Single color centers for silicon-based quantum technologies

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European Research Council
Established by the European Commission

PROGRAMME DE RECHERCHE QUANTIQUE

Color centers in crystals

Example : **diamond**

nitrogen impurities

Breeding *et al., Gems & Gemology* **56**, 194-219 (2020)

boron impurities

Gaillou *et al., American Mineralogist* **97**, 1-18 (2012)

Color centers in crystals

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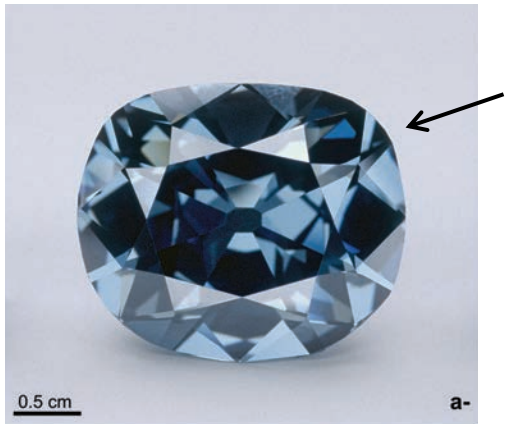
nitrogen impurities

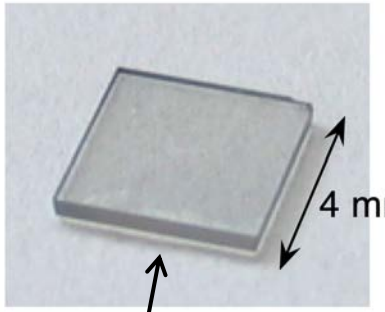
Breeding *et al., Gems & Gemology* **56**, 194-219 (2020)



boron impurities

Gaillou *et al., American Mineralogist* **97**, 1-18 (2012)

ultrapure diamond

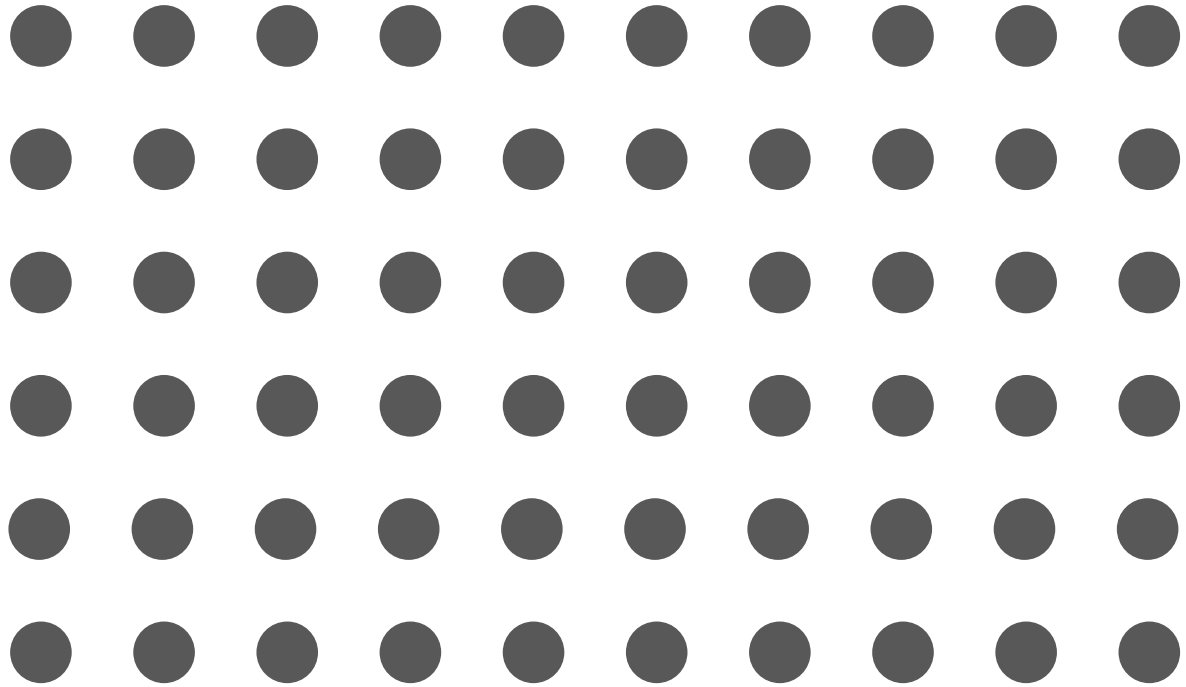


impurity concentration ~10^{-9}

single color center detection using advanced mycroscopy techniques

Color centers = artificial atoms trapped in the crystal

perfect crystal lattice



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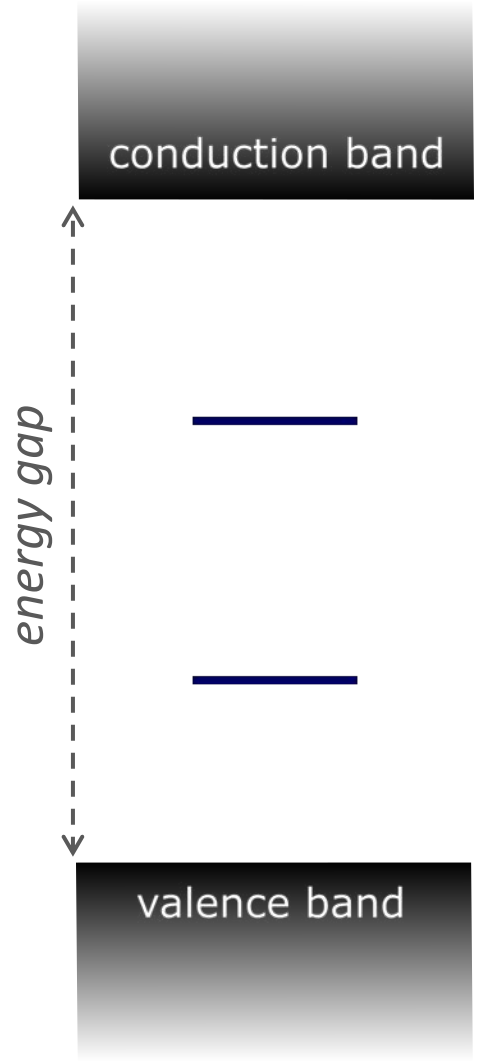

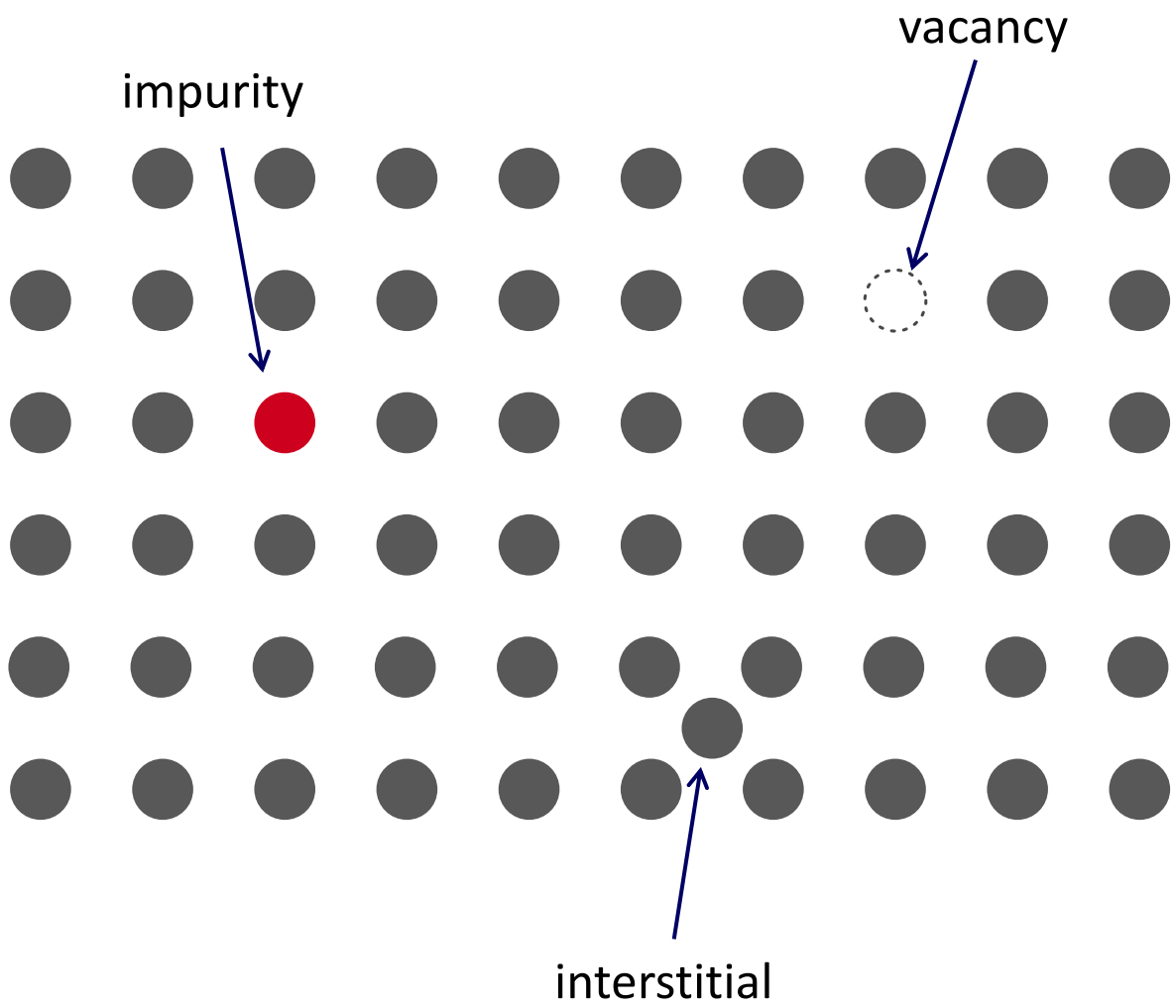

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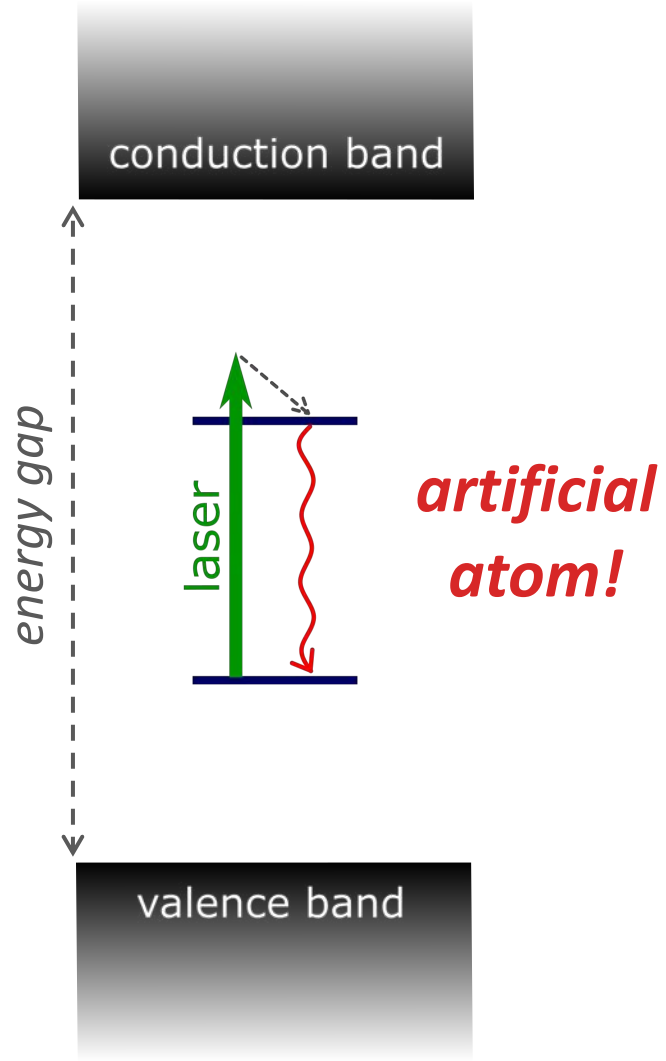
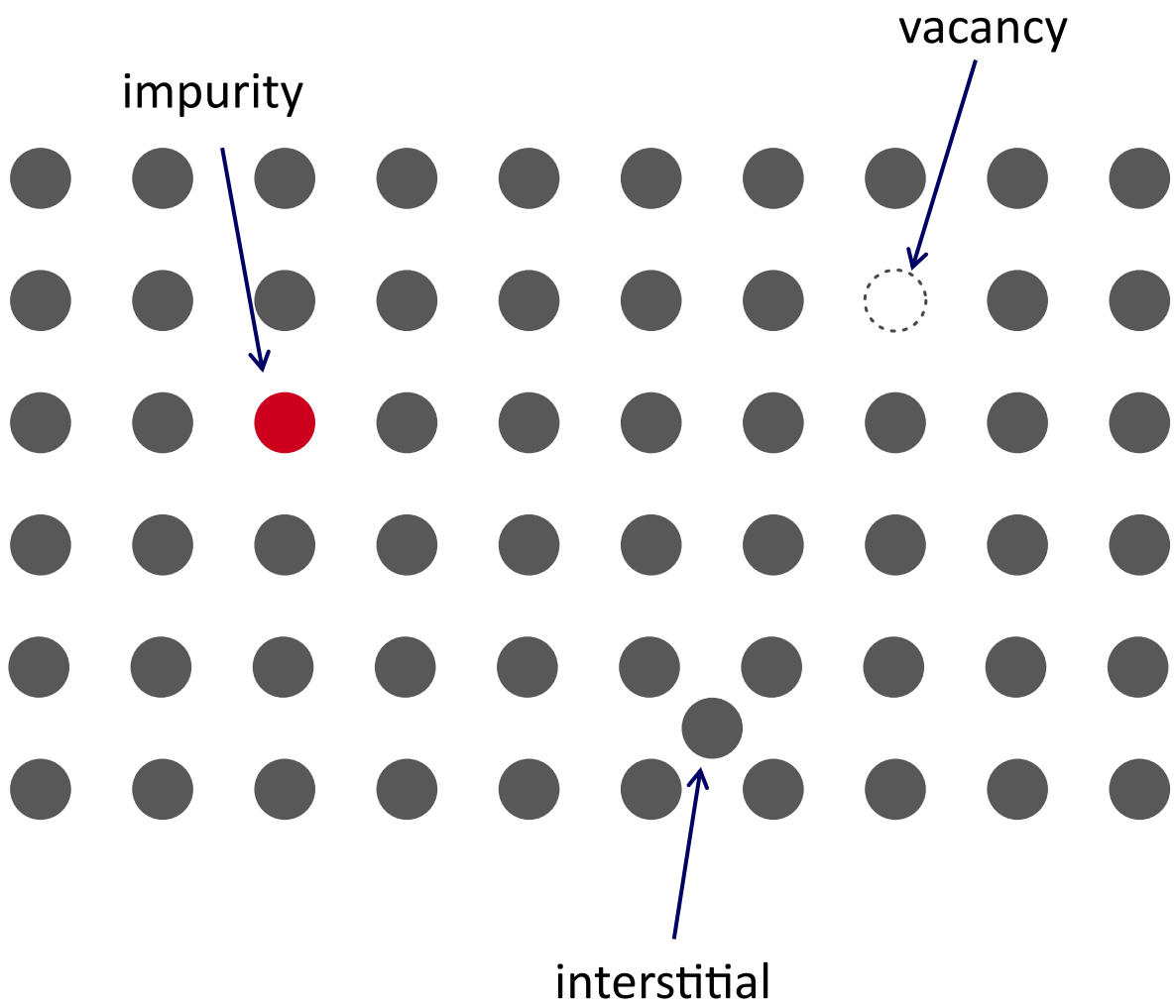
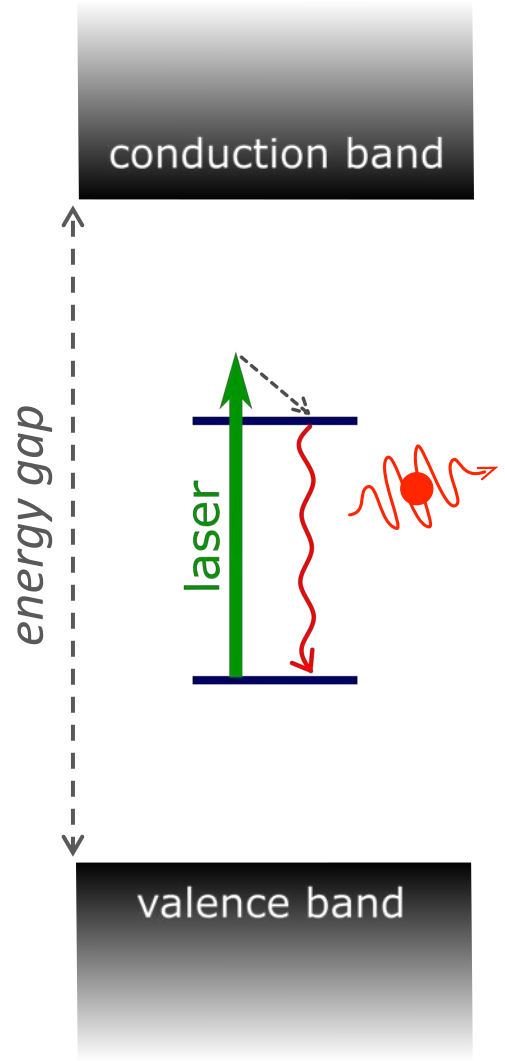


artificial atom!



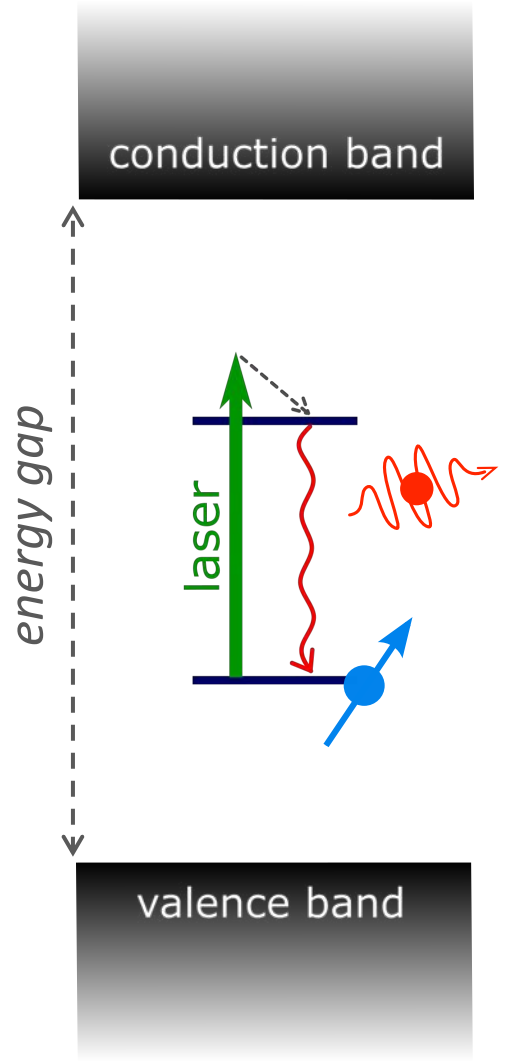
Quantum degrees of freedom of single color centers



photon

quantum communications
quantum integrated photonics

Quantum degrees of freedom of single color centers



photon

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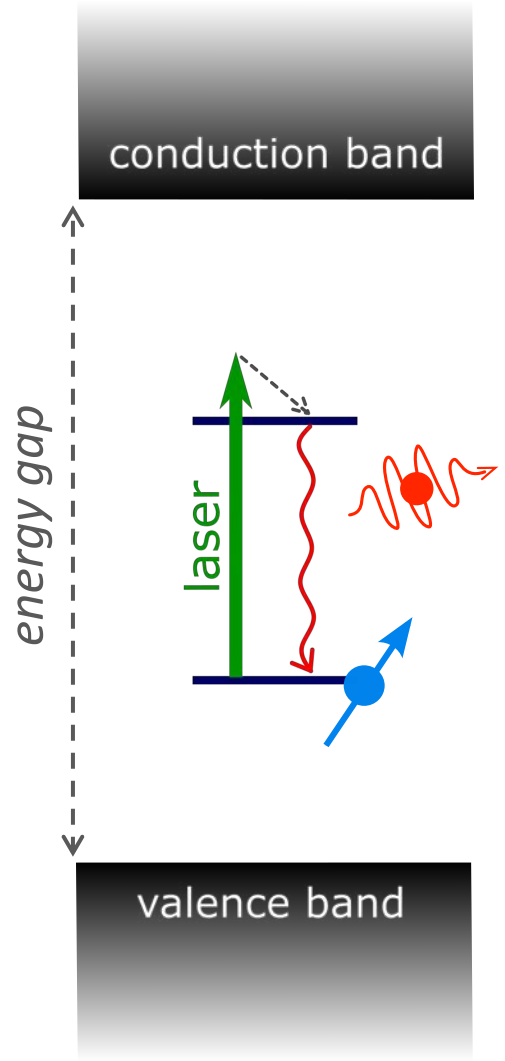
spin

quantum memory and computing
quantum sensing

Quantum degrees of freedom of single color centers



photon

quantum communications
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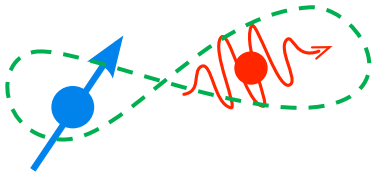
spin

