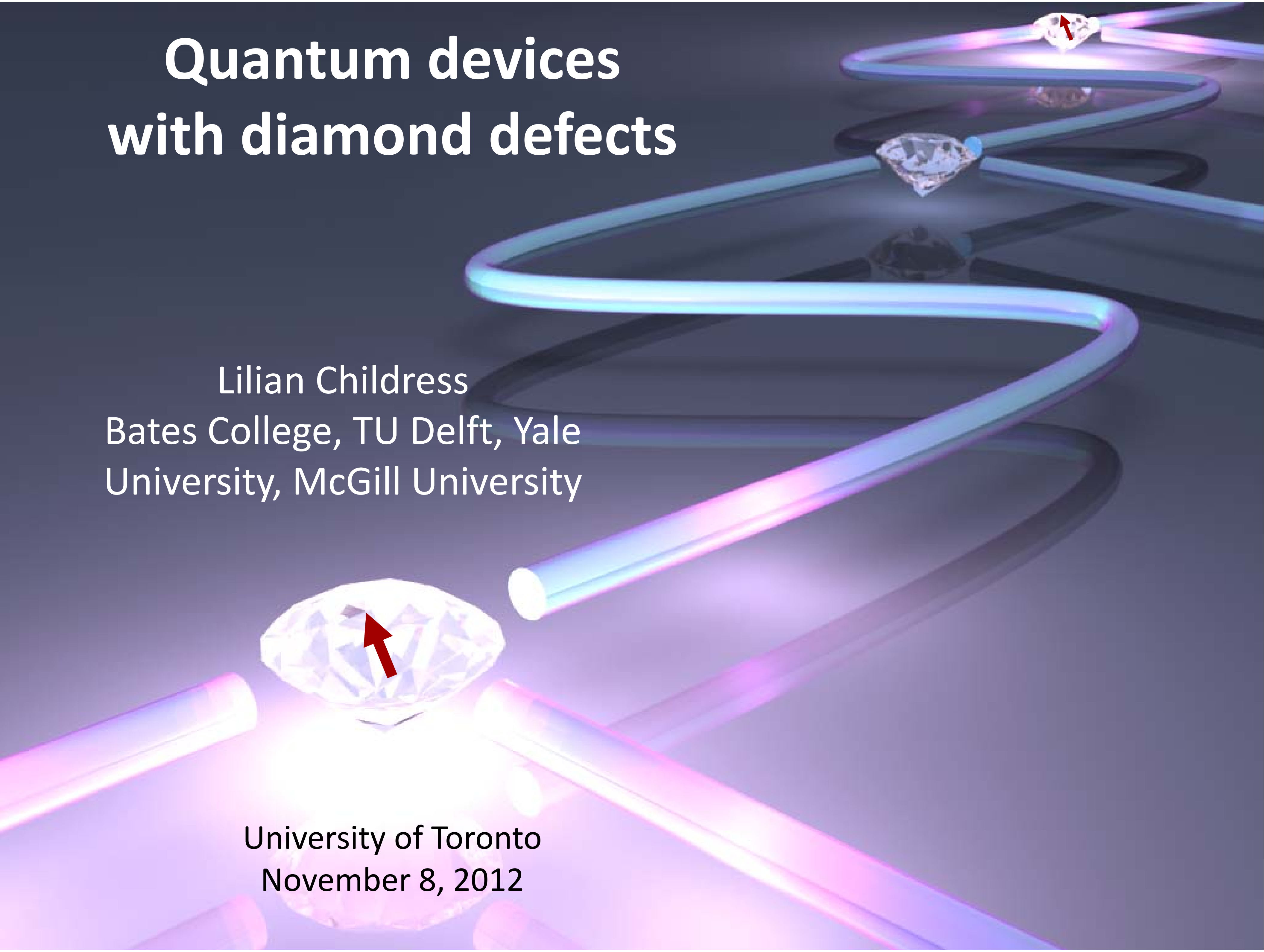
Quantum devices with diamond defects



Lilian Childress

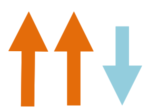
Bates College, TU Delft, Yale University, McGill University

University of Toronto

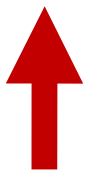
November 8, 2012

A few applications of diamond defect centers

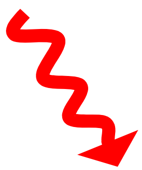
Quantum information science



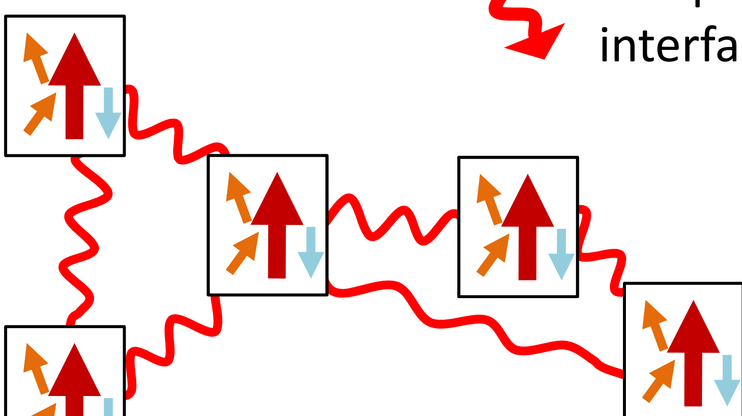
Long-lived nuclear spin quantum memory



Electronic spin mediates gates



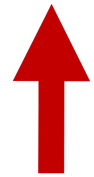
And provides an optical interface

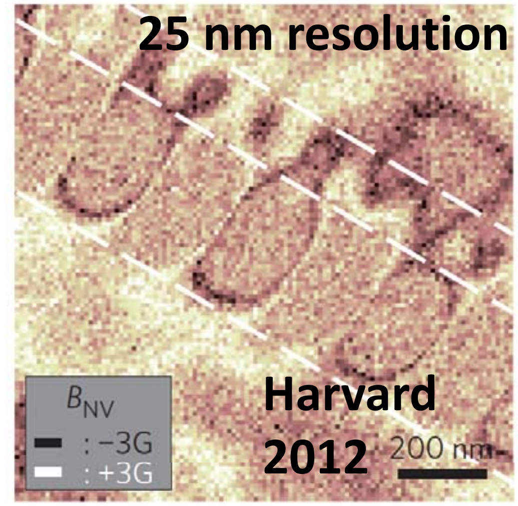


for quantum repeaters and quantum networks

Metrology

Spin as sensor of electric and magnetic fields, acceleration , time





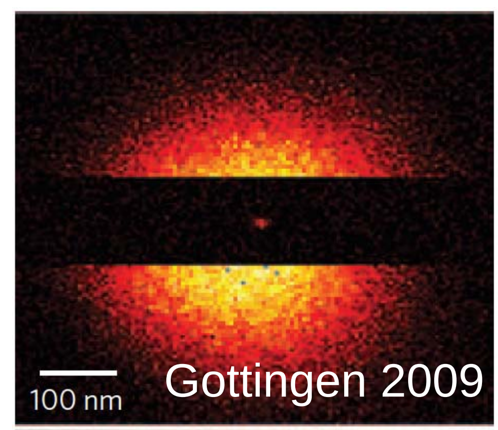
Scanning magnetometer

Optical devices

Single photon source

Stable emitter for fluorescence markers

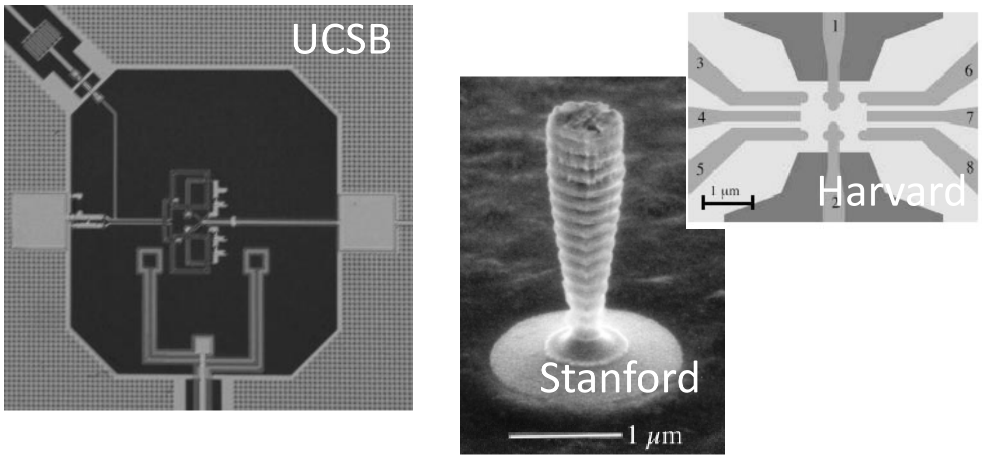
Subwavelength resolution



The quest for quantum bits

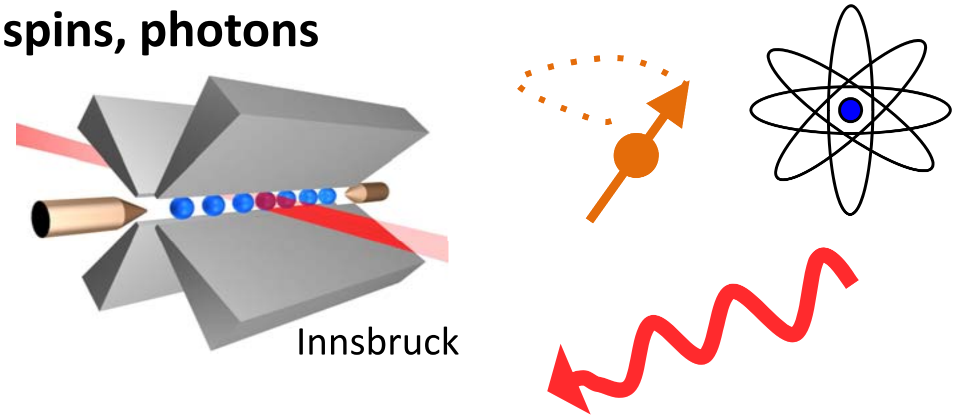
Controllability vs coherence

•Solid state quantum systems



✓ Fast electrical or optical gating
✓ Typically short coherence times
✓ Inconsistent fabrication outcomes

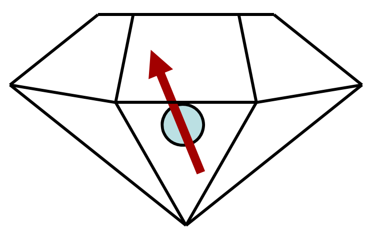
•Atoms & molecules, isolated nuclear spins, photons



✓ Longest coherence times
✓ Excellent selection rules
✓ Difficult to prepare, control, and measure on fast timescales

•Impurity-based electronic spins in solids

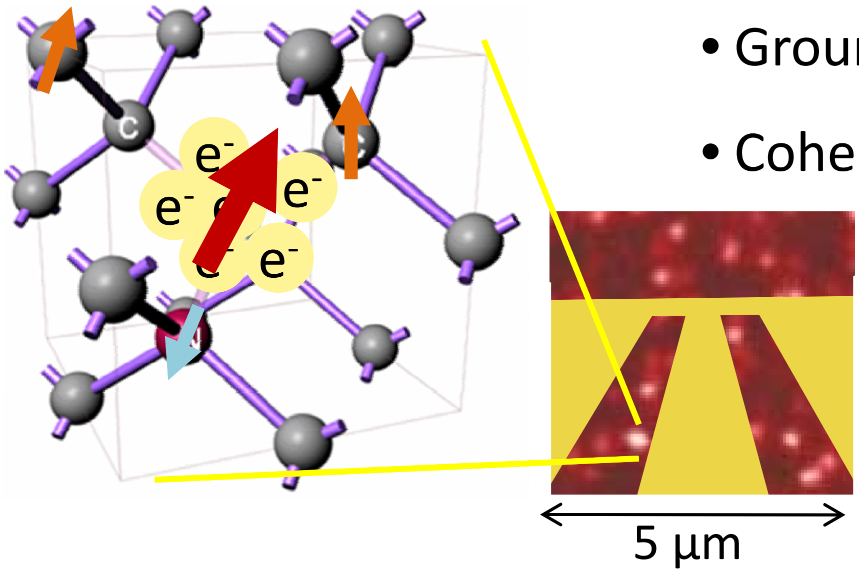
✓ Fast control possible with microfabricated gates



✓ Long coherence times in spinless hosts

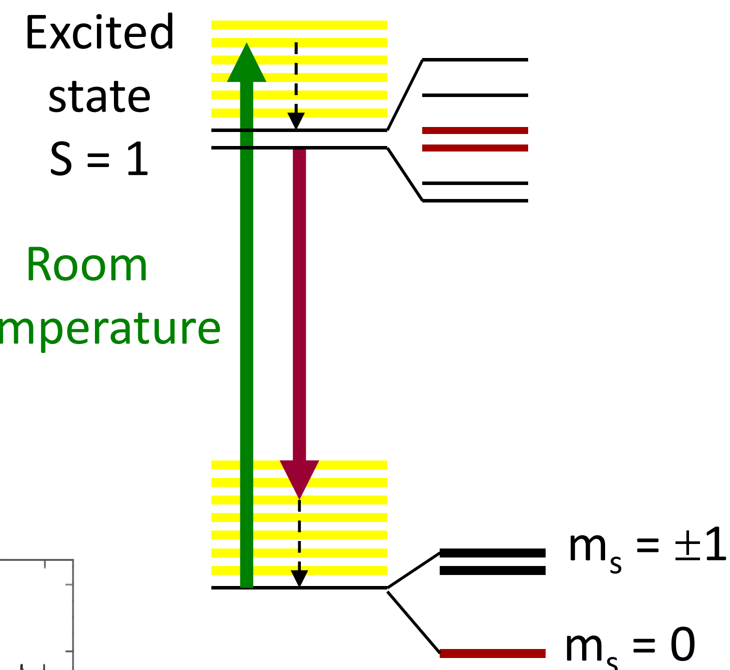
✓*NV diamond: An interface between nuclear spins and photons*

