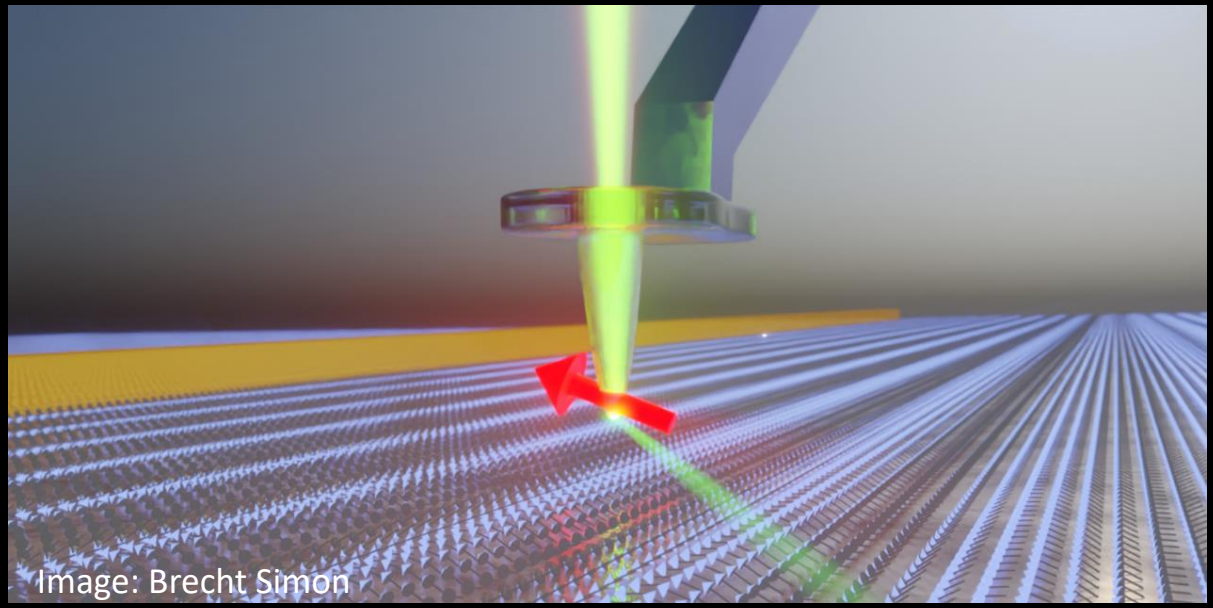
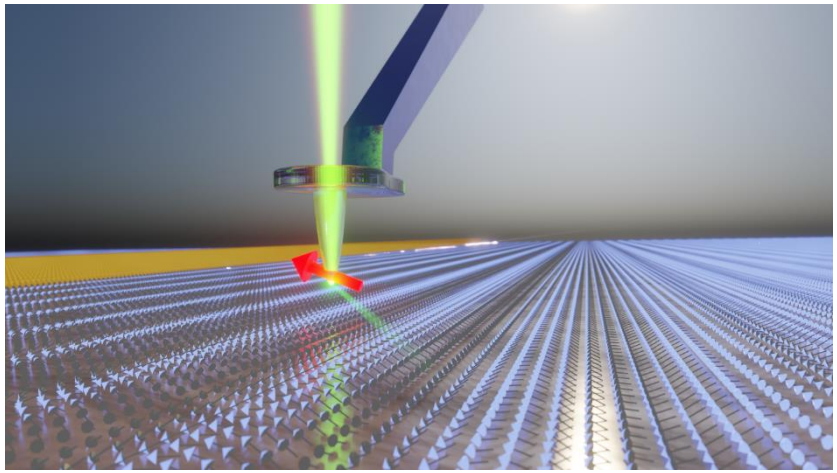
Coherent manipulation of spins in diamond via spin-wave mixing



Toeno van der Sar

Department of Quantum Nanoscience

Opening the quantum world for innovation



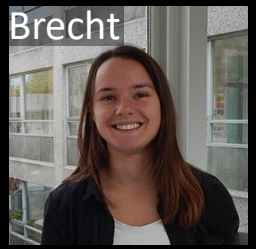
Quantum MATTER

Quantum SENSING

Quantum TRANSDUCTION

qn.tudelft.nl

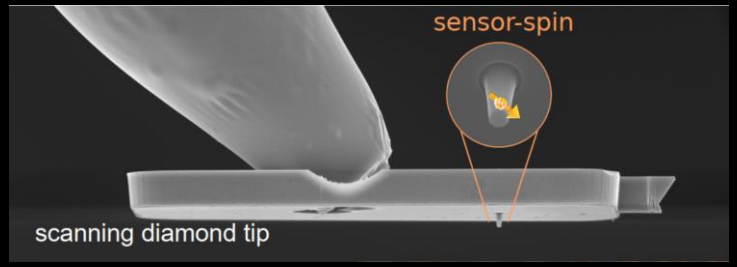
Group & collaborators



Fabian

Theory:

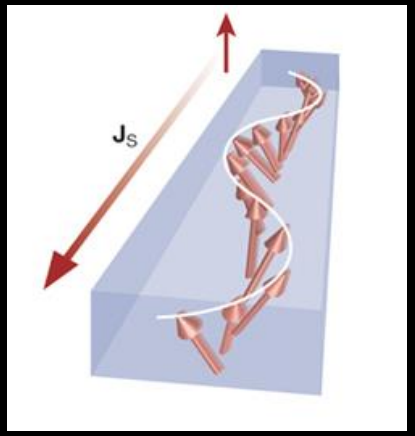
- *Mehrdad Elyasi*
- *Yaroslav Blanter*
- *Gerrit Bauer*
- *Tao Yu*



www.tudelft.nl/vandersarlab

Spin waves

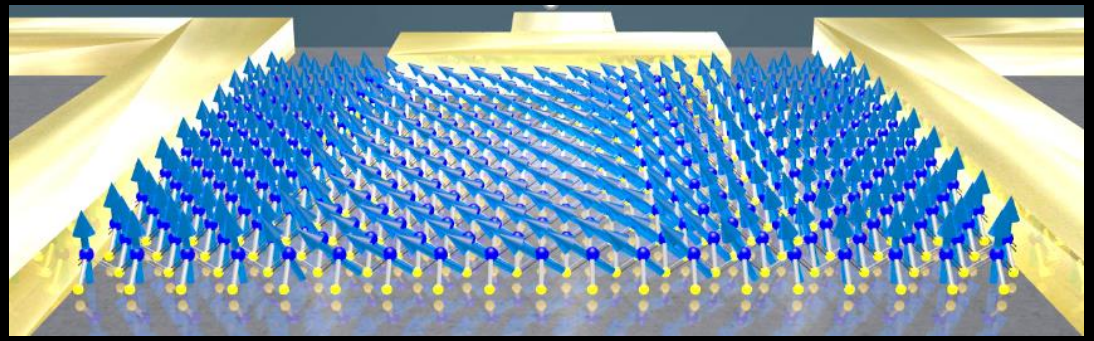
The elementary spin excitations of magnets



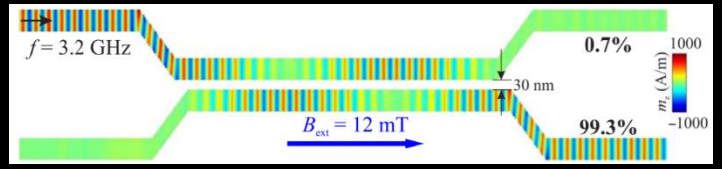
Kajiwara et al., Nature 2010

+ many new active research topics

- **Quantum applications**
- **Van der Waals magnets**

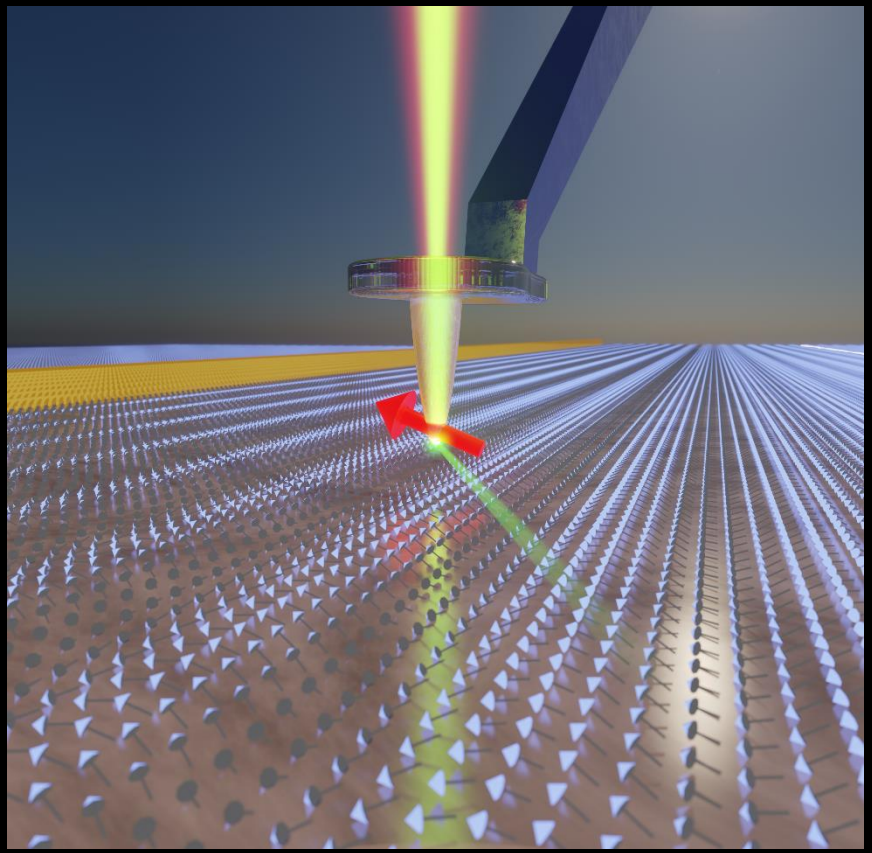


Key drive: information processing



Wang et al., Sci. Adv. 2018
Roadmap: Chumak et al, IEEE Trans. Magn. (2022)