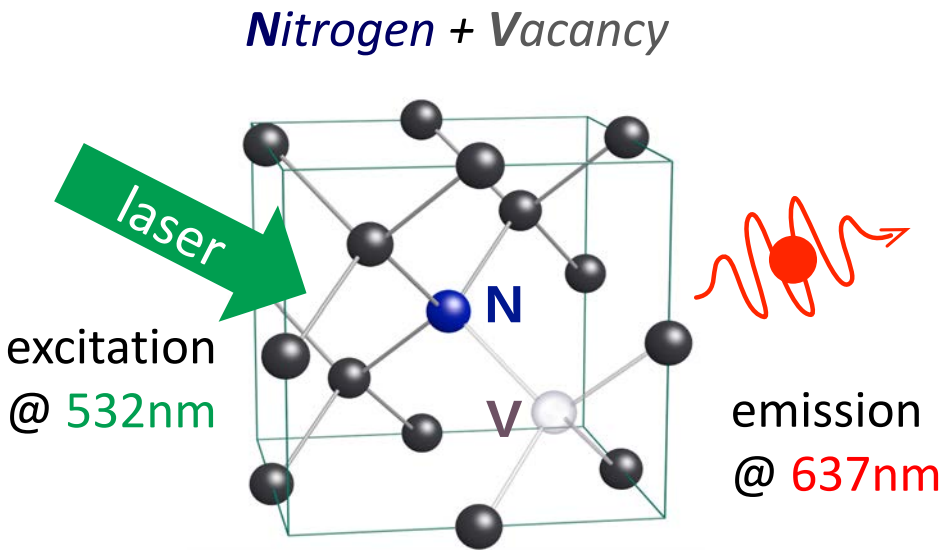
quantum memory and computing
quantum sensing

spin-photon interface



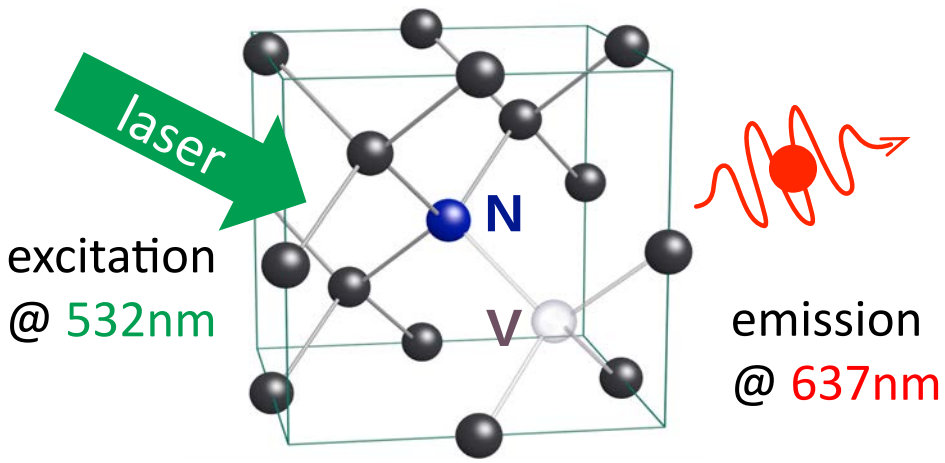
quantum networks

The NV center in diamond

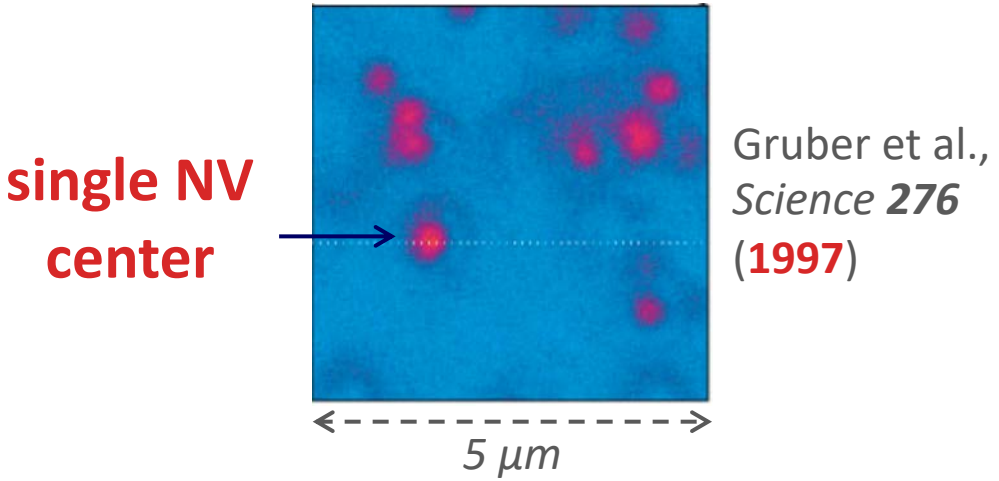


The NV center in diamond

***N**itrogen + **V**acancy*



➢ 1st isolation at single defect scale



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

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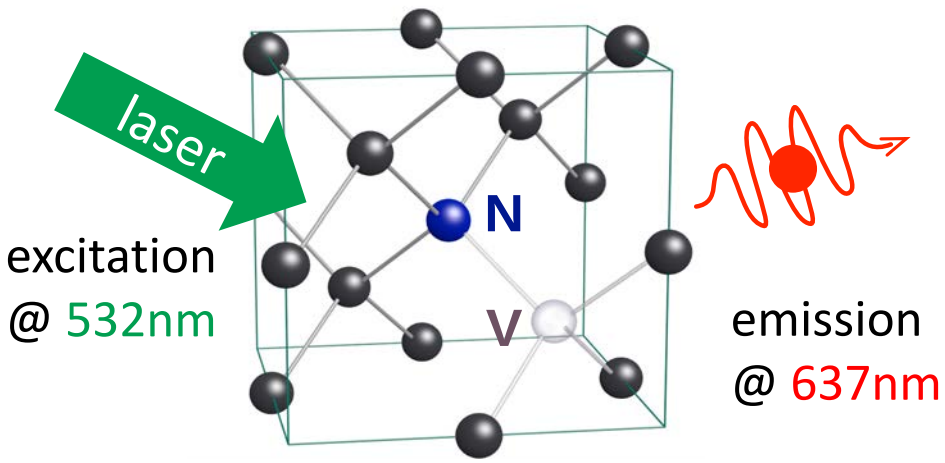

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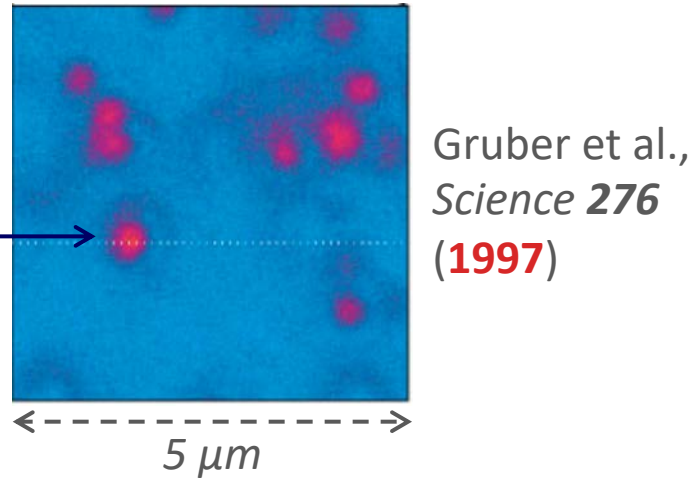


Gruber et al., *Science* ***276*** (**1997**)

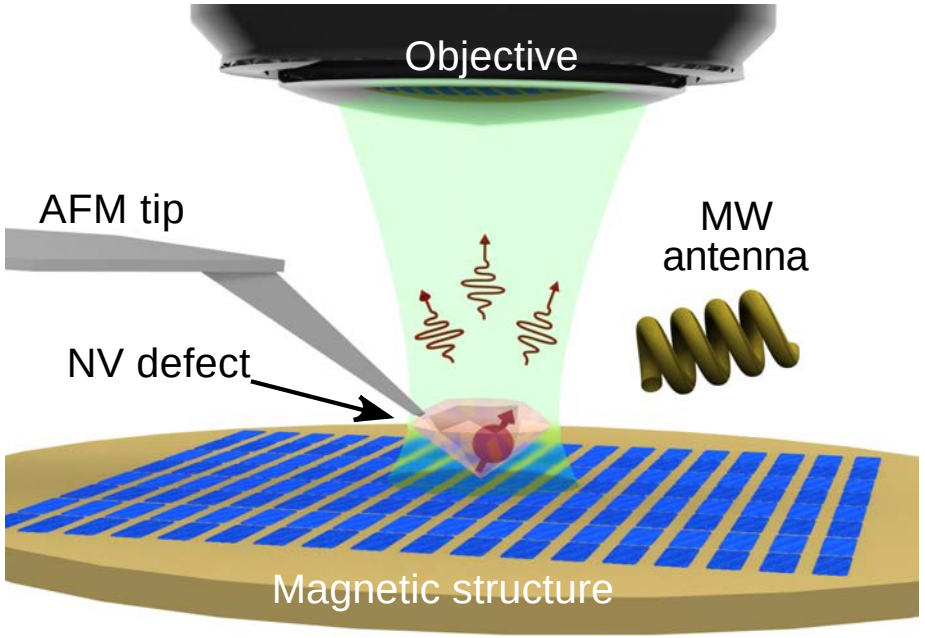
⇨ **exceptional spin properties** even at **room-temperature**!

coherence time T_2 (@300K)~ **2 ms**

Naydenov et al., *PRB* **83** 081201 (2011)

Quantum technologies with the NV center in diamond

➢ Quantum sensing



Rondin *et al.*, *APL* **100** (2012)

⇨ *commercial machines since 2010!*

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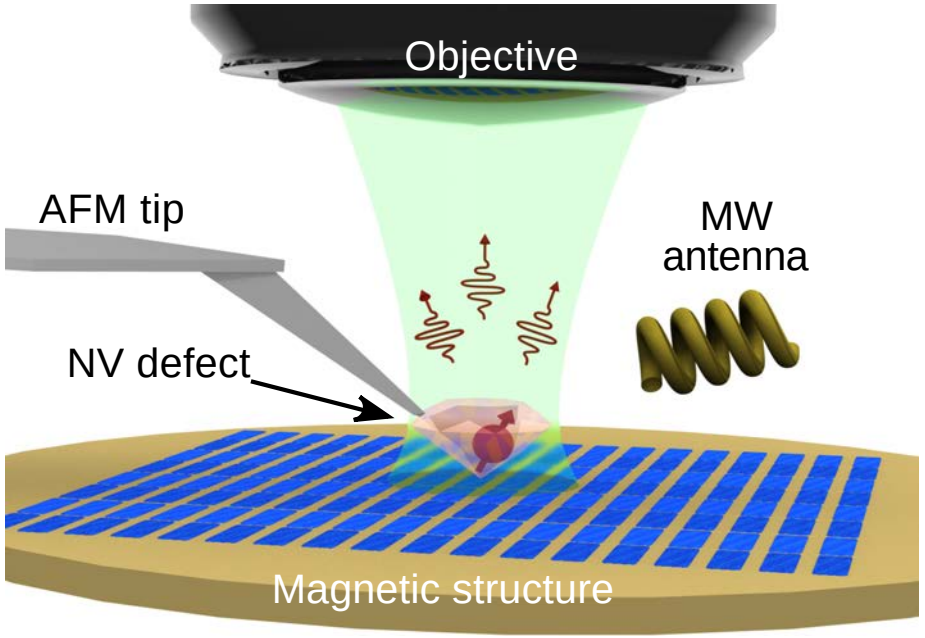

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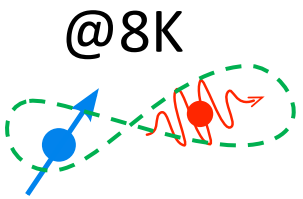
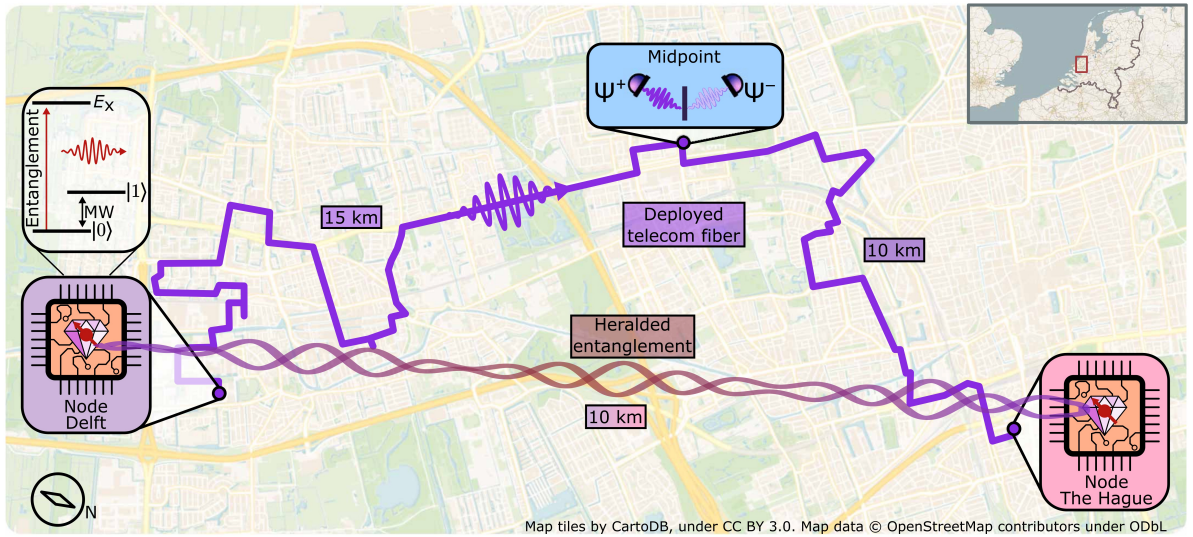
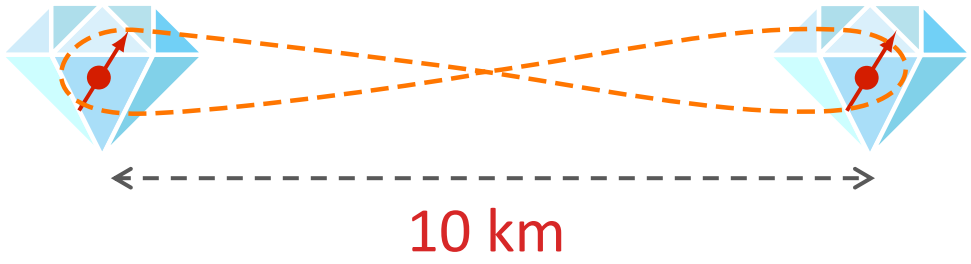
➢ Quantum network



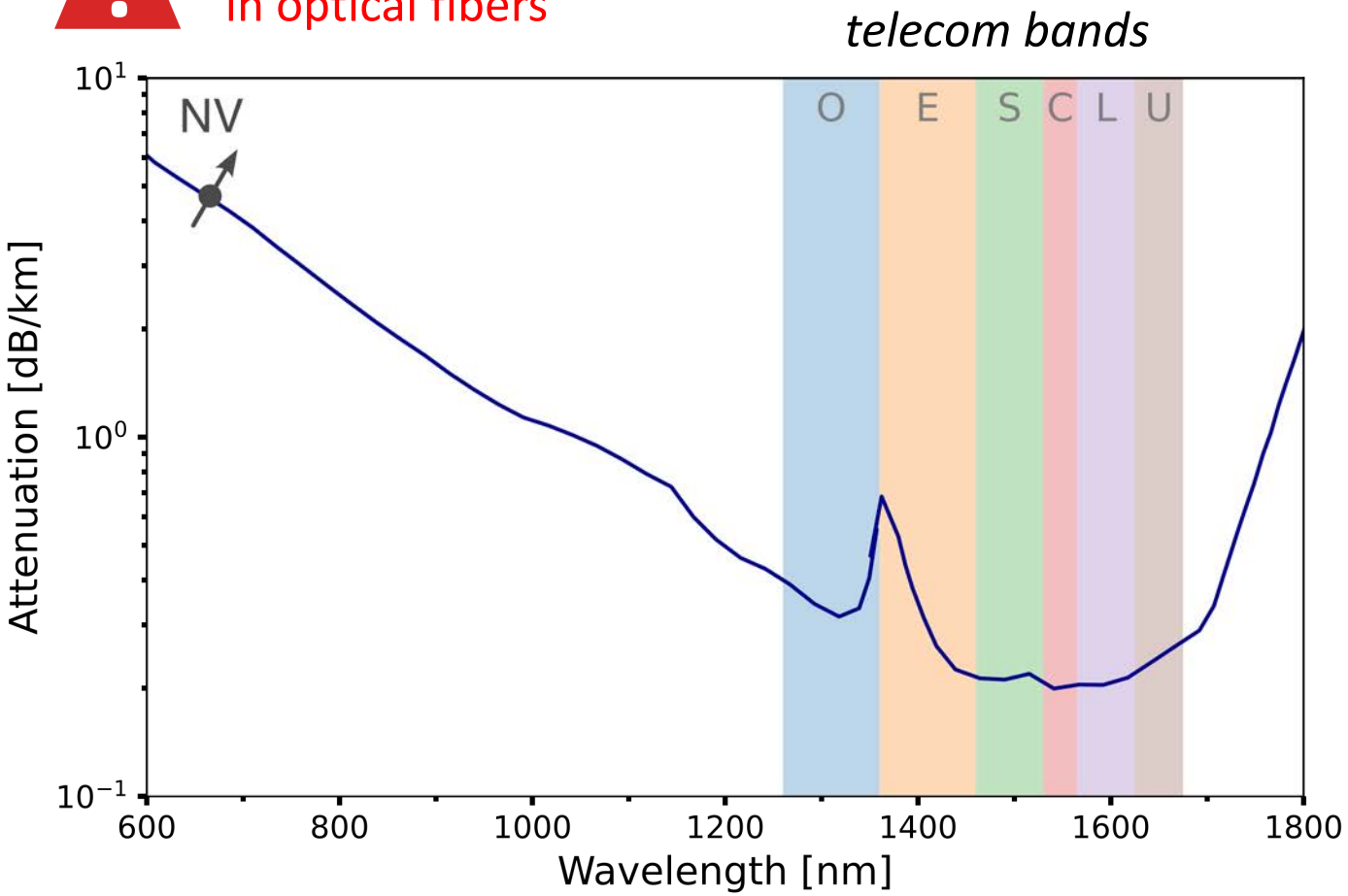


Stolk et al., Sci. Adv. **10** (2024)



Issue with propagation in optical fibers

strong attenuation
in optical fibers



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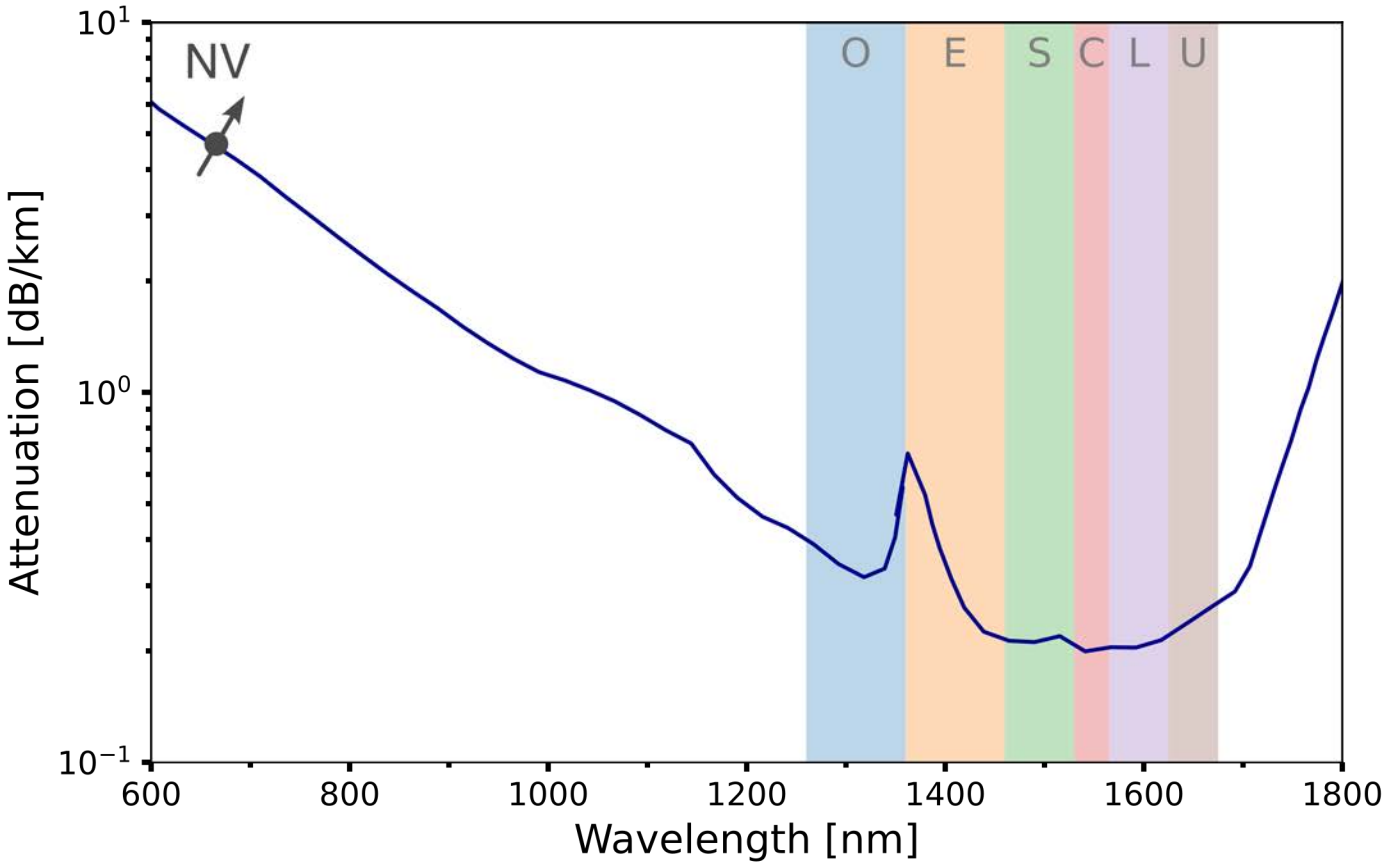
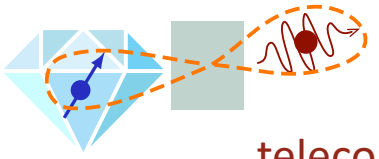


