Quantum Information Science Center

Quantum manipulation of NV centers in diamond

12.09.2014

The University of Virginia

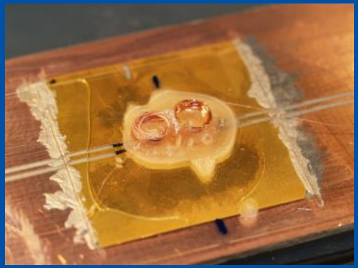
Physics Colloquium

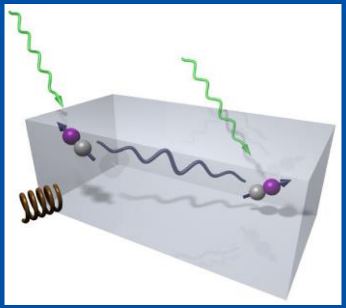
Alex Retzker

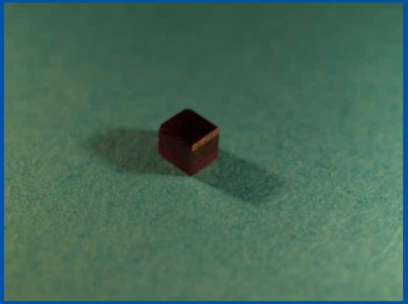
Jianming Cai, Andreas Albrect, M. B. Plenio,Fedor Jelezko, P. London, R. Fisher,B. Nayedonov, L. Mcguiness, Guy Koplovitz, Shira Yochelis,Danny Porath, Yuval Nevo, Oded Shoseyov, Yossi Paltiel, Paz London. Ran Fischer

NJP 15 013020 (2013), Nature Physics **9**, 168 (2013)

PRL. 111, 067601 (2013), NJP. 16 093002 (2014)

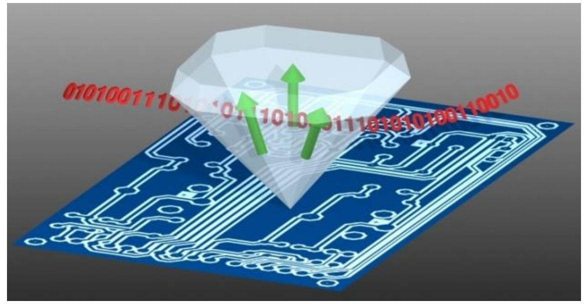




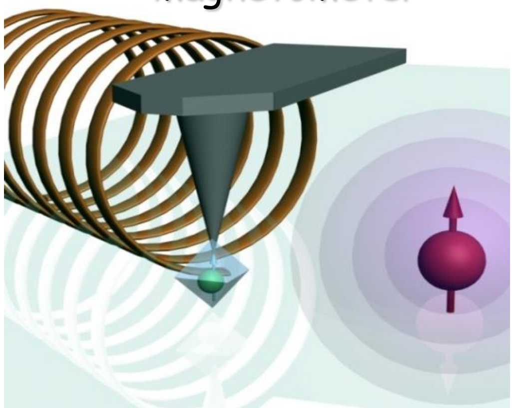


Quantum computing/Simulations

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

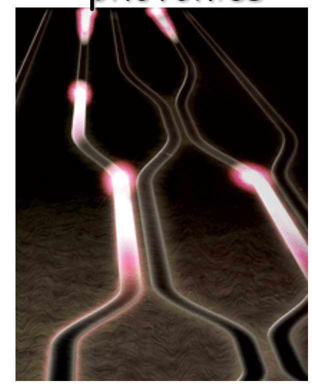


Scanning probe magnetometer



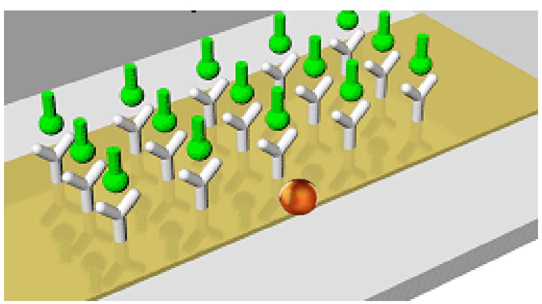
G. Balasubramanian, et al. *Nature* 455, 648 (2008)
J.Maze, et al, Nature 455, 644 (2008)

Quantum devices and photonics



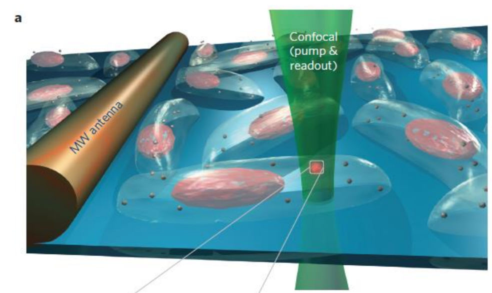
R. Kolesov et al. *Nat. Phys.* 5, 470 (2009)

NV in diamond



Biosensor technology & Molecular Spin sensors

Nanodiamonds for cellular imaging



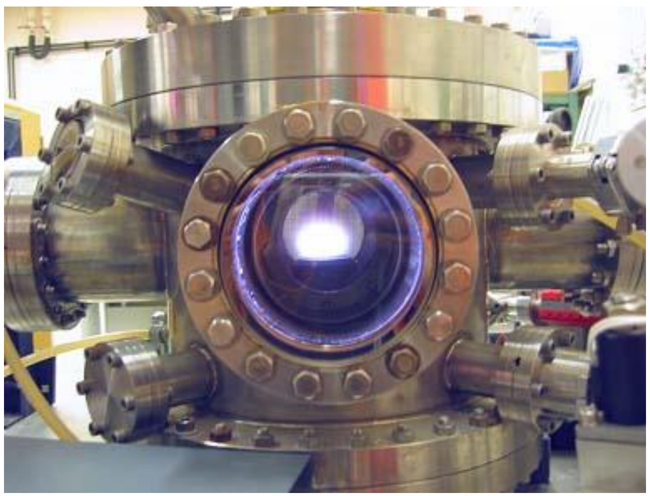
L. C. L. Hollenberg, et al, Nature Nanotec 6, 358 (2011).

Diamond

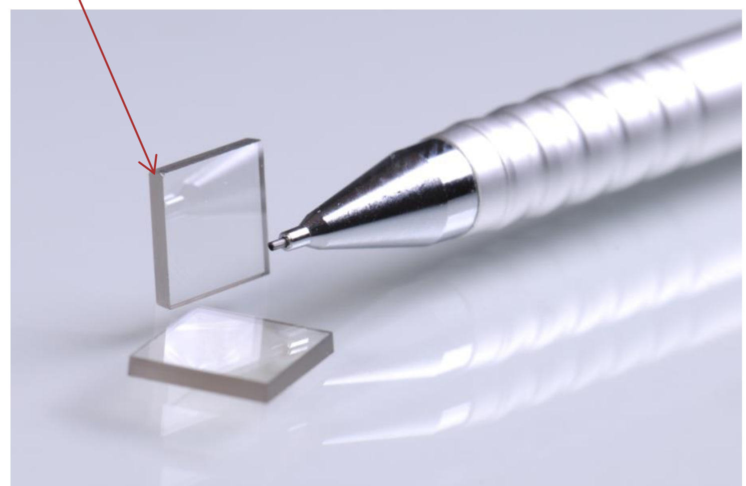
The Color is given by the color centers

Concentration of impurities: below 10^{12} cm^{-3} (optical resolution)

Isotope: 99.998% ^{12}C



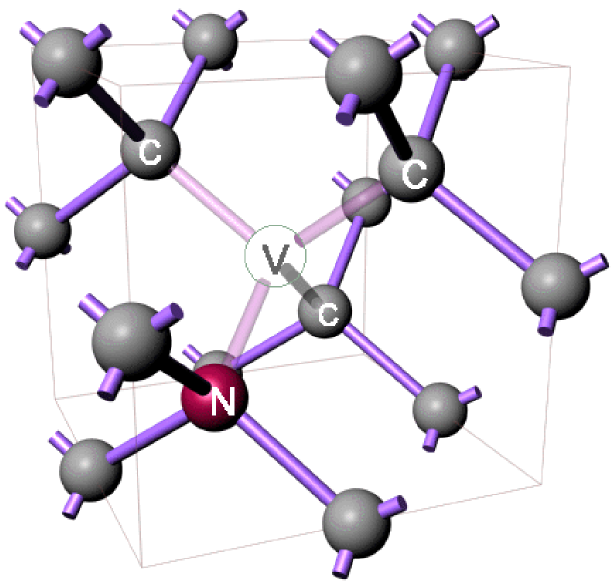
CVD reactor: University Paris XIII (Villtaneuse) J. Achard

