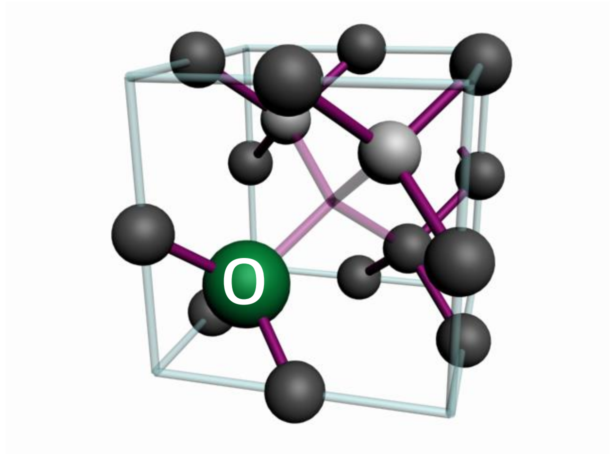
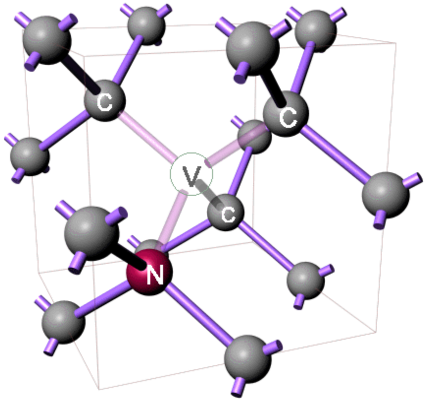
Colour centers in diamond

Slides provided by:
Joerg Wrachtrup
Ronald Hanson
Lilly Childress

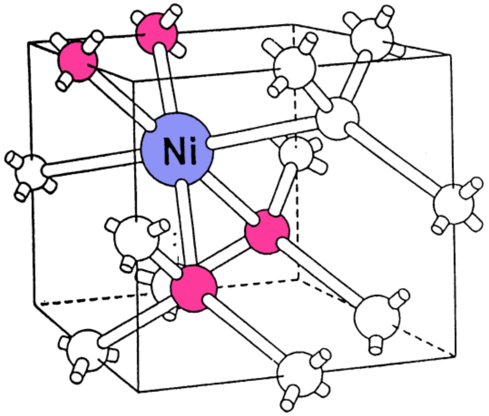
The dopants



TR12



NV

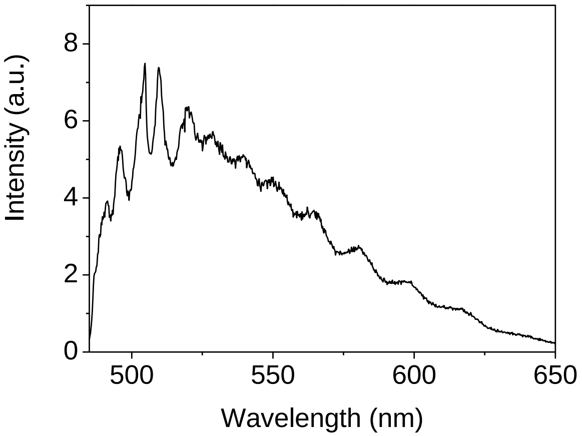


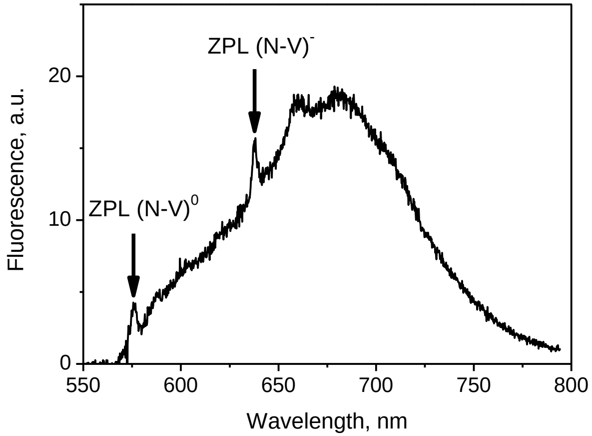
NE8b

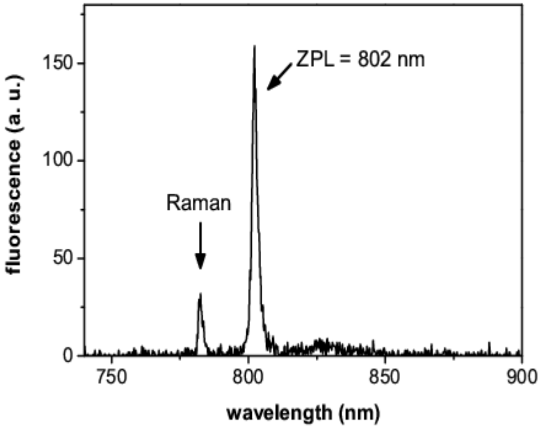
PRB 72, 035214 2005

Science 276, 2012-2014 (1997)

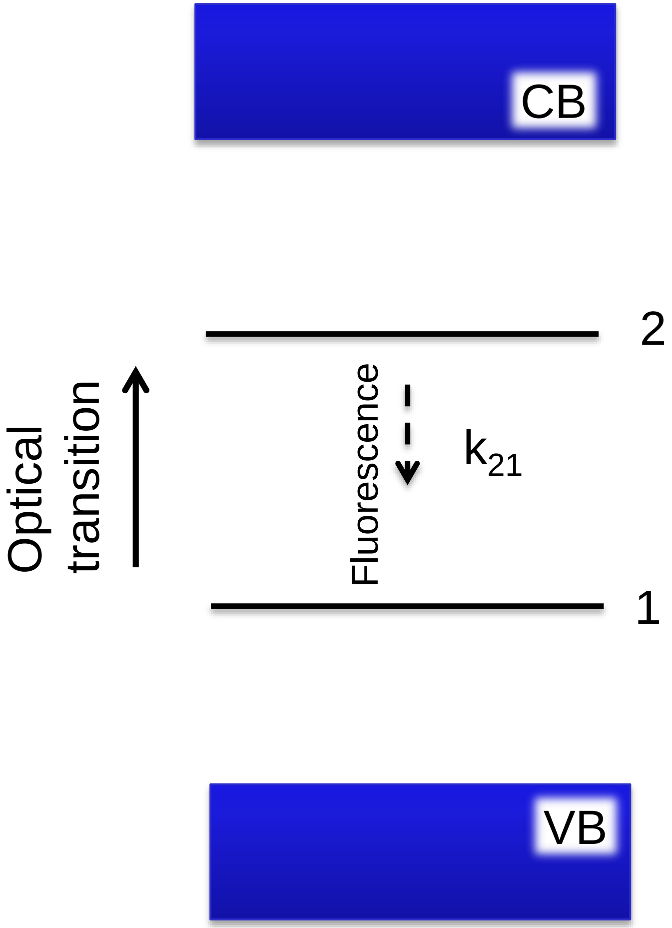
Phys. Rev. Lett. **94**, 180602 (2005)







Level scheme of color centers



CB

2

Optical transition

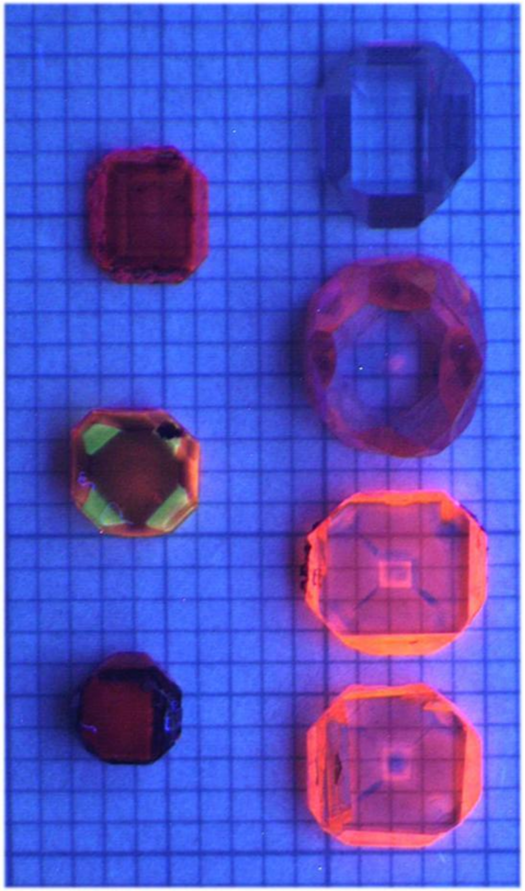
Fluorescence

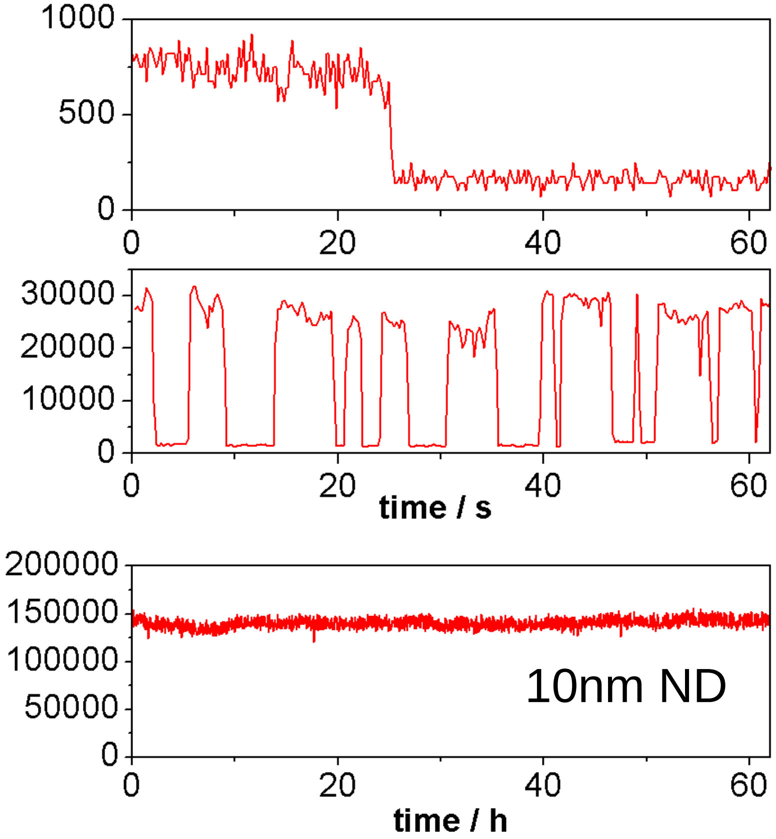
k_{21}

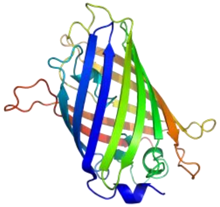
1

VB

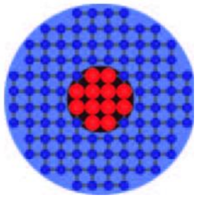
Shielding by the diamond lattice provides perfect photostability





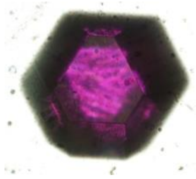


⇒Oxidation



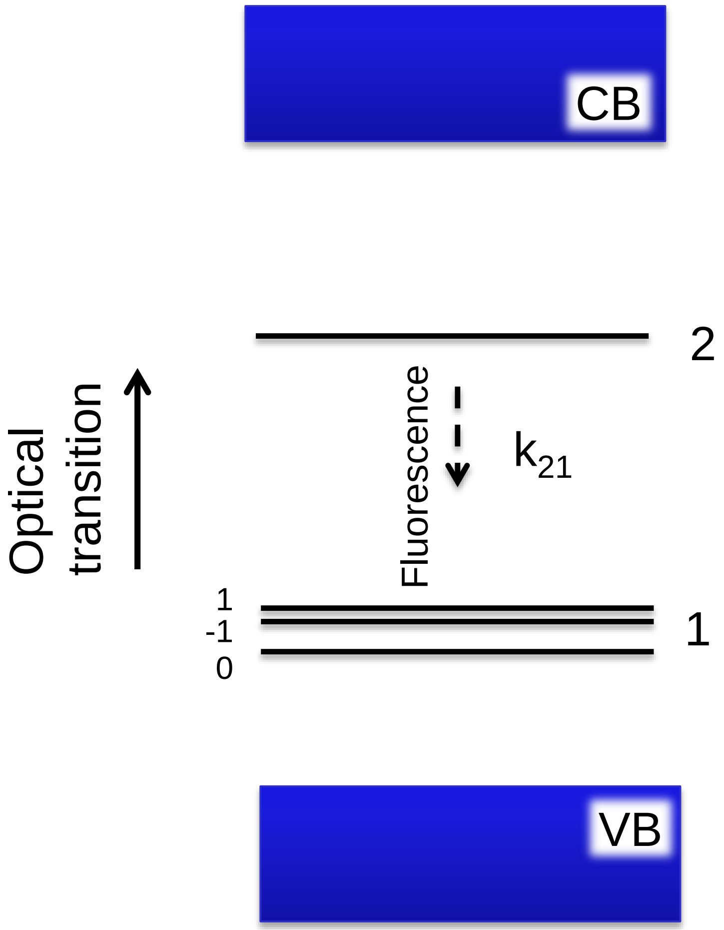
⇒ionization

QD



⇒ perfect stability

Level structure of color centers



Even electron spin states are resolvable

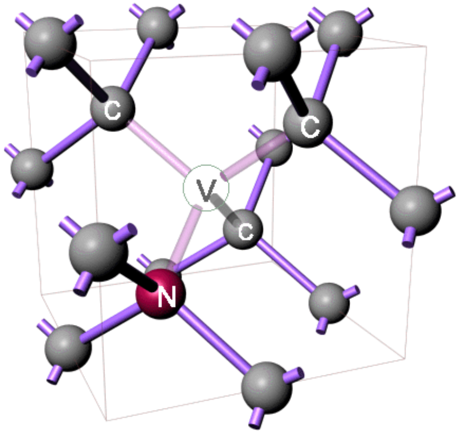
Defect behaves as a single atom, trapped in the diamond lattice

