Torino, 08-06-2023

Quantum sensing con centri NV in diamante

Workshop Tecnologie quantistiche
INFN CSN4 & CSN5 - Università di Torino

Jacopo Forneris
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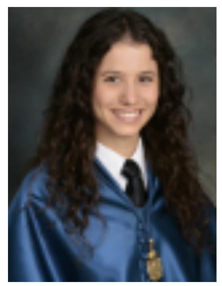
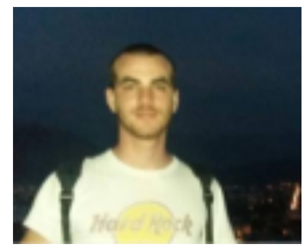
Istituto Nazionale di Ricerca Metrologica

Research activities @ Torino: don't miss the posters!

http://www.solid.unito.it


P. Olivero


E. Nieto Hernandez


E. Corte

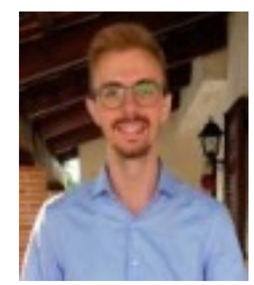

G. Andrini


E. Vittone


F. Picollo


V. Pugliese


E. Redolfi


G. Zanelli


S. Ditalia Tchernij

MINISTERO DELL' ISTRUZIONE, DELL'UNIVERSITÀ E DELLA RICERCA

L232/2016 Dept. Excellence

INFN Istituto Nazionale di Fisica Nucleare

2020 CSN5 QT Call "QUANTEP"

EMPIR EURAMET

Research Projects, "SEQUME", "QADET"

PIQUET PIEMONTE QUANTUM ENABLING TECHNOLOGY

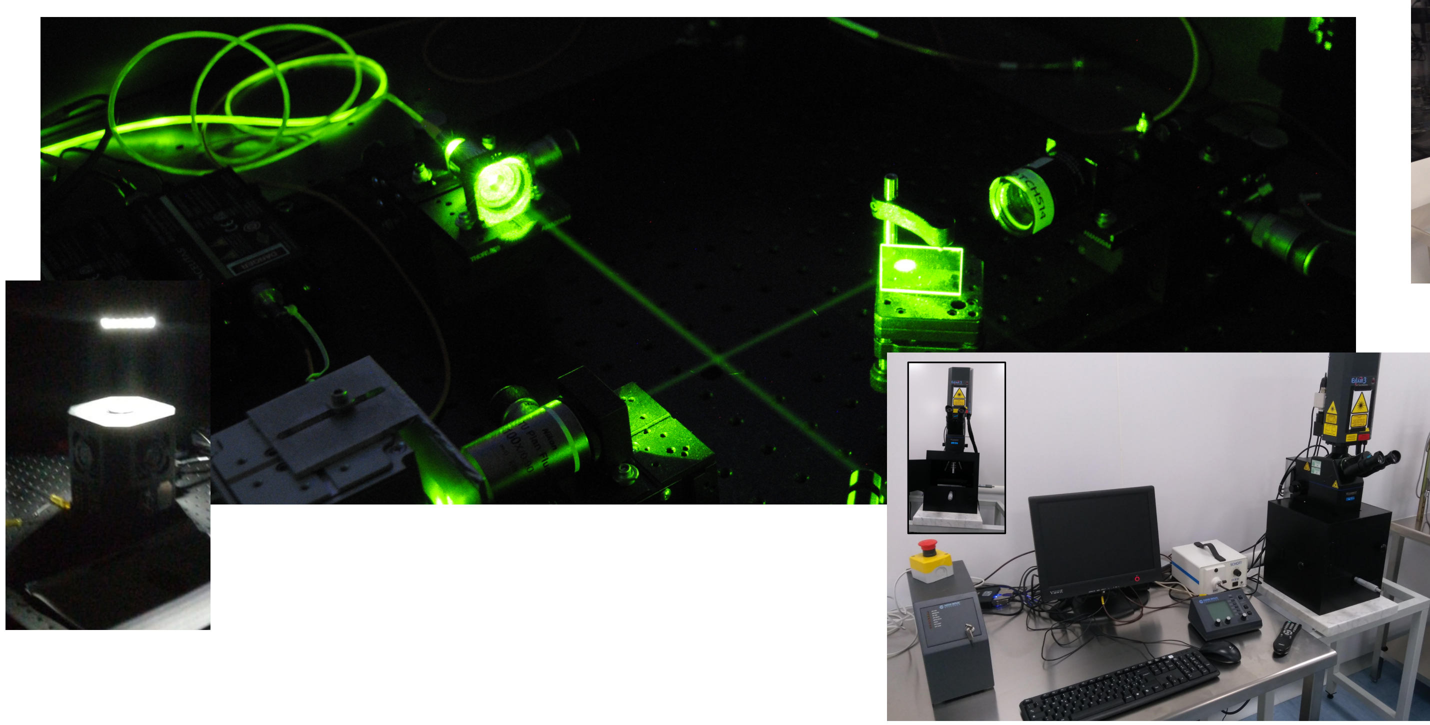
European Commission

Marie-Curie "LasIonDef" Project

Experimental research at UniTO - Physics Department

Multi-elemental **ion implanter** embedded in ISO-6 cleanroom environment

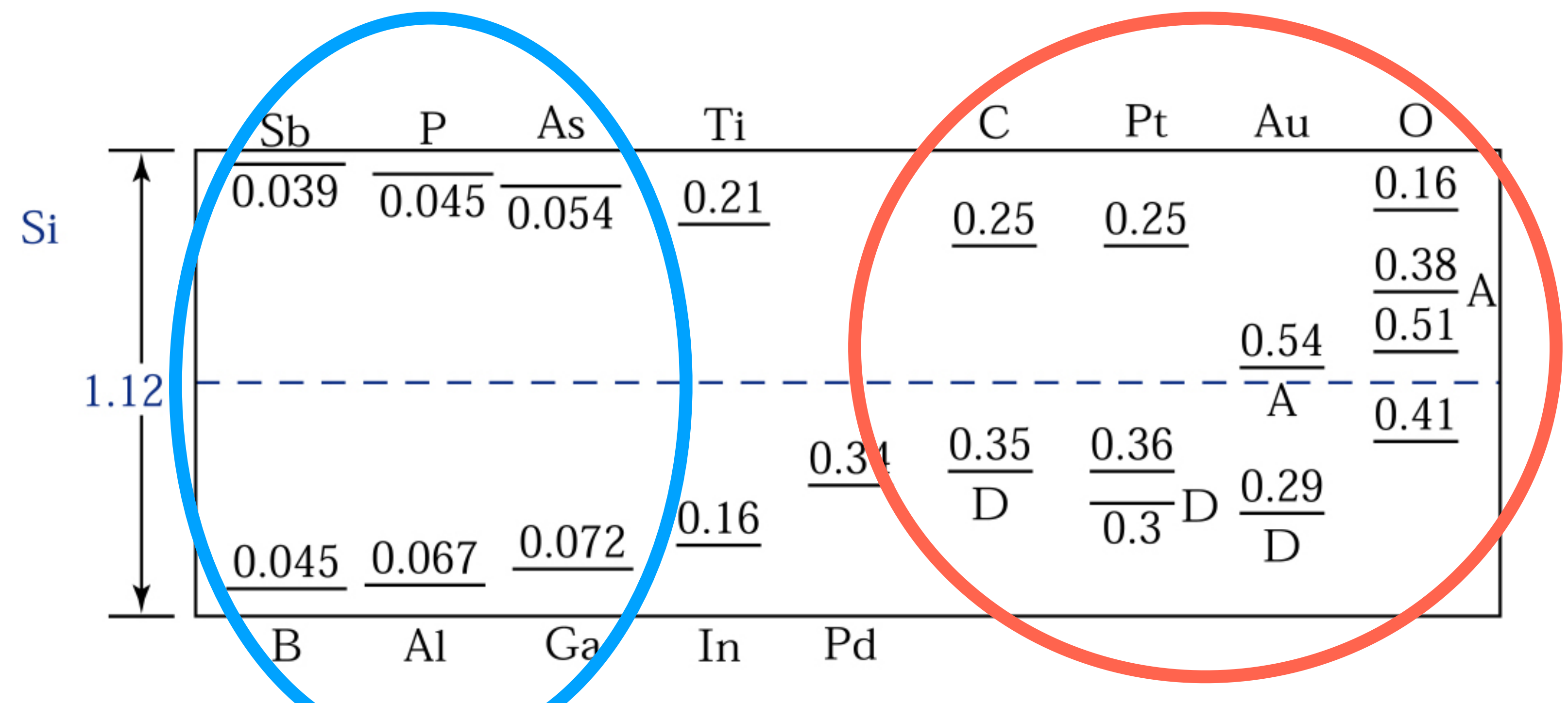
RT and 4K **confocal microscopy** setups

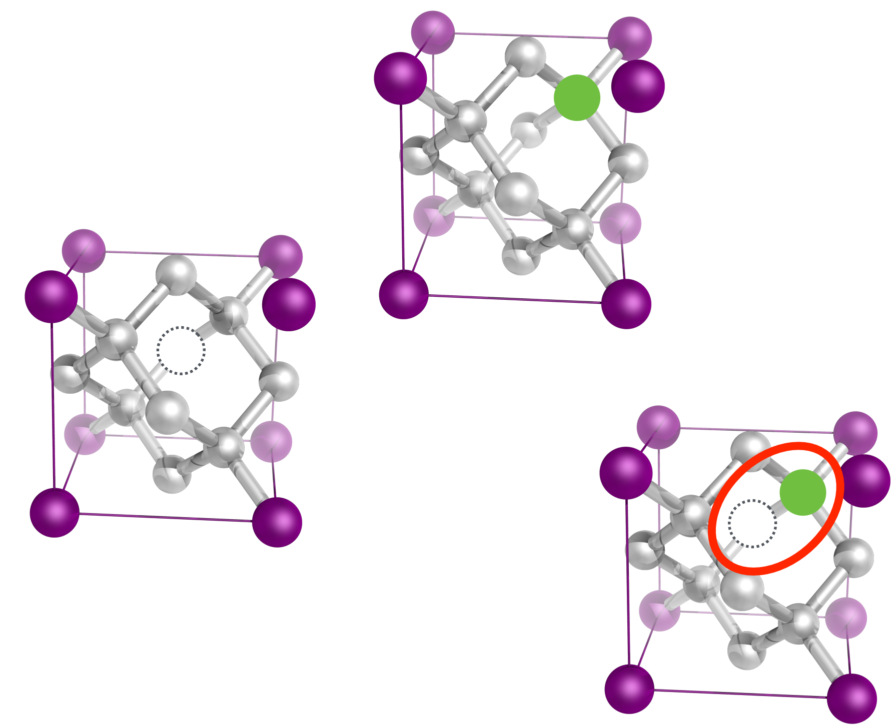


Electrical Probe Stations

Color centers in semiconductors

Simplified band diagram of Silicon
Energy levels of impurity-related point defects



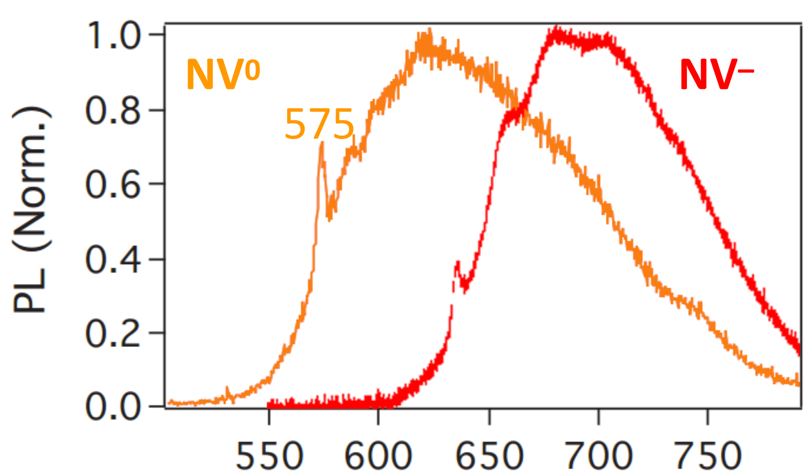


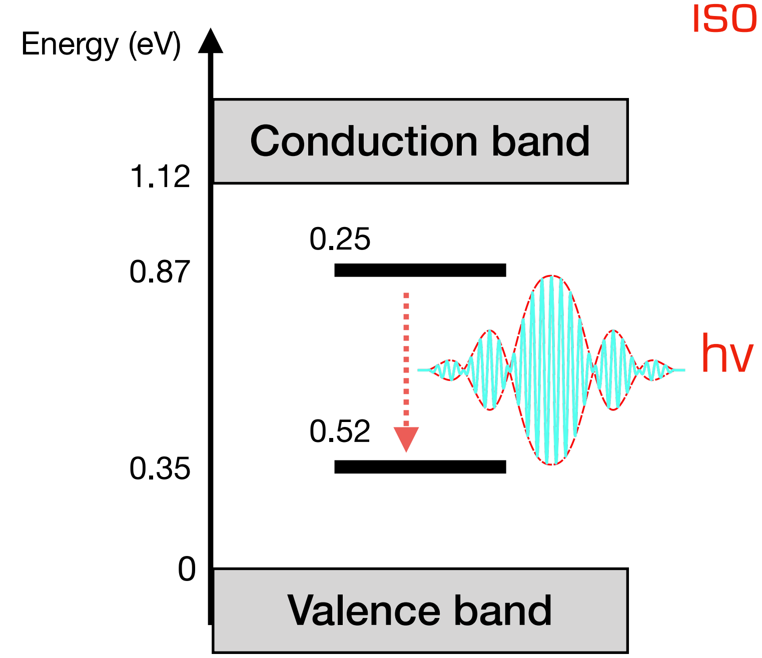
deep energy levels

optical transitions
isolated quantum systems

electrical doping

NV center
in diamond



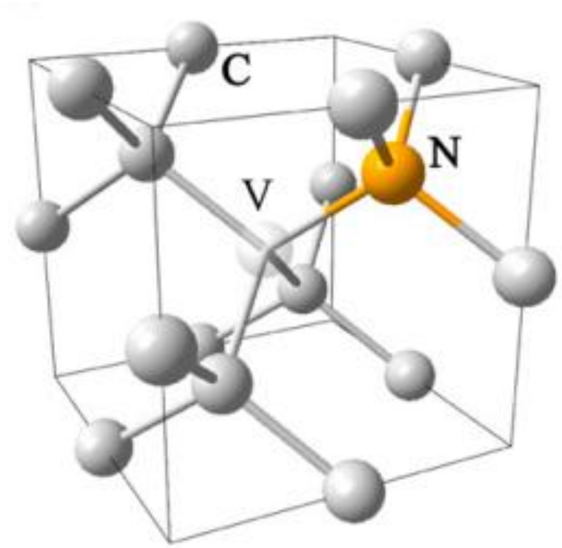


Point defects in solids

Monoatomic crystal control on defects formation

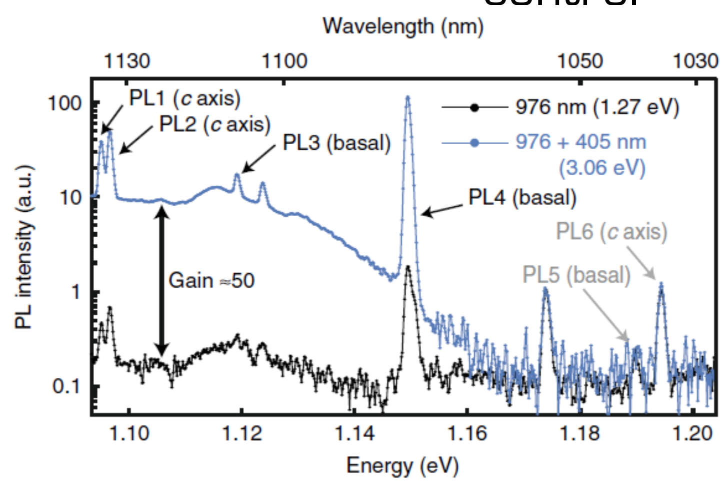
Room temperature operation

Diamond



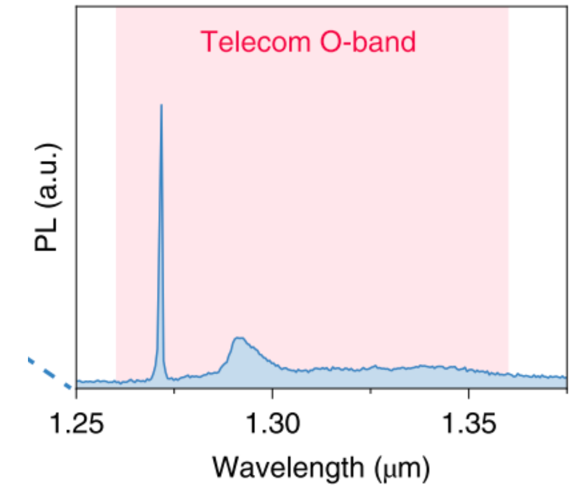
SiC

Electrical control



Nat. Comm 8 (2018) 1876

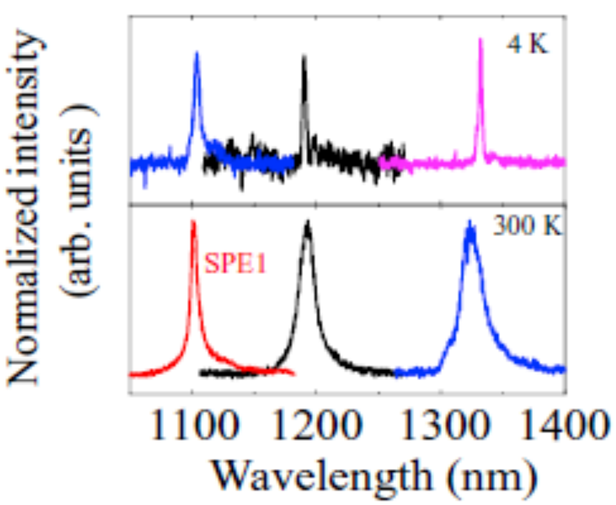
Silicon



Nature Electronics 3 (2020) 738

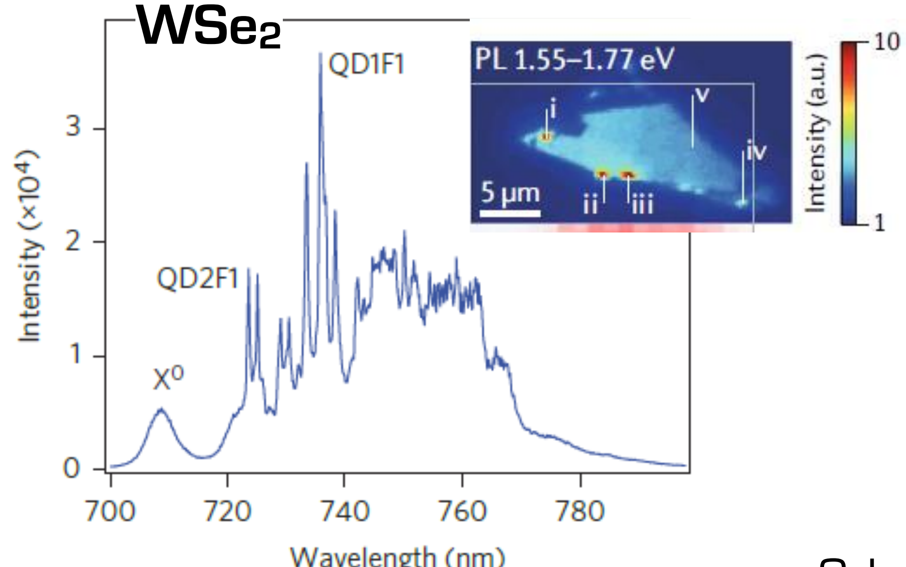
Telecom wavelengths!!!

GaN IR emission



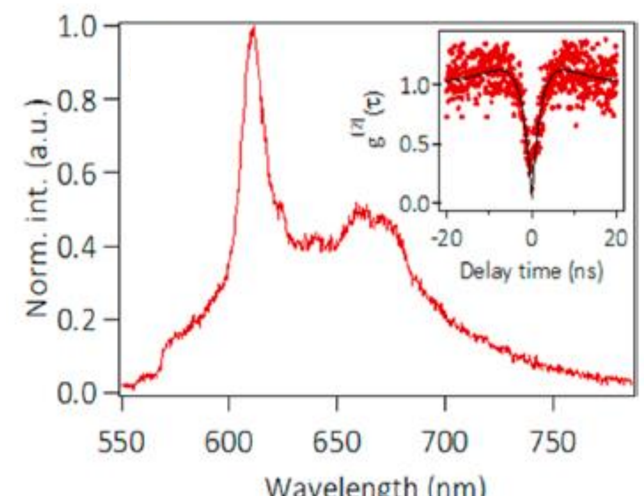
Sci. Advances 4 (2018) 3580

WSe_2



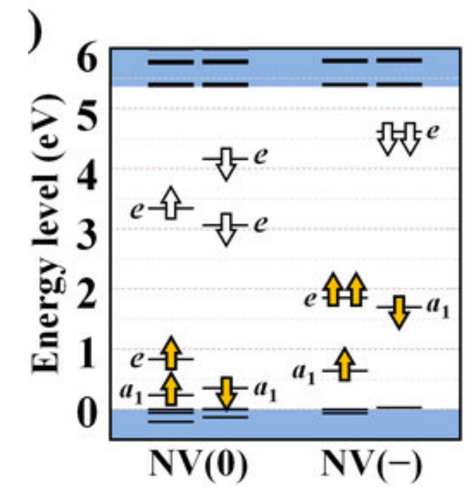
Nature Nanotech. 10 (2015) 491

hBN



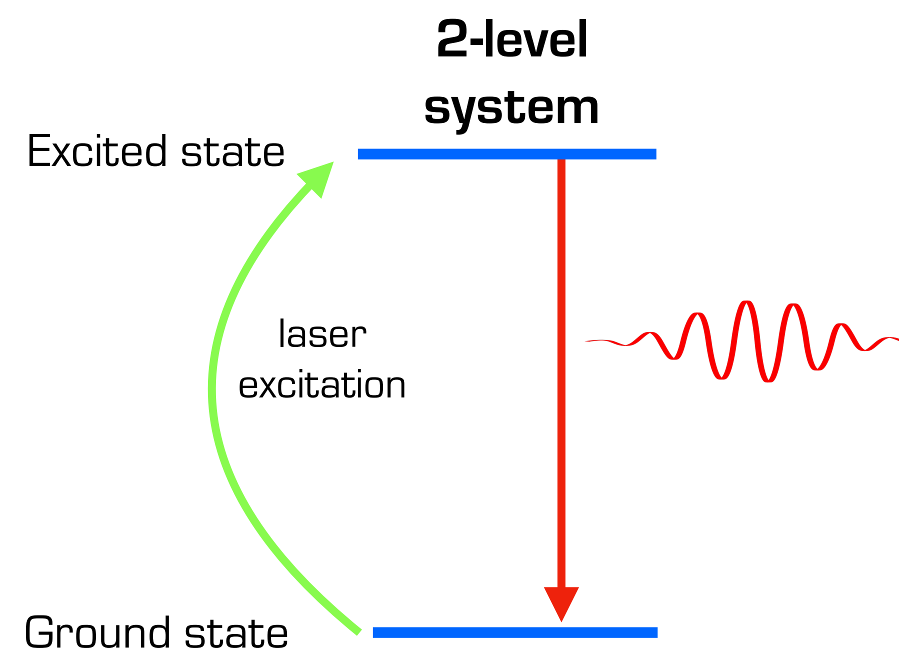
2d materials

Diamond color centers



Point defects (vacancies, interstitials, substitutional impurities)
Formation of discrete energy levels with optical transitions

