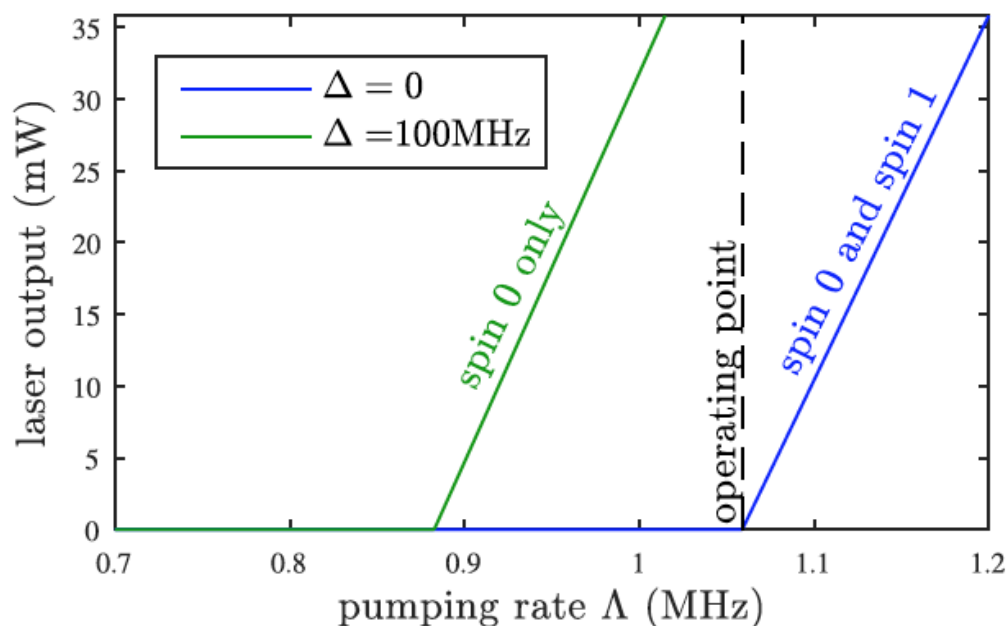
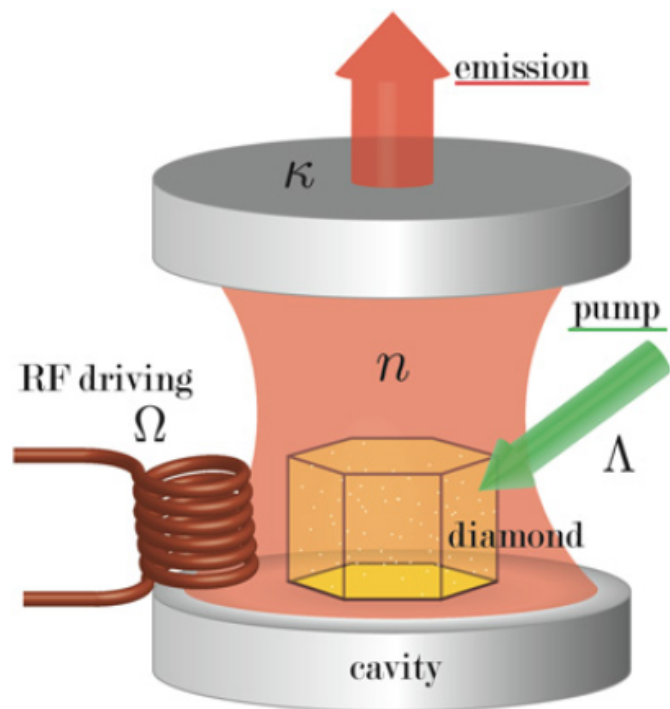


Laser Magnetometry: A New Approach to Magnetometry and Sensing with Single Crystal Diamond

Jeske et al., New Journal of Physics 18, 013015 (2016)

Jeske et al., Nature Communications 8, 14000 (2017)



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Australian Research Council



ARC CENTRE OF EXCELLENCE FOR
ENGINEERED QUANTUM SYSTEMS



**Centre for
Nanoscale
BioPhotonics**
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Outline

- Magnetometry
- Diamond
- Diamond for magnetometry
- Laser thresholding
- Ionisation
- Stimulated Emission

Magnetometry as a bio and geo sensor

Areas of magnetometry:

- Medical imaging
- Mining exploration (LANDTEM \$4B)
- Unexploded Ordinance detection
- Submarine detection (MAD)
- Airplane navigation

E.g. medical imaging: MEG

Machine: \$3-4 million,
running cost: \$300'000 / year



Photo: NIMH, National Institutes of Health, Department of Health and Human Services

SQUID magnetometer

- Operated at cryogenic temperature
- Sensitivity: $\sim 1 \text{ fT}/\sqrt{\text{Hz}}$
- Helium cooling is expensive and restrictive
- Helium is a finite resource

→ Strong interest in a *sensitive* magnetometer operated at *room-temperature*

E.g. microtesla MRI imaging

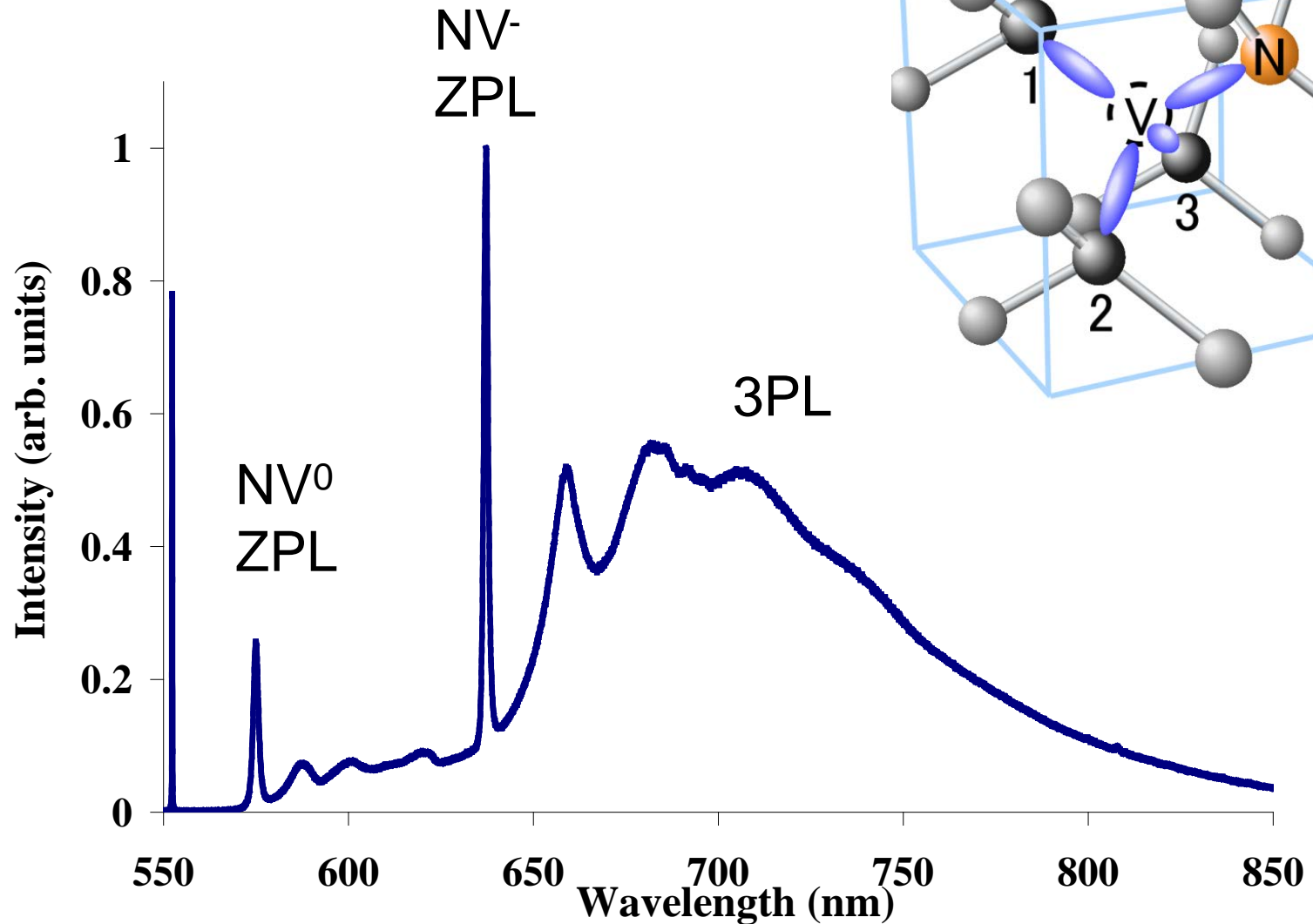
- Sensitive sensors with low magnetic fields
- Replace helium-cooled magnets
- Cuts cost and technical effort



