Hyperspectral imaging with undetected photons in the mid-IR

QSL 26, Linz

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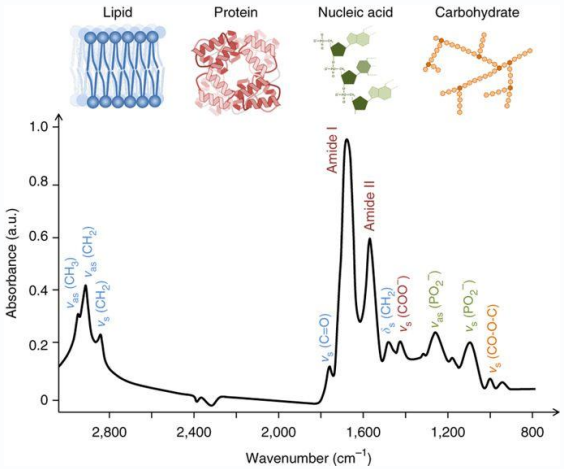
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Features of MIR sensing

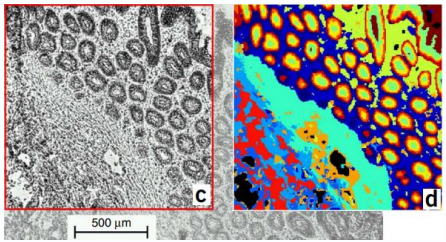
- MIR contains (sharp) characteristic vib-resonances (fingerprints) of molecular bonds

→ sample compositions can be identified with high specificity

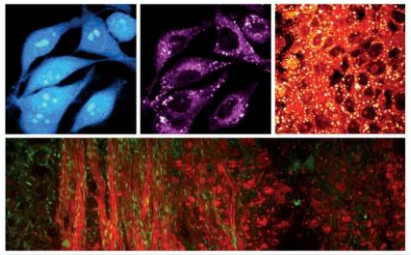
- Capacity for label-free, non-destructive testing and below-surface penetration
- Applications: high-throughput bio-sample classification, dynamical mixing or in-vivo monitoring



FTIR imaging*



Raman microscopy**

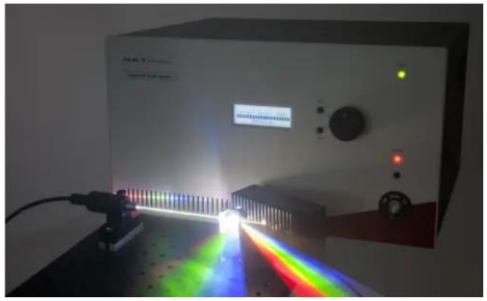


*Baker et al., Nature Protocols 9, 1771–1791 (2014)

**Cheng & Xie, Science 350, 6264 (2015)

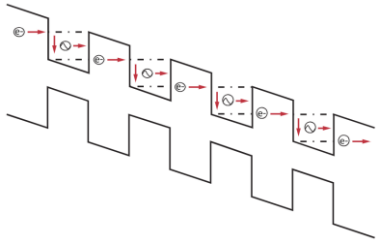
Major drawbacks

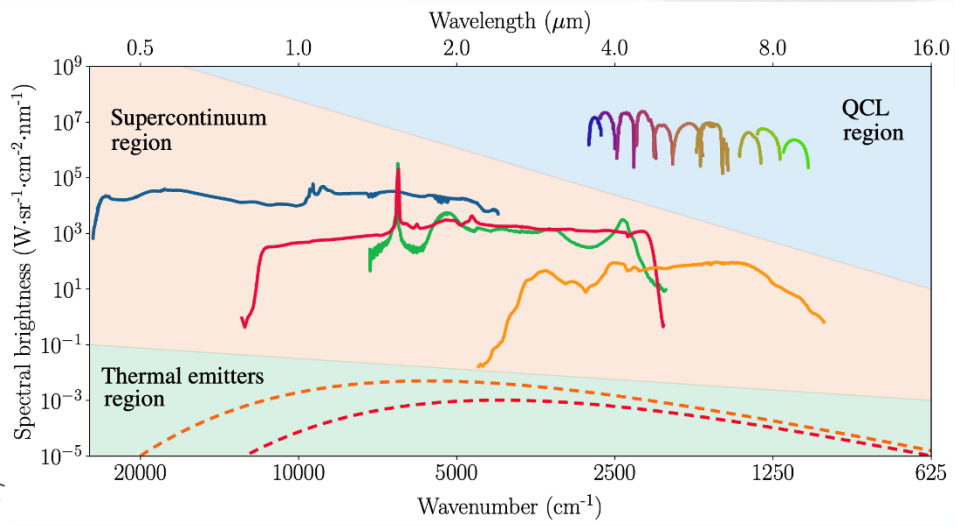
- Noisy, low-resolution, and cost-inefficient detectors
- Light-sources with trade-offs in spectral brightness vs. coverage vs. resolution/speed
- Spatial resolution is often limited to MIR diffraction