➢ 1st strategy: Quantum frequency conversion

Dréau *et al.*, *PRApplied* **9** (2018)
Tchebotareva et al., *PRL* **6** (2019)



telecom
photon

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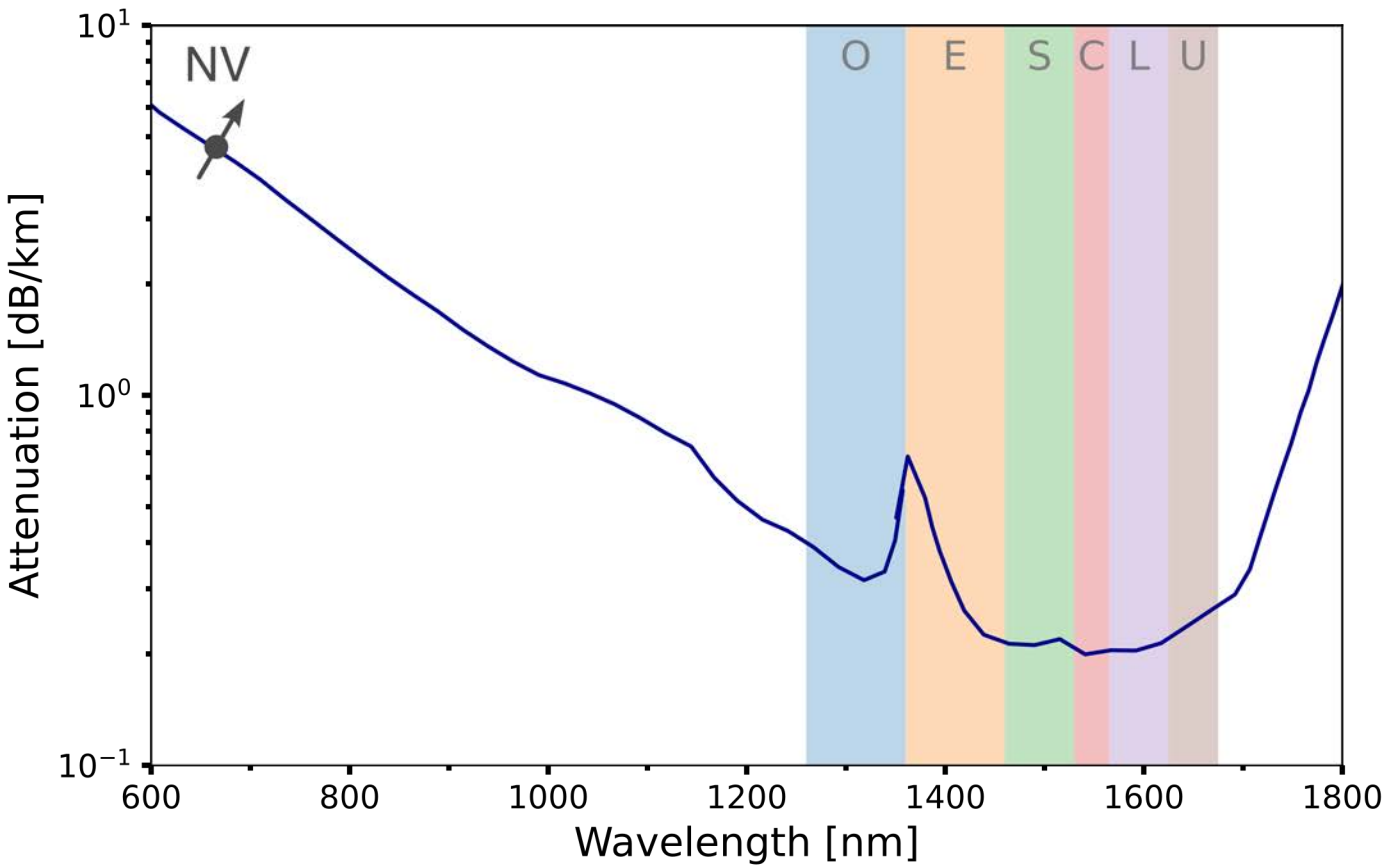

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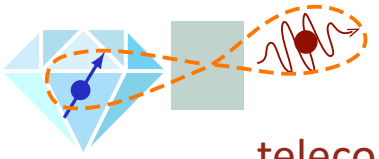


telecom
photon

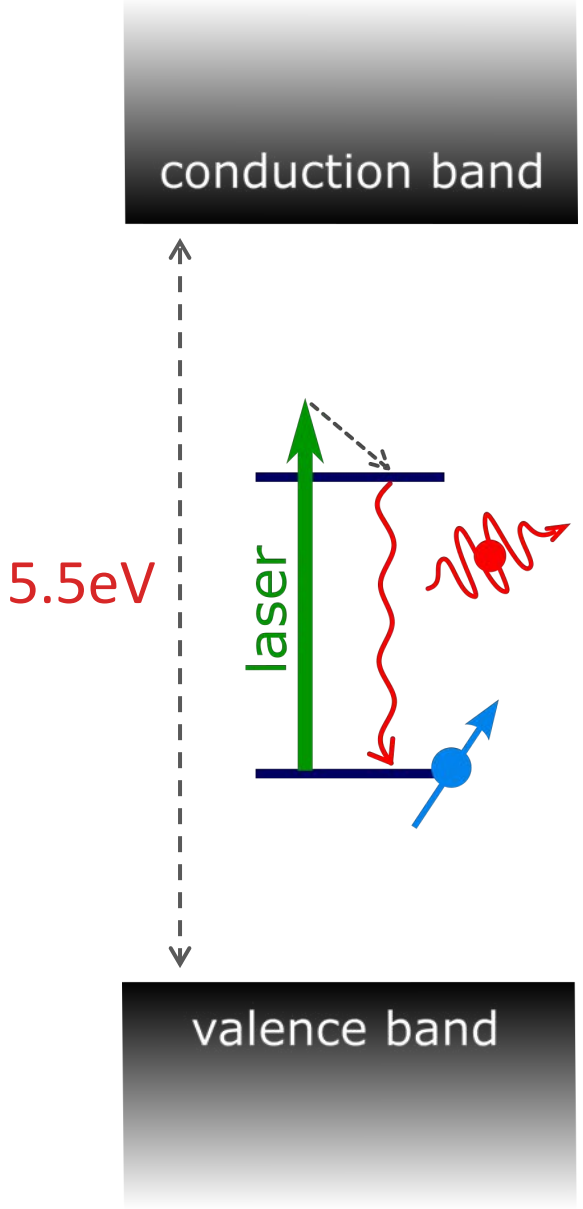
➢ 2nd strategy: **color centers emitting directly in the telecom bands**

no telecom color centers in diamond

Rogers, *Physics Procedia* **3** (2010)

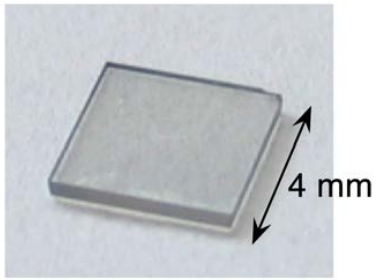
⇨ investigating other materials

From diamond to silicon



DIAMOND

not adapted to large-scale industrial nanofabrication



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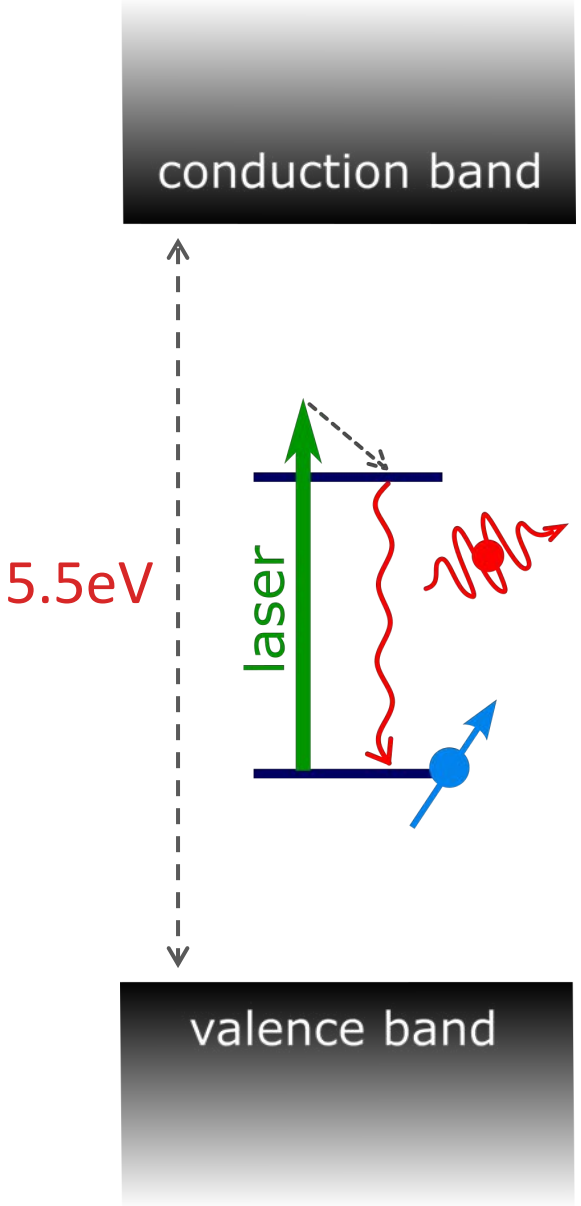

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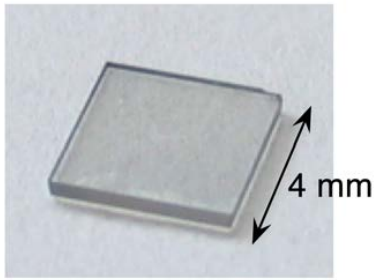
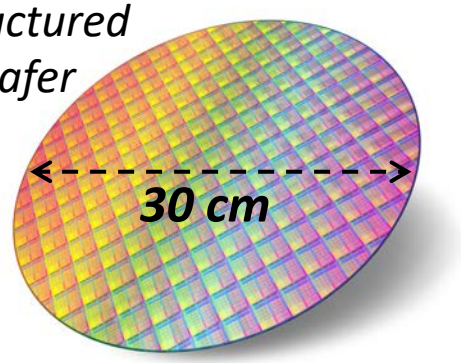


SILICON?

nanostructured silicon wafer



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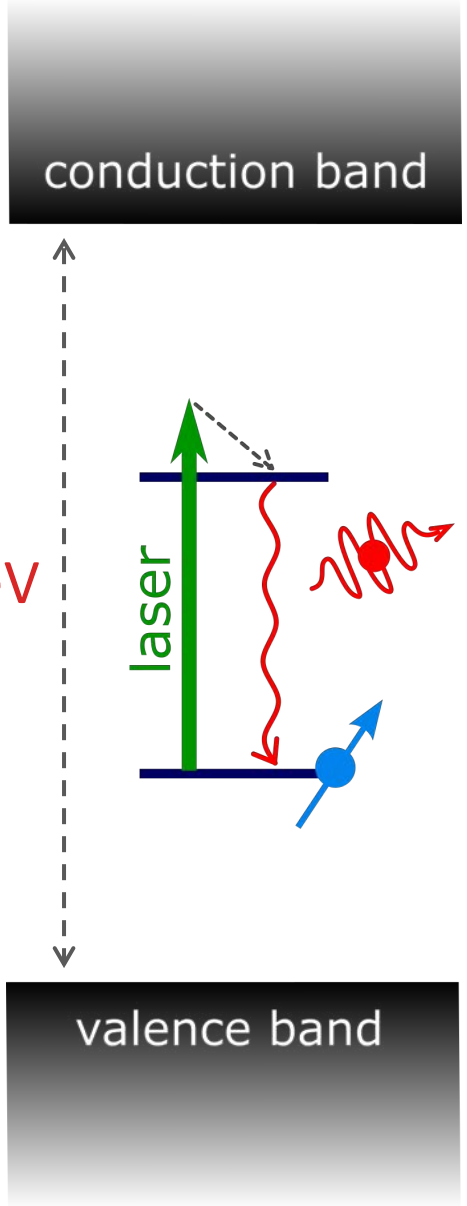

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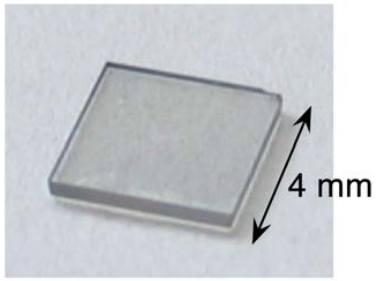

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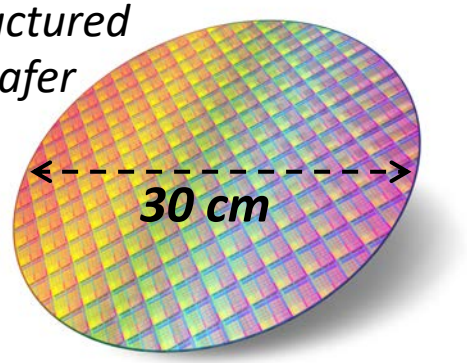
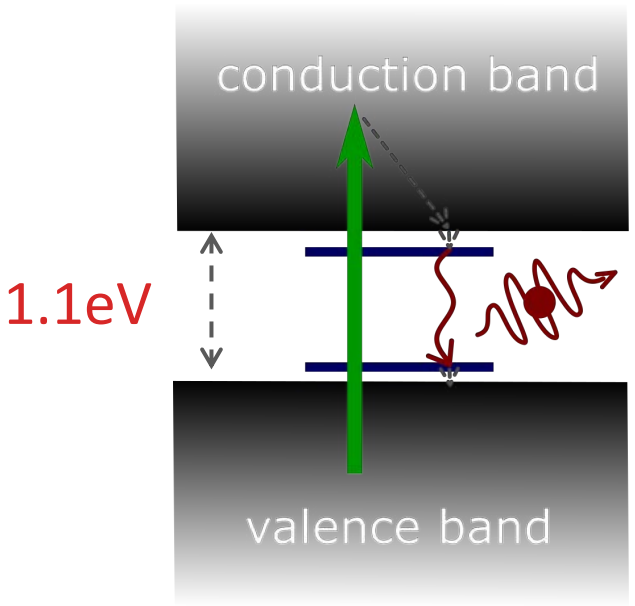




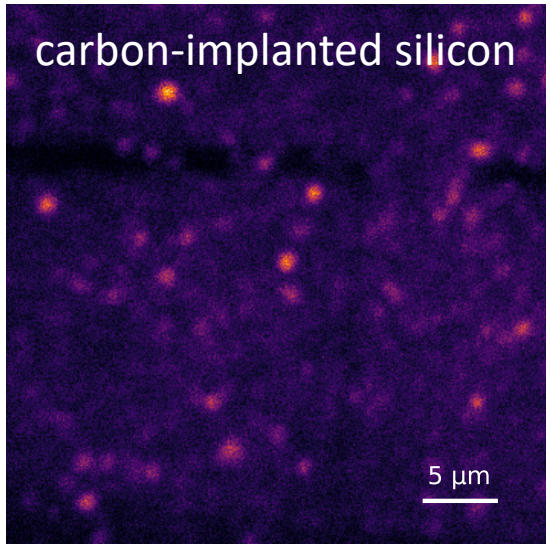
- **1st detection of a single color center: 2020 (@10K)**

Redjem *al.*, *Nat Elec.* ***3*** (2020)

Single color centers in silicon

First detection of individual color centers in silicon

*Optical scan at **10 K***



Redjem*, Durand* *et al*., Nat. Electron. **3** (2020)

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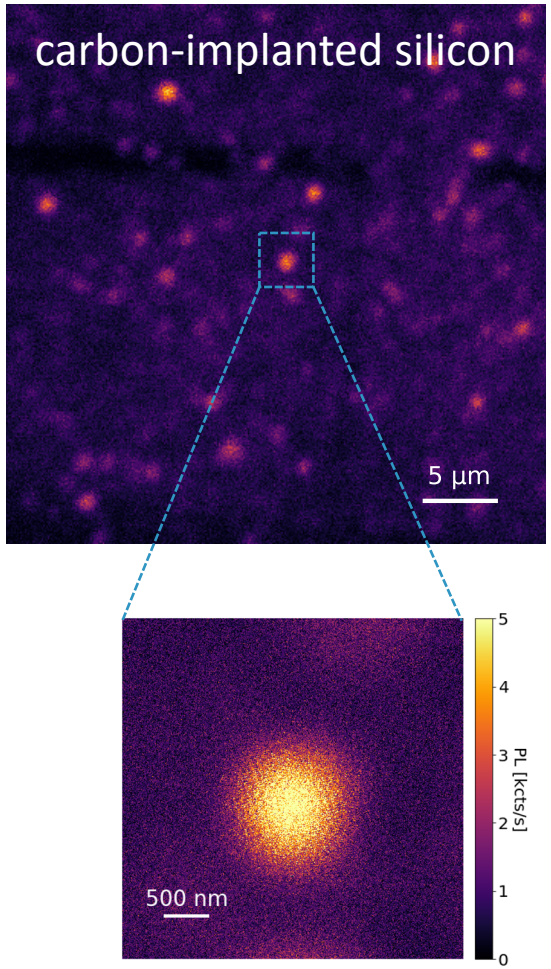
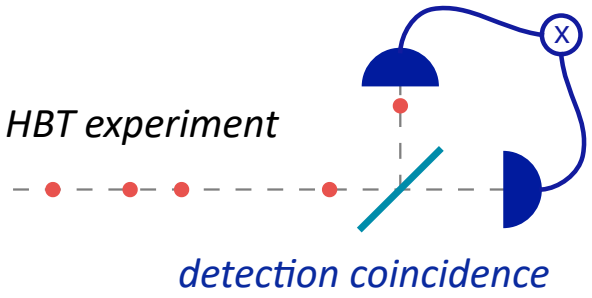


single color center?



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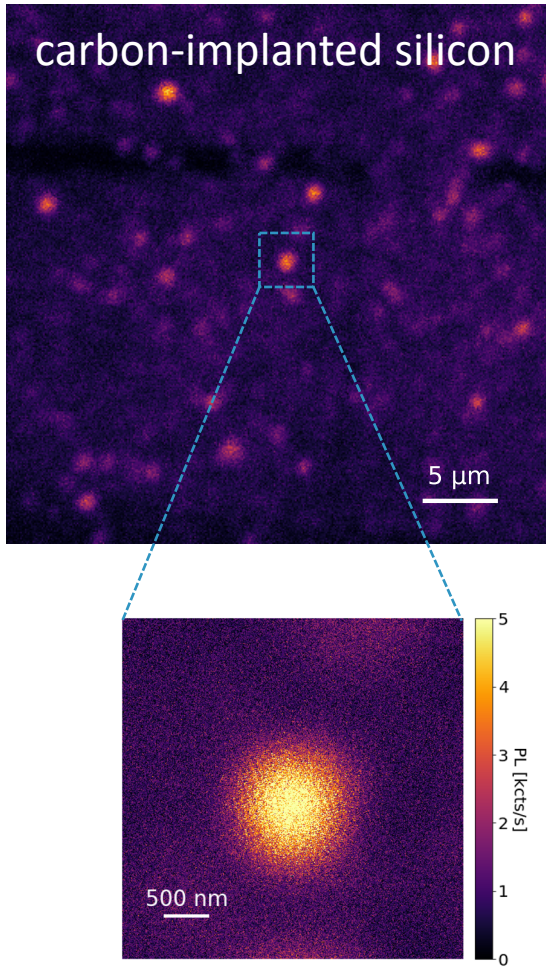
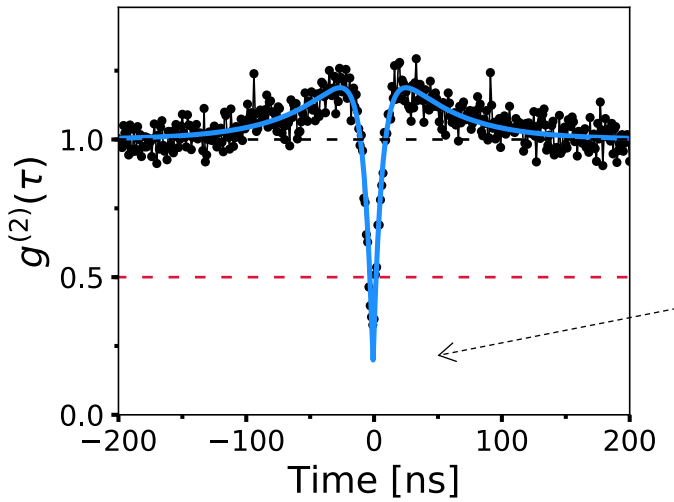


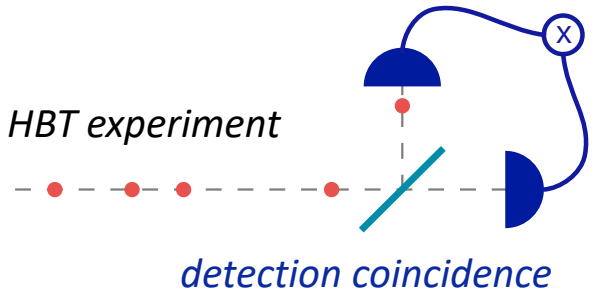
autocorrelation function



single photon emission

antibunching $g^{(2)}(0) < 0.5$

single color center



Redjem*, Durand* *et al.*, Nat. Electron. **3** (2020)

First detection of individual color centers in silicon

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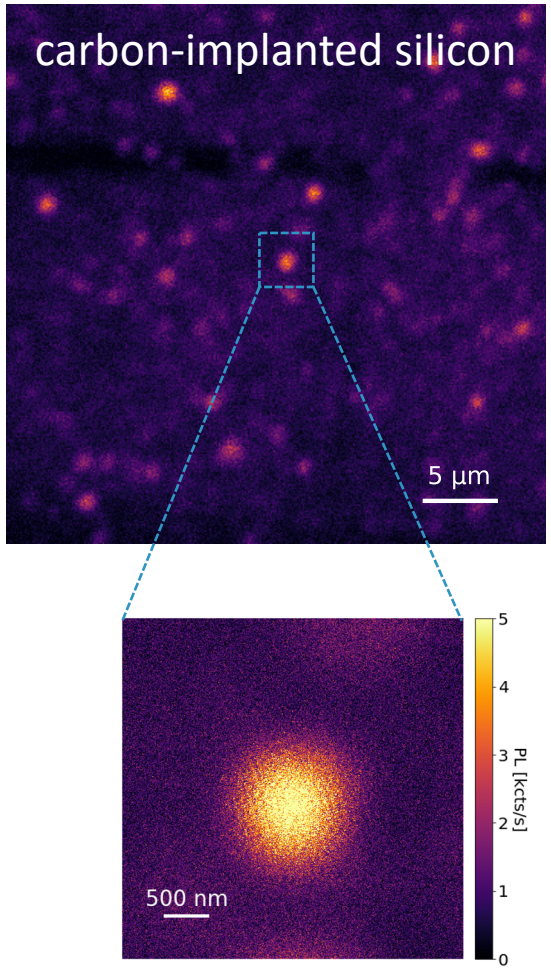

