

Imaging non-collinear antiferromagnetic textures via single spin relaxometry

Aurore Finco

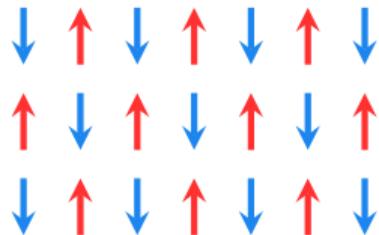
Laboratoire Charles Coulomb, Université de Montpellier and CNRS, Montpellier, France



EMA online seminar, November 12th 2020

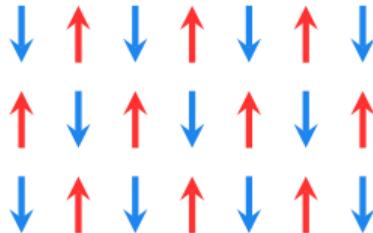
slides available at <https://magimag.eu>

Why is it interesting to look at antiferromagnets?



Alternating magnetic moments

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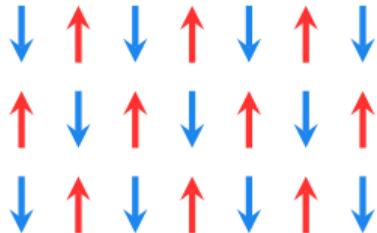
Alternating magnetic moments

► **Spintronics:** robust, fast, efficient

■ T. Jungwirth *et al.* *Nat. Nano.* 11 (2016), 231

■ V. Baltz *et al.* *Rev. Mod. Phys.* 90 (2018)

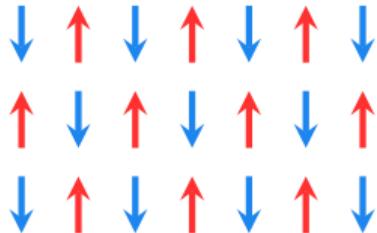
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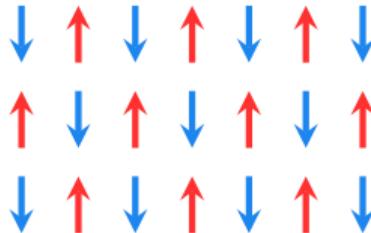
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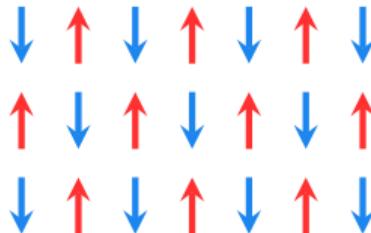


Alternating magnetic moments

No net magnetization
Weak signals

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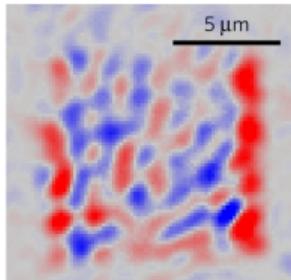
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→ Antiferromagnetic structures are difficult to image!

▣ S.-W. Cheong *et al.* *npj Quant. Mat.* 5 (2020), 1

How to look at antiferromagnetic states?

SHG

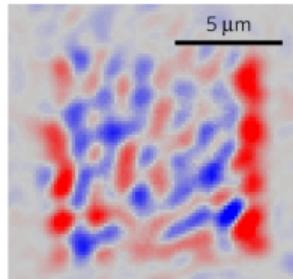


J.-Y. Chauleau et al. *Nat. Mat.* 16 (2017), 803

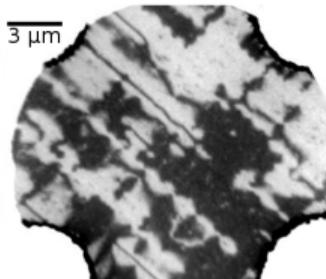


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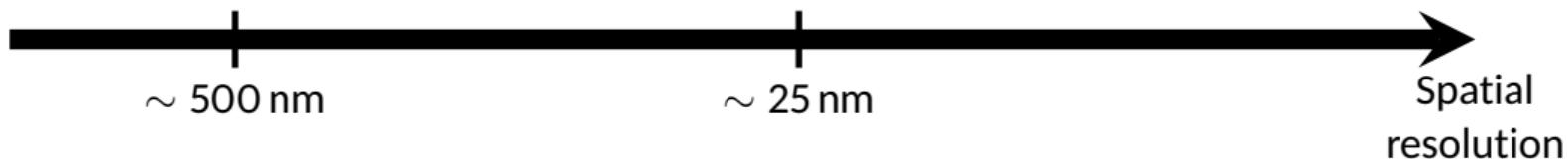


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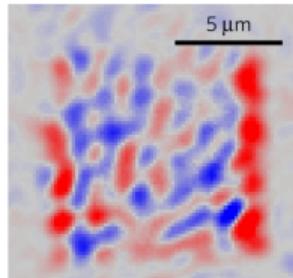
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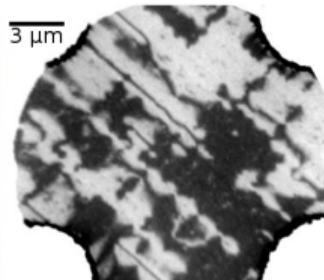
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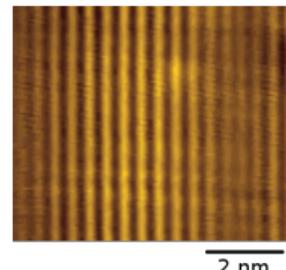
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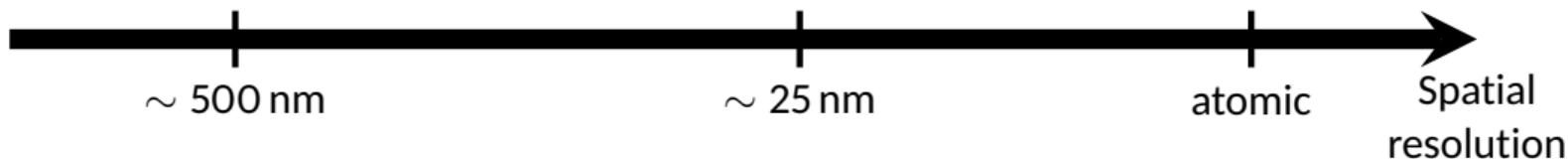


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SP-STM

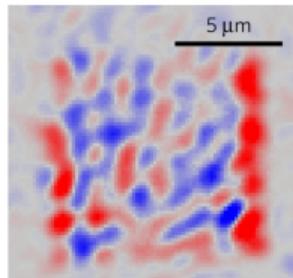


■ M. Bode et al. *Nature* 447 (2007), 190



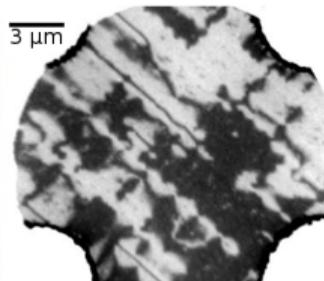
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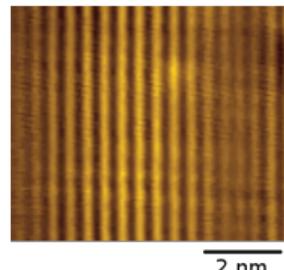
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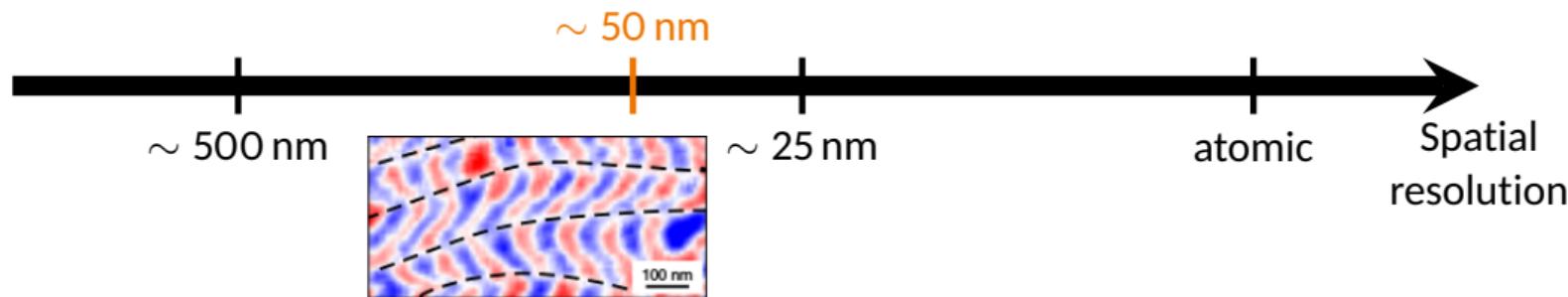


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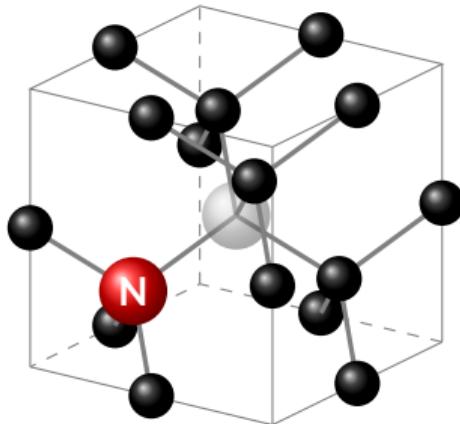
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NV magnetometry

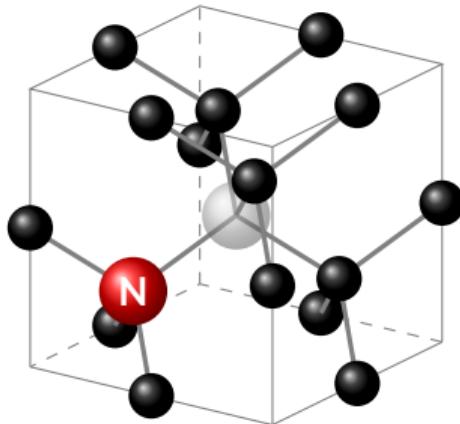
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NV centers

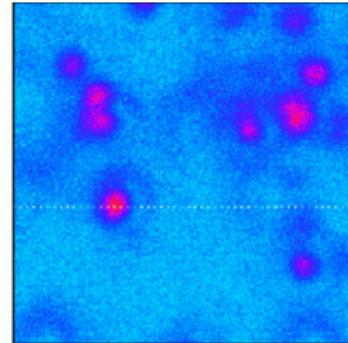


Defect in diamond

NV centers

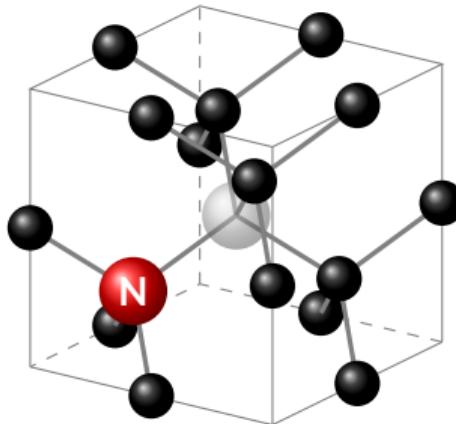


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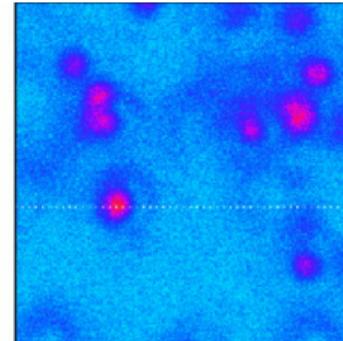


■ A. Gruber et al. *Science* 276 (1997), 2012

NV centers



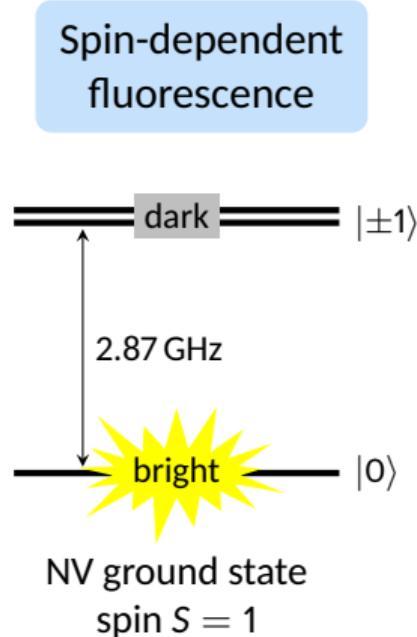
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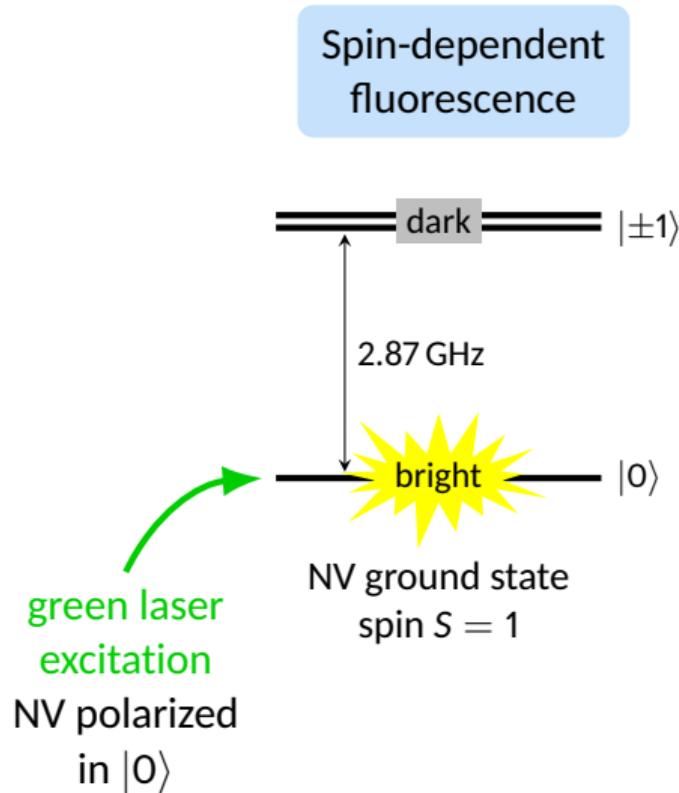
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- ▶ Stable photoluminescence
- ▶ Spin $S = 1$
- ▶ Optical manipulation and reading
- ▶ Ambient conditions

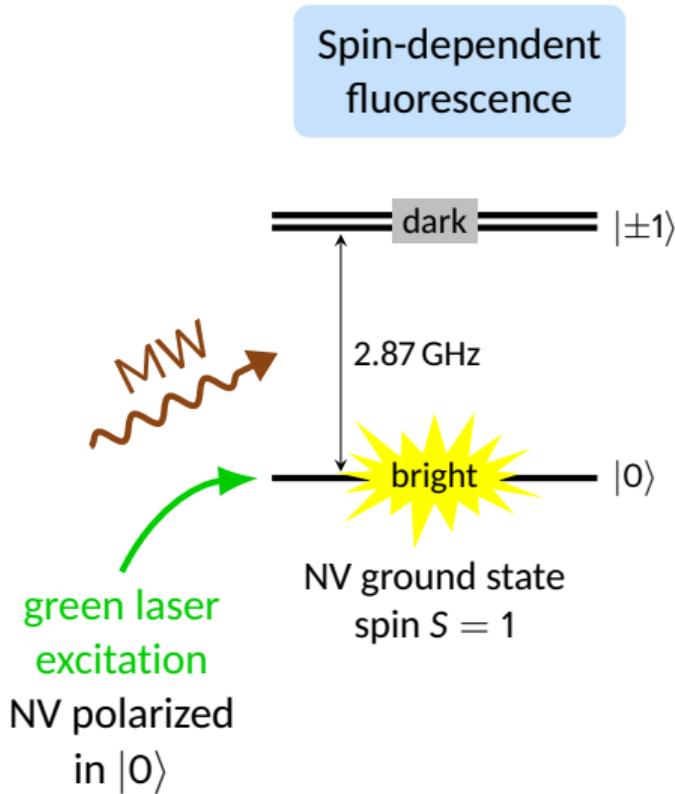
NV centers as quantum sensors for weak magnetic fields



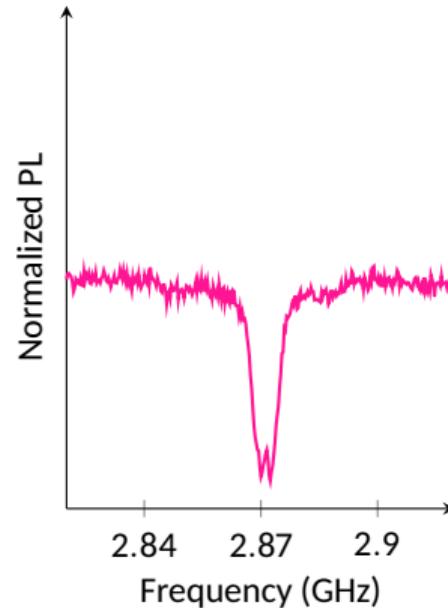
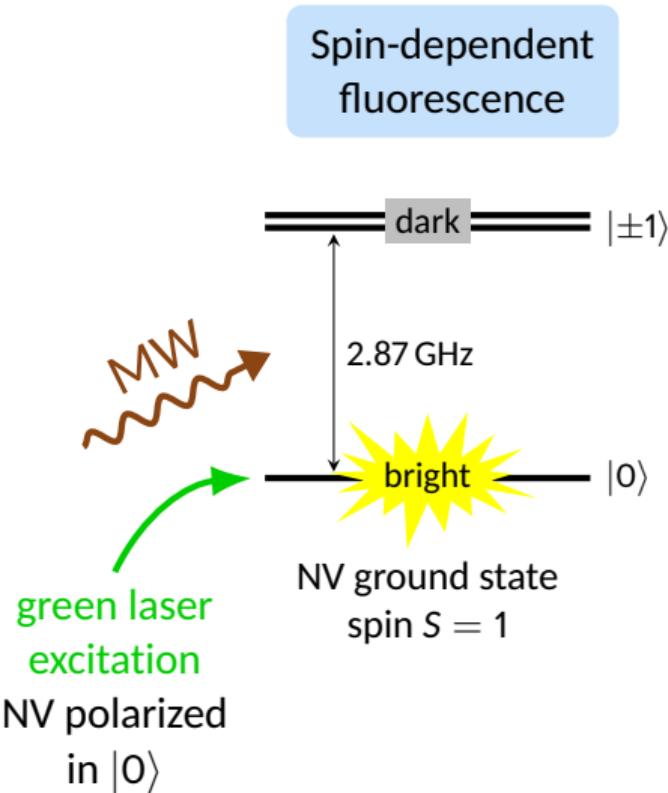
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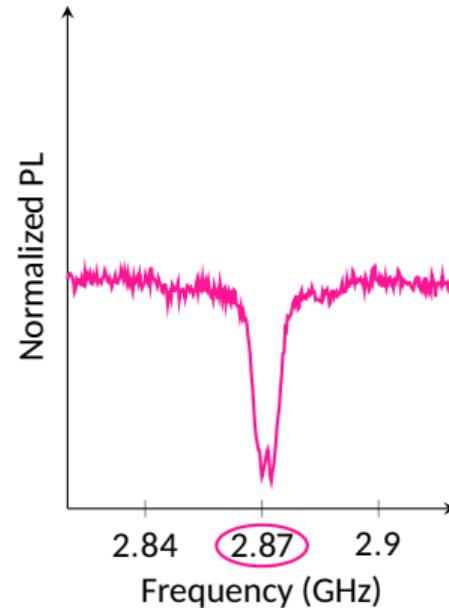
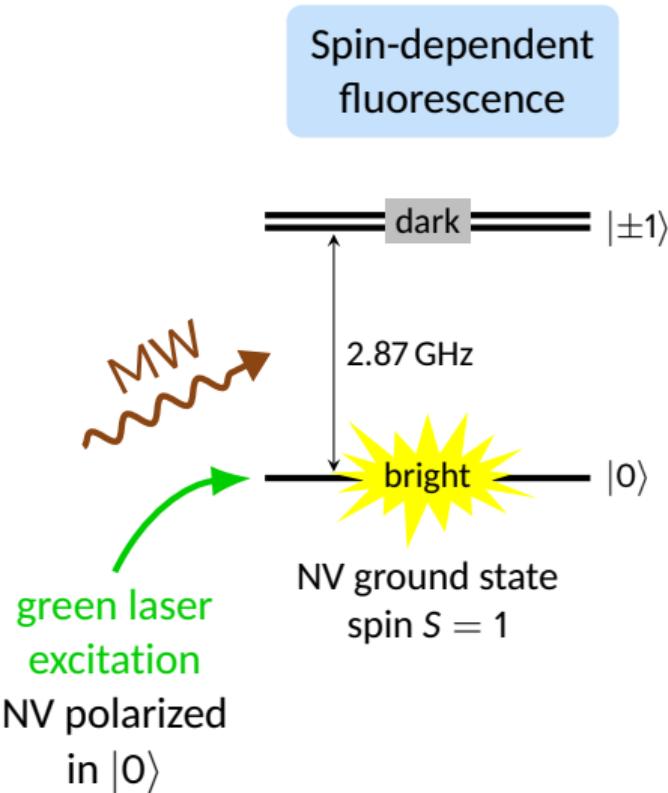
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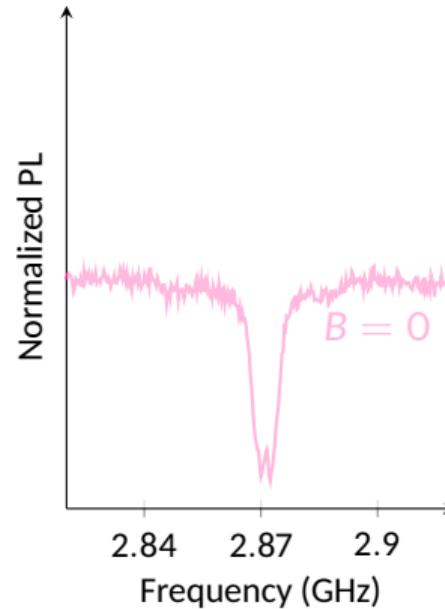
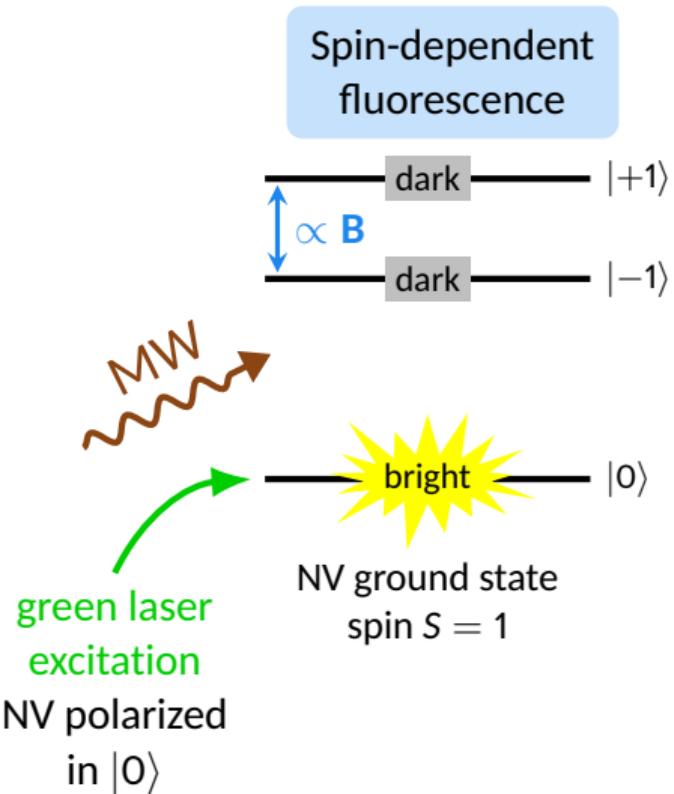
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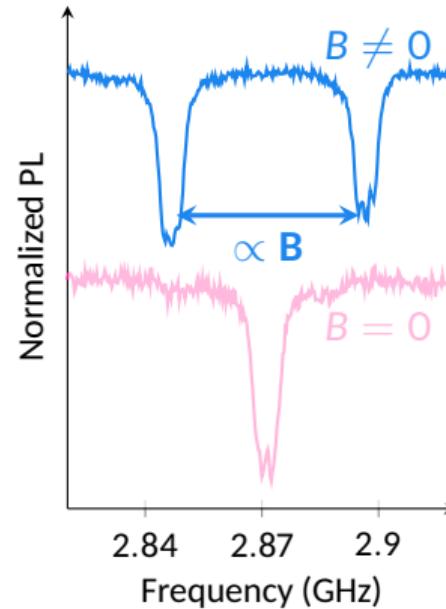
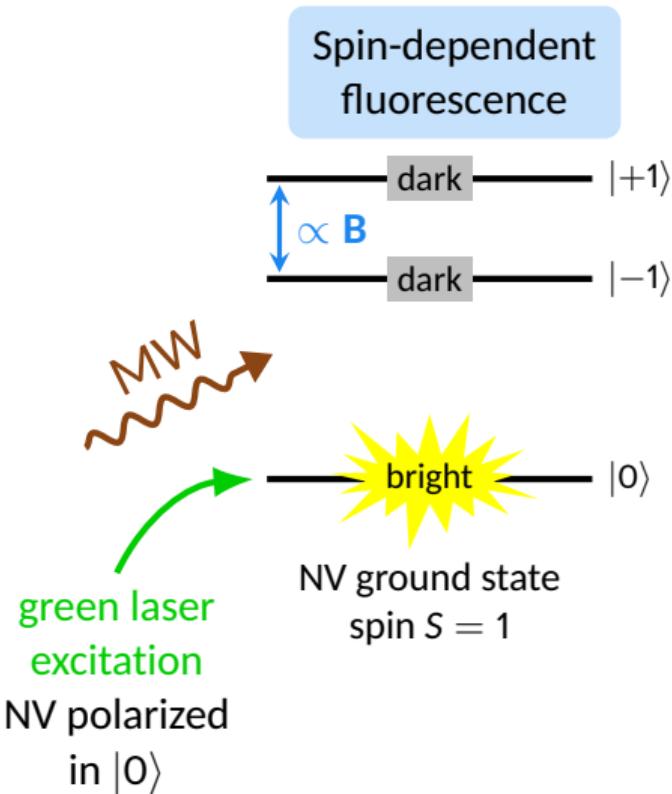
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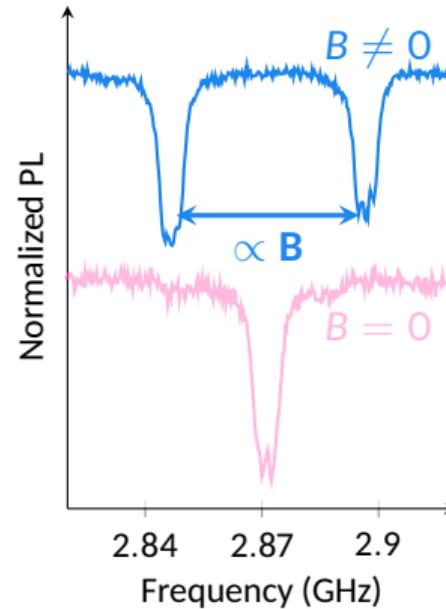
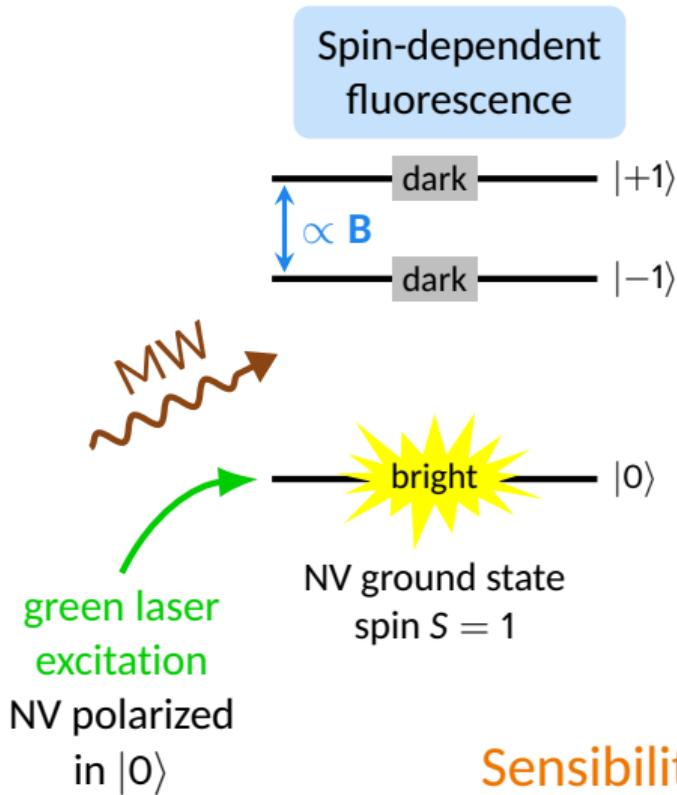
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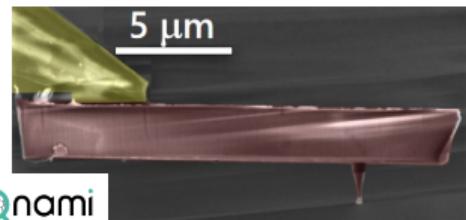
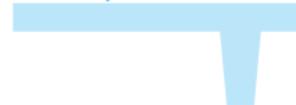
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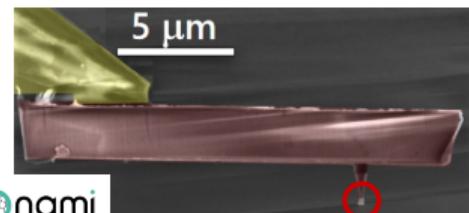
Sensibility: a few $\mu\text{T}/\sqrt{\text{Hz}}$

