



Diamonds are a nuclear engineer's best friend

Clarice D. Aiello, Masashi Hirose, Paola Cappellaro

March 5th 2013



Magnetic sensing with a single spin in diamond

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To measure things better is to understand nature better

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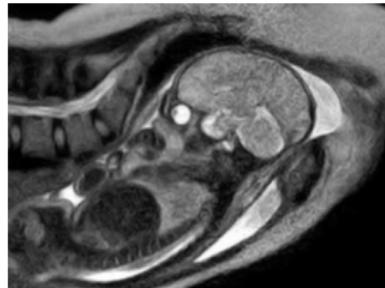


better frequencies

To measure things better is to understand nature better



better frequencies

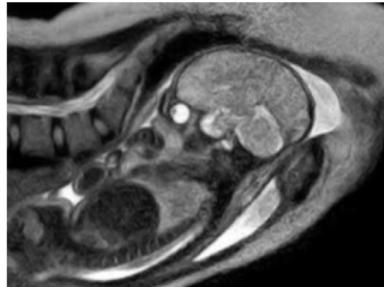


better magnetic fields

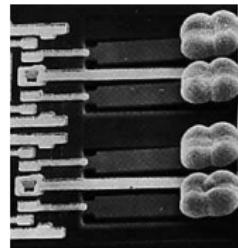
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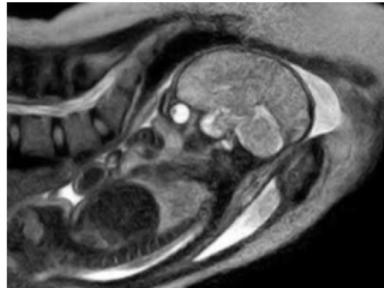


better accelerations

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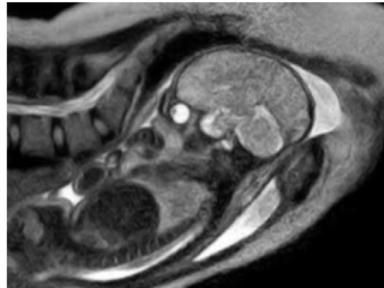
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what if...



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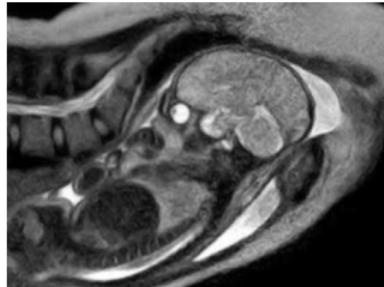


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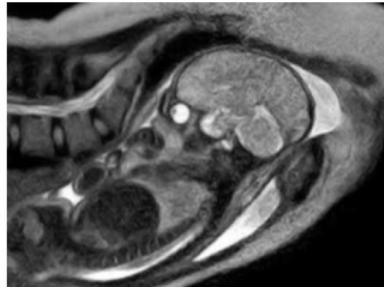
what if...

...the quantity to be measured is way too small?

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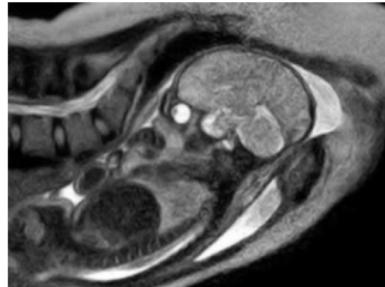
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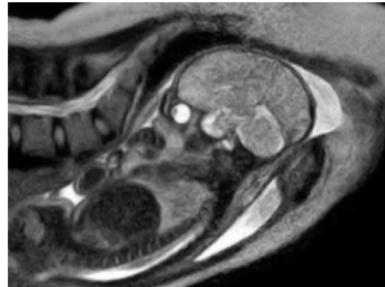
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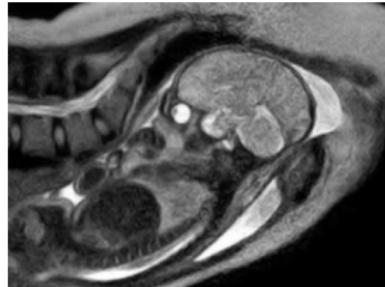
here:

sensing tiny magnetic fields with the nitrogen-vacancy center in diamond

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sensing tiny magnetic fields with the

'NV'

center in diamond

The sensor's quantumness enhances the measurement

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The sensor's quantumness enhances the measurement

- NV center is a very sensitive magnetometer
- clever use of quantum mechanical techniques improves real-life applications

- 1 The NV center is a remarkable, controllable quantum system
- 2 Magnetic sensing with a single NV center
- 3 Other quantum-enhanced applications of NV centers

1 The NV center is a remarkable, controllable quantum system

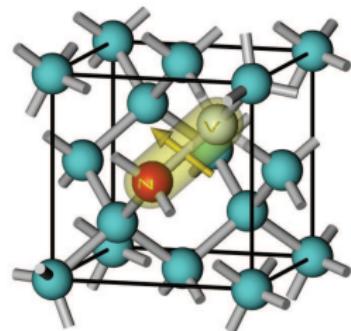
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NV center is one of many defects in diamond

500+ naturally occurring defects in diamond!

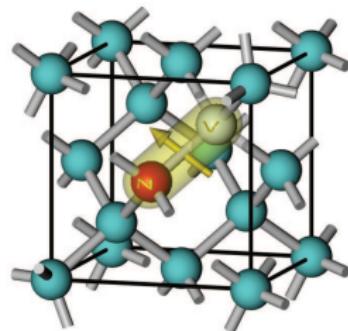
- vacancy next to substitutional nitrogen
- localized
- also created by irradiation + annealing
- absorbs light and fluoresces



