



arXiv:2607.01123

Investigating plenoptic imaging of particle interactions in scintillation detectors

CPAD 2026, Seattle, WA

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Prepared by LLNL under Contract DE-AC52-07NA27344.

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Supported by:

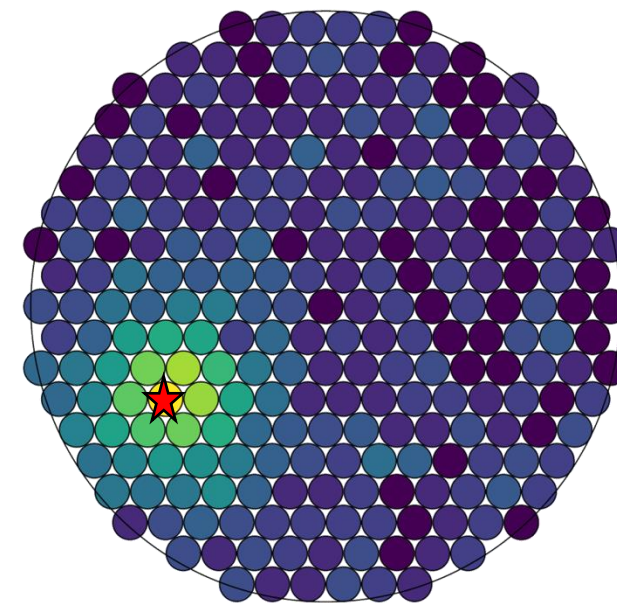
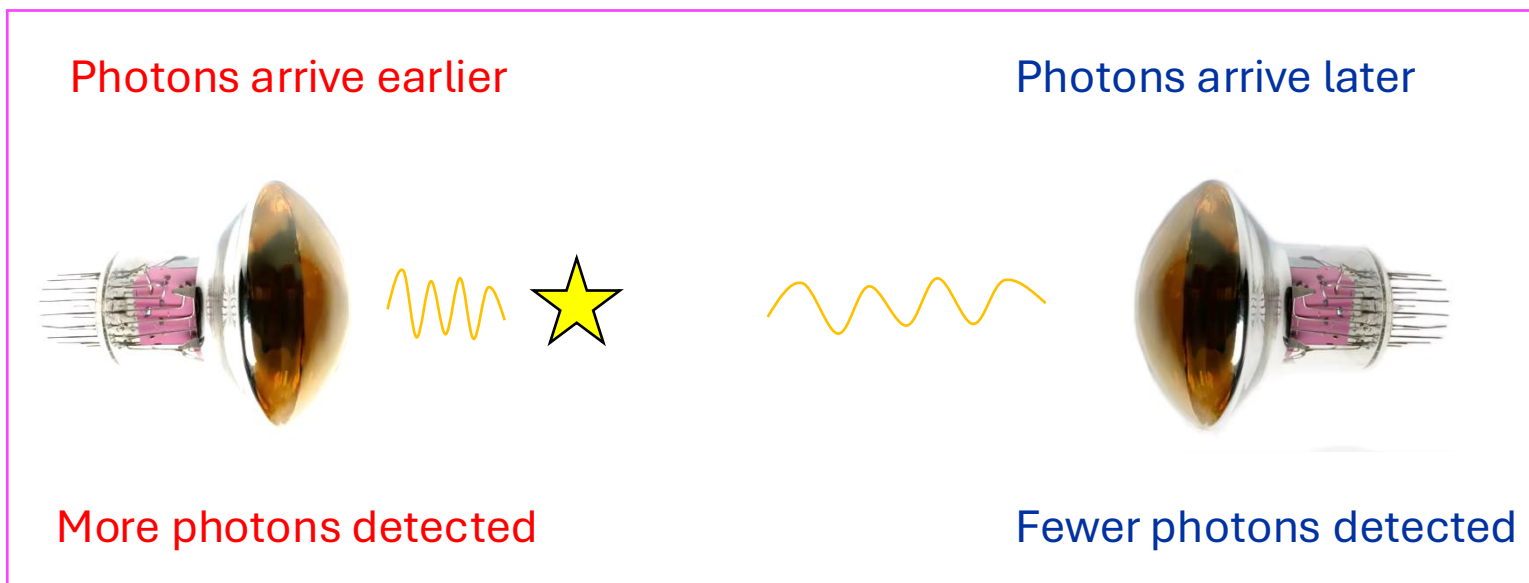
- LLNL LDRD
- DNN R&D
- Consortium for Enabling Technologies and Innovation

Position reconstruction in scintillation detectors

A scintillation detector can provide event timing, energy, **position**, interaction type, etc

Time-based position reconstruction: photons travel at finite speed

Intensity-based position reconstruction: photon flux decreases with distance



Example PMT hit pattern in a dual-phase TPC

Position information of a single photon

Scintillation detectors usually infer event positions statistically

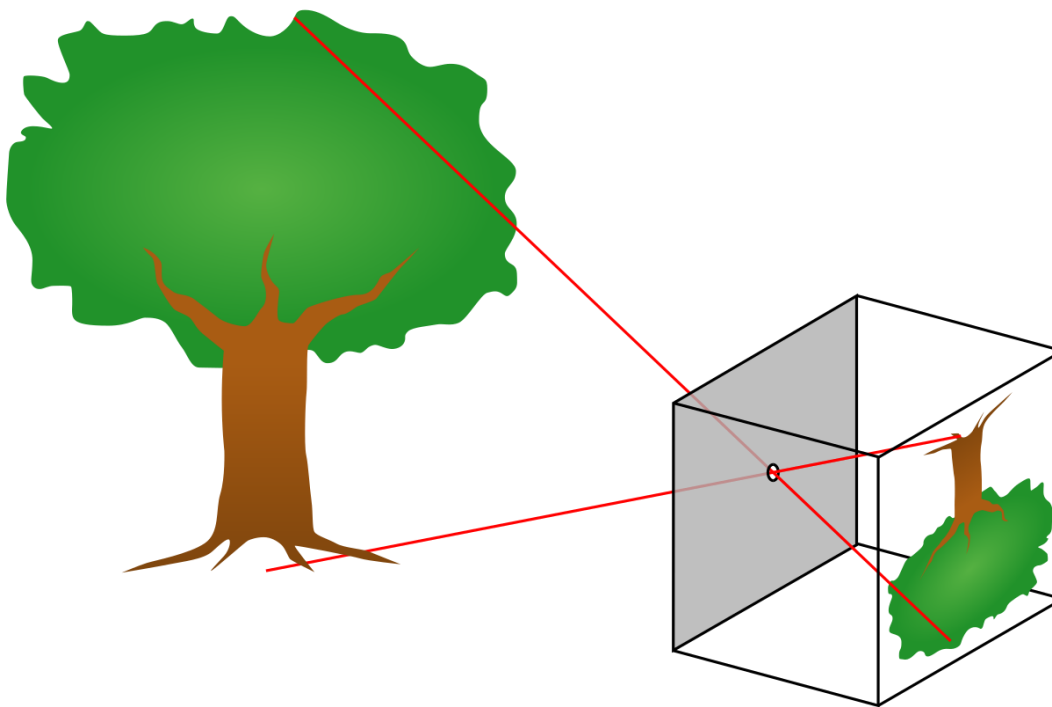
- Each photon carries little information

