ulm university universität uulm

Group-IV defects in diamond for quantum networks

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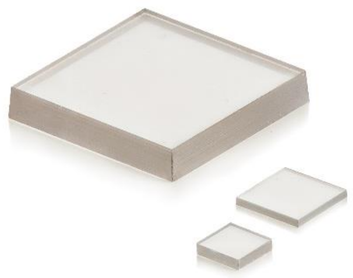
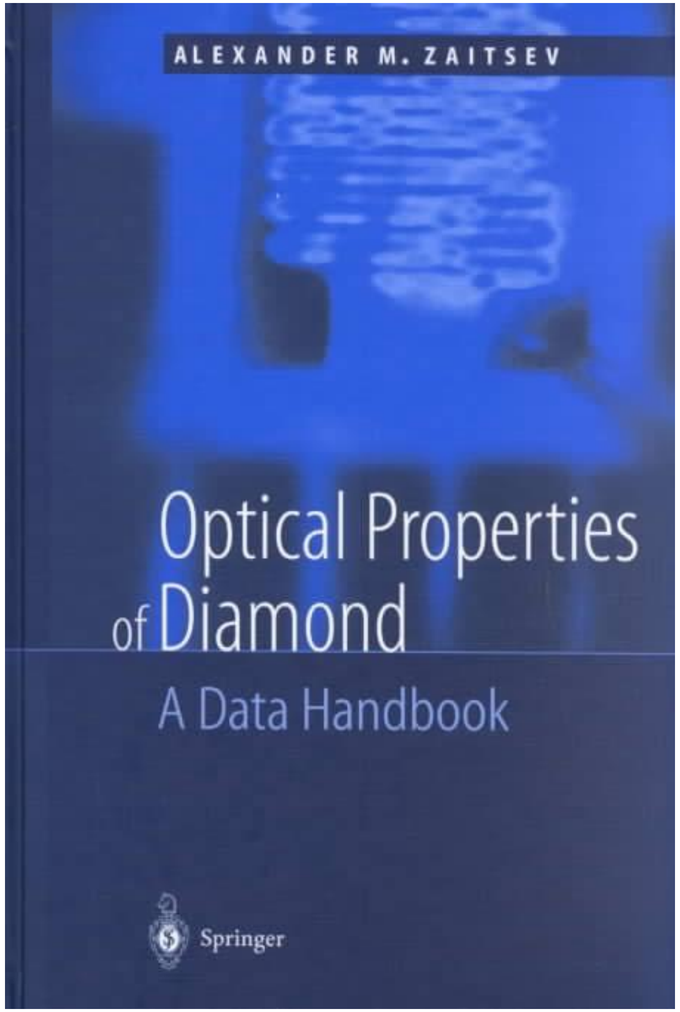
Quantum Optics

www.quantenoptik.de

Color centers in diamond



Boring electronic grade diamonds

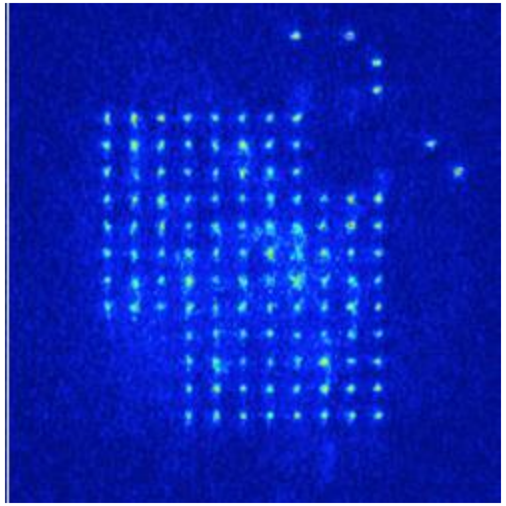


Besides Nitrogen and Boron, more than 500 defects are known!

but structurally only about 20 are explored

Color centers in diamond

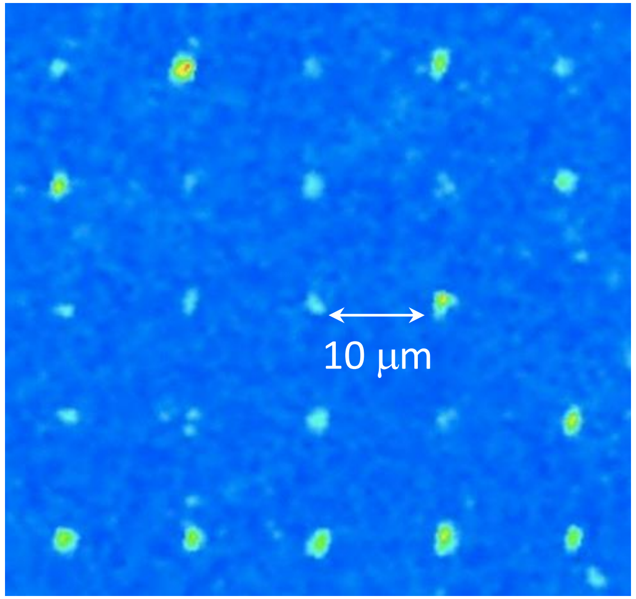
Trapped atoms



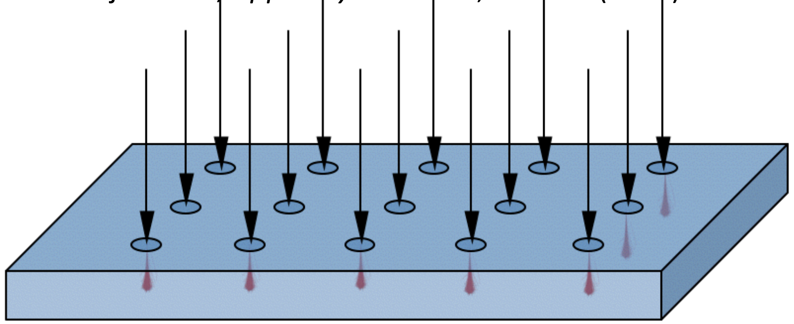
D. Ohl de Mello et al., *Phys. Rev. Lett.* **122**, 203601 (2019)

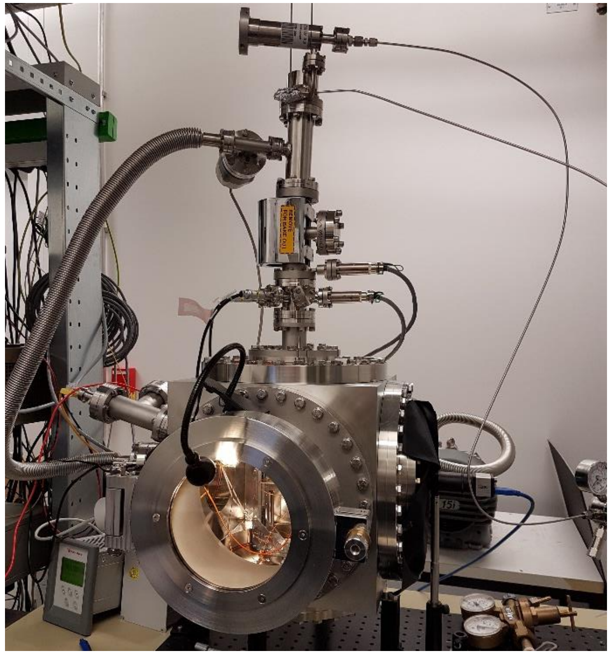
- ✓ Well isolated
- ✓ Well controllable
- × Difficult to trap and store

“Trapped” color centers in crystal



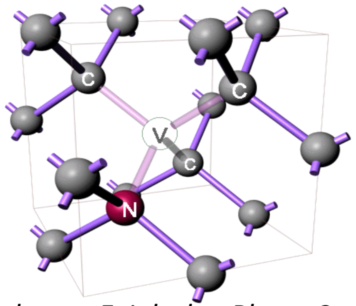
Meijer et al., *Appl. Phys. Lett.* **87**, 261909 (2005)





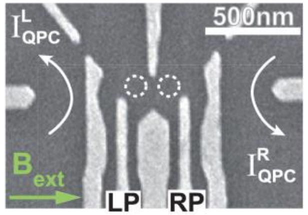
- ✓ Defects are atomic like systems
- ✓ Intrinsically trapped in solids
- ✓ Full quantum control
- ✓ Potentially scalable

Solid-state spin qubits



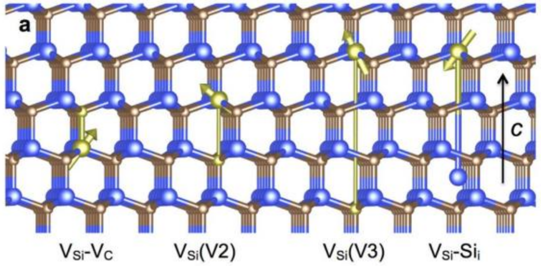
J. Wrachtrup, F. Jelezko, Phys.: Condens. Matter ***16****, R1089–R1104 (2004)*

NV centers In diamond



K. C. Nowack et al. Science ***333****, 1269-1272 (2011)*

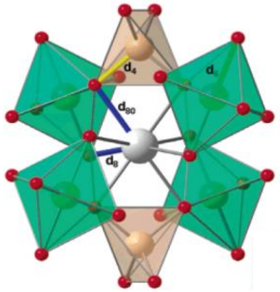
Quantum dots



H. Kraus et al. Sci. Rep. ***4****, 5303 (2014)*

V_{Si}, V_{Si}-V_C in SiC

Solid-state spin qubits



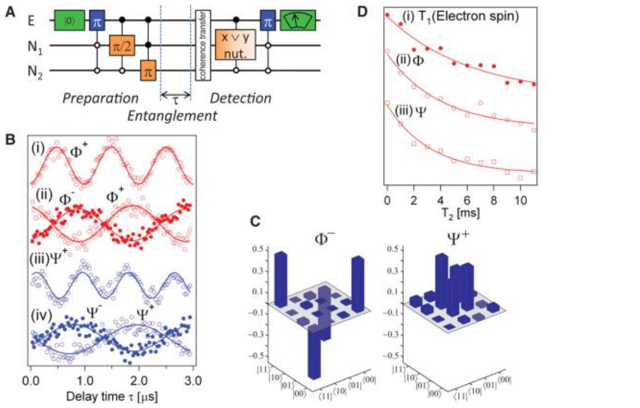
P. Siyushev et al. Nat. Commun. ***4****, 3895 (2014)*

Rare-earth ions

Others…

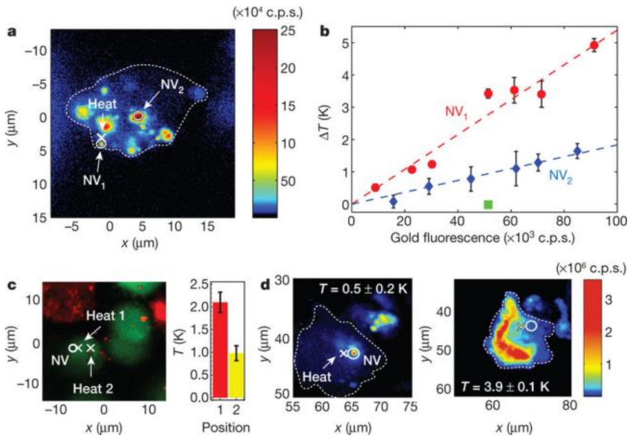
can be used as

Qubit



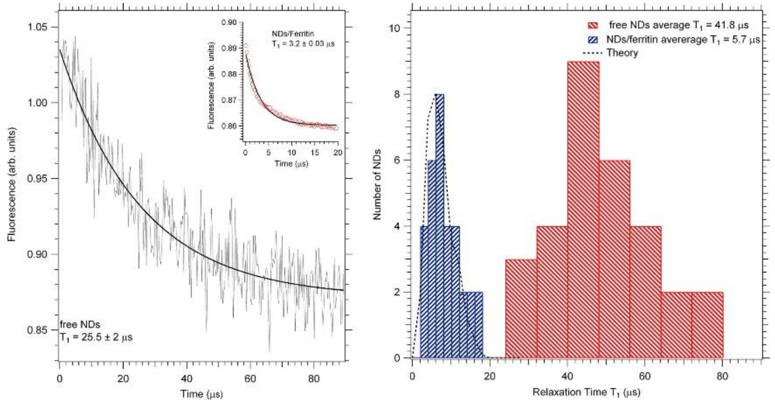
P. Neumann et al., Science ***320,*** *1326-1329 (2008)*

Temperature sensor



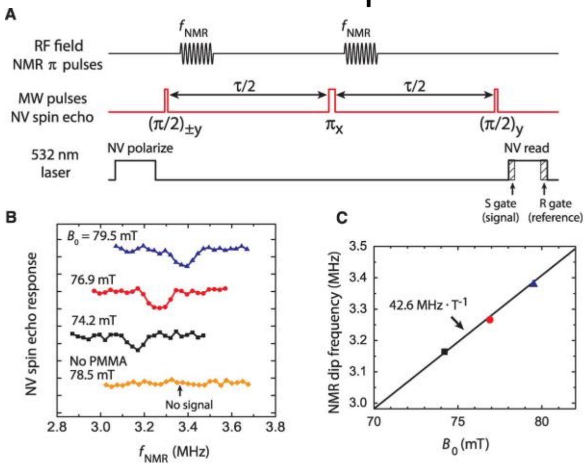
G. Kucsko et al., Nature ***500****, 54-58 (2013)*

Magnetic sensor



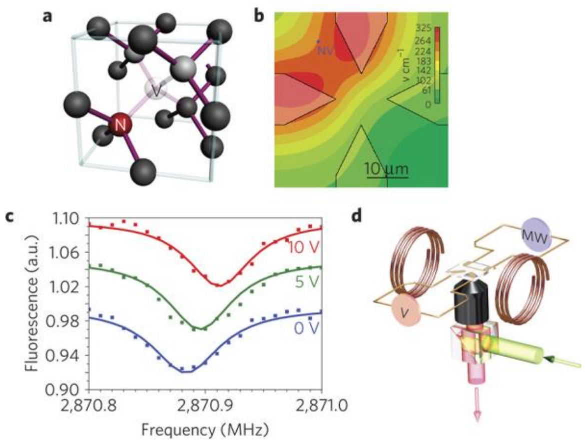
A. Ermakova et al., Nano Lett. ***13****, 3305-3309 (2013)*

Nanoscale NMR probe



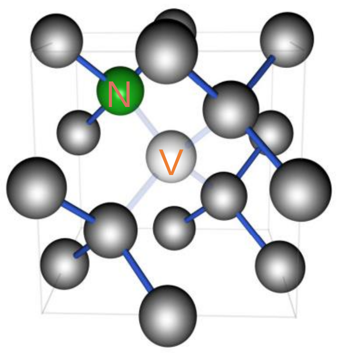
H. J. Mamin et al., Science ***339****, 557-560 (2013)*

Electric field sensor



F. Dolde et al., Nat. Phys. ***7****, 459-463 (2011)*

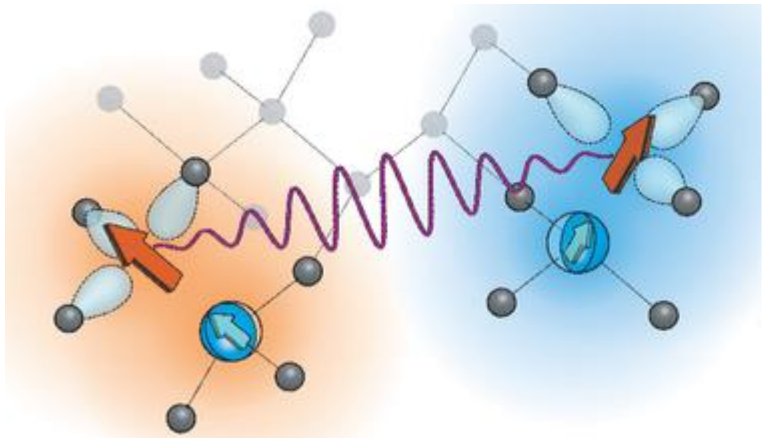
Why searching for new defects?



Optical initialization and readout

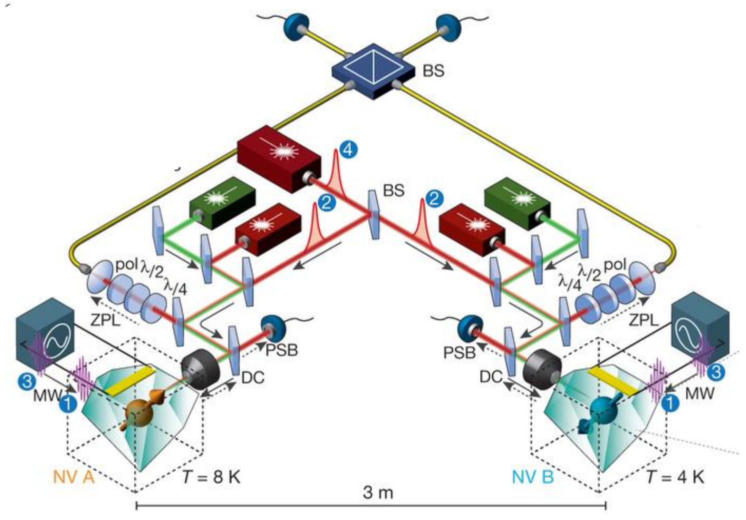
Long spin coherence time

Spin manipulation by MW field



Entanglement between two NV centers

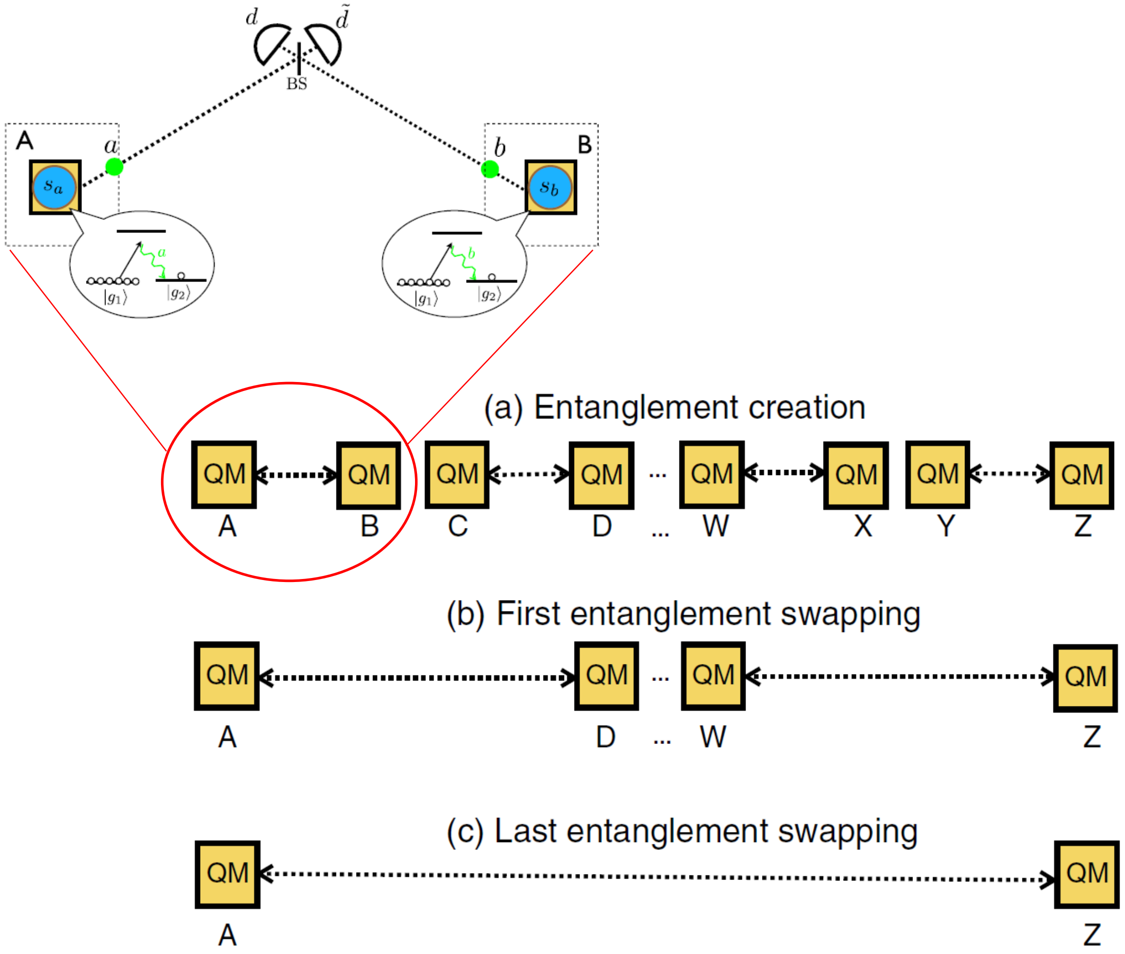
F. Dolde et al., Nat. Phys. ***9****, 139–143 (2013)*