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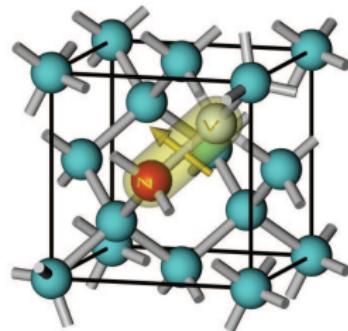
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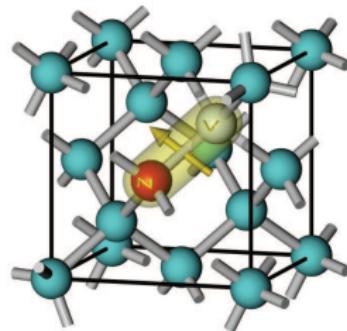
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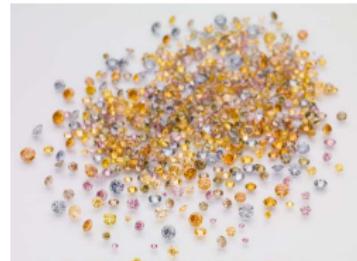
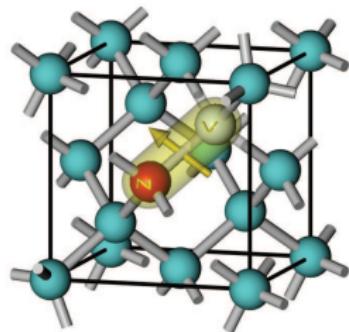
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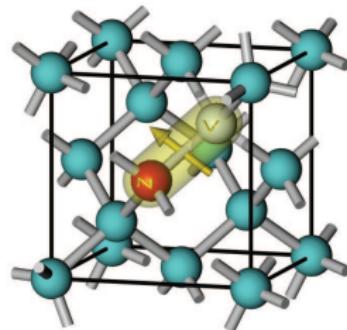
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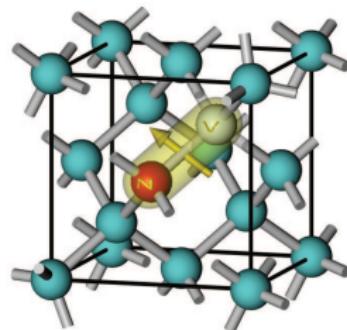
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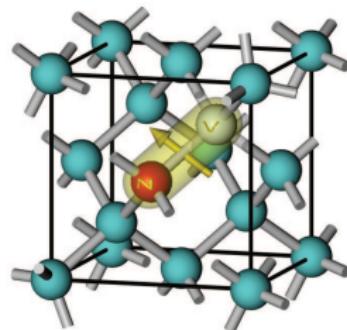
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- absorbs light and fluoresces
⇒ state-dependent fluorescence intensity



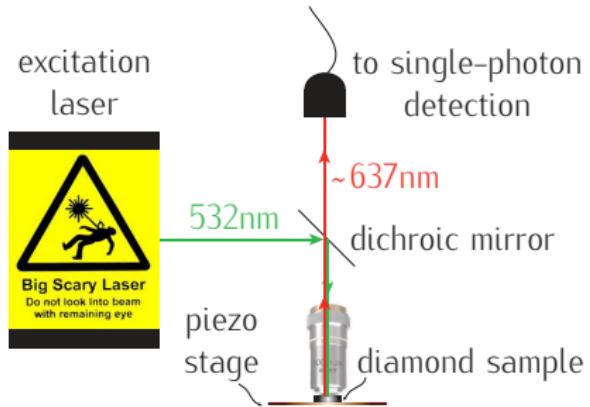
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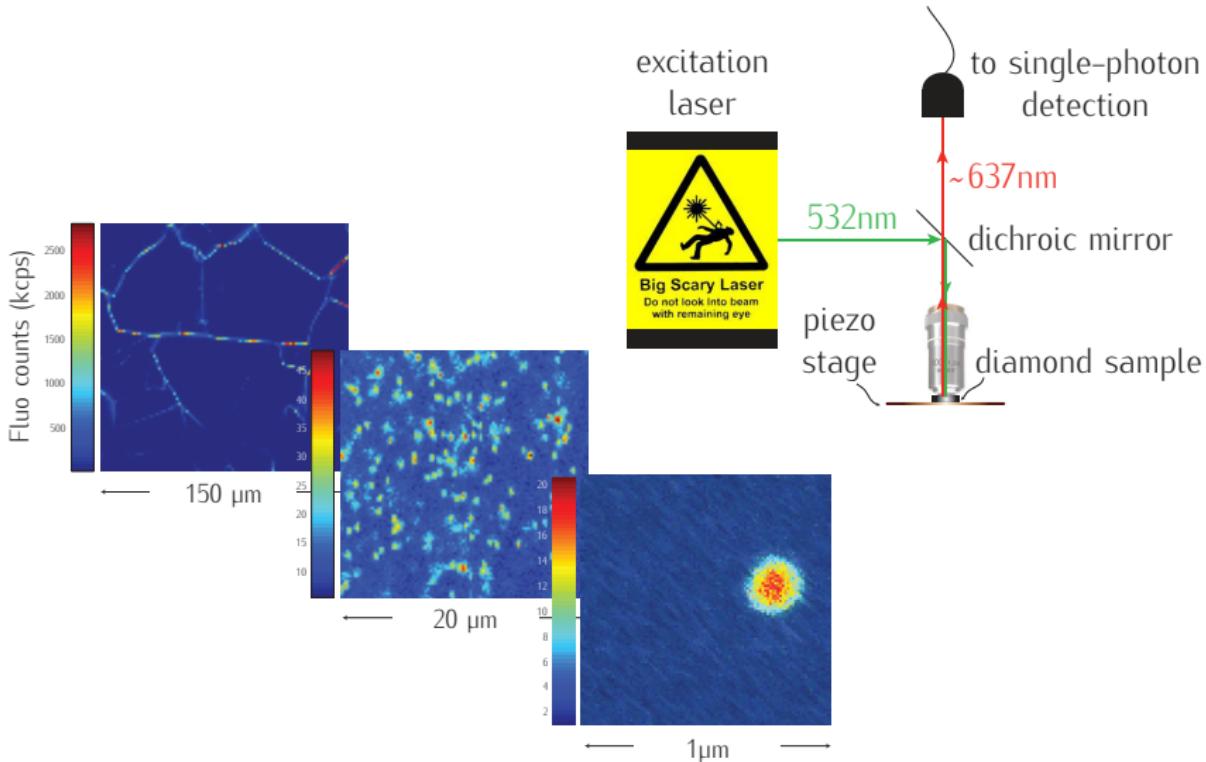
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⇒ energy levels of electronic spin 1
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- also created by irradiation + annealing
⇒ engineer properties
- absorbs light and fluoresces
⇒ state-dependent fluorescence intensity
- very long coherence times *at room temperature*
('retains its quantum character for long')