Today: *Magnetic detection* of spin waves using spins in diamond

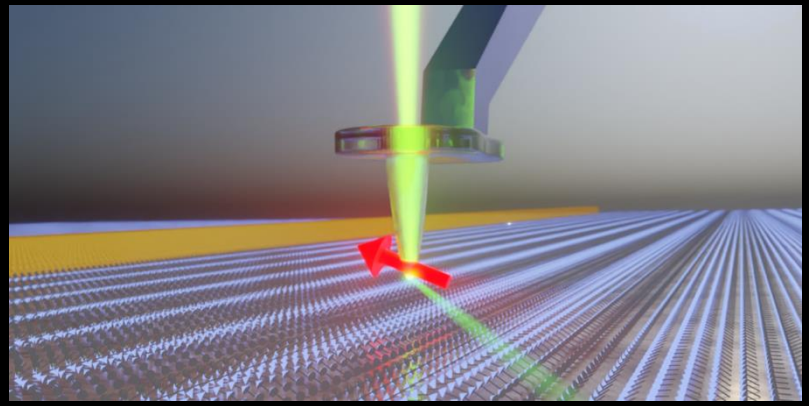


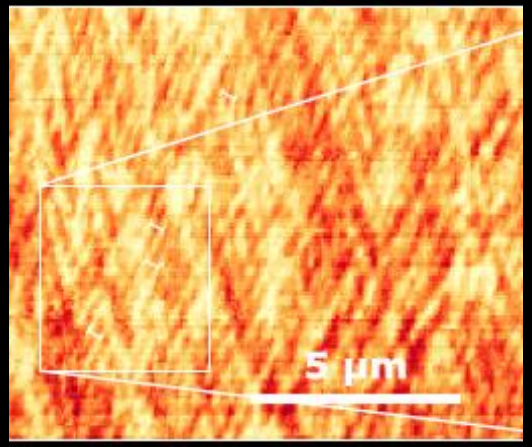
Key features:

1. Detects spin-wave magnetic fields
2. Can ‘look through’ materials
3. Nanoscale resolution
4. Sensitive
5. Table-top

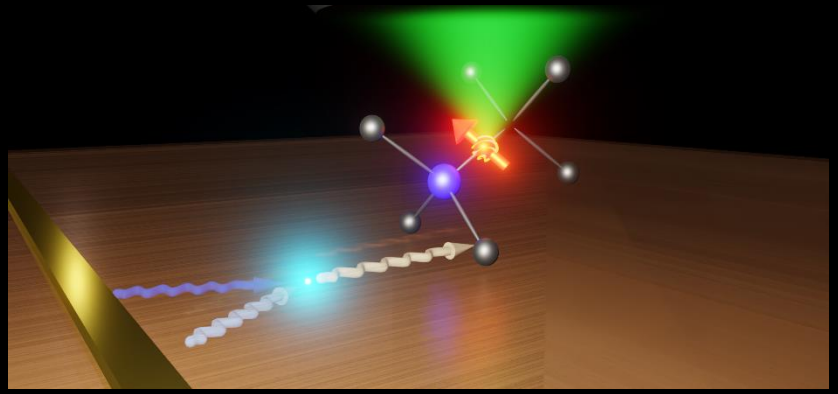
This talk

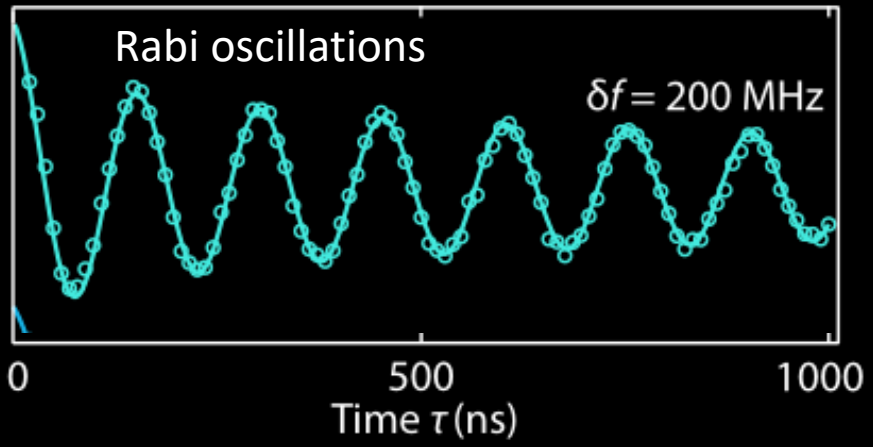
Magnetic imaging of spin waves





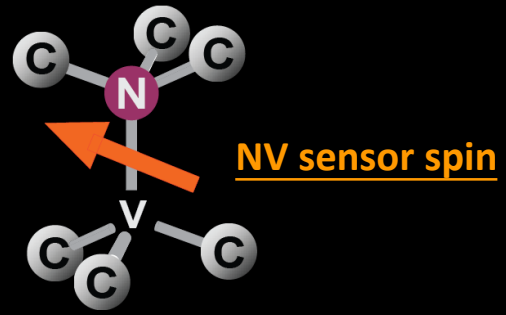
Coherent spin control via spin-wave mixing



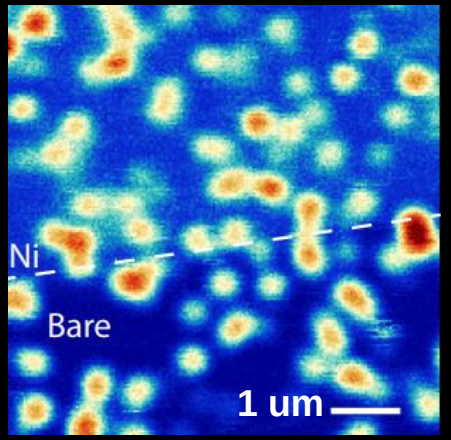


The sensor: nitrogen-vacancy center in diamond

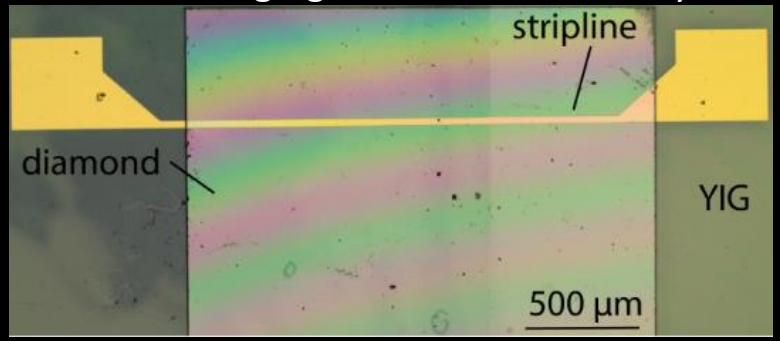
"Nitrogen-vacancy (NV) center"



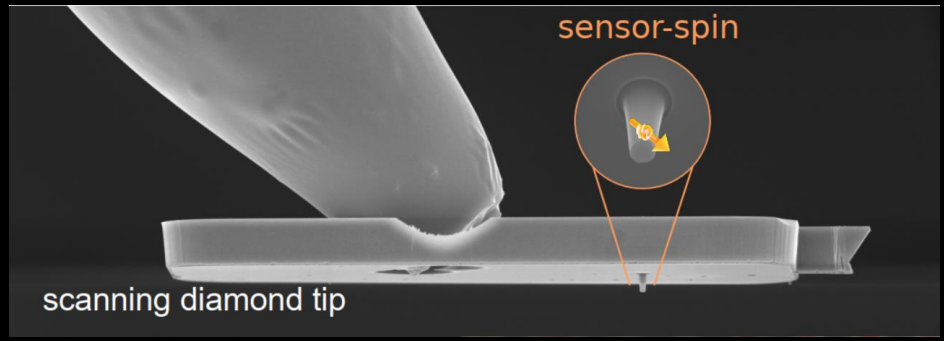
NV photoluminescence



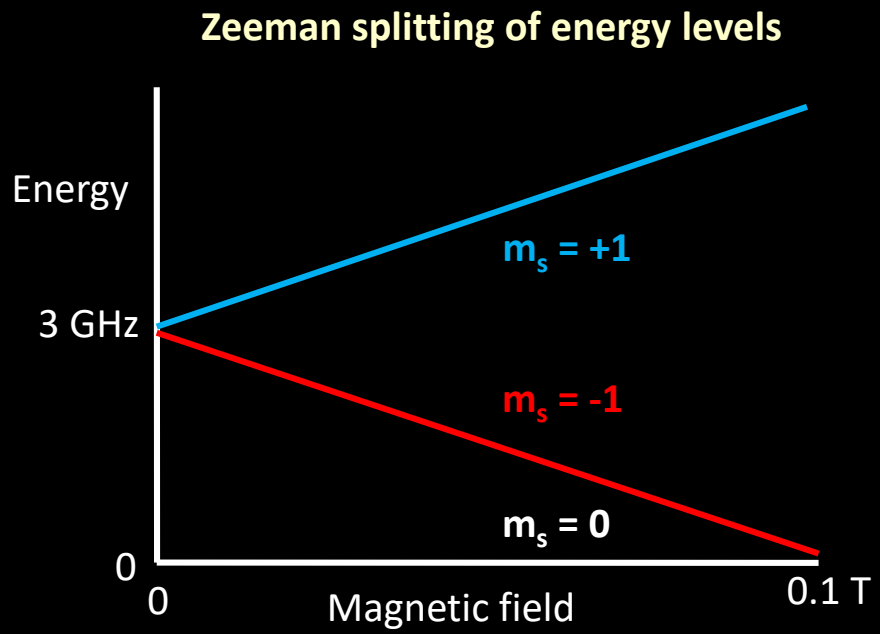
Wide-field imaging: diamond with many NVs

