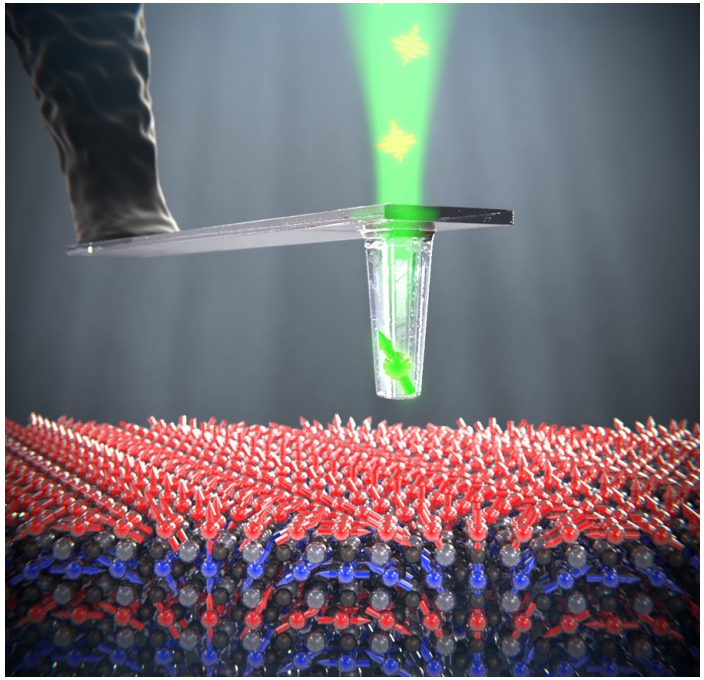
Introduction aux capteurs quantiques

Vincent JACQUES

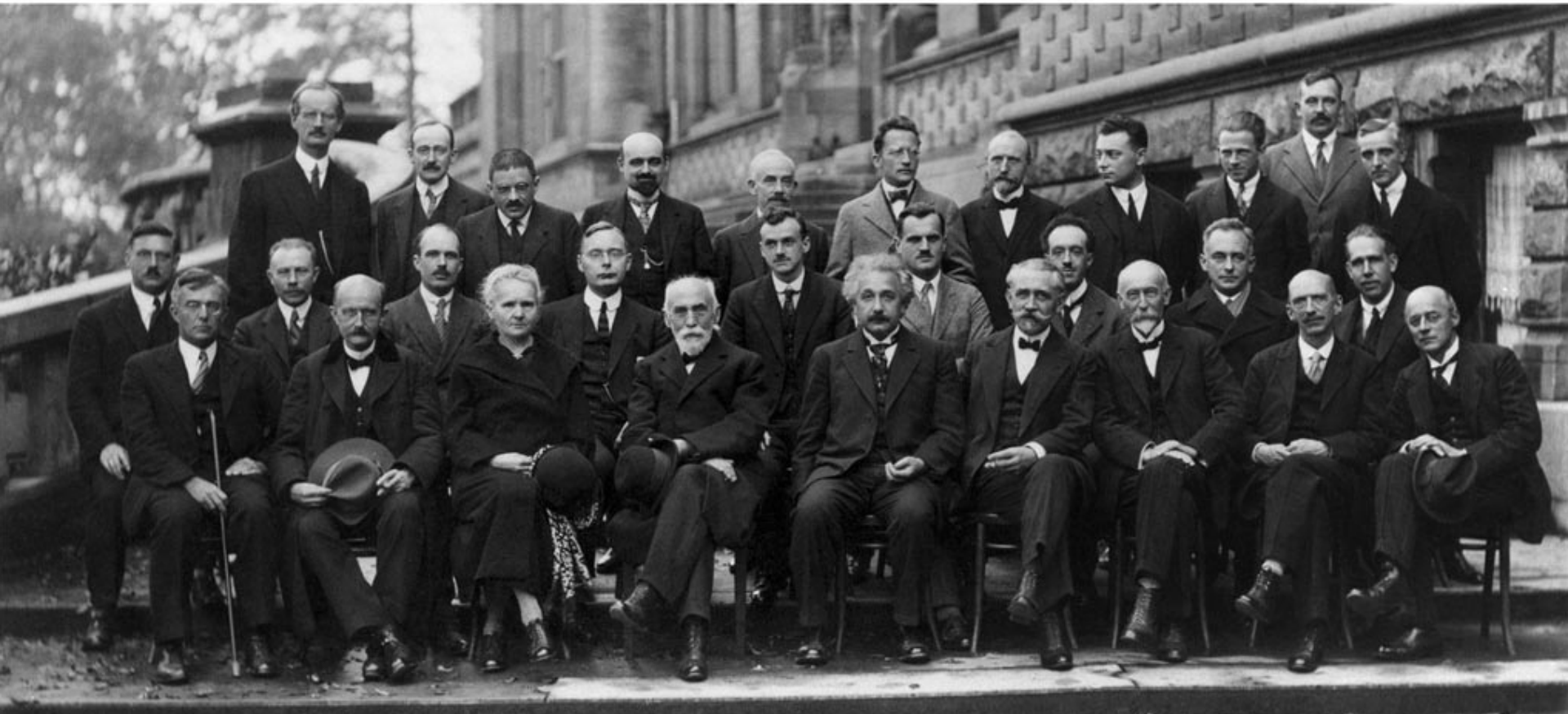


The first quantum revolution (1900 – 1940)

Deep modifications of ideas and concepts in Physics

The « fathers » of quantum physics at the Solvay congress 1927

A. PICCARD E. HENRIOT P. EHRENFEST Ed. HERZEN Th. DE DONDER E. SCHRÖDINGER E. VERSCHAFFELT W. PAULI W. HEISENBERG R.H. FOWLER L. BRILLOUIN
P. DEBYE M. KNUDSEN W.L. BRAGG H.A. KRAMERS P.A.M. DIRAC A.H. COMPTON L. de BROGLIE M. BORN N. BOHR
I. LANGMUIR M. PLANCK Mme CURIE H.A. LORENTZ A. EINSTEIN P. LANGEVIN Ch.E. GUYE C.T.R. WILSON O.W. RICHARDSON
Absents : Sir W.H. BRAGG, H. DESLANDRES et E. VAN AUBEL

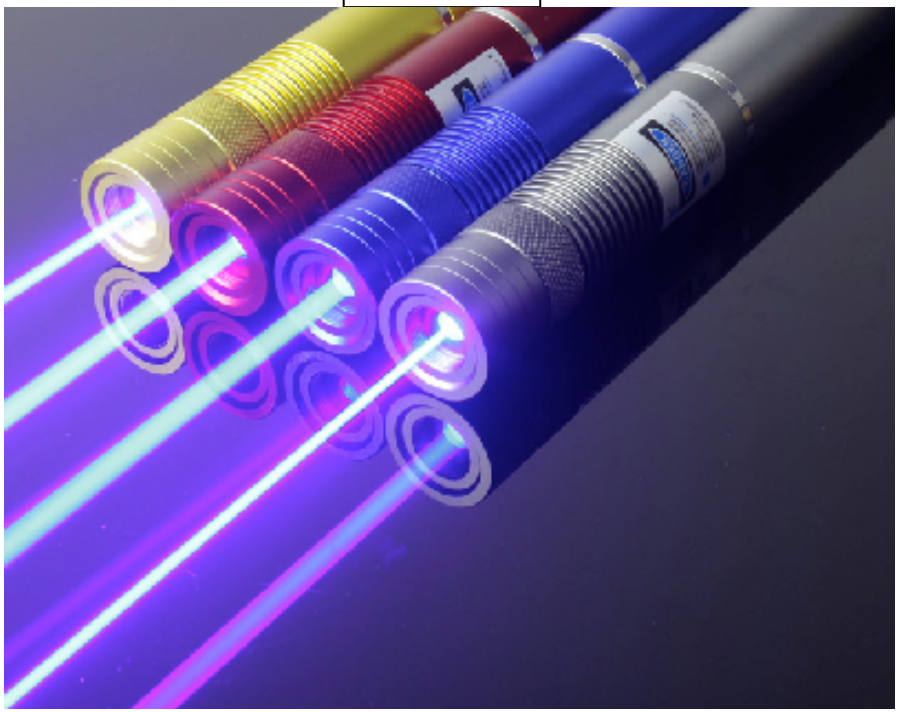


The first quantum revolution (1900 – 1940)

Deep modifications of ideas and concepts in Physics

→ Led to *unexpected* groundbreaking technologies

laser

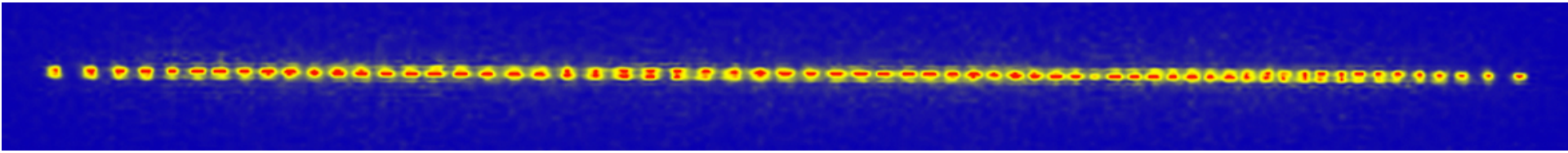


transistor

Bell lab, 1947

A second quantum revolution (1980 – ??)

Observation and manipulation of **individual** quantum systems
(atoms, ions, photons, superconducting circuits…)



Chain of individual ions (R. Blatt, Innsbruck)

A second quantum revolution (1980 – ??)

Observation and manipulation of **individual** quantum systems
(atoms, ions, photons, superconducting circuits…)

Nobel Prize 2012

D. Wineland

S. Haroche

New fundamental studies

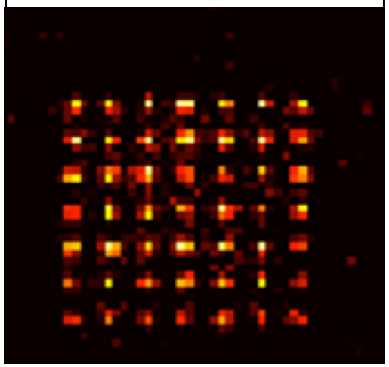
- Quantum superposition
- entanglement
- decoherence
- Wave-particle duality
- …

New applications **?????**

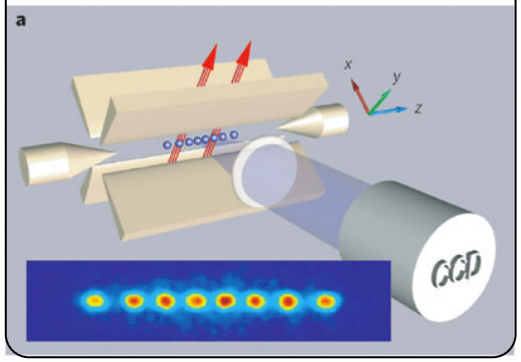
- Quantum information
- Sensing
- Quantum simulator
- Bioapplications
- …????...????...???