The color of diamond

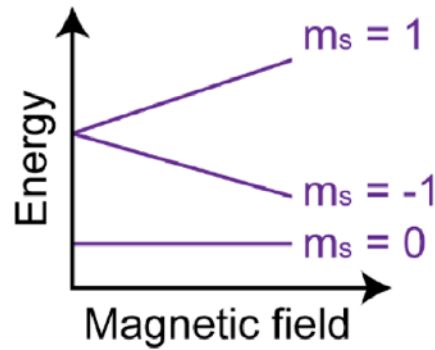
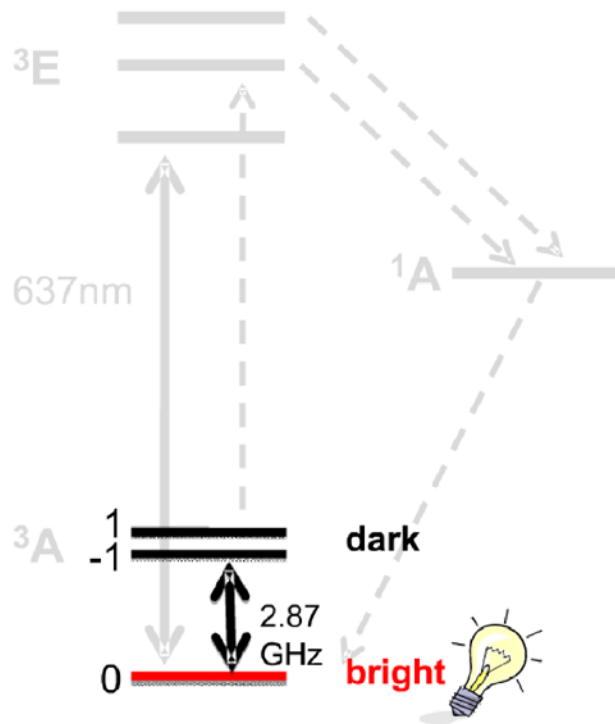
NV Centre – spectrum 77K

Picture: Phys. Rev. B, 80, 041201



NV Centre – magnetic field sensor

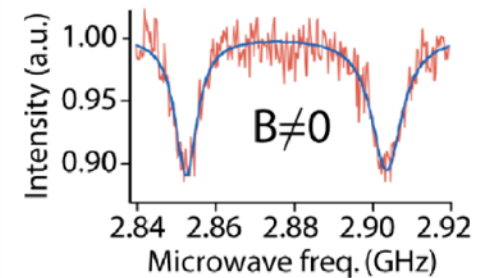
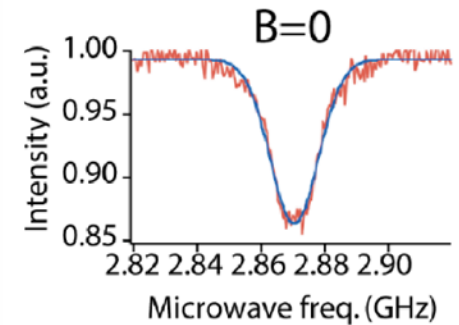
Zeeman shift of the ground state levels



Ground state sublevels are sensitive to magnetic fields

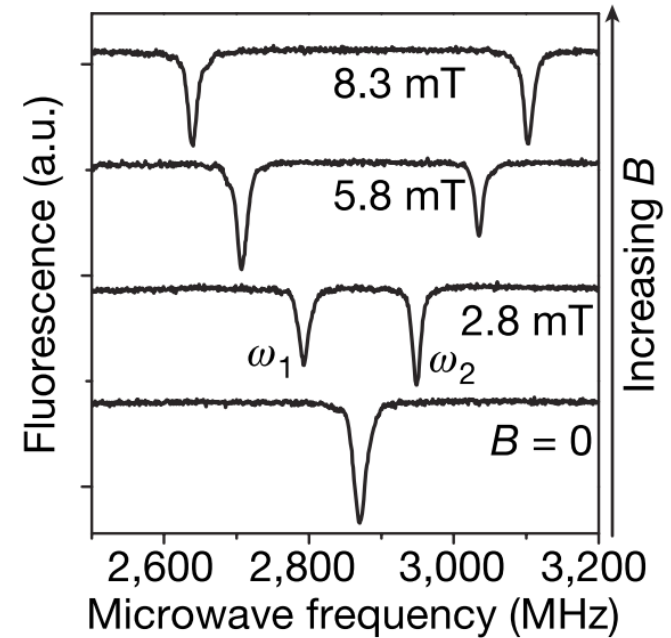
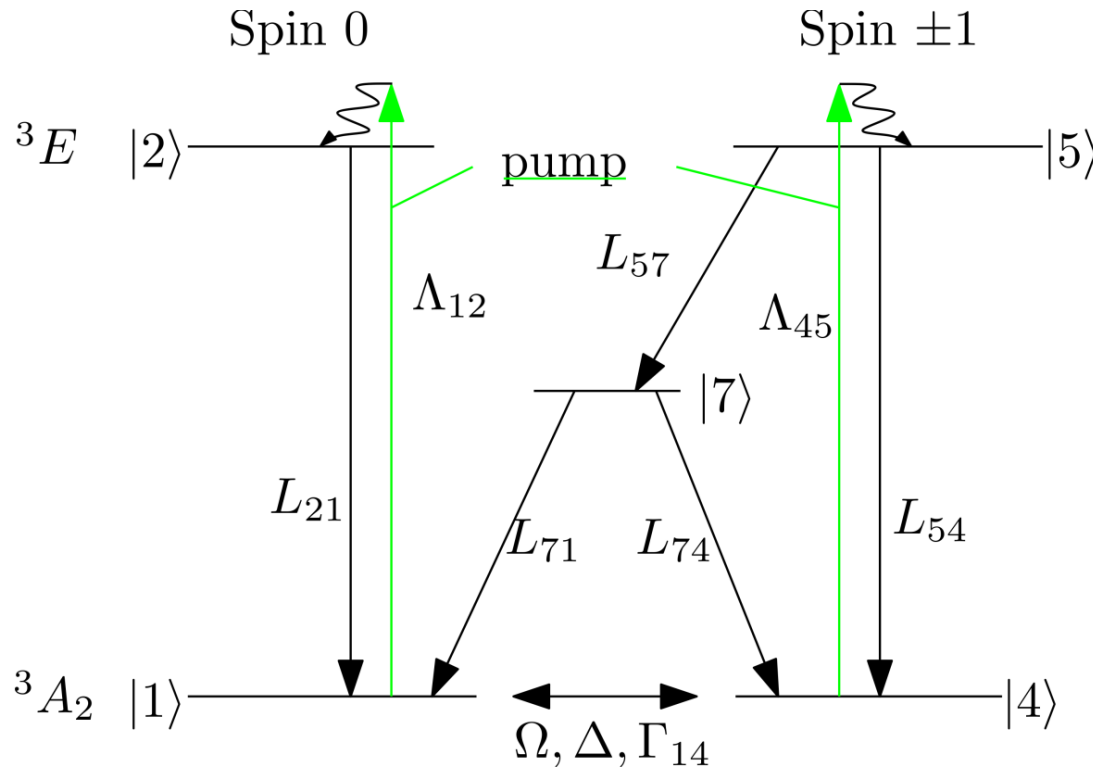
Zeeman shift:
- 3nT at kHz frequencies
(ultra pure diamond sample)

