

# Room Temperature Diamond Quantum Computer

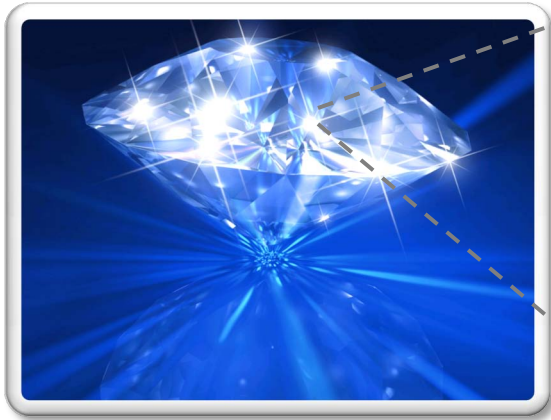
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(ITAMP 2010.8.5)

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Ignacio Cirac, Mikhail Lukin*

# Diamond & Spin Impurities



A diamond crystal

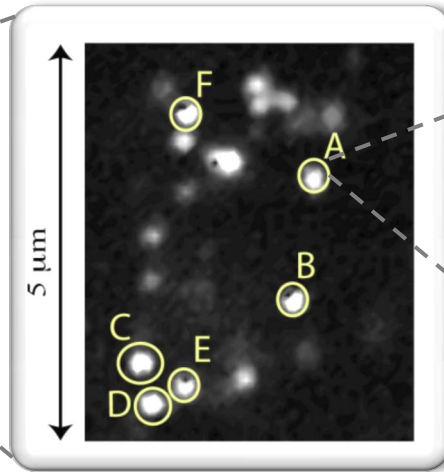
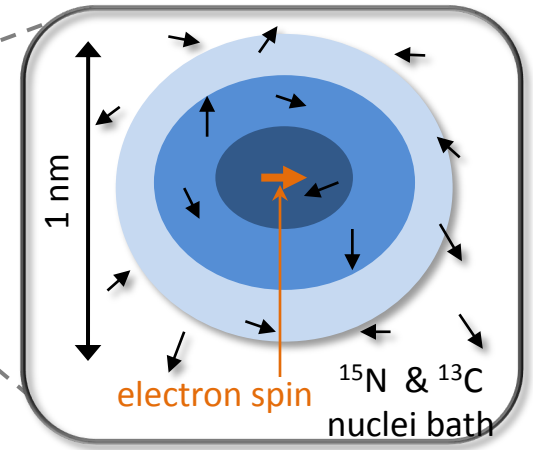


Image of impurity color centers  
(NV- centers)

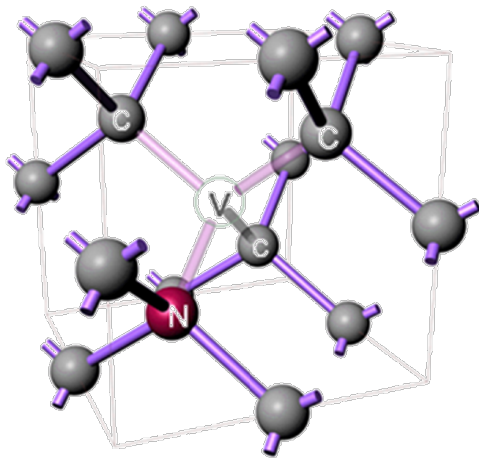


Local spin system  
of a single impurity center

1. Coherently control of electron and nuclear spins @RT
2. Scalable quantum computer @ RT
3. Unpolarized spin chain for quantum transfer @ RT

# Nitrogen-Vacancy (NV-) Center: “Trapped ion in diamond lattice”

✓ **Stable** impurity in diamond

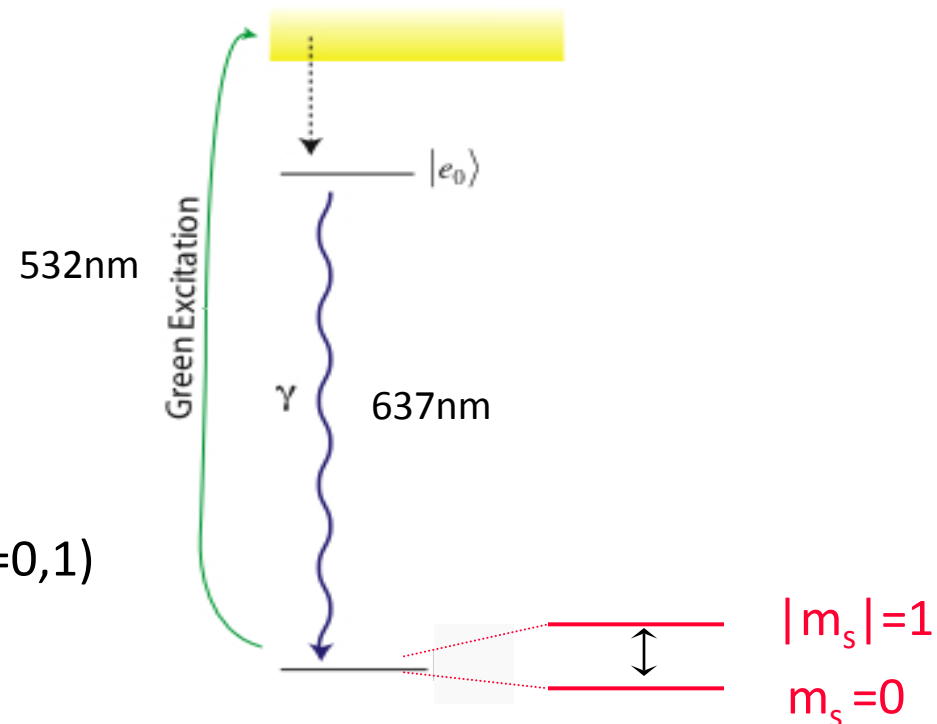


✓ **Ground state properties**

- Non-zero electronic spin ( $S=1$ ,  $|m_s|=0,1$ )
- Microwave transition: zero-field splitting  $\Delta=2.88$  GHz