A large number of promising quantum systems

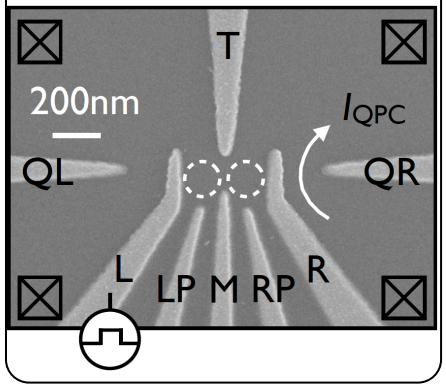
Neutral Atoms



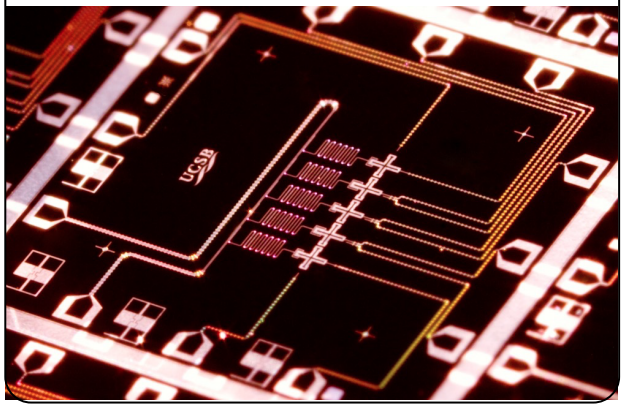
Ions in a Paul trap



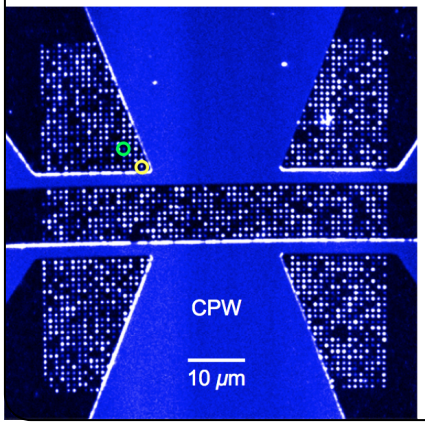
Quantum dot

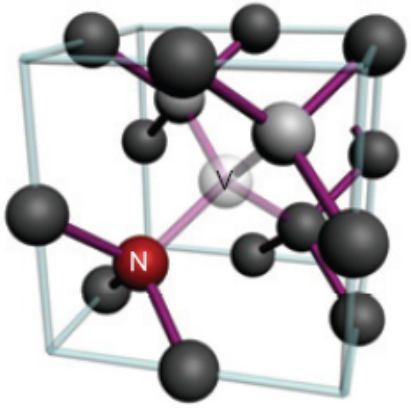


Superconducting circuits



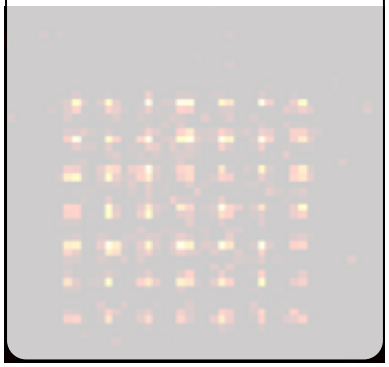
Defects in semiconductors



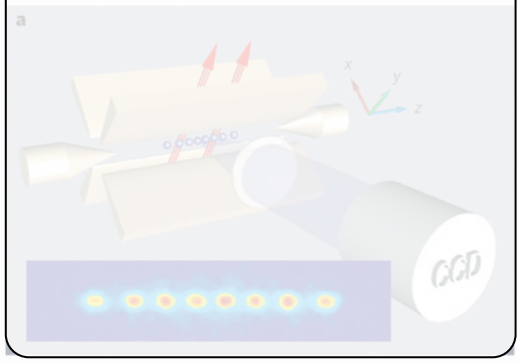


A large number of promising quantum systems

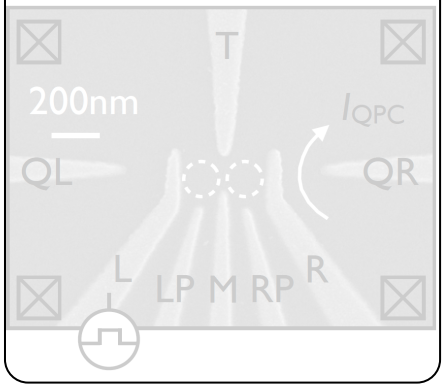
Neutral Atoms



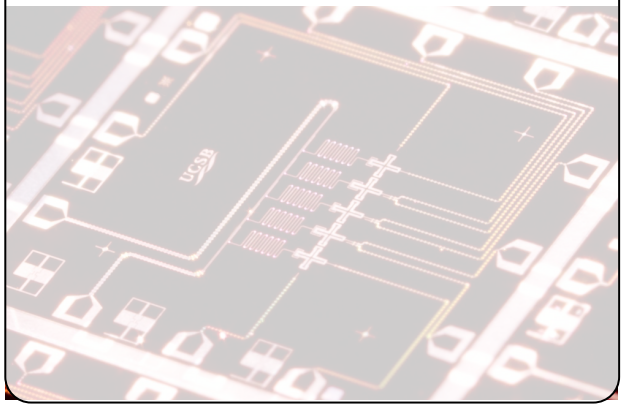
Ions in a Paul trap



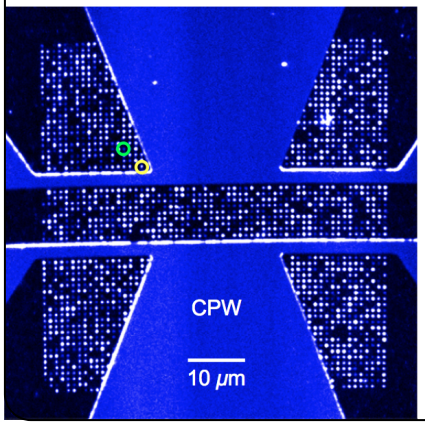
Quantum dot

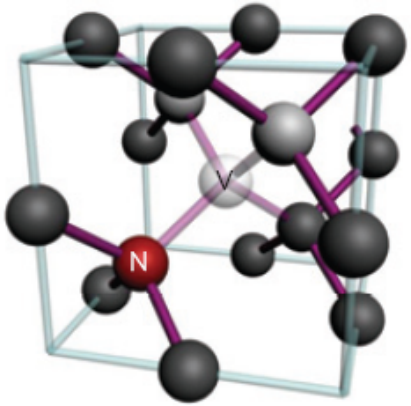


Superconducting circuits

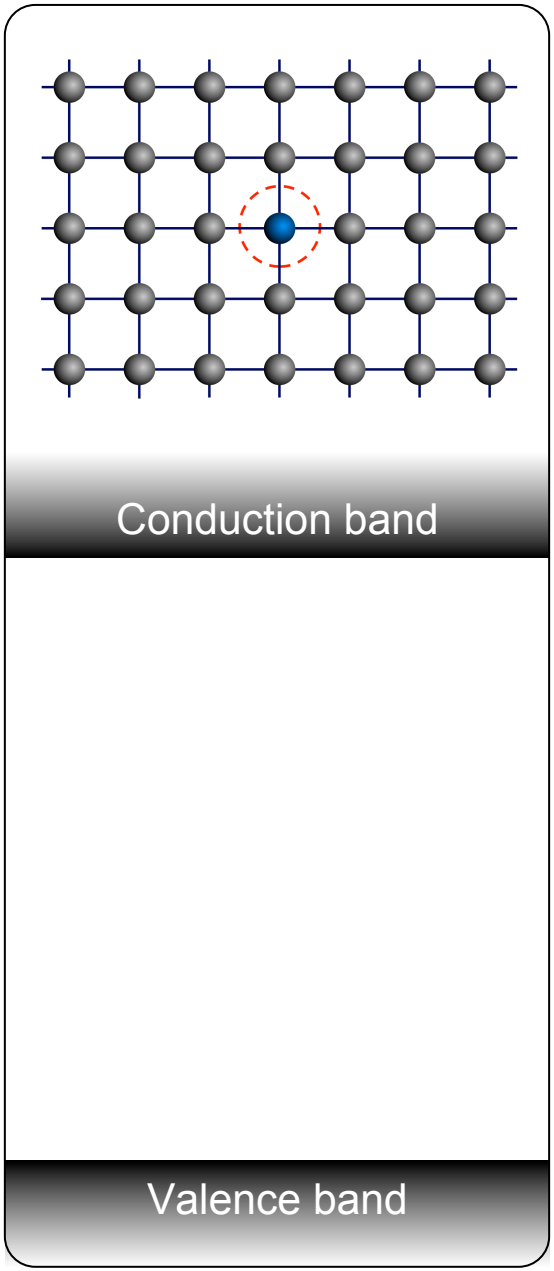


Defects in semiconductors

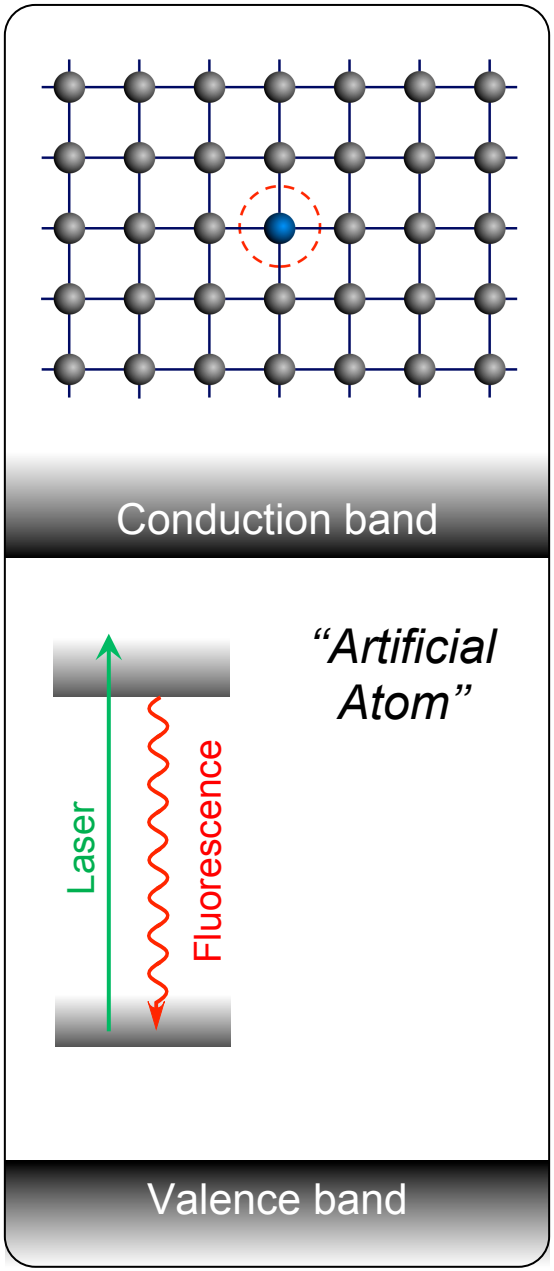




Deep defects in wide-bandgap materials

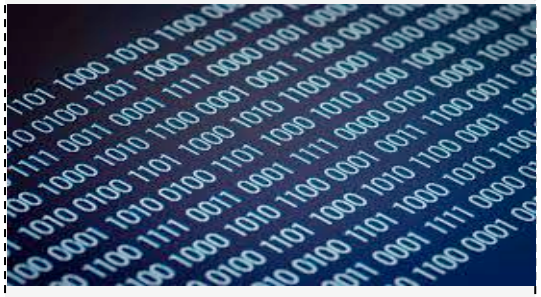


Deep defects in wide-bandgap materials

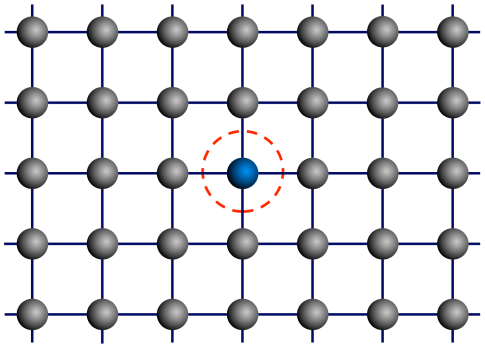


Deep defects in wide-bandgap materials

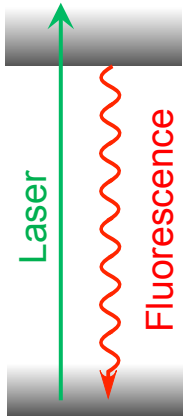
Single Photon Source



- Quantum cryptography
- Single photon interference



Conduction band

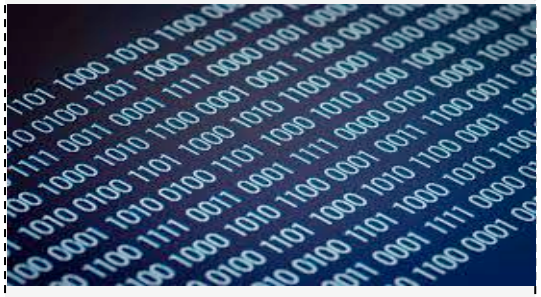


"Artificial Atom"

Valence band

Deep defects in wide-bandgap materials

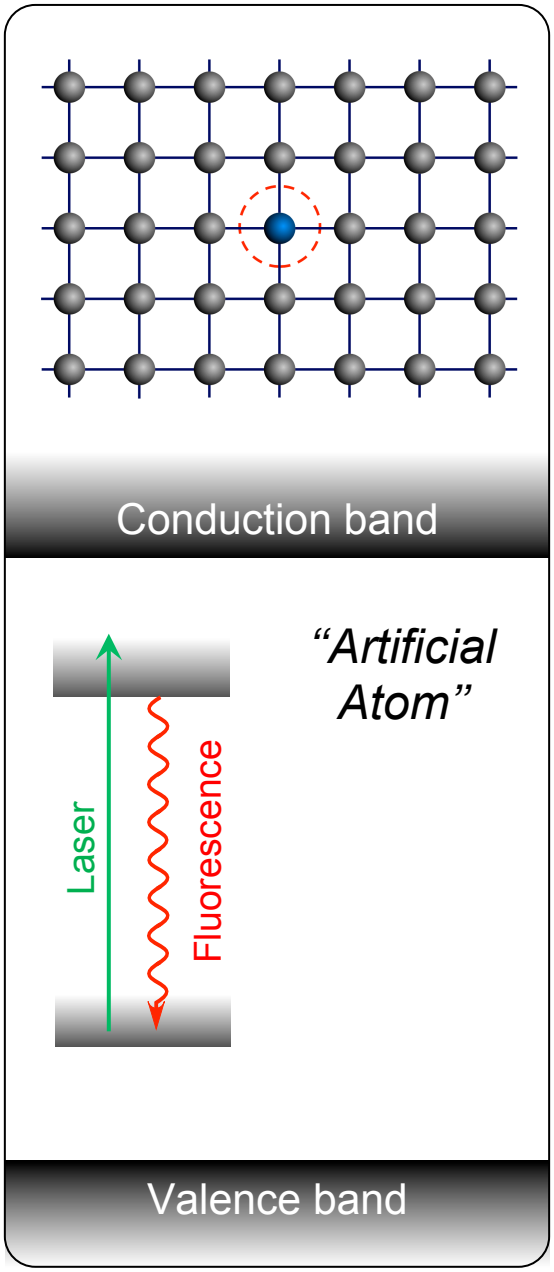
Single Photon Source



- Quantum cryptography
- Single photon interference

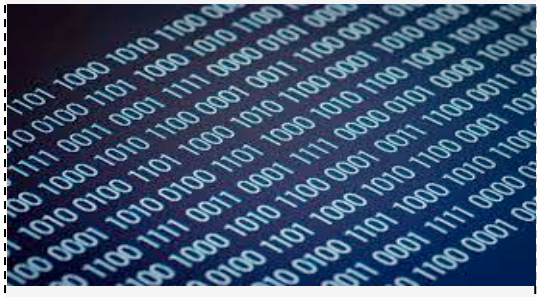
Fluorescent Biomarkers

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



Deep defects in wide-bandgap materials

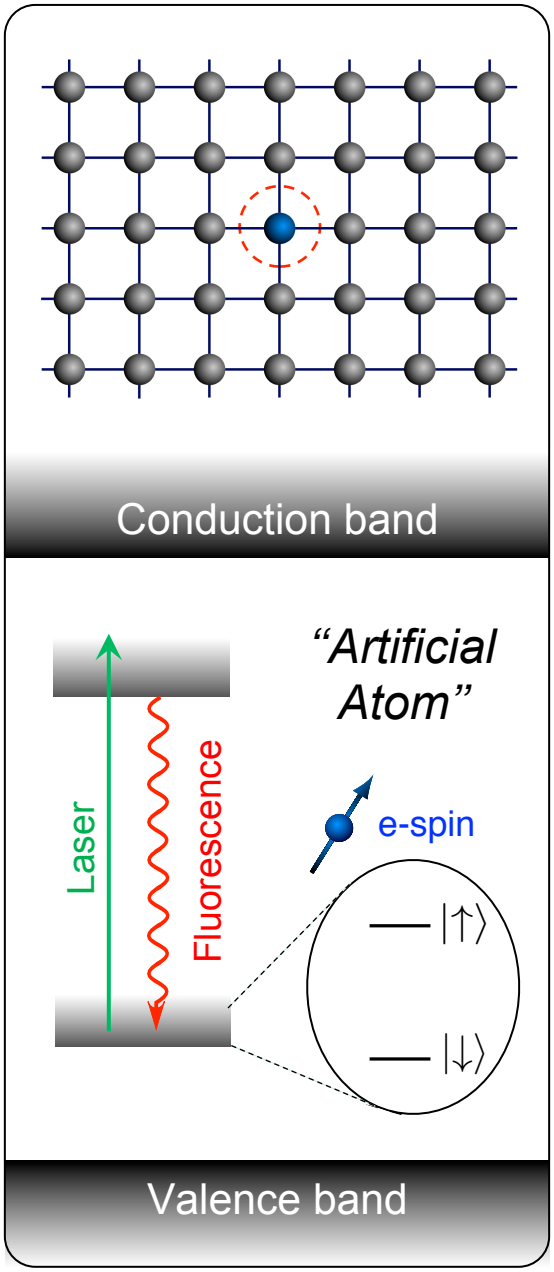
Single Photon Source



- Quantum cryptography
- Single photon interference

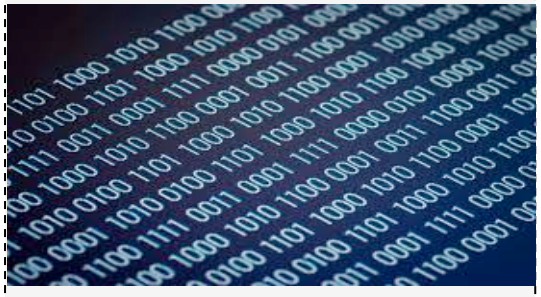
Fluorescent Biomarkers

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



Deep defects in wide-bandgap materials

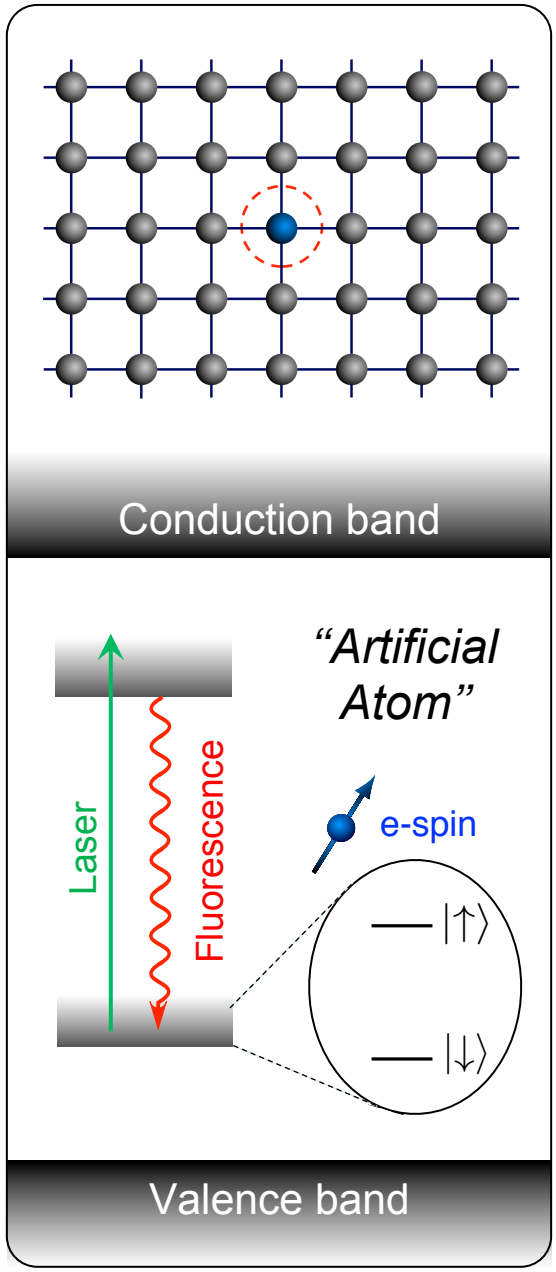
Single Photon Source



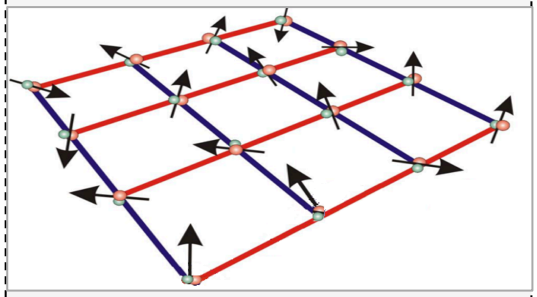
- Quantum cryptography
- Single photon interference

Fluorescent Biomarkers

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

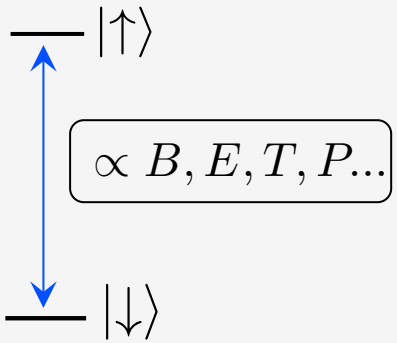


Quantum Information



- Spin physics
- Spin/photon interface

Quantum sensing



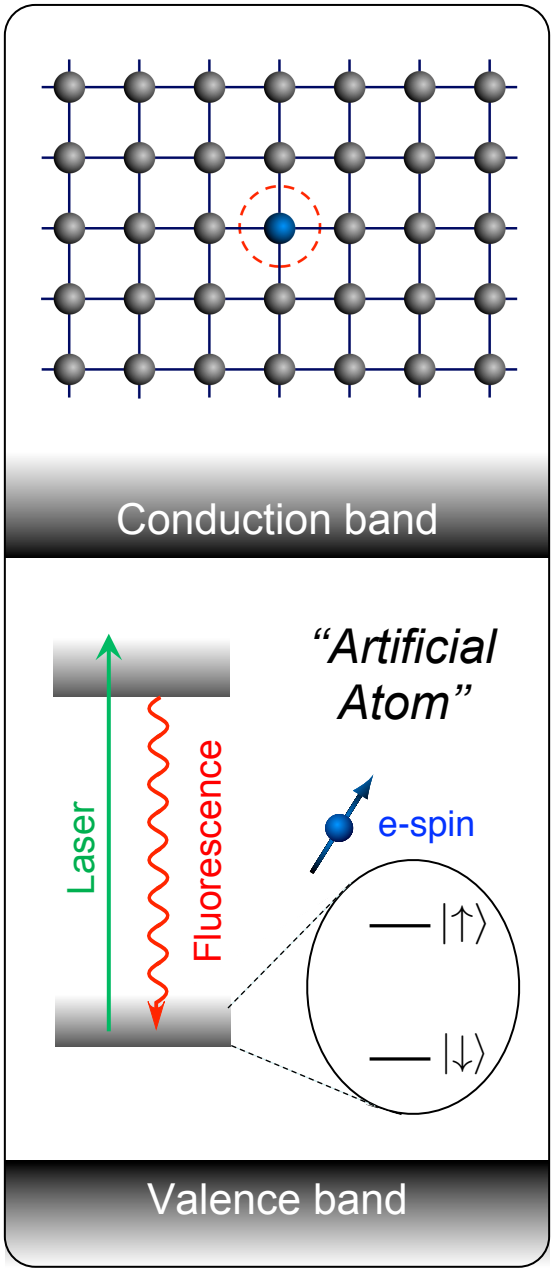
Deep defects in wide-bandgap materials

Single Photon Source

- Quantum cryptography
- Single photon interference

Fluorescent Biomarkers

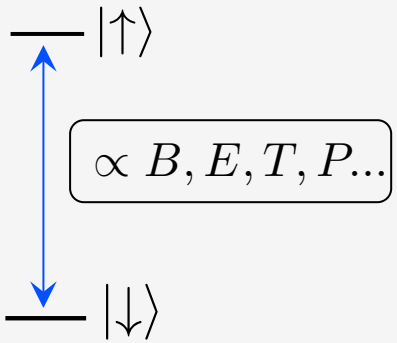
Mohan, *Nano Lett.* **10**, 3692 (2010)



Quantum Information

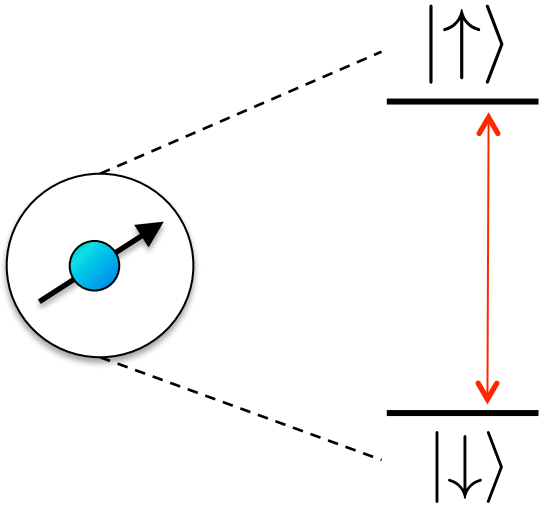
- Spin physics
- Spin/photon interface

Quantum sensing

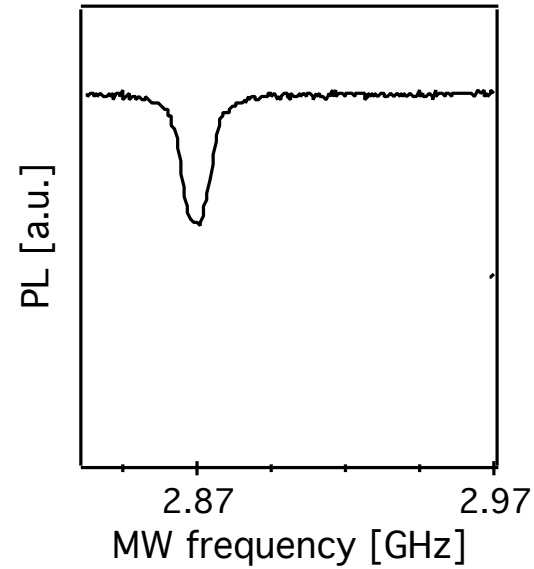


Magnetic field sensing with a single spin

Single e-spin

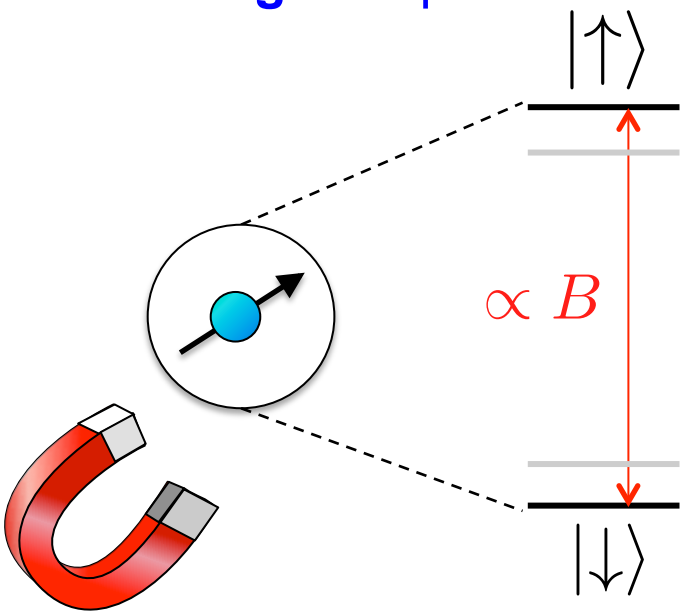


Electron Spin Resonance (ESR)

