NV defects in diamond
Physics and applications

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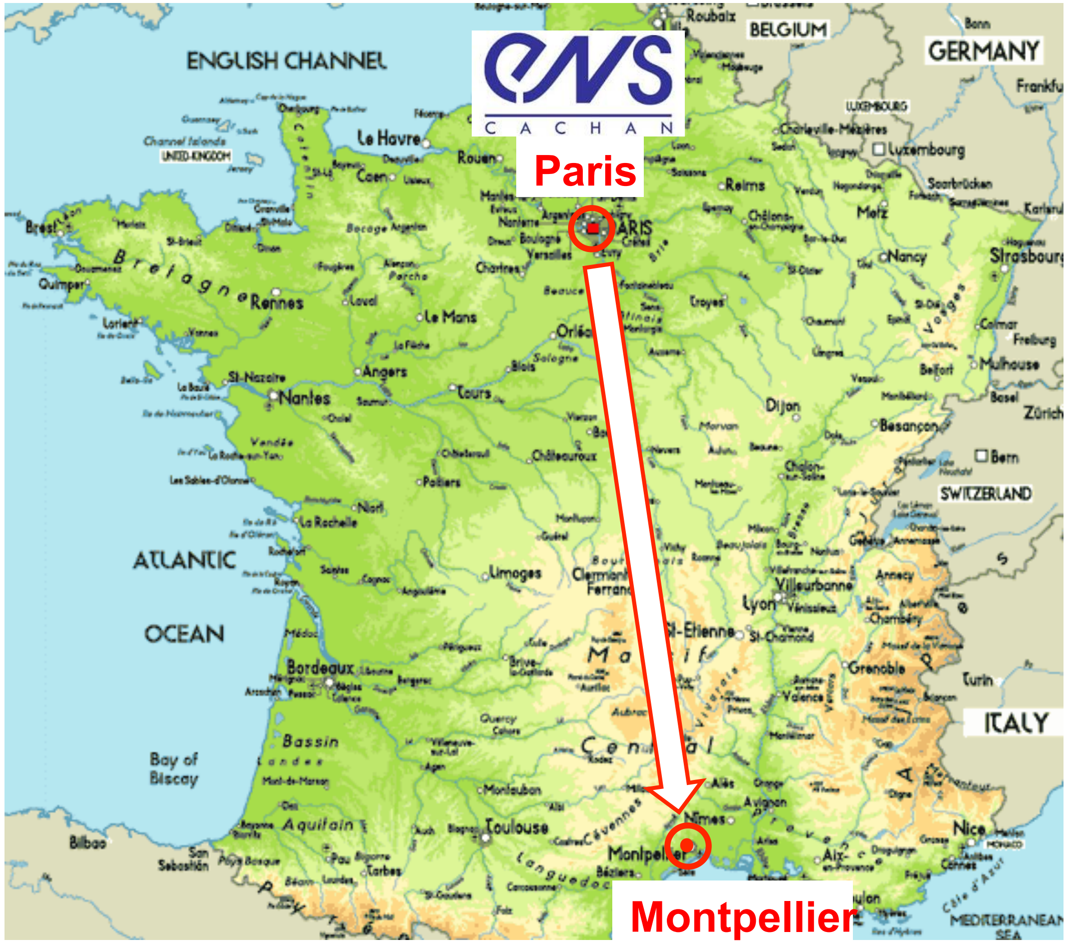
From Paris to Montpellier…



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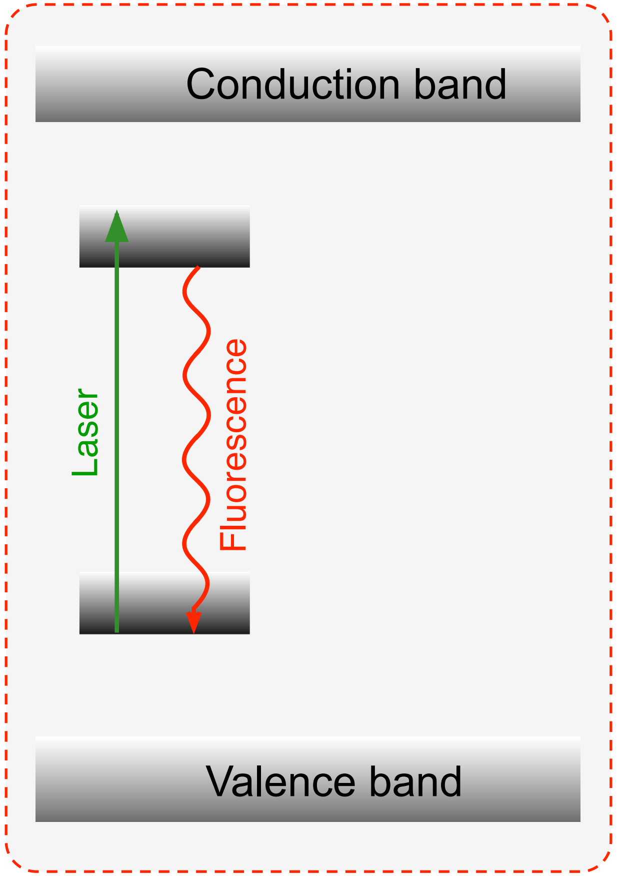
Deep defects in wide-bandgap materials

Artificial atom

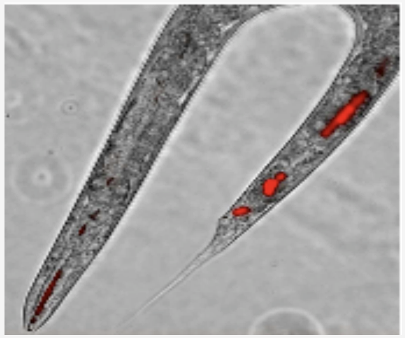


Deep defects in wide-bandgap materials

Single Photon source

Quantum cryoptography

Fluorescent Bio-label



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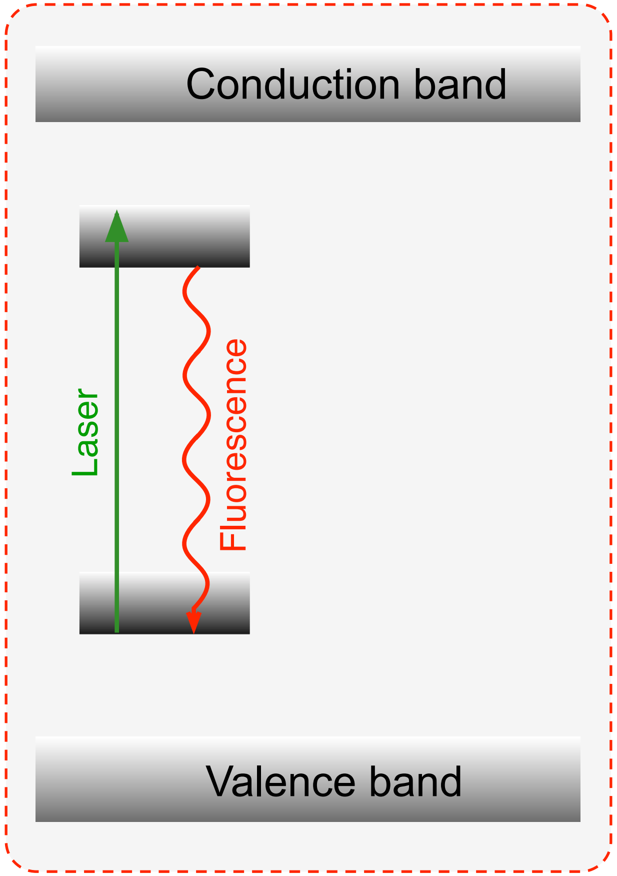

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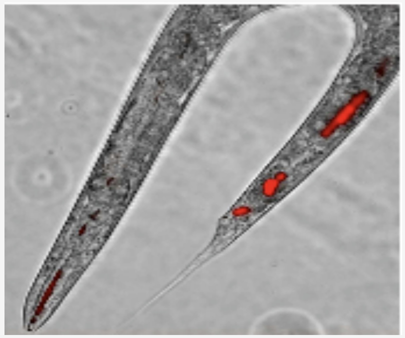

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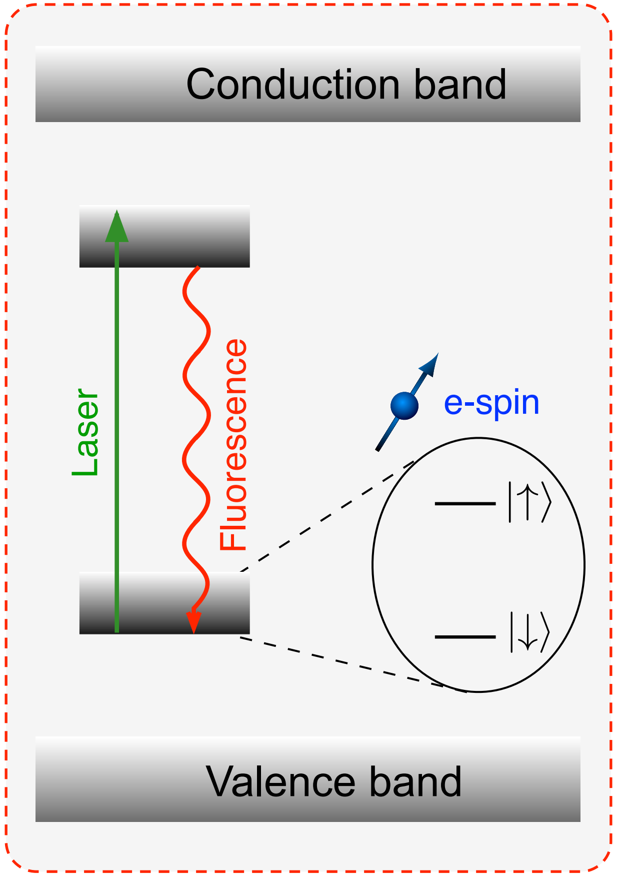

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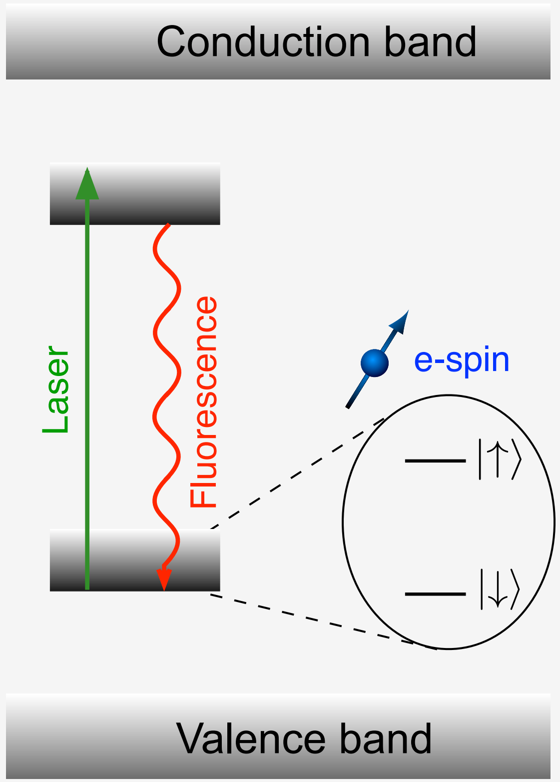
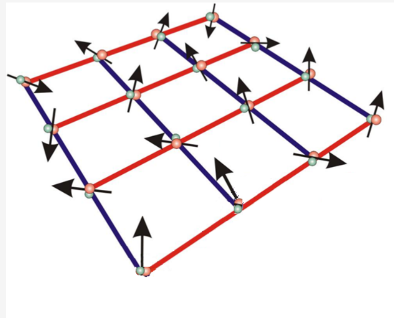


Quantum information



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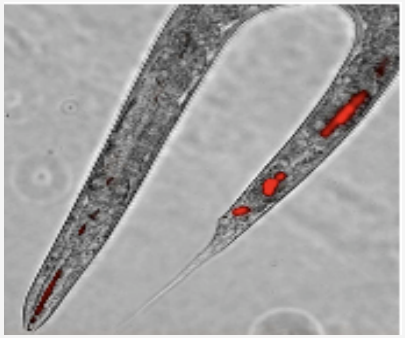
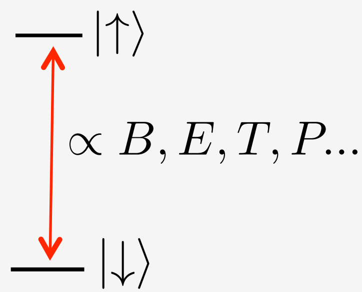
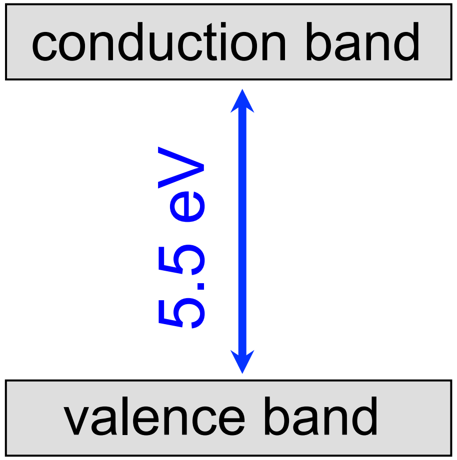


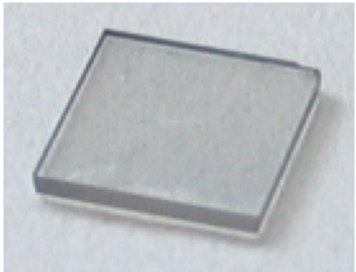
High resolution sensor



An appealing material : **Diamond**



A perfect diamond would not absorb visible light…



…but many defects are optically active

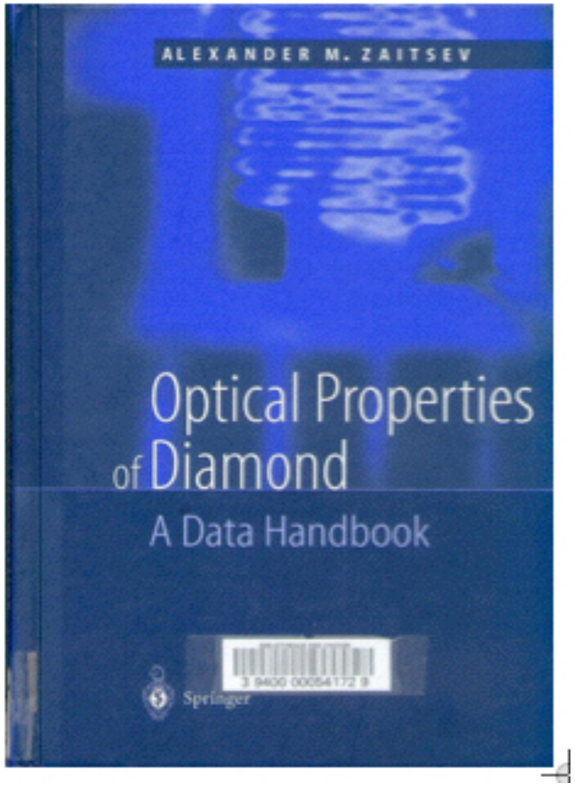
→ Color centers

The « Hope » diamond
(diamant bleu de la couronne, Louis XIV)

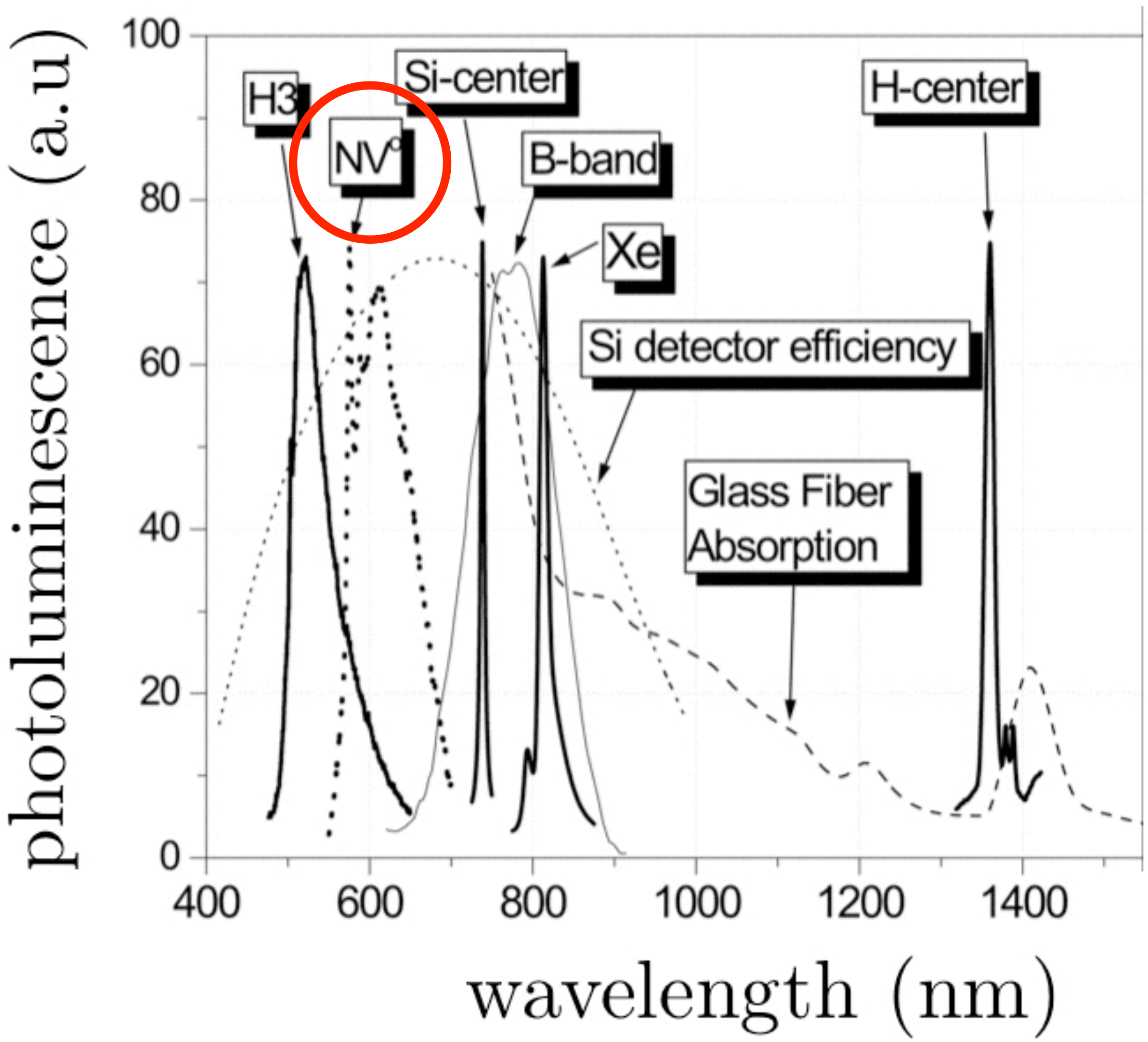
The « Hortensia » diamond
(diamant rose de la couronne, Louis XIV)

Defects in diamond, a real zoology…

more than 500 optically-active defects are known in diamond



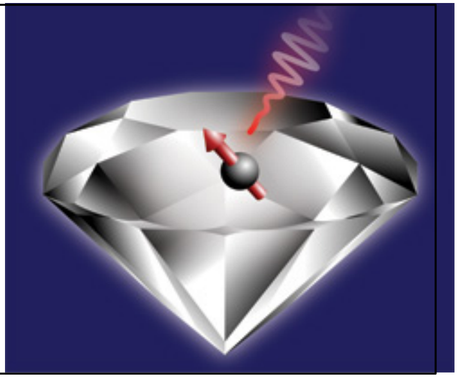
– A. M. Zaitsev –



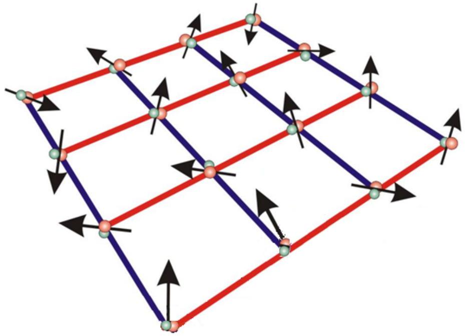
Outline

1. The NV defect in diamond

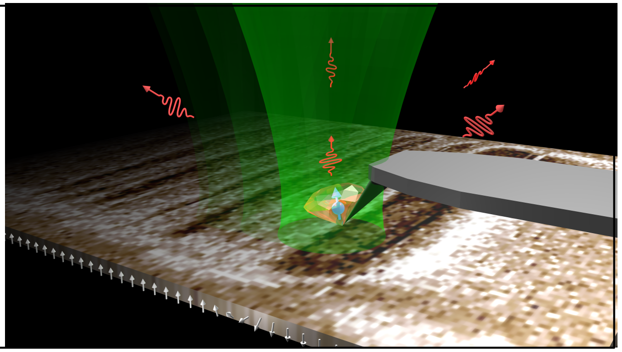
Main properties



2. Applications in 'quantum information science'



3. Magnetic sensing with a single NV defect



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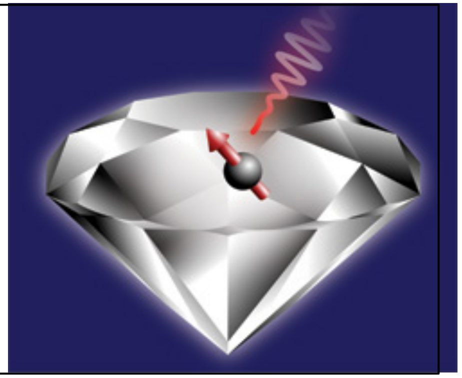

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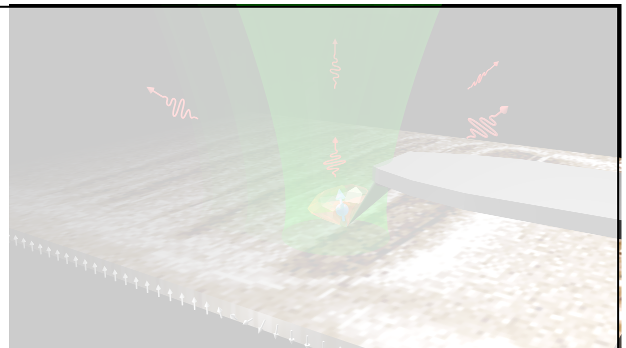
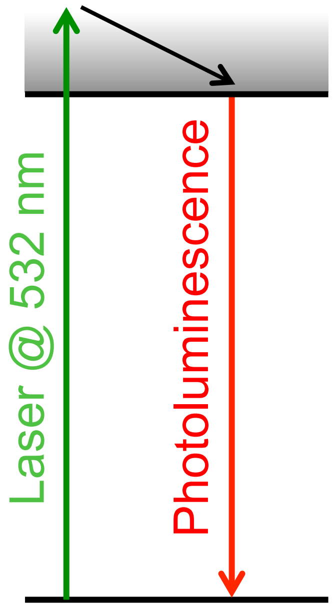
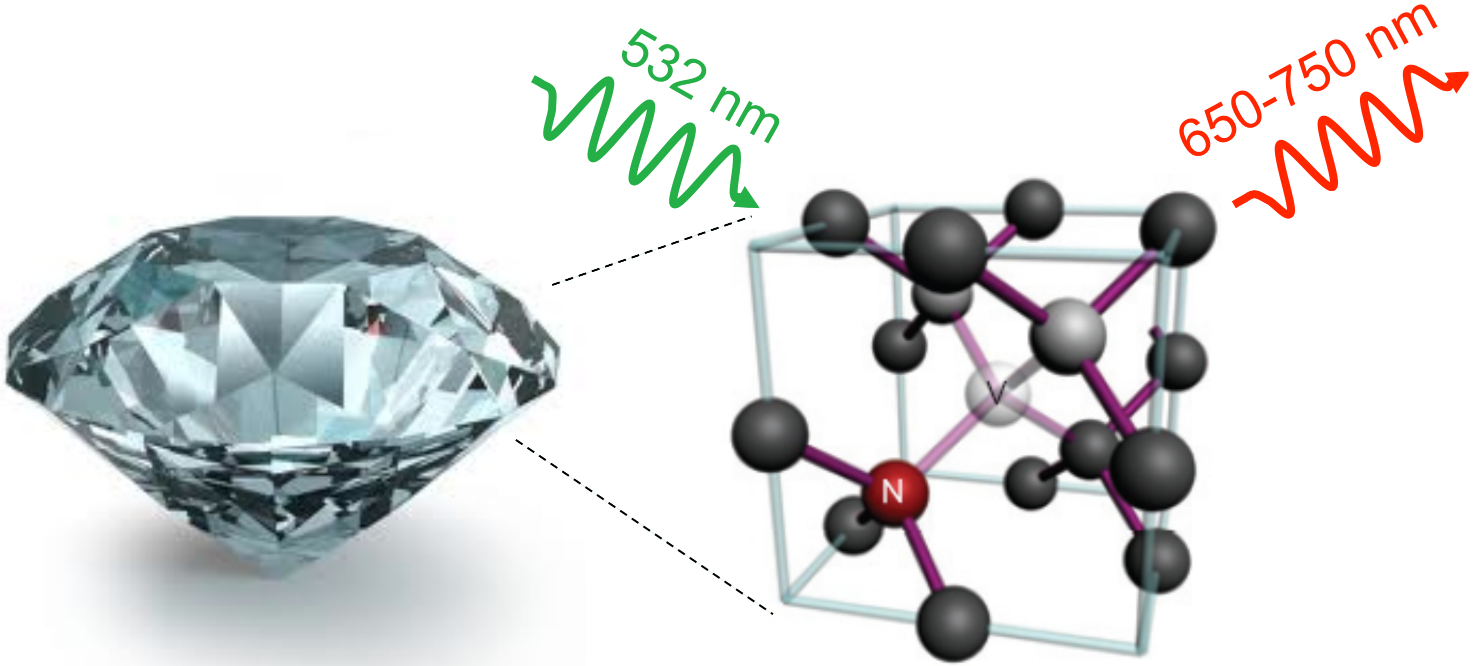
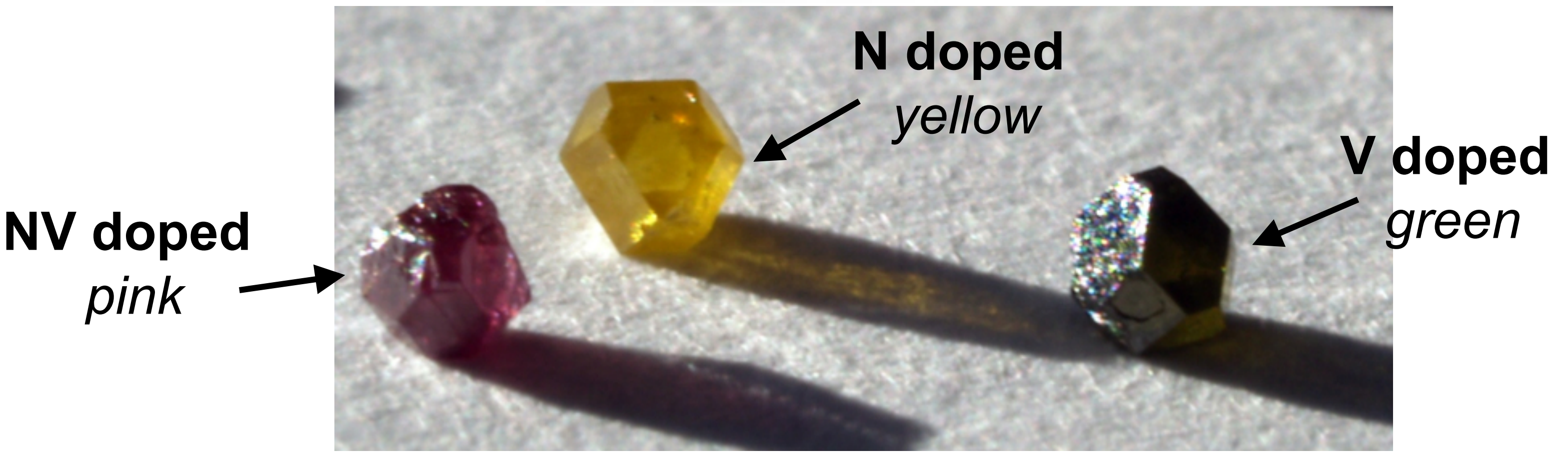


Nitrogen-Vacancy (NV) defect in diamond

- An artificial atom « trapped » in the diamond lattice







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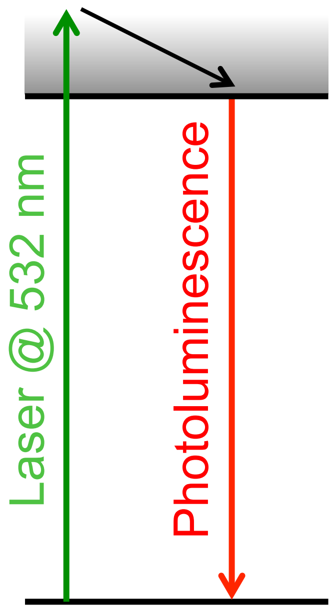
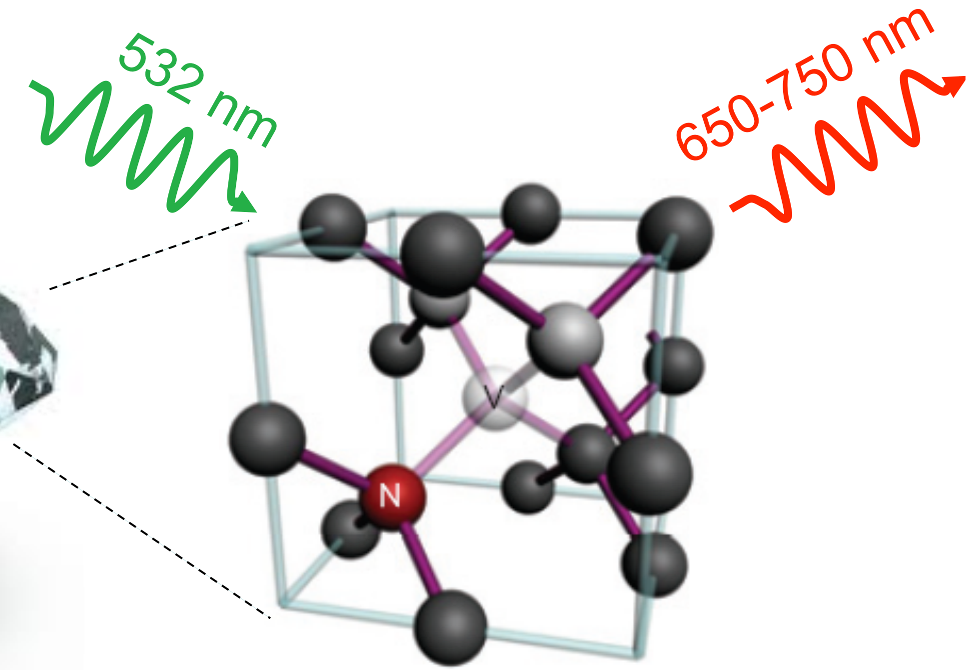
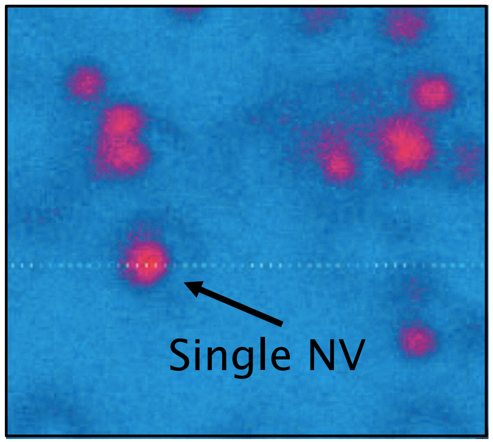


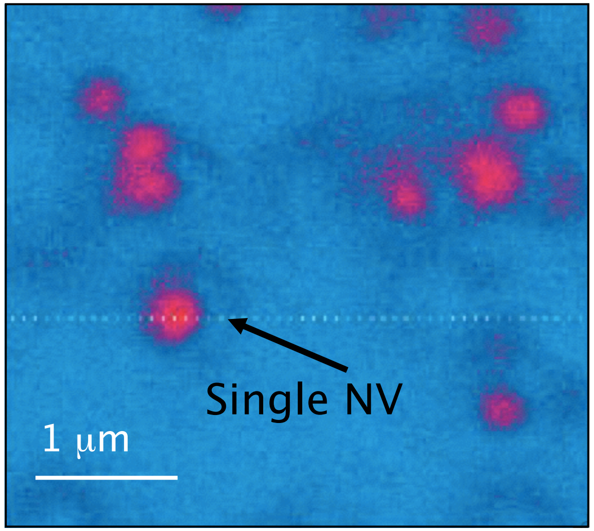


- Detection at the single emitter level **at room T –** *perfect photostability*

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

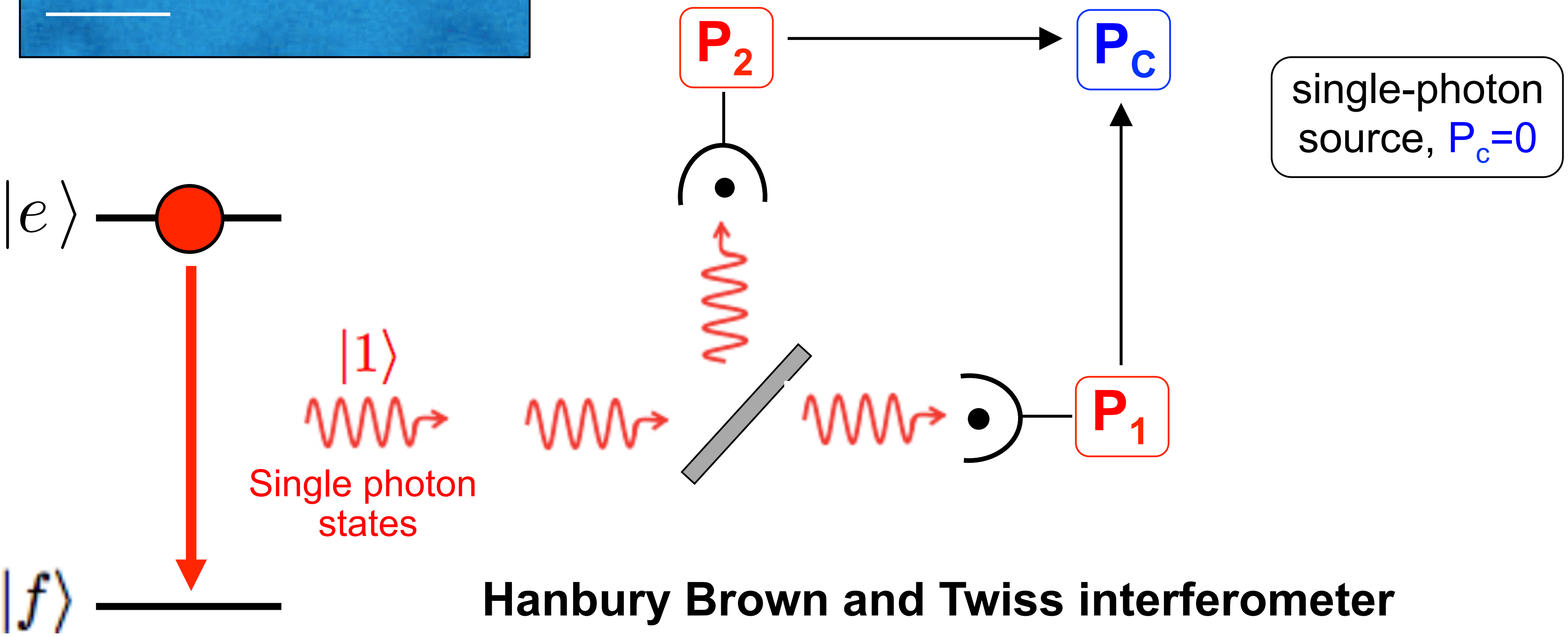


A robust single photon source



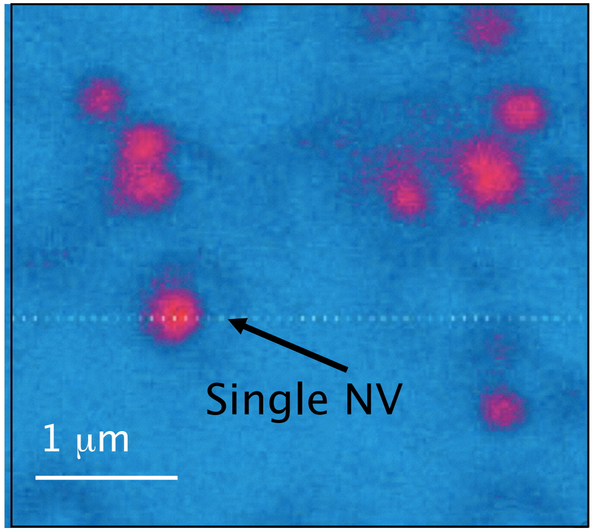
$$g^{(2)}(\tau) = \frac{\overline{\mathcal{I}(t)\mathcal{I}(t+\tau)}}{\overline{\mathcal{I}(t)} \times \overline{\mathcal{I}(t+\tau)}}$$

$$\longrightarrow \quad g^{(2)}(0) = \frac{P_c}{P_1 \times P_2}$$



Hanbury Brown and Twiss interferometer

A robust single photon source



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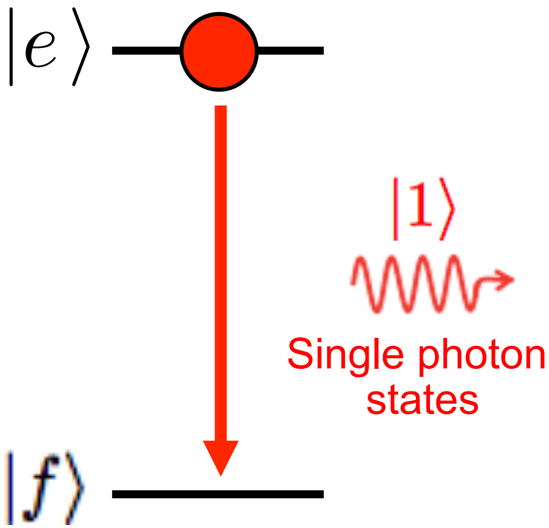
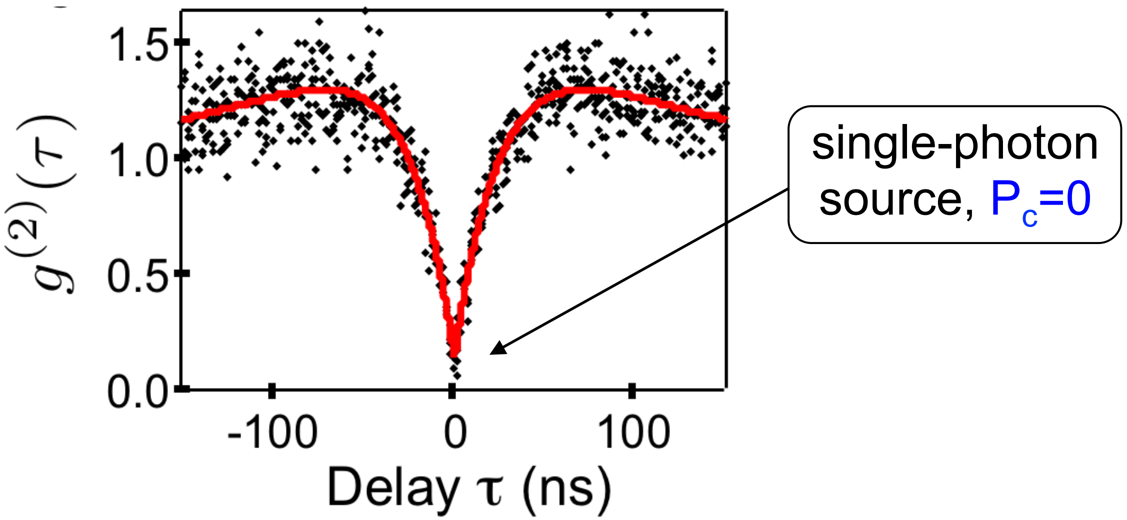


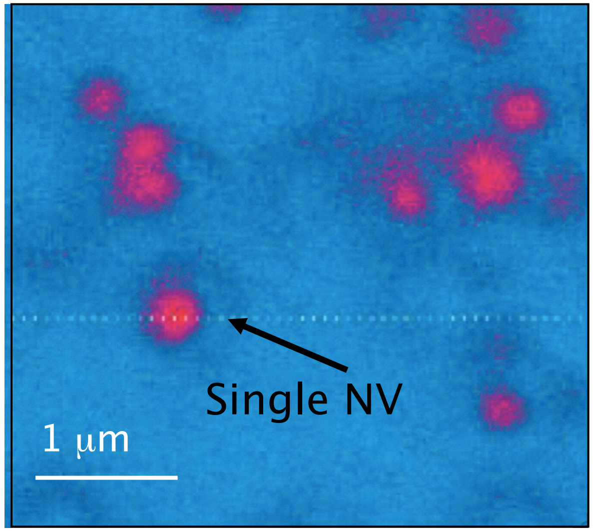


Applications to Quantum Cryptography

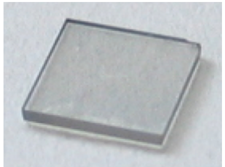
Beveratos *et al.*, *PRL* (2002)
Alleaume *et al.*, *NJP* (2004)

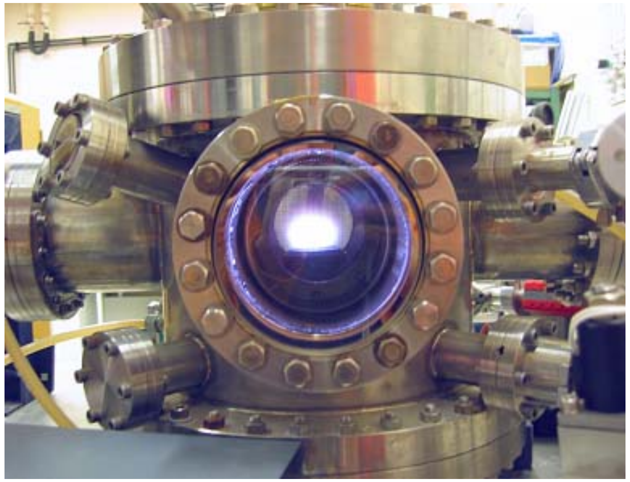
Engineering NV defect in diamond

1997



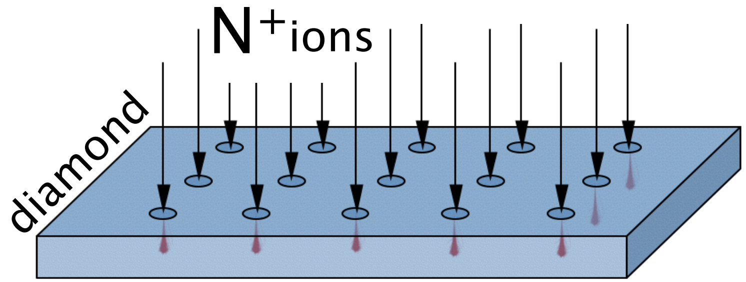
High purity diamond using **CVD growth**





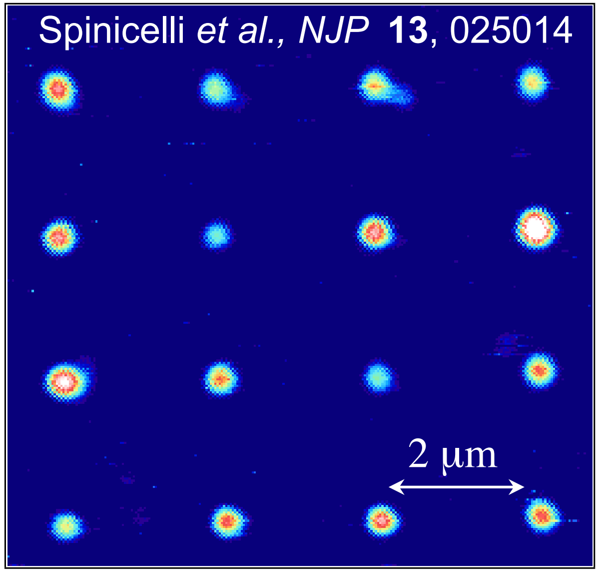
Gicquel and Achard group(Villetaneuse)

NV defect engineering through **nanoscale ion implantation**



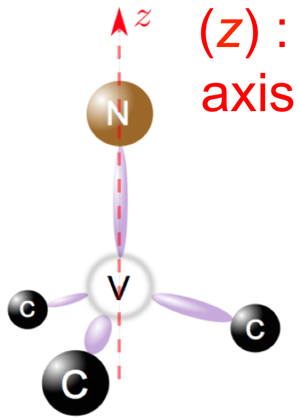
Meijer group (Leipzig)

2012

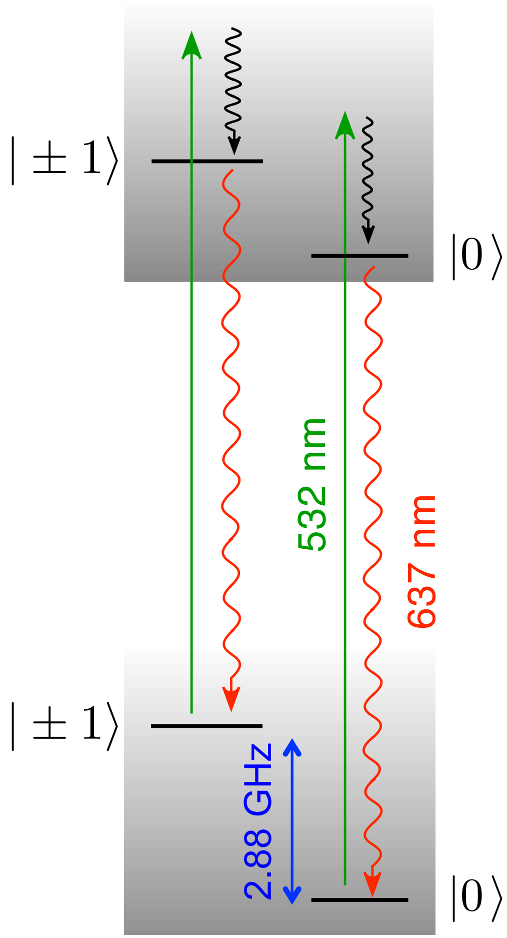


Spin properties

spin triplet (S=1)
ground state



(z) : quantization
axis of the defect



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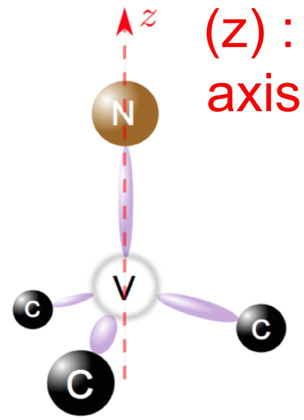

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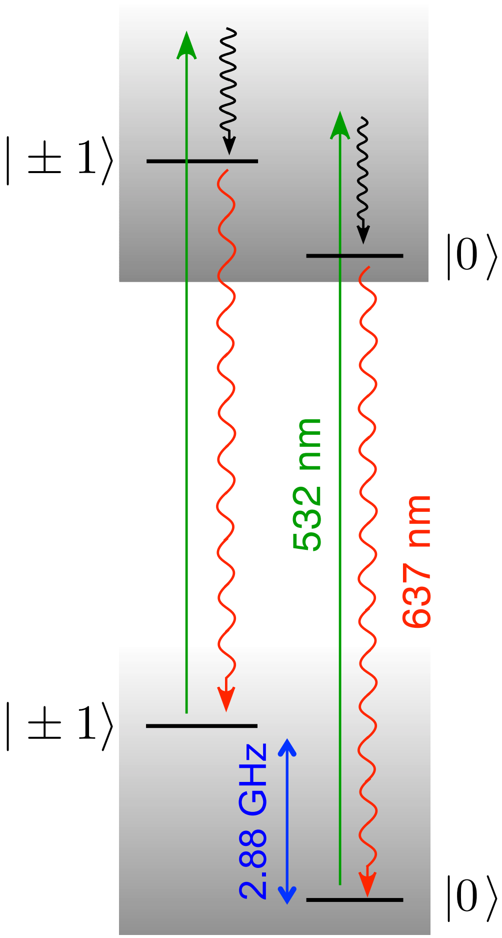
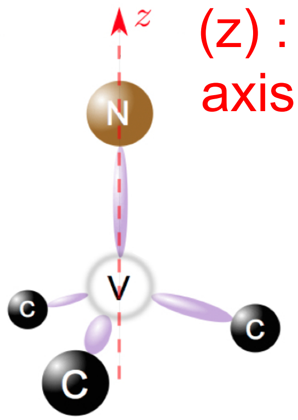


Important properties

- Spin-conserving optical transition Δm_s=0.