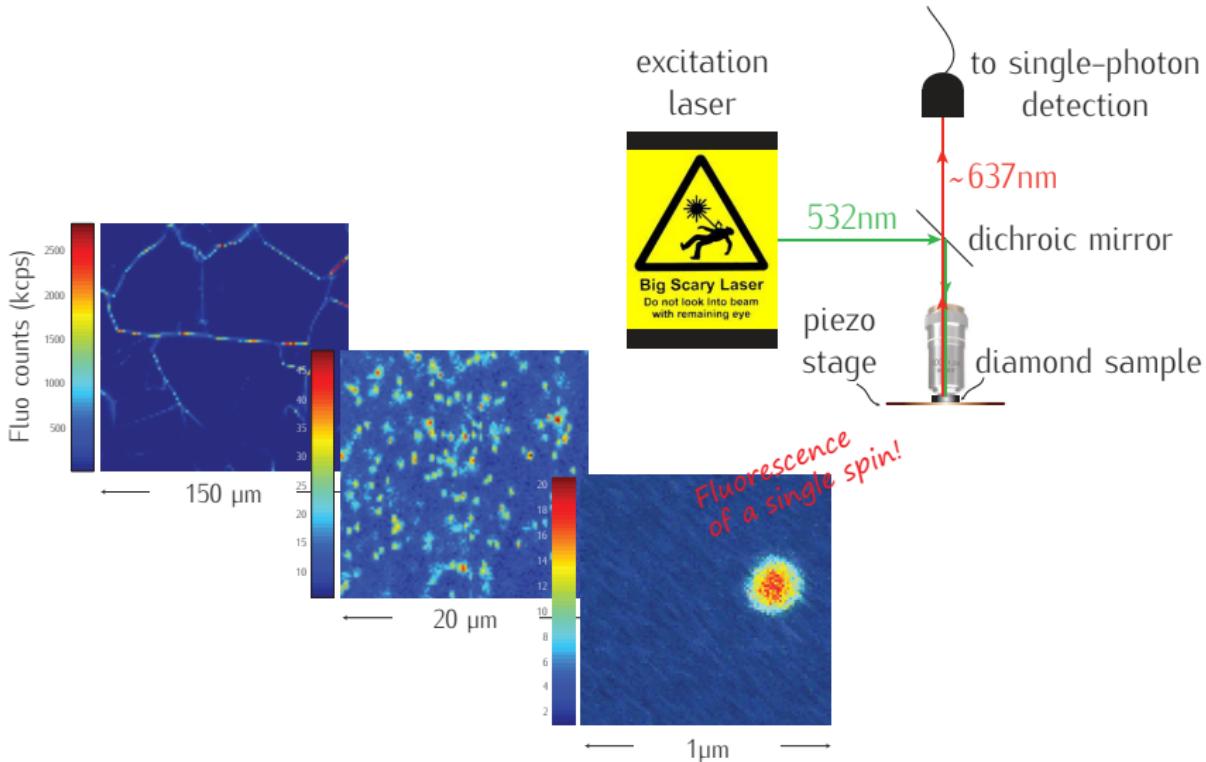
Tracking individual NV centers: confocal imaging



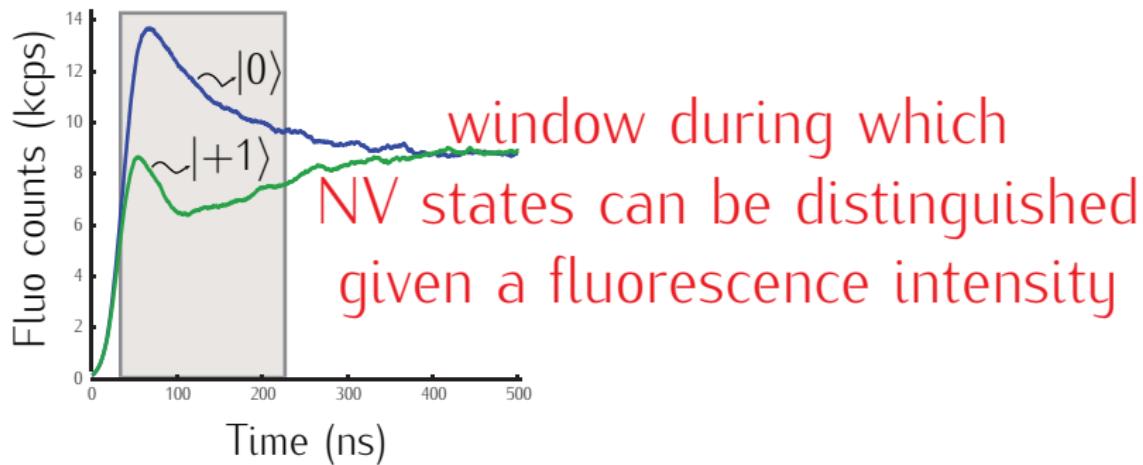
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Single NV quantum state is observed by fluorescence

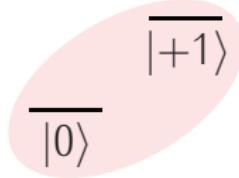


compare:

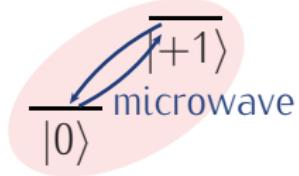
unobservable NMR signal from the tiny magnetic moment of a single spin

- 1 The NV center is a remarkable, controllable quantum system
- 2 Magnetic sensing with a single NV center
- 3 Other quantum-enhanced applications of NV centers