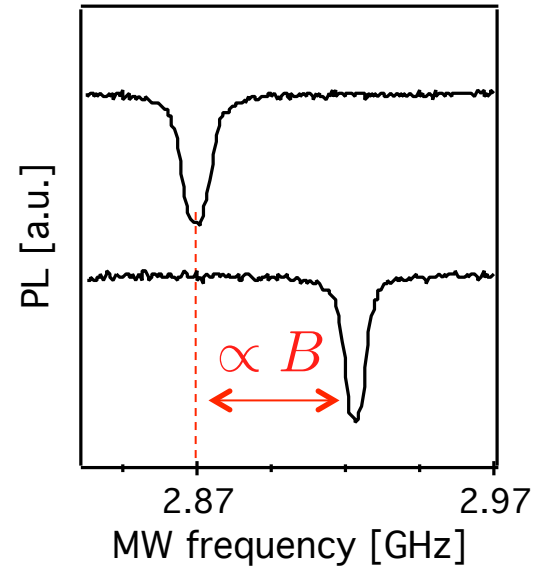


Magnetic field sensing with a single spin

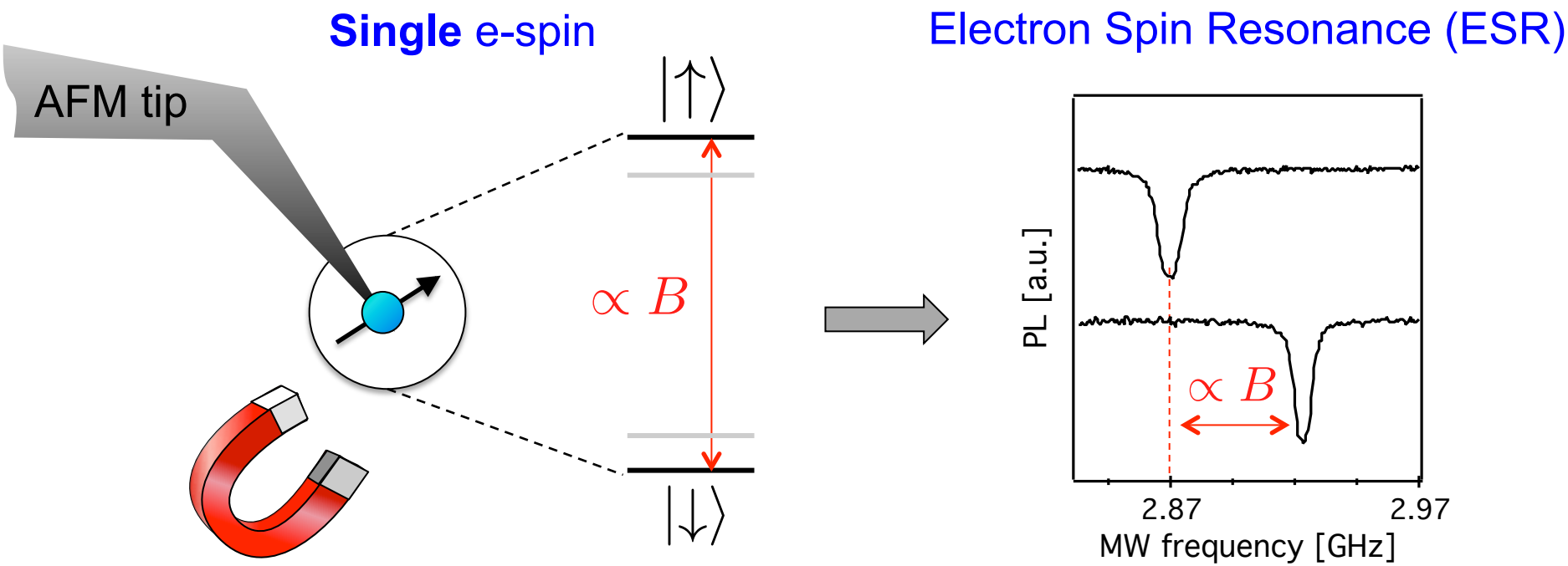
Single e-spin



Electron Spin Resonance (ESR)



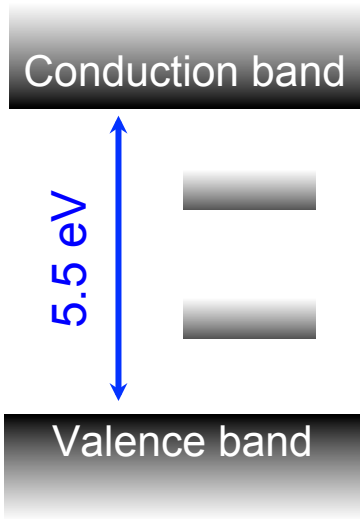
Magnetic field **imaging** with a single spin



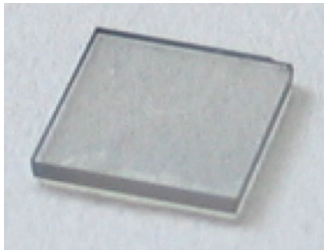
Seminal proposal: Chernobrod and Berman
"Spin microscope based on optically detected magnetic resonance"
J. Appl. Phys. **97** 014903 (2005).

Can be realized with **NV defects in diamond**
Maze, *Nature* (2008), Balasubramanian, *Nature* (2008)

Diamond for quantum technologies

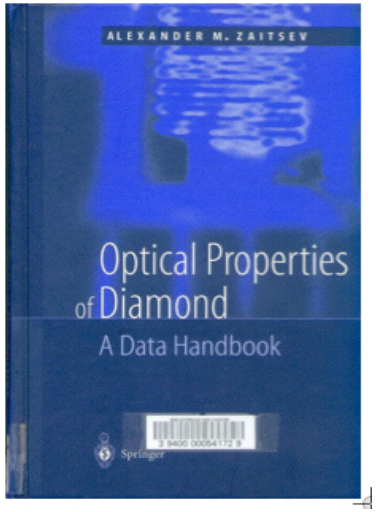


A *"perfect"* diamond would not absorb visible light…



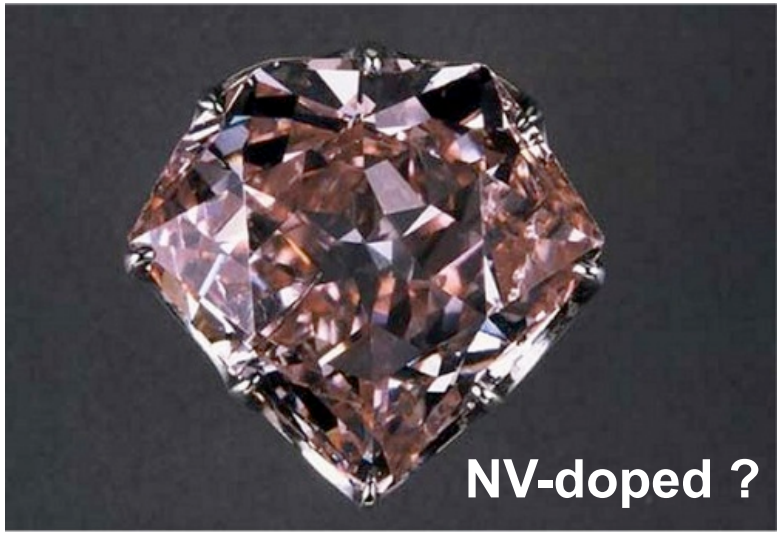
… but more than 500 defects are optically active

→ Color centers



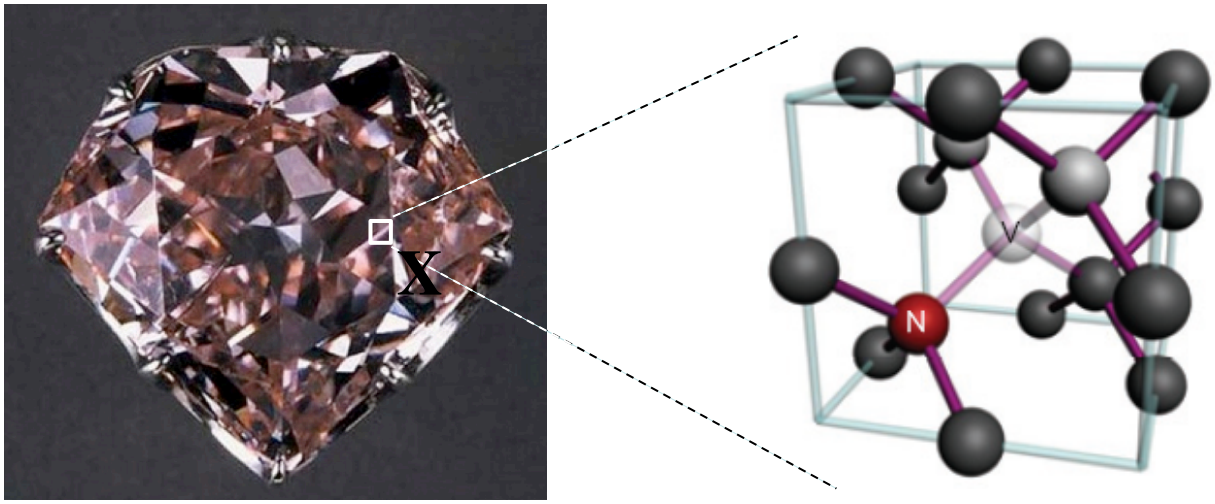
The « Hope » diamond
(Washington)

The « Hortensia » diamond
(Louvre, Paris)



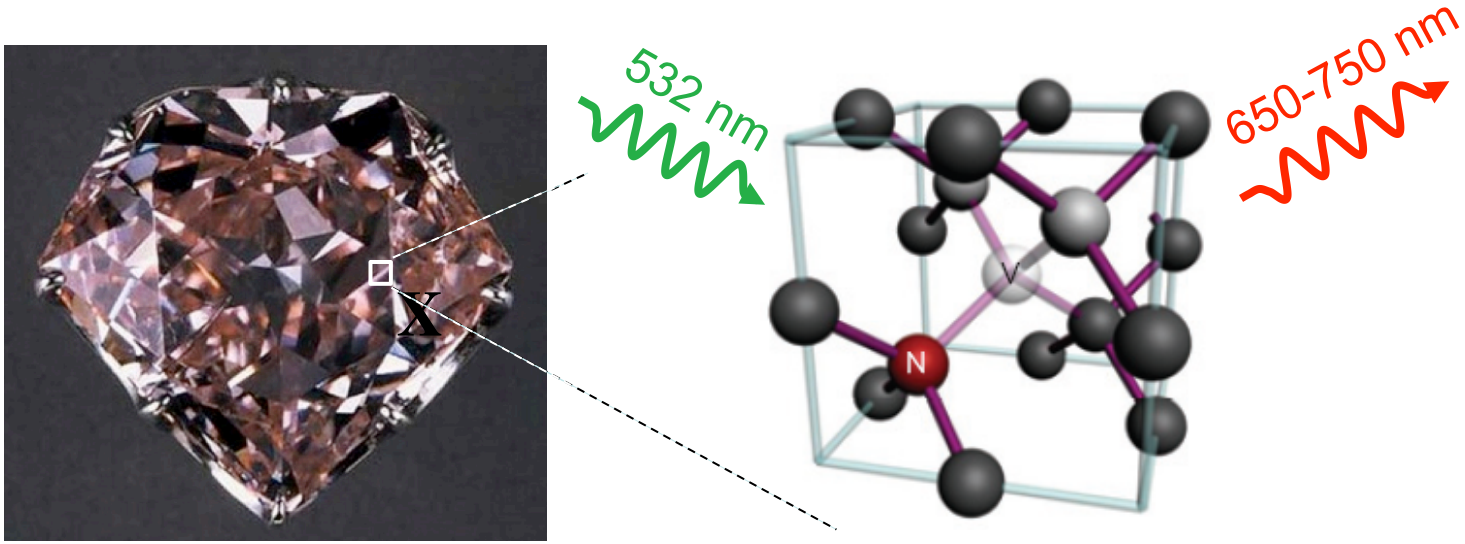
Nitrogen-Vacancy (NV) defect in diamond

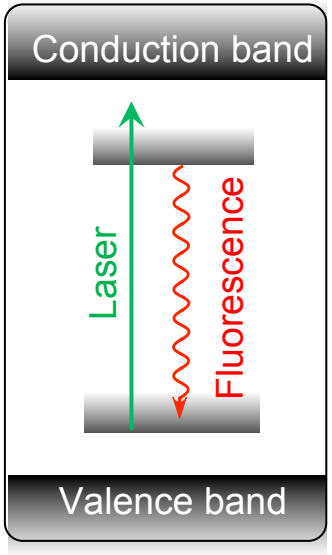
- An artificial atom *"nestled"* in the diamond lattice



Nitrogen-Vacancy (NV) defect in diamond

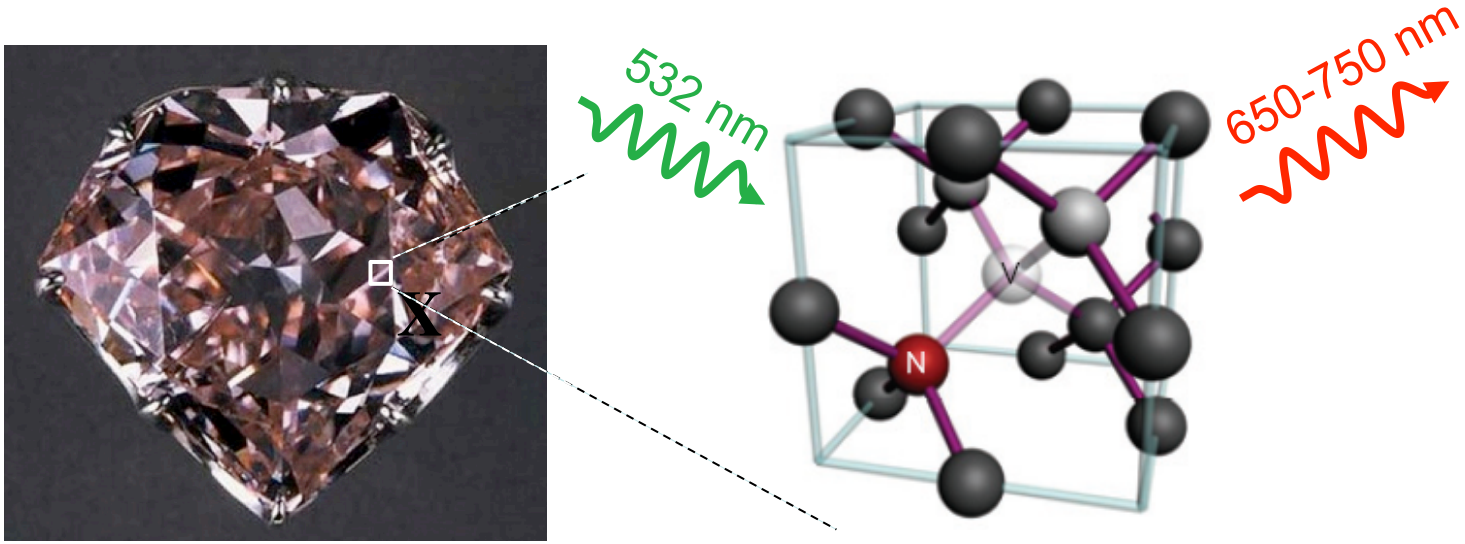
- An artificial atom *"nestled"* in the diamond lattice

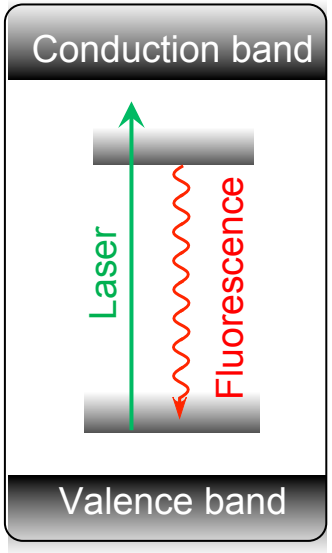




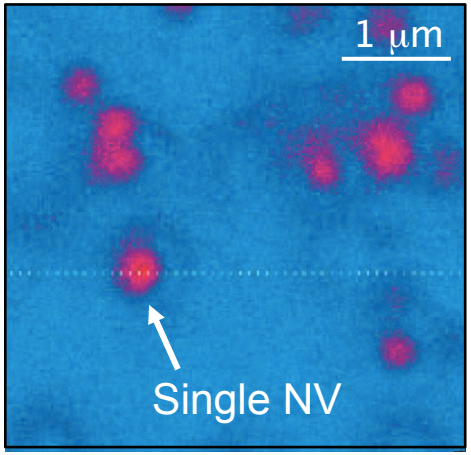
Nitrogen-Vacancy (NV) defect in diamond

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





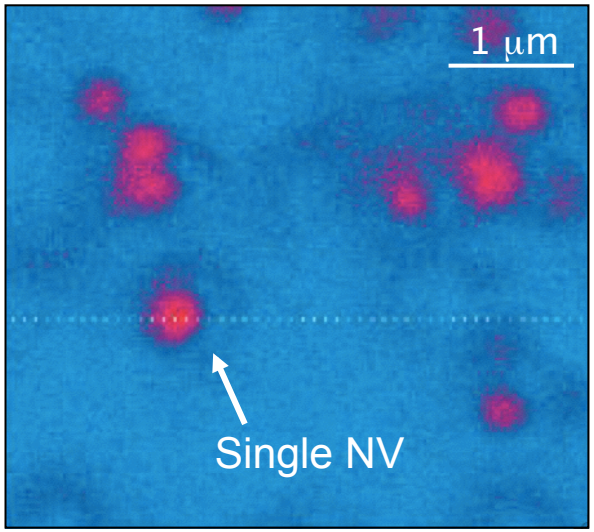
- Detection at the single emitter level **at room T –** *perfect photostability*



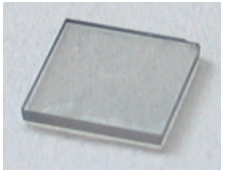
Gruber *et al.*, *Science* **276**, 2012 (1997)

