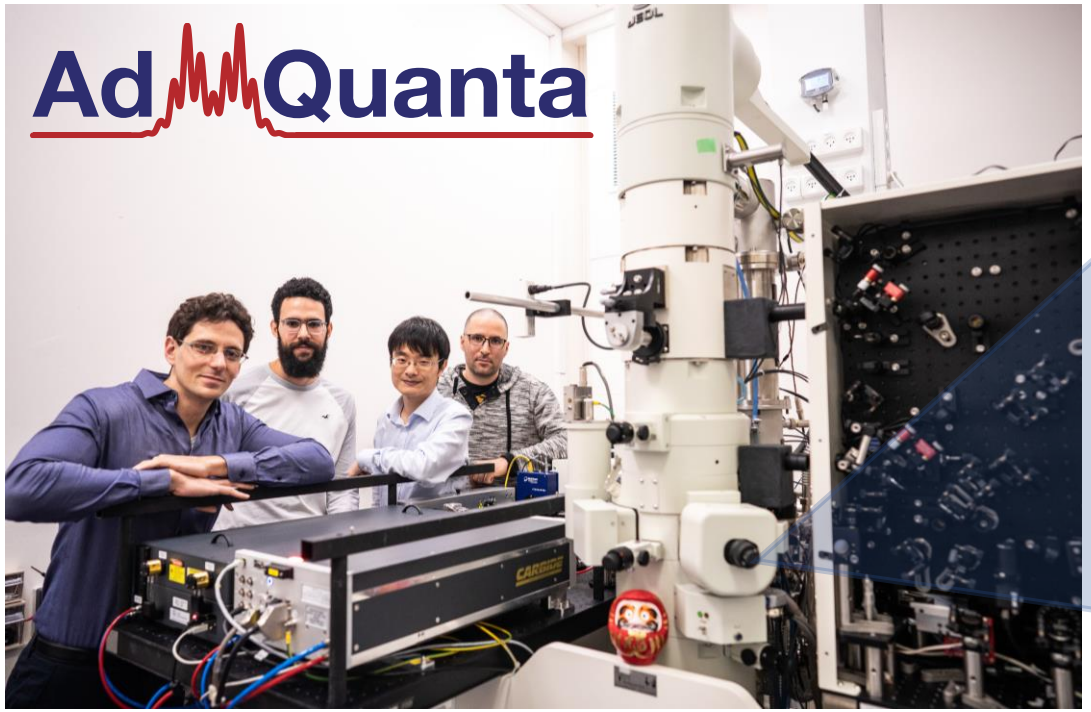
Nanophotonic particle detectors

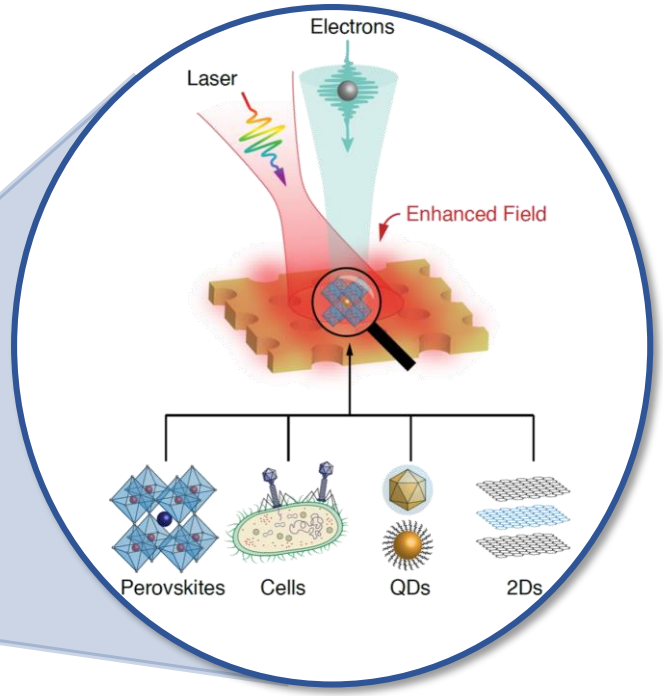
+ how quantum optics can contribute to scintillators and Cherenkov detectors

Technion
Israel Institute of Technology

Ido Kaminer

Our group: photonics and quantum tech *experiment & theory*





available ERC-funded positions for experienced postdocs

FET OPEN HORIZON 2020 (European Commission)

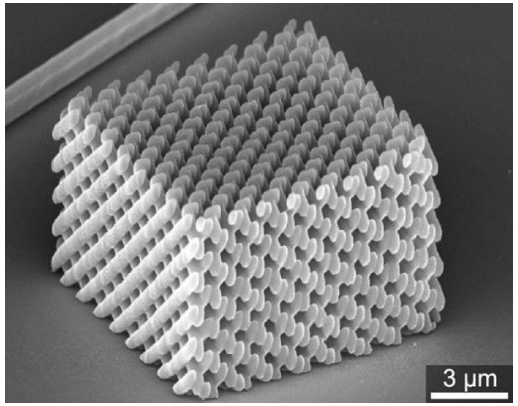
erc

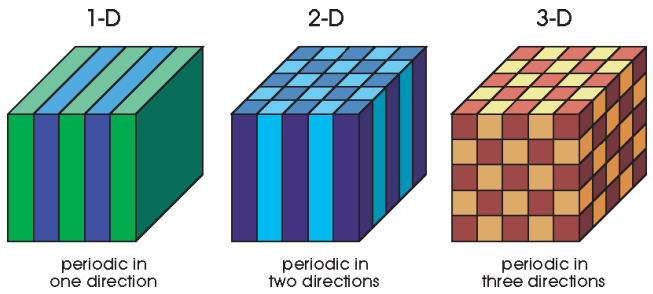
BSF ISRAEL SCIENCE FOUNDATION

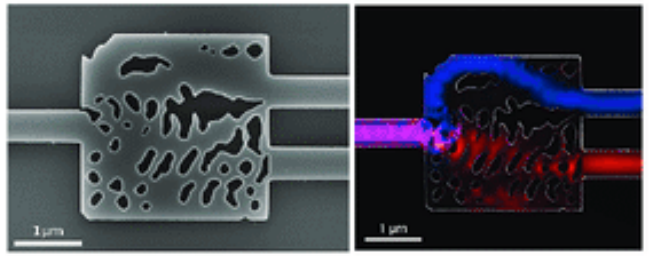
רשות החדשנות Israel Innovation Authority

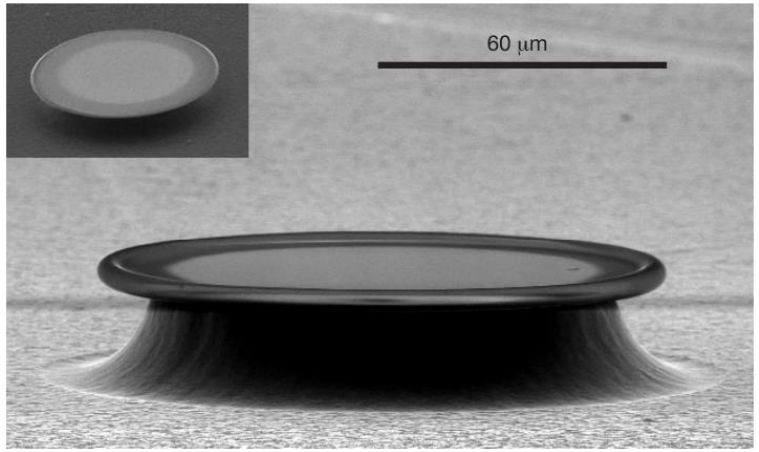
The Azrieli Foundation

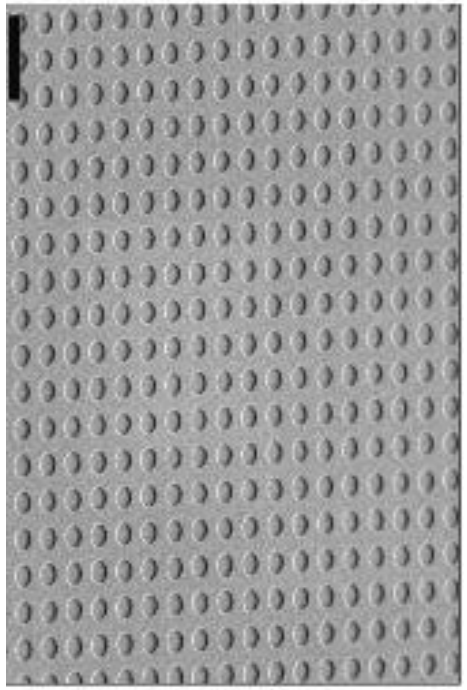
Nanophotonics

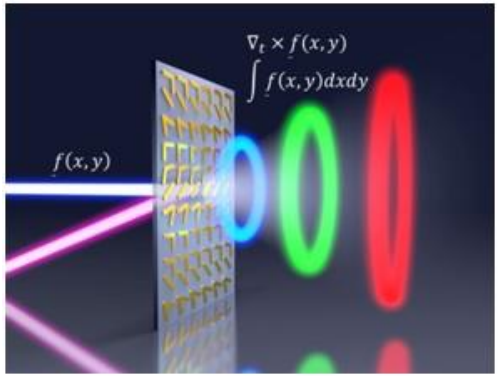


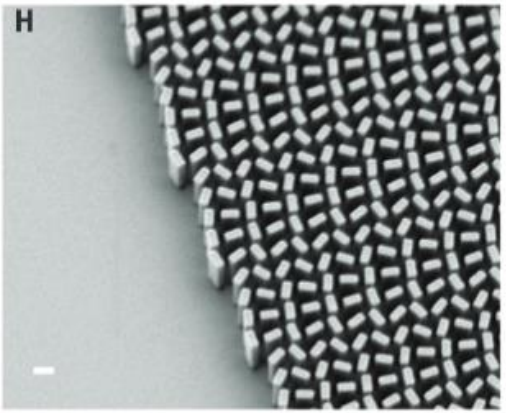












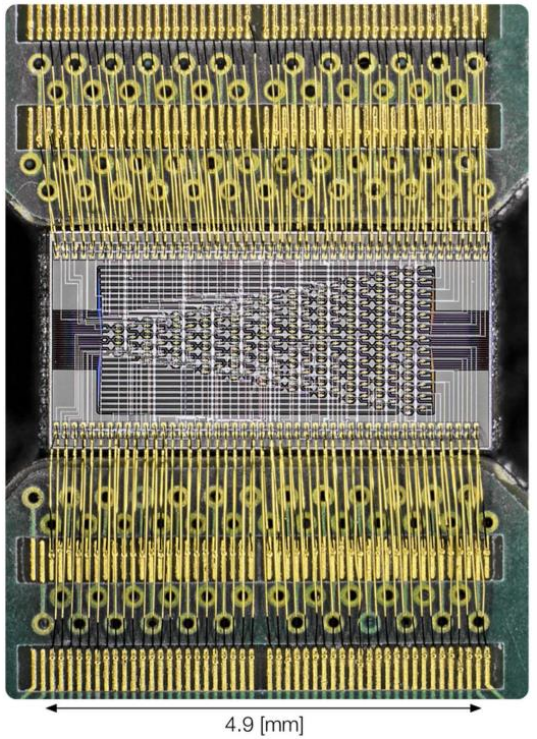
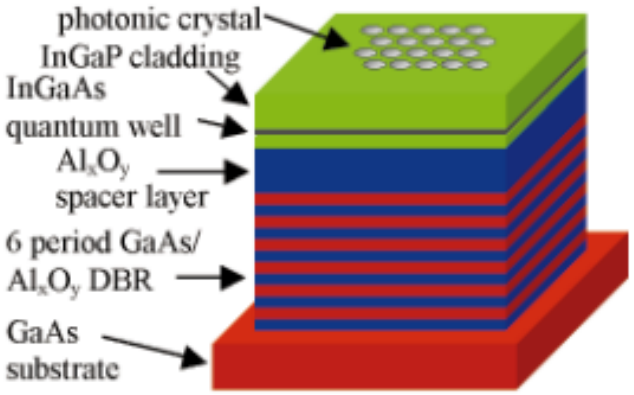


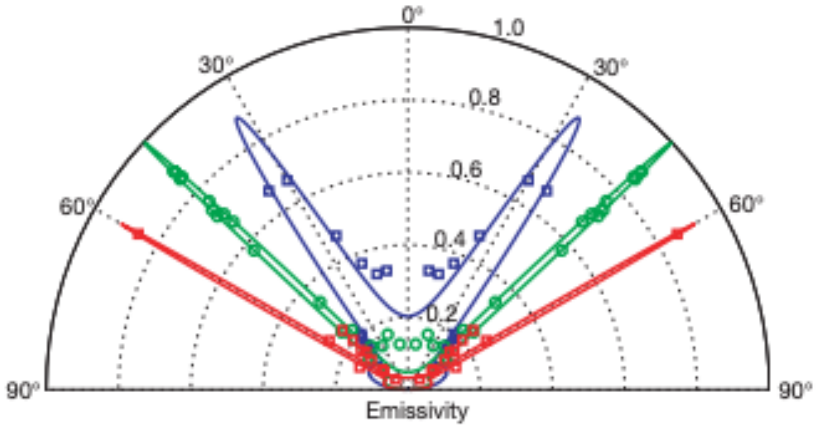
Image sources: Capasso (Harvard), Soljačić (MIT), Joannopoulos (MIT), Johnson (MIT), Polman (AMOLF), Vuckovic (Stanford), Vahala (Caltech), Englund (MIT) research groups.