Sensitivity down to 0.9 pT/Hz^{1/2}
Phys. Rev. X 5, 041001 (2015)



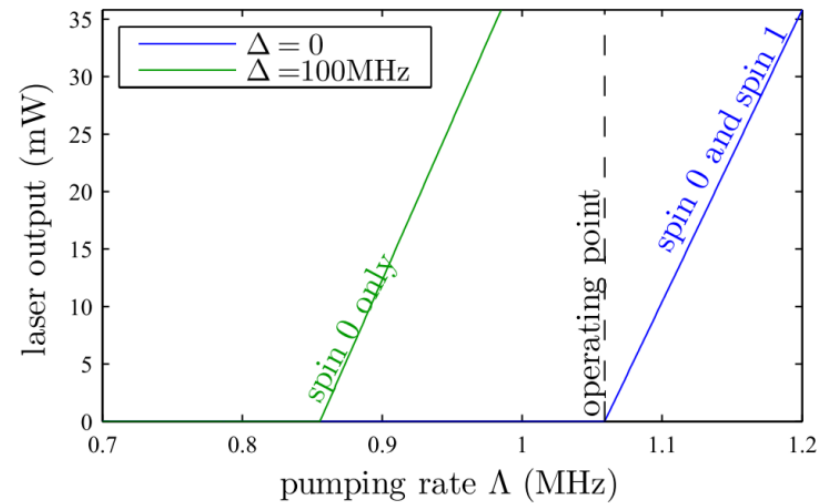
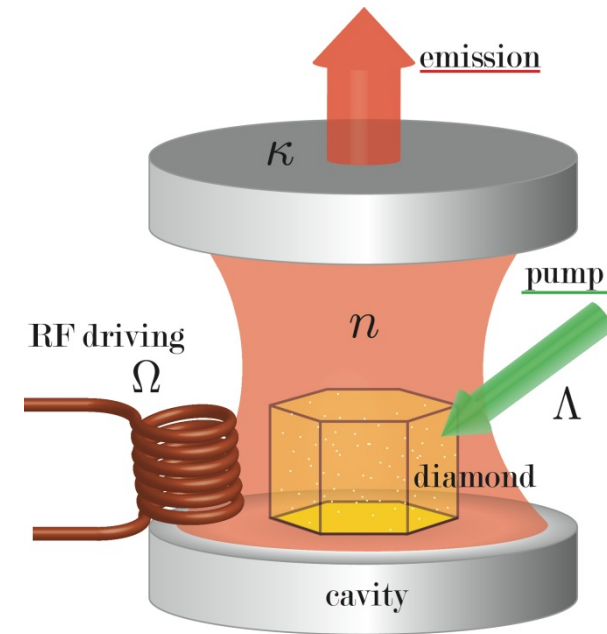
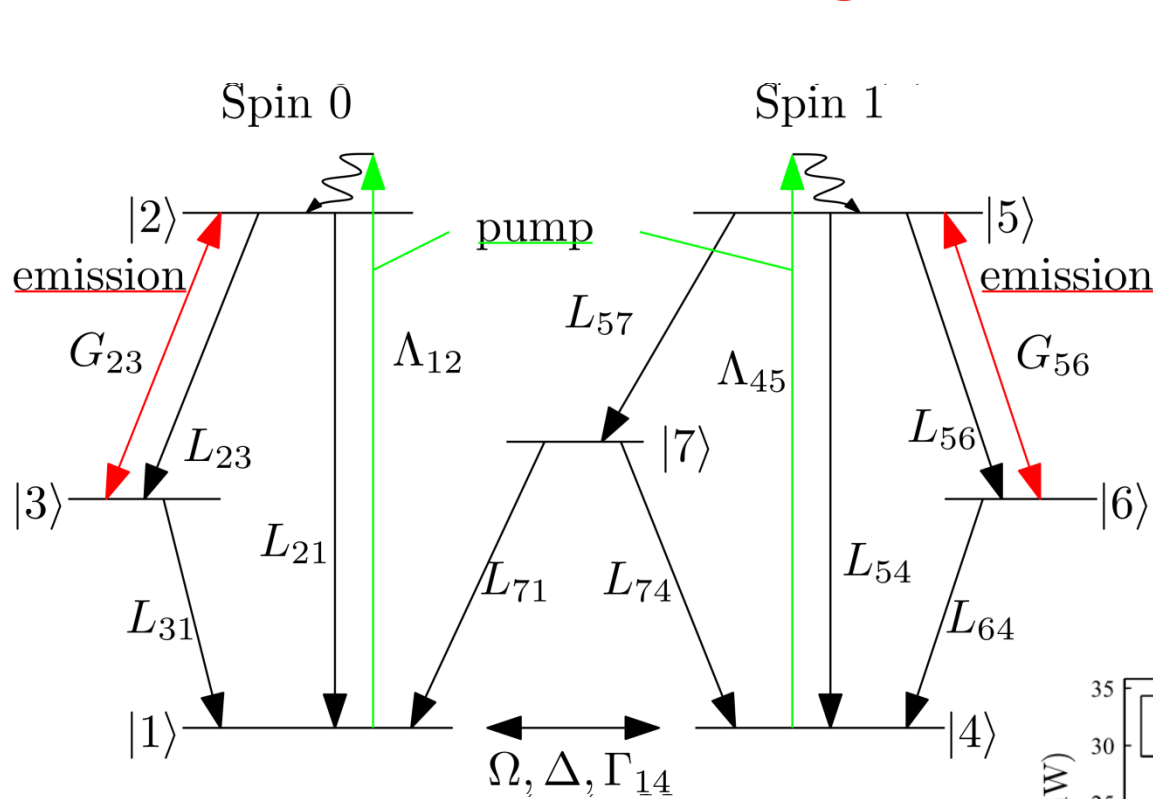
Non-ideal ODMR
Record single centre contrast
~30%

Optically-detected magnetic resonance

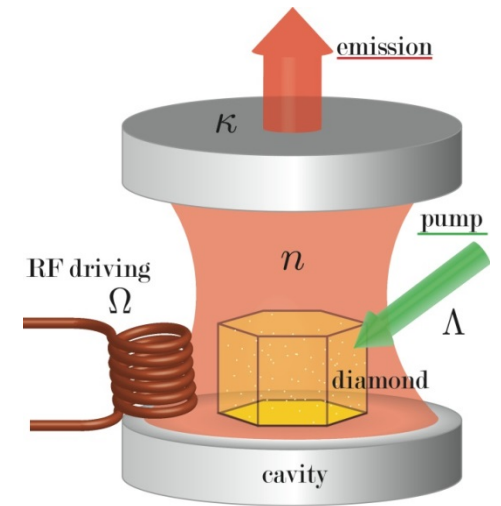
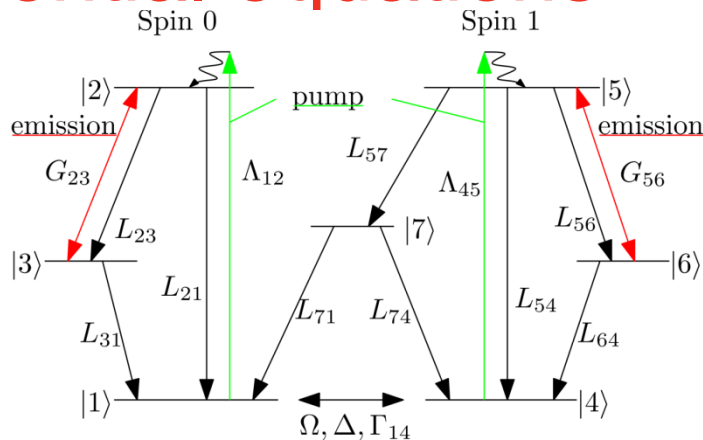


→ Nature **455**, 648

Laser Threshold Magnetometry (LTM)