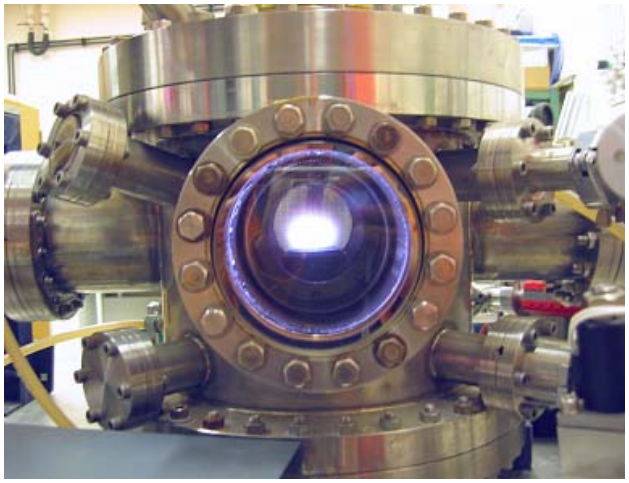
Engineering NV defect in diamond

1997



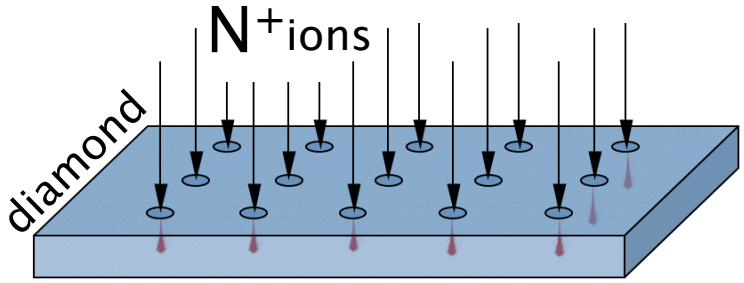
High purity diamond using **CVD growth**





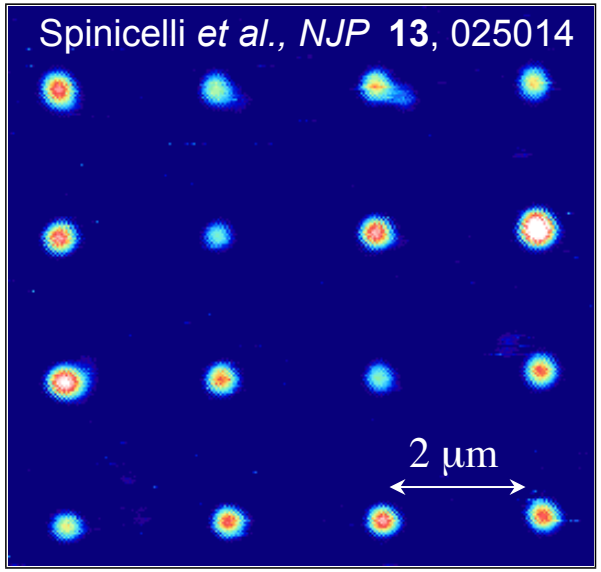
A. Tallaire and J. Achard (Villetaneuse)

NV defect engineering through **nanoscale ion implantation**



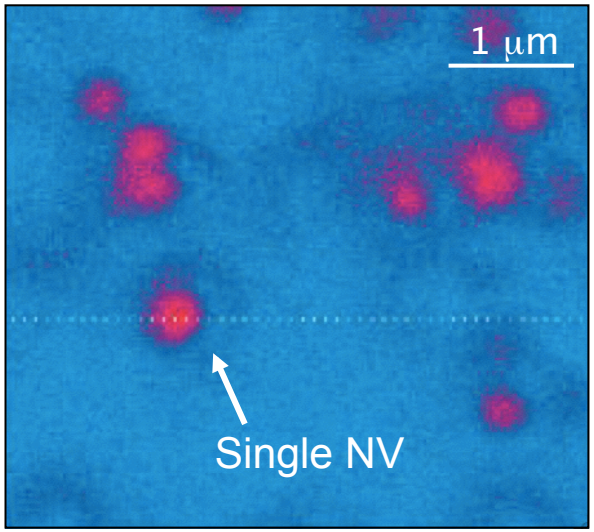
Meijer group (Leipzig)

2012

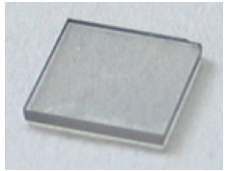


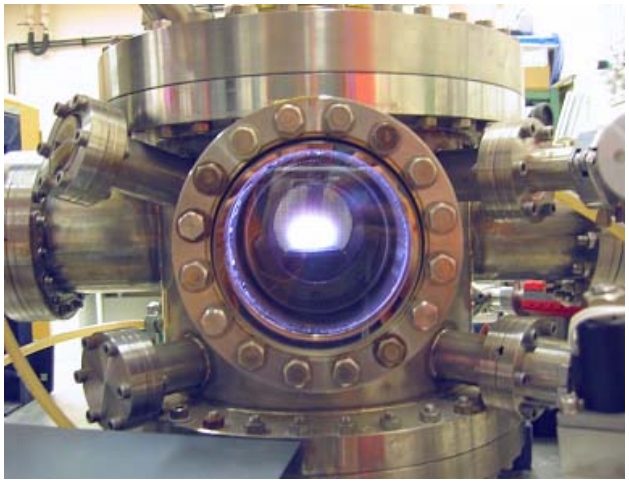
Engineering NV defect in diamond

1997

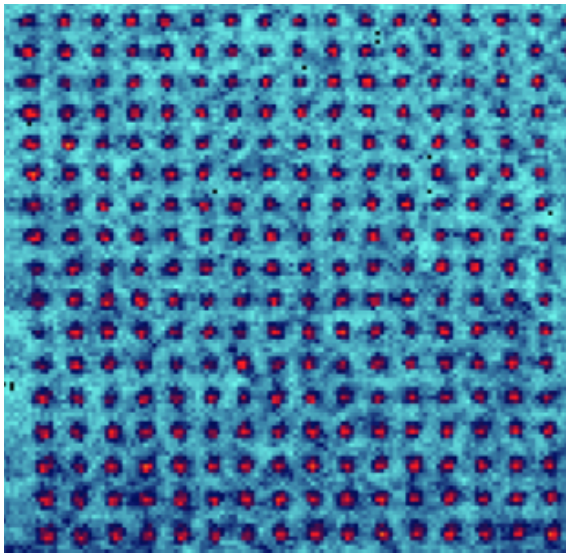


High purity diamond using **CVD growth**





A. Tallaire and J. Achard (Villetaneuse)



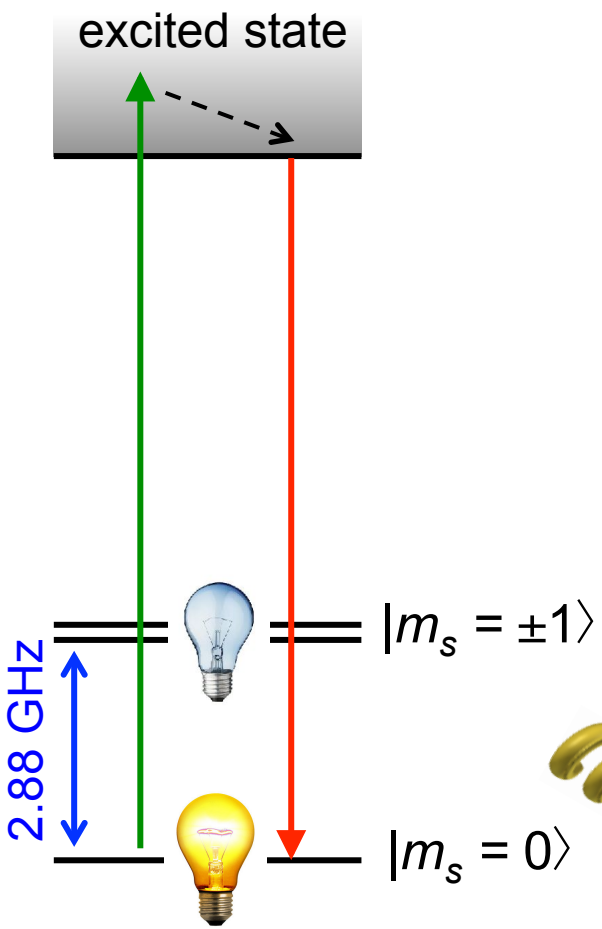
Lesik *et al., PSSA* **210,** 2055 (2013)

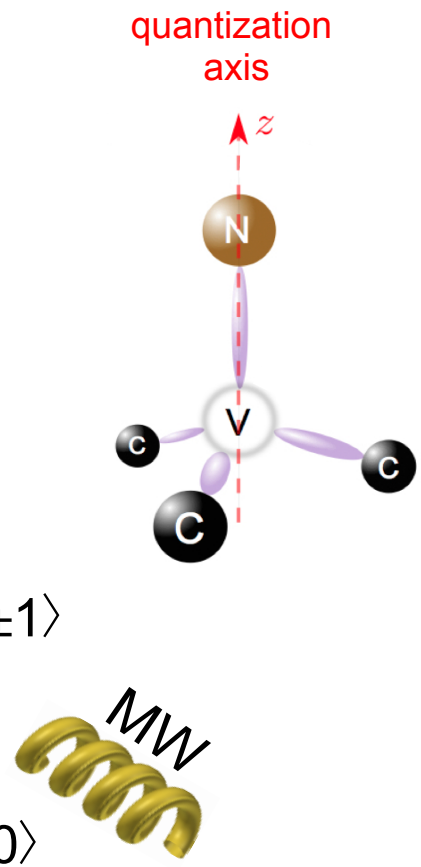
NANOSOLUTIONS by ORSAYPHYSICS

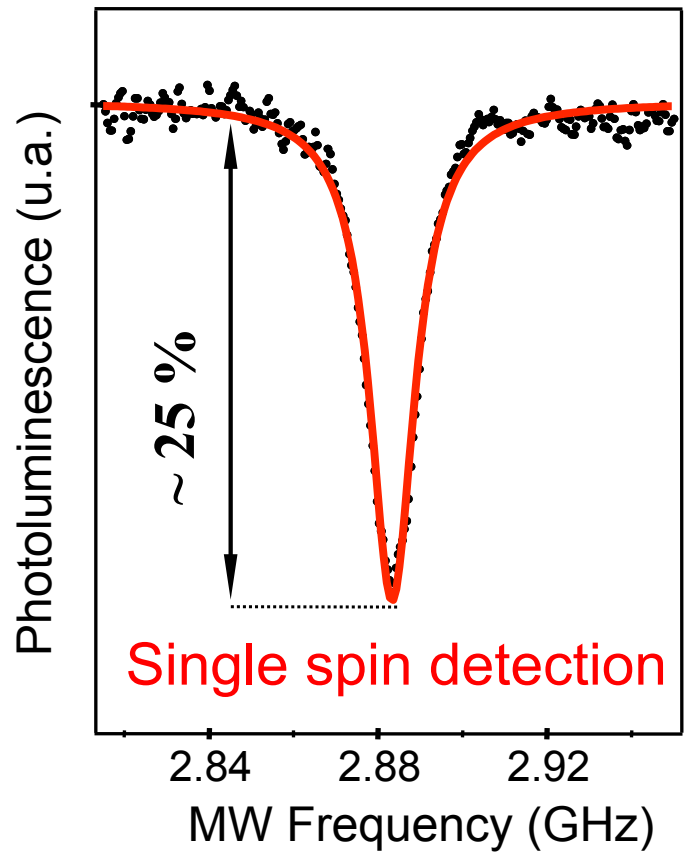
Focused Ion Beam (FIB) for nanoscale implantation of NV defects

Spin properties

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







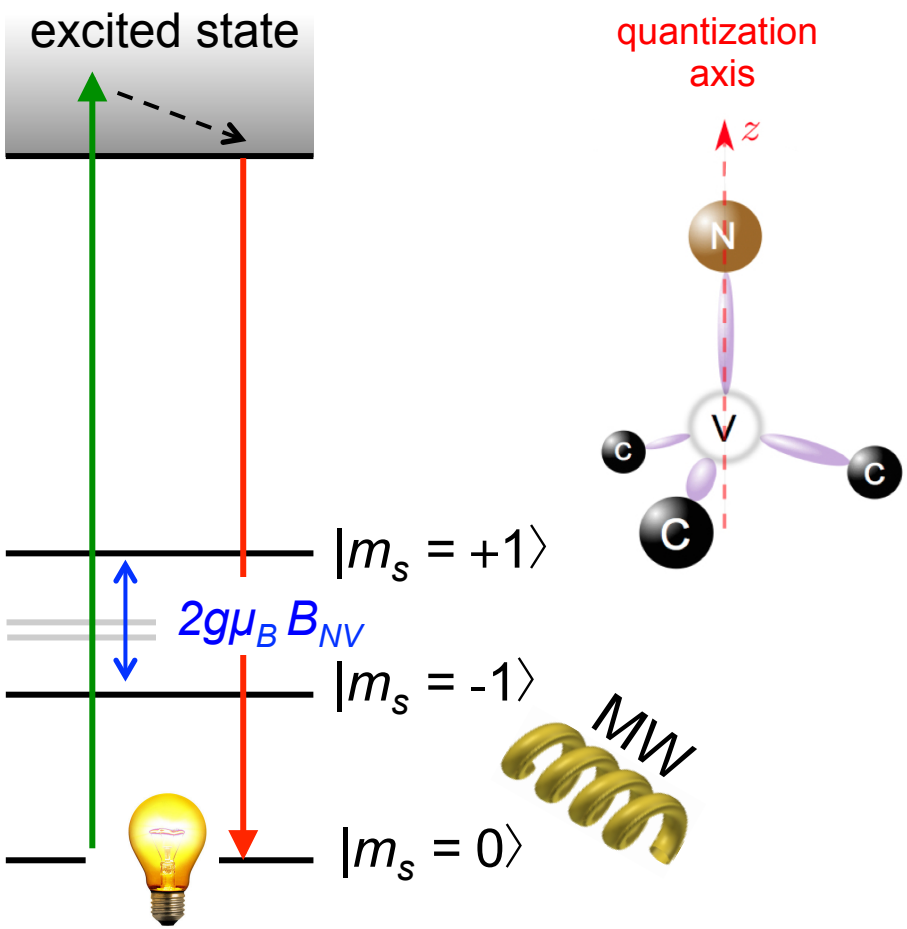
Spin-dependent fluorescence

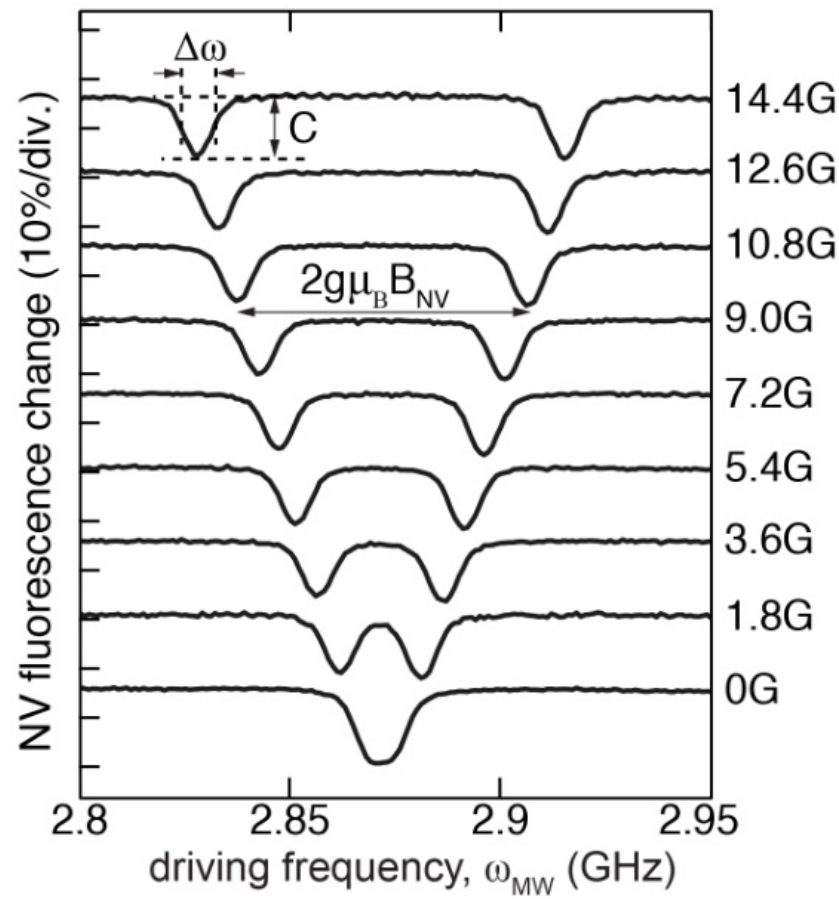
NV = e-spin qubit

Coherence time T_2 ~ms @ room T

Spin properties

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



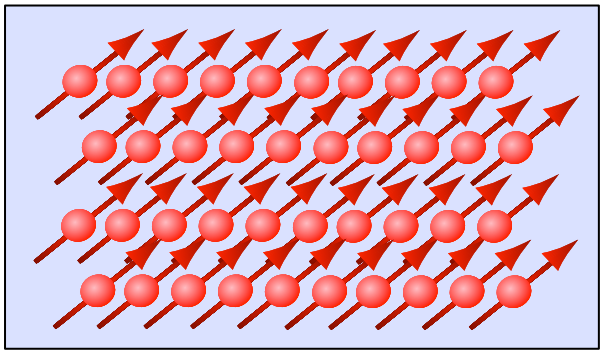


Spin-dependent fluorescence

NV defect
= magnetometer

Various experimental configurations

- Magnetic sensing with an ensemble of NV defect



Sensitivity

$$\eta \propto \frac{1}{C\sqrt{NRT_2^\star}}$$

ESR contrast

Number of NVs

Collection effciency

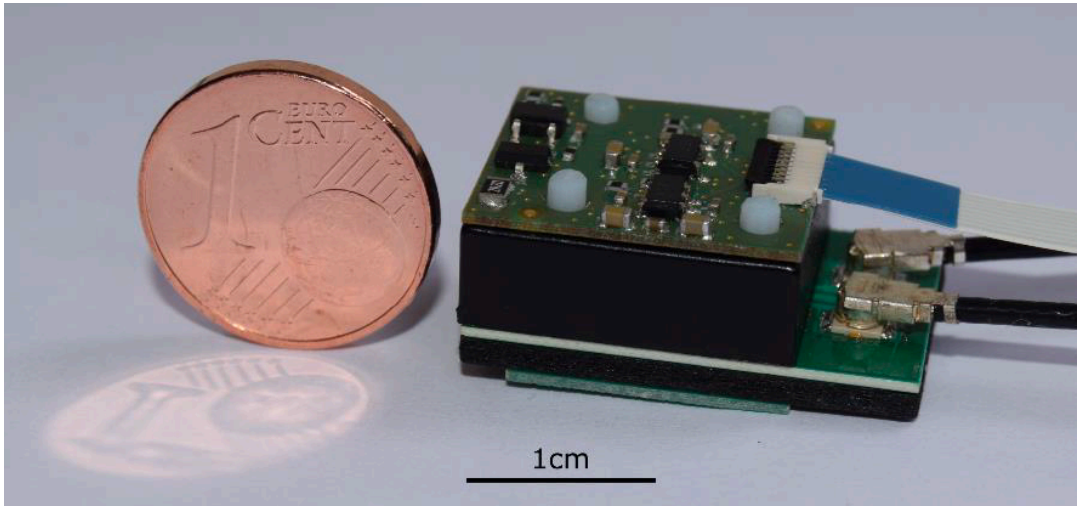
Coherence time

See recent review – arXiv:1903.08176

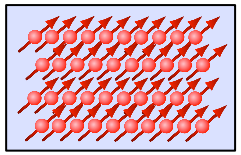
BOSCH

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

Sturnër, *DRM* (2019)