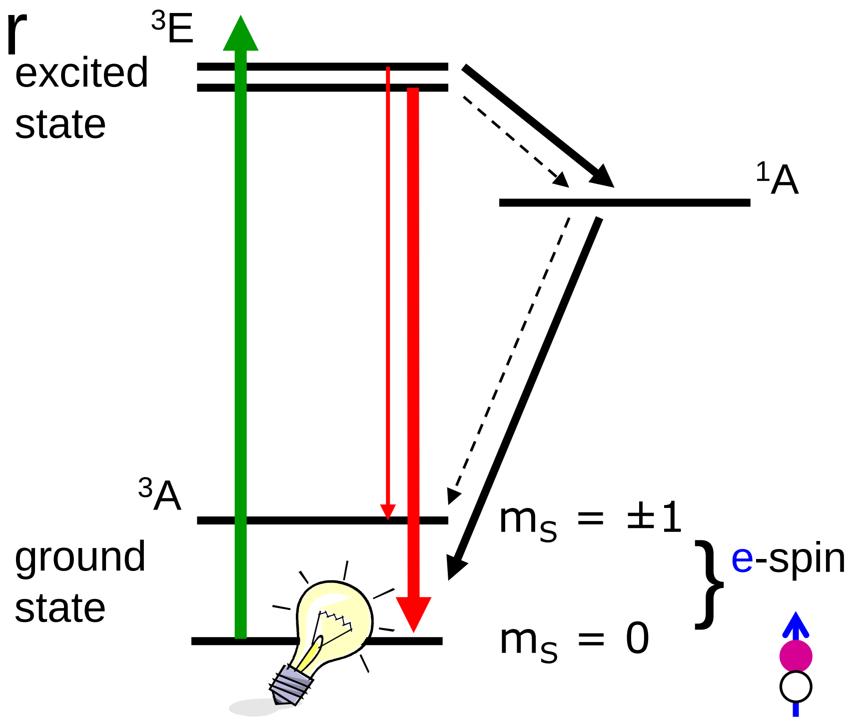


D. Twitchen, Element 6 Ltd

Color Centers

Nitrogen-Vacancy color center



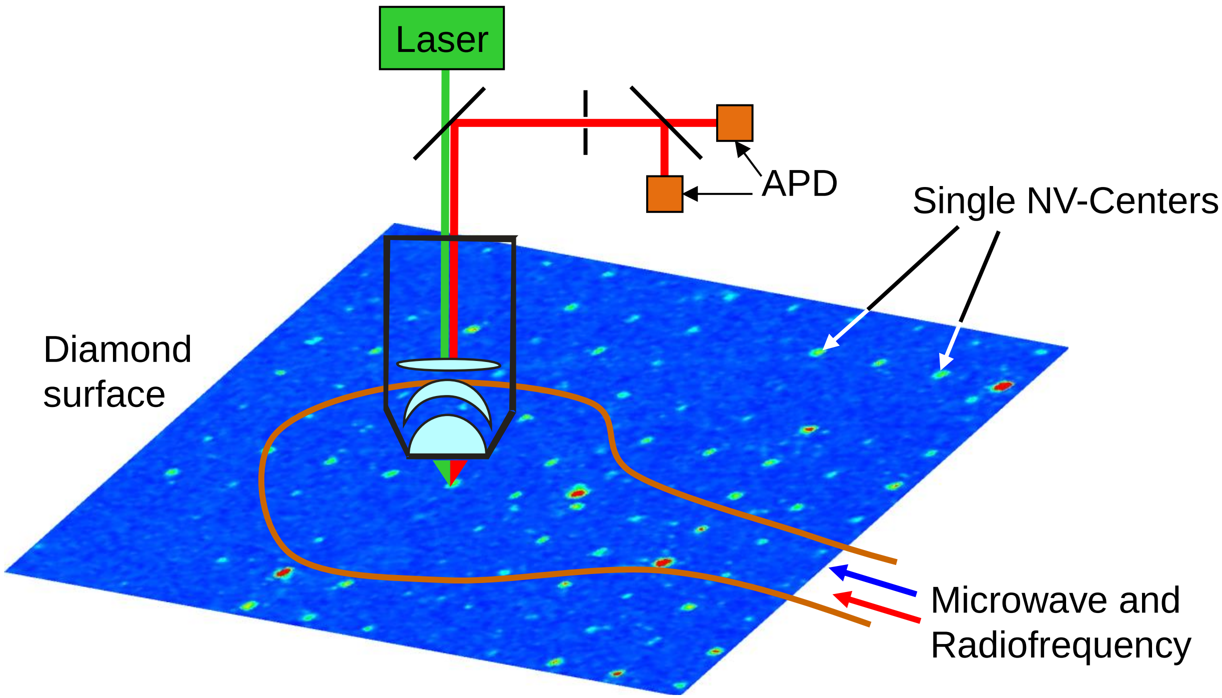


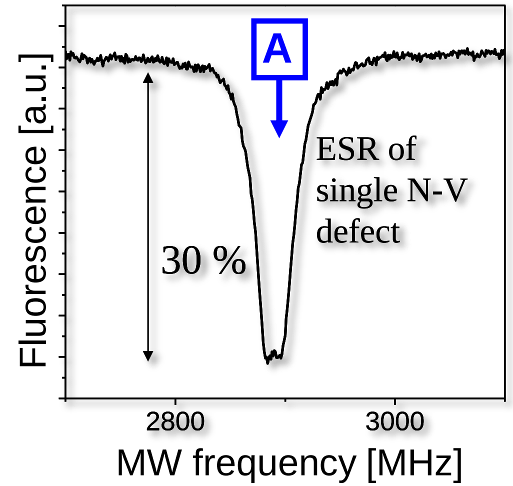
Optical excitation: read out and initialization: ≥96%

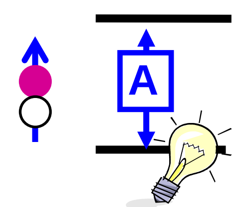
Early work: Manson, Glasbeek, Hemmer (ensembles)
Single center detection Gruber A et al., Science 276 2012 (1997)

Single spin deteciton

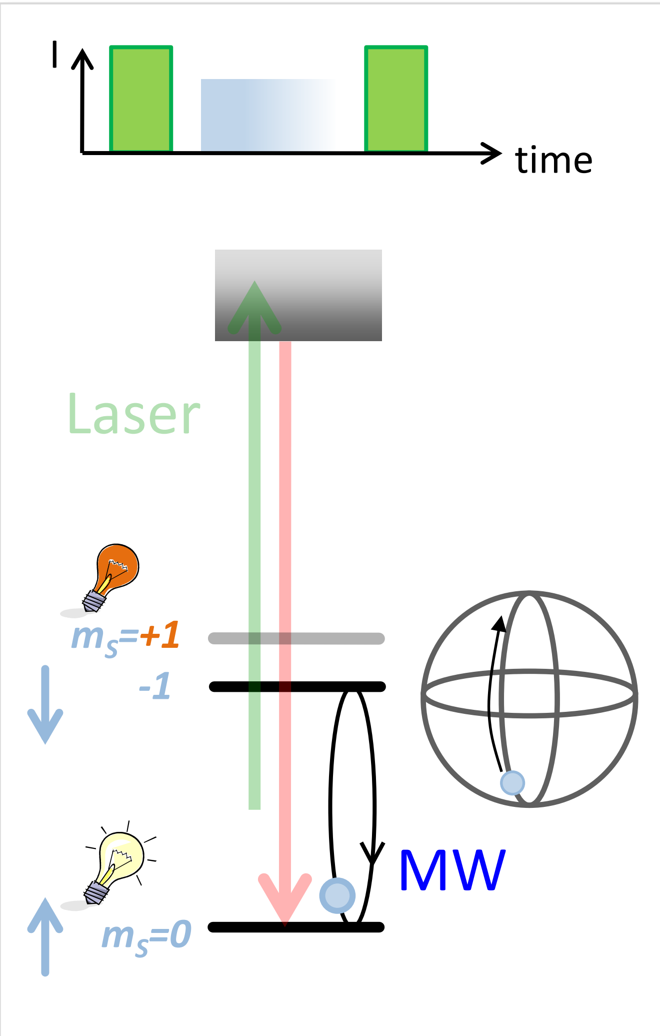
Ambient condition =
Room temperature!
No vacuum!

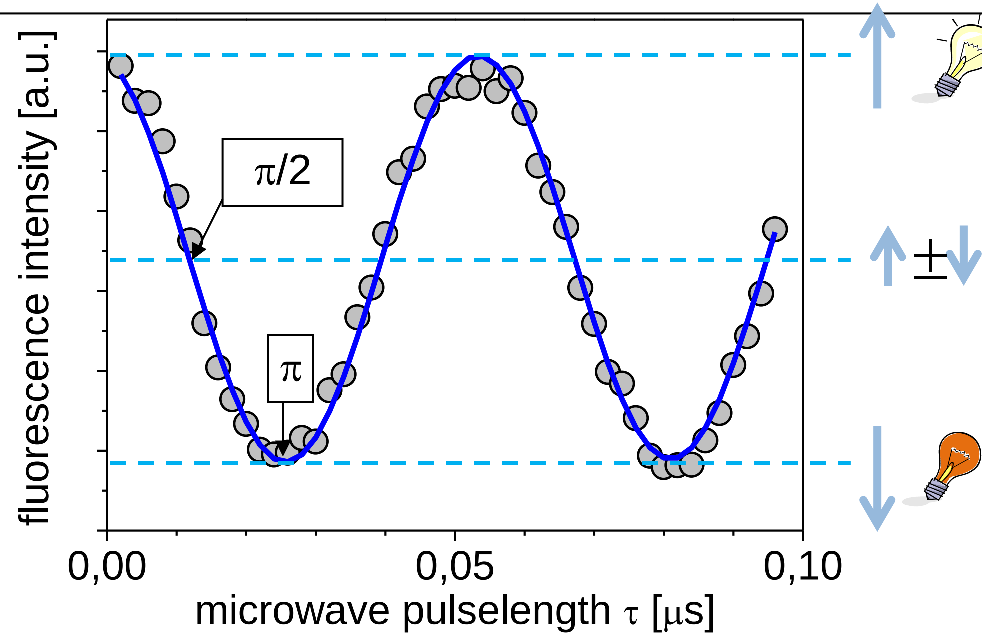






Coherent control

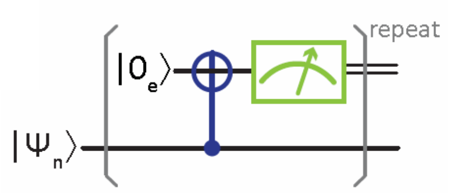




Jelezko et al., PRL 2004, Epstein Nat. Phys (2005), Childress Science (2006) …
up to GHz control, Fuchs et al., *Science* **326**, 1520 (2009)
figure of merit:

