

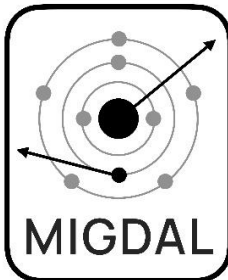
Quantifying and Correcting Optical Broadening in Gaseous Electron Multipliers (GEMs)

Dustin Edgeman

CPAD 2026 – October 22, 2026



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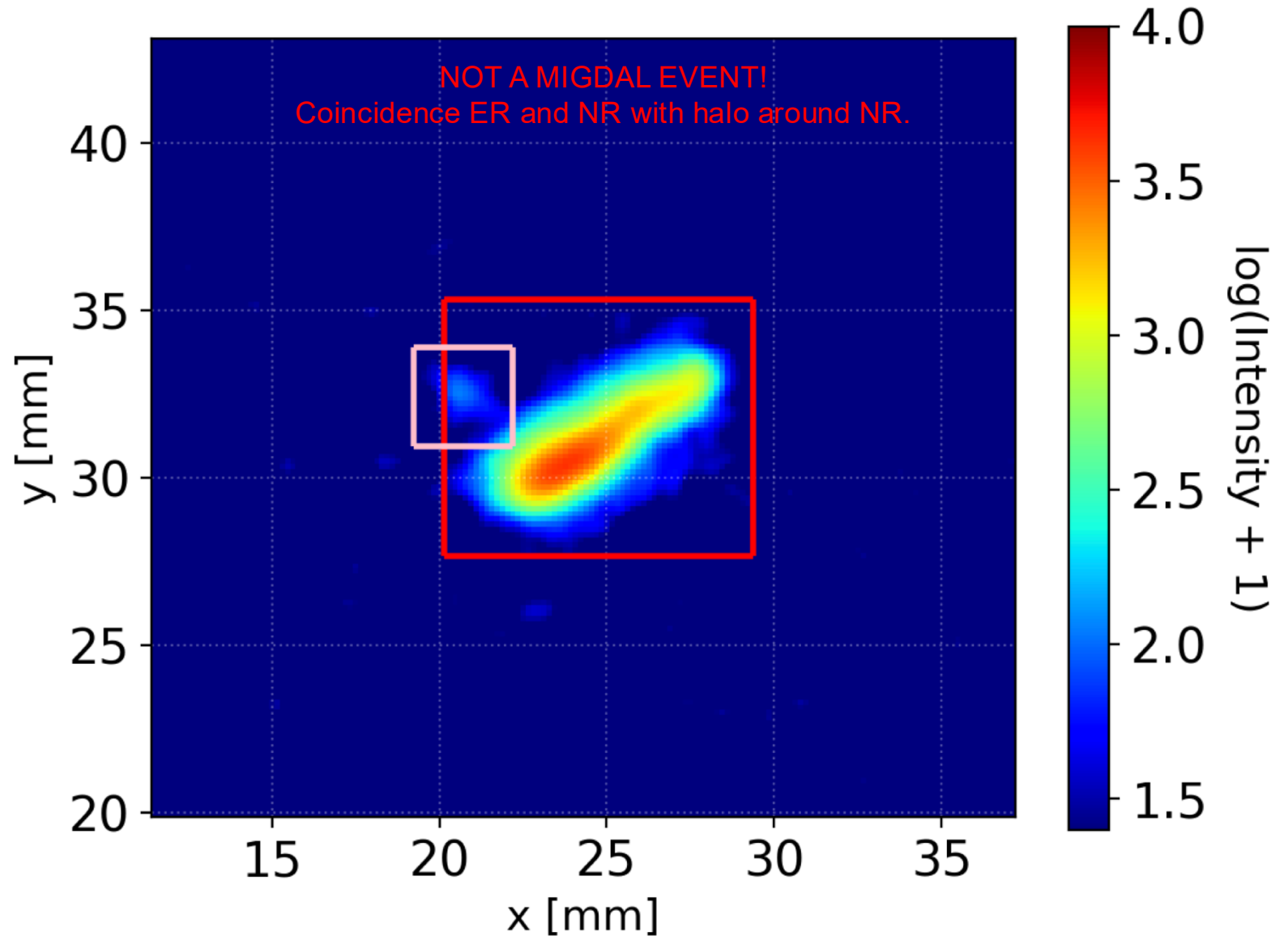


Outline

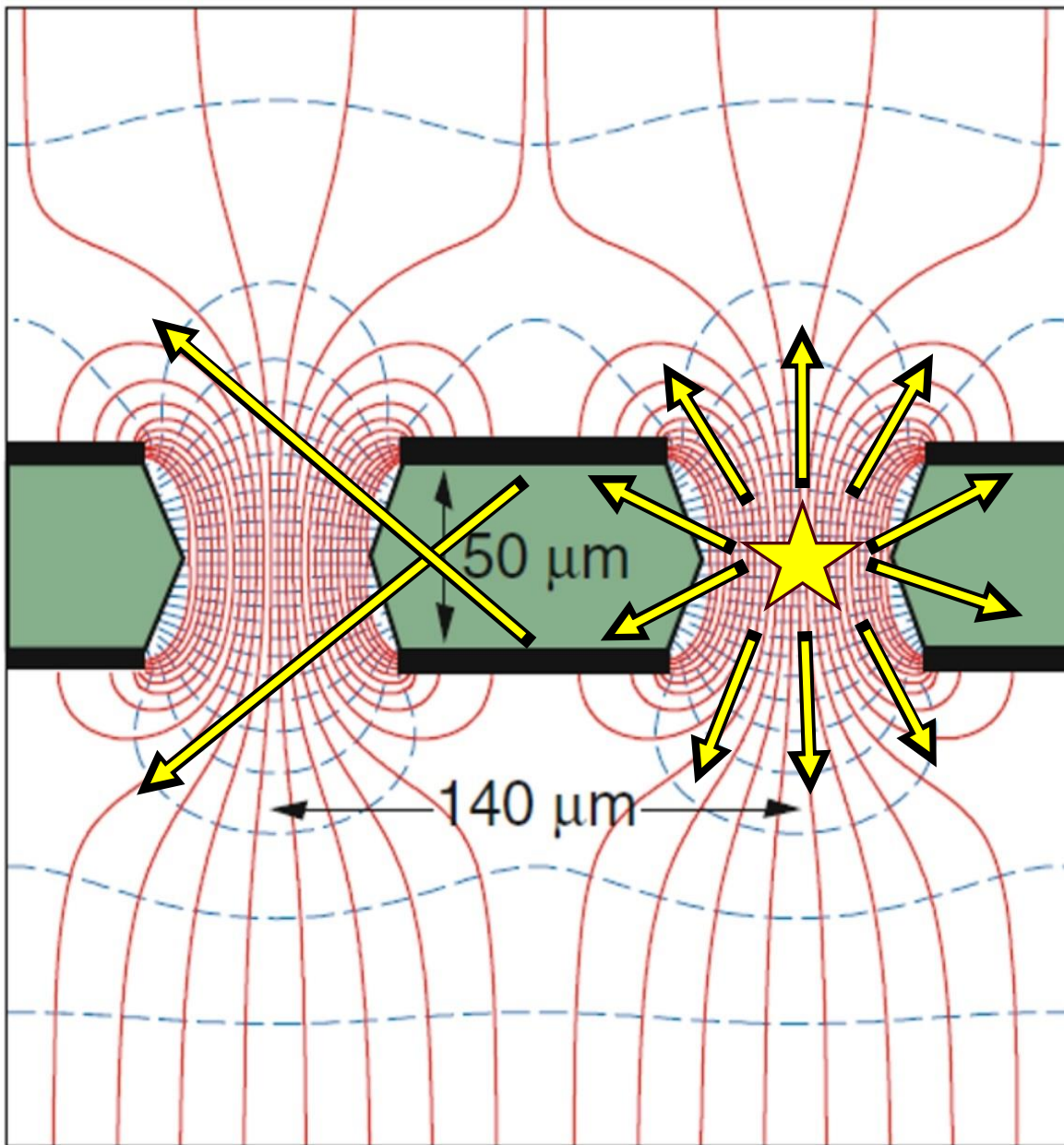
1. GEM based OTPC **observations**
2. **Hypothesis** for GEM optical effects
3. **Measurements**
 - a. Method for lab testing GEM optical effects
 - b. Measurement results
4. **Simulations**
 - a. Creating GEM optical effects simulations
 - b. Recreating lab measurements
 - c. Realistic charge avalanche GEM optical effects
5. GEM optical **effects on observables**
 - a. How to apply GEM optical effects to simulated particle tracks
 - b. Track changes due to GEM optical effects
6. **Correcting** optical broadening
 - a. What is needed to correct optical broadening
 - b. Examples of correcting simulations and real data

MIGDAL searches for a rare event where a neutron scatters off an atom leaving an electron recoil (**ER**) and nuclear recoil (**NR**) sharing a **common vertex**.

MIGDAL observes “**halos**” in the camera, causing **NRs** to appear **brighter** and **larger** vs what is observed in charge readout or predicted by simulation (Schueler et al., Phys. Rev. D 111, 072004, 2025).



Optical broadening “halos” around NRs can obscure ERs sharing a common vertex.

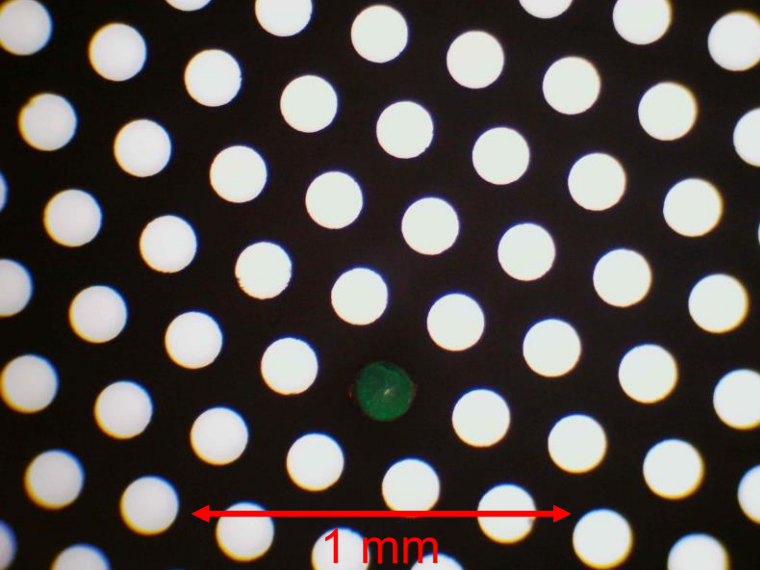


Hypothesis: Scintillation within GEM holes allows some of the light to travel through the GEM substrate (glass for MIGDAL) and exit other holes, providing more light toward the camera and broadening of tracks.

MIGDAL Simulations assume photons follow electric charge.

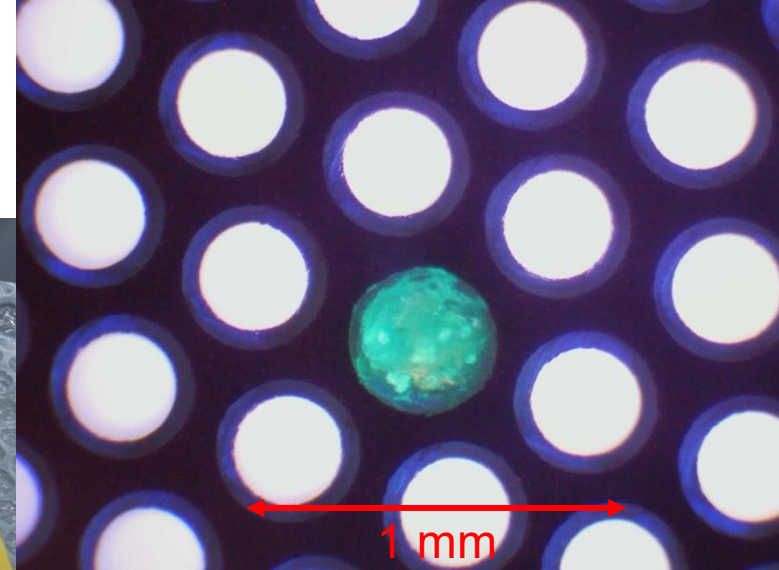
Test of hypothesis: measure light emitted from a single GEM hole.

