The Planar Scanning Probe Microscope: A Novel Platform for Quantum Sensing and Near-Field Microscopy

Friedemann Reinhard, Technical University Munich

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- Nearly 3000 members worldwide
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- Where to find us:

➢ **OSA Webpage** https://www.osa.org/oq

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Welcome to the Quantum Optical Science and Technology Technical Group Webinar!

The Planar Scanning Probe Microscope: A Novel Platform for Quantum Sensing and Near-Field Microscopy

31 March 2021 • 12:00 EDT (UTC -4:00)

OSA Quantum Optical Science and Technology Technical Group

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A Planar Scanning Probe Microscope

a novel approach to magnetic imaging and near-field microscopy

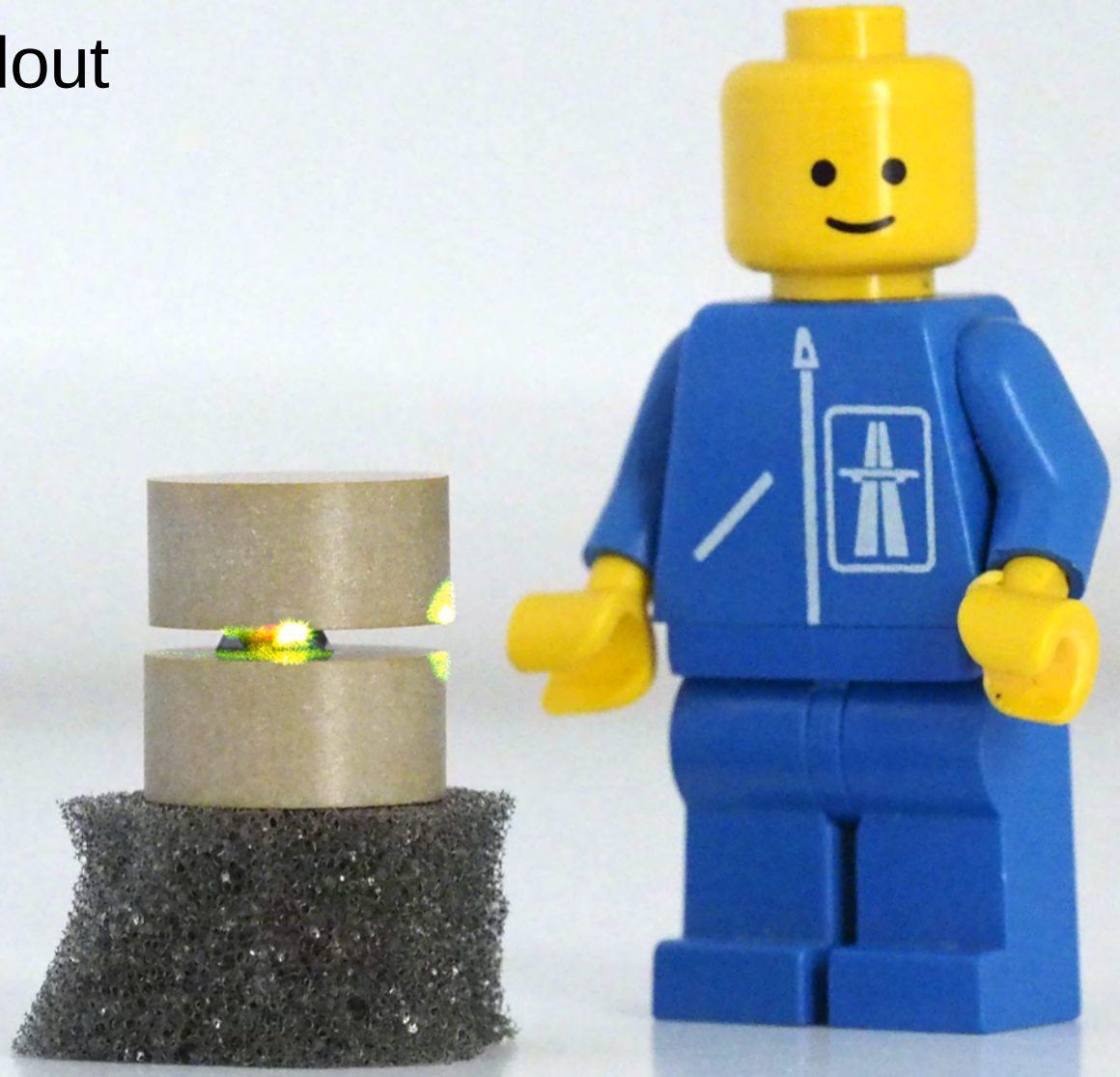
Paul Weinbrenner, Stefan Ernst, Dominik Irber
Friedemann Reinhard

Walter Schottky Institut
Technical University of Munich

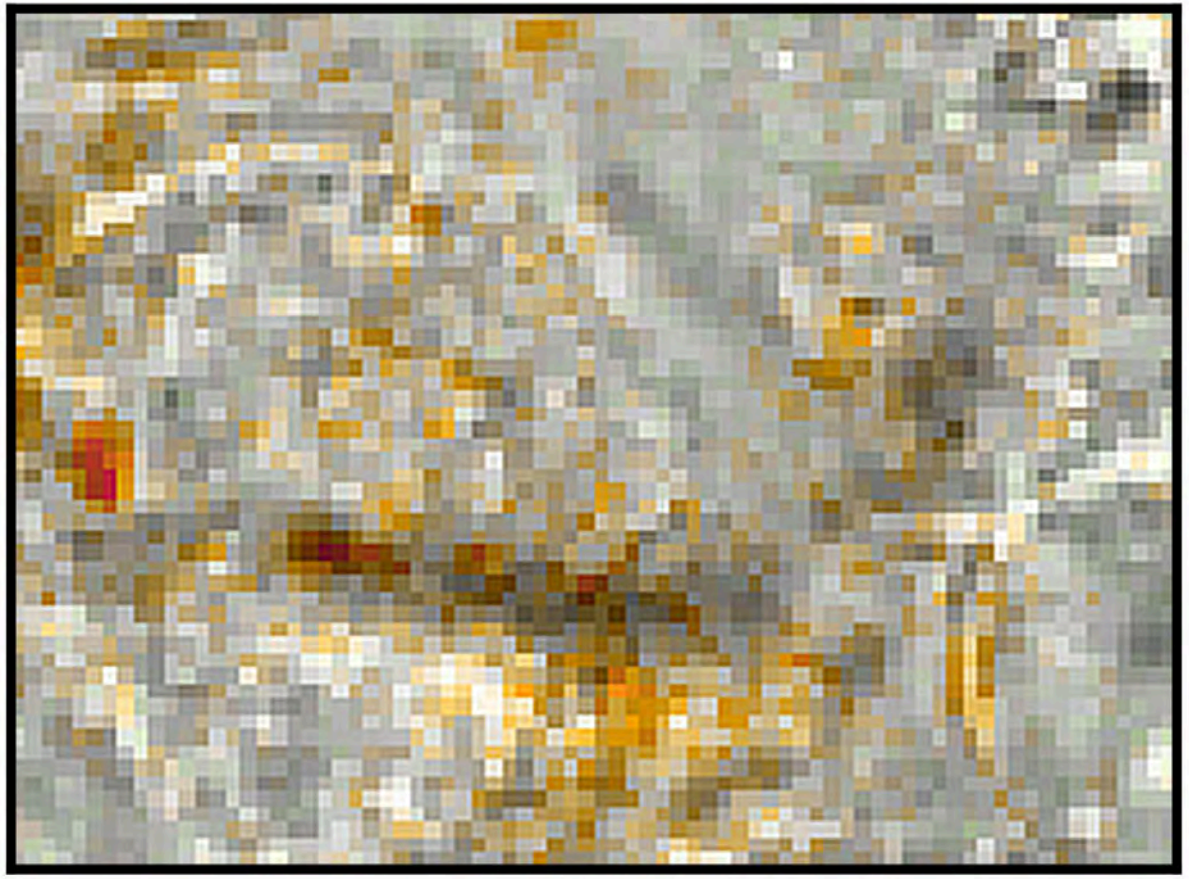
Institut für Physik
University of Rostock

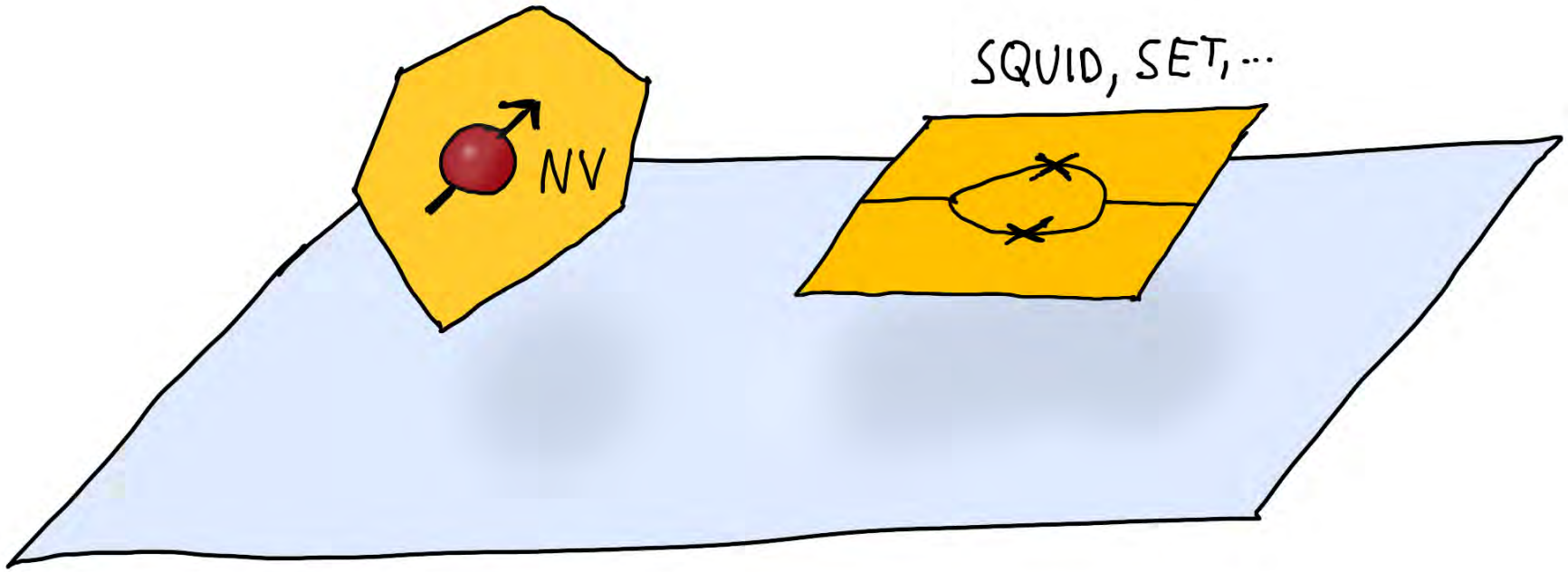
Ernst ... Reinhard, ACS Photonics **6**, 327 (2019)