Level structure similar to trapped ions or atoms

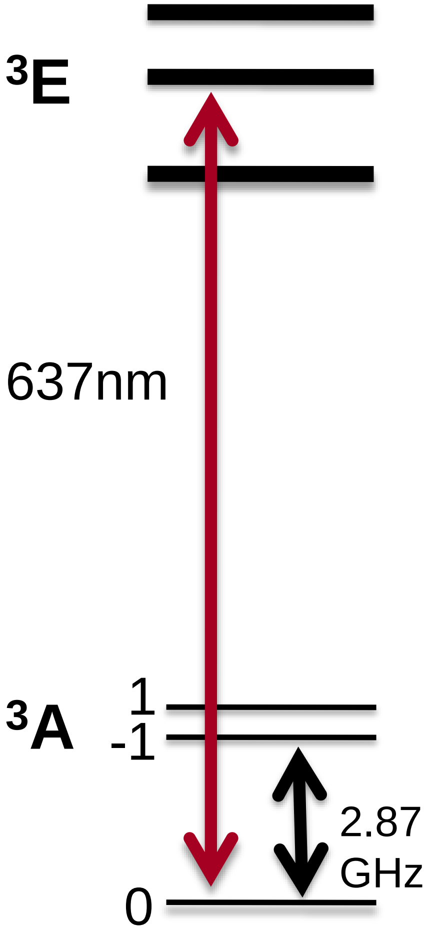
⇒ Diamond provides a solid state ion trap

⇒ Experimental power similar to trapped particles, but much easier to transform into applications

The NV center



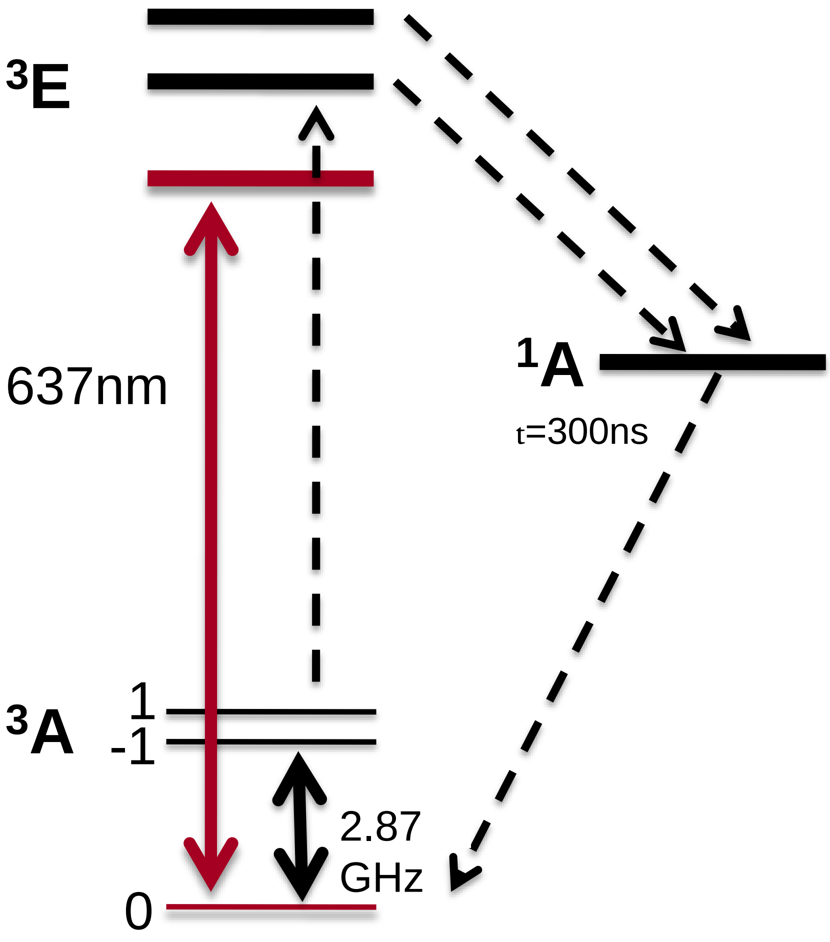
- Joint defect consisting of
  - Vacancy
  - Neighbouring substitutional N
- Negatively charged (NV^-)
- Six electron (= two hole) system



The NV center

Amazing features:

- Optical detection of the spin state
- Optical spin polarisation of the ground state (« Laser cooling »)
- Narrow lines, T_2 = 1ms, Linewidth of ground state levels: 1 kHz.



The NV center

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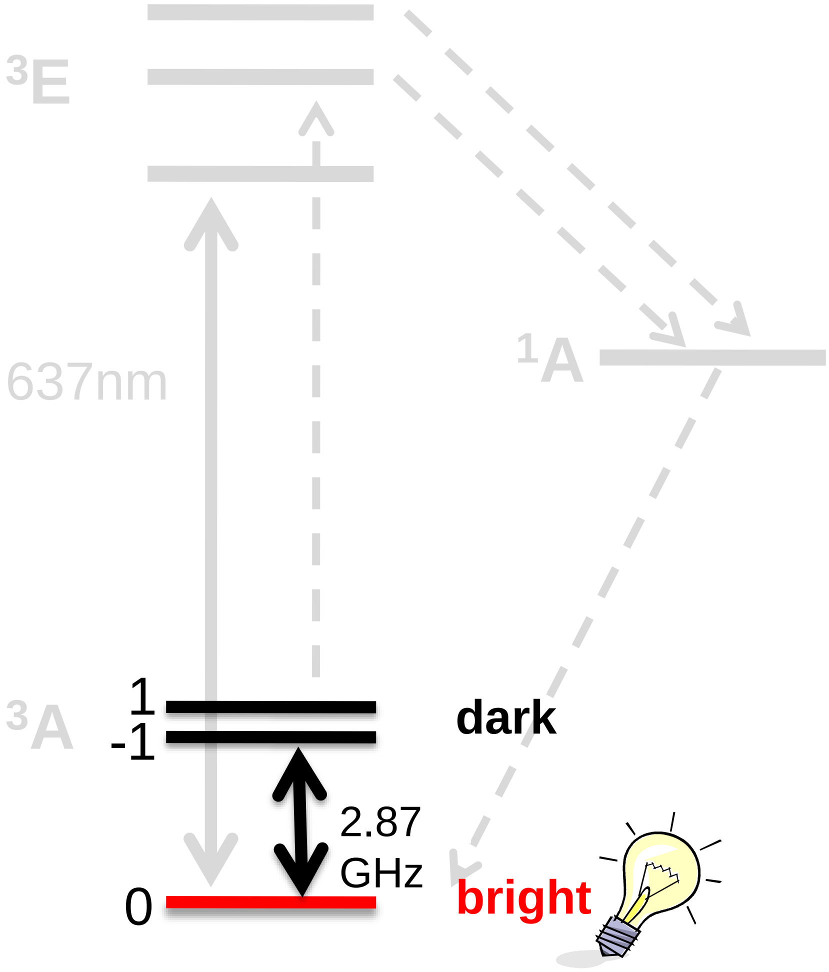


www.pi3.uni-stuttgart.de

Experimental setup for optical spin readout

Confocal microscope
with microwave access

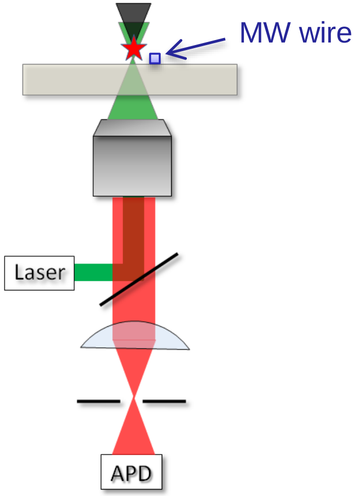
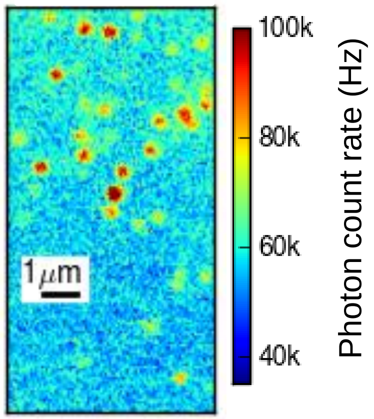
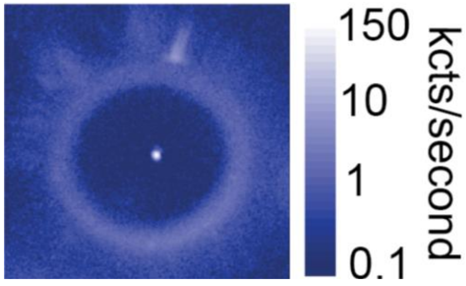


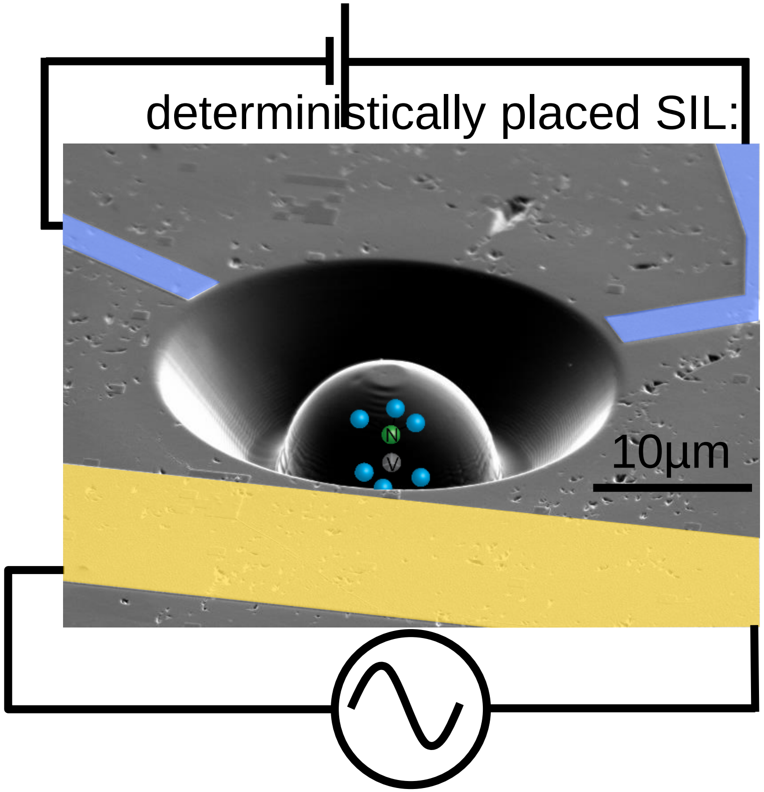
Image of implanted diamond



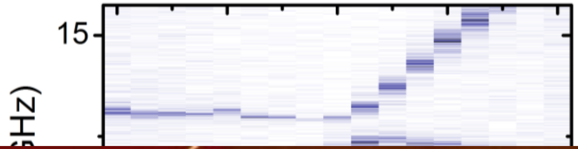
Wiring up NV centers

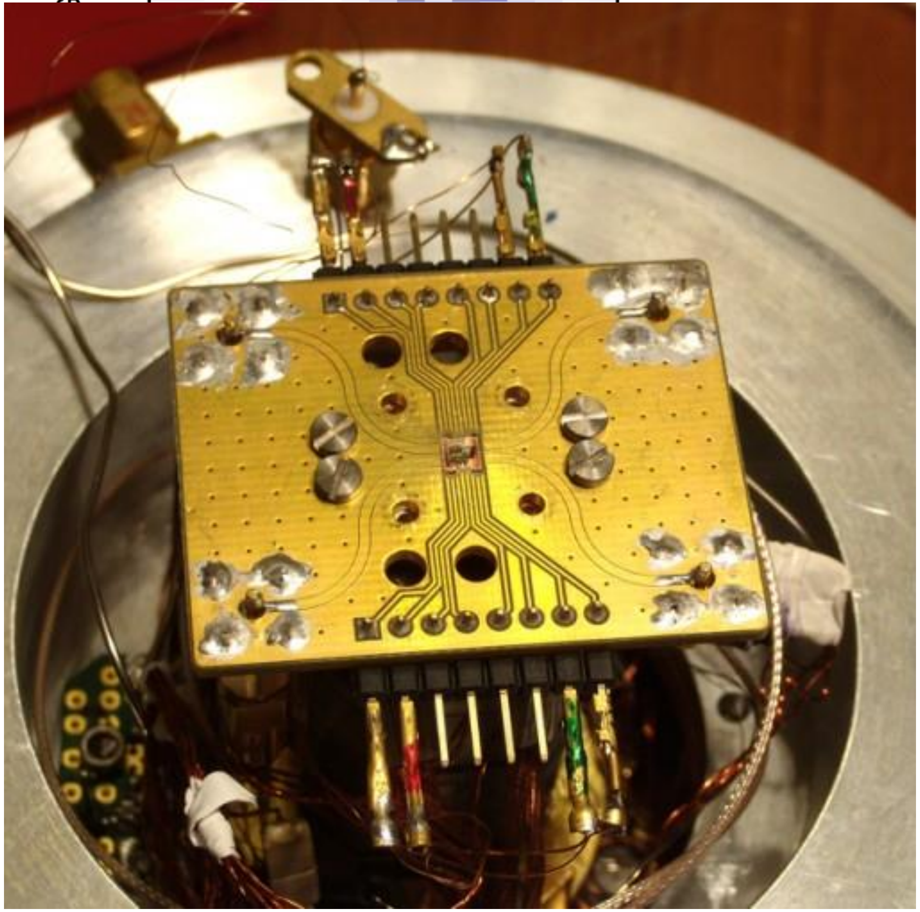


deterministically placed SIL:



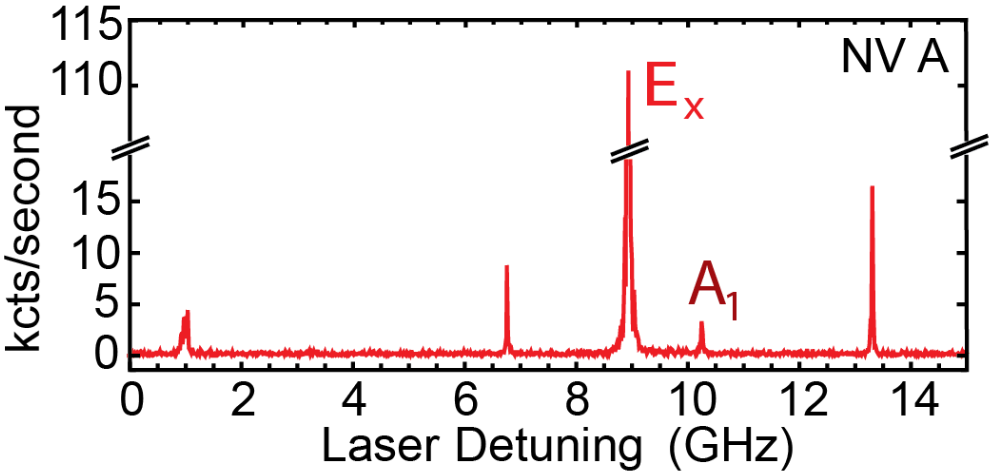
dc Stark tuning:

