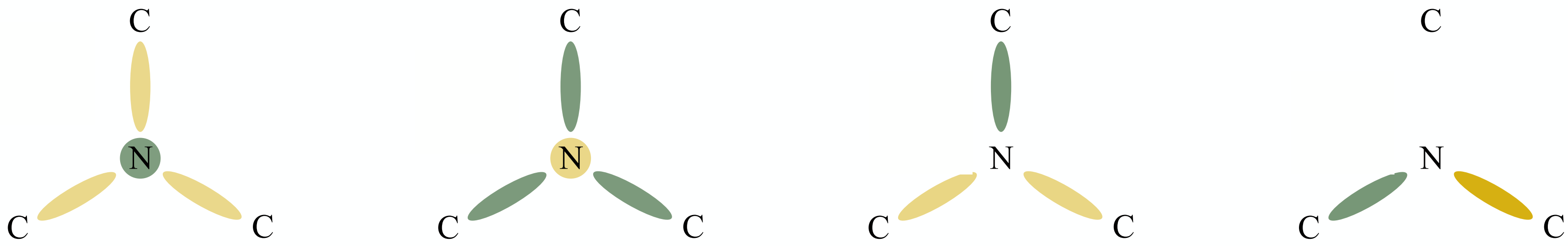
The NV center in diamond:

Spectroscopy at room temperature
Optically detected magnetic resonance

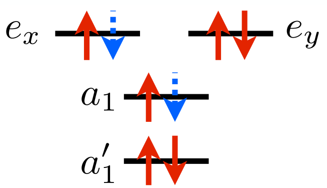
Spectroscopy of the NV center



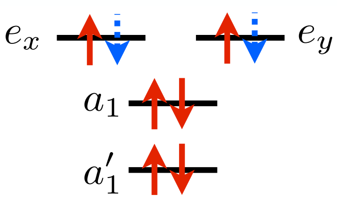
orbital $\otimes$ spin

$$|Y\rangle = |ae_y - e_y a\rangle \otimes \begin{cases} |\uparrow\downarrow + \downarrow\uparrow\rangle \\ |\uparrow\uparrow\rangle \\ |\downarrow\downarrow\rangle \end{cases}$$

$$|X\rangle = |ae_x - e_x a\rangle \otimes \begin{cases} |\uparrow\downarrow + \downarrow\uparrow\rangle \\ |\uparrow\uparrow\rangle \\ |\downarrow\downarrow\rangle \end{cases}$$



$$|e_x e_y - e_y e_x\rangle \otimes \begin{cases} |\uparrow\downarrow + \downarrow\uparrow\rangle \\ |\uparrow\uparrow\rangle \\ |\downarrow\downarrow\rangle \end{cases}$$



selection rule
for optical transition

$$\langle \psi_f \,|\, \vec{d} \cdot \vec{E} \,|\, \psi_i \rangle \neq 0$$

$$\langle a \,|\, \vec{x} \cdot \hat{\vec{r}} \,|\, e_x \rangle = \langle a \,|\, \vec{y} \cdot \hat{\vec{r}} \,|\, e_y \rangle \neq 0$$

What is the influence of the electron spin ?

Hamiltonian – Difference with atomic physics

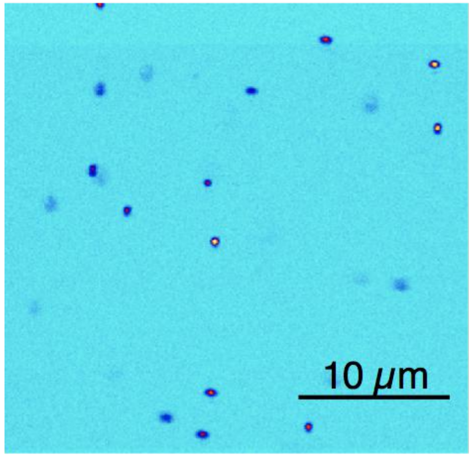
$$H = H_{\text{spin}-\text{orbit}} + H_{\text{spin}-\text{spin}} + H_{\text{strain}}$$

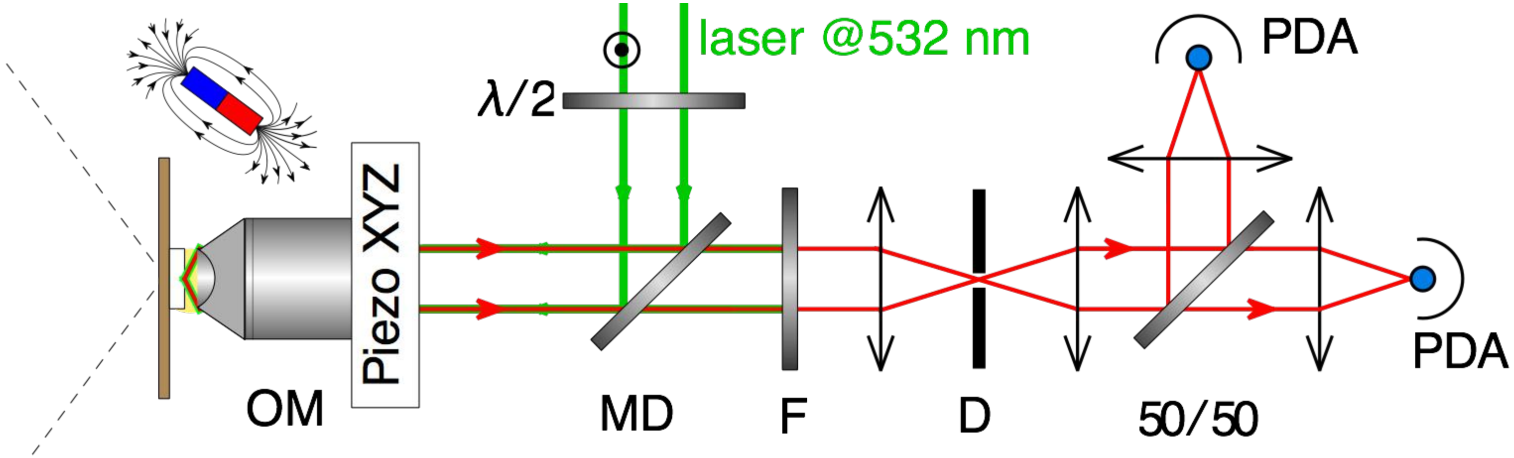
- In alkali atoms, spin–orbit interaction is ~THz
  Total spin projection can be optically modified.
- In the NV center, spin–orbit coupling split the excited orbitals by ~5 GHz.
  At low T, transitions that alter m_S are allowed leading to spin–photon entanglement schemes.
- At room temperature, phonons induce orbital averaging in the excited state or strain is the dominant perturbation.

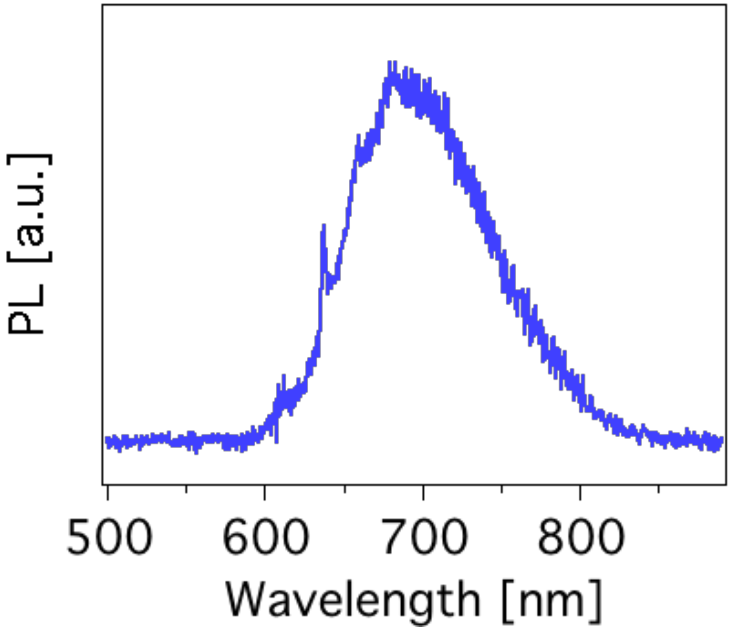
$\longrightarrow$ selection rule $\Delta m_S = 0$

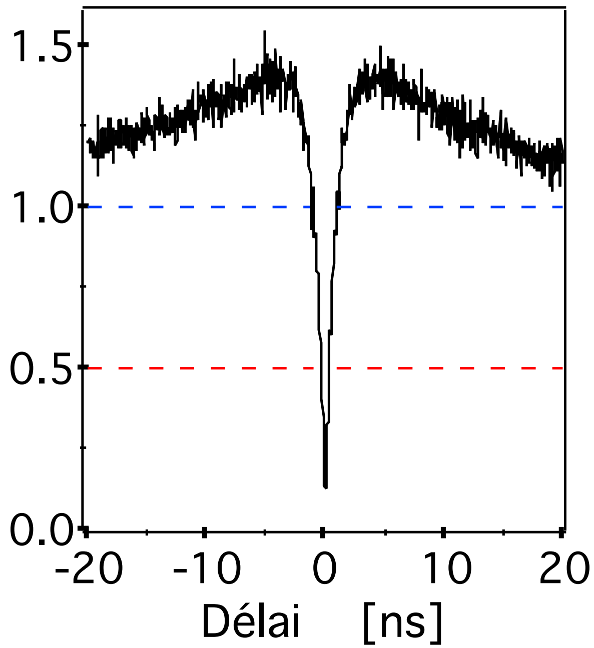
$\longrightarrow$ 2 incoherent optical dipoles $\perp$ NV axis

Confocal microscopy for single-emitter detection





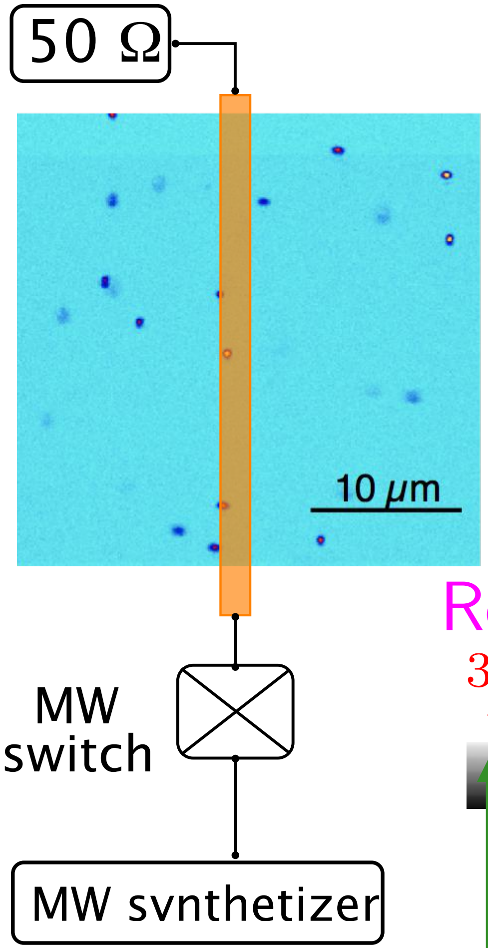


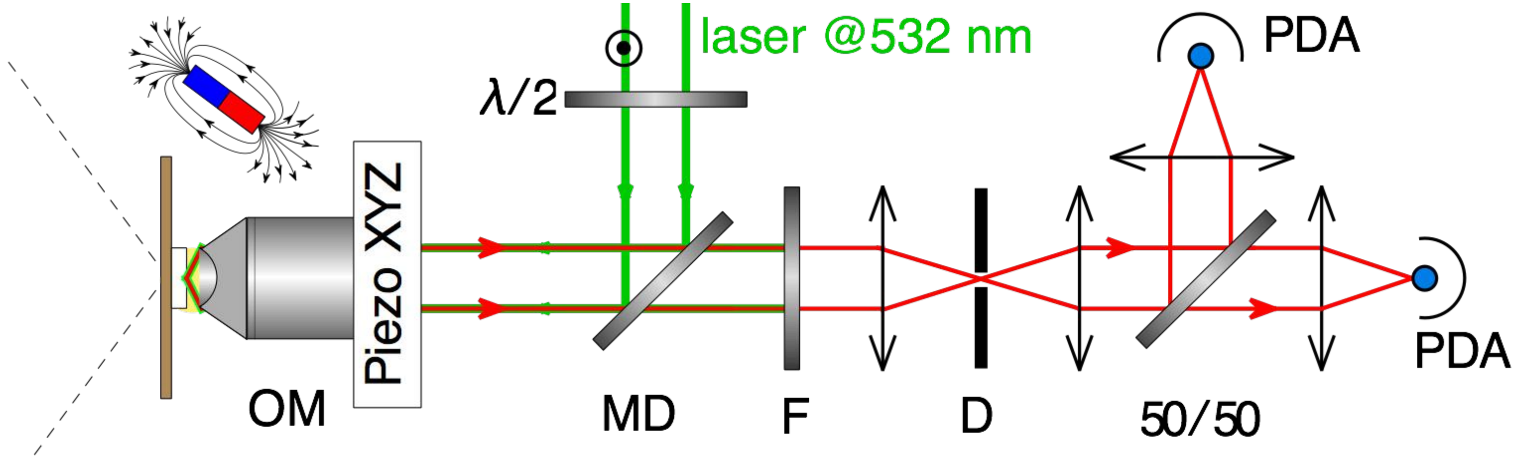


NV^- center

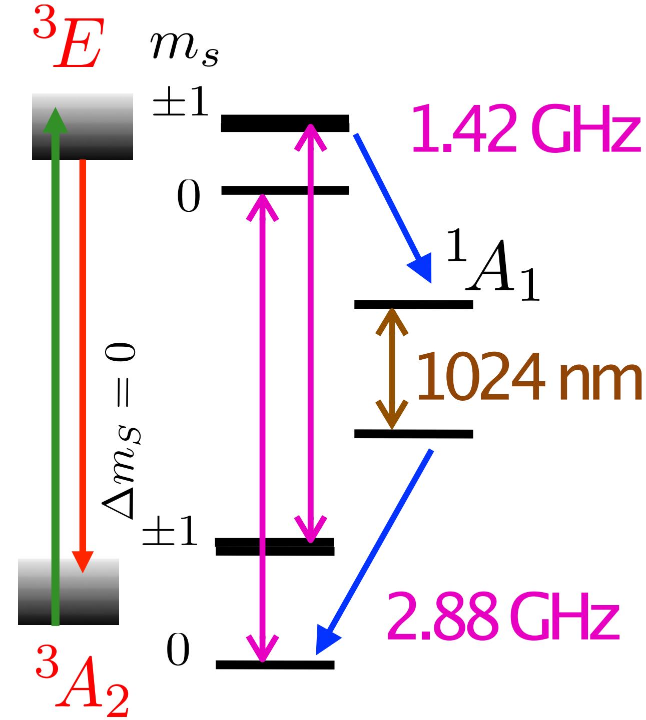
single emitter

Optical polarization and luminescence

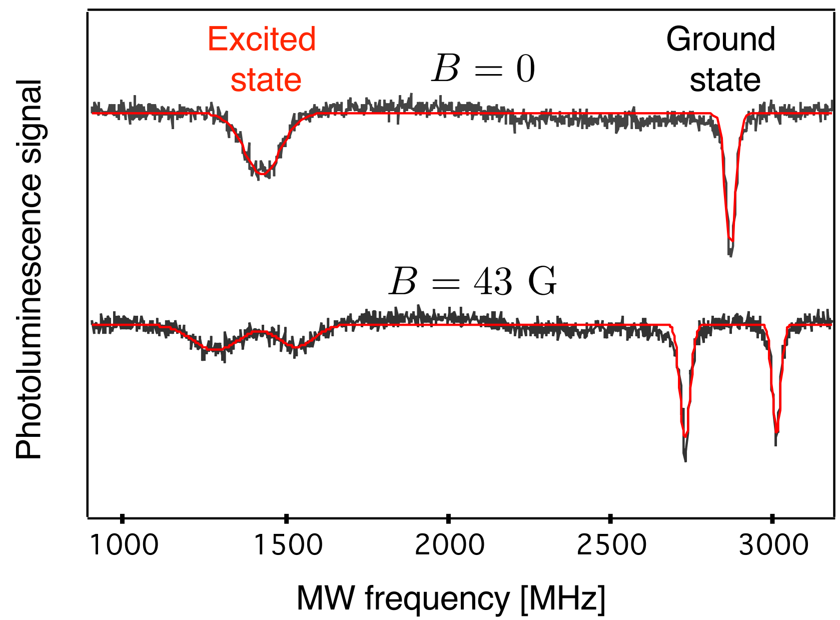




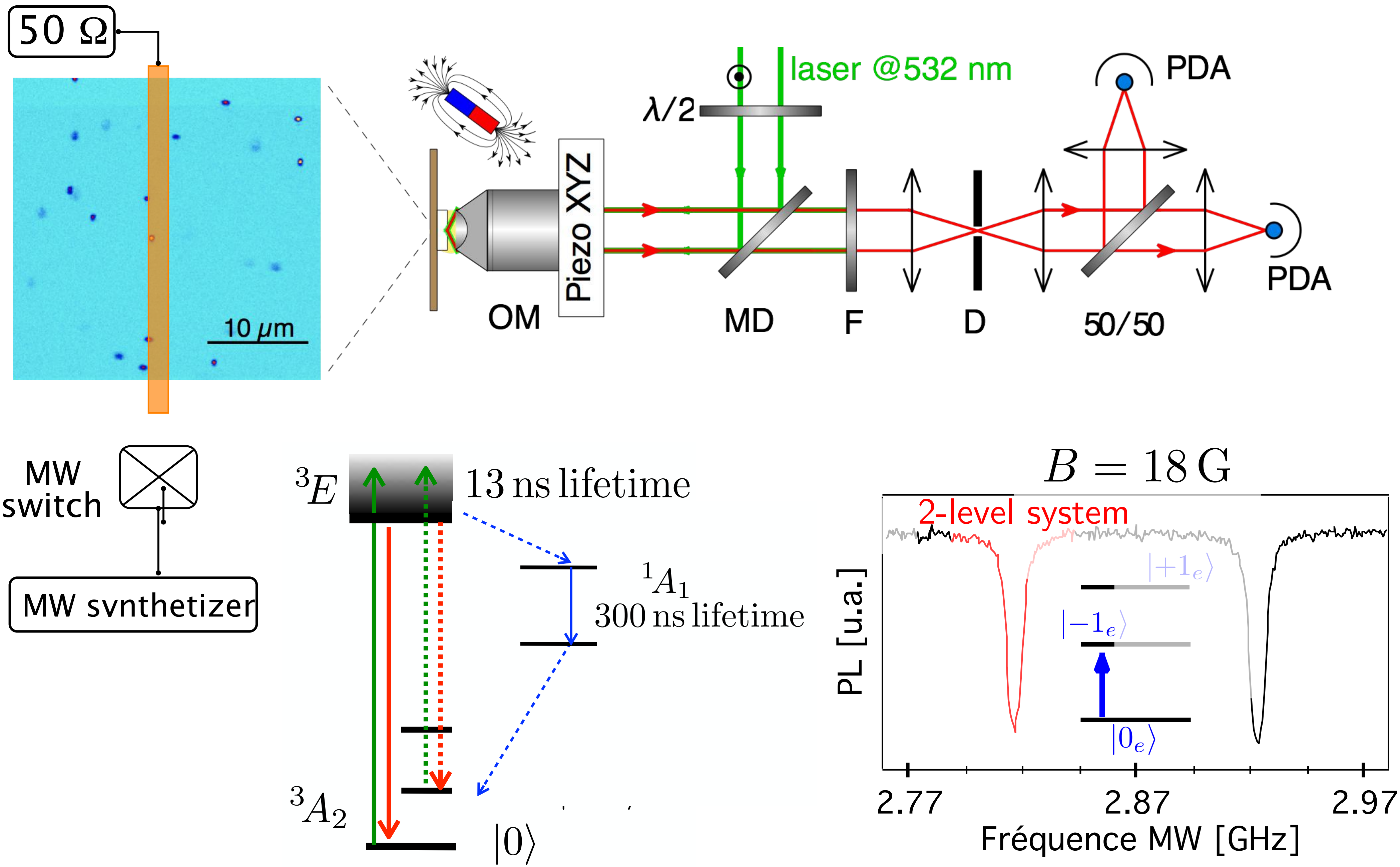
Room temperature



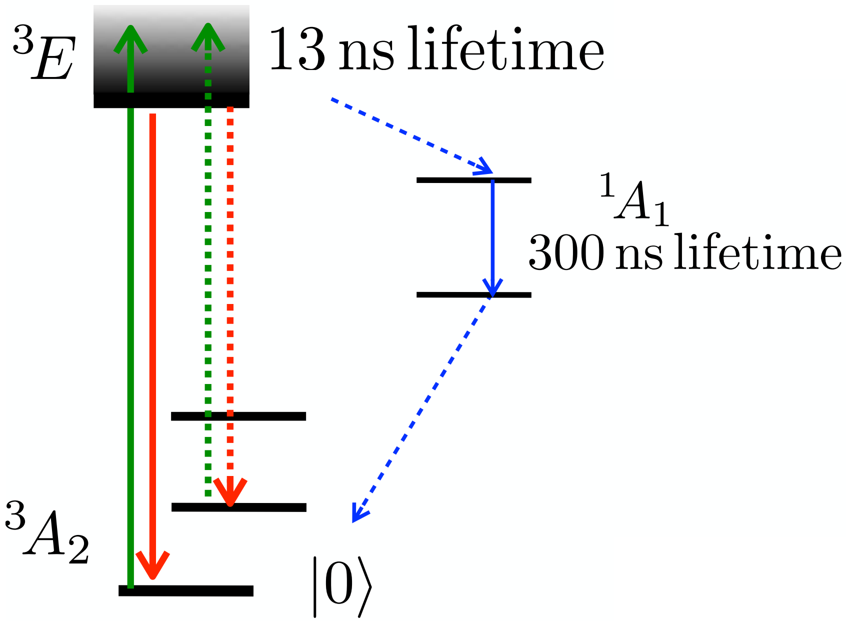
- ^3E excited state: $\tau \simeq 13\,\mathrm{ns}$
- $^1A_1$ metastable level: $\tau \simeq 200\,\mathrm{ns}$