Individual defects: single-photon sources

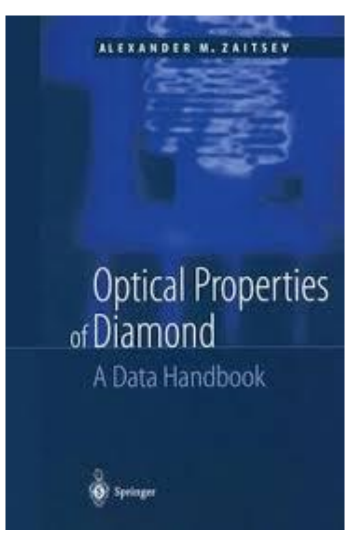


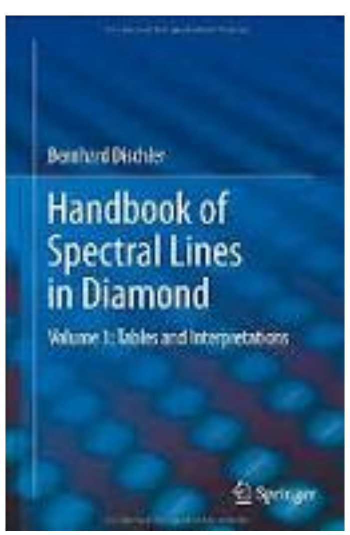
Large band gap (5.5 eV):

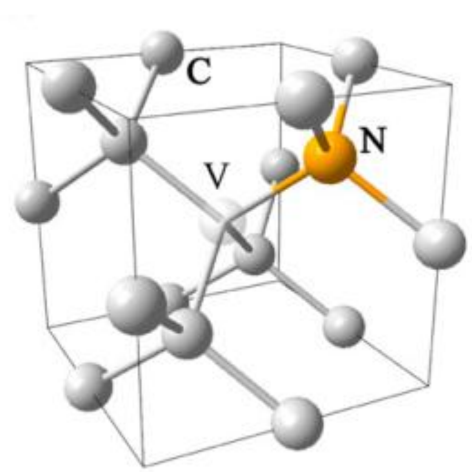
- Emission in the visible light spectrum
- Operation at high temperatures

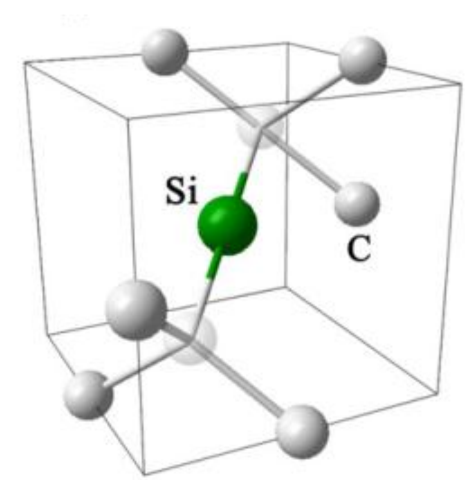
Hundreds of optically active defects

Many having **high quantum efficiency** and **RT photo-stability**

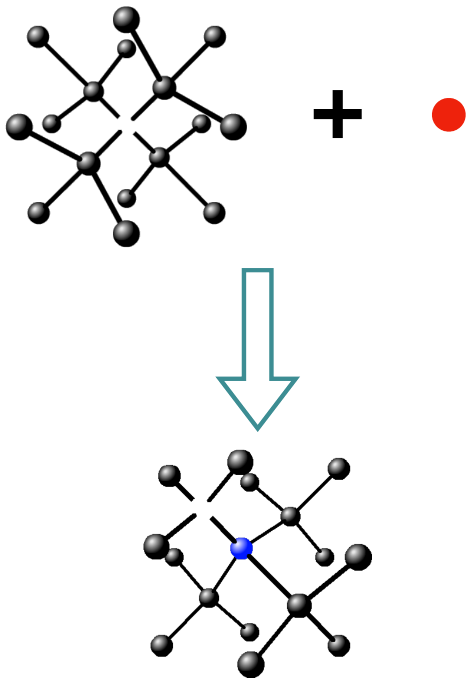








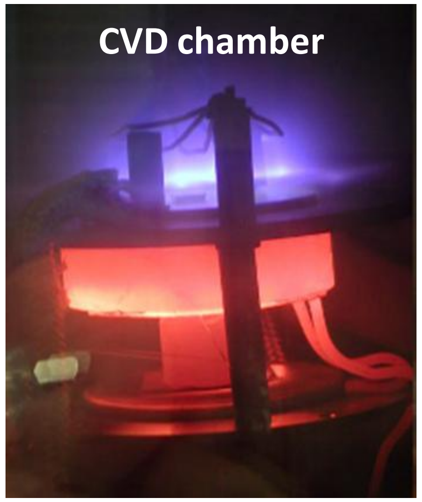
Color centers formation

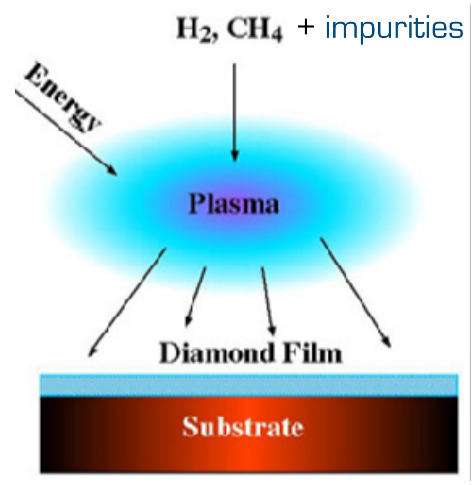


Incorporation during synthesis (homoepitaxial growth)

Excellent defect quality

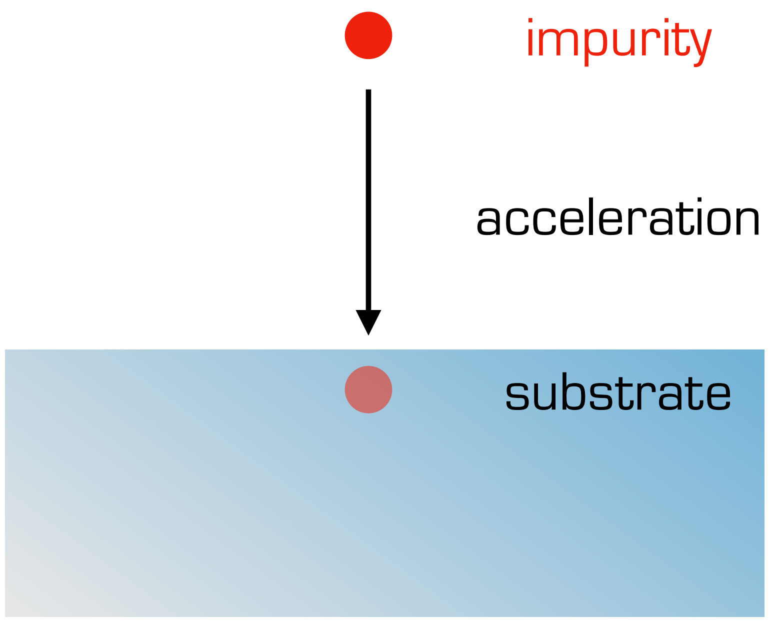
Lack of control on number, position of impurities

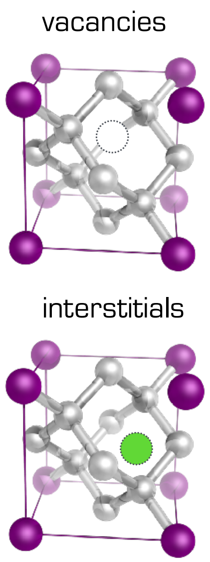


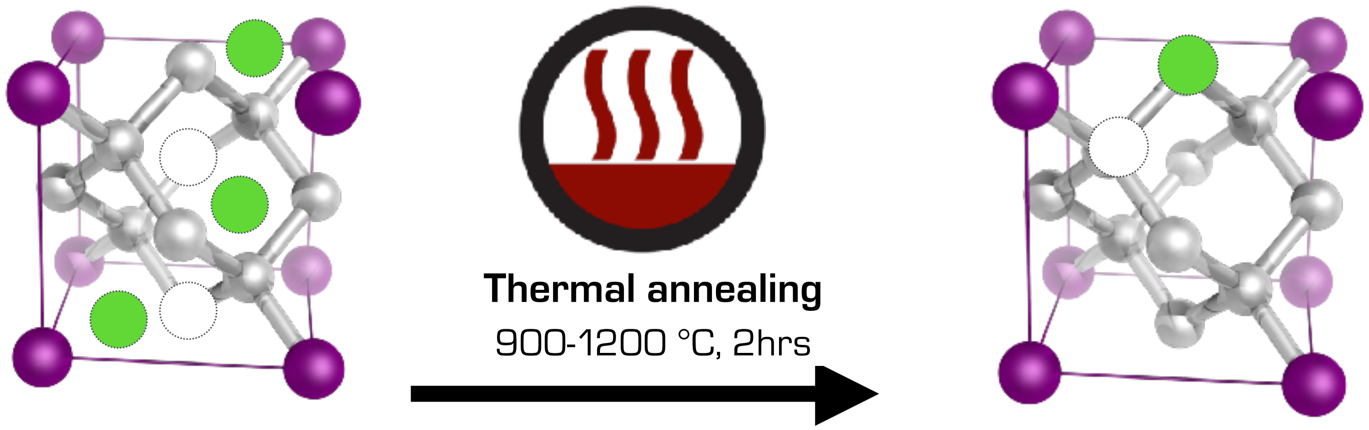


Ion implantation: introduction of external impurities

Subsequent thermal treatment for defect formation



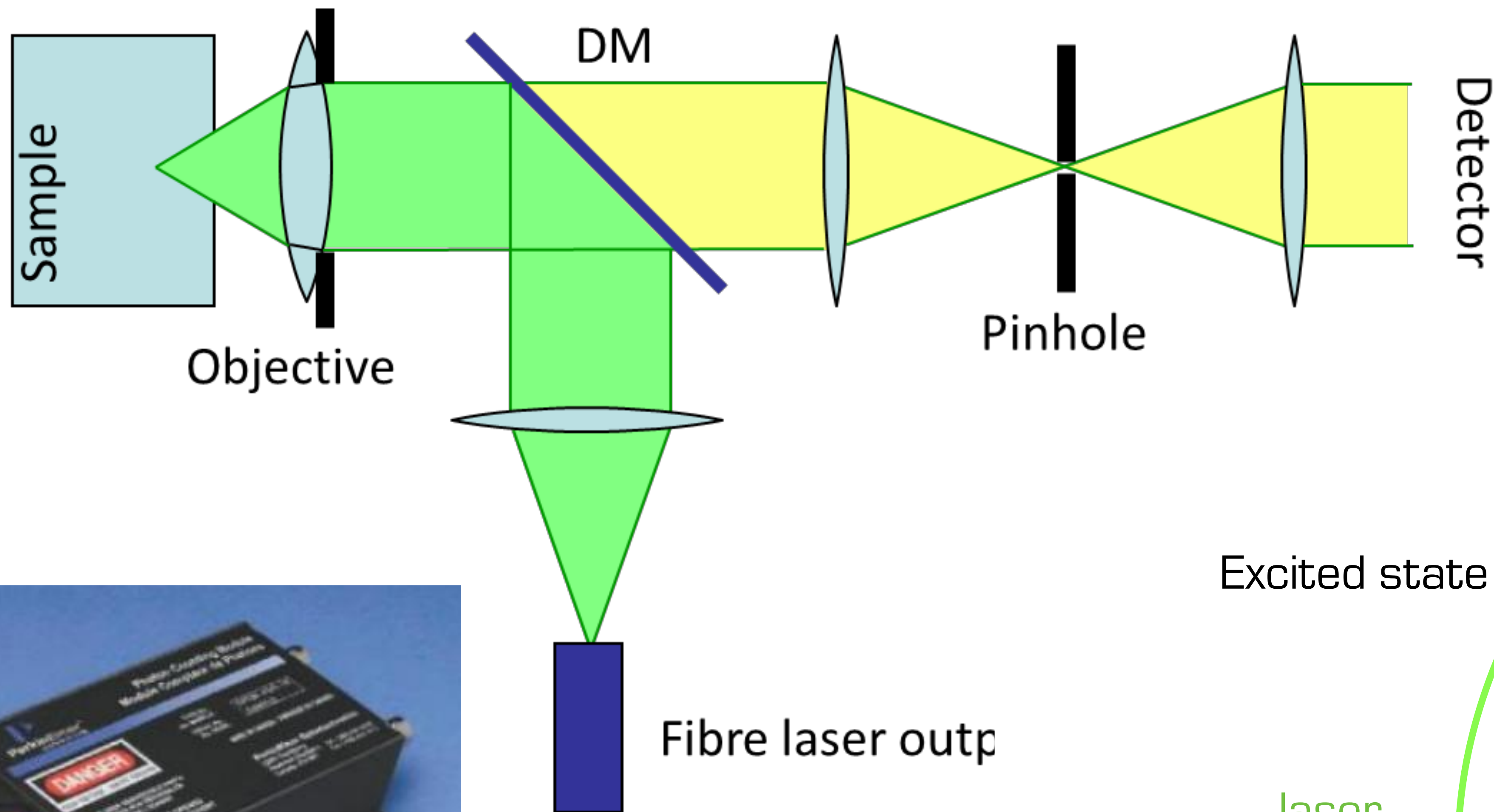




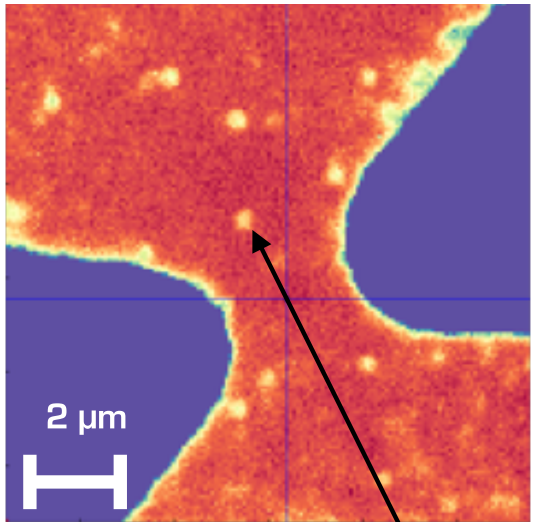
Single-photon confocal microscopy

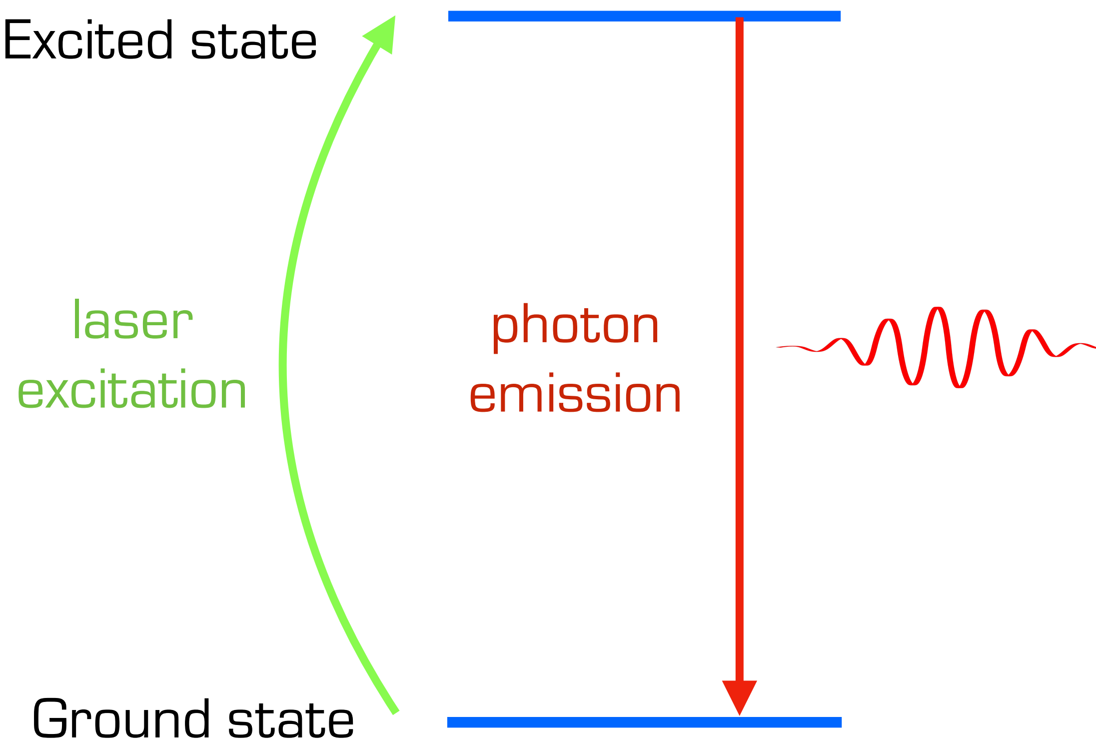
Experimental configuration

Photo-luminescence detection



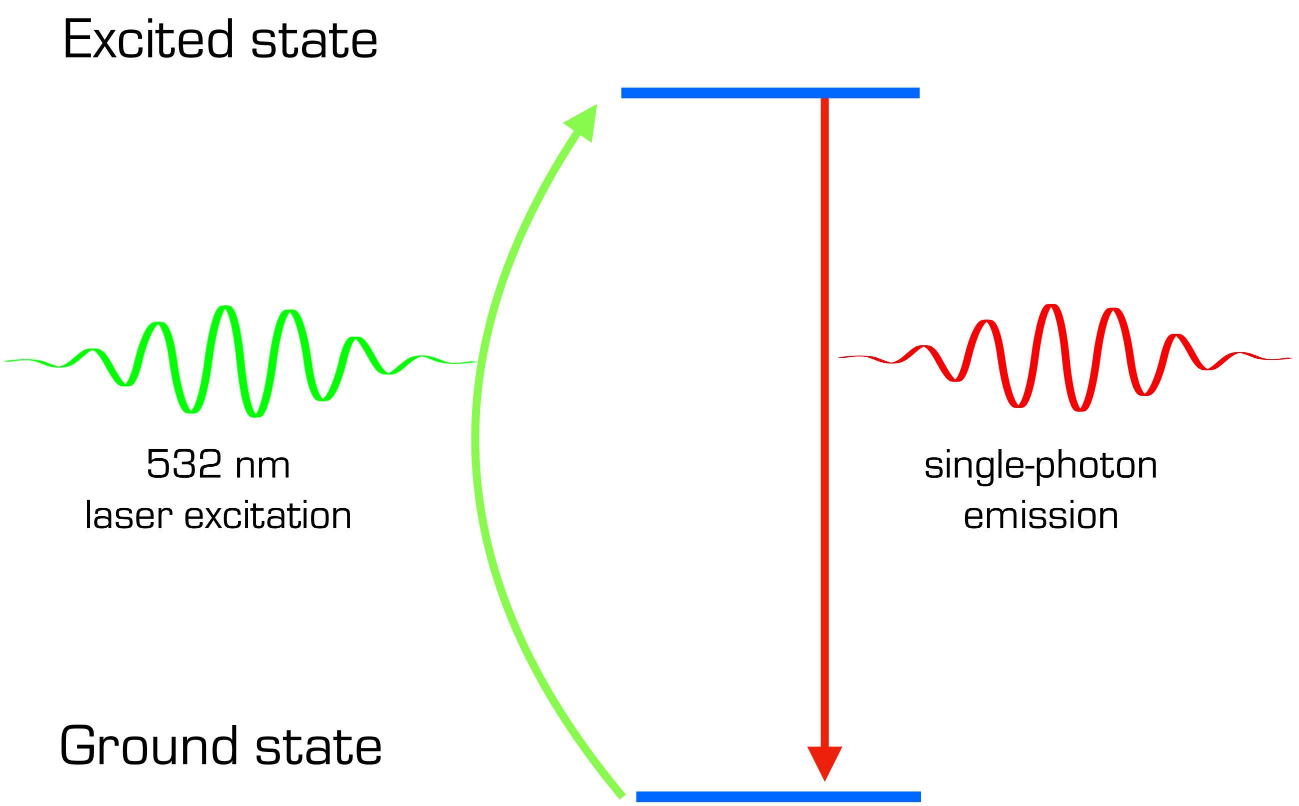
Optical sectioning: diffraction-limited 3D resolution