The nitrogen-vacancy center in diamond

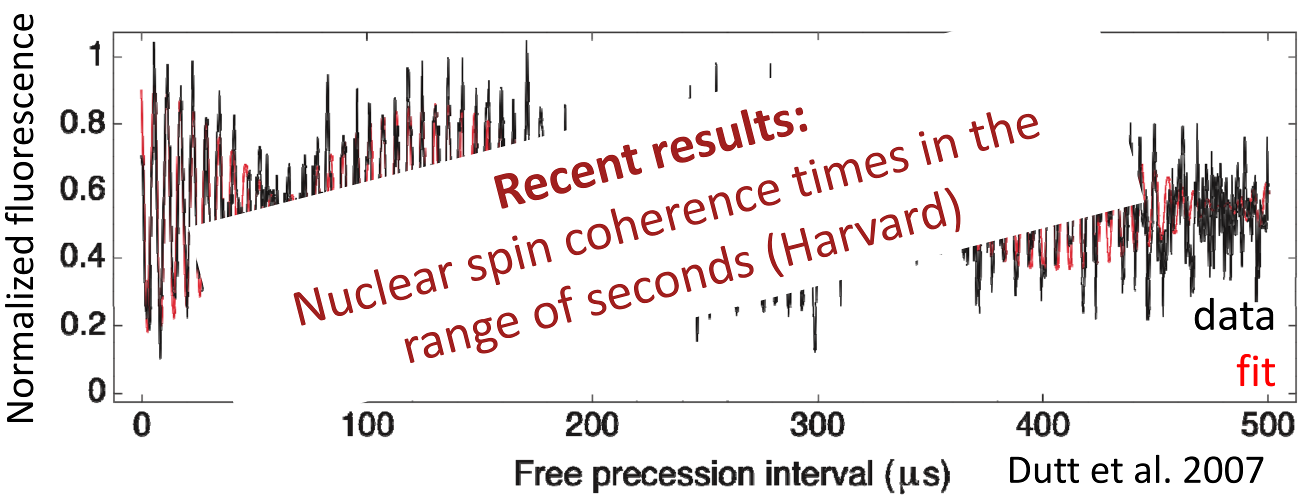


- Ground state electronic spin triplet
- Coherent interactions with proximal nuclear spins

Fast control
~ ns (electron)
~ µs (nuclear)



- Optical transitions: single-defect isolation, preparation & detection of the electronic spin and the nuclear spins with which it interacts

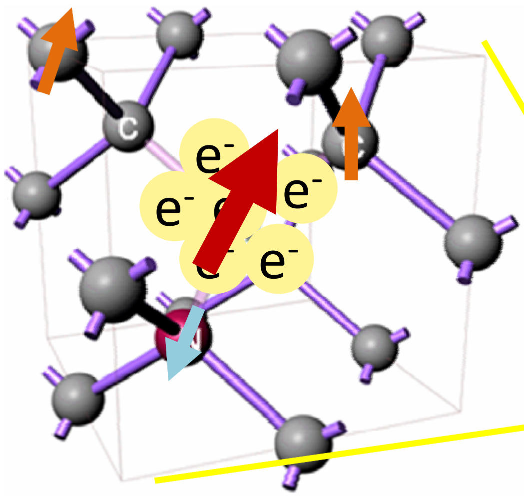


Dutt et al. 2007

Precession of a single ^{13}C nuclear spin

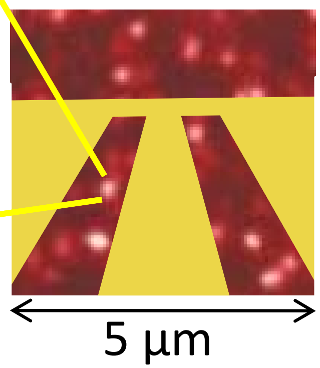
Stuttgart, Harvard, U CSB, Canberra

The nitrogen-vacancy center in diamond

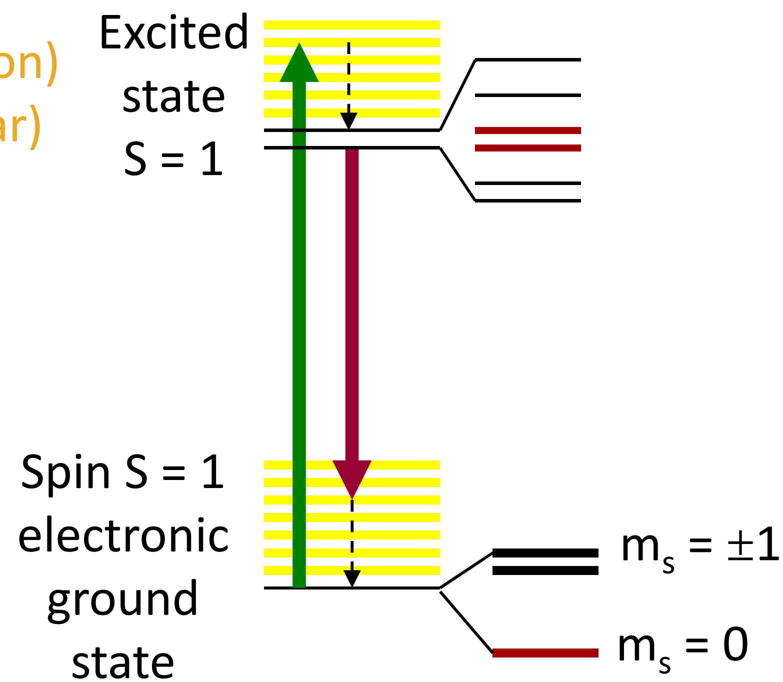


- Ground state electronic spin triplet
- Coherent interactions with proximal nuclear spins

an NMR molecule



Fast control
~ ns (electron)
~ µs (nuclear)



- Optical transitions:
  preparation & detection of the electronic spin

Conventional approach: non-resonant excitation

Higher fluorescence from $m_s = 0$

Optical polarization into $m_s = 0$

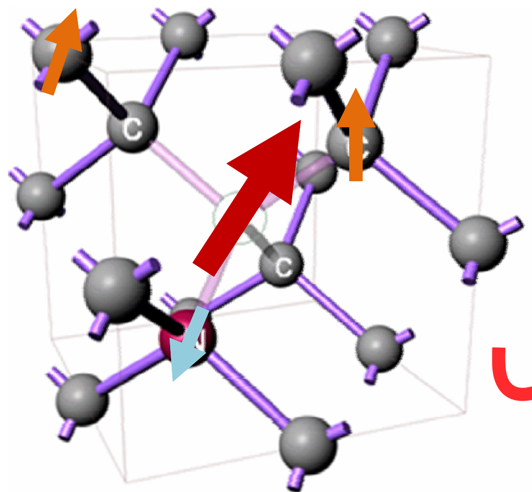
Enables measurements of a single NV spin

even at room temperature

Stuttgart, Harvard, UCSB, ANU

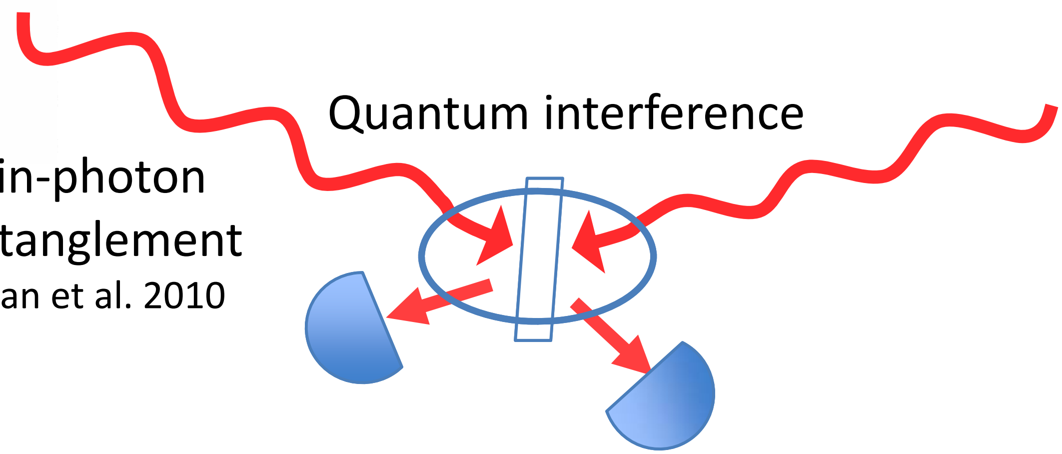
A new arena for exploring quantum phenomena and investigating applications

The nitrogen-vacancy center in diamond



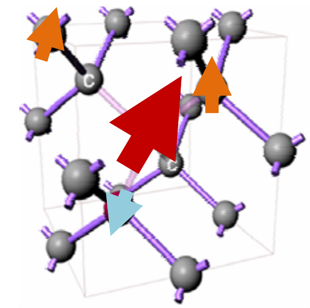
The vision:

- A few-spin-qubit register with preparation, coherent control, and measurement
- Scalability via optical connections



Quantum interference

Spin-photon entanglement
Togan et al. 2010



Fast magnetic r
based 1-
Stutt

Recent results:
Grover search with
decoherence-protected gates
Van derSar 2012 (Delft)

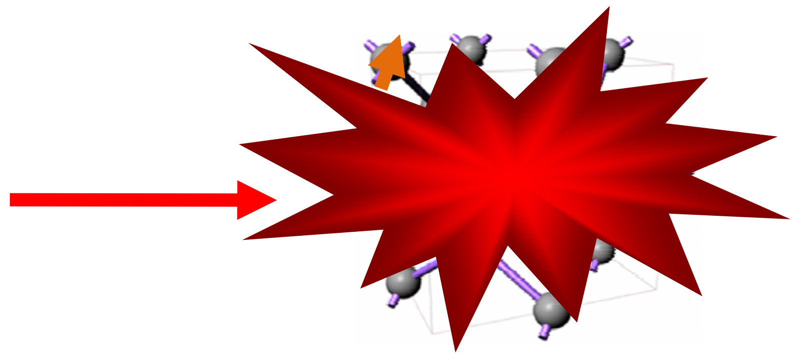
, Harvard

Coincidence detection
→ leaves spins entangled

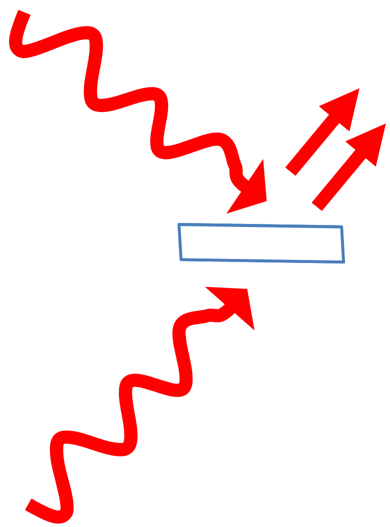
a quantum channel
between the registers

Outline

1. Optical spin readout

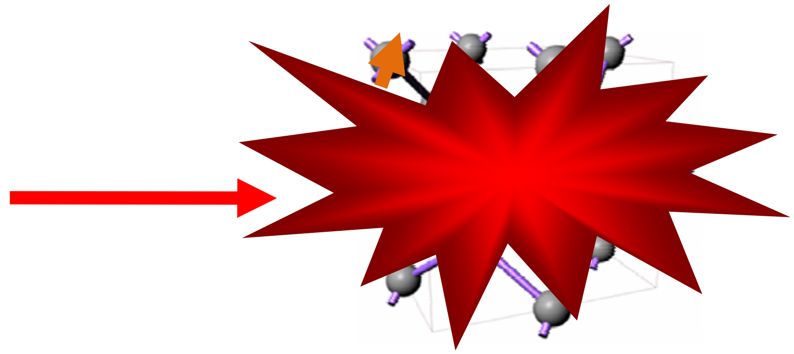


2. Two photon quantum interference



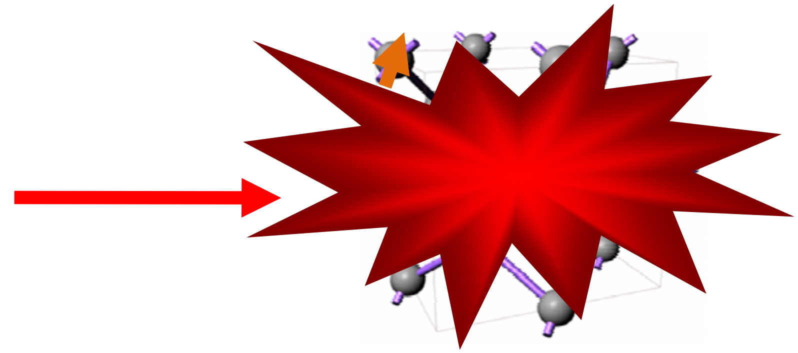
Outline

1. Optical spin readout



Outline

1. Optical spin readout



Challenge:

High fidelity preparation and single-shot detection of multiple spins

Conventional approach: non-resonant excitation

Higher fluorescence from $m_s = 0$

Optical polarization into $m_s = 0$

Time-averaging or repetition* required!

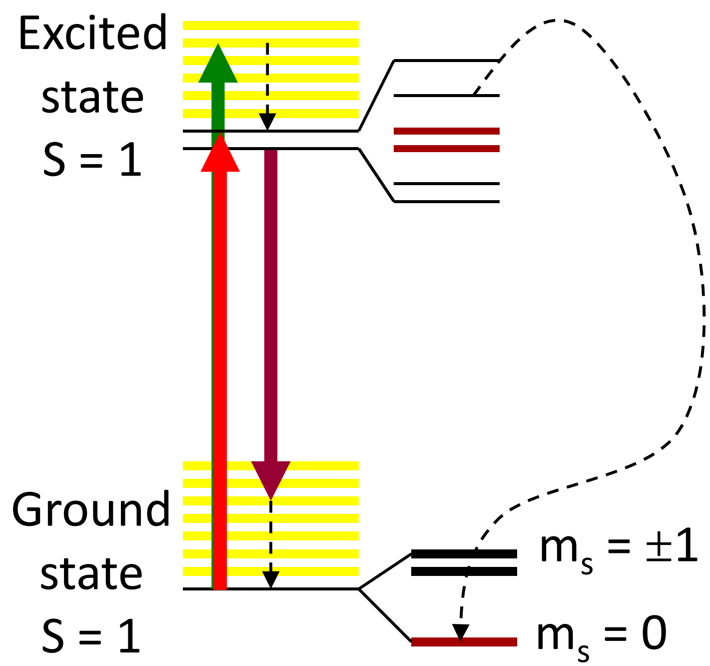
?