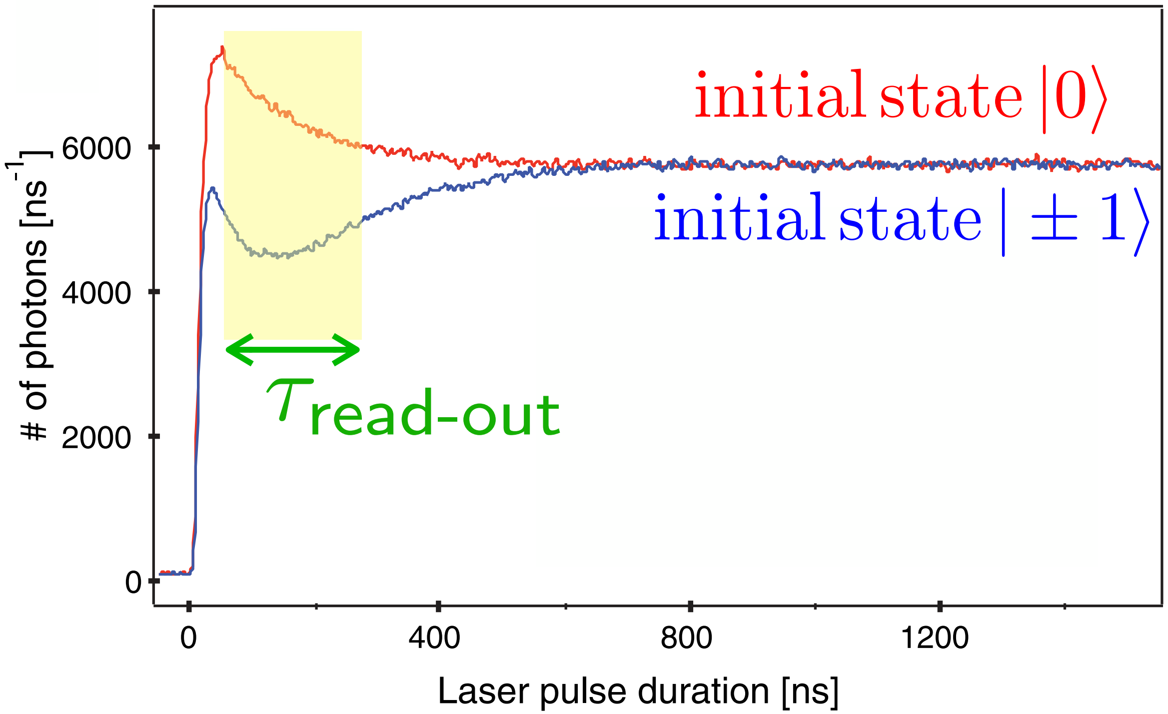


Spin-based 2-level quantum system

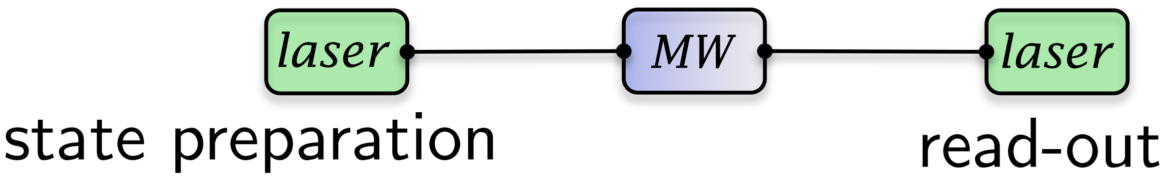


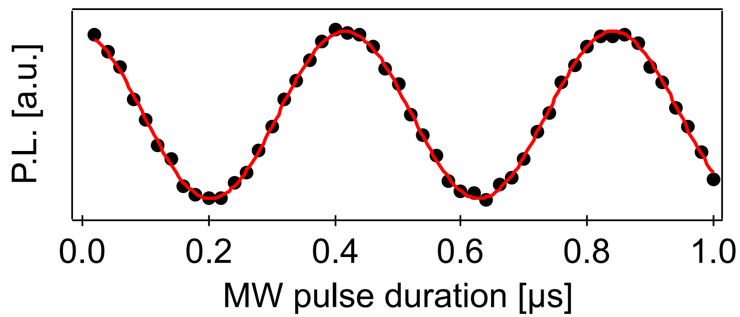
(|0>,|1>) quantum states



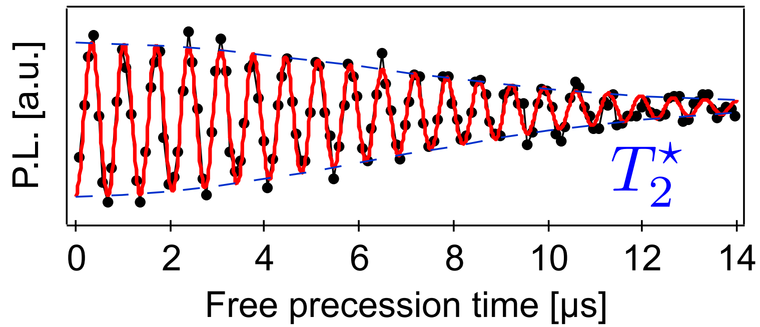


- Rabi oscillation de Rabi



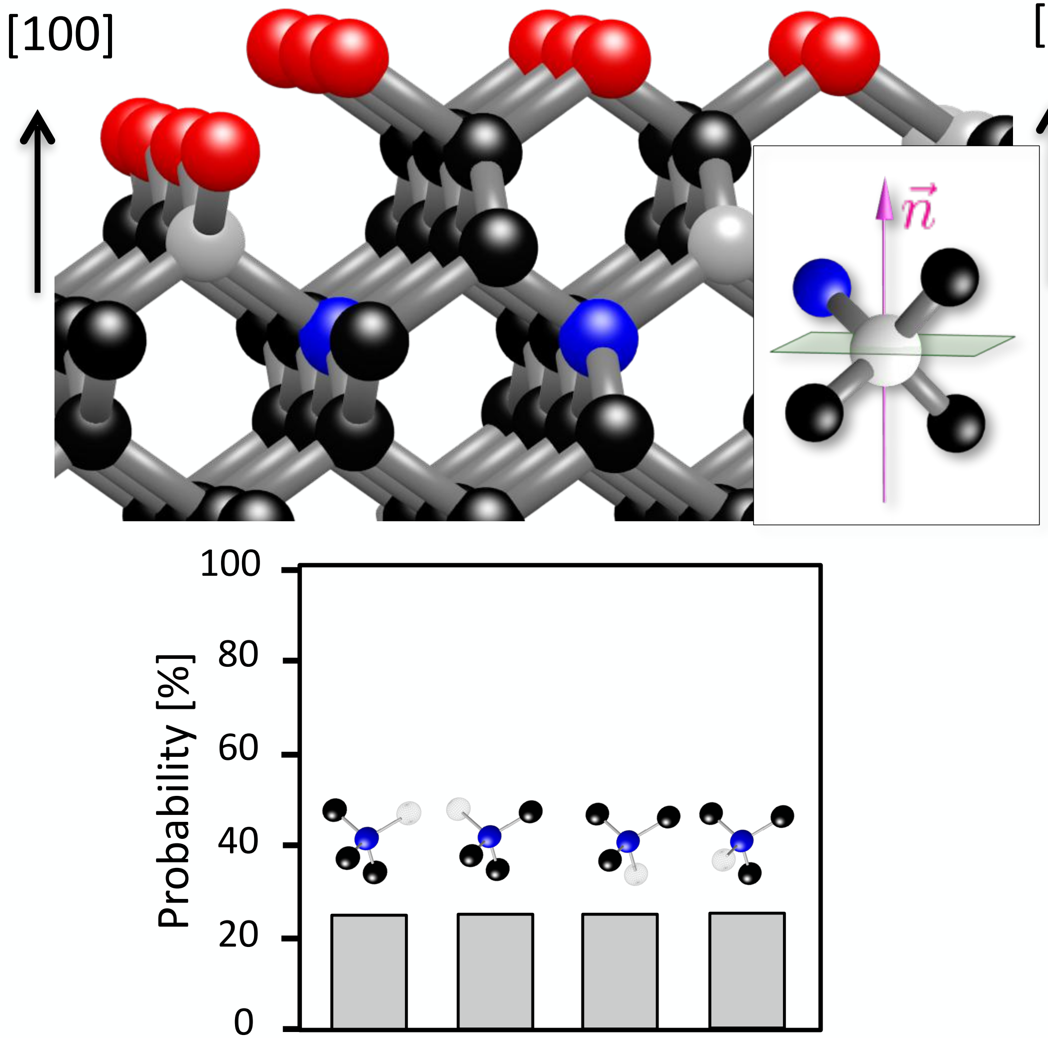


- Ramsay fringes

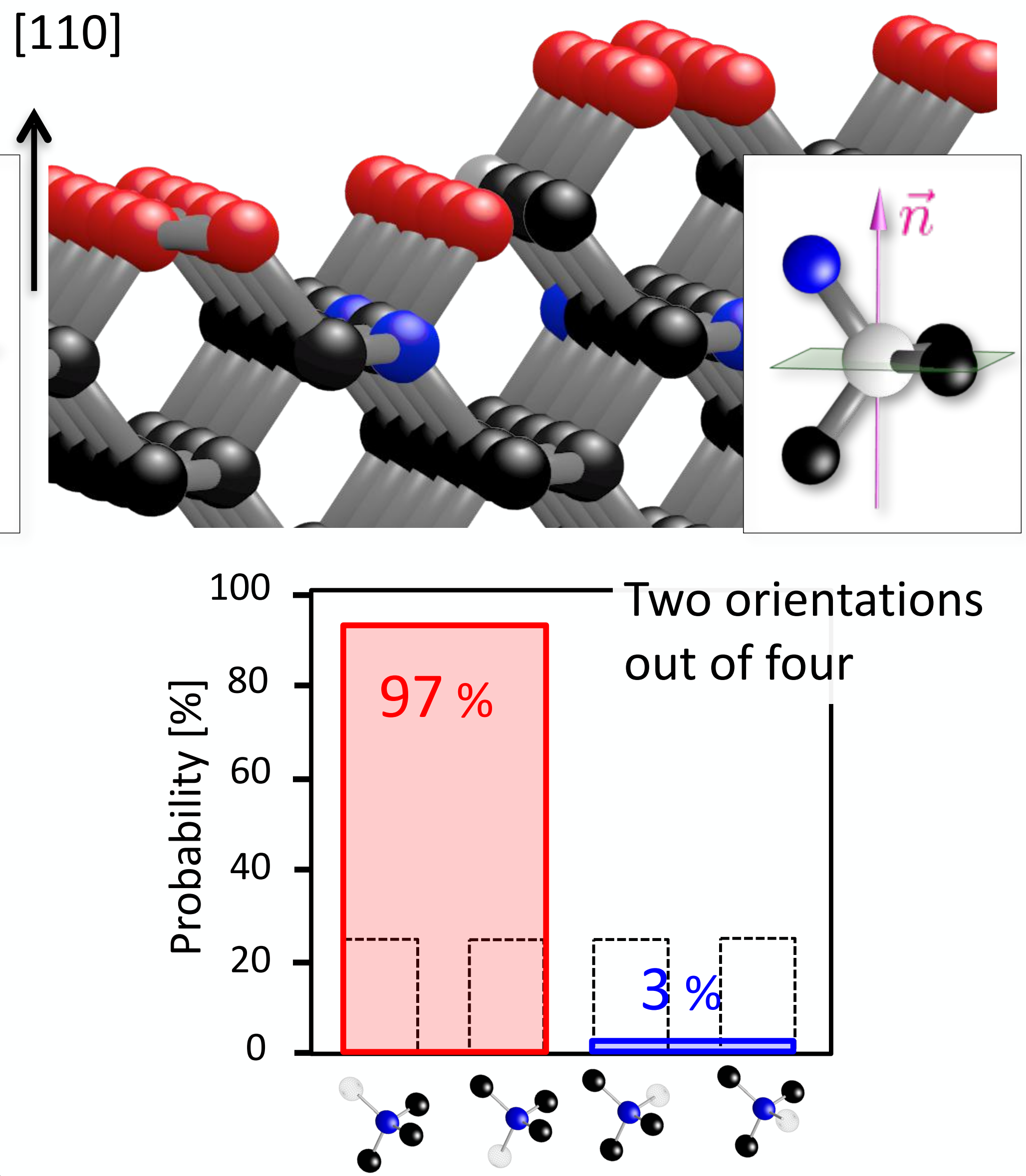


NV center orientation is the intrinsic quantization axis

(100)-oriented growth:



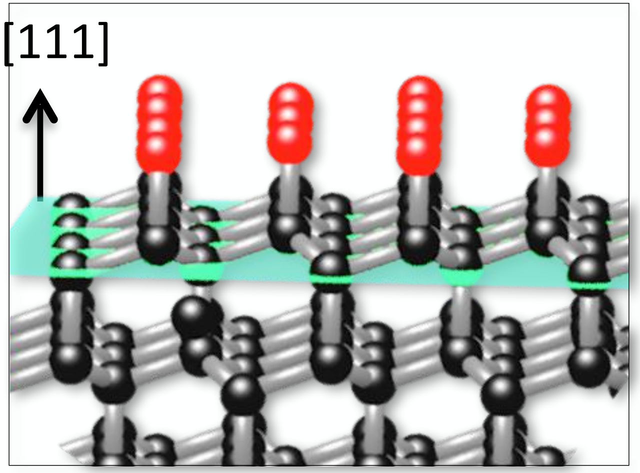
(110)-oriented growth:

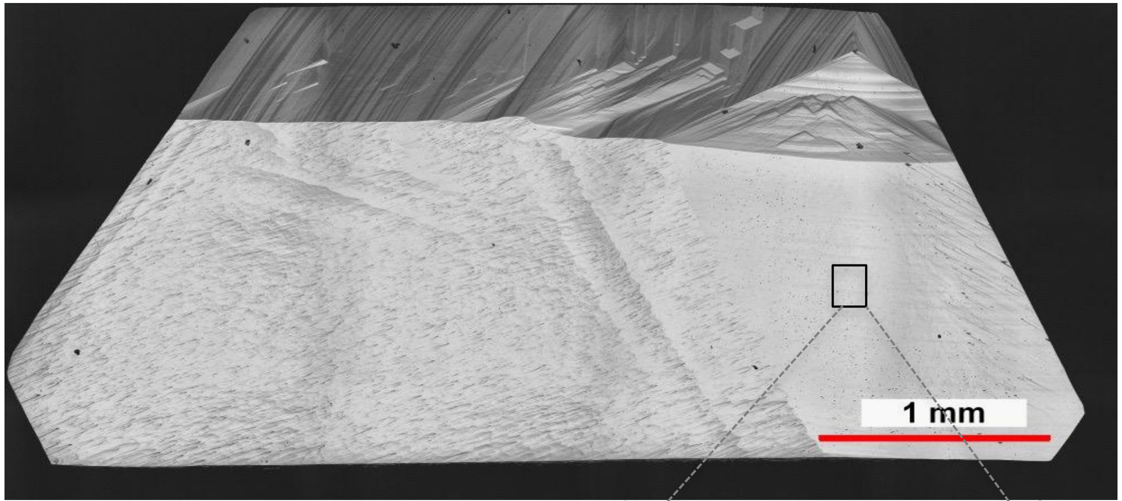


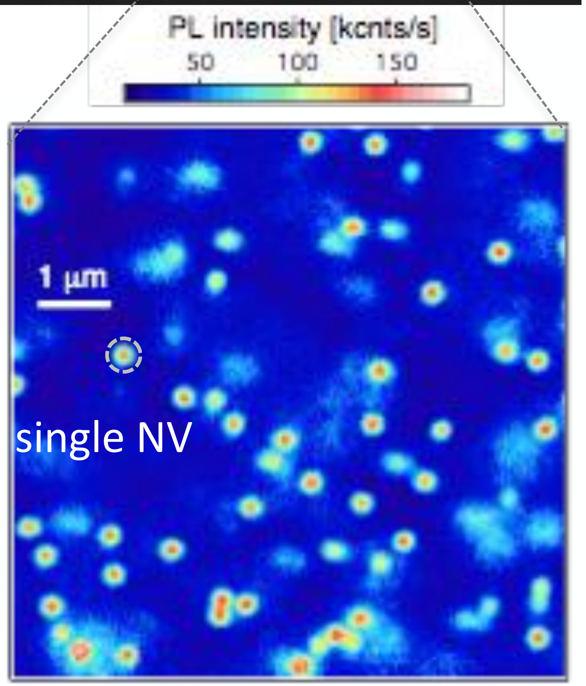
* Pham, et al., Phys. Rev. B 86, 121202(R) (2012).

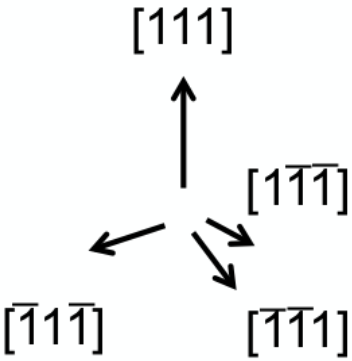
** Edmonds, et al., Phys. Rev. B 86, 035201 (2012).

(111) – oriented diamond growth





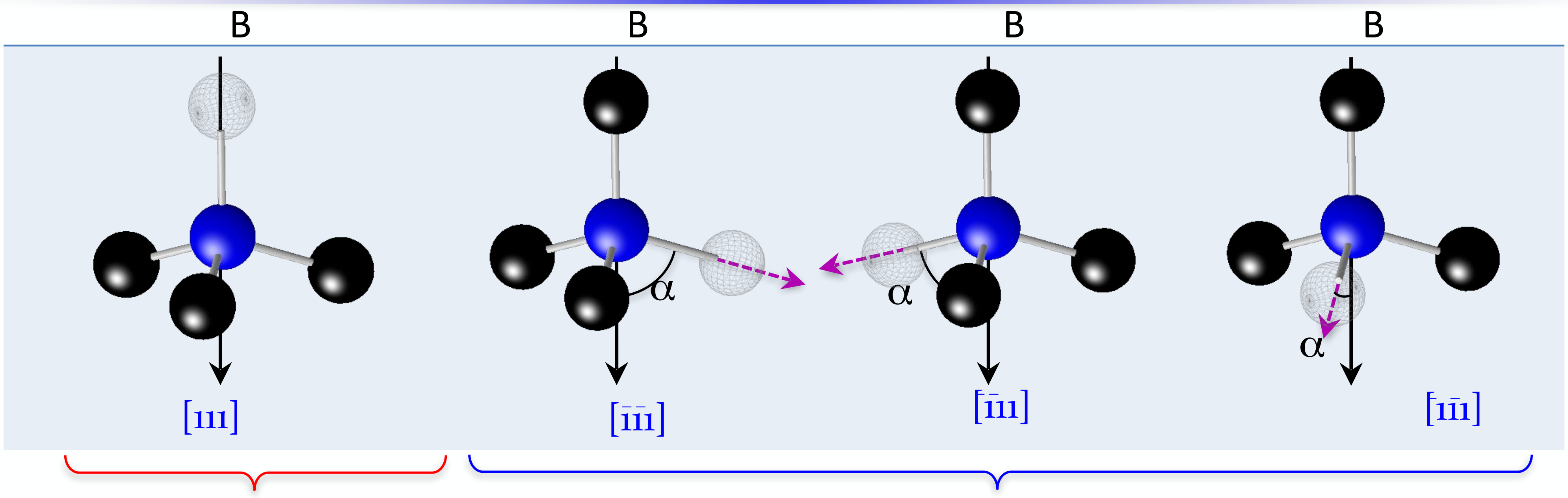




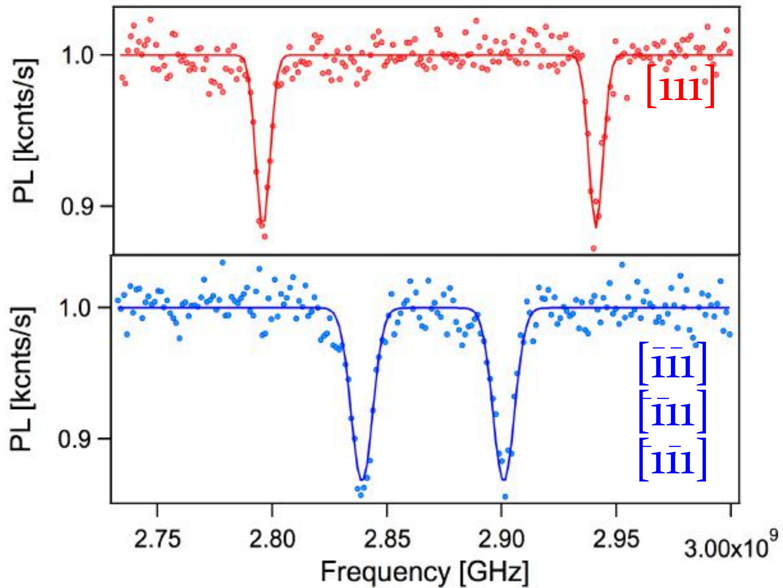
CVD diamond film
111 - grown
50 µm thick

Alexandre Tallaire
Jocelyn Achard

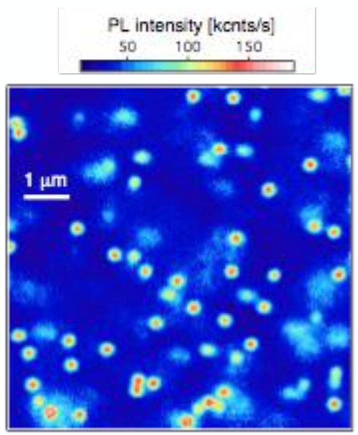
ESR shift measurement

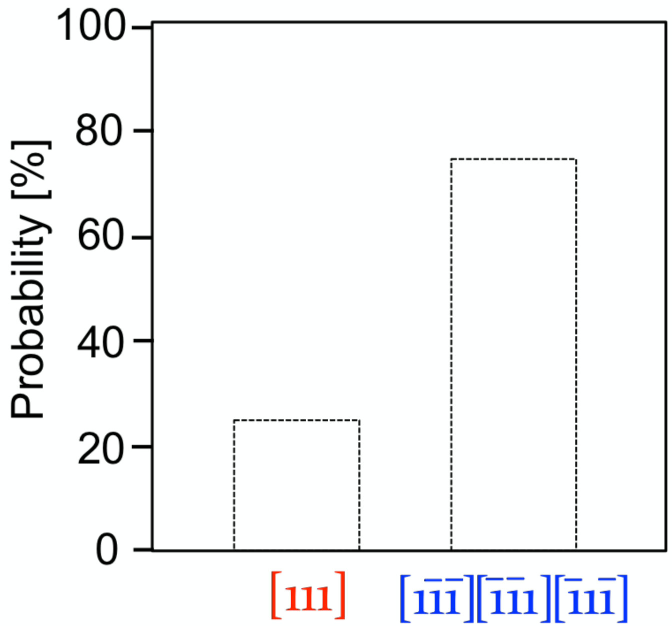


NV center orientation discrimination by ESR shift measurements

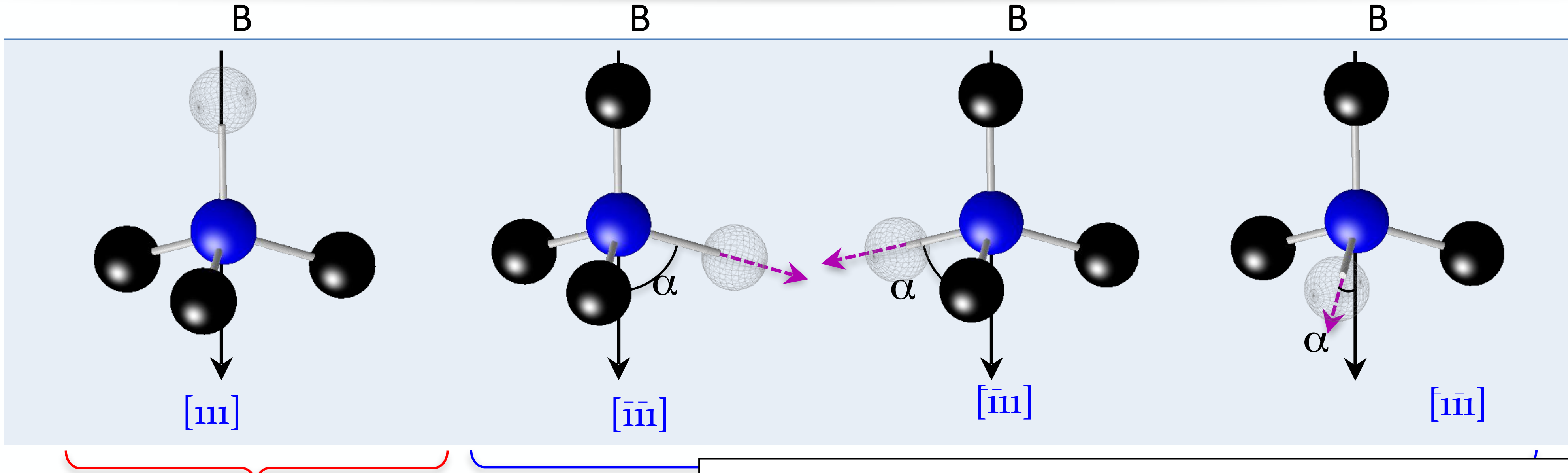


Statistics on more than 200 NVs





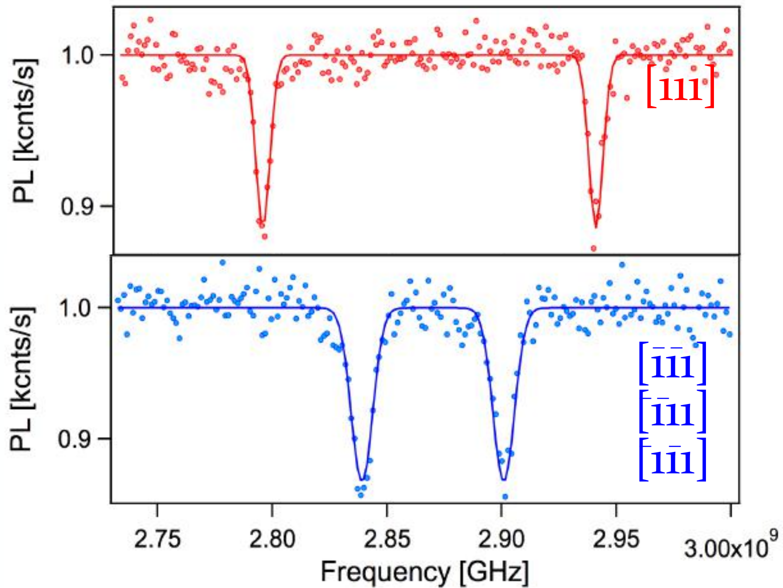
ESR shift measurement



$B_{NV} = B$

* M. Lesik, et al., Appl. Phys. Lett., 104, 113107 (2014)
** J. Michl, et al., Appl. Phys. Lett., 104, 102407 (2014)
*** T. Fukui, et al., Appl. Phys. Expr., 7, 055201 (2014)