Image: Adapted from https://institut2a.physik.rwth-aachen.de/de/teaching/praktikum/Anleitungen/T08_20210310.pdf

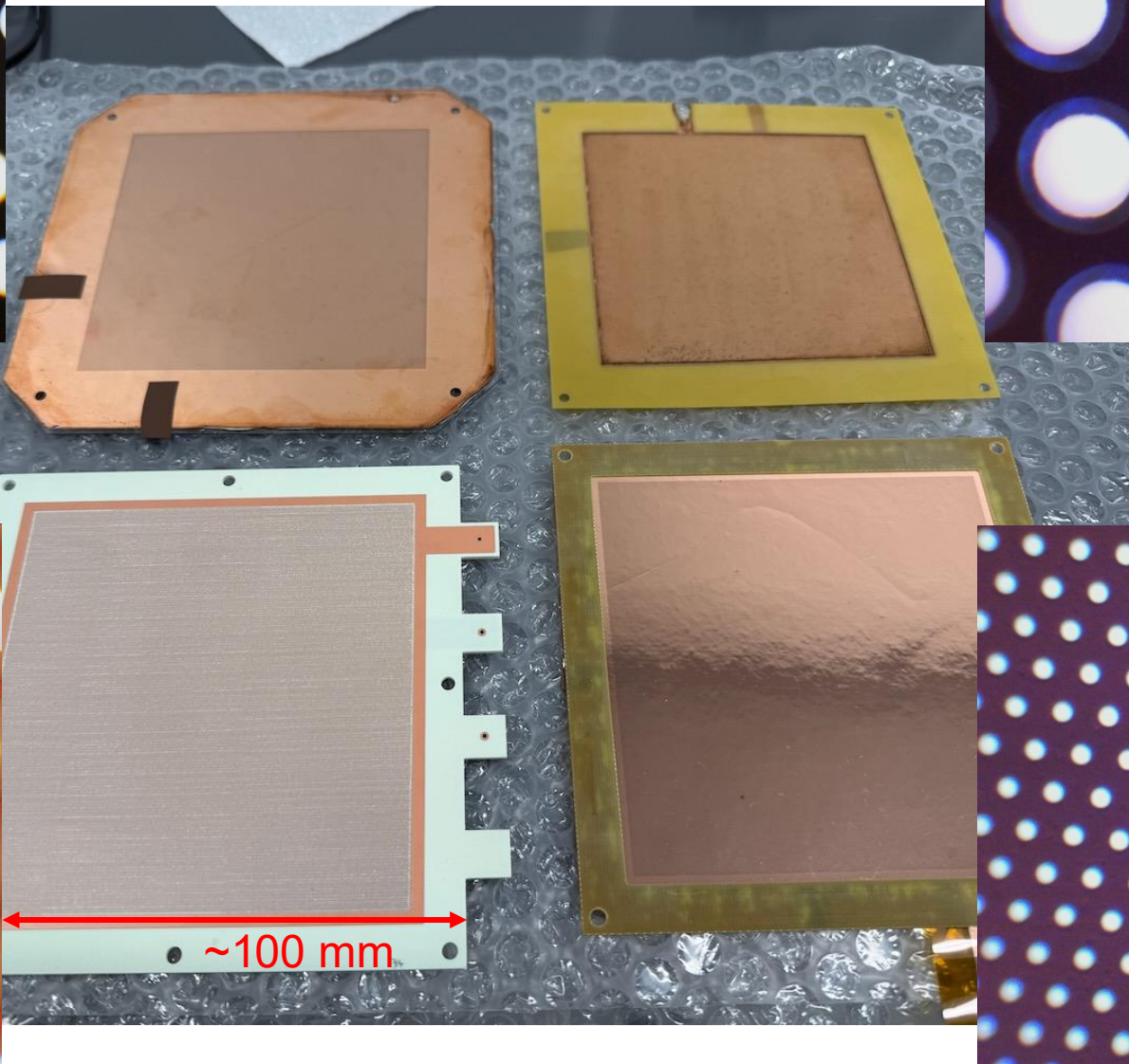
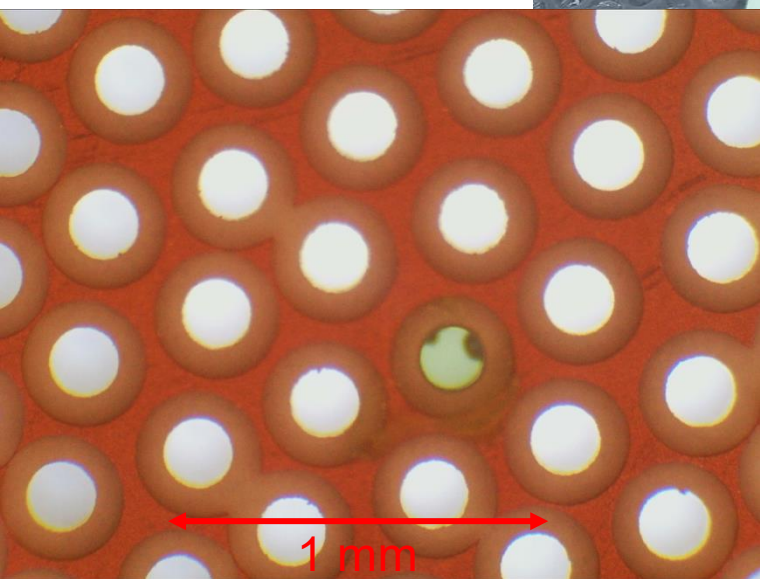


Glass GEM
PEG3 Glass + Cu

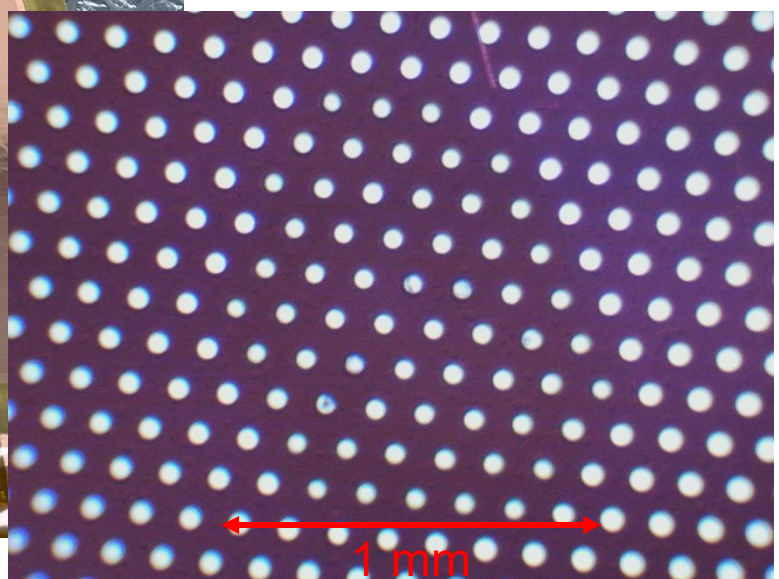
Thick GEM
FR4 (fiberglass) + Cu



M-Thick GEM
Ceramic + Cu



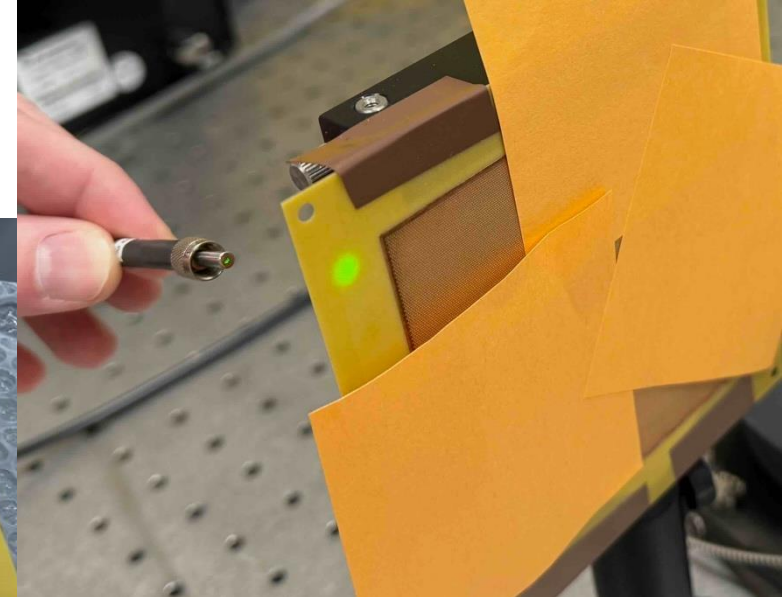
Thin GEM
Kapton (plastic) + Cu



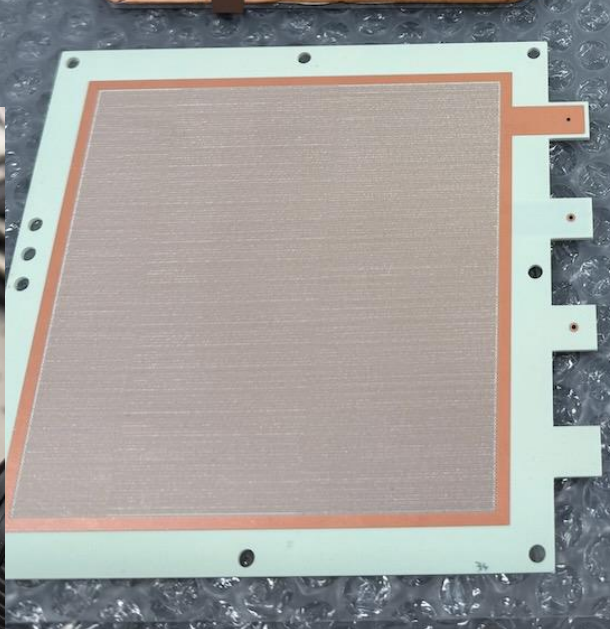
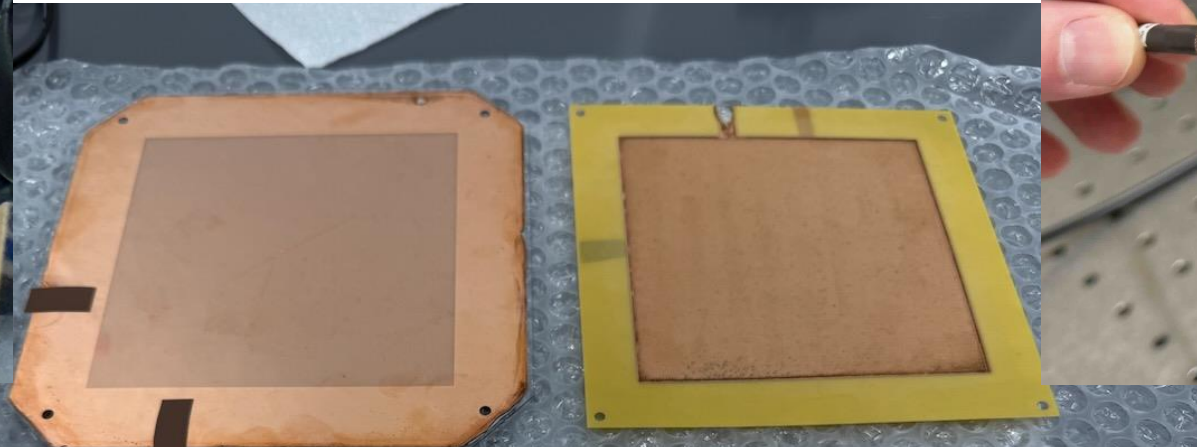
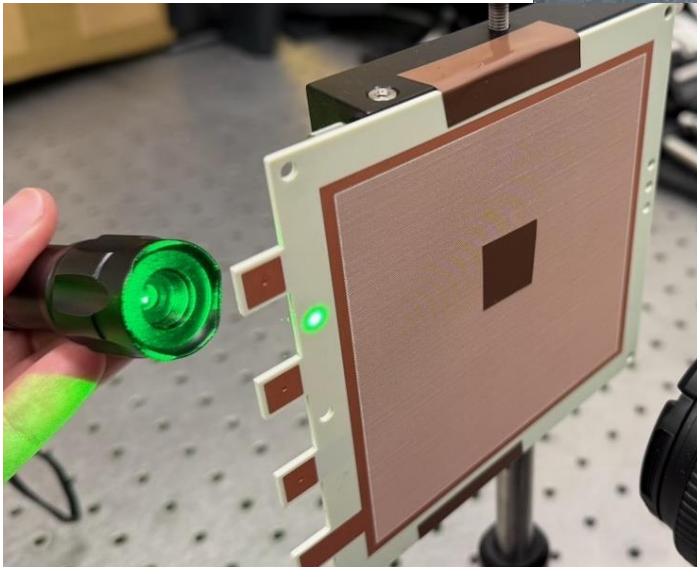