A pinhole camera is the opposite example

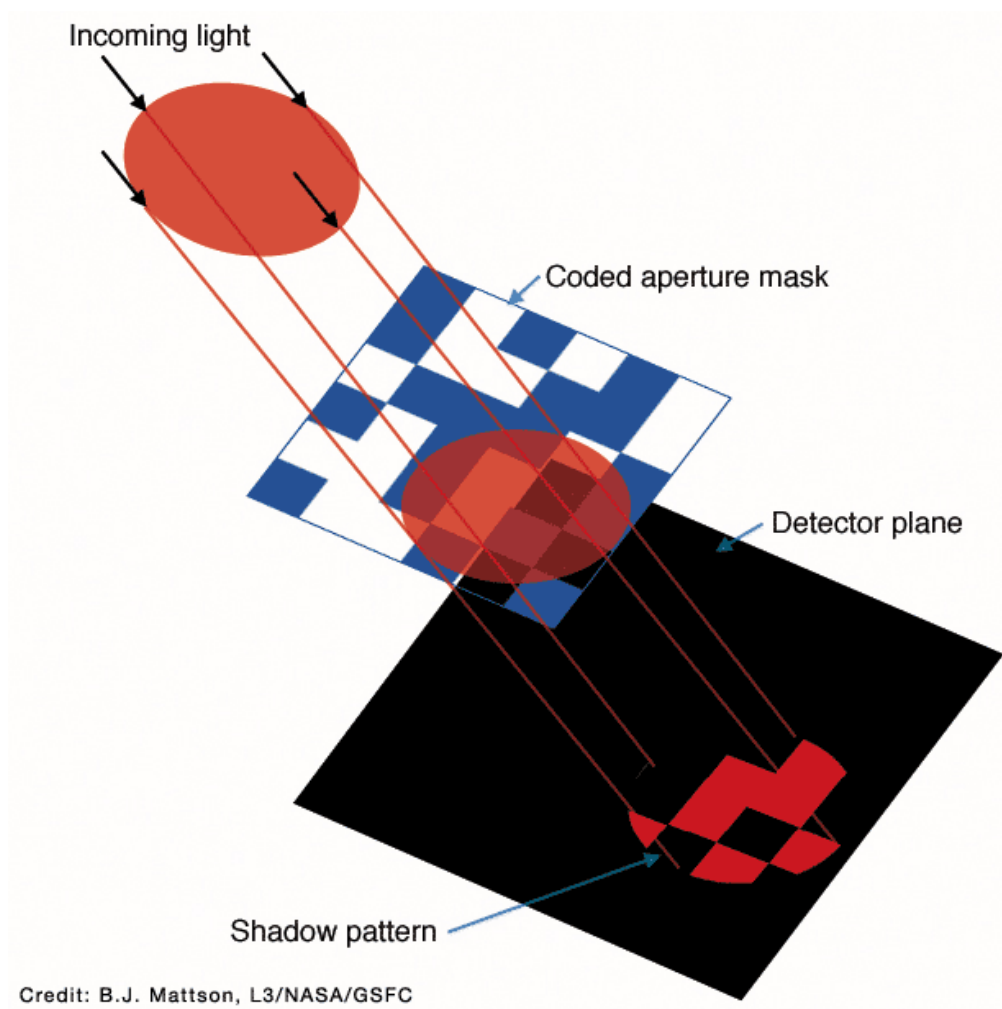
- Each detected photon tells:
 - where it is detected
 - from which direction it comes