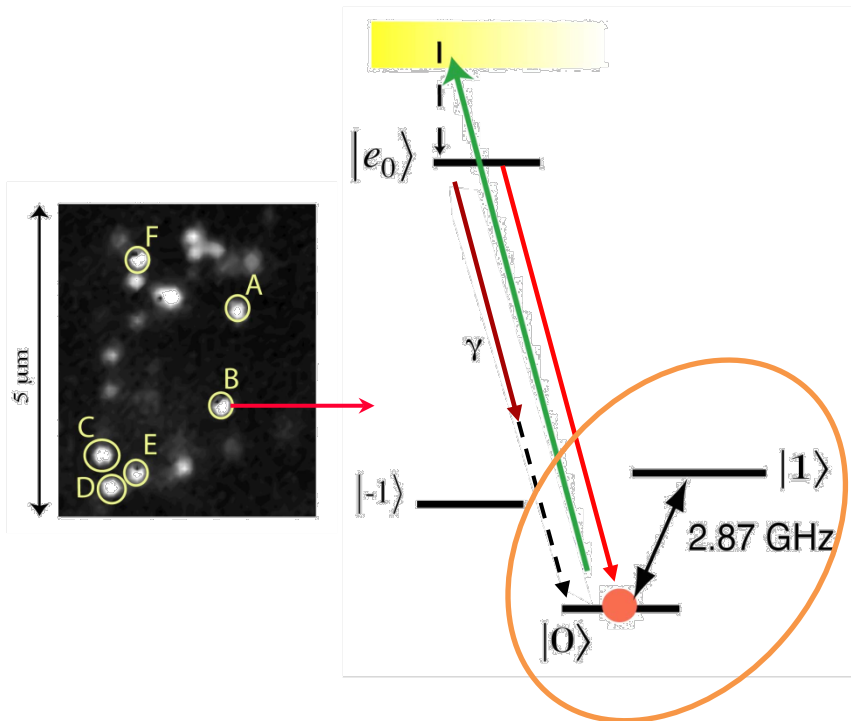
✓ **Optical properties**

- Sharp zero-phonon emission line @ 637 nm
- Can be excited either by 637 nm or 532 nm

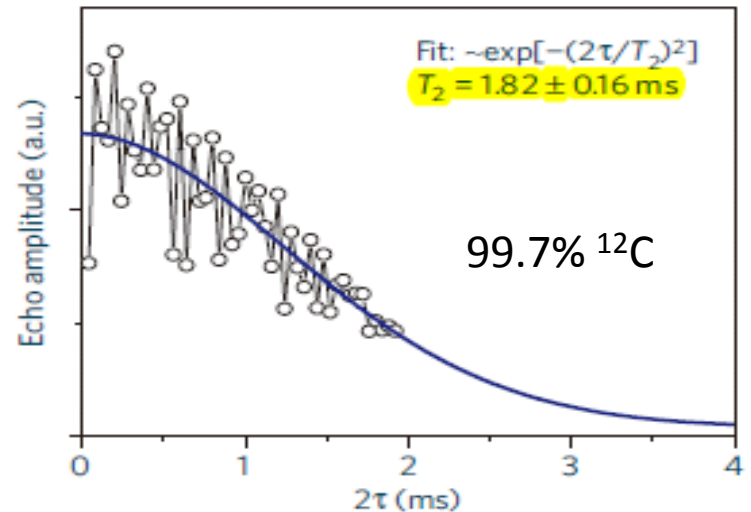
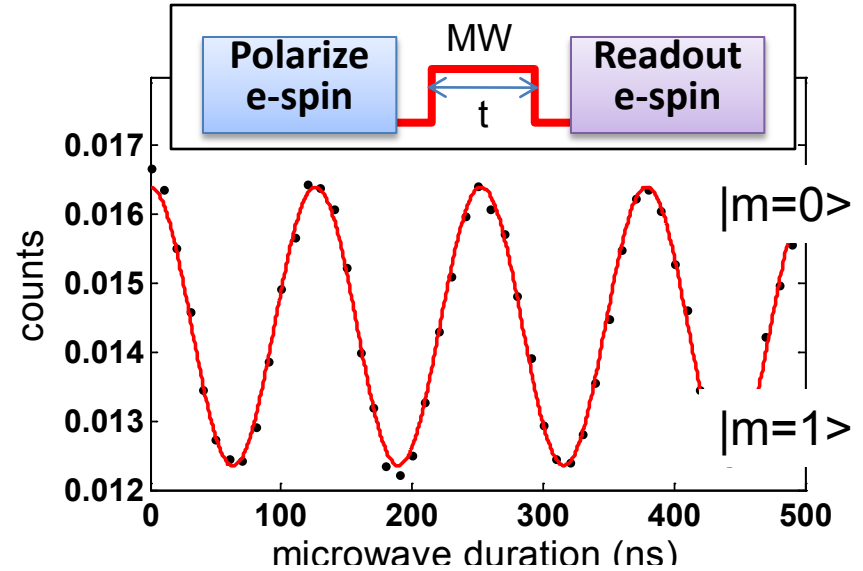