Spin properties



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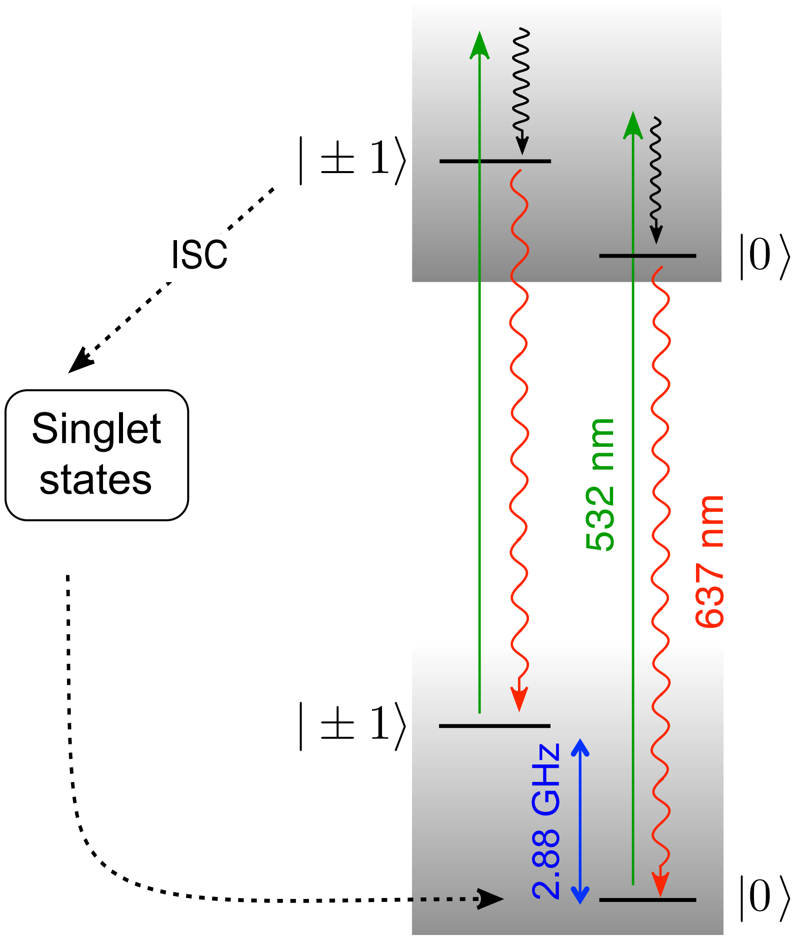

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- Spin-conserving optical transition Δm_s=0.
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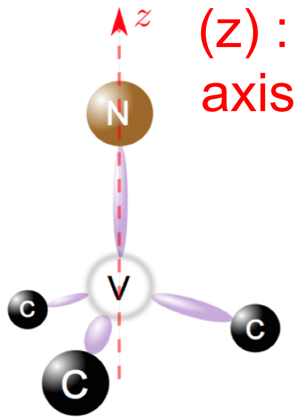
Spin properties



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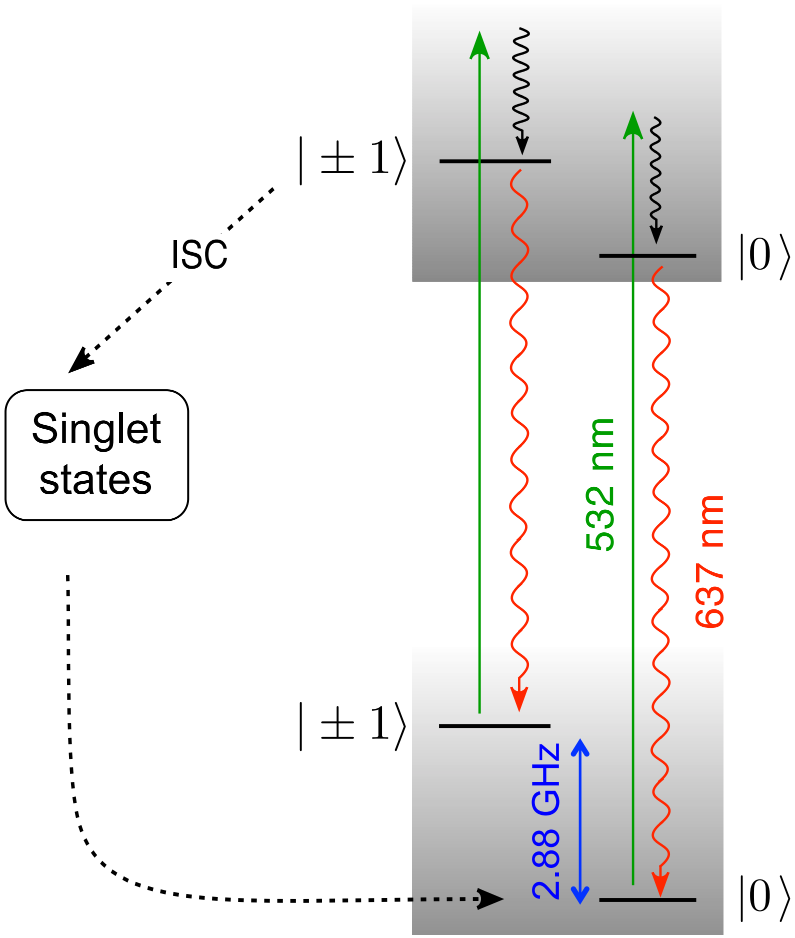

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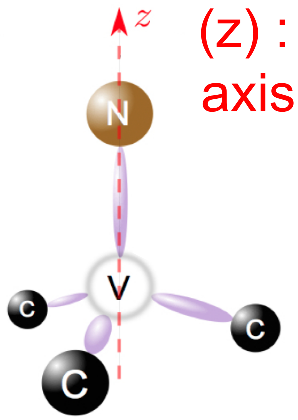
Consequences

- Polarization in m_s=0 by optical pumping.

Spin properties



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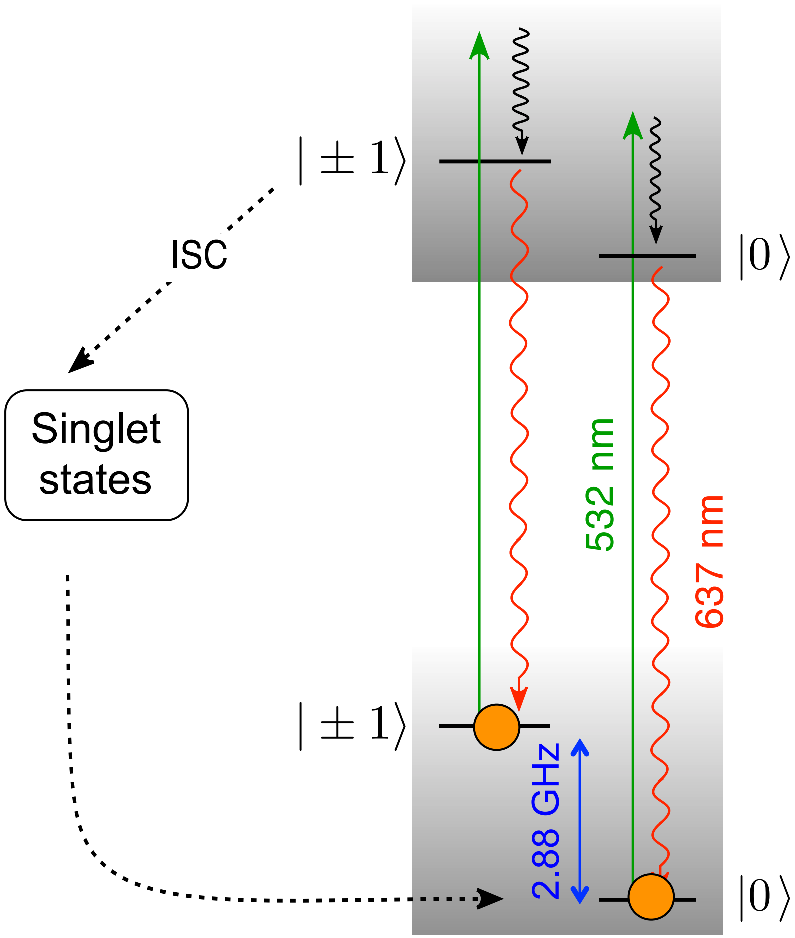

Important properties

- Spin-conserving optical transition $\Delta m_s=0$.
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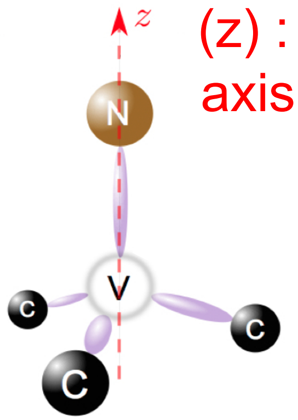
- Polarization in $m_s=0$ by optical pumping.

Spin properties



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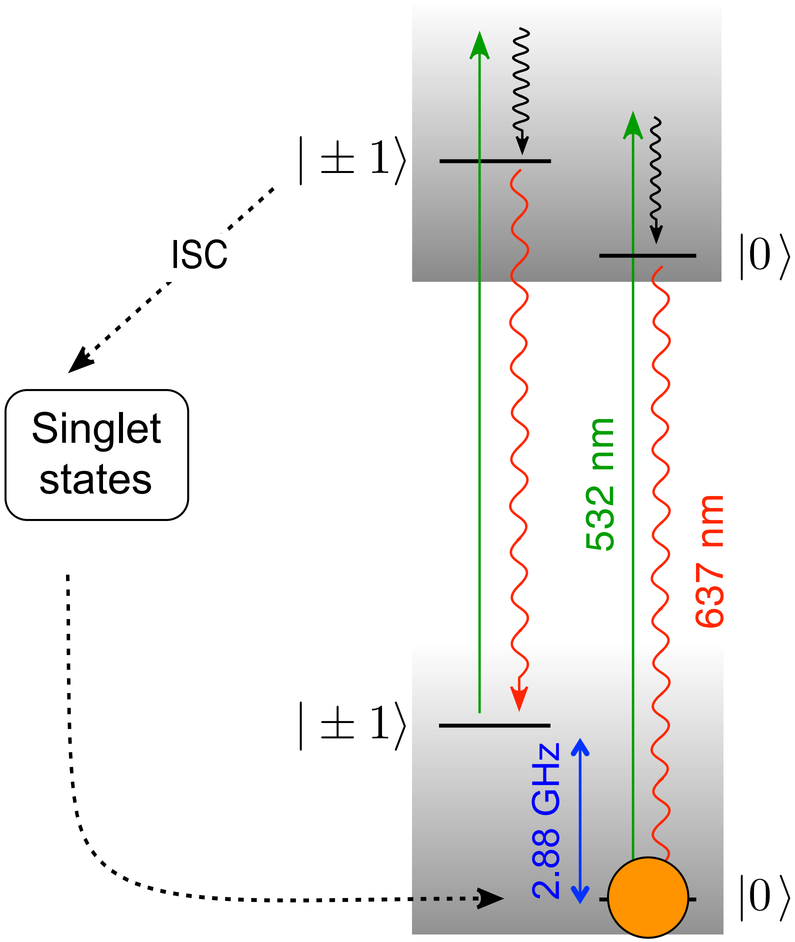

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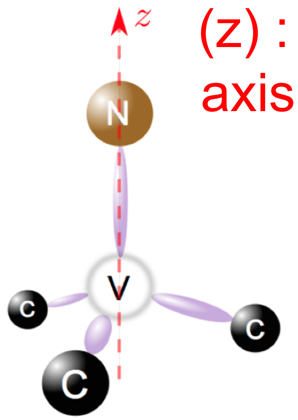

(z) : quantization axis of the defect

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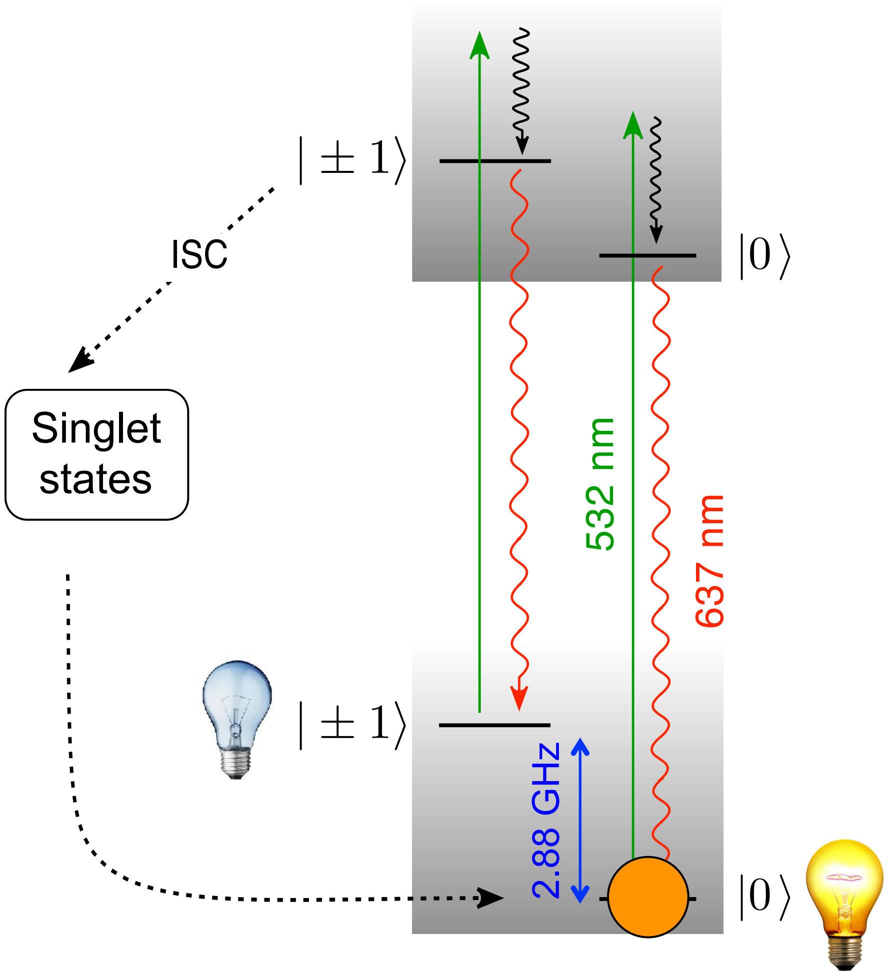


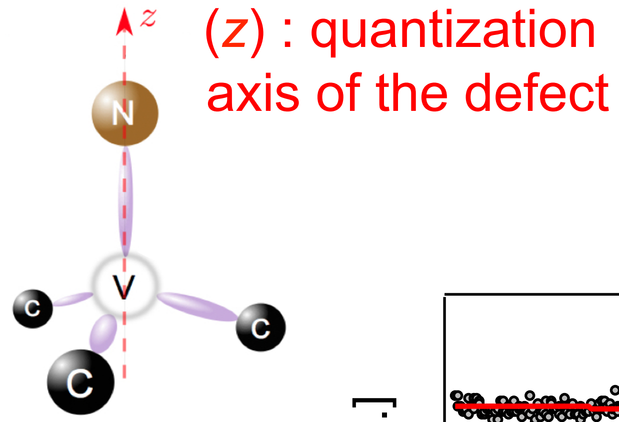
Important properties

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

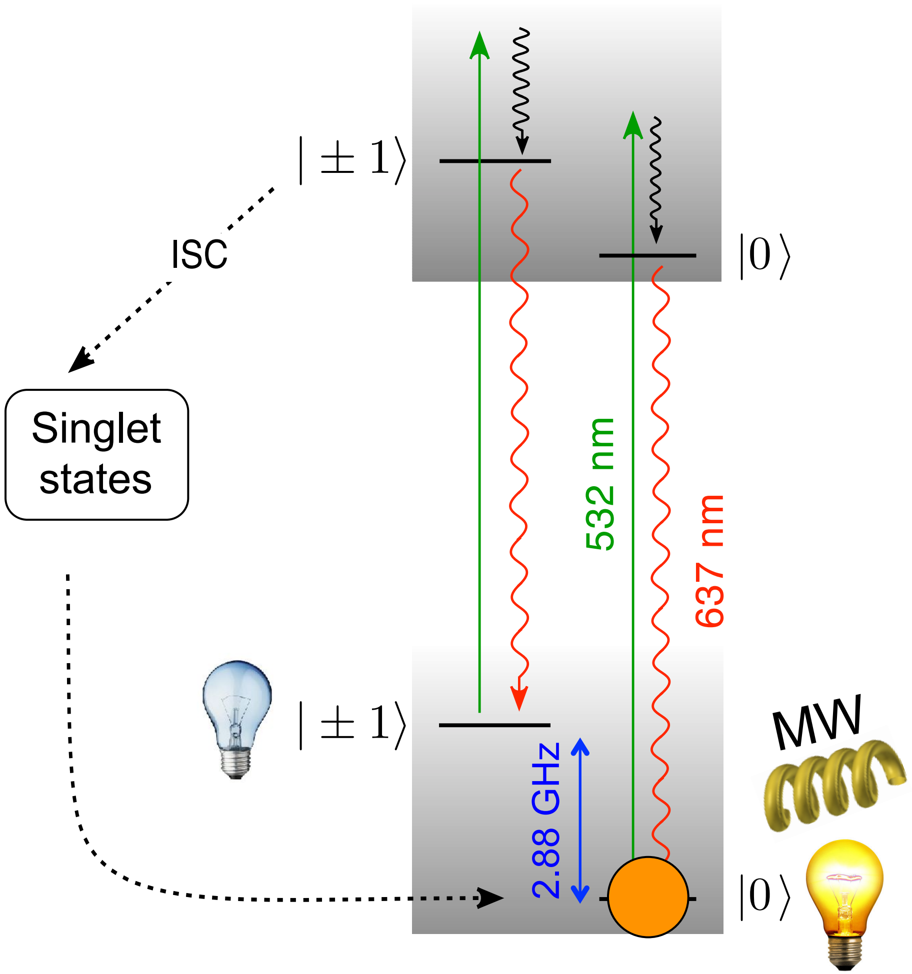
Consequences

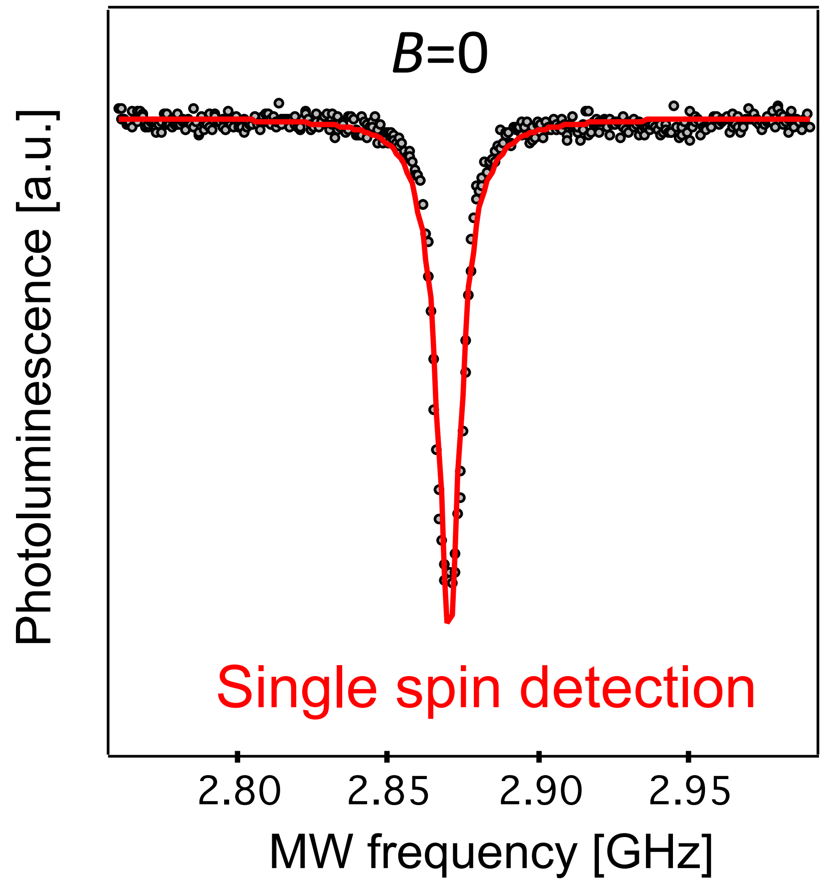
- Polarization in m_s=0 by optical pumping.
- Spin-dependent fluorescence.

Spin properties



spin triplet (S=1)
ground state





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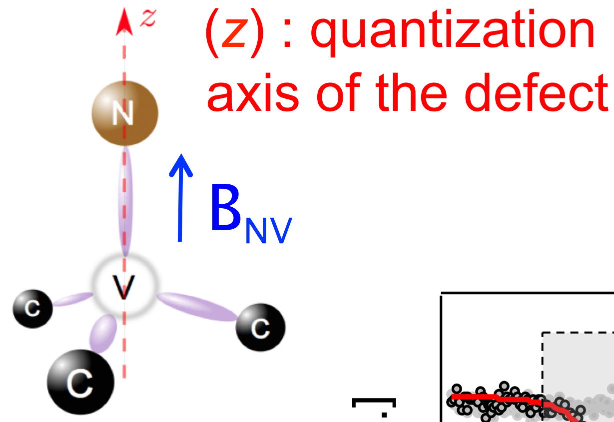
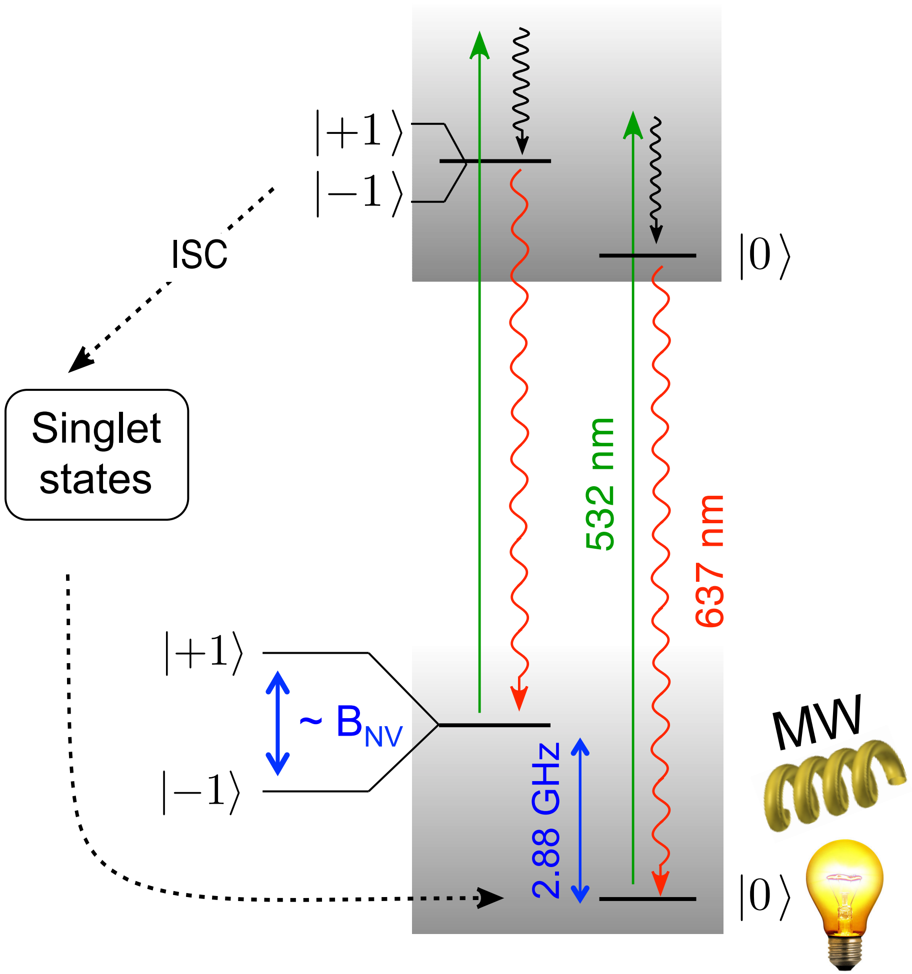
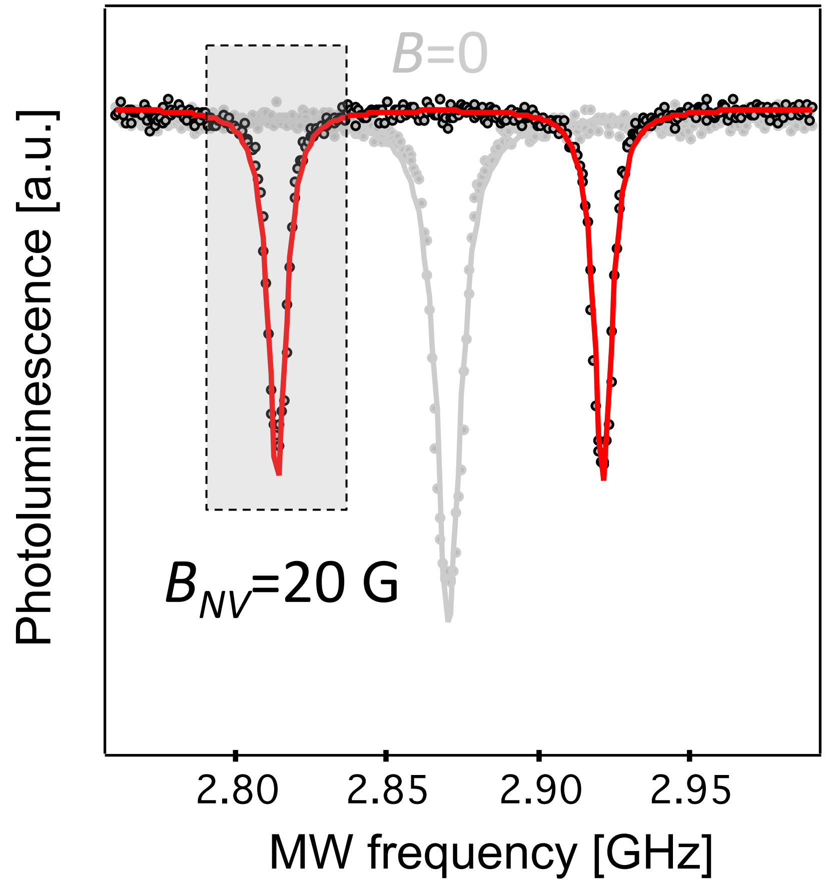


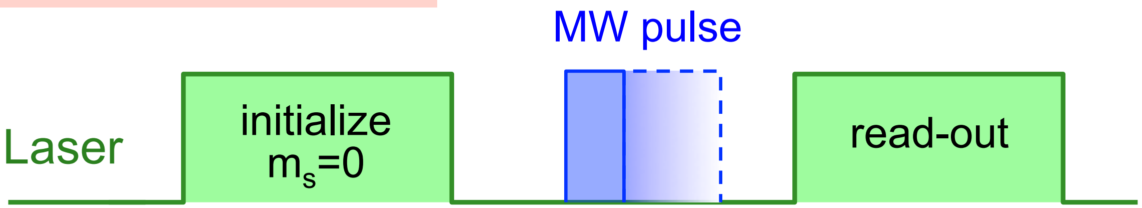


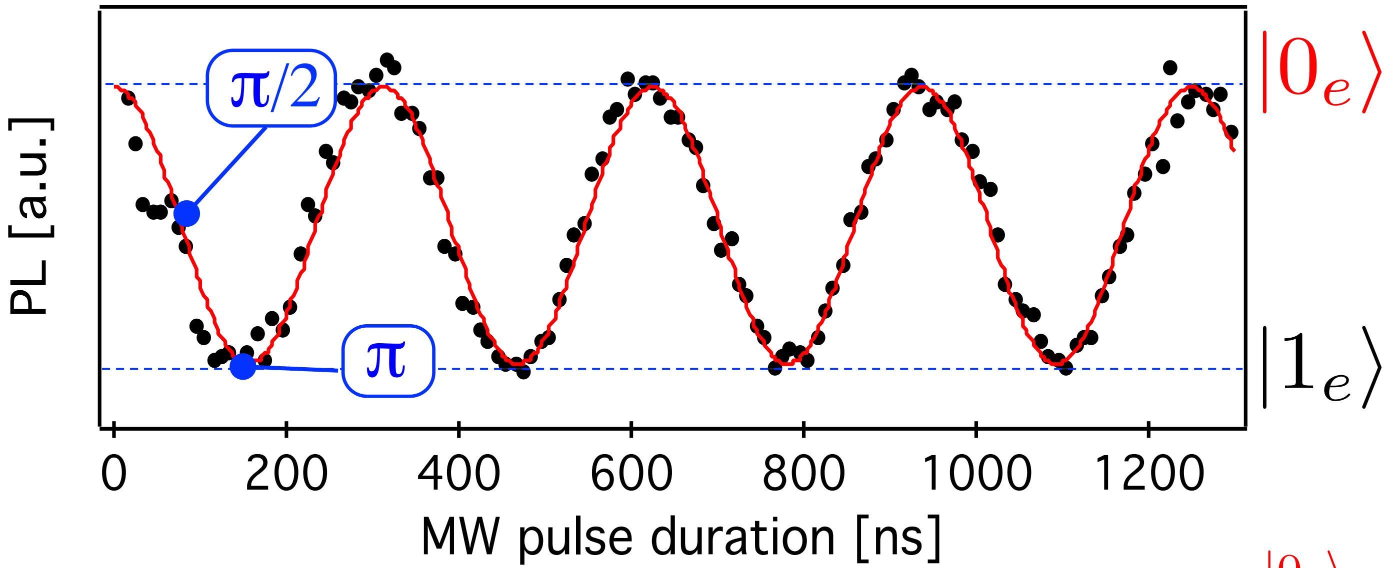


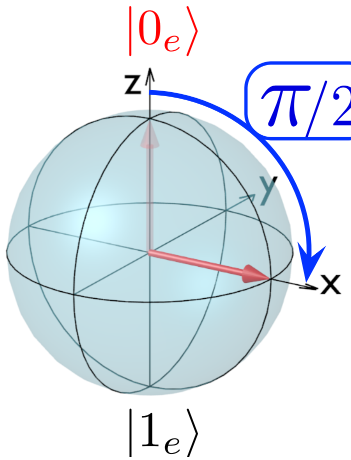
NV = e-spin qubit

Coherent spin manipulation

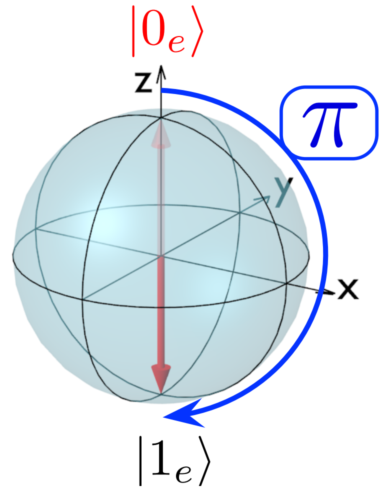
➢ Rabi oscillations





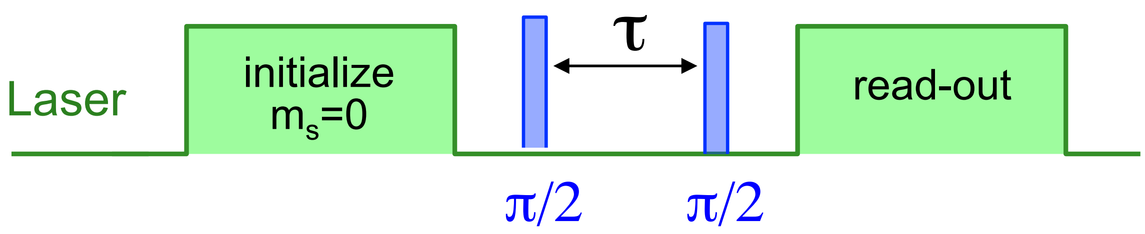


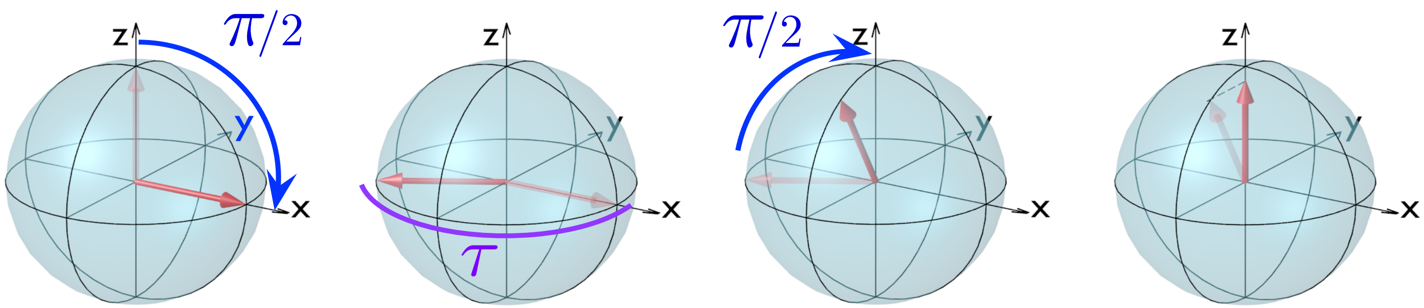
$$\frac{1}{\sqrt{2}}\left[|0_e\rangle + |1_e\rangle\right]$$



Coherent spin manipulation

- Coherence time – Ramsey fringes





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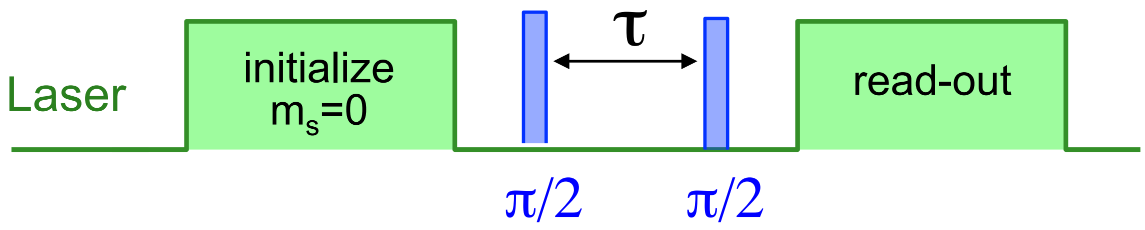
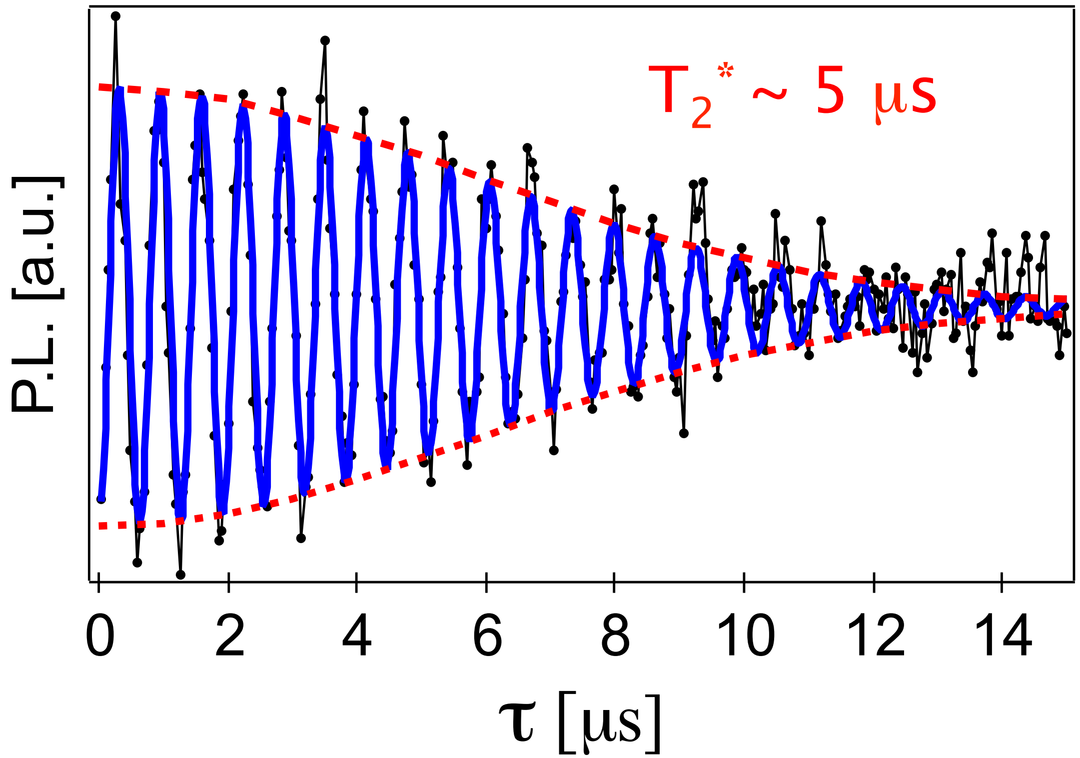
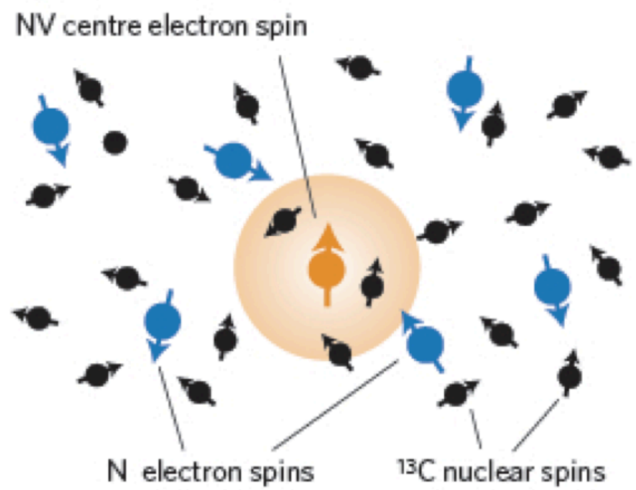