H. Bernien et al., Nature ***497****, 86–90 (2013)*

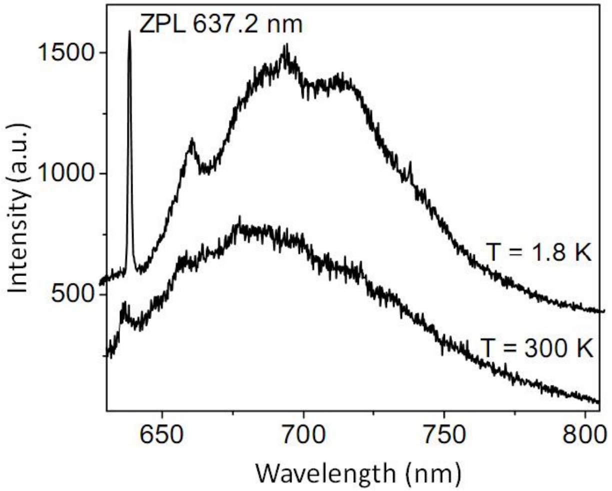
One entanglement event per 10 minutes!

Spin-photon interface is essential…



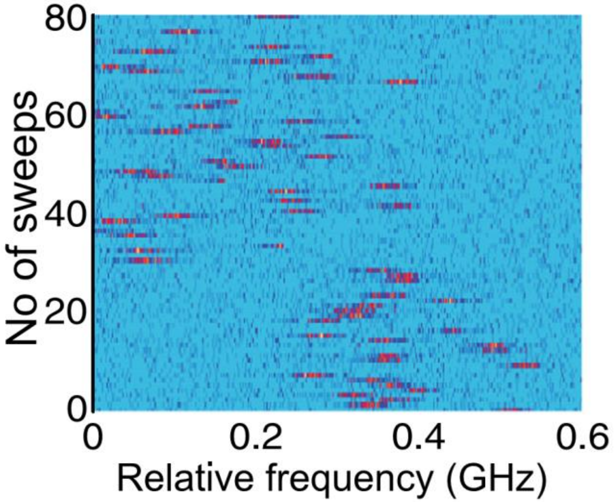
N. Sangouard et al., *Rev. Mod. Phys.* **83**, 33 (2011)

Entanglement rate is poor?



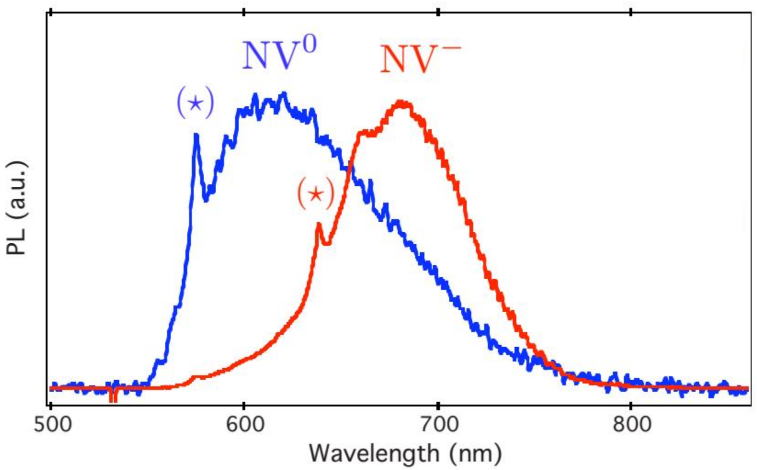
F. Jelezko and J. Wrachtrup, Phys. Stat. Solidi ***204*** *3207 (2006)*

Low Debye-Weller factor ~0.4



P. Siyushev et al., Phys. Rev. Lett. ***110****, 167402 (2013)*

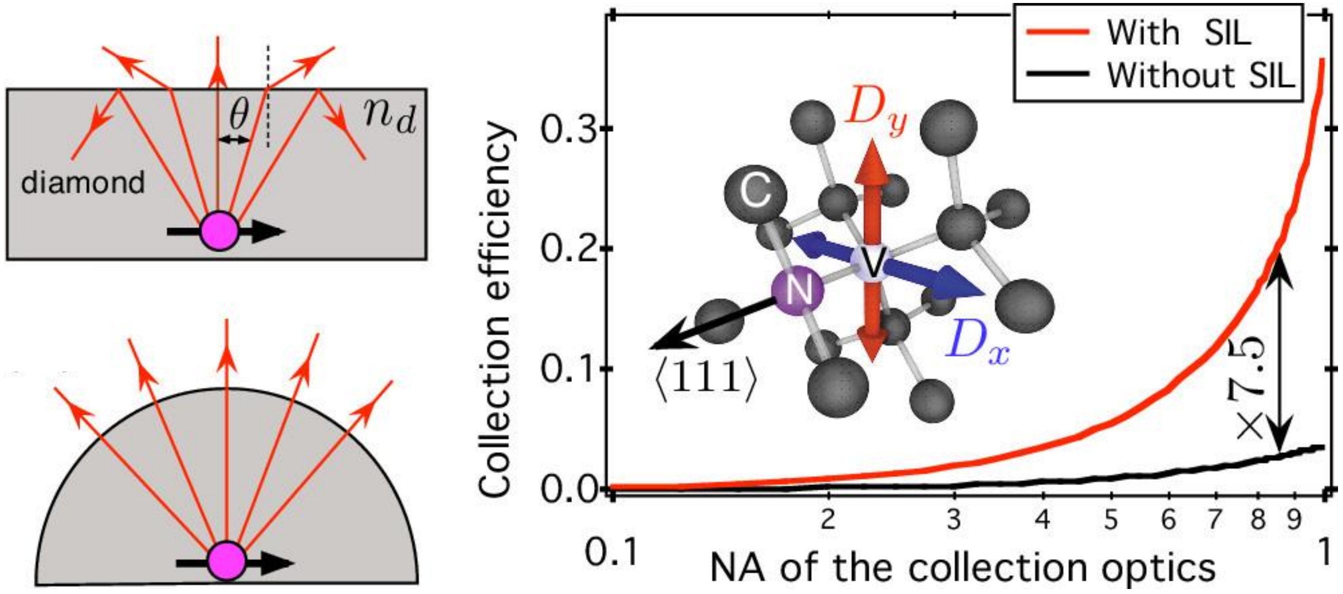
Spectral jumps



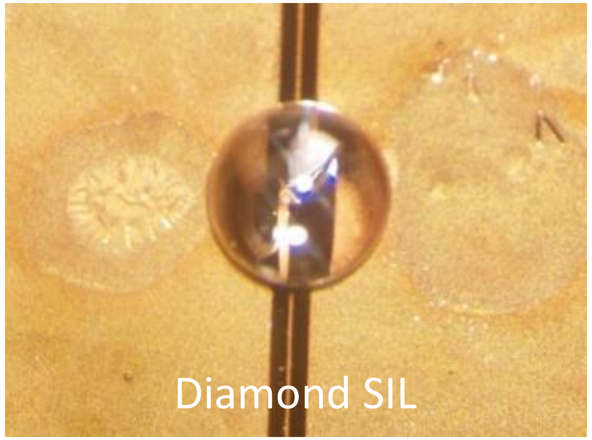
L. Rondin et al., Phys Rev. B ***82****, 115449 (2010)*

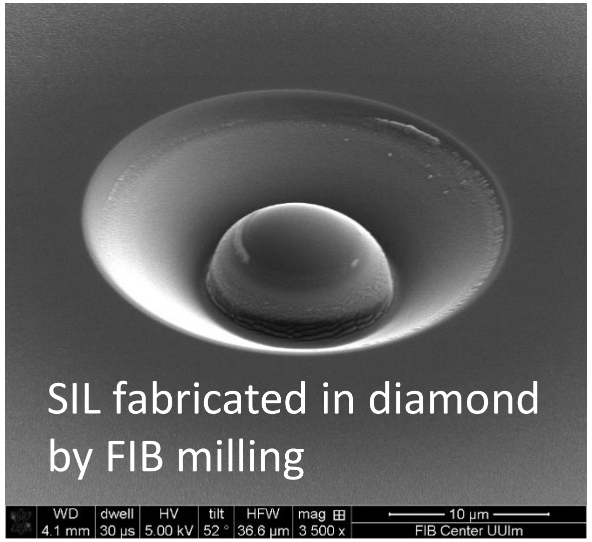
Emission from NV^0

Collection efficiency enhancement

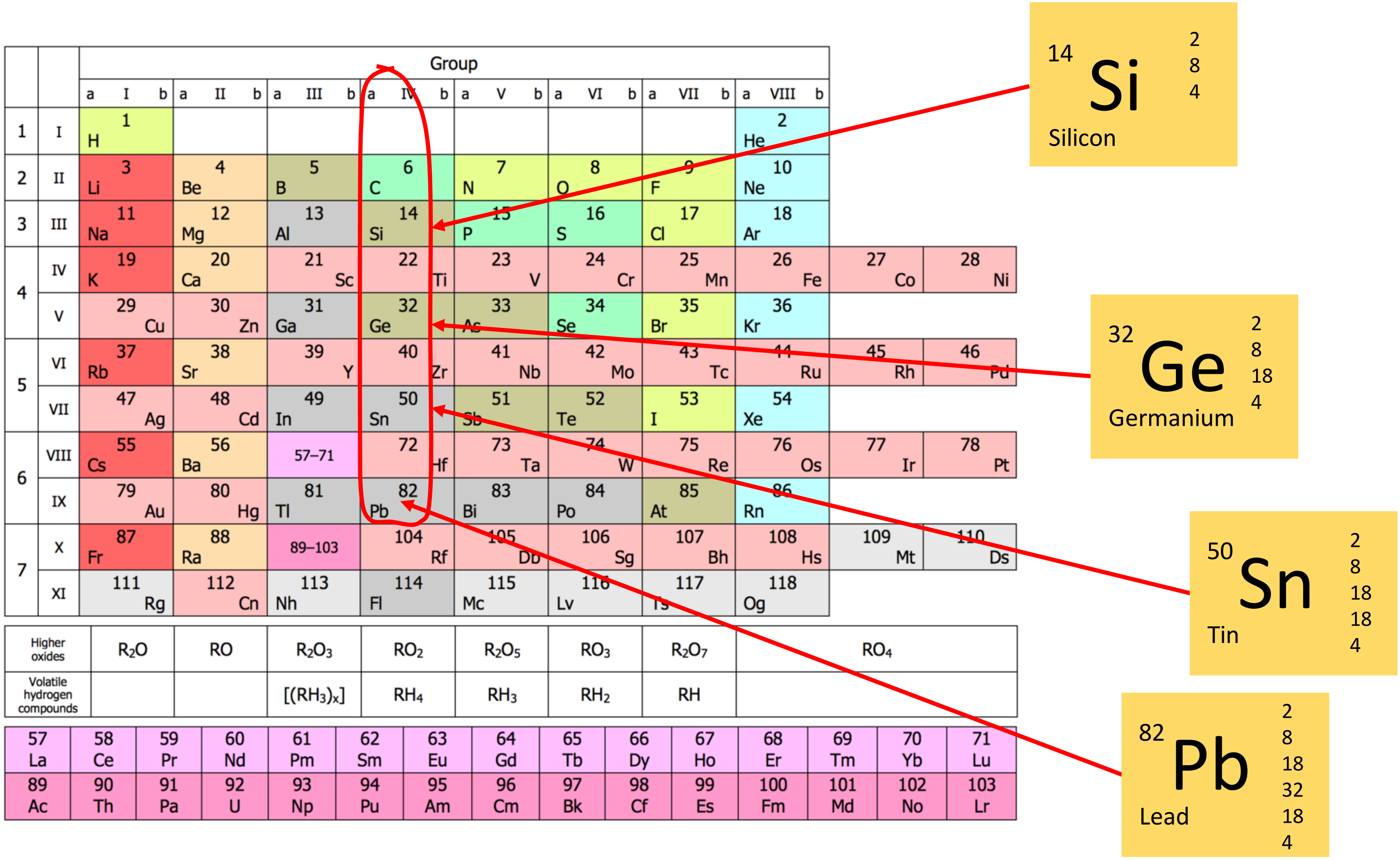


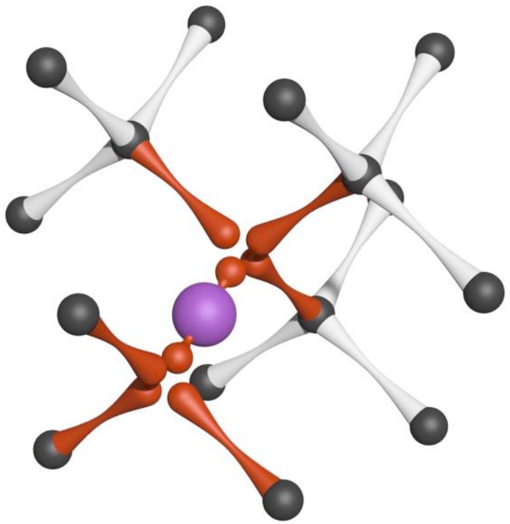
P. Siyushev et al., *Appl. Phys. Lett.* **97**, 241902 (2010)



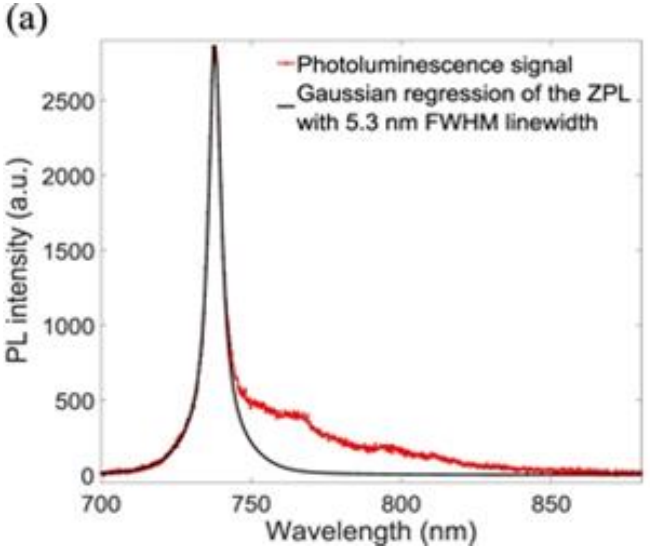


Other candidates…





Other candidates…

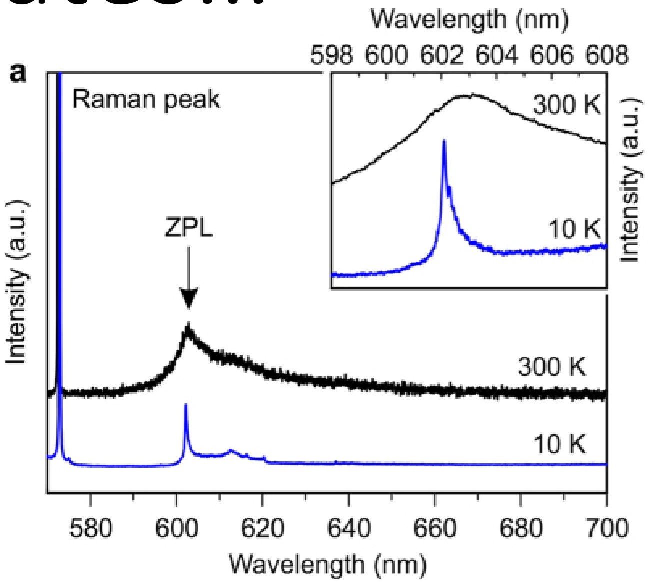


S. Häußler et al. *New J. Phys.* **19** 063036 (2017)

C. Wang et al.
J. Phys. B: At., Mol. Opt. Phys. **39**, 37 (2006)
C. Hepp et al. *Phys. Rev. Lett.* **112**, 036405 (2014)
L. Rogers et al. *Phys. Rev. B* **89**, 235101 (2014)
A. Sipahigil et al.
Phys. Rev. Lett. **113**, 113602 (2014)

Many others…

737 nm

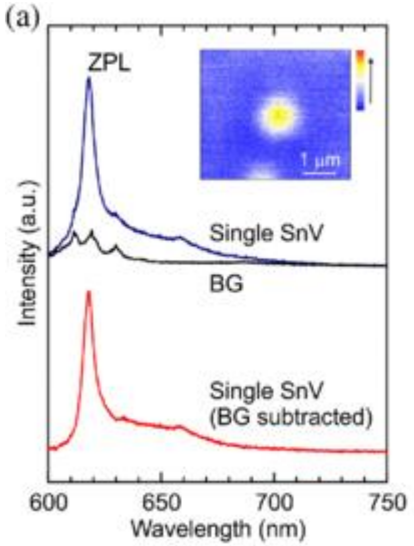


T. Iwasaki et al. *Sci. Rep.* **5**, 12882 (2015)

Y. N. Palyanov et al. *Sci. Rep.* **5**, 14789 (2015)
E. A. Ekimov et al. *JETP Lett.* **102**, 701 (2016)
P. Siyushev et al. *Phys. Rev. B* ***96***, 081201 (2017)
M. Bhaskar et al.
Phys. Rev. Lett. **118**, 223603 (2017)