Other approaches

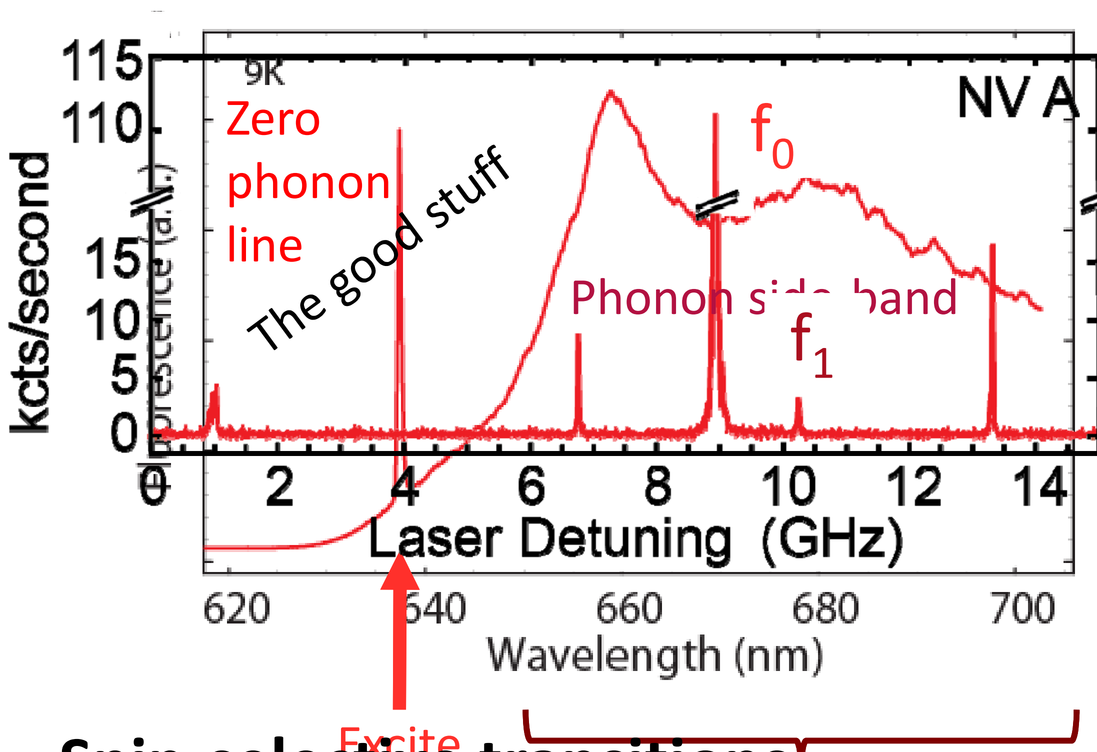
e.g. Buckley et al. Science 2010

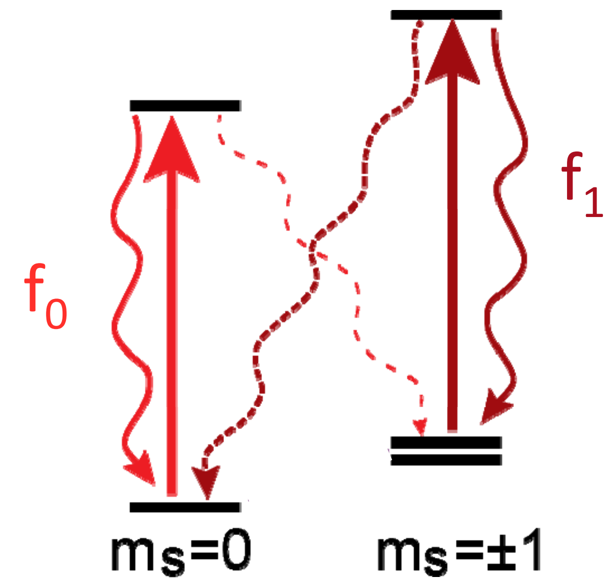
Our approach: resonant excitation

*Single shot readout of a nuclear spin, Neumann et al. Science 2010



Resonant excitation of a single NV center at low temperature





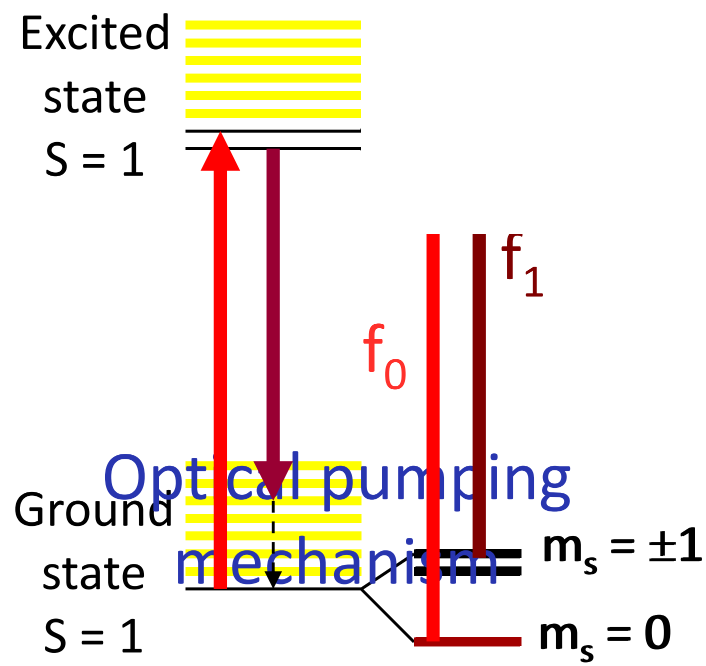
Spin-selective transitions

f_0 only excited from m_s = 0 ground state

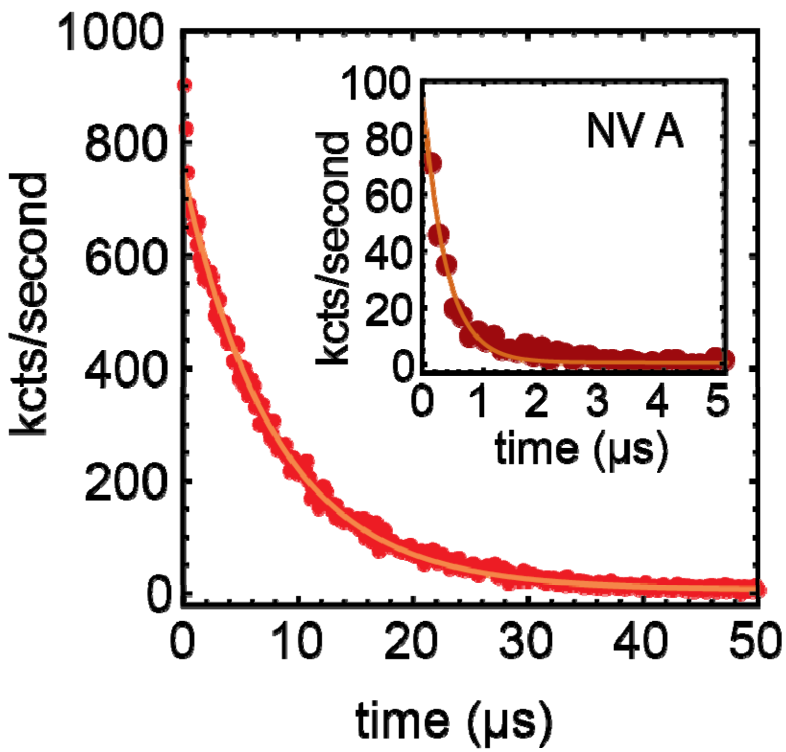
f_1 only excited from m_s = ± 1 ground state