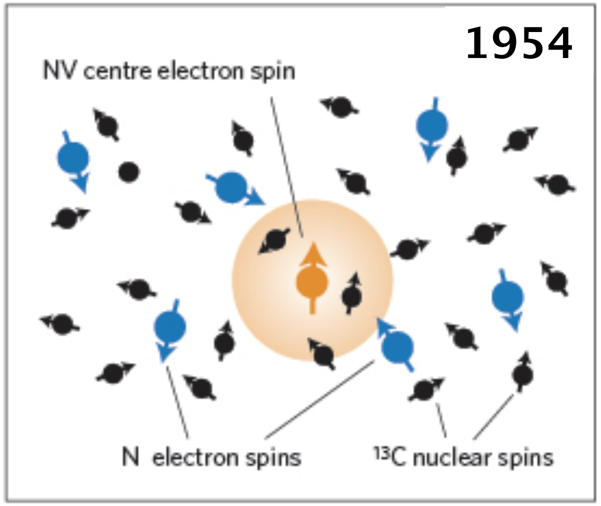
"spin bath" produces random magnetic fields

N atoms, S=1/2

^{13}C atoms, I=1/2



Engineering the diamond lattice

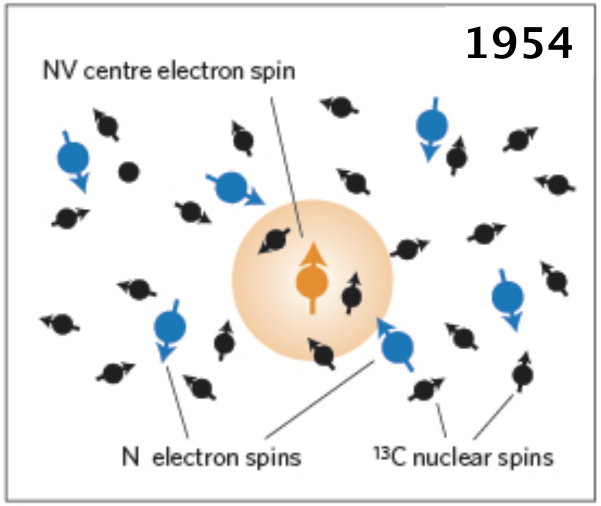


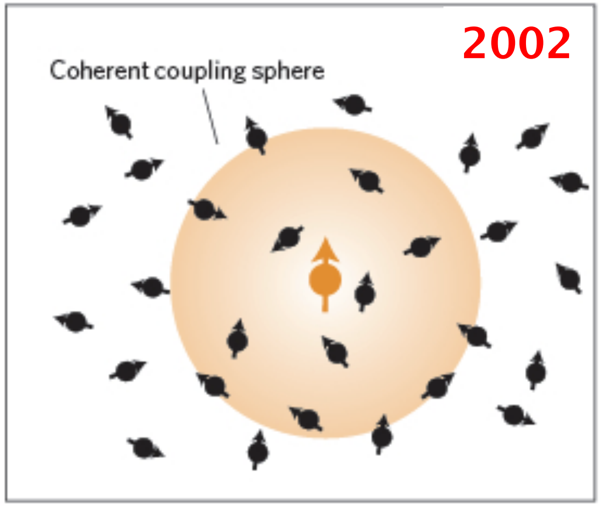
High Pressure High Temperature
(HPHT diamond)

$$[\mathrm{N}] \simeq 100\,\mathrm{ppm}$$
$$[^{13}\mathrm{C}] \simeq 1,1\%$$

$T_2^* \sim 100$ ns

Engineering the diamond lattice



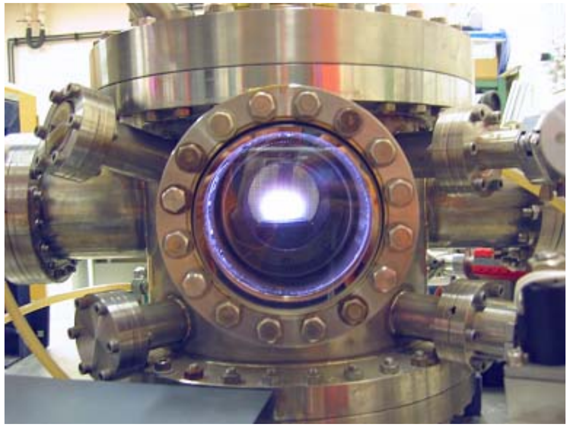


High Pressure High Temperature *(HPHT diamond)*

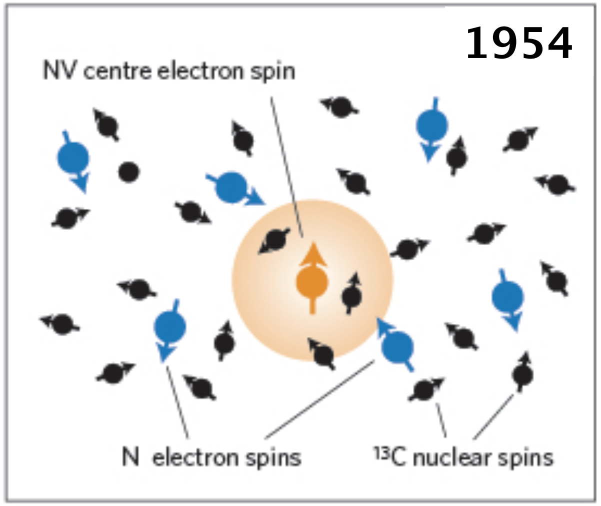
$$[\mathrm{N}] \simeq 100\,\mathrm{ppm}$$
$$[^{13}\mathrm{C}] \simeq 1,1\%$$

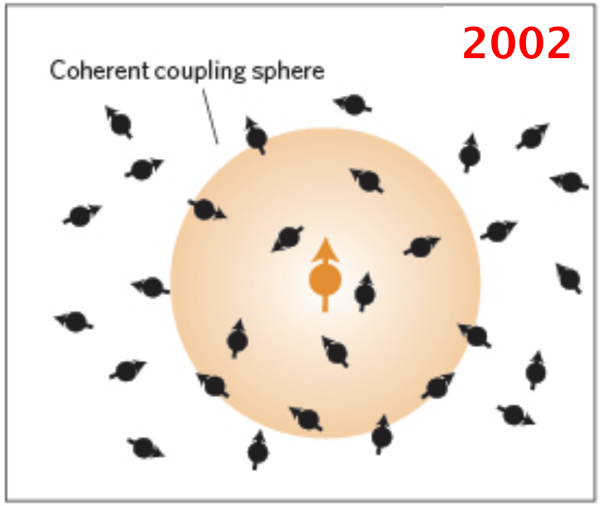
$T_2^* \sim 100$ ns

CVD diamond



Engineering the diamond lattice





High Pressure High Temperature *(HPHT diamond)*

$[\mathrm{N}] \simeq 100\,\mathrm{ppm}$

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$T_2^* \sim 100$ ns

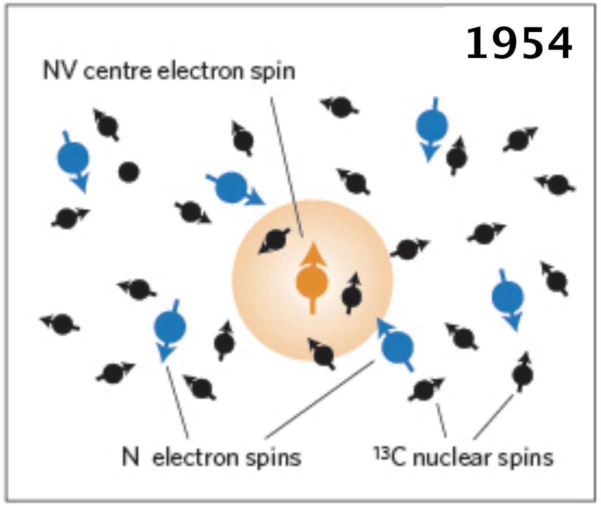
CVD diamond

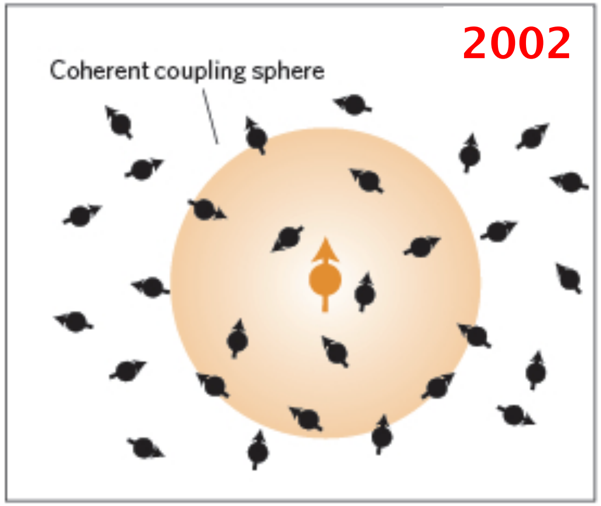
$[\mathrm{N}] \simeq 1\,\mathrm{ppb}$

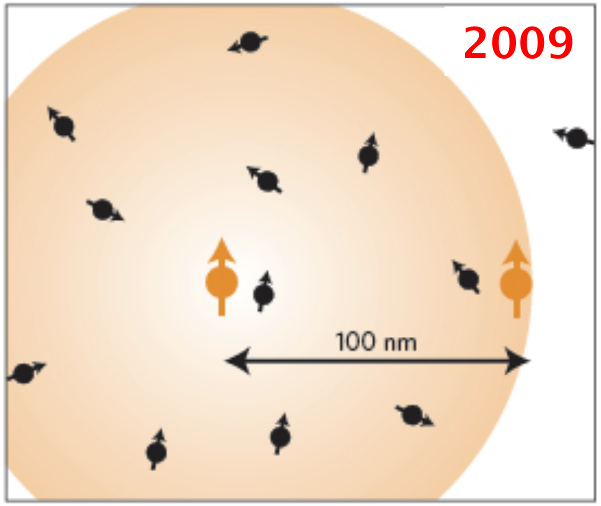
$[^{13}\mathrm{C}] \simeq 1,1\%$

$T_2^* \sim 5\ \mu$s

Engineering the diamond lattice







High Pressure High Temperature
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CVD diamond

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$[^{13}\mathrm{C}] \simeq\ 1,1\%$

$T_2^* \sim 5\ \mu s$

Isotopically modified CVD-diamond

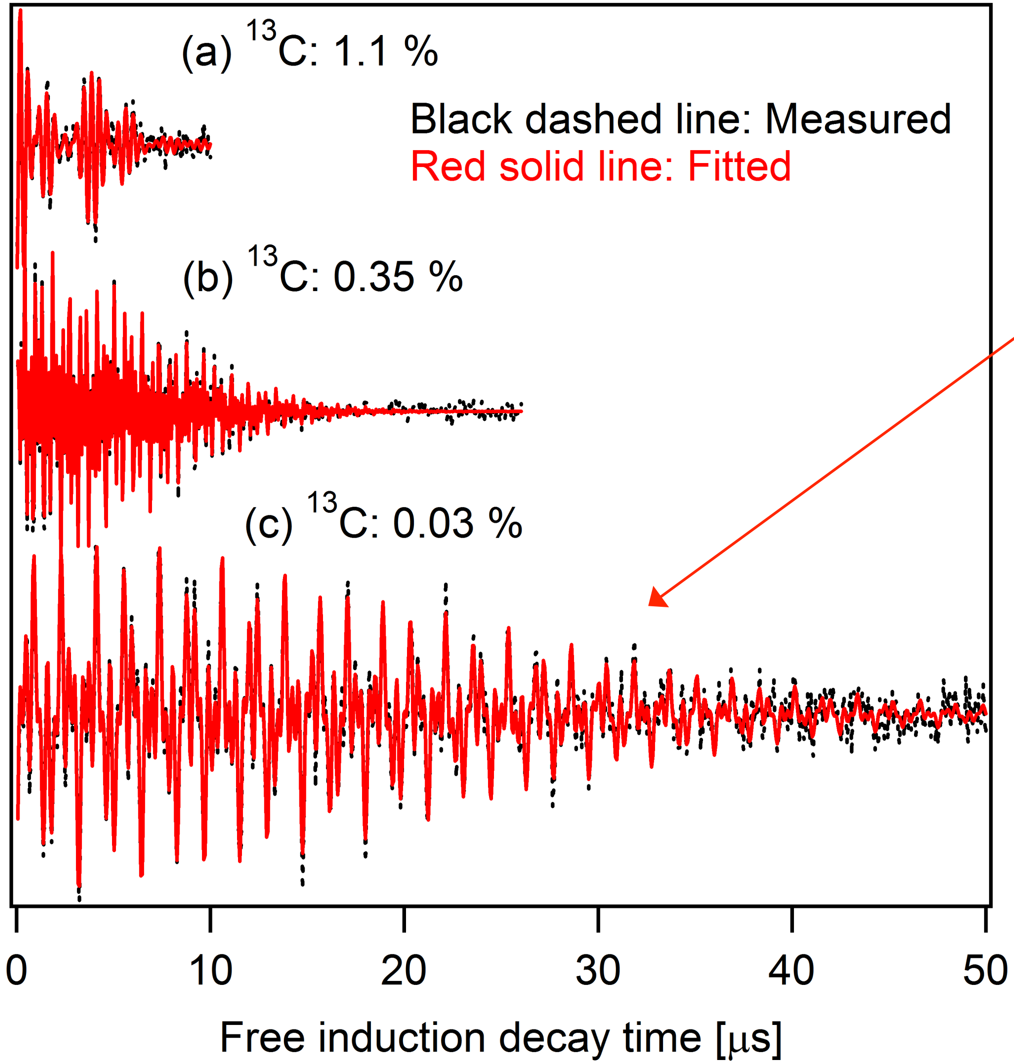
$[\mathrm{N}] \simeq 1\,\mathrm{ppb}$
$[^{13}\mathrm{C}] \simeq\ 0,01\%$

Spin-free lattice

Engineering the diamond lattice

Isotopically modified CVD-diamond

D. Twitchen, *Element 6*



99,97 % ^{12}C diamond
Spin free matrix

$T_2^* \sim 50\ \mu s$

- Balasubramanian, *Nat. Mater.* **8**, 383 (2009)
- Mizuochi, *PRB* **80**, 041201 (2009)

99,999 % ^{12}C diamond

$$T_2^* \approx 500\ \mu s$$

@ room T

Maurer, *Science* 336, 1283 (2012)

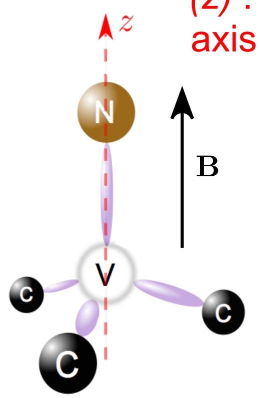
Engineering the spin Hamiltonian

$$\mathcal{H} = DS_z^2 + \gamma_e B S_z + E(S_x^2 - S_y^2)$$

zero-field splitting ~ 3 GHz

e-spin Zeeman ~ 3 MHz/G

Strain/electric field *E*~100 kHz



(z) : quantization axis of the defect

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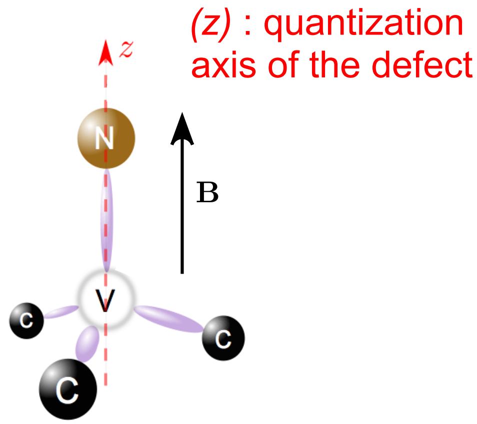
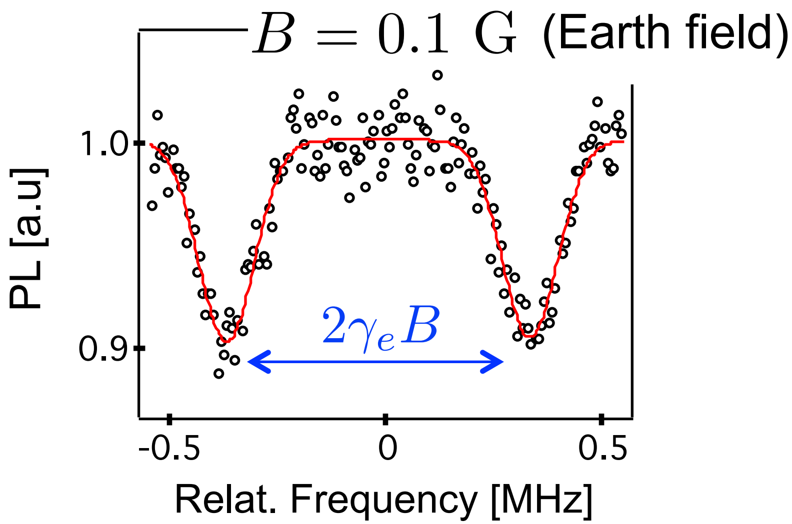


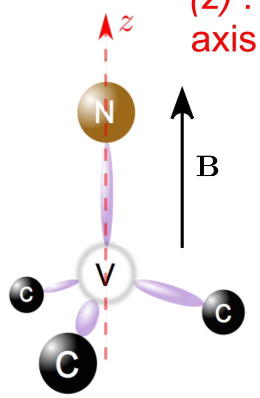
- If $|\gamma_e B| \gg E$

$\{|0_e\rangle, |+1_e\rangle, |-1_e\rangle\}$

$\nu_\pm = D \pm \gamma_e B$



Engineering the spin Hamiltonian



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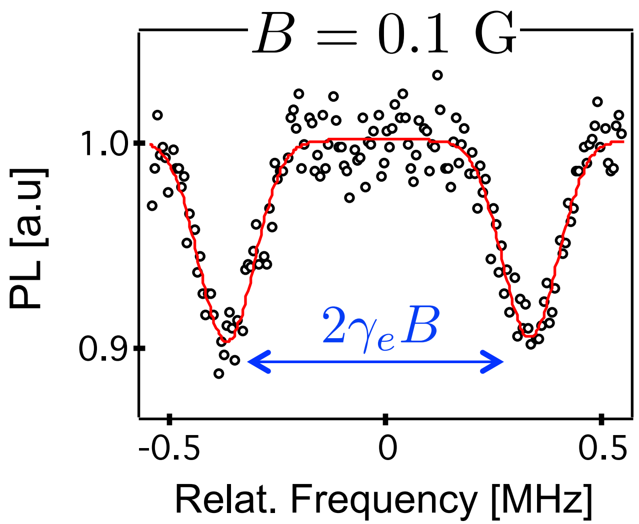

- If $|\gamma_e B| \ll E$

$$\{|0_e\rangle, |+_e\rangle, |-_e\rangle\}$$

$$|+_e\rangle = \frac{1}{\sqrt{2}}(|+1_e\rangle + |-1_e\rangle)$$

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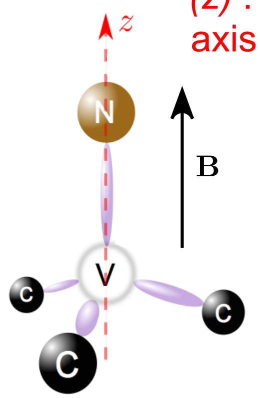

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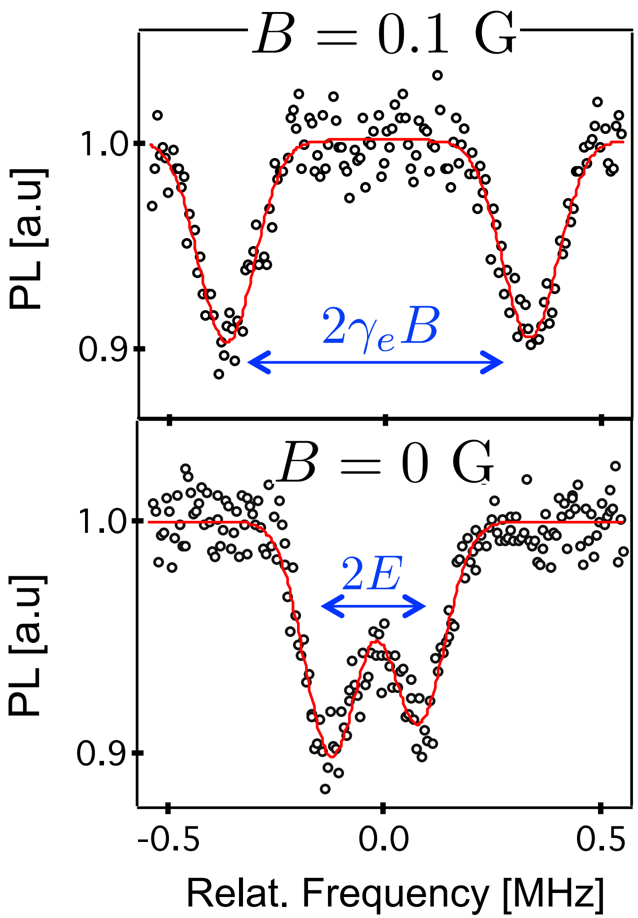

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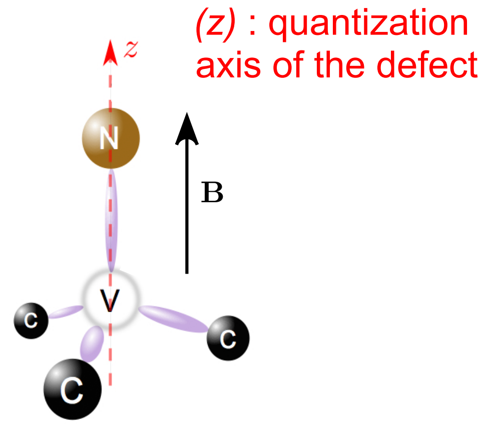

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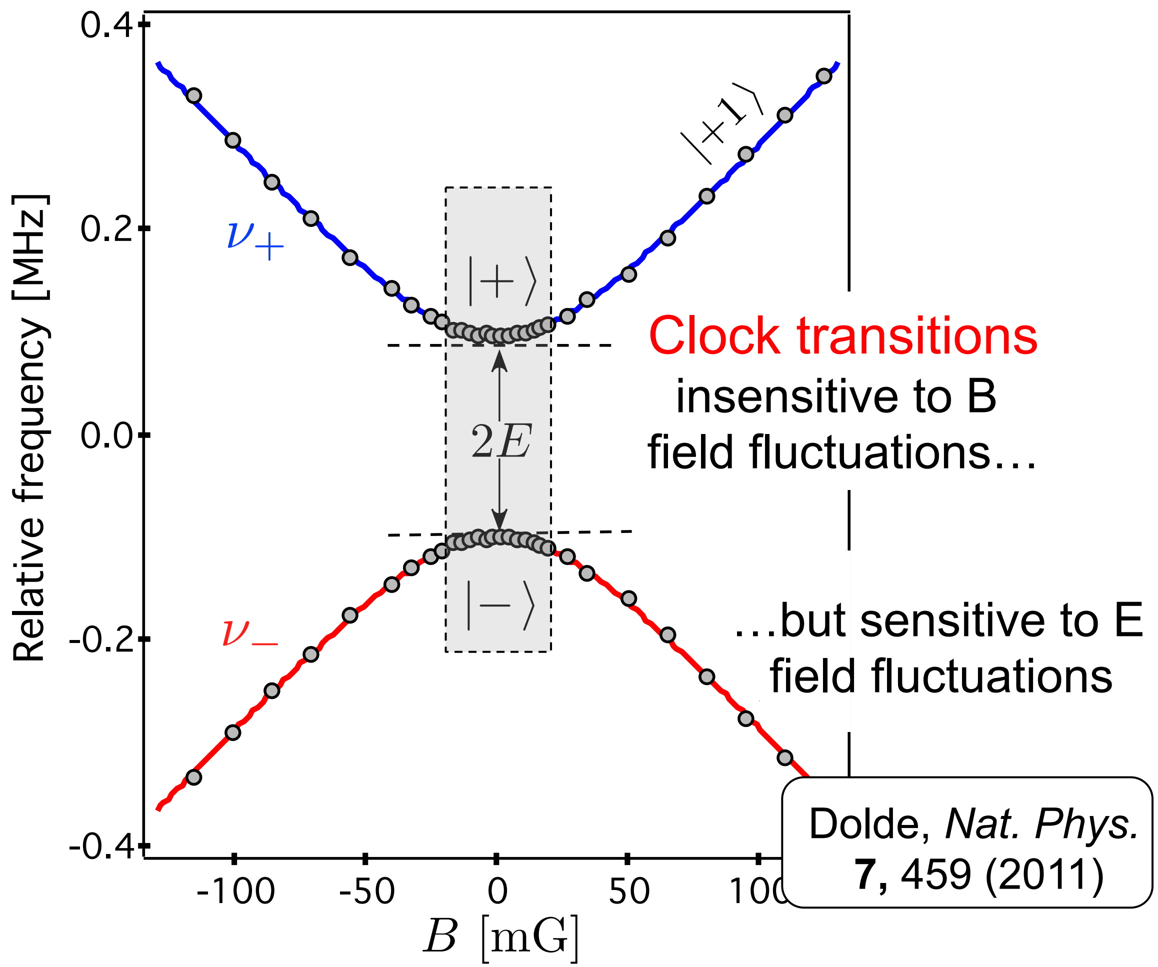
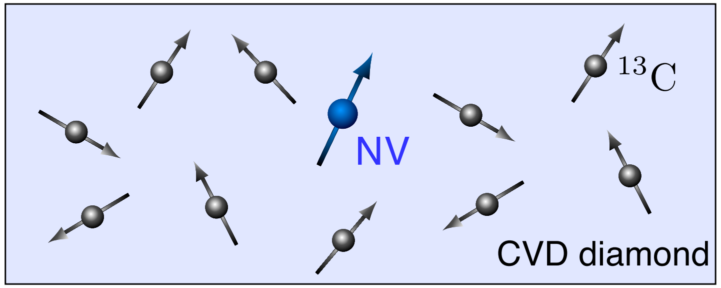
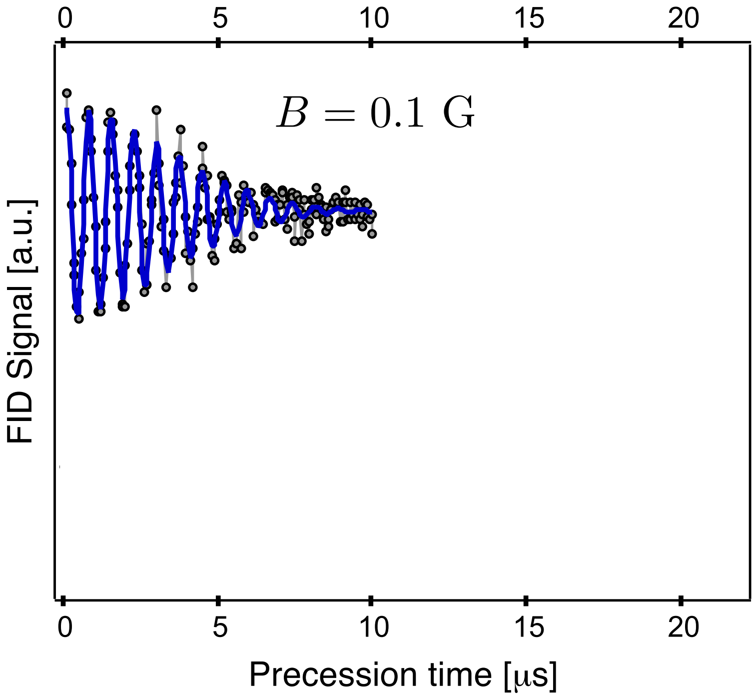


Working at the clock transitions…

Jamonneau, PRB **93**, 024305 (2016)



$$[^{13}\mathrm{C}] = 1.1\%$$



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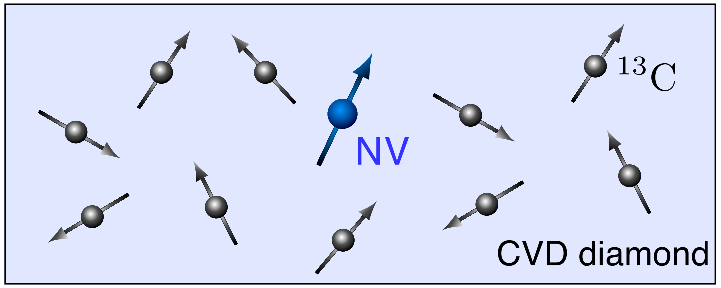

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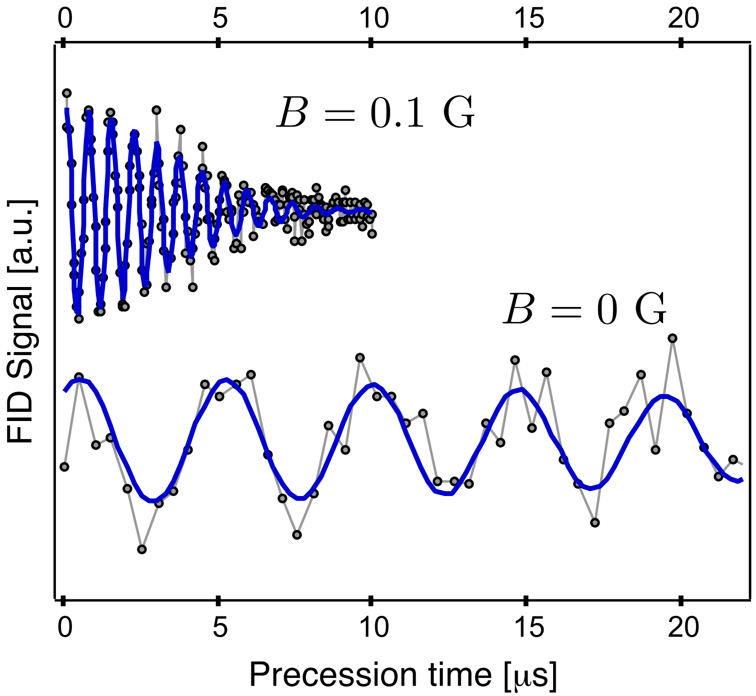

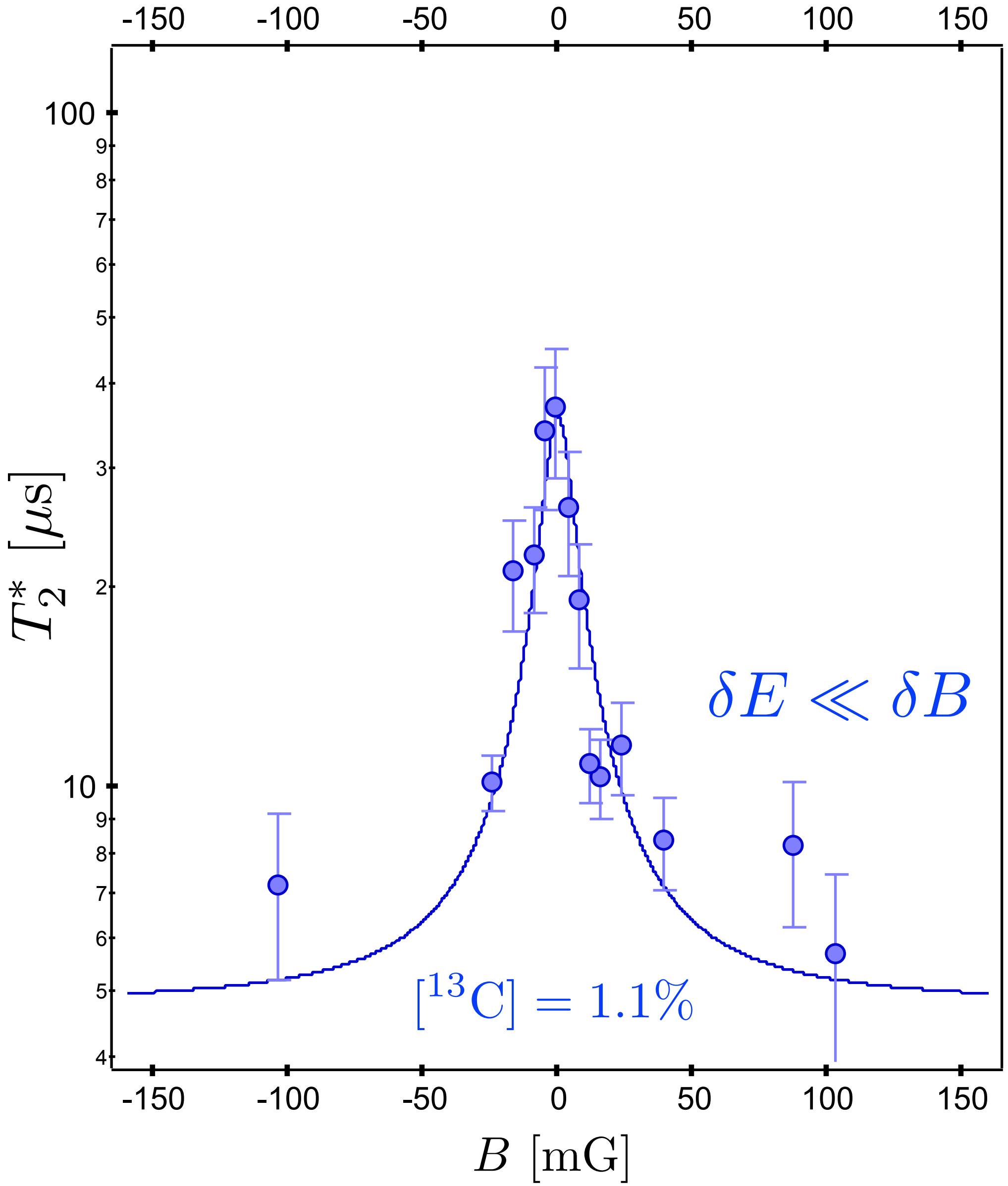

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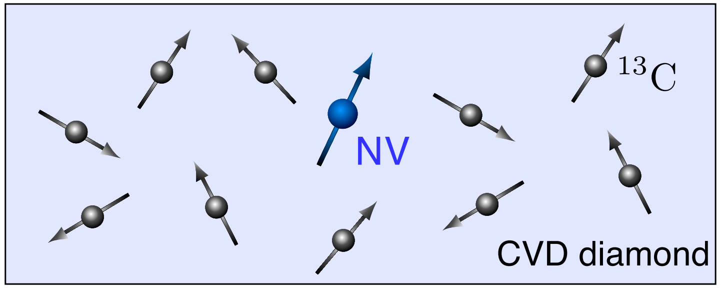
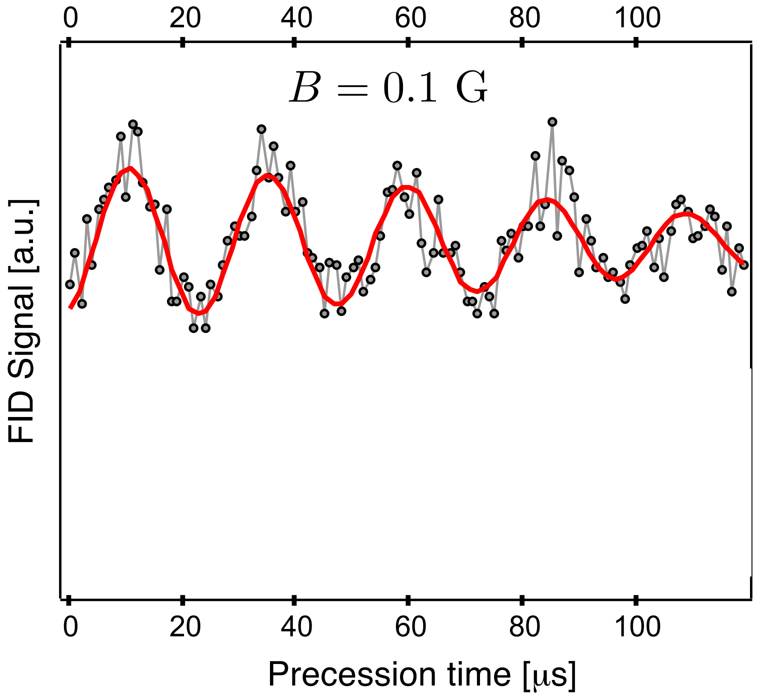
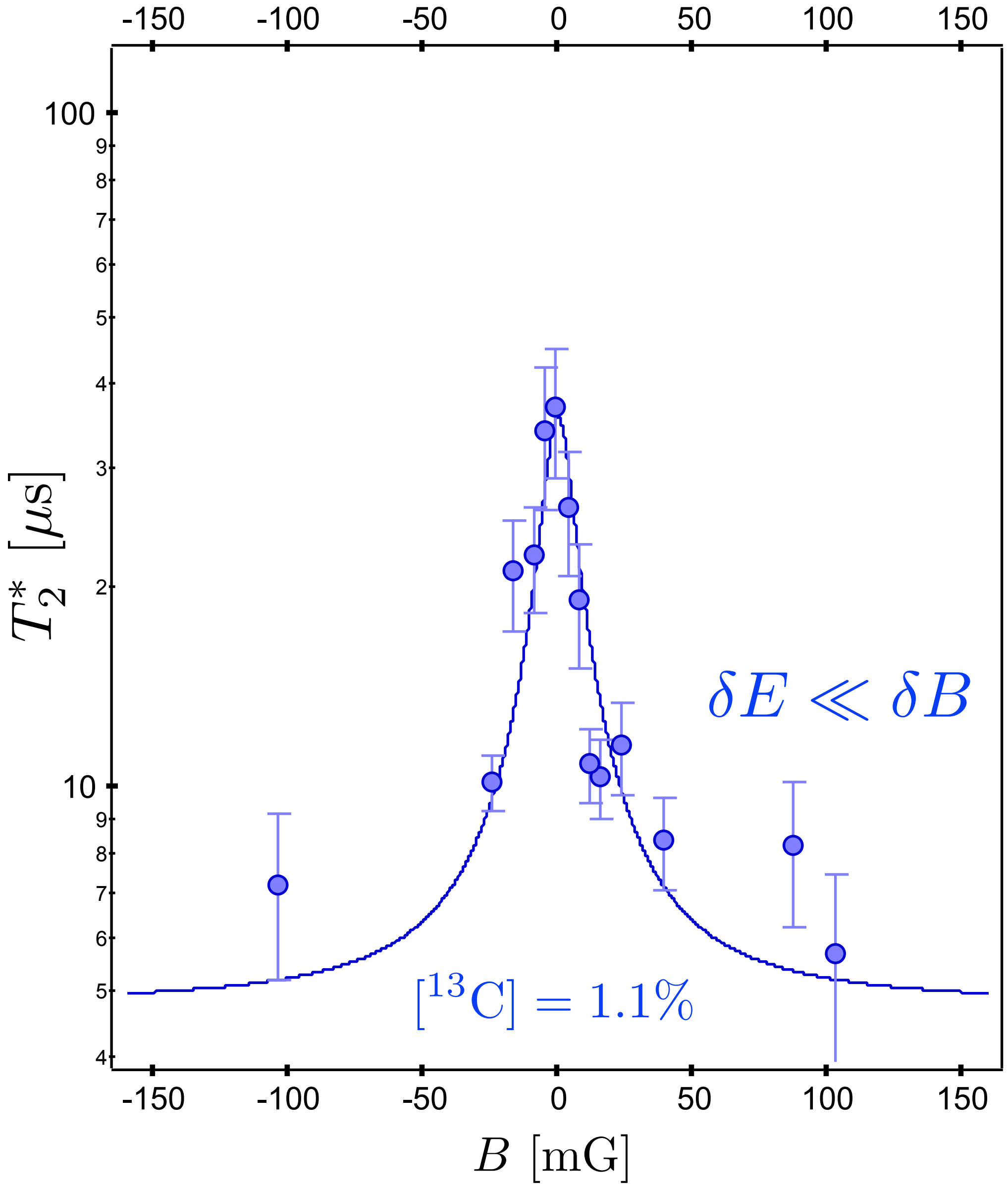
Jamonneau, PRB **93**, 024305 (2016)



$[^{13}\mathrm{C}] = 0.002\ \%$





Working at the clock transitions…

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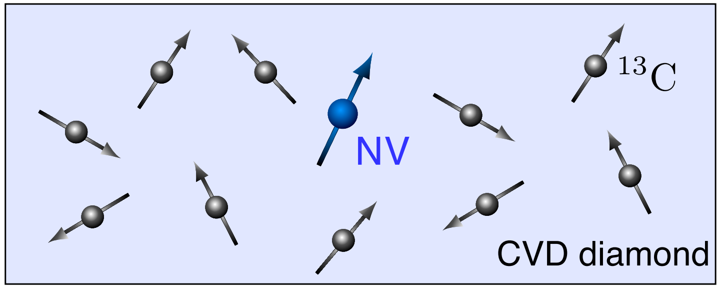