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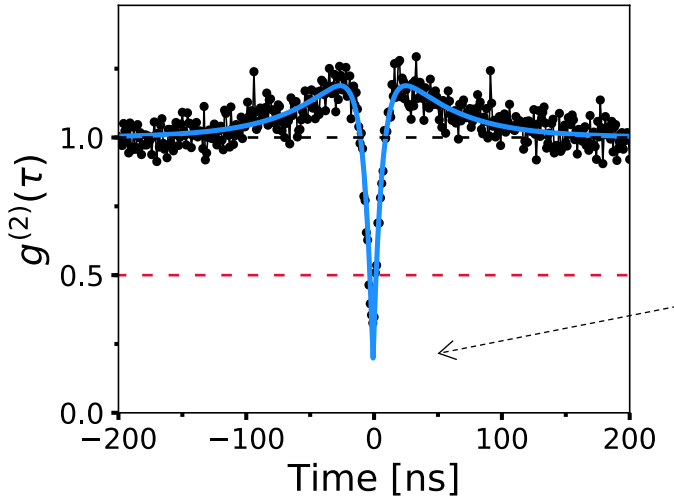

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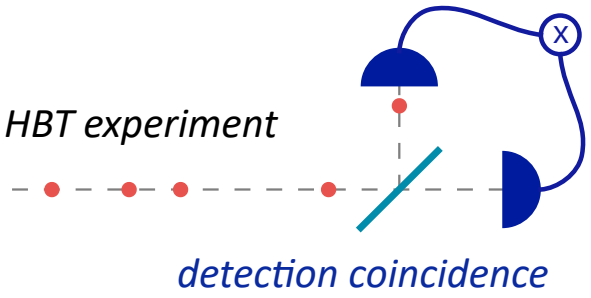
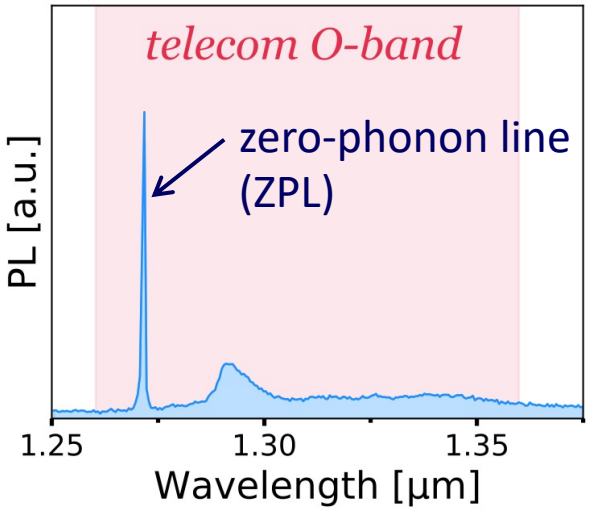
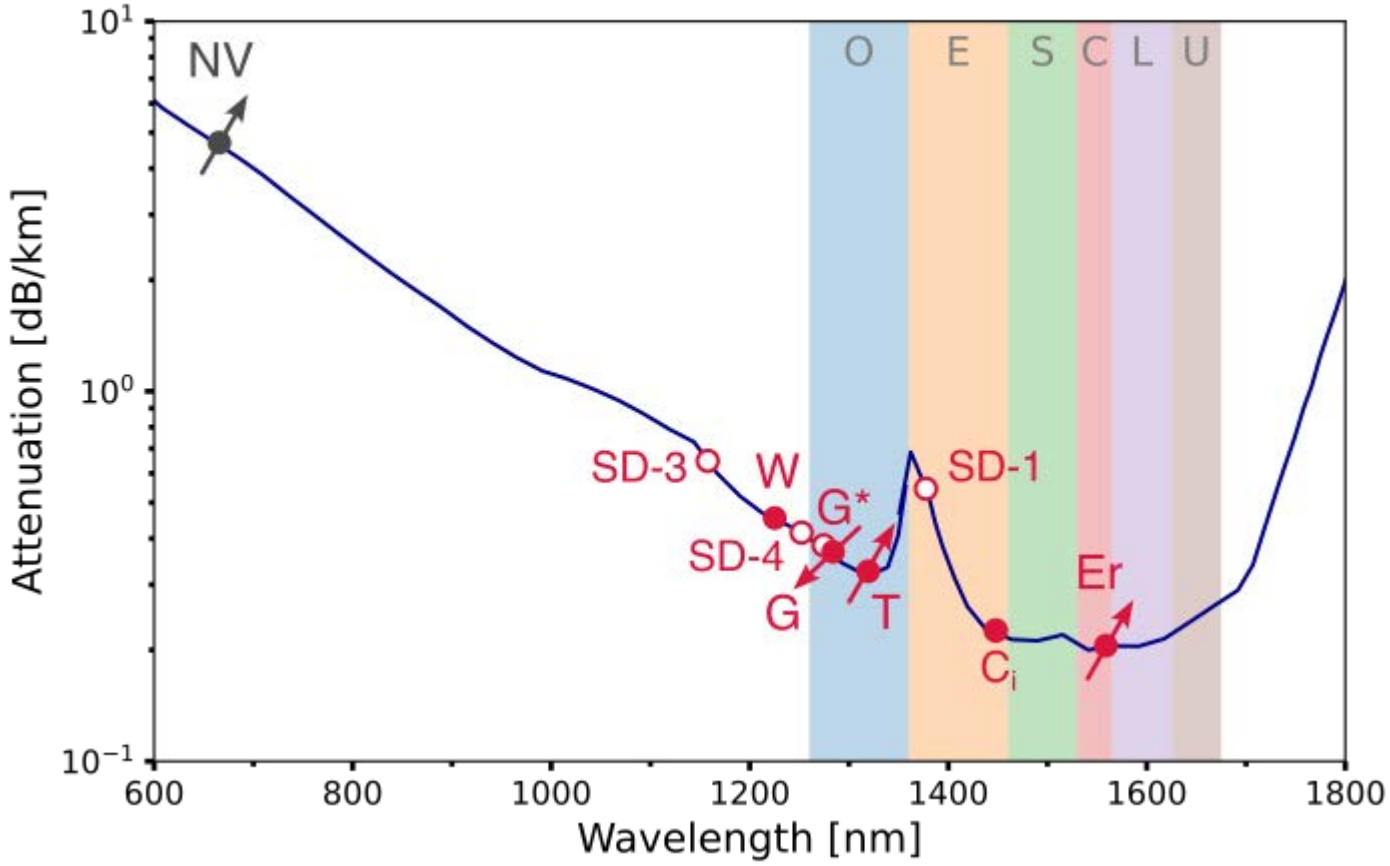


+ telecom emission



Redjem*, Durand* *et al.*, Nat. Electron. **3** (2020)

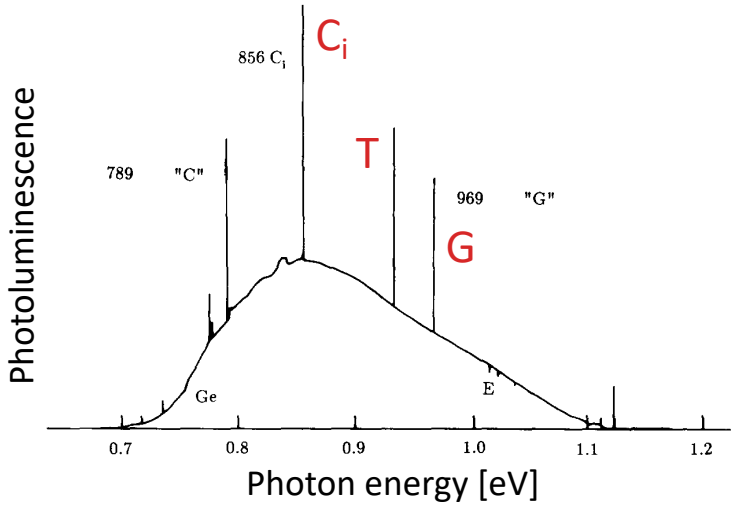
11 families of individual fluorescent defects in silicon



➢ unidentified defects: **G***: Redjem *et al.*, Nat. Electron. **3** (2020)
SD1,SD3-SD6: Durand *et al.*, *PRL* ***126*** (2021)

➢ well-known color centers from the literature

Davies, *Physics Reports* ***176*** (1989)



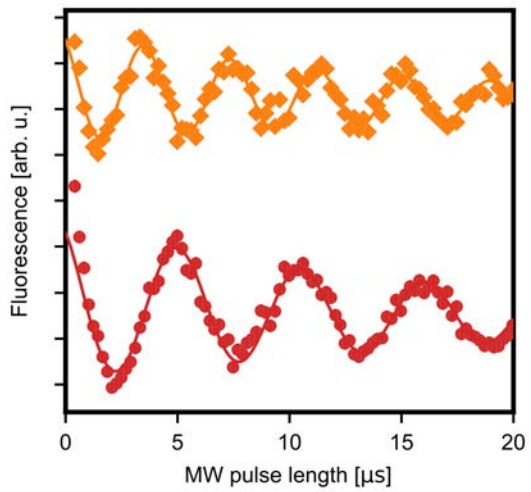
G: Baron *et al.*, *APL* **121** (2022);
Hollenbach *et al.*,*Nat. Comm.* **10** (2022)
W: Baron *et al.*, ACS Photonics **9** (2022)
T: Higginbottom et. *al., Nature* **607** (2022)
Er: Gritsch et. *al., Optica* **10** (2023)
C_i: Durand *et al.*, *PRL* ***126*** (2021)
Jhuria *et al., Nat. Comm.* **15** (2024)

Spin control of single color centers in silicon

single Er dopants

➢ coherent control of the electron spin

Rabi oscillations



Gritsch *et al., Nat. Comm.* **16** (2025)

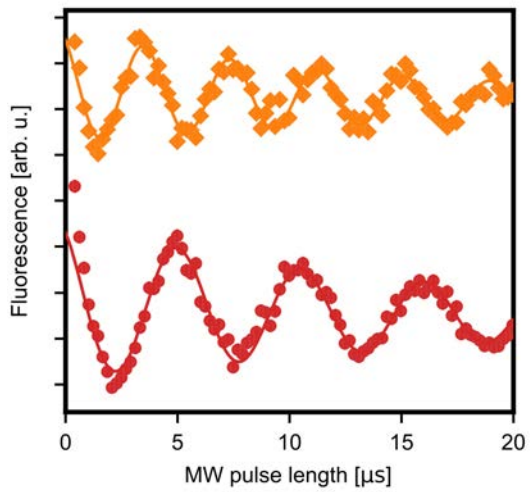
T_2 ~50 µs
+ single shot readout

Spin control of single color centers in silicon

single Er dopants

- coherent control of the electron spin

Rabi oscillations

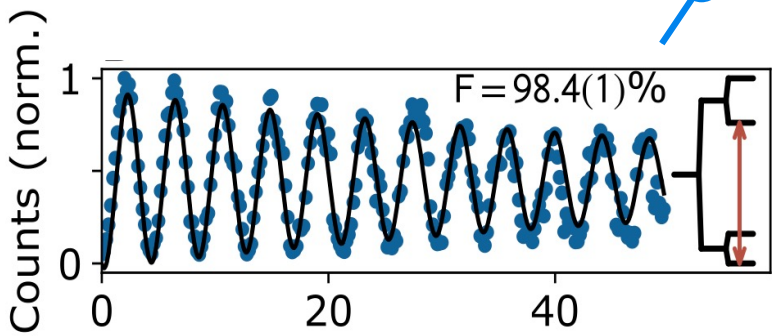


Gritsch *et al., Nat. Comm.* **16** (2025)

T_2 ~50 µs
+ single shot readout

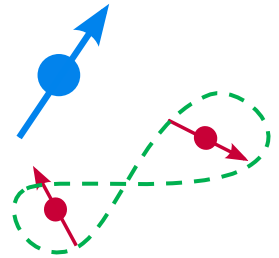
single T centers

- coherent control of electron  and nuclear spins 



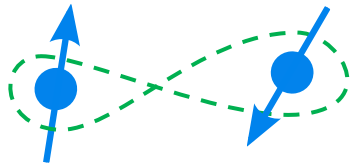
Afzal *et al.*, *arXiv:2406.01704* (2024)

- $T_{2,e}$ ~ 2 ms
  $T_{2,n}$ ~ 220 ms
- entanglement between 2 nuclear spins



Song *et al., Nature Nano.* ***21,*** 53 (2026)

- entanglement between 2 separated electron spins

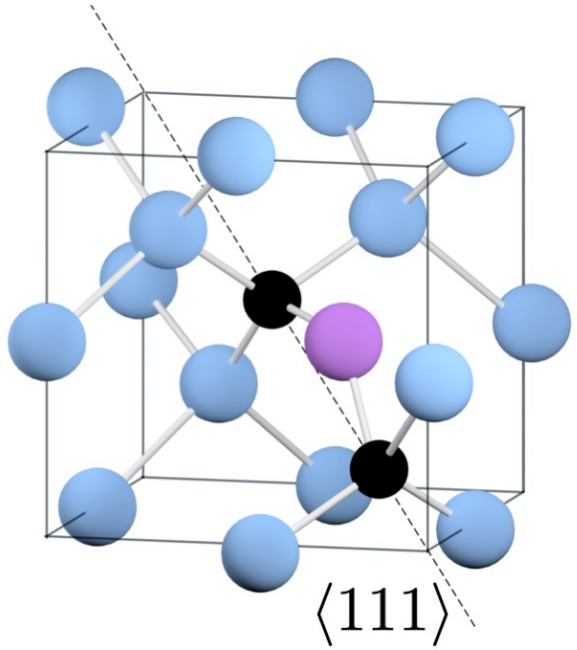


Afzal *et al., arXiv:2406.01704* (2024)

The G center in silicon

The G-center in silicon

- carbon-related complex



$C_{(s)} - Si_{(i)} - C_{(s)}$

Donnell et al., Physica B+C **116** (1983)
Udvarhelyi et al., *Phys. Rev. Lett.* ***127*** *(2021)*

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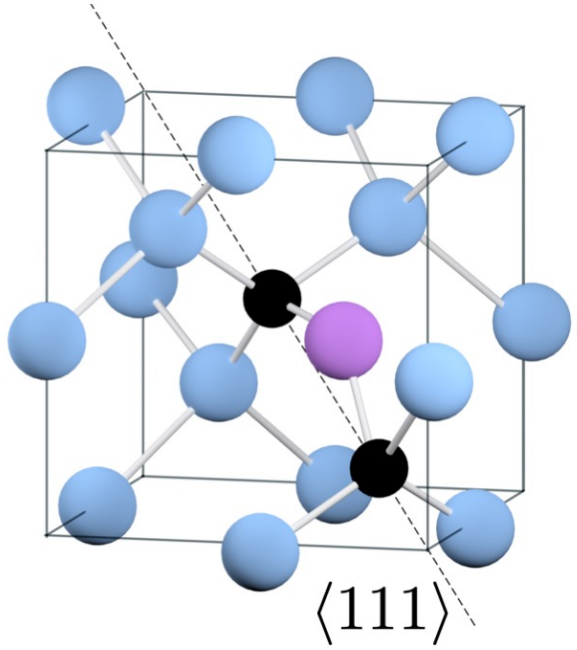

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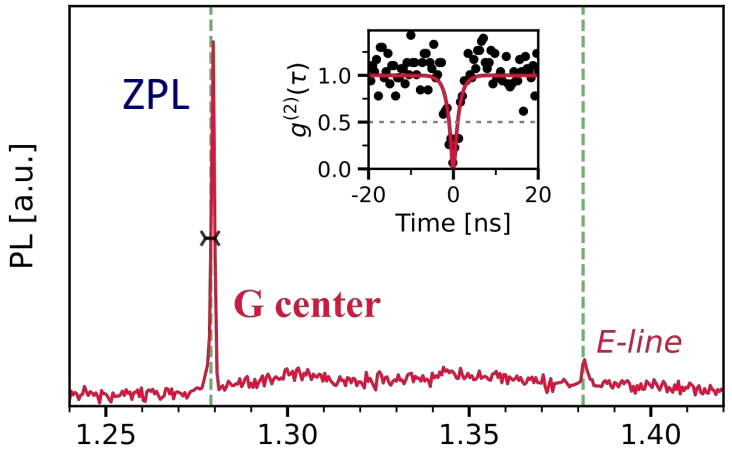
Donnell et al., Physica B+C **116** (1983)
Udvarhelyi et al., *Phys. Rev. Lett.* ***127*** *(2021)*

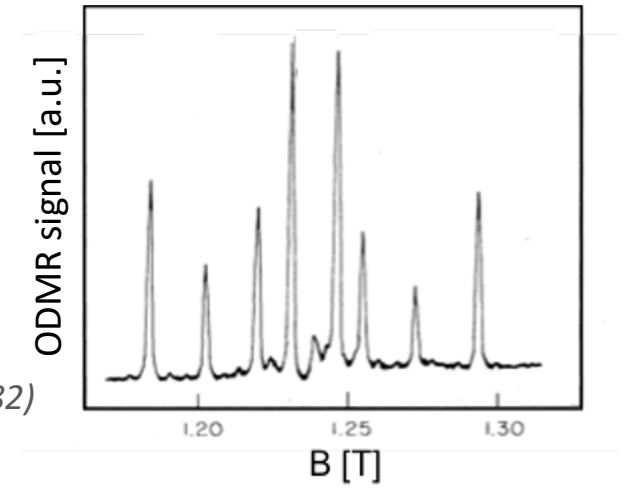
telecom emission
ZPL @ 1.28 µm

+

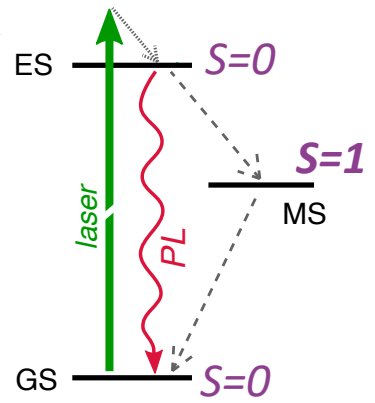
metastable spin triplet
optically detectable



Baron *et al.*, *APL* **121** (2022)

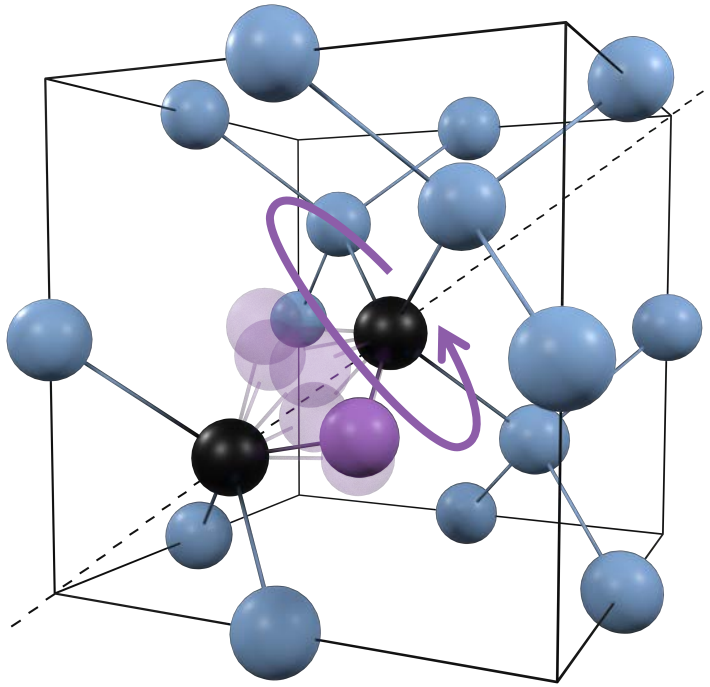


Lee et. al., PRL (1982)



A reorienting defect!

