

# Quantum Sensing Workshop

February 29,  
2024

# Agenda

1. Introduction to NV lecture
2. Hands on NV's (zero field)
3. Break (snacks & coffee)
4. Discussion
5. Introduction to sensing with NV lecture
6. Hands on NV's (with field)
7. Discussion/Applications



**Michael Grabowecky**

Quantum Technology Lab  
Co-ordinator

*TQT*



**Carola Purser**

Senior Scientist

*QVIL*

# About TQT

February 29,  
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# Our Vision



To develop and deliver impactful quantum devices to further Canada's leadership position in the next quantum revolution.

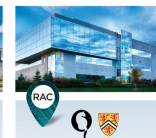
# Our Program

## Collaborative Research Initiative

- Recruitment of the “best and the brightest”
- Grand Challenge research & seed fund
- Connect to early adopters, industry & others
- Shared research infrastructure
- Technology development and commercialization



**Quantum Valley Investments**  
A quantum technology investment fund established in 2015 by Mike Lazardis and Doug Fregin with a commitment of \$100 million in investment capital. QVI has developed as a quantum technology commercialization incubator with the necessary components to enable and accelerate the commercialization of new transformative quantum technologies in the Quantum Valley.



**RAC Complex**  
A community of academic, not-for-profit, commercial and startup researchers with access to laboratories and tools for developing and testing quantum devices. A collaborative experiment to speed the development and adoption of quantum technologies. RAC2 is home to QVI Commercialization Labs including the Quiet Labs and will be the home of the Magnetic Field Lab once completed.



**Quantum Valley Ideas Lab**  
A dedicated application focused research lab that will help address the gap between foundational research done in academic research labs and commercialization. The Ideas Lab will connect with industries to identify strategic opportunities for new quantum technologies with practical applications based on existing foundational physics principles.



**Institute for Quantum Computing at the University of Waterloo**  
An internationally recognized scientific research institute at the University of Waterloo pushing the frontier of quantum information theory, practice and applications. Scientific research focuses on harnessing the quantum laws of nature to develop powerful new technologies that will transform information technology and drive the 21st century economy. Home of a collaborative training program for areas of computer science, engineering, mathematics and physical science.



**Quantum NanoFab**  
A fabrication facility of shared tools and expertise for quantum device fabrication. For example, it is used for fabricating superconducting qubits and electronics, for deposition of thin film devices including spintronics, for patterning of semiconductor devices including quantum dot qubits. The facility is open to academic and industrial users across Canada.



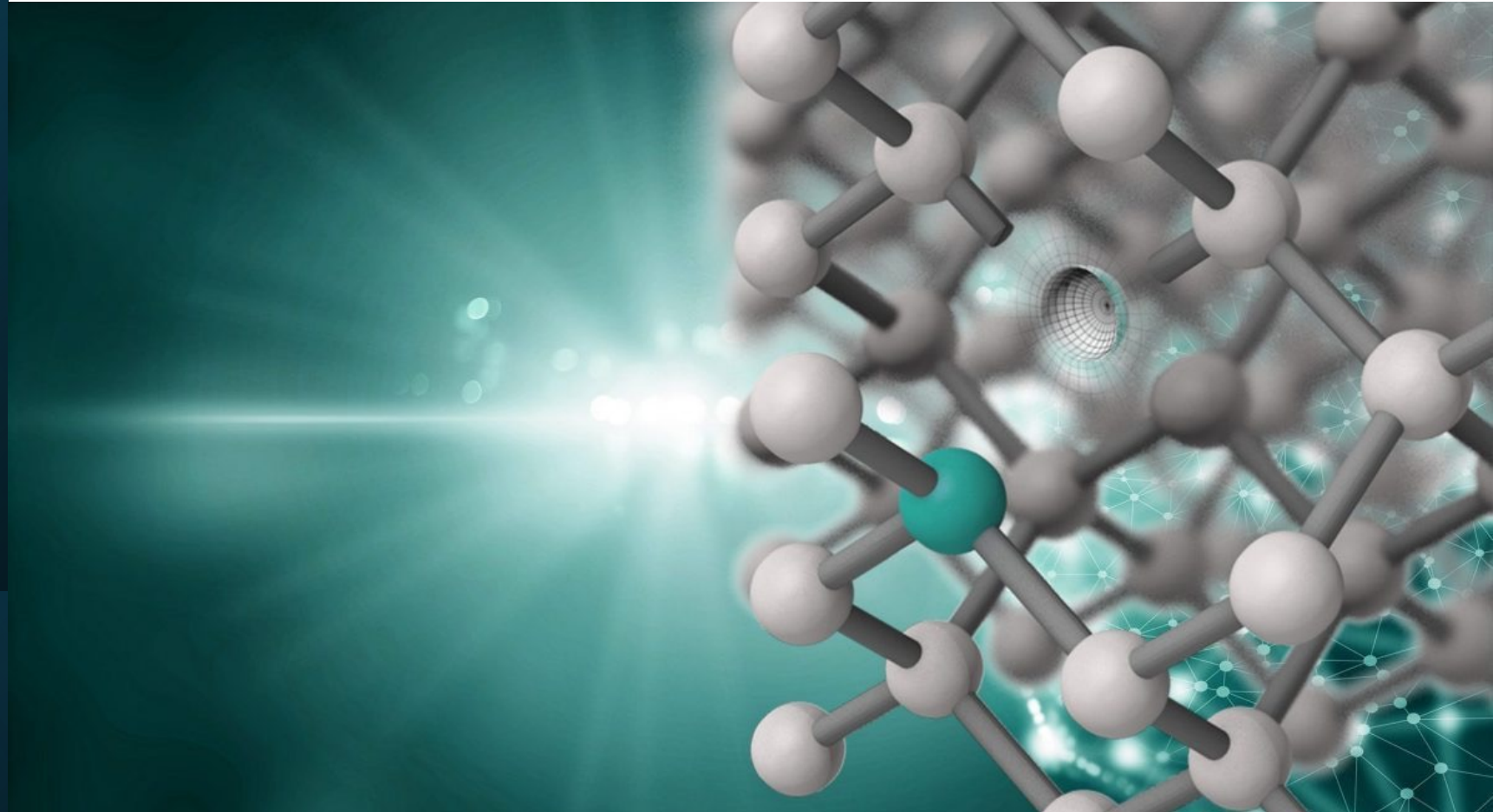
**Lazardis Institute for the Management of Technology Enterprises**  
An institute for developing training and research programs, which will produce exceptional technology business managers and leaders that Canadian technology companies need to grow and scale globally.



**The Perimeter Institute for Theoretical Physics**  
A leading centre for scientific research, training and educational outreach in foundational theoretical physics. Founded in 1999 in Waterloo, Ontario, Canada, its mission is to advance our understanding of the universe at the most fundamental level, stimulating the breakthroughs that could transform our future. Perimeter also trains the next generation of physicists through innovative programs, and shares the excitement and wonder of science with students, teachers and the general public.