# Control single electron spin

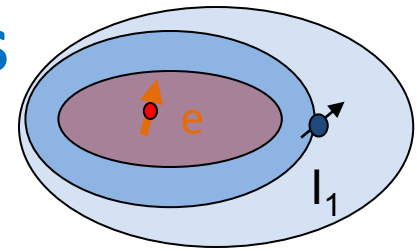
Use light to isolate, polarize, readout electron spin qubit @ RT



$$H_e = \Delta_0 \hat{S}_z^2 + \mu_e B_z S_z$$



# Manipulating individual nuclear spins



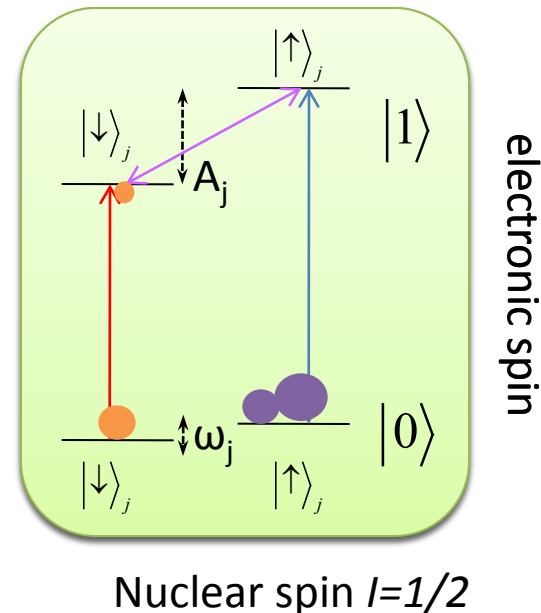
- ✓ Make use of unique hyperfine of proximal nuclei (individual addressability)

$$H_{hf} = A_1 S_z I_z$$

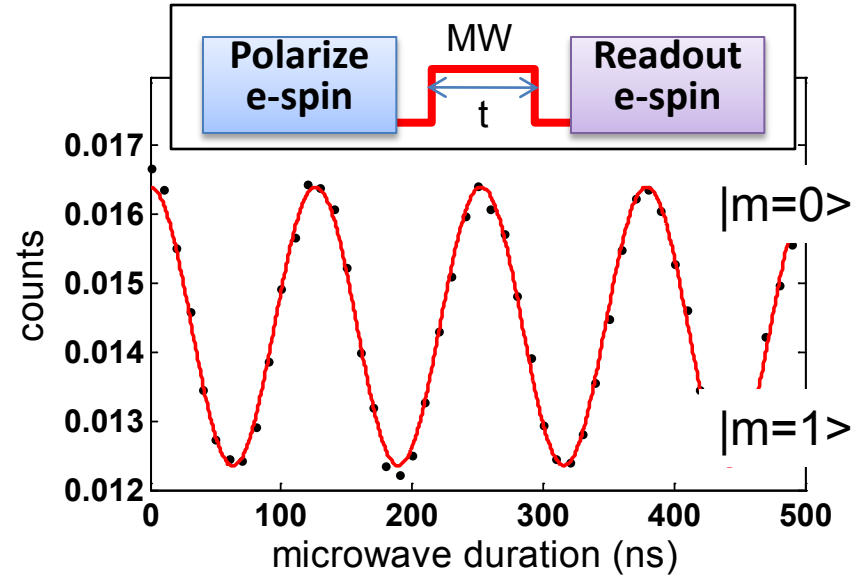
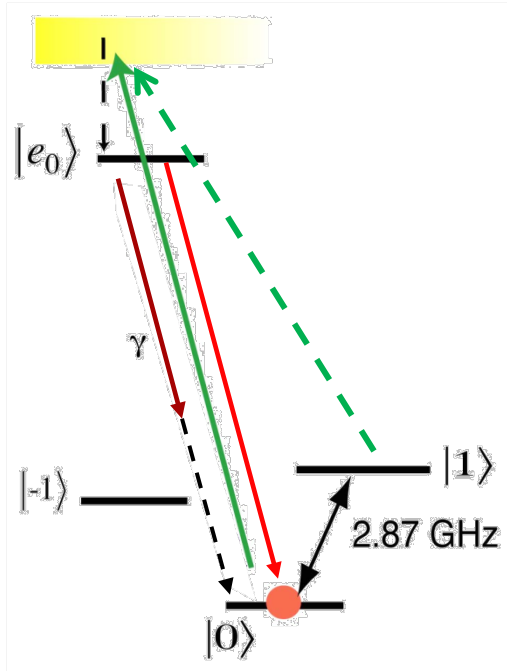
E.g. selective microwave excitation  
@  $2.88 - (A_1 - \omega_1)/2$  GHz  
@  $2.88 + (A_1 - \omega_1)/2$  GHz

E.g. resonant radio-freq excitation  
@  $A_1 = 13.67$  MHz

- ✓ Can be used to
  - polarize, rotate, & readout individual nuclear spins
  - map arbitrary states between electron and nuclei



# Improving Readout with Nuclear Spins



☀ Inefficient readout at **room T**

Low contrast ( $\sim 30\%$ )

Limited by detected photons ( $15 \times 10^{-3}$ )