Differential equations



$$\begin{aligned}\dot{\rho}_{11} &= 2i\Omega\Im(\rho_{14}) - \Lambda_{12}\rho_{11} + L_{21}\rho_{22} + L_{31}\rho_{33} + L_{71}\rho_{77}, \\ \dot{\rho}_{14} &= (i\Delta - \Gamma_{14} - \Lambda_{12}/2 - \Lambda_{45}/2)\rho_{14} - i\Omega(\rho_{44} - \rho_{11}), \\ \dot{\rho}_{22} &= \Lambda_{12}\rho_{11} - (L_{21} + L_{23})\rho_{22} - G_{34}(\rho_{22} - \rho_{33})n, \\ \dot{\rho}_{33} &= L_{23}\rho_{22} - L_{31}\rho_{33} - G_{23}(\rho_{33} - \rho_{22})n, \\ \dot{\rho}_{44} &= -2i\Omega\Im(\rho_{14}) - \Lambda_{45}\rho_{44} + L_{54}\rho_{55} + L_{64}\rho_{66} + L_{74}\rho_{77}, \\ \dot{\rho}_{55} &= \Lambda_{45}\rho_{44} - (L_{54} + L_{56} + L_{57})\rho_{55} - G_{56}(\rho_{55} - \rho_{66})n, \\ \dot{\rho}_{66} &= L_{56}\rho_{55} - L_{64}\rho_{66} - G_{56}(\rho_{66} - \rho_{55})n, \\ \dot{\rho}_{77} &= L_{57}\rho_{55} - (L_{71} + L_{74})\rho_{77}, \\ \dot{n} &= G_{23}(\rho_{22} - \rho_{33})n + G_{56}(\rho_{55} - \rho_{66})n - \kappa n,\end{aligned}$$

n = Number of cavity photons per NV centre

Quantum coherence

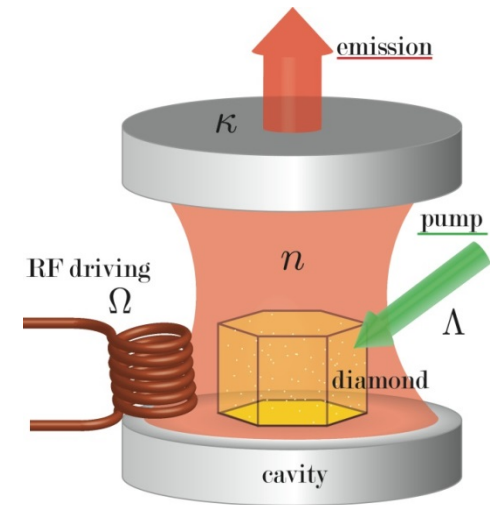
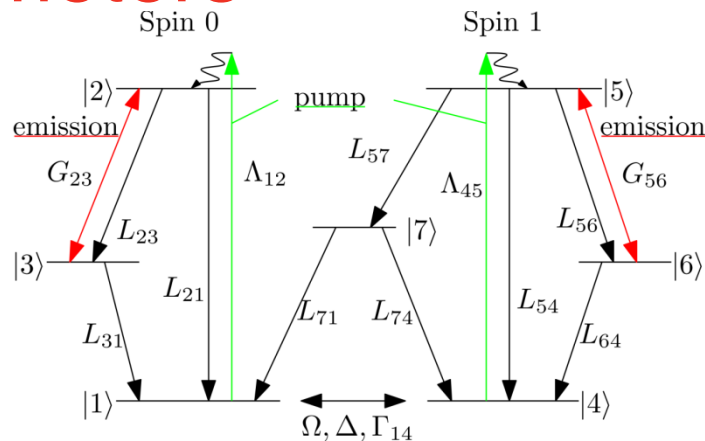
Laser induced noise

Laser pumping (incoherent)

Stimulated emission

Cavity loss

Parameters



NV parameters:
(fixed)

$$L_{57} = (24.9\text{ns})^{-1} = 40.1\text{MHz}$$

$$L_{74} = (461\text{ns})^{-1} = 2.17\text{MHz}$$

$$L_{71} = L_{74}/2$$

$$L_{23} = L_{56} = 18\text{MHz}$$

$$L_{21} = L_{54} = 68.2\text{MHz}$$

$$L_{31} = L_{64} = 1\text{THz}$$

Probe/cavity parameters:

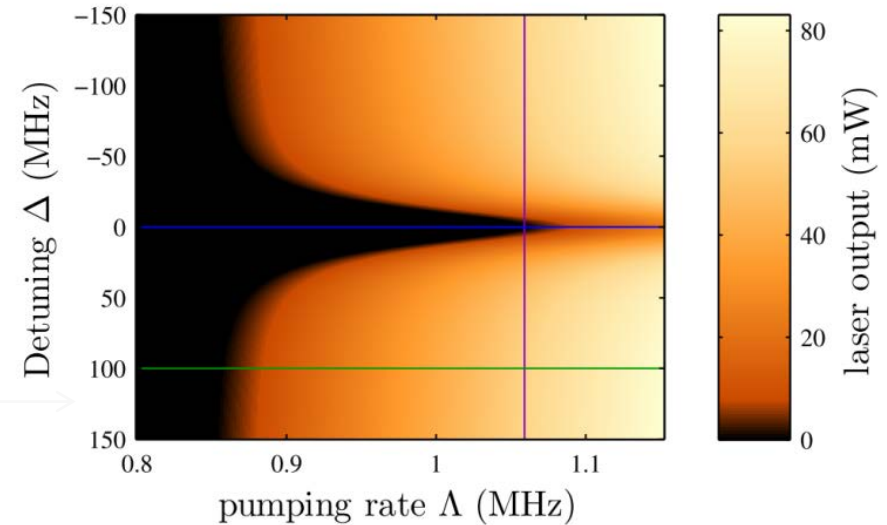
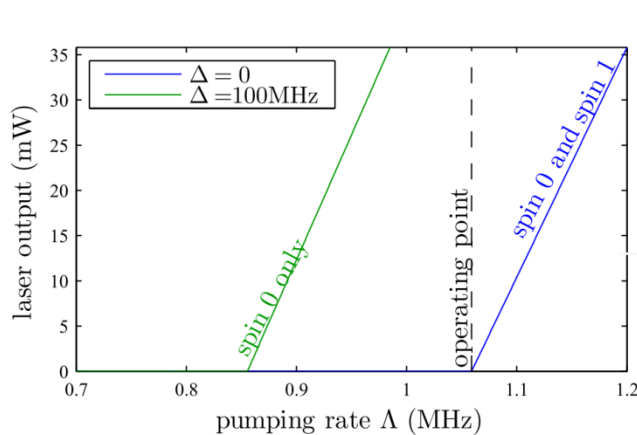
1 mm³ of diamond
with 1 NV per (100nm)³ \Leftrightarrow 0.0057ppm
and $T_2^* = 1\mu\text{s}$
cavity volume: 2mm³
cavity loss rate $\kappa = 3\text{MHz} \Leftrightarrow Q = 8.9 \times 10^8$

$$G = \frac{3\nu_{23}L_{23}\lambda^3N_{at}}{4\pi^2\Delta\nu_{23}V_c}$$

Tunable parameters:

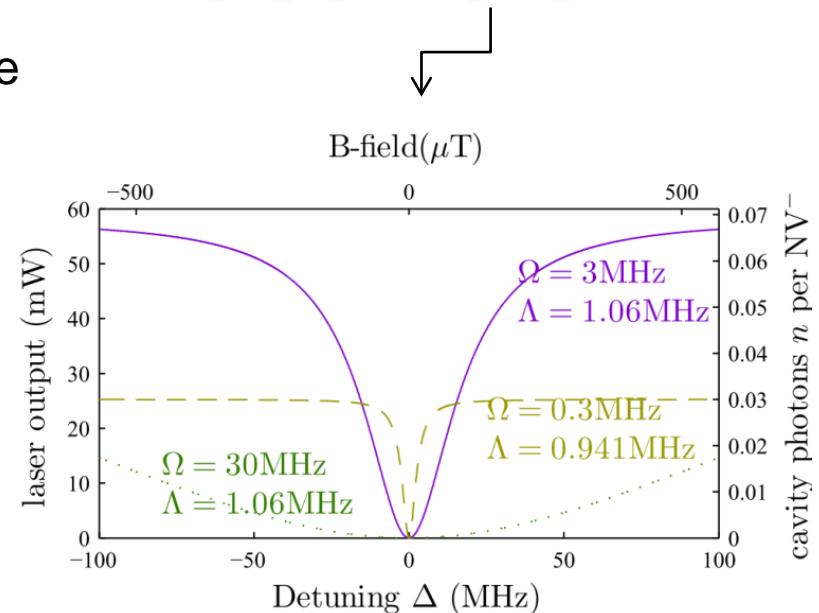
$$\Lambda, \Omega, \Delta$$

Laser Threshold Magnetometry



LTM vs. ensemble magnetometry:

- Laser threshold vs fluorescence change
stronger signal
contrast $\sim 100\%$ vs. $\sim 3\%$
- Stimulated vs. spontaneous emission
Collection efficiency $\sim 100\%$ vs. few %
- CW vs. pulsing
- Fibre-coupled laser output
- Improved sensitivity



Sensitivity

One measurement is performed within δT
and repeated $N = \frac{T}{\delta T}$ times.

