Hyperbolic phonon polaritons in periodic structures

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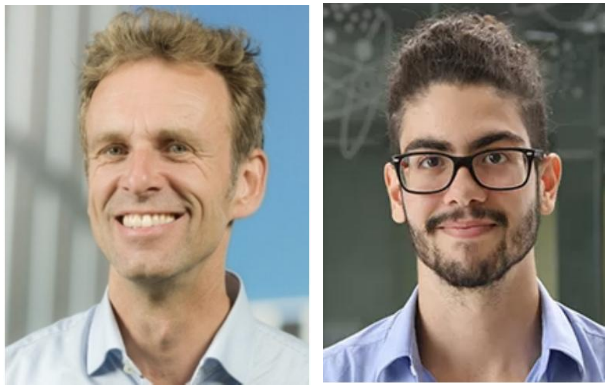

Elisa Mendels

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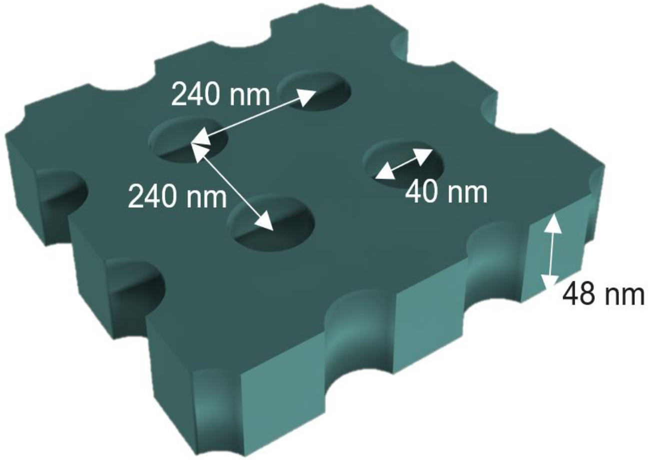
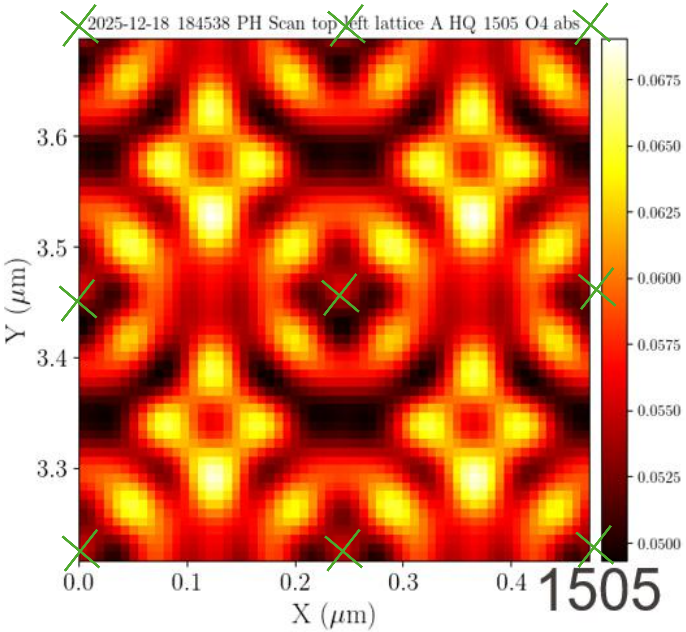
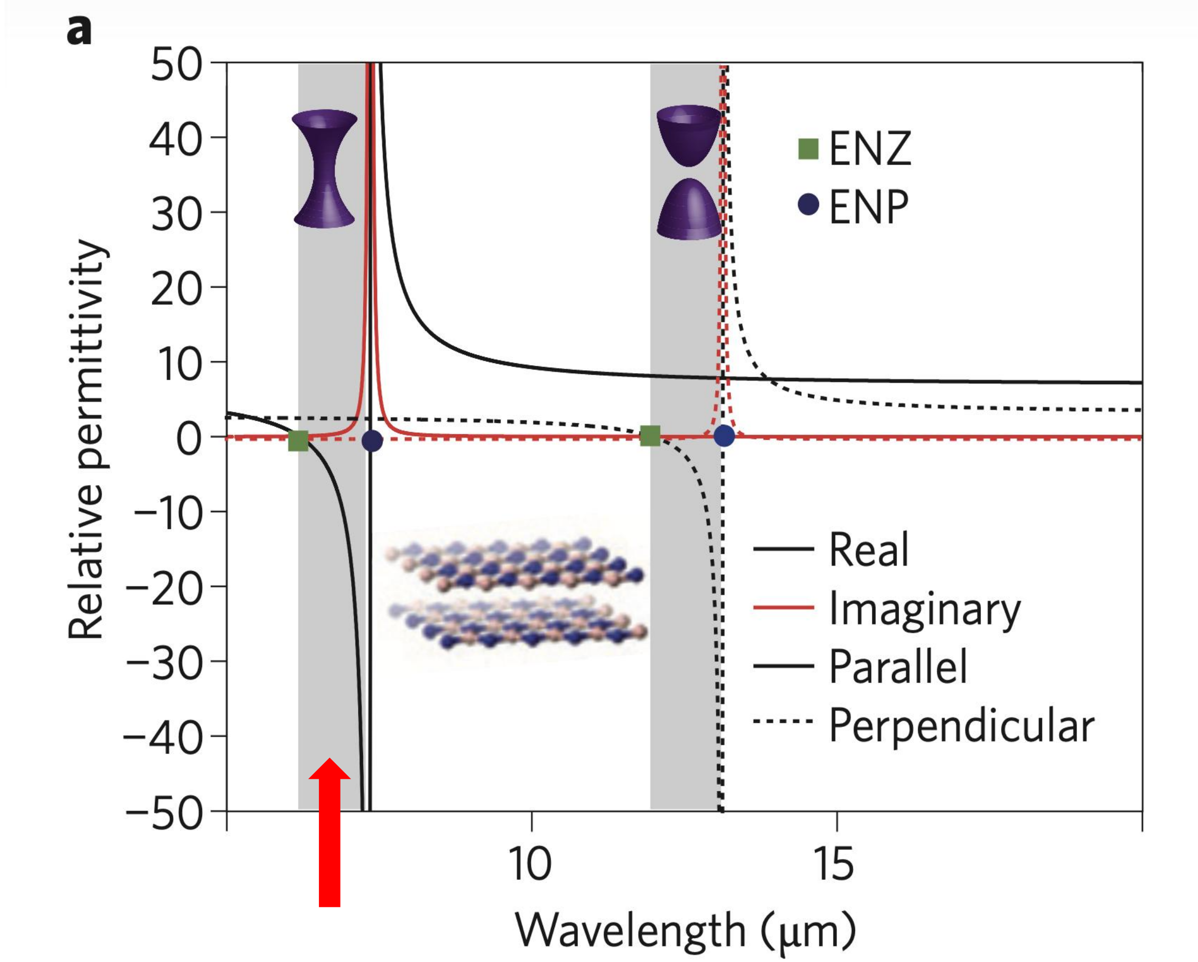