- motion of the Si_i atom between 6 sites



Donnell et al., Physica B+C **116** (1983)
Udvarhelyi et al., *Phys. Rev. Lett.* ***127*** *(2021)*

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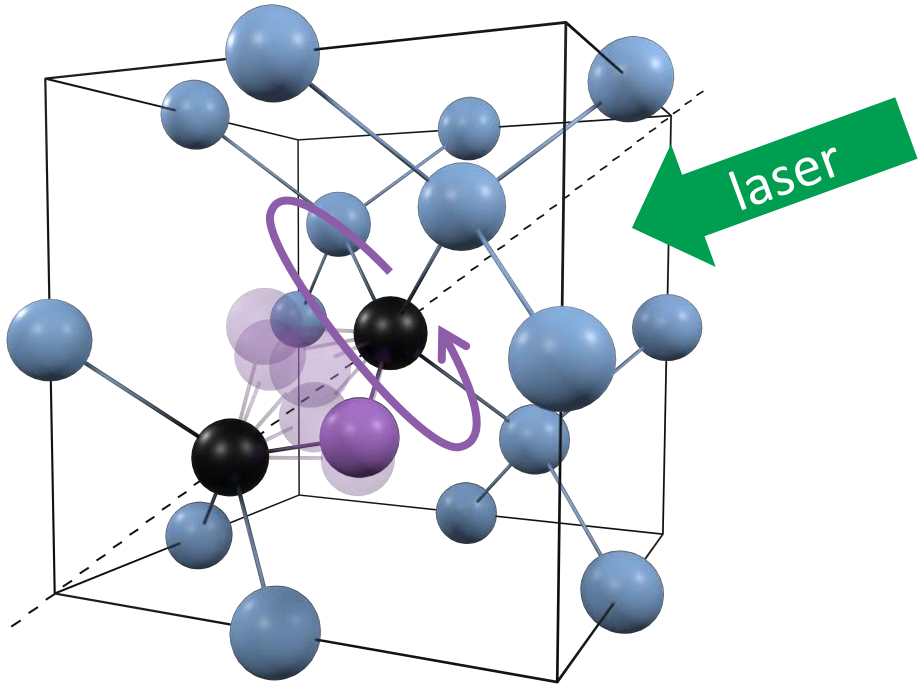
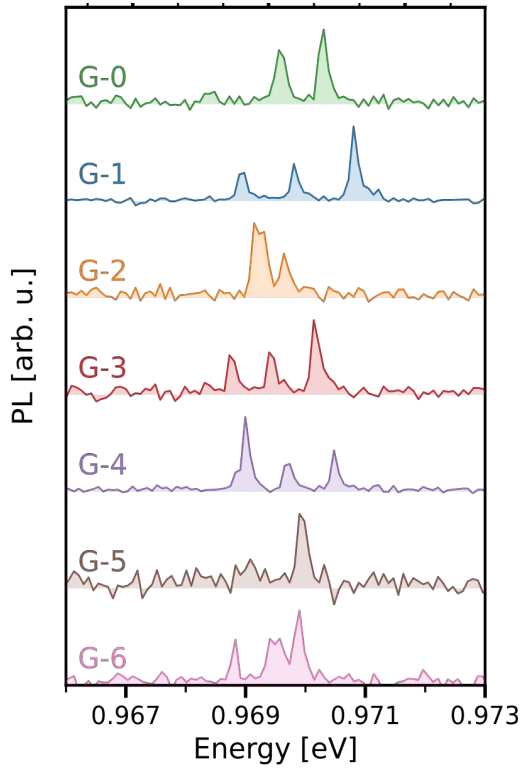
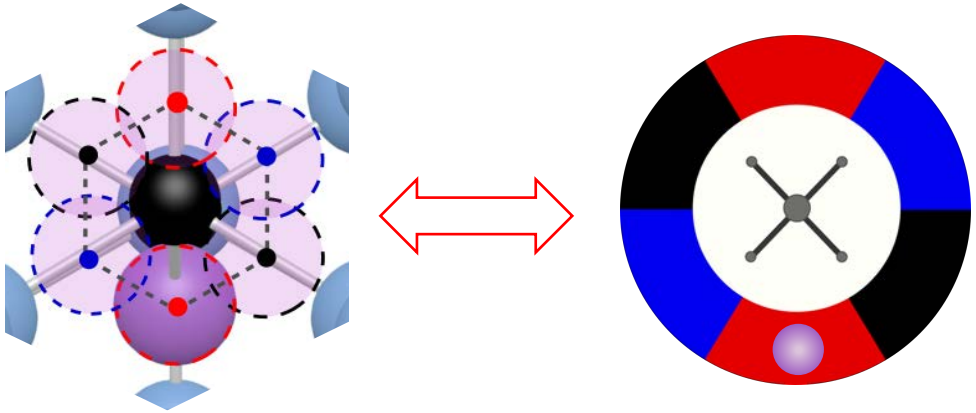


Donnell et al., Physica B+C **116** (1983)
Udvarhelyi et al., *Phys. Rev. Lett.* ***127*** *(2021)*

- optical signature of the Si_i motion on single G centers in SOI samples

Durand *et al., PRX* **14** (2024)



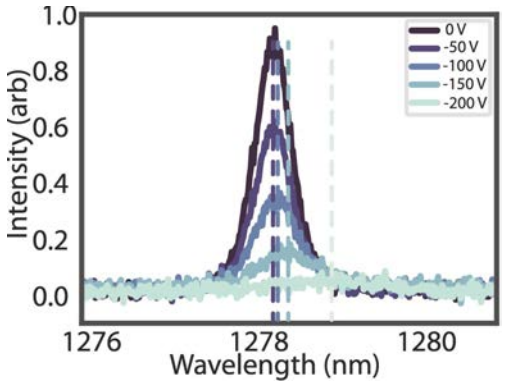


under above bandgap excitation, the Si_i behaves like a ball in a 6-slot roulette wheel

Controlling the G center emission with integration

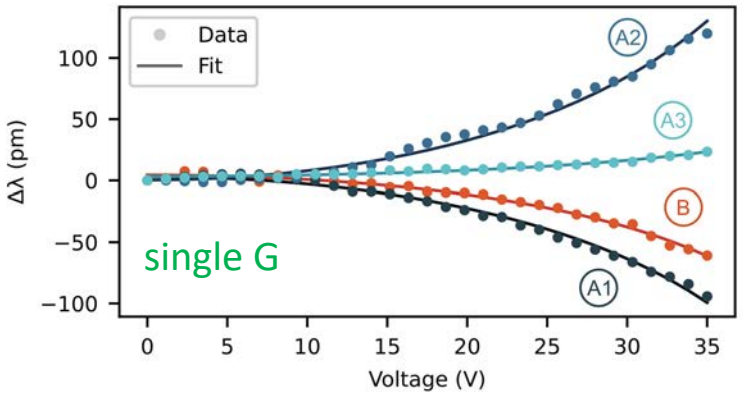
- Stark tuning in p-i-n junction

G ensemble



Day et al.,
Nat. Comm. **15** (2024)

- strain tuning in a MEMS cantilever



Buzzi et al.,
Nat. Comm. **16** (2025)

Controlling the G center emission with integration

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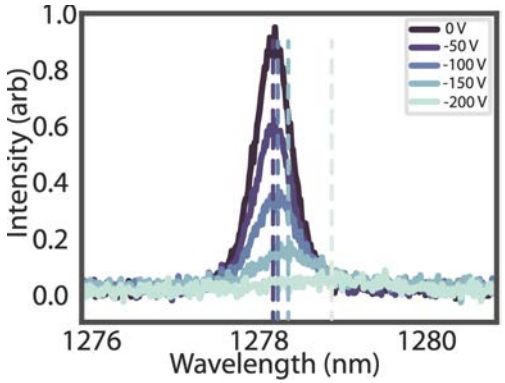

Day et al.,
Nat. Comm. **15** (2024)

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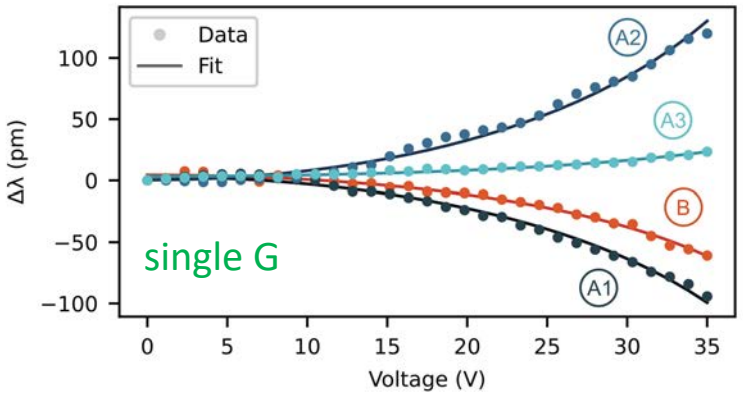
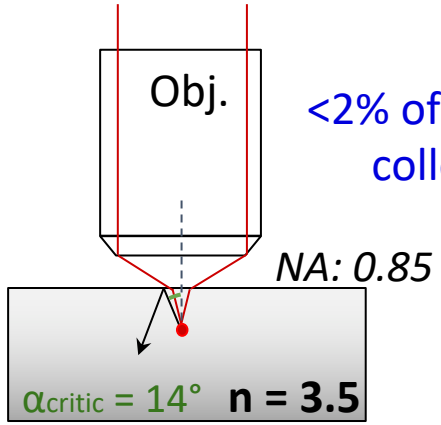


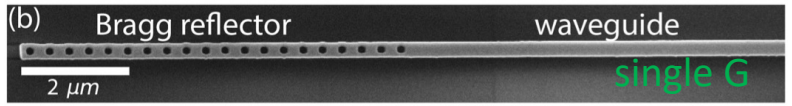
Buzzi et al.,
Nat. Comm. **16** (2025)

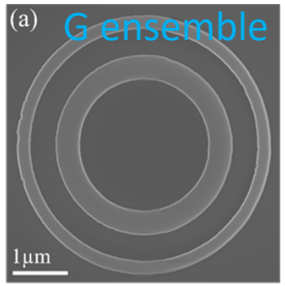


<2% of photons collected

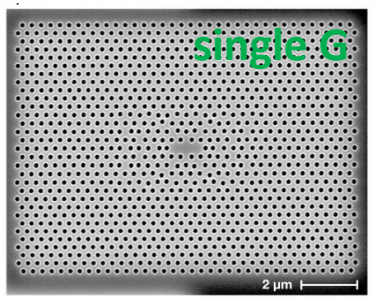
- G center integration in photonic cavities

Komza et al., Nat. Comm. **15** (2024)

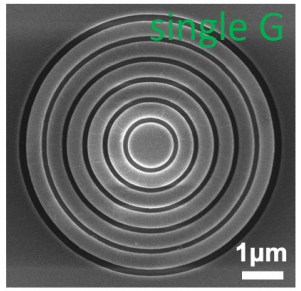




Lefaucher et al, APL **122** (2023)



Saggio et al, Nat. Comm. **15** (2024)



Ma et al., ACS Photonics **12**(2025)

Single G center integration in cavities

sample simul. & fabrication @Leti & Pheliqs

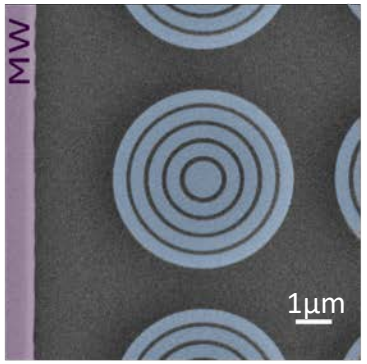
Jean-Michel Gérard

Yoann Baron

Baptiste Lefaucher

Jean-Baptiste Jager

- circular Bragg grating cavity



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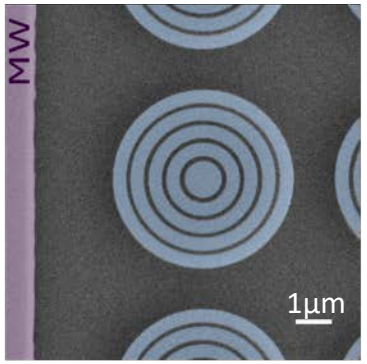
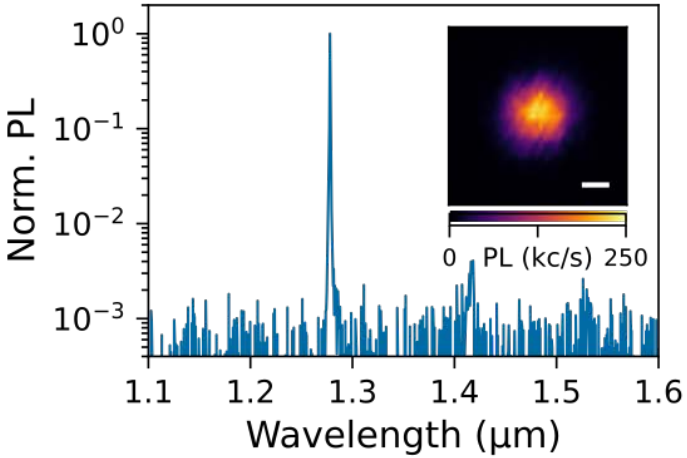
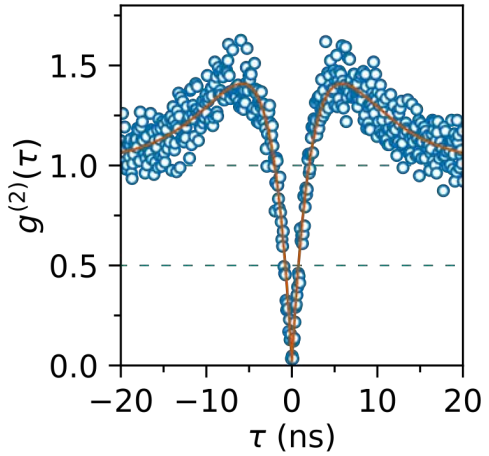




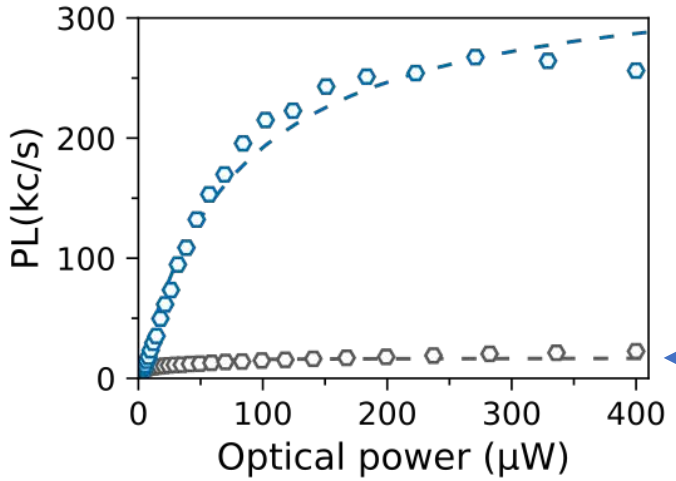
% of photons collected in the ZPL: **94%**

➢ high-purity single photon emission



raw data

$g^{(2)}(0) = 0.02 \pm 0.01$



>260kcounts/s

x100 in ZPL counts

← in unparterned SOI

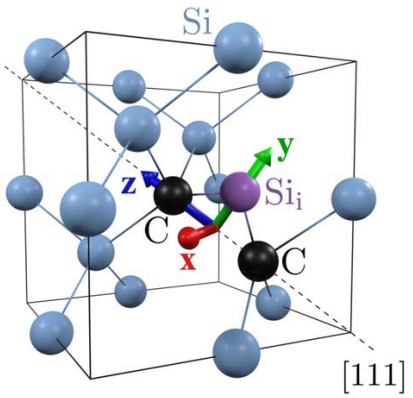
Durand *et al.*, *PRB* **110** (2024)

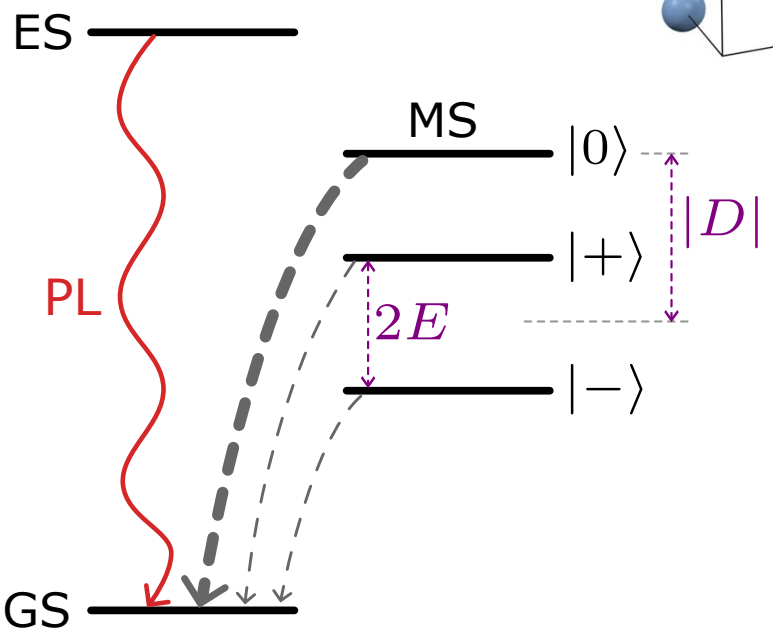
Electron spin control of single G centers

Optical detection of magnetic resonance on single G centers

- (MS) electron spin triplet:
  zero-field splitting interaction

$$\hat{\mathcal{H}}_0 = D\hat{S}_z^2 + E(\hat{S}_x^2 - \hat{S}_y^2)$$





Udvarhelyi al., PRL **127** (2021)

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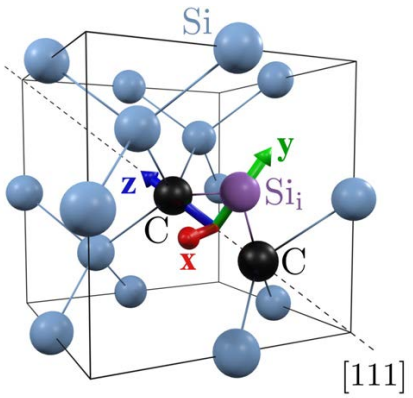
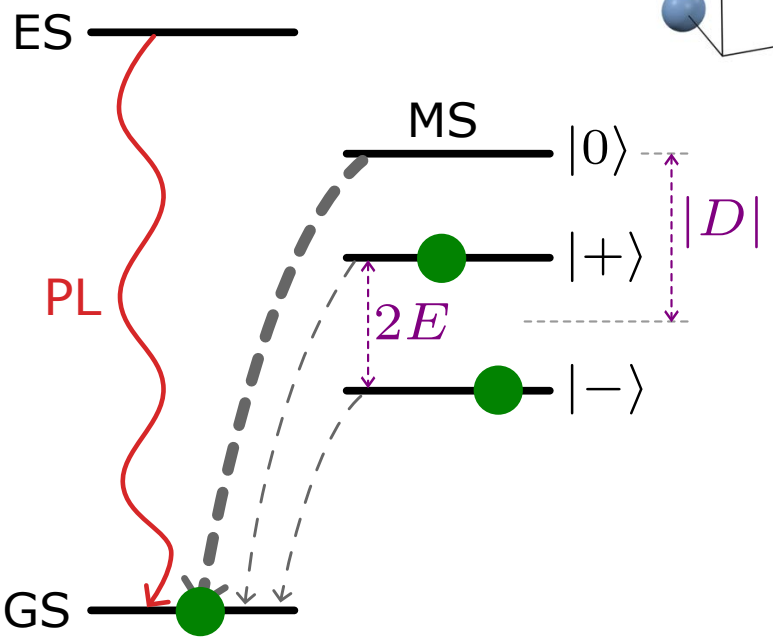
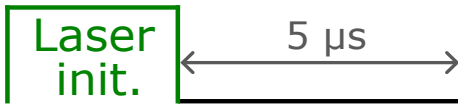




1 spin initialization



Udvarhelyi al., PRL **127** (2021)

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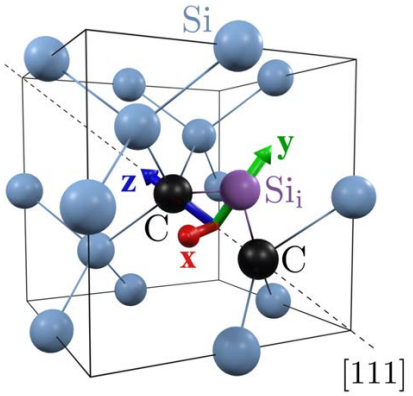

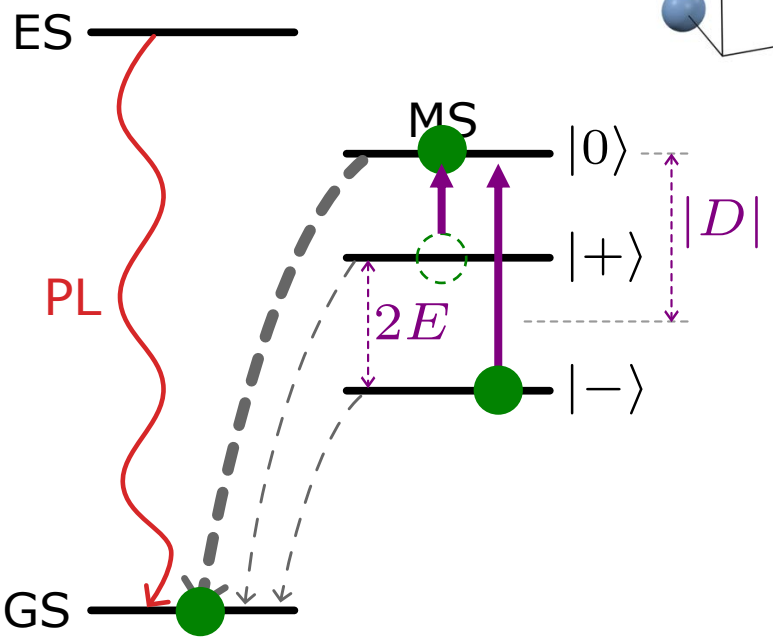

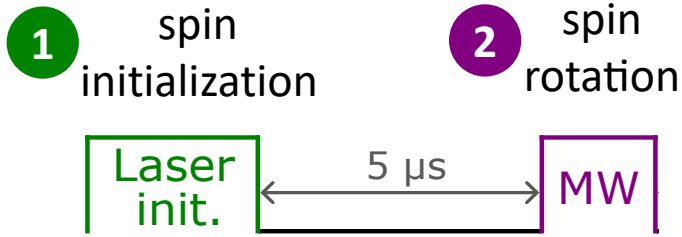

- 2 spin transitions $\Delta m_s = \pm 1$

Optical detection of magnetic resonance on single G centers

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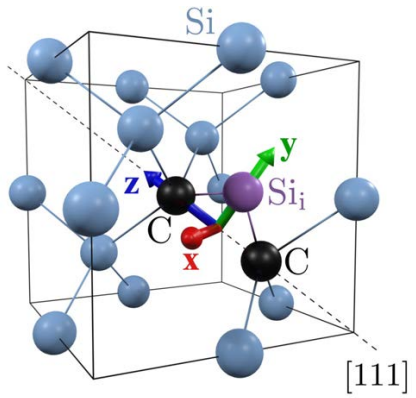

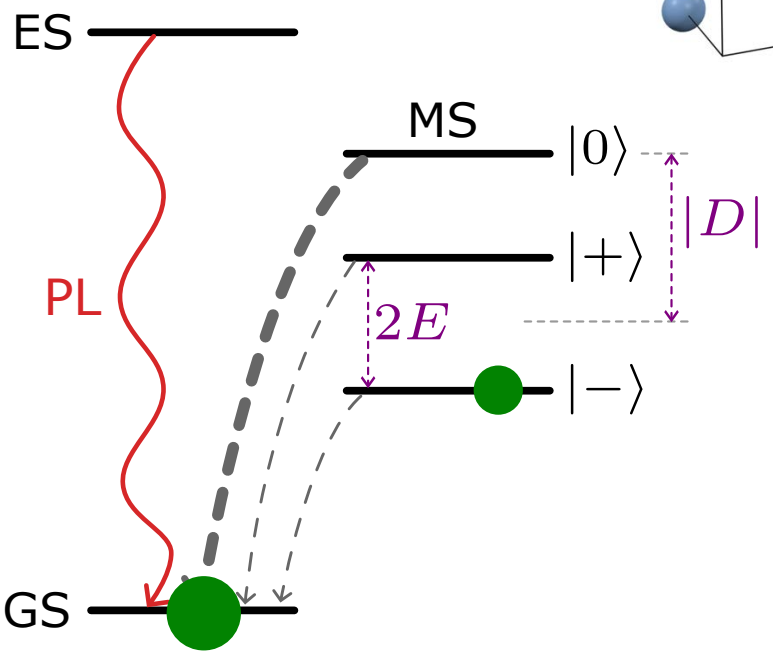

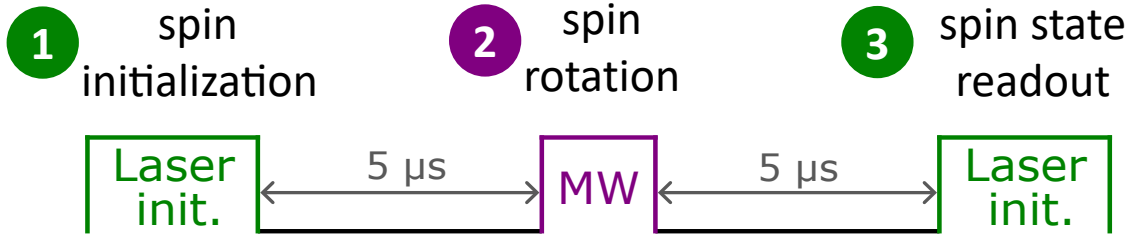

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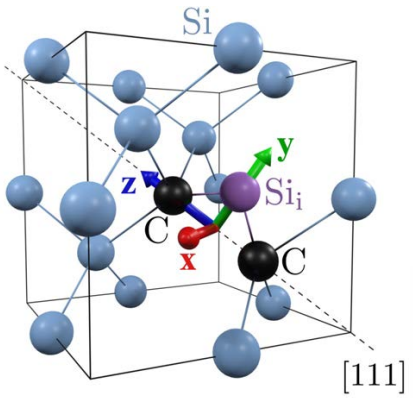