# Impact of spin-based quantum sensors & intro to nitrogen vacancy centers

Michael Grabowecky,  
mgrabowe@uwaterloo.ca



UNIVERSITY OF  
**WATERLOO**

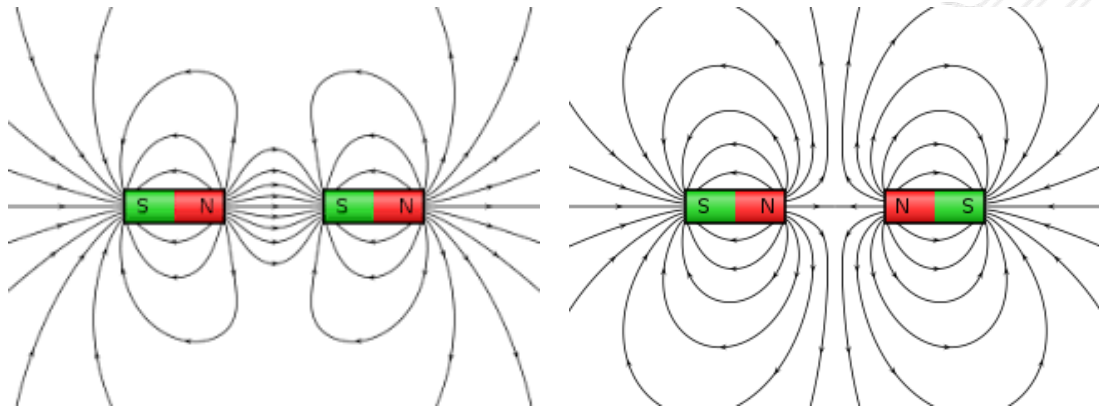
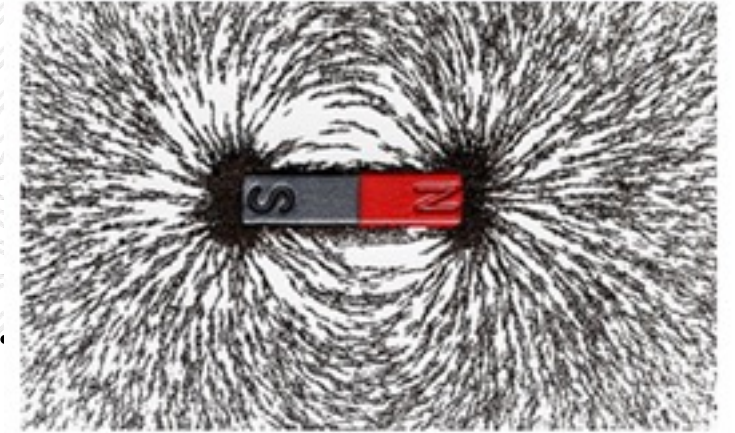
Department of  
Physics and Astronomy



# Classical Magnetic Field Sensing

Consider naïve approaches classically

- Two magnets have high/low energy orientations.



Low Energy

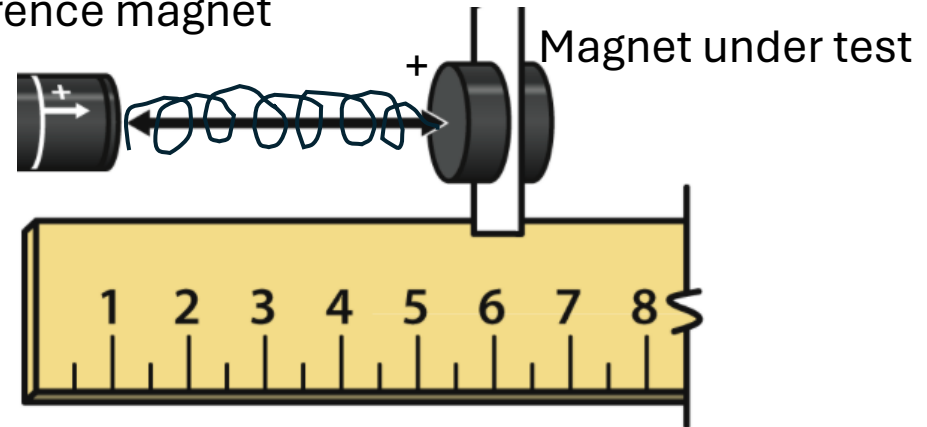
0

High Energy

1

Easy to tell between these two

Reference magnet

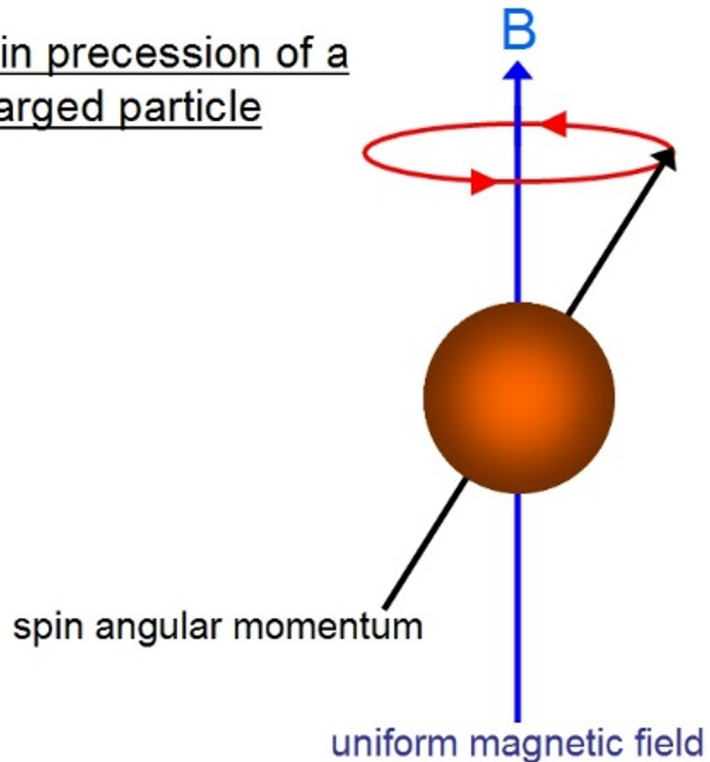


# Quantum mechanical magnets: Spins

- Consider a single electron. Behaves like a tiny bar magnet (2 orientations, Zeeman interaction)
- External fields produce a torque on the electron yielding “Larmor” **precession**

$$f_L = \gamma|B|$$

Spin precession of a charged particle



**Resonance:** consider a swing set. Need to push at just the right times (frequency) to swing higher.



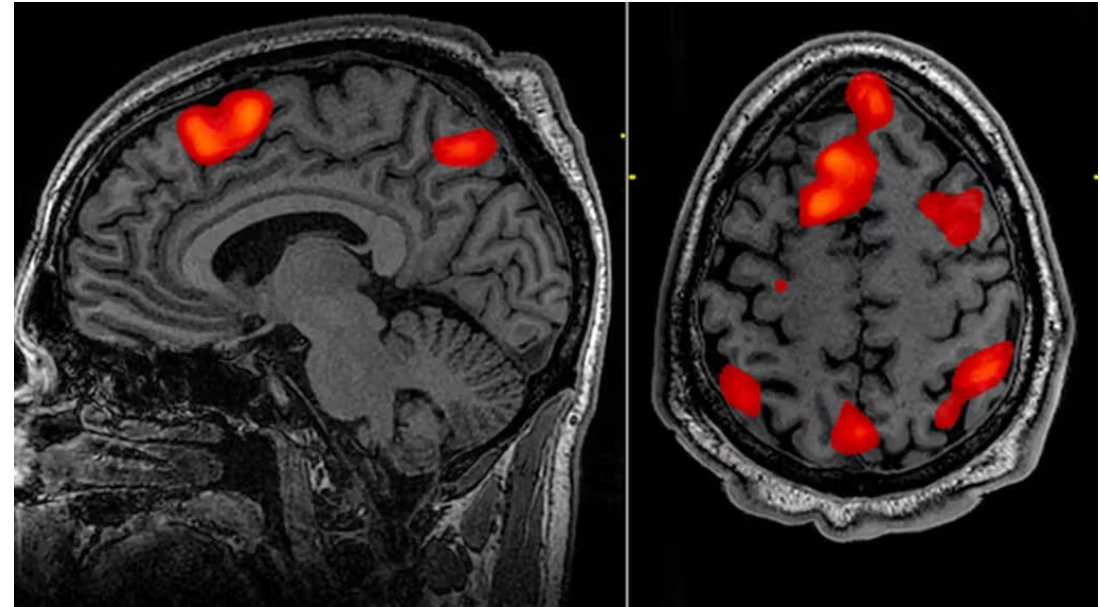
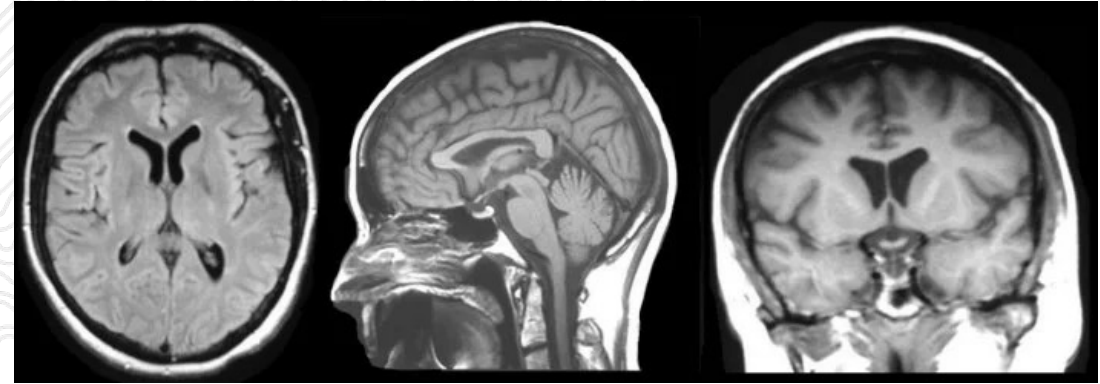
Same principle for spins, need to apply magnetic field fluctuations at just the right frequency (Larmor frequency) to change the spin quantum state