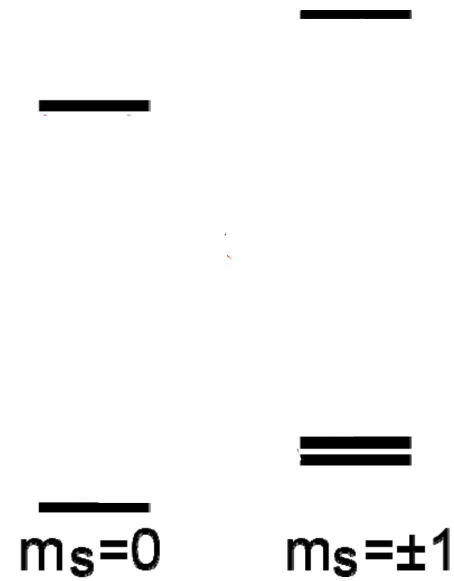
Mostly spin-conserving transitions

Some spin-mixing within the excited state



High fidelity spin preparation: Optical pumping



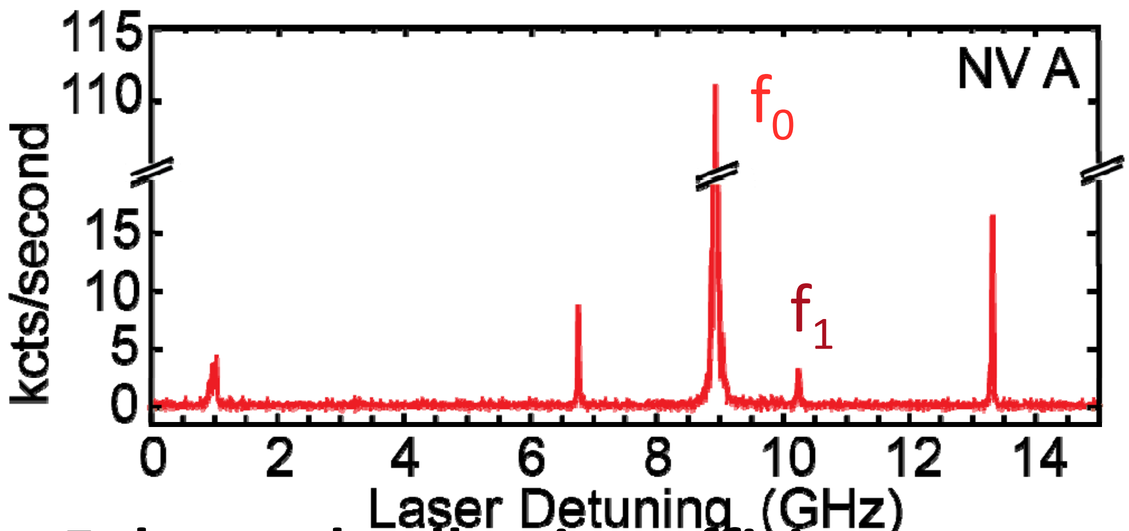


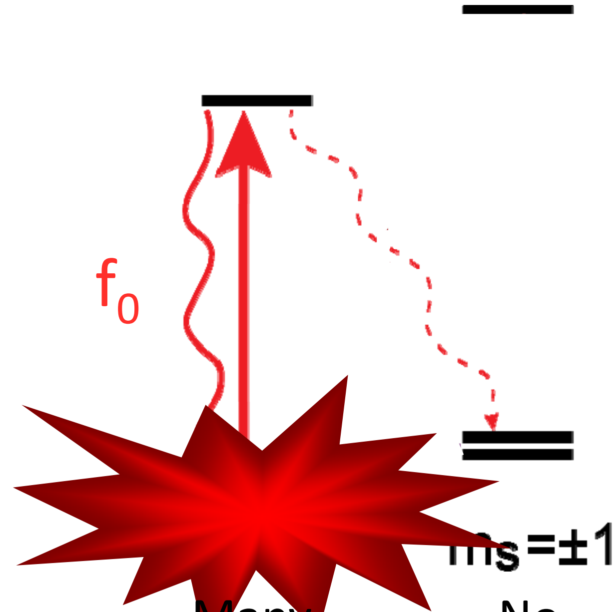
>99% preparation fidelity

Long spin-flip time under $f_0$excitation

An order of magnitude reduction in error rate

Resonant readout of the NV center spin





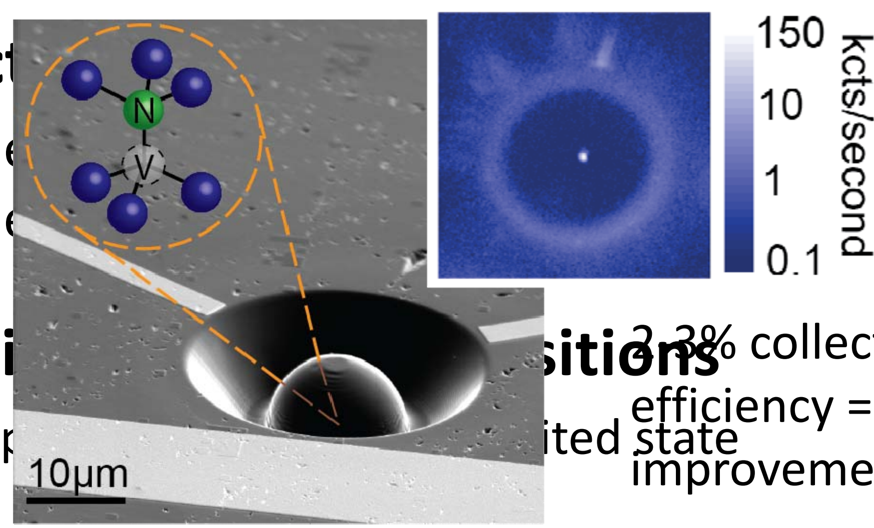
Enhanced collection efficiency

Microfabricated SILs

Spin-select

$f_0$only e

$f_1$only e



2.3% collection efficiency = 10x improvement

Readout mechanism

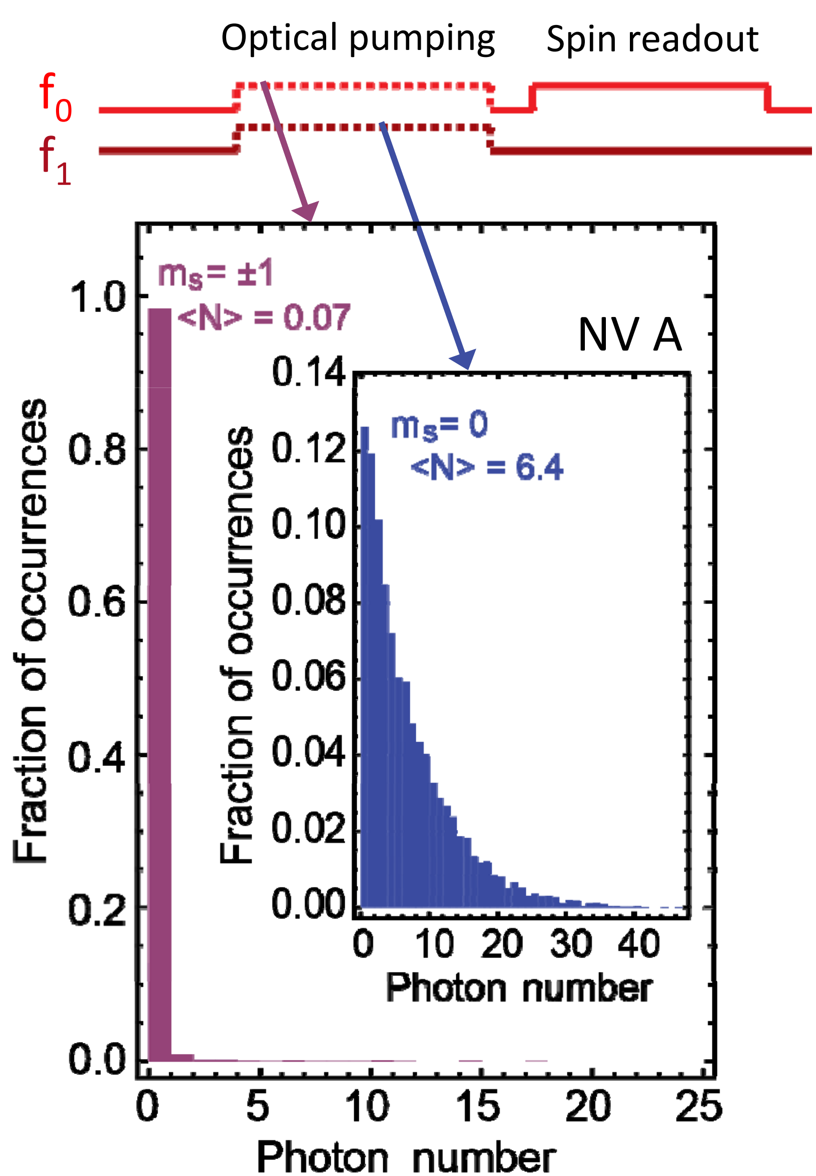
Mostly spi sitions

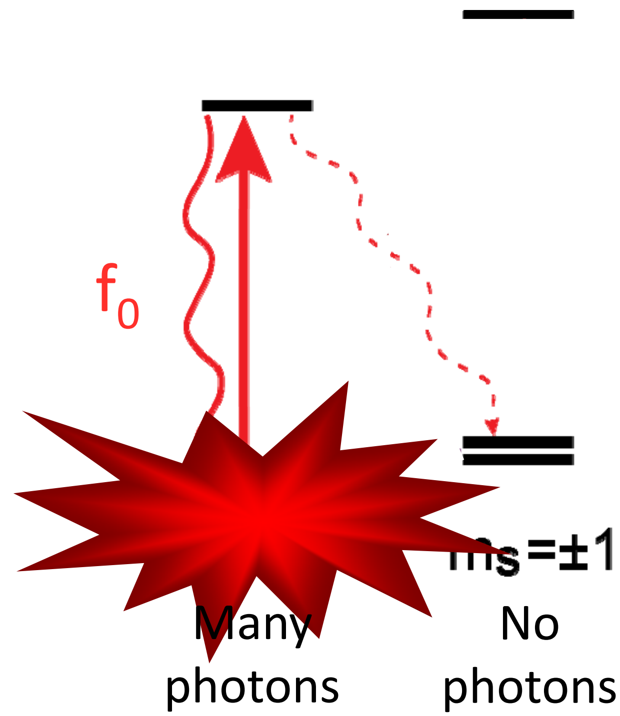
Some sp ited state

Challenge:

Can we collect enough photons to measure the spin before it flips? **Yes!**

Resonant readout of the NV center spin

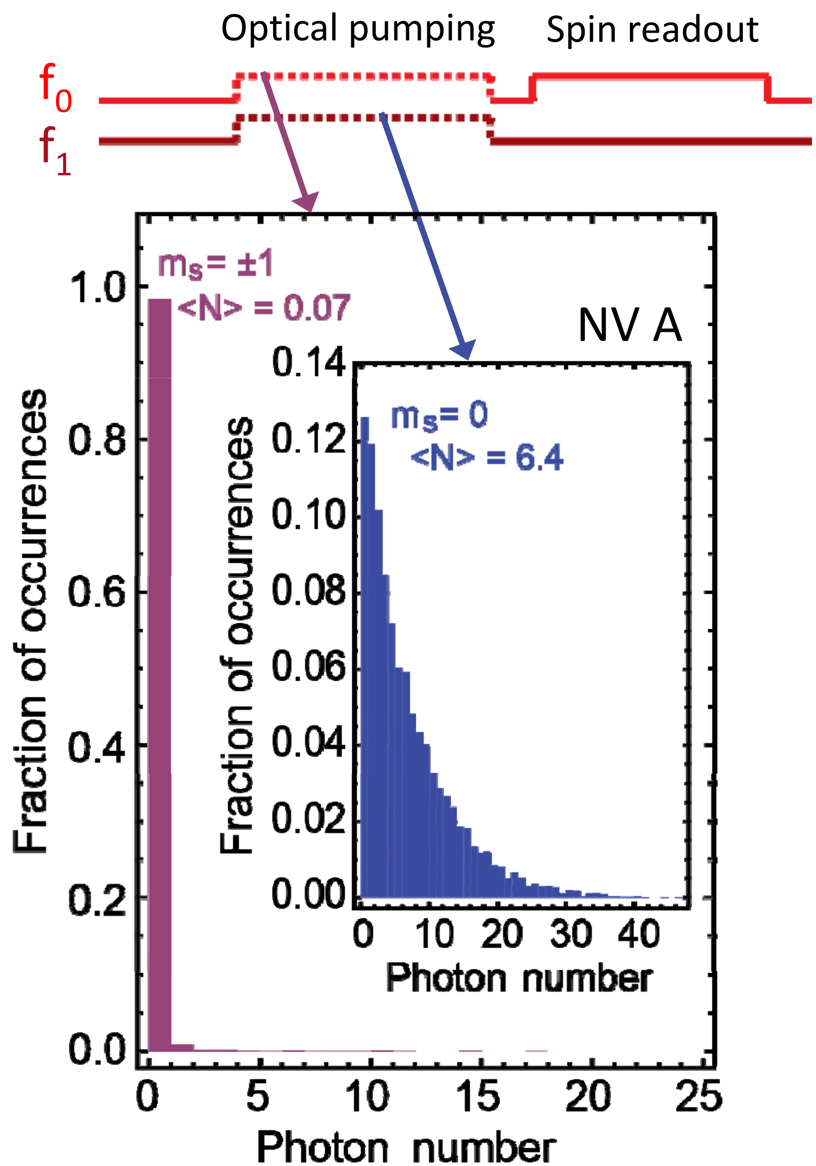




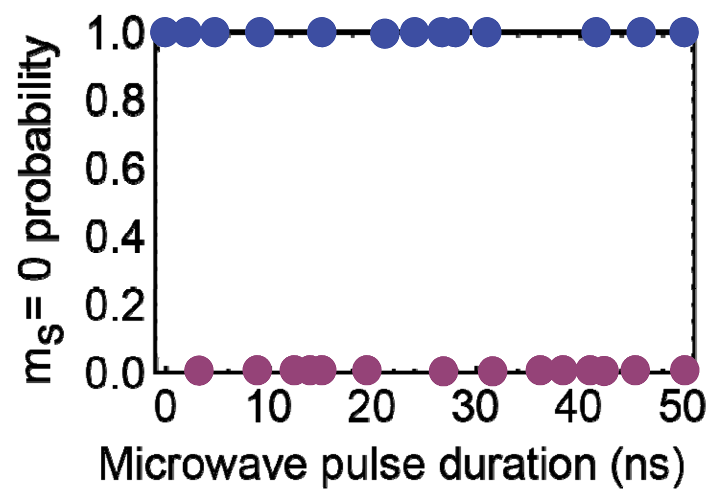
Single shot detection fidelity(lower bound)

$F_{avg} = 93\%$

Resonant readout of the NV center spin



Do the fluorescence levels indicate spin?



Single shot detection fidelity(lower bound)

F_{avg} = 93%

How ideal is our quantum measurement?

Partially destructive: readout also optically pumps the spin

But:
The shorter the readout duration, the less likely a spin flip is to occur

Short duration readout:

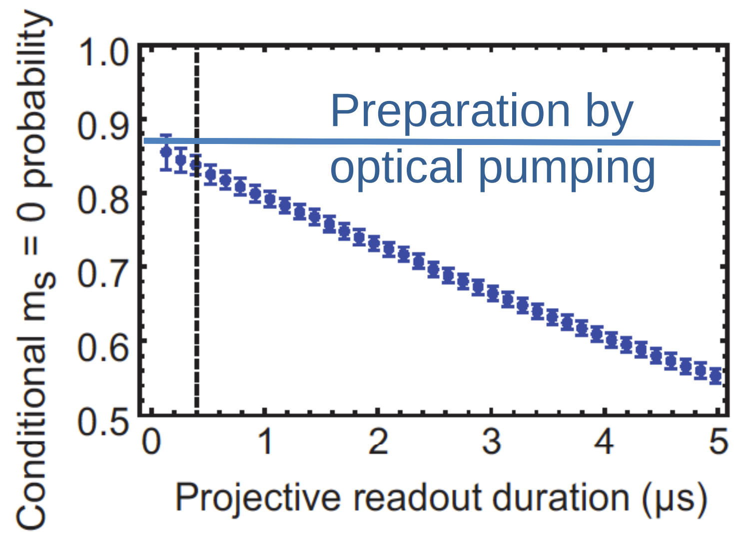
spin super-position

Very short readout pulse (400 ns)

0 photons
=> Virtually no information about the spin state

1+ photons
=> Only if initially m_s=0

Probably still in m_s=0

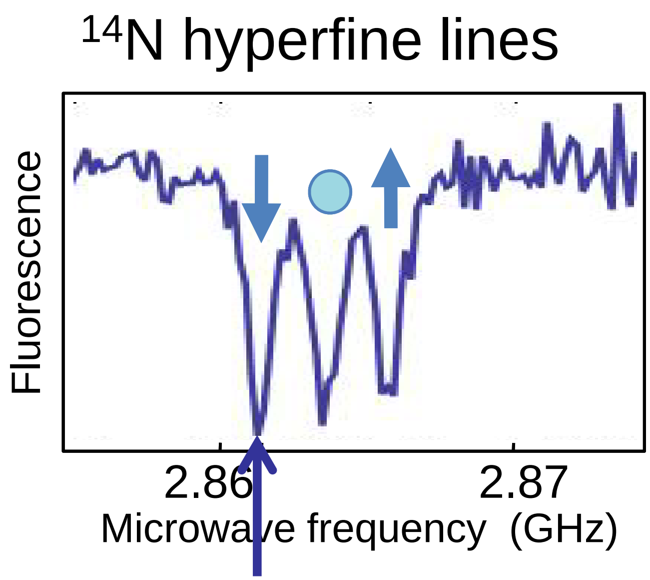


Allows measurement-based quantum state preparation

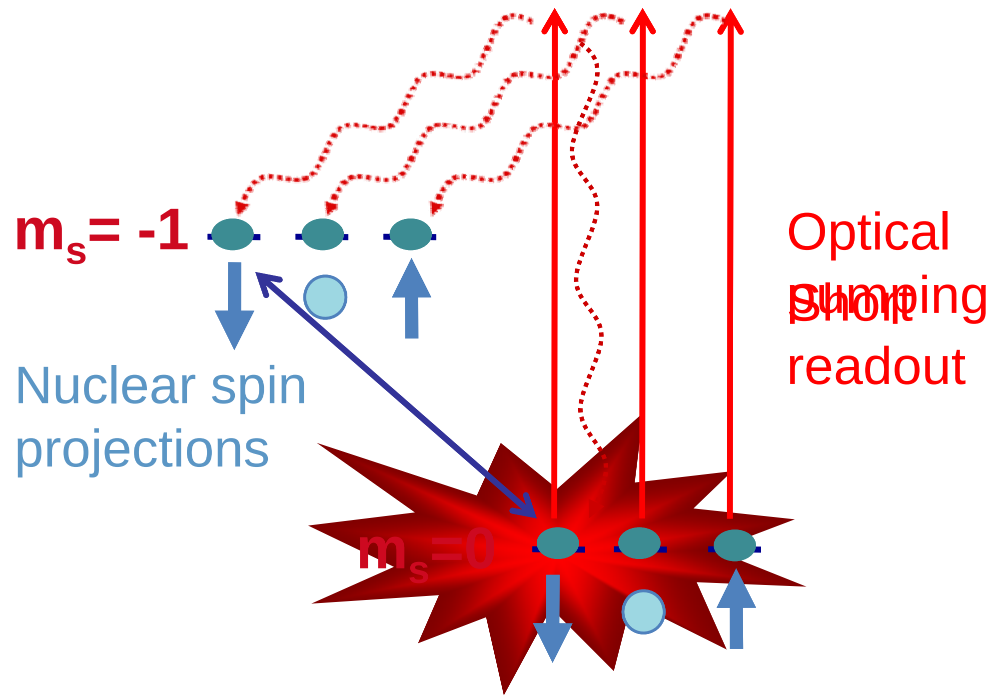
Measurement-based initialization of a multi-spin register

