Réseau Optique Photonique

MOI oTOP 2020

Métrologie Optique et Instrumentation

école Technologique du réseau Optique et Photonique

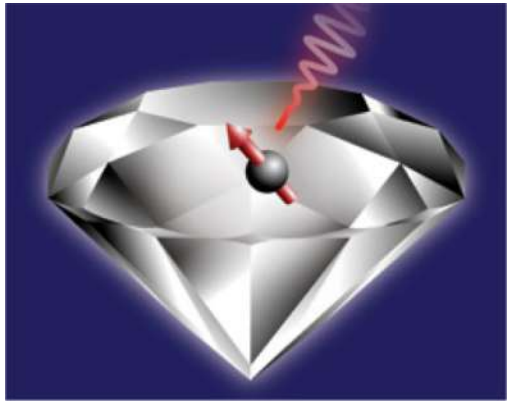
11 mars 2021

Microscopie magnétique à spin unique

Vincent JACQUES

Laboratoire Charles Coulomb UMR 5221, Université Montpellier, and CNRS

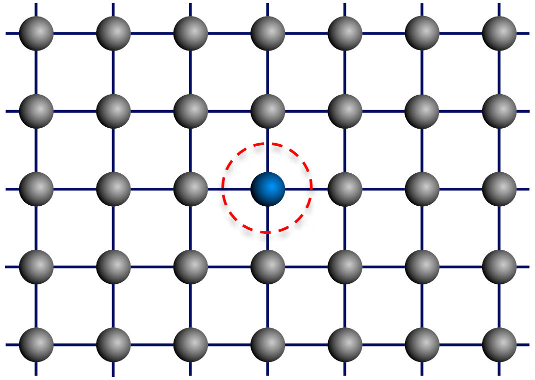
LABORATOIRE CHARLES COULOMB MONTPELLIER



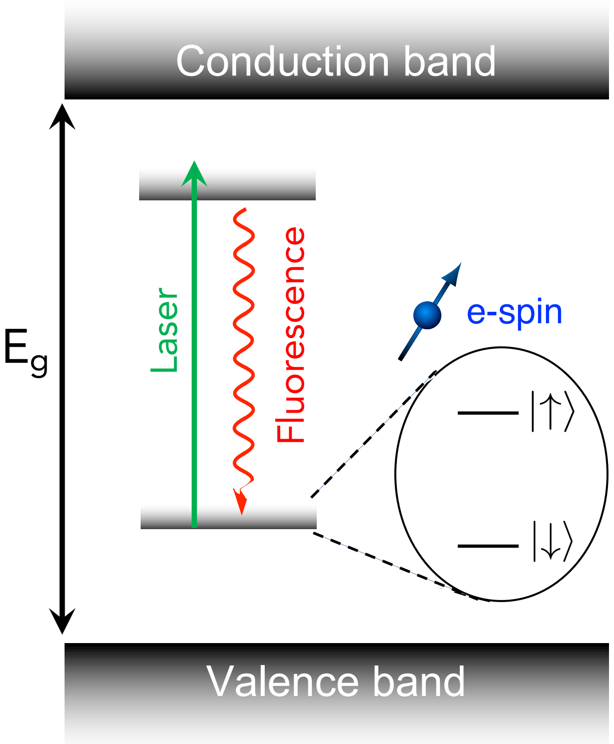
UNIVERSITÉ MONTPELLIER

cnrs

Optically active point defects in wide bandgap materials



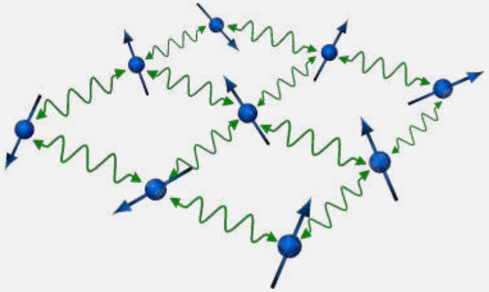
Solid-state "artificial atom"



Single Photon Source

- Quantum cryptography
- Single photon interference

Quantum Information

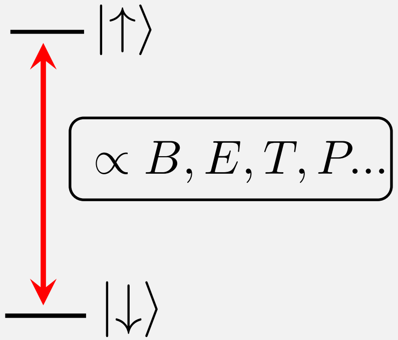


- Spin physics
- Spin/photon interface

Fluorescent Biomarkers

Mohan, *Nano Lett.* 10, 3692 (2010)

Quantum sensing



Optically active point defects in wide bandgap materials

Single Photon Source

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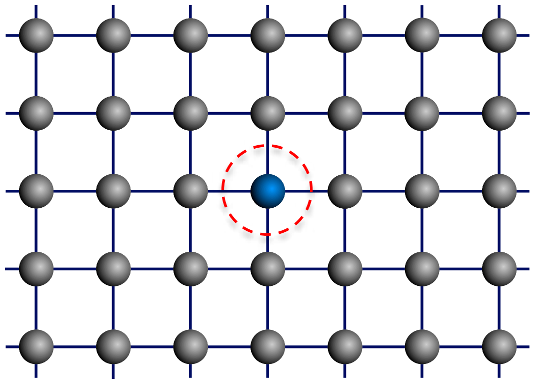

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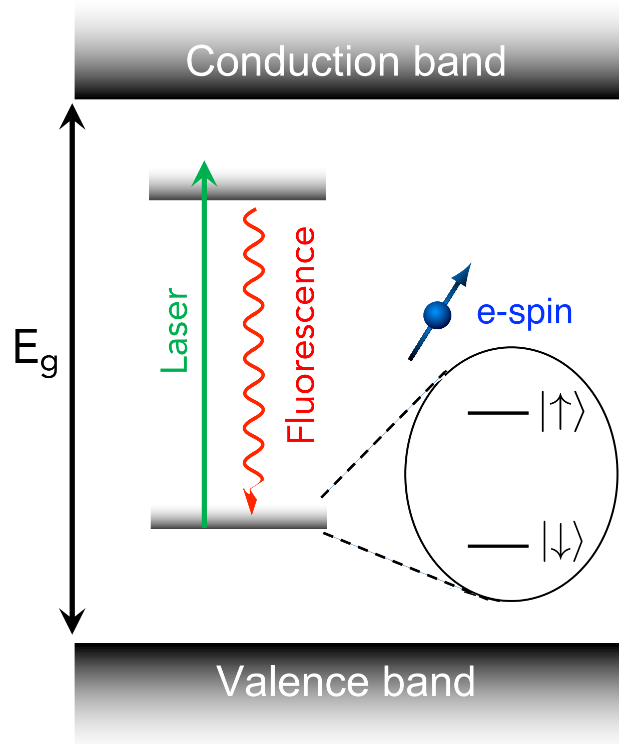

Quantum Information

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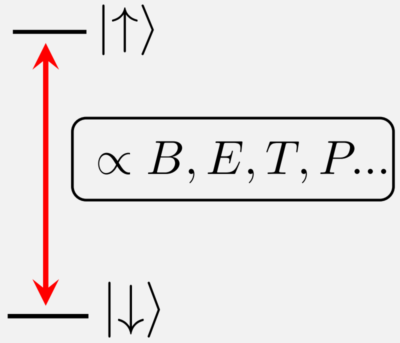
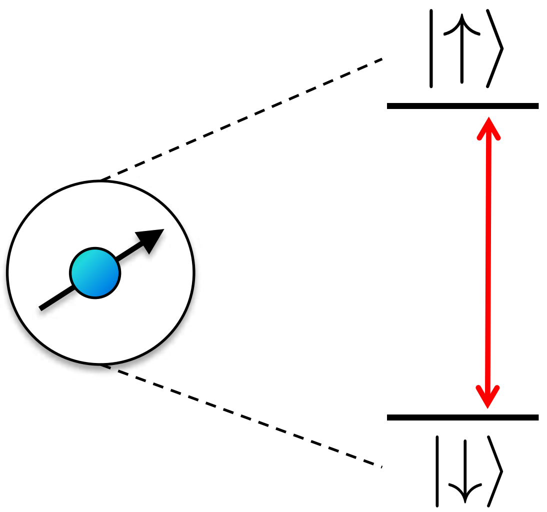
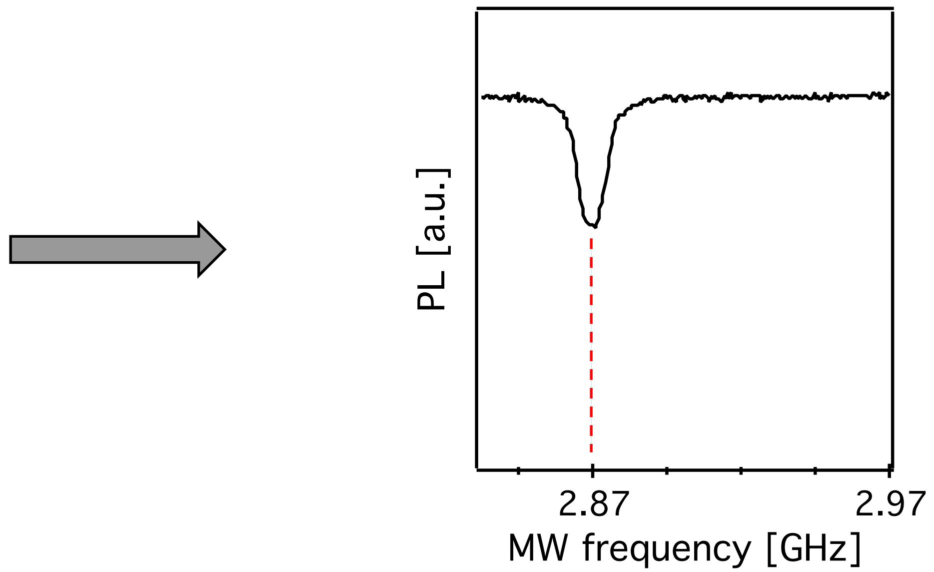


Magnetic field sensing with a single spin

Single e-spin



Electron Spin Resonance (ESR)



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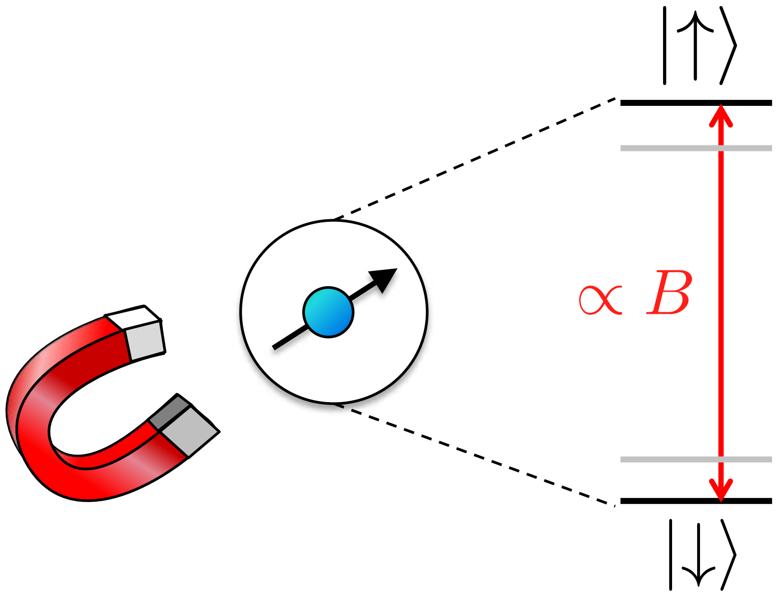
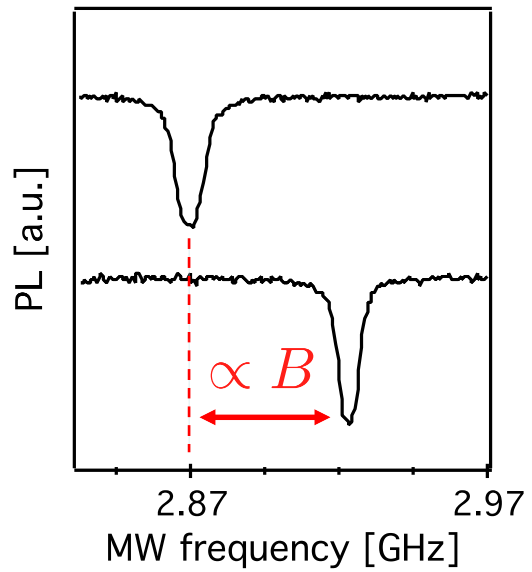


Electron Spin Resonance (ESR)



Magnetic field sensing with a single spin

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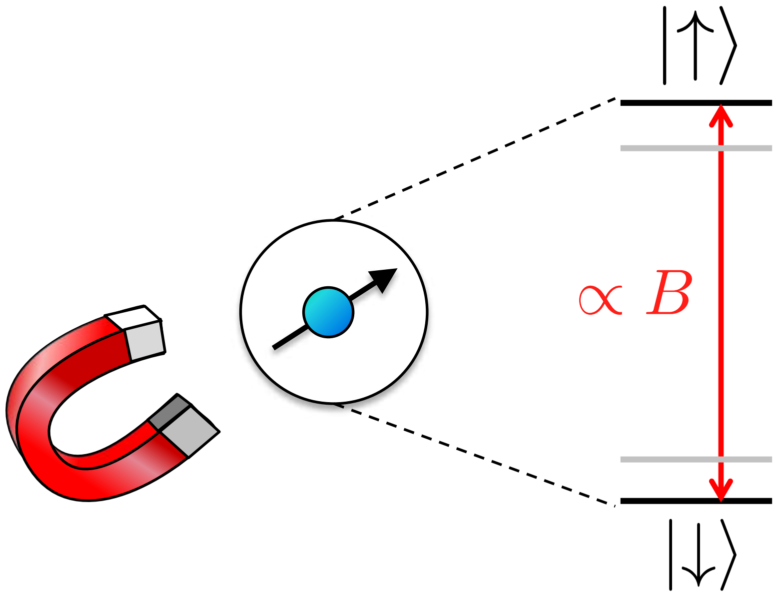

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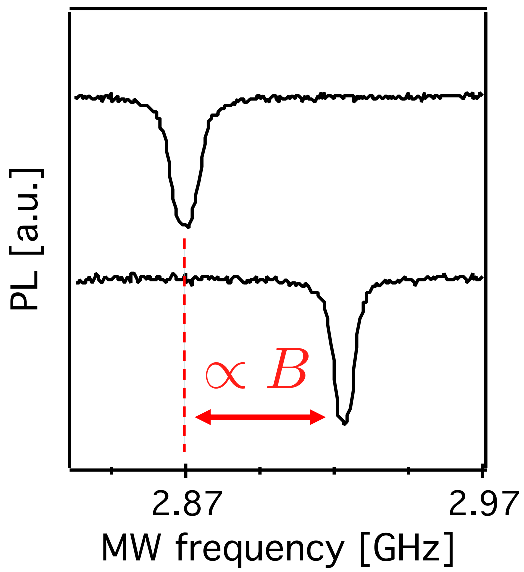
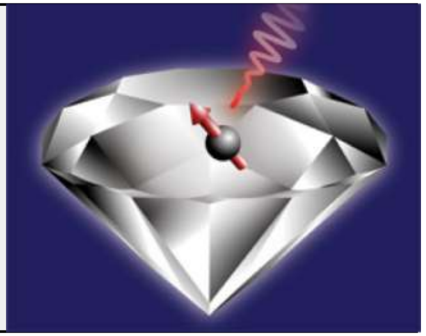
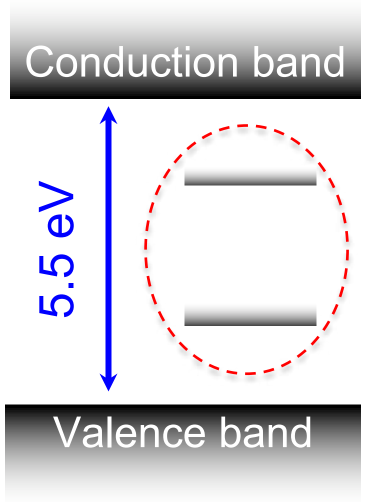


Can be realized with **NV defects in diamond**

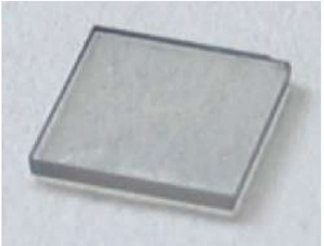
Maze, *Nature* (2008), Degen, *APL* (2008)
Balasubramanian, *Nature* (2008)



Point defects in diamond

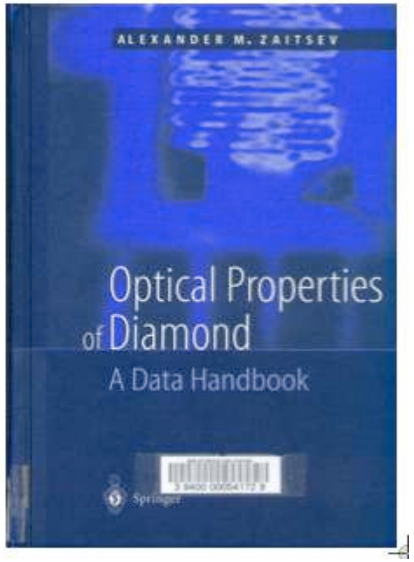


A *"perfect"* diamond would not absorb visible light…



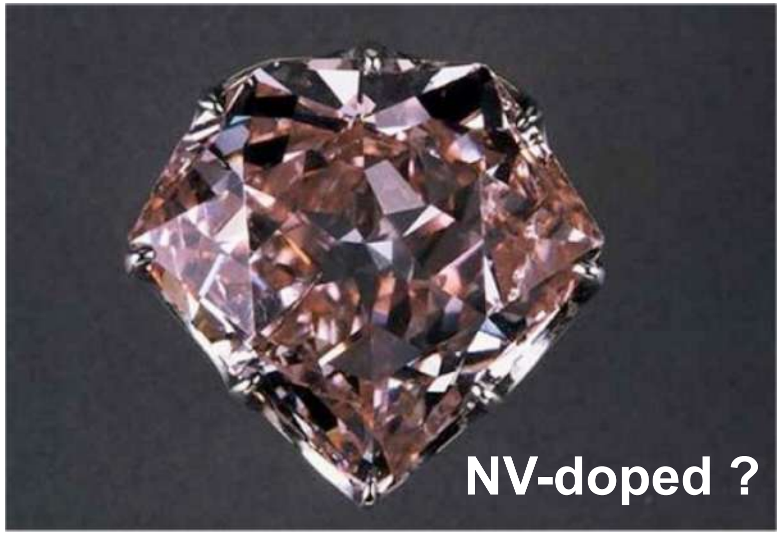
… but more than 500 defects are optically active

→ Color centers



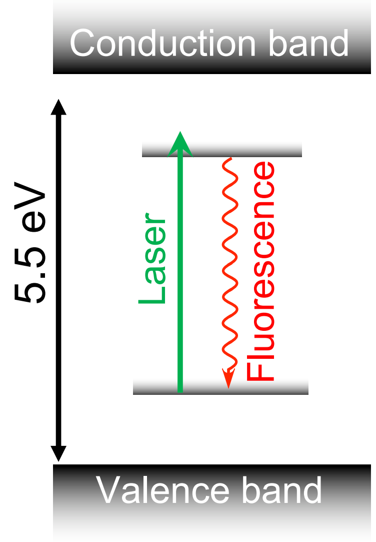
The « Hope » diamond
(Washington)

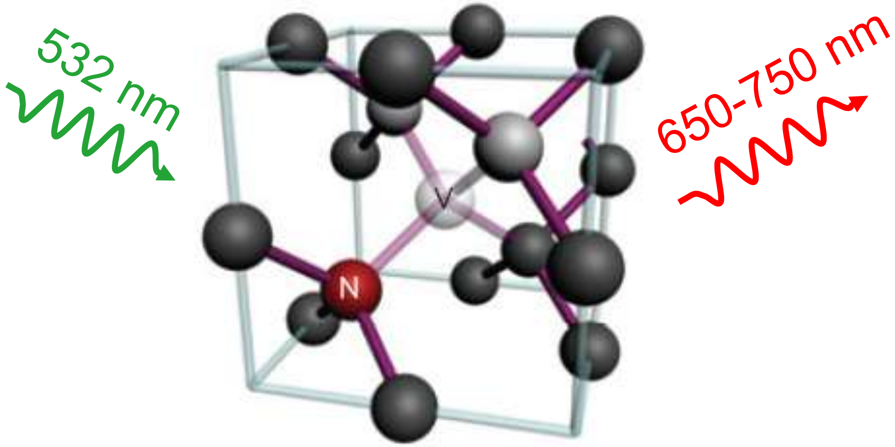
The « Hortensia » diamond
(Louvre, Paris)