Hyperbolic phonon polaritons (HPhPs) in hBN



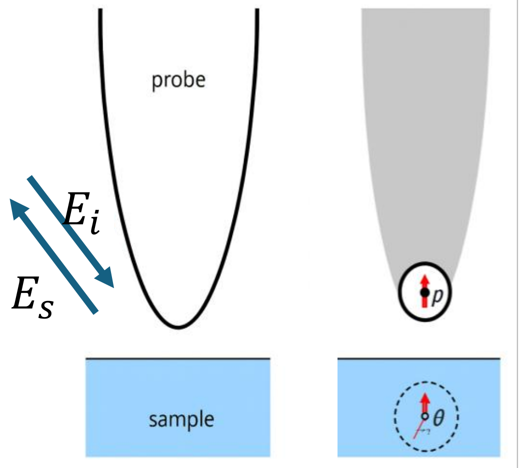
Type II: In-plane $\varepsilon_{xx} = \varepsilon_{yy} < 0$

$$\varepsilon(\omega) \approx -\varepsilon_x^{\infty}\left(\frac{\omega_{LO}^2 - \omega^2}{\omega^2 - \omega_{TO}^2}\right)(1 - i\delta)$$

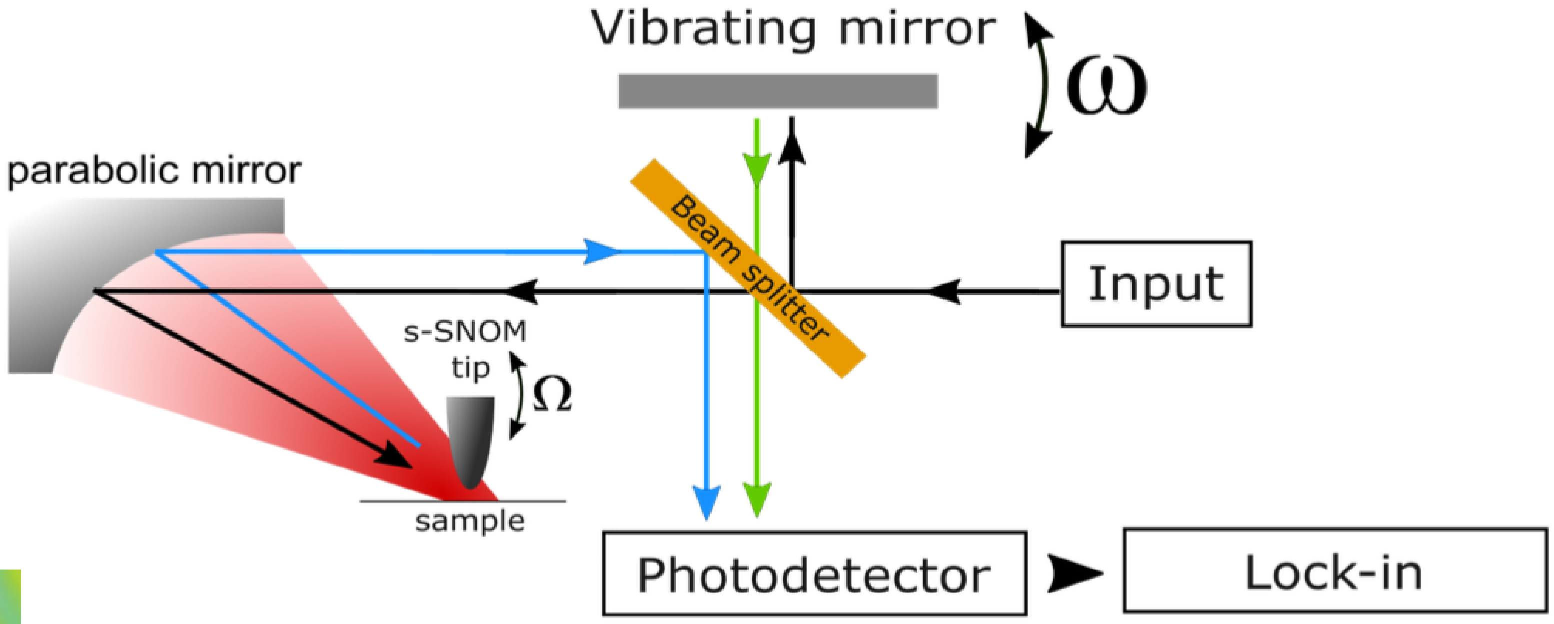
$$\frac{k_x^2}{\varepsilon_{zz}} + \frac{k_z^2}{\varepsilon_{xx}} = k_0^2$$

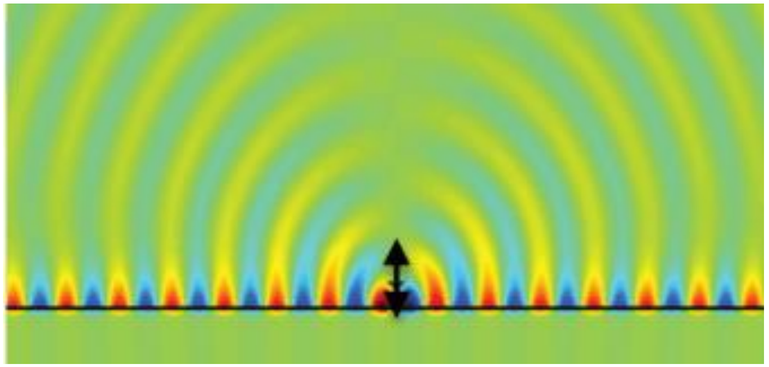
$\lambda \approx 6 - 7.5\ \mu m$; $1/\lambda \approx 1350\text{-}1650\ cm^{-1}$

Scanning Near-field Optical Microscope (SNOM)