Modern, still advancing MIR sources: QCL (1994), Supercontinuum (2005), Dual combs (2008).

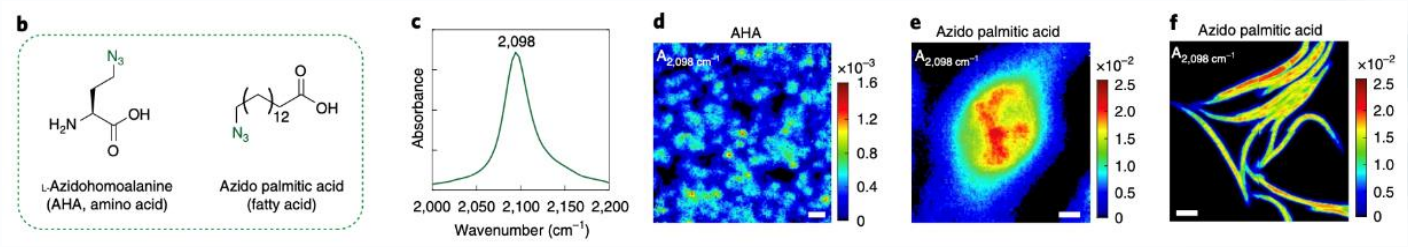
Source: rp-photonics.com/

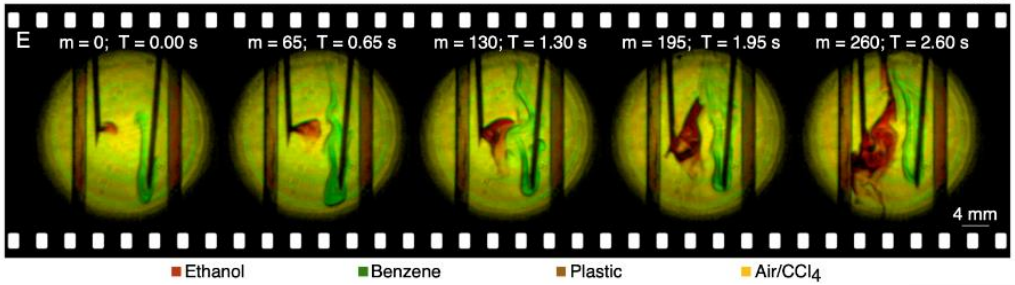


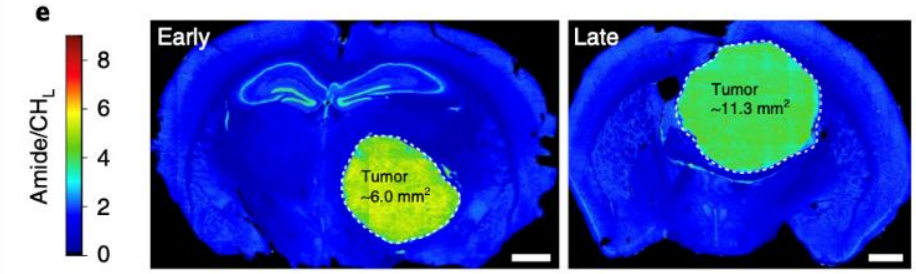


Zorin, Ivan, et al. "Advances in mid-infrared spectroscopy enabled by supercontinuum laser sources." Optics express 30.4 (2022): 5222-5254.

