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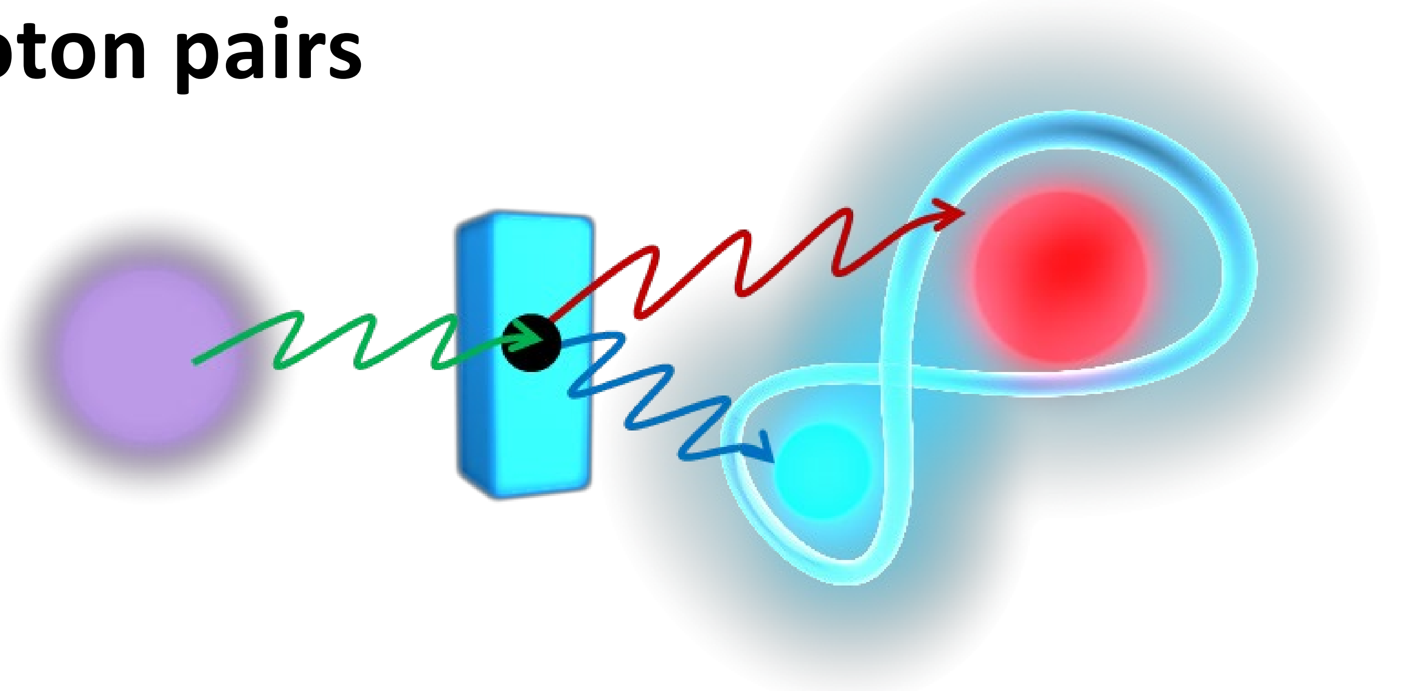
Quantum sensing with photon pairs

Frank Setzpfandt



19th Photonics Workshop, 09.03.2026

Acknowledgement

Vira Besaga

Mohit Kumar

Josue Torres

Collaborators

TECHNISCHE UNIVERSITÄT DARMSTADT

Aston University BIRMINGHAM UK

UNIVERSITY OF OULU

Fraunhofer IOF

QUANTUM OPTICS JENA

Australian National University

UNIVERSITY OF BELGRADE INSTITUTE OF PHYSICS | BELGRADE

UNIVERSITÄTS KLINIKUM jena

Funding

European Commission

BioQantSense

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Federal Ministry of Research, Technology and Space

Spontaneous parametric down conversion (SPDC)

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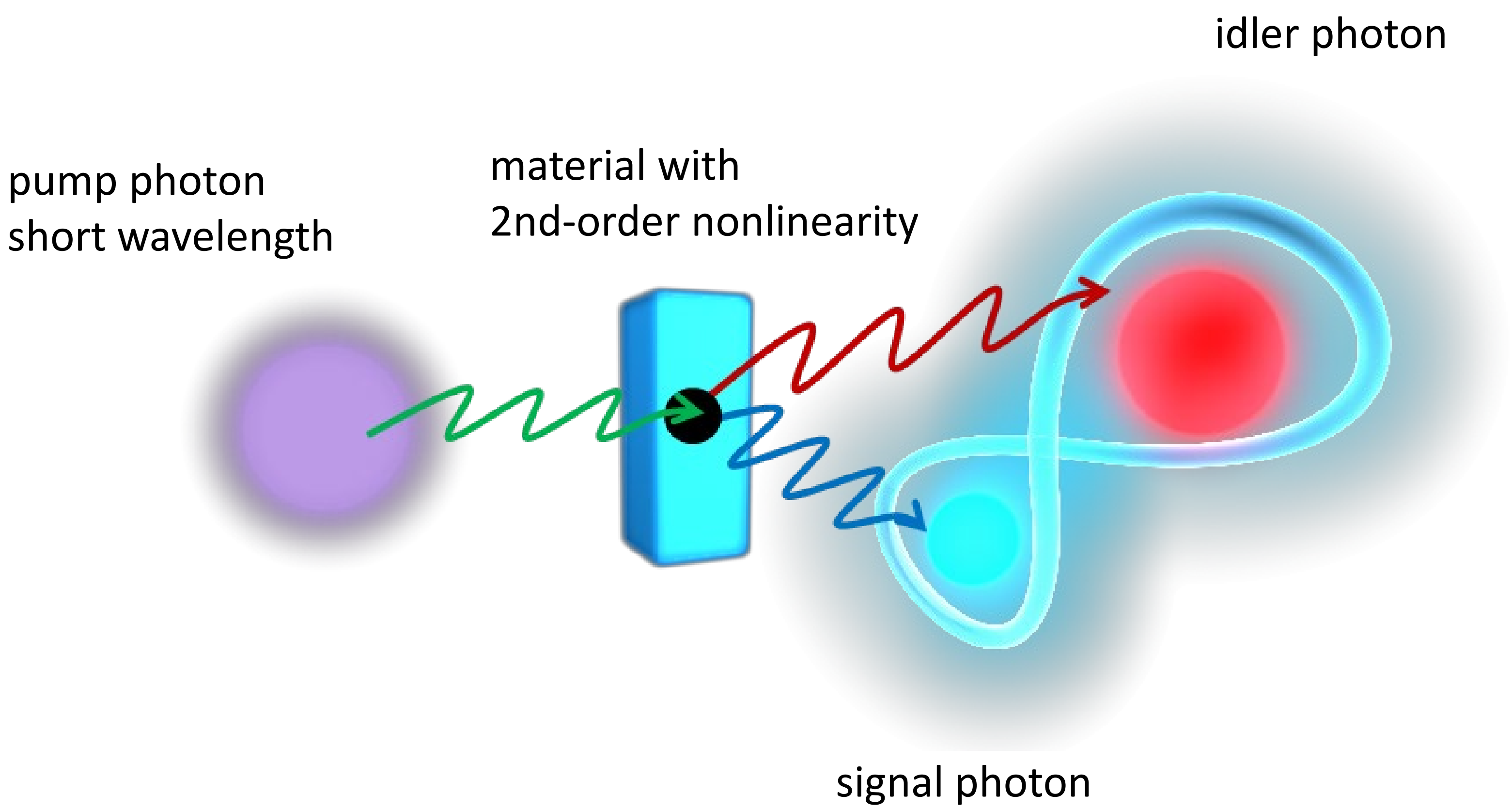
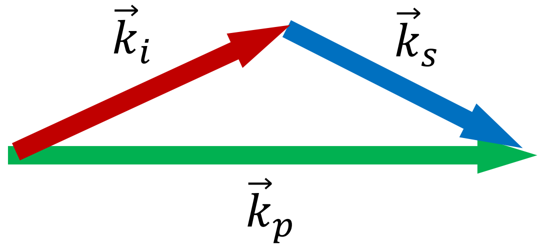
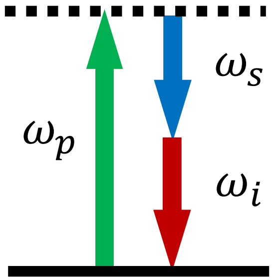


phase matching

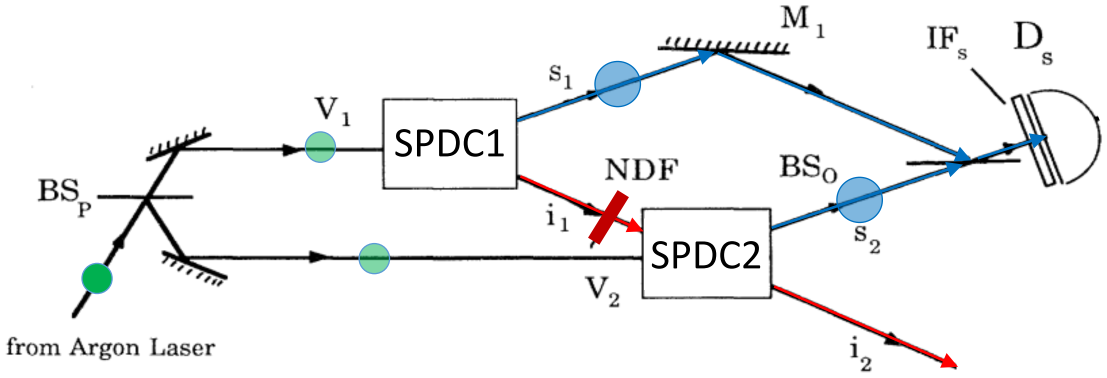


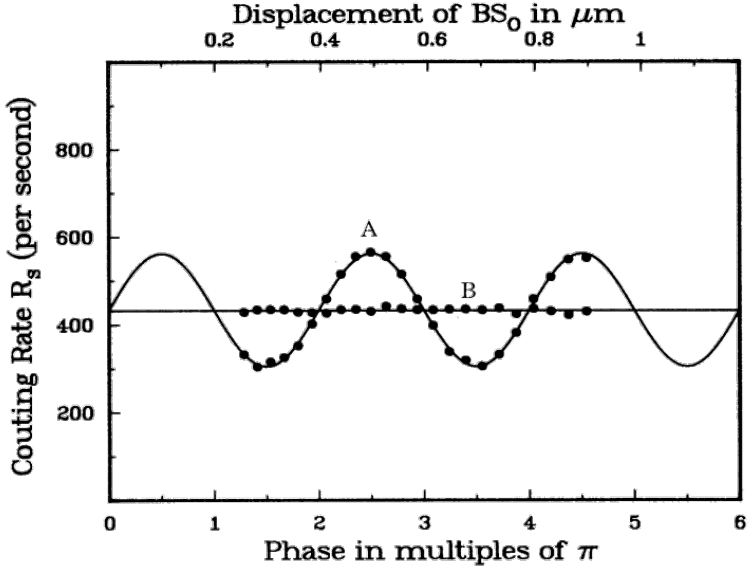
energy conservation



signal / idler can have different wavelength

Measurements with undetected photons

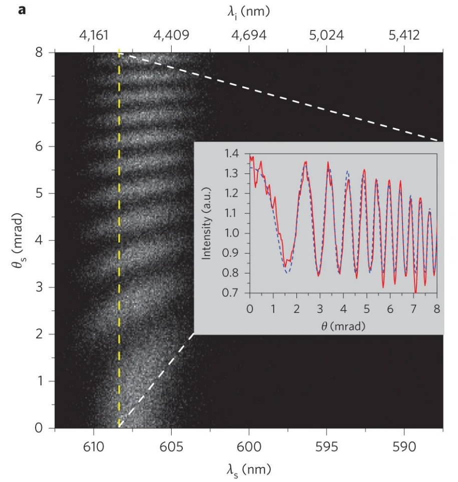




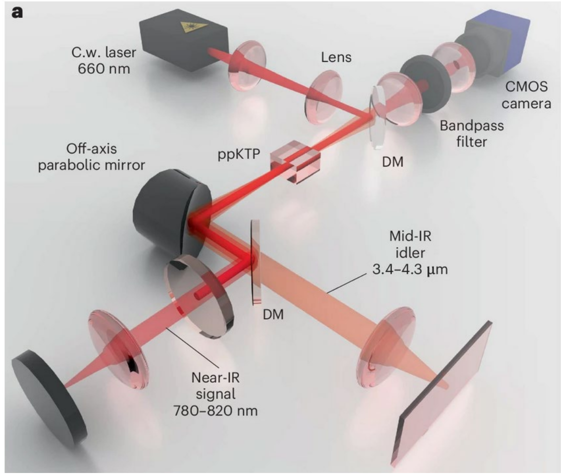
detection at signal wavelength

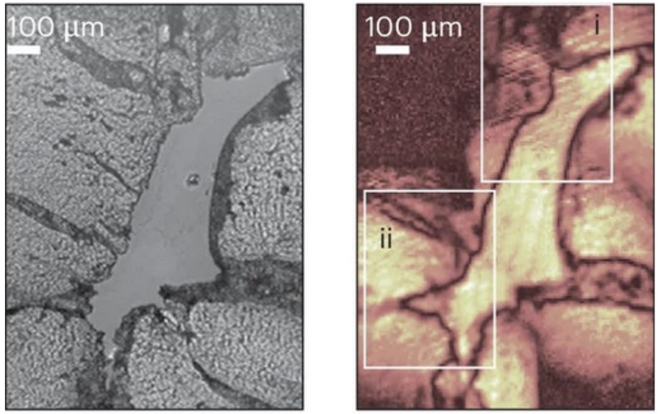
no detector at measurement wavelength needed

Wang, et al. *Physical Review A* **44,** 4614 (1991)
Zou, et al. *Physical review letters* **67,** 318 (1991)



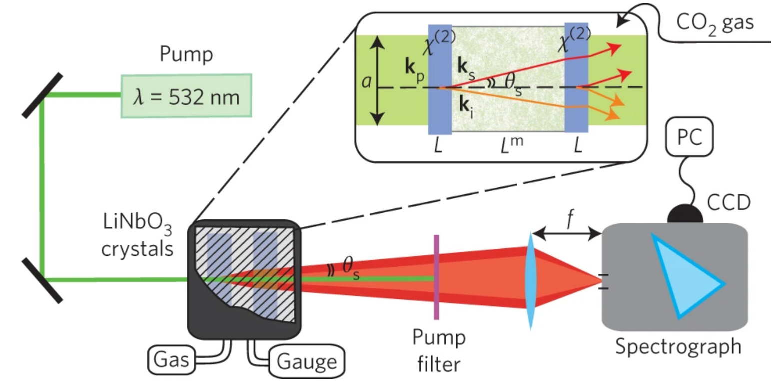
application in imaging



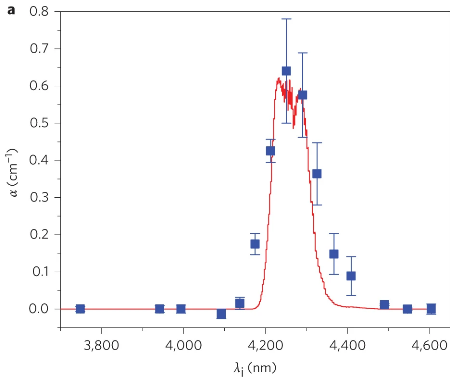


Kviatkovsky, I. et al., Opt. Express 30, 5916 (2022).

