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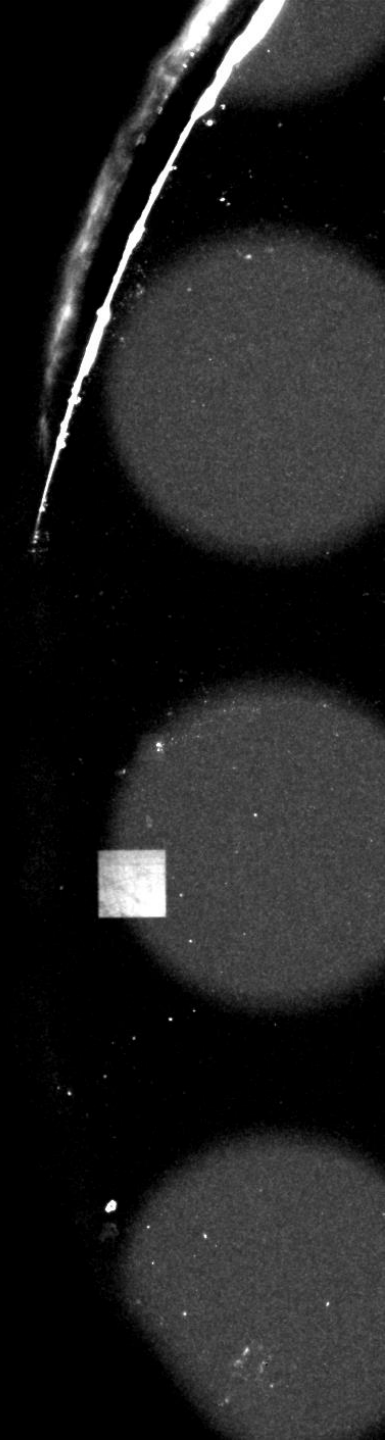
# Clear and Bright X-Ray Imaging with Nanophotonic Scintillators

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Steven Kooi, Louis Martin-Monier, Juejun Hu, Marin Soljačić (MIT)

Simo Pajovic (CalTech), Charles Roques-Carmes (Stanford University)



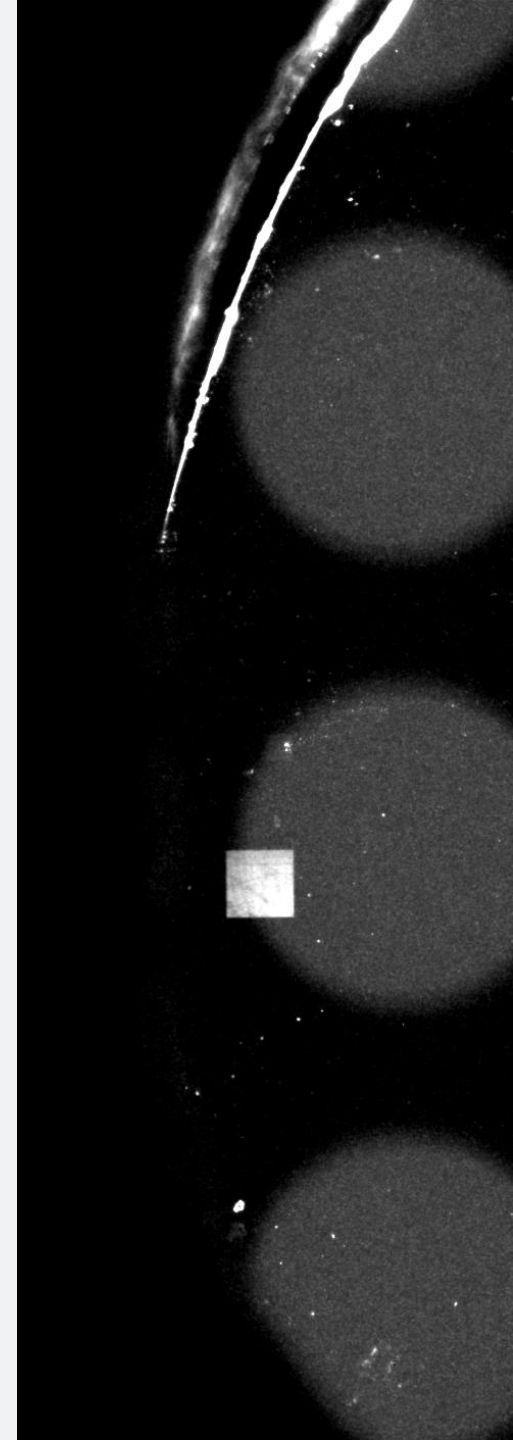
# Outline

**1** Limitations of Lens-Coupled Scintillators  
for X-ray Imaging

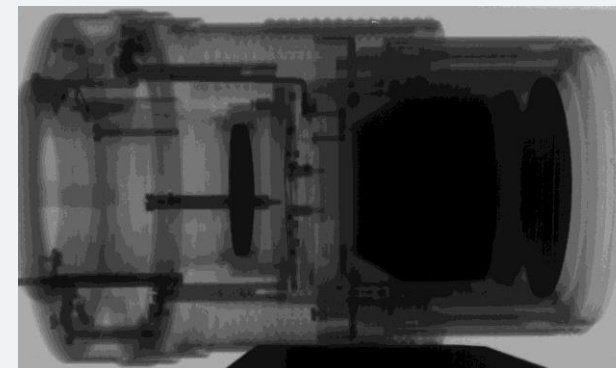
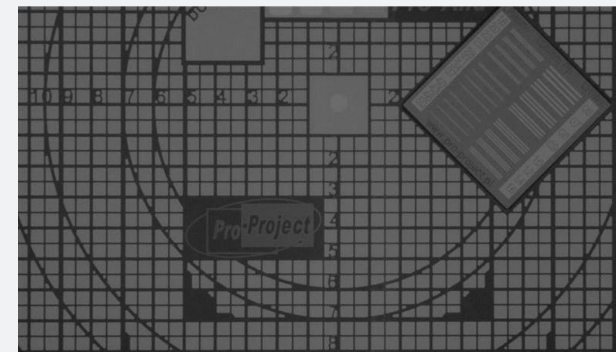
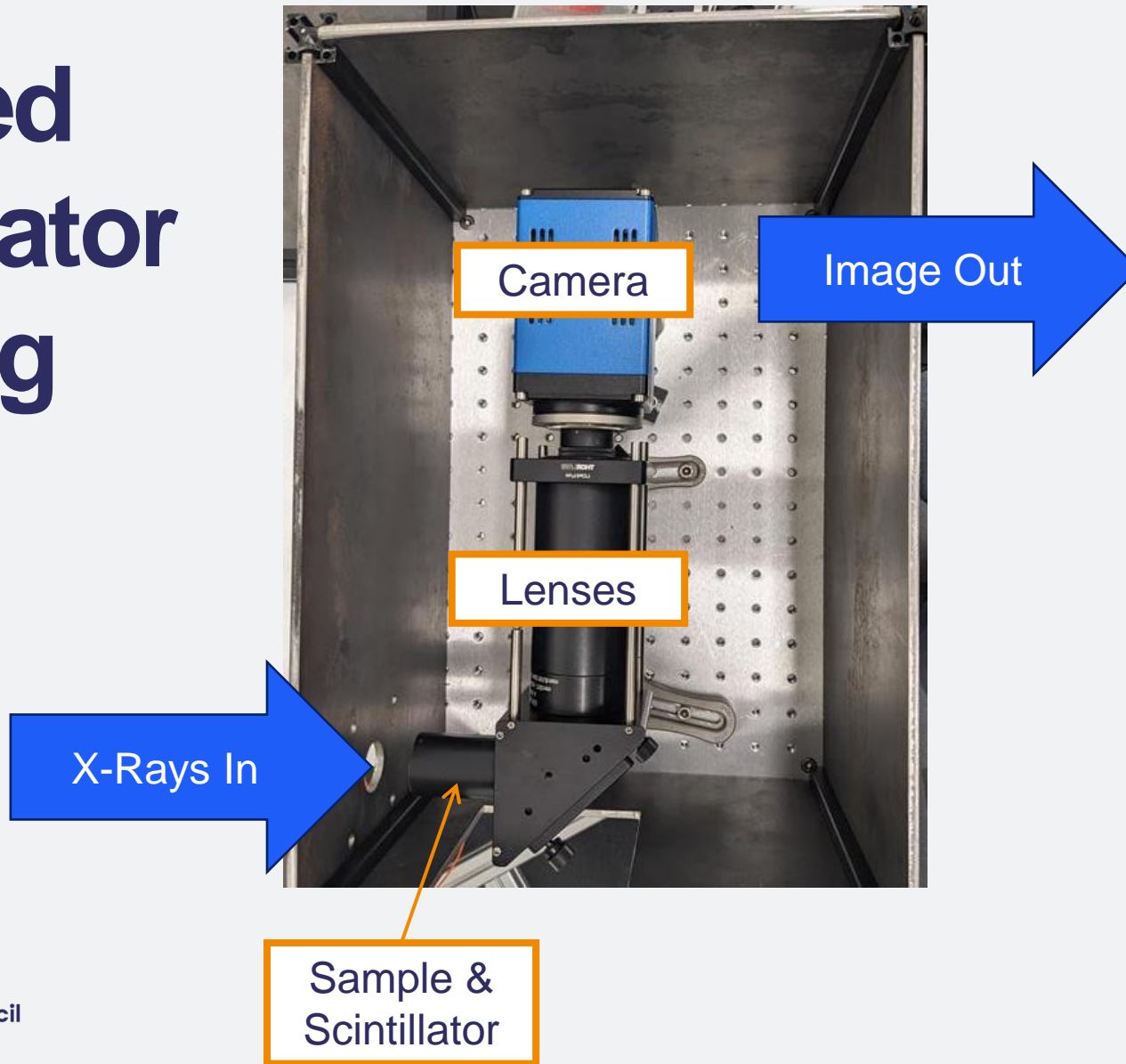
**2** Nanophotonic Scintillator Theory