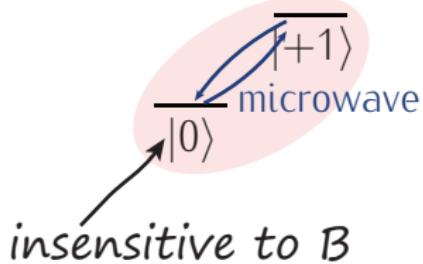
NV magnetometer: principle of operation



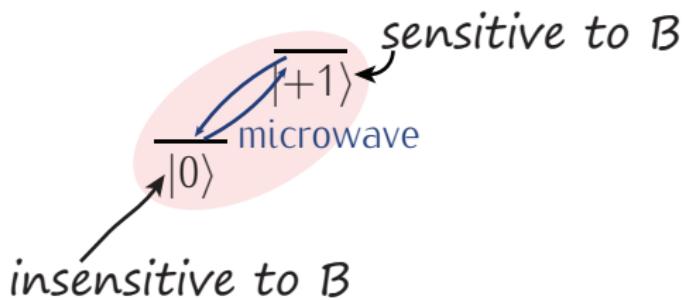
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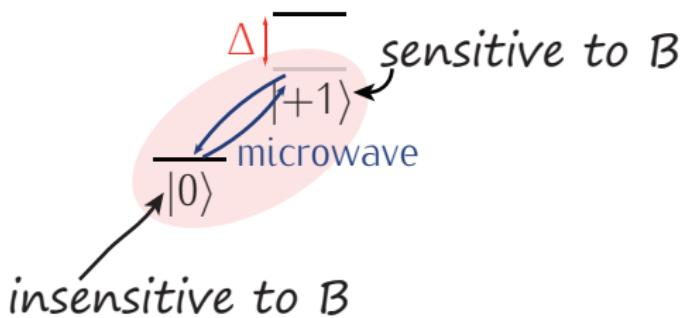


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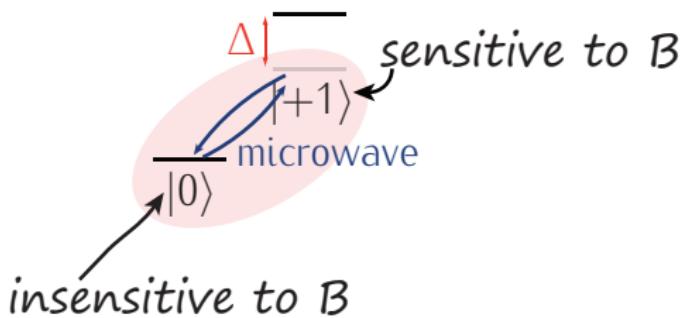
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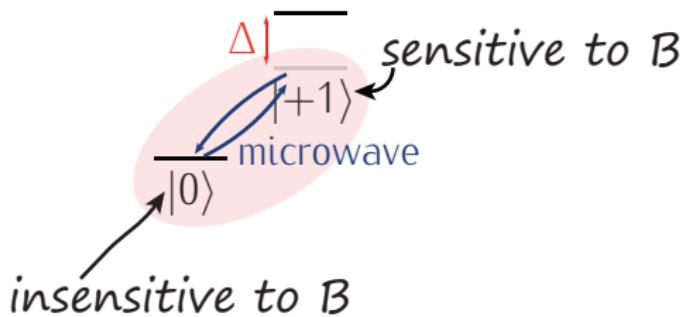
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measure B
↔
measure
detuning from resonance Δ

NV magnetometer: principle of operation

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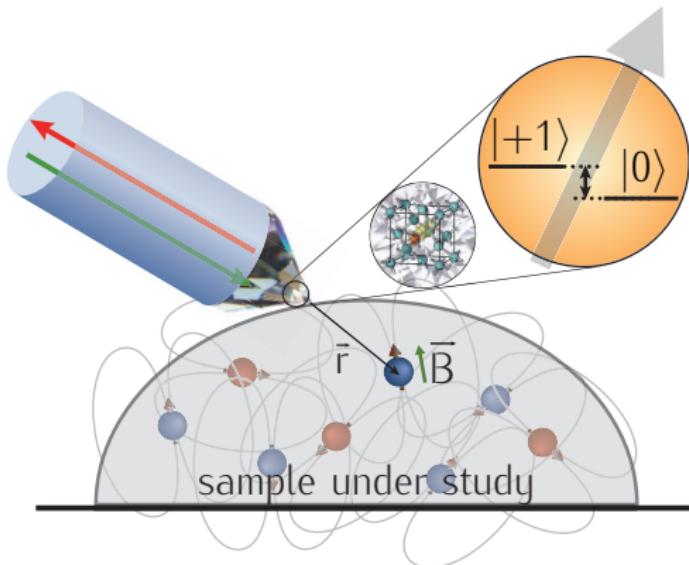
catch: only works while
quantum properties last

The tiny NV magnetometer senses tiny magnetic fields

The tiny NV magnetometer senses tiny detunings

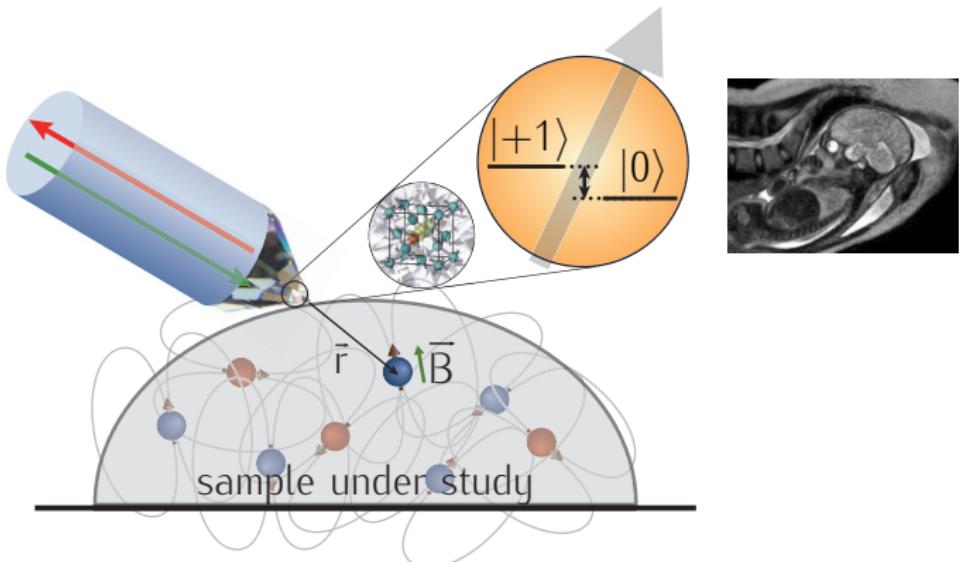
The tiny NV magnetometer senses tiny detunings

- nanoscale probe brought to proximity of sample
- senses detunings caused by few or individual spins



