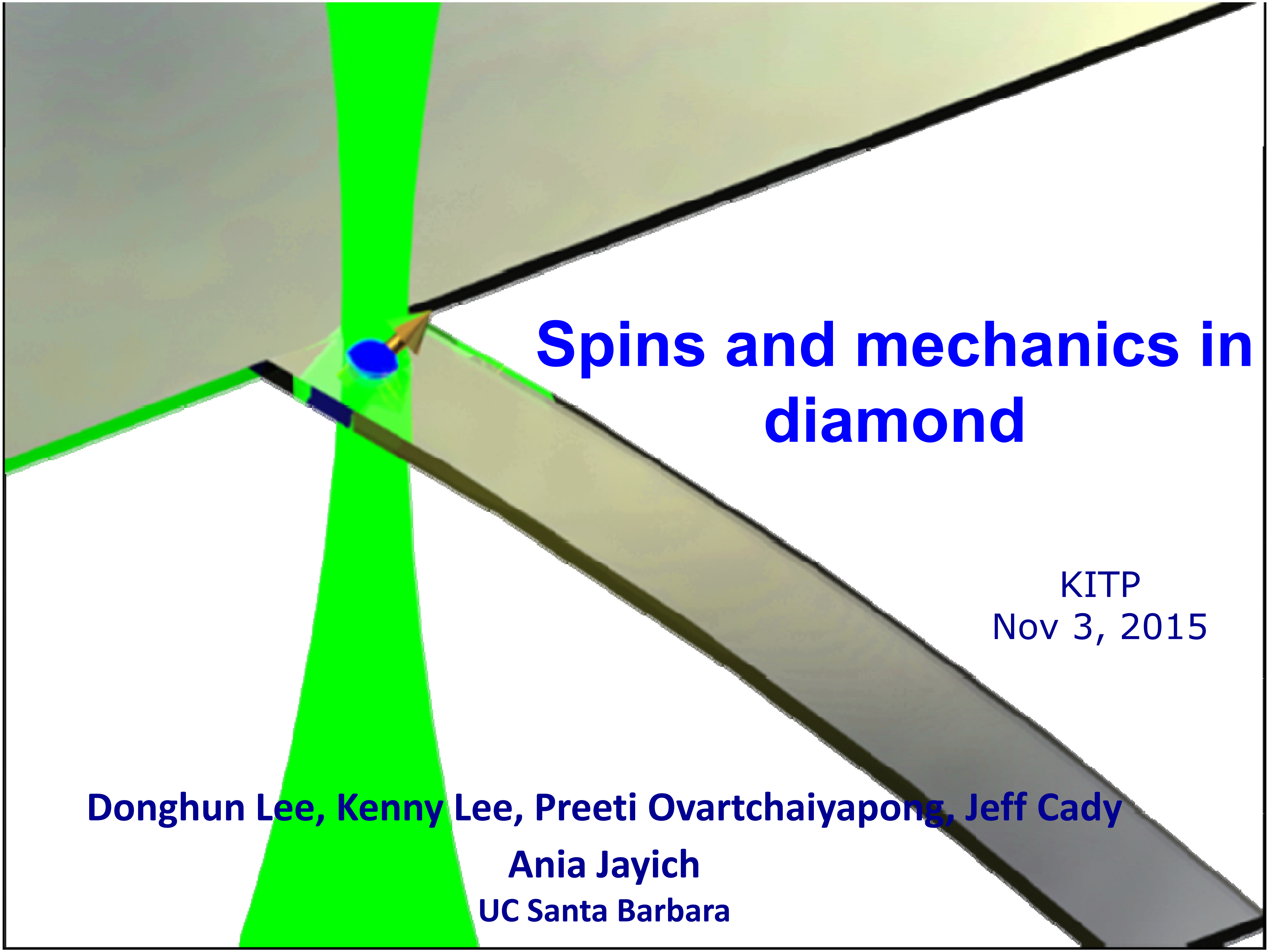

Spins and mechanics in diamond

KITP
Nov 3, 2015

Donghun Lee, Kenny Lee, Preeti Ovartchaiyapong, Jeff Cady

Ania Jayich

UC Santa Barbara

Nitrogen-vacancy centers in diamond

- A defect in the diamond lattice.
- Has an associated electronic spin and an optical transition
- Marries solid state and atomic physics

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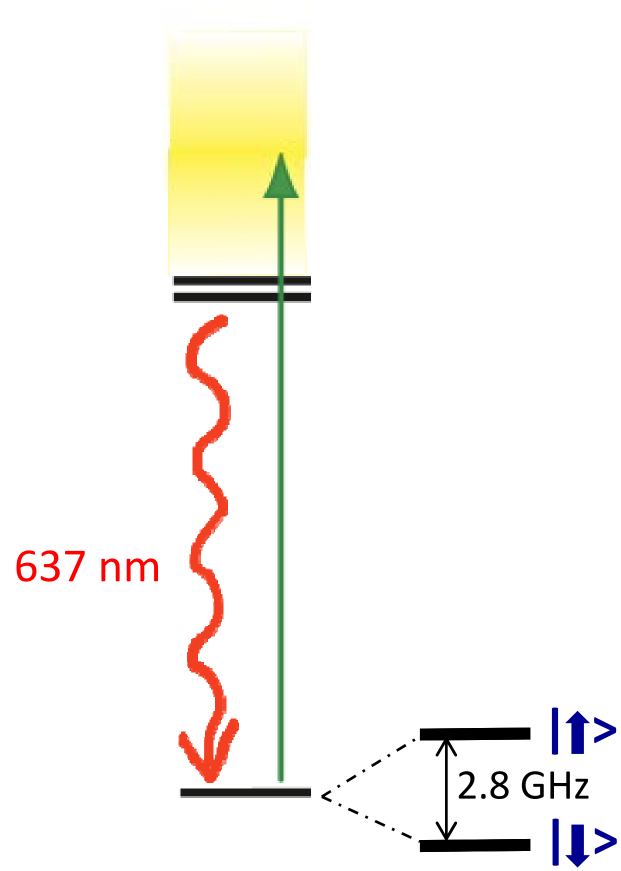
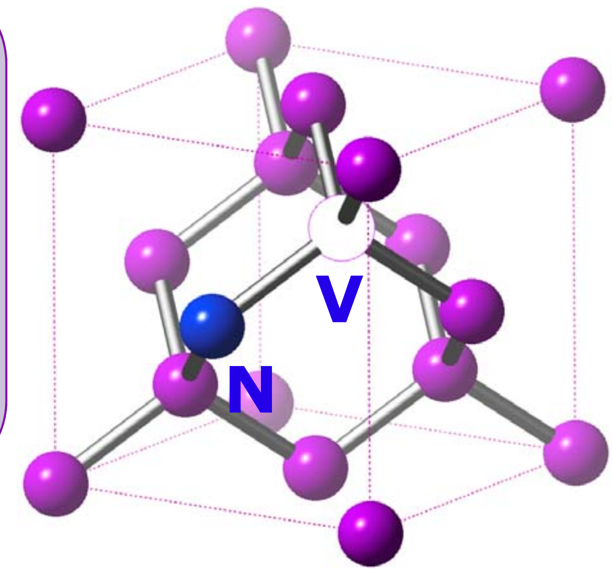


David D. Awschalom, Diamond Age of Spintronics. *Scientific American* (October 2007).

Nitrogen Vacancy Centers in Diamond

Interesting for quantum devices

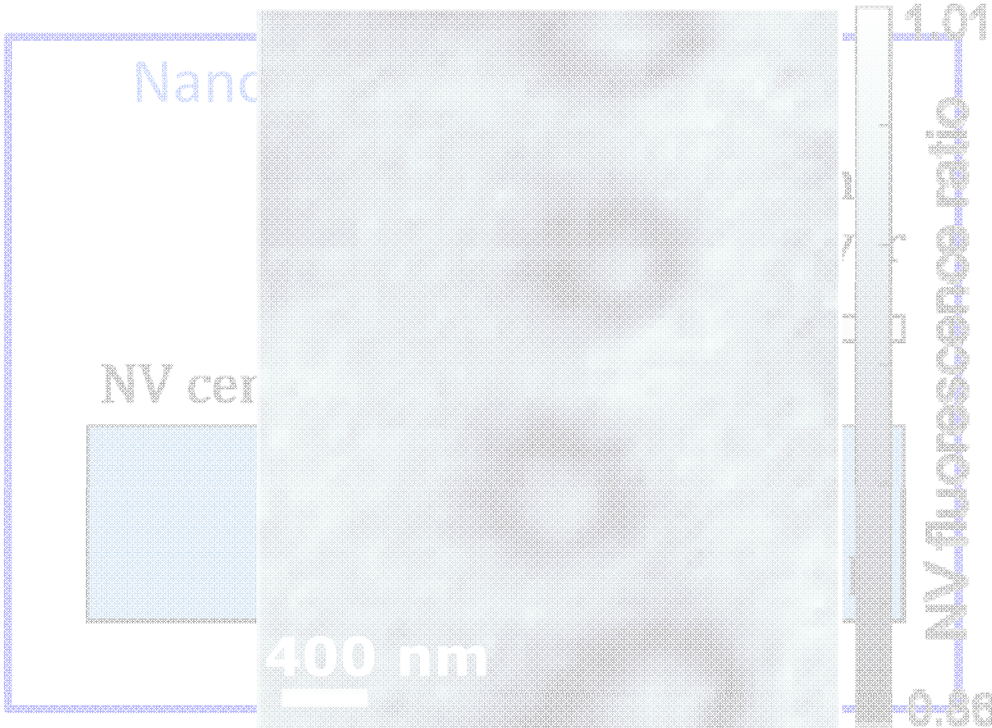
- Long (~ 5 ms) spin coherence times at 300 K
- Solid-state system
- Spin state can be optically initialized, coherently controlled with microwaves, and optically readout



Applications

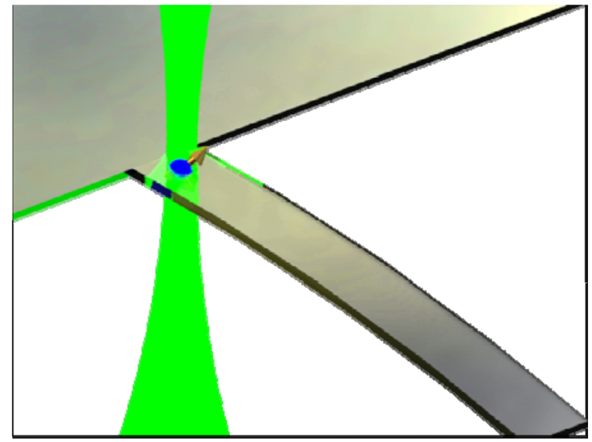
- magnetometry **
- quantum information processing *
- single photon sources
- fluorescent biomarkers
- electrometry, thermometry

Jayich research group thrusts

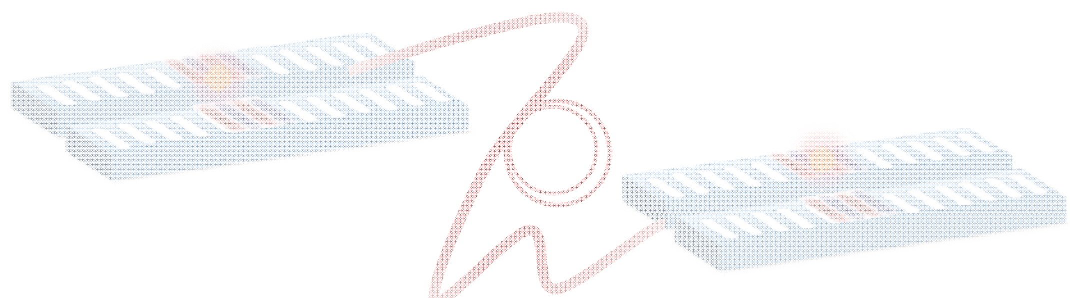


Vortices in $BaFe_2(As_{0.7}P_{0.3})_2$

Spin-phonon hybrid quantum systems



Spin-photon hybrid quantum systems:



Mechanical coupling to spin: motivation

- Enhanced control of NV spin state
  - Strain tuning of NV^- zero phonon line

Electric field tuning

Tamarat *et al*, *NJP* **10**, 045004 (2008)
Basset et al., *PRL* **107**, 266403 (2011)

  - Enhanced spin state control

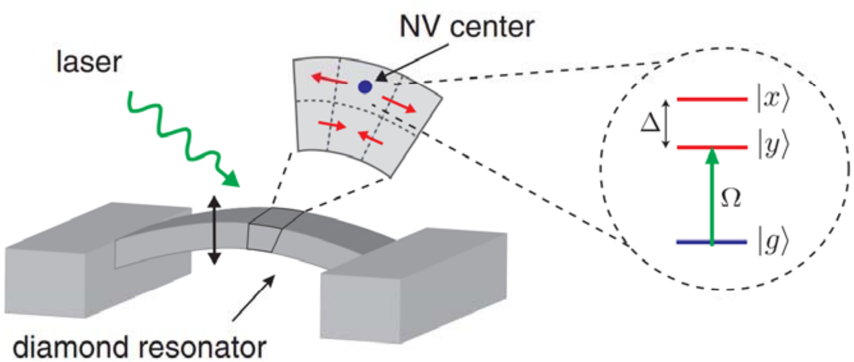
E. R. MacQuarrie, *et al Optica* **2**, 233 (2015)

- Transduction of quantum information
  - Phonons can mediate spin-spin or spin-photon interactions

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

  - Quantum control of mechanical resonator

Phonon Cooling and Lasing

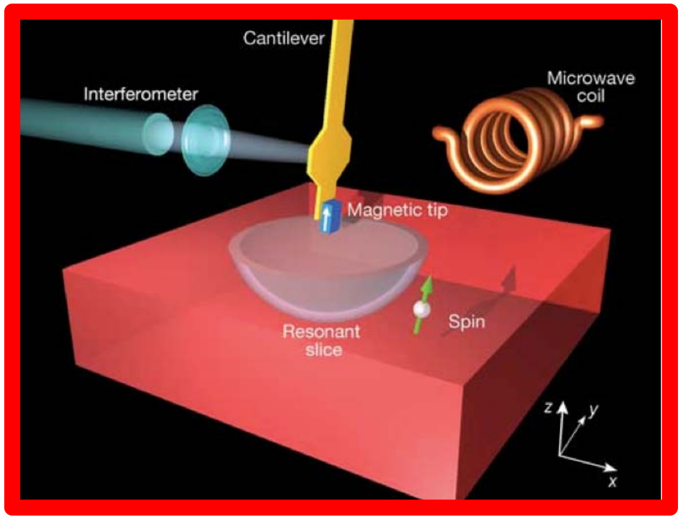


Kepesidis *et al*., *PRB* **88**, 064105 (2013).

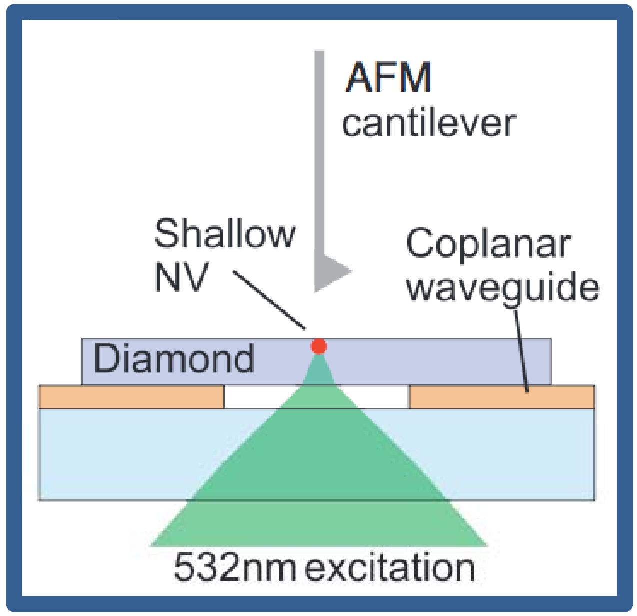
- Strain and phonons play an important role for NVs as quantum memories

M.L. Goldman, *et al Phys. Rev. Lett*. **114**, 145502 (2015).

