# The nitrogen vacancy center: exploring spin dynamics in diamond

**Lily Childress**
**Bates College**
**CUWP, Yale University**
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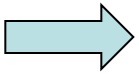
# Quantum mechanics:

## A new way to encode information



*A new way to communicate*

*A new way to compute*

**Classical information**

Encoded in classical bits = classical systems with two possible values

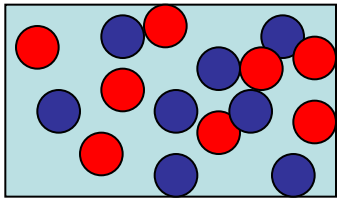
**Quantum information**

Encoded in quantum bits = quantum systems that can be any superposition of two quantum states

# Classical vs quantum bits

$\downarrow$ or $\uparrow$

Statistical mixture of the two states



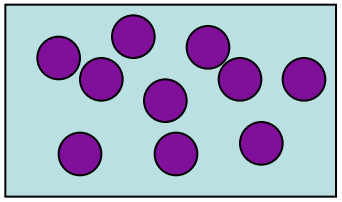
$|\downarrow\rangle$ or $|\uparrow\rangle$ or $\alpha|\downarrow\rangle + \beta|\uparrow\rangle$

Key concept: well defined phase

$|\downarrow\rangle + |\uparrow\rangle$ $\quad$ $|\downarrow\rangle - |\uparrow\rangle$

Orthogonal states

Coherent superposition!



- Possible measurements:

Only one basis:

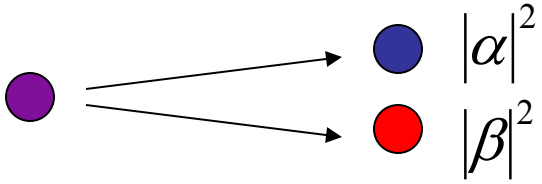
$\downarrow$ or $\uparrow$

Many possible bases:

$|\downarrow\rangle$ or $|\uparrow\rangle$

$|\downarrow\rangle + |\uparrow\rangle$ or $|\downarrow\rangle - |\uparrow\rangle$

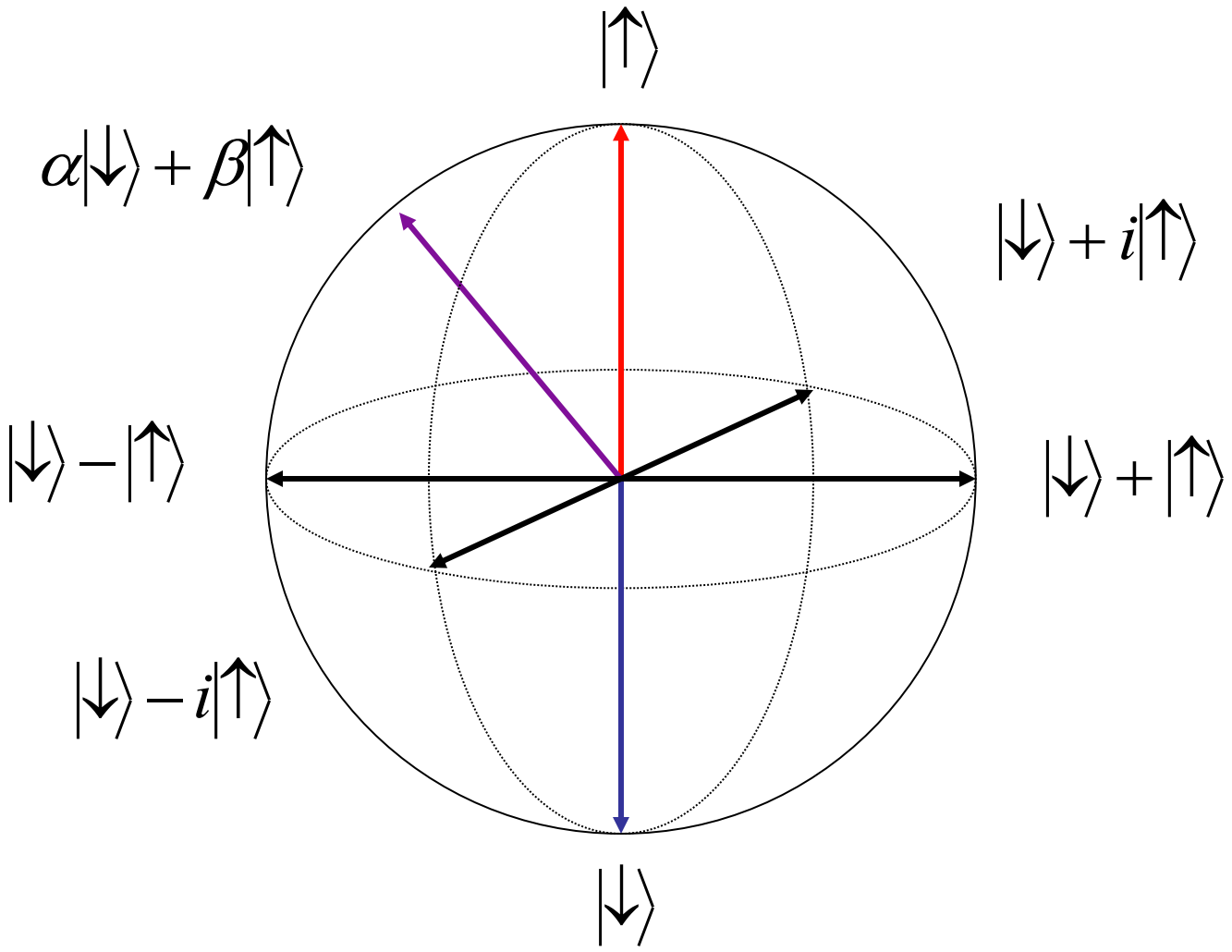
$\alpha|\downarrow\rangle + \beta|\uparrow\rangle$ or $\beta|\downarrow\rangle - \alpha|\uparrow\rangle$




Measurement does not change the state of the classical bit

Measurement collapses the quantum superposition onto the state that you measure

# Classical bits vs quantum bits: The Bloch sphere picture

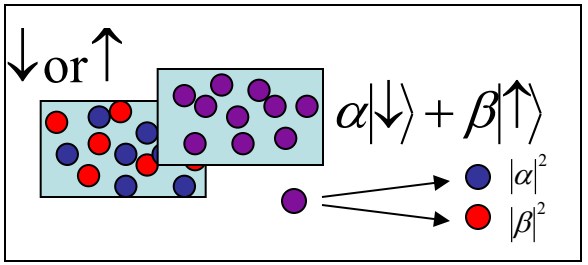


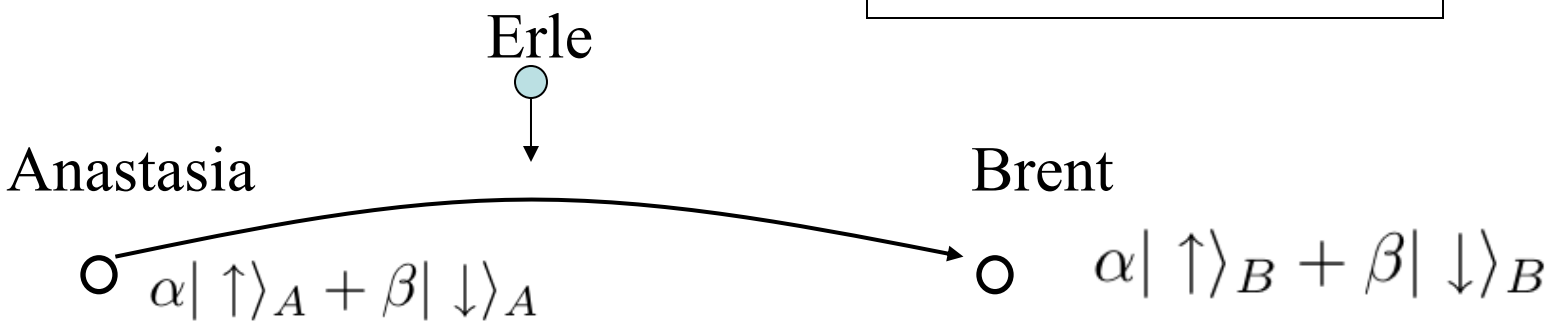
# Quantum states:

## A new way to encode information

*A new way to communicate*

*A new way to compute*



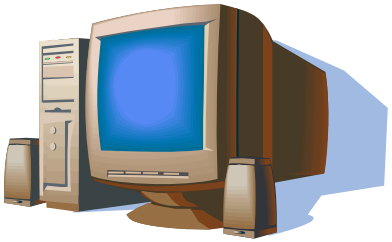

Quantum mechanics: Erle can't listen in!