The simplest system:

NV + host ^{14}N nuclear spin (I = 1)



Rotates electronic spin conditional on the nuclear spin state – a CNOT gate

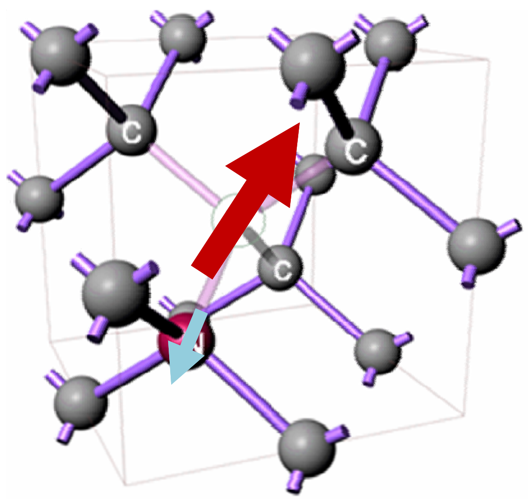


Probabilistic state preparation for the nuclear spin

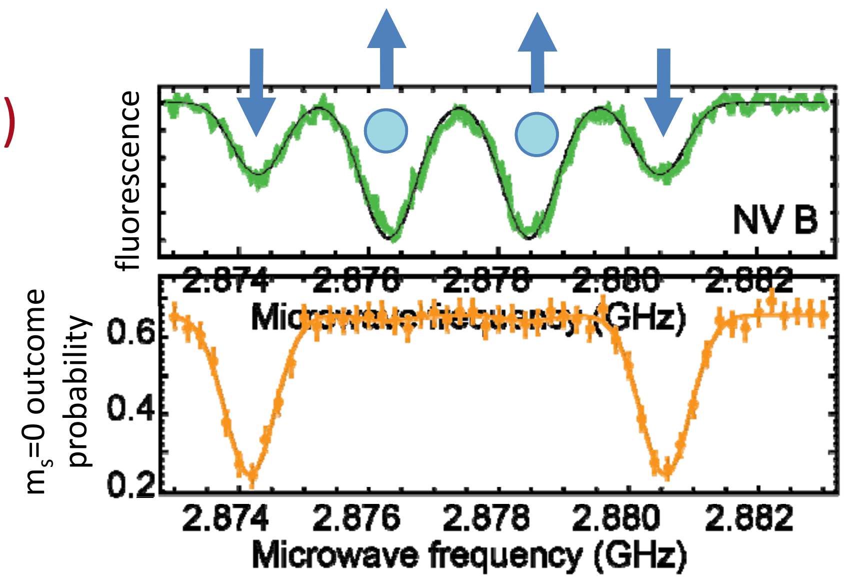
Measurement-based initialization of a multi-spin register

The simplest system:

NV + host ^{14}N nuclear spin (I = 1)



NV B:
No proximal ^{13}C
isotopic impurities



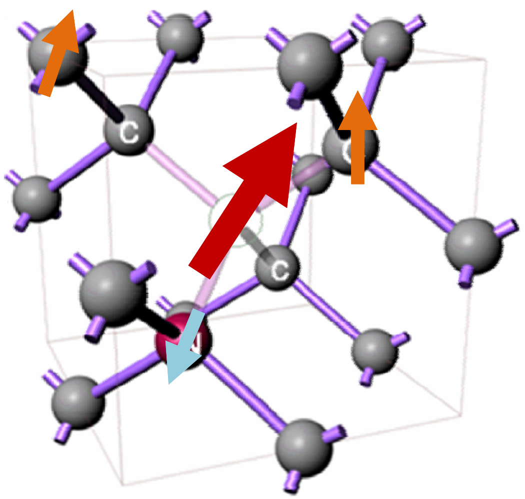
No preparation

With preparation into ↓

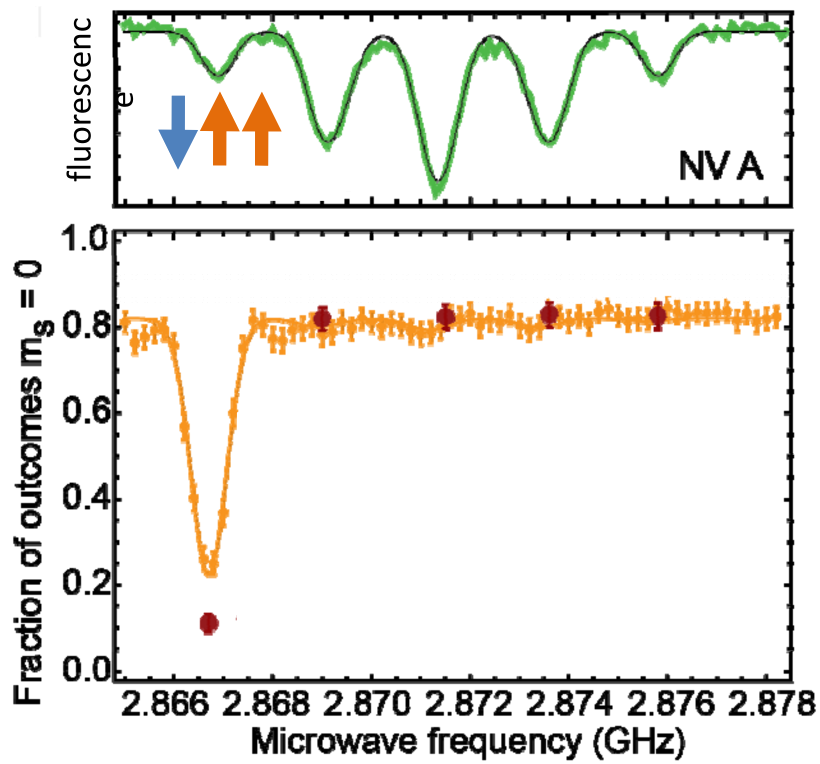
Straightforward extension to larger numbers of nuclear spins

Measurement-based initialization of a multi-spin register

Three nuclear spins:



NV A:
Two proximal ^{13}C
isotopic impurities

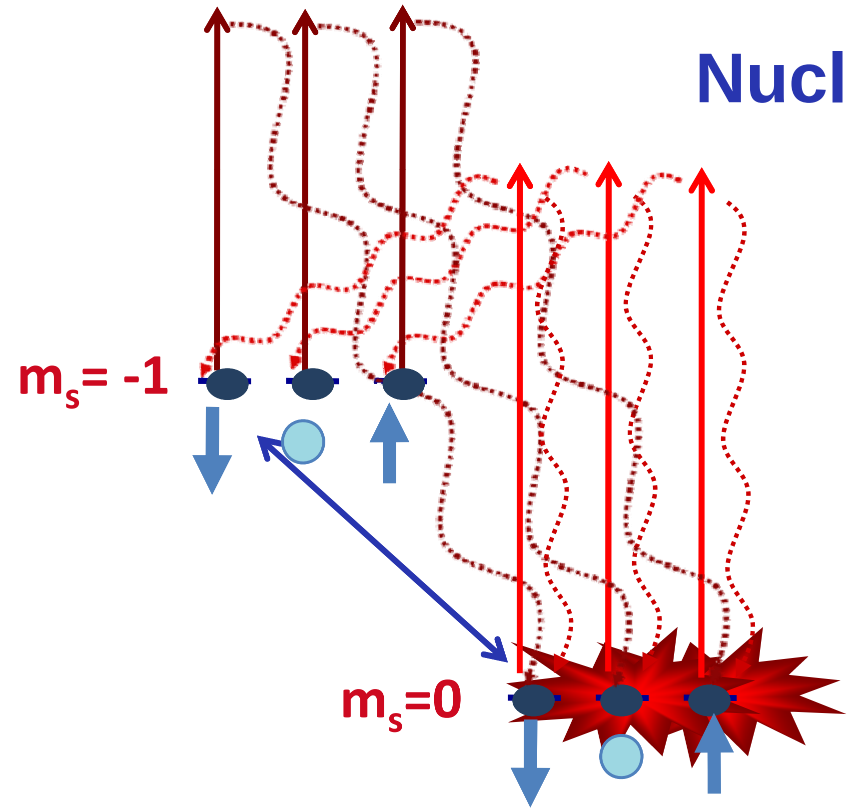


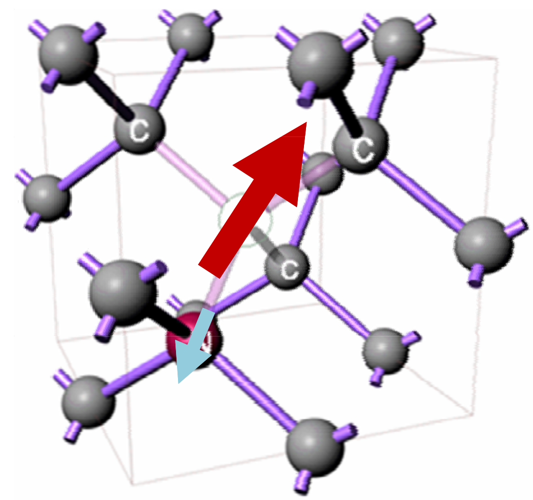
No preparation
12 partially
overlapping lines

With
preparation
into ↓↑↑

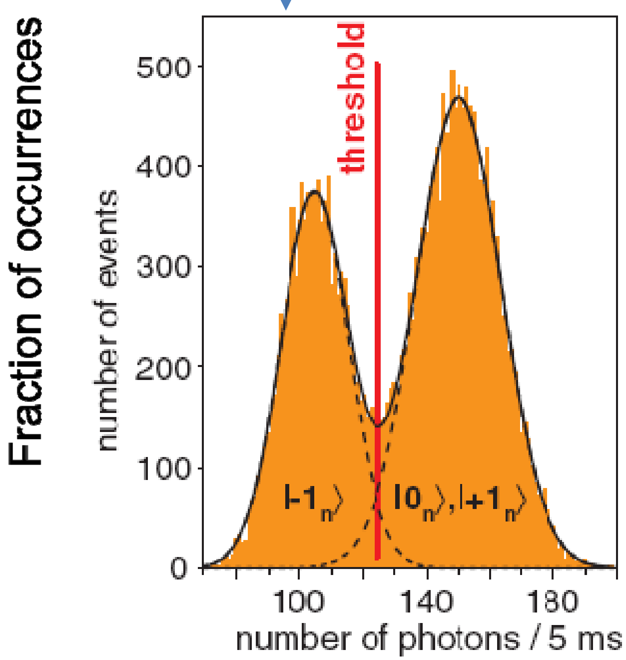
Initialization by measurement into
1 of 36 electron-nuclear spin configurations

Nuclear spin readout





No proximal ^{13}C isotopic impurities



NV B

Pioneering work with conventional detection: single-shot nuclear spin detection at room temperature

Neumann et al. 2010

See also Jiang et al. 2009

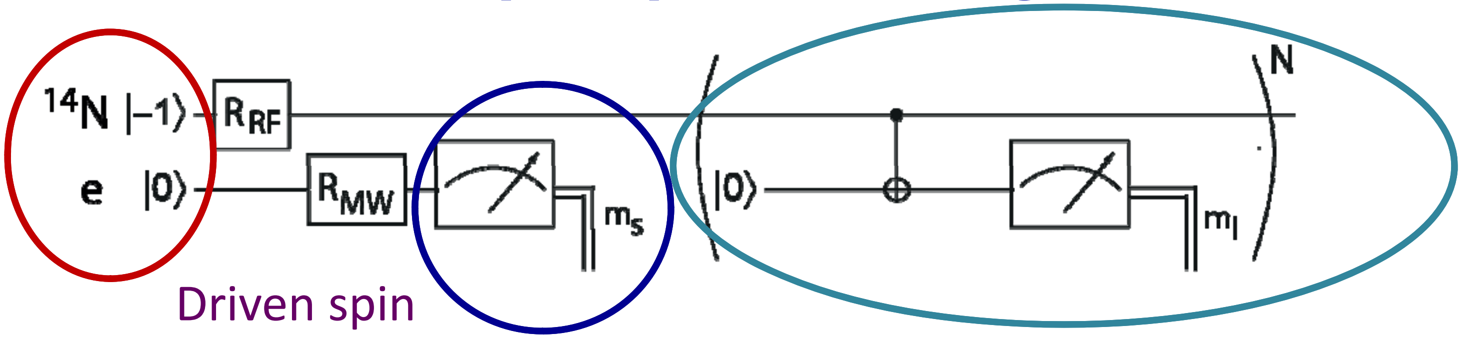
15

titions

92% average fidelity

Compatible with sequential readout of electronic and nuclear spin

Preparation, manipulation, and single-shot readout of a two-spin quantum register



