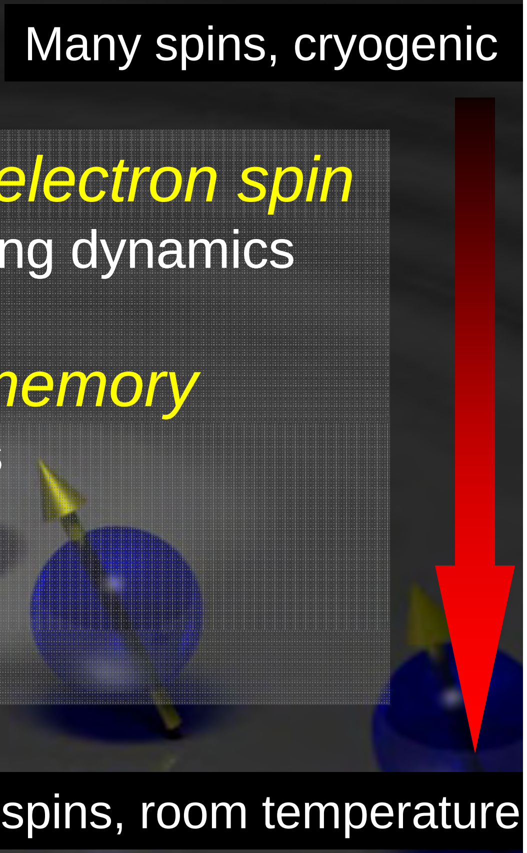
Quantum control and engineering of single spins in semiconductors

David D. Awschalom
Center for Spintronics and Quantum Computation
University of California, Santa Barbara



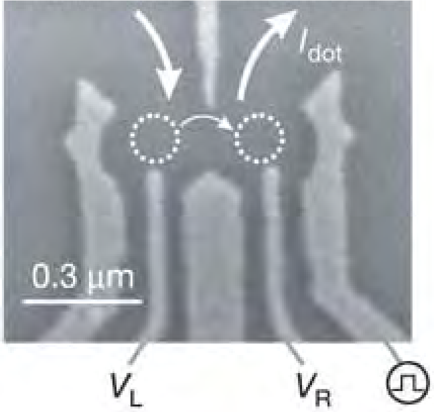
Many spins, cryogenic

- *high-speed coherent control of a single electron spin*
  driving to gigahertz frequencies yields surprising dynamics
- *demonstration of a single nuclear spin memory*
  room temperature coherent SWAP operations
- *nanofabrication of spins and arrays*
  implanting spins and environmental effects

Single spins, room temperature

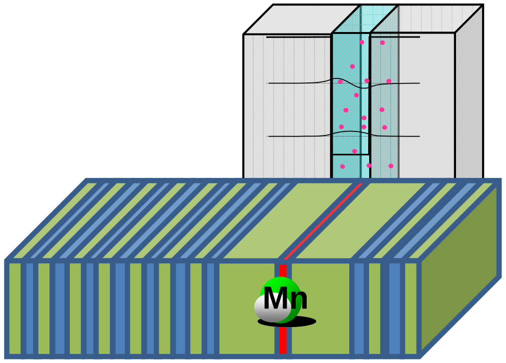
Single spins in the solid state: tremendous progress ~ 6 years

Electrically defined quantum dots



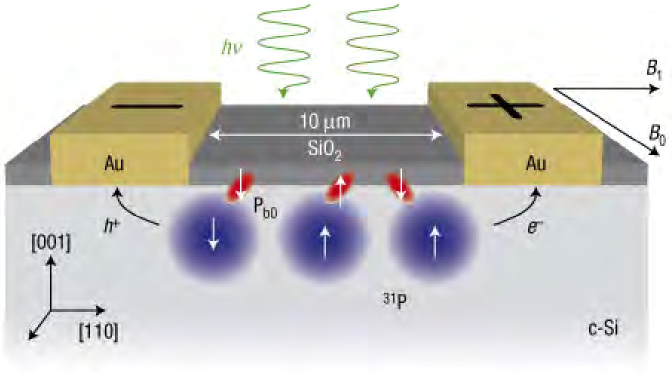
Hanson *et al*., Rev. Mod. Phys. **79**, 1217 (2007)

Engineered magnetic ion dopants



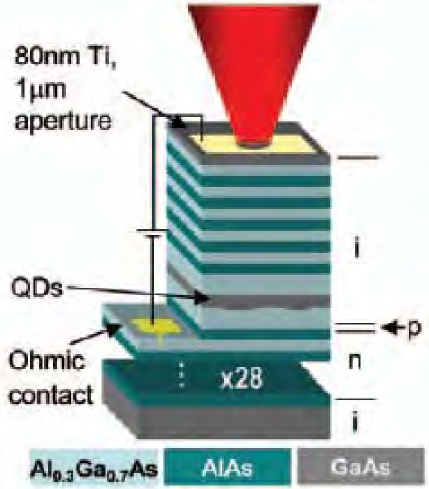
Myers *et al.,* Nature Materials **7**, 203 (2008)

Single dopants in Si



Stegner *et al.,* Nat. Phys. **2**, 835 (2006)

MBE-grown quantum dots



Berezovsky *et al.,* Science **314**, 1916 (2006)

Review: R. Hanson and D.D. Awschalom, *Nature* **453**, 1043 (2008)

Why study single quantum systems (one spin)?

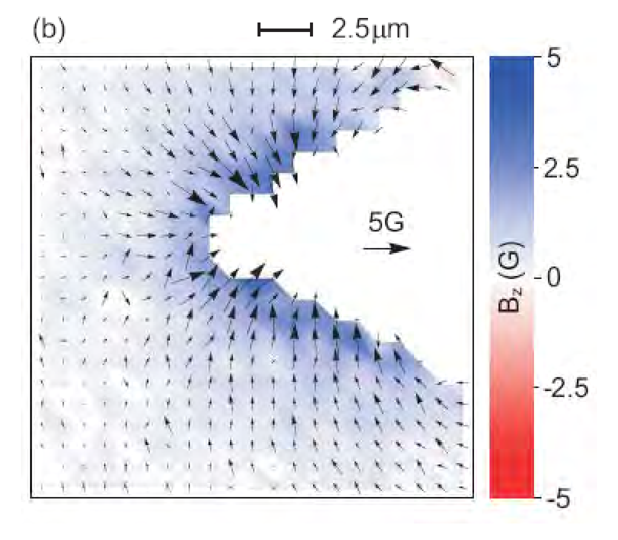
Science

- individually addressable solid state “trapped atoms”
- test ideas of quantum theory with a simple system
- atomic-scale probe of local environment

Technology

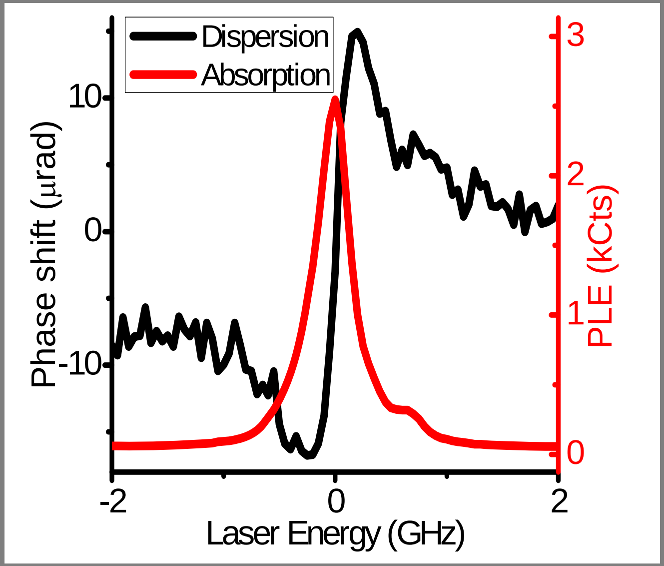
- quantum information processing (computing, secure communication)
- quantum-limited sensing and magnetometry