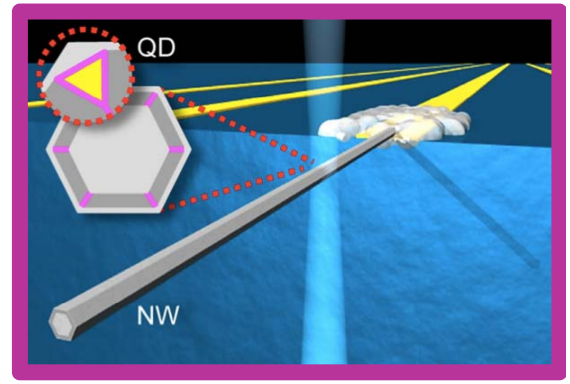
Variety of spin-mechanical systems



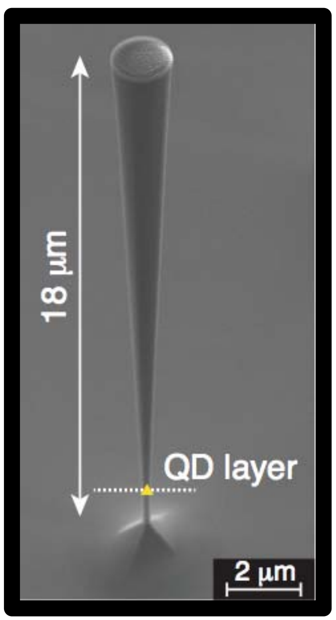
Rugar et al, Nature **430**,329 (2004)



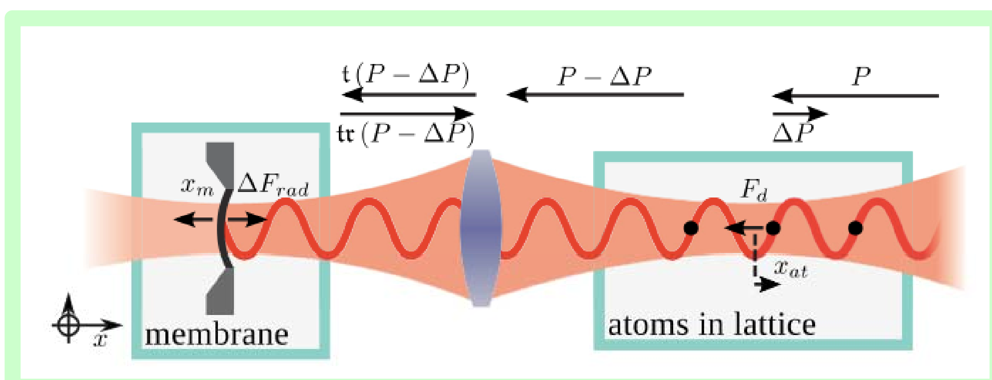
Kolkowitz *et al, Science* **335**, 1603 (2012)



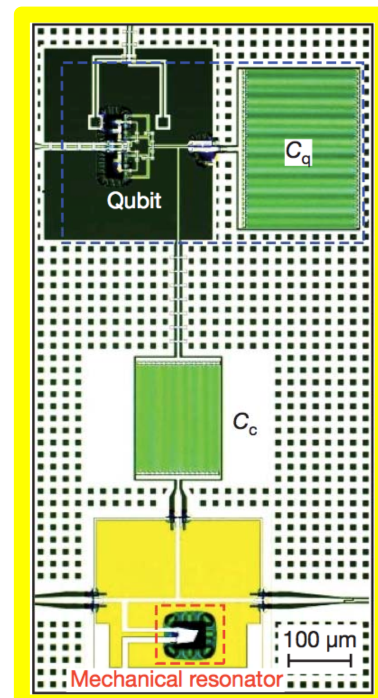
Montinaro, *et al, Nano Lett.* **14**, 4454 (2014)



Yeo et *al, Nature Nano* **9**, 106 (2014)



Camerer et al, PRL **107**, 223001 (2011),

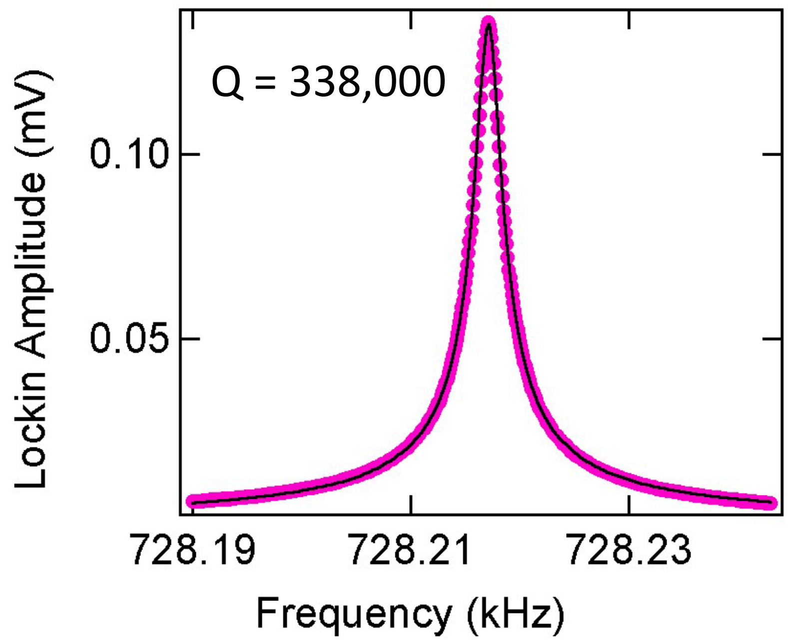


O'Connell *et al, Nature* **464**, 697 (2010)

The diamond platform: benefits and challenges

Benefits:

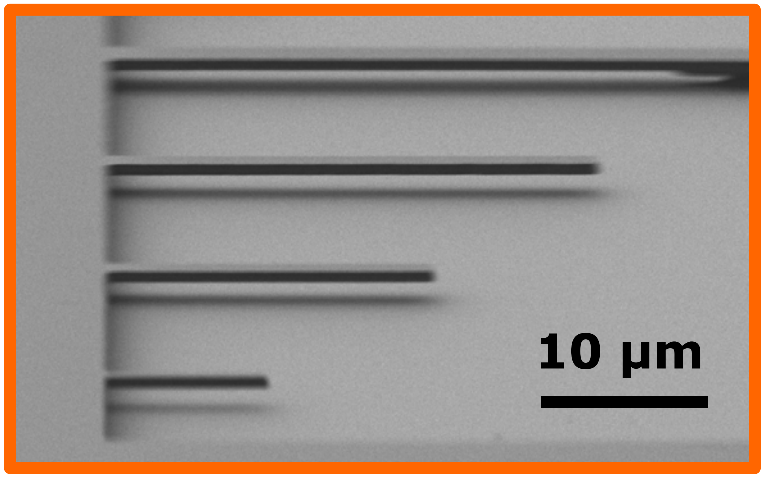
- Long NV spin coherence times
- Low intrinsic mechanical dissipation
- Integrated, monolithic structure



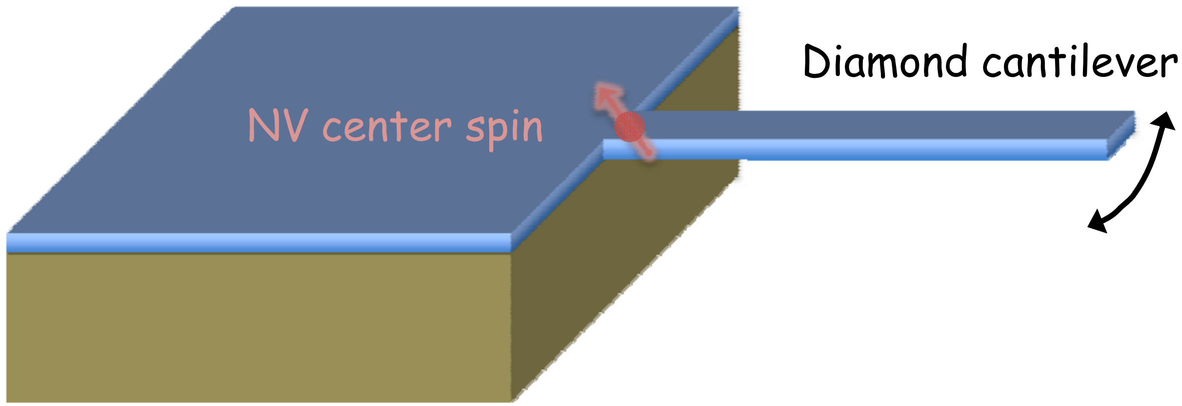
Ovartchaiyapong *et al*, *APL* **101**, 163505 (2012)

Challenges:

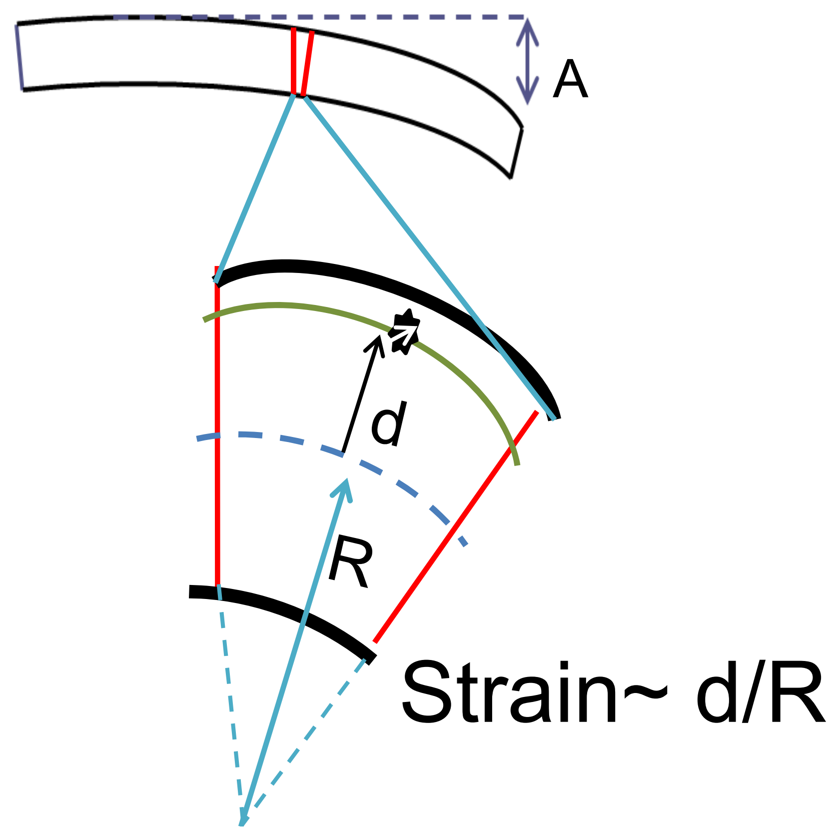
- Diamond nanofabrication was immature
- NV strain interaction was not well characterized



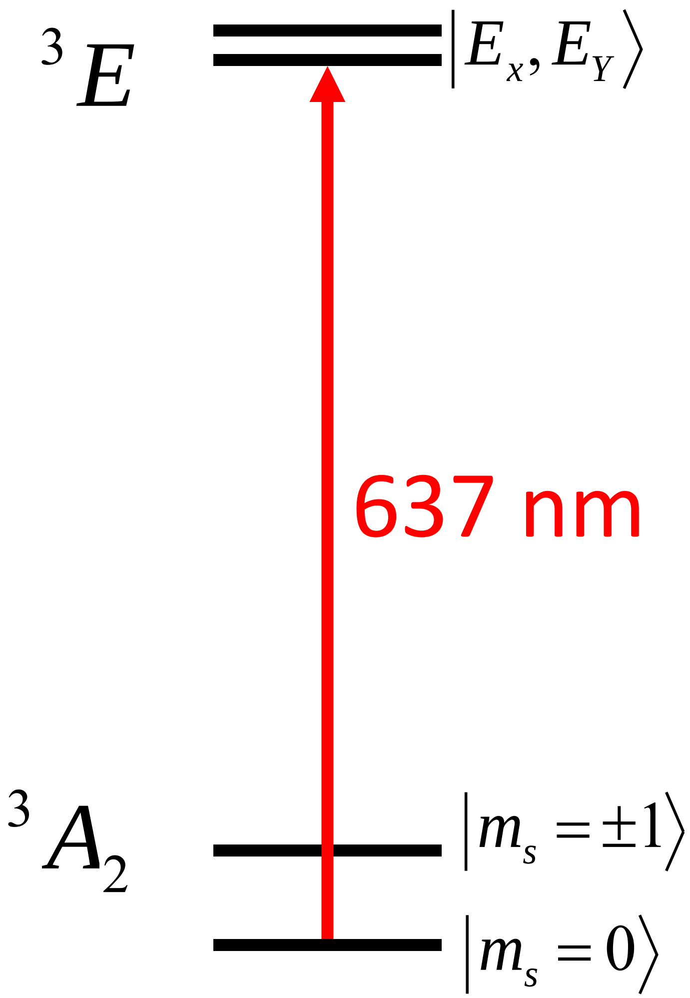
Strain-mediated coupling



- Can control strain with NV depth and amplitude of bending
- Can control angle of strain with respect to NV axis
- Highly controlled platform for strain application



Ground and excited state NV strain coupling

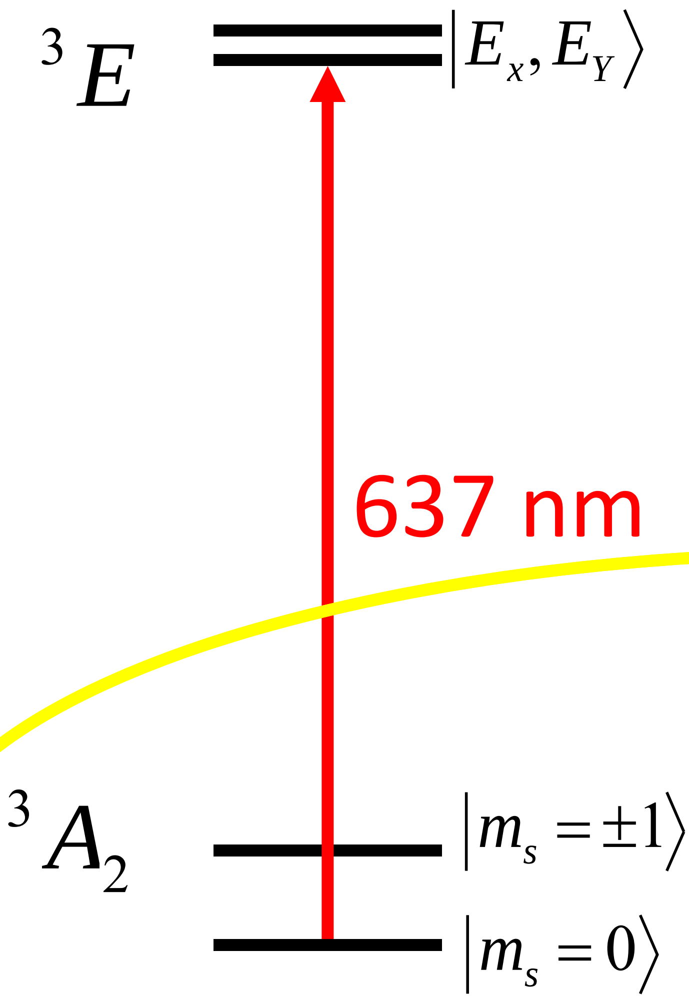


- Excited state:
  - Large strain coupling (1 PHz/strain)
  - Useful for coupling to photons
  - Good for quantum control (cooling)

- Ground state:
  - Long spin coherence time (ms) – good for storage
  - Useful for spin squeezing[1]
  - Relatively small (GHz/strain) coupling

[1] S. Bennett, *et al, PRL* **110**, 156402 (2013).

Ground and excited state NV strain coupling



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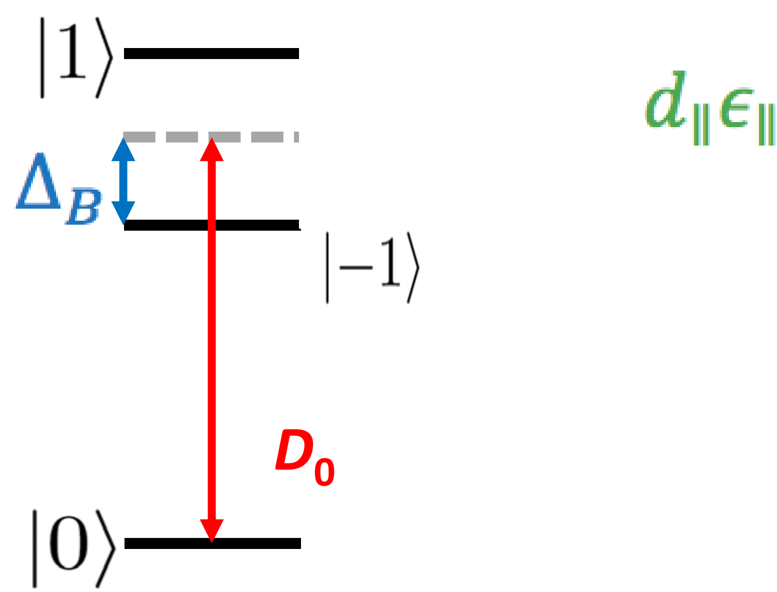
Strain interaction with NV ground state

$$H_{NV} = (D_0 + d_{||}\epsilon_{||})S_z^2 + \mu_B g \vec{S} \cdot \vec{B} - \frac{d_\perp \epsilon_\perp}{2}(S_+^2 + S_-^2)$$

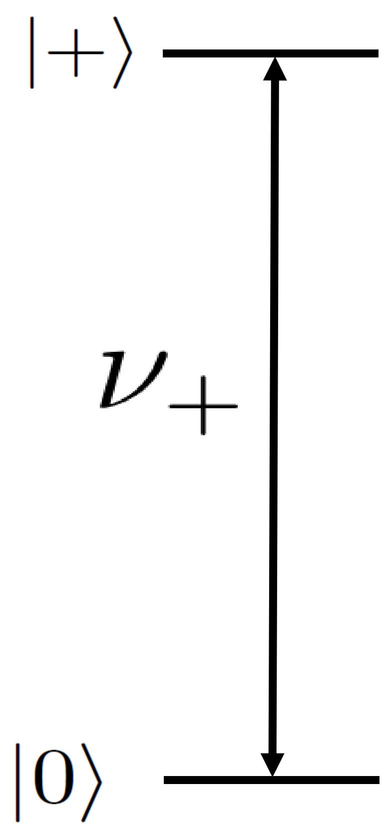
- Simple picture equates strain to electric field
- $d_{||}$ and $d_{\perp}$: strain susceptibilities, $\varepsilon_{||}$ and $\varepsilon_{\perp}$: strain
- Strain parallel to NV axis shifts *D* (crystal field splitting)
- Perpendicular strain mixes |+1> and |-1>

Ground state energy level structure in presence of strain and magnetic field:



Defining the spin qubit

$$\nu_+ = D_0 + d_{||}\epsilon_{||} + \sqrt{(\gamma_{NV} B_z)^2 + (d_\perp \epsilon_\perp)^2}$$



AC parallel strain modulates at cantilever frequency!