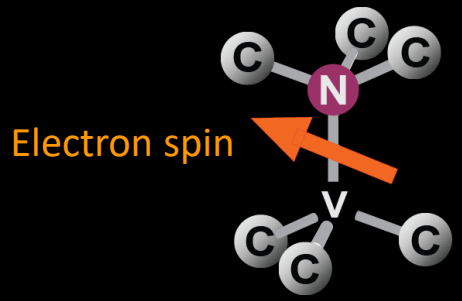


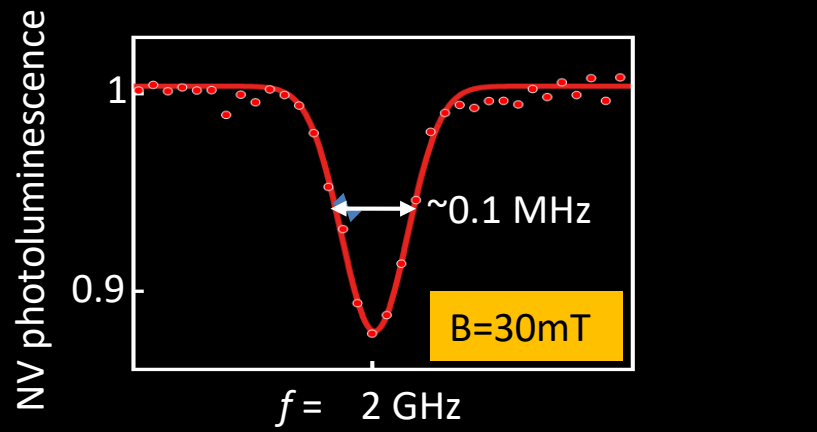
Nanoscale imaging: scanning-NV tip



The NV electron spin – level structure and readout

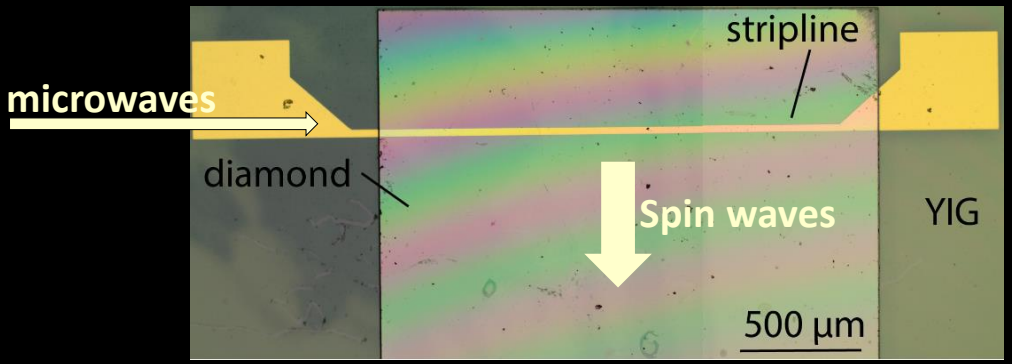




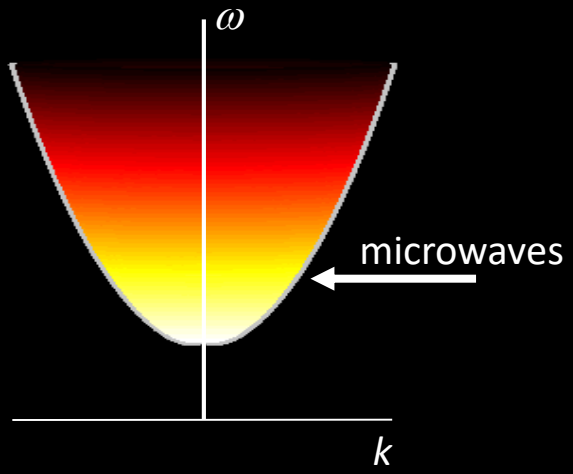


Imaging spin waves using NV magnetometry

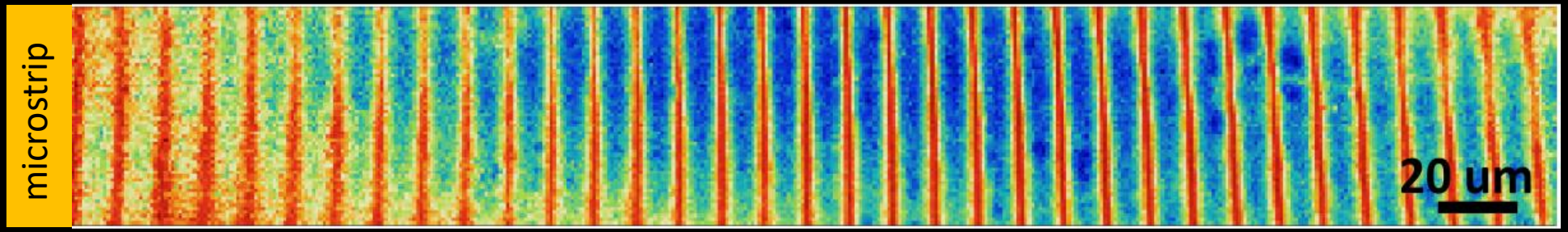
NV-diamond placed on top of YIG film



Wavelength of excited spin waves

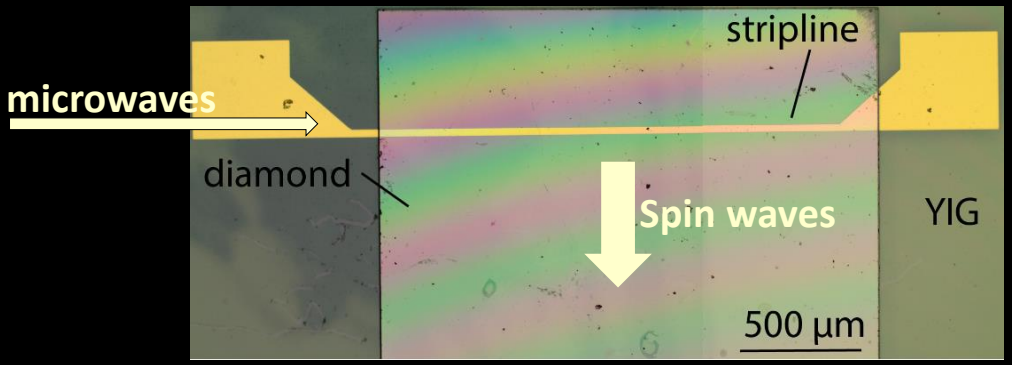


NV spin rotation rate reveals the wavefronts

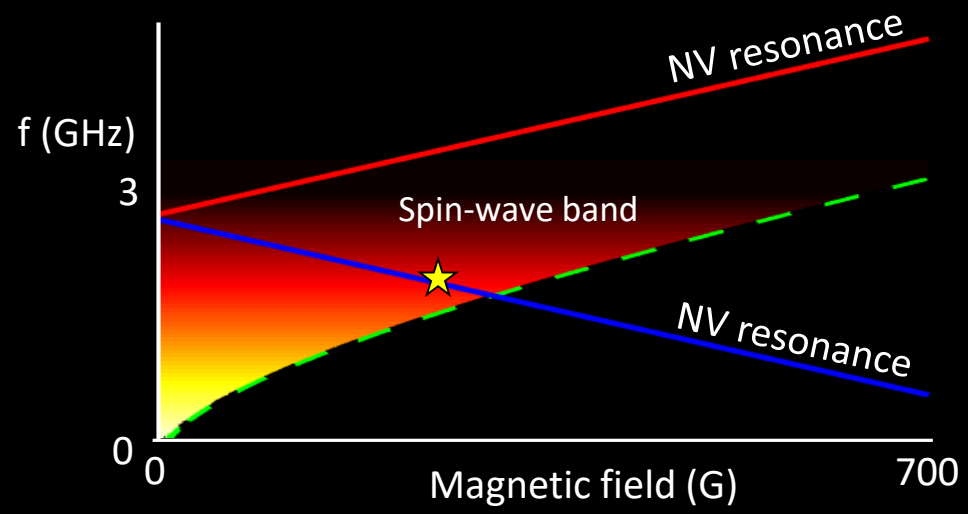


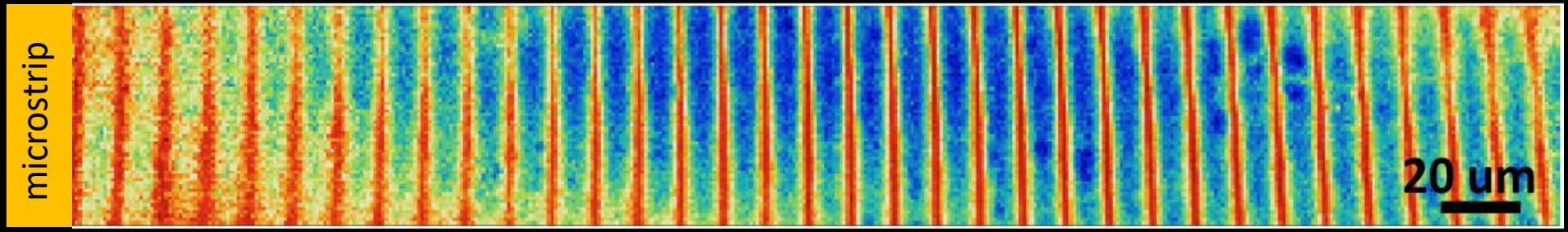
Imaging spin waves using NV magnetometry

NV-diamond placed on top of YIG film



How does it work spectrally?