NV scanning magnetometry applied to antiferromagnets

Diamond
AFM tip

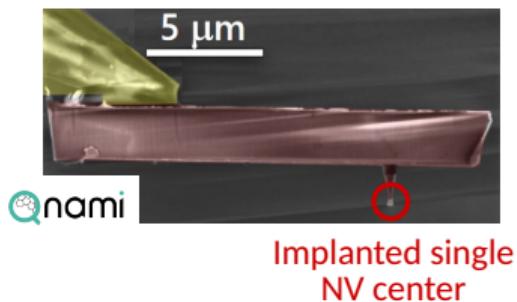
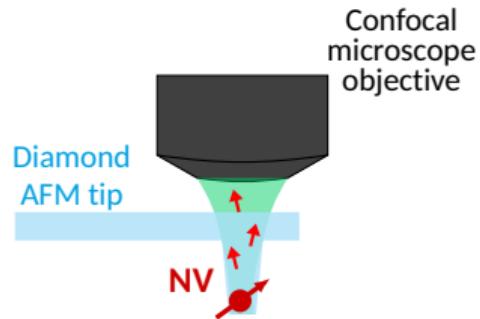


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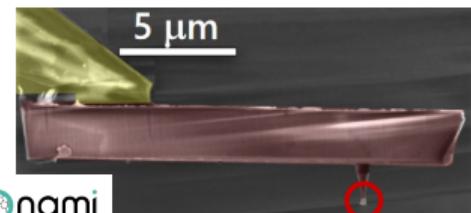
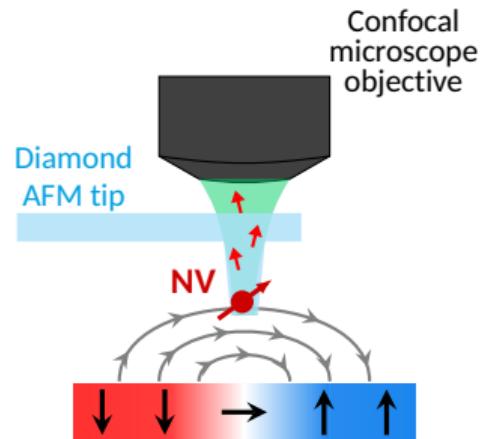


Implanted single
NV center

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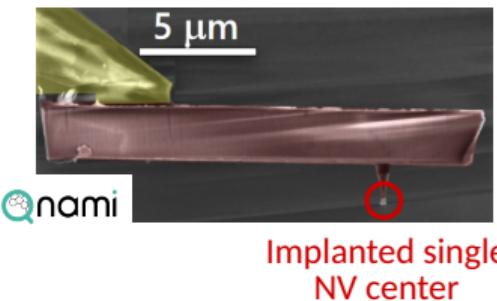
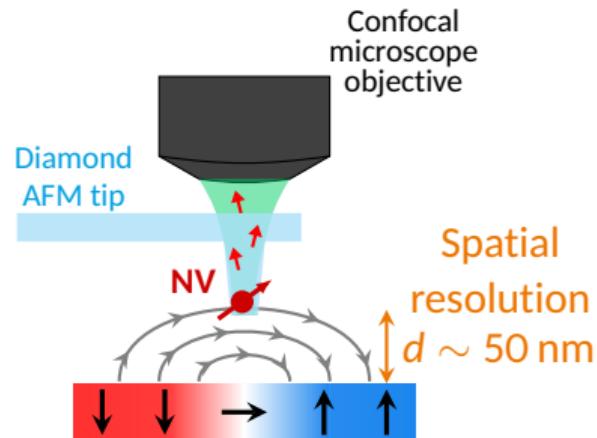


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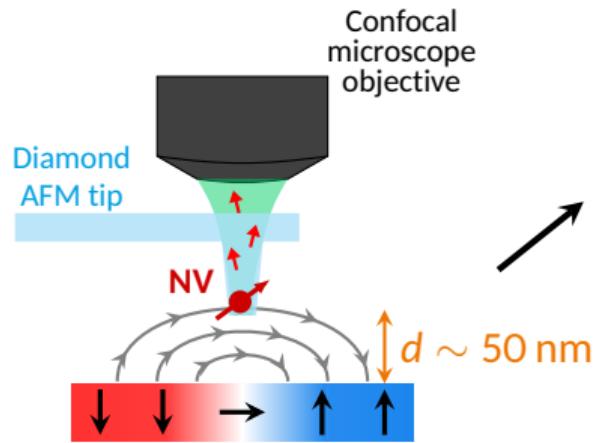


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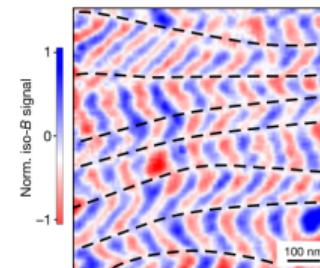
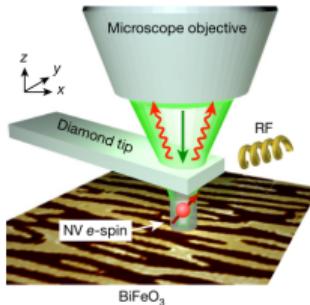
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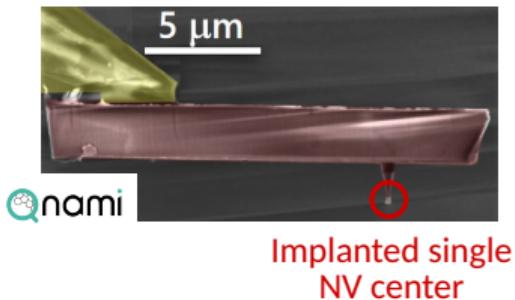


BiFeO₃: a room-temperature multiferroic

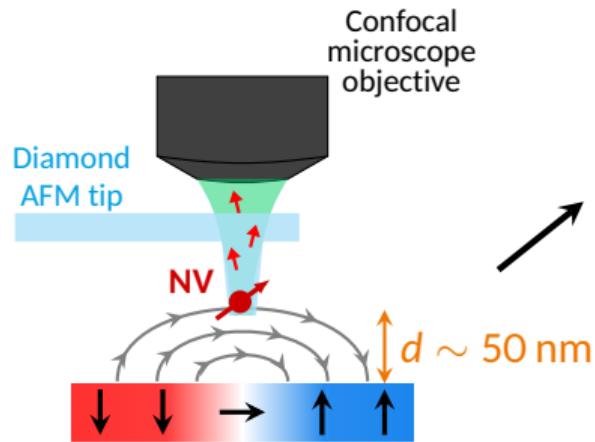


I. Gross et al. *Nature* 549 (2017), 252

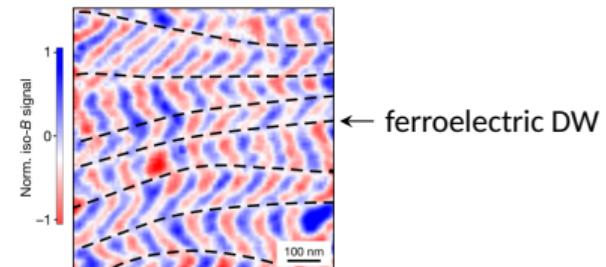
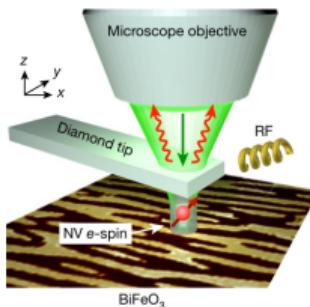
A. Haykal et al. *Nat. Comm.* 11 (2020), 1704



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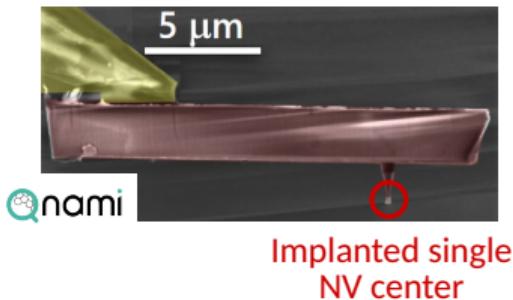


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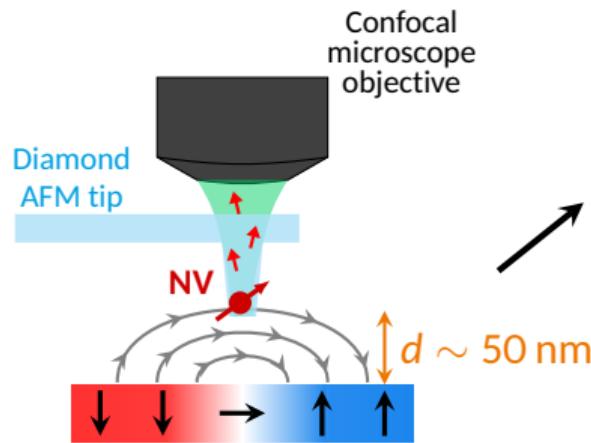


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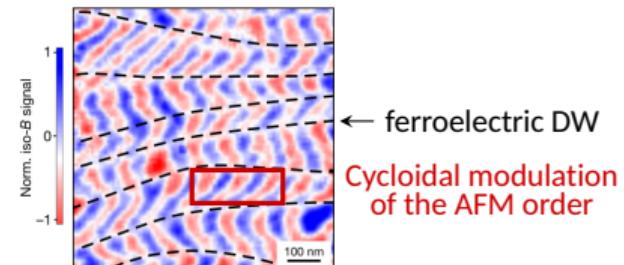
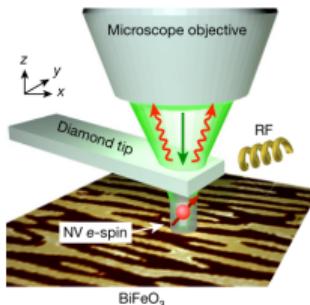
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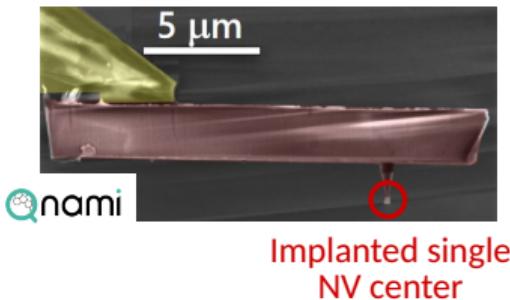


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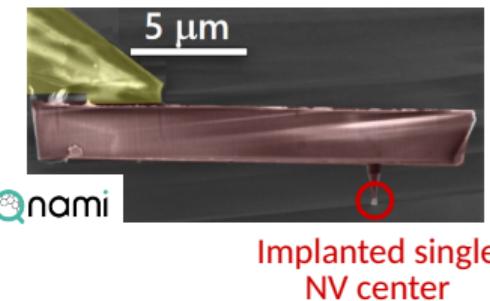
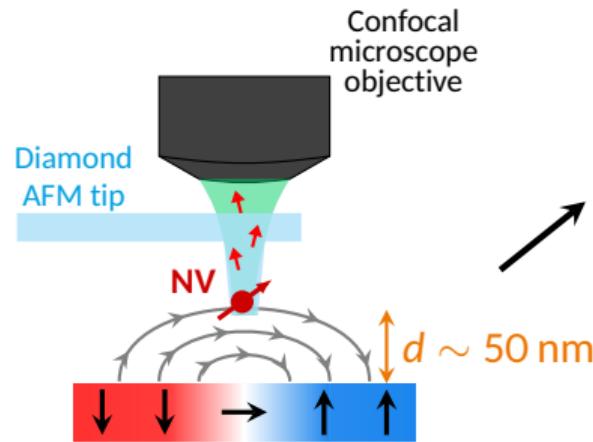


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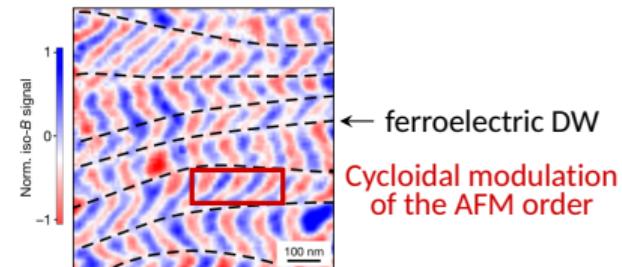
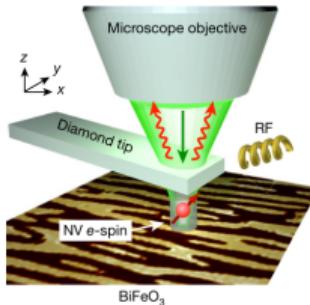
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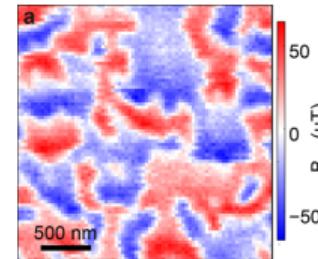
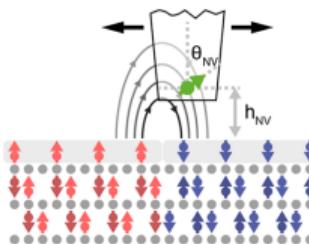
BiFeO_3 : a room-temperature multiferroic



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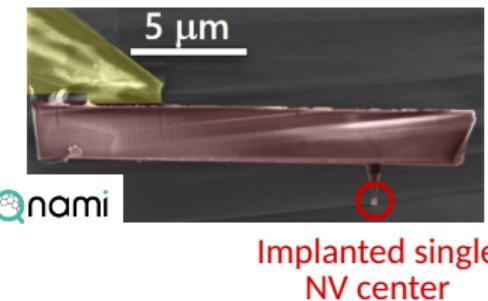
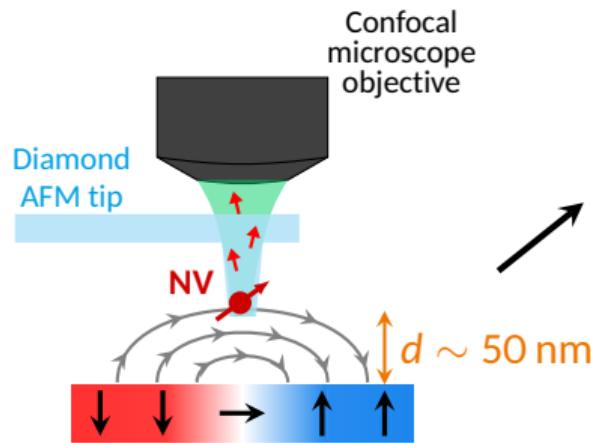
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Cr_2O_3 : a layered antiferromagnet

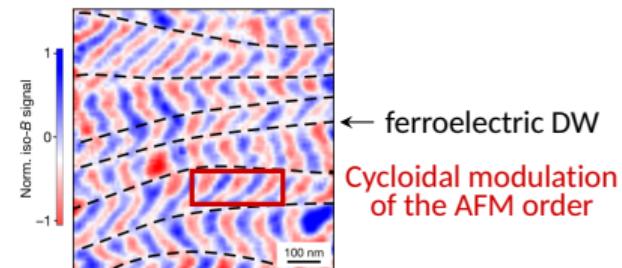
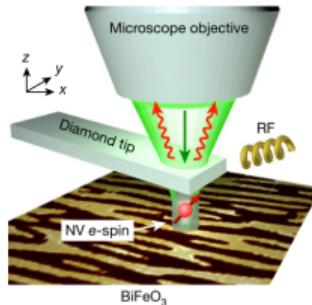


P. Appel et al. *Nano Lett.* 19 (2019), 1682

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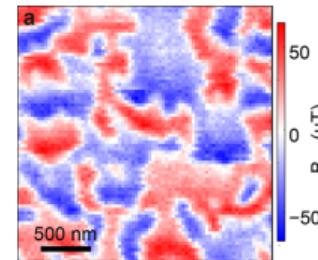
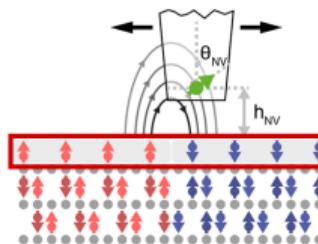
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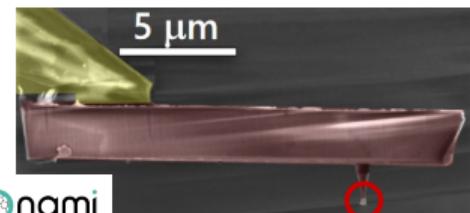
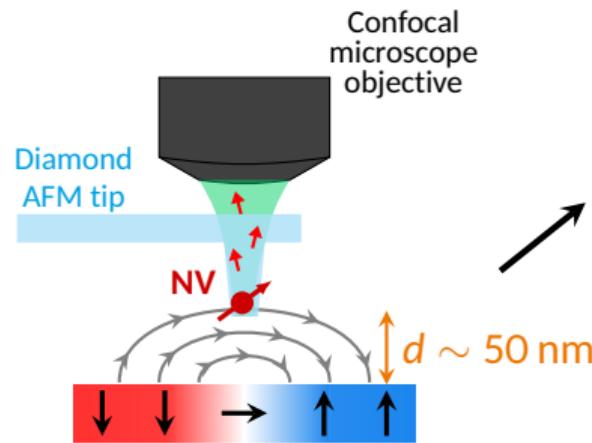
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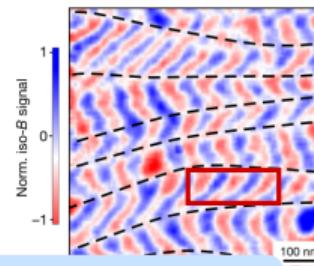
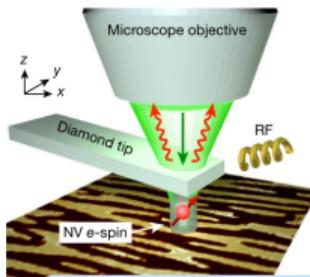
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BiFeO_3 : a room-temperature multiferroic

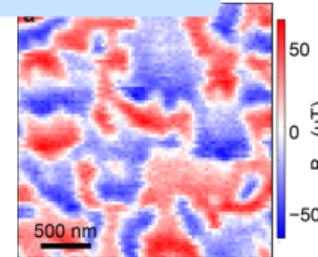
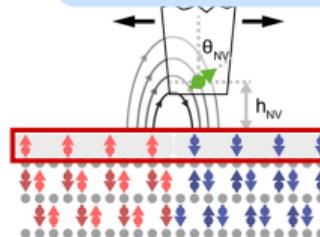


Cycloidal modulation
of the AFM order

Nature 549 (2017), 252
Comm. 11 (2020), 1704

Antiferromagnets with small
uncompensated moments

What if this is not the case?