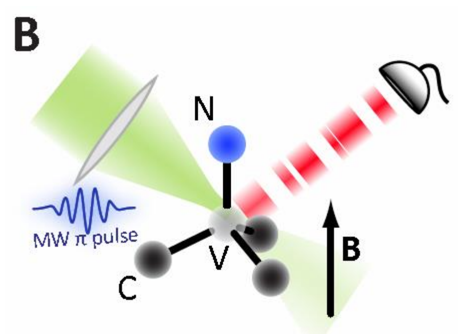
- Phase memory time T_2^*=110μs, T_2=2.6 ms (e6)
  - ultrapure CVD diamonds (no electron spins)
- 10^6 Rabi oscillations within T_2

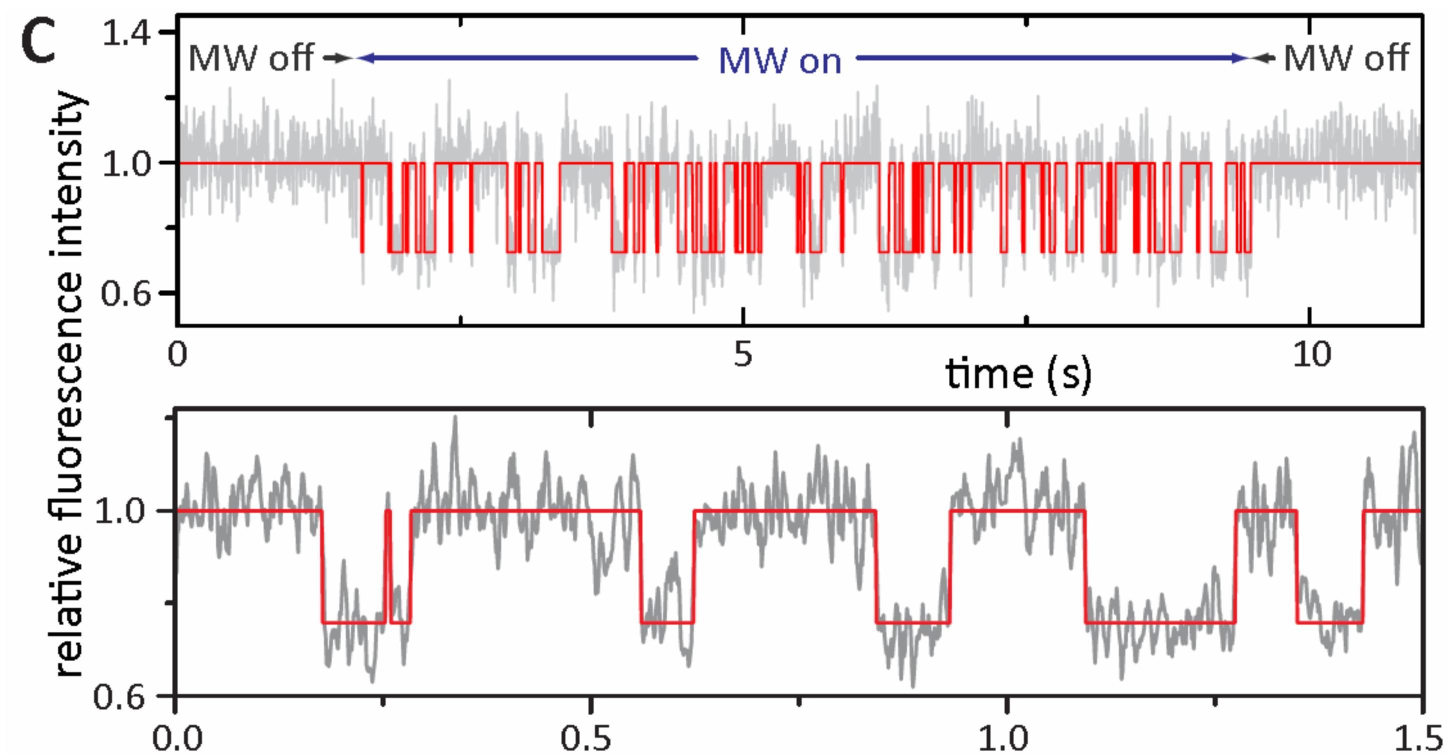
Single shot readout single nuclear spin



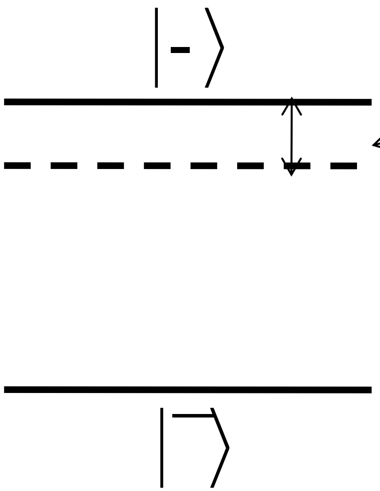
Repetitive QND measurements reveal quantum jumps of a single nuclear spin (in diamond at room temperature)

Neumann et al., Science 2010

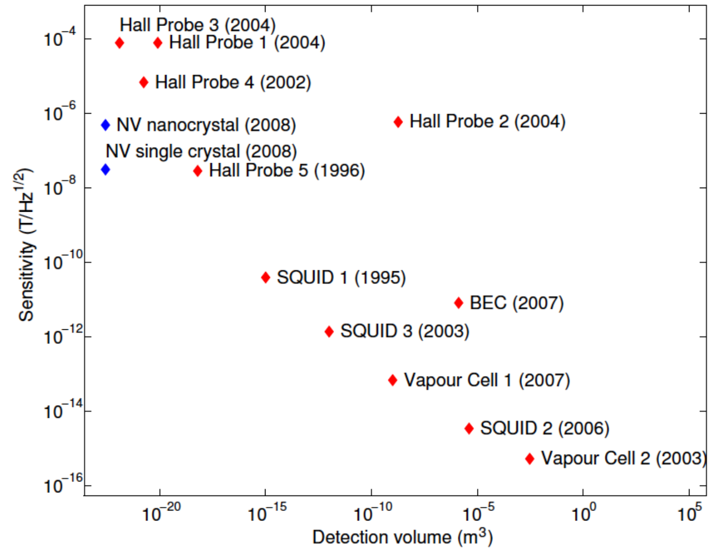




Ramsey magnetometer



$$|\overline{\ }\rangle + e^{i\omega t}|-\rangle$$



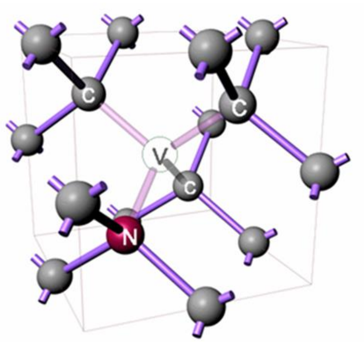
$$\Delta\omega = \frac{\sqrt{P(1-P)/N}}{dP/d\omega} = \frac{1}{\sqrt{nTt}}$$

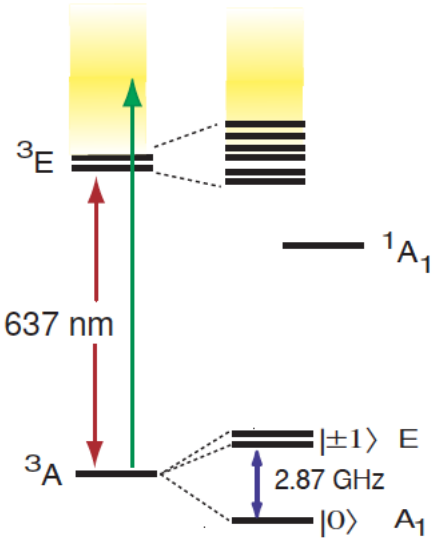
Measurement error

Total time

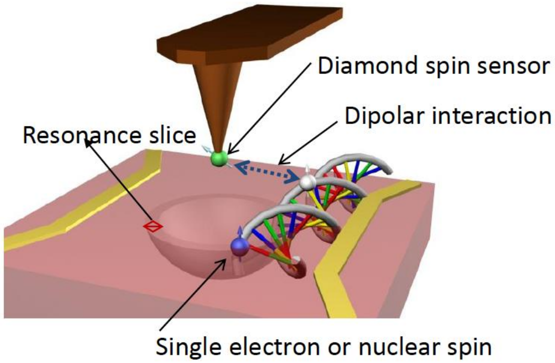
Coherence time

NV center in diamond as a nano-scale quantum sensor





- Chemical and thermal stability
- Optical readout of spin state
- Coherent control with microwave
- Long coherence time: spin bath
- Non-toxic: biological/medical application



How to detect a single nucleus?

- Long measurement time: small magnetic moment
- Single out the target nucleus from environment noise

Our proposal: Continuously driven diamond spin sensor

→ Single molecule magnetic resonance spectroscopy

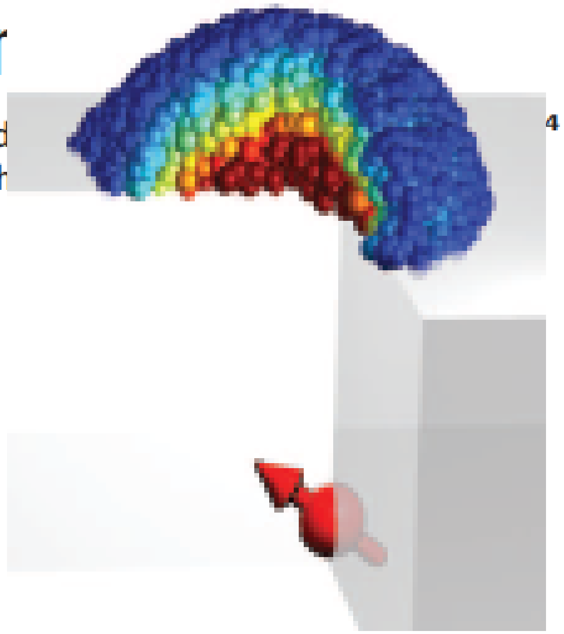
J. R. Maze, et al, Nature 455, 644 (2008).