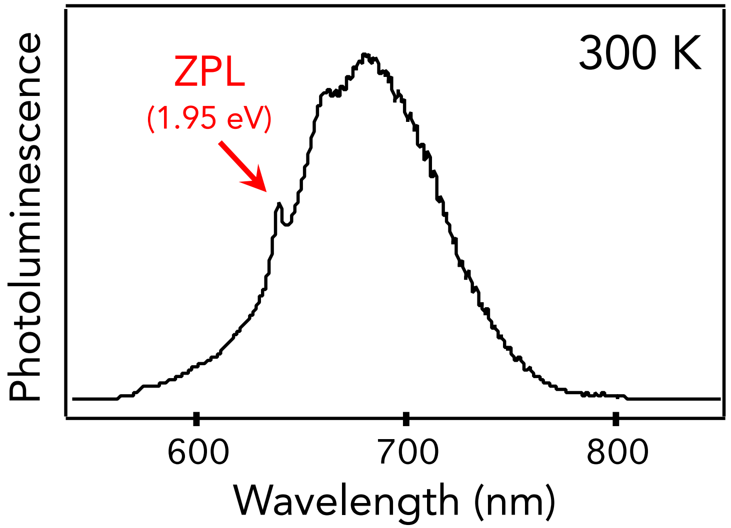


The Nitrogen-Vacancy (NV) defect in diamond

- An artificial atom *"nestled"* in the diamond lattice

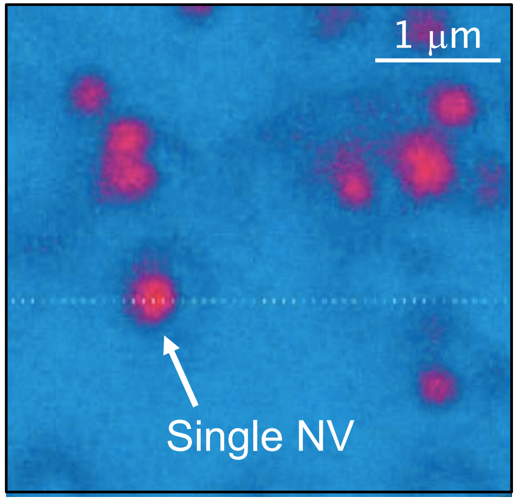




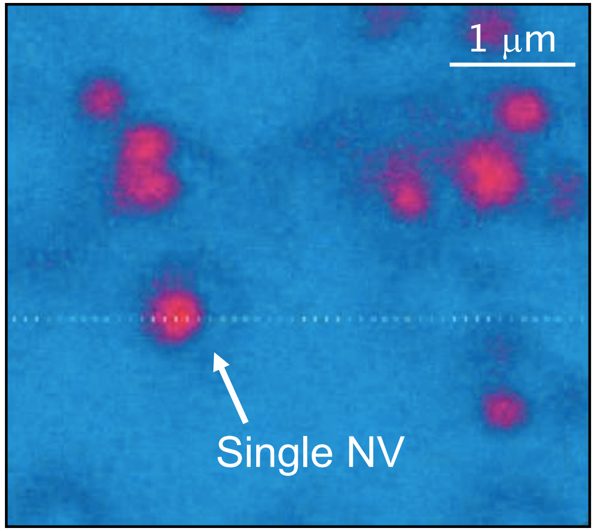


- Detection at the single emitter level **at room T**
  (perfect photostability)

Gruber, *Science* **276**, 2012 (1997)

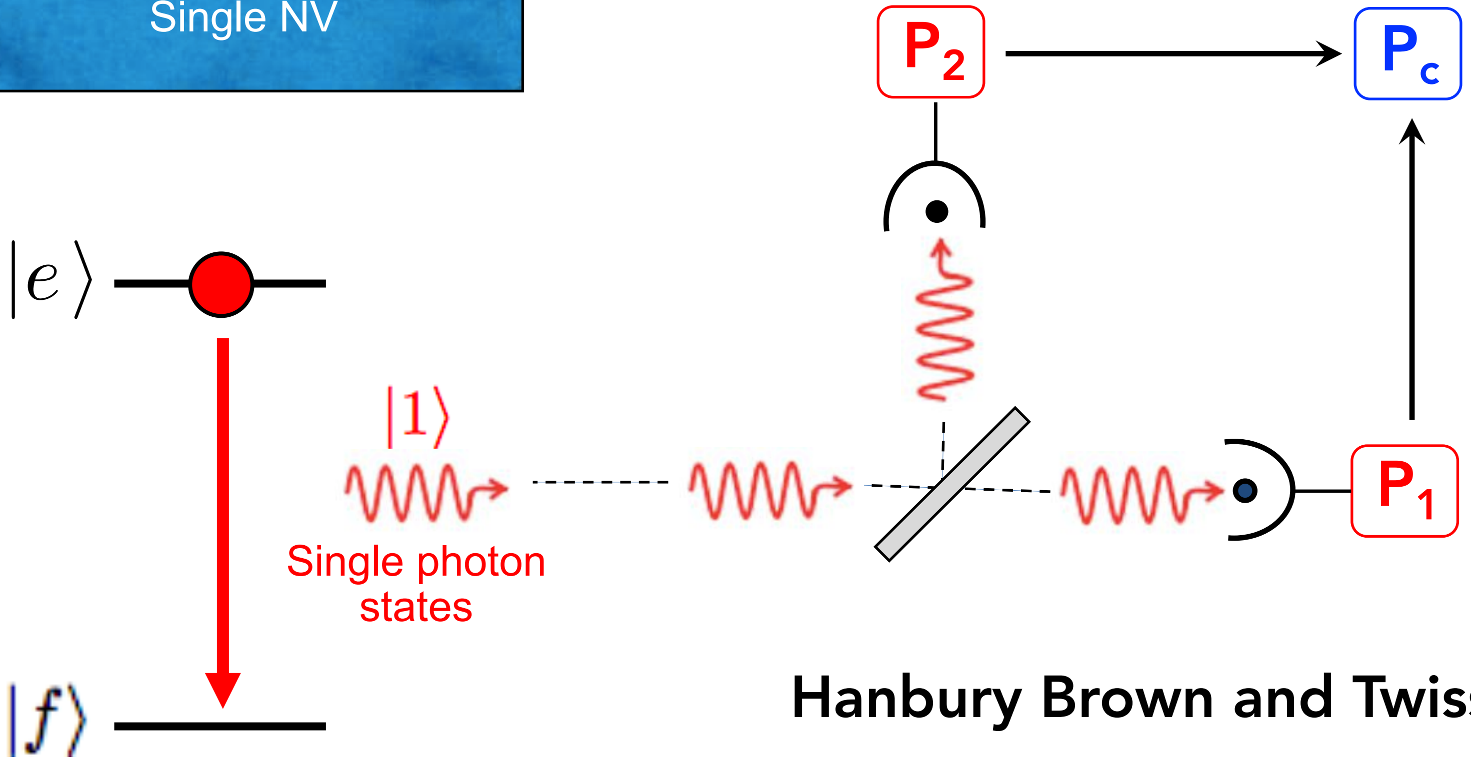


A robust single photon source



Second-order correlation function

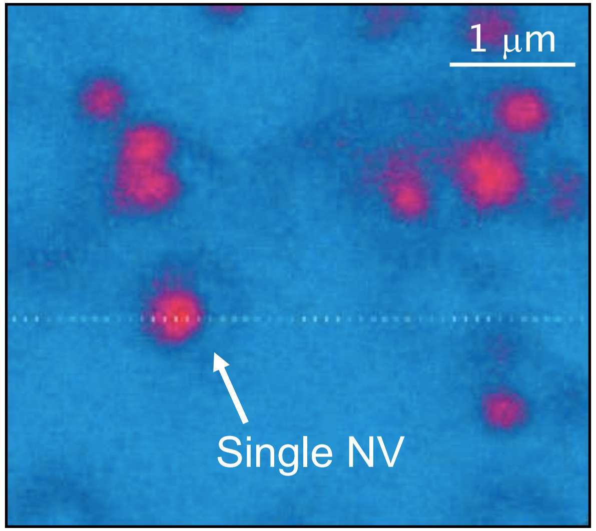
$$g^{(2)}(\tau) = \frac{\overline{\mathcal{I}(t)\mathcal{I}(t+\tau)}}{\overline{\mathcal{I}(t)} \times \overline{\mathcal{I}(t+\tau)}} \Rightarrow g^{(2)}(0) = \frac{P_c}{P_1 \times P_2}$$



single-photon source, P_c=0

Hanbury Brown and Twiss interferometer

A robust single photon source



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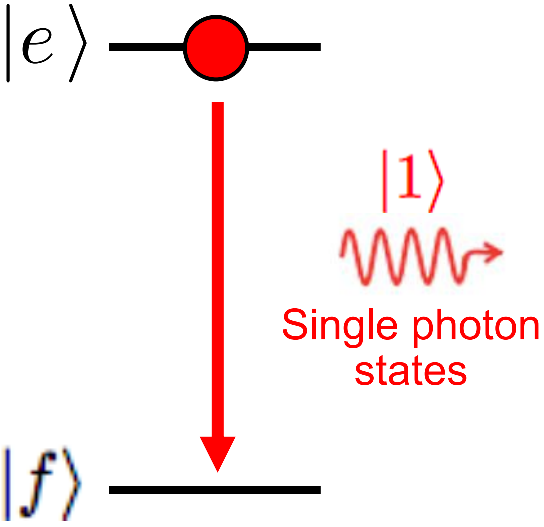

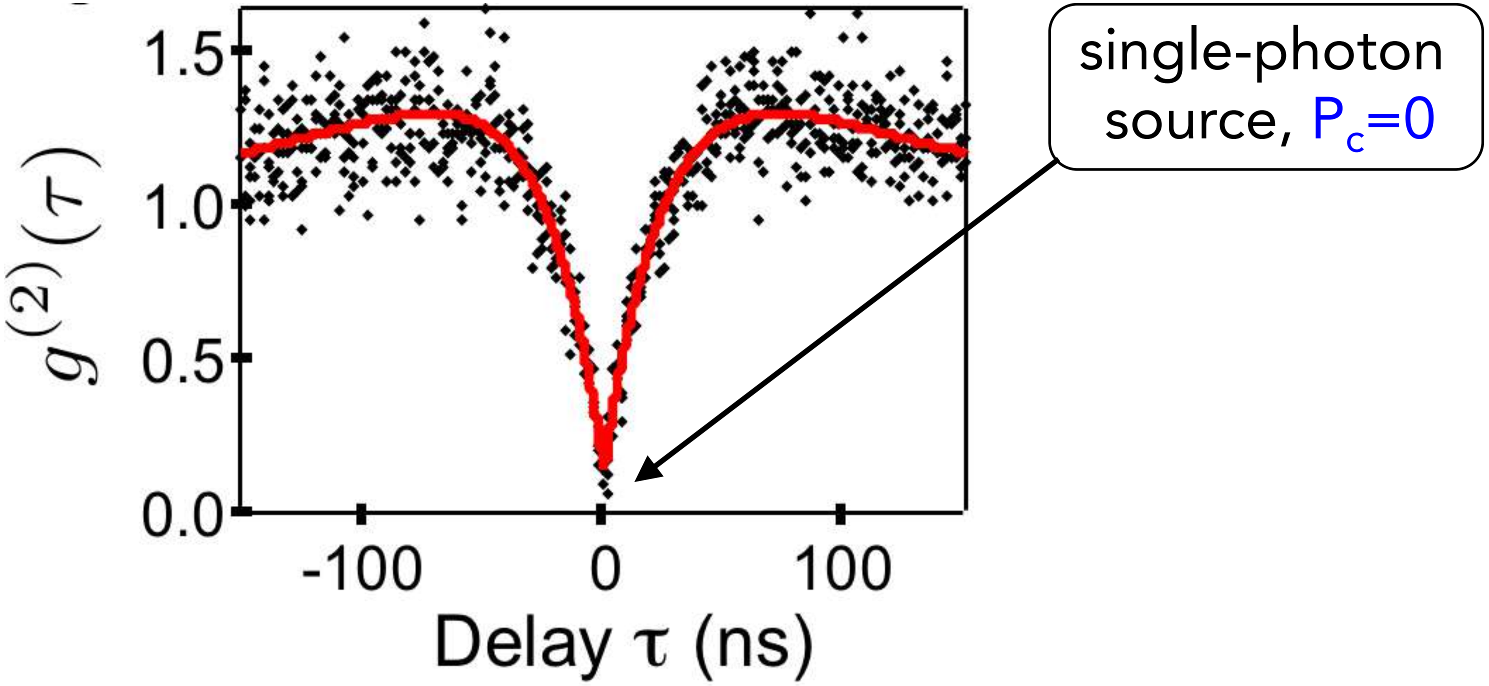

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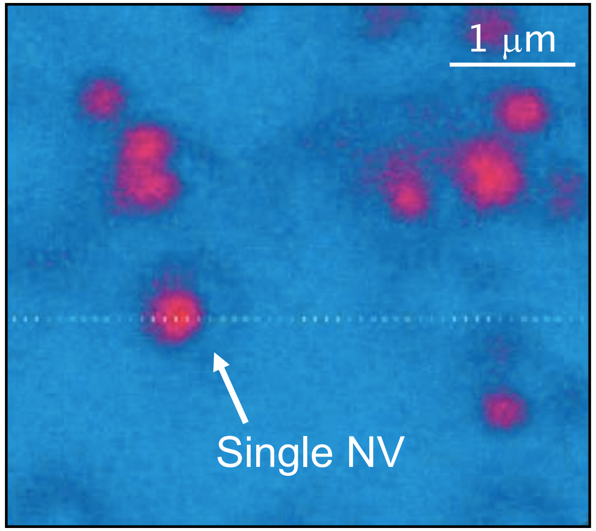
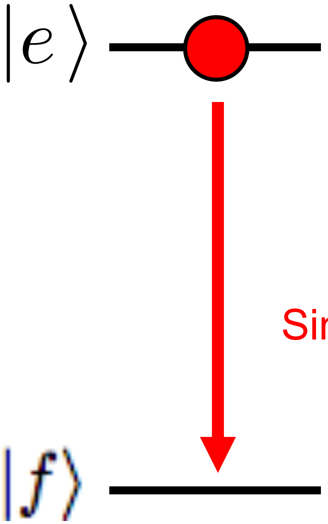
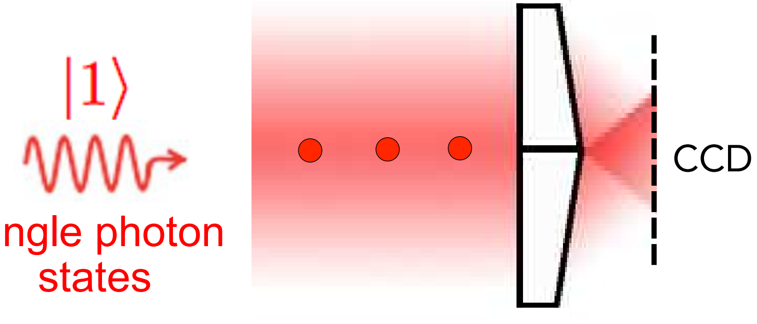
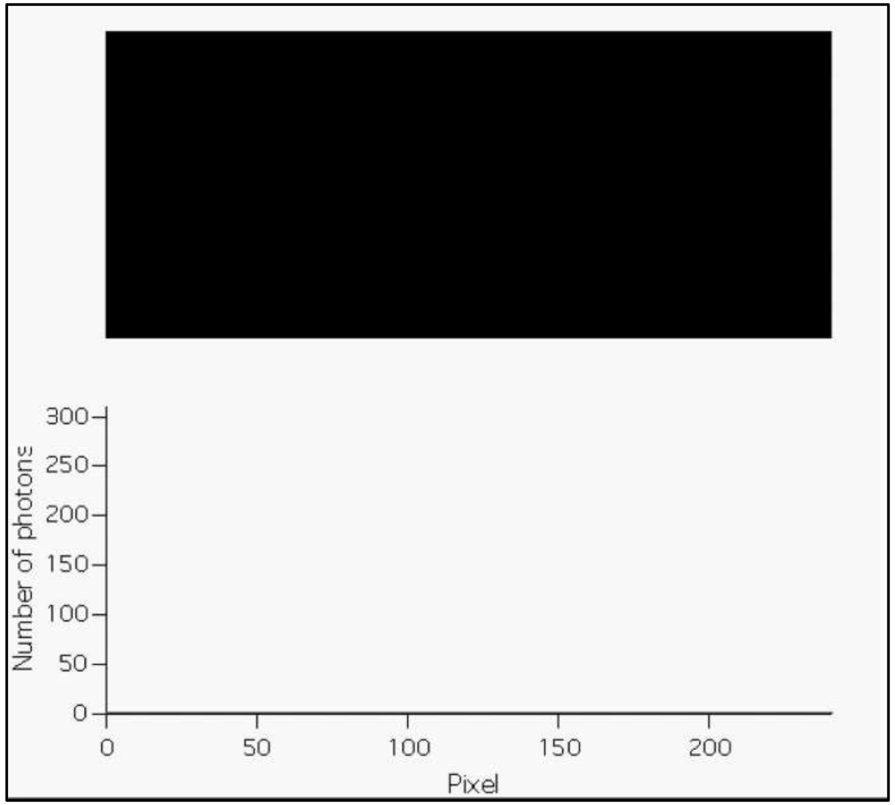


Single photon interference

Jacques, *EPJD* (2005)