Others…

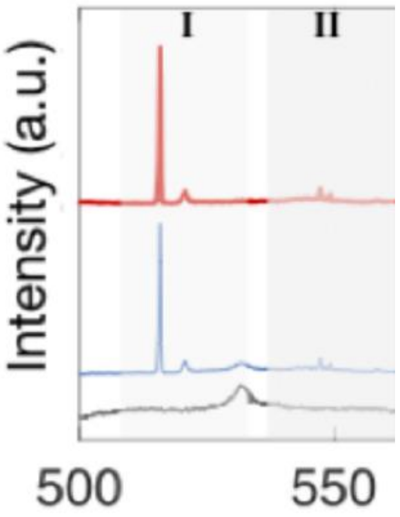
602 nm



T. Iwasaki et al.
Phys. Rev. Lett. **119**, 253601 (2017)

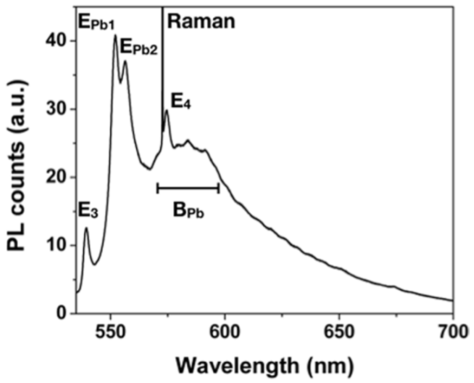
S. Ditalia Tchernij et al.
ACS Photonics **4**, 2580 (2017)
M. Alkahtani et al.
Appl. Phys. Lett. **112**, 241902 (2018)
M. Trusheim et al. arXiv:1811.07777

619 nm



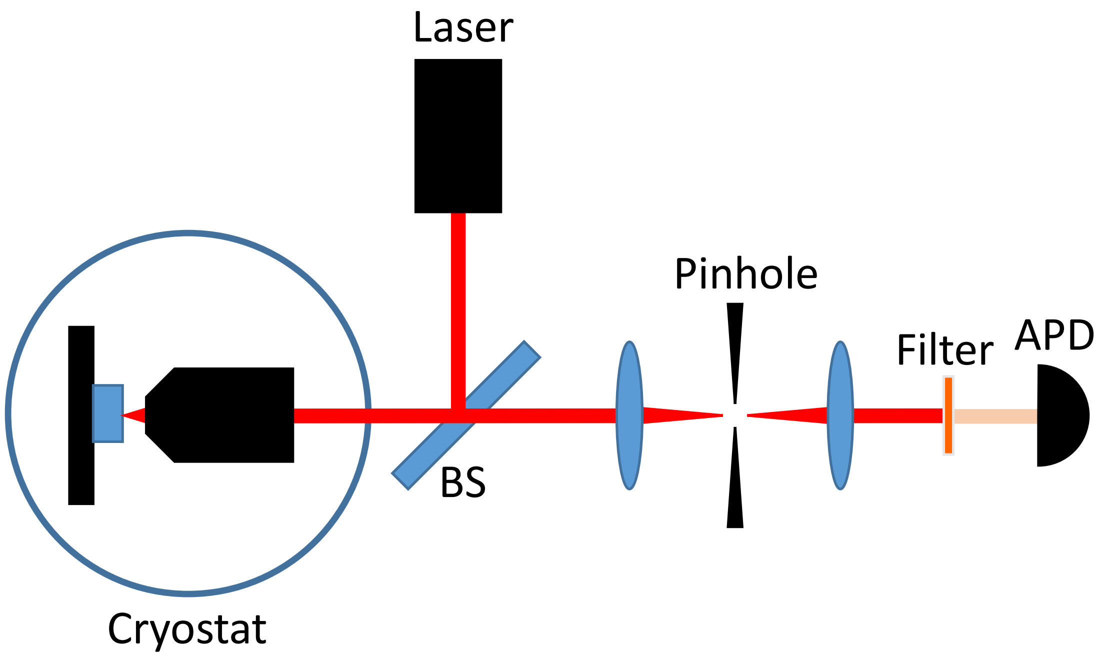
M. Trusheim et. al,
Phys. Rev. B **99**, 075430 (2019)

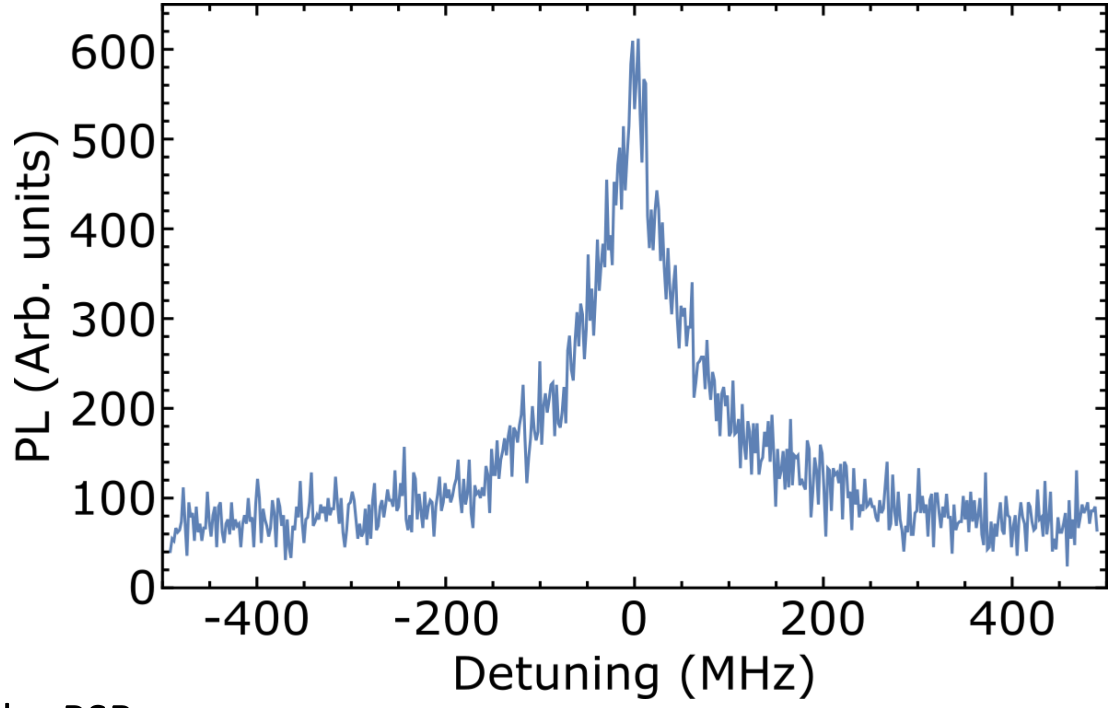
OR



S. Ditalia Tchernij et al, *ACS Photonics* **5**, 4864 (2018)

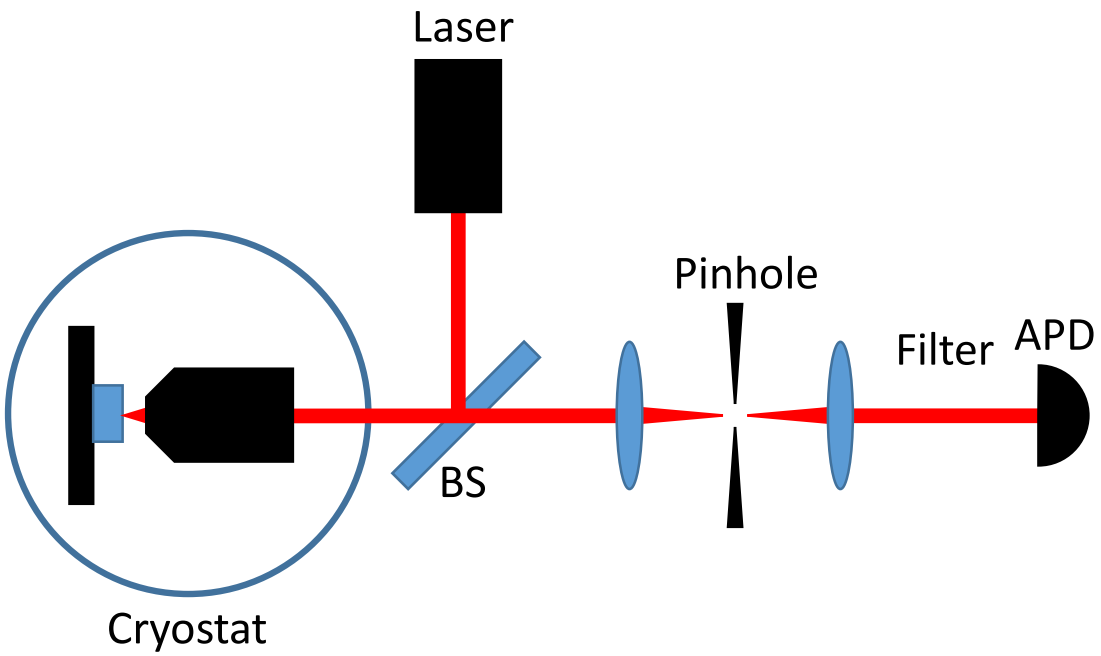
Why so special?

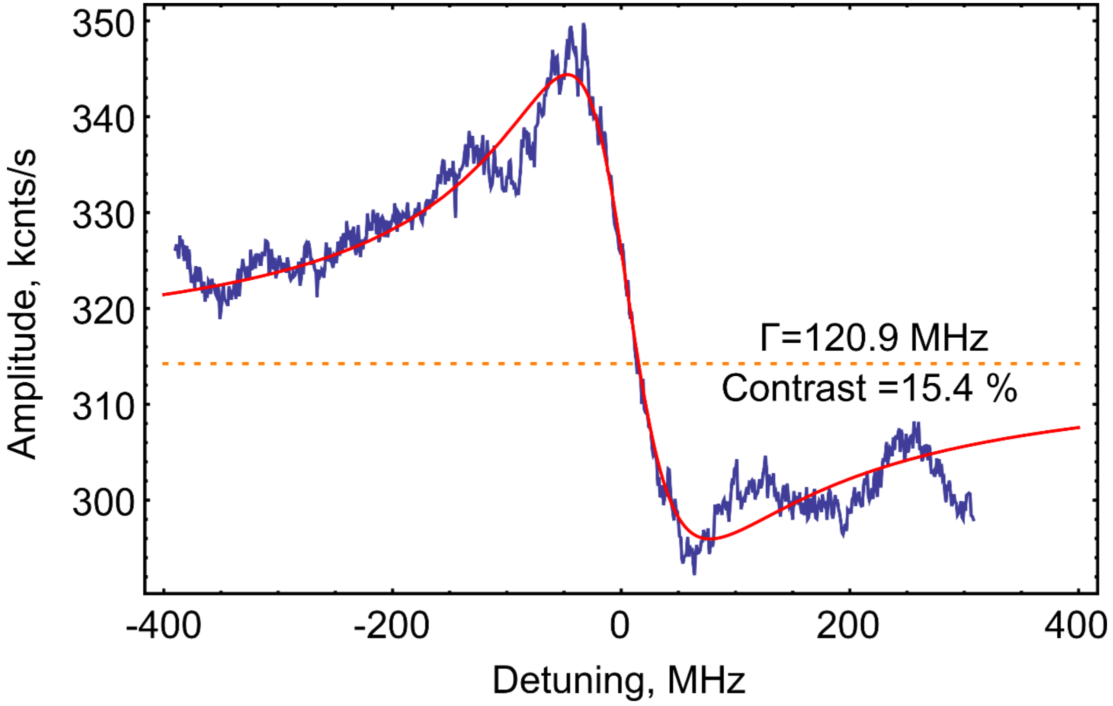




Laser is scanned over ZPL, photons are detected from the PSB
- photoluminescence excitation spectroscopy (PLE)

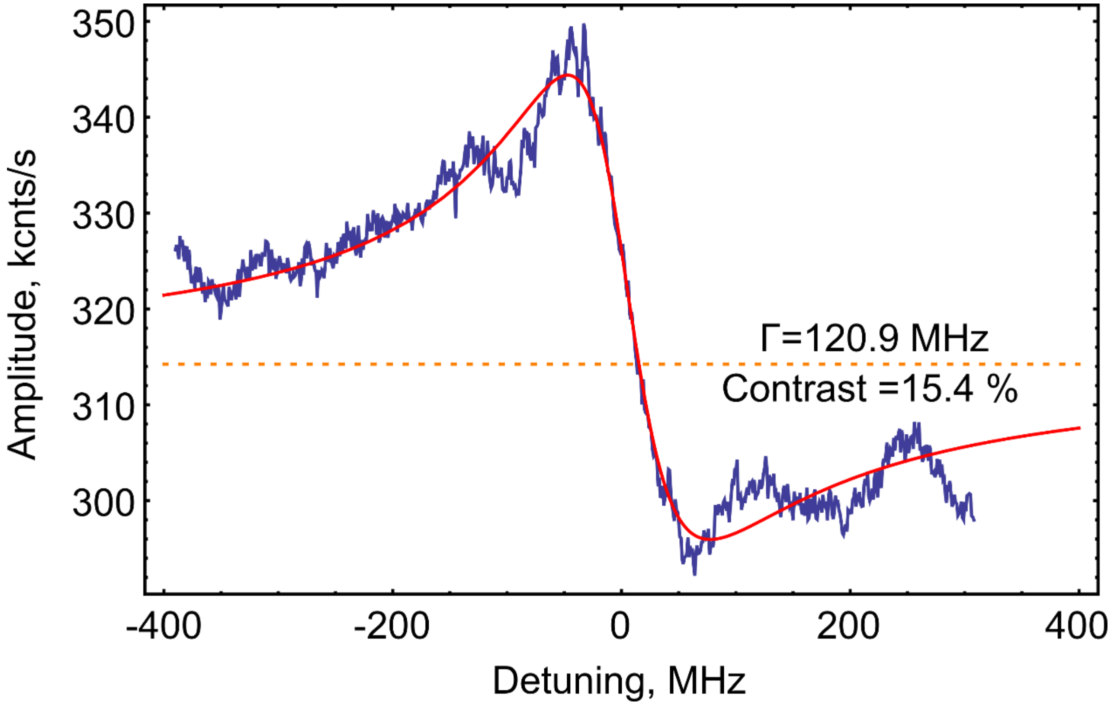
Why so special?



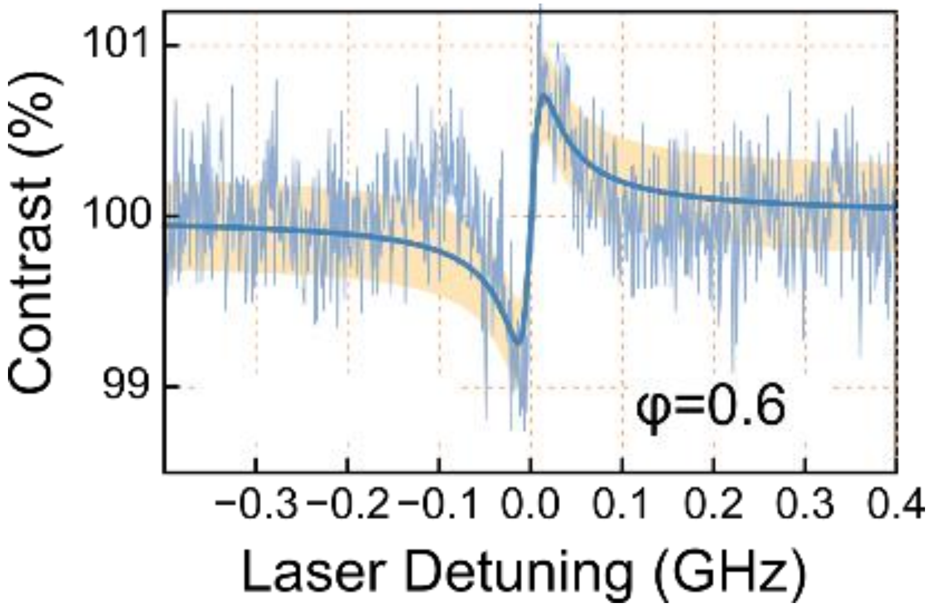


Filter is removed from the detection channel
“extinction” measurements

Why so special?



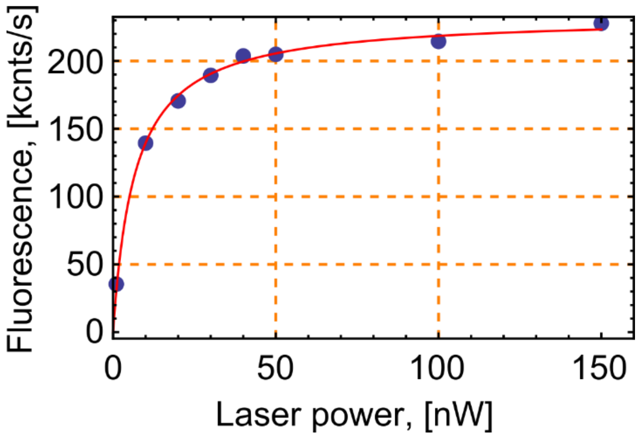
Extinction on NV center gives only about 2%

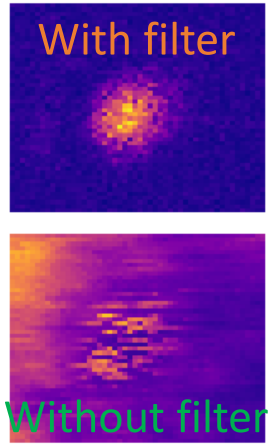


T. Hien et al., *Phys Rev A* **95**, 053831 (2017)

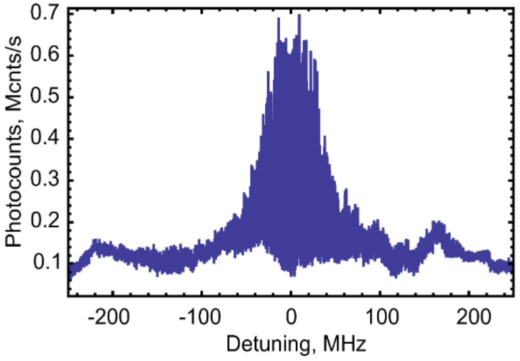
Why so special?