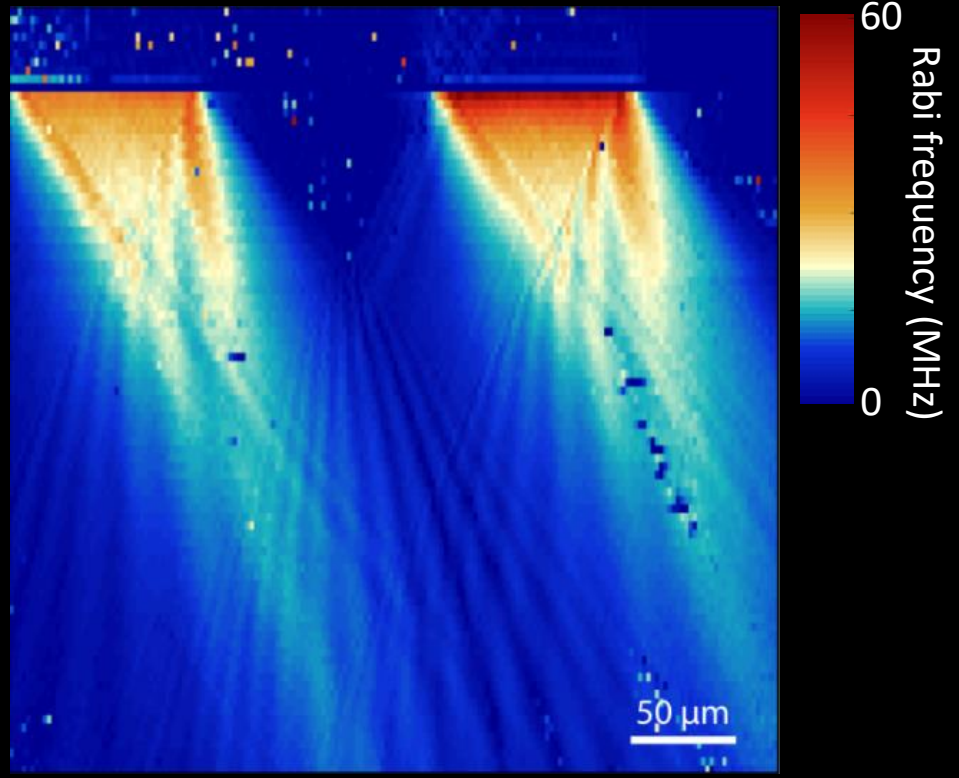


Bertelli et al., Science Adv. 2020

Related work: *Zhou et al, PNAS 2021*

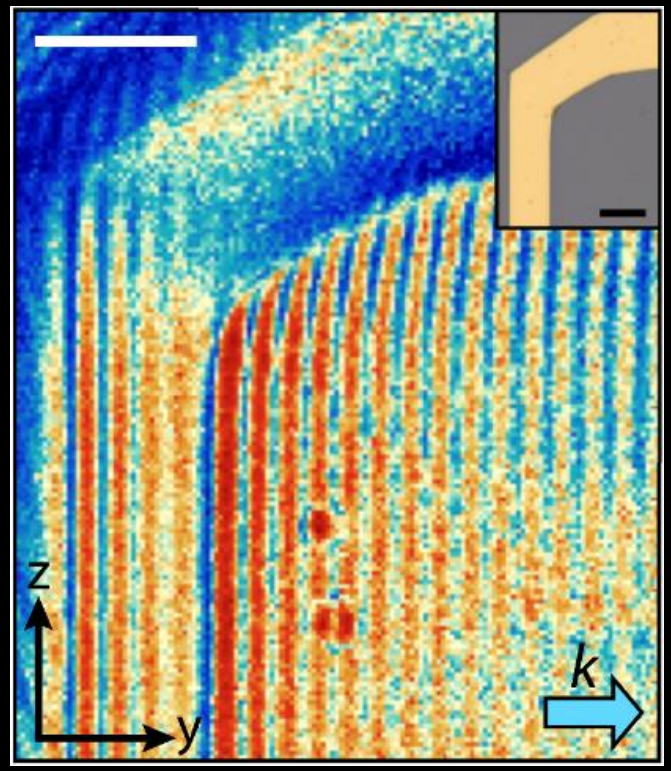
Using spin waves to drive NV spins

Large-range microwave delivery



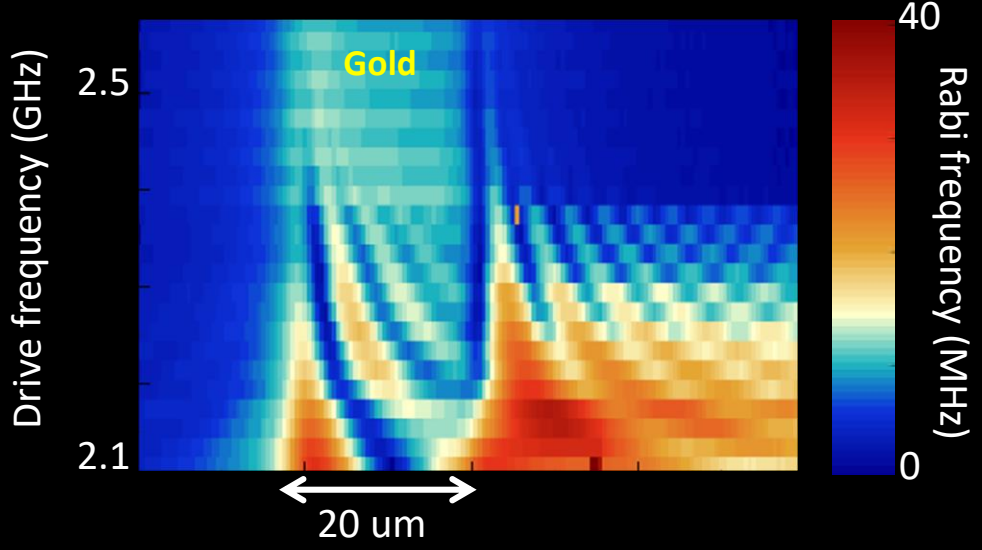
Bertelli et al., *Science Adv*. 2020

Imaging *through* metals



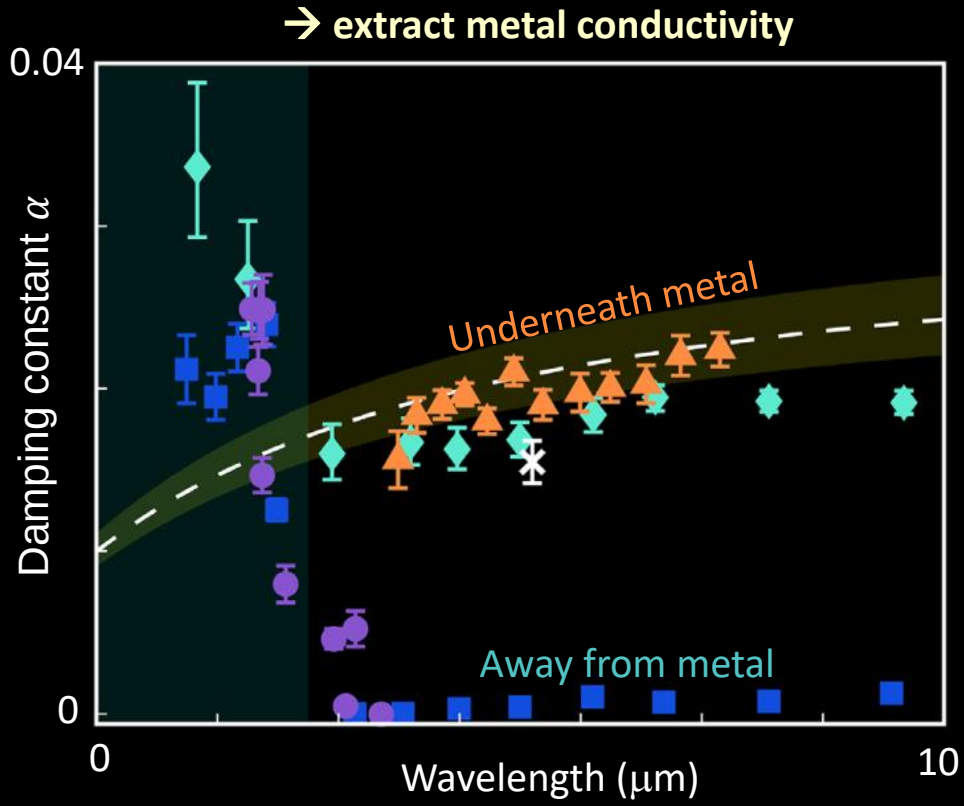
Bertelli et al., *Adv. Quantum Technol.* 2021

Extracting spin-wave damping underneath gold



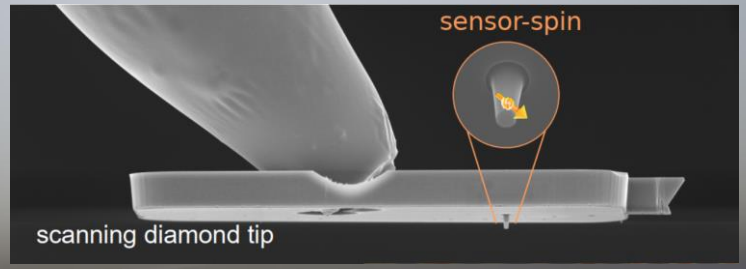
Access to:

- permeability, skin depth, conductivity
- interaction with materials
- gated devices (e.g. magnon transistors)



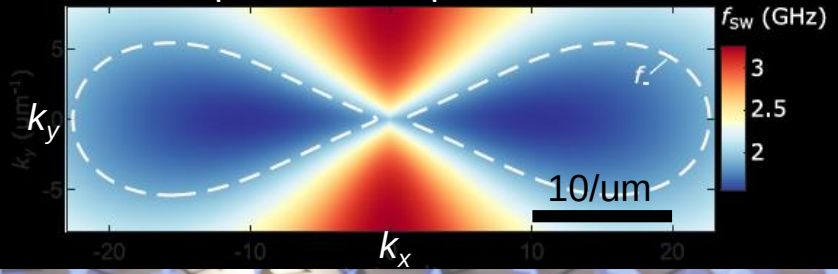
I Bertelli et al., Advanced Quantum Technologies 2021

Imaging spin-wave scattering using a single NV spin



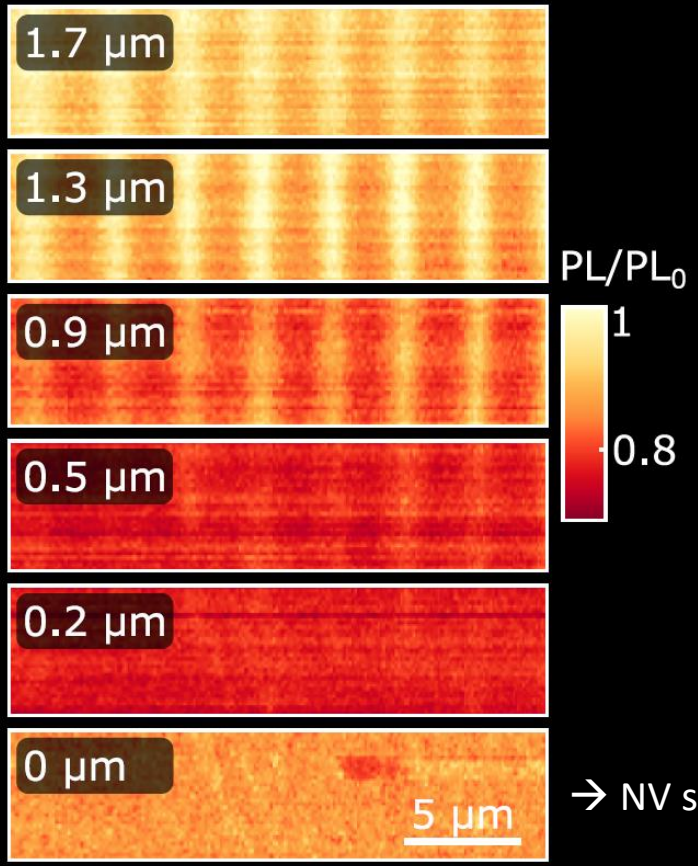
What to expect?