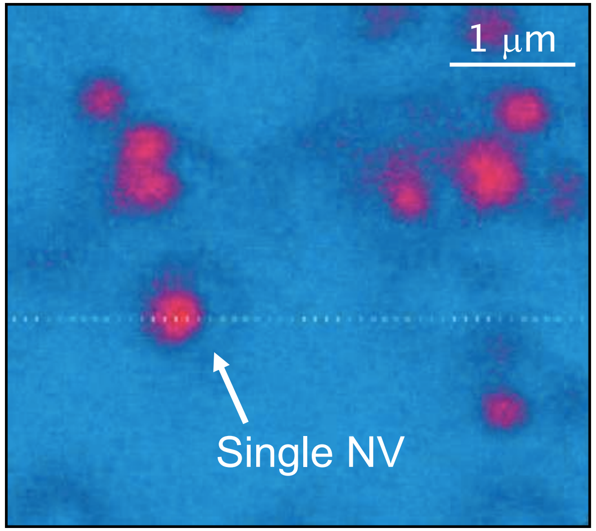




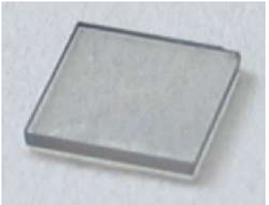


Engineering NV defects in diamond

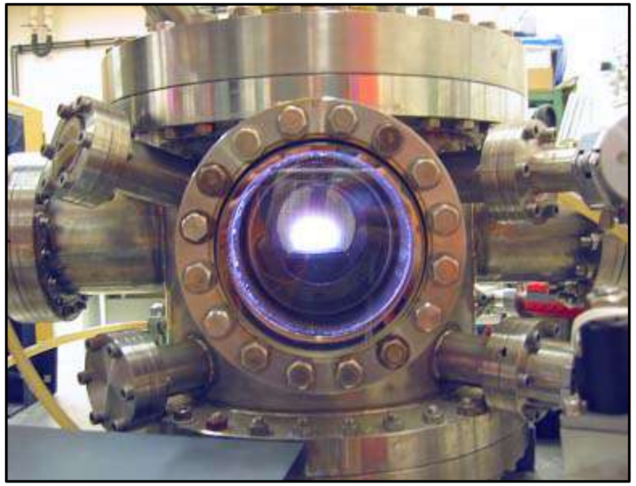
1997



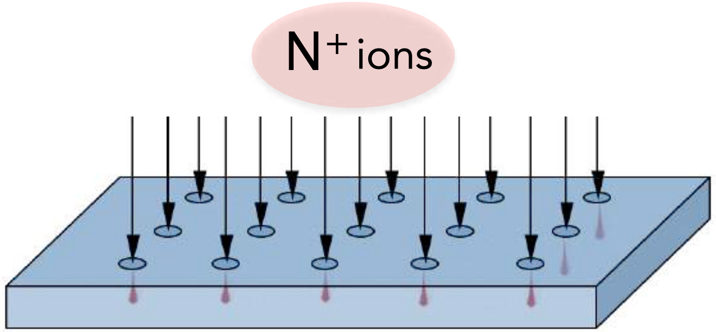
High purity diamond using
CVD growth



A. *Tallaire and J. Achard (Villetaneuse)*



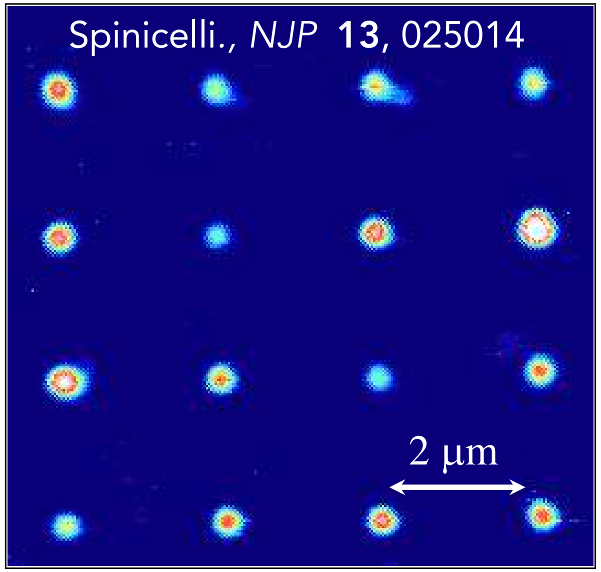
nanoscale ion implantation



J. Meijer and S. Pezzagna (Leipzig)

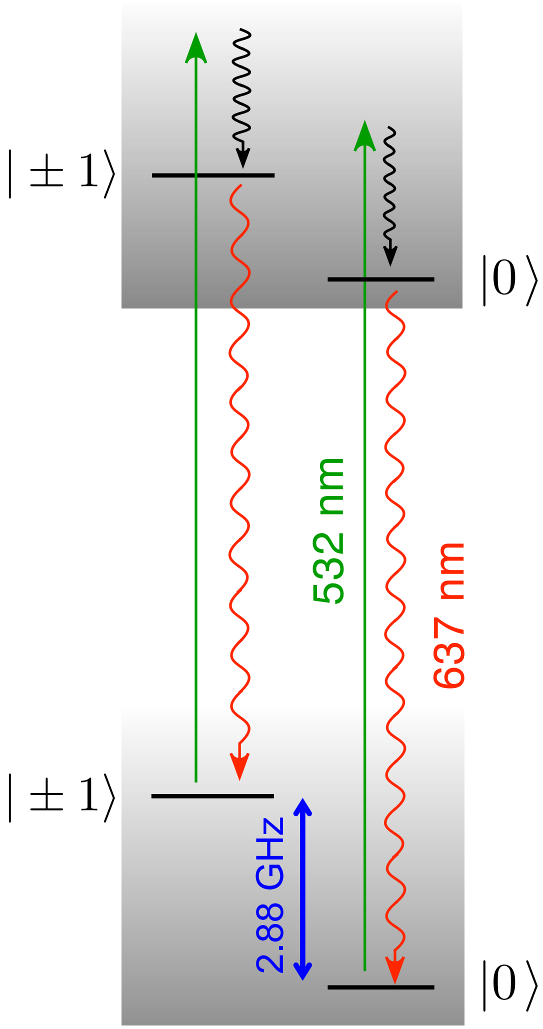
Array of NV defects

2012



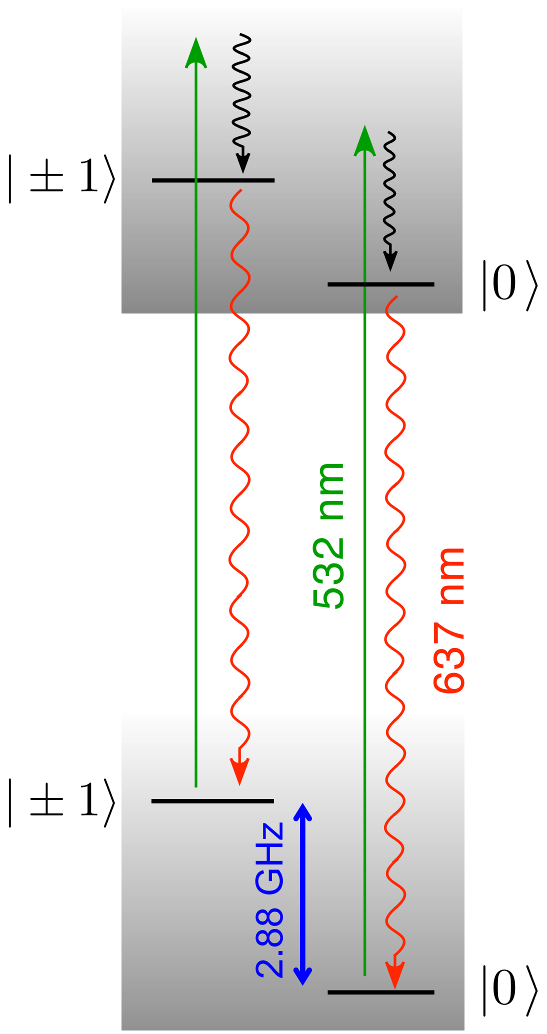
Spin properties

- Artificial atom with a spin triplet (S=1) ground state



Spin properties

- ❑ Artificial atom with a spin triplet (S=1) ground state



Important properties

- ➢ Spin-conserving optical transition Δm_s=0.

Spin properties

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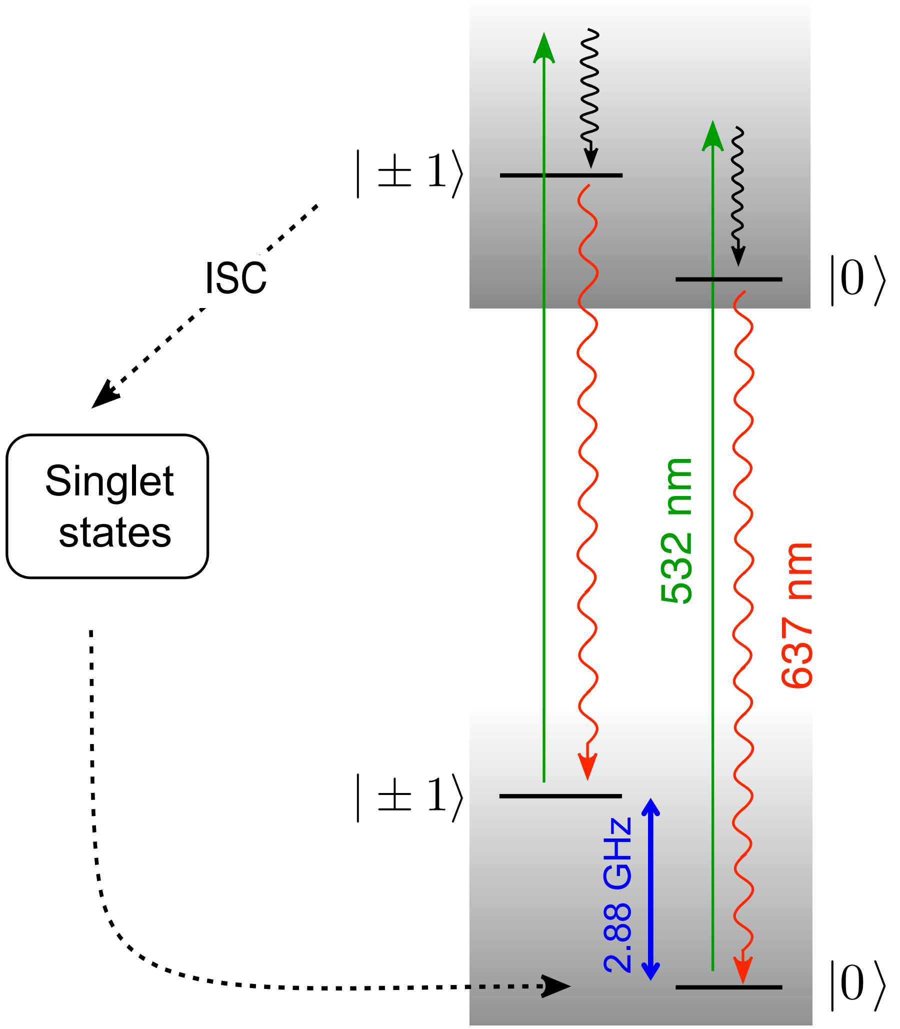
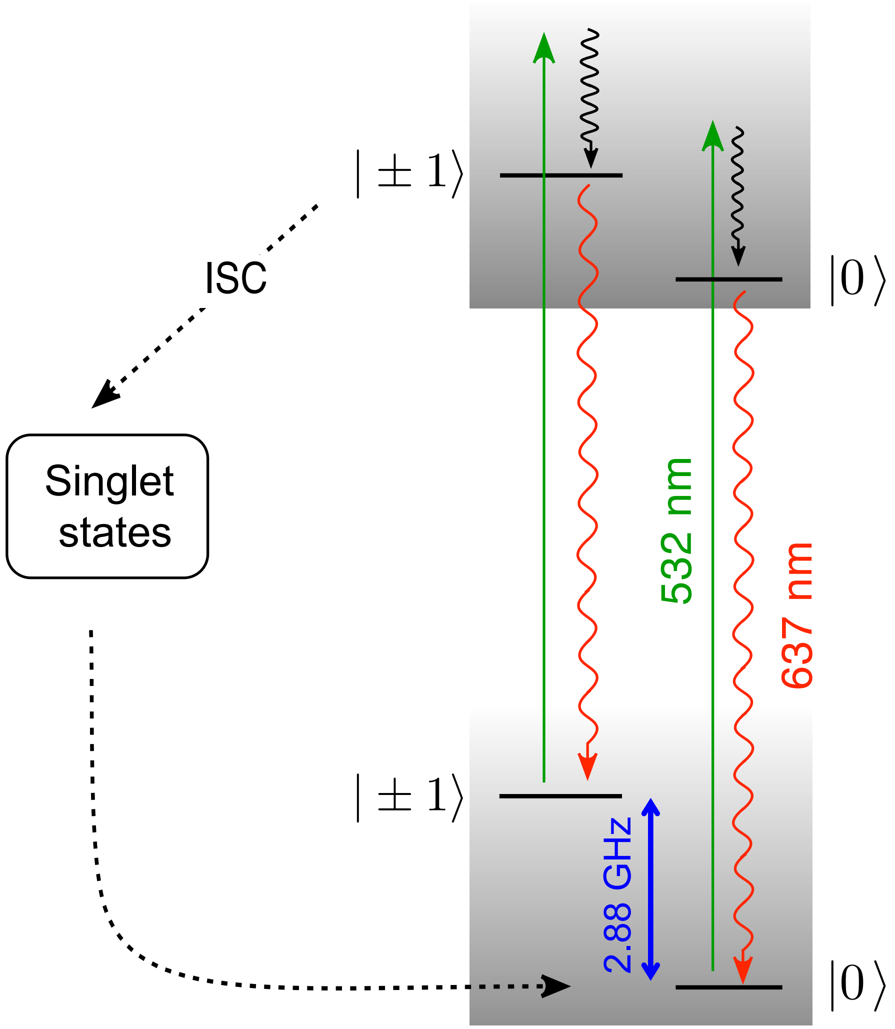


Important properties

- Spin-conserving optical transition Δm_s=0.
- Spin-dependent ISC to singlet states.

Spin properties

❑ Artificial atom with a spin triplet (S=1) ground state



Important properties

- Spin-conserving optical transition Δm_s=0.
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Consequences

- Polarization in m_s=0 by optical pumping.

Spin properties

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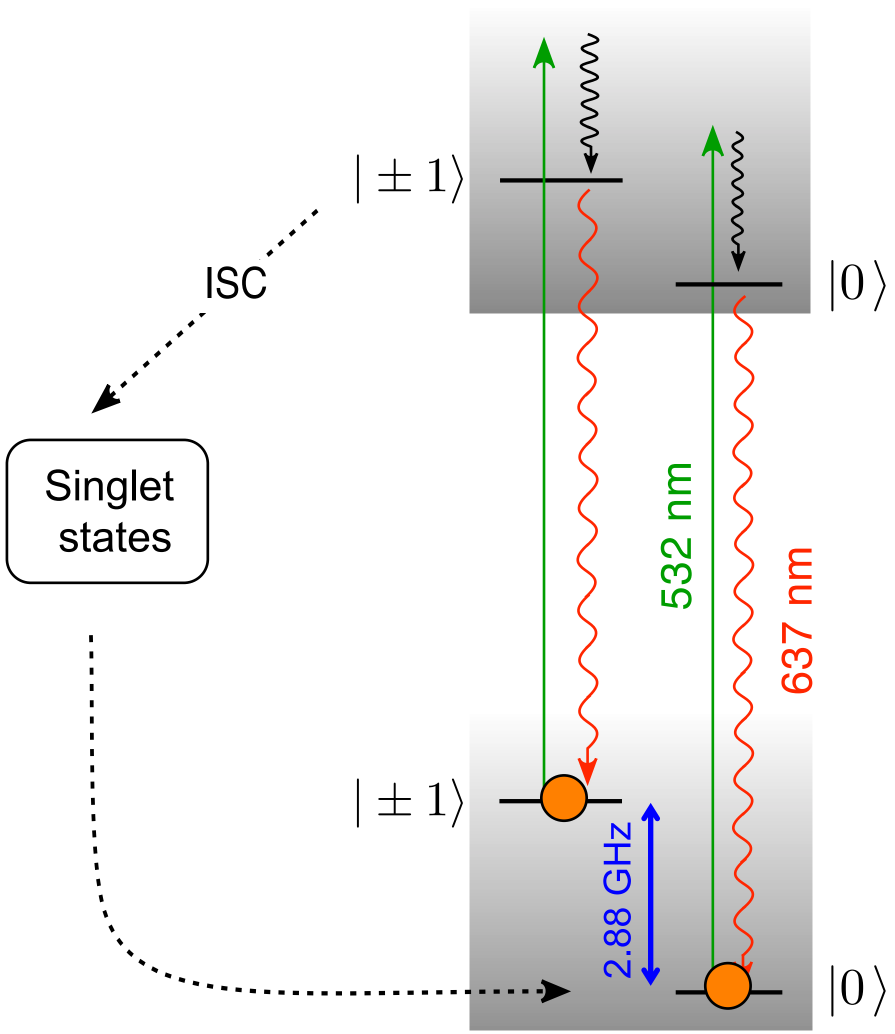

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⇓

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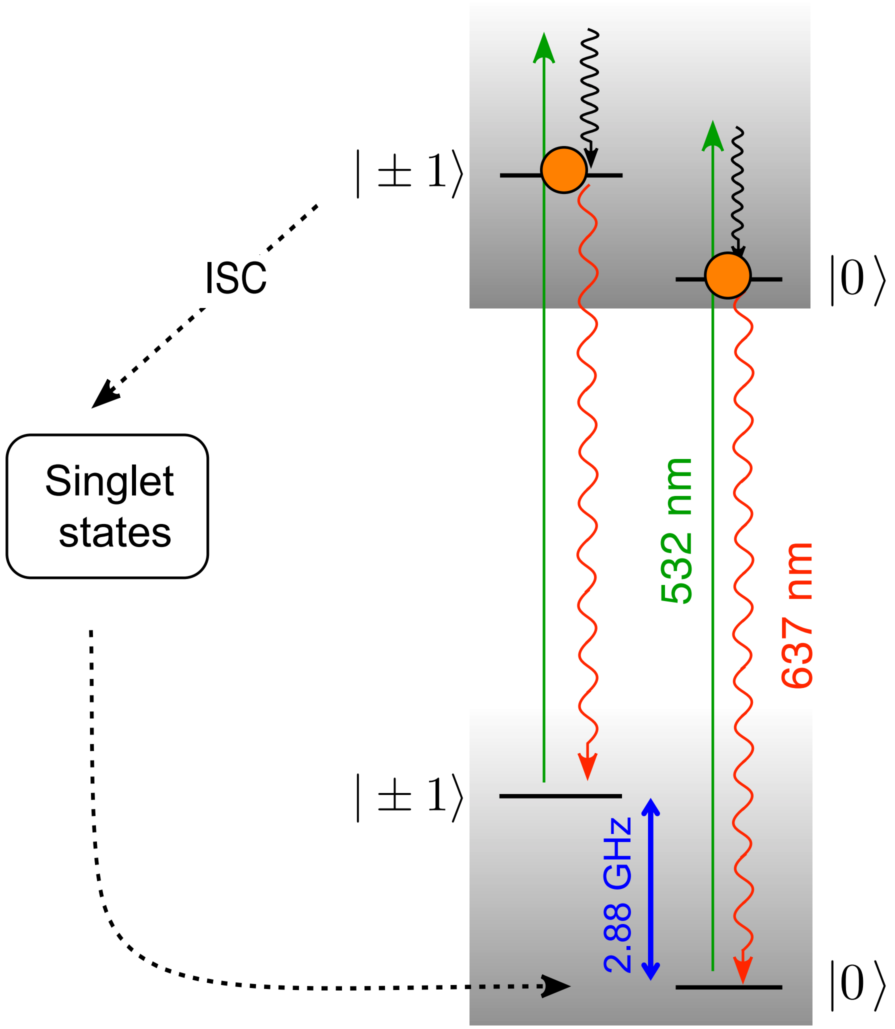

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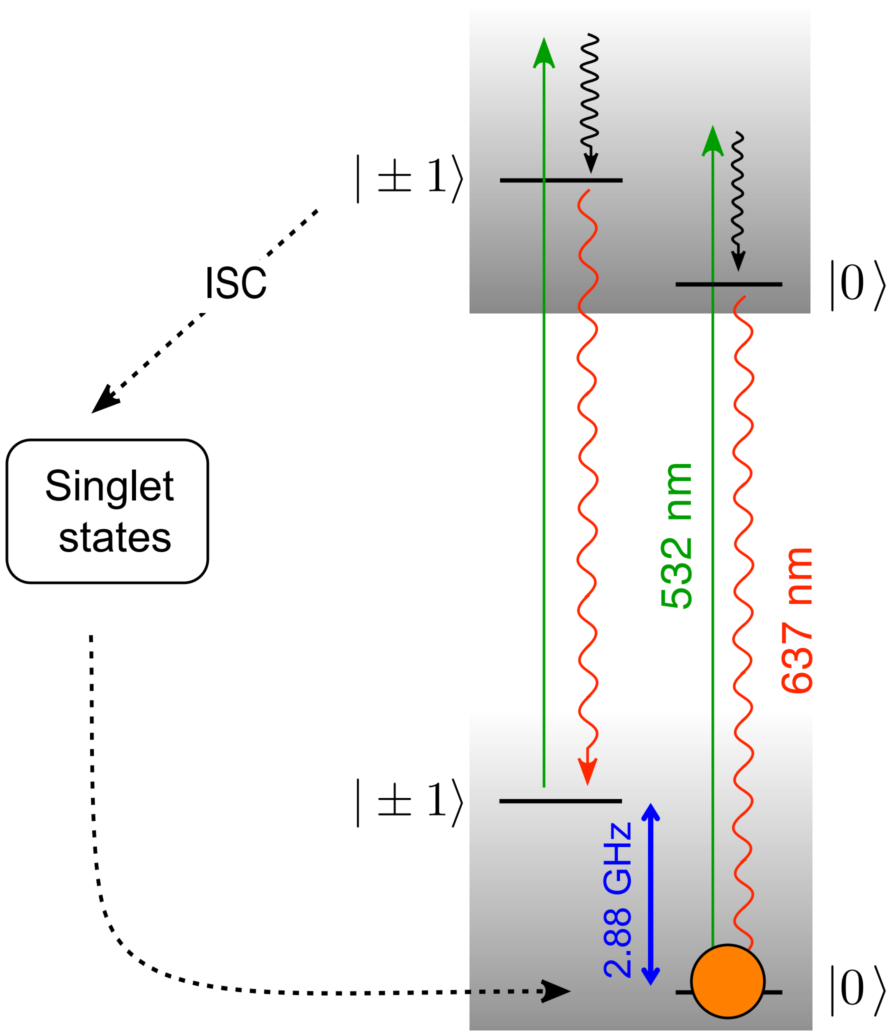