Mid-IR sensing: a real-world analysis task





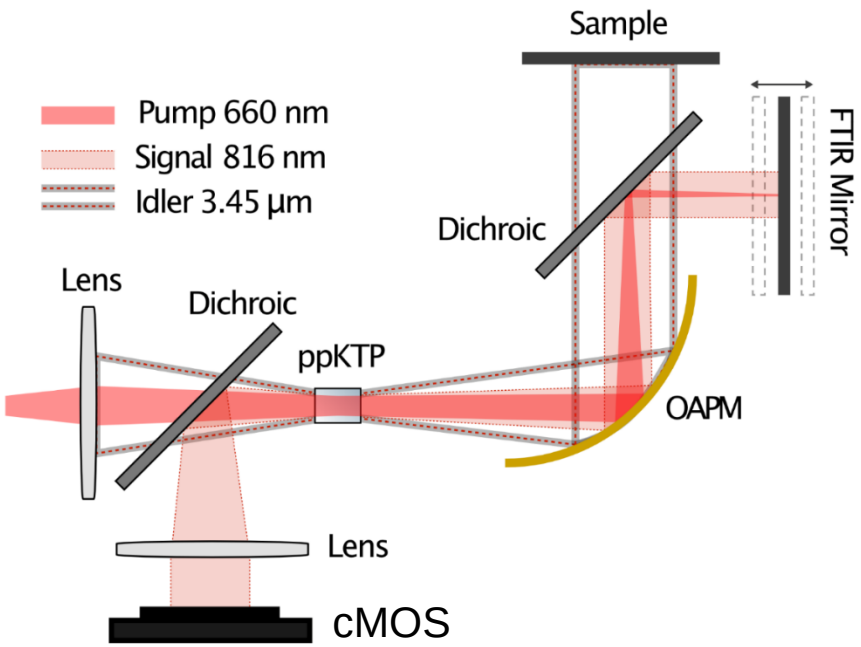


- For medicine: Microscopic resolution needed
- For dynamical processes: high framerates needed
- For early diagnostics: high throughput needed

Fang, Jianan, et al. "Wide-field mid-infrared hyperspectral imaging beyond video rate." Nature Communications 15.1 (2024): 1811.

Shi, Lixue, et al. "Mid-infrared metabolic imaging with vibrational probes." Nature methods 17.8 (2020): 844-851.

Our approach: quantum imaging with undetected photons (QIUP)

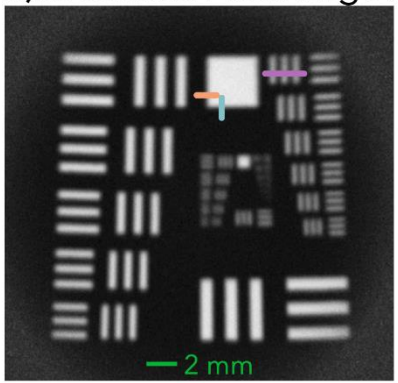


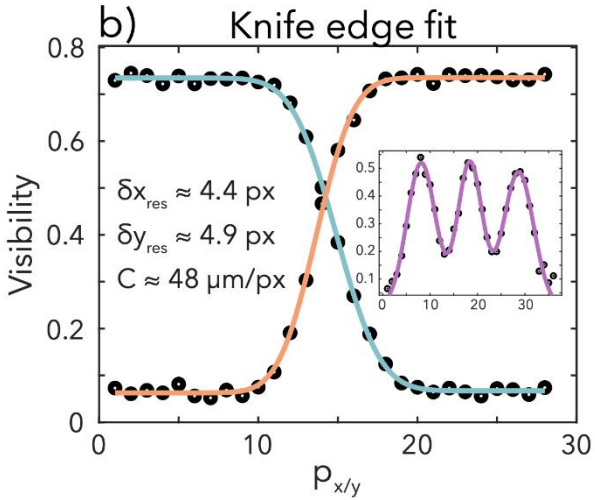
- Generation of broadband NIR + MIR biphoton (downconversion of VIS pump)
- Quantum interference of two indistinguishable SPDC processes
- Sample‘s MIR idler transmission imprinted on interferogram → NIR detectable
- Pixelwise (hyper)spectral acquisition via FTIR-scanning