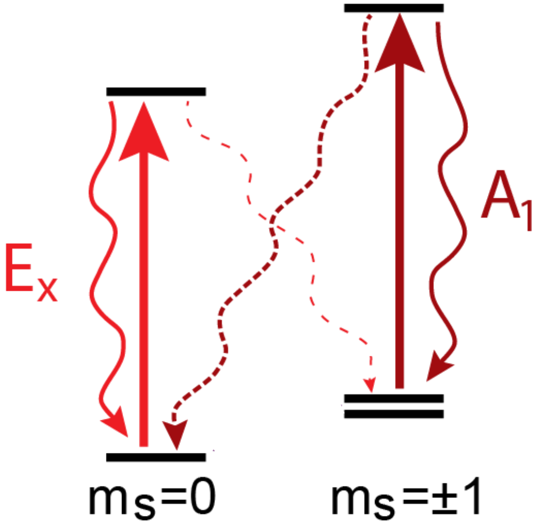




CVD diamonds grown by Element6

Spin-resolved optical excitation (T < 10K)



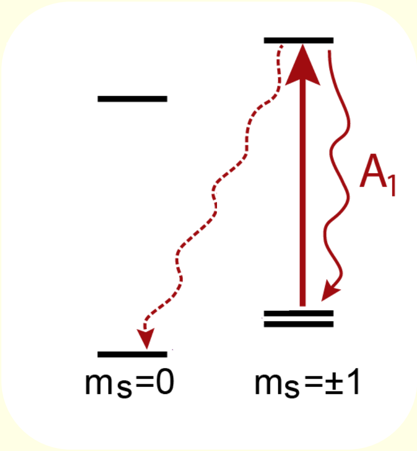


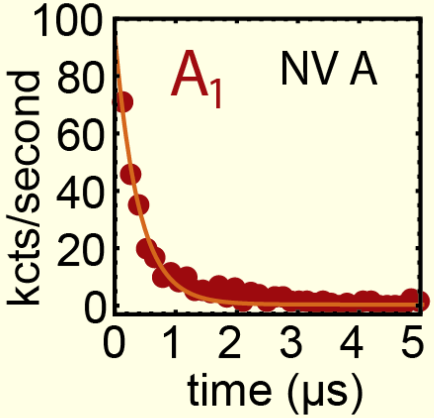
Early work by Stuttgart, Harvard, HP Labs

Initialization and readout by resonant excitation

Nature 477, 574 (2011)

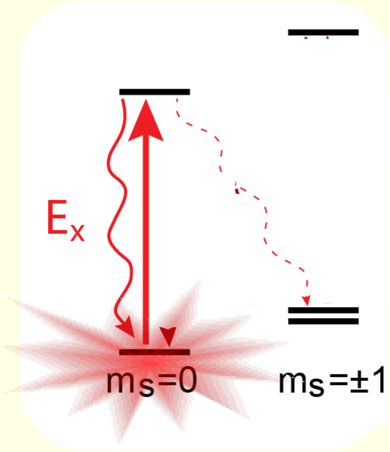
Initialization



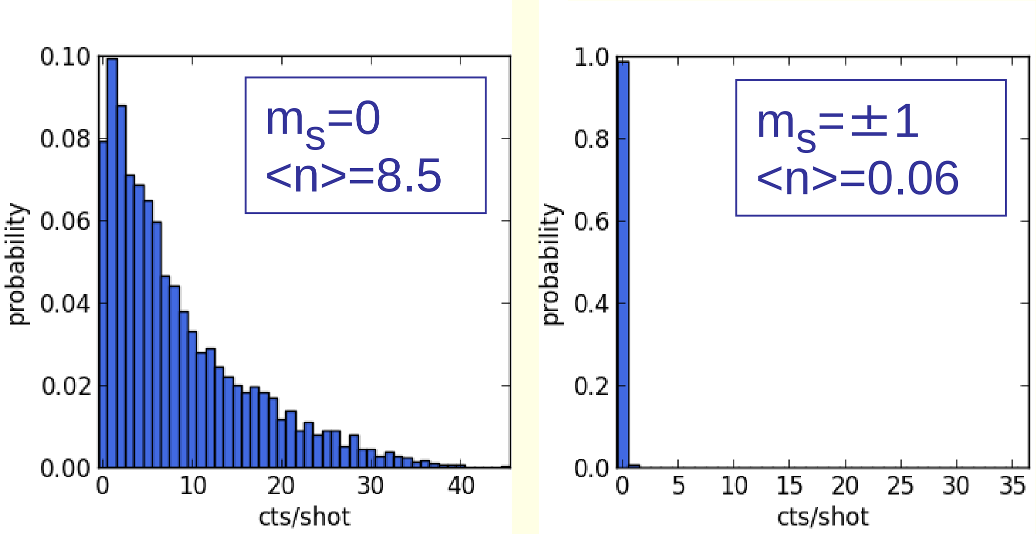


fidelity > 99.7%

Single-Shot Readout

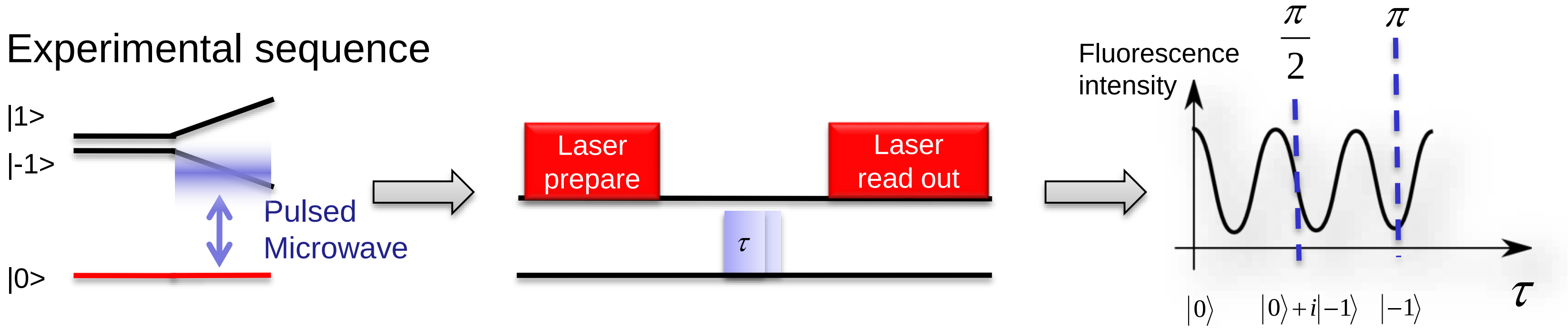


our best fidelity ≈ 98%



Manipulating a single spin

Experimental sequence



- Pulsed sequence consisting of
  laser cooling, spin manipulation and detection

- Signal is <1photon/repetition => many repetitions

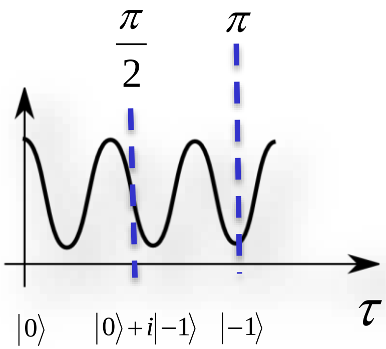
⇒Similar to ion trap, but experimentally easier

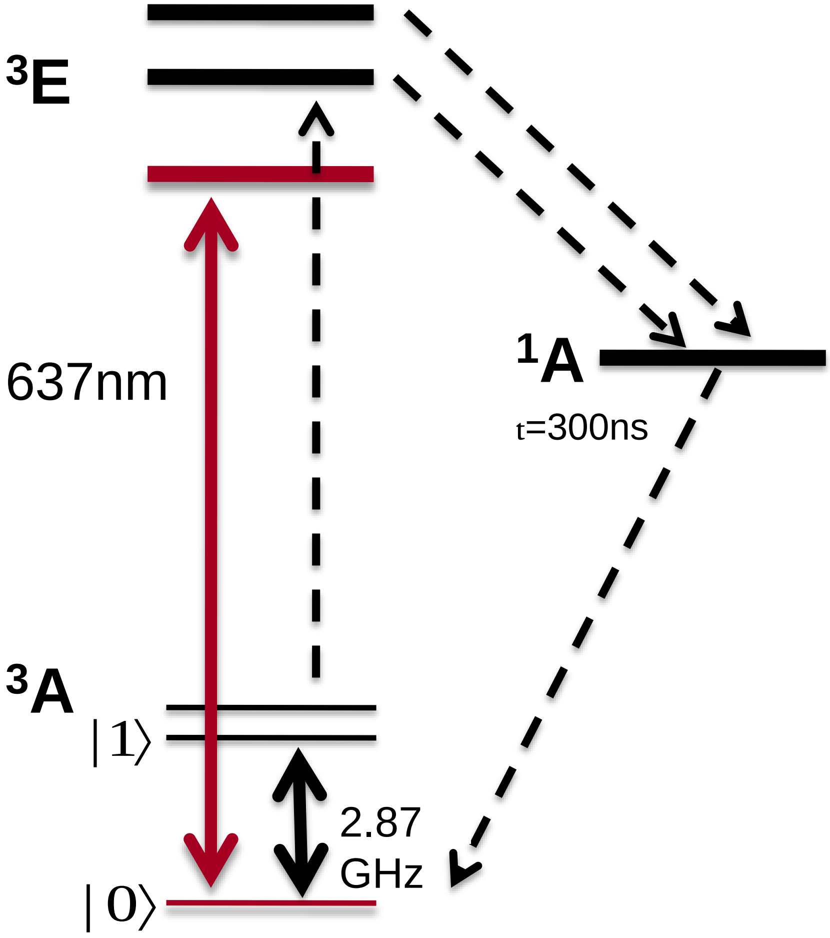
The NV center

Amazing features:

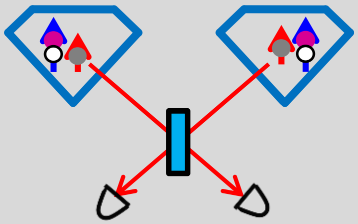
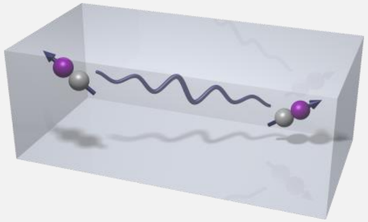
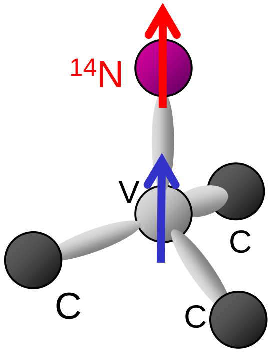
- Optical detection of the spin state
- Optical spin polarisation of the ground state (« Laser cooling »)
- Narrow lines, T_2 = 1ms, Linewidth of ground state levels: 1 kHz.

Single Qubit gates: Microwave pulses



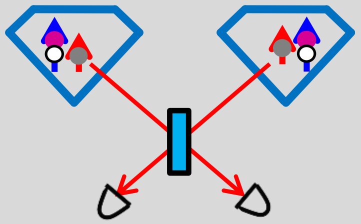


Coupling NV centers

Photons	Magnetic Dipolar coupling	Use nuclear spin qubits
 Cirac, Zoller Lukin `06 ➢Proper levels and transitions Manson, Hemmer, Santori ➢Transfer limited photons: Batalov et al. PRL 08 ➢But: bad coupling efficiency	 ➢Magnetic dipoles $d_{coherent} \propto \sqrt[3]{T_2}$	 ➢Couple NV to surrounding nuclei ➢Couple nuclei via NV ➢Read out single nuclei

Coupling NV centers

Photons



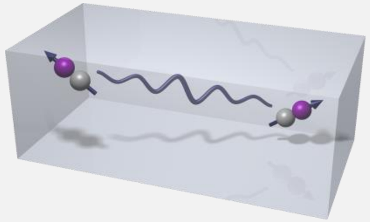
Cirac, Zoller
Lukin `06

- Proper levels and transitions
Manson, Hemmer, Santori

- Transfer limited photons:
Batalov et al. PRL 08

- But: bad coupling efficiency

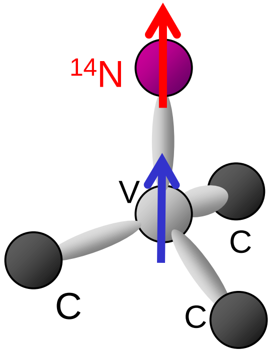
Magnetic Dipolar coupling



- Magnetic dipoles

$$d_{coherent} \propto \sqrt[3]{T_2}$$

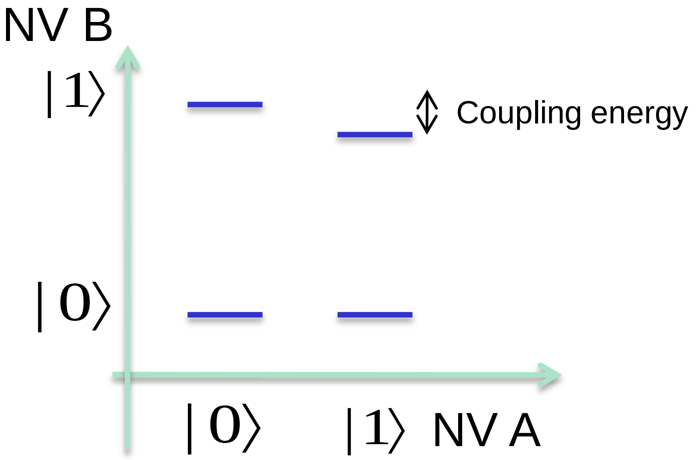
Use nuclear spin qubits



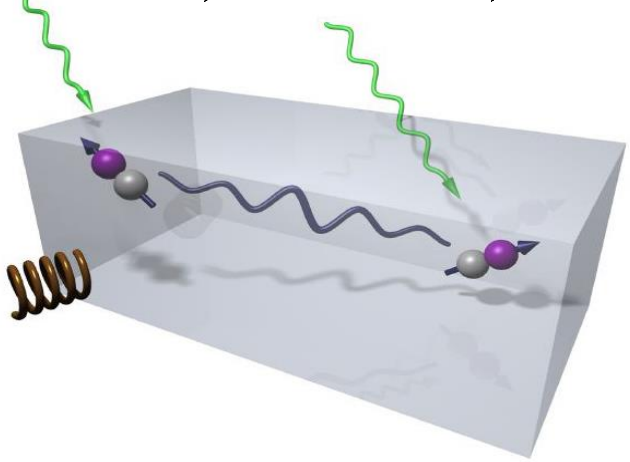
- Couple NV to surrounding nuclei
- Couple nuclei via NV
- Read out single nuclei

Coupling by dipolar interaction

ground state energy levels:



$$H = g\beta \mathbf{B}\mathbf{S}_{A,B} + (\mathbf{S}\bar{D}\mathbf{S})_{A,B}$$



Idea:

⇒NV B feels the magnetic dipole of NV A

⇒Depending on the state NV A, NV B has another resonance frequency

Nuclear spin Hamiltonian

Coupled spins

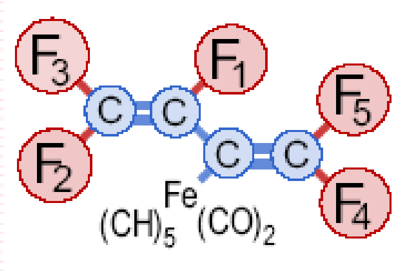
J>0: antiferro mag.