Spin-wave dispersion:



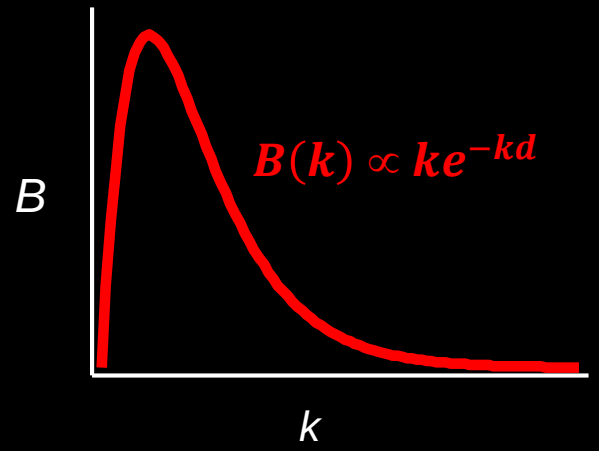
Characterizing the evanescent spin-wave fields

Varying the NV-sample distance:

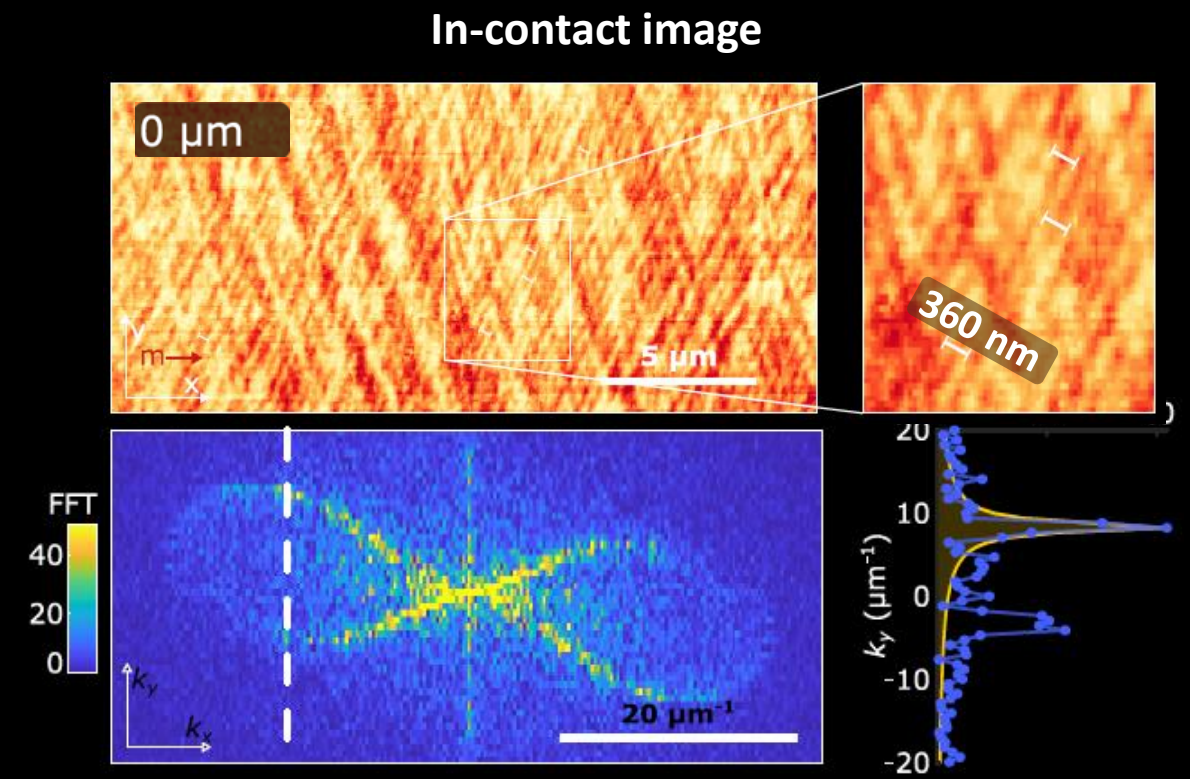


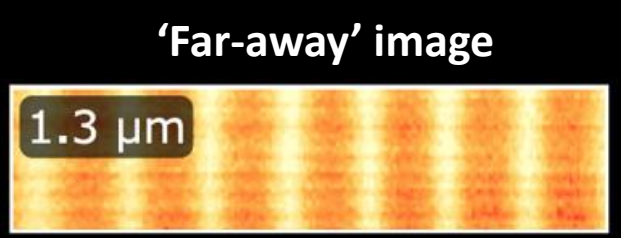
→ NV saturates in contact

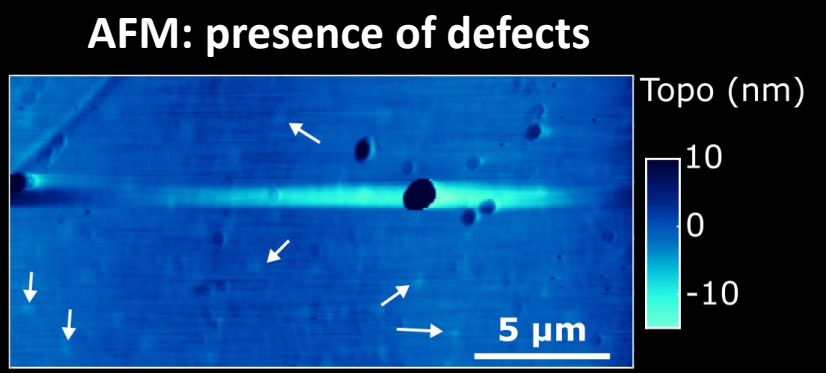
Consistent with exponential increase of spin-wave field



Revealing the multitude of stripline-excited spin waves





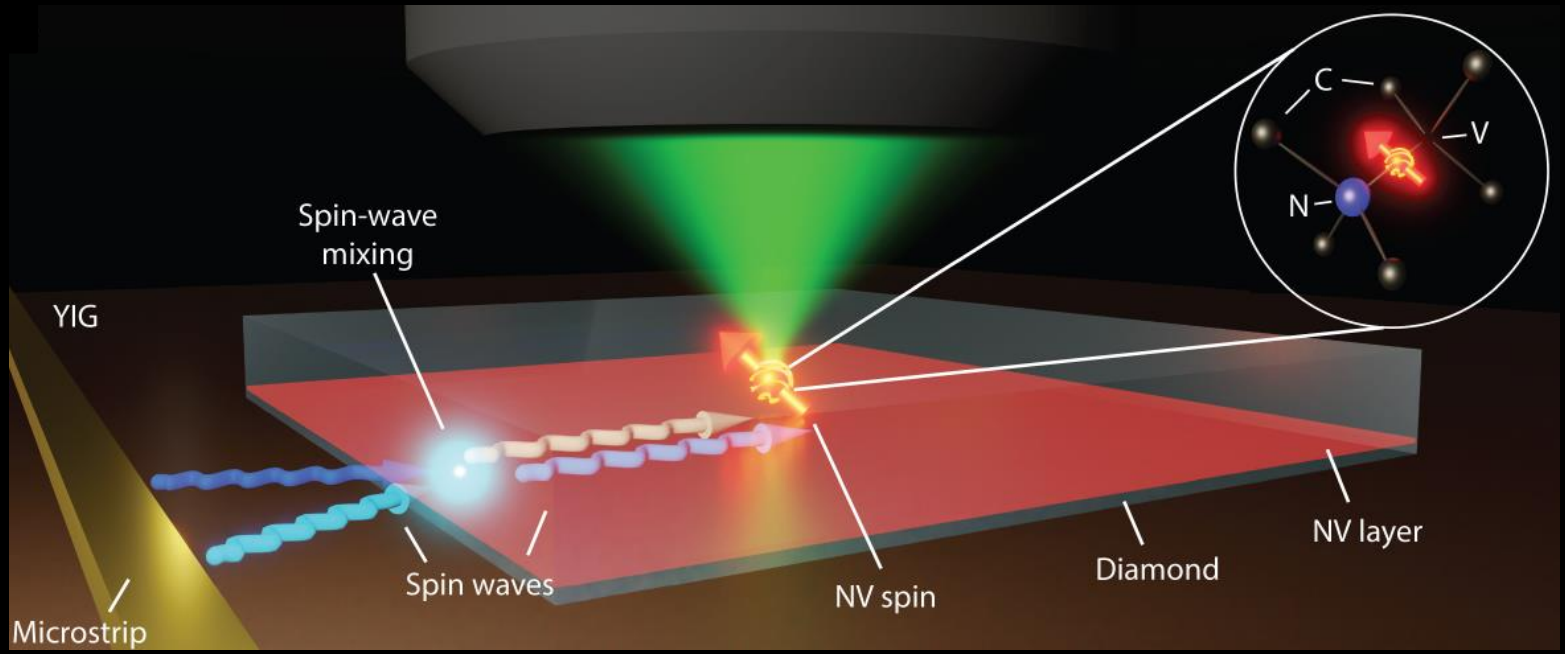


Occupation of entire iso-frequency contour

λ_{min} *= 240 nm*

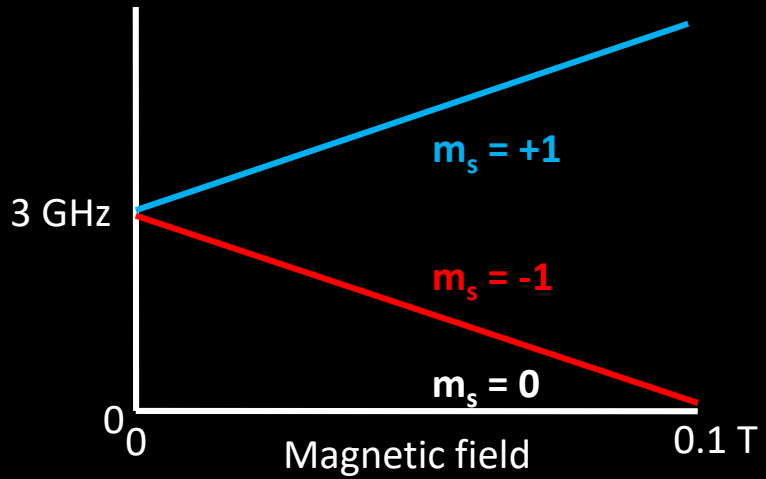
B Simon, S Kurdi et al, Nano Lett. 2022

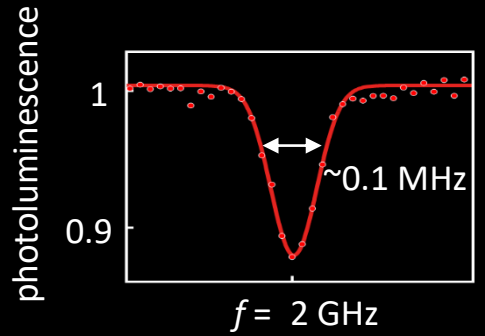
Coherent spin control via spin-wave mixing