**3** Experimental Results:  
Illumination-Dependent Signal Enhancement

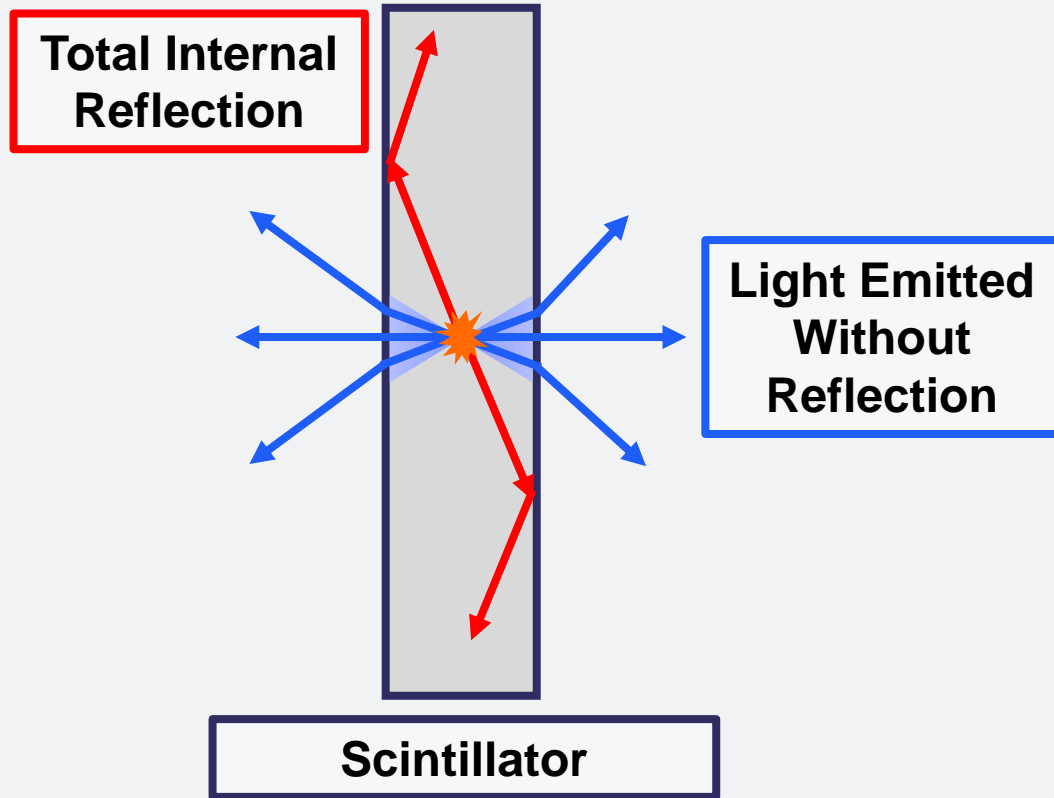
**4** Summary & Future Work



# Lens-Coupled Scintillator Imaging



# Cameras Only Measure Light that Reaches Them

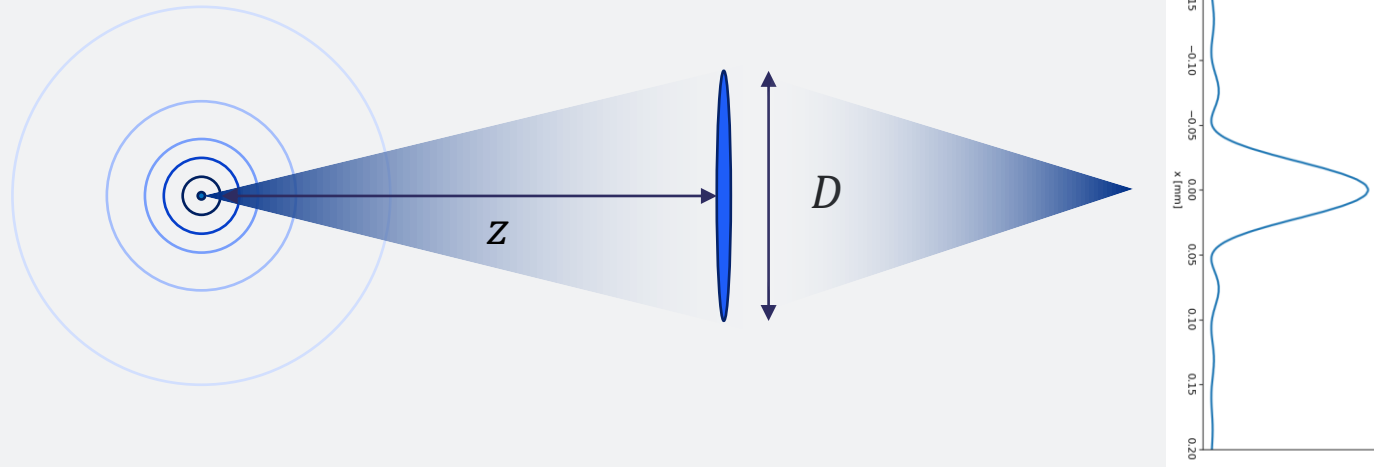


Scintillator	Refractive Index	Fraction of Forward-Emitted Light
LYSO	1.71	9%
CsI(Tl)	1.8	8%
YAG	1.82	8%
LuAG	1.84	8%
GAGG	1.9	7%
CdWO4	2.3	5%

$$\text{Critical Angle, } \theta_c = \arcsin\left(\frac{n_2}{n_1}\right)$$

$$\text{Fraction Emitted in Forward Direction} = \frac{\Omega}{4\pi} = \frac{2\pi(1 - \cos\theta_c)}{4\pi} = \frac{1}{2} \left( 1 - \sqrt{1 - \left(\frac{n_2}{n_1}\right)^2} \right)$$

# Cameras Only Measure Light that Reaches Them (and typically, not much does...)



Point source emitter

Lens

Image

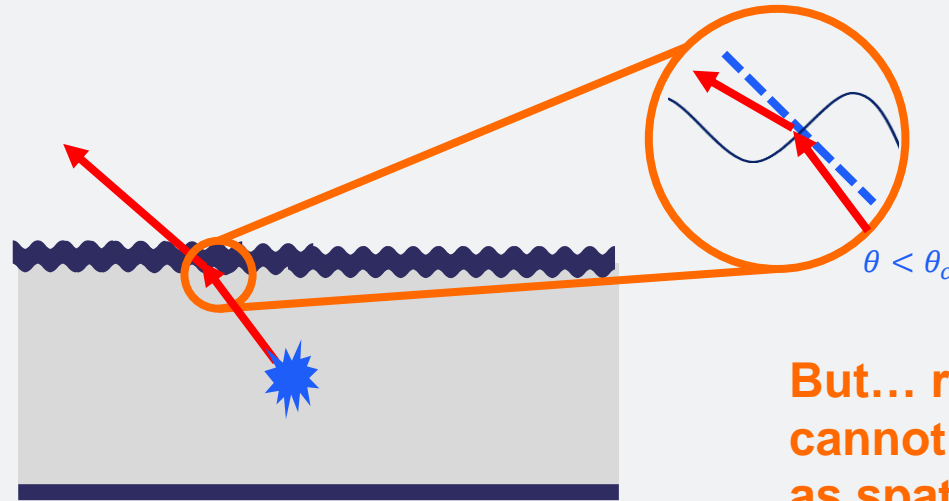
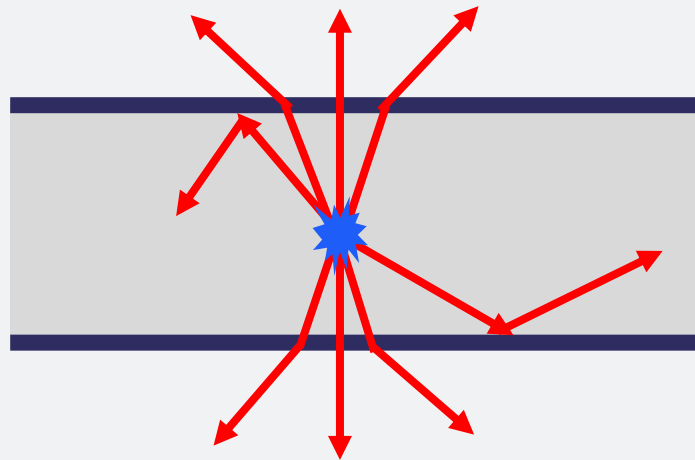
Numerical Aperture of Lens	Fraction of Collected Light
1	50%
0.4	4.2%
0.27	1.9%
0.16	0.6%
0.1	0.25%

$$NA = n \sin \theta = n \sin \left( \arctan \left( \frac{D}{2z} \right) \right)$$

$$\text{Collected Fraction} = \frac{\Omega}{4\pi} = \frac{2\pi(1 - \cos \theta)}{4\pi} = \frac{1}{2} \left( 1 - \sqrt{1 - \left( \frac{NA}{n} \right)^2} \right)$$