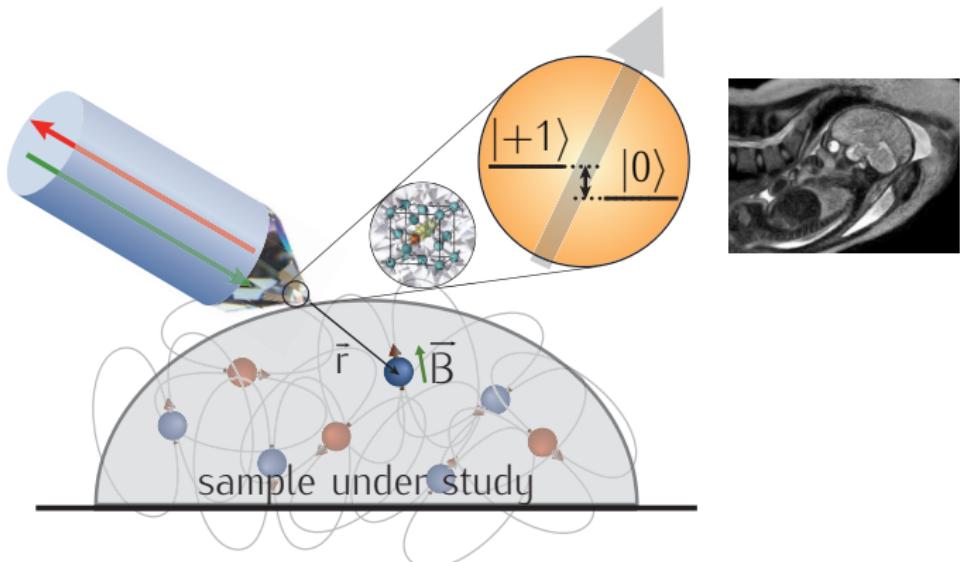
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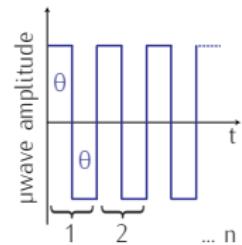


... but what's the best way to measure those detunings?

One answer: applying special microwave pulses

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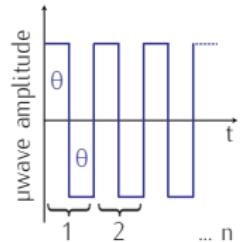
sequence of rotary-echoes



One answer: applying special microwave pulses

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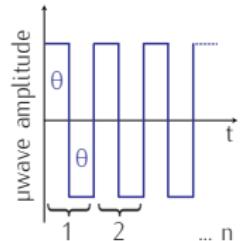
- originally used as 'correction sequence' in NMR
- known not to correct for detunings from resonance ✓
- length of pulse $\sim \theta$



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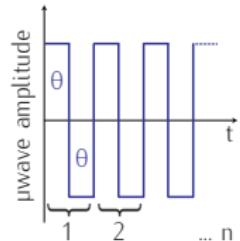


- 1 apply resonant microwaves using sequence of rotary-echoes
- 2 acquire fluorescence signal
- 3 Fourier transform it
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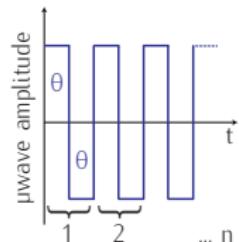


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- 5 longer signal acquisition, more precise reading of detunings

One experimental measurement of detunings

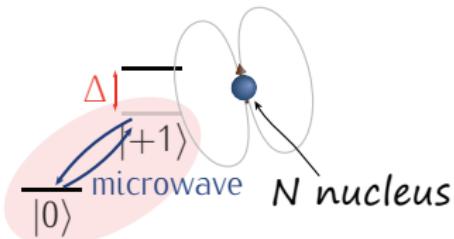
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the NV has a built-in testbed magnetic field source

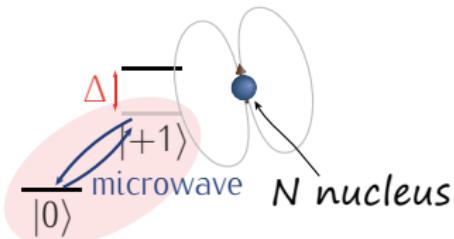
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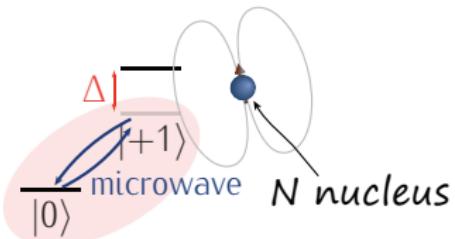
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measure the magnetic field of a single nuclear spin

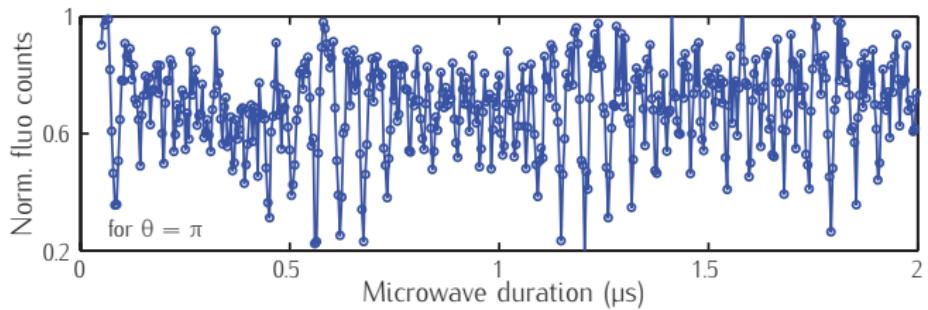
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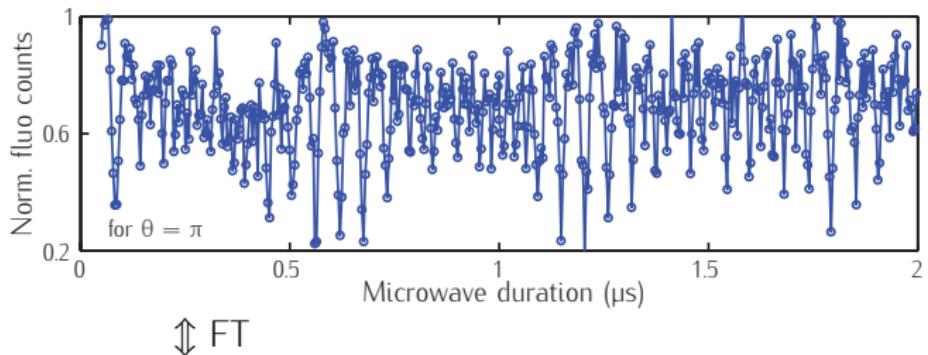