Glass GEM
PEG3 Glass + Cu

Thick GEM
FR4 (fiberglass) + Cu

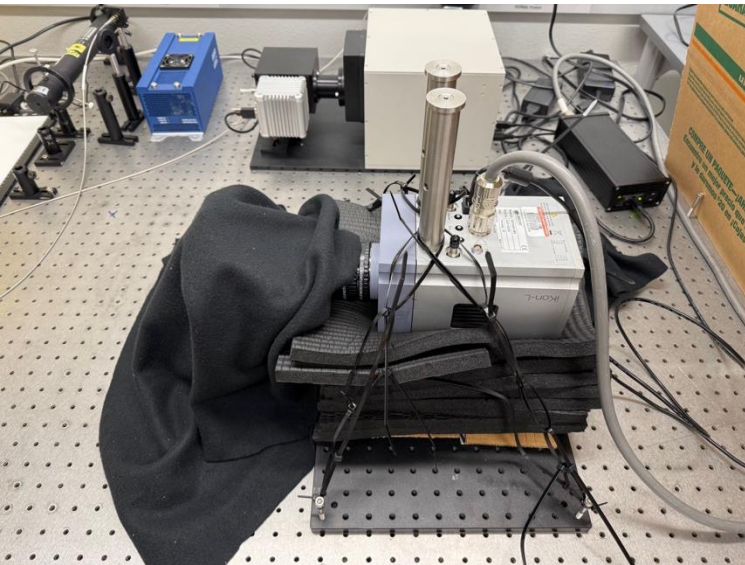
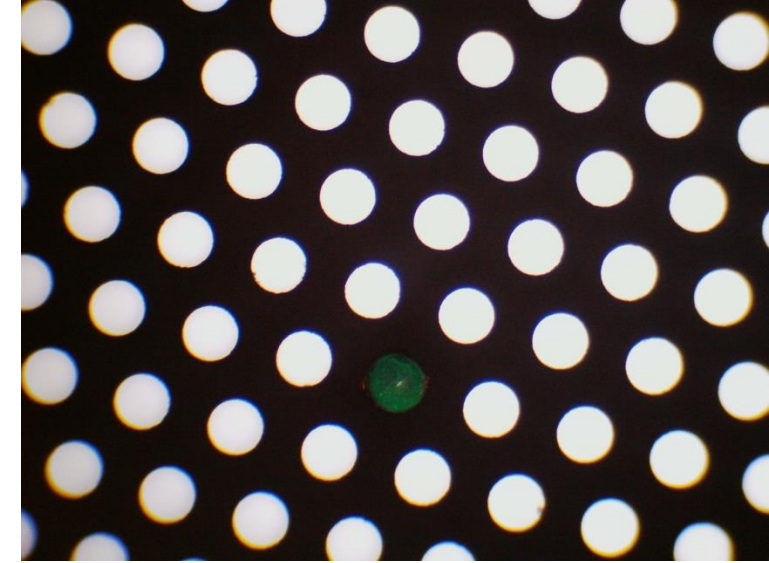
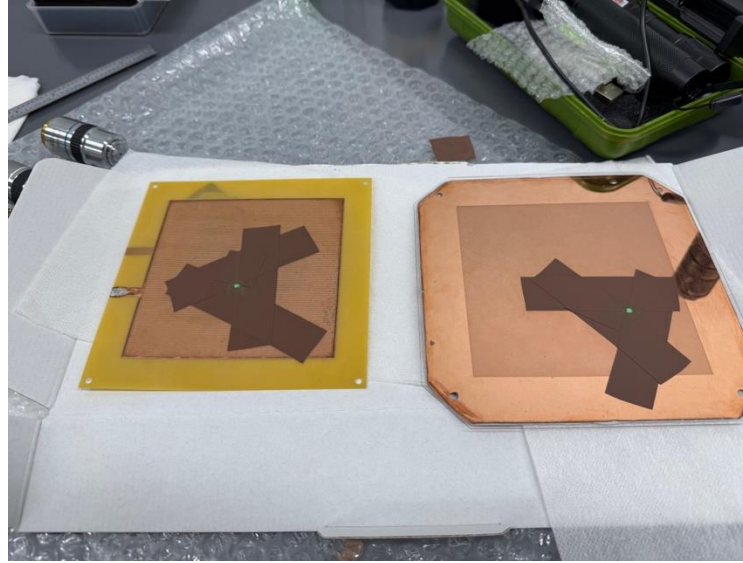
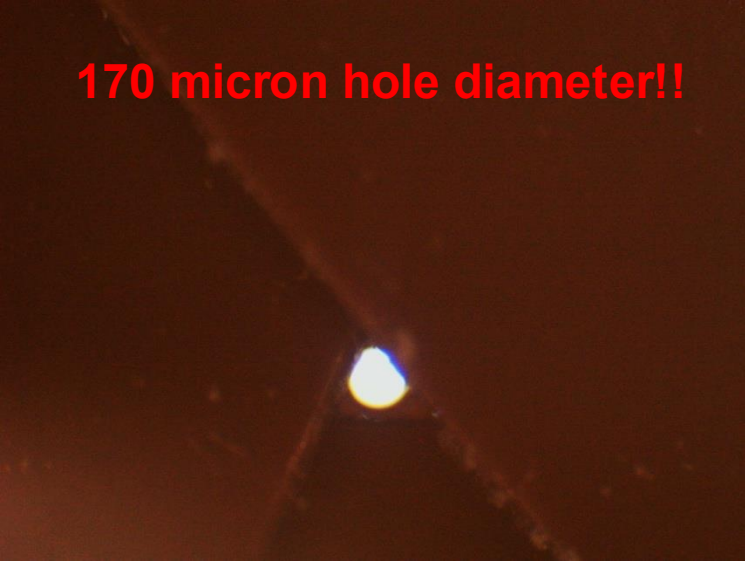


M-Thick GEM
Ceramic + Cu



Light will clearly travel through GEM substrate!

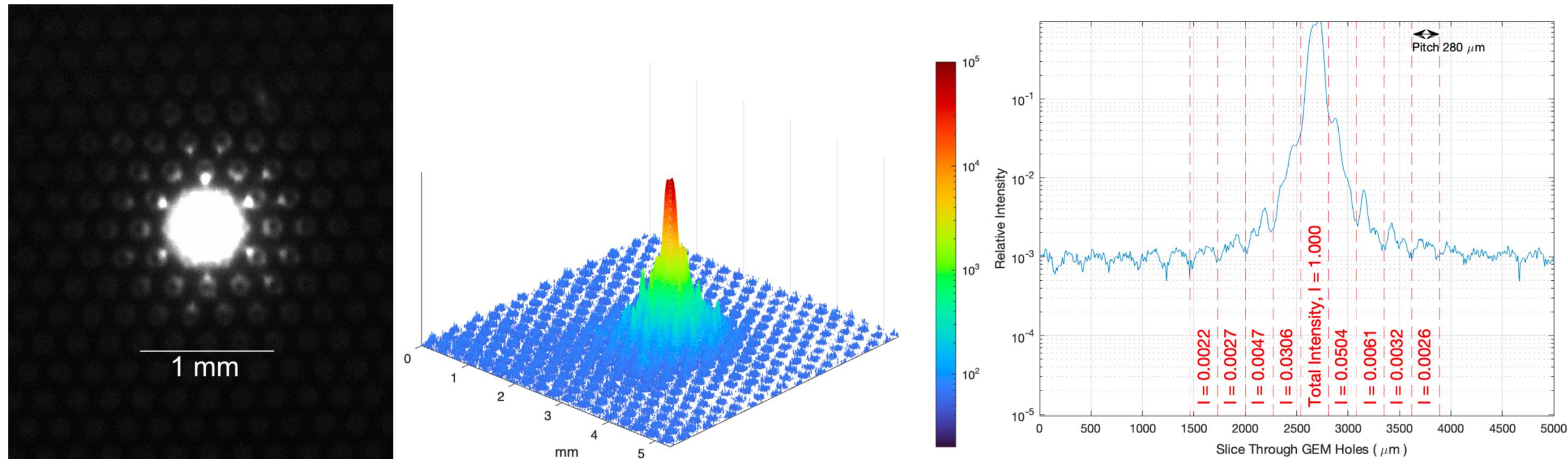
170 micron hole diameter!!



- Tape off single hole
- Drop glow-in-the-dark phosphorescent paint/water mix let dry
- Remove tape, check under microscope confined to hole
- Charge paint with UV light for 5 minutes
- Image for 30s – 10 minutes depending on GEM

Scientific grade CCD camera model (Andor iKon-L 936) Gillon et al. used for exoplanet discovery around TRAPPIST-1 2016