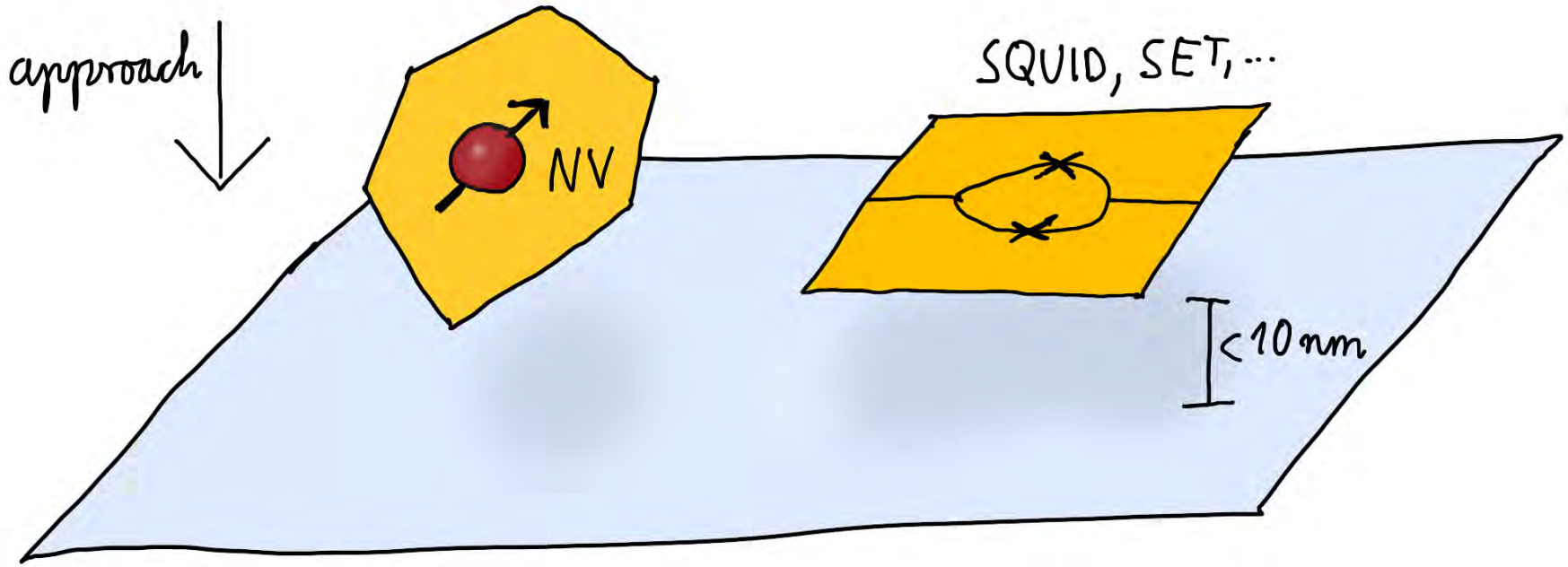
Our research – electric readout

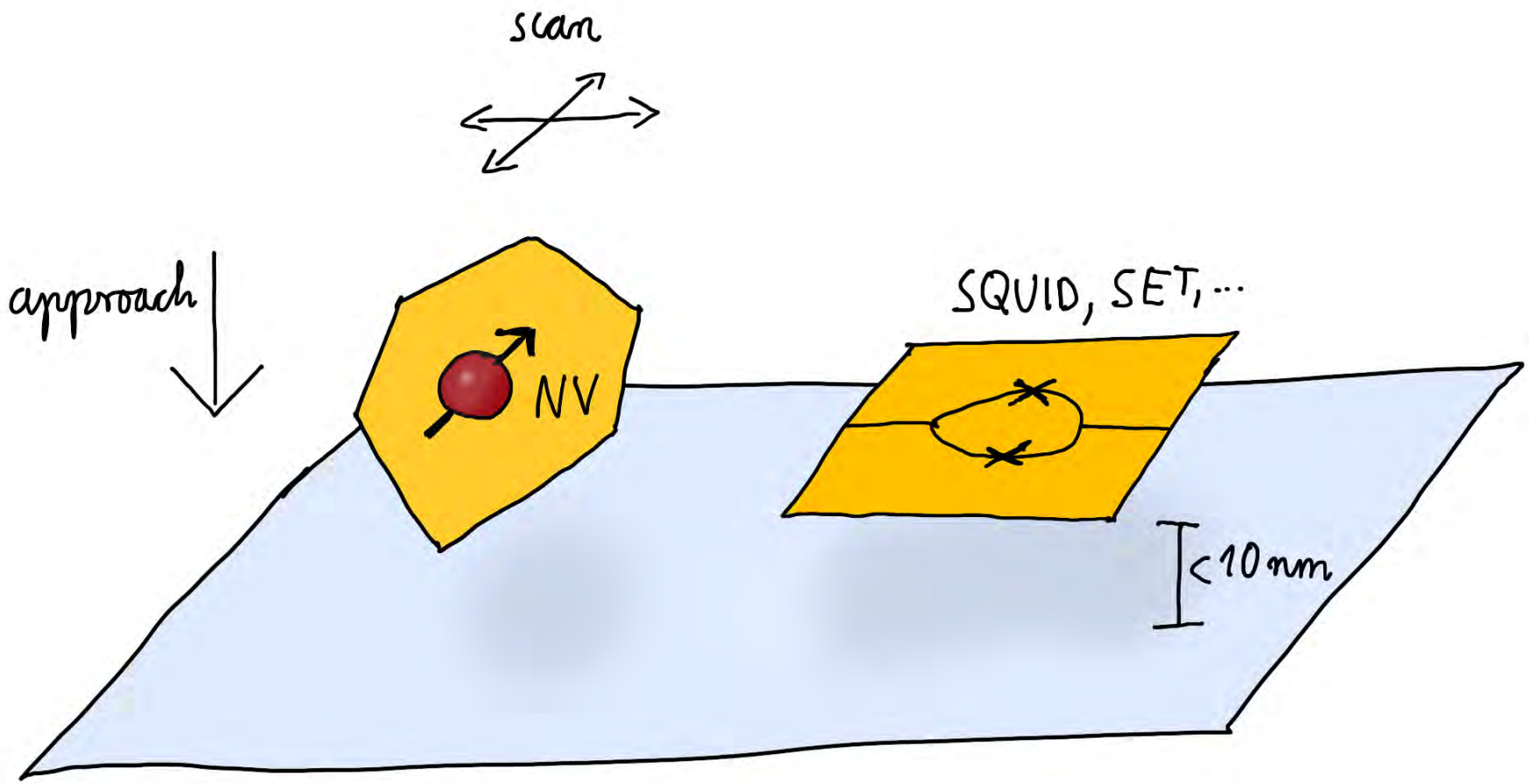


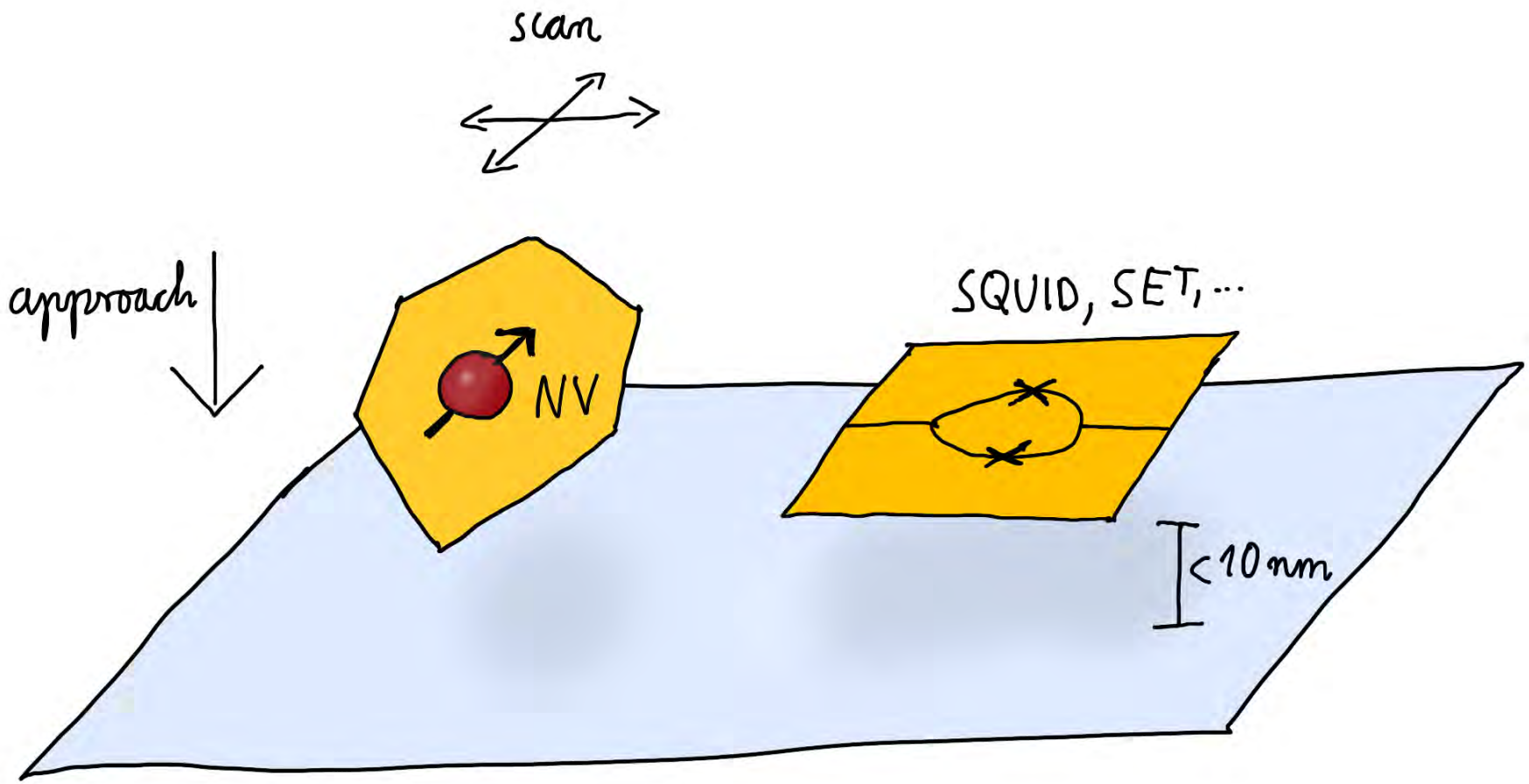
Our research – novel microscopy schemes

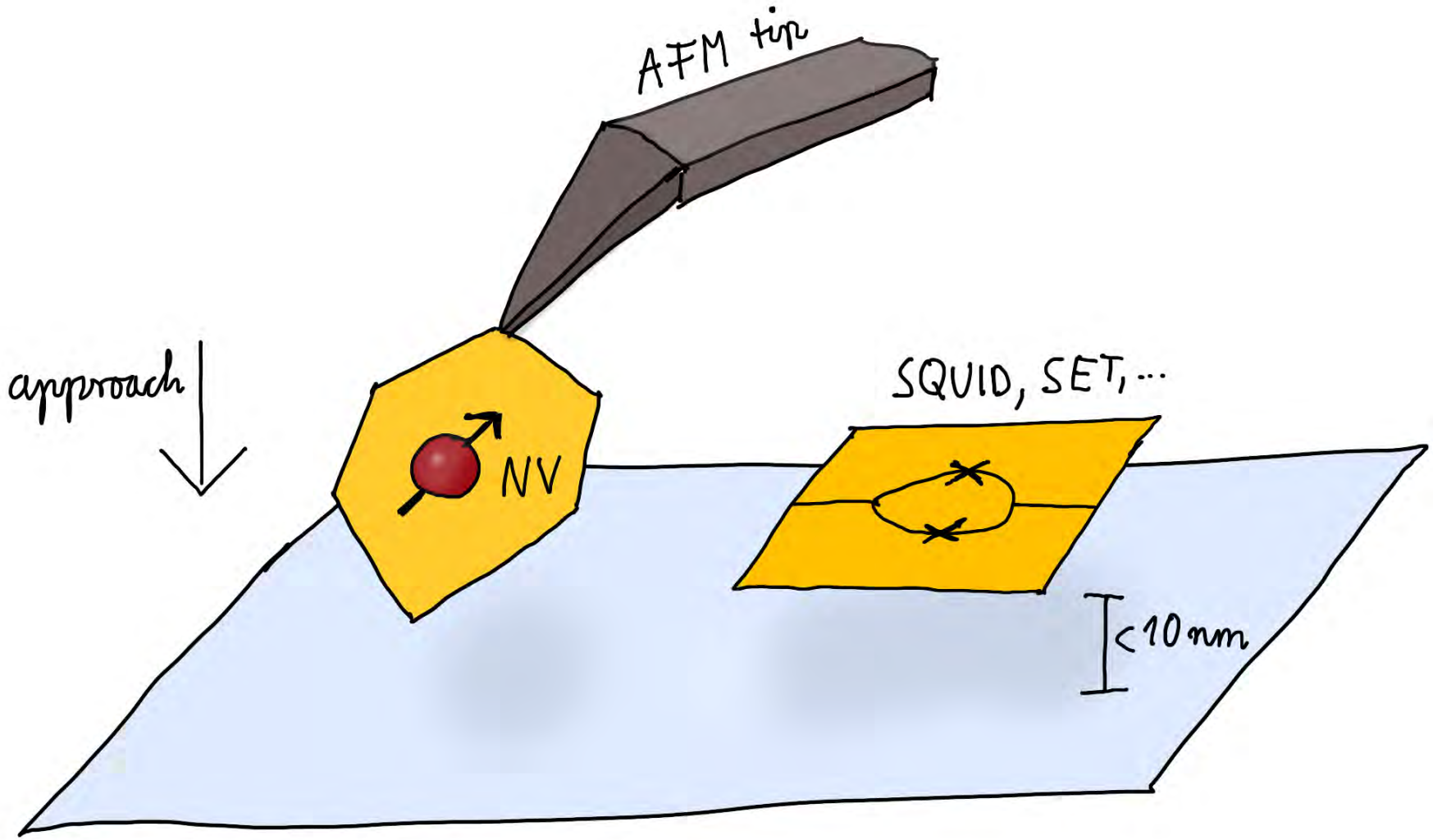



SQUID, SET, ...
NV

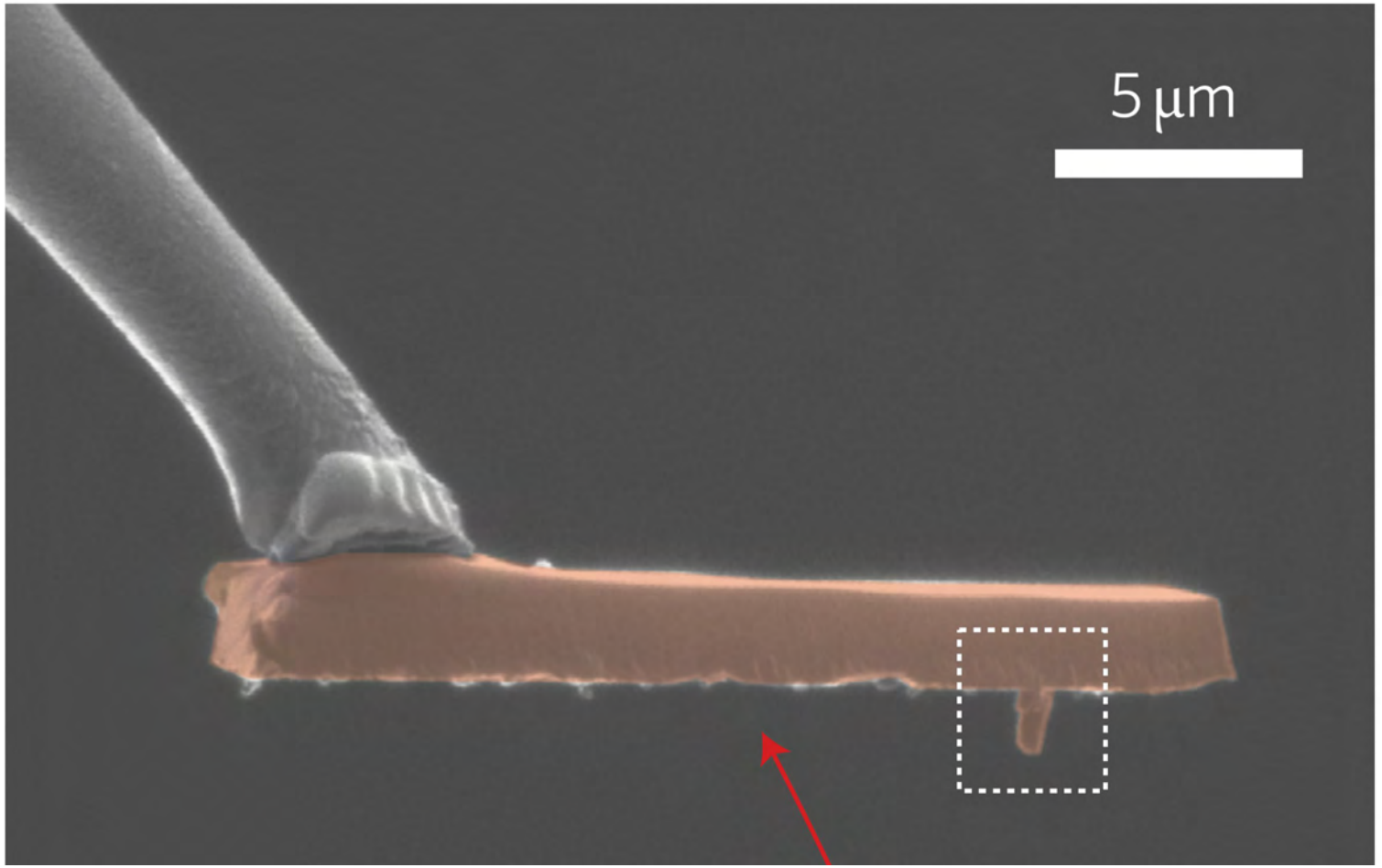

approach
NV
SQUID, SET, ...
< 10 nm


scan
approach
NV
SQUID, SET, ...
< 10 nm


scan
approach
NV
SQUID, SET, ...
< 10 nm

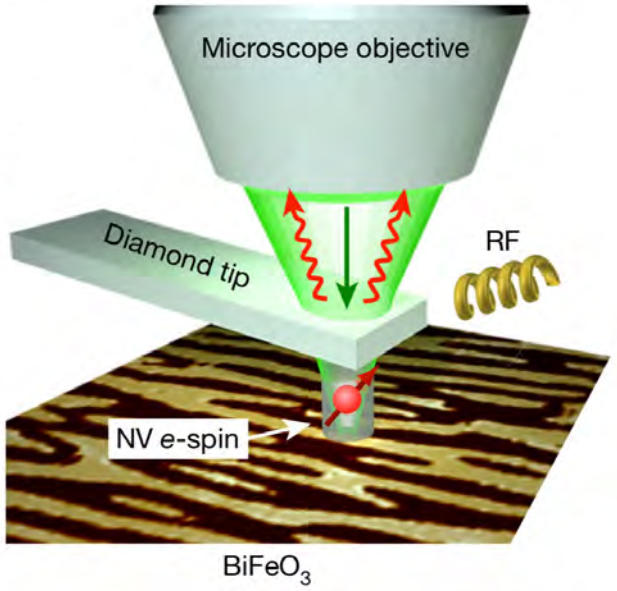

AFM tip
approach
NV
SQUID, SET, ...
< 10 nm

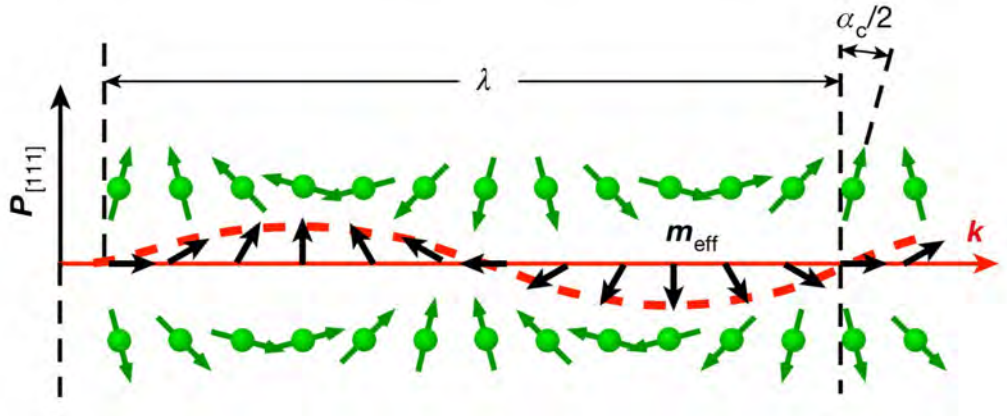
Magnetic microscopes

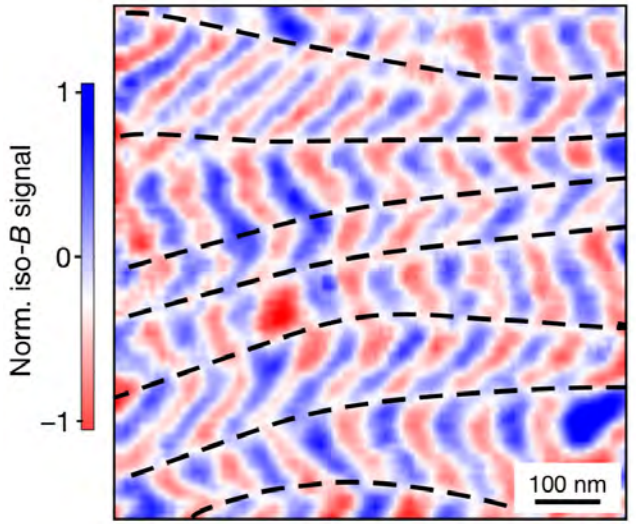


Maletinsky … Yacoby, Nat Nano **7**, 320 (2012)