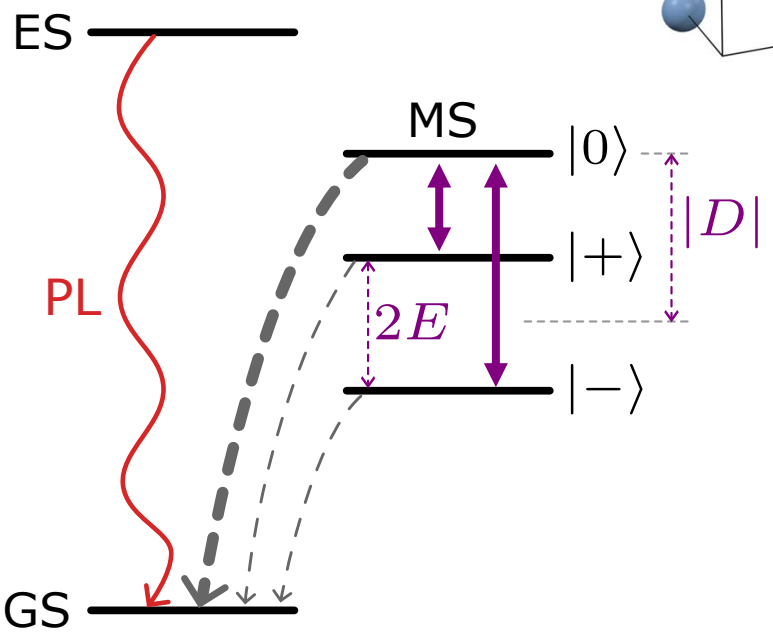

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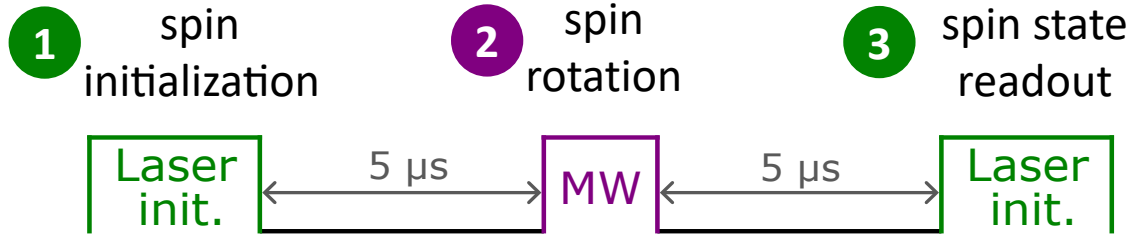
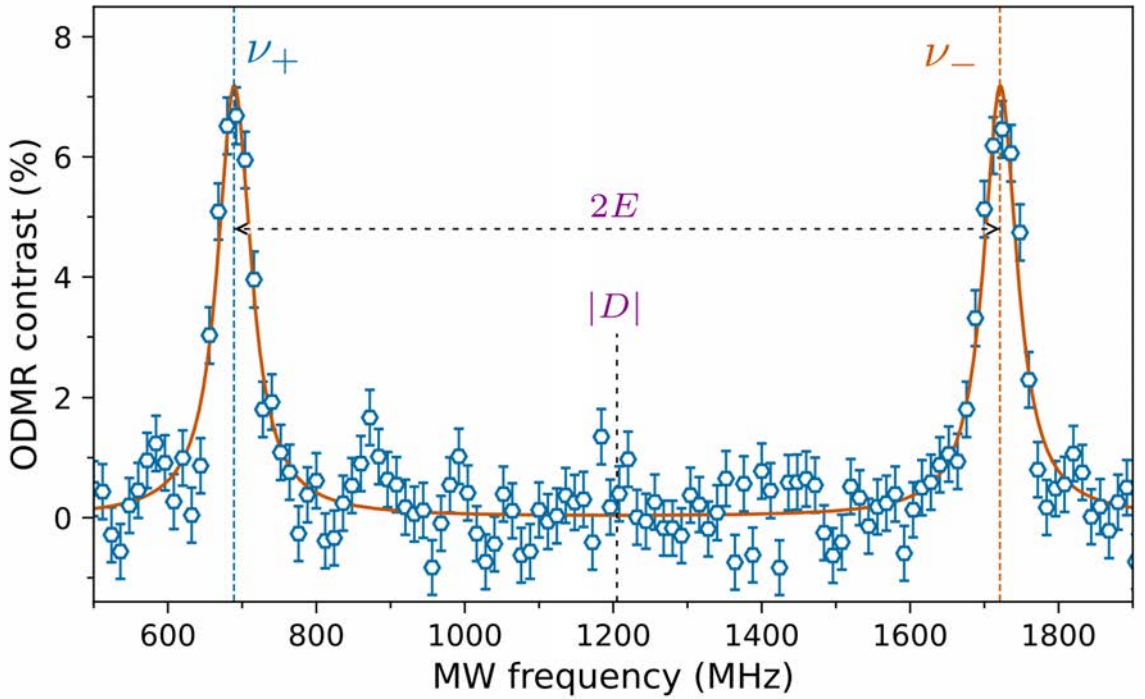


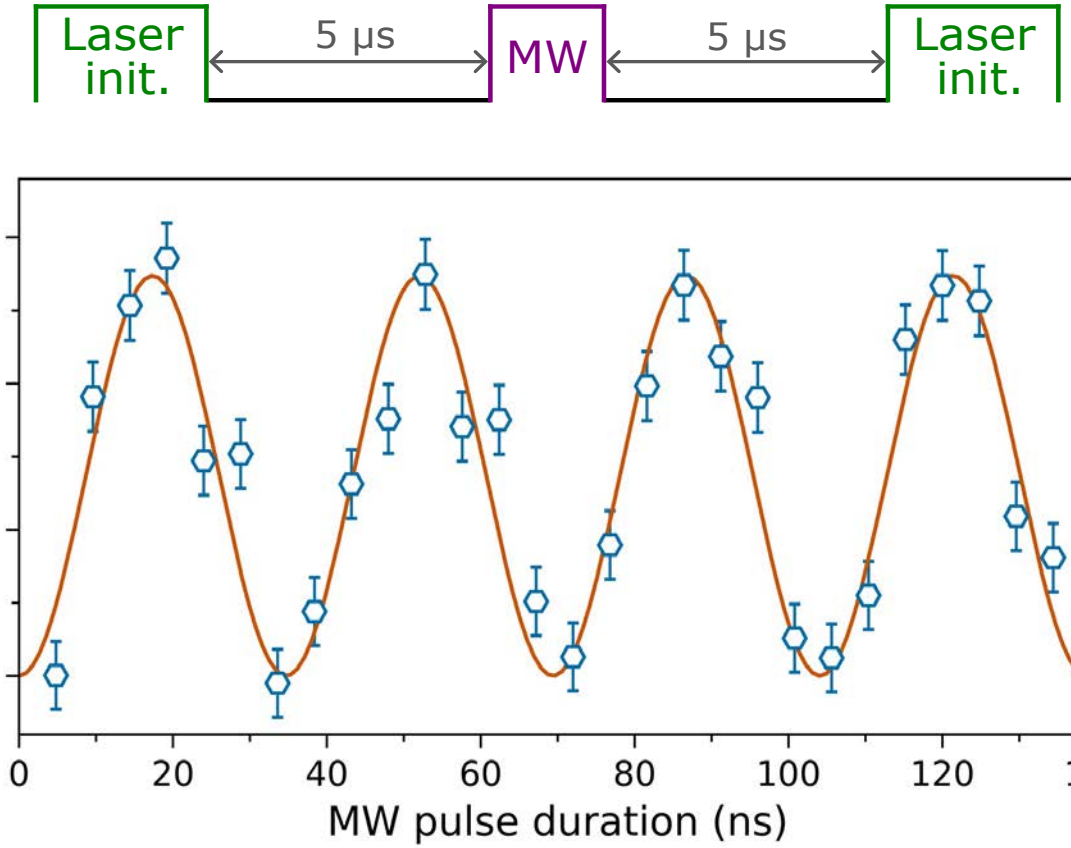


1st ODMR on a single G center

|D| = 1205 ± 1 GHz
E = 516 ± 1 GHz

Coherent manipulation of a single G center

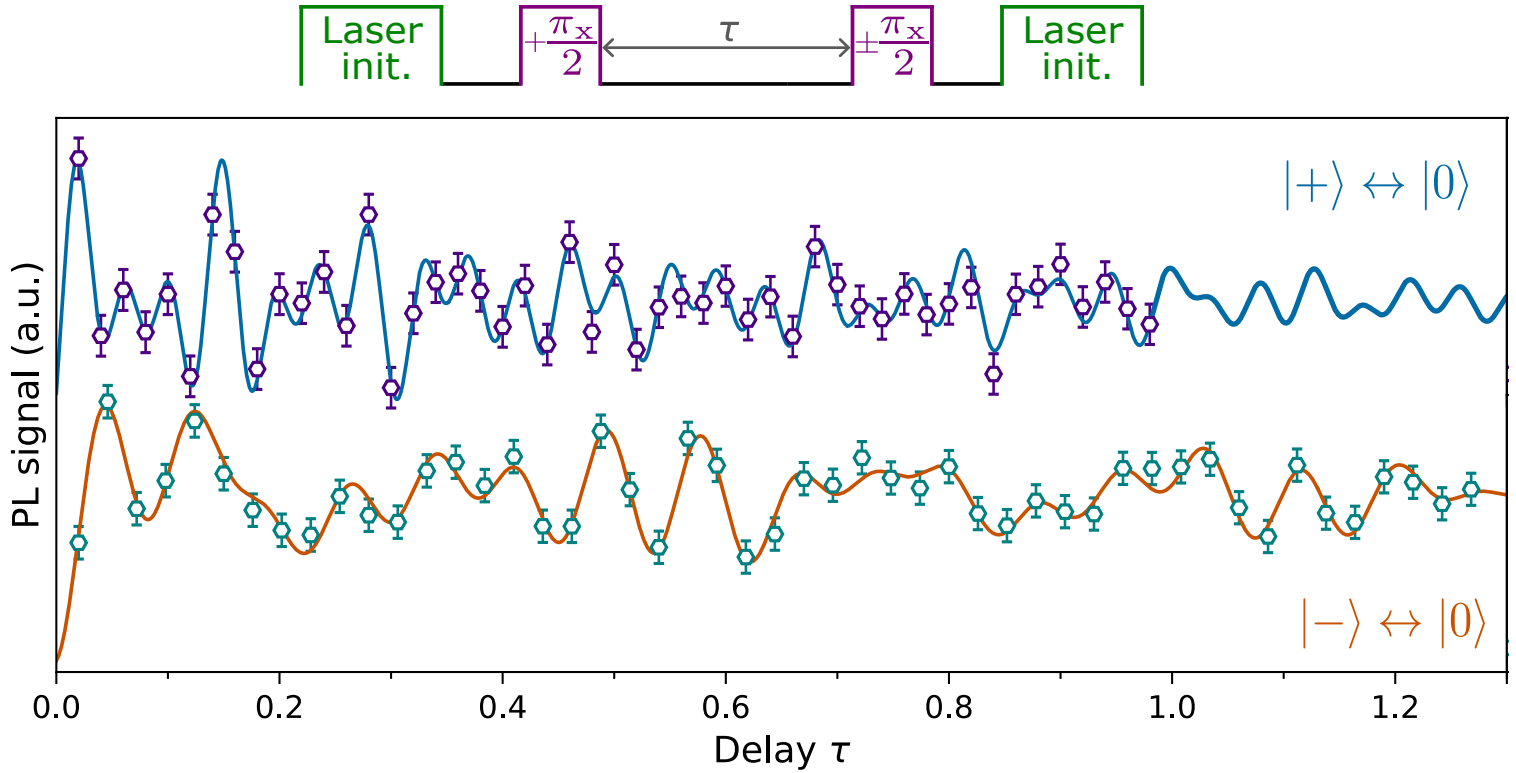
➢ Rabi oscillations on a single G in silicon



first coherent control of the G center electron spin

Ramsey spectroscopy on a single G center

- Ramsey fringes or free-induction decay



coherence times:

$$T^*_{2_{\nu_+}} = 0.8 \pm 0.1\,\mu\text{s}$$

$$T^*_{2_{\nu_-}} = 1.1 \pm 0.2\,\mu\text{s}$$

Ramsey spectroscopy on a single G center

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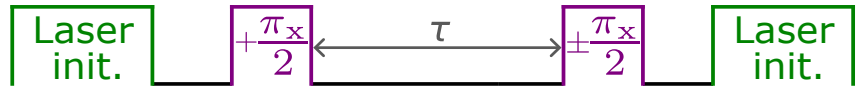
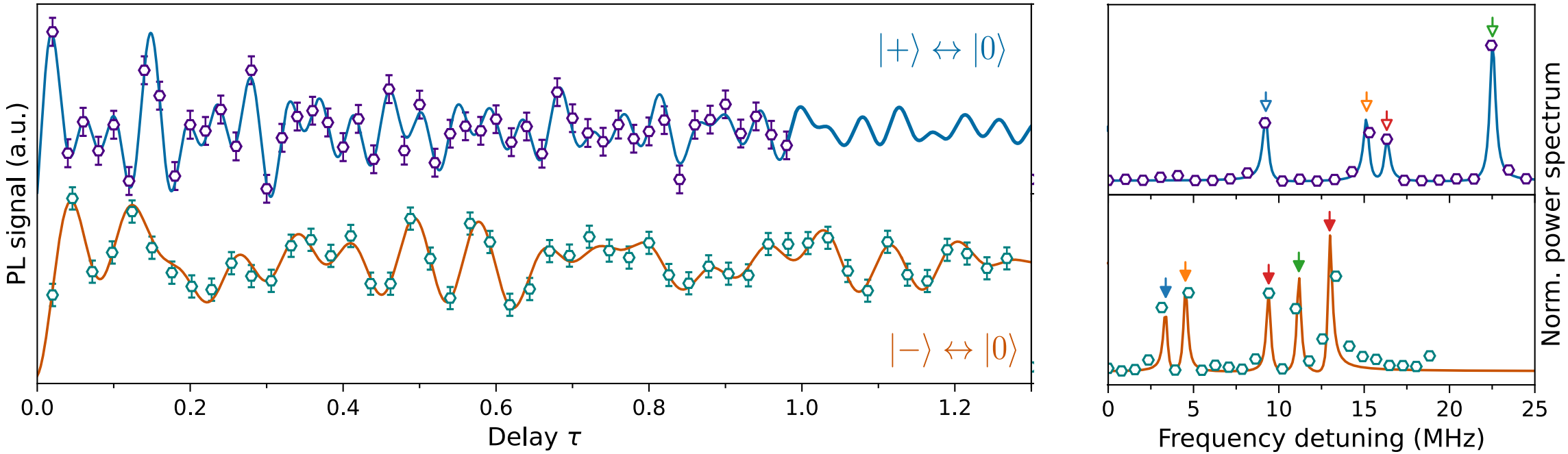


multiple spin transitions!



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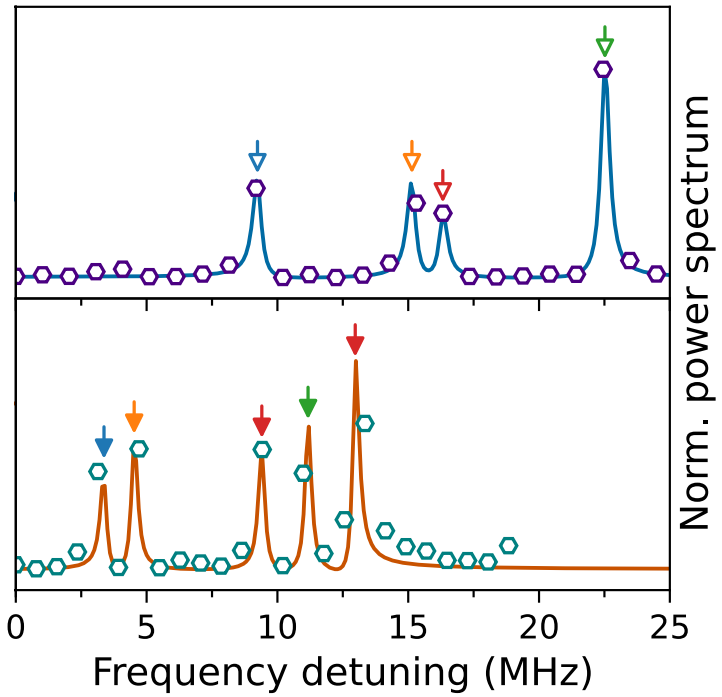
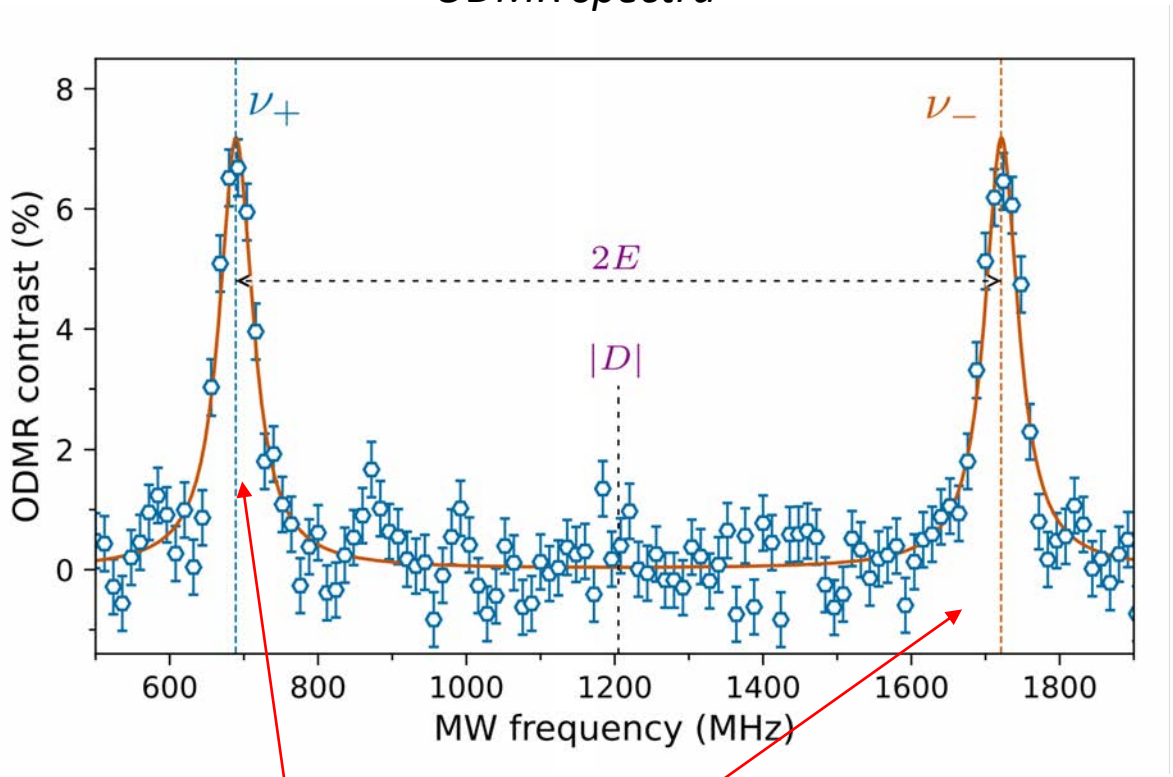
$$T^*_{2_{\nu_-}} = 1.1 \pm 0.2\,\mu\text{s}$$

Fine spin structure

Ramsey spectroscopy



ODMR spectra

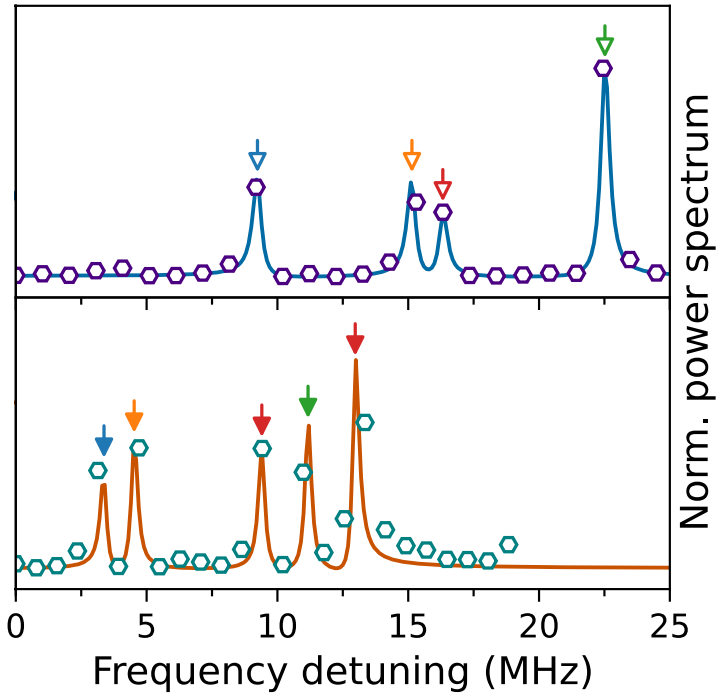


! MW power broadening !