Vector magnetometry



Diamond

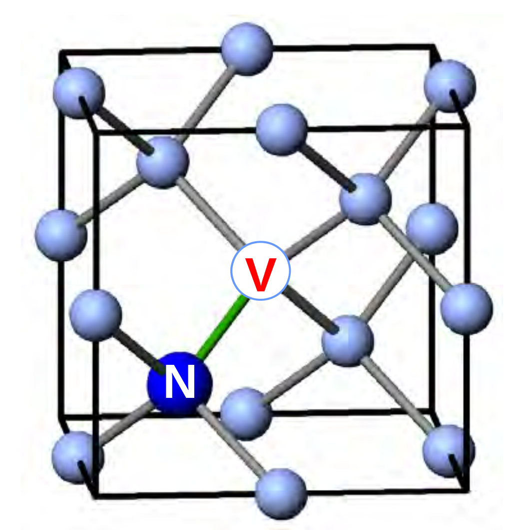
Non-destructive measurement



B. Maertz et al., Appl. Phys. Lett. (2010)

B. Buckley et al., Science **330**, 1212 (2010)

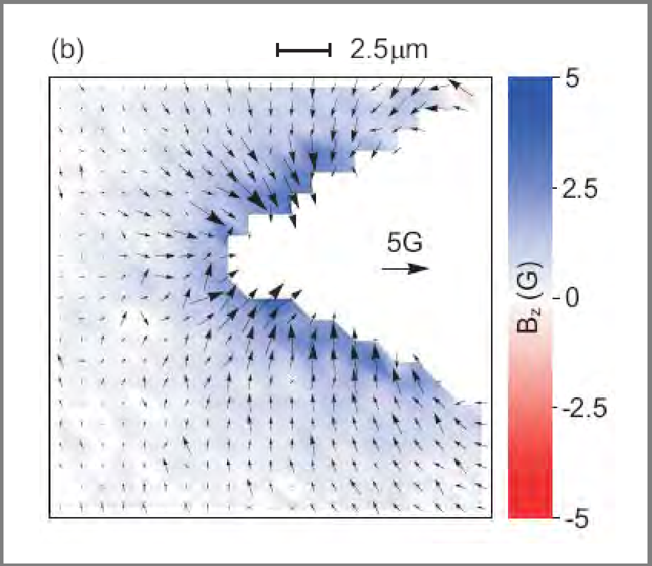
Why nitrogen vacancy centers (NV centers) ?



NV centers provide:

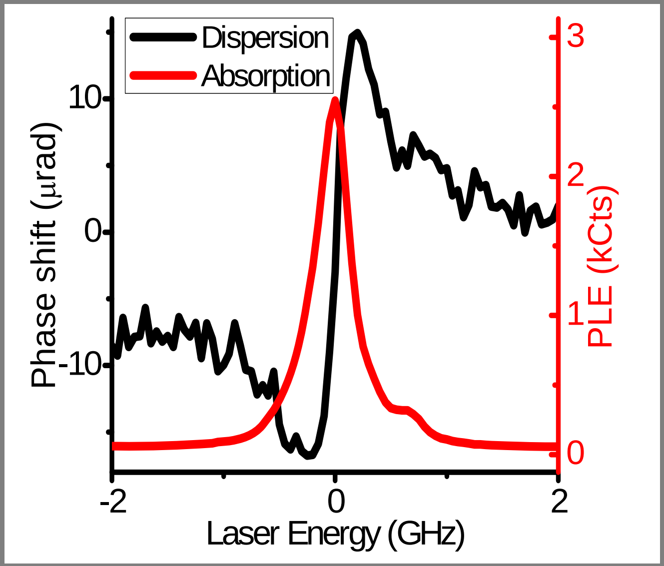
- room temperature quantum coherence
- long spin coherence (T_2 ~ 10 ms)
- optical initialization and readout
- solid state system
- reduced nuclear spin environment

Vector magnetometry



Diamond

Non-destructive measurement

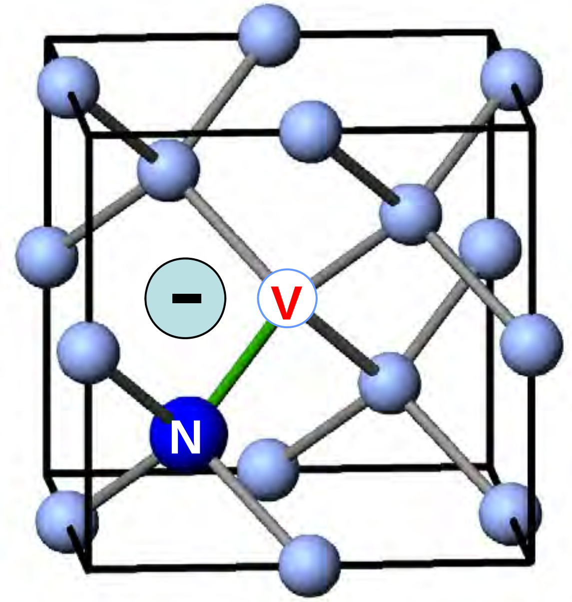


B. Maertz et al., Appl. Phys. Lett. (2010)

B. Buckley et al., Science **330**, 1212 (2010)

Properties of the Nitrogen-Vacancy center

Nitrogen-Vacancy center ($S = 1$)



Electronic ground state is a spin triplet, with spin Hamiltonian (z-axis // [111]):

$$H_{NV} = D\, S_z^2 + g\mu_B \mathbf{B}\, \mathbf{S} + \mathbf{S}\, A\, \mathbf{I}$$

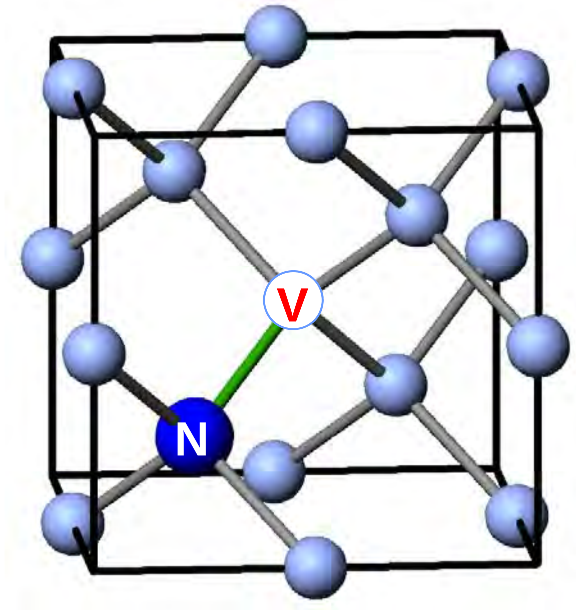
Zero-field splitting along symmetry axis
D = 2.87 GHz (~12 μeV)

Zeeman energy, *g*-factor=2.00:
Zeeman shift ~28 GHz/T = 2.8 MHz/G

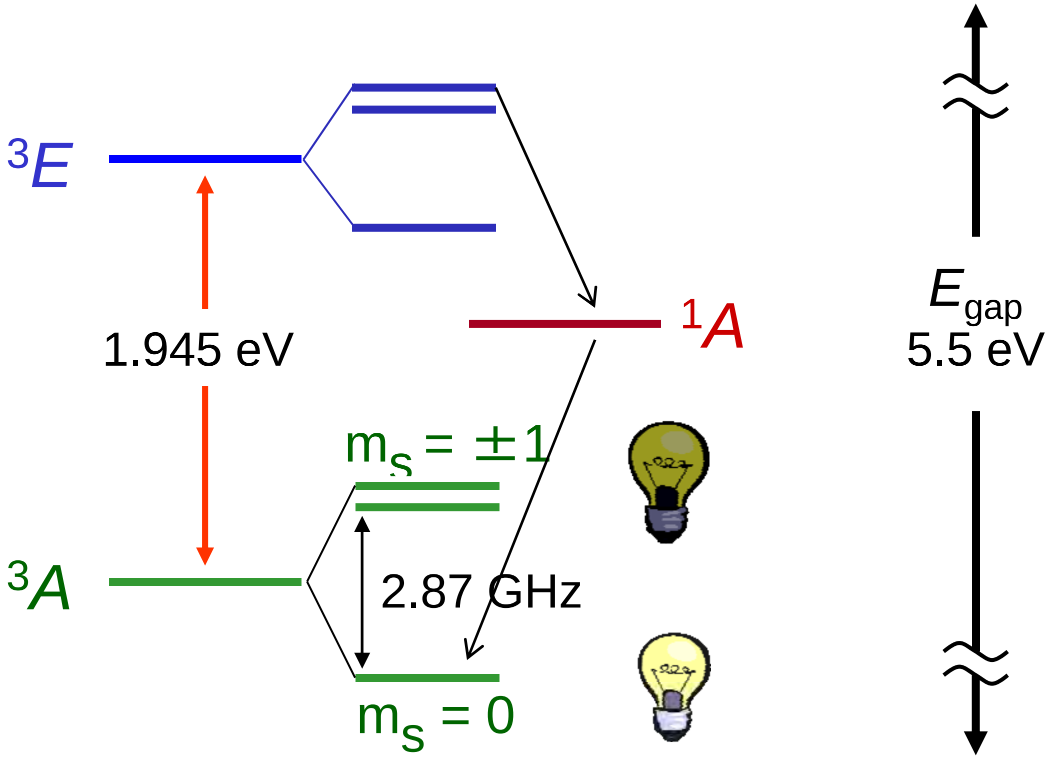
Hyperfine interaction with N nuclear spin;
2-3 MHz