=> Requiring thousands of averages

**Challenge:**

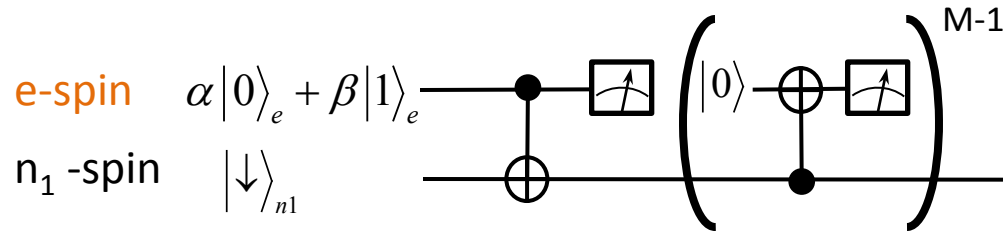
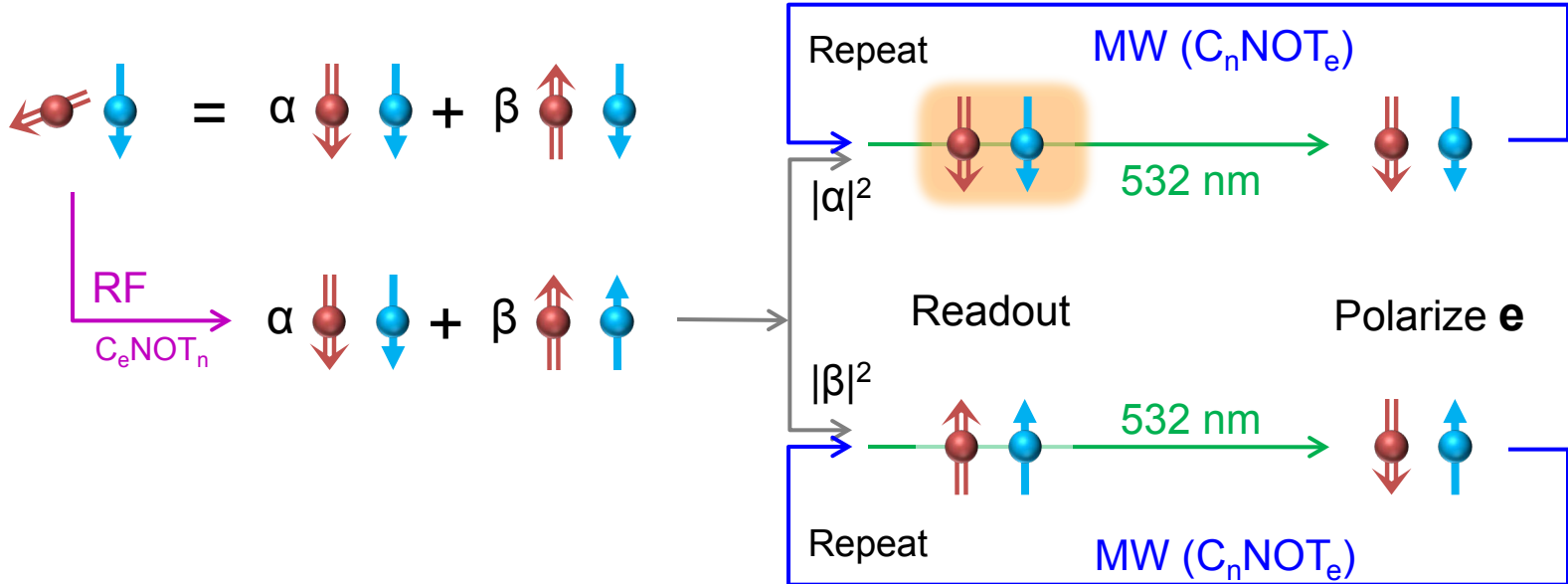
**How to Improve the readout efficiency?**

Application: NV nano magnetometer

Sensitivity 30nT/√Hz, limited by readout efficiency.