$$(\alpha|\downarrow_A\rangle + \beta|\uparrow_A\rangle)|\downarrow_E\rangle \rightarrow (\alpha|\downarrow_A\rangle + \beta|\uparrow_A\rangle)(\alpha|\downarrow_E\rangle + \beta|\uparrow_E\rangle)$$

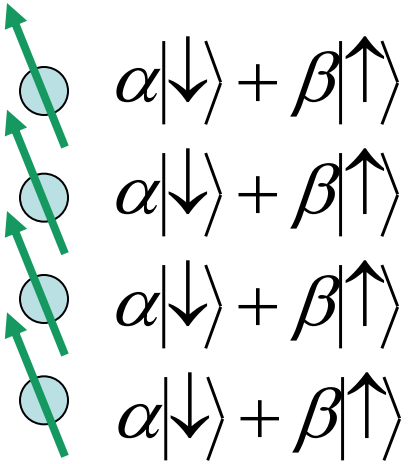
# Quantum states:

## a new way to compute

Feynman:



$\neq$




Quantum parallelism

$$\left.\begin{array}{l}(|\downarrow_1\rangle + |\uparrow_1\rangle)\\(|\downarrow_2\rangle + |\uparrow_2\rangle)\\(|\downarrow_3\rangle + |\uparrow_3\rangle)\\(|\downarrow_4\rangle + |\uparrow_4\rangle)\end{array}\right\} = |\downarrow_1\downarrow_2\downarrow_3\downarrow_4\rangle + |\uparrow_1\downarrow_2\downarrow_3\downarrow_4\rangle + |\downarrow_1\uparrow_2\downarrow_3\downarrow_4\rangle + |\downarrow_1\downarrow_2\uparrow_3\downarrow_4\rangle + \ldots$$

*N quantum bits encode $2^N$ quantum states*

*Quantum computations manipulate $2^N$ superposed quantum states simultaneously*

Exponential speedup possible*

# Quantum states:
# A new way to encode information

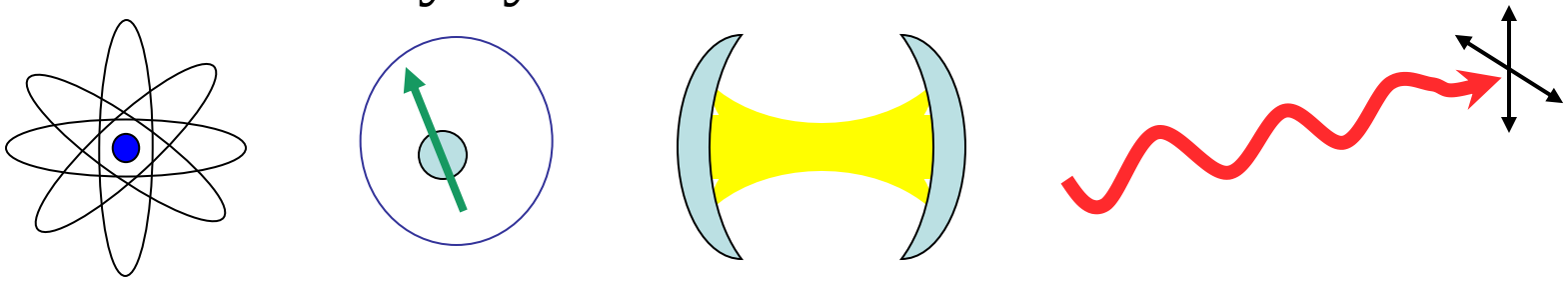
*A new way to communicate*

*A new way to compute*

**Challenge: implementation**

(It's hard to maintain coherence!)

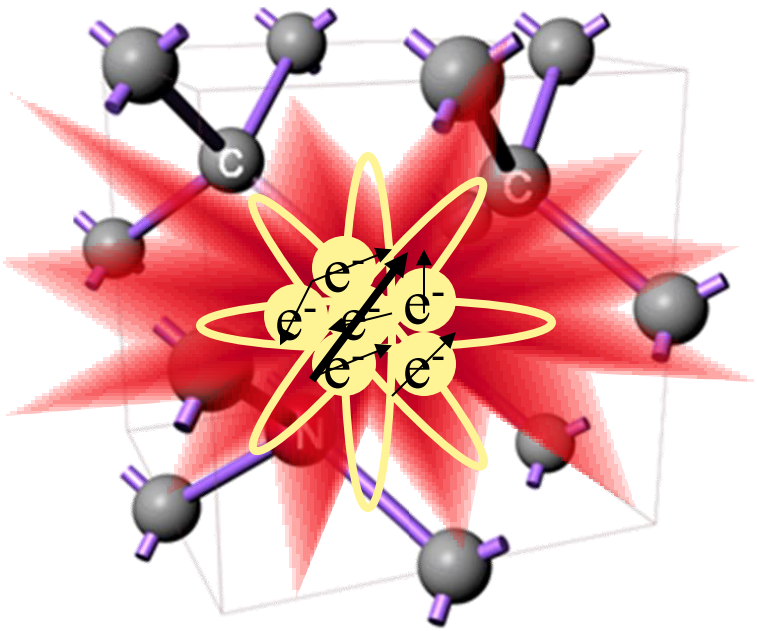
Potential laboratory systems:



Our work:

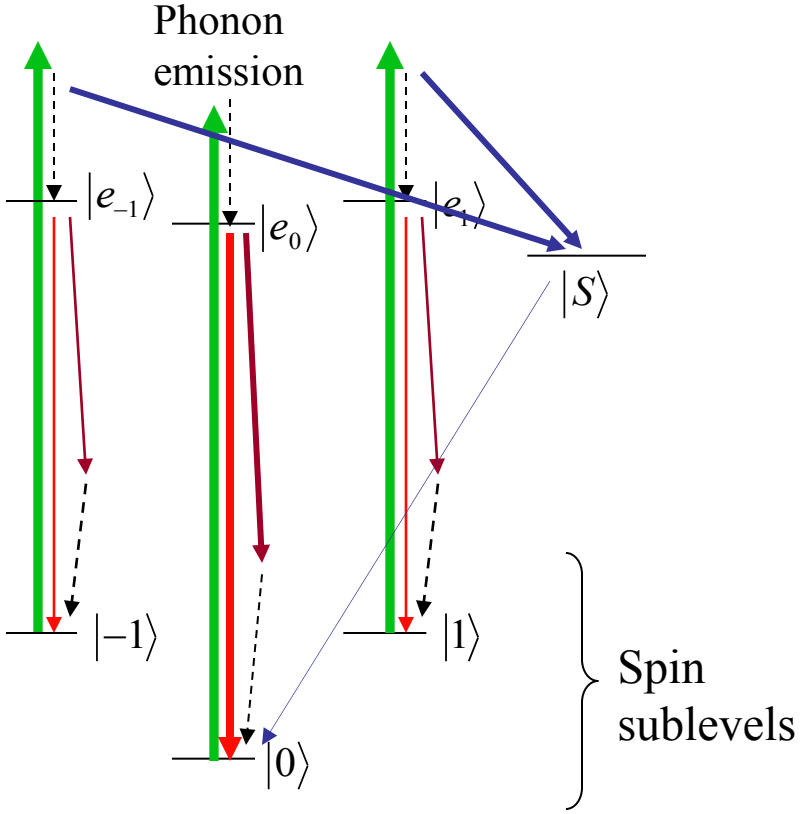
single electronic spins associated with the nitrogen-vacancy center in diamond

# The nitrogen-vacancy (NV) center in diamond



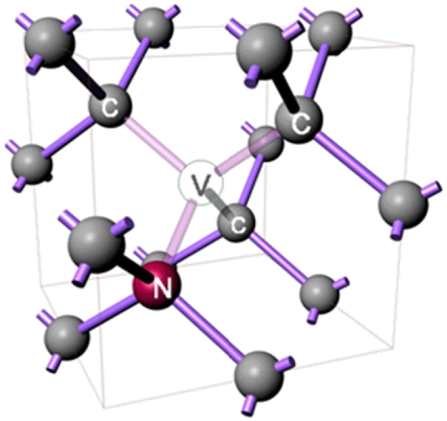

Laser excitation

- Why the NV?
  - ✓ optically active
  - ✓ electron spin triplet
  - ✓ optical spin polarization and detection