Imaging antiferromagnetic (!) order

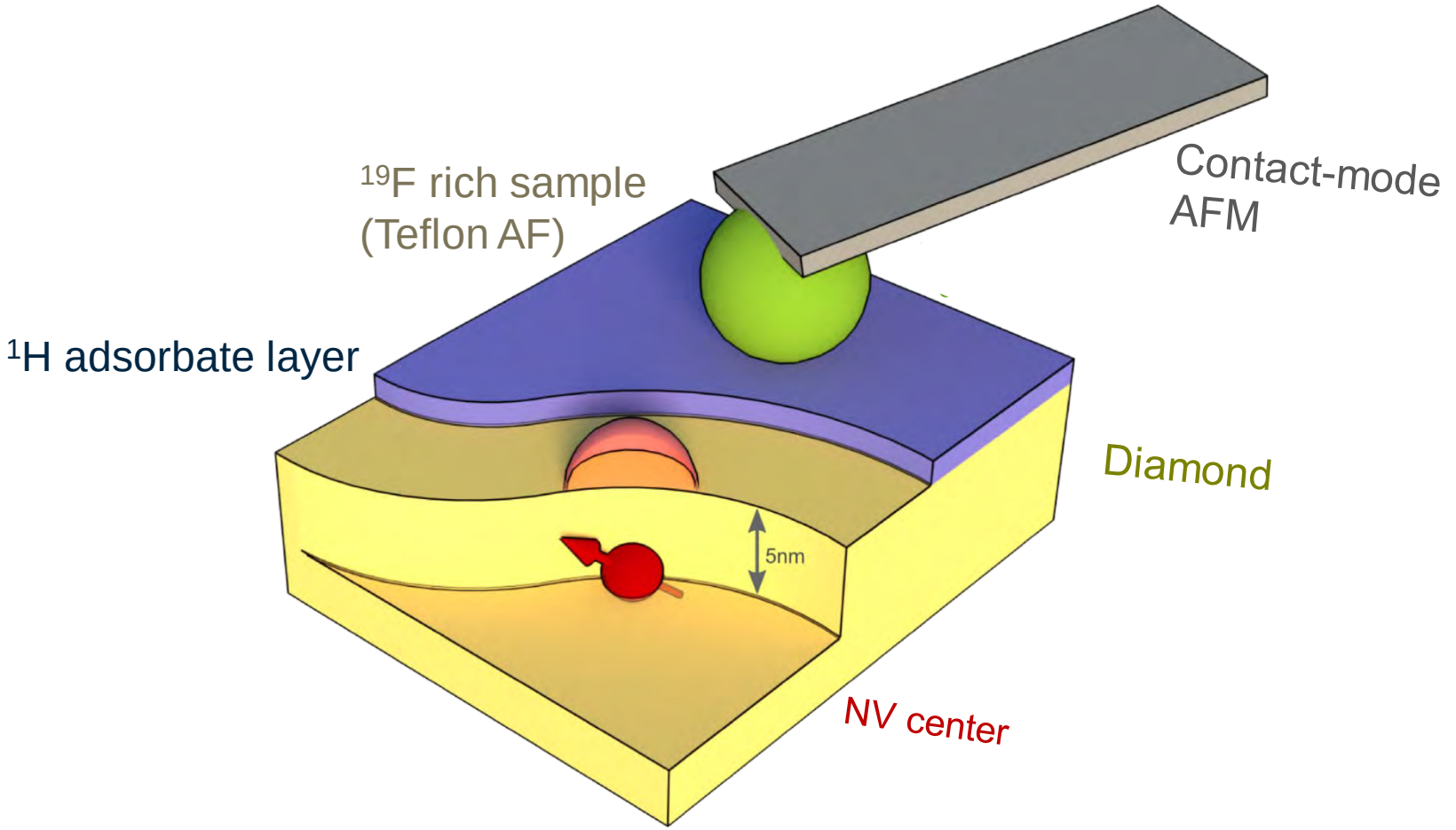






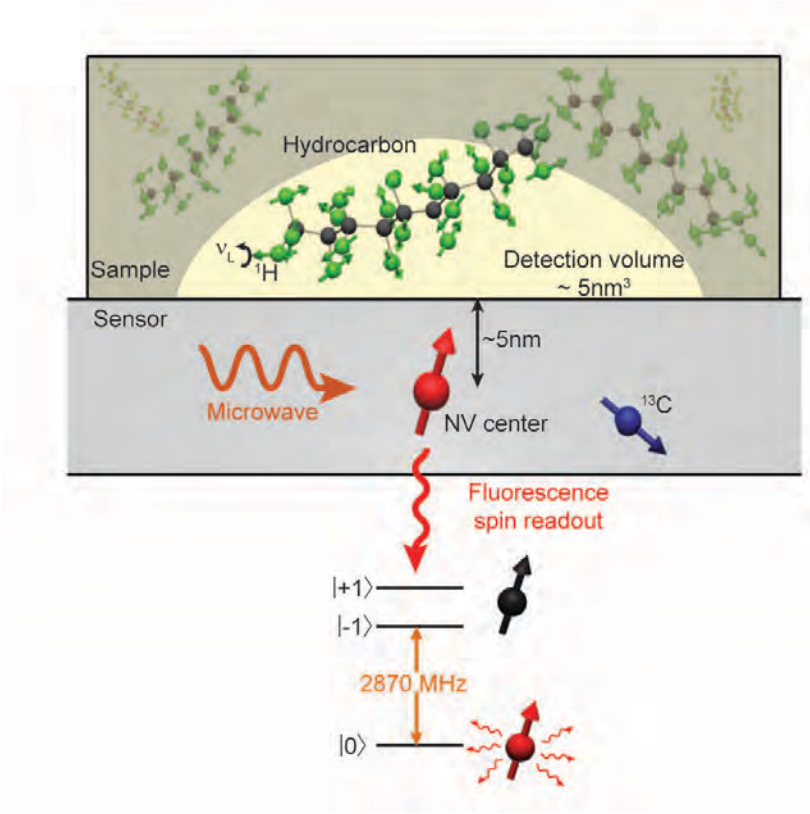
Gross ... Jacques, Nature **549**, 252 (2017)

Scanning Probe Magnetic Resonance Imaging (MRI)



Häberle ..., Reinhard, Wrachtrup, Nature Nanotechnology **10**, 125 (2015)
Rugar ... Awschalom, Nature Nanotechnology **10**, 120 (2015)

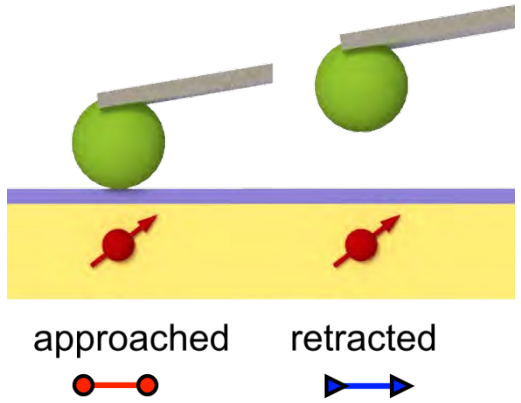
NMR spectroscopy on a $(5nm)^3$ sample volume[1,2]



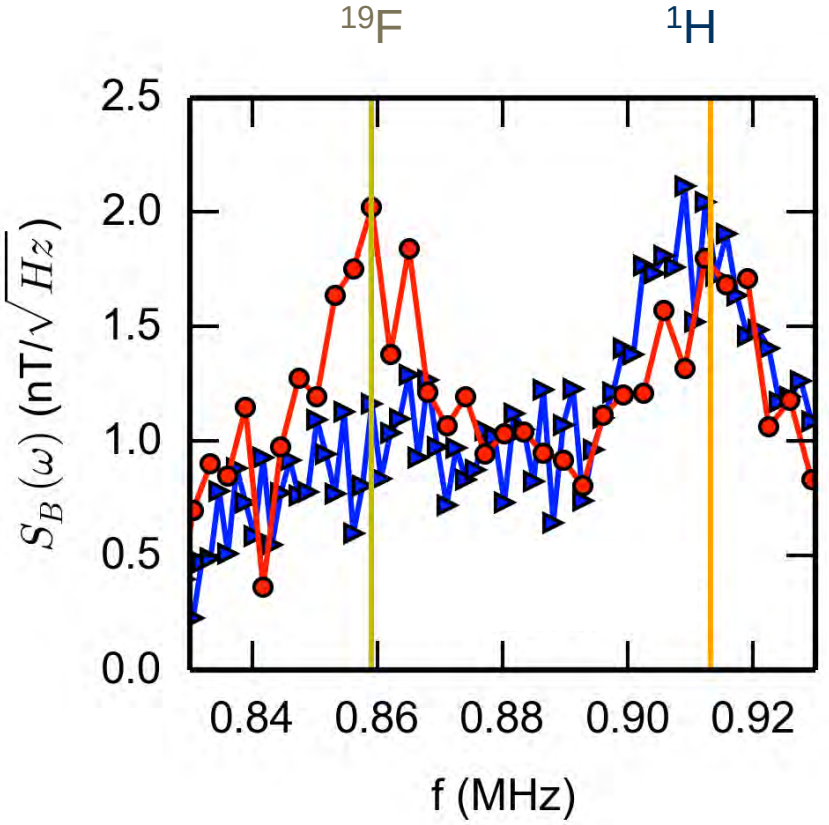
- Coat diamond surface with organic sample (containing ^{1}H nuclei)
- Detect NMR signal by single NV center few nanometers beneath the surface

[1]T. Staudacher et al., Science **339**, 561 (2013)
[2]H.J. Mamin et al., Science **339**, 557 (2013)

Detection of multiple nuclear species

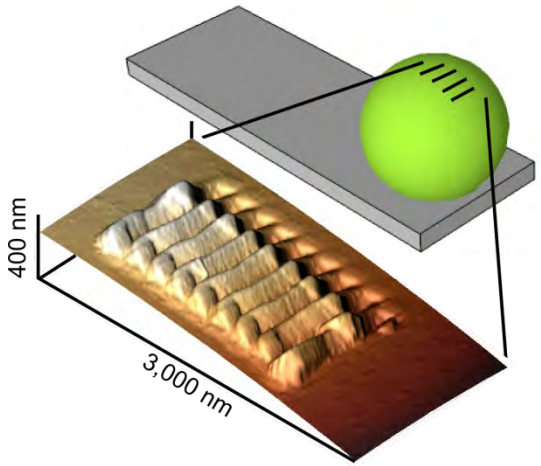


- ^{1}H signal, constant
- ^{19}F signal, switchable



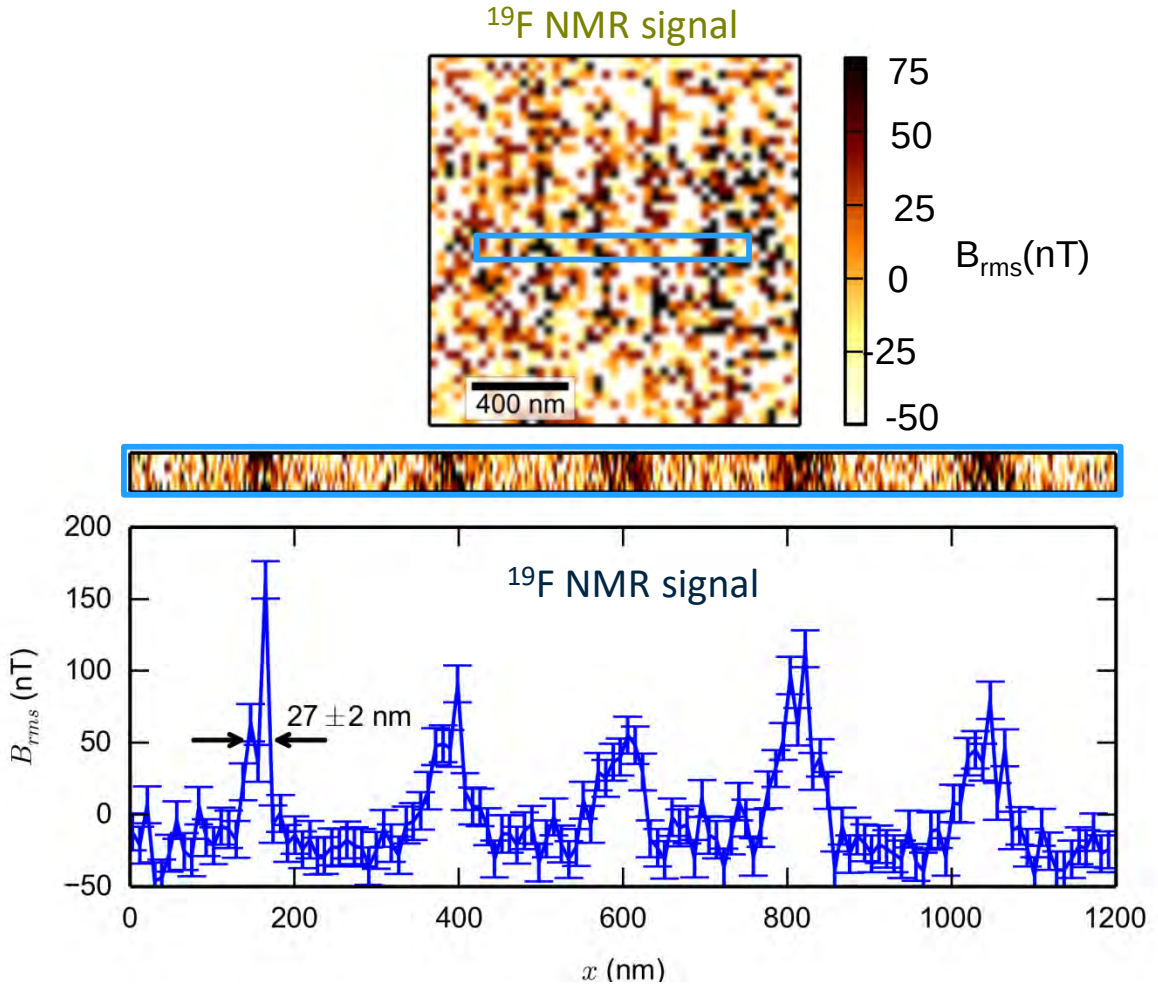
Häberle ..., Reinhard, Wrachtrup, Nature Nanotechnology **10**, 125 (2015)
Rugar ... Awschalom, Nature Nanotechnology **10**, 120 (2015)

Magnetic Resonance Imaging



nano-structured Teflon® AF sample

- Smallest structure ever imaged by MRI @300K

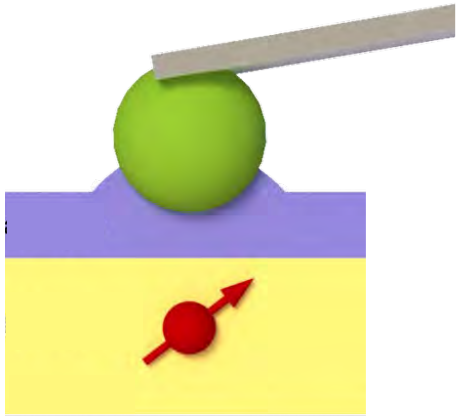


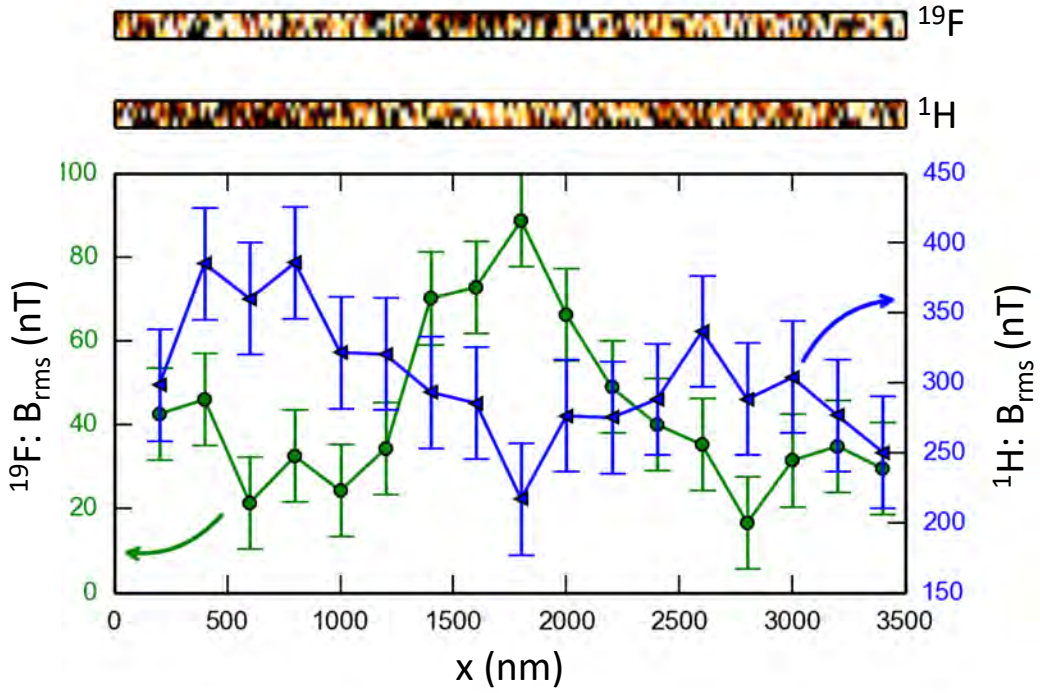
Häberle ..., Reinhard, Wrachtrup, Nature Nanotechnology **10**, 125 (2015)
Rugar ... Awschalom, Nature Nanotechnology **10**, 120 (2015)