# Where spin-based sensors are used today

## MRI & fMRI

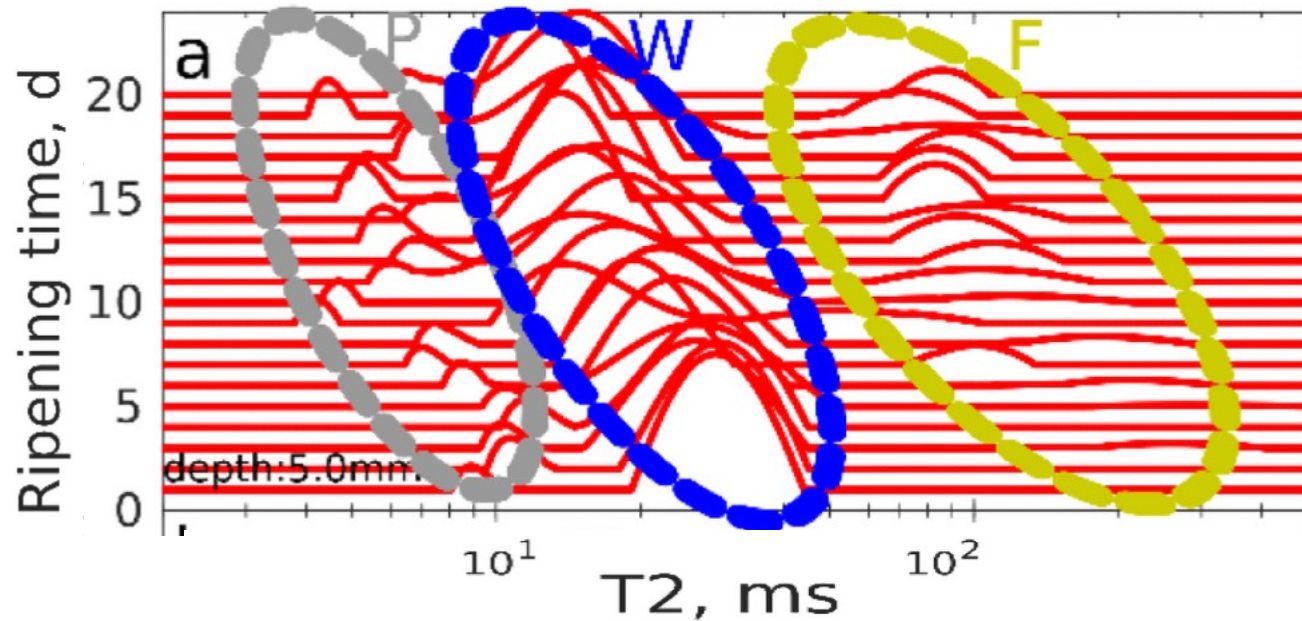
- Produce high contrast images of the body
- Monitor blood flow and electrical activity in the brain



# Where spin-based sensors are used today

Food quality assurance:

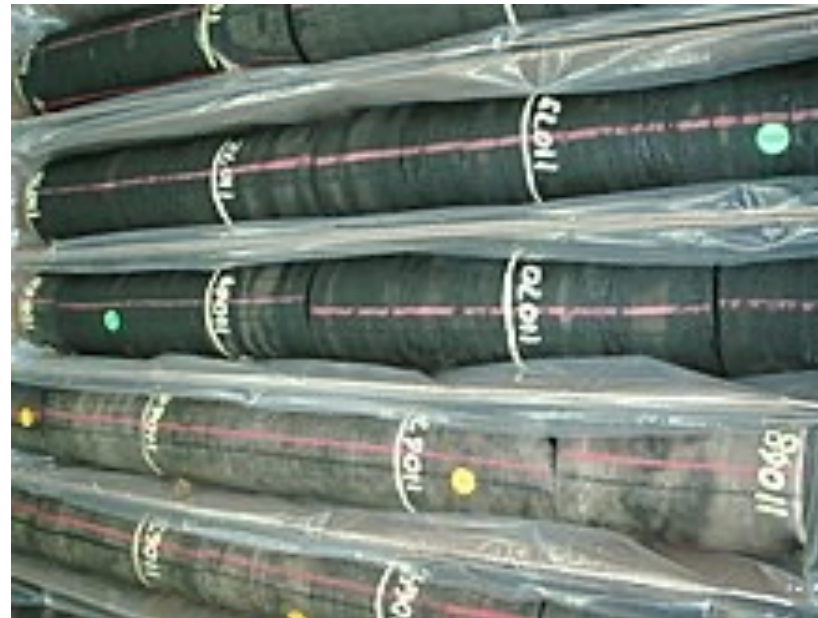
- Cheese ripening (flavor)
- Chocolate texture (slimy vs. chalky)