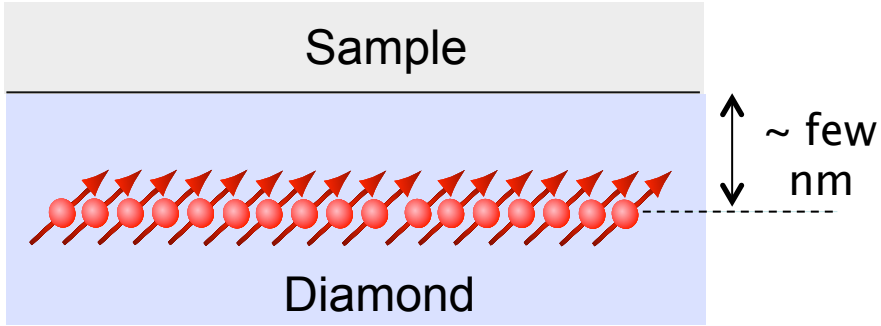


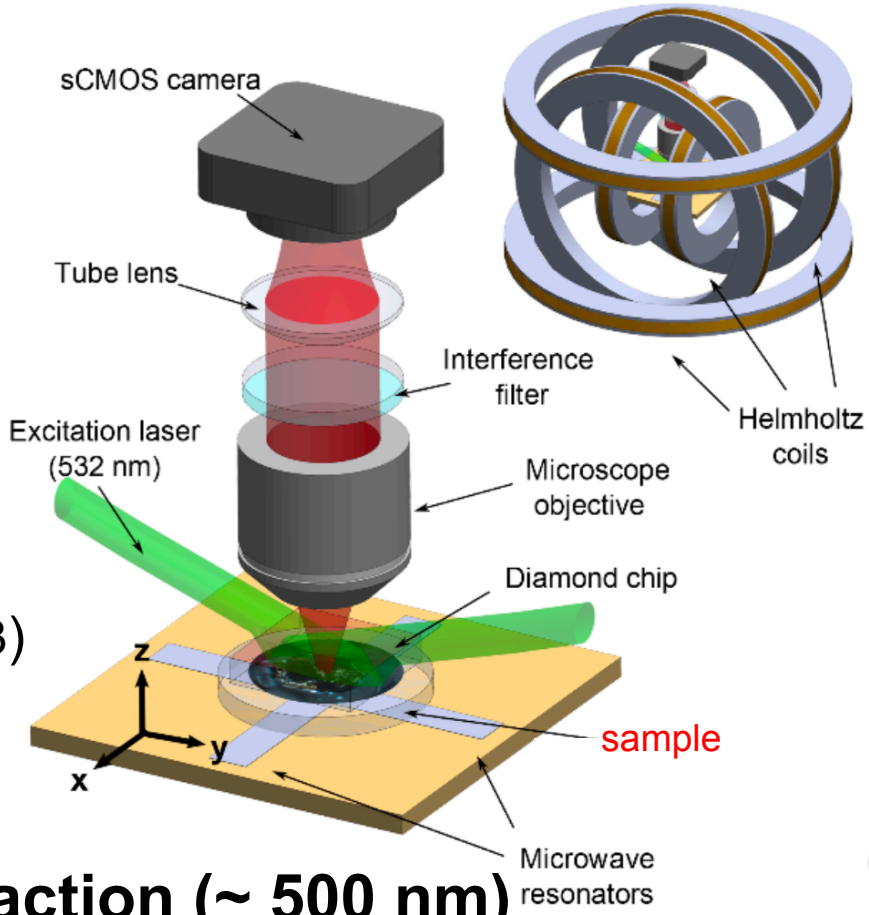
Various experimental configurations



- Magnetic sensing with an ensemble of NV defects
- Magnetic **imaging** with an ensemble of NV defect

requires NV-doped layers close to the surface





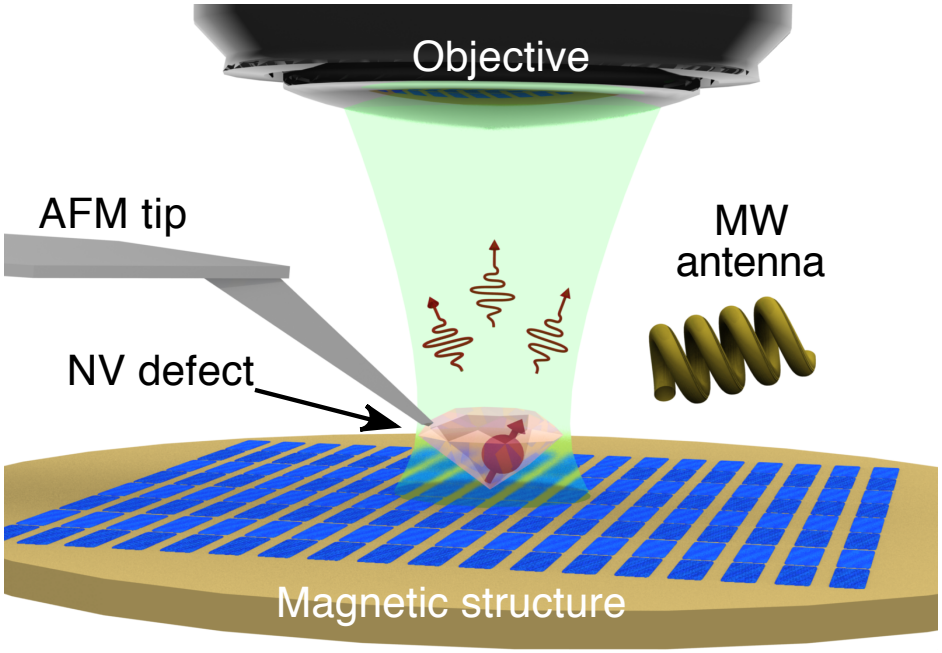
Some applications

- Paleomagnetism – Fu, Science (2014)
- Biomagnetism - Le Sage, Nature (2013)
- MRI – Glenn, Nature (2018)
- Neuron activity - Barry, PNAS (2016)

Spatial resolution limited by diffraction (~ 500 nm)

Scanning-NV magnetometry

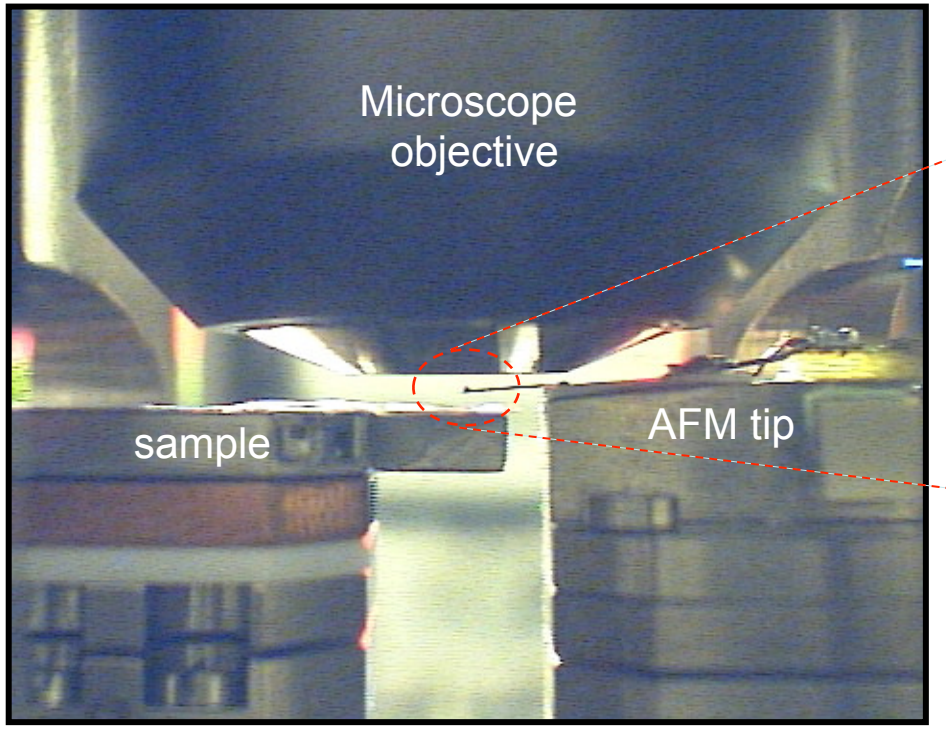
Related works
Harvard, Basel, Stuttgart, Ulm, ETHZ, UCSB…



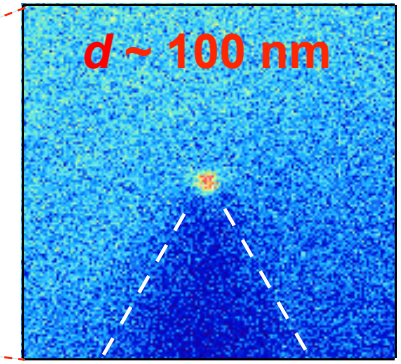
- ★ Quantitative and vectorial (sensitivity - **1 μT/Hz$^{-1/2}$**)
- ★ No magnetic back-action
- ★ Operation from 4K to 300K
- ★ Spatial resolution limited by the probe-to-sample distance ***d***

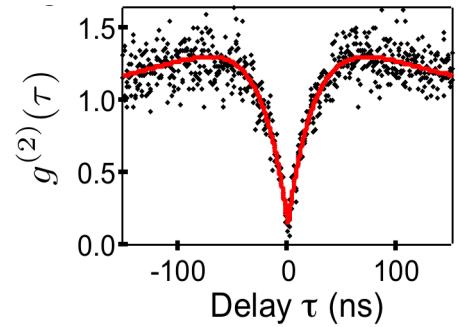
Scanning-NV magnetometry

Related works
Harvard, Basel, Stuttgart, Ulm, ETHZ, UCSB…



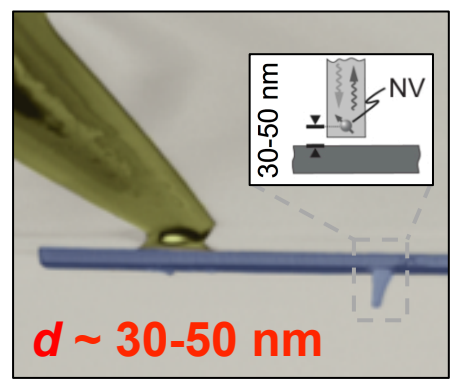
First experiments with nanodiamonds

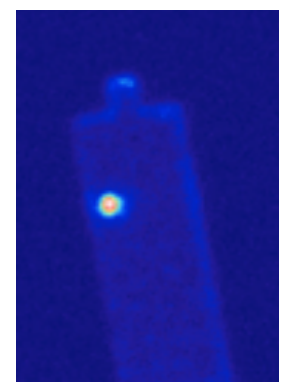




Rondin, *APL* (2012), *Nat Com.* (2013)

All-diamond scanning probe tips

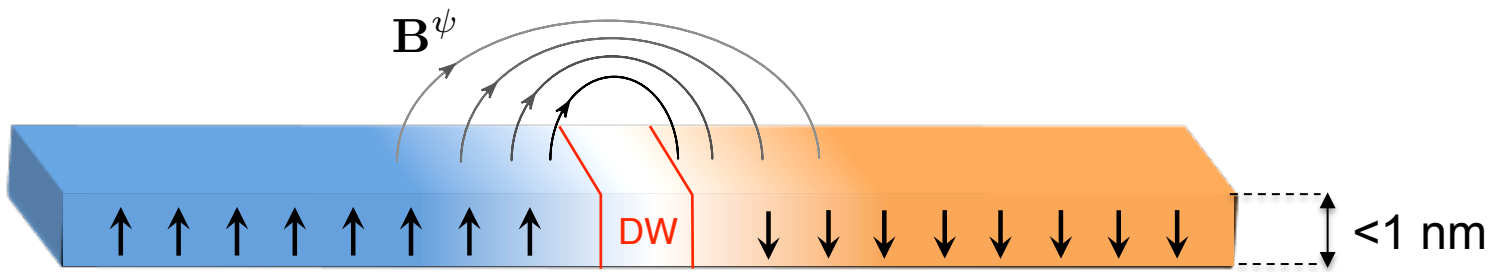




Commercially available since 2018

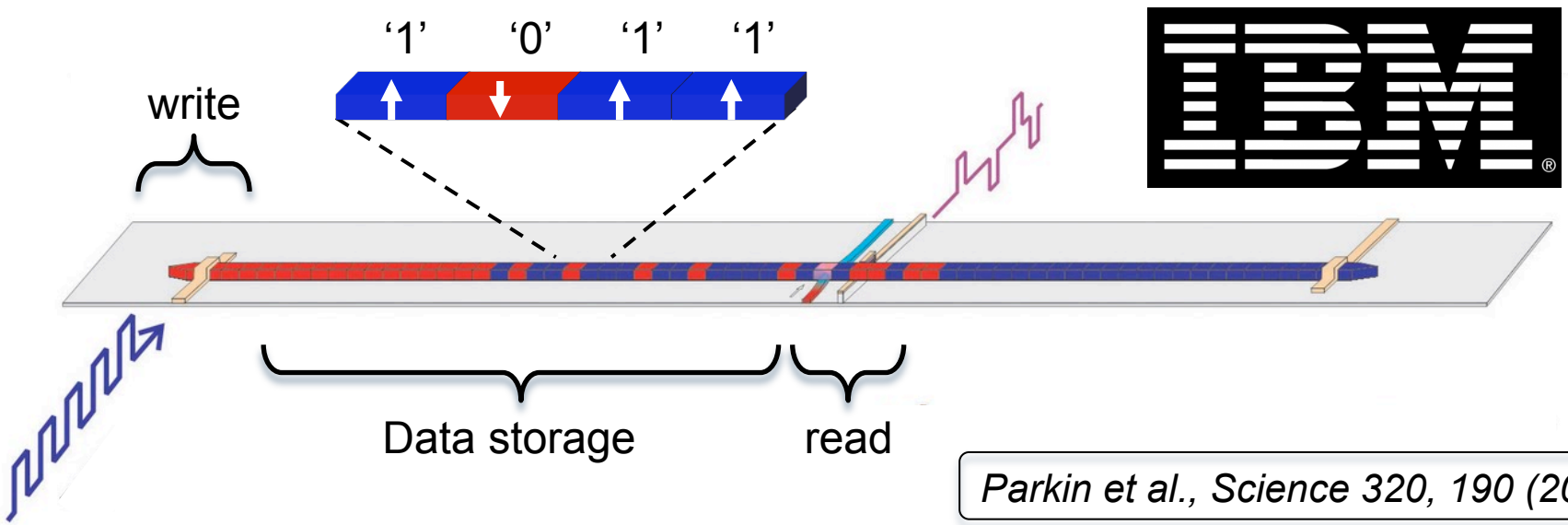
- ★ Quantitative and vectorial (sensitivity - **1 μT/Hz$^{-1/2}$**)
- ★ No magnetic back-action
- ★ Operation from 4K to 300K
- ★ Spatial resolution limited by the probe-to-sample distance ***d***

Physics of spin textures in ultrathin ferromagnets



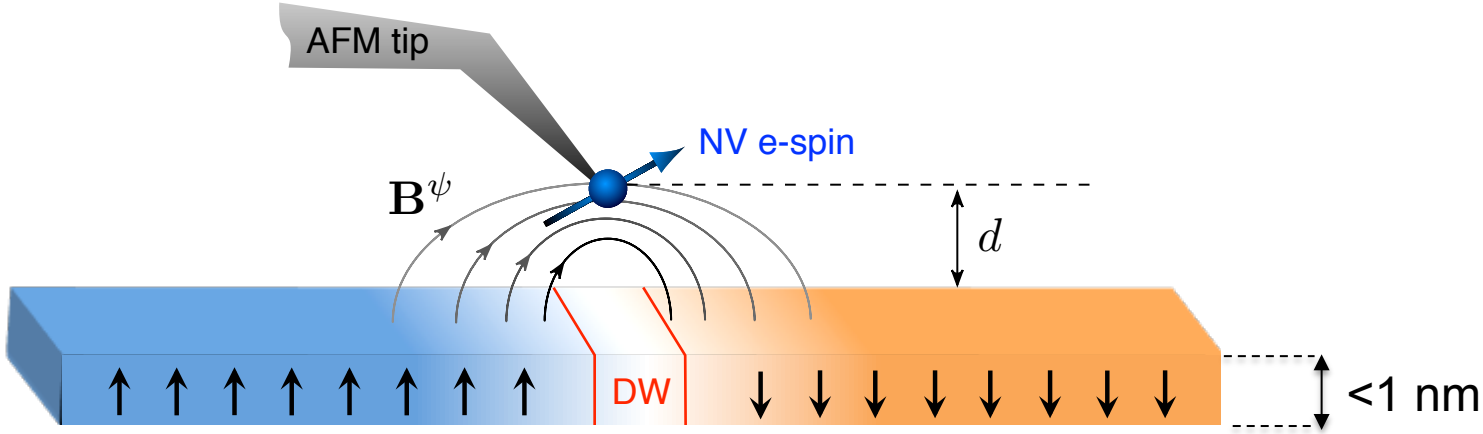
Applications for a new generation of spintronic devices

e. g. *:* the domain wall (DW) "racetrack memory"



Parkin et al., Science 320, 190 (2008)

Physics of spin textures in ultrathin ferromagnets

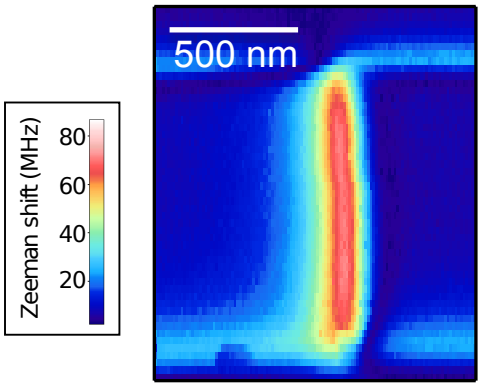


Thermal jumps of domain walls

Tetienne, *Science* (2014)

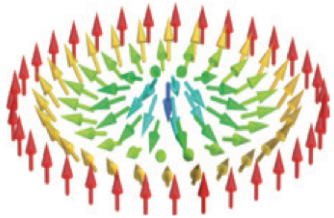
DW inner structure

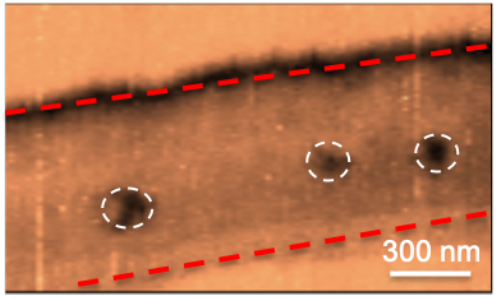
Bloch vs Néel



Tetienne, *Nat. Comm.* (2015)