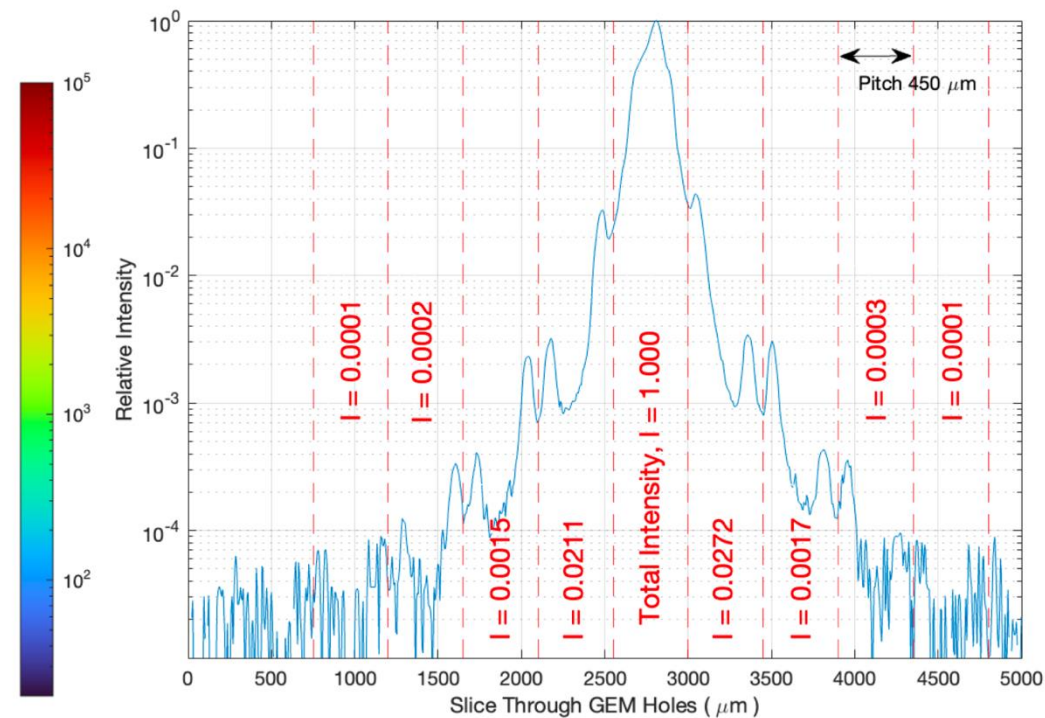
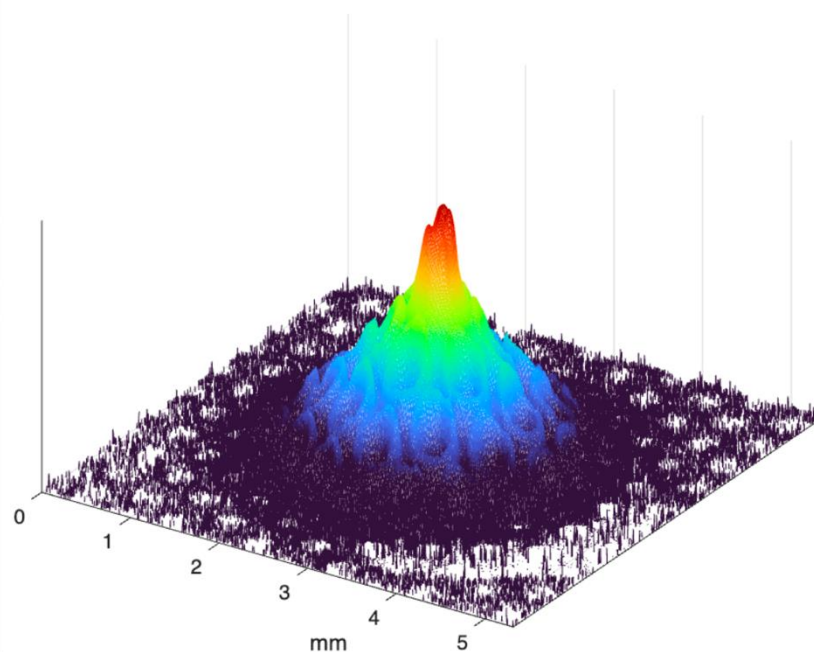
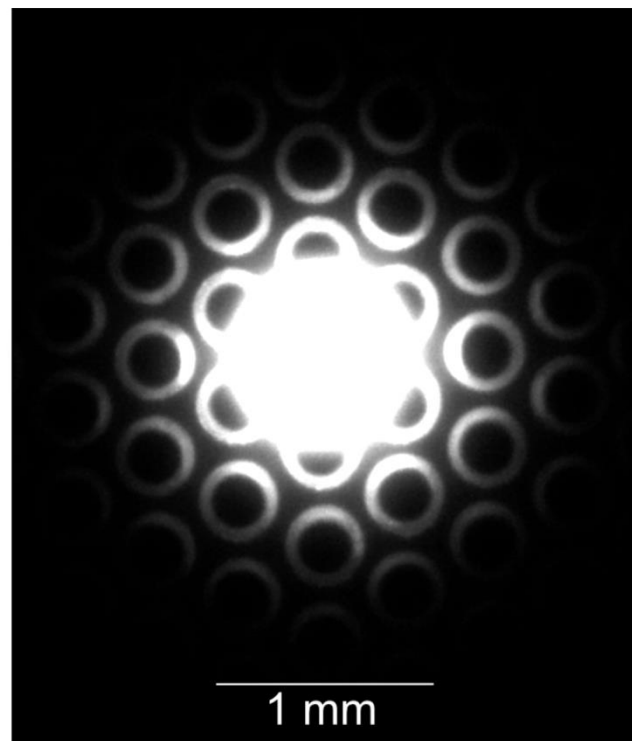
Glass GEM



Light travels through GEM substrate and exits neighboring holes. Hypothesis confirmed!

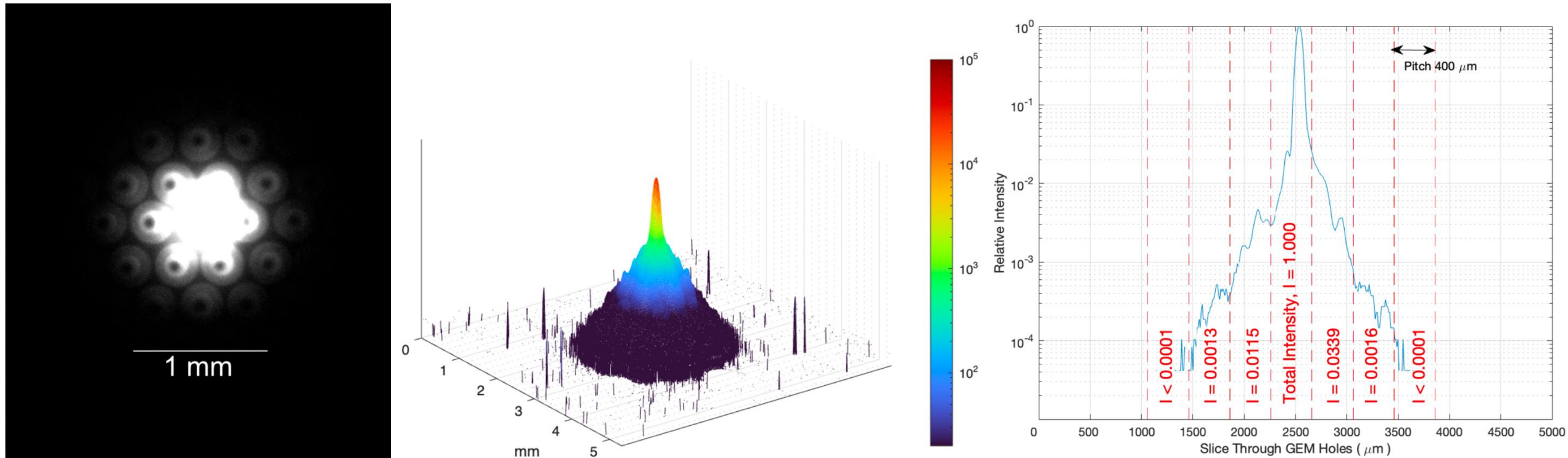
Light in a single GEM hole will create a multi-hole point spread function (**MH-PSF**).

Thick GEM



MH-PSF depends on GEM substrate and geometry.

M-Thick GEM

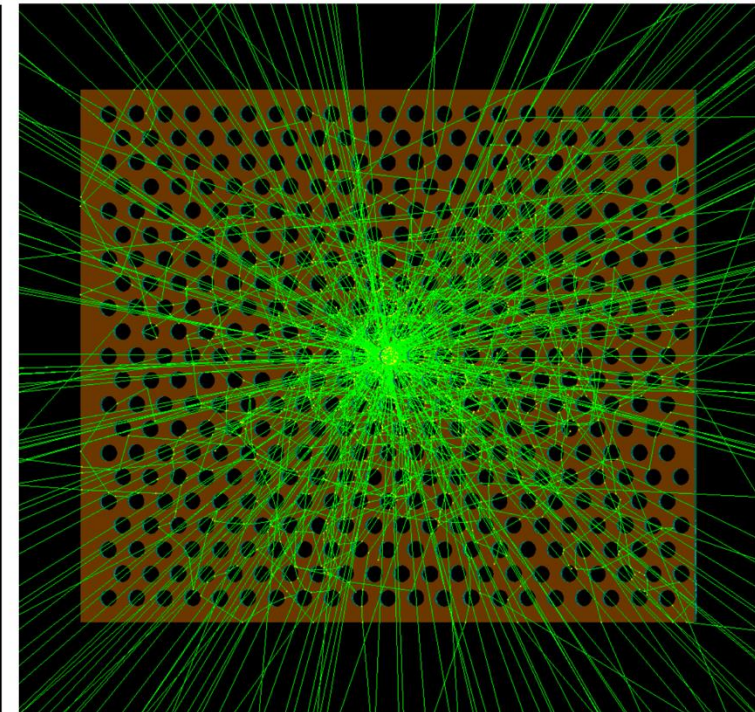
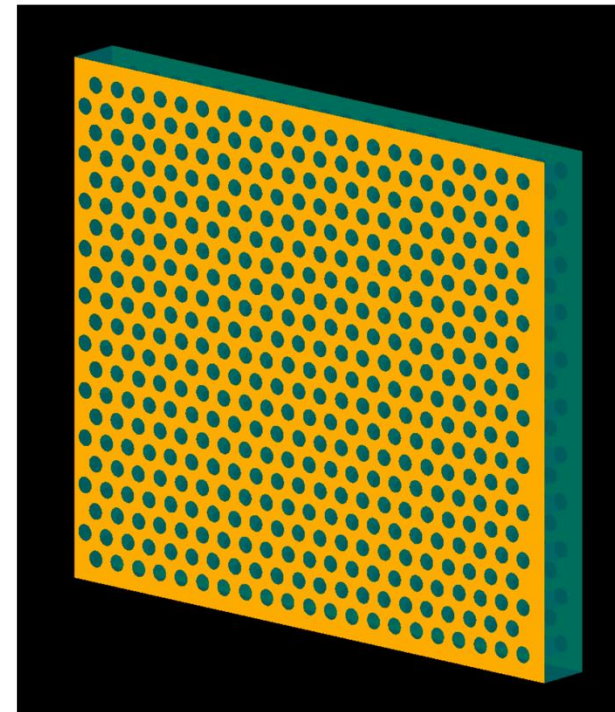


Even thick ceramic substrate will have photon transport!

Geant4 (GEometry ANd Tracking)

experimental setup particle tracking

Geant4 is a toolkit written in C++ to create Monte Carlo simulations of the passage of particles or radiation through matter.



GEM simulations. Left: A 21x21 GEM pitch portion of a G-GEM. Right: 500 photons simulated inside G-GEM hole.