👍 one photon gives useful position clue

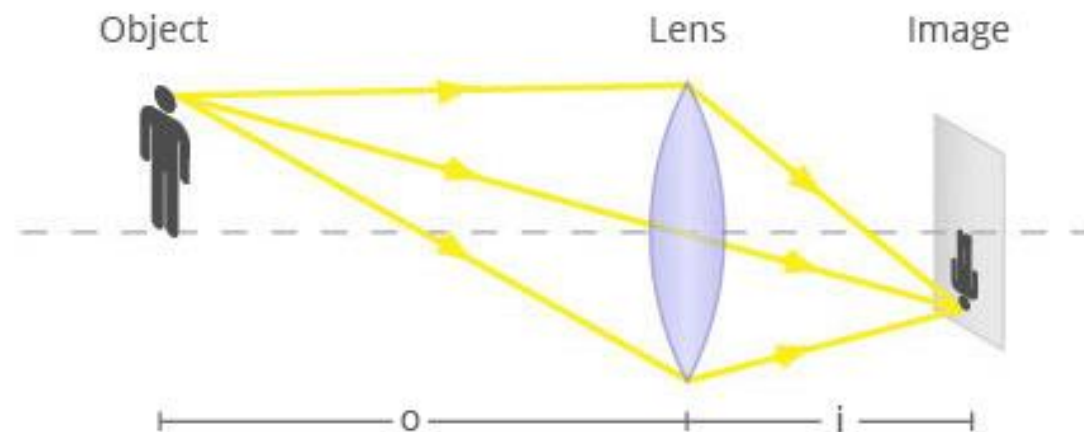
👎 Infinitesimal efficiency



Imaging with efficiency



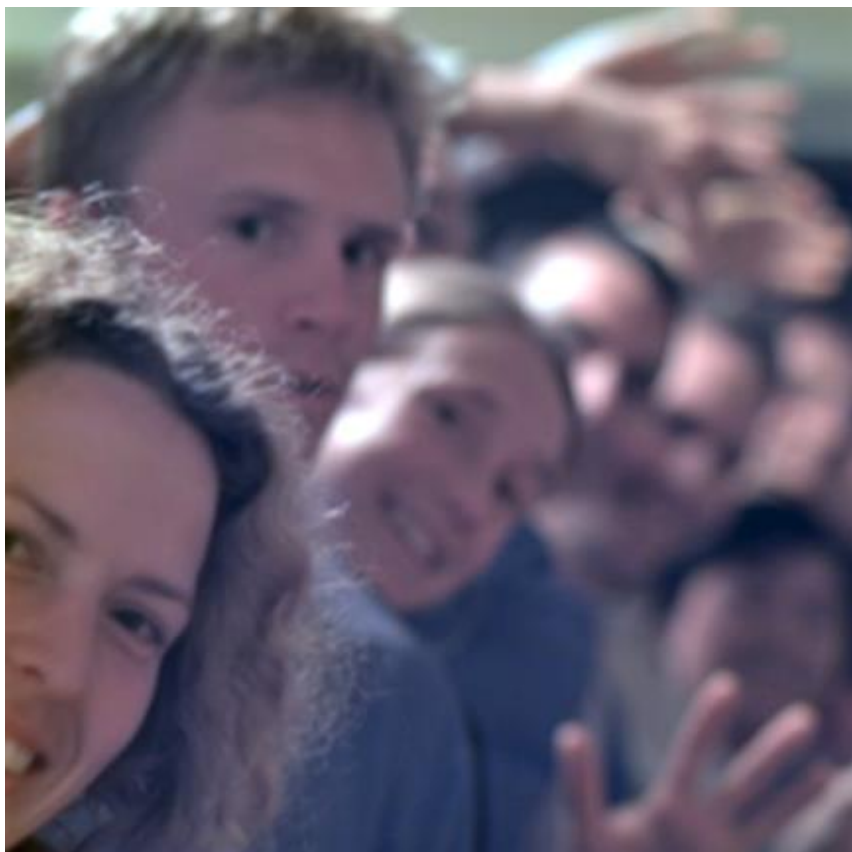
- ← Add more pinholes → coded aperture (less definitive information per detected photon)
- ↓ Add a lens → optical imaging (direct all light from the same source to the same sensor location)



* Optical imaging requires a prior knowledge on distance to object (not possible for transient scintillation events in a sizeable detector volume)

Light-field imaging – snap now, focus later

Near



Middle



Far

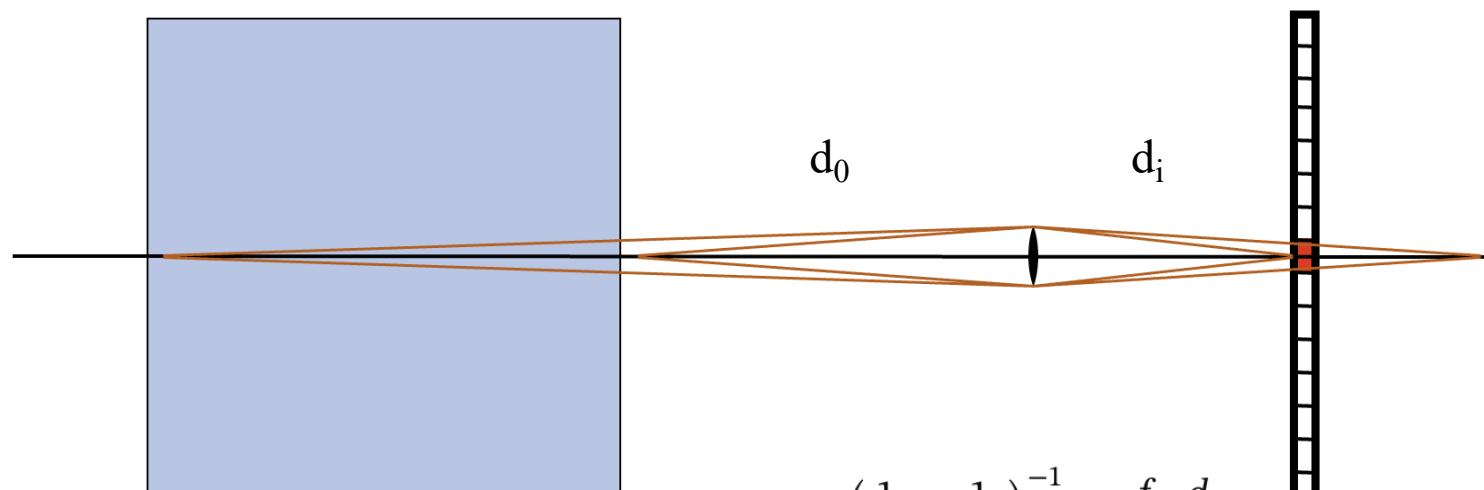
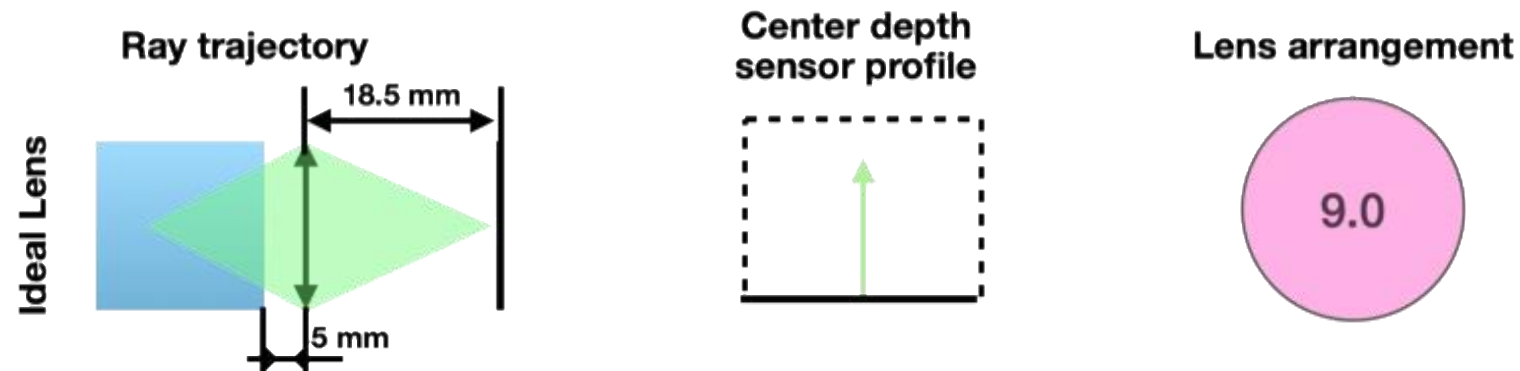


Ren Ng, Digital Light Field Photography, Ph.D. dissertation, Stanford University (2006).