Jelezko PRL 2004, Manson PRB 2007

# The nitrogen-vacancy (NV) center in diamond

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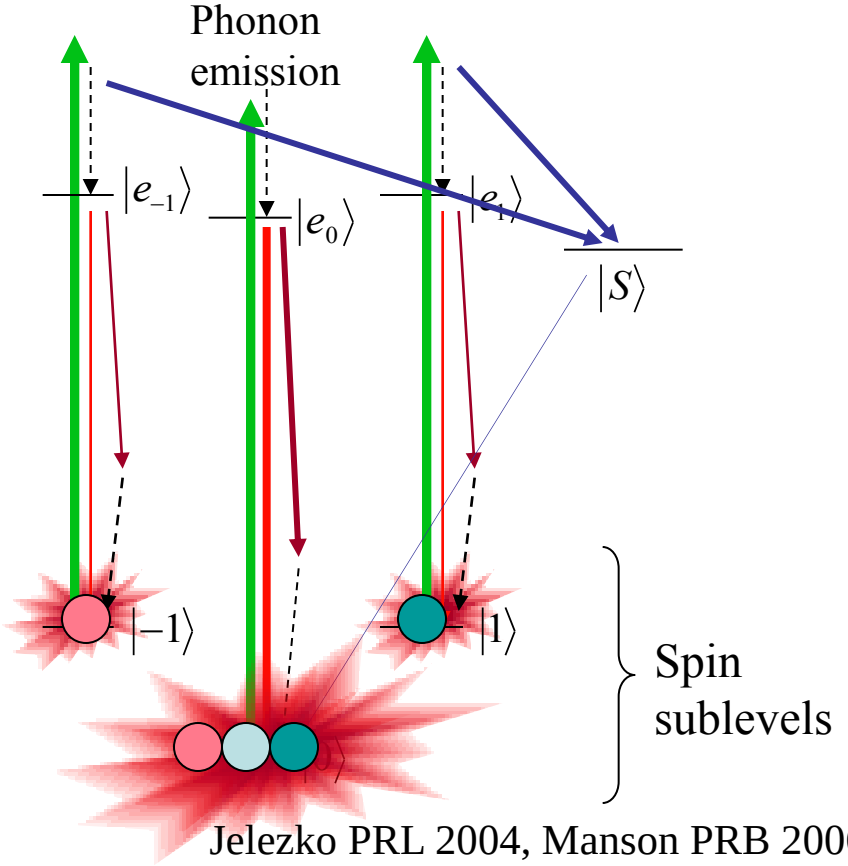
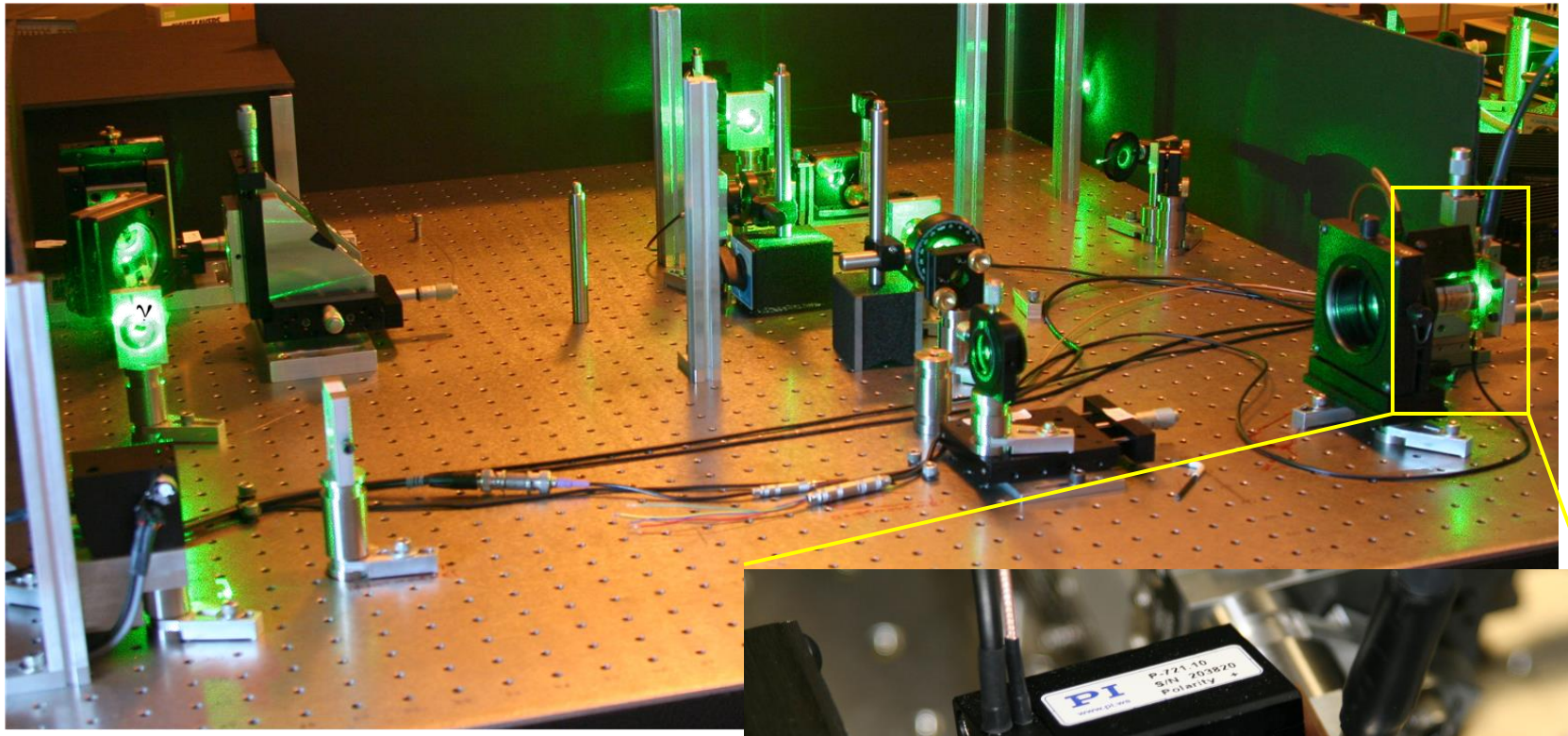


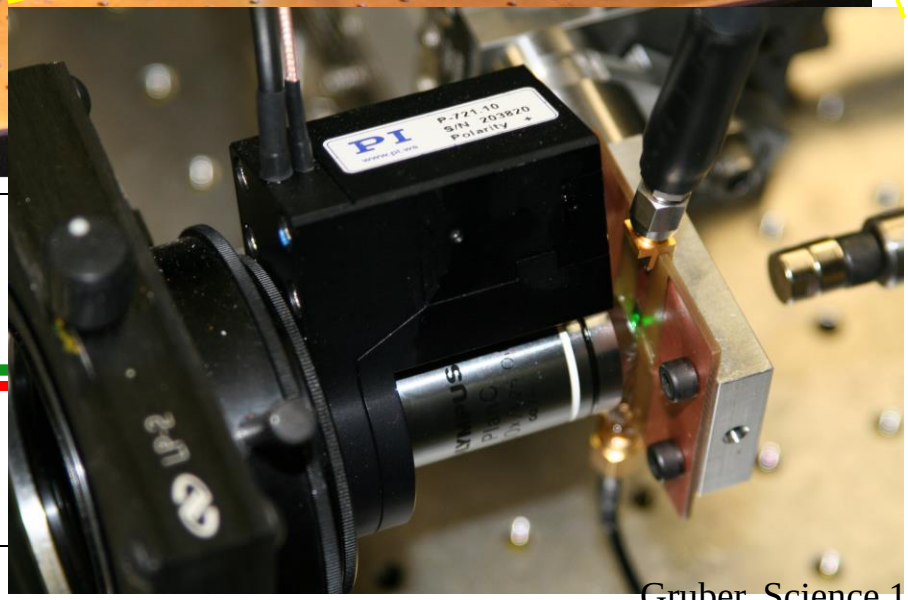

Jelezko PRL 2004, Manson PRB 2006

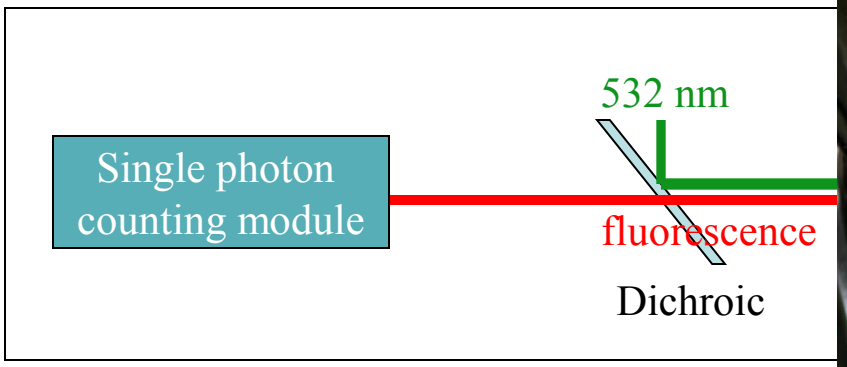
## Under green excitation

- Initially, $|0\rangle$ fluoresces more strongly than $|\pm 1\rangle$
- Eventually (after about 1 μs), the NV center polarizes into $|0\rangle$