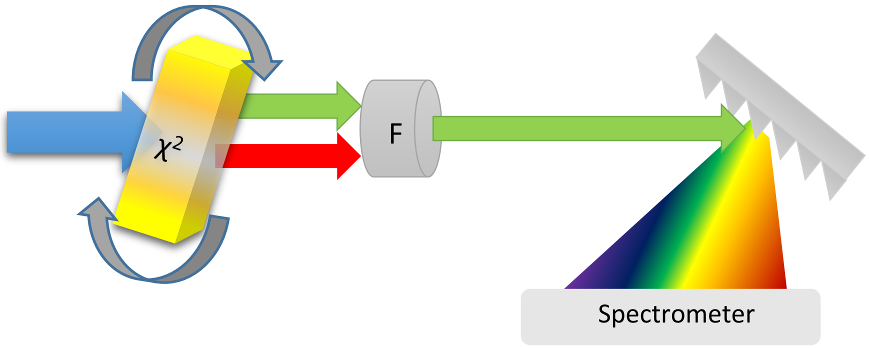
application in spectroscopy



Kalashnikov et al., Nature Photonics 10, 98 (2016)

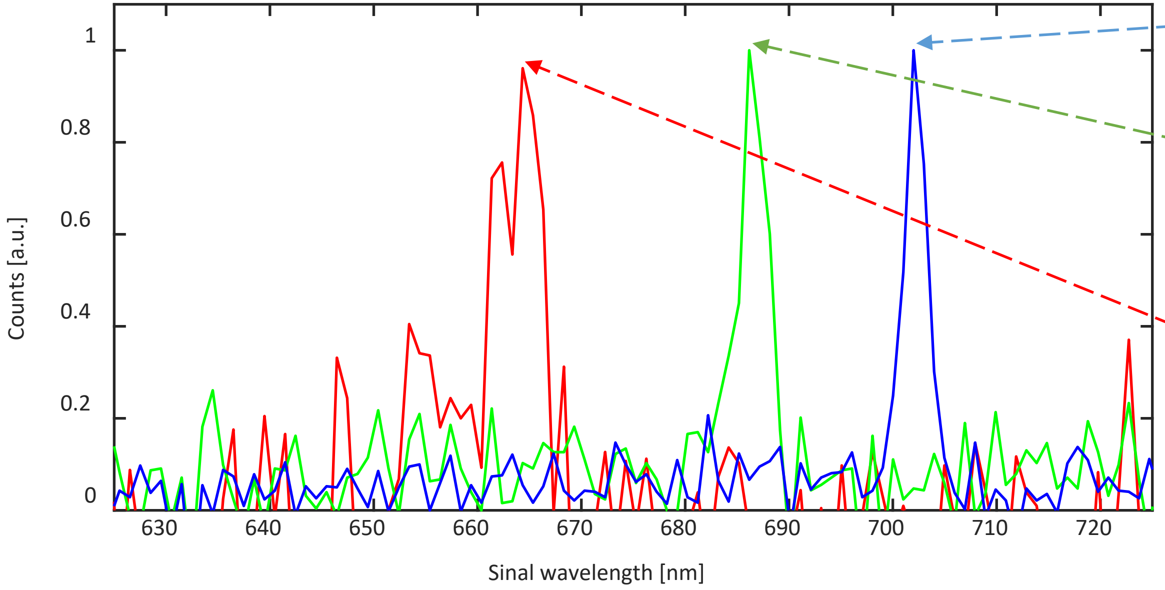


Photon-pair source using $AgGaS_2$ (AGS)

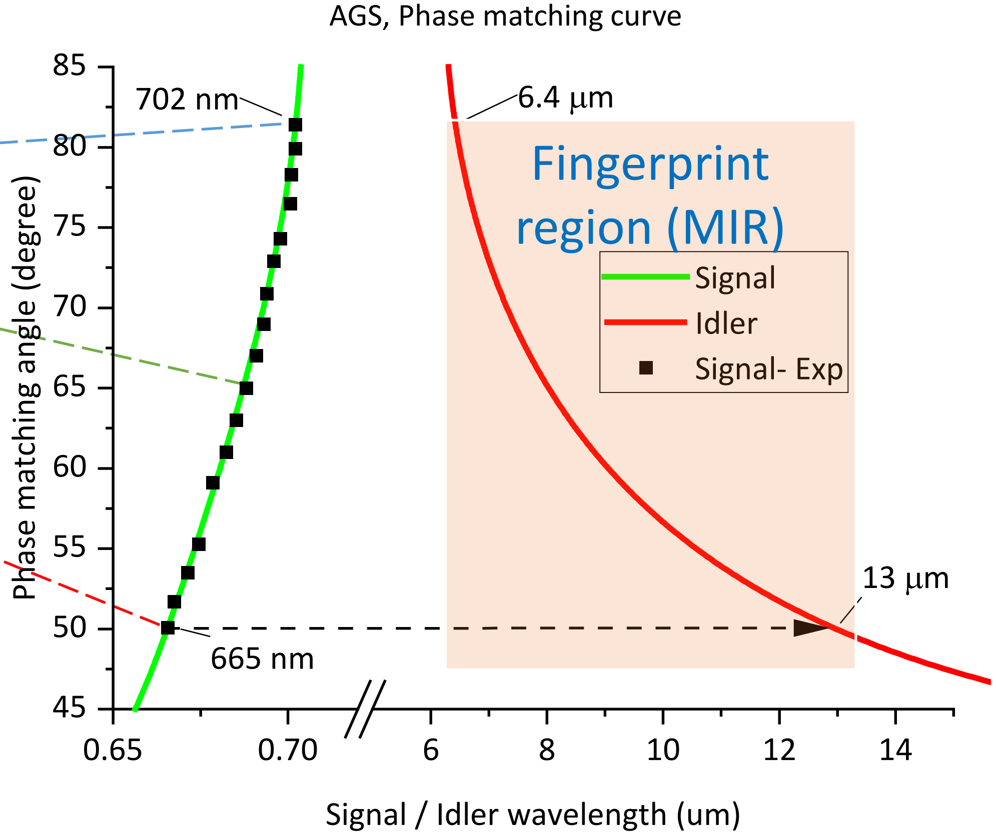


Crystal rotation -> Changes the phase matching angle (conditions)

Resulting in a **change** in the Signal / idler wavelengths

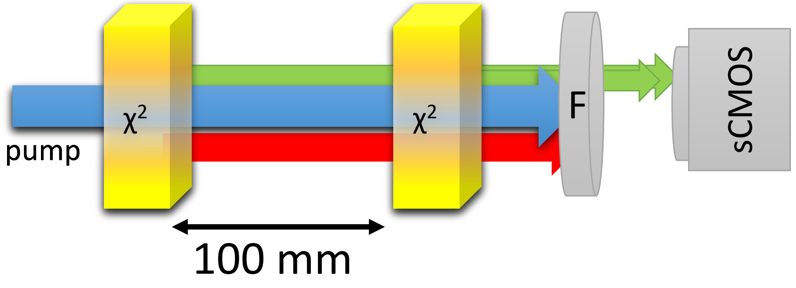


Experimentally observed spectra of the signal photons as a function of Phase matching angle



MIR photon pair source with broad tunable spectral range from **6** to **13** μm while keeping the signal in the visible spectral range.

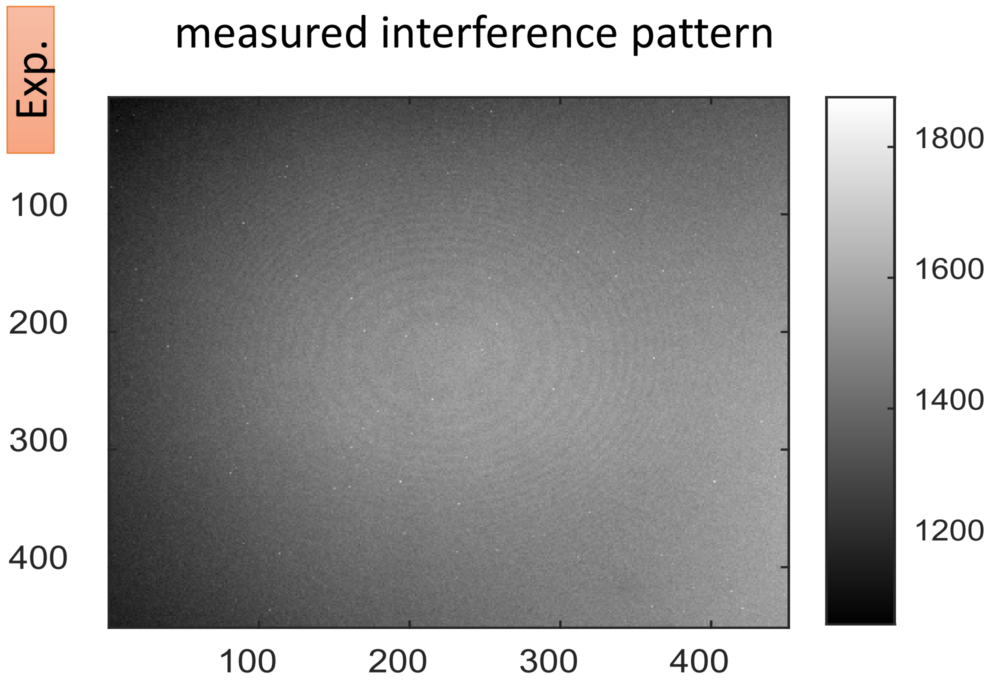
Interference of AGS sources for spectroscopy



interference can be measured also with just camera

A. Paterova et al., Scientific Reports 7, 42608 (2017)

but: contrast very low with AGS sources, not useful for measurements



Interference of AGS sources for spectroscopy

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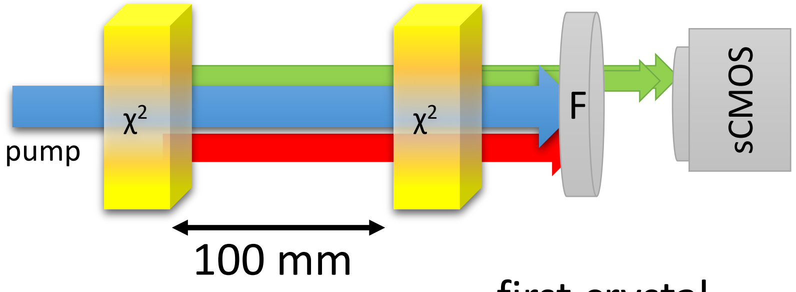
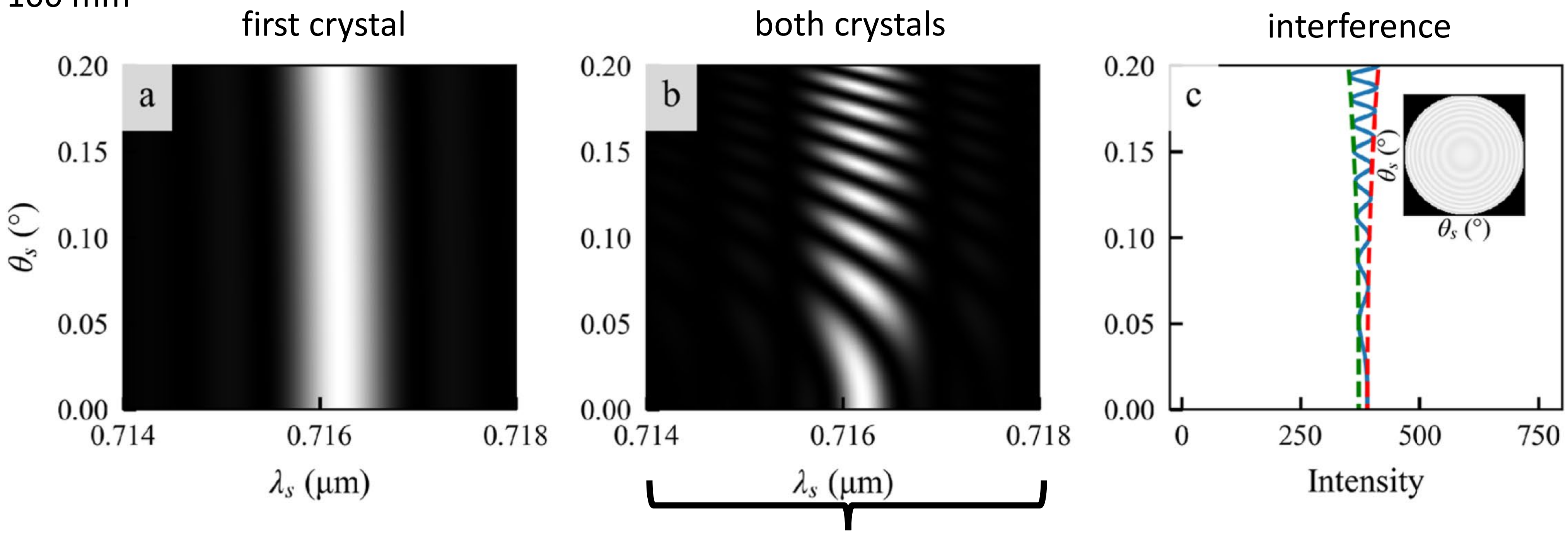


simulation of spectral / angular distribution

$$I(\theta_s) \propto \int \operatorname{sinc}^2\left(\frac{\phi_{nl}}{2}\right)\left[1 + |\tau_i| \cdot \cos\left(\phi_t(\omega_s, \theta_s)\right)\right] d\omega_s$$

Sim.

