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Sensitivity and spatial resolution considerations for NV magnetometry and imaging

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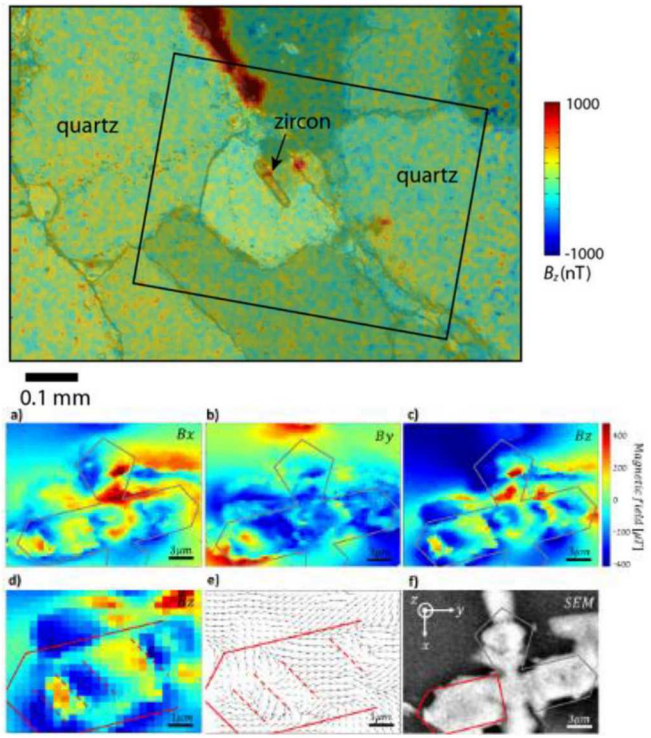
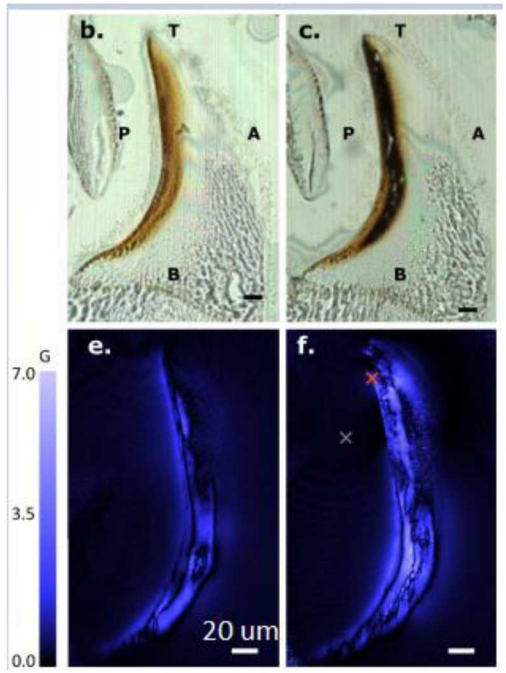
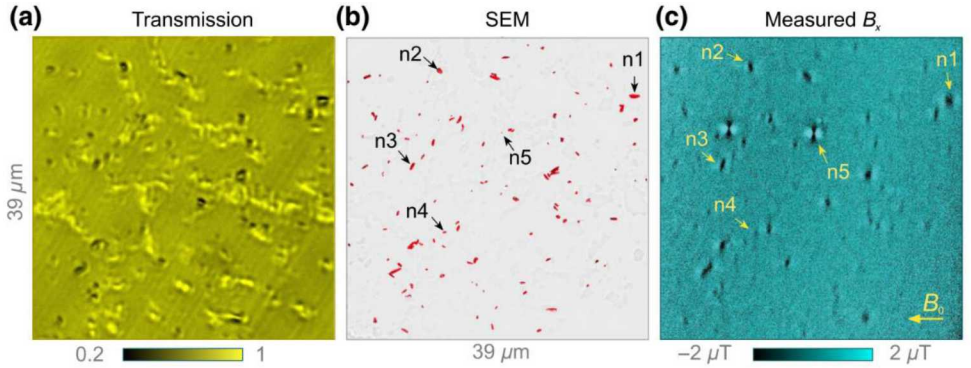
NV magnetic imaging applications