Designing a light-field scintillator imager

Conventional imaging

- Large aperture and small focal length desired
- Impossible combination
- For a fixed object-lens-sensor distance with a given pixel size, smaller focal lengths provides larger depth of field
- A spherical lens's focal length is fundamentally limited by its radius

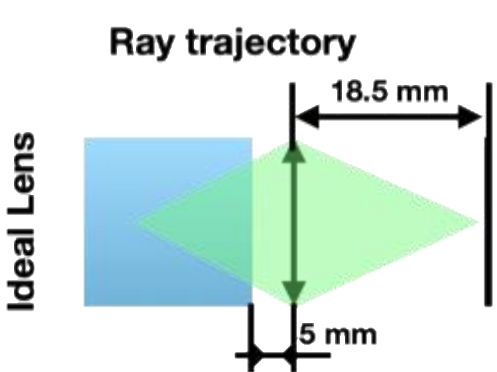


$$d_i = \left(\frac{1}{f} - \frac{1}{d_o} \right)^{-1} = \frac{f \cdot d_o}{d_o - f}$$

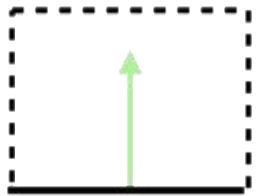
Designing a light-field scintillator imager

Conventional imaging

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- Impossible combination



Center depth sensor profile

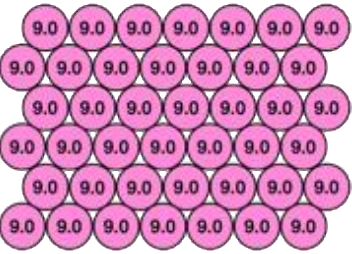
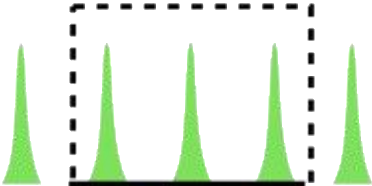
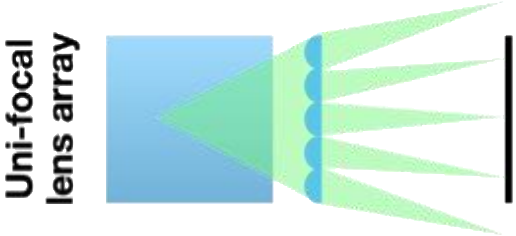


Lens arrangement



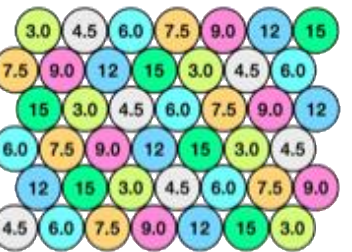
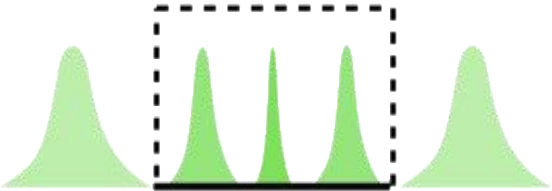
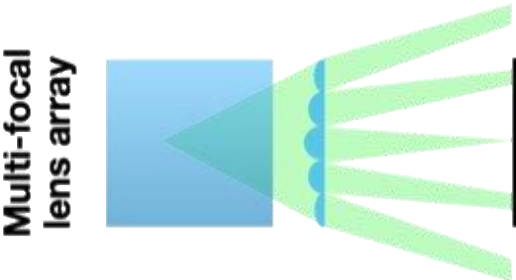
Light-field imaging

- Distributed aperture, small focal length now possible
- Increased depth of field

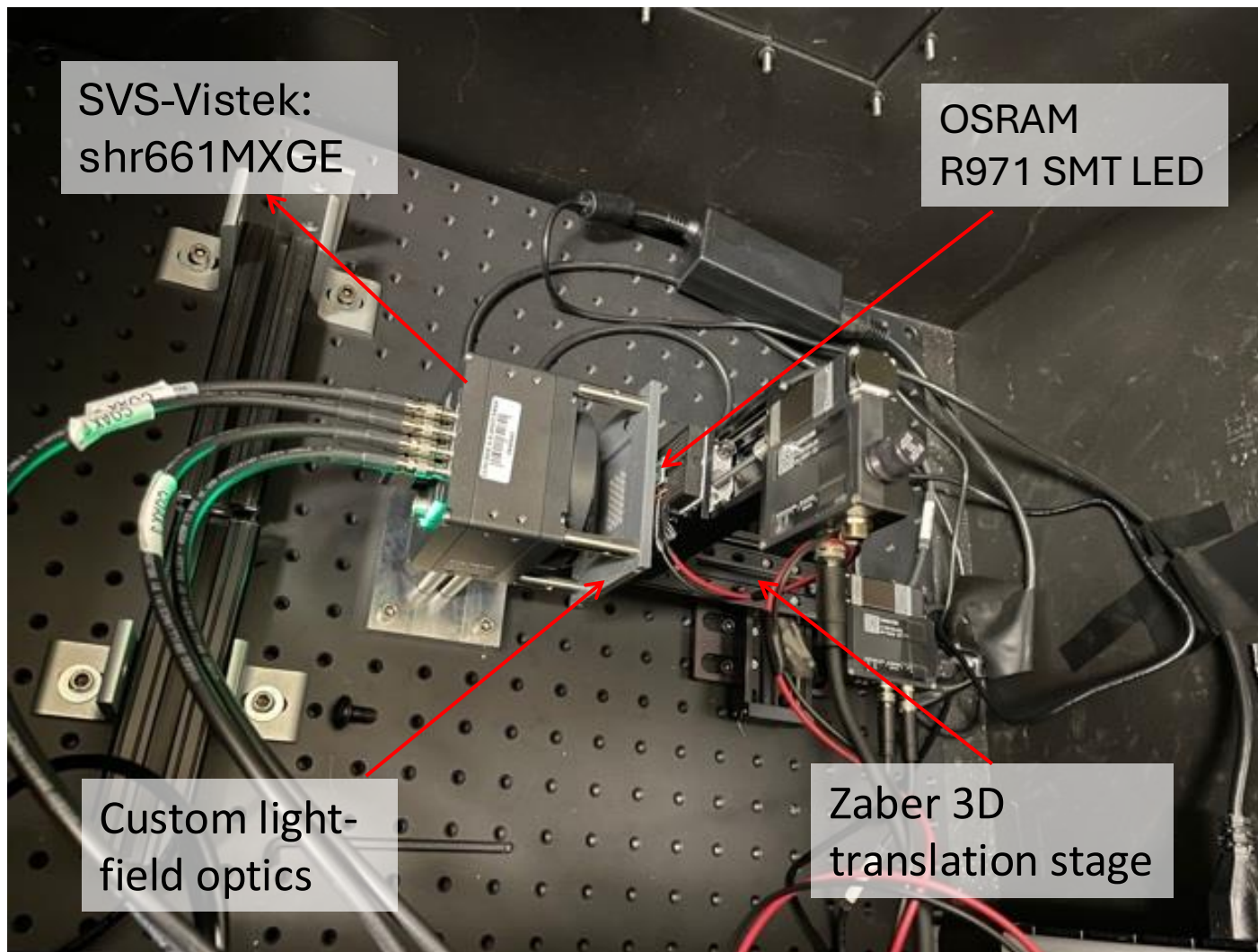


Multifocal light-field imaging

- Distributed aperture with varying small focal length
- More homogeneous depth sensitivity