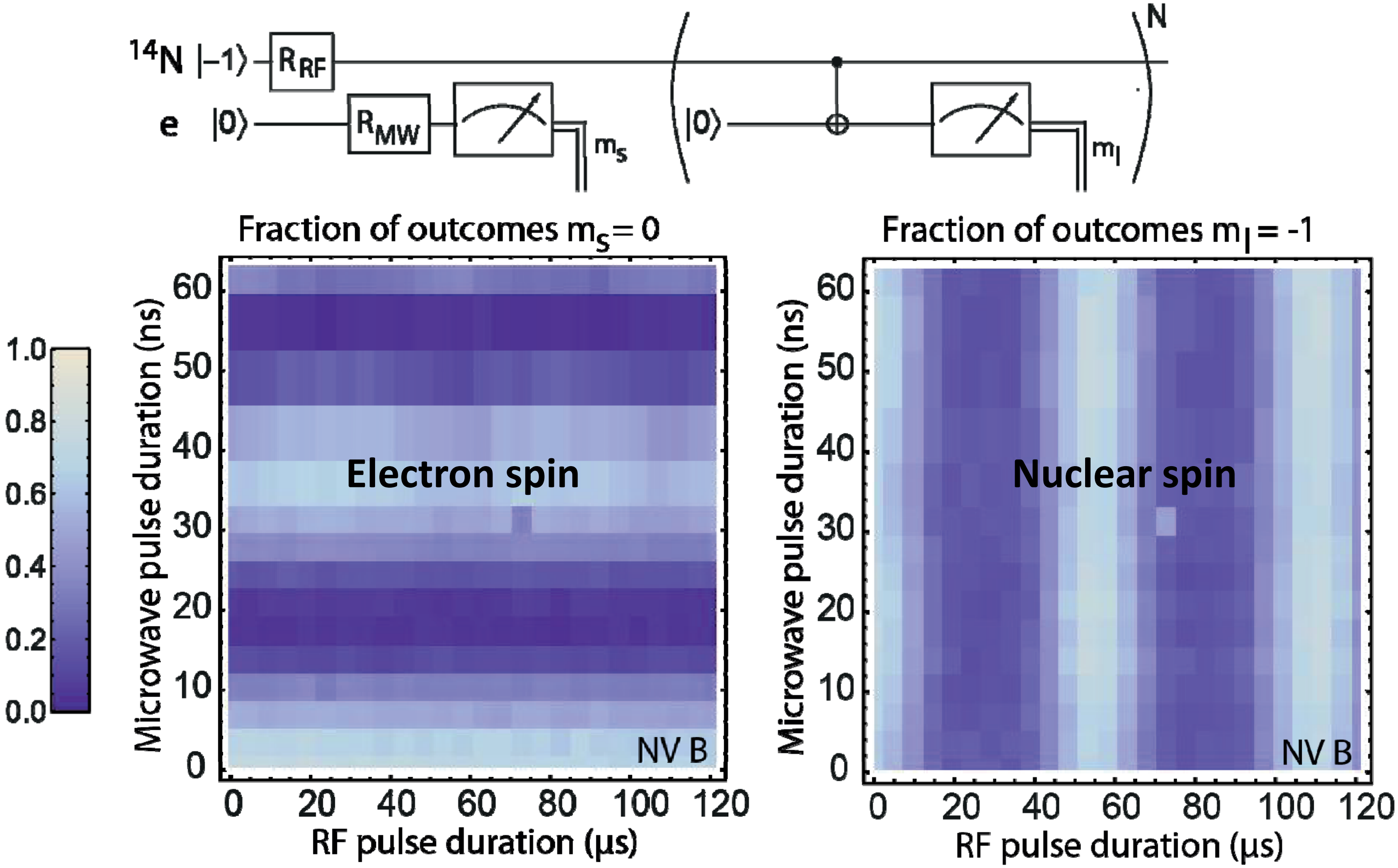
Measurement based state preparation

Driven spin rotations

Single shot electron spin qubit readout

Repetitive single shot readout of the nuclear spin qubit

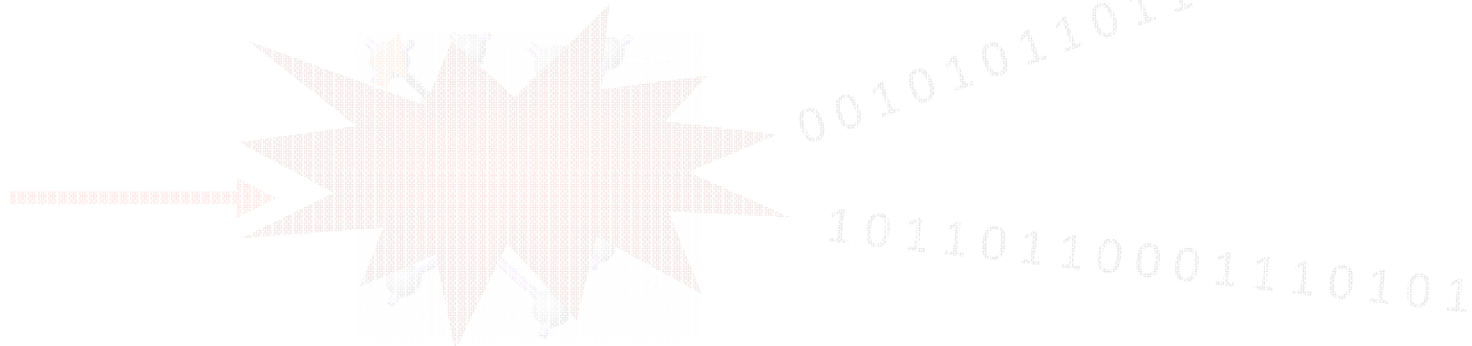
Preparation, manipulation, and single-shot readout of a two-spin quantum register



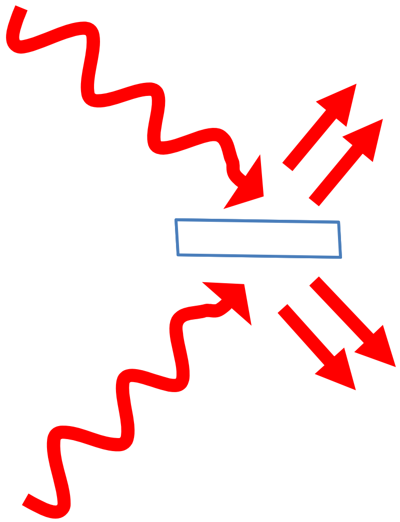
Single-shot detection of *two* spin qubits

Outline

1. Single shot readout



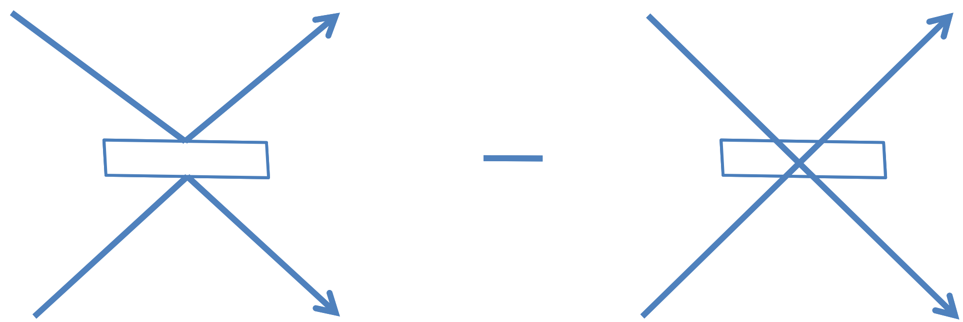
2. Two photon quantum interference



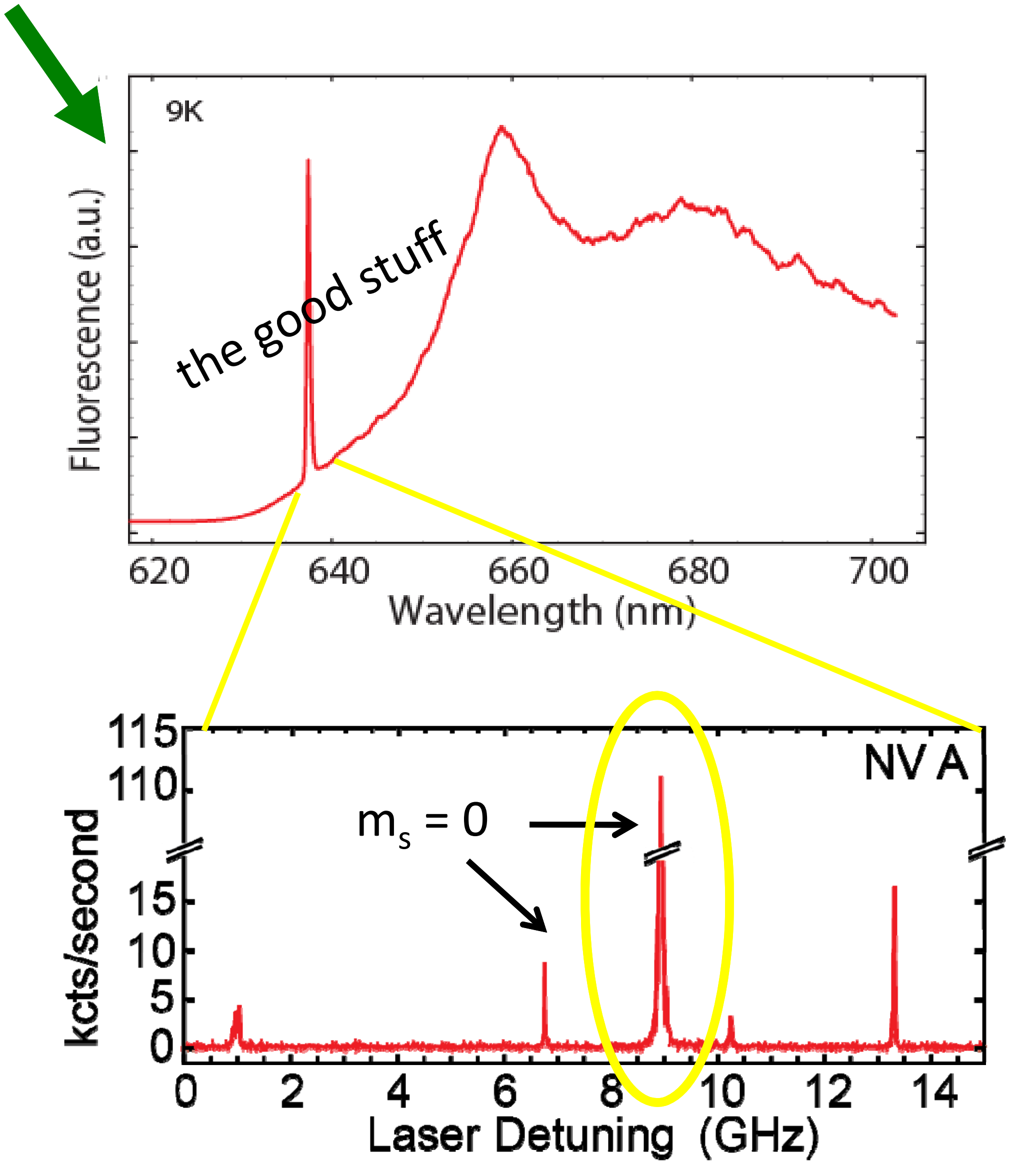
Quantum interference between photons emitted by different NVs can be used to establish long-distance entanglement

Photons cannot emerge from different ports

Indistinguishable photons => destructive interference



Resonant emission:
Towards two photon quantum interference



These two lines are orthogonally polarized

Wanted: indistinguishable photons

same polarization, same timing, same spatial mode

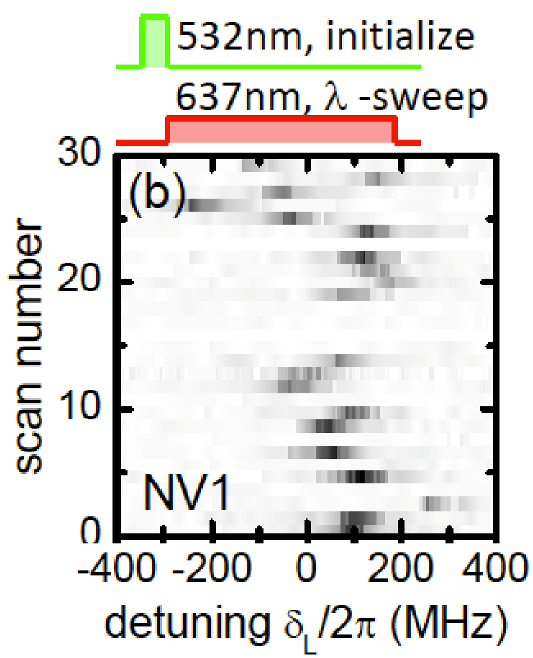
Recipe:

1. Spectral filters to isolate ZPL
2. Spin pumping into m_s=0
3. Polarization filtering

But…

Inhomogeneity between NVs

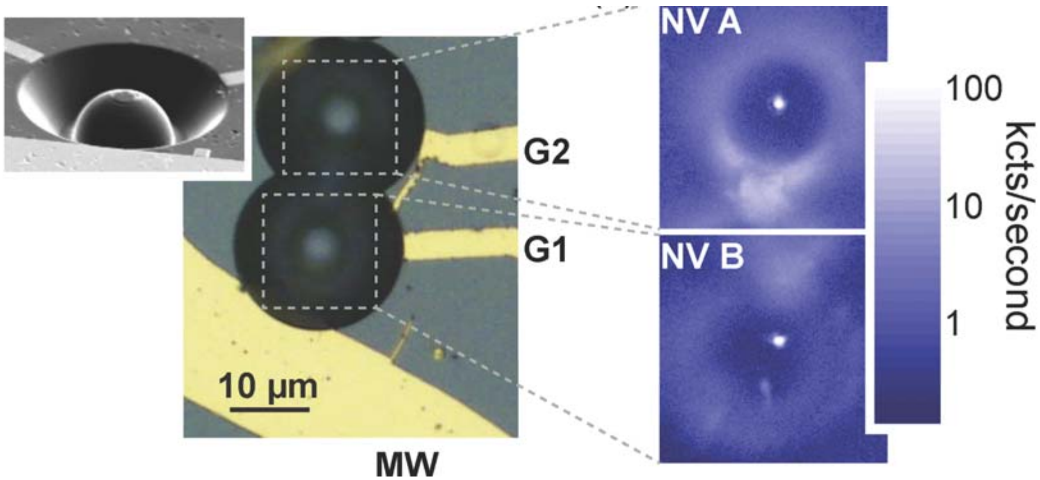
Spectral diffusion in time



Robledo et al. 2010

Resonant emission:
Towards two photon quantum interference

Solution # 1: Tune



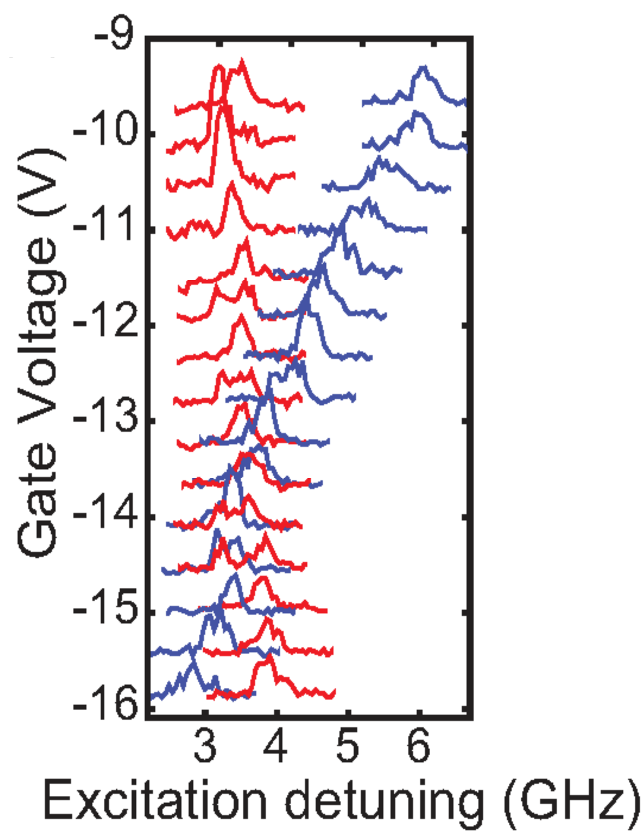
Tunable optical transitions:

Strong DC Stark shifts

Wanted: indistinguishable photons

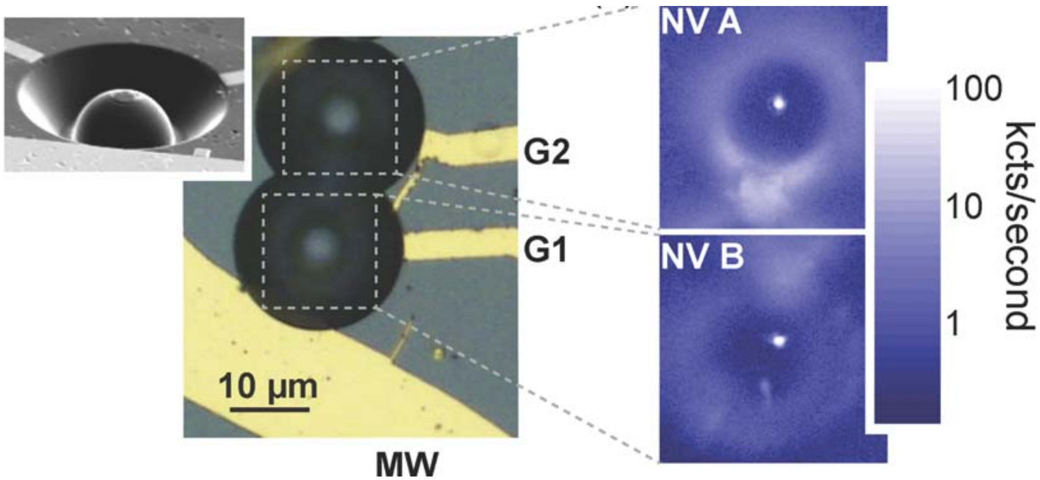
Recipe:

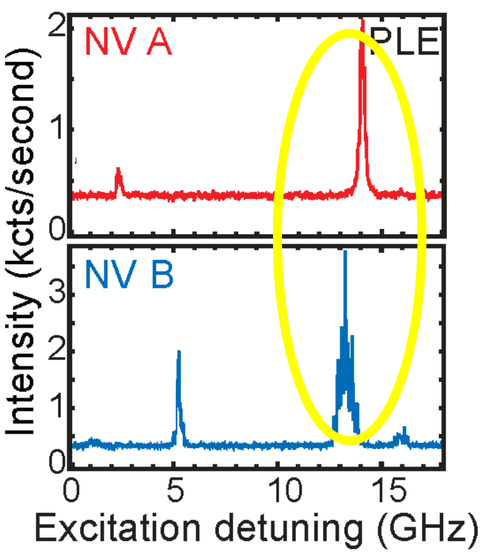
1. Spectral filters to isolate ZPL
2. Spin pumping into m_s=0
3. Polarization filtering



Resonant emission:
Towards two photon quantum interference

Solution # 2: Get lucky





Wanted: indistinguishable photons

Recipe:
1. Spectral filters to isolate ZPL
2. Spin pumping into m_s=0
3. Polarization filtering

But...

Inhomogeneity between NVs

Spectral diffusion in time

Natural linewidth = 15 MHz

Spectral diffusion broadened linewidth ~ 500 MHz

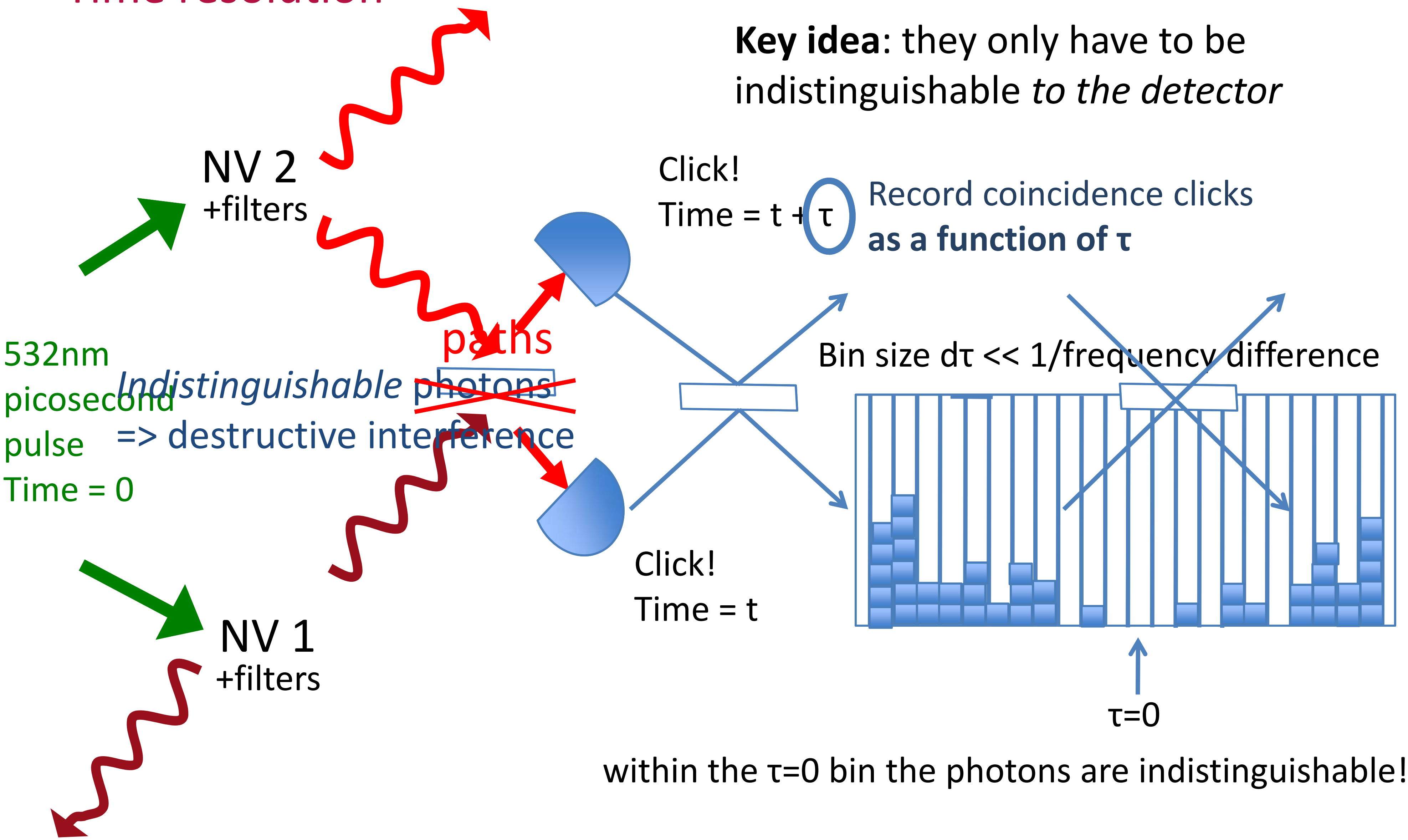
Coping with spectral diffusion

Legero et al. 2003

Solution #3: Time resolution

Wanted: indistinguishable photons

Key idea: they only have to be indistinguishable *to the detector*



within the τ=0 bin the photons are indistinguishable!

Coping with spectral diffusion

Solution #3: Time resolution

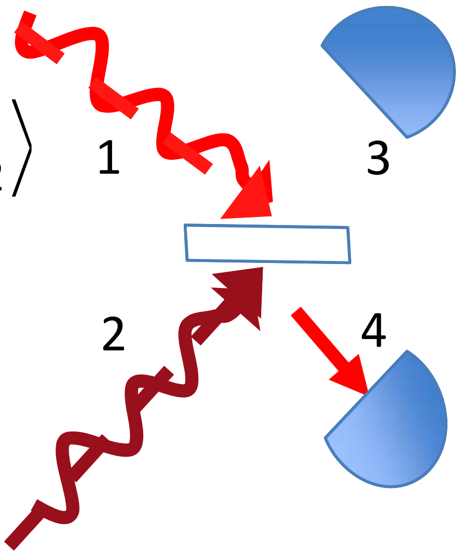
Wanted: indistinguishable photons

$$\hat{a}_3 = \hat{a}_1 + \hat{a}_2$$

$$\hat{a}_4 = \hat{a}_1 - \hat{a}_2$$

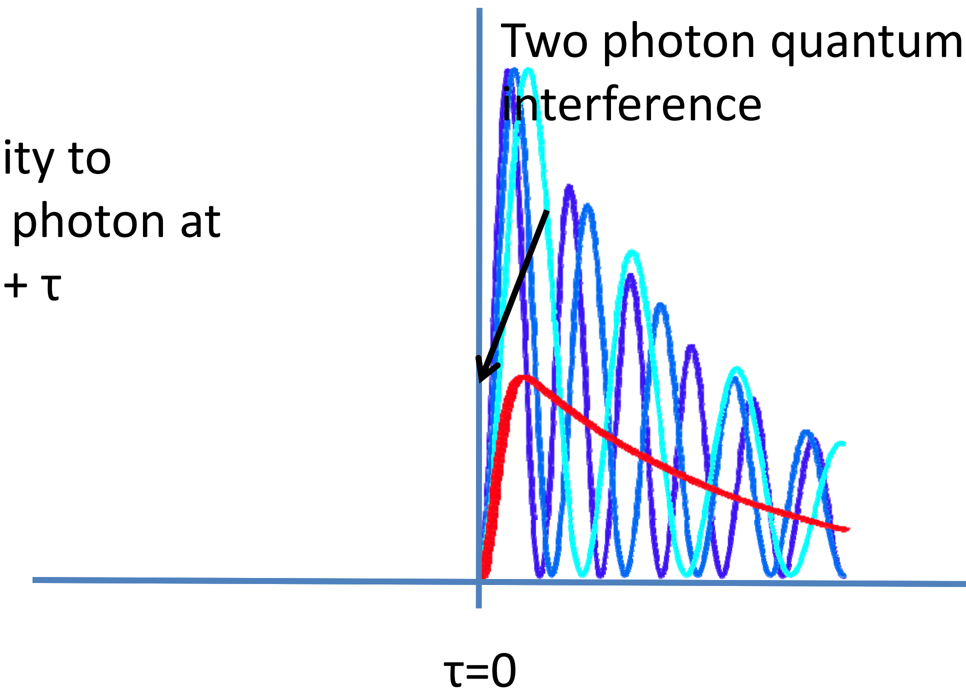
Initial state:

$$\hat{a}_1^{+}\hat{a}_2^{+}|0\rangle = |1_1 1_2\rangle$$



Probability to detect a photon at time = t + τ

Click!
Time = t



Remaining photon state (immediately afterwards):

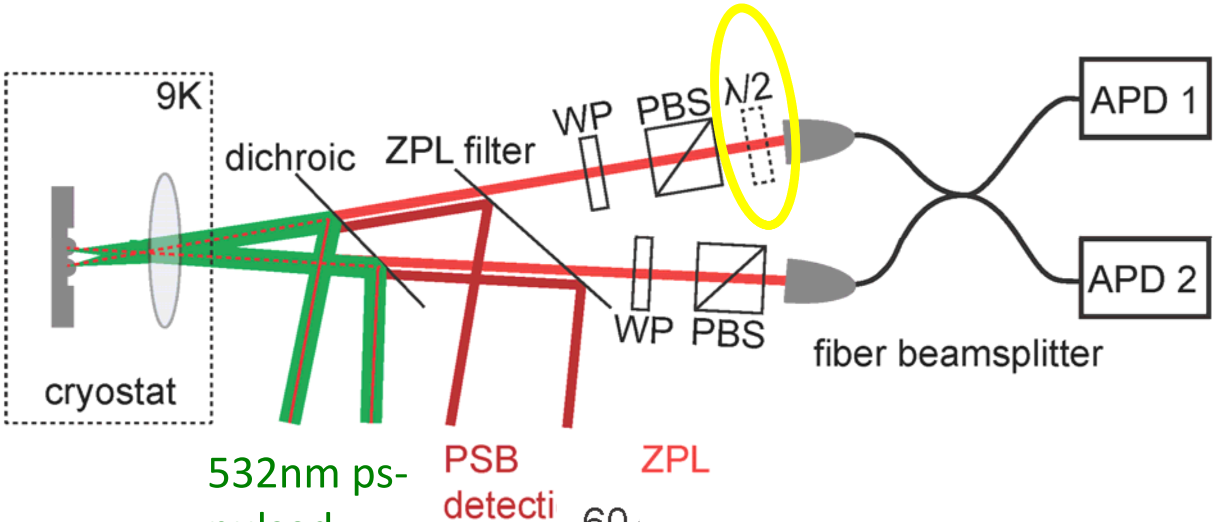
$$\hat{a}_4|1_1 1_2\rangle = |0_1 1_2\rangle - |1_1 0_2\rangle = -\hat{a}_4^{+}|0\rangle$$