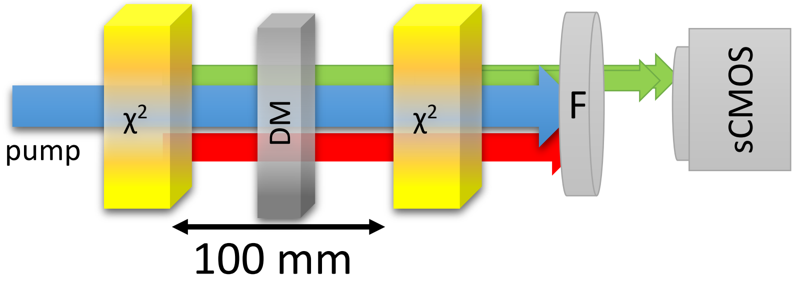


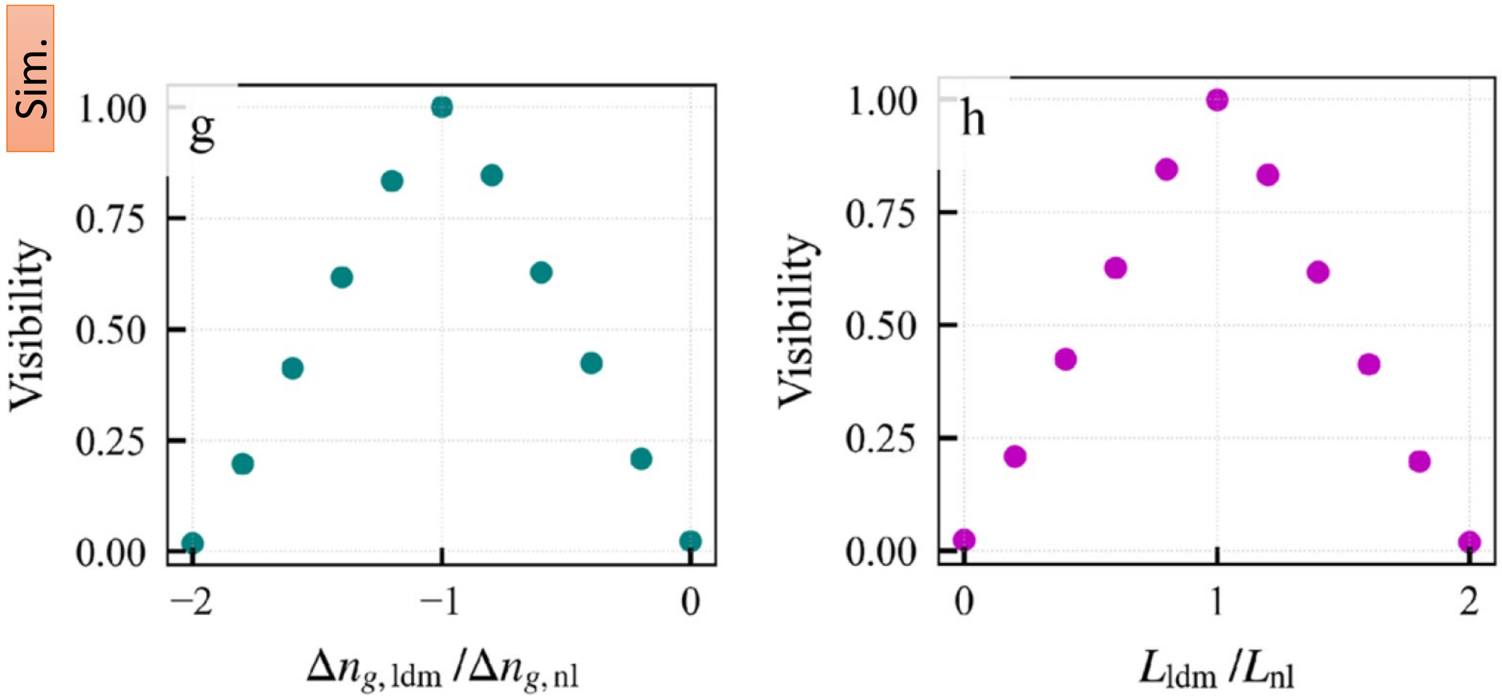
camera integrates, interference is averaged

reason is dispersion of nonlinear crystal that induces angular-spectral correlations of interference

→ can be corrected by additional dispersive medium with opposite dispersion

Dispersion compensation





visibility depends on:

difference of signal/idler group indices

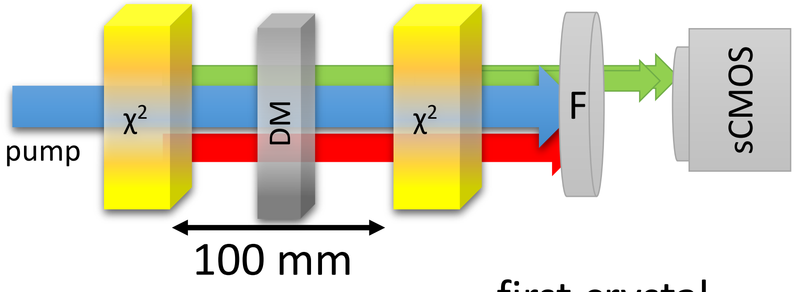
$$\Delta n_{g,x} = n_{g,i} - n_{g,s}$$

length of dispersive medium

$$L_{\mathrm{ldm}}$$

M. Kumar et al., APL Photonics 10, 106121 (2025)

Interference of AGS sources for spectroscopy



simulation of spectral / angular distribution

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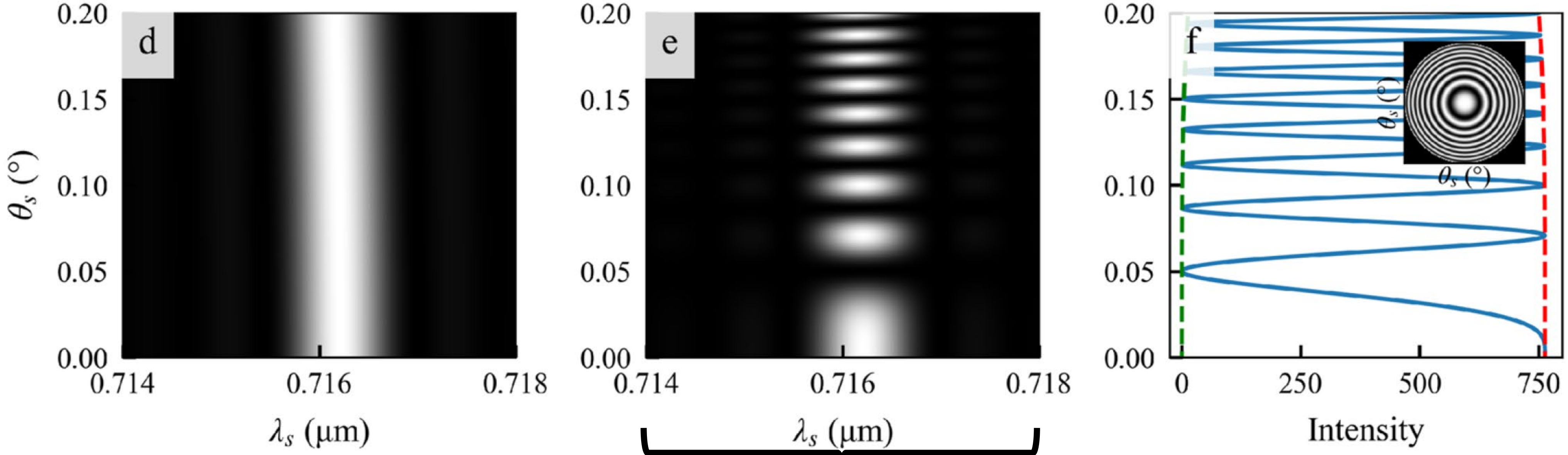
Sim.

first crystal

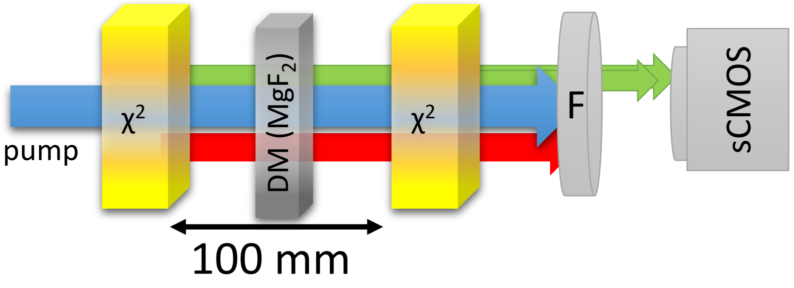
both crystals



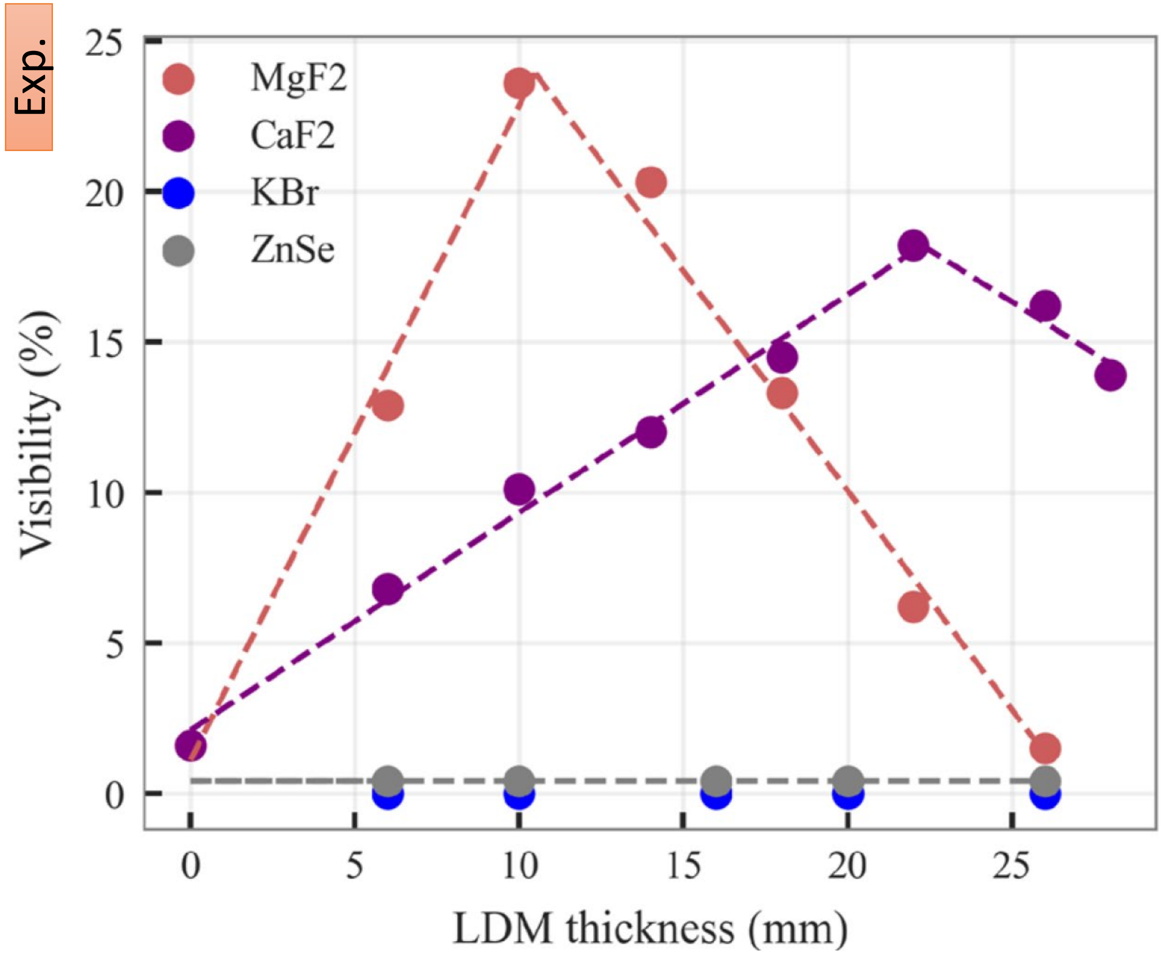
camera integrates, interference is averaged