The PRISM imaging prototype



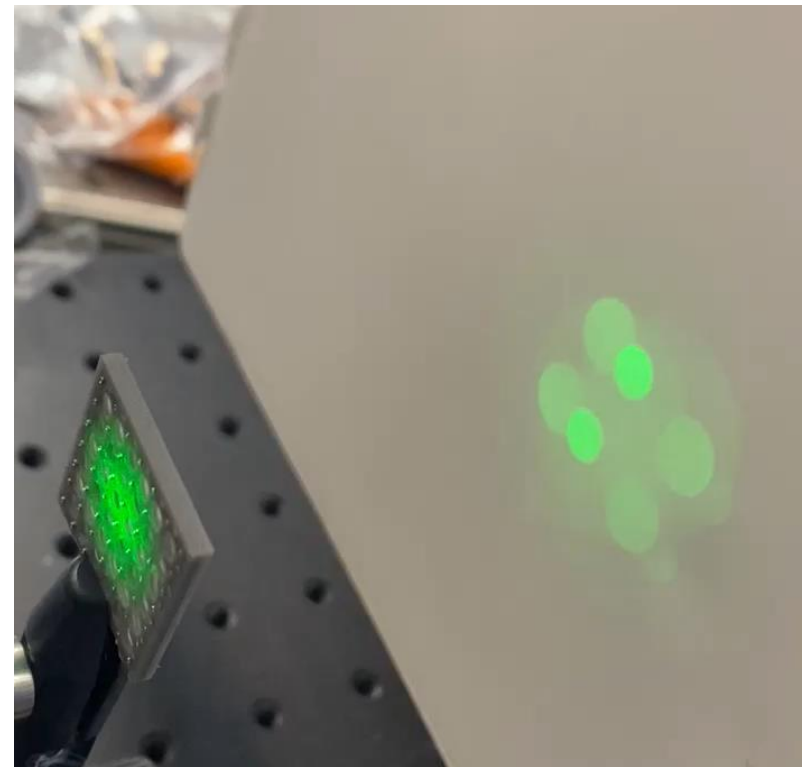
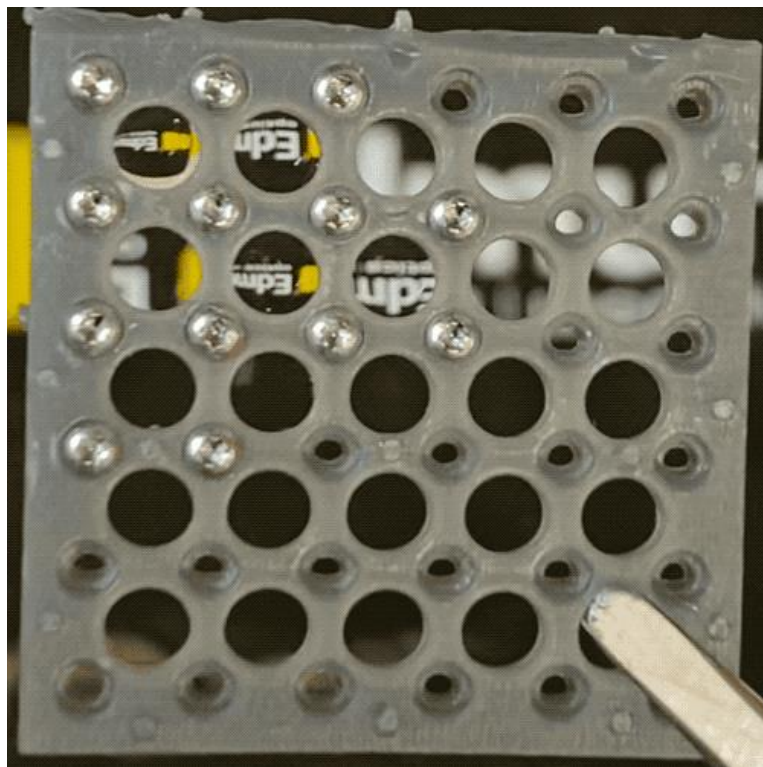
- Compact multi-focal lens array
- Calibrated LED point source on 3D linear stage
- Medium format CMOS sensor (no demagnification, no main lens)



Multifocal lens array

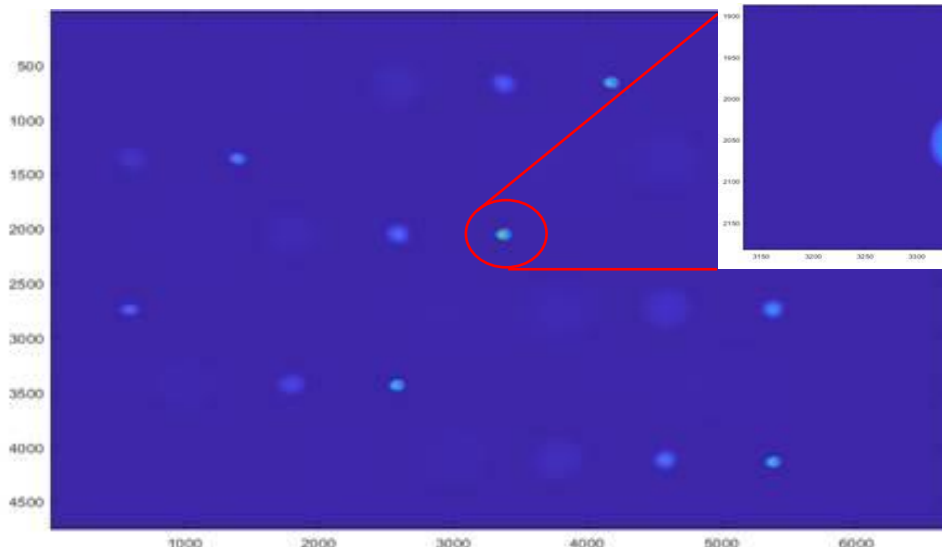
Multifocal lens array response

- Commercial lenses of various optical focal lengths
- 3D-printed lens holder structure
- Lens array can be assembled and disassembled for rearrangement