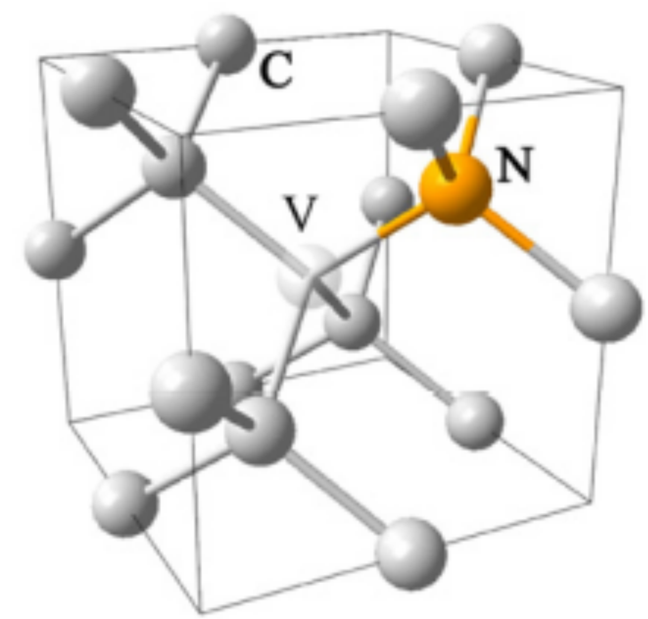


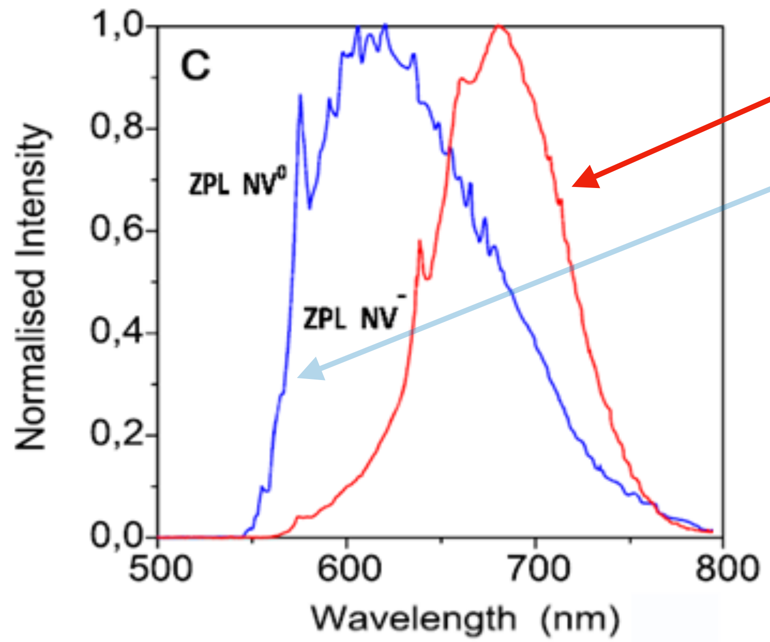


The nitrogen-vacancy complex in diamond

First order approximation:
2-level system



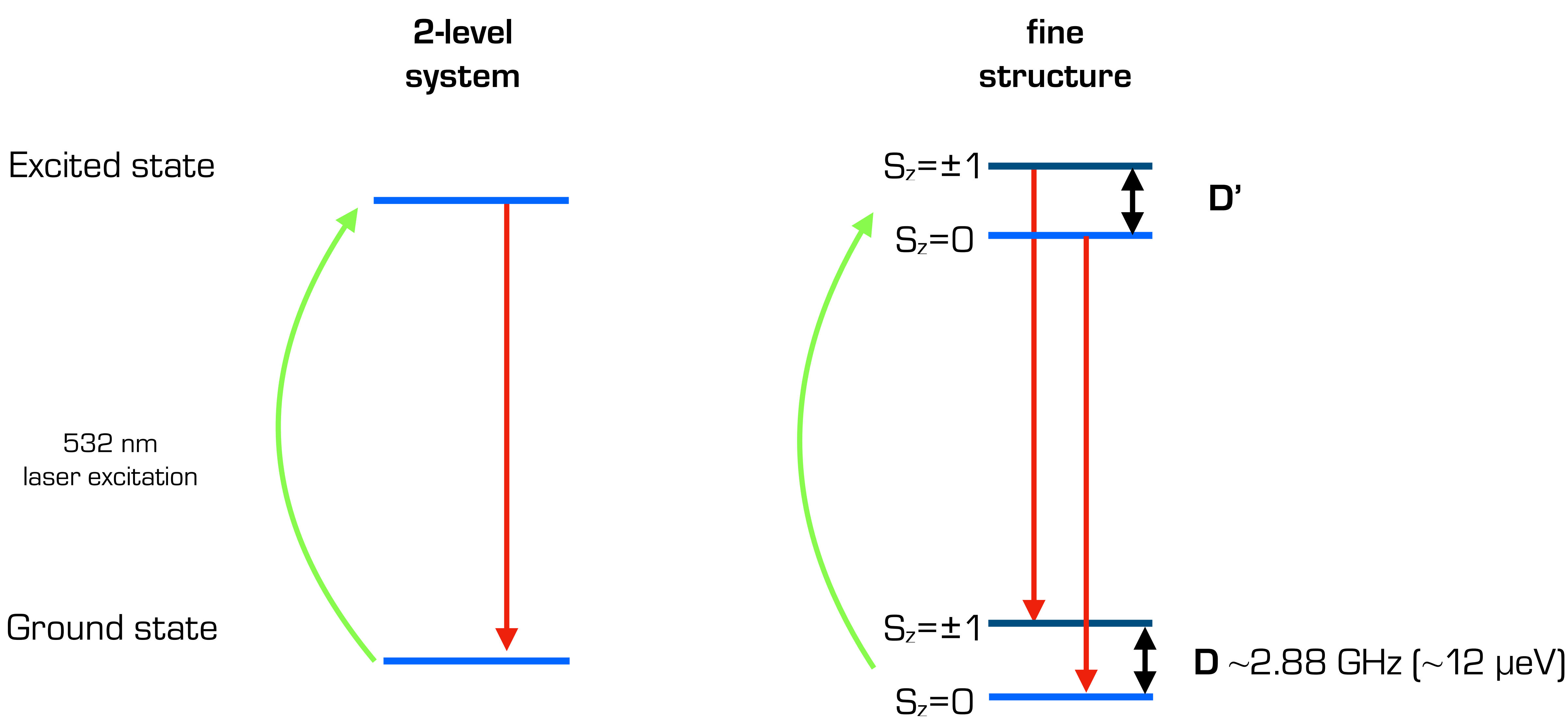




Negative charge state NV$^-$

Competing with the **neutral charge state NV^0**

The NV⁻ center ground state spin properties



NV⁻ center
6 bound electrons
spin triplet: $S=1$, $S_z=-1,0,+1$

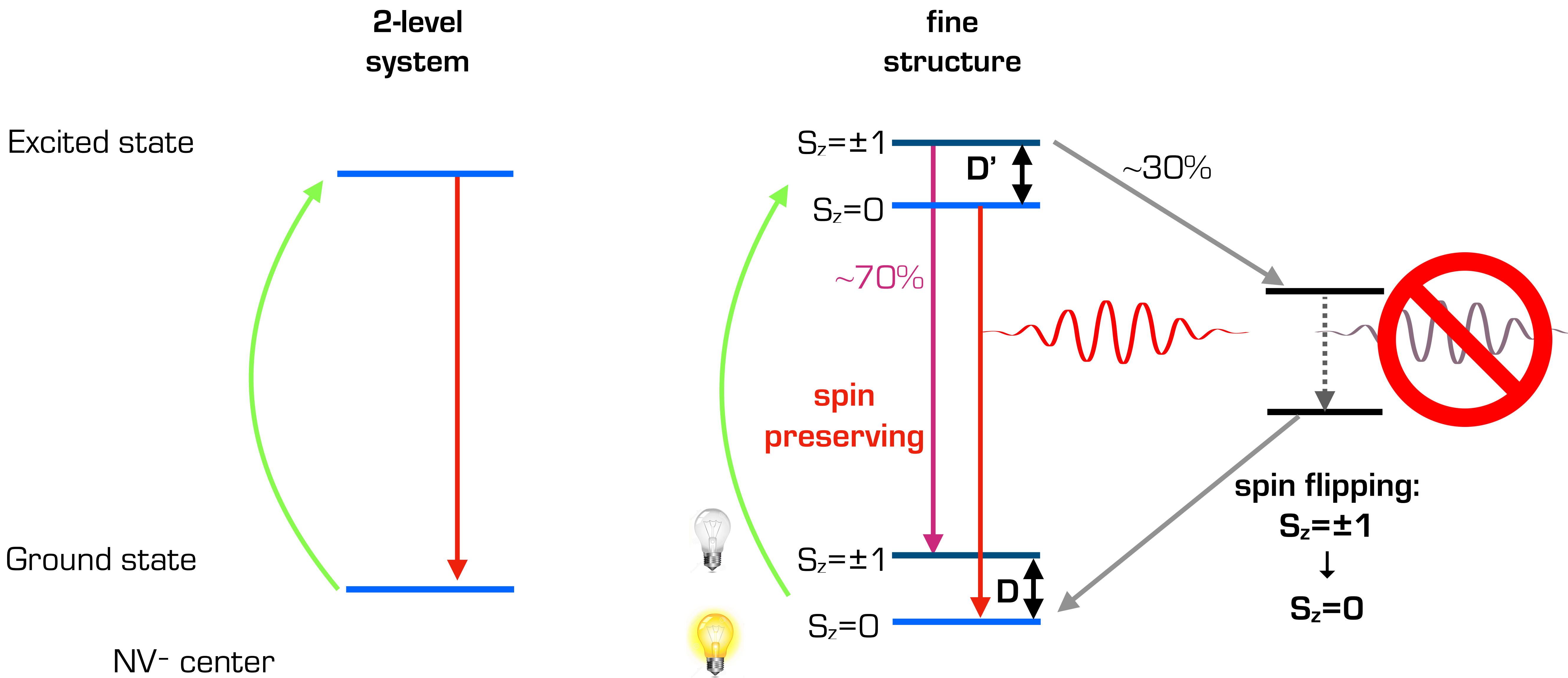
$$H = D\ (S_z^{\,2} - S(S+1)/3\ ) + H_f$$

spin-spin interaction interacting fields

D~2.88 GHz fine structure splitting

Ground state interaction Hamiltonian
Phys. Reports 528 (2013) 1

The NV⁻ center ground state spin properties



NV⁻ center
6 bound electrons
spin triplet: S=1, S_z=–1,0,+1

$$H = D\ \left(S_z^{\,2} - S(S+1)/3\ \right) + H_f$$

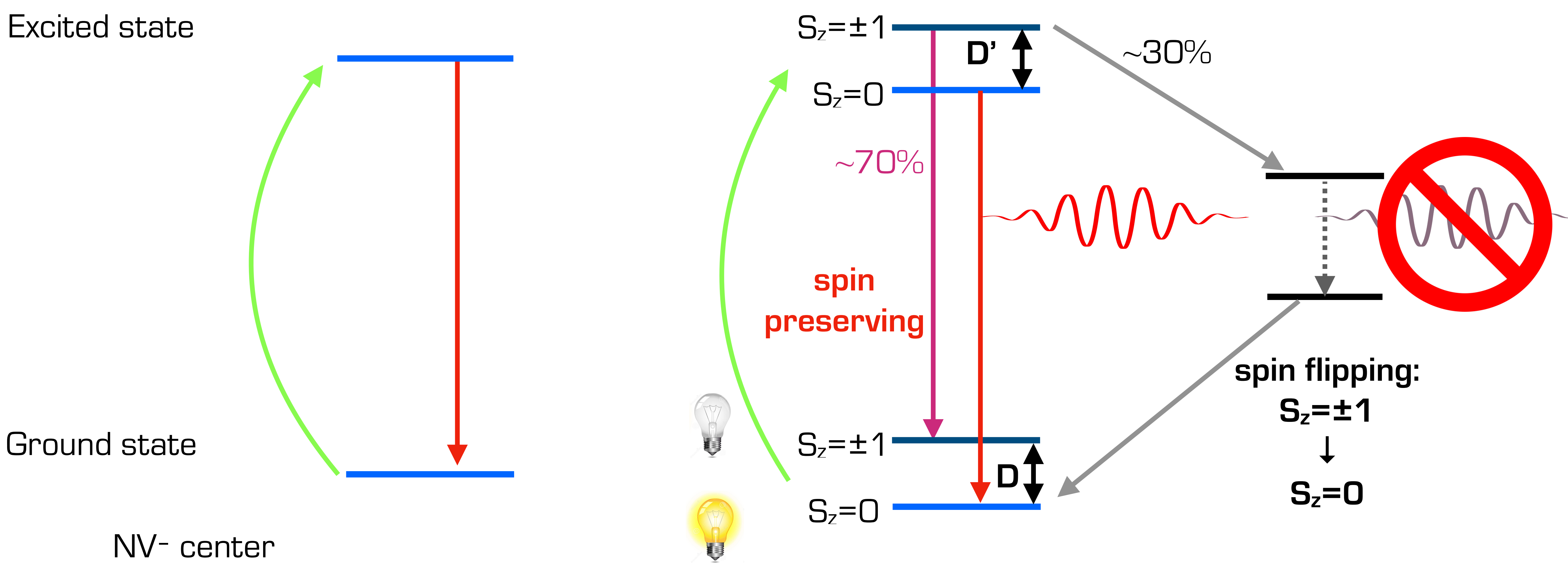
spin-spin interaction

D~2.88 GHz fine structure splitting

Ground state interaction Hamiltonian
Phys. Reports 528 (2013) 1

The NV⁻ center ground state spin properties

2-level system | **fine structure**



NV⁻ center
6 bound electrons
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$$H = D\ \left(S_z{}^2 - S(S+1)/3\ \right) + H_f$$

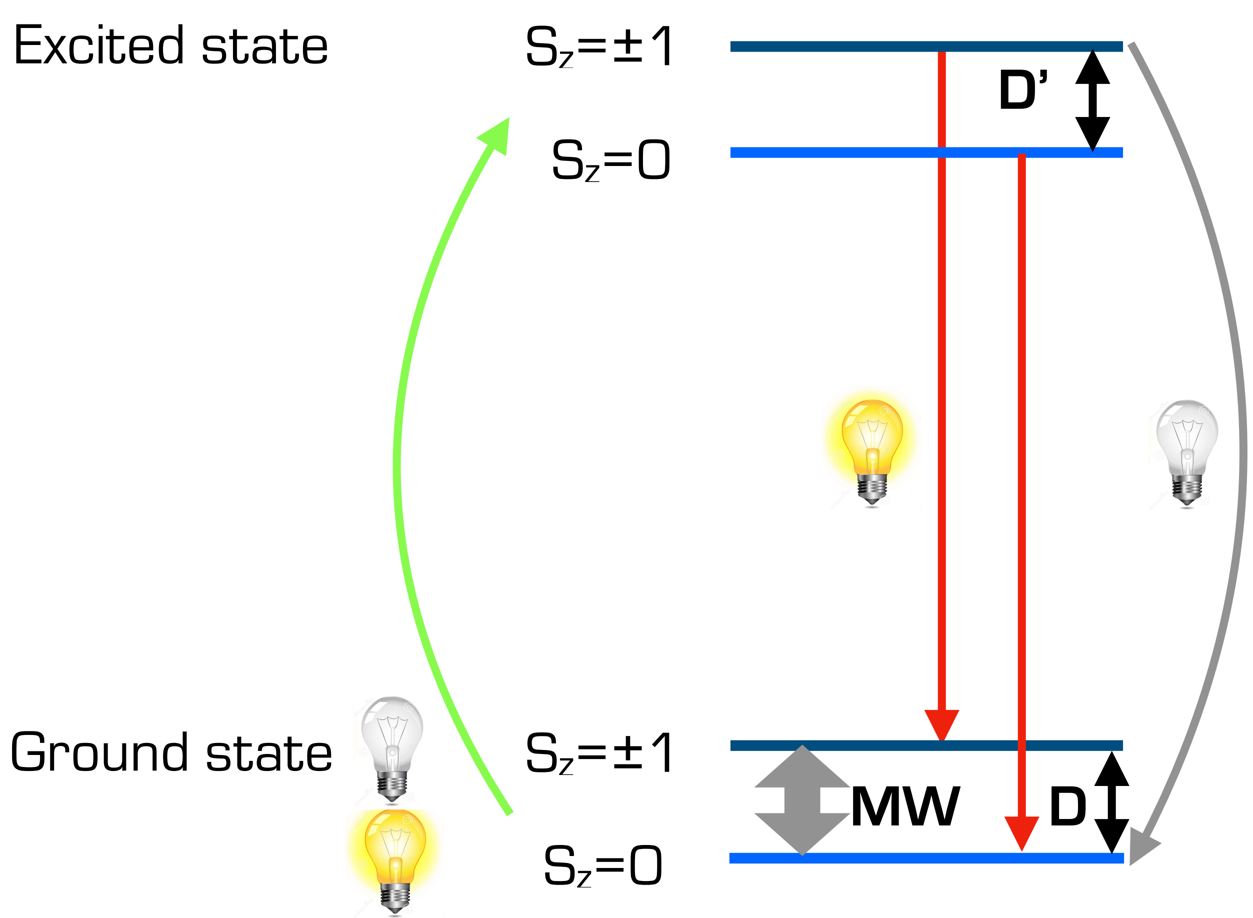
↙ spin-spin interaction

D~2.88 GHz fine structure splitting

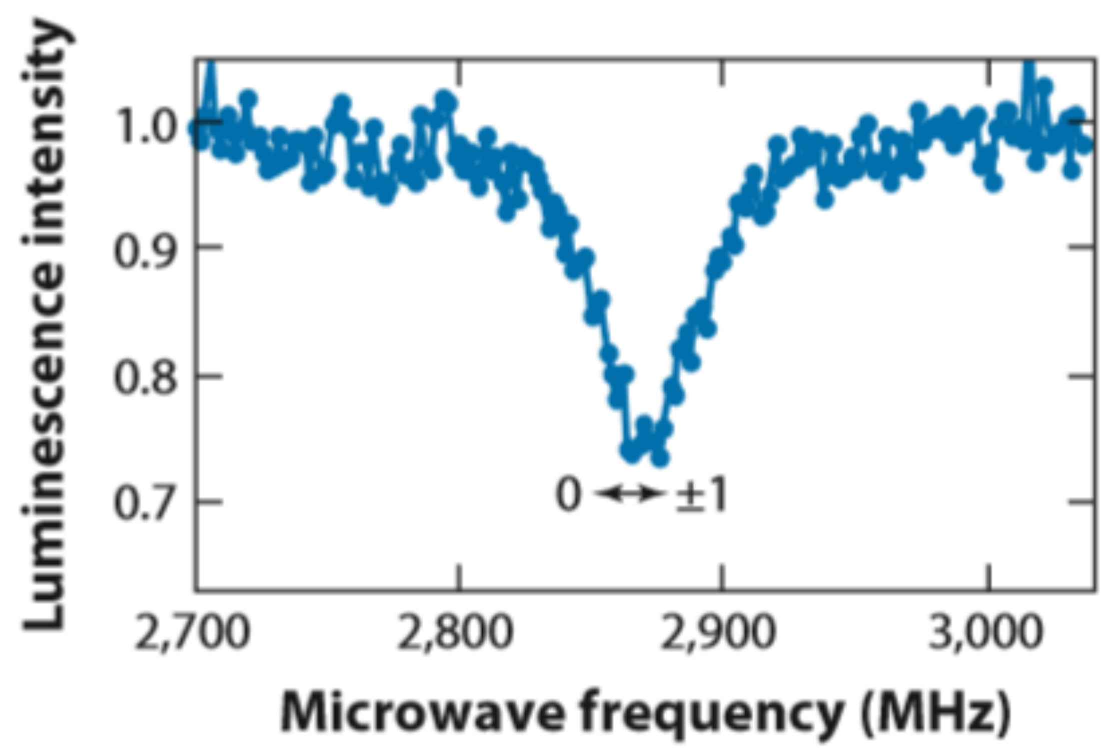
Ground state interaction Hamiltonian
Phys. Reports 528 (2013) 1

SIMPLIFIED MODEL

Optical readout of the NV⁻ center's spin



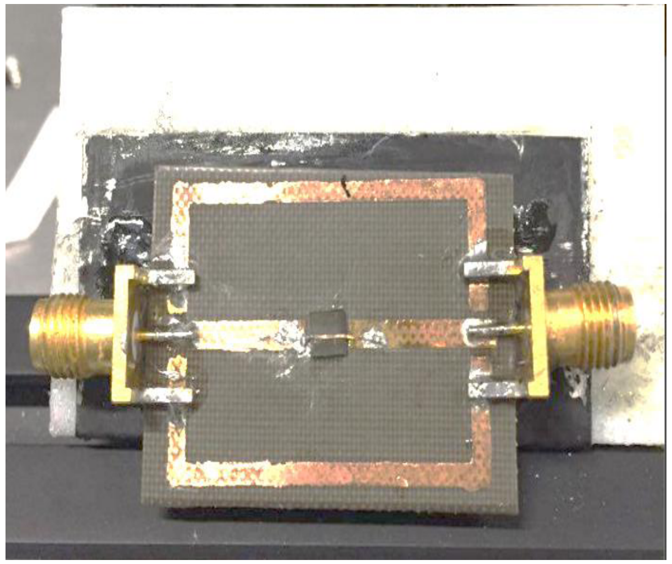
Optically detected magnetic resonance (ODMR)
Annu. Rev. Phys. Chem. 2014. 65:83