Geomagnetism

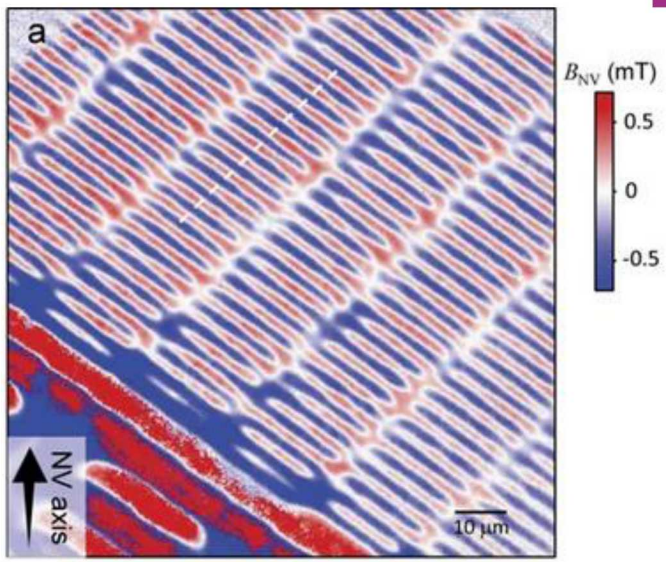


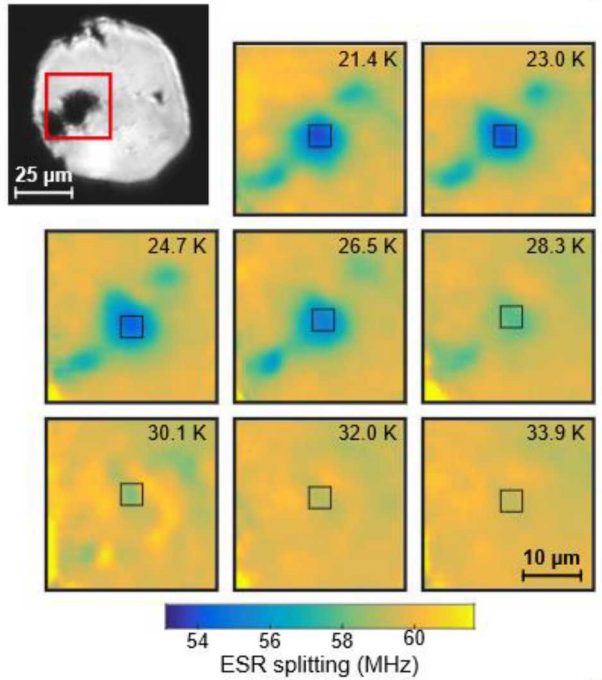
Biomagnetism





Condensed-matter physics





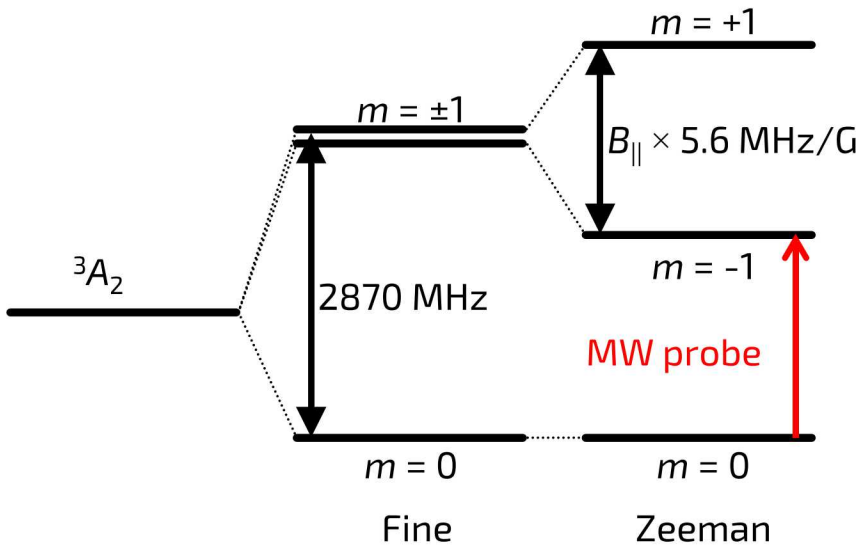
B. P. Weiss et al., Geology 46 5, 427-430 (2018)
E. Farchi et al., Spin 07 03 1740015 (2017)
I. Fescenko et al., Phys. Rev. Applied 11 034029 (2019)
J. M. McCoey et al., arXiv:1902.09637 (2019)
M. Lesik et al., arXiv:1812.09894 (2018)
D. A. Simpson et al., Sci. Rep. 6 22797 (2016)

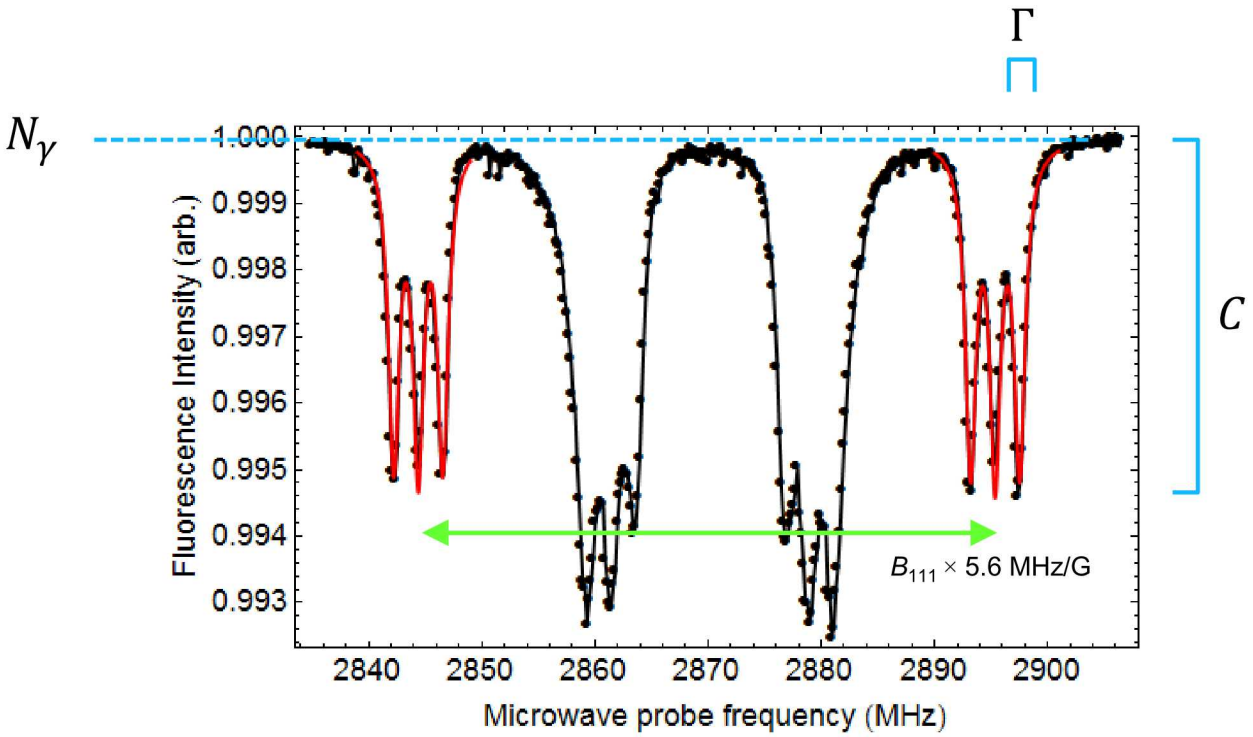
Photon shot noise limit

NV magnetic noise floor: $\Delta B \sim \frac{\Gamma}{C\sqrt{N_\gamma}}$ (smaller is better)

Examples of other noise contributions:

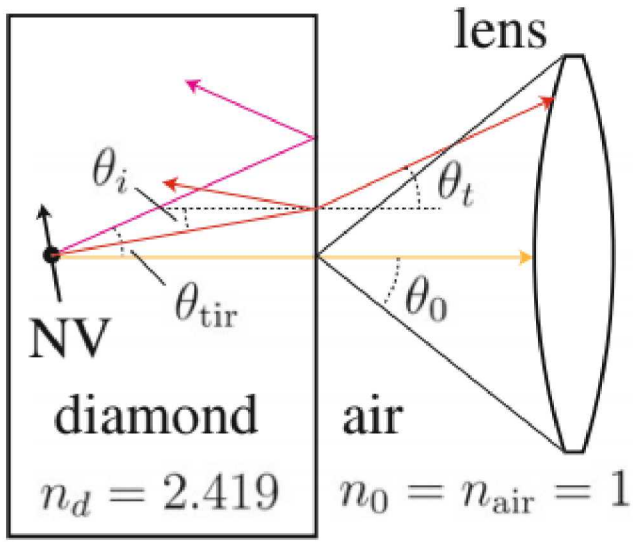
- Fluorescence intensity technical noise
- Dark current noise
- …