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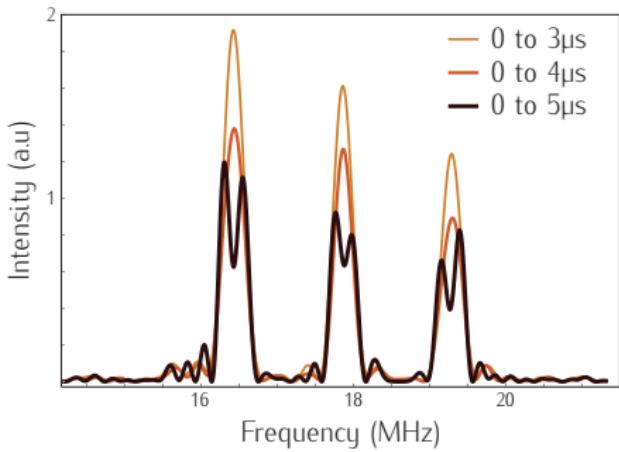
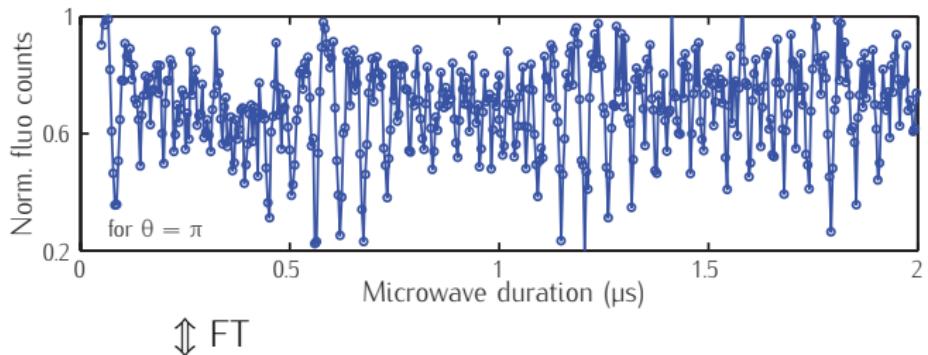
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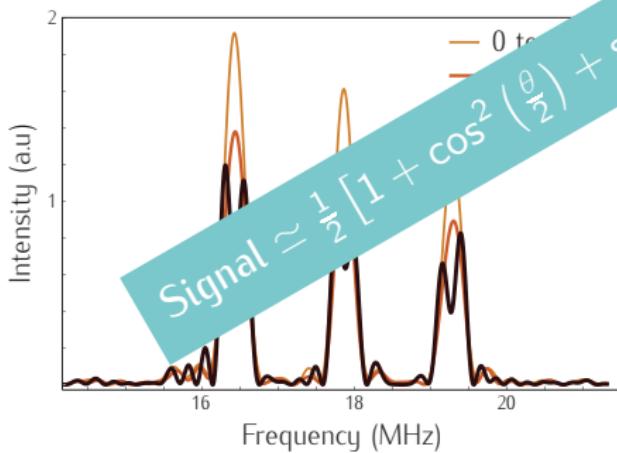
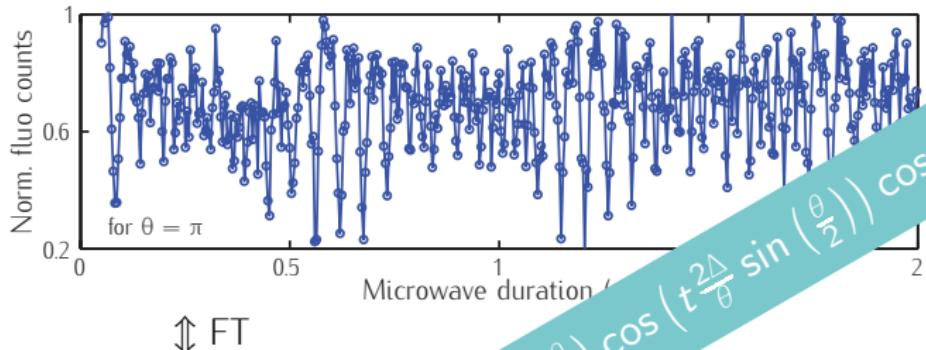
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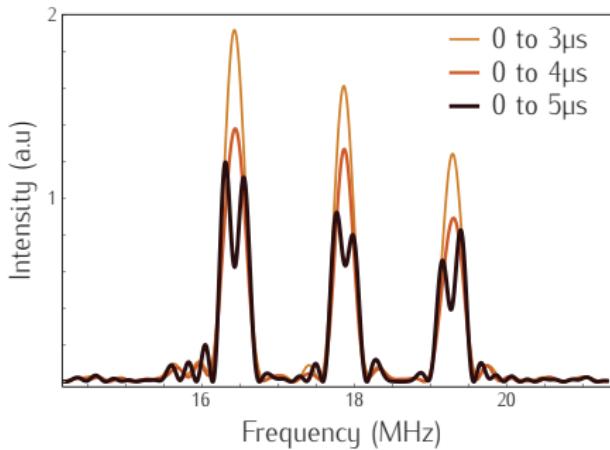
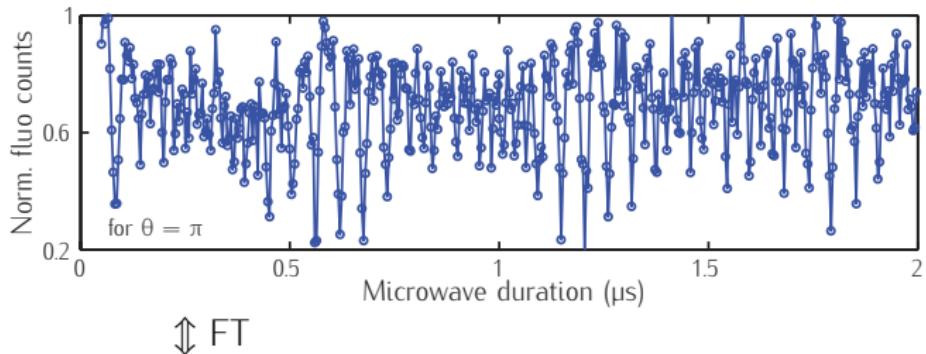
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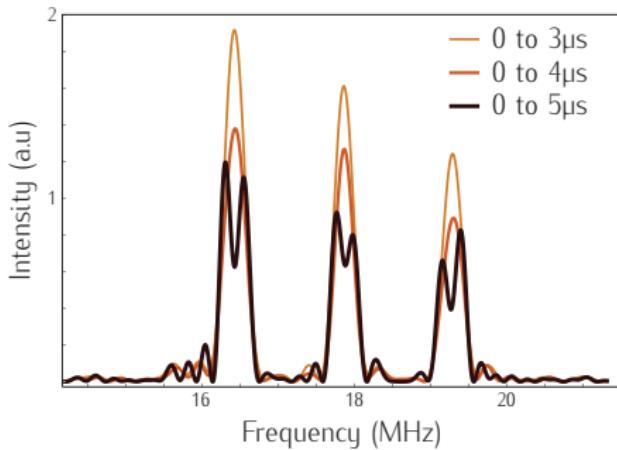
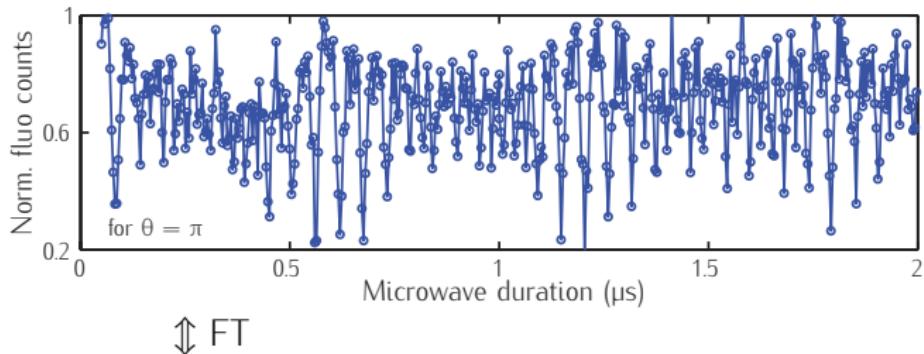


