Coupling a mechanical resonator to a spin qubit in diamond

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Quantum Coherent Properties of Spins III
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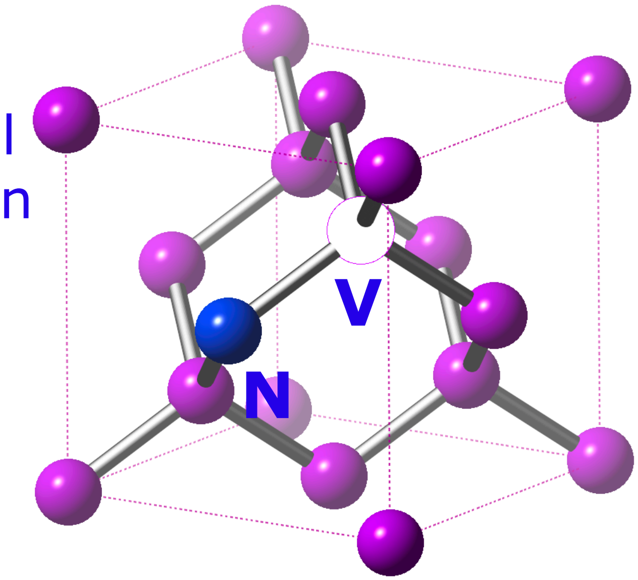
The Nitrogen-Vacancy Center in Diamond

What are they?

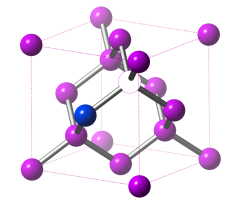
- A lattice defect consisting of a substitutional nitrogen atom adjacent to a missing carbon
- has an associated electron spin
- has an associated optical transition
- Occur naturally or with ion implantation

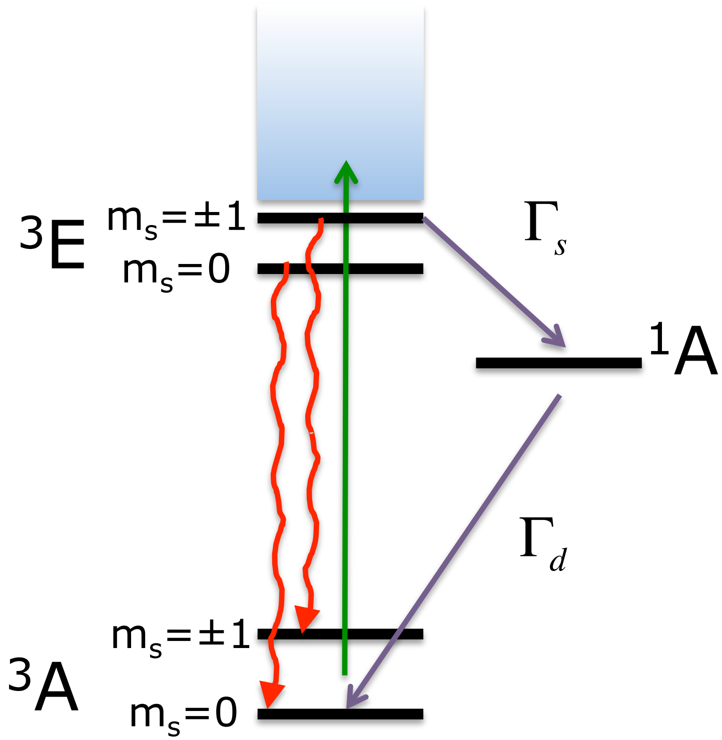


Why are they interesting?

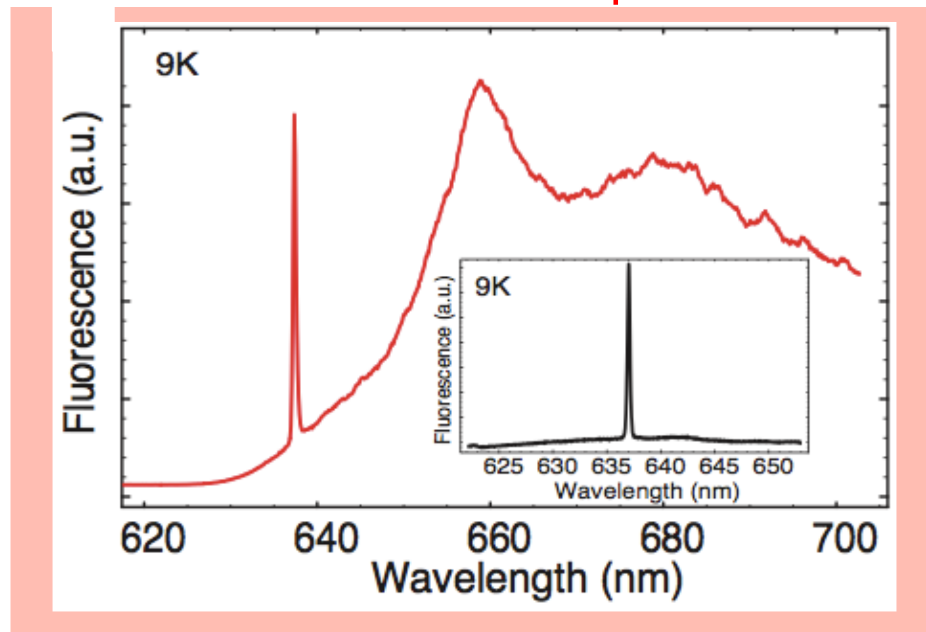
- Good for quantum devices
  - Long (~ 20 ms) spin coherence times at ROOM TEMPERATURE
  - Solid-state system: stationary, scalable, individual addressability
  - Spin state can be initialized (visible light), coherently controlled (microwaves) and readout (visible light)
- Applications: magnetometers, qubits, single photon sources, biomarkers

NV-Centers in Diamond





NV fluorescence spectrum



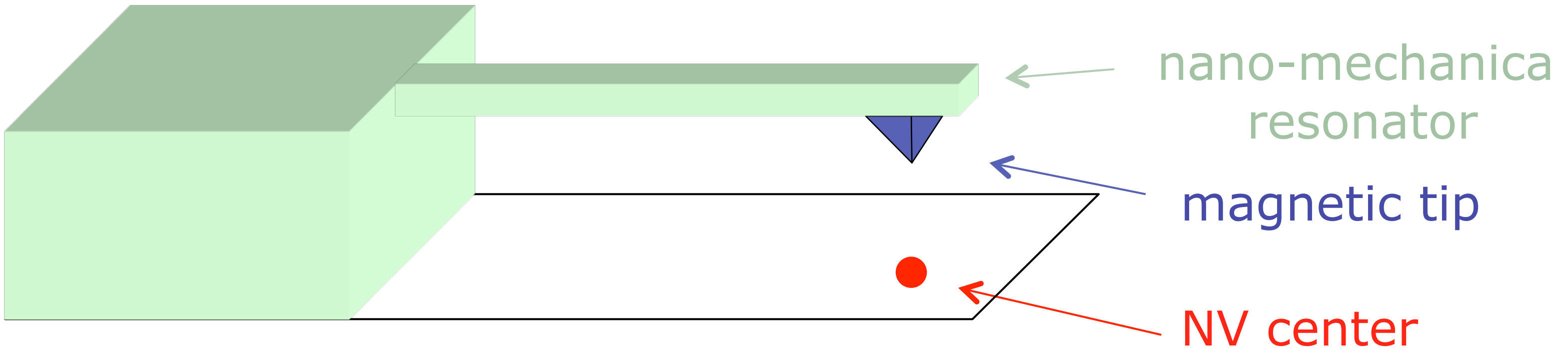
- Ground state split by crystal field
- Optical readout of spin state is possible

  $m_s=0$ state is brighter than the $m_s=1$ state

- Ground state is further split by a magnetic field - magnetometer

Coupling an NV to a Resonator

Goal: entangle spin state of NV with motional state of resonator



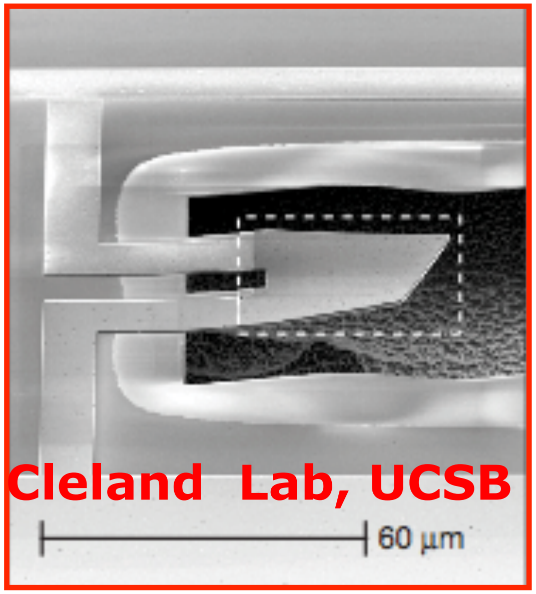
A nano-resonator positioned near an NV center.

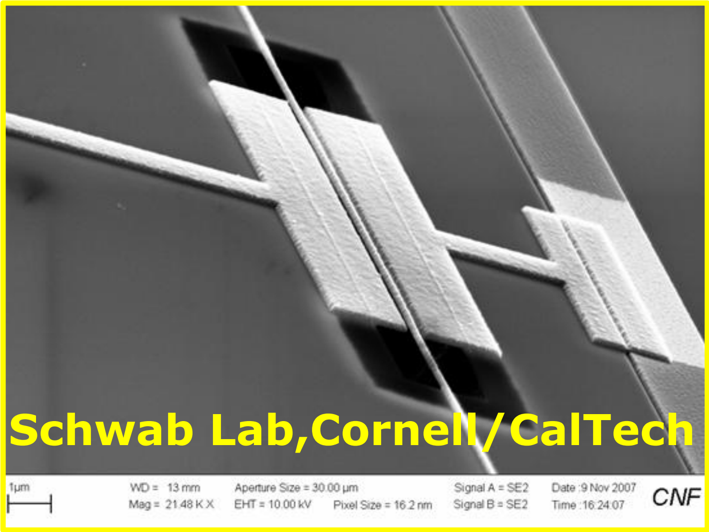
Applications:

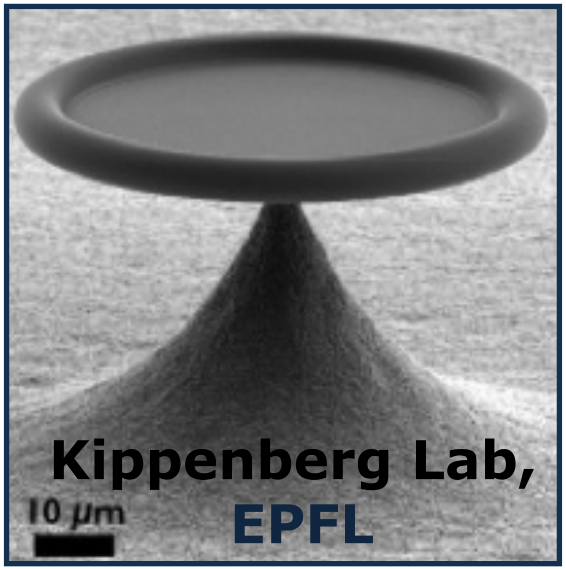
- Ground state cooling of the mechanical resonator[1]
- Quantum Spin Transducer[2]
  - a means towards coupling distant qubits

[1] Rabl *et al*, PRB **79**, 041302 (2009)
[2] Rabl *et al*, Nature Physics **6**, 602 (2010).