MRI with chemical contrast

^{19}F sample

^{1}H sample (oil)

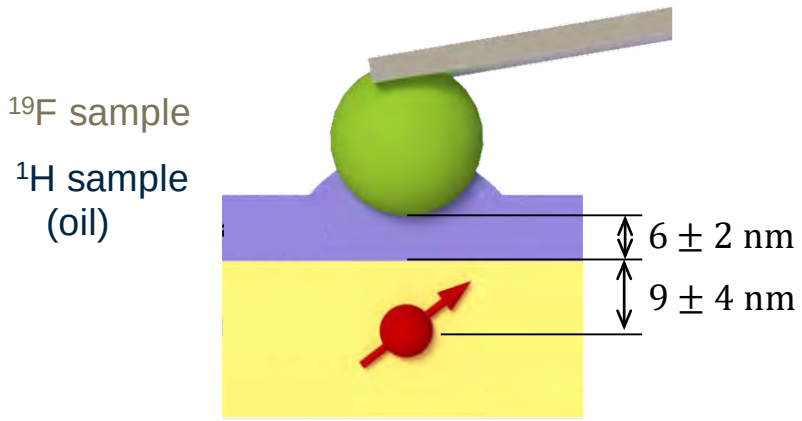


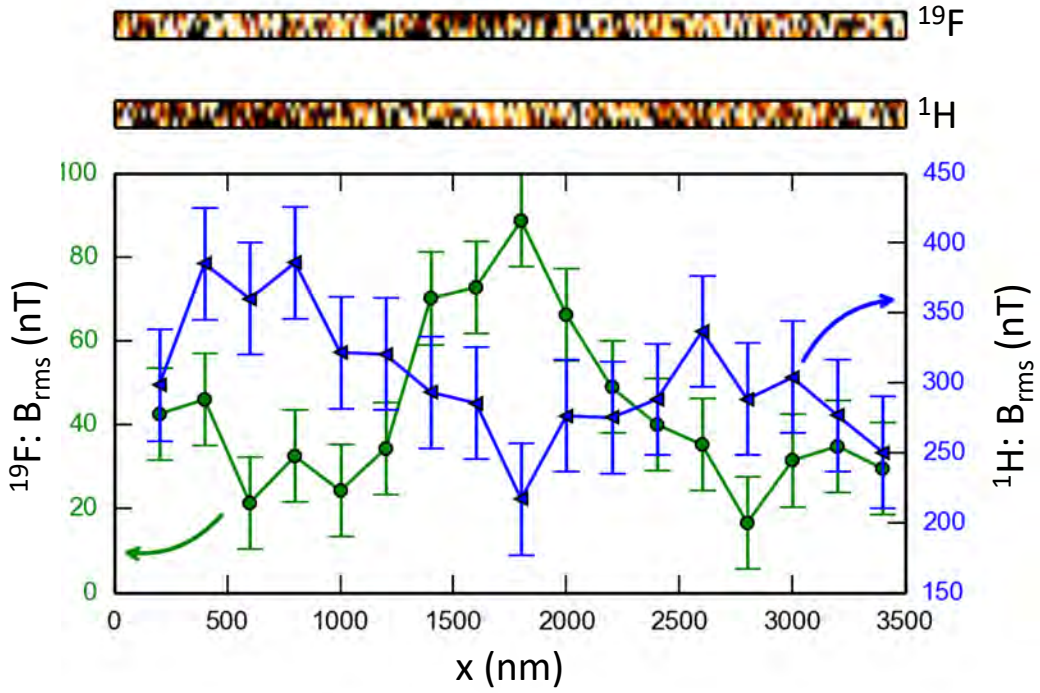


- Distinguish different chemical species in one scan
- Image indentation of ^{1}H layer

Häberle ..., Reinhard, Wrachtrup, Nature Nanotechnology **10**, 125 (2015)
Rugar ... Awschalom, Nature Nanotechnology **10**, 120 (2015)

MRI with chemical contrast

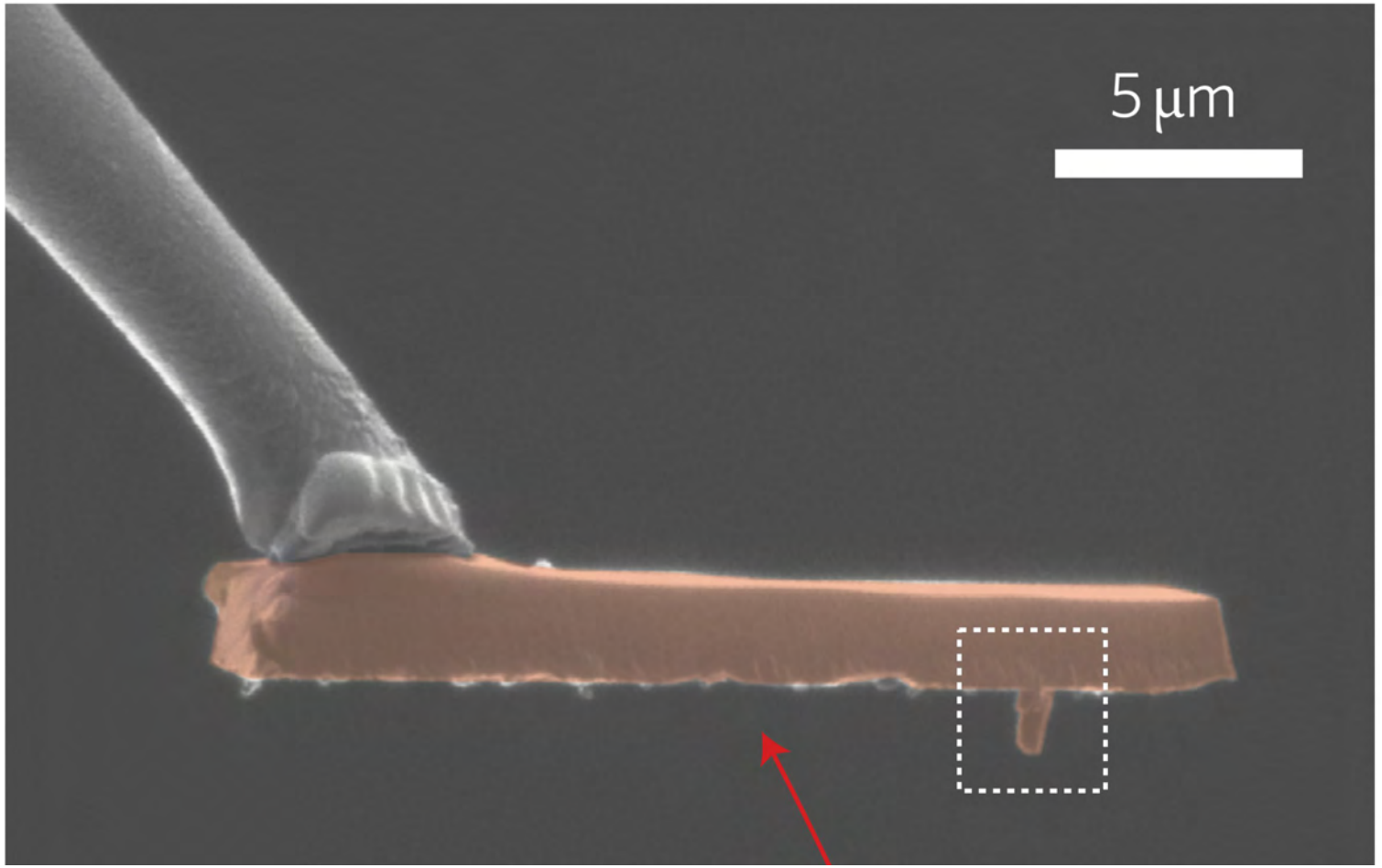




- Quantitative NMR
  ⇒ Distance estimation
- 3D imaging of multilayer system
- Distinguish different chemical species in one scan
- Image indentation of ^{1}H layer

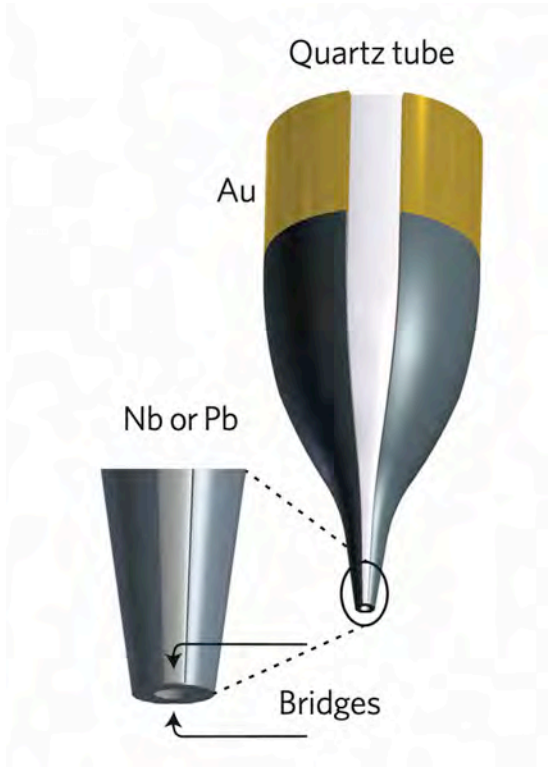
Häberle ..., Reinhard, Wrachtrup, Nature Nanotechnology **10**, 125 (2015)
Rugar ... Awschalom, Nature Nanotechnology **10**, 120 (2015)

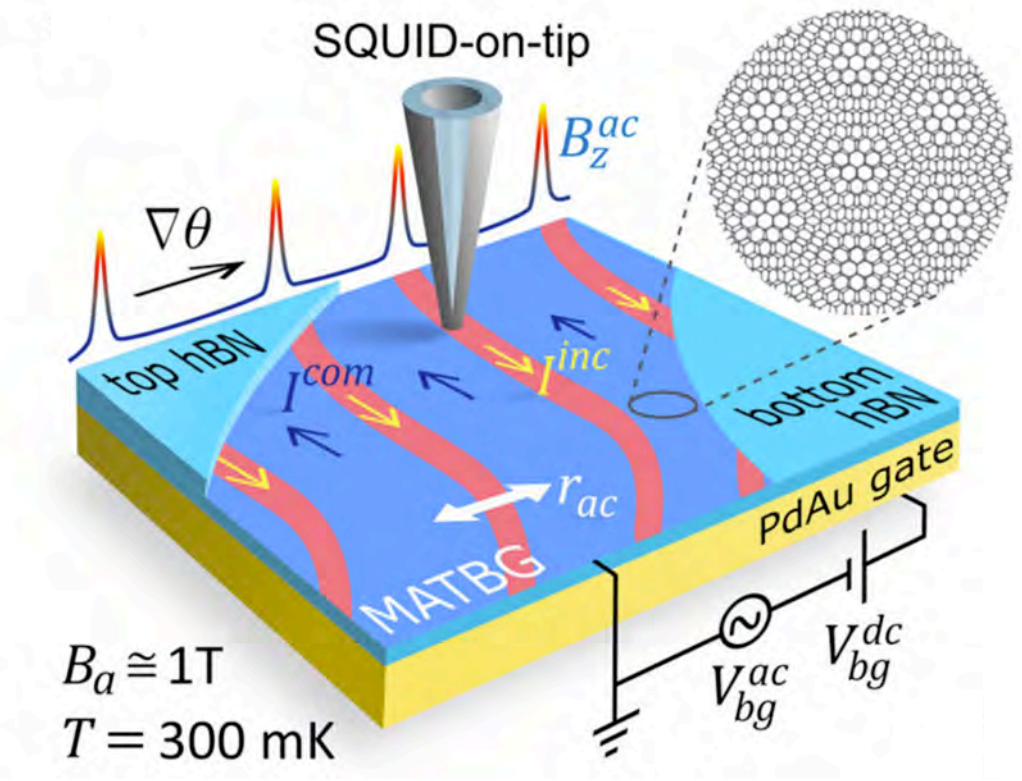
Magnetic microscopes



Maletinsky … Yacoby, Nat Nano **7**, 320 (2012)