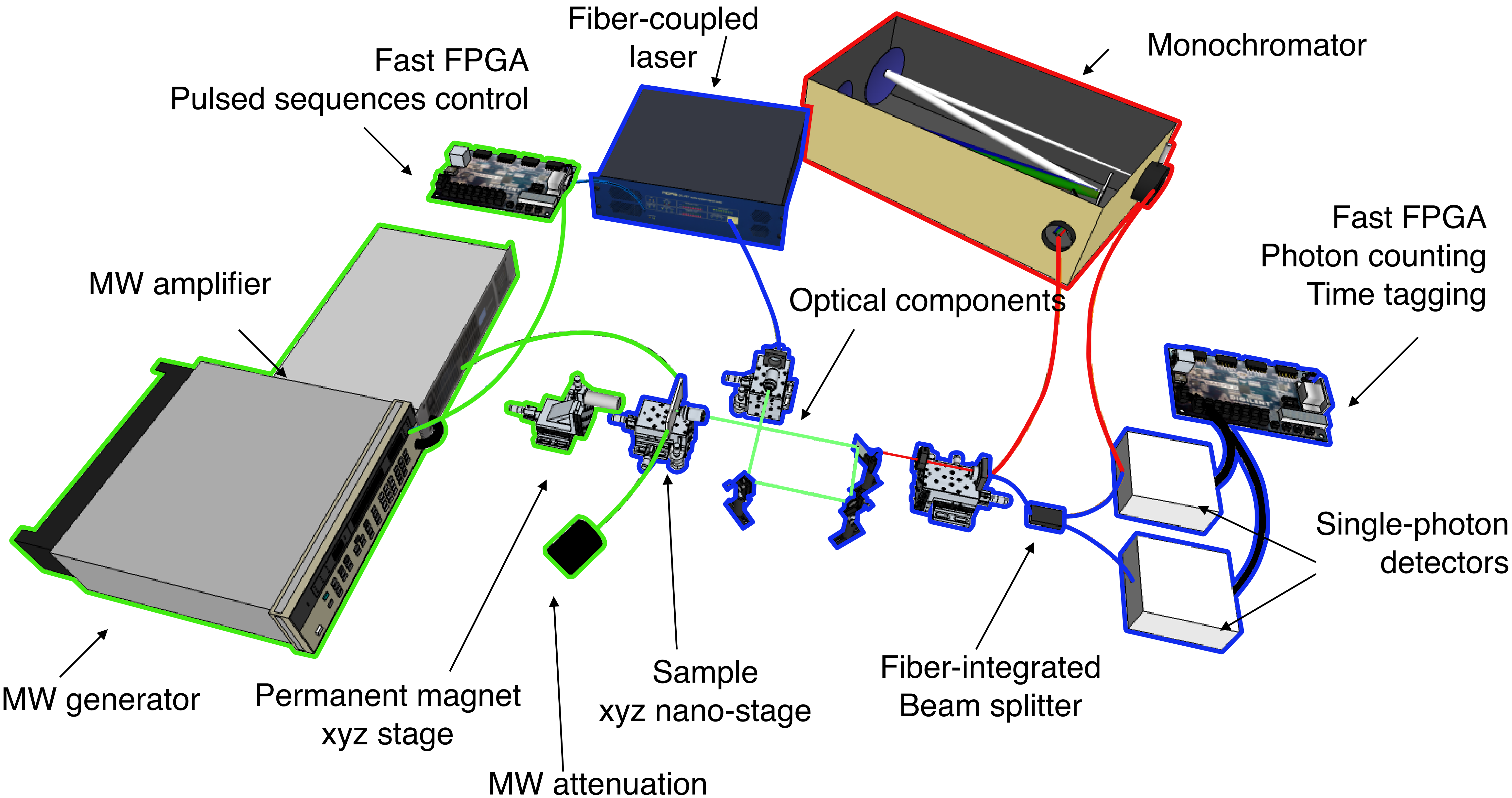
$$H = D\ (S_z{}^2 - S(S+1)/3\ ) + H_f$$

spin-spin interaction

D~2.88 GHz fine structure splitting



Optical readout of the NV⁻ center's spin

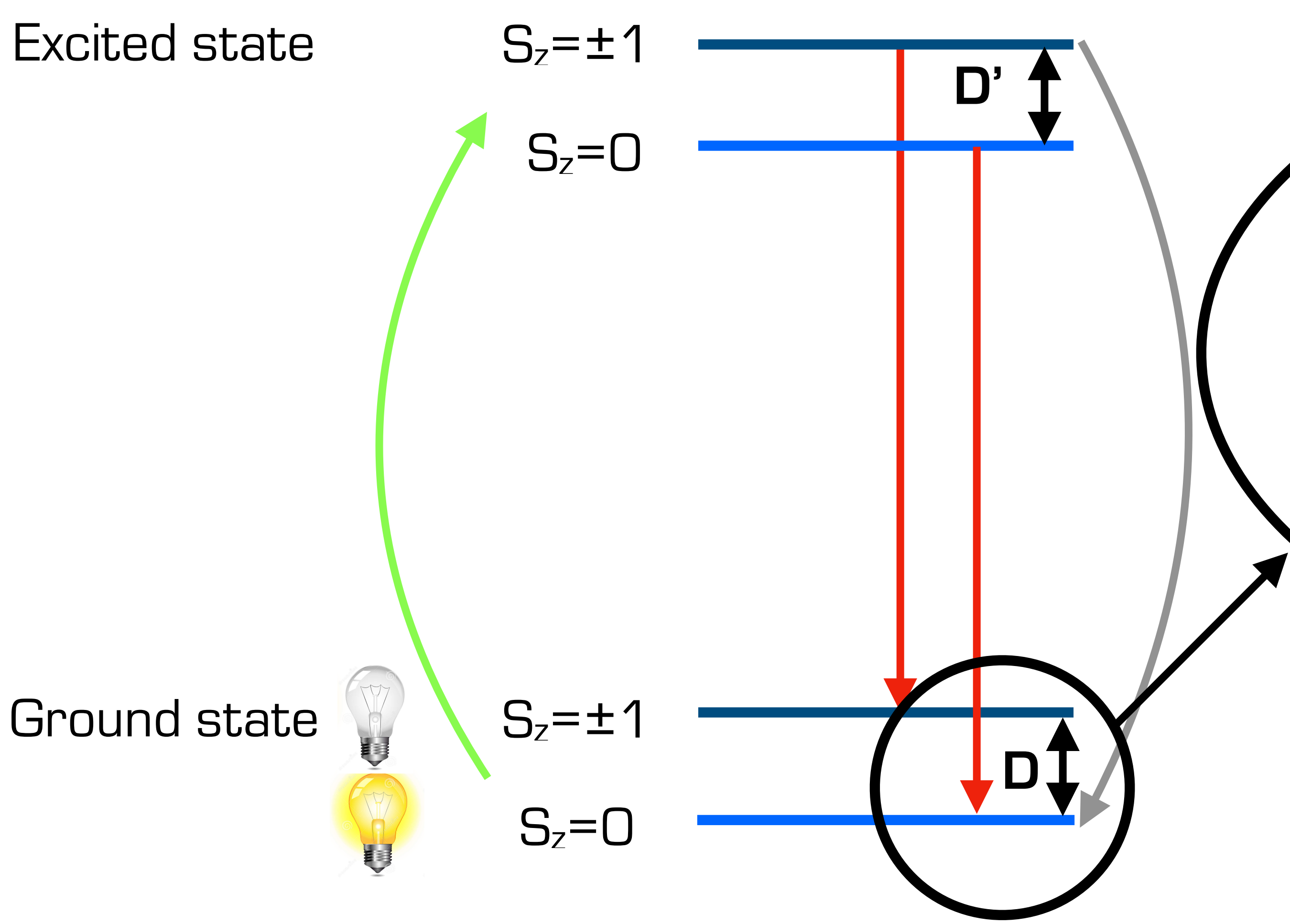


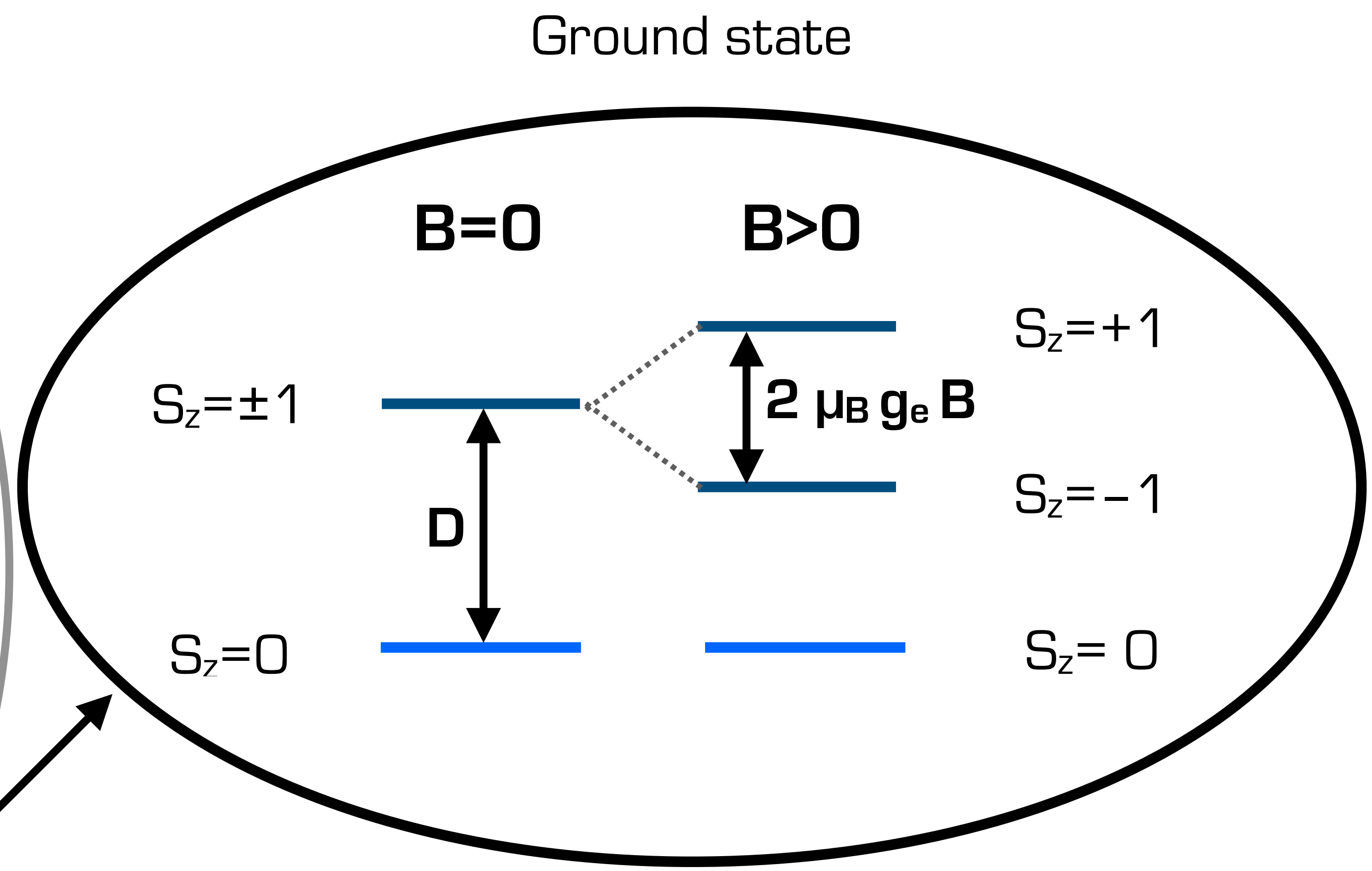
Single-photon confocal microscope

Monochromator

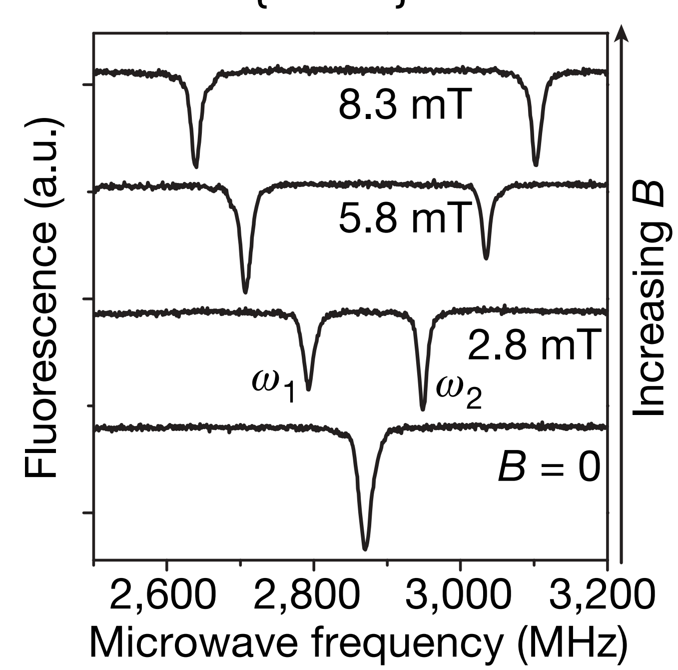
ODMR

The NV center as a nanoscale magnetometer





Zeeman splitting of the NV center ground state
Nature 455 (2008) 648 Harvard



$$H = H_0 + \mu_B\, g_e\, \mathbf{S}\cdot\mathbf{B} + H_{f2}$$

spin-spin interaction

other fields

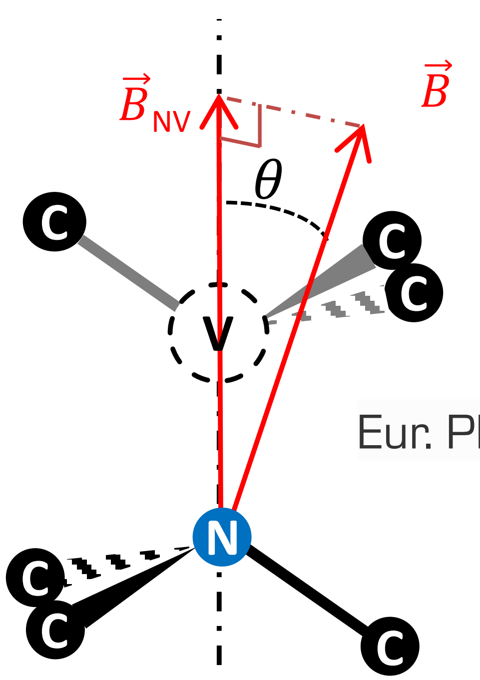
Zeeman Effect

g_e electron g-factor
μ_B Bohr magneton

The NV⁻ center as a nanoscale magnetometer

$$B_{||} = \frac{\nu_+ - \nu_-}{2\,\mu_B\,g_e}$$

$\frac{\mu_B\,g_e}{h}$ = 28 MHz mT⁻¹



Eur. Phys. J. D (2015) 69: 166

$$H = H_0 + \mu_B\, g_e\, \mathbf{S}\cdot\mathbf{B} + H_{f2}$$

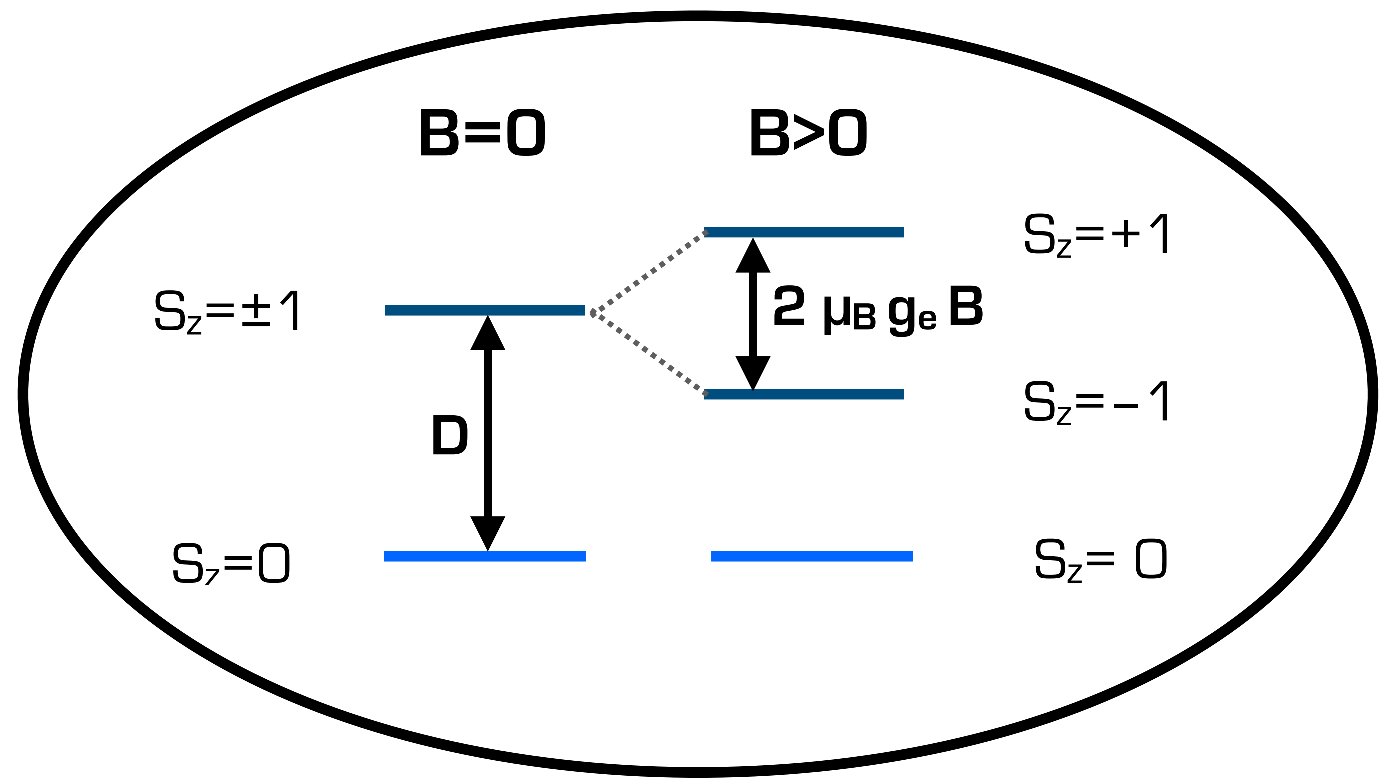
spin-spin interaction

other fields

Zeeman Effect

g_e electron g-factor
μ_B Bohr magneton

Ground state



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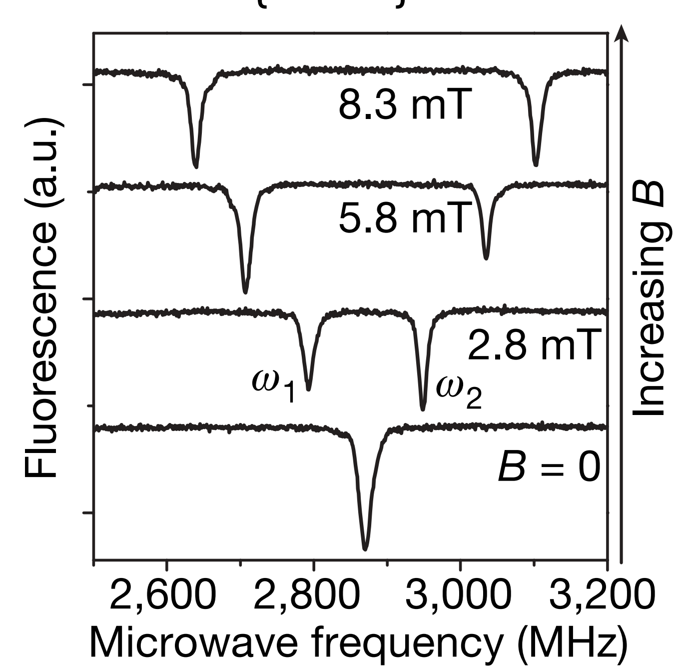
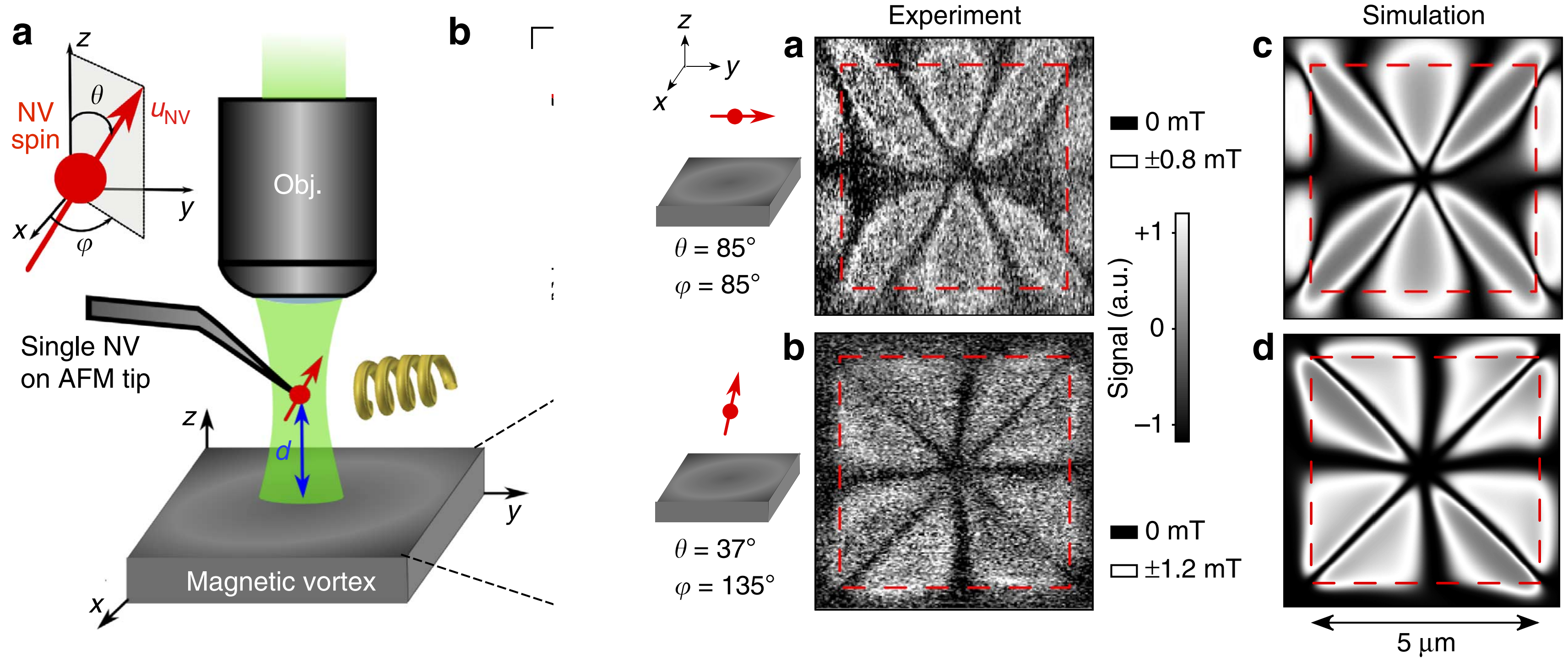


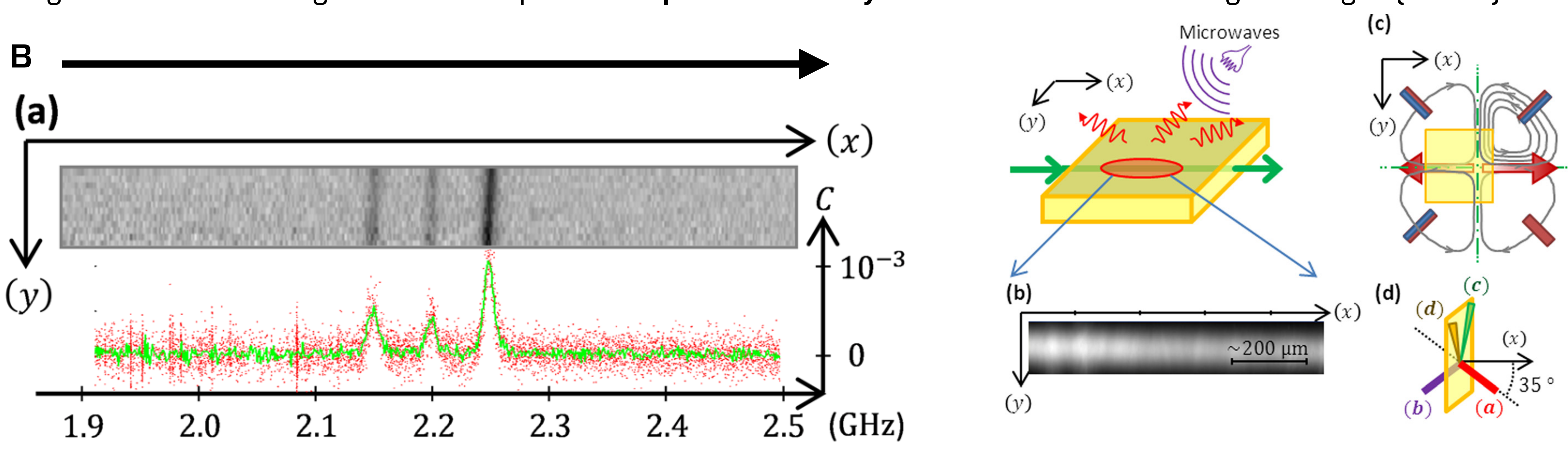
Magnetic field sensing: applications and perspectives

Individual NV centers

Nanoscale imaging of magnetic domains, Nat. Commun. 4 (2013) 2279 Paris

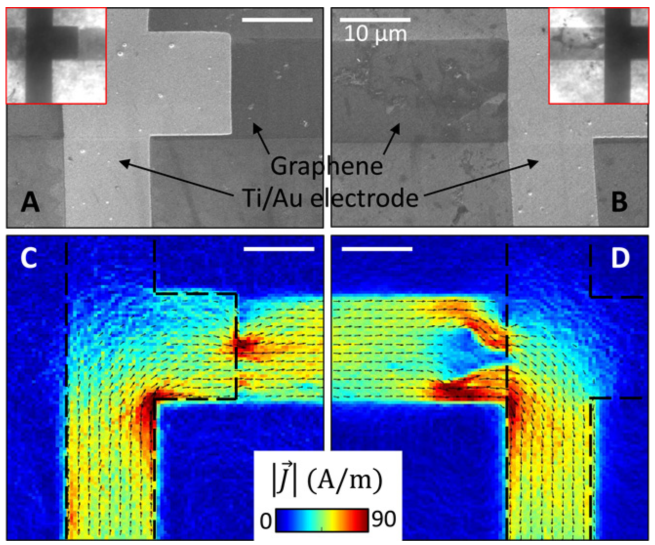


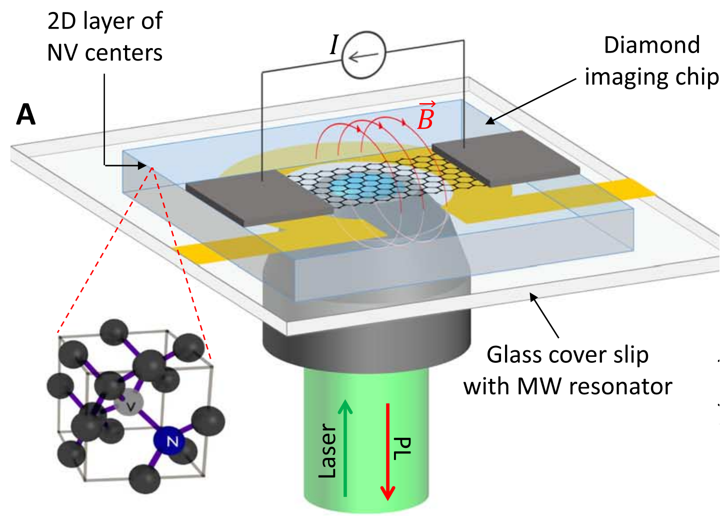
Spatial gradient of the magnetic field: a quantum **spectrum analyzer**. Communications engineering 1 (2022) 19 Thales

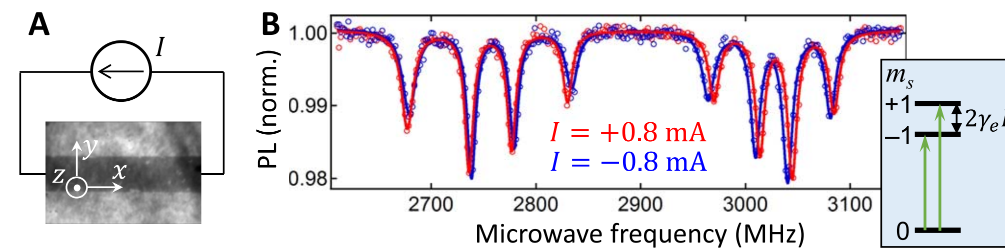


Magnetic field sensing: applications and perspectives

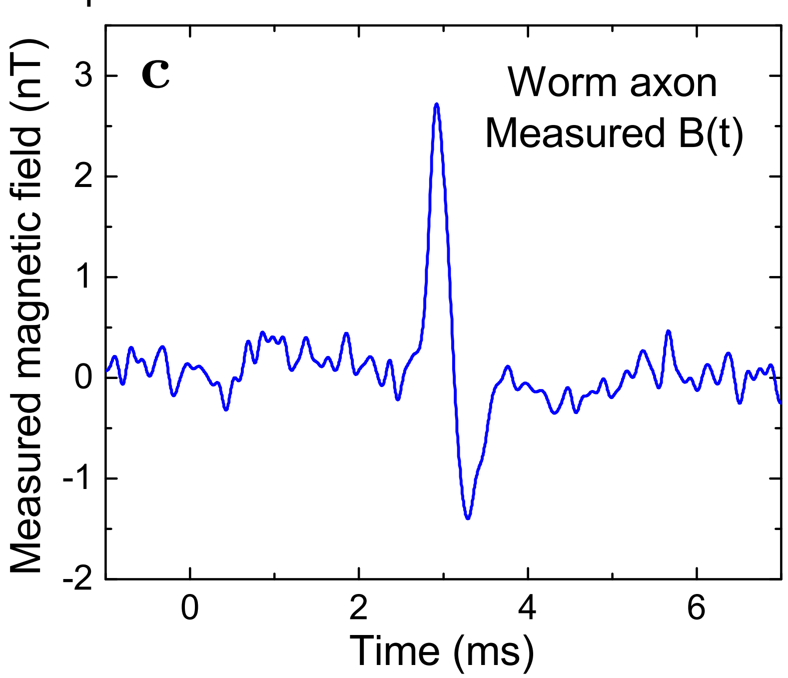
Current imaging in 2D materials using NV centers arrays. Science Advances 2017, 3 e1602429. Melbourne