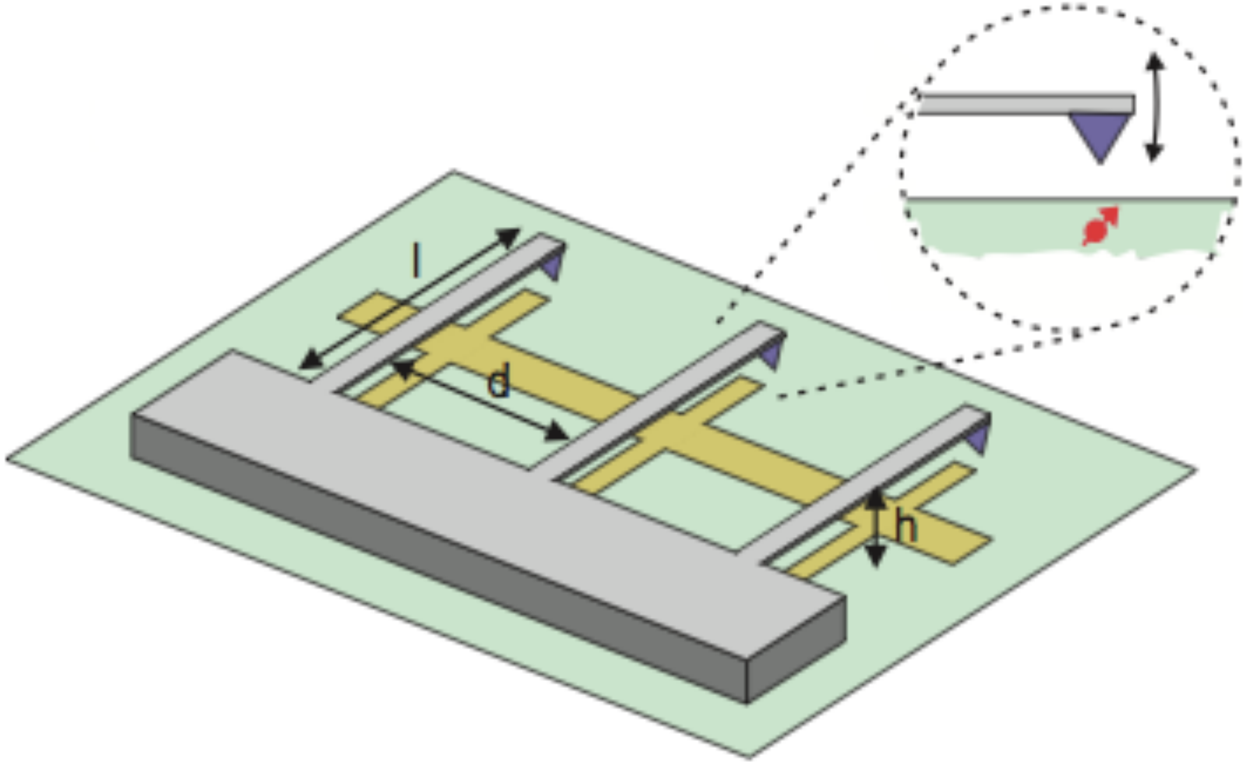
Routes to Ground State Cooling







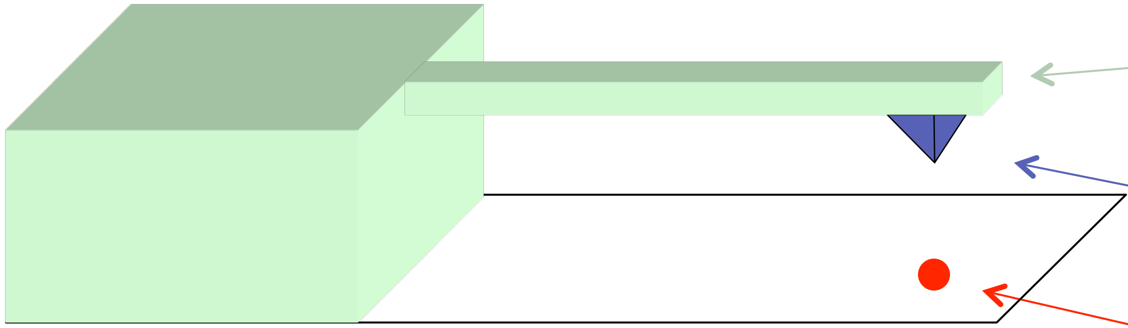
Coupling an NV to a Resonator



An array of resonators could enable long distance communication between distant qubits (NV's)

Rabl *et al*, Nature Physics **6**, 602 (2010).

Coupling an NV to a Resonator



A nano-resonator positioned near an NV center.

$$H_S = H_{NV} + \hbar\omega_r a^\dagger a + \hbar\lambda(a + a^\dagger)S_z \, .$$

Magnetic Spin-Resonator Coupling

Coupling strength: $\lambda = g_s \mu_B \nabla B a_0 / \hbar$

a_0: zero-point motion

∇B: magnetic field gradient

$$\lambda >> 1/T_2, \; \Gamma_m = K_B T / \hbar Q$$

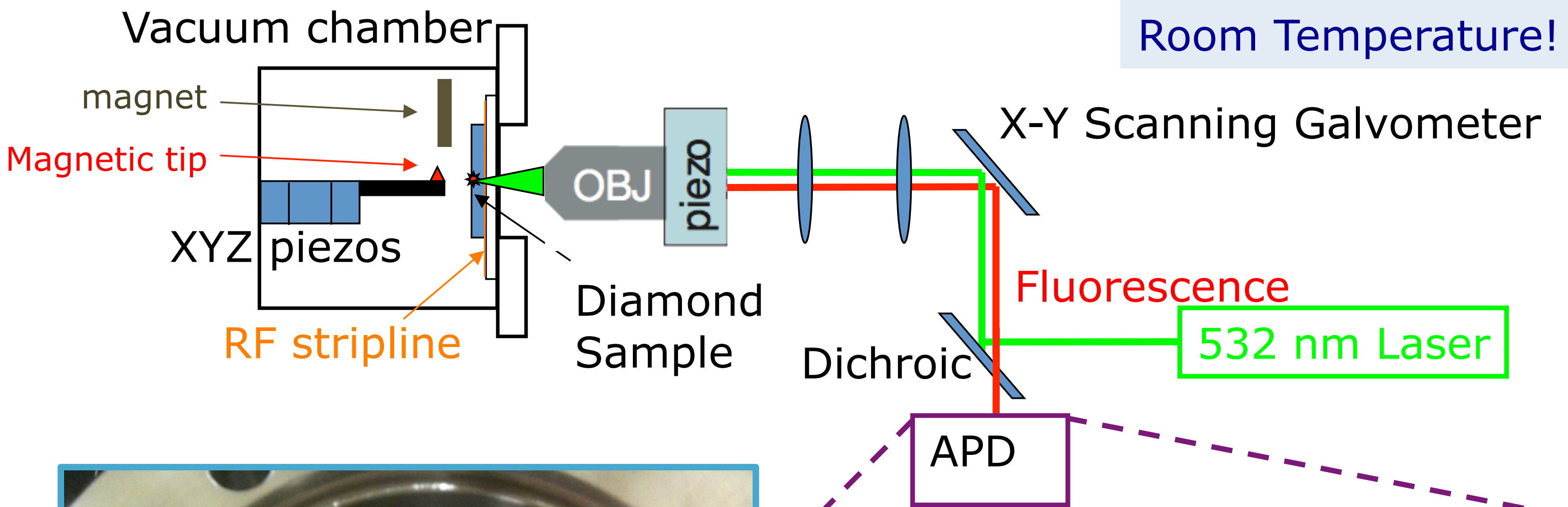
strong coupling between a single spin and a mechanical resonator!

Spin dephasing

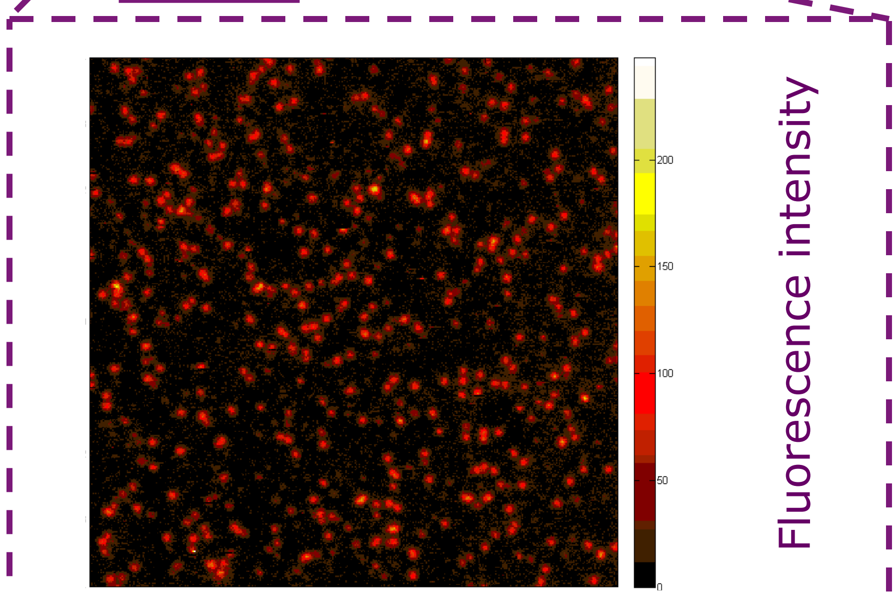
Mechanical dissipation

Experimental Setup – Confocal Microscope

Room Temperature!

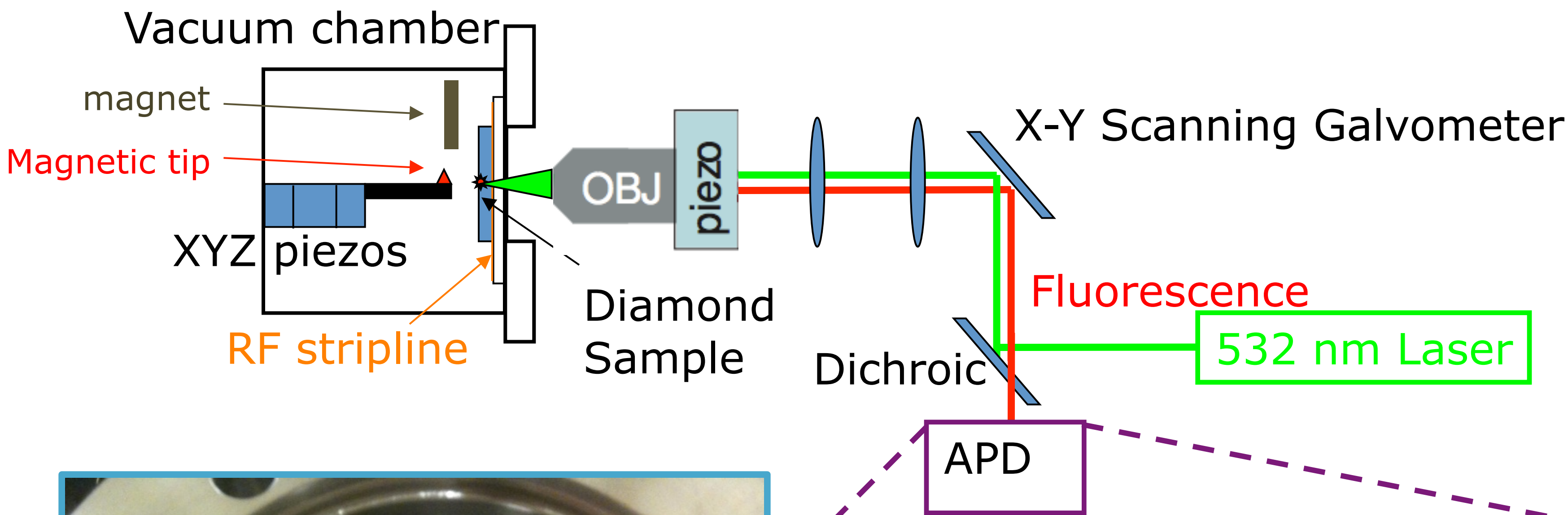


Diamond, piezo stack and resonator seen through chamber window.