Poster: Makoto Asai, SLAC National Accelerator Laboratory

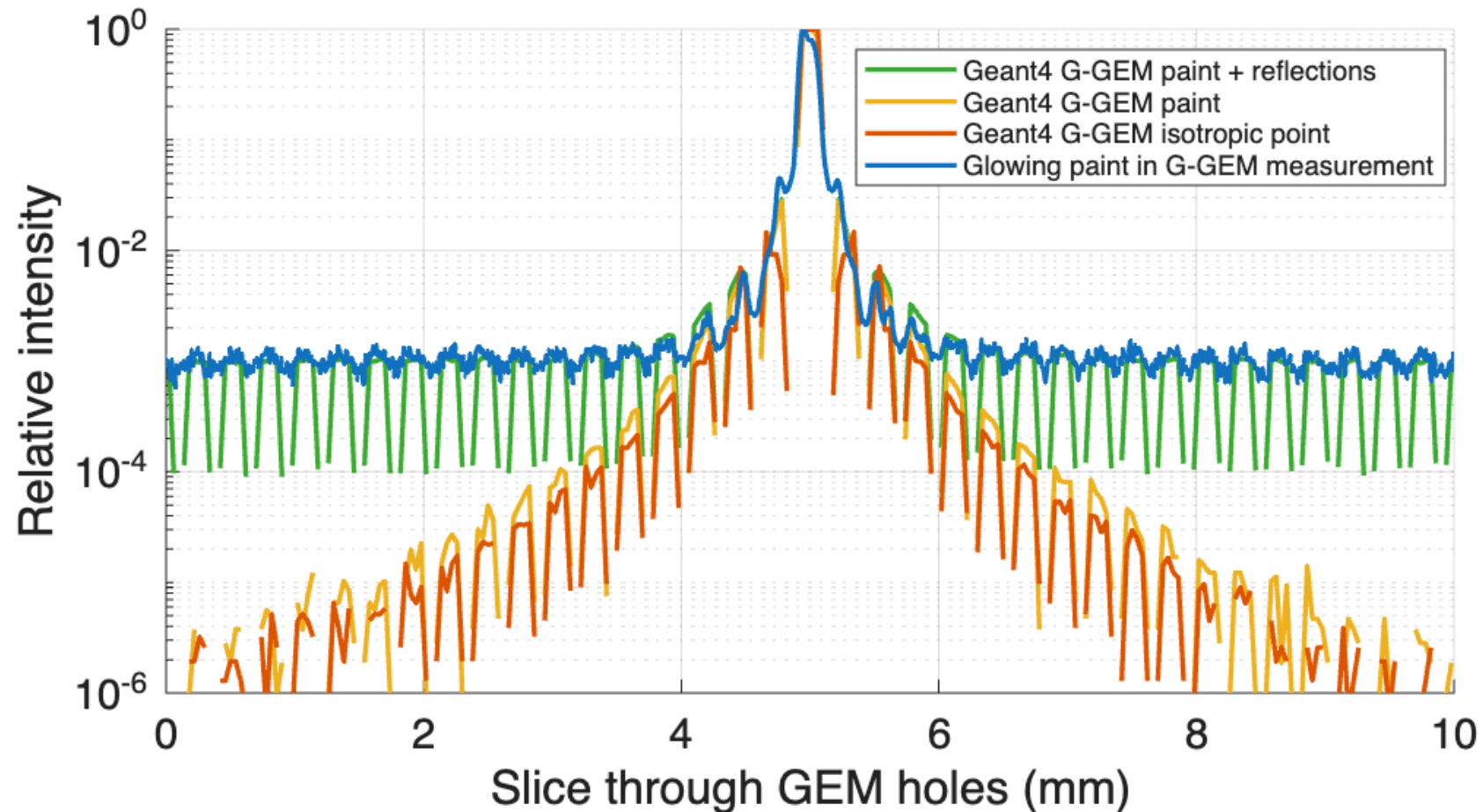
4. Simulations

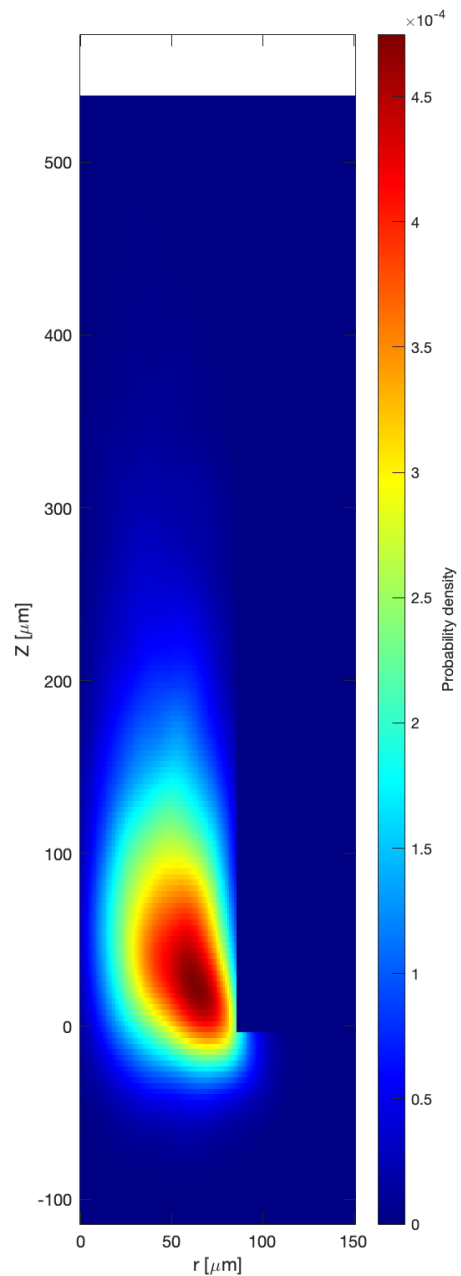
GEANT4 **simulations** can **recreate** paint **measurements** using 2 parameters;

1. the fraction of GEM hole filled with a cylinder of paint (50% shown **yellow**)
2. intensity of uniform light from behind (2.6% that of the photons emitted in the GEM hole shown **green**)

Paint is not representative of charge avalanche.

Simulations validated to create realistic MH-PSF.

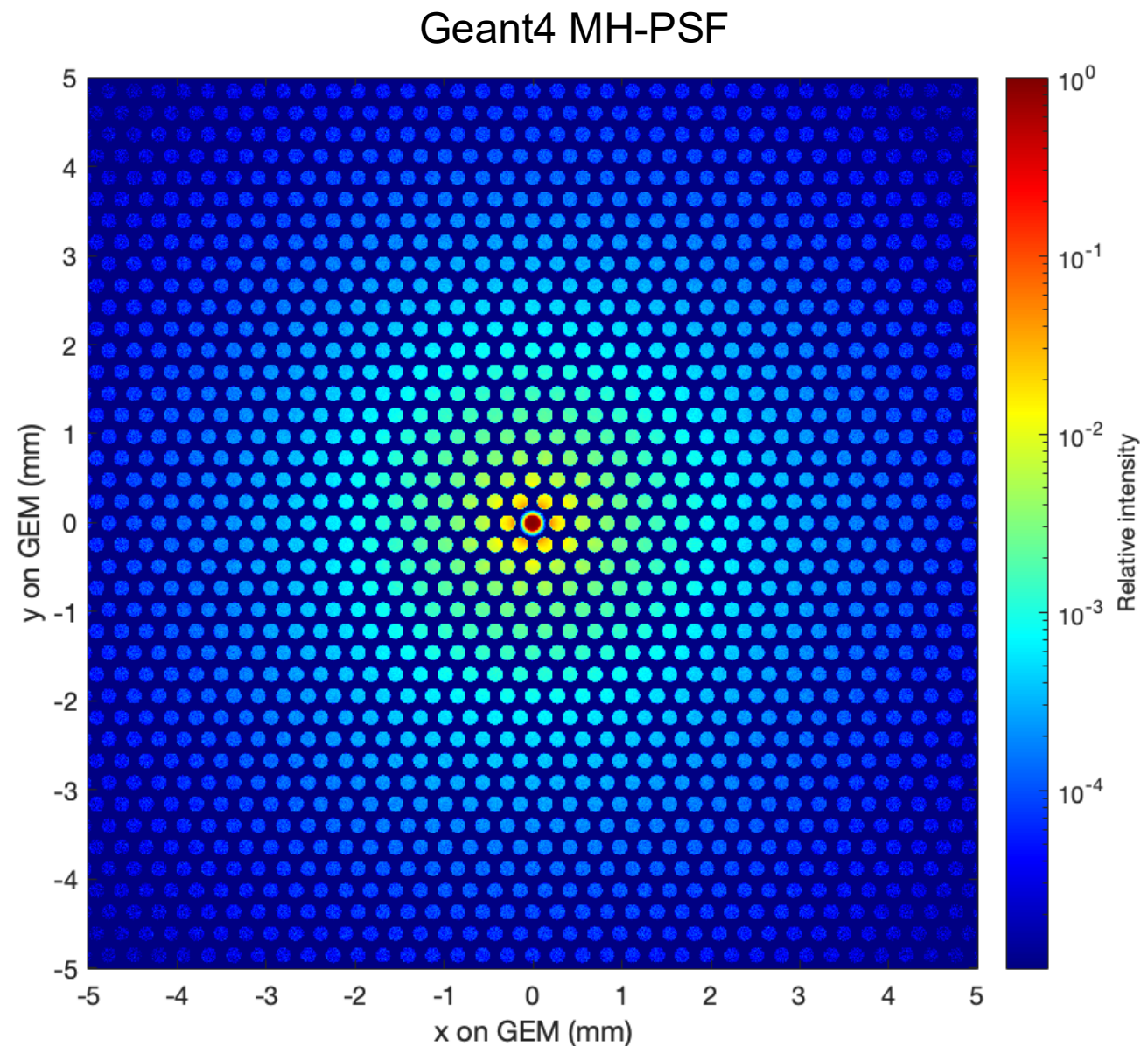




From paint to realistic MH-PSF.

Garfield++ electron production during charge avalanche used as proxy for scintillation distribution.

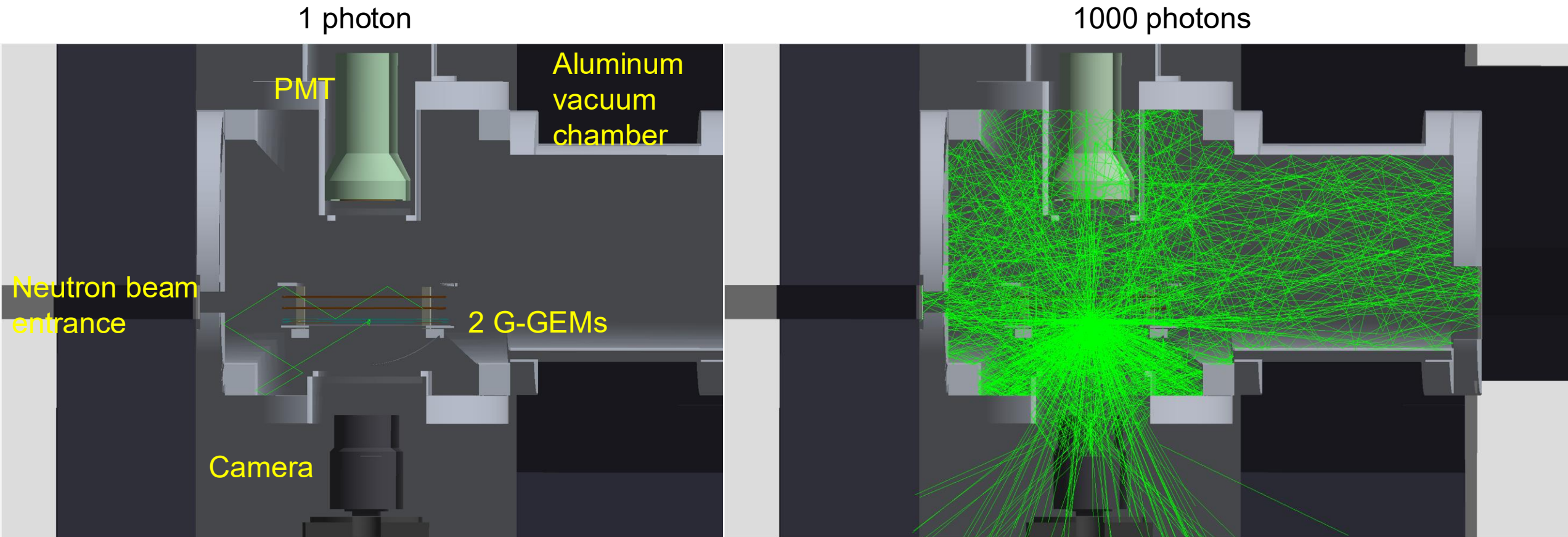
Scintillation probability distribution is used as photon start locations for Geant4.



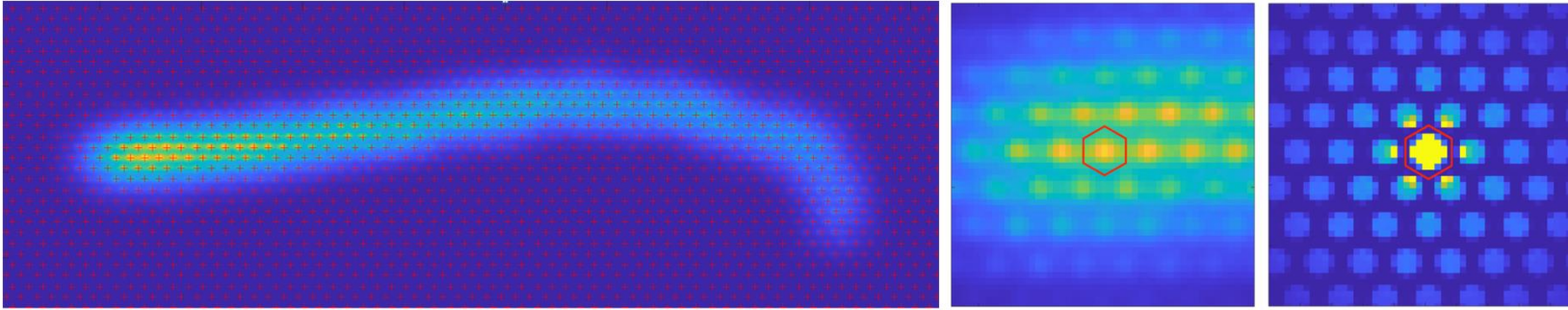
Garfield++ simulations by Max Gardner

Geant4 simulations can be extended to include **FULL GEMs**, (10cm)² active region with 147,647 holes and surrounding solid glass/copper regions. Also the **full MIGDAL detector** with accurate surface boundaries/**reflections** for **all materials inside** the gas chamber!