Applications of nanophotonics

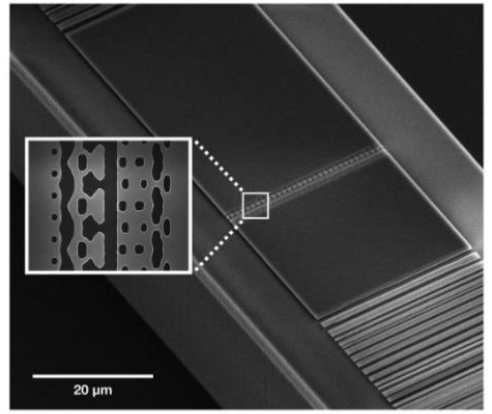
LED and lasers



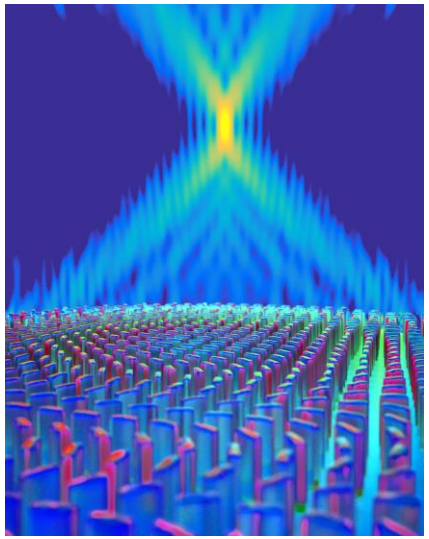
Thermal emitters



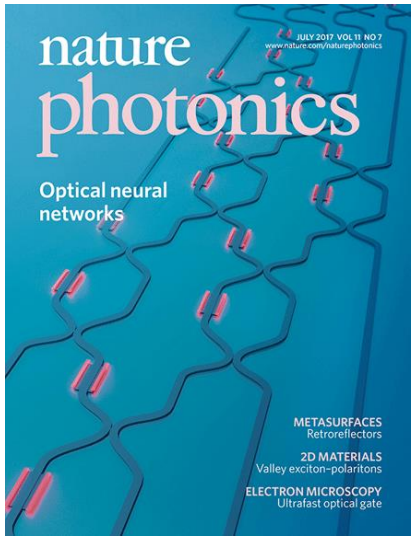
Particle accelerators



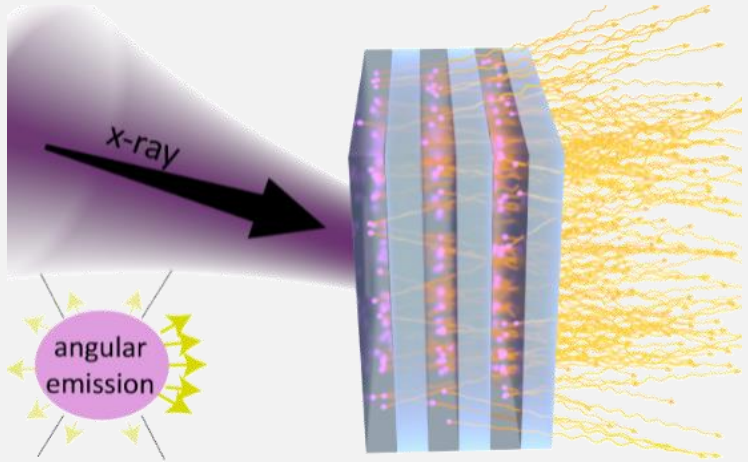
Flat optics



Photonic computing



nanophotonic scintillators



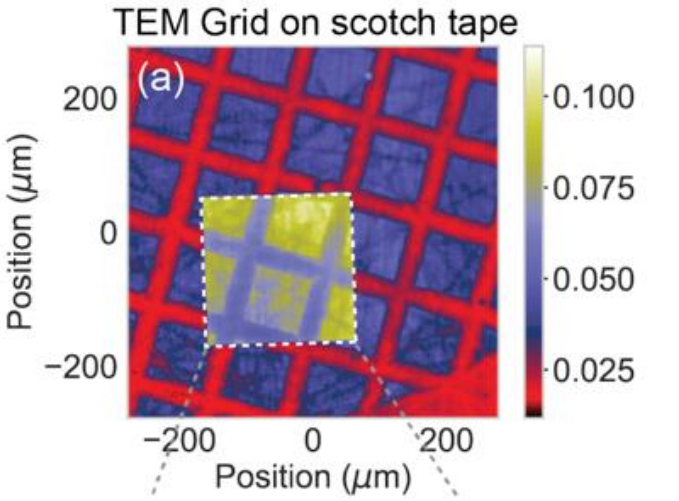
Apply nanophotonics to scintillator science?

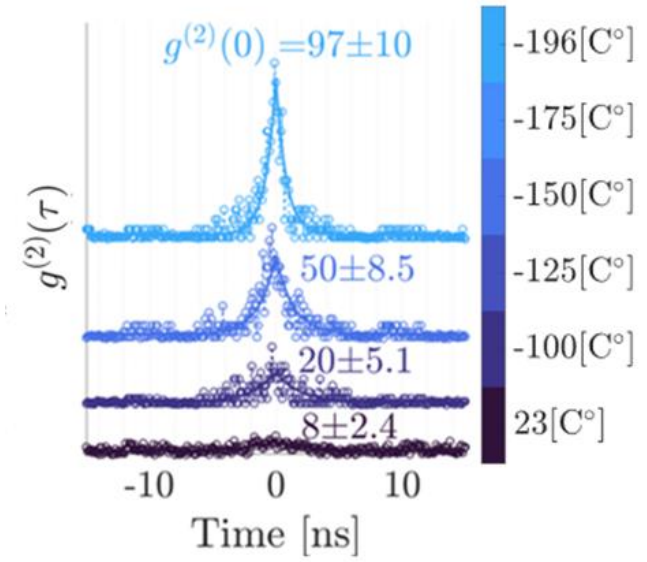
- Control light-outcoupling
  - *Nanophotonic scintillators*

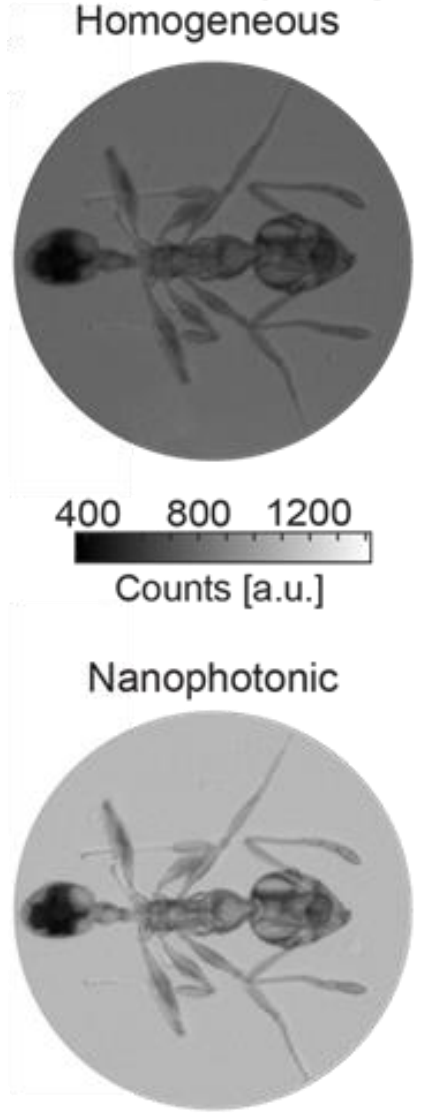
Nanophotonic Cherenkov detectors, with S. Easo @ LHCb
X. Lin, **Nature Physics** (2018), **Nature Comm** (2021)

- Enhance light-emission
  - Purcell scintillators

- Inspiration from quantum optics?







Apply nanophotonics to scintillator science?

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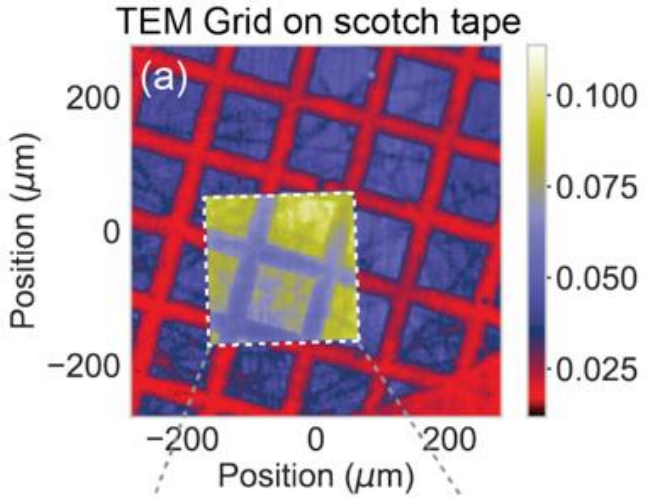
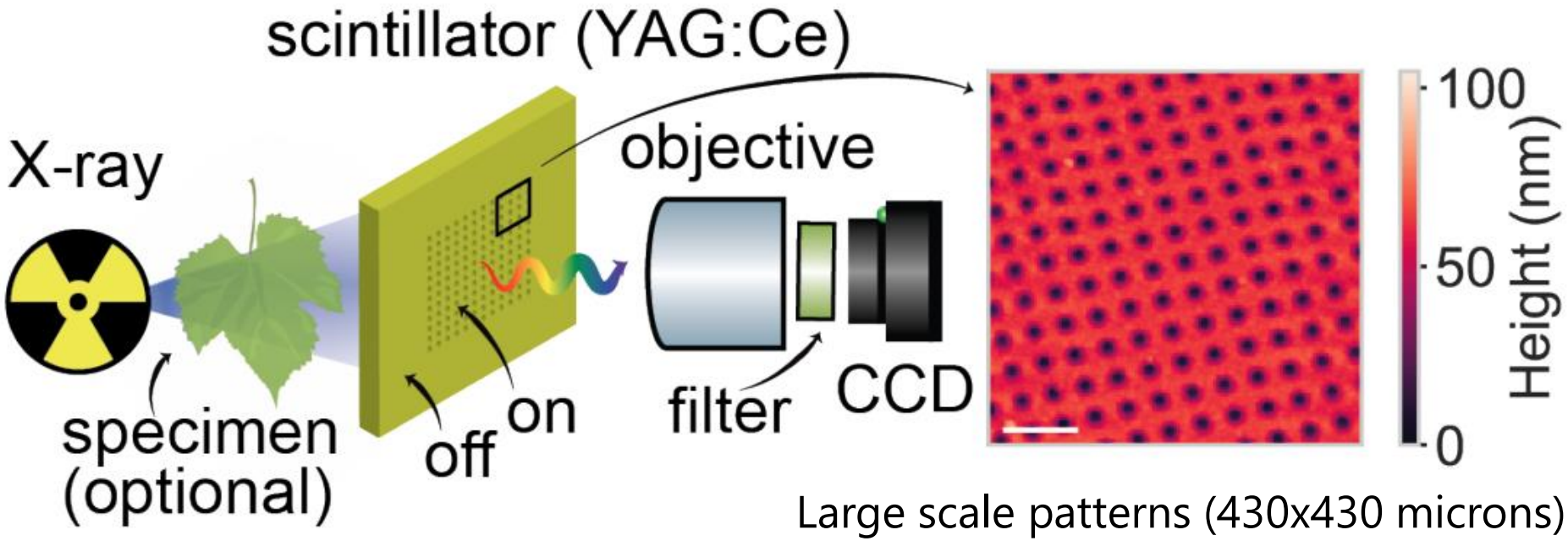
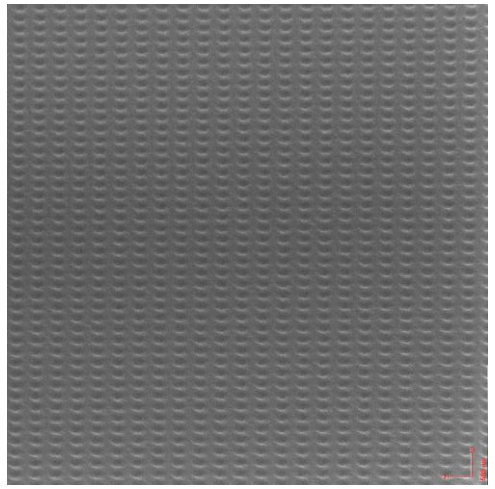