Probability = 0 to detect in 3 at τ=0

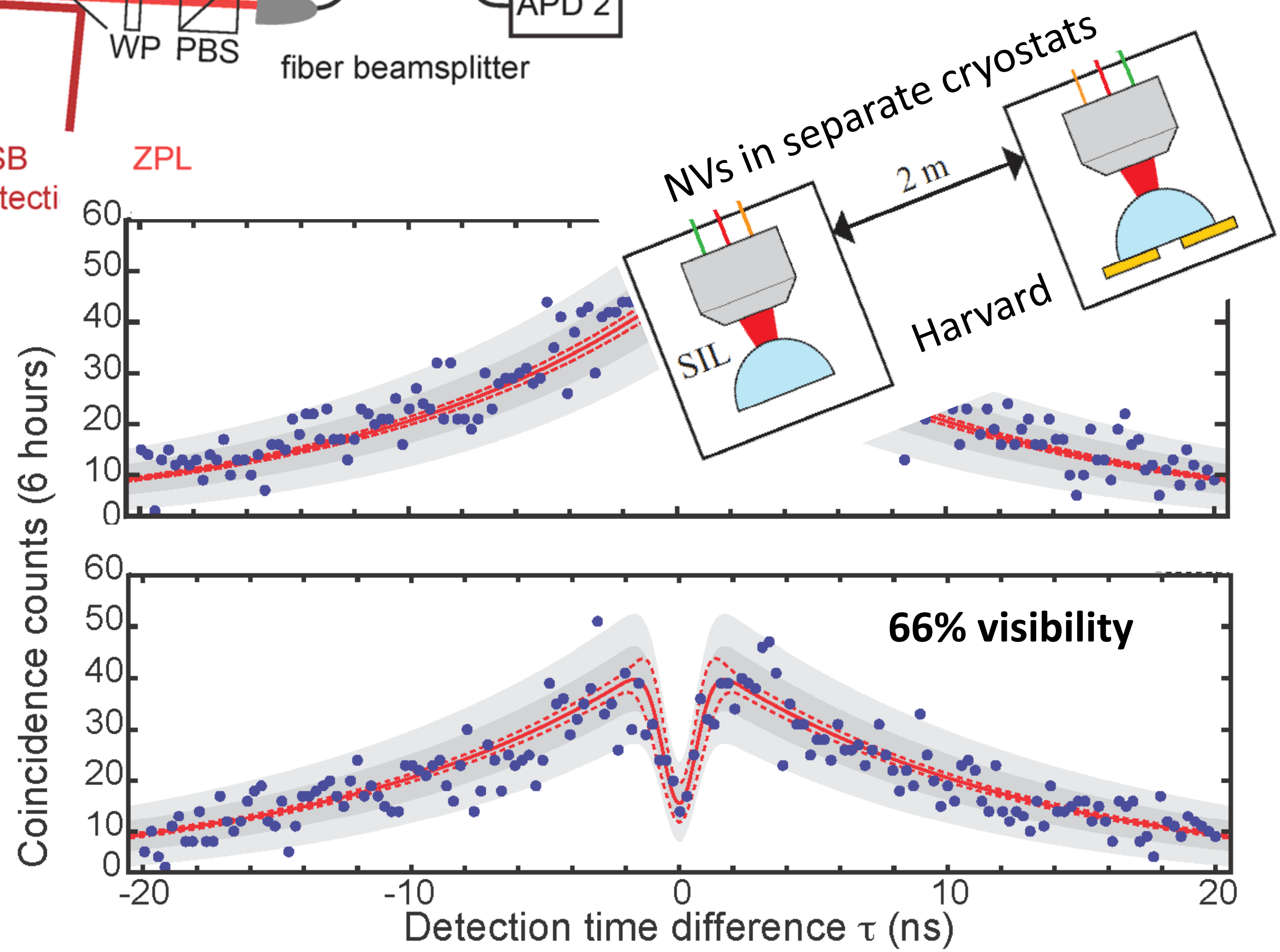
$$\rightarrow \quad e^{-i\omega_2\tau}|0_1 1_2\rangle - e^{-i\omega_1\tau}|1_1 0_2\rangle$$

Probability oscillates as $(\omega_1-\omega_2)\tau$

Time resolved two-photon quantum interference



Record time-resolved coincidence counts



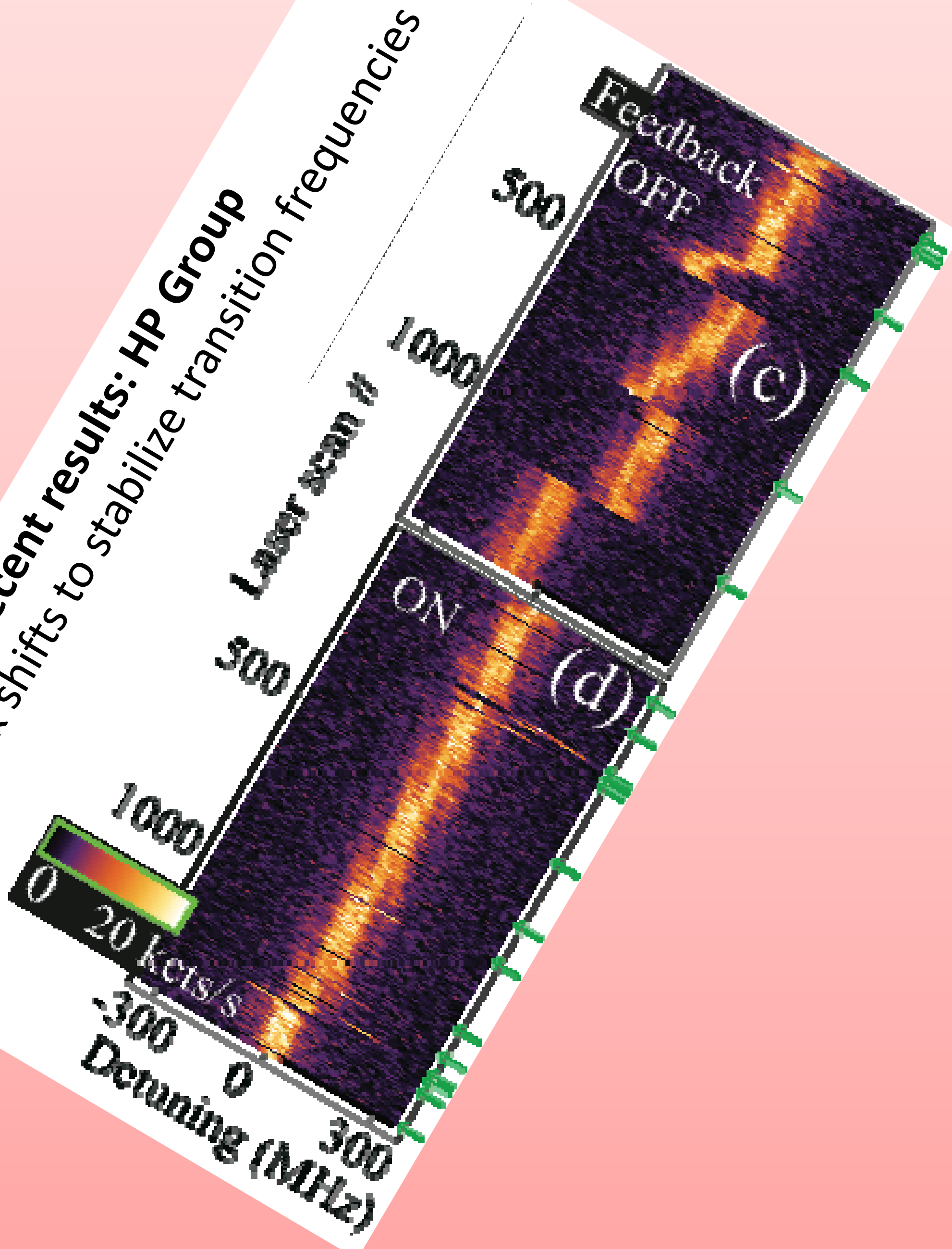
Perpendicular polarization:

Parallel polarization:

Zero-free-parameter simulation

Recent results: HP Group

Use Stark shifts to stabilize transition frequencies

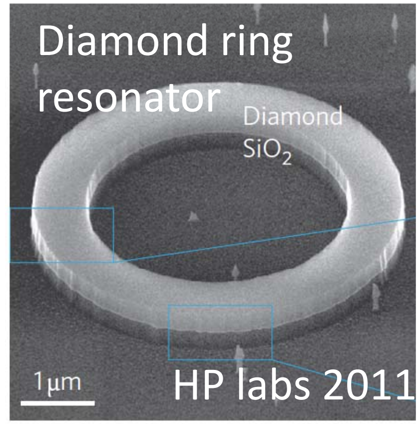


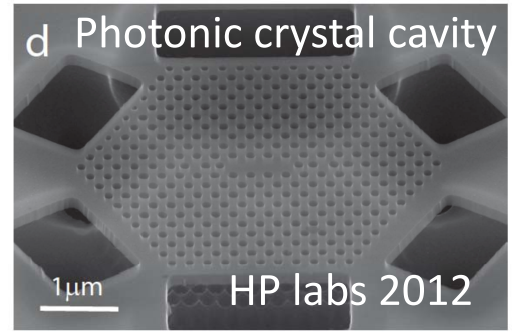
Outlook: Integrated optics

Critical technology:

Collection efficiency typically << 1%
ZPL only 3% of total emission

Cavity quantum electrodynamics





Also
Loncar, Fu, Becher, Barclay, A wschalom, Englund

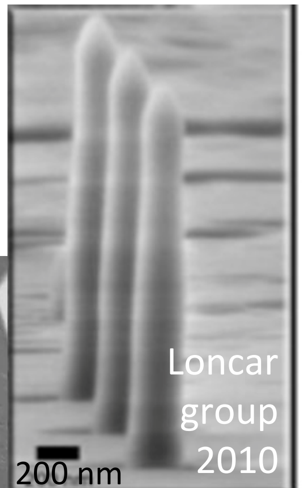
Emission on cavity resonance enhanced by

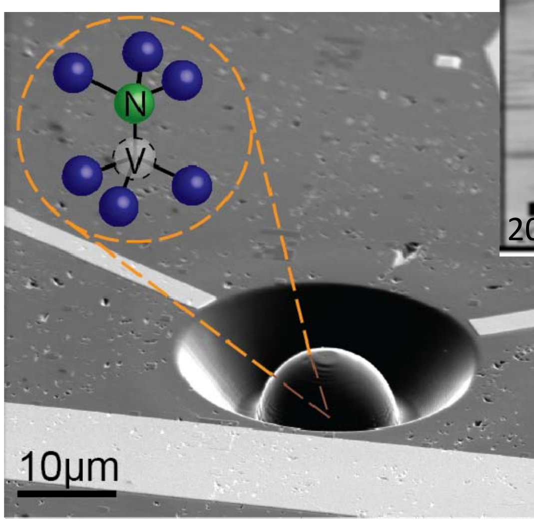
$$F_P = \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3 \frac{Q}{V}$$

Quality factor

Mode volume

Directed emission



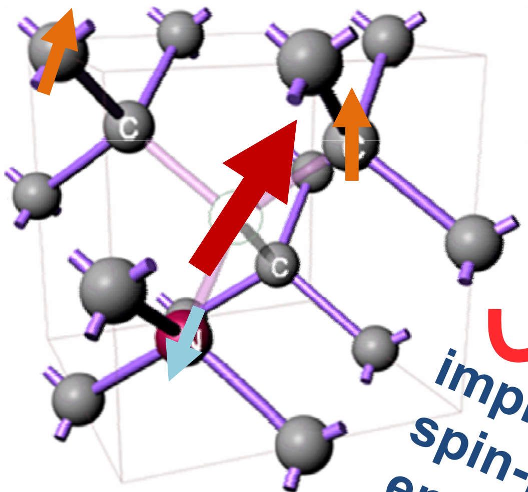


Only increases overall collection efficiency

Diamond nanophotonics

Promising avenue to enhance ZPL emission fraction *and* improve collection efficiency

Summary



The vision:

- A few-spin-qubit register with preparation, coherent control, and readout
- Scalability via interactions between NV registers

higher fidelity

improved spin-photon entanglement

ZPL collection efficiency!!

control strain, phonon processes, spectral diffusion

Theoretical models

Efficient protocols

Integration in optical cavities

Materials science

Heading towards entanglement distribution for quantum communication and quantum networks

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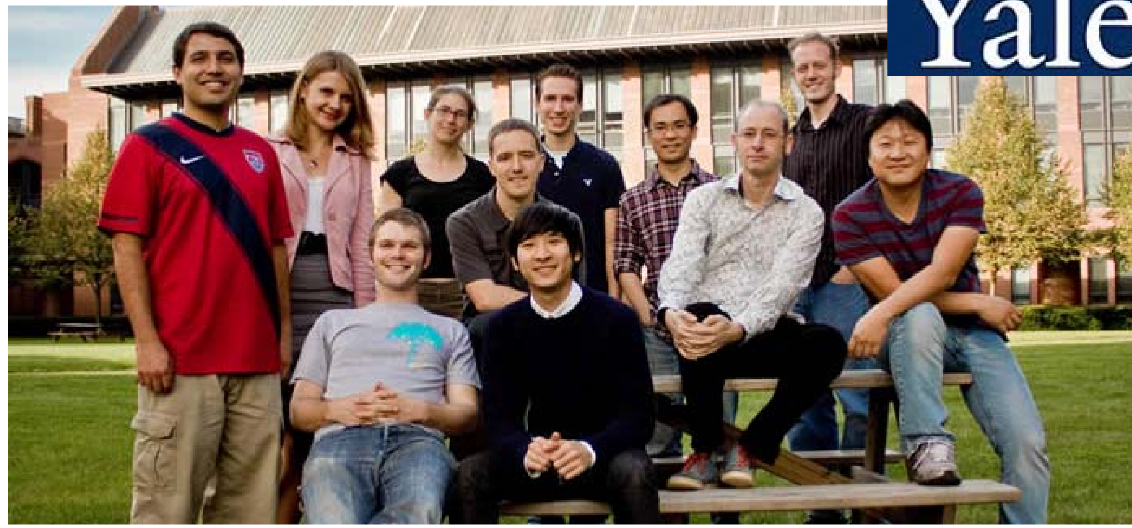

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Brian Yang
Mitchell Underwood
Jack Harris

Starting January 2013
…positions available!