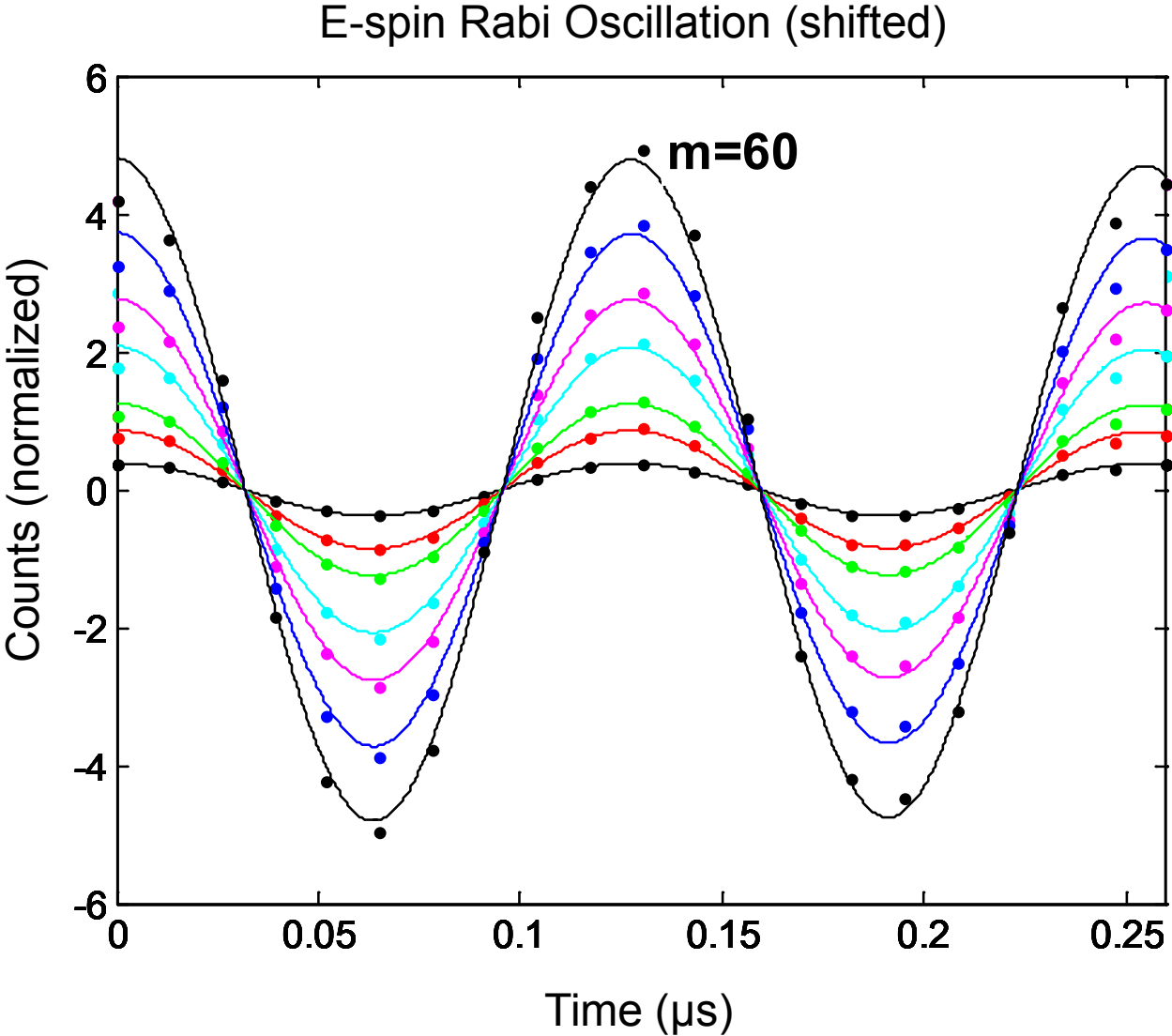
# QND Readout

**Idea:** Map electron spin to nearby nuclear spin, repetitively measure nuclear spin.



\*Assuming Laser pulses do not flip n-spin.

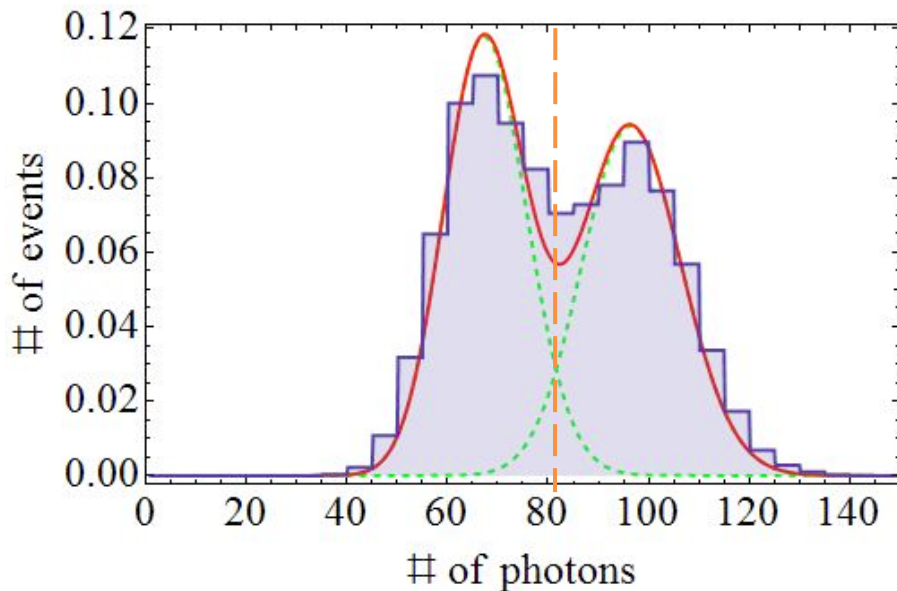
# Repetitive Readout: Experimental Results



# Single-Shot Readout

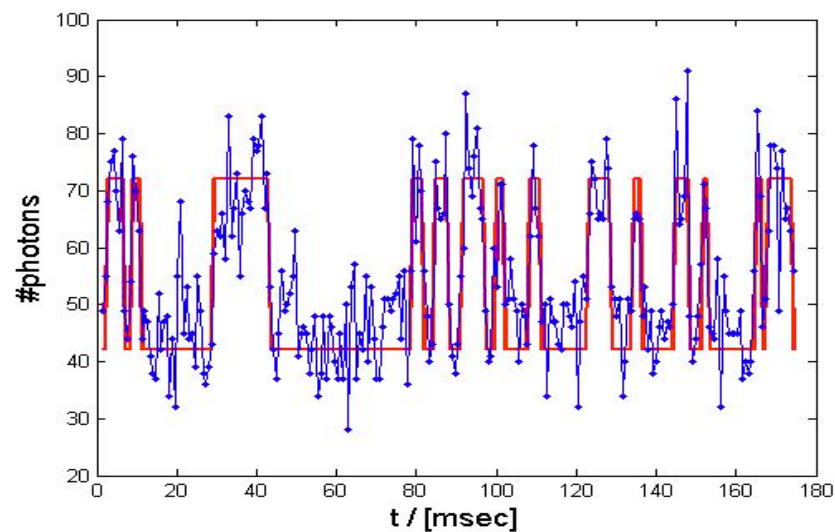
Use high magnetic field  $B \sim 0.5T$ , to suppress  $S_+I_-$

Photon distribution ( $10^3$  rep.)