# Where spin-based sensors are used today

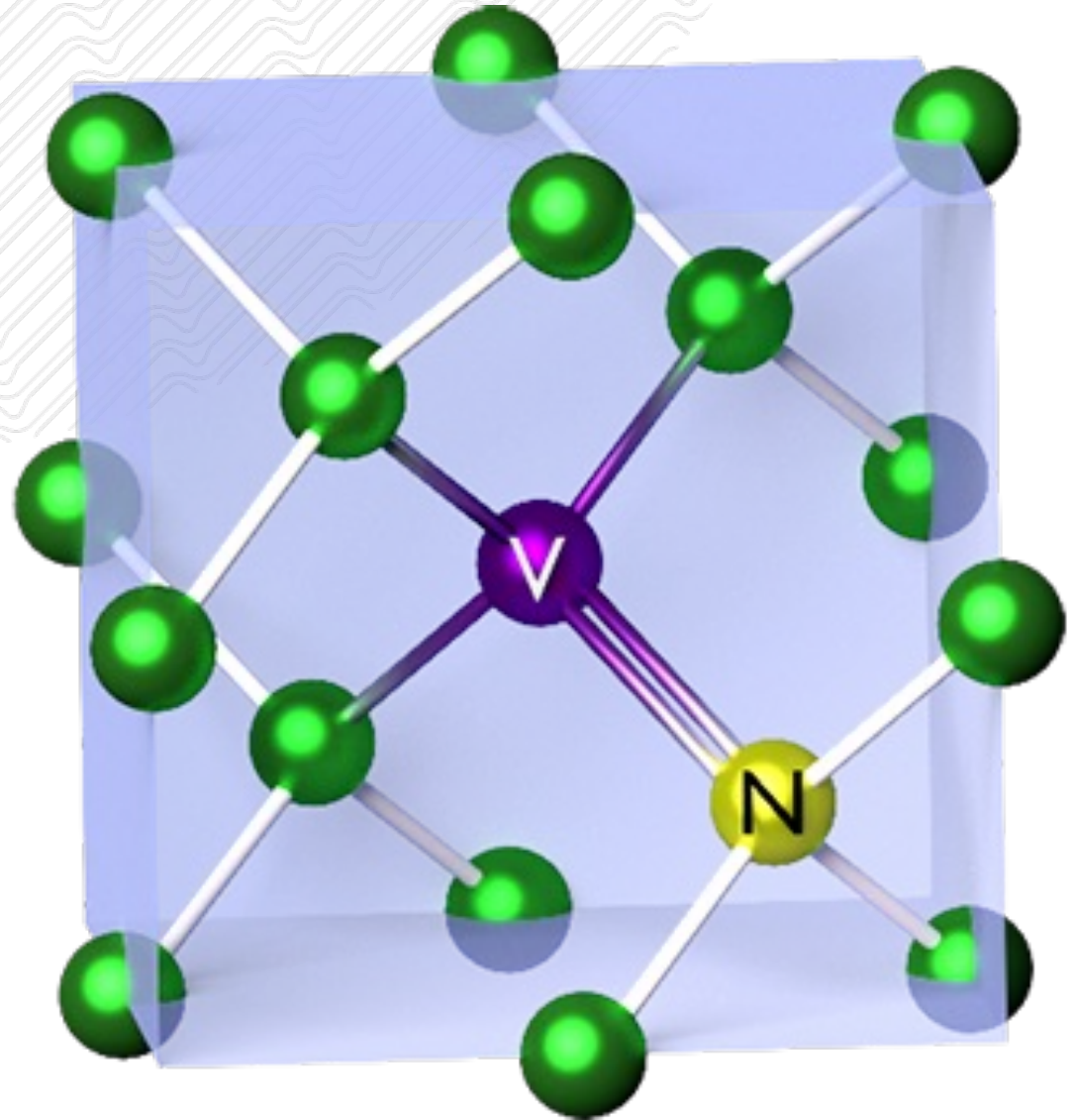
## Oil Industry:

- Refining (wax content to monitor viscosity)
- Oil exploration (porosity and permeability of core samples)



# What is an NV Center in diamond?

- Diamond consists of carbon crystal lattice (green in figure)
- Nitrogen atom (N) appears as a defect in this lattice causing a vacant adjacent lattice site (V)
- Electrons are trapped in the vacancy



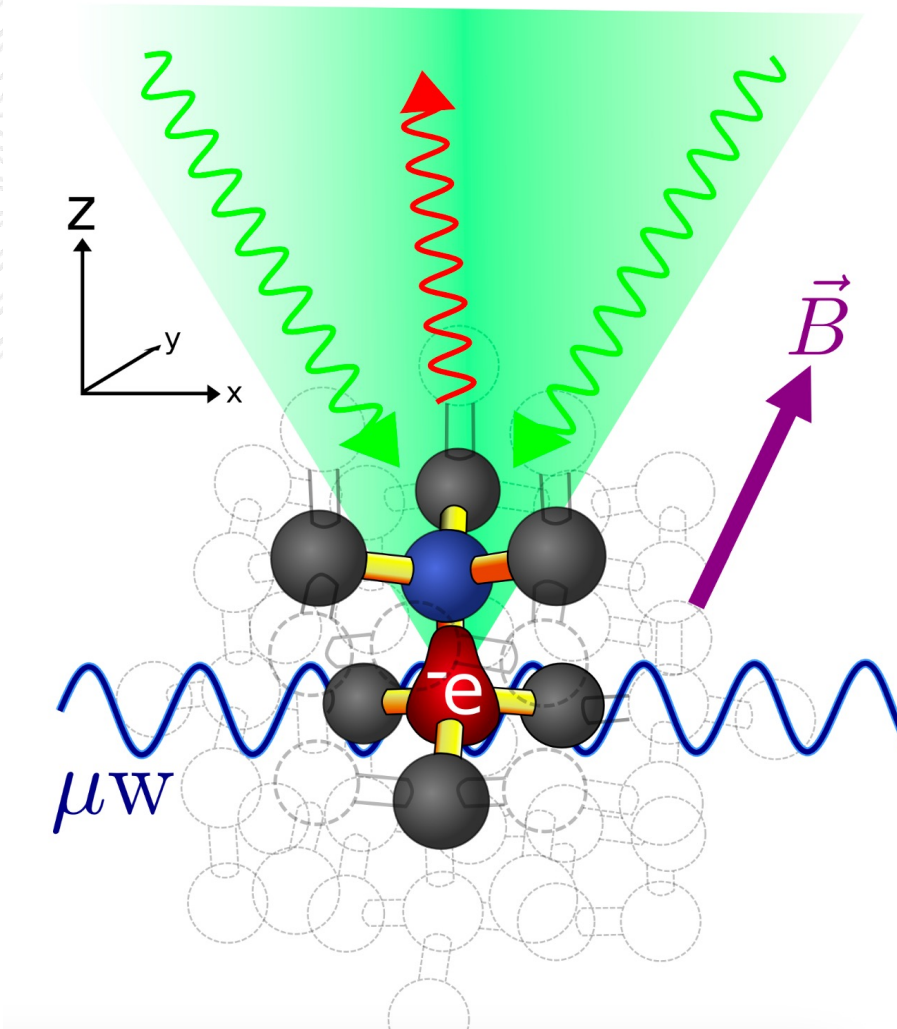
# Optical properties of NV centers

Simplest quantum experiment needs only 3 things:

- Diamond
- Laser (reset the sensor, turn on measurement)
- Photodiode

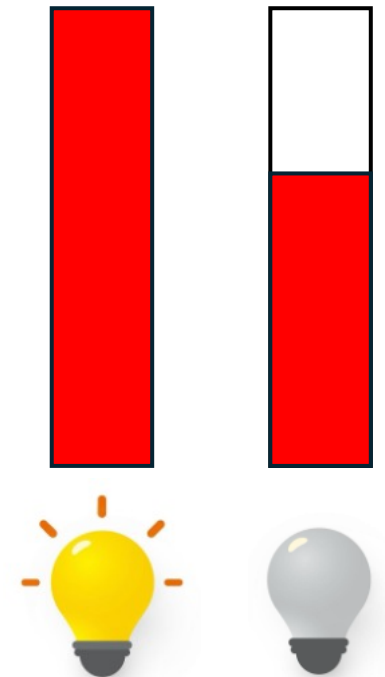
Resonant microwave radiation causes oscillations of the NV electrons

$f_{\mu W} = 2.87\text{GHz}$  (similar frequency to your microwave at home)



Oscillations are observed via a change in red light observed over time

Relative Red Light



# Why use NV quantum sensors?

- Can be built compactly
- Relatively simple to operate
- Robust: Diamonds are strong!
- Room temperature operation

Useful when:

- Have a small change in field and want to detect that change
- There is something happening at the surface of a material

# First hands-on session (roadmap)

1. Overview of the apparatus
2. Use a laser to initialize the sensor
3. Use microwave radiation to start oscillations of the NV electrons (Resonance)
4. Explore how long the quantum behavior lasts