NV center orientation discrimination by ESR shift measurements



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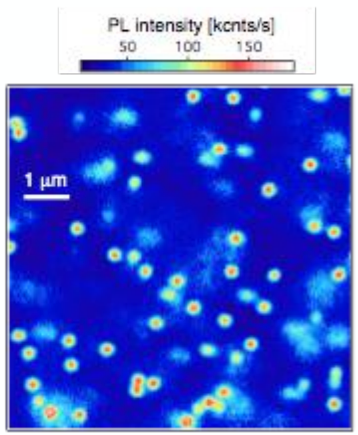
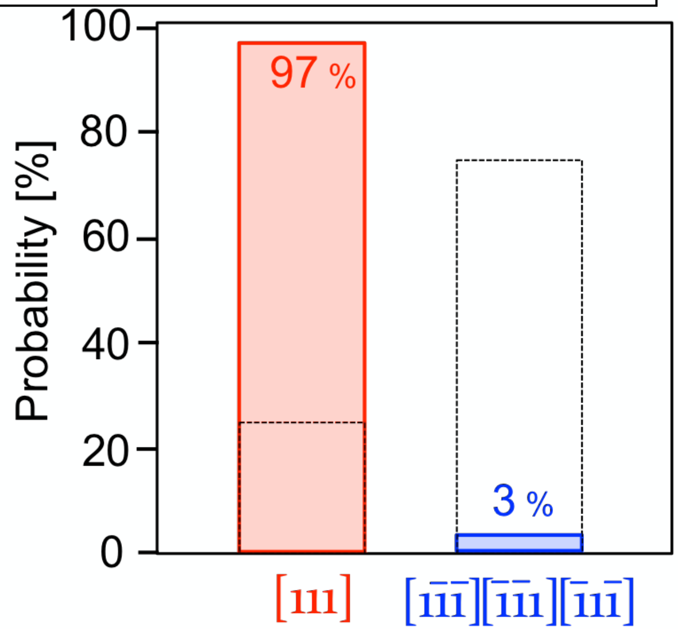
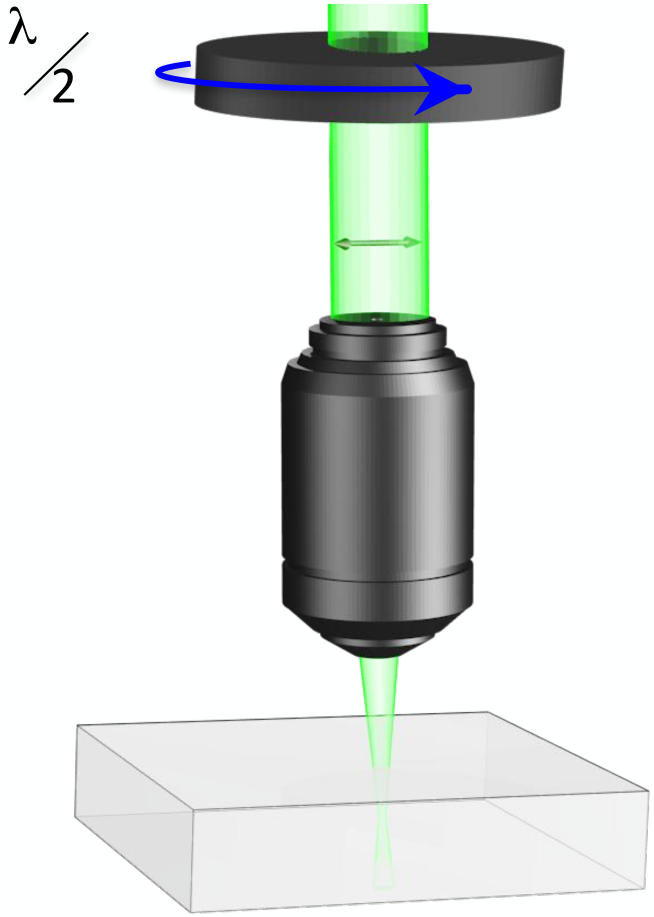
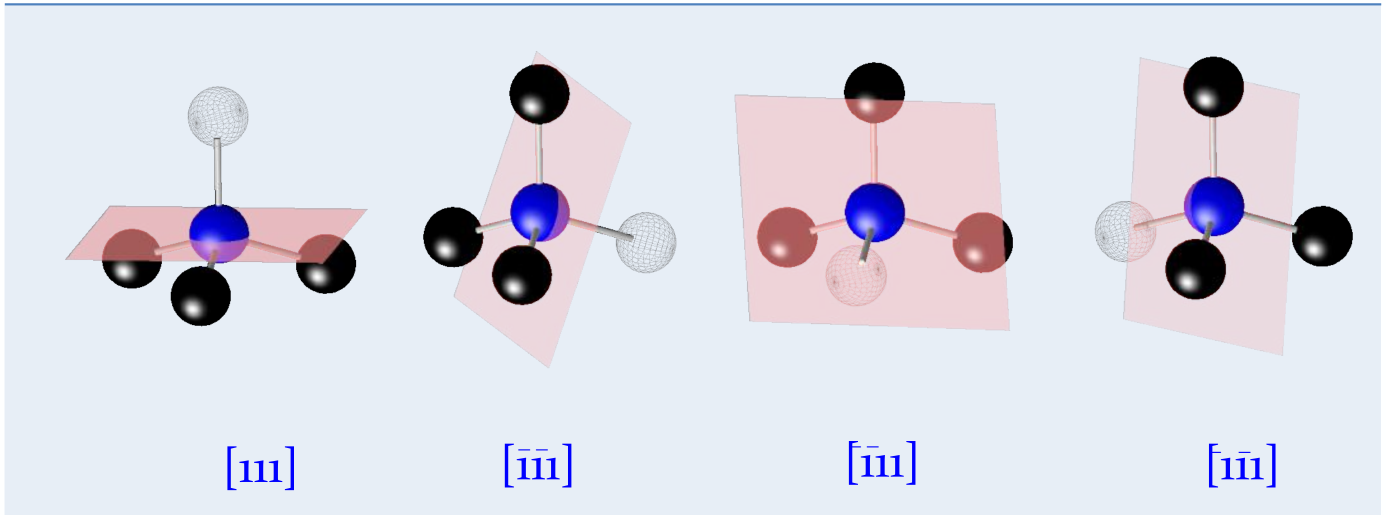


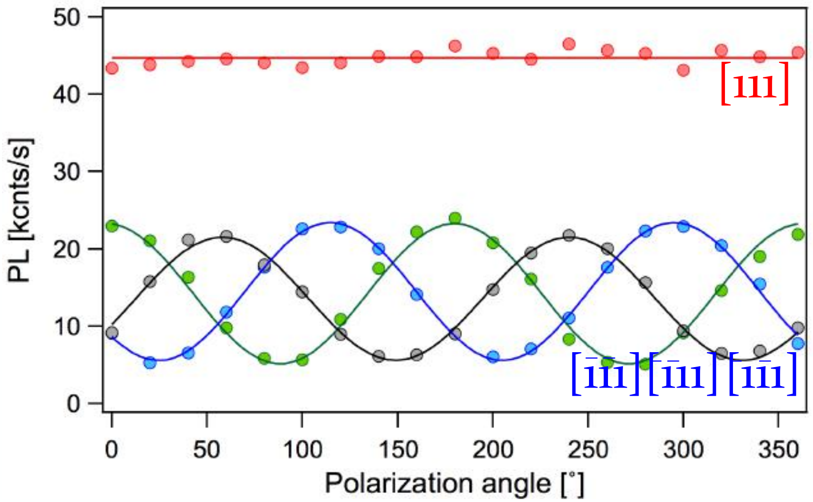


Polarization dependent luminescence



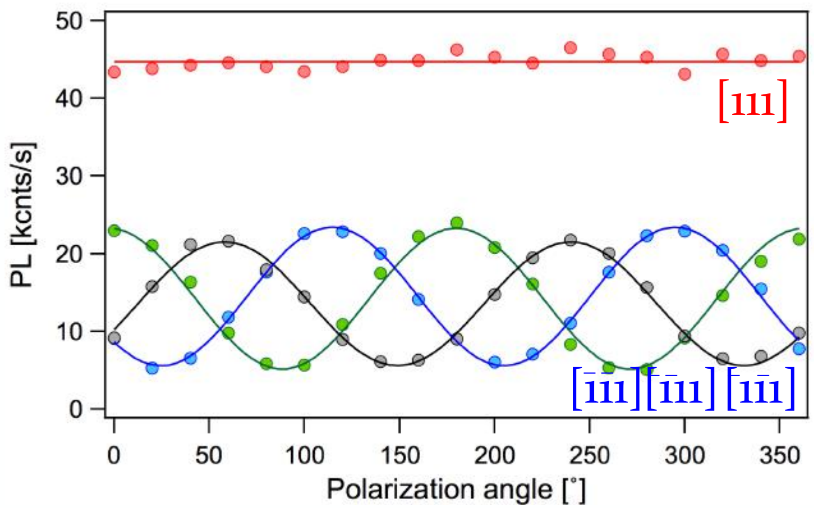


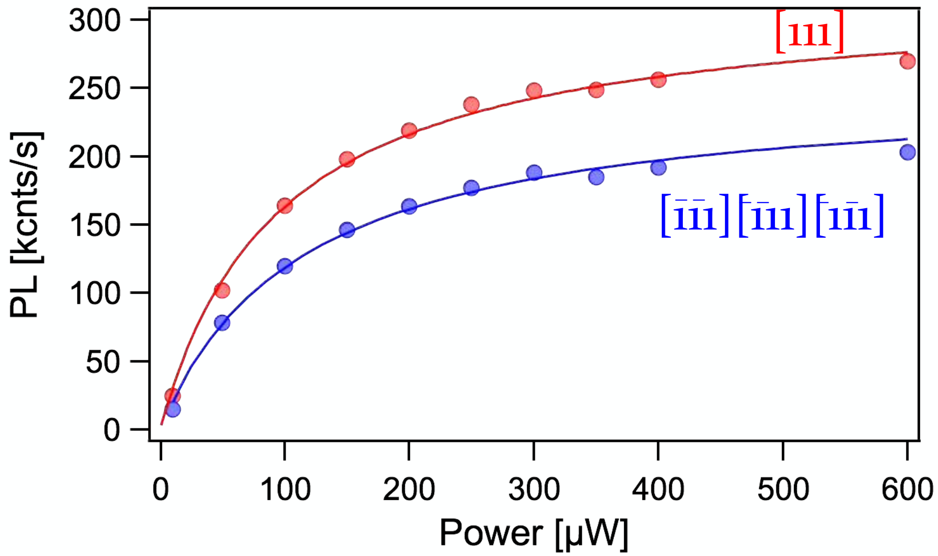
Polarization dependance



Polarization dependent PL can distinguish all 4 possible orientations

Orientation analysis (111)-oriented sample



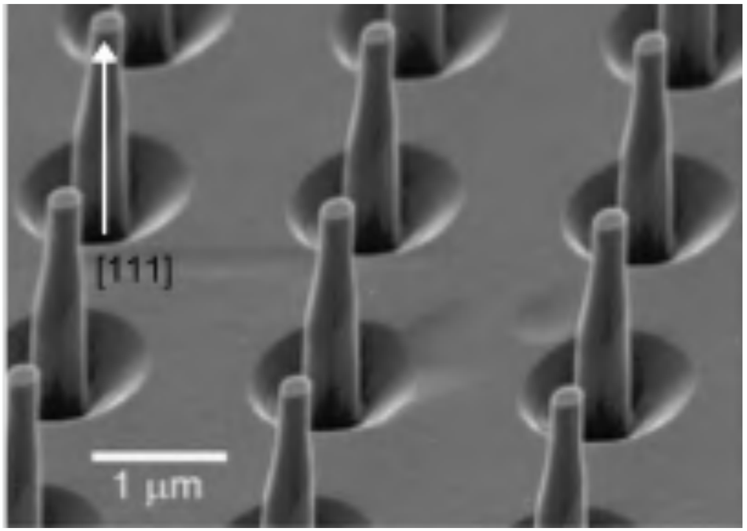


Higher collection efficiency for 111-oriented NVs

P. Maletinsky, University of Basel

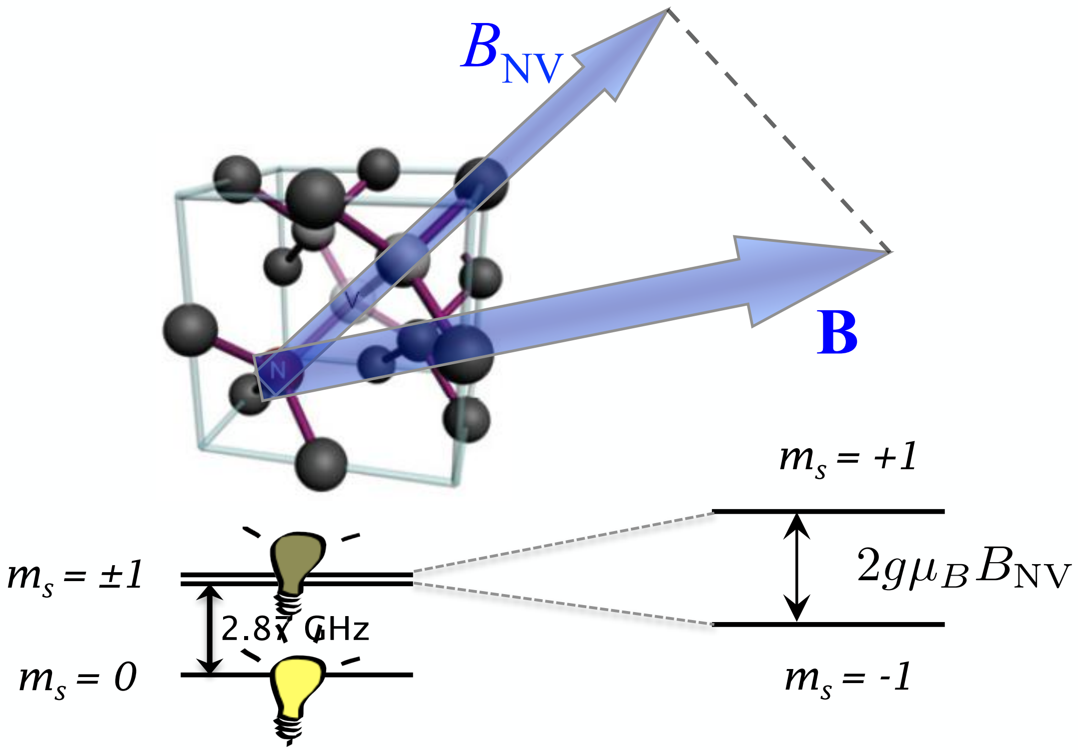
Single NV center in a [111]-oriented nanopillar

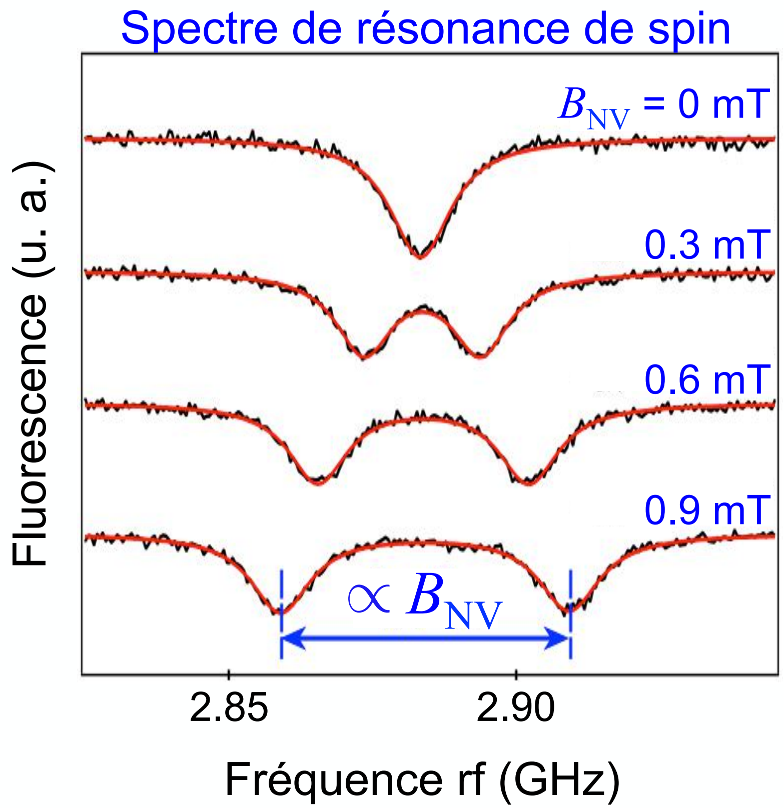
PL signal of about 10^6 counts/s



* E. Neu, et al., Appl. Phys. Lett. 104, 153108 (2014)

The NV center in diamond:
“Direct” magnetometry techniques



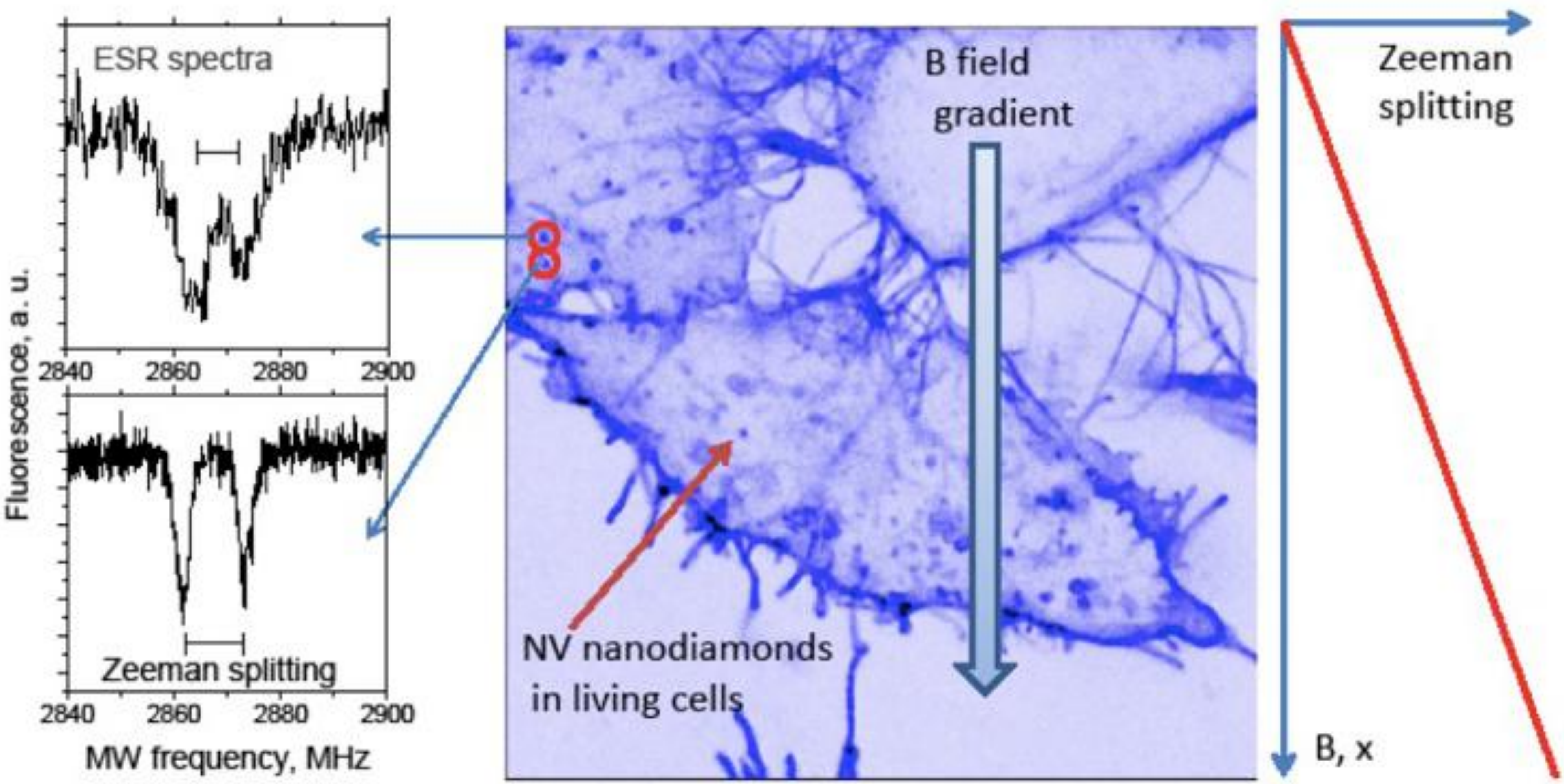


ODMR of NV centers in cells

Dynamics of Diamond Nanoparticles in Solution and Cells

Felix Neugart,† Andrea Zappe,† Fedor Jelezko,† C. Tietz,† Jean Paul Boudou,‡ Anke Krueger,§ and Jörg Wrachtrup*,†