# Imaging NV Centers

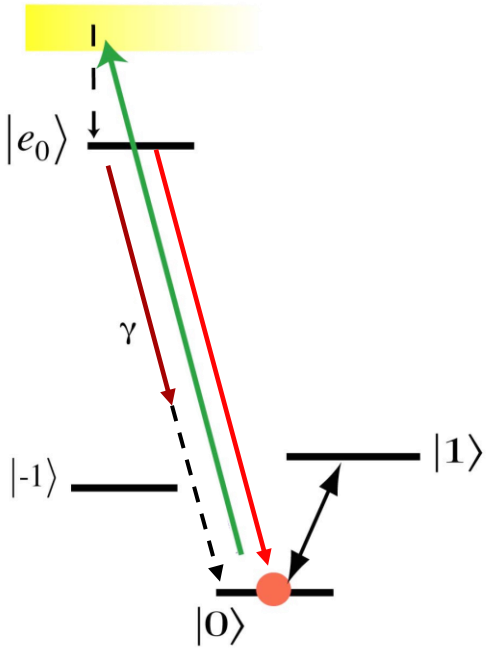


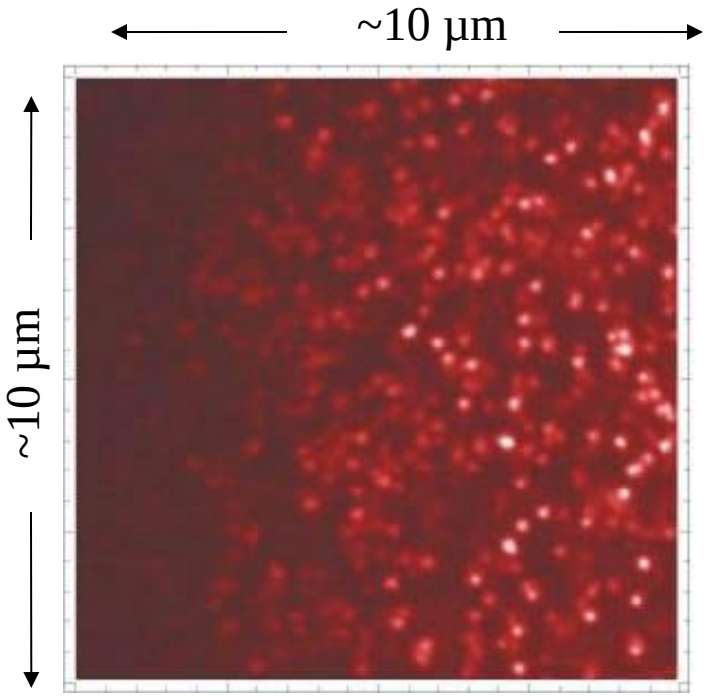



Gruber, Science 1997

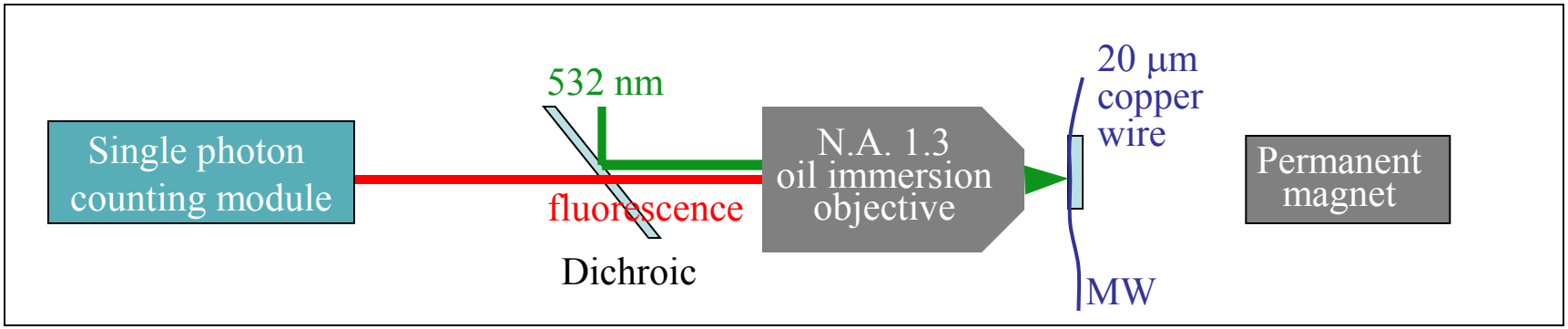
# Imaging NV Centers




**Close to diffraction-limited resolution**

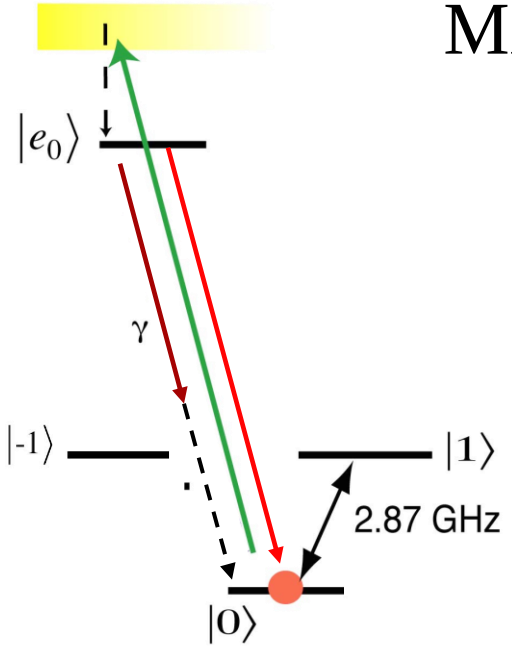
**100 kcts/sec typical**

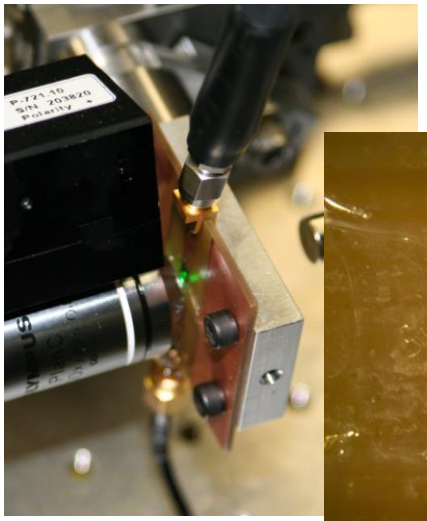


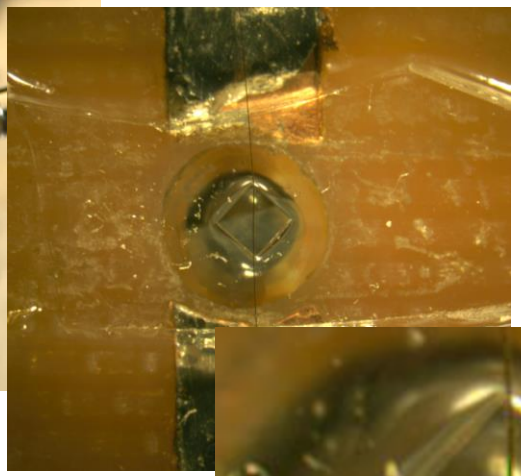

Gruber, Science 1997