Important properties

- Spin-conserving optical transition $\Delta m_s=0$.
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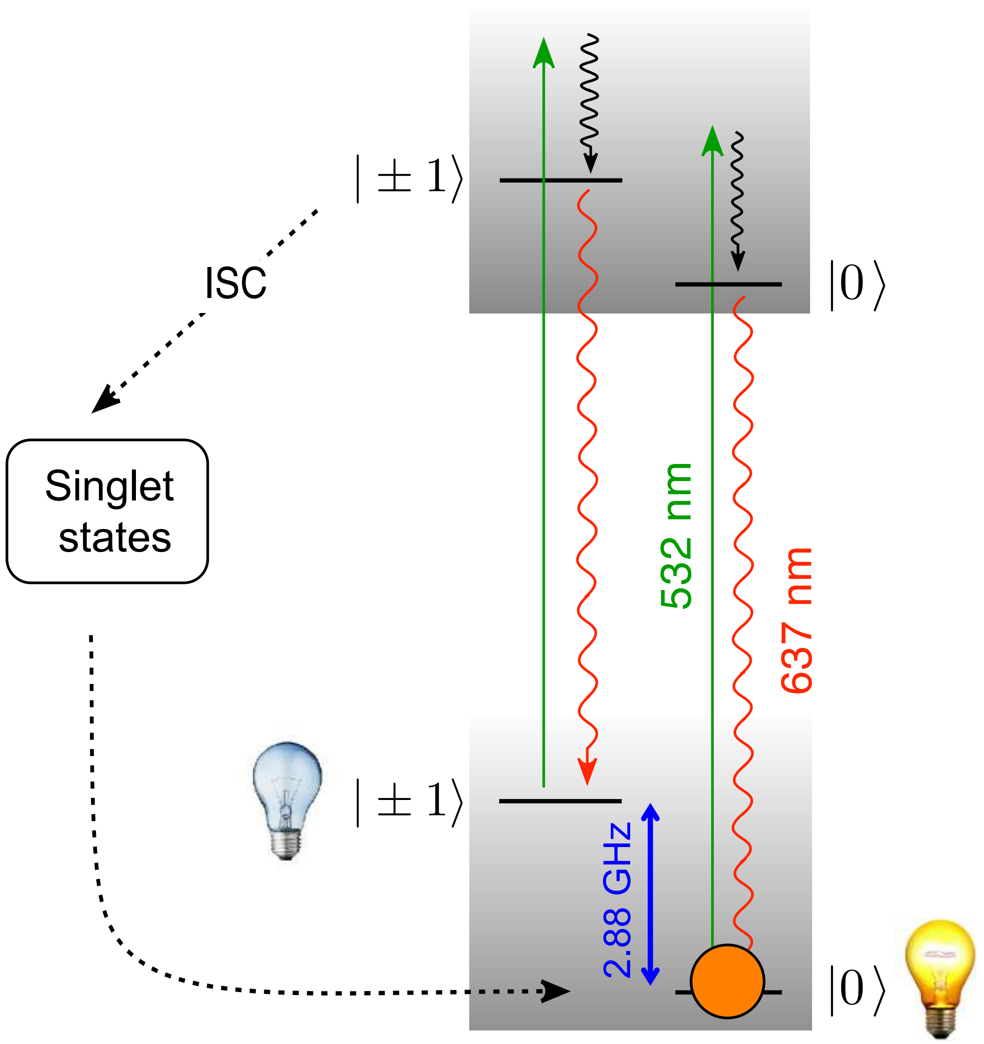
Consequences

- Polarization in $m_s=0$ by optical pumping.

Spin properties

❑ Artificial atom with a spin triplet (S=1) ground state



Important properties

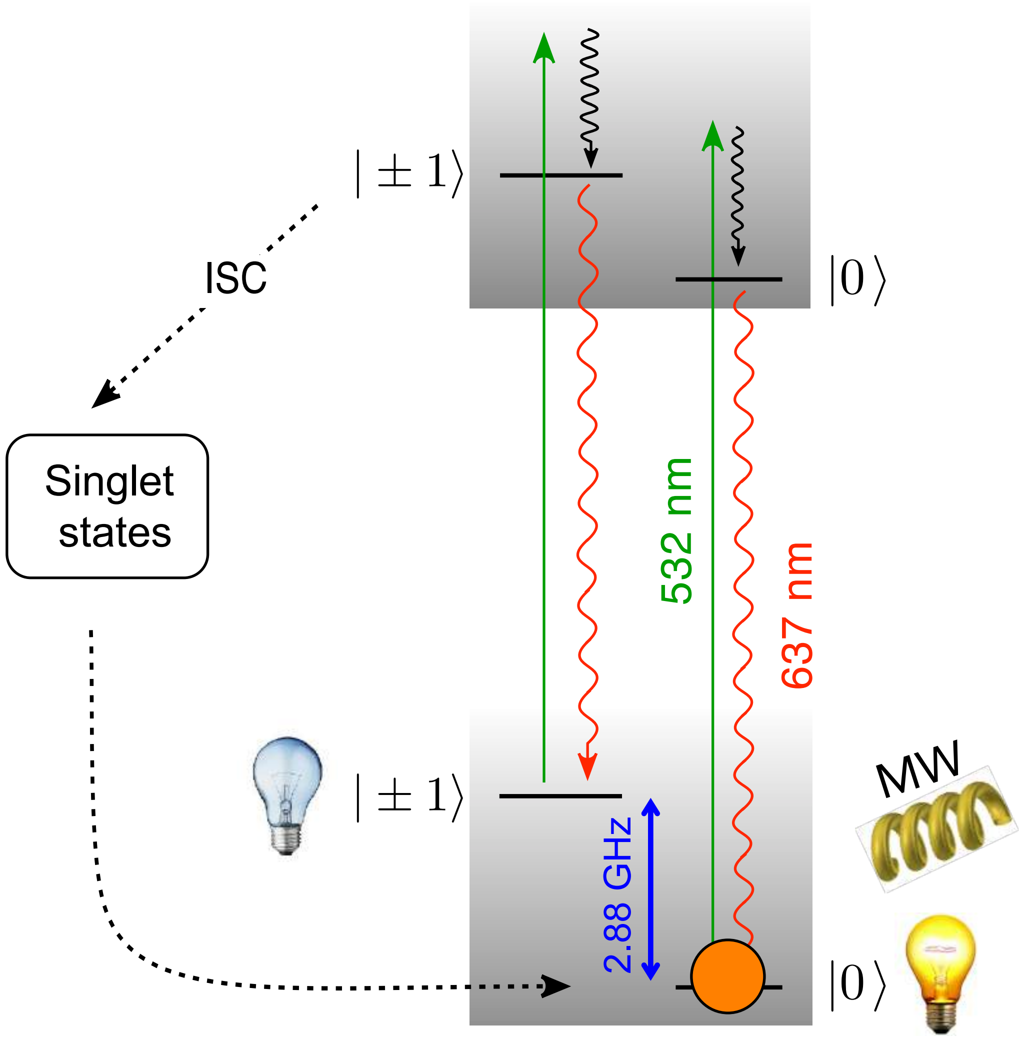
- Spin-conserving optical transition Δm_s=0.
- Spin-dependent ISC to singlet states.

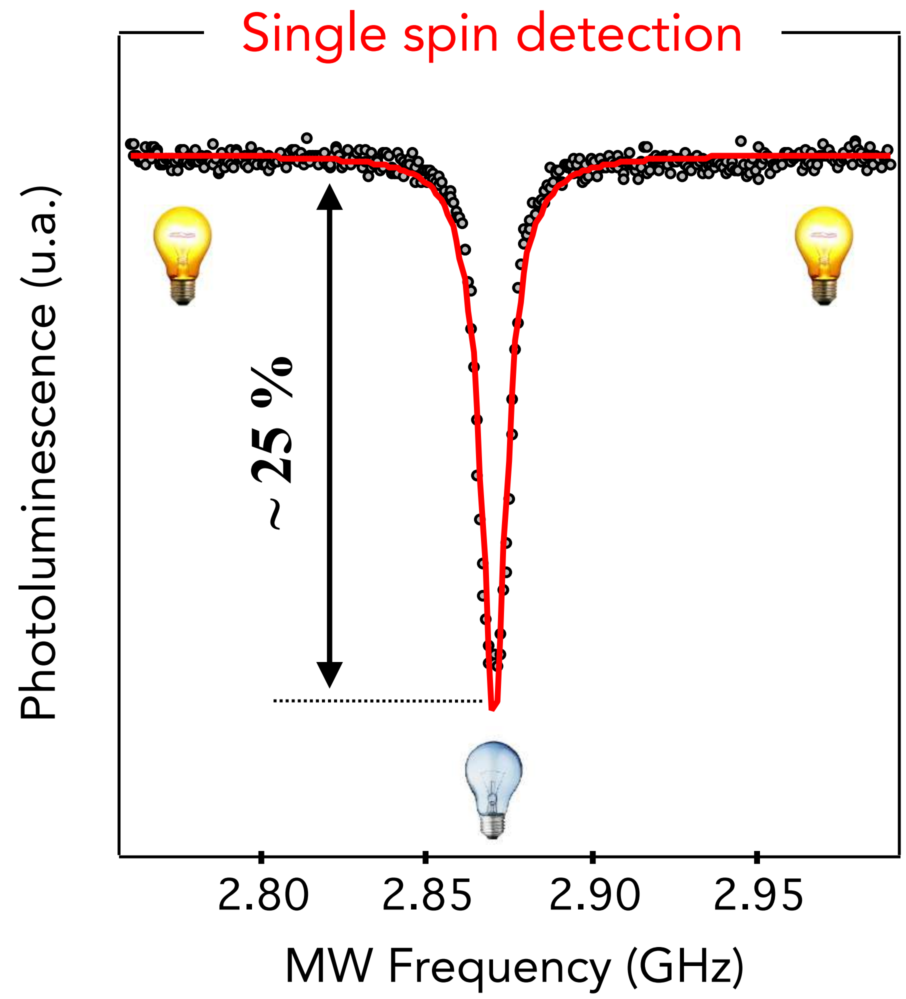
Consequences

- Polarization in m_s=0 by optical pumping.
- Spin-dependent fluorescence signal

Spin properties

- Artificial atom with a spin triplet (S=1) ground state





Rondin, *Rep. Prog. Phys.* (2014)

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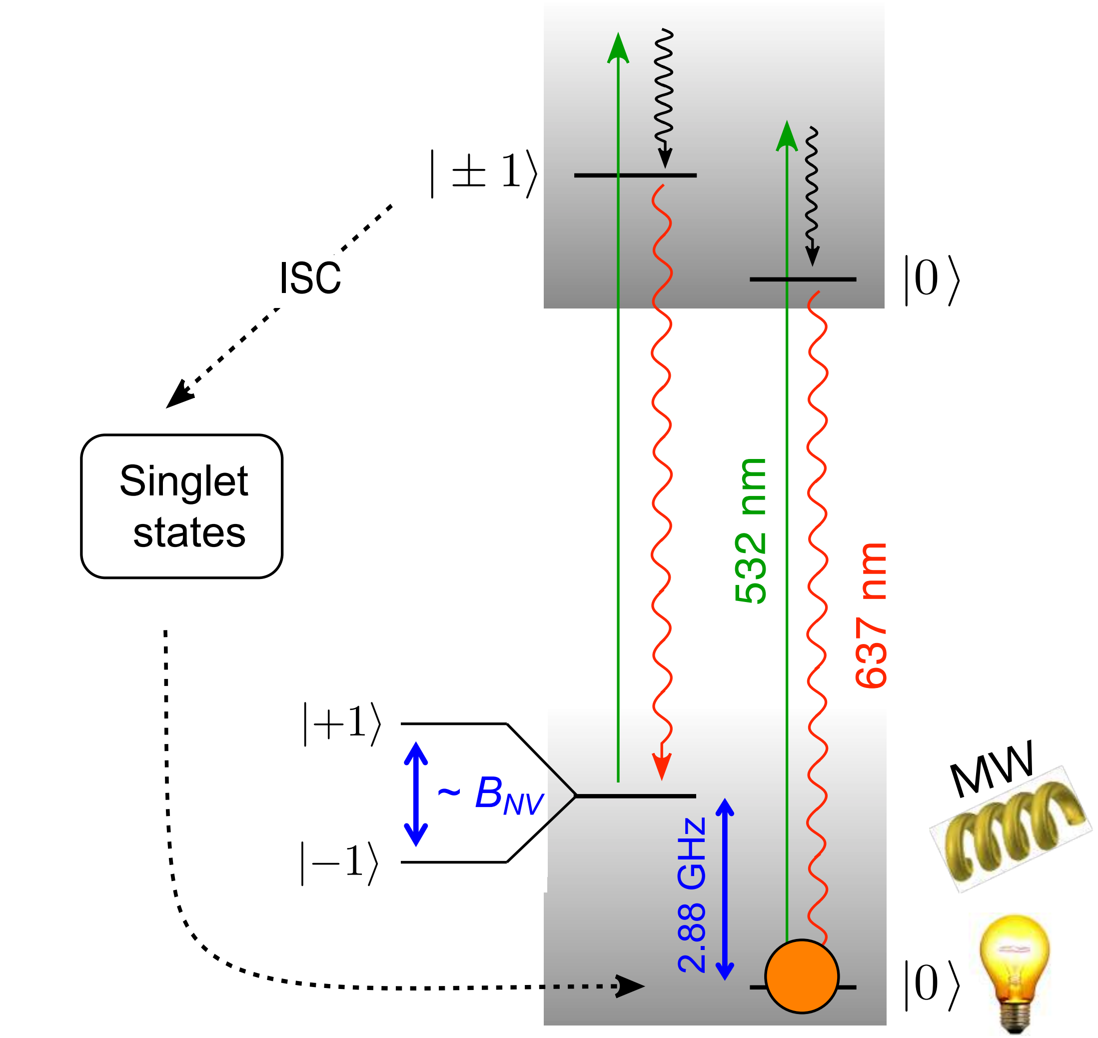
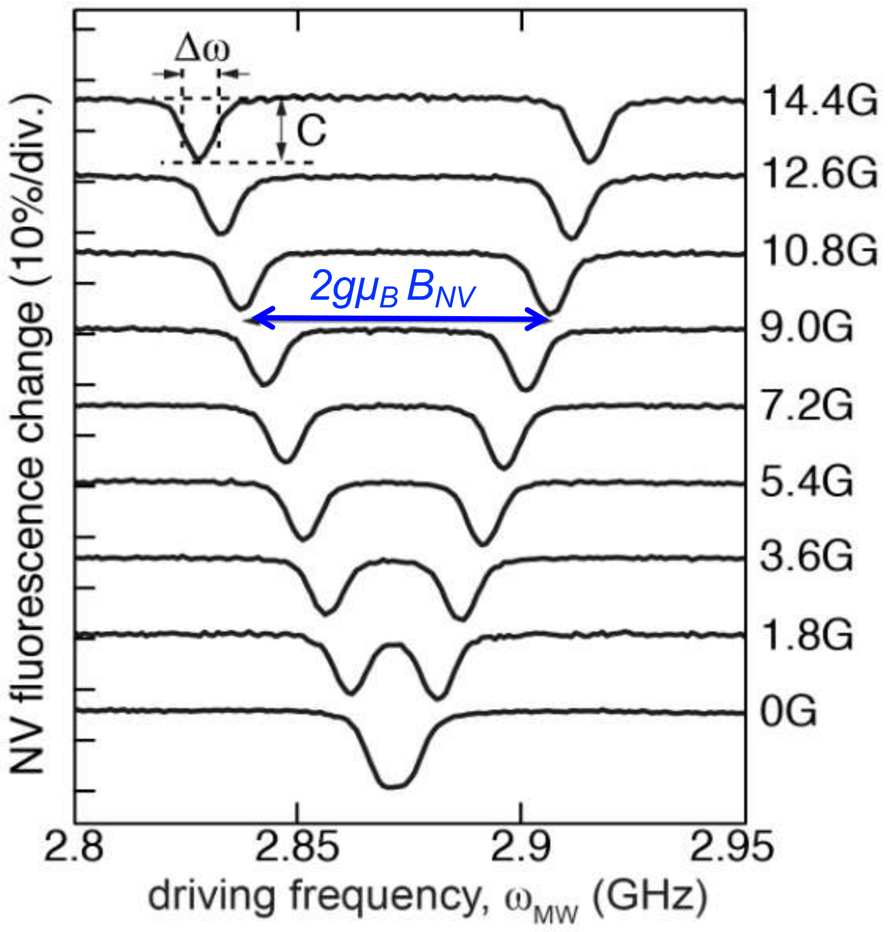


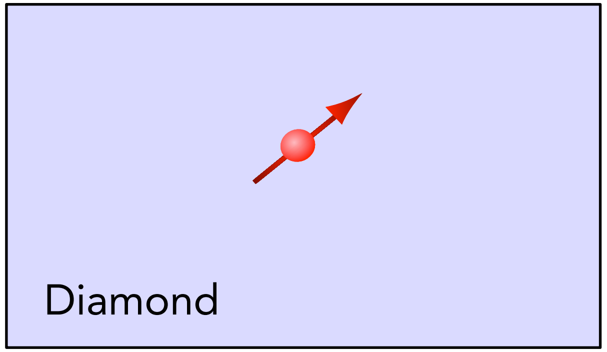
Rondin, *Rep. Prog. Phys.* (2014)



NV = magnetometer

Magnetic **sensing** with NV defects

Single NV defect



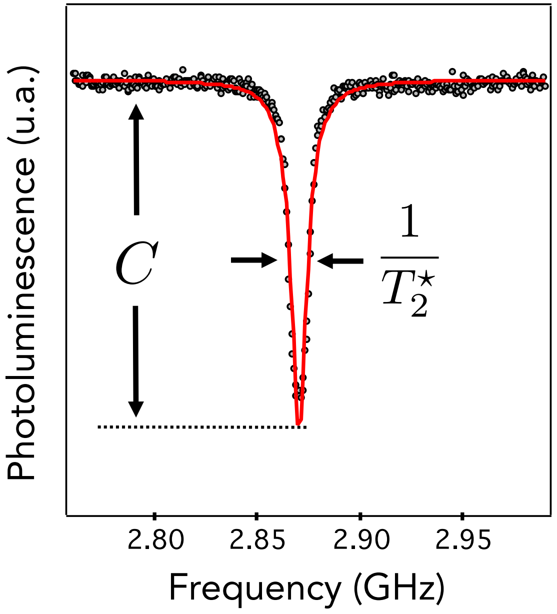
Field sensitivity

$$\eta \propto \frac{1}{C\sqrt{RT_2^\star}}$$

ESR contrast

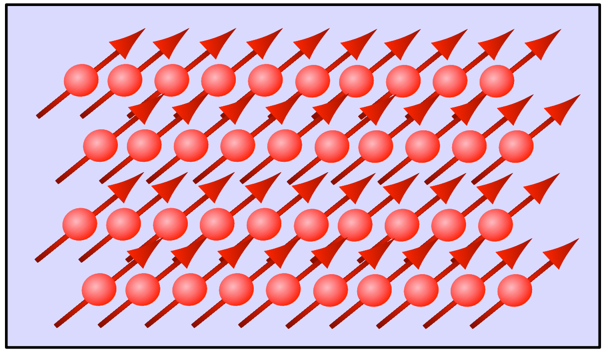
Collection effciency

Coherence time



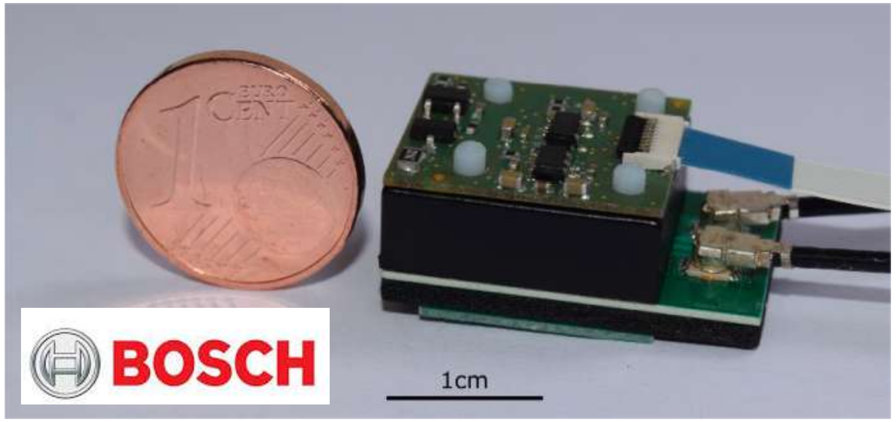
Barry *et al.*, *Rev. Mod. Phys.* **92**, 015004 (2020)