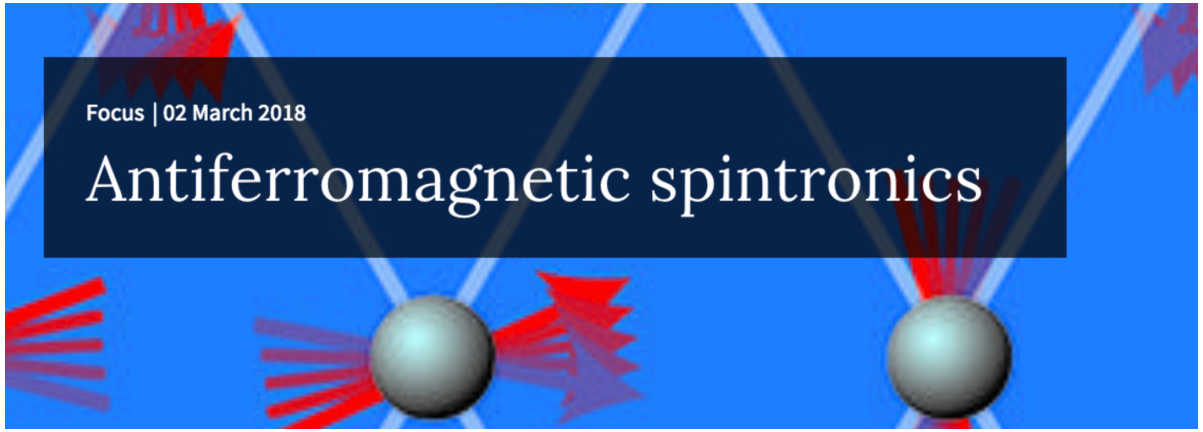
From DW to skyrmions

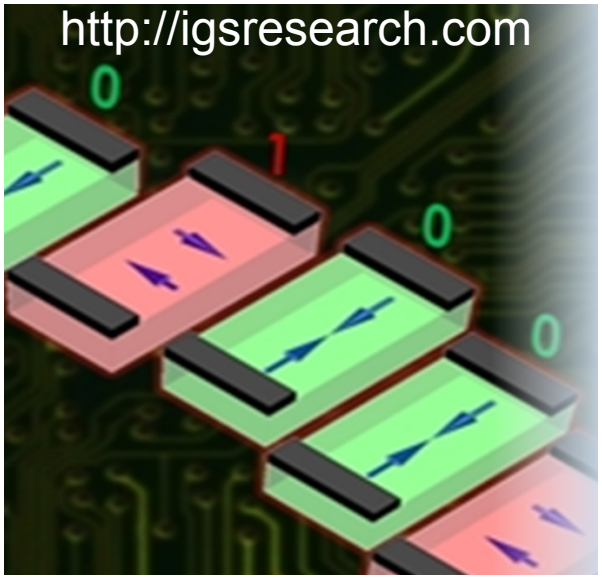




Emerging field of antiferromagnetic spintronics

Special focus, Nature Physics (2018)





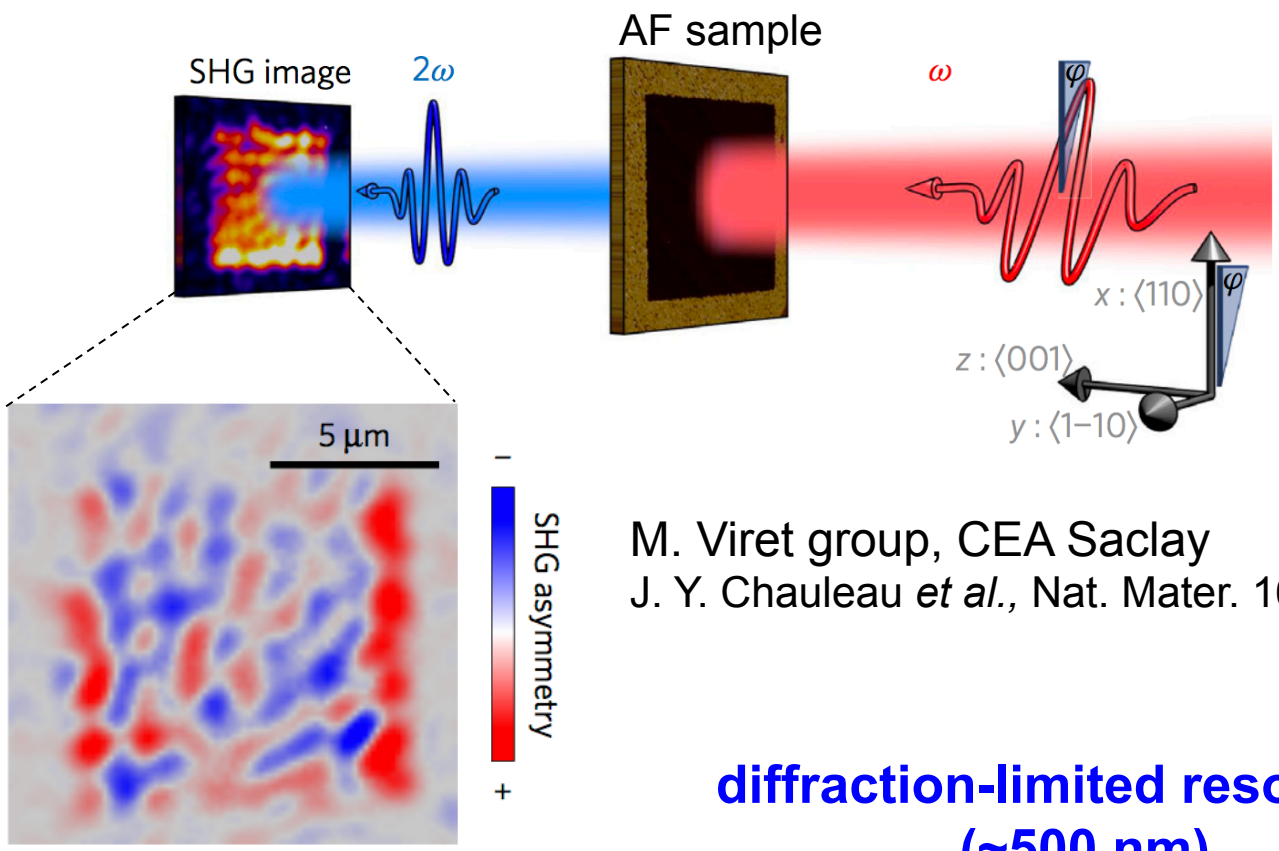
- Higher switching frequency (*THz vs GHz for ferromagnets*)
- Almost no magnetic field generated,
  - Highly stable devices
  - No cross-talk between neighboring cells (high density device)

Imaging spin textures in antiferromagnets (AFs)

Second Harmonic Generation (SHG) microscopy

Fiebig *et al., JOSA B* **22**, 96-118 (2005) – review paper

A recent example



AF domains in highly strained BFO

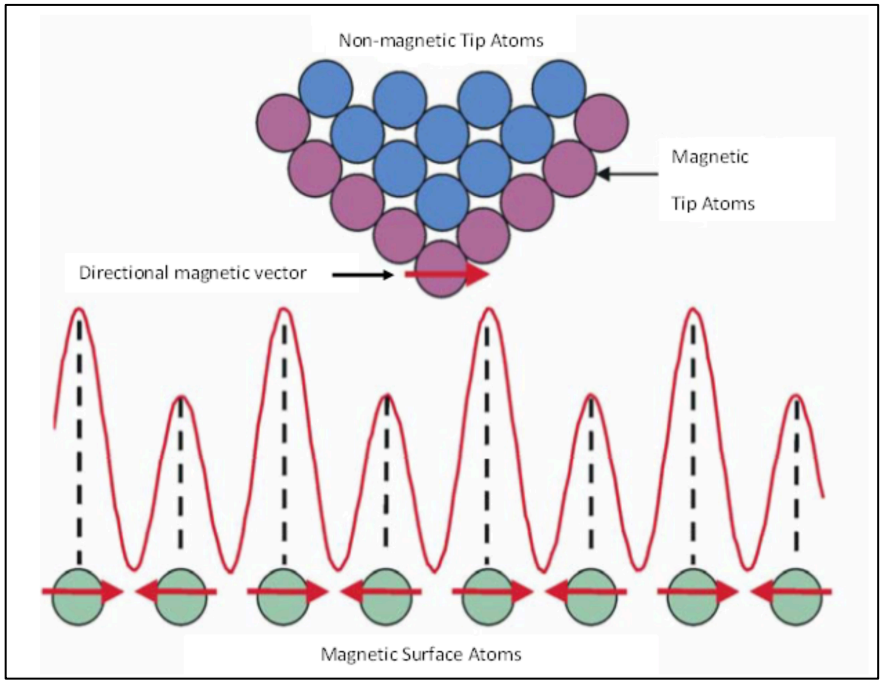
M. Viret group, CEA Saclay
J. Y. Chauleau *et al.,* Nat. Mater. 16, 803 (2017)

diffraction-limited resolution (~500 nm)

Imaging spin textures in antiferromagnets (AFs)

Spin-polarized STM

Wiesendanger, Rev. Mod. Phys. 81, 1495 (2009)

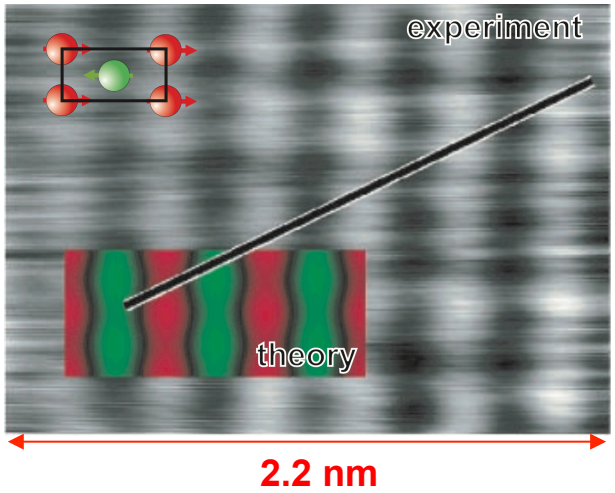


Atomic scale resolution!!!!!

…but limited to <u>conductive samples</u> and requires UHV conditions.

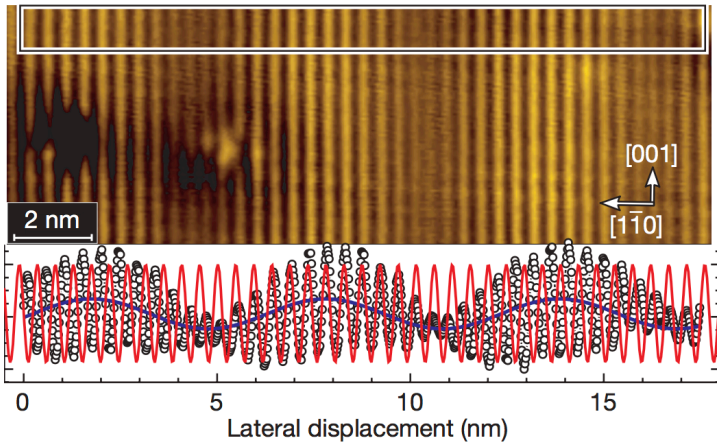
Mn monolayer on W(110)

Heinze, *Science* **288**, 1805 (2000)



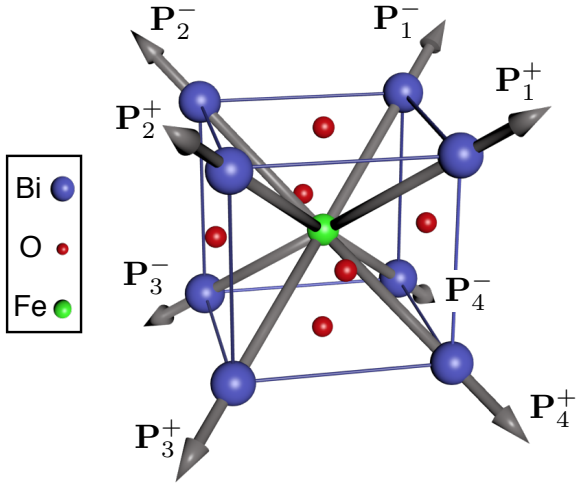
Cycloidal AF order

Bode, *Nature* **447**, 190 (2007)



Antiferromagnetic order in multiferroics

$BiFeO_3$: ferroelectricity….

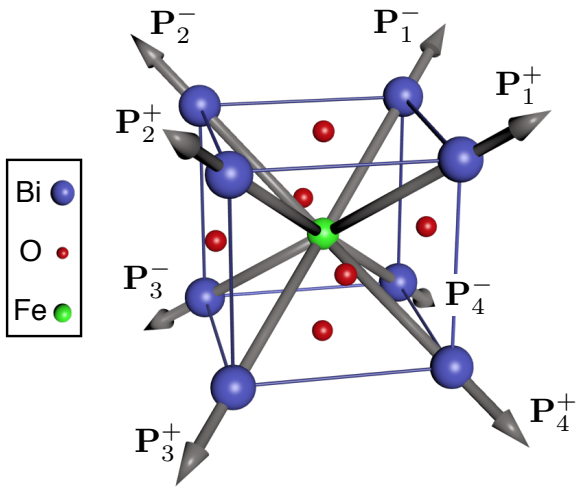


S. Fusil
V. Garcia
A. Barthélémy
M. Bibes

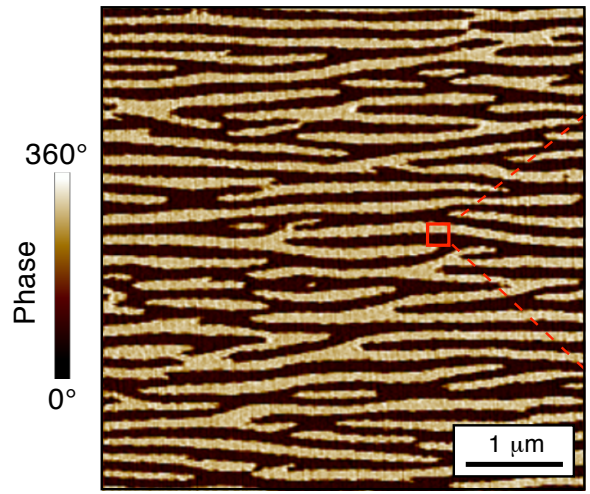
G. Catalan and J.F. Scott
Adv. Mater. **21,** 2463 (2009)

Antiferromagnetic order in multiferroics

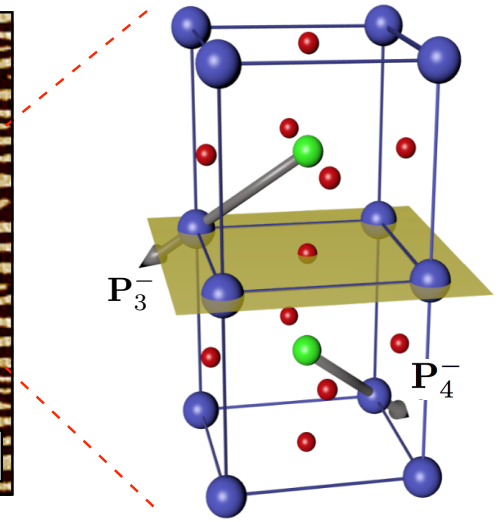
$BiFeO_3$: ferroelectricity….



PFM image
30-nm thick BFO film



71° Domain wall

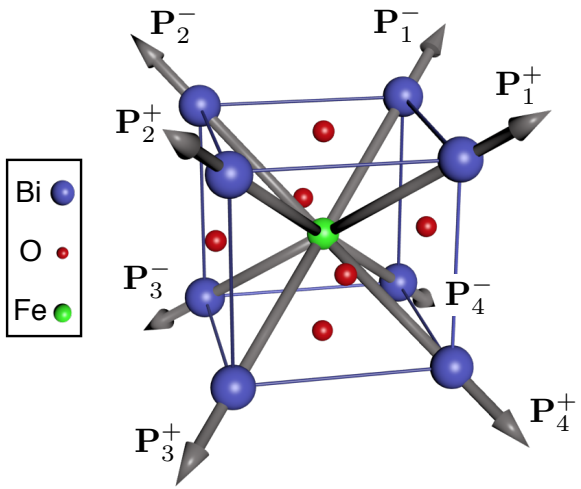


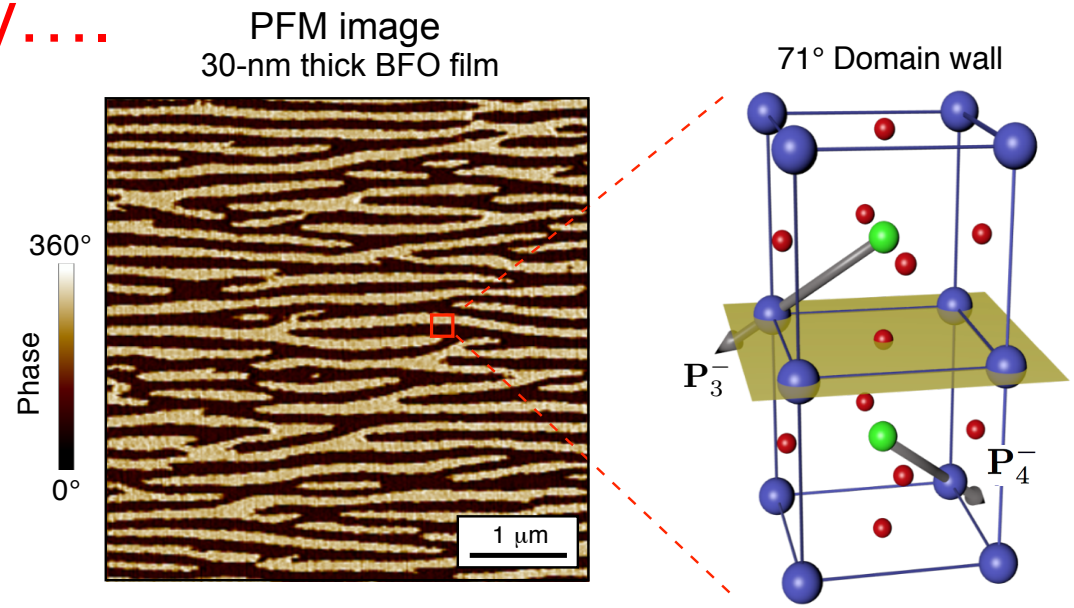
S. Fusil
V. Garcia
A. Barthélémy
M. Bibes

G. Catalan and J.F. Scott
Adv. Mater. **21,** 2463 (2009)

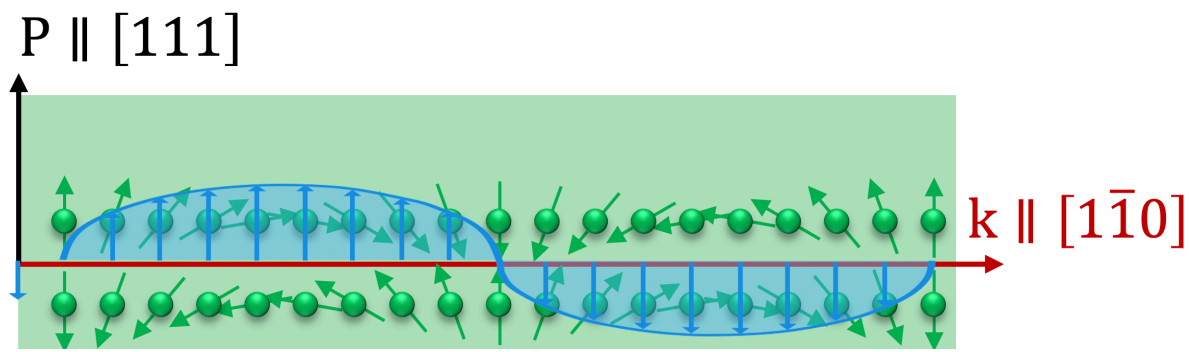
Antiferromagnetic order in multiferroics

$BiFeO_3$: ferroelectricity….