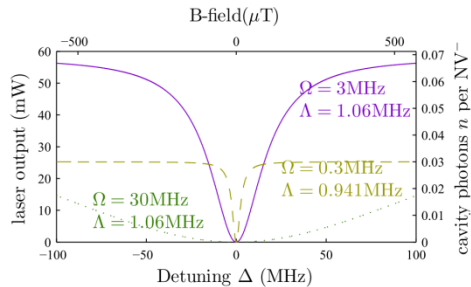
probability of one photon: $p_1 = \overbrace{n N_{NV}}^{\text{Number of cavity photons}} \underbrace{\kappa \delta T}_{\text{Cavity loss rate}}$
probability of no photon: $p_0 = 1 - p_1$

uncertainty $\sigma_{p_1} = \sqrt{p_1(1 - p_1)/N}$

$$\sigma_B = \frac{dB}{dn} \frac{dn}{dp_1} \sigma_{p_1}$$

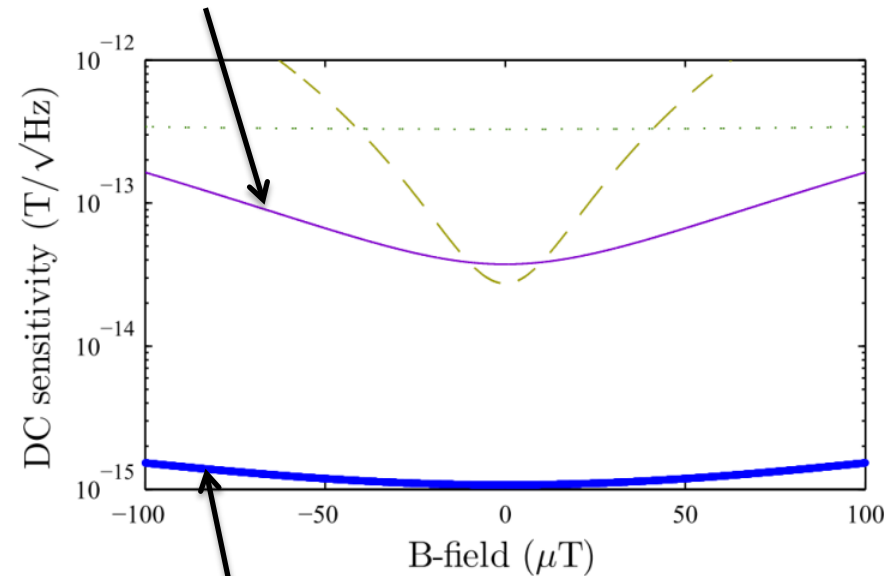
sensitivity $\eta = \sigma_B \sqrt{T} = \left(\frac{dB}{dn} \sqrt{\frac{n}{N_{at} \kappa}} \right)$

Obtained numerically



Free evolution magnetometry:
typically $1 \text{ nT}/\sqrt{\text{Hz}}$
recent ensemble record: $1 \text{ pT}/\sqrt{\text{Hz}}$
→ arXiv:1411.6553

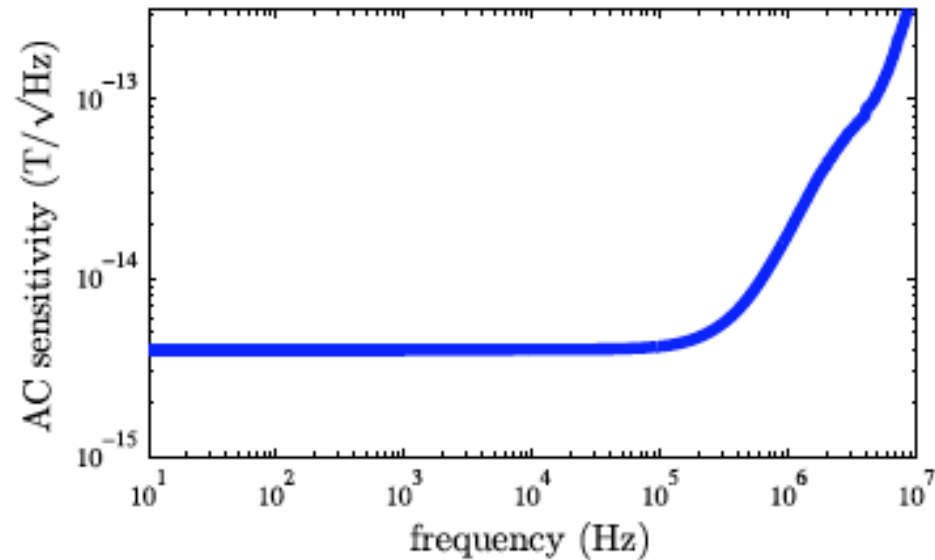
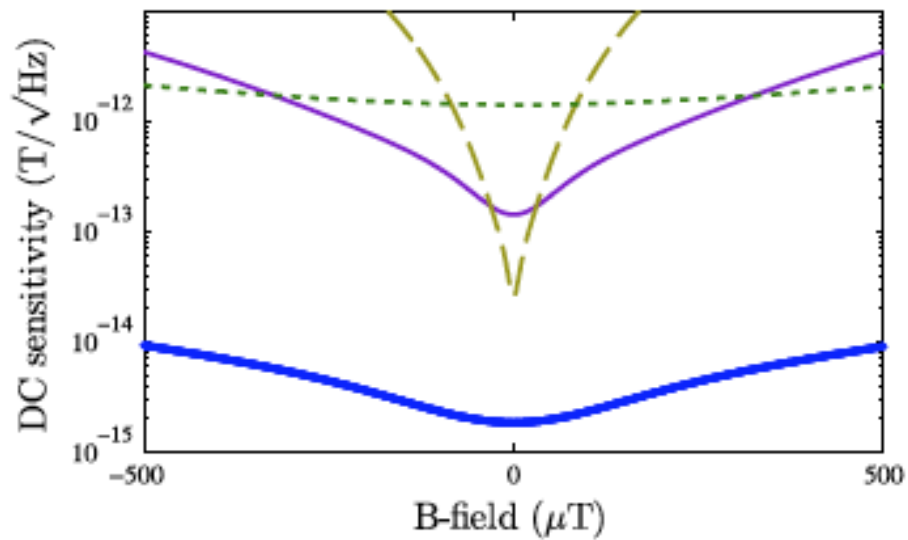
Achieved with 1 mm^3 diamond
with 5.7ppb NV with $T_2^* = 1 \mu\text{s}$



Achieved with different sample:
16ppm NV with $T_2^* = 118 \text{ ns}$

Such a sample was characterised in:
Phys. Rev. B **80**, 115202

DC vs AC sensitivity



Jeske, Cole and AG, NJP 2016

Conditions for lasing

Density NV

$$n_{\text{NV}} = \frac{4\pi^3 c \Delta \nu_{23} n^3 \frac{V_{\text{cav}}}{V_{\text{diam}}}}{3 \nu_{23} L_{23} \lambda^3 n l_{\text{cav}} \mathcal{F}} = \frac{V_{\text{cav}}}{V_{\text{diam}}} \frac{3.6 \text{ p.p.m.}}{\mathcal{F}(l_{\text{cav}} \text{ in mm})}$$