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$$\Delta_1 \simeq 2.1\text{MHz}, \Delta_2 \simeq 0.5\text{MHz}$$

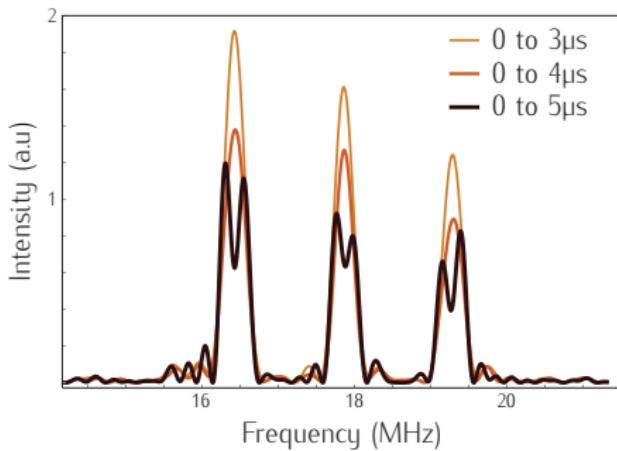
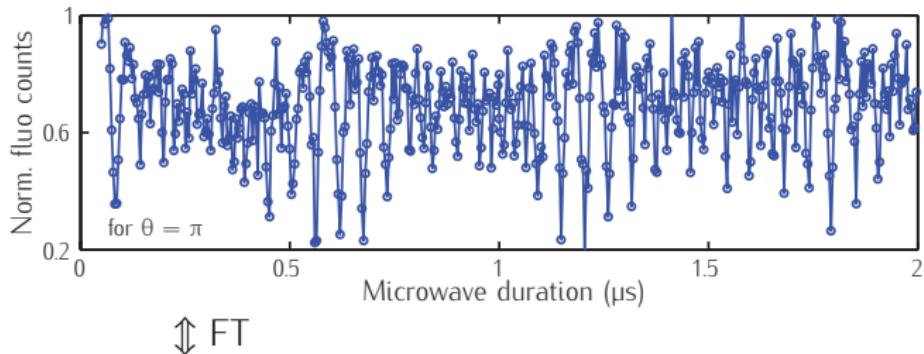
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compare: Earth B $\simeq 0.5\text{G}$

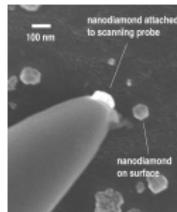
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Practical applications of NV centers include...

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- scanning magnetic tip

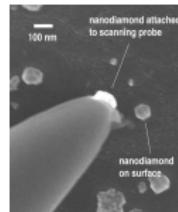
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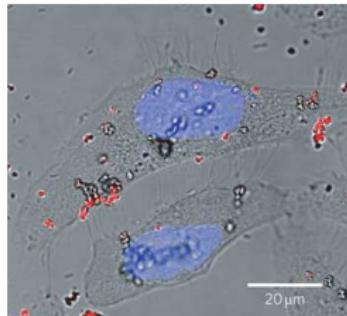
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- bio-sensors

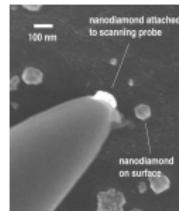
L. P. McGuinness *et al.*, Nature Nanotechnology **6**, 358 (2011)



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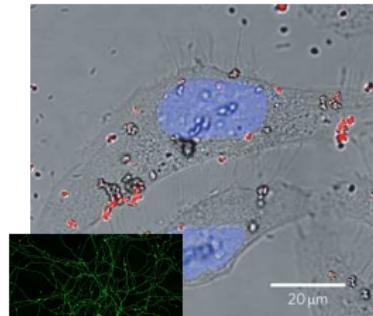
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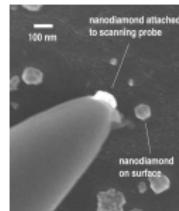
- mapping of magnetic surfaces



Practical applications of NV centers include...