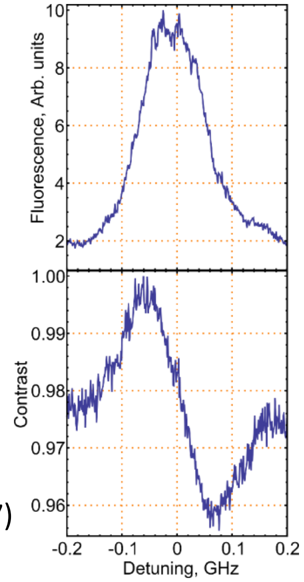
Only phonon sideband



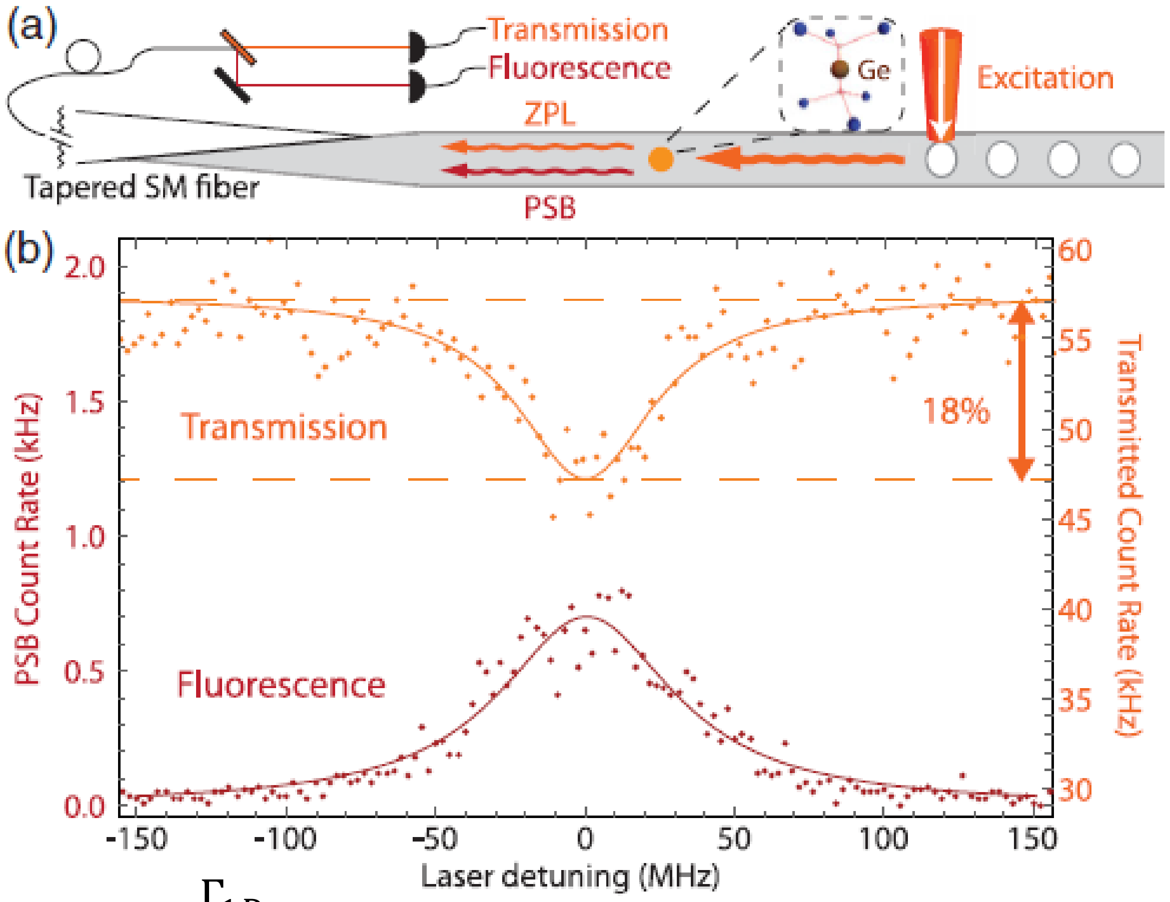


All fluorescence





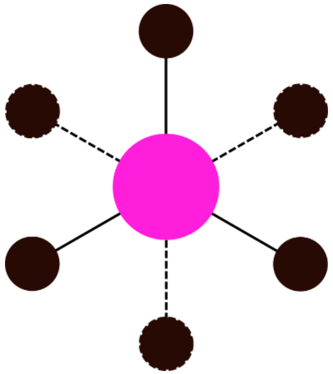
P. Siyushev et al. *Phys. Rev. B* **96**, 081201 (2017)



$$C = \frac{\Gamma_{1D}}{\Gamma'} \geq 0.1$$

M. K. Bhaskar et al. *Phys. Rev. Lett.* **118**, 223603 (2017)

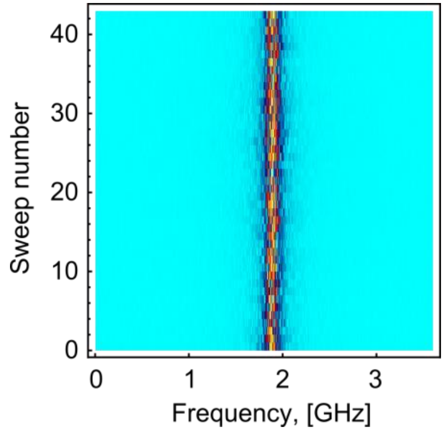
Why so special?

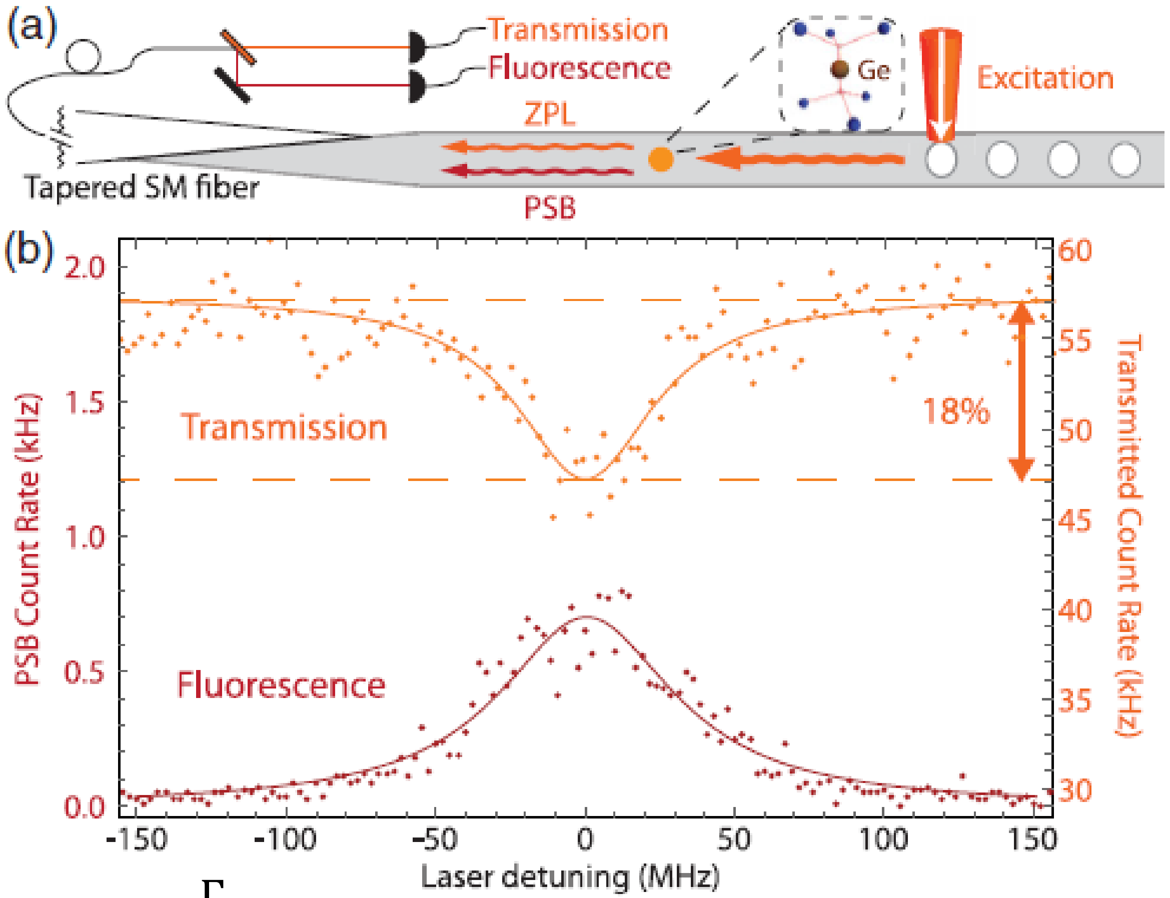


High Debye–Waller factor

D_{3d} point group symmetry

$$\Delta E = -\mathbf{d}_{nn}\mathcal{E} - \frac{1}{2}\alpha_{kl}\mathcal{E}_k\mathcal{E}_l$$



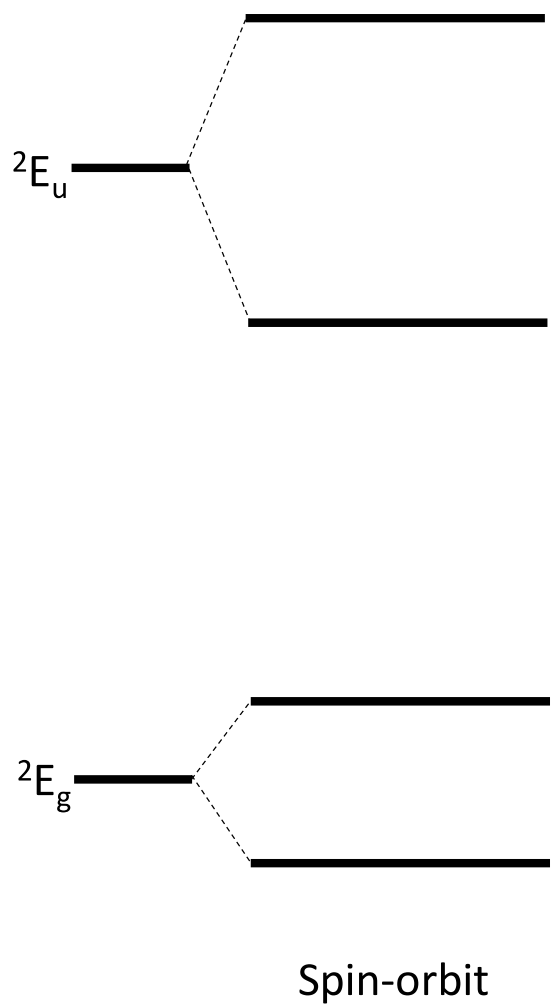


$$C = \frac{\Gamma_{1D}}{\Gamma'} \geq 0.1$$

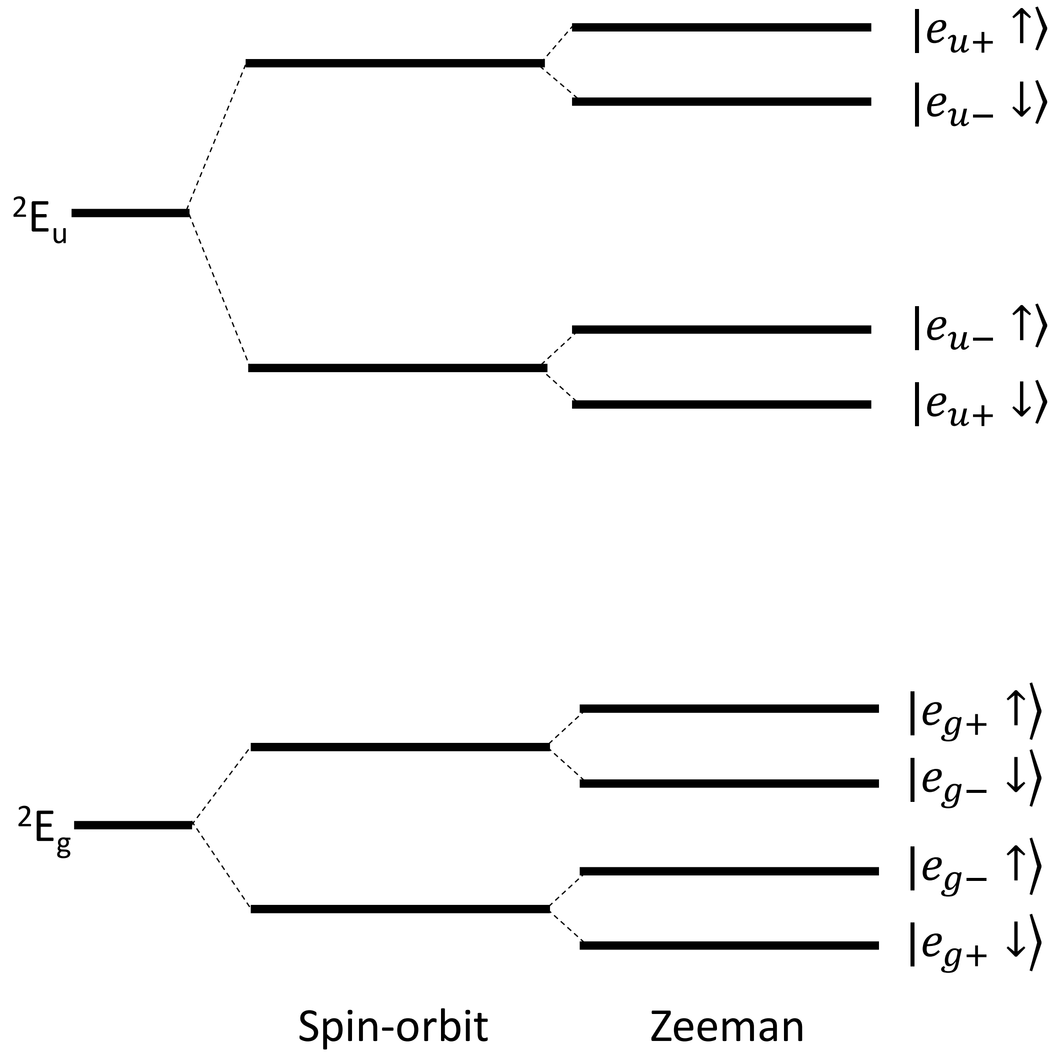
P. Siyushev et al. *Phys. Rev. B* **96**, 081201 (2017)

M. K. Bhaskar et al. *Phys. Rev. Lett.* **118**, 223603 (2017)

Energy level structure



Energy level structure



Ground state splitting:

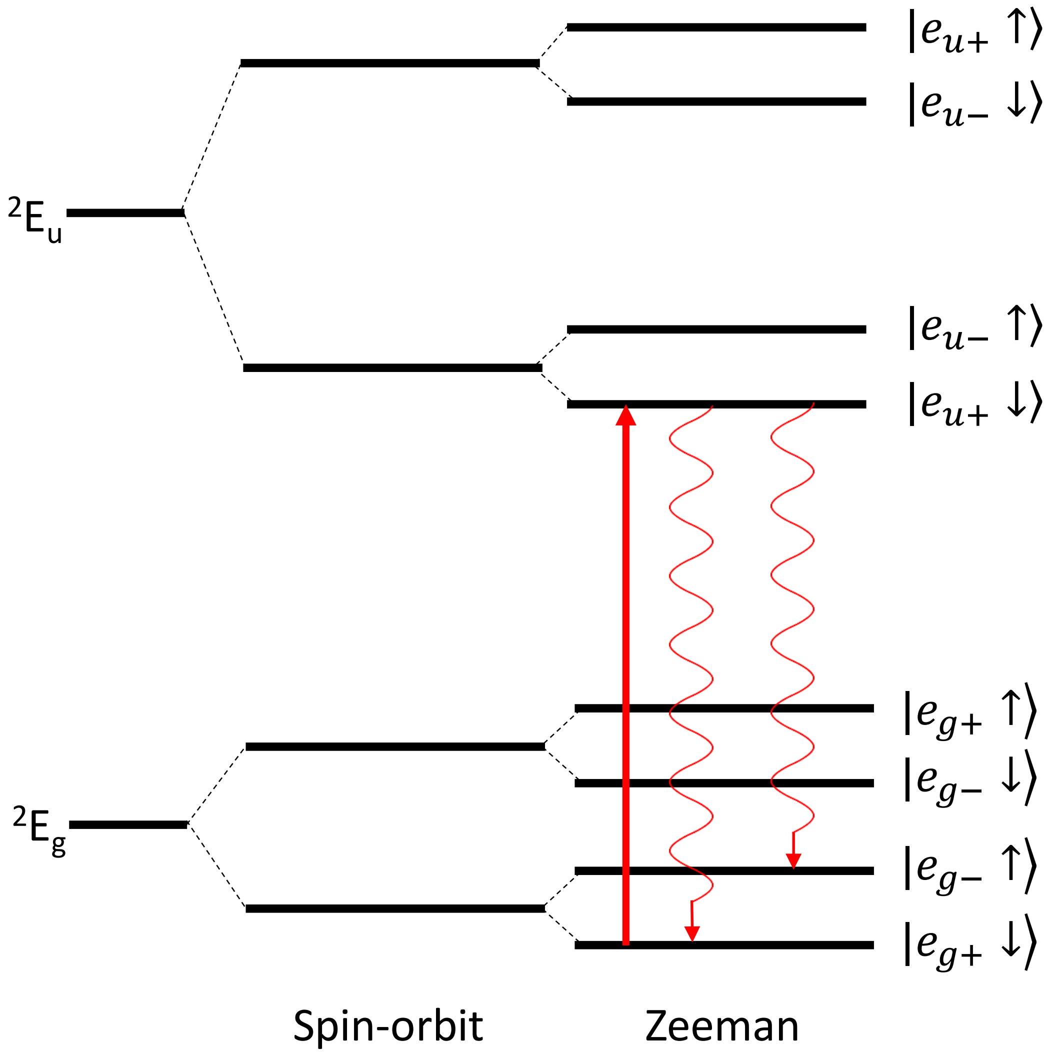
~50 GHz (SiV), *C. Hepp et al. Phys. Rev. Lett.* ***112****, 036405 (2014)*

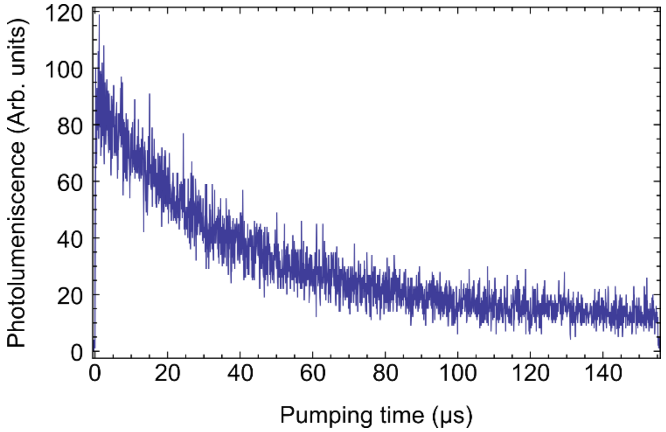
~150 GHz (GeV), *P. Siyushev et al. Phys. Rev. B* ***96****, 081201 (2017)*

~850 GHz (SnV), *T. Iwasaki et al. Phys. Rev. Lett.* ***119****, 253601 (2017)*

~5700 GHz (PbV) M. Trusheim et. al, *Phys. Rev. B* **99**, 075430 (2019)

Energy level structure





Optical pumping

Ground state splitting:
~50 GHz (SiV),
~150 GHz (GeV),
~850 GHz (SnV),
~5700 GHz (PbV)