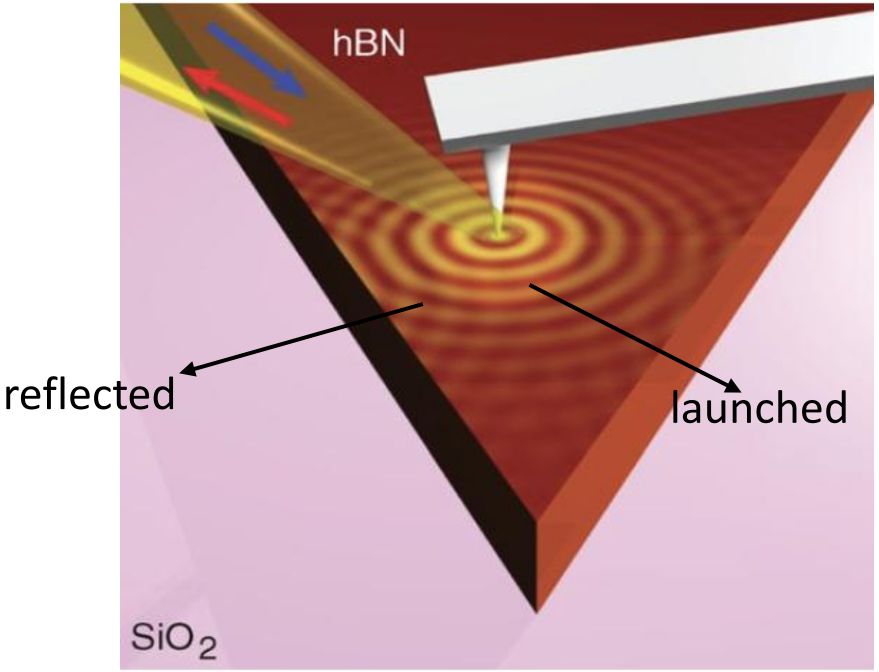
Schematic of tip action

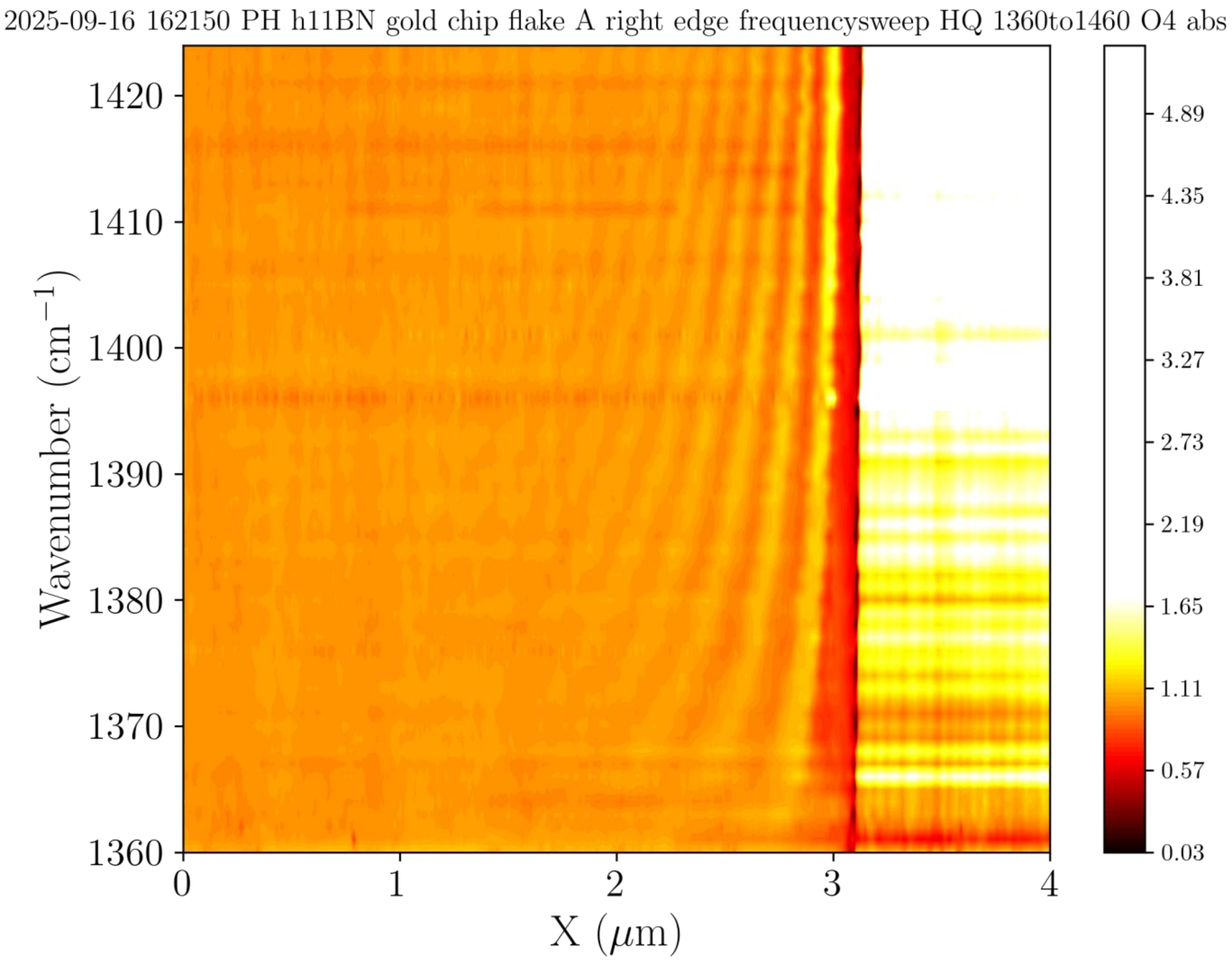




Schematics of propagation of polaritons from sSNOM tip

Earlier observations of HPhPs in hBN

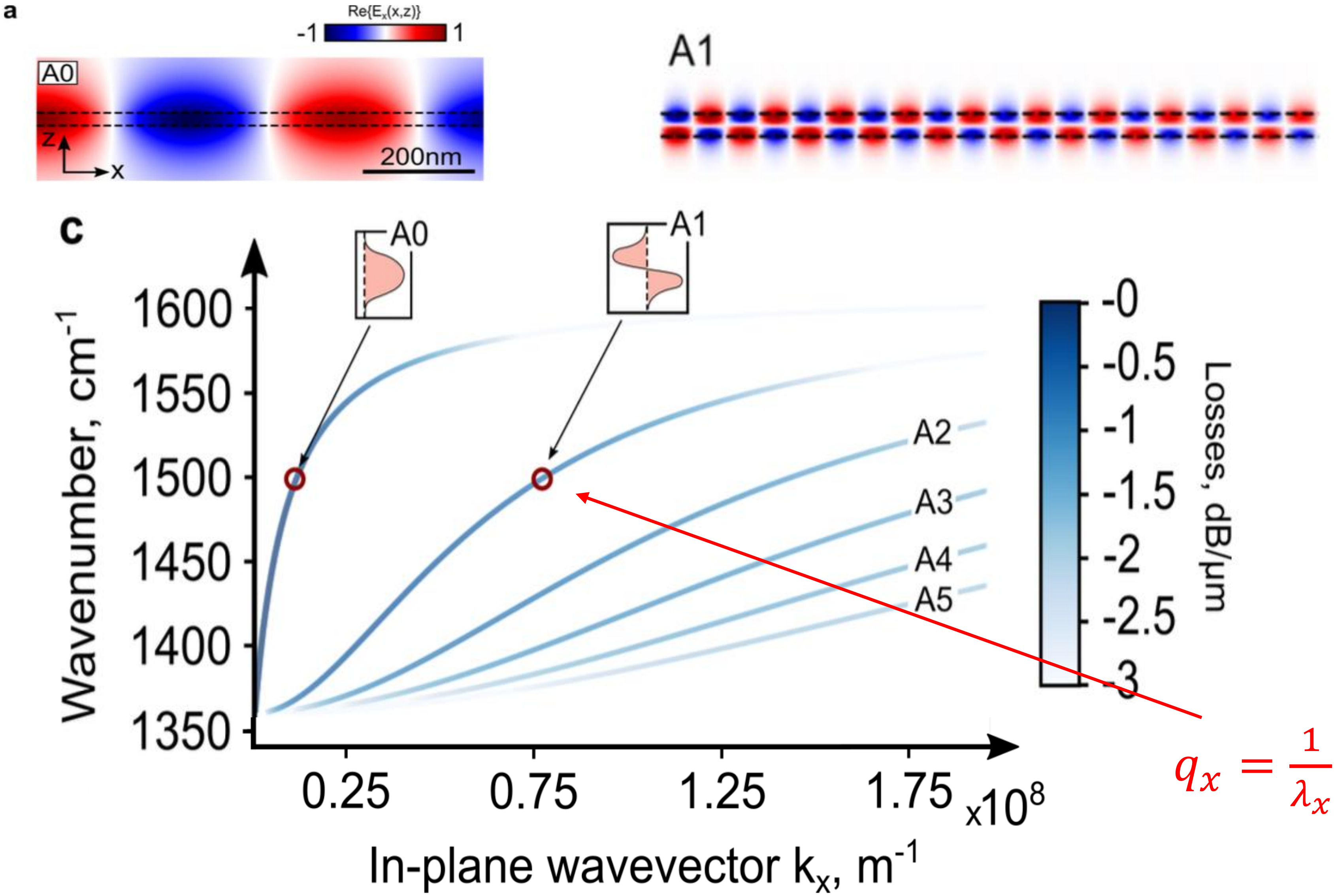




Frequency sweep on an hBN edge

S. Dai et al., 'Tunable phonon polaritons in atomically thin van de Waals crystsals of boron nitride', Science 343, 1125 (2014)