Confocal Image of NVs

Experimental Setup – Confocal Microscope



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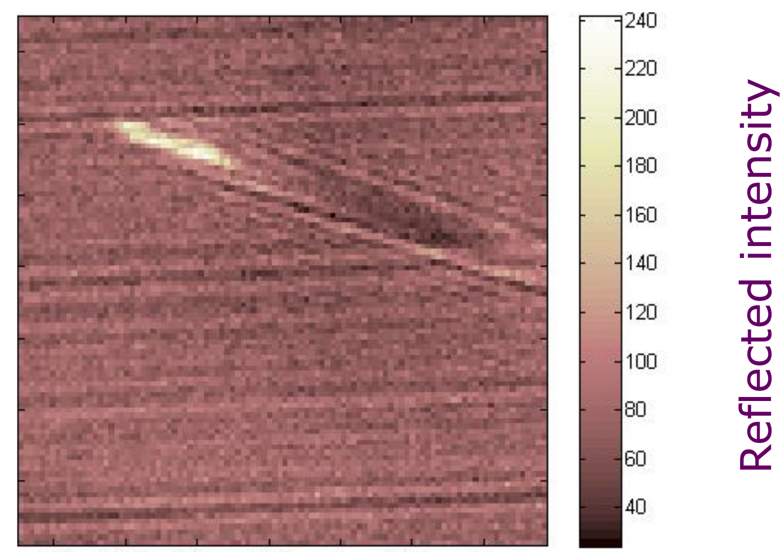
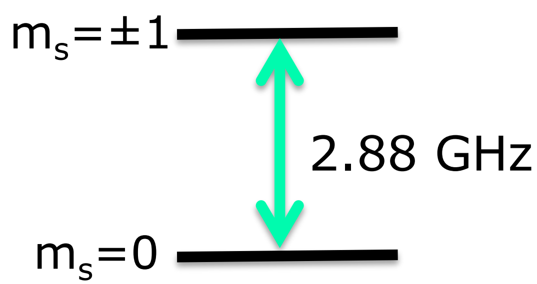


Light Reflected off the Tip

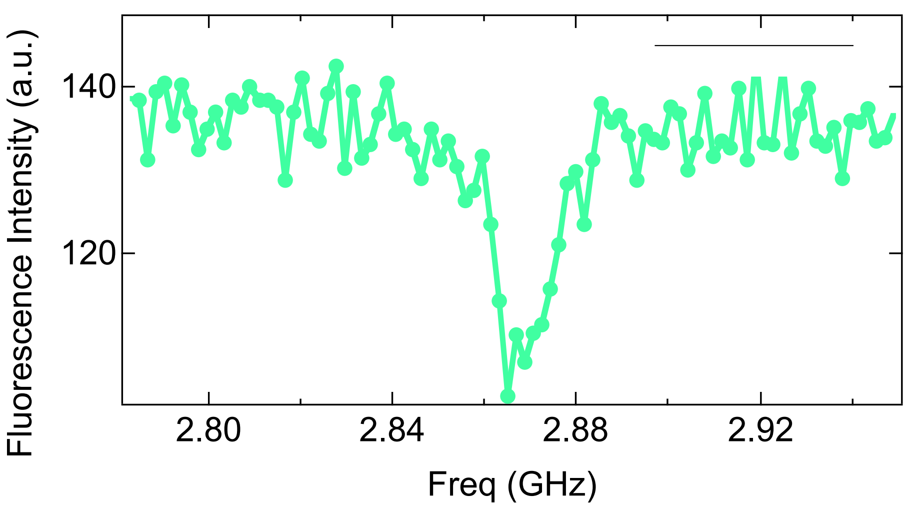
Sensing a Magnetic Field with an NV

No Magnetic Field



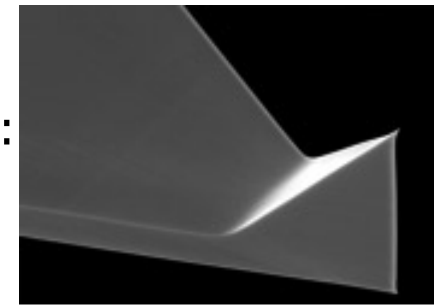
0 state is brighter than the 1 state

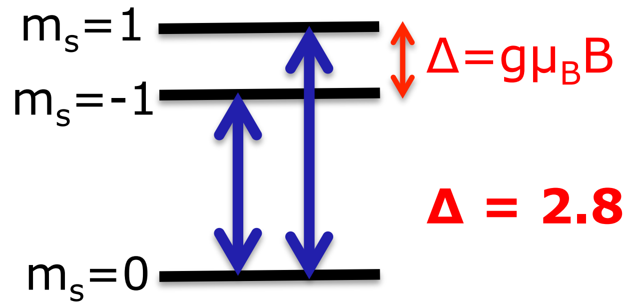
Optically Detected Magnetic Resonance



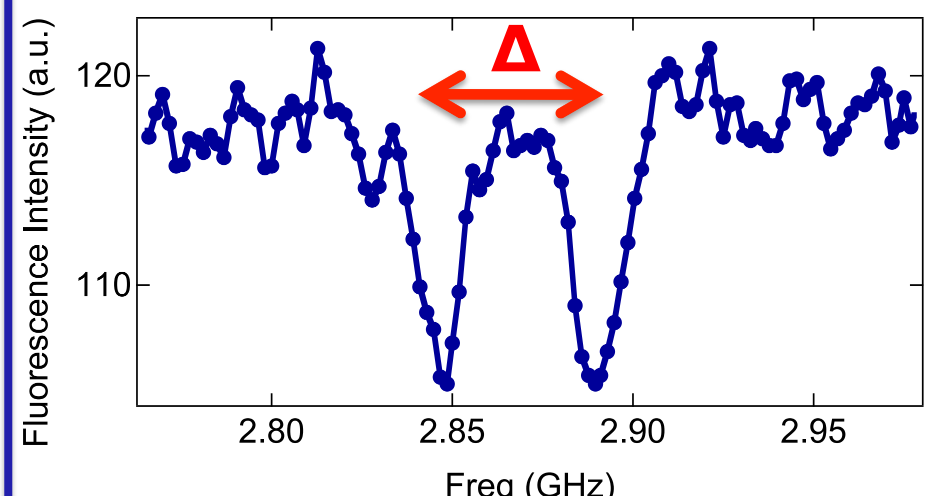
Magnetic Tip Nearby

Commercial MFM tip:

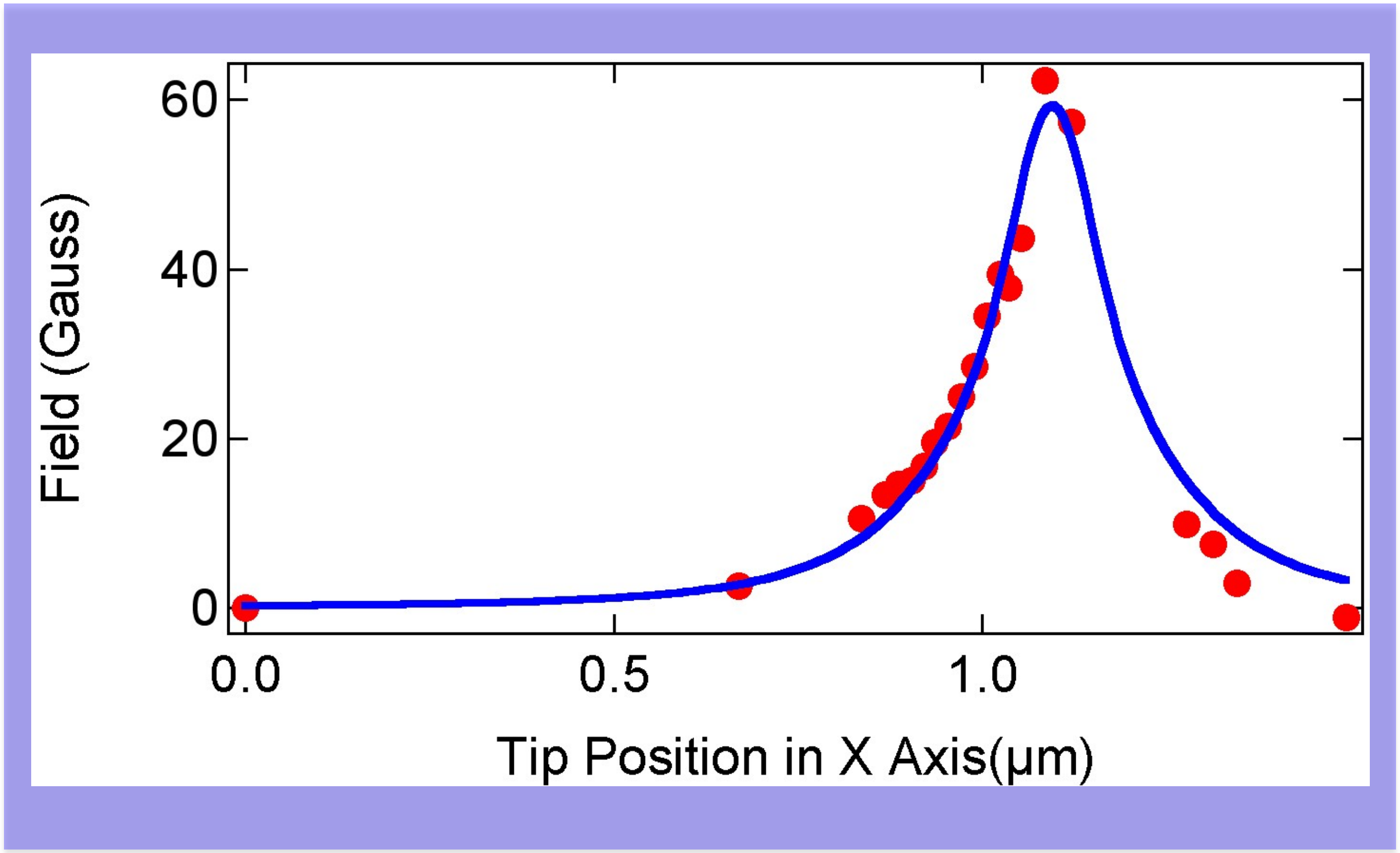


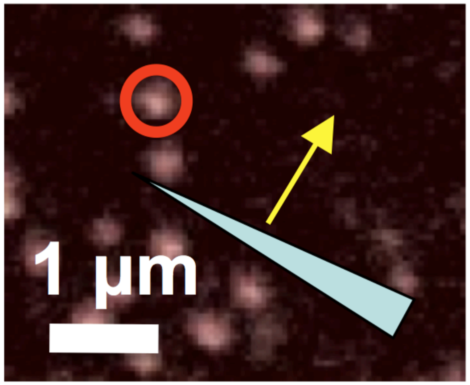


Δ = 2.8 MHz/G



Mapping Magnetic Field of Tip



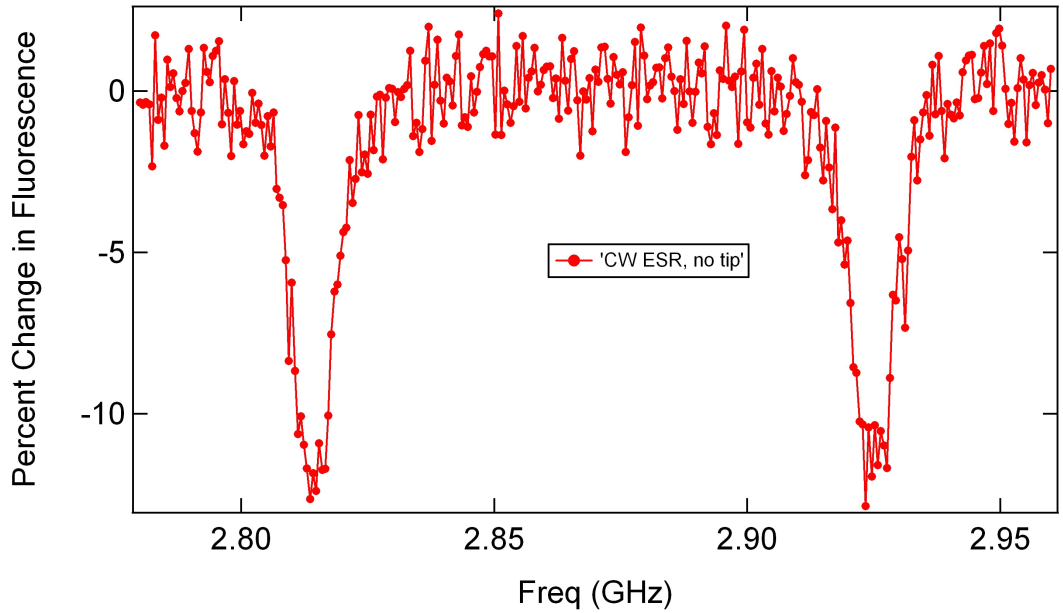


Tip scanned along yellow line

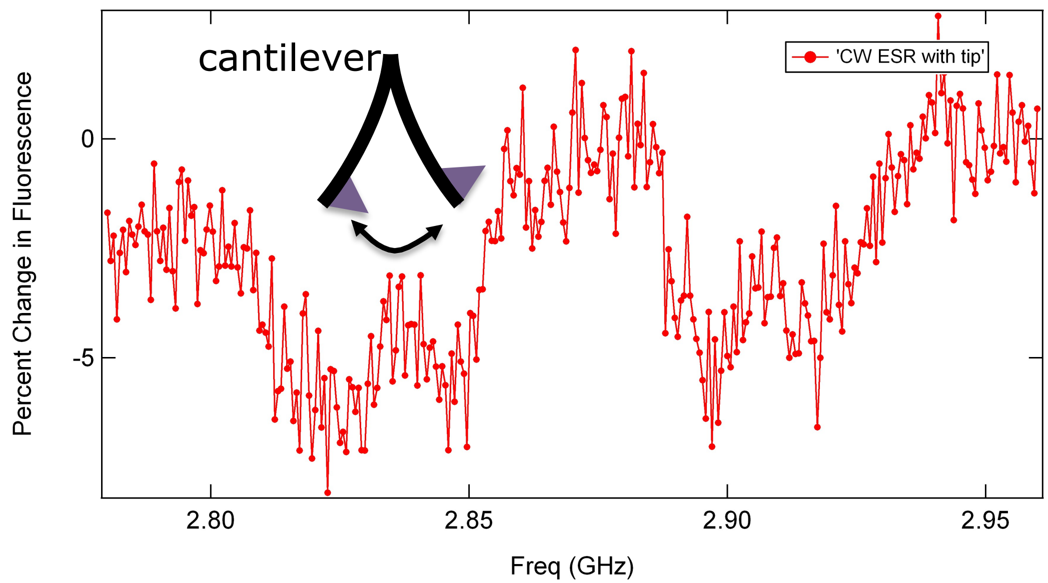
- NV can spatially map out field profile of the magnetic tip
- Fit is to an ideal dipole

Effect of tip motion on ESR Spectrum:

- **No tip**



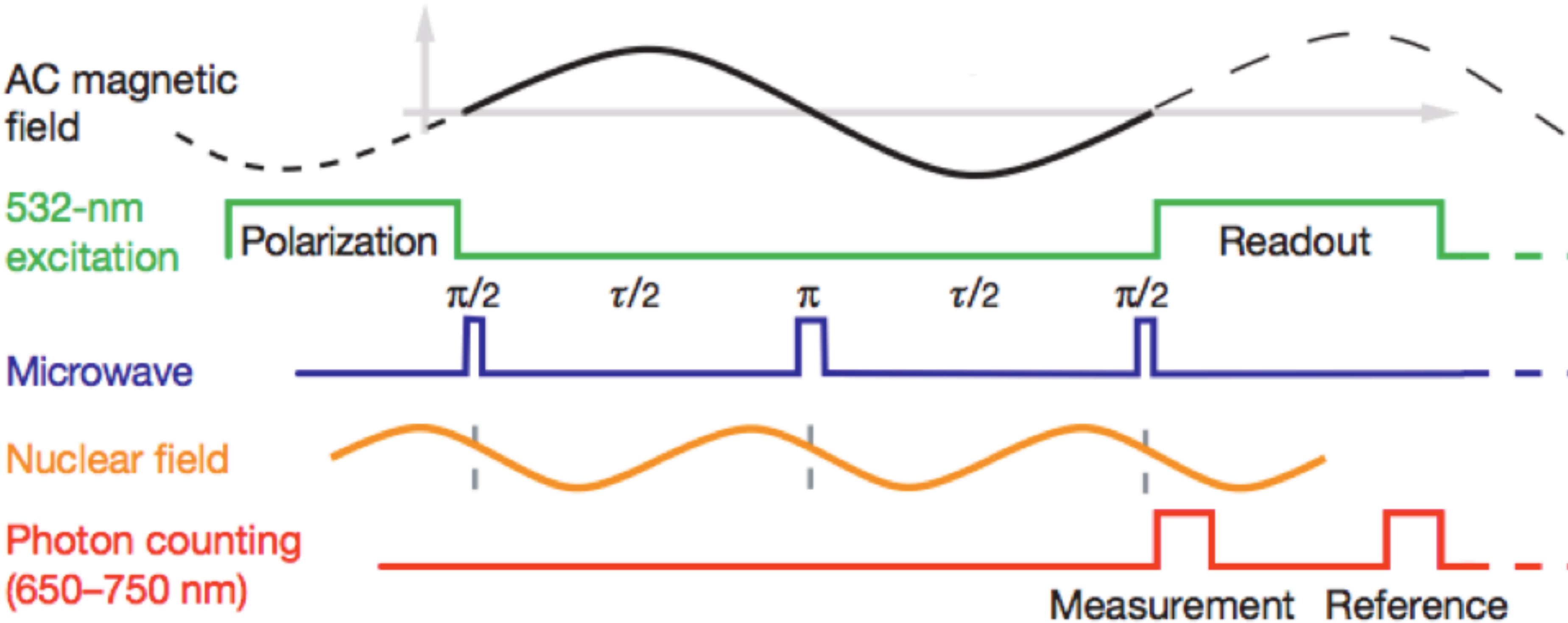
- **Tip Nearby**



AC magnetic field from tip broadens the ESR dip – but not decoherence!

AC Magnetometry With Spin Echo Techniques

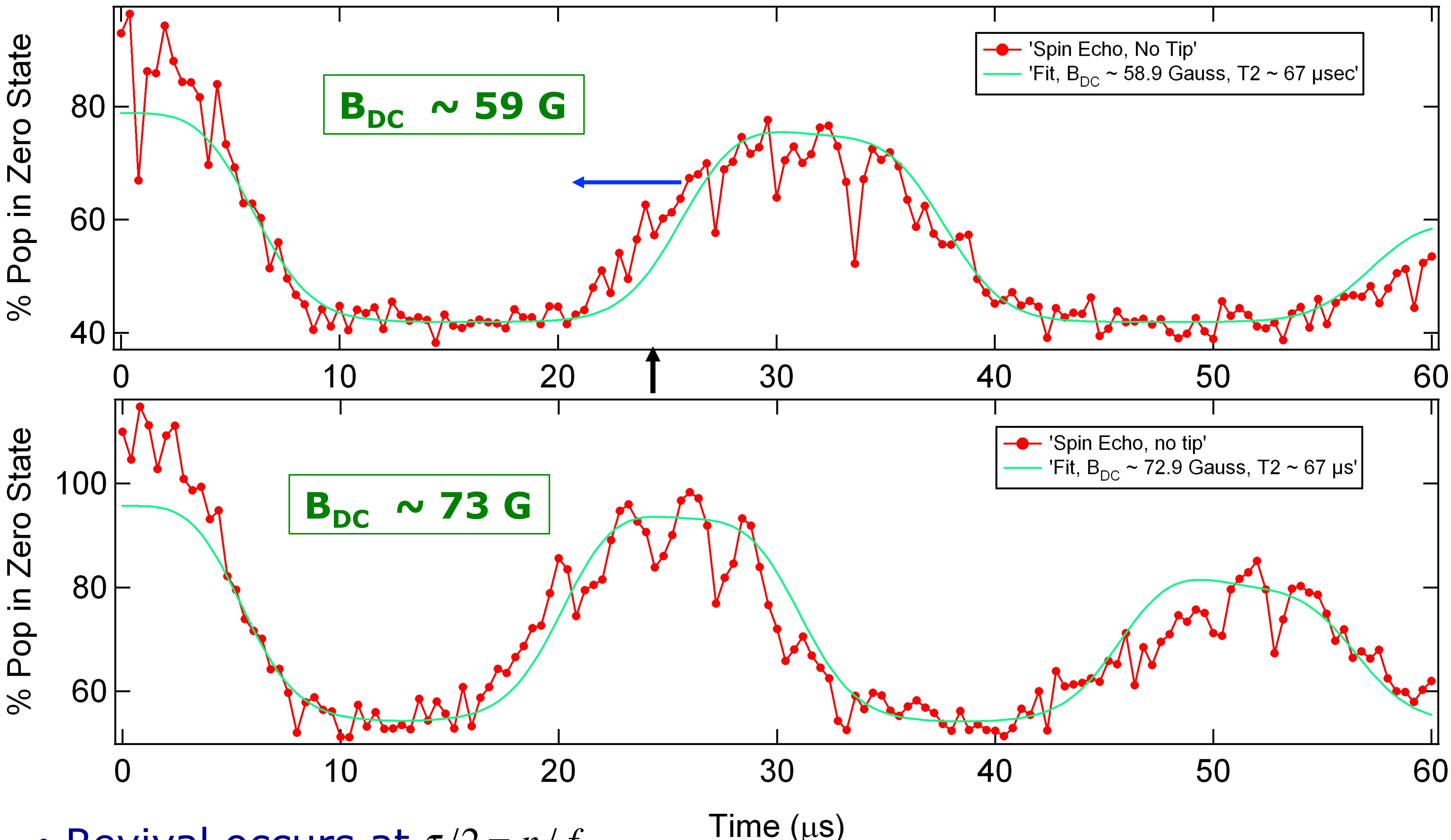
$$B(t) = B_{AC}\cos(\omega_r t + \phi_o)$$



- Starting phase, φ_0, varies randomly between measurements

  Hence, we are sensitive to the **variance** of AC field

NV Center in a ^{13}C Spin Bath

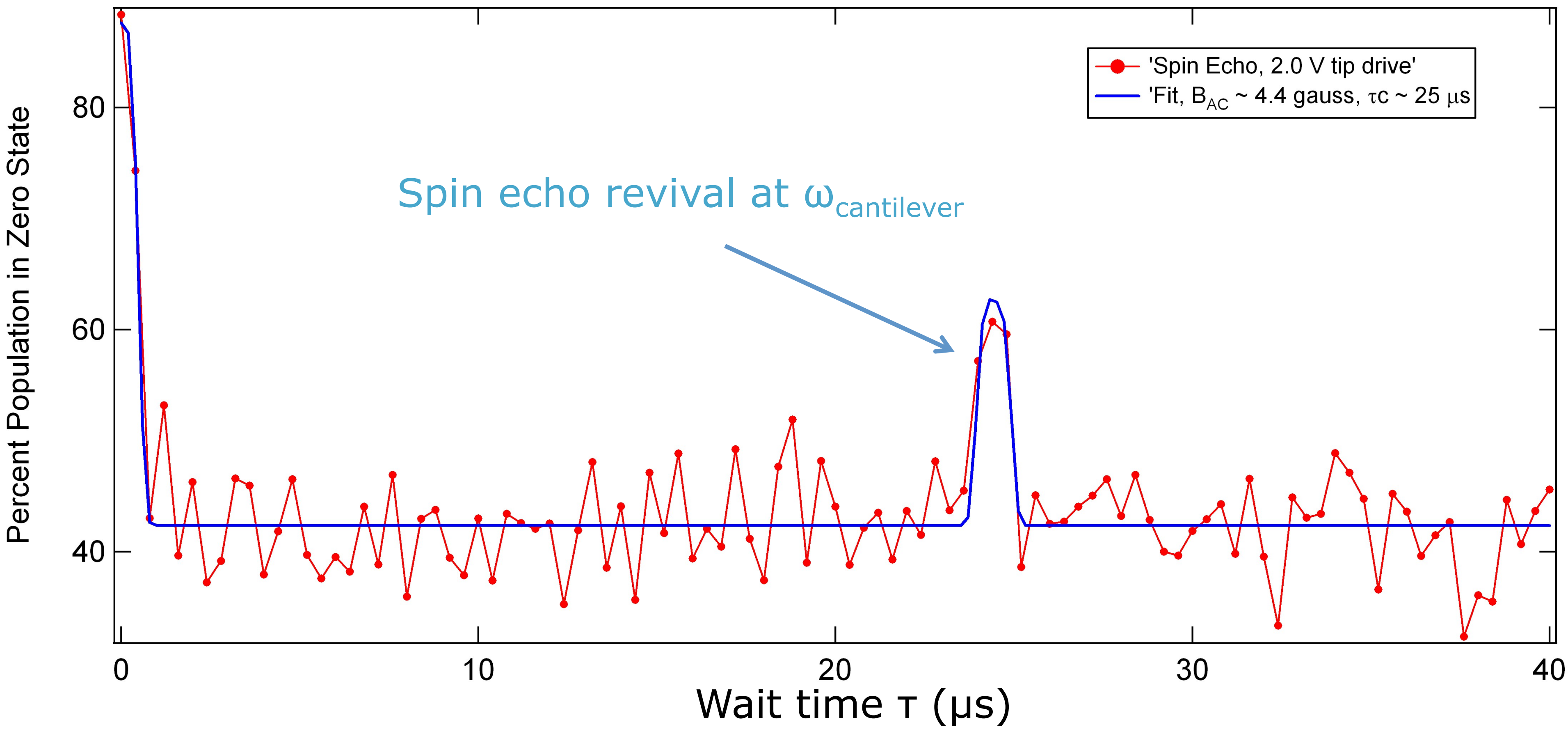


- Revival occurs at $\tau/2 = n/f_{Larmor}$

  $f_{Larmor} = 1\ kHz/G$

- Functional form of fit: $P_{|0\rangle} = \frac{1}{2}\left(1 + e^{-2\left(\frac{g\mu_B B}{\omega\hbar}\right)^2 Sin^4\left(\frac{\omega\tau}{4}\right)} e^{-(\tau/T_2)^2}\right)$