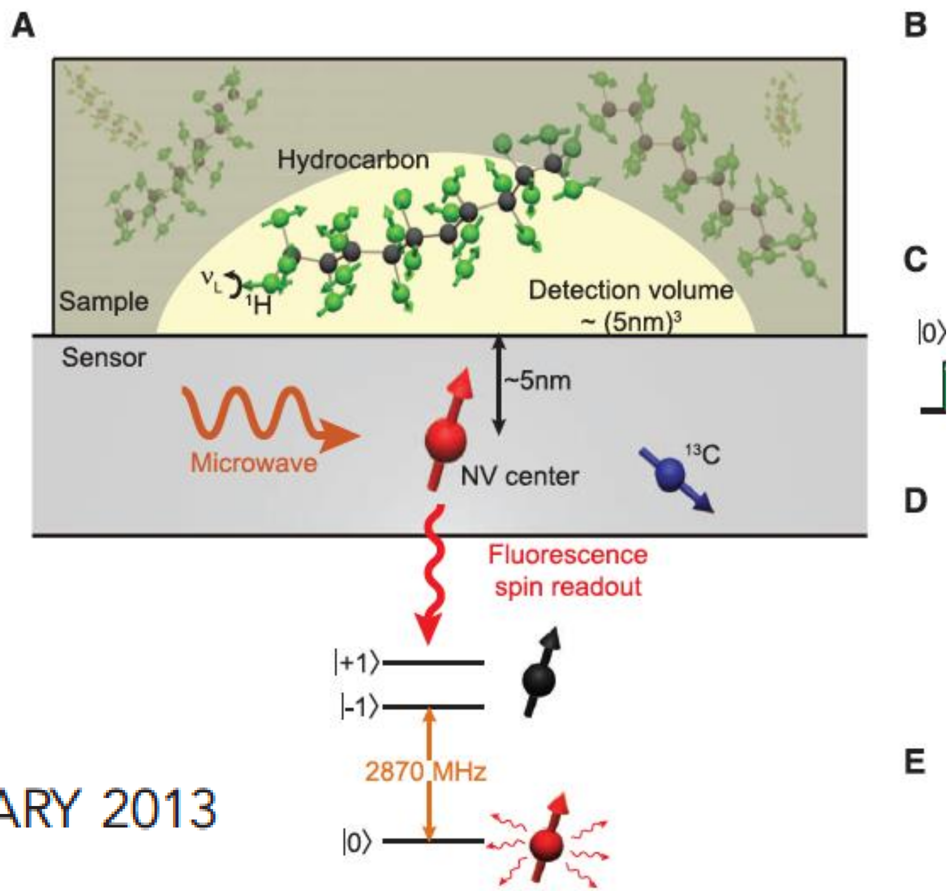
G. Balasubramanian, et al, Nature 455, 648 (2008).

Nuclear Magnetic Resonance Spectroscopy on a

Sar

T. Staud [4] J. Me
F. Reinh





SCIENCE VOL 339 1 FEBRUARY 2013

Atomic-scale nuclear spin imaging using quantum-assisted sensors in diamond

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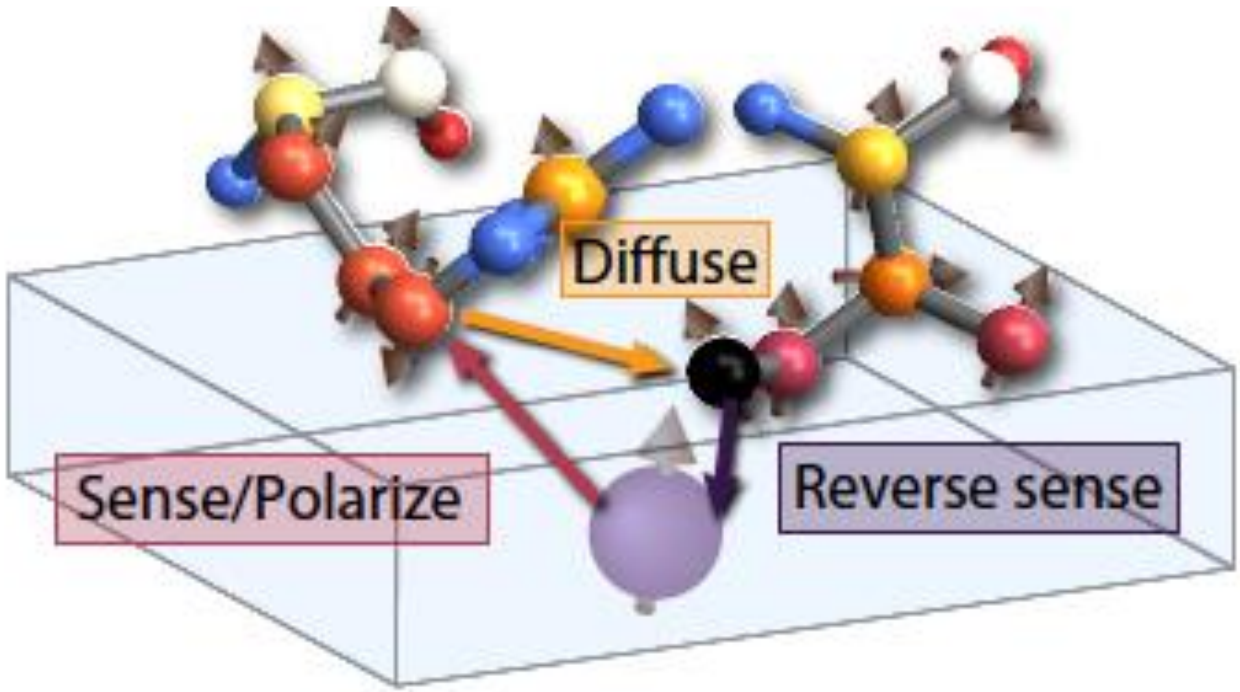
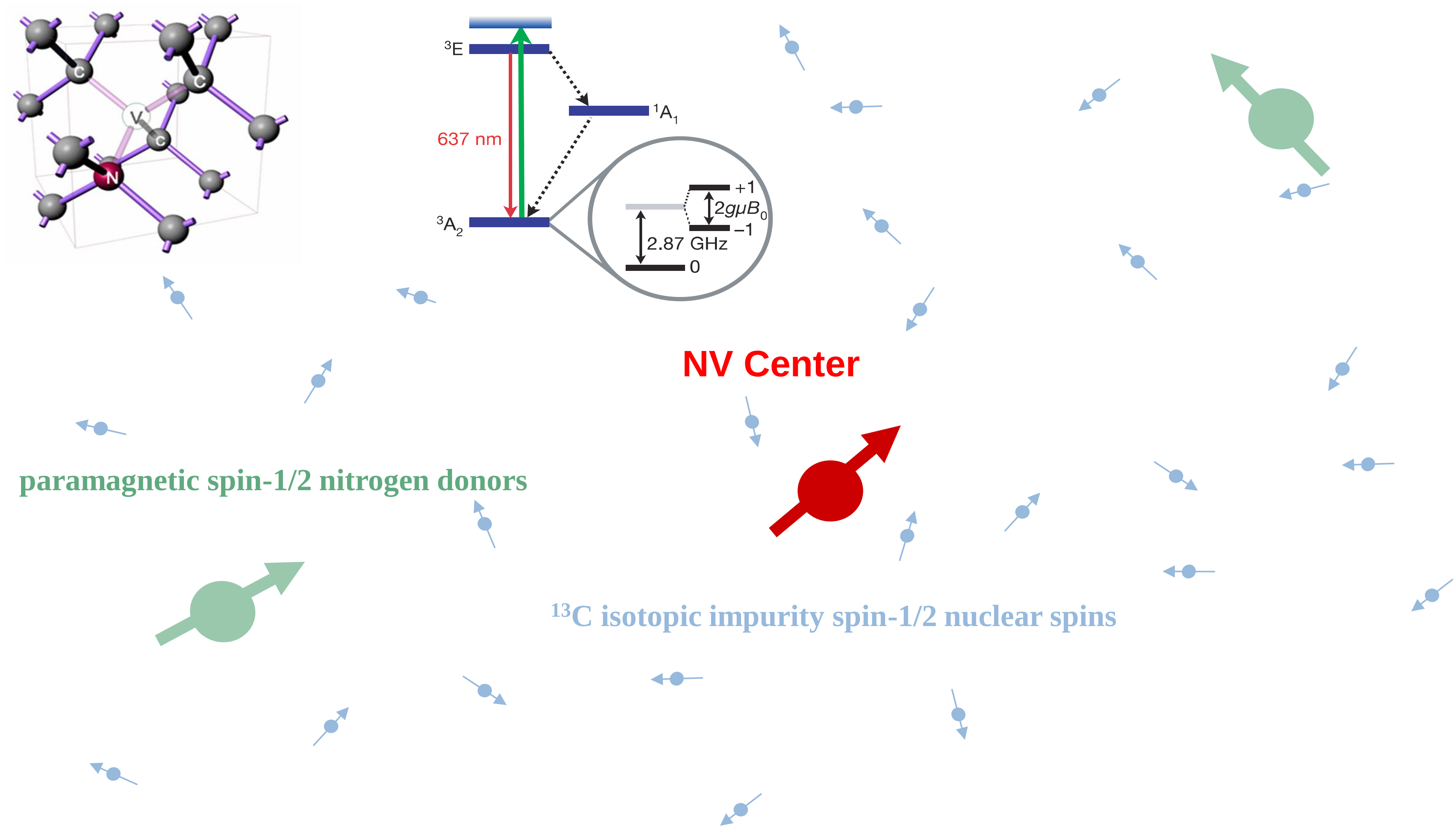
[*]Research Laboratory of Electronics and Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA,[†]Singapore University of Technology and Design, 138682 Singapore,[‡]Physics Department Harvard University, and [§]Harvard-Smithsonian Center for Astrophysics and Center for Brain Science, Cambridge, Massachusetts 02138, USA