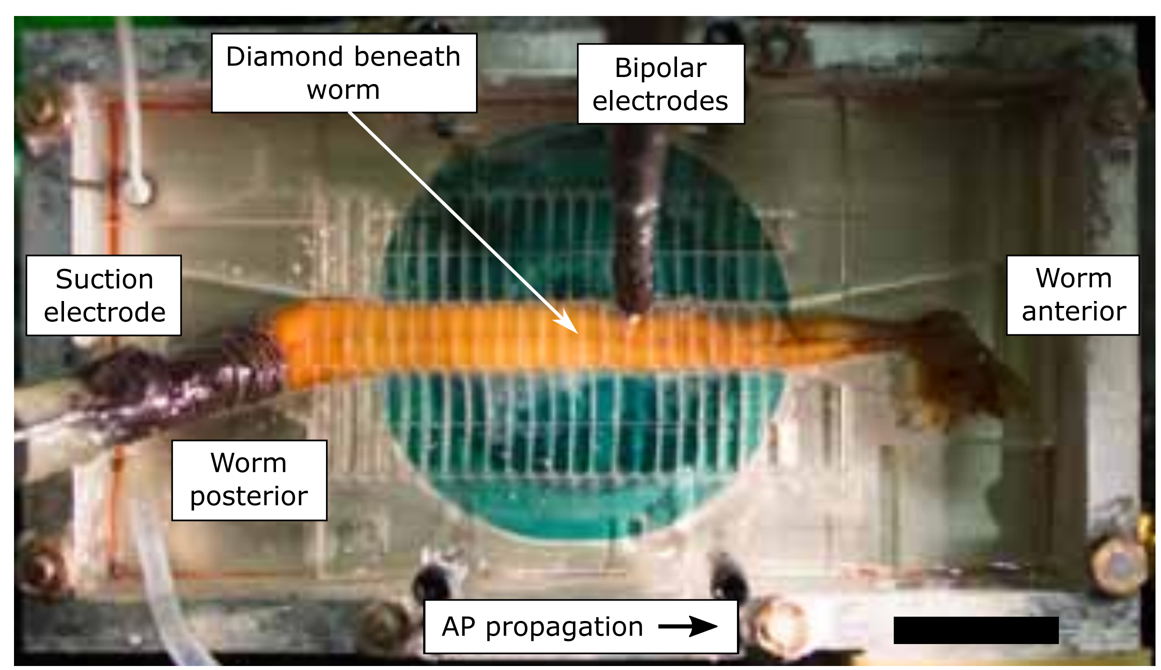




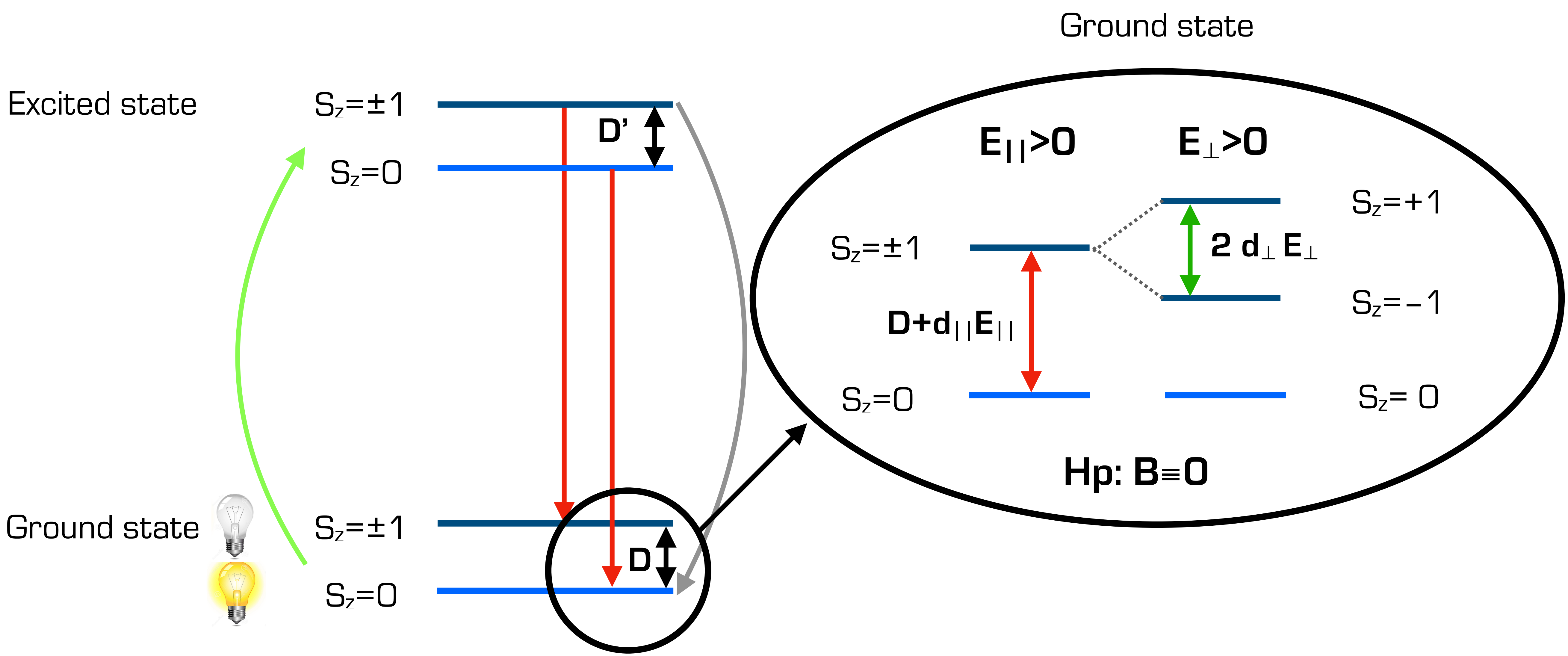


Real time detection of **action potential** from biological specimens. PNAS 2016 113 (49) 14133 Harvard Marine worm specimen





The NV⁻ center as a nanoscale electrometer



$$H = H_0 - d_{||}\, E_z\, [S_z^2 + S(S+1)/3] + d_\perp\, [E_x\, (S_x S_y + S_y S_x) - E_y\, (S_x^2 - S_y^2)] + H_{f3}$$

spin-spin interaction

Electric field parallel to the NV axis

Electric field perpendicular to the NV axis

other fields

Stark Effect

$d_\perp$ = 17 Hz V⁻¹ cm

$d_{||}$ = 0.35 Hz V⁻¹ cm

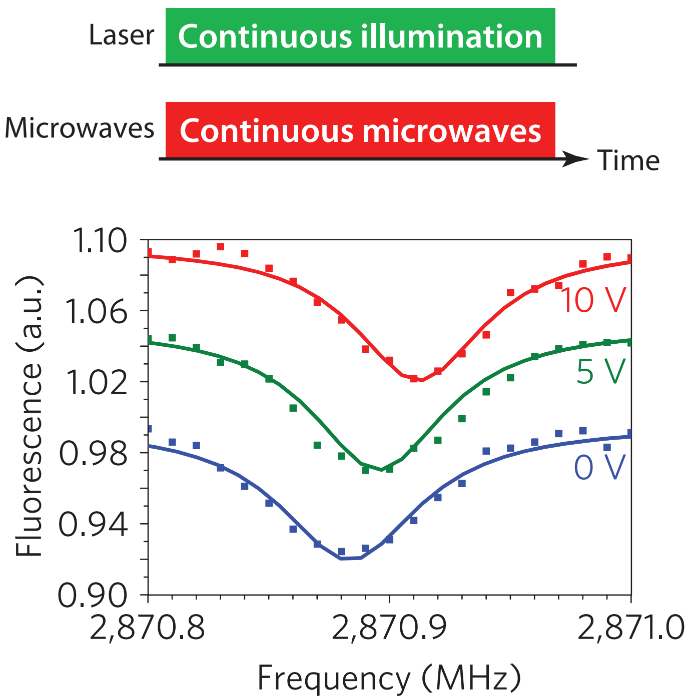
Nat. Phys. 7 (2011) 459
Stuttgart

Electric field sensing: applications and perspectives

Individual centers

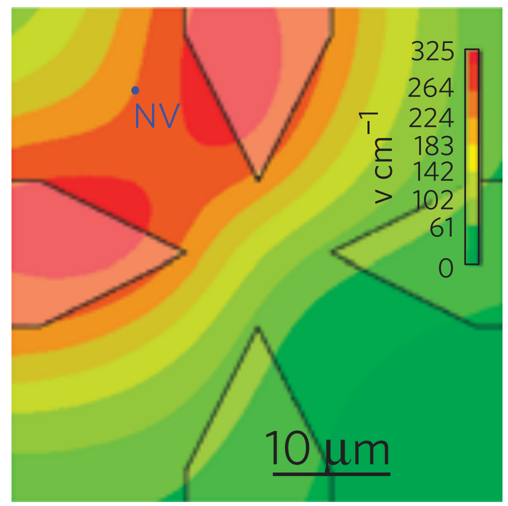
~ kV cm^{-1} sensitivity

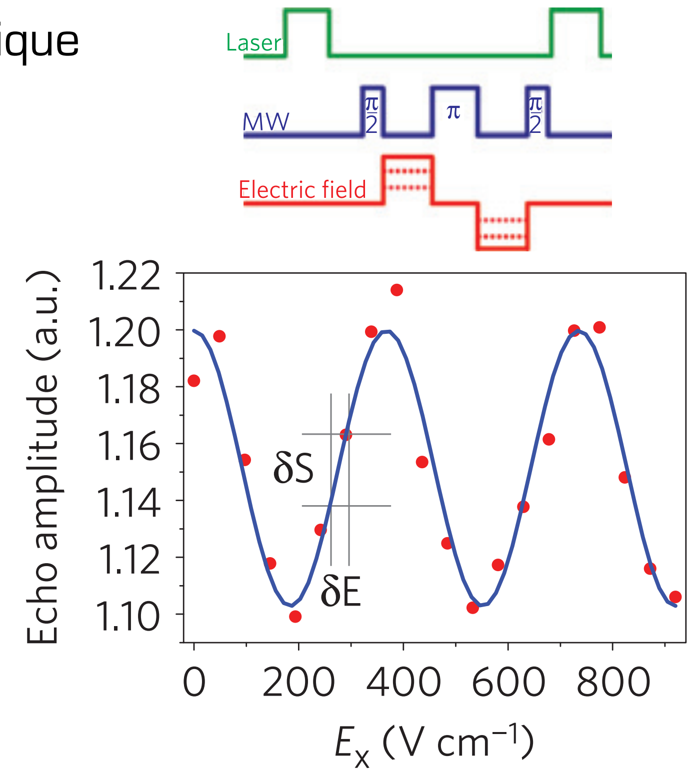
a



d

Demonstration of the sensing technique
Nat. Phys. 7 (2011) 459

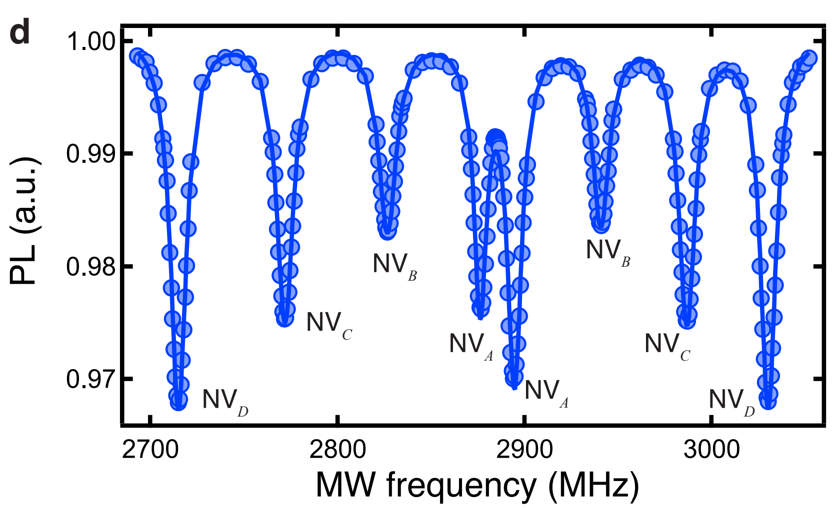


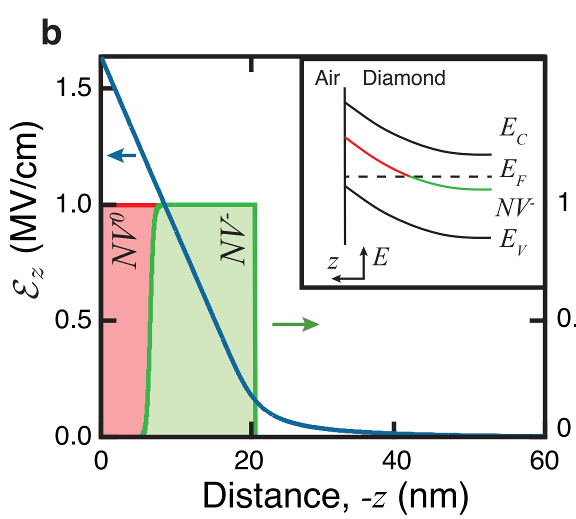


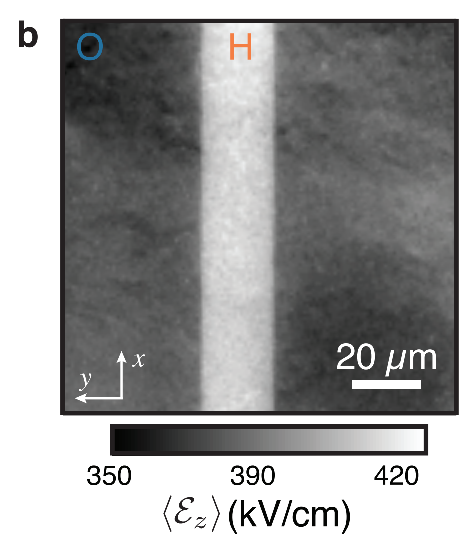
Pulsed sequences: ~100 V cm^{-1}

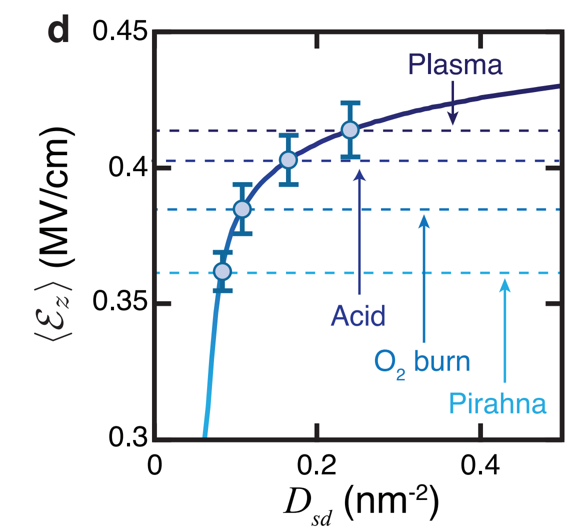
NV ensembles

Direct measurement of band bending in surface functionalized diamond
Nat. Electr. 1 (2018) 502 Melbourne



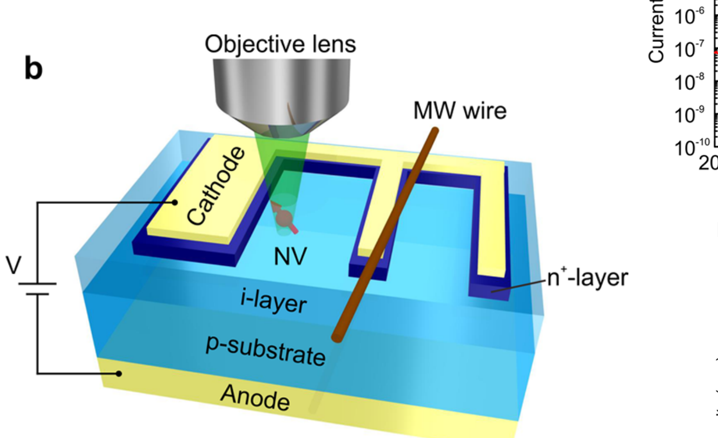


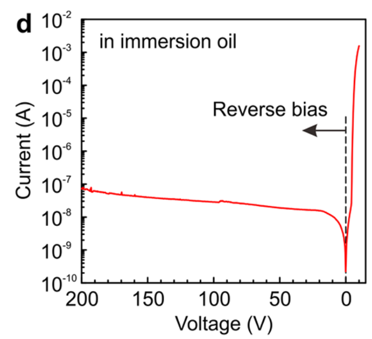


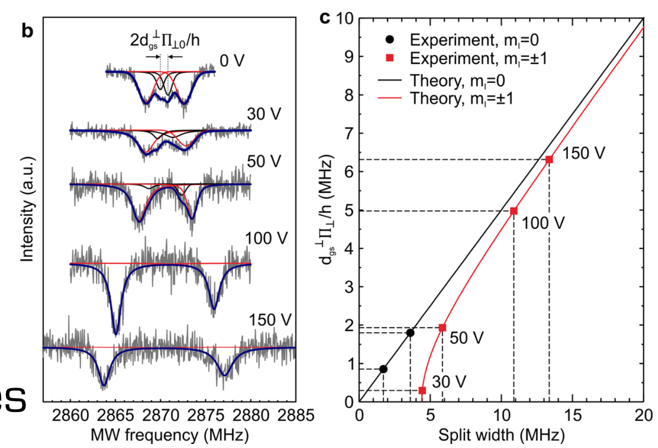


Electric field sensing: device diagnostics

~ kV cm^{-1} sensitivity





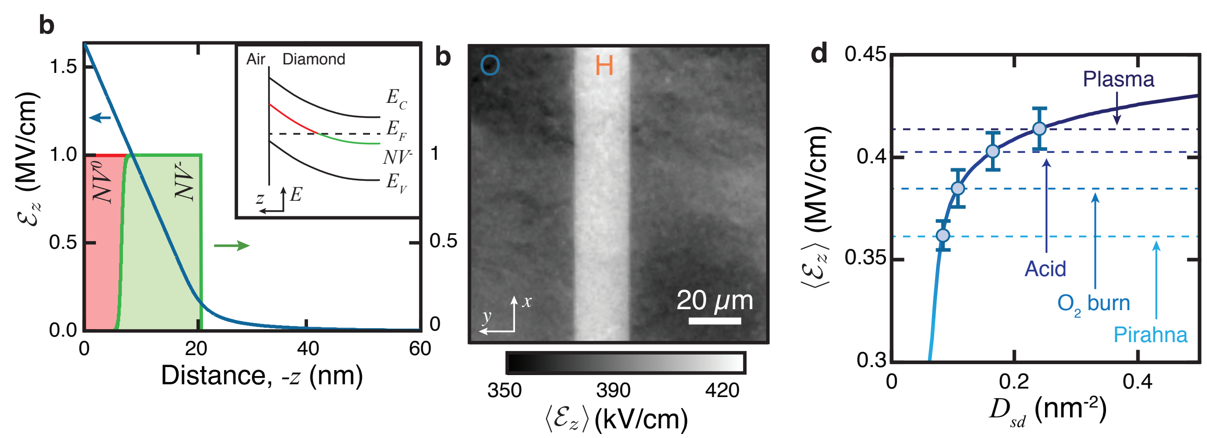


Power devices

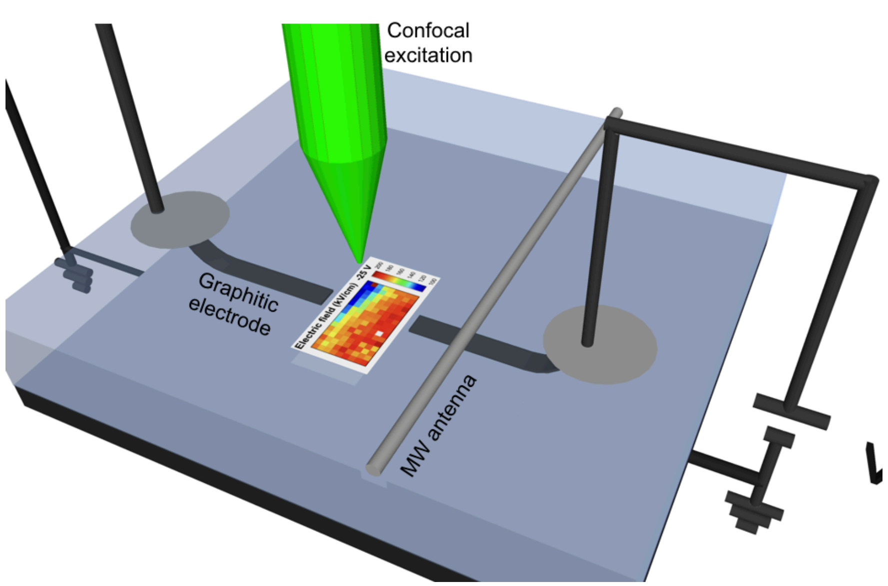
Assessment of the internal electric field in diamond p-i-n diodes ACS Nano **2017**, 11 1238 Tokyo

Material functionalization

Direct measurement of band bending upon surface termination Nat. Electr. 1 (2018) 502 Melbourne

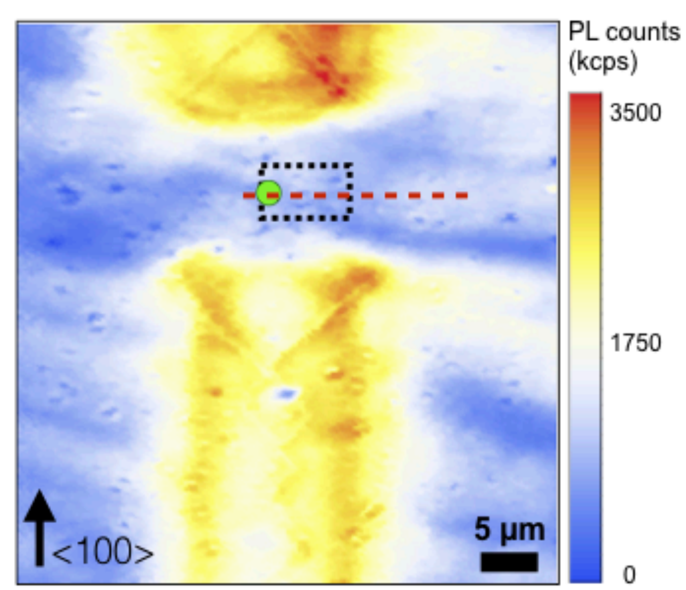


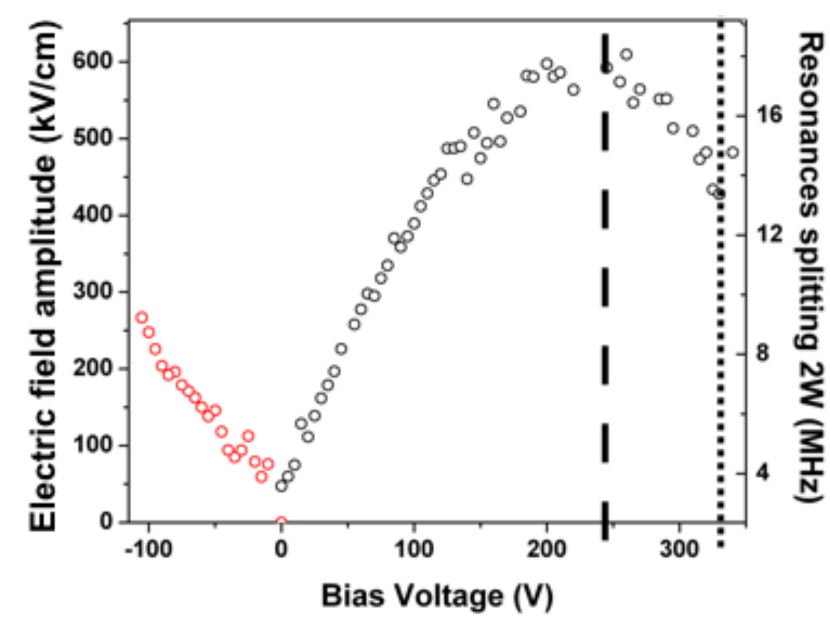
NV ensembles



Experimental observation of **memory effects upon radiation damage** in diamond devices and detectors. Phys. Rev. Applied 10, 014024 (**2018**) Torino