# Increasing Light Collection by Surface Modification:

YAG Scintillator ( $\theta_c = 33^\circ$ ):



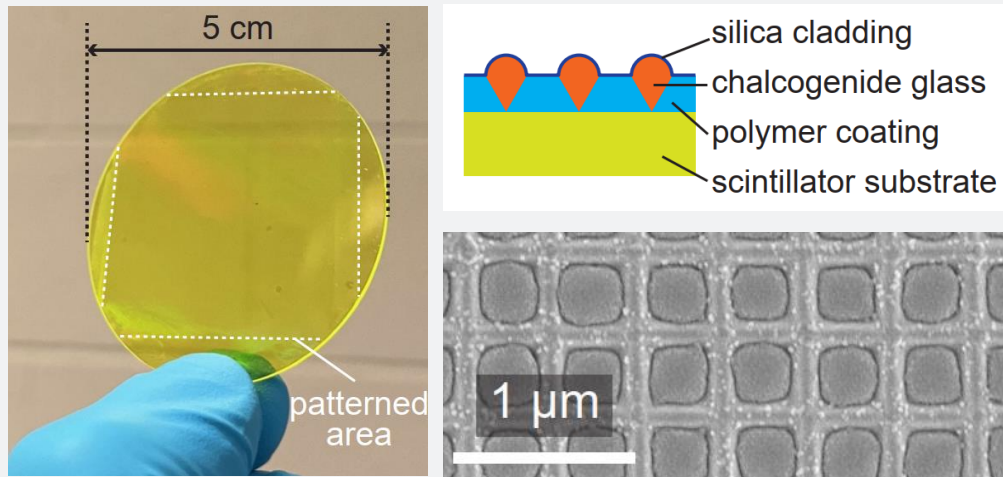
But... roughened scintillators cannot be used for imaging, as spatial information is degraded

Smooth front surface  $\rightarrow$  8% rays emitted forward without internal reflection

Rough front surface  $\rightarrow$  16% rays emitted forward without internal reflection

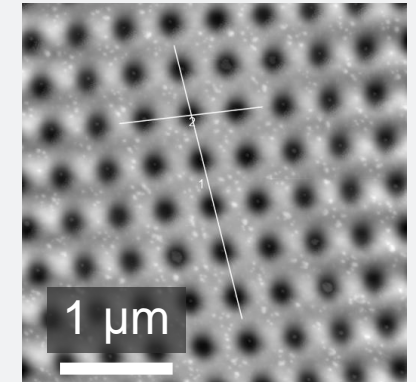
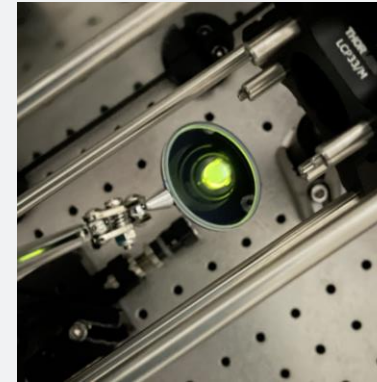
# Nanophotonic Scintillators

Nanophotonic structures are **highly ordered**, with the **same length scale as the wavelength** of the emitted light



Large area nanophotonic pattern produced on 500  $\mu\text{m}$  thick YAG via interference lithography

<https://doi.org/10.1038/s41467-025-60953-5>



200  $\times$  200  $\mu\text{m}$  nanophotonic pattern produced on 100  $\mu\text{m}$  thick YAG via focussed ion beam lithography

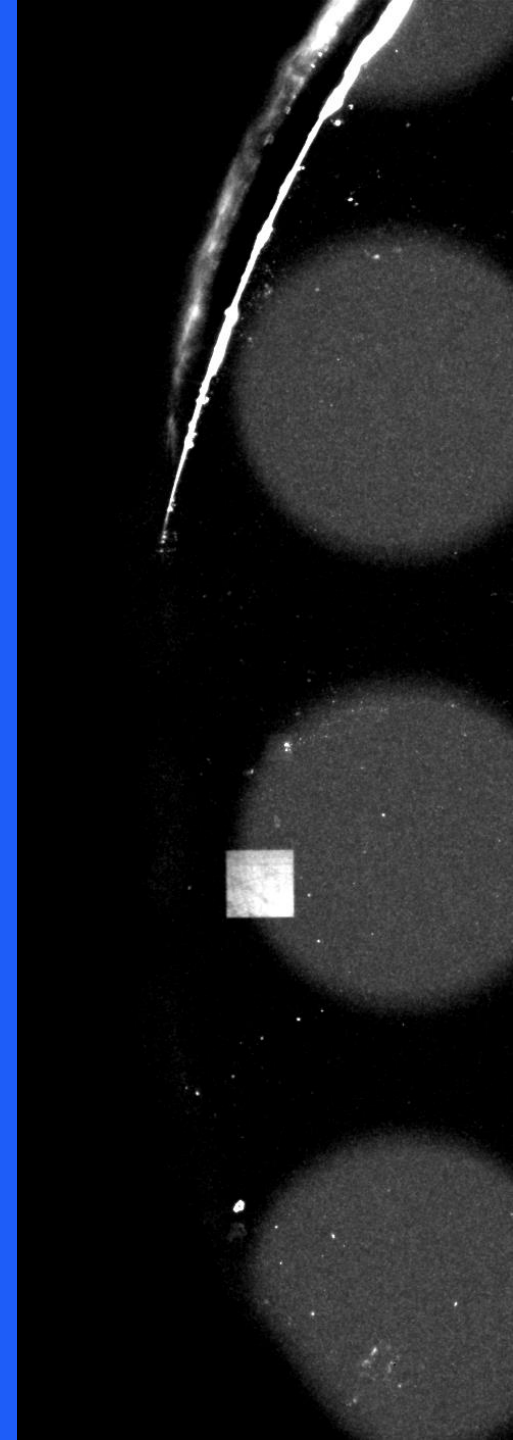
<https://doi.org/10.1126/science.abm9293>