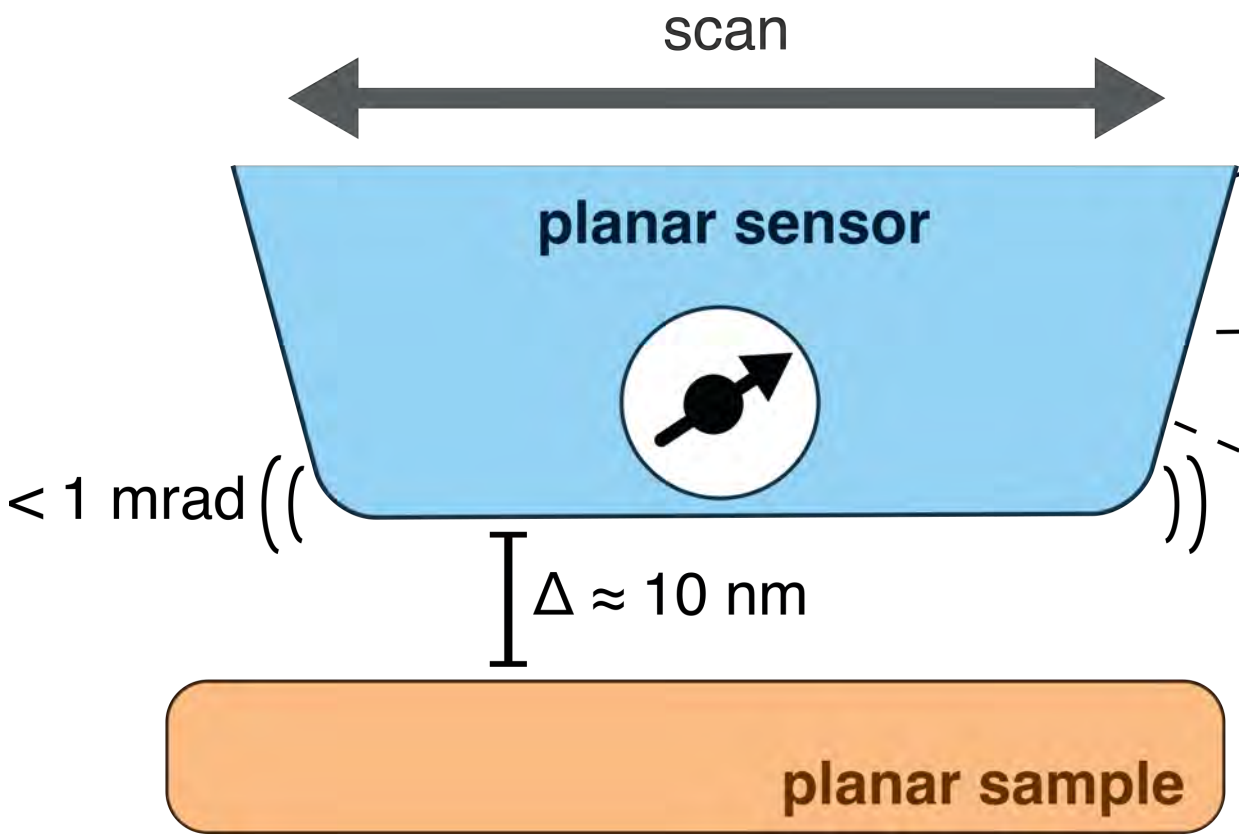
Nano-SQUIDs





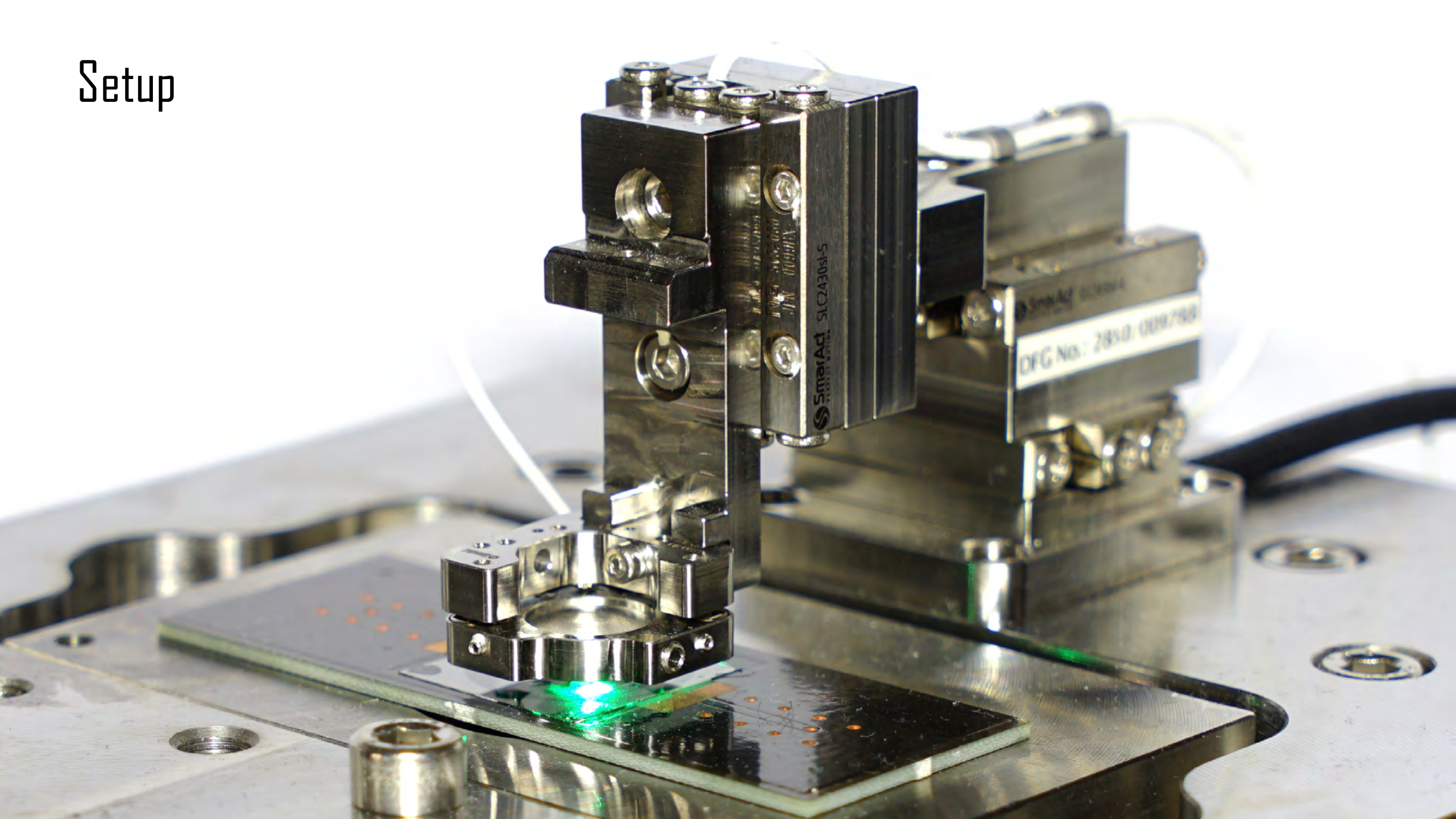
Finkler ... Zeldov, Yacoby, Nano Letters **10**, 1046 (2010)
Vasyukov ... Zeldov, Nature Nanotechnology **8**, 639 (2013)
Uri ... Zeldov, Nature **581**, 47 (2020)

Do we really need a tip?

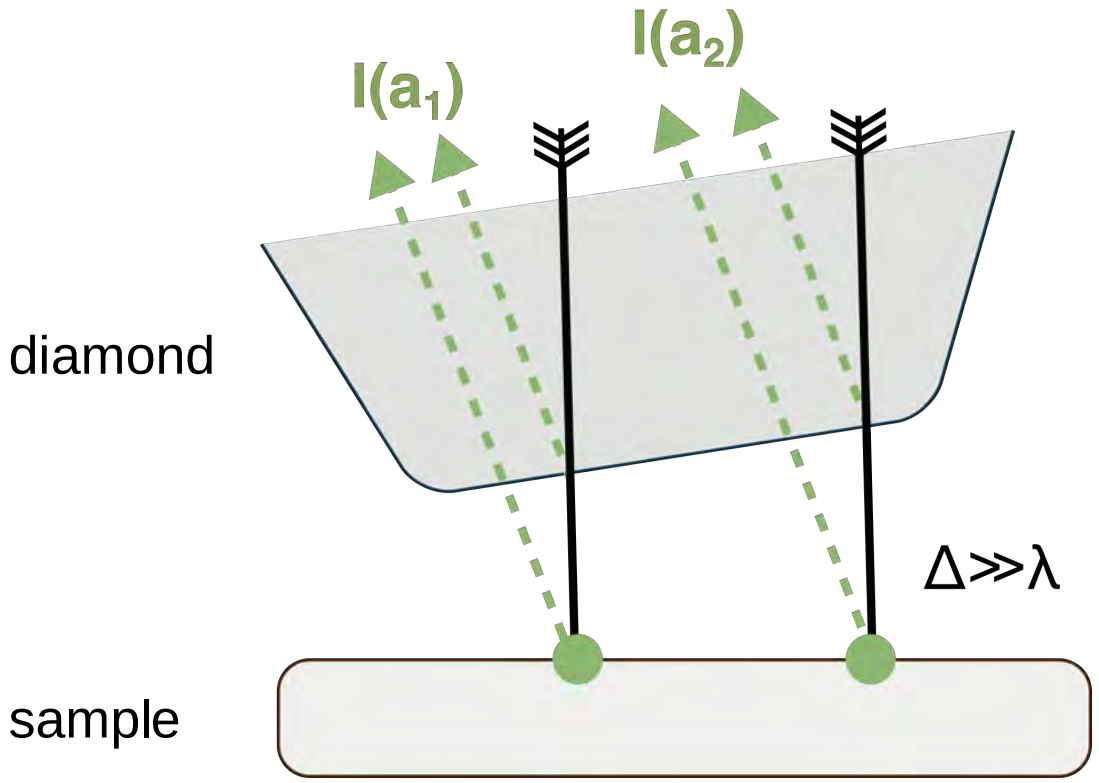


Ernst ... Reinhard, ACS Photonics **6**, 327 (2019)
Fringes ... Knoll, Beilstein J. Nanotechnology **9**, 301 (2018)