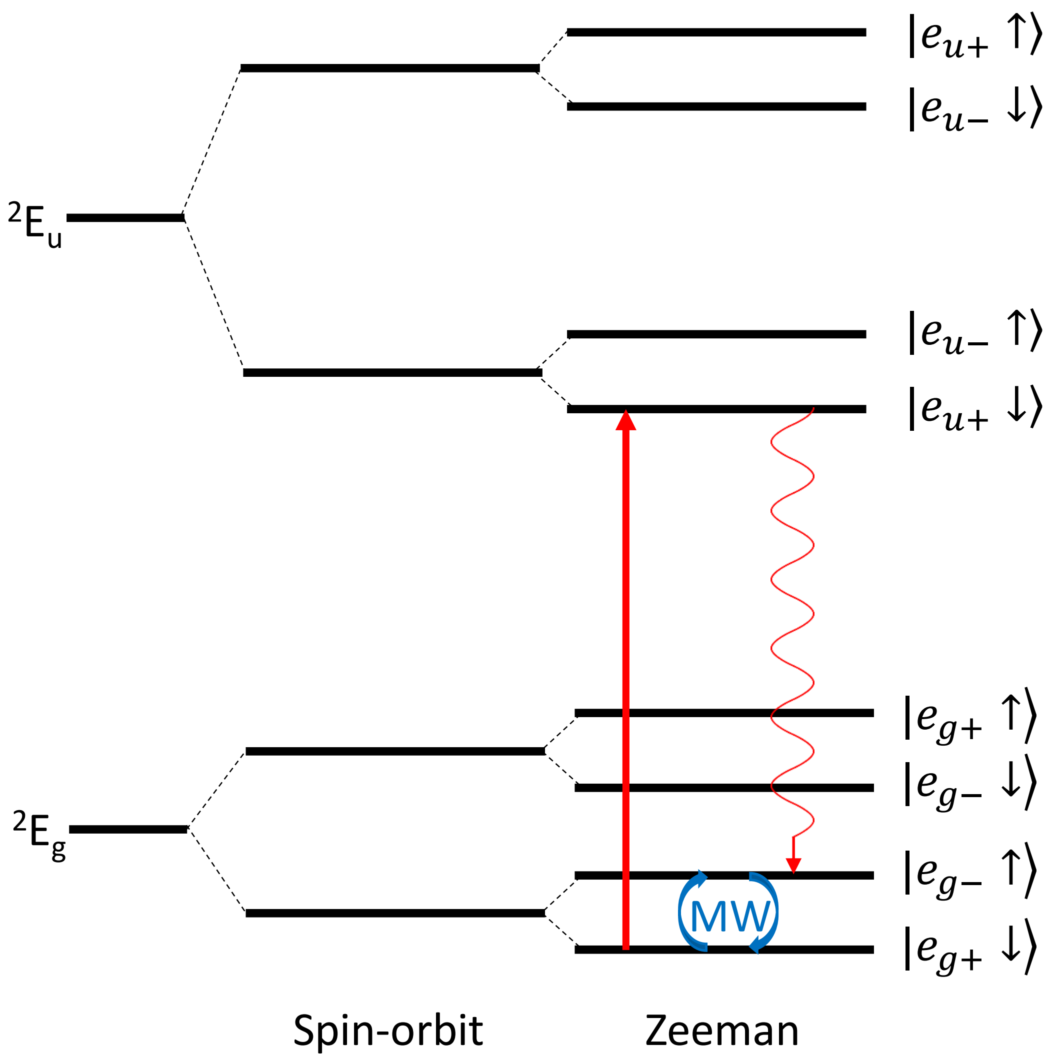
C. Hepp et al. Phys. Rev. Lett. ***112****, 036405 (2014)*

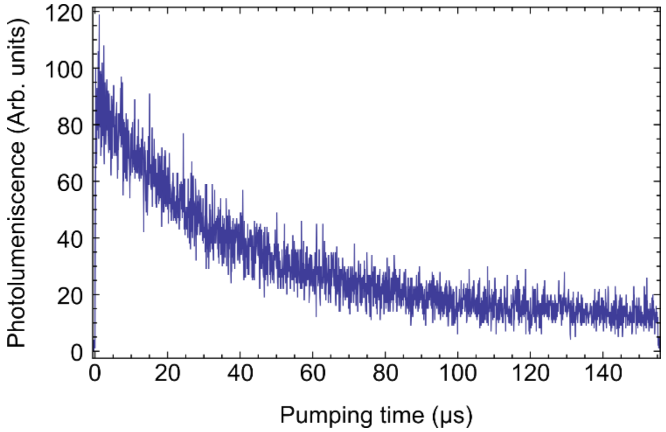
P. Siyushev et al. Phys. Rev. B ***96****, 081201 (2017)*

T. Iwasaki et al. Phys. Rev. Lett. ***119****, 253601 (2017)*

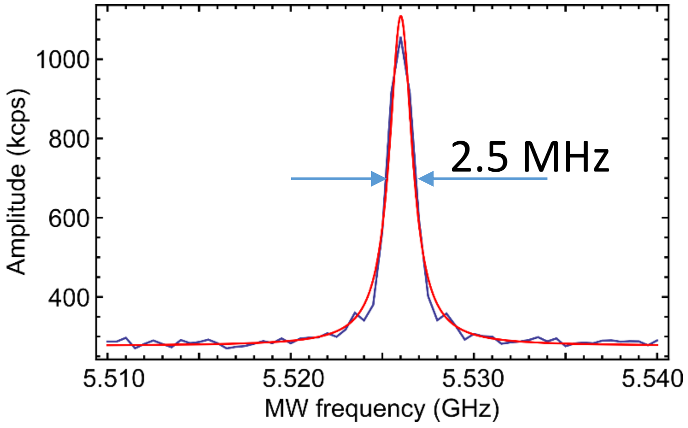
M. Trusheim et. al, *Phys. Rev. B* **99**, 075430 (2019)

Energy level structure





Optical pumping



Example of ODMR

Ground state splitting:
~50 GHz (SiV),
~150 GHz (GeV),
~850 GHz (SnV),
~5700 GHz (PbV)

C. Hepp et al. Phys. Rev. Lett. ***112****, 036405 (2014)*

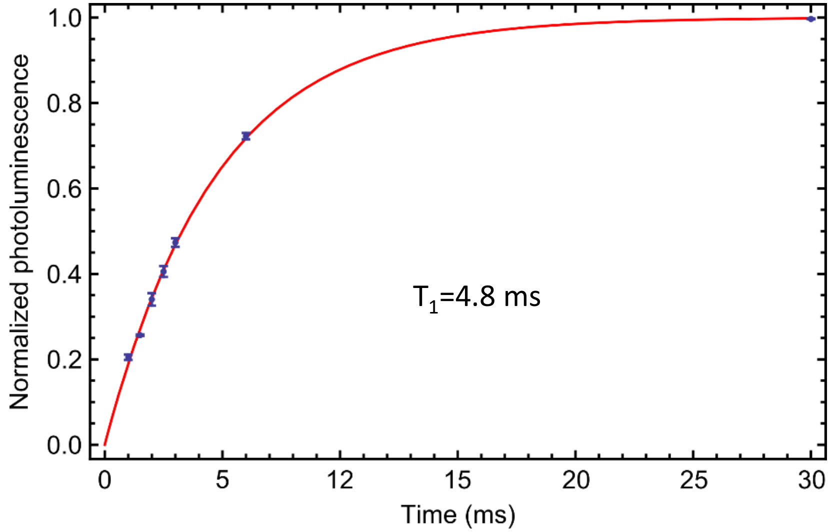
P. Siyushev et al. Phys. Rev. B ***96****, 081201 (2017)*

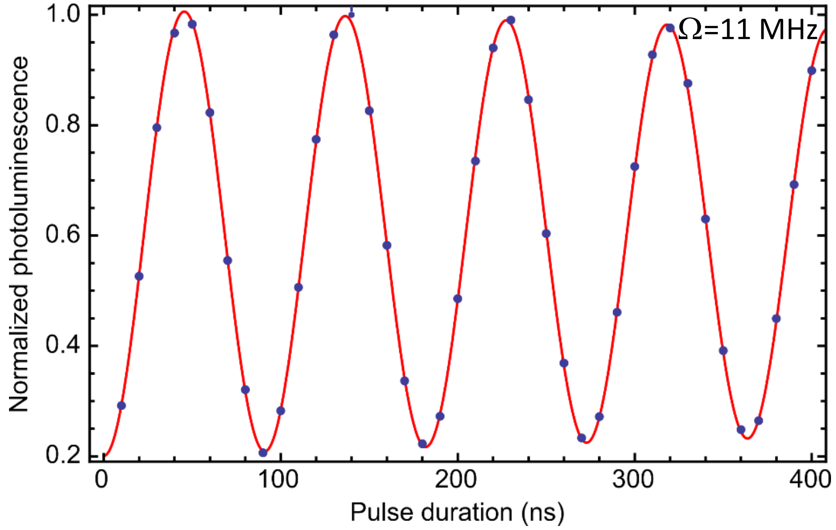
T. Iwasaki et al. Phys. Rev. Lett. ***119****, 253601 (2017)*

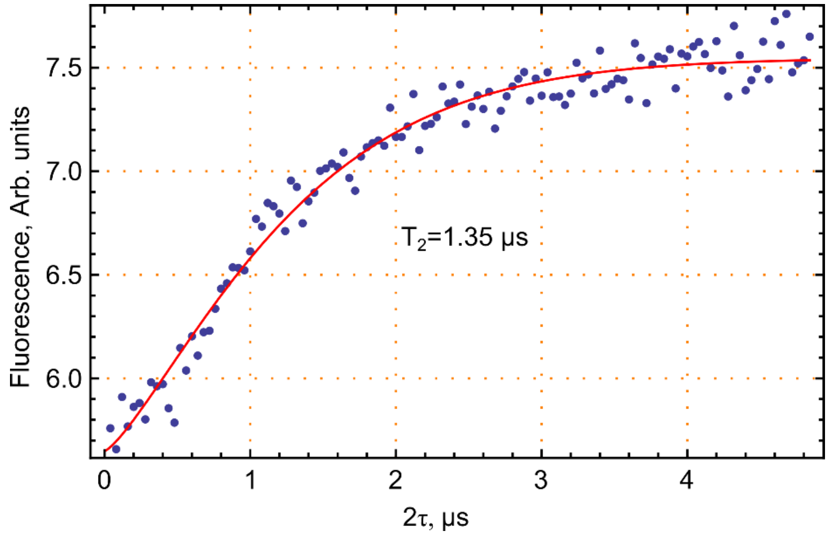
M. Trusheim et. al, *Phys. Rev. B* **99**, 075430 (2019)

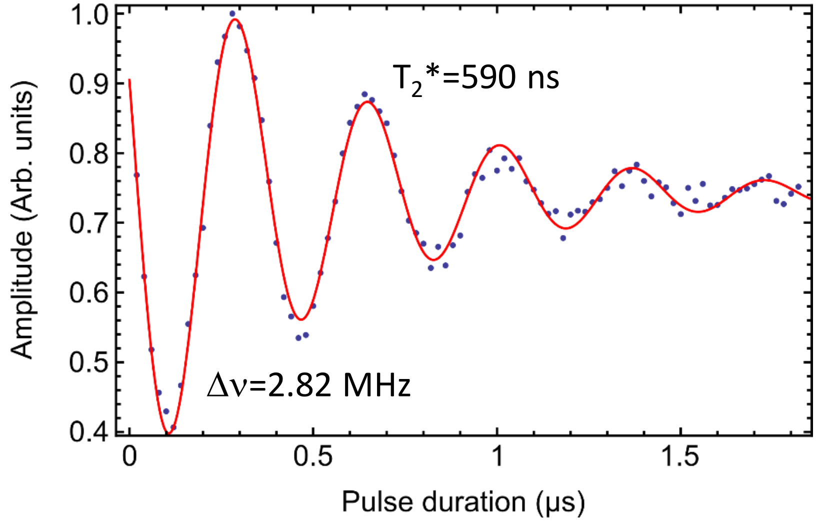
Electron spin properties of SiV center

T ≈ 2 K

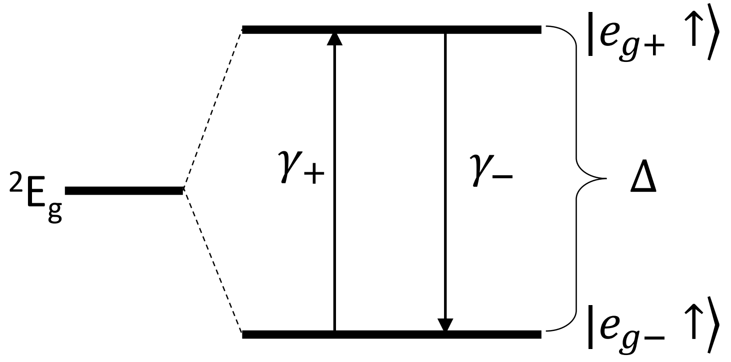








Orbital relaxation



$$\gamma_+ = 2\pi\chi\rho\Delta^3 n(\Delta,T)$$

$$\gamma_- = 2\pi\chi\rho\Delta^3 [n(\Delta,T) - 1]$$

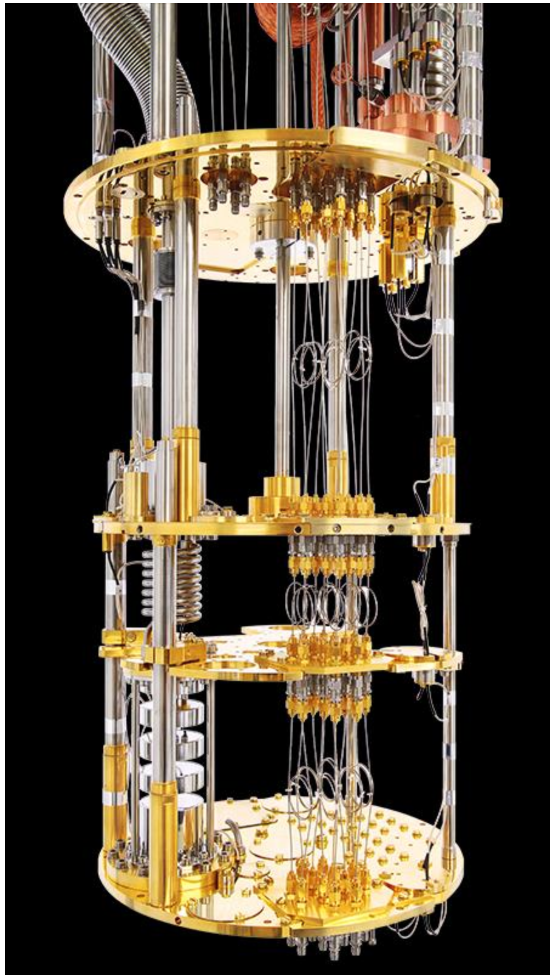
$$n(\Delta,T) = \frac{1}{e^{\frac{\hbar\Delta}{k_B T}} - 1}$$

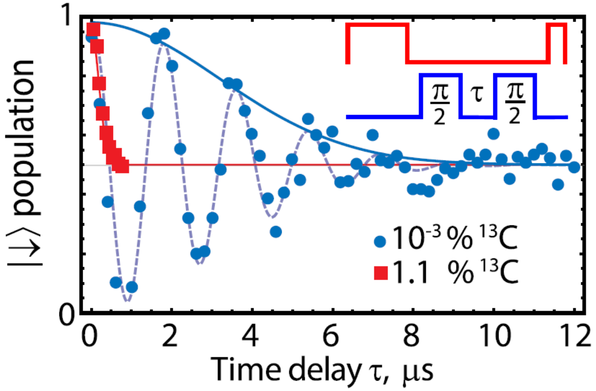
For $T > \frac{\hbar\Delta}{k_B}$ linear scaling with temperature

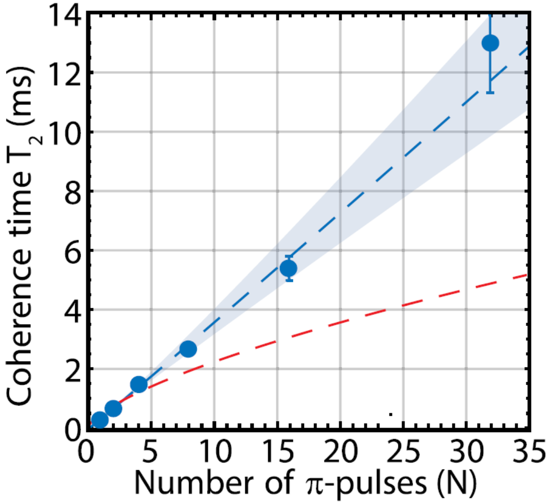
in opposite case decreasing as $e^{\frac{\hbar\Delta}{k_B T}}$

K. Jahnke et al., New J. Phys. ***17****, 043011 (2015)*

How to avoid it?