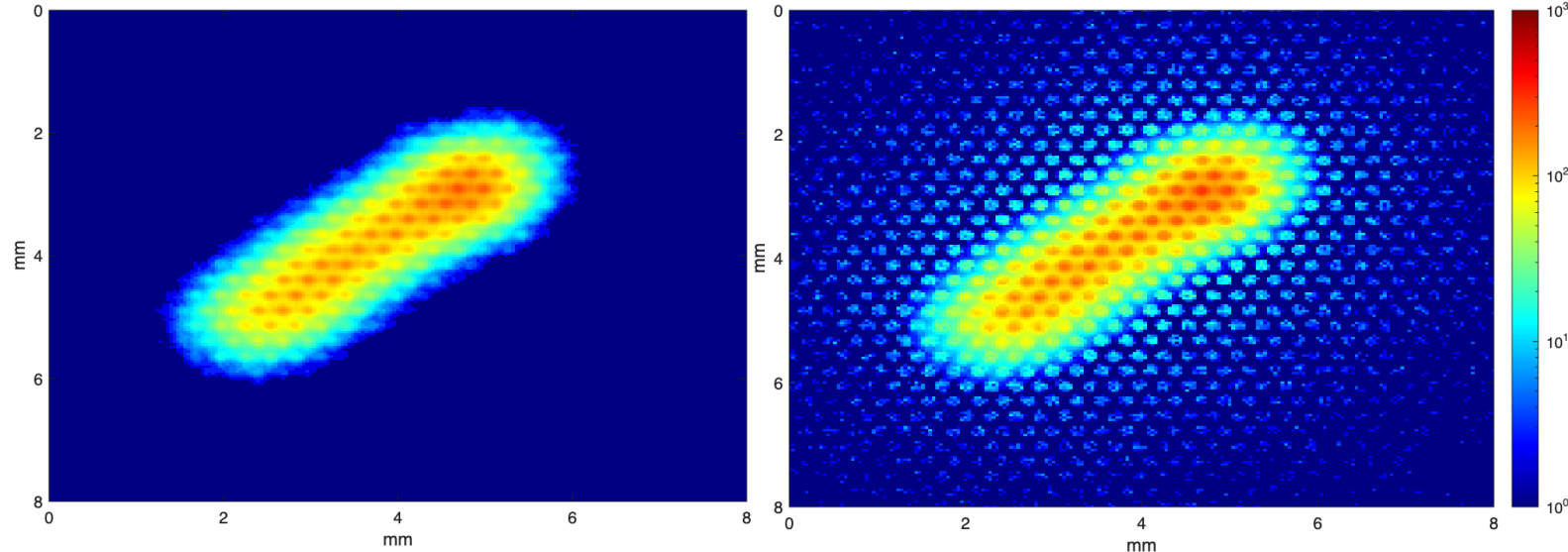
Full detector MH-PSF can be created!



MH-PSF is applied to simulated particle tracks** (“convolution”) to determine effects on observables.



No noise or image processing example of convolving MH-PSF with a simulated particle track.



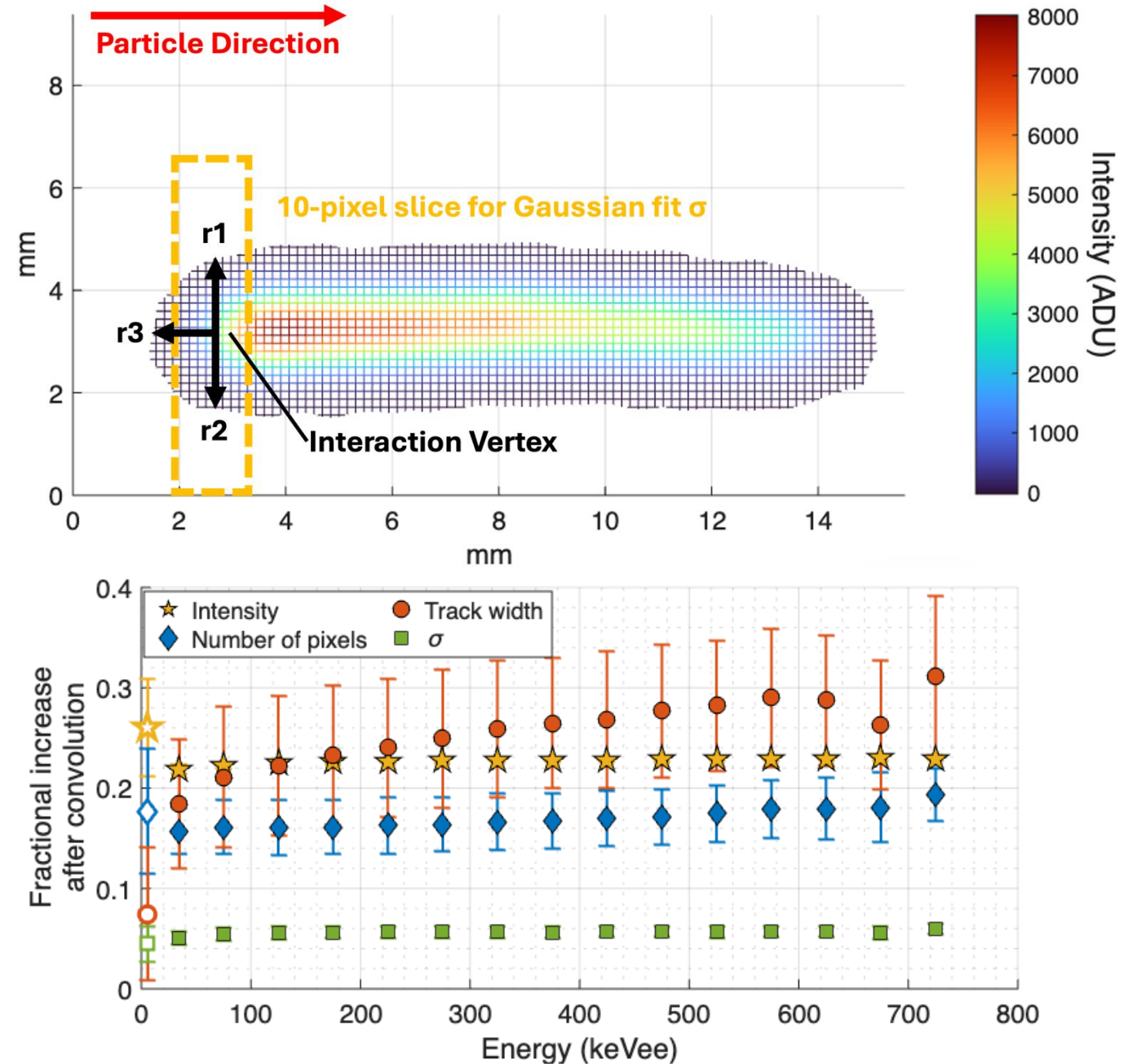
Convolution of simulated particle tracks

1. Assign each image pixel to a GEM hole (**left image**).
2. Measure the original scintillation intensity in each source hole (**middle image**).
3. Normalize the MH-PSF to that source-hole intensity (**right image**).
4. Add the normalized MH-PSF outside the source hole using Poisson statistics.
5. Repeat for all GEM holes.

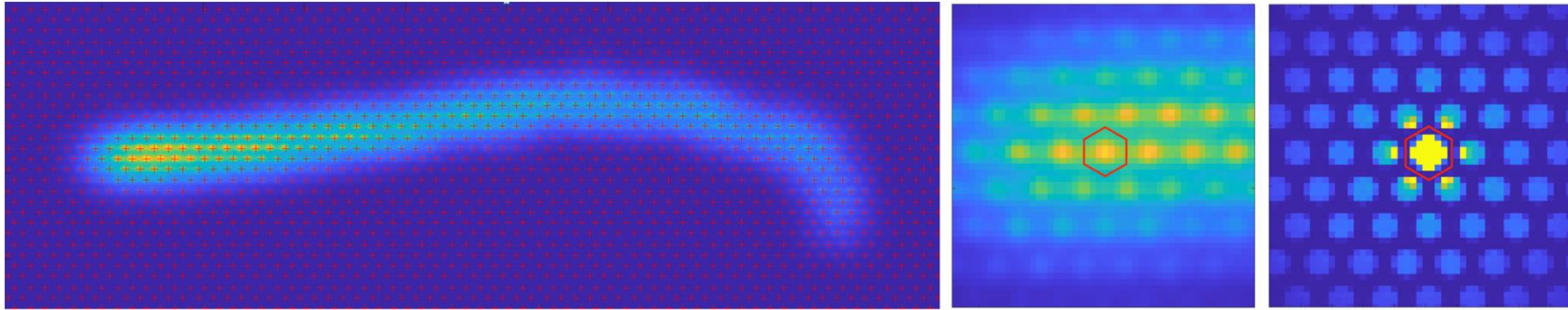
**Simulated particle tracks described in;
Araújo et al. (2023) Astroparticle Physics 151, 102853
Schueler et al. (2025) Phys. Rev. D 111,072004

Measurements of simulated particle tracks include total **intensity**, **number of pixels** in the track, **distance** from interaction vertex to **track edge** (r1,r2,r3), and slice through the interaction vertex for **Gaussian** fitting to the track width and calculation of the standard deviation σ . All measured after adding real noise and image processing used in real analysis.

Intensity increase up to **23%**
NR track widths increase up to **31%**



Correcting optical broadening



Convolution of simulated particle tracks

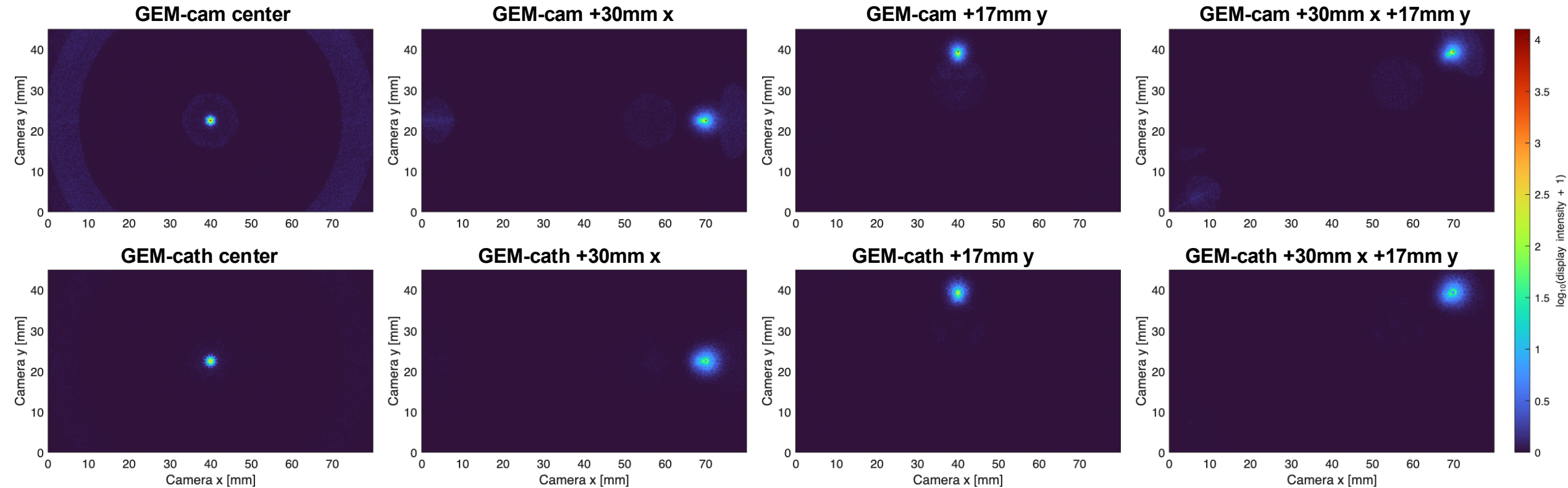
1. Assign each image pixel to a GEM hole ([left image](#)).
2. Measure the original scintillation intensity in each source hole ([middle image](#)).
3. Normalize the MH-PSF to that source-hole intensity ([right image](#)).
4. Add the normalized MH-PSF outside the source hole using Poisson statistics.
5. Repeat for all GEM holes.