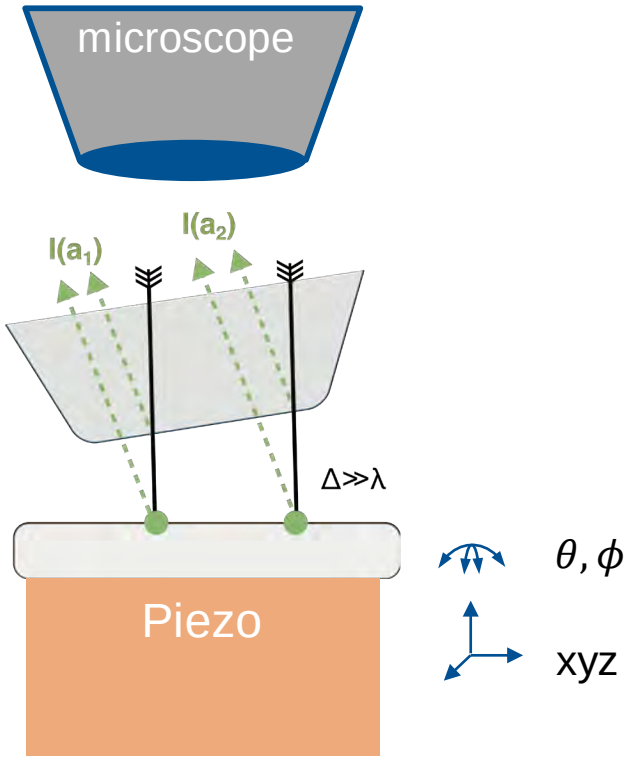
Setup



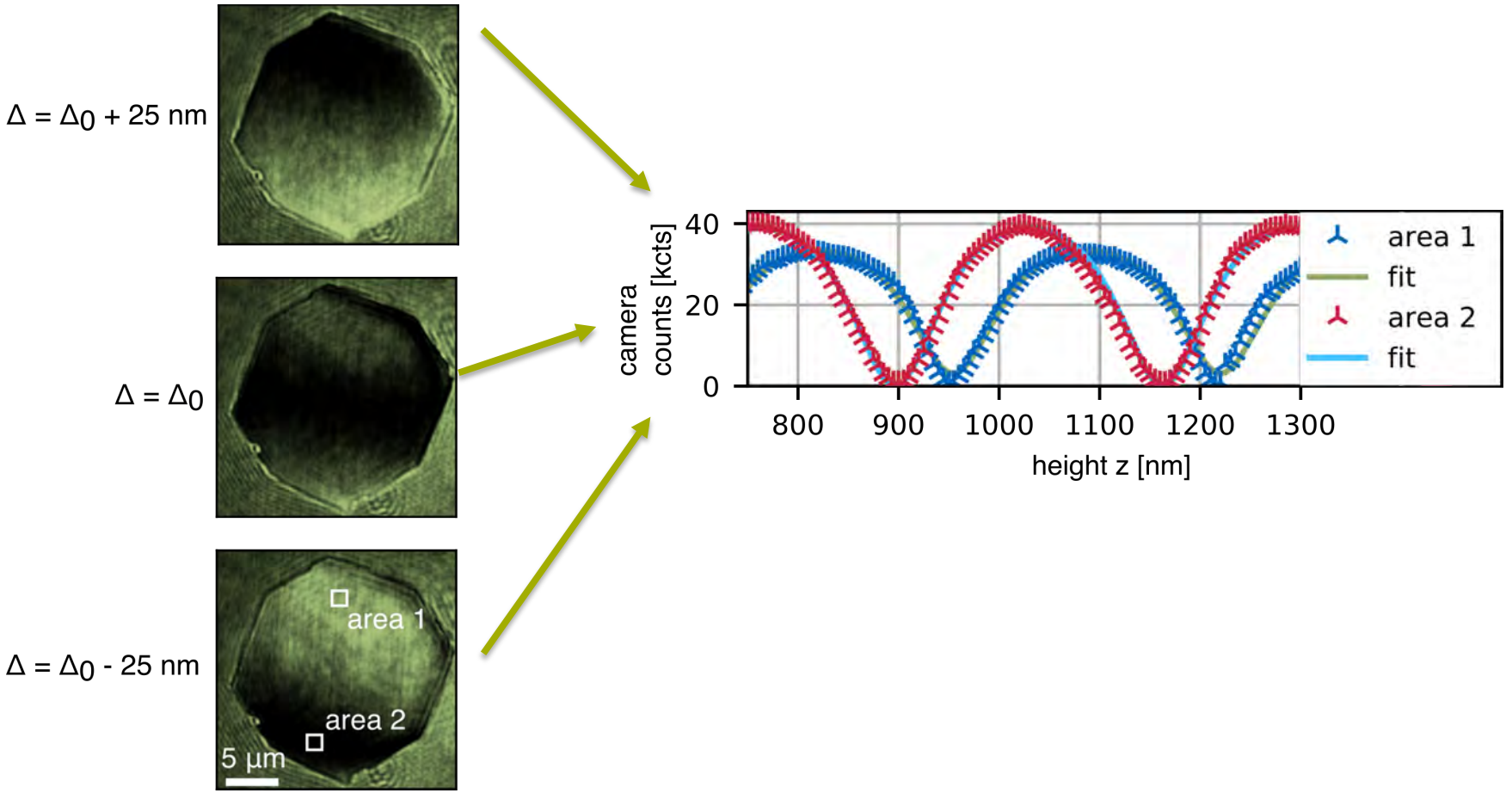
Alignment – Newton's fringes



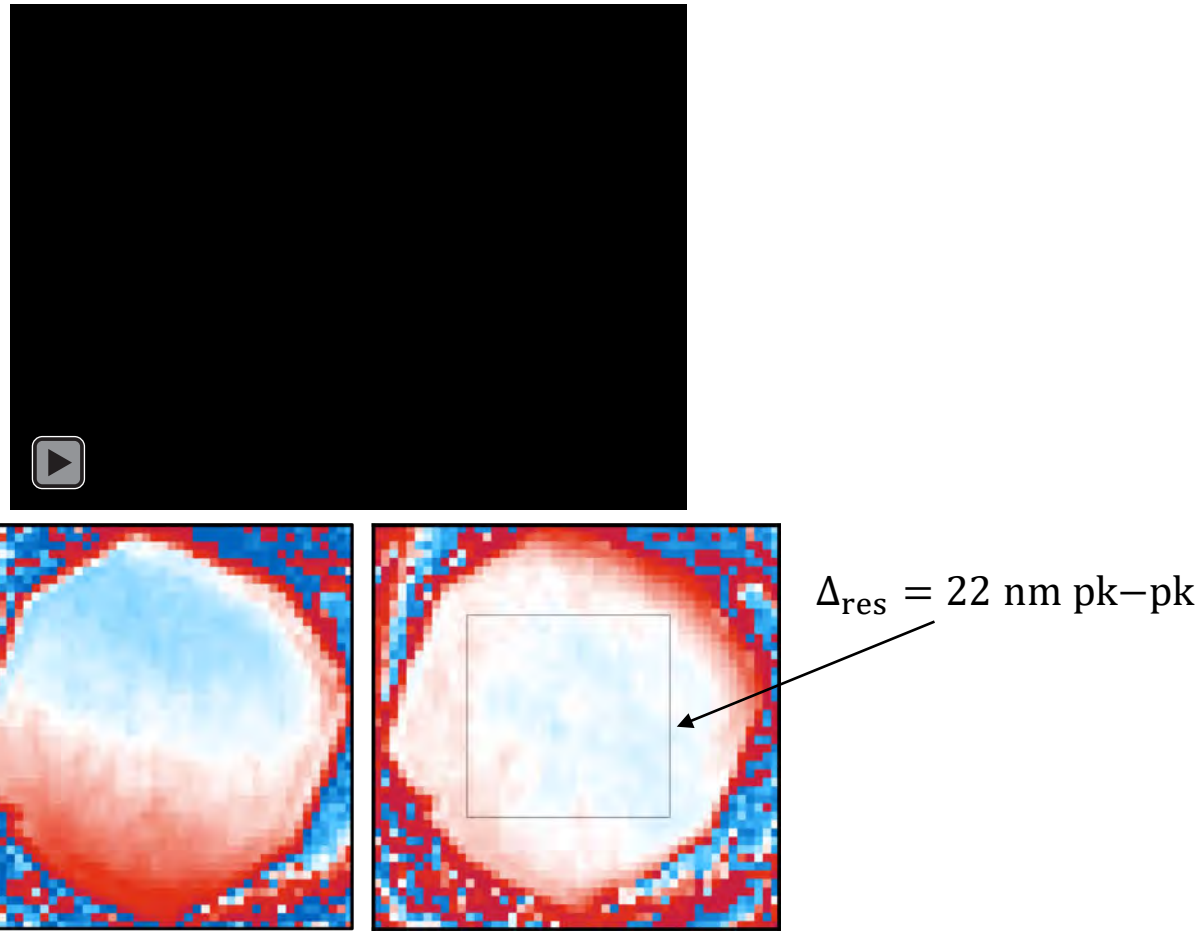
Alignment – Newton's fringes



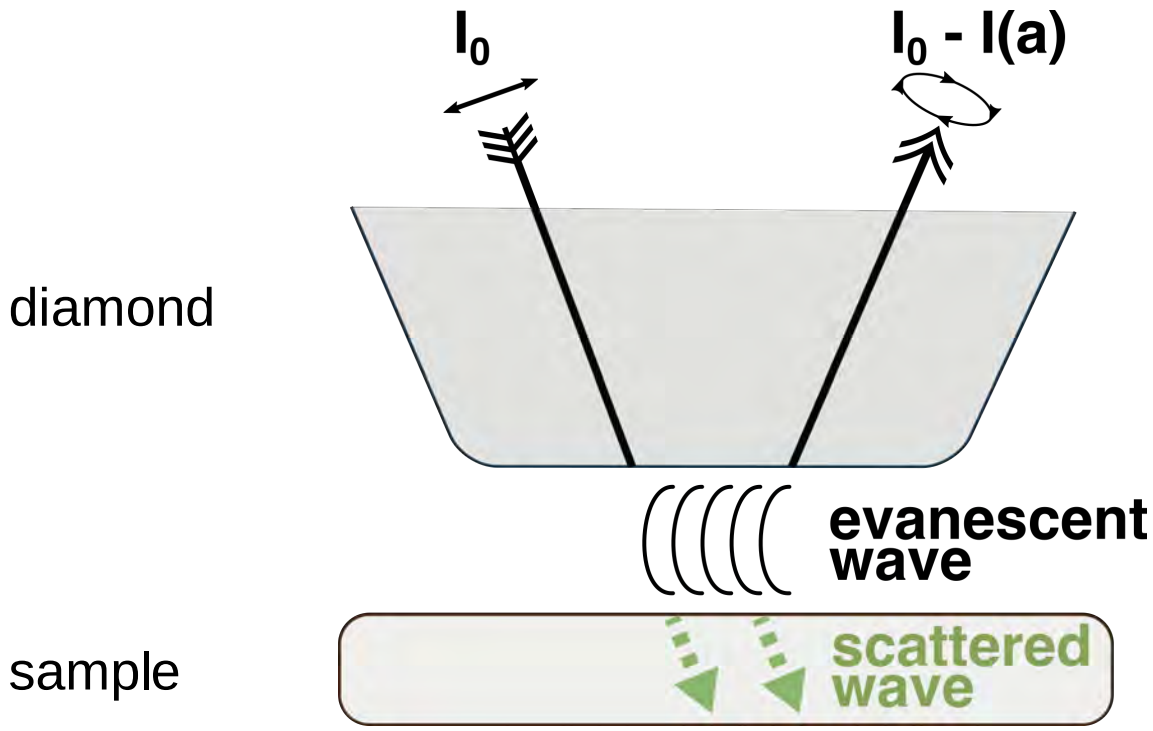
Alignment – Newton's fringes



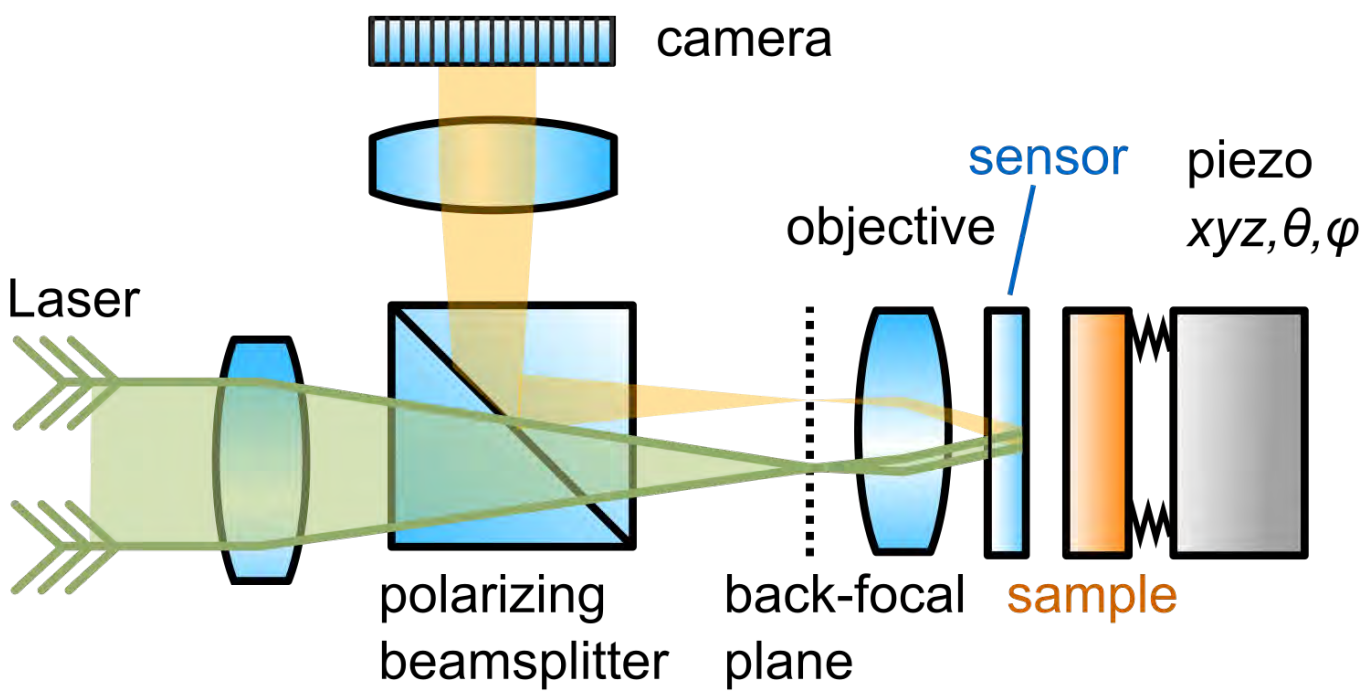
Alignment – Newton's fringes



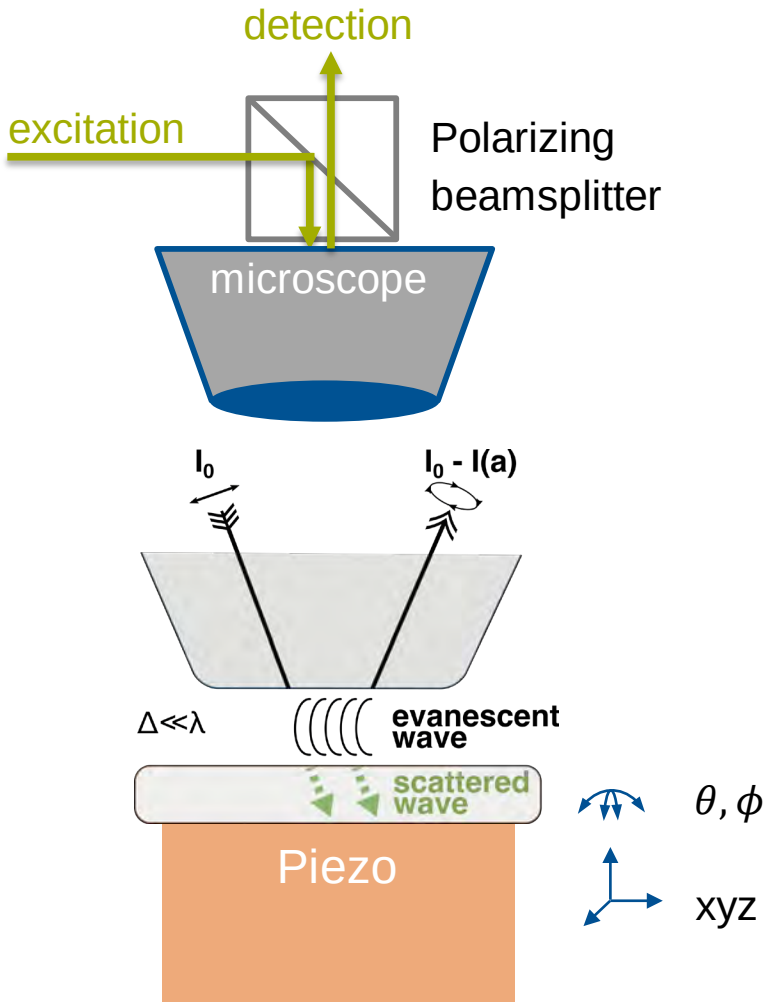
Distance control – polarisation TIR microscopy



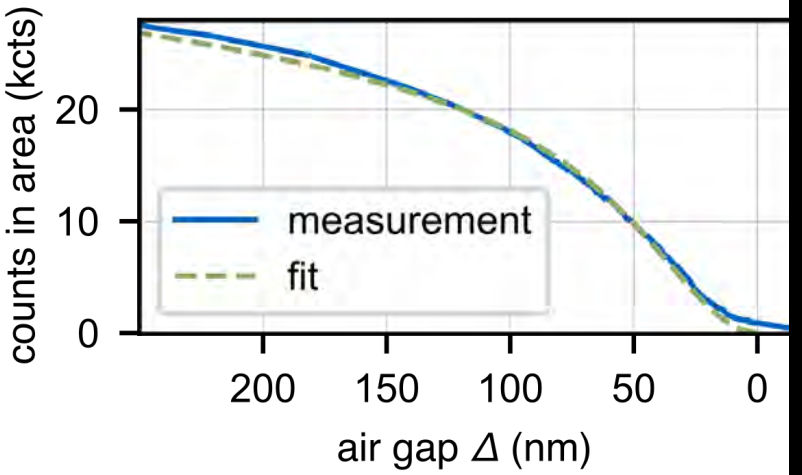
Distance control – polarisation TIR microscopy



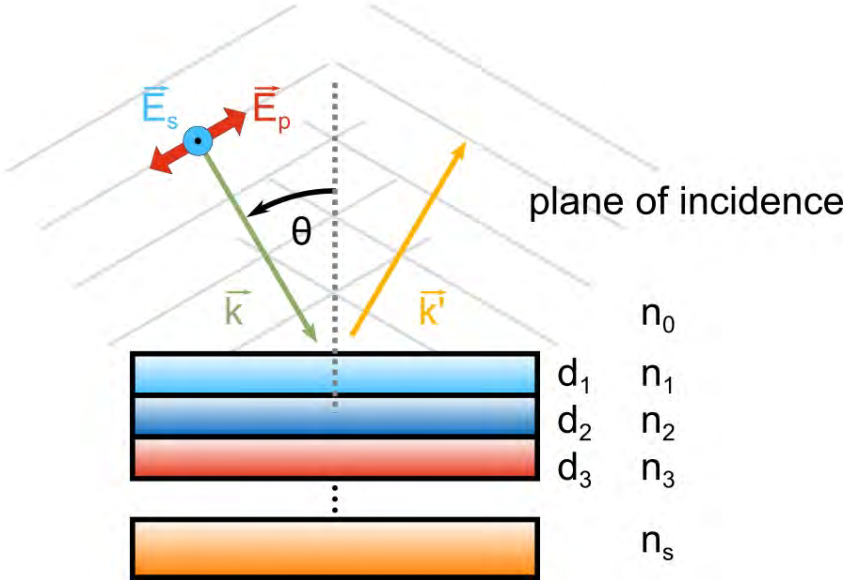
Distance control – polarisation TIR microscopy



Distance control – polarisation TIR microscopy

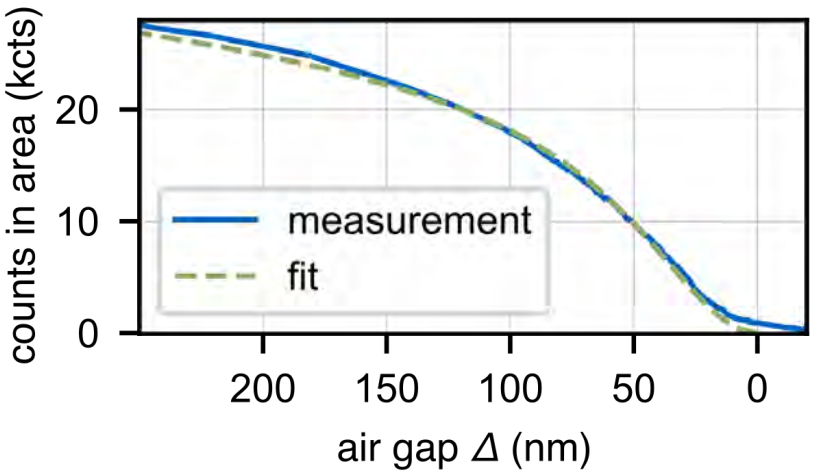


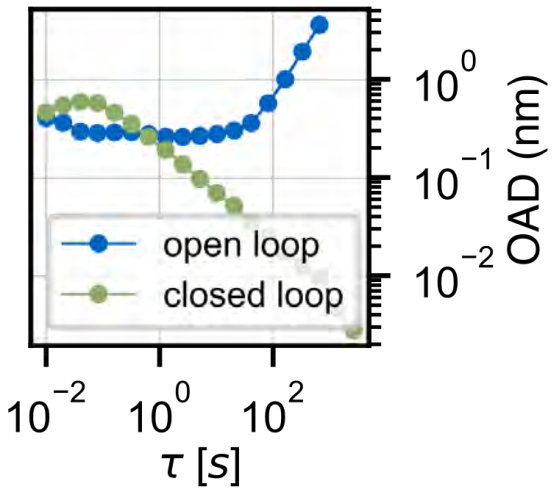
Distance control – polarisation TIR microscopy



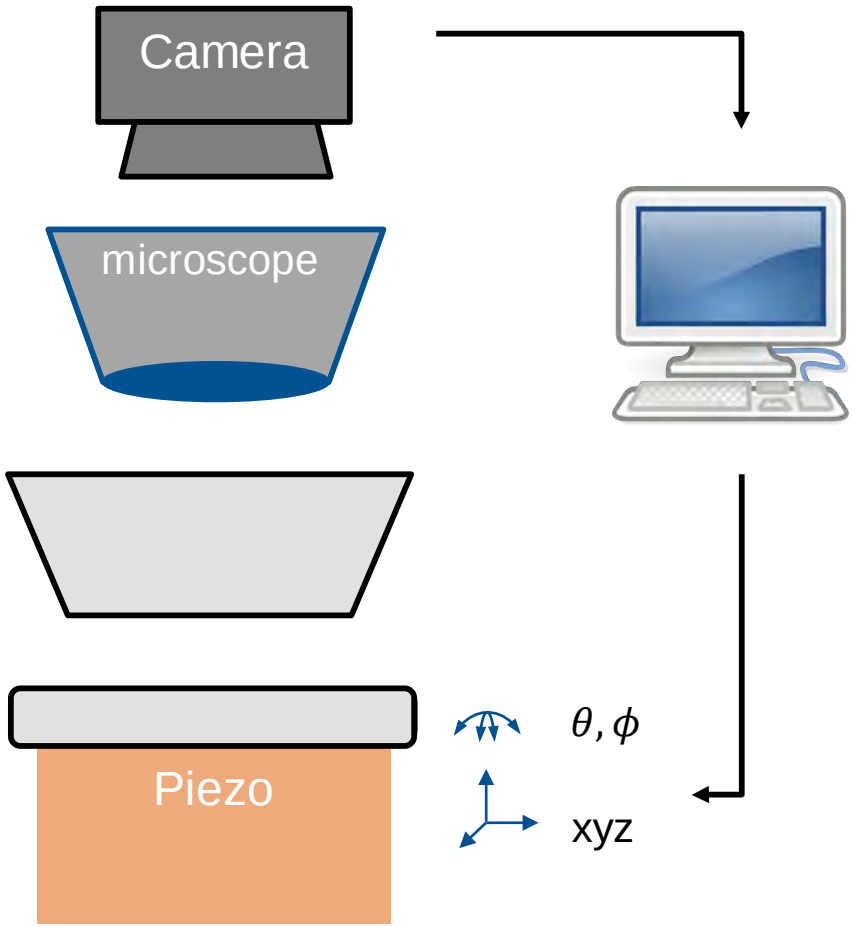
$$c_{\mathrm{TIRM}} = \left| \frac{\sin\left(\frac{2\pi\Delta p_{\mathrm{air}}}{\lambda}\right)\left(p_{\mathrm{Dia}}p_{\mathrm{Si}} - 1 + n_{\mathrm{Dia}}^2\sin(\theta)^2\right) + i\cos\left(\frac{2\pi\Delta p_{\mathrm{air}}}{\lambda}\right)p_{\mathrm{air}}\left(p_{\mathrm{Dia}} - p_{\mathrm{Si}}\right)}{\sin\left(\frac{2\pi\Delta p_{\mathrm{air}}}{\lambda}\right)\left(p_{\mathrm{Dia}}p_{\mathrm{Si}} + 1 - n_{\mathrm{Dia}}^2\sin(\theta)^2\right) + i\cos\left(\frac{2\pi\Delta p_{\mathrm{air}}}{\lambda}\right)p_{\mathrm{air}}\left(p_{\mathrm{Dia}} + p_{\mathrm{Si}}\right)} + \right.$$
$$\left. \frac{\cos\left(\frac{2\pi\Delta p_{\mathrm{air}}}{\lambda}\right)p_{\mathrm{air}}\left(n_{\mathrm{Si}}^2 p_{\mathrm{Dia}} - n_{\mathrm{Dia}}^2 p_{\mathrm{Si}}\right) - i\sin\left(\frac{2\pi\Delta p_{\mathrm{air}}}{\lambda}\right)\left(p_{\mathrm{Dia}}p_{\mathrm{Si}} - n_{\mathrm{Dia}}^2 n_{\mathrm{Si}}^2\left(1 - n_{\mathrm{Dia}}^2\sin(\theta)^2\right)\right)}{\cos\left(\frac{2\pi\Delta p_{\mathrm{air}}}{\lambda}\right)p_{\mathrm{air}}\left(n_{\mathrm{Si}}^2 p_{\mathrm{Dia}} + n_{\mathrm{Dia}}^2 p_{\mathrm{Si}}\right) - i\sin\left(\frac{2\pi\Delta p_{\mathrm{air}}}{\lambda}\right)\left(p_{\mathrm{Dia}}p_{\mathrm{Si}} + n_{\mathrm{Dia}}^2 n_{\mathrm{Si}}^2\left(1 - n_{\mathrm{Dia}}^2\sin(\theta)^2\right)\right)} \right|^2$$

Distance control – polarisation TIR microscopy





Closed-loop control – is it realistic?