Ensemble of NV defects



$$\eta \propto \frac{1}{C\sqrt{RT_2^\star}} \times \frac{1}{\sqrt{N}}$$

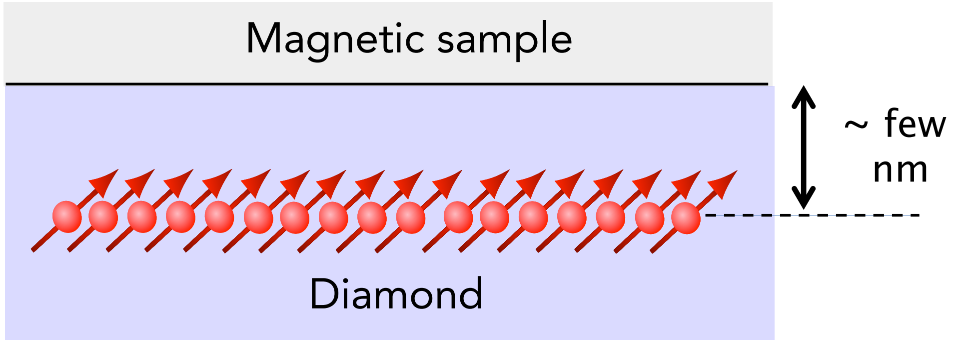
Number of NVs

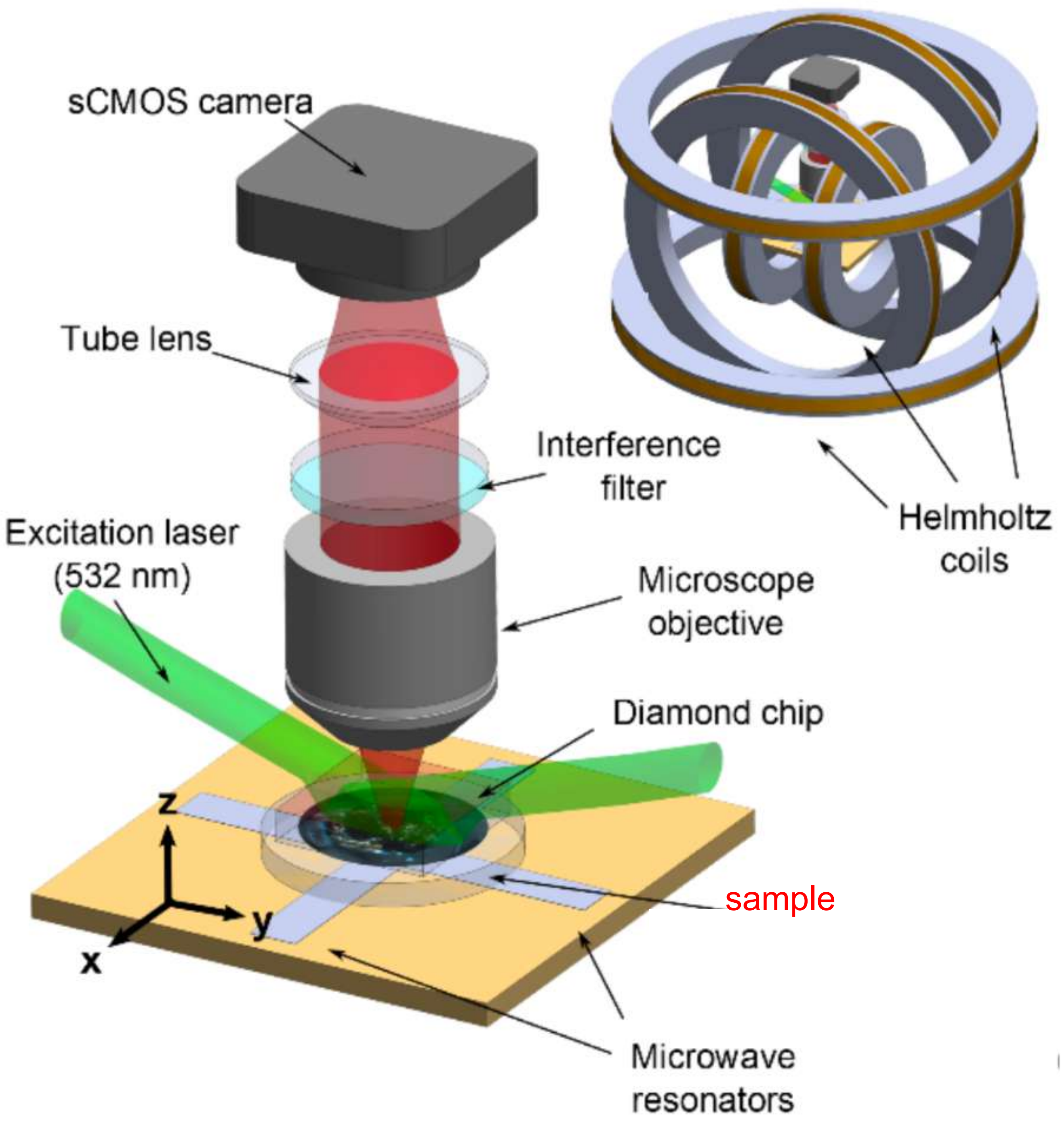


Sensitivity down to few nT.Hz$^{-1/2}$

Magnetic **imaging** with an ensemble of NV defects

Using NV-doped layers close to the surface





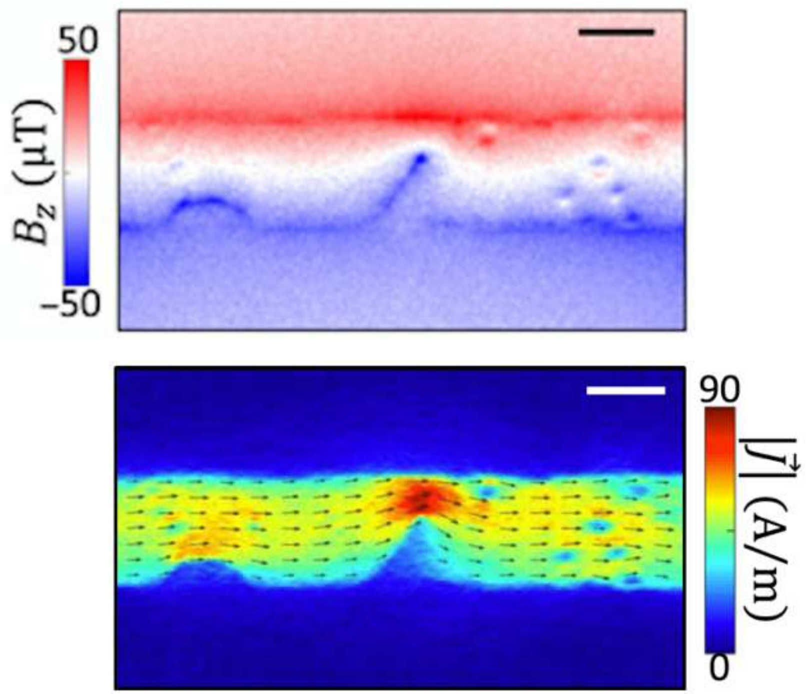
Glenn *et al.*, *Nat. Methods* ***12***, 736 (2015)

Levine *et al.*, *Nanophotonics* ***8***, 1945 (2019)

Magnetic **imaging** with an ensemble of NV defects

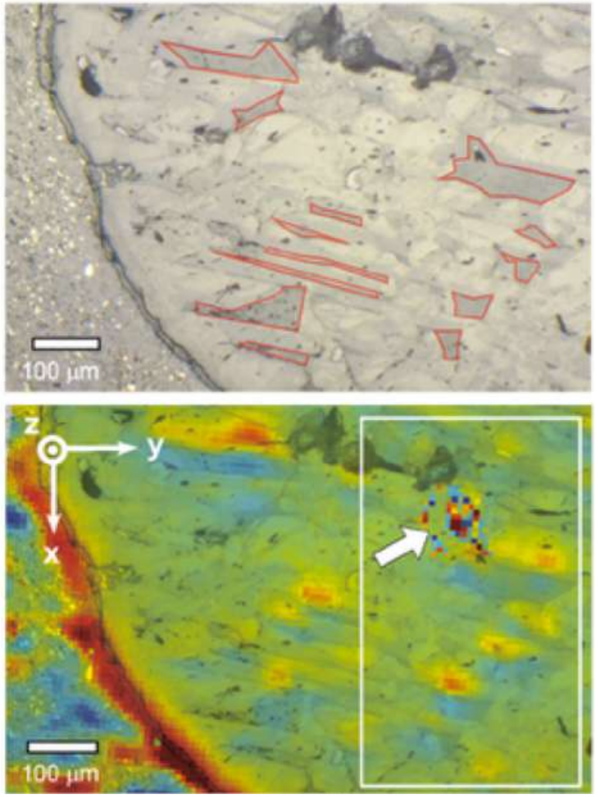
➡ Condensed matter physics

current flow in graphene



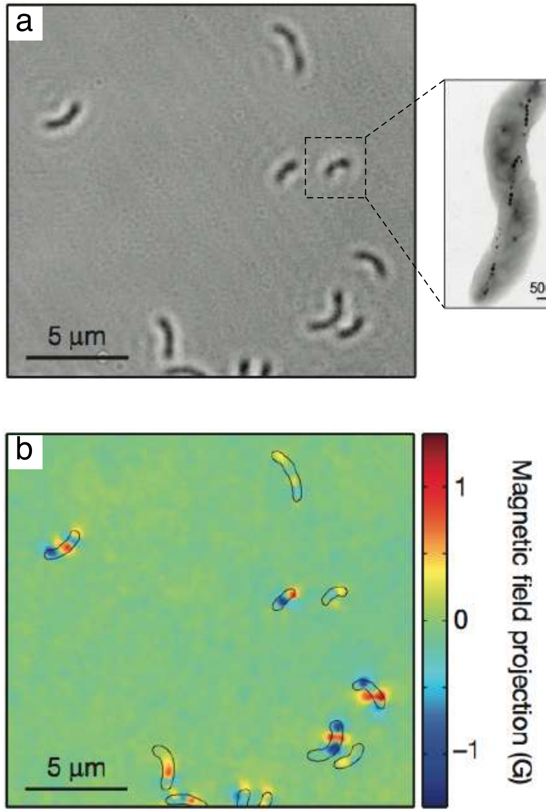
Tetienne, *Sci. Adv.* (2017)

➡ Paleomagnetism



Glenn, *Geochem. GeoPhys.* (2017)

➡ Biomagnetism

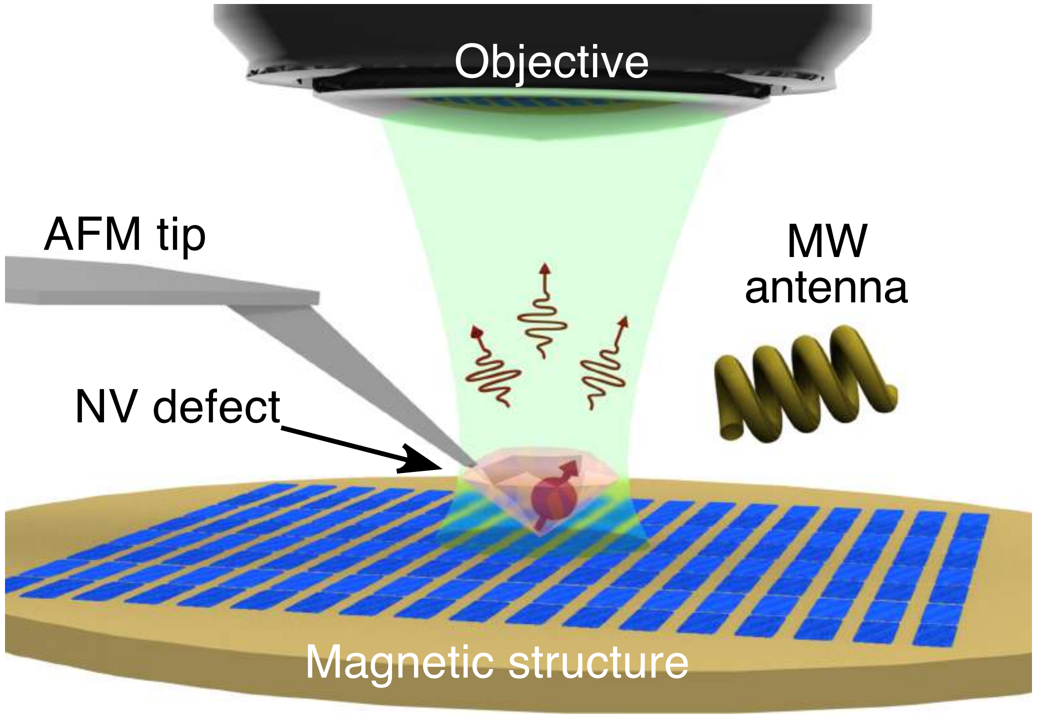


Le Sage, *Nature* (2013)

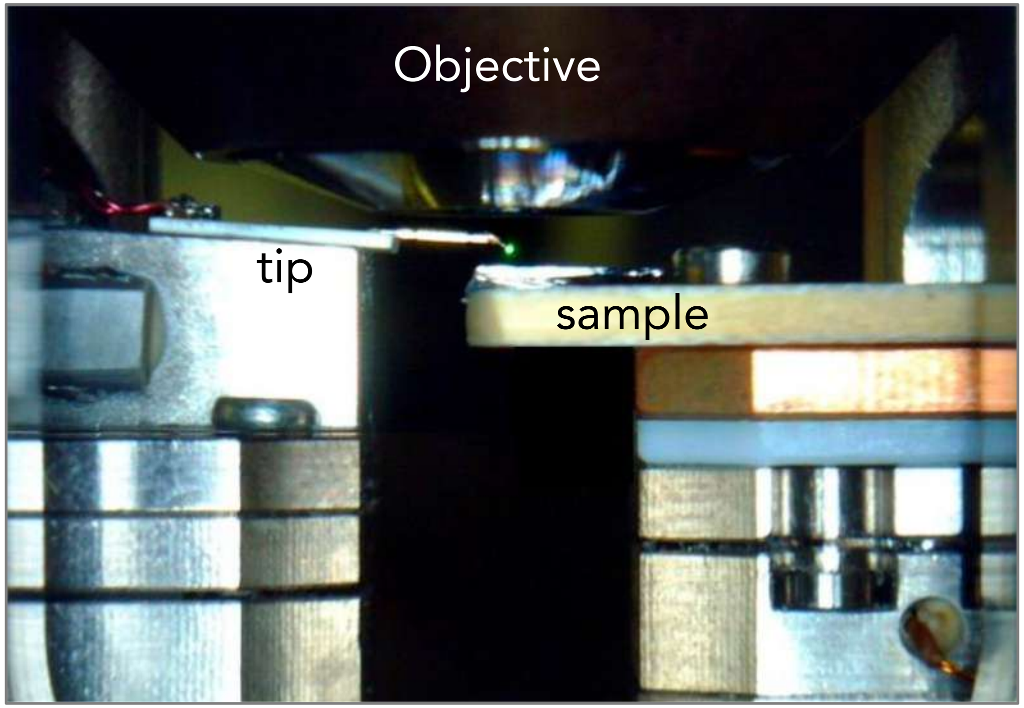
Spatial resolution limited by diffraction (~ 500 nm)

Magnetic imaging with a single NV defect

Scanning-NV magnetometry



Experimental setup

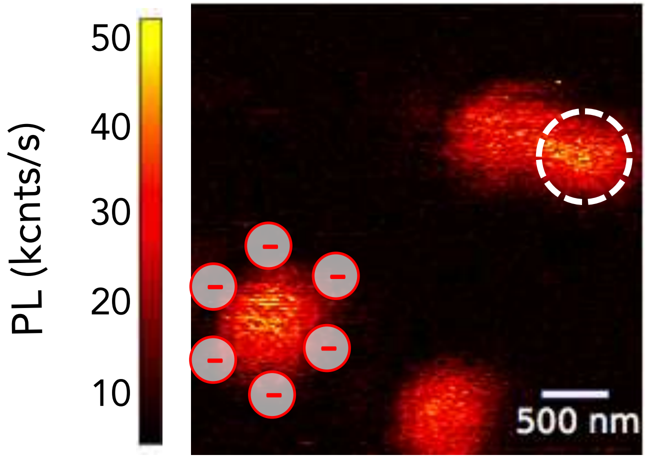


- ⋆ Quantitative/vectorial (sensitivity - **1 μT/Hz$^{-1/2}$**)
- ⋆ No magnetic back-action, operation from 4K to 300K
- ⋆ Atomic-size detection volume

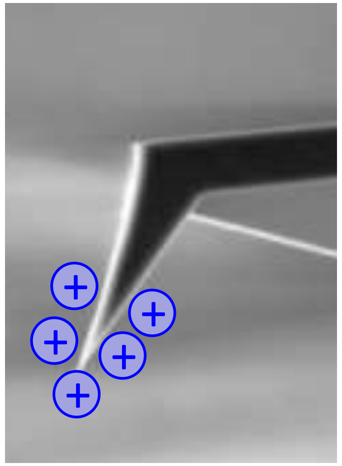
Rondin, Appl. Phys. Lett. (2012)

Engineering the NV-based sensor

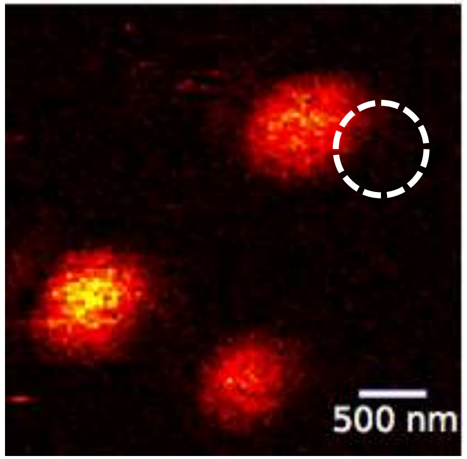
PL map of 20-40 nm
diamond nanocrystal



Tip covered
with a cationic polymer



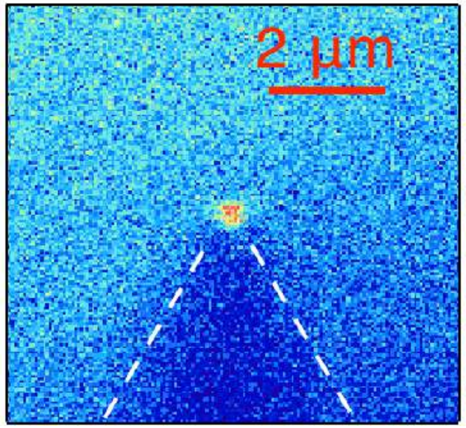
Grafting by
electrostatic interaction



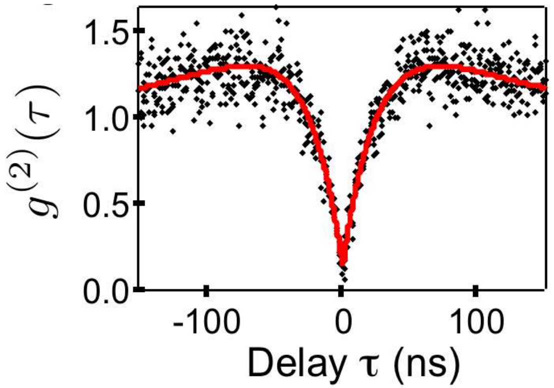
Cuche, *Opt. Exp.* 17, 19969 (2009)

➡️ Photoluminescence raster scan of the AFM tip after grafting

Rondin, Appl. Phys. Lett. (2012)



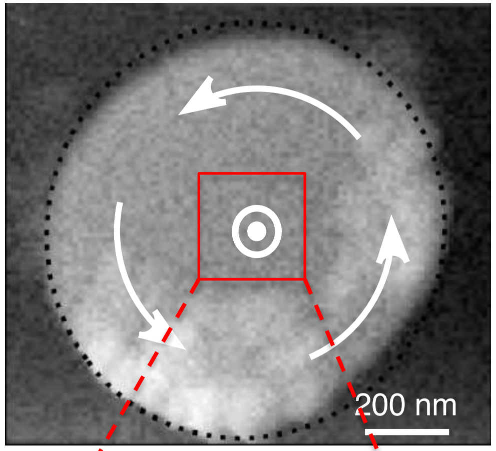
Single NV at
the tip apex !