…+ antiferromagnetism @ 300 K

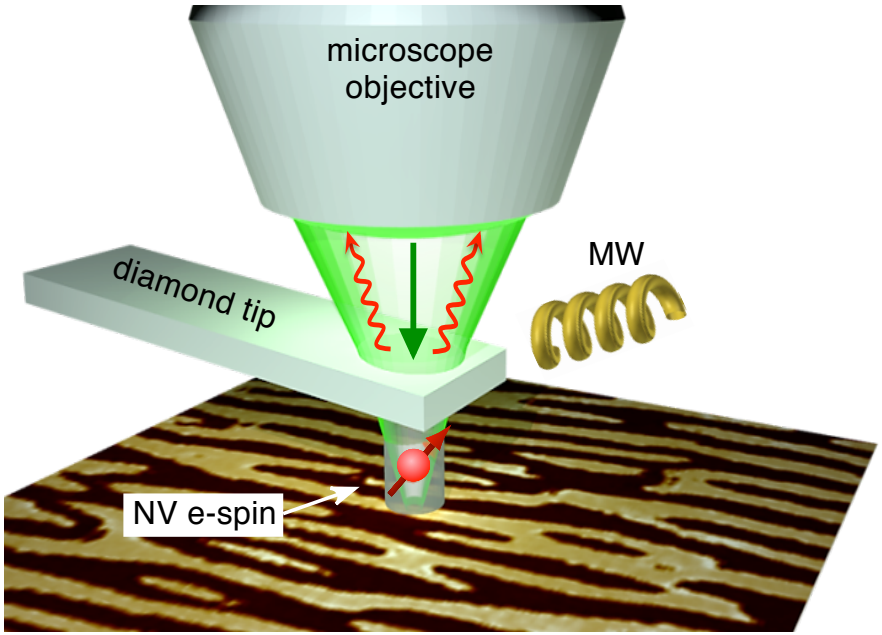


- Propagation direction **k** is perpendicular to the ferroelectric polarization vector **P**

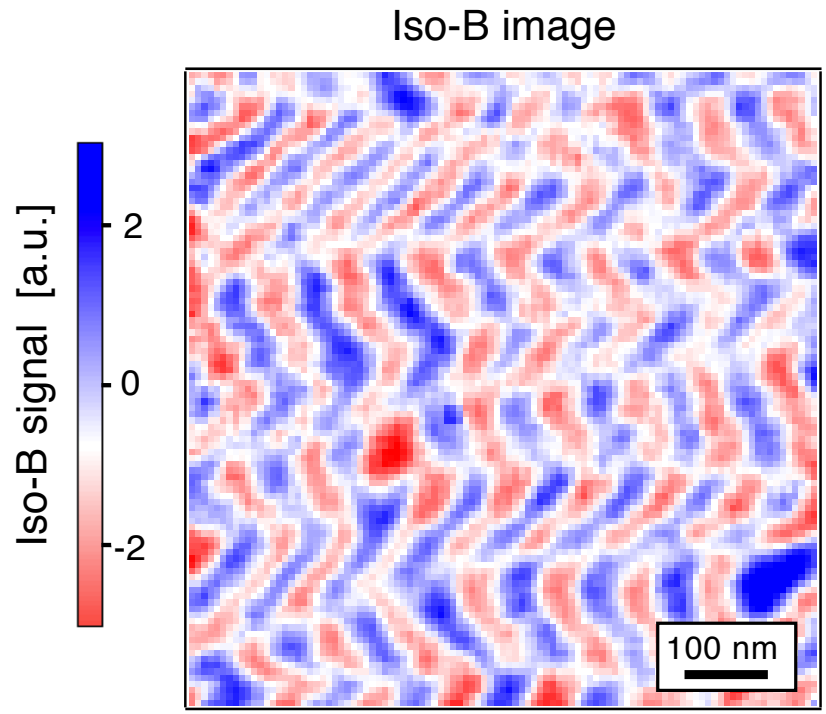
S. Fusil
V. Garcia
A. Barthélémy
M. Bibes

G. Catalan and J.F. Scott
Adv. Mater. **21,** 2463 (2009)

Imaging antiferromagnetic order in BFO

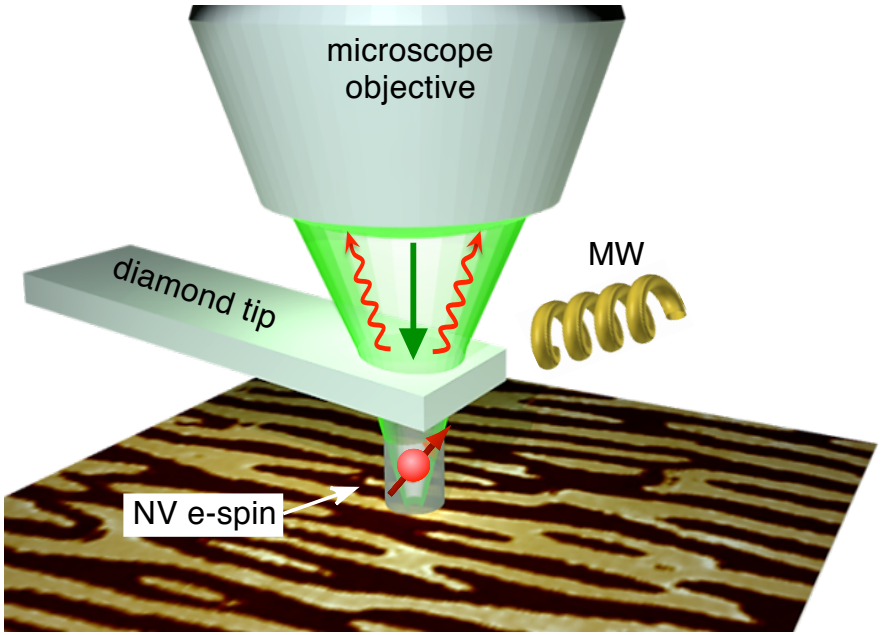


30 nm thick (001)-$BiFeO_3$

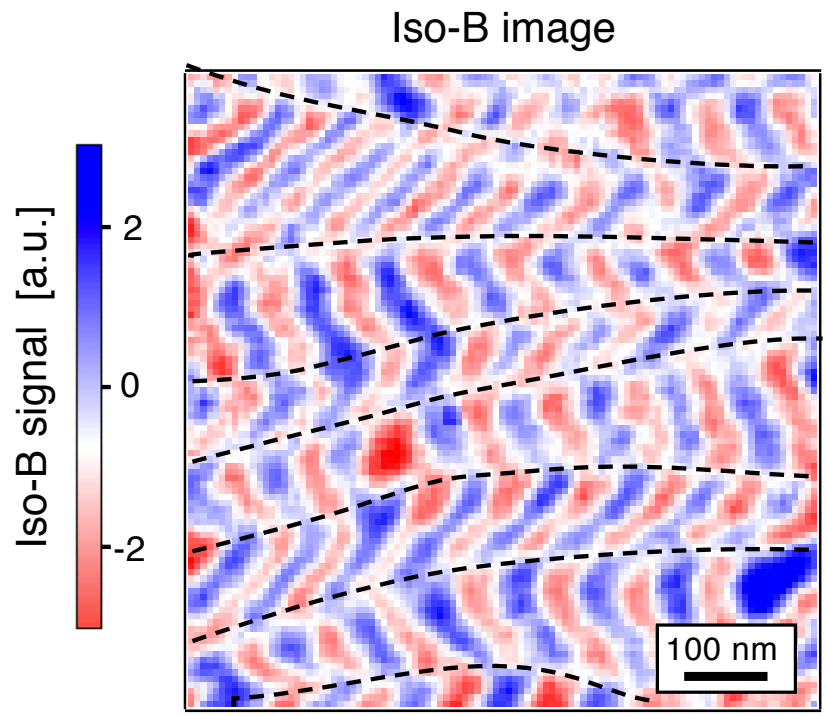


First real-space observation of the cycloidal antiferromagnetic order in BFO

Imaging antiferromagnetic order in BFO

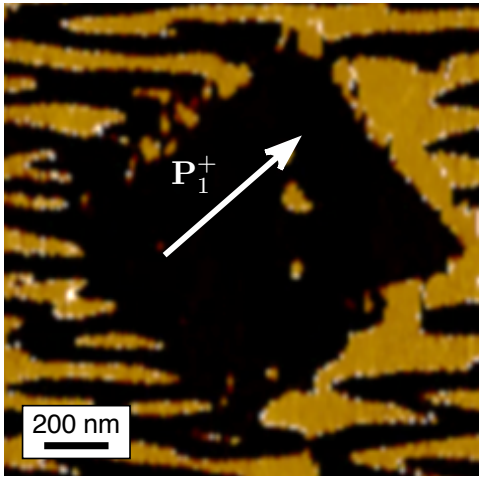


30 nm thick (001)-$BiFeO_3$



First real-space observation of the cycloidal antiferromagnetic order in BFO

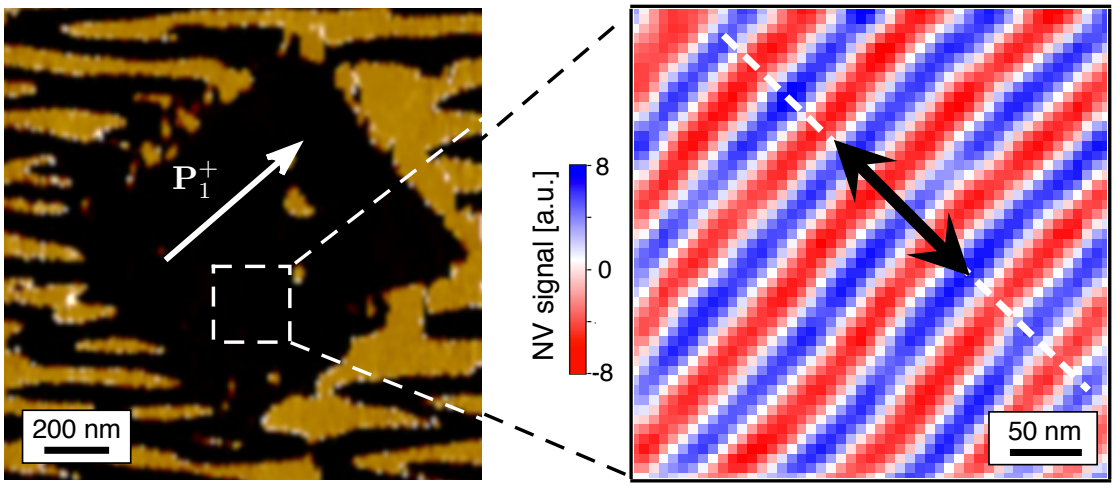
Controlling the spin cycloid in BFO



PFM images

Controlling the spin cycloid in BFO

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

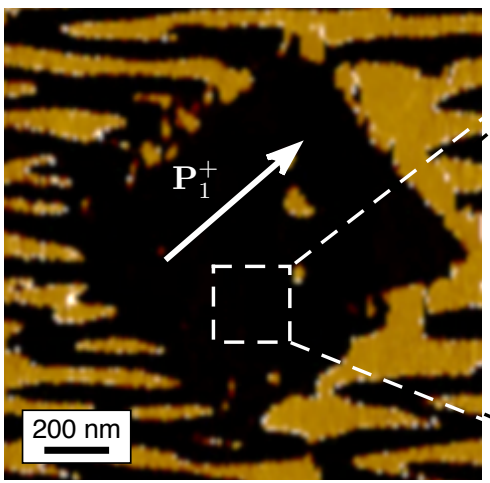


PFM images

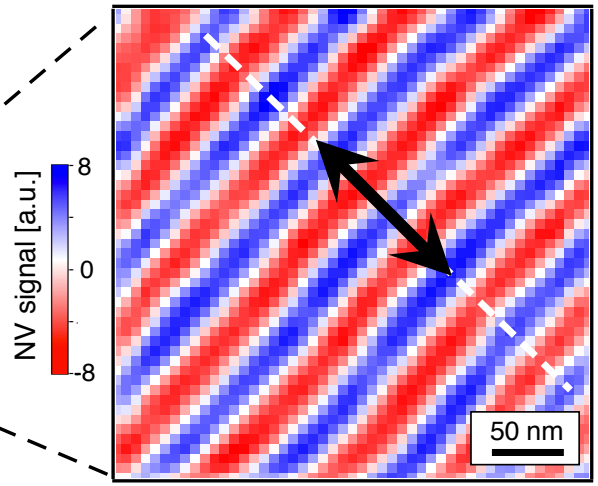
NV images

Controlling the spin cycloid in BFO

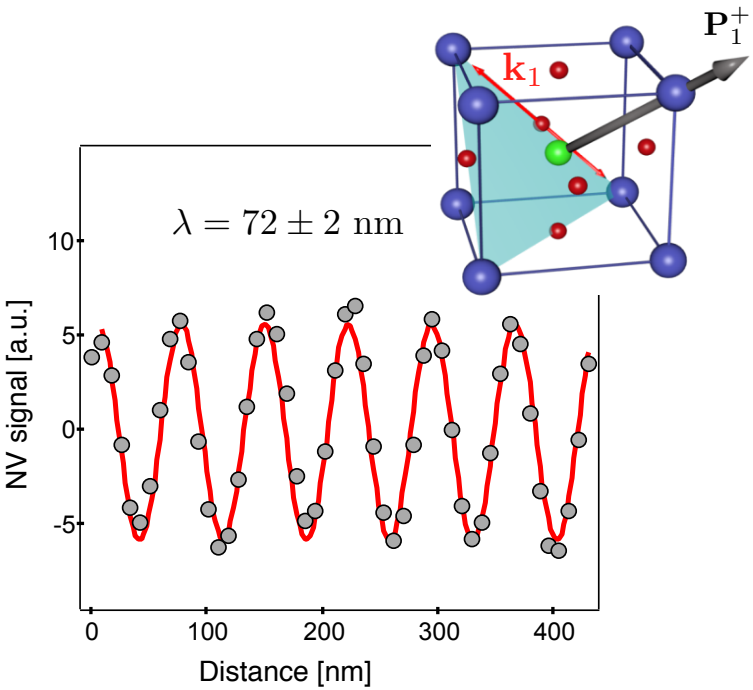
Gross, *Nature* **549**, 252 (2017)