Hamiltonian is tunable with static magnetic field

Properties of the Nitrogen-Vacancy center



N = Nitrogen
V = Vacancy (missing Carbon)



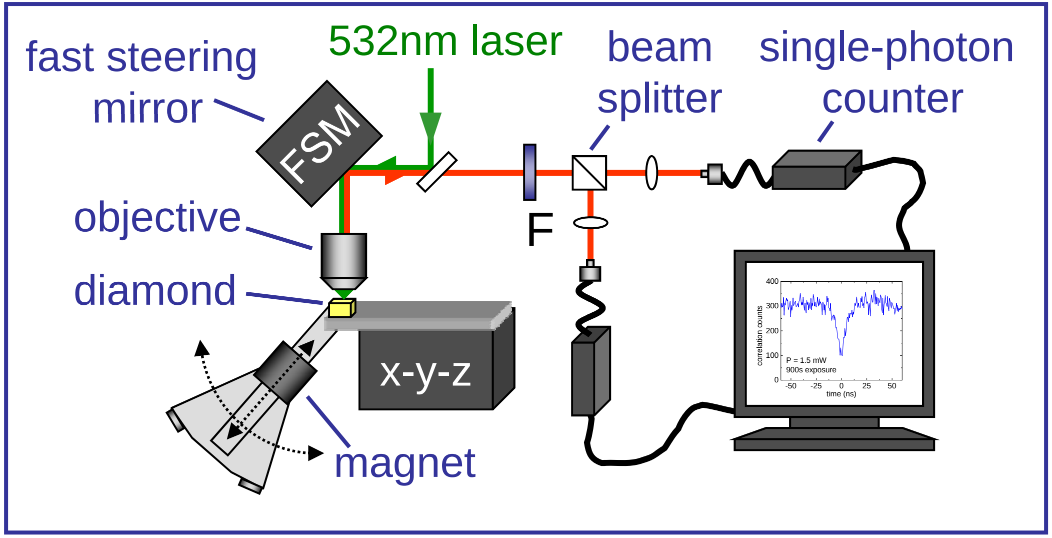
- Spin-conserving optical transitions allowed between ^3A and ^3E triplet states
- Spin-dependent crossing between ^3E and ^1A singlet state leads to:

  Optical pumping into ground state $m_S = 0$
  Spin-dependent photoluminescence (m_S =0 “bright”, m_S =±1 “dark”)

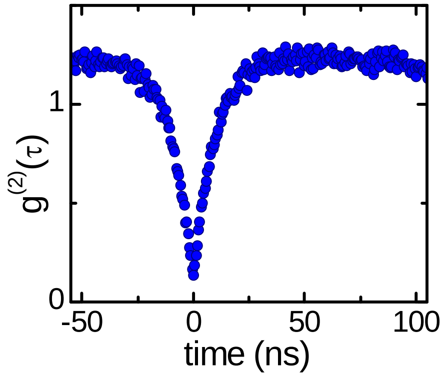
Details of level structure:
Manson *et al.*, PRB 74, 104303 (2006)

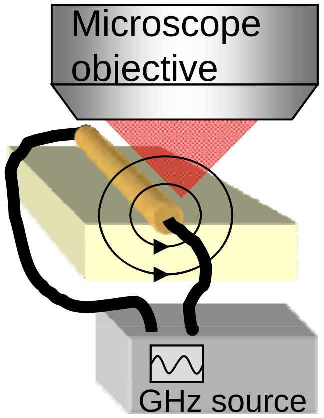
Imaging single spins at room temperature

Confocal microscope: spatial resolution ~400 nm

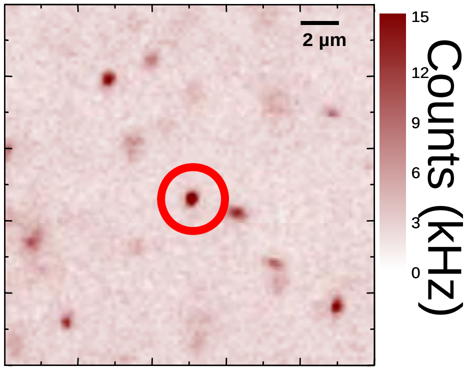


Photon correlations

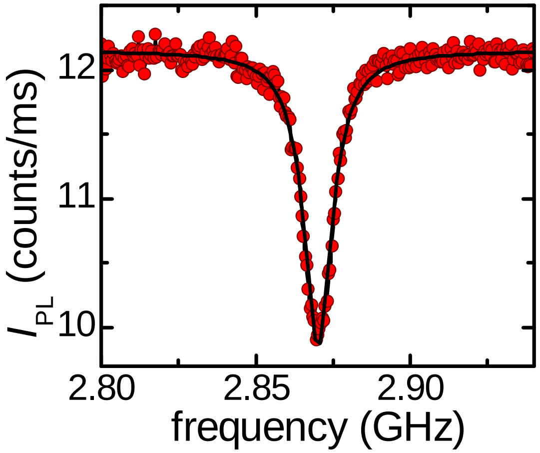




Spatial map of photoluminescence



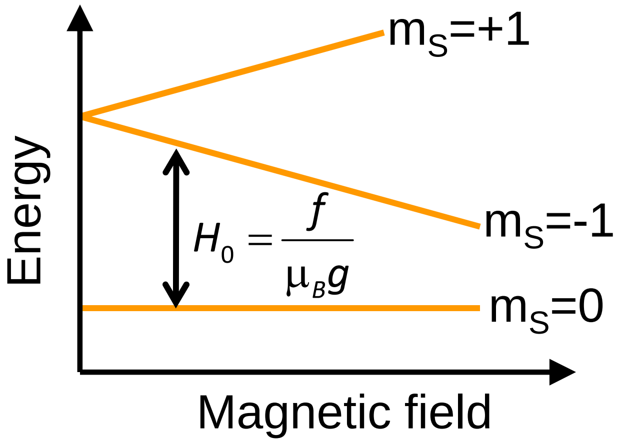
Electron spin resonance (one spin, zero field, 300 K)



A. Gruber *et al.*, *Science* **276**, 2012 (2004)

R.J. Epstein *et al.*, *Nat. Phys*. **1**, 94 (2005)