X-ray scintillation enhancement



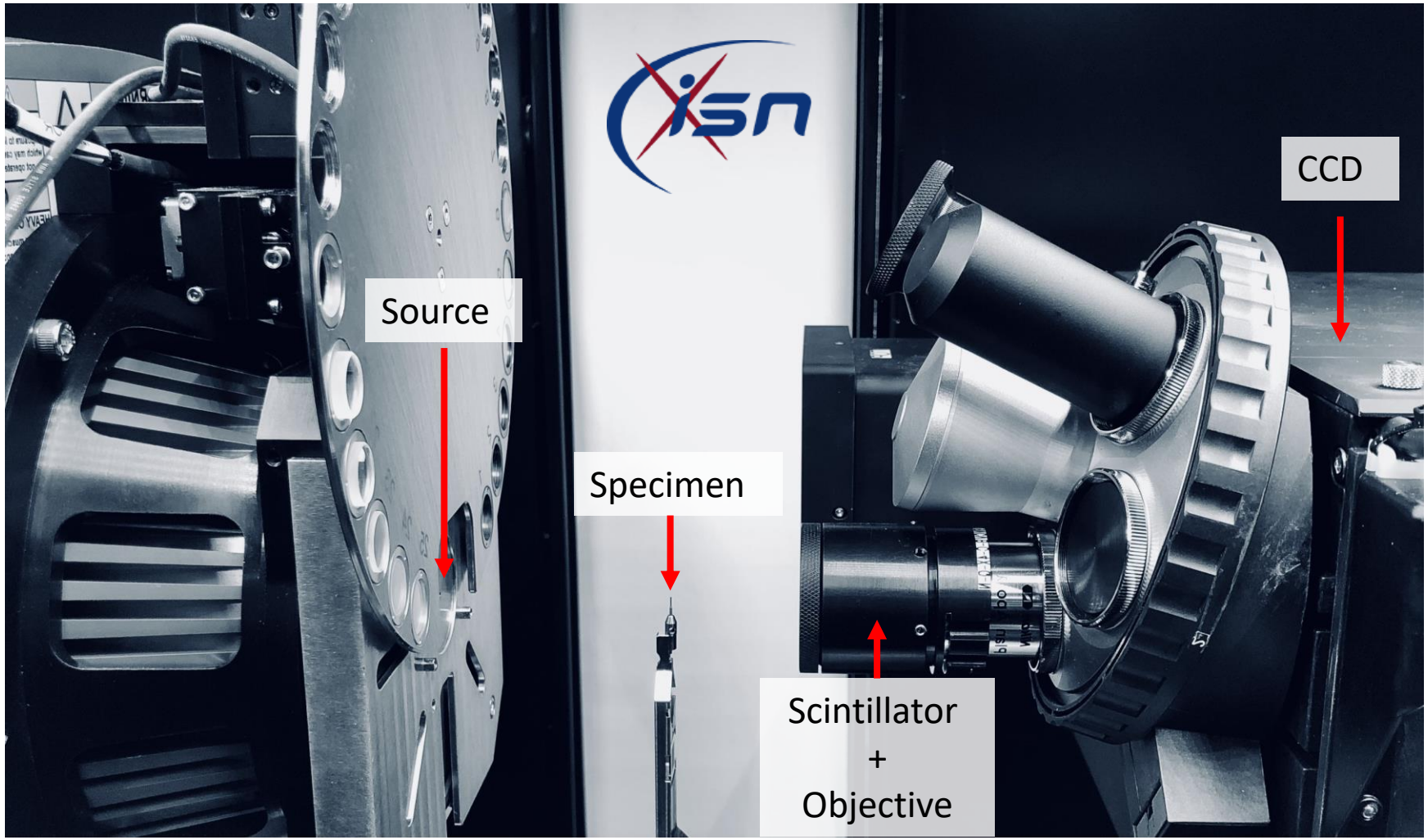
Large scale patterns (430x430 microns)



SEM

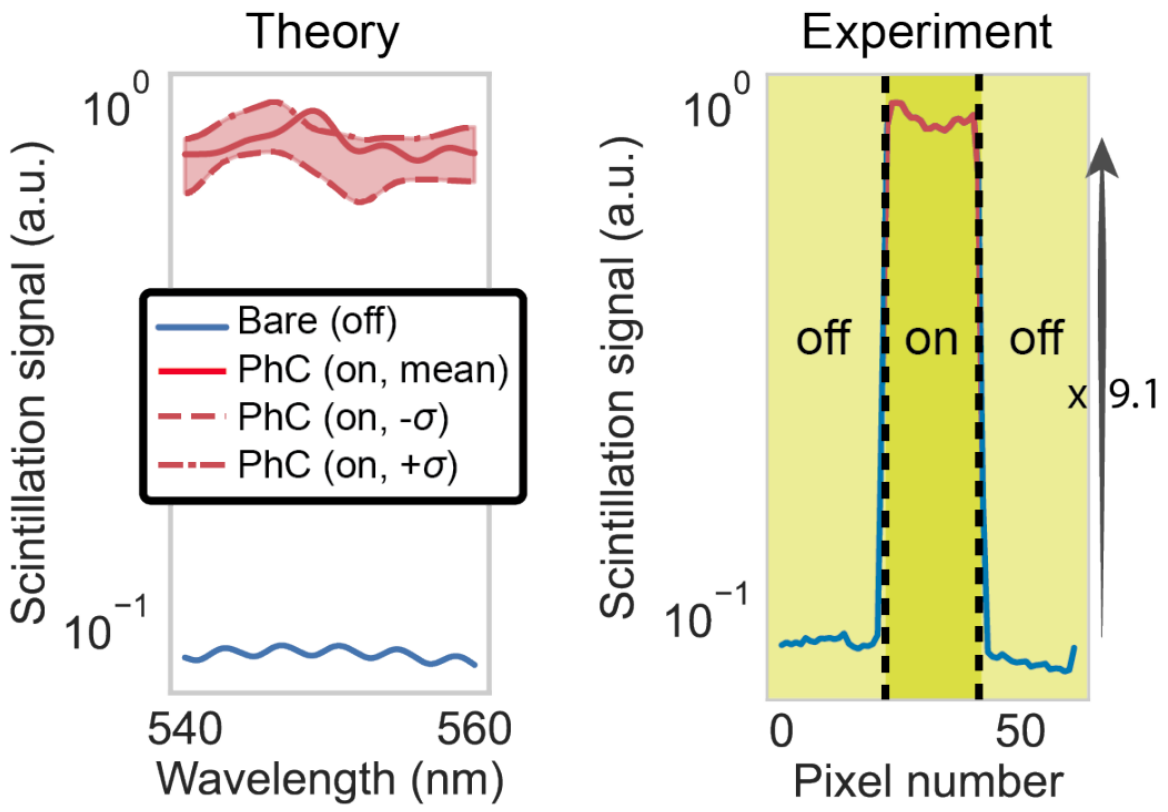
Roques-Carmes*, Rivera*, et al., **Science** (2022)

Setup at MIT (based on a micro-CT)



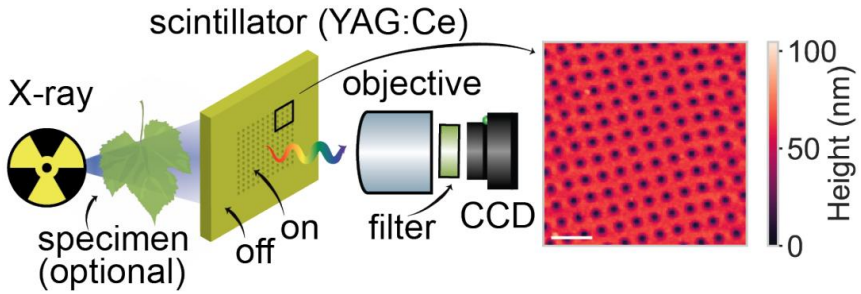
Roques-Carmes*, Rivera*, et al., **Science** (2022)

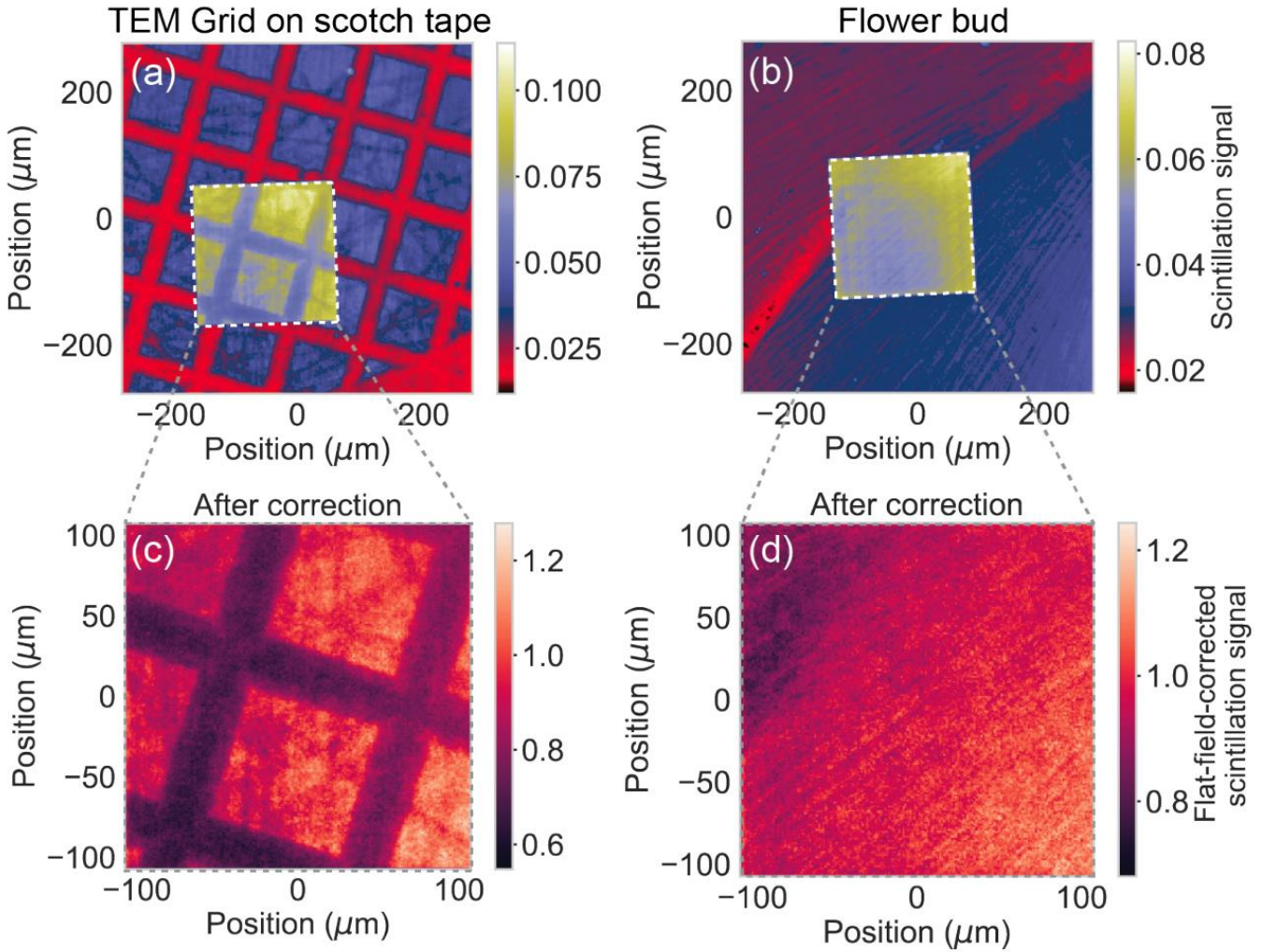
X-ray scintillation enhancement



Roques-Carmes*, Rivera*, et al., **Science** (2022)

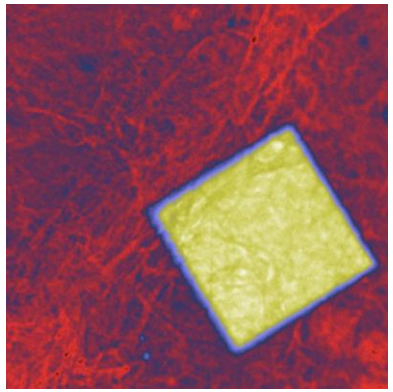
X-ray scintillation imaging



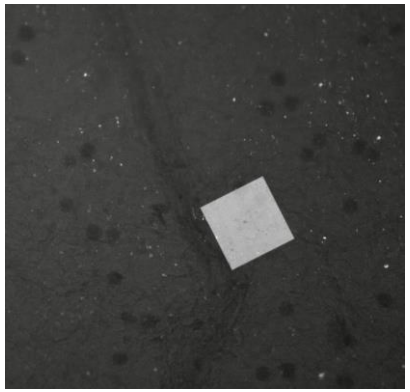


Roques-Carmes*, Rivera*, et al., **Science** (2022)