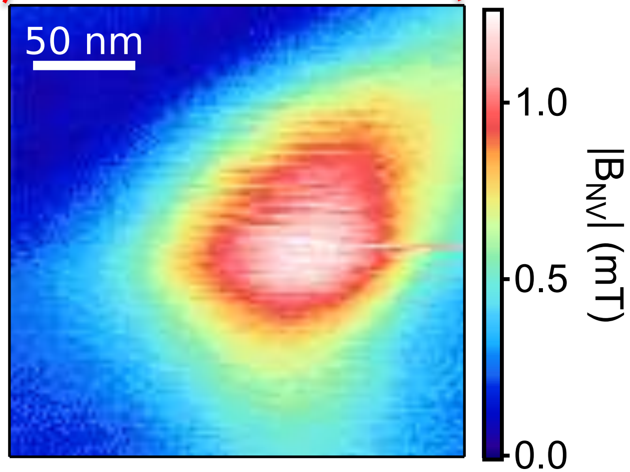
Imaging the core of a magnetic vortex

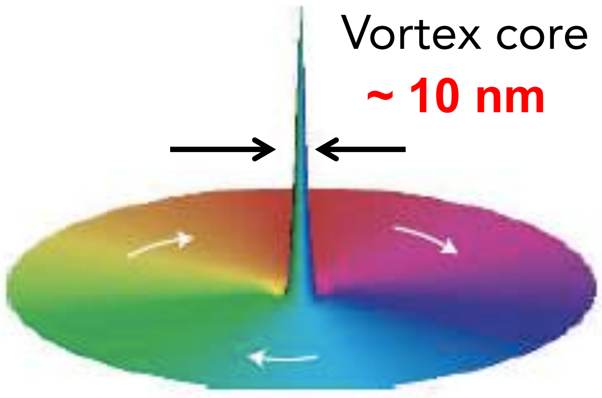
AFM image

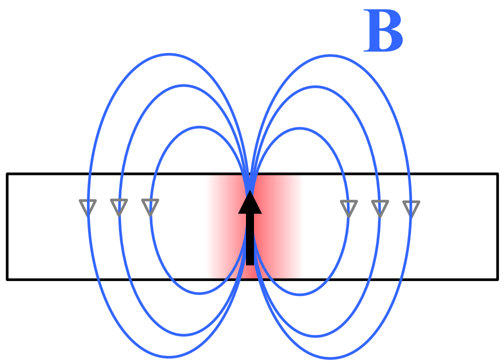
50-nm thick disk of FeNi



NV image

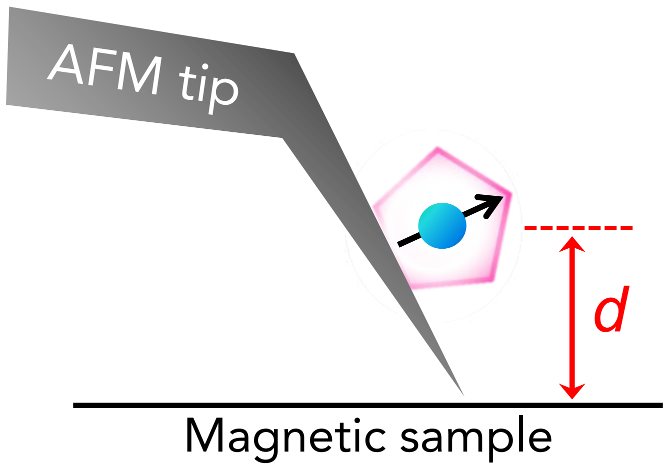






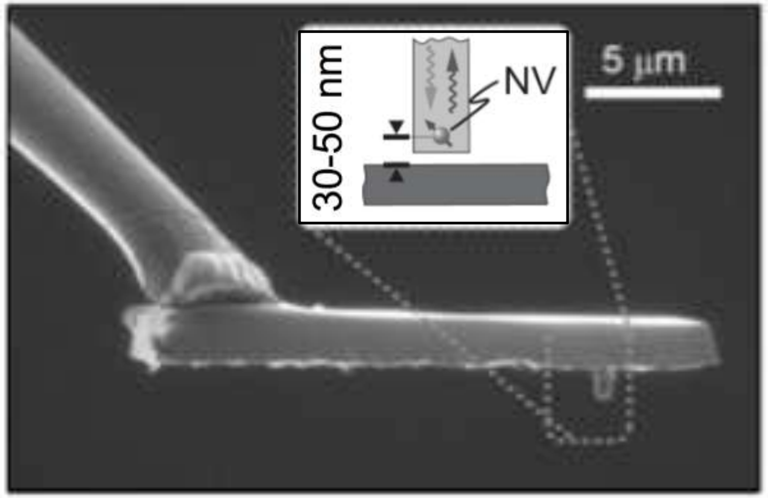
➡️ Resolving power ~ 100-150 nm

Limited by the probe-to-sample distance *d*



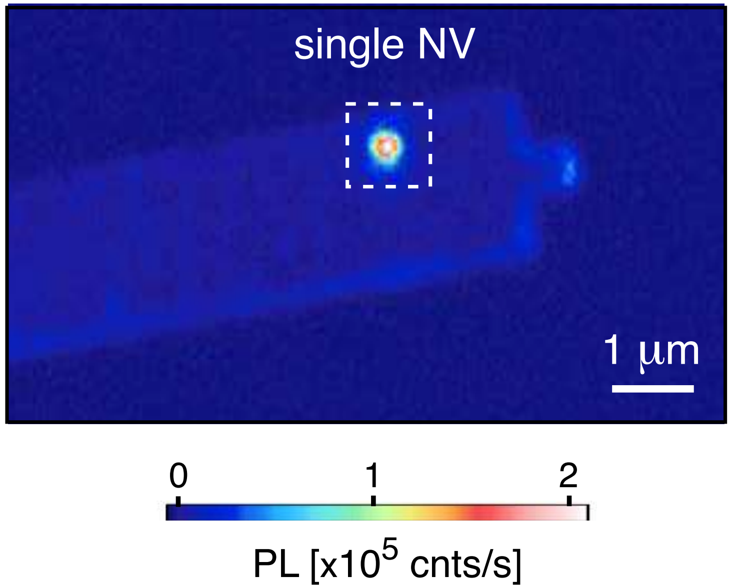
Improving the resolving power with all-diamond scanning tips

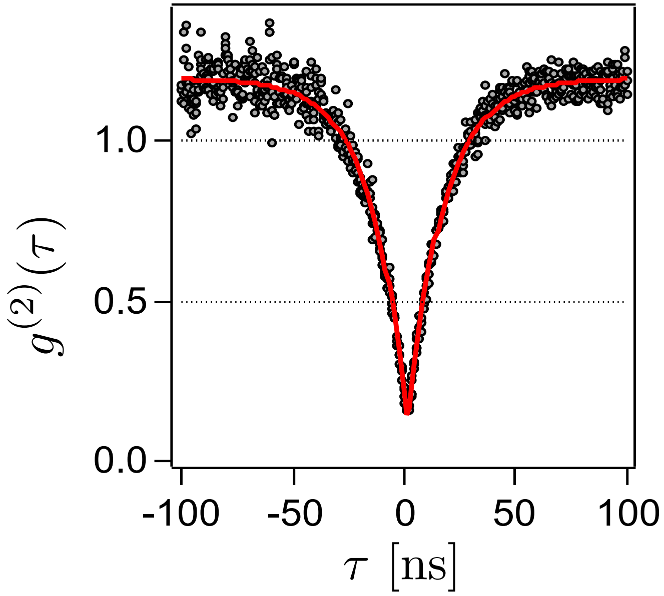
SEM image



Maletinsky, Nat. Nano. (2012)
Appel, Rev. Sci. Inst. (2016)

PL map of the diamond tip



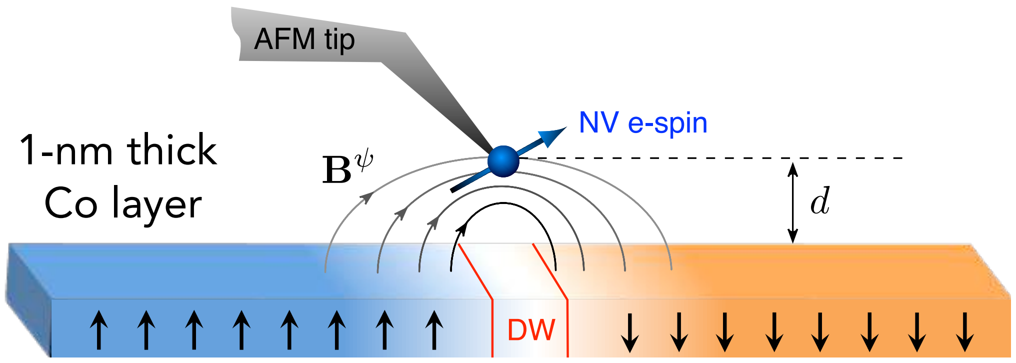


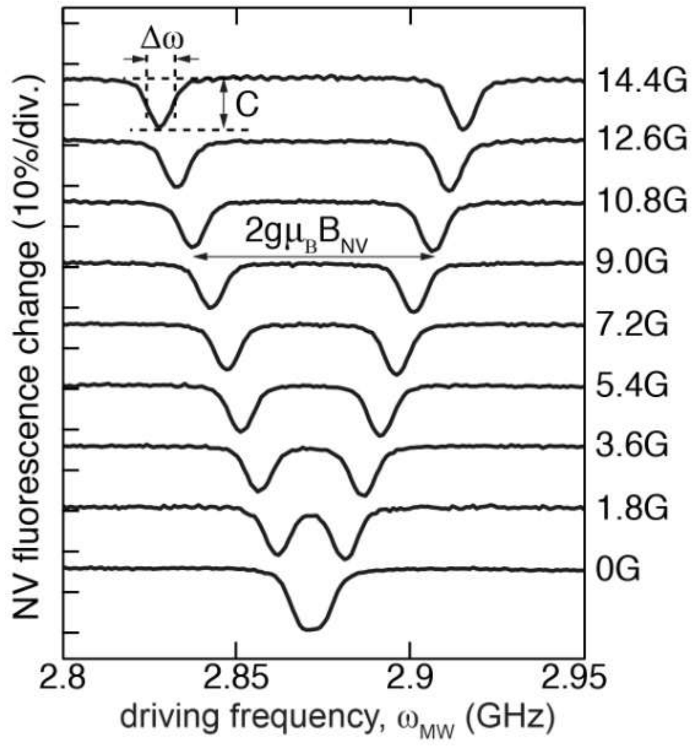
➡️ Resolving power ~ 30-50 nm

Now even commercially available !

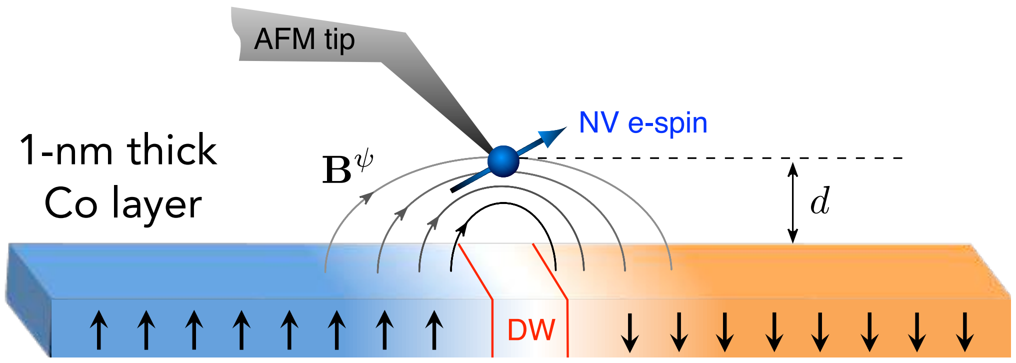
qnami QZABRE

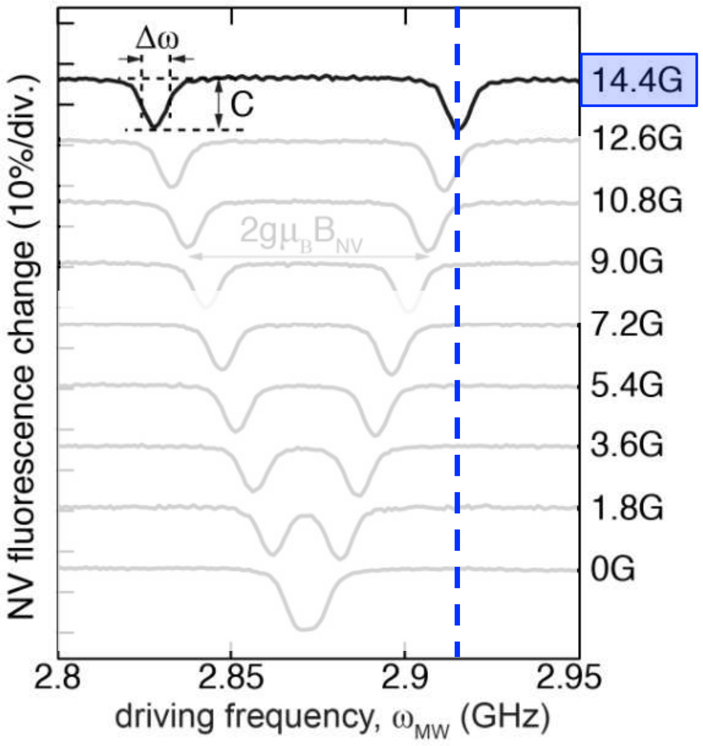
One application: Imaging domain walls in thin ferromagnets





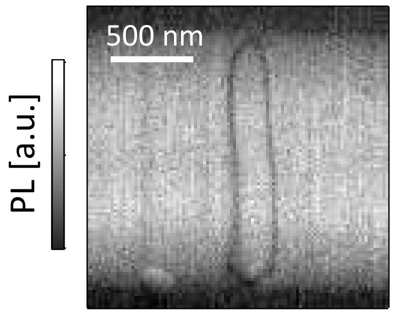
One application: Imaging domain walls in thin ferromagnets



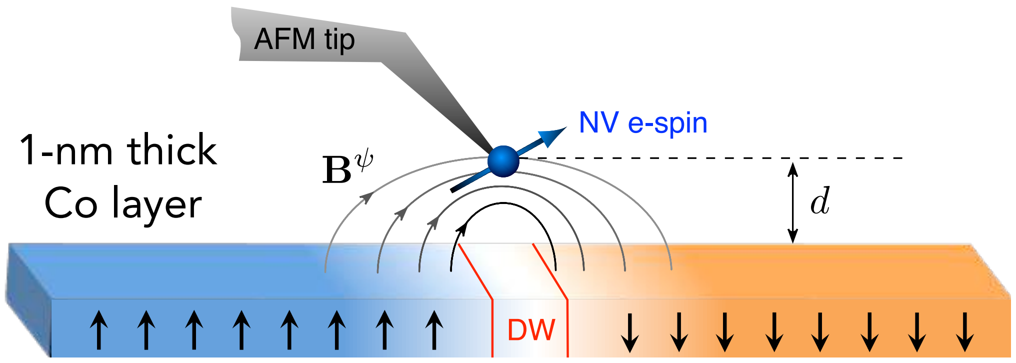


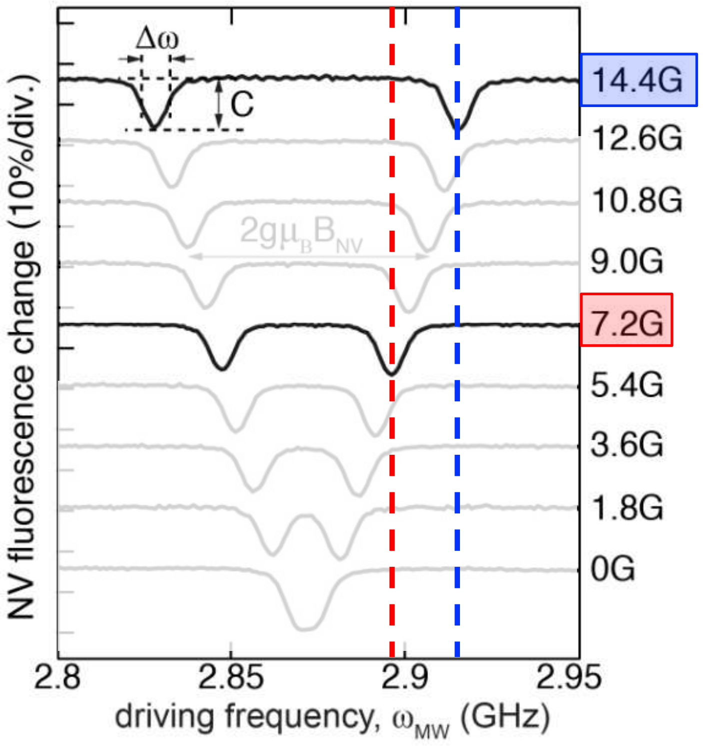
➡ *"Iso-B"* imaging mode

f_0 = 2915 MHz [14G]