Spin resonance: conventional approach

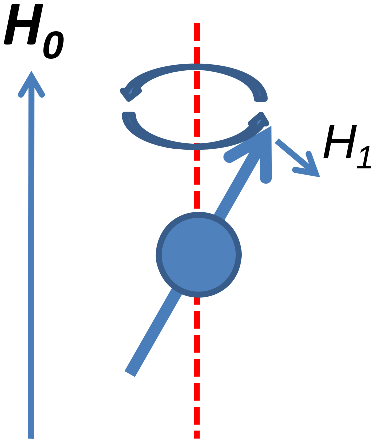


Rotating field

$$\mathbf{V_{0\rightarrow -1}=\gamma e^{i2\pi ft}}$$

Larmor field

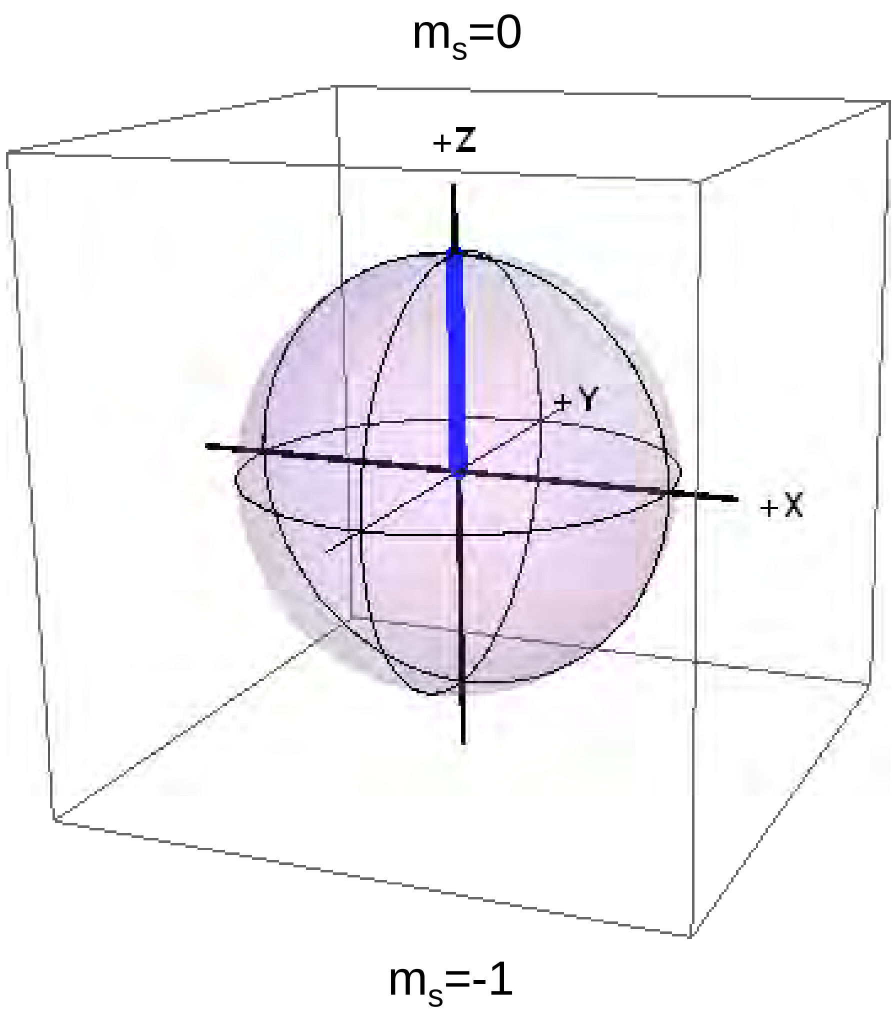
$\boldsymbol{H_0}$



Rabi frequency

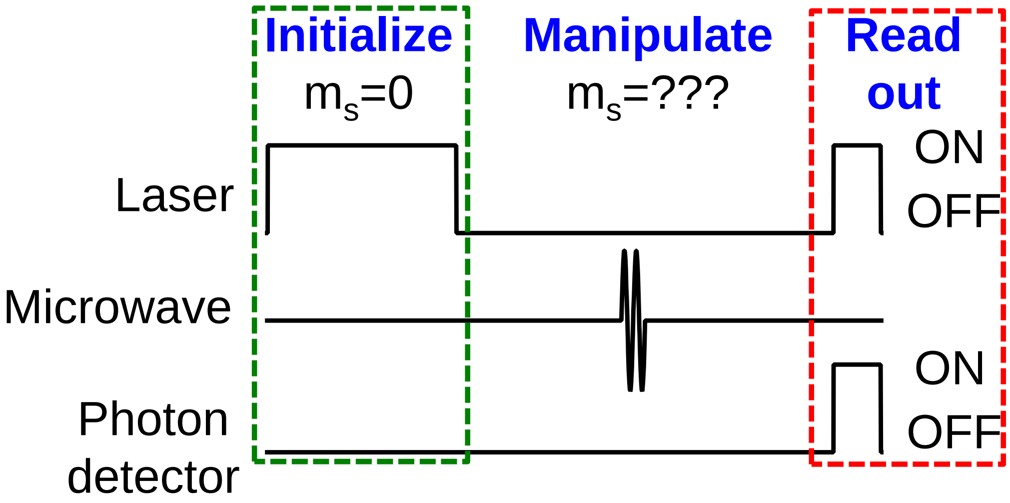
$$\Omega_{Rabi} = \frac{\gamma}{\hbar} = H_1$$

(on resonance)



Spin resonance in the time domain: calibrating one spin

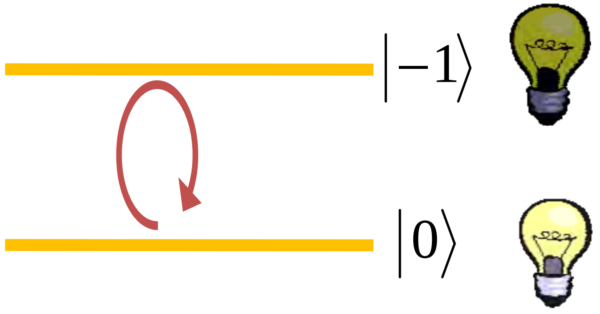
A ‘sampling’ scheme:



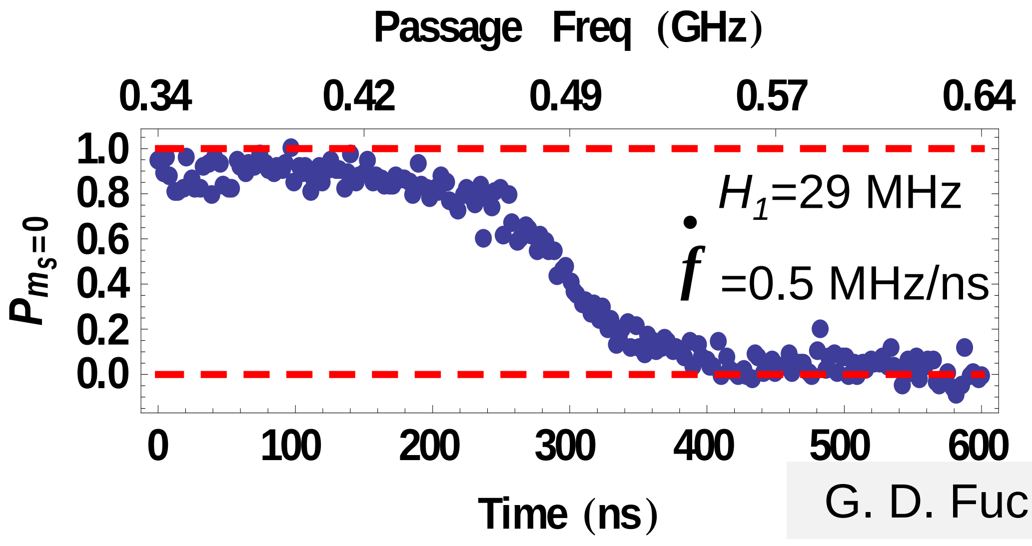
Initialize
m_s=0

Manipulate
m_s=???

