Towards a quantum internet

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entangled states
global distances
many particles ?

What is entanglement?

- Let’s consider two-qubit states
- Possible basis: $|0\rangle_A|0\rangle_B$, $|0\rangle_A|1\rangle_B$, $|1\rangle_A|0\rangle_B$, $|1\rangle_A|1\rangle_B$
- General state: $a_{00}|0\rangle_A|0\rangle_B + a_{01}|0\rangle_A|1\rangle_B + a_{10}|1\rangle_A|0\rangle_B + a_{11}|1\rangle_A|1\rangle_B$
- Different types of states:
  - Product states: $|\varphi\rangle_{AB} = |\varphi_a\rangle_A \otimes |\varphi_b\rangle_B$
  - Entangled states: $|\varphi\rangle_{AB} \neq |\varphi_a\rangle_A \otimes |\varphi_b\rangle_B$
- Bell states as basis for maximally entangled states

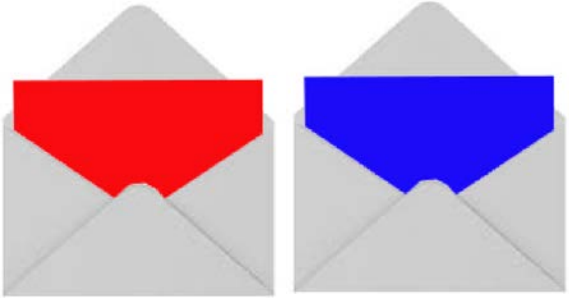
$$|\psi^{\pm}\rangle_{AB} = {}^{1}\!/_{\sqrt{2}}\left(|0\rangle_A|1\rangle_B \pm |1\rangle_A|0\rangle_B\right)$$
$$|\phi^{\pm}\rangle_{AB} = {}^{1}\!/_{\sqrt{2}}\left(|0\rangle_A|0\rangle_B \pm |1\rangle_A|1\rangle_B\right)$$

- General state: $a_1|\psi^+\rangle_{AB} + a_2|\psi^-\rangle_{AB} + a_3|\phi^+\rangle_{AB} + a_4|\phi^-\rangle_{AB}$

What does entanglement mean?

$$|\psi^{\pm}\rangle_{AB} = {}^{1}\!/_{\sqrt{2}}\left(|0\rangle_A|1\rangle_B \pm |1\rangle_A|0\rangle_B\right) \qquad |\phi^{\pm}\rangle_{AB} = {}^{1}\!/_{\sqrt{2}}\left(|0\rangle_A|0\rangle_B \pm |1\rangle_A|1\rangle_B\right)$$

- Observation of a single particle: no useful information about the state (looks like a maximally mixed state!)
- Observations on entangled pair: results are random but correlated, even for distant entangled particles
- Correlations are *nonclassical* → tonight



THE NEW YORK TIMES, SATURDAY, MAY 4, 1935.

EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.

Copyright 1935 by Science Service.

PRINCETON, N. J., May 3.—Professor Albert Einstein will attack science's important theory of quantum mechanics, a theory of which he was a sort of grandfather. He concludes that while it is "correct" it is not "complete."

With two colleagues at the Institute for Advanced Study here, the noted scientist is about to report to the American Physical Society what is wrong with the theory of quantum mechanics, it has been learned exclusively by Science Service.

The quantum theory, with which science predicts with some success inter-atomic happenings, does not meet the requirements for a satisfactory physical theory, Professor Einstein will report in a joint paper with Dr. Boris Podolsky and Dr. N. Rosen.

In the quantum theory as now used, the latest Einstein paper will point out that where two physical quantities such as the position of a particle and its velocity interact, a knowledge of one quantity precludes knowledge about the other. This is the famous principle of uncertainty put forward by Professor Werner Heisenberg and incorporated in the quantum theory. This very fact, Professor Einstein feels, makes the quantum theory fail in the requirements necessary for a satisfactory physical theory.

Two Requirements Listed.

These two requirements are:

1. The theory should make possible a calculation of the facts of nature and predict results which can be accurately checked by experiment; the theory should be, in other words, correct.

2. Moreover, a satisfactory theory should, as a good image of the objective world, contain a counterpart for things found in the objective world; that is, it must be a complete theory.

Quantum theory, Professor Einstein and his colleagues will report, fulfills the correctness requirement but fails in the completeness requirement.

While proving that present quantum theory does not give a complete description of physical reality, Professor Einstein believes some later, still undeveloped, theory will make this possible. His conclusion is:

"While we have thus shown that the wave function [of quantum theory] does not provide a complete description of the physical reality, we left open the question of whether or not such a description exists. We believe, however, that such a theory is possible."

The development of quantum mechanics has proved very useful in exploring the atom. Six Nobel Prizes in physics, including one to Einstein, have been awarded for various phases of the researches leading up to quantum mechanics. The names of Planck, Bohr, de Broglie, Heisenberg, Dirac and Schroedinger, as well as Einstein, are linked with quantum mechanics.

The exact title of the Einstein-Podolsky-Rosen paper is: "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?"

Explanation by Podolsky.

In explaining the latest view of the physical world as revealed in their researches Dr. Podolsky, one of the authors, said:

"Physicists believe that there exist real material things independent of our minds and our theories. We construct theories and invent words (such as electron, positron, &c.) in an attempt to explain to ourselves what we know about our external world and to help us to obtain further knowledge of it. Before a theory can be considered to be satisfactory it must pass two very severe tests. First, the theory must enable us to calculate facts of nature, and these calculations must agree very accurately with observations and experiments. Second, we expect a satisfactory theory, as a good image of objective reality, to contain a counterpart for every element of the physical world. A theory satisfying the first requirement may be called a correct theory while, if it satisfies the second requirement, it may be called a complete theory.

"Hundreds of thousands of experiments and measurements have shown that, at least in cases when matter moves much slower than light, the theory of Planck, Einstein, Bohr, Heisenberg and Schroedinger known as quantum mechanics is a correct theory. Einstein, Podolsky and Rosen now discuss the question of the completeness of quantum mechanics. They arrive at the conclusion that quantum mechanics, in its present form, is not complete.

"In quantum mechanics the condition of any physical system, such as an electron, an atom, &c., is supposed to be completely described by a formula known as a 'wave function.' Suppose that we know the wave function for each of two physical systems, and that these two systems come together, interact, and again separate (as when two particles collide and move apart). Quantum mechanics, although giving us considerable information about such a process, does not enable us to calculate the wave function of each physical system after the separation. This fact is made use of in showing that the wave function does not give a complete description of physical reality. Since, however, description of physical systems by wave functions is an essential step of quantum mechanics, this means that quantum mechanics is not a complete theory."

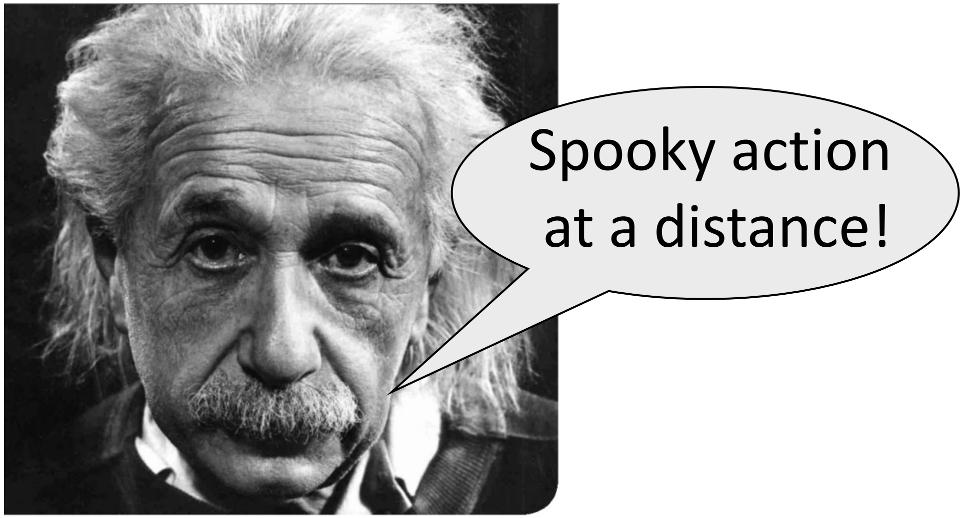
Raises Point of Doubt.

Special to THE NEW YORK TIMES.

PRINCETON, N. J., May 3.—Asked to comment on the new ideas of Professor Einstein and his collaborators, Professor Edward U. Condon, mathematical physicist of Princeton University, said tonight:

"Of course, a great deal of the argument hinges on just what meaning is to be attached to the word 'reality' in connection with physics. They have certainly discussed an interesting point in connection with the theory. Dr. Einstein has never been satisfied with the statistical causality which in the new theories replaces the strict causality of the old physics.

"It is reported that when he first learned of the work of Schroedinger and Dirac, he said, 'Der lieber Gott wuerfelt nicht, [the good Lord does not throw dice]. For the last five years he has subjected the quantum mechanical theories to very searching criticism from this standpoint. But I am afraid that thus far the statistical theories have withstood criticism."



What does entanglement mean?

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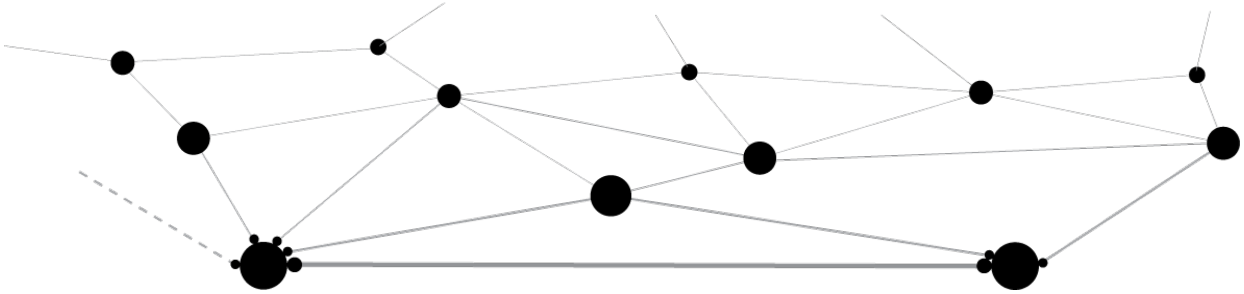
- Observation of a single particle: no useful information about the state (looks like a maximally mixed state!)
- Observations on entangled pair: results are random but correlated, even for distant entangled particles
- Correlations are *nonclassical* → tonight
- Transformation between Bell states by manipulating only one qubit
- Transformation between product state and Bell state: CNOT gate

E.g. $${}^{1}/_{\sqrt{2}}\left(|0\rangle_A + |1\rangle_A\right)|0\rangle_B \xrightarrow{CNOT} |\phi^{+}\rangle_{AB} \xrightarrow{CNOT} {}^{1}/_{\sqrt{2}}\left(|0\rangle_A + |1\rangle_A\right)|0\rangle_B$$

Part I:
An introduction to quantum networks

Quantum Networks



Quantum nonlocality

Secure communication [1]
Provably random numbers [1]

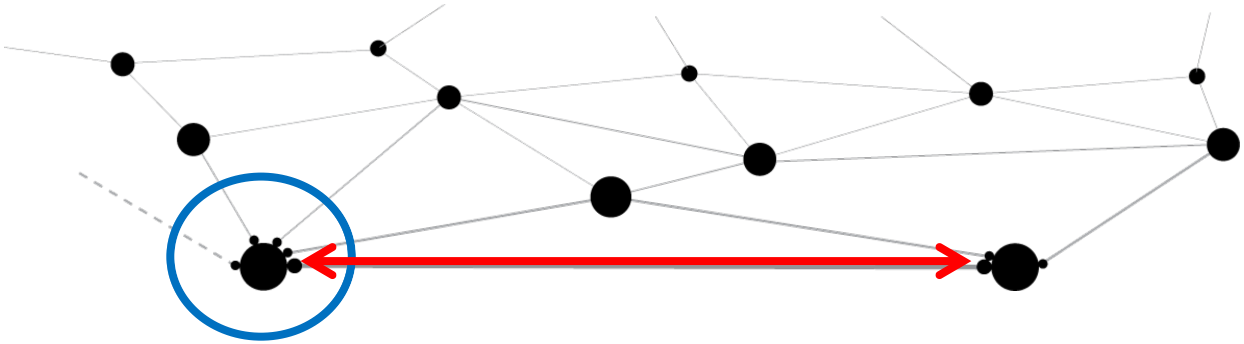
Many-particle entanglement

Quantum simulation [2]
Distributed and blind Q computing[3]
Precision measurement [4]

Many unknown applications

[1] Brunner et al. Rev. Mod. Phys. **86** 419 (2014)
[2] Houck et al. Nat. Phys. **8** 292 (2012); Georgescu et al. Rev. Mod. Phys. **86** 153 (2014)
[3] Monroe and Kim, Science **339** 1164 (2013); Barz et al. Science 335 (2012)
[4] Kómár et al. Nat. Phys. **10** 582 (2014); Gottesman et al. Phys. Rev. Lett. 109, 070503 (2012)

Quantum Networks



Nodes ⟷ Channels

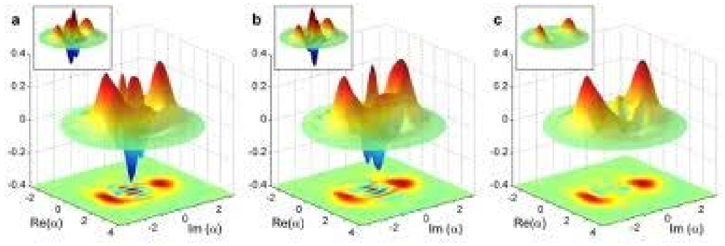
Nodes
- Store
- Control
- Measure

Channels

Mediate interaction
- Fast
- Controlled
- Long-distance

Optical photons

Photons as carriers of quantum information



Continuous quantum light fields

Braunstein and van Loock, Rev. Mod. Phys. 77, 513 (2005)
Lvovsky and Raymer, Rev. Mod. Phys. 81, 299 (2009)

Single photon states

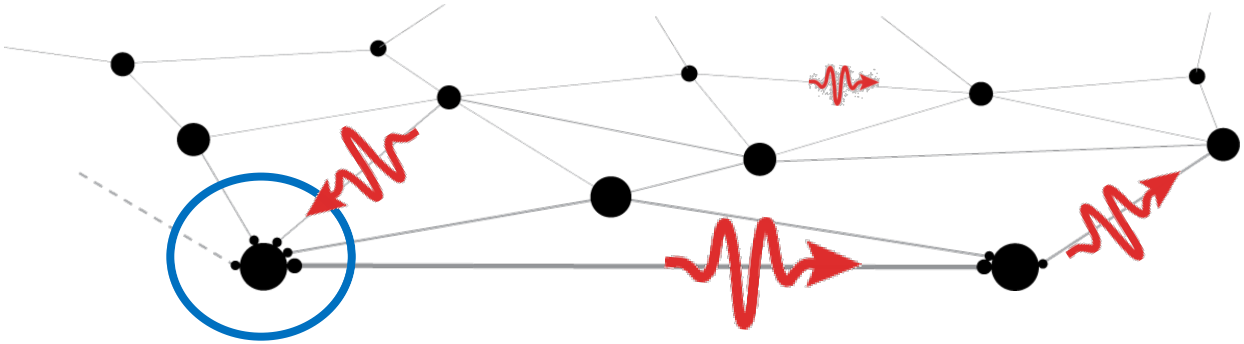
- "Most simple qubit": Number state $|0\rangle \equiv |n=0\rangle \quad |1\rangle \equiv |n=1\rangle$
  - Problematic: single qubit manipulations, qubit detection, photon loss

- Polarization qubit (L: left-circular; H: horizontal) $|0\rangle \equiv |L\rangle \quad |1\rangle \equiv |R\rangle$
  - Easy single qubit rotations (waveplates), easy measurement (polarizer)
  - loss does not *rotate* the qubit, but *destroy* it
  - Difficult to maintain polarization in long glass fibers

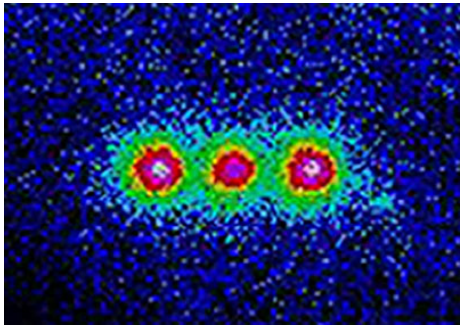
- Time-bin qubit (E: Early, L: Late) $|0\rangle \equiv |E\rangle \quad |1\rangle \equiv |L\rangle$
  - Qubit states travel same path with short temporal spacing
  - Measurement in rotated basis requires stable interferometers

- Which-path qubit, frequency qubits…

Quantum Networks

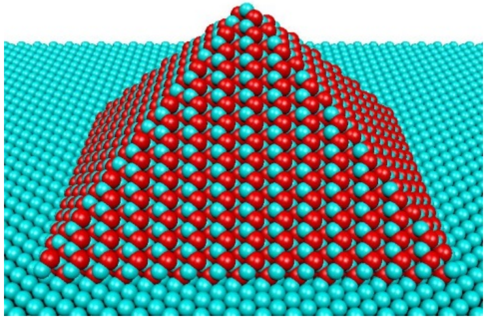


Nodes ⟷ Channels



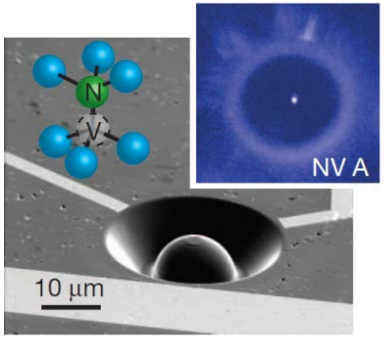
Trapped atoms

Perfect isolation
Good coherence (min)
Ultra-high vacuum
Difficult to control
High-power lasers



Artificial atoms

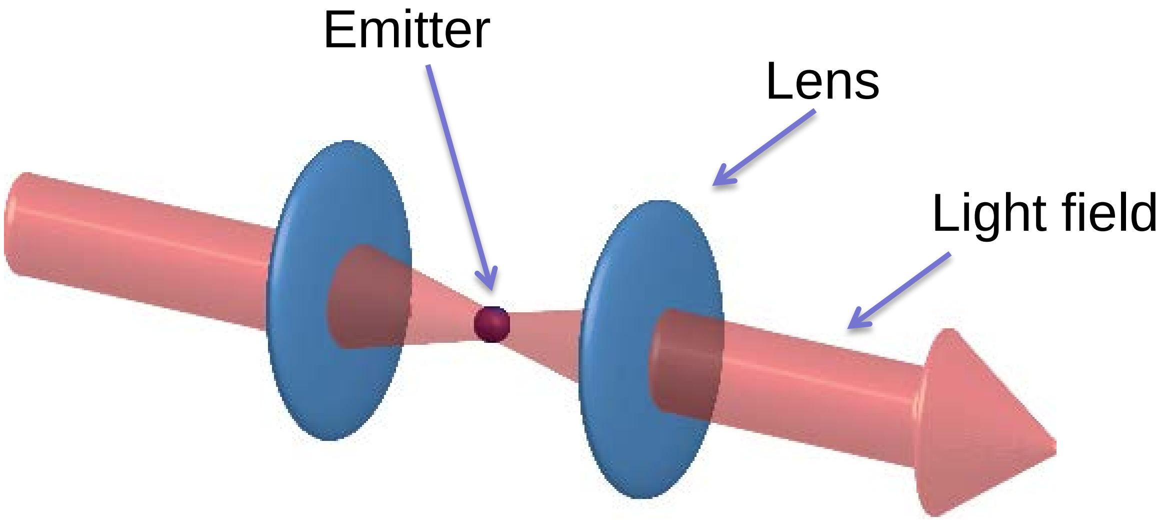
Can be mass-fabricated
but may not be identical
Less coherent (→Cryostat)



Impurities

Electron coherence <s
Nuclear spin: hours
Cryostat (?)
May not be identical
Inefficient photon coupling

Coupling efficiency



Absorption cross section $\sim\frac{\lambda^2}{2} \xcancel{\gg} \sim\frac{\lambda^2}{4}$ Photon area

Coupling of single emitters and single photons is difficult.