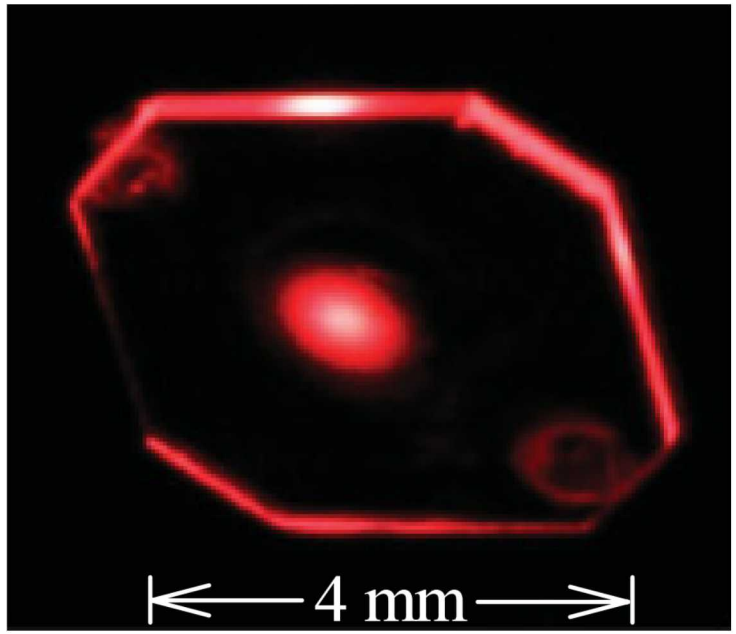


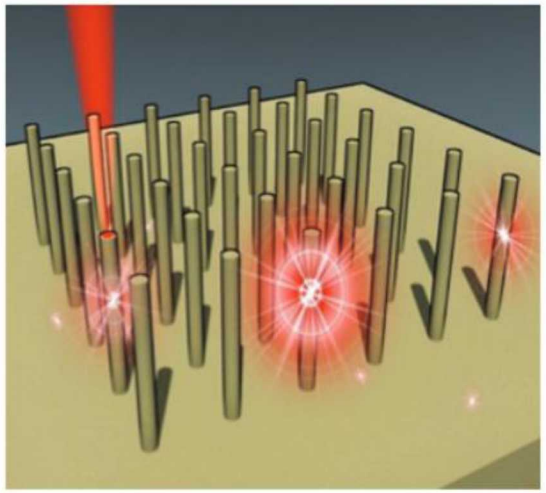


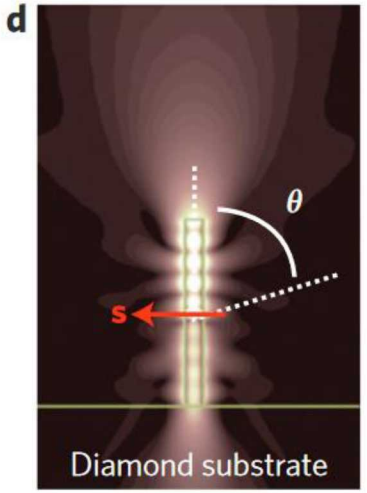
Tactics for improved photon shot noise

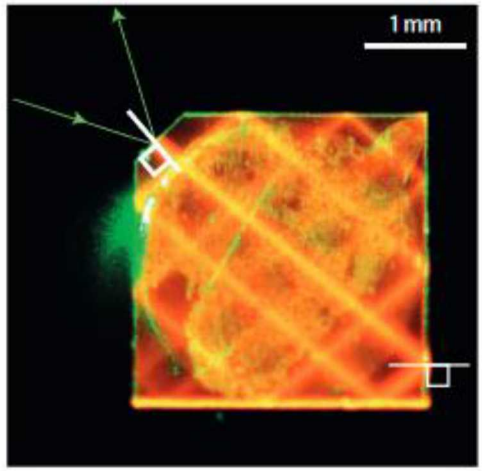
1. Boost the photon collection
   - High-NA collection optics
   - Side collection
   - Optical waveguides
   - Total internal reflection









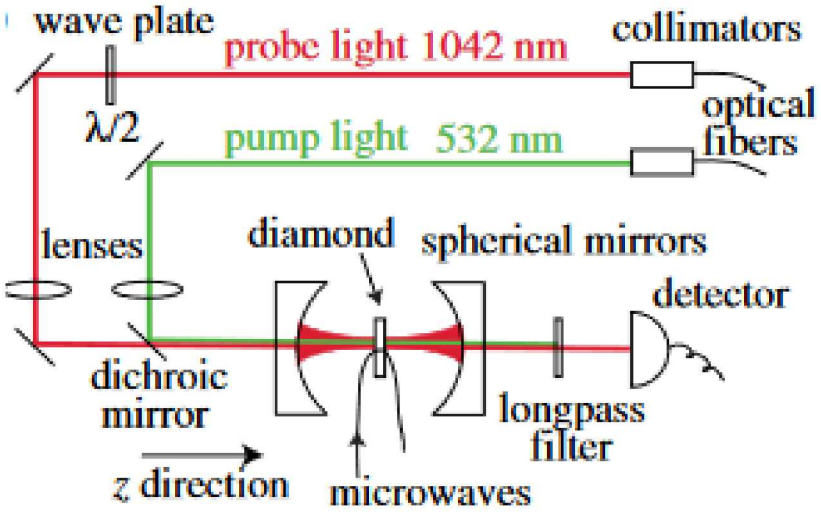


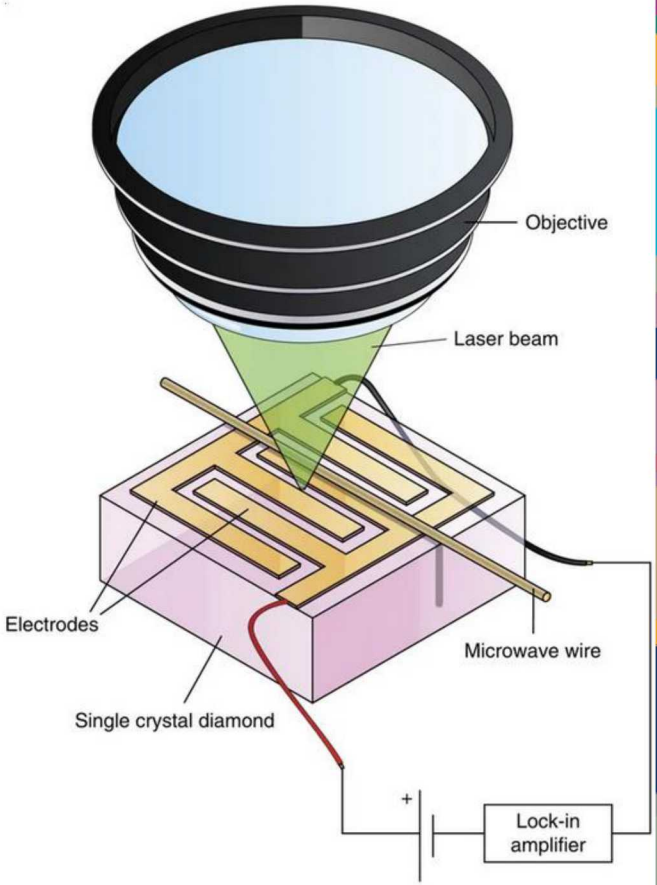
$$\Delta B \sim \frac{\Gamma}{C\sqrt{N_\gamma}}$$

K. Jensen et al., High Sensitivity Magnetometers pp. 553-576 (2017)
D. Le Sage et al., PRB 85 121202(R) (2012)
T. Babinec et al., Nature Nano 5, 195–199 (2010)
H. Clevenson et al., Nat Phys 11, 878 (2015)

Tactics for improved photon shot noise

1. Boost the photon collection
   - High-NA collection optics
   - Side collection
   - Optical waveguides
   - Total internal reflection
2. Circumvent fluorescence collection
   - Infrared absorption
   - Photocurrent readout