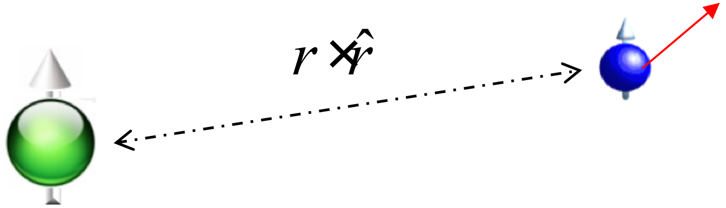
Decoherence of NV centers in diamond



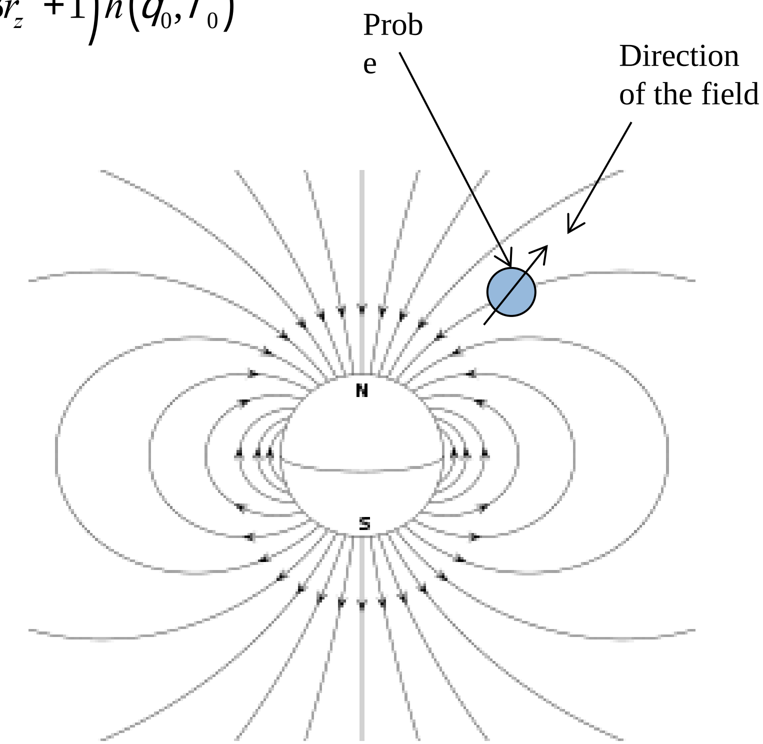
SIGNAL

NV in diamond

Measure position of a single nucleus: Idea



$$\vec{A} = \left(g\sqrt{3r_z^2+1}\right)\hat{h}\left(q_0, f_0\right)$$



Dipole - Dipole

↓

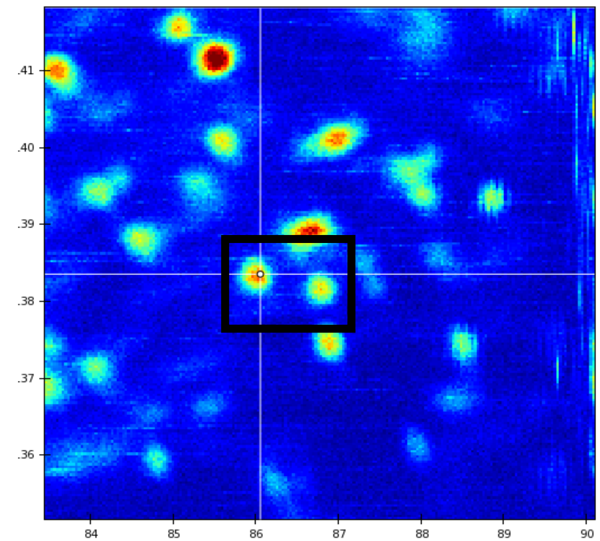
- Flip-flop process between NV sensor and target system

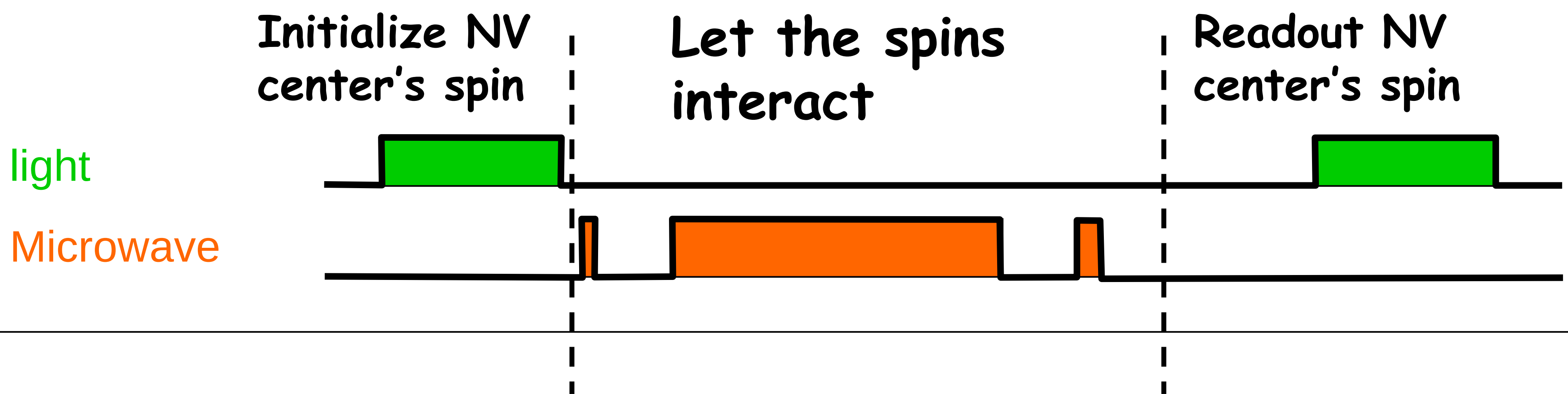
$$S(t) = \frac{1}{2} + \frac{1}{4}\left[1 + \cos\left(Jt\right)\right]$$

$$J = \frac{1}{4}\left[g(r)\sqrt{3r_z^2+1}\right]\left(1 - \left|\hat{h}\cdot\hat{b}\right|\right)$$

Experimental setup and procedure

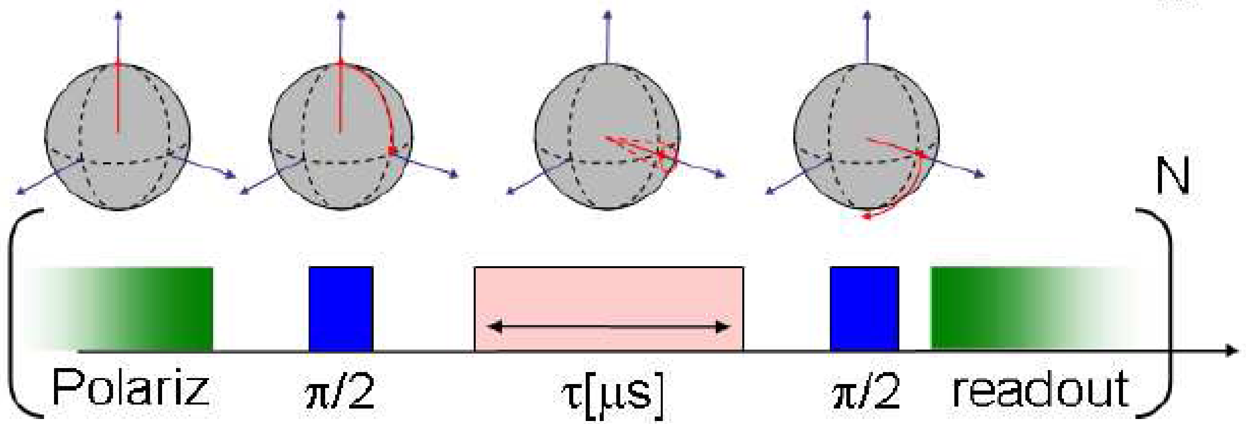
- Magnetic Field of 0.54T. Nuclear ^{13}C energy scale (Larmor frequency) at this field is ~6MHz.
- We apply the spin-locking sequence.
- The sequence is repeated ~10^5 times to average photons statistics.