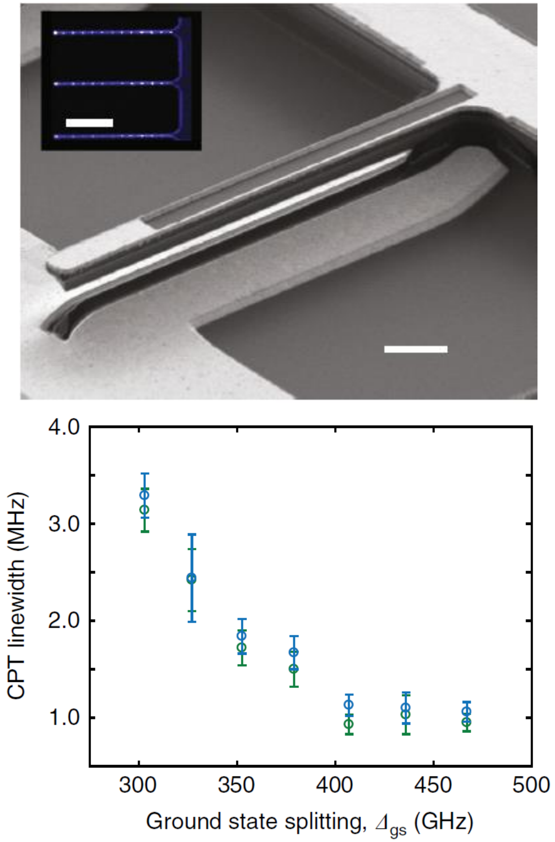






T_2 exceeds 10 ms @ 100 mK

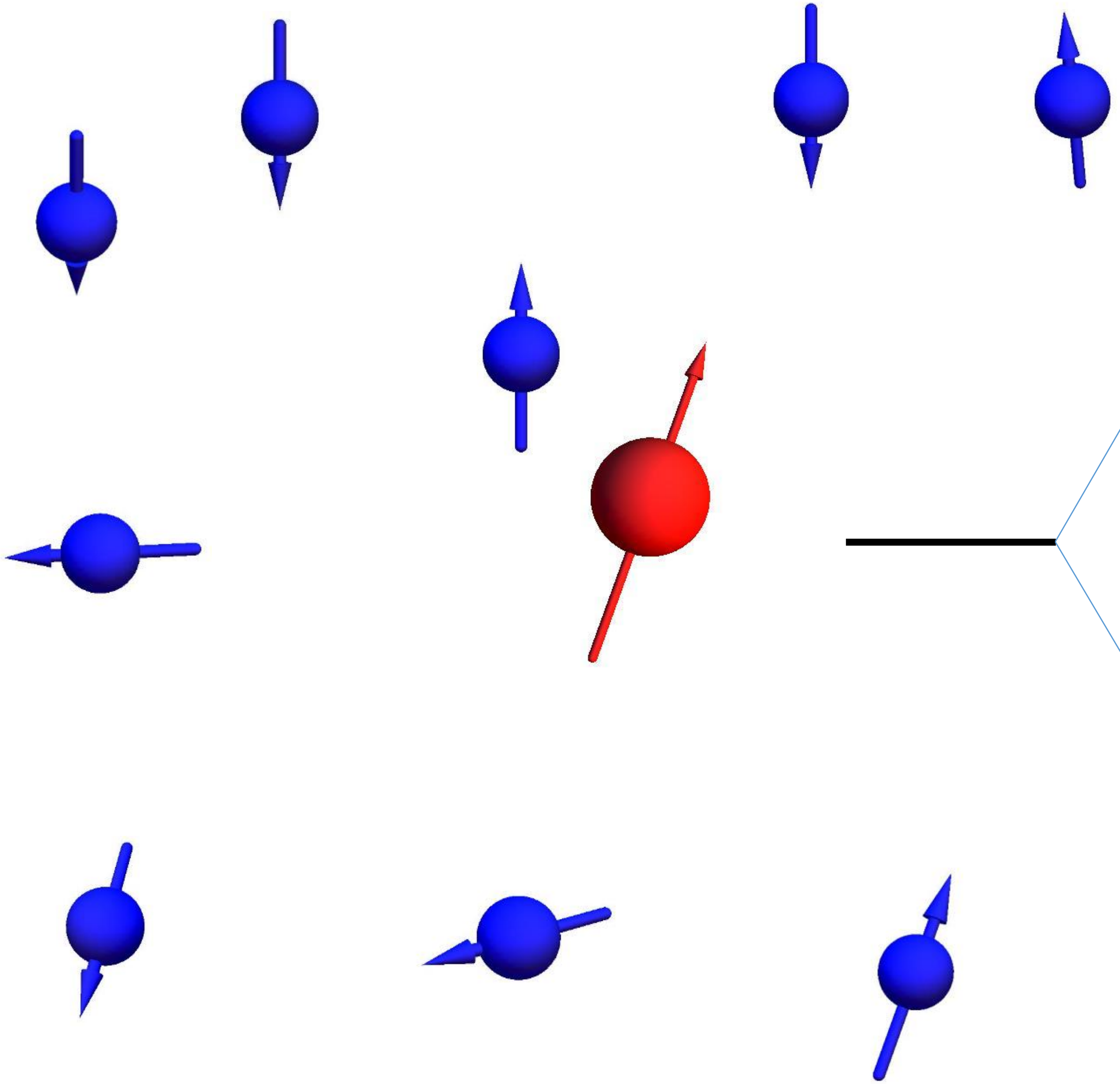
D. Sukachev et. al, Phys. Rev. Lett. ***119****, 223602 (2017)*



T_2*=0.25 μs

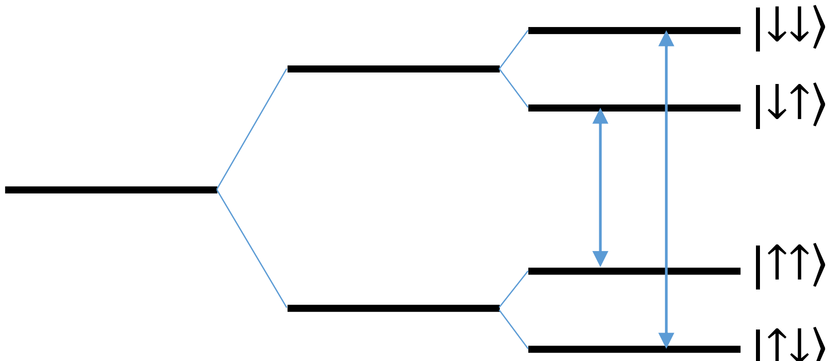
Y.-I. Sohn et. al, Nat. Commun. ***9****, 2012 (2018)*

Electron coupled to nuclear spins



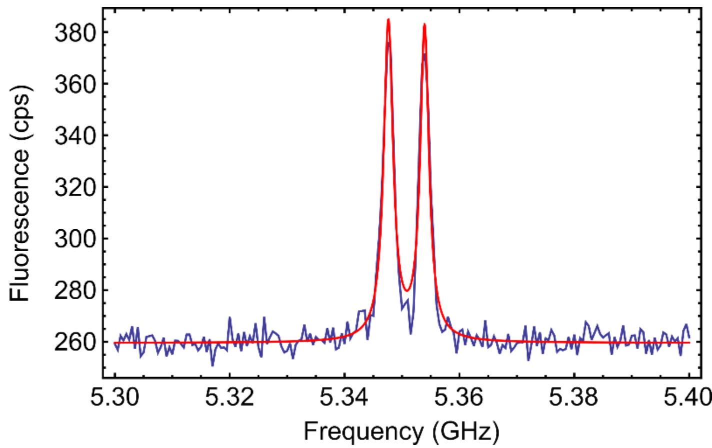
Nuclear spin

weak interaction with environment



Zeeman

Hyperfine

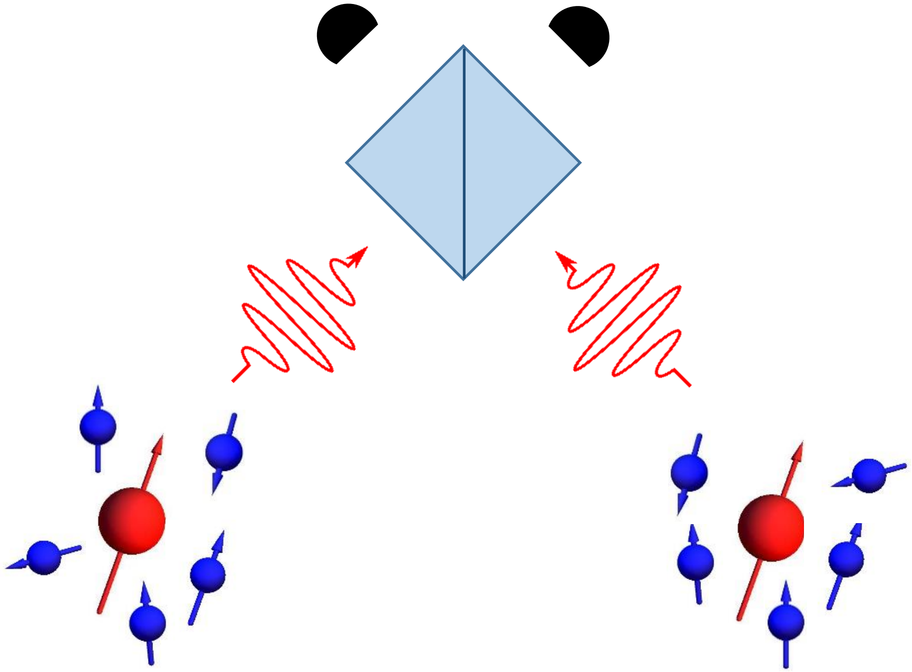


Splitting ~ 6.3 MHz

Linewidth ~ 2 MHz

$$\hat{H}_{hf} = \frac{\hbar}{2}\frac{A_{\parallel}}{2}\hat{S}_z\hat{I}_z + \frac{\hbar}{2}\frac{A_{\perp}}{2}\hat{S}_z\hat{I}_x$$

Electron coupled to nuclear spins



Overall strategy:

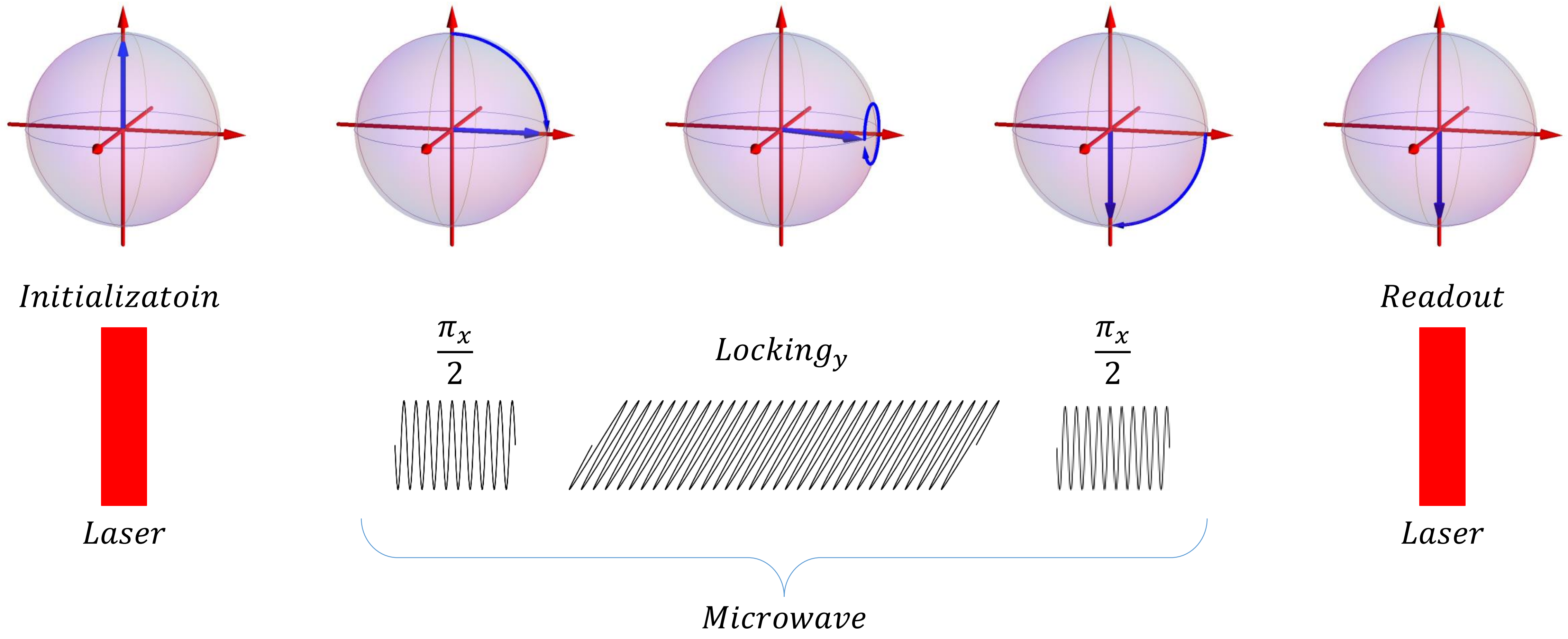
- Use Si(Ge,Sn…)V only as SPIN-PHOTON interface
- Use nuclear spin as a stationary qubit

Nuclear spin should be

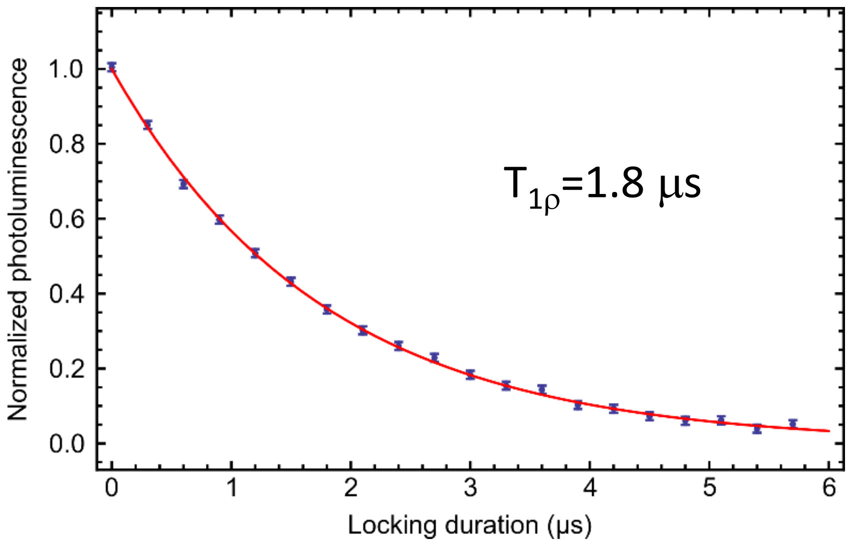
- initialized
- readout

M. Metsch et al., *Phys. Rev. Lett.* **122**, 190503 (2019)

Spin locking

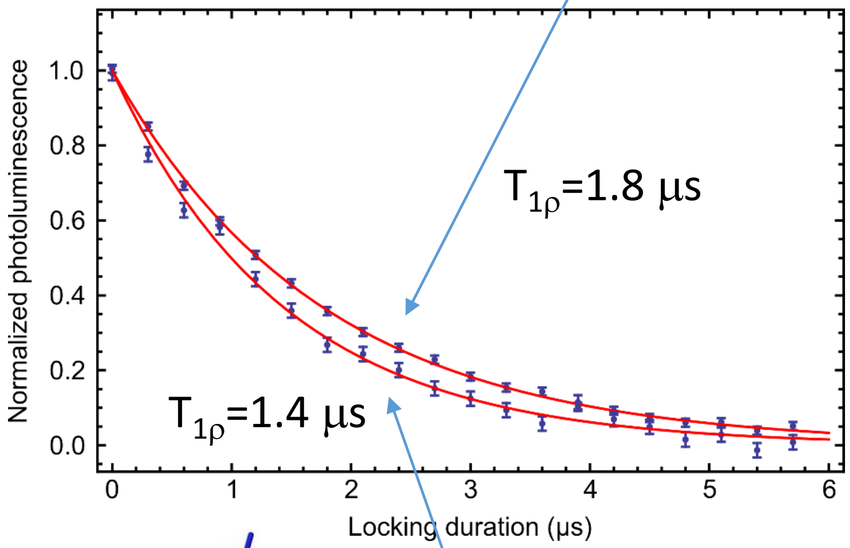


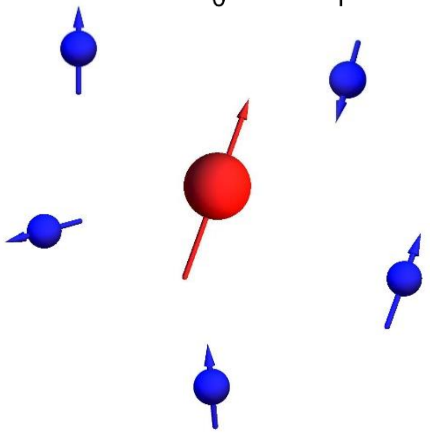
Spin locking and Hartmann-Hahn



Spin locking and Hartmann-Hahn

Away from nuclear Larmor frequency

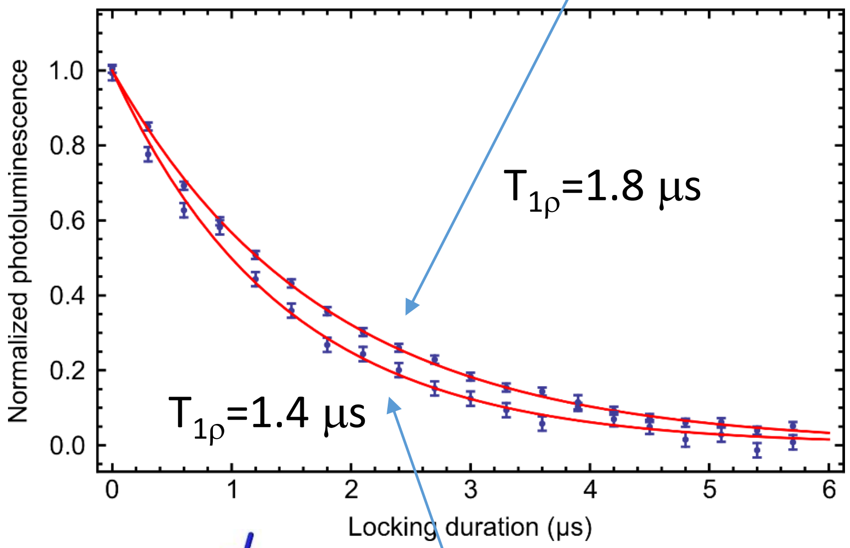


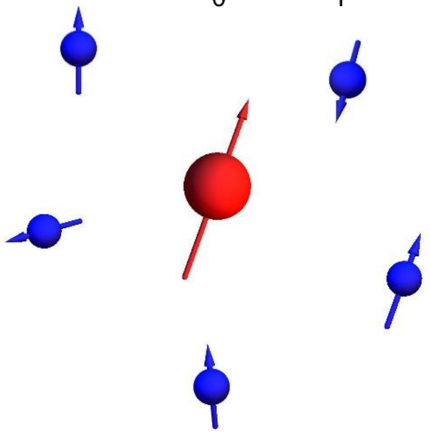


At resonance with nuclear Larmor frequency

Spin locking and Hartmann-Hahn

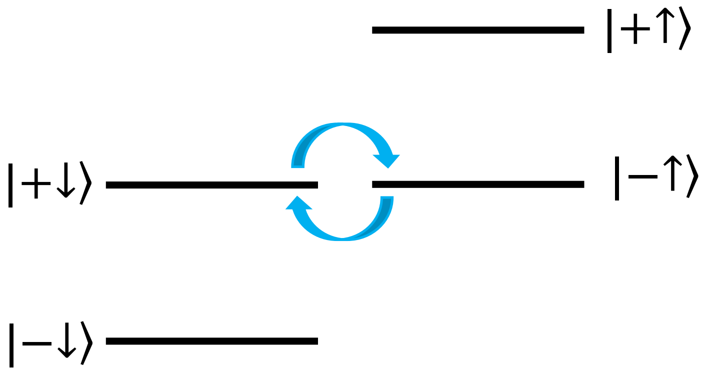
Away from nuclear Larmor frequency





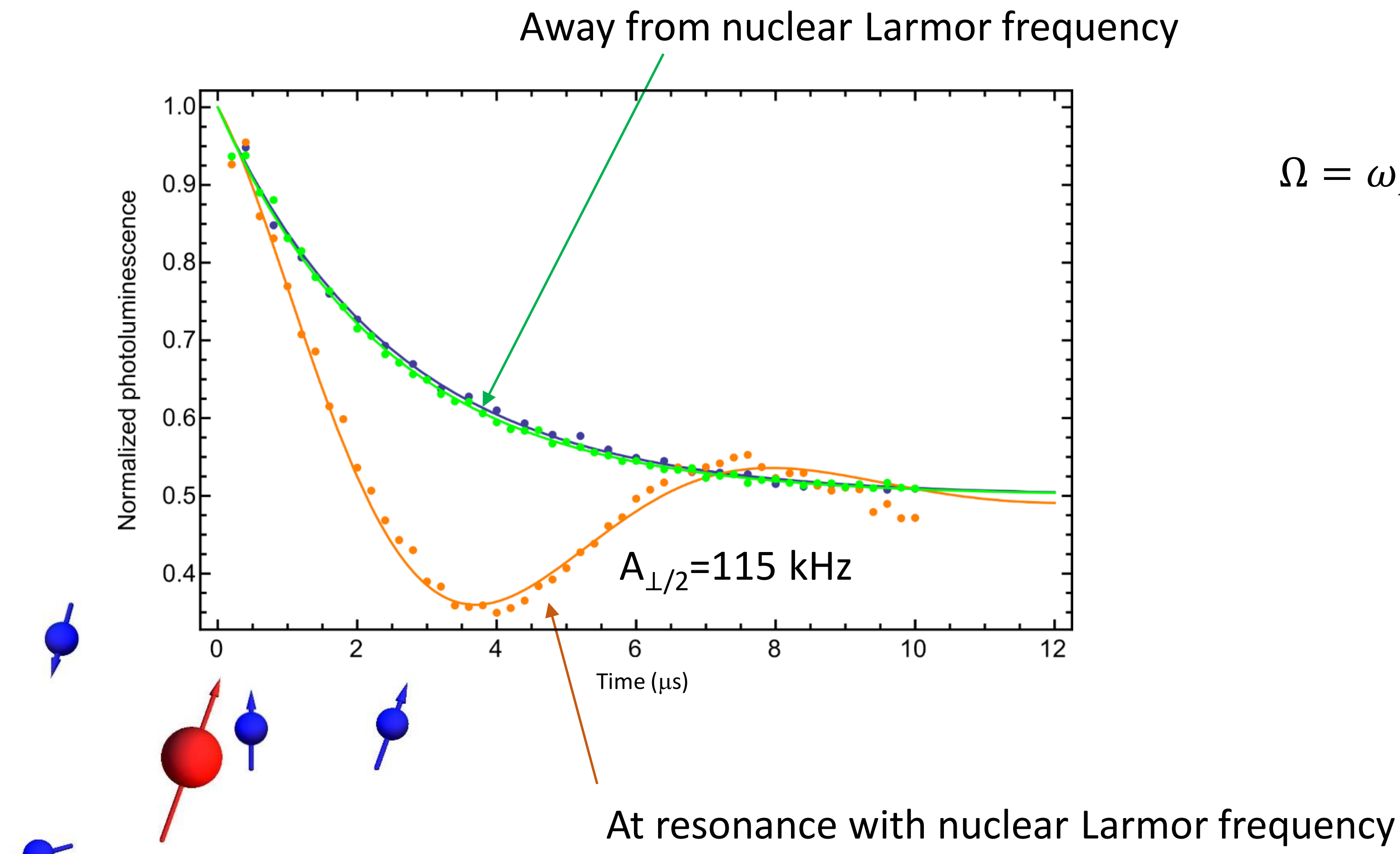
At resonance with nuclear Larmor frequency