Why? Strong spatial confinement of light

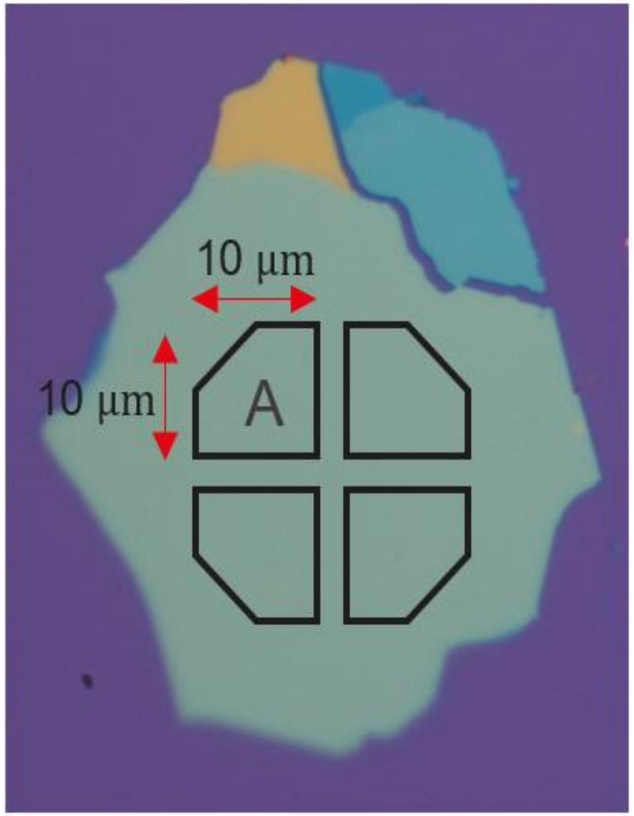


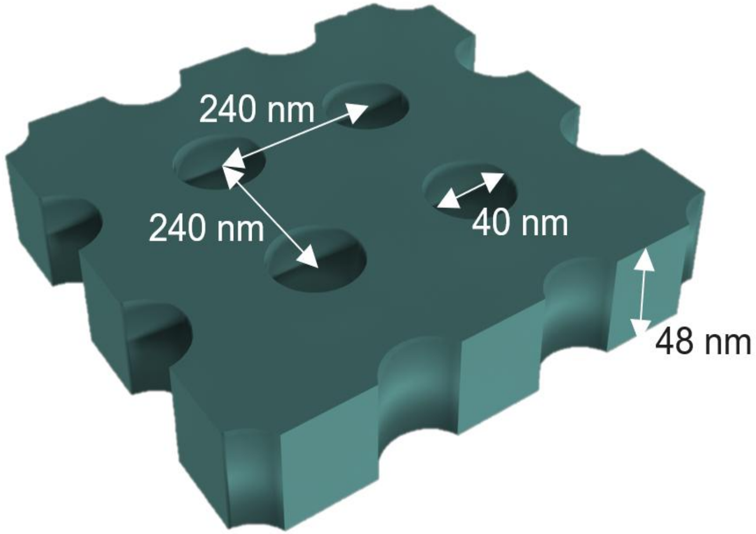
Higher-order HPhPs (A1, …) have stronger confinement

$q_x = \frac{1}{\lambda_x} = \frac{k_x}{2\pi} \approx 120{,}000\ \text{cm}^{-1}$

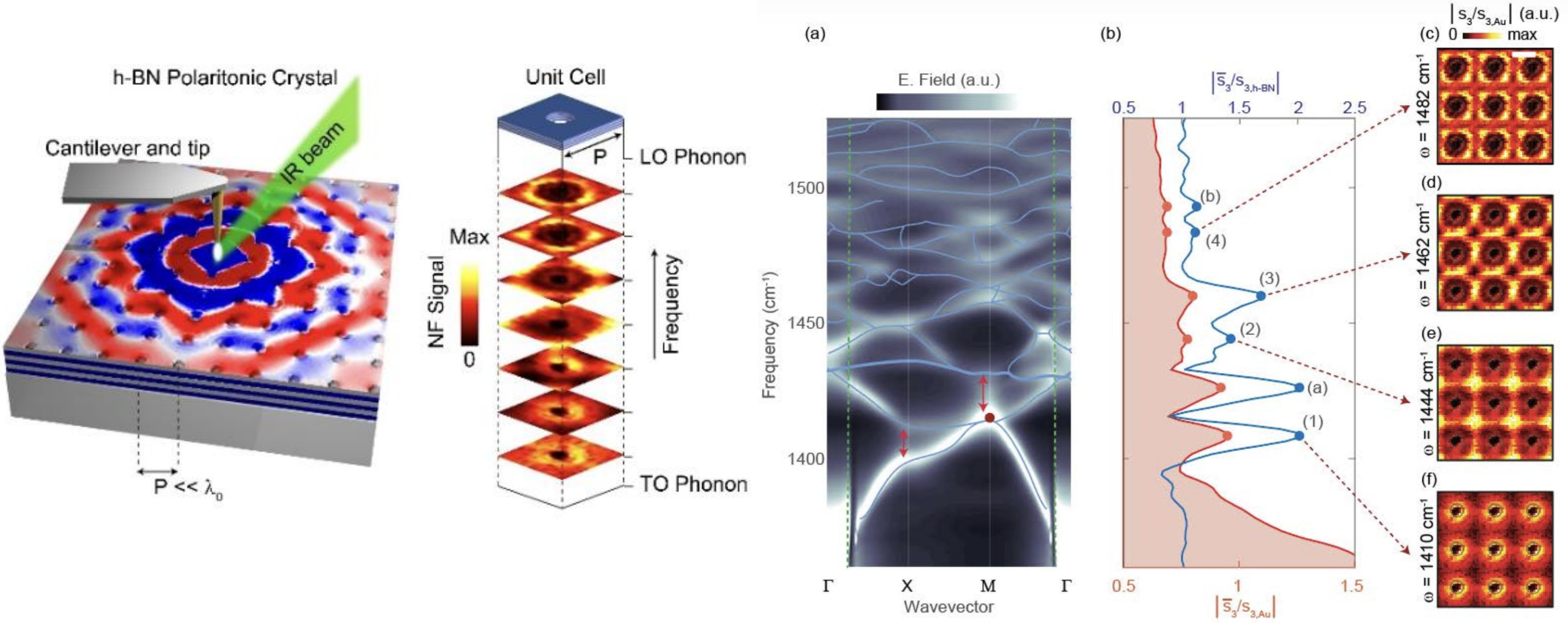
$\approx 12\ \mu\text{m}^{-1}$

Geometry: periodic array of holes in hBN film



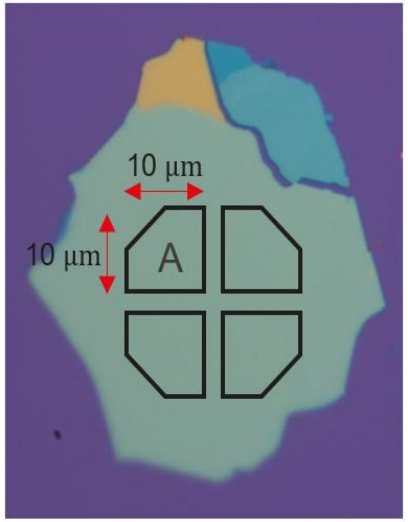


Earlier work on ‘Hole arrays in hBN = polaritonic crystals’