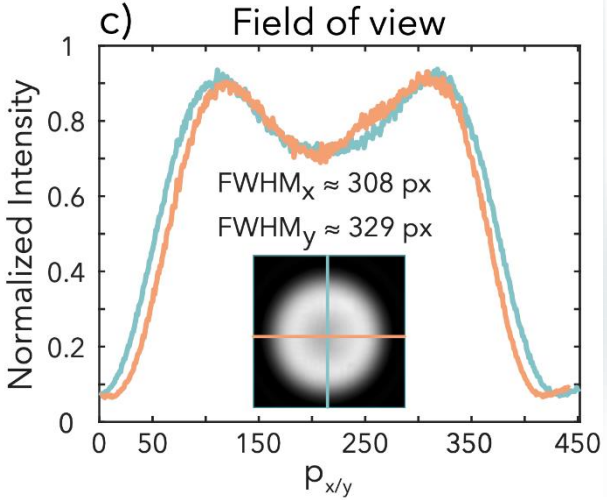
Zou, Wang, Mandel, PRL 67 3 (1991)
Lemos et al., Nature 512, 7515 (2014)
Kviatkovsky et al., Sci. Adv. **6**, eabd0264 (2020)

Imaging performance

a) Resolution test target







- MIR visibility images with approx. 70x70 spatial modes (350x350 px) recorded with narrow bandpassfilter
- 1.5 cm field of view & 220 µm resolution in the far-field of the nonlinear crystal close to theory

	Resolution	Field of View	$N_{modes, 1D}$
Experiment	220 ± 20 µm	15.3 ± 0.5 mm	69 ± 7
Theory	181 µm	14.5 mm	80

SNR scaling

- SNR derived from the ratio of mean sample-free transmission to standard deviation