AC perpendicular strain modulates at ~ twice cantilever frequency!

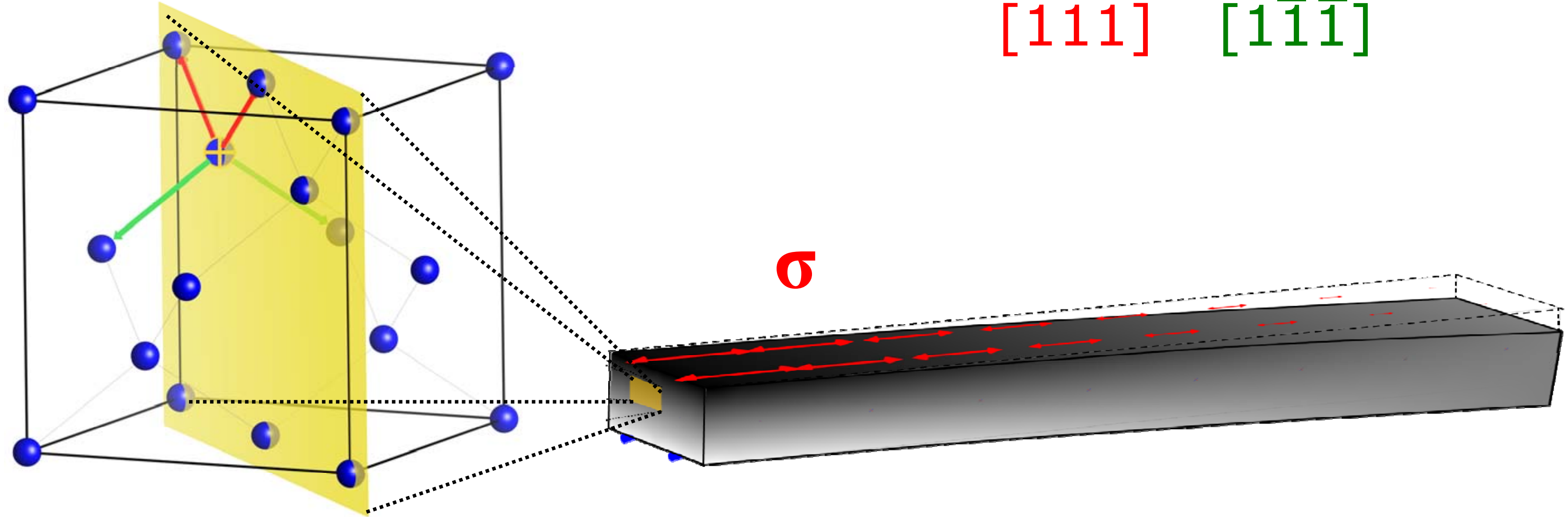
Sensing strain with directionality

Red class: perpendicular strain is predominant

4 possible NV orientations:

$[111]$ $[\bar{1}1\bar{1}]$

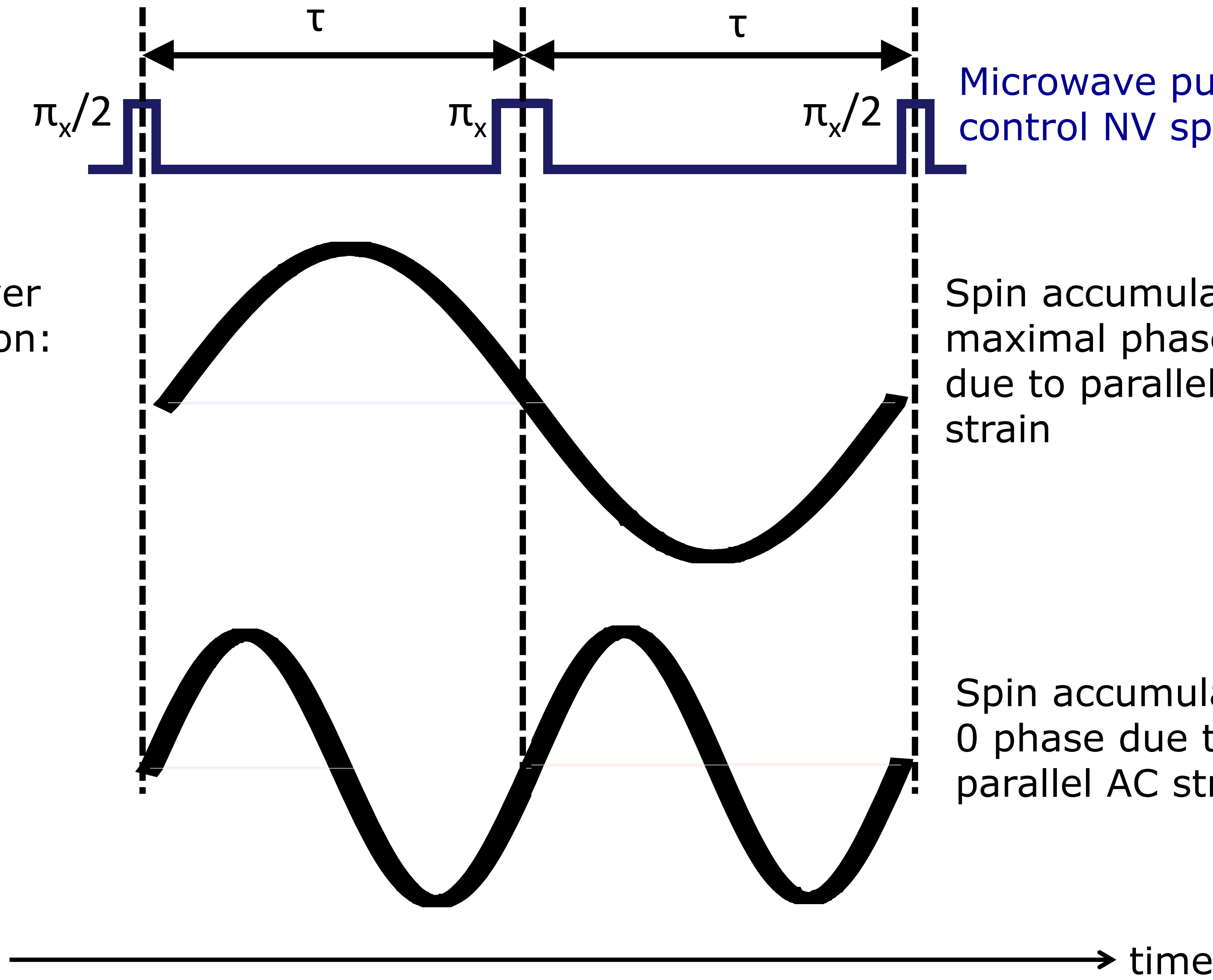
$[\bar{1}\bar{1}1]$ $[1\bar{1}\bar{1}]$



Green class: parallel strain is predominant

Quantum control to reveal strain coupling

Hahn echo



Microwave pulses control NV spin

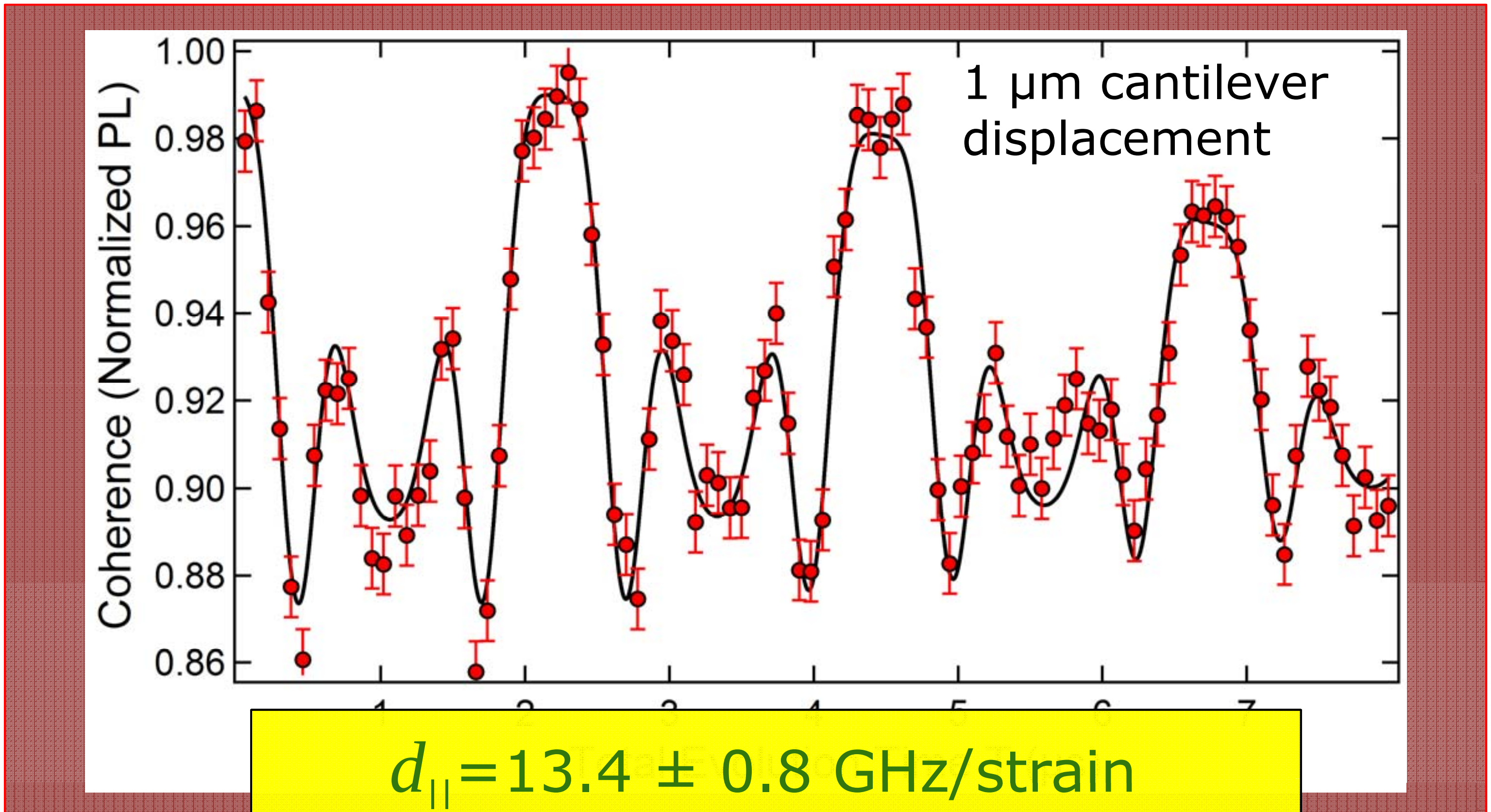
Cantilever oscillation:

Spin accumulates maximal phase due to parallel AC strain

Spin accumulates 0 phase due to parallel AC strain

Coherent detection of strain coupling

Hahn Echo Signal



$d_{||}$=13.4 ± 0.8 GHz/strain

$d_{\perp}$ =21.5 ± 0.8 GHz/strain

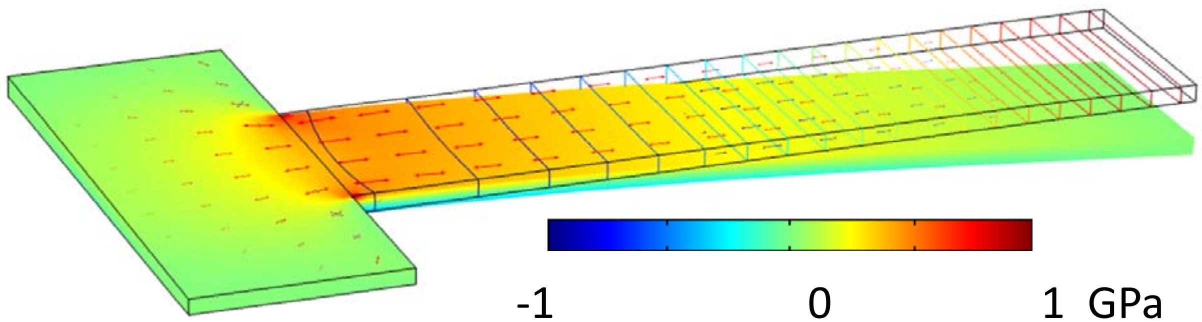
- AC strain coherently drives spin evolution: Coherence revival at $\tau = 2\pi/\omega_{cant}$
- Parallel strain modulates qubit frequency at the resonator frequency

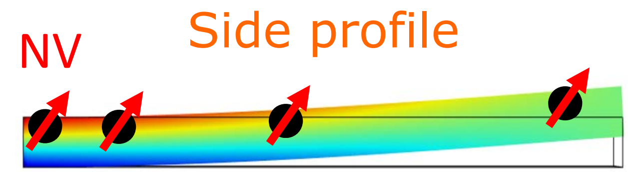
P. Ovartchaiyapong *et al, Nature Communications* **5**, 4429 (2014)

Related work: Tessier *et al, PRL* 133, 020503 (2014)

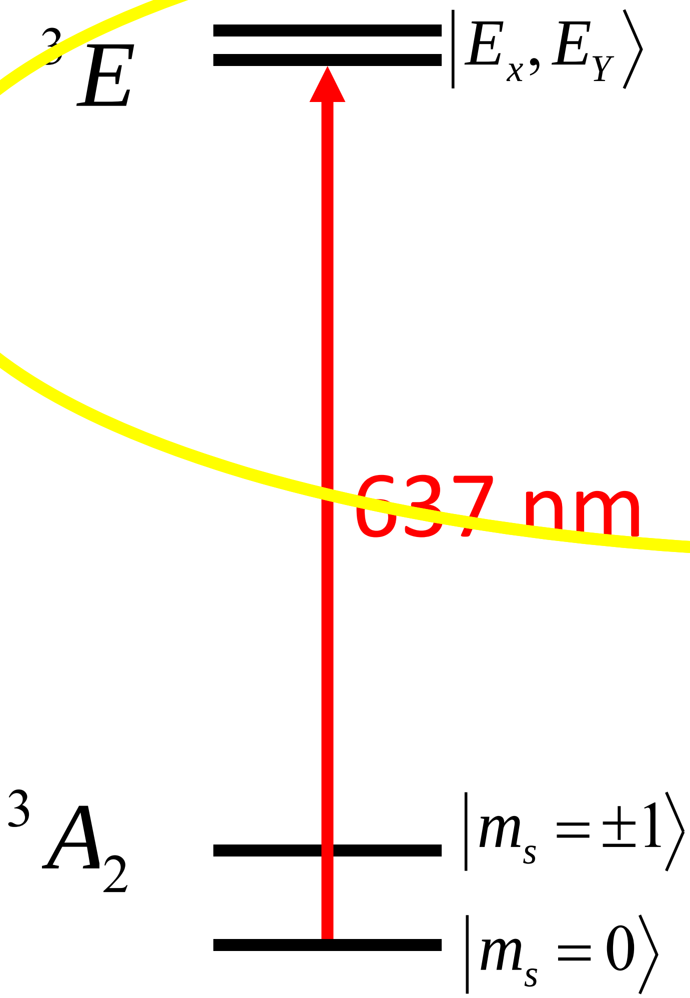
Nanoscale strain imaging along cantilever

Stress profile along cantilever:





Ground and excited state NV strain coupling



- Excited state:
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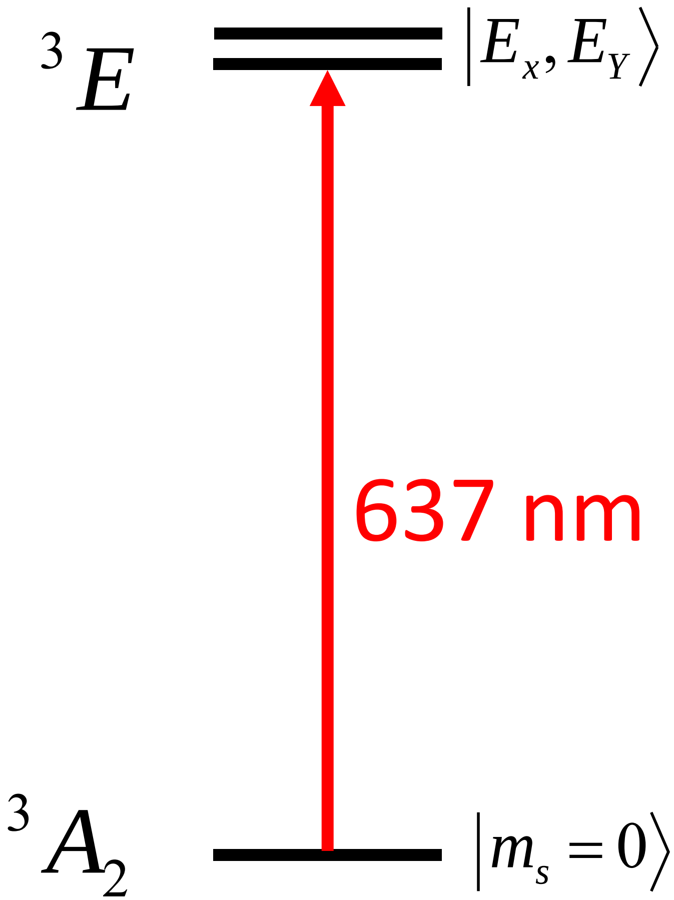
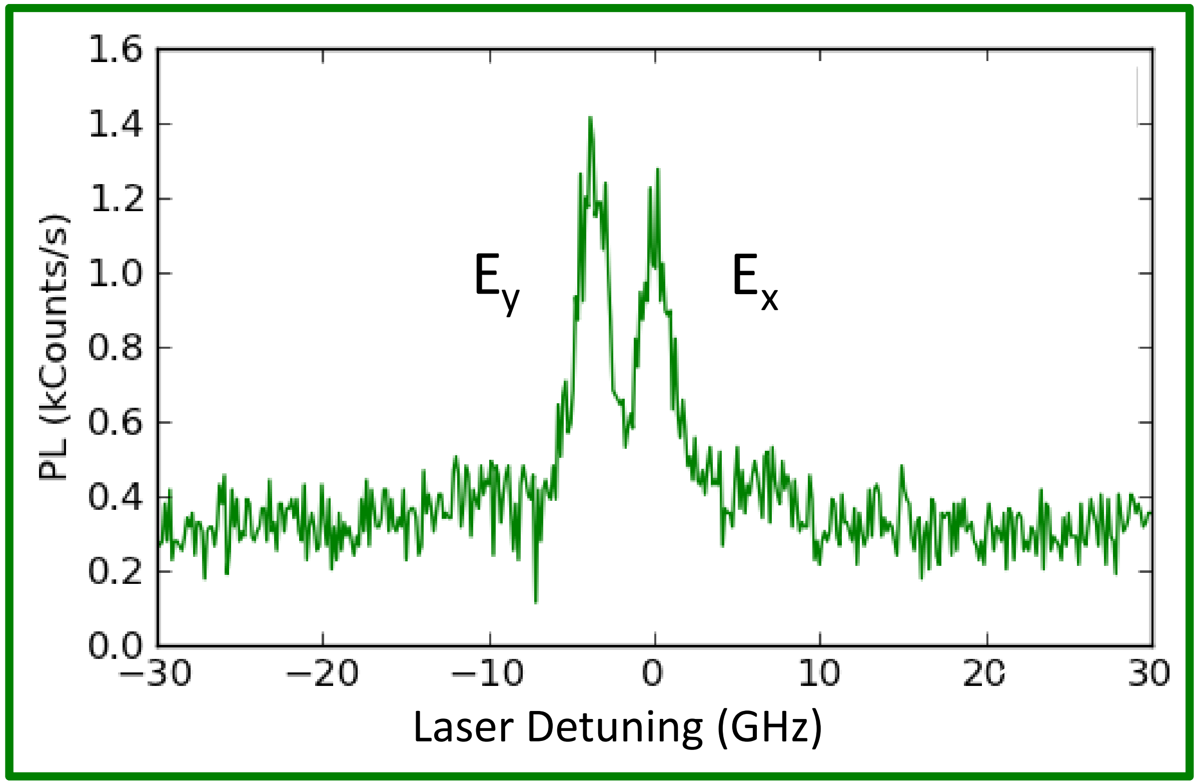
[1] S. Bennett, *et al, PRL* **110**, 156402 (2013).

Excited state spectroscopy of NV in cantilever

- Resonant excitation of NV center at 5 K

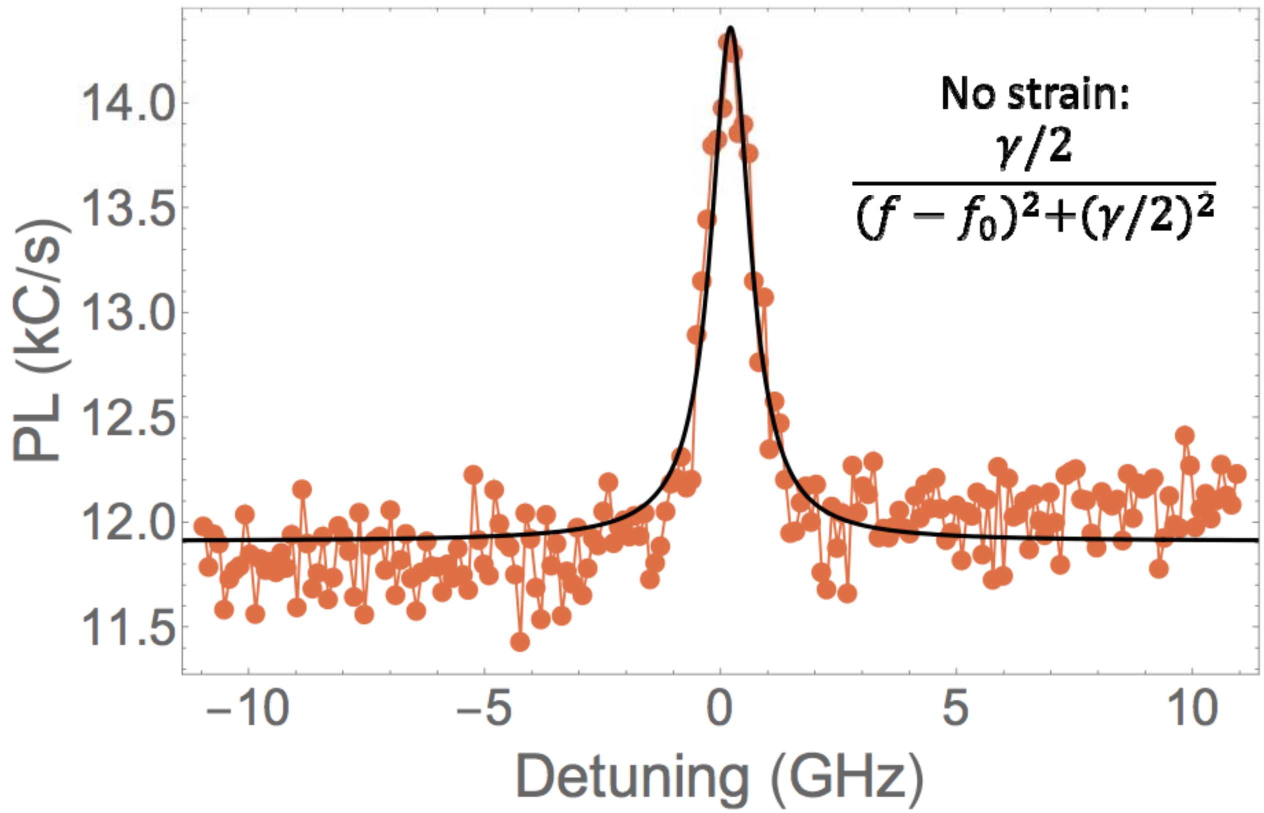


Photoluminescence excitation spectrum:

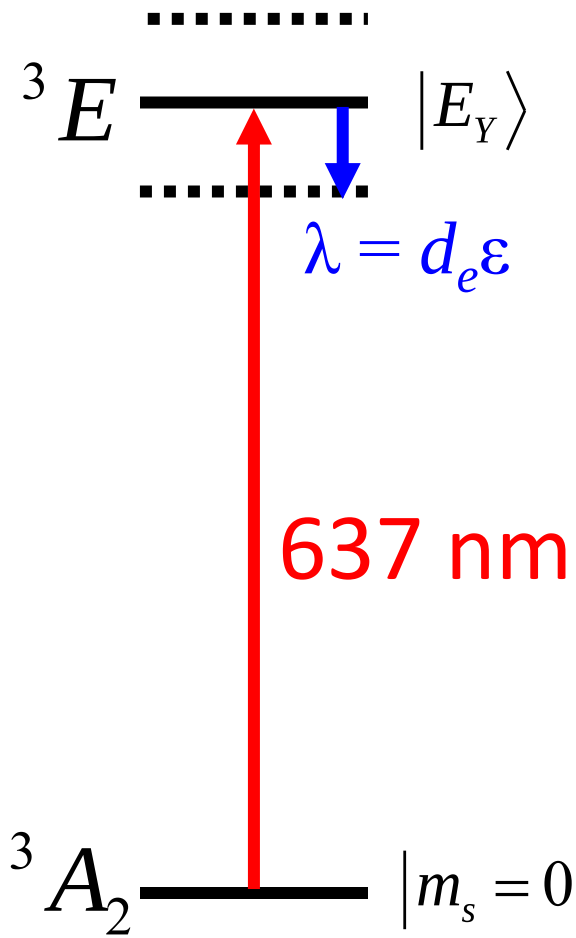


Excited state spectroscopy of NV in cantilever

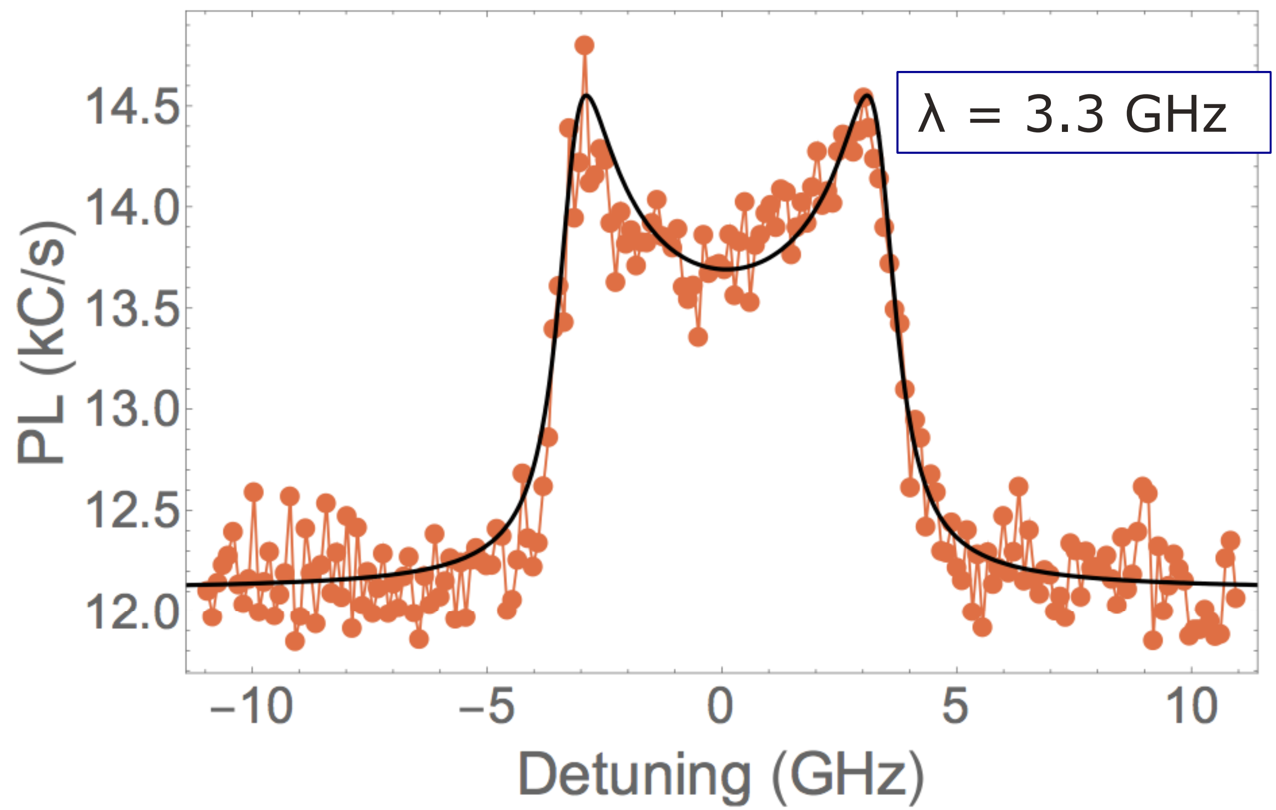
Photoluminescence excitation spectrum for stationary cantilever:



Strain induced modulation of NV excited state

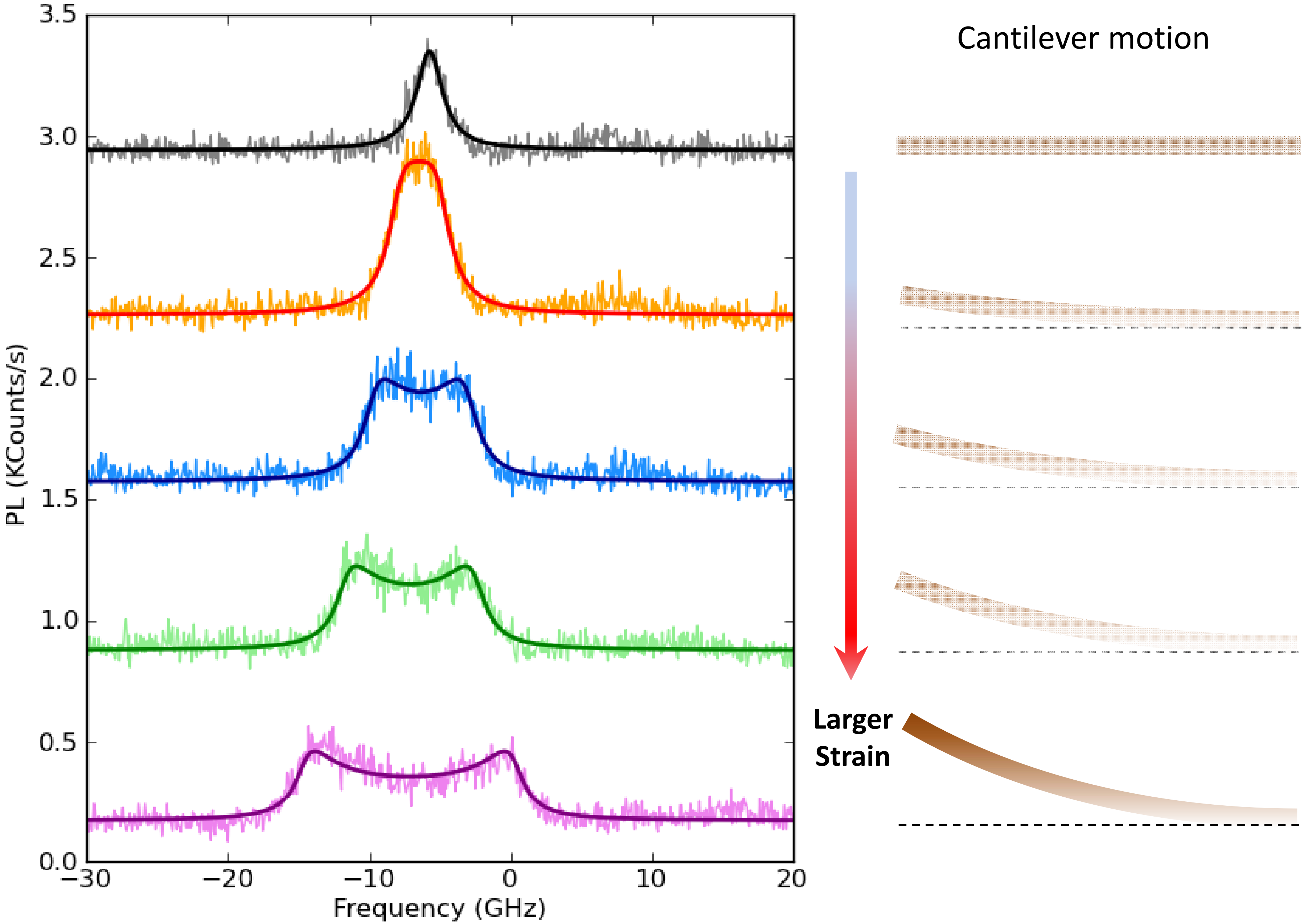


Photoluminescence excitation spectrum in the presence of 6 nm cantilever drive:

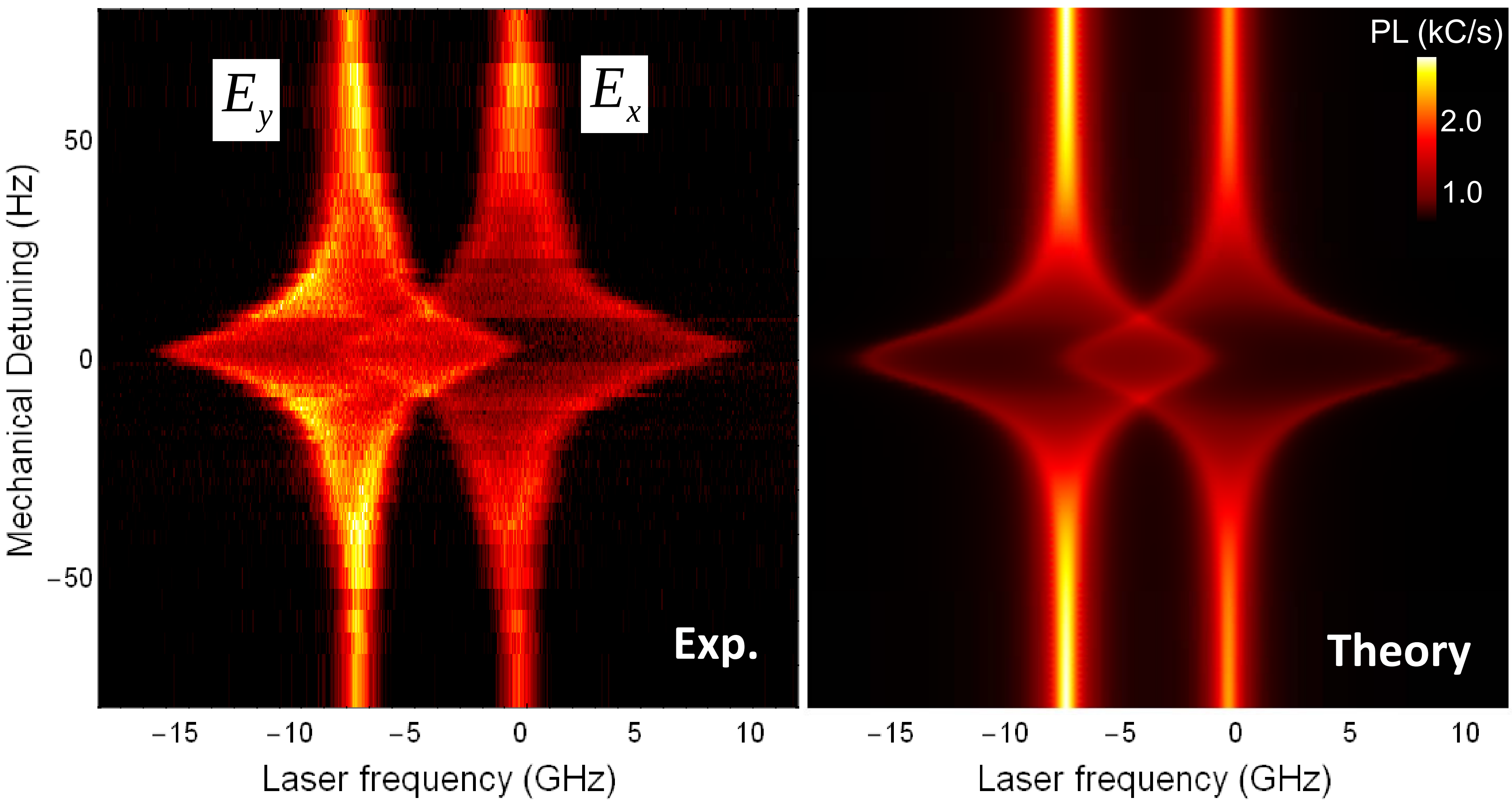


Fit: $$\int_0^t dt \frac{\gamma/2}{\{f - f_0 + \lambda \sin(2\pi f_m t)\}^2 + (\gamma/2)^2}$$

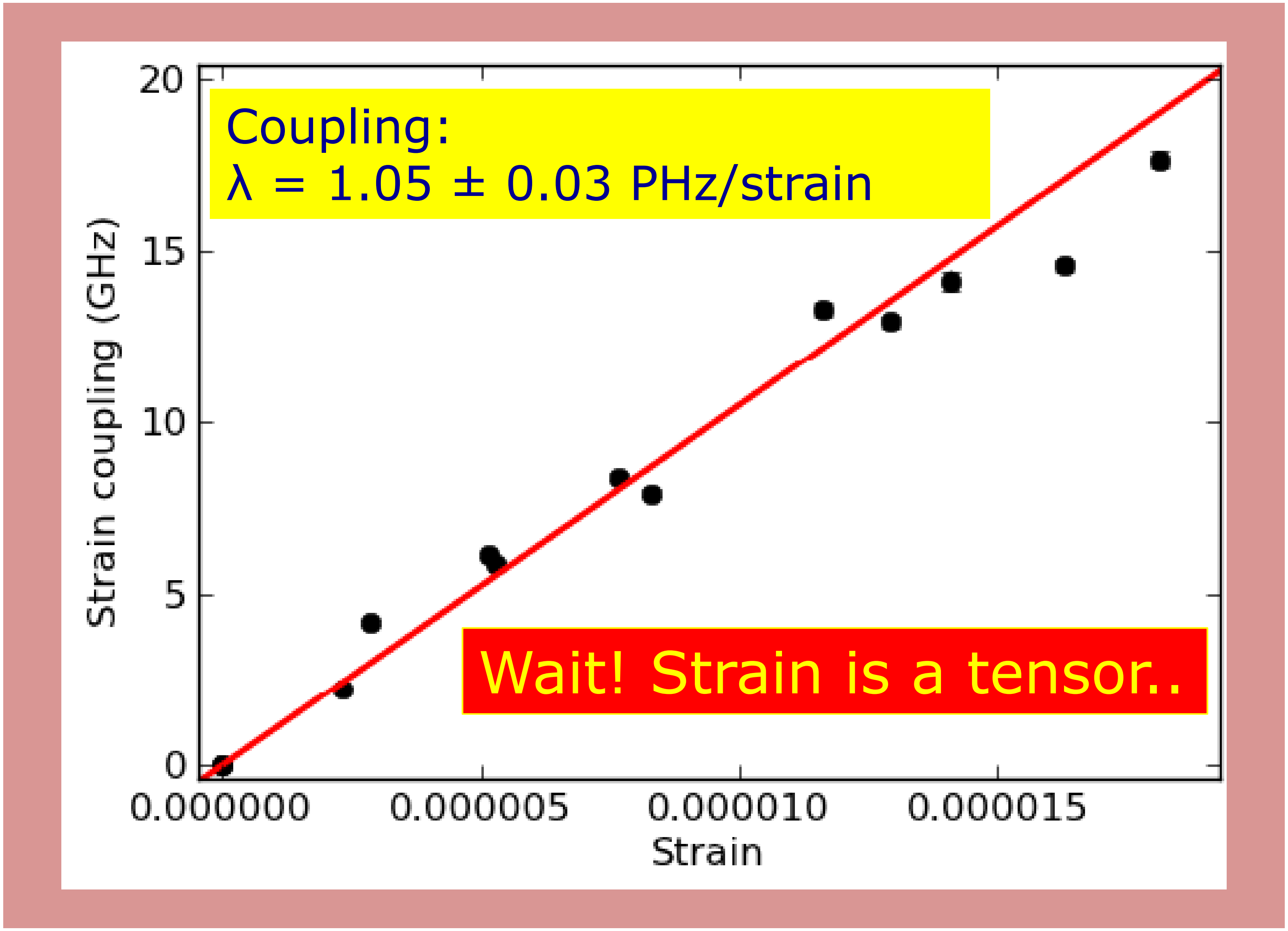
Strain induced modulation of NV excited state



Mechanical modulation of optical transitions



Strain coupling to NV excited state



But strain is a tensor…

Strain tensor:

$$\epsilon = \begin{pmatrix} \epsilon_{xx} & \epsilon_{xy} & \epsilon_{xz} \\ \epsilon_{xy} & \epsilon_{yy} & \epsilon_{yz} \\ \epsilon_{xz} & \epsilon_{yz} & \epsilon_{zz} \end{pmatrix}$$

NV-strain coupling characterized by 4 parameters:

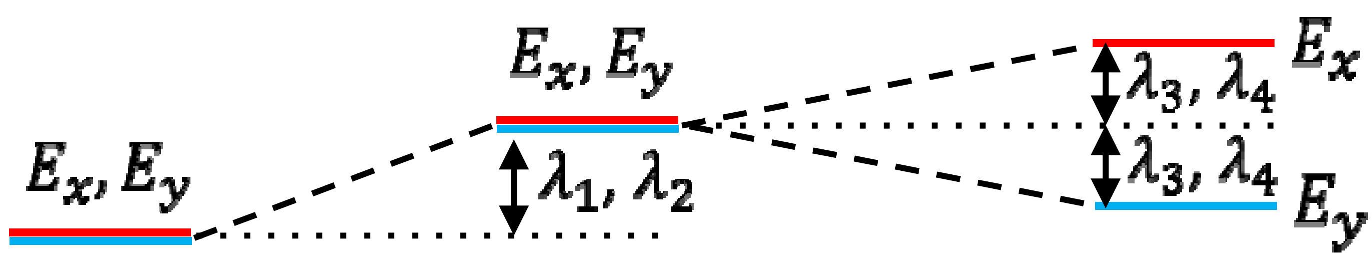
λ_1, λ_2: A_1 symmetry

λ_3, λ_4: E symmetry

E_x, E_y energies:

$$E_{x,y} = \lambda_1 \varepsilon_{zz} + \lambda_2(\varepsilon_{xx} + \varepsilon_{yy}) \pm \sqrt{\{\lambda_3(\varepsilon_{xx} - \varepsilon_{yy}) + \lambda_4(\varepsilon_{xz} + \varepsilon_{zx})\}^2 + \{\lambda_3(\varepsilon_{xy} + \varepsilon_{yx}) + \lambda_4(\varepsilon_{xz} + \varepsilon_{zx})\}^2}$$

No strain | Strain (A_1 symmetry) | Strain (E symmetry)



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NV-strain coupling characterized by 4 parameters:

λ_1, λ_2: A_1 symmetry

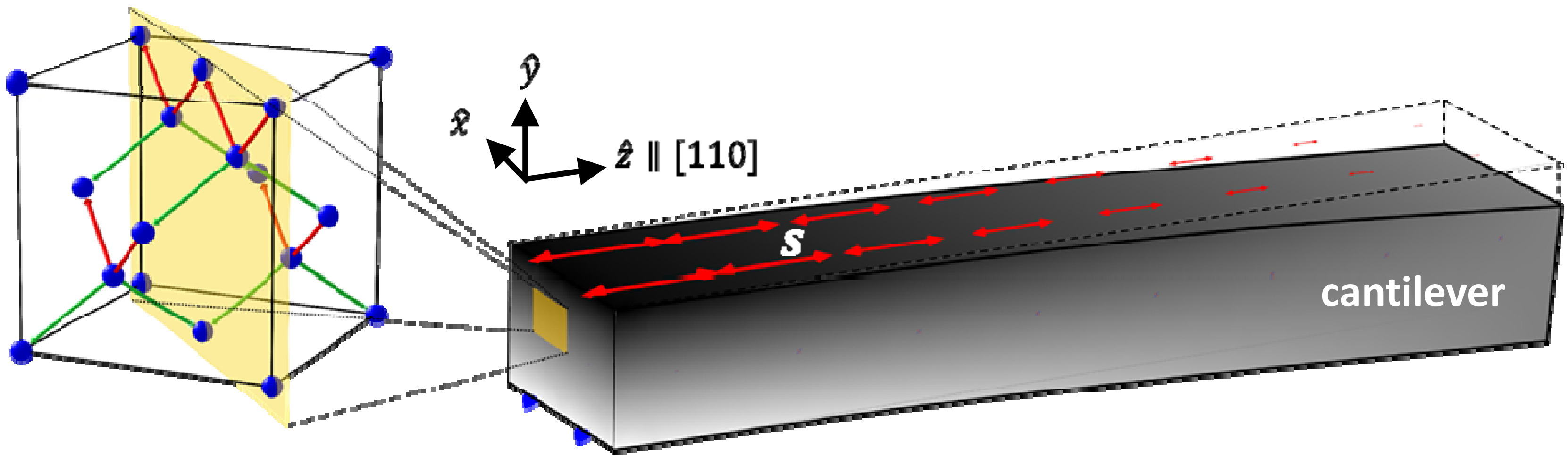
λ_3, λ_4: E symmetry

- We want to measure λ_1, λ_2, λ_3, and λ_4 carefully!

We utilize:

- Both E_x and E_y transitions
- Different NV orientations
- Photon polarization

Strain tensors for two groups of NVs



Strain tensor in cantilever coordinate system:

$$\varepsilon^{c} = \begin{pmatrix} -\nu s & 0 & 0 \\ 0 & -\nu s & 0 \\ 0 & 0 & s \end{pmatrix}$$

s : strain along cantilever axis
ν : Poisson ratio, 0.11

Strain tensor in NV coordinate

NV axis ∥ $[\bar{1}\bar{1}\bar{1}]$, $[11\bar{1}]$

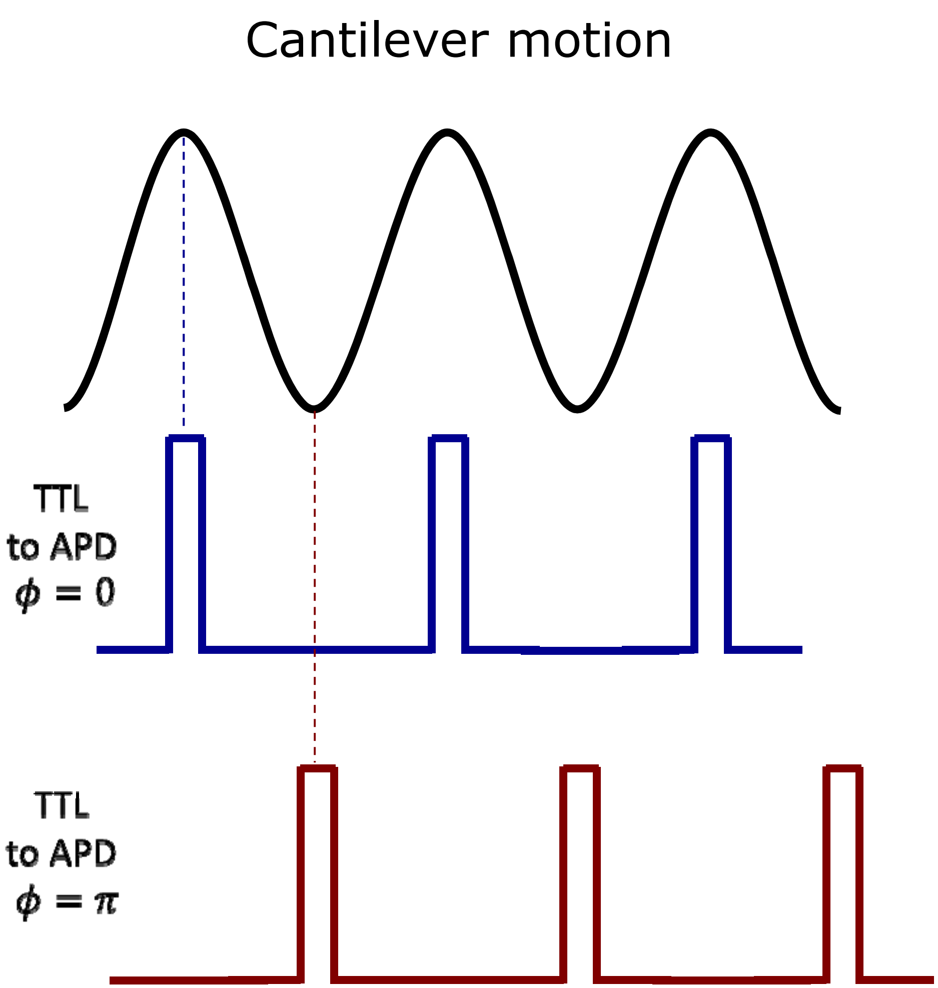
$$\varepsilon^{NV} = \begin{pmatrix} \frac{s}{3}(1-2\nu) & 0 & -\frac{\sqrt{2}s}{3}(1+\nu) \\ 0 & -\nu s & 0 \\ -\frac{\sqrt{2}s}{3}(1+\nu) & 0 & \frac{s}{3}(2-\nu) \end{pmatrix}$$

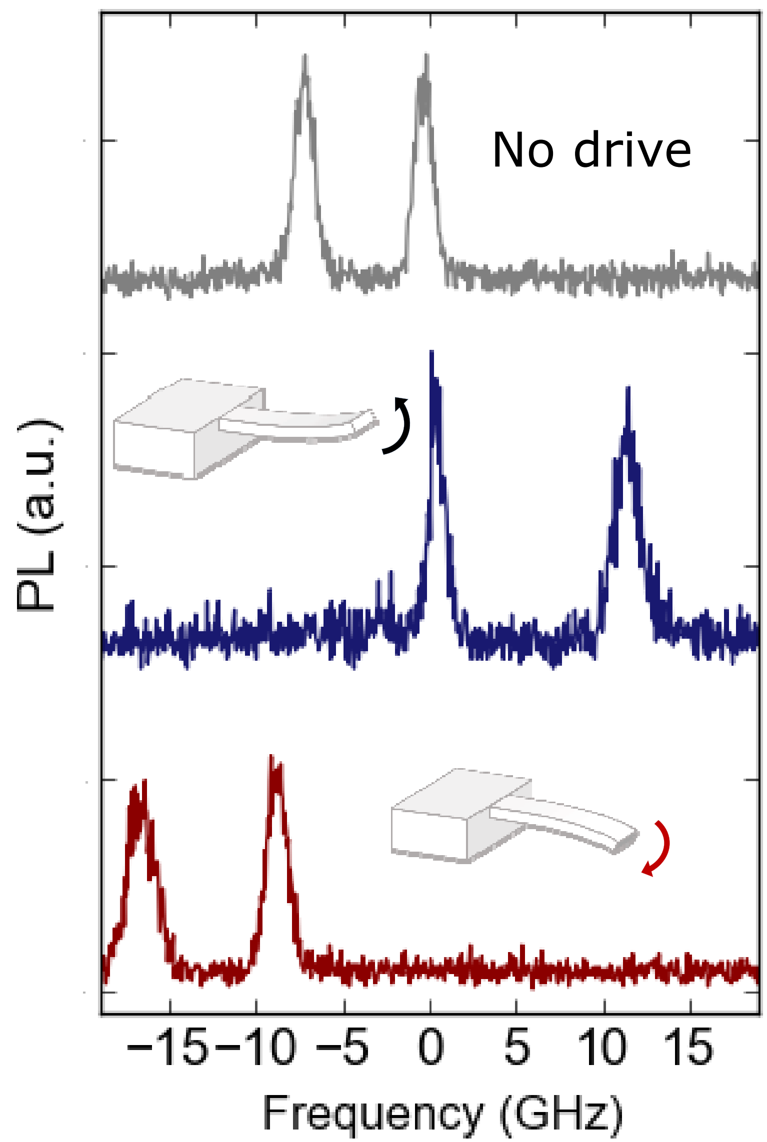
Strain tensor in NV coordinate

NV axis ∥ $[\bar{1}11]$, $[1\bar{1}1]$

$$\varepsilon^{NV} = \begin{pmatrix} -\nu s & 0 & 0 \\ 0 & s & 0 \\ 0 & 0 & -\nu s \end{pmatrix}$$