$\Omega = \omega_L = \gamma_N B/\hbar$ Hartmann-Hahn condition

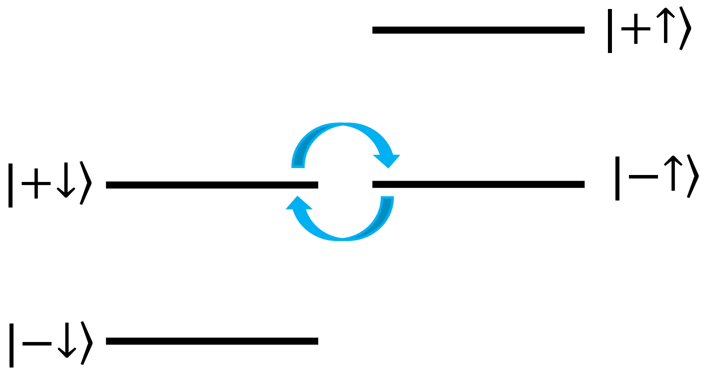


S. R. Hartmann and E. L. Hahn, Phys. Rev. ***128****, 2042 (1962)*

Spin locking and Hartmann-Hahn



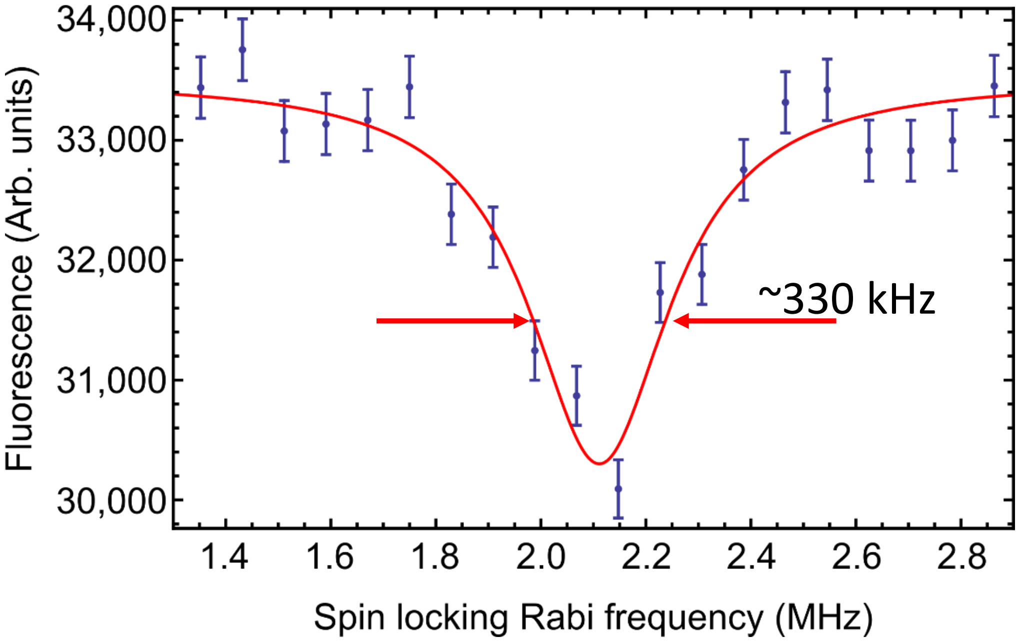
$\Omega = \omega_L = \gamma_N B/\hbar$ Hartmann-Hahn condition

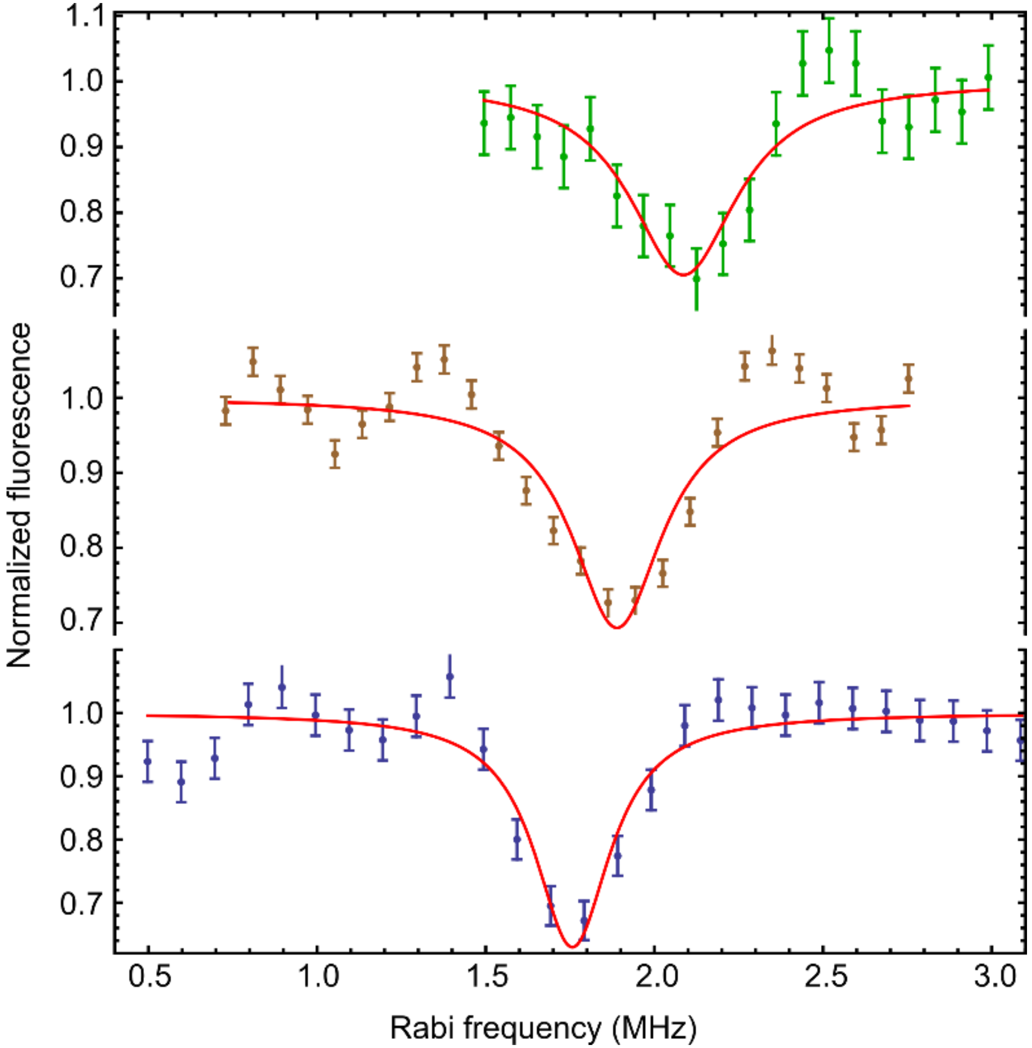


Oscillatory behavior reveals coupling to a single nuclear spin

S. R. Hartmann and E. L. Hahn, Phys. Rev. ***128****, 2042 (1962)*

Nuclear Larmor frequency

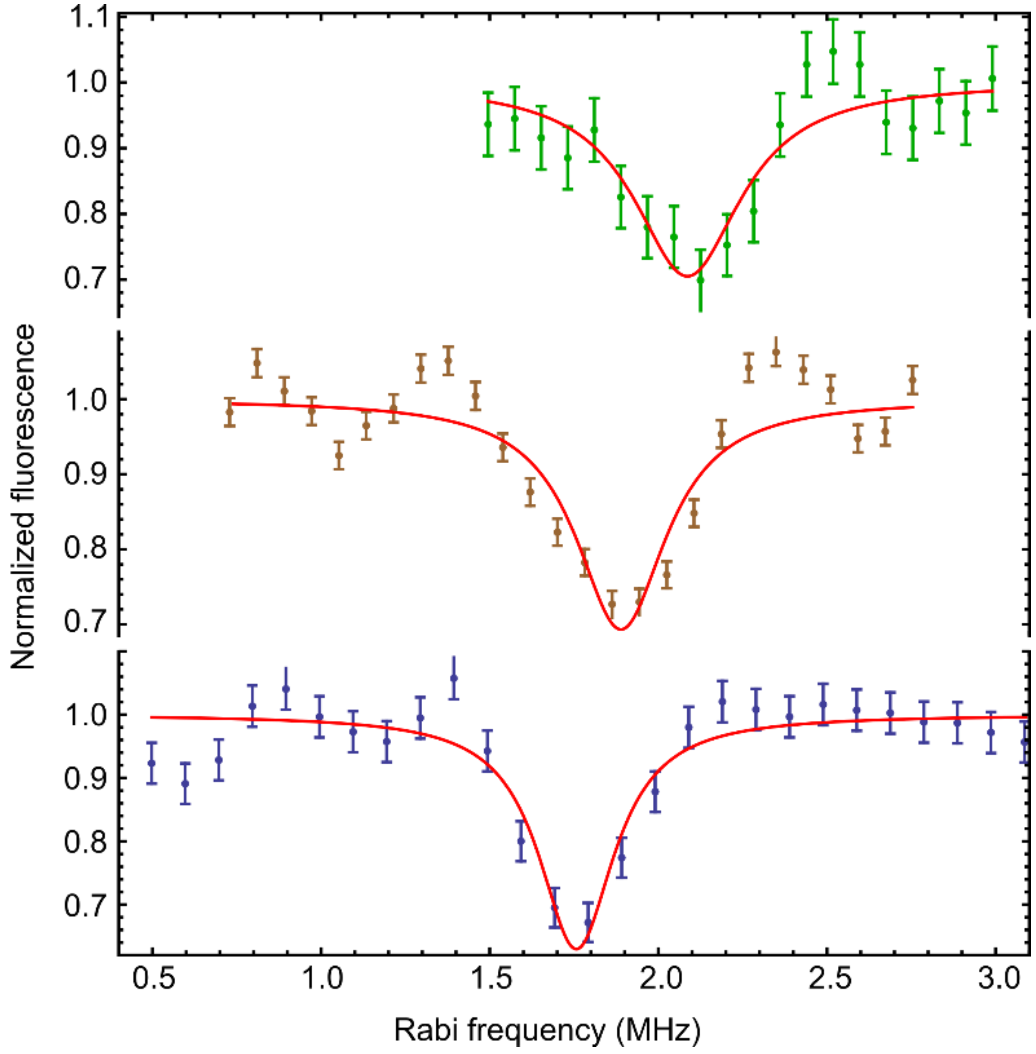


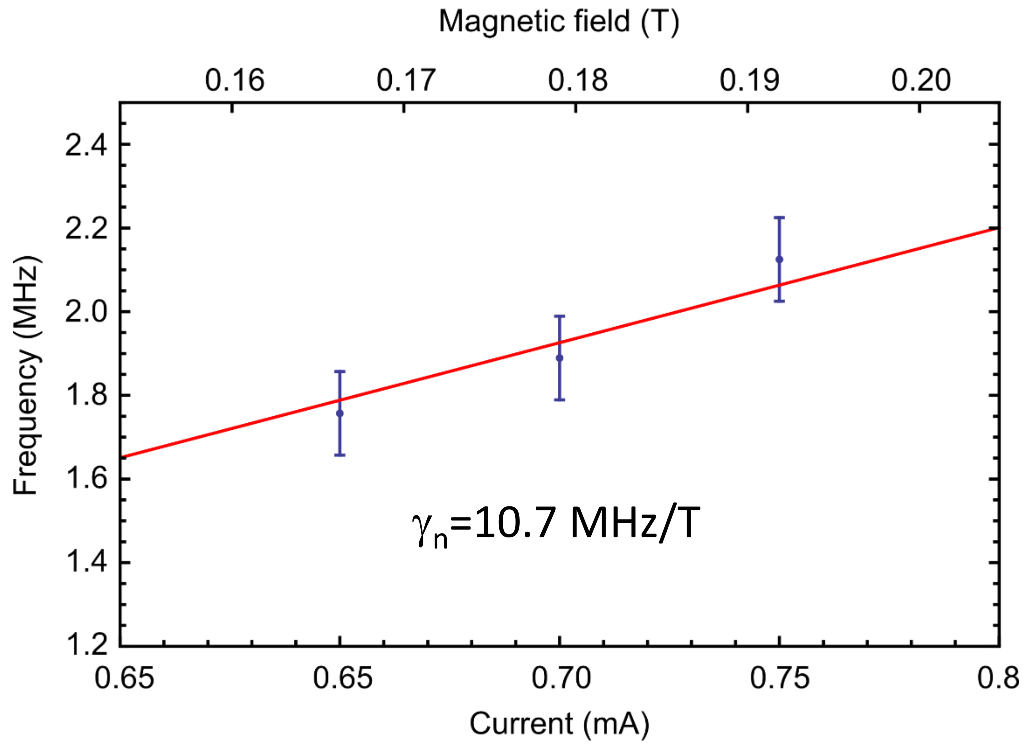


Larmor frequency of 2.1 MHz corresponds to 1970 G.

Width of the dip is most probably governed by the short pulse length of the locking pulse (in the order of 1 μs)

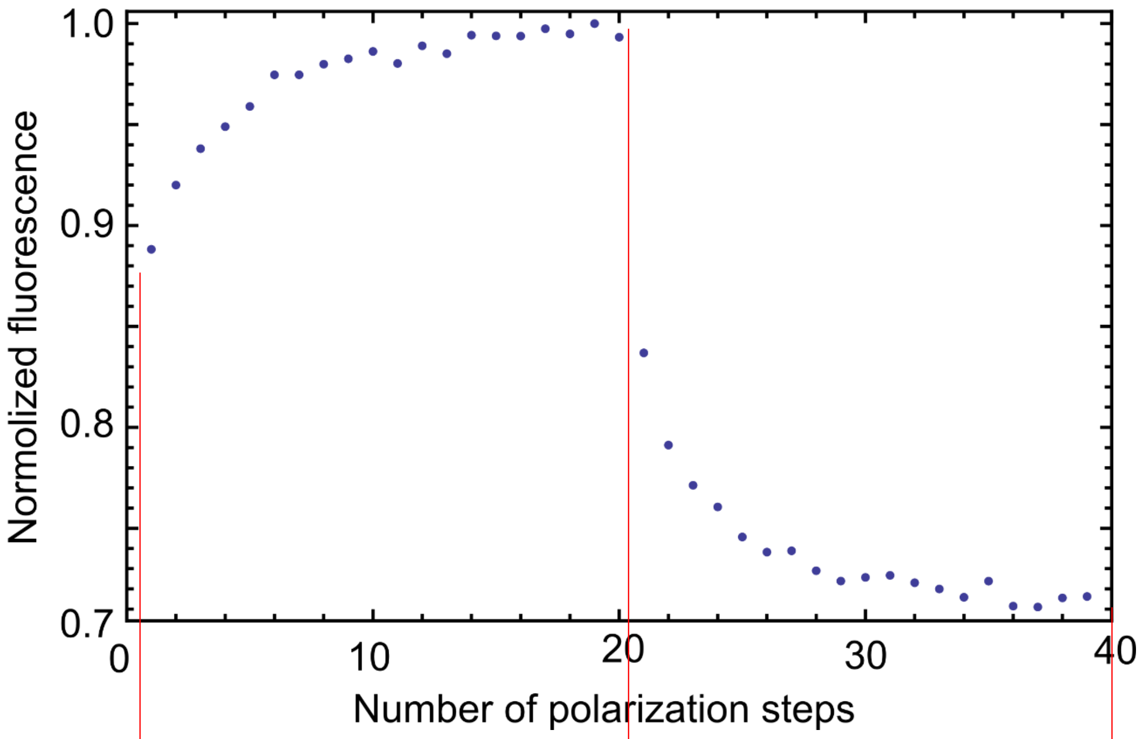
Nuclear Larmor frequency





Carbon-13 gyromagnetic ratio γ_n=10.705 MHz/T

Polarization of ^{13}C spin bath



Polarization in one direction

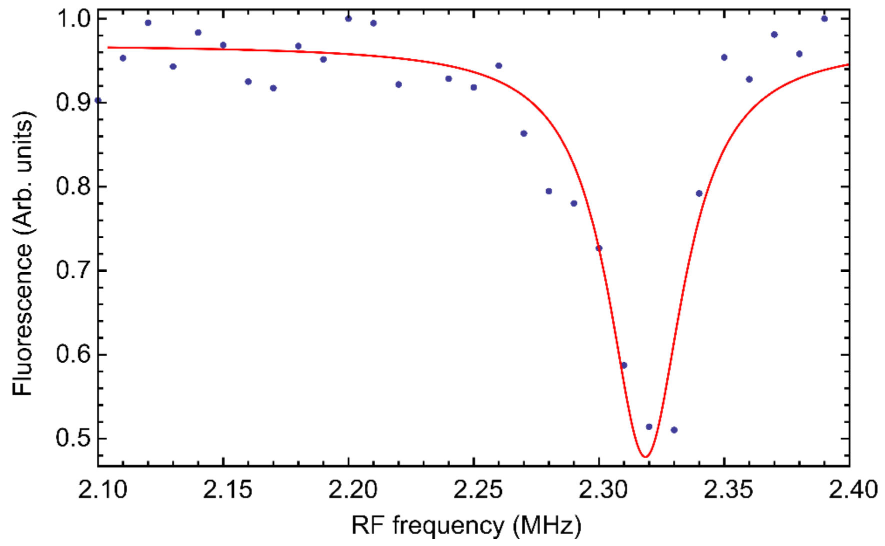
Polarization in opposite direction

Polarization of a spin bath using Hartmann-Hahn technique

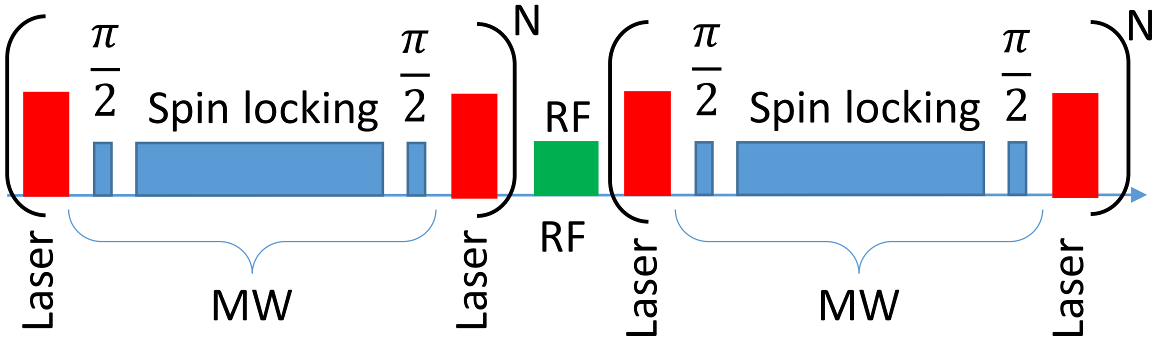
This can be used to readout nuclear spin state