# References

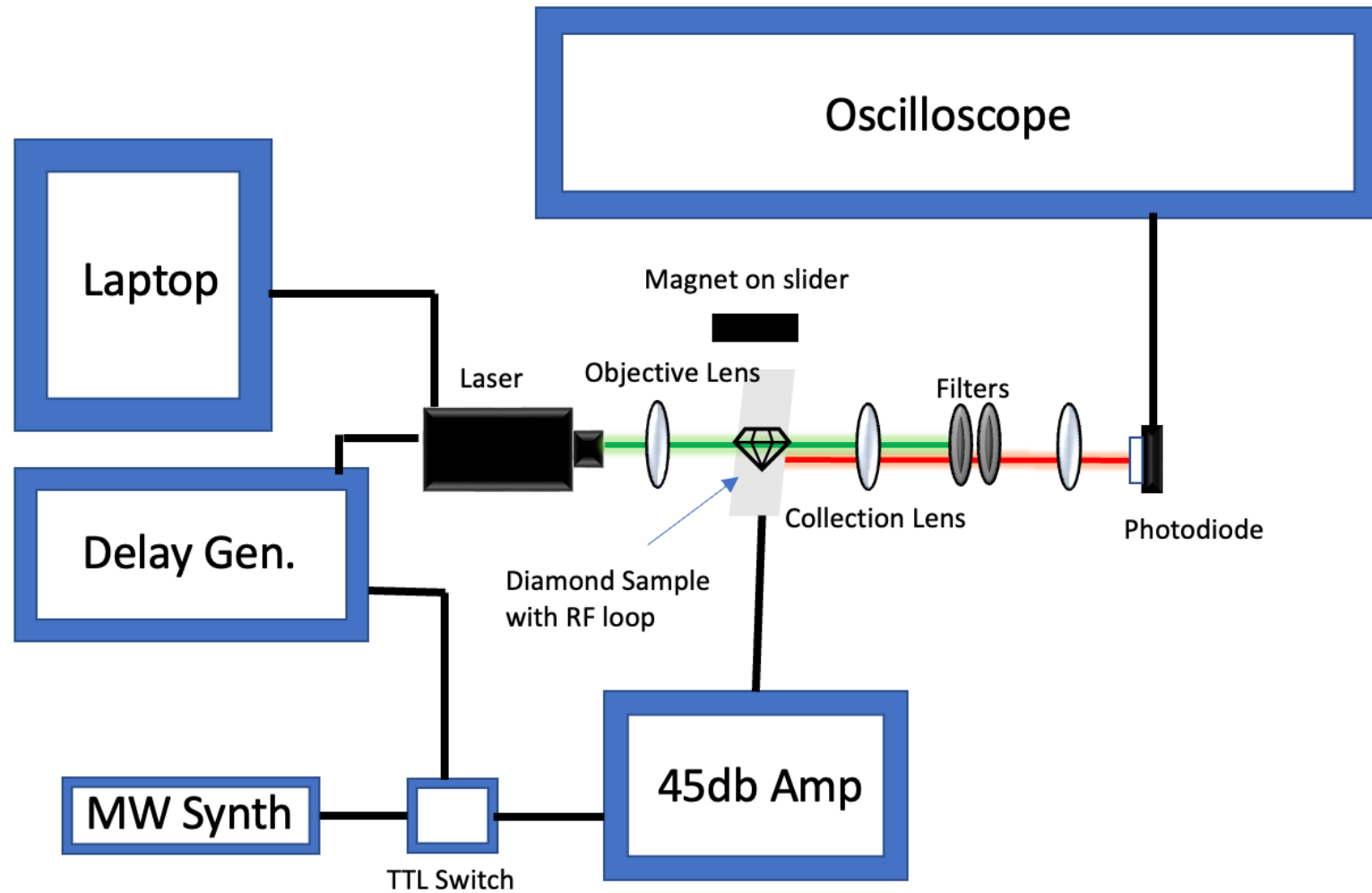
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- <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2999310/>
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# Experimental Setup

Simplest experiment needs only 3 things:

- Laser
- Diamond
- Photodiode



# Sensing modalities and technologies with NV centers

DR. CAROLA PURSER

QUANTUM VALLEY IDEAS LAB

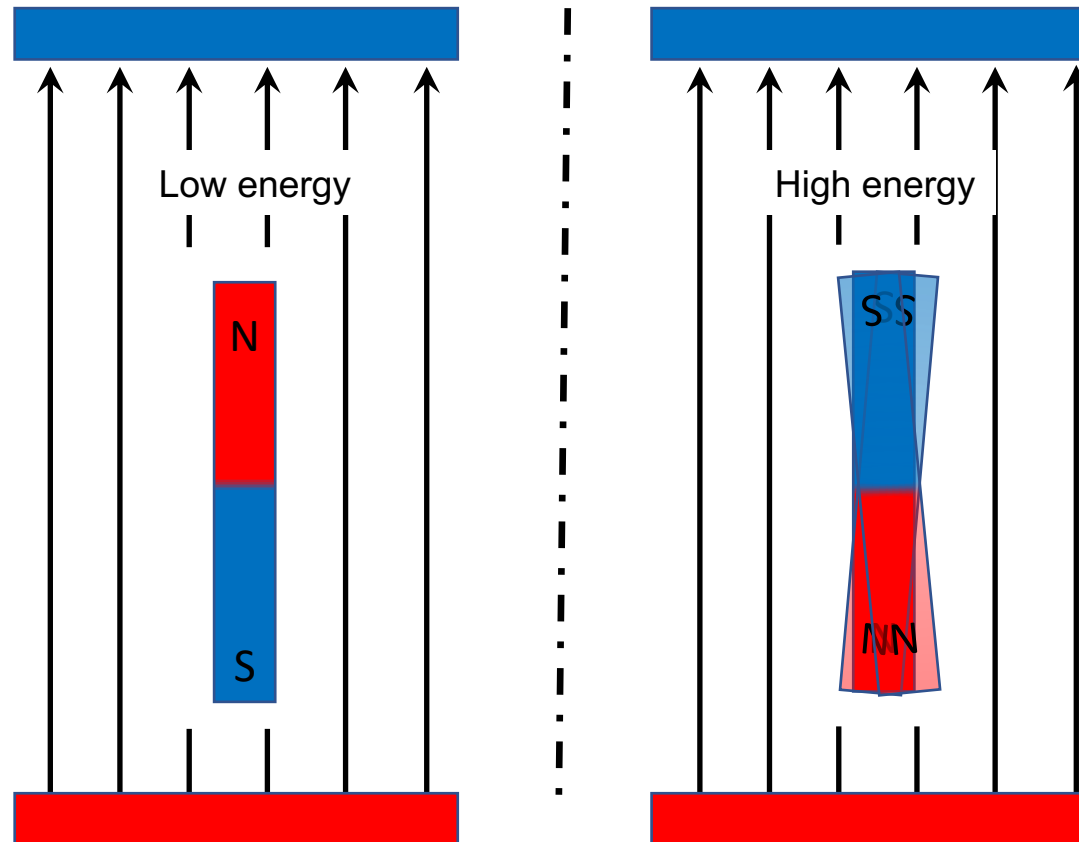
# Measuring a magnetic field

With no magnetic field, the orientations of these bar magnets have no energy difference.