P. Appel et al. Nano Lett. 19 (2019), 1682

Proposal: use relaxometry

- Completely compensated antiferromagnets = **no static stray field** to probe

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 B. Flebus *et al.* *Phys. Rev. B* 98 (2018), 180409

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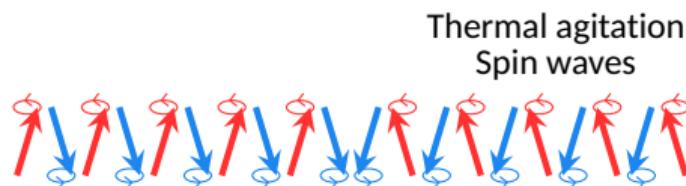
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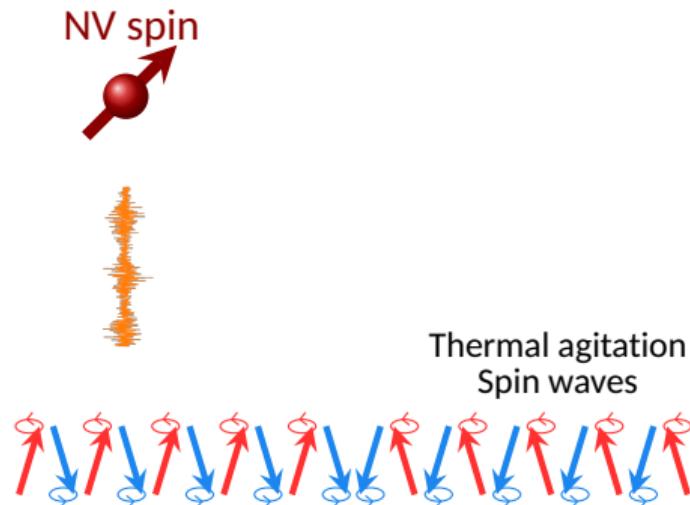
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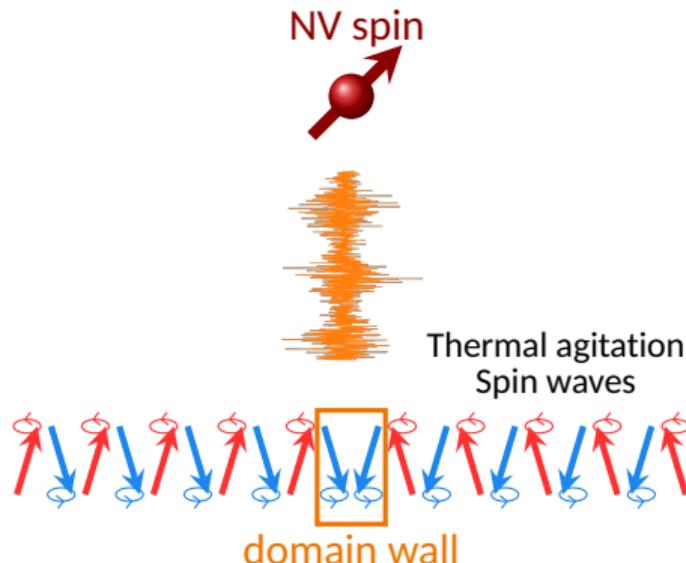
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Outline

Collaborations: C2N: Thibaut Devolder, Jean-Paul Adam, Joo-Von Kim

UMR CNRS/Thales: William Legrand, Fernando Ajejas,
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Vincent Cros



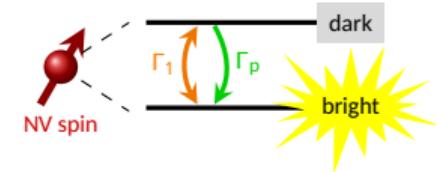
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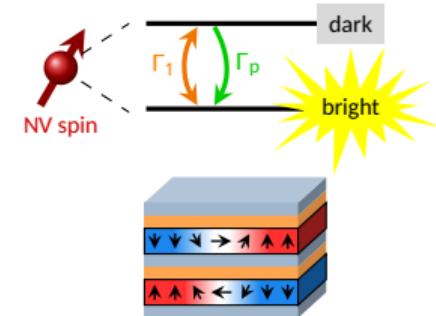
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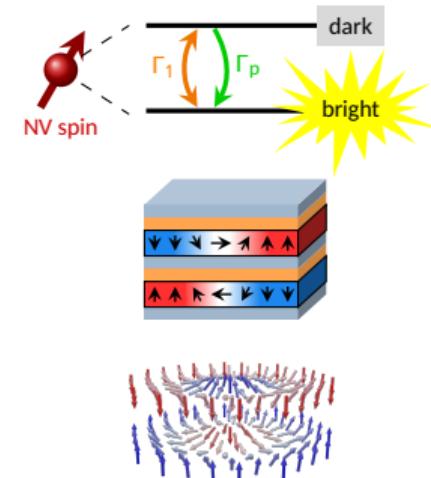
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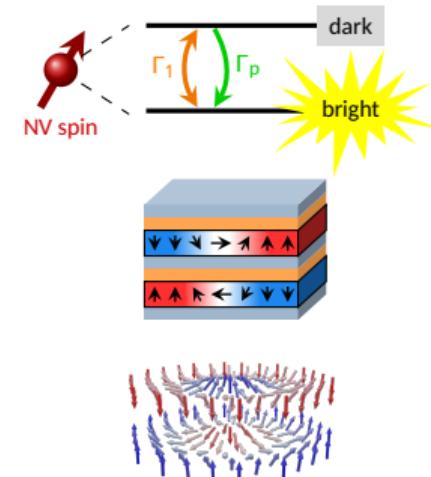
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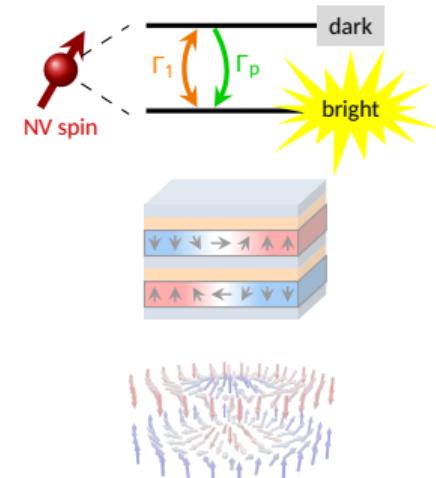
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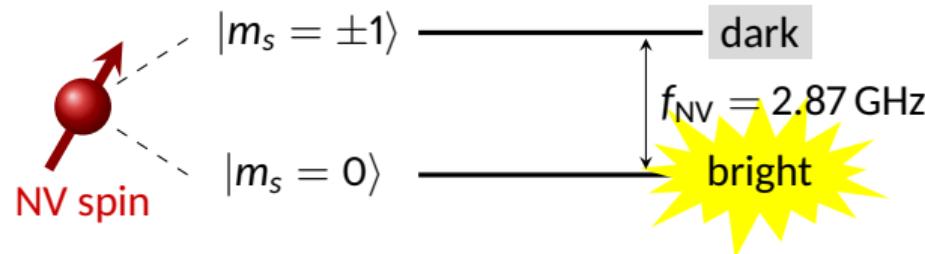
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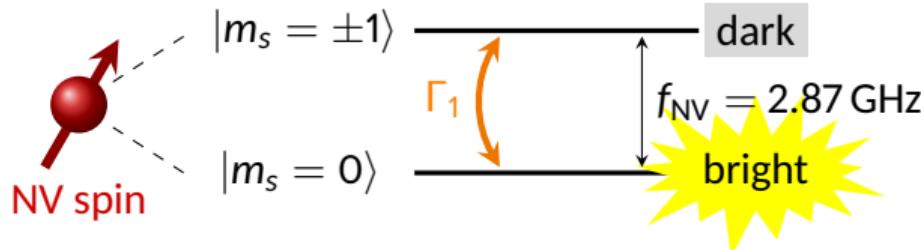
Detecting magnetic noise from the emitted PL



→ Static \vec{B} field

Zeeman shift of the
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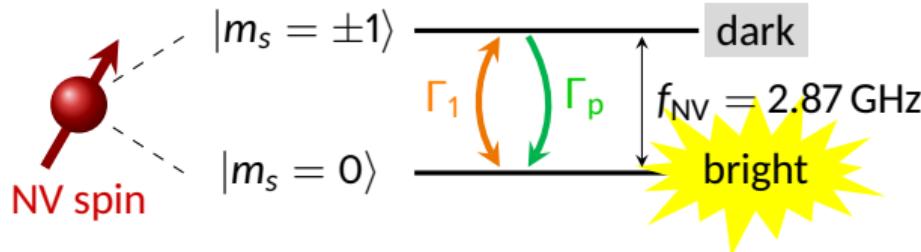
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Acceleration of the spin relaxation

Relaxation rate $\Gamma_1 \propto S_{B_\perp}(f_{\text{NV}})$
magnetic field spectral density at the resonance frequency f_{NV}

Detecting magnetic noise from the emitted PL



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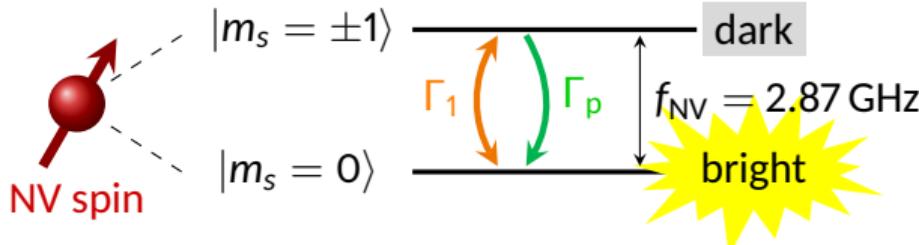
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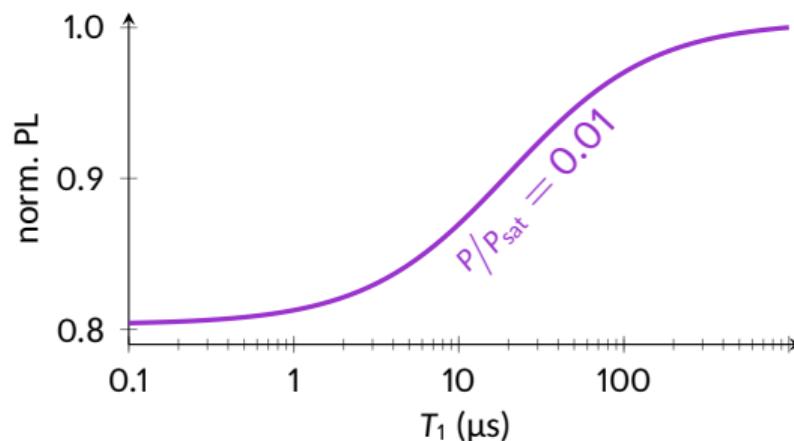
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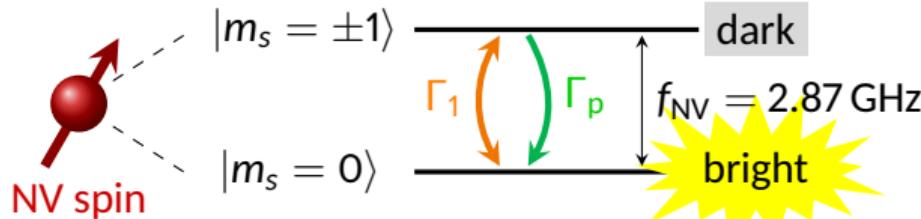
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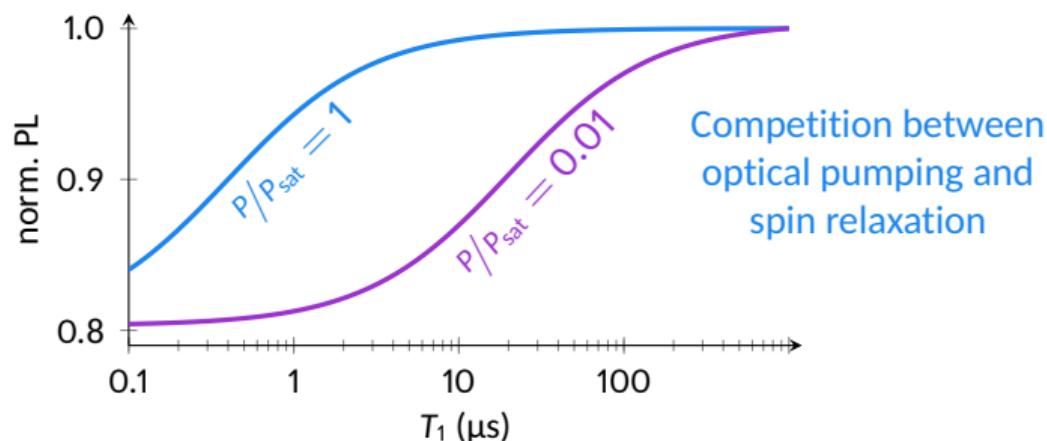
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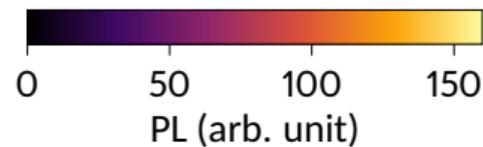
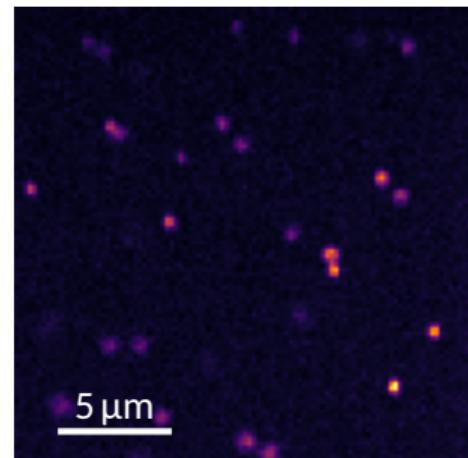


Experimental investigation of the effect of magnetic noise

Collaboration C2N: Thibaut Devolder

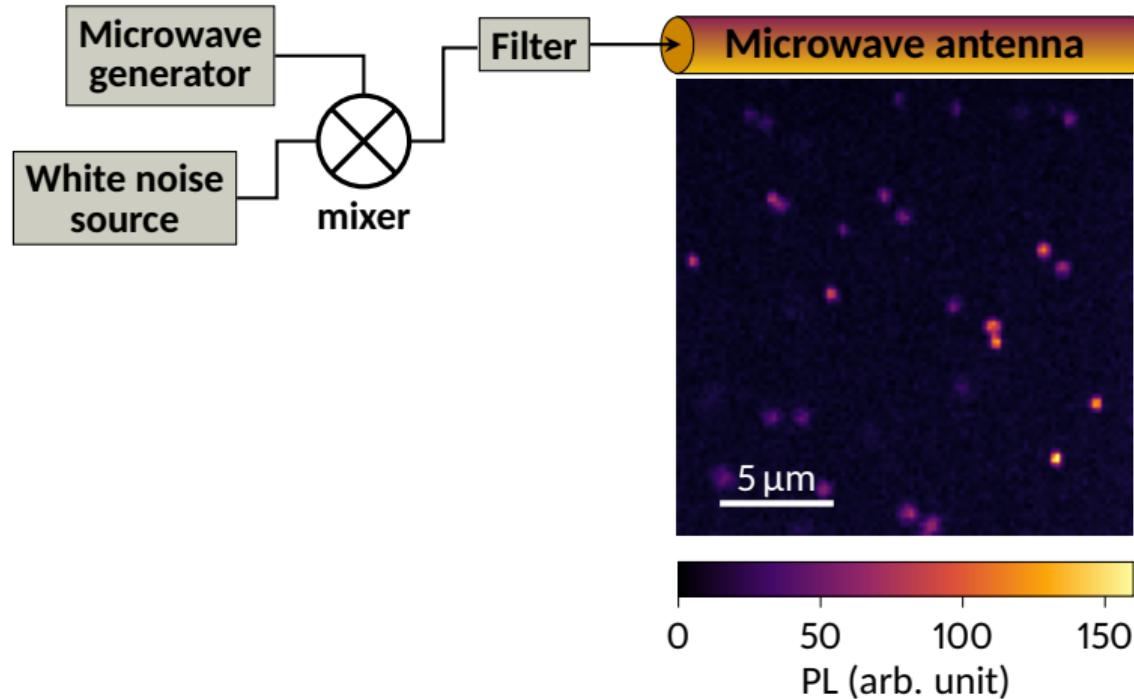


Bulk diamond sample



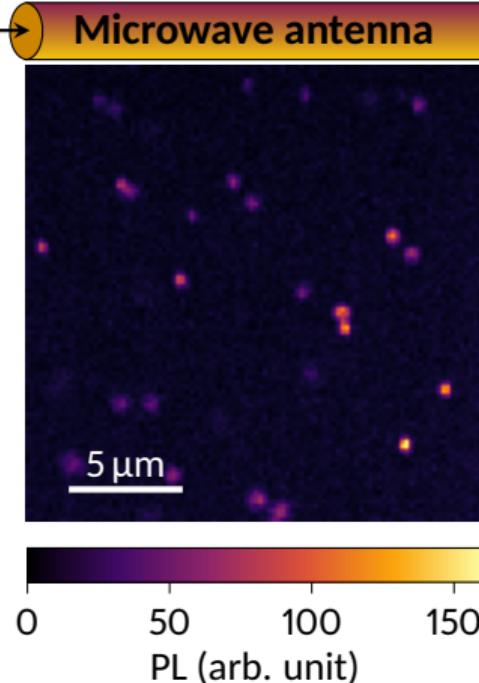
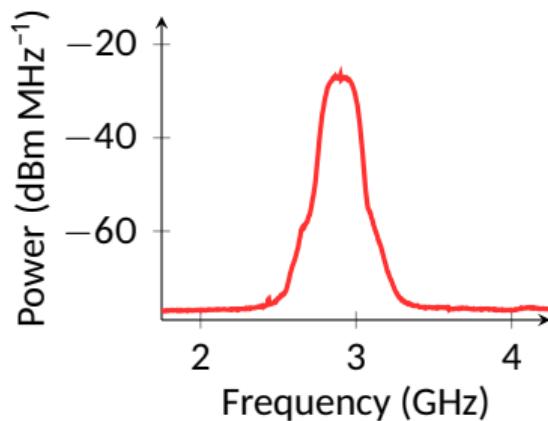
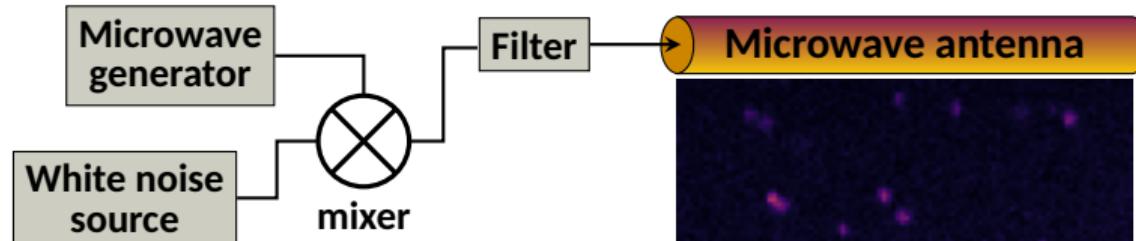
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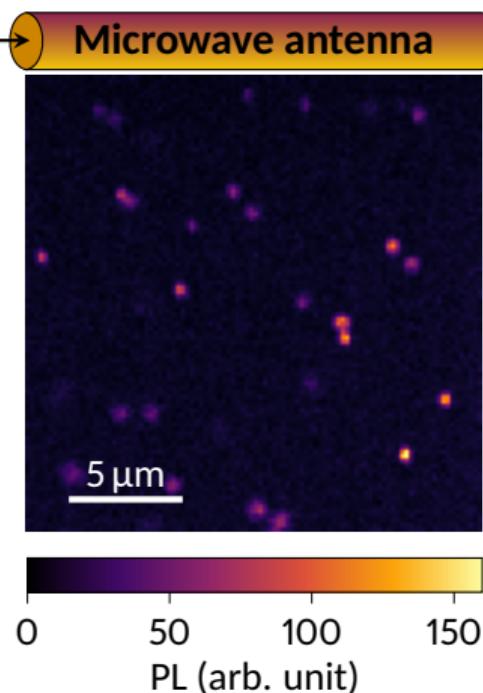
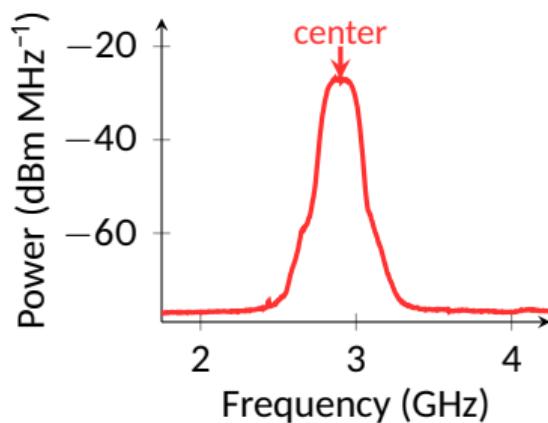
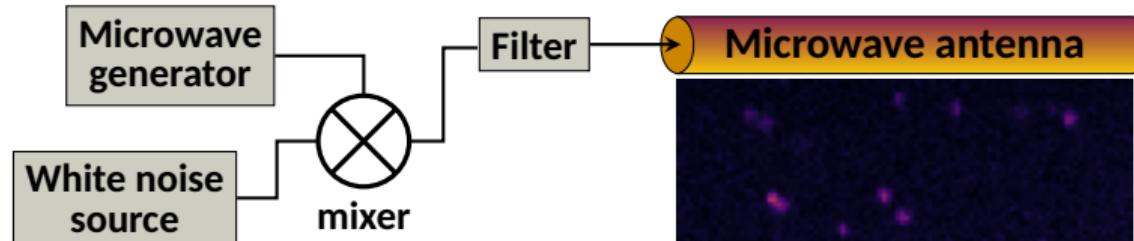
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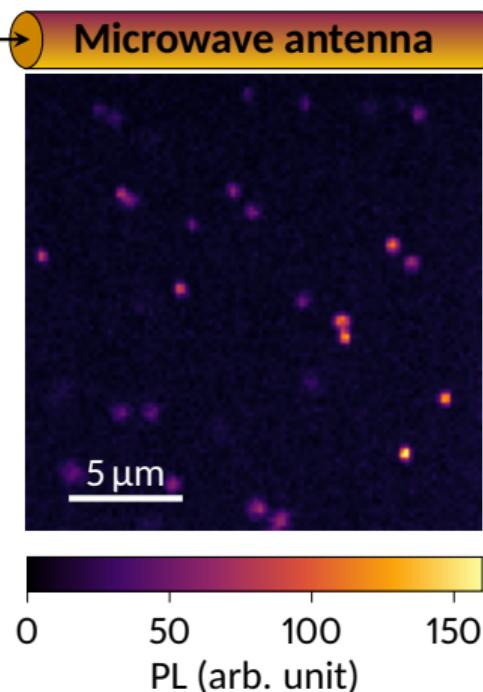
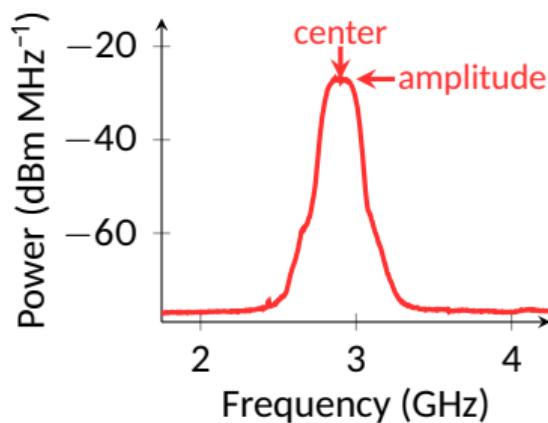
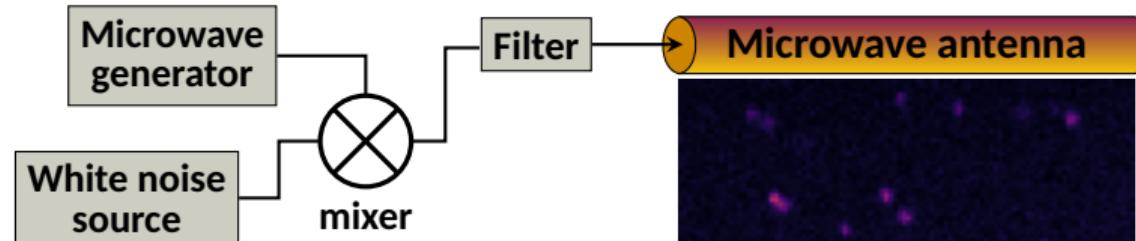
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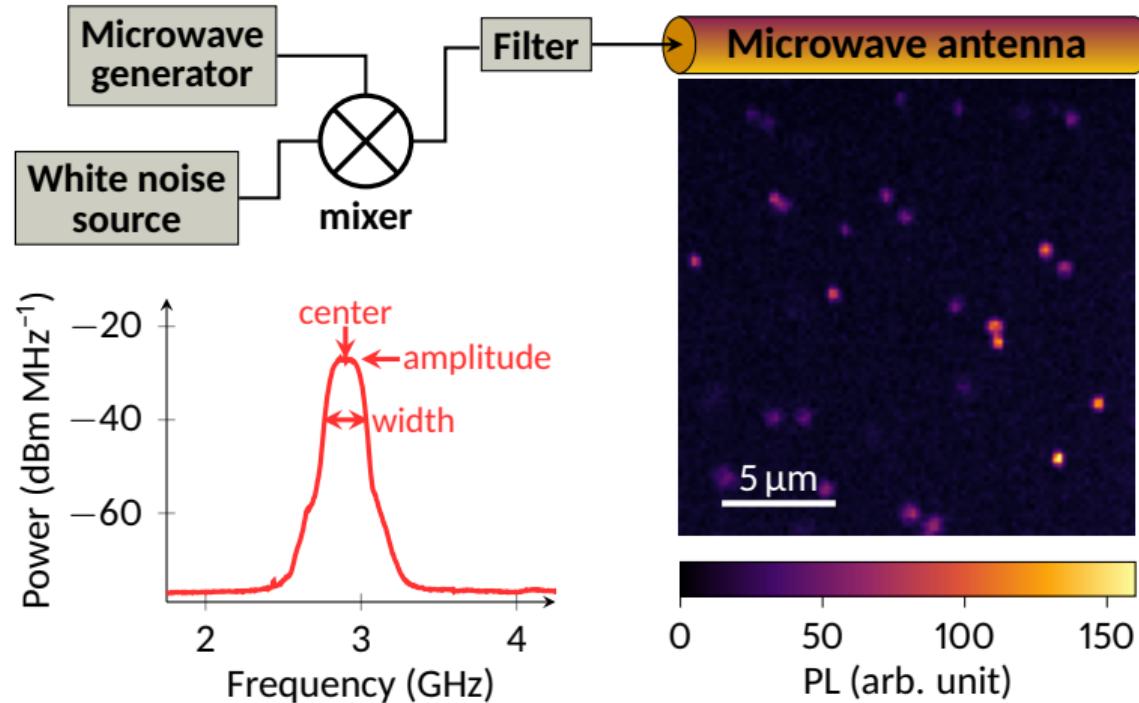
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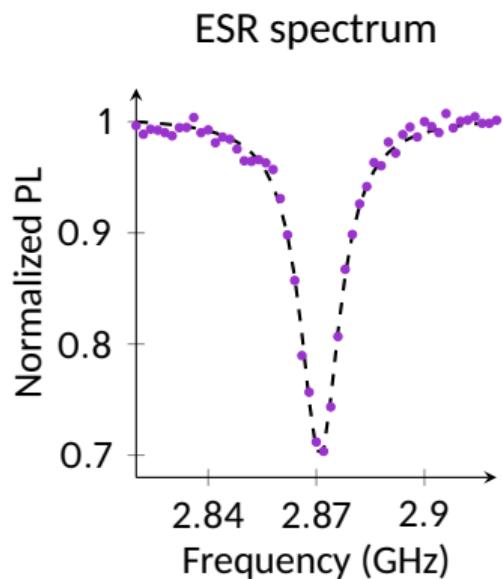
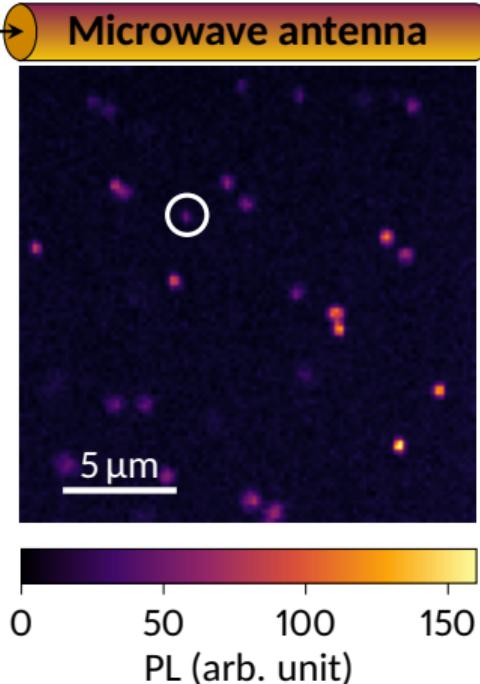
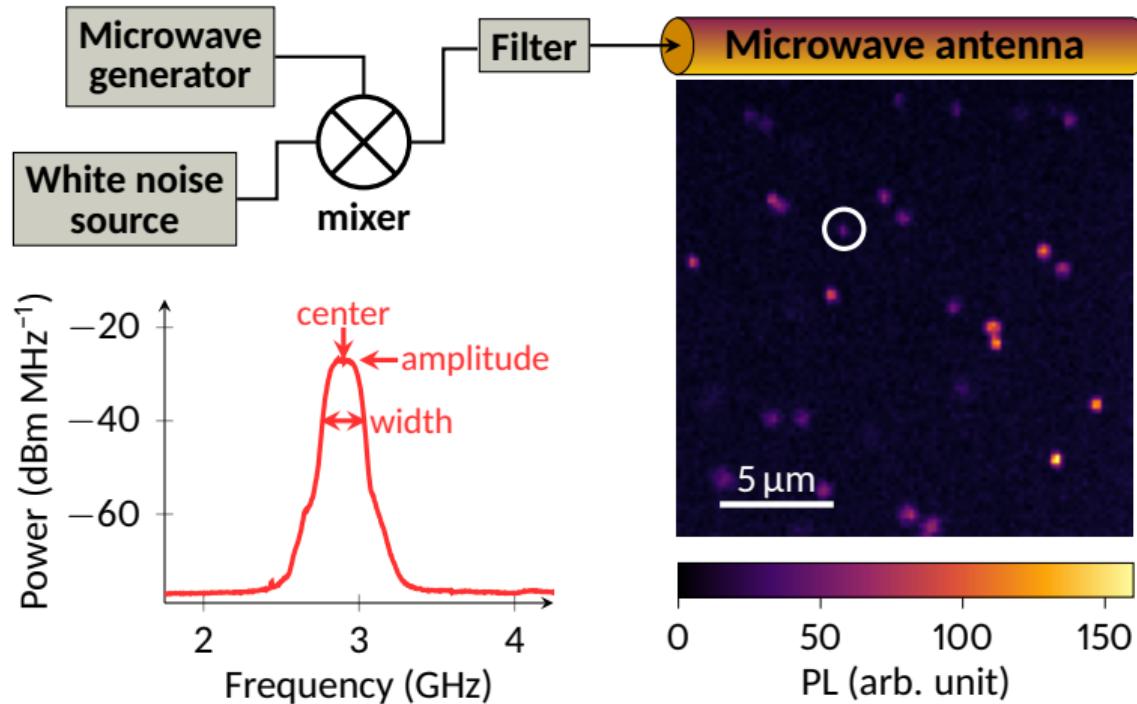
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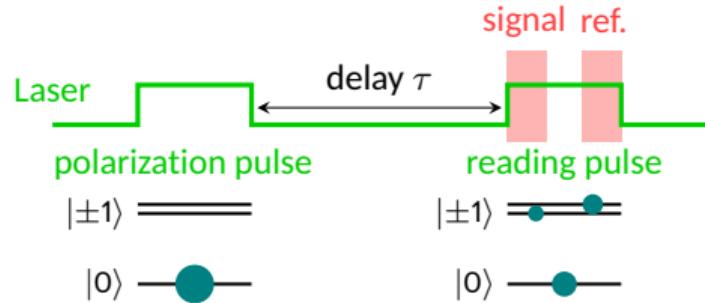