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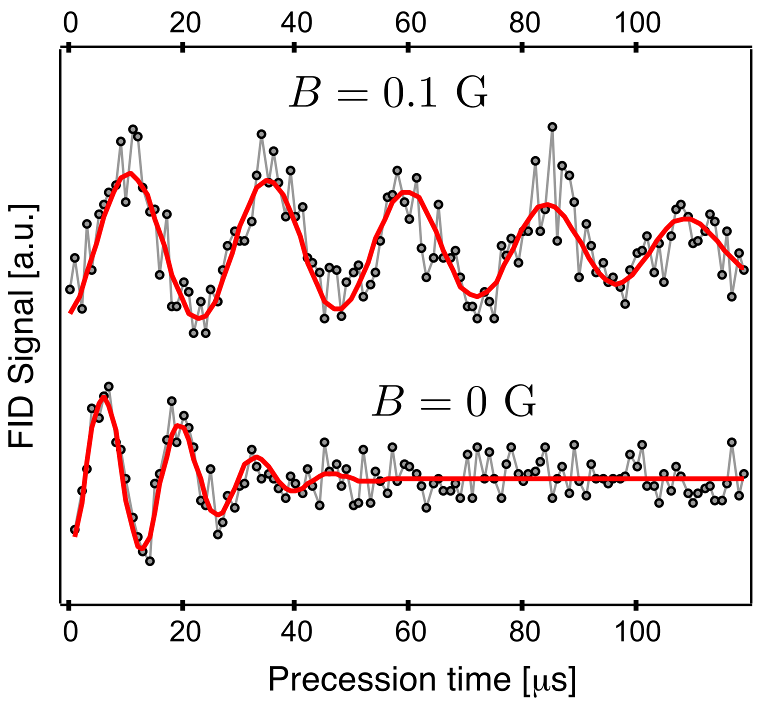

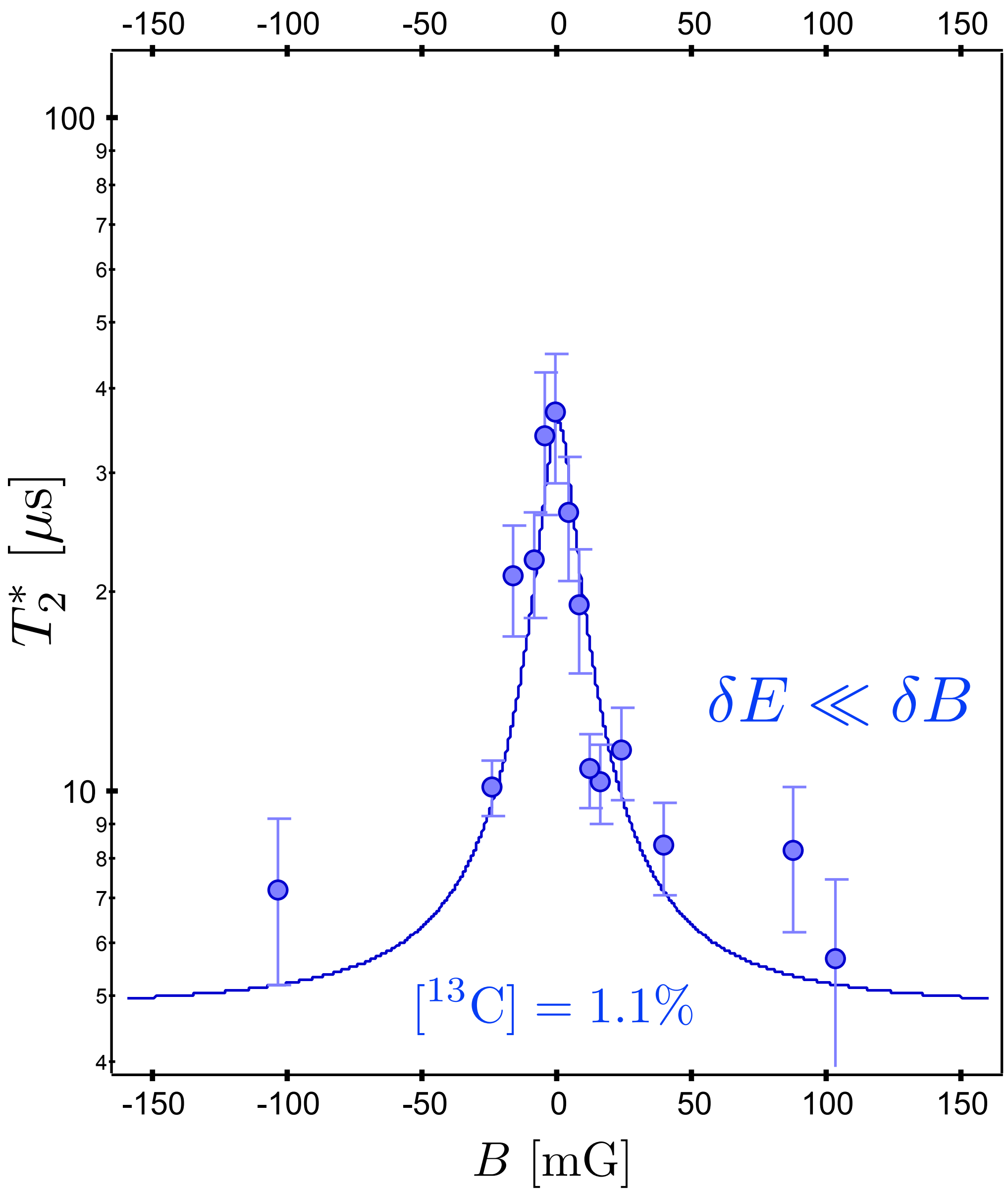

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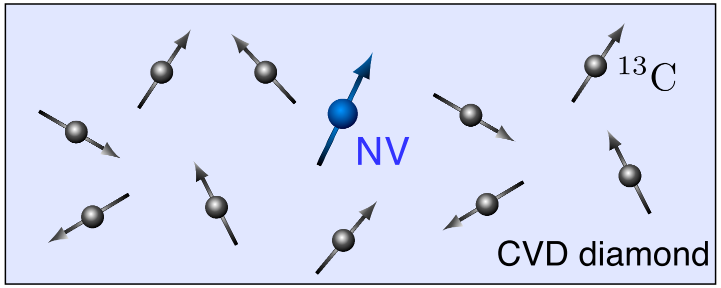

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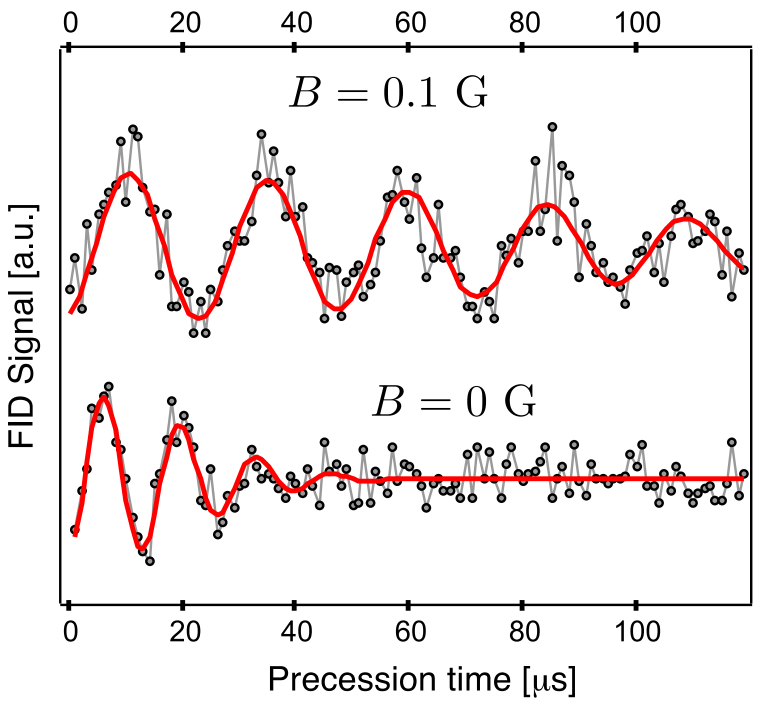
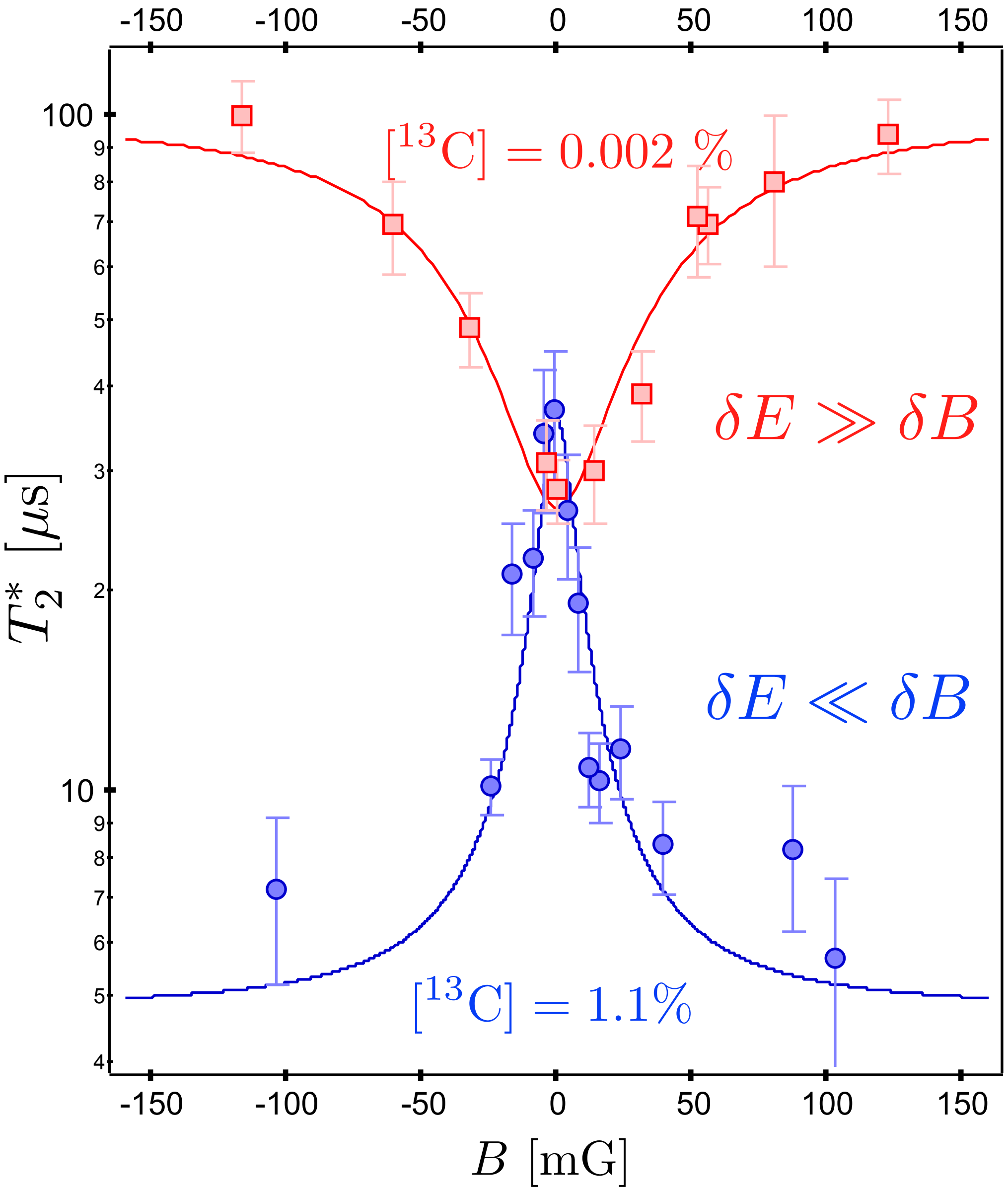
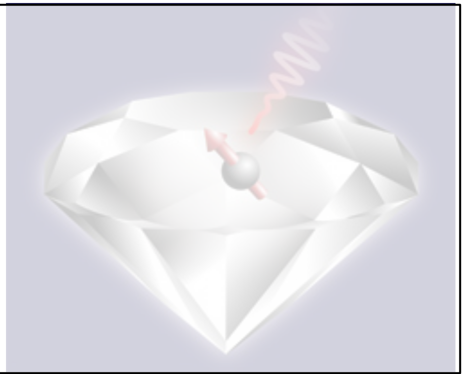




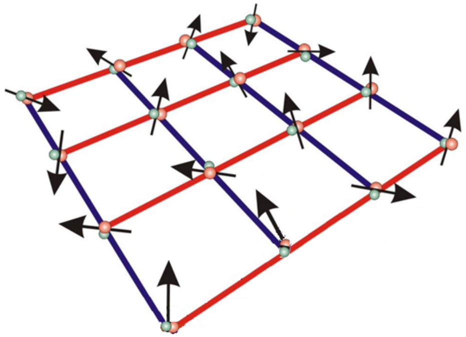
Outline

1. The NV defect in diamond

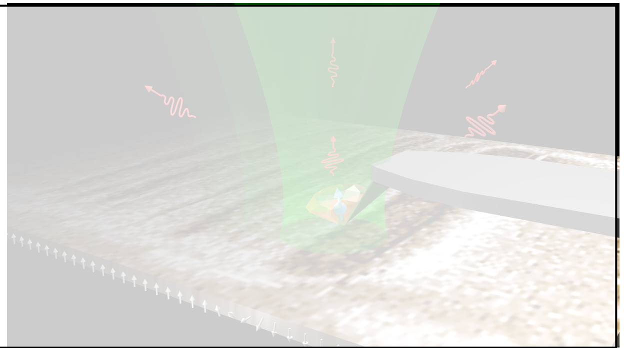
Main properties



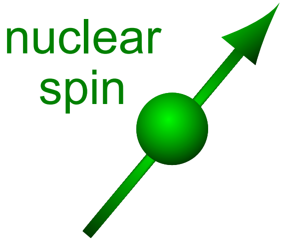
2. Applications in 'quantum information science'



3. Magnetic sensing with a single NV defect



Nuclear spins as qubits

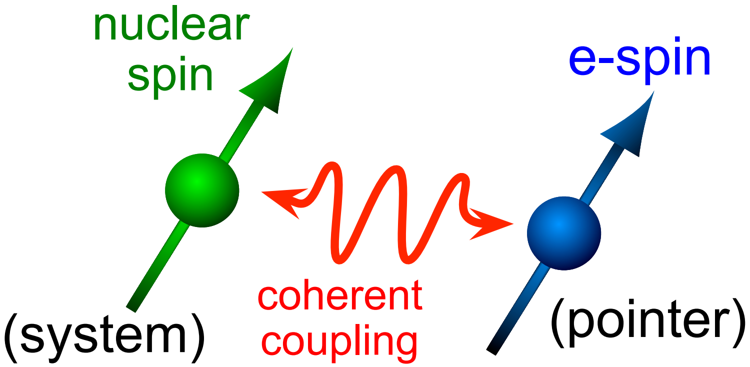


High isolation from the environment

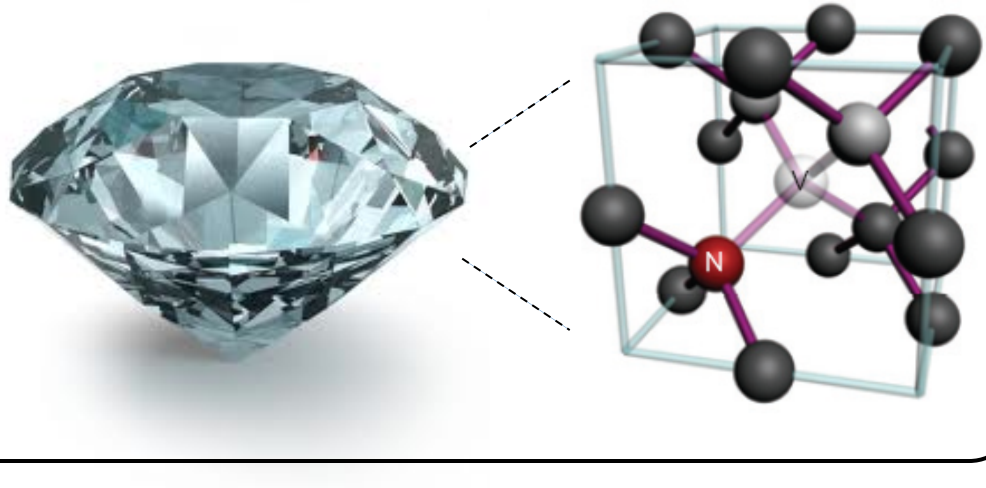
- ➢ long coherence times
- ➢ hard to detect and control single nuclear spin

One strategy : use an ancillary electronic spin as a detector

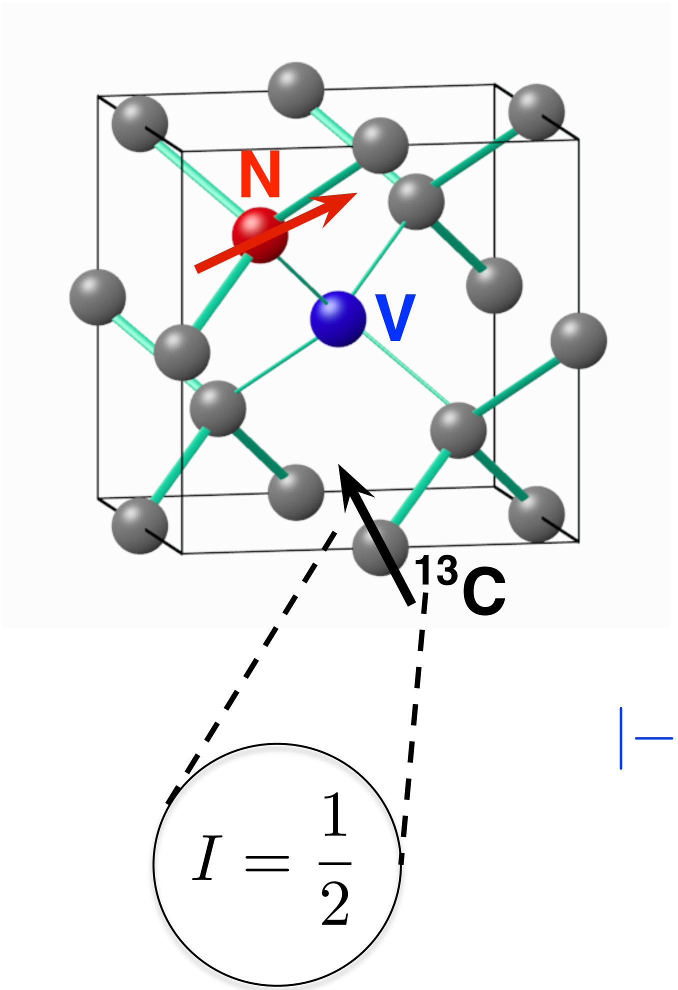
Steger *et al*. *Science* **336**, 1280 (2012)
Neumann *et al*. *Science* **320**, 1326 (2008)

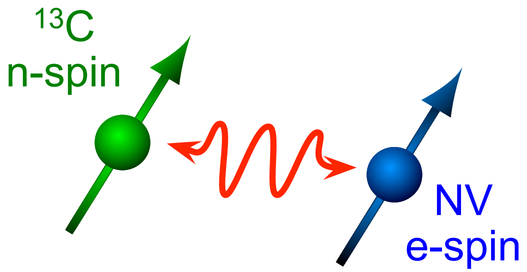


single NV defect in diamond



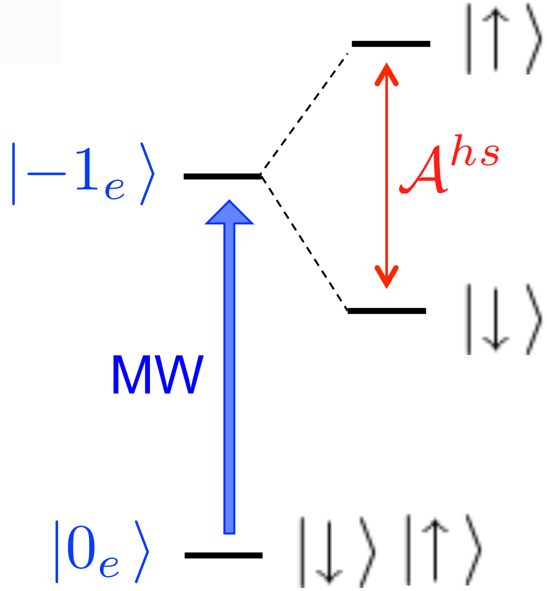
Coupling with nearby nuclear spins

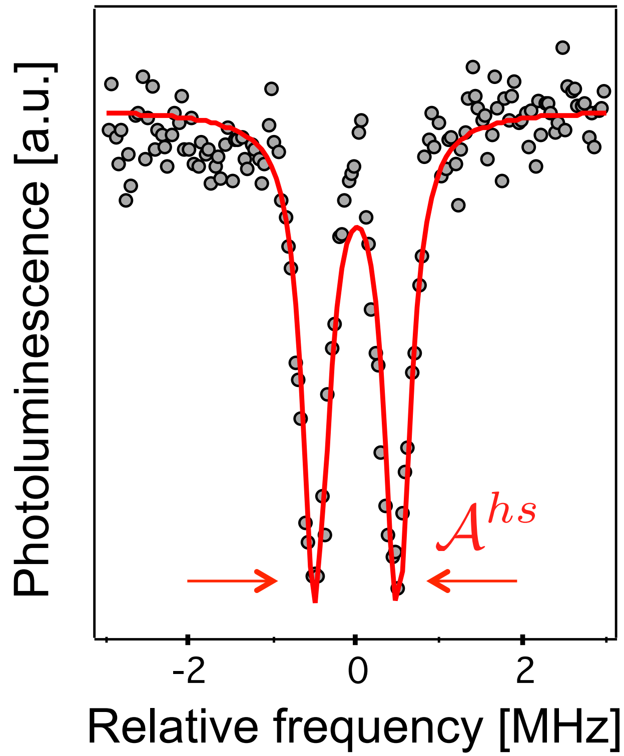




Hyperfine interaction

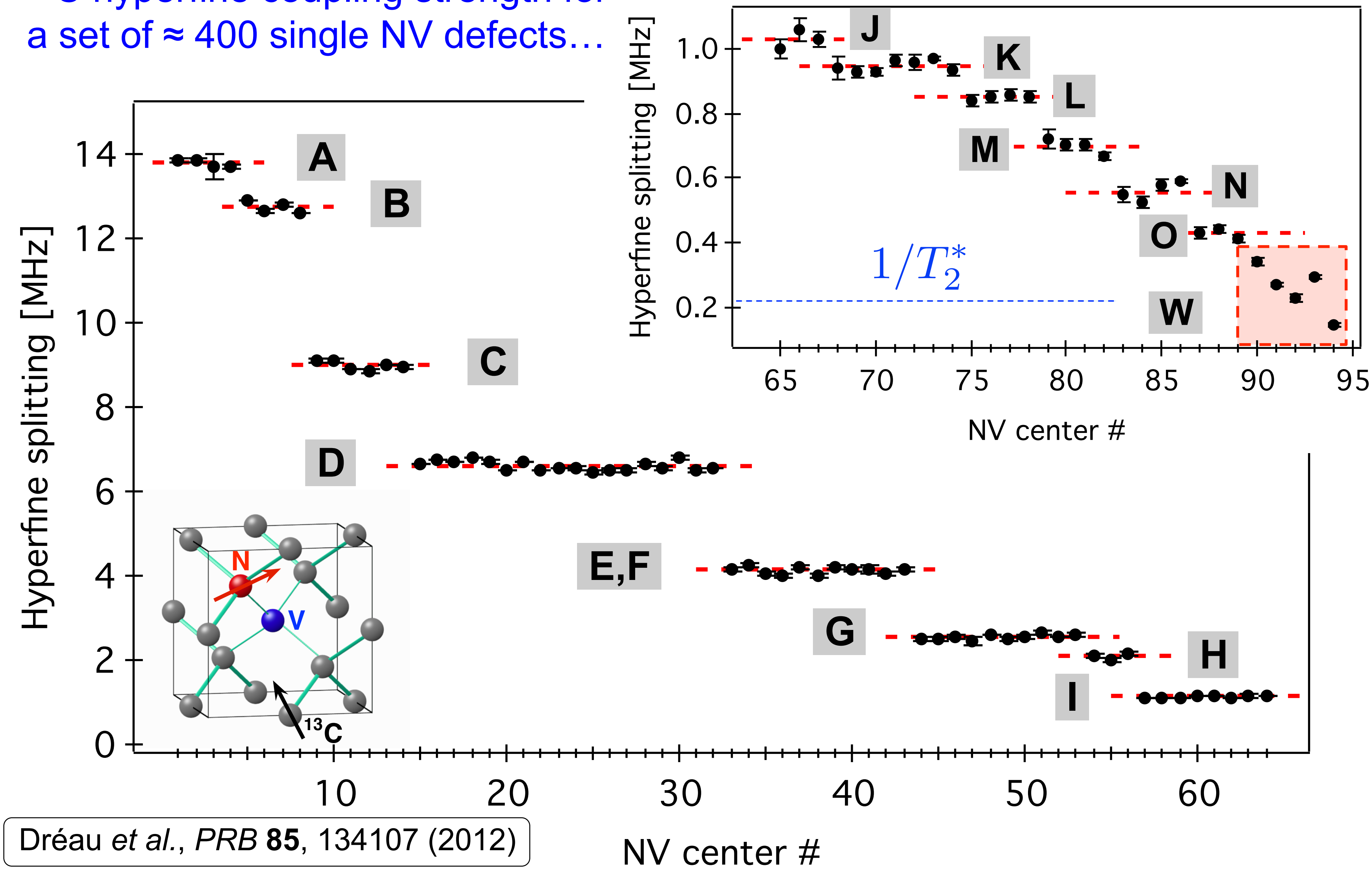
$$\mathcal{H}_{hi} \simeq \mathcal{A}^{hs}\,\hat{S}\cdot\hat{I}$$





Discrete values of ^{13}C hyperfine splittings

- ^{13}C hyperfine coupling strength for a set of ≈ 400 single NV defects…

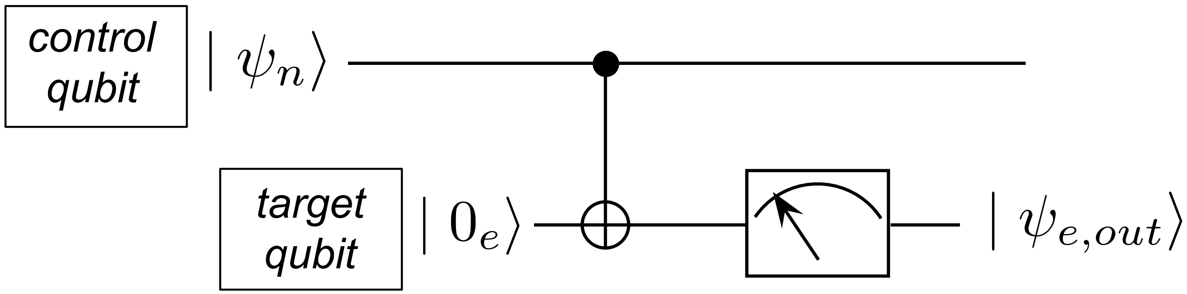


Dréau *et al.*, *PRB* **85**, 134107 (2012)

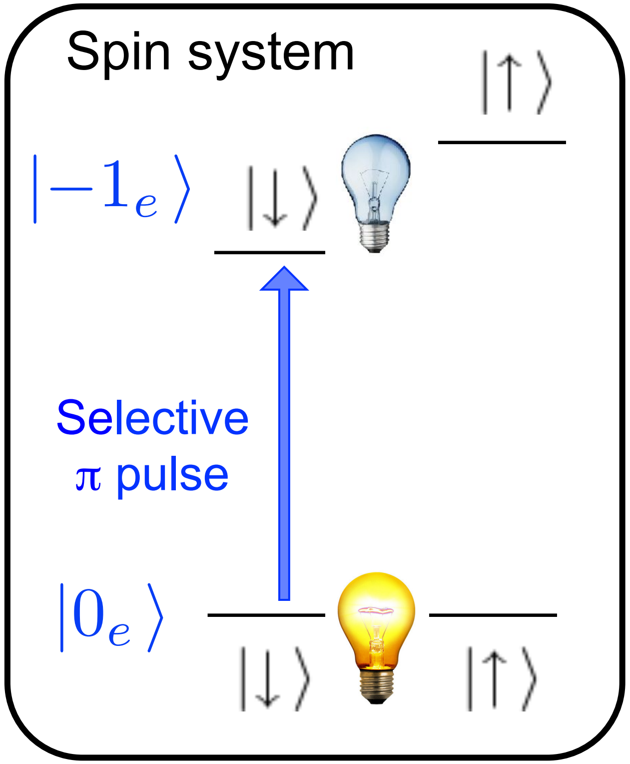
Single-shot readout of a single nuclear spin

➢ Principle

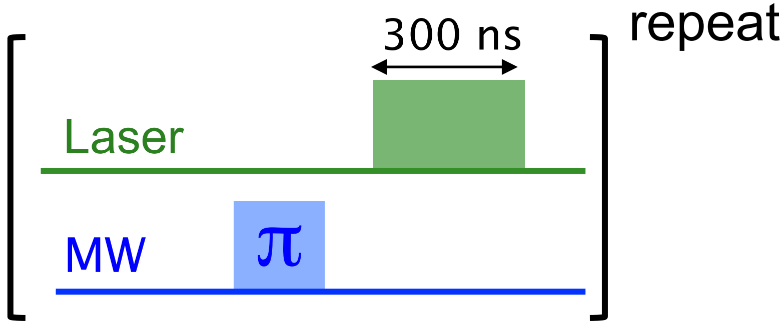
Neumann *et al.*, *Science* **329**, 542 (2010)



$\|\psi_n\rangle$	$\|\psi_{e,out}\rangle$	PL signal
$\|\downarrow\rangle$	$\|-1_e\rangle$	**low**
$\|\uparrow\rangle$	$\|0_e\rangle$	**high**

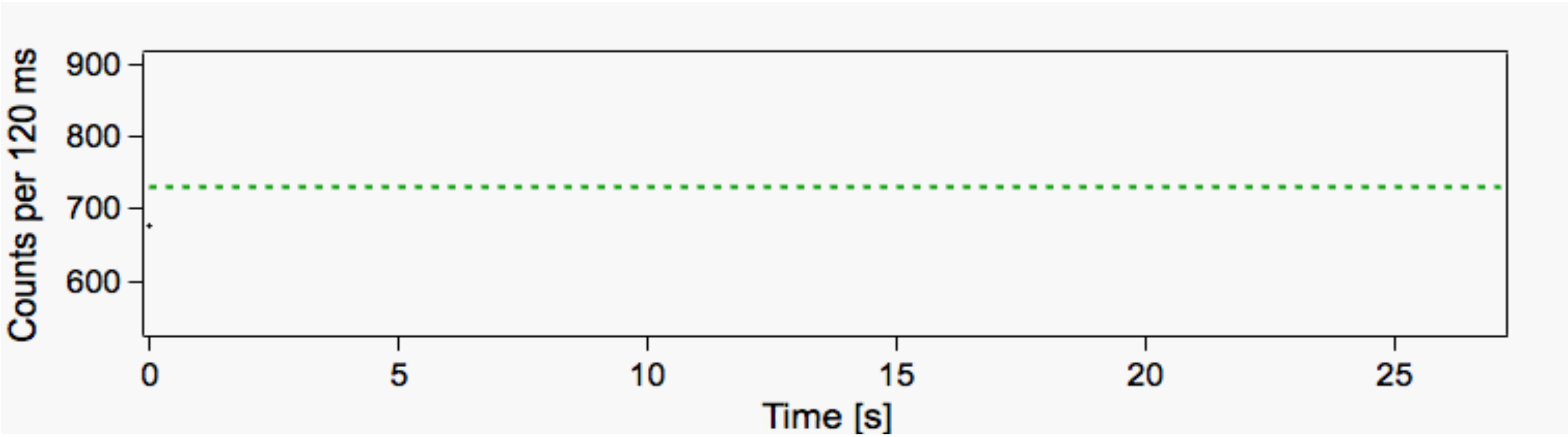


➢ Experimental sequence



Single-shot readout of a single nuclear spin

- Real-time evolution of a single ^{13}C nuclear spin @ room T



Dréau *et al*. *PRL* **110**, 060502 (2013)

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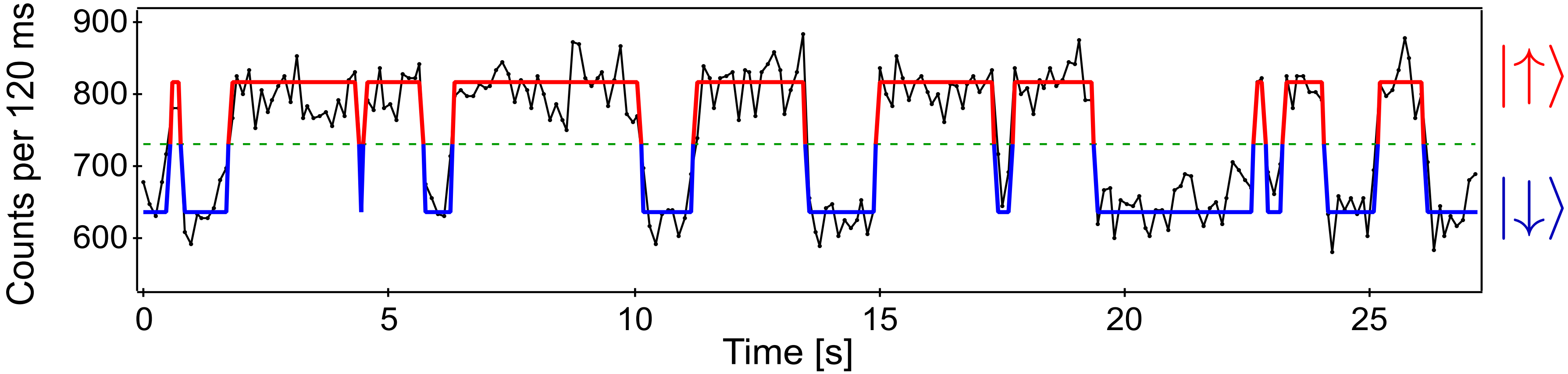

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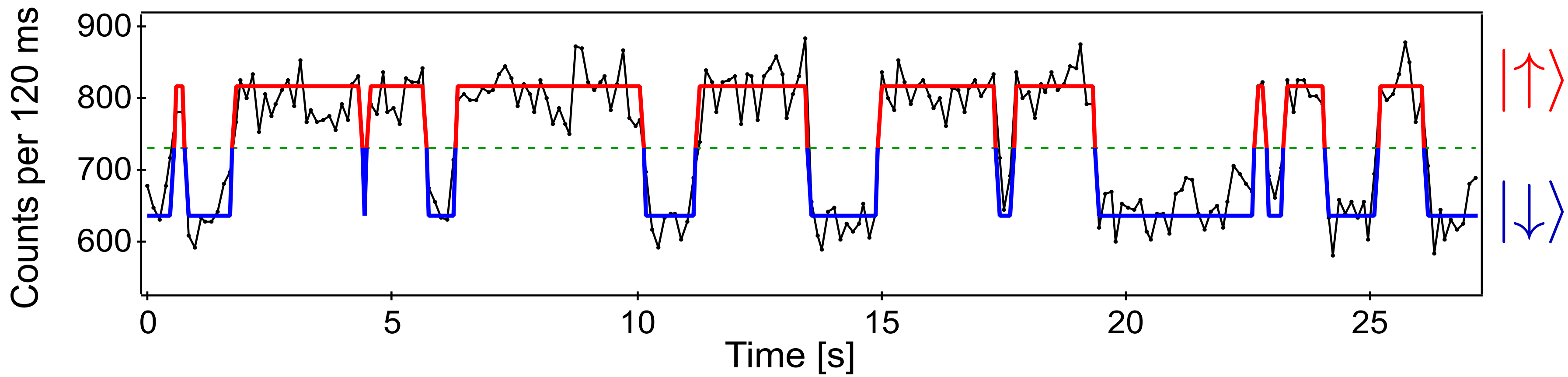
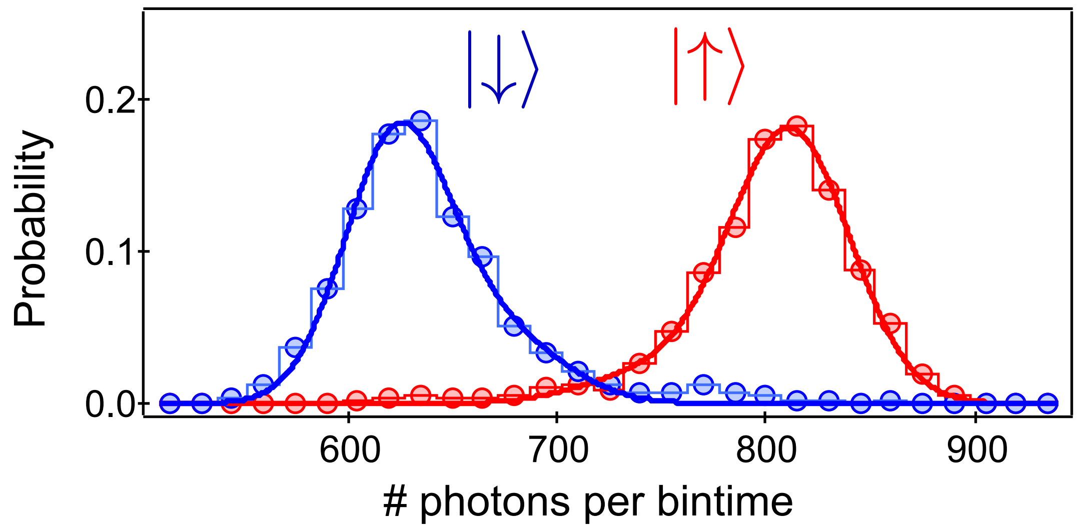


- Nuclear-spin dependent photon counting distributions



Dréau *et al*. *PRL* **110**, 060502 (2013)

Single-shot readout of a single nuclear spin

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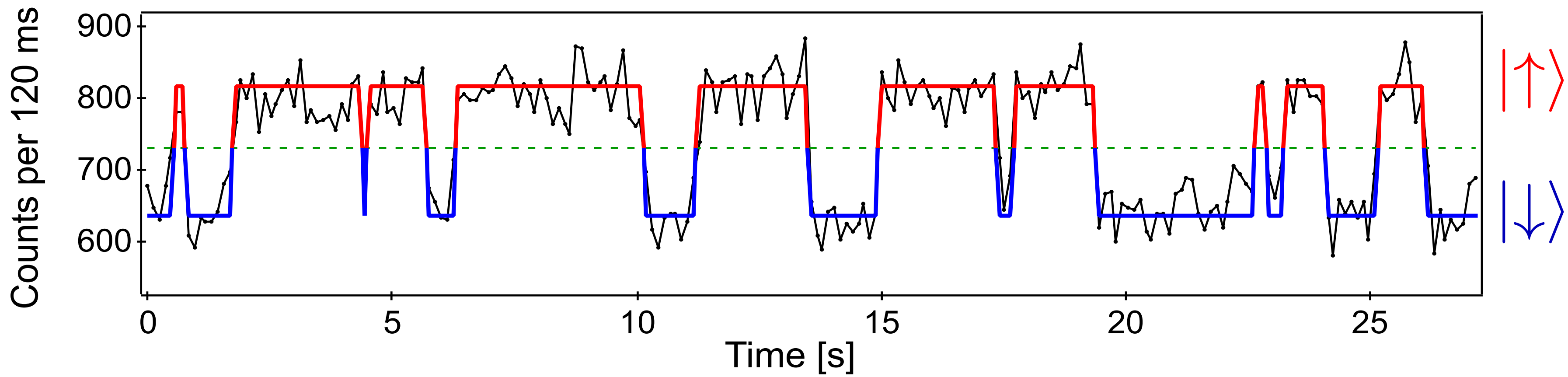

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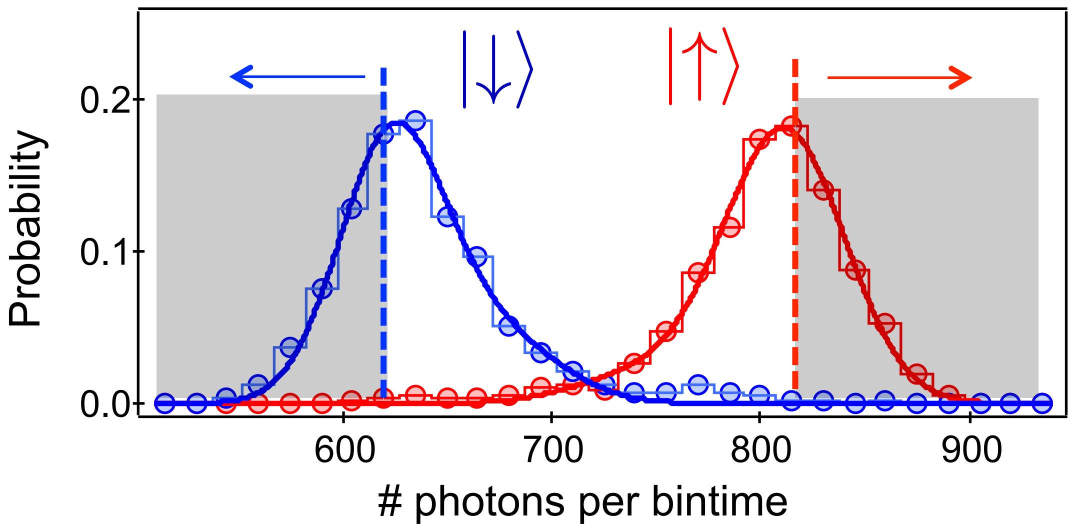

Initialization Fidelity

$$\mathcal{F}_i > 99\%$$

Dréau *et al*. *PRL* **110**, 060502 (2013)

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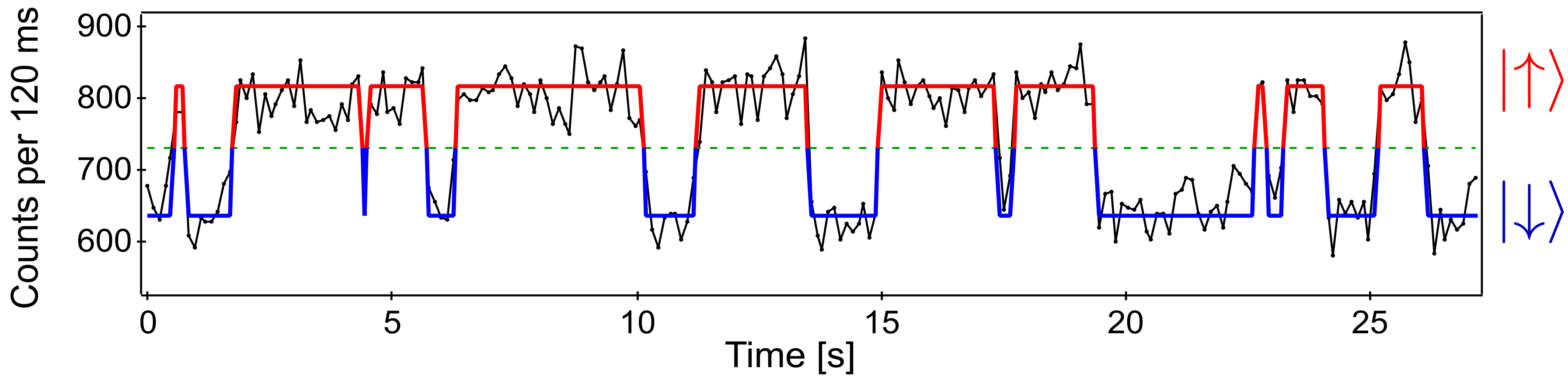