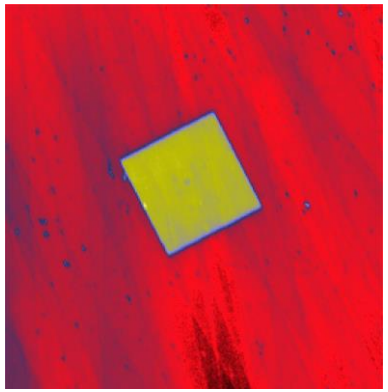
Other x-ray scans



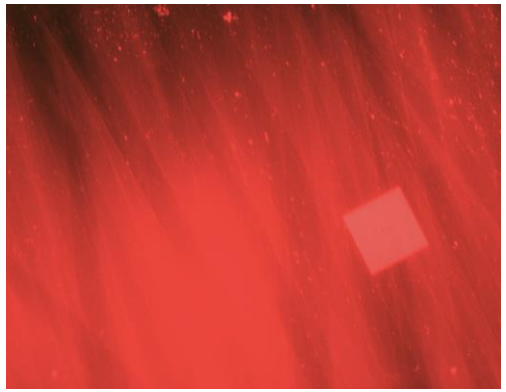
Leaf



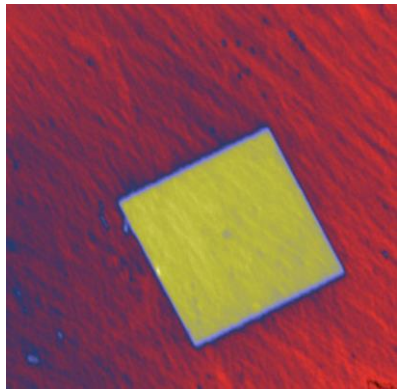
Leaf



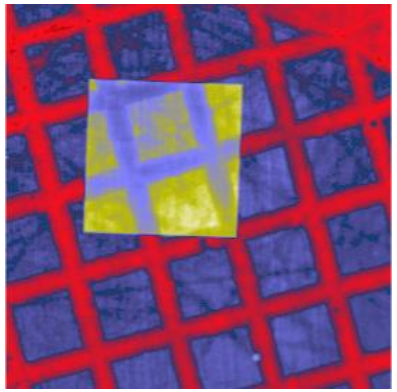
Human hair



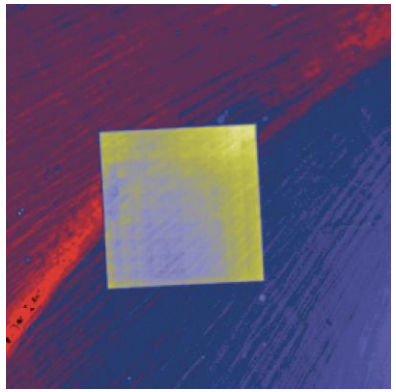
Human hair



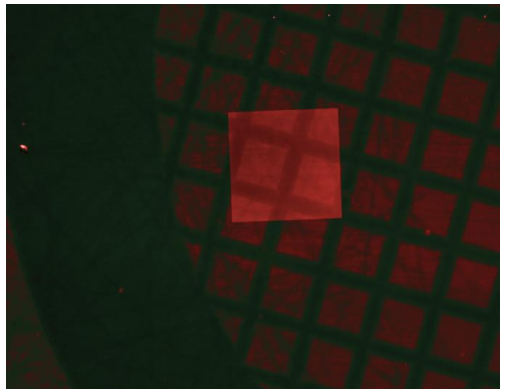
Flower bud



TEM Metallic grid



Flower bud



TEM Metallic grid

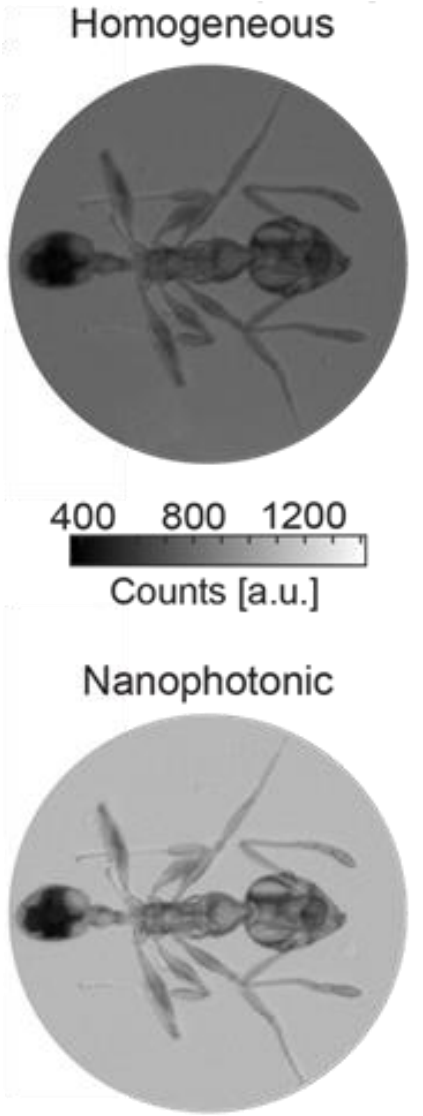
Roques-Carmes*, Rivera*, et al., **Science** (2022)

Apply nanophotonics to scintillator science?

- Control light-outcoupling
  - *Nanophotonic scintillators*

- **Enhance light-emission**
  - Purcell scintillators

- Inspiration from quantum optics?



The Purcell effect

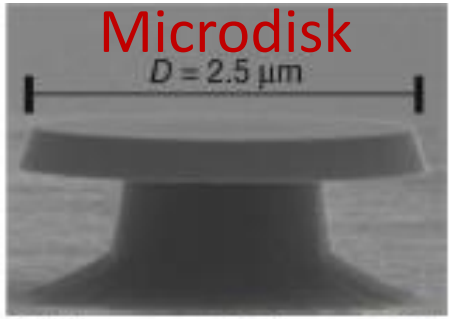
The spontaneous emission rate depends on the EM environment

The Purcell factor $\boxed{F_{\mathrm{P}} = \frac{\Gamma}{\Gamma_0}}$

For a dipole in a cavity: $F_{\mathrm{P}} = \frac{3\lambda^3}{4\pi^3}\frac{Q}{V}$

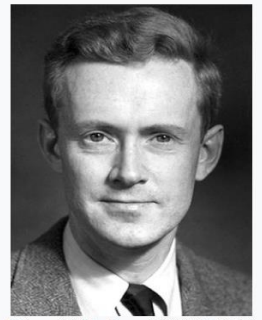
General design rule: highest Q and smallest V

(Reithmaier *et al.*, 2004)



(Srinivasan and Painter, 2007)

P. Lodahl et al. **Rev. Mod. Phys.** (2015)



Edward Mills Purcell (1912–1997)

B10. Spontaneous Emission Probabilities at Radio Frequencies. E. M. PURCELL, *Harvard University*.—For nuclear magnetic moment transitions at radio frequencies the probability of spontaneous emission, computed from

$$A_\nu = (8\pi\nu^2/c^3)h\nu(8\pi^3\mu^2/3h^2) \text{ sec.}^{-1},$$

is so small that this process is not effective in bringing a spin system into thermal equilibrium with its surroundings. At 300°K, for $\nu = 10^7$ sec.$^{-1}$, $\mu = 1$ nuclear magneton, the corresponding relaxation time would be 5×10^{21} seconds! However, for a system coupled to a resonant electrical circuit, the factor $8\pi\nu^2/c^3$ no longer gives correctly the number of radiation oscillators per unit volume, in unit frequency range, there being now *one* oscillator in the frequency range ν/Q associated with the circuit. The spontaneous emission probability is thereby increased, and the relaxation time reduced, by a factor $f = 3Q\lambda^3/4\pi^2V$, where V is the volume of the resonator. If a is a dimension characteristic of the circuit so that $V\sim a^3$, and if δ is the skin-depth at frequency ν, $f\sim\lambda^3/a^2\delta$. For a non-resonant circuit $f\sim\lambda^3/a^3$, and for $a<\delta$ it can be shown that $f\sim\lambda^3/a\delta^2$. If small metallic particles, of diameter 10^{-3} cm are mixed with a nuclear-magnetic medium at room temperature, spontaneous emission should establish thermal equilibrium in a time of the order of minutes, for $\nu = 10^7$ sec.$^{-1}$.

E. M. Purcell **Phys. Rev.** (1946)

Purcell effect for scintillation applications


Yaniv Kurman

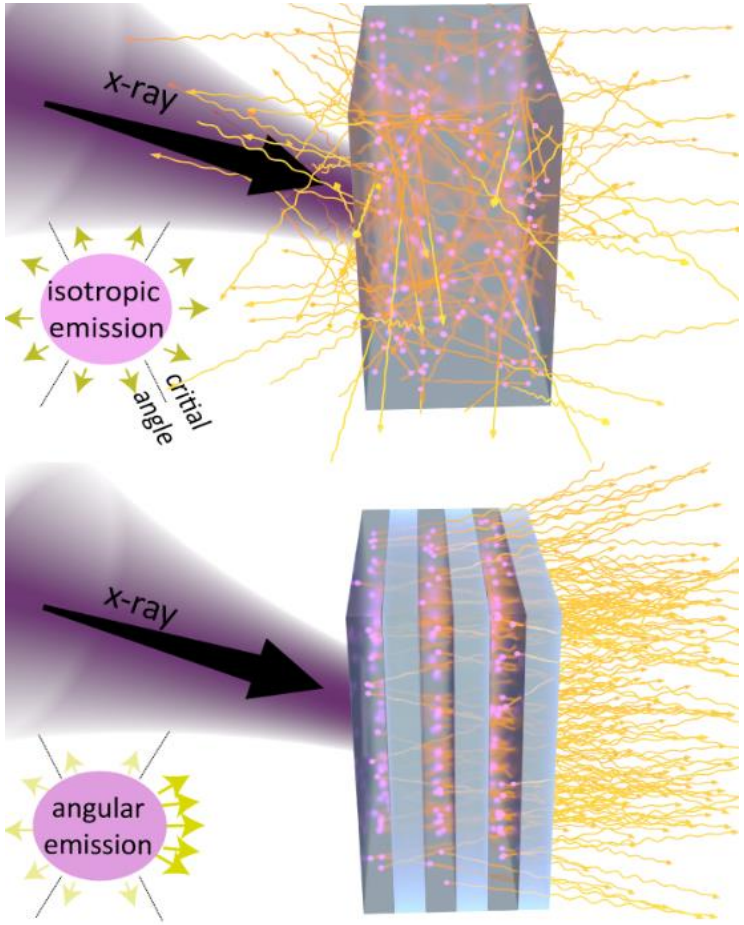
We proposed the concept of Purcell-enhanced scintillators

But we cannot use the Q/V design rule

The scintillator needs:

- Large V for the optical modes
- Low Q for good extraction

Use of the Purcell effect in an untraditional manner



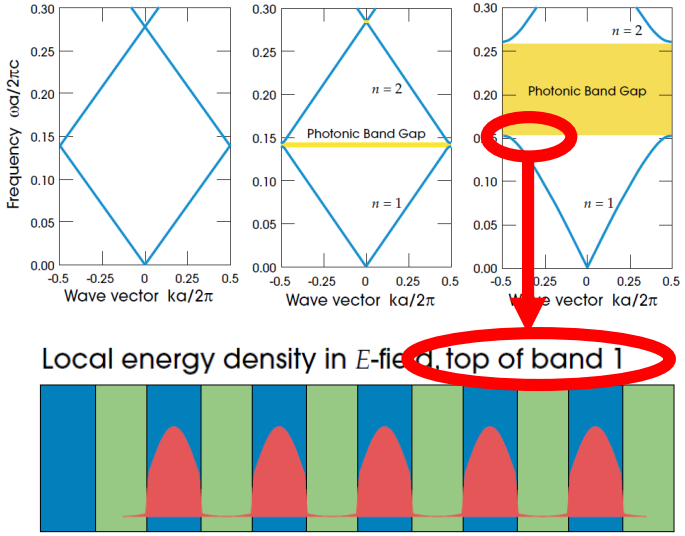
Kurman, et al. "Photonic-crystal scintillators: Molding the flow of light to enhance X-ray and γ-ray detection." **PRL** 125, 040801 (2020).