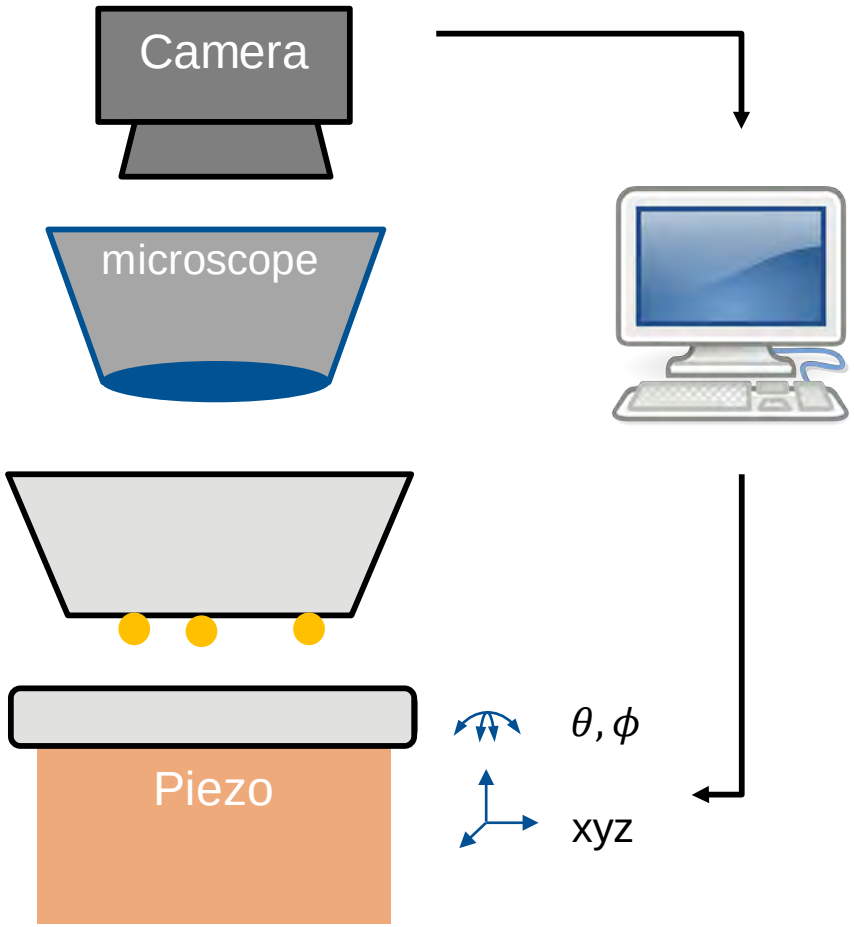


Exposure + Transfer (GigE)	4.3 ms	
Image Analysis	1.4 ms (FPGA)	13.8 ms (CPU)
Actuation	100µs	

⇒ 10 ms reaction time

⇒ Future: smart cameras, processing in camera

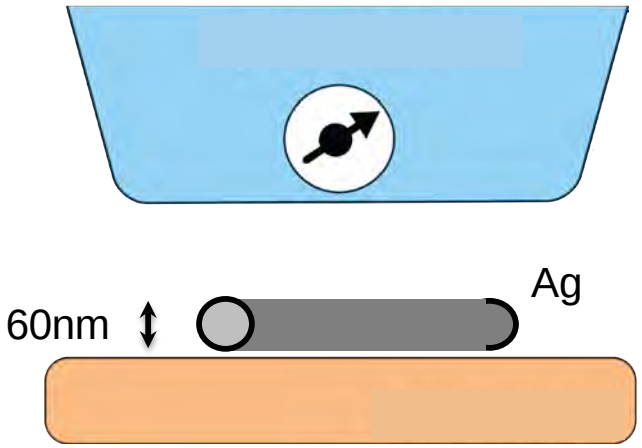
Closed-loop control - future

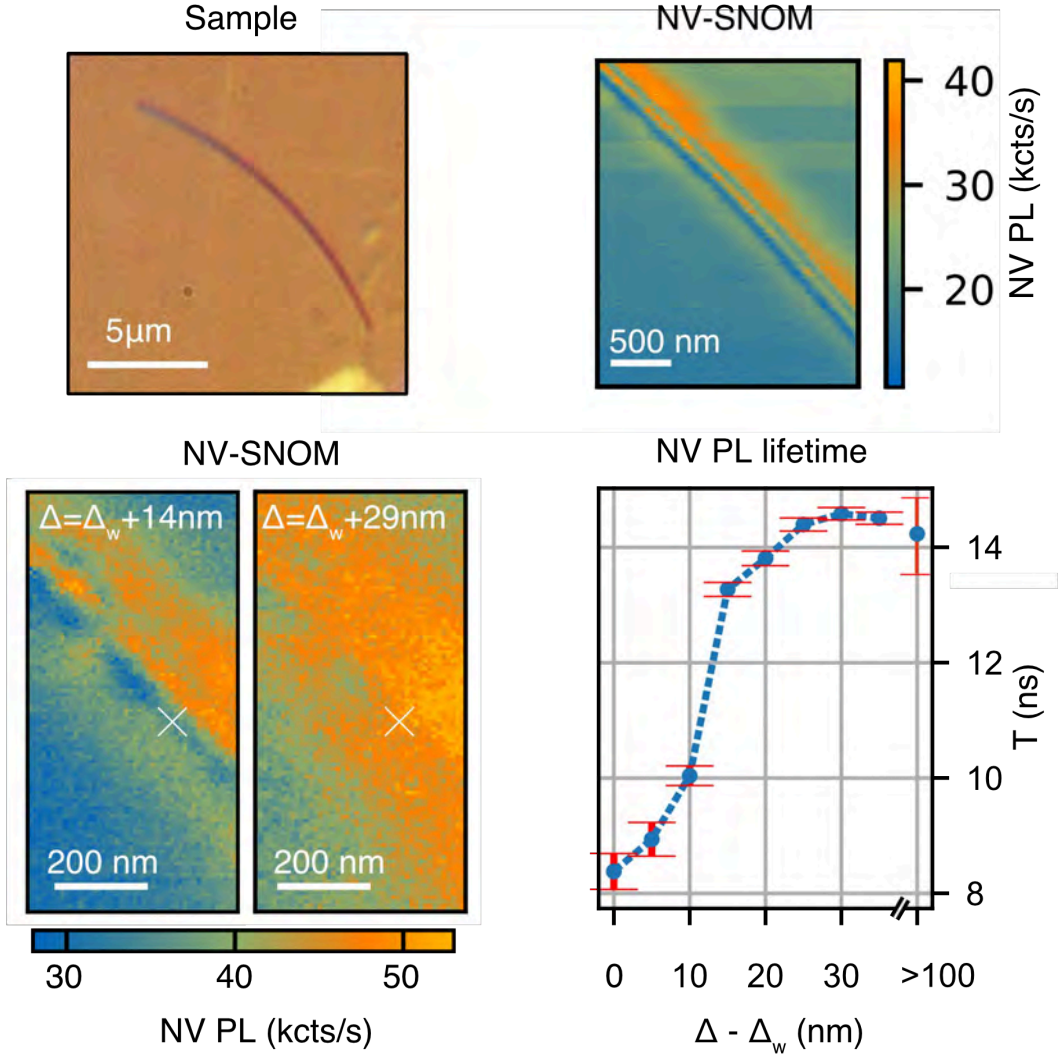


Add lateral closed-loop control by interferometric techniques

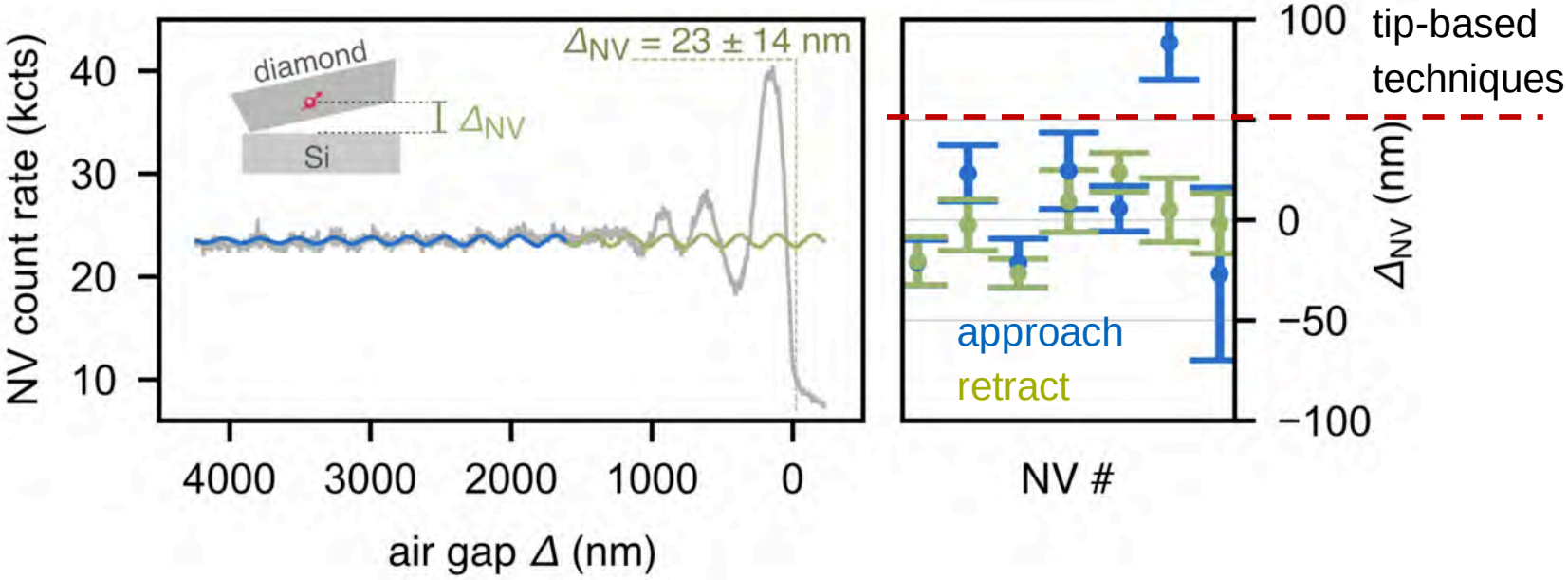
- iSCAT
  Taylor, Sandoghdar, Nano Letters 19, 4827 (2019)
- Speckle interferometry

SNOM with NV centers





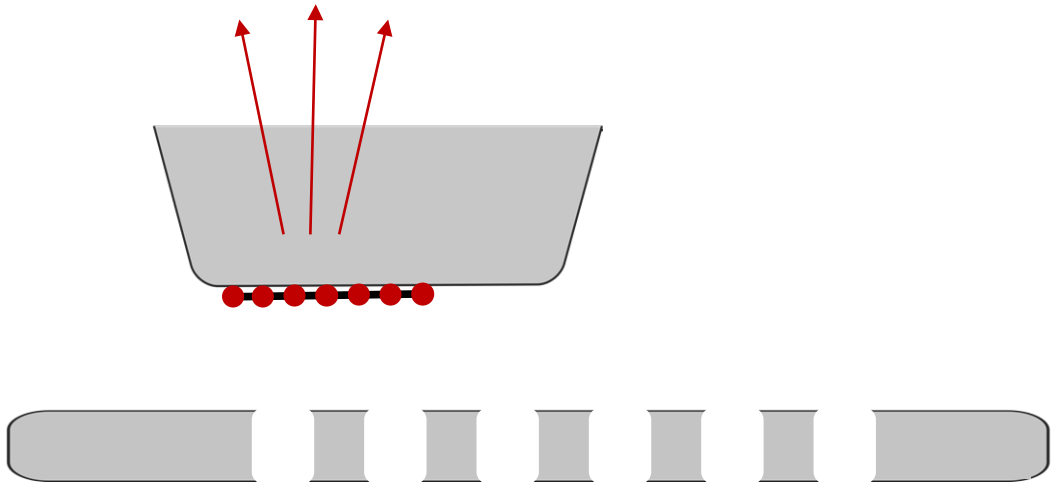
How close can we come?