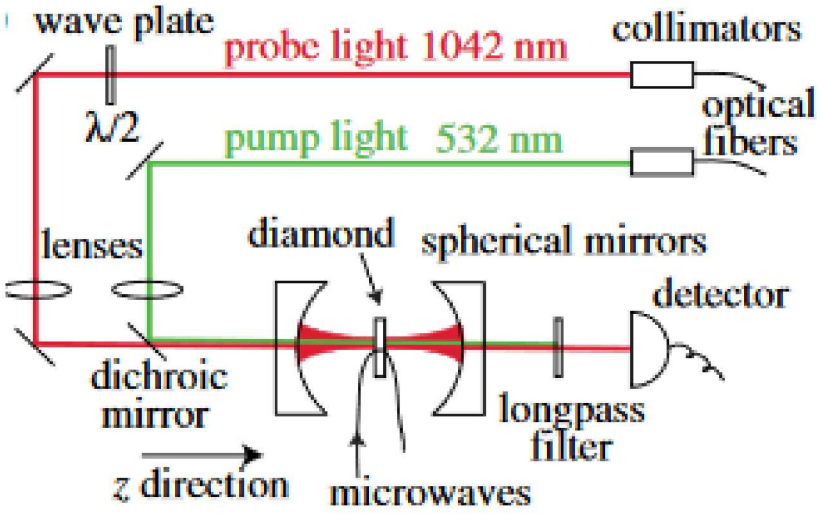


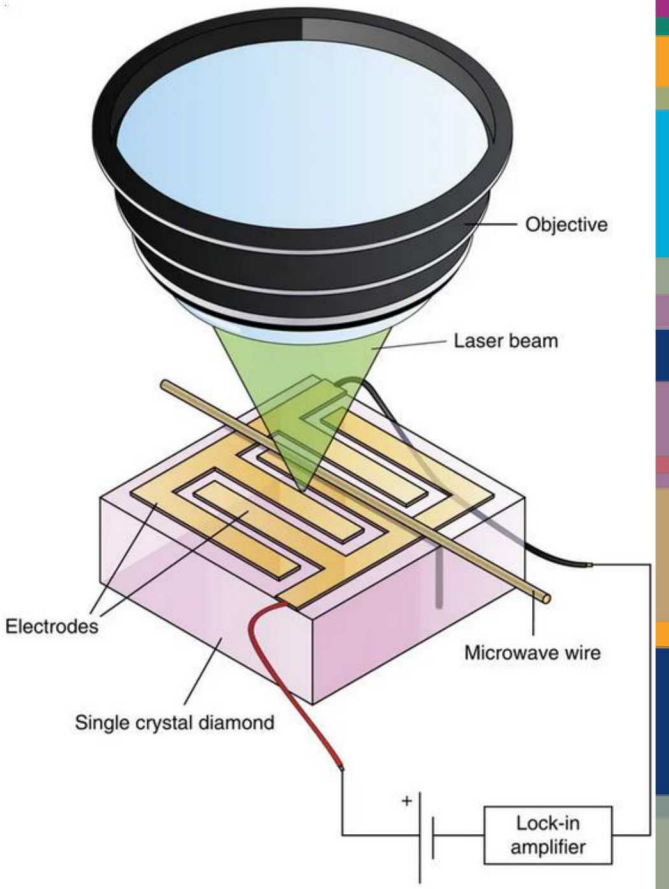
$$\Delta B \sim \frac{\Gamma}{C\sqrt{N_\gamma}}$$

K. Jensen et al., PRL112,160802 (2014)
E. Bourgeois et al., Nat Comm 6 8577 (2015)

Tactics for improved photon shot noise

1. Boost the photon collection
   - High-NA collection optics
   - Side collection
   - Optical waveguides
   - Total internal reflection
2. Circumvent fluorescence collection
   - Infrared absorption
   - Photocurrent readout
3. Limitations
   - Diminishing returns (thermal management, $\sqrt{N_\gamma}$ scaling)
   - Hardware constraints (intensity noise, bit quantization noise, optical saturation)
   - Many schemes incompatible with imaging



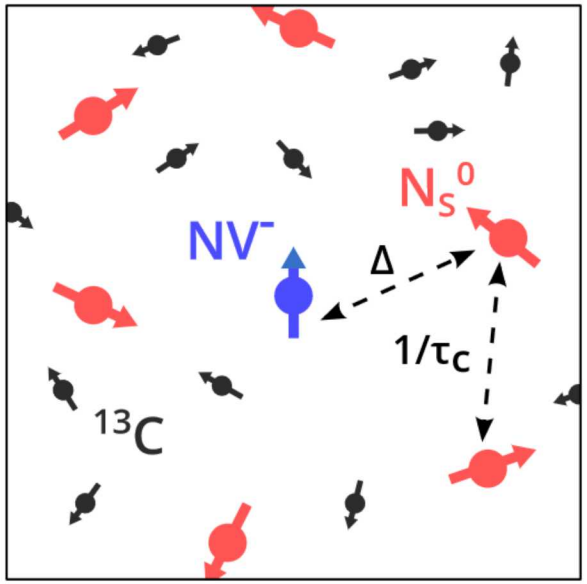


$$\Delta B \sim \frac{\Gamma}{C\sqrt{N_\gamma}}$$

K. Jensen et al., PRL112,160802 (2014)
E. Bourgeois et al., Nat Comm 6 8577 (2015)

Tactics for improved linewidth & contrast

1. Limitations
   - Magnetic defects (^{13}C, P1, ...)
   - Strain & electric field inhomogeneity
   - NV^- / NV^0 charge-state ratio



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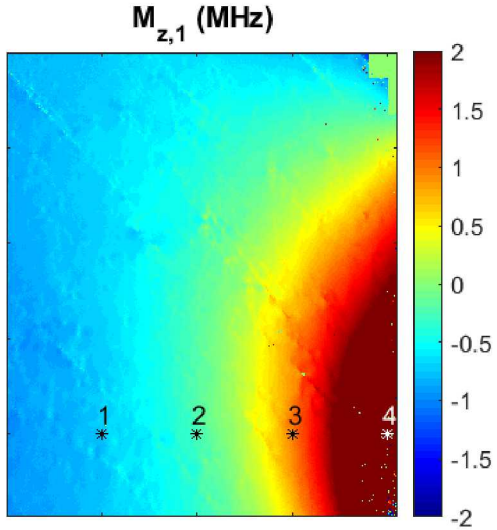
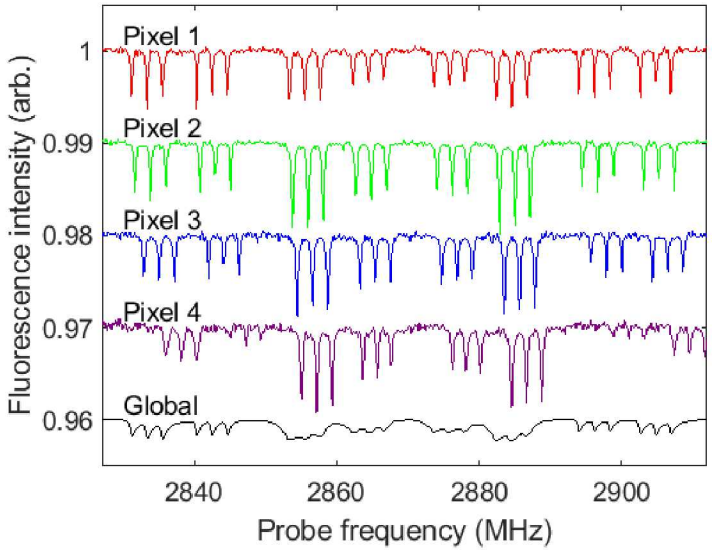
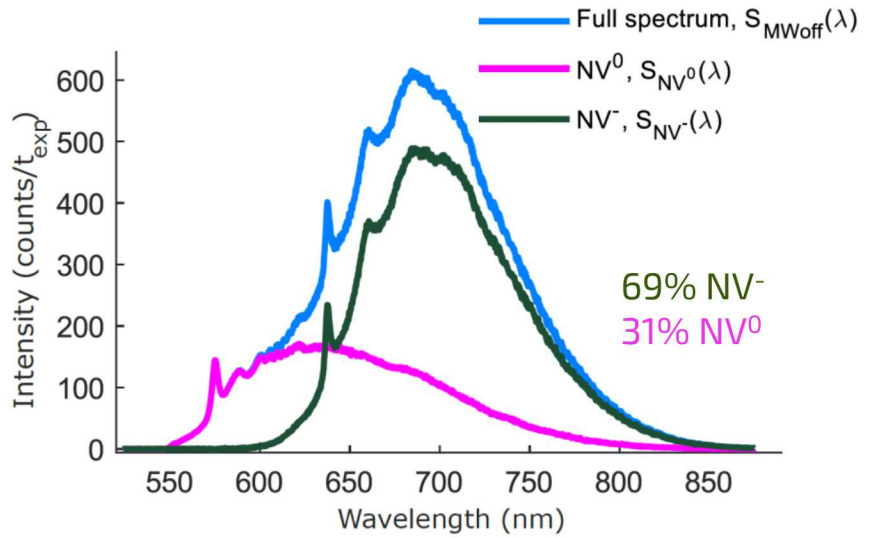