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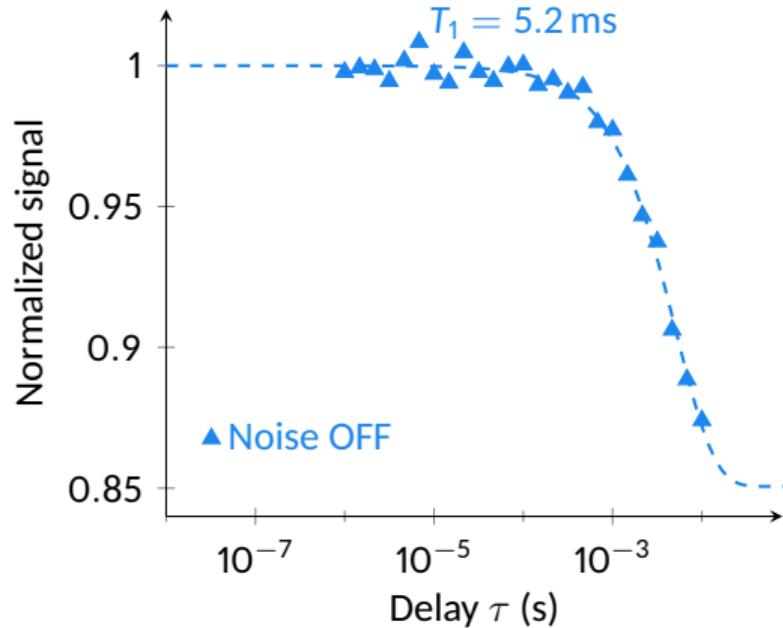
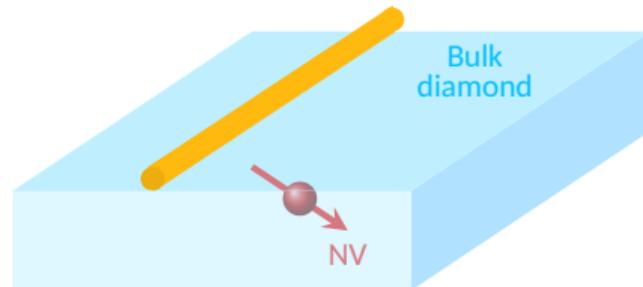
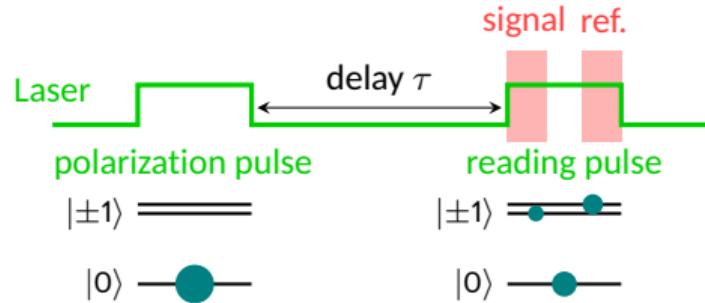
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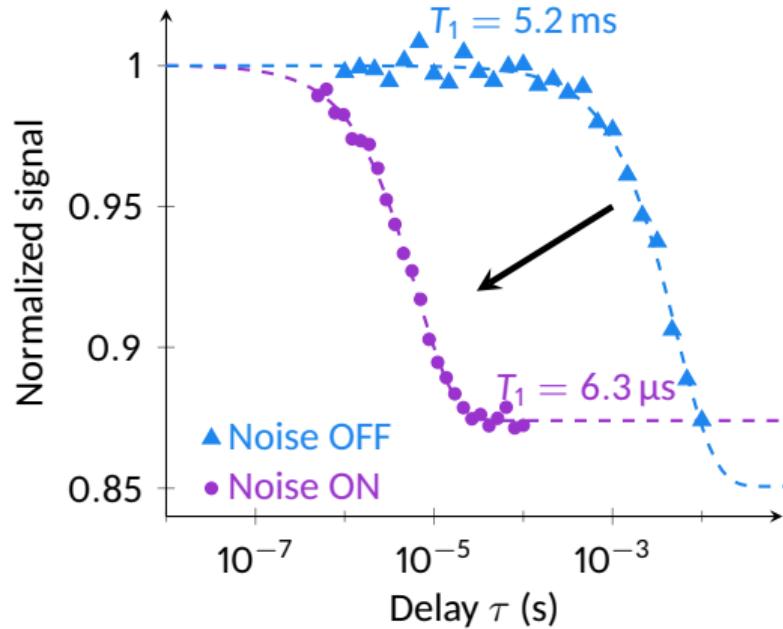
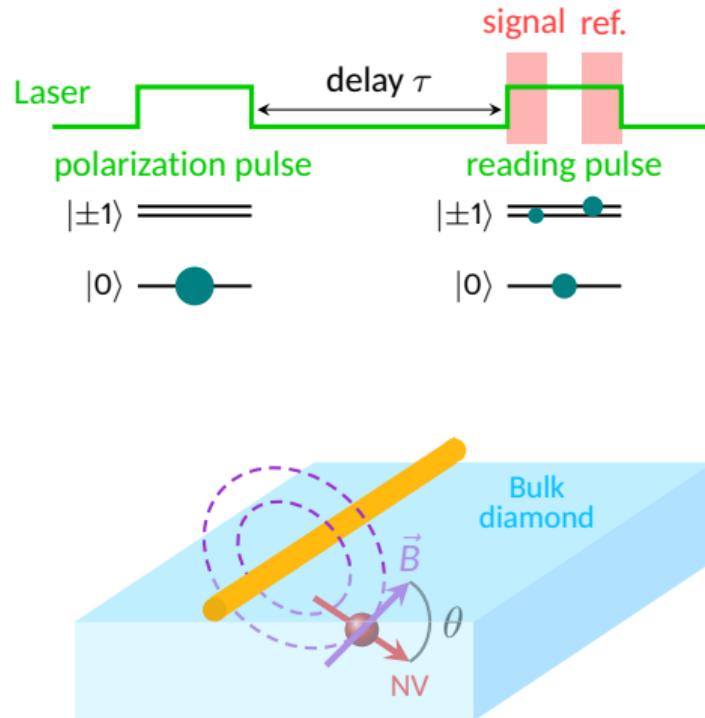
Acceleration of the longitudinal spin relaxation



Acceleration of the longitudinal spin relaxation

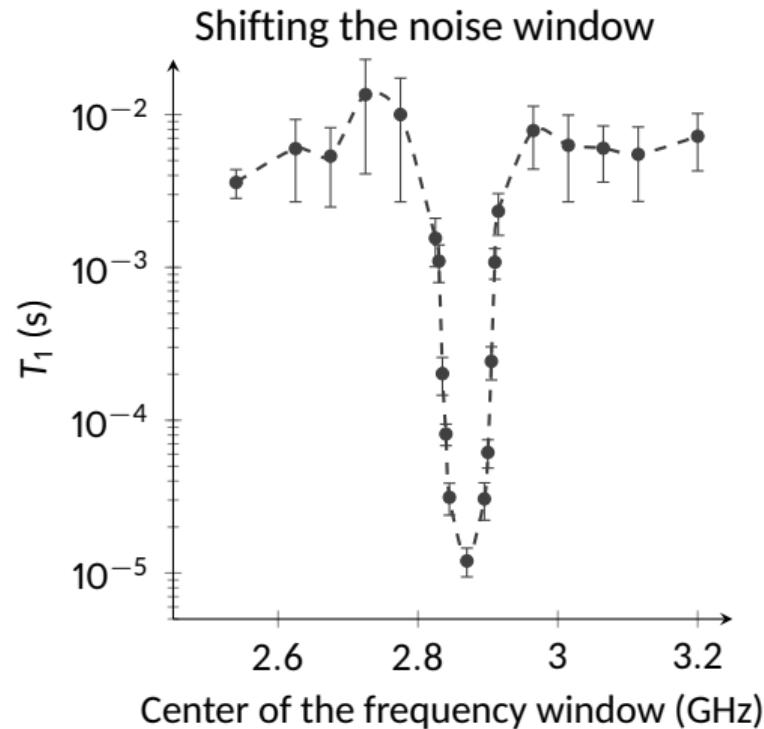
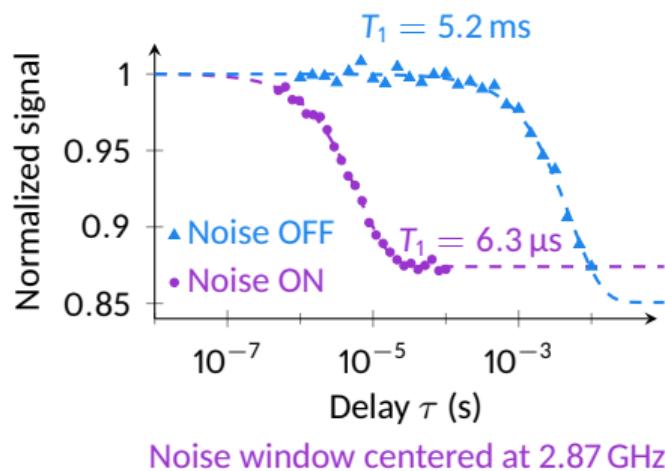
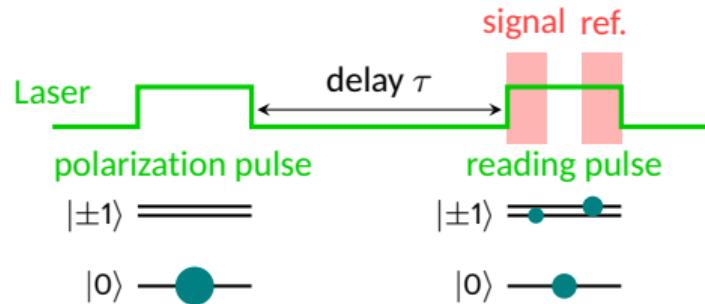


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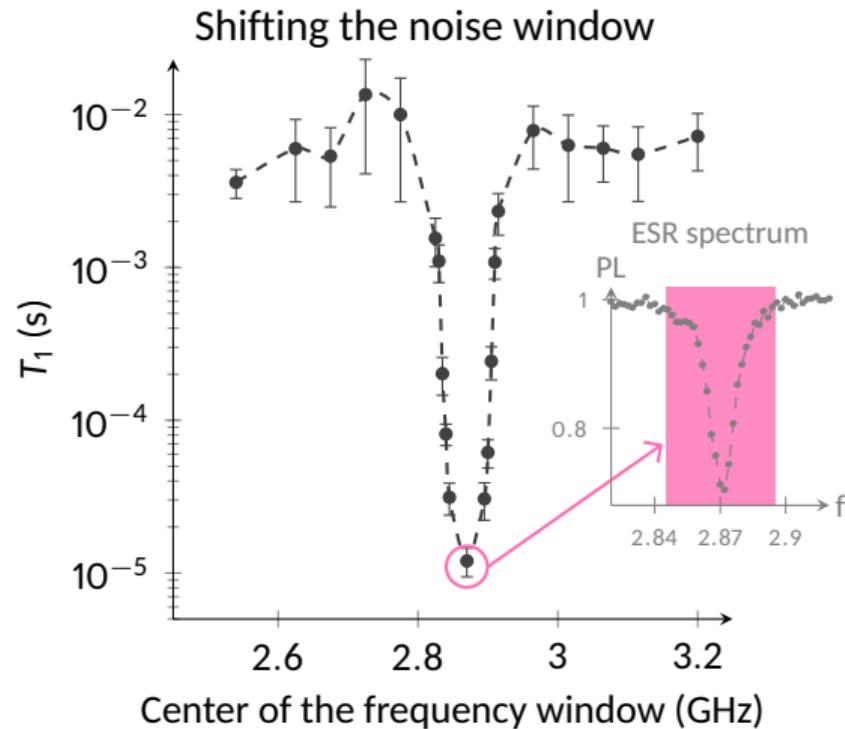
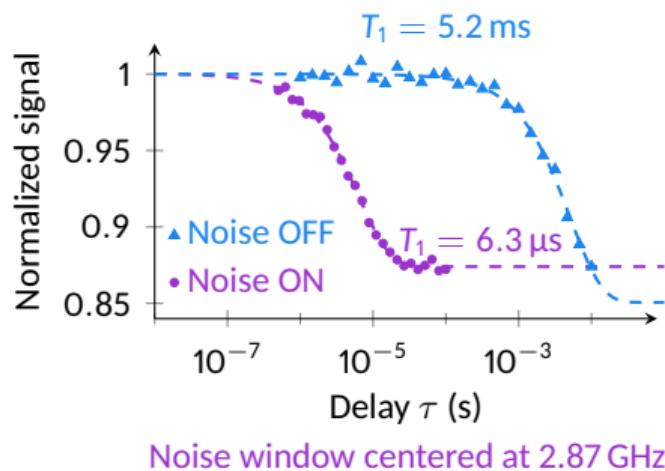
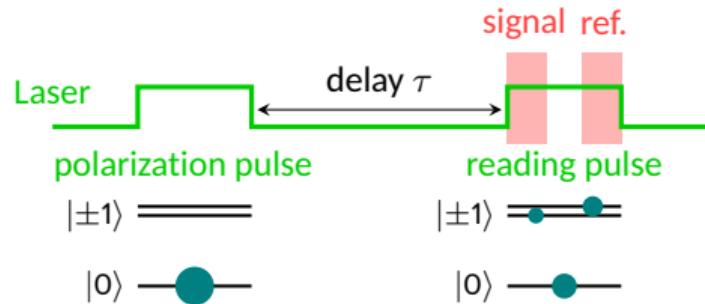


Noise window centered at 2.87 GHz

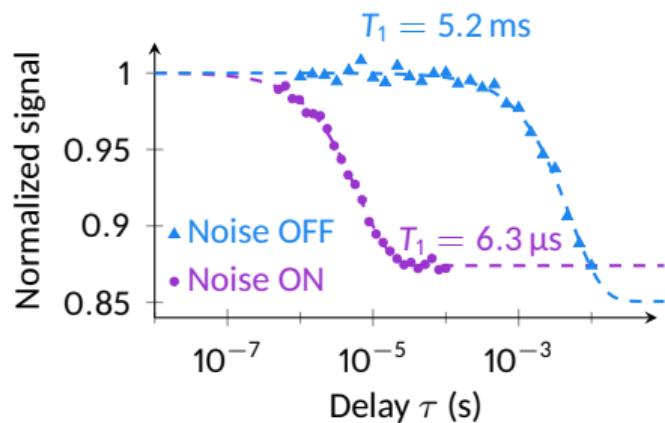
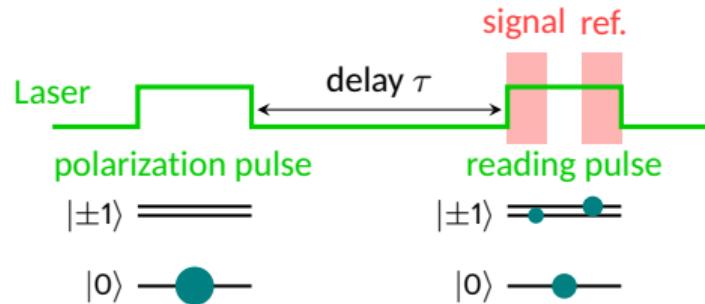
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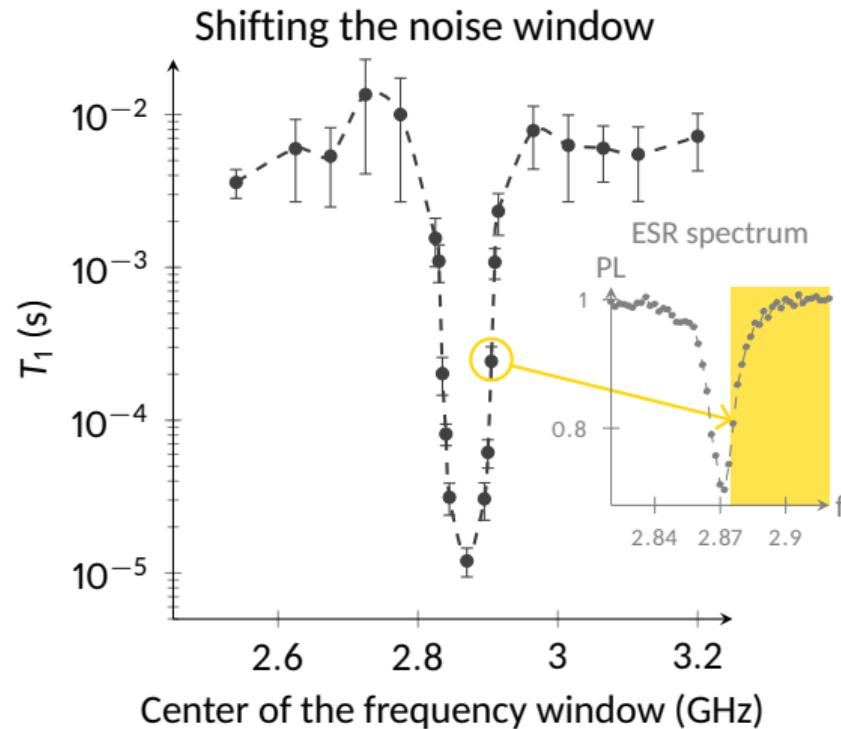
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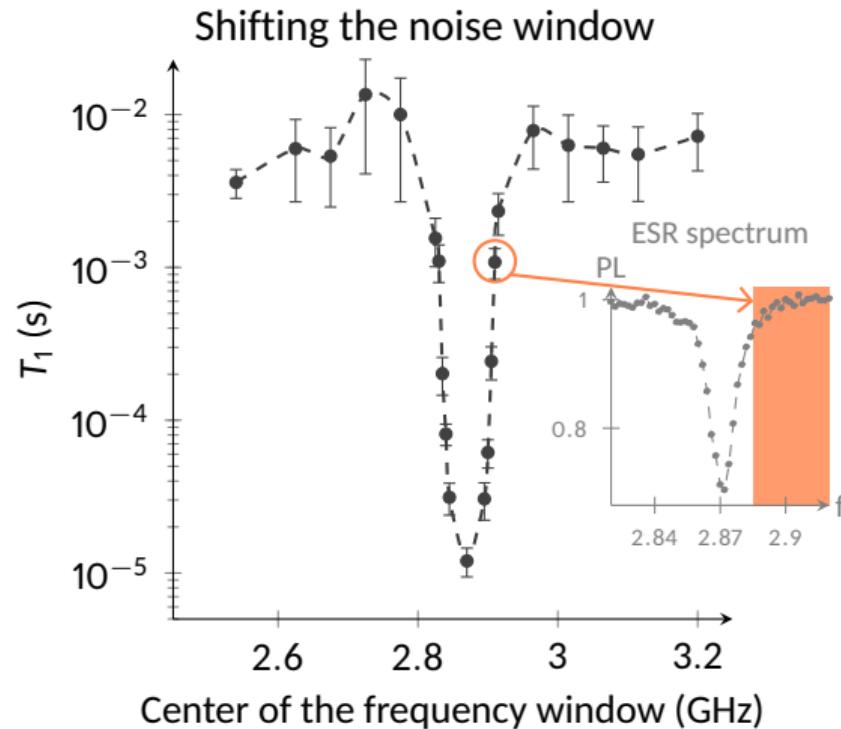
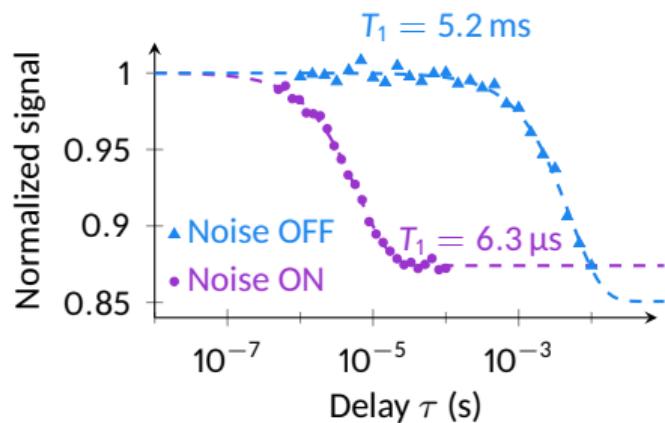
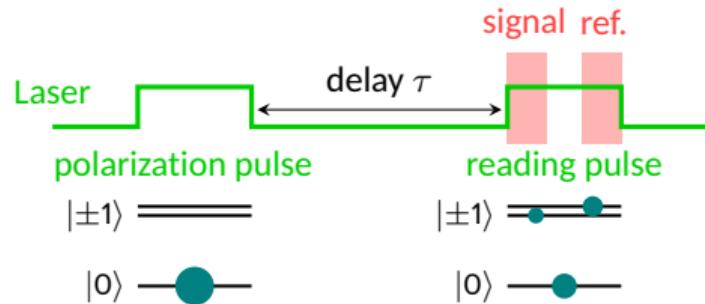
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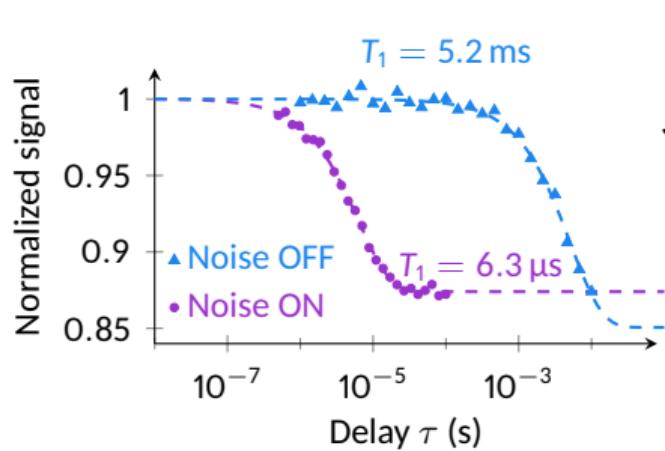
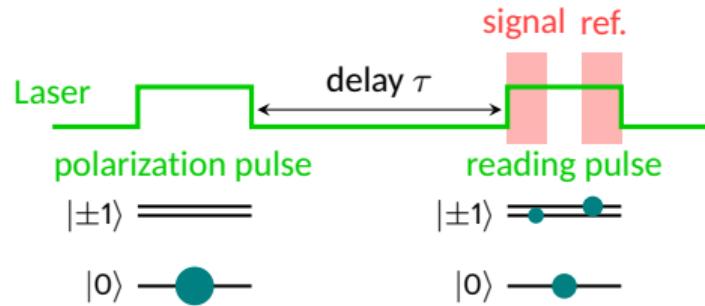
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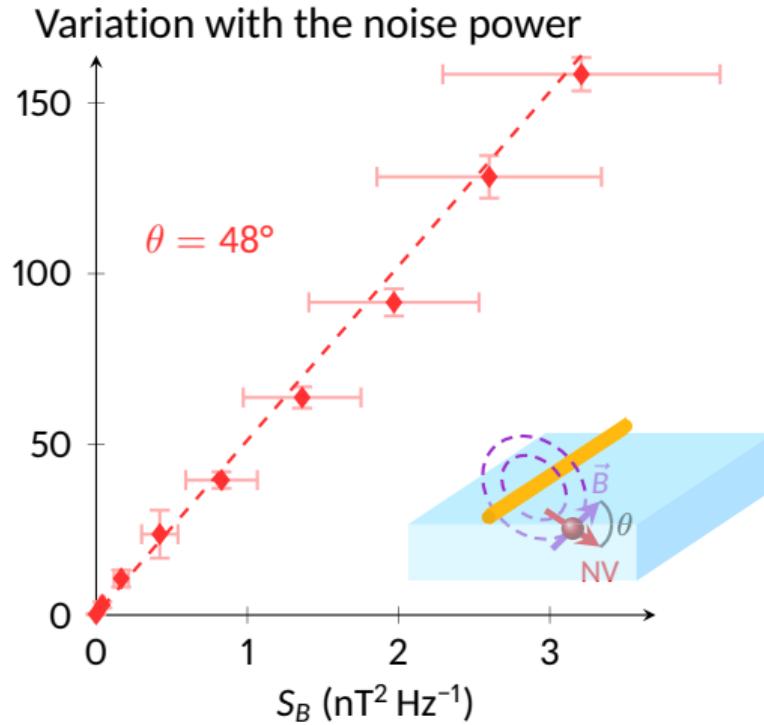
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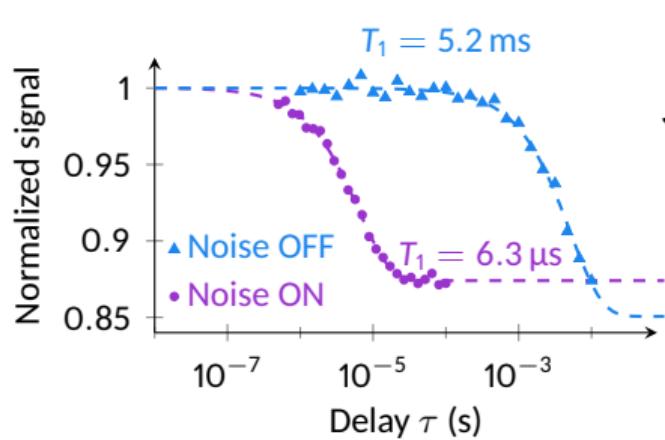
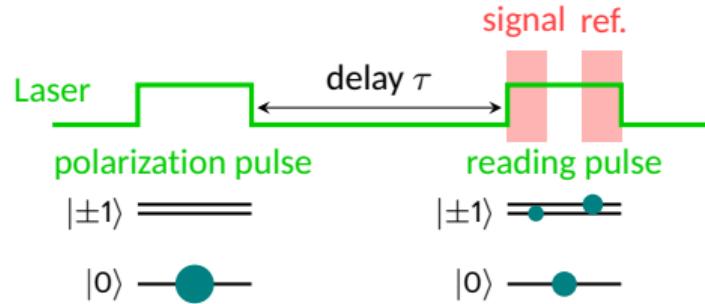