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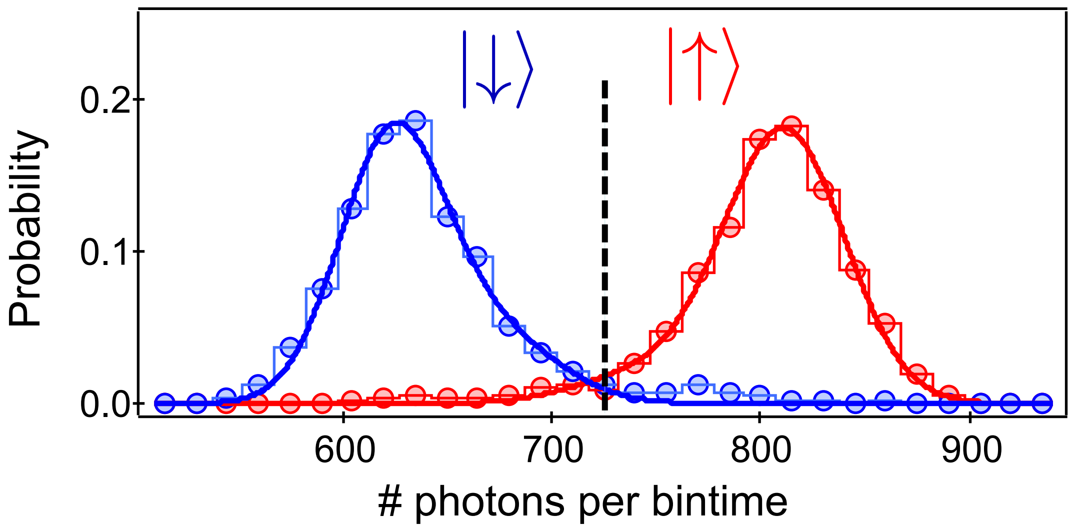


Initialization Fidelity

$$\mathcal{F}_i > 99\%$$

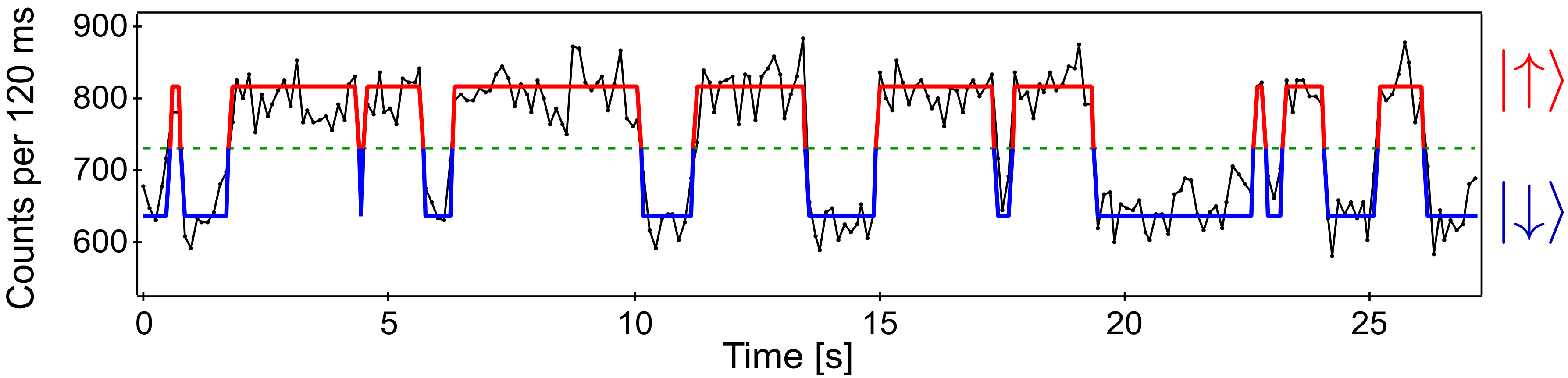
Readout fidelity

$$\mathcal{F}_r = 96 \pm 1\%$$

Dréau *et al*. *PRL* **110**, 060502 (2013)

Single-shot readout of a single nuclear spin

- Real-time evolution of a single ^{13}C nuclear spin @ room T



Probability for « no spin-flip » over a time δt :

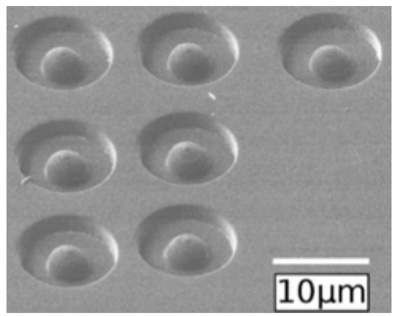
$$e^{-\delta t / T_1}$$

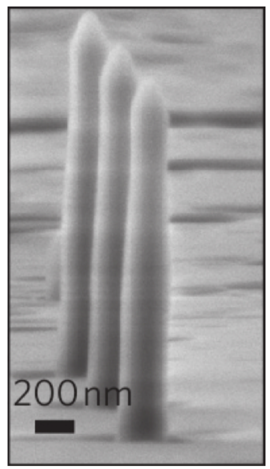
T_1 : nuclear spin lifetime

- Increasing the collection efficiency

  e.g. with SIL or nanopillars

- Increasing the T_1





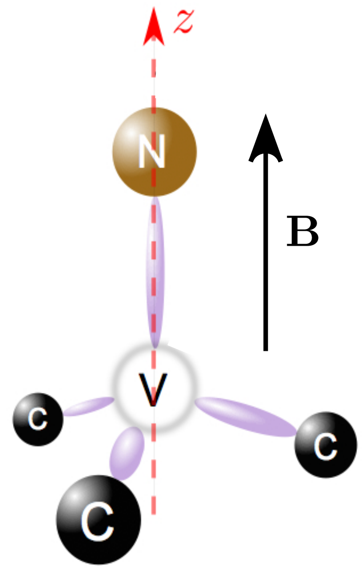
Hadden *et al., APL* (2010)
Babinec *et al., Nat. Nano* (2010)

Nuclear spin relaxation time

Spin Hamiltonian…

$$\mathcal{H} = \underbrace{D_{gs}\hat{S}_z^2 + \gamma_e B \hat{S}_z}_{\mathcal{H}_0} + \underbrace{\gamma_n B \hat{I}_z}_{\text{n-spin Zeeman}} + \underbrace{\hat{\mathbf{S}} \cdot \mathcal{A} \cdot \hat{\mathbf{I}}}_{\text{hyperfine coupling}}$$

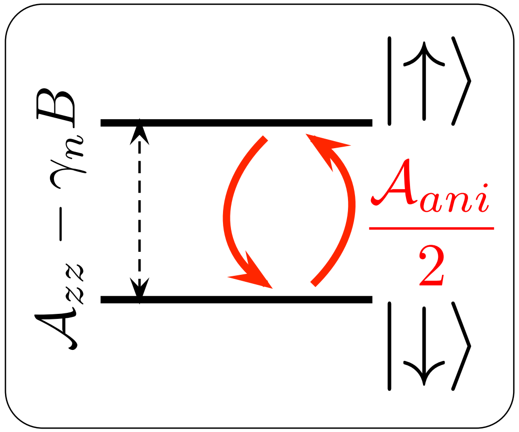
zero-field splitting — $\mathcal{H}_0$ — e-spin Zeeman — n-spin Zeeman — hyperfine coupling



…with secular approximation

$$\mathcal{H} = \mathcal{H}_0 + \gamma_n B \hat{I}_z + \mathcal{A}_{zz}\hat{S}_z\hat{I}_z + \boxed{\frac{\mathcal{A}_{ani}}{2}\left[\hat{S}_z\hat{I}_+ + \hat{S}_z\hat{I}_-\right]}$$

Nuclear-spin flip term

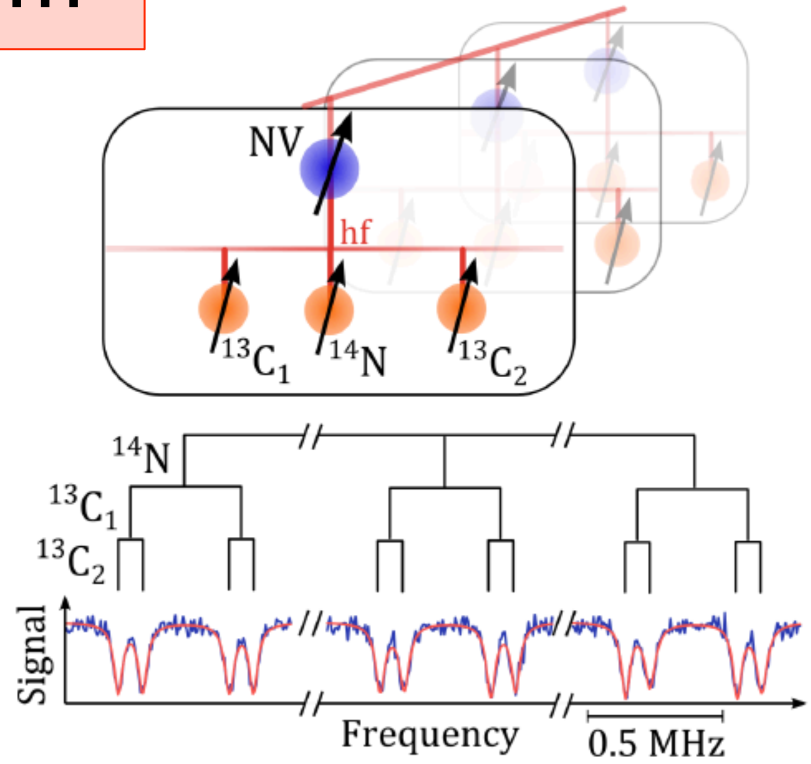


Strength of the depolarization process ⇒

$$\frac{1}{T_1} \propto \frac{\mathcal{A}_{ani}^2}{\mathcal{A}_{ani}^2 + (\mathcal{A}_{zz} - \gamma_n B)^2}$$

Adding more nuclear spins…

- Quantum error correction
  [3 nuclear spins] @ room T



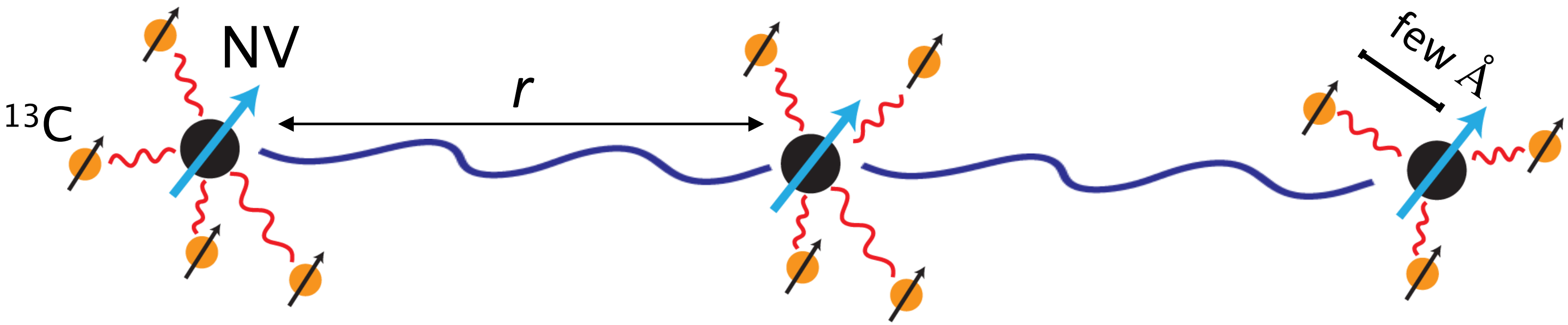
Walderr *et al. Nature* **506**, 204 (2014)

- Real-time observation of the Overhauser field produced by a diluted nuclear spin bath
  [N nuclear spins] @ room T

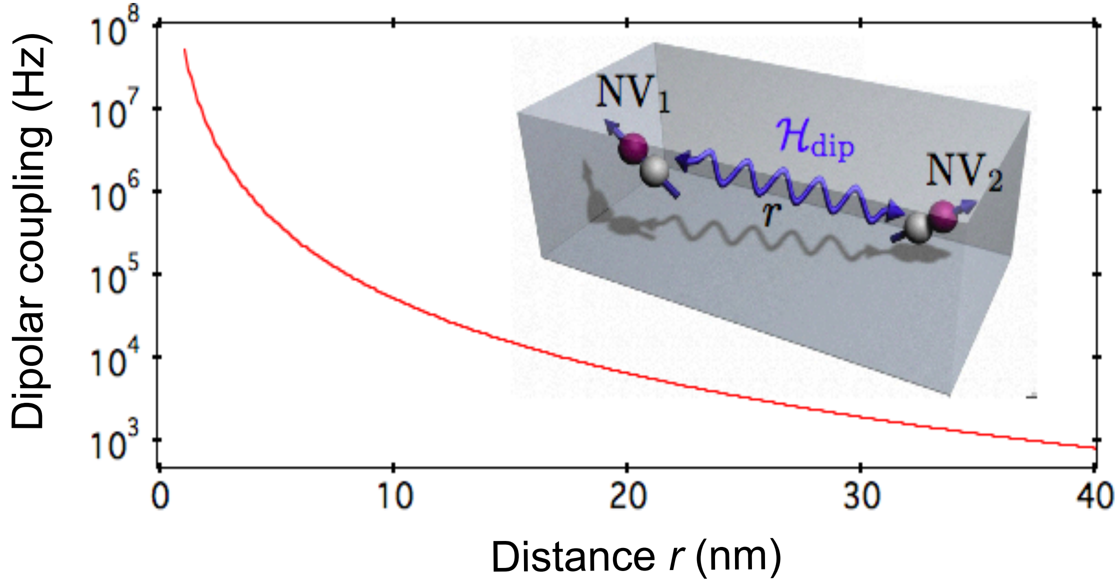
Dréau *et al*. *PRL* **113**, 137601 (2014)

Scaling-up…

P. Neumann, *Nat. Phys.* **6**, 249 (2010)



$$\mathcal{H}_{\rm dip} = \hbar\Omega_{\rm dip} = \frac{\mu_0 g^2 \mu_B^2}{4\pi r^3}\left[\hat{S}_1\cdot\hat{S}_2 - 3(\hat{S}_1\cdot\mathbf{e}_r)(\hat{S}_2\cdot\mathbf{e}_r)\right]$$

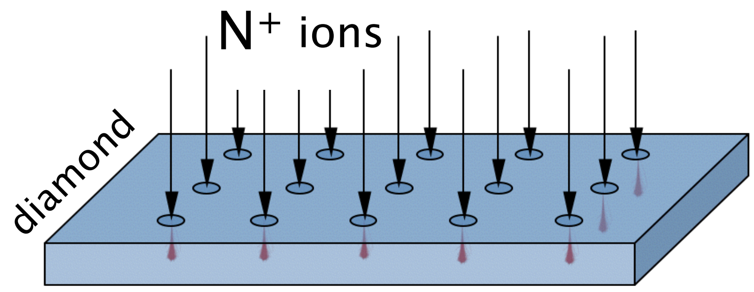


Interaction useful if

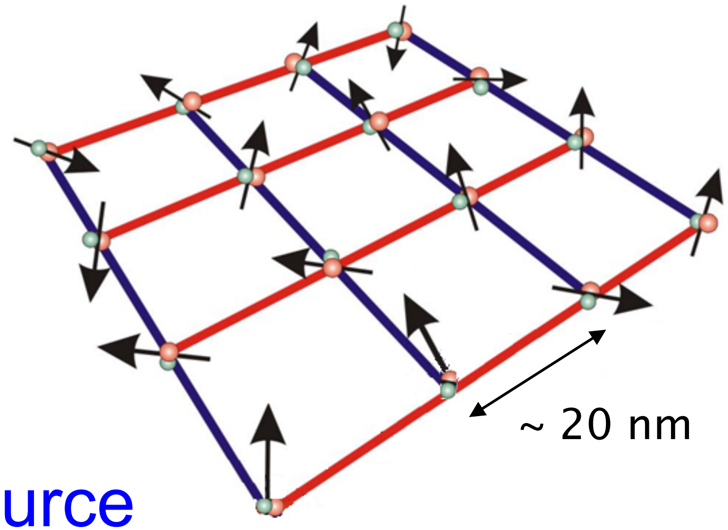
$$\Omega_{\rm dip} > T_2^{-1}$$

$T_2 \sim 1$ ms → $r < 40$ nm

Engineering NV defects by ion implantation



objective



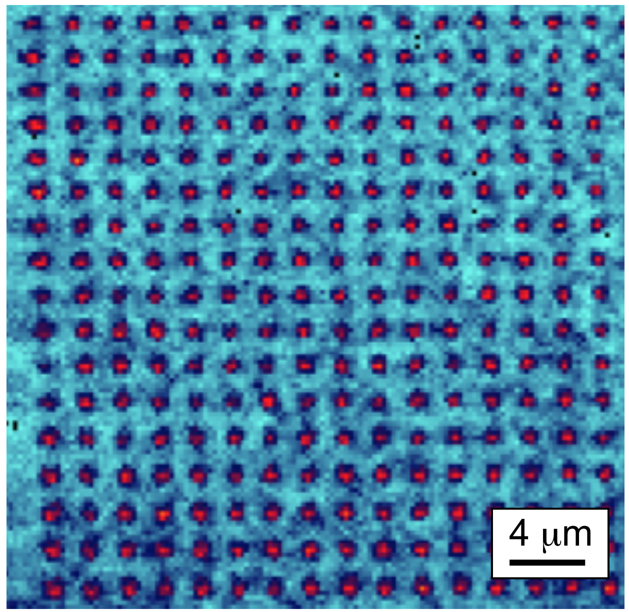
Focused ion beam (FIB) with a N source

NANOSOLUTIONS by ORSAYPHYSICS

J.-F. Roch (LAC)

Current resolution (spot size)

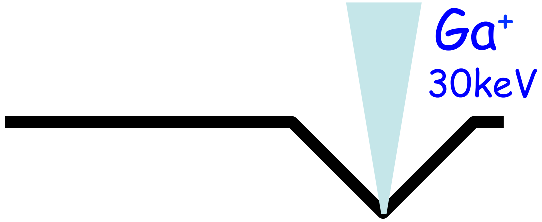
100-150 nm

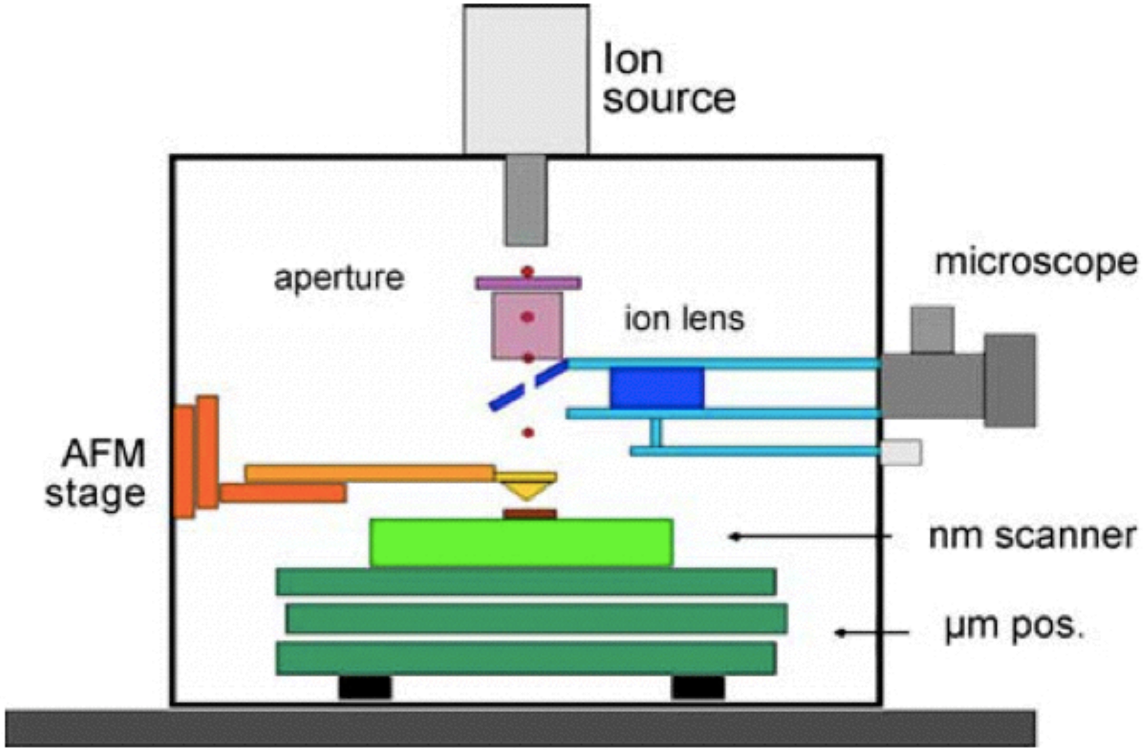


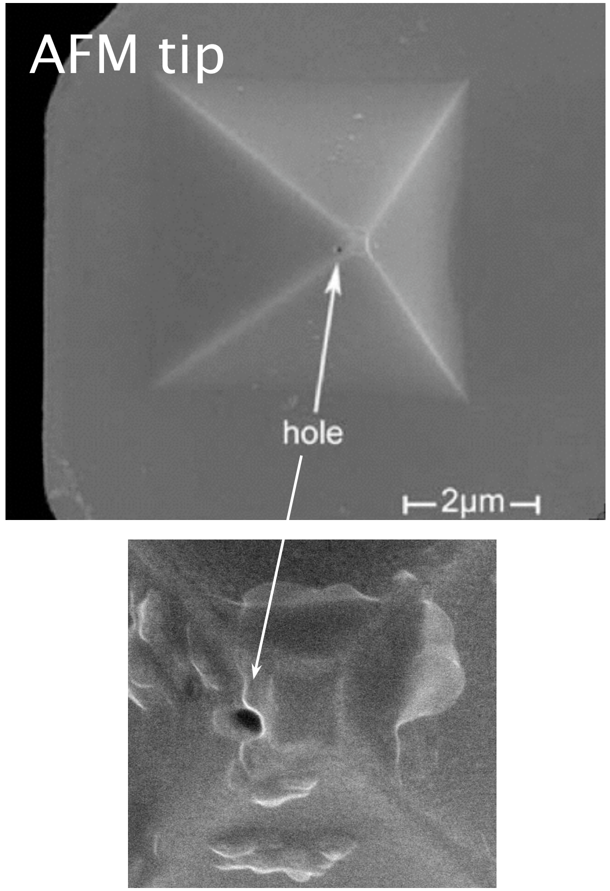
Improving the spatial resolution

Ion beam focused into an AFM tip

Hole made by Focused Ion Beam





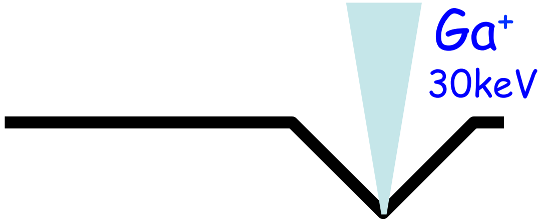


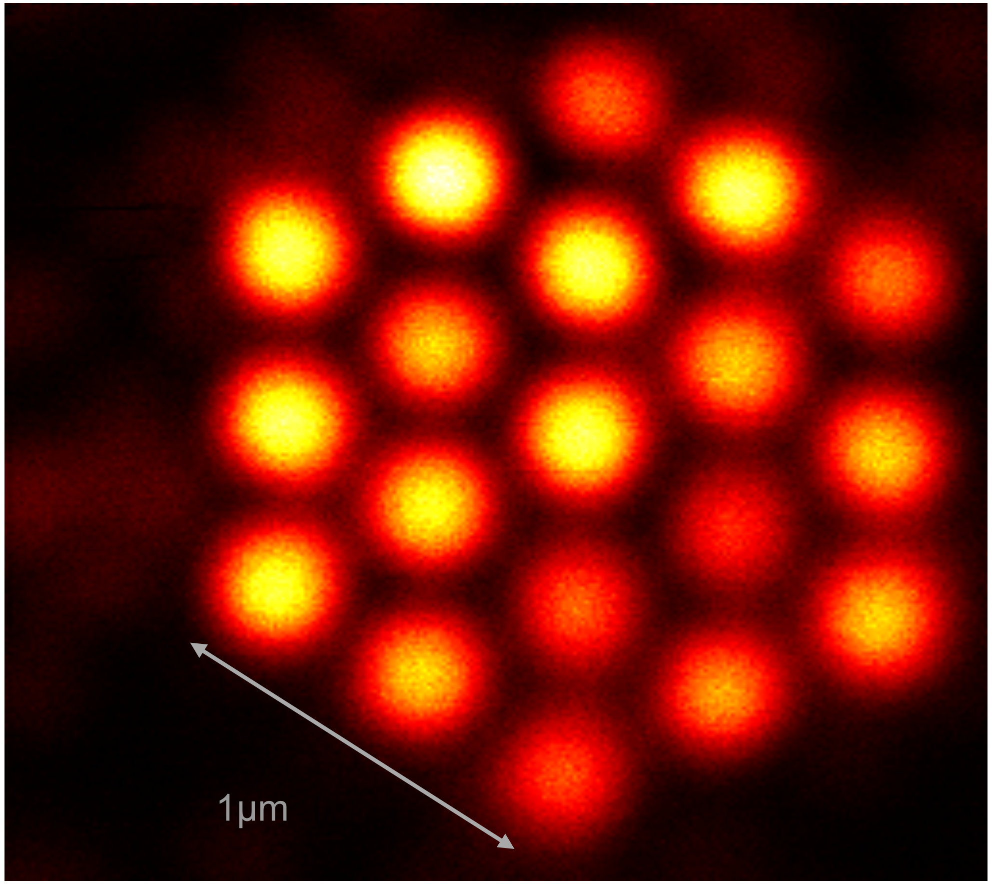
Meijer, *Appl. Phys. A* **91**, 567 (2008)

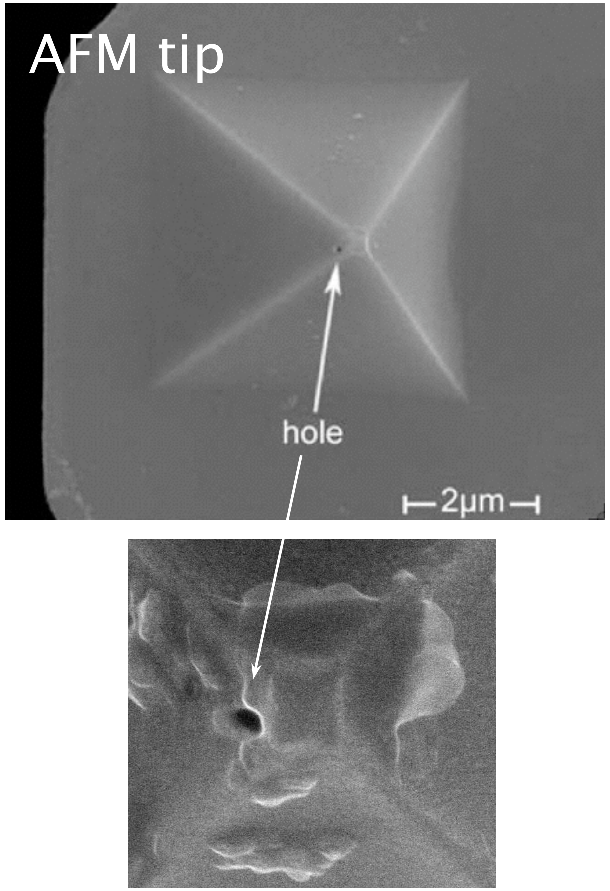
Improving the spatial resolution

Ion beam focused into an AFM tip

Hole made by Focused Ion Beam



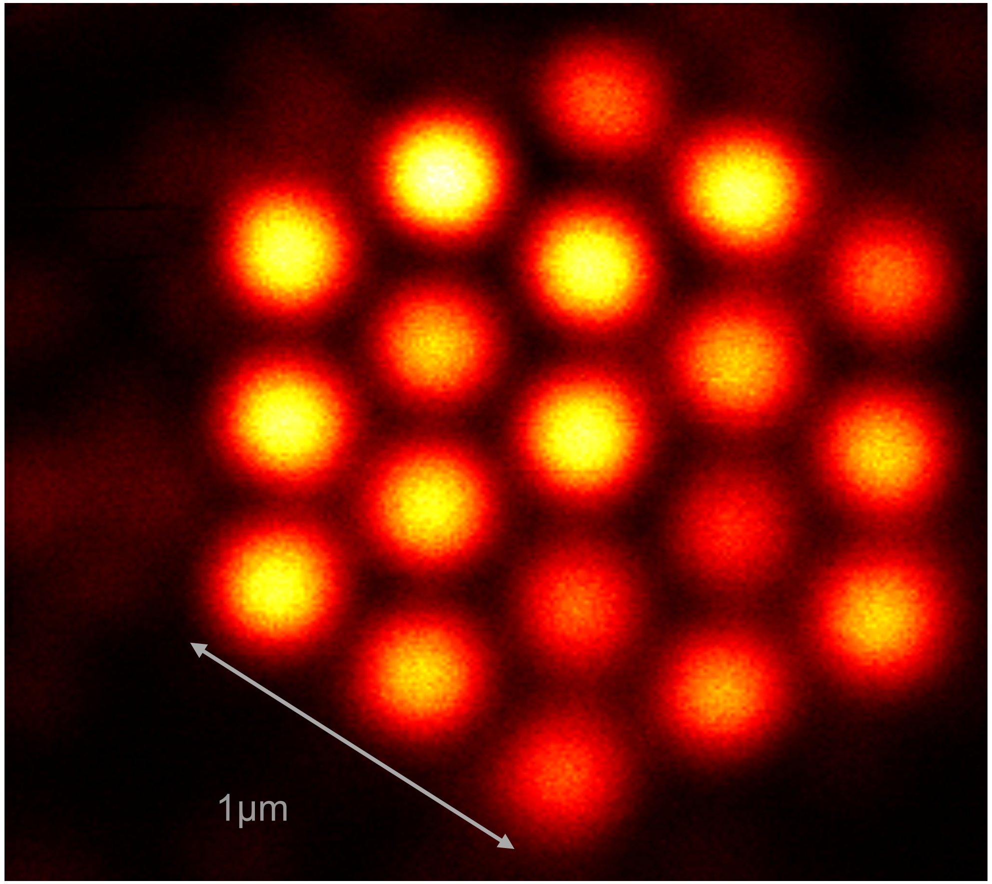




Cortesy of S. Pezzagna and J. Meijer (Leipzig)

Improving the spatial resolution

Ion beam focused into an AFM tip



Cortesy of S. Pezzagna and J. Meijer (Leipzig)

Spatial resolution limited by diffraction

$$\sim \lambda/2$$

↓

Sub-diffraction optical imaging is required

STED

Hell, *Opt. Lett.* **19**, 780-782 (1994)

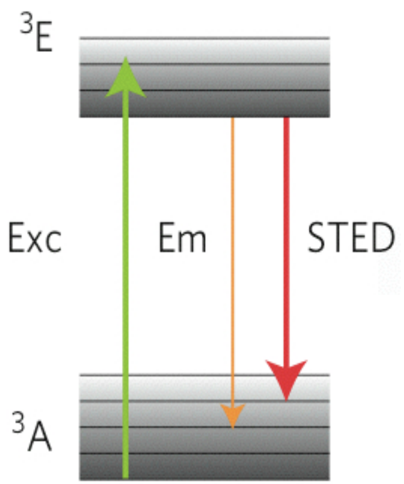
Beating the diffraction limit with STED

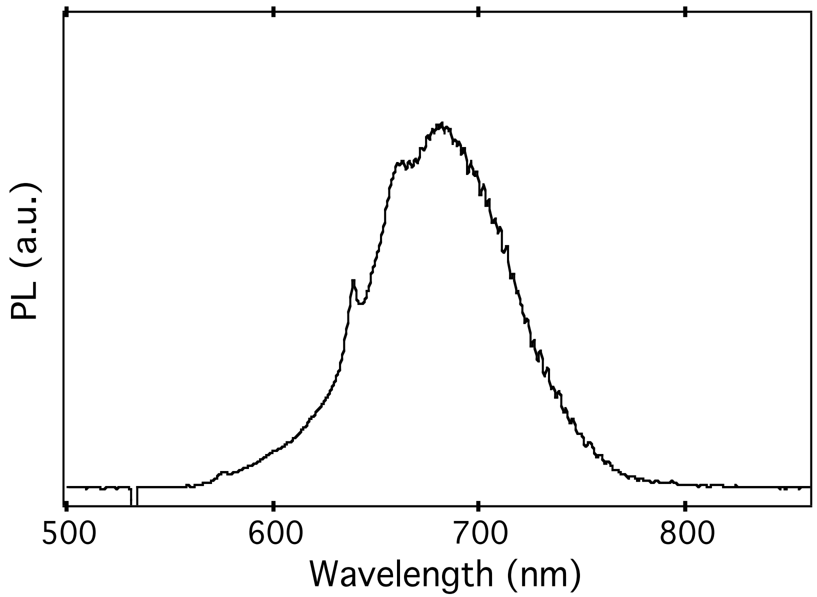
- Principle of STED - **ST**imulated **E**mission **D**epletion

Hell, *Opt. Lett.* **19**, 780-782 (1994)

Nobel Prize Chemistry 2014

S. Hell





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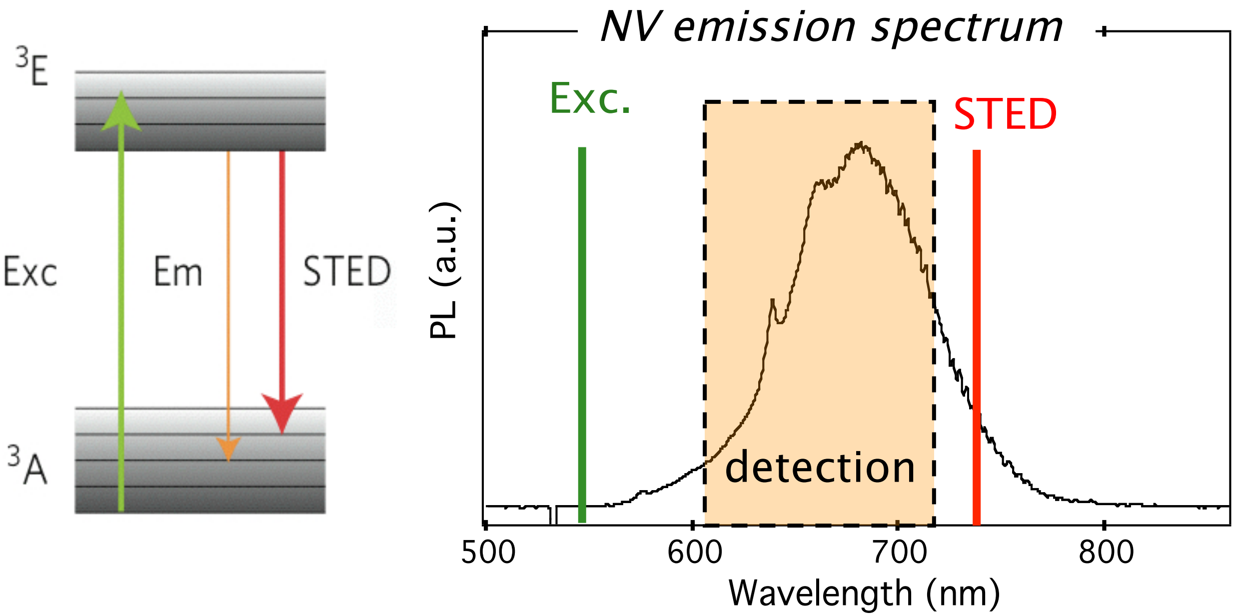
Hell, *Opt. Lett.* **19**, 780-782 (1994)



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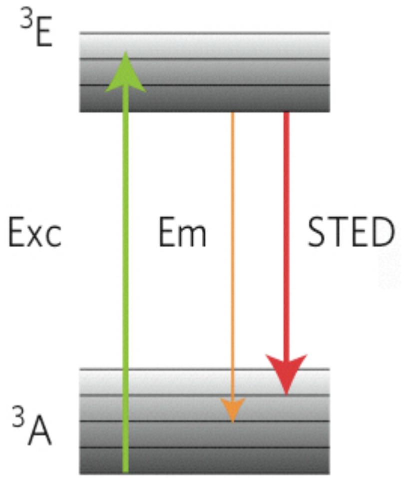

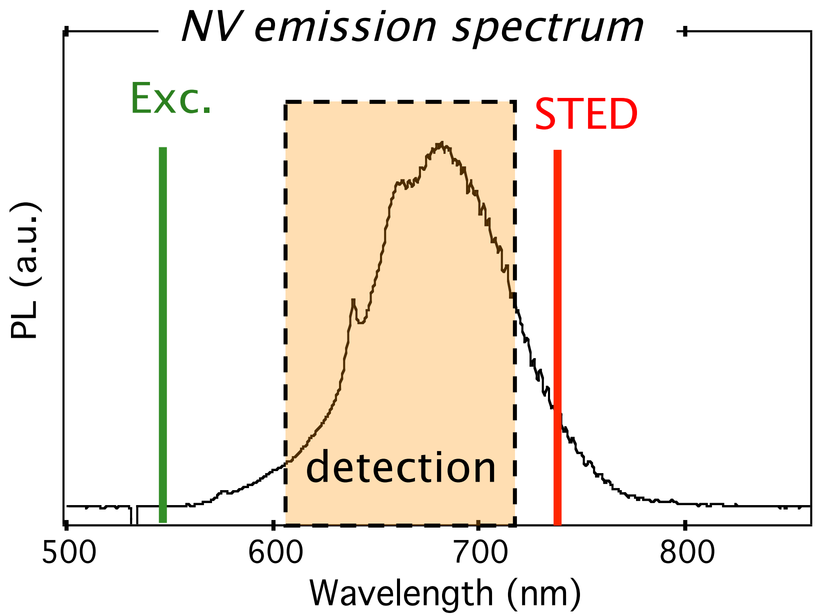

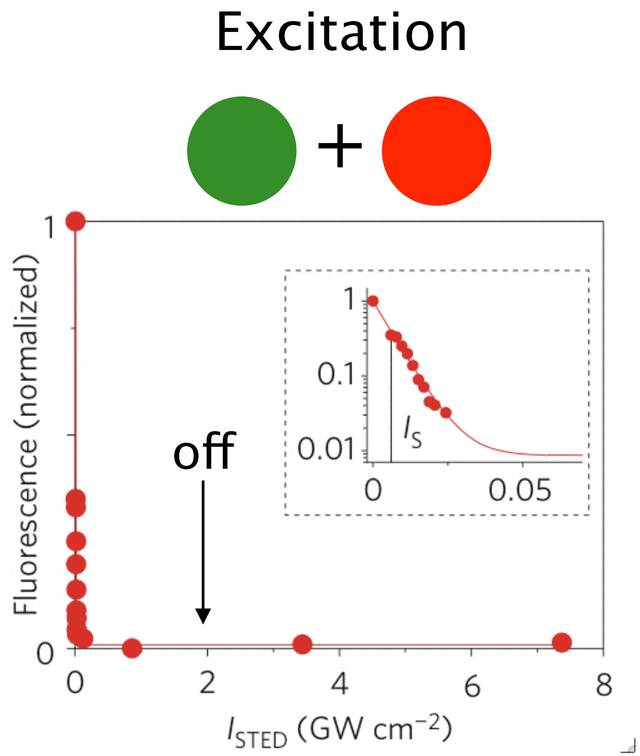

Rittweger, *Nat. Phot.* (2009)

Beating the diffraction limit with STED

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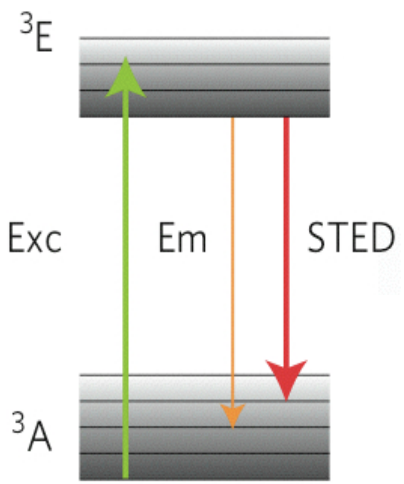
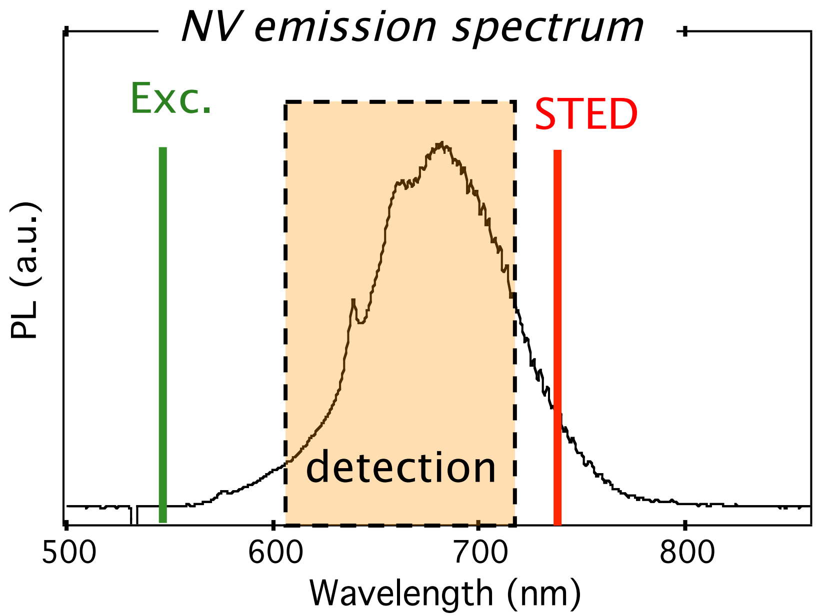
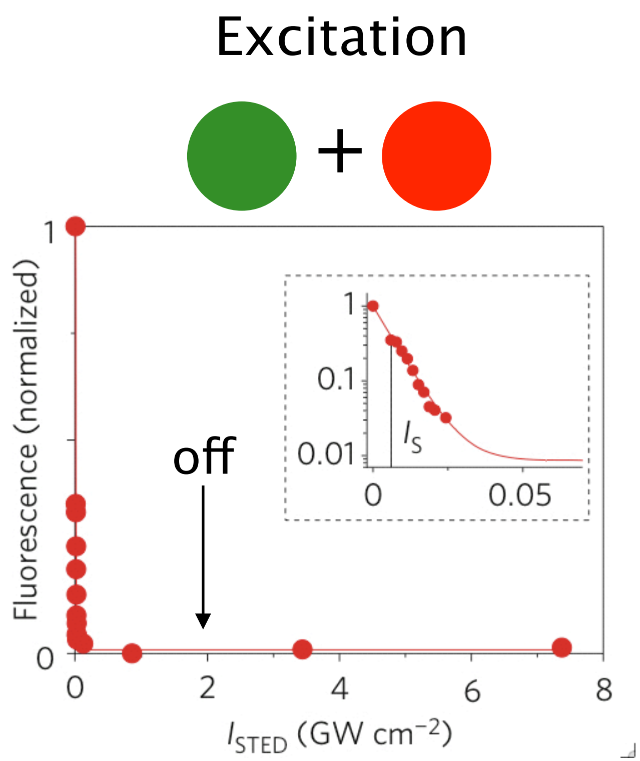
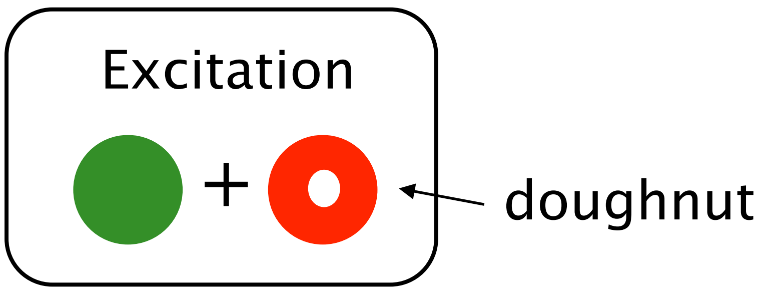