F.J. Alfaro-Mozaz, ..., L. Martin-Moreno, R. Hillenbrand, A.Y. Nikitin,
‘Hyperspectral nanoimaging of van der Waals polaritonic crystals’, Nano Lett. 21, 7109 (2021)

Our SNOM image of hole array in hBN @ 1520 cm^{-1}



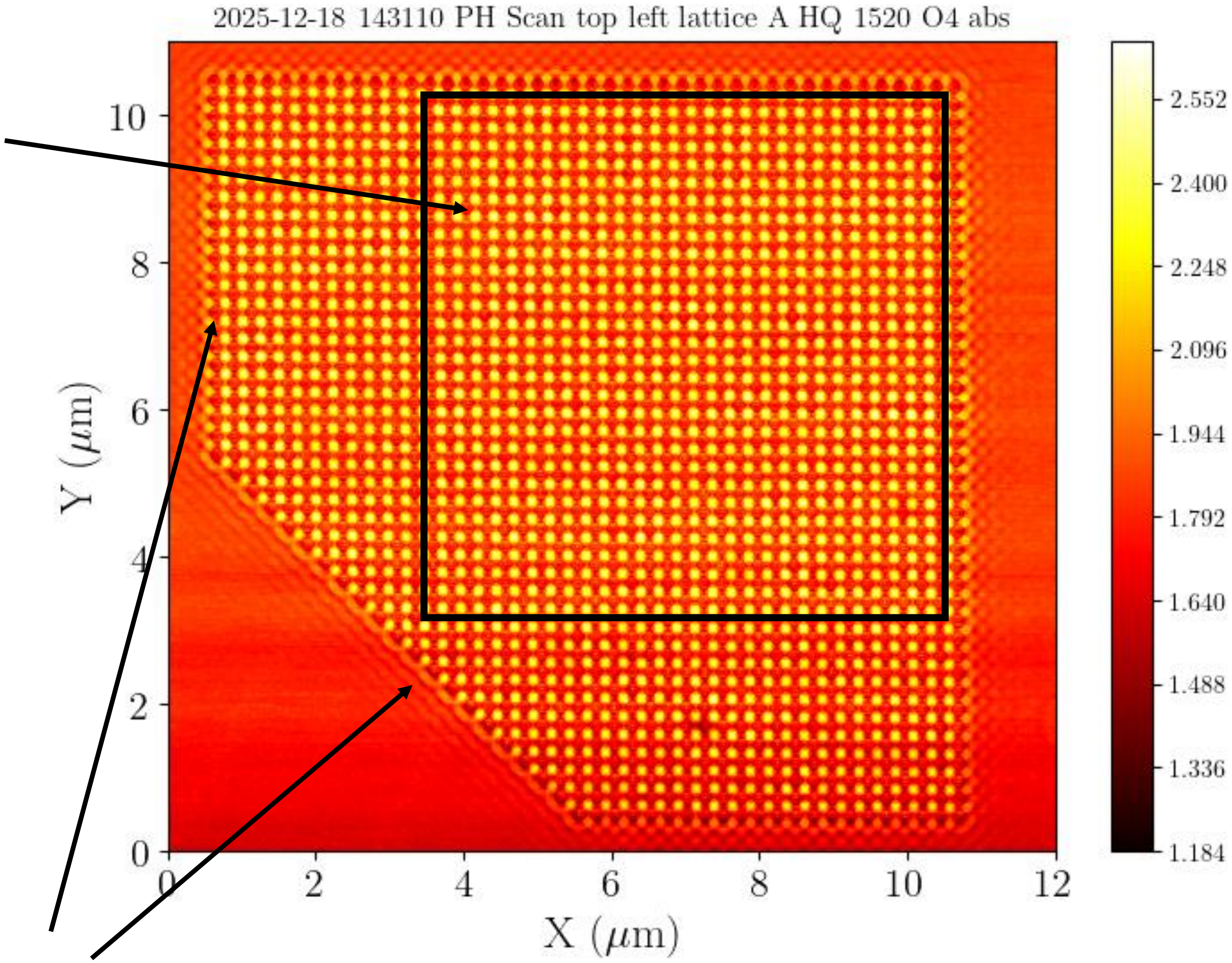
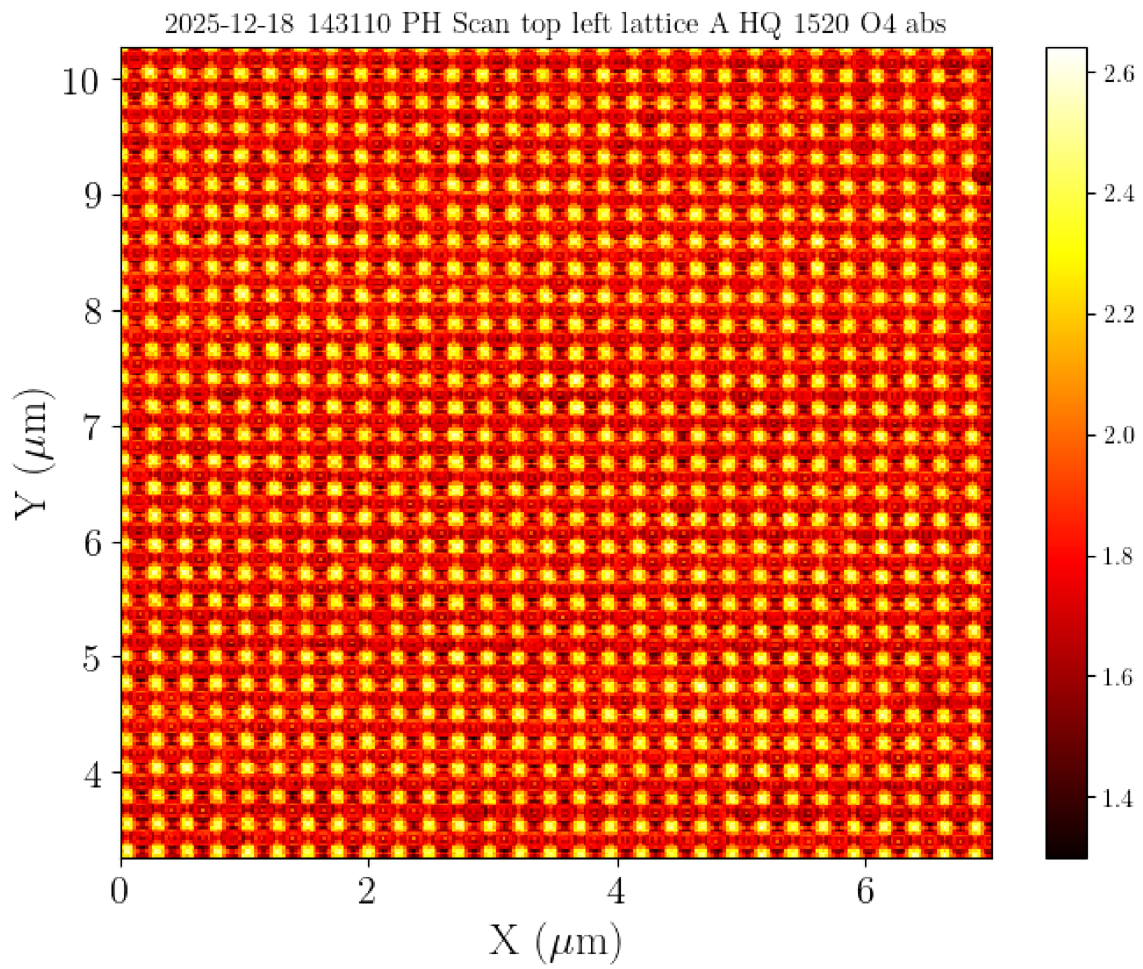
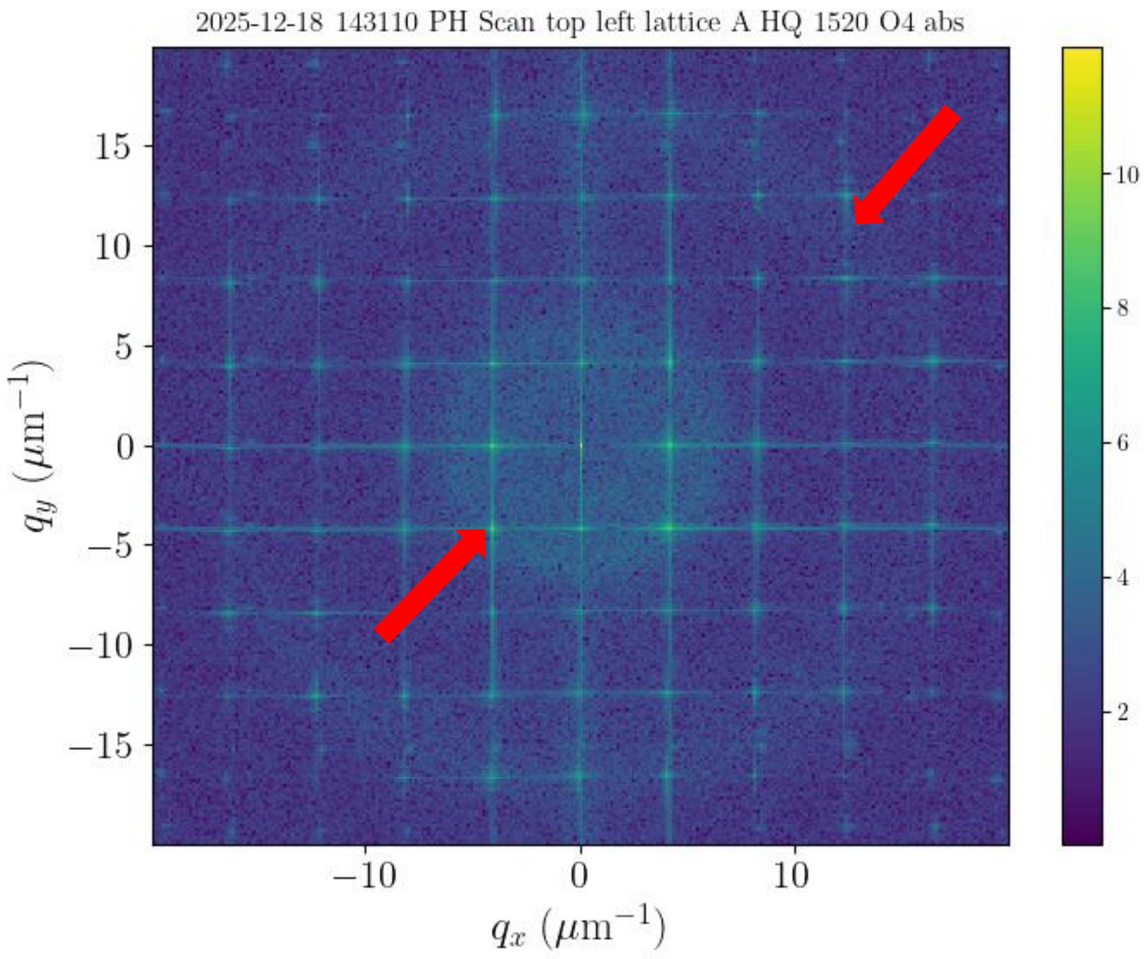