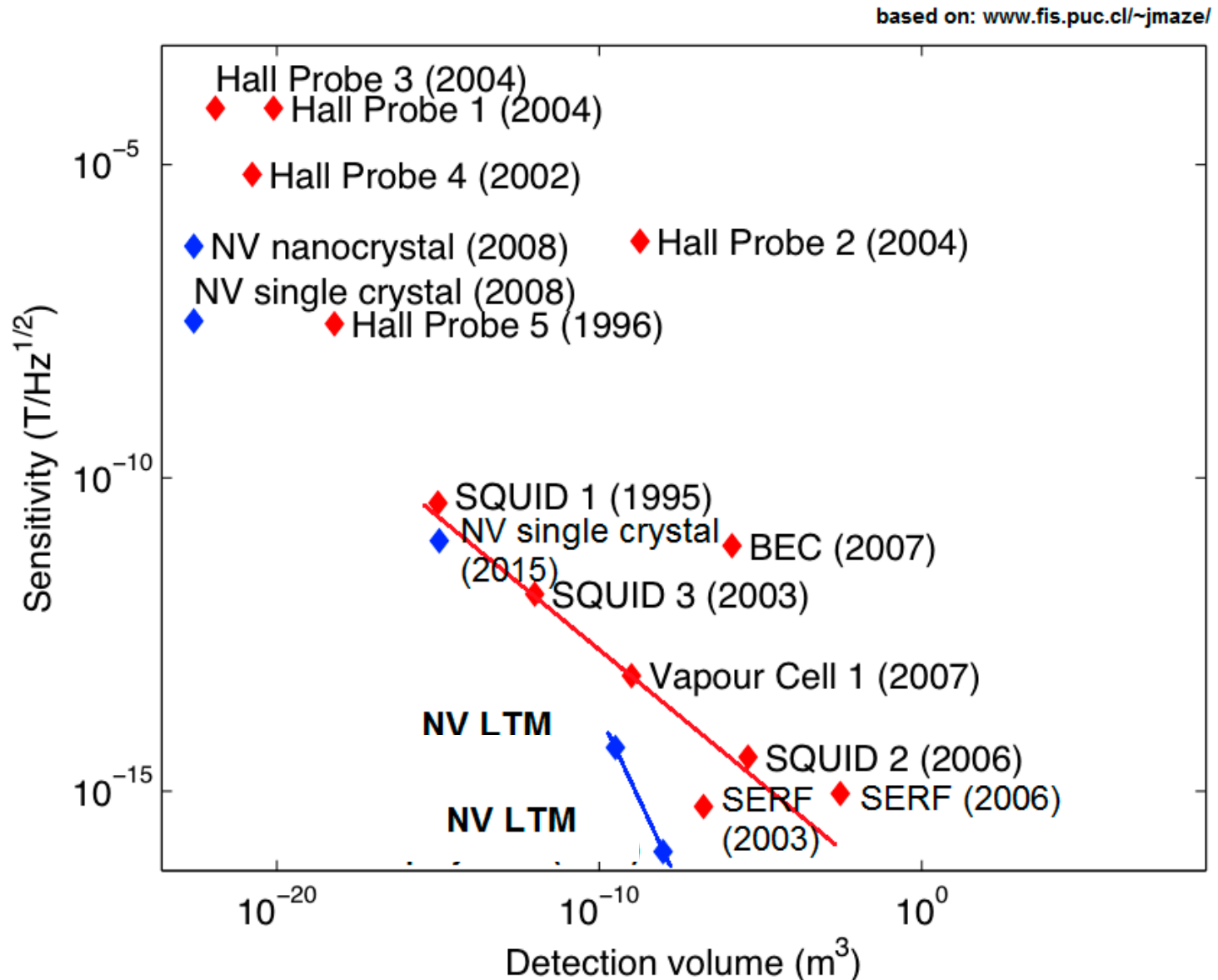
Cavity volume
Diamond volume
Finesse

Threshold
Pump power

$$P_{\text{thresh}} = \frac{1.2 \times 10^4 \text{ W } (A_{\text{cav}} \text{ in mm}^2)}{\mathcal{F}(l_{\text{cav}} \text{ in mm}) (n_{\text{NV}} \text{ in p.p.m.}) \frac{V_{\text{diam}}}{V_{\text{cav}}}}$$

Cavity length	1 mm
Cavity Area	1 mm ²
Finesse	10 ⁵
[NV]	1 ppm
Pump power	240 mW
Predicted sensitivity	fT/Hz ^{1/2}