J<0: ferro-mag.

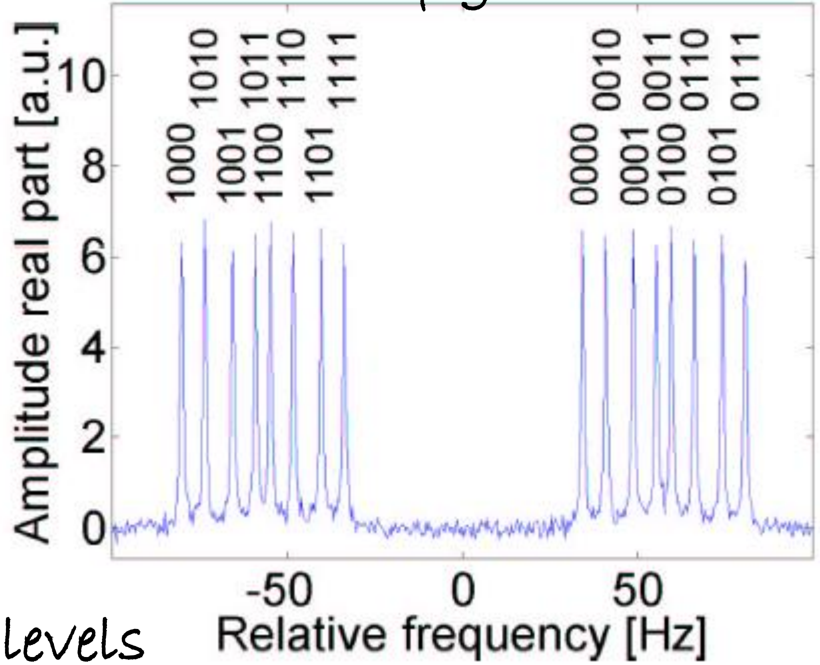
coupling term

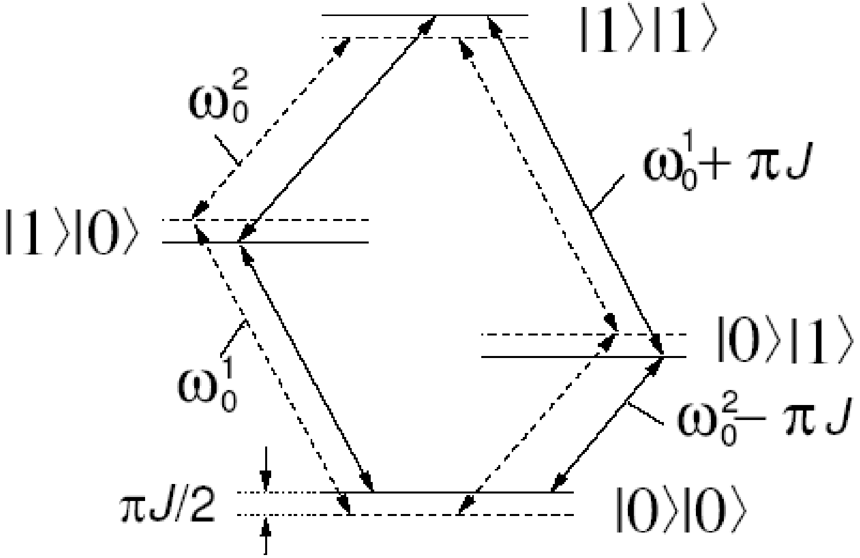
$$\mathcal{H}_J = \hbar \sum_{i<j}^{n} 2\pi J_{ij} I_z^i I_z^j$$

Typical values: *J* up to few 100 Hz



16 configurations

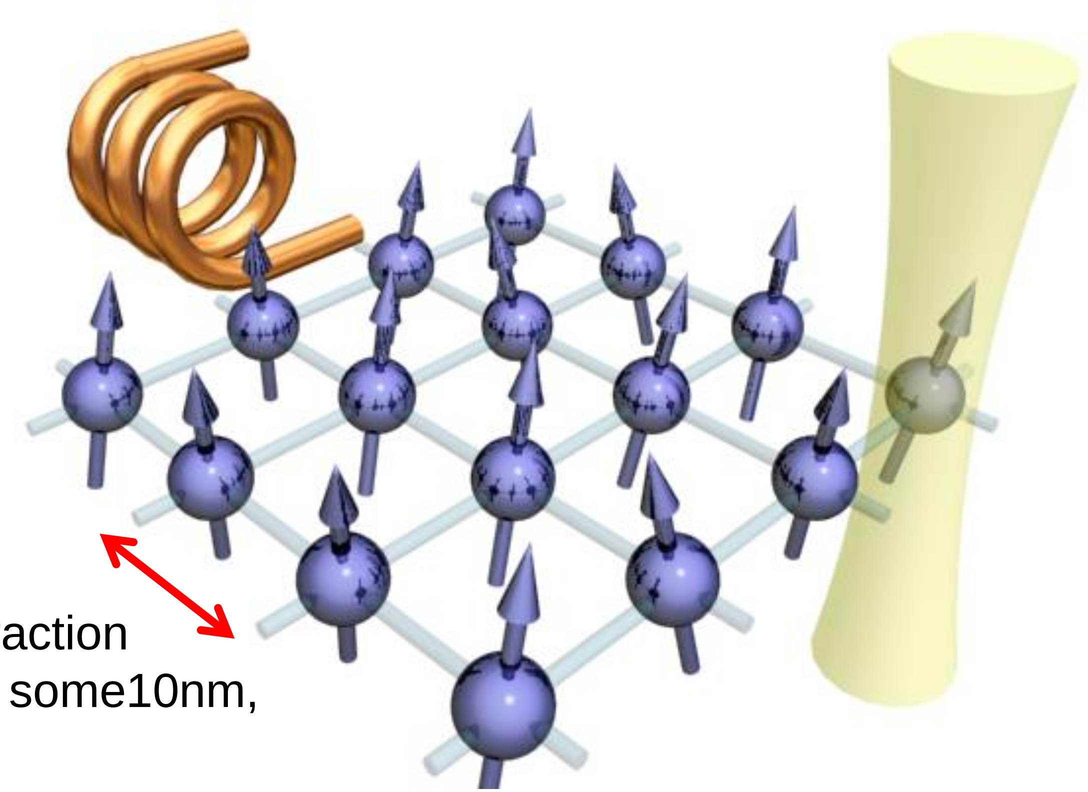




solid (dashed) lines are (un)coupled levels

Magnetic dipole coupled spin arrays

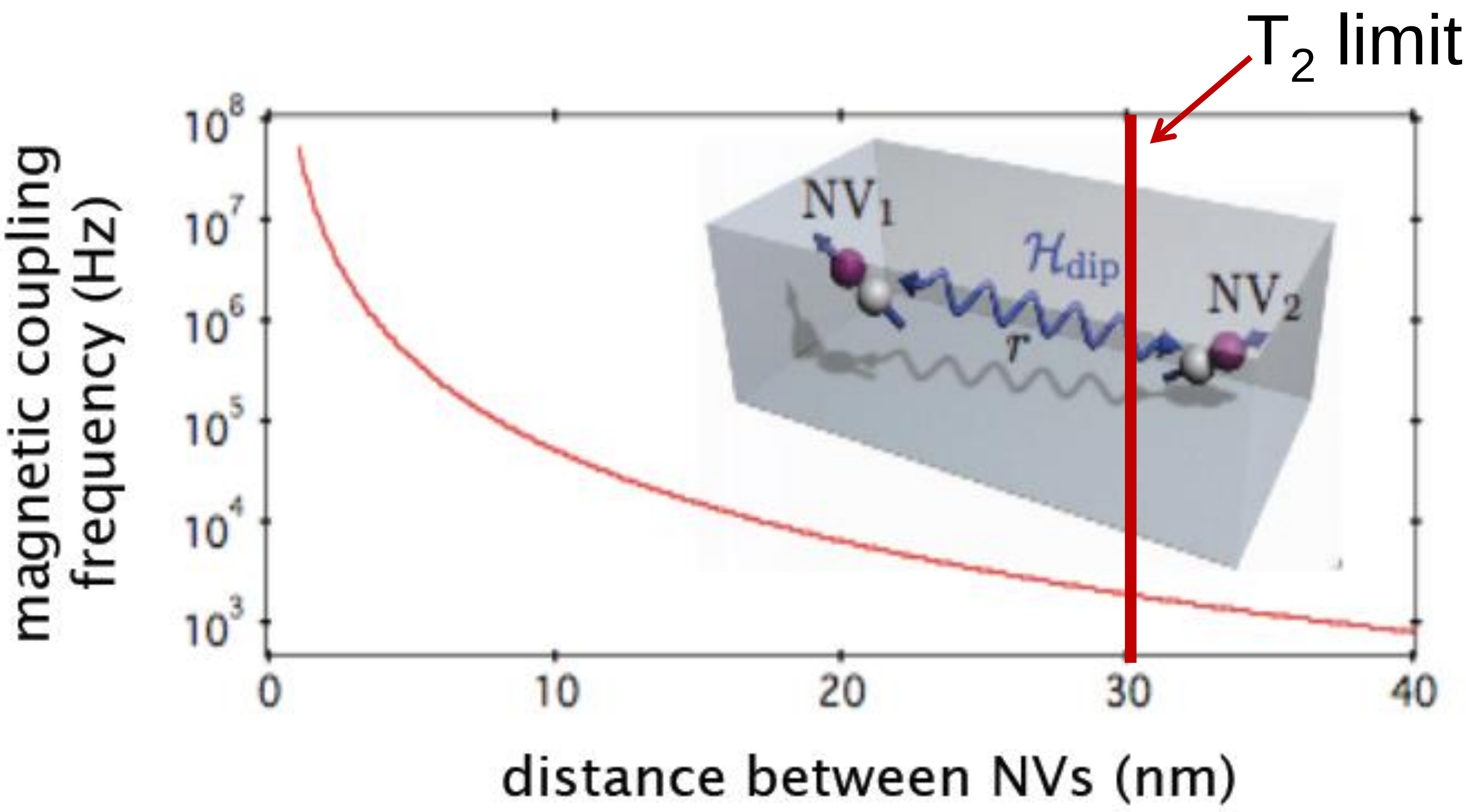
Single spin readout



Coherent interaction
Length scale ~ some10nm,

STED on NV: 10nm resolution (Hell et al. Nat. Phot. 2009)

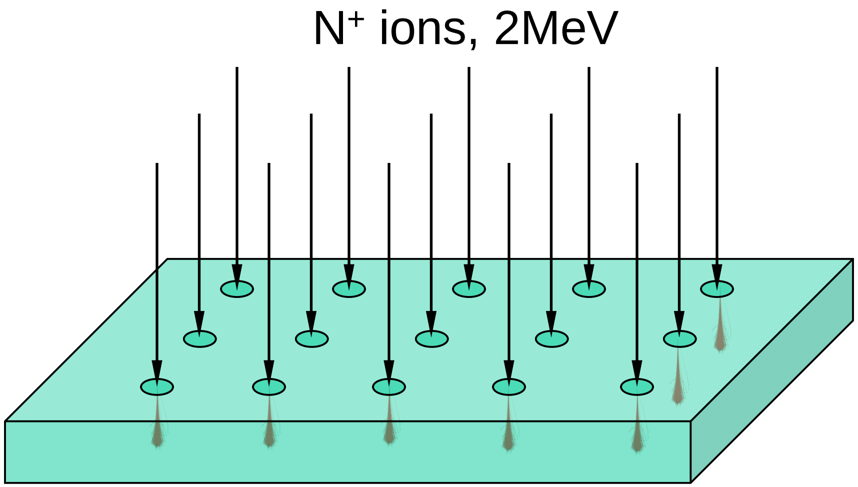
Magnetic dipole coupled spin arrays

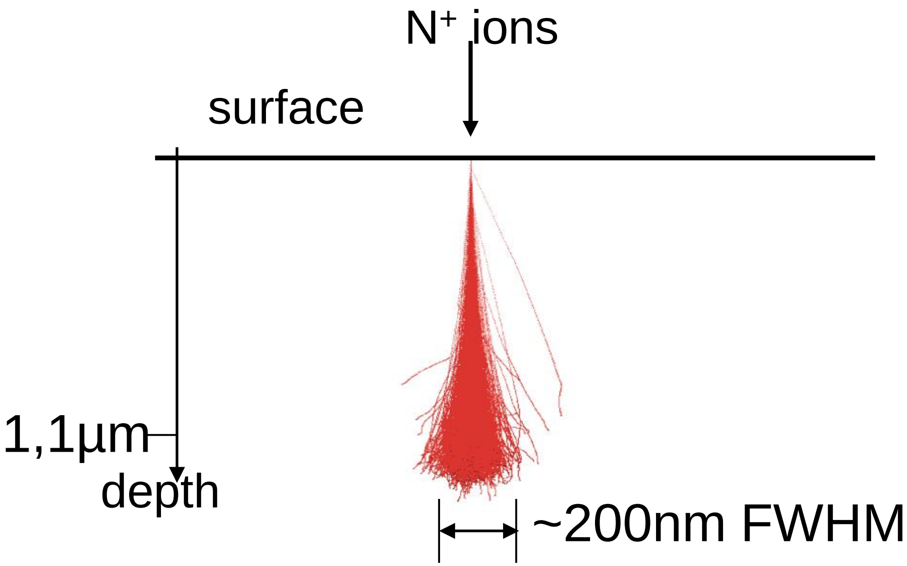


Take pure (CVD) diamond… *

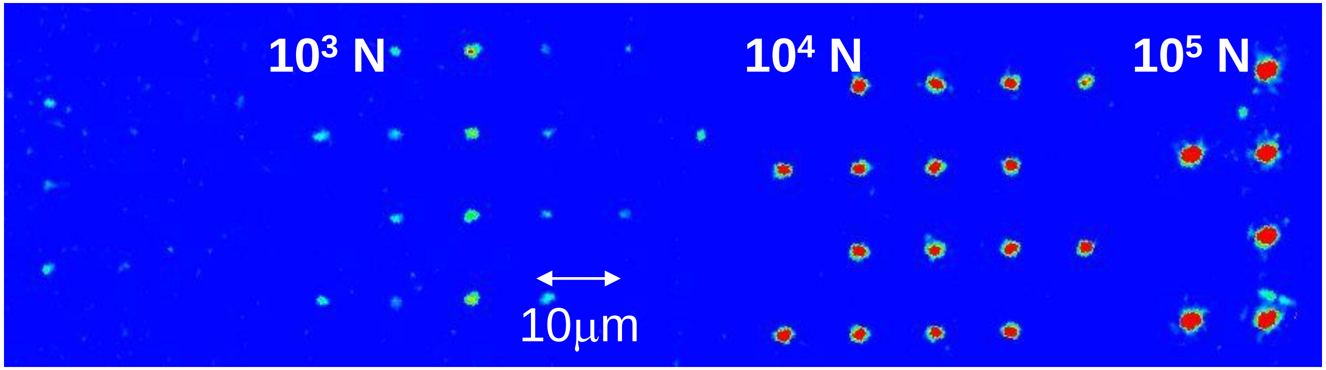
*Element Six Ltd., UK

..and implant nitrogen*! (*J.Meijer; S. Prawer)