Image processing: Cut & apply Fourier transform

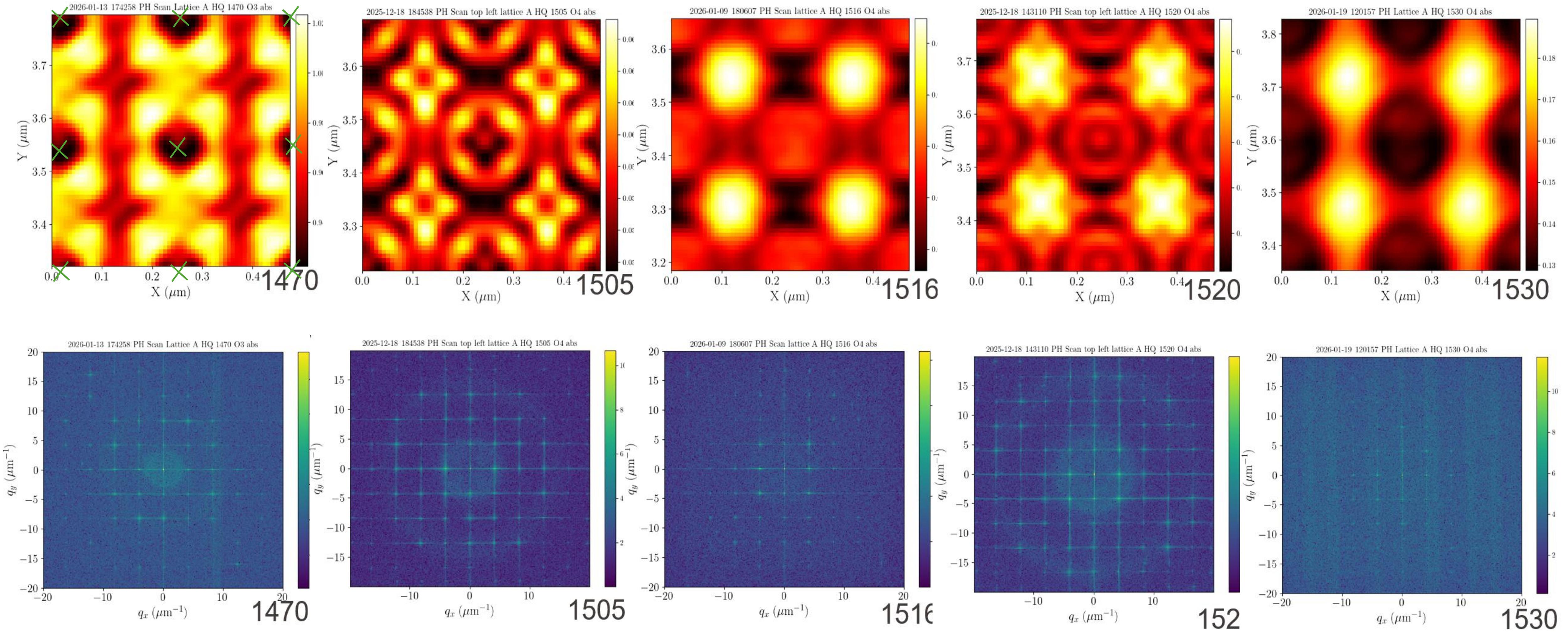




Fourier lattice: $\left(q_x, q_y\right) = (m_x, m_y)/a$

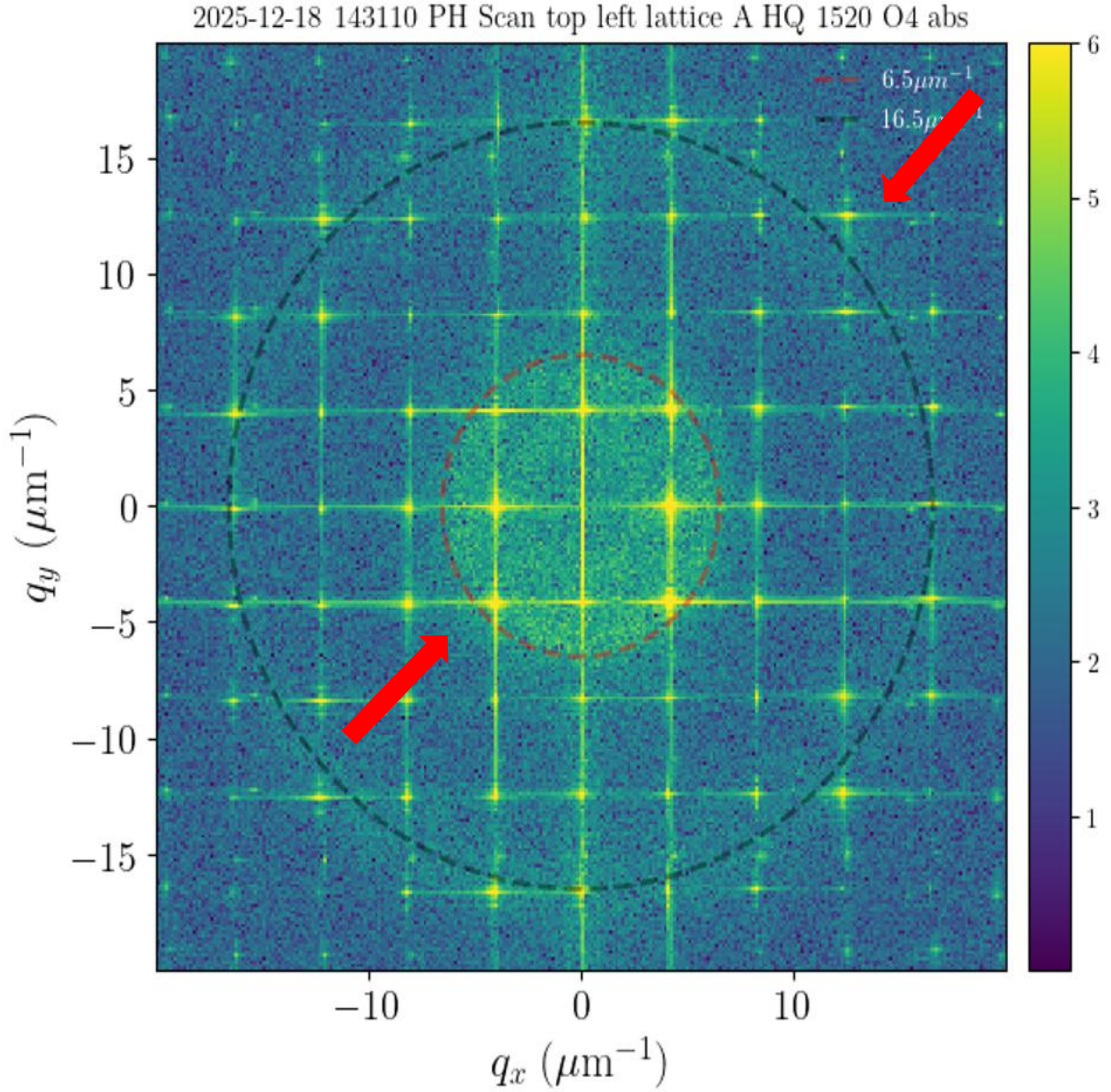
Angle (deg): -0.02 ± 0.44 , FFT Lattice const (um-1): 4.13 ± 0.04 ,Real-space lattice const (um): 0.242 ± 0.002

SNOM & Fourier images at different wavelength



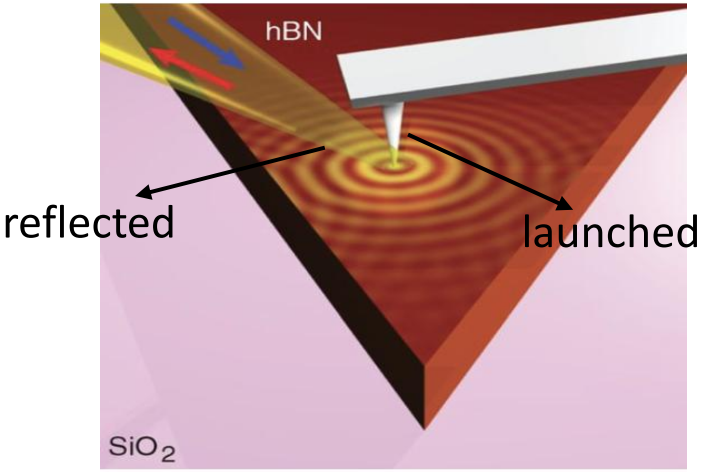
Faint rings in Fourier images

Sketched rings at:
$q_x = \ \ 6.5\ \mu\text{m}^{-1}$ (A0)
$q_x = 16.5\ \mu\text{m}^{-1}$ (A1)