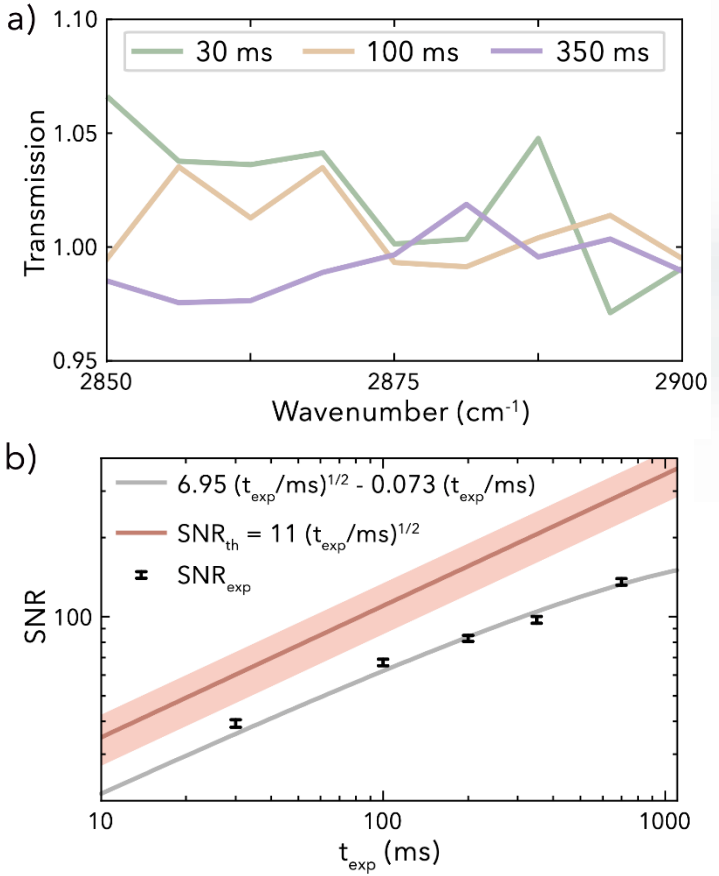
- *Exp. SNR* = 50 for t_{exp} ≈ 62 ms

  → *Hyperspectral acquisition > 350 Voxel/s*

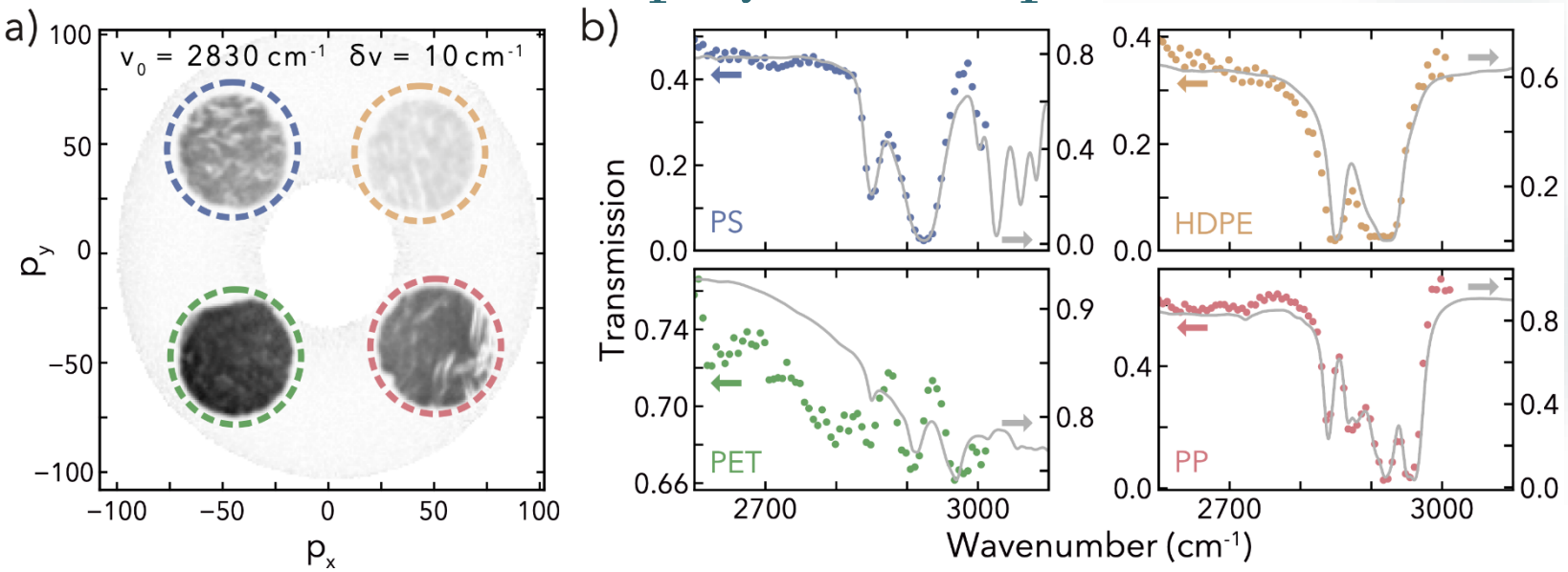
≈ 4000 XY-modes x 40 freq-modes / 410 s ≈ 390 Voxel/s @ *SNR* = 50

P_p = 310 mW @ 660 nm

- SNR approaching the shot noise limit for short to intermediate integration times