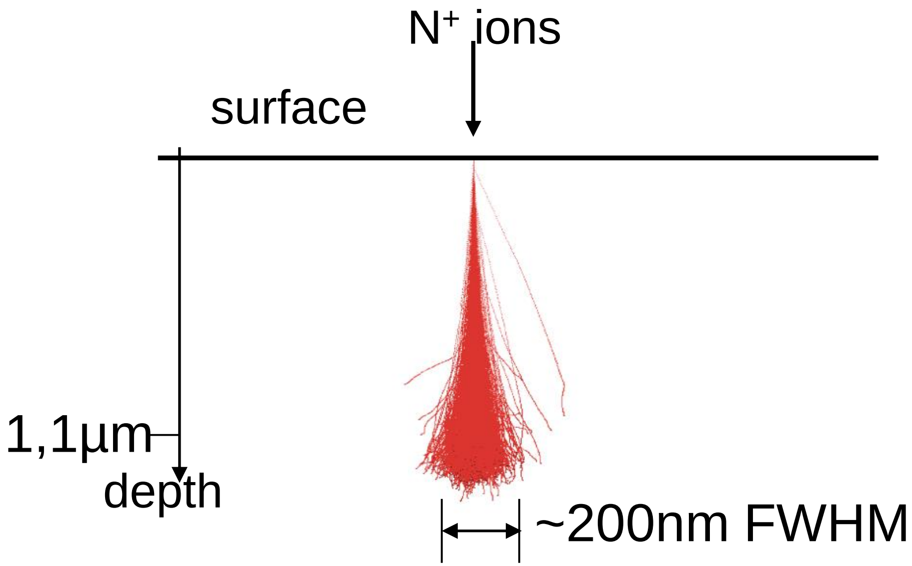




Annealing
at
900° C



Fundamental problem: Straggle



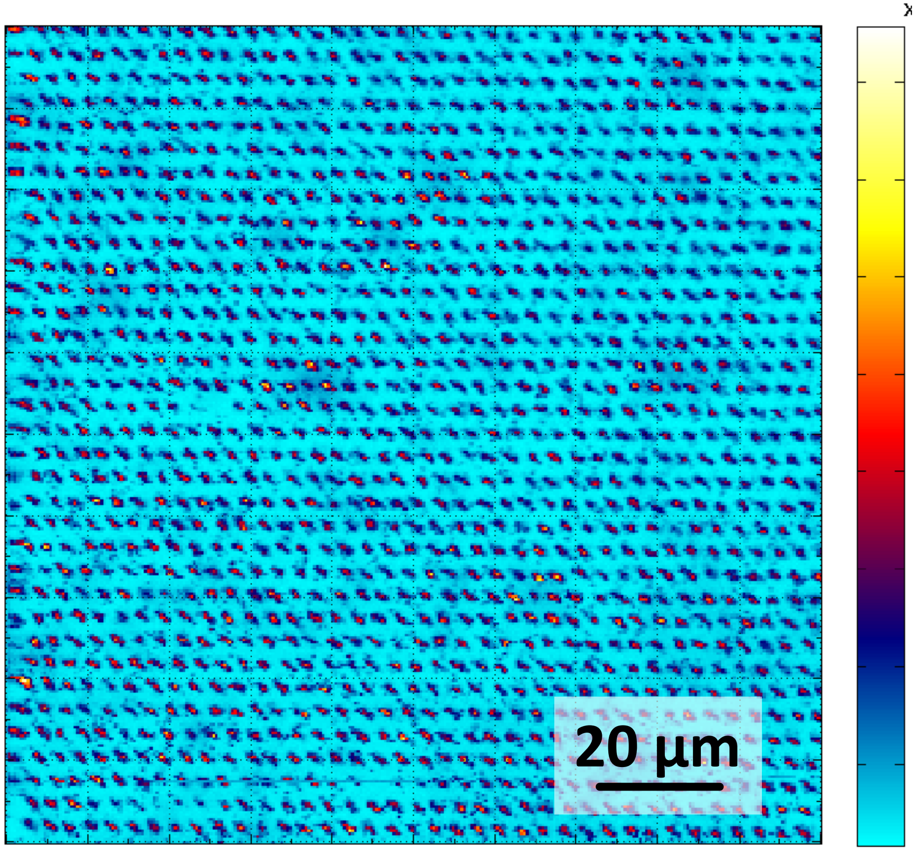
⇒Position is not controlled
⇒Straggle on the order of the implantation depth

⇒ Deep implant ←→ high distance between NVs
Shallow implant ← → bad T2 time due to surface

⇒ Solutions:
Shallow implant + Overgrowth
deep implant + extensive search

Writing Defect Dimers with 10 MeV µbeam implantation

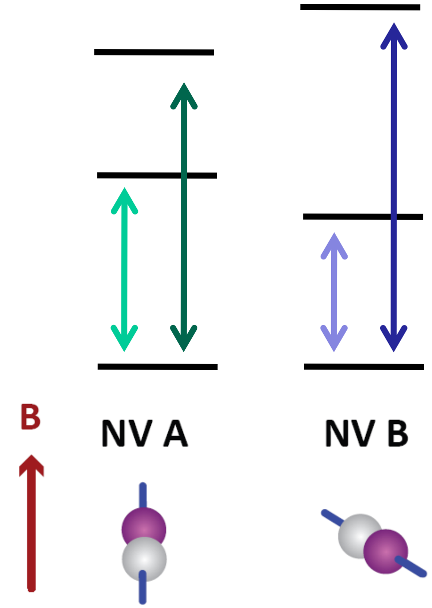
- Success chance 1% to have two coherently interacting dimers

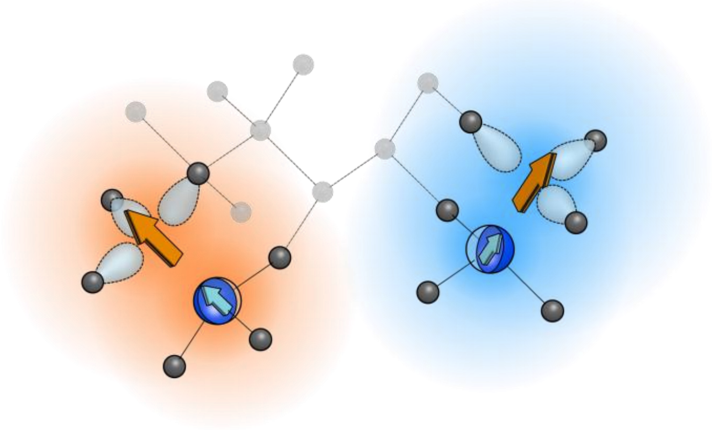


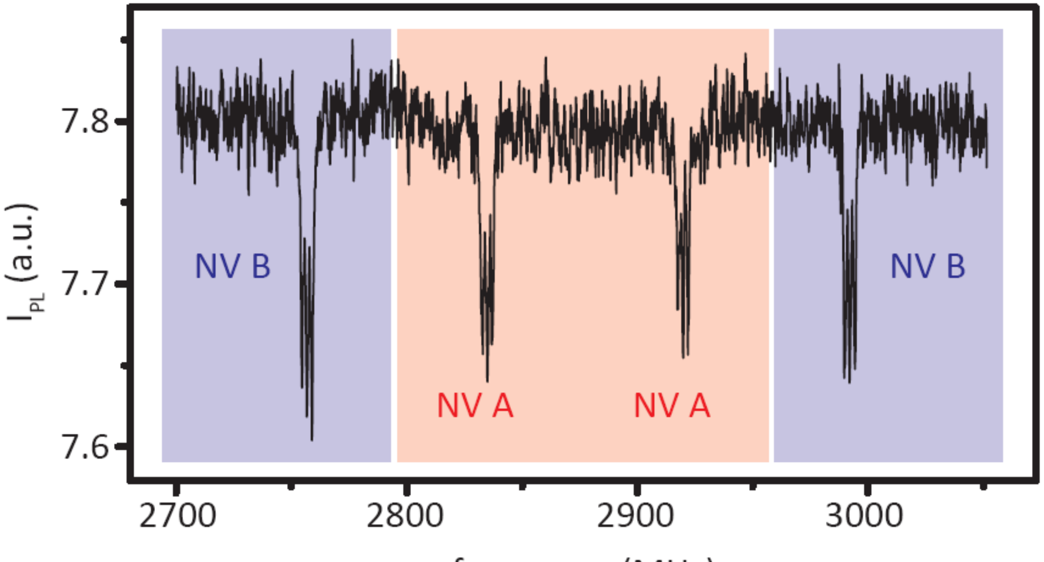
Two defect centers

Electron spin ground state:

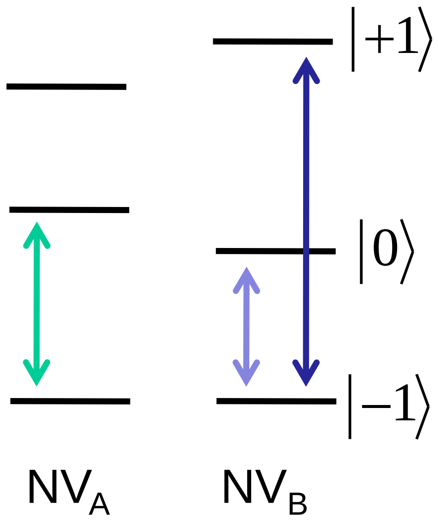
$$H = g\beta \mathbf{B}\mathbf{S}_{A,B} + (\mathbf{S}\bar{D}\mathbf{S})_{A,B} + S_A \bar{T} S_B$$

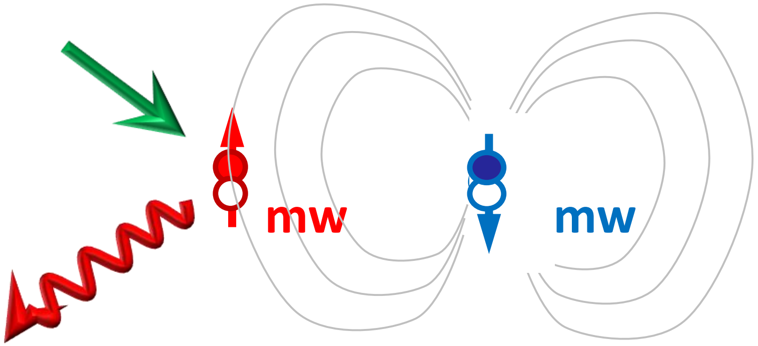




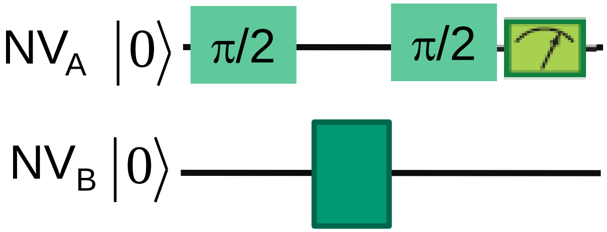


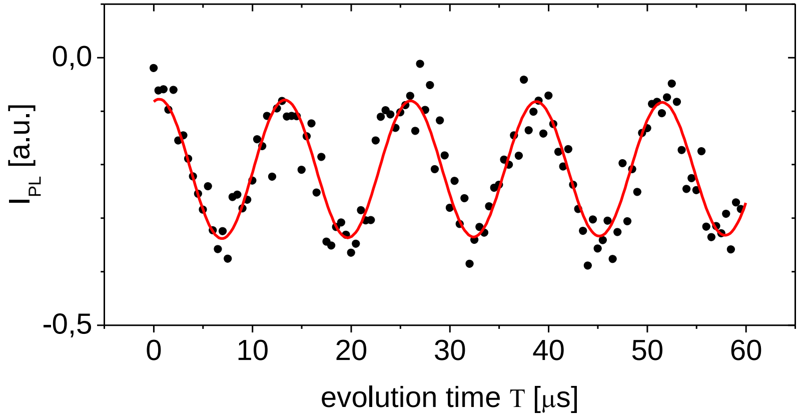
Dipolar coupling: Switching of Spin B





Ramsey fringe on NV_A





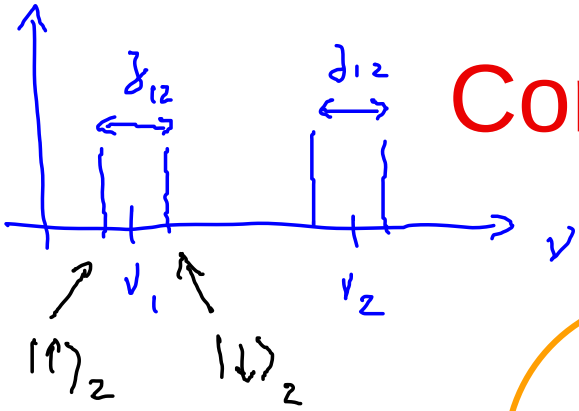
Initial state F≥85%

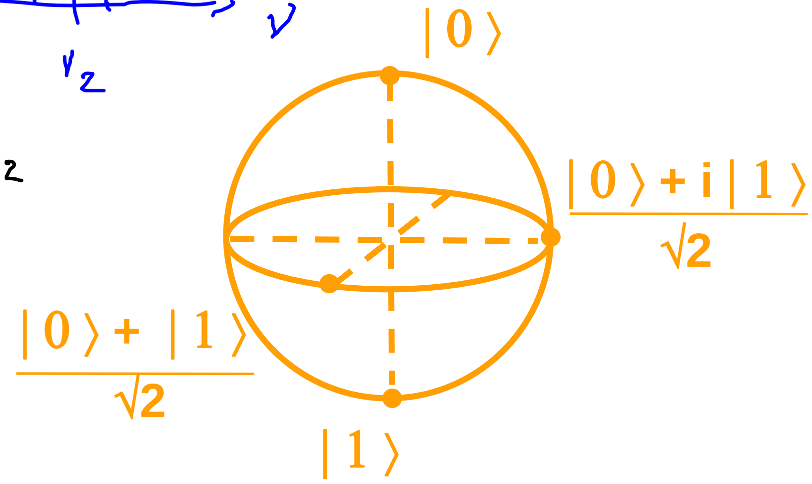
Switchable interaction! Coupling between defect: 0,5,10,20 kHz