Stroboscopy: a quasi-DC measurement

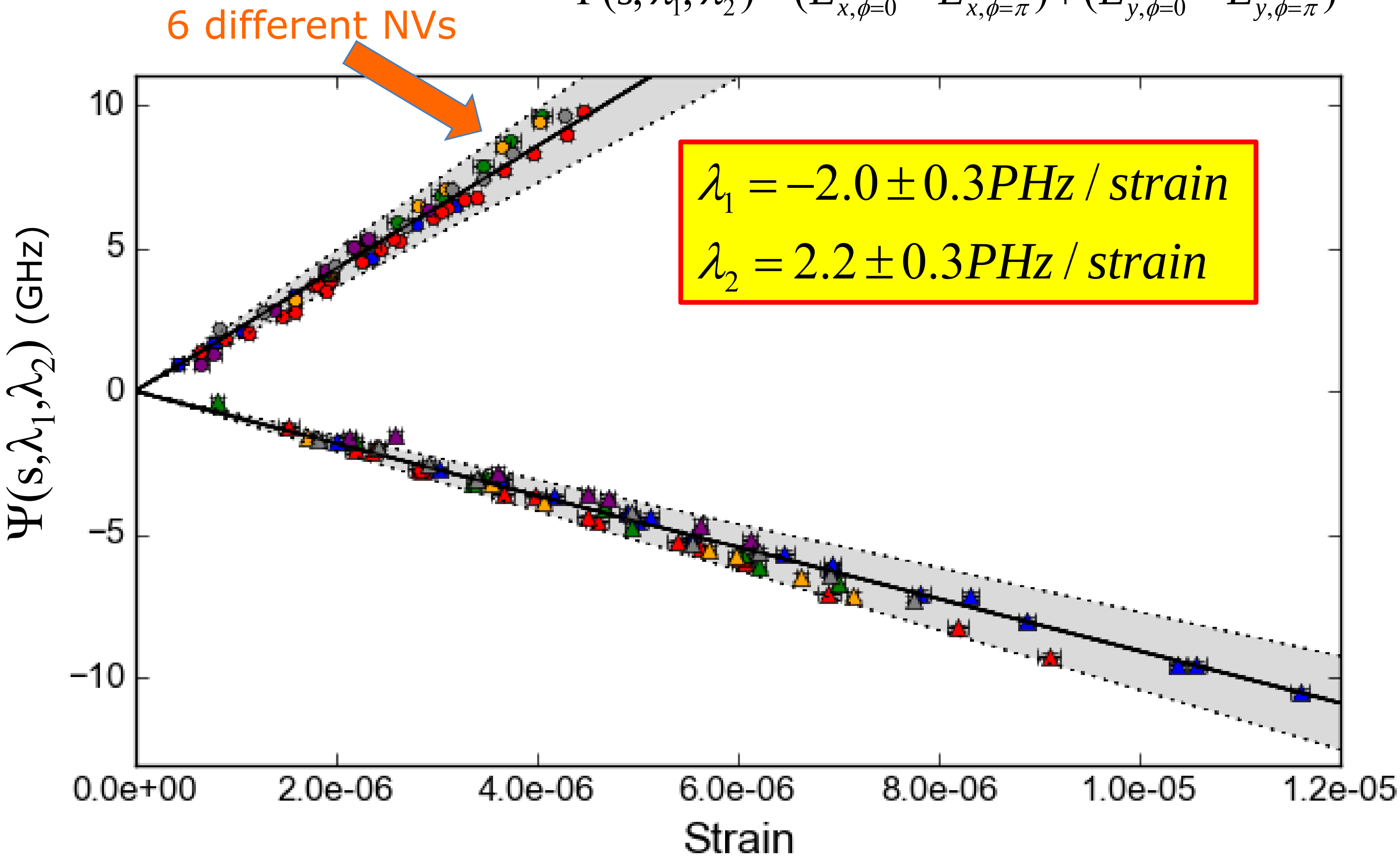




Extracting A_1-symmetric coupling parameters (λ_1 and λ_2)

- Constructed a quantity that only depends on λ_1 and λ_2:

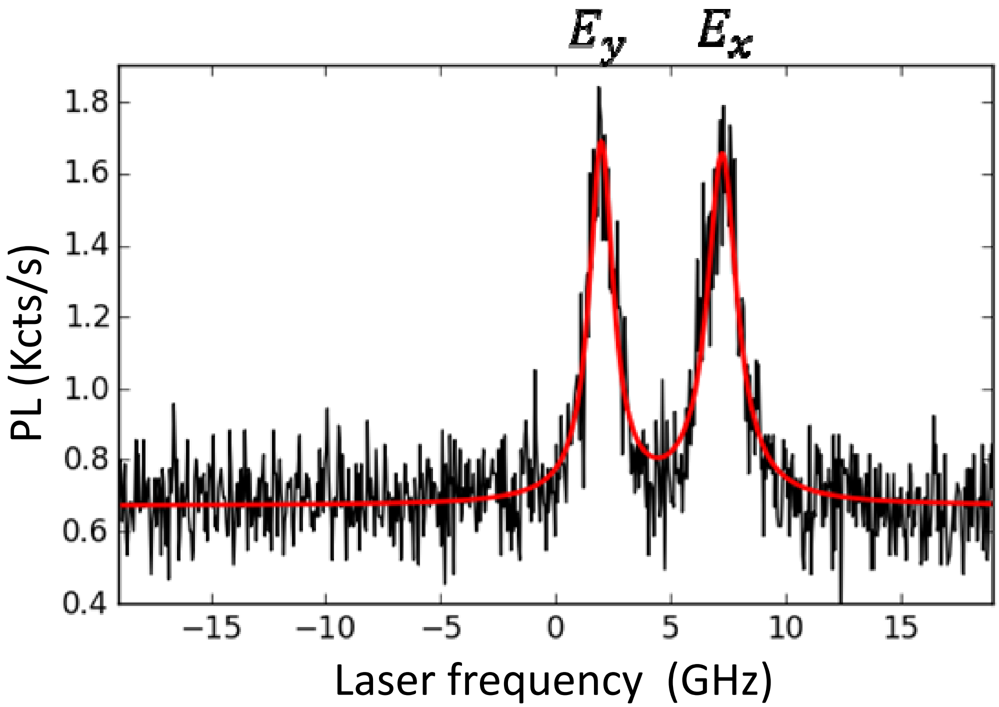
$$\Psi(s,\lambda_1,\lambda_2)=(E_{x,\phi=0}-E_{x,\phi=\pi})+(E_{y,\phi=0}-E_{y,\phi=\pi})$$



$$\lambda_1=-2.0\pm0.3PHz/strain$$
$$\lambda_2=2.2\pm0.3PHz/strain$$

Role of intrinsic strain

- Without cantilever motion, the NV experiences intrinsic strain:



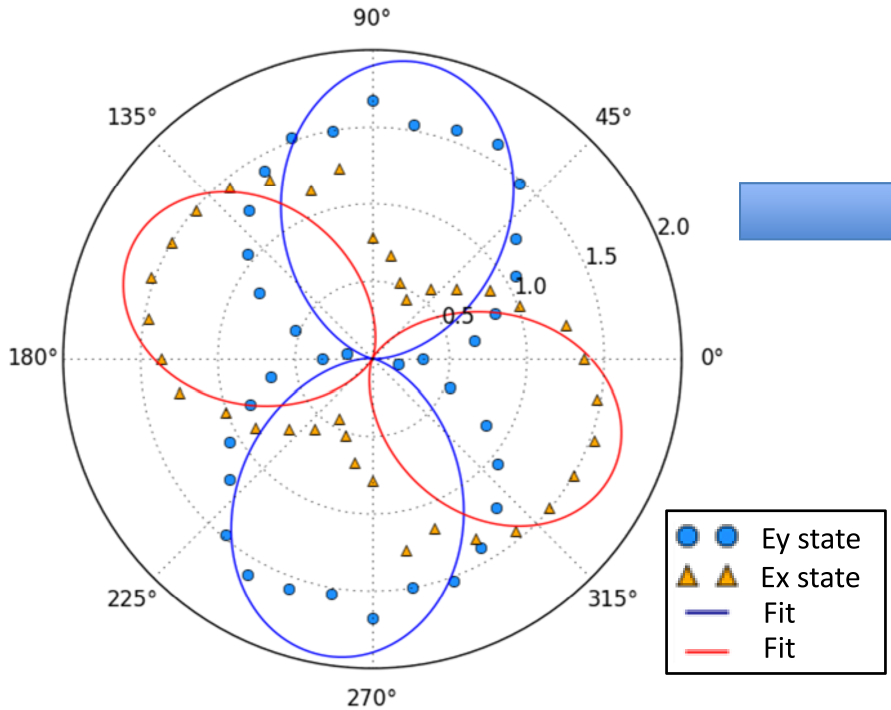
- But direction of the intrinsic strain (E-type) is important for λ_3 and λ_4!

$$E_{x,y} = \lambda_1 \varepsilon_{zz} + \lambda_2(\varepsilon_{xx} + \varepsilon_{yy}) \pm \sqrt{\{\lambda_3(\varepsilon_{xx} - \varepsilon_{yy}) + \lambda_4(\varepsilon_{xz} + \varepsilon_{zx}) + V_{E1}\}^2 + \{\lambda_3(\varepsilon_{xy} + \varepsilon_{yx}) + \lambda_4(\varepsilon_{xz} + \varepsilon_{zx}) + V_{E2}\}^2}$$

- How do we know the direction of the intrinsic strain??

Polarization and strain

Polarization angle of E_x and E_y states:

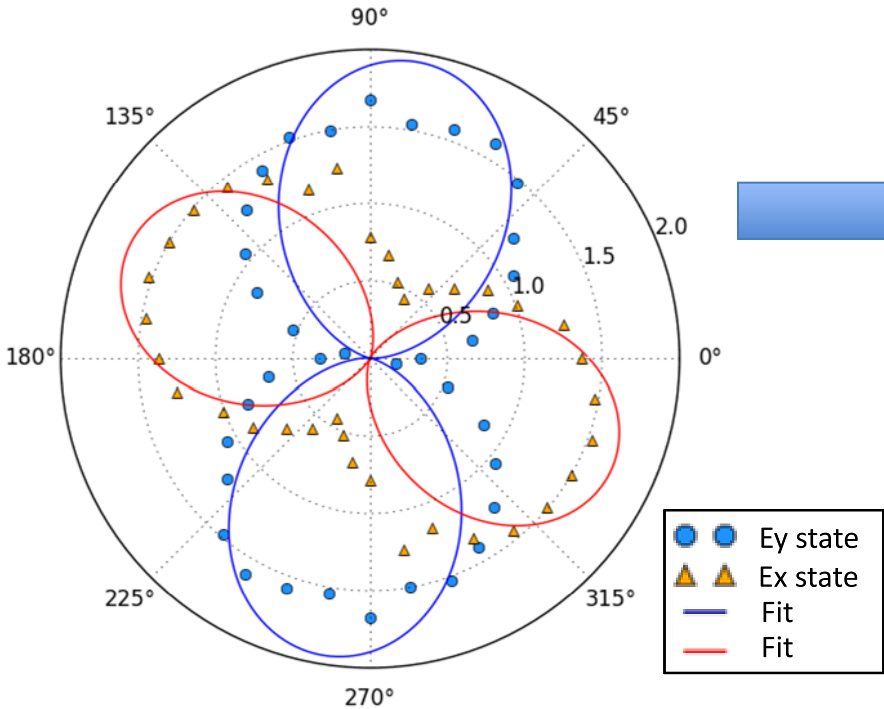


$$\theta = \frac{1}{2}\arctan(V_{E2}/V_{E1})$$

Still only gives us a ratio..

Polarization and strain

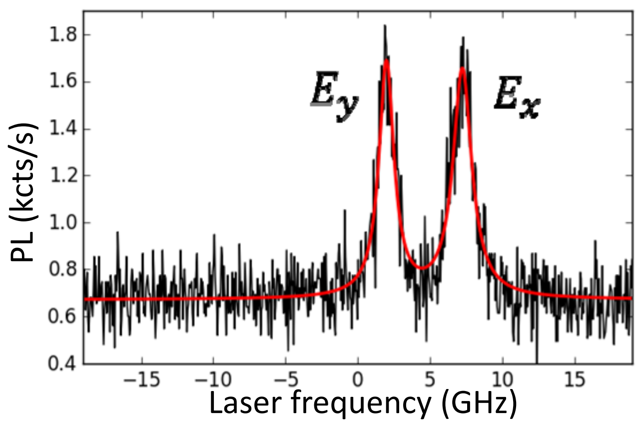
Polarization angle of E_x and E_y states:



$$\theta = \frac{1}{2}\arctan(V_{E2}/V_{E1})$$

Still only gives us a ratio..

Intrinsic strain splitting:

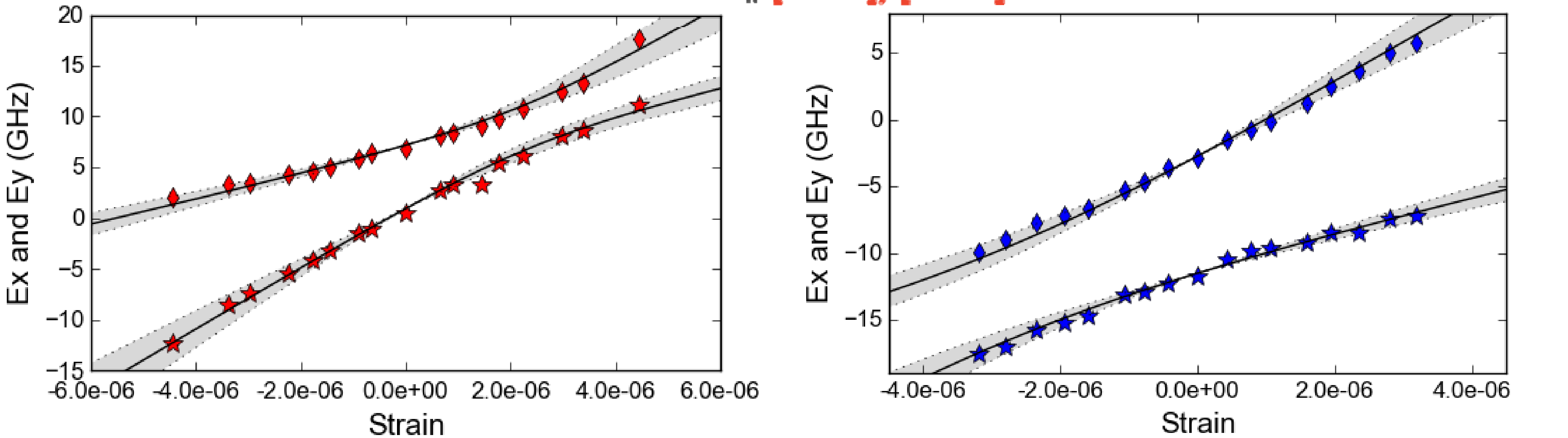


$$E_x - E_y = 2\sqrt{{V_{E1}}^2 + {V_{E2}}^2}$$

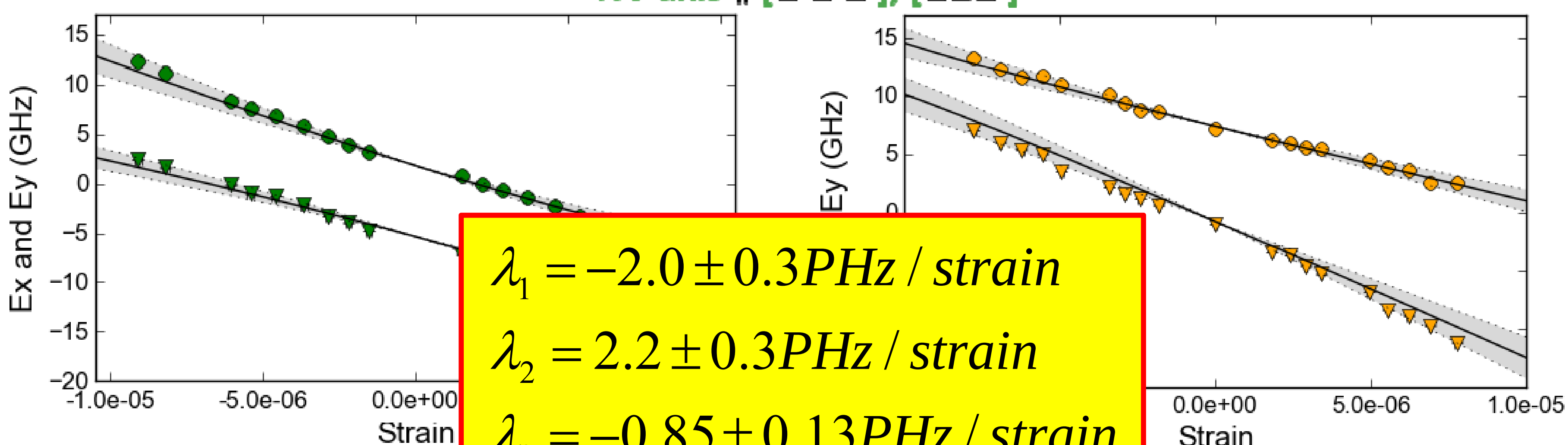
Now, we know V_{E1} and V_{E2}!!