Rittweger, *Nat. Phot.* (2009)

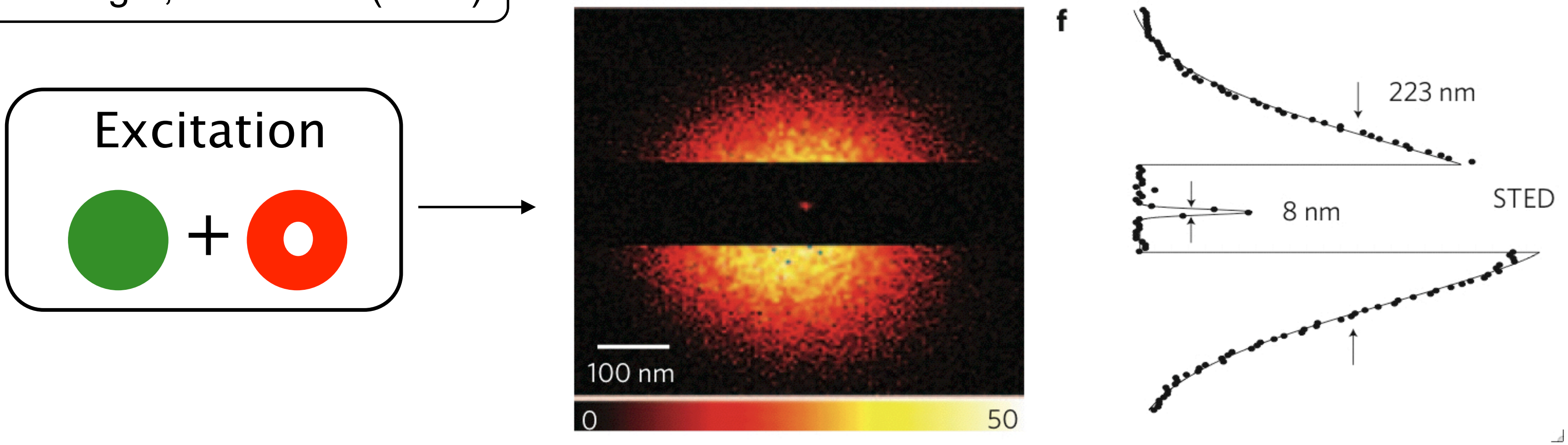
- Nanoscale optical resolution



Main advantage of NV defects …
its perfect photostability

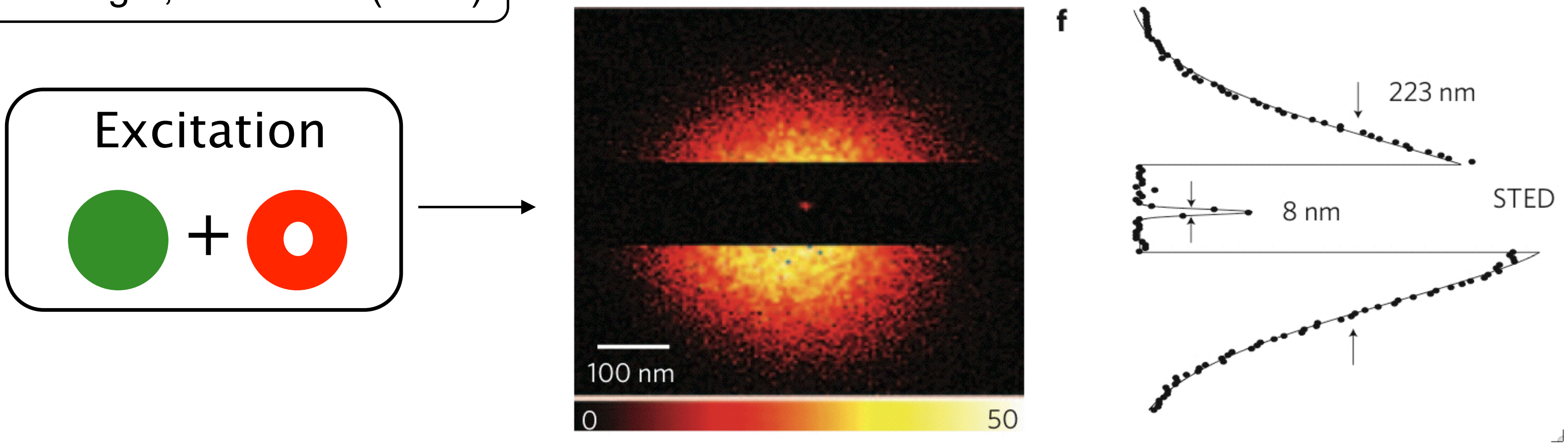
Beating the diffraction limit with STED

Rittweger, *Nat. Phot.* (2009)

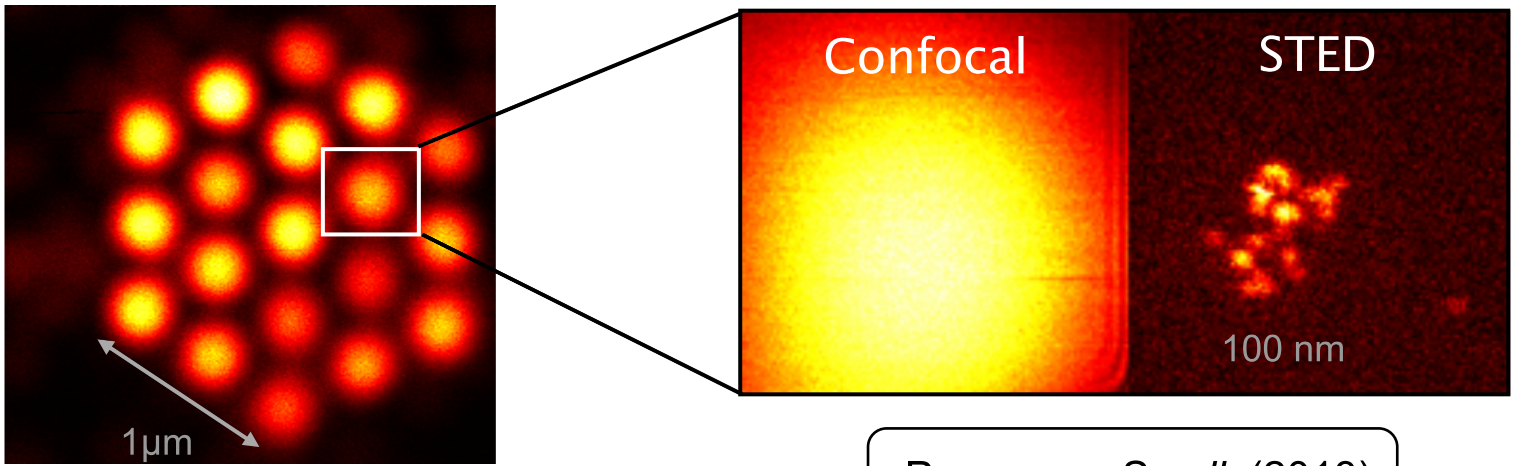


Beating the diffraction limit with STED

Rittweger, *Nat. Phot.* (2009)



• Back to the implantation through the AFM tip

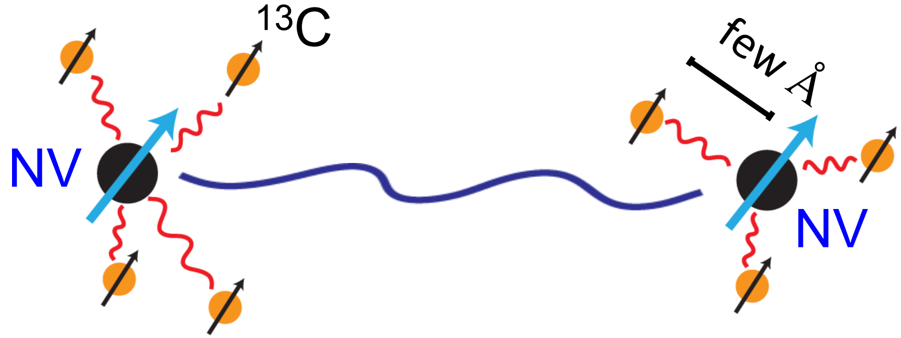


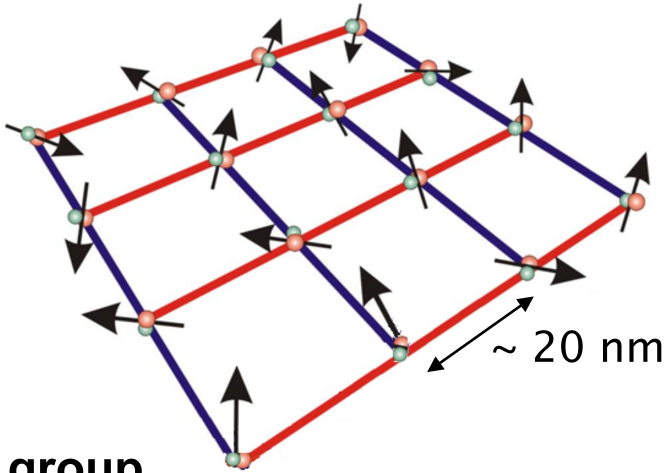
Pezzagna, *Small* (2013)

Scaling-up…

- Array of NV defects coupled by dipolar coupling

(remains highly challenging…)

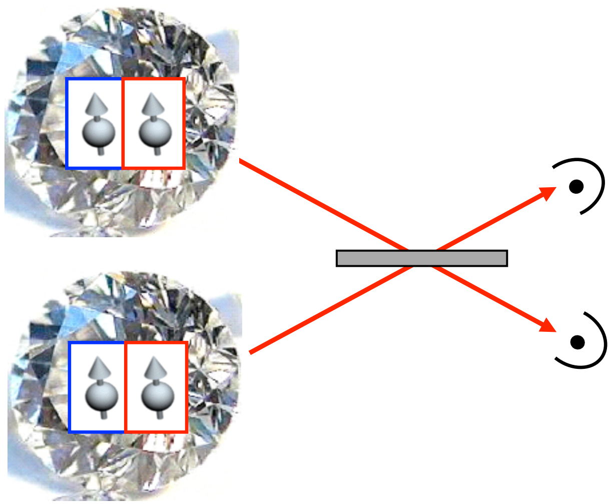




2 NV - ** Dolde, Nat. Phys. 9,139 (2013) – **Wrachtrup group

- Long distance entanglement with a spin/photon interface

Low T
4K



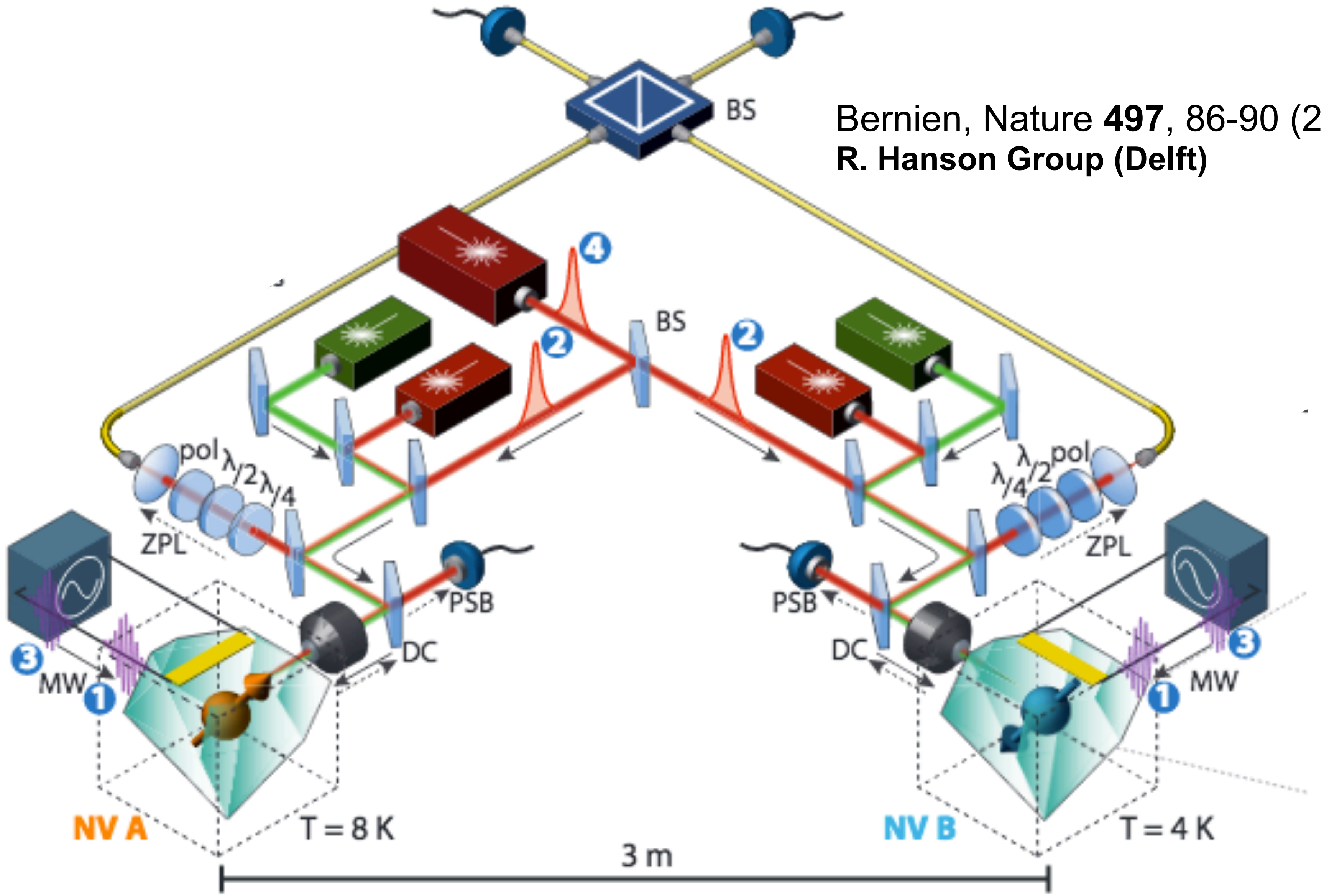
(with trapped ions)

Moehring, *Nature* 449, 68 (2007)
Olmshenk, *Science* 323, 486 (2009)

challenging as well…

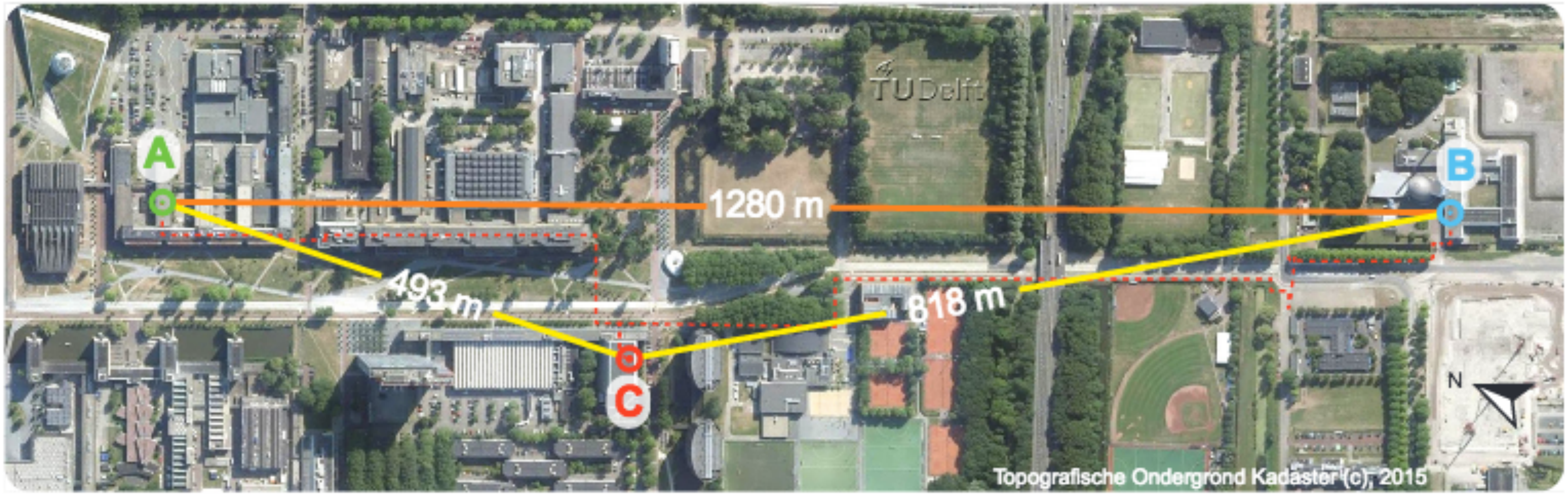
Long-distance entanglement with a spin/photon interface

Bernien, Nature **497**, 86-90 (2013)
R. Hanson Group (Delft)



Long-distance entanglement with a spin/photon interface

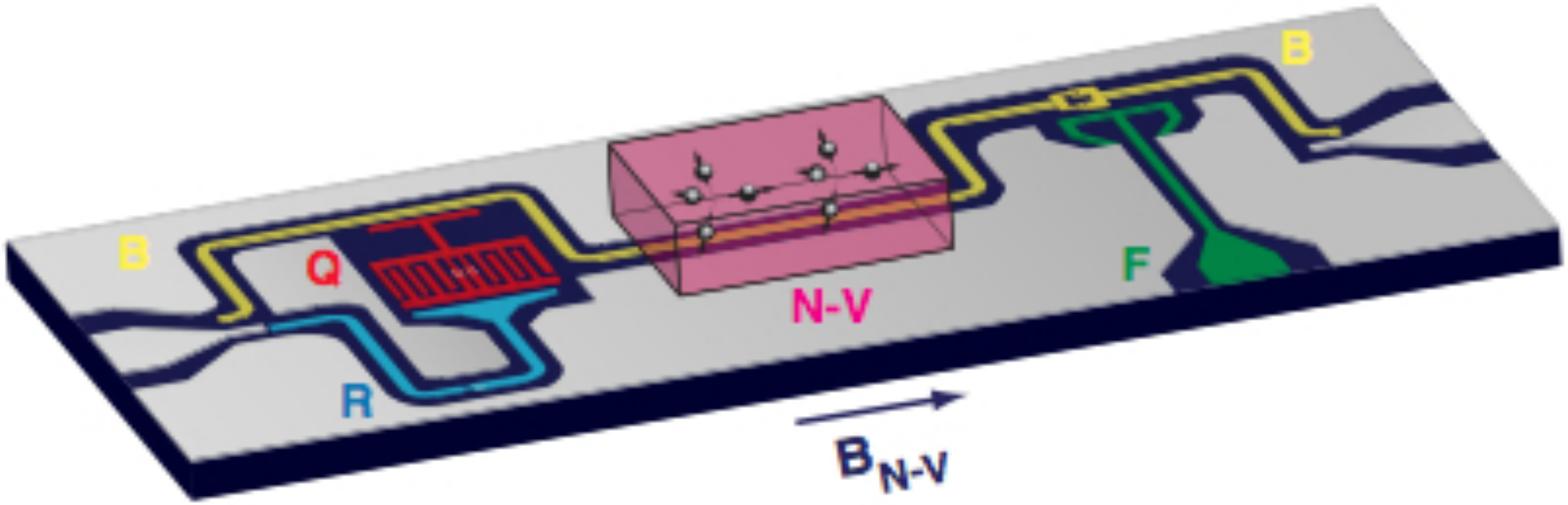
Loophole-free violation of a Bell inequality using entangled electronspins separated by 1.3 km



Hansen, Nature **526**, 682 (2015) – **R. Hanson group (Delft)**

Scaling-up…

Hybrid quantum systems

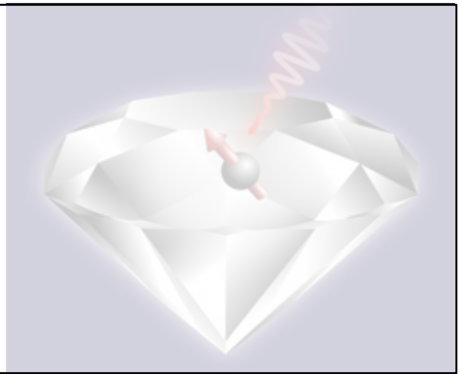


Kubo *et al.*, *Phys. Rev. Lett.* **107**, 220501 (2011) – **P. Bertet (CEA)**

Outline

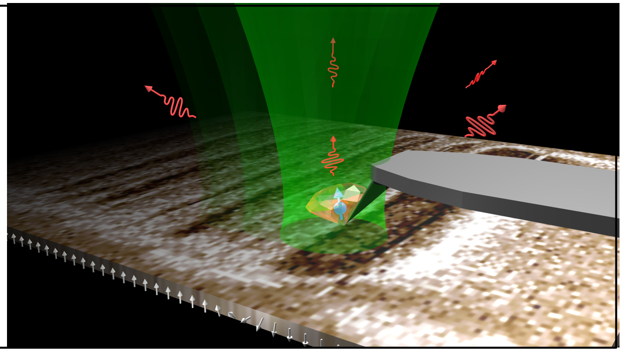
1. The NV defect in diamond

Main properties



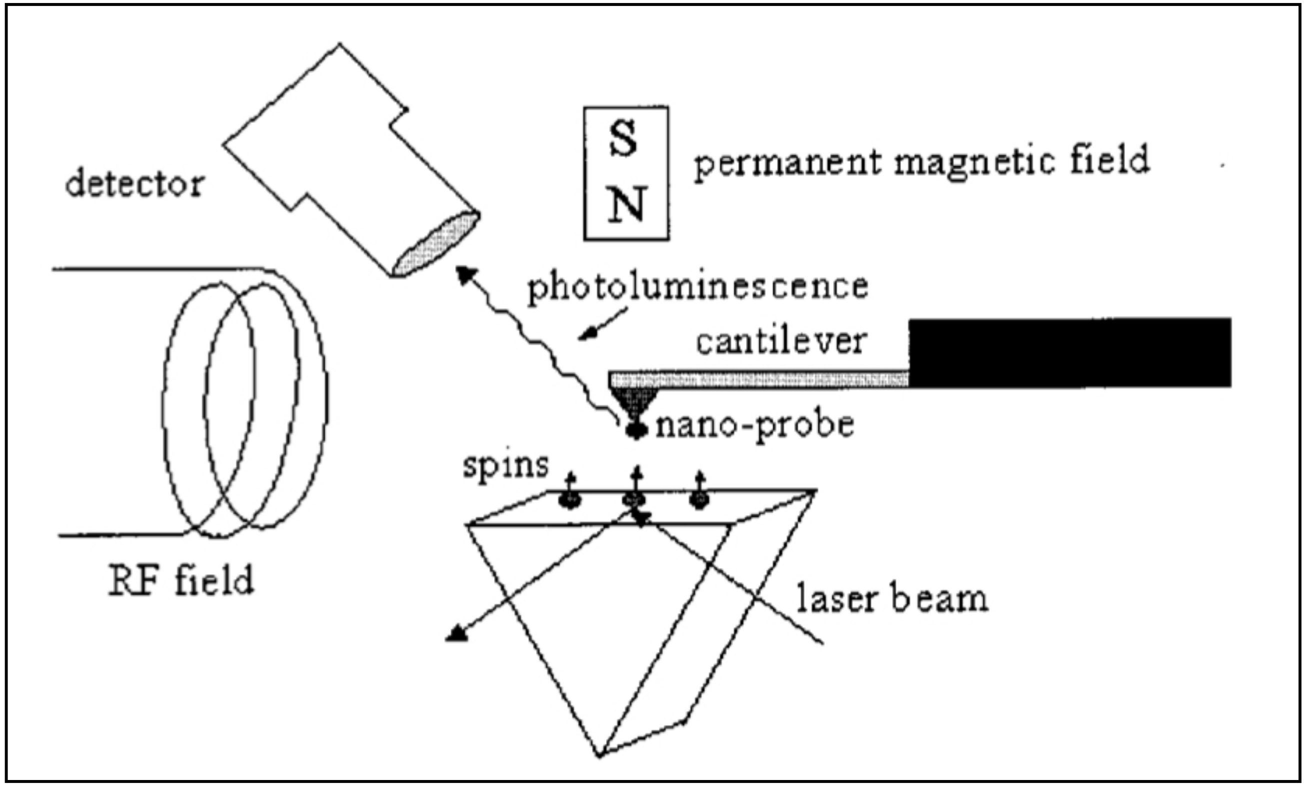
2. Applications in ‘quantum information science’

3. Magnetic sensing with a single NV defect



The seminal proposal

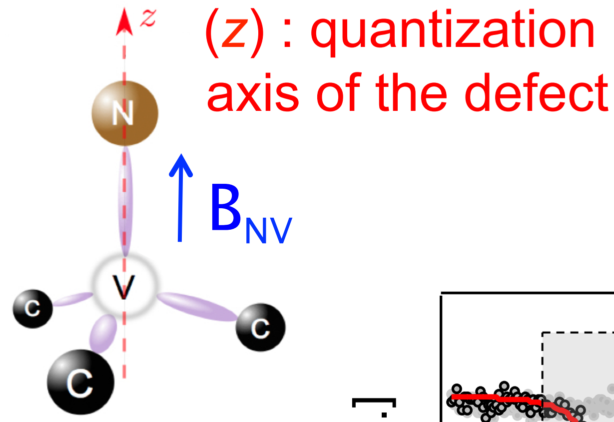
Chernobrod and Berman
"Spin microscope based on optically detected magnetic resonance"
J. Appl. Phys. **97** 014903 (2005).

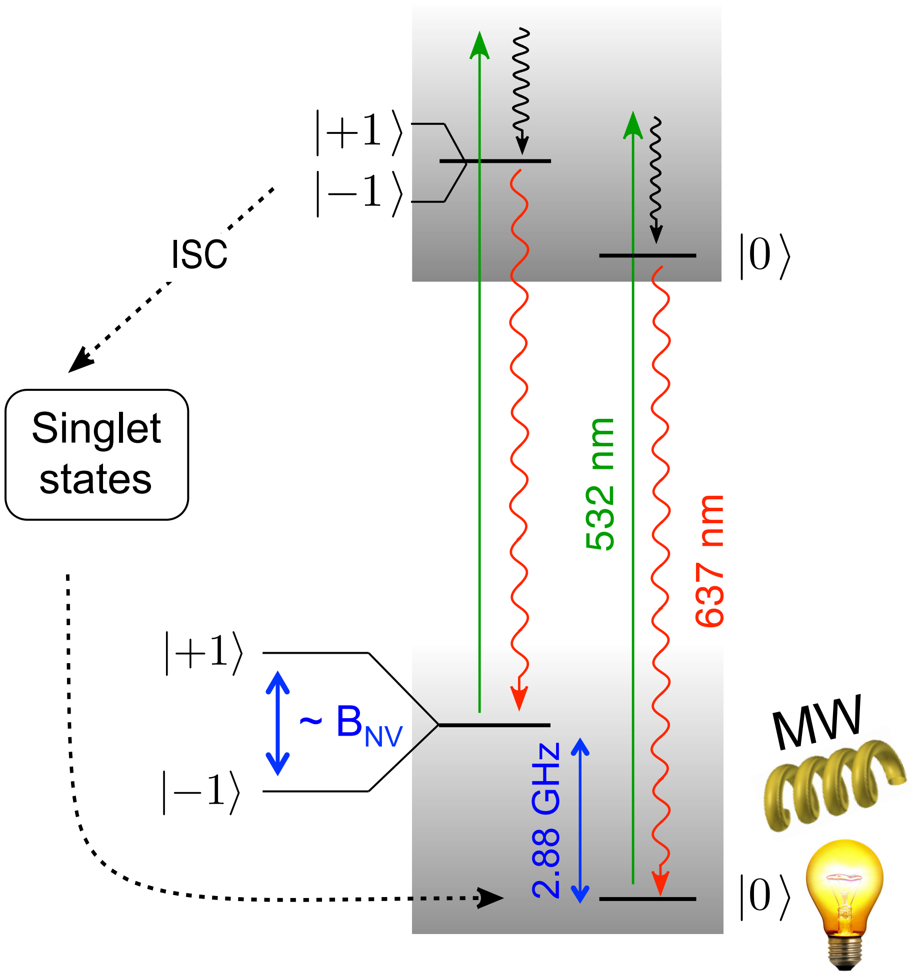


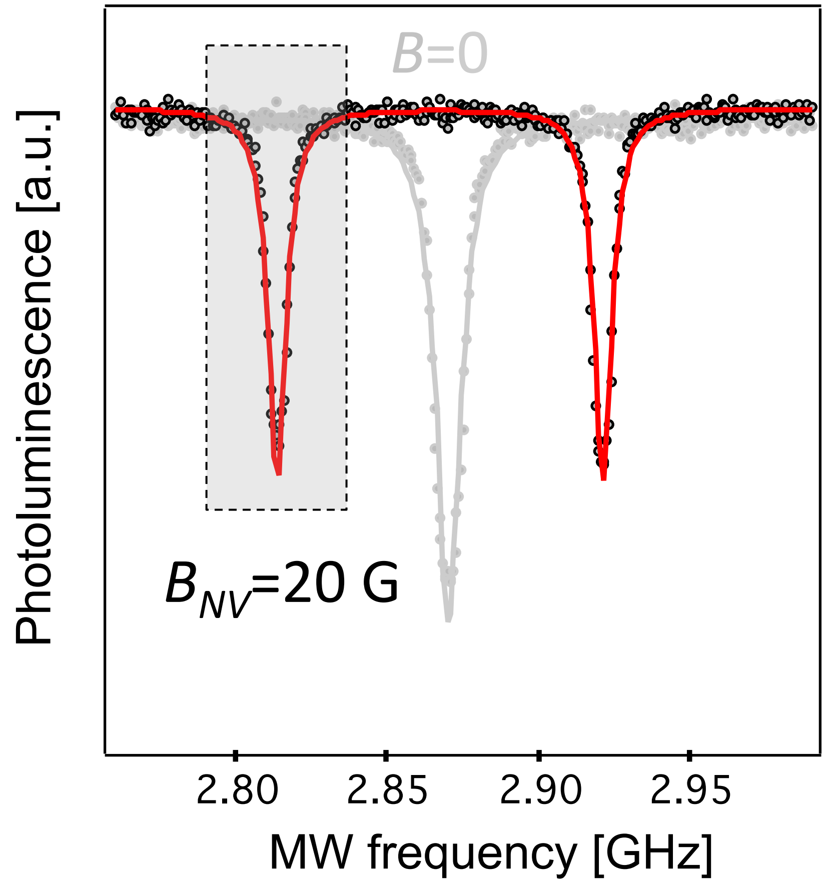
Proposal for NV defects : Taylor, Nat. Phys. (2008), Degen, APL (2008)
First proof of principle : Maze, Nature (2008), Balasubramanian, Nature (2008)

Spin properties

spin triplet (S=1)
ground state



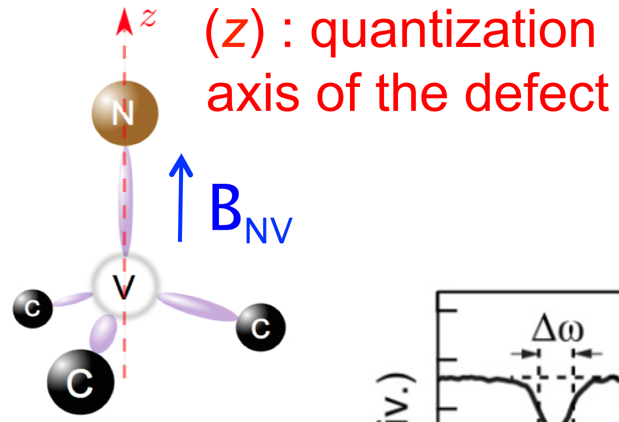


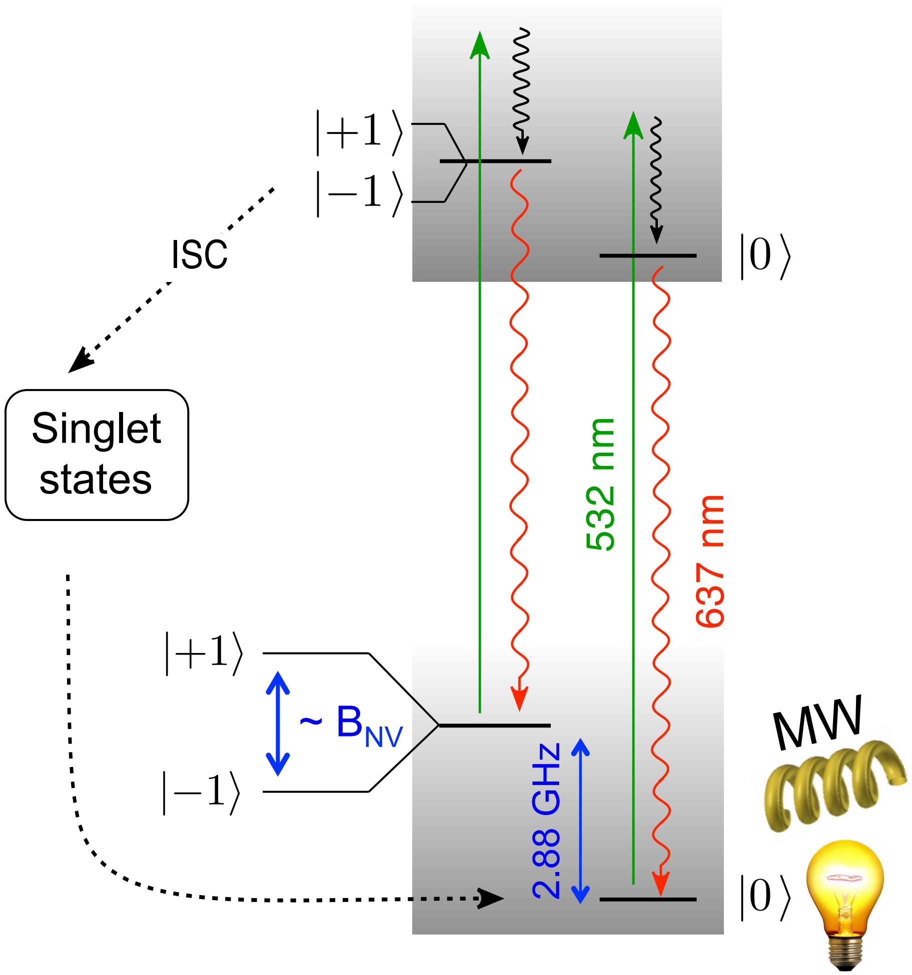


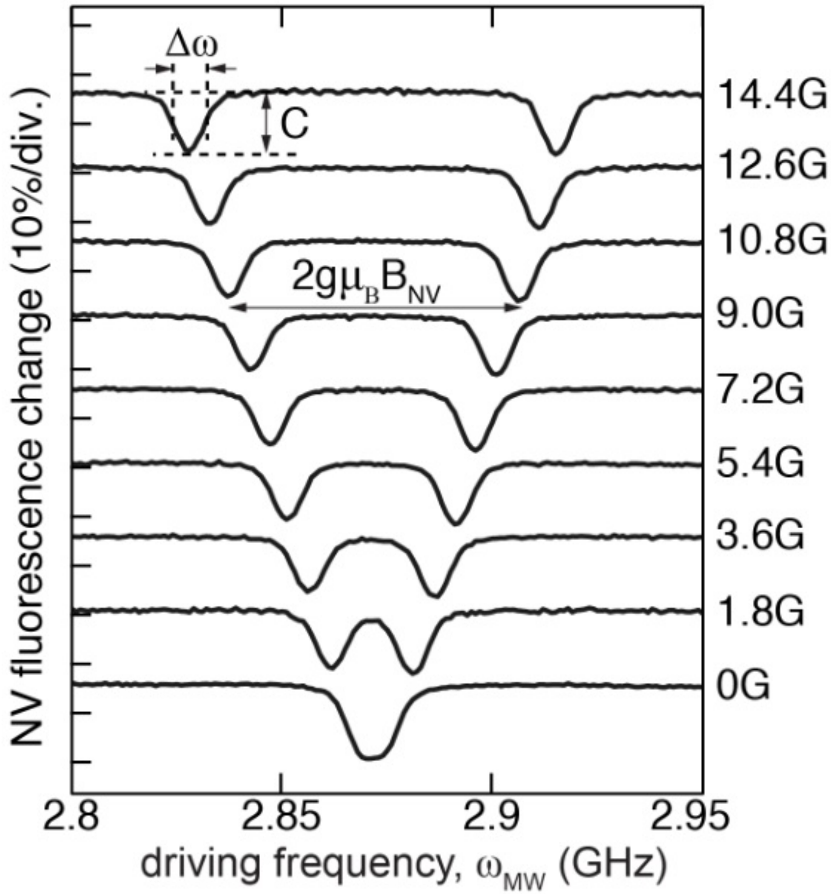
NV = e-spin qubit

Spin properties

spin triplet (S=1)
ground state





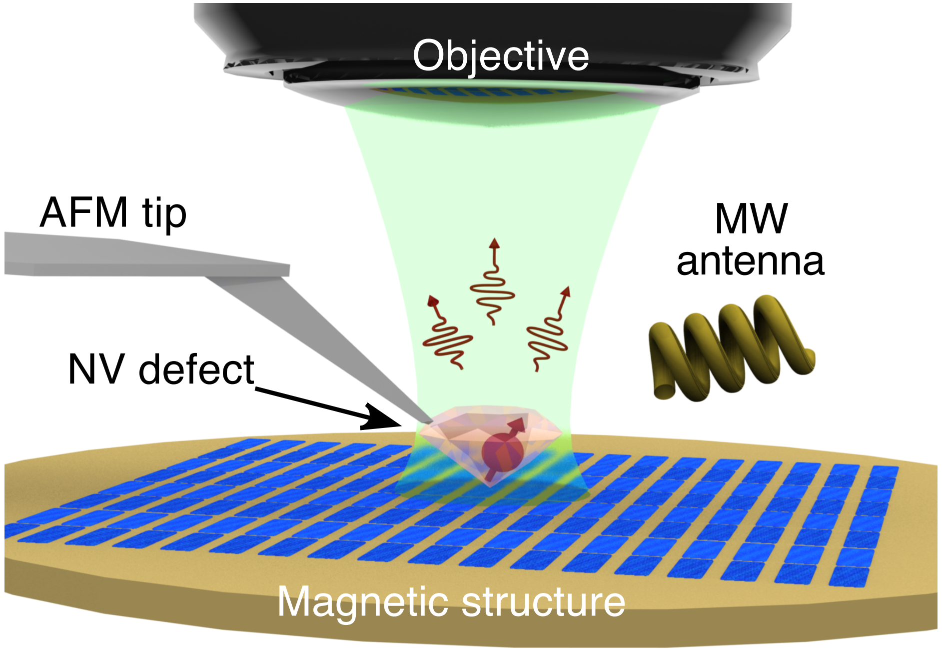


NV defect
= magnetometer

Scanning-NV magnetometry

➢ Principle

Balasubramanian *et al.*,
Nature **455**, 648 (2008)

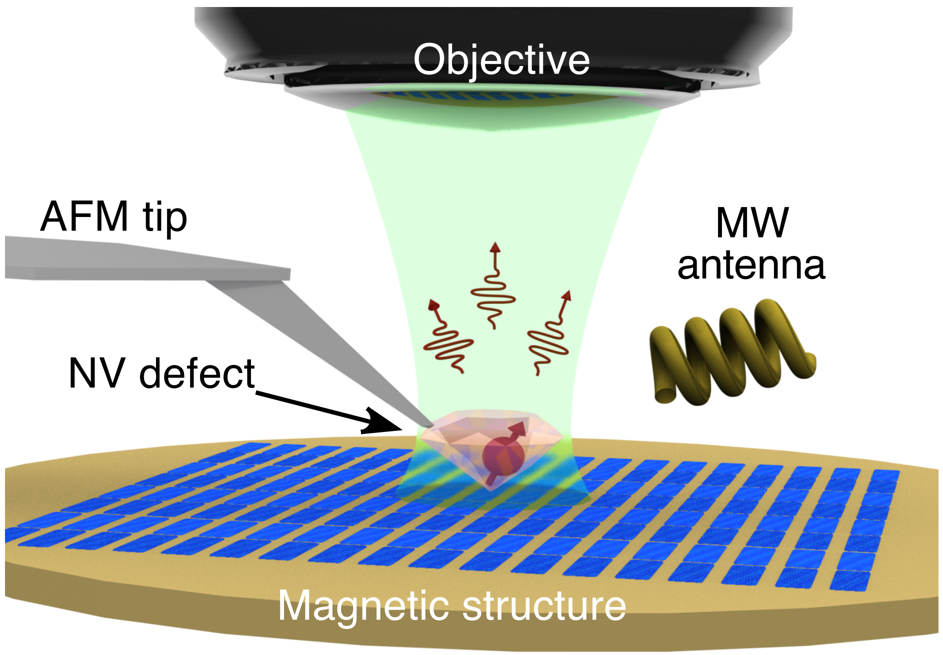


- ⋆ Atomic-sized detection volume
- ⋆ Quantitative and vectorial
- ⋆ No magnetic back-action