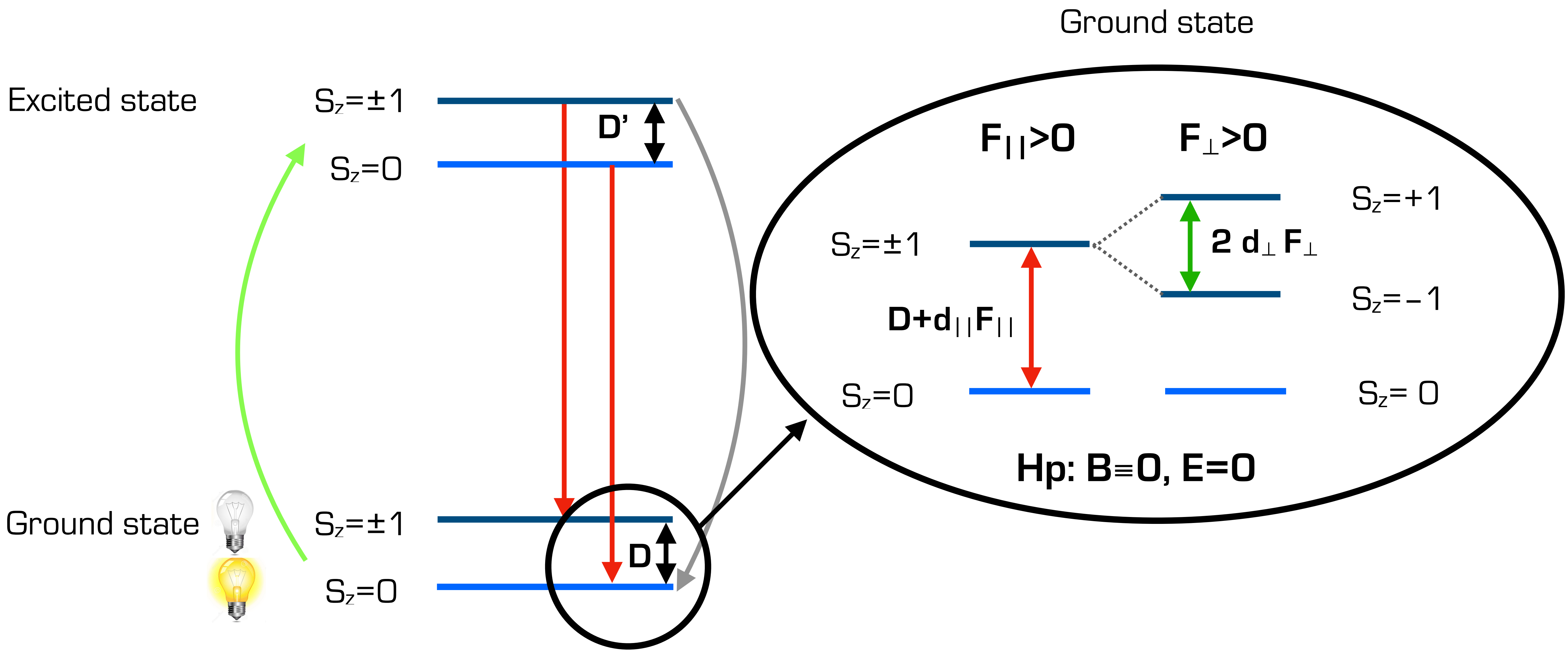
a





c

The NV center under pressure



$$H = H_0 - d_{||}\, F_z\, [S_z^2 + S(S+1)/3] + k_{\perp}\, [F_x\, (S_x S_y + S_y S_x) - F_y\, (S_x^2 - S_y^2)] + H_{f3}$$

spin-spin interaction

Strain field parallel to the NV axis

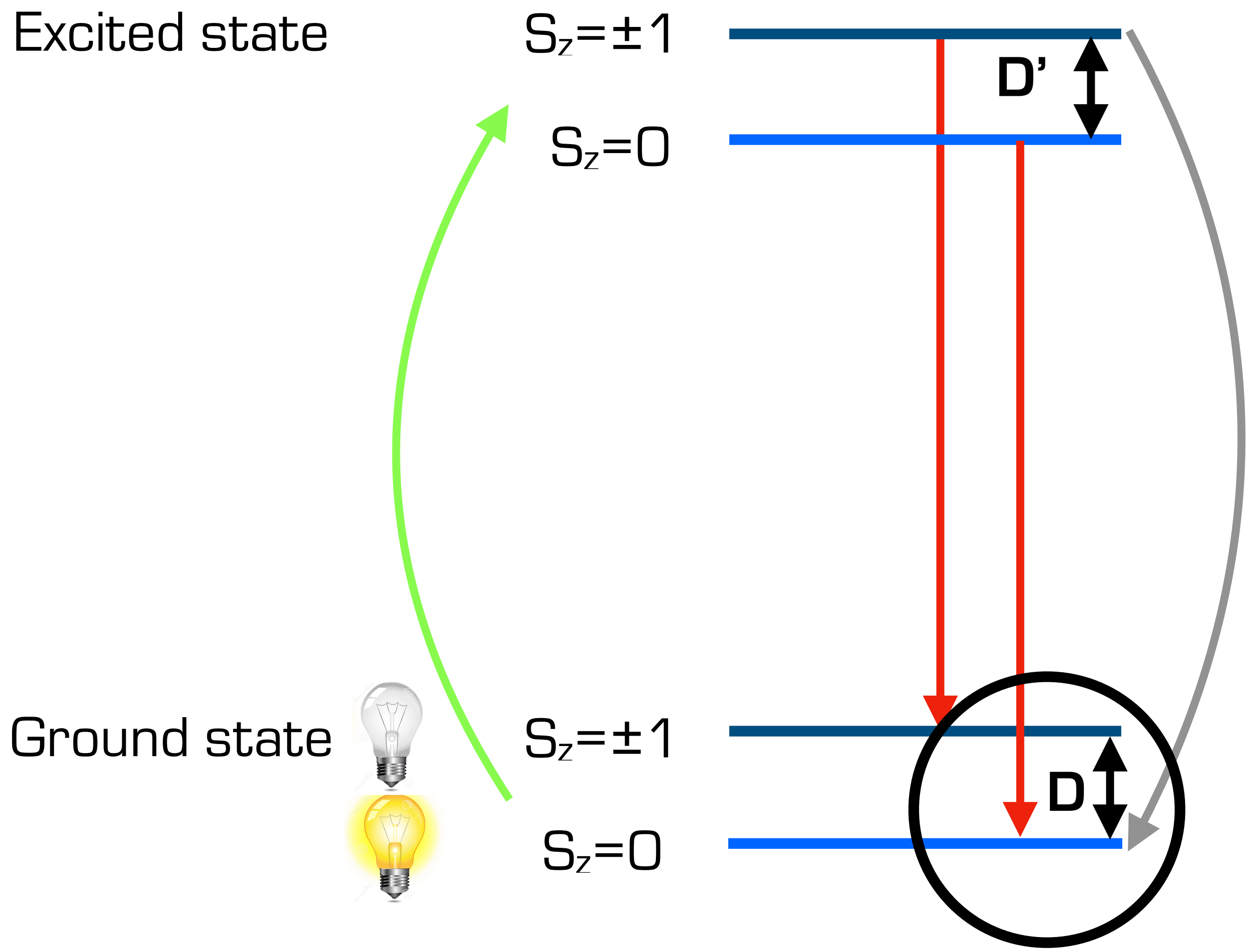
Strain field perpendicular to the NV axis

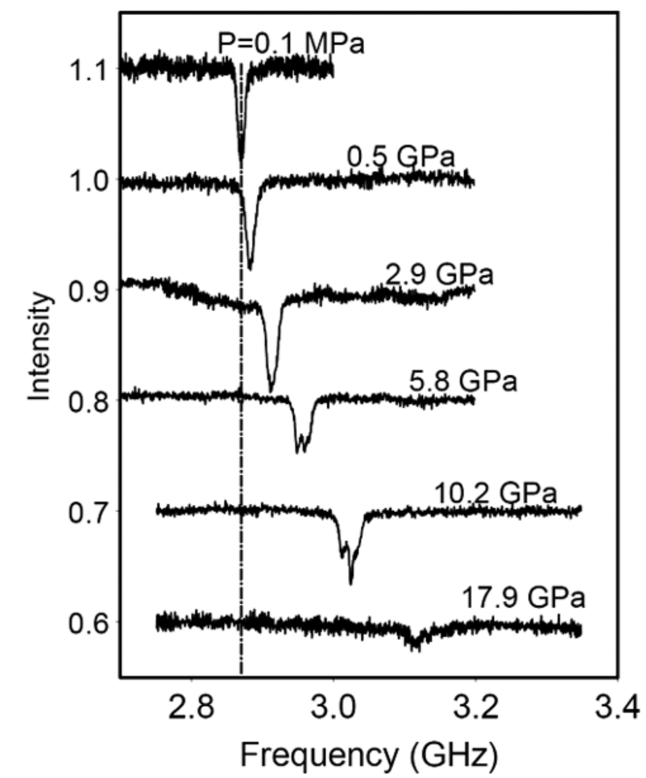
other fields

F is the stress field. If both E, F: F ⇒ **P** = (**E**+**F**)

In this case a proper deconvolution is necessary

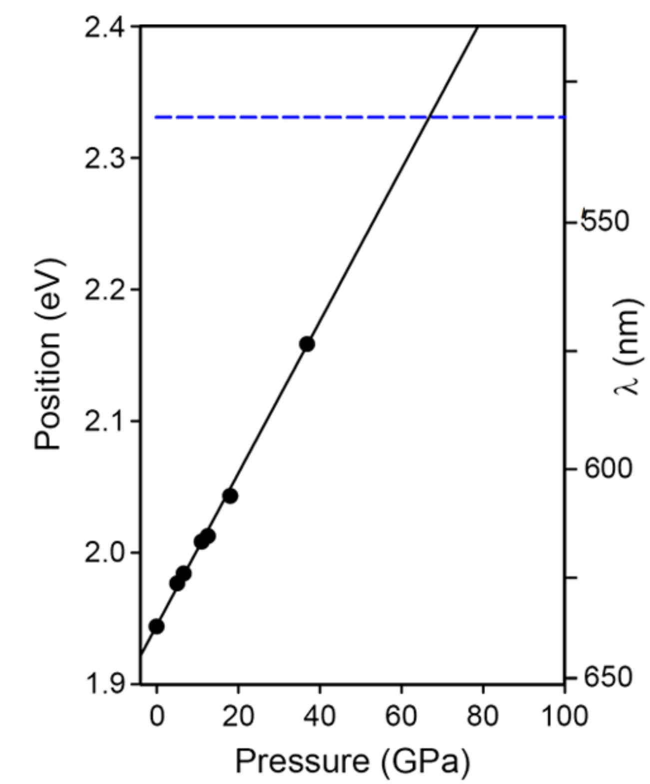
The NV center under pressure



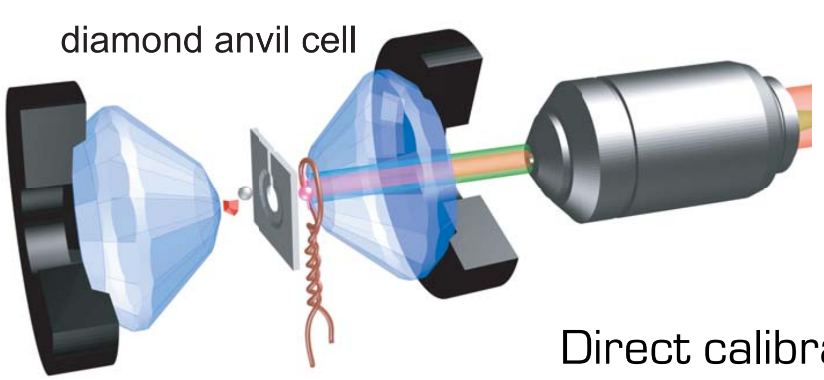


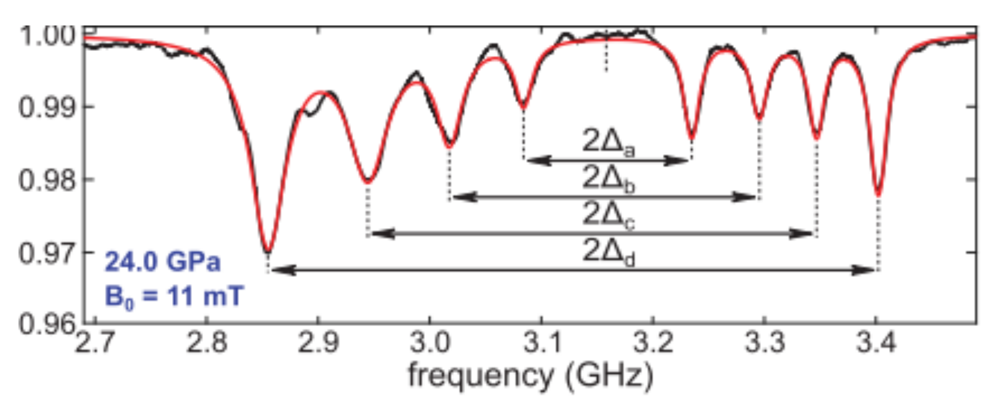
Resonance shift

$k_{||}$**=14.6 MHz GPa^{-1}**



Phys. Rev. Lett. 112, 047601 (2014)
Canberra

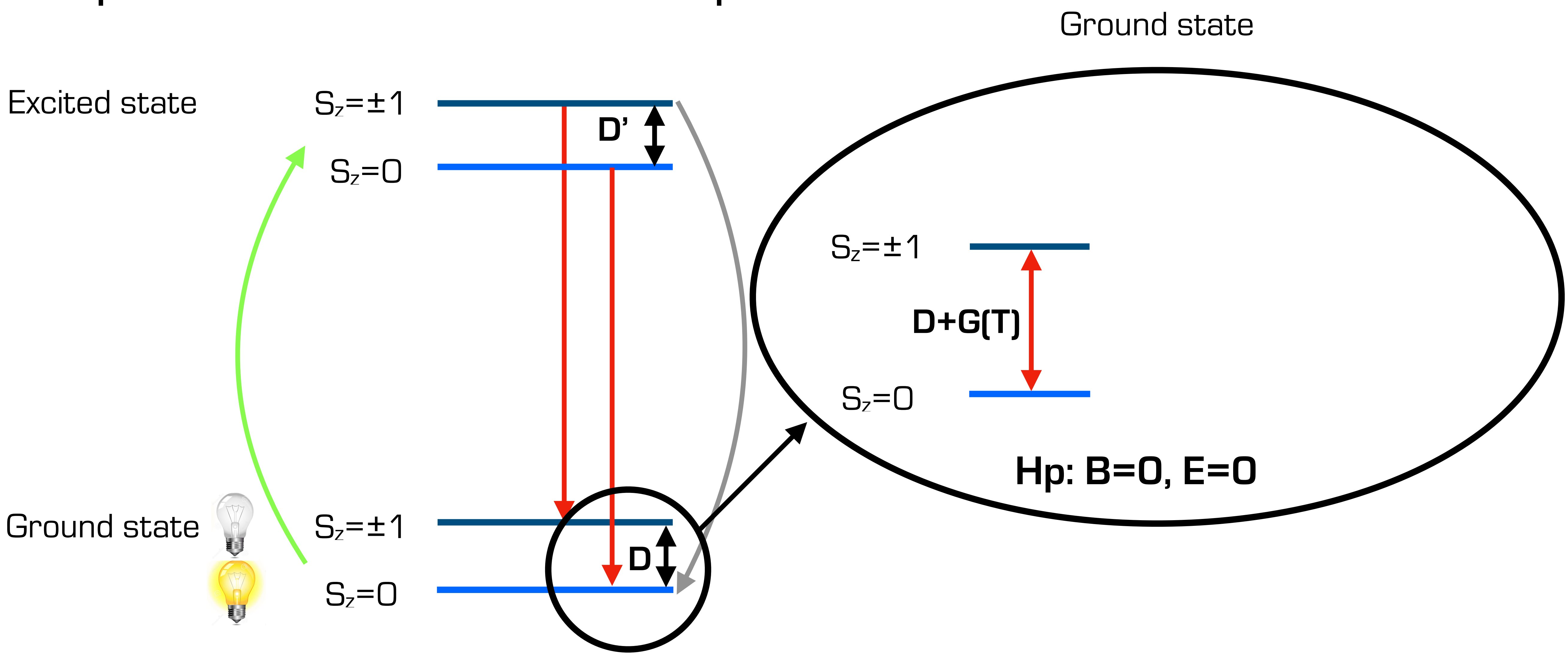




Direct calibration of high pressures (up to 10s GPa) using ODMR on **diamond anvil cells**
Synchrotron radiation experiments. Science 366 (2019) 1359. Paris