→ visibility can be enhanced significantly

Experimental implementation



comparison of different dispersive media



much higher visibiliy is reached

below 1 due to experimental imperfections

M. Kumar et al., APL Photonics 10, 106121 (2025)

Experimental implementation

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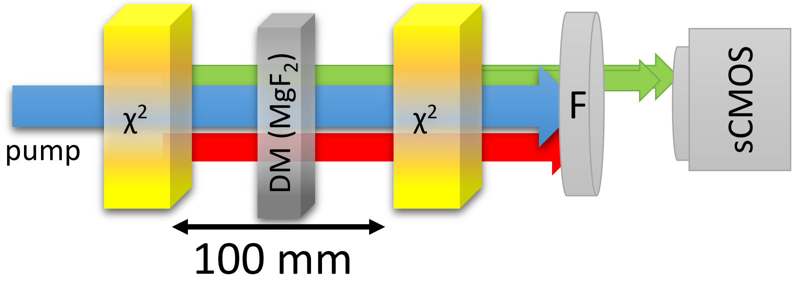
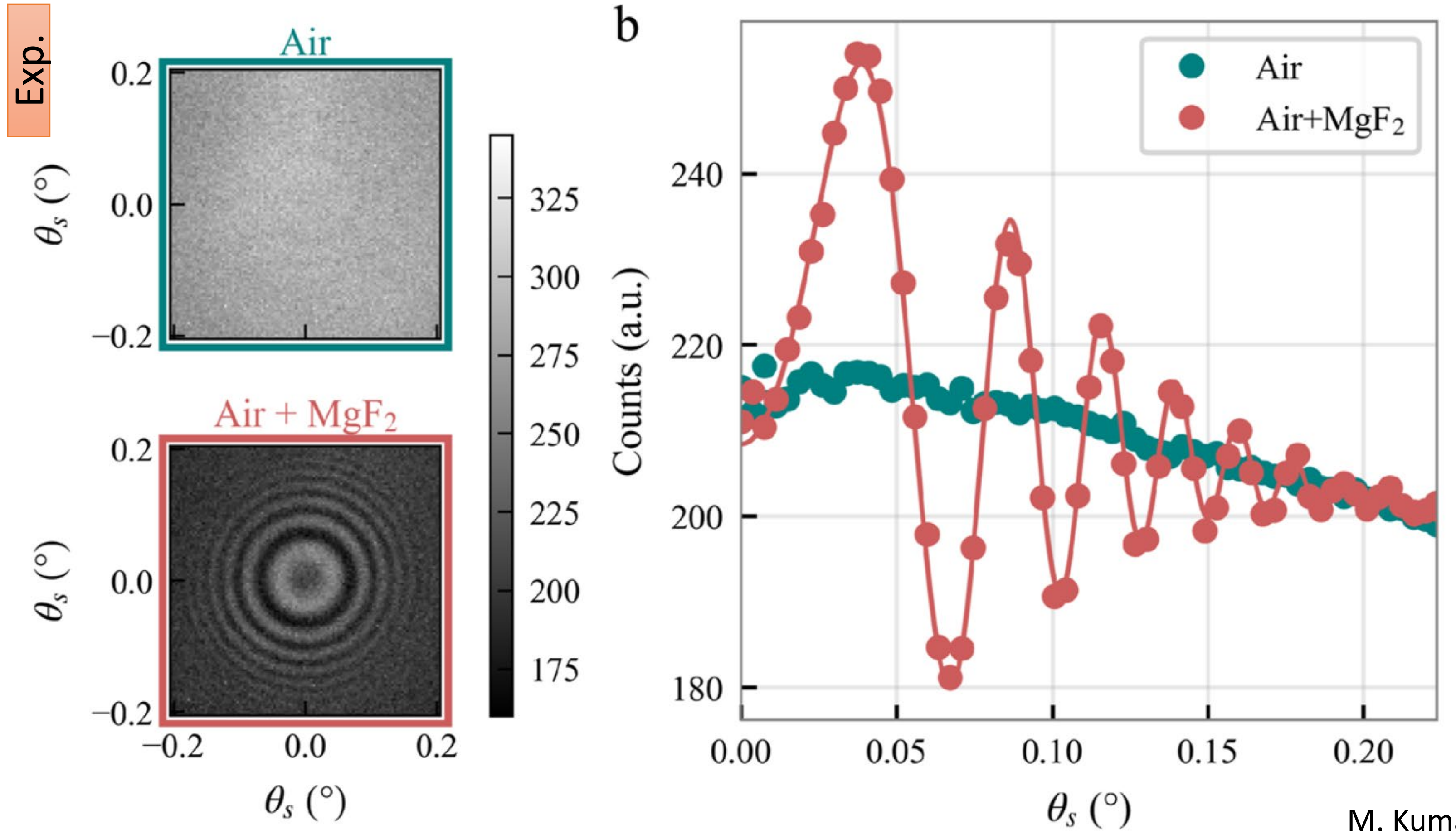
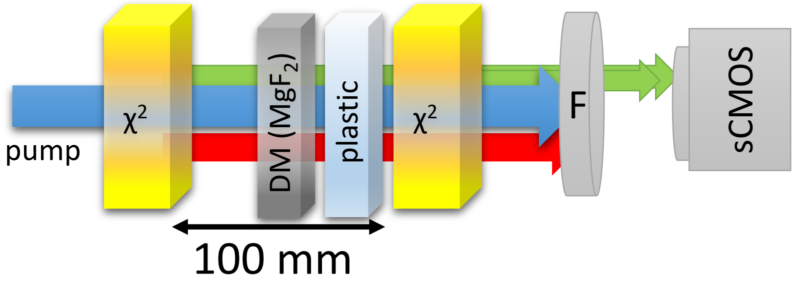


experimental implementation with MgF_2 at wavelength ~ 0.72 µm / 6.2 µm



M. Kumar et al., APL Photonics 10, 106121 (2025)

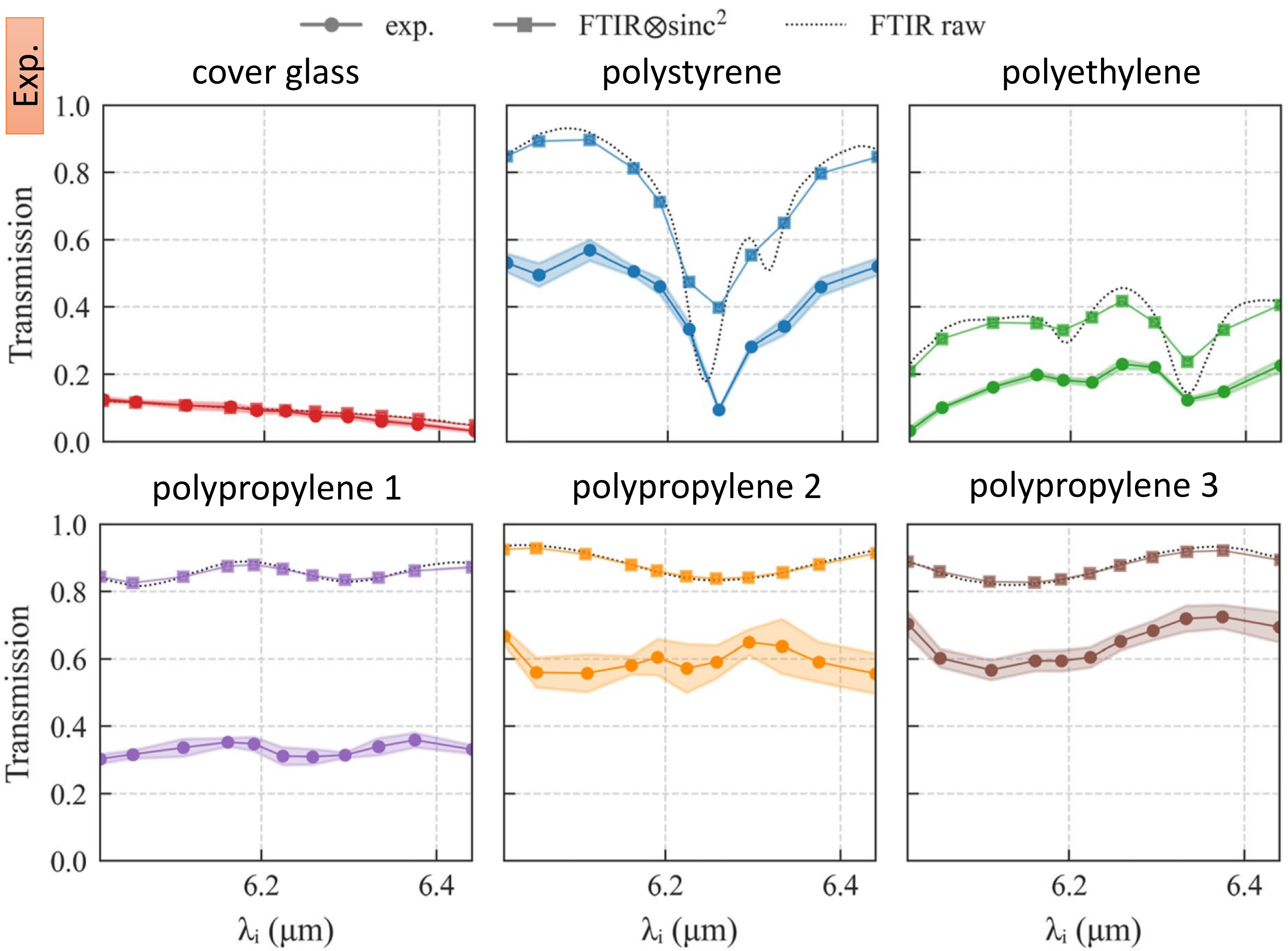
Spectroscopy at 6.2 µm



spectroscopy of different materials

significant features are captured

offset for absolute transmission with respect to FTIR measurement
→ due to surface roughness / scattering



M. Kumar et al., APL Photonics 10, 106121 (2025)

Spatial resolution in imaging with undetected photons

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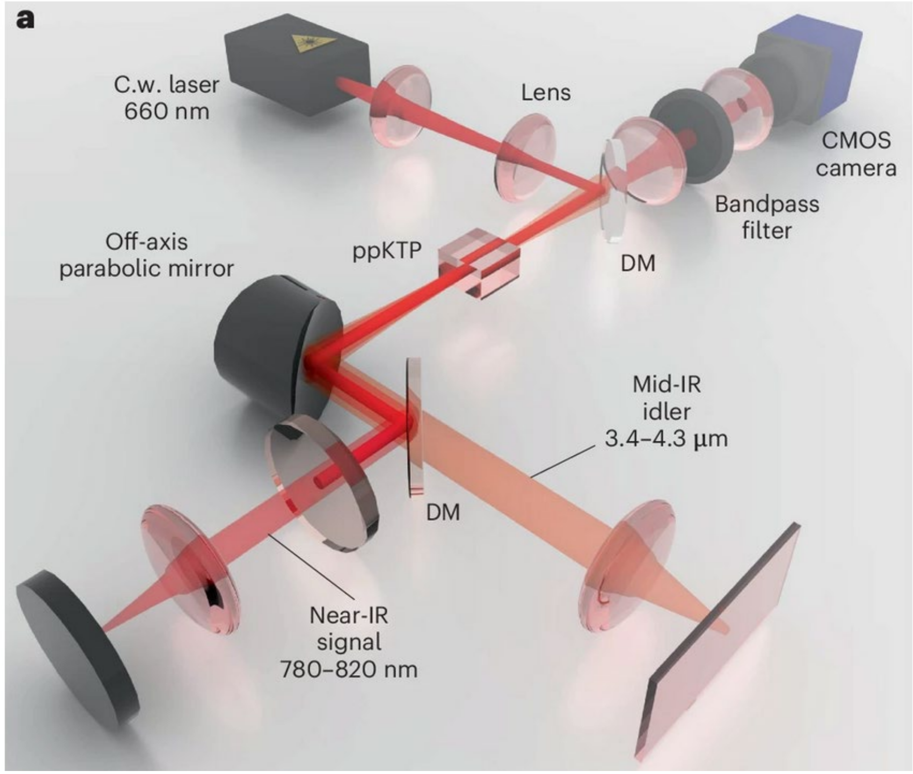
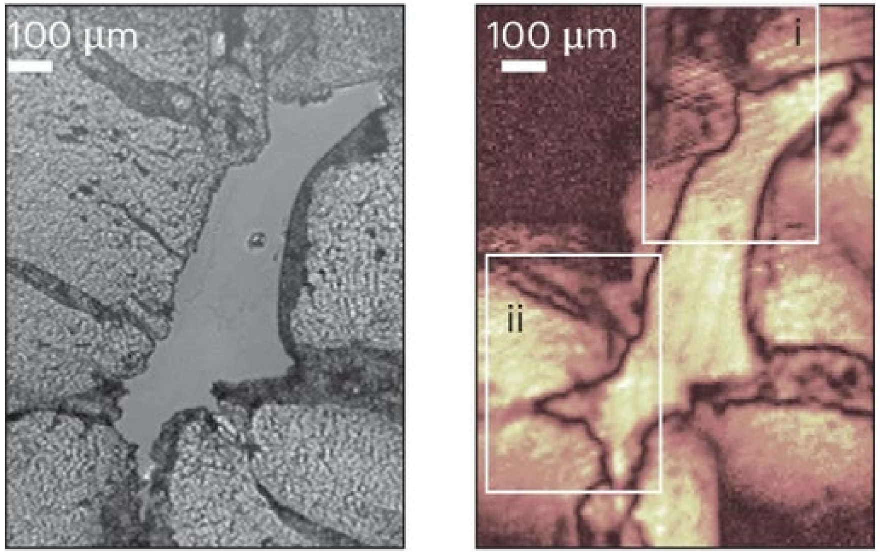




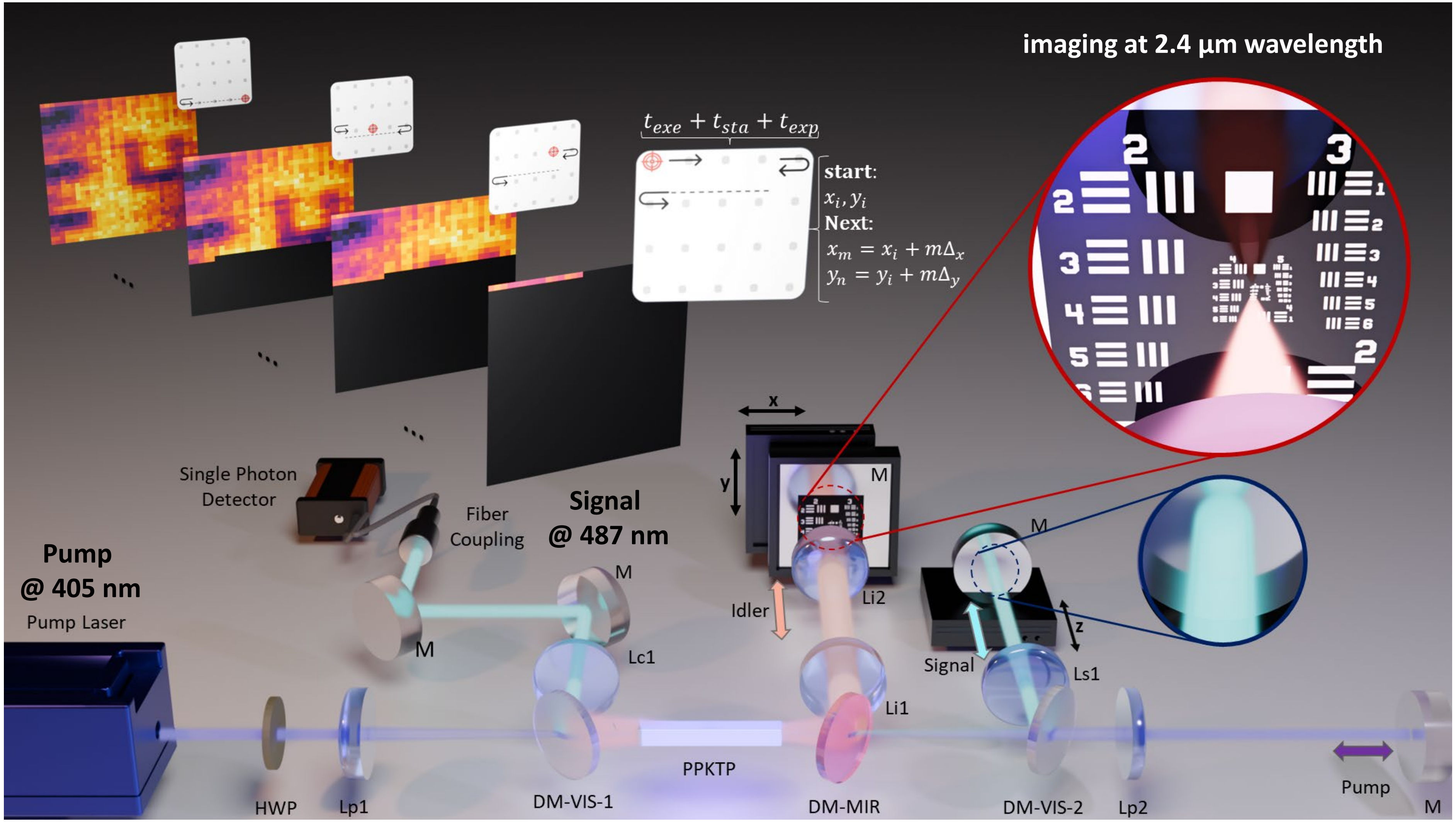
Kviatkovsky, I. et al., Opt. Express 30, 5916 (2022).