Read out



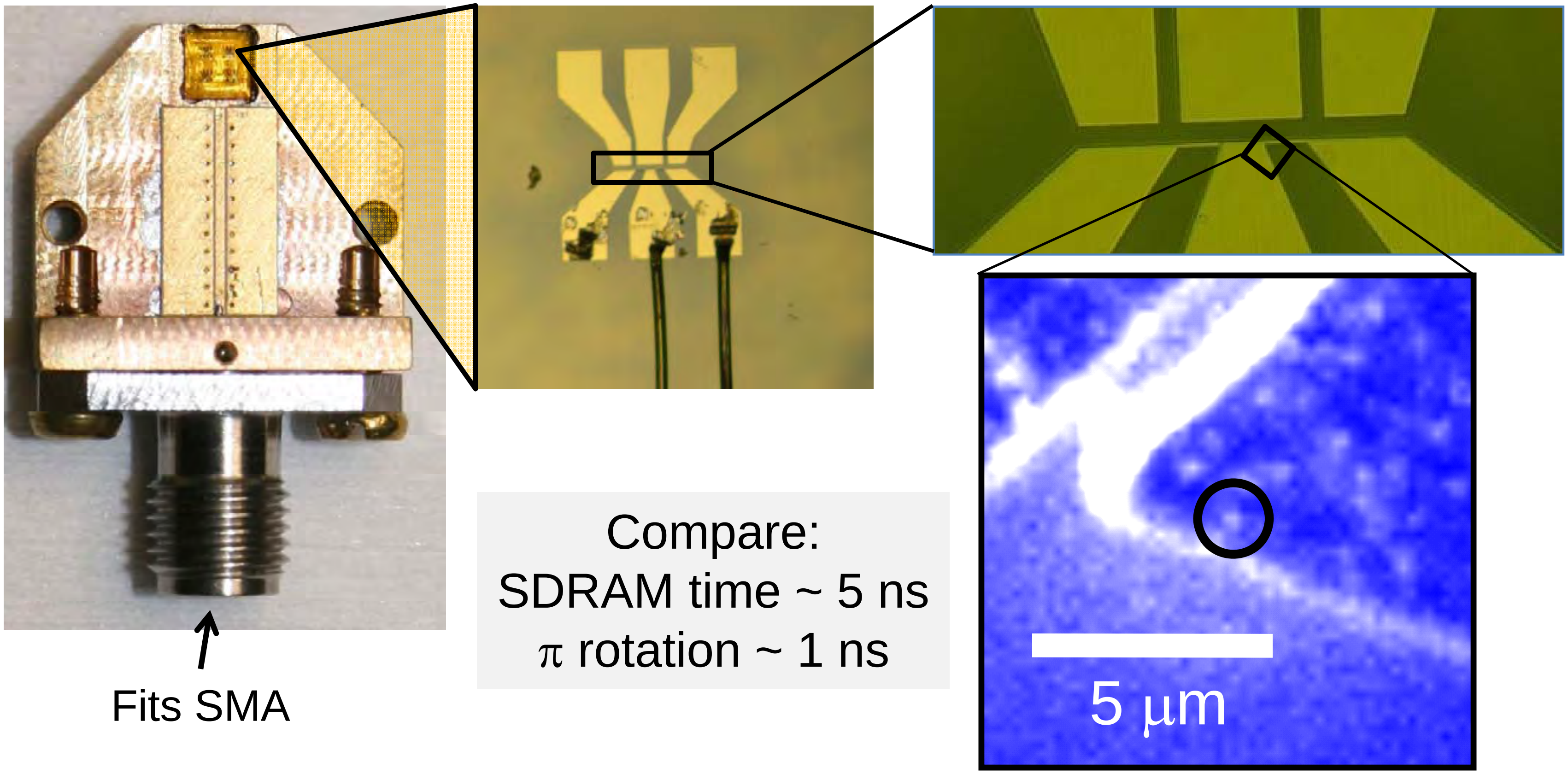
- Measure the state after a pulse (longer the pulse, greater the rotation)
- Need to calibrate I_{PI} for each eigenstate (m_s=0,-1)



Calibrating a single spin:
passing adiabatically through
the resonance, the spin is
flipped

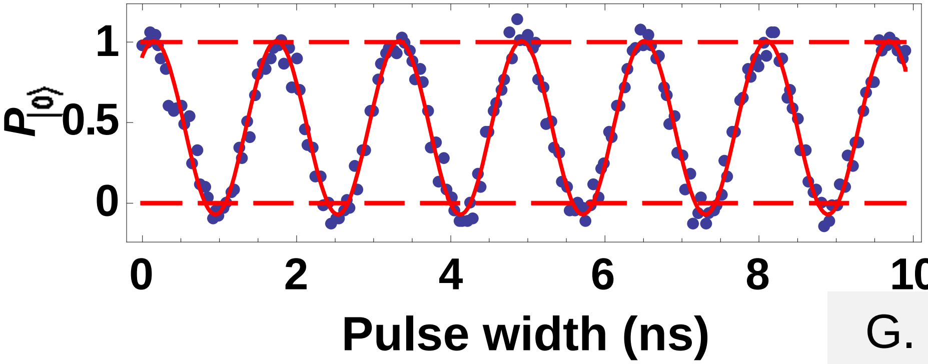
G. D. Fuchs *et al*., Science 326, 1520 (2009)

On-chip gigahertz coherent control of a single spin



Fits SMA

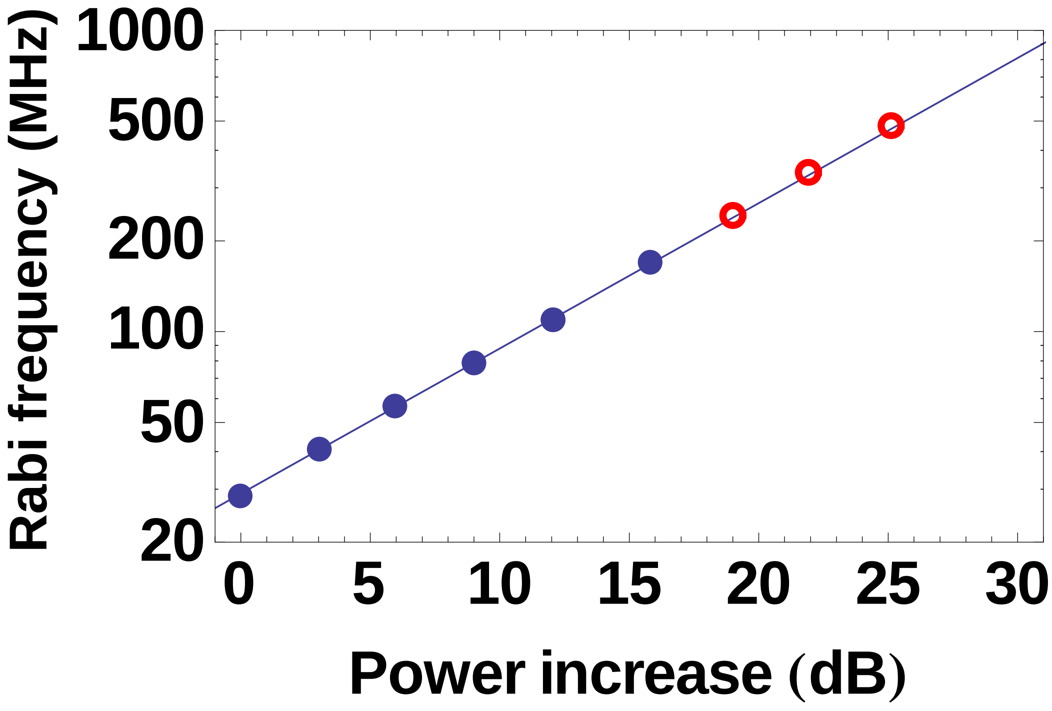
Compare:
SDRAM time ~ 5 ns
π rotation ~ 1 ns