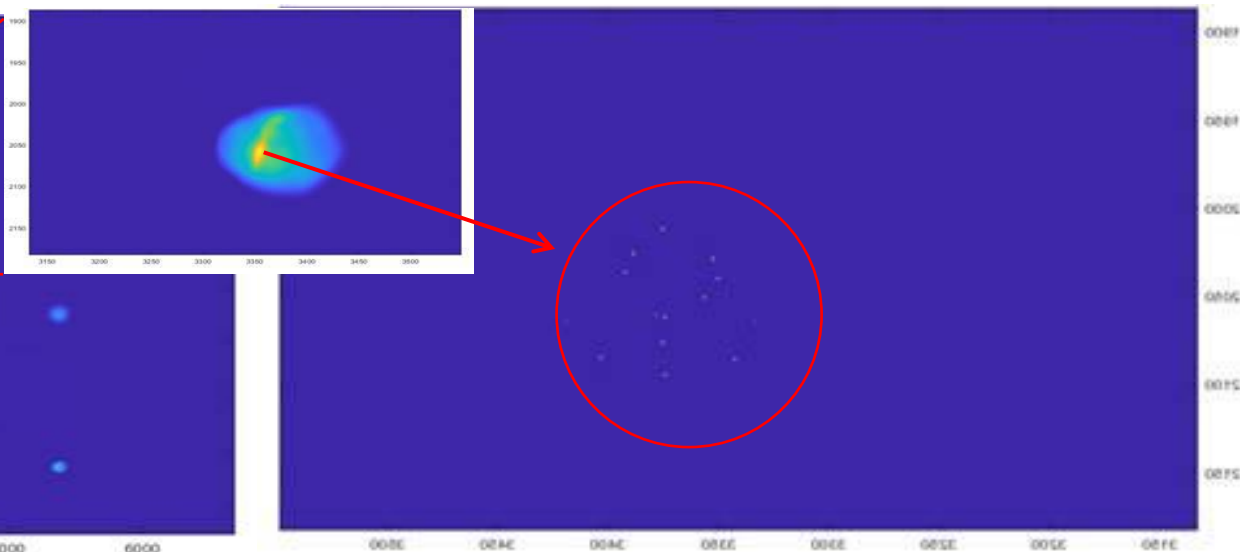


Data-driven low-light images

High light intensity (LED)



Light starved (scintillation-like)



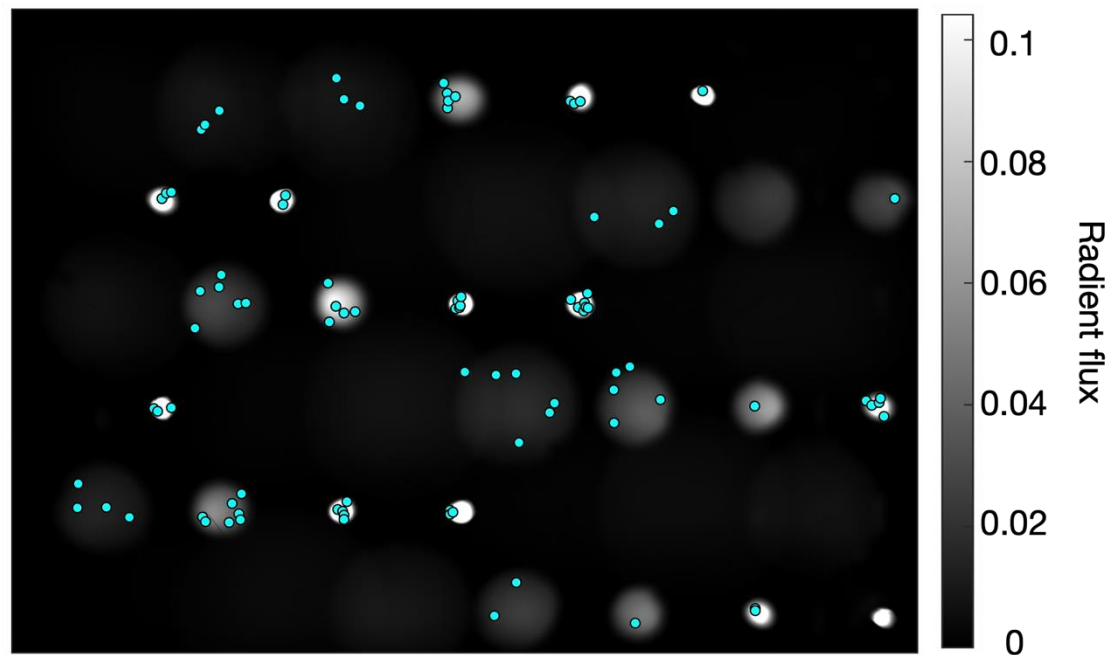
- Take images of LED light source with different exposures at the same source position
- Denoise image with HDR (high dynamic range)
 - Signal scales with exposure, while noise doesn't
 - Slope of signal strength wrt exposure represents noise-free system response
- Down-sample noise-free image to simulate scintillation imaging conditions