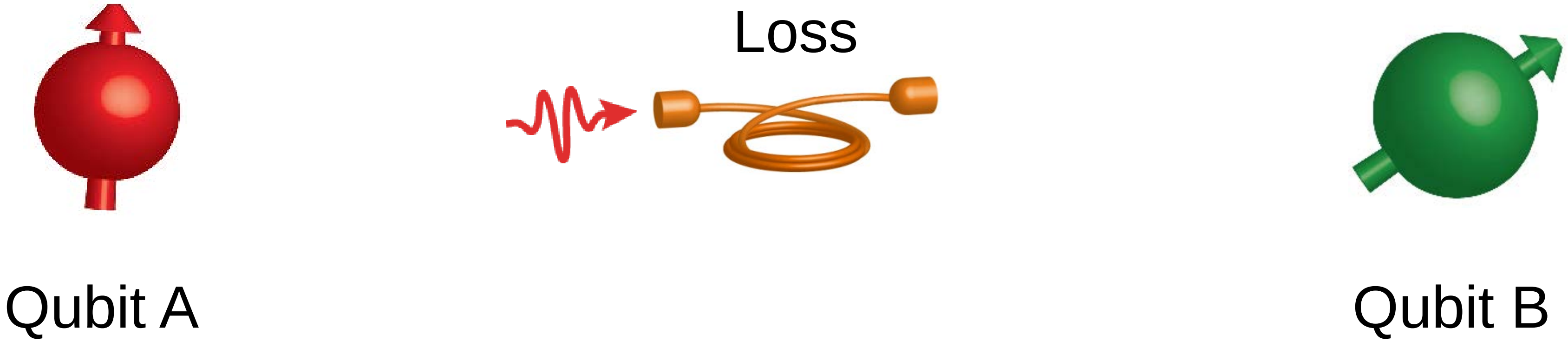
Coupling efficiency

Absorption cross section $\sim \frac{\lambda^2}{2} \gg \sim \frac{\lambda^2}{4}$ Photon area

- Near-field optics [1]
  - Focus the photon to a smaller area
  - Proximity of surfaces, absorption, decoherence of the emitter…
- Ensembles [2]
  - N emitters enhance the absorption by $\sqrt{N}$
  - Emitters need to be identical
  - Difficult to control and measure the qubit (in the memory)
- Optical resonators [3]
  - Many bounces of a photon between mirrors enhance interaction probability
  - Fabrication of good resonators can be challenging (depending on emitter)

Interaction between remote emitters is still probabilistic (photon loss)
Solution: Heralded protocols

[1] Vetsch et al. PRL **104** 203603 (2010); Tame et al. Nat. Phys. **9** 329 (2013);
[2] Hammerer et al. Rev. Mod. Phys. **82** 1041 (2010); Sangouard et al. Rev. Mod. Phys. **83** 33 (2011)
[3] Reiserer, Rempe Rev. Mod. Phys. (2015) arXiv:1412.2889; Lončar, Faraon, MRS Bulletin 38, 144 (2013)



Deterministic networks with probabilistic channels

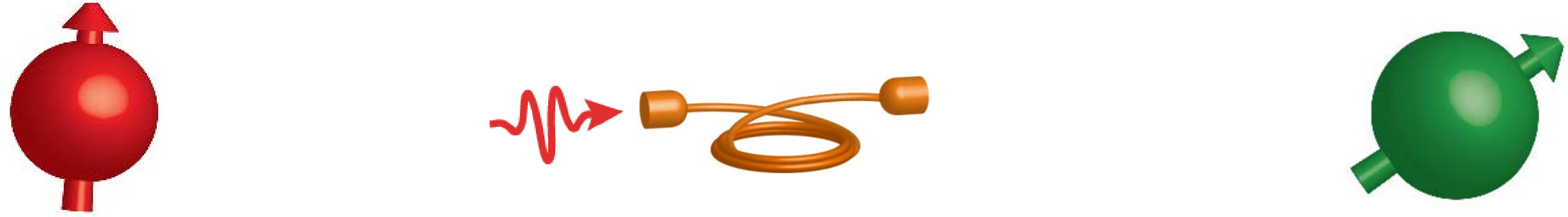
Deterministic networks with probabilistic channels

Qubit A

Qubit B

- Task: Deterministically transfer a qubit from A to B
- Assumption: Local operations can be deterministic
- Approach: Transfer A to a photon P, send it over, absorb in B
- Problems: Photonic channel is lossy and thus probabilistic
- Solution: Copy the state of A?

Copy the state



Qubit A

Qubit B

- Task: Deterministically transfer a qubit from A to B
  - Make a copy of the quantum state of A, repeat sending until success…
  - Copy operation: $|0\rangle_A \rightarrow |0\rangle_A |0\rangle_P \qquad |1\rangle_A \rightarrow |1\rangle_A |1\rangle_P$
  - General state $(\alpha|0\rangle + \beta|1\rangle)_A \rightarrow \alpha|0\rangle_A|0\rangle_P + \beta|1\rangle_A|1\rangle_P$
  - This can be an entangled state. Measurement of P will affect A

→ Copying is not possible: Quantum No-Cloning Theorem

Wooters and Zurek Nature (1982)

The solution

Qubit A

Idea: Keep the qubit in A!
Send the photon from B to A!

Qubit B

Teleporting an Unknown Quantum State via Dual Classical and Einstein-Podolsky-Rosen Channels

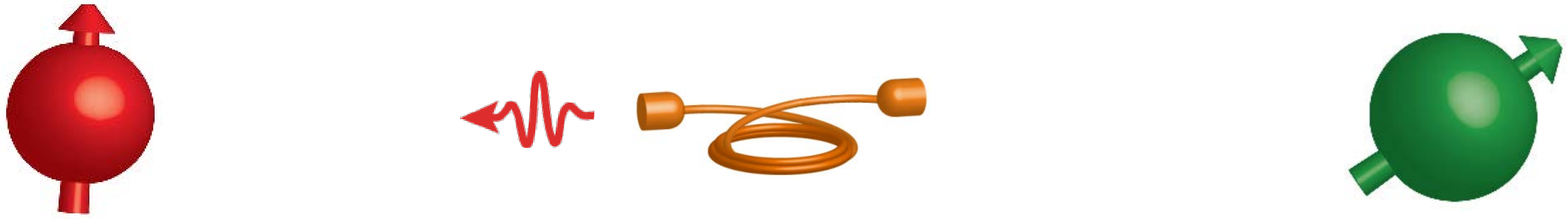
Charles H. Bennett,(1) Gilles Brassard,(2) Claude Crépeau,(2),(3)
Richard Jozsa,(2) Asher Peres,(4) and William K. Wootters(5)

Alice could then teleport quantum states to Bob over arbitrarily great distances, without worrying about the effects of attenuation and noise on, say, a single photon sent through a long optical fiber.

PRL 70, 1895 (1993)

Teleportation allows for quantum state transfer with
unit efficiency and **unit fidelity**, **independent of the distance**

Quantum Teleportation



- Task: Deterministically transfer a qubit $|\varphi\rangle_A$ from A to B
- B,P are prepared in one of the Bell states, e.g. $|\psi^-\rangle_{BP}$

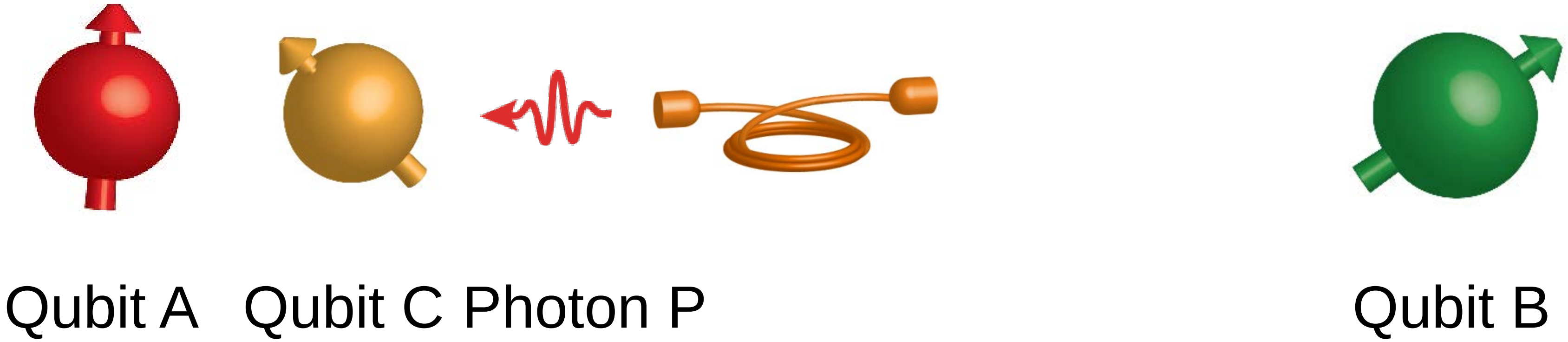
$$|\psi^\pm\rangle = {}^{1}/_{\sqrt{2}}\left(|0\rangle|1\rangle \pm |1\rangle|0\rangle\right) \qquad |\phi^\pm\rangle = {}^{1}/_{\sqrt{2}}\left(|0\rangle|0\rangle \pm |1\rangle|1\rangle\right)$$

- Then the combined state of A, B and P can be rewritten:

$$|\varphi\rangle_A|\psi^-\rangle_{BP} = {}^{1}/_{2}\left(|\phi^+\rangle_{AP}\sigma_x\sigma_z|\varphi\rangle_B - |\phi^-\rangle_{AP}\sigma_z|\varphi\rangle_B + |\psi^+\rangle_{AP}\sigma_x|\varphi\rangle_B - |\psi^-\rangle_{AP}|\varphi\rangle_B\right)$$

Measure the Bell state of A and P (locally!), and the initial state $|\varphi\rangle_A$ appears in B (except for a result-dependent rotation)

Quantum Teleportation



$$|\varphi\rangle_A|\psi^-\rangle_{BP} = {}^1/_2\,(|\phi^+\rangle_{AP}\sigma_x\sigma_z|\varphi\rangle_B - |\phi^-\rangle_{AP}\sigma_z|\varphi\rangle_B + |\psi^+\rangle_{AP}\sigma_x|\varphi\rangle_B - |\psi^-\rangle_{AP}|\varphi\rangle_B)$$

Prerequisites:

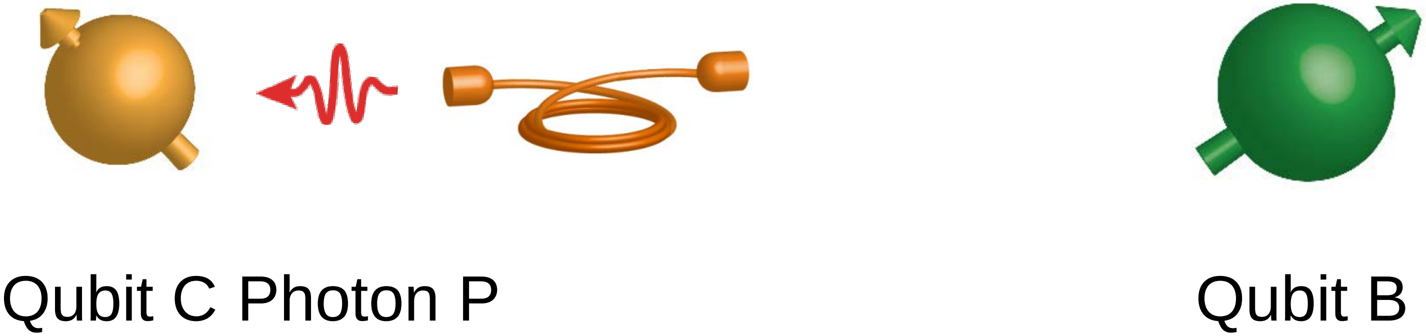
- Deterministic or heralded creation of the “resource state” $|\psi^-\rangle_{BP}$
- Measurement of the state of A and P in the Bell basis
- Classical communication and feedback on B

Problem: A-P quantum gates [1] and P measurement are still probabilistic
Solution: Another ancilla qubit C (with local deterministic CA operations)

Problem: Need to create $|\psi^-\rangle_{BC}$ is via probabilistic photonic channel
Solution: Heralded scheme, repeat until success

[1] Reiserer et al. Nature (2014)

Heralded remote entanglement



Task: Heralded generation of the resource state $|\psi^{\pm}\rangle_{BC}$

Resource: Local generation of qubit-photon entanglement
Solution #1: Heralded storage of the photonic qubit in C [1]
Solution #2: “entanglement swapping” [2] =
Teleport photon into the memory qubit

[1] Kalb et al. PRL (2015)
[2] Żukowski et al. PRL 71 (1993)

Remote entanglement via entanglement swapping

Qubit C Photon Q Photon P Qubit B

- Task: Teleport the state of P (entangled with B) into qubit C
- Resource: Local generation of qubit-photon entanglement $|\psi^-\rangle_{CQ}$
- Teleportation equation in this new scenario:

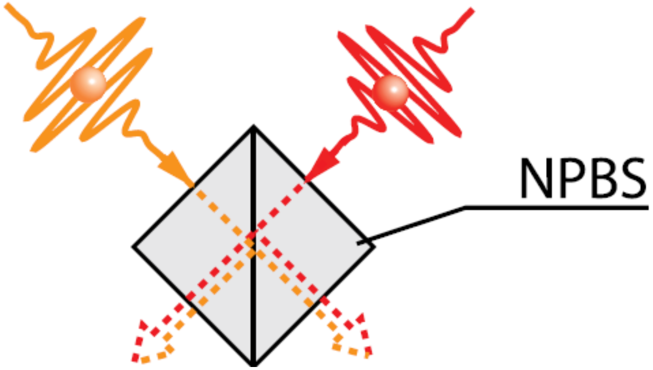
$$|\varphi\rangle_P |\psi^-\rangle_{CQ} = {}^1\!/_2\,(|\phi^+\rangle_{PQ}\sigma_x\sigma_z|\varphi\rangle_C - |\phi^-\rangle_{PQ}\sigma_z|\varphi\rangle_C + |\psi^-\rangle_{PQ}\sigma_x|\varphi\rangle_C - |\psi^-\rangle_{PQ}|\varphi\rangle_C)$$

- Remaining Task: Measure the Bell state of two photons

Photonic Bell state measurement

- Wavefunction of two photons: symmetric under particle exchange (Bosons!)
- Consider two photons impinging on a beam splitter (NPBS)
- They can leave the NPBS
  - in the same port: symmetric wavefunction
  - in different ports: antisymmetric wavefunction
- Result: Two indistinguishable photons will always leave in the same port: Hong-Ou-Mandel effect

Hong, Ou, and Mandel, Phys. Rev. Lett. 59, 2044 (1987)

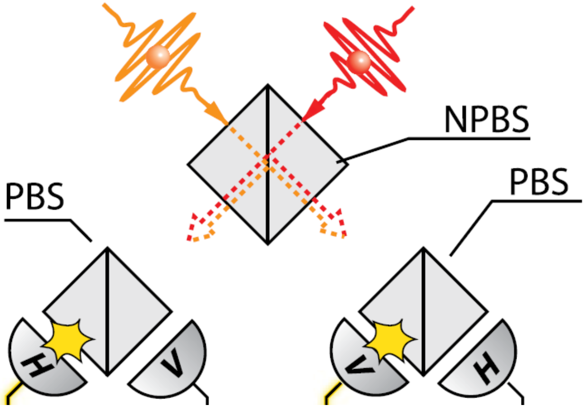


Photonic Bell state measurement

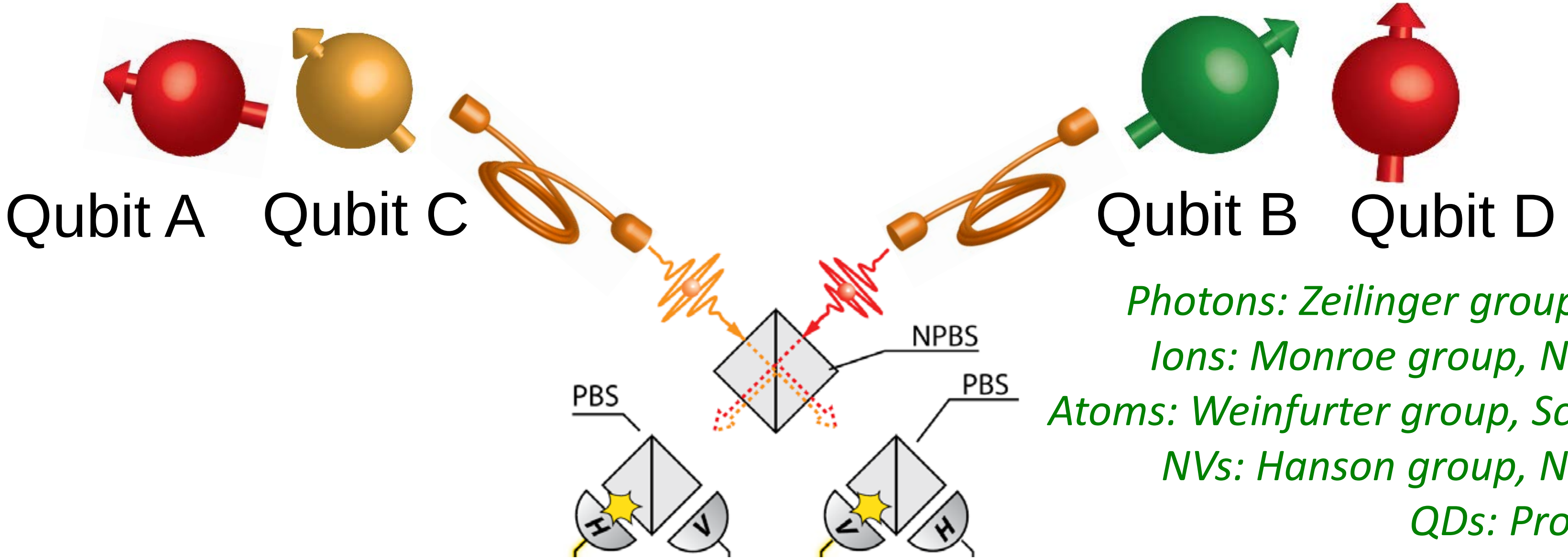
- What if photons have another degree of freedom (e.g. polarization or arrival time, which encode a qubit)
- Recall the Bell basis states of the two photonic qubits

$$|\psi^{\pm}\rangle_{BC} = {}^{1}\!/_{\sqrt{2}}\left(|0\rangle_B|1\rangle_C \pm |1\rangle_B|0\rangle_C\right) \qquad |\phi^{\pm}\rangle_{BC} = {}^{1}\!/_{\sqrt{2}}\left(|0\rangle_B|0\rangle_C \pm |1\rangle_B|1\rangle_C\right)$$

- $|\psi^{-}\rangle_{BC}$ is antisymmetic, the other Bell states are symmetric
- To obtain a symmetric overall wavefunction, two photons in $|\psi^{-}\rangle_{BC}$ will leave in different output ports
- On total, two out of four Bell states can be identified using two-photon interference Calsamiglia and Lütkenhaus, Appl. Phys. B 72, (2001)



Remote entanglement via entanglement swapping



Photons: Zeilinger group, PRL 1998
Ions: Monroe group, Nature 2007
Atoms: Weinfurter group, Science 2012
NVs: Hanson group, Nature 2012
QDs: Probably soon

- “Standard” procedure to entangle two remote qubits (C and B):
  - Create qubit-photon entanglement on both sides
  - Interfere the photons on a beam splitter
  - Repeat until coincidence detection is observed
- Prerequisite: Qubits emit indistinguishable photons
  (Frequency, emission time, temporal envelope, spatial mode …)
- With heralded remote entanglement: deterministic interaction of remote qubits A and D via probabilistic photonic channels

van Enk, Cirac, Zoller, Science **279** (1998); Gottesman and Chuang, Nature **402** (1999)

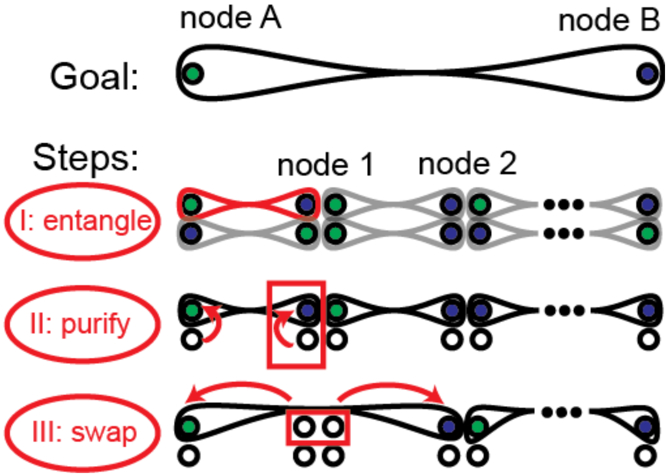
Towards a quantum internet

Teleportation and entanglement swapping overcome inefficiencies and loss in photonic channels.