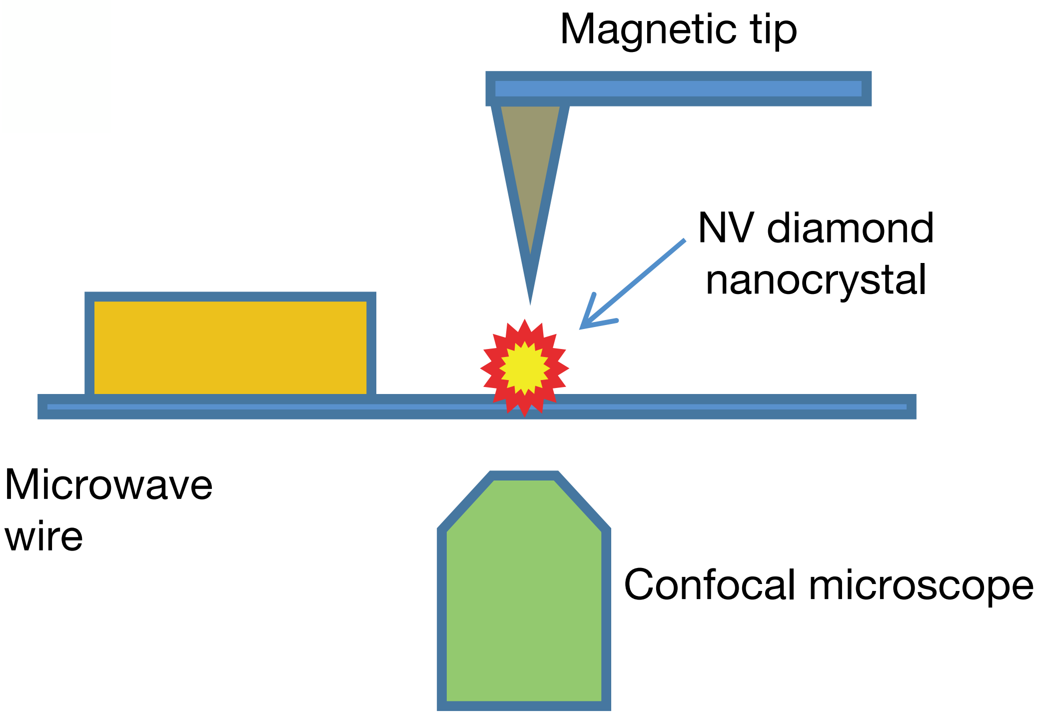
Nano Letters 7, 3588 (2007)

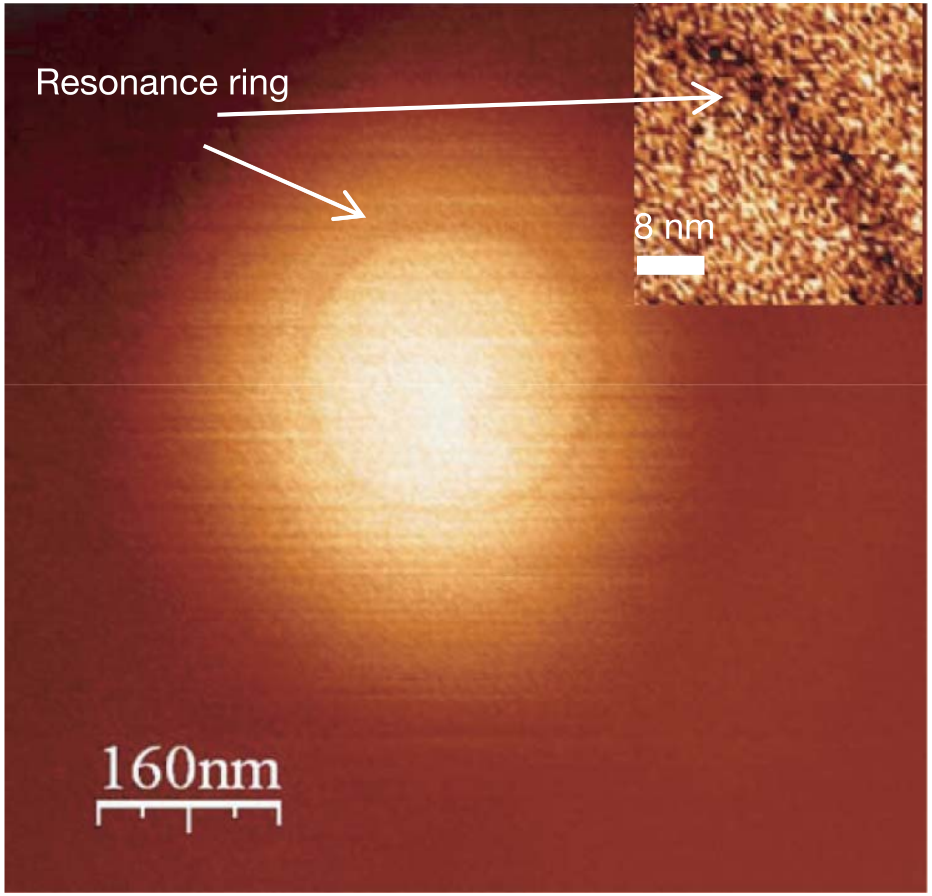


Nanoscale imaging magnetometry with diamond spins under ambient conditions

Nature **455**, 648 (2008)

Gopalakrishnan Balasubramanian[1], I. Y. Chan[2]†, Roman Kolesov[1], Mohannad Al-Hmoud[1], Julia Tisler[1], Chang Shin[3], Changdong Kim[3], Aleksander Wojcik[3], Philip R. Hemmer[3], Anke Krueger[4], Tobias Hanke[5], Alfred Leitenstorfer[5], Rudolf Bratschitsch[5], Fedor Jelezko[1] & Jörg Wrachtrup[1]



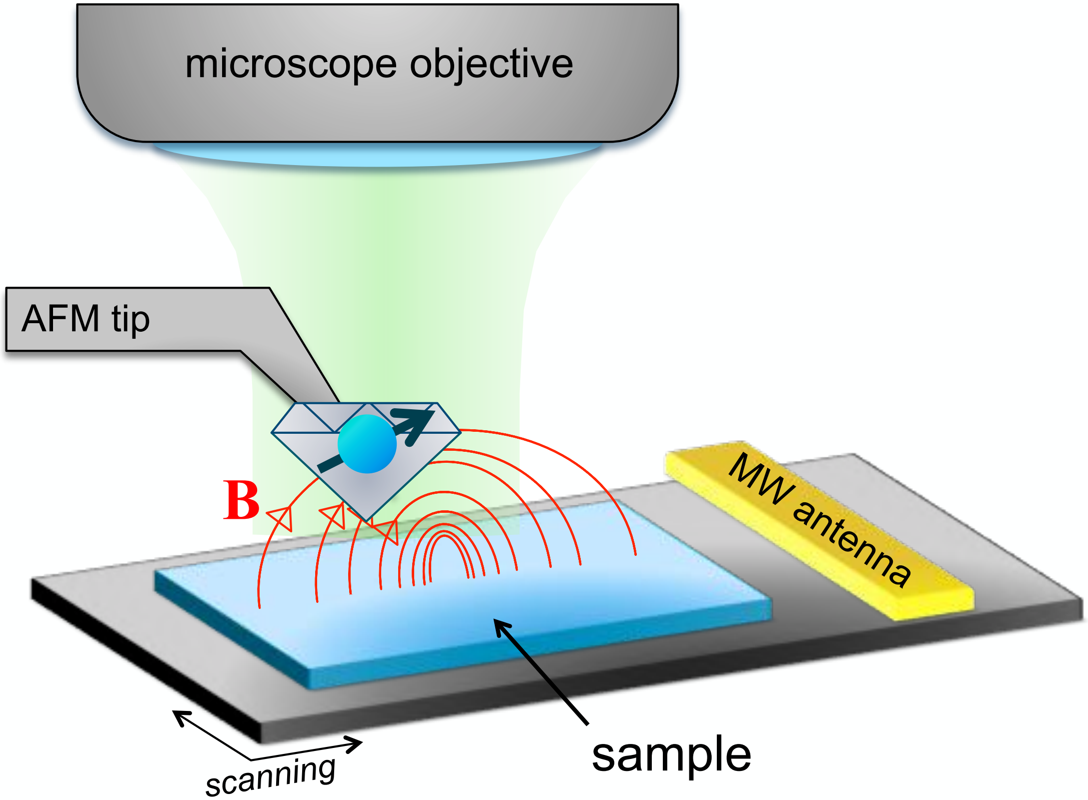


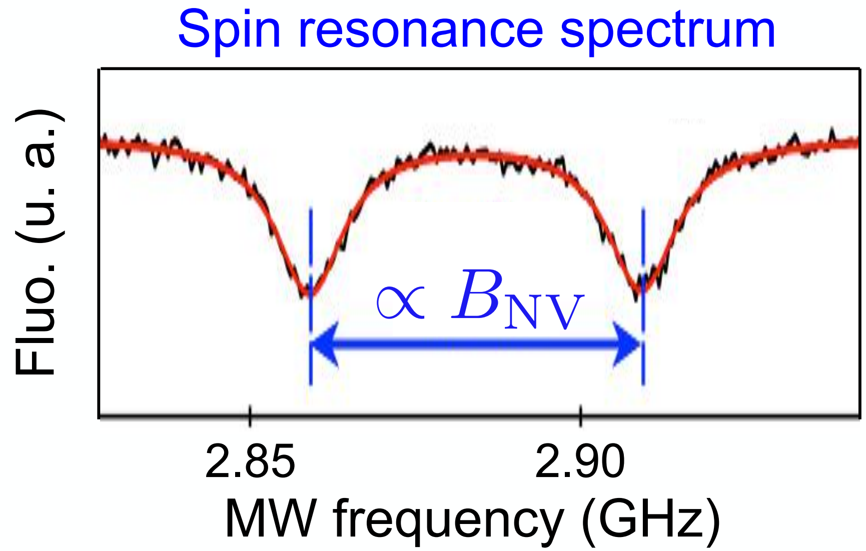
$$\text{Field gradient} \approx 0.1\,\mathrm{G/nm} \text{ at } 1\,\mu\mathrm{m} \text{ distance of the tip}$$

$$\Delta\nu_{\mathrm{FWHM}} \approx 1\,\mathrm{kHz} \rightarrow \text{ultimate resolution} \approx 0.1\,\text{Å}$$

Magnetic probe based on a single NV spin

Proposal : B. M. Chernobrod & G. P. Berman,
J. Appl. Phys. 97, 014903 (2005)

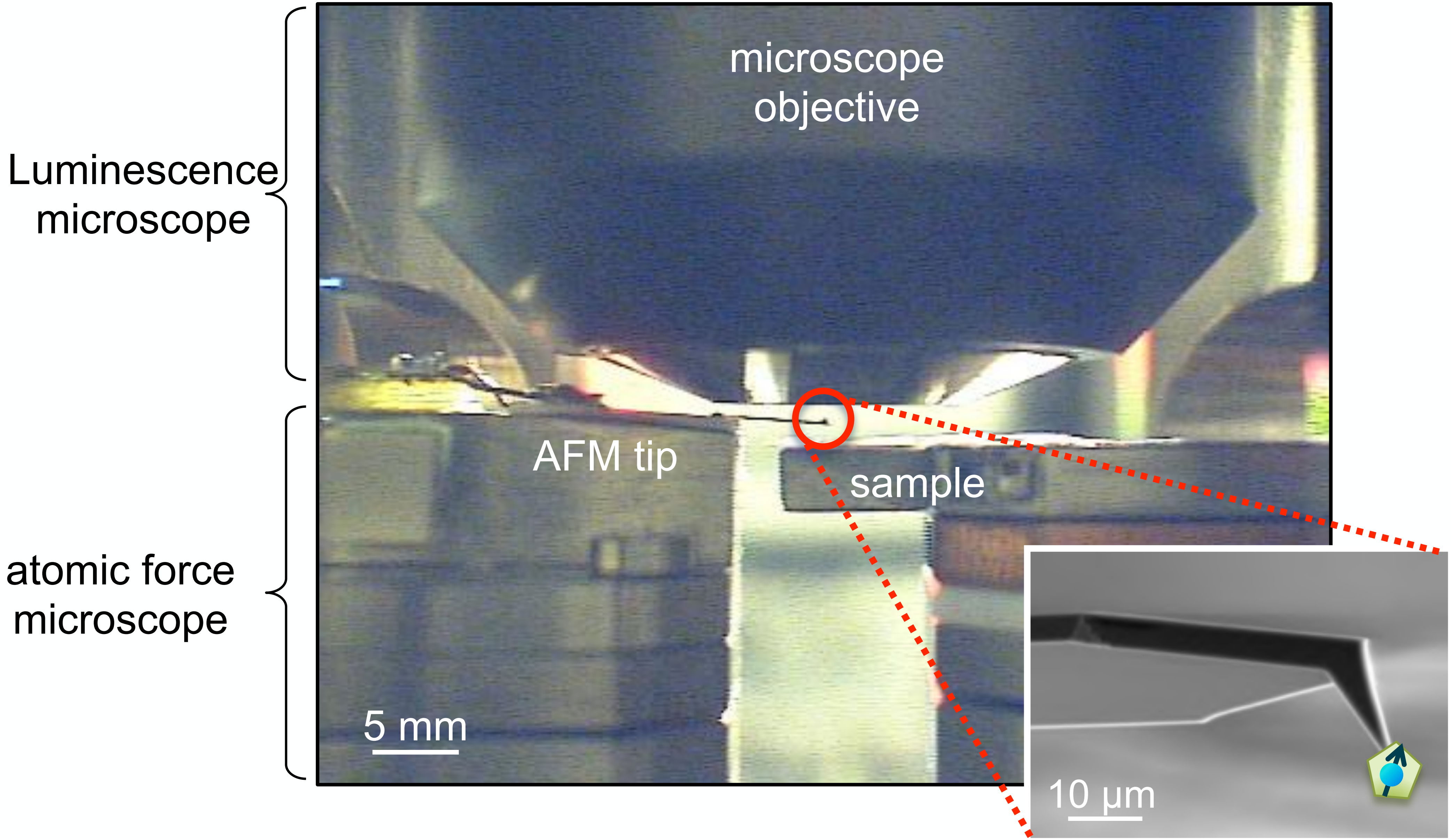




- Quantitative measure of B_{NV} component
- Averaged over a volume < (1 nm)^3
- Ambiant conditions without magnetic back-action (≠ MFM)

- First realization: G. Balasubramanian et al., Nature 455, 648 (2008)
- Review: L. Rondin et al., Rep. Prog. Phys. **77**, 056503 (2014)

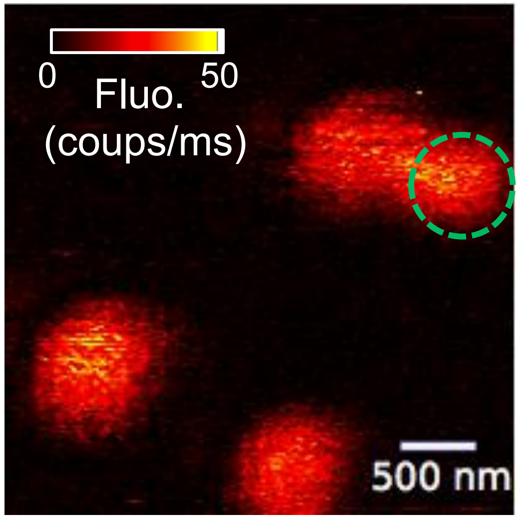
Practical implementation



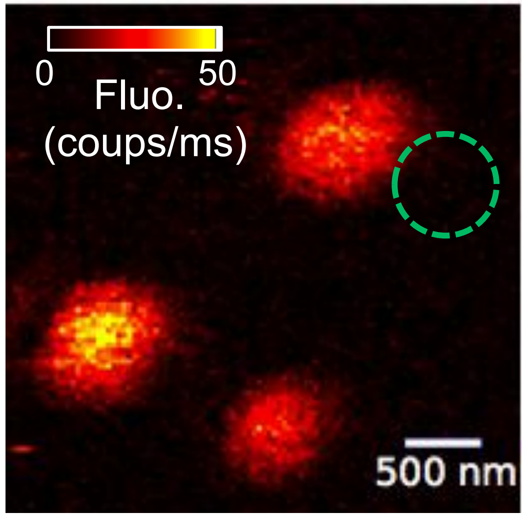
L. Rondin et al., Appl. Phys. Lett. **100**, 153118 (2012)