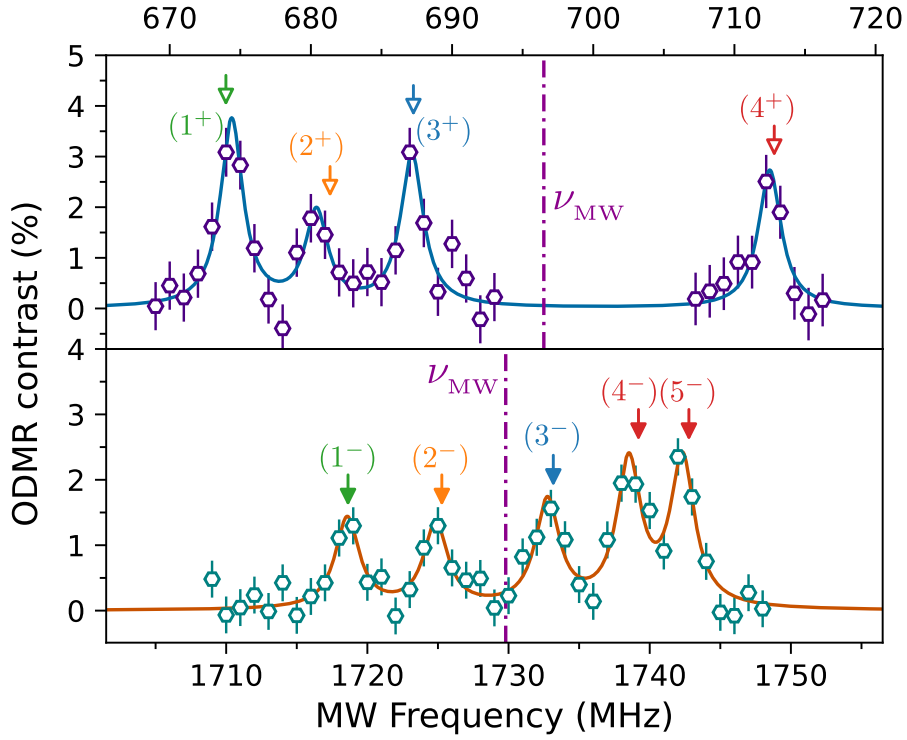
Dréau et al., PRB 84 (2011)

Fine spin structure

Ramsey spectroscopy

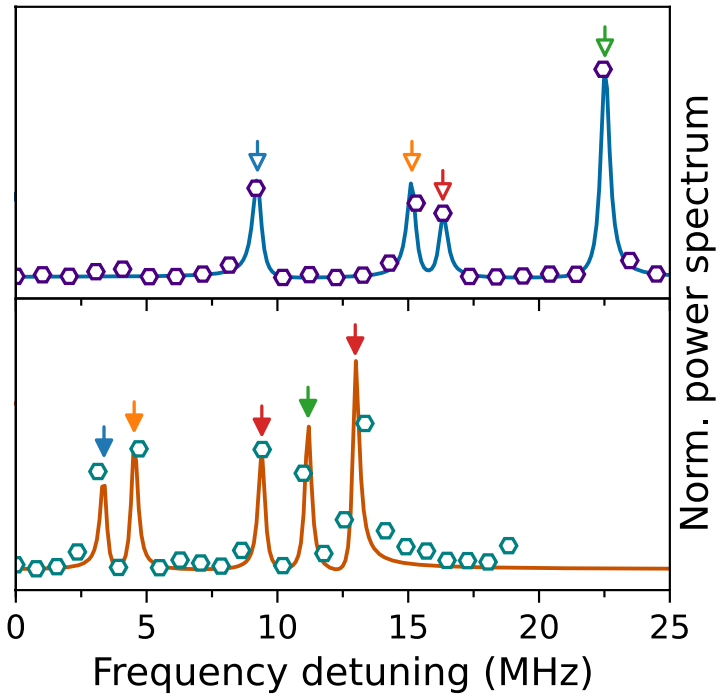


High-resolution ODMR spectra



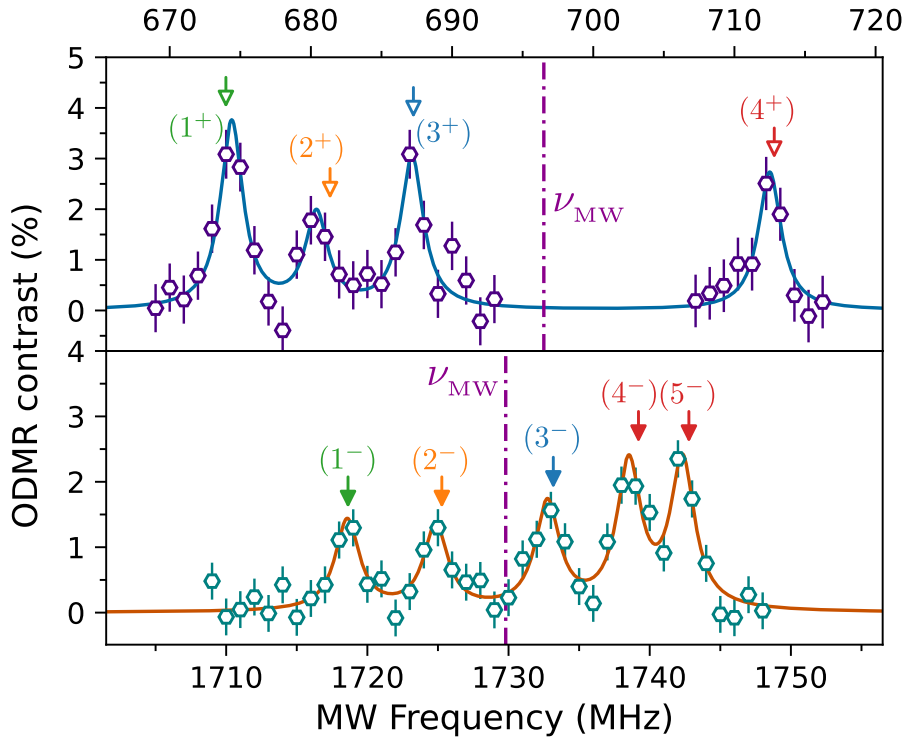
Fine spin structure

Ramsey spectroscopy

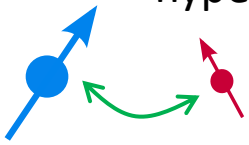


Fine structure origine?

High-resolution ODMR spectra



hyperfine coupling to nuclear spins?



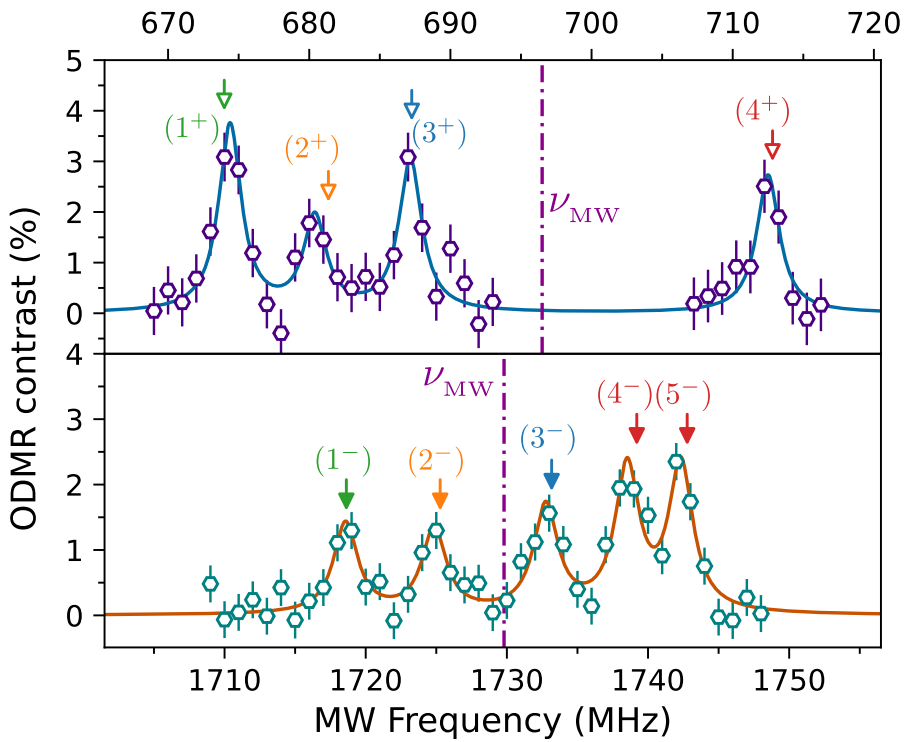
^{29}Si or ^{13}C (both I = 1/2)

(-> no hyperfine splitting at B = 0)

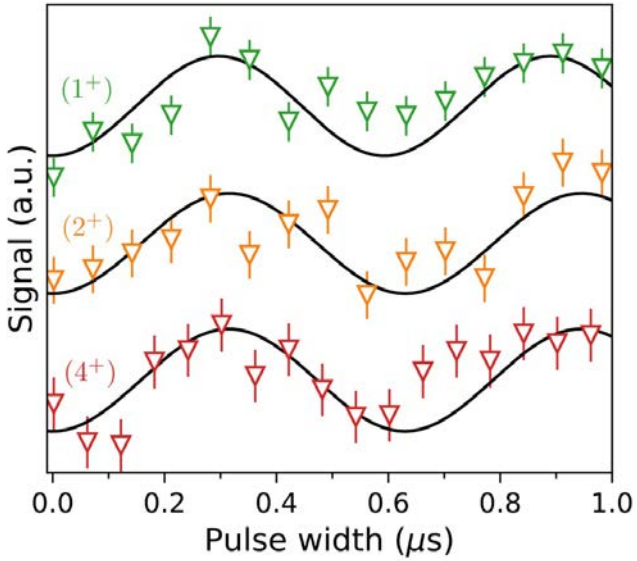
Lee *et al.*, Nat. Nano **8** (2013)

Transition-selective Rabi oscillations

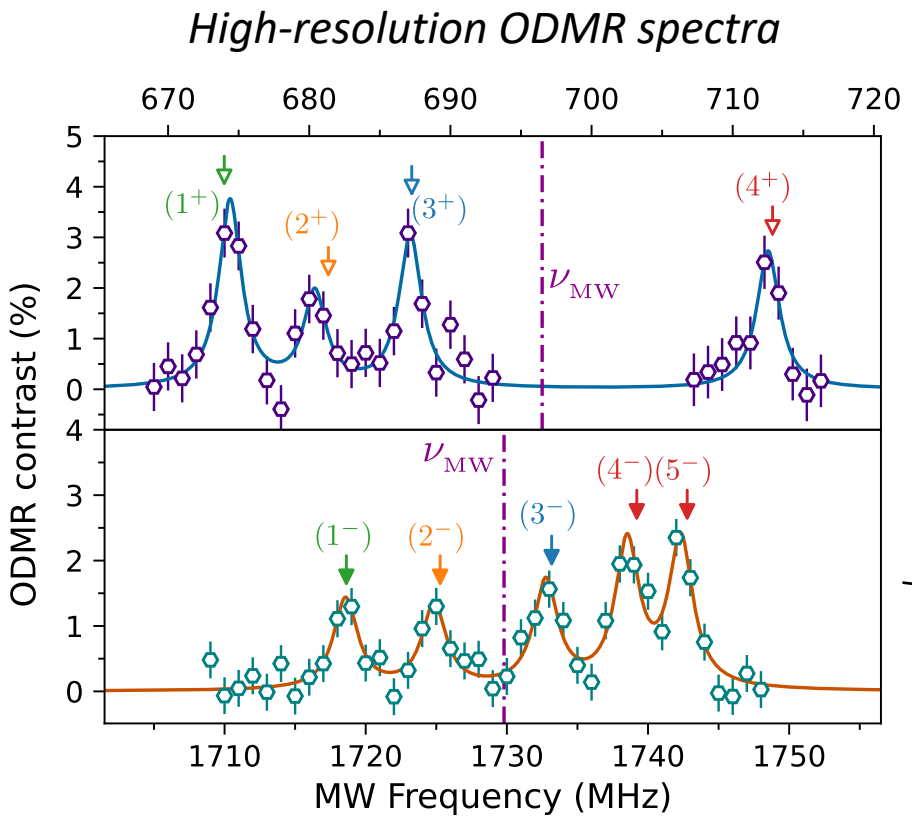
High-resolution ODMR spectra



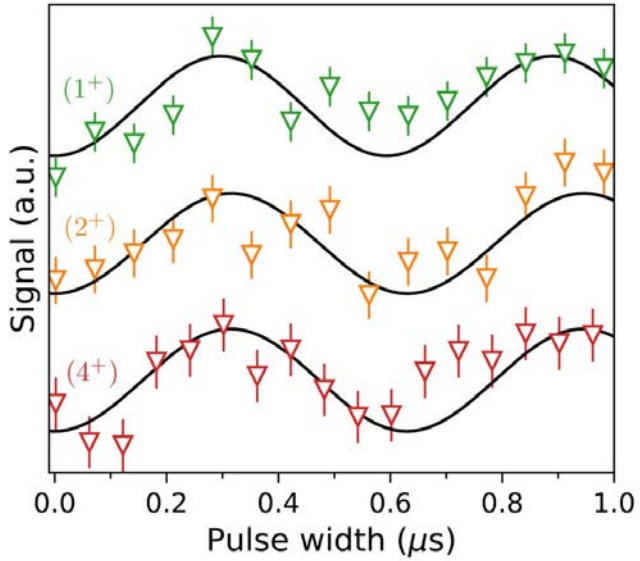
selective Rabi oscillations



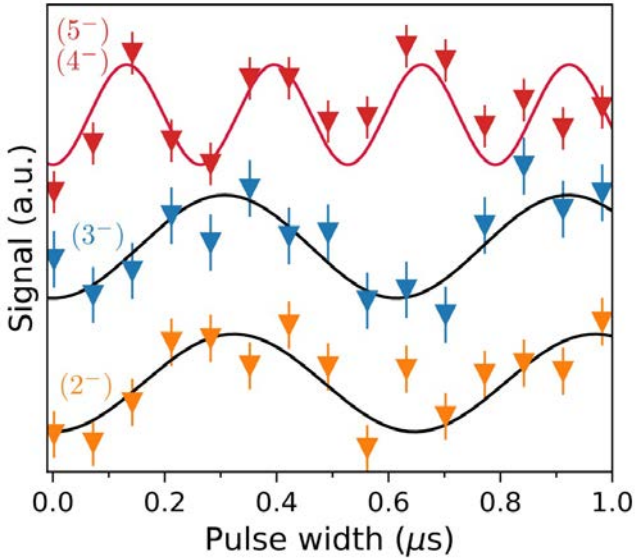
Transition-selective Rabi oscillations



selective Rabi oscillations

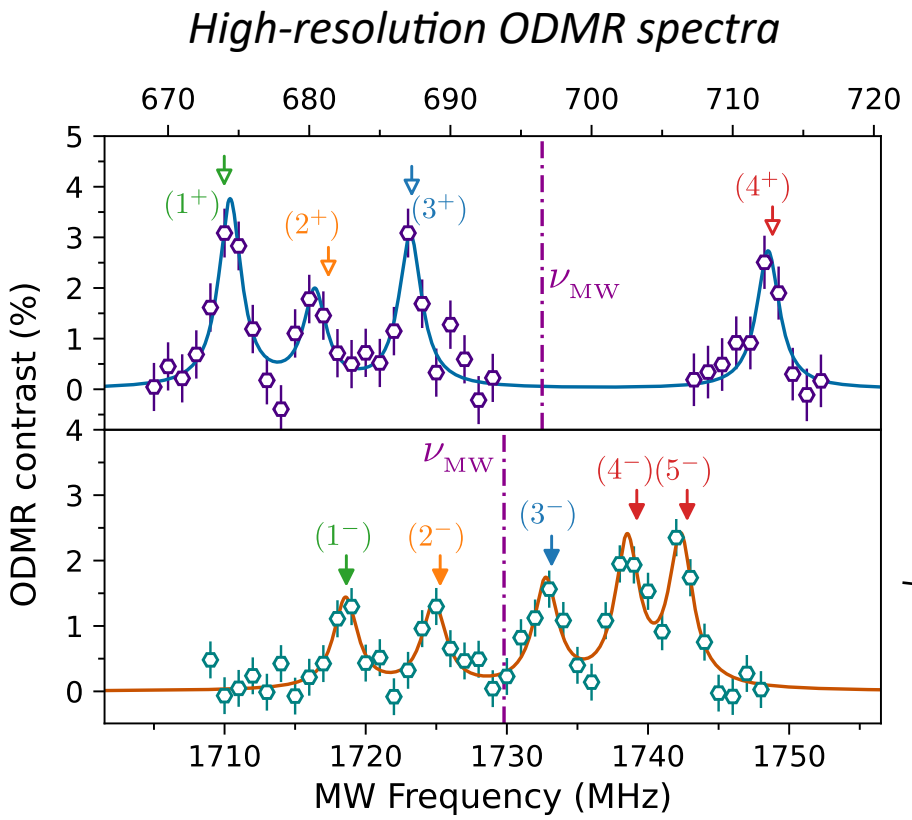


selective Rabi oscillations

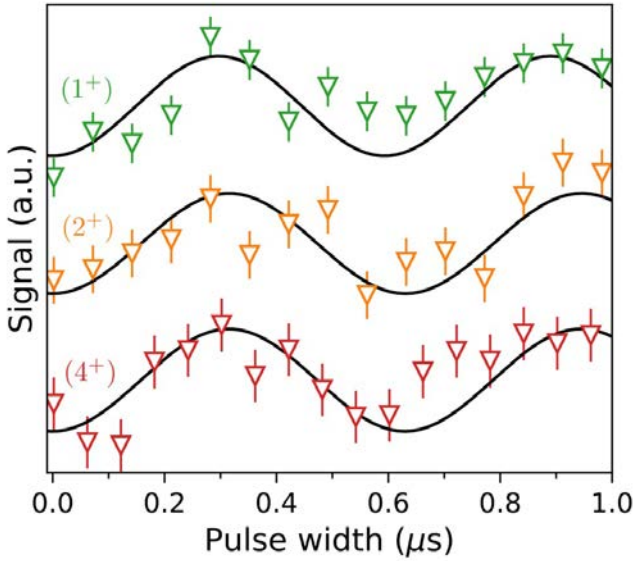


different Rabi frequencies!!

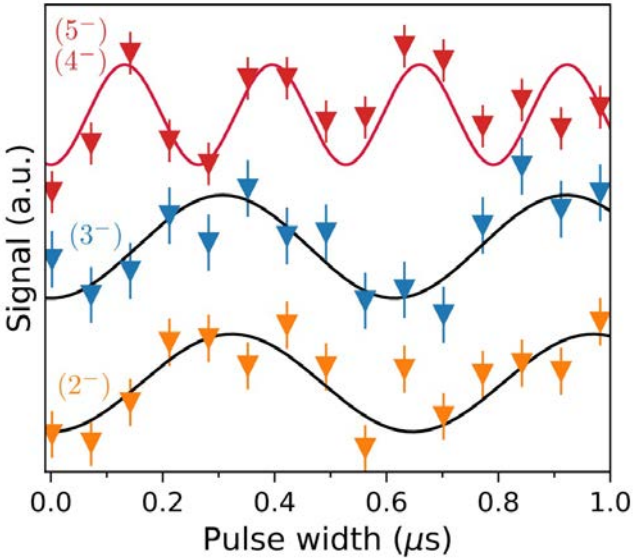
Transition-selective Rabi oscillations



selective Rabi oscillations

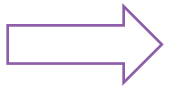


selective Rabi oscillations

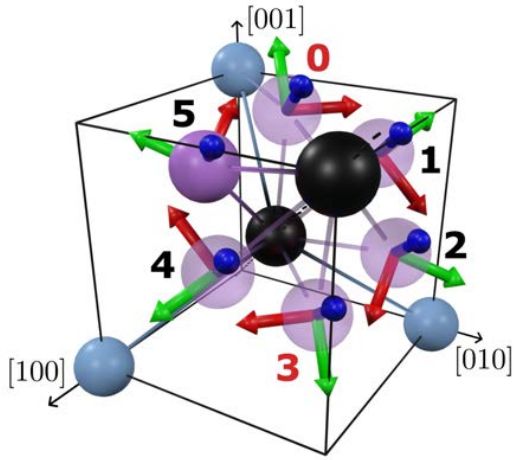


different Rabi frequencies!!

$$\Omega_{\pm} = |\langle 0| - \gamma_e \mathbf{B}_{\mathrm{MW}} \cdot \hat{\mathbf{S}} |\pm\rangle|$$