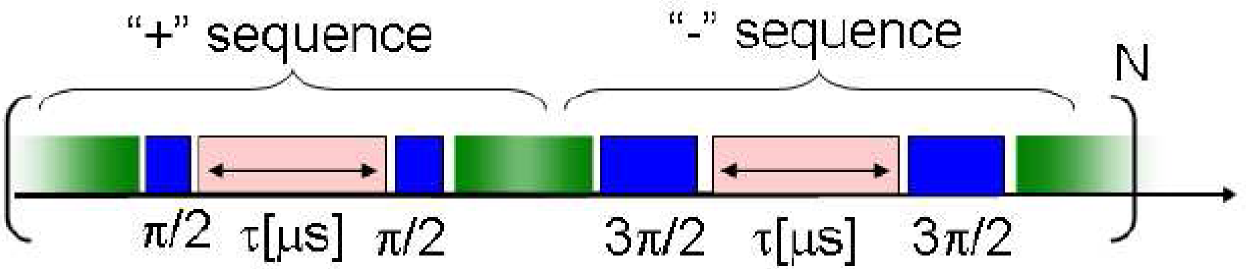


Experiment

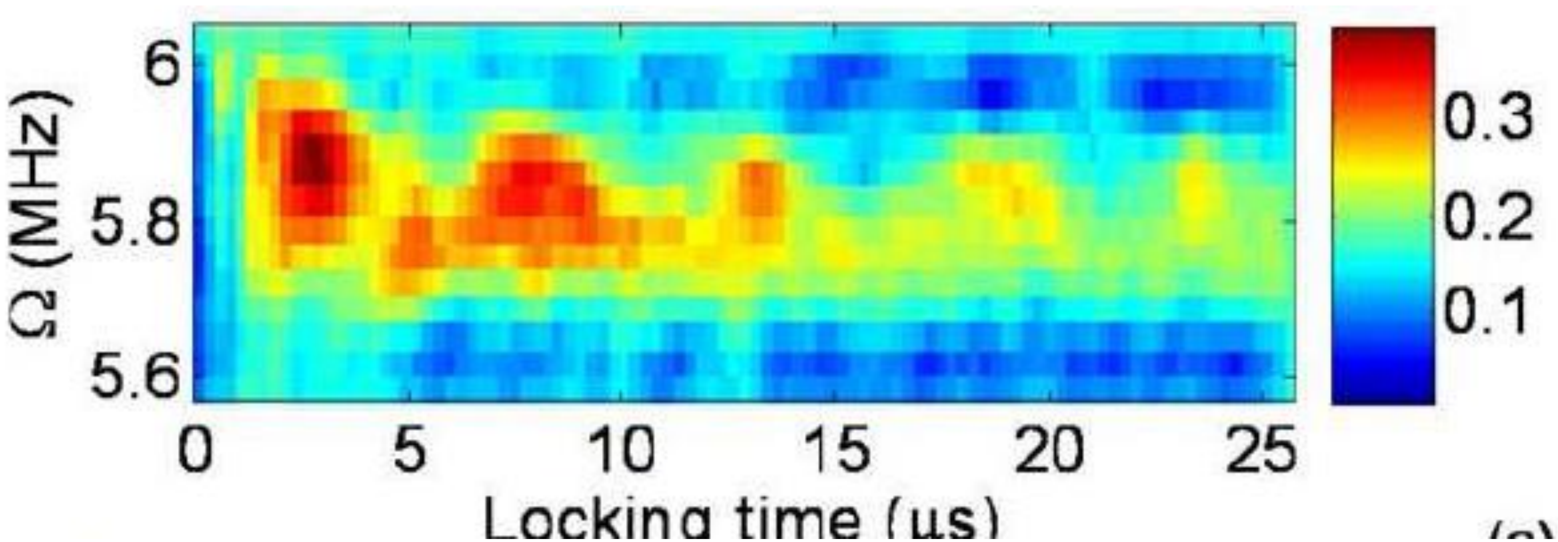
Non-Alternating, Polarizing sequence:



Alternating sequence:



Experiment



^{13}C located 0.43 nm from the NV center

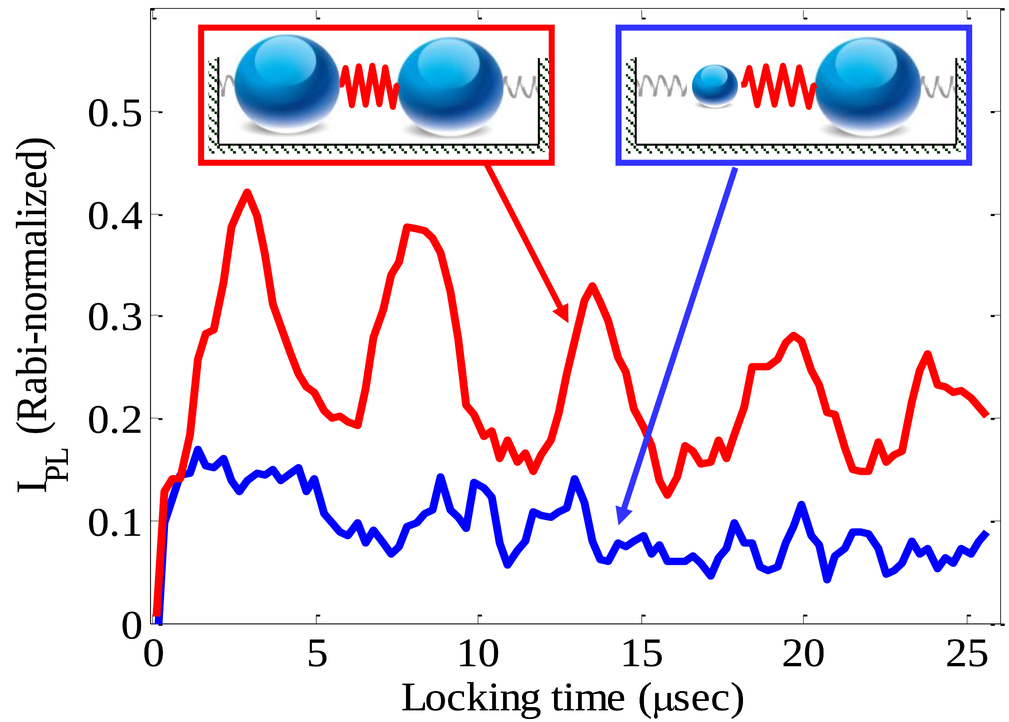
Precision of 0.5 Angstrom

Detecting and polarizing nuclear spins

Experimental results

Outside the double resonance, the NV center's spin is locked and decoupled from the environment

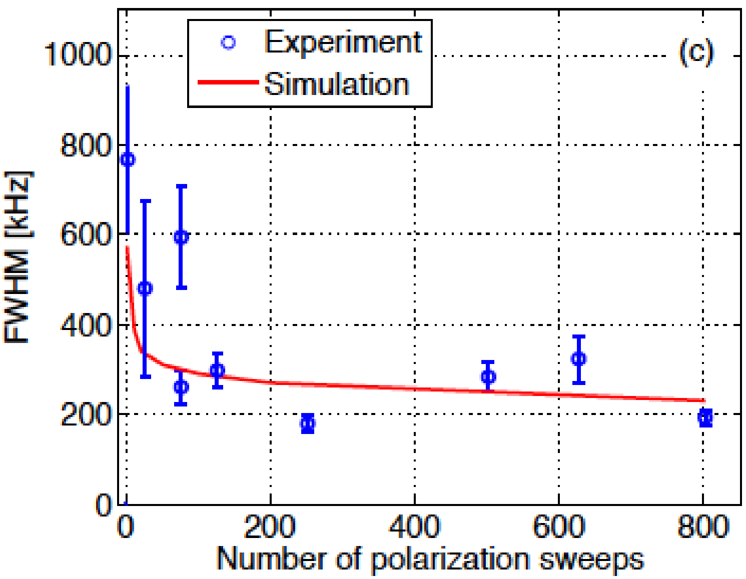
At resonance, we witness oscillations of population between the spins.

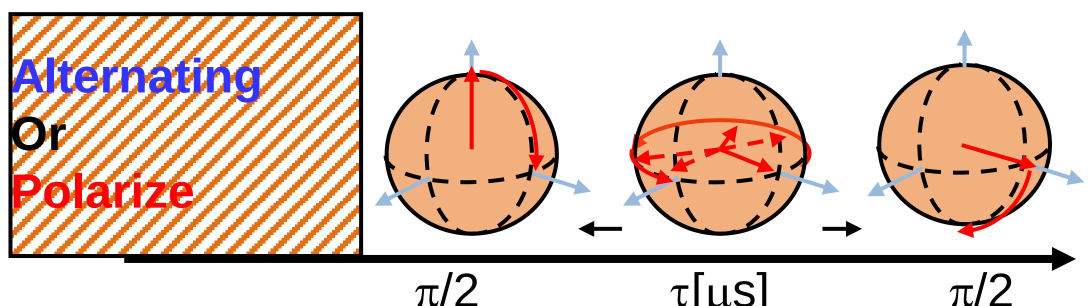


Polarizing Nuclei using Hartmann-Hahn sequence

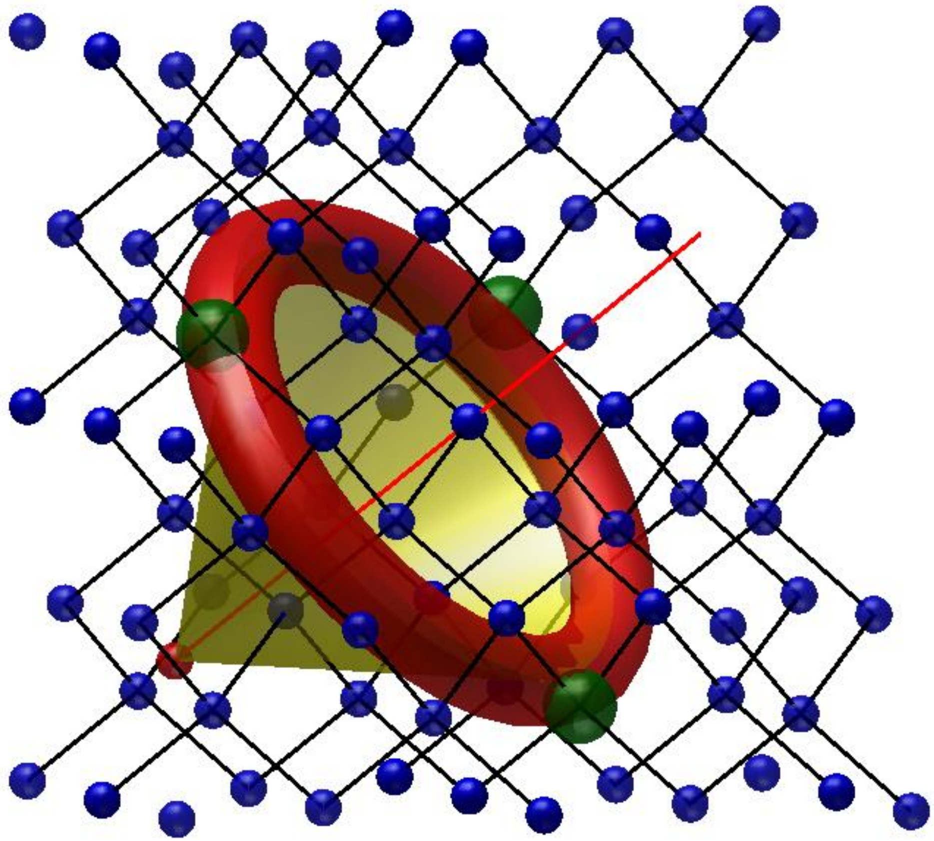
Polarization –Direct measurements

We can actually play with polarization by controlling the rates of the two sequences





Detecting and polarizing nuclear spins



Analong Quantum simulator

Proposed by Feynman
in 1982

Much easier than a quantum computer since does not require the usual error correction but a simplified version of it?