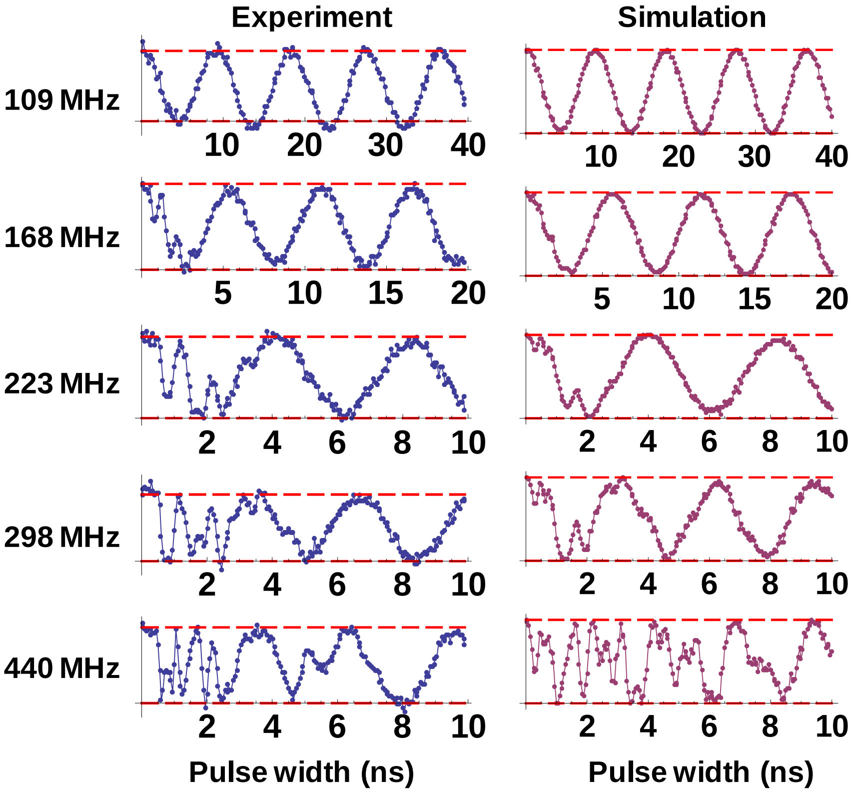


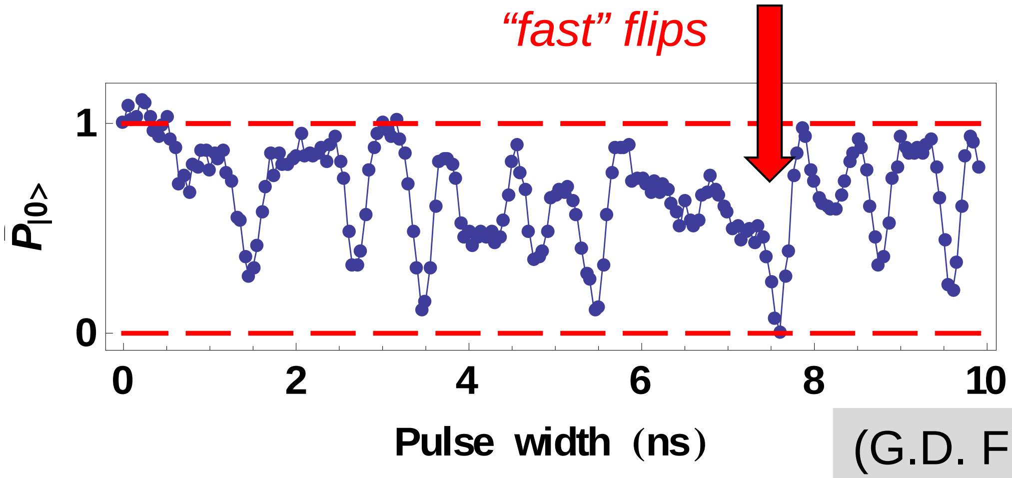
Example: 630 MHz Rabi oscillations
In conventional regime

G. D. Fuchs *et al.*, Science 326, 1520 (2009)

Pushing the limits: strong-driving dynamics of a single spin



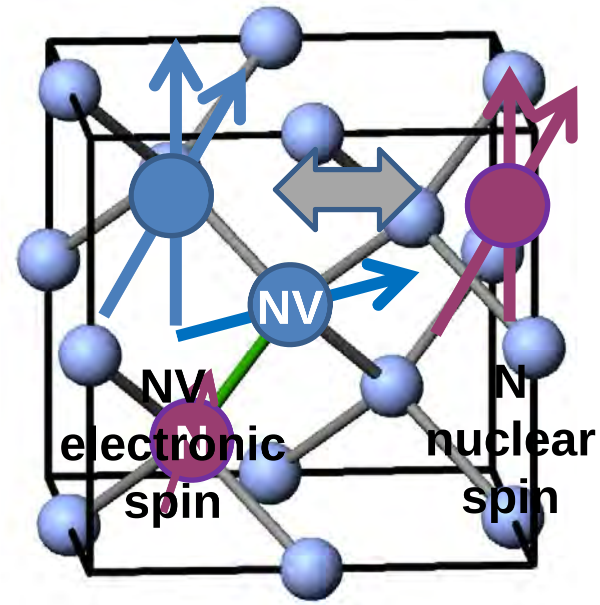




(G.D. Fuchs *et al.*, *Science* **326**, 1520 (2009))

Nuclear spin quantum memory (exchange electron & nuclear spin)

Electron-nuclear SWAP operation:



- quantum memories are building blocks for information processing
- nuclear spins have long-lived spin coherence (milliseconds → seconds)
- ideal to use *intrinsic* nitrogen nuclear spin (scalable)

Require coupling between the spins and control over the interaction

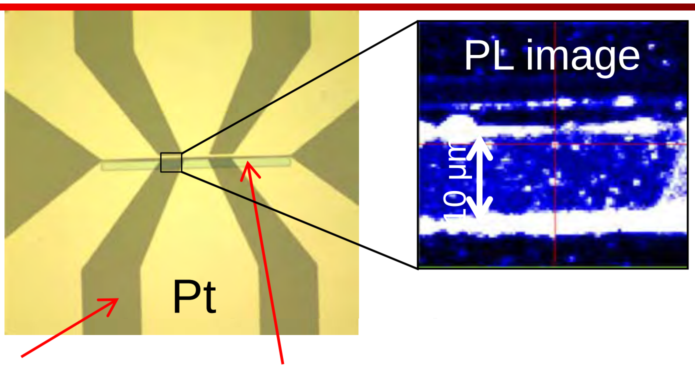
Approach: Use the ***hyperfine interaction*** + a ***Landau-Zener transition***

Electron-nuclear coupling

(quasi-) adiabatic transition
through a level anti-crossing
(time of interaction)

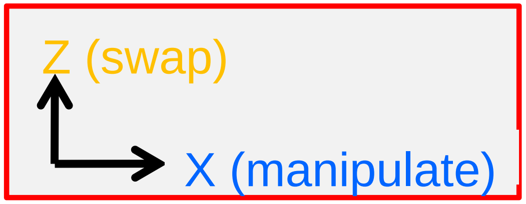
GS electron-nuclear spin SWAP: Landau-Zener

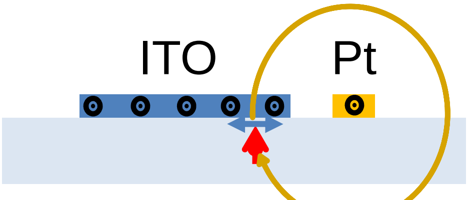
High-bandwidth
2-axis vector
magnet



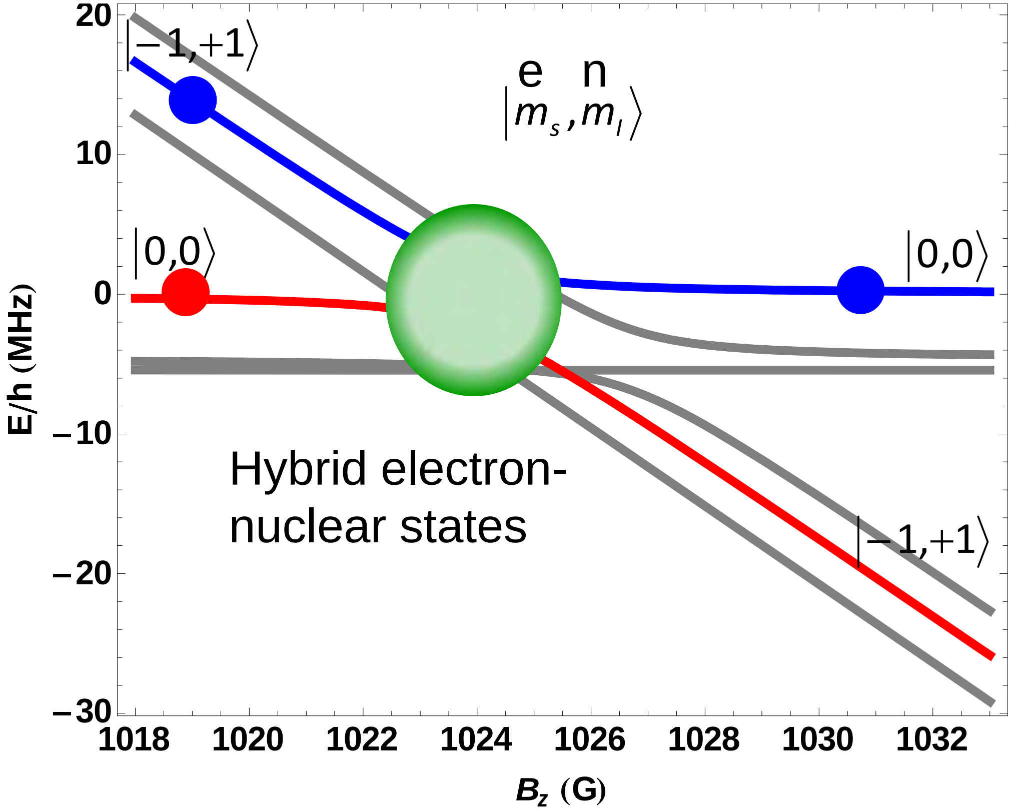
[111] Diamond

ITO (indium tin oxide)