→ wide-field imaging uses spatial correlations

→ in wide-field imaging, spatial resolution is limited by source properties

→ competition between field of view and spatial resolution

Scanning imaging with undetected photons



Animation of the scanning process. At every position of the object an intensity count is registered.

J. R. Leon Torres et al., Laser & Photonics Reviews, e02356 (2025)

Achievable resolution

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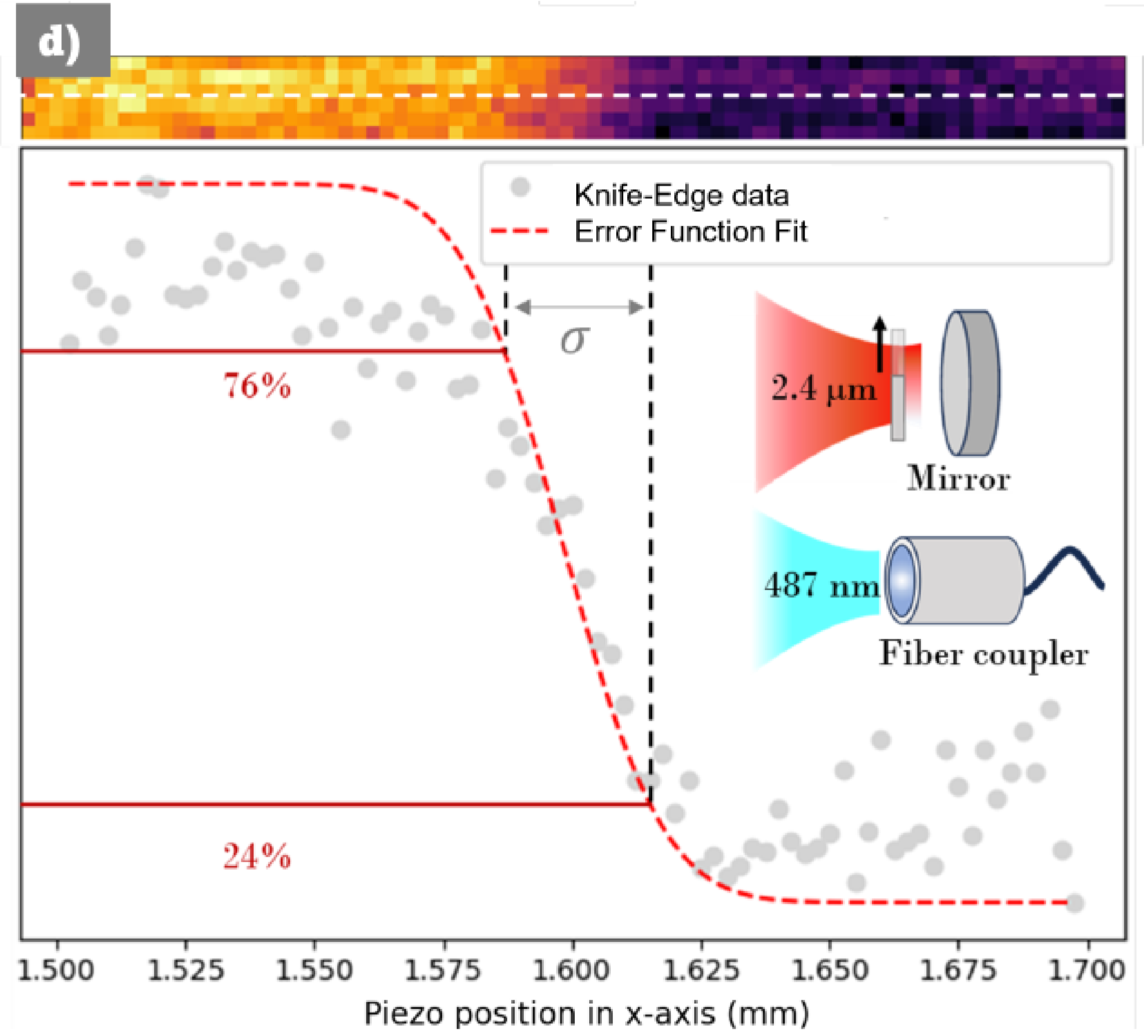

spatial resolution measured with knife-edge scan

found resolution of 16 µm @ 2.4 µm wavelength

corresponds to numerical aperture of illumination lens

→ not limited by source

J. R. Leon Torres et al., Laser & Photonics Reviews, e02356 (2025)

Achievable resolution

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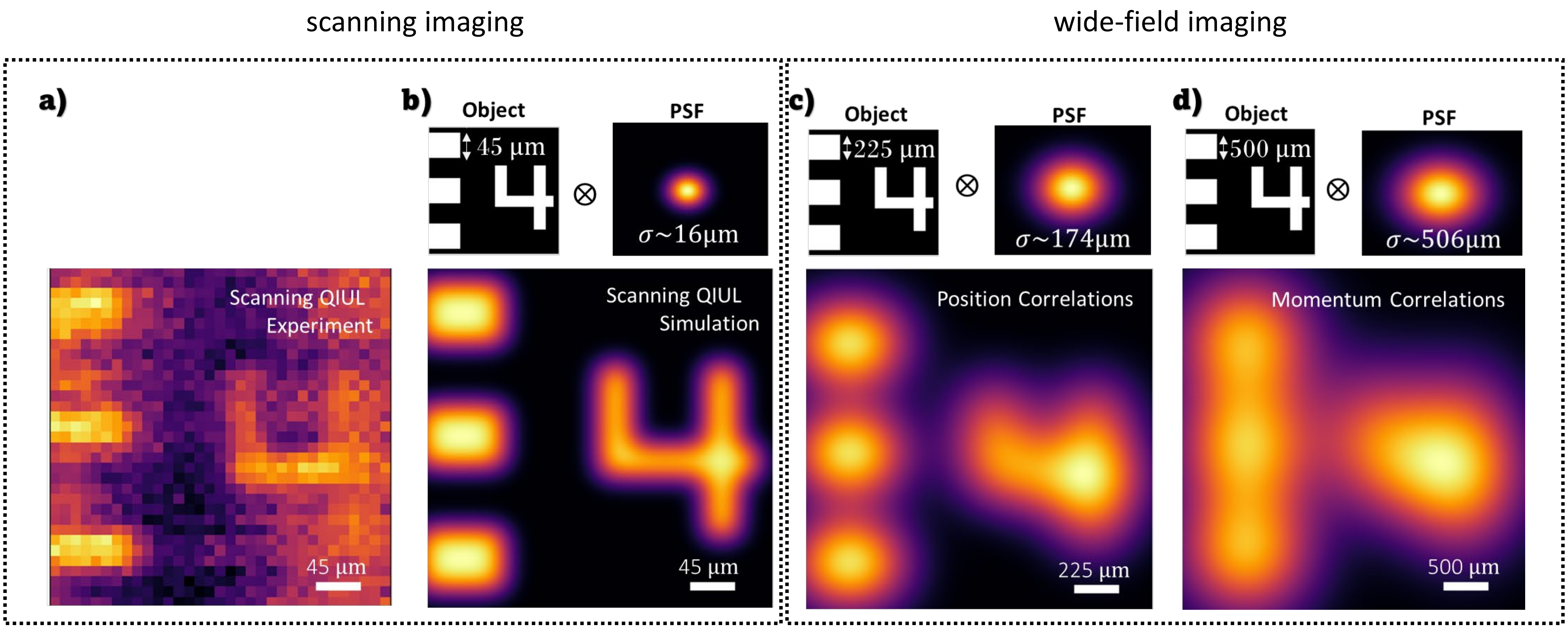

scanning imaging achieves much higher resolution than wide-field with similar configuration

J. R. Leon Torres et al., Laser & Photonics Reviews, e02356 (2025)

Scanning quantum imaging

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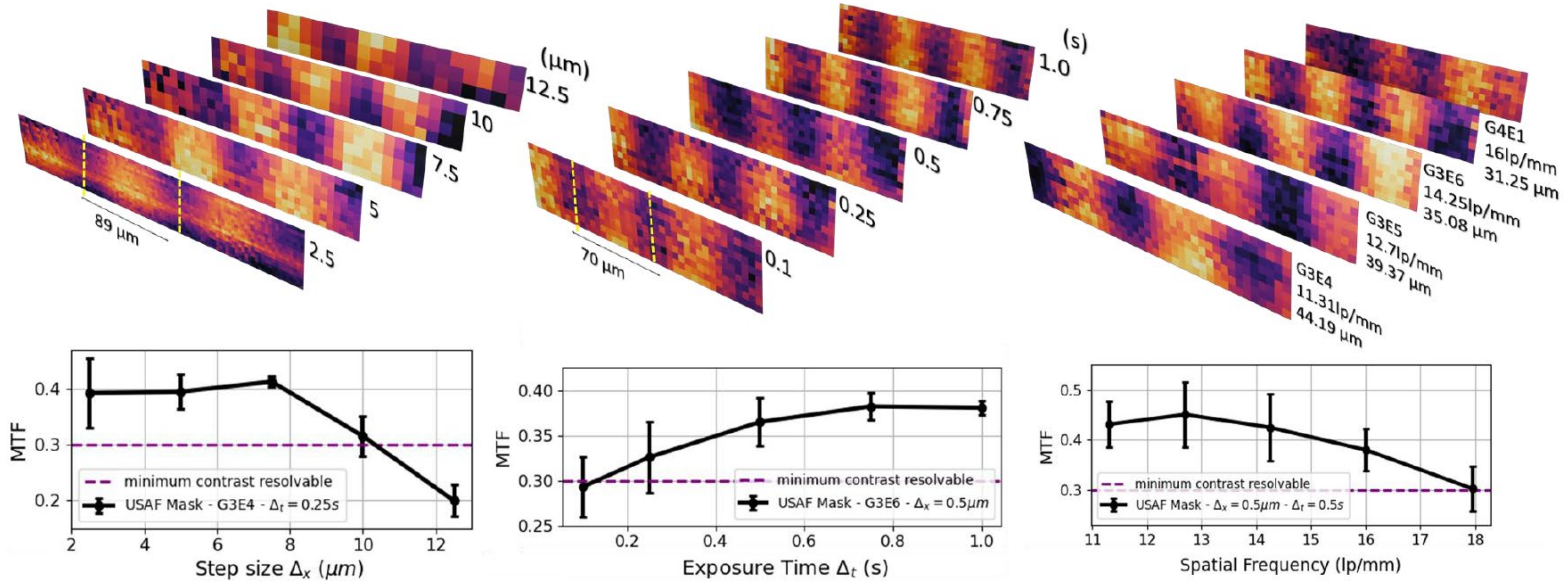
Dependence of contrast on different parameters