Requirements: Heralded remote entanglement, Network nodes with two (or more) qubits and long coherence time, local (deterministic) gates, measurement and feedback

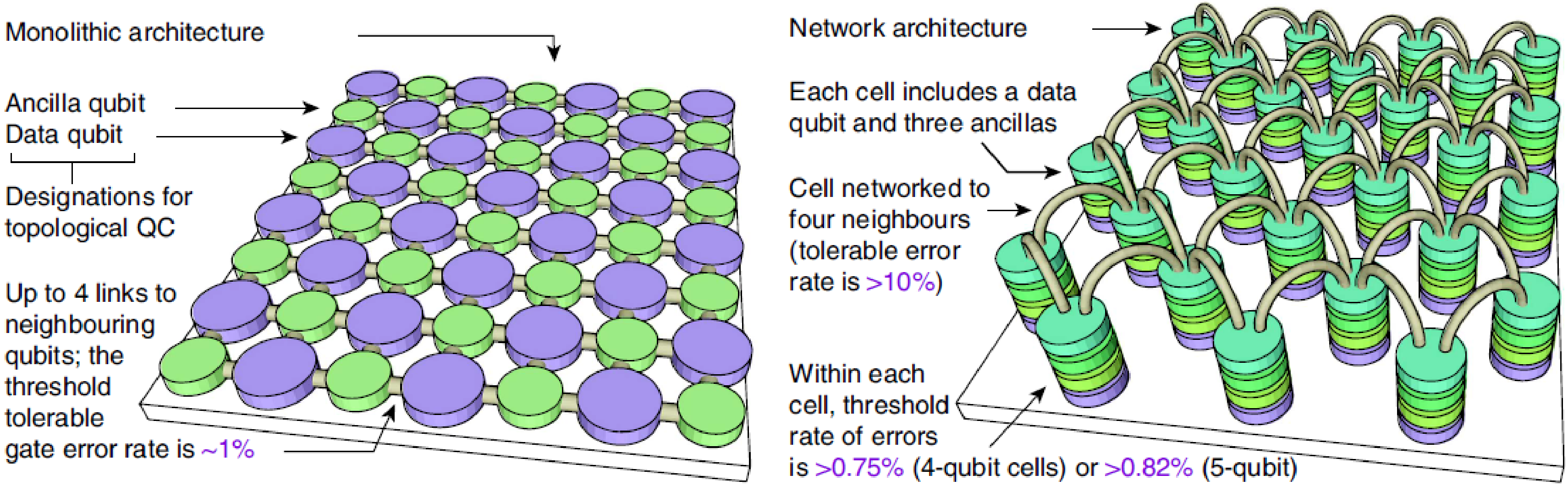
Quantum repeater protocols overcome control imperfections.

Additional requirement: High rates and fidelities



Briegel, Dür, Cirac, Zoller, Phys. Rev. Lett. 81(1998); Dür and Briegel Rep. Prog. Phys. **70** (2007)

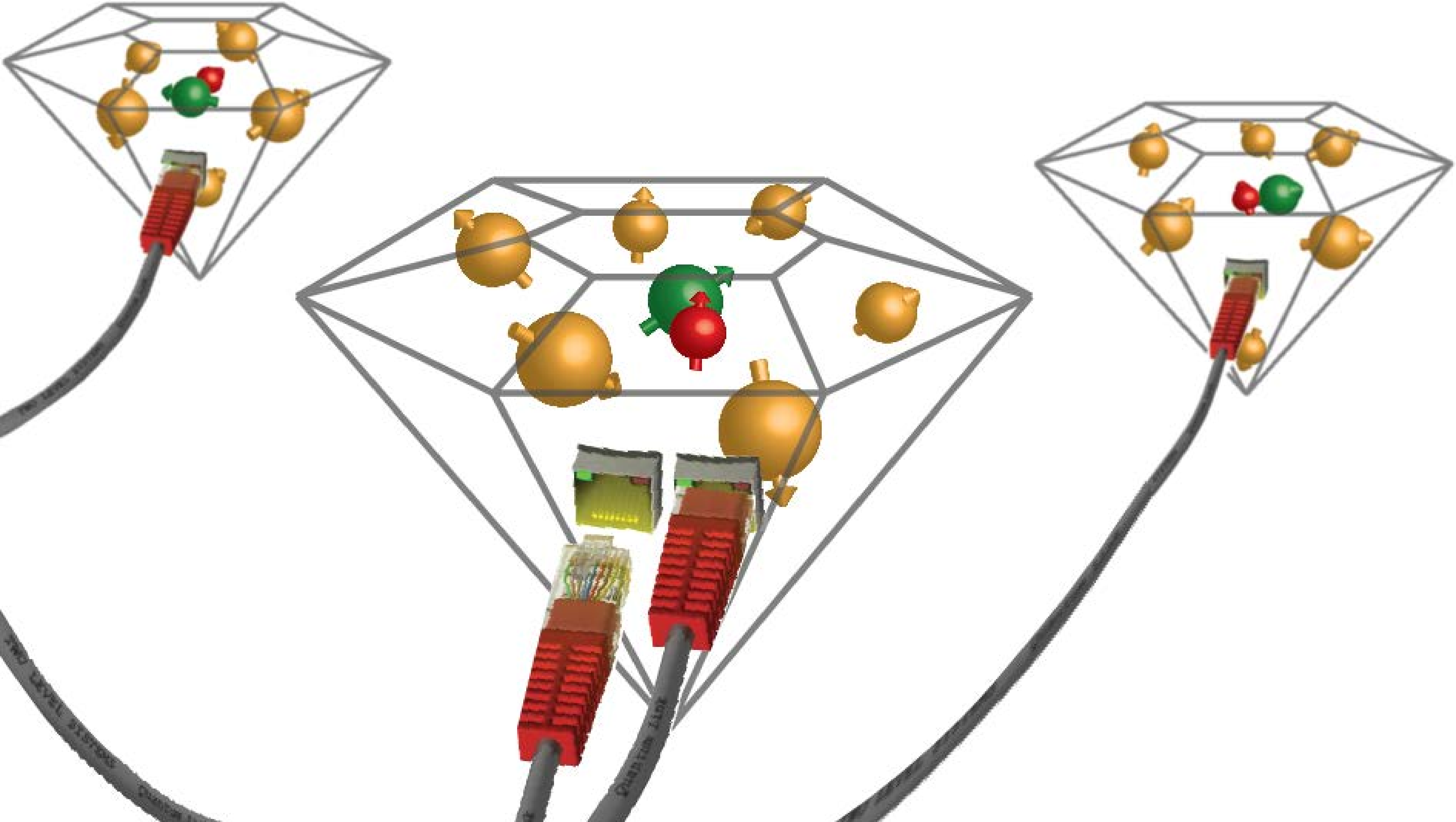
Towards distributed quantum computation



Nickerson, Li, Benjamin, Nat. Comm. 4, 1756 (2013)

- Realization of surface codes via communication and storage qubits ('broker' and 'client')
- Prerequisites: Identical to quantum repeater
- Geometry not restricted to 2D
- Reduced problems with correlated errors (qubit separation)

Part II: Quantum networks with spins in diamond



NV center research

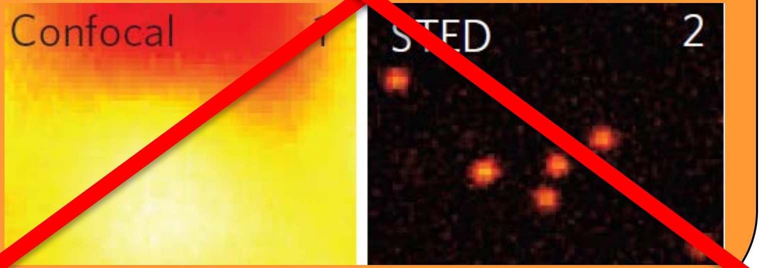
Fundamental quantum science

- Decoherence
- Entanglement; Bell-tests
- Quantum measurement

Tonight

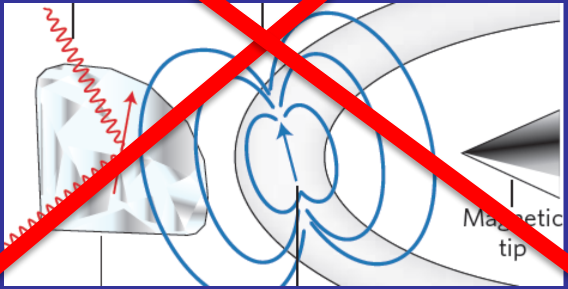
~~Fluorescence (bio)imaging~~

- ~~Nonbleaching, nontoxic marker~~
- ~~Subwavelength STED imaging~~



~~Metrology (E/M fields)~~

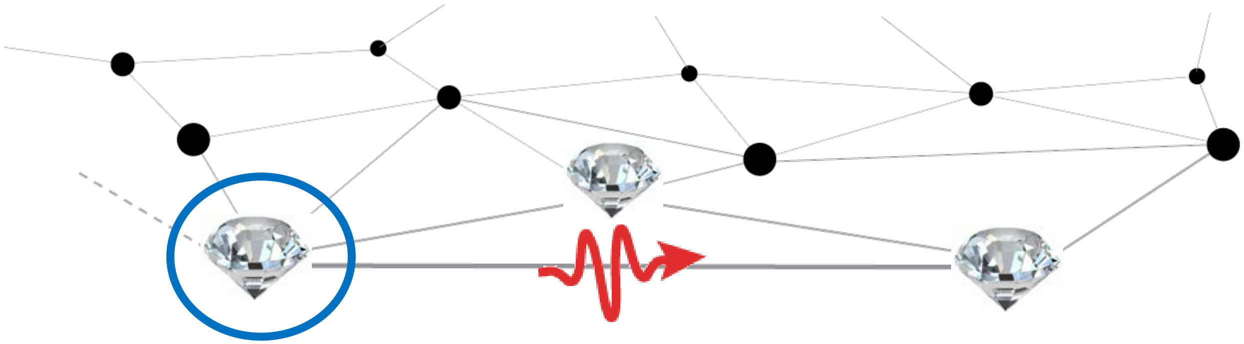
- ~~High-NV-density magnetometry~~
- ~~Single-spin sensors~~



Quantum information technologies

- Quantum communication with photons
- Quantum computing with spin qubits
- **Quantum networks**

Quantum Networks



Nodes ↔ Photons

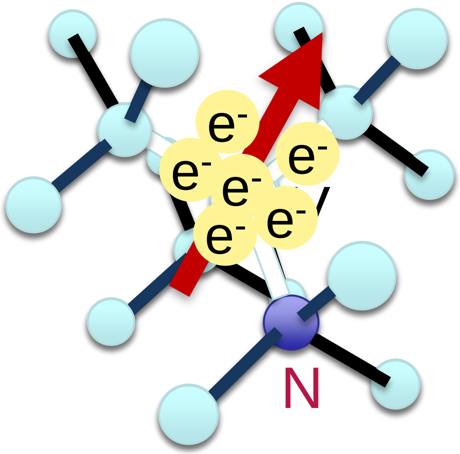
Nodes
- Store
- Control
- Measure

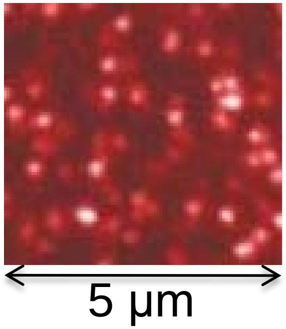
Photons

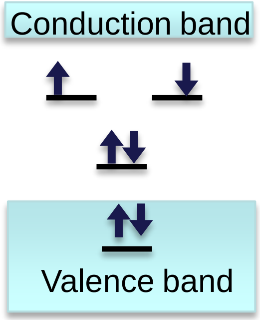
Mediate interaction
- Fast
- Controlled
- Long-distance

The basic properties of the nodes

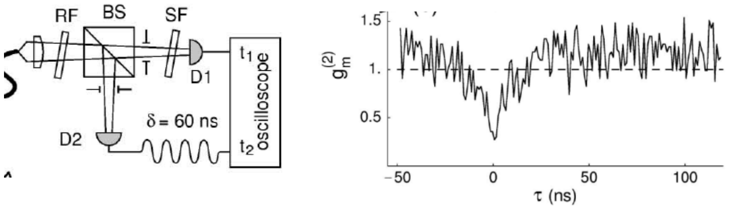
The Nitrogen Vacancy Center





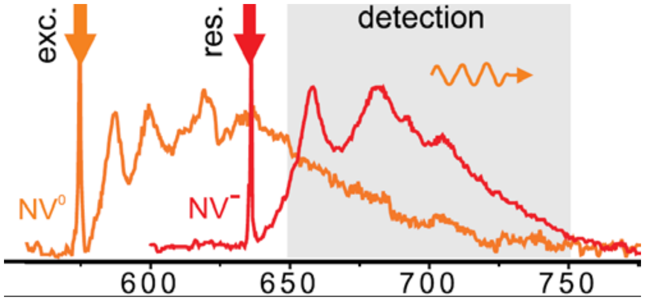

Conduction band

Valence band



Photon anti-bunching

Kurtsiefer et al. PRL 85 (2000)



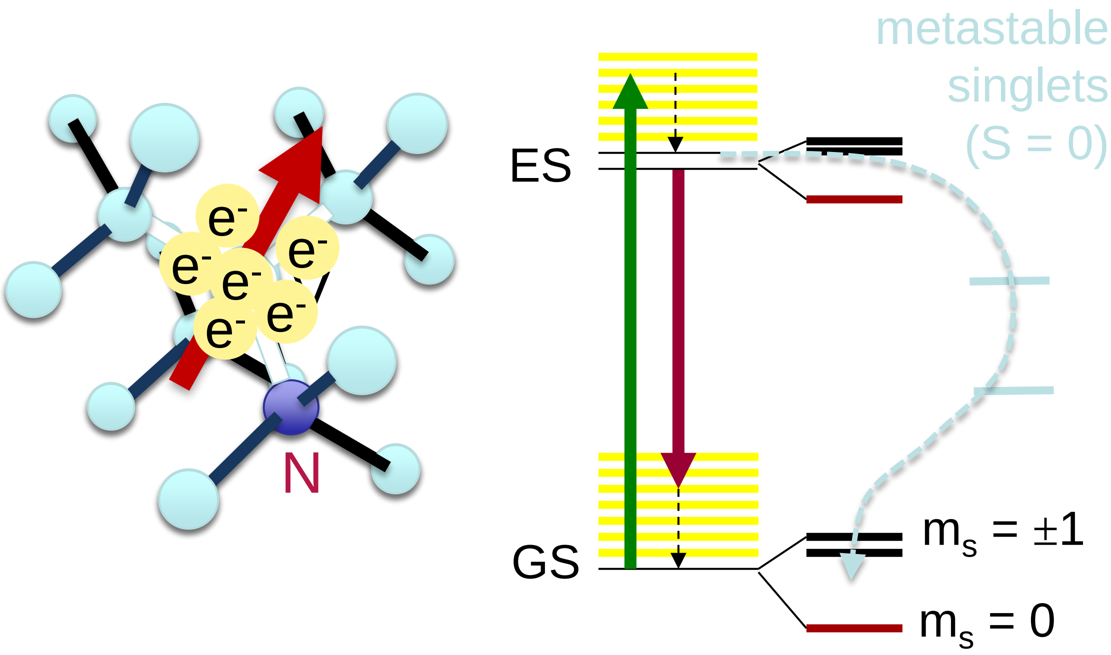
Siyushev et al., PRL **110** (2013)

- Microscope scan under green (532nm) excitation: Red fluorescence
- Individual spots emit single photons → single NV centers
- Two charge states: NV^0 (5 electrons) and NV^- (6 electrons)
- Distinguished by their fluorescence spectra
- Zero-phonon line and Phonon sideband emission (less energy)
- Charge state initialization via resonant excitation

575 nm transition

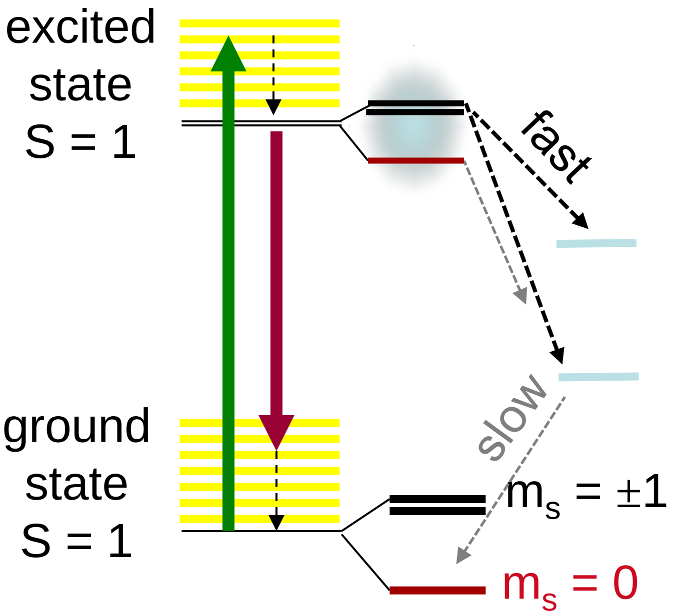
637 nm transition

The negatively charged NV



- NV^- ground state (GS): spin triplet (S=1)
- Zero-field splitting of the m_s=0 and the m_s=±1 states: ~3GHz
- Optically excited state (ES): orbital doublet, spin triplet
- At room temperature:
    - Optical initialization and readout via metastable singlet states

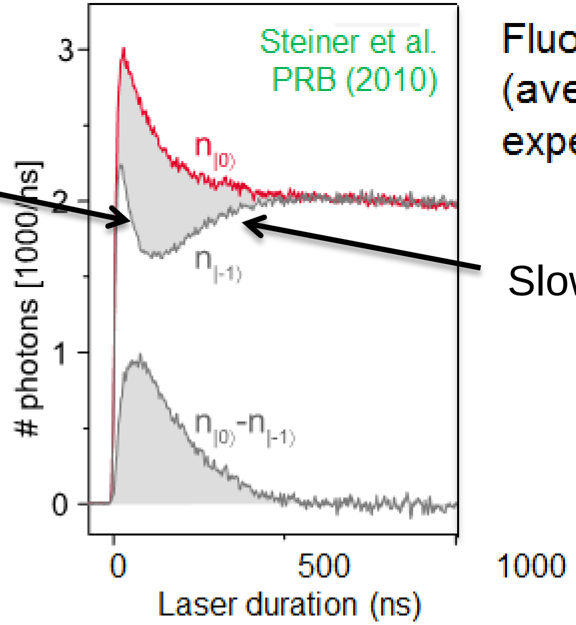
Initialization and readout at room temperature



Nearly spin-conserving excitation
Fuchs et al. PRL (2012)

Excited state lifetimes: ~ 6-12 ns
Goldman et al. PRL 114 (2015)

Singlet lifetimes: >200ns Acosta et al. PRB(2010)



Fluorescence time trace (averaged over many experiments!)

Fast population of singlets from $m_s = \pm 1$

Slow decay out of singlets

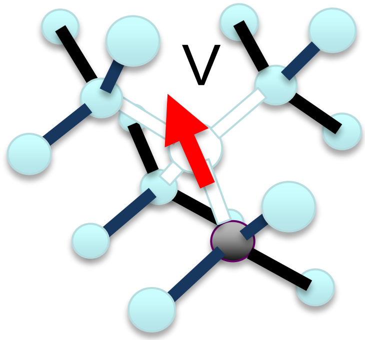
Typical SNR = 0.1 in a single shot

Optical polarization into m_s= 0 ~ 70-90%

Fuchs et al. 2010 Nat. Phys

Spin polarization and detection at room temperature – no fancy lasers required!