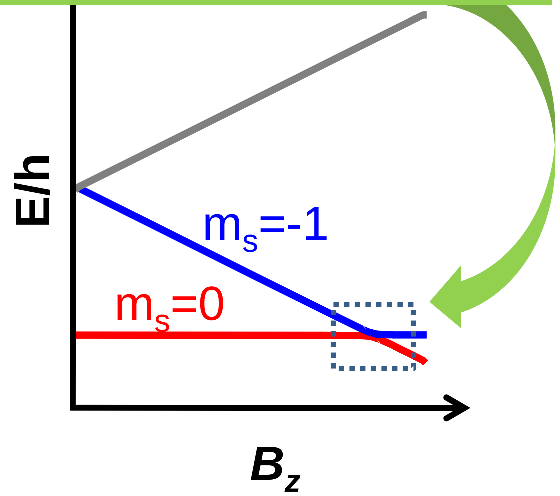




$$P_{LZ} = Exp\left(\frac{-2\pi E_{gap}^{2}}{\gamma \dot{B}_z}\right)$$



Hyperfine interaction mediates avoided crossing



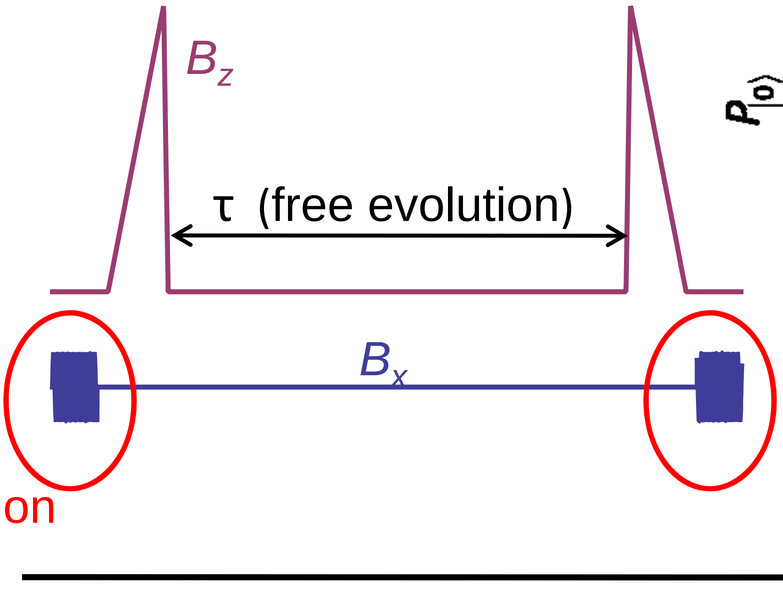
Traversing the region at different rates controls the state composition on the other side

GS electron-nuclear spin SWAP: retrieve coherence

To show that we've really achieved a quantum swap:

- Retrieve the coherence
- Show it is longer lived than the electronic state ($T_2^* \approx 3\ \mu s$)
- Show it evolves as the nuclear spin

Swap & retrieval (Ramsey measurement):

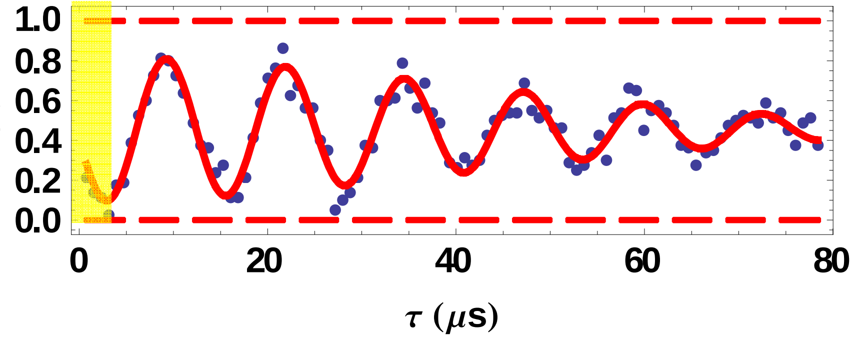


SWAP to nuclear spin

Retrieve from nuclear spin

Prepare electronic superposition

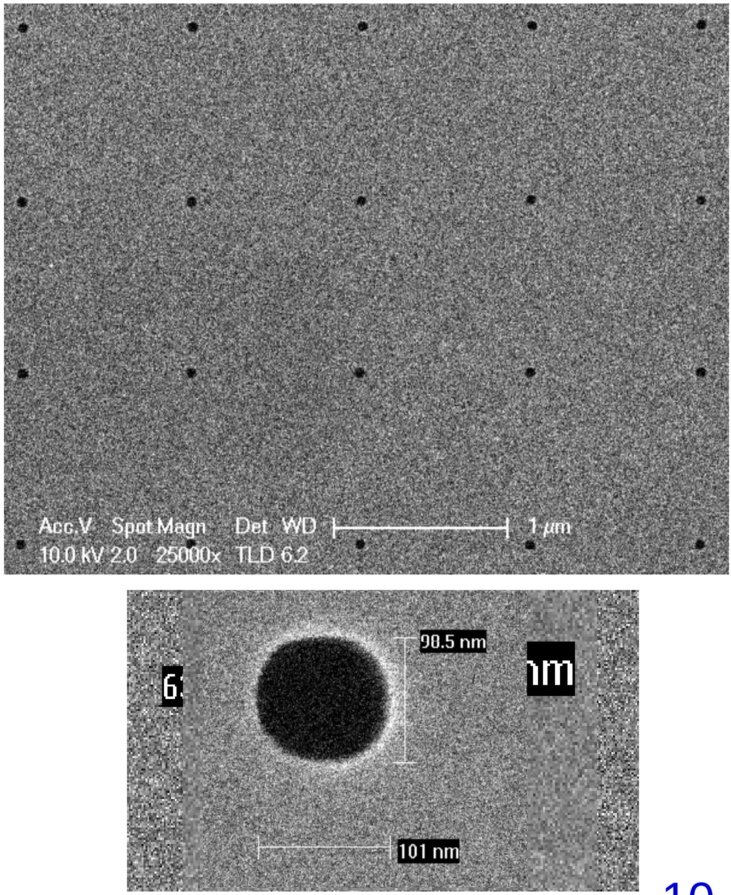
Map superposition to measurement basis



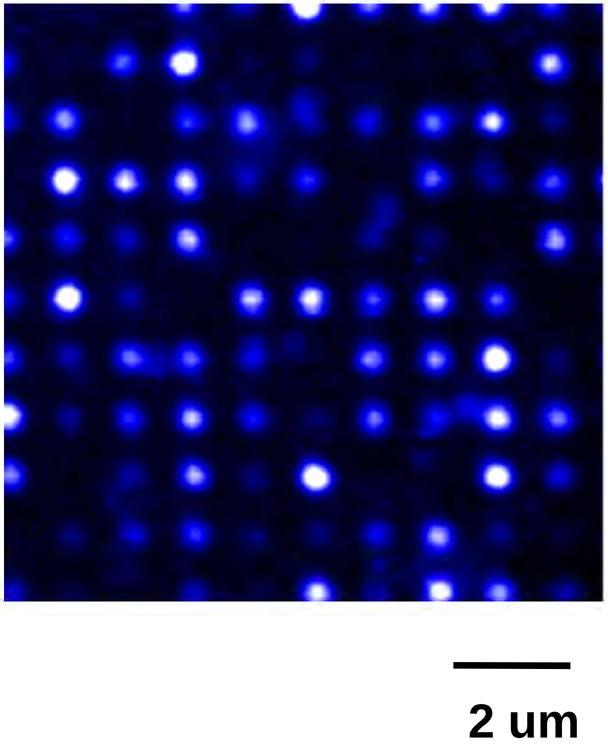
88±6% single-SWAP fidelity
10 μs storage

G.D. Fuchs *et al*., *Nature Physics, 26 June 2011 (DOI: 10.1038/nphys2026)*

Nanofabrication of single spins & arrays: chip-scale



(^{15}N-V centers)