Addressing individual nuclear spin

The nuclear resonance is shifted from the Larrmor by $A_{||}/2$

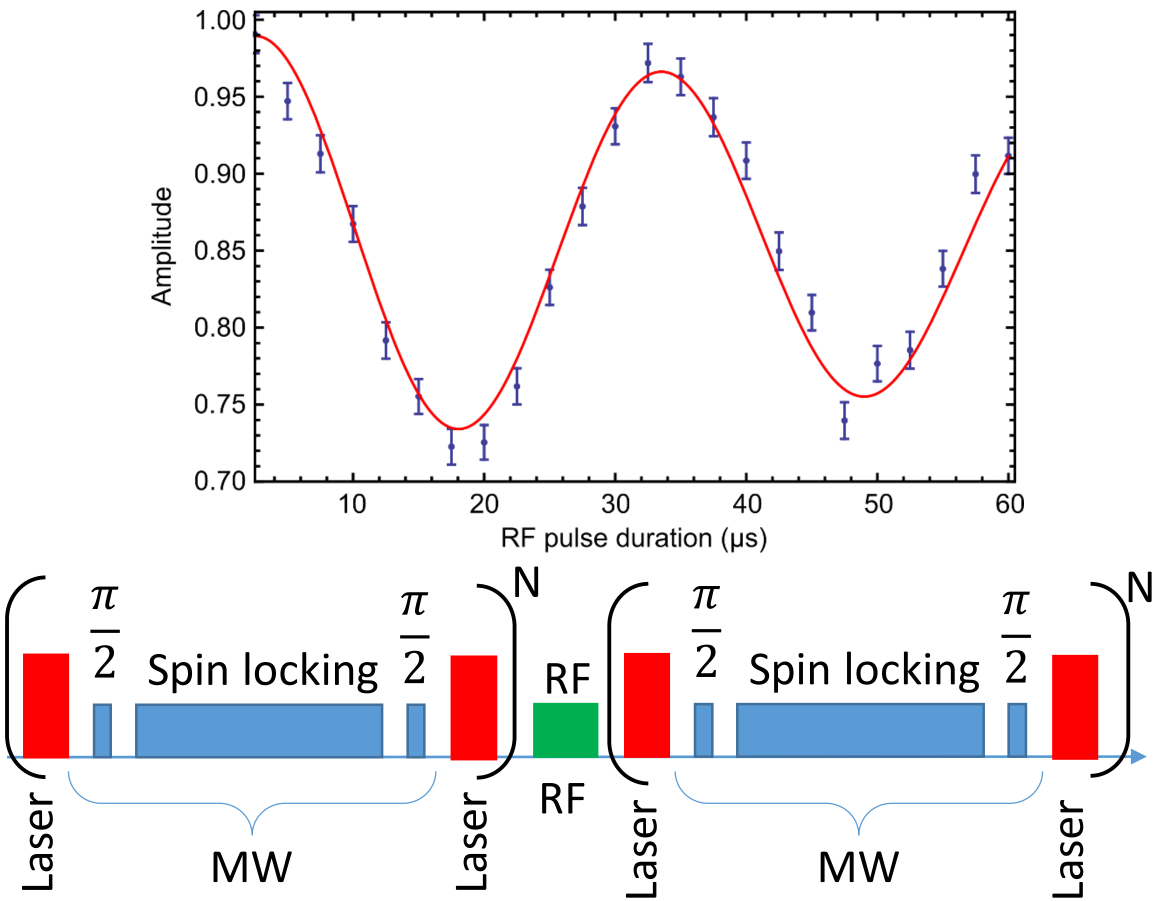


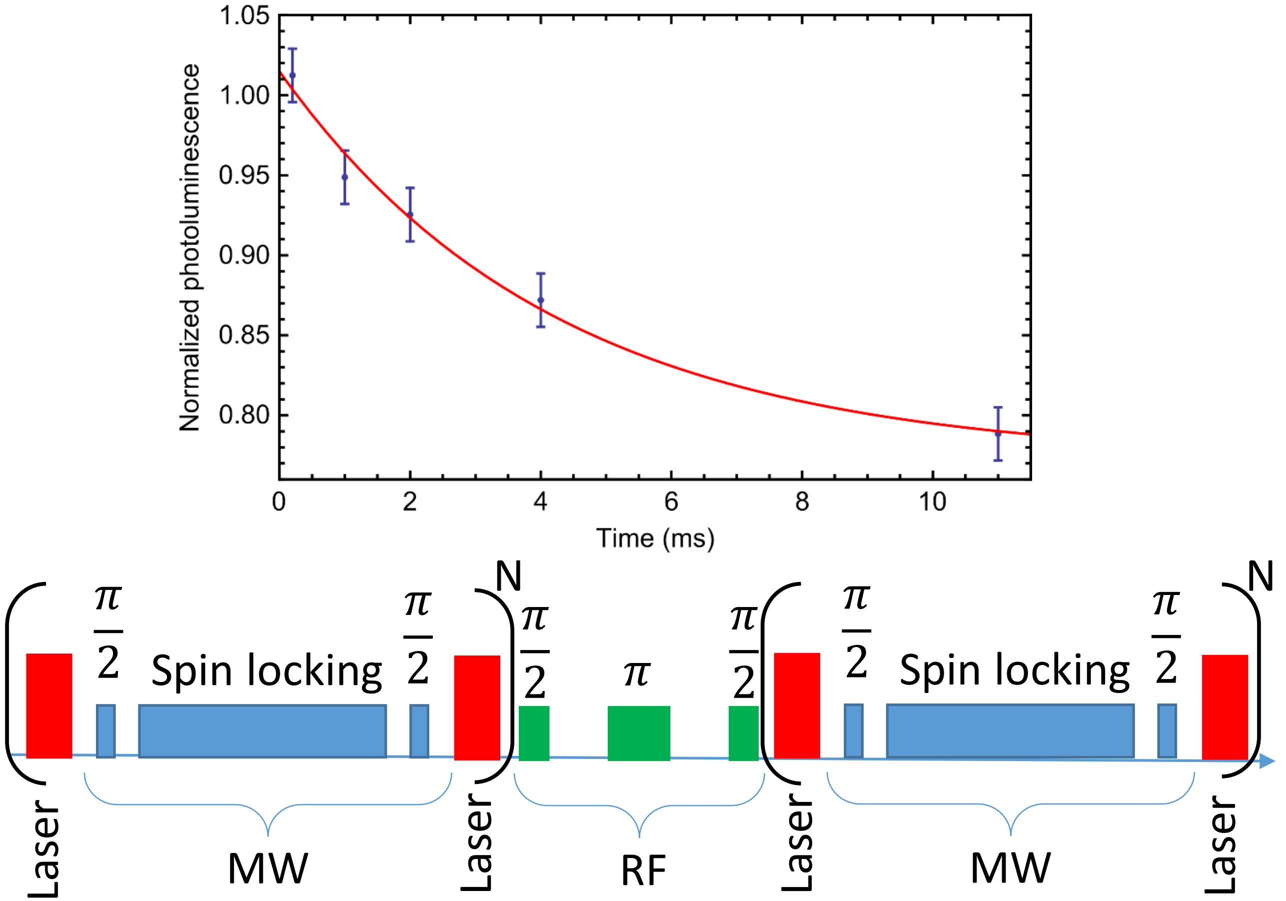
RF frequency is swept



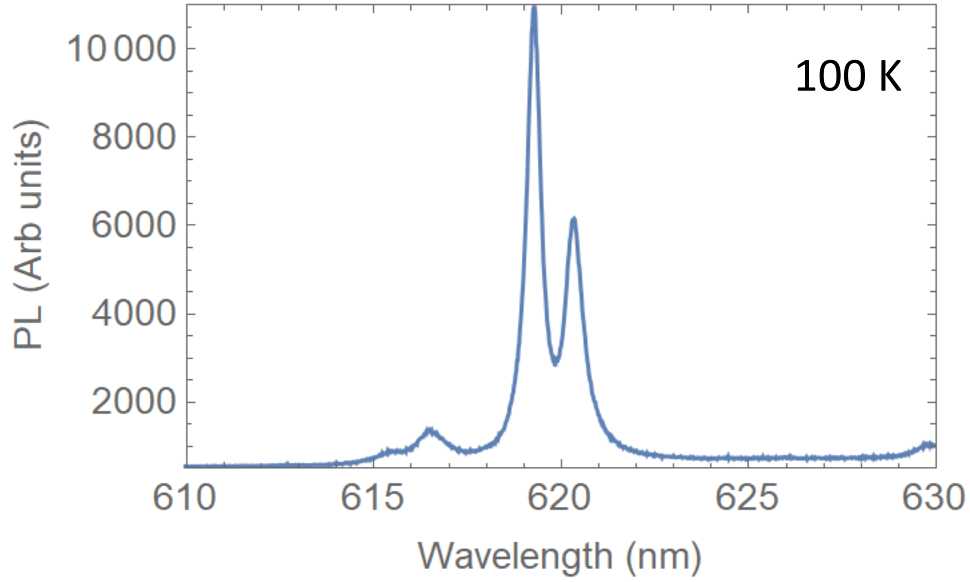
$\omega_L = 2\pi \times 1.96$MHz
$A_{||}/2 = 360$ KHz
$\omega_{res} = 2\pi \times 2.32$ MHz

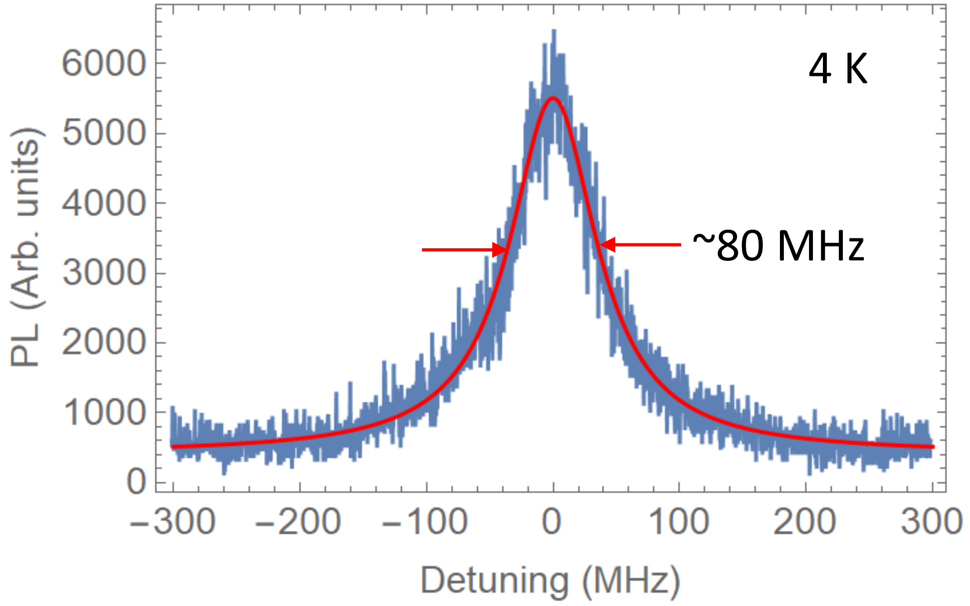
Readout of nuclear spins



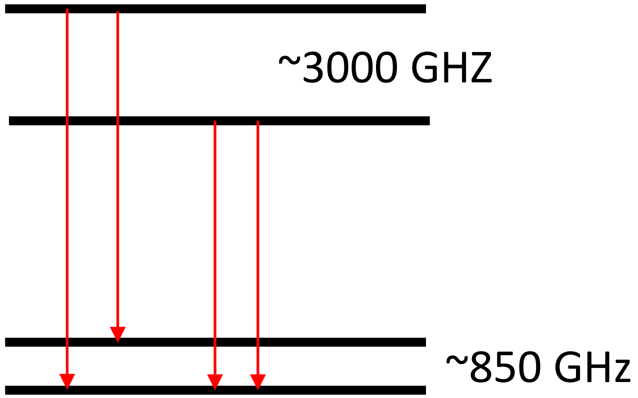


SnV spectra





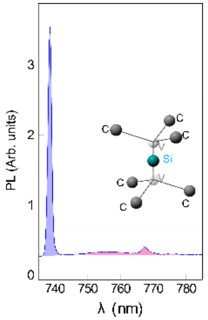
Not lifetime limited (~30MHz)…



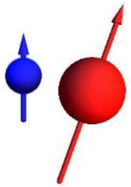
The relaxation time should increase by factor of 17

Conclusion

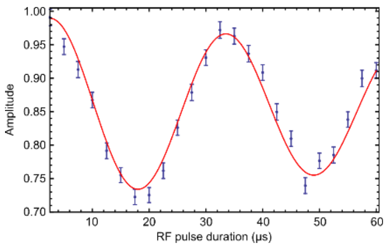
- Excellent optical properties



- Electron spin can be initialized, coherently manipulated and read out
- Defect can be coupled to nuclear spin



- Nuclear spin can be polarized and read out via electron spin



- SnV should enable longer electron coherence time

Our collaborators who produce diamonds

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(Tokyo Institute of Technology)

Jocelyn Achard
Alexandre Tallaire
(Université Paris 13)

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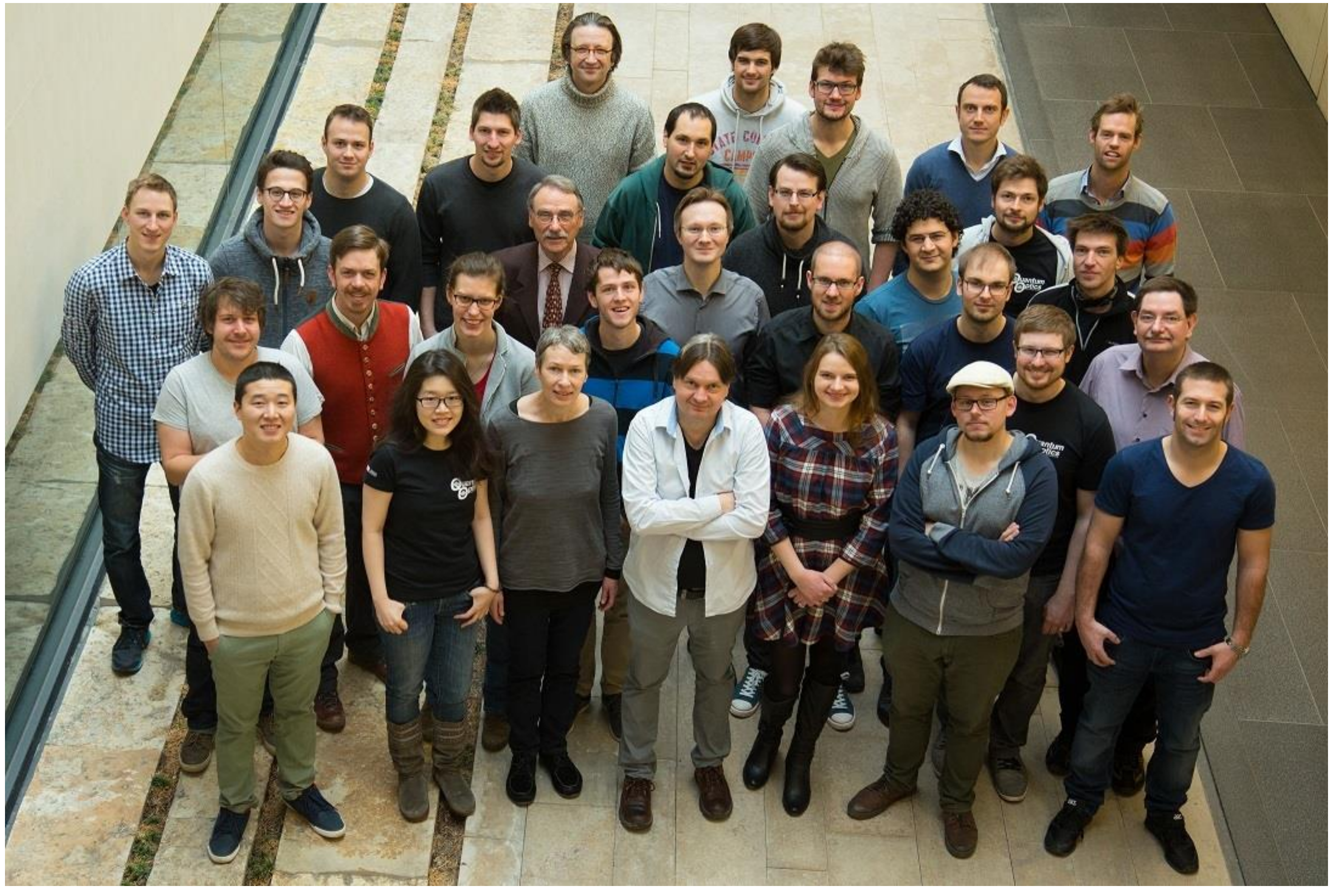
Quantum Optics
www.quantenoptik.de



Thank you for your attention!