Grafting a nanodiamond on the AFM tip

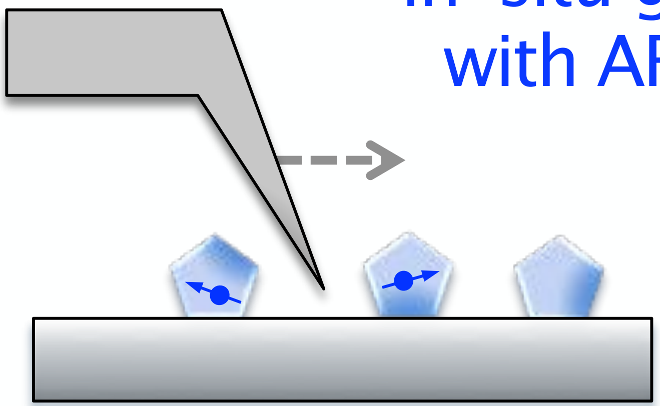
before grafting



after grafting

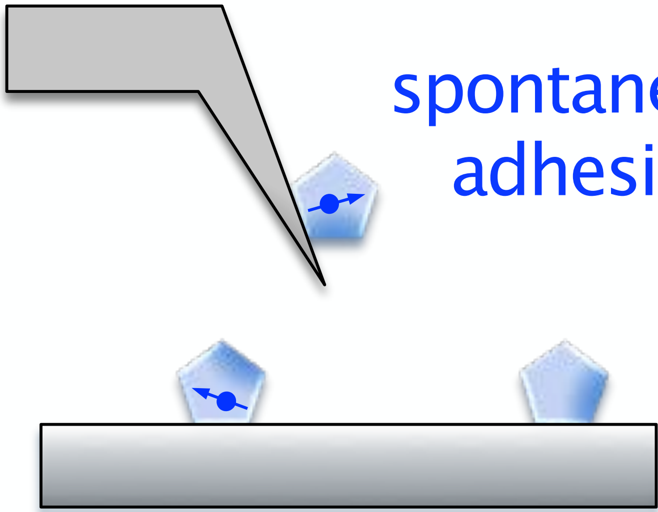


in–situ grafting
with AFM tip

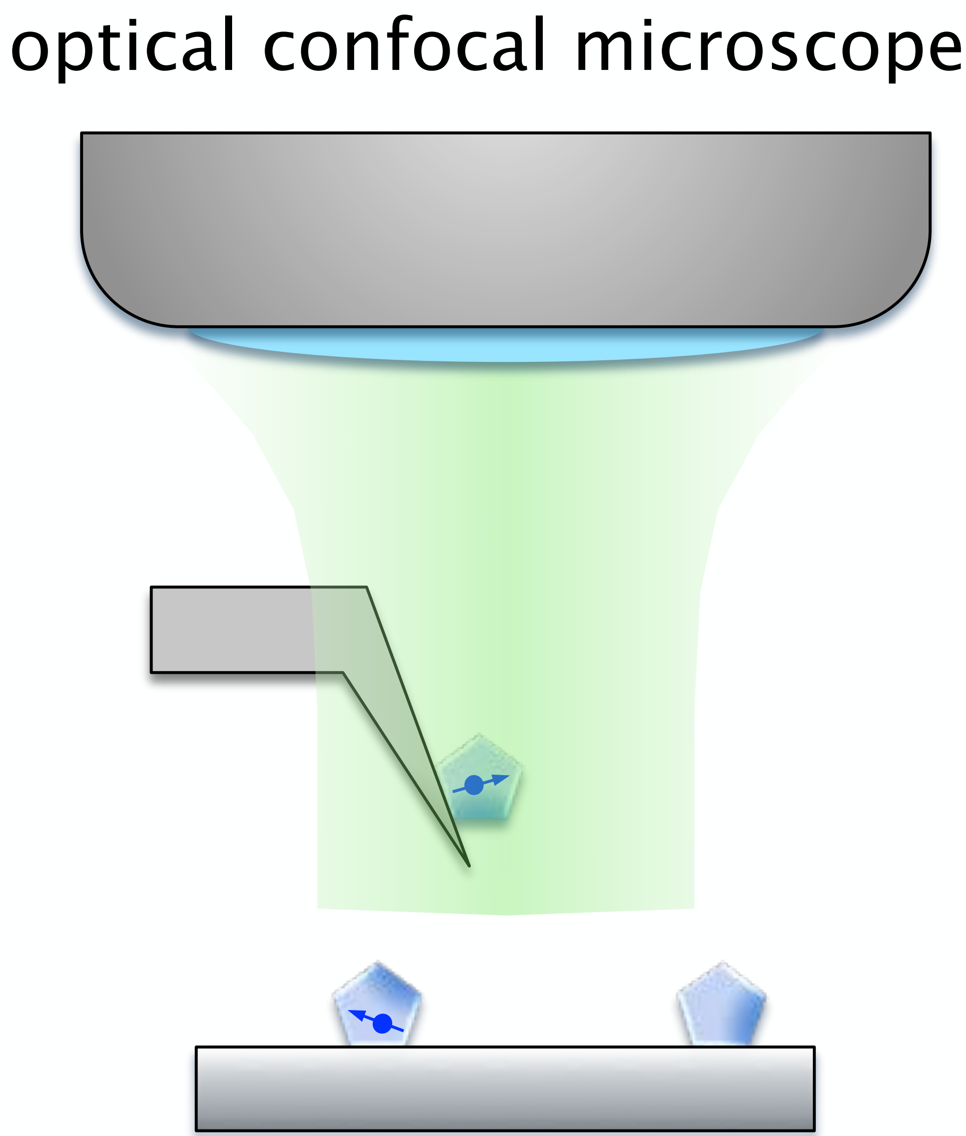


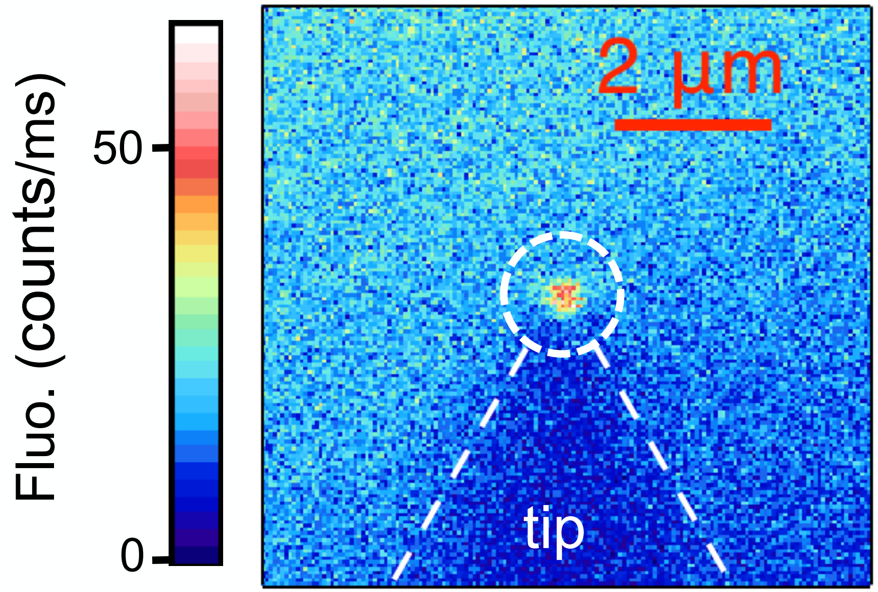
nanodiamonds
on a glass coverslip

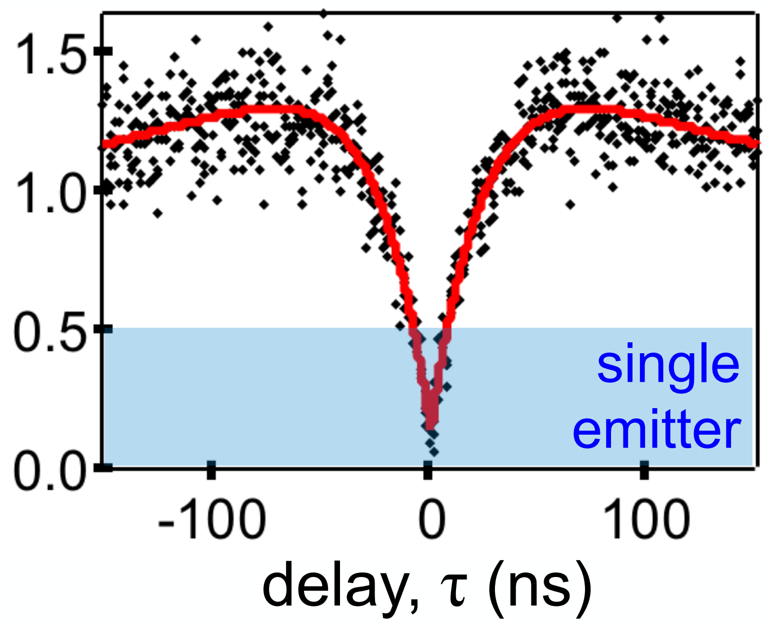
spontaneous
adhesion



A single NV at the apex of the AFM tip

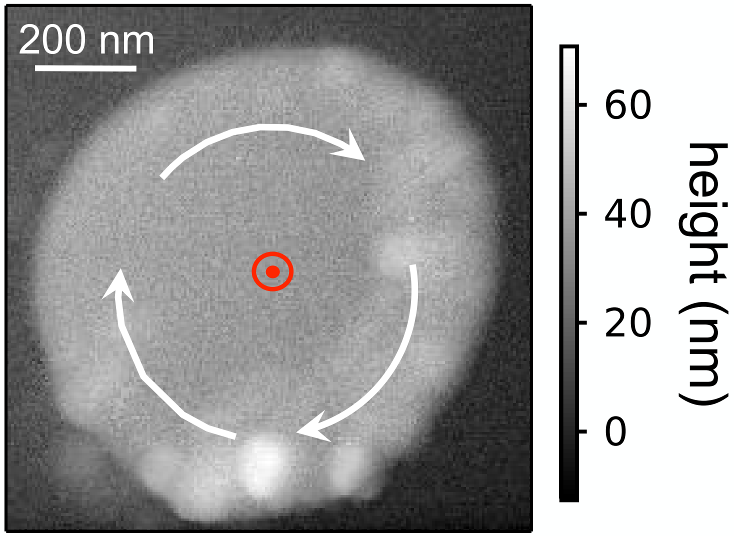






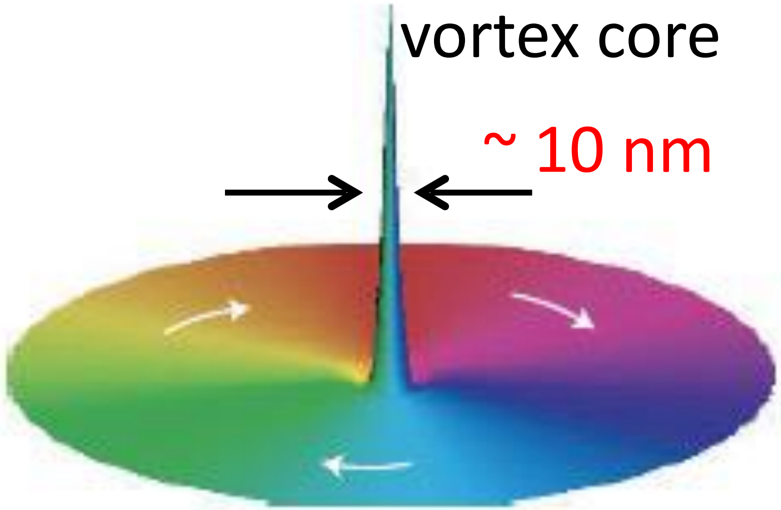
Proof-of-principle: core of magnetic vortex

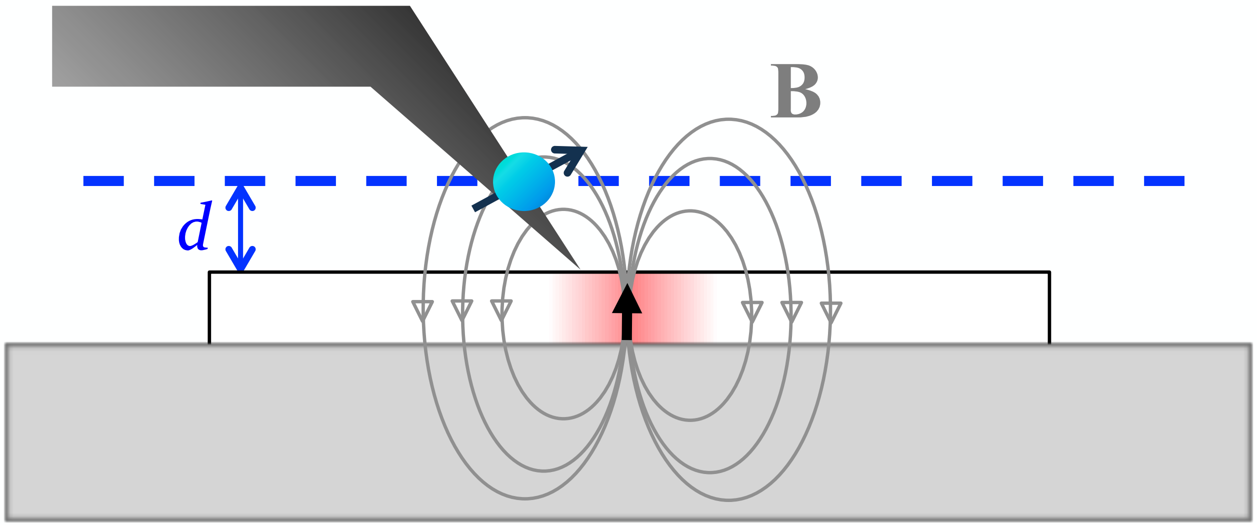
AFM image



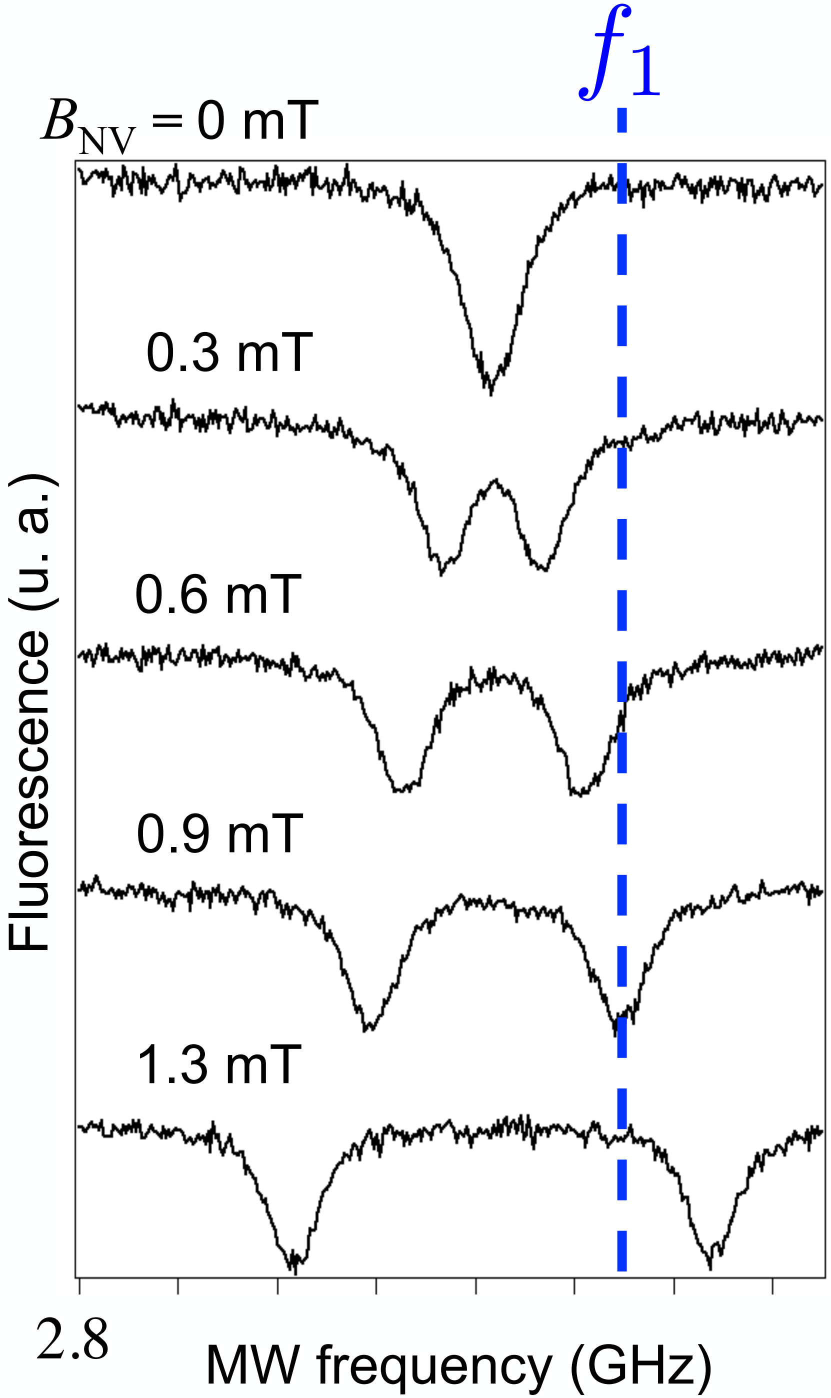
microdisk of $Ni_{80}Fe_{20}$

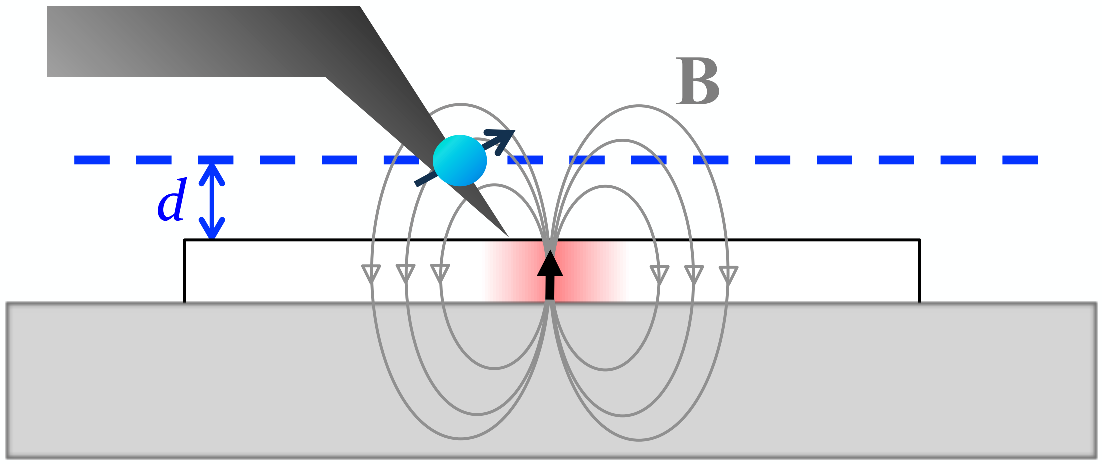
magnetization

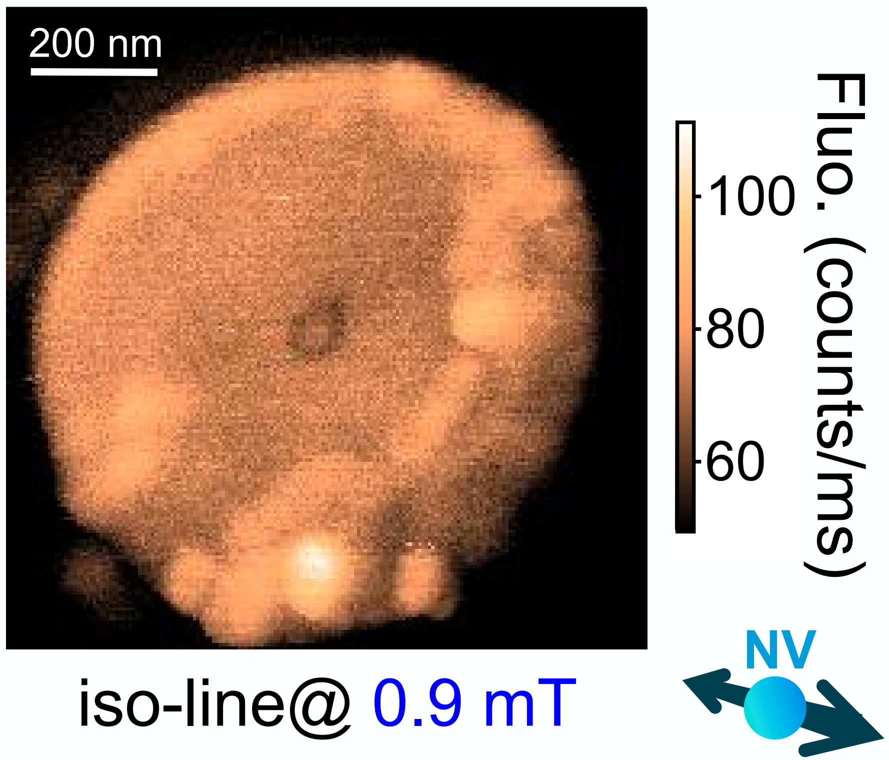




Magnetic imaging techniques (2)

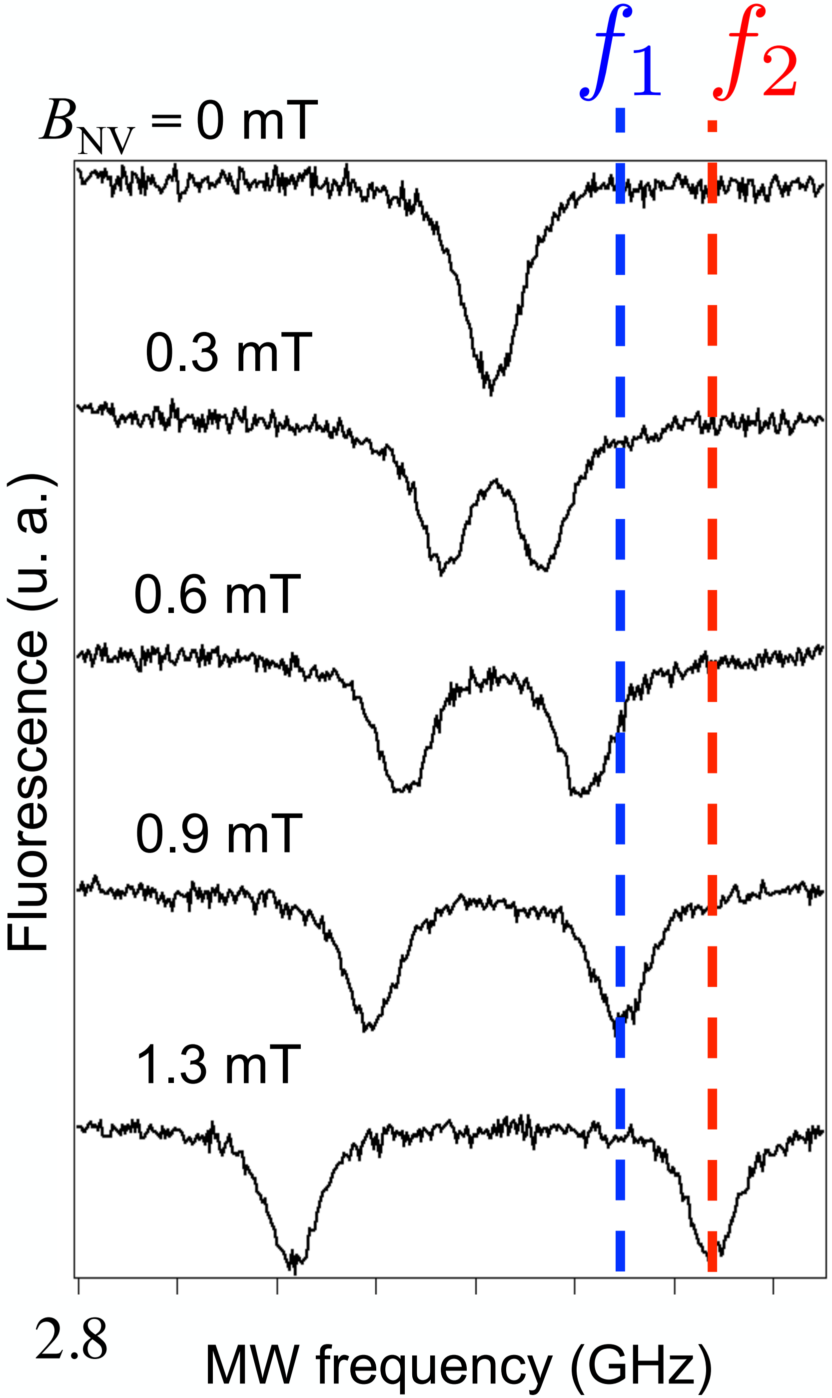


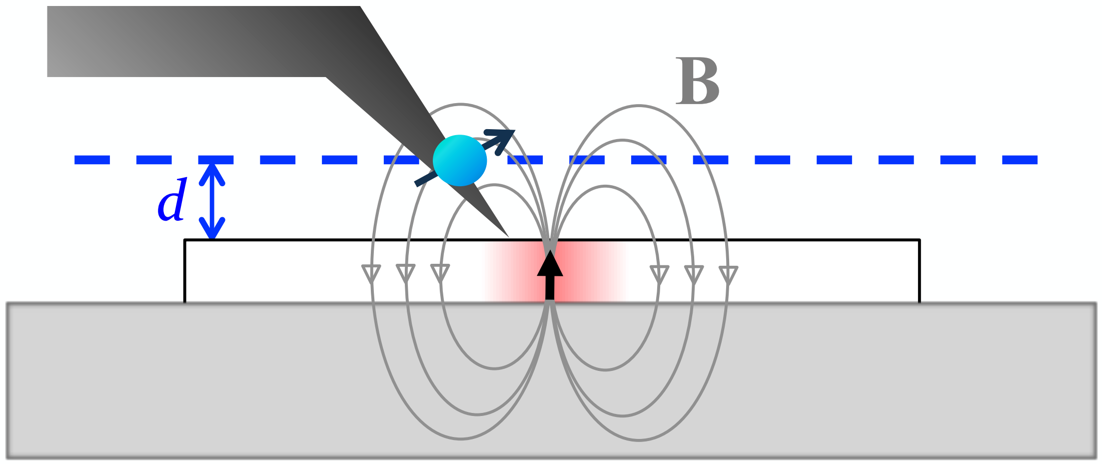


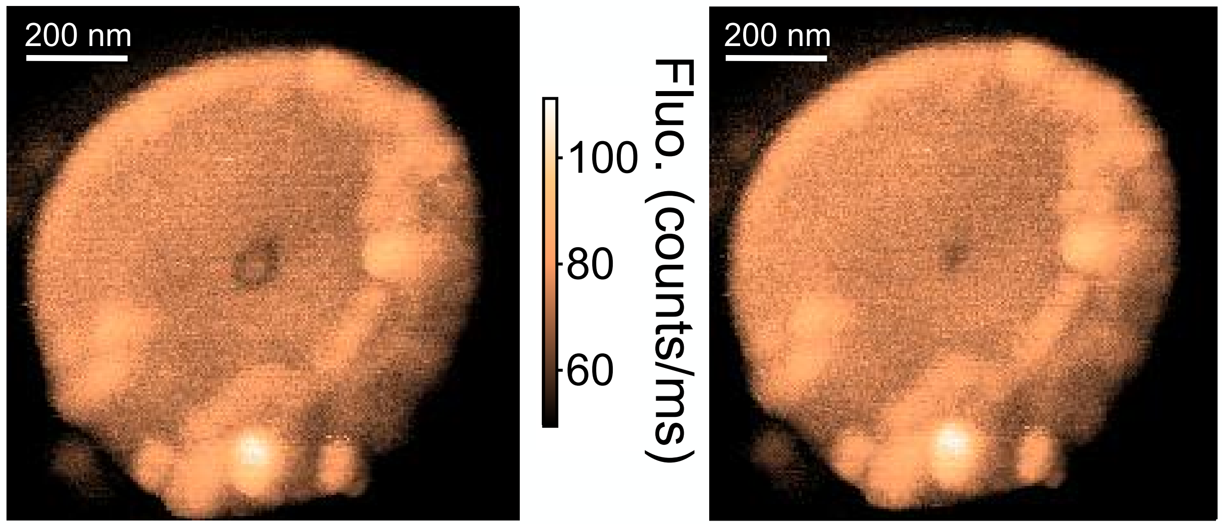


iso-line@ 0.9 mT

Magnetic imaging techniques (3)