Event reconstruction in scintillation-like conditions

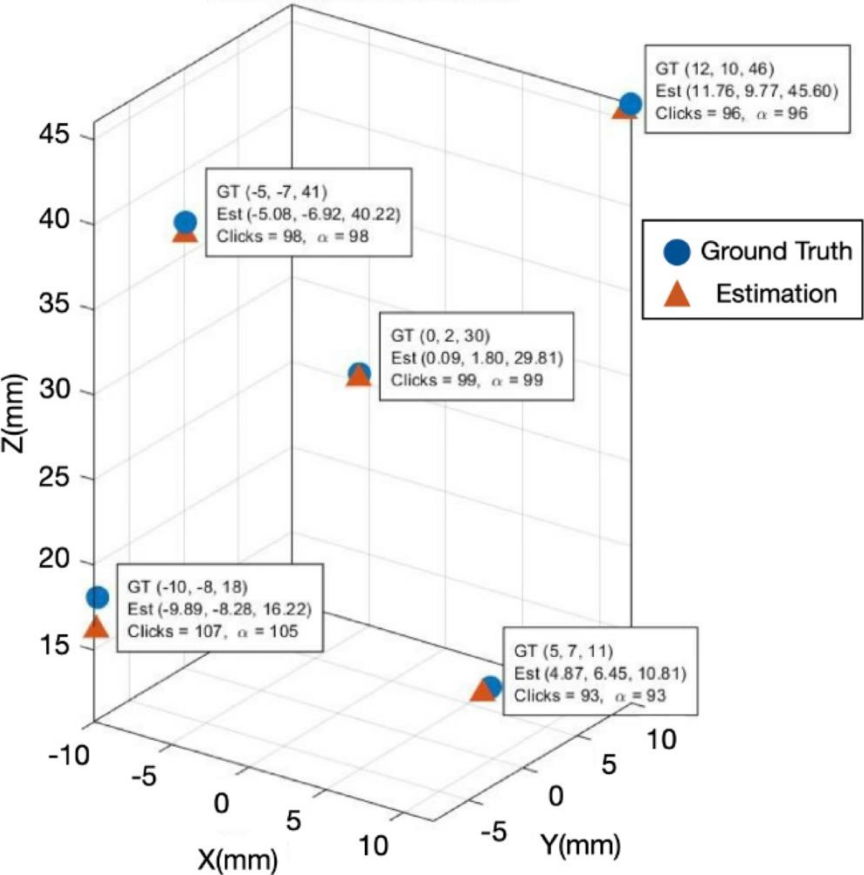
Based on the Alternating Descent Conditional Gradient (ADCG) Method

Prebuilt library of measured point spread function (PSF) on a grid (denoised with HDR)

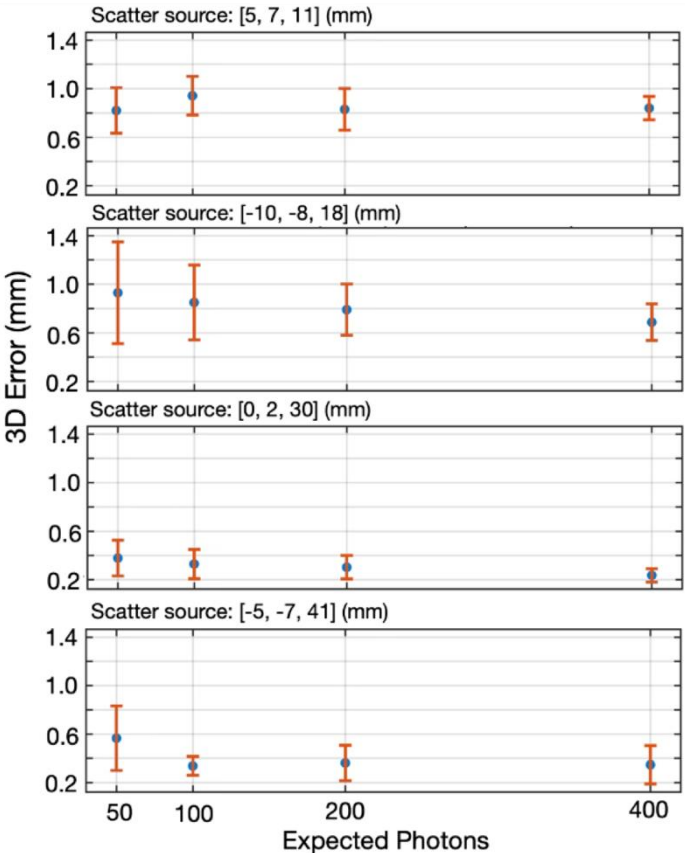
- Define loss function as binary cross entropy (negative log-likelihood)
- Compare data with PSF template library and obtain best match
- Refine position estimate near best-match grid point using local shift invariance
- Method can be extended to searches of multiple light sources



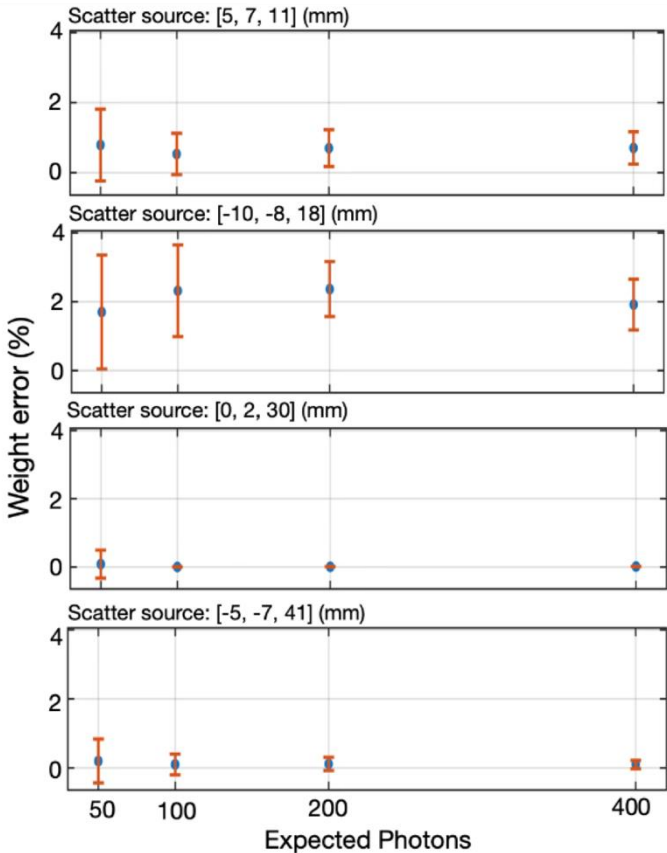
Single-site event reconstruction results