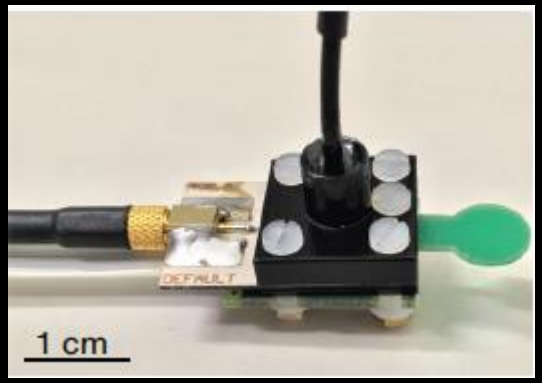
Broadband NV microwave detection via spin-wave mixing

Challenge: NV is narrowband





Commercial NV-sensor

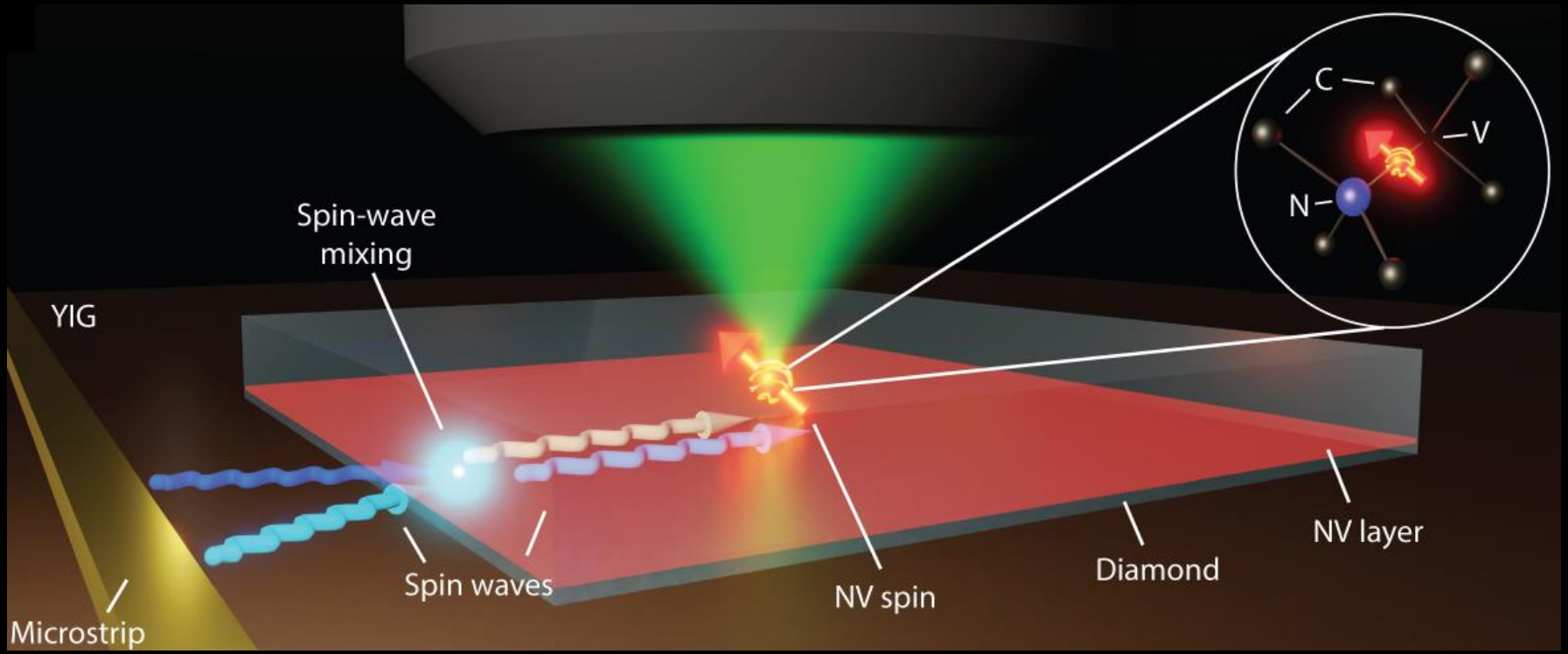


F Stürner et al., Adv. Quantum Technol. 2021, 2000111

Envisioned usecases:

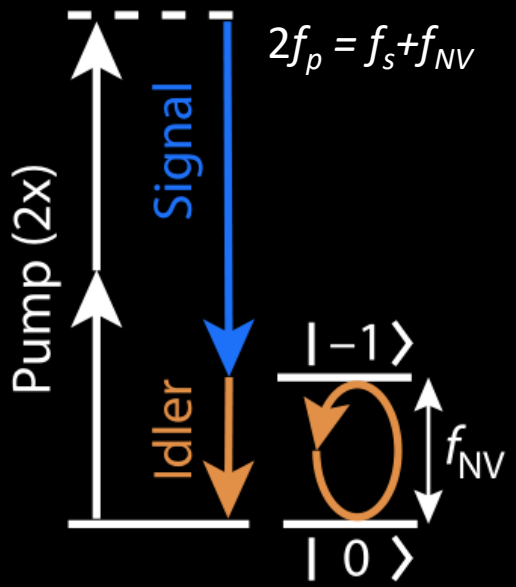
- Probing high-frequency materials
- Probing on-chip oscillators
- Controlling quantum systems

Idea: use spin-wave mixing to convert microwaves

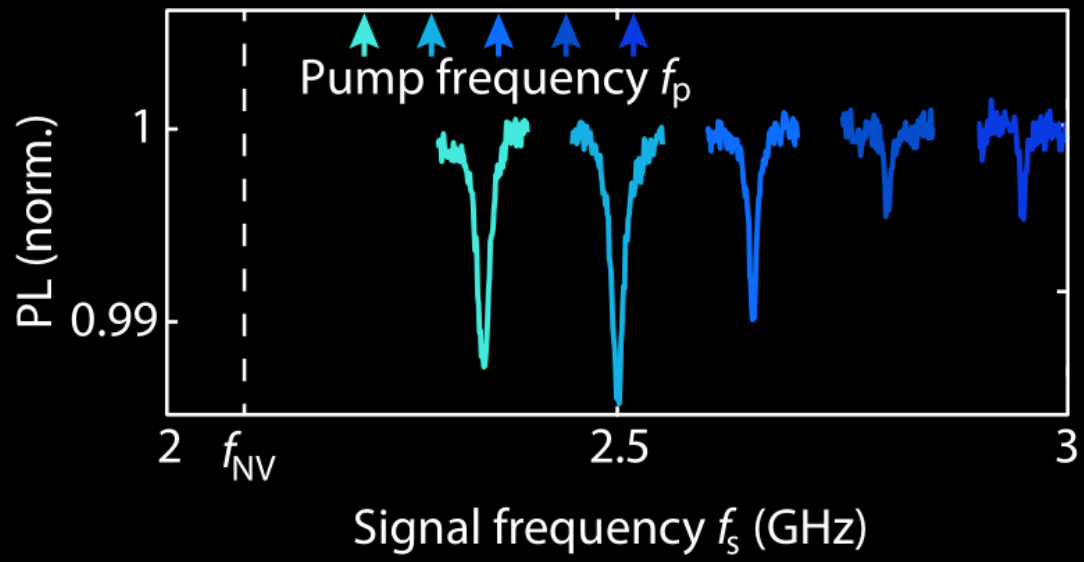


Driving the NV electron spins via four-spin-wave-mixing

Four-spin-wave mixing



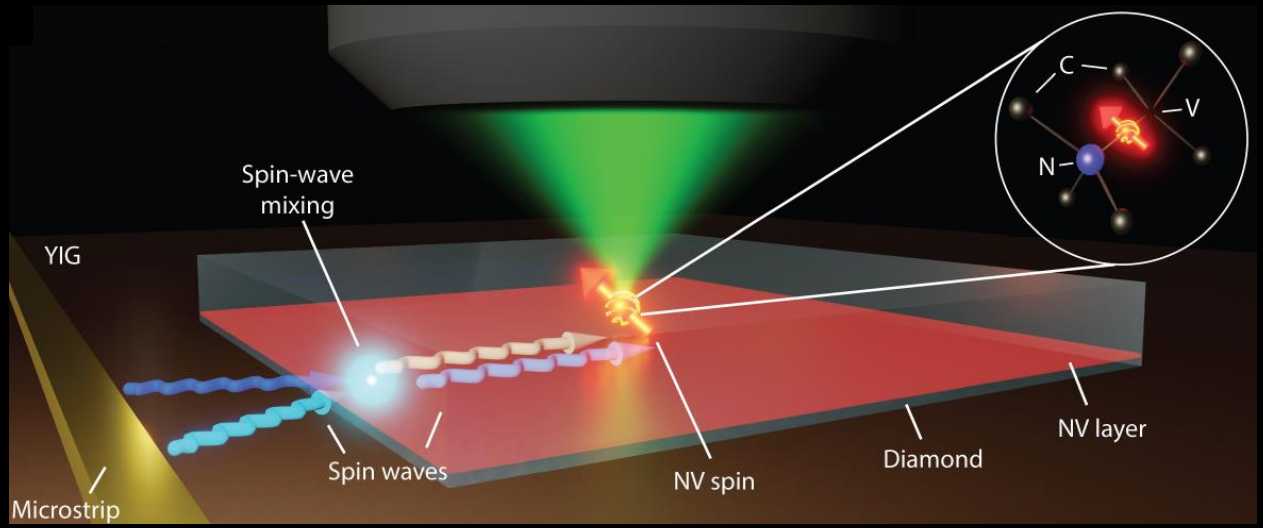
Spin-wave-mixing-driven ESR



Theory: Mehrdad Elyasi (Nat. Comm. 2023)