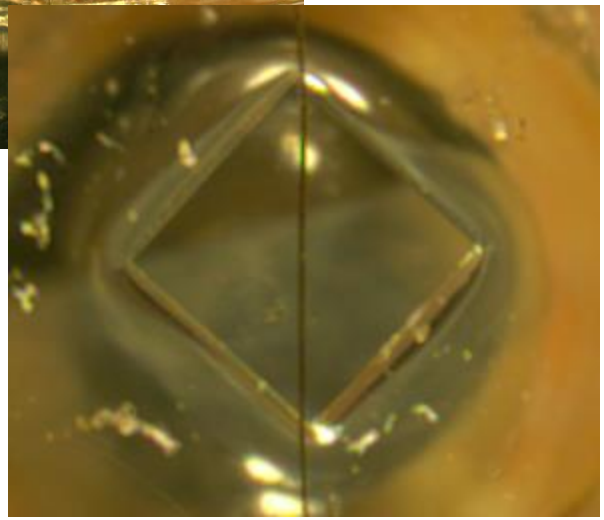
# Manipulating NV spins

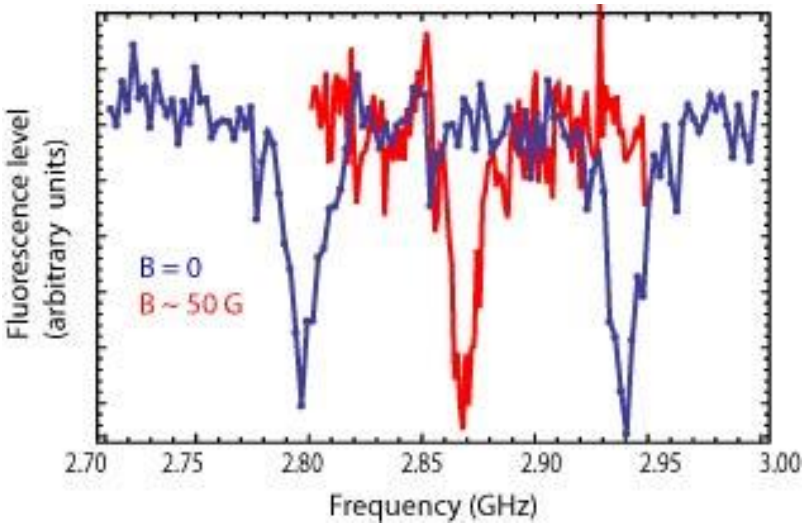
## Microwave excitation:



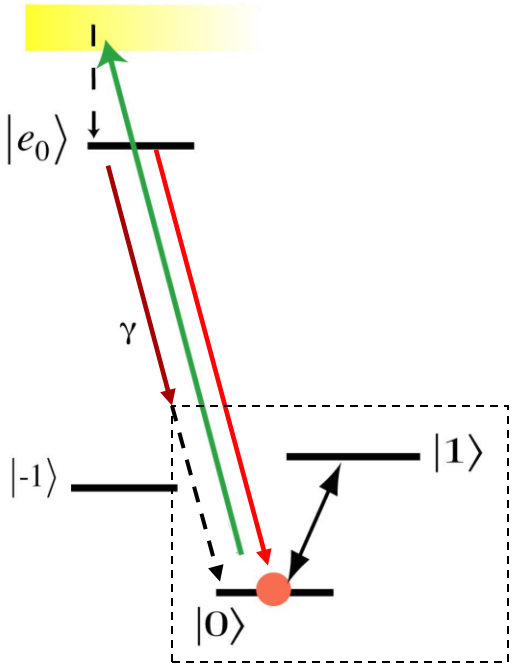




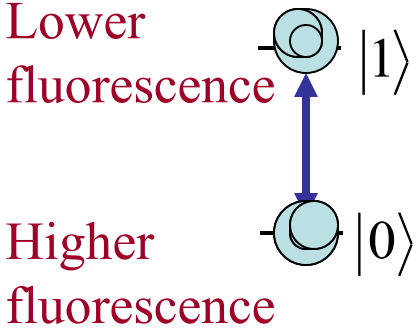


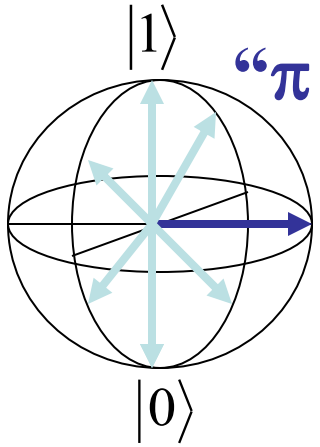

Gruber, Science 1997, Hanson PRB 2006

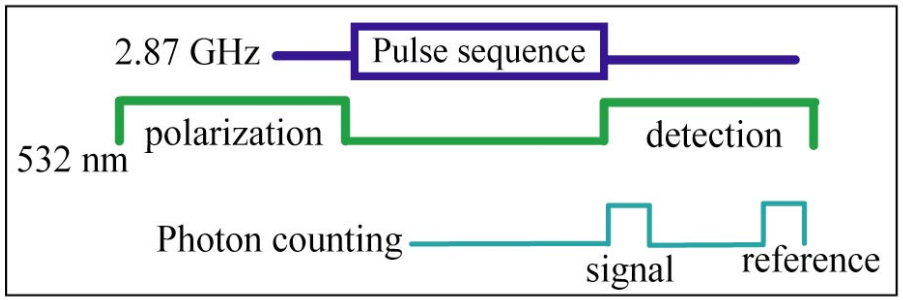
# Manipulating single NV spins



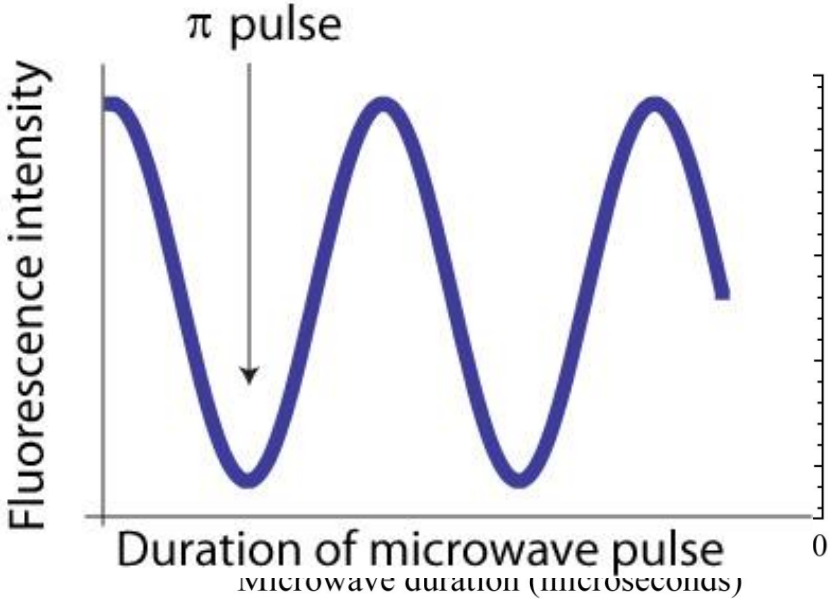

Driving Rabi oscillations:



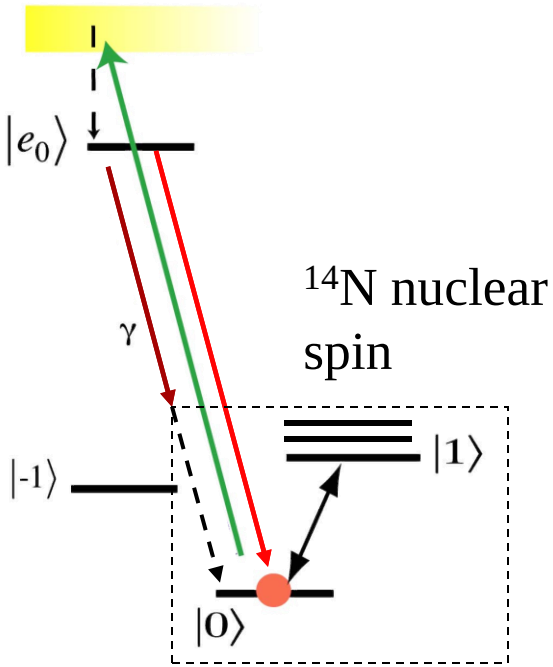




…and repeat 10,000 to 100,000 times

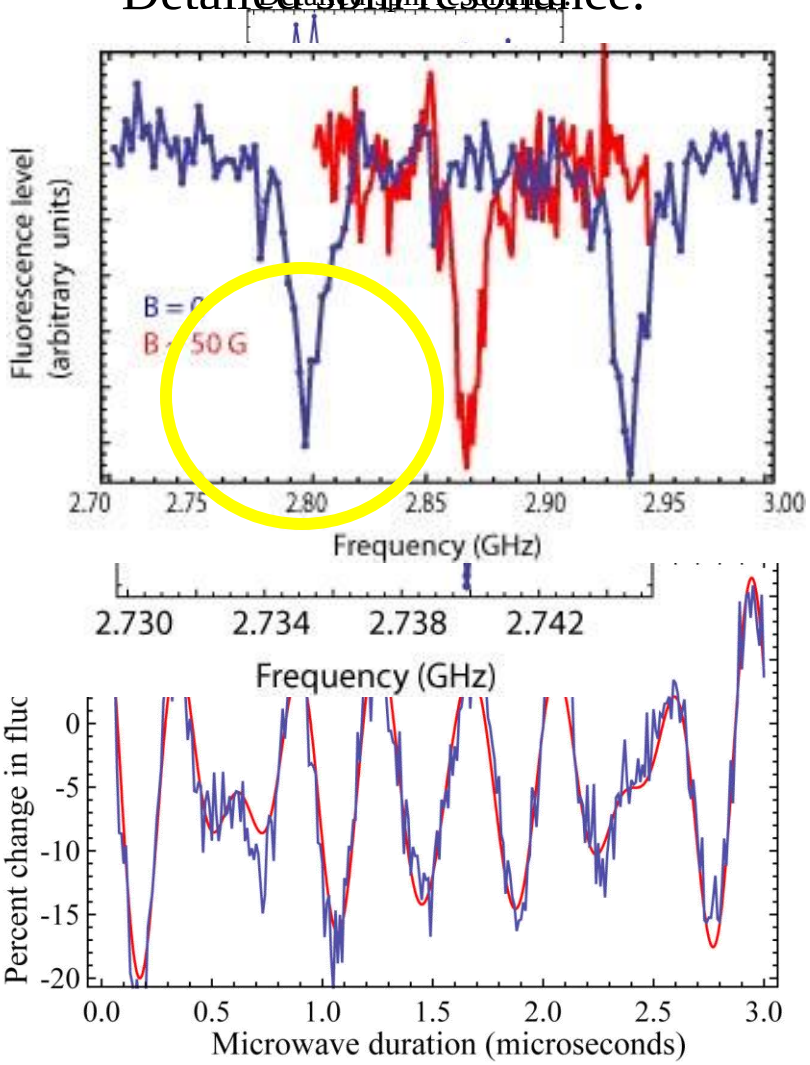


# Hyperfine coupling to nitrogen nuclear spin




$^{14}$N nuclear spin

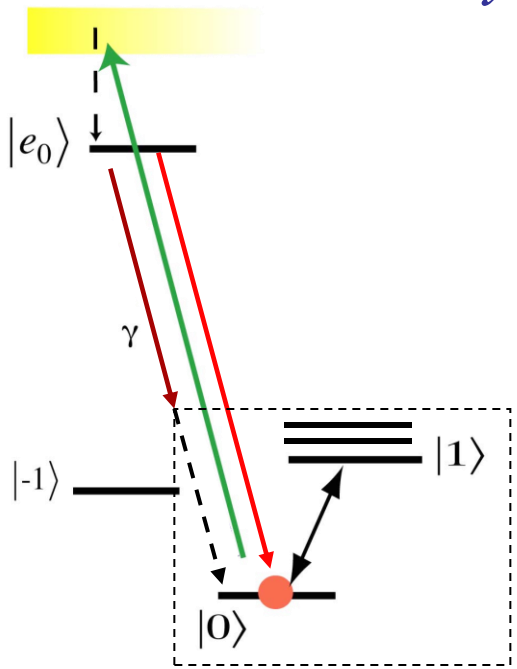
Detailed spin resonance:




He, PRB 1993

# Ramsey sequence:

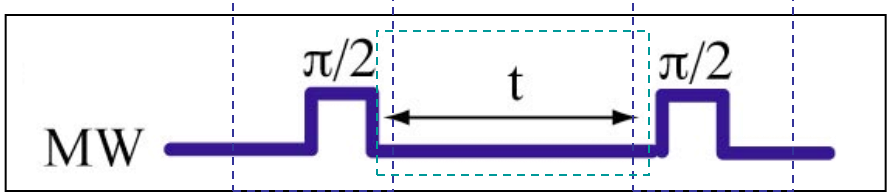
## *Another way to see $^{14}N$ hyperfine structure*

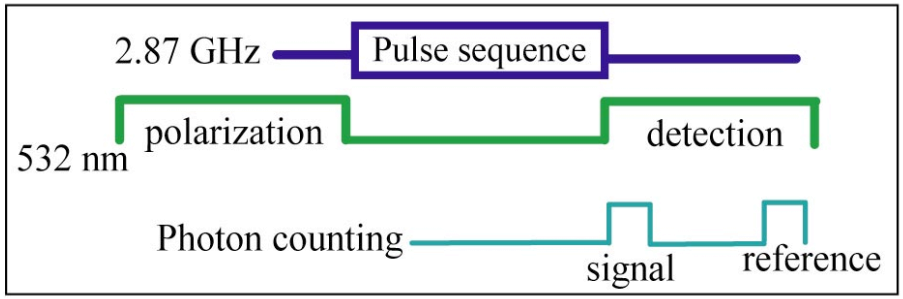


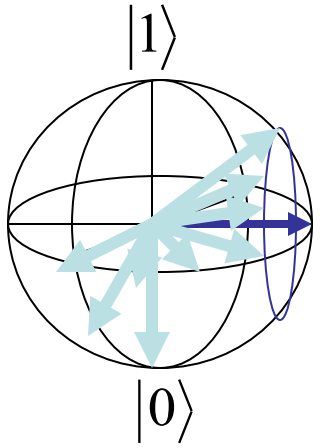

Create superposition state

Allow relative phase to evolve

Convert phase to population



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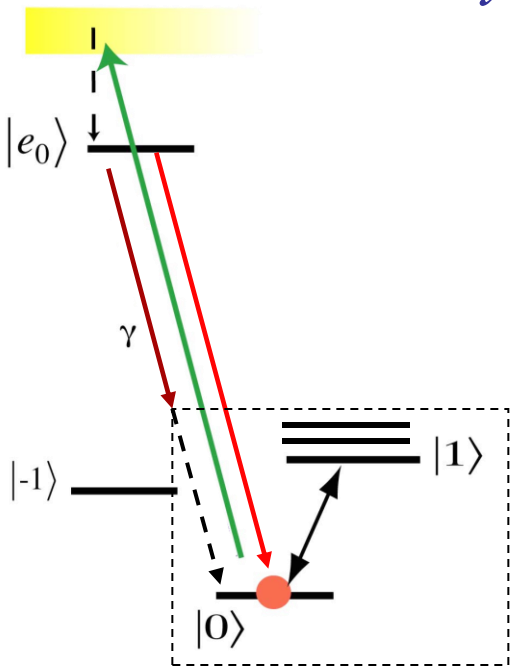


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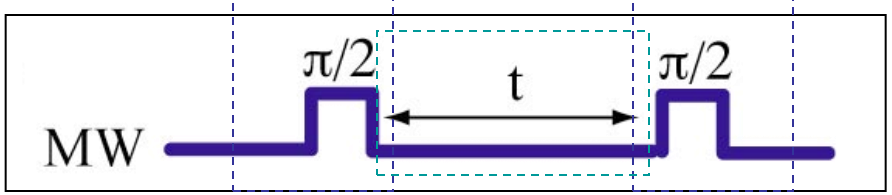
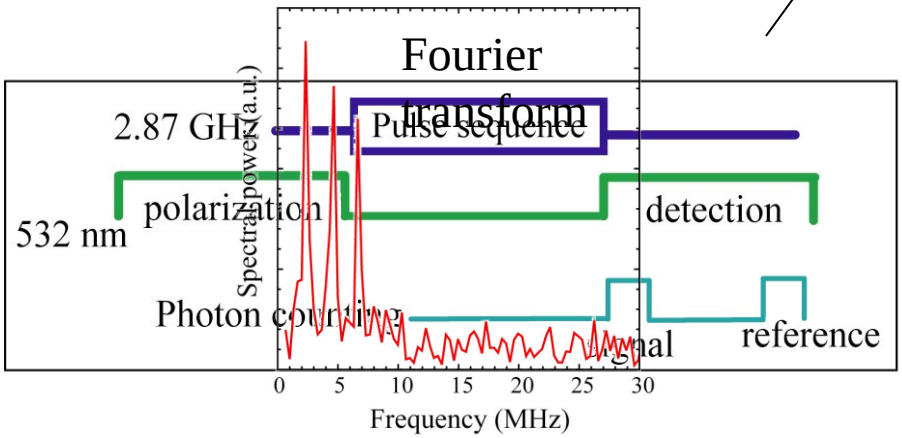
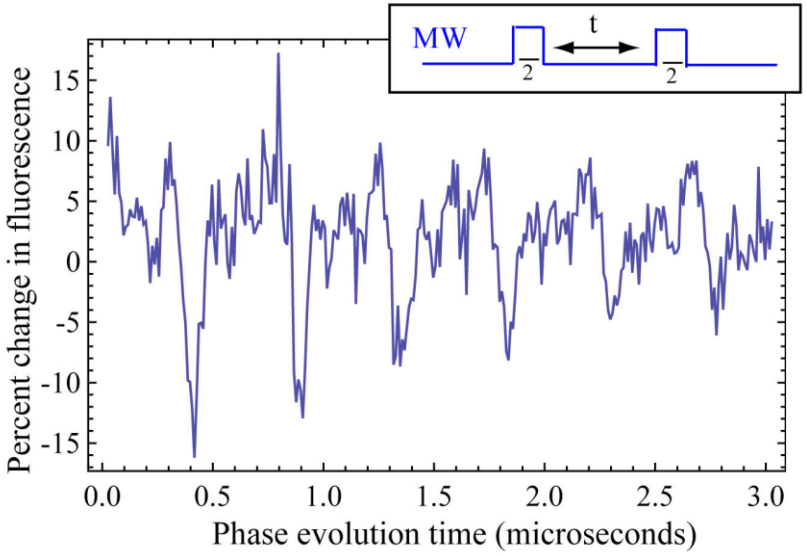
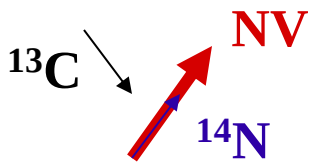