Deconvolution follows the same physical model, but the original source-hole intensity is **unknown** because the measured image already contains MH-PSF broadening and noise. The first step is therefore to **fit the original scintillation intensity of each GEM hole**. The fitted source intensities are then used to normalize and subtract the MH-PSF halo.

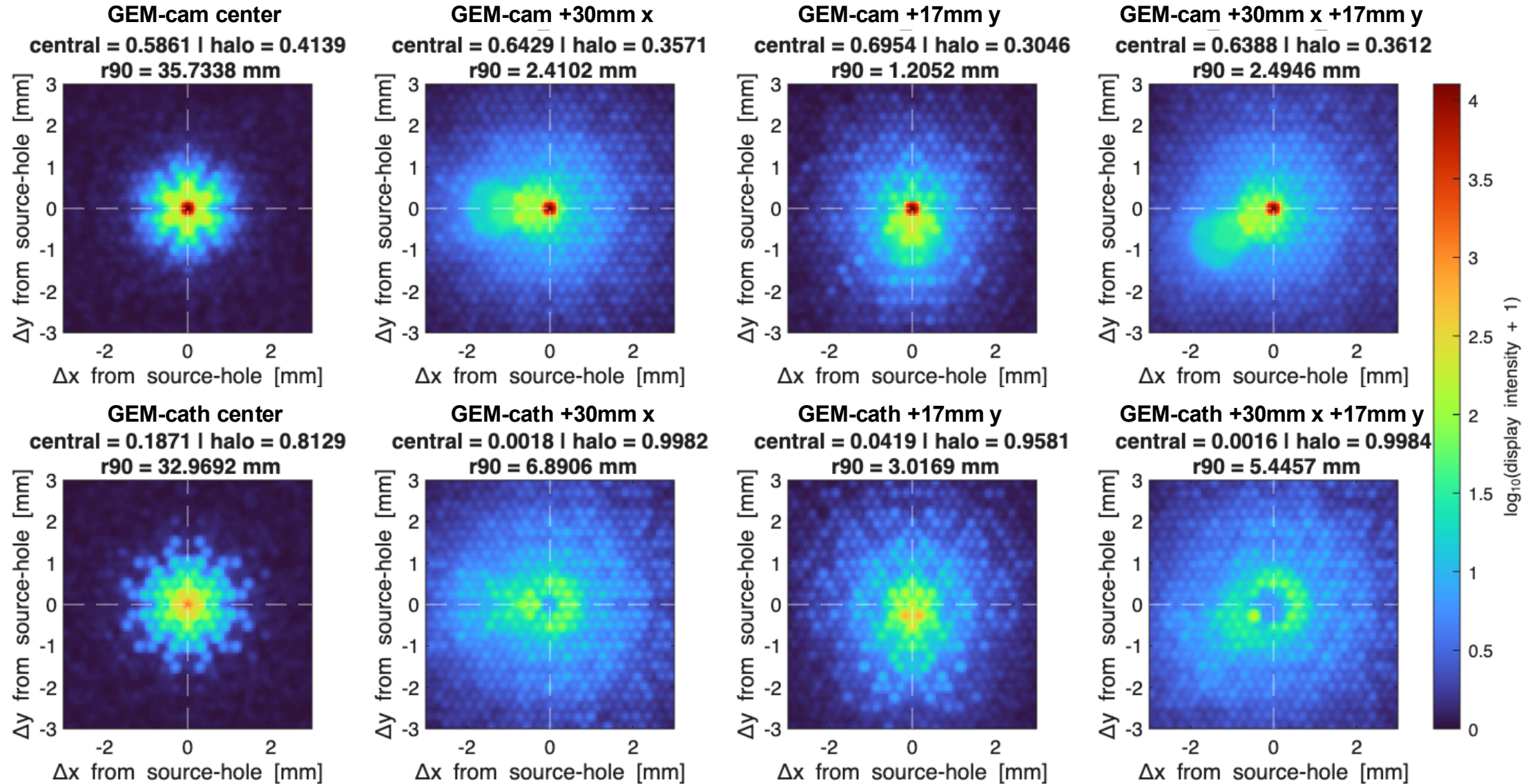
In order to fit the original intensity, a **MH-PSF library** is needed (MH-PSFs across the imaging plane for each GEM).

Creating MH-PSF libraries

2 stacked Glass GEM Simulation, comparing single hole scintillation from each GEM across the imaging plane



Same images as 18, zoomed into each hole



Note the MH-PSF is **position dependent AND orientation dependent!** Particle tracks will have different halos depending on their location in the camera and their orientation!

How to determine the GEM hole original source intensity

Simple 3-hole example

Assume three holes in a row: A , B , C .

Each hole contributes 100% of its own source intensity to its measured central-hole signal, plus 10% to the nearest neighbor and 2% to the next neighbor. Measured intensities:

$$M_A = S_A + 0.10S_B + 0.02S_C$$

$$M_B = 0.10S_A + S_B + 0.10S_C$$

$$M_C = 0.02S_A + 0.10S_B + S_C$$

Matrix form:

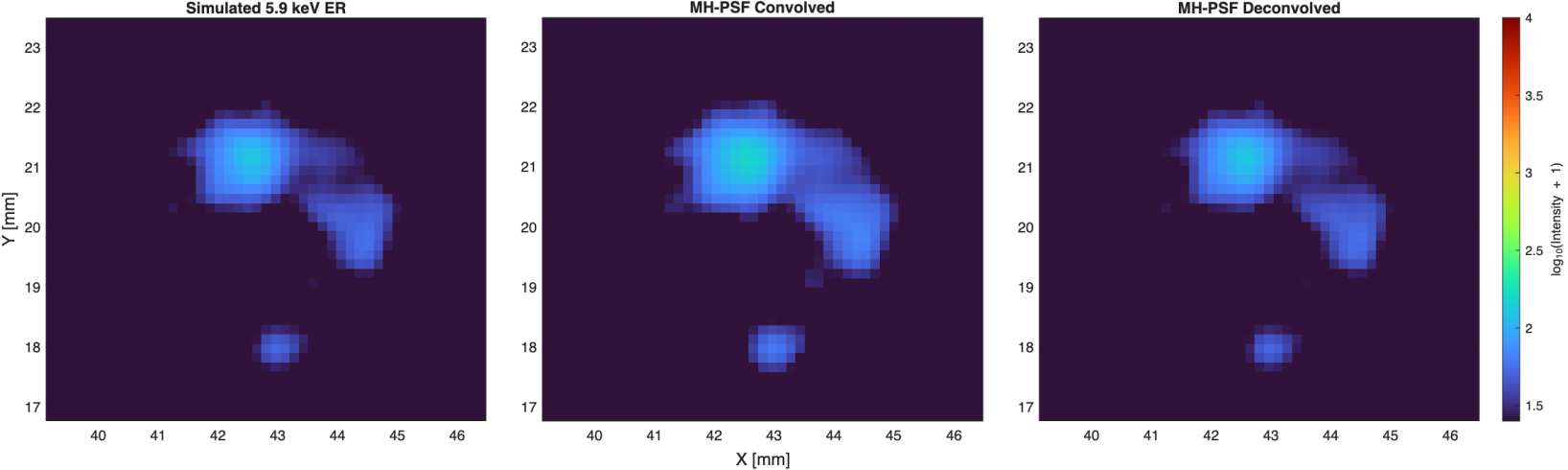
$$\begin{bmatrix} M_A \\ M_B \\ M_C \end{bmatrix} = \begin{bmatrix} 1 & 0.10 & 0.02 \\ 0.10 & 1 & 0.10 \\ 0.02 & 0.10 & 1 \end{bmatrix} \begin{bmatrix} S_A \\ S_B \\ S_C \end{bmatrix}$$

MATLAB/Python solves for S_A, S_B, S_C , requiring them to be non-negative (can't have negative intensity).

(<https://www.mathworks.com/help/matlab/ref/lsqnonneg.html>)

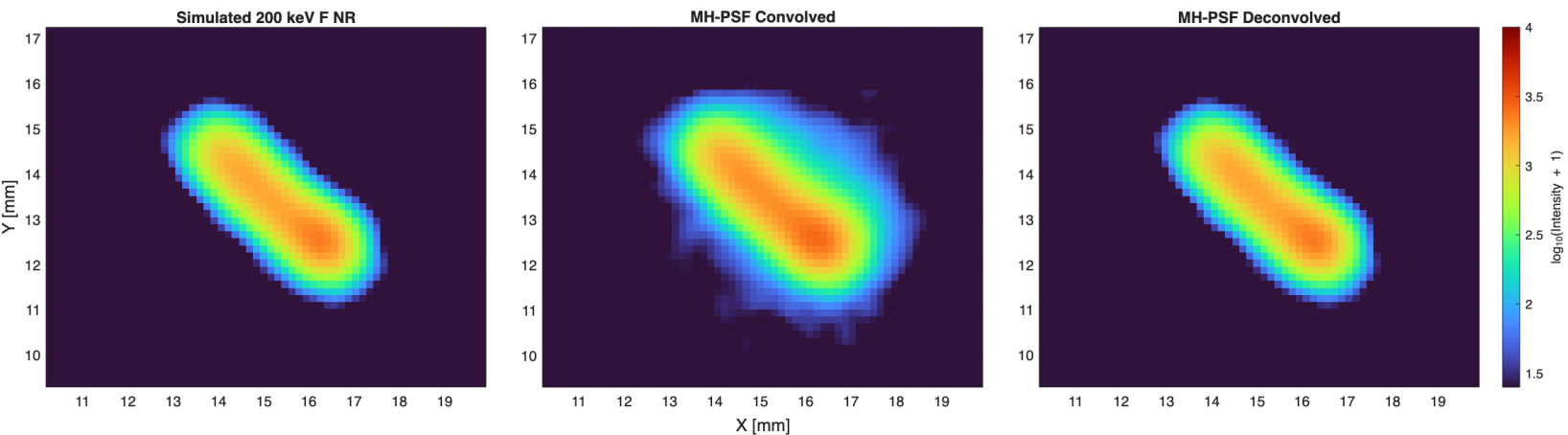
Those fitted S values estimate the original scintillation before GEM optical redistribution.

MH-PSF library provides exactly the missing information, for any given GEM hole the intensity contribution to neighboring holes can be measured.



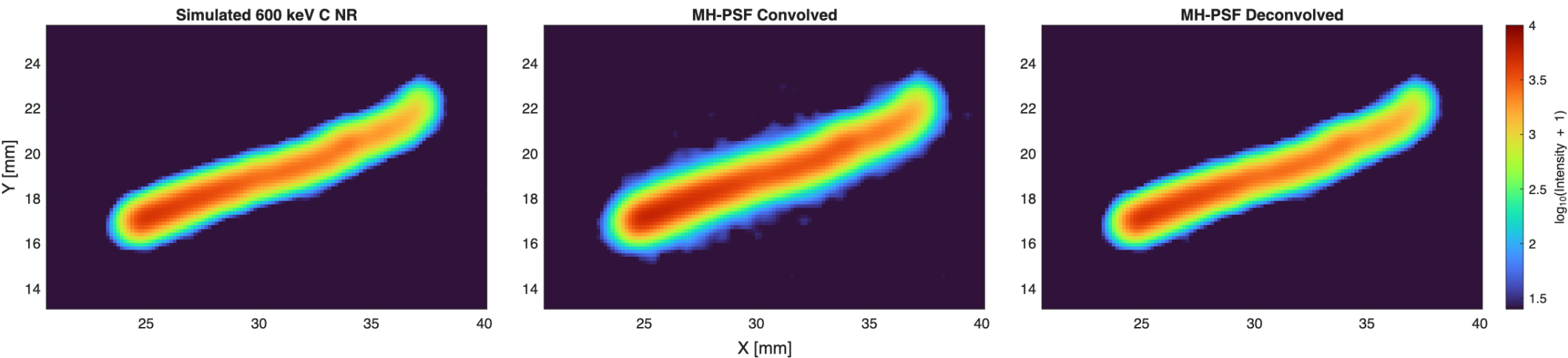
Adding/removing optical broadening from simulated particle tracks.

5.9 keV ER (top), 200 keV F (middle), 600 keV C (bottom). All shown after adding real noise and image processing used in real analysis.