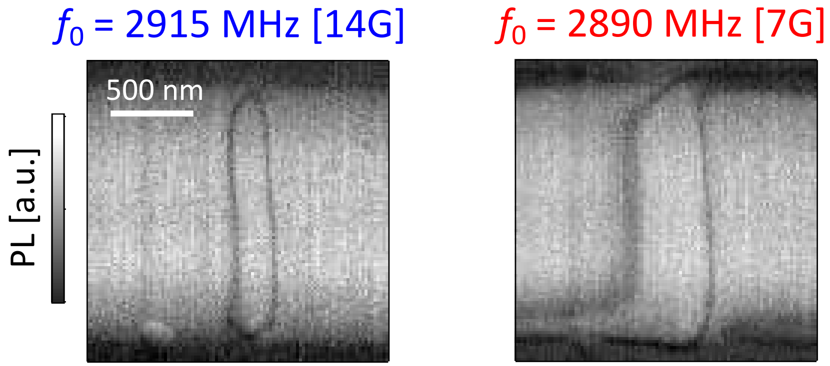


One application: Imaging domain walls in thin ferromagnets

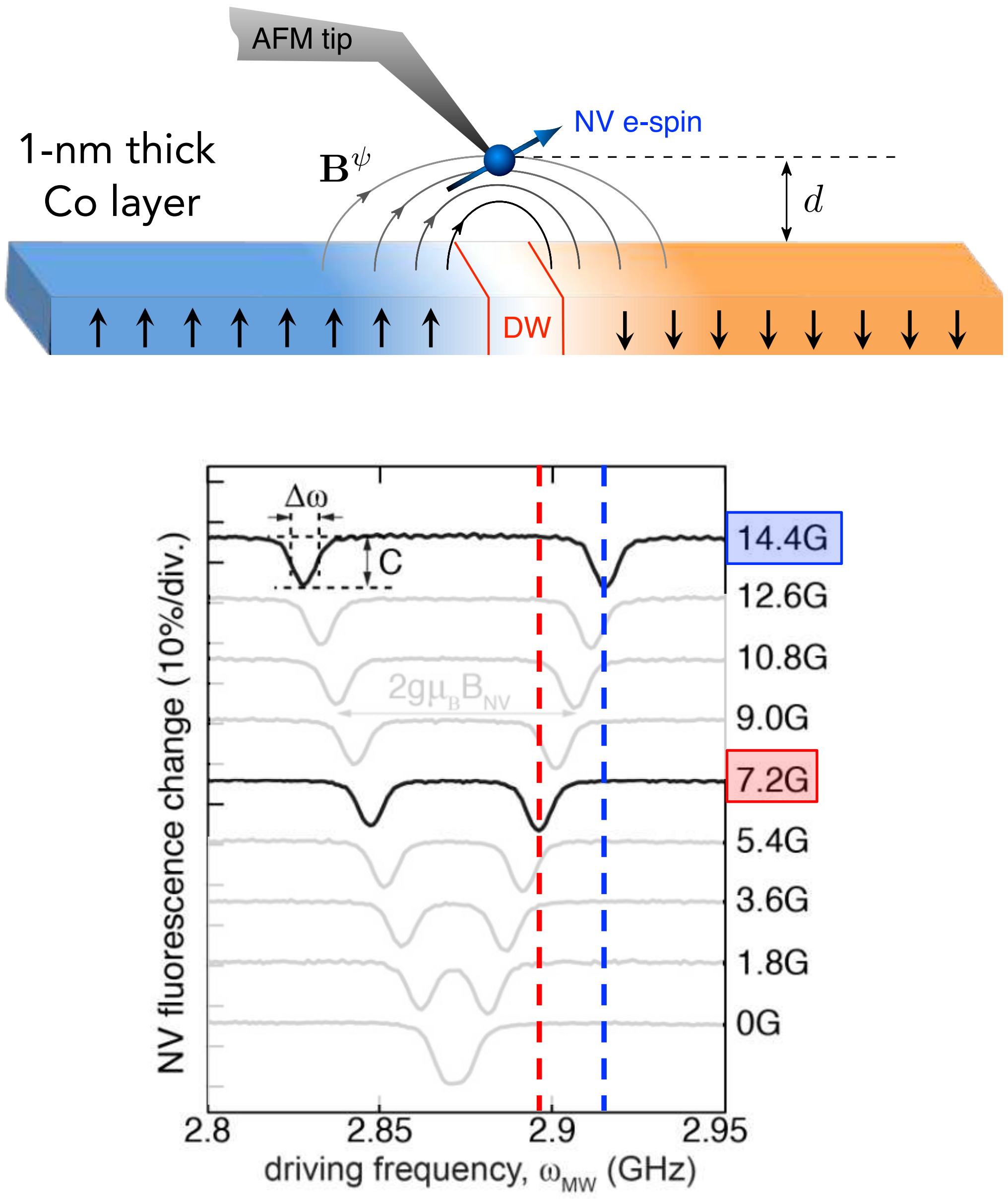




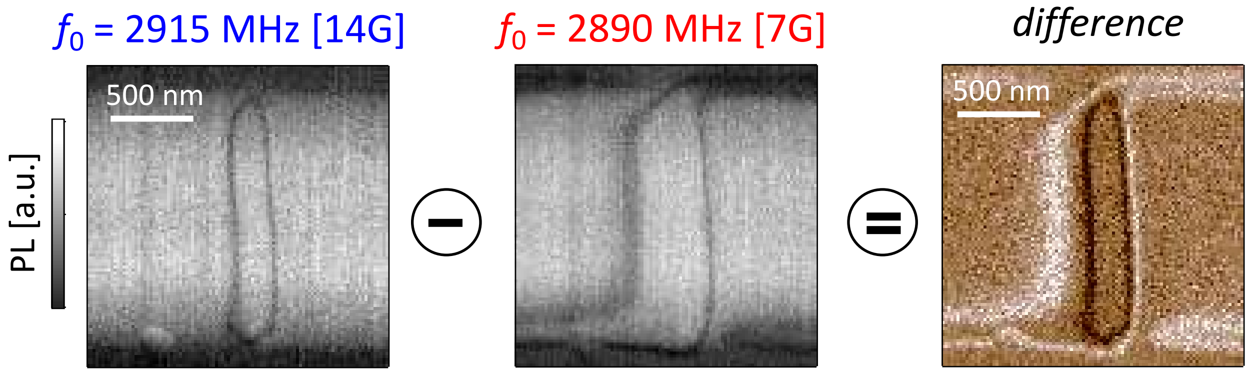
➡ *"Iso-B"* imaging mode



One application: Imaging domain walls in thin ferromagnets

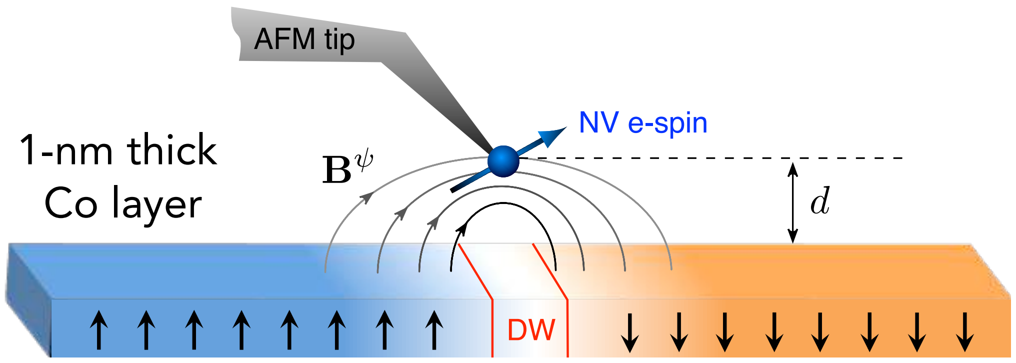


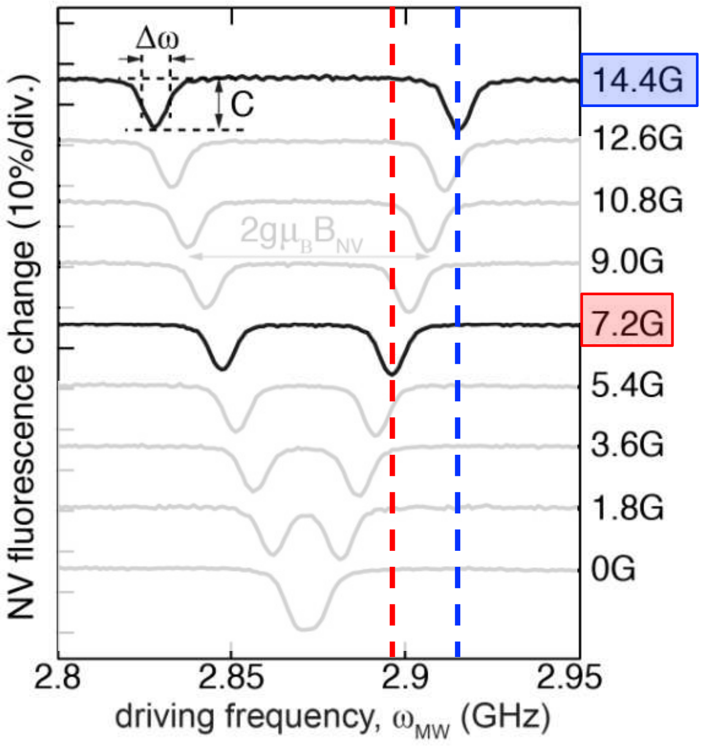
➡ *"Iso-B"* imaging mode



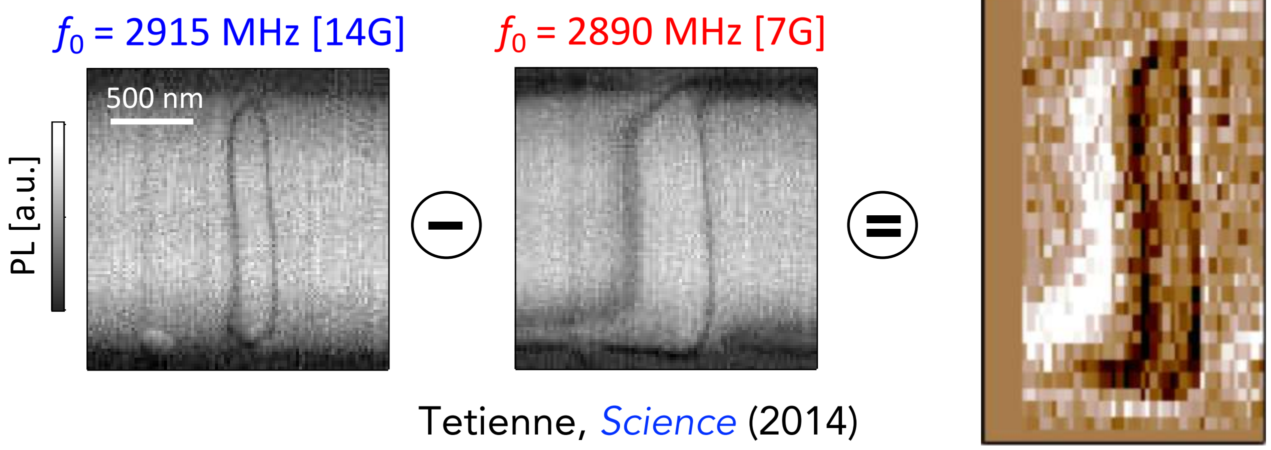
Tetienne, *Science* (2014)

One application: Imaging domain walls in thin ferromagnets



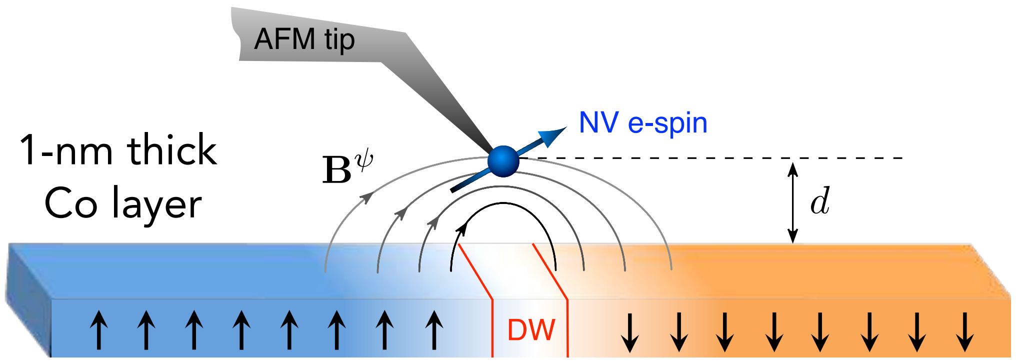


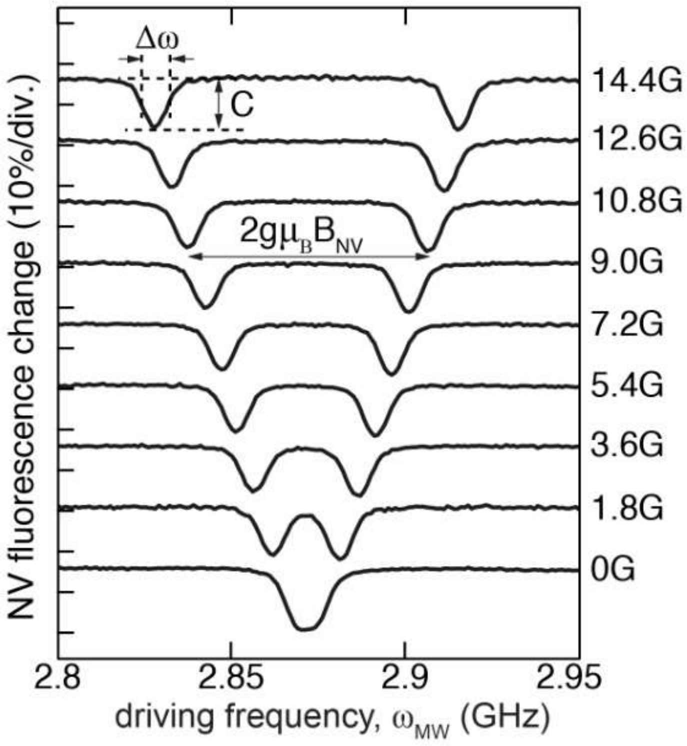
➡ *"Iso-B"* imaging mode



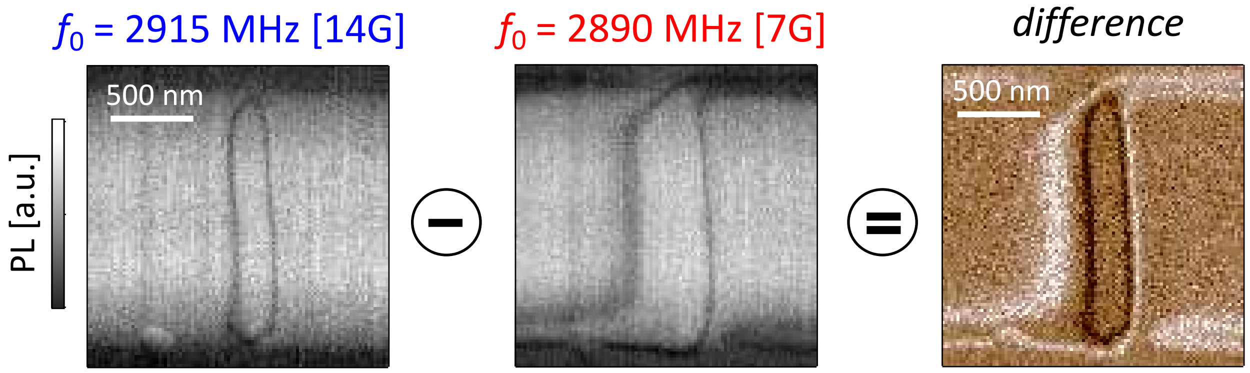
Tetienne, *Science* (2014)

One application: Imaging domain walls in thin ferromagnets



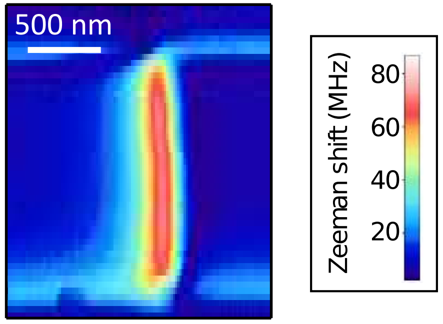


"*Iso-B*" imaging mode



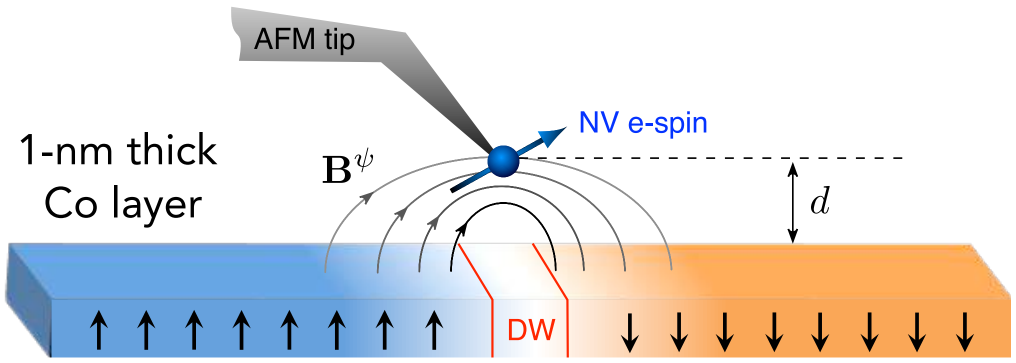
Tetienne, *Science* (2014)

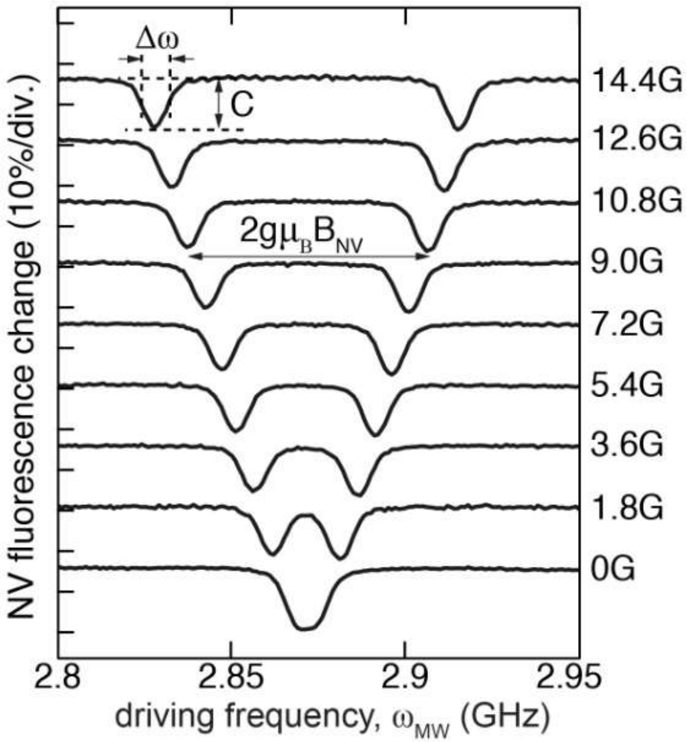
"*full-B*" imaging mode



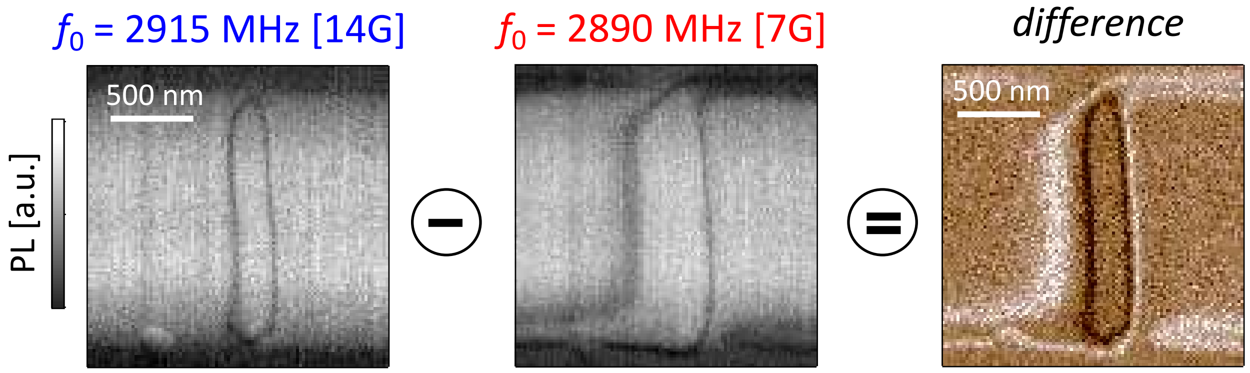
Tetienne, *Nat. Com.* (2015)

One application: Imaging domain walls in thin ferromagnets





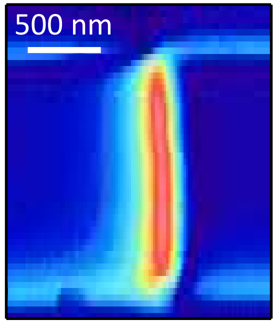
"*Iso-B*" imaging mode

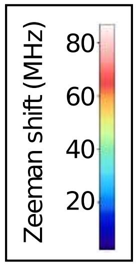


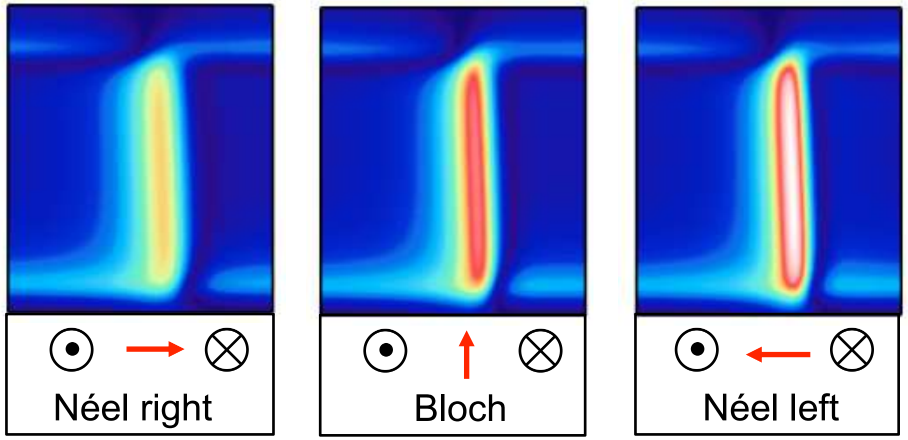
Tetienne, *Science* (2014)