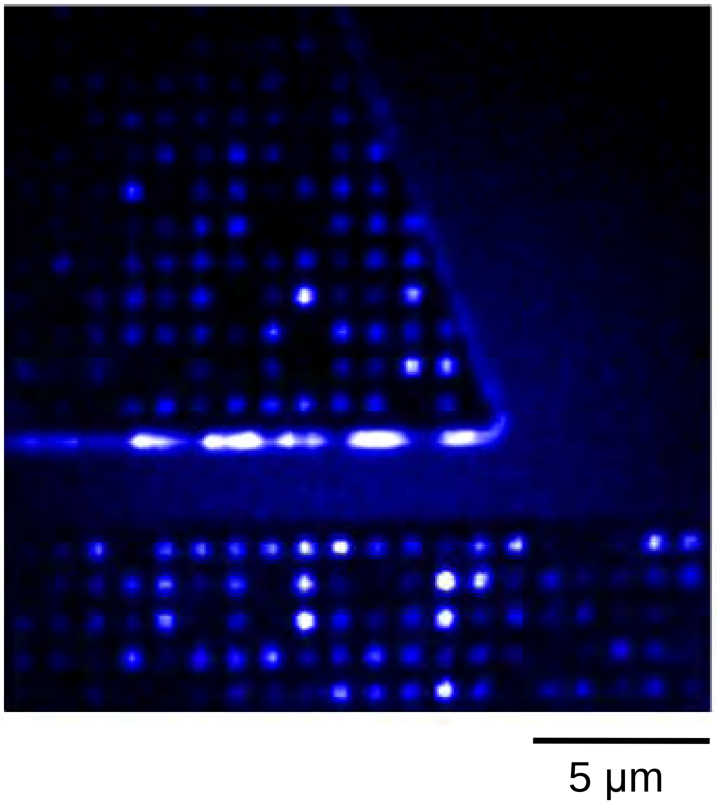


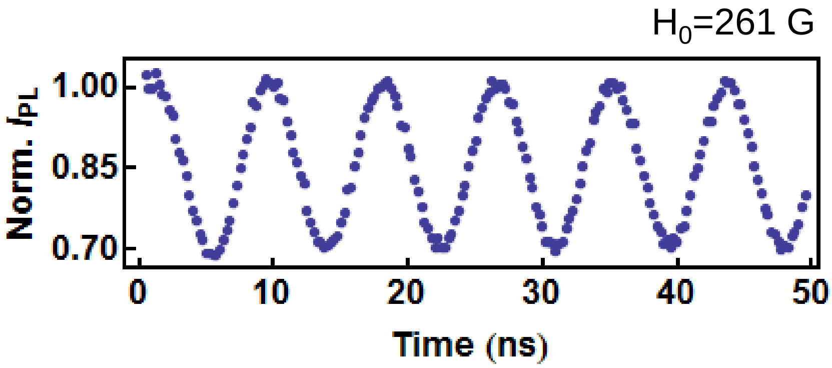
… 10 million apertures per hour (4 mm x 4 mm sample)

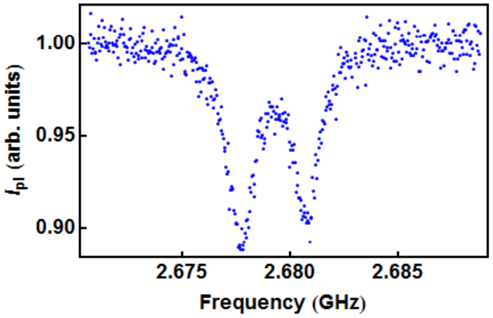
- Ion implantation mask from apertures in ebeam lithography resist
- Anneal (~800 ºC); creation efficiency 10% ± 2%
- ±20nm aperture diameter demonstrated; minimal background emission

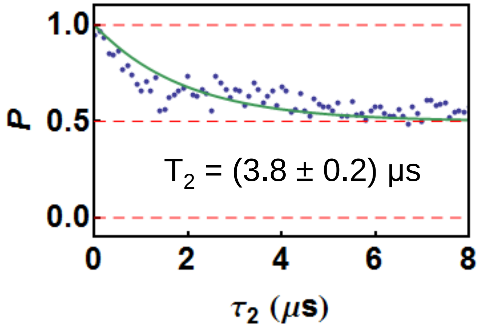
D. Toyli *et al*., *Nano Lett.* **10**, 3168 (2010)

Spin resonance characterization of arrays





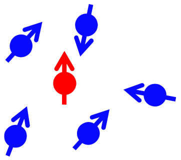




- Integrated waveguides for spin resonance
- Isotopic control of NV formation: ^{15}N-V centers
- Characterize spin coherence of implanted NVs

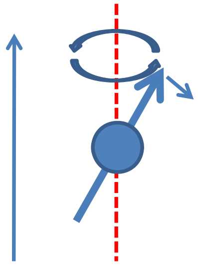
D. Toyli *et al.*, *Nano Lett.* **10**, 3168 (2010)

Questions, challenges, and opportunities



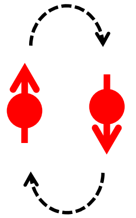
How can we engineer better spin coherence?

- Materials, implanting (reduce spin impurities, both electronic and nuclear)
- Control orbital relaxation? Strain? Temperature?



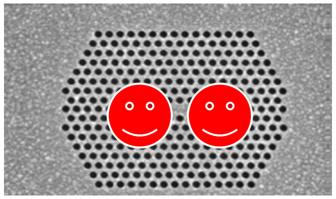
Can we manipulate even faster (or more fidelity)?

- New geometries for microwave manipulation?
- Time-optimal quantum control?



How do we scale up for quantum machines?

- Dipole-coupled entanglement? Photonic entanglement? Cavities?



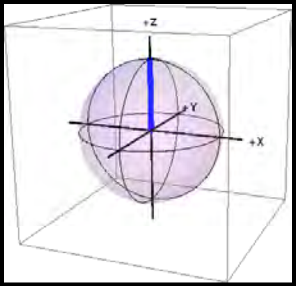
Why diamond? Why NV centers? Computing with defects?

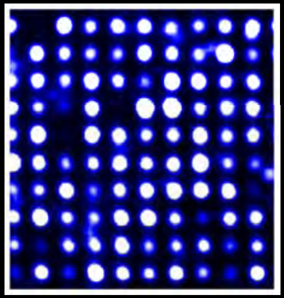
- >500 color centers in diamond alone
- Single photons on-demand for cryptography and quantum communication
- Many other suitable wide-band gap semiconductors with a zoo of defects (see Weber *et al*., *Proc. Nat. Acad. Sci*. **107**, 8513 (2010))

What new physics/devices/technology could emerge? Quantum engineering?

Quantum information/simulation, atomic-scale magnetic sensing, bio-labeling....

Summary: single spin control at room temperature

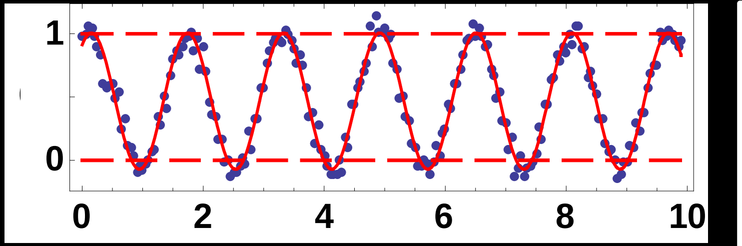


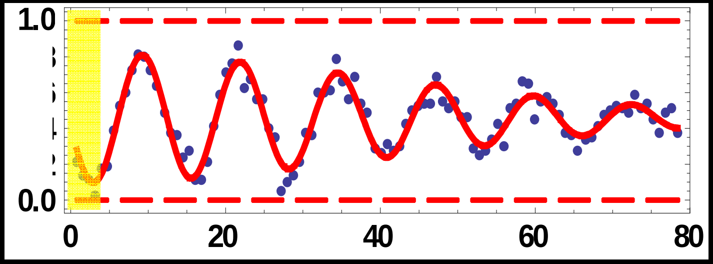


Control

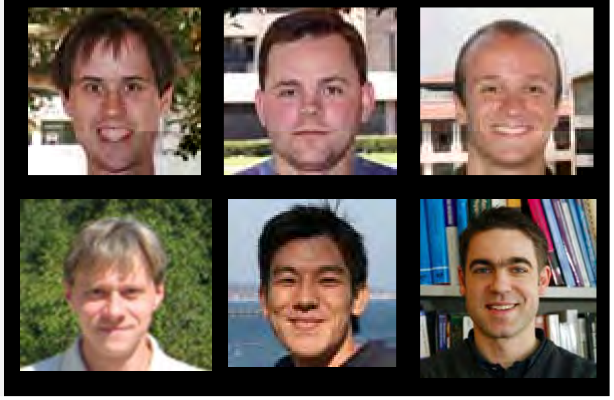
Measurements

- high speed coherent manipulation of a single spin
  sub-nanosecond, faster than expected, deterministic
- patterned ion implantation of NV centers
  isotopic and spatial control of NV formation
- demonstration of single nuclear spin memory
  coherent storage and retrieval of information
- emerging applications: vector magnetometry
  extraction of all three field components & flux imaging





Team Diamond
Greg Fuchs
Bob Buckley
David Toyli
Ken Ohno
Slava Dobrovitski
Guido Burkard



www.physics.ucsb.edu/~awschalom