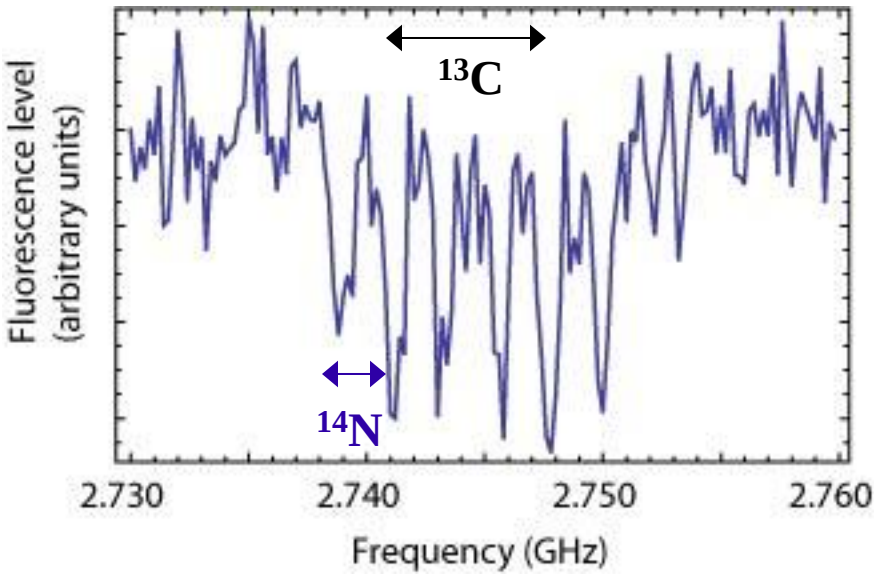
# Hyperfine coupling to $^{13}C$ nuclear spins




$^{14}N$ quadrupole moment anchors it to the NV axis

Spin ½ $^{13}C$ is free to precess

Hyperfine structure visible in spin resonance:

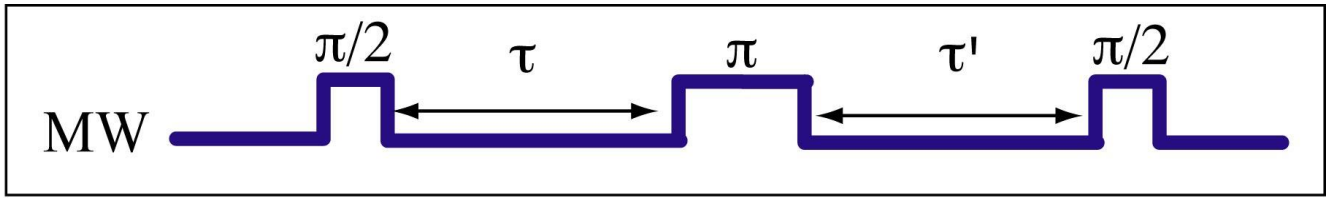



$^{13}C$ dynamics visible with spin-echo spectroscopy

LC, Dutt Science 2006

# Coherence properties of the NV spin

Spin-echo pulse sequence:




The π pulse flips the spin, so that during the second free precession period it unwinds the phase accumulated during the first free precession period

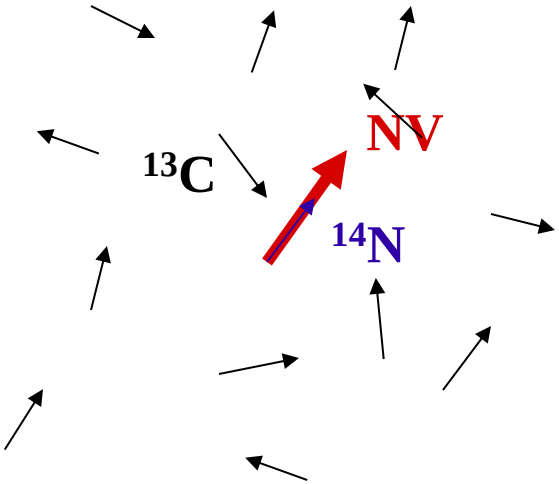
=> only see a signal if the environment *changes faster than* $2\tau$

- The spin-echo gets rid of slow fluctuations in the environment

  => gives the decoherence time rather than the dephasing time

- Allows you to observe *dynamics* of the environment

# Hyperfine coupling to $^{13}C$ nuclear spins

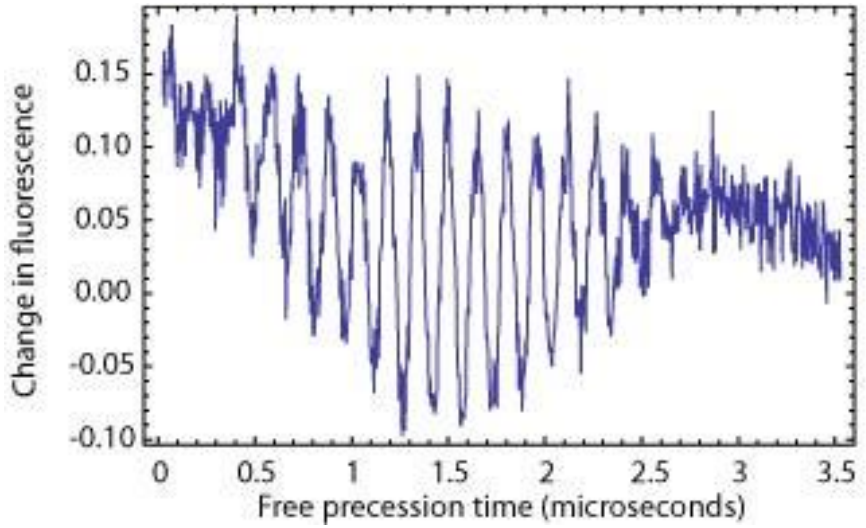


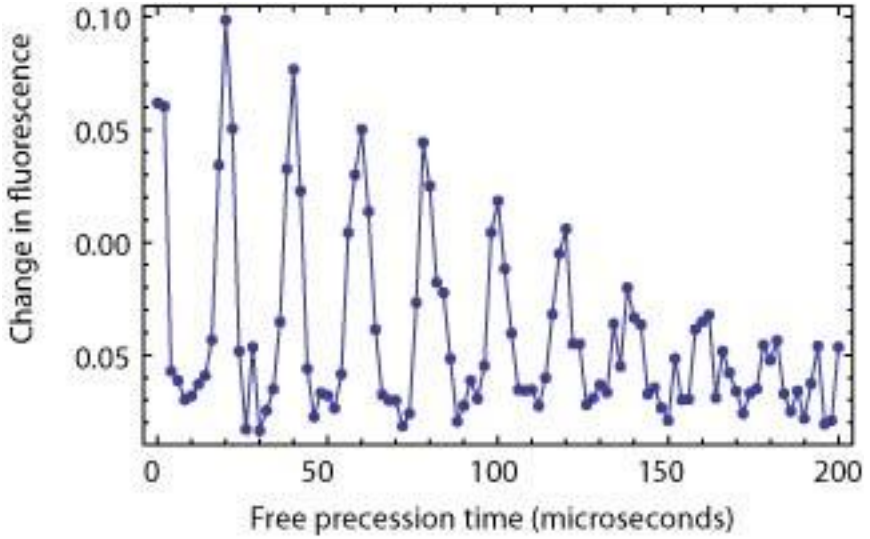

$^{14}N$ quadrupole moment anchors it to the NV axis

Spin ½ $^{13}C$ is free to precess

⟹ $^{13}C$ Spin-echo modulation at short times…

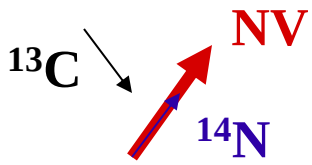
⟹ $^{13}C$ Spin-echo collapse and revival at long times…