PFM images

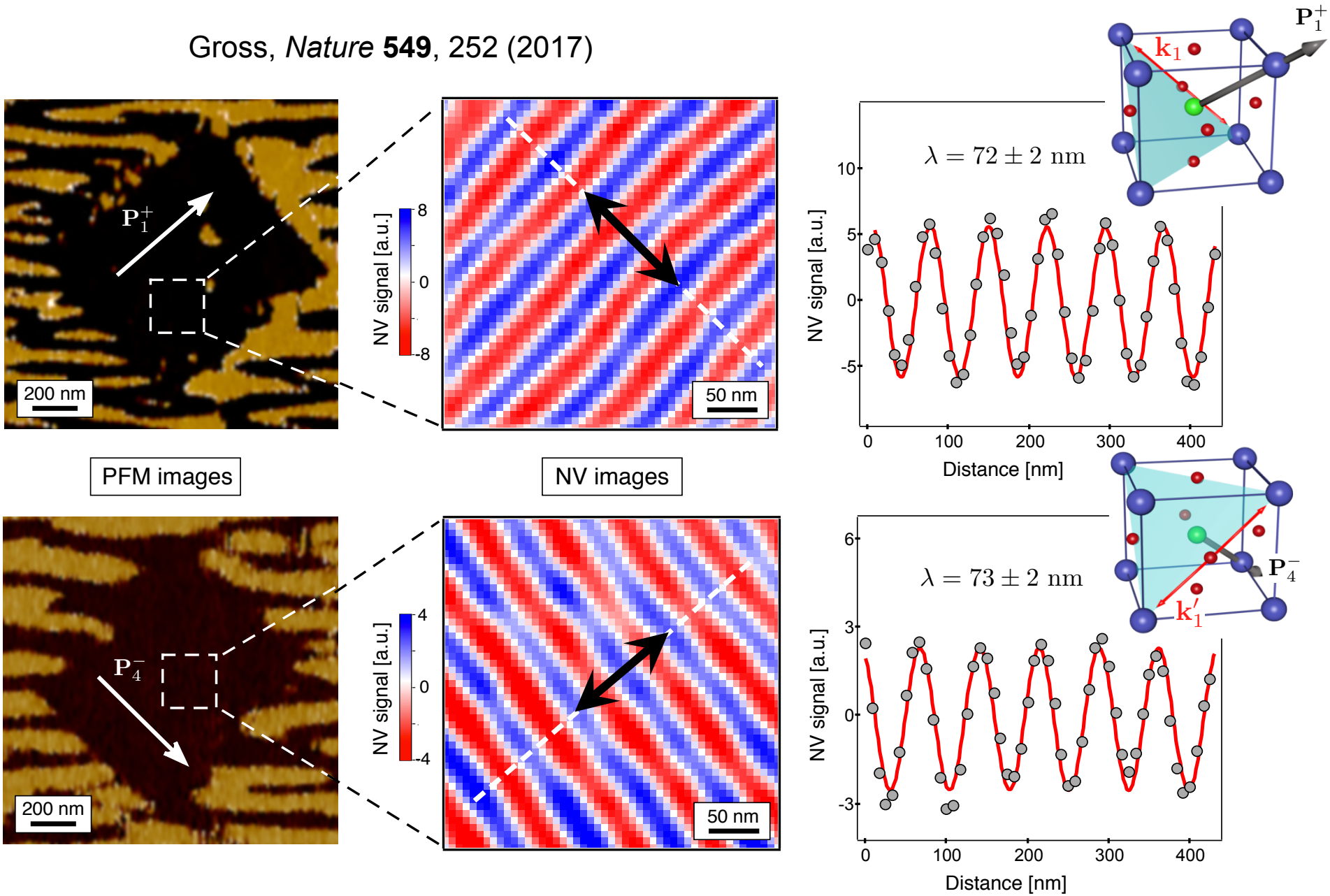


NV images

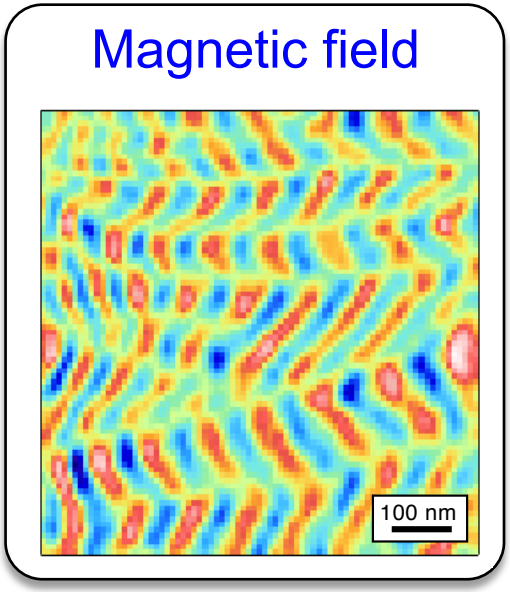


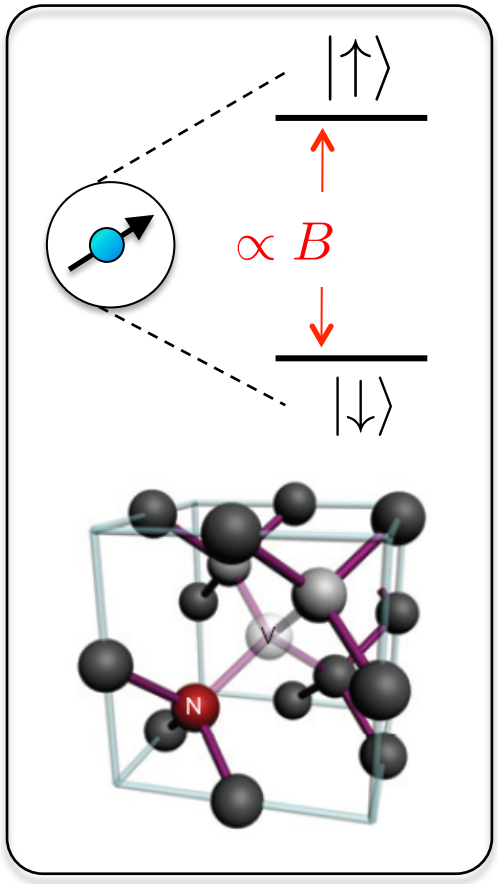
Controlling the spin cycloid in BFO

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



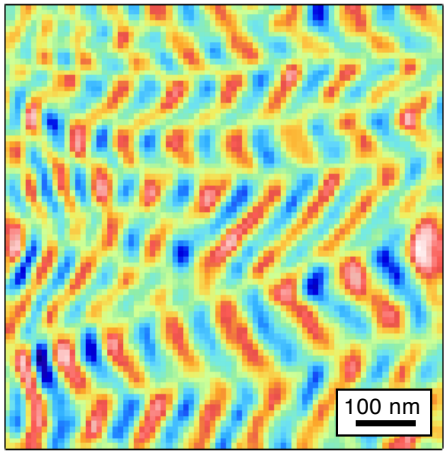
A multimode sensor

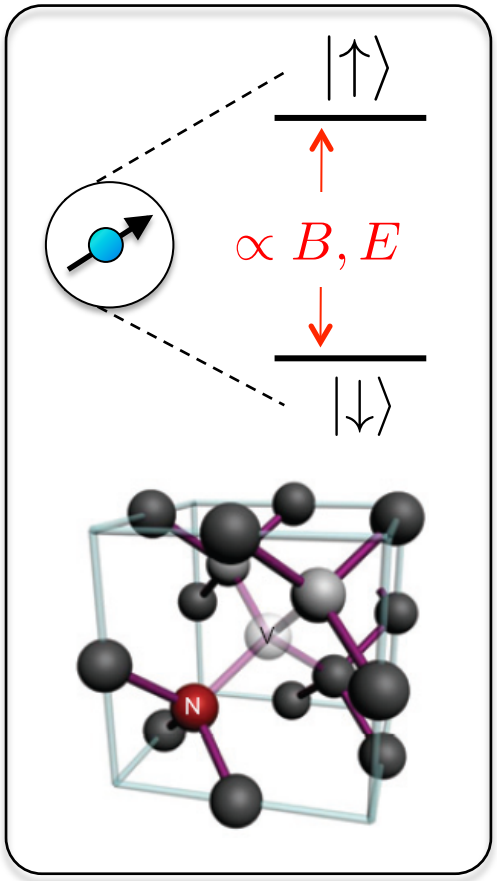




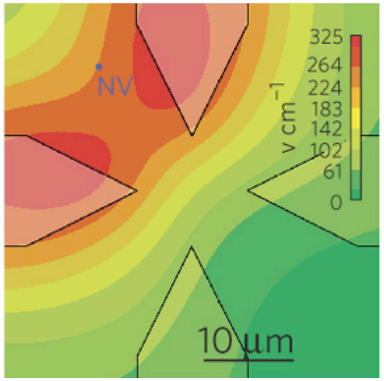
A multimode sensor

Magnetic field





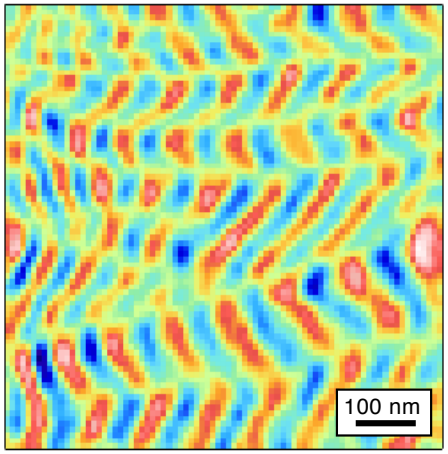
Electric field

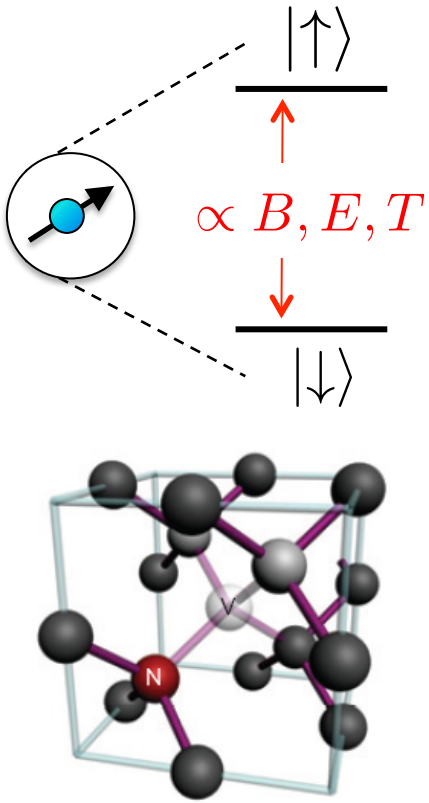


Dolde, *Nat. Phys.* **7**, 459 (2011)

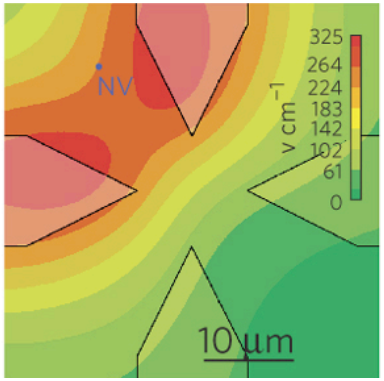
A multimode sensor

Magnetic field



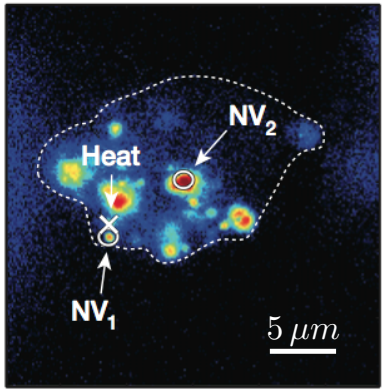


Electric field



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

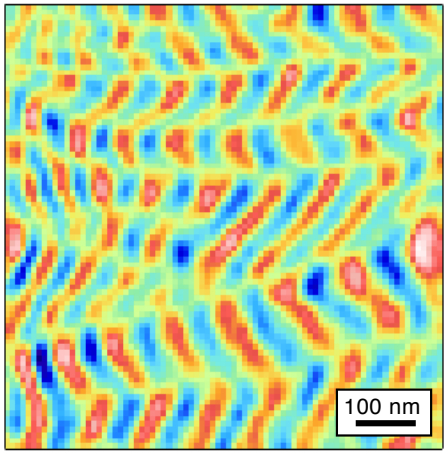
Temperature

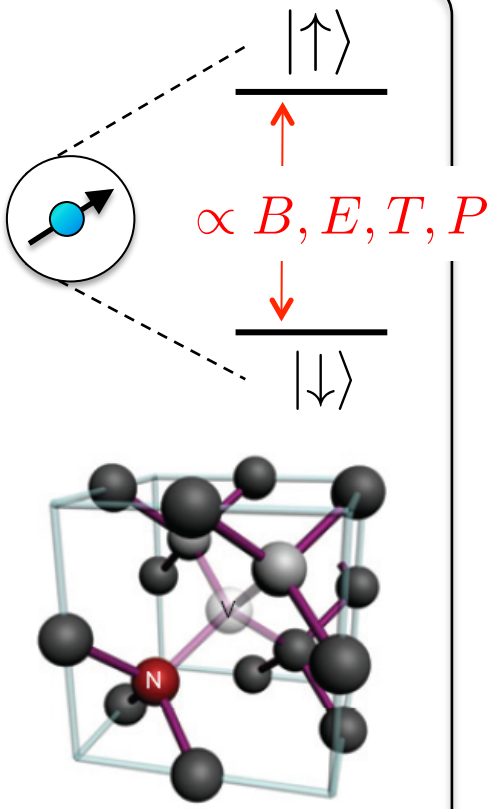


Kucsko, *Nature* **500**, 54 (2013)

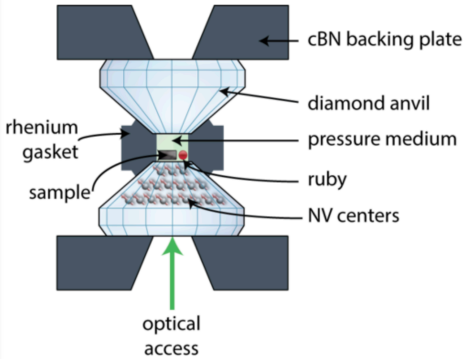
A multimode sensor

Magnetic field



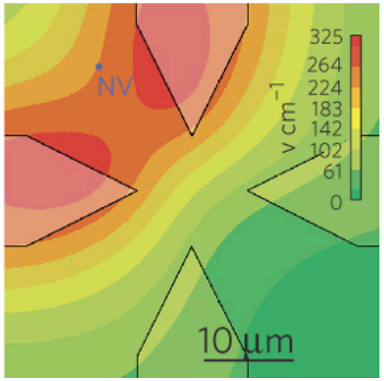


Pressure



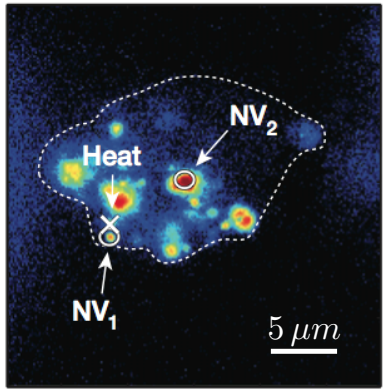
N. Yao – Berlekey
J.-F. Roch – ENS Cachan

Electric field



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

Temperature



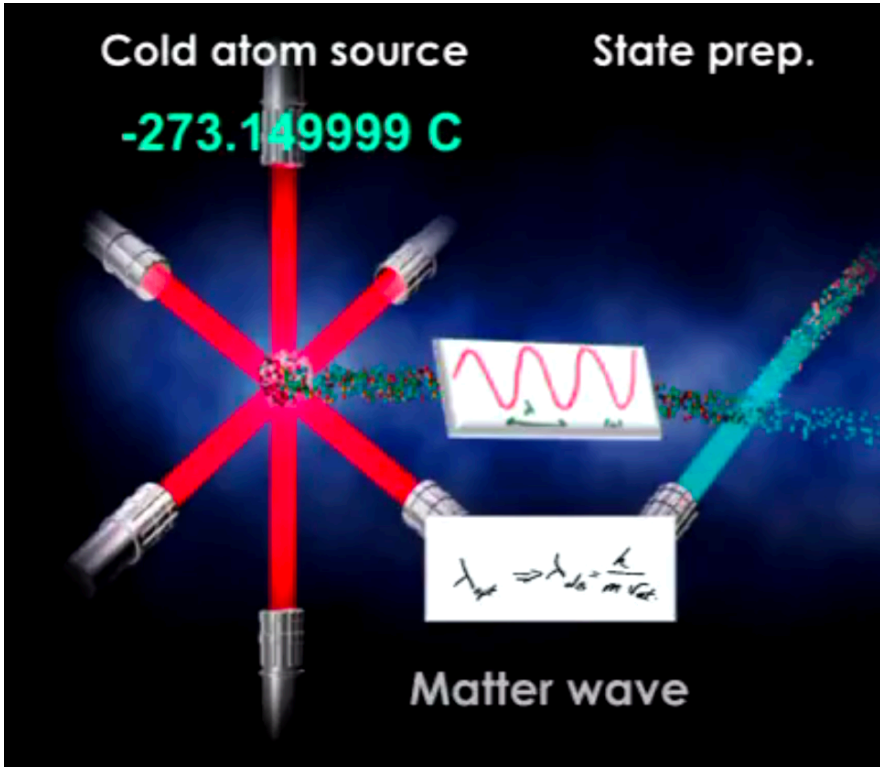
Kucsko, *Nature* **500**, 54 (2013)

Other directions in quantum sensing

Matter waves in a « Mach-Zehnder » interferometer

Other directions in quantum sensing

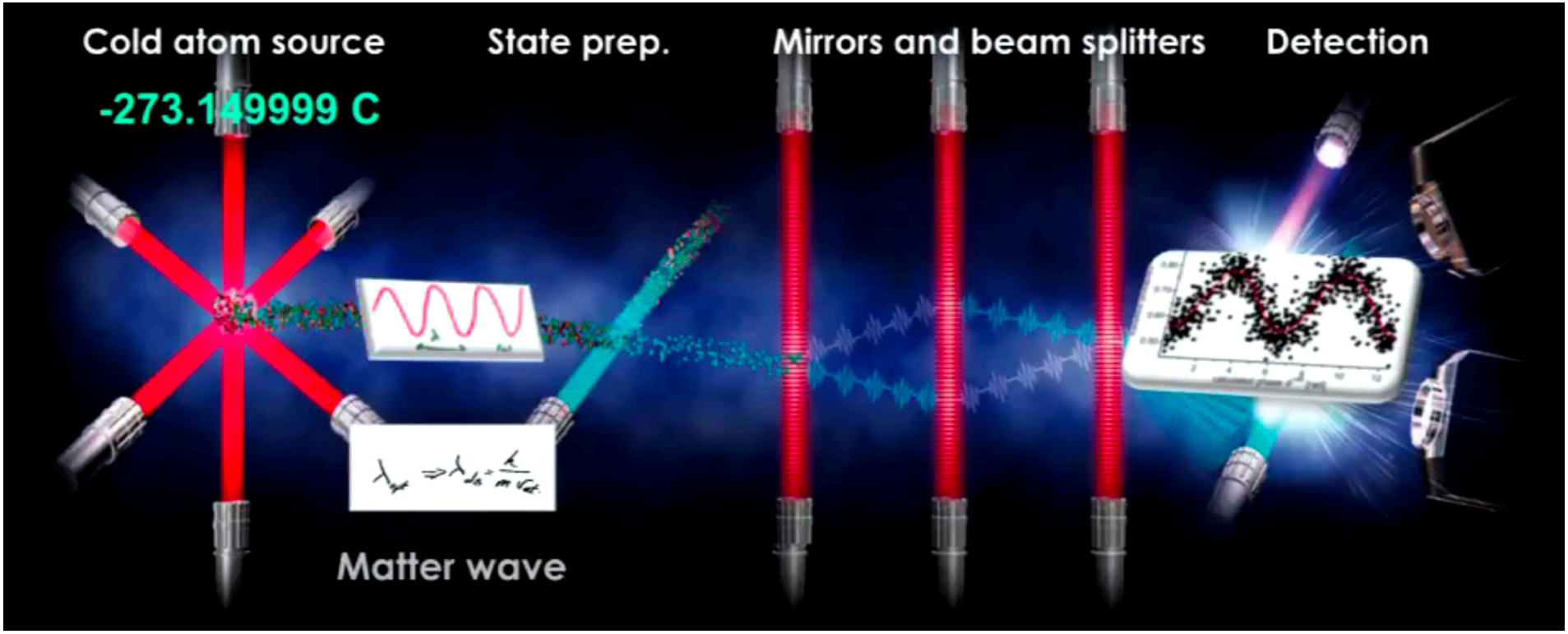
Matter waves in a « Mach-Zehnder » interferometer



Philippe Bouyer, LP2N, Bordeaux

Other directions in quantum sensing

Matter waves in a « Mach-Zehnder » interferometer



Philippe Bouyer, LP2N, Bordeaux

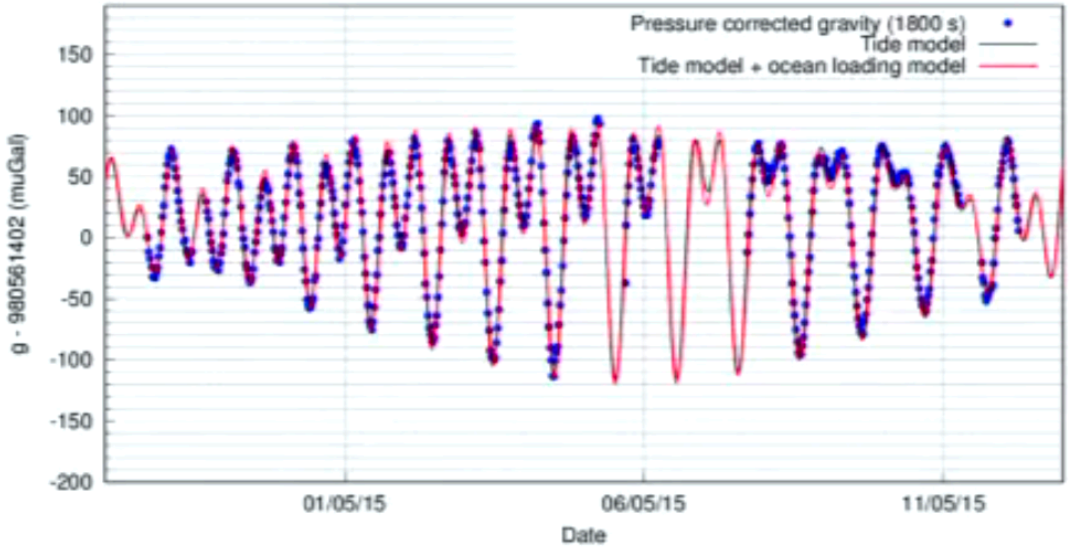
Highly sensitive gravimeters and gyroscopes

Other directions in quantum sensing

Commercial products already available!!

μQUANS

Bordeaux



Thank you for your attention