The NV center as a nanoscale thermometer

Temperature increase : lattice thermal expansion



$$H = H_0 + G_z(T)\,[S_z^2+S(S+1)/3] + H_{f3}$$

spin-spin interaction

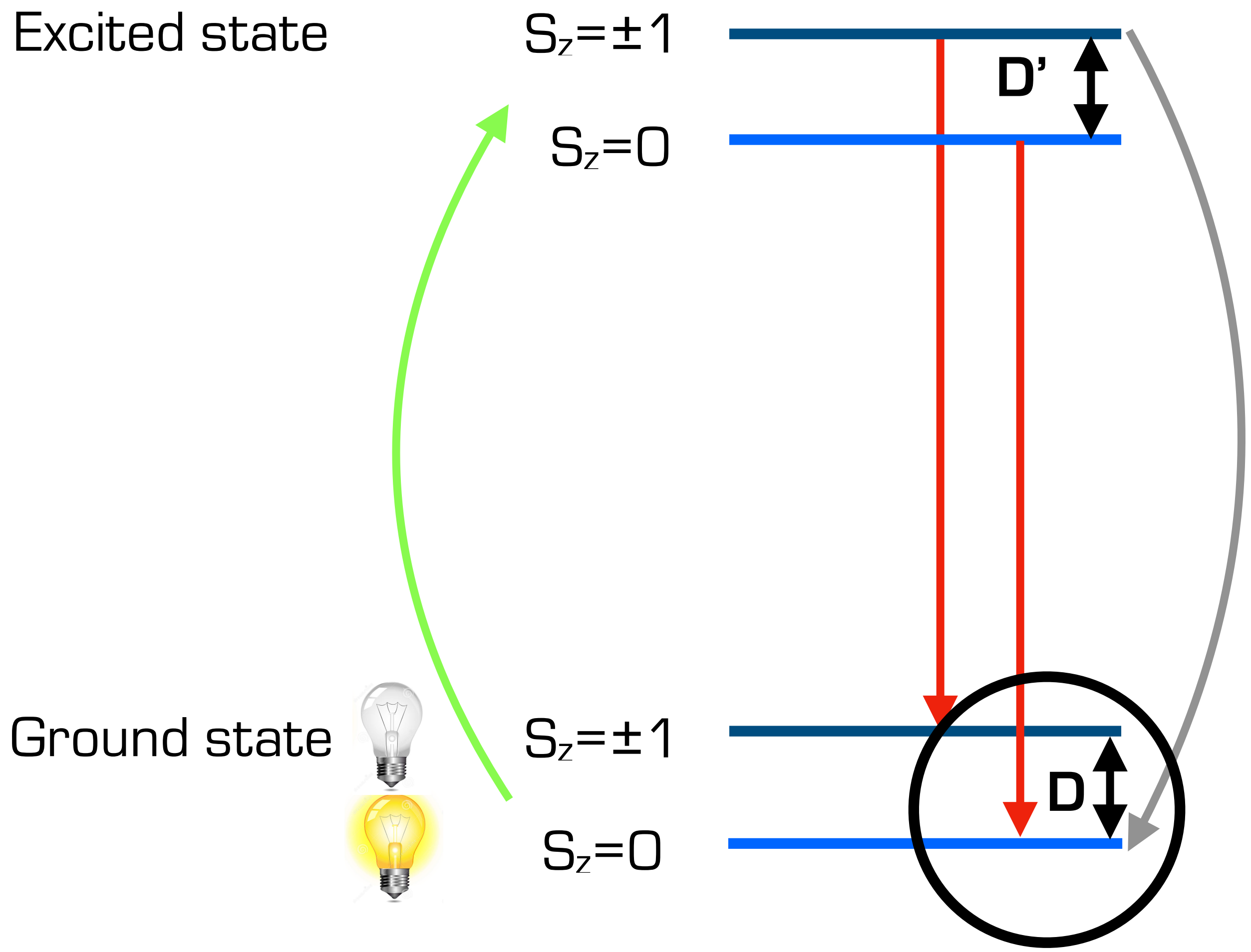
Strain field parallel to the NV axis

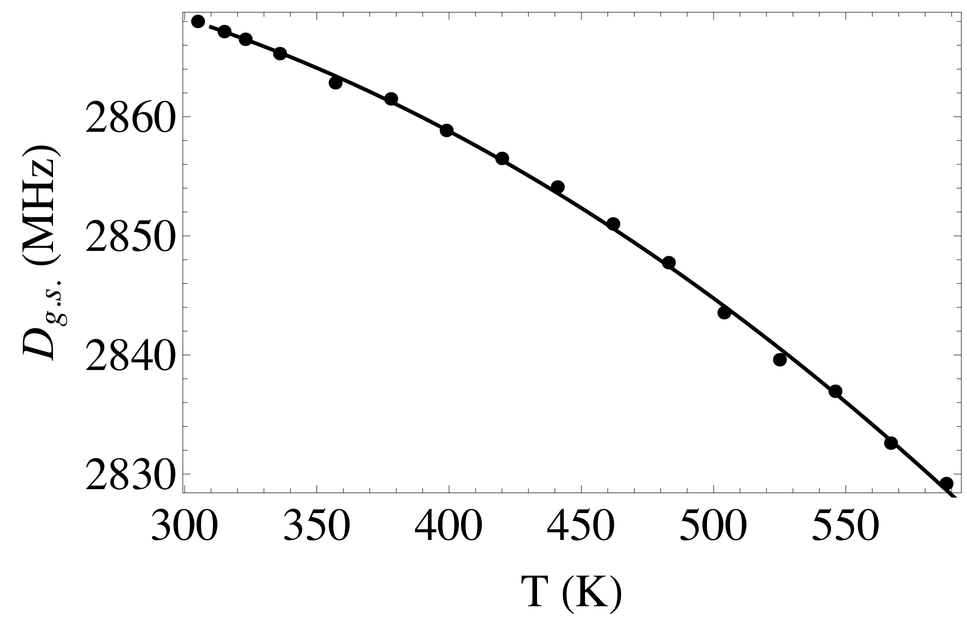
other fields

Splitting due to lattice expansion: negligible

The NV center as a nanoscale thermometer

Temperature increase : lattice thermal expansion





$G_z(T) = a\,T + bT^2$

a ~70 kHz/K

b ~ 0.2 kHz/K

$$H = H_0 + G_z(T)\,[S_z^2 + S(S+1)/3] + H_{f3}$$

spin-spin interaction

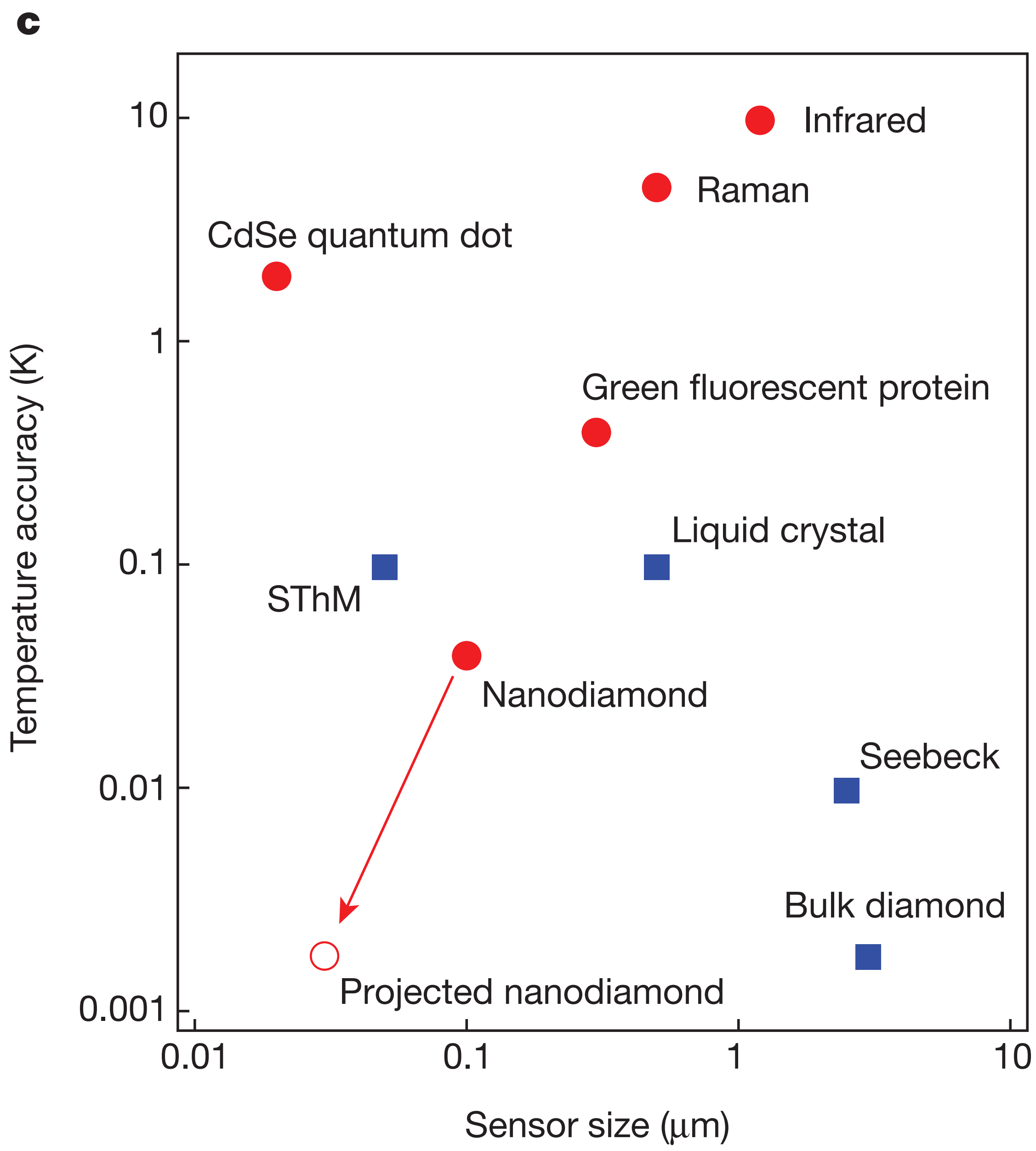
Strain field parallel to the NV axis

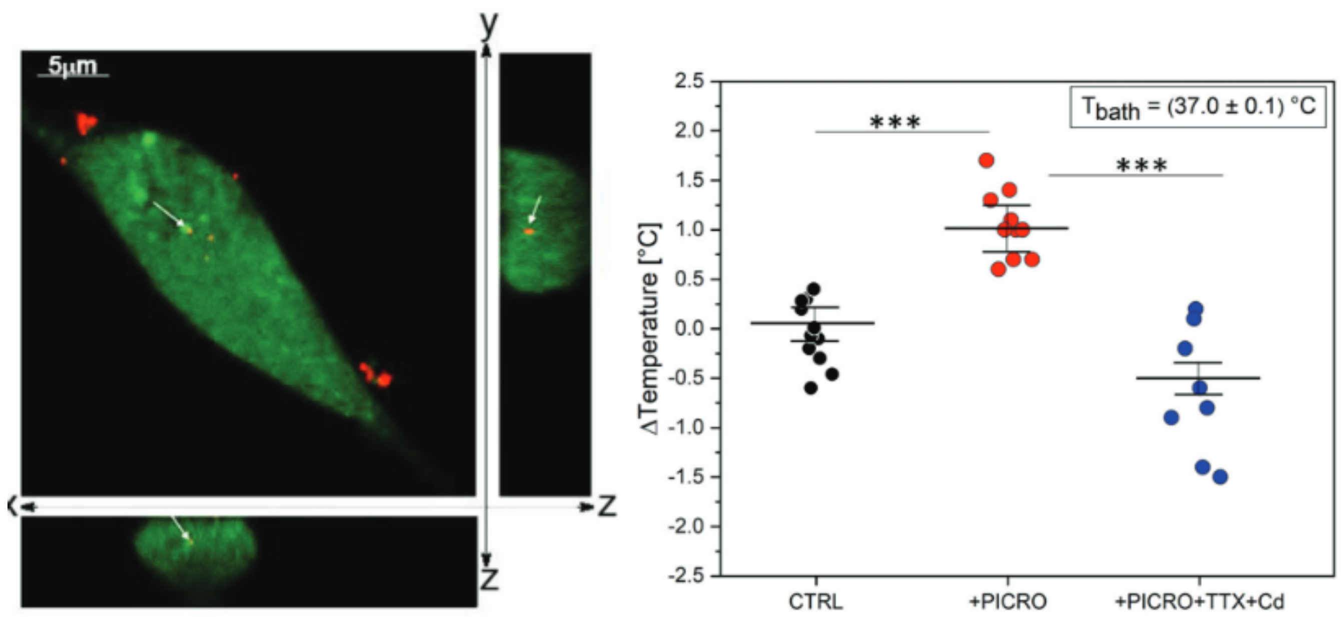
other fields

Splitting due to lattice expansion: negligible

Nano Lett., 2014, 14 (9) 4989

Thermometry: applications and perspectives

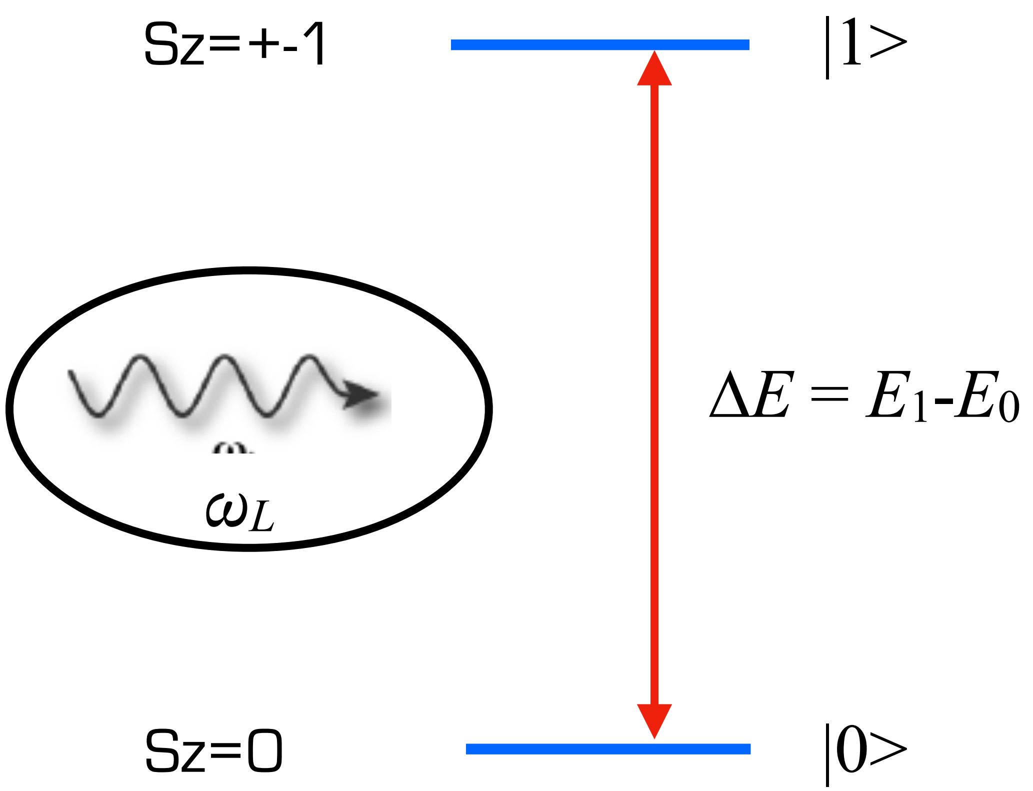




First direct measurement of cell temperature increase related to the activity of hyppocampal neurons Advanced Science 9 (2022) 14. **Torino**

Coherent control

2-level system interacting with resonant EM field



Hamiltonian of the system

$$\hat{H} = \hat{H}_0 + \hat{H}_1(t)$$

$$\left.\begin{aligned} \hat{H}_0\,\psi_0 &= E_0\,\psi_0 \\ \hat{H}_0\,\psi_1 &= E_1\,\psi_1 \\ \psi_i &= a_i(\mathbf{r})\,e^{-i\omega_i t} \end{aligned}\right\}$$ unperturbed system

perturbation theory

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t) = \left[\hat{H}_0 + \hat{H}_1(t)\right]\Psi(\mathbf{r},t)$$

where $\Psi(\mathbf{r},t)$ is a superposition (with time-dependent coefficients of the solution to the unperturbed system

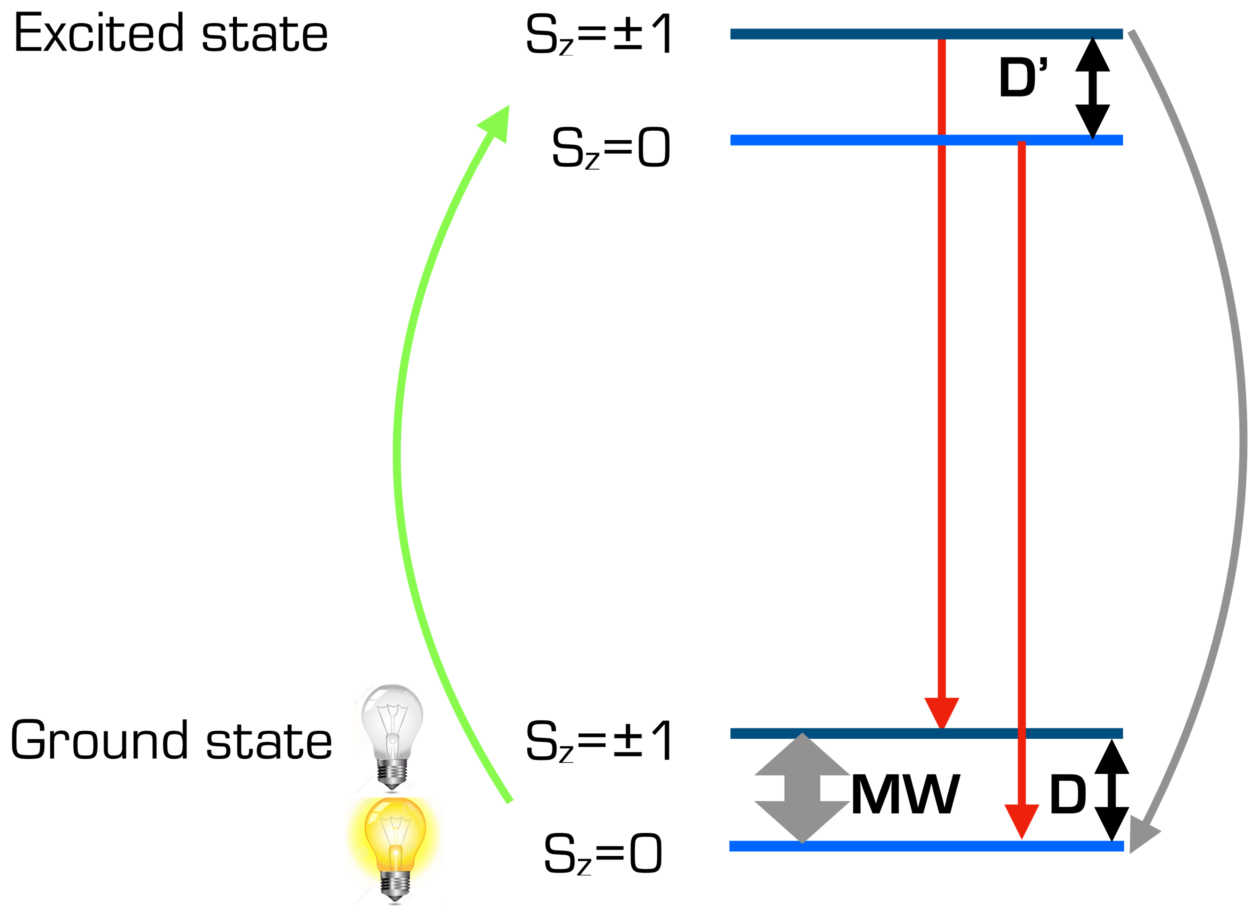
$$\Psi(\mathbf{r},t) = c_0(t)\psi_0(\mathbf{r}) + c_1(t)\psi_1(\mathbf{r}) = c_0(t)e^{-i\omega_0 t}a_0(\mathbf{r}) + c_1(t)e^{-i\omega_1 t}a_1(\mathbf{r})$$

Rabi oscillations, coherent control of the spin state of the NV center

$$\begin{cases} |c_0(t)|^2 = \cos^2\left(\frac{\Omega t}{2}\right) \\ |c_1(t)|^2 = \sin^2\left(\frac{\Omega t}{2}\right) \end{cases}$$

$$\Omega = \frac{E_0}{\hbar}\int d^3 a_0^*(\mathbf{r})\, e\,\hat{r}\, a_1(\mathbf{r})$$

Rabi oscillations for a NV center

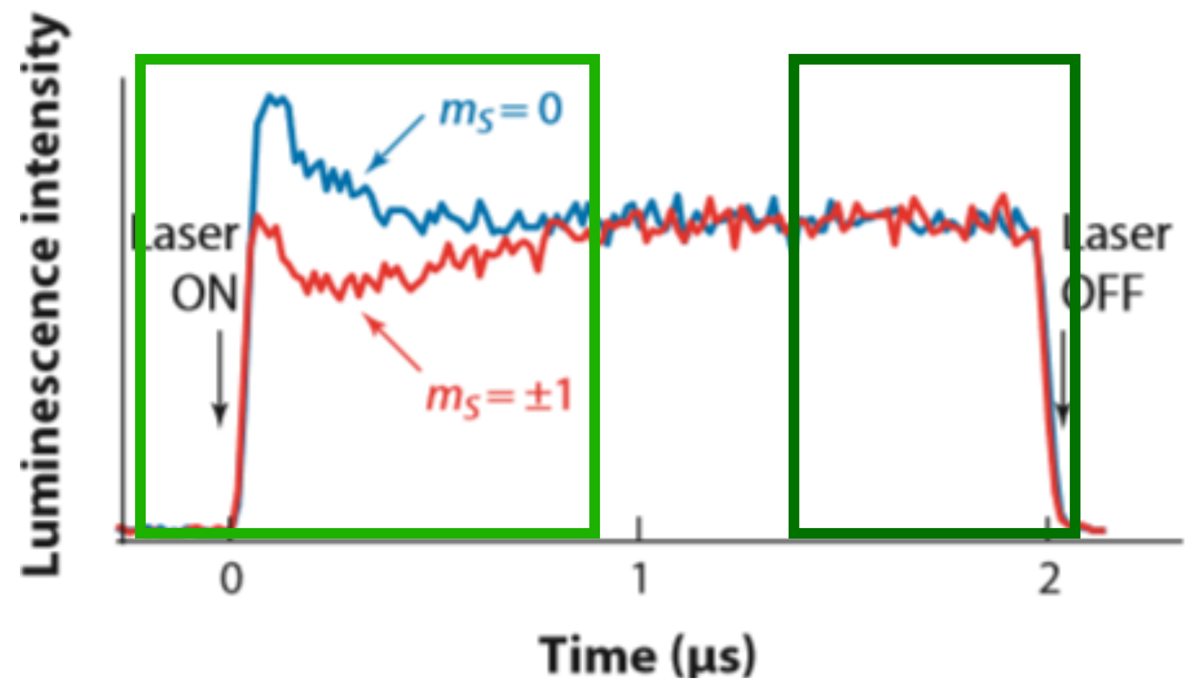


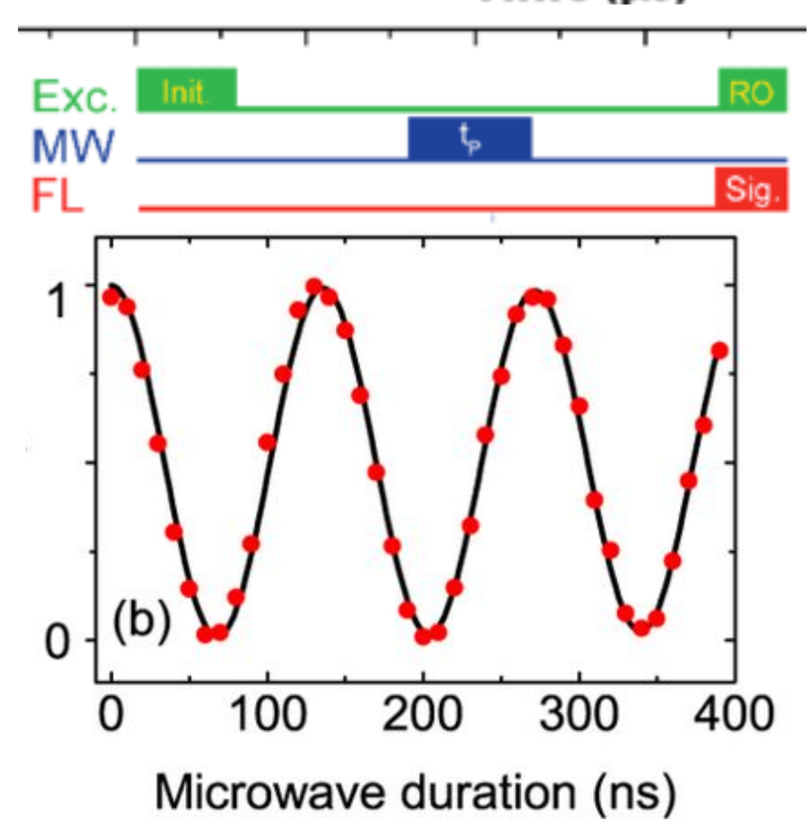
$$H = D\ \left(S_z^{\,2} - S(S+1)/3\ \right) + H_f$$

spin-spin interaction

D~2.88 GHz fine structure splitting

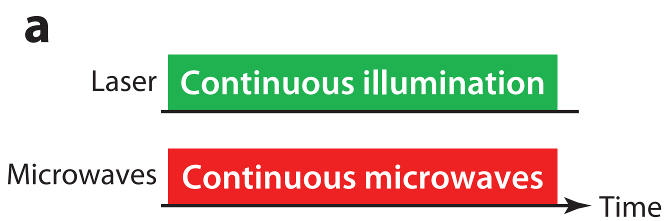
Readout and initialization of the NV center's spin
Annu. Rev. Phys. Chem. 2014. 65:83

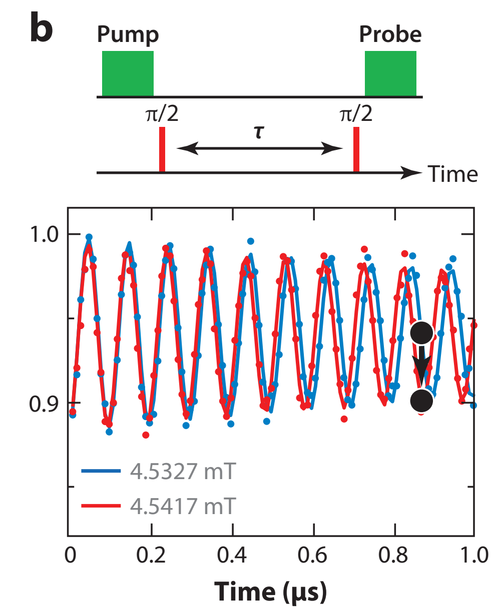




Rabi Oscillations of a single NV center Sci. Rep. 2, 432 (2012)

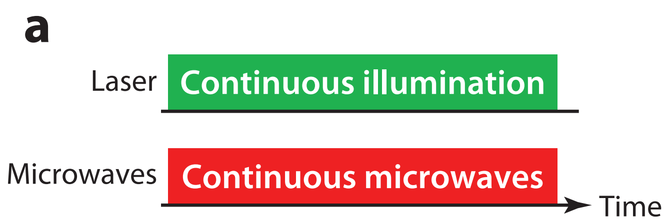
Pulsed ODMR protocols

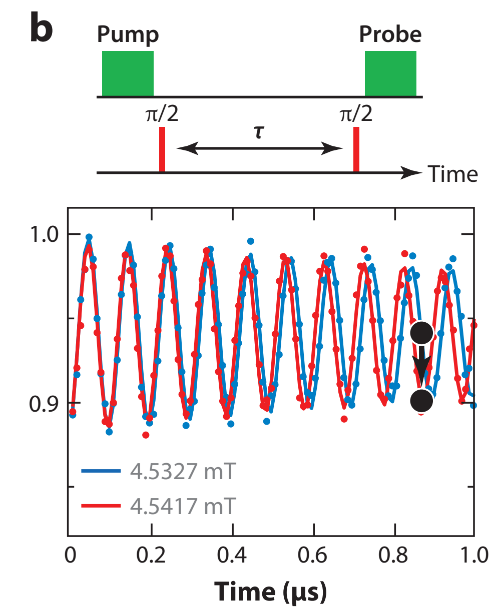




	sensitivity	
Magnetic field	~ 0.1 μT	~ nT
Electric field	~ kV cm^{-1}	~ 0.1 kV cm^{-1}
Temperature	~ mK	~ K with < μs temporal resolution
Strain/stress		~ 100 Pa

Pulsed ODMR protocols





	sensitivity	
Magnetic field	~ 0.1 μT	~ nT
Electric field	~ kV cm^{-1}	~ 0.1 kV cm^{-1}
Temperature	~ mK	~ K with < μs temporal resolution
Strain/stress		~ 100 Pa

Property	Coupling coefficient		Typical sensitivity[a]
Magnetic field[b]	γ	28 GHz/T	$0.36\ \mu T/\sqrt{Hz}$
Electric field[b]	ϵ_z	0.17 Hz/(V/m)	$5.8\ kV\ cm^{-1}/\sqrt{Hz}$
Electric field[c]	ϵ_{xy}	3.5×10^{-3} Hz/(V/m)	$280\ kV\ cm^{-1}/\sqrt{Hz}$
Strain[d]	$\sim\epsilon_{xy}/d^c$	$\sim 10^{11}$ Hz/$(\delta l/l)$	$\sim 10^{-7}/\sqrt{Hz}$
Orientation[e]	γB	100 kHz/°	$0.1°/\sqrt{Hz}$
Temperature	$\partial D/\partial T$	−74 kHz/K	$0.13\ K/\sqrt{Hz}$
Pressure	$\partial D/\partial P$	1.5 kHz/bar	$6.8\ bar/\sqrt{Hz}$