scan step size | exposure time | object modulation



J. R. Leon Torres et al., Laser & Photonics Reviews, e02356 (2025)

Scanning imaging at 2.4 µm

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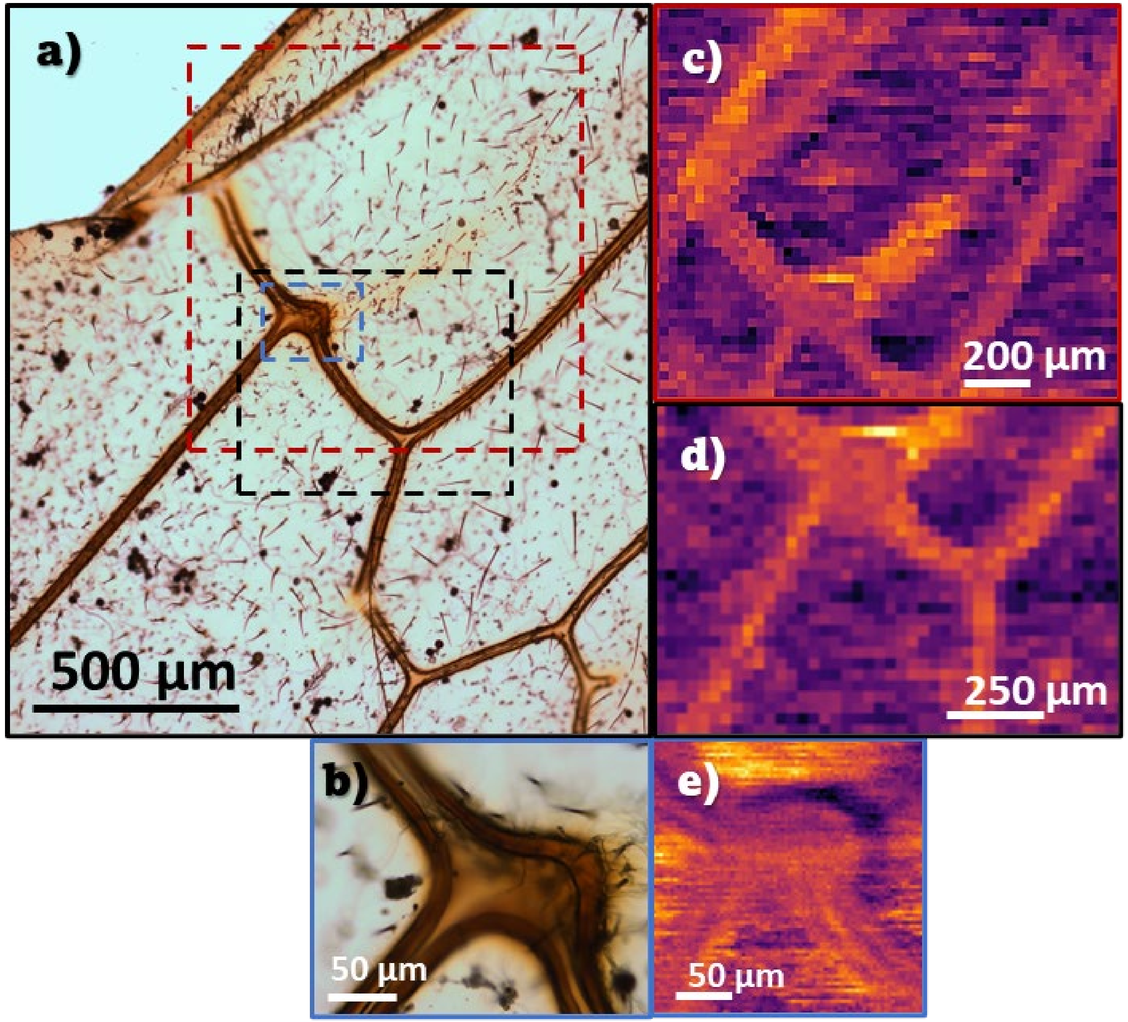
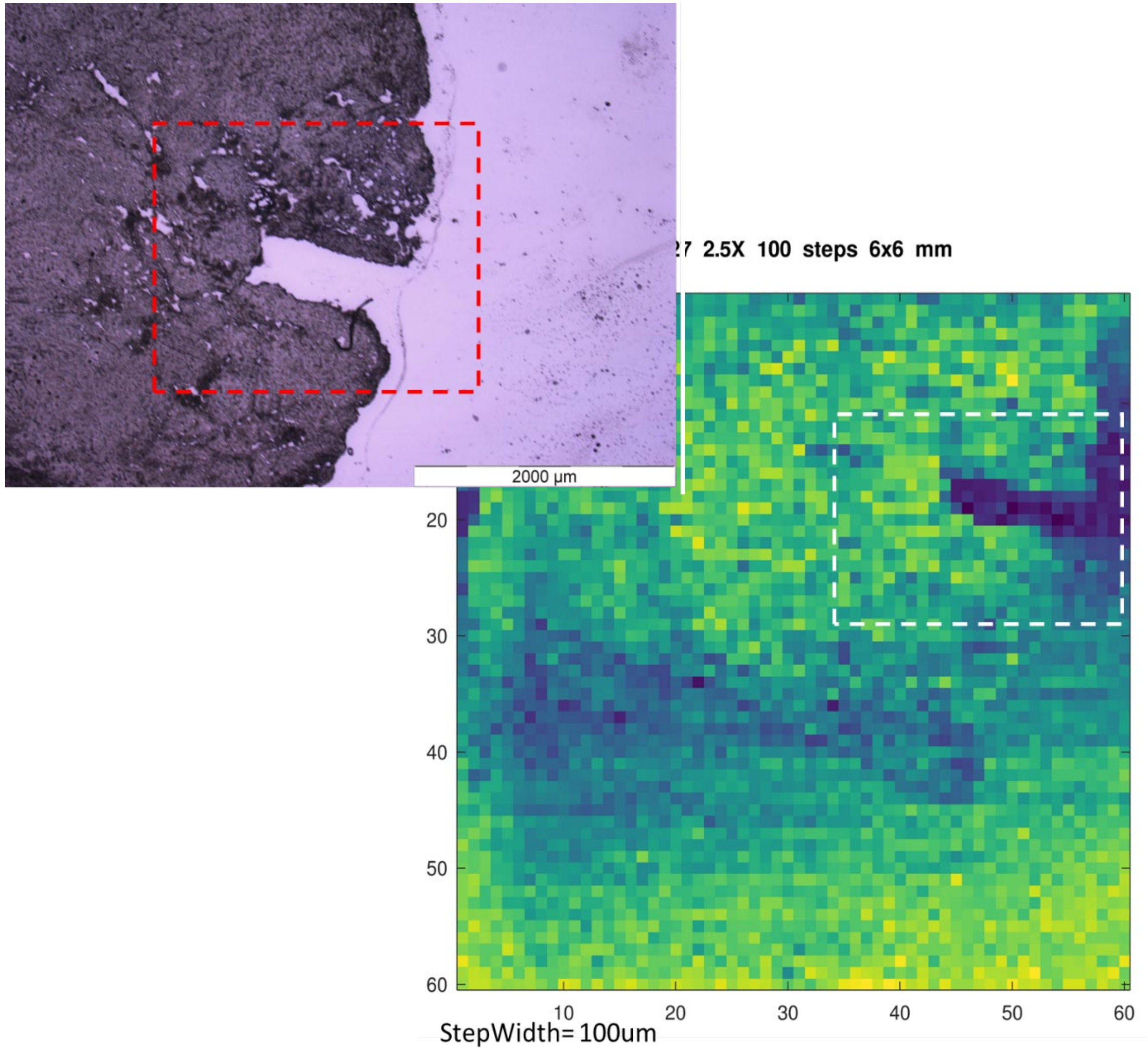
fly wing

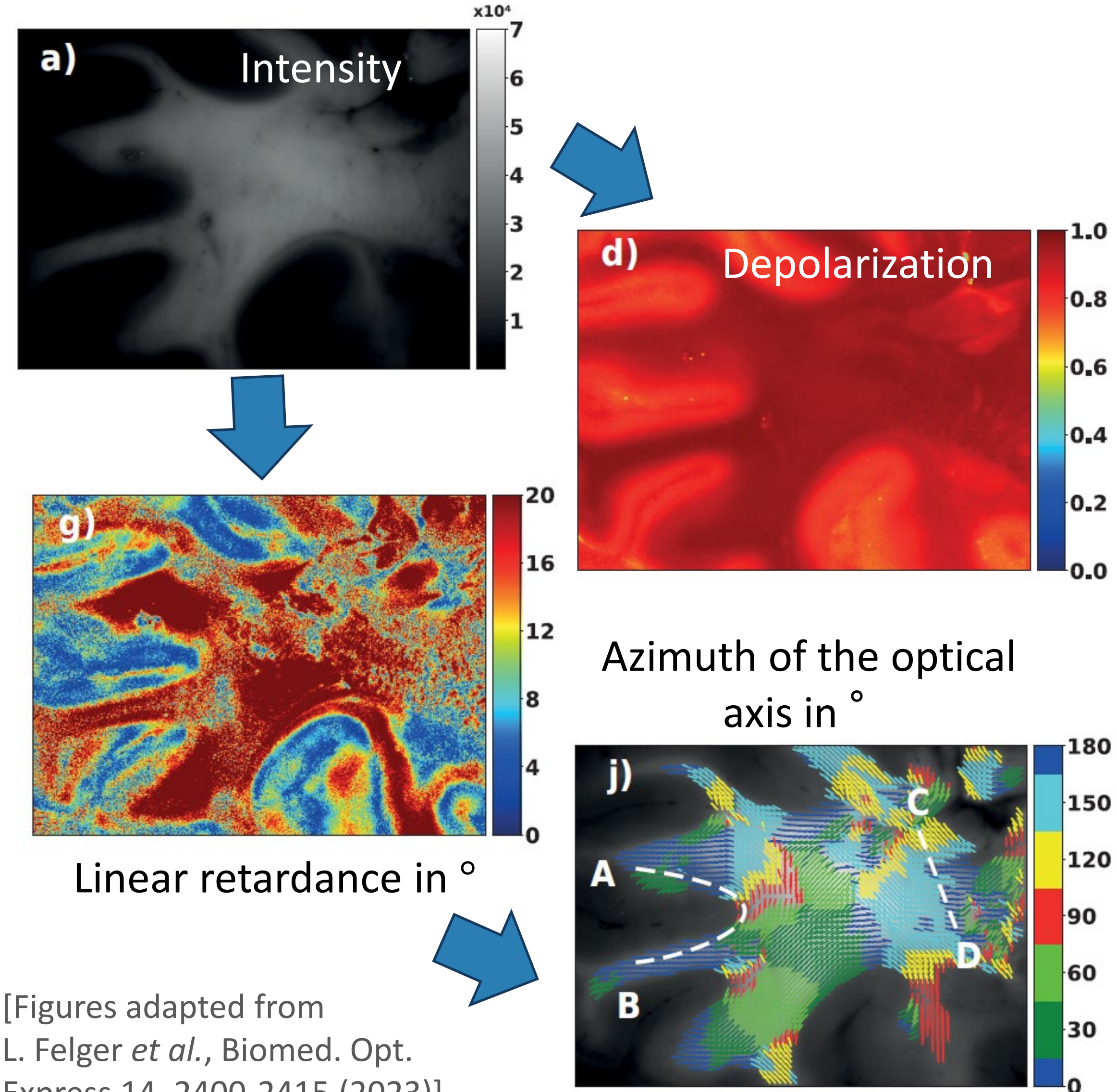


neck tissue with cancer cells



J. R. Leon Torres et al., Laser & Photonics Reviews, e02356 (2025)

Quantum polarimetry: motivation



[Figures adapted from L. Felger *et al.*, Biomed. Opt. Express 14, 2400-2415 (2023)]

Polarization response can be used for:

detection of morphological changes in cells and tissues

D. Ivanov *et al.*, Biomed. Opt. Express 12, 4560-4572 (2021).
O. Sieryi *et al.*, Biomed. Opt. Express 13, 6019-6034 (2022).

chemical compound diagnostics using optical activity

A. Thomas et al., J. Phys. Chem. C 122 (25), 14205-14212 (2018).

thickness and surface characterization

S. Yoo and Q-H. Park, Nanophotonics 11(12), 2811-2825 (2022).

classically done with **Stokes or Mueller polarimetry**

Probing tissue with polarization-entangled states

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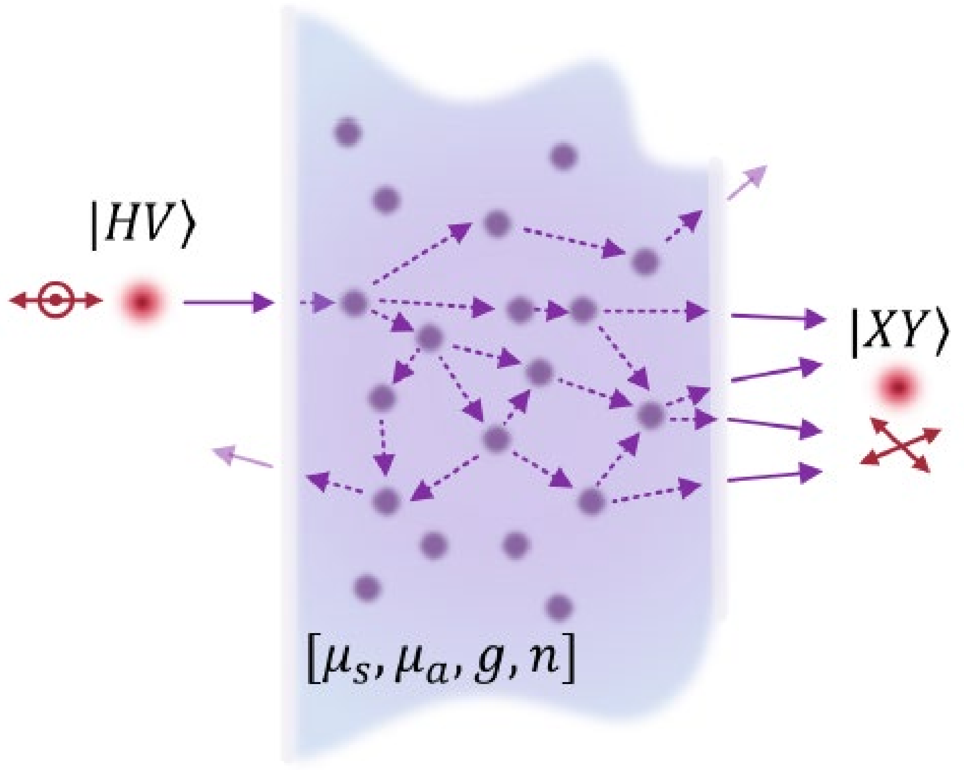
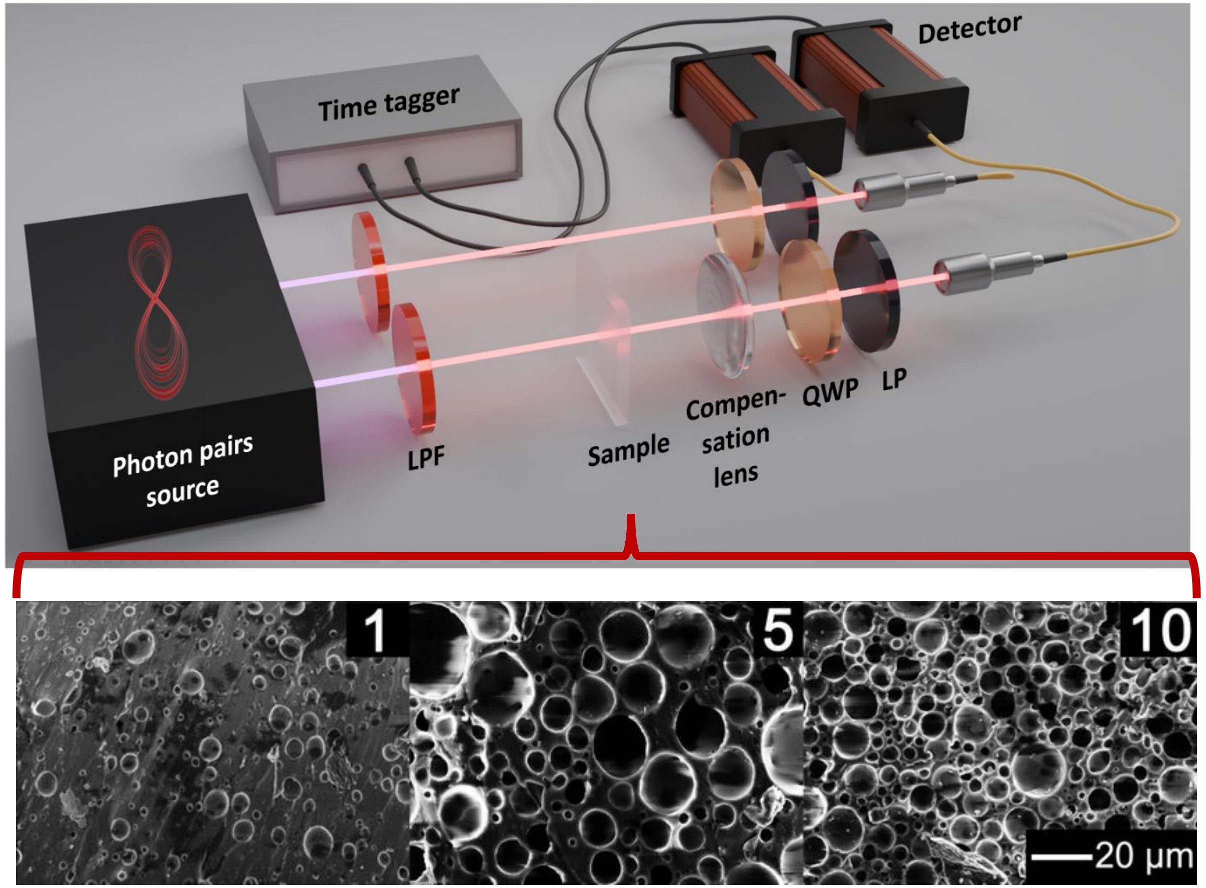
theoretical modelling