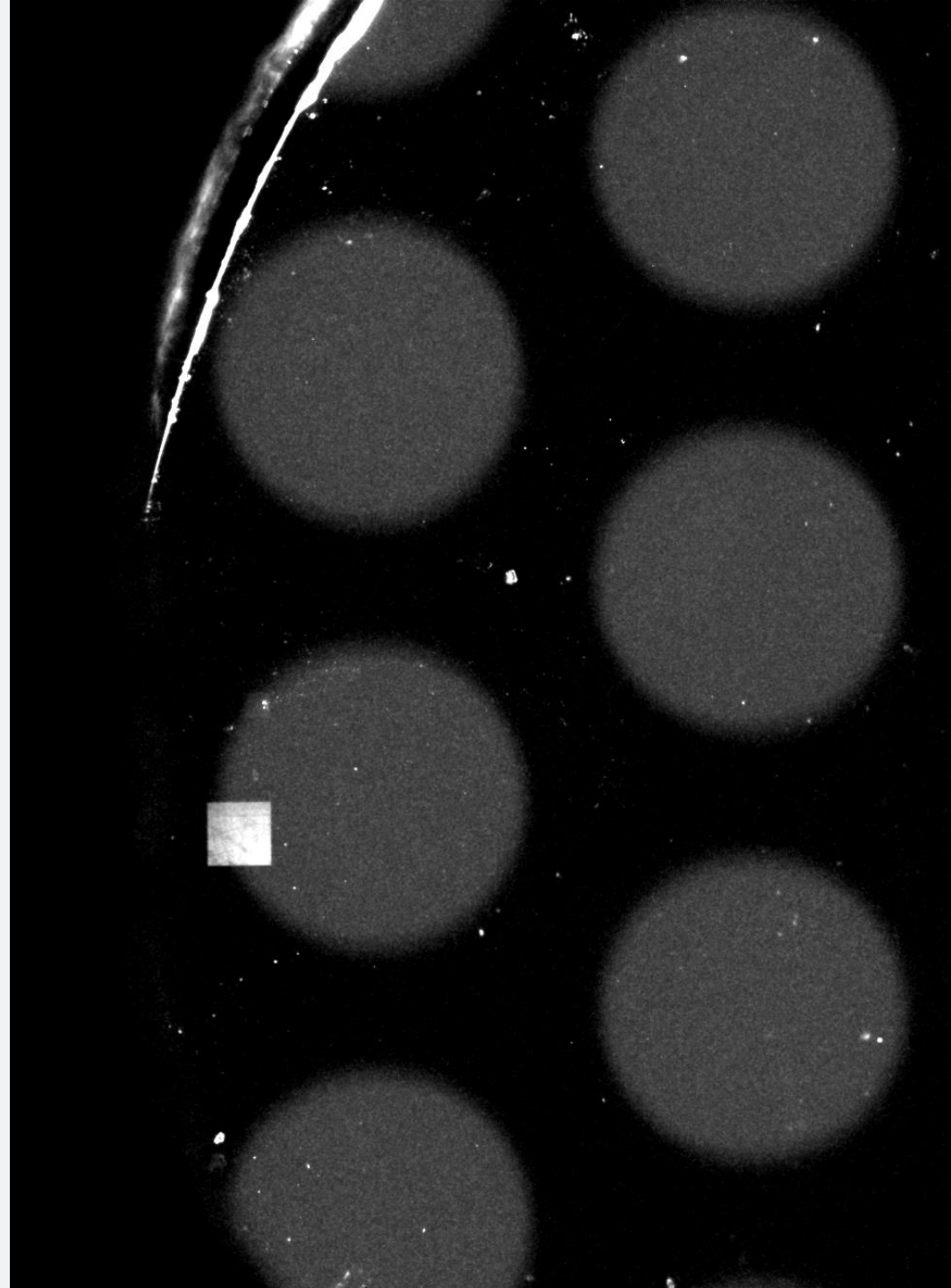
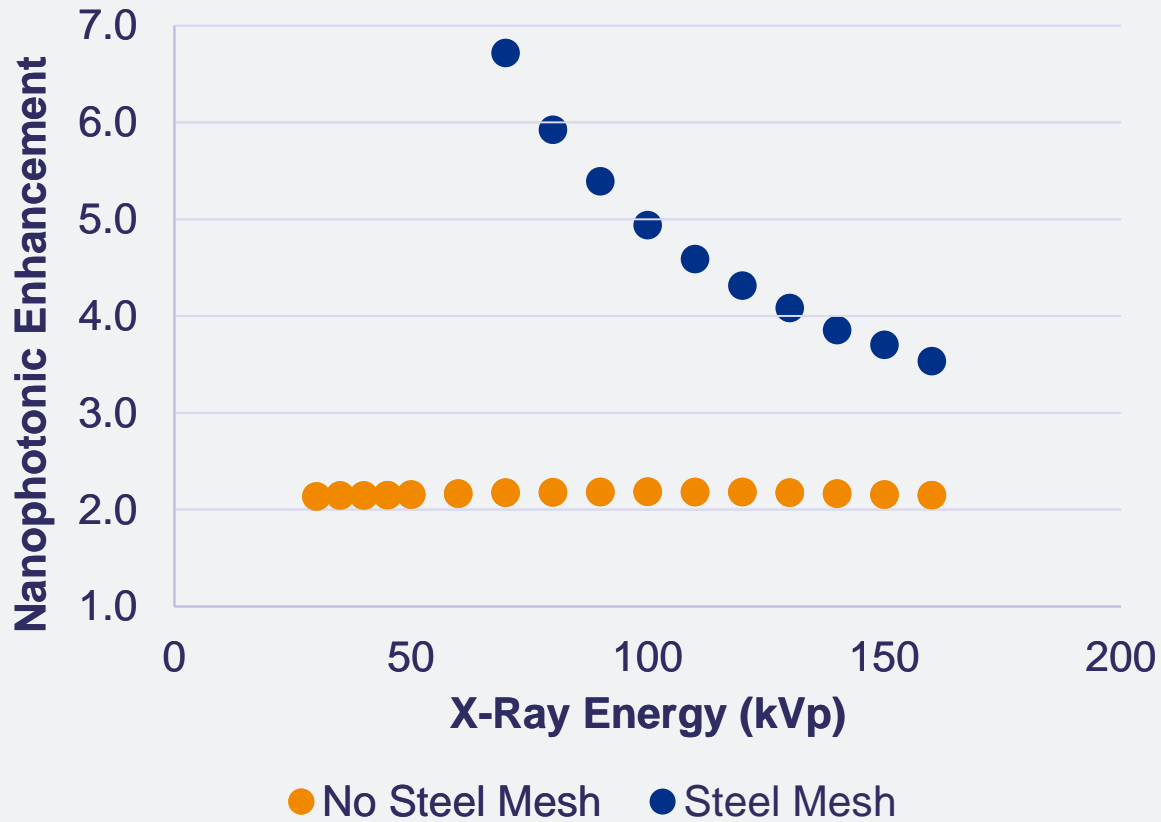
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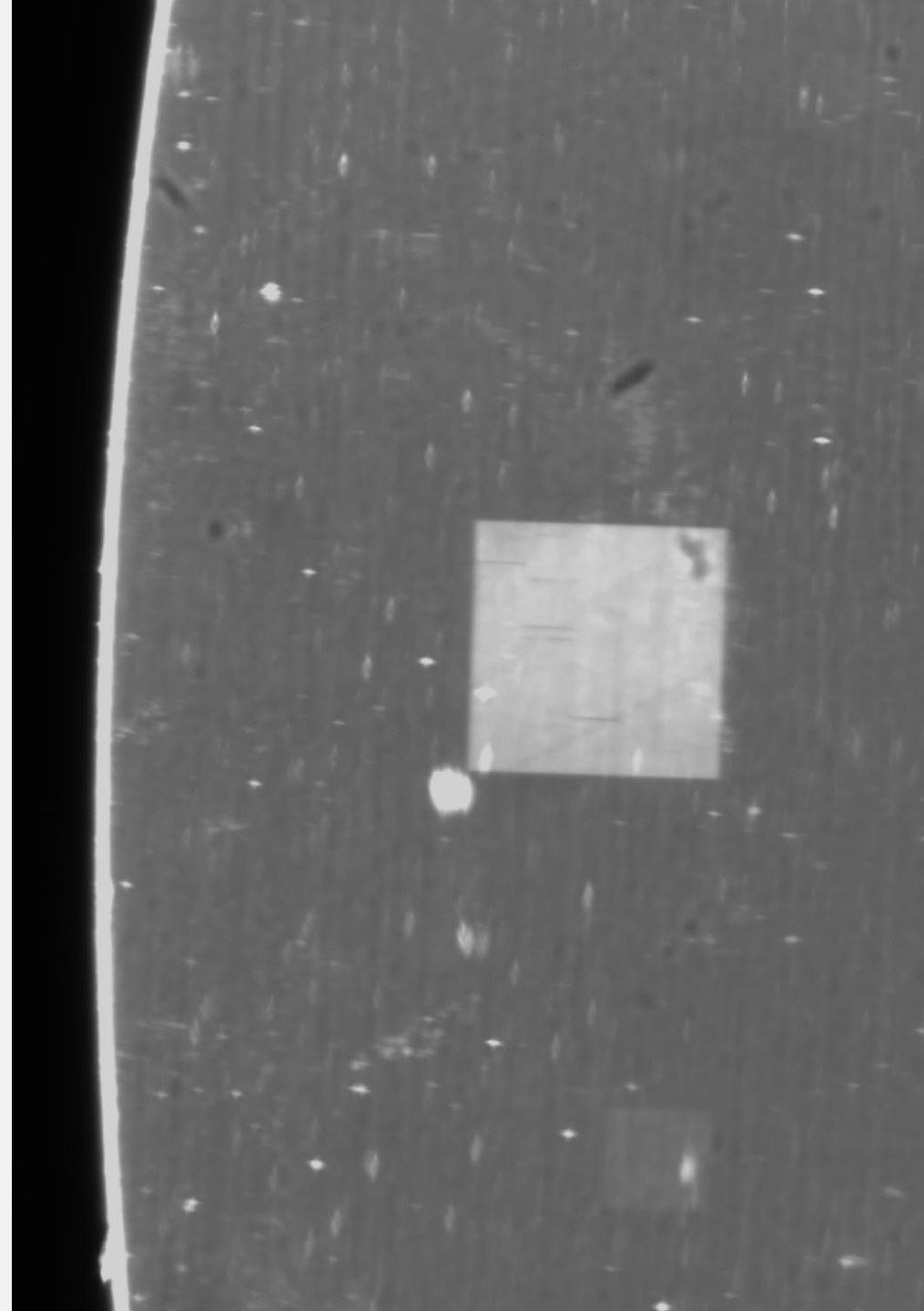
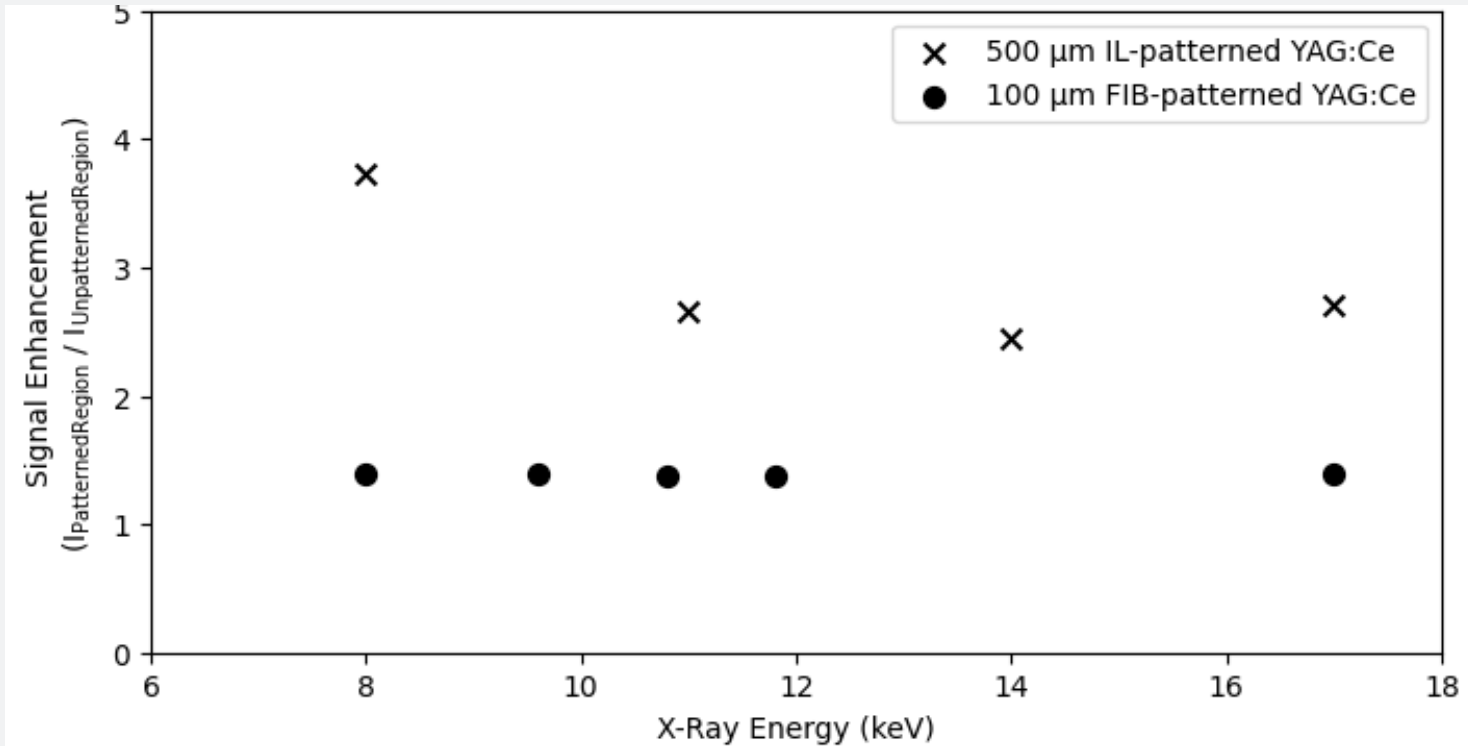
# Results