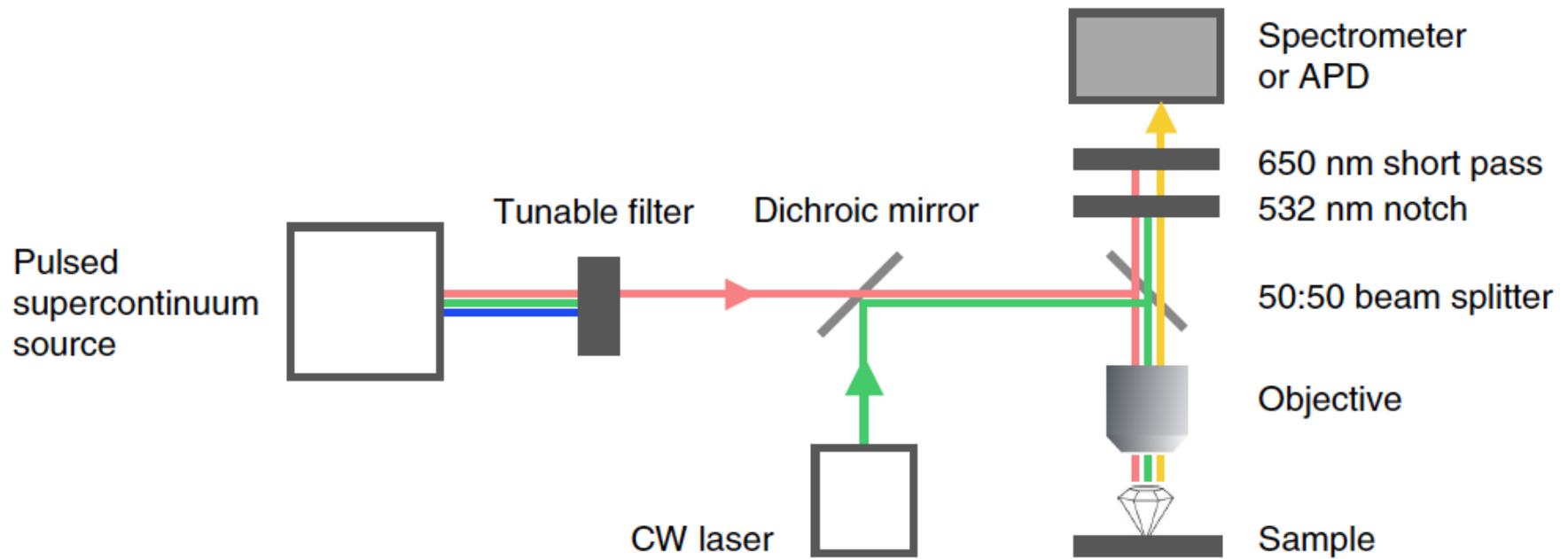
Magnetometers



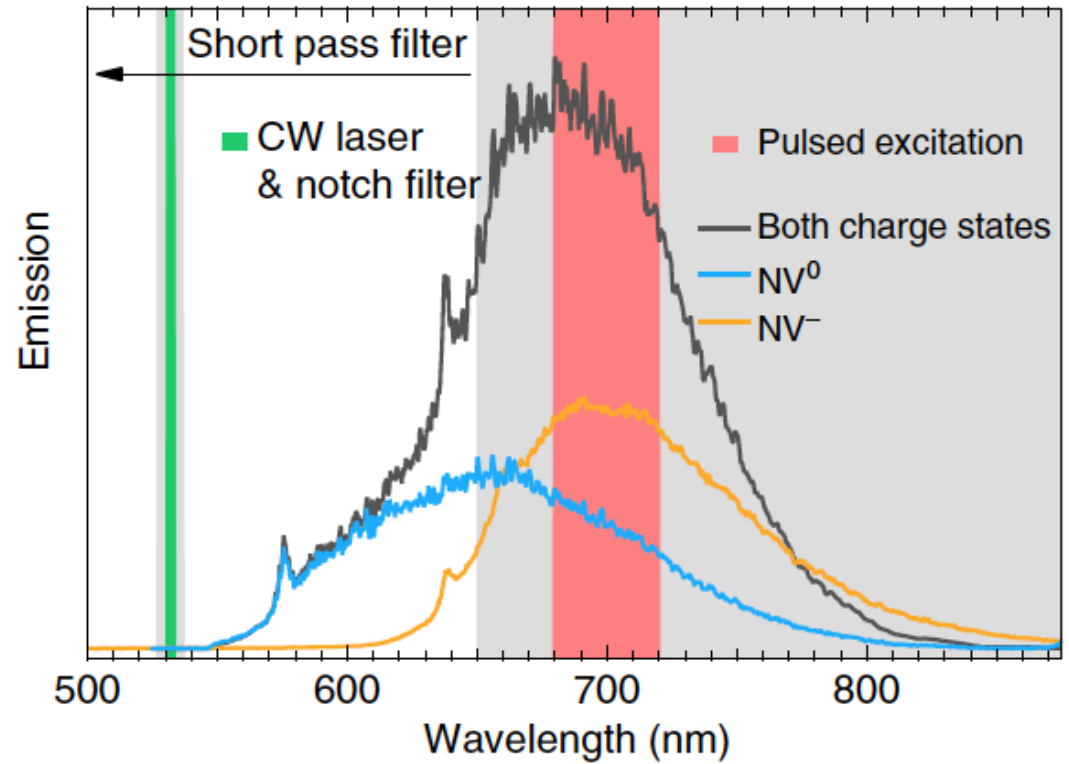
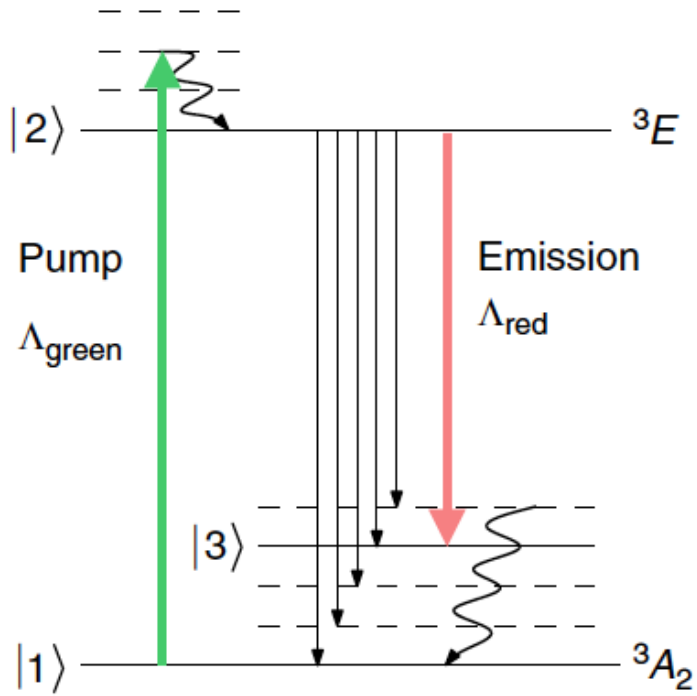
Stimulated emission experiments

- Jeske *et al.*, Nature Communications 8, 14000 (2017)

Experimental setup



Spectra



Photochromism (ionisation)

Appl. Phys. B 82, 243–246 (2006)

DOI: 10.1007/s00340-005-2056-2

Applied Physics B

Lasers and Optics

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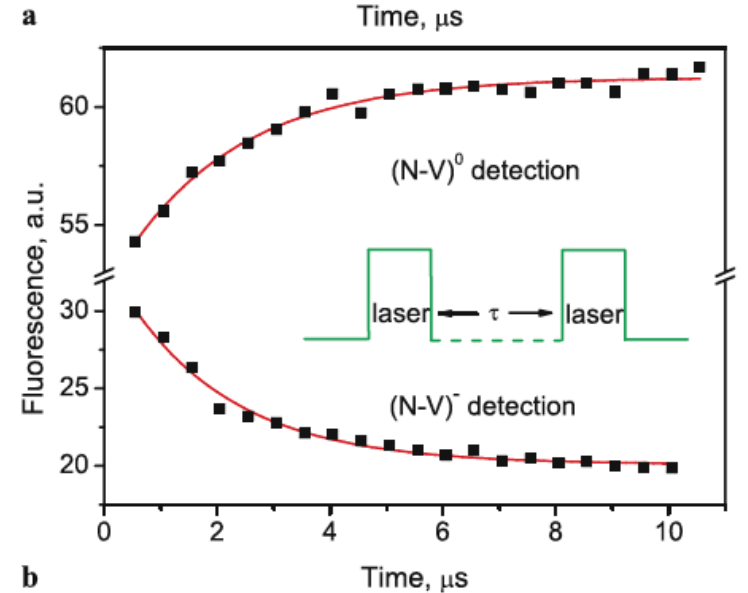
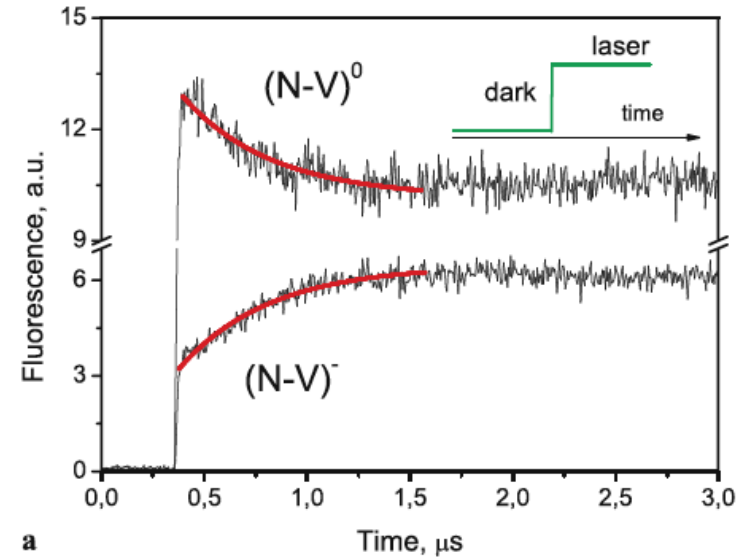
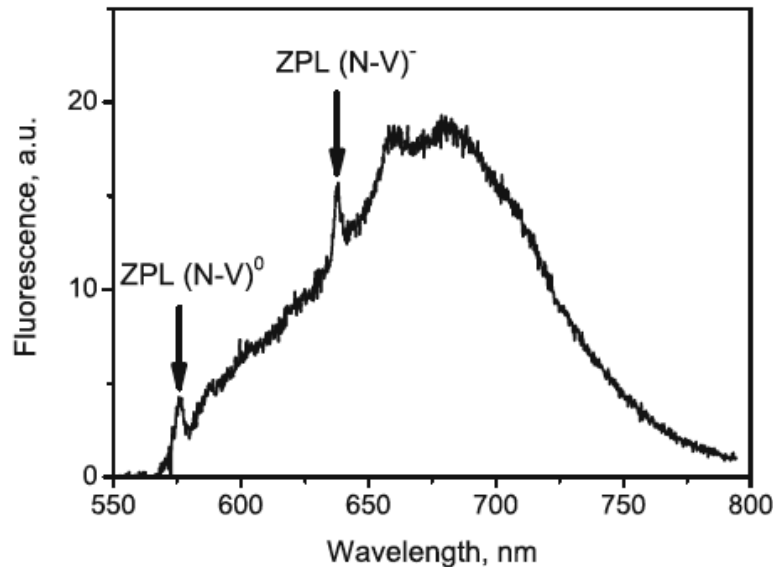
Photochromism in single nitrogen-vacancy defect in diamond