Measurement of tip motion using revivals:

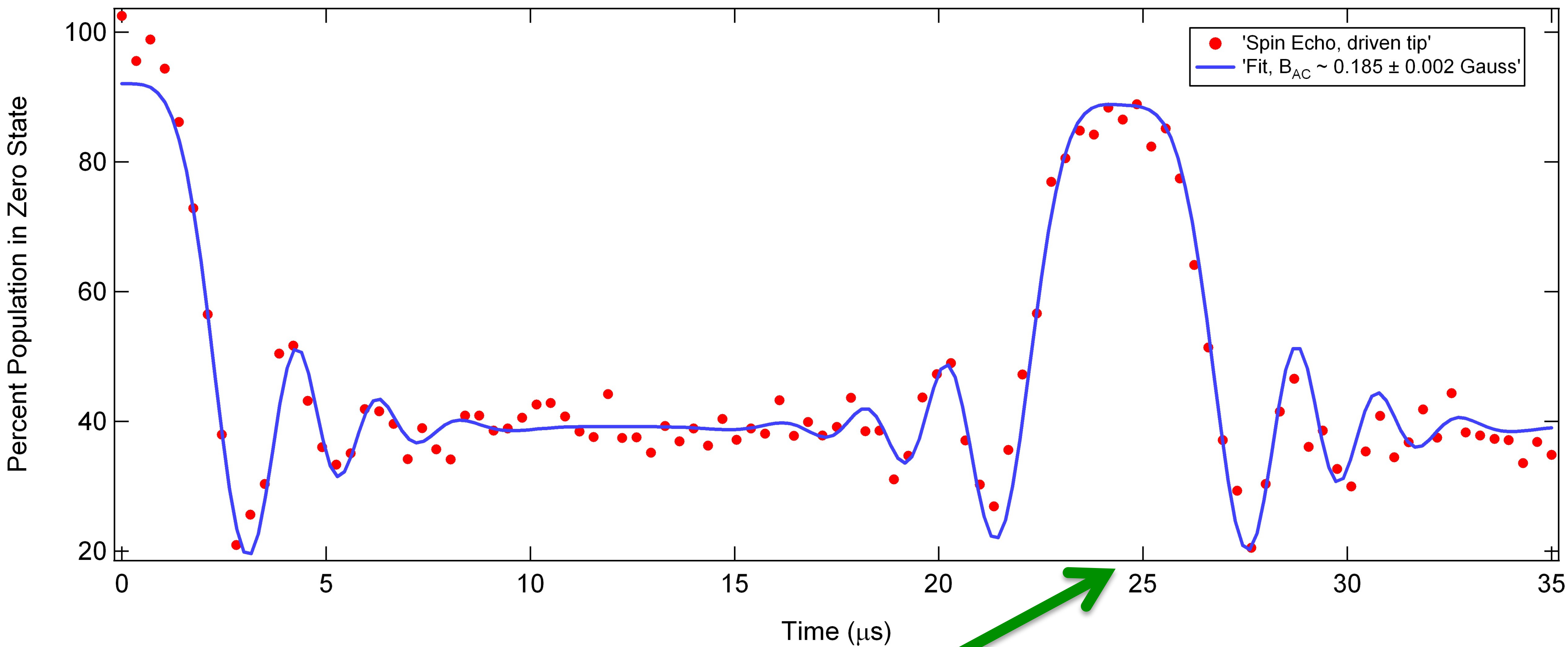


- Revival due to the tip motion is within the first ^{13}C collapse

$$\omega_{Larmor} << \omega_{cantilever}$$

- Measurement corresponds to ~ 20 nm amplitude of tip motion!!

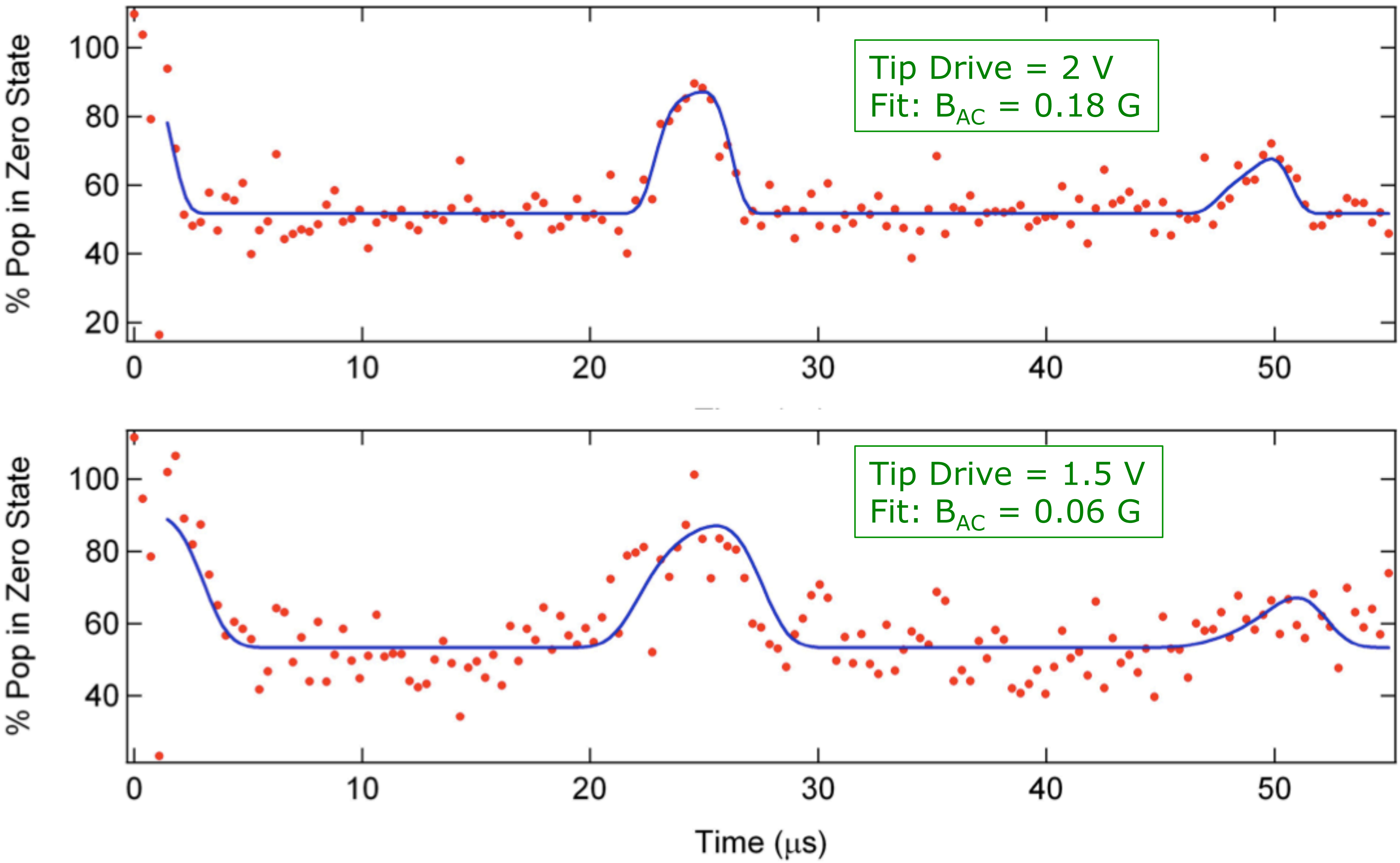
Revivals due to Driven Tip Motion



- Cantilever frequency is matched to ^{13}C Larmor frequency $\omega_{Larmor} = \omega_{cantilever}$
- Fixed amplitude of AC magnetic field, unlike ^{13}C spin contribution, gives a different functional form of the revivals

$$P_{|0\rangle} = \frac{1}{2}(1 + J_0(-\alpha B_{AC}{}^2 Sin^4(\frac{\omega_{tip}\tau}{4})))$$

Measuring AC motion of Cantilever

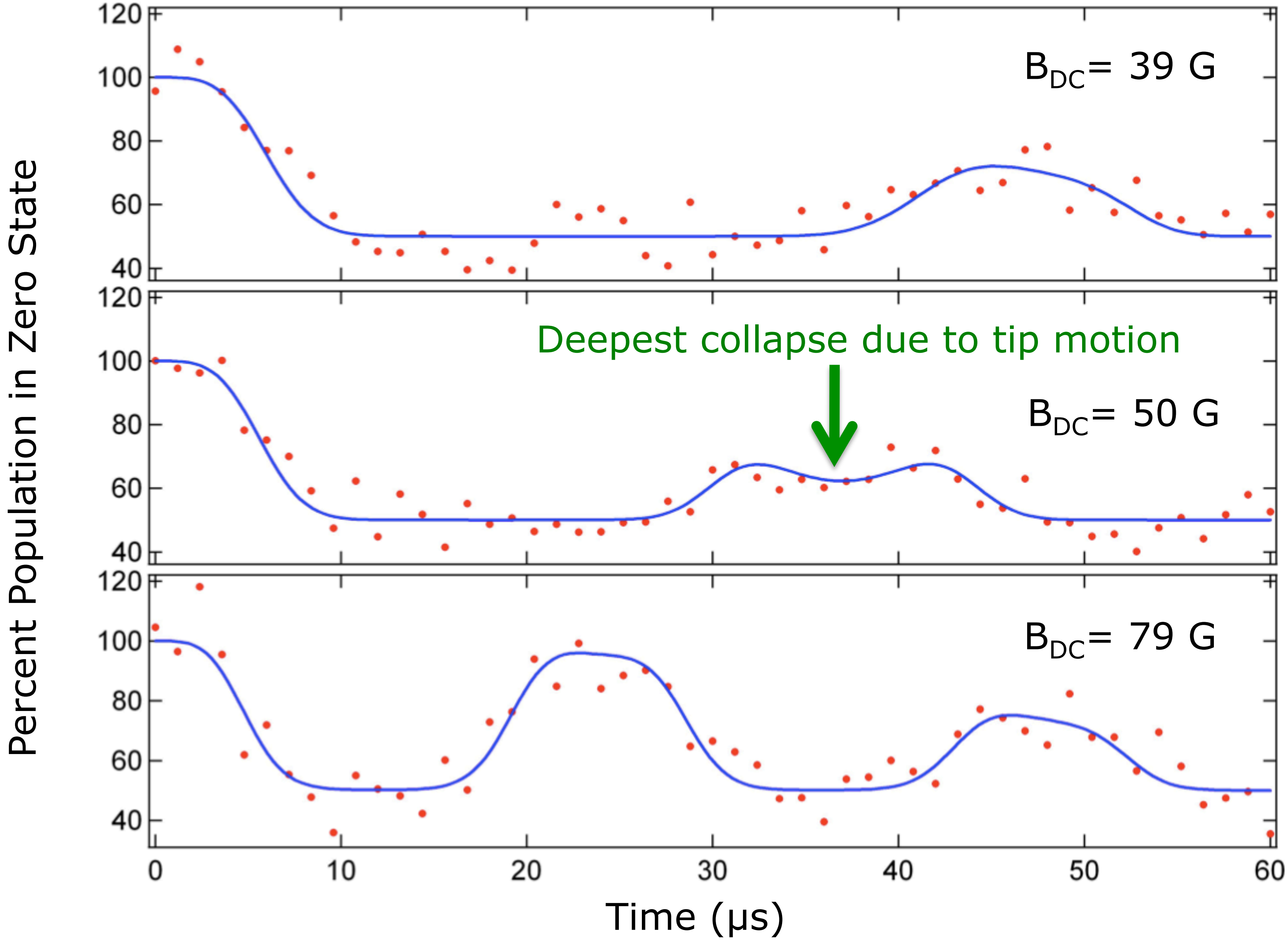


As AC tip motion decreases, revival peak approaches bare ^{13}C revival peak

- not a very sensitive measure of small B_{AC} (Brownian motion)