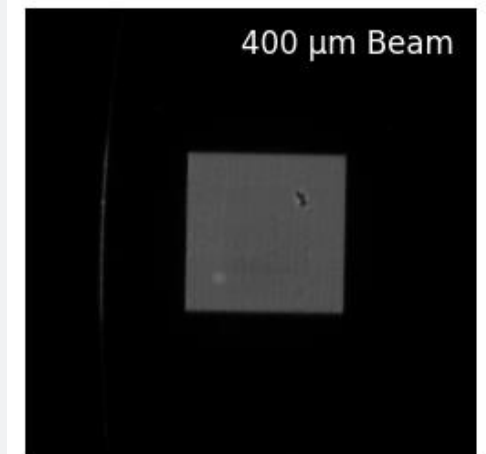
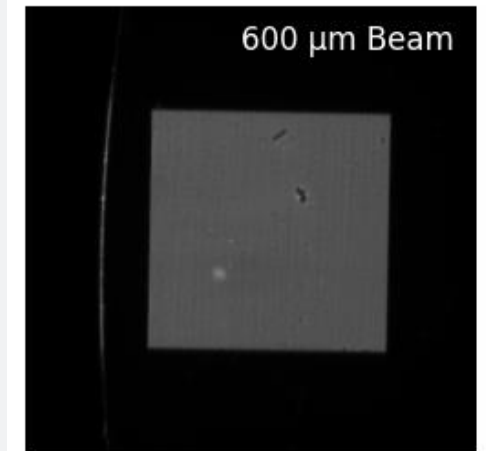
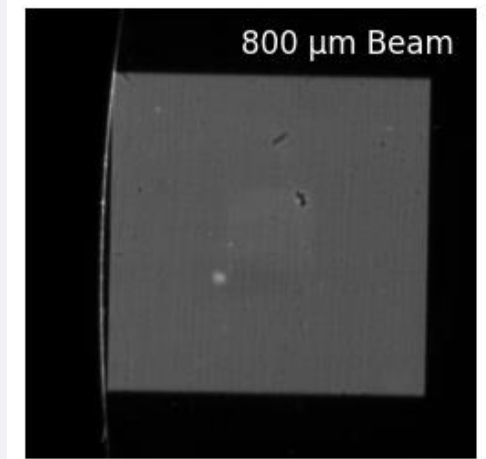
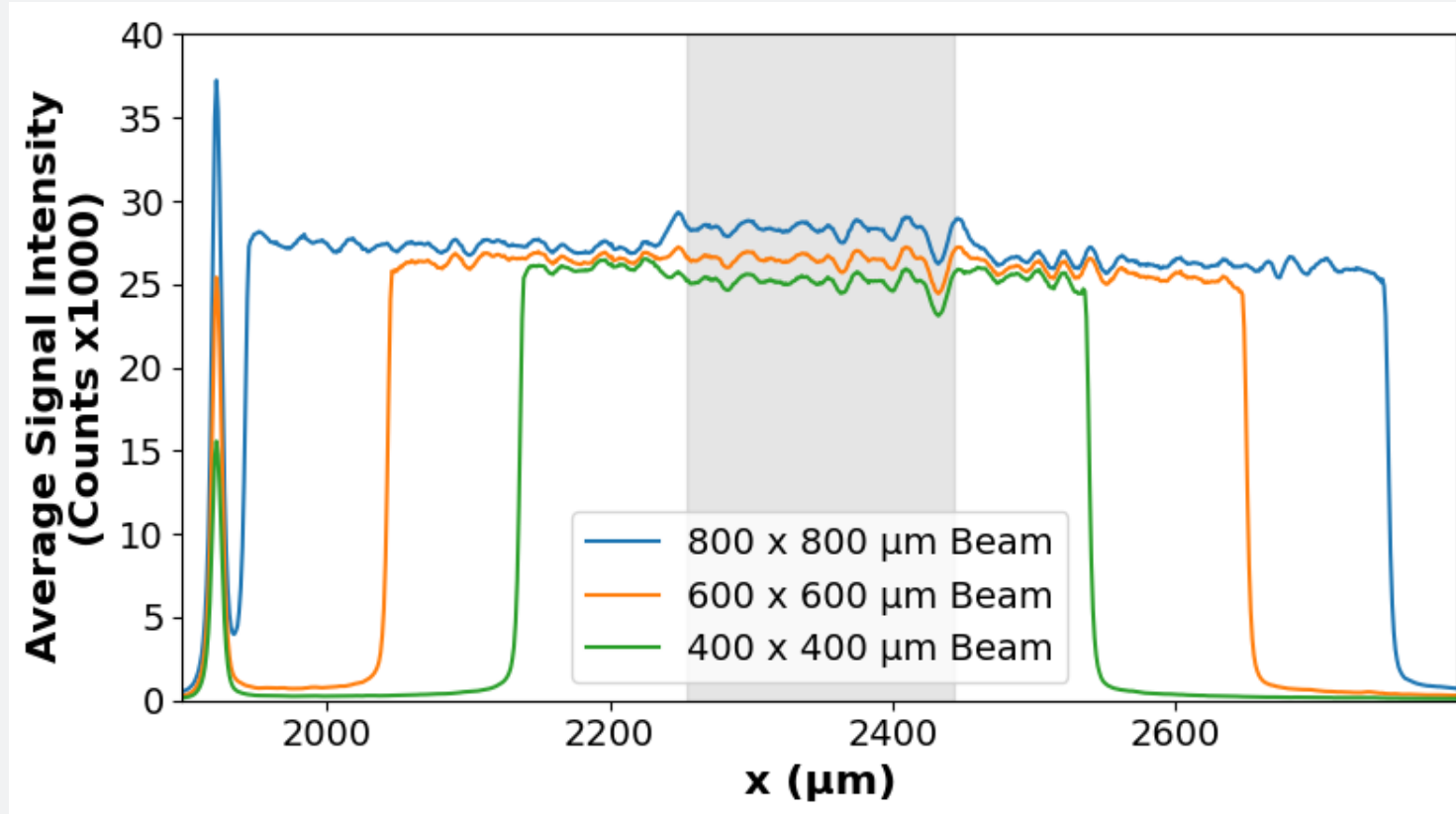
# Signal Enhancement (Lab Measurements)