statistical analysis of photon propagation through scattering tissue

model is based on Monte-Carlo simulations of photon trajectories and polarization

experiment

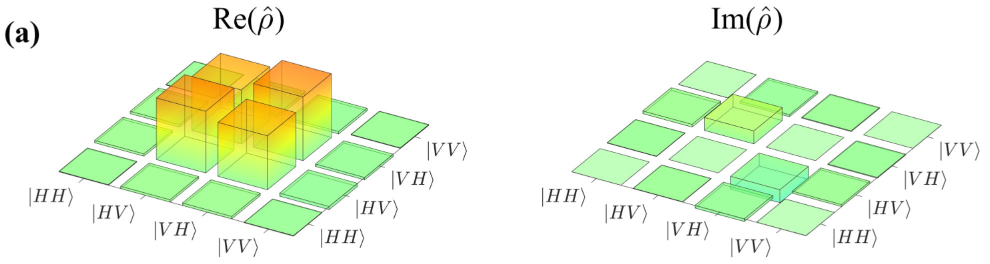


glucose-based tissue phantoms

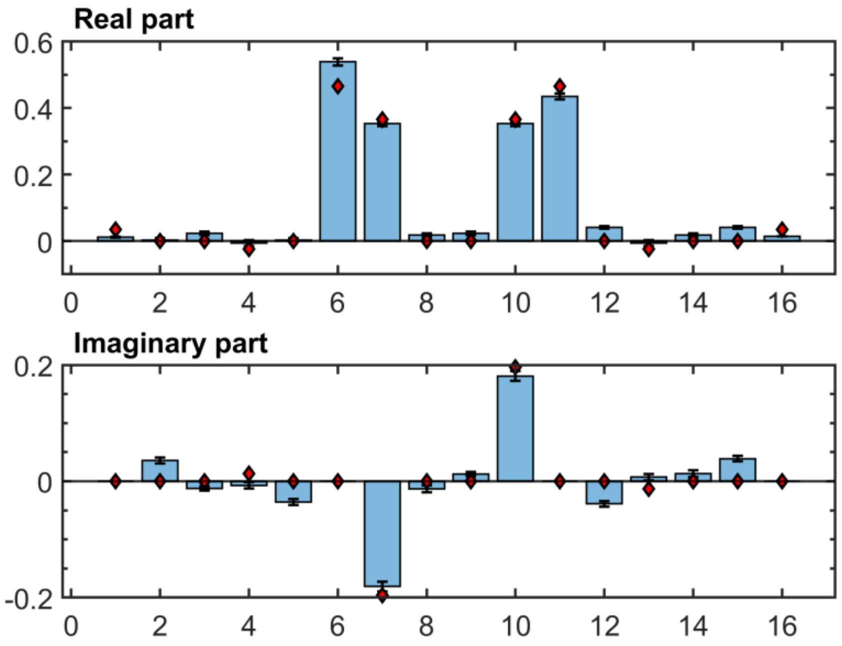
O. Sieryi et al. "Tissue-mimicking phantoms for biomedical applications." Tissue Optics and Photonics. Vol. 11363. SPIE, 2020.

Verification of model

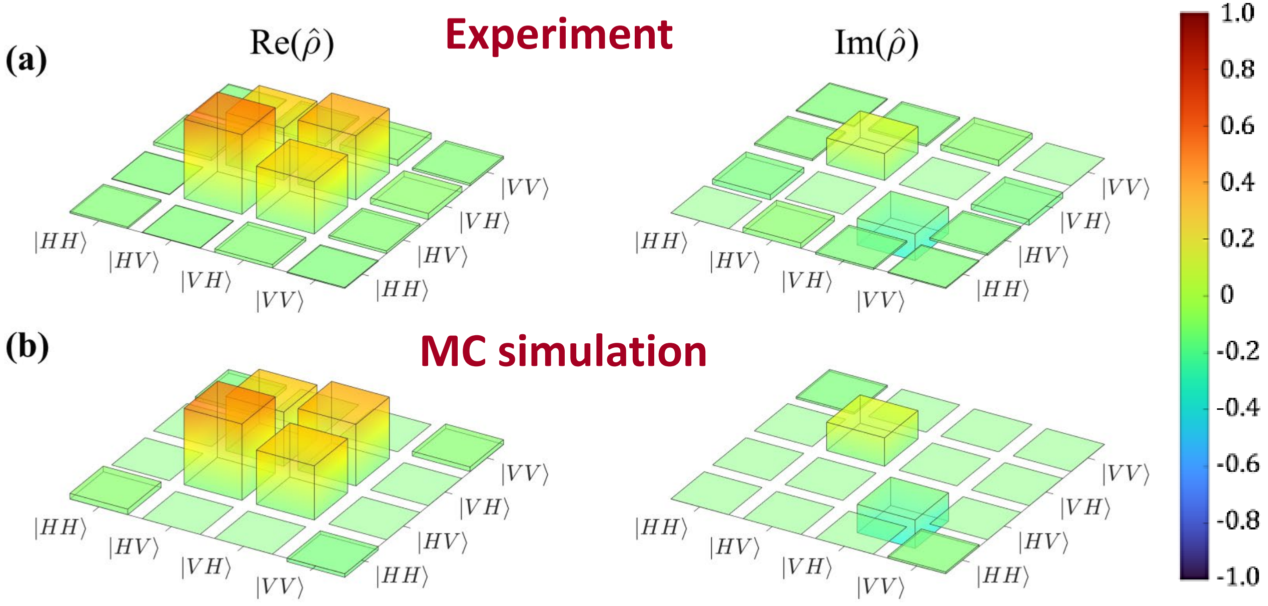
entangled input quantum state



matrix elements of output state



output quantum state



model describes changes well

V. R. Besaga, Laser & Photonics Reviews, e01172 (2025)

Verification of model

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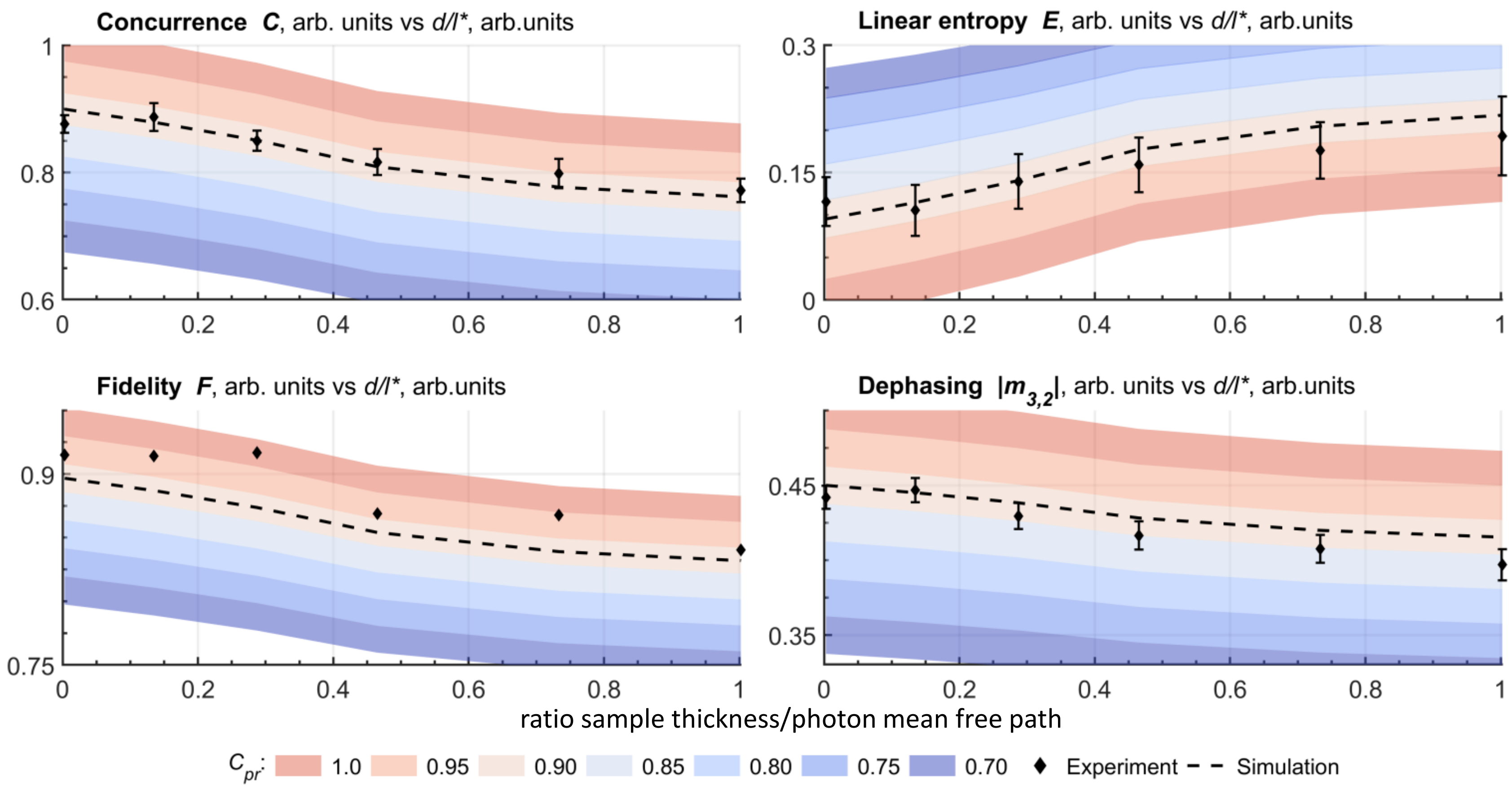
modelling of different properties of quantum state

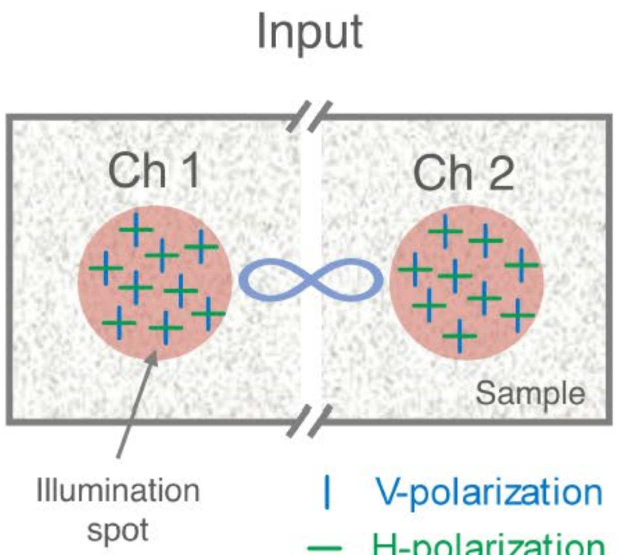


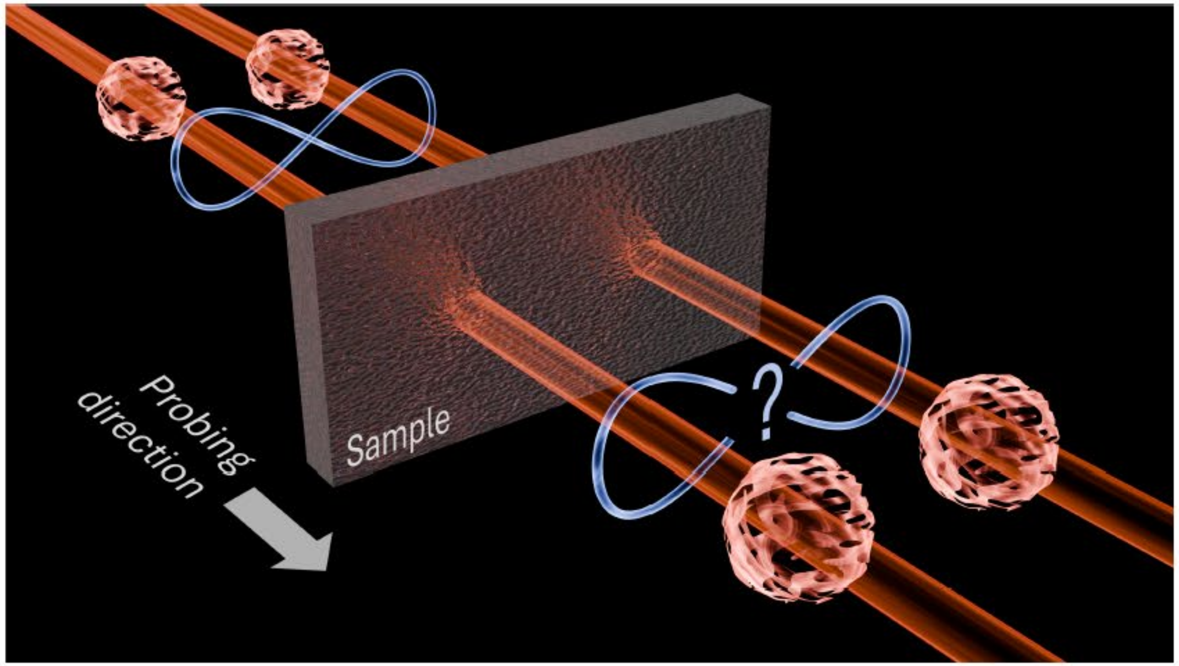
good matching of general properties

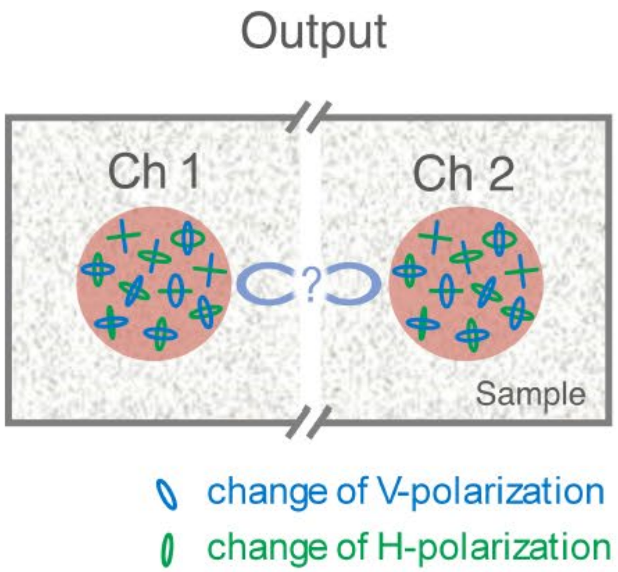
V. R. Besaga, Laser & Photonics Reviews, e01172 (2025)