$$\frac{1}{T_1} (\text{ms}^{-1})$$

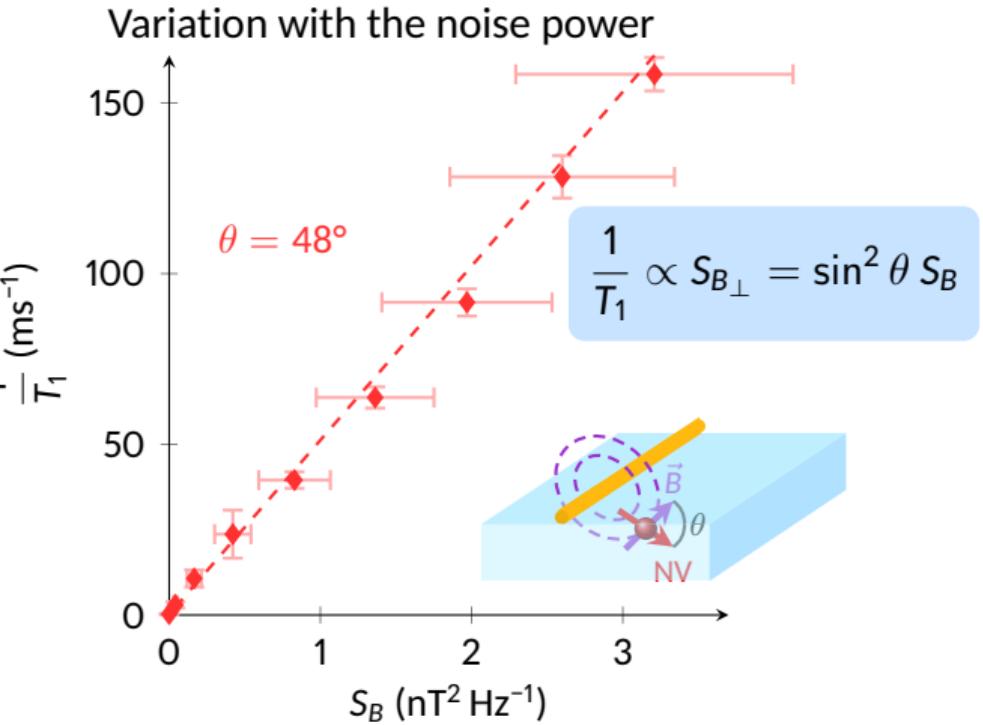


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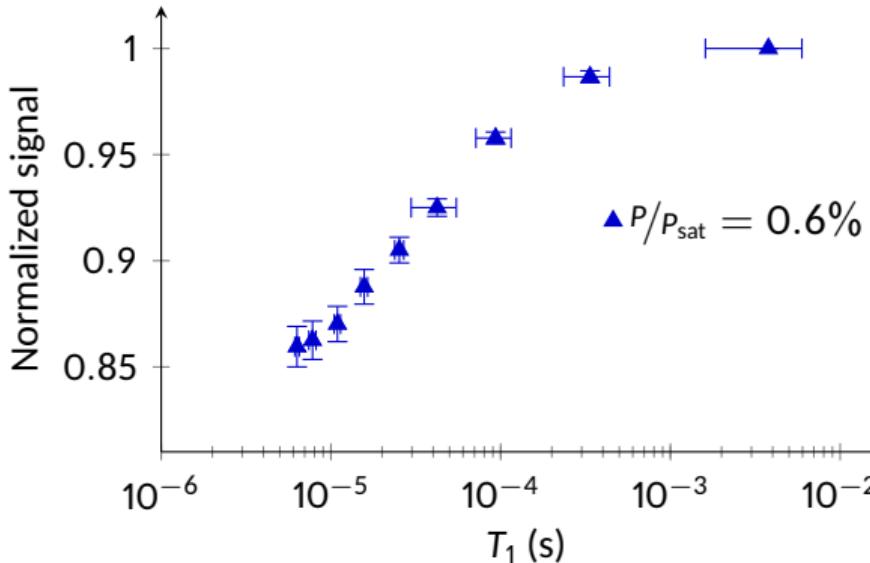
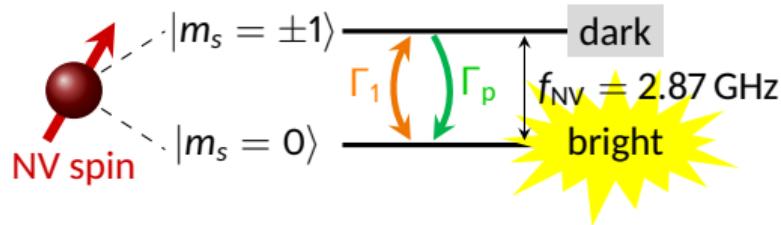
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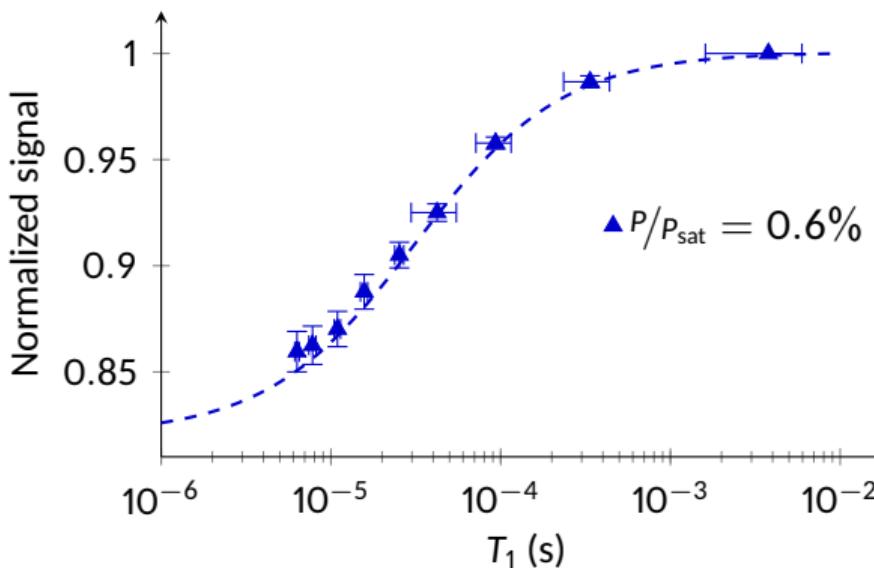
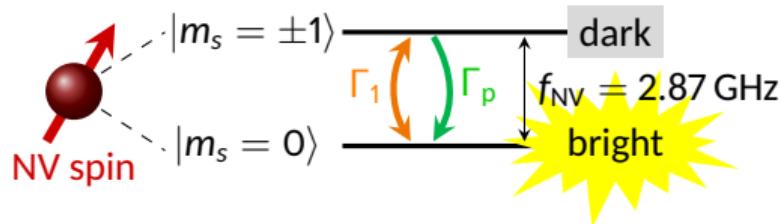
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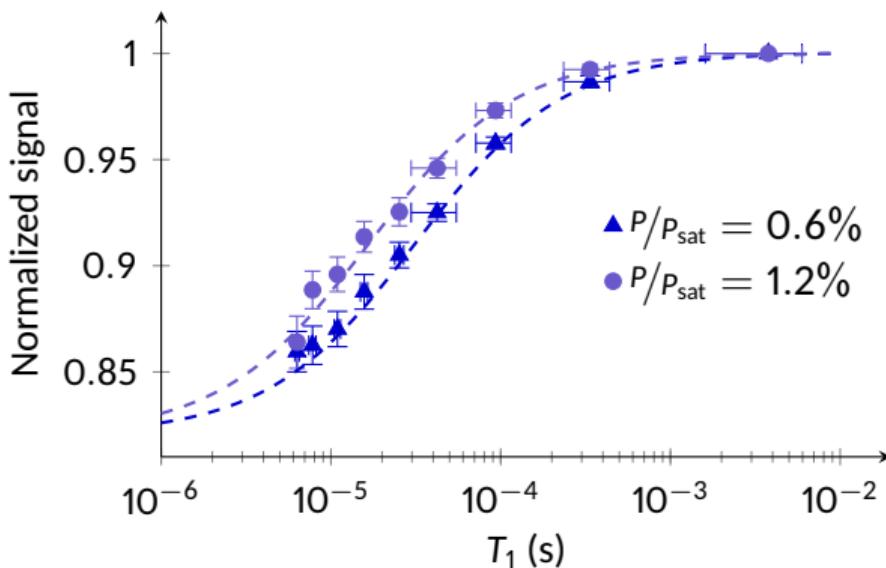
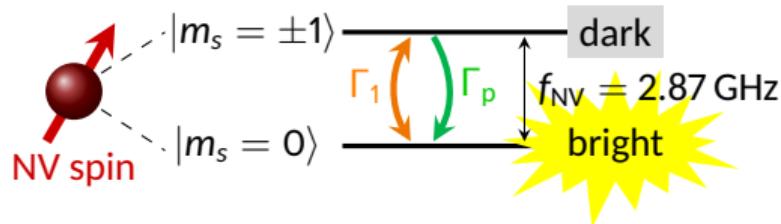
Effect on the emitted photoluminescence



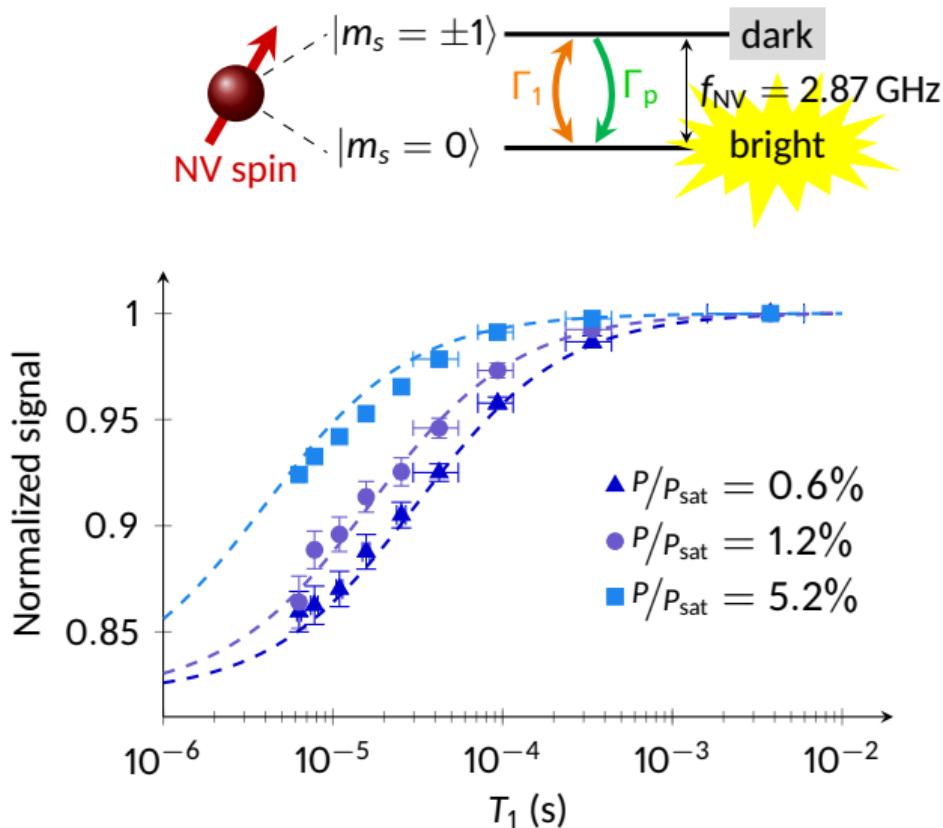
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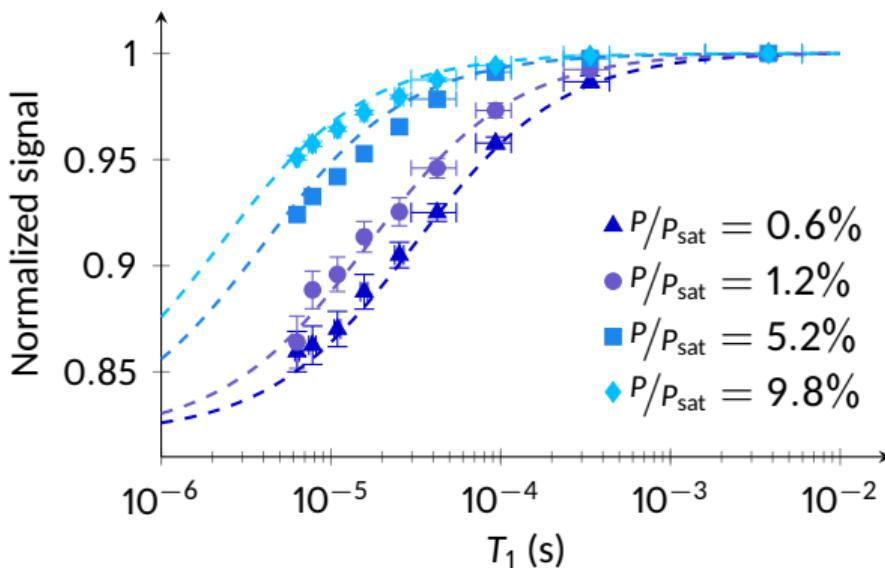
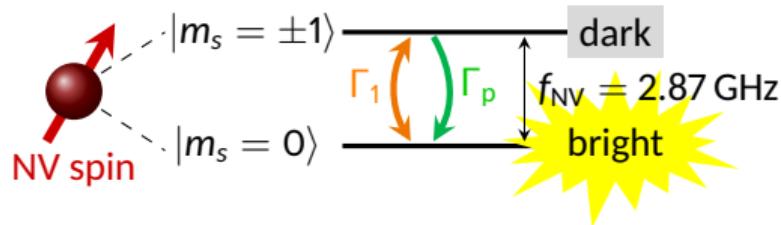
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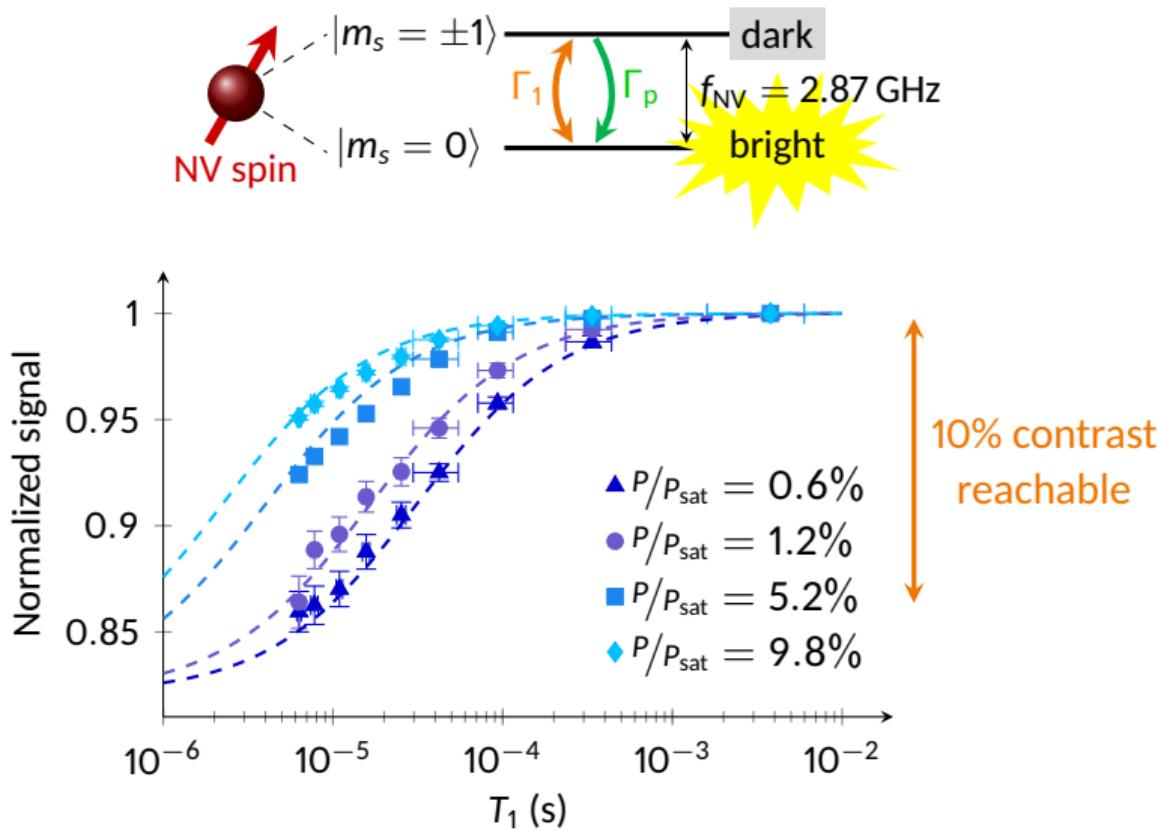
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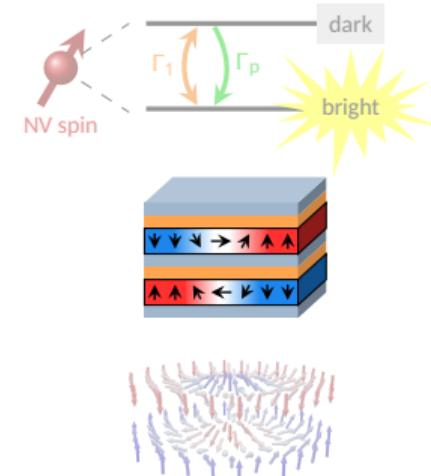
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Synthetic antiferromagnets

Collaboration UMR CNRS/Thales: William Legrand, Fernando Ajejas, Karim
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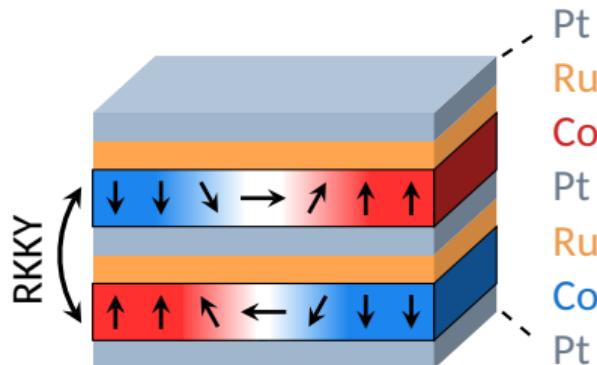
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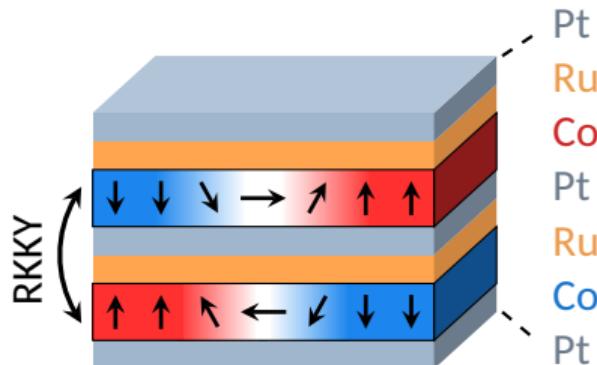
W. Legrand et al. Nat. Mat. 19 (2020), 34

Synthetic antiferromagnets

Collaboration UMR CNRS/Thales: William Legrand, Fernando Ajejas, Karim Bouzehouane, Nicolas Reyren, Vincent Cros



Two **ferromagnetic** layers coupled **antiferromagnetically**



- ▶ No net magnetic moment
- ▶ Small stray field (vertical shift)
- ▶ Highly tunable properties

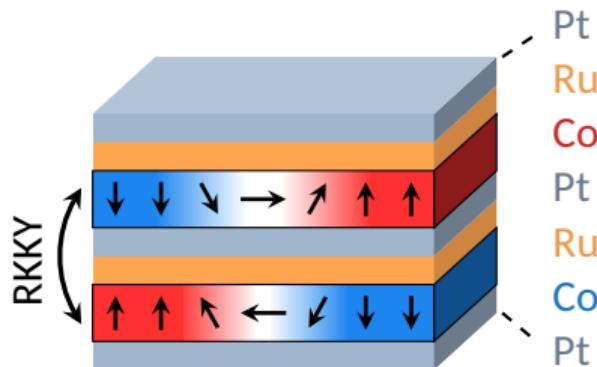
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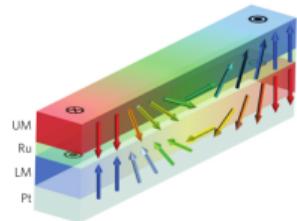
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Perfect **test system** for noise imaging!