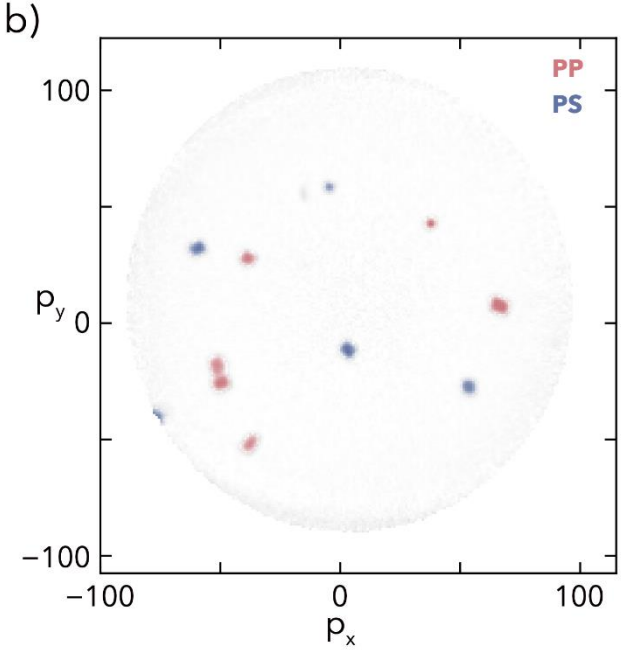
Multi-polymer samples

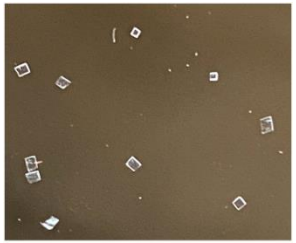


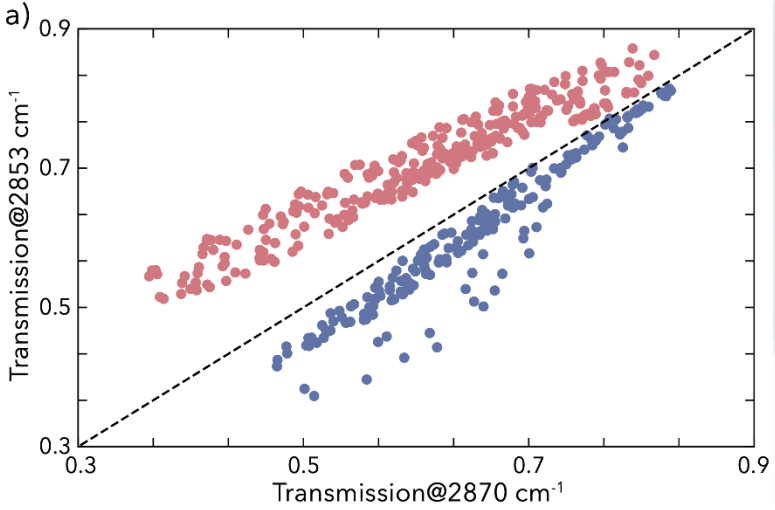
- Common polymer films with mid-IR fingerprints around 2900 cm^{-1}

- Close resemblance with **reference data from commercial FTIR spectrometer**
  - Provides training data for microplastics classification

Microplastics annotation







- Sample: PP and PS particles of Ø ≈ 250 to 500 µm on silver mirror

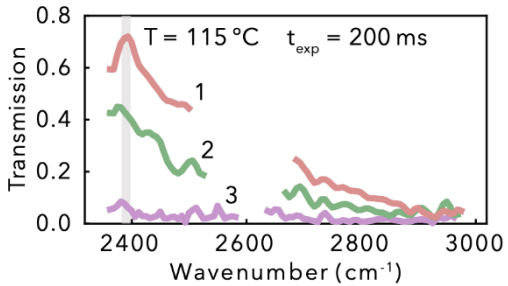
✓ Species identification by mid-IR fingerprints

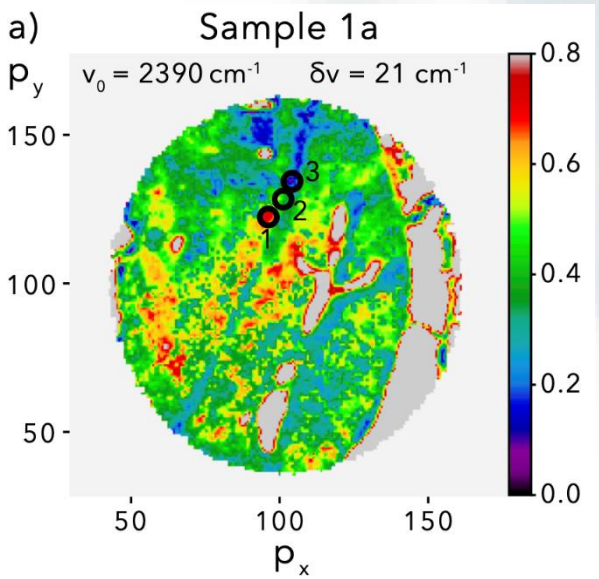
✓ Unambiguous annotation from linear decision boundaries in the joint spectral transmission diagram