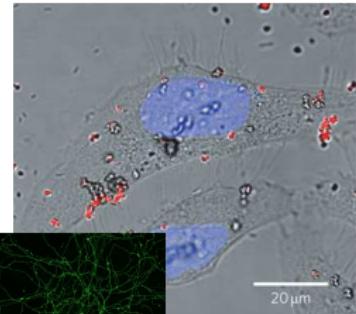
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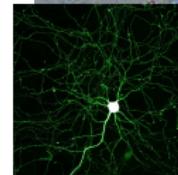


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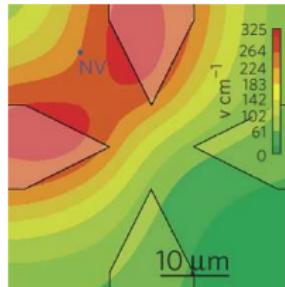


- mapping of magnetic surfaces



- measurement of electric fields

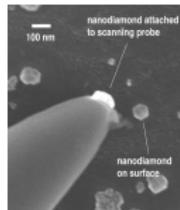
F. Dolde *et al.*, Nature Physics **7**, 457 (2011)



Practical applications of NV centers include...

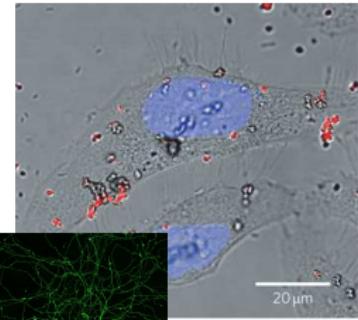
- scanning magnetic tip

C. L. Degen, Appl. Phys. Lett. **92**, 243111 (2008)



- bio-sensors

L. P. McGuinness *et al.*, Nature Nanotechnology **6**, 358 (2011)

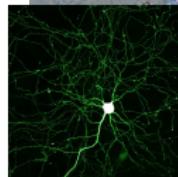


- mapping of magnetic surfaces



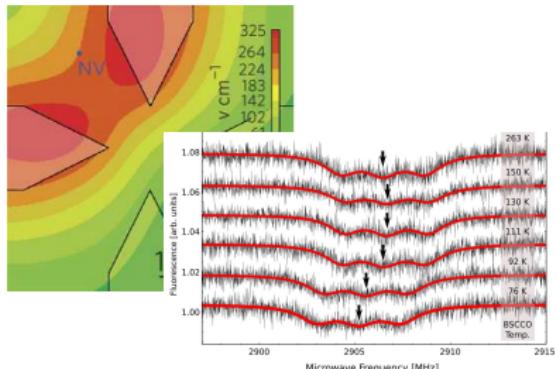
- measurement of electric fields

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- measurement of temperature/phase transitions

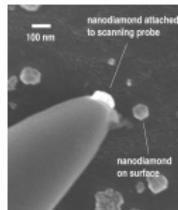
L.-S. Bouchard *et al.*, New Journal of Physics **13**, 025017 (2011)



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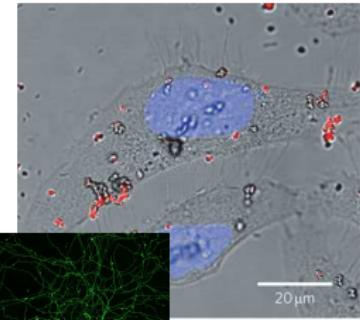
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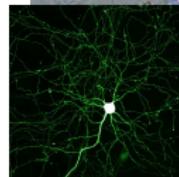


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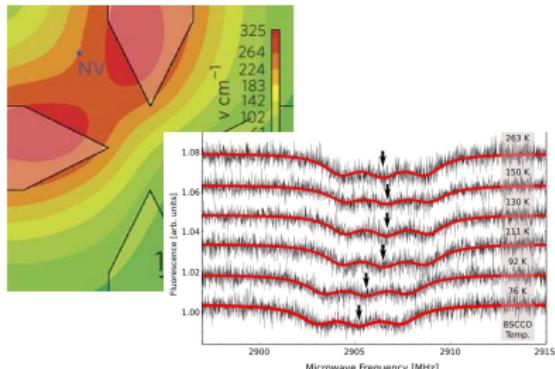
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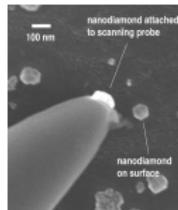
- time keeping

J. S. Hedges *et al.*, arXiv:1109.3241v1 [physics.atom-ph]

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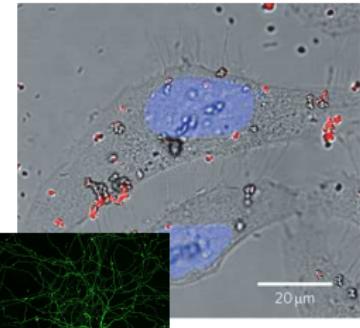
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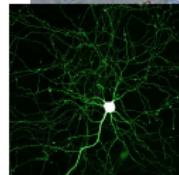


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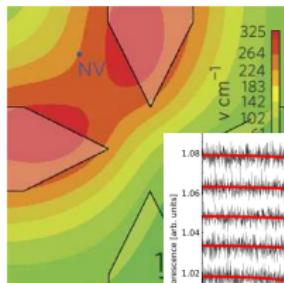


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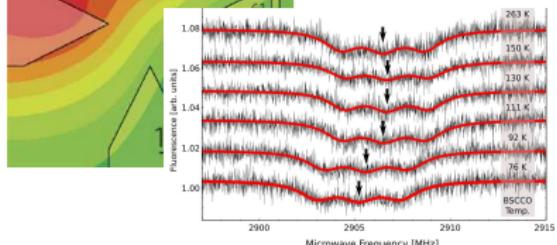
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- fundamental unit of a quantum computer

1 The NV center is a remarkable, controllable quantum system

quantum states detected and controlled with photons

2 Magnetic sensing with a single NV center

sensing the magnetic field of a single nuclear spin

3 Other quantum-enhanced applications of NV centers

quantum is the new classical

The sensor's quantumness enhances the measurement

- NV center is a very sensitive magnetometer
- clever use of quantum mechanical techniques improves real-life applications

Quantum Engineering Group @ MIT



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