Position reconstruction uncertainty

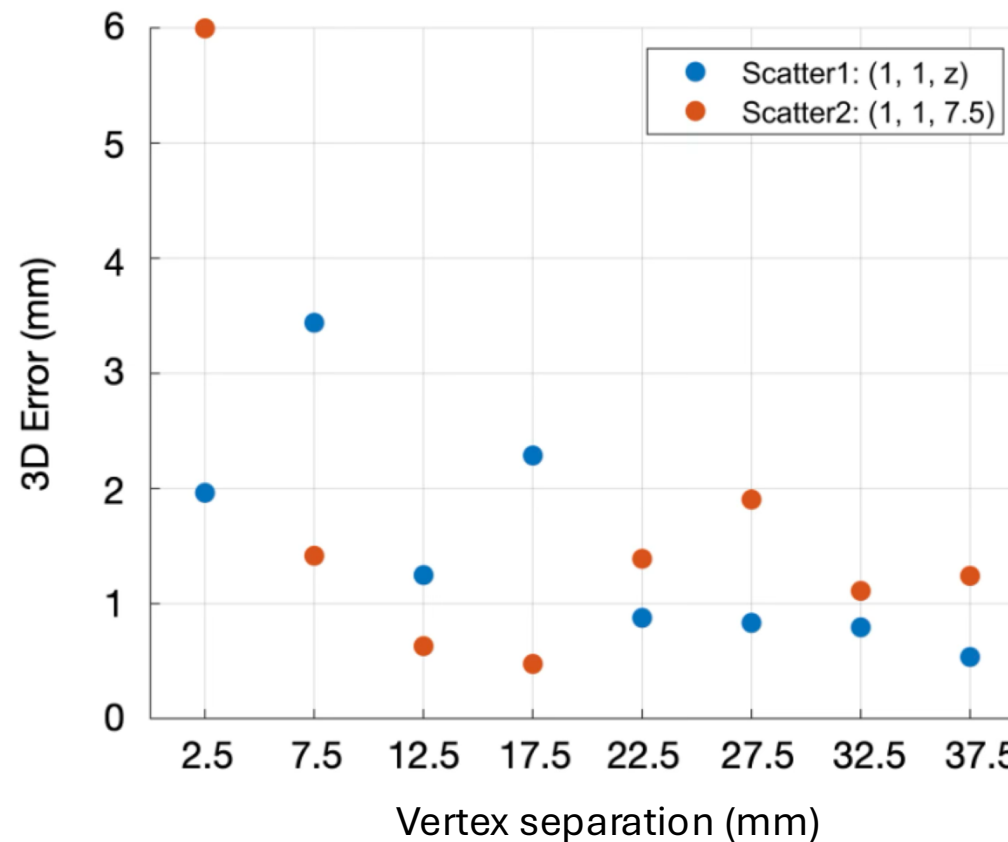


Energy reconstruction uncertainty



Double-site reconstruction results

- Optics creates sharper photosensor patterns than in conventional scintillation detectors
- Multi-site scintillation event positions can be reliably estimated
- mm-scale resolution for 3D positions of 2 sources separated by $>2.5\text{mm}$ with 125 expected photons each
- Slight degradation relative to single-site events at small vertex separations



Conclusion

- Optical imaging concepts are applied to position reconstruction in scintillation detectors
- A prototype is constructed using a tunable LED light source
- LED data is denoised and downsampled to simulate scintillation events
- ADCG-based reconstruction can faithfully recover event position at mm precision
- Position reconstruction is demonstrated for mm-separated double-site events
- Future development will focus on instrumenting a real scintillator and reconstructing true scintillation events



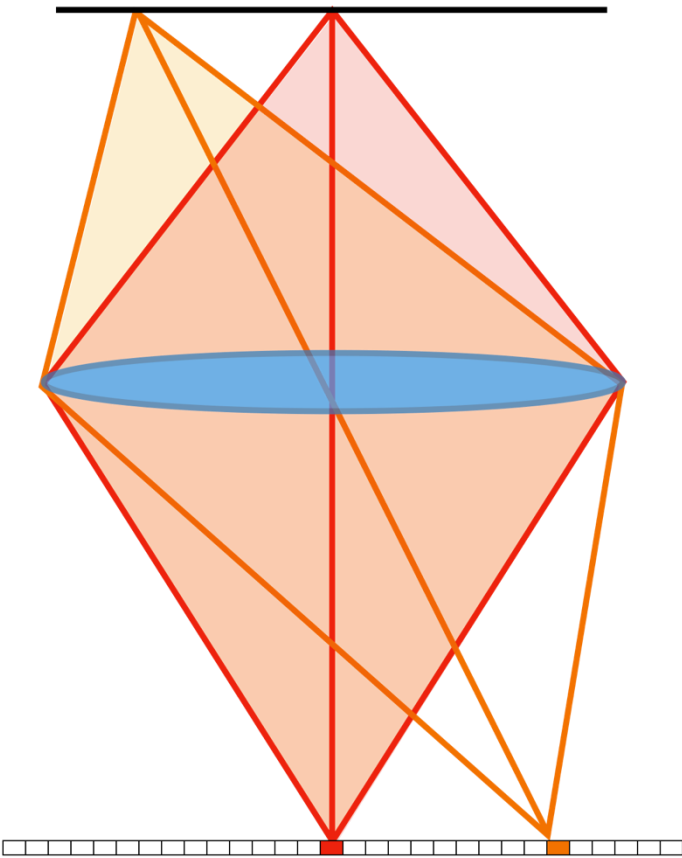
Backup

How does a light field camera work?

Traditional camera

Aperture plane

Records position

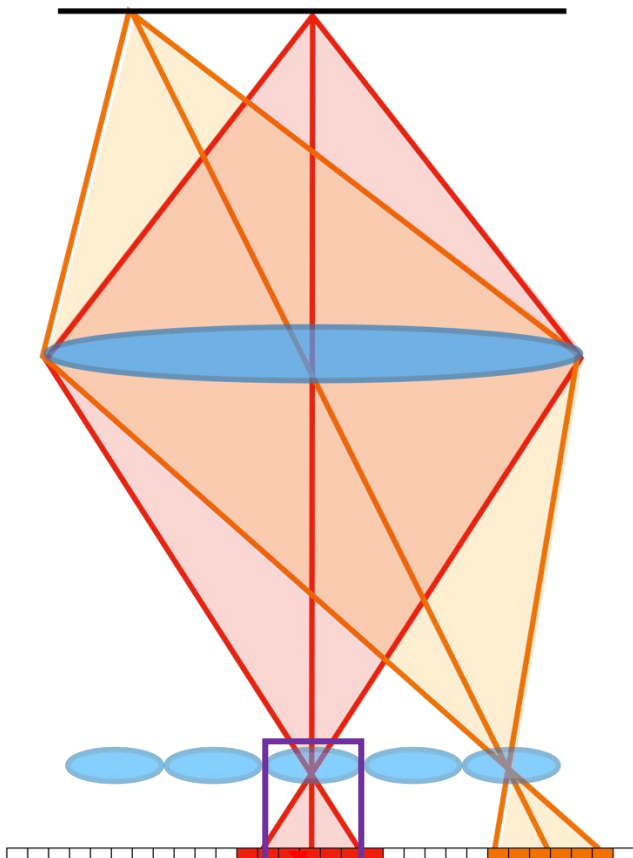


Light field camera

Aperture plane

Records position

Records direction



Approximate photon position Photon direction