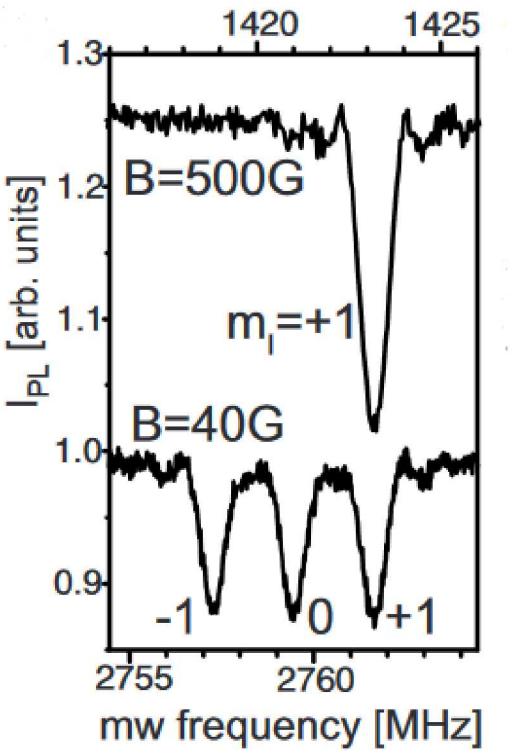
E. Bauch et al., arXiv:1904.08763 (2019)
P. Kehayias et al., PRB 100, 174103 (2019)
D. P. L. Aude Craik et al., arXiv:1811.01972 (2018)

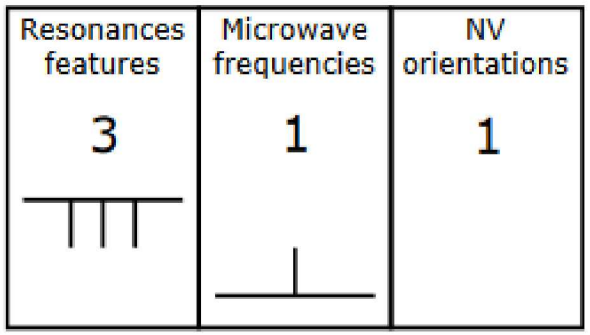
Tactics for improved linewidth & contrast

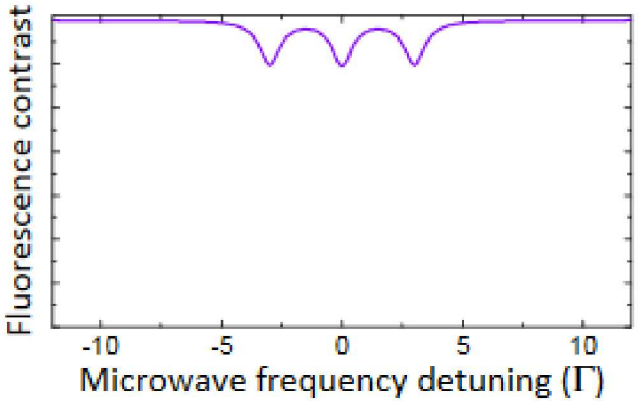
$$\Delta B \sim \frac{\Gamma}{C\sqrt{N_\gamma}}$$

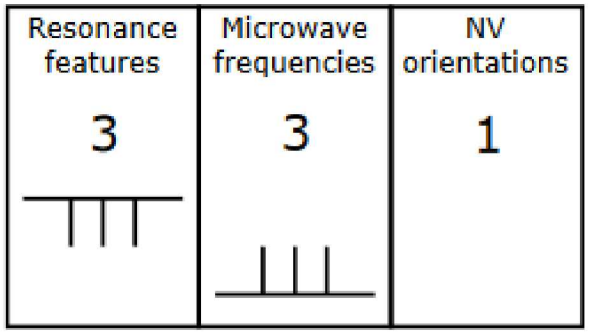
2. Approaches

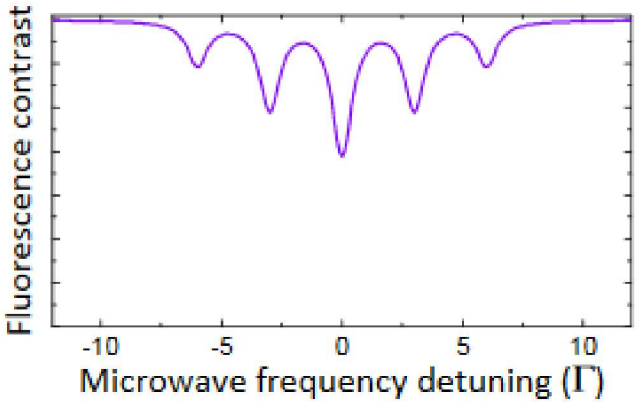
- Optimized diamond growth & NV formation
- Overlap all NV orientations for ~4x more contrast (but $\sqrt{3}$x weaker response)
- NV nuclear polarization; probe each hyperfine line
- Spin bath driving