The Photonic-crystal scintillator

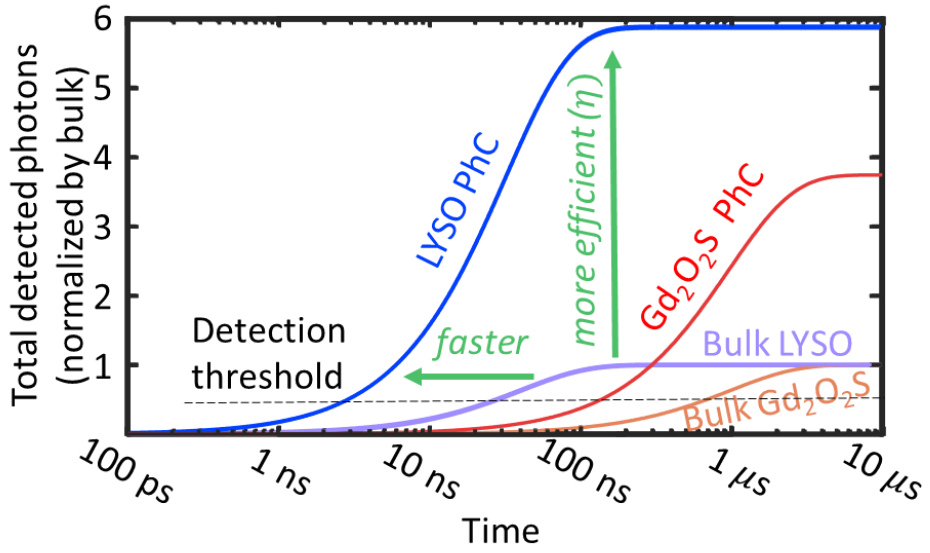
Use of the **photonic band gap** to increase emission in desired angles while reducing emission into undetectable directions

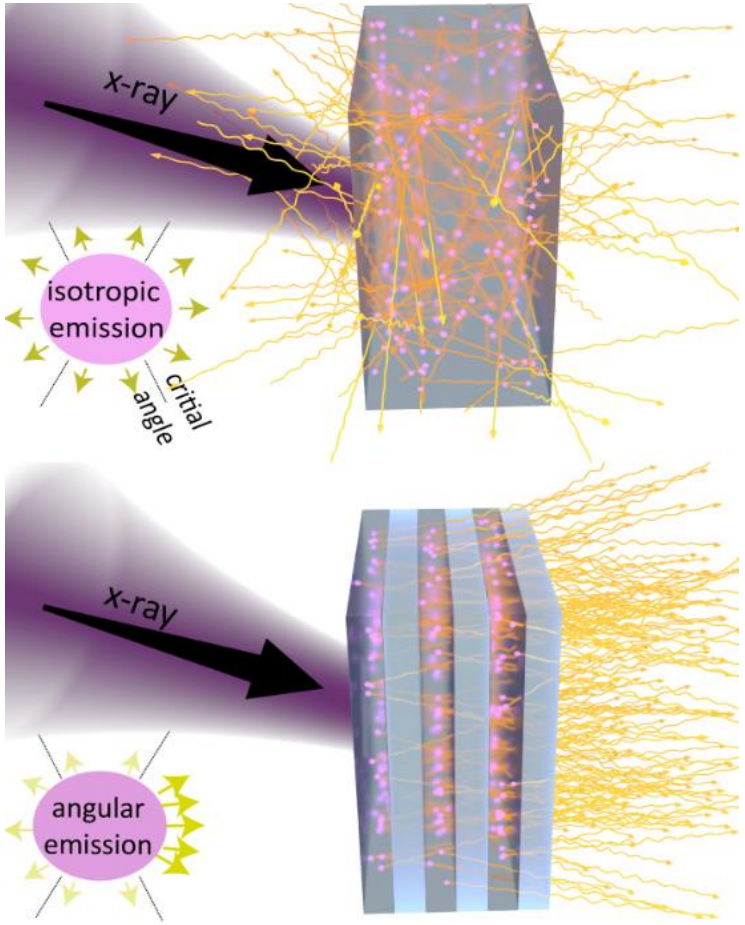
Yaniv Kurman

Angular Purcell Enhancement



Joannopoulos, et al.,
Molding the flow of light (2008)

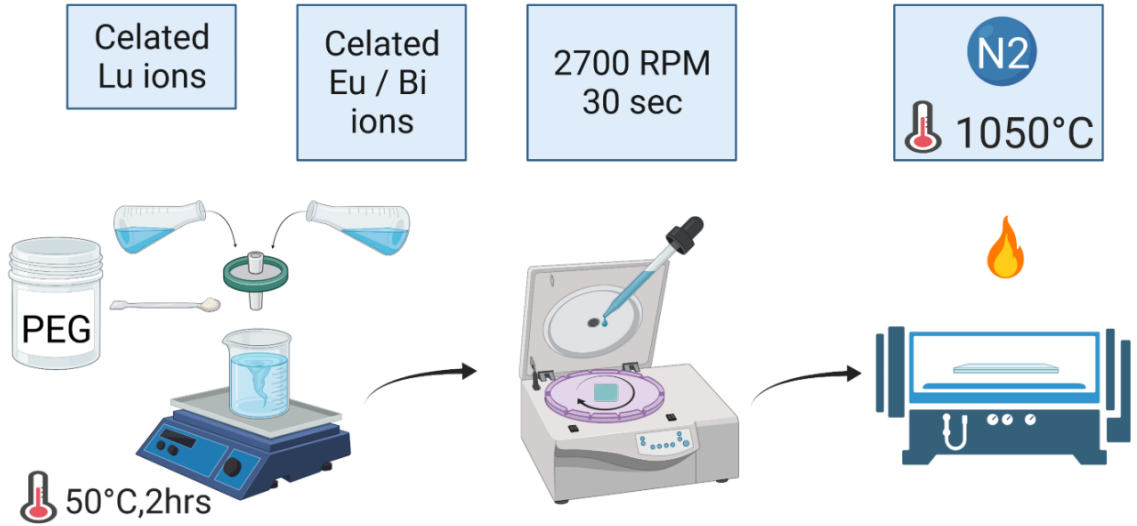




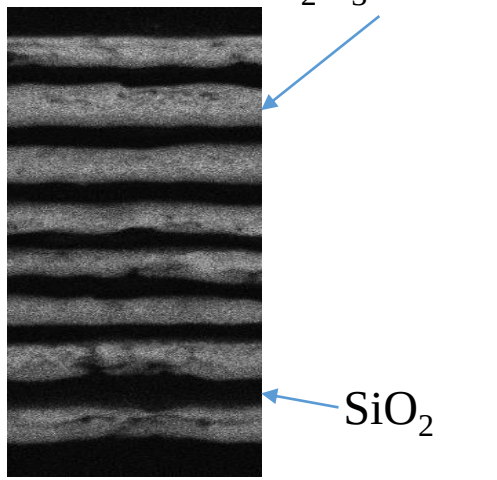
Kurman, et al. "Photonic-crystal scintillators: Molding the flow of light to enhance X-ray and γ-ray detection." **PRL** 125, 040801 (2020).

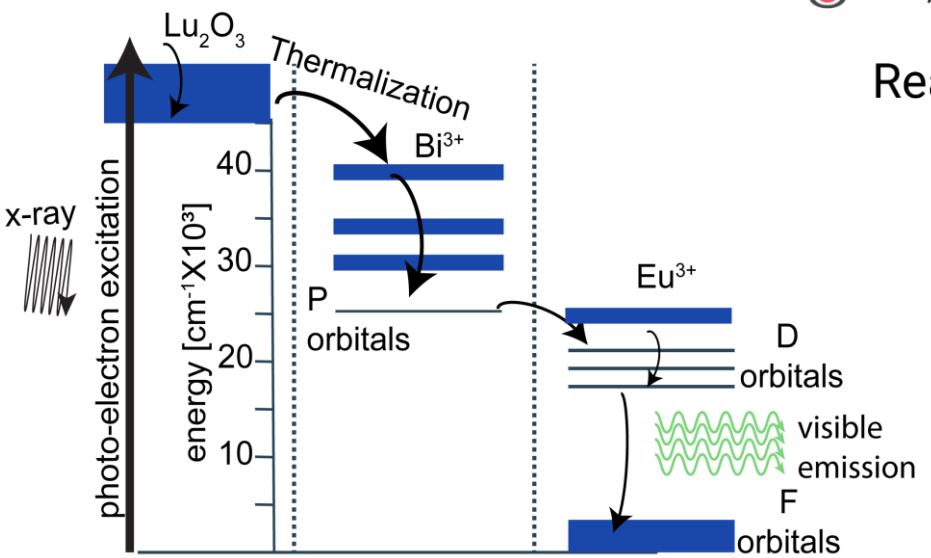
Experimental realization

Neta Lahav



Growth method: sol-gel, layer by layer





Co-dopant sensitizer

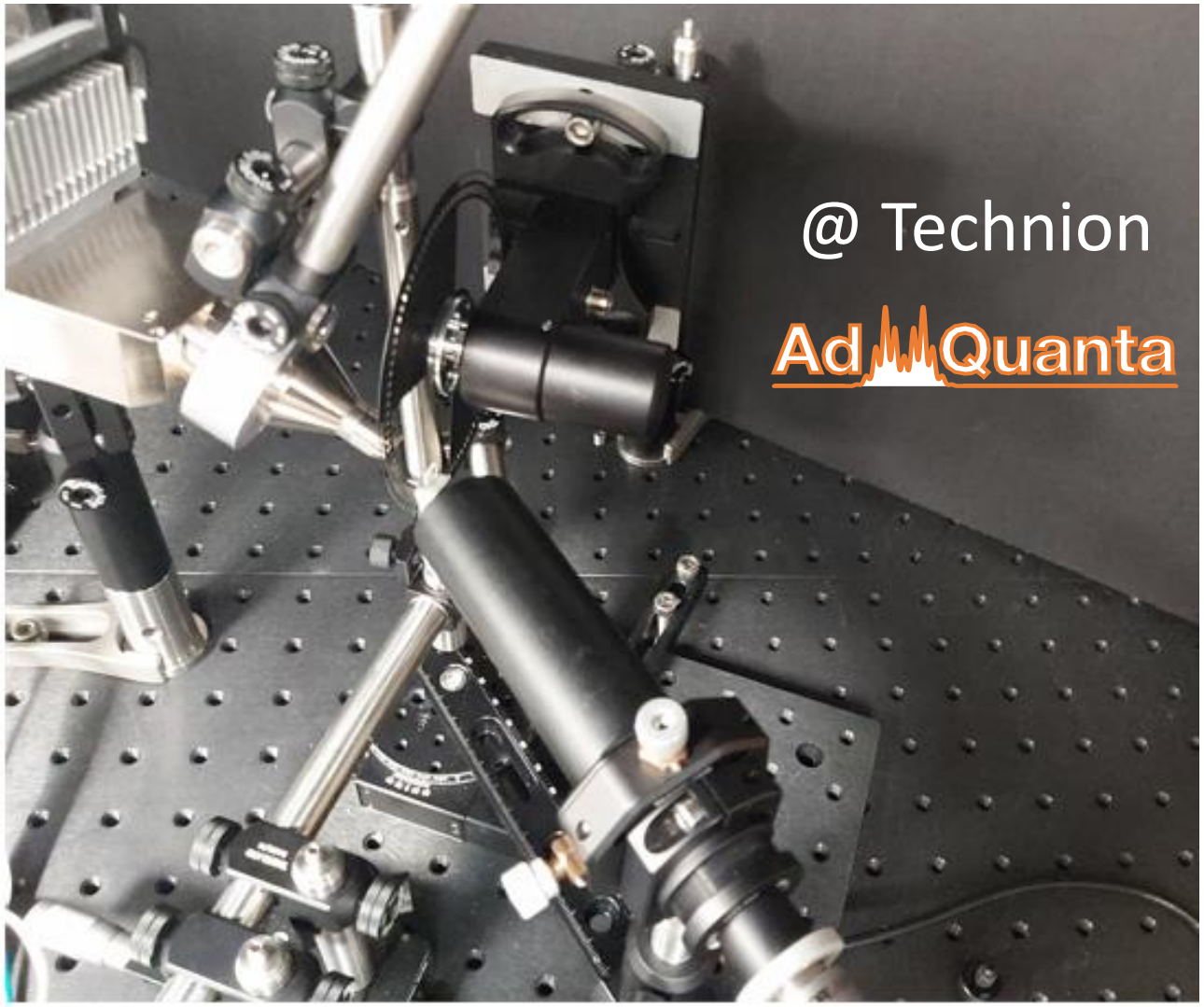
- Morales Ramírez et al., J. Mater. Res. 28, 1365 (2013)
- Nedelec, J. Nanomaterials 2007, 036392 (2007)