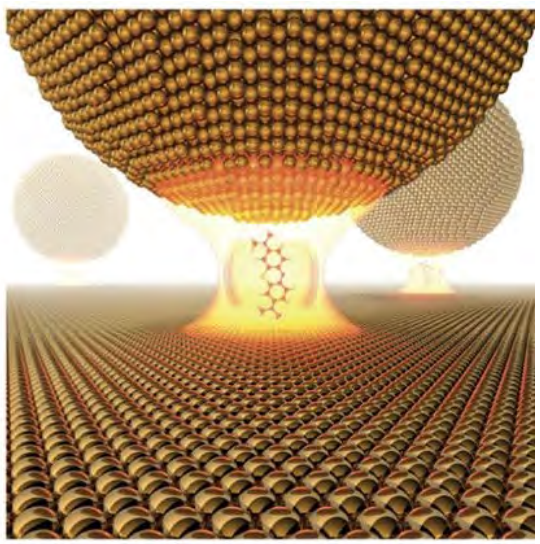
Applications: 2D materials to map optical modes

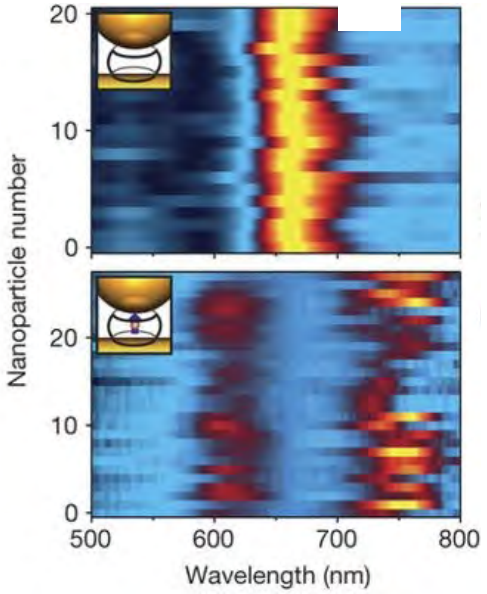
2D material nanoflake

Photonic crystal



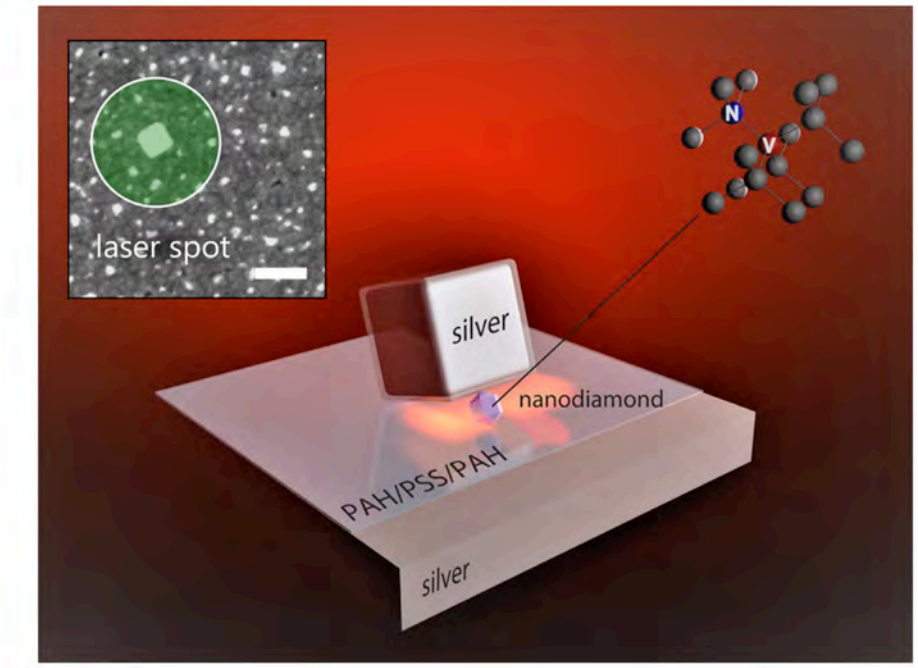
Scanning nano-gap cavities

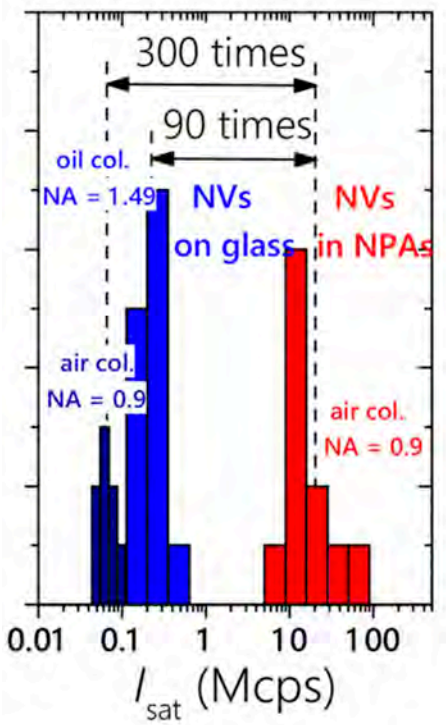




Chikkaradi ... Hess, Baumberg, Nature 535, 127 (2016)

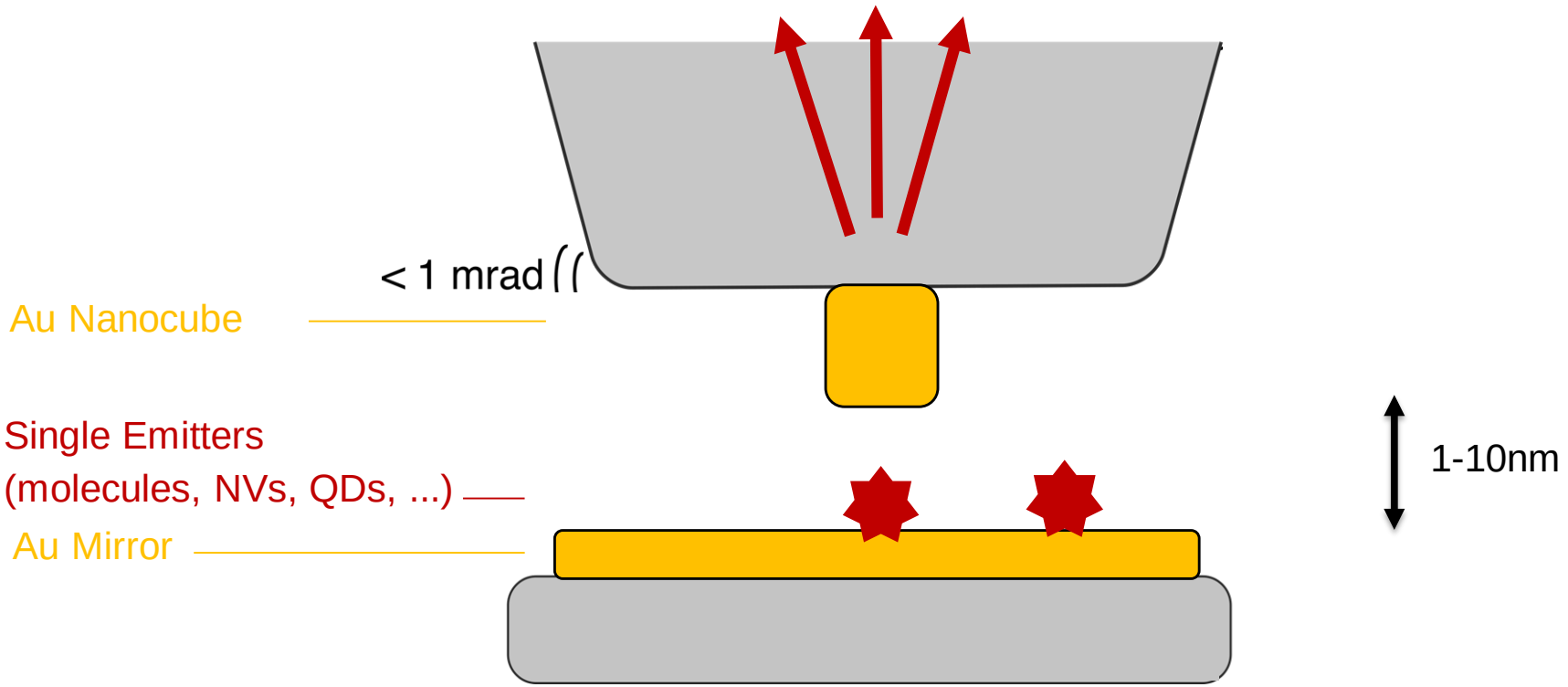
Scanning nano-gap cavities



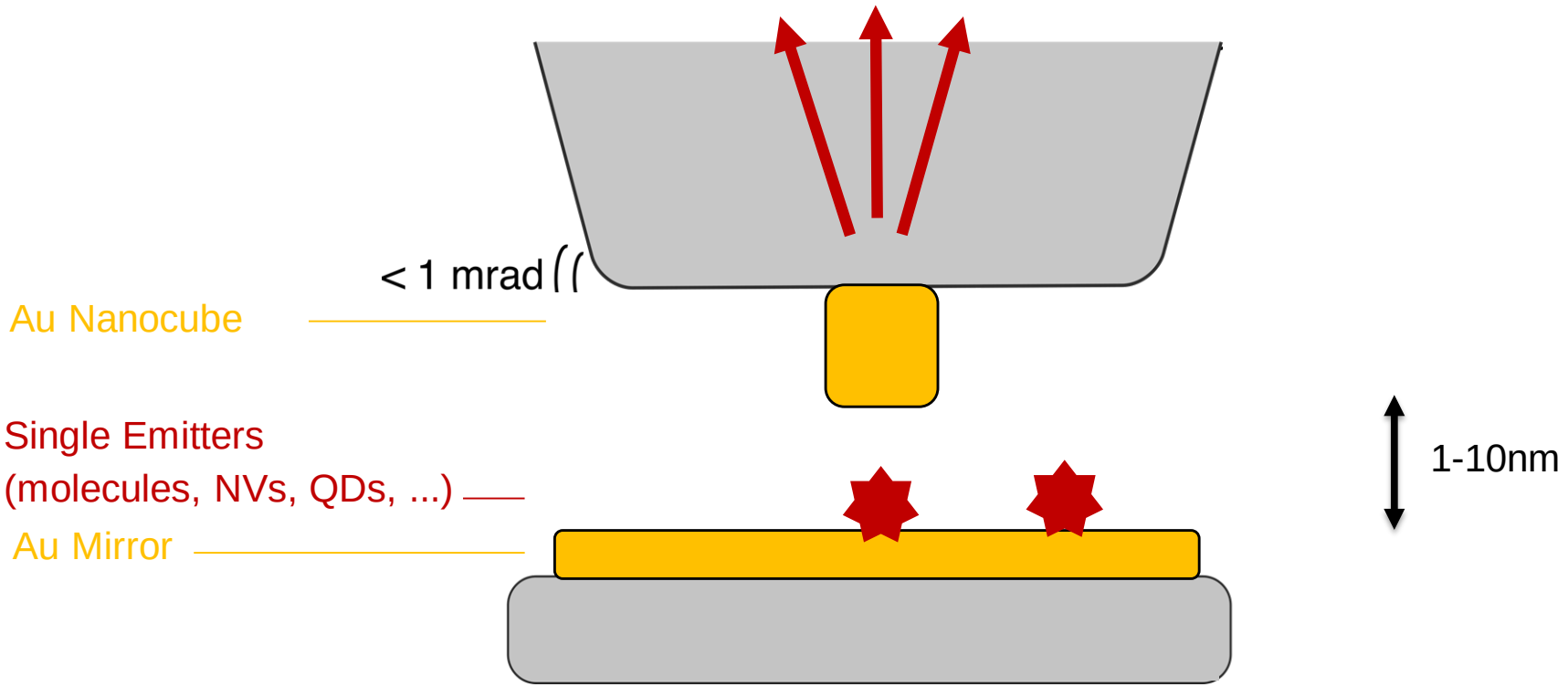


Bogdanov ... Shalaev, Nano Letters **18**, 4837 (2018)

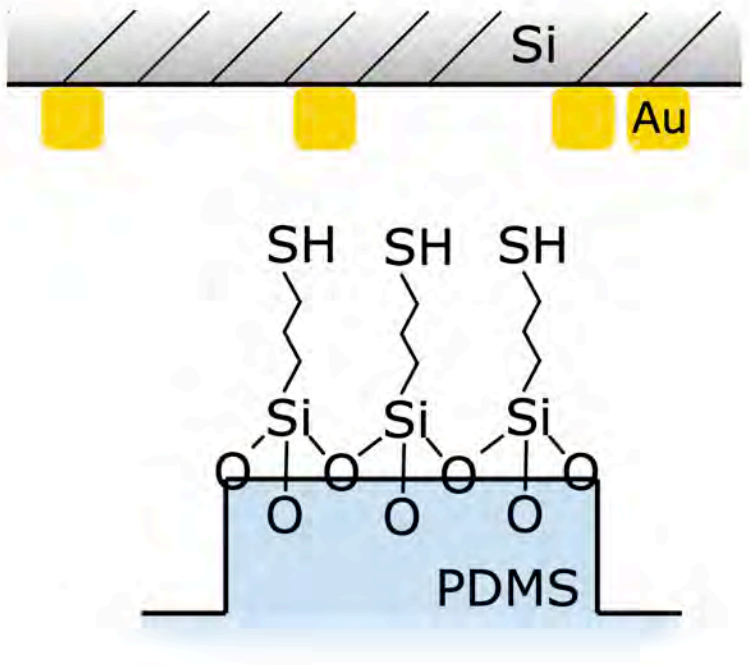
Scanning nano-gap cavities

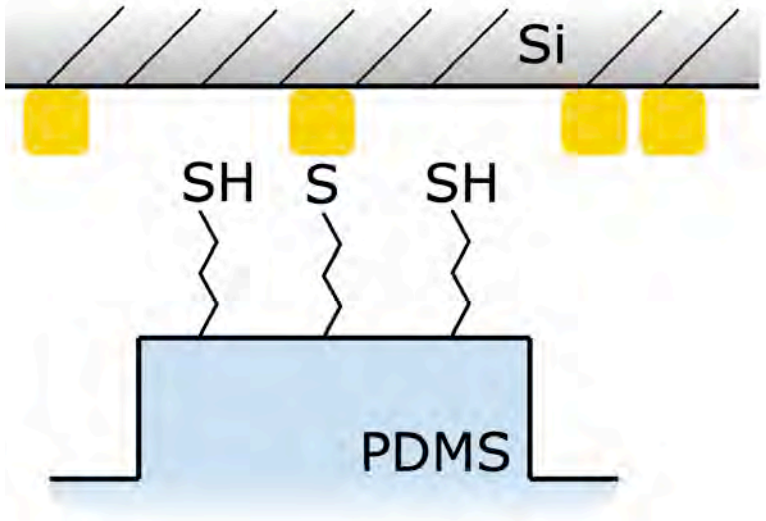


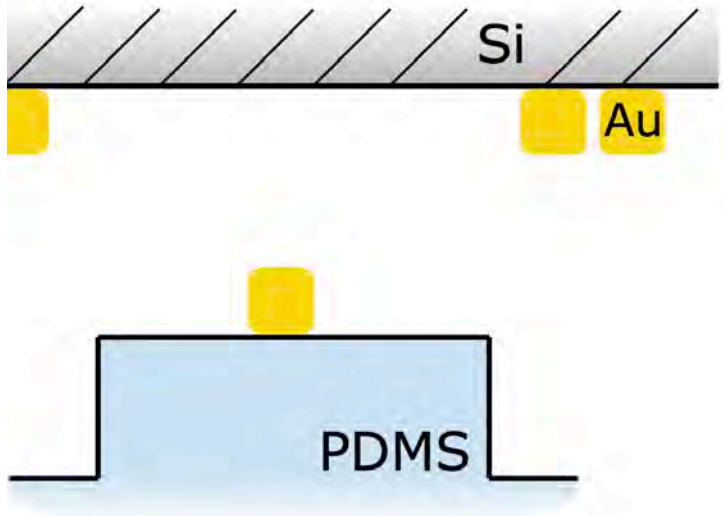
Scanning nano-gap cavities



Scanning nano-gap cavities - Fabrication

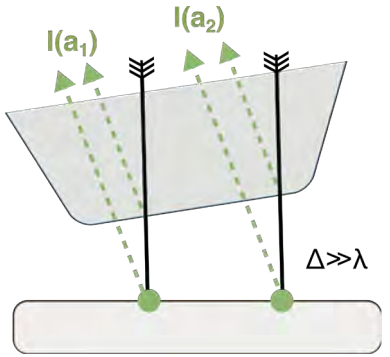


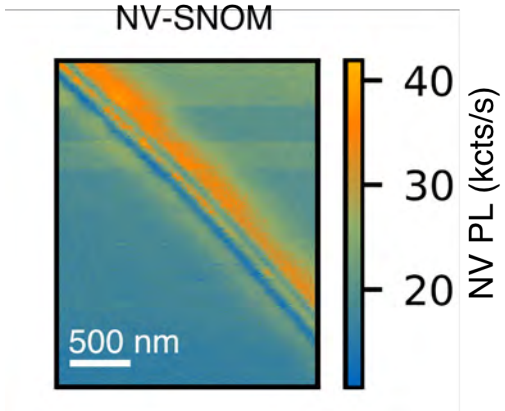




Summary

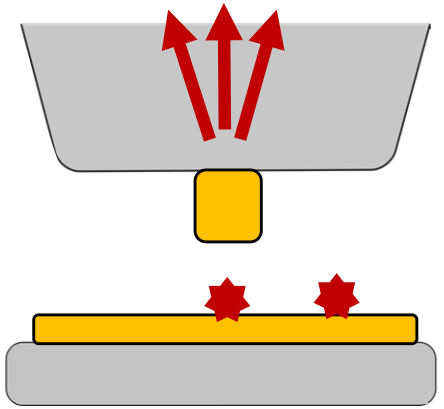
Interferometric feedback enables scanning probe microscopy with planar sensors





Application I: Near-field microscopy and magnetic imaging using NV centers

Application II: Scanning Nanogap Cavities



Ernst ... Reinhard, ACS Photonics **6**, 327 (2019)
Fringes ... Knoll, Beilstein J. Nanotechnology **9**, 301 (2018)

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Fringes ... Knoll, Beilstein J. Nanotechnology **9**, 301 (2018)