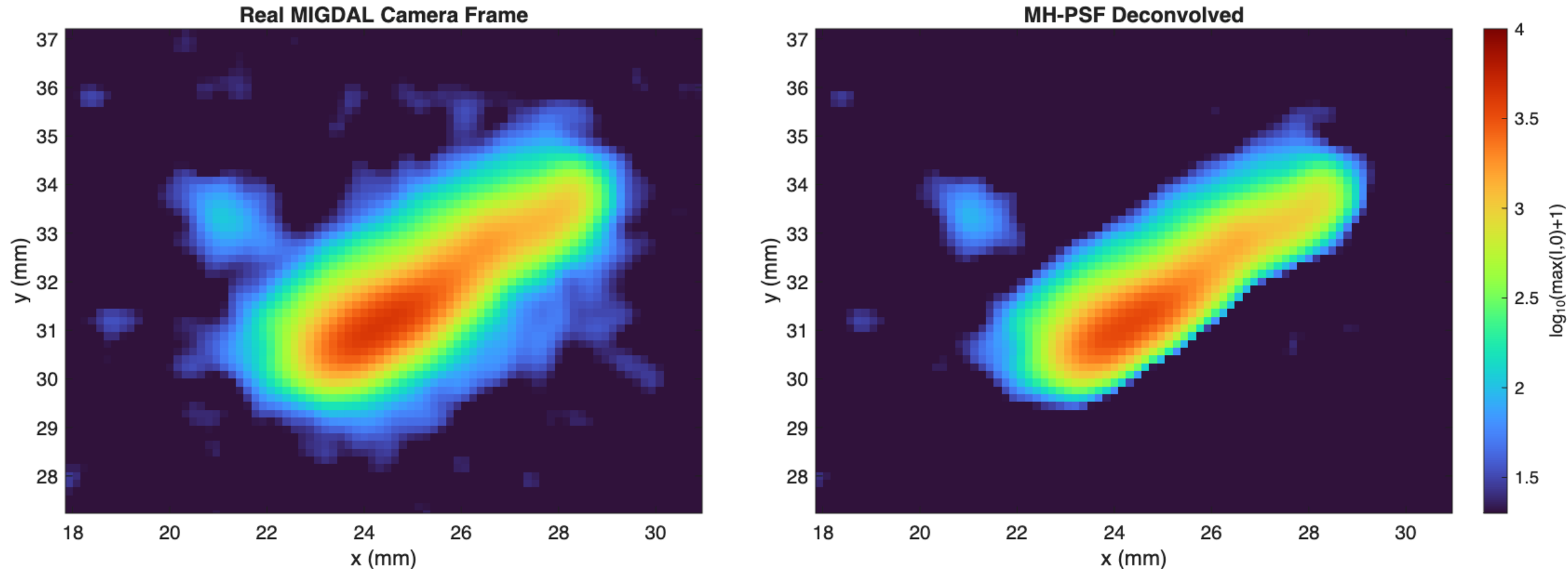


Original image (left), MH-PSF convolved image (center), MH-PSF deconvolved image (right).

Same color intensity scale, different xy scale (zoomed per track).



Correcting optical broadening from REAL DATA!! This is the same camera frame as slide 3 with coincident ER and NR.



Summary

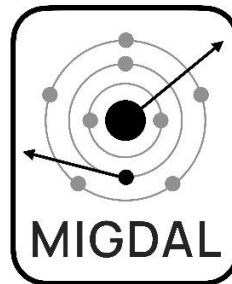
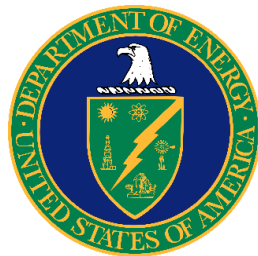
Light will travel through GEM substrate and exit neighboring holes.

All GEM based OTPCs are expected to observe brighter and larger particle tracks vs charge measurements or charge based simulations.

GEM optical effects can be modeled to characterize optical readouts.

Accurate characterization of optical readouts allow deconvolution methods to be created, reducing the effects and improving the spatial resolution for particle tracks.

Paper is available on the arXiv (<https://arxiv.org/abs/2604.27399>) and accepted for publication with Nuclear Inst. and Methods in Physics Research, A!



Backup

Inputs that constrain the fit

1. MH-PSF library

MH-PSFs across the imaging plane for each GEM layer.

2. Relative charge production per GEM

Determined with Garfield++. Changes in GEM gain can alter the combined MH-PSF because the different GEM layers have different halo fractions.

*Expected to be a relatively **small correction** because the GEM closest to the camera dominates the detected light.*

3. Charge diffusion between GEMs

Determined with Garfield++. Used to determine where contributions from additional GEM layers are expected across the track.

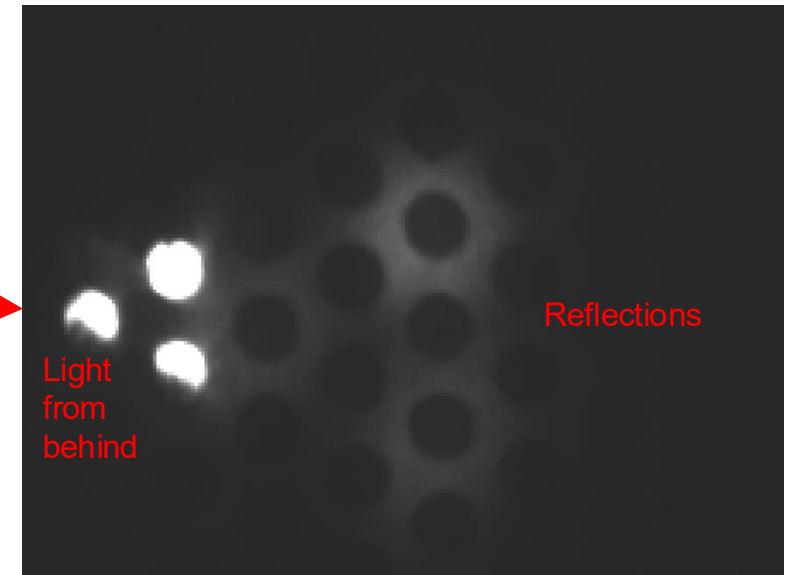
*Also expected to be a relatively **small correction**.*

$$\text{Fractional increase} = \left\langle \frac{\text{convolved} - \text{original}}{\text{original}} \right\rangle \pm 1 \text{ std}$$

4,900 5.9 keV ERs, 4,000 fluorine NRs, and 6,500 carbon NRs. The simulated NR energy spectra are uniformly distributed between 50 and 450 keVr for fluorine and 50 and 700 keVr for carbon, with the upper limits chosen to approximately match the elastic scattering endpoint energies of 2.5 MeV neutrons in CF₄. The energy bin widths are from left: 0 for 5.9keV ERs, 35 keVee for the lowest energy NRs, 50 keVee for all other NR bins.

What is the secondary source?

- 1) Outside light leaking into experiment (will always have some light leak)
- 2) Reflections within experiment (old experiments with mirror-like filter created bright reflections on GEM) 



Experiment possible reflective surfaces

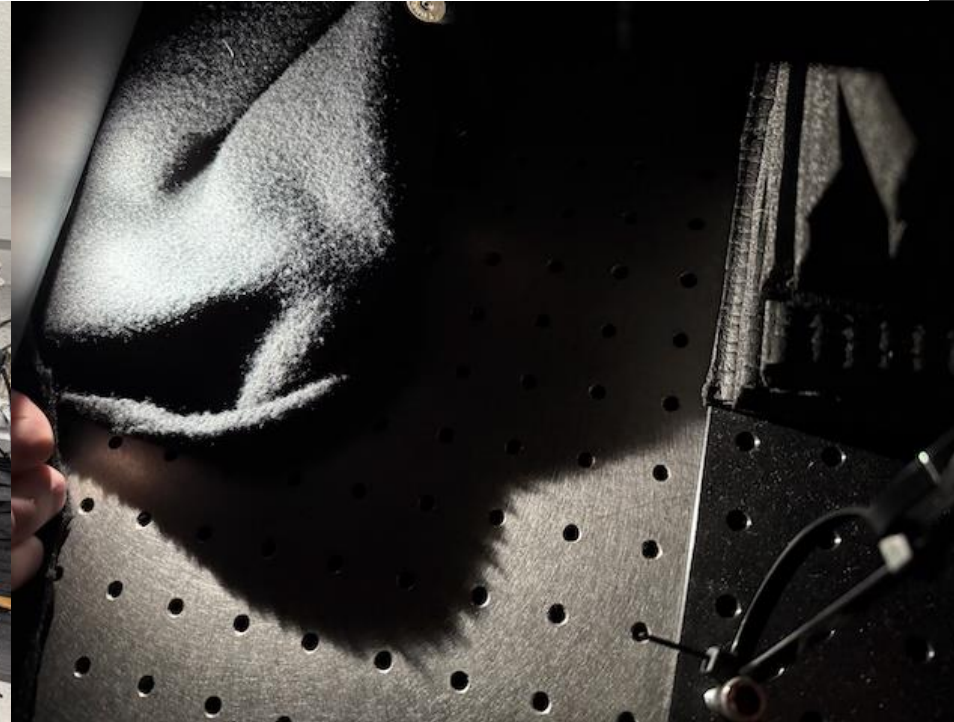
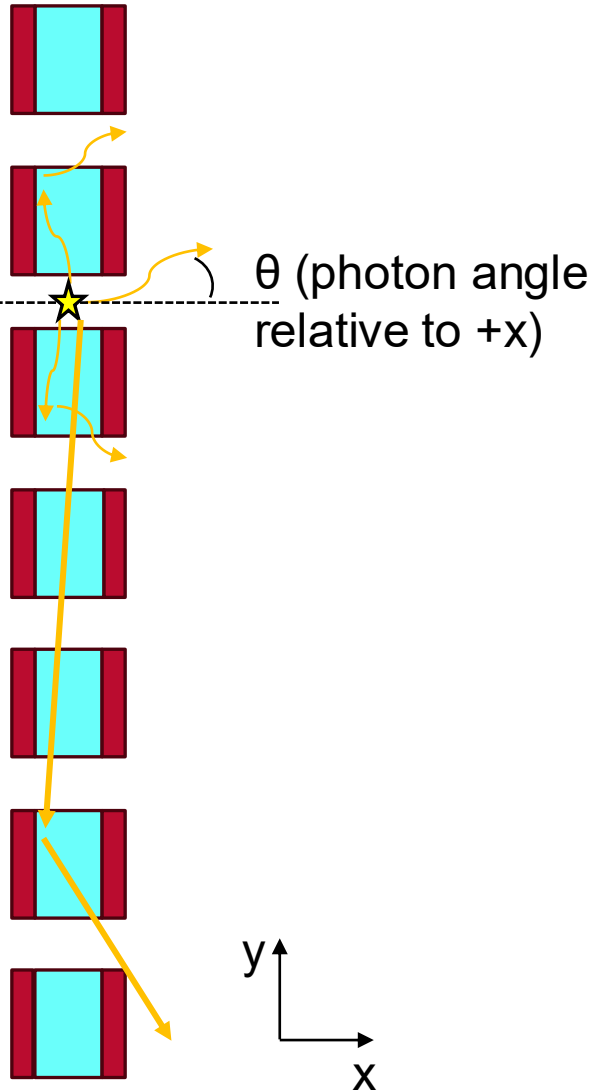
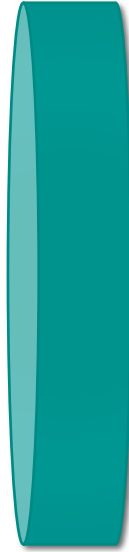


IMAGE FORMATION

Geant4 handles photon **position** and **direction** after leaving GEM surface



Python / MATLAB handles **disk intersection** method for determining which photons would hit a camera lens. For each photon **hit**, the **position** at the **GEM surface** is used assuming lens would **focus** back to that point.



Thin lens approximation** (numbers matching MIGDAL):
Distance = 119mm
Radius = 14.7mm

Separating disk intersection method allows Geant4 simulation to be applied to various experiment geometries.

**Complete ray-tracing for lens may not be possible due to proprietary complex lens systems used