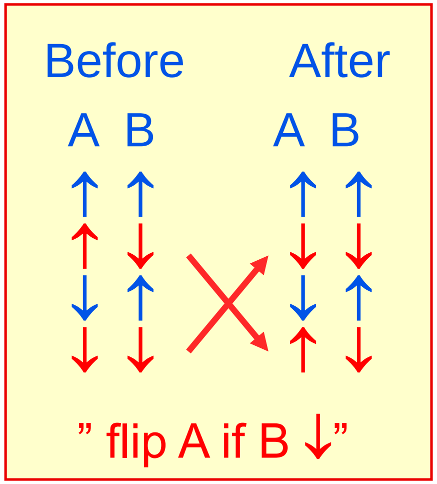
Controlled-NOT in NMR

A target bit

B control bit

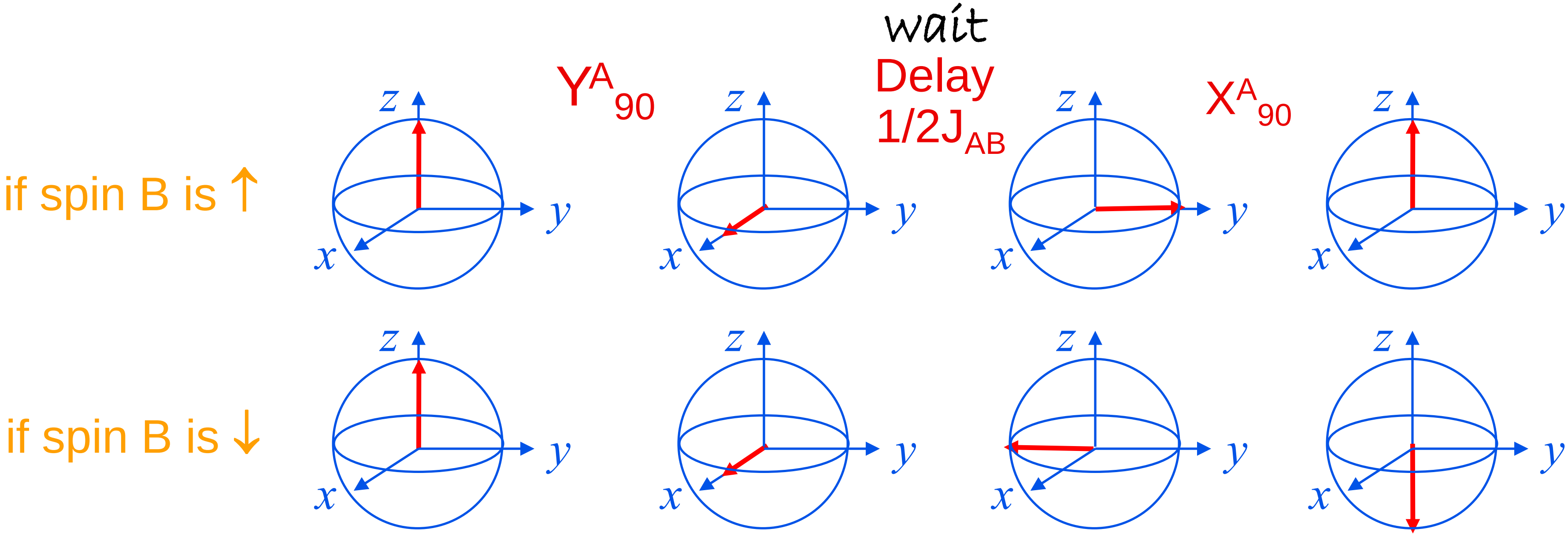






Before A	Before B	After A	After B
↑	↑	↑	↑
↑	↓	↓	↓
↓	↑	↓	↑
↓	↓	↑	↓

" flip A if B ↓"

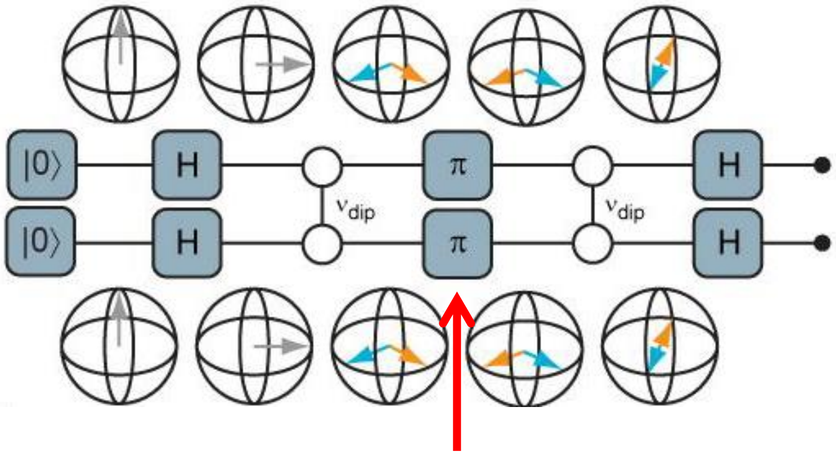


different rotation direction depending on control bit

⟶ time

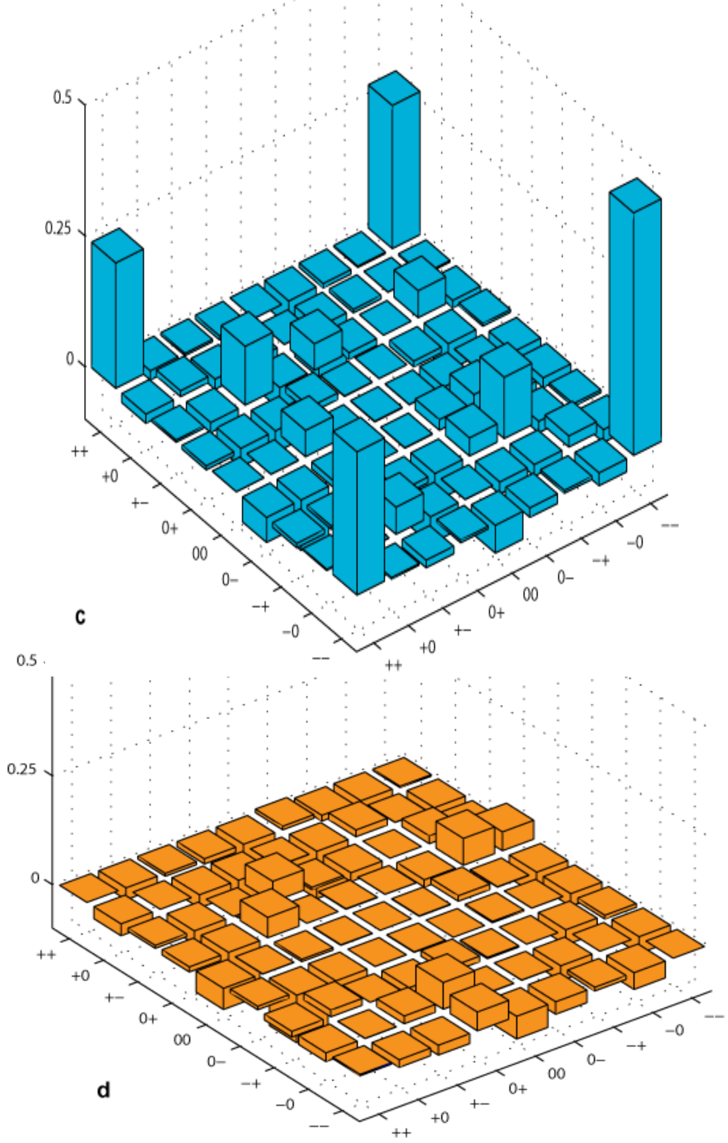
Bell state: Density matrix tomography

$$\Phi_+ = \frac{1}{\sqrt{2}}(|+\,+\rangle + |-\,-\rangle)$$



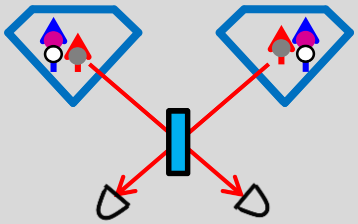
decoupling

Fidelity Φ+: 0.67
(theoretically: 0.9)



Coupling NV centers

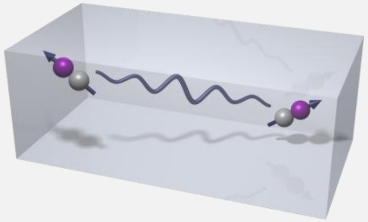
Photons



Cirac, Zoller
Lukin `06

- Proper levels and transitions
Manson, Hemmer, Santori
- Transfer limited photons:
Batalov et al. PRL 08
- But: bad coupling efficiency

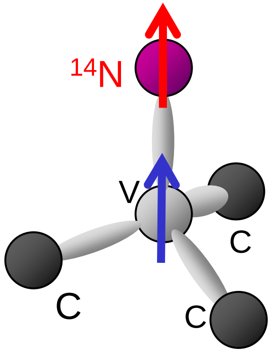
Magnetic Dipolar coupling



- Magnetic dipoles

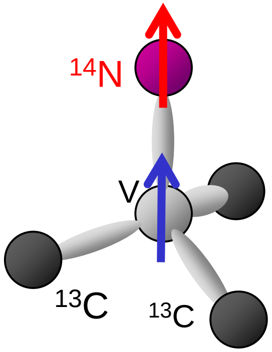
$$d_{coherent} \propto \sqrt[3]{T_2}$$

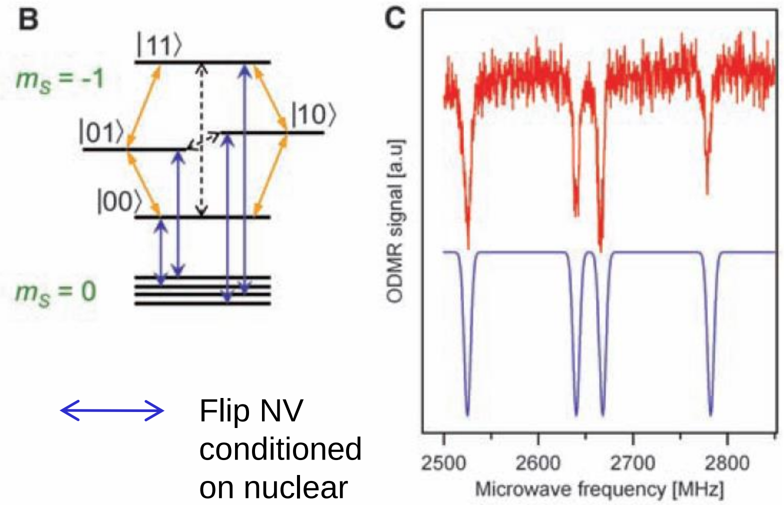
Use nuclear spin qubits



- Couple NV to surrounding nuclei
- Couple nuclei via NV
- Read out single nuclei

Coupling nearby ^{13}C nuclei



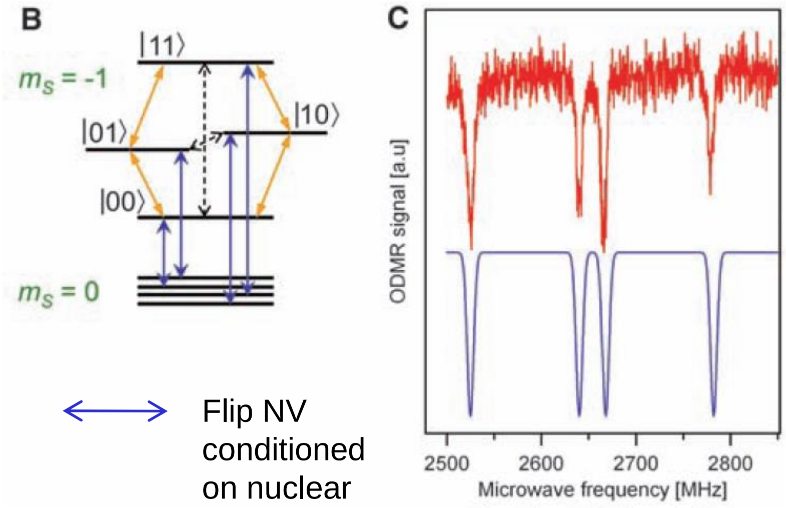


- ^{13}C nuclear spin creates magnetic field at NV
- CNOT gate is implemented by selective microwave transition
(flip nucleus if other nucleus is in |0>)

↔ Flip NV conditioned on nuclear state

↔ Flip nuclei conditioned on NV and nuclear state

Creation of entangled states



↔ Flip NV conditioned on nuclear state

↔ Flip nuclei conditioned on NV and nuclear state

- Creation of entangled states possible
  $|00\rangle \mp |11\rangle$

  P. Neumann et.al., Science **320**, 1326 (2008)

- Scaling up to four nuclear spins straightforward,

- Scaling to 10-20spins presumably possible

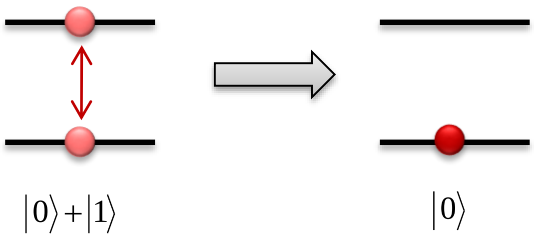
Different development: QND readout of nuclear spins