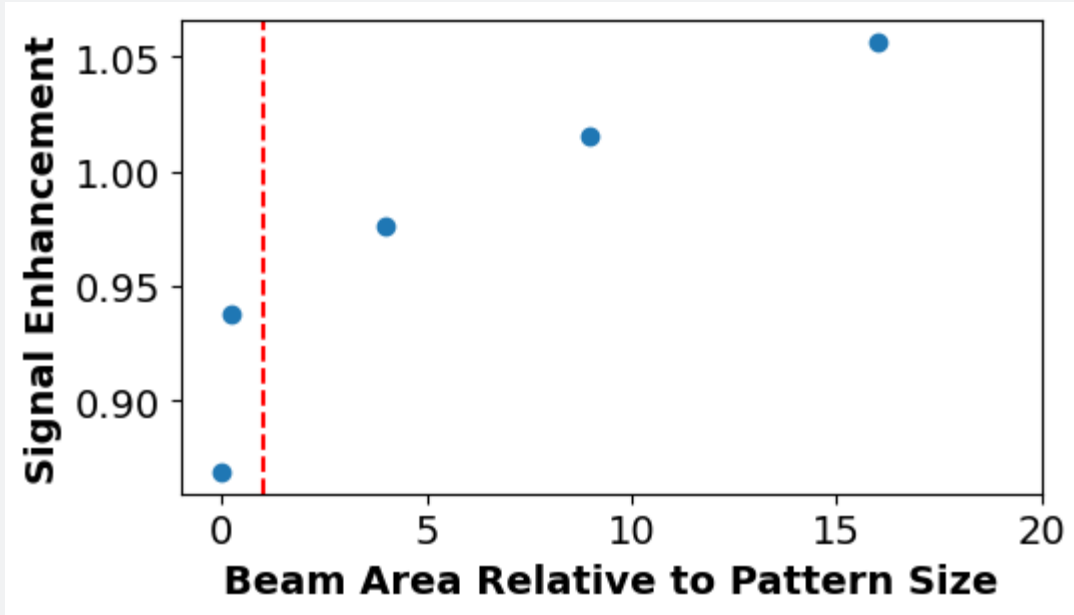
# Signal Enhancement (Synchrotron Measurements)



# Illumination Effects: Beam Size



# Illumination Effects: Beam Size

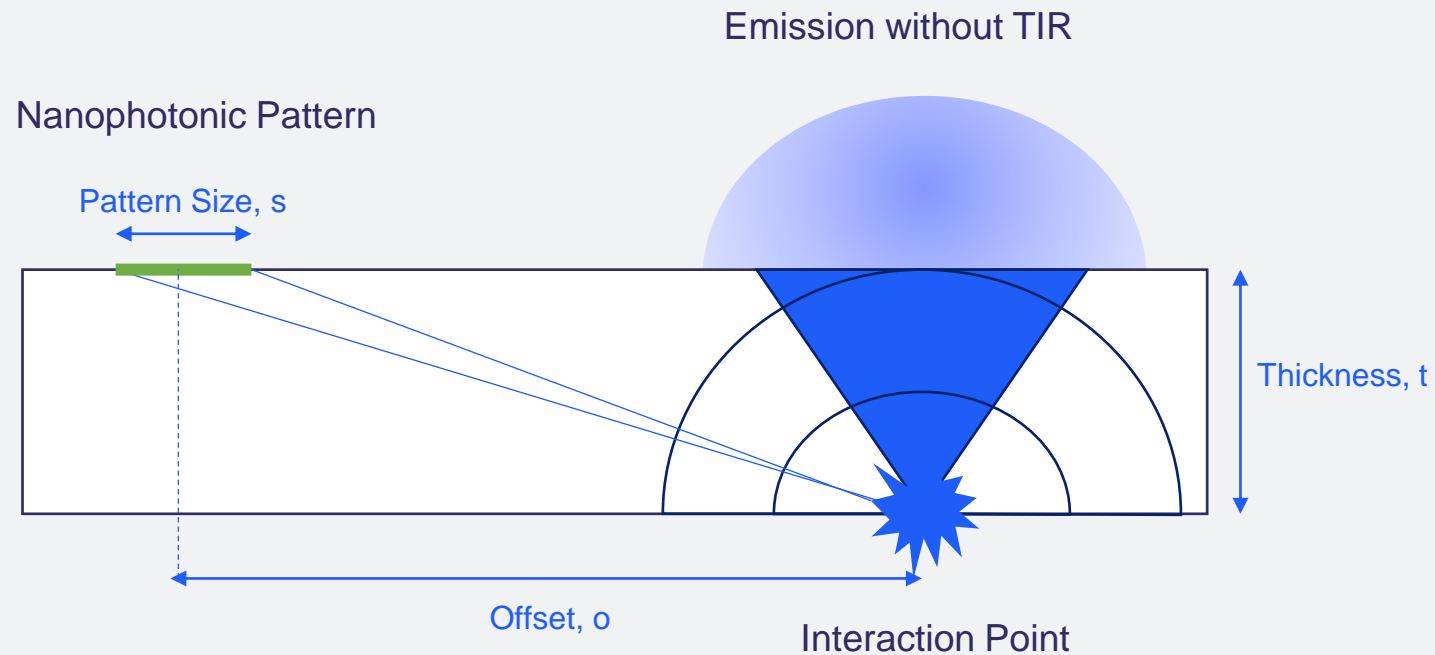


- Smaller beam leads to reduced enhancement
- De-enhancement after a certain reduction in beam size
- Illumination of an area smaller than the pattern causes a rapid drop off in light generated

**In partially patterned nanophotonic scintillators, light generated elsewhere in the crystal contributes to enhancement**

# Illumination Effects

The nanophotonic patterned area provides a window for light striking at a shallow angle to escape.



# Summary & Future Work

- **Lens-coupled scintillators offer sub-micron resolution but are inefficient because of poor light extraction from the scintillator and poor light collection by lenses.**
- **Highly-ordered, wavelength-scale nanophotonic structures can enhance light extraction under certain circumstances.**
- **For partially patterned samples, we have measured a range of enhancements depending on beam conditions and configuration:**
  - **Up to 6.7× in a polychromatic X-ray beam with beam filtration (FIB Sample).**
  - **Up to 3.7× in a monochromatic synchrotron X-ray beam (IL Sample).**
- **In a partially-patterned nanophotonic scintillator, the patterned region acts as a window for outcoupling of light generated elsewhere in the scintillator.**
- **We are now working with Oxford University to develop scalable methods for fully patterned nanophotonic scintillators. James Pratt hopes to present this work at Scint2026.**
  - **Initial lab-based measurements show a 2× signal increase for these fully-patterned samples**



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An abstract graphic consisting of multiple overlapping, semi-transparent blue lines that form a complex, geometric pattern. The lines are primarily horizontal and vertical, with some diagonal elements, creating a sense of depth and movement. The pattern is centered on the page and overlaps the 'Questions?' text.

# Questions?

# Nanophotonic Scintillators

Nanophotonic structures are **highly ordered**, with the **same length scale as the wavelength** of the emitted light

Crystal (mm <sup>3</sup> ) and Coupling	Pattern	LY Gain
LYSO 1.2 × 2.6 × 5	Hexagonal holes Si <sub>3</sub> N <sub>4</sub>	1.15
LYSO 1.2 × 2.6 × 5	Square holes Si <sub>3</sub> N <sub>4</sub>	1.39
LYSO 1.2 × 2.6 × 5	Square pillars Si <sub>3</sub> N <sub>4</sub>	1.32
LYSO 1.2 × 2.6 × 5	Square pillars Si <sub>3</sub> N <sub>4</sub>	1.56
LYSO 1 × 1 × 1 Teflon+o.c.	Hexagonal cones polymer RI = 1.68	1.05
LYSO 20 × 10 × 1	PMMA spheres + ALD	2.49
Cylinder LYSO φ12 × 25 Teflon	PMMA Spheres + ALD	1.4
LYSO 20 × 10 × 1	AAO + ALD	1.95
LYSO 20 × 10 × 1	AAO + ALD	1.62
LYSO 20 × 10 × 1 Teflon	PMMA conical square-placed holes ALD	1.95
LYSO 10 × 10 × 10	Square-placed pyramids polymer RI = 1.83	1.68
LYSO 10 × 10 × 10	Conical square-placed holes polymer RI = 1.83	1.64
Trapezoid LYSO50 × 50 readoutblack paint	Square-placed pillars	1.34

Enhancements reported by various groups for nanophotonic crystal slabs applied to scintillators