"*full-B*" imaging mode

Comparison with theoretical predictions

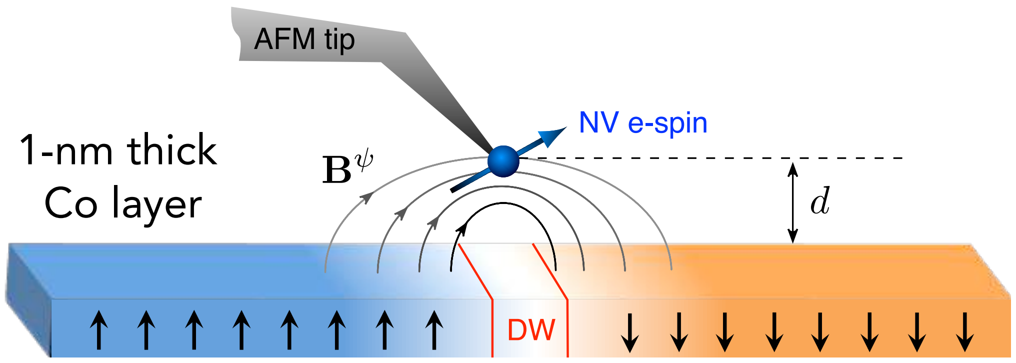


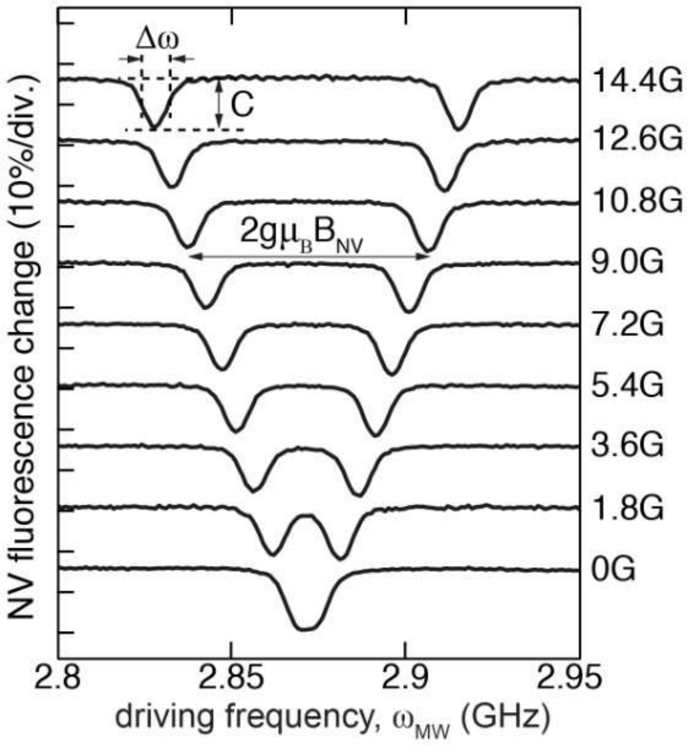




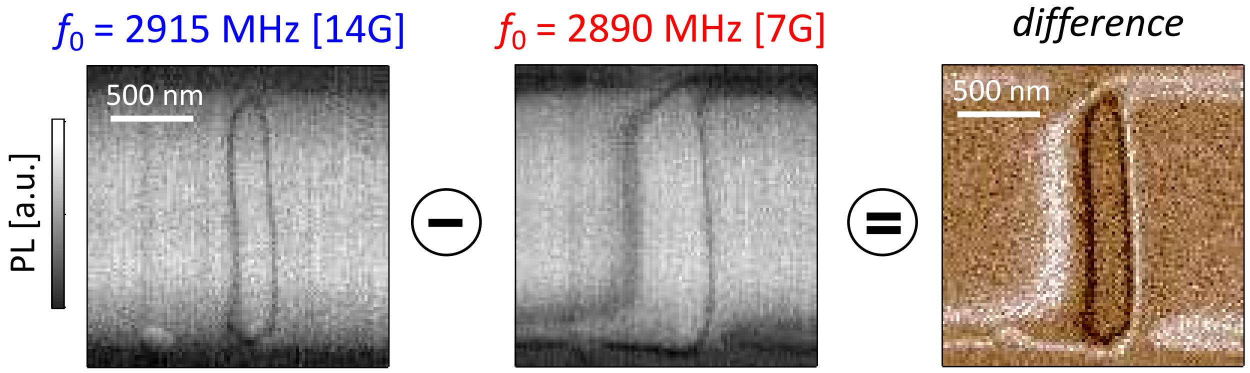
Tetienne, *Nat. Com.* (2015)

One application: Imaging domain walls in thin ferromagnets





"*Iso-B*" imaging mode



Tetienne, *Science* (2014)

"*full-B*" imaging mode

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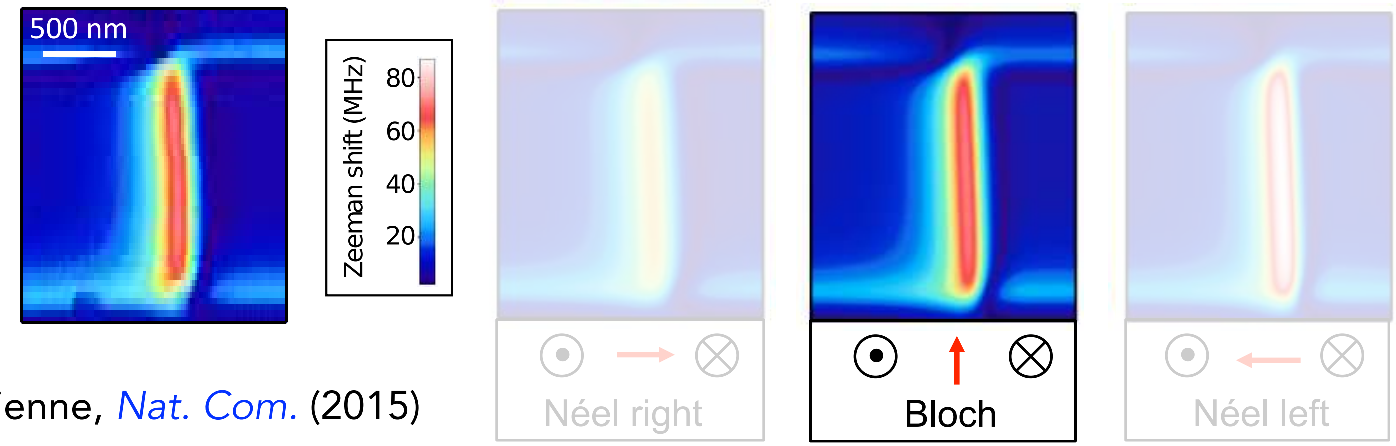
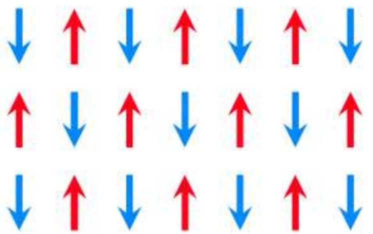


Tetienne, *Nat. Com.* (2015)

Exploring the physics of antiferromagnetic (AF) materials

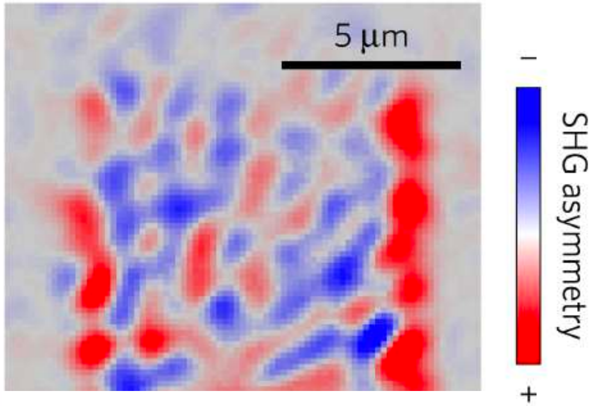


- ★ Robust against magnetic perturbations;
- ★ Ultrafast dynamics *(THz vs GHz for ferromagnets);*

⟶ Appealing materials for spintronics — Baltz, *Rev. Prog. Phys.* (2018)

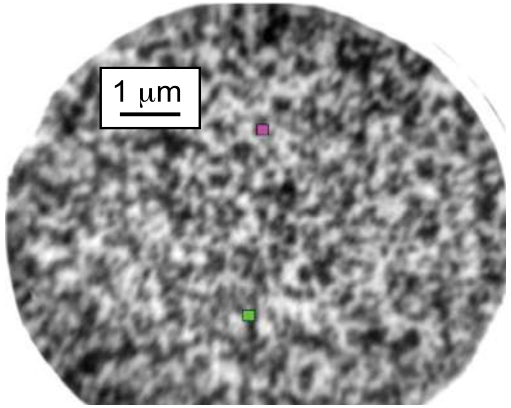
One challenge ⟶ imaging the antiferromagnetic order at the nanoscale

SHG microscopy



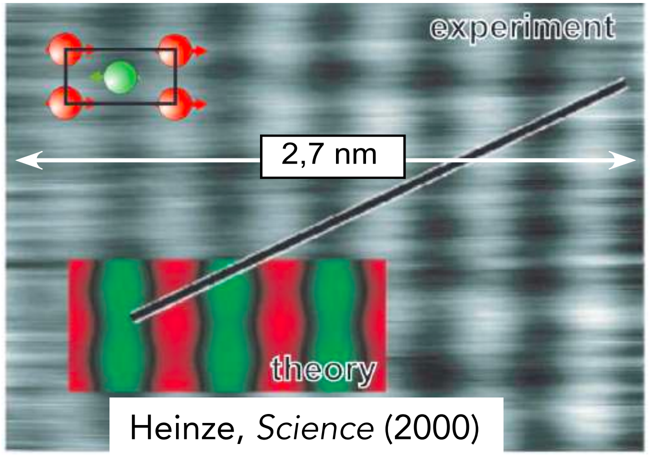
Chauleau, *Nat. Mater.* (2017)

XMLD-PEEM



Grzybowski, *PRL* (2017)

SP-STM



Heinze, *Science* (2000)

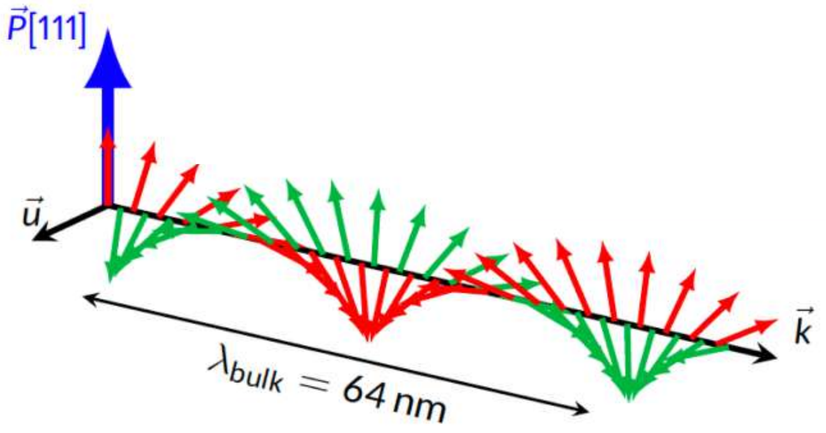
~ 500 nm — ~ 100 nm — < 1 nm ⟶ **Spatial resolution**

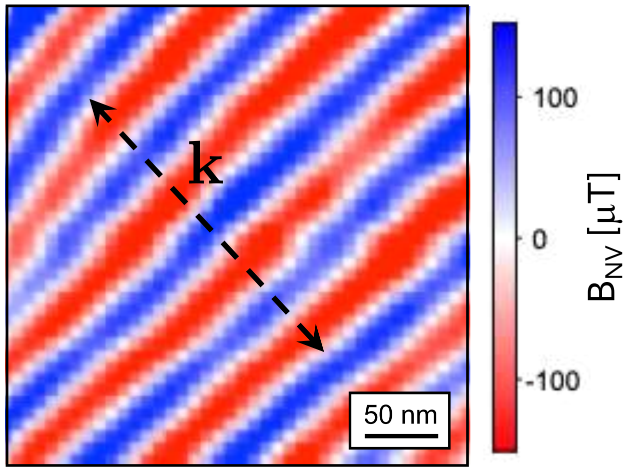
NV microscopy

50 nm resolution, ambient conditions on any kind of magnetic samples

Imaging the AF order with scanning-NV magnetometry

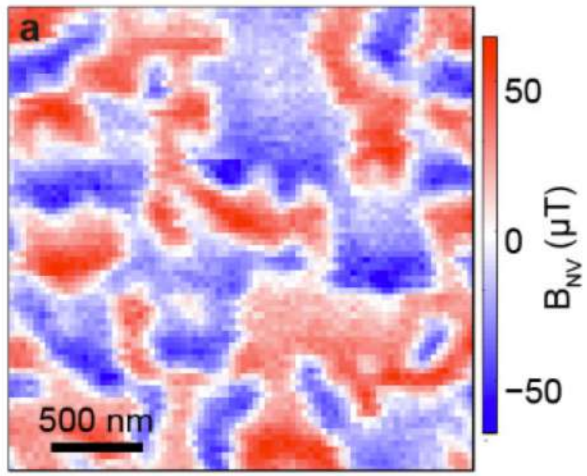
Cycloidal AF order in $BiFeO_3$





Gross, *Nature* **549**, 252 (2017)
Chauleau, *Nat. Materials* **19**, 386 (2020)
Haykal, *Nat. Commun.* **11**, 1704 (2020)

AF domain walls in Cr_2O_3

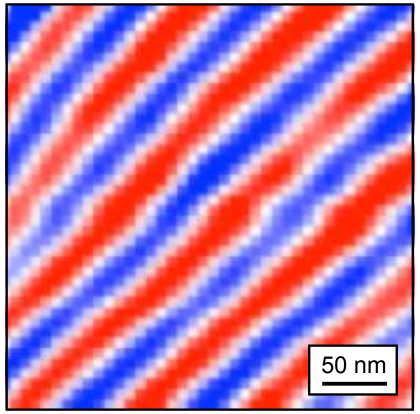


Appel, *Nano Lett.* **19**, 1682 (2019)
Hedrich, *arXiv:2009.08986*
Wornle, *arXiv:2009.09015*

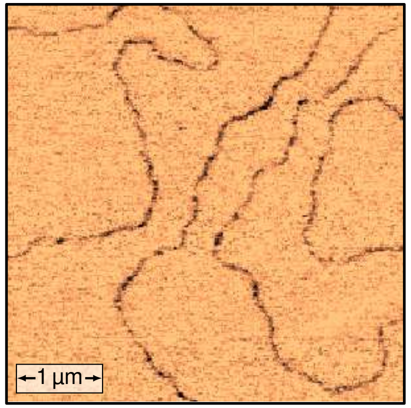
Very promising techniques to investigate the physics of antiferromagnetic materials

A multimode sensor

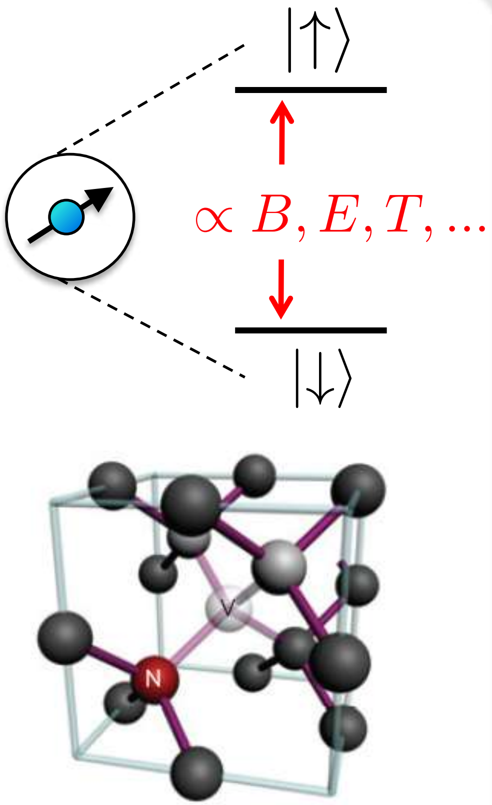
Static magnetic field



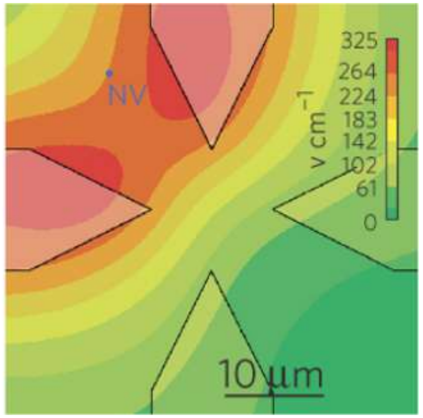
Magnetic noise



Finco, *Nat. Comm.* (2021)

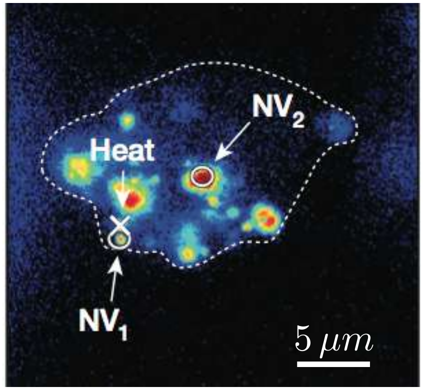


Electric field



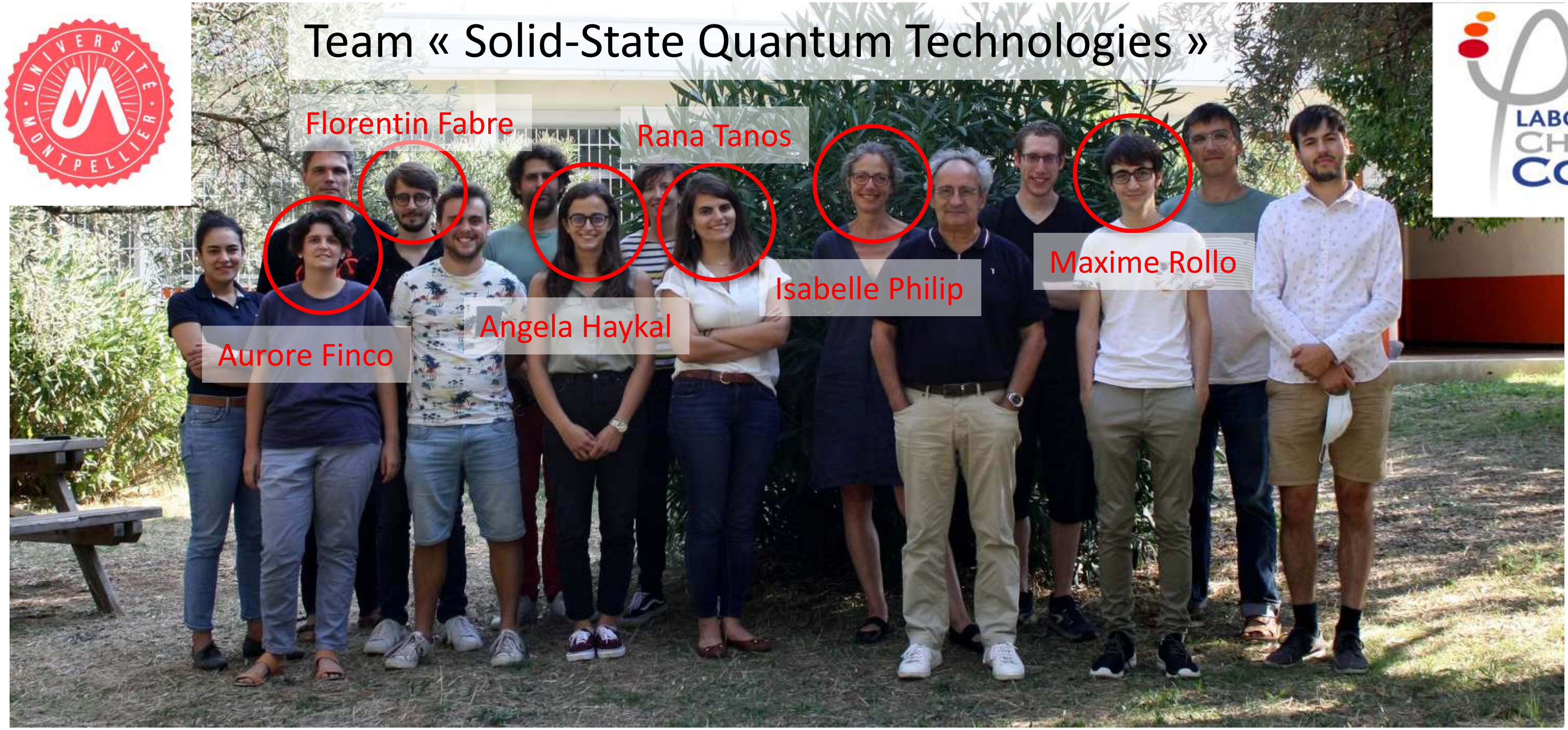
Dolde, *Nat. Phys.* **7**, 459 (2011)

Temperature



Kucsko, *Nature* **500**, 54 (2013)

Team « Solid-State Quantum Technologies »



Collaborations

- W. Legrand, K. Bouzehouane, V. Garcia, S. Fusil, V. Cros – UMPhi Thales
- M. Viret, J.-Y. Chauleau – CEA Saclay
- J. V. Kim, T. Devolder, J.-P. Adam – C2N
- N. Jaouen - Soleil

Fundings