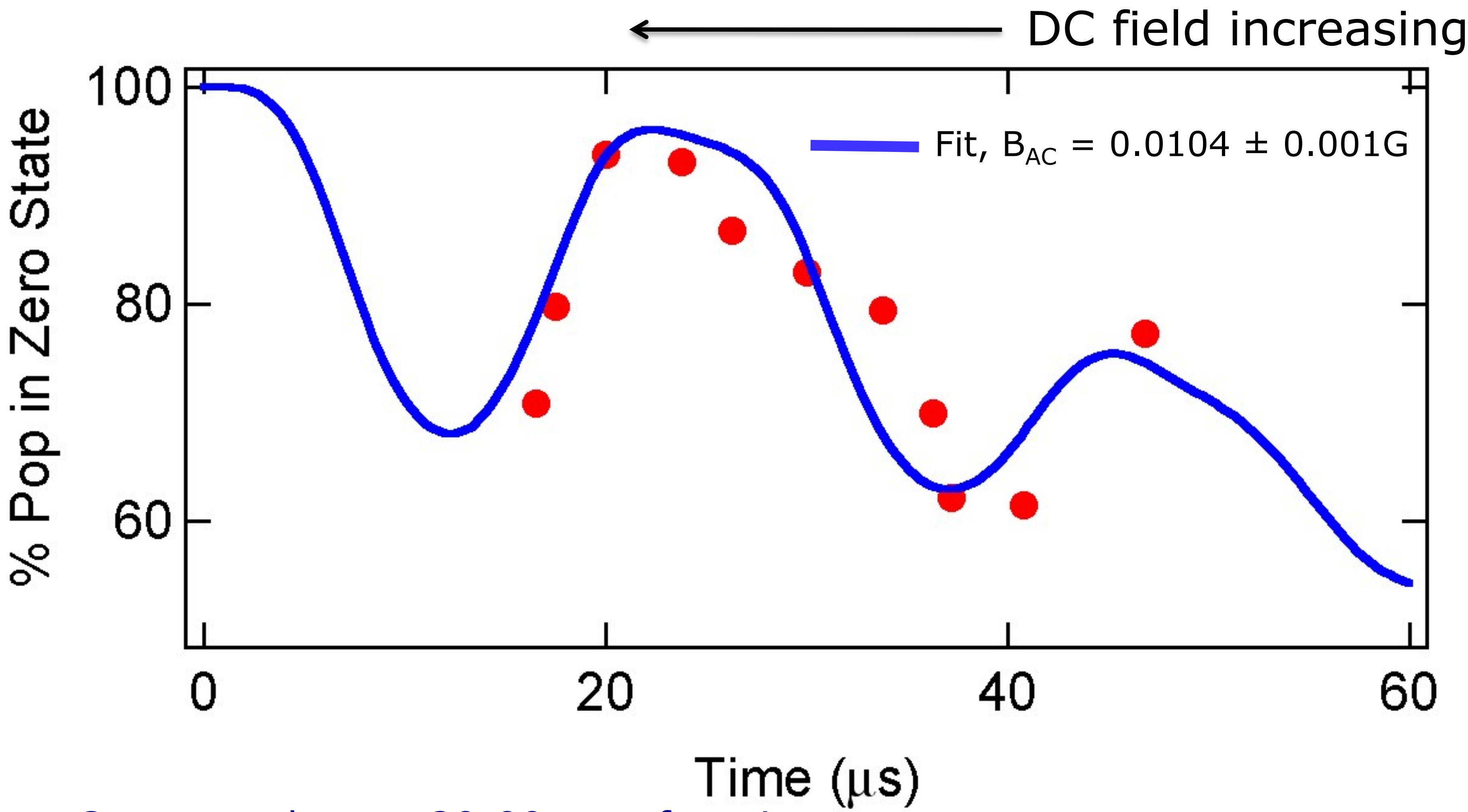
NV Detection of Thermal Motion

Sweeping ^{13}C revival peaks through tip collapse by varying B_{DC}



Thermal Motion

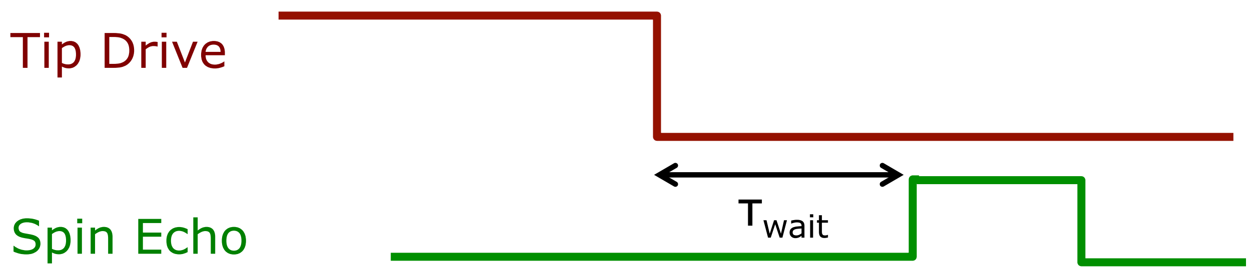
^{13}C revival maximum as DC magnetic field is shifted

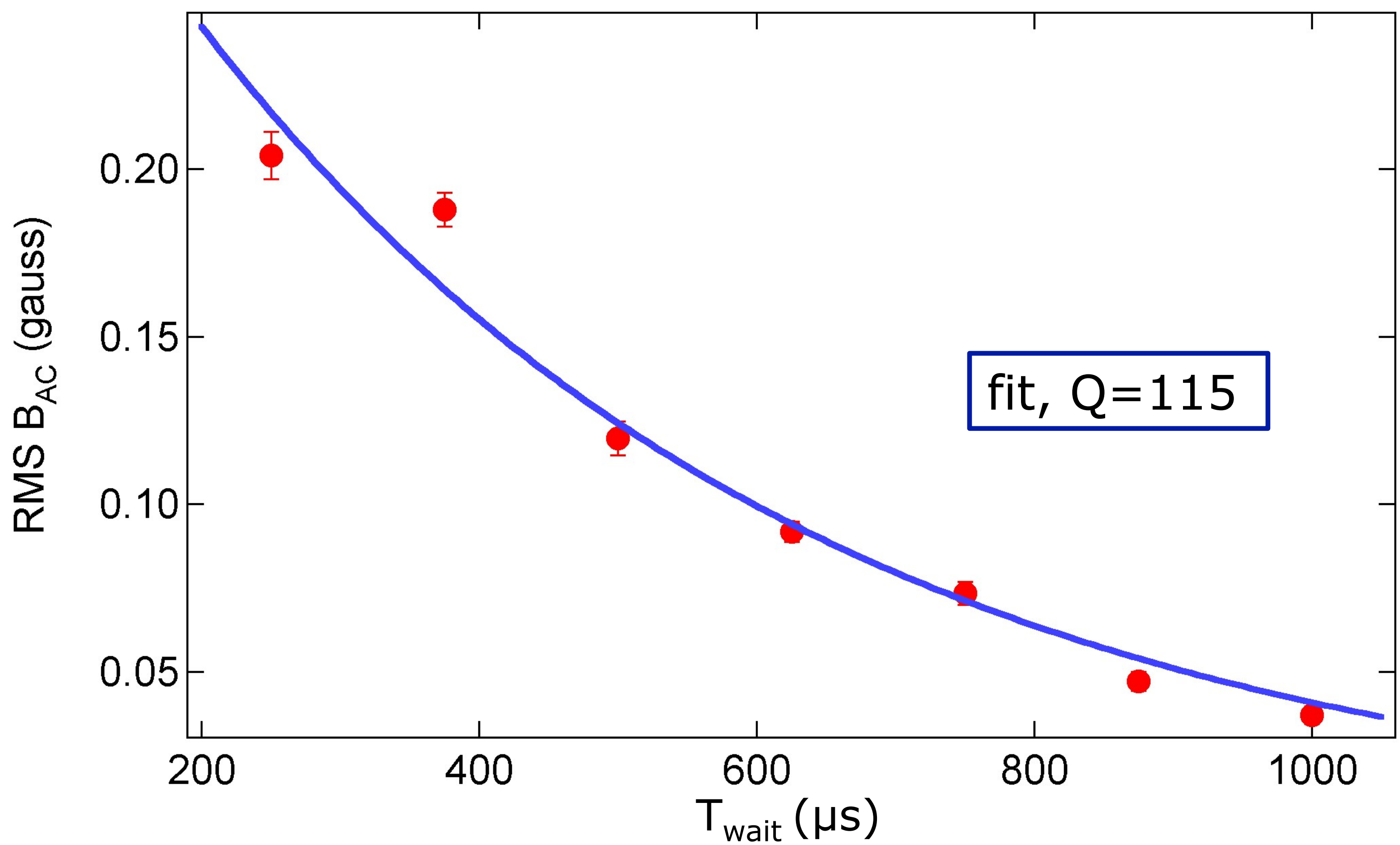


- Corresponds to ~ 20-90 pm of motion

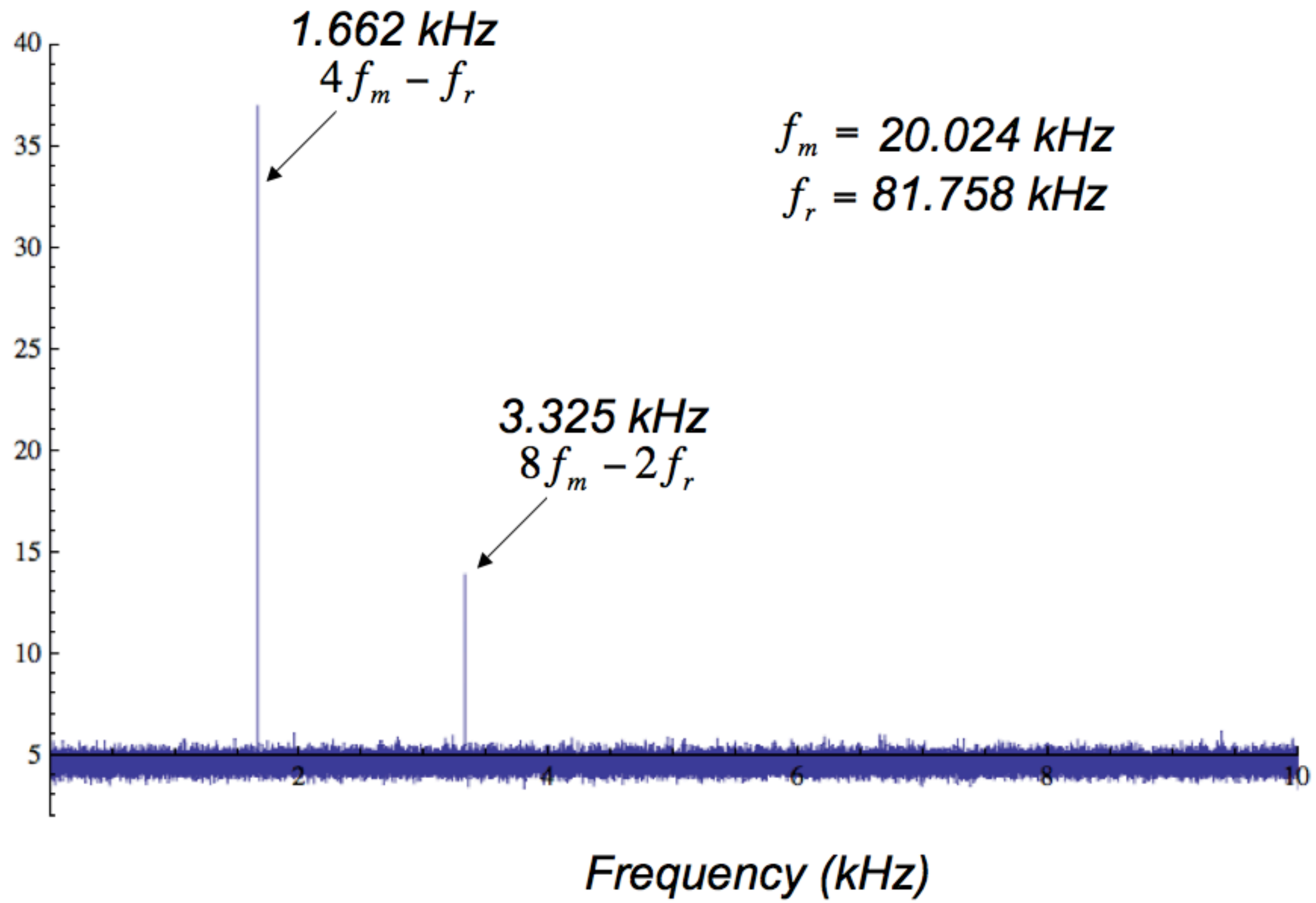
  in good agreement with the geometrical estimate of 50 pm