Digital Quantum Simulator

Seth Lloyd
1996

The idea behind this is the trotter decomposition and BCH

For two noncommuting operators

$$e^{ieH_1} e^{-ieH_2} \; 1 \; e^{ie(H_1 - H_2)}$$

However in the limit:

$$\left(e^{i\frac{\varepsilon}{n}H_1} e^{-\frac{\varepsilon}{n}H_2} \right)^n \xrightarrow[n \to \infty]{} e^{i\varepsilon(H_1 - H_2)}$$

Coherent control:

$$e^{eH_1 + eH_2} = e^{eH_1} e^{eH_2} e^{-\frac{e^2}{2}[H_1, H_2]} e^{e^3()} \ldots$$

Quantum Simulator: spin arrays

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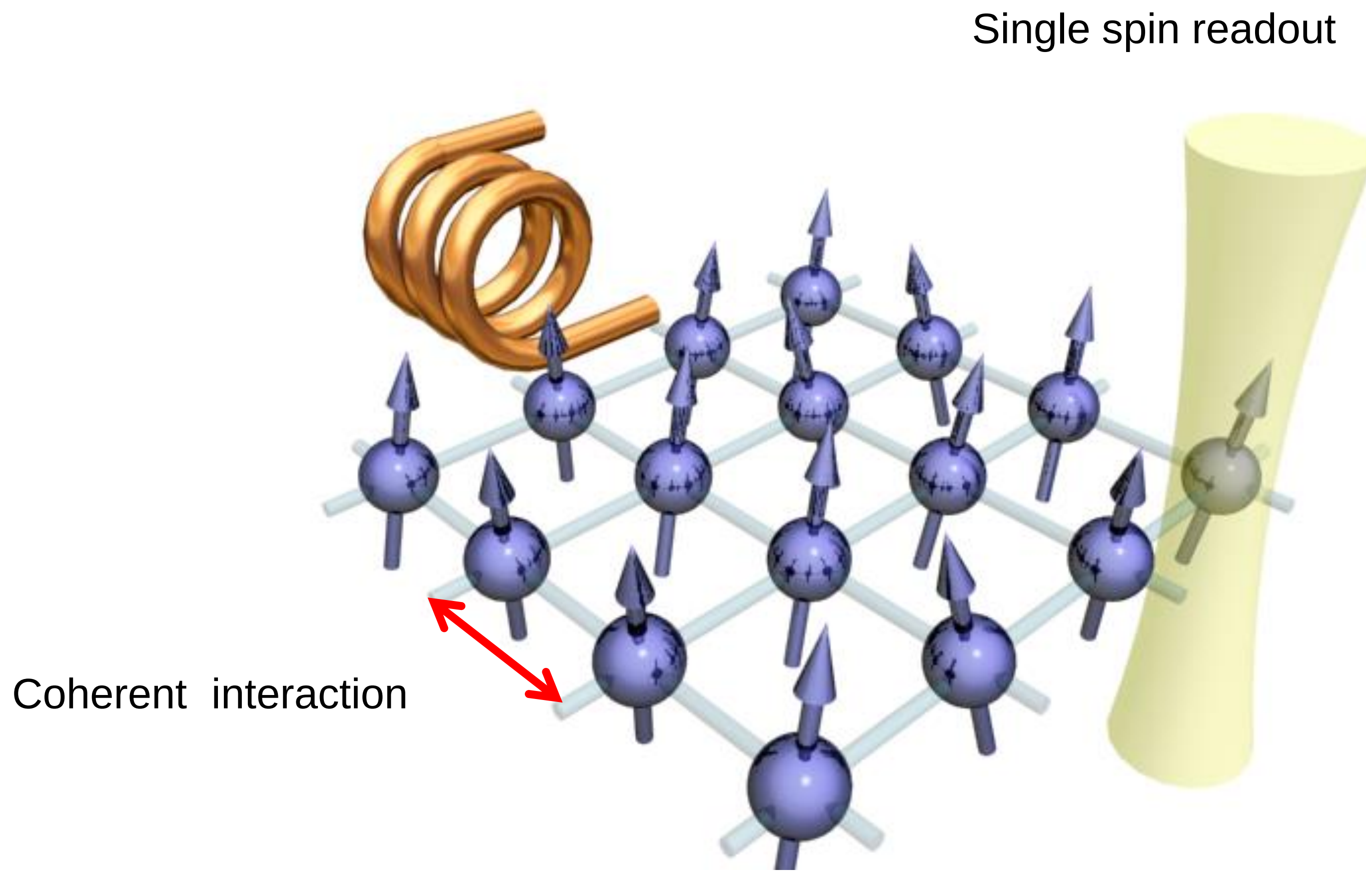
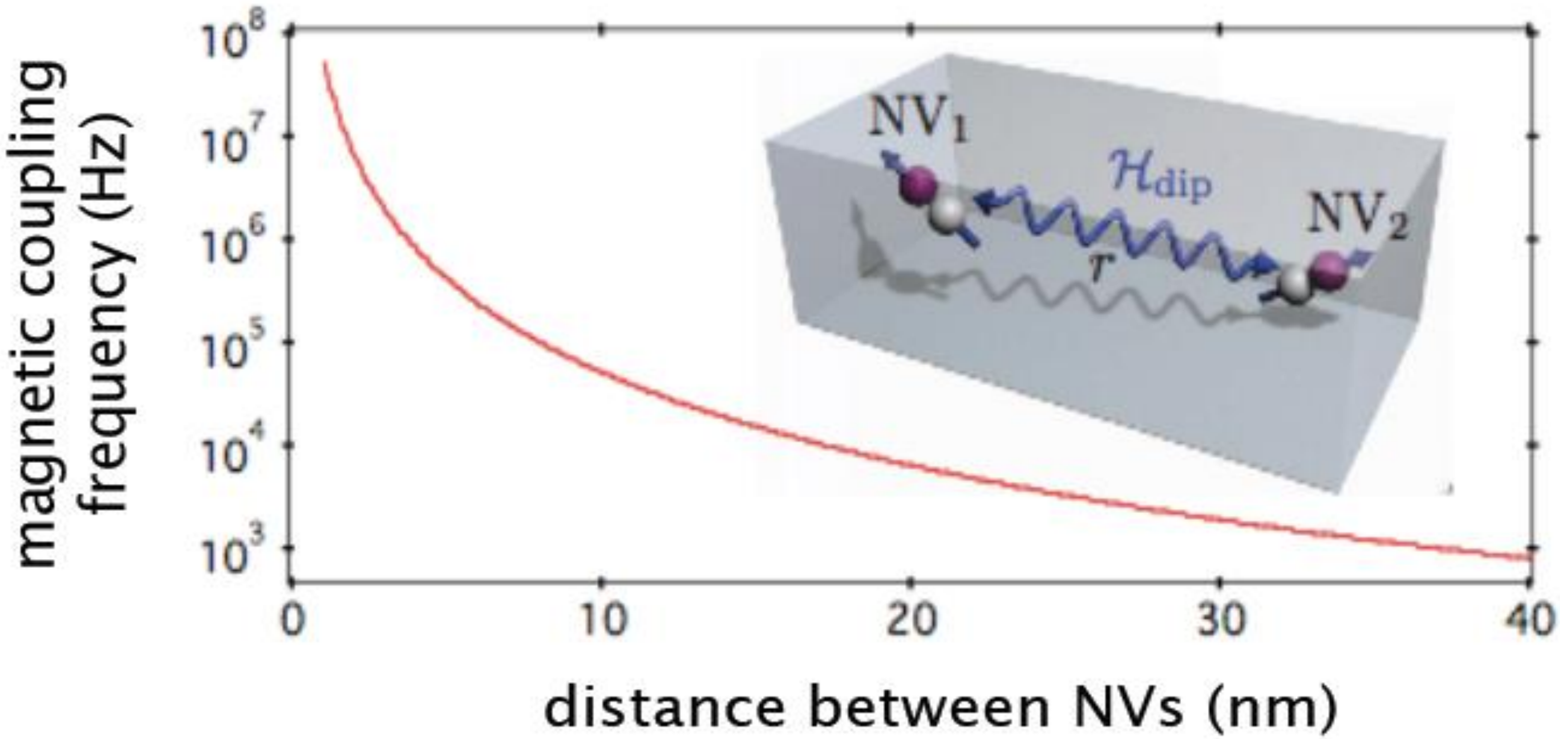