Readout fidelity  $\sim 95\%$

Time trace

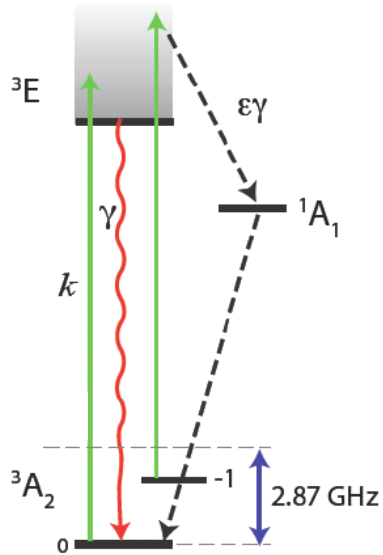


observe individual quantum jumps

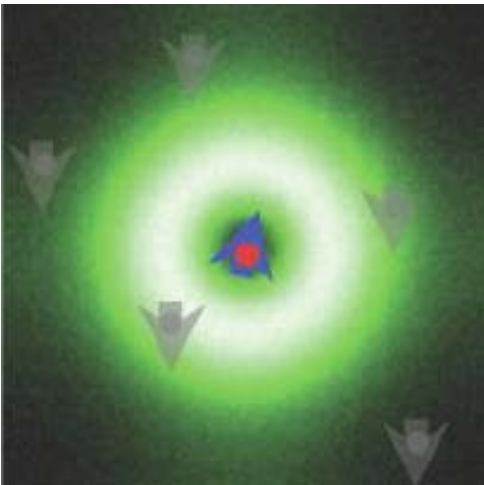
# Subwavelength Readout

## -- Spin-RESOLFT

Energy levels for NV



Schematic Plot



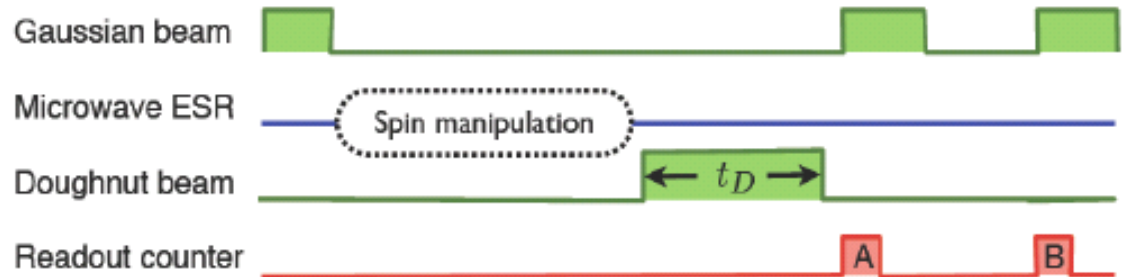
Green Gaussian beam

- Fluorescent readout
- Optically pump all NVs to  $|ms=0\rangle$  spin state

Green **Doughnut** (vortex) beam:

- Optically pump all NVs (**except for** the NV at the dark spot) to  $|ms=0\rangle$  spin state
- After doughnut beam, the readout only depends on the spin in the dark spot.

Pulse sequences for spin-RESOLFT



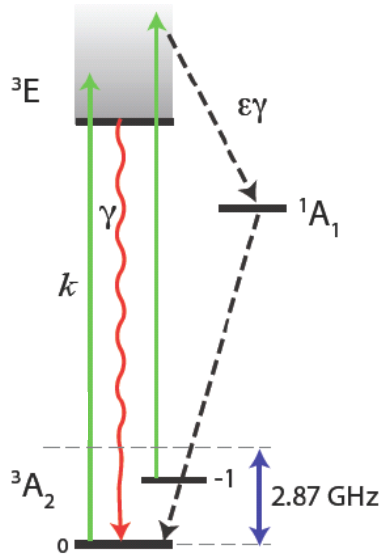
Maurer, Maze, Stanwix, et al., Nature Physics (in press).

RESOLFT: Reversible Saturable Optical Linear Fluorescent Transition

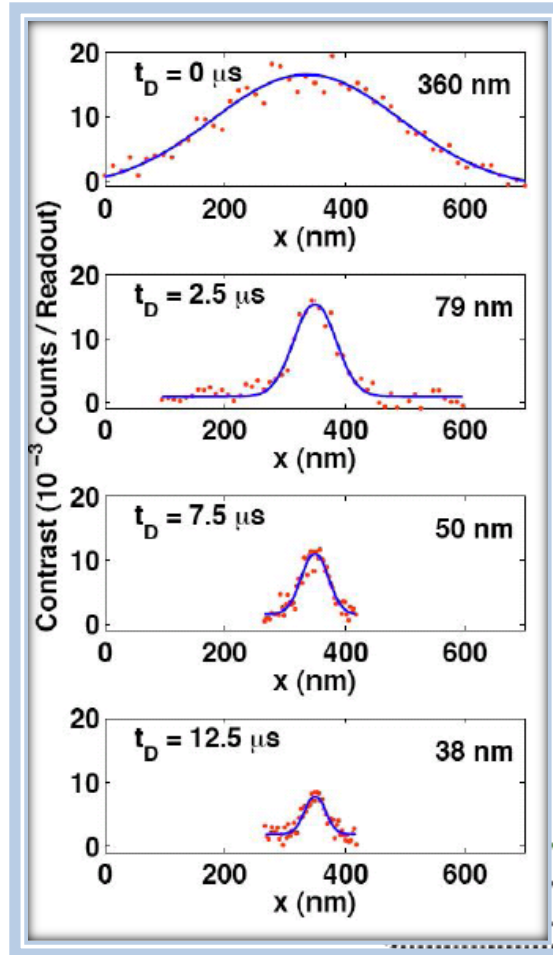
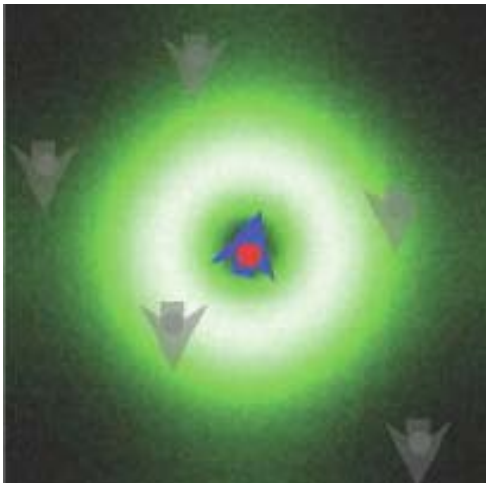
# Subwavelength Readout