<https://doi.org/10.3390/cryst8020078>

Sample (thickness)	A1 (100 μm)	B1 (100 μm)	C1 (20 μm)
Measured enhancement	2.85	1.50	9.1
Holes diameter (nm)	234	192	195
Holes depth (nm)	37	19	50
Patterned area (μm × μm)	215×215	215×215	215×215

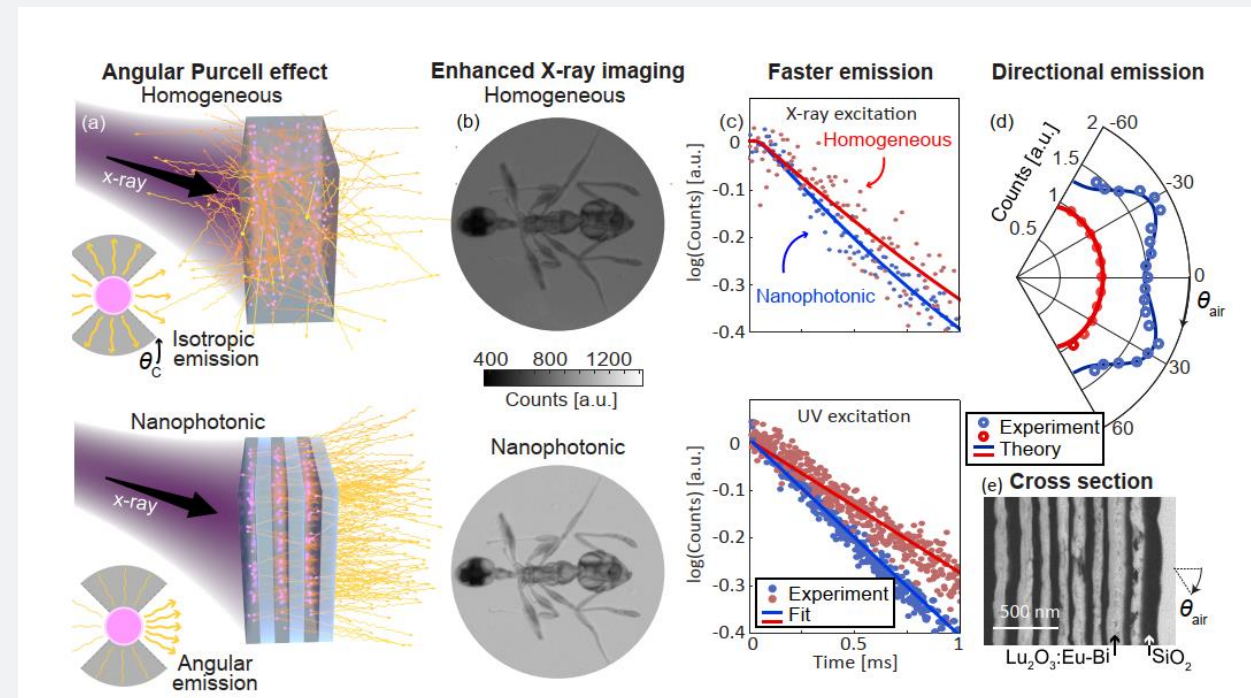
Enhancements reported by MIT for FIB-patterned nanophotonic scintillators

<https://doi.org/10.1126/science.abm9293>

# Nanophotonic Scintillators

Nanophotonic coatings on top of a bulk scintillator work by **improving light extraction**.

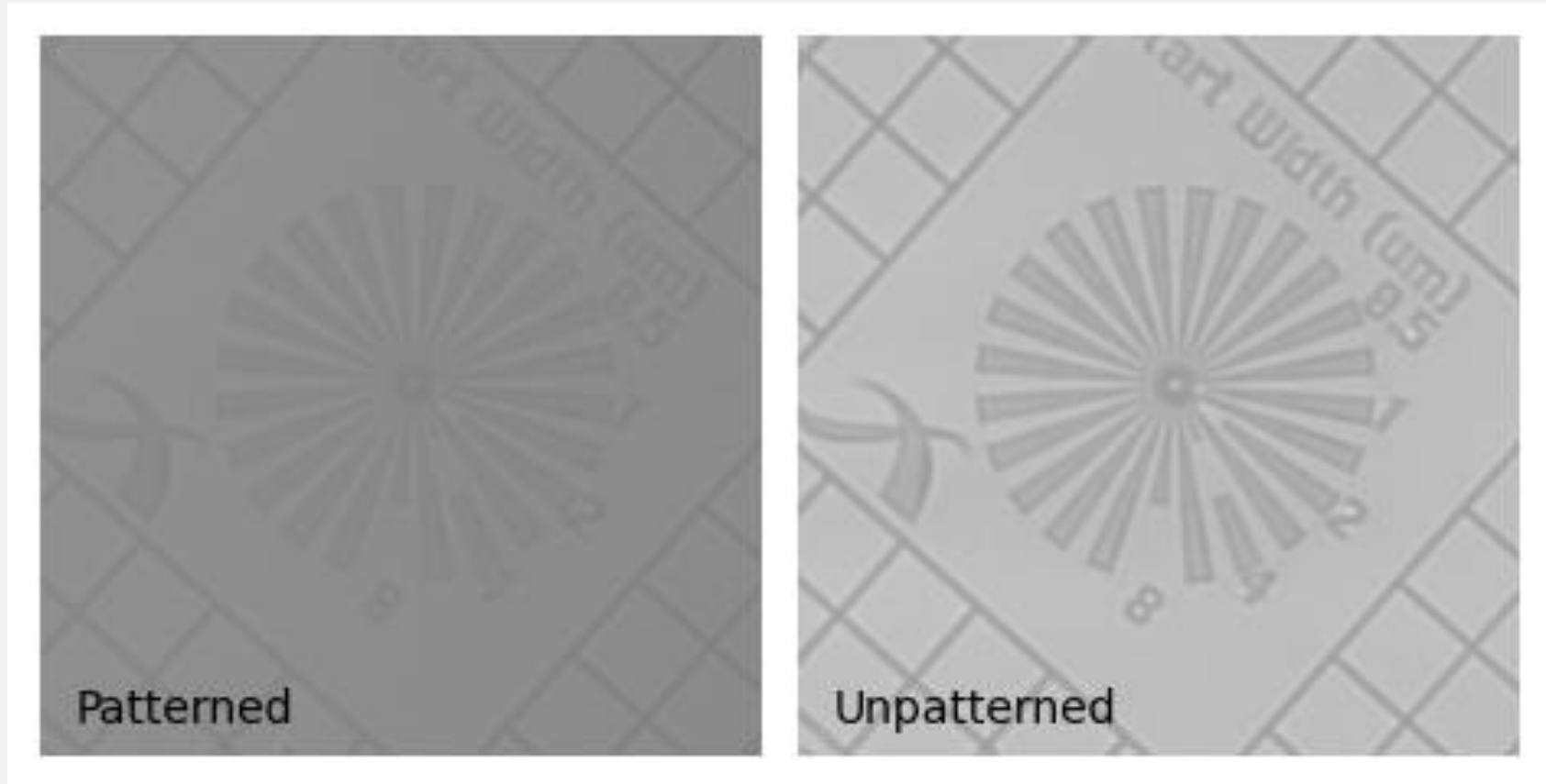
Light yield gains are also possible via **direct enhancement of the rate of spontaneous emission**. In this case, the Purcell effect is used to shape the local density of optical states.



A layered nanophotonic structure may use the Purcell effect to enhance scintillation only in detectable angles