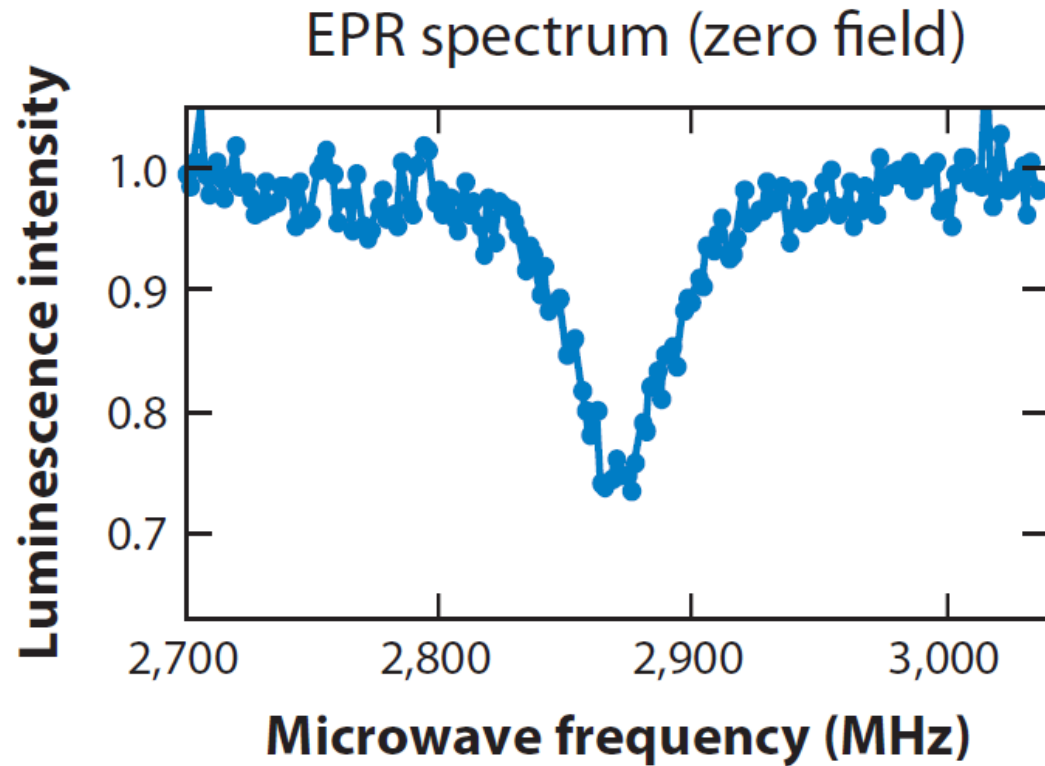
# Measuring a magnetic field

In the presence of a field, one orientation has lower energy than the other.

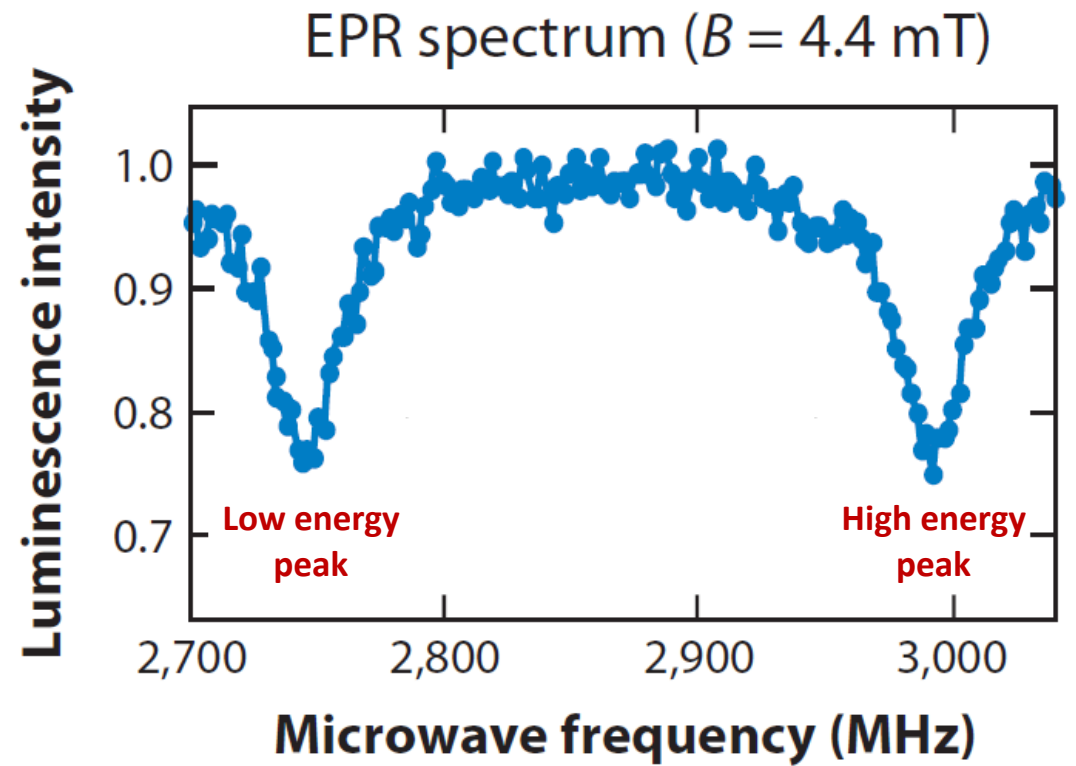


# Measuring a magnetic field with NV spins

Zero field: single dip



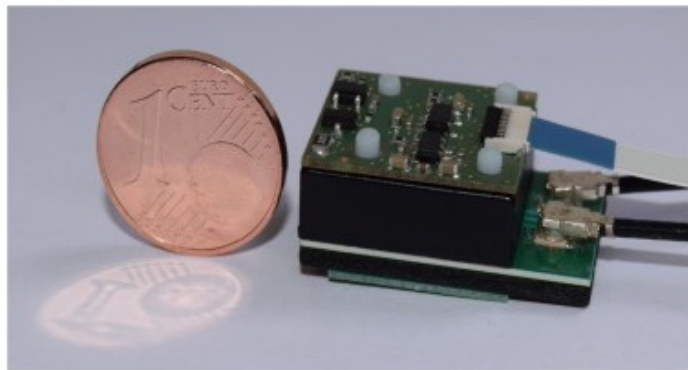
Applied field: two dips



# Commercial NV: packaged sensors

Commercial interests can take a lab from benchtop to packaged sensor

How else might a packaged magnetometer be useful?

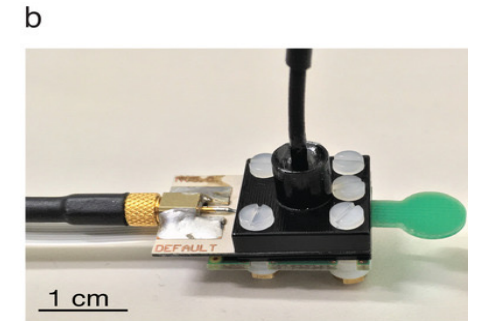
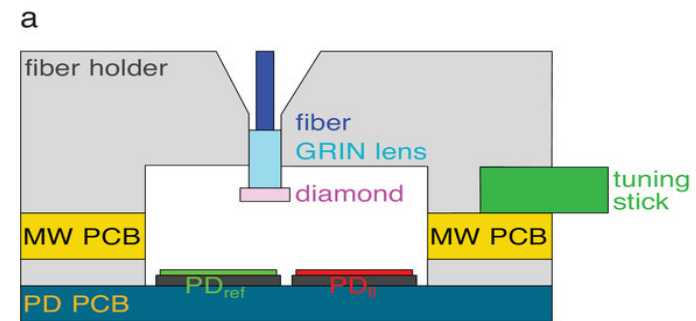