Scanning-NV magnetometry

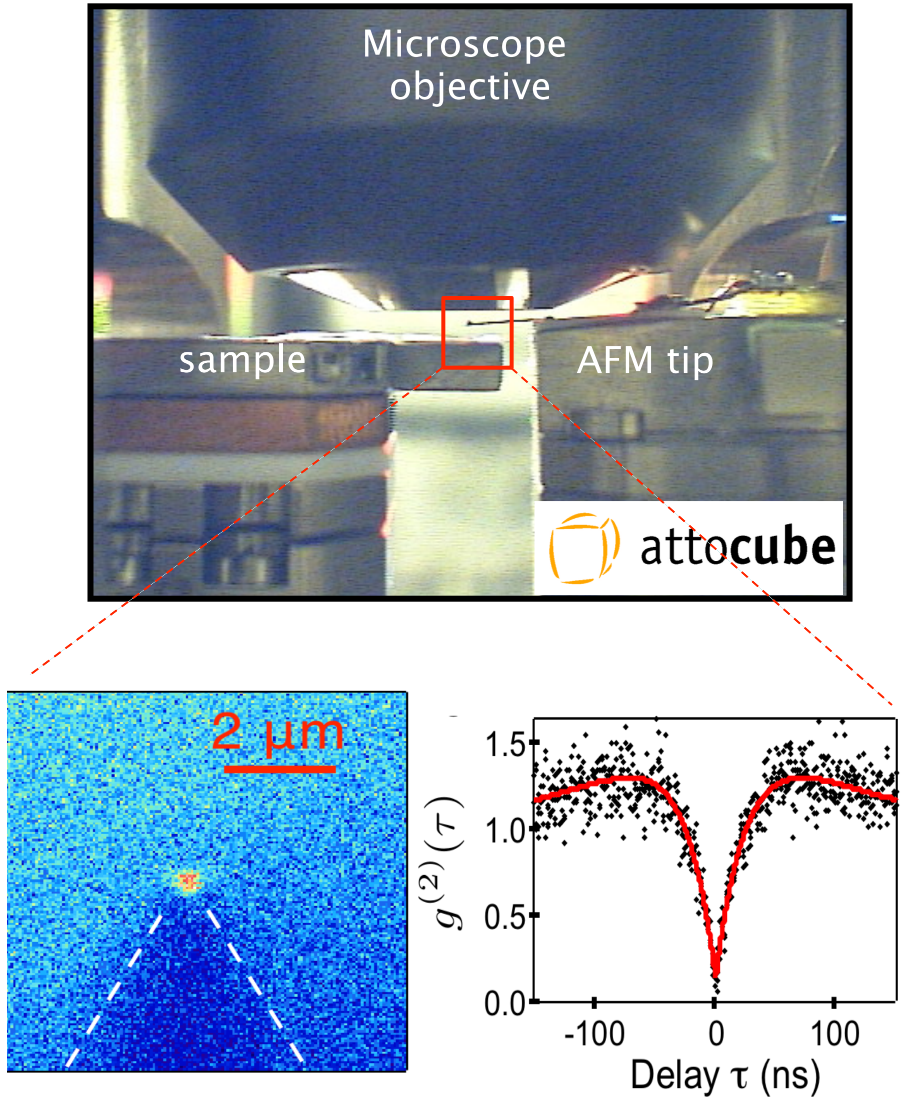
➢ Principle

Balasubramanian *et al.*,
Nature **455**, 648 (2008)



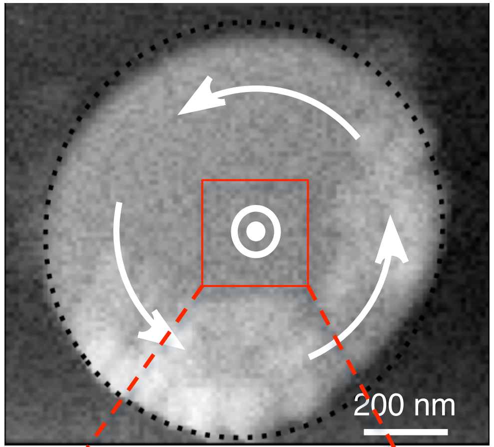
- ★ Atomic-sized detection volume
- ★ Quantitative and vectorial
- ★ No magnetic back-action

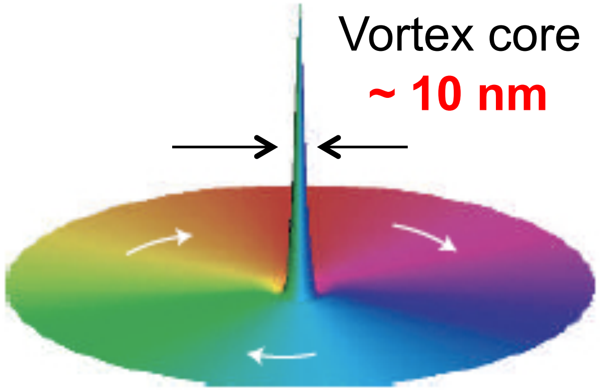
➢ Experiment

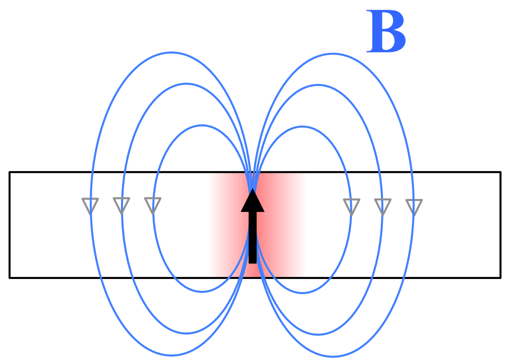


Imaging the core of a magnetic vortex

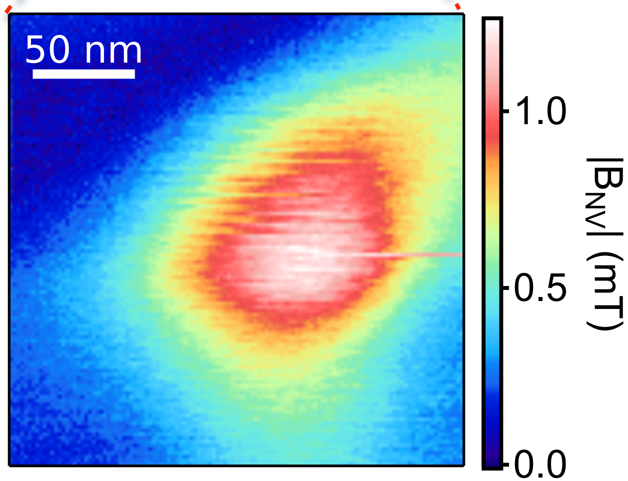
AFM image





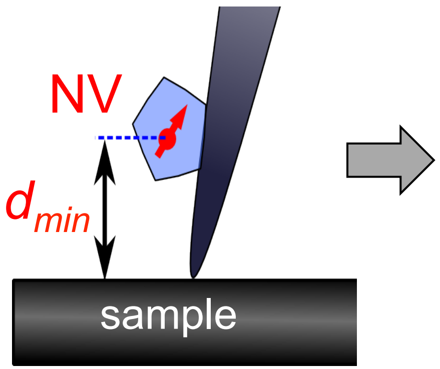


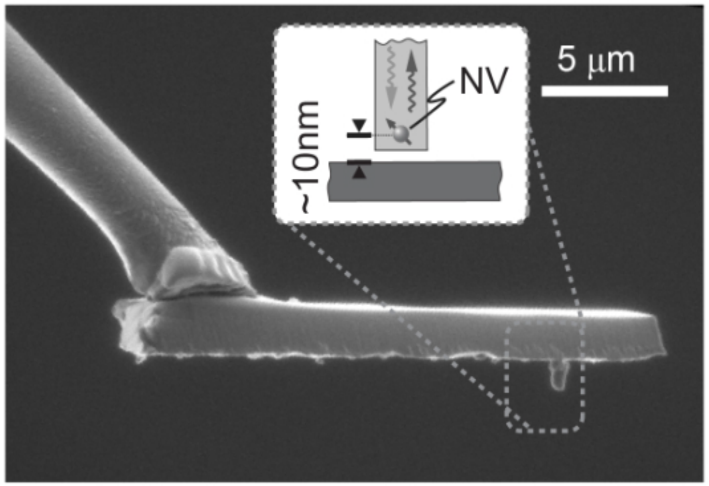
NV image



- **Resolving power ~ 100 nm**

Limited by the probe-to-sample distance d_{min}





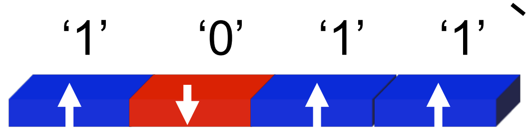
Rondin, *Nat. Com.* **4**, 2279 (2013)

Maletinsky group (Basel)

Information storage and processing

HDD : mechanical motion

large energy consumption

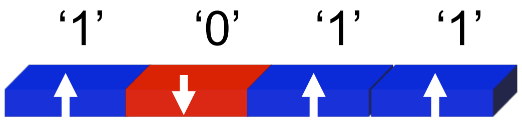


Information storage and processing

~~HDD : mechanical motion~~

large energy consumption

➢ use current-induced motion (spin torque)



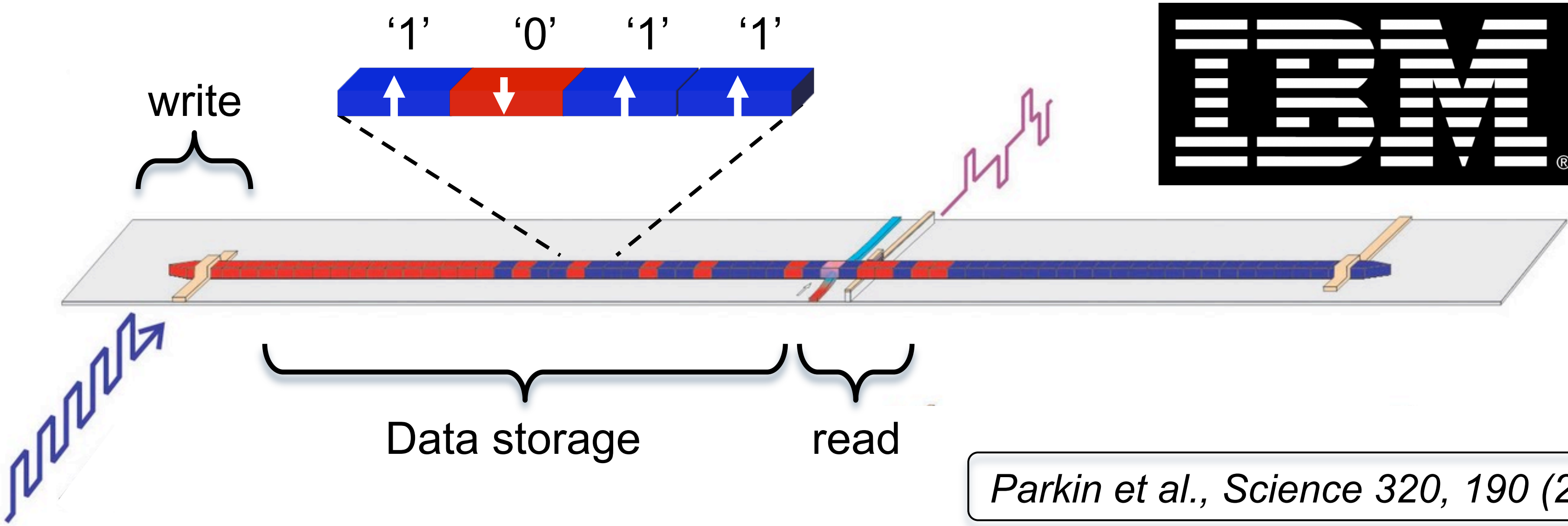
Information storage and processing

~~HDD : mechanical motion~~

large energy consumption

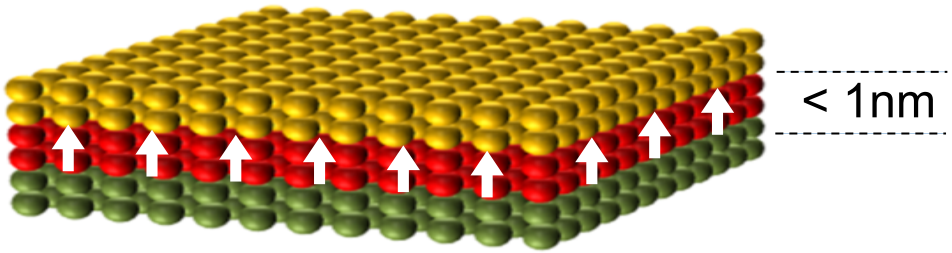
➢ use current-induced motion (spin torque)

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



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

Ferromagnets “shrink” to few atomic layers…

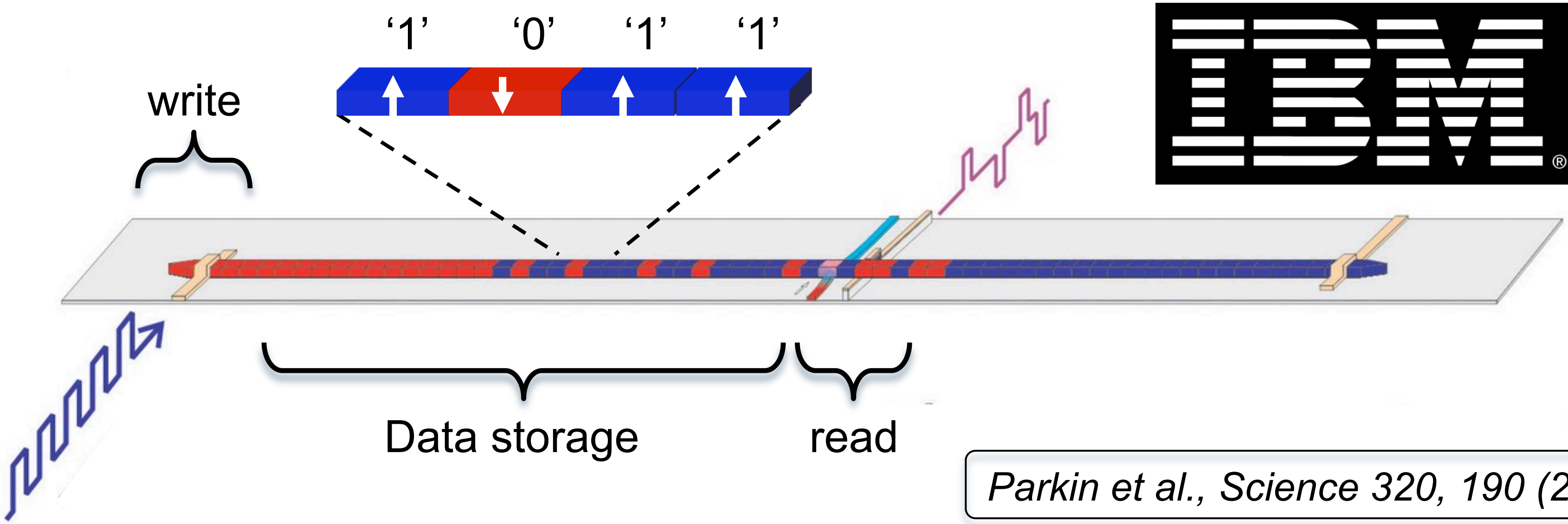


Surface energy ≈ Volume energy

Interface interactions — Anisotropy, exchange…

- ★ **Technological interest** (spintronic devices with low power consumption)
- ★ **Rich new physics** mediated by the interface

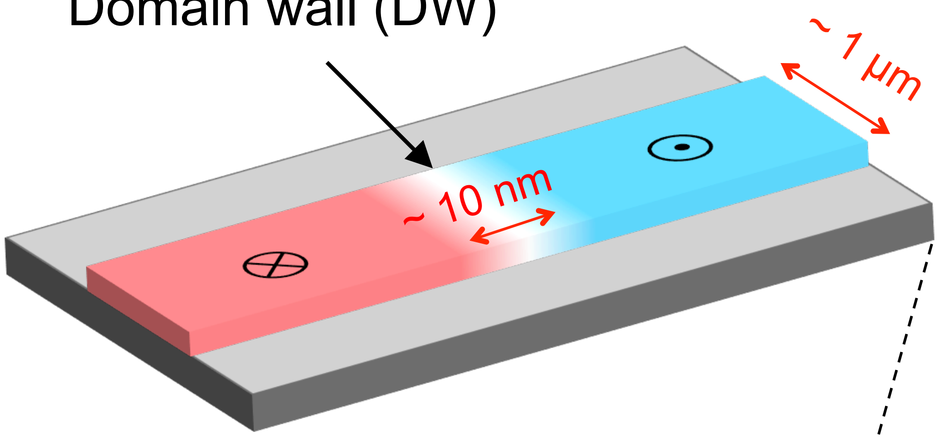
e. g. *:* the domain wall (DW) “racetrack memory”



IBM

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

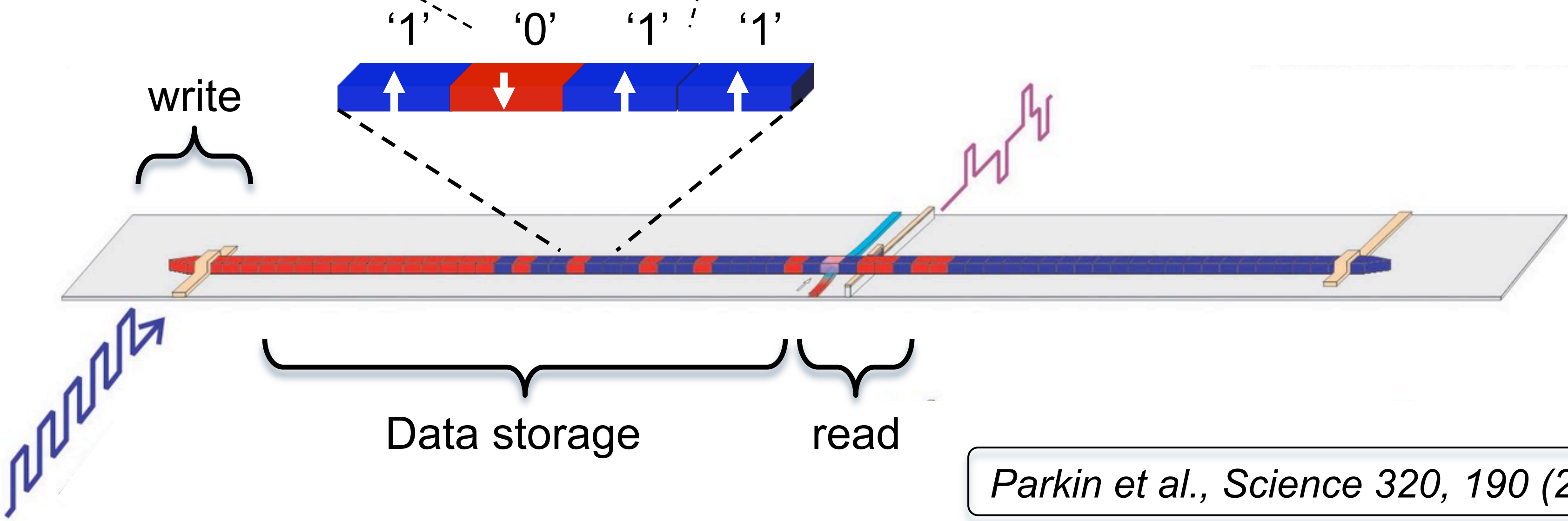
Domain walls in ultrathin ferromagnets



One important issue

What is the effect of the interface on the DW structure ?

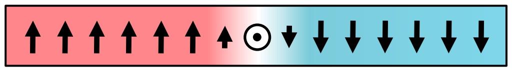
Direct impact on DW motion



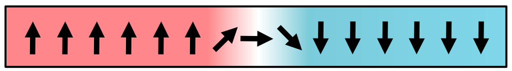
Parkin et al., Science 320, 190 (2008)

Inner structure of a domain wall

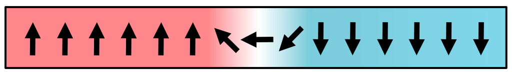
Bloch wall



Néel wall (right)



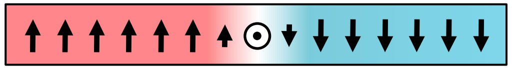
Néel wall (left)



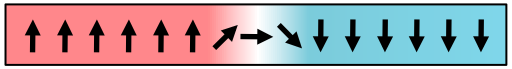
- Bloch walls are predicted by elementary magnetostatic theory

Inner structure of a domain wall

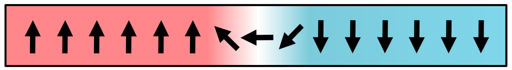
Bloch wall



Néel wall (right)

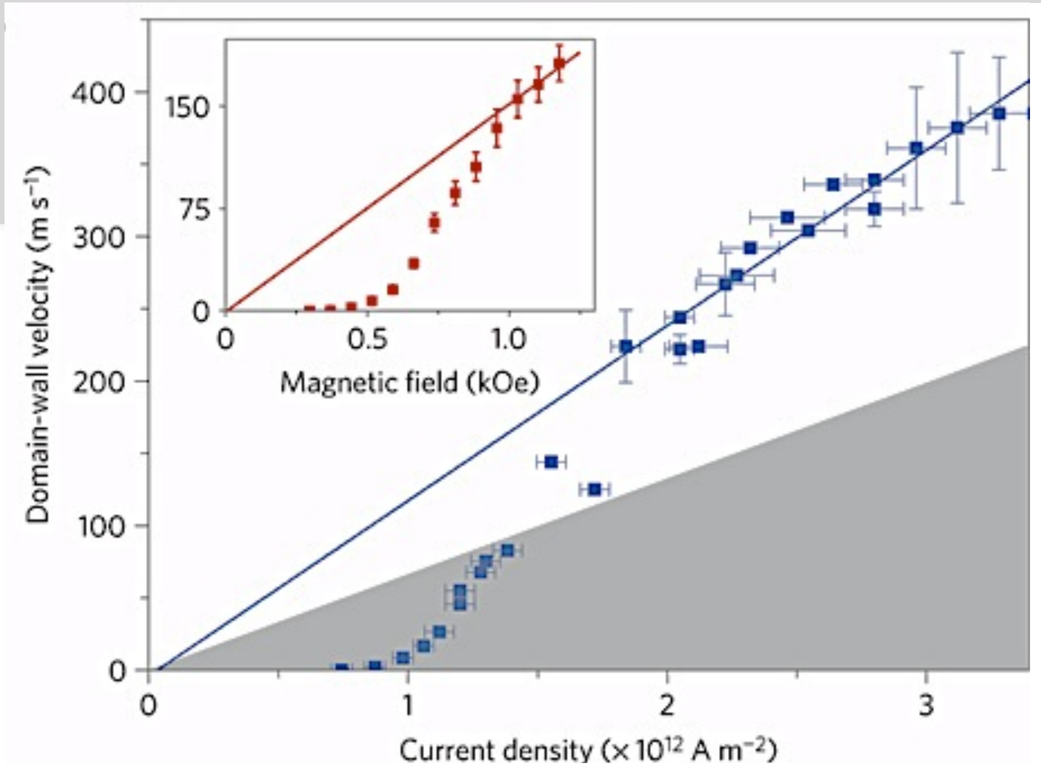


Néel wall (left)



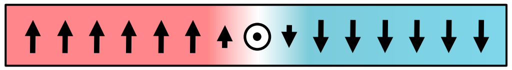
- Bloch walls are predicted by elementary magnetostatic theory
- But inconsistencies in recent current-induced domain wall motion experiments

Miron et al., Nat. Mater. 10, 419 (2011)
Ryu et al., Nat. Nano. 8, 527 (2013)

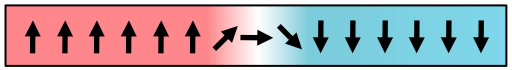


Inner structure of a domain wall

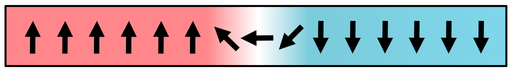
Bloch wall



Néel wall (right)



Néel wall (left)



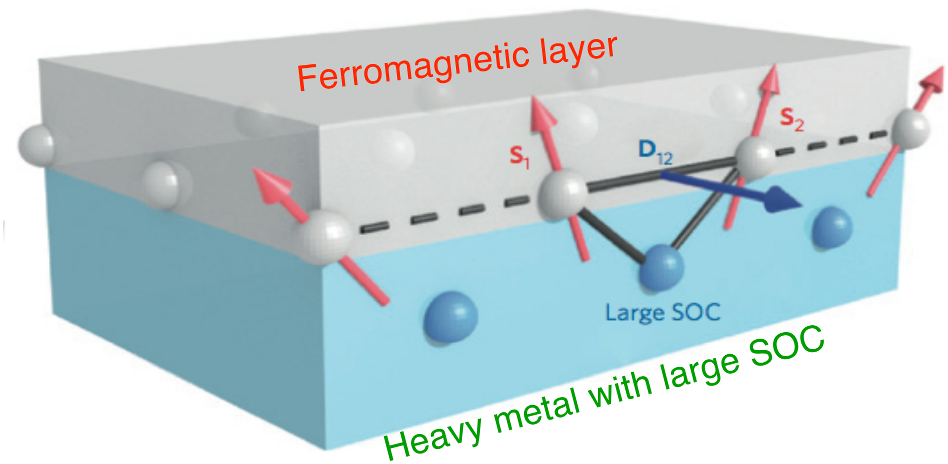
Fert *et al. Nat. Nano.* **8**, 152 (2013)

- Bloch walls are predicted by elementary magnetostatic theory
- But inconsistencies in recent current-induced domain wall motion experiments

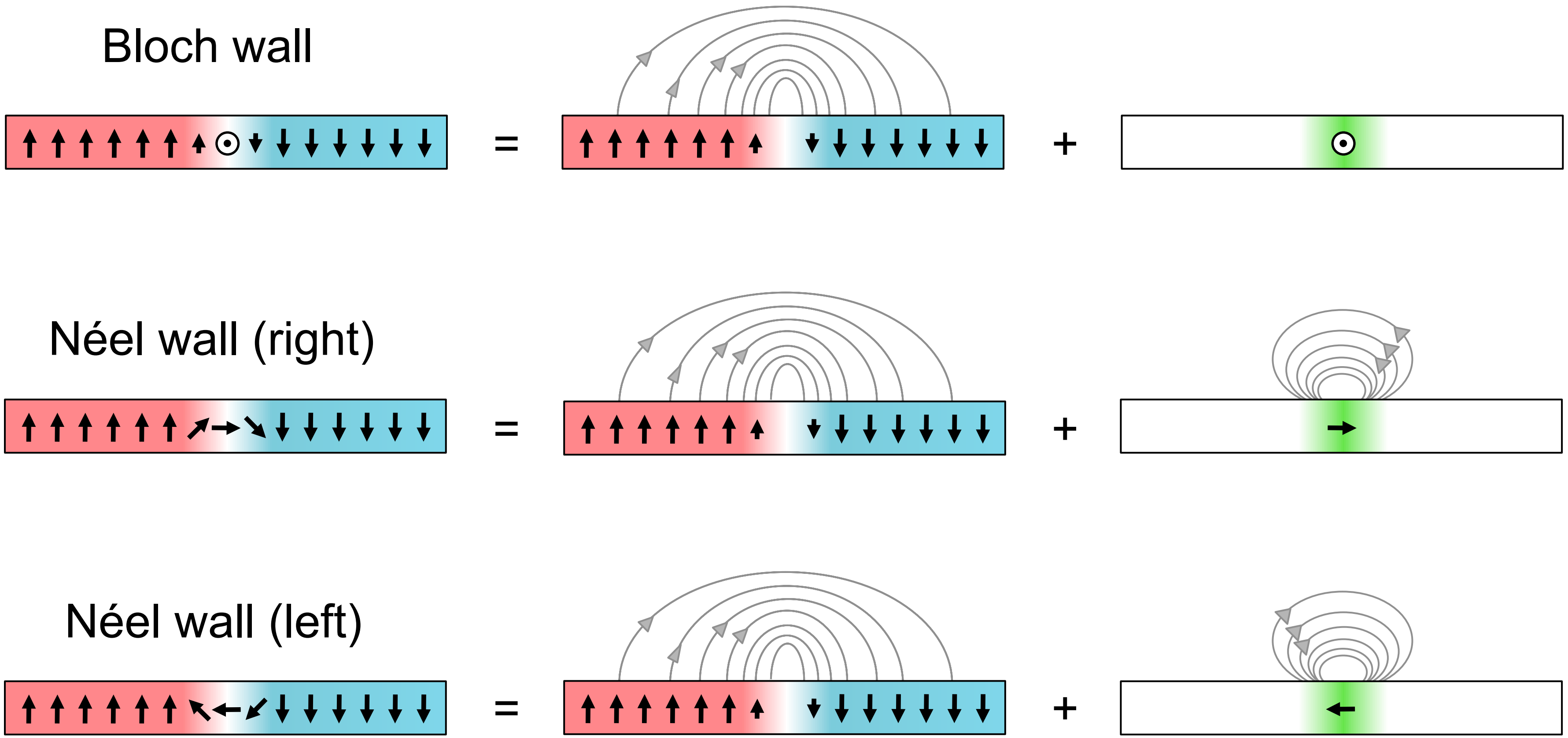
Miron et al., Nat. Mater. 10, 419 (2011)
Ryu et al., Nat. Nano. 8, 527 (2013)

- Interfacial Dzyaloshinskii-Moriya interaction proposed as a way to stabilize Néel walls

Thiaville et al., EJP 100, 57002 (2012)

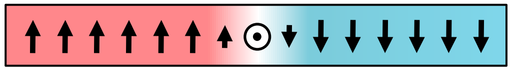


Determining the structure of the DW

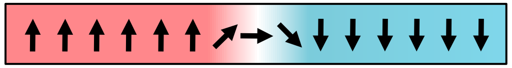


Determining the structure of the DW

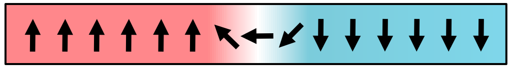
Bloch wall

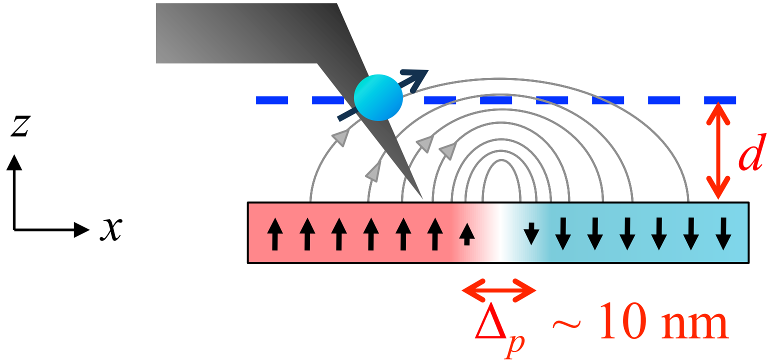


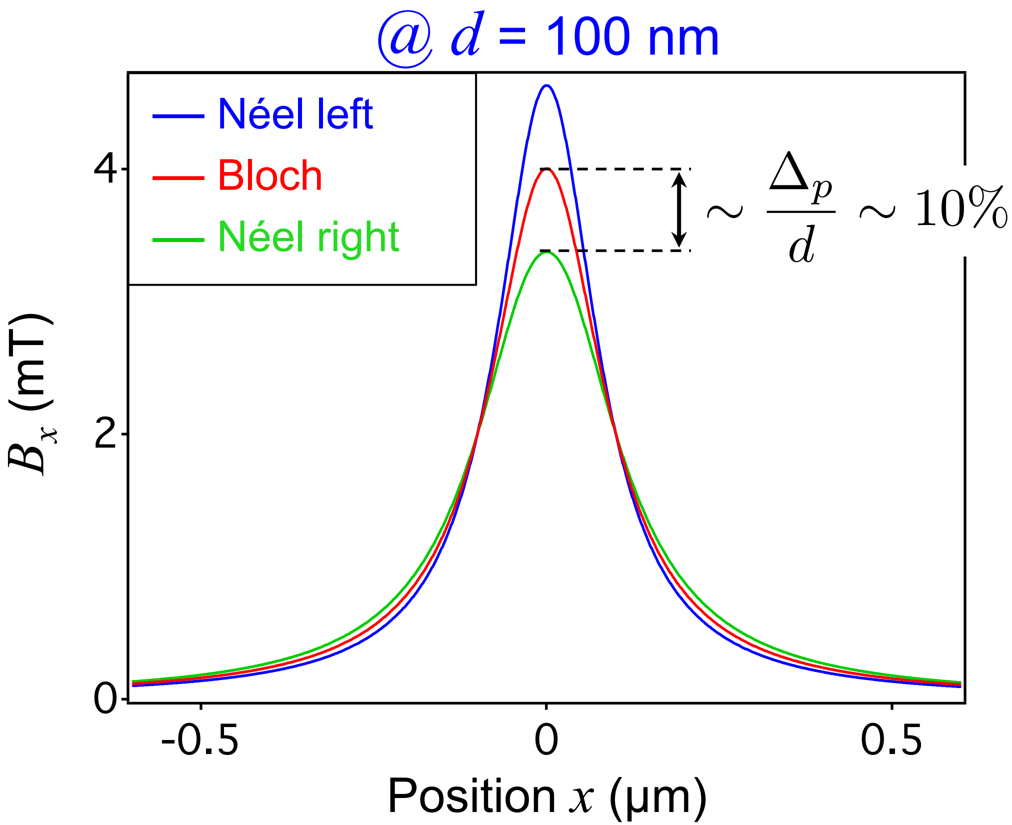
Néel wall (right)



Néel wall (left)



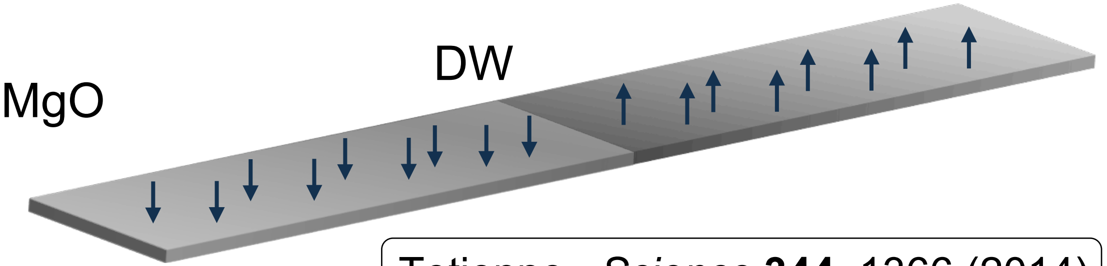




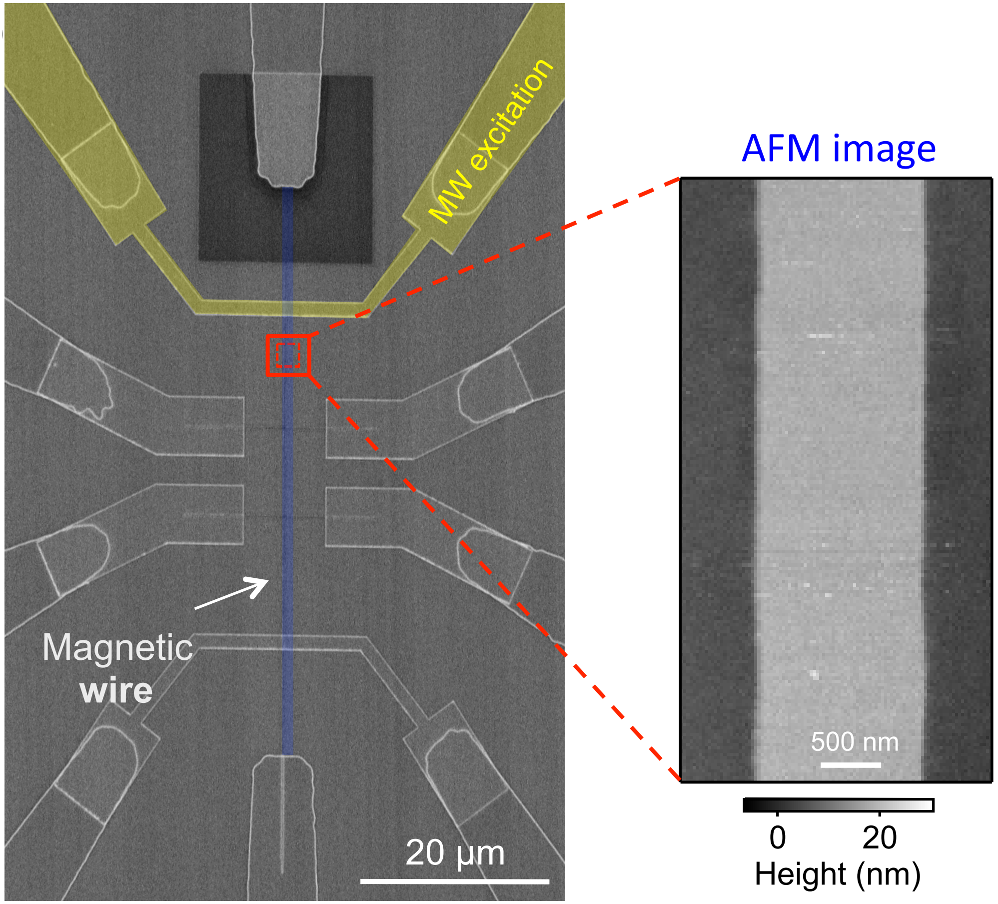
DW imaging with a scanning NV magnetometer

Magnetic wire

Ta / $Co_{40}Fe_{40}B_{20}$(1 nm) / MgO



Tetienne , *Science* **344**, 1366 (2014)



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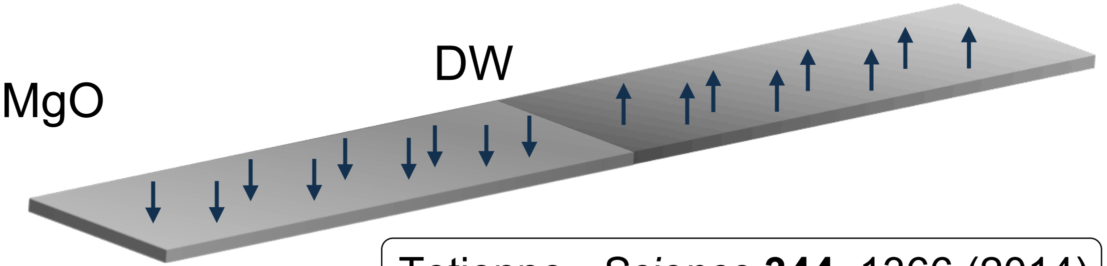
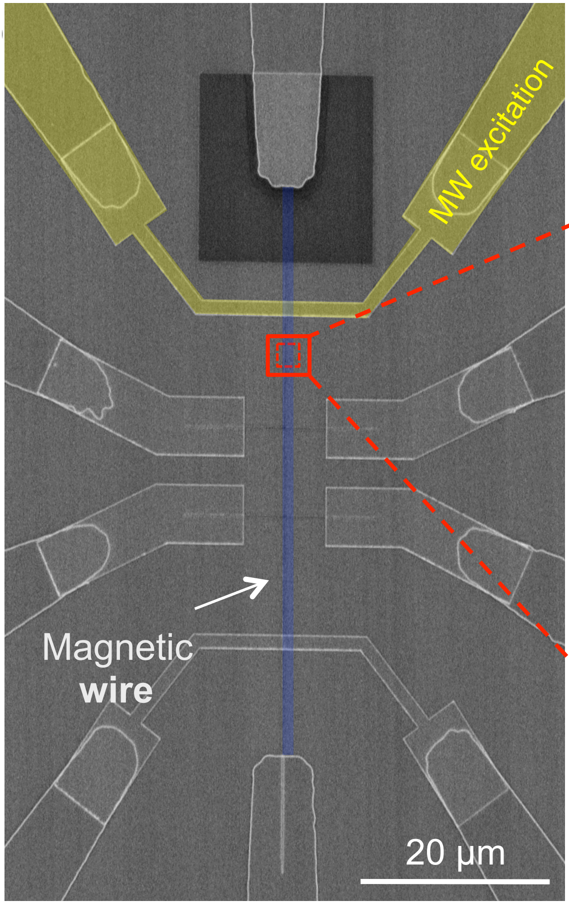
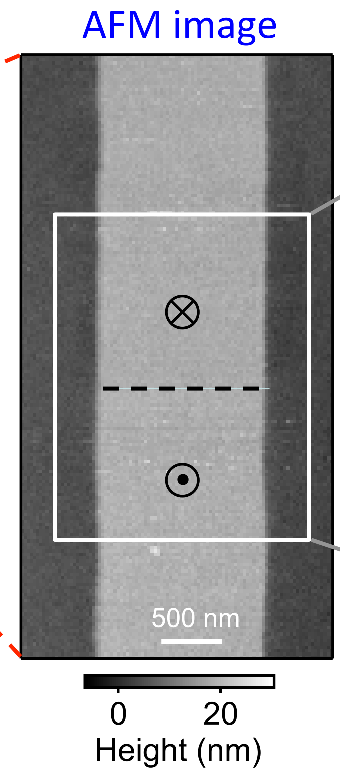
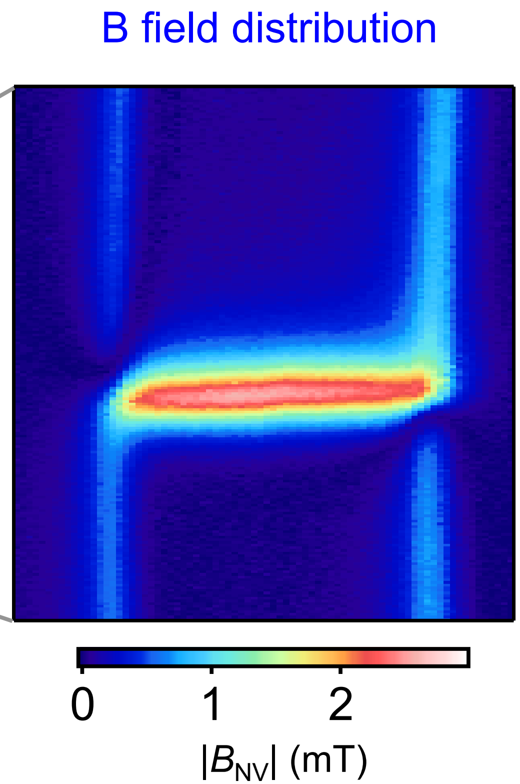