Detectable frequency shift

$$\Delta\omega \approx \frac{a}{2\eta\sqrt{I_0 T}},$$

a: resonance linewidth
eta: optical contrast (≤30%)
I_0: photon count rate
T: integration time

Perspectives

$$|\psi>= c_0(t)|0> + c_1(t)|1>$$

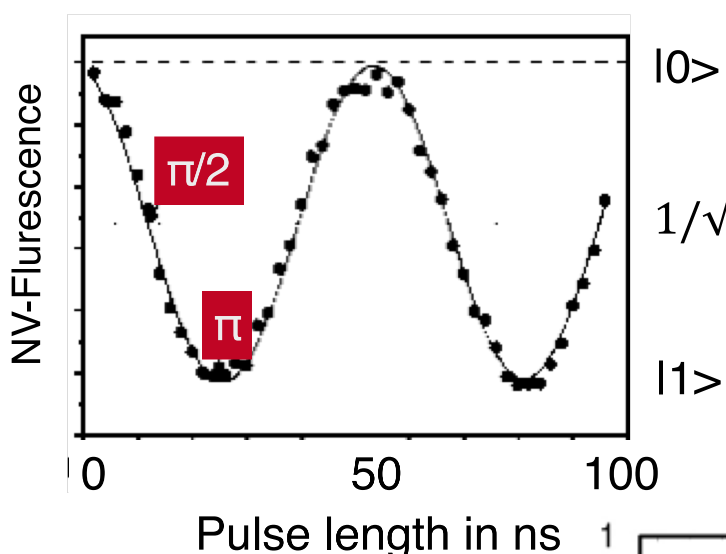
$$\begin{cases} c_0(t) = i\cos\left(\frac{\Omega t}{2}\right) \\ c_1(t) = \sin\left(\frac{\Omega t}{2}\right) \end{cases}$$

MW pulses: Qubit preparation and control

Optical fluorescence: Qubit readout

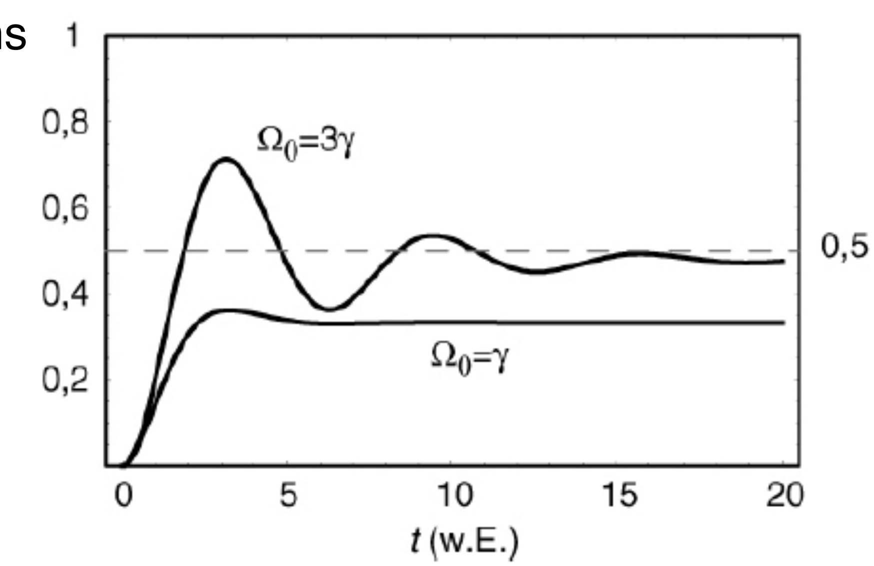
Several issues to be addressed

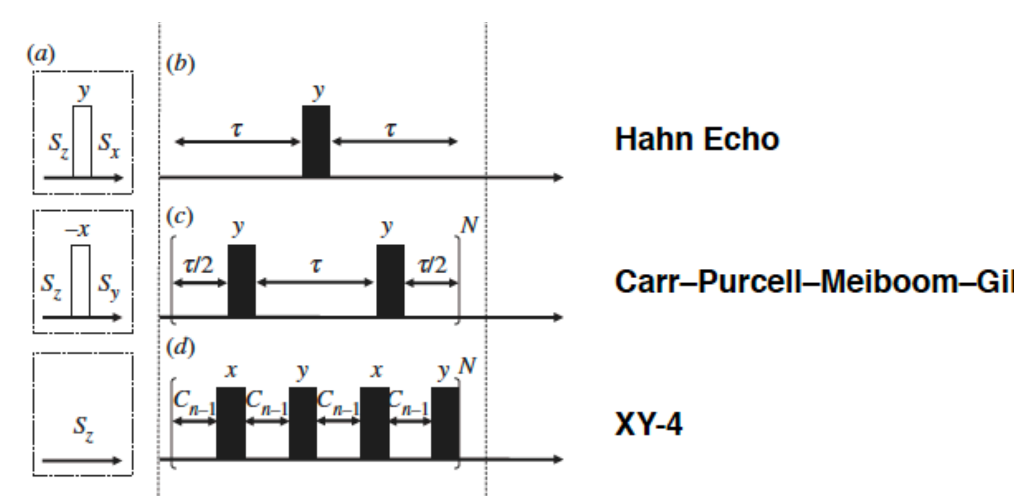
Decoherence of the quantum state



Interaction with external noise (fields, spin bath) alterates the spin state

Dynamical decoupling methods: periodical spin flipping to preserve coherence





Perspectives

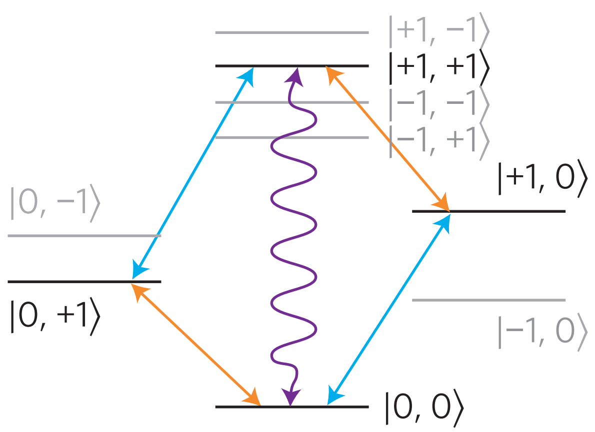
$$|\psi >= c_0(t)|0> + c_1(t)|1>$$

$$\begin{cases} c_0(t) = i\cos\left(\frac{\Omega t}{2}\right) \\ c_1(t) = \sin\left(\frac{\Omega t}{2}\right) \end{cases}$$

MW pulses: Qubit preparation and control
Optical fluorescence: Qubit readout

Path towards quantum computing

Several issues to be addressed



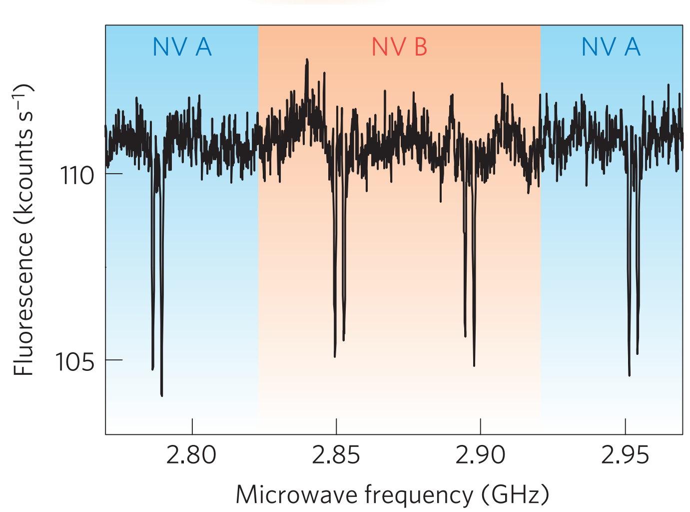
Qubits entanglement

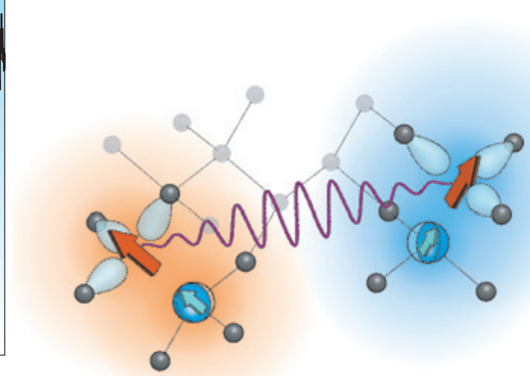
First demonstration from Stuttgart

Requires:
Adjacent qubits (deterministic implantation, < 20 nm spacing)
Control and interaction gate (MW pulses for e-e- interaction)
Information swap on nuclear spin (longer coherence, but ^{15}N)
Remove centers electron for longer storage (electrical control)

Efficient fabrication of close NV centers?
How to scale up to many qubits?

c



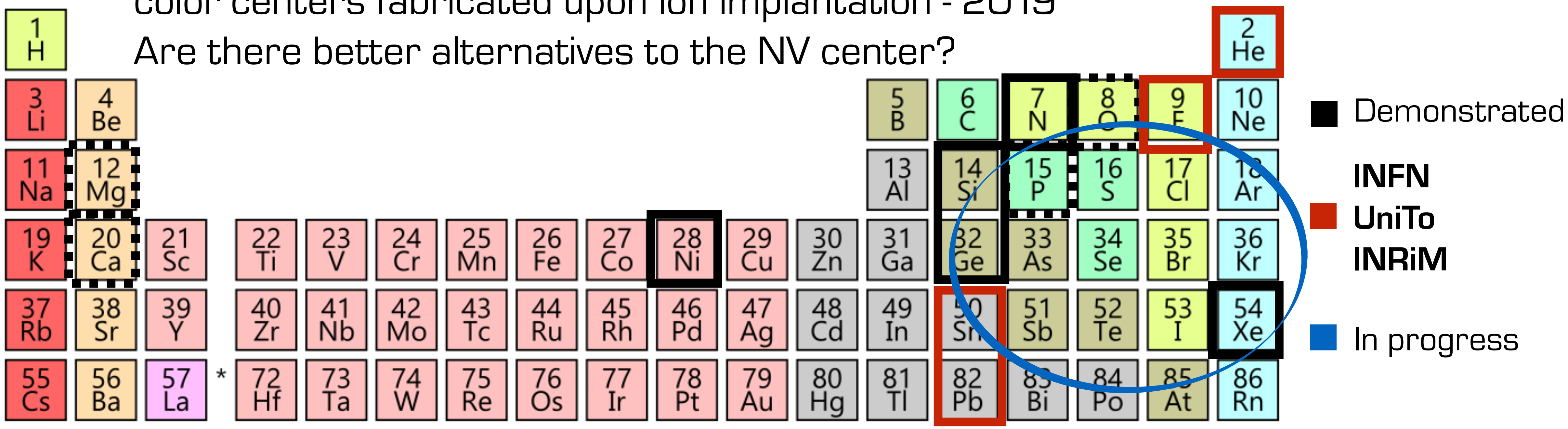


Color centers zoology in diamond

diamond: **most studied** material for single-photon generation

color centers fabricated upon ion implantation - 2019

Are there better alternatives to the NV center?



NV center - J. Appl. Phys. 109, 083530 (2011)
SiV center - J. Phys. B 39 (2006) 37
Xe-center - J. Lumin 107 (2004) 26
NE8 Center - J. Appl. Phys. 107 (2010) 093512

SnV center - ACS Phot. 4 (2017) 2580
- PRL 119, 253601 (2017)
PbV center - ACS Phot. 5 (2018) 4864
He-center - J. Lumin 179 (2016) 59
F-center

GeV center - Sci. Reports 5 (2015) 12882
- Sci. Reports 5 (2015) 14789

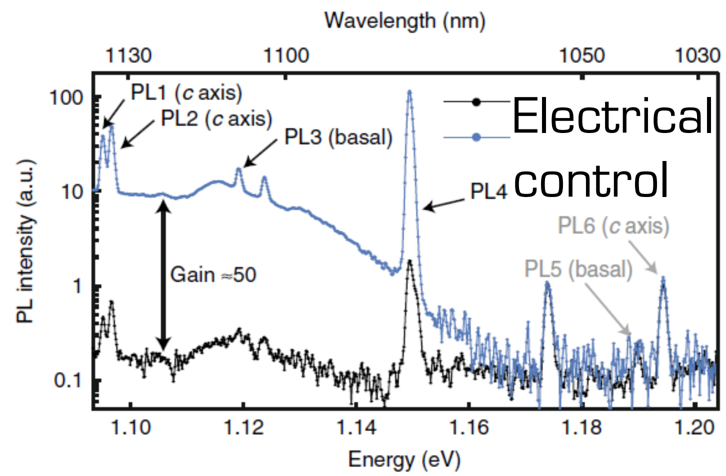
O-center - J. Phys. D 51 (2018) 483002
P-center
Ca-center
Mg-center
F-center

Color centers zoology in semiconductors

Color centers in semiconductors

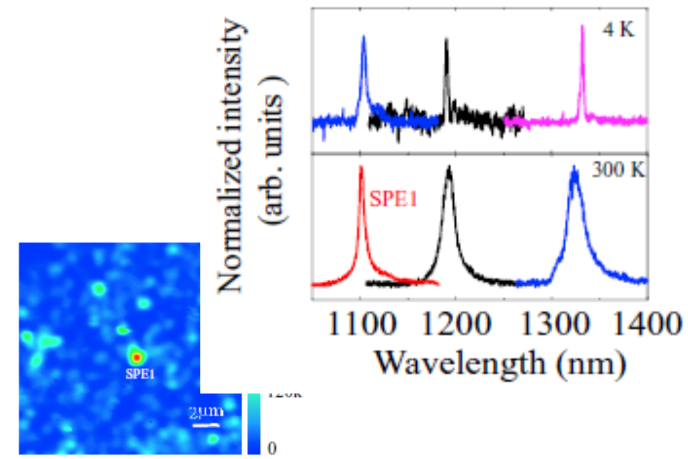
Are there better alternatives to the **diamond** NV center?

SiC



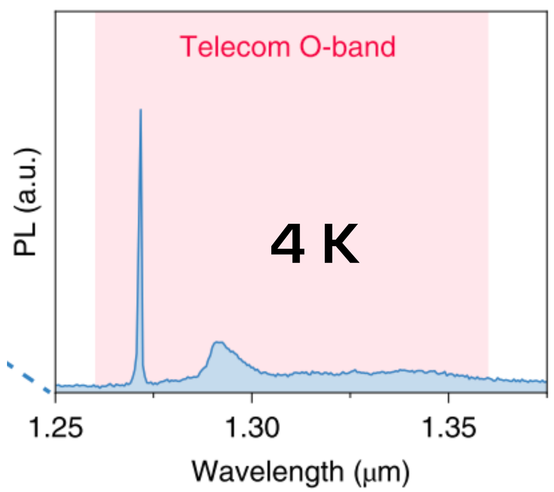
G. Wolfowicz et al., Nat. Comm. **8**, 1876 (2018)

GaN



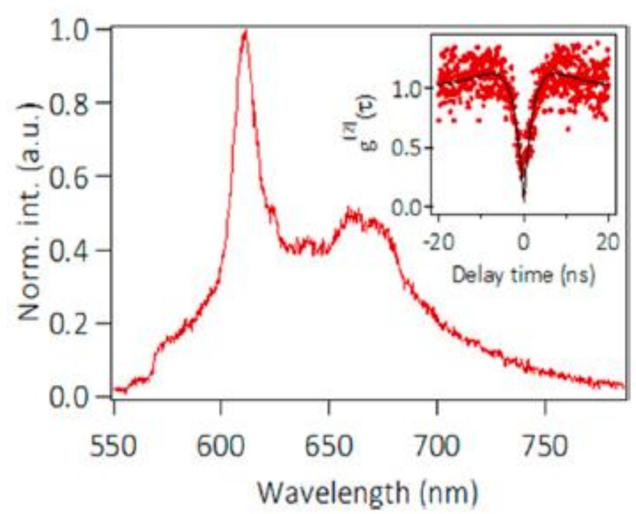
Y. Zhou et al., Sci. Adv. **4**, 3580 (2018)

Silicon

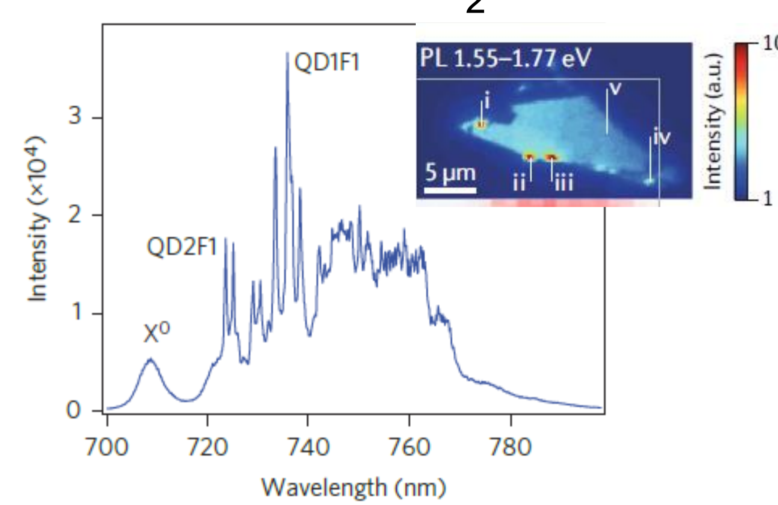


Nature Electronics 3 (2020) 738
Telecom wavelengths!!!

hBN



WSe$_2$



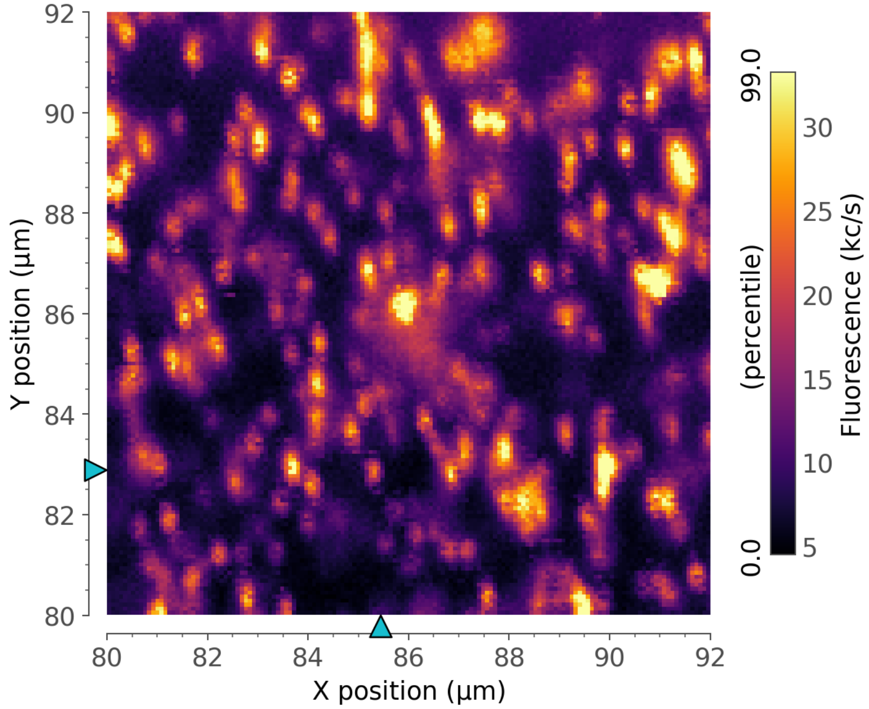
A. Stivastava et al., Nat. Nanotech. **10**, 491-496 (2015)

binary materials: difficult fabrication of specific defects
intrinsic defects only
handful of emitters overall
very **active** research field

Color centers manufacturing in integrated platforms

Integration in photonic chips by means of ion implantation

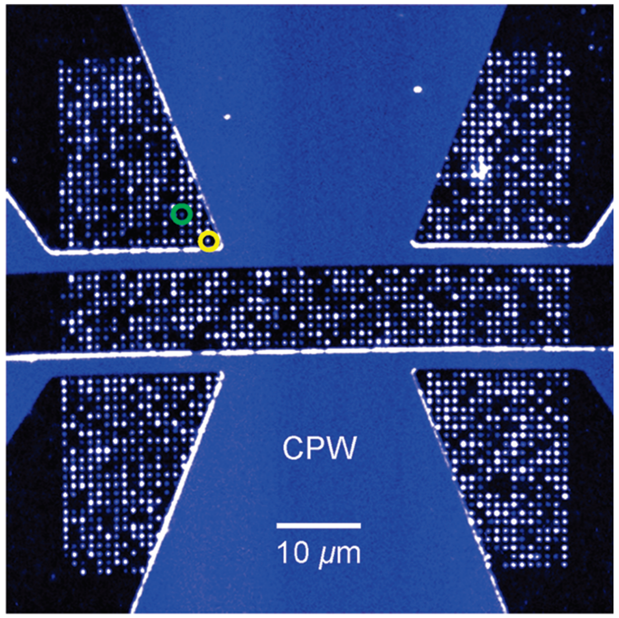
Random distribution of color centers following low-dose ion implantation (some are single-photon sources)



ACS Photonics 2017, 4, 2580

You Are Here

Ordered array of individual emitters



Nano Lett., 2010, 10 3168

in practice, we need to **fabricate** sources **deterministically.** Each implanted ion ⇒ One single photon emitter

Limiting factors:
- delivery of predefined number of ions (Poisson statistics, unless ion detection technique implemented)
- nanoscale ion implantation (enabling entanglement between adjacent centers)
- conversion of implanted ions in color centers (typical: <10%. state of the art: >50 %)
- center environment for charge state configurations (e.g., device doping)

Summary

NV center in diamond

Promising, versatile tool for environment sensing

Solid state, portable

Nanoscale system

Biocompatible

High sensitivities for vector and scalar field measurements

Challenges

Increase coherence time

Controlled fabrication schemes and protocols

Alternative systems vastly unexplored

Potential for industry

Standardization

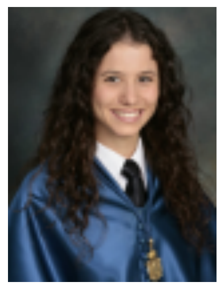
Integration

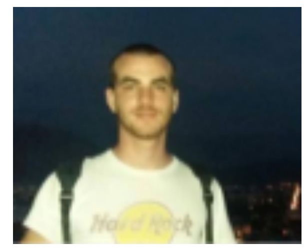
Best practices, optimal procedures

Thank you for your kind attention!

http://www.solid.unito.it


P. Olivero


E. Nieto Hernandez


E. Corte

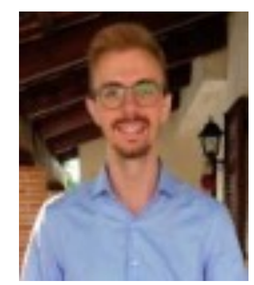

G. Andrini


E. Vittone


F. Picollo


V. Pugliese


E. Redolfi


G. Zanelli


S. Ditalia Tchernij

MINISTERO DELL' ISTRUZIONE, DELL'UNIVERSITÀ E DELLA RICERCA
L232/2016 Dept. Excellence

INFN Istituto Nazionale di Fisica Nucleare
2020 CSN5 QT Call "QUANTEP"

EMPIR EURAMET
Research Projects, "SEQUME", "QADET"

PIQUET PIEMONTE QUANTUM ENABLING TECHNOLOGY

European Commission
Marie-Curie "LasIonDef" Project