Towards a simple theory

- Traditional theory: excitation & detection of HPhPs



- Alternative theory: Green's function & LDOS

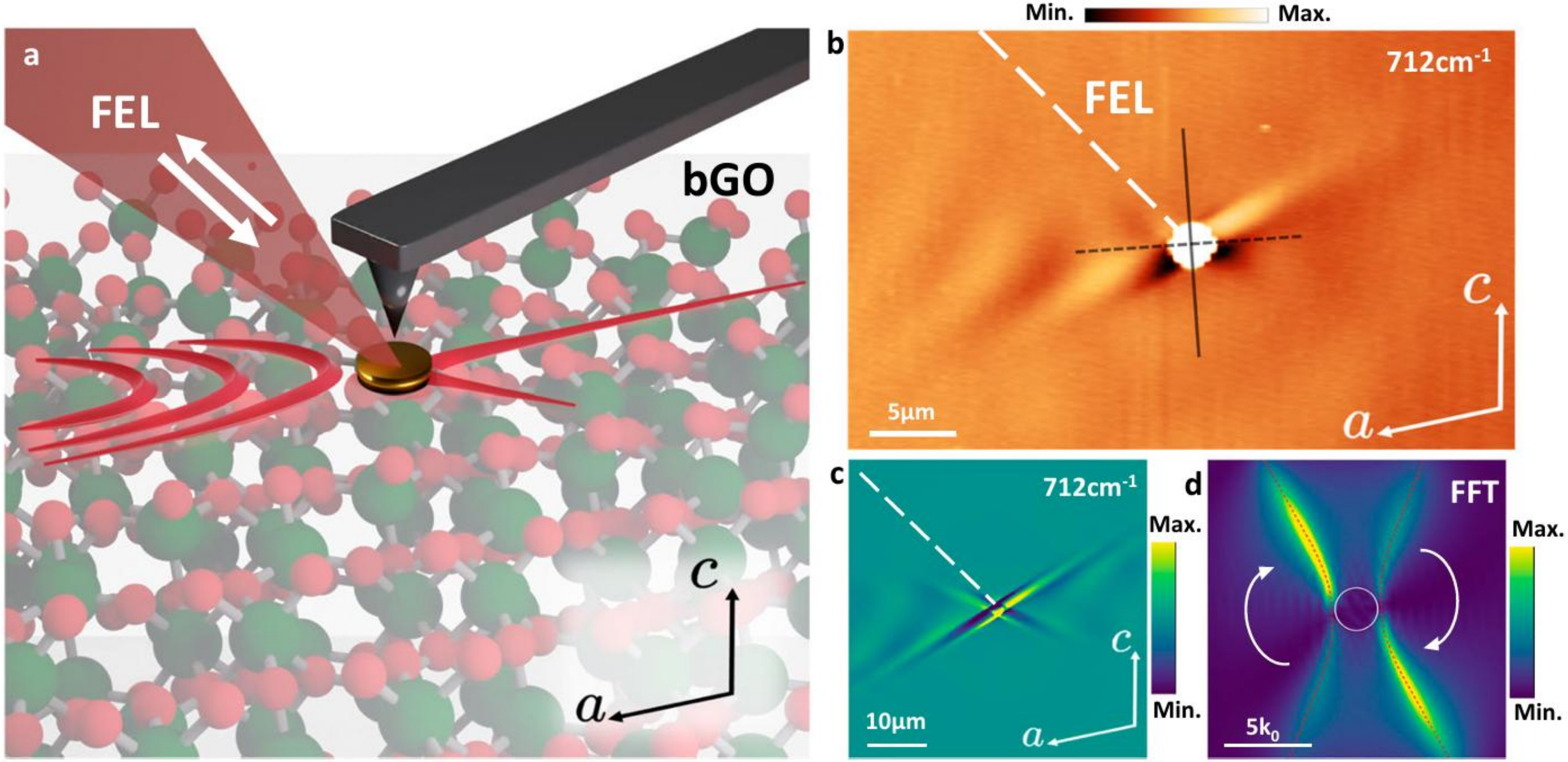
- Hypothesis 1: $E_{SNOM}(\vec{r},\omega) \propto G_{2D}(\vec{r},\vec{r},\omega)$

- Hypothesis 2: $E_{SNOM}(\vec{r},\omega) \propto \sum_j \frac{\left|\psi_j(\vec{r})\right|^2}{1-i(\omega-\omega_j)/\gamma_j}$

Suggestions for future experiments

- Quantitative comparison theory-experiment
- Randomly positioned holes?
- Single hole?

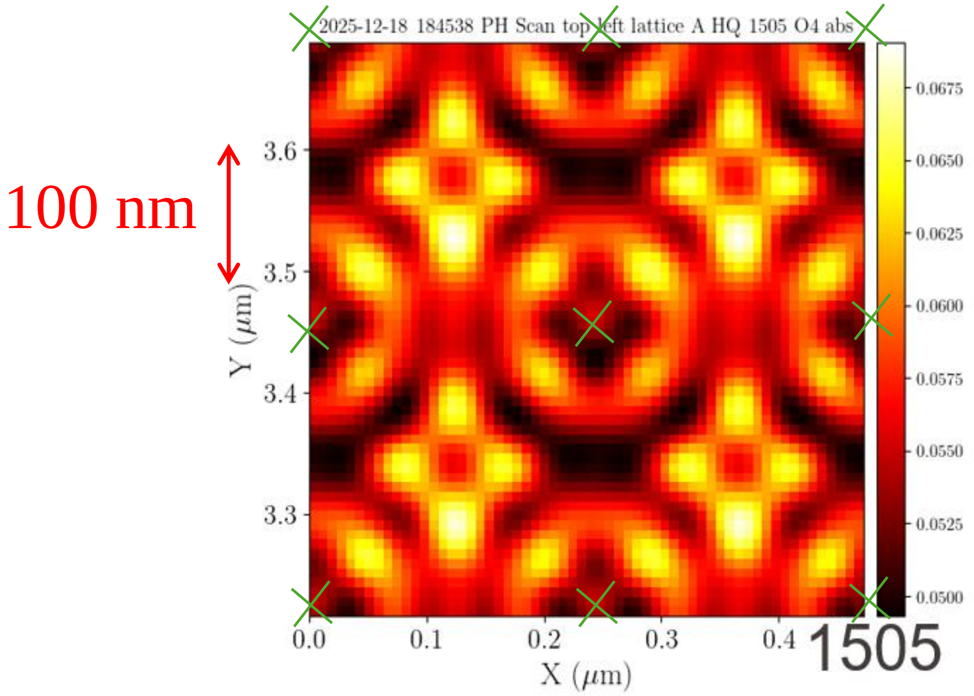
Link to talk of Alex Paarmann on ‘hyperbolic shear polaritons’

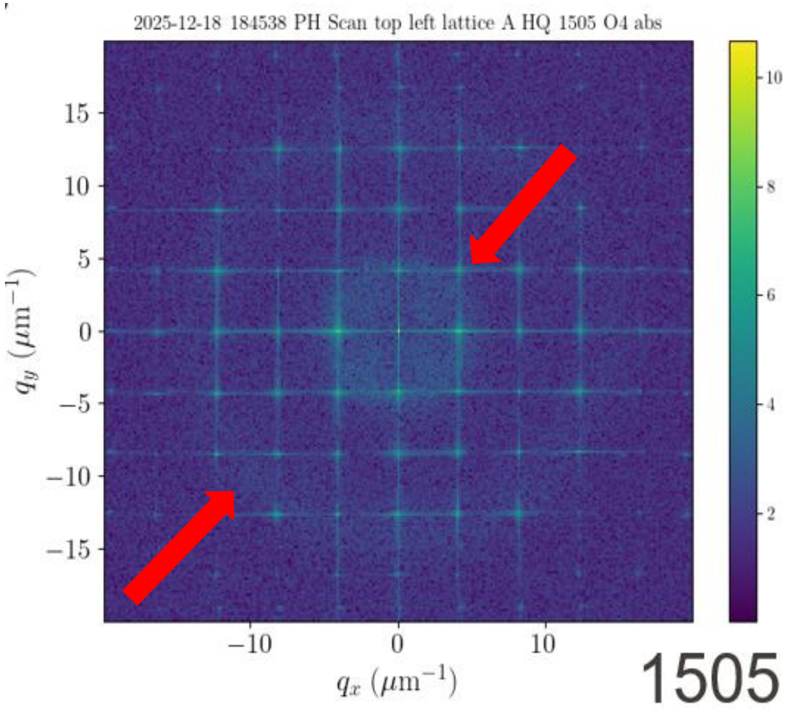


J. Matson, …, A. Paarmann, J.D. Caldwell, ‘Controlling the propagation asymmetry of hyperbolic shear polaritons in beta-gallium oxide’, Nature Comm. 14, 5240 (2023)

Concluding summary

- SNOM images show fascinating details, < 40 nm ($\lambda_{SNOM} \approx 6\ \mu m$)





- Higher-order hyperbolic phonon polaritons are visible
- Different lattice modes are visible
- Theoretical support would be appreciated ☺