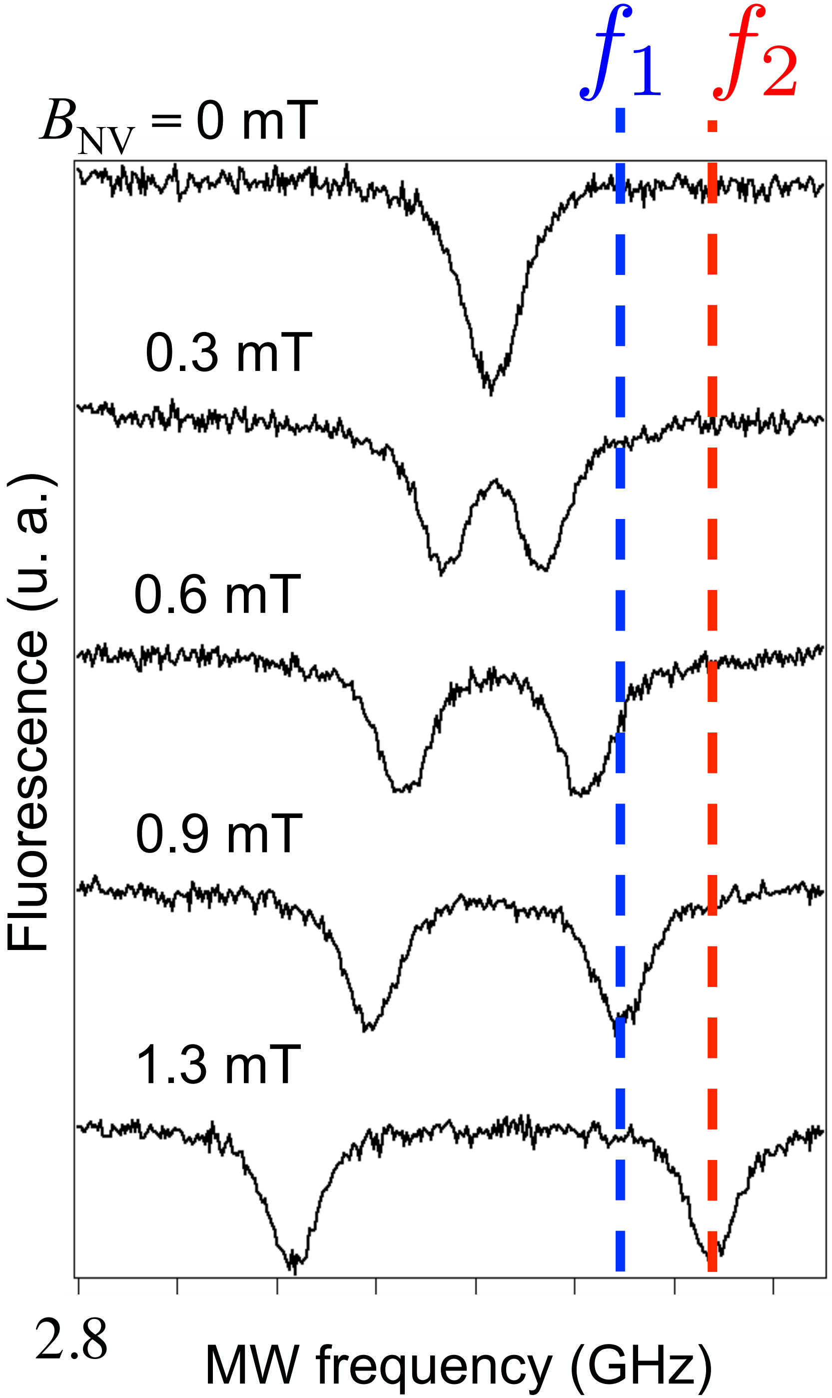


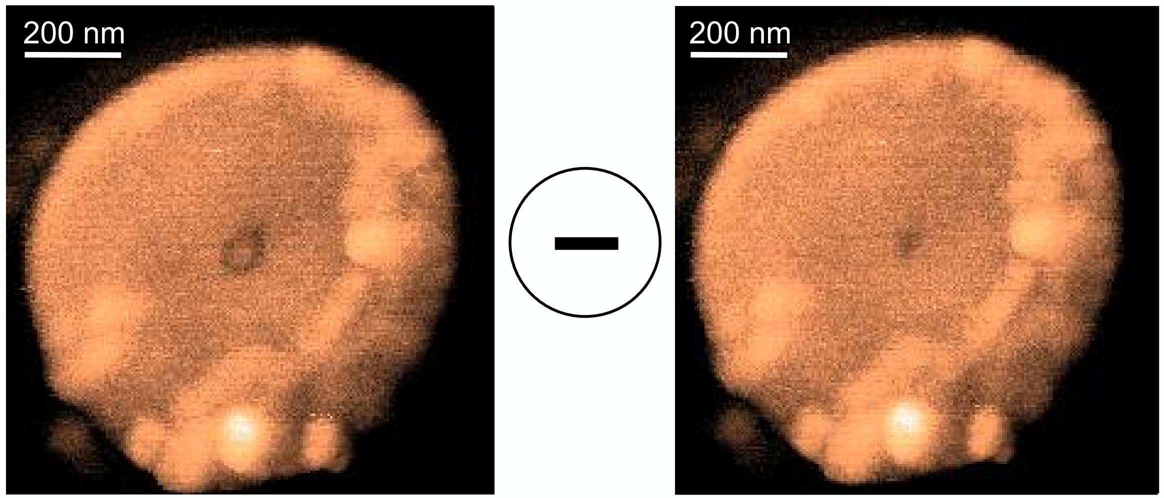


Iso-line @ 0.9 mT

Iso-line @ 1.3 mT

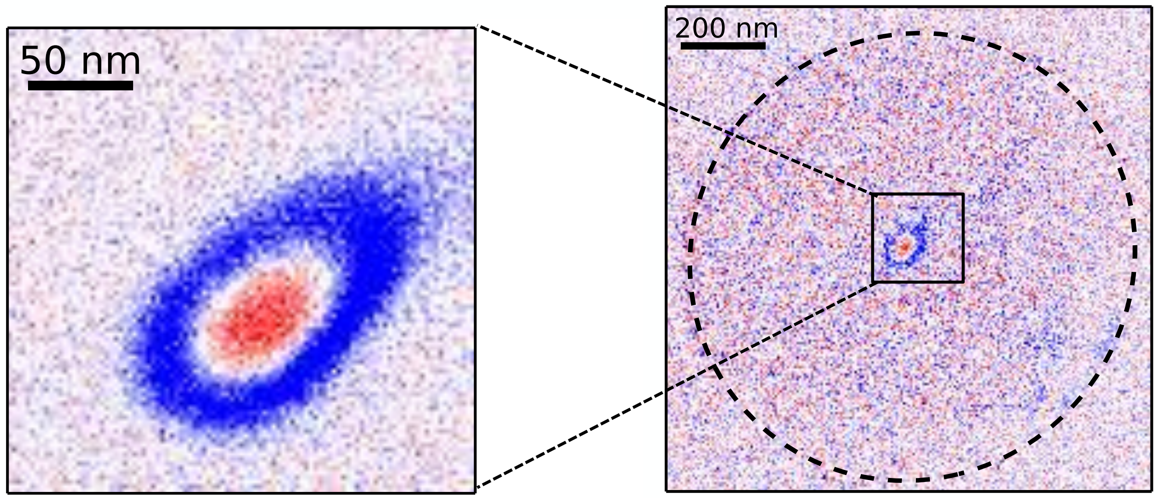
Magnetic imaging techniques (4)





Iso-line @ 0.9 mT
Image

Iso-line @ 1.3 mT



~ 50 ms per pixel

B_{NV} = 1.3 mT
B_{NV} = 0.9 mT

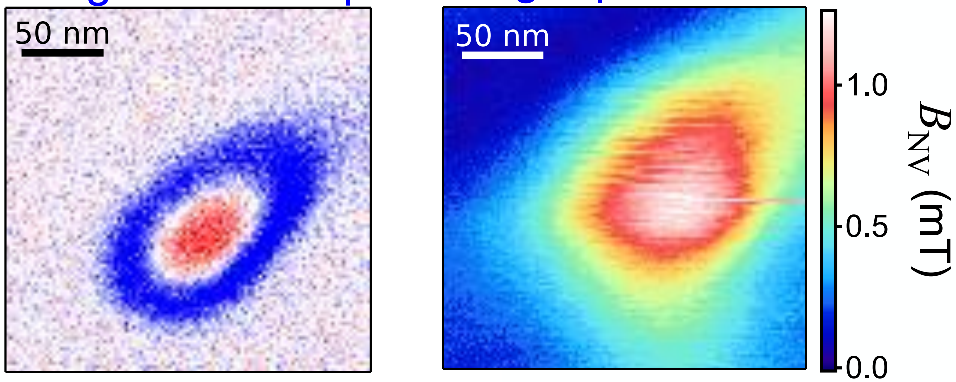
NV magnetometry

- Images of a vortex core

  Rondin et al., Nature Communications **4**, 2279 (2013).

  Tetienne et al., Phys. Rev. B **88**, 214408 (2013).

Image iso-champ | Image quantitative

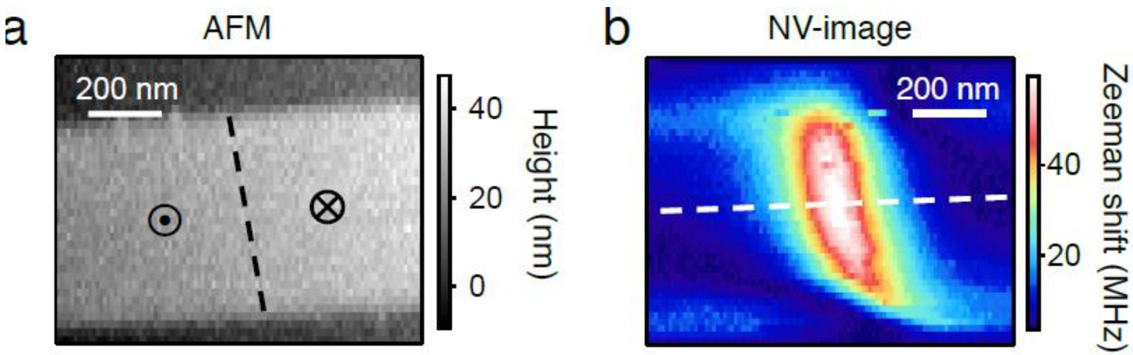


~ 50 ms par pixel | ~ 500 ms par pixel

- Technique well suited for **quantitative** measurements on magnetic systems with nanoscale dimension

  – Domain wall motion in a magnetic wire and Barkhausen noise
  Tetienne, Hingant et al., Science 344, 6190 (2014)

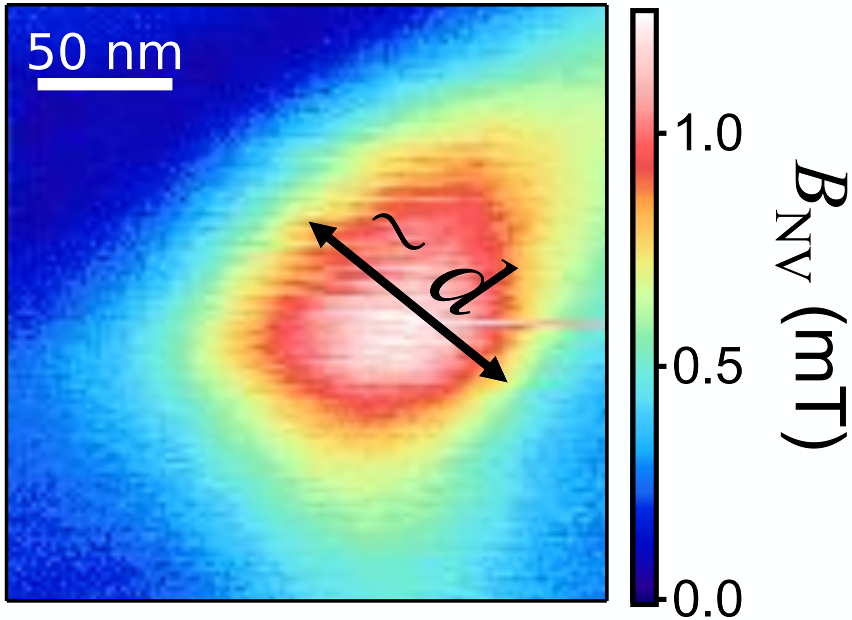
  – Determine the structure of a single domain wall: Bloch or Néel
  Tetienne, Hingant, et al., Nature Com. 6, 6733 (2015)



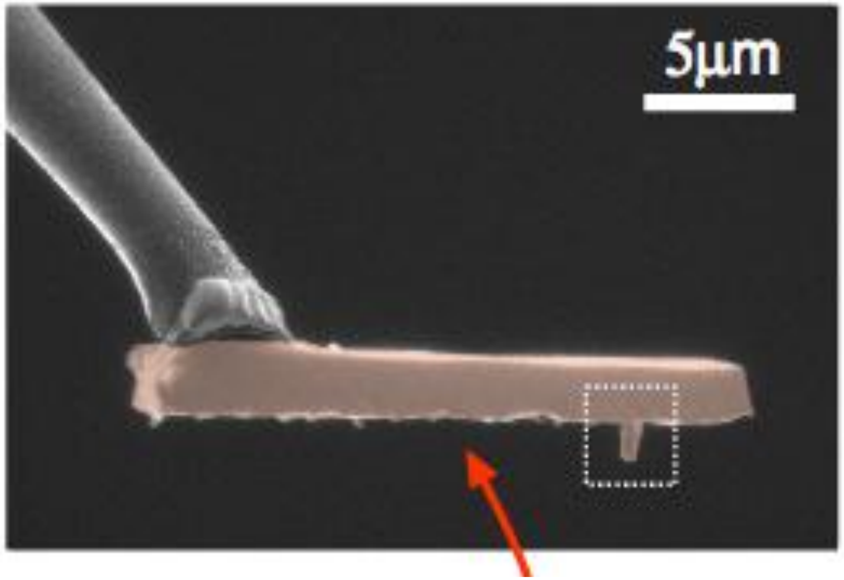
L. Rondin et al., Rep. Prog. Phys. ***77****, 056503 (2014).*

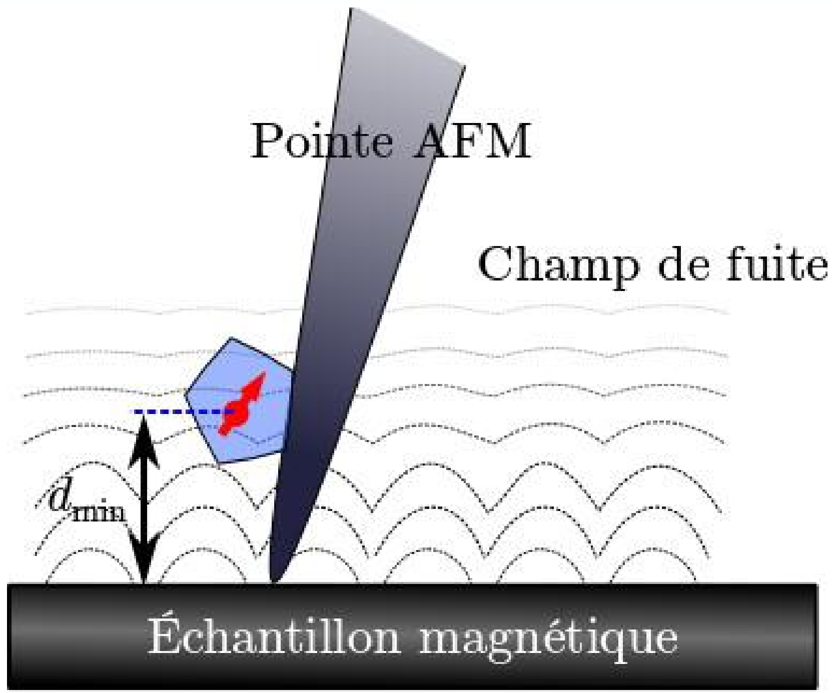
Resolution and magnetic sensitivity

- Resolving power limited by "height of flight" (50 à 100 nm)
- B–field detected on a sampling volume of ~(1 nm)³
- Sensitivity limited by:
  – coherence time of NV spin
  – photon collection efficiency



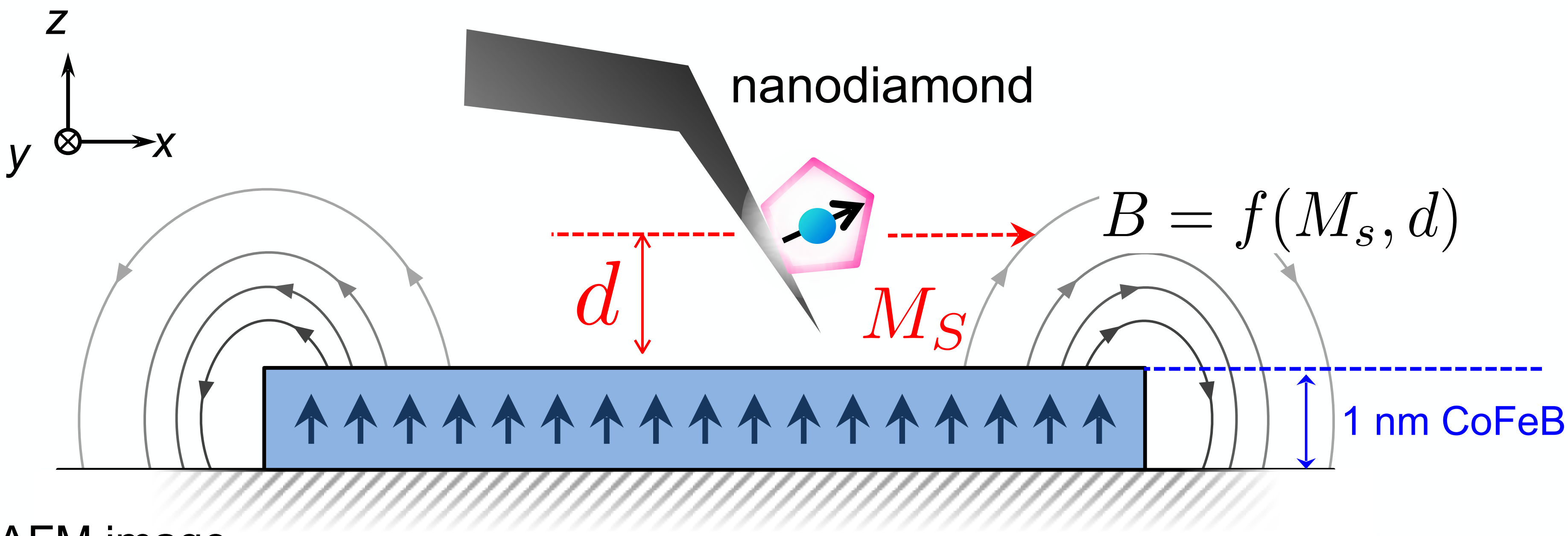
Improvement: diamond tip



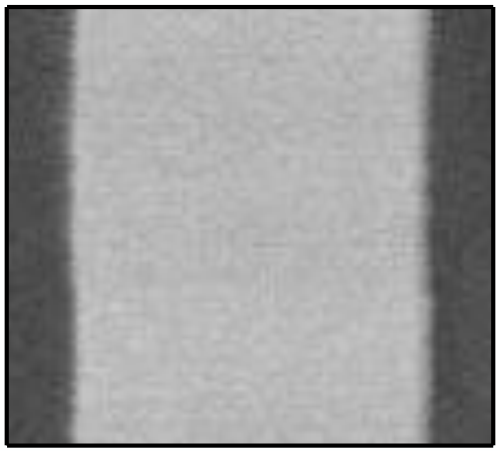


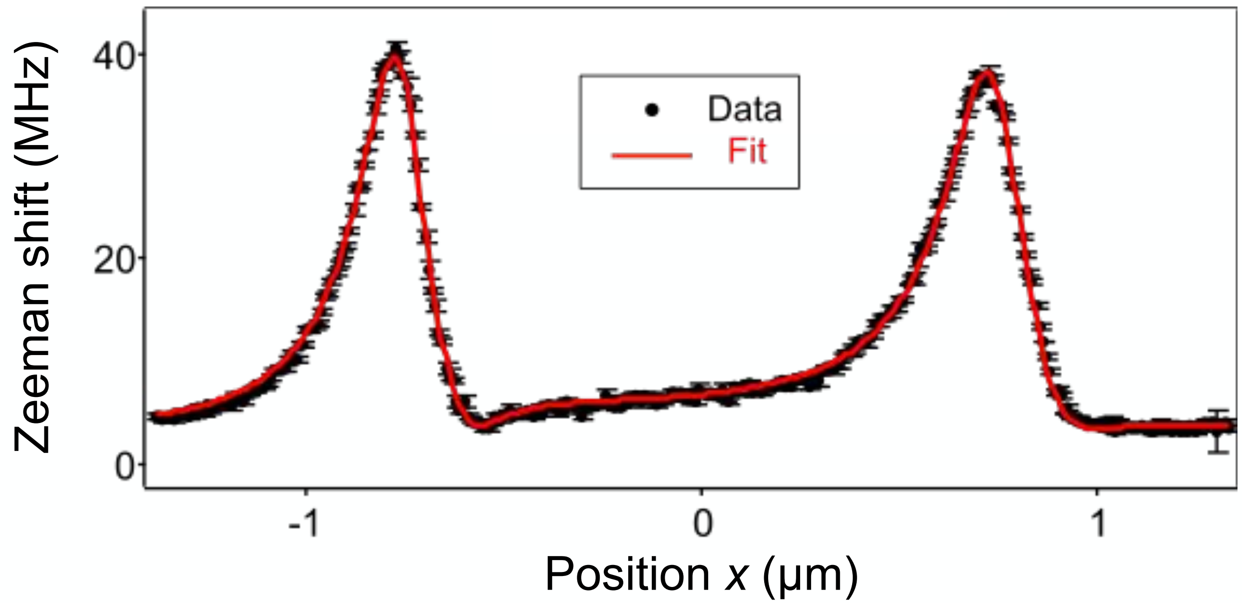
P. Maletinsky et al., *Nat. Nano*. **7**, 320 (2012)