## -- Spin-RESOLFT

Energy levels for NV



Schematic Plot



Resolution is estimated by:

$$\Delta r = \frac{\lambda}{2N_A \sqrt{1 + \Gamma t_D}}$$

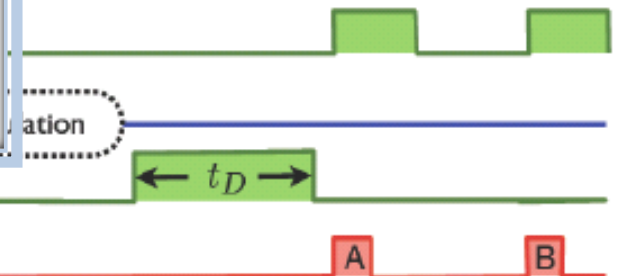
$\Gamma$ : doughnut power

$t_D$ : doughnut duration

spin-RESOLFT

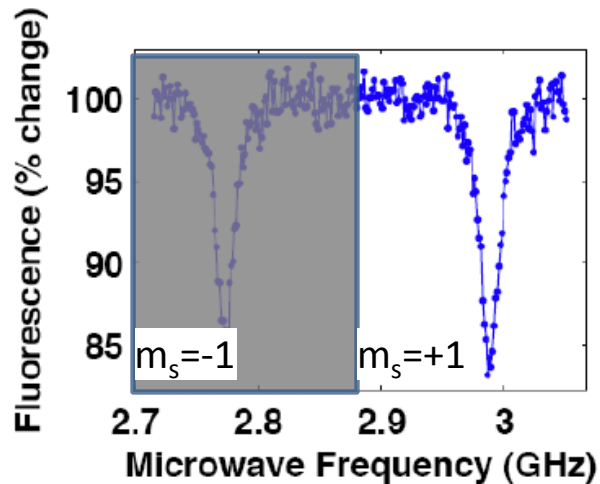
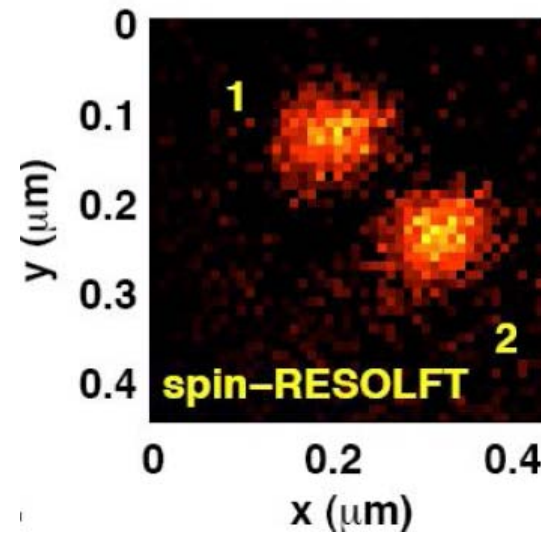
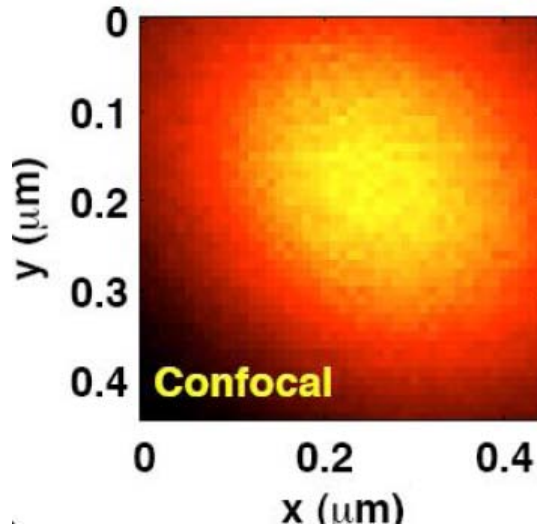
Doughnut beam

Readout counter



# Subwavelength Readout

-- Resolving two NV centers

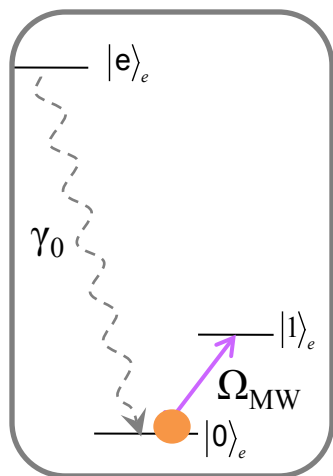
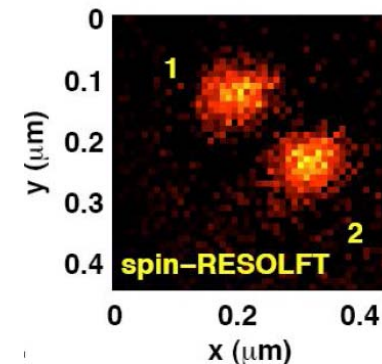
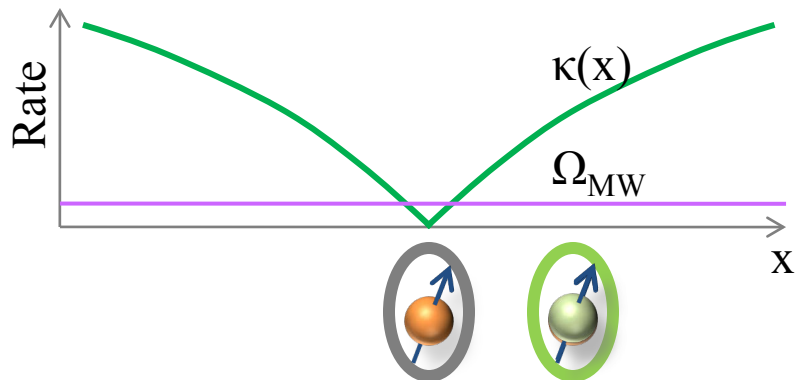