Extension to two-photon probing

both photons of entangled state interact with sample







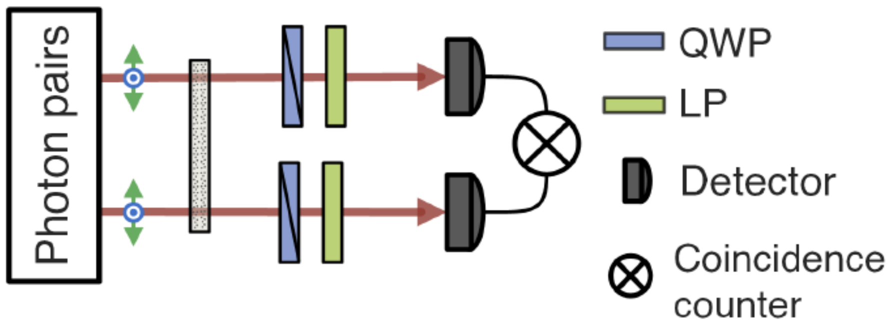
model is extended to this case

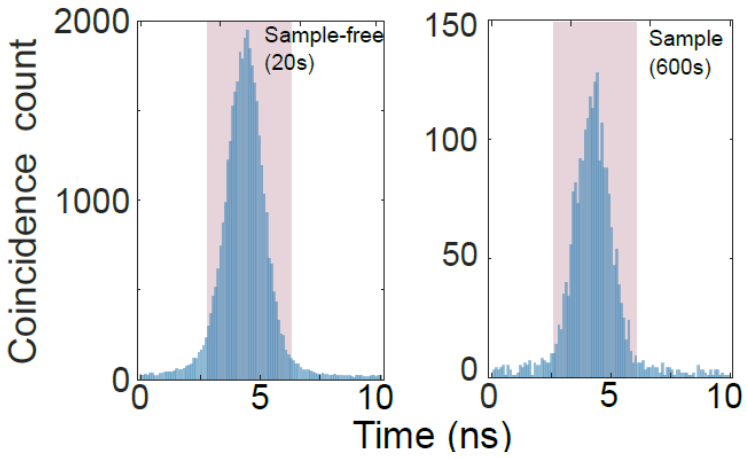
State evolution

measurements

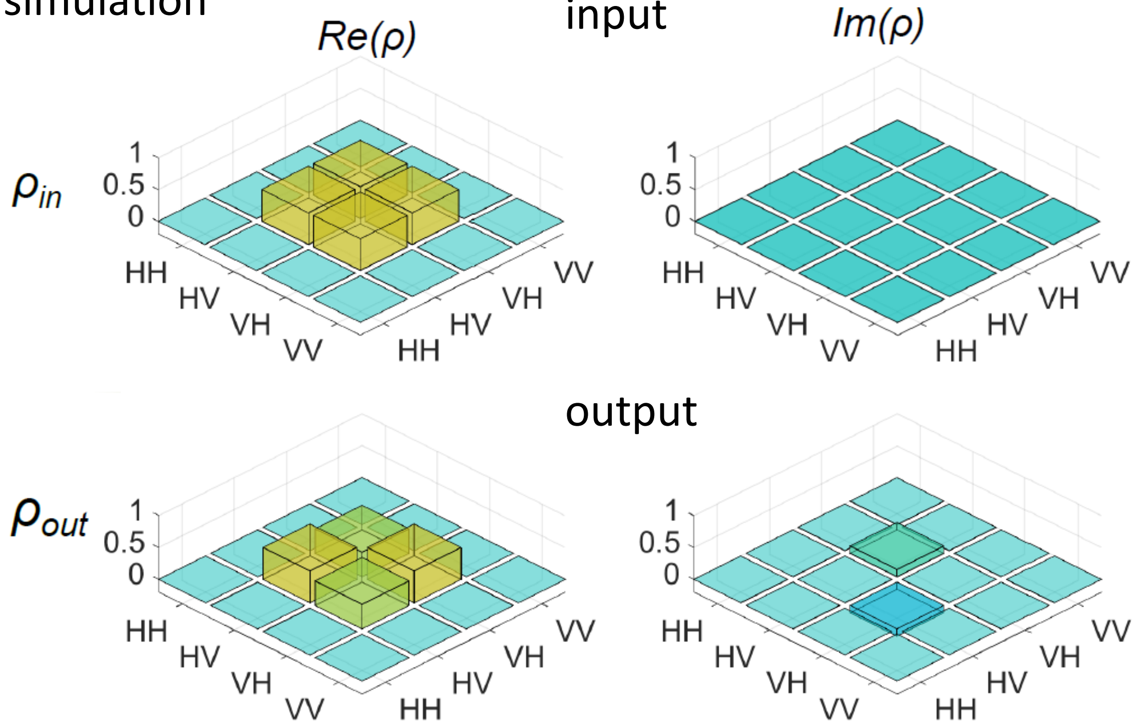
in phantom samples

measurement setup

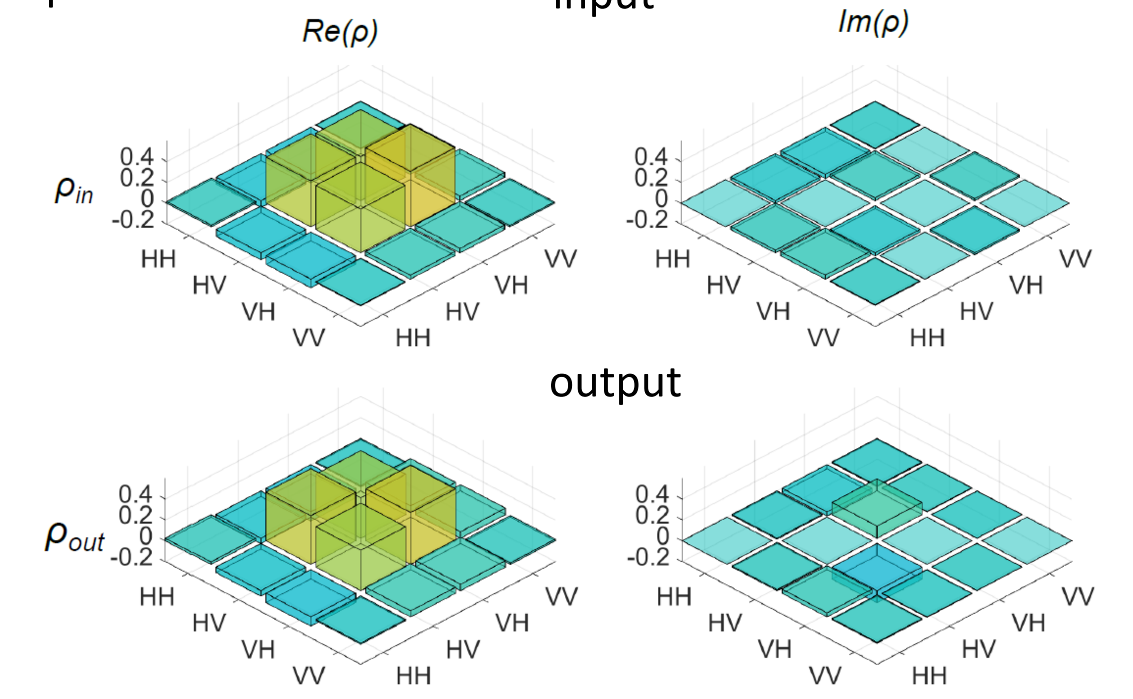




simulation



experiment



Analysis of samples

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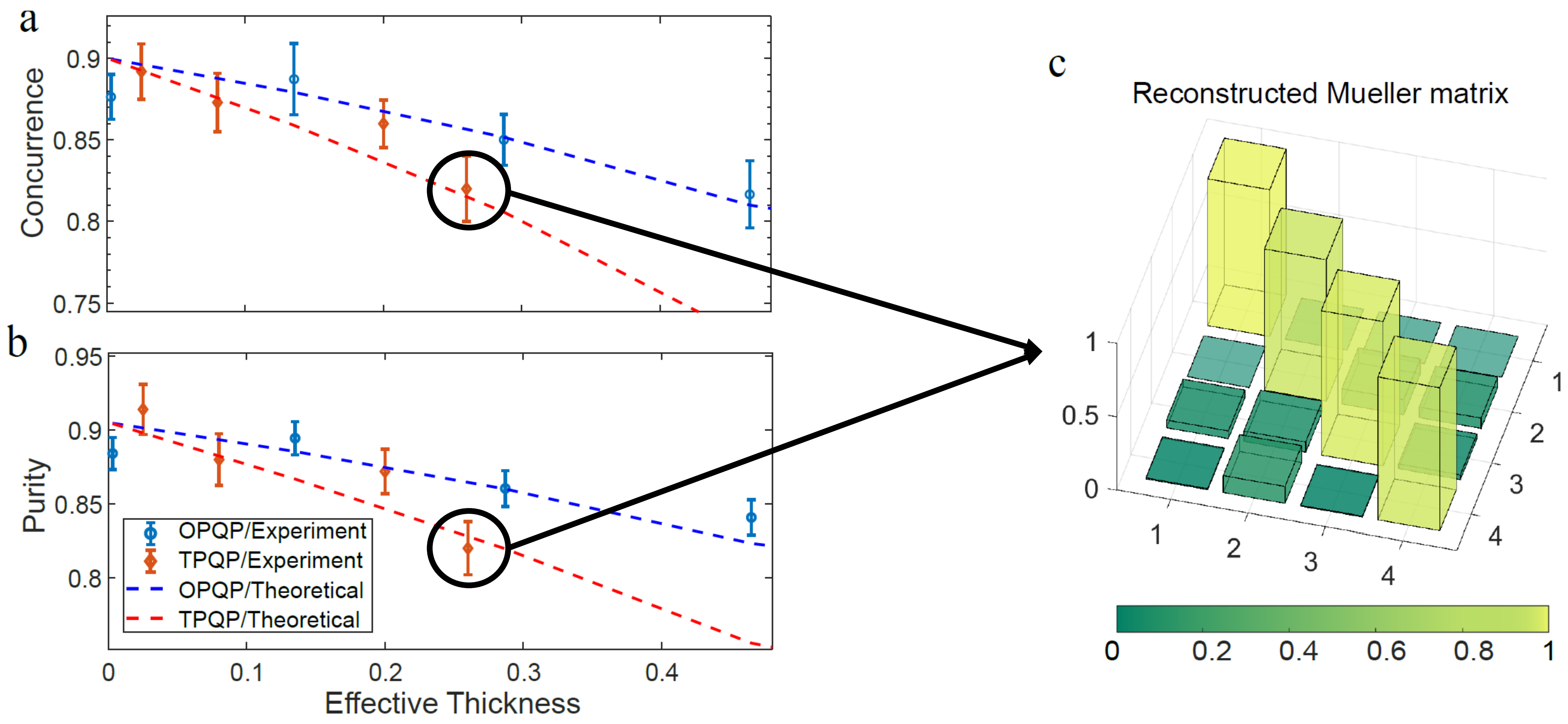
measurements of different phantom samples

can be used to deduce polarization properties



two-photon measurement is more sensitive

Summary

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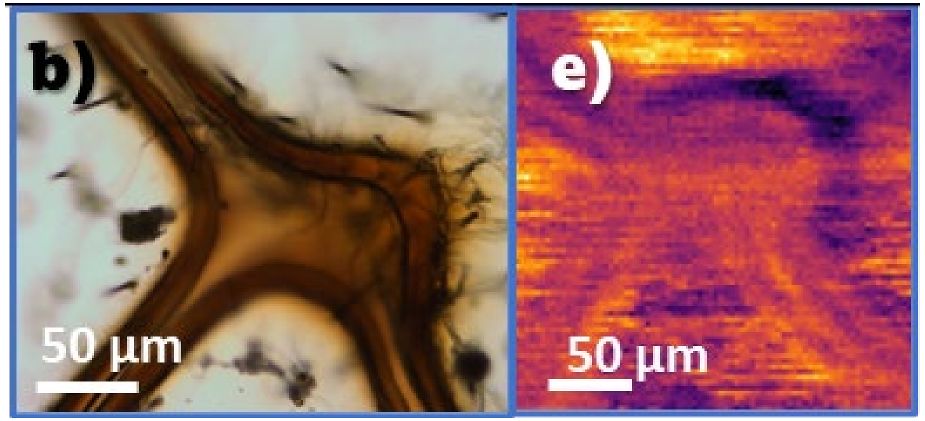
could realize scanning imaging with undetected photons



established quantum spectroscopy protocol at 6.4 µm

established tools for quantum polarization sensing in scattering media