Calibration of probe-to-sample distance



AFM image



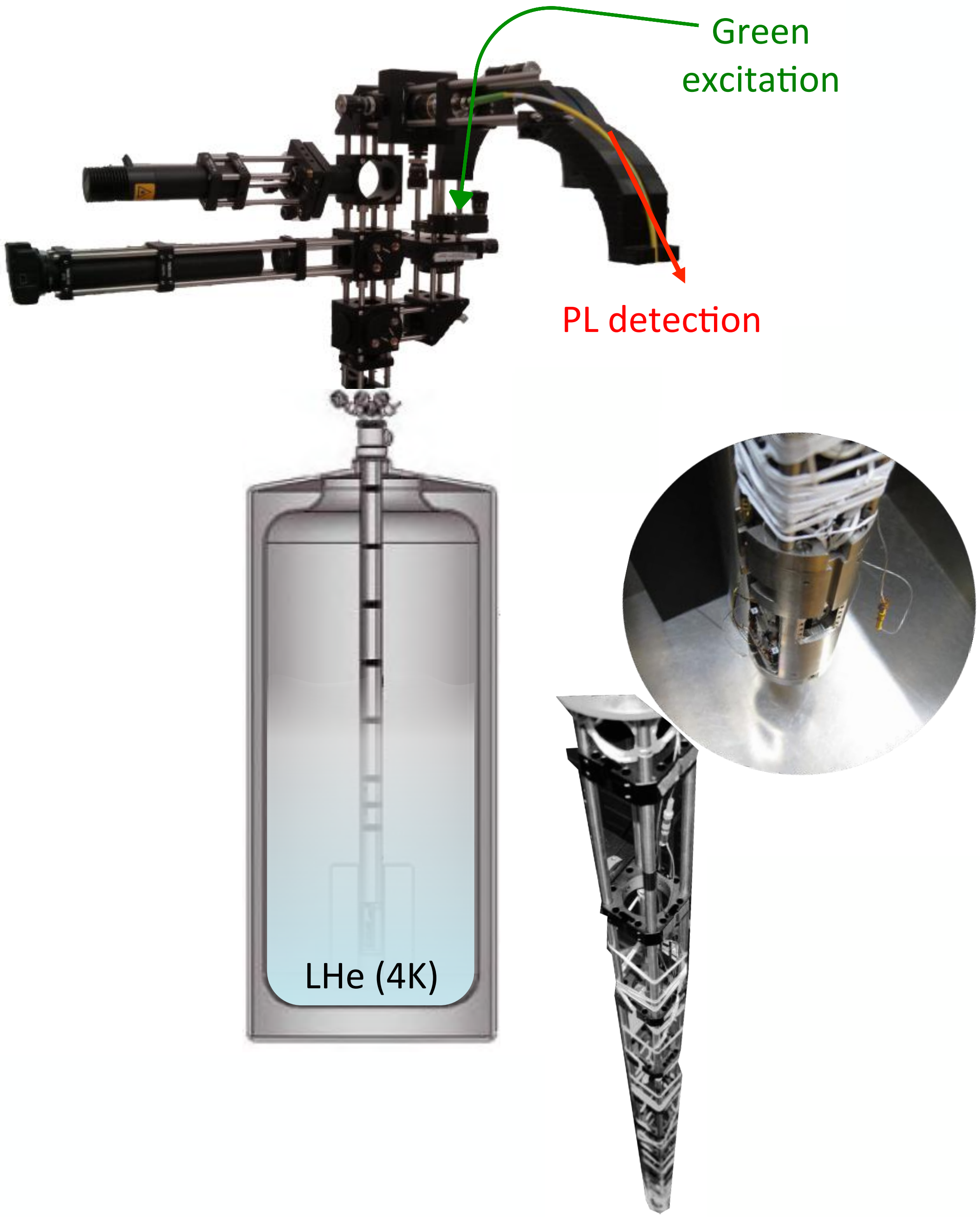


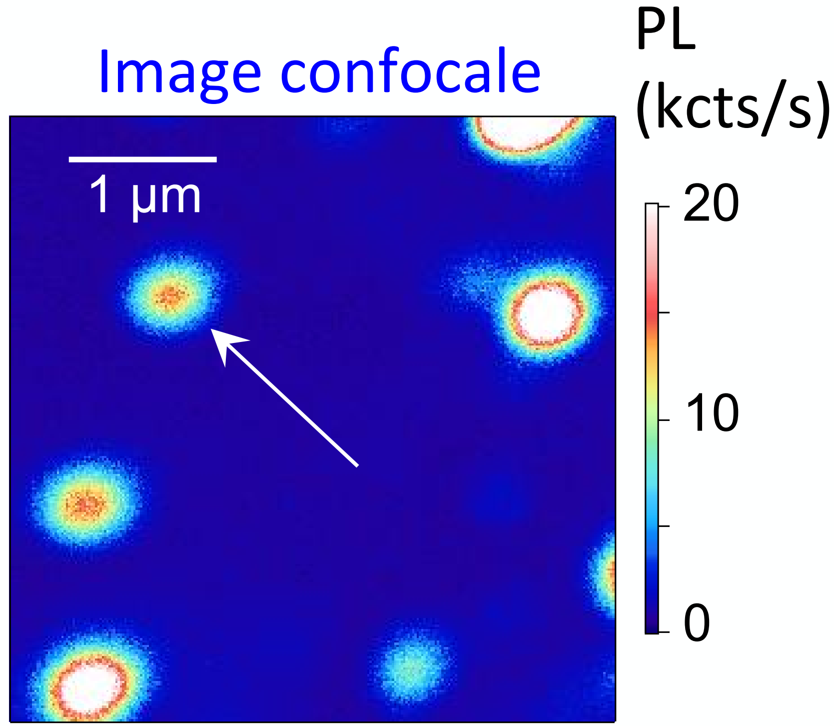
M_s = 0.93 ± 0.03 MA/m

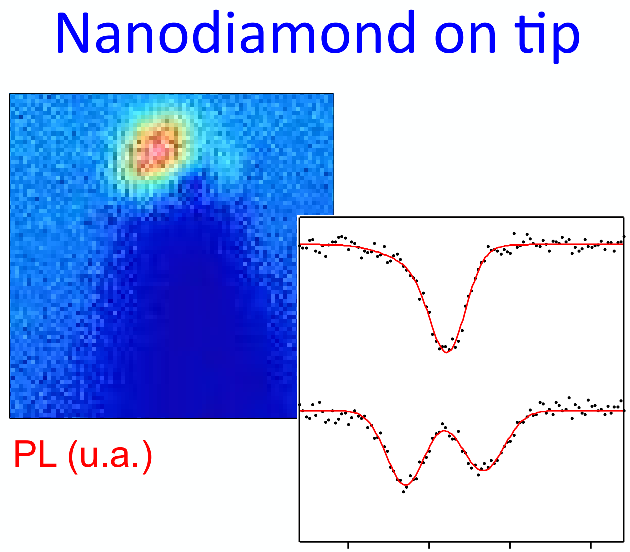
d = 123 ± 3 nm

T. Hingant et al., Phys. Rev. Applied **4**, 014003 (2015)

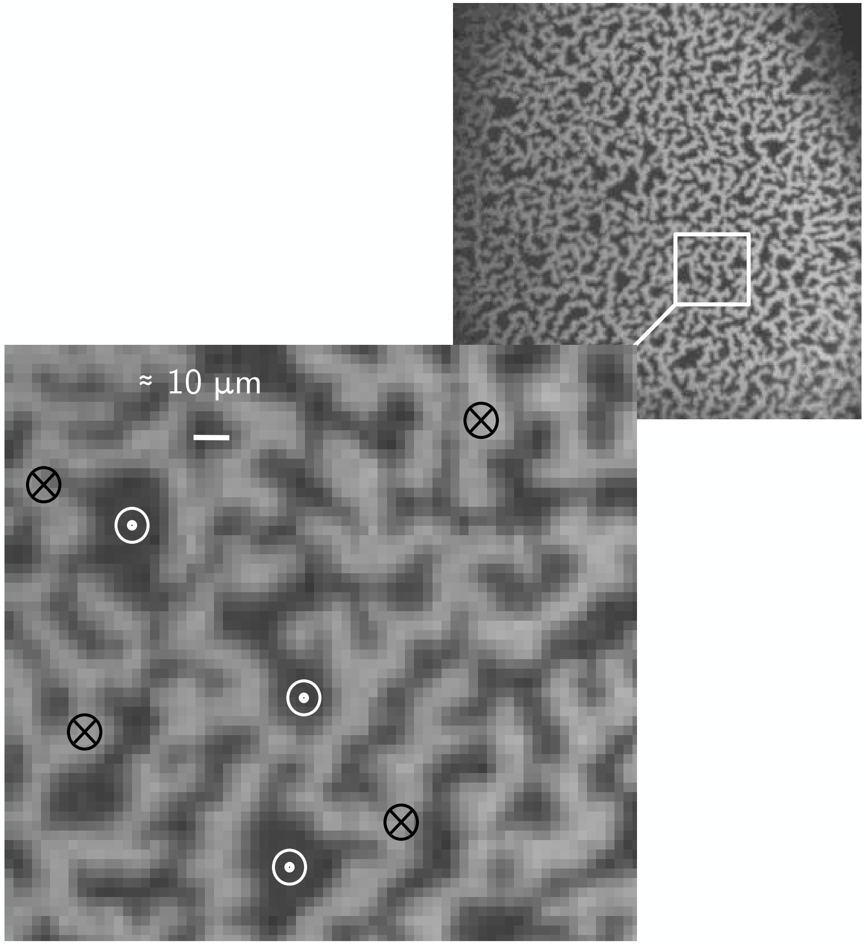
Under development:
low-temperature NV scanning microscope





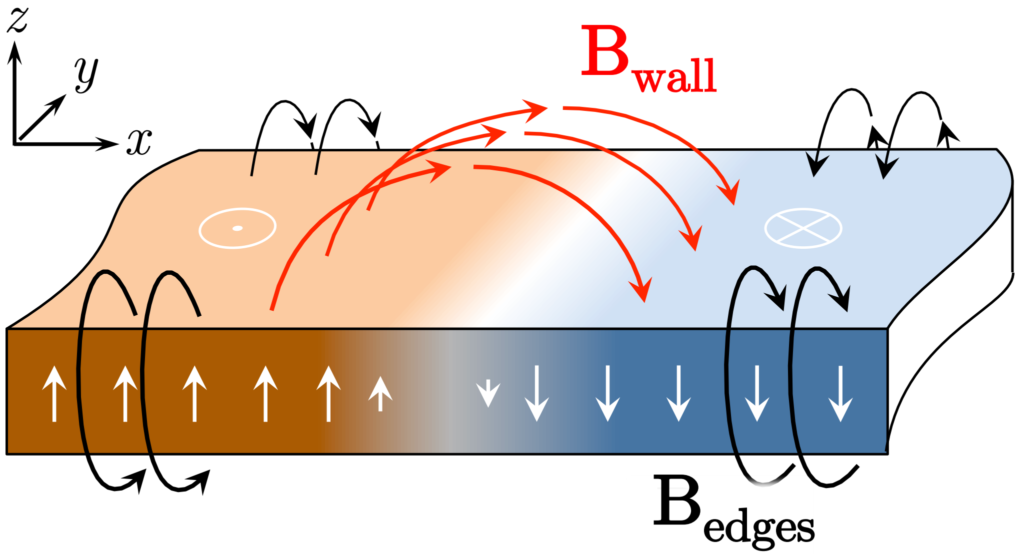


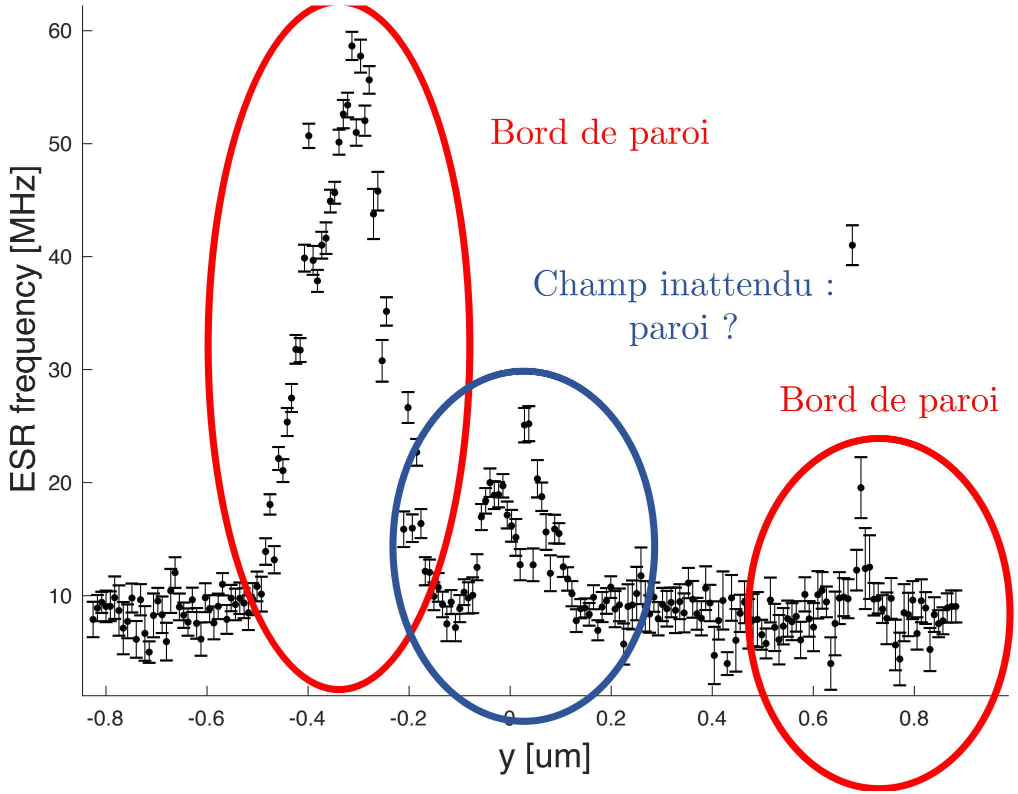
Domain wall imaging at 4 K : GaMnAsP



Sample fabricated by Aristide Lemaître (C2N)

Kerr microscope imaging by Vincent Jeudy (LPS)

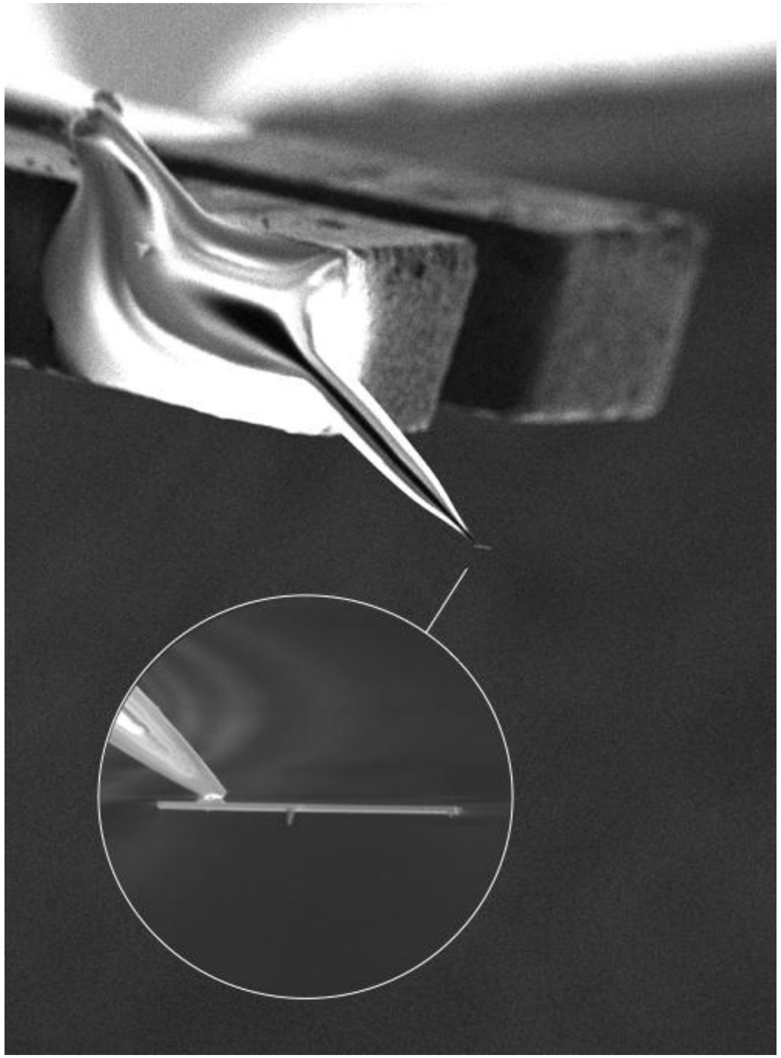


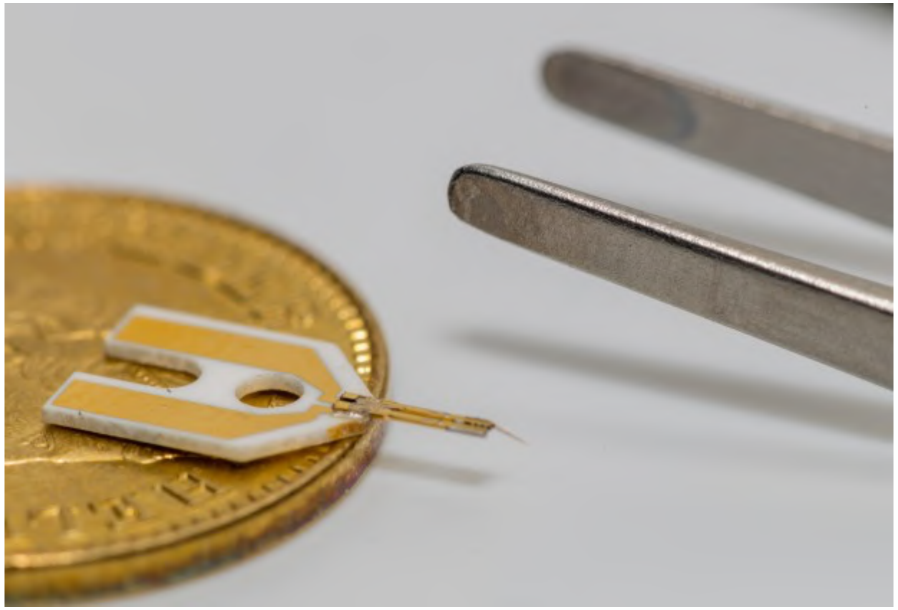


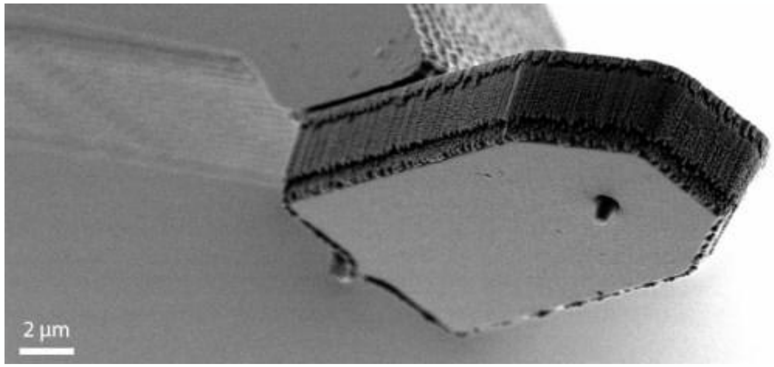
Now (almost) commercial diamond tips

Qnami

ZABRE
QUANTUM SENSING
AT THE CUTTING EDGE





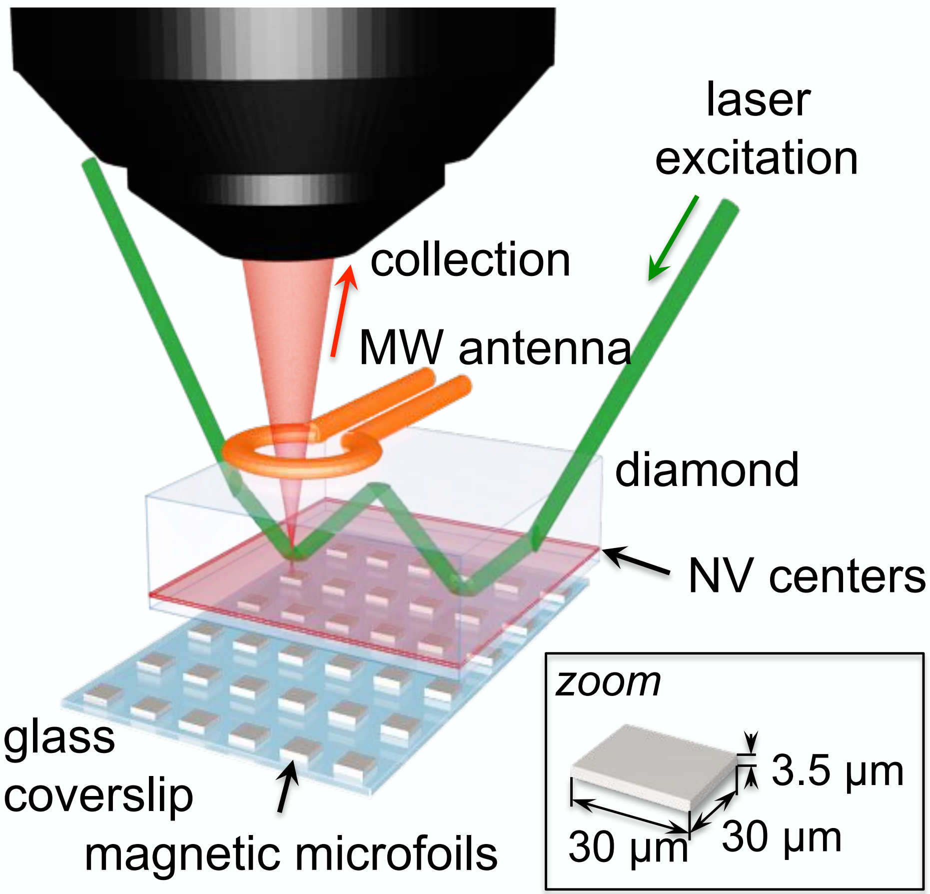


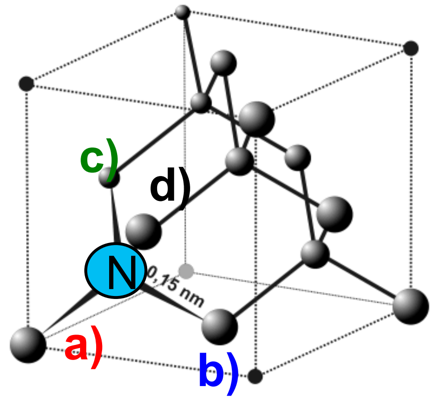
Wide–field magnetic imaging

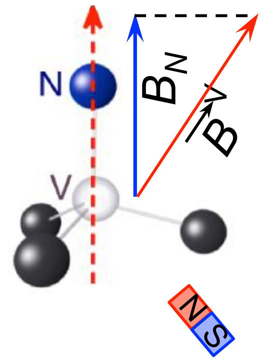
CCD camera: Each pixel = 1 magnetic resonance spectrum