Separation  $\sim 150$  nm

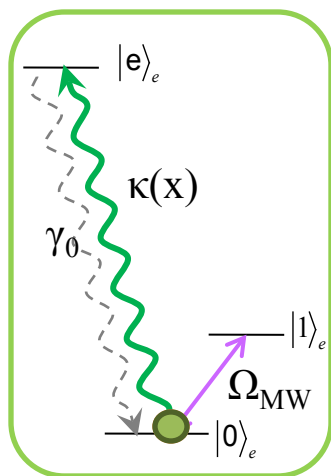
- Beyond diffraction limit
- Confocal not resolvable
- Nominal identical ESR spectrum

# Subwavelength Manipulation

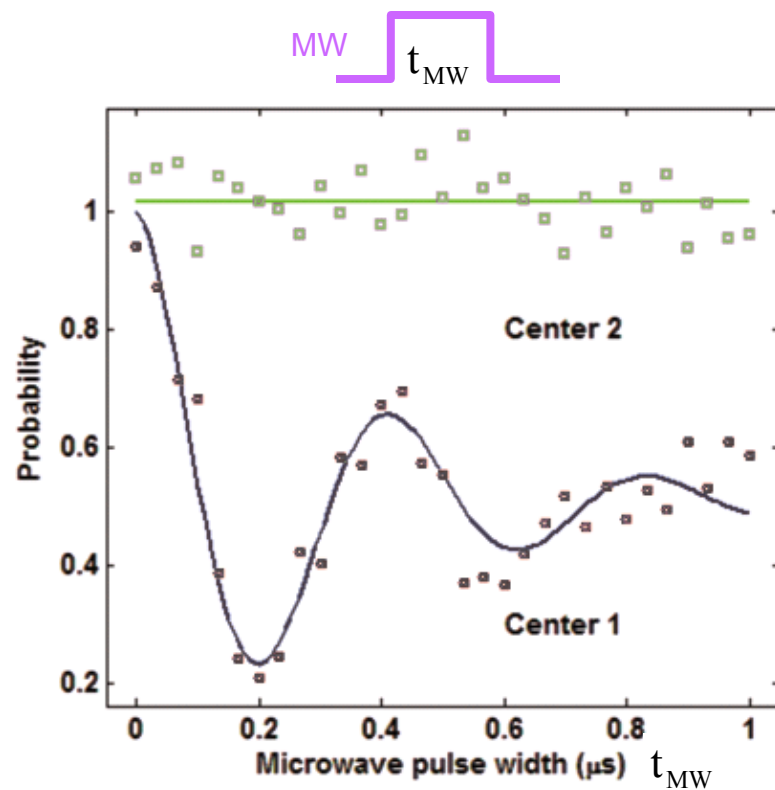
Idea: Use quantum Zeno effect.



Rabi oscillation



No Rabi oscillation  
(Quantum-Zeno Effect)



# Summary:

## Recent Experimental Progress @ Room Temp

### Long **electron spin** coherence time [A9.5]

- ✓  $T_2 \sim \text{ms}$  (for >99.7%  $^{12}\text{C}$  diamond)  
[Childress, et al., Science (2006); Balasubramanian, et al., Nat. Mat. (2009)]
- ✓ Magnetic dipole coupling (e.g., 50kHz for 10nm spacing)  
[Neumann, et al., Nature Physics (2010)]
- **Coherent two-qubit gate**

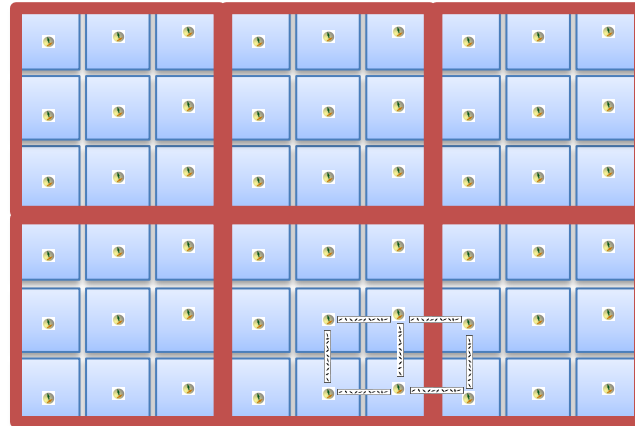
### Good **nuclear spin** quantum memory

- ✓ Extremely long  $T_2$  ( $\gg 20\text{ms}$ ) in dark [Dutt, et al., Science (2007)]
- ✓ Slow decoherence in bright [Jiang, et al., PRL (2008), Science (2009)]
- ✓ **Single-shot QND readout**  
[Jiang, Hodges, Maze, et al., Science (2009); Neumann, et al., Science (2010)]

### **Subwavelength** addressability

- ✓ Spin-RESOLFT (and STED) readout [Rittweger, et al., Nat. Photon. (2009), Maurer, Maze, Stanwix et al., submitted]
- ✓ Selective control using quantum Zeno effect [Maurer, Maze, Stanwix, et al., submitted]
- ✓ Use magnetic field gradient [Balasubramanian, Nature 2008]
- **Selective single-qubit manipulation with high fidelity**

# Architecture of Room Temperature Diamond Quantum Computer



# Summary

- Recent progresses in NV experiments @ RT
  - Good NV registers
  - Single-shot readout
  - Subwavelength addressing
- Architecture for RT diamond QC
- Unpolarized spin chain data bus