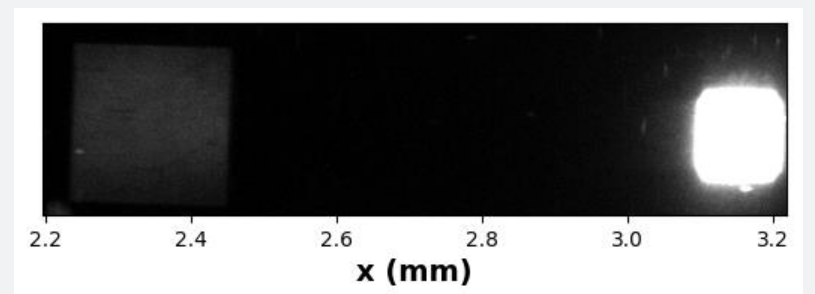
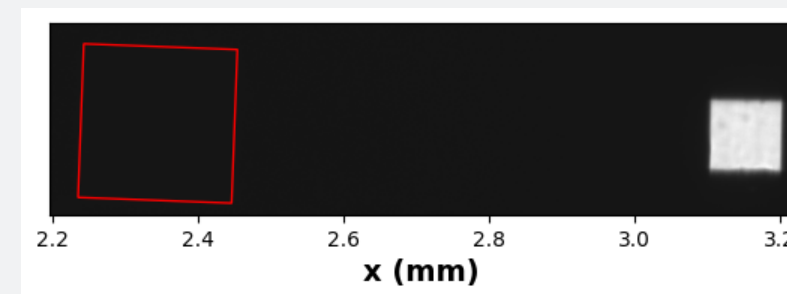
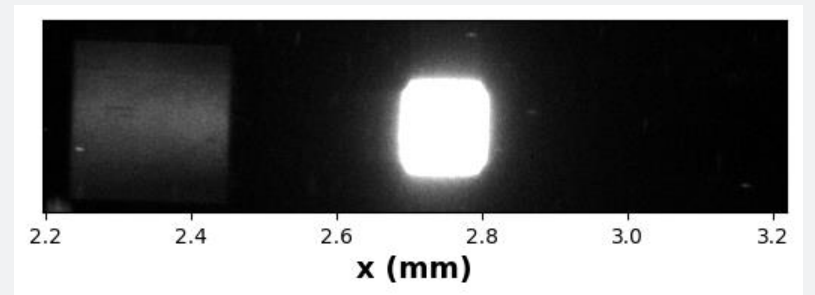
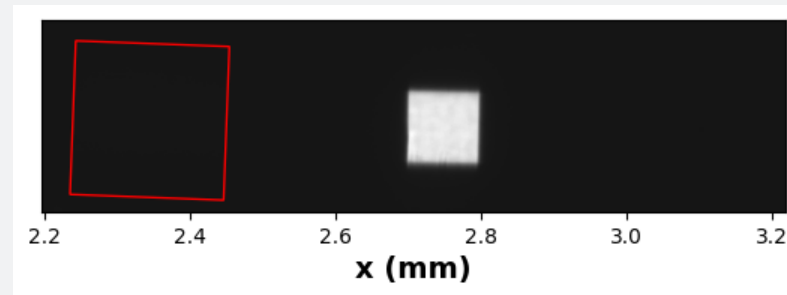
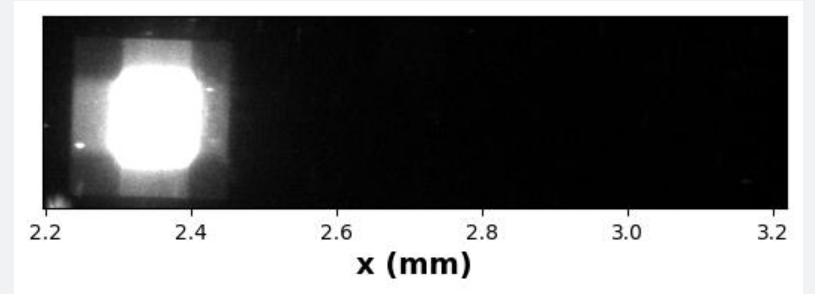
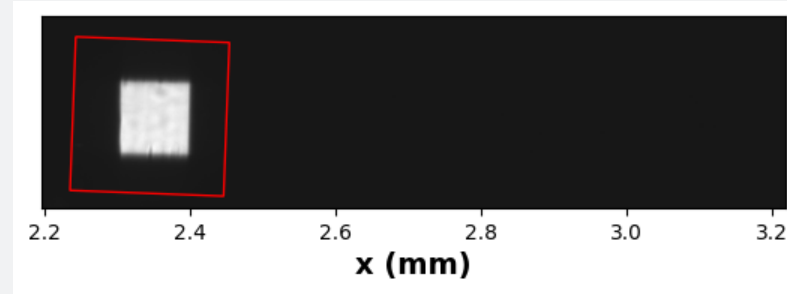
<https://doi.org/10.1126/sciadv.adq6325>

# Spatial Resolution



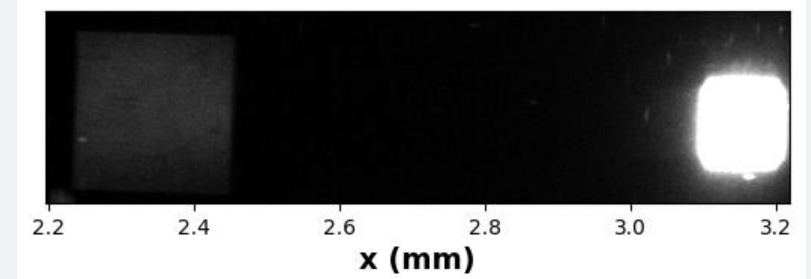
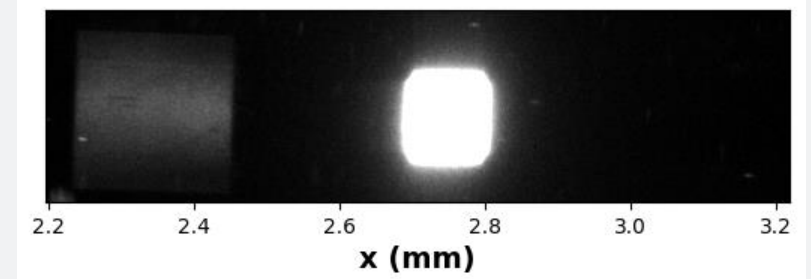
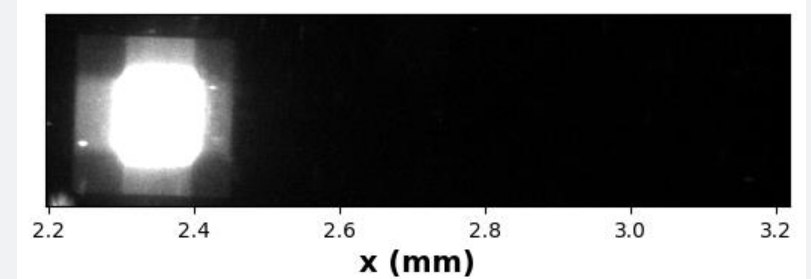
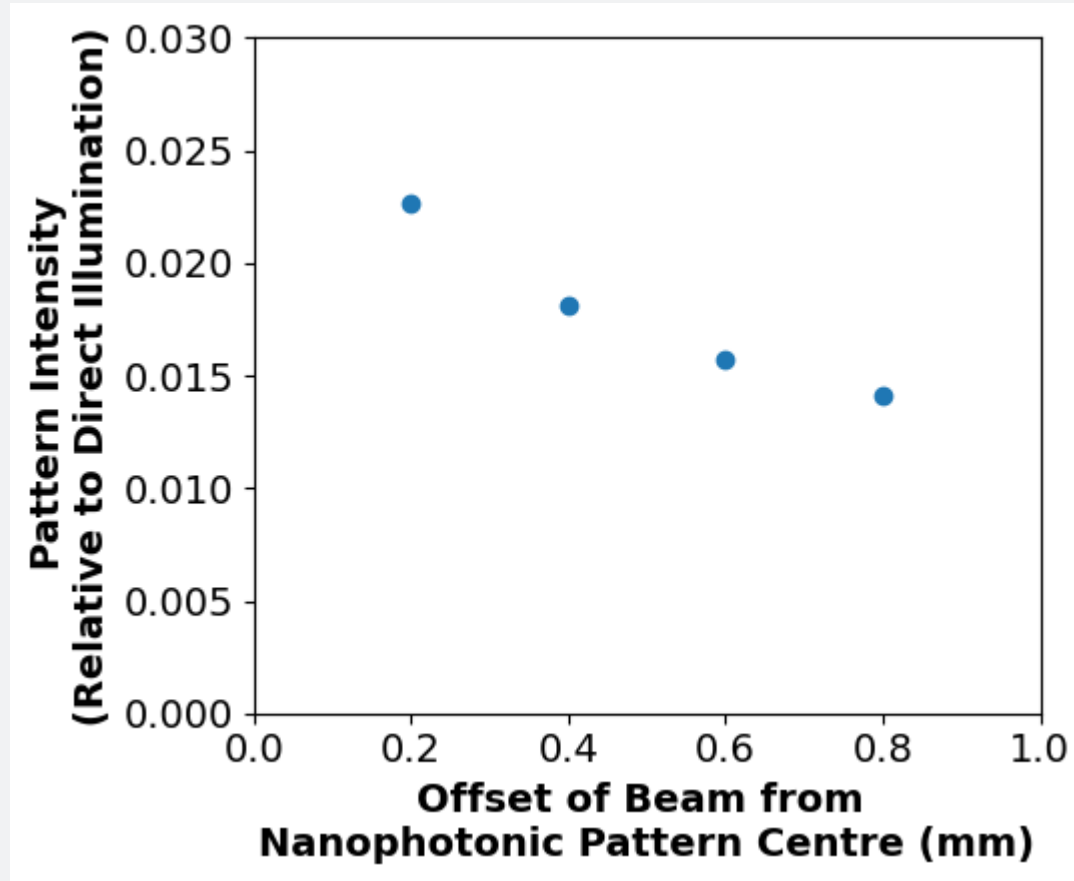
Feature size maintained, contrast reduced.

# Illumination Effects: Beam Position



**Nanophotonic pattern remotely outcouples light generated elsewhere in the scintillator**

# Illumination Effects: Beam Position



**Nanophotonic pattern remotely outcouples light generated elsewhere in the scintillator**

# Numerical Aperture