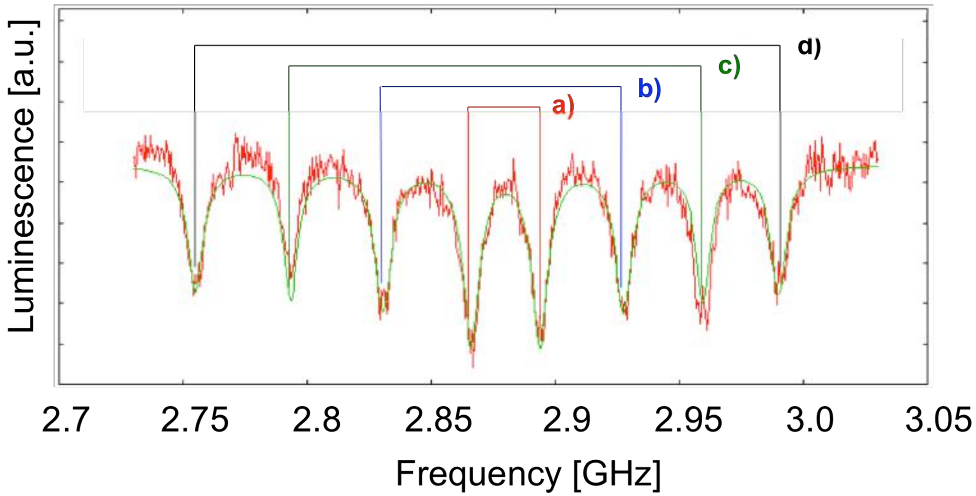
THALES

Th. Debuisschert







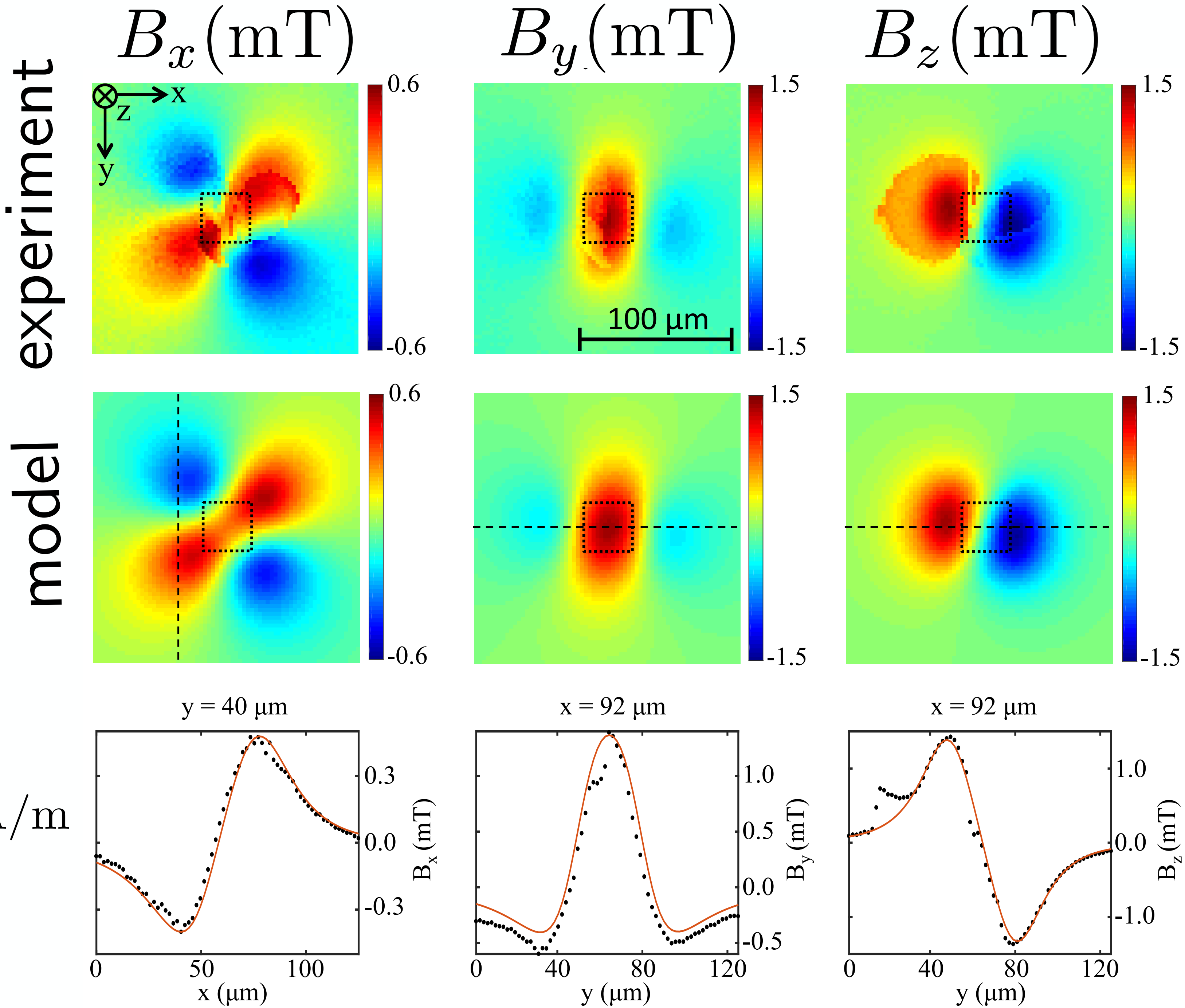


set of 4 correlated informations

maximum likelihood $\longrightarrow$ (B_x, B_y, B_z)

J. Wrachtrup (Stuttgart), R. Walworth (Harvard)

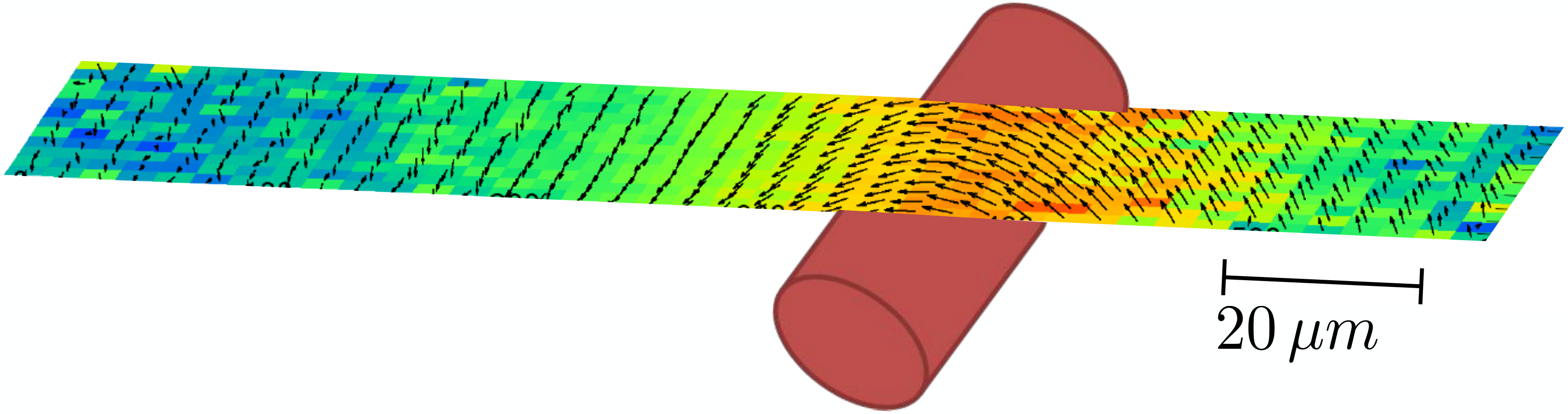
B–field produced by a permalloy dot



magnetic dipole

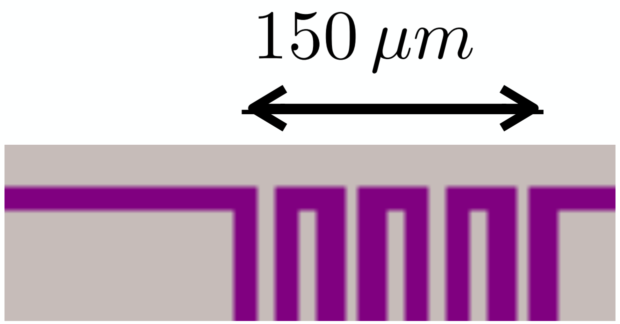
$$M = 7.9 \times 10^4\ \mathrm{A/m}$$
$$z = 19.5\,\mu\mathrm{m}$$

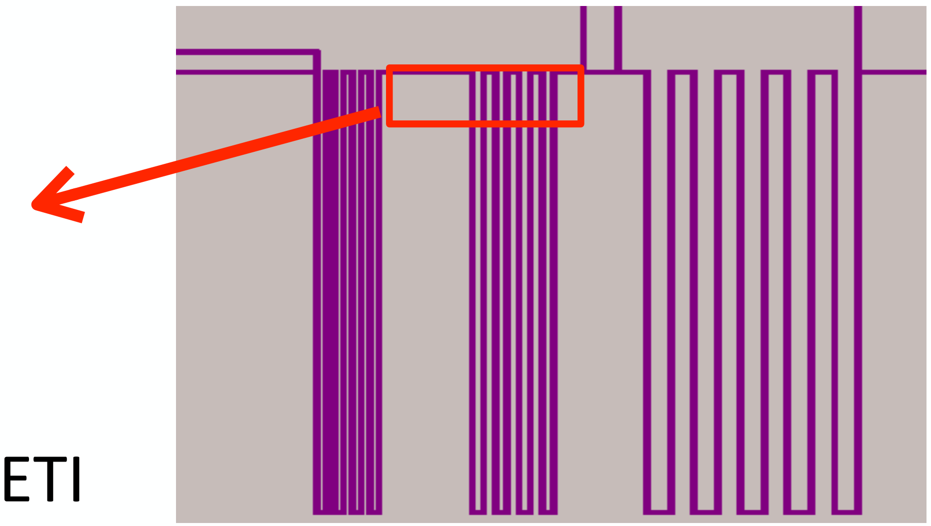
Image of magnetic field distribution
Resolution : standard optical microscopy ~400 nm



M. Chipeaux et al., Eur. Phys. J. D **69**, 166 (2015)

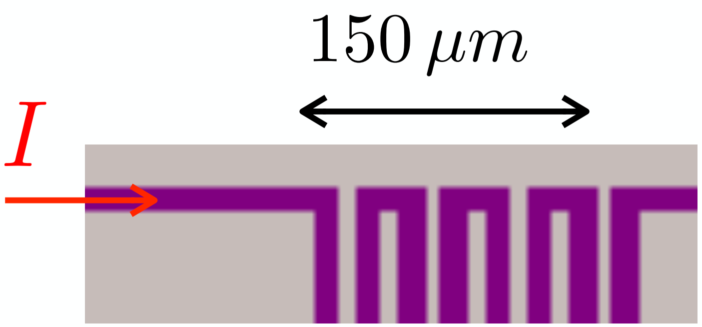
…can be used to retrieve a current distribution in microelectronics



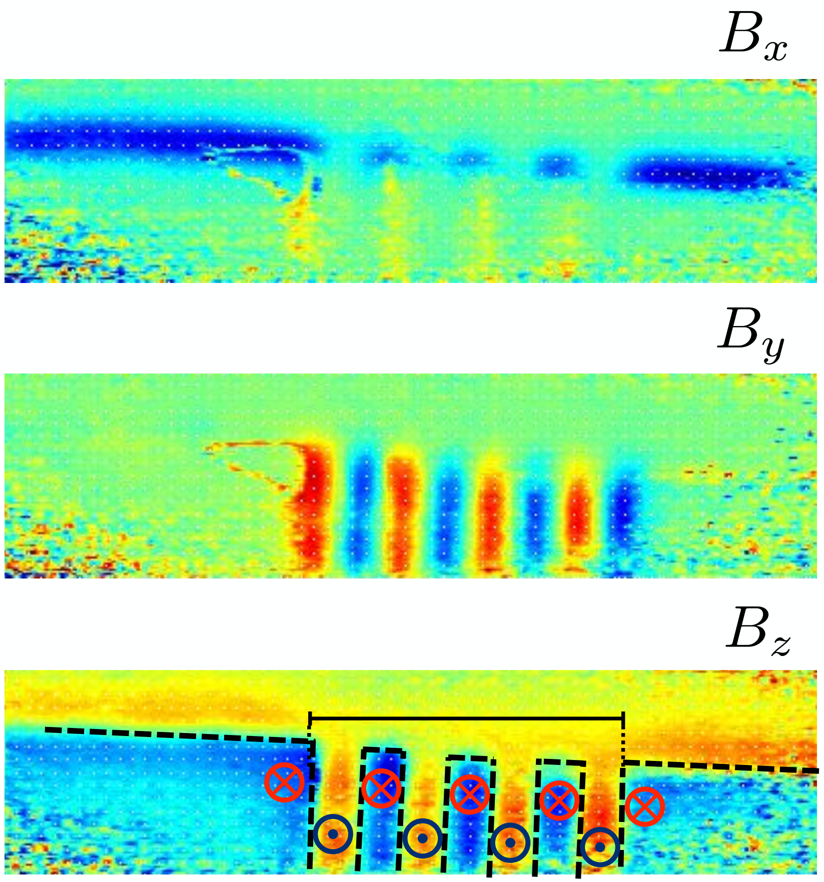


Coll. A. Nowodzinski - CEA-LETI

Mapping current density in microelectronics



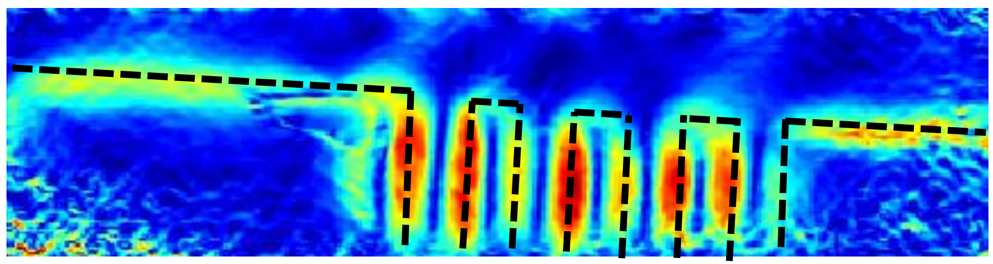
$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi} \int \frac{\vec{j}(\vec{r}-\vec{r'}) \times (\vec{r}-\vec{r'})}{|\vec{r}-\vec{r'}|} \, d^3\vec{r'}$$



Biot-Savart law can be inverted by FT

unicity of solution for 2D current

$\longrightarrow$ map of $||\vec{j}(\vec{r})||$

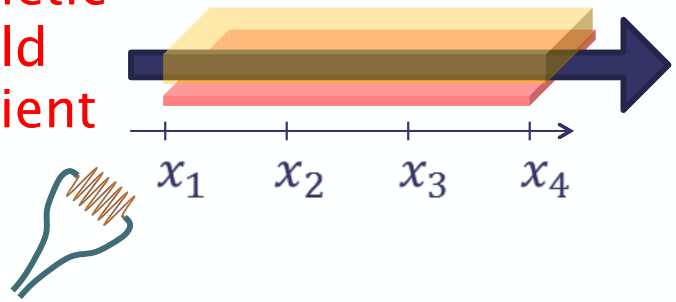


Spatial resolution on $\vec{B}$ measurement has a key influence on the accuracy on the $\vec{j}$ reconstruction

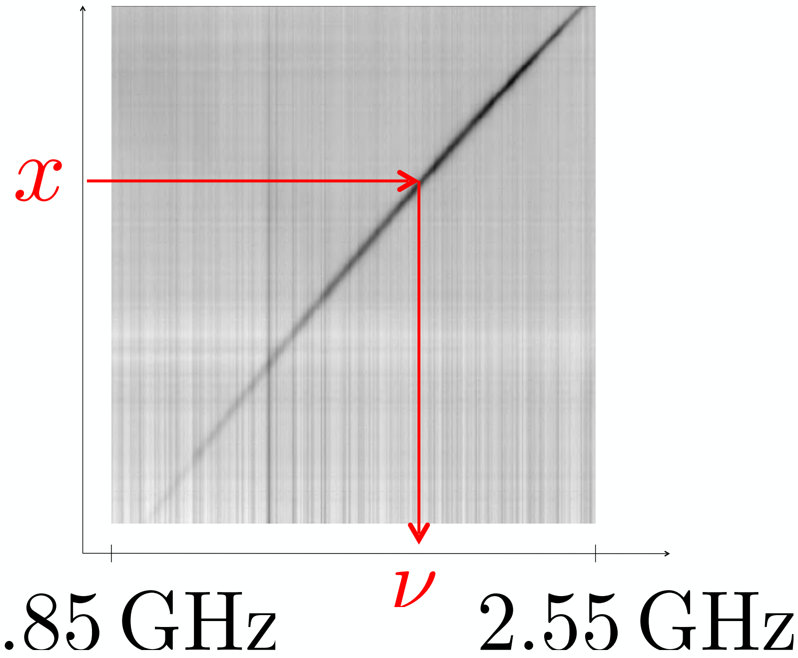
A. Nowodzinski et al., Microelectronics Reliability **55**, 1549-1553 (2015)

NV center = magnetometer and reciprocally it is also a microwave **spectrum analyzer**

Magnetic field gradient

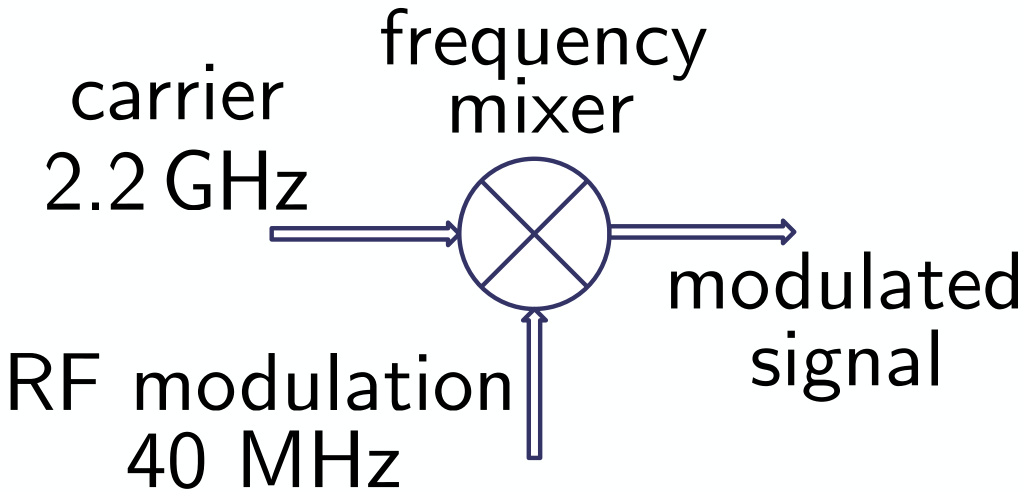


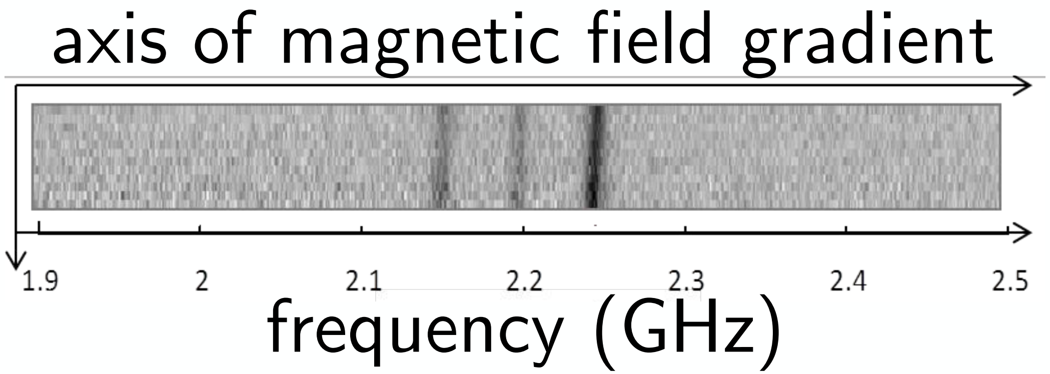
Correspondance between MW frequency and position
M. Chipeaux et al., Appl. Phys. Lett. 107, 233502 (2015)



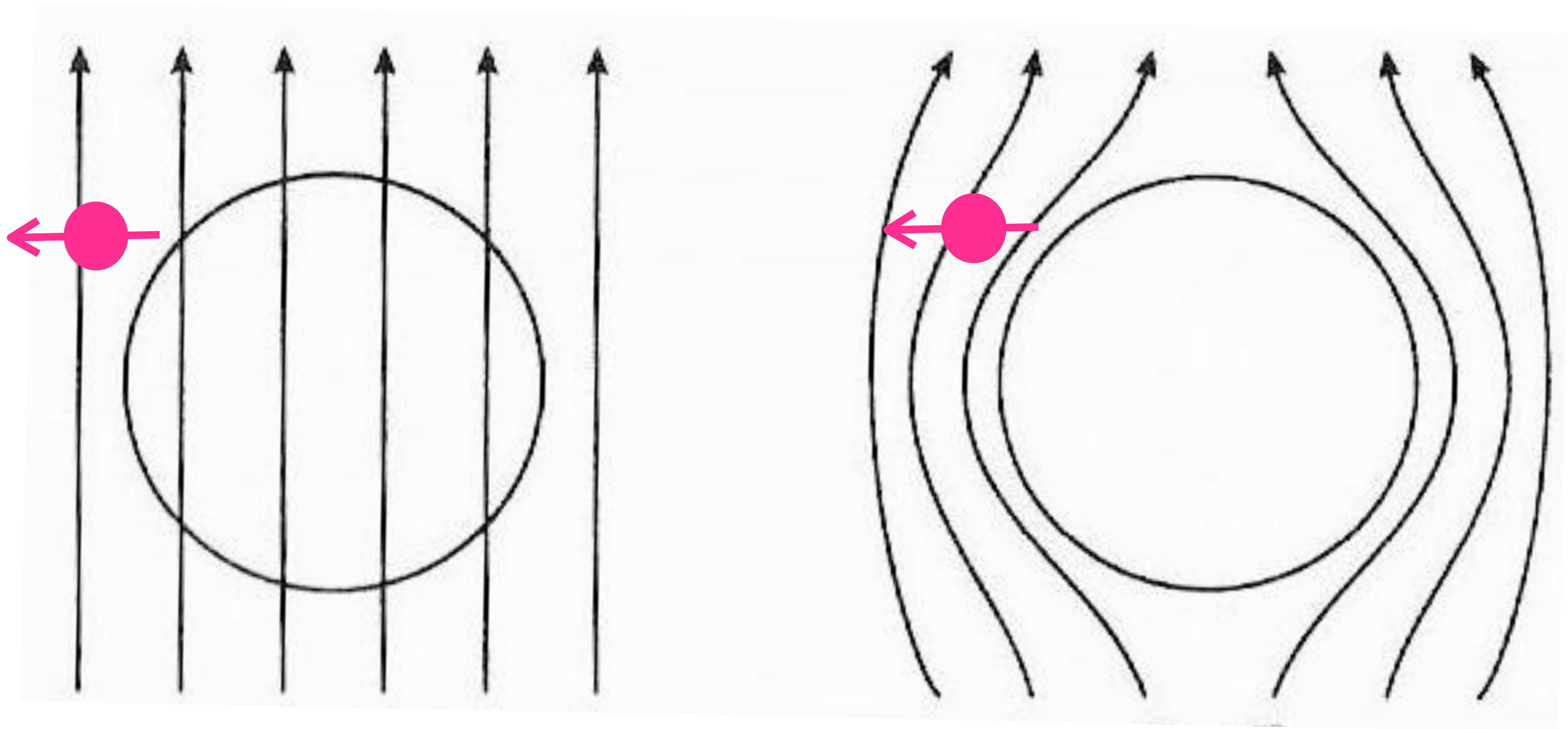
T. DEBUISSCHERT et L. MAYER

THALES





NV-based diagnostic of superconductivity: Observation of the Meissner effect

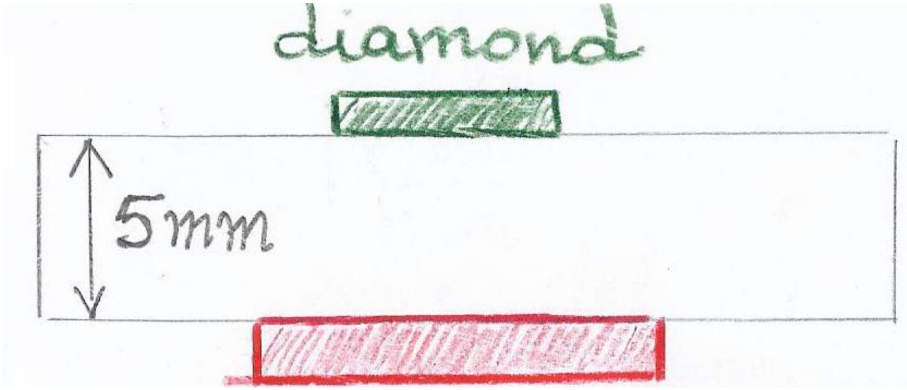


$T > T_C$ $\qquad$ $T < T_C$

Detection of the Meissner effect with a diamond magnetometer

Louis-S Bouchard[1,3], Victor M Acosta[2], Erik Bauch[2] and Dmitry Budker[2]

New Journal of Physics **13**, 025017 (2011)



BSCCO $(T_C = 105\,\mathrm{K})$

- Diamond with (111) orientation
- Three Lorentzian resonances (hyperfine coupling with ^{14}N)
- Zeeman shift (Meissner) competes with temperature shift