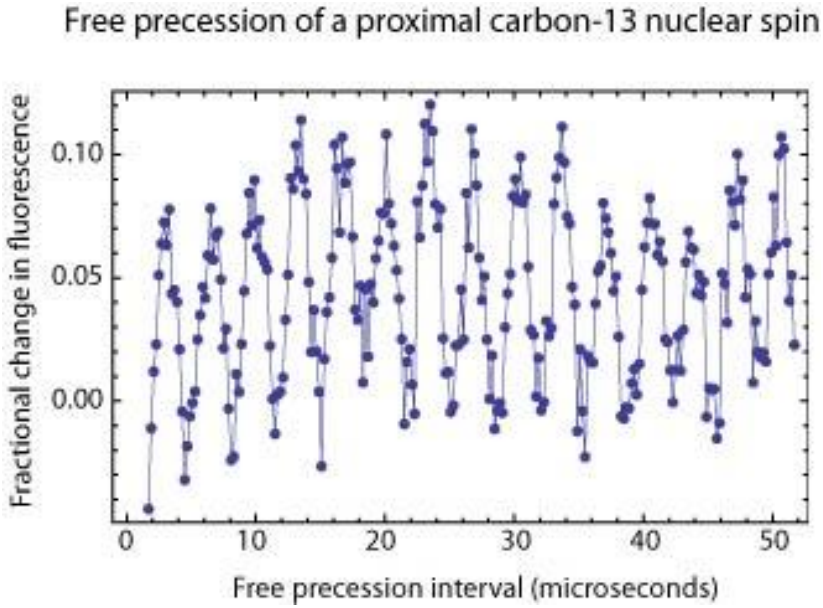

LC, Dutt Science 2006

# Hyperfine coupling to $^{13}C$ nuclear spins




"Full control" over proximal $^{13}C$ nuclear spins by turning on and off the NV dipole field

- nuclear polarization




- NV-$^{13}C$ CNOT gate

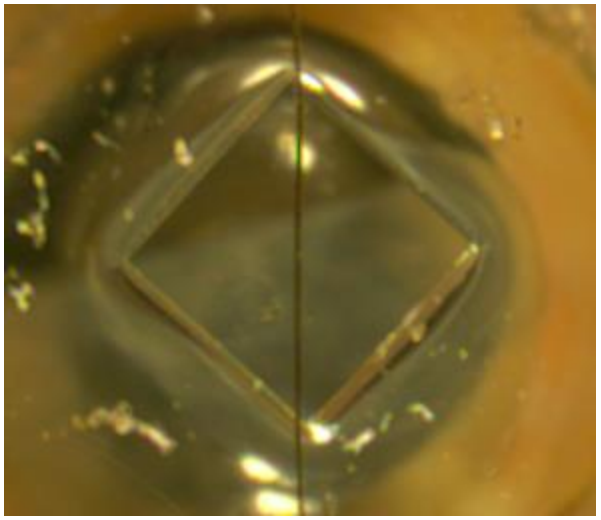
- $^{13}C$ fidelity limited by uncontrolled $^{14}N$ nuclear spin

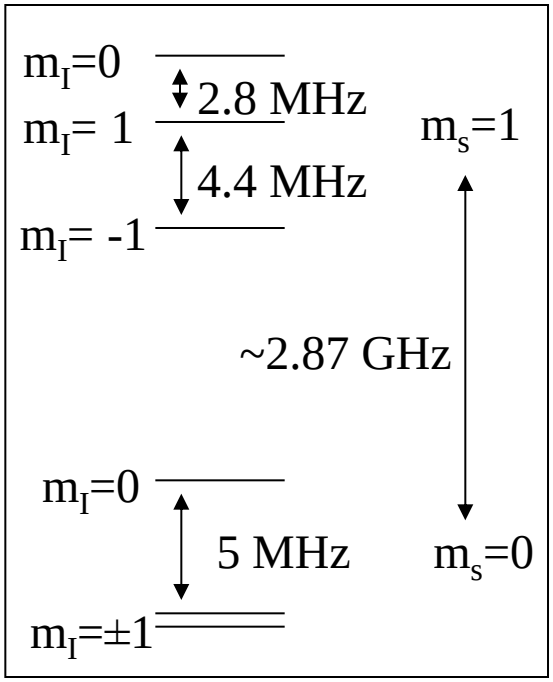
- Why not *use* $^{14}N$?

Motivates combined NMR and ESR techniques

# Current project: combining MW and RF manipulation of spins in diamond

RF (MHz) MW (GHz)

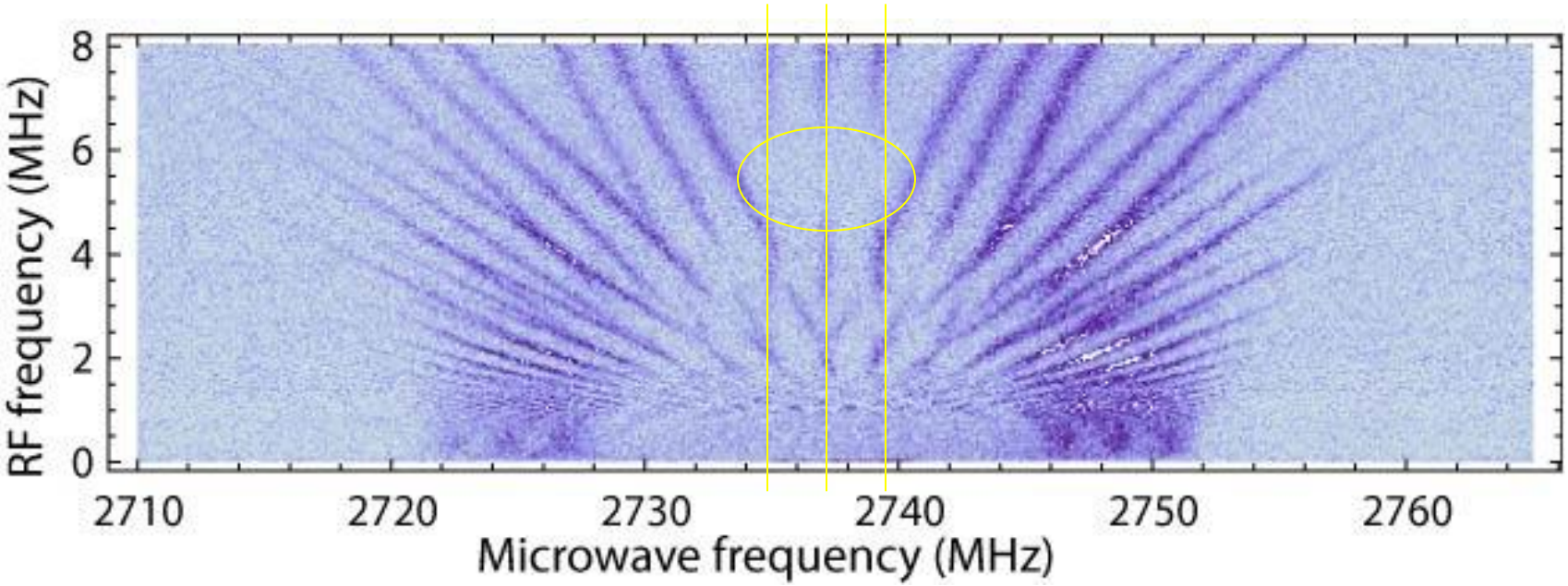





- Should allow polarization and manipulation of $^{14}N$ …
- …and direct manipulation of $^{13}C$

Ensemble ENDOR: He, PRB 1993

# Current project: combining MW and RF manipulation of spins in diamond




…pulsed techniques to come…

# In summary…

**Quantum systems**

A new way to communicate
A new way to compute

Requires control over coupled quantum mechanical systems

Like spins!

**Single electronic spins in diamond**

An opportunity to study a quantum system (the NV spin) and its interactions with its environment (surrounding nuclear spins)

A promising system for applications in quantum information science and metrology

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