W. Legrand et al. *Nat. Mat.* 19 (2020), 34

Spintronics with synthetic antiferromagnets

Fast domain wall motion

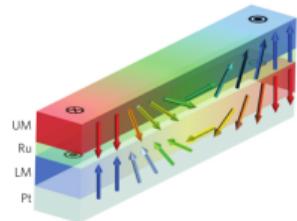


S.-H. Yang *et al.* *Nat. Nano.* 10 (2015), 221

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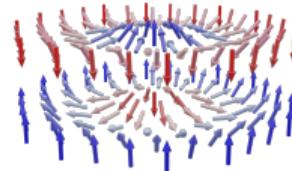
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Stabilisation of small skyrmions



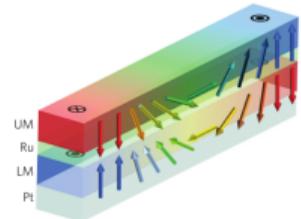
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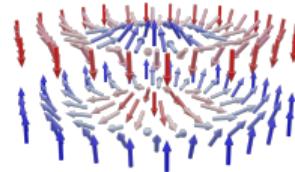
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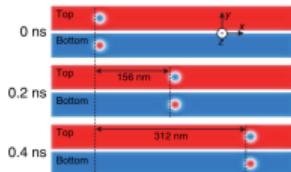
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No skyrmion Hall effect



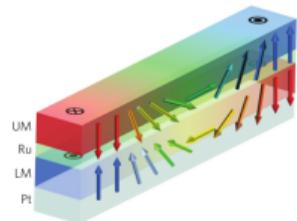
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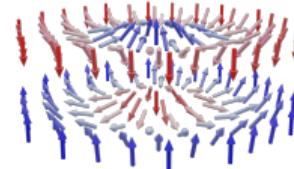
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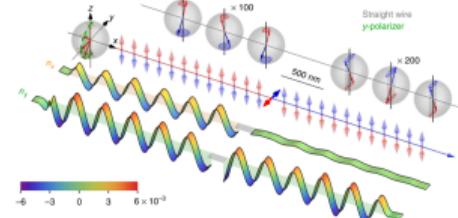
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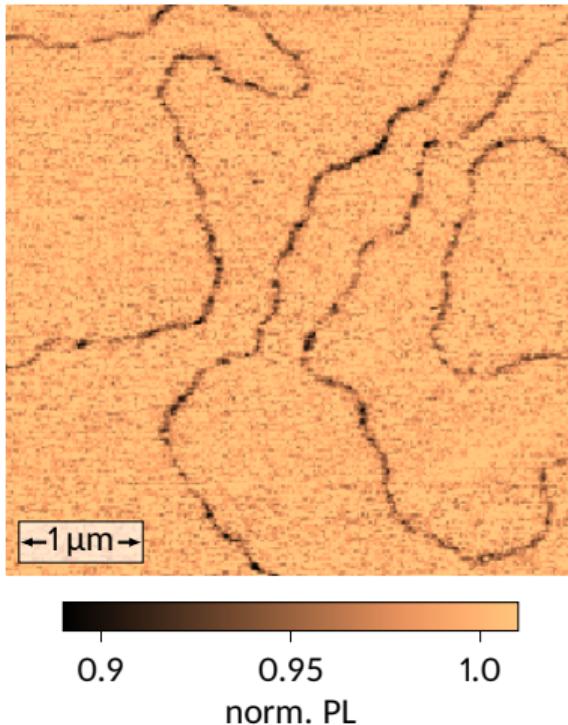
Magnonics



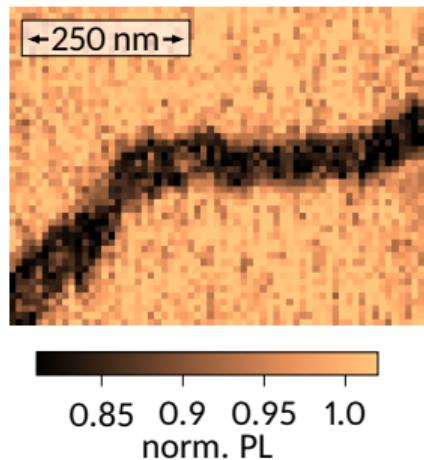
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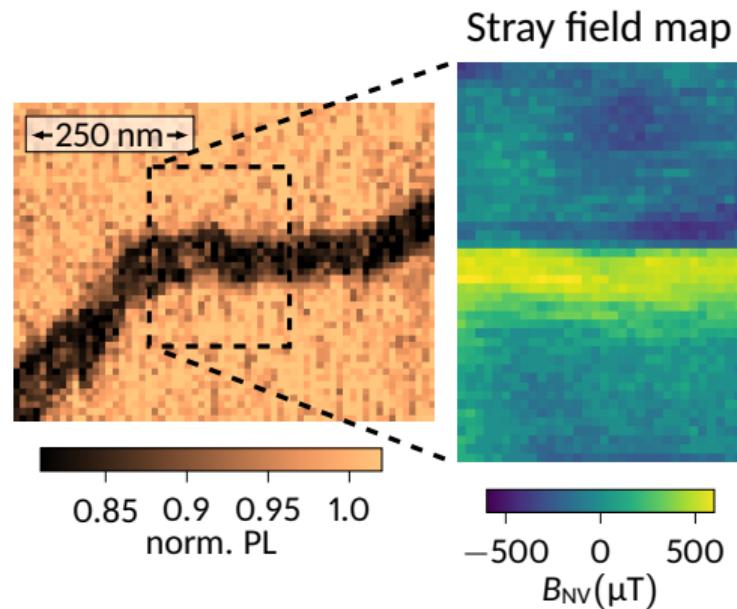
Detection of domain walls by relaxometry



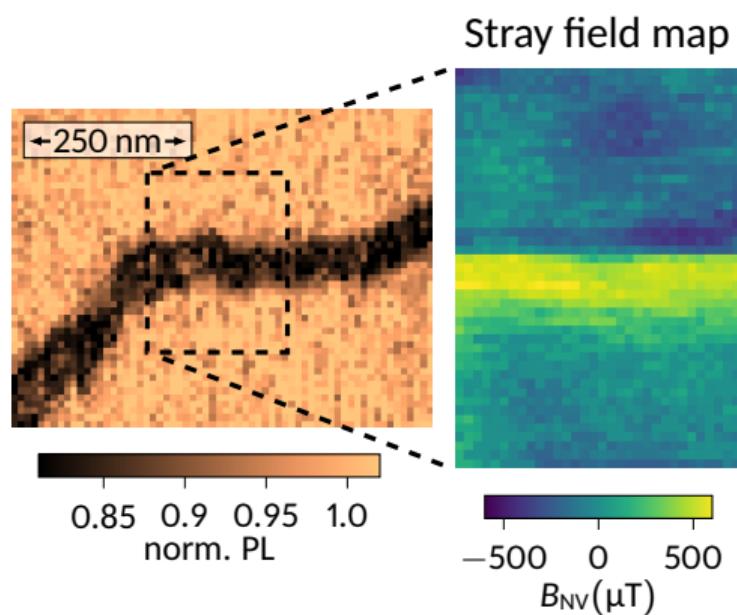
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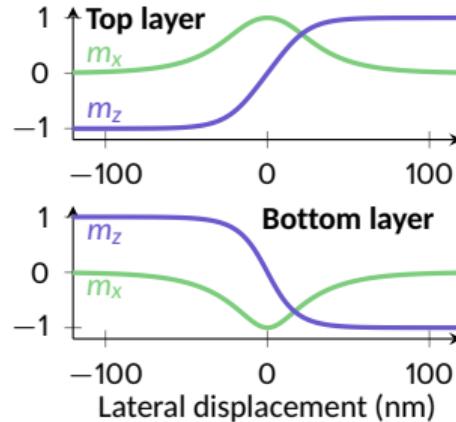
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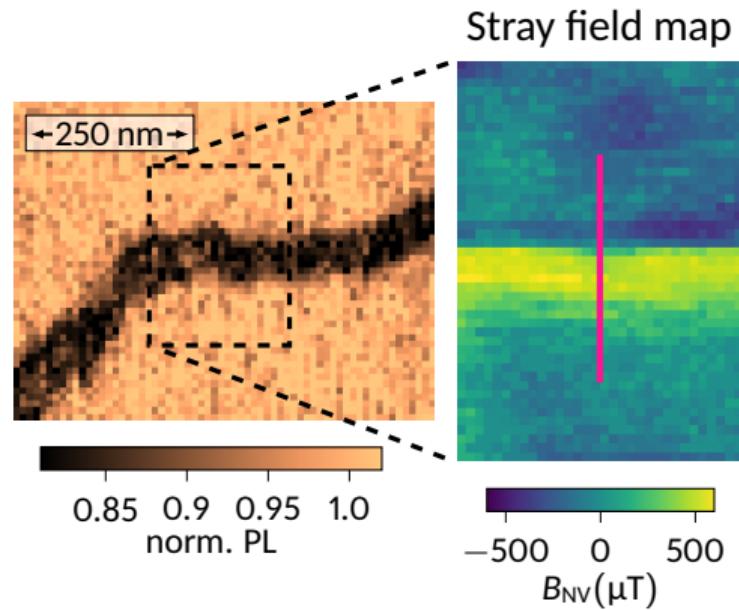
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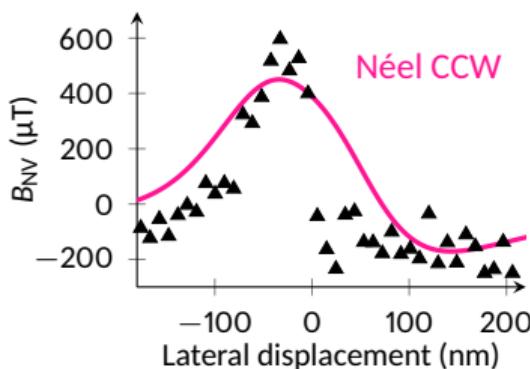
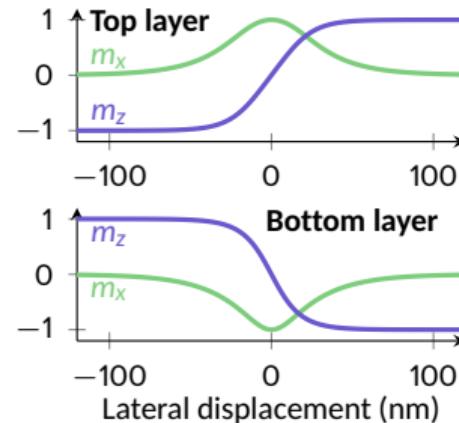
Simulated profile



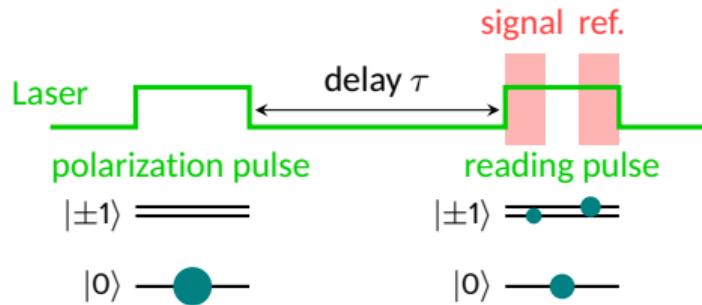
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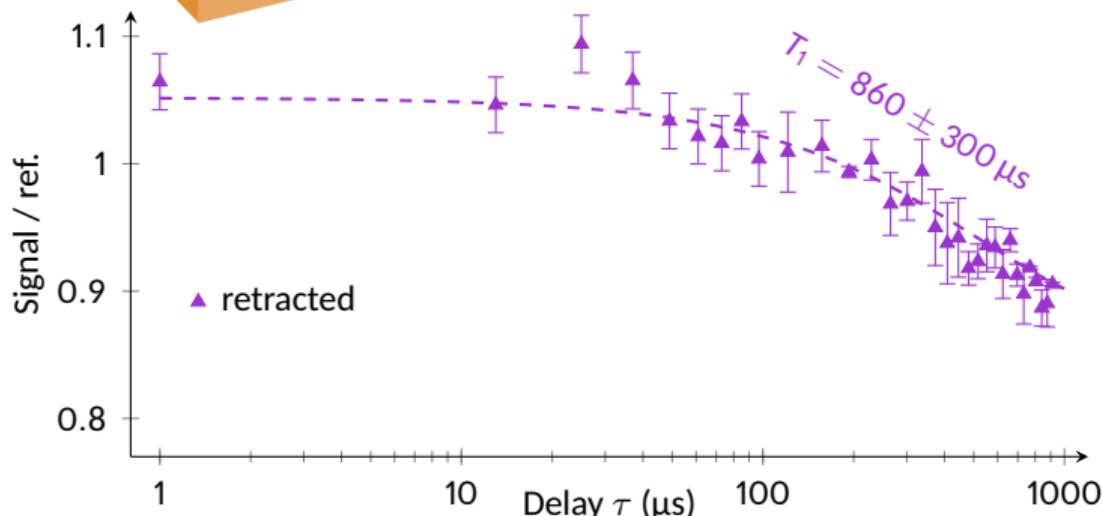
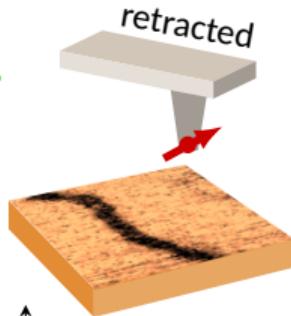
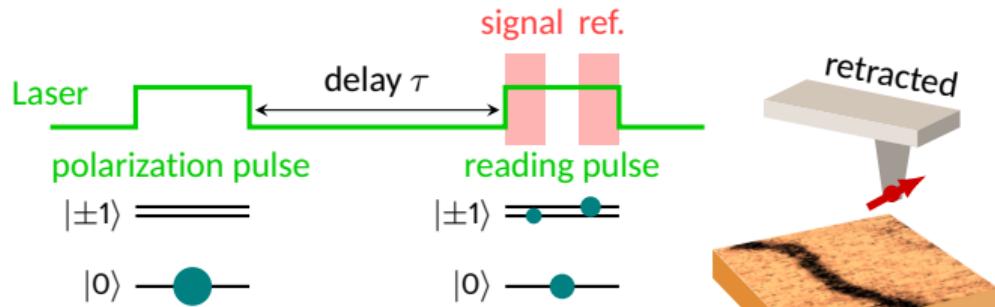
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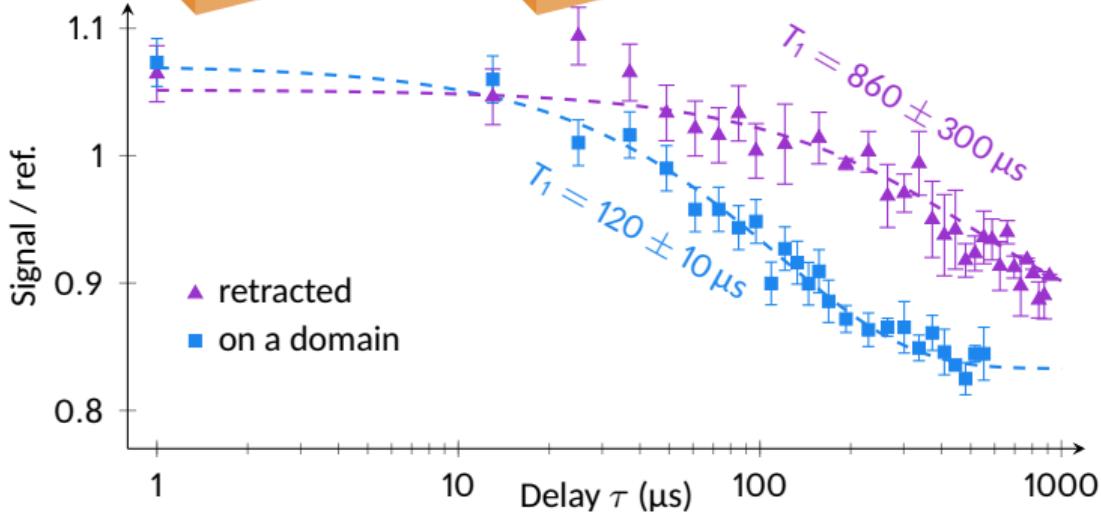
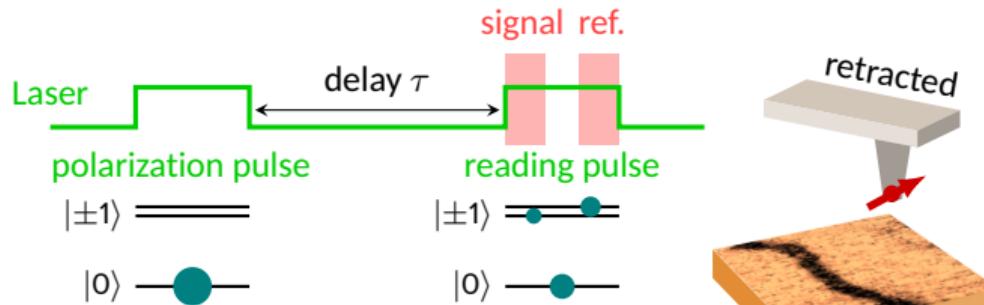
Local variation of the relaxation time



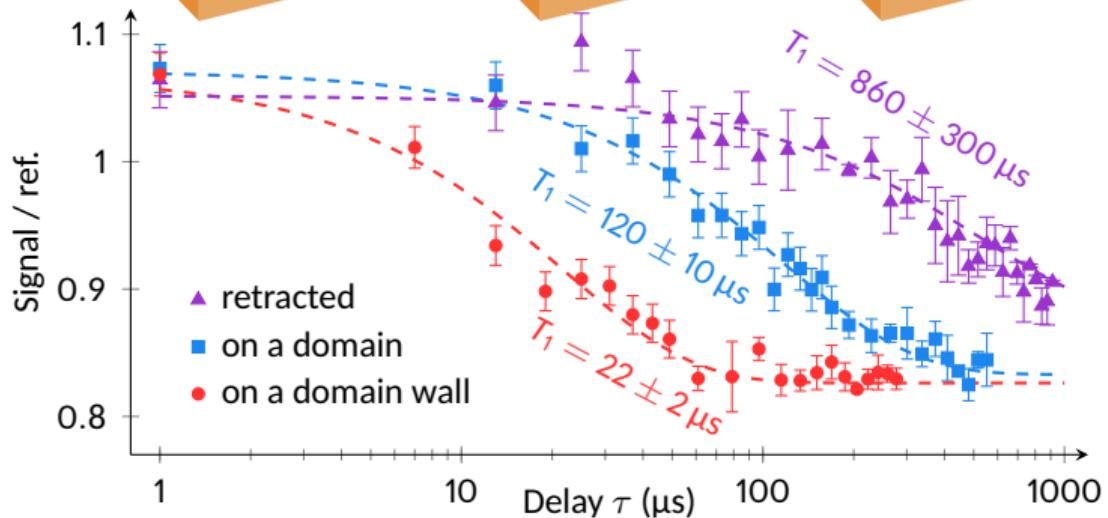
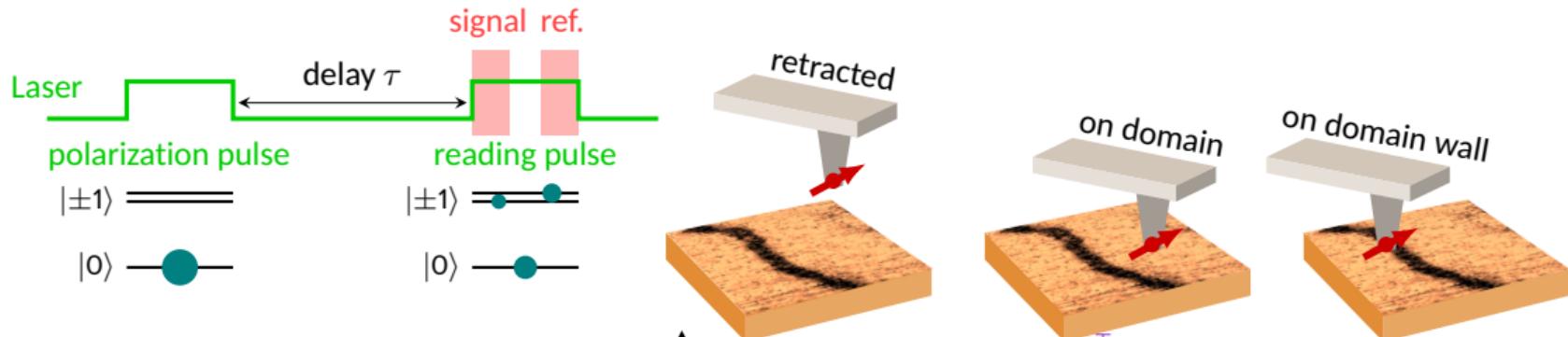
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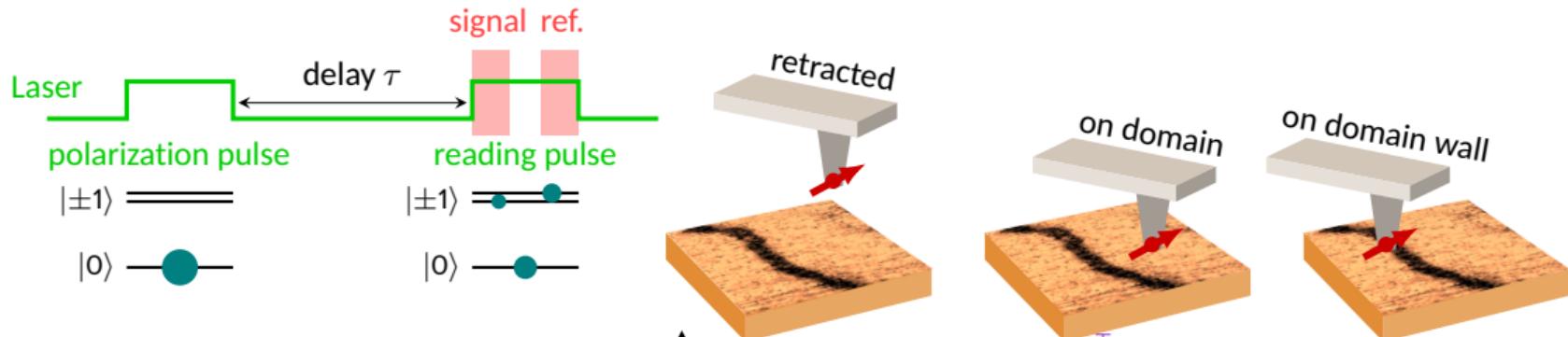
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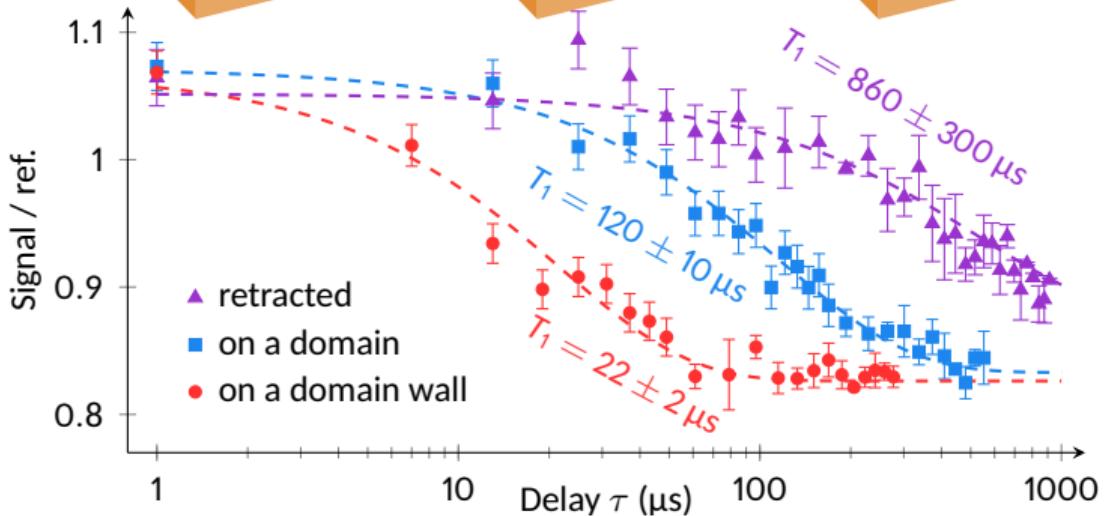
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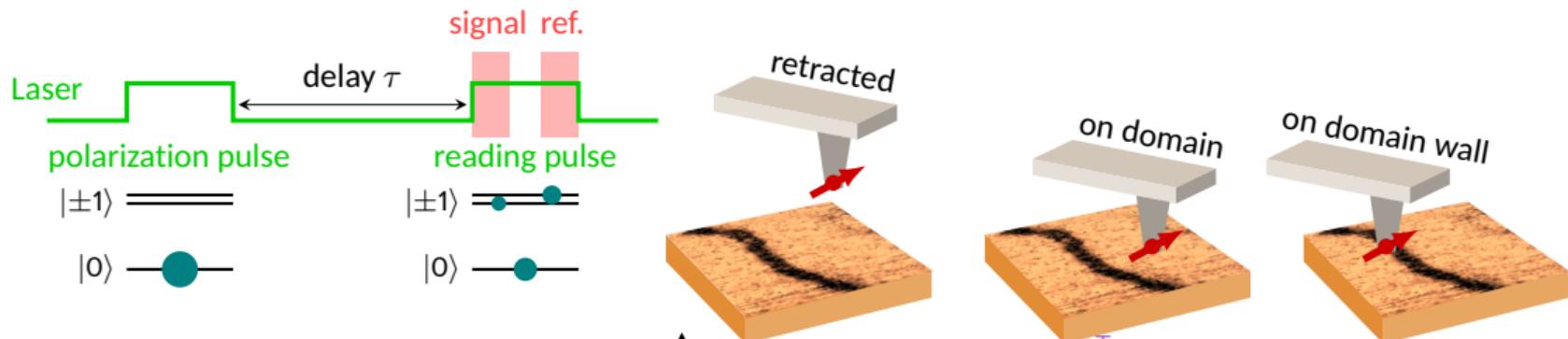
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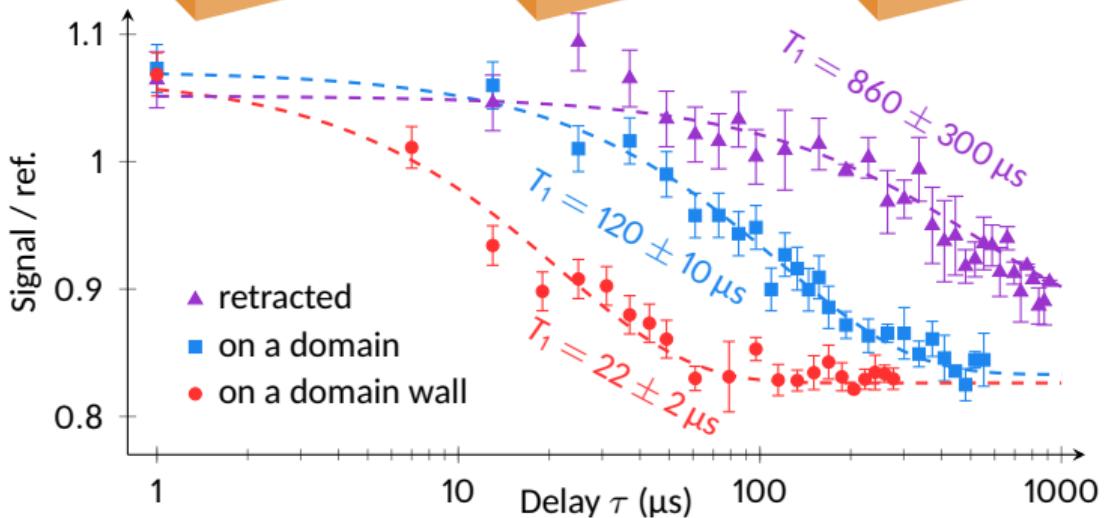
Clear diminution of T_1
above the domain wall