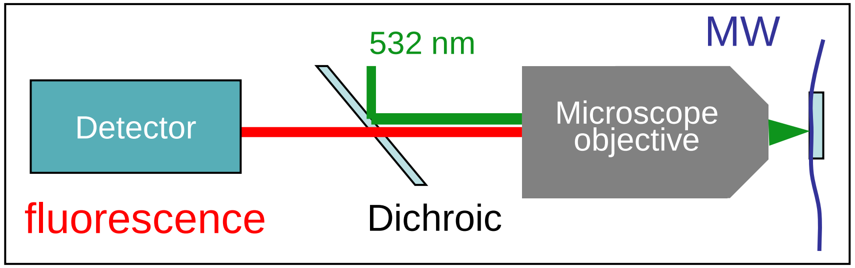
ODMR of the NV electron spin



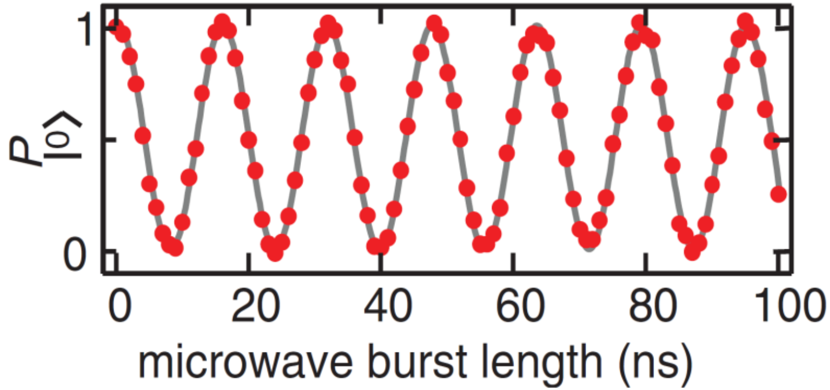
Small magnetic field:
Zeeman splitting $m_s = \pm 1$
→ resolved MW transitions

$$H_B = g\mu_B \vec{B} \cdot \vec{S}$$
$$g \approx 2$$

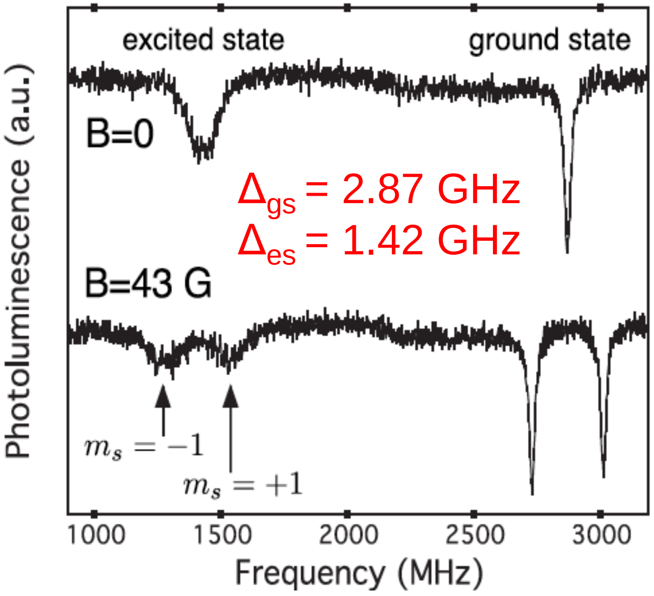
Gruber et al. Science (1997)



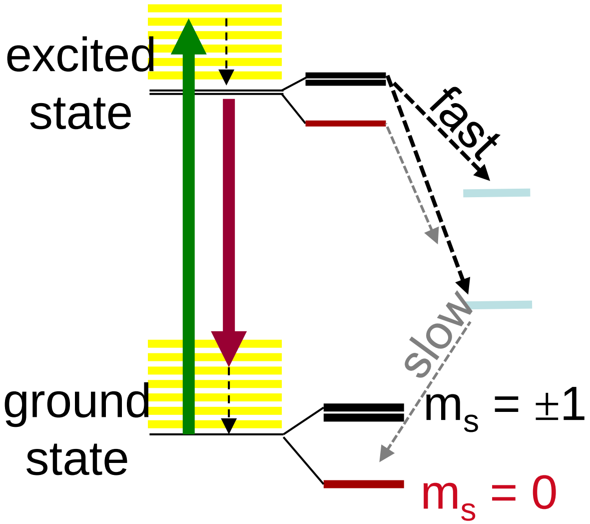
High-fidelity GS spin control



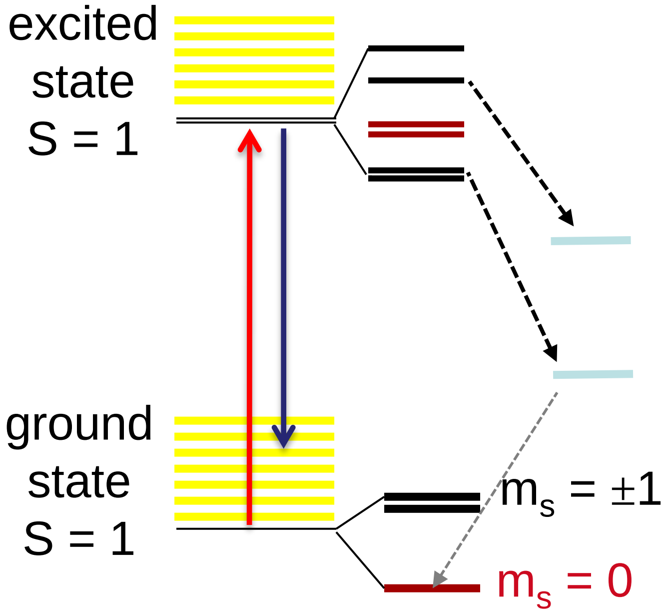
Neumann et al. NJP (2009)

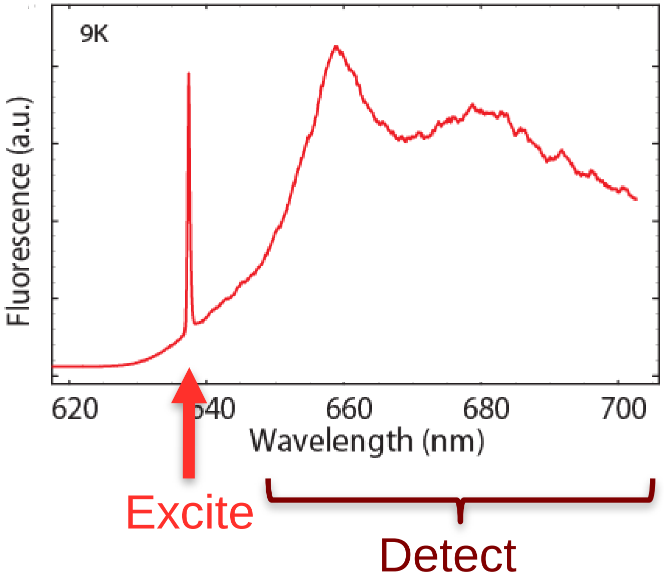


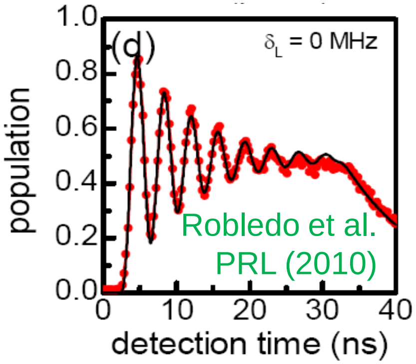
Δ_{gs} = 2.87 GHz
Δ_{es} = 1.42 GHz



The NV$^-$ excited state at low temperature

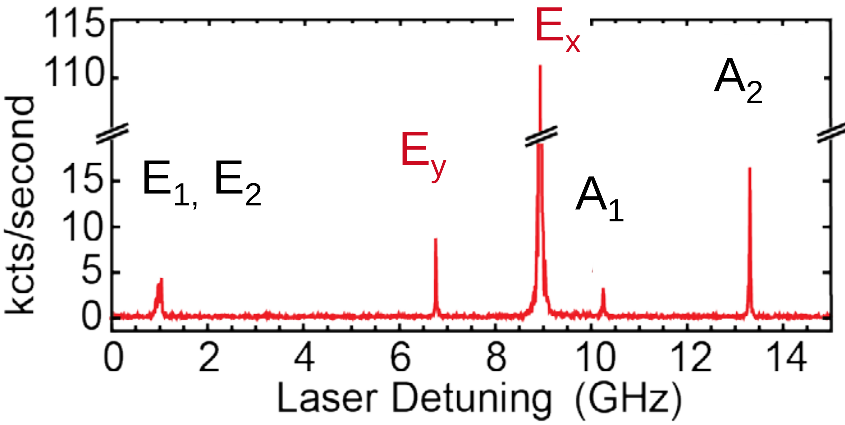




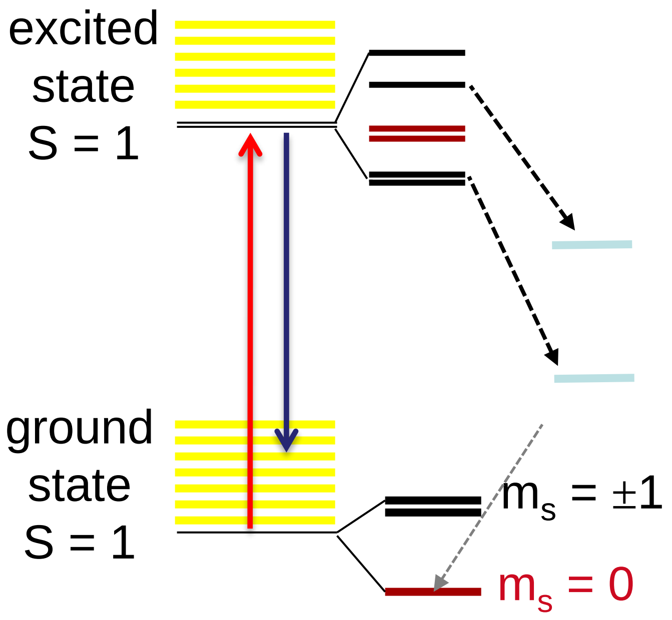


Nearly lifetime-limited optical Rabi oscillations

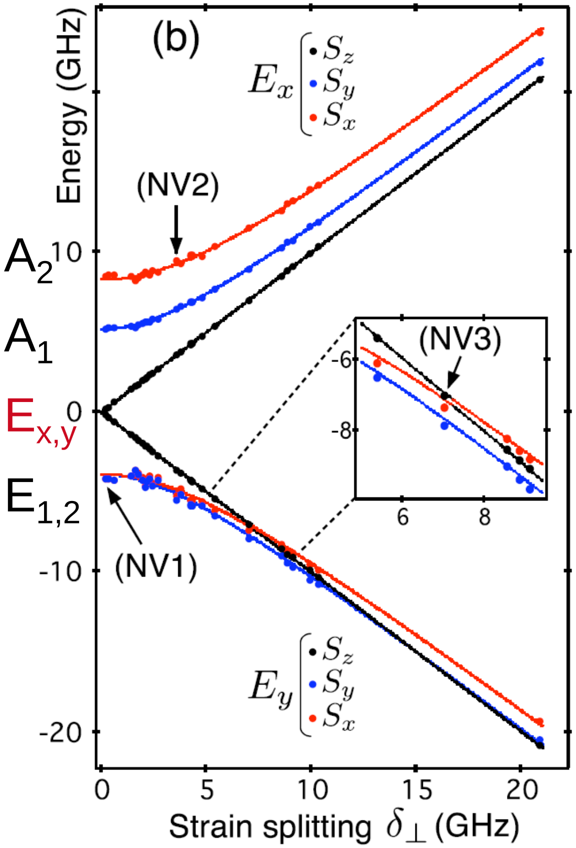
- **Low temperature: No fast mixing in the excited state**
- **Resonant excitation, PSB detection**
- **Laser frequency scan: spin-selective transitions**
  Visible with MW, else: pumping to dark states
- **Nearly lifetime-limited linewidth (~12 ns)**
  Only in pure (electronic-grade) samples
- **Local strain strongly affects the excited state**
  These spectra look different from NV to NV
  Spectral diffusion because of charge fluctuations



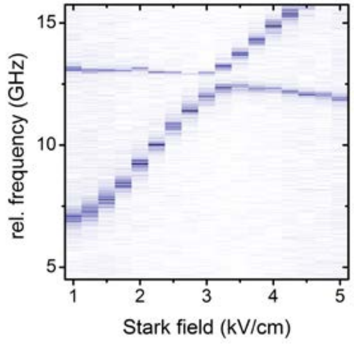
Strain effects at low temperature



Batalov et al. PRL (2009)

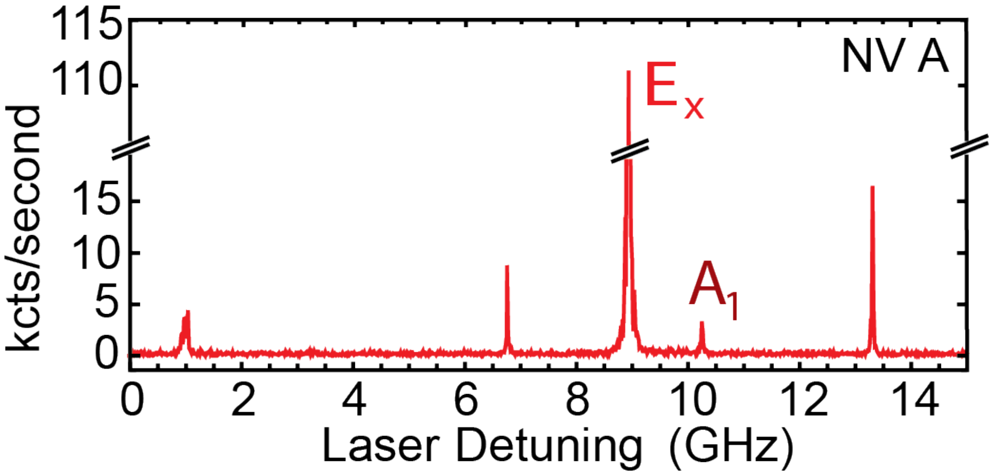


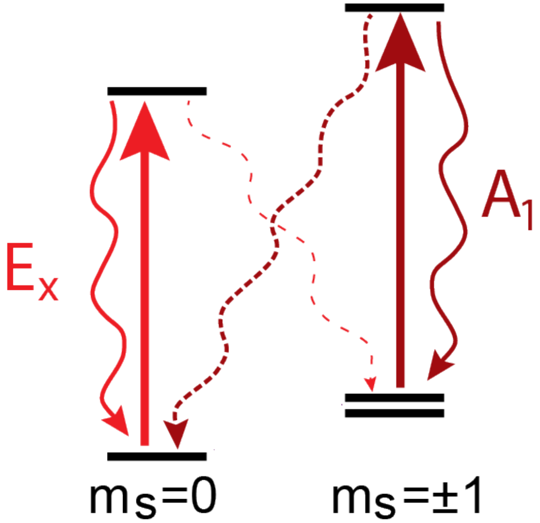
- Axial strain: common shift of all energy levels
- High transverse strain:
  - Two S=1 orbital branches
  - Spin-preserving, linearly polarized emission
  - Significant mixing between spin states in lower branch
- Electric field has the same effect as strain
  - Charges and stray fields can perturb the transitions
  - Can be used for frequency tuning (Tamarat et al. PRL 2006)



The toolbox:
Initialization, control, readout

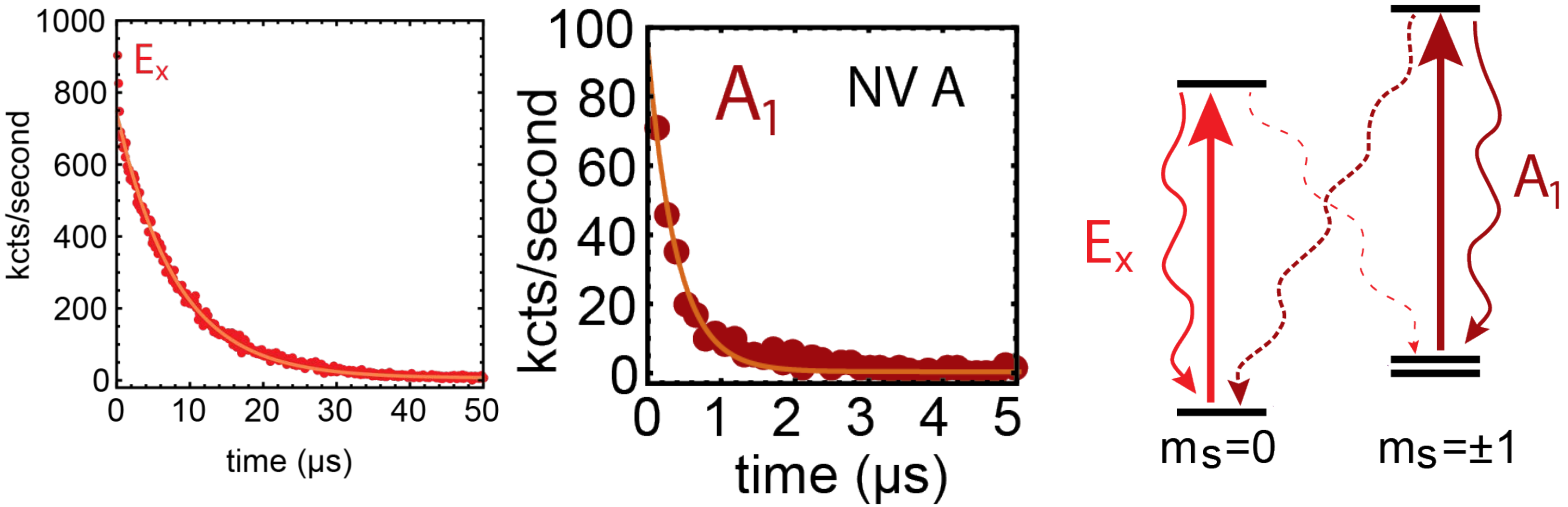
Spin-resolved optical excitation (*T* < 8K)





- Simplified level scheme:
  - E_x as cycling transition
  - A_1 as spin-flip transition

State preparation: spin pumping



Fast preparation in m_s=0

Preparation fidelity > 99.7%
(for comparison: ~90% with conventional off-resonant method)

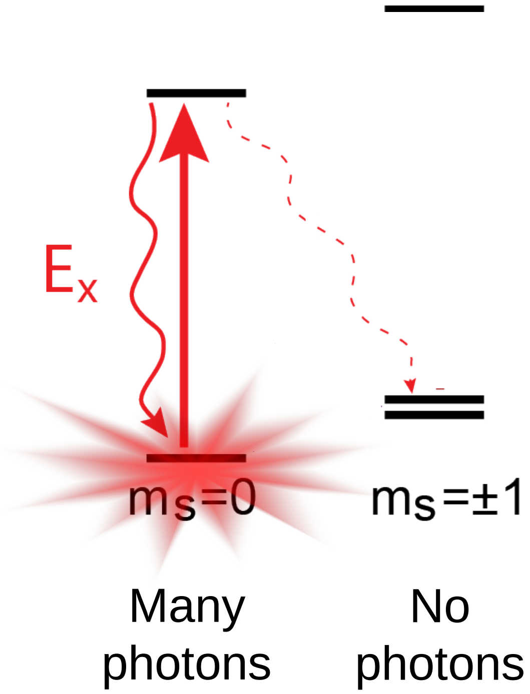
Single-shot readout of NV electron spin

If we catch at least one photon before the spin flips: readout in single shot!