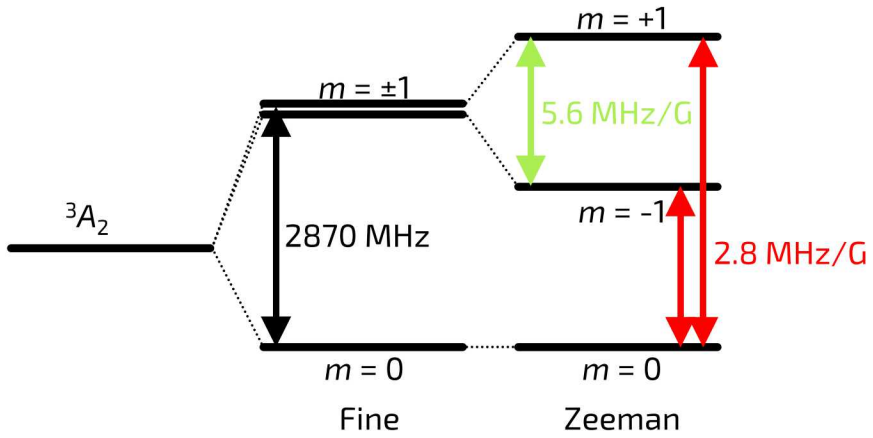


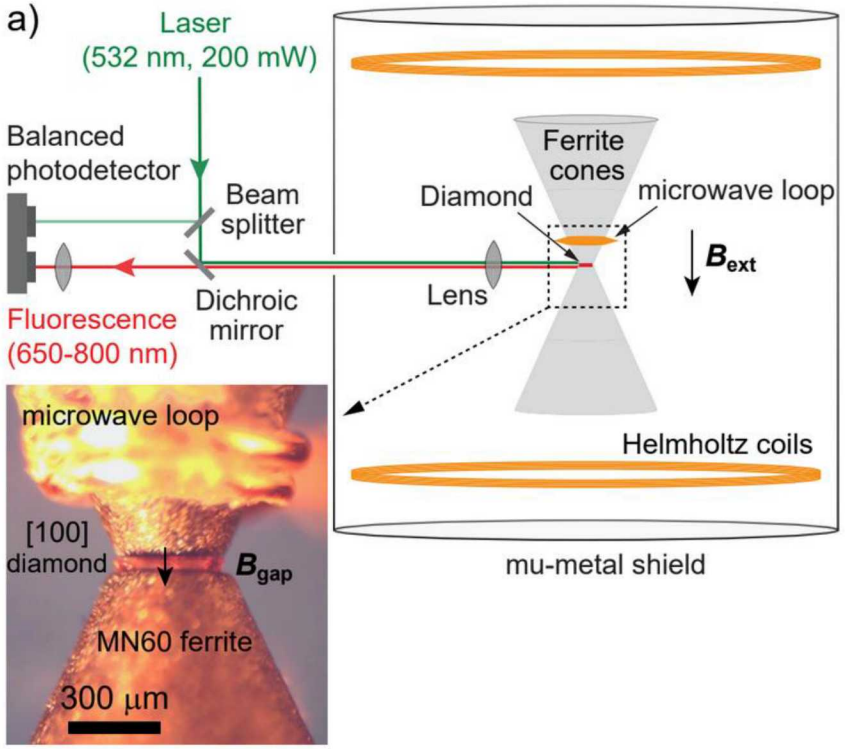
M. Steiner et al., PRB 81 035205 (2010
E. Bauch et al., PRX 8, 031025 (2018)
J. F. Barry et al., PNAS 113 49 (2016)

Tactics for improved magnetic response

1. 'Double-quantum' magnetometry
2. Magnetic flux concentrators

$$\Delta B \sim \frac{\Gamma}{C\sqrt{N_\gamma}}$$



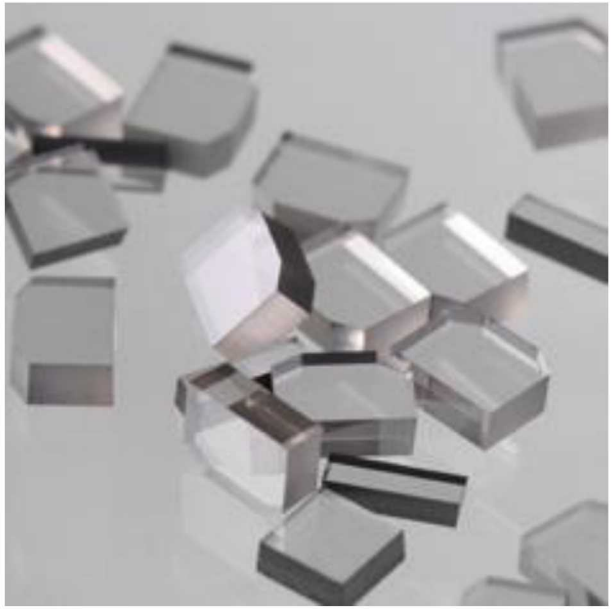


E. Bauch et al., PRX 8, 031025 (2018)
I. Fescenko et al., arXiv:1911.05070 (2019)

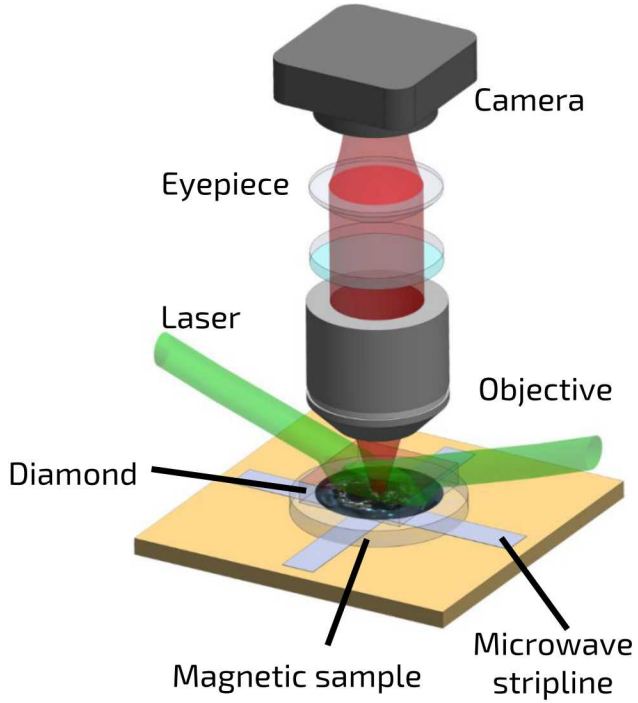
How do we optimize an NV magnetic imager?

Diamond prep stage

Synthetic diamond chips (few mm) from Element Six



Experimental implementation stage

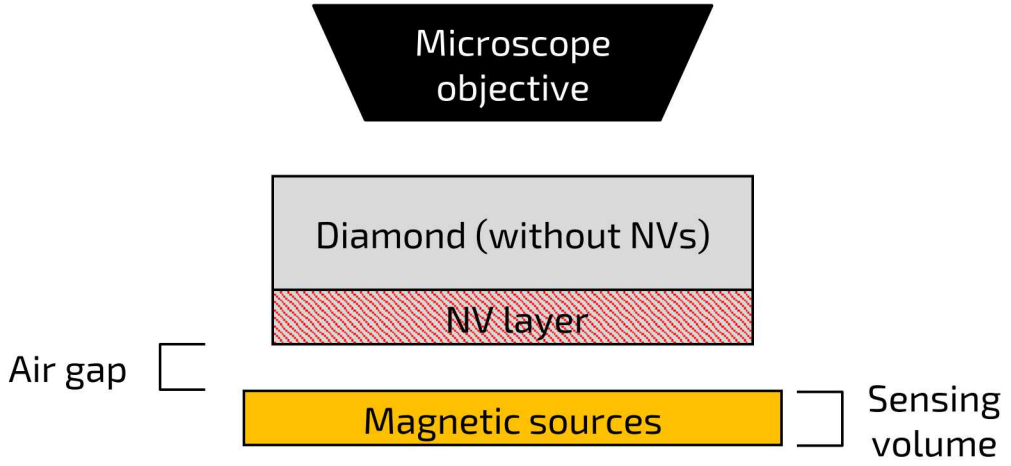


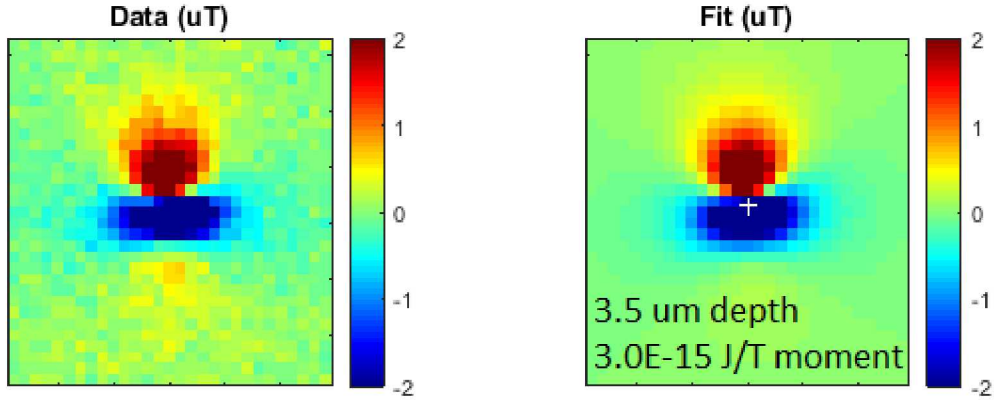
D. R. Glenn et al., Geochem Geophys Geosyst 18, 8 (2017)