Cantilever Ringdown Measurement

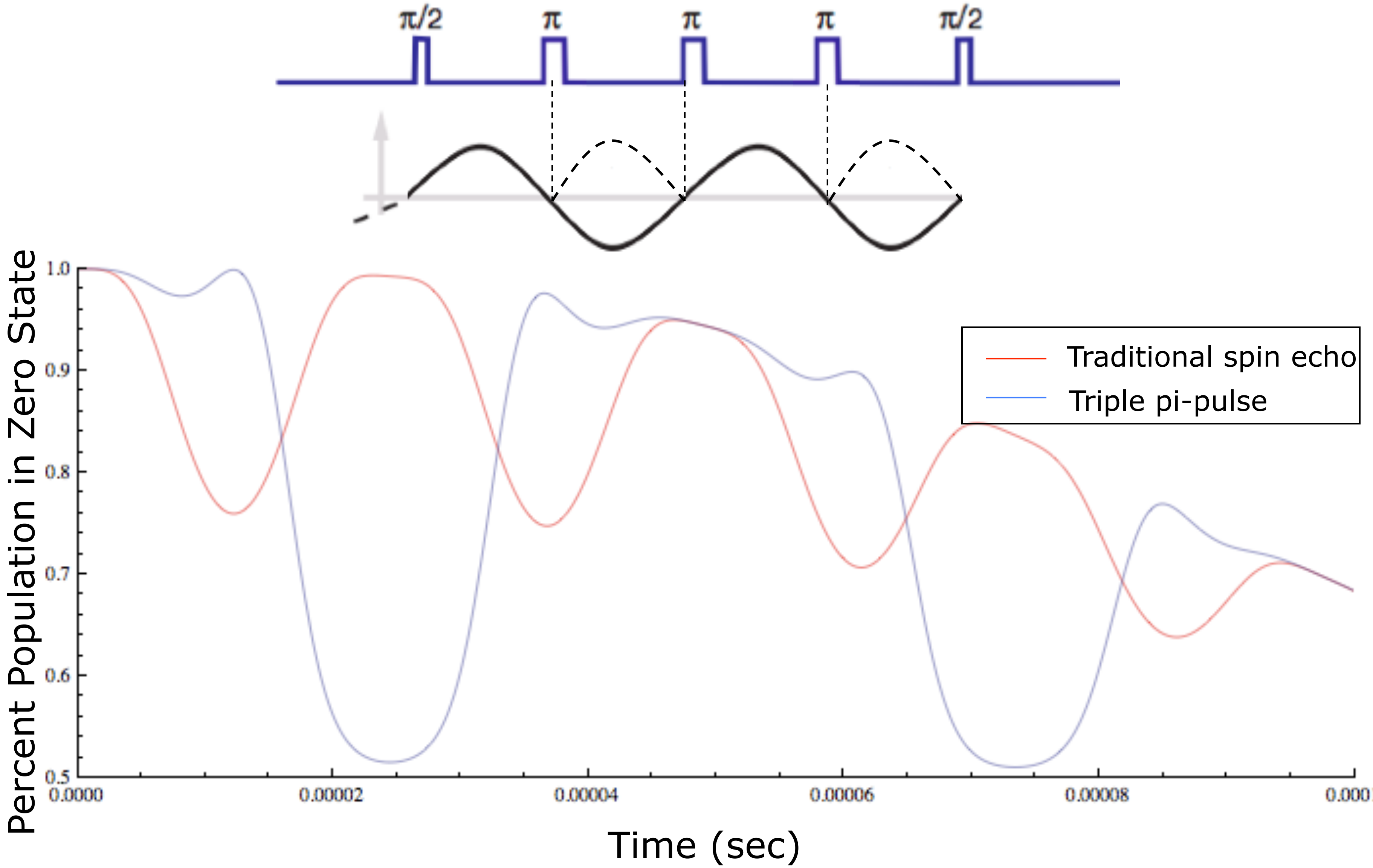




Power Spectral Density of Driven Motion

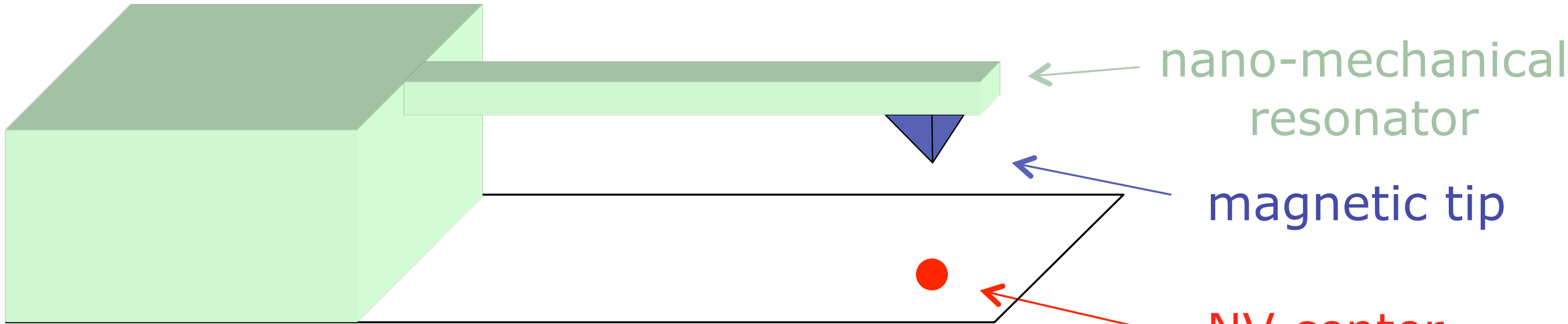


Smarter Pulse sequences to increase sensitivity



- Collapses due to tip motion are much deeper with triple pi-pulse

Optimizing Cantilevers for Strong Coupling



Coupling strength: $$\lambda = g_s \mu_B \nabla B a_0 / \hbar$$

$$\lambda >> 1/T_2,\ \Gamma_m = K_B T / \hbar Q$$

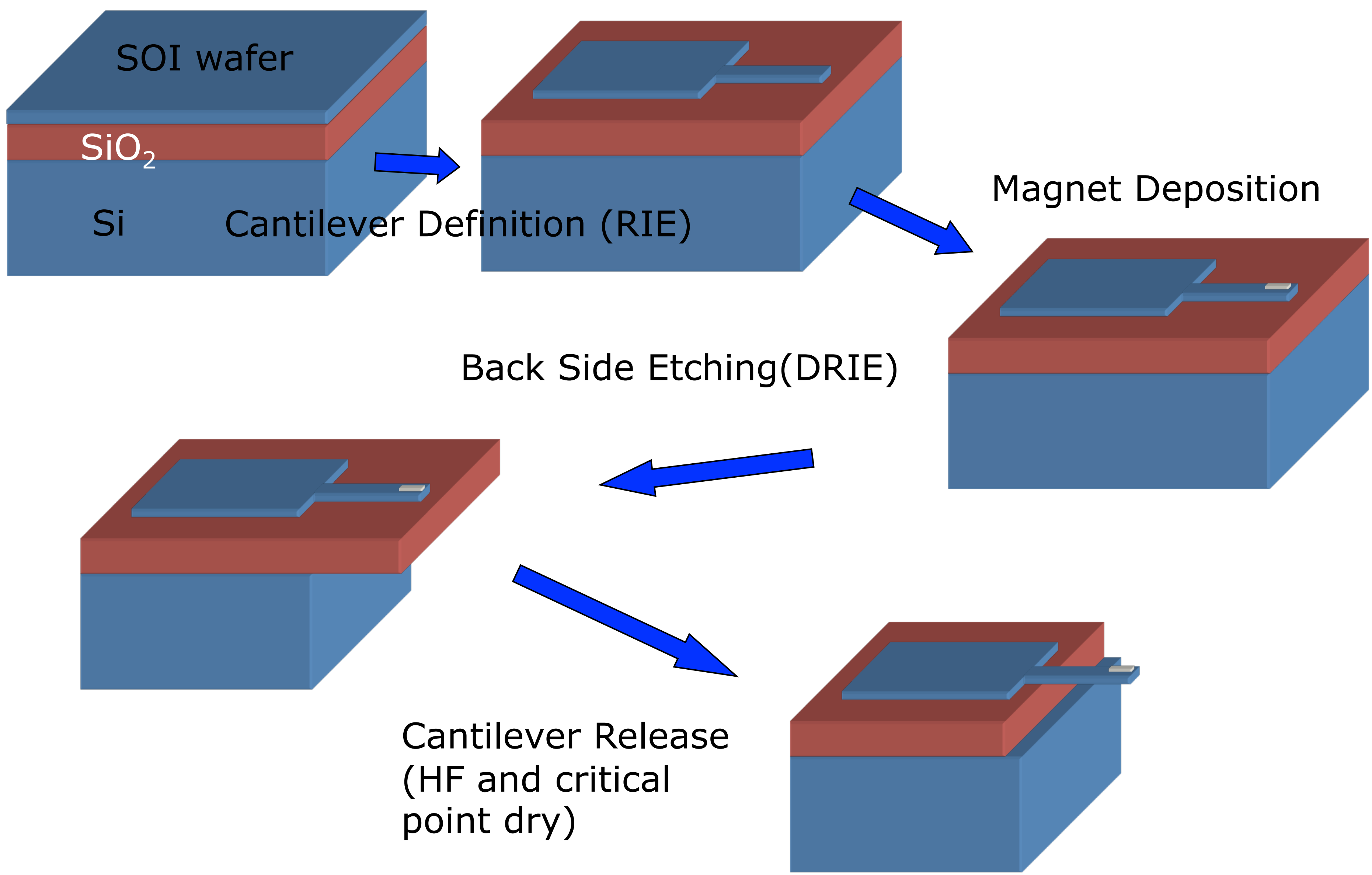
Design requirements for strong coupling:

- **Large field gradient**
- **Large zero-point motion**

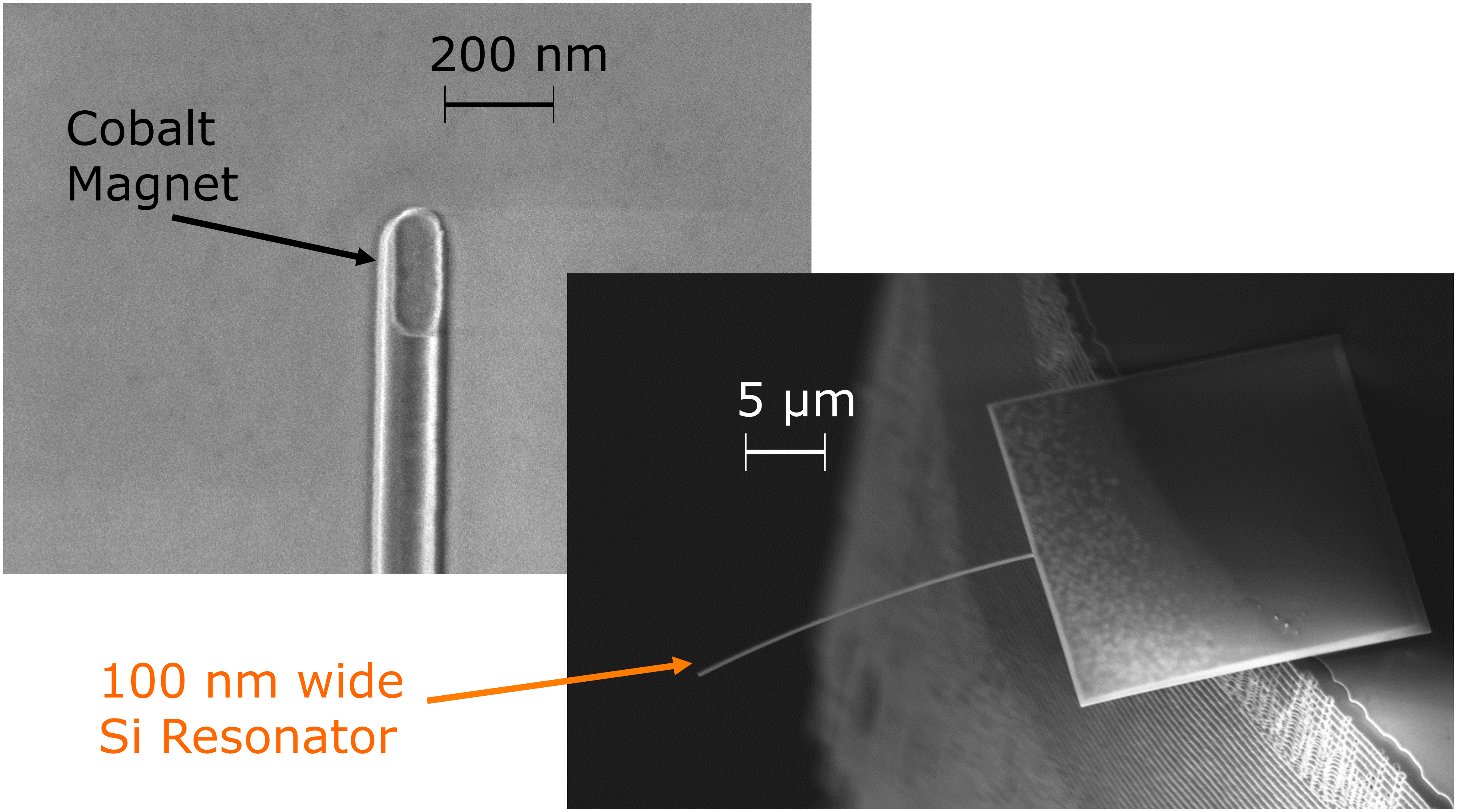
  long, skinny, thin cantilevers $$a_0 = \sqrt{\frac{\hbar}{2m\omega_r}}$$
- **Hiqh Q cantilever**
- **Long T_2 for qubit**

  NV Center

Cantilever Fabrication



Cantilever Fabrication



Optimistic Projected $\lambda = 100\ kHz$

Summary and Outlook

- Nitrogen vacancy centers are attractive for applications in quantum information, magnetometry, and imaging.

- Strong coupling between a cantilever and an NV will open the door to a novel method of cooling resonators down to their ground states.

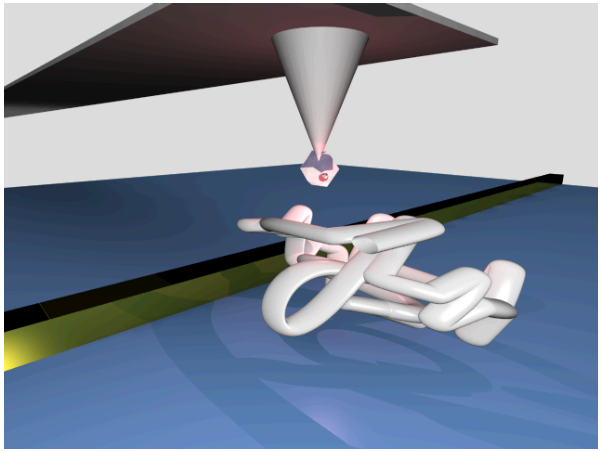
- A coupled resonator/NV system is the building block for a "quantum transducer," which would provide controllable and coherent long range spin-spin coupling.

- Used a single quantum system to readout thermal motion of a mechanical resonator at room temperature using a novel AC magnetometry technique

Route to Single Spin Sensitivity

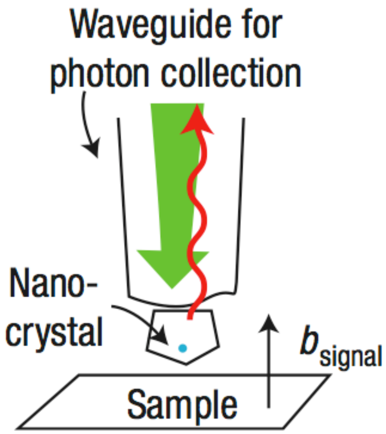
- Make a scanning diamond magnetometer

  for resolution and sensitivity, NV must be close to diamond surface



- Increase photon collection

  design photonic structures: solid immersion lenses, photonic crystals, photonic waveguides



- Increase T_2 coherence time

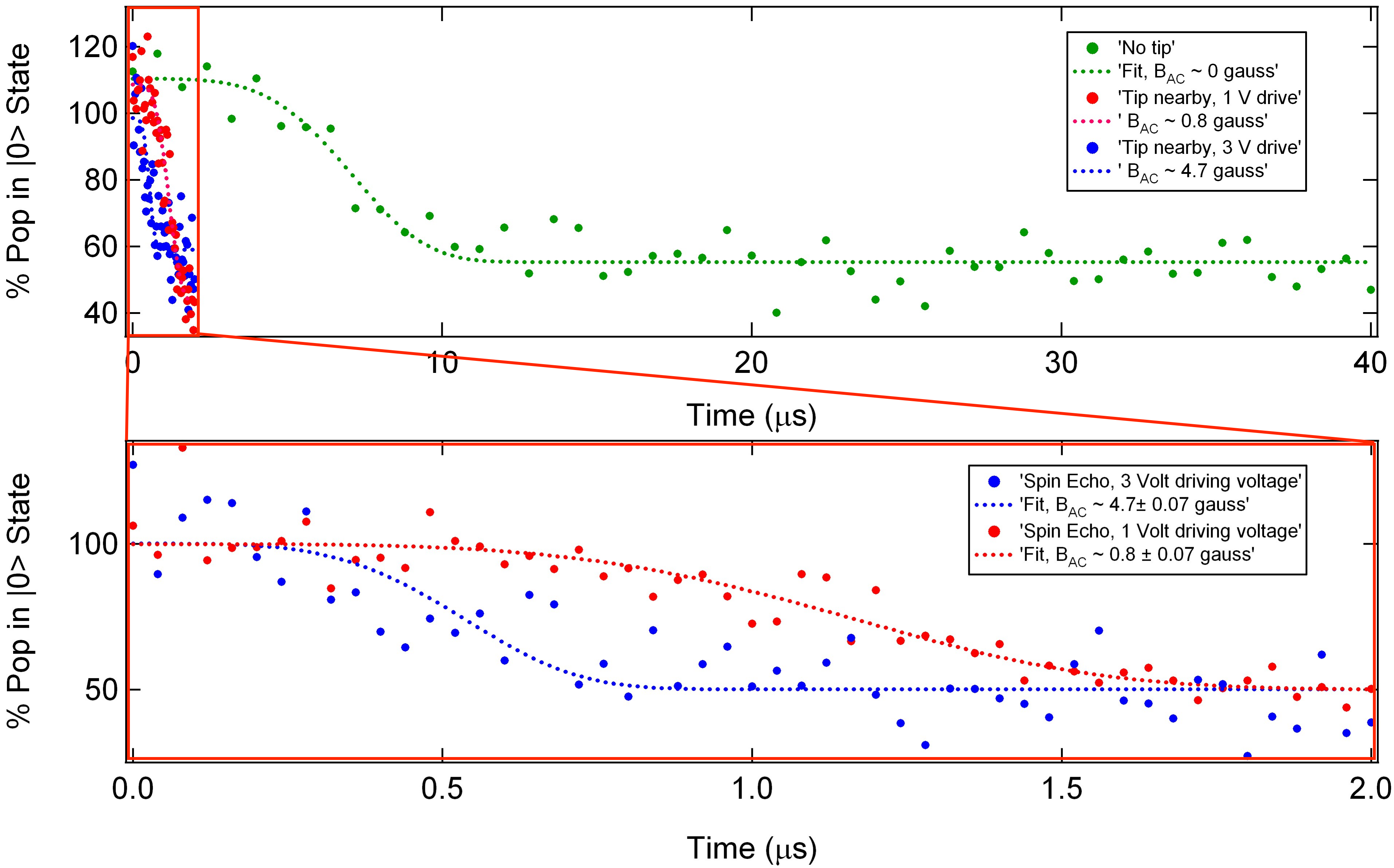
  understand mechanisms of decoherence

$$\delta B_{\min} \approx \frac{\hbar}{g\mu_B\sqrt{T_2 T}}$$

- Increase contrast between |0> and |1> states

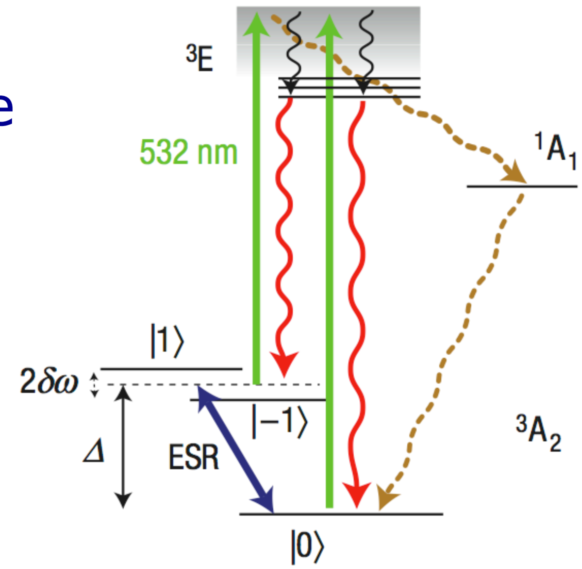
  strain engineering and low temperature operation

Measurement of tip motion using collapses:



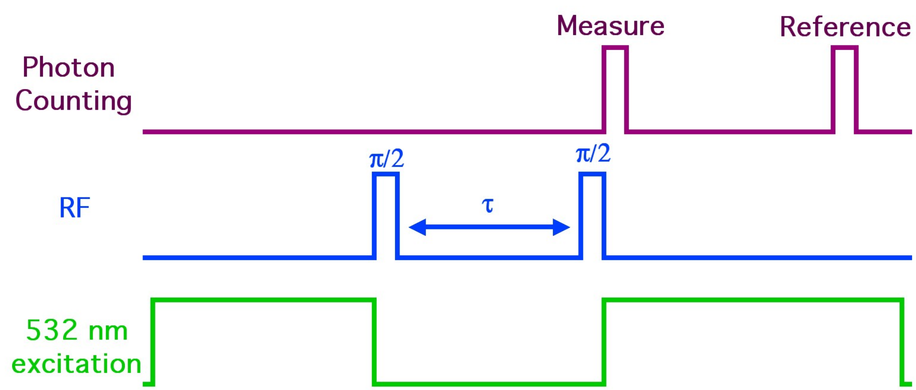
NV Center as a Magnetometer

- Magnetic field *b* induces a relative energy shift between |1> and |-1>



- Ramsey pulse sequence detects a Zeeman shift

$$\phi \propto (g\mu_B / \hbar) b\tau$$



- Photoluminescence measures spin population

- Magnetometer signal: $S \approx (g\mu_B / \hbar) b\tau$

Taylor et al, *Nature Physics* **4**, 810 (2008). Maze et al, *Nature* **455**, 644 (2009), C. Degen, *APL* **92**, 243111 (2008).