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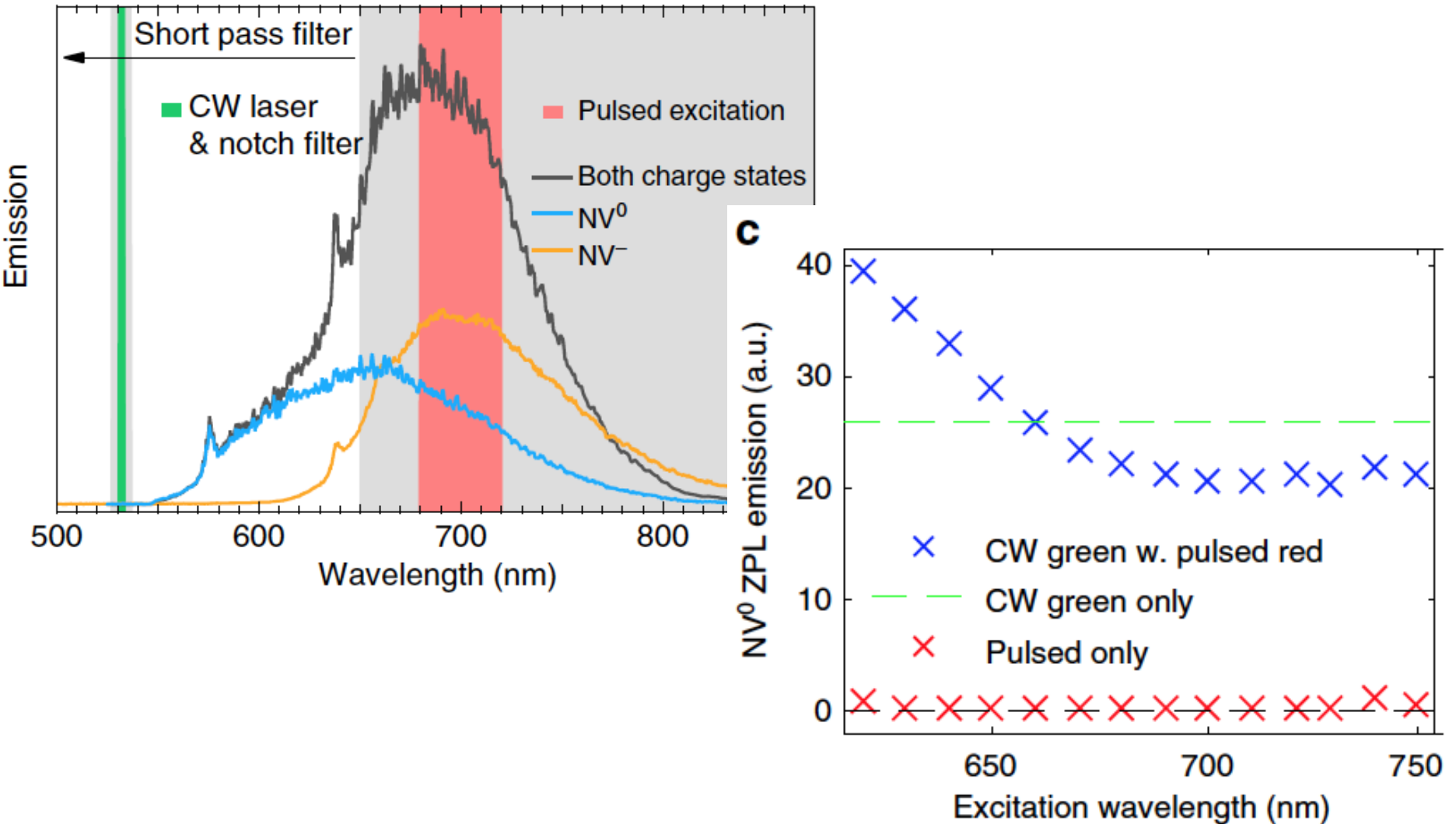
² School of Physics, University of Melbourne, Victoria, Australia

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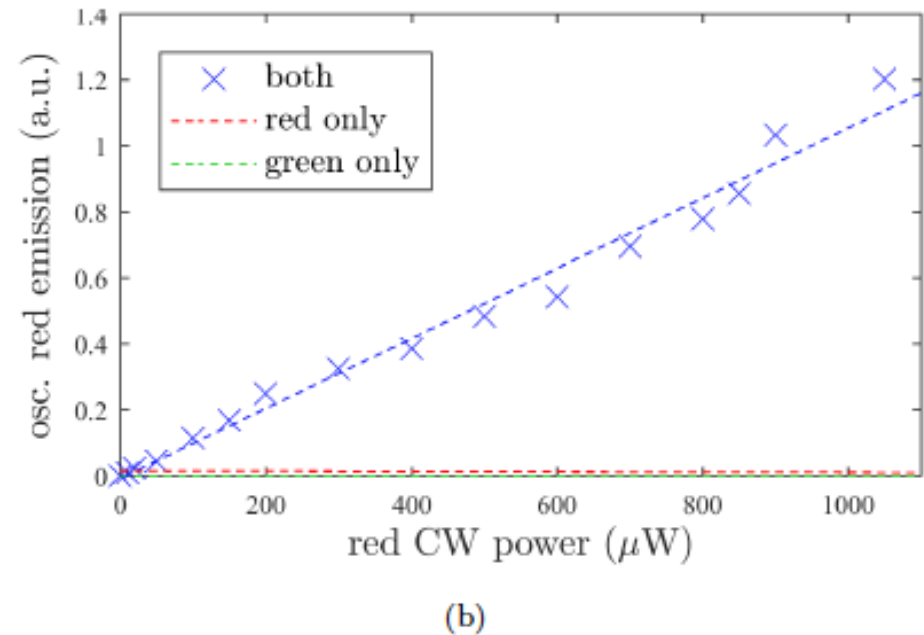
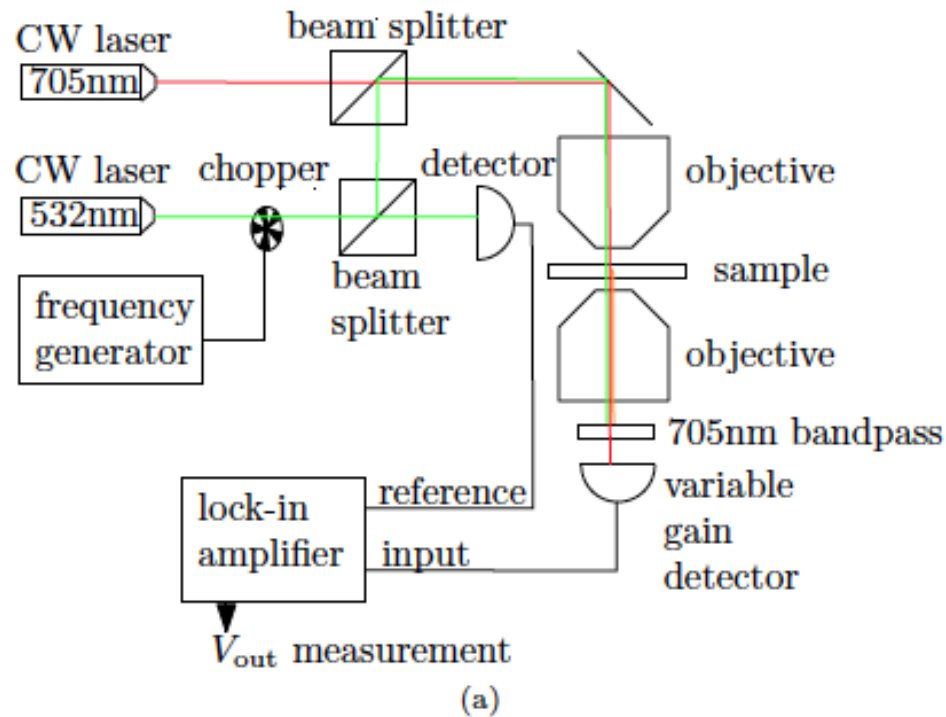
Single centre signal



Changing red pulsed wavelength



Stimulated Emission Demonstration



Where to from here?

- Cavity experiments
- Magnetic field measurements
- Alternatives to NV diamond?
- Mitigation of technical noise?
- Optimisation of laser design?
- Integration for ambulatory MEG

Conclusions