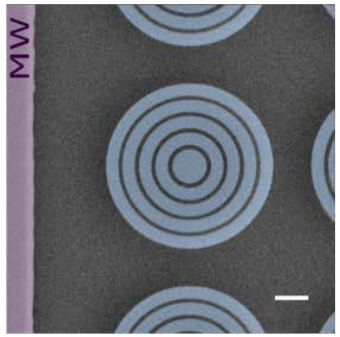
electron spin tumbling

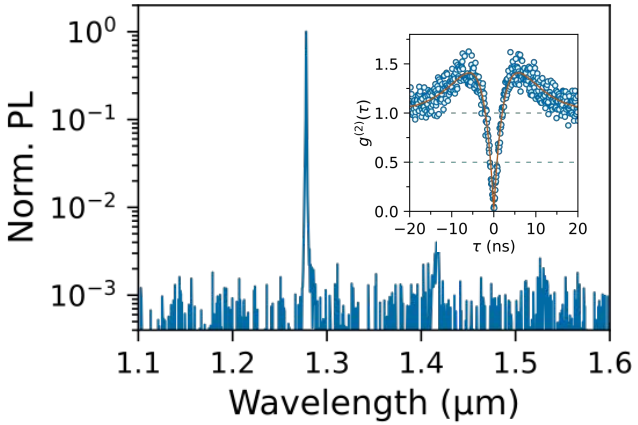


Conclusion & outlook

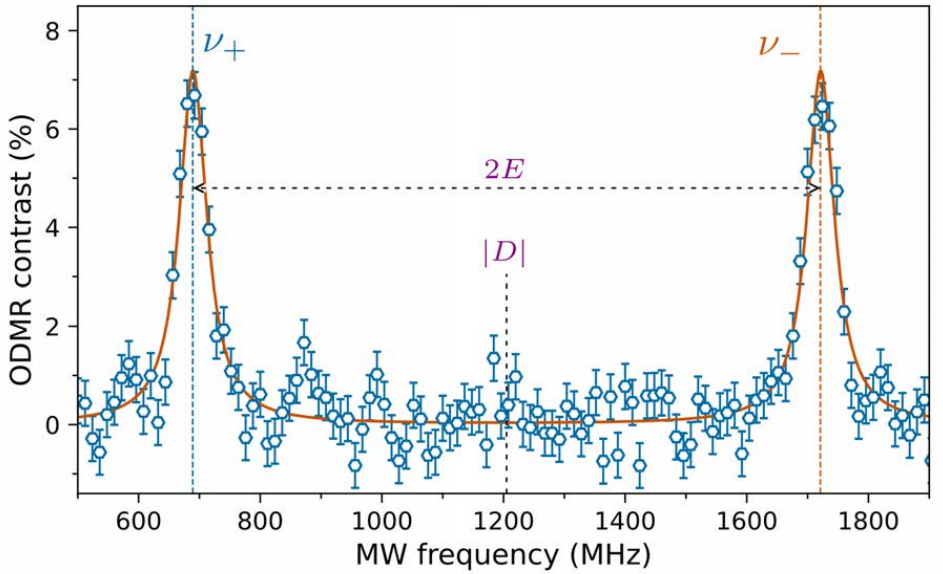
Conclusion for G center spin control

- high-purity single photon emission from a single G

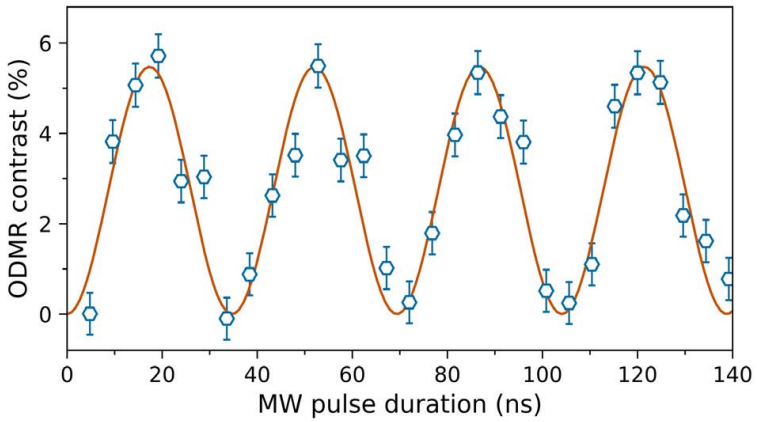


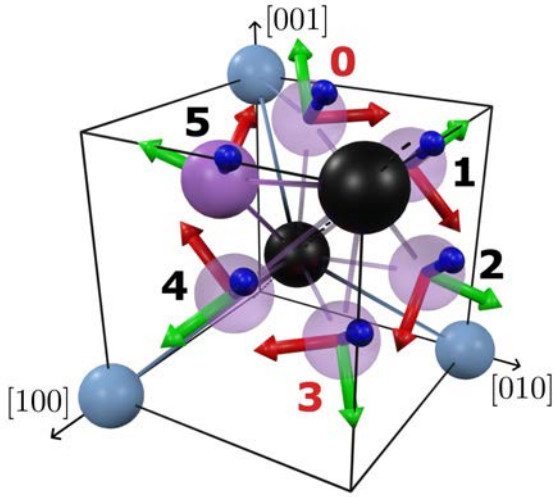


- ODMR of an individual G center



- G electron spin coherent control

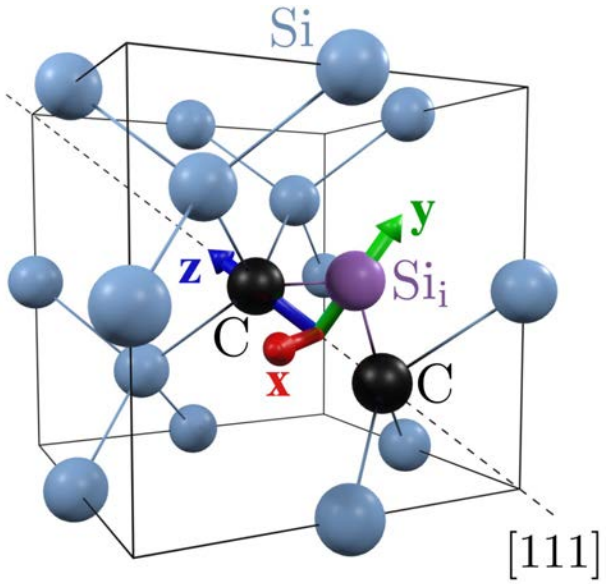


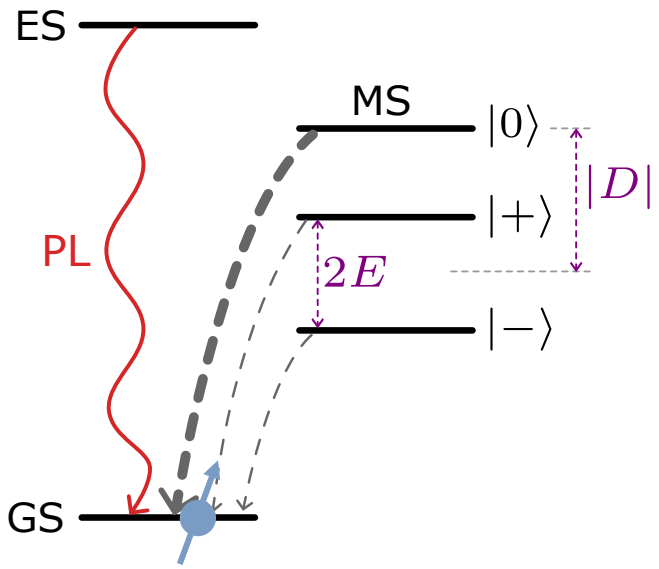


- **single spin tumbling**

Cache et al., arXiv:2510.15590 (2025)

Outloook for the G center in silicon



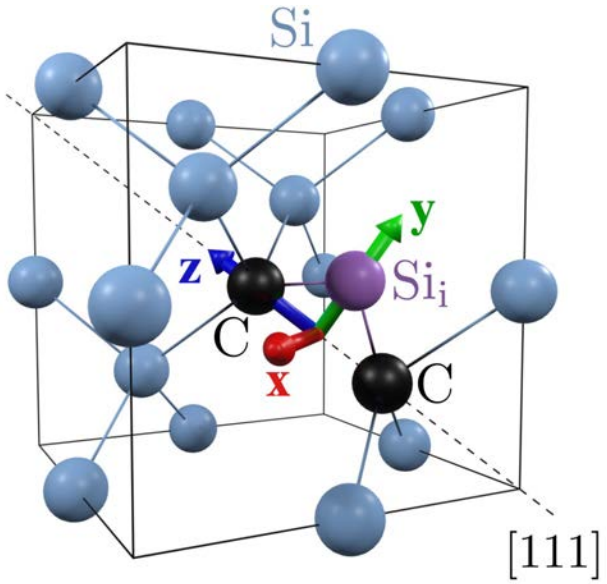


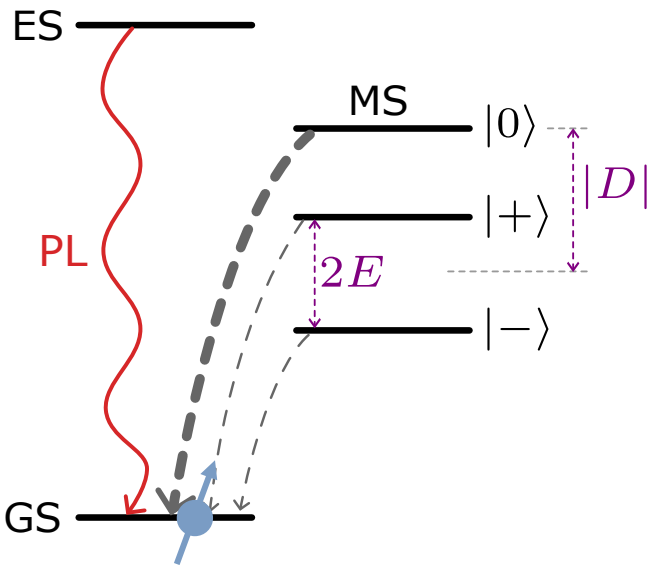
➢ **nuclear spin control?**

electron-spin free GS -> extra long nuclear spin T_2

4h for ionized donors in ^{28}Si: Saeedi et al., Science 342 (2013)

Outloook for the G center in silicon





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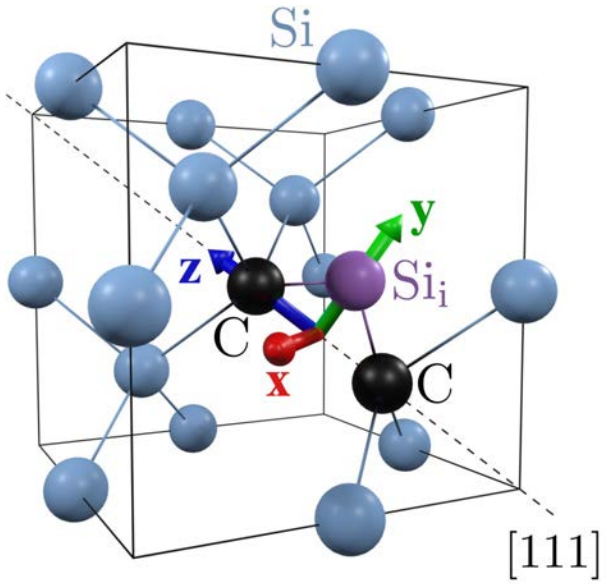
➢ **spin tumbling control?**

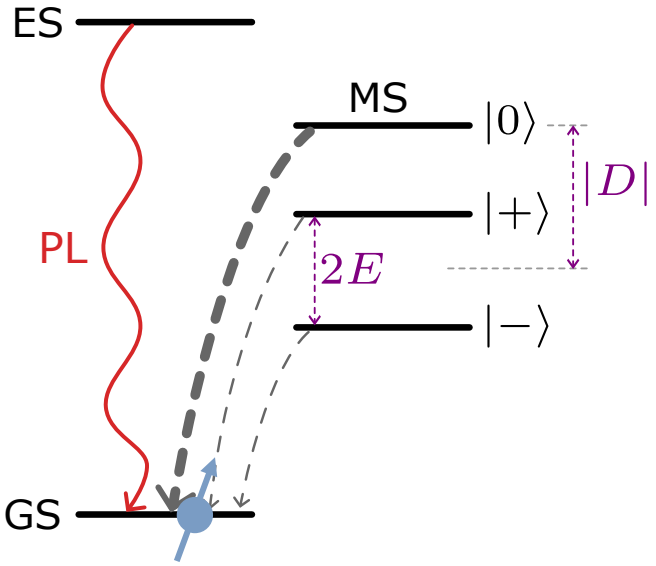
above bandgap excitation
« casino roulette » dynamics

resonant excitation
spin orientation locking?

Durand *et al., PRX* **14** (2024)

Outloook for the G center in silicon





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above bandgap excitation
« casino roulette » dynamics

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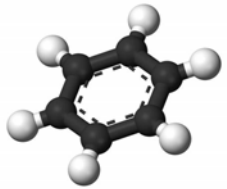
spin orientation locking?

Durand *et al., PRX* **14** (2024)

➢ spin to investigate the G rotation?



delocalized rotational states ? ⇨ strain engineering

Udvarhelyi et al., *Phys. Rev. Lett.* ***127*** *(2021)*

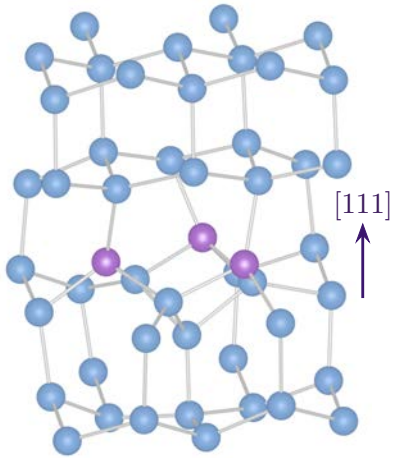
top- or rotor-like dynamics ⇨ temperature

Donnell et al., Physica B+C **116** (1983)

Enhancing the emission of single W centers

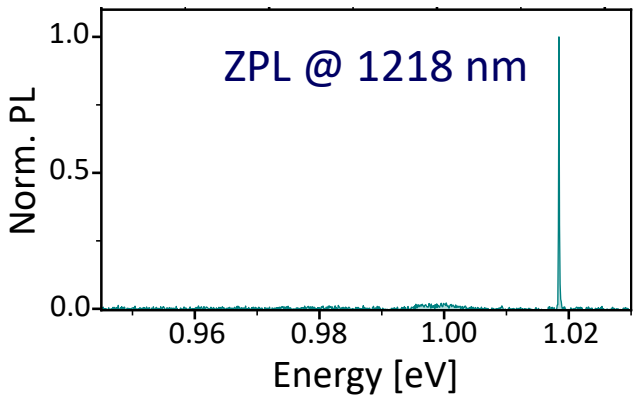
- the W center in silicon

tri-interstitial defect



Baron*, Durand* *et al.*, ACS Photonics 9 (2022)

single W centers



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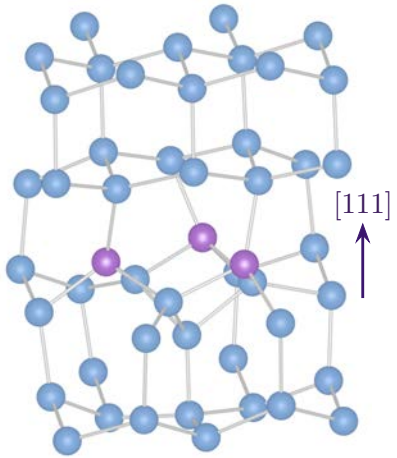

Baron*, Durand* *et al.*, ACS Photonics 9 (2022)

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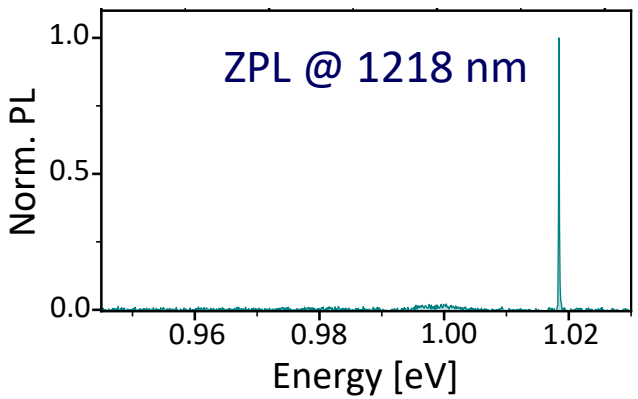
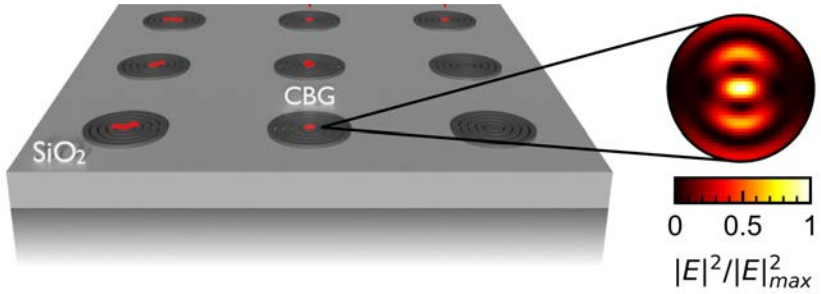
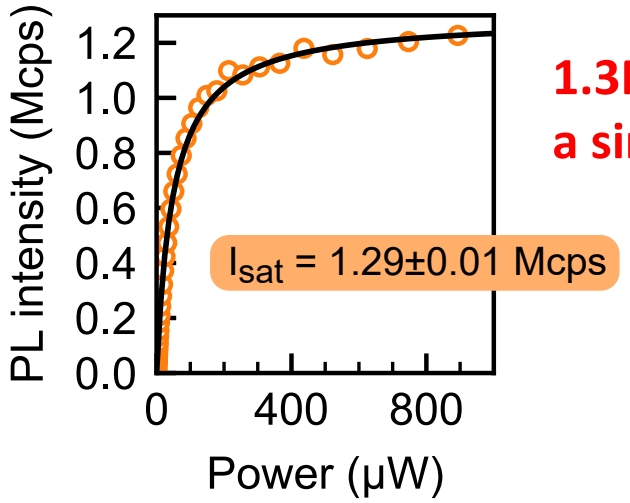


- integration of single W centers in CBG cavities with deterministic positioning

Lefaucher et al., arXiv:2501.12744 (2025)





1.3Mcounts/s from a single W center

Leti & Pheliqs

Baptiste Lefaucher

Yoann Baron

Jean-Baptiste Jager

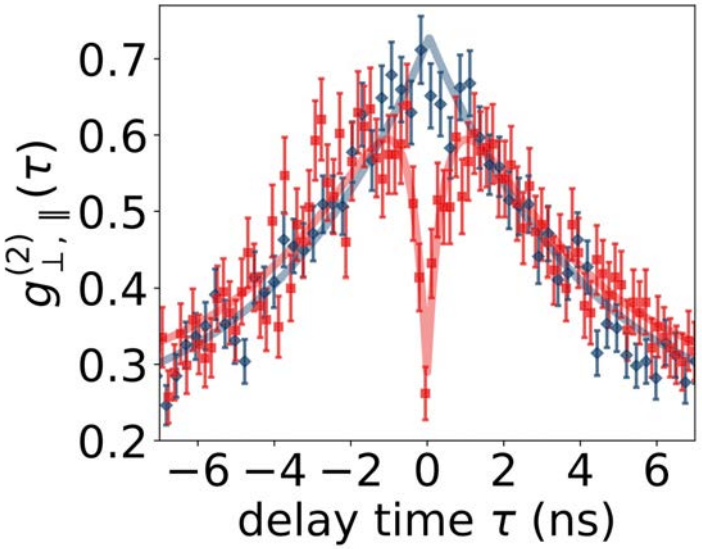
Jean-Michel Gérard

Controlling the optical interface of color centers in silicon

The next challenge: long-term indistinguishable photon emission !

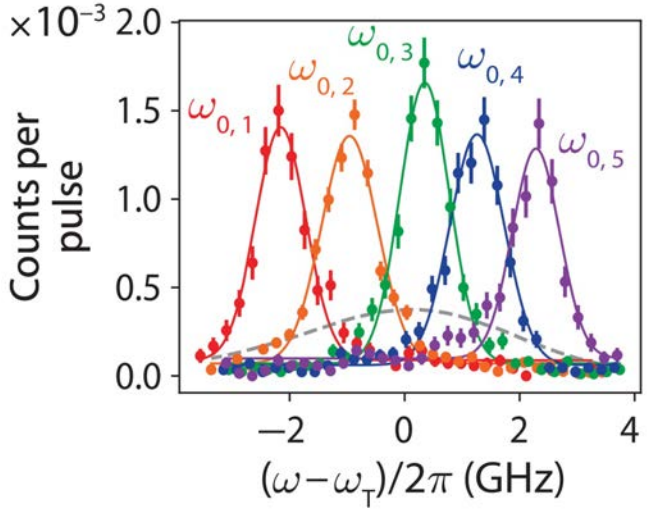
solid-state emitters -> spectral diffusion, dephasing, inhomogeneous static environment

- HOM on a single integrated G center



Komza et al., Nat. Comm. **15** (2024)

- spectral wandering on a single integrated T center



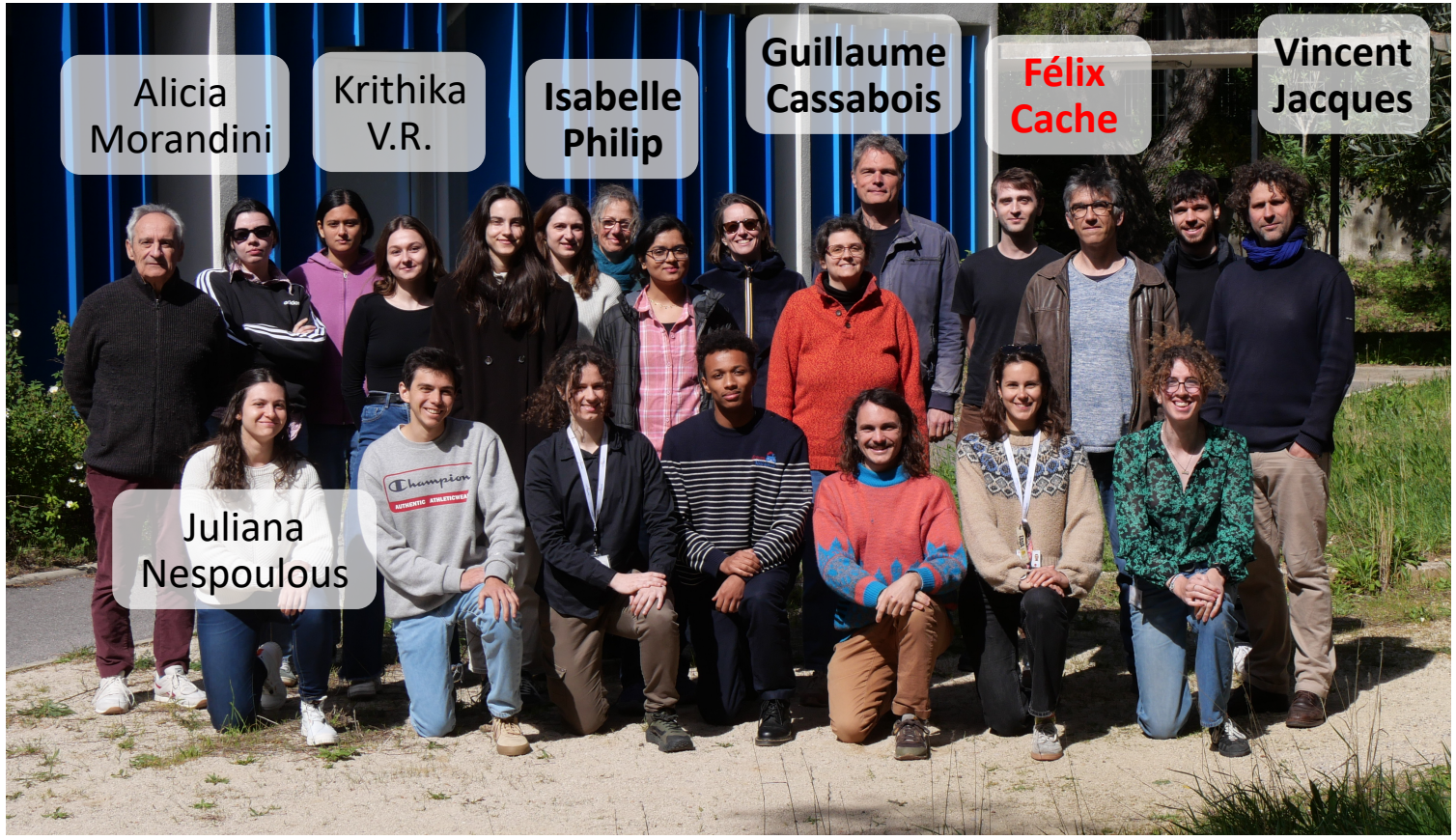
Zhang et al., PRX Quantum. **6** (2025)

integration degrades the optical coherence

Bowness et al., PRX Quantum **6** (2025)

Thanks for your attention !

the Solid-State Quantum Technologies group @L2C Montpellier



Project SILEQS

Project OQulus

Thanks to our collaborators!

Baptiste Lefaucher
Jean-Baptiste Jager
Jean-Michel Gérard



Yoann Baron
Frédéric Mazin
Frédéric Milési
Sébastien Kerdilès