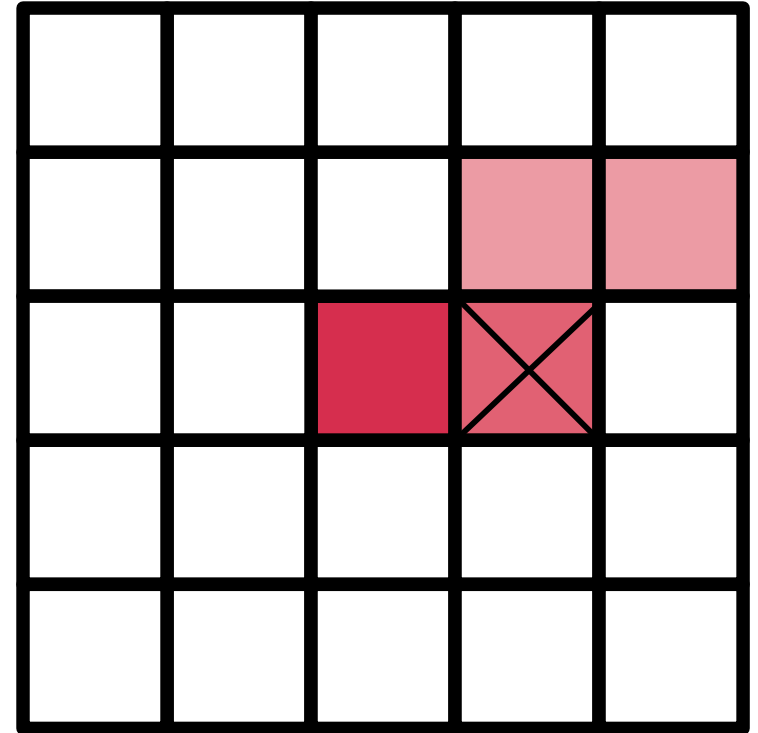
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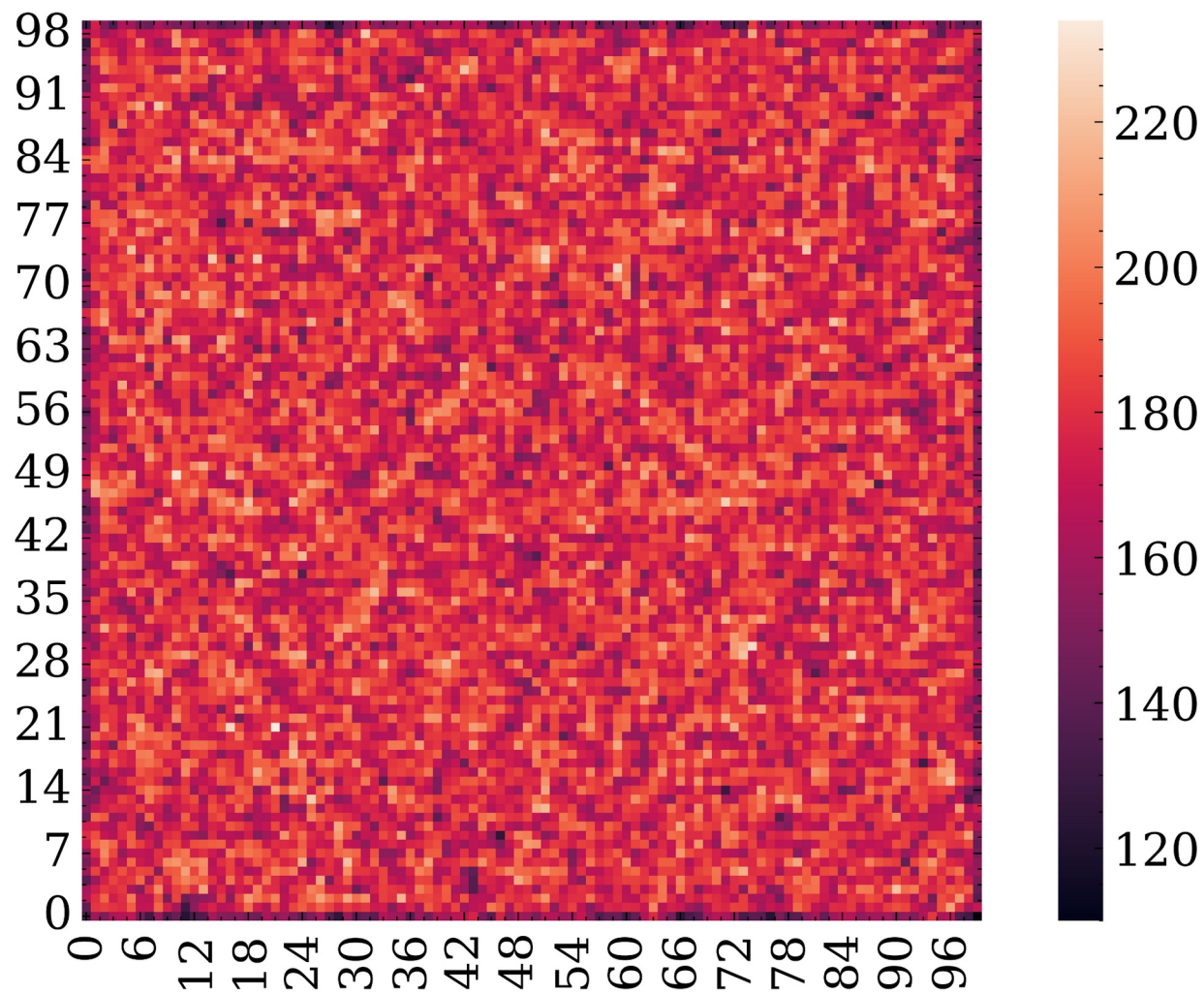
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Project CA
simulation onto
one axis