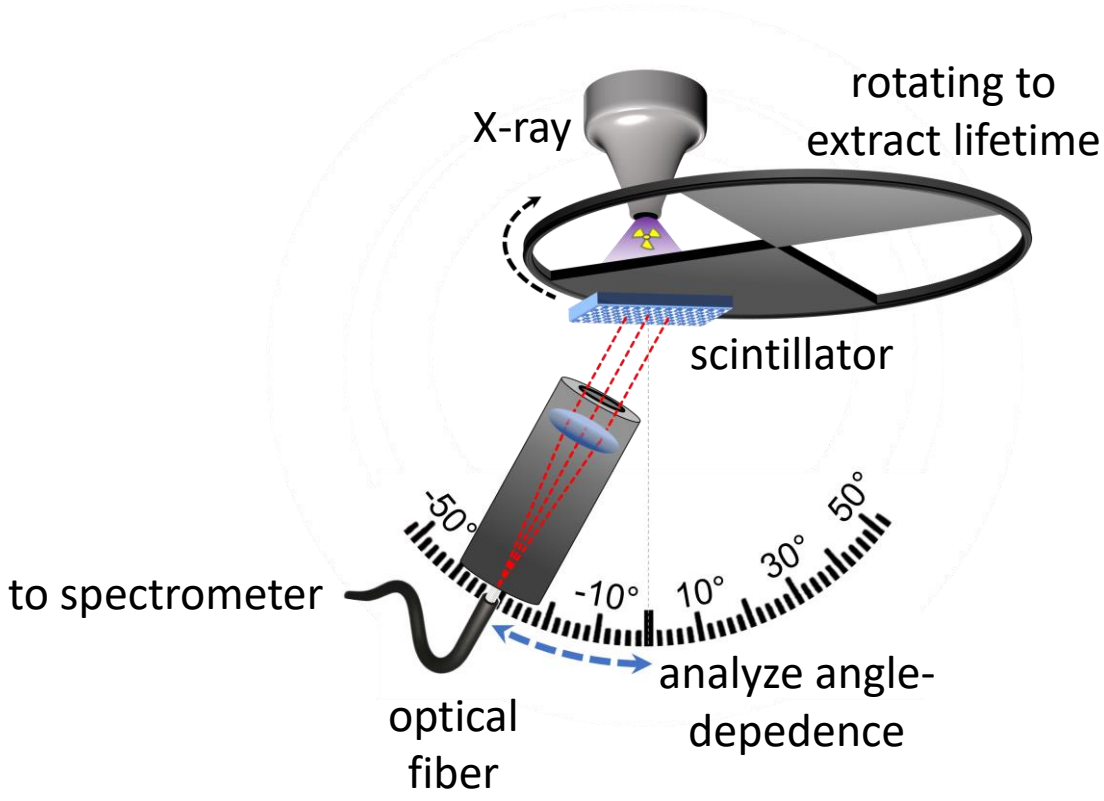
Review: Sol-Gel Processing of Nanostructured Inorganic Scintillating Materials

Kurman*, Lahav*, Schuetz*, et al. *Purcell enhancement of X-ray scintillation*, **in preparation** (2022)

Building a new scintillation lab

Roman Schütz

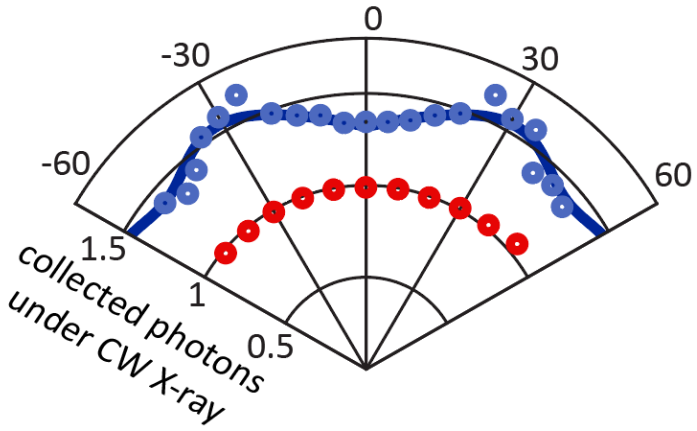




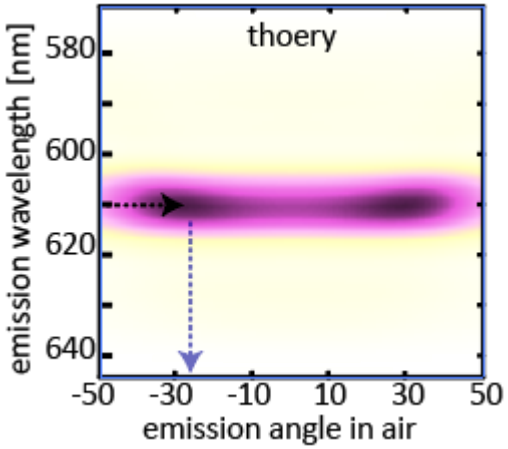
Kurman*, Lahav*, Schuetz*, et al. *Purcell enhancement of X-ray scintillation*, **in preparation** (2022)

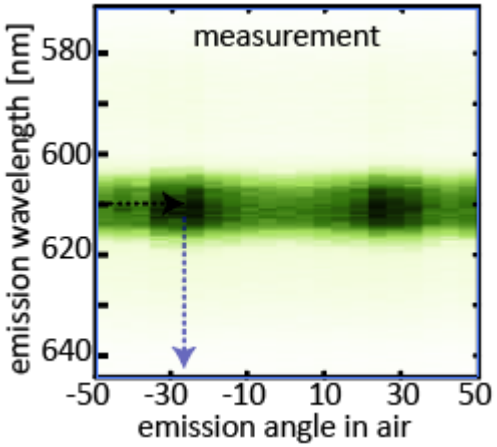
Proof-of-concept measurements

More photons

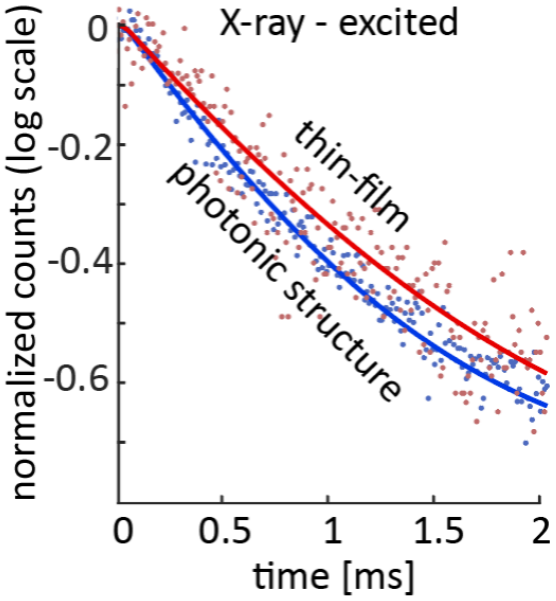


Angular emission





Faster emission



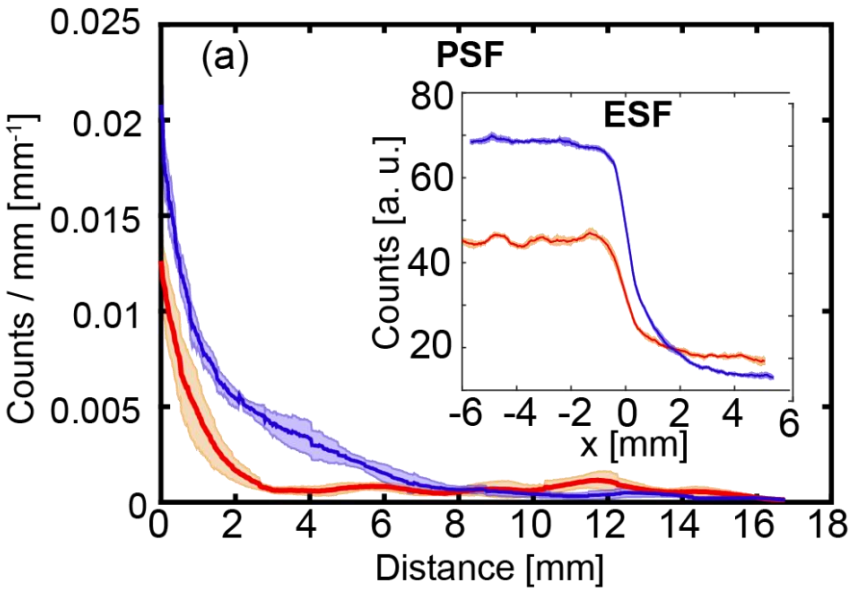
From 1.635 ms to 1.107 ms

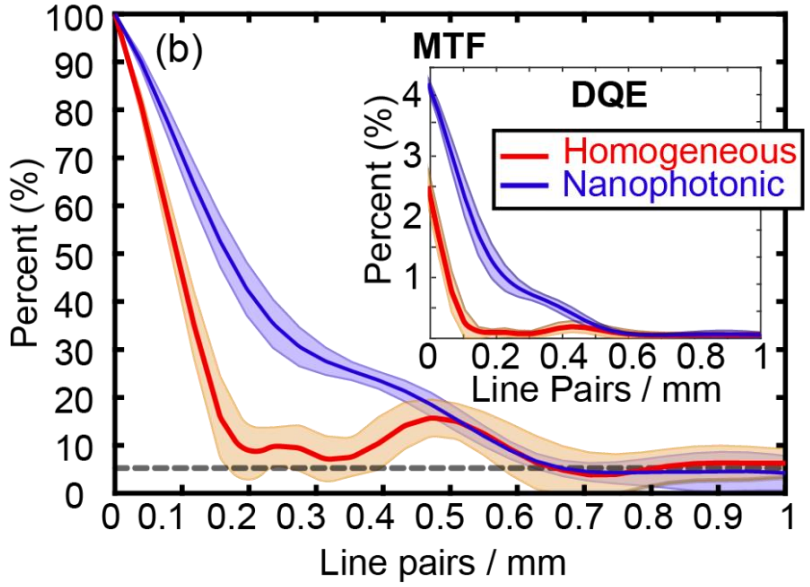
Light yield

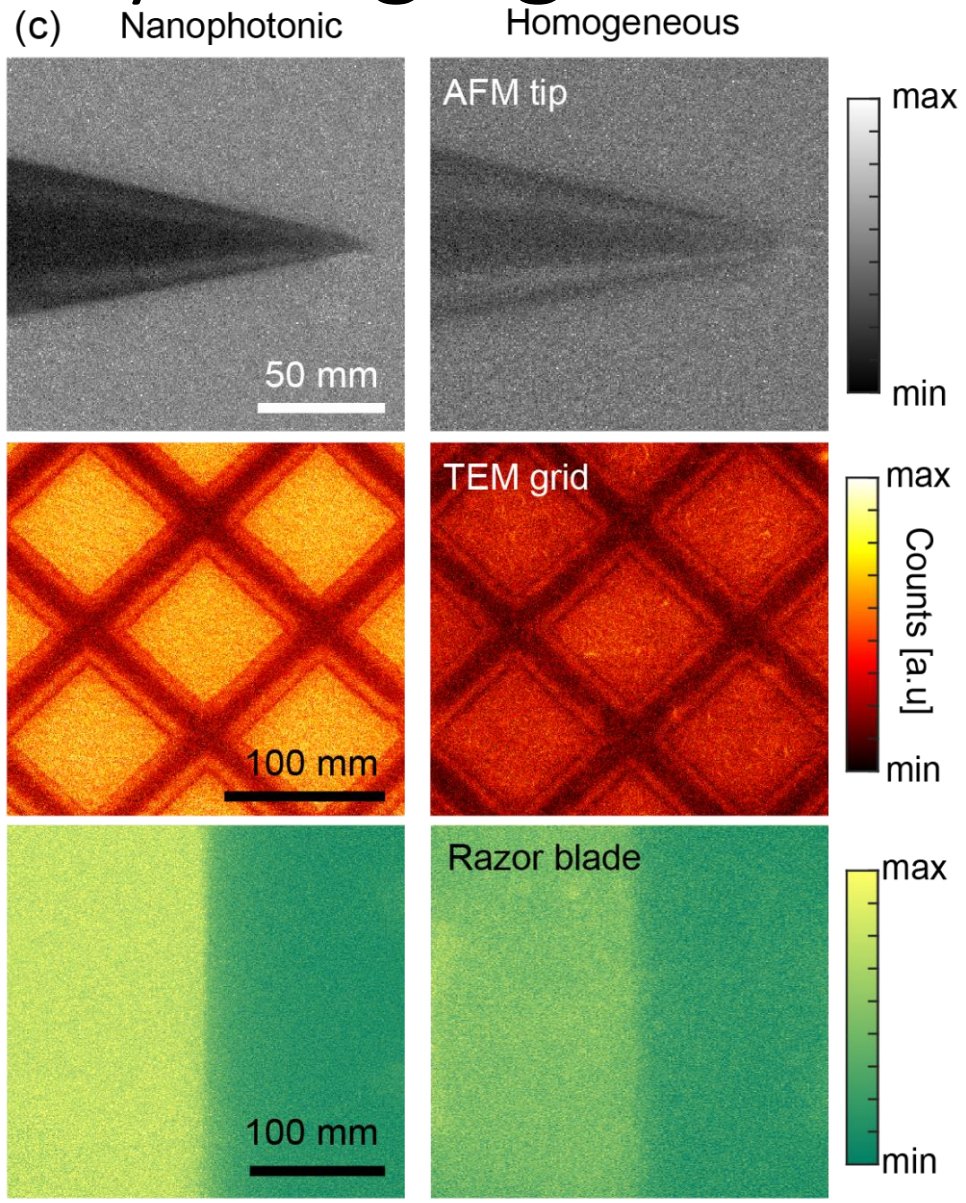
LYSO (literature):	22000 ph/MeV
Lu2O3 bulk (literature):	19750 ph/MeV
Our thin film:	14550 ph/MeV
With our PhC structure:	26000 ph/MeV