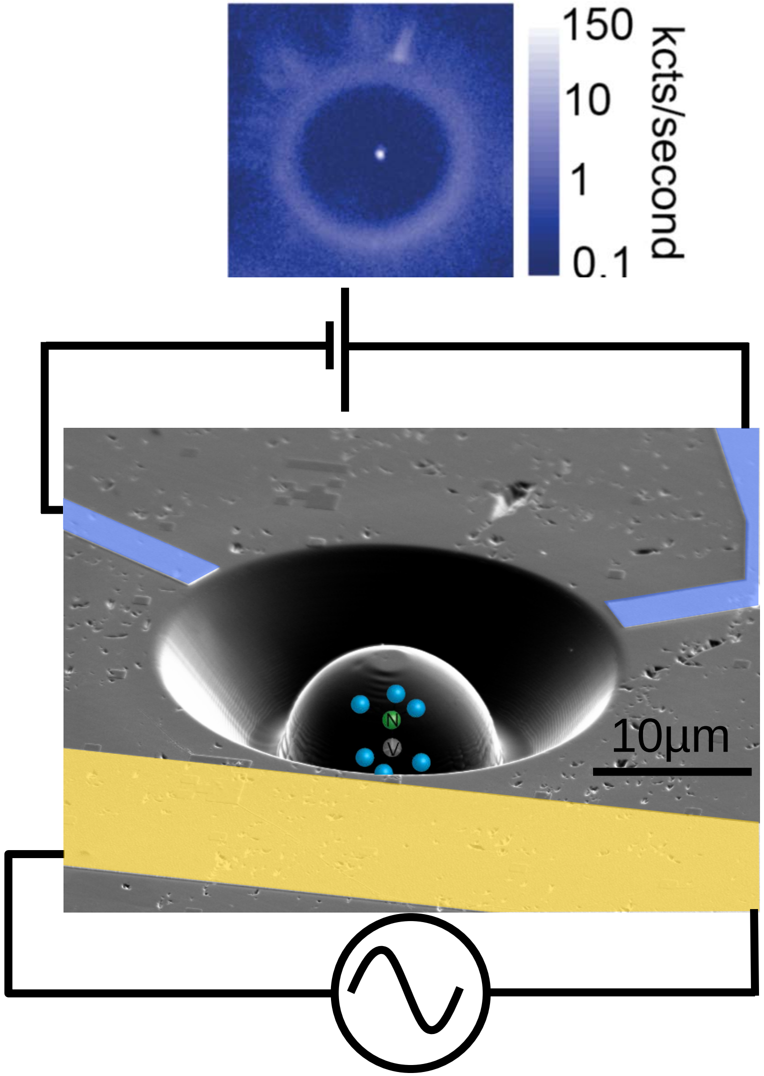
We need:

1. low spin flip rate in optically excited state
   → choose low-strain NVs
   → work at *T* < 10K

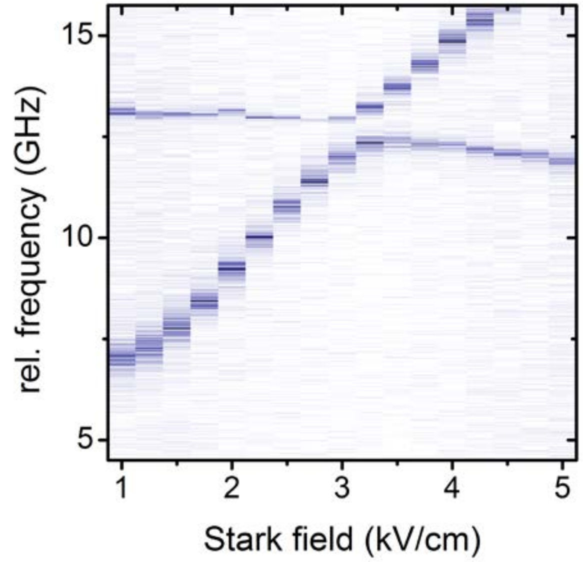
2. high detection efficiency
   → new generation of devices

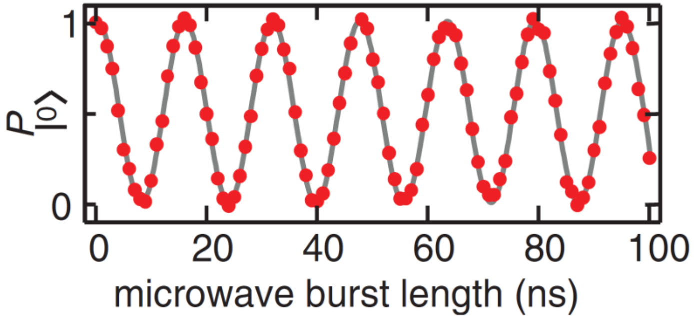


Wiring up NV centers



dc Stark tuning:

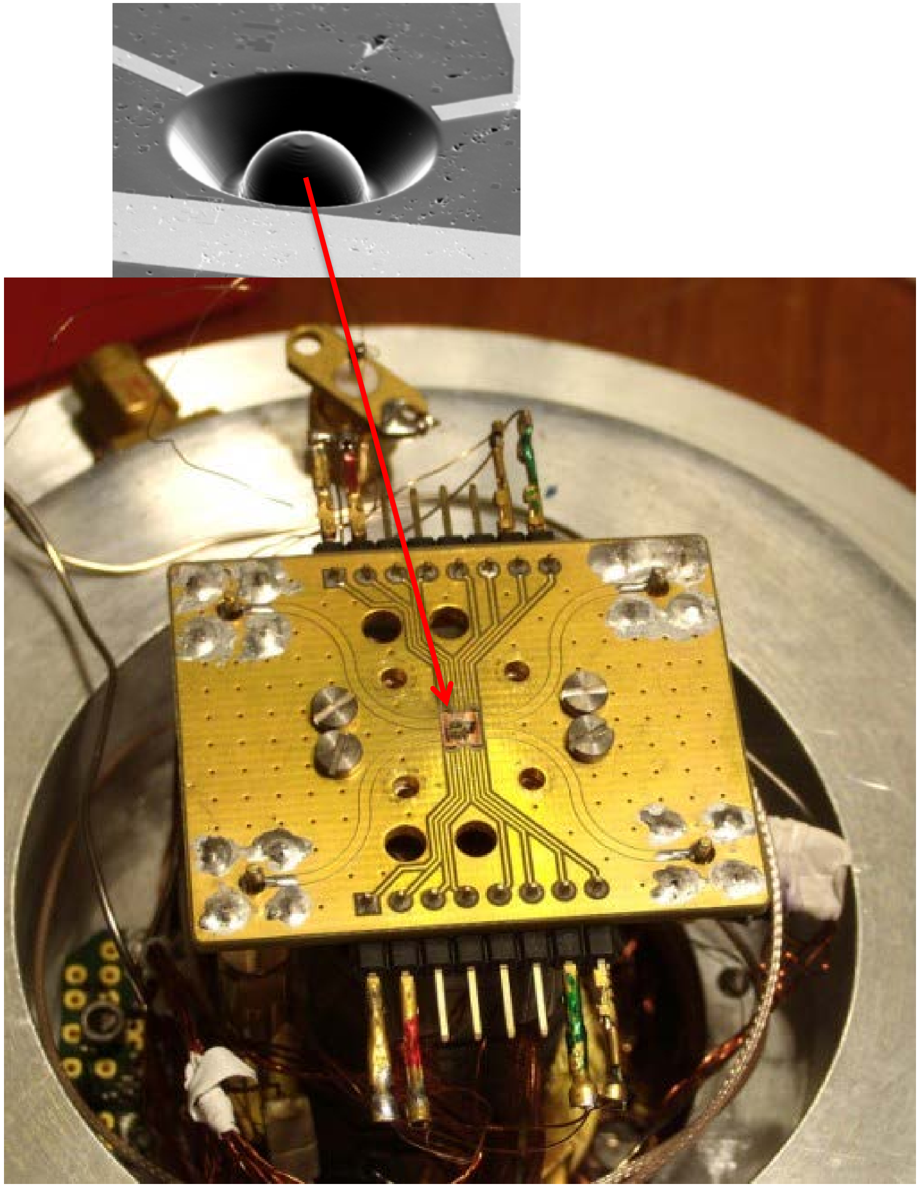


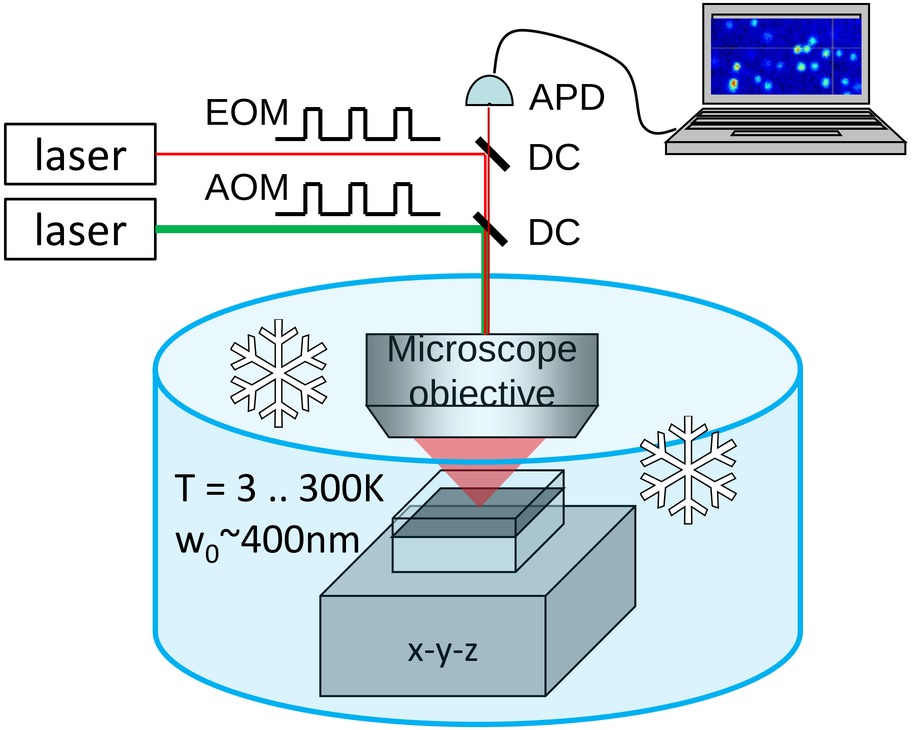


AR coated solid immersion lens (SIL): High photon outcoupling (no total int. ref.)
DC electrodes: Strain tuning of the ES
AC stripline: Microwave control of the GS spin

CVD diamonds grown by Element6

Wiring up NV centers

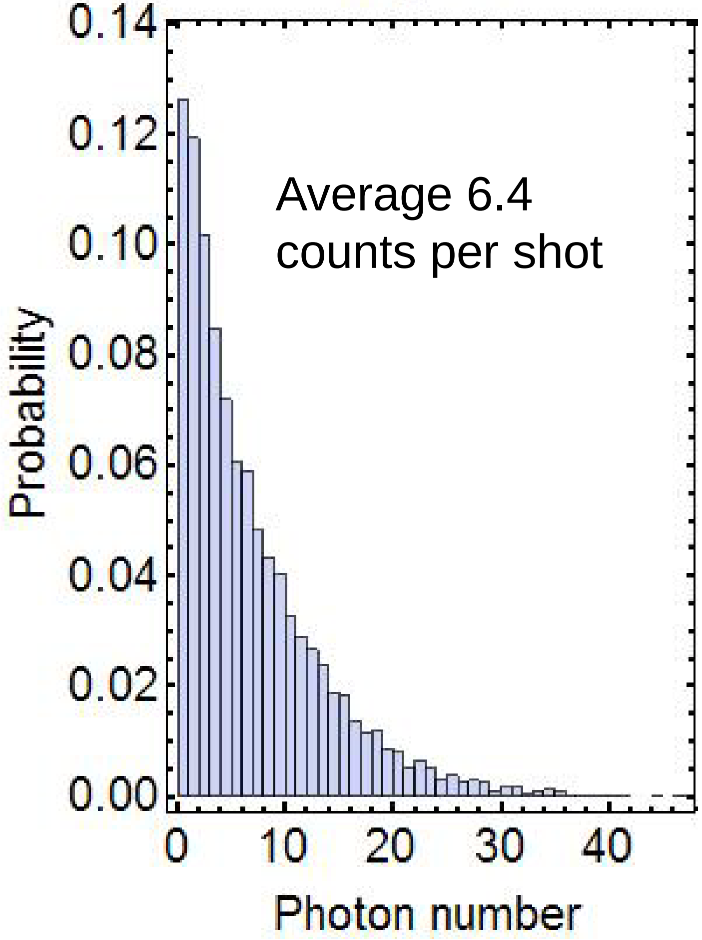




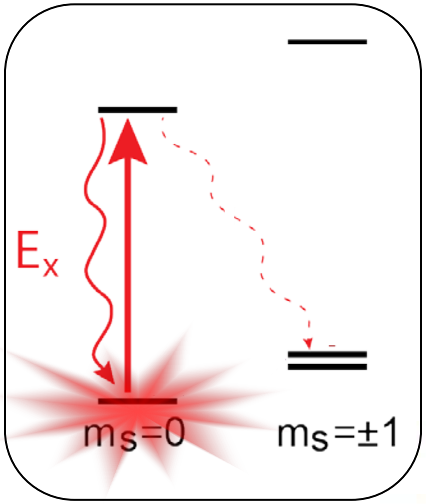
Flow / bath / closed-cycle cryostat

Single-shot readout of NV electron spin

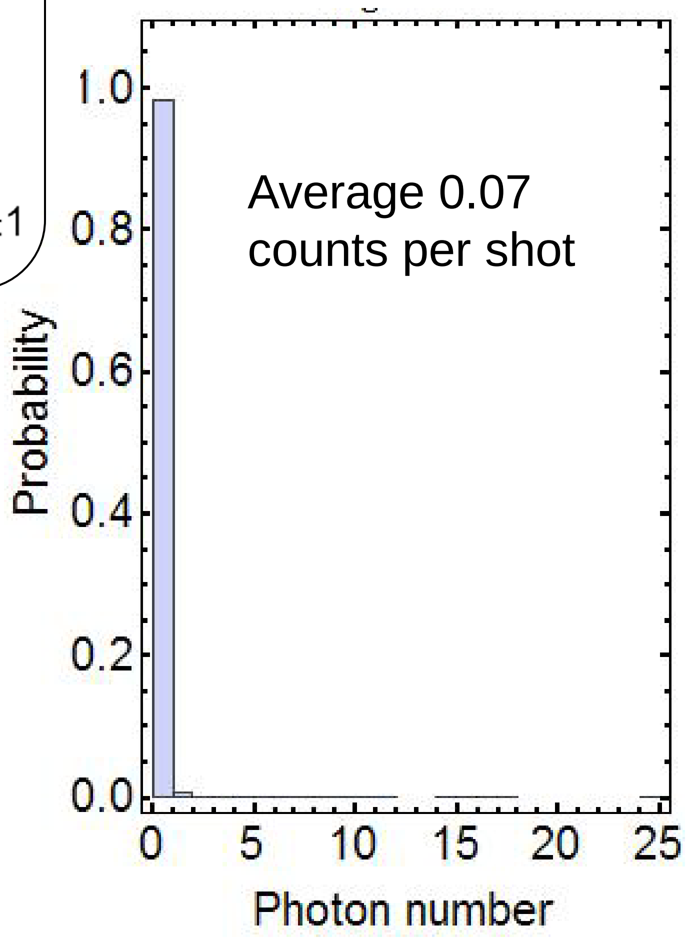
$m_s = 0$ preparation



Average 6.4
counts per shot



$m_s = \pm 1$ preparation



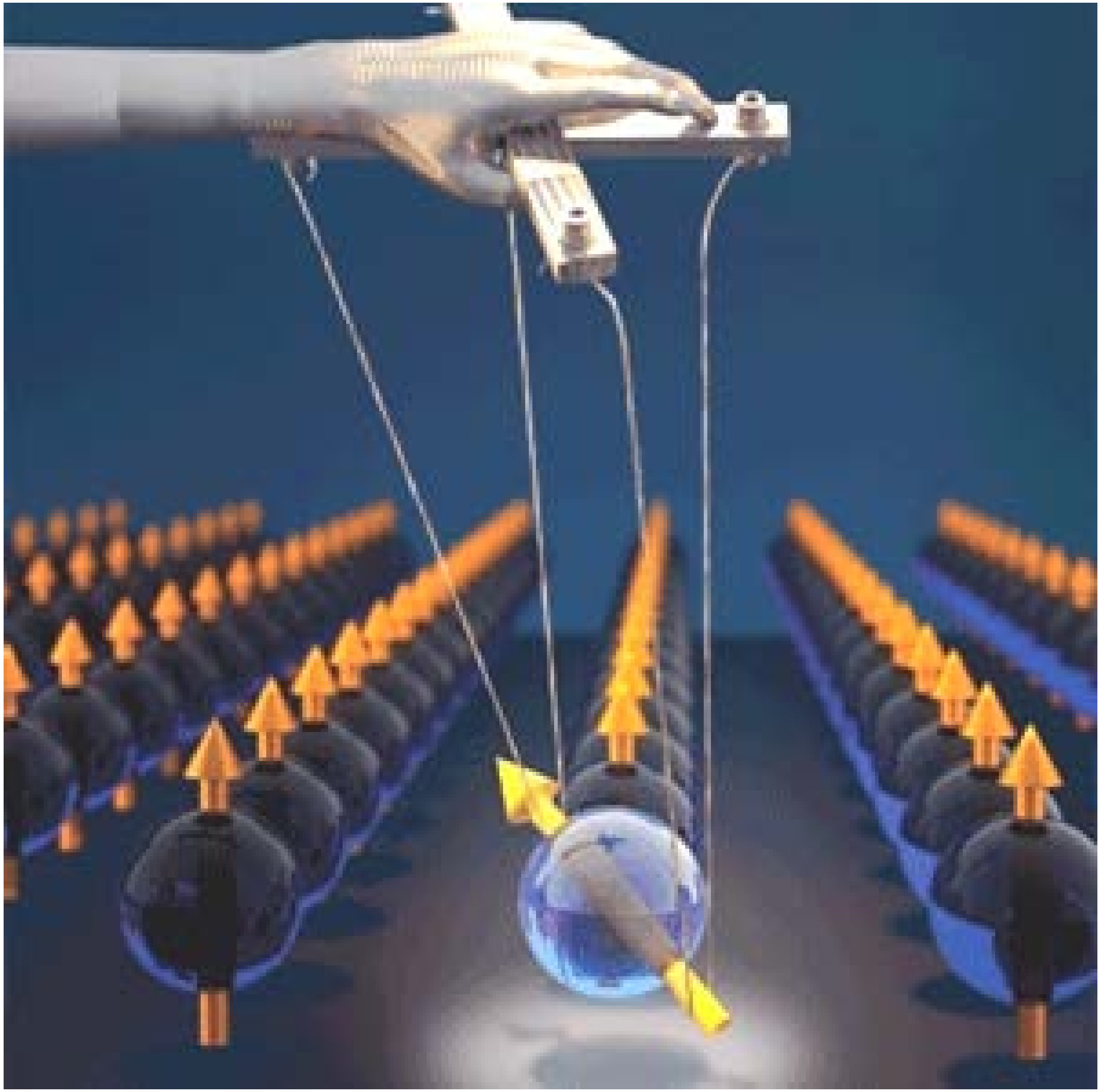
Average 0.07
counts per shot

Best
achieved
average
readout
fidelity
>98%

readout duration: 100 µs … down to 4 µs

Robledo et al. Nature **477** (2011)

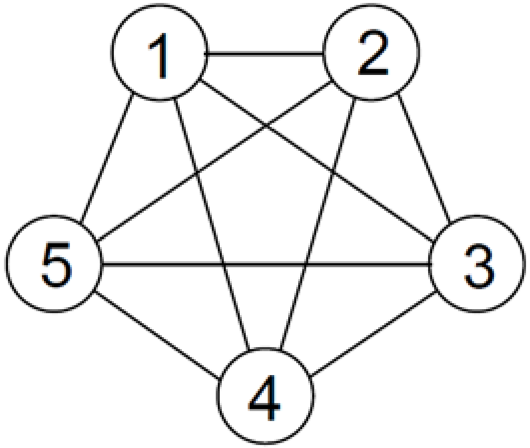
Manipulation of nuclear spins



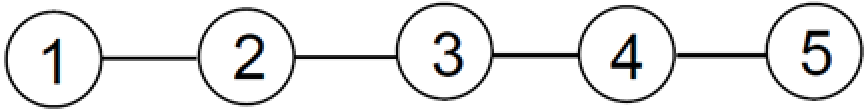
Qubit coupling

- So far:
  - Only one qubit: The NV electron
  - Good initialization, rotation and readout
- Now: Nuclear spins as additional qubit