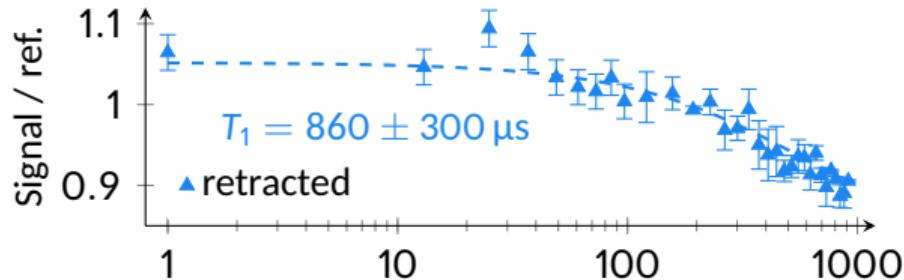
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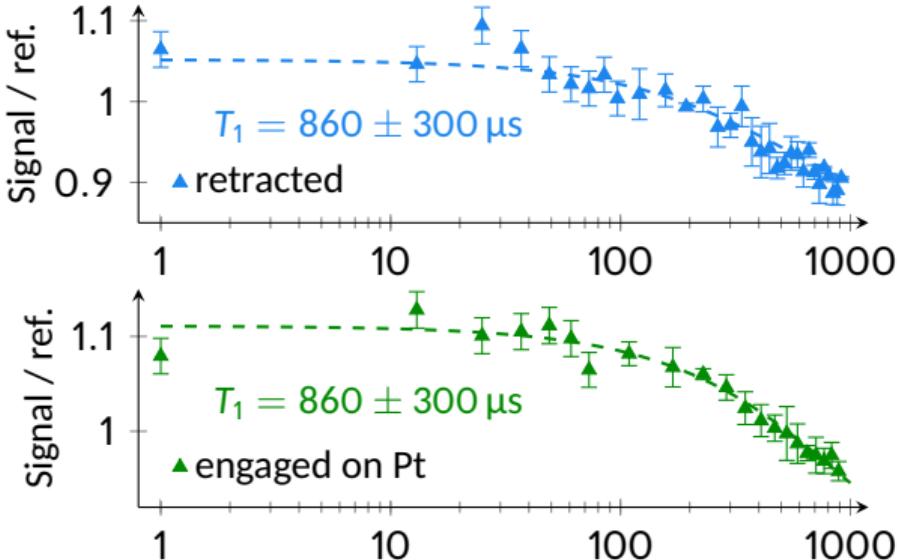
Clear diminution of T_1
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→ Enhancement of the
spin relaxation



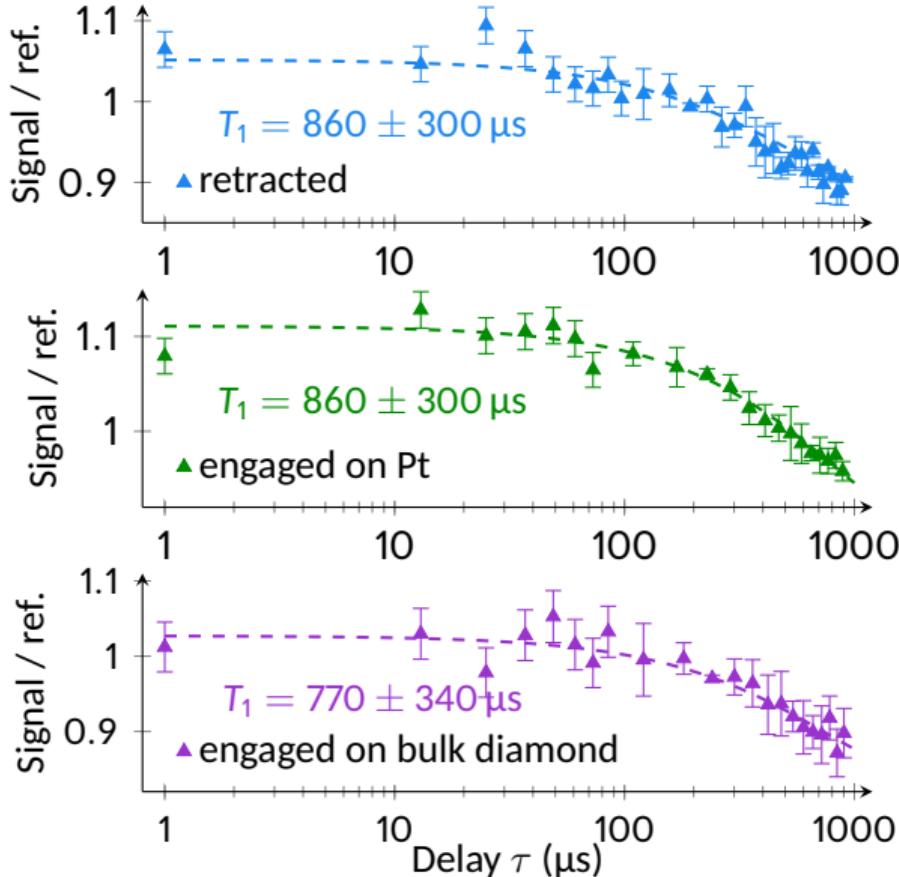
Magnetic origin of the noise



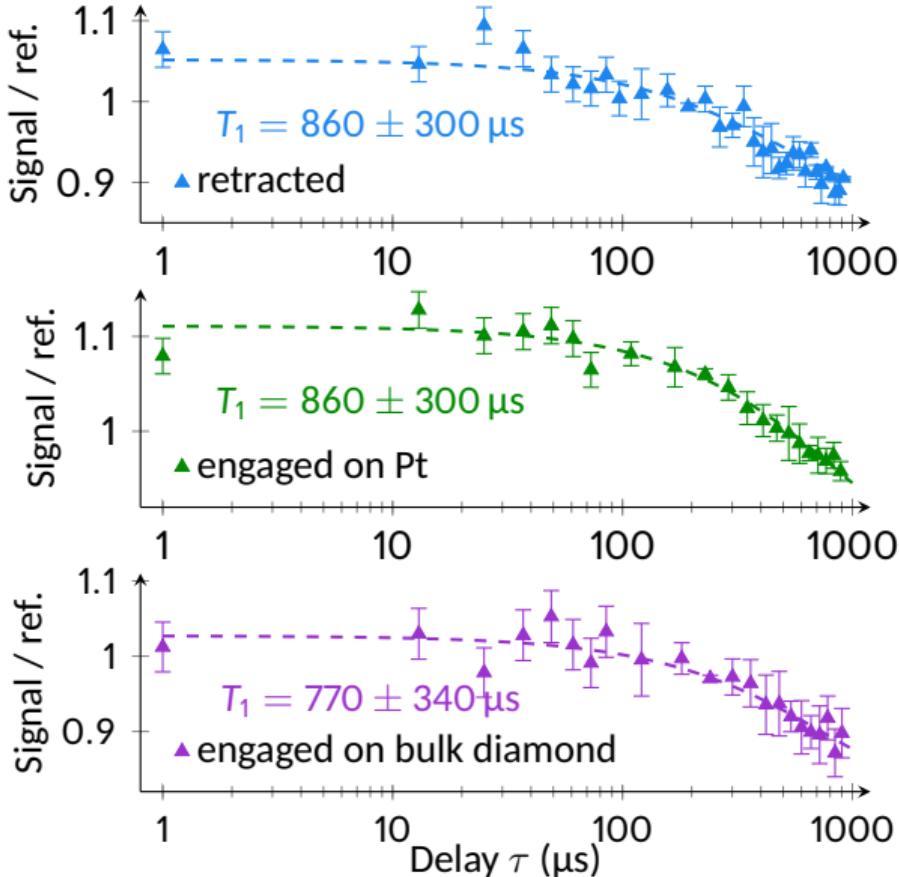
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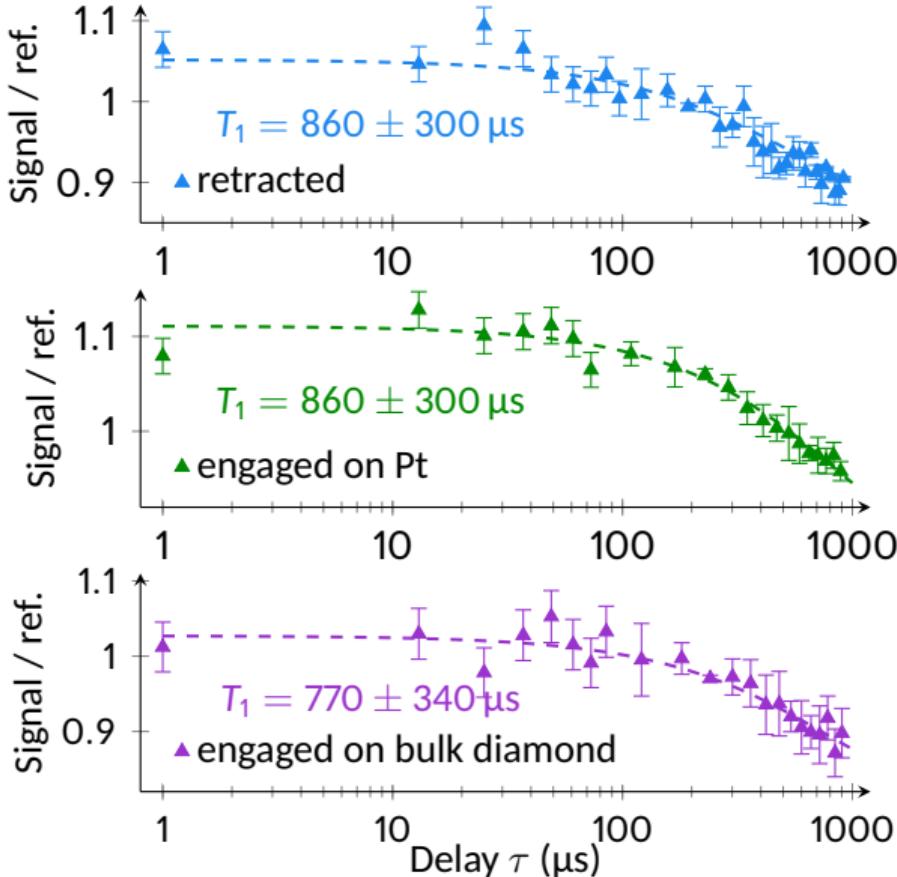


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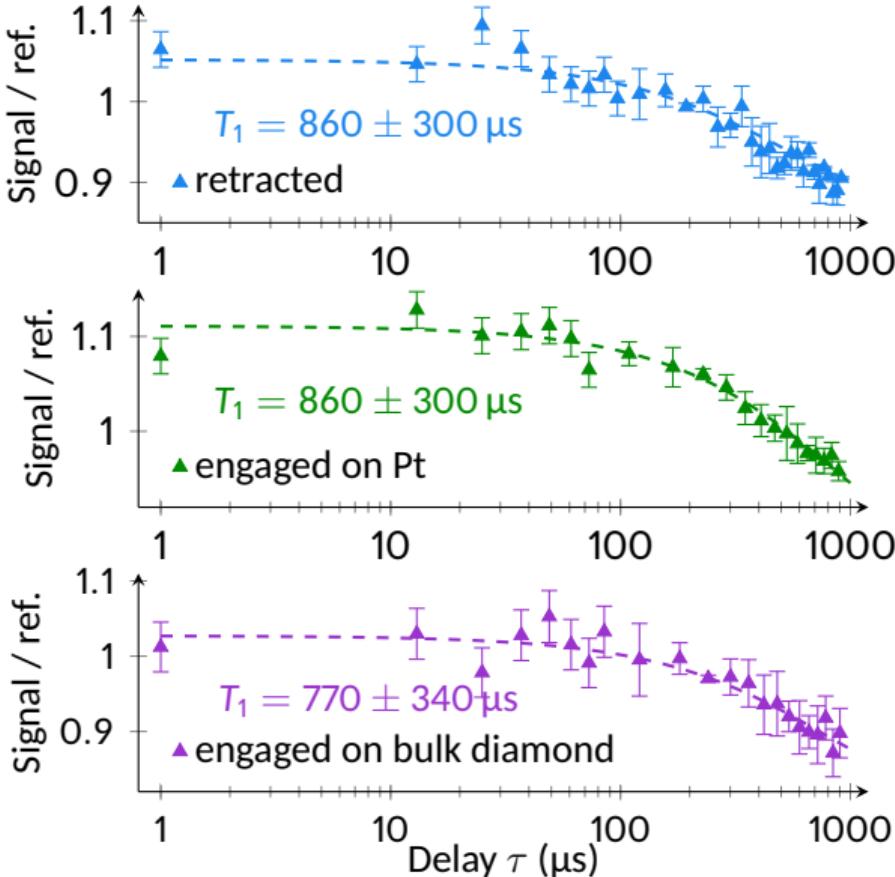
- Same T_1 with the tip retracted or engaged on Pt or bulk diamond

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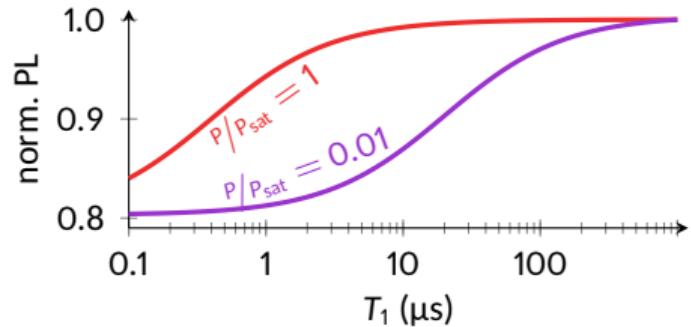
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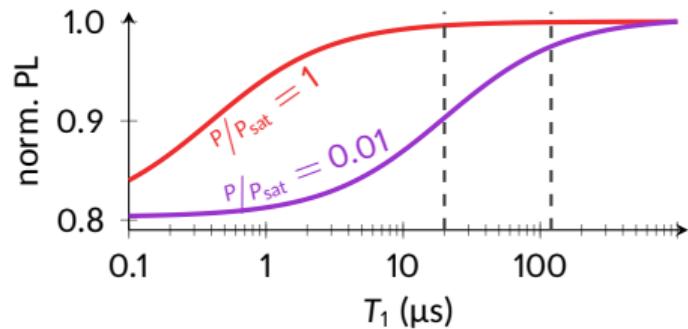


- Same T_1 with the tip retracted or engaged on Pt or bulk diamond
- We exclude Johnson noise (no effect on Pt)
- Also not an effect unrelated to the sample, like modification of the NV charge state

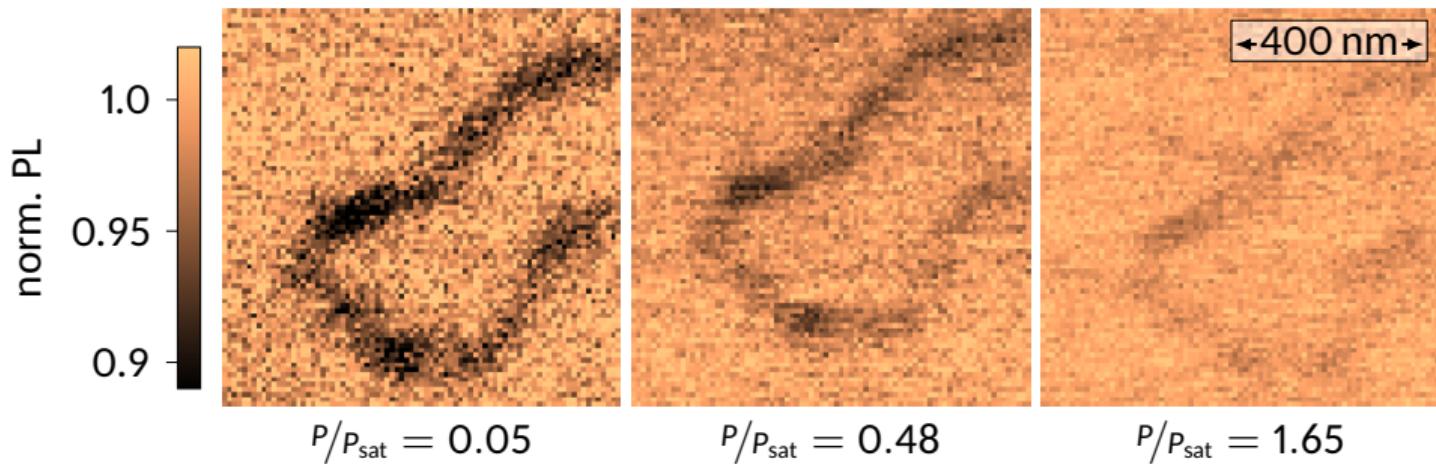
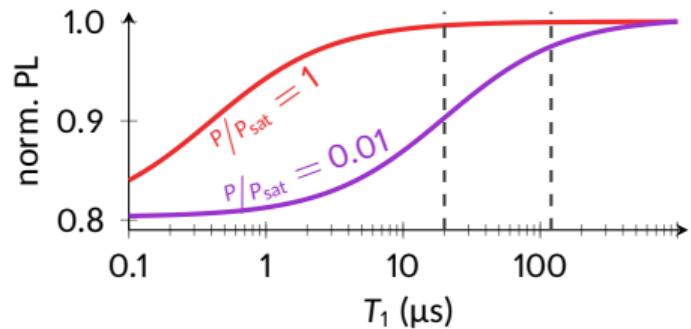
Dependence on the optical power



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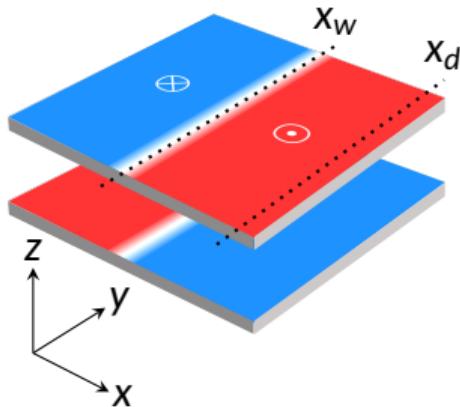
Origin of the noise: spin waves

Collaboration C2N: Jean-Paul Adam, Joo-Von Kim



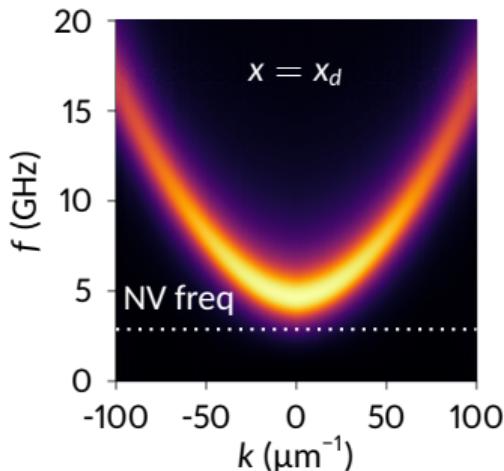
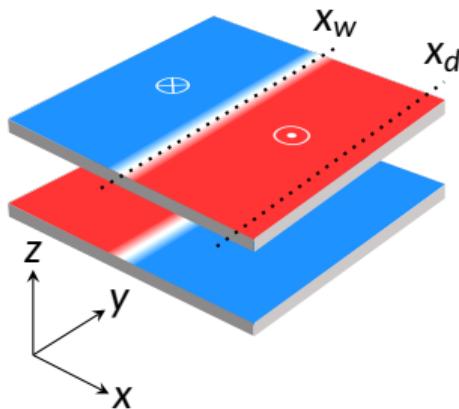
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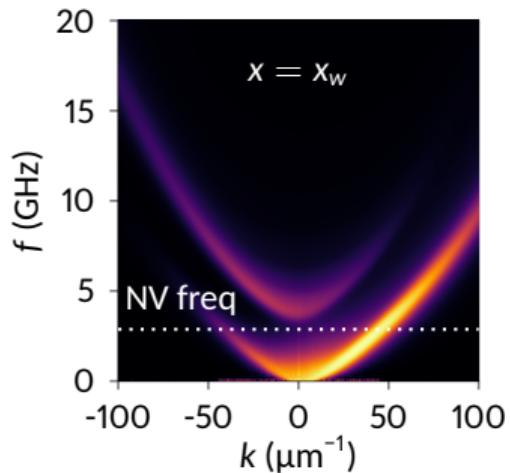
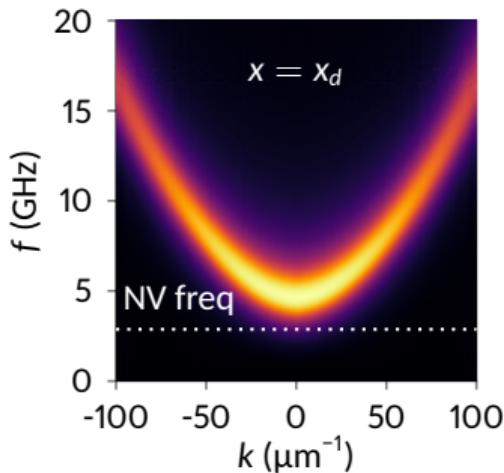
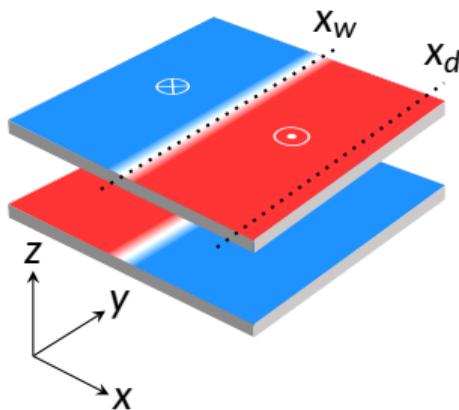
Collaboration C2N: Jean-Paul Adam, Joo-Von Kim



- NV frequency in the tail of the dispersion relation, almost below the gap: we are only sensitive to a few modes in the domains

Origin of the noise: spin waves

Collaboration C2N: Jean-Paul Adam, Joo-Von Kim



- ▶ NV frequency in the tail of the dispersion relation, almost below the gap: we are only sensitive to a few modes in the domains
- ▶ No gap in the domain walls, presence of modes at the NV frequency: **we are much more sensitive to the noise from the walls!**

Map of the detectable noise

Simulation of the expected noise map
above a domain wall
(at 2.87 GHz and at 80 nm from the surface)

Map of the detectable noise

Simulation of the expected noise map
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- Disorder in the static magnetic configuration (anisotropy variations)

Map of the detectable noise

Simulation of the expected noise map
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- ▶ Disorder in the static magnetic configuration (anisotropy variations)
- ▶ Driving field at 2.87 GHz with random spatial variations

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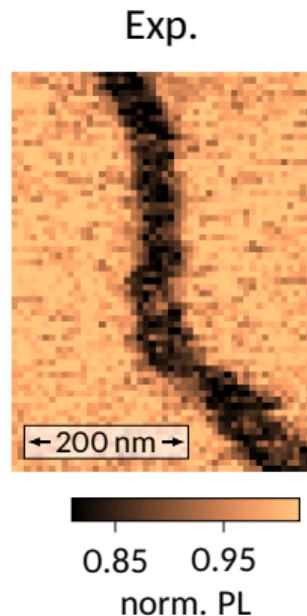
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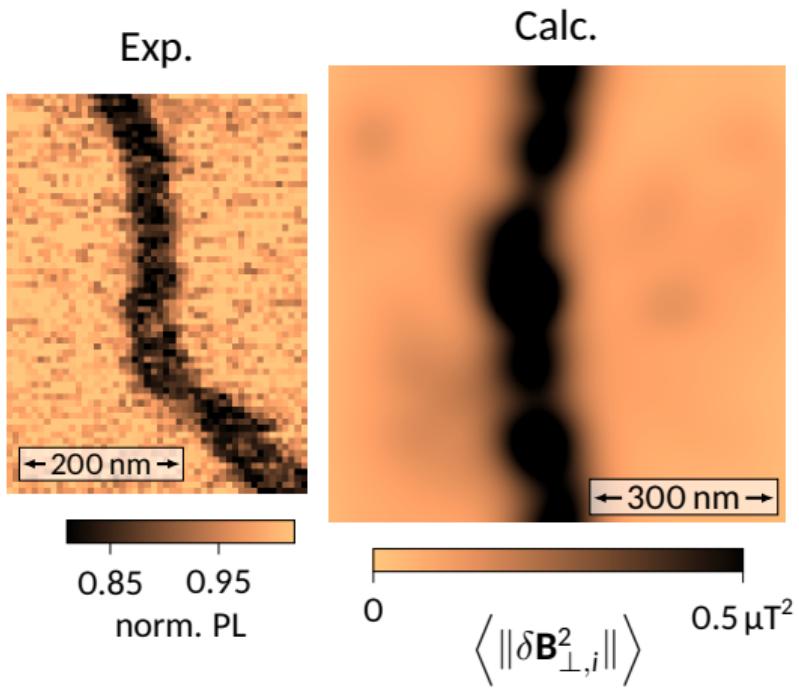
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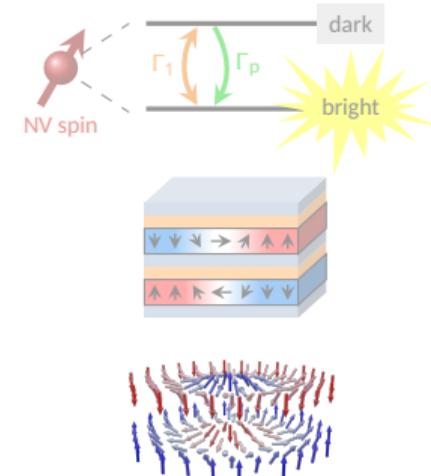
Outline