Kurman*, Lahav*, Schuetz*, et al. *Purcell enhancement of X-ray scintillation*, **in preparation** (2022)

Enhanced X-ray imaging

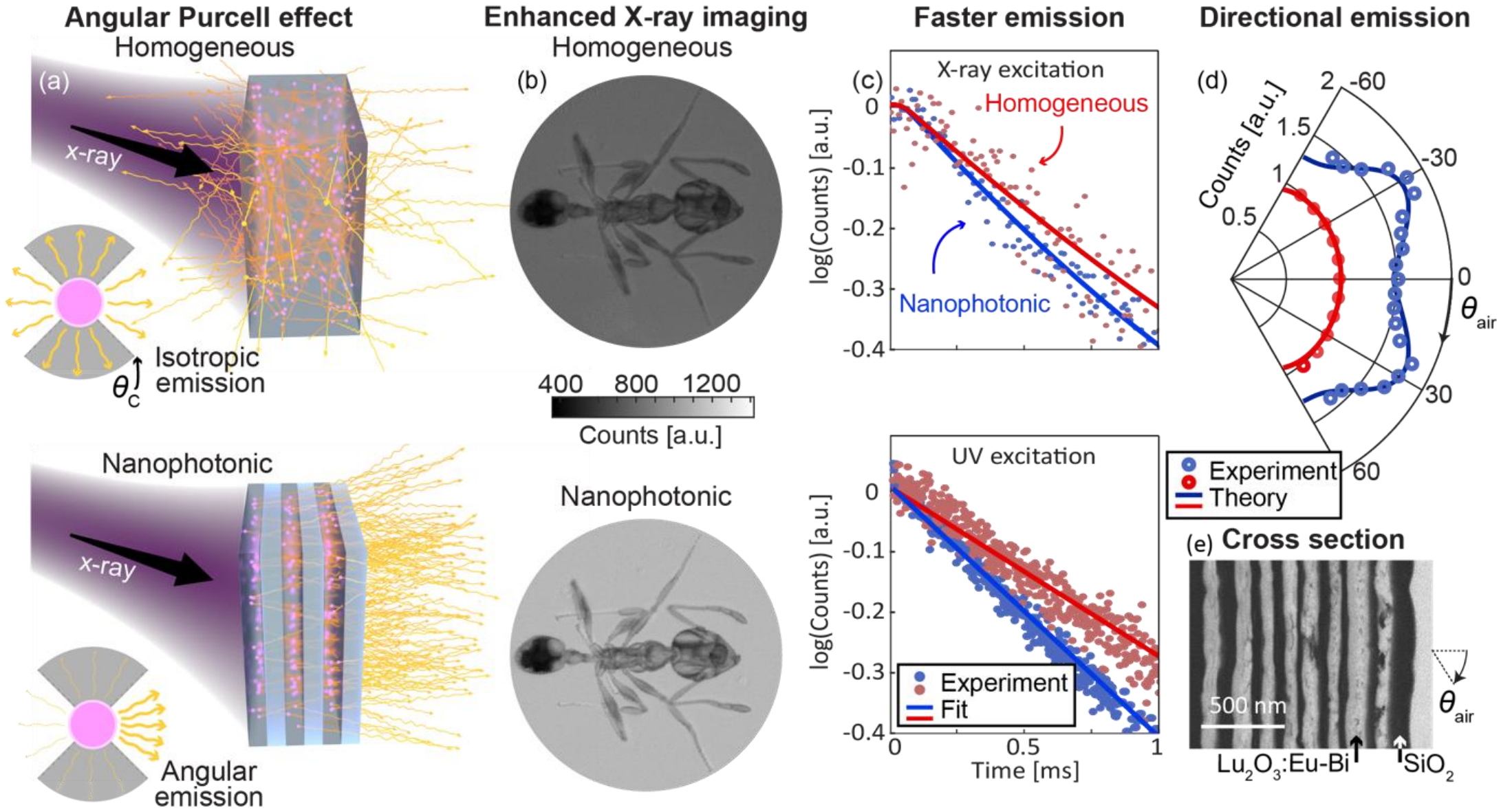






Kurman*, Lahav*, Schuetz*, et al. *Purcell enhancement of X-ray scintillation*, **in preparation** (2022)

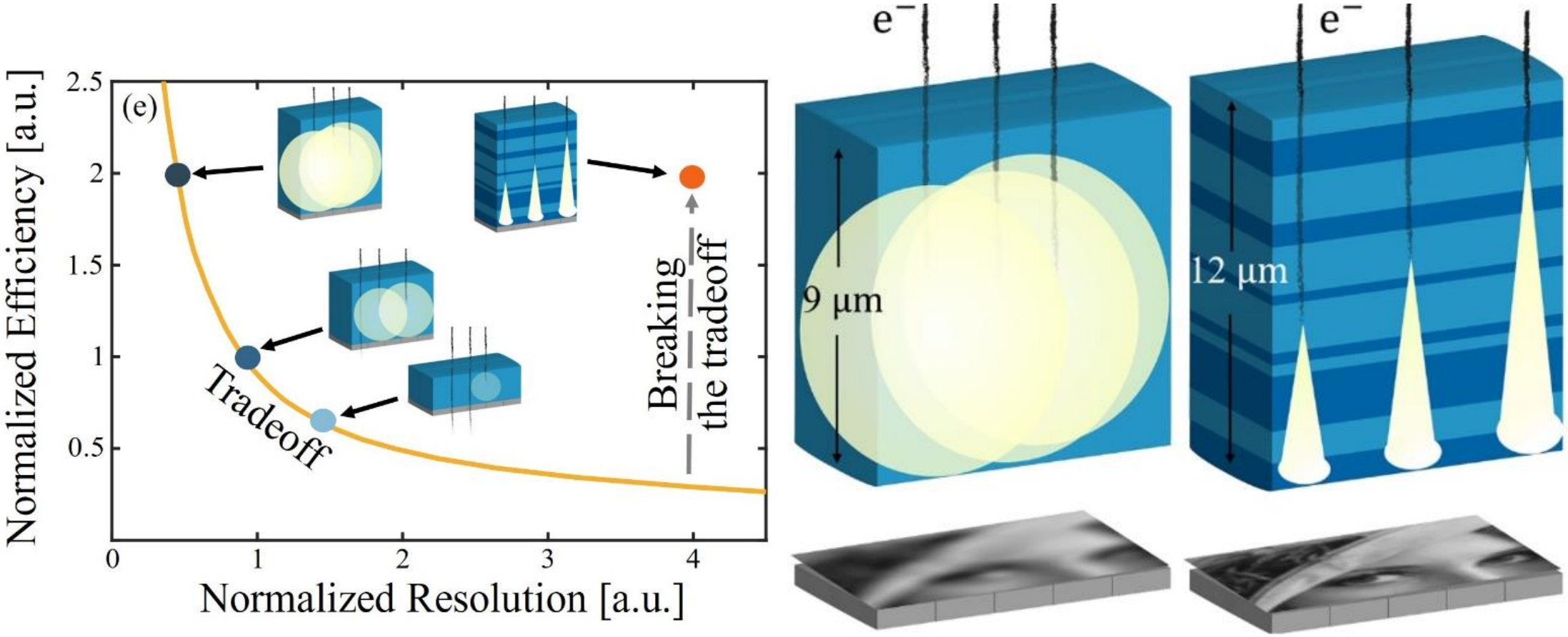
Purcell nanophotonic scintillators



Kurman*, Lahav*, Schuetz*, et al. *Purcell enhancement of X-ray scintillation*, **in preparation** (2022)

High resolution X-ray detectors: breaking their intrinsic trade-off

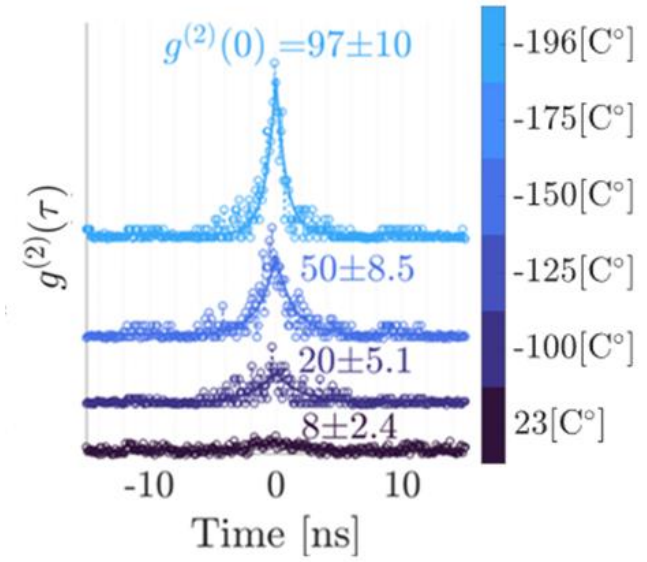
regular scintillator vs photonic-crystal scintillator



Shultzman*, Segal*, et al., *Purcell-Enhancement of X-ray Imaging and Phosphor-Screens*, **under review** (2022)

Apply nanophotonics to scintillator science?

- Control light-outcoupling
  - *Nanophotonic scintillators*
- Enhance light-emission
  - Purcell scintillators
- **Inspiration from quantum optics?**



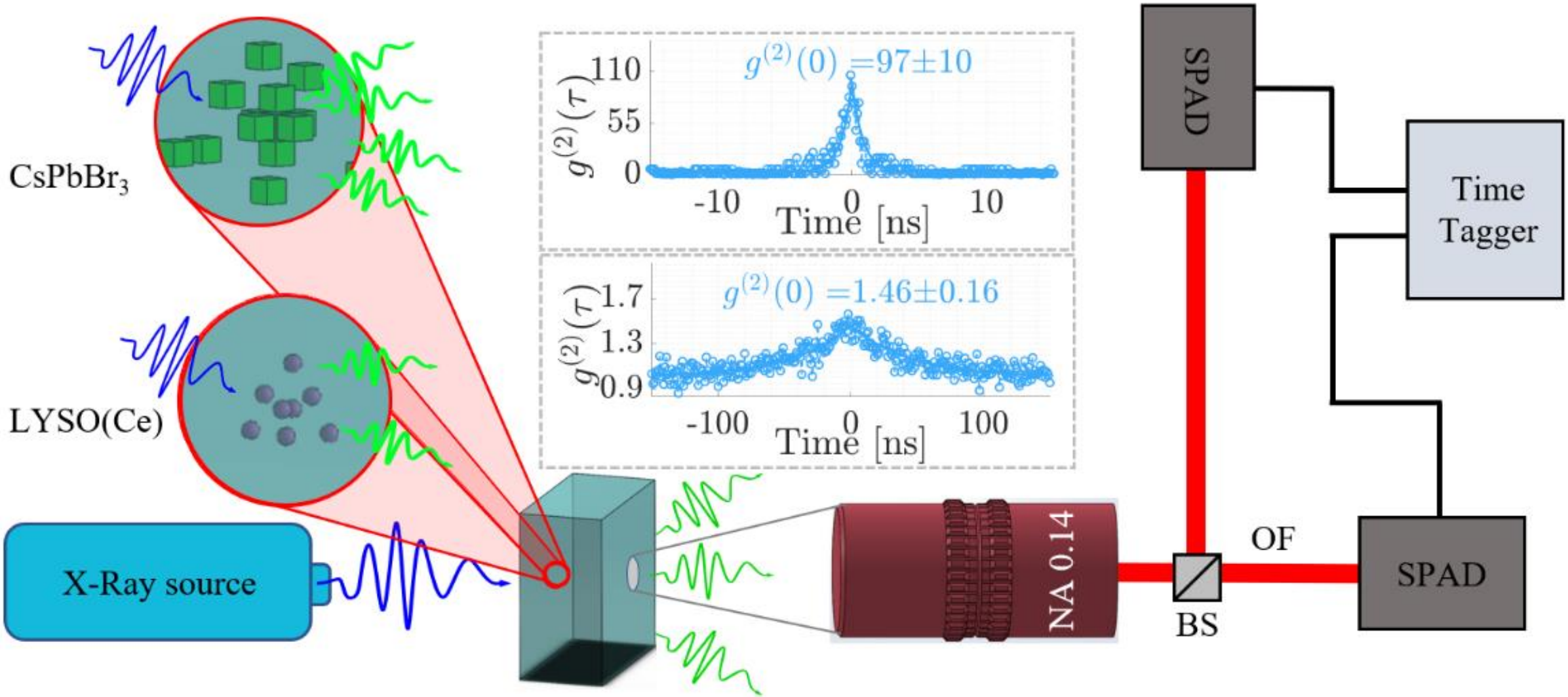
Inspiration from quantum optics

- Sensitive light detectors:
  - number-resolved single-photon detectors
- Ultrafast light detectors:
  - tens of ps time res

- But it’s not just about counting the photons!
- More information in photon correlations
  - Can we use this information to improve the bottom line? image quality?