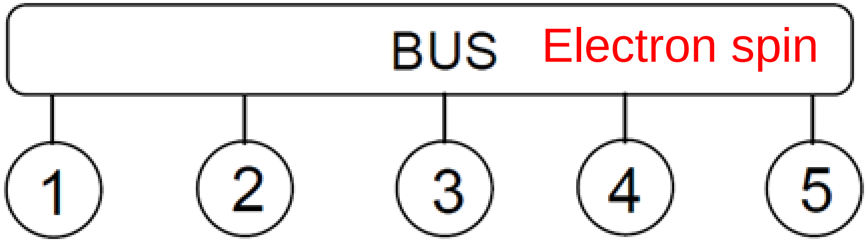
- General schemes for coupling qubits



Full coupling
(NMR; hard to control)



Nearest-neighbor coupling (superconducting qubits, quantum dots, atoms in optical lattices, NVs)



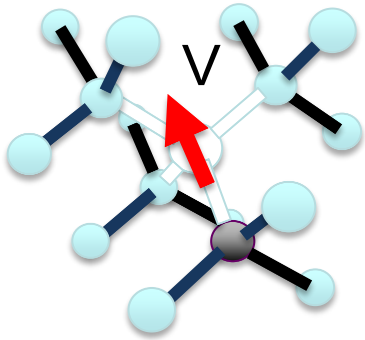
Electron spin

Nuclear spins

Coupling via a common bus
(ions, NV nuclear spins, other impurities)

Vandersypen and Chuang, Rev. Mod. Phys. 76 (2005)

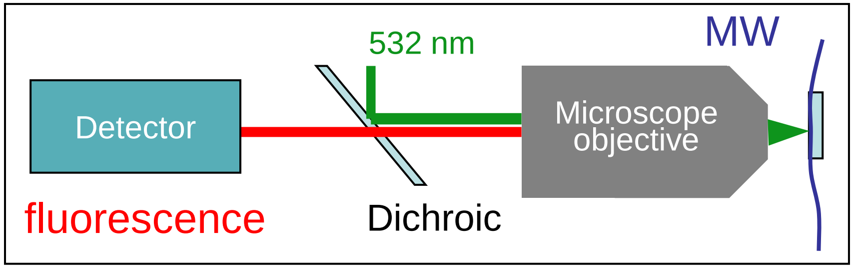
Reminder: ODMR of the NV electron spin



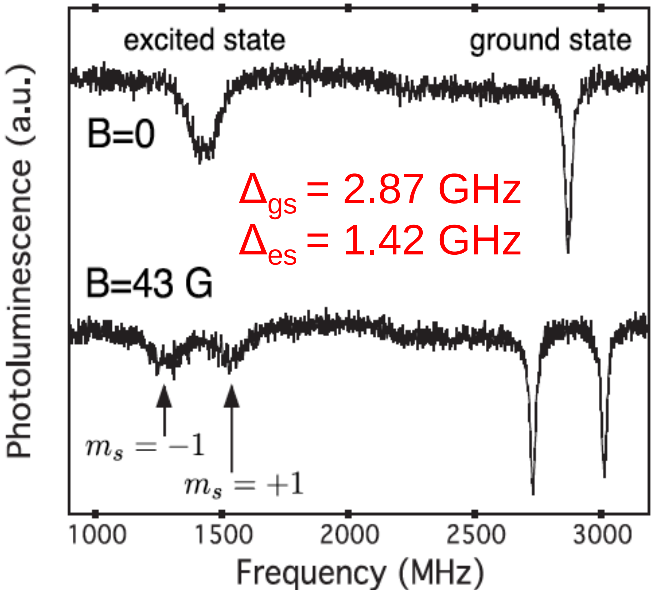
$$H_B = g\mu_B \vec{B}\cdot\vec{S}$$

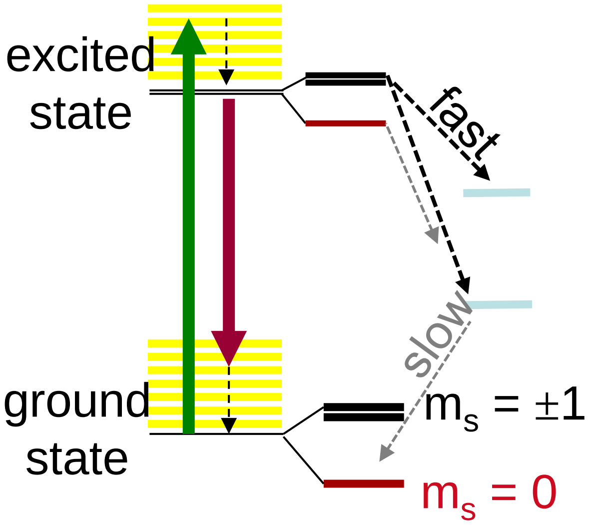
$$g \approx 2$$

Gruber et al. Science (1997)

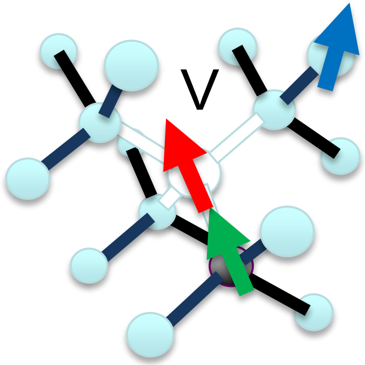


Neumann et al. NJP (2009)





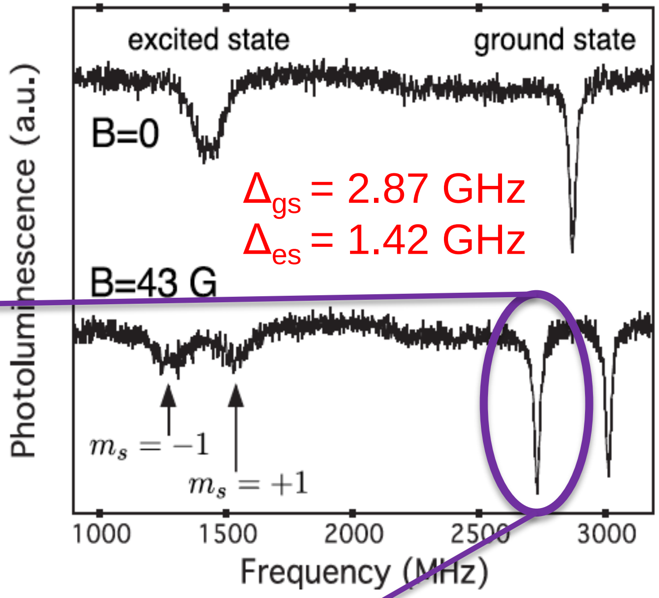
ODMR of the NV electron spin

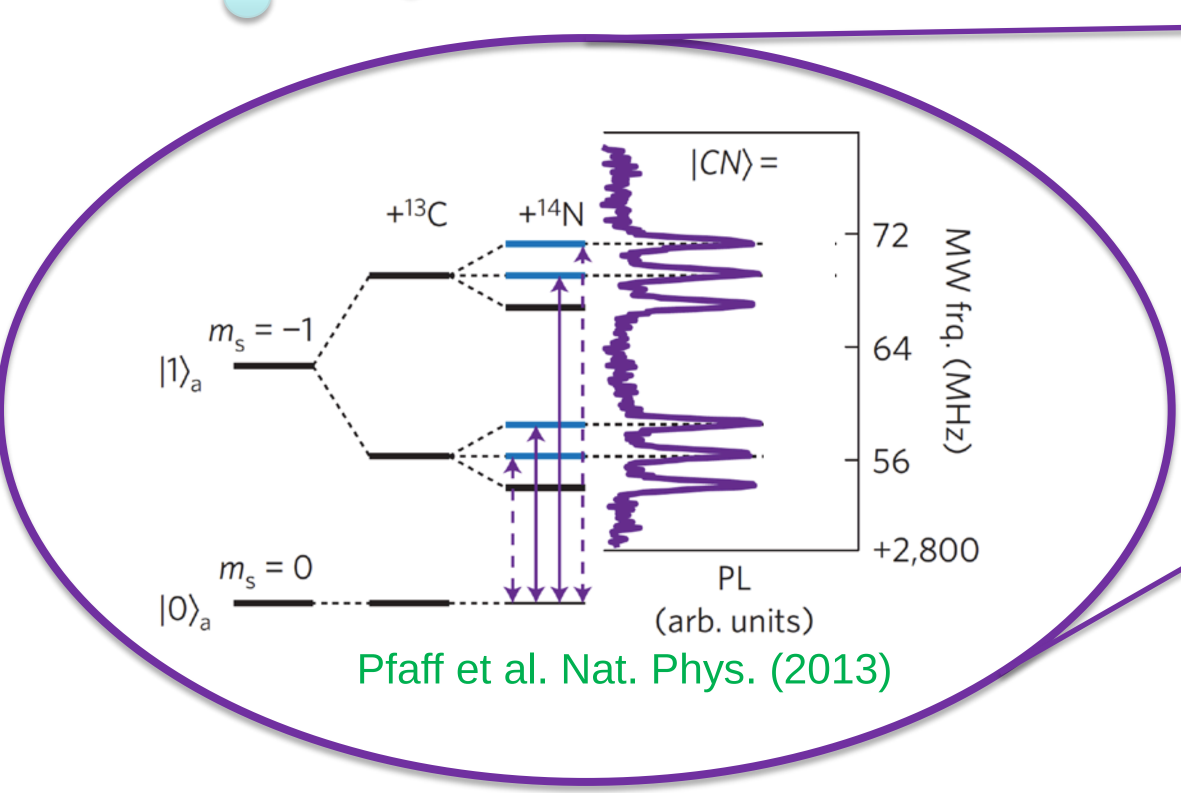


$$H_B = g\mu_B \vec{B}\cdot\vec{S} + A_N\overrightarrow{I_N}\cdot\vec{S} + \sum_{i} A_{C,i}\overrightarrow{I_{C,i}}\cdot\vec{S}$$

$A \sim \mathrm{MHz}$

Neumann et al. NJP (2009)

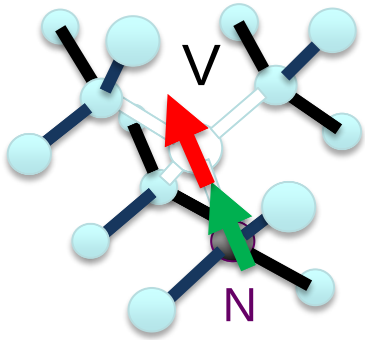




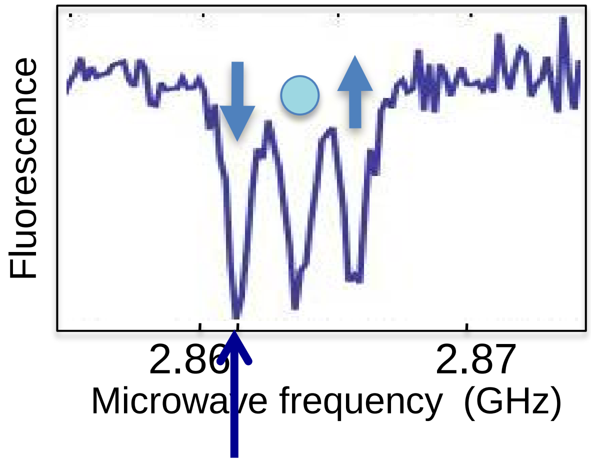
Pfaff et al. Nat. Phys. (2013)

Hyperfine interaction leads to a splitting of the lines

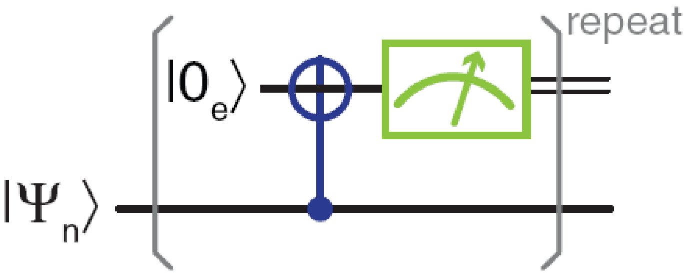
Addressing individual nuclear spins



^{14}N hyperfine lines

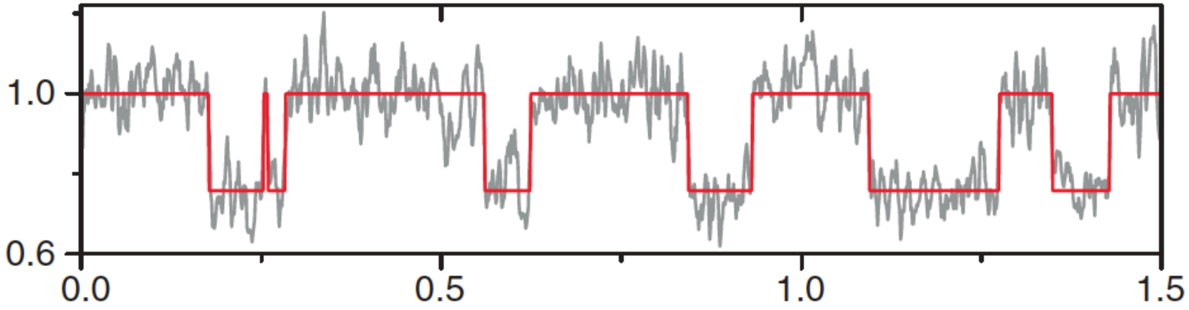


Rotates electronic spin conditional on the nuclear spin state – a CNOT gate



Readout of the electron can be achieved without flipping the nuclear spins
→ Single shot detection and preparation by measurement

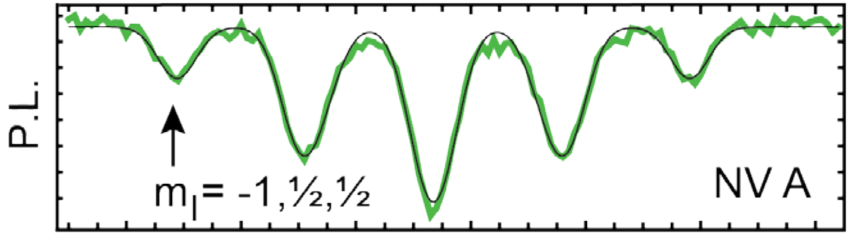
Repetitive, non-destructive detection of a single nuclear spin:

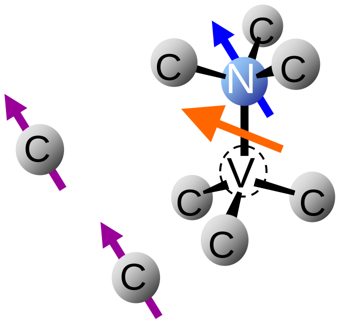


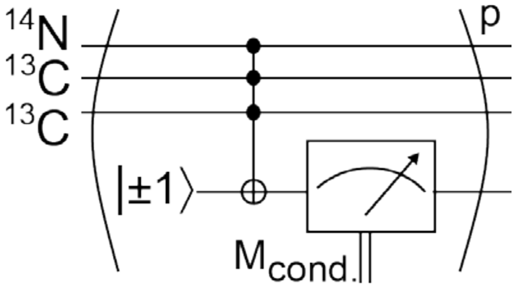
Neumann et al. Science (2010)

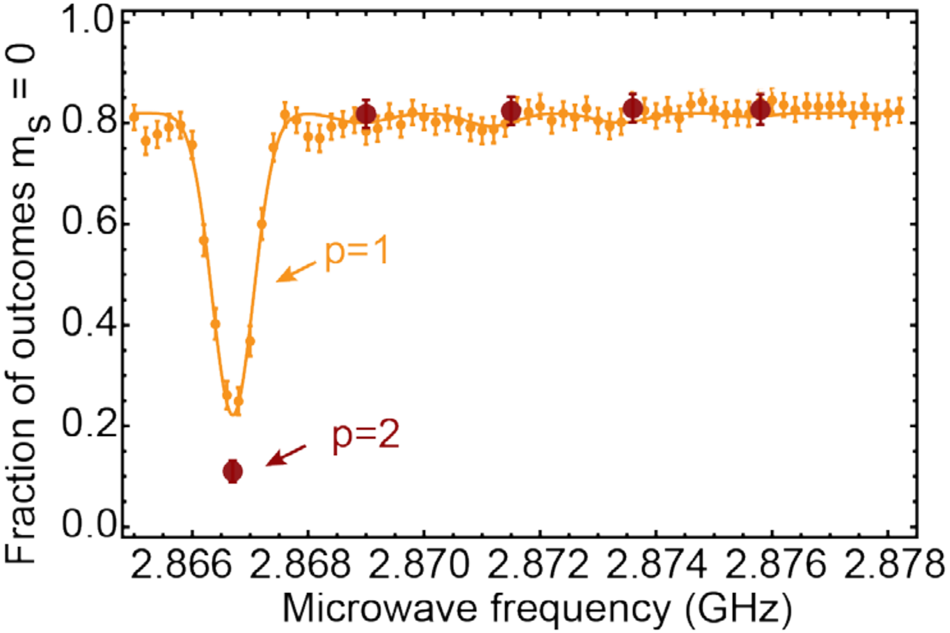
Measurement-based preparation of nuclear spins

ESR spectrum (part of it)





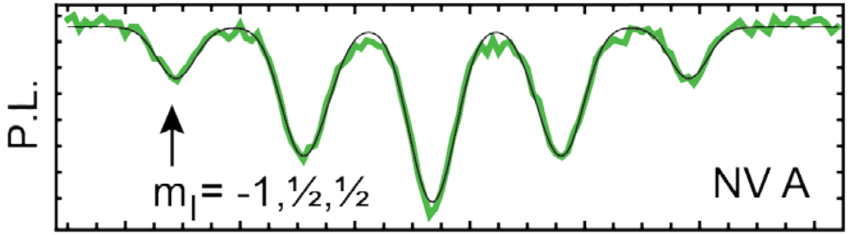


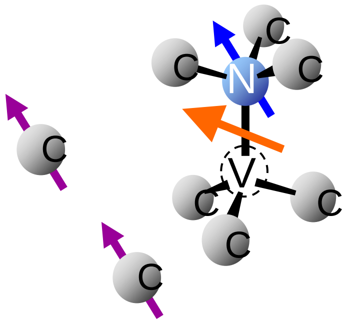


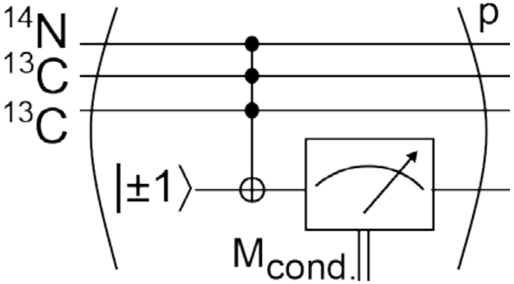
Single-shot readout of nuclear spin register

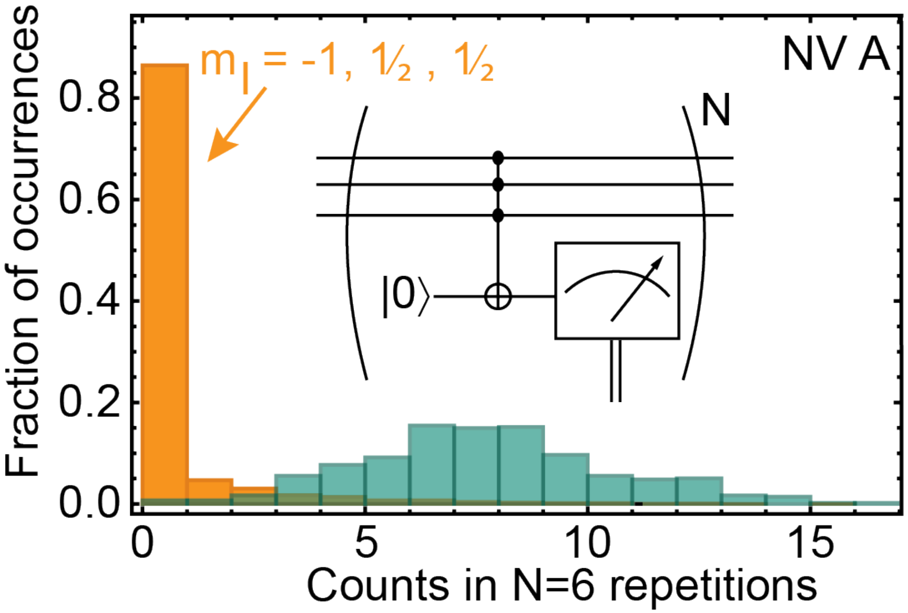
By systematically flipping nuclear spins followed by readout, whole quantum register can be measured!