NV layer thickness

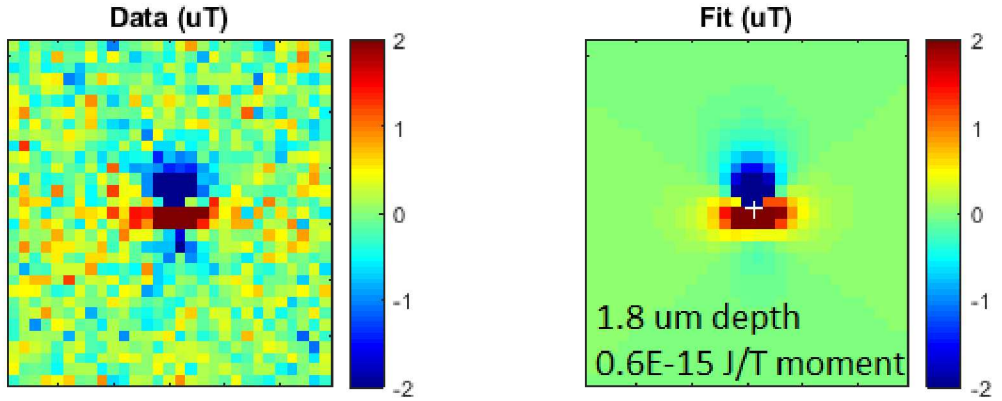
Contributions to magnetic spatial resolution
- Standoff distance
- NV layer thickness
- Optical diffraction limit

Naively, match the standoff distance, NV layer thickness, and sample thickness



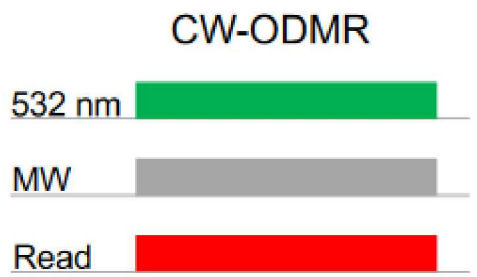


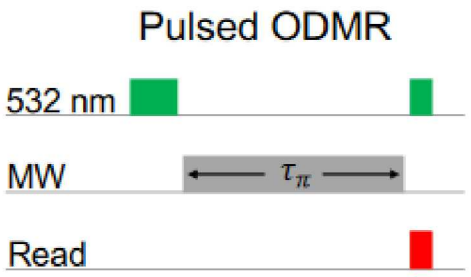
Few-micron NV layer (30x30 micron patch)

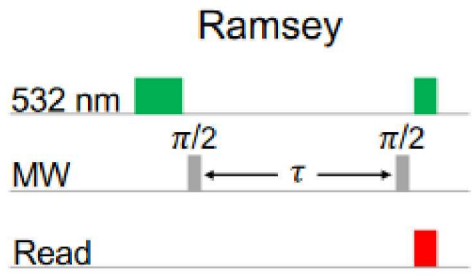


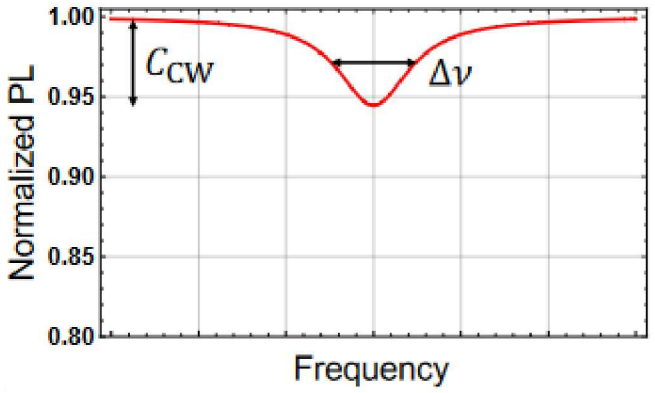
150 nm NV layer (30x30 micron patch)

DC NV magnetic imager techniques

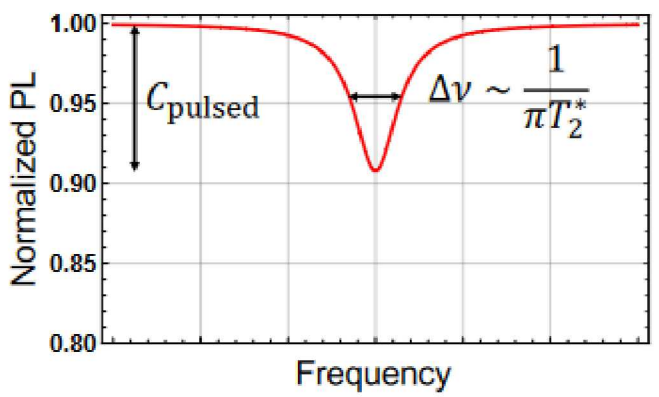








- Easiest implementation
- Contrast/linewidth tradeoff



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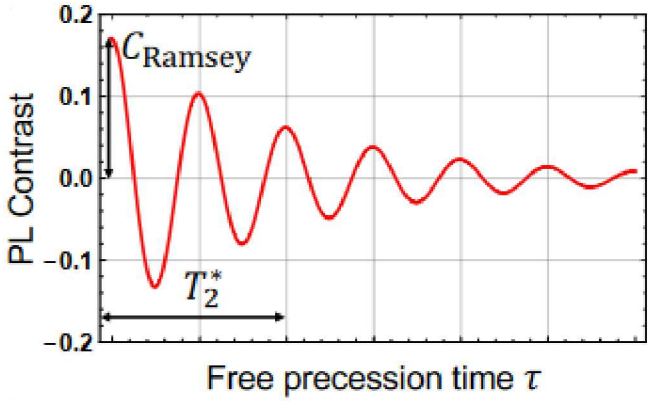


- Best sensitivity
- Hardest to implement over a large area

J. F. Barry et al., arXiv:1903.08176 (2019)

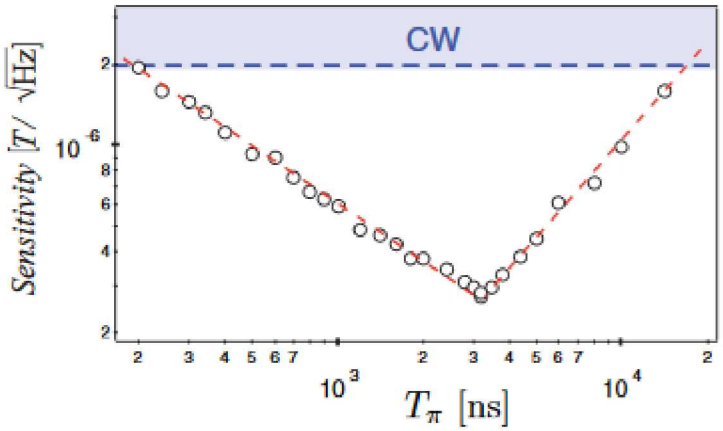
Sensitivity as a function of laser & MW power