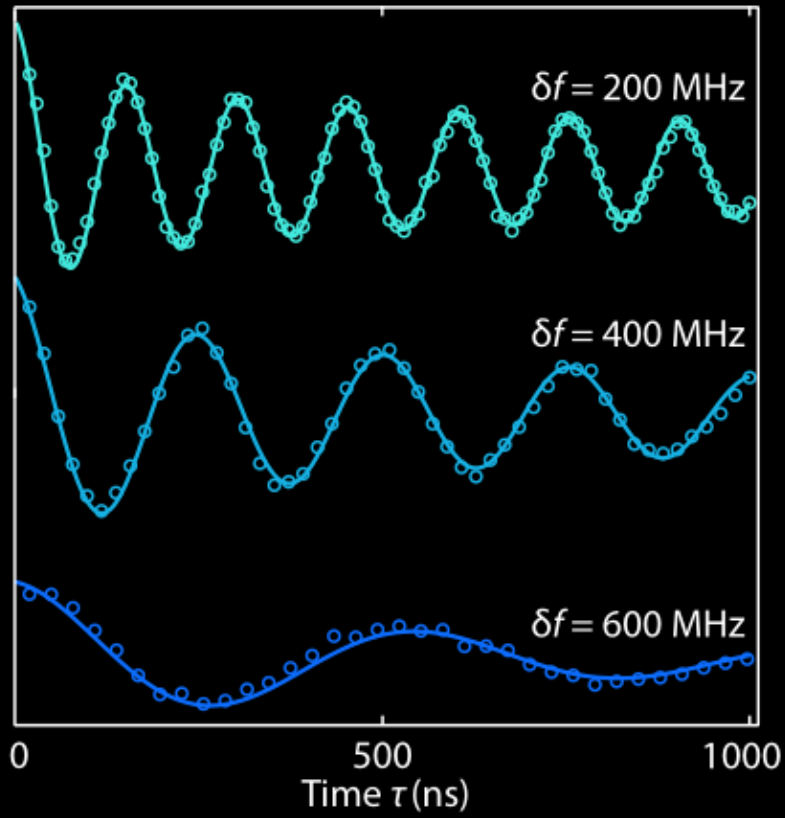
JJ Carmiggelt et al, Nat Comm 2023

Coherent NV-spin control via spin-wave mixing



Testing the coherence of the frequency conversion

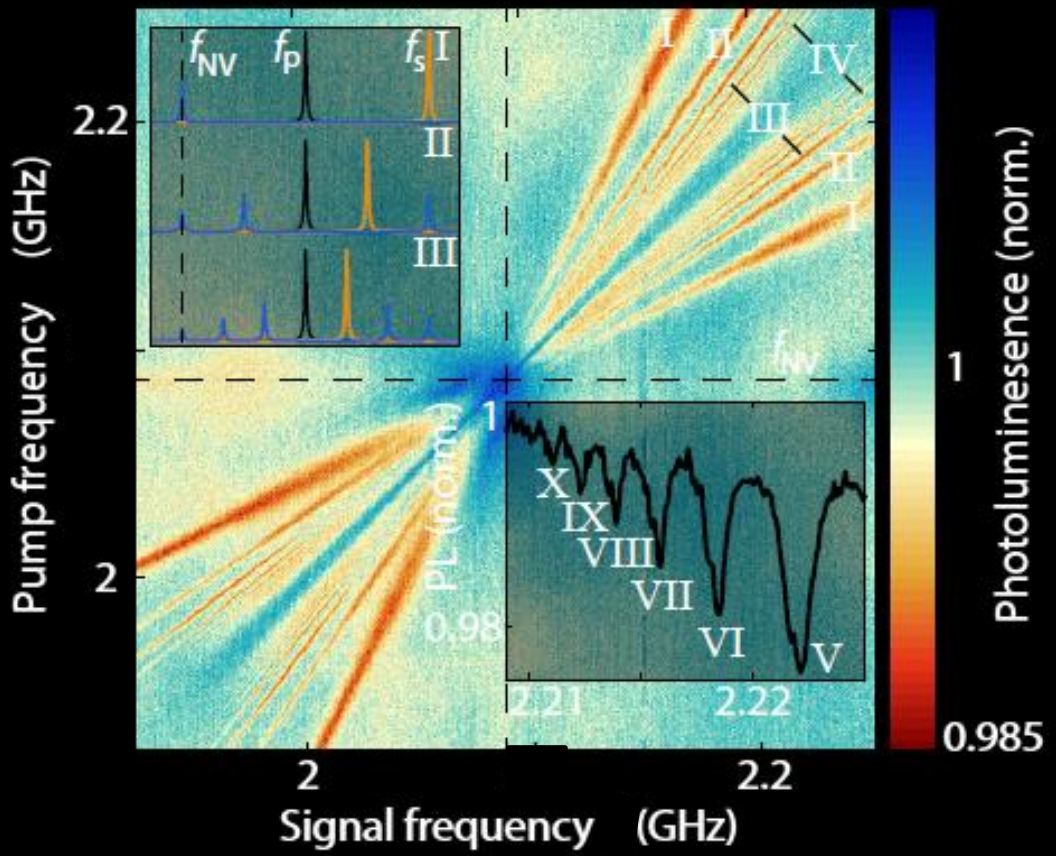
NV Rabi oscillations



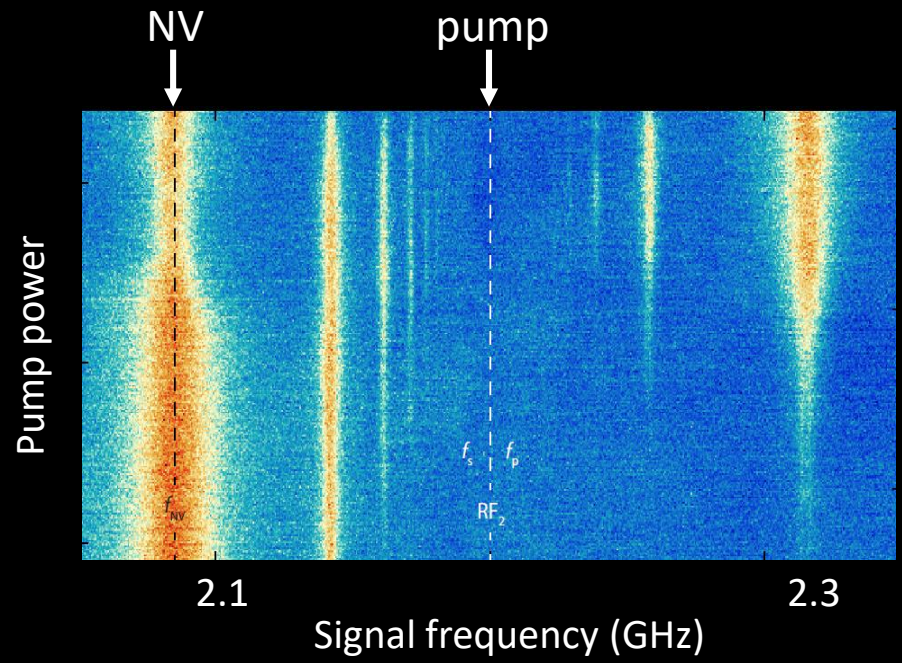
JJ Carmiggelt et al, Nat Comm 2023

Driving electron spins using spin-wave frequency combs

Sweeping the comb frequency



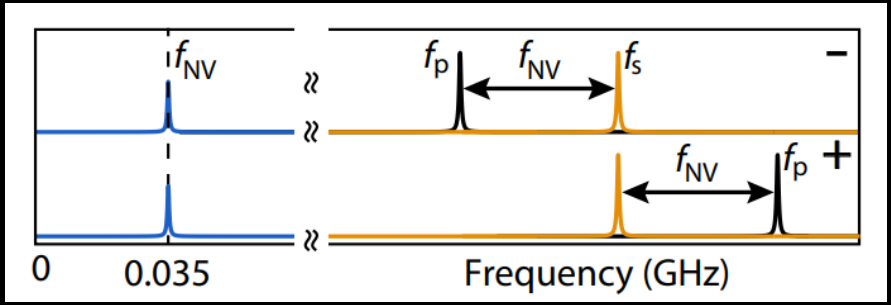
Varying the pump power

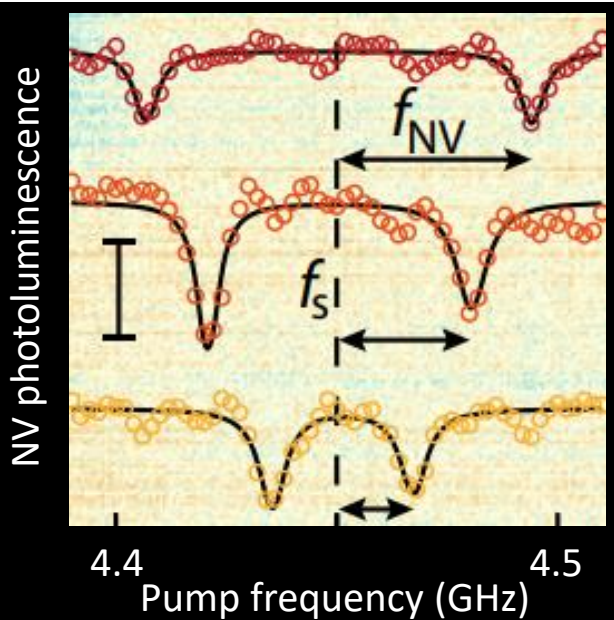


JJ Carmiggelt et al, Nat Comm 2023

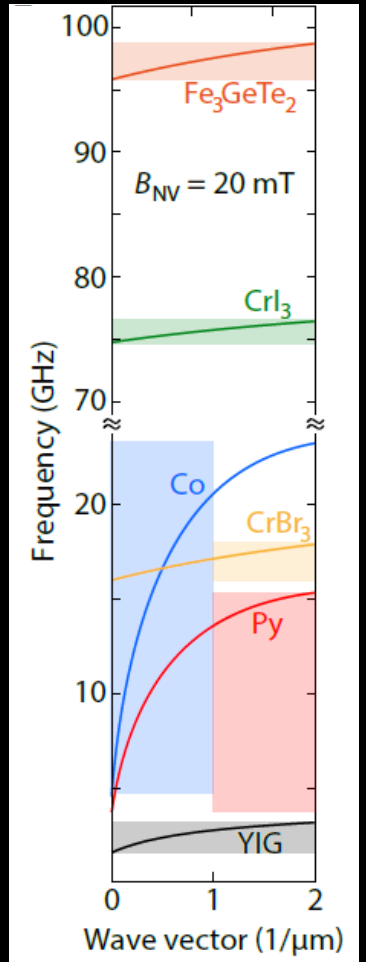
Driving NV spins via difference-frequency generation