ESR spectrum (part of it)





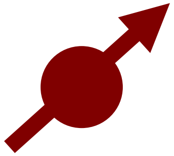




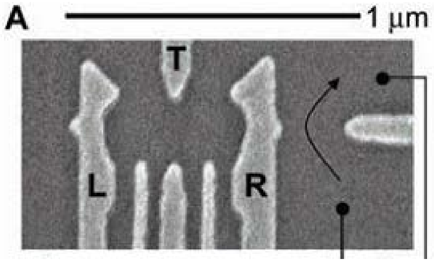
Robledo et al. Nature (2011)

See also Jiang et al. Science (2009), Neumann et al. Science (2010)

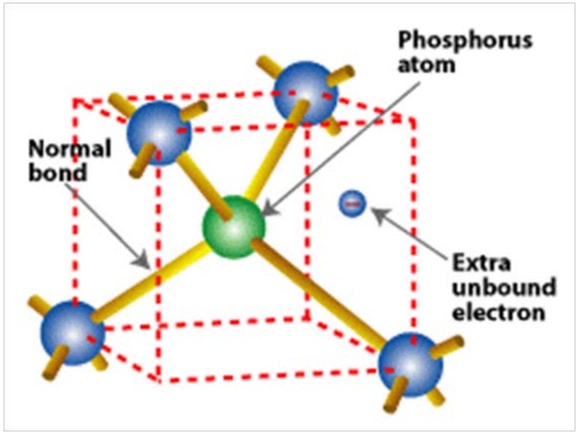
(Fighting) qubit decoherence



NV electron spin



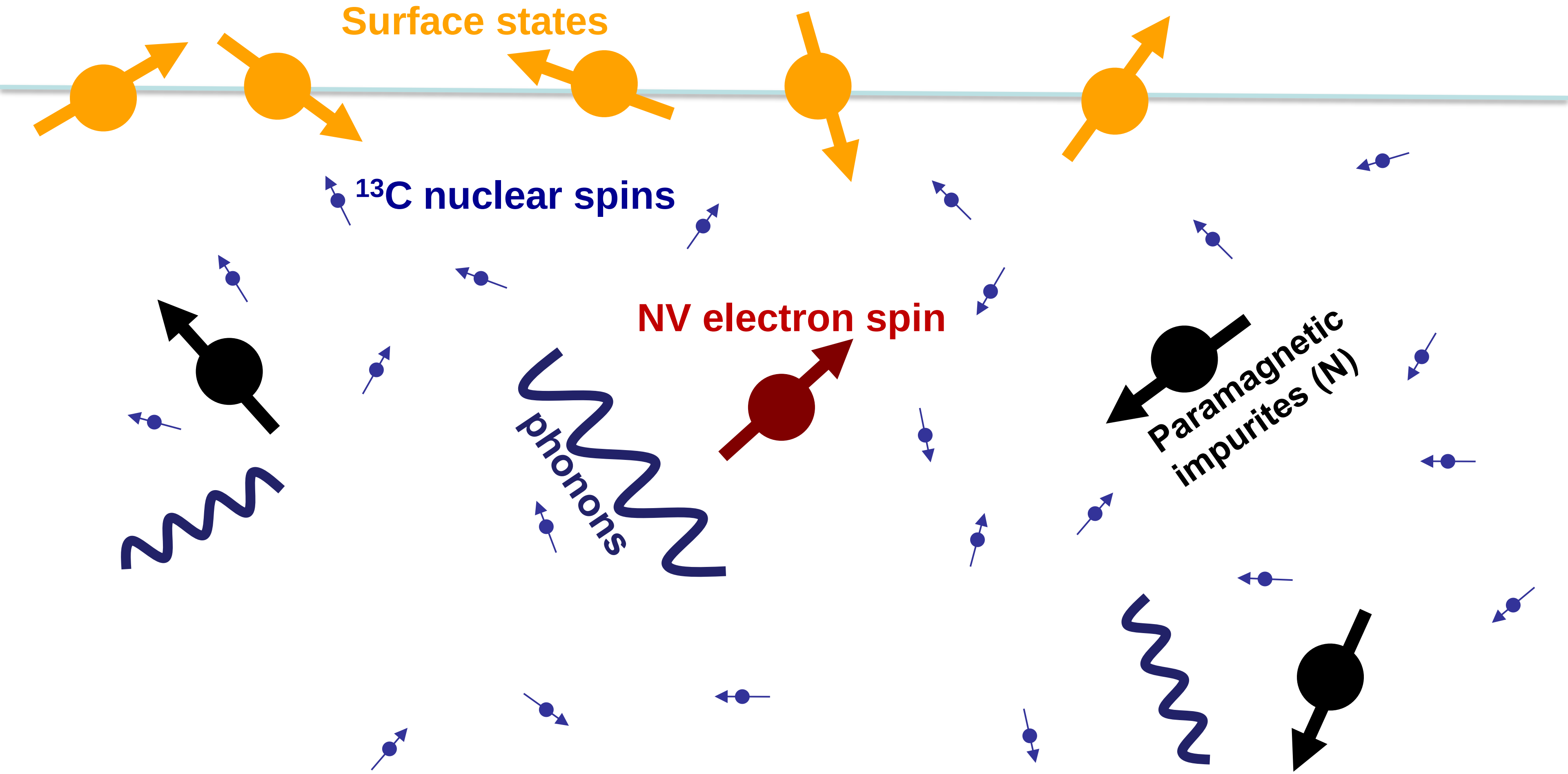
Quantum dots



Donors in silicon

Decoherence of the NV center

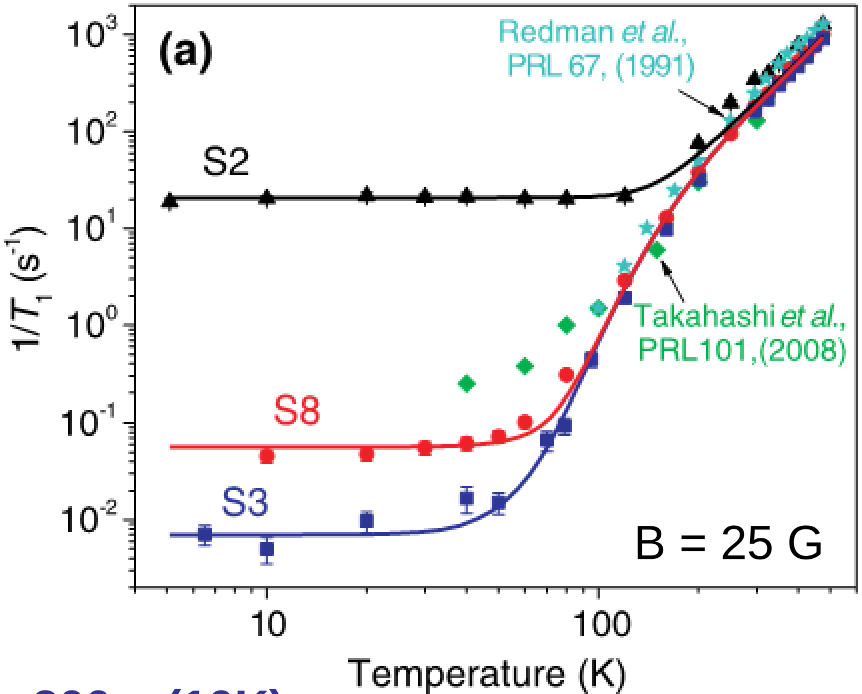
- Coherence properties are sample and temperature dependent
- Two different processes: Longitudinal spin flips (T_1) or dephasing (T_2^* and T_2)
- Dominant sources of decoherence for the NV:



Longitudinal relaxation

T_1 – longitudinal relaxation time
Ultimate limit to the coherence time ($T_2 \leq 2T_1$)
Measurement: Prepare a spin eigenstate, wait, read out

6 ms (300K)



200 s (10K)

Jarmola et al. PRL(2012)

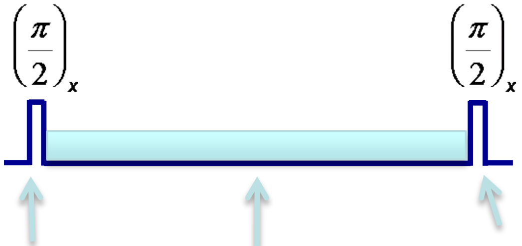
Mechanisms:

- Coupling to local and lattice phonons
- ➢ Highly temperature-dependent
- Cross-relaxation with other impurities
- ➢ Depends on sample and magnetic field

S2: HPHT, high [N], [NV]
S8: HPHT, high [N], low [NV]
S3: CVD, low [N], very low [NV]

Dephasing - T_2*

- **T_2^* - Qubit dephasing**
- Measurement (free induction decay):
  Prepare a spin superposition, wait, convert phase to population, read out
- ^{12}C has no spin → Dominant source of dephasing: ^{13}C nuclei (S=1/2)



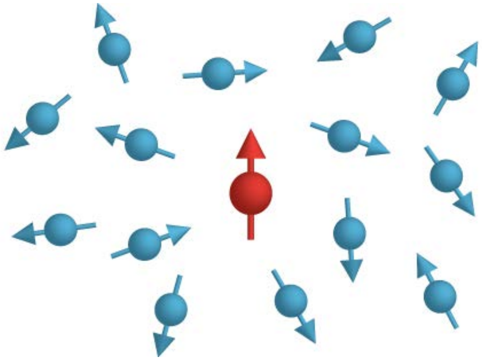
Create spin superposition

Phase accumulation

measure average phase accumulation
$\langle e^{-i\varphi} \rangle$

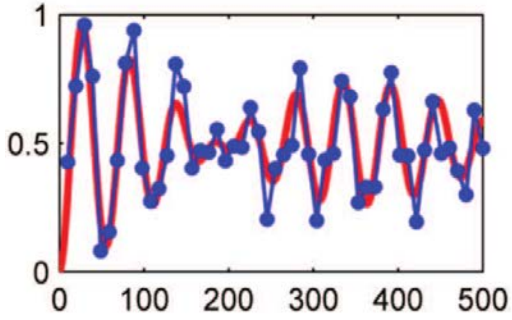
$$H = A(t)S_z$$

$$\varphi \propto \int_0^\tau A(t)dt$$



Natural ^{13}C concentration (1%): T_2^*≈μs
Purified samples: up to a millisecond!

Maurer et al. Science (2012)

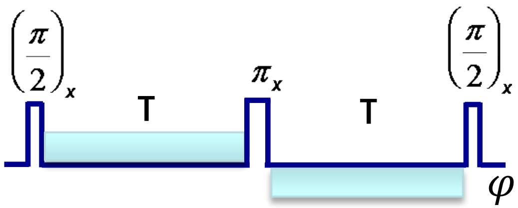


0.01% ^{13}C
$T_2^* = 0.5 \pm 0.1$ ms

Beating from different ^{13}C hyperfine transitions

Dephasing - T_2

T_2 – “coherence time”
Measurement: Hahn echo



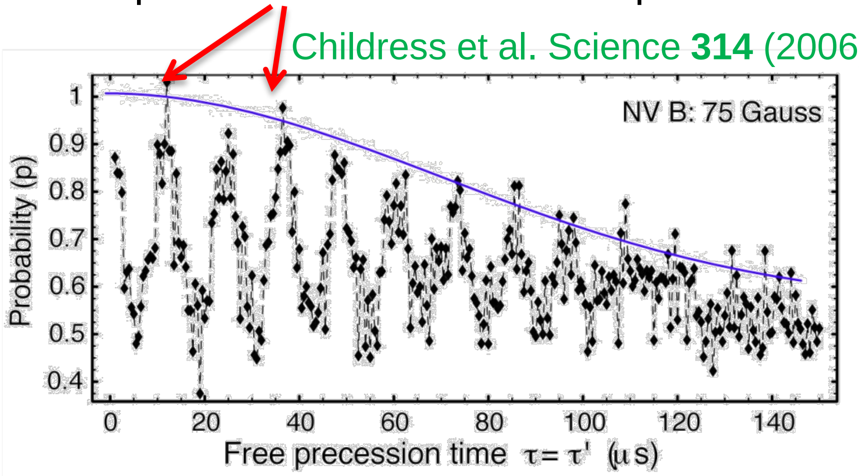
$$\varphi \propto \int_0^T A(t) S_z dt \approx \pm AT$$

- Environment has opposite effect during first and second period T
- Extends the coherence time when the environment is (quasi-) static… or periodic
- What if the environment changes?

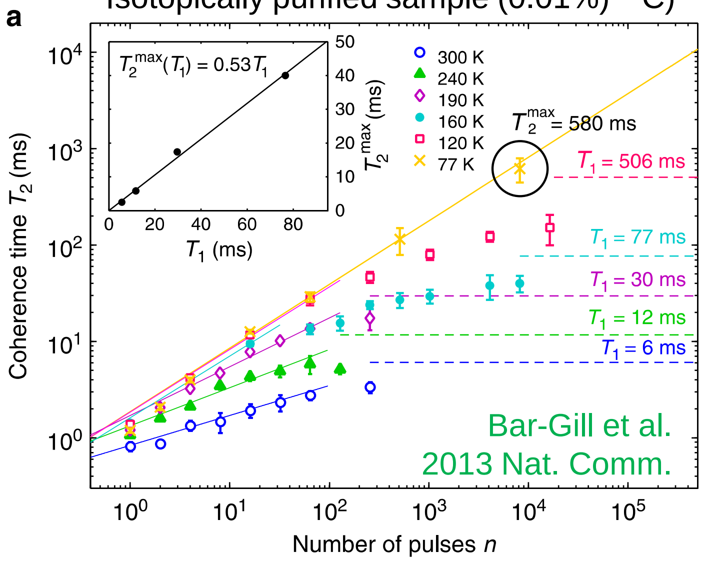
➢ Use dynamical decoupling sequence

Can reveal environment dynamics: Revivals due to precession of the carbon spin bath

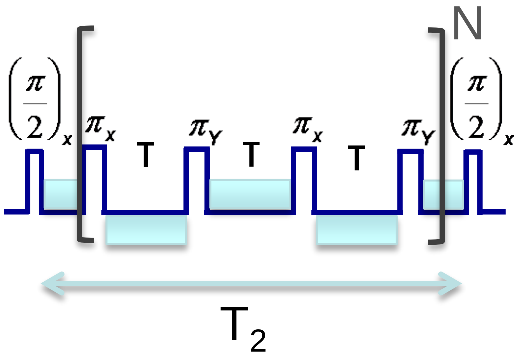
Childress et al. Science **314** (2006)



Isotopically purified sample (0.01%) ^{13}C)



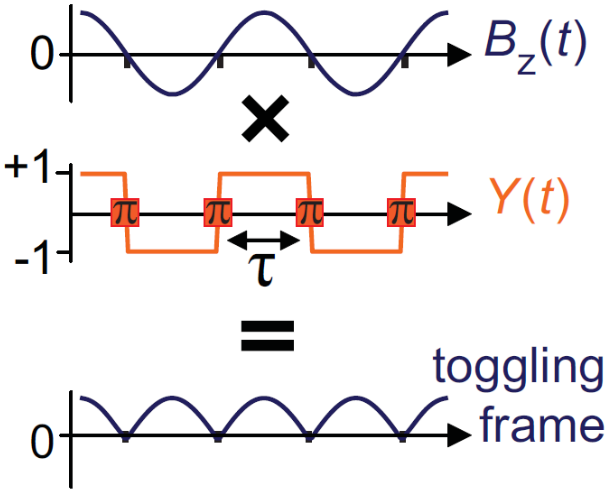
Bar-Gill et al.
2013 Nat. Comm.



Theory work by Viola, Lloyd, Das Sarma, Lidar, Dobrovitski, Sham, Liu, Hollenberg,…

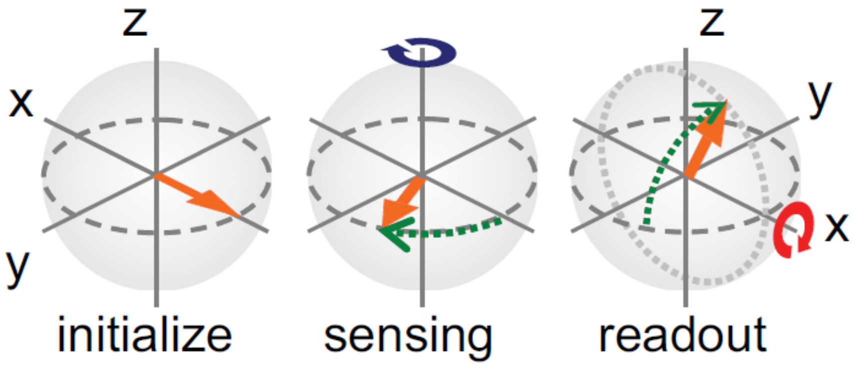
Failure of dynamical decoupling

Decoupling fails for frequency that matches interpulse delay

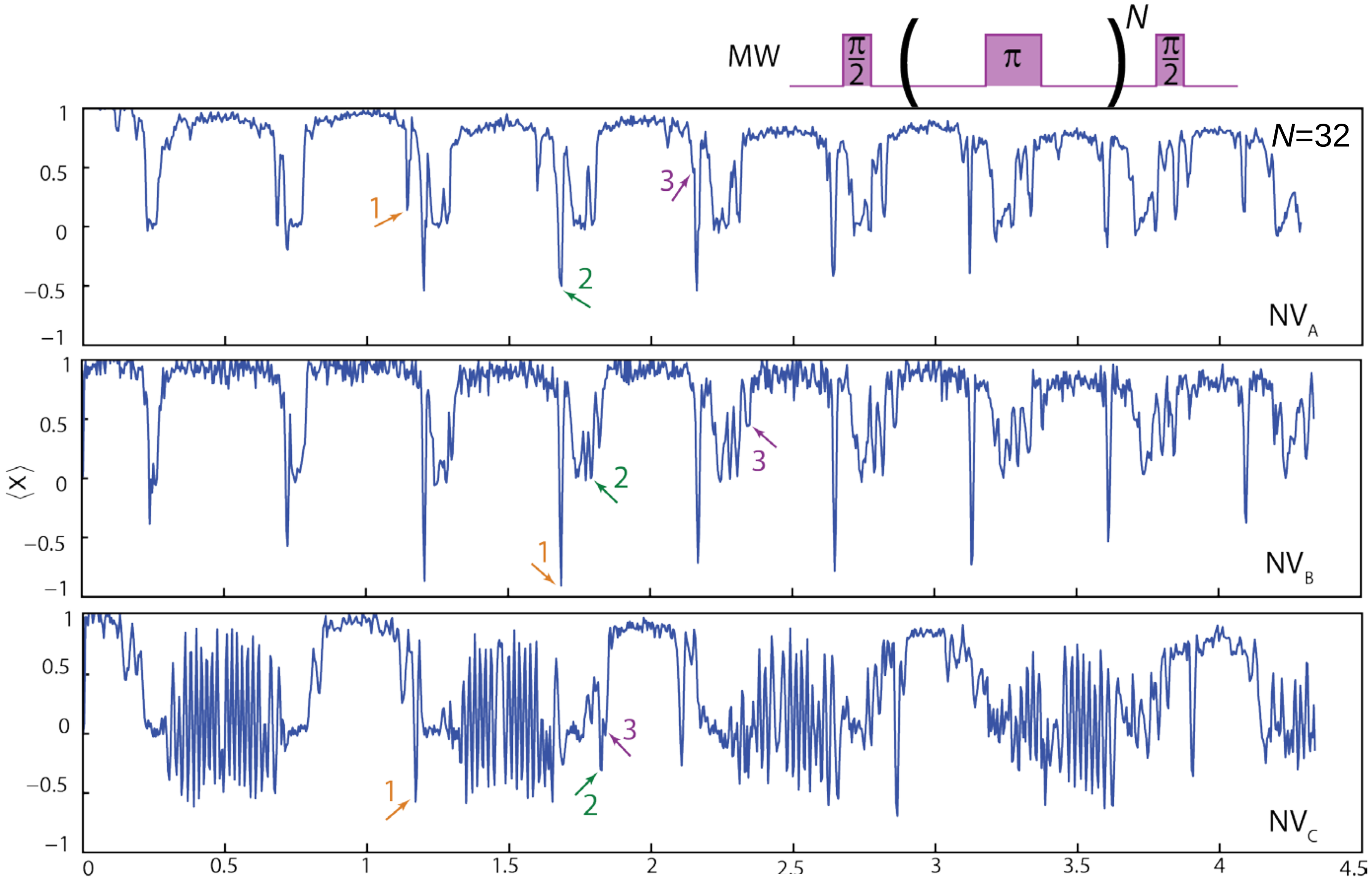


Use for ultrasensitive magnetometry!