MW power broadening: larger C, broader Γ

Laser power: larger N_γ, weaker C, narrower Γ

$$\Delta B \sim \frac{\Gamma}{C\sqrt{N_\gamma}}$$

Pulsed ODMR



CW ODMR (single-pixel)

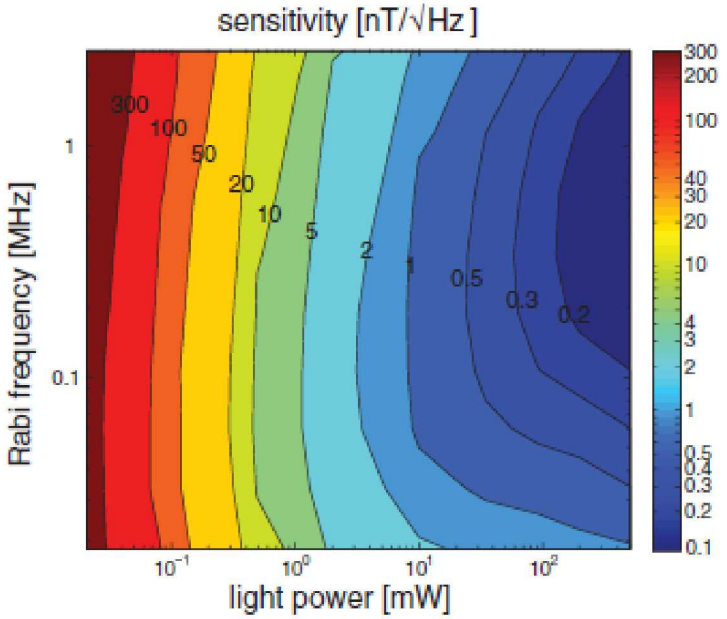
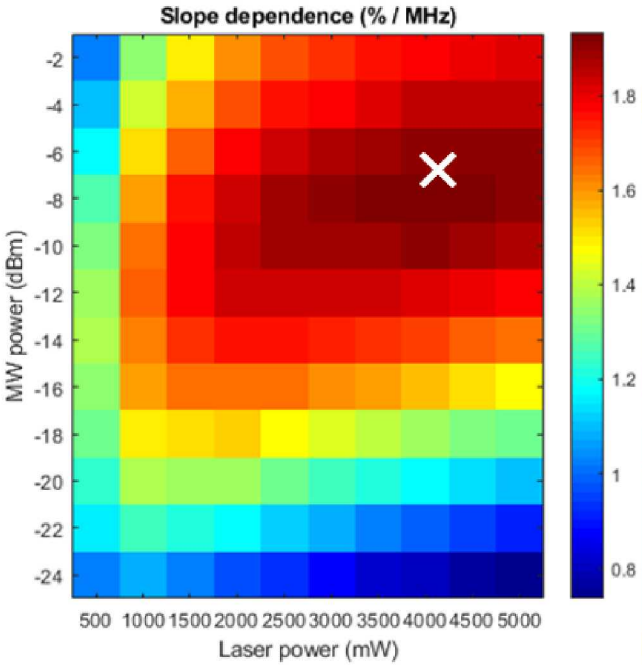


FIG. 5. (Color online) Contour plot of the experimental magnetic-field sensitivity S_B as a function of light power P and Rabi frequency f_R. Notice the logarithmic scales.

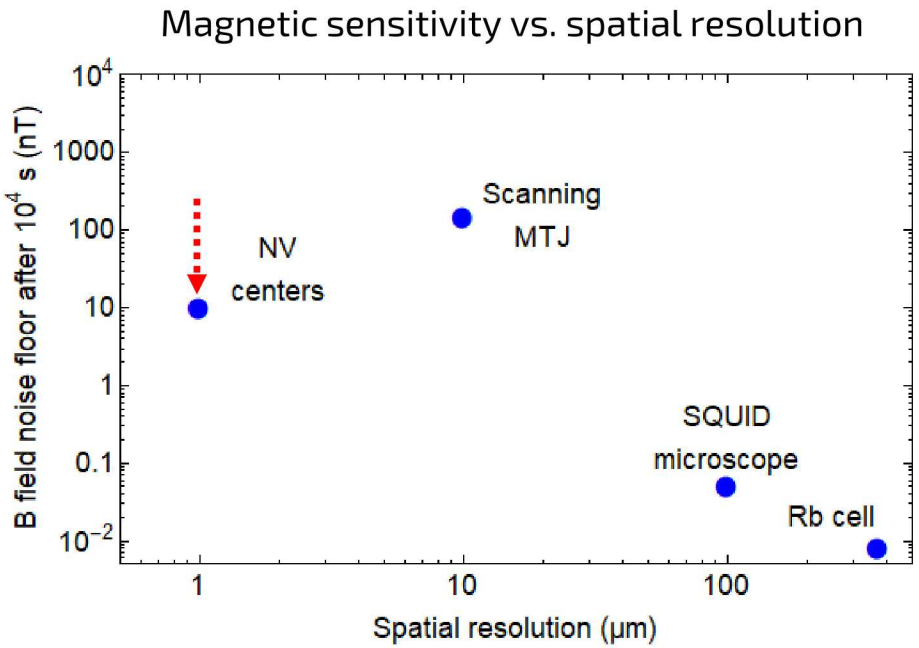
CW ODMR (imager)

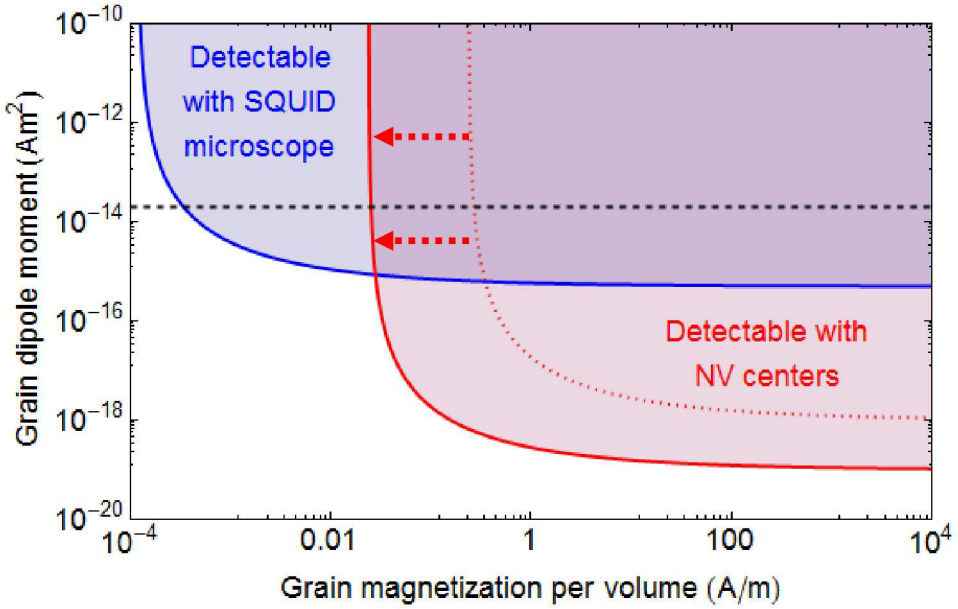


A. Dréau et al., PRB 84 195204 (2011)
K. Jensen et al., PRB 87, 014115 (2013)

Outlook

NV sensitivity improvements will enable new applications





Still much room for improvement

- Improved linewidth and contrast
- Current sensitivity still far from the spin projection noise 'hard limit'
- Equal emphasis needed on diamond characteristics and technical implementations