miniaturised magnetometer

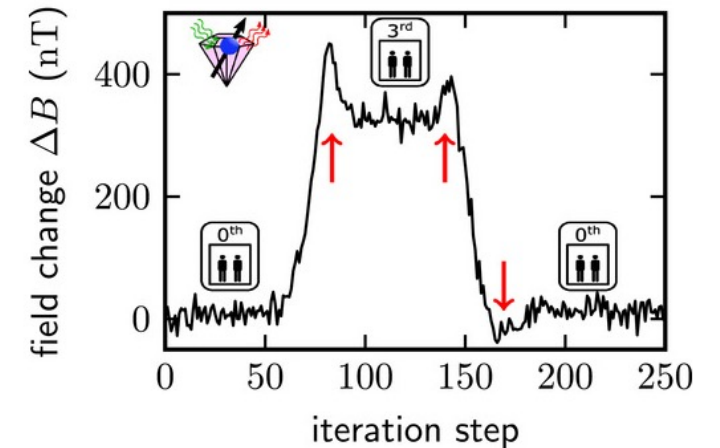


nanotesla sensitivity

<https://doi.org/10.1016/j.diamond.2019.01.008>

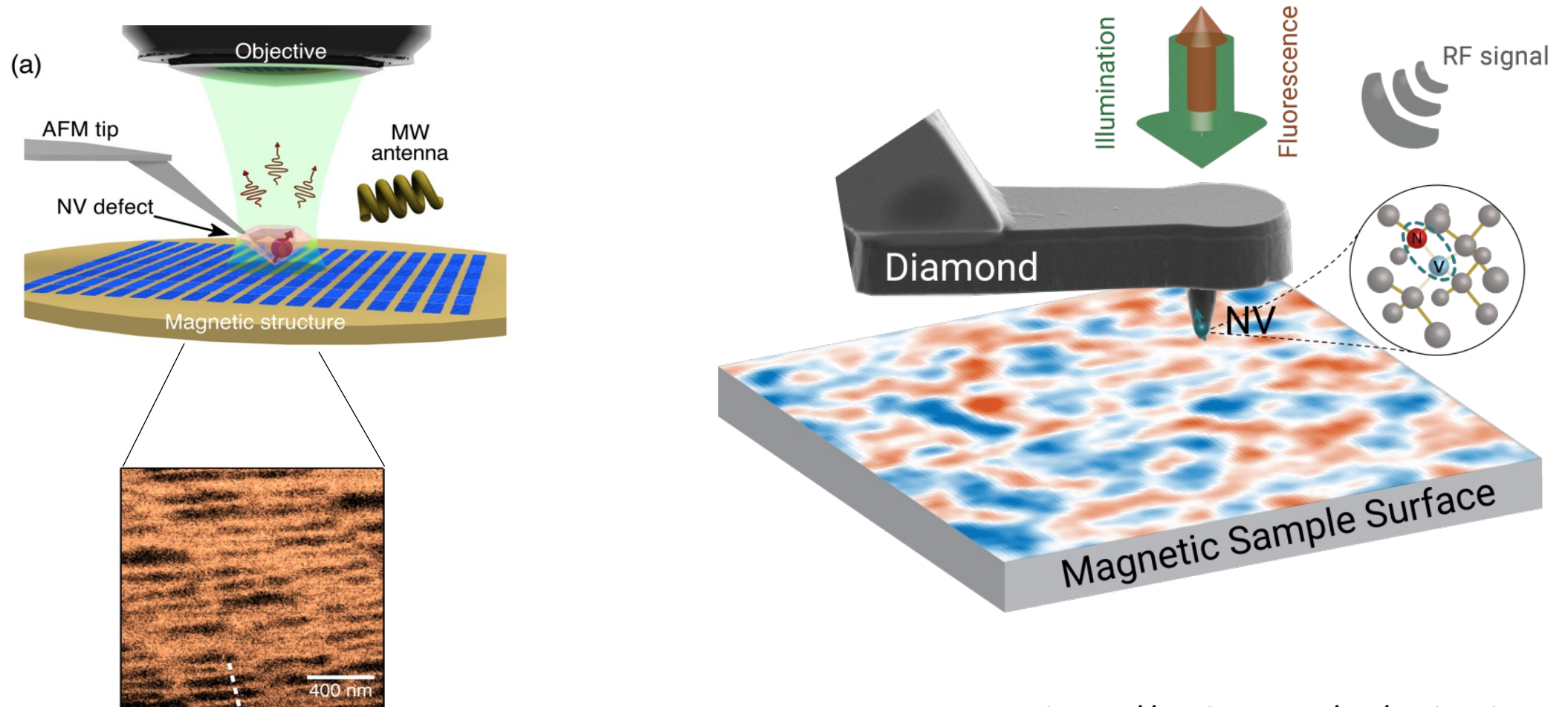


Sensing motion of an elevator with magnetometer placed on 3<sup>rd</sup> floor



Felix M. Stürner, Andreas Brenneis et al., “Integrated and Portable Magnetometer Based on Nitrogen-Vacancy Ensembles in Diamond,” Advanced Quantum Technologies, 2021

# Example sensing with scanning NV



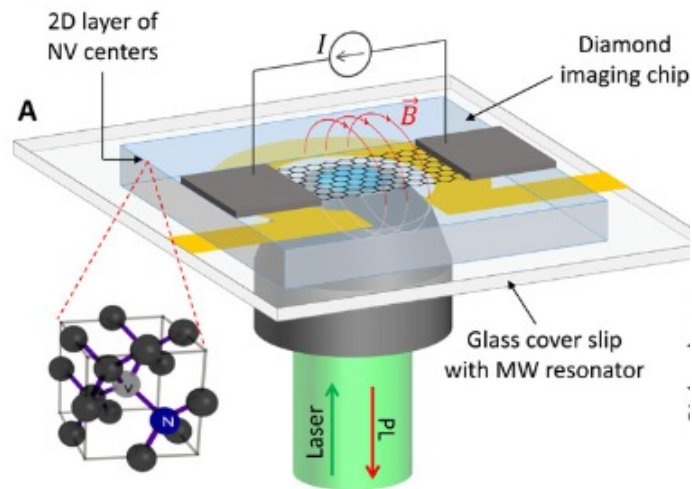
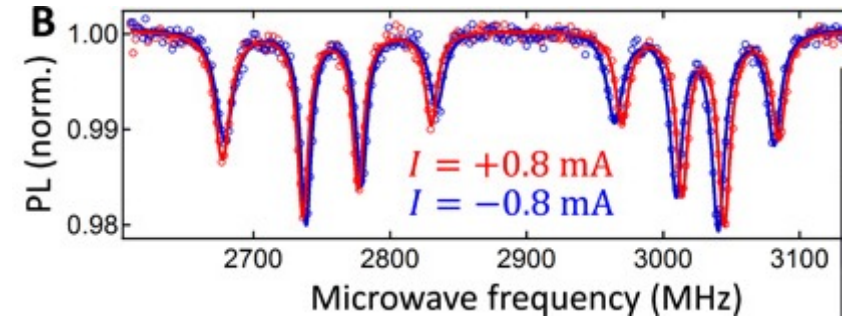
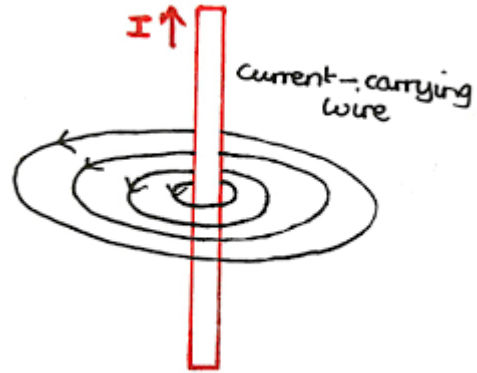
L. Rondin ,et al., "Nanoscale magnetic field mapping with a single spin scanning probe magnetometer," Appl. Phys. Lett. (2012)

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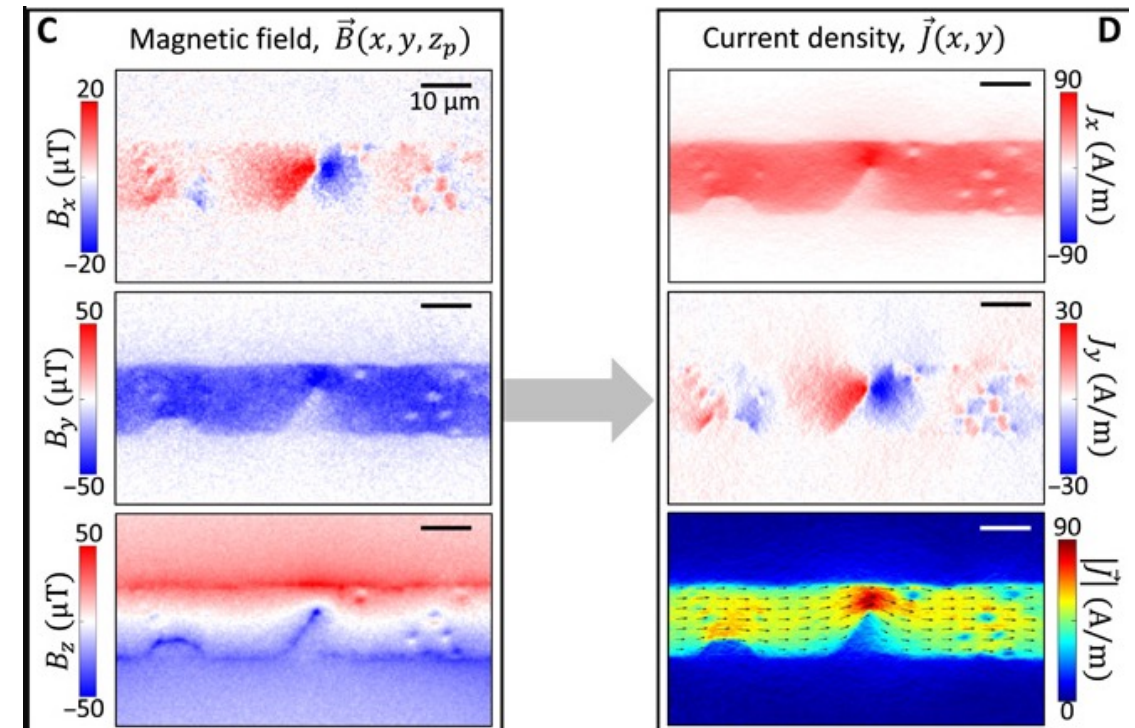
# Imaging currents with an NV sensor