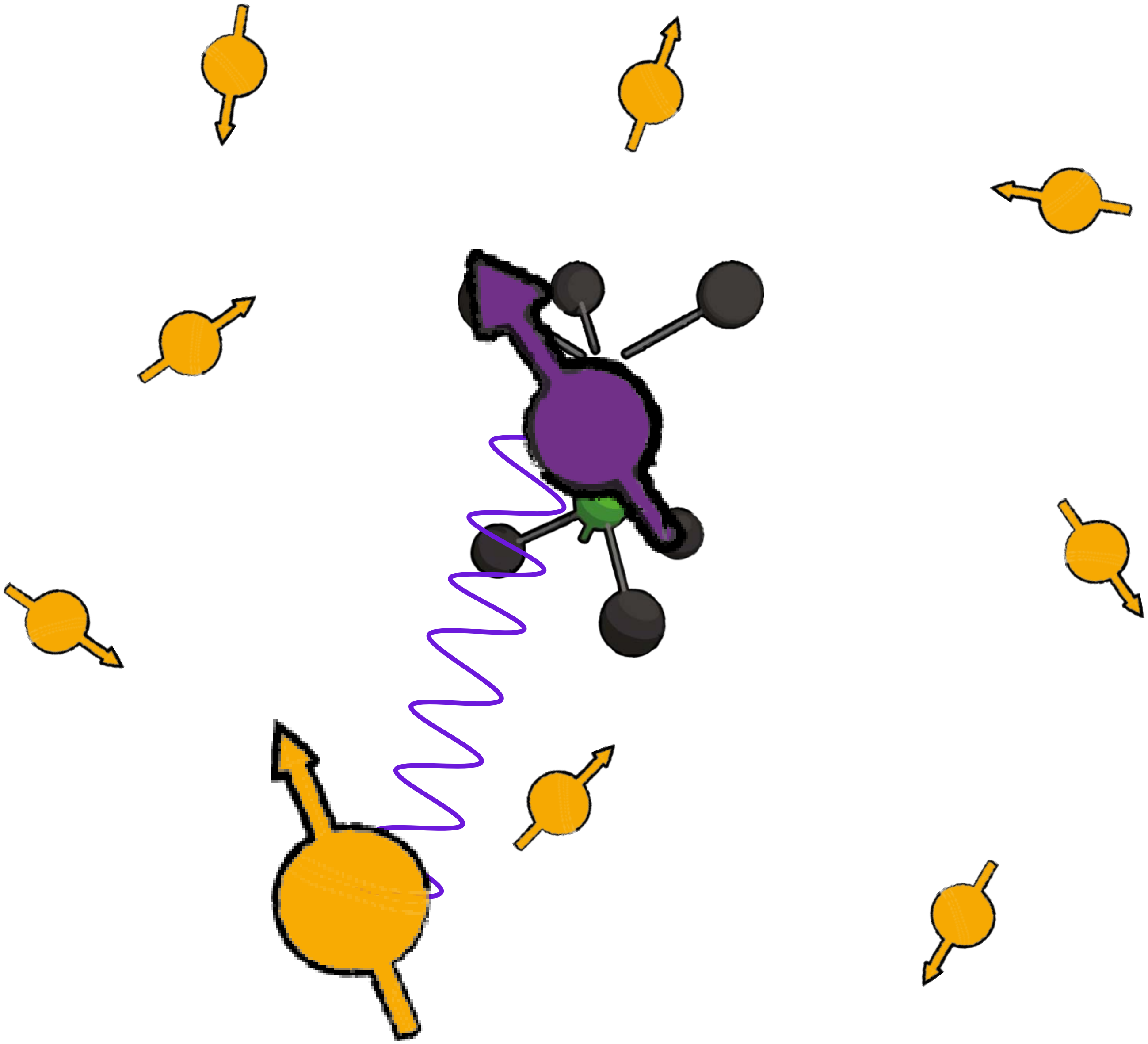
Degen, APL 2008
Taylor et al., Nature Physics 2008



Sensing of the carbon environment



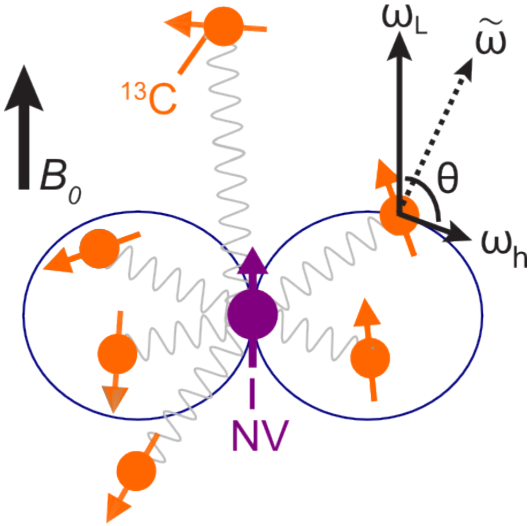
Taminiau et al. Nature Nanotechnology 9 (2014); related work by Jelezko/Wrachtrup and Lukin



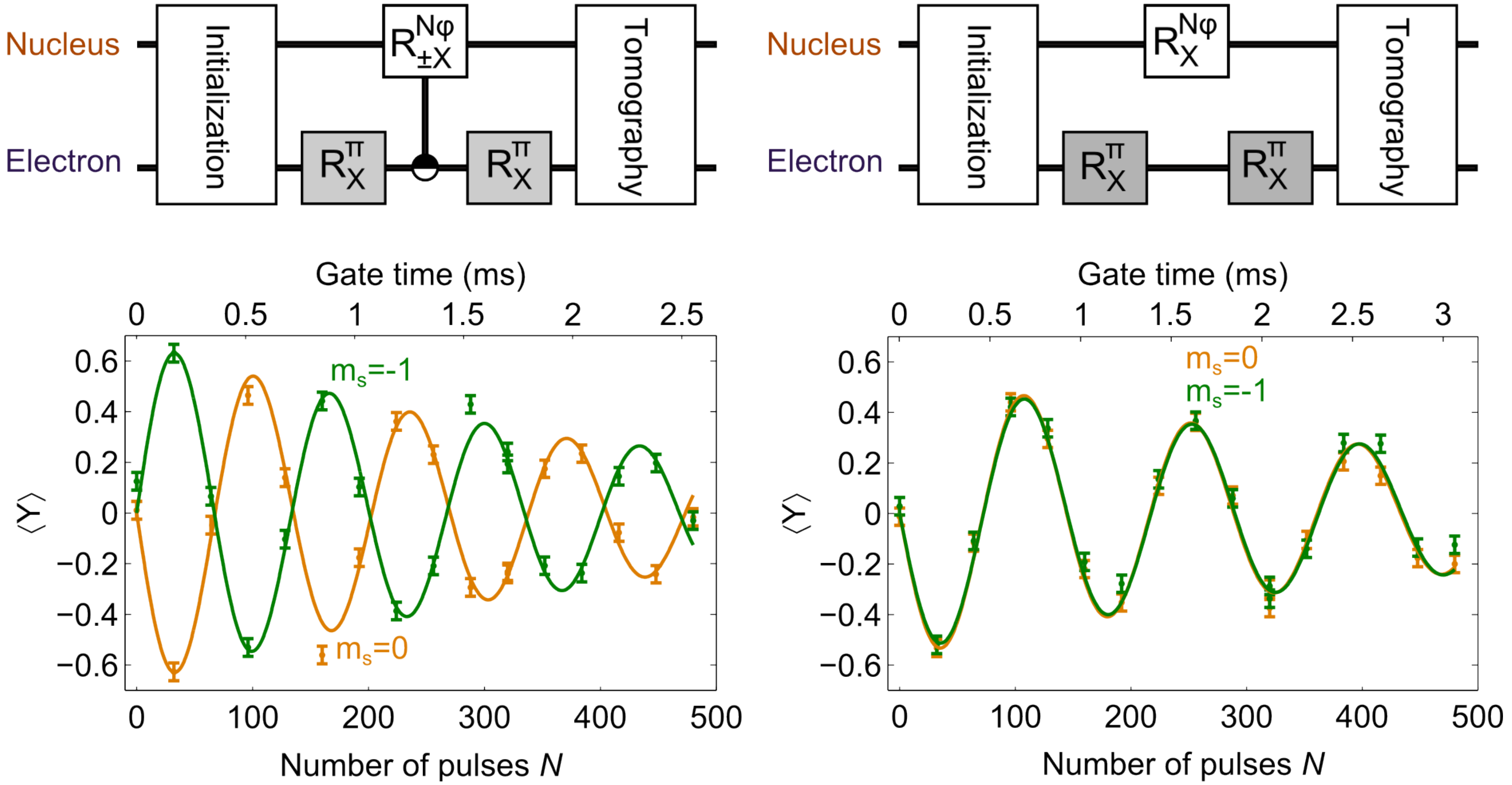
Controlling weakly coupled bath spins

Key concepts:

- nuclear spin evolution depends (slightly) on electron spin state: conditional evolution
- dynamical decoupling leads to selective coupling of the electron to one nuclear spin while switching undesired couplings off



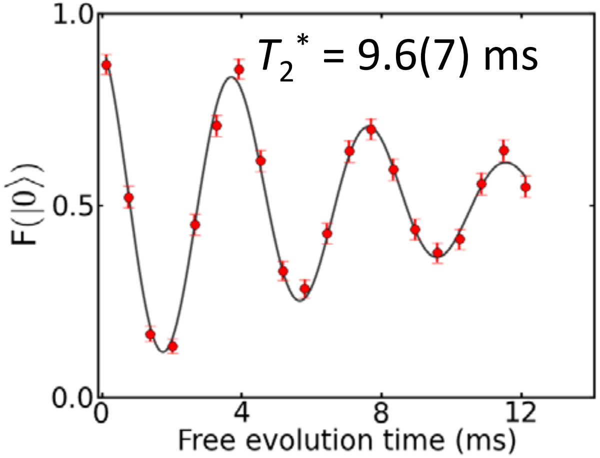
Coherent control of a weakly coupled nuclear spin



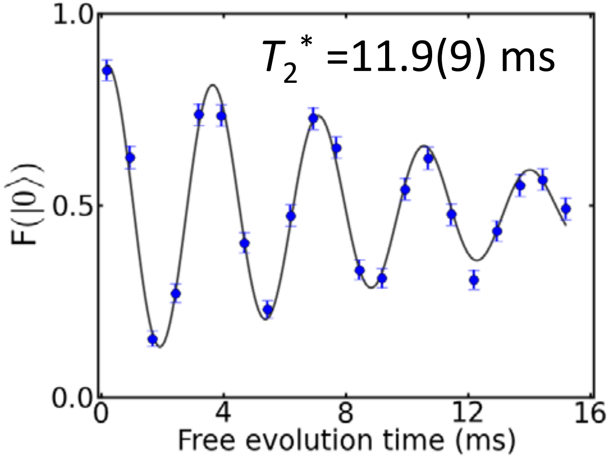
- Coherent control of weakly coupled nuclear spin by only driving electron
- Conditional vs unconditional operation set by interpulse delay

Taminiau et al. Nature Nanotechnology 9 (2014)

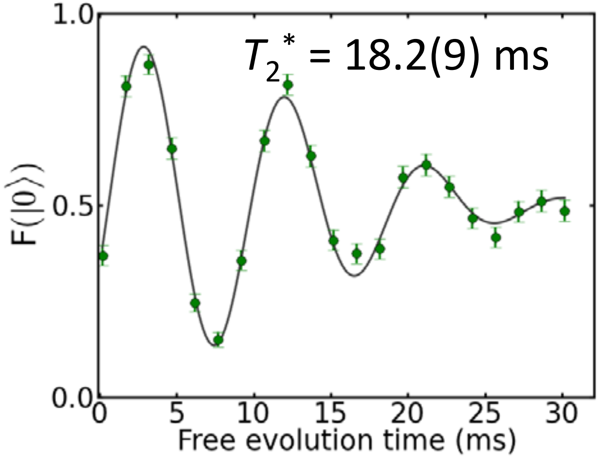
Nuclear spin coherence



Nuclear spin 1



Nuclear spin 2



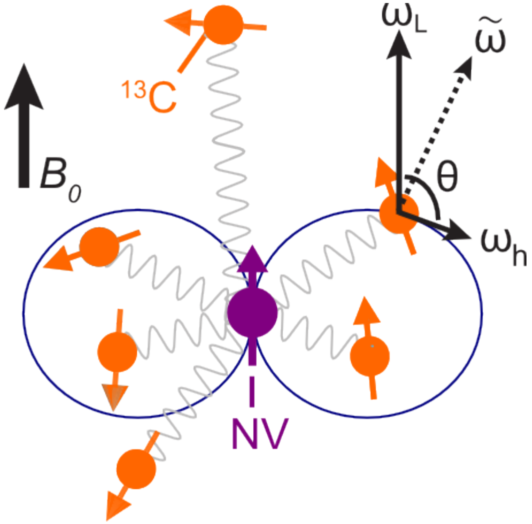
Nuclear spin 5

- Free induction decay of individual nuclear spins shows different decay time
- Qubit coherence can be extended by spin echo / dynamical decoupling
- Coherence times exceeding one second have been measured at room T

Maurer et al. Science (2012)

Strong VS weak coupling

- Several carbons are available in every NV
- Remote carbons can have better decoherence properties
- No RF pulses required, only MW
- Reduced coupling → increased gate time



Summary and outlook

Summary and outlook

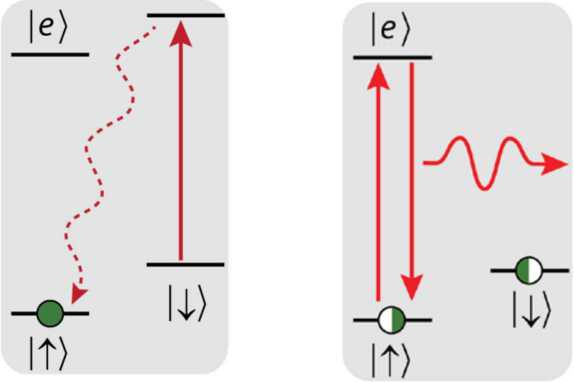
Part one:

How can one generate entangled states that span global distances and involve many particles?

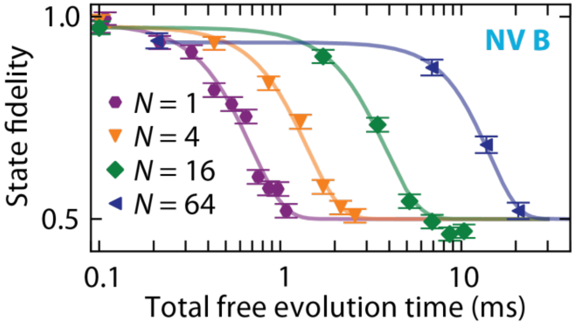
→ Heralded schemes enable deterministic interactions via probabilistic channels

Part 2: The NV toolbox

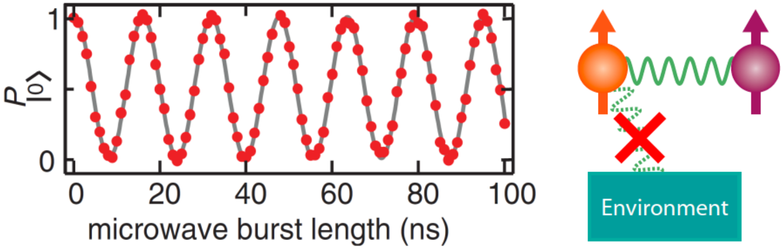
Spin initialization and readout



Long coherence times



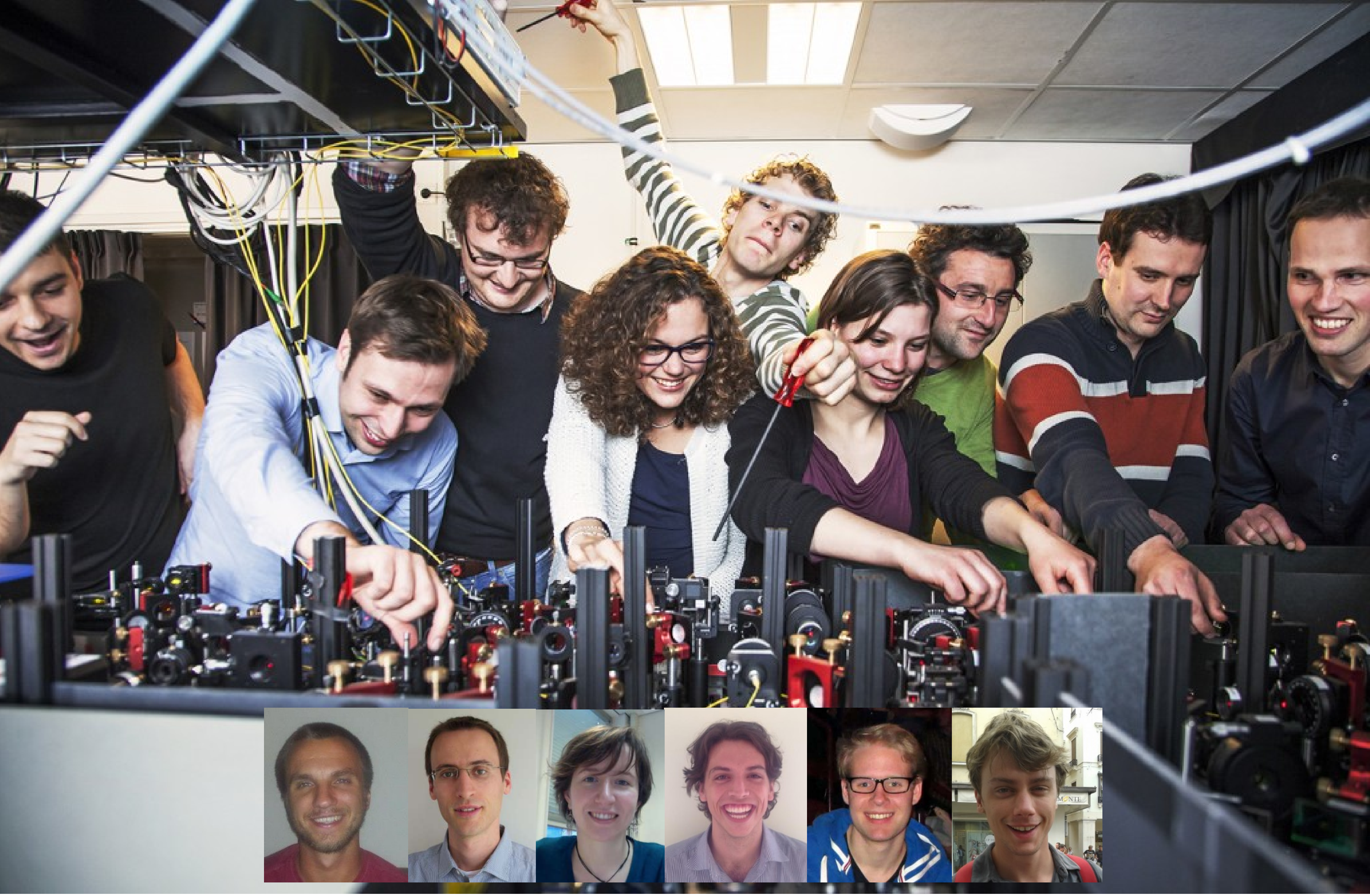
High-fidelity spin control



Remote entanglement

Tonight

Many related works by Stuttgart, Harvard, Chicago, Ulm,…



http://hansonlab.tudelft.nl

Discussion

- What are the main difficulties that have to be overcome in order to build a large-scale quantum network?

- How can probabilistic quantum channels mediate a deterministic interaction? What are the prerequisites for this?

- (Why / when) do you need heralding?

- How can nuclear spins in diamond be controlled? Is this control universal?

- What limits the NV center’s coherence? What are typical timescales? What can be done to extend qubit coherence?

- Does the NV center fulfill all of DiVincenzo’s criteria? How?

(Qubits, inititialization, universal set of gates, measurement, long coherence time)