Label-free histology





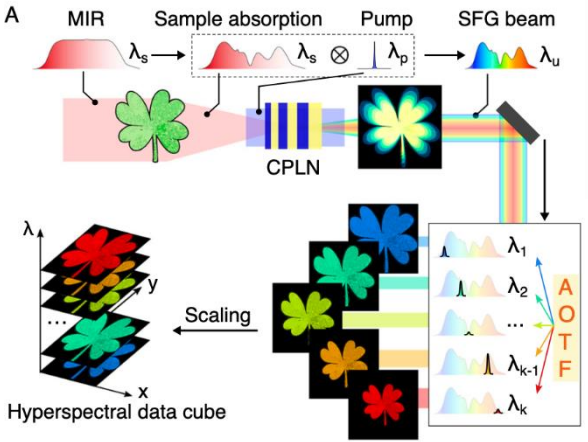




- Sample: paraffine-removed rat liver tissue
- Opaque images around CH stretch modes ~ 2850 cm^{-1}, partially high transparency around 2400 cm^{-1}
- Shortwave loss beyond Rayleigh scaling (~ λ^{-2}) → true absorption witnesses

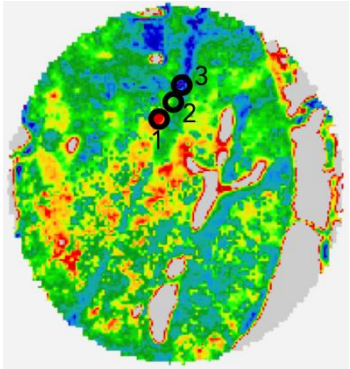
Hyperspectral methods comparison

Method	Special resources	Downsides	Upsides	Cost	Hyperspectral frame rate	Refs
FTIR imager	MIR detector arrays	Detector cooling, Full scans required	Robust, benchmark technology	>200 k€	Sub Hz to Hz	10.1039/C5CS00846H Pilling et al. *Chemical Society reviews* 45.7 (2016): 1935-1957.
Raman spectroscopy (mapping)	Fast, synchronized, tunable lasers, EMCCDs, mapping stage	High intensity exposure, expensive	High spatial resolution, λ-selective	>300 k€	Hz to video rate	10.1126/science.1197236 Saar et al. *Science* 330.6009 (2010): 1368-1370.
Supercont. upconversion	Broadband MIR lasers+tunable NIR filter, fast CMOS camera, NL crystal		Highest frame rates, λ-selective	>120 k€	Video and beyond (20 to 100 Hz)	doi.org/10.1038/s41467-024-46274-z Fang et al. Nat. Comm. (2024)
NLI FTIR	CMOS camera, NL crystal	Full scans required, Low light conditions	Low cost, Low sample exposure	>20 k€	Sub mHz to sub Hz	This work Placke et al. Optica (2026)
Dual Comb Spectroscopy (mapping)	Dual comb source, mapping stage	Bandwidth-Resolution tradeoff	High spectral resolution possible	>180 k€	sub Hz	arXiv:2407.01973v1 Chang, Peter, et al. *APL photonics* 9.10 (2024).

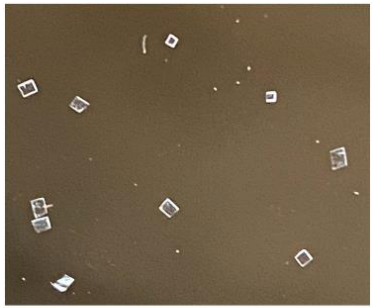


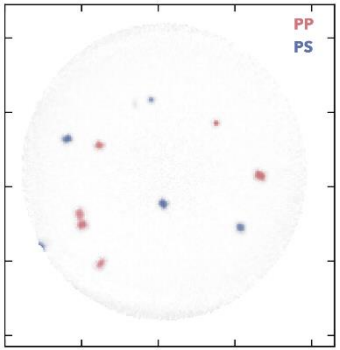
Conclusions

- Hyperspectral imaging is a real-world analytics task actively evolving with advancements in modern MIR instruments
- Undetected photons enable a cost-efficient label-free and nondestructive detection best-suited for photosensitive samples
- First demonstration verified applicability to bio-tissue and microplastics detection and found nearly shot noise limited acquisition
- Next step: improve acquisition speed and spatial resolution via cavity enhanced SPDC and microscope objectives









– 2 mm

For details see: M. Placke et al., "Mid-IR hyperspectral imaging with undetected photons," Optica 13, 328-335 (2026)