Collaborations: C2N: Thibaut Devolder, Jean-Paul Adam, Joo-Von Kim

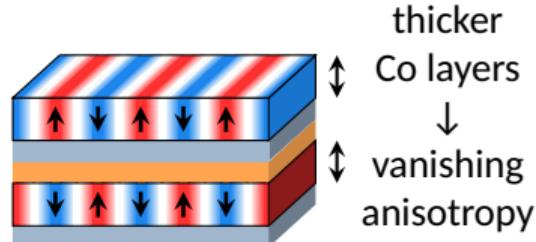
UMR CNRS/Thales: William Legrand, Fernando Ajejas,
Karim Bouzehouane, Nicolas Reyren,
Vincent Cros



1. Experimental investigation of the NV center response to magnetic noise
2. Application to the detection of domain walls in a synthetic antiferromagnet
3. Extension of the relaxometry mode to spirals and skyrmions

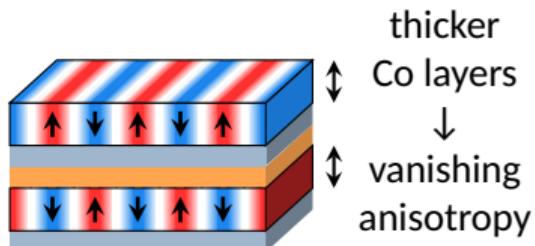


Single-spin relaxometry on spin spirals

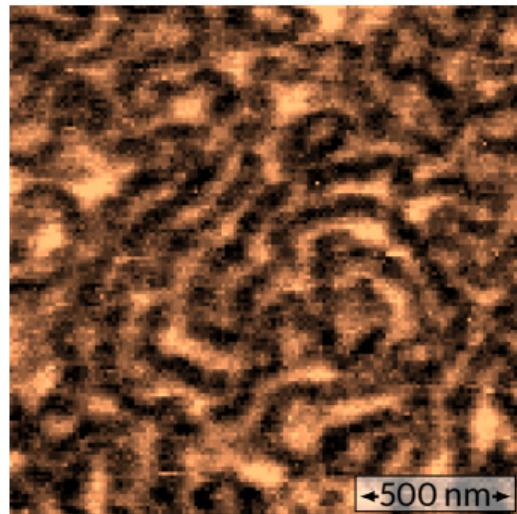


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Single-spin relaxometry on spin spirals

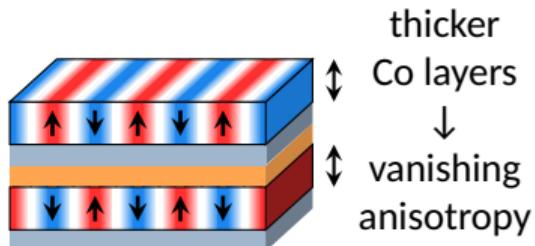


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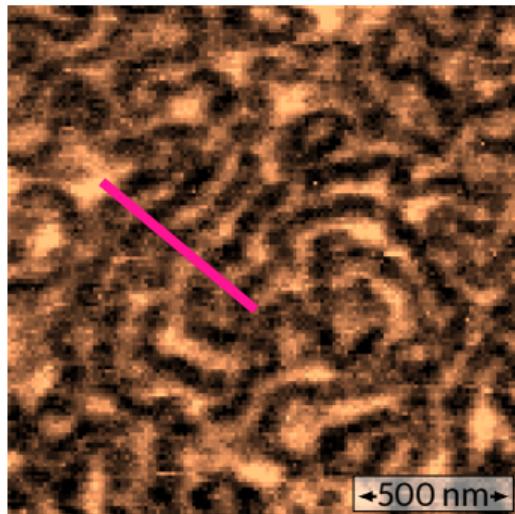
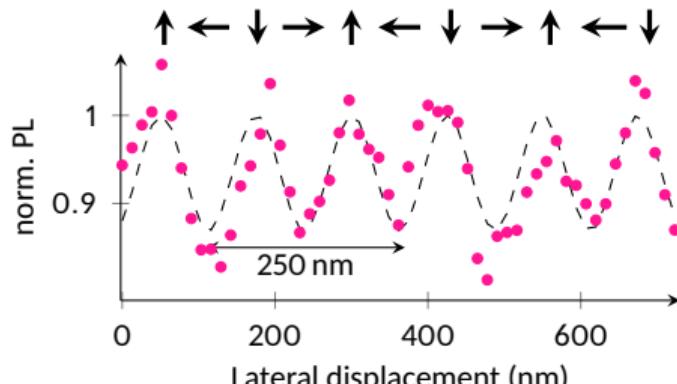


0.8 0.9 1.0
norm. PL

Single-spin relaxometry on spin spirals

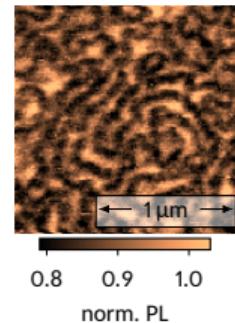
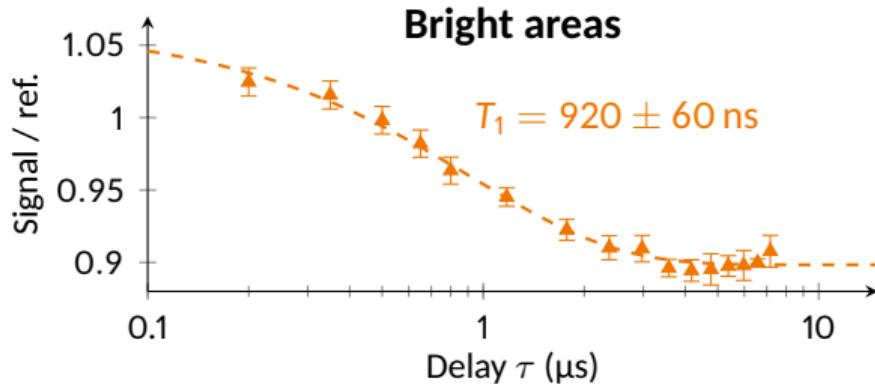


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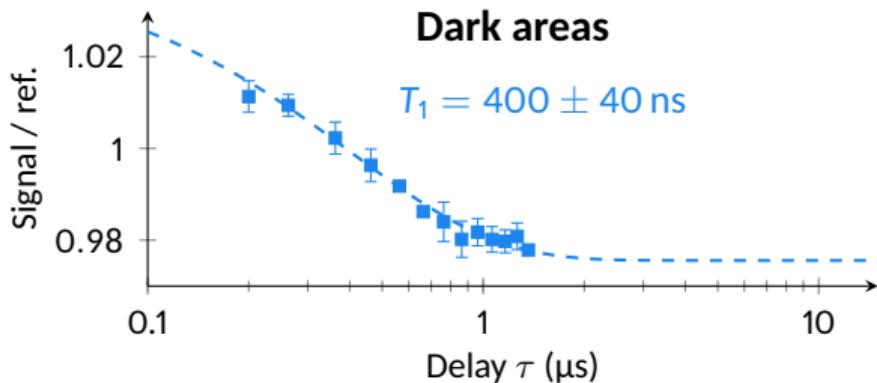
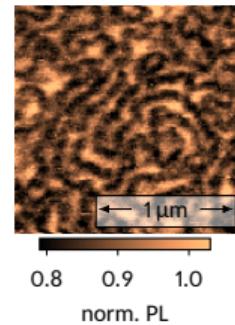
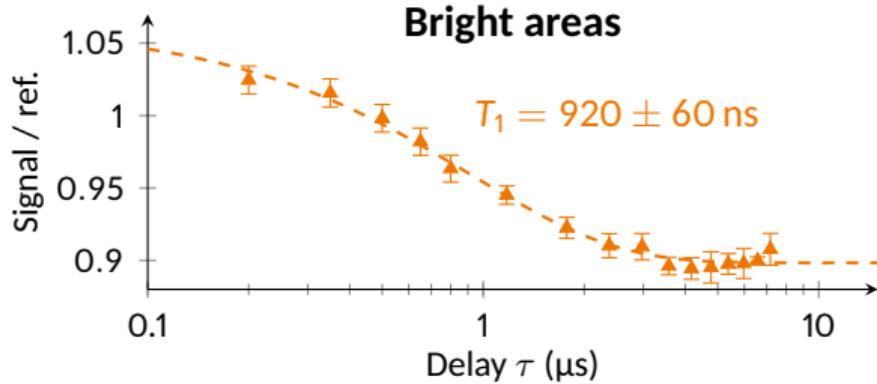


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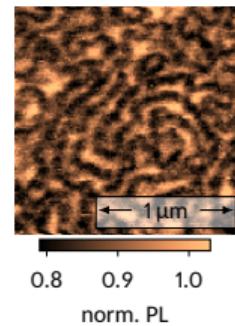
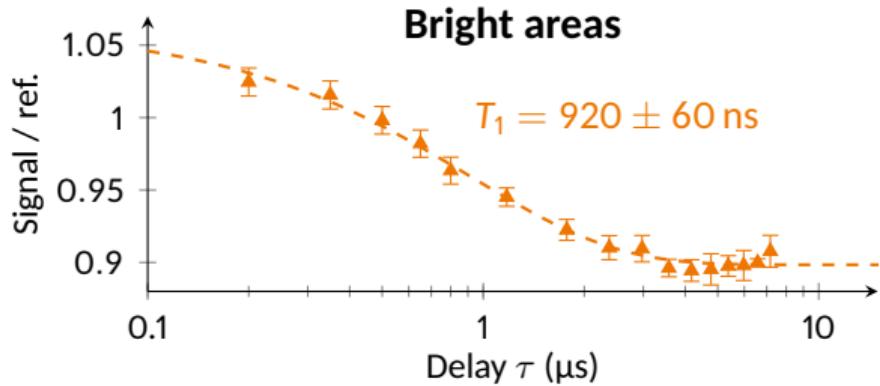
T1 measurements and expected noise map



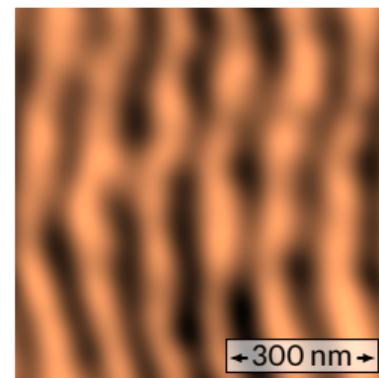
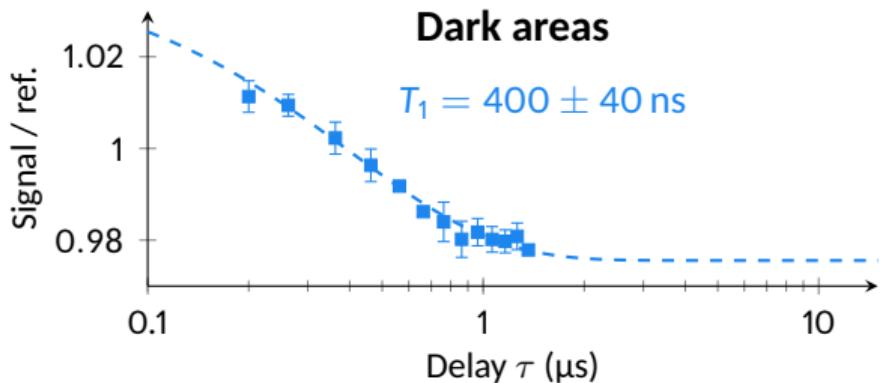
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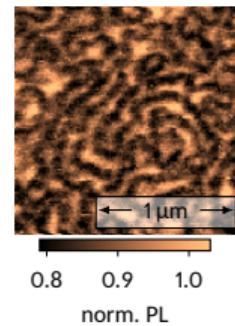
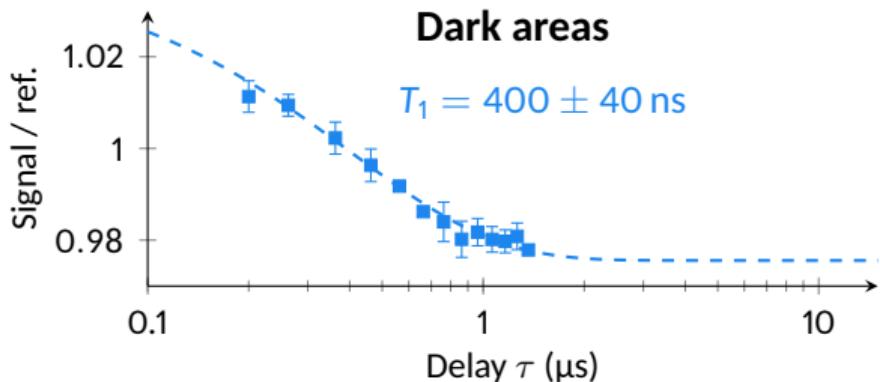
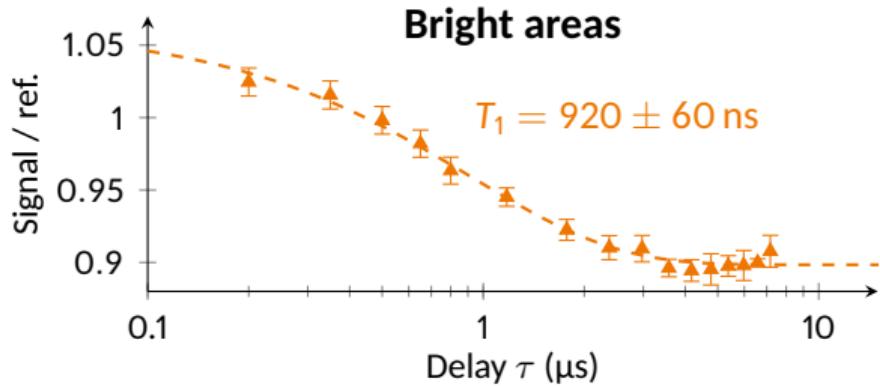
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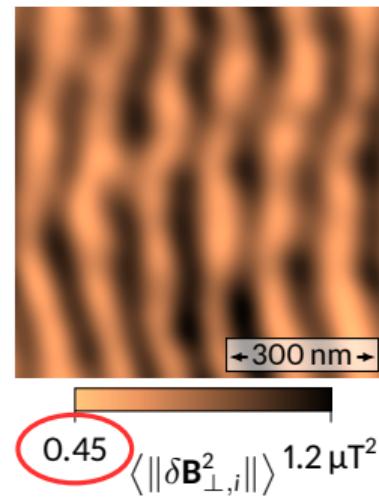
Calculated noise map



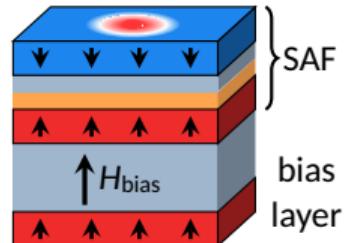
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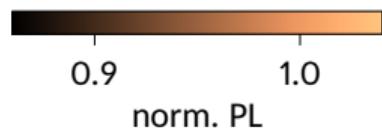
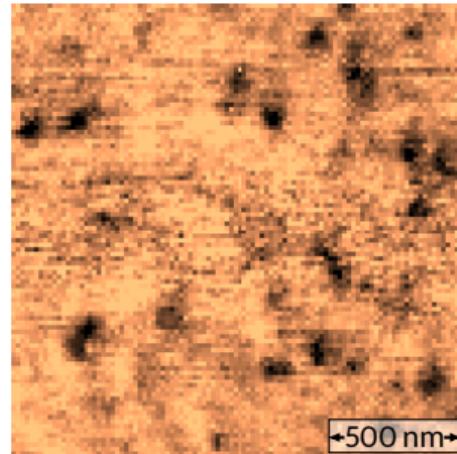
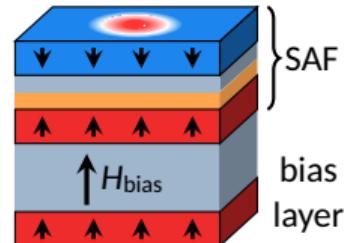


Antiferromagnetic skyrmions



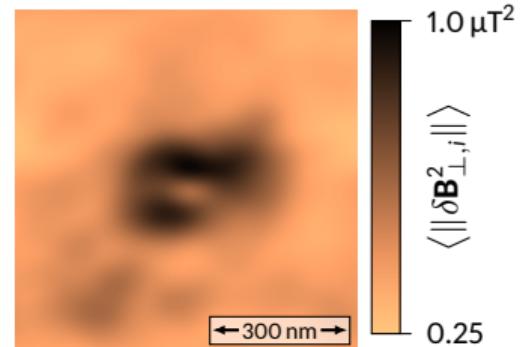
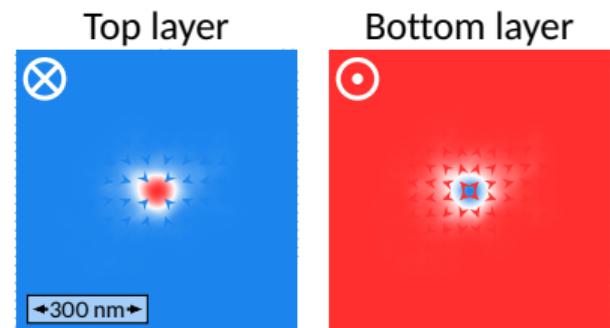
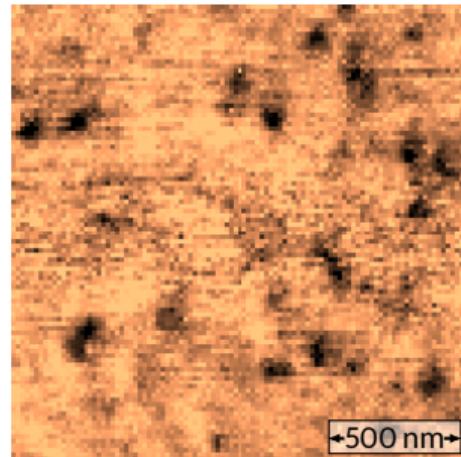
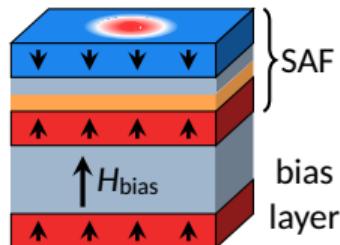
W. Legrand et al. *Nat. Mat.* 19 (2020), 34

Antiferromagnetic skyrmions



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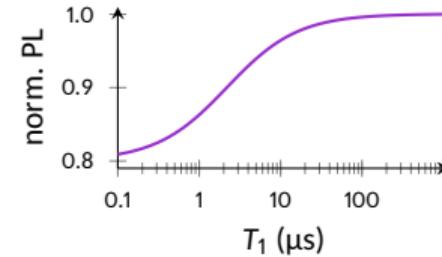
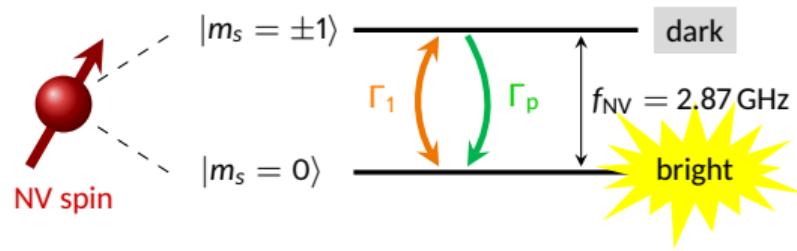
Antiferromagnetic skyrmions



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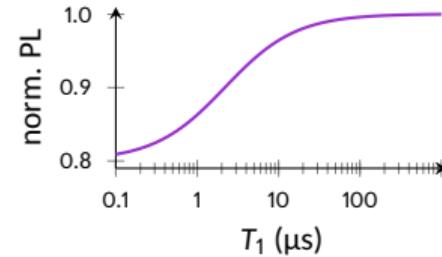
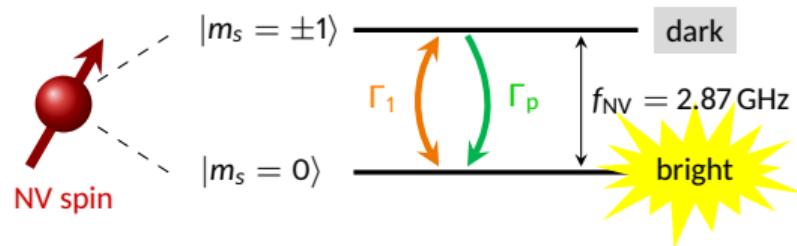
Summary

→ All optical detection of magnetic noise with NV centers

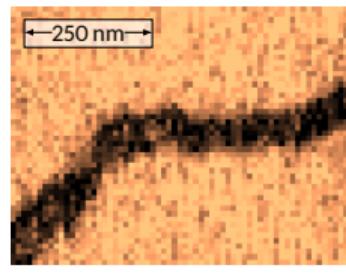
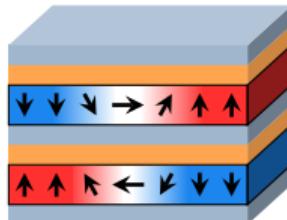


Summary

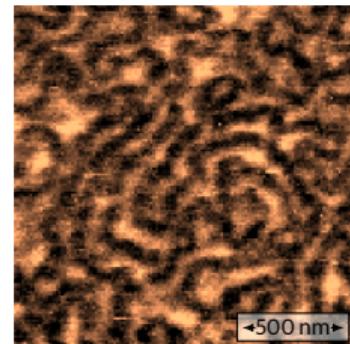
→ All optical detection of magnetic noise with NV centers



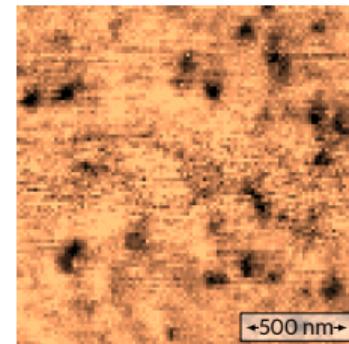
→ Application to the imaging of magnetic textures in synthetic antiferromagnets



0.85 0.9 0.95 1.0
norm. PL



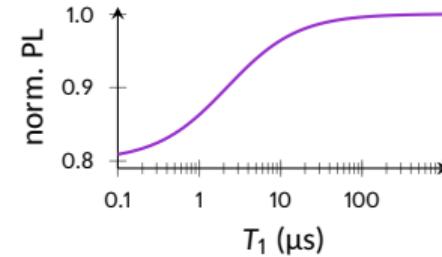
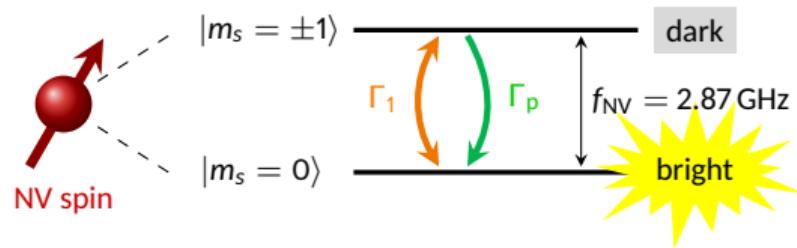
0.8 0.9 1.0
norm. PL



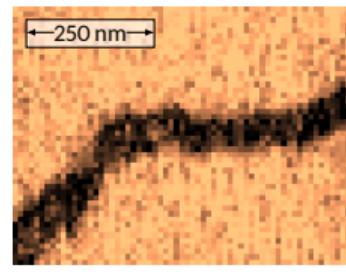
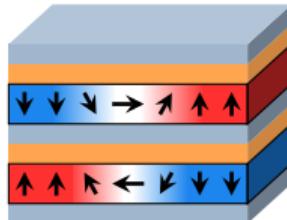
0.9 1.0
norm. PL

Summary

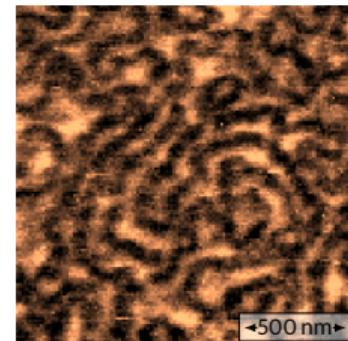
→ All optical detection of magnetic noise with NV centers



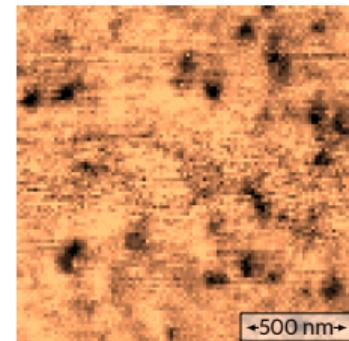
→ Application to the imaging of magnetic textures in synthetic antiferromagnets



0.85 0.9 0.95 1.0
norm. PL



0.8 0.9 1.0
norm. PL



0.9 1.0
norm. PL

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