Readout of single quantum systems

Standard readout
- <1 photon per run
- limited by photon shot noise (at best)
- Example: fluorescence detection of single NV

Single shot readout
- determine spin state in a single run but
- destroy the system or its quantum state
- (requires >1 photon per run)
- limited by quantum shot noise
- Example: Photon detection in Photomultiplier

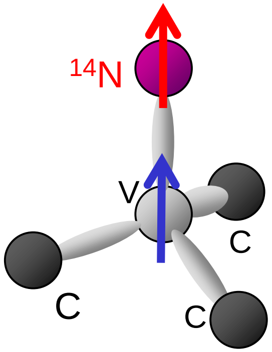
Quantum non demolition (QND) readout
- >1 photon per run
- **and preservation of the system and its spin state**
- Projective measurement
- Example: Microwave photons in cavity (Haroche)

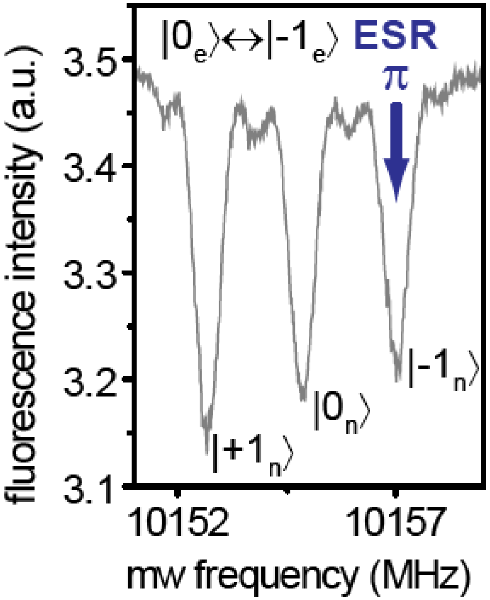


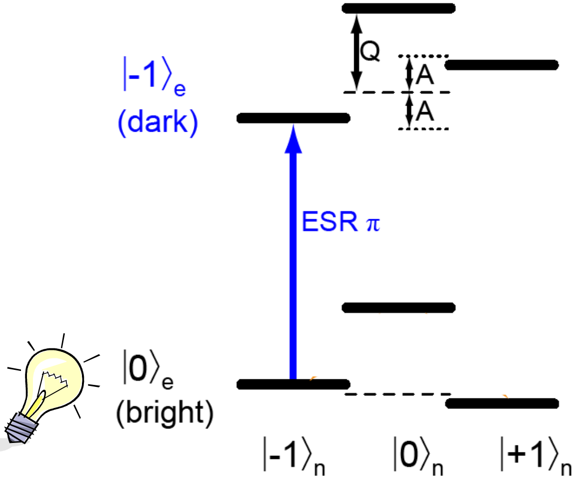
$|0\rangle + |1\rangle$

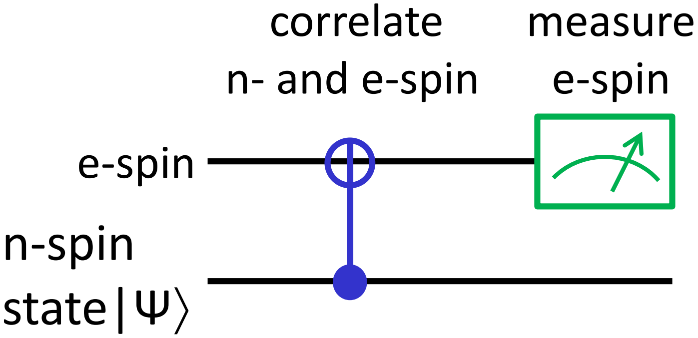
$|0\rangle$

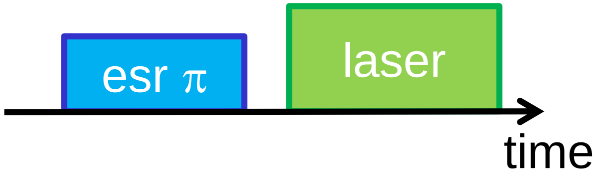
QND readout of a single nuclear spin





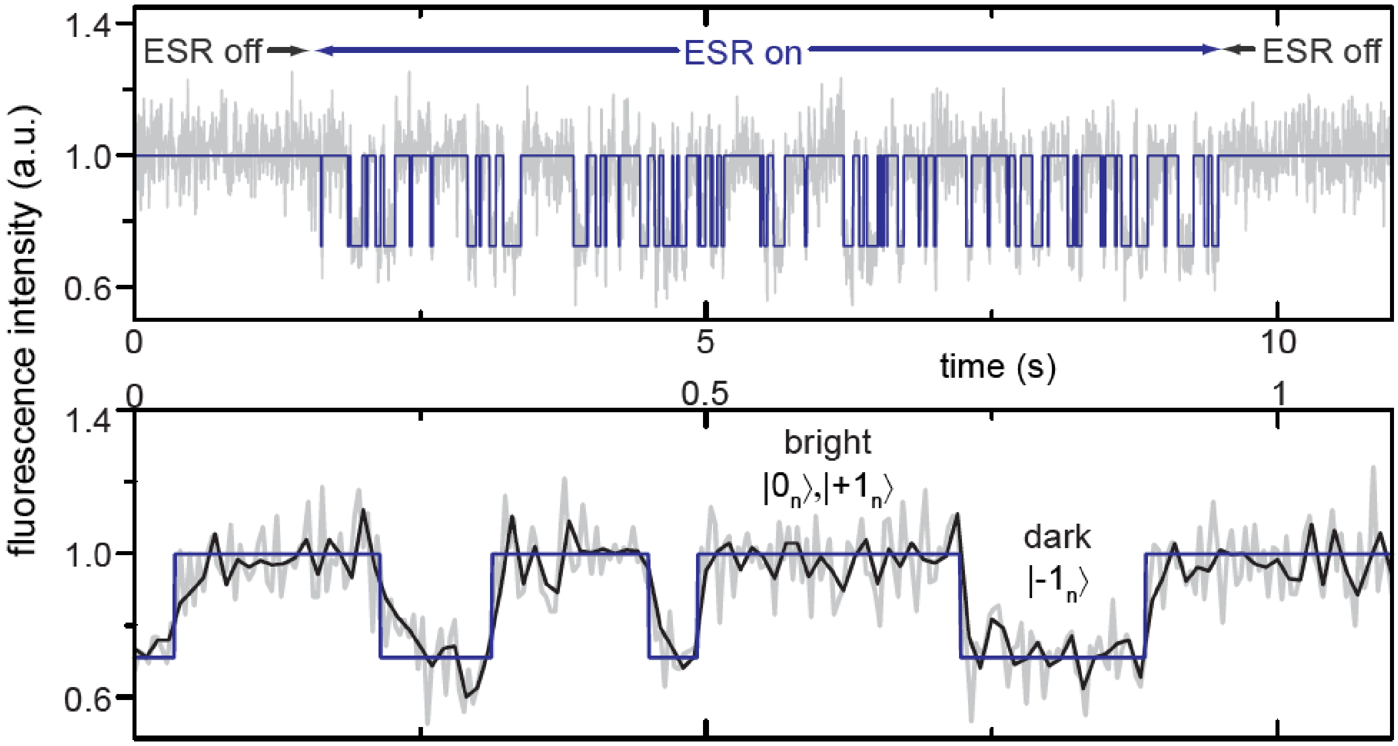






Observing flips of a single nuclear spin

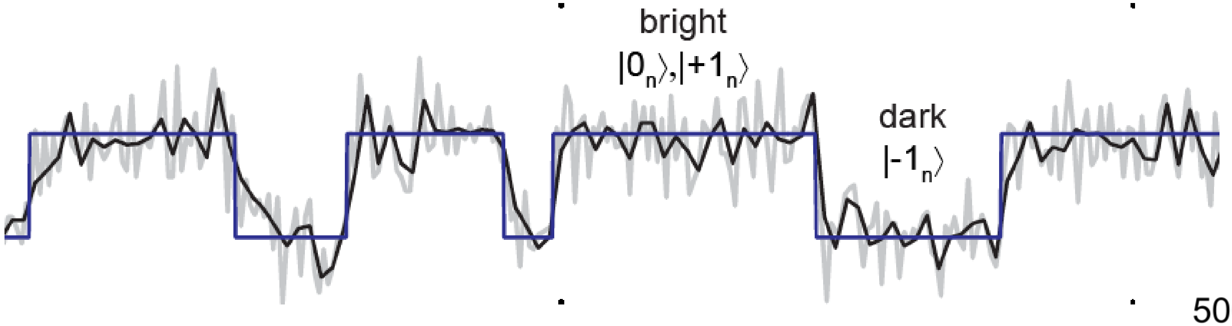
- Repetetive QND measurements reveal quantum jumps of a single nuclear spin (in diamond at room temperature)

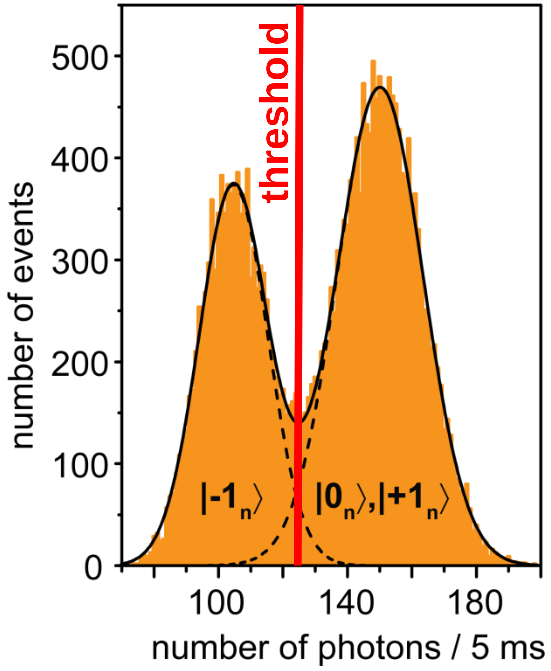


P.Neumann et.al., Science **329**, p.542 (2010)

Fidelity of spin state detection

- Photon counting histogram of timetrace

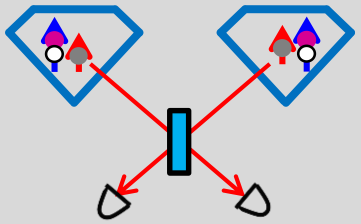




- Two almost perfect Poissonians
- Threshold for state discrimination
  - Fidelity from overlap 99%
  - Fidelity to detect given state 92%

Coupling NV centers

Photons



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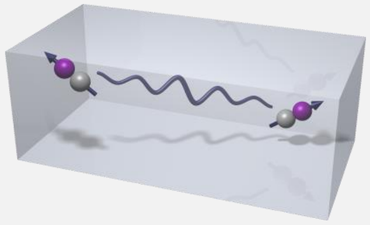

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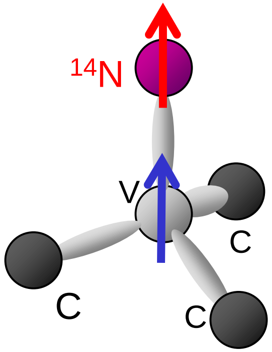
Use nuclear spin qubits



- Couple NV to surrounding nuclei
- Couple nuclei via NV
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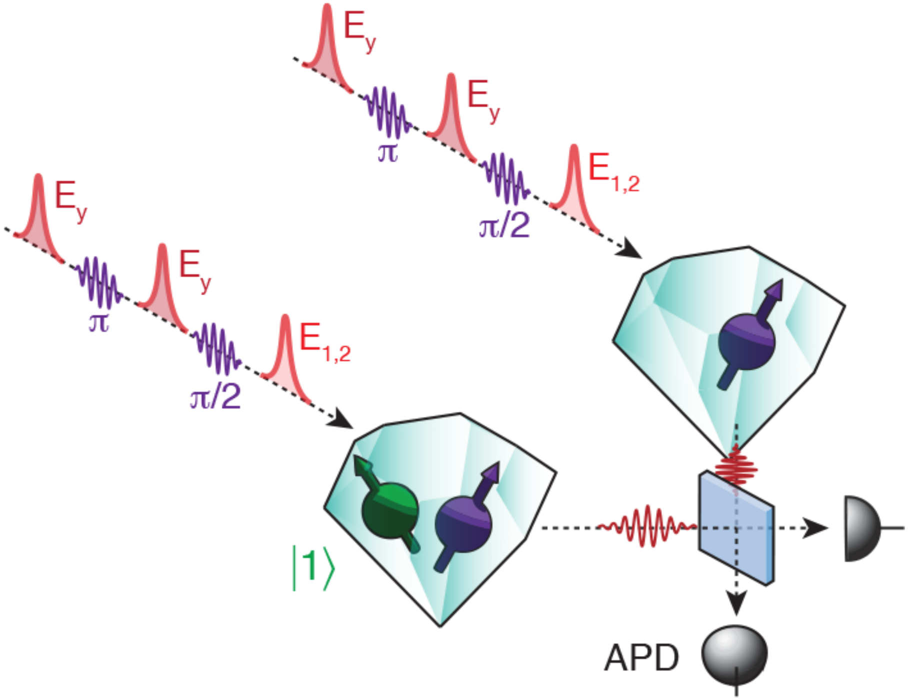
Preparing the teleporter: entangling remote qubits



Experiments with trapped atoms:
Monroe group, Nature 2007
Weinfurter group, Science 2012
Rempe group, Nature 2012