Idea: driving 2 spin waves generates a difference frequency

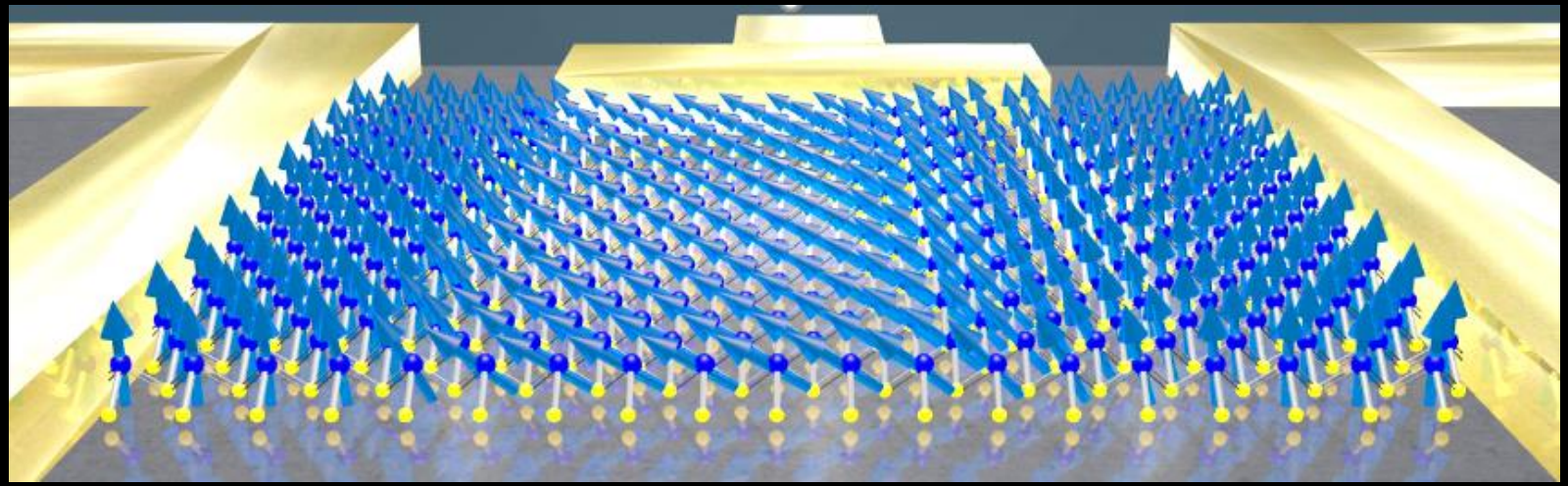




Other magnets → higher frequencies



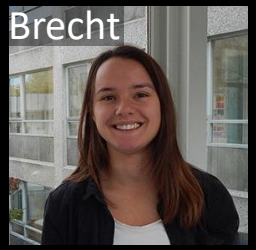
Outlook: probing spin-wave mixing in atomically thin magnets



Many unknowns:

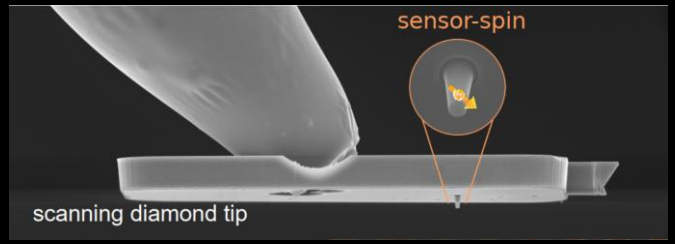
- Magnetization?
- Ferromagnetic resonance?
- Spin wave spectrum?
- Spin diffusion length?
- …

Acknowledgements



Theory:

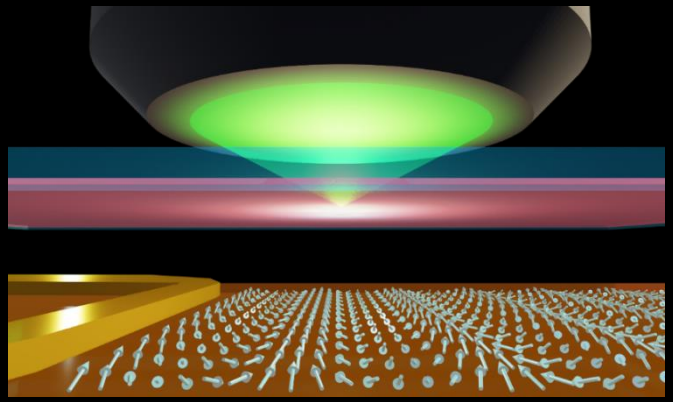
- *Mehrdad Elyasi*
- *Yaroslav Blanter*
- *Gerrit Bauer*
- *Tao Yu*



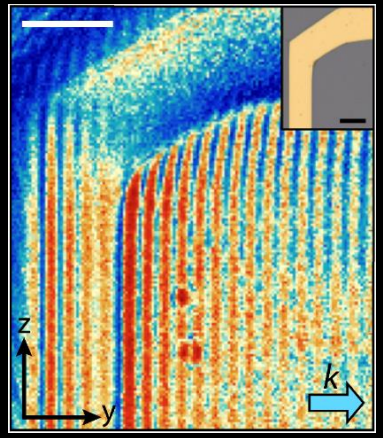
Simon, Kurdi, et al, Nano Lett. 2021
Bertelli et al. Science Adv. 2020
Bertelli et al, Adv. Quant. Technol. 2021
C Du, TS, et al, Science 2017
Carmiggelt et al, Arxiv:2206:07013
Simon, Kurdi et al, Nano Letters 2022

Summary

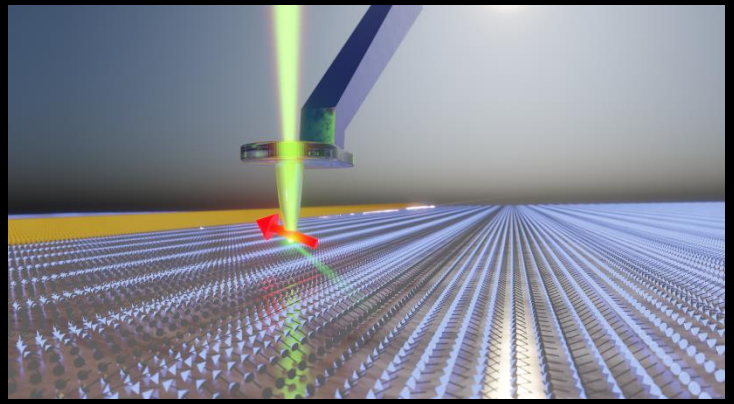
Magnetic spin-wave imaging

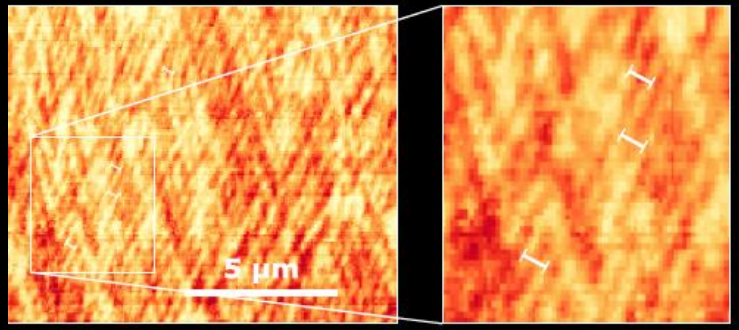


Metal-spin-wave interaction

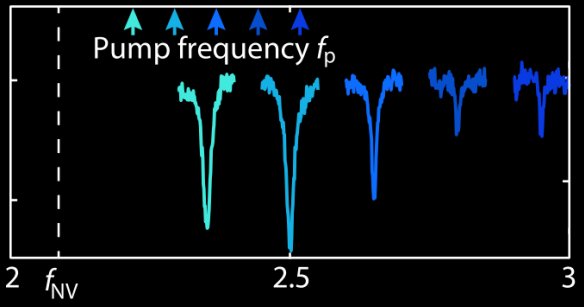


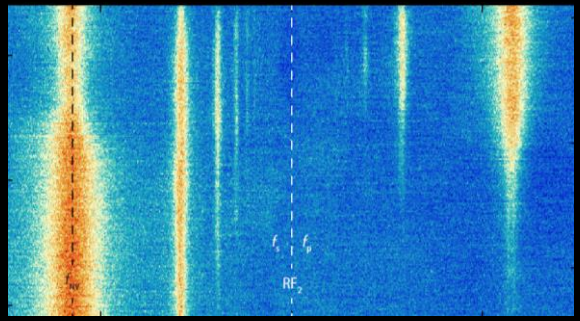
Nanoscale imaging of spin-wave scattering





Coherent spin control via spin-wave mixing





Towards 10-100GHz

Review on NV magnetometry: Casola, TS, Yacoby, Nat. Rev. Mat. 2018