Recall: electric currents generate magnetic fields.

Since we can detect magnetic fields using NV centers, we can also measure proximate electric currents



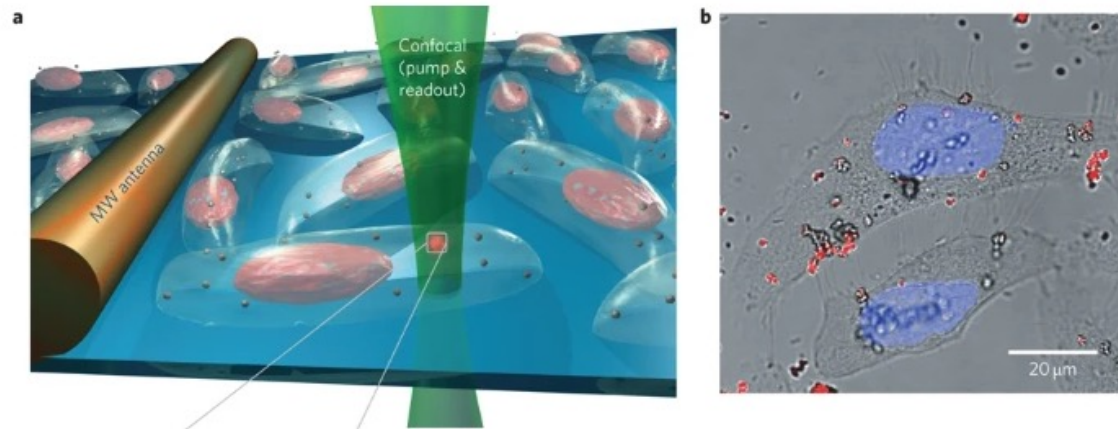
Jean-Philippe Tetienne, et al., "Quantum imaging of current flow in graphene," Science Advances, 2017.





# Biosensing applications

- Intrinsic bio-compatibility of diamond means that NV-based quantum sensors can be placed in cells
- Diamonds can take the form of nanocrystals >10 nm
- Surface functionalization can be used to place diamonds in desired regions or bind molecules of interest to the diamond surface



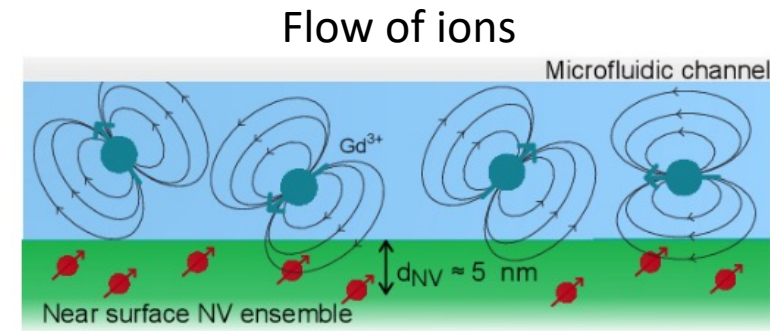
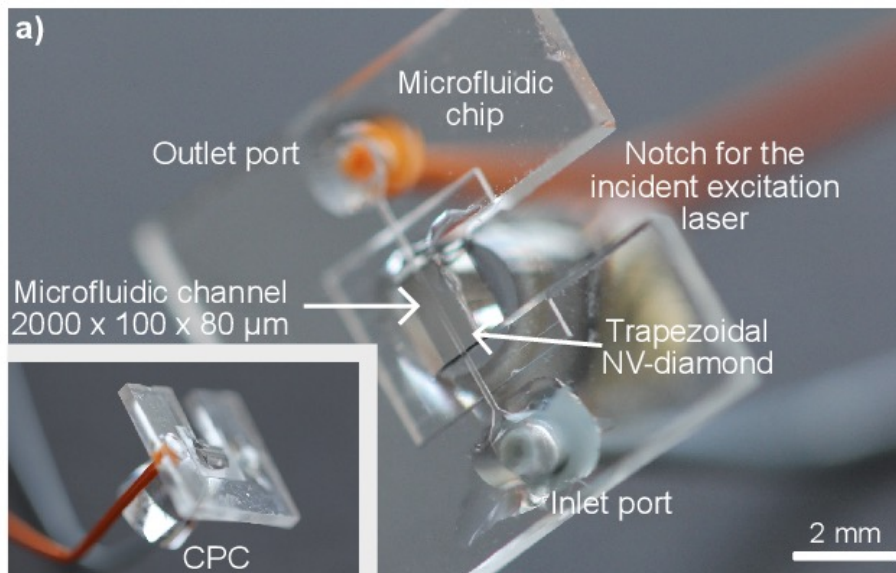
McGuinness, L., Yan, Y., Stacey, A. *et al.* Quantum measurement and orientation tracking of fluorescent nanodiamonds inside living cells. *Nature Nanotech* **6**, 358–363 (2011).



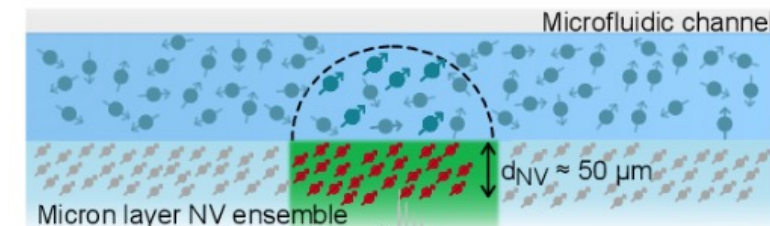
Takuya F. Segawa, Ryuji Igarashi, "Nanoscale quantum sensing with Nitrogen-Vacancy centers in nanodiamonds – A magnetic resonance perspective," *Progress in Nuclear Magnetic Resonance Spectroscopy*, 2023.

# Diamond-based lab on a chip

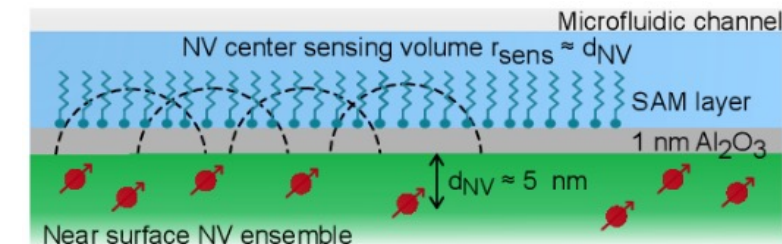
Designing microfluidic channels in the diamond or at the diamond surface enables chemical analysis using the sensitivity of NV centers to magnetic fields



Flow and concentration of spins (magnetic moments)



Screening for bio-molecules



R. D. Allert, F. Bruckmaier, N. R. Neuling, et al. "Microfluidic quantum sensing platform for lab-on-a-chip Applications" Lab on a Chip, 2022.