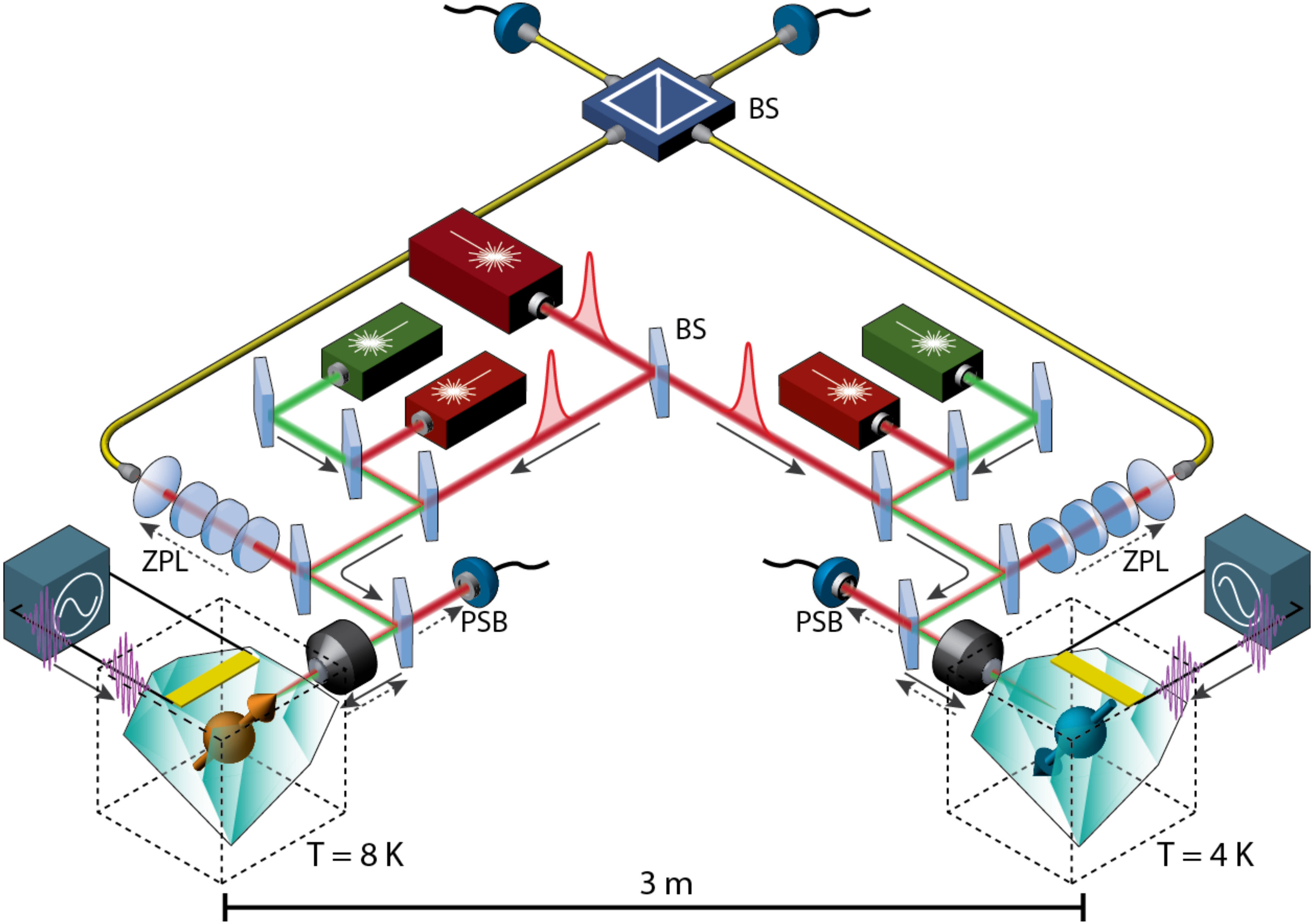
we use the scheme proposed in:
Barrett and Kok, PRA 71, 060310 (2005)

- locally entangle electron spin and photon
- project photons onto entangled state by joint measurement

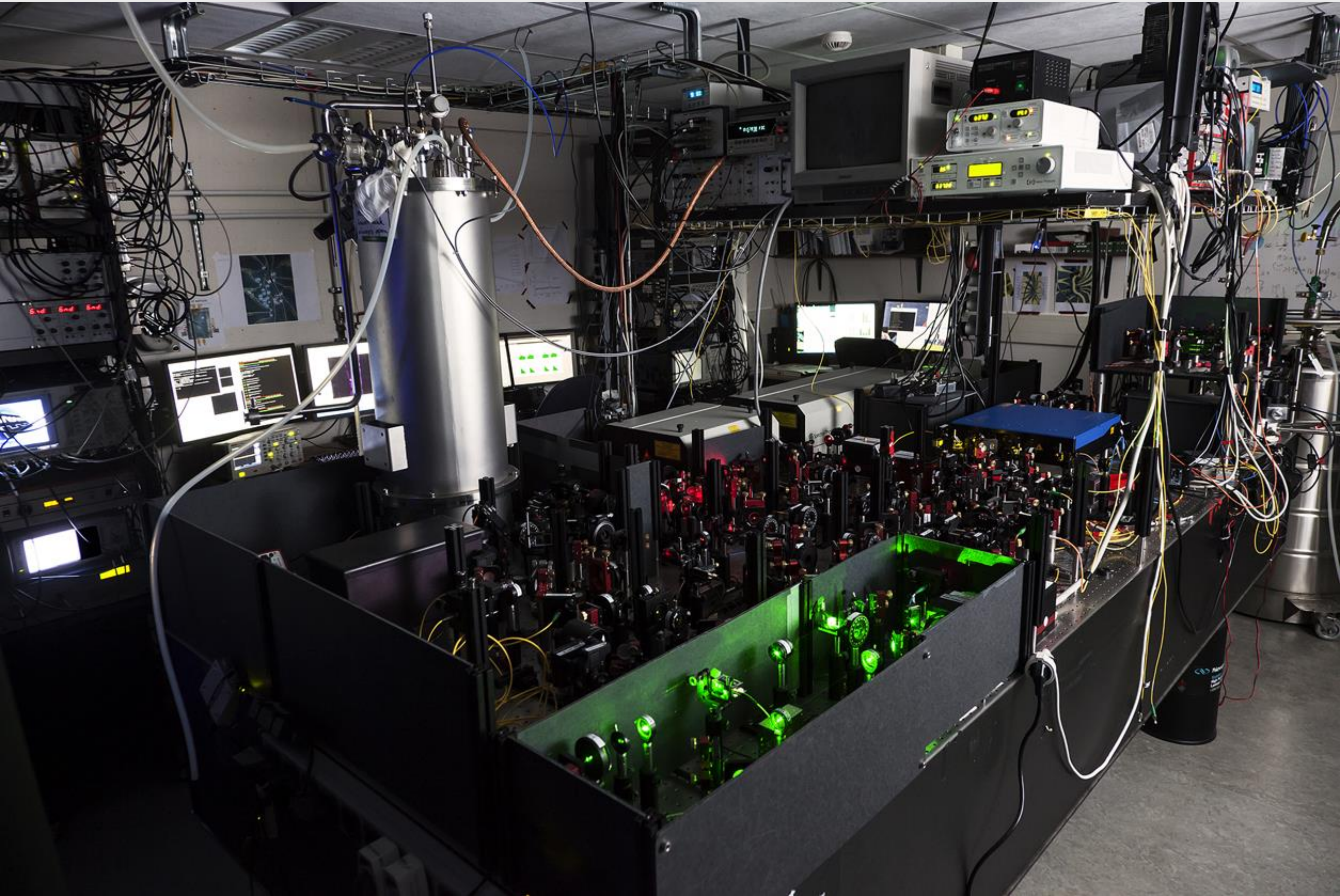
entanglement is heralded by photon detection:

photon loss reduces success rate, but not fidelity of final state

Remote entanglement: setup



Remote entanglement: setup



Remote entanglement: results

Nature 497, 86 (2013)

$$|\psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|\downarrow_{\mathrm{A}}\uparrow_{\mathrm{B}}\rangle \pm |\uparrow_{\mathrm{A}}\downarrow_{\mathrm{B}}\rangle)$$

State fidelity

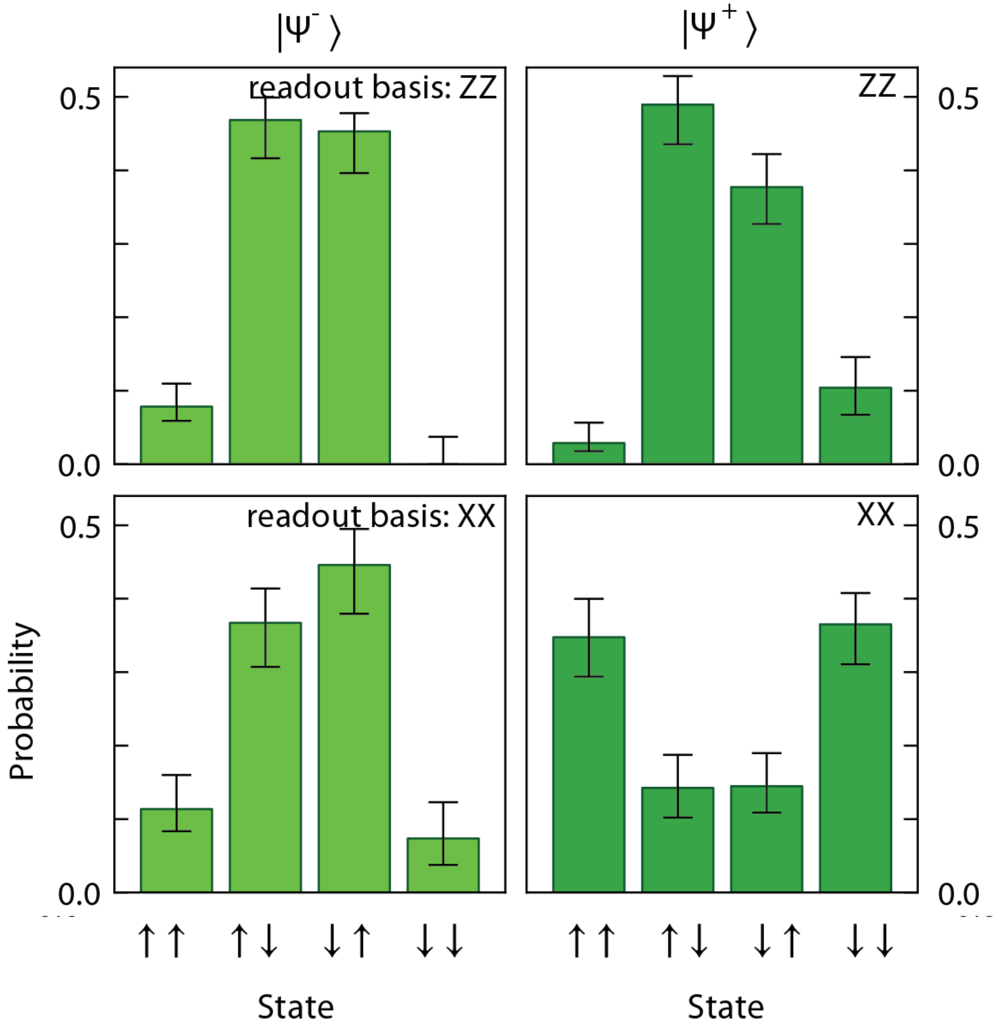
$F\,(\Psi^-) \approx 73\ \%$

$F\,(\Psi^-) \approx 87\ \%$

Success probability

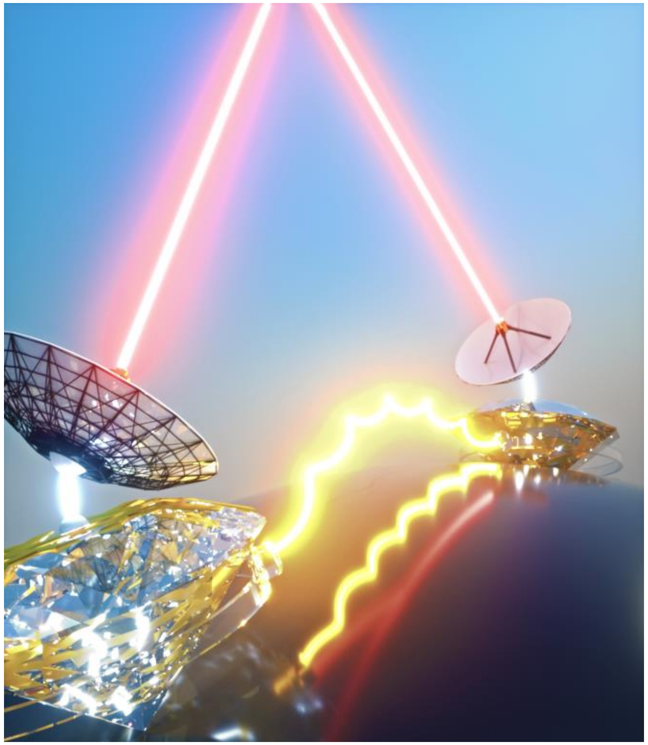
$\approx 10^{-7}$; one event per 10 minutes

$\approx 3*10^{-6}$; one event per 100 s



Prospects in quantum information processing with NV centers in diamond: **quantum networks**

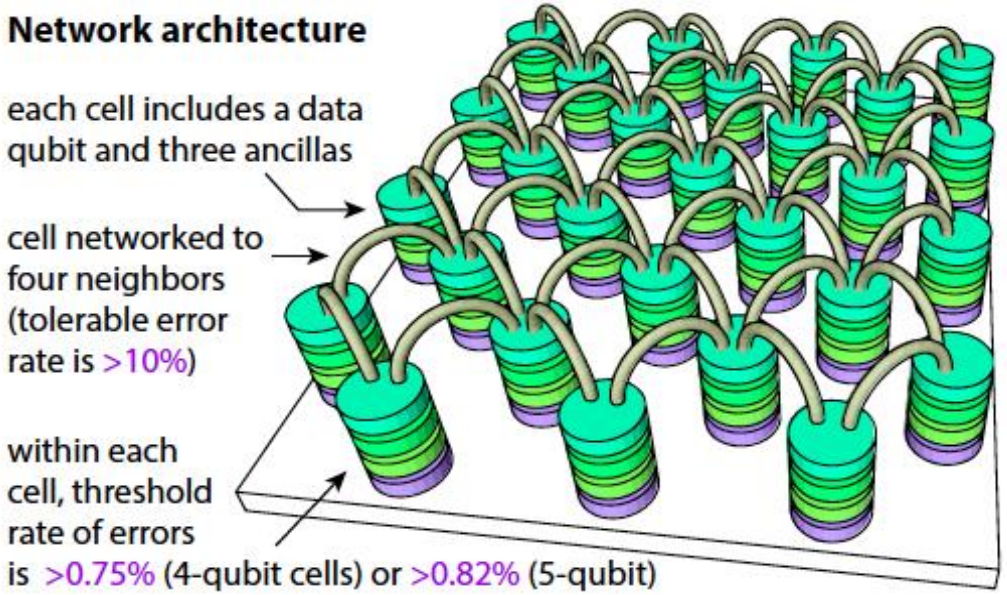
Quantum Internet



- Loophole-free Bell test
- Device-independent quantum key distribution
- Quantum cloud computing

Barz et al., Science 2012

Topological quantum computing



Nickerson, Li, Benjamin, Nature Communication 2013