Extracting λ_3 and λ_4

NV axis ‖ [1 11], [11 1]



NV axis ‖ [1 1 1], [111]



$$\lambda_1 = -2.0 \pm 0.3 PHz / strain$$

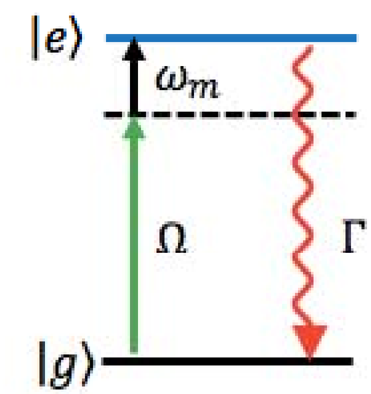
$$\lambda_2 = 2.2 \pm 0.3 PHz / strain$$

$$\lambda_3 = -0.85 \pm 0.13 PHz / strain$$

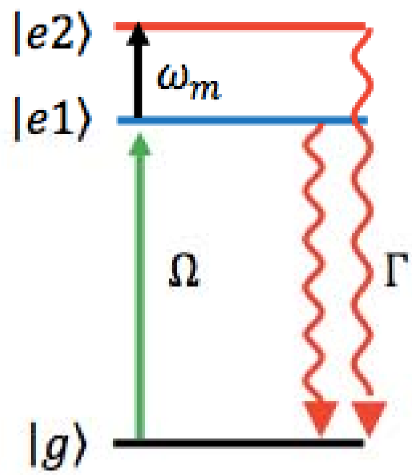
$$\lambda_4 = 0.02 \pm 0.01 PHz / strain$$

Toward phonon cooling

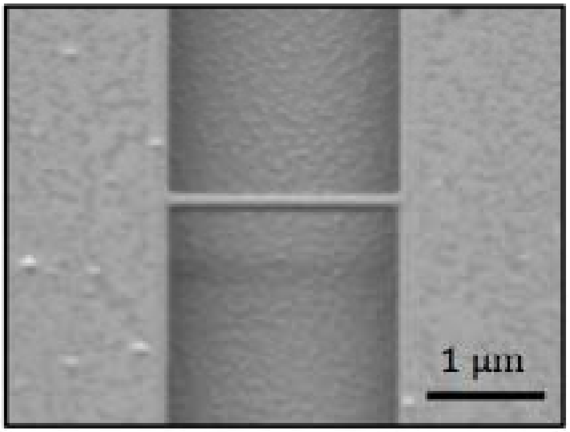
Off-resonant cooling



Resonant cooling



Kepesidis *et al*., *PRB* **88**, 064105 (2013).



System parameters:

- 2 μm × 100 nm × 50 nm
- Q = 5 × 10^5
- T = 4 K
- λ_{off} = 1 PHz/strain
- λ_{on} = 1 PHz/strain
- Ω = 100 MHz
- Γ = 500 MHz

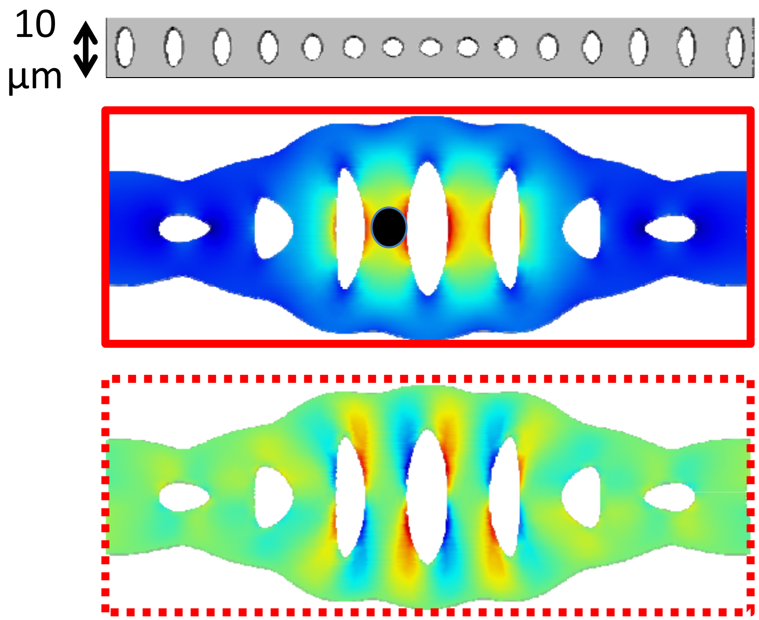
$$\tilde{\Gamma}_{off} \approx \frac{{\lambda_{off}}^2}{\Gamma}\frac{\Omega^2}{{\omega_m}^2}$$

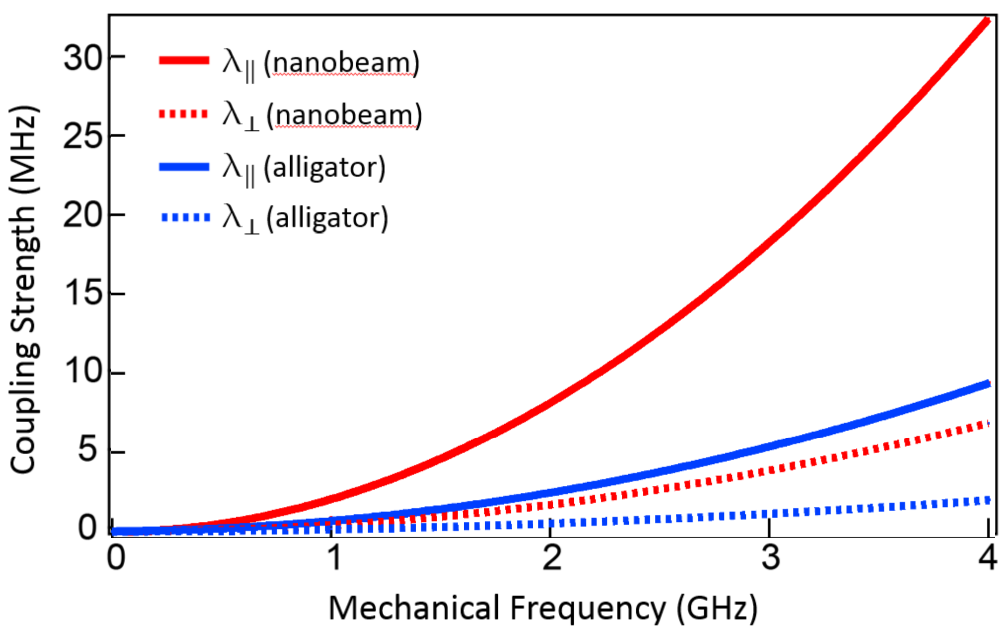
$$\tilde{\Gamma}_{on} \approx \frac{{\lambda_{on}}^2}{\Gamma}\frac{4\Omega^2}{\Gamma^2}$$

$$n_{off} \approx \frac{\gamma N_{th}}{\tilde{\Gamma}_{off}} \approx 4$$

$$n_{on} \approx \frac{\gamma N_{th}}{\tilde{\Gamma}_{on}} \approx 0.9$$

Strain coupling in diamond mechanical crystals





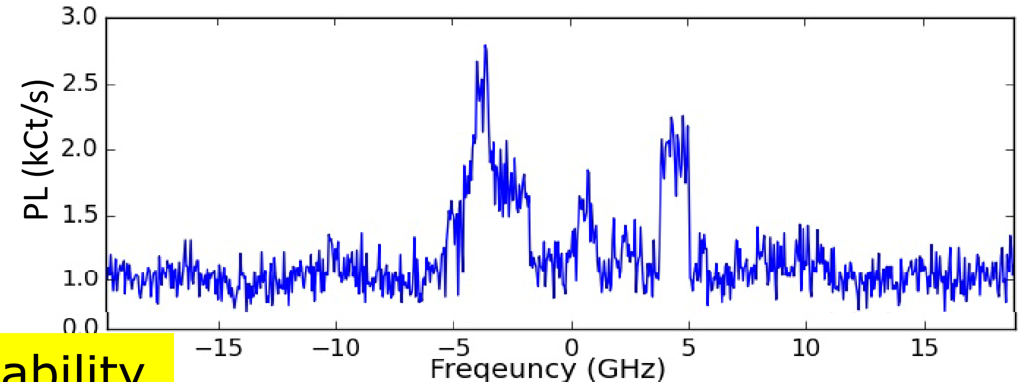
f_0 = 500 MHz

T = 4 K,Q = 10^5:

$n_f < 1$

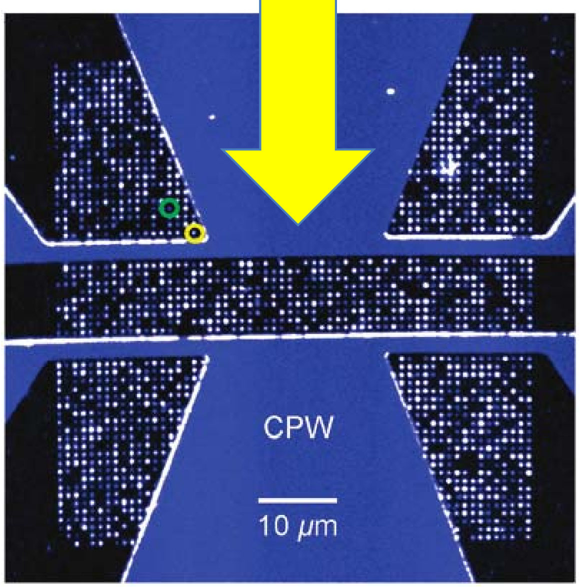
Challenge: NV quantum memories/spin-photon entanglement

Challenge: NV spectral diffusion

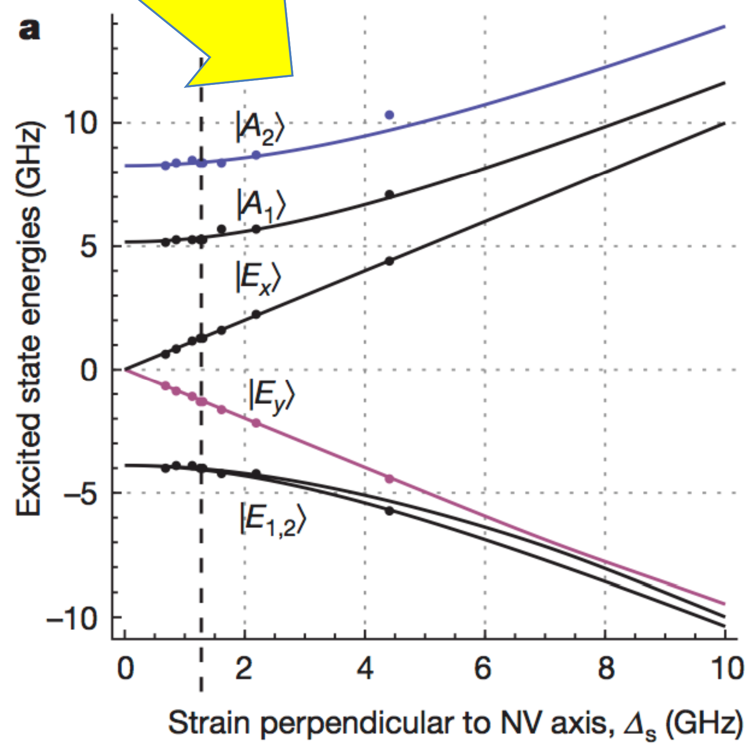


Challenge: indistinguishability of NV's due to local strain

Challenge: deterministic placement of NV's

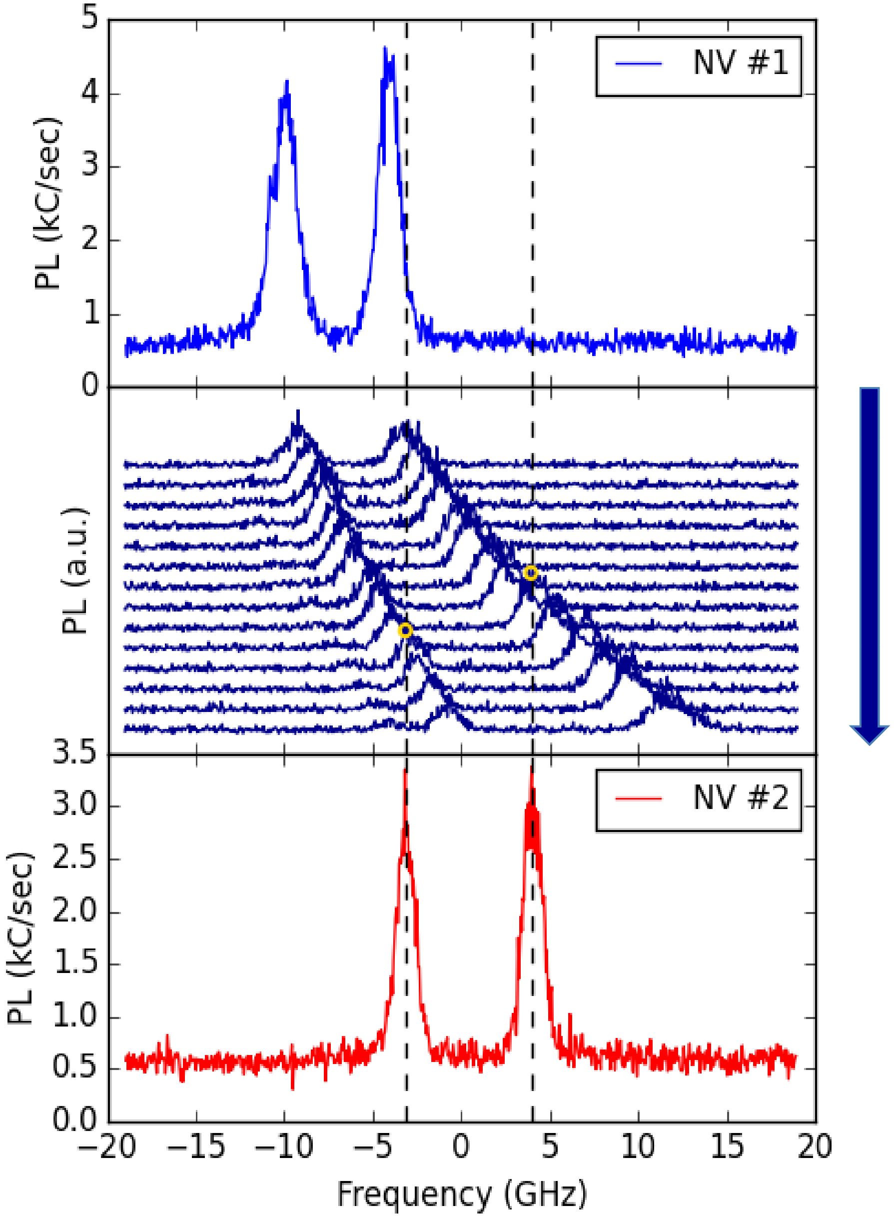


D. Toyli *et al*. *Nano Lett.* **10** (2010)



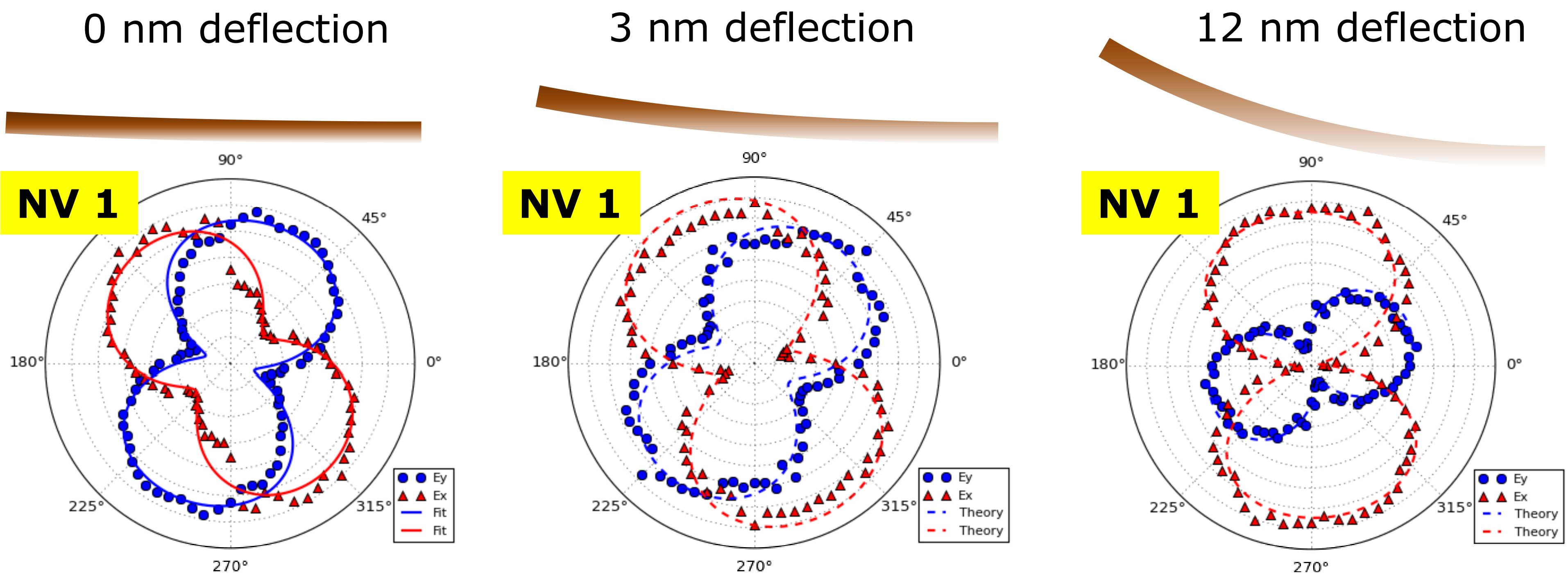
Togan et al, Nature 466, 730 (2010)