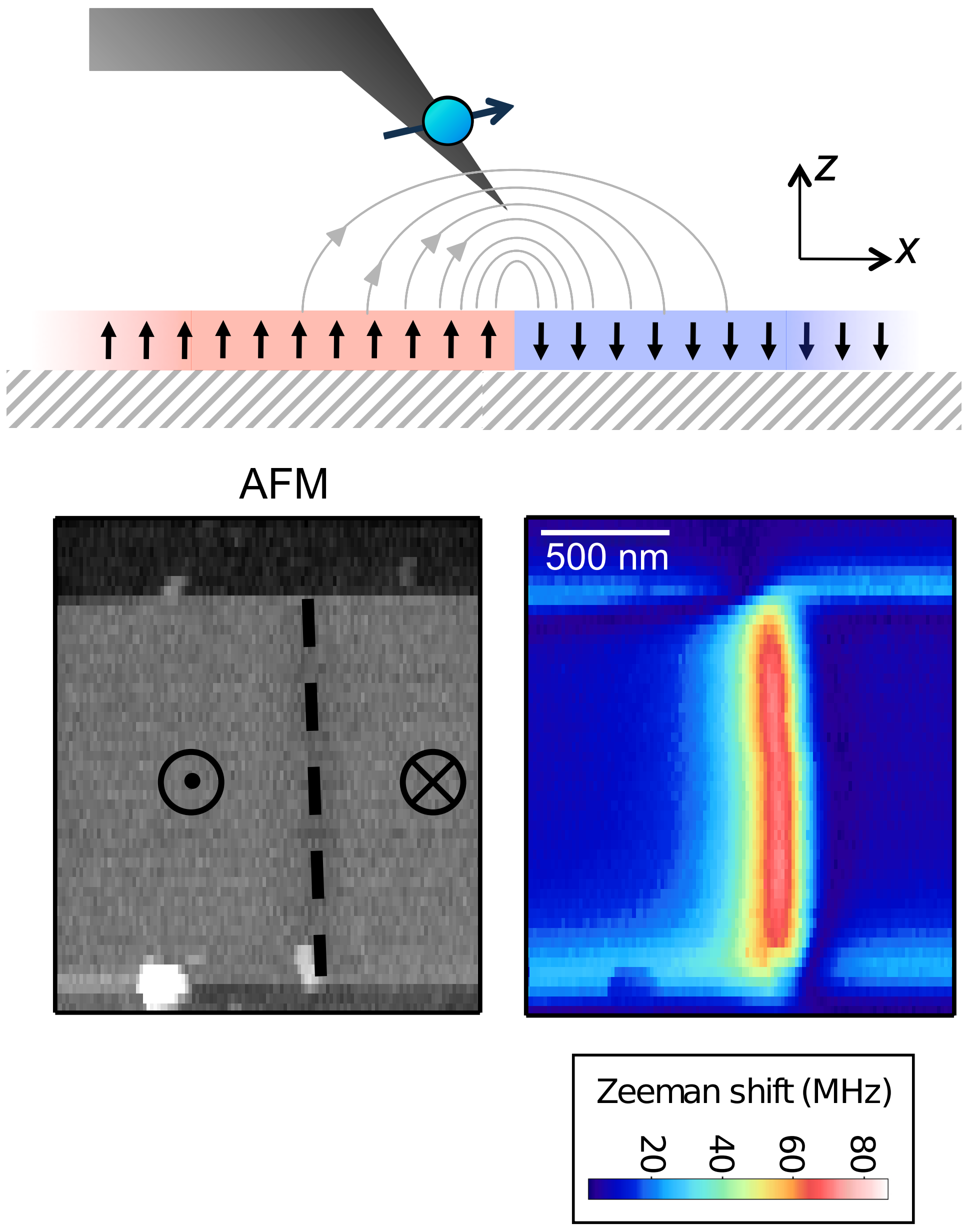
Tetienne , *Science* **344**, 1366 (2014)



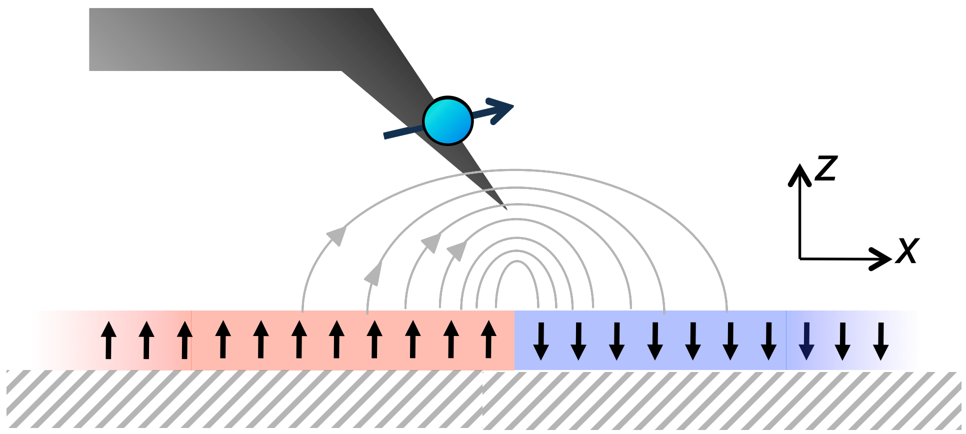


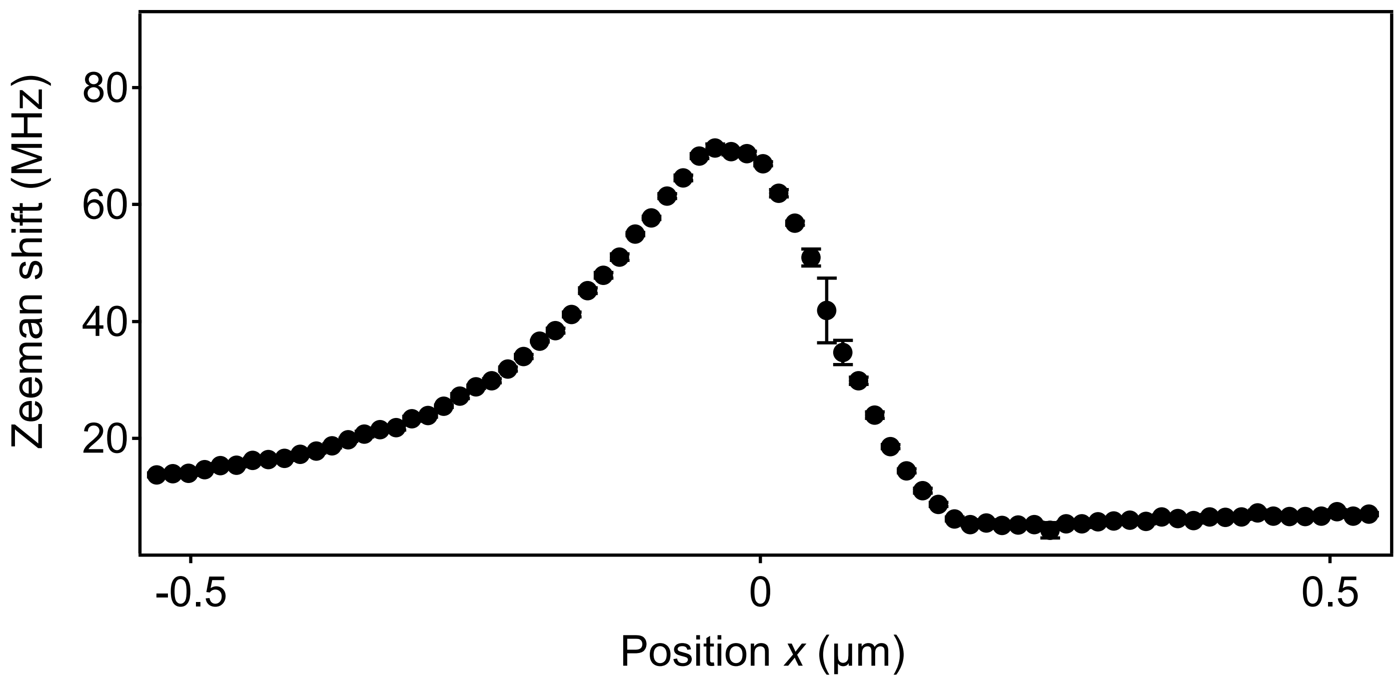


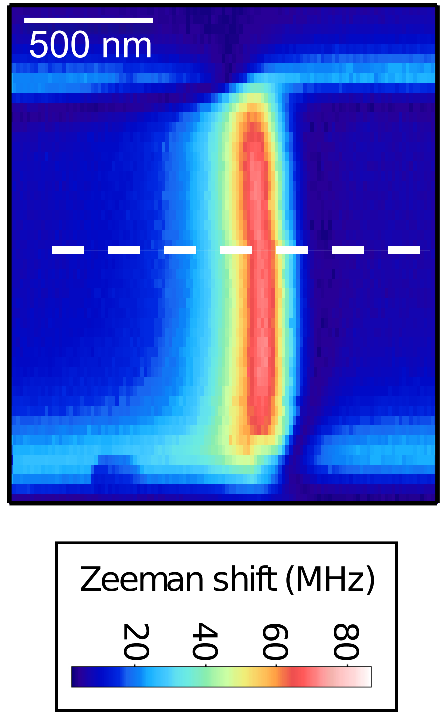
Extracting the nature of the domain wall



Extracting the nature of the domain wall







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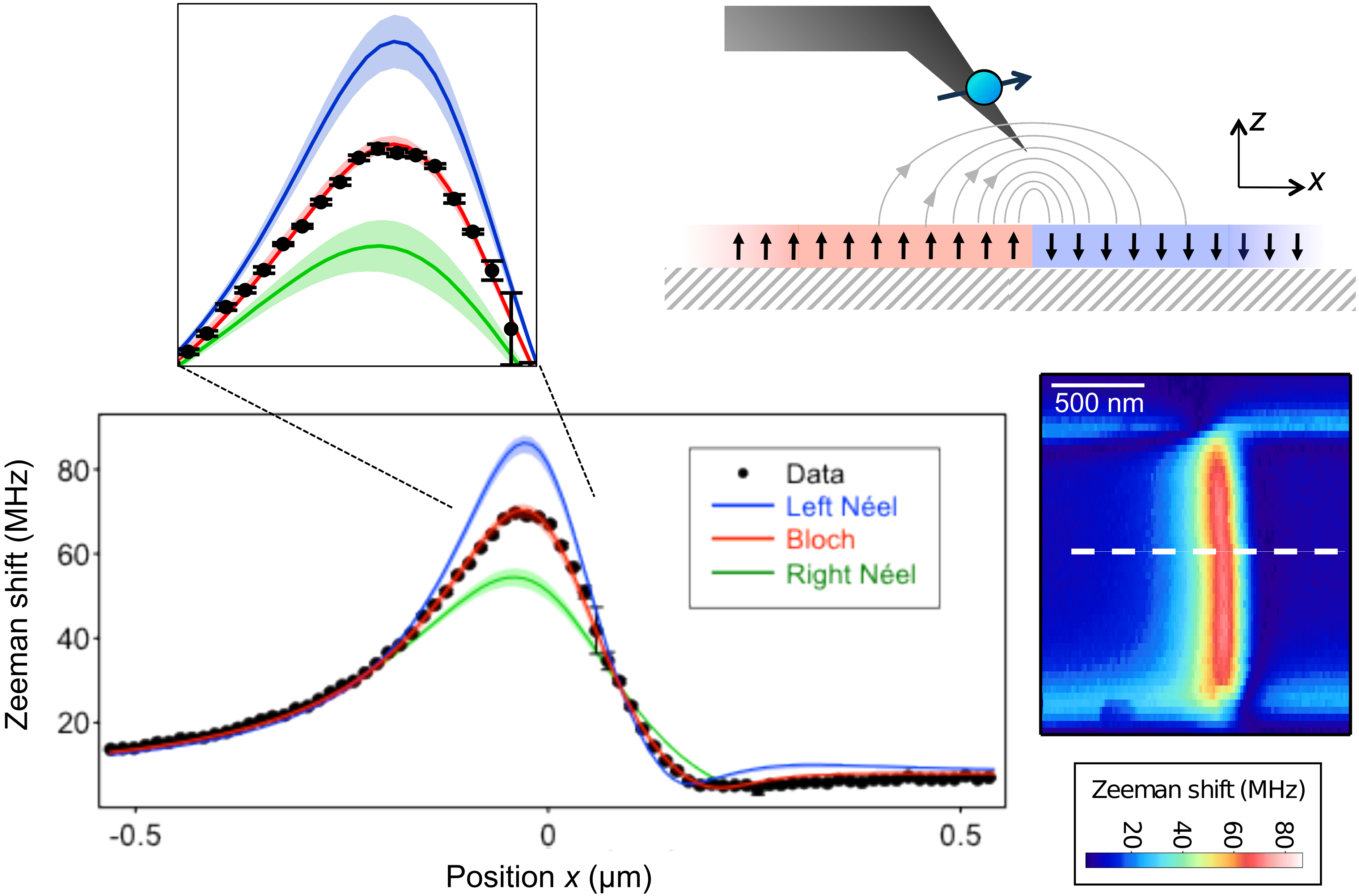
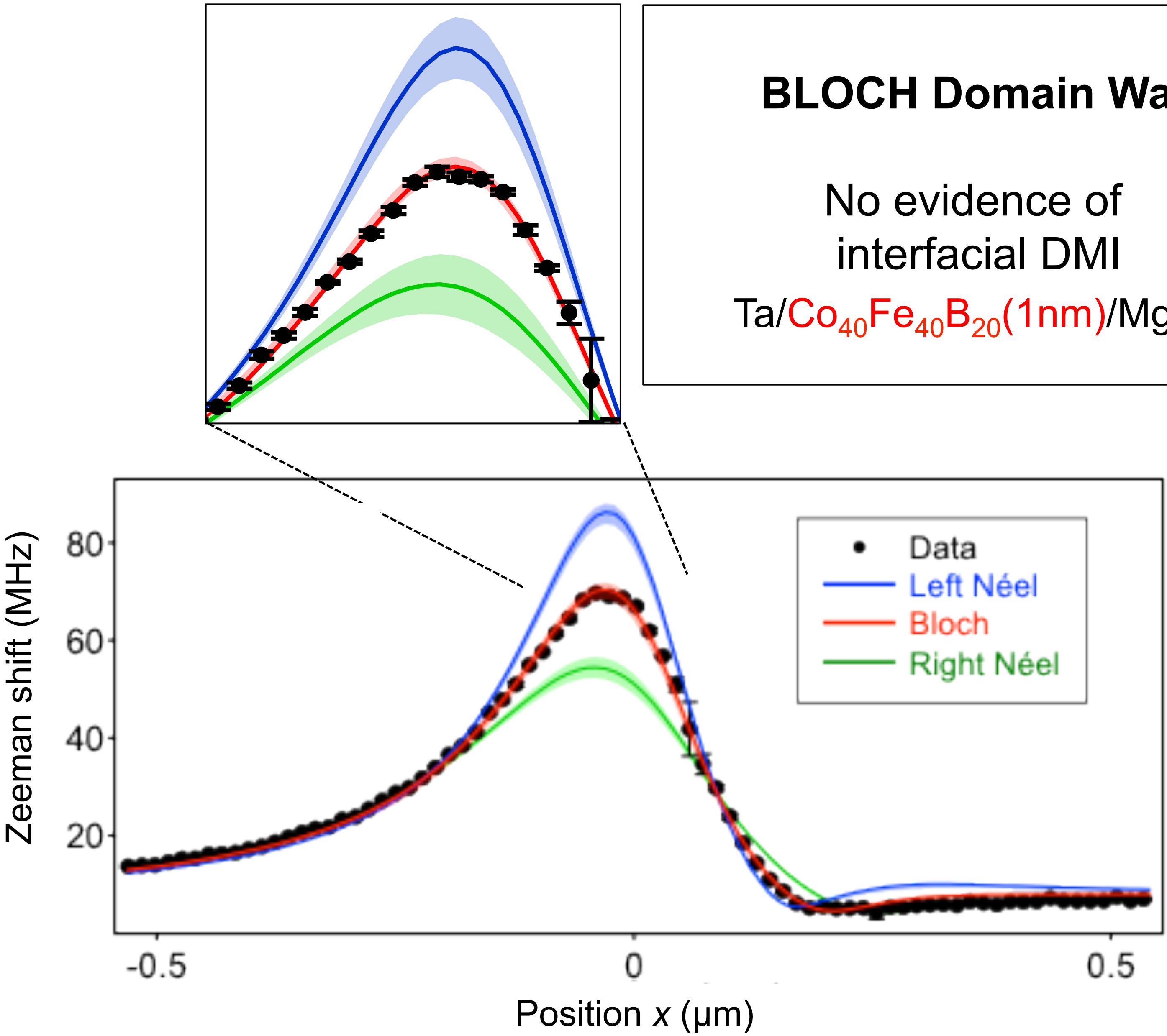


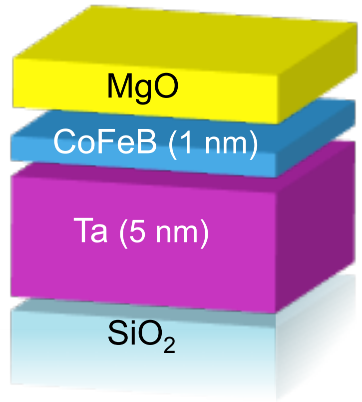
Extracting the nature of the domain wall

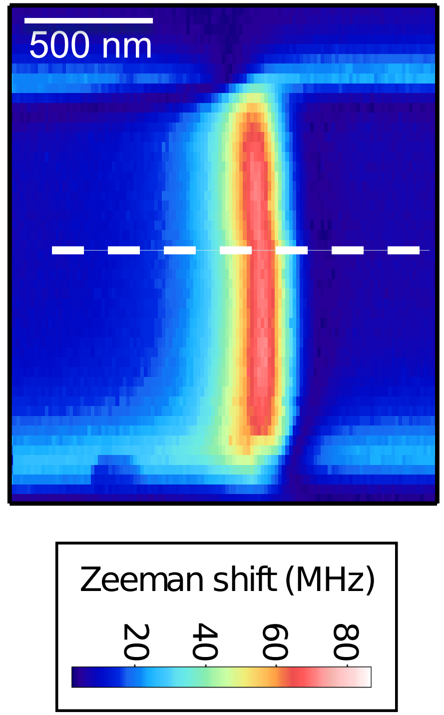


BLOCH Domain Wall

No evidence of interfacial DMI

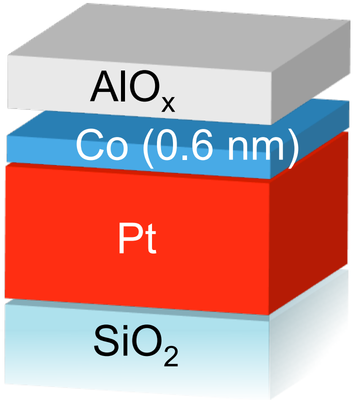
Ta/$Co_{40}Fe_{40}B_{20}$(1nm)/MgO



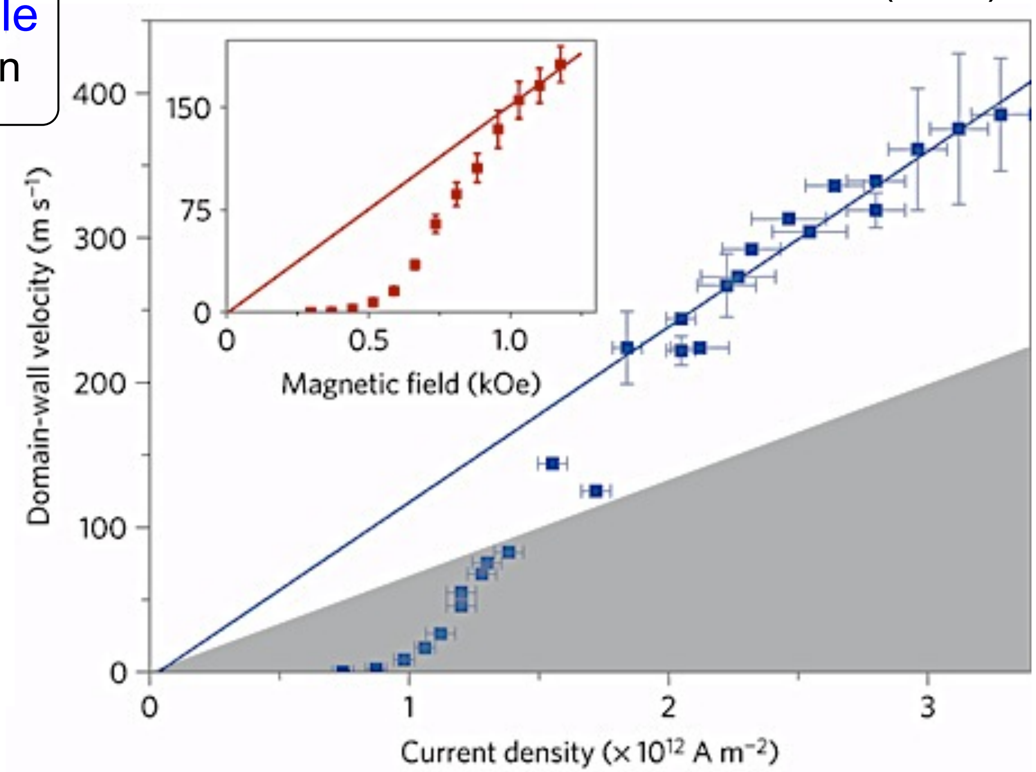


What about Pt/Co(0.6nm)/AlOx ?

SPINTEC Grenoble
G. Gaudin, M. Miron



I. M. Miron *et al.*, *Nat. Mater.* 10, 419 (2011)



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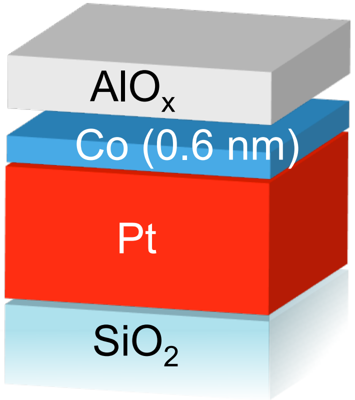

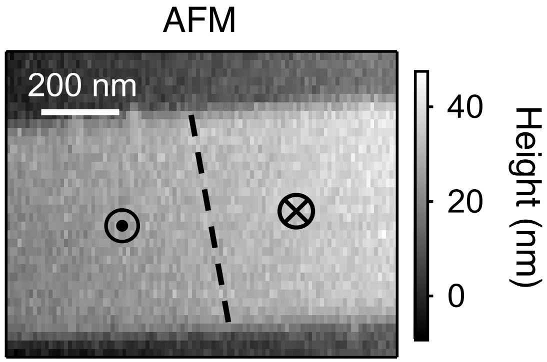

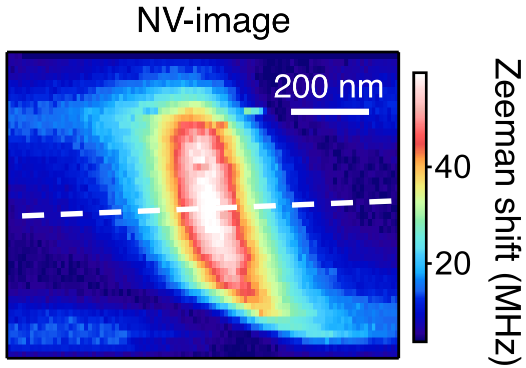

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SPINTEC Grenoble
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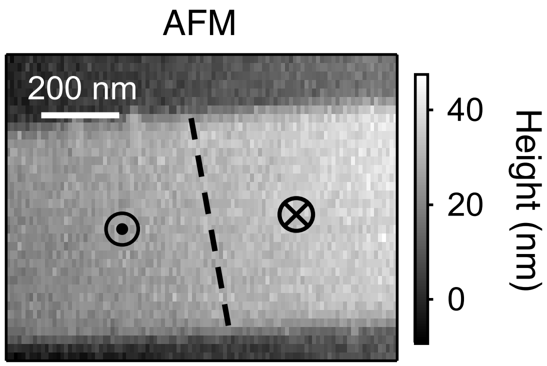

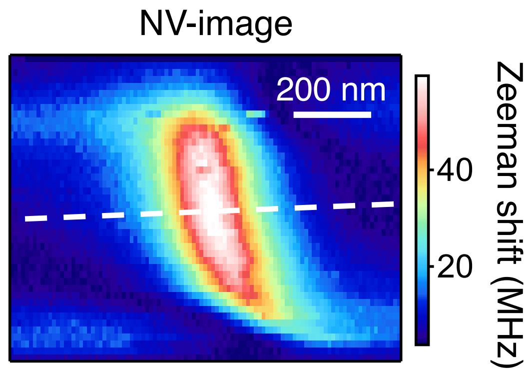

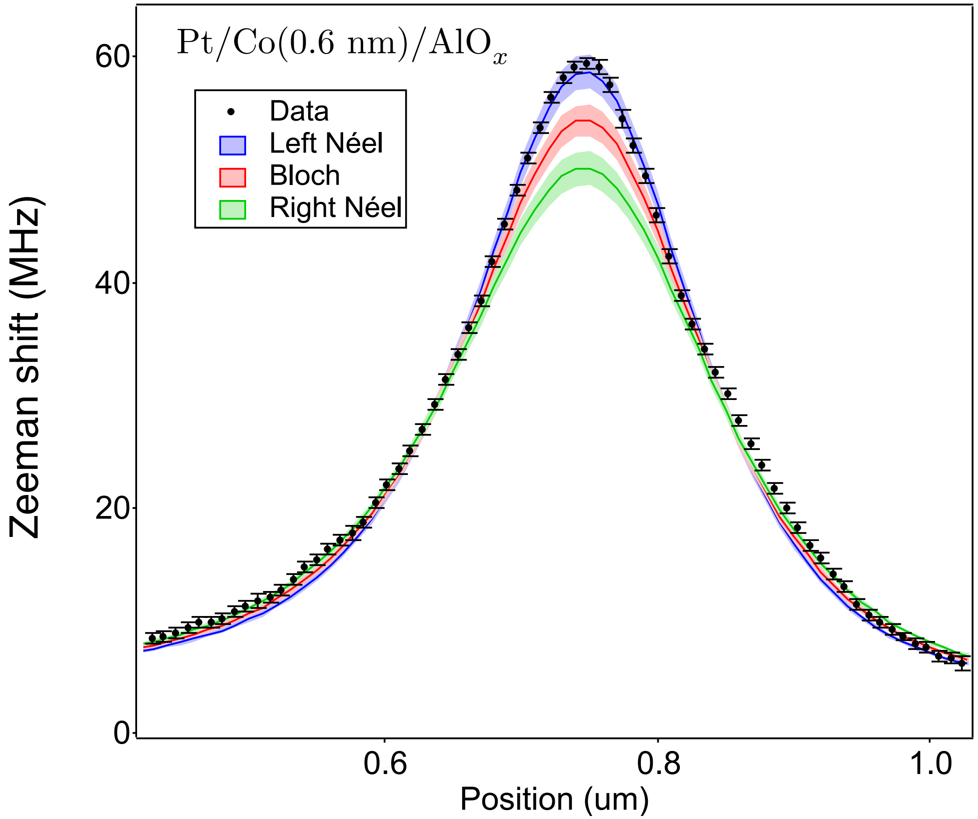

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SPINTEC Grenoble
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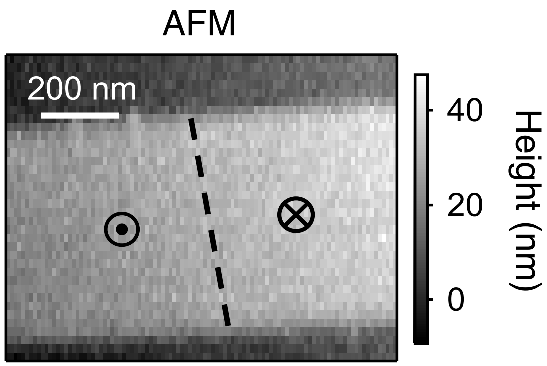
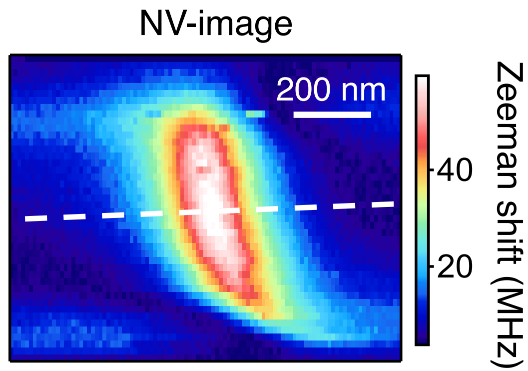
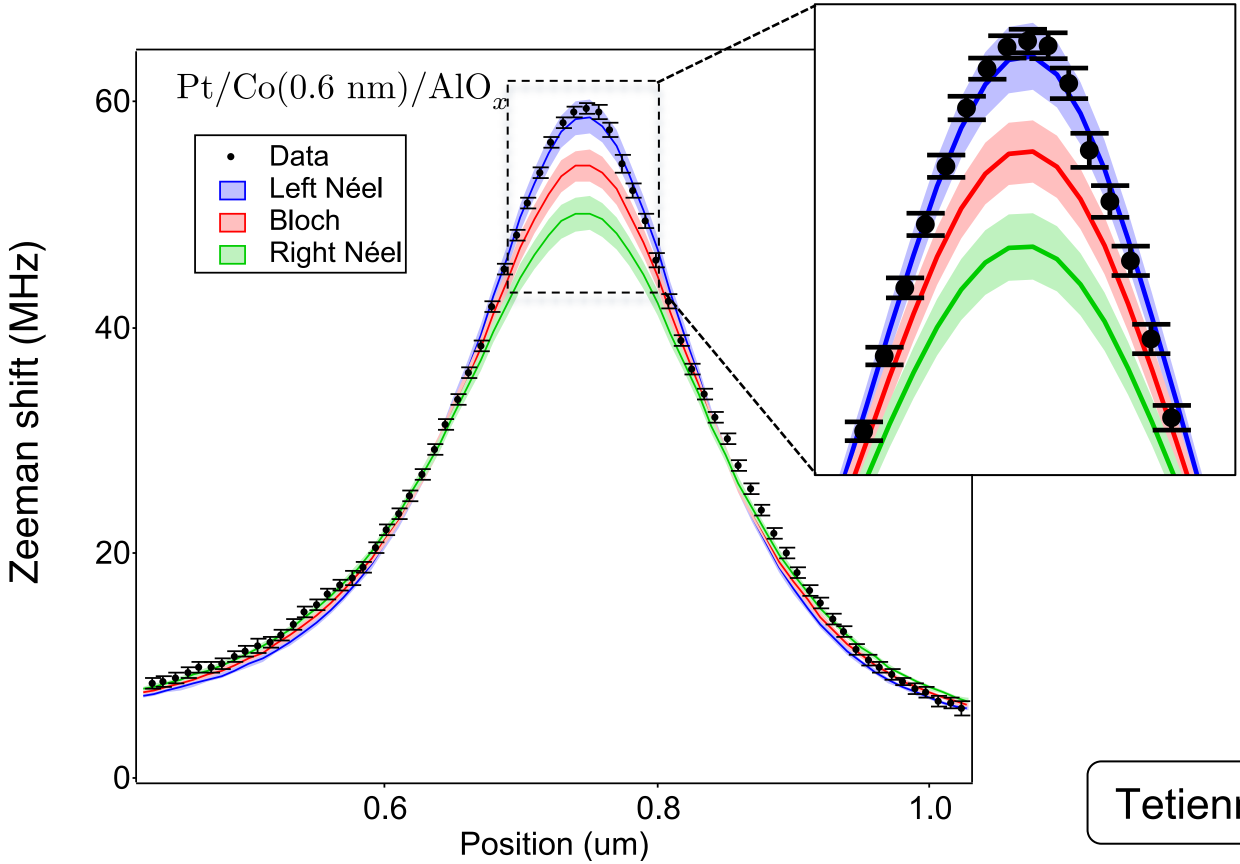






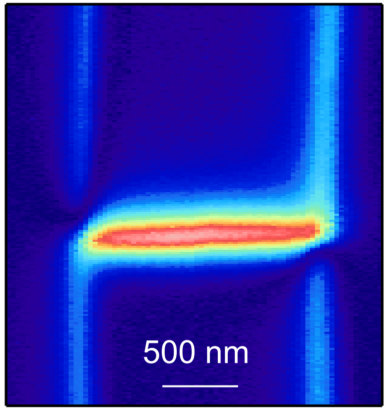
Néel left DW

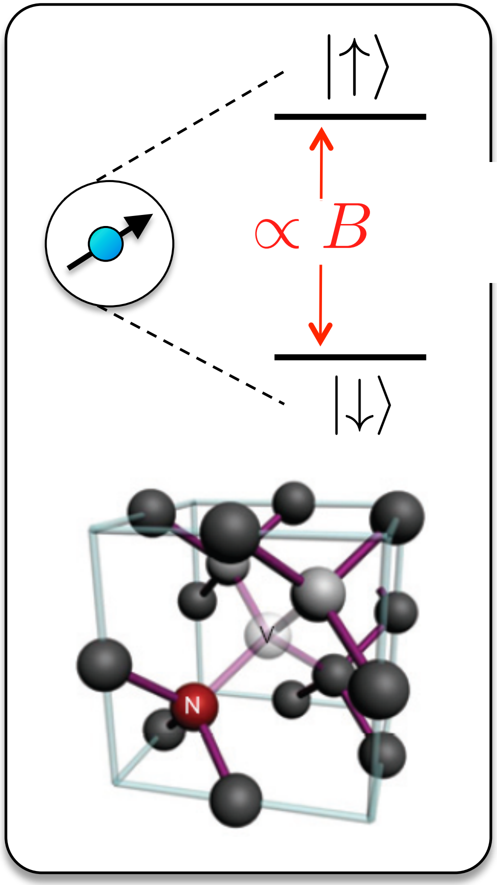
Direct evidence of a sizable interfacial DMI at the Pt/Co interface

Tetienne, *Nat. Com.* **6**, 6733 (2015)

Quantum sensing with NV defects

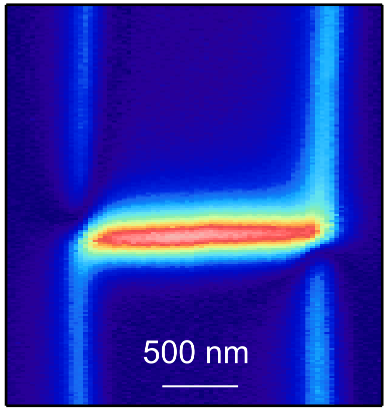
Magnetometry

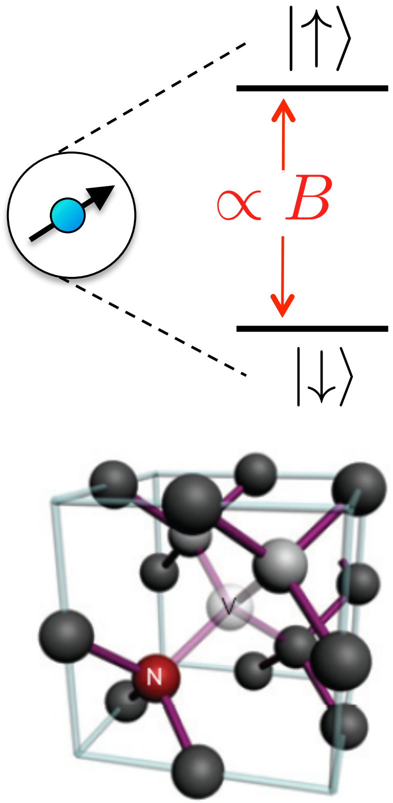




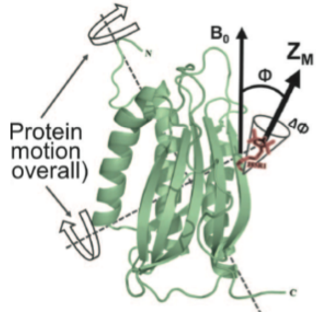
Quantum sensing with NV defects

Magnetometry





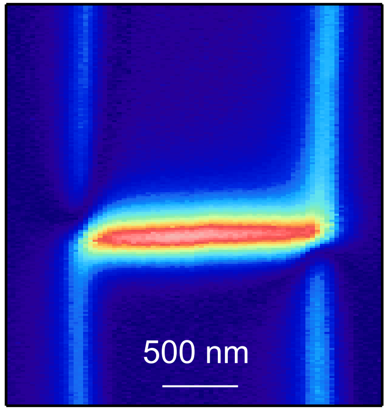
nanoMRI
Protein imaging

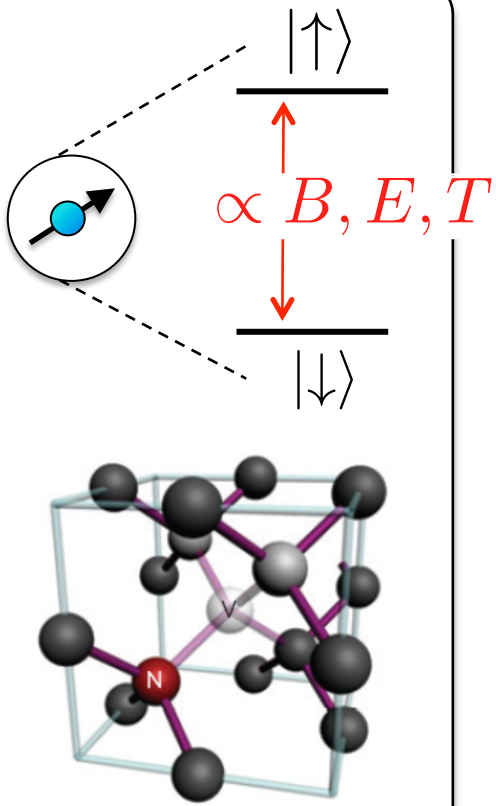


Shi *et al.*, *Science* (2015)
Sushkov *et al.*, *PRL* (2014)

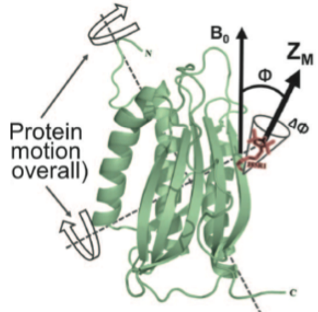
Quantum sensing with NV defects

Magnetometry



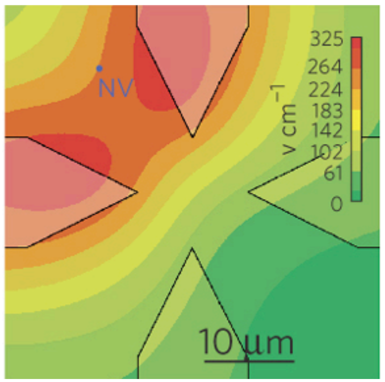


nanoMRI Protein imaging



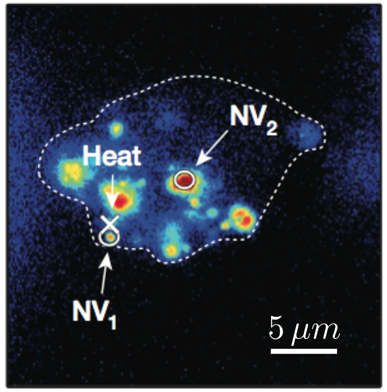
Shi *et al.*, *Science* (2015)
Sushkov *et al.*, *PRL* (2014)

Electrometry



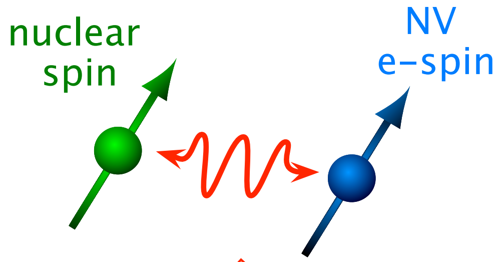
Dolde et al., *Nat. Phys.* **7**, 459 (2011)

Thermometry

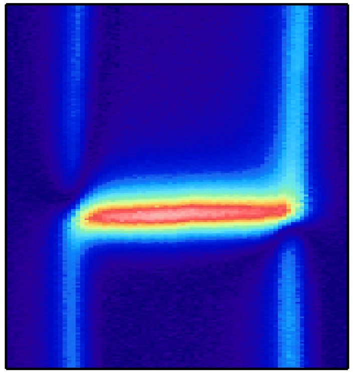


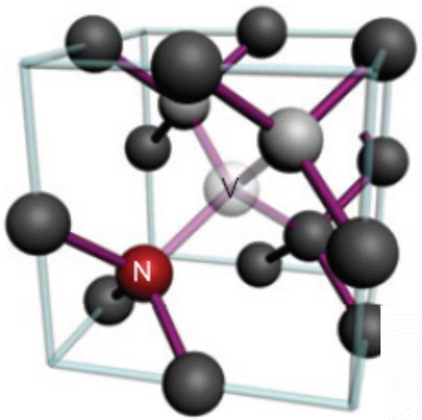
Kucsko *et al.*, *Nature* **500**, 54 (2013)

Quantum information, Spin physics

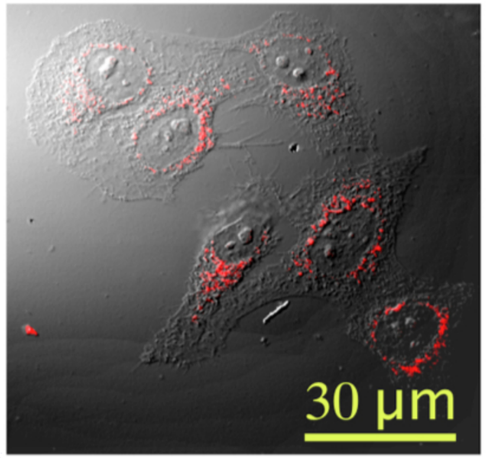


Nanoscale sensing

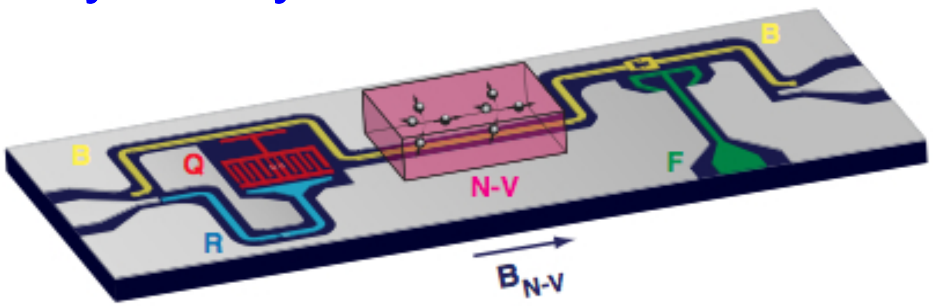




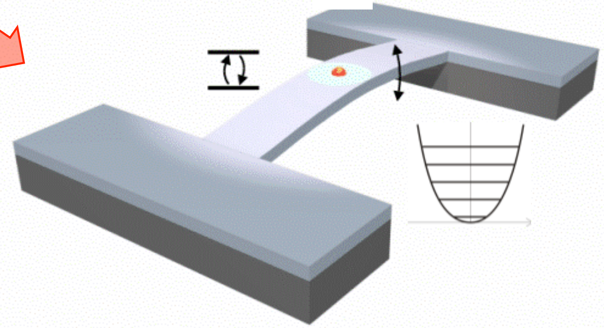
Fluorescent label in Biology



Hybrid systems



Kubo *et al., Phys. Rev. Lett.* **107**, 220501 (2011)



Arcizet *et al., Nat. Phys.* **7**, 879 (2011)