- The duration of Cherenkov pulses (*entanglement!*)
  - Karnieli et al., **Science Advances** (2021)
- Photon bunching in scintillators

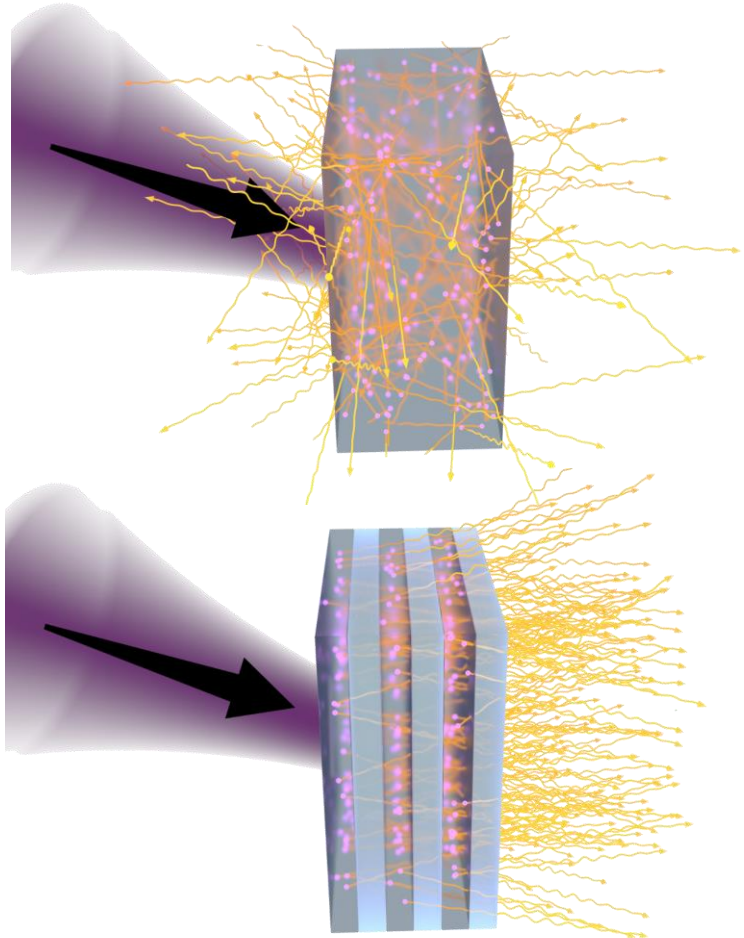
Quantum optical characterization of scintillators



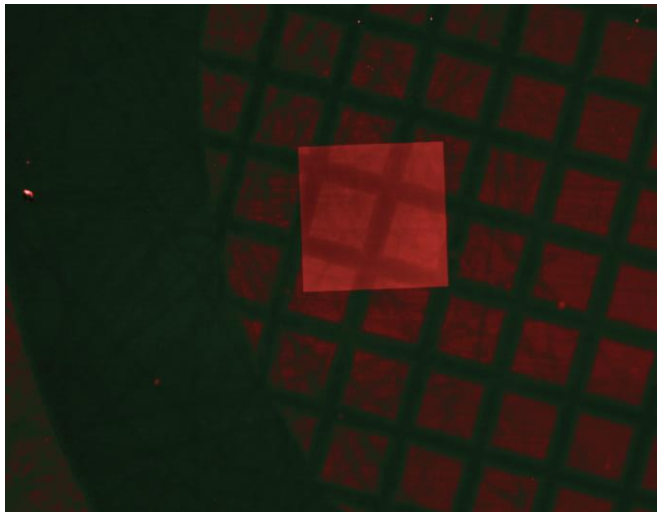
AdQuanta

available ERC-funded positions for students and postdocs

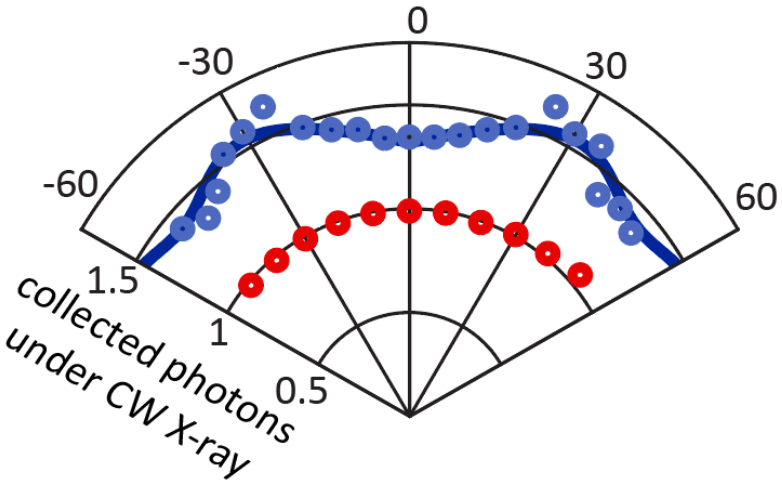
Technion
Israel Institute of Technology



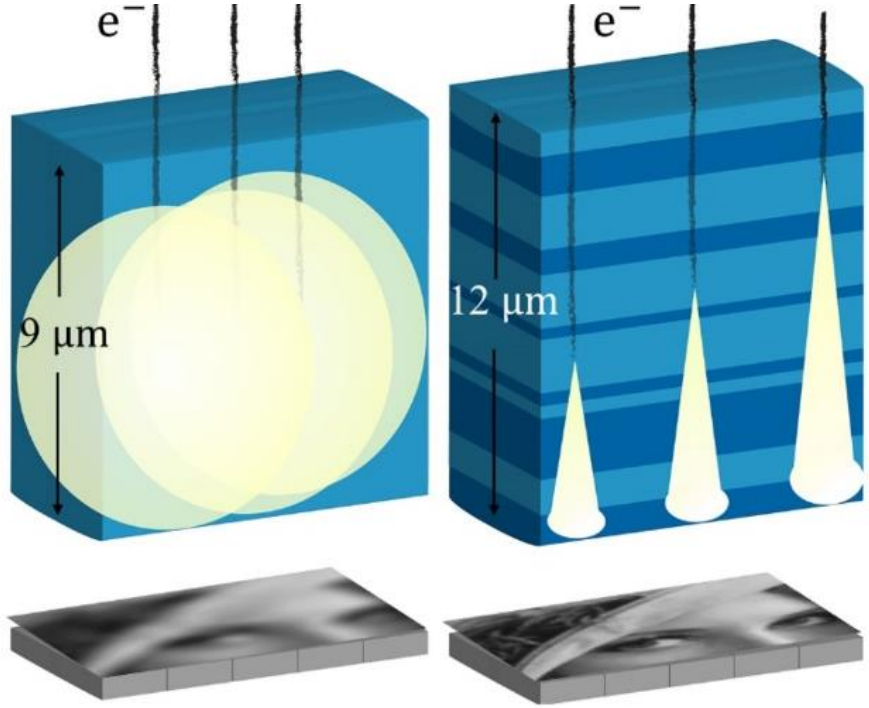
Kurman, et al. **PRL** 125, 040801 (2020)



Roques-Carmes*, Rivera*, et al., **Science** (2022)



Kurman*, Lahav*, Schuetz*, et al., **in preparation** (2022)



Shultzman*, Segal*, et al., **under review** (2022)

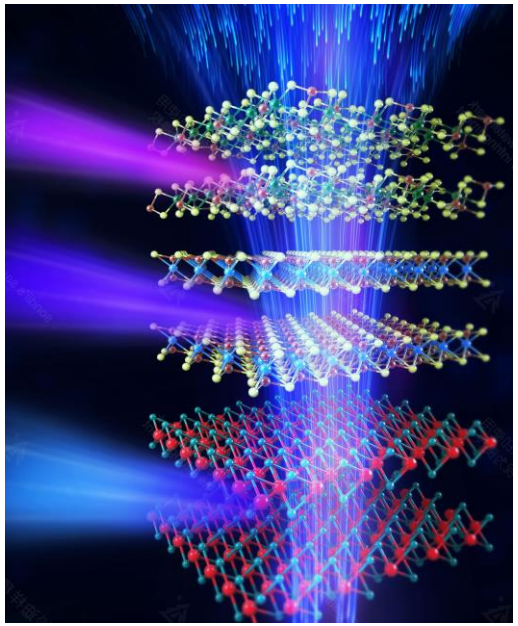
More on Cherenkov detectors, quantum optics, and other ideas:

Karnieli et al., **Science Advances** (2021)

kaminer.technion.ac.il

Why we like doing physics with free electrons

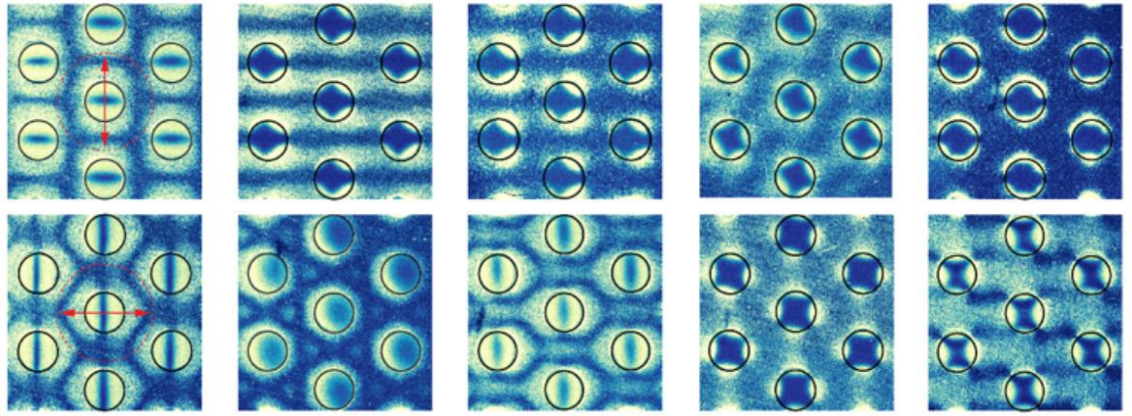
Radiation sources



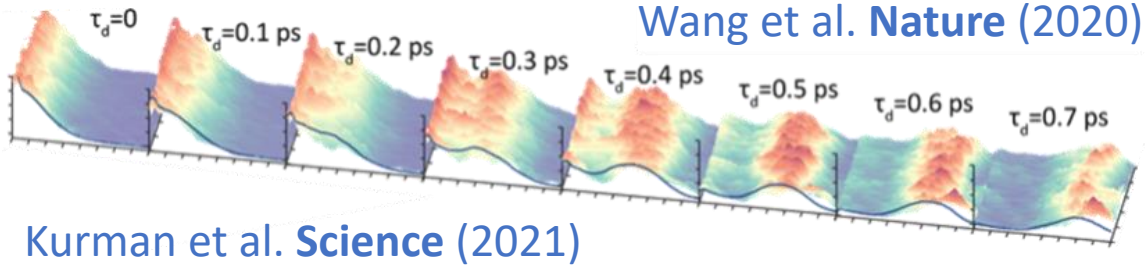
tunable X-rays

Shentcis et al. **Nature Photonics** (2020)

Nearfield optical microscopy



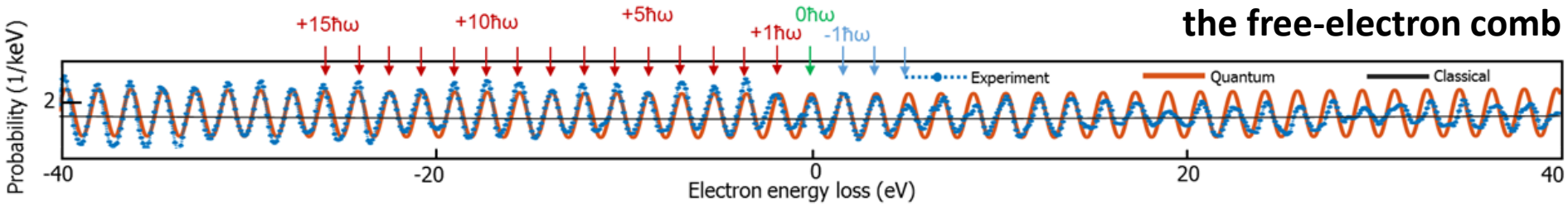
Wang et al. **Nature** (2020)



4D imaging

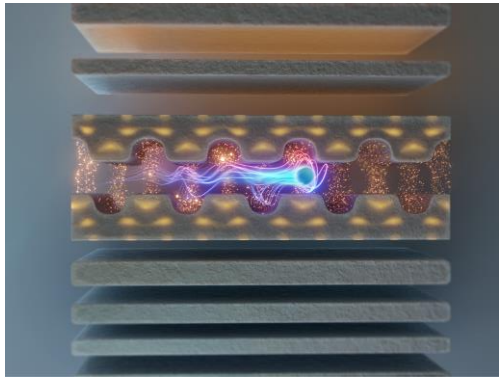
Kurman et al. **Science** (2021)

Shaping single-electron wavepackets



the free-electron comb

Dahan*, Nehemia* et al. **Nature Physics** (2020)



Dahan et al. **Science** (2021)