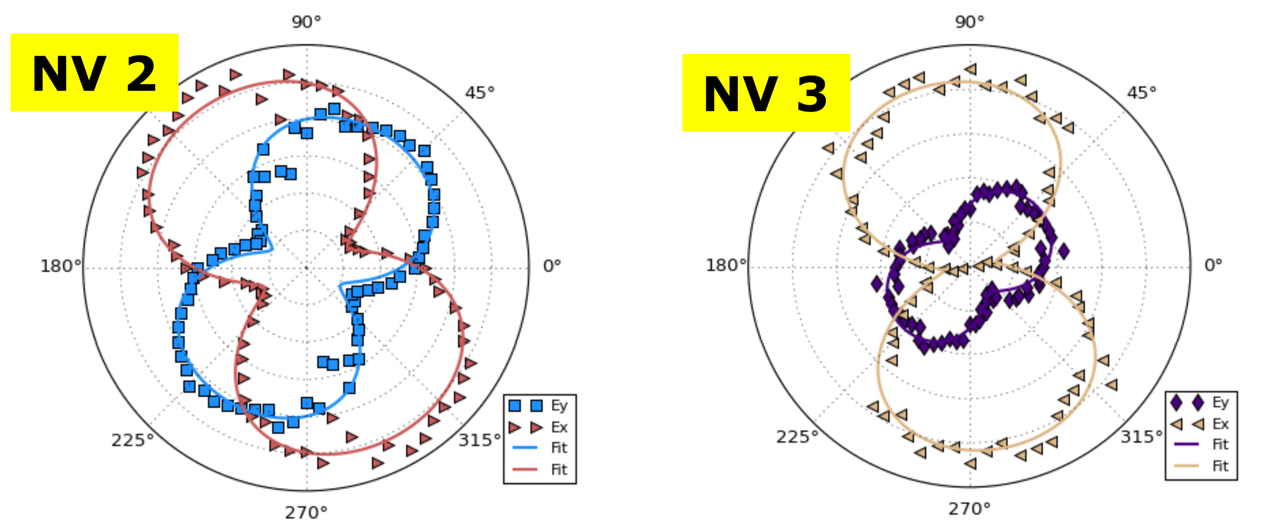
Strain tuning two NVs into resonance



- NV#1 and NV#2 are initially distinguishable due to strain inhomogeneities in crystal
- Increasing cantilever oscillation amplitude (data is only taken at one extremum of cantilever motion)
- Matched optical transition energies of NV#1 and NV#2 through motionally-induced strain

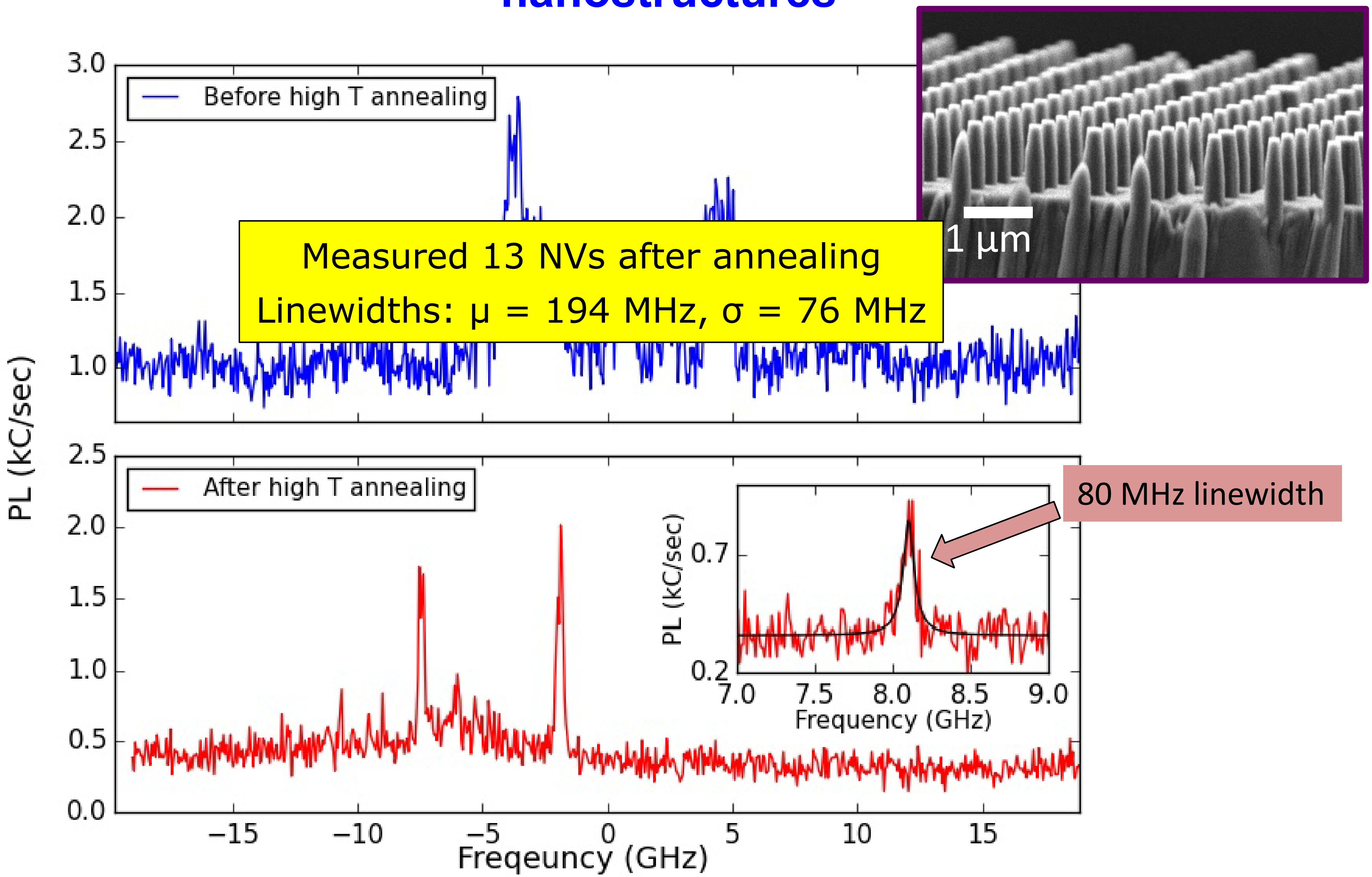
On-chip strain control of polarization state





- Emitted photon polarization depends on intrinsic strain

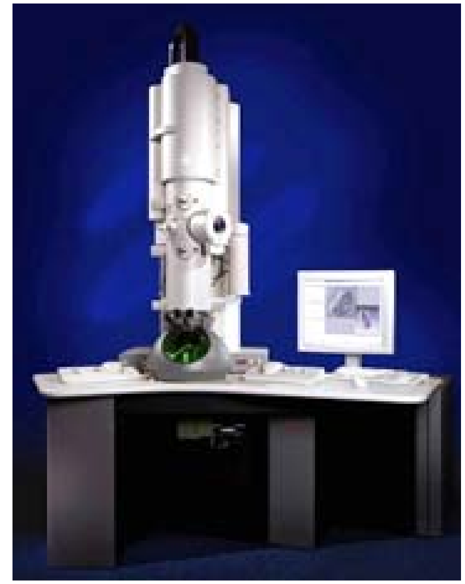
Suppressing spectral diffusion in nanostructures

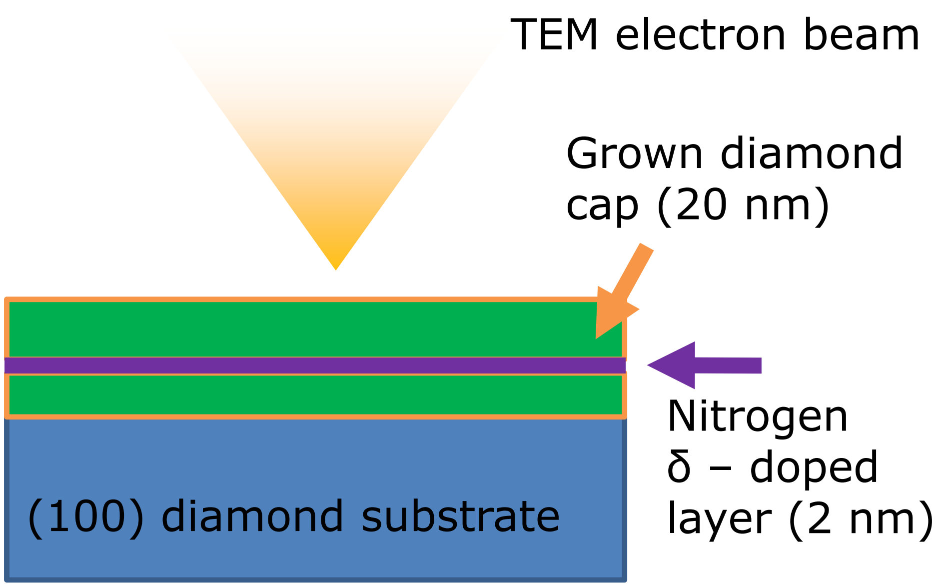


Nanoscale localization of NV centers

- Vacancies introduced via transmission electron microscope (TEM) allows for

  3-d nanoscale NV localization

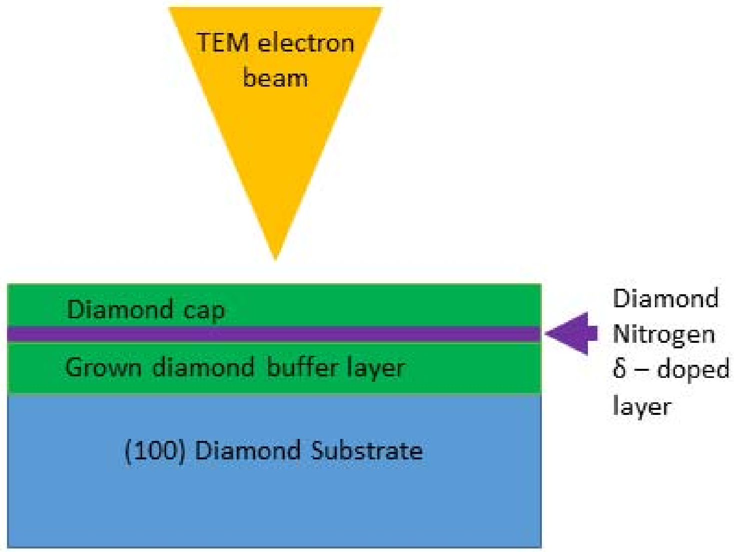


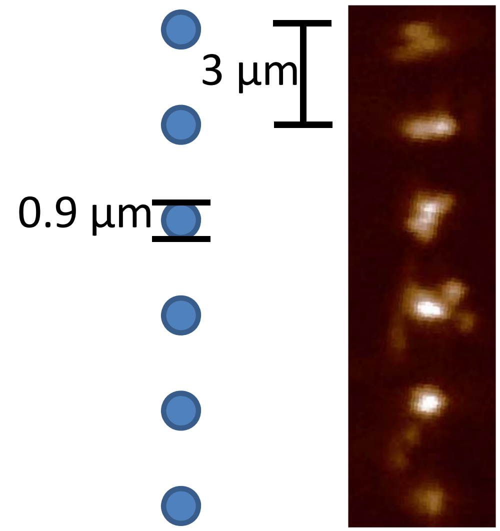


- Can finely tune dose, flux, and energy of electrons
- Can focus electron beam to give nanoscale spatial resolution

Ohno, *et al*, *APL* **101**, 082413 (2012)
Myers *et al, PRL* **113**, 027602 (2014)
McLellan *et al, in preparation*

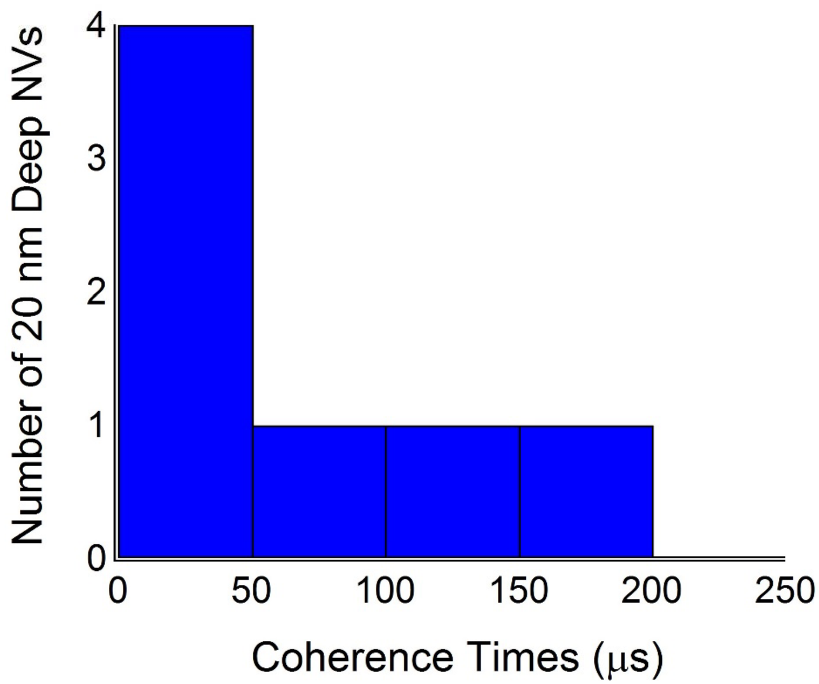
Patterned, highly coherent NV centers





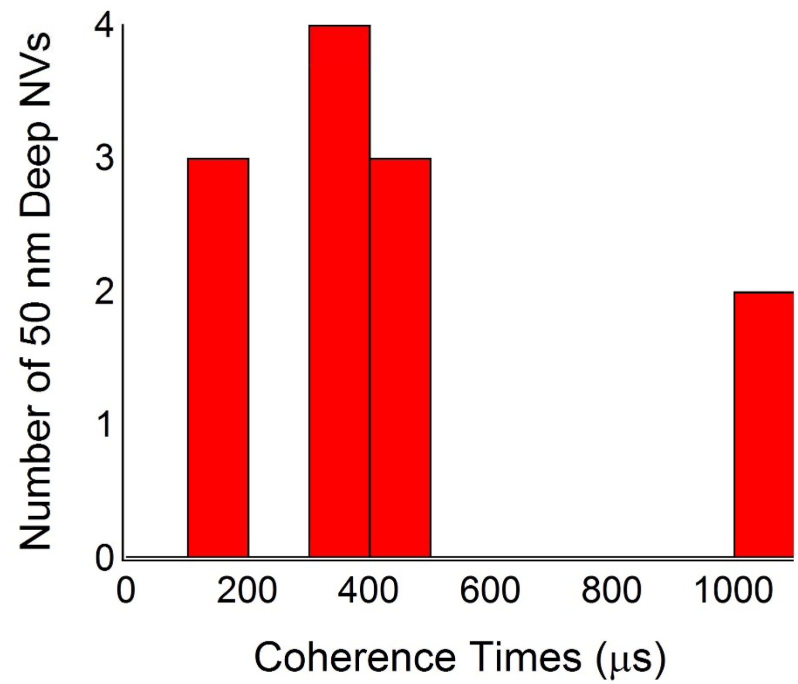
Coherence time spread

20 nm deep NV coherence times



- $T_{2,avg}$ = 65 μs

50 nm deep NV coherence times



- $T_{2,avg}$ = 442 μs

Coherence times are long, even at the highest NV densities with > 10 NV's/⌠m²

Summary

- Strain coupling to ground spin states and excited orbital states
- Tunable control over energy and polarization via strain
- Annealing to significantly reduce spectral diffusion
- Deterministic patterning of highly coherent NV centers