Magnetic dipole coupled spin arrays

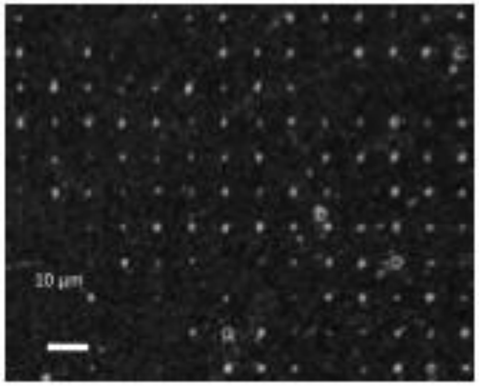
$$B^{dip} = \left(\frac{\mu_0}{4\pi} \mu \right) \sqrt{3\cos^2\theta - 1} \Big/ r^3$$

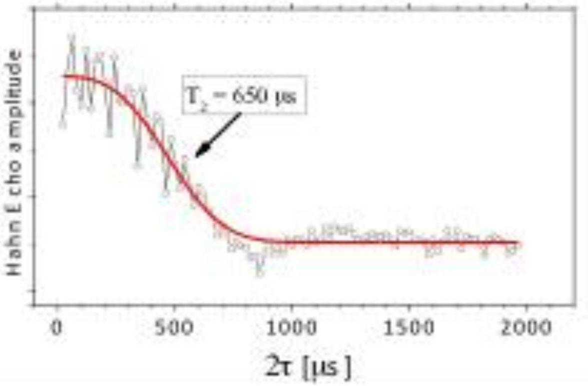


Challenge: creation and addressing single qubits

Bulck Diamond

Precision is limited by 1µm with regular implantation

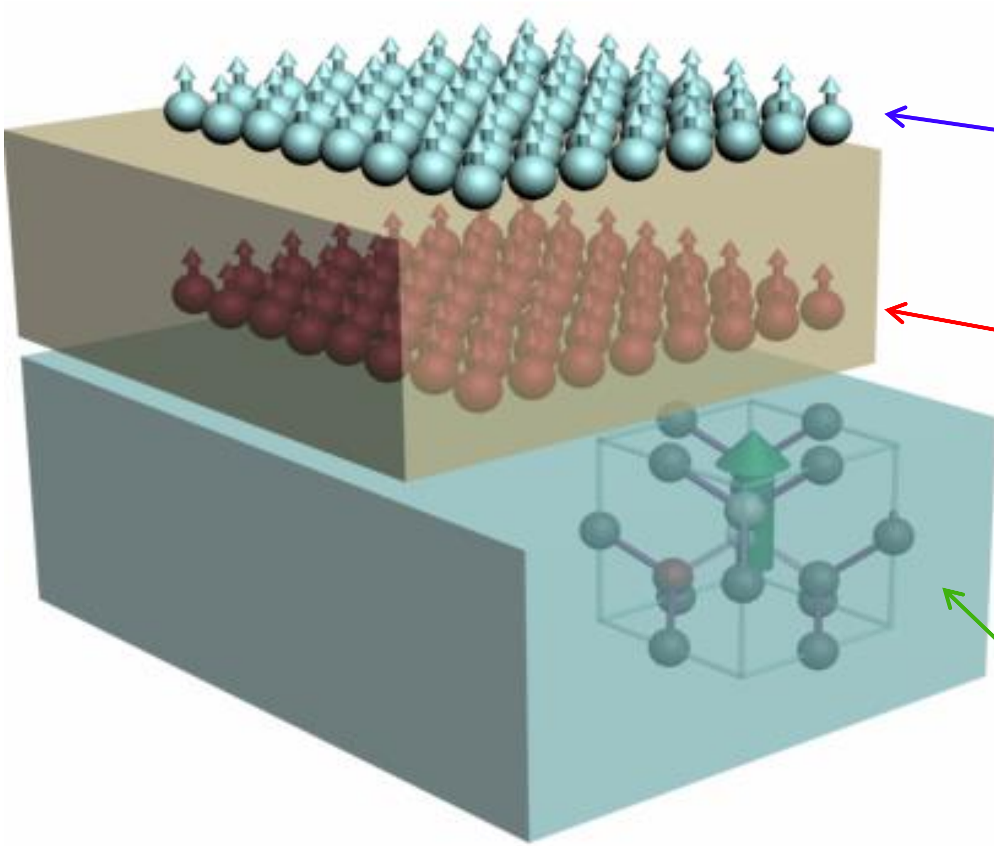




However, for dipole dipole interaction a distance of 10 nm is necessary

Diamond-based quantum simulator: architecture

Wolfgang Pauli: “God made the bulk;
the surface was invented by the devil”



Fluorine nuclear spins (directly linked to diamond or linked to a graphene sheet)

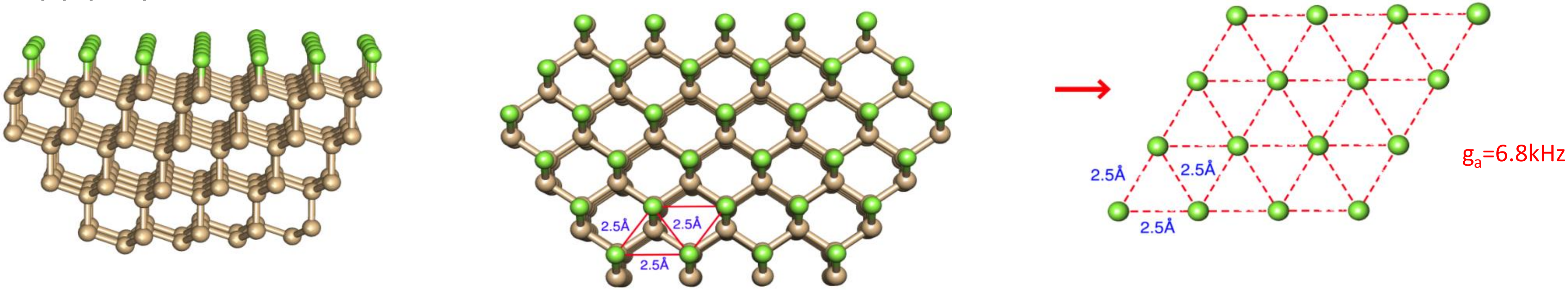
Electron and nuclear spin arrays in diamond (P donor, ^{13}C)

NV center in nuclear spin free ^{12}C diamond

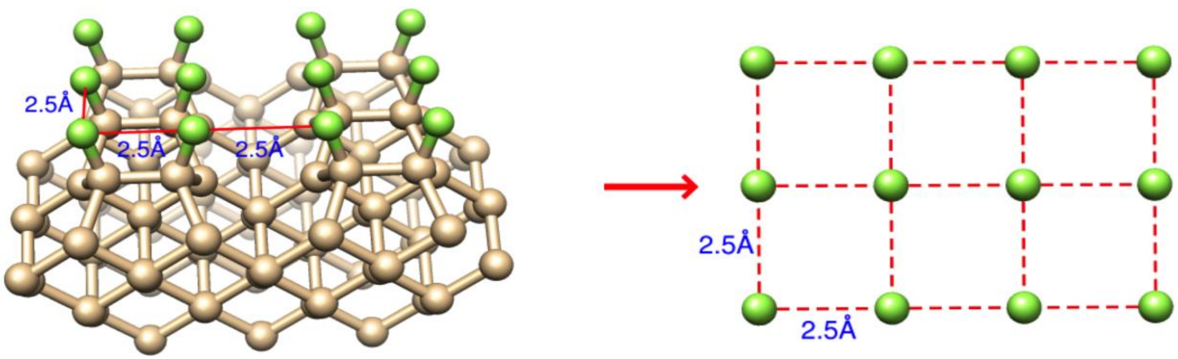
J.-M. Cai, AR , Fedor Jelezko, Martin B. Plenio, Nature Physics **9**, 168 (2013)

Diamond-based quantum simulator: architecture

(a) (111) surface



(b) (100) surface

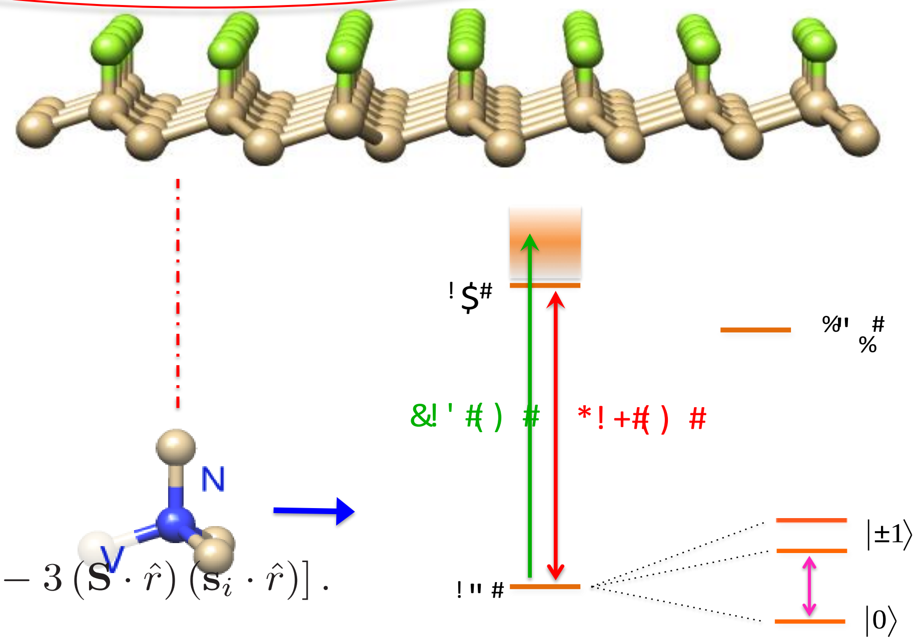


J.-M. Cai, , Fedor Jelezko, Martin B. Plenio, Nature Physics **9**, 168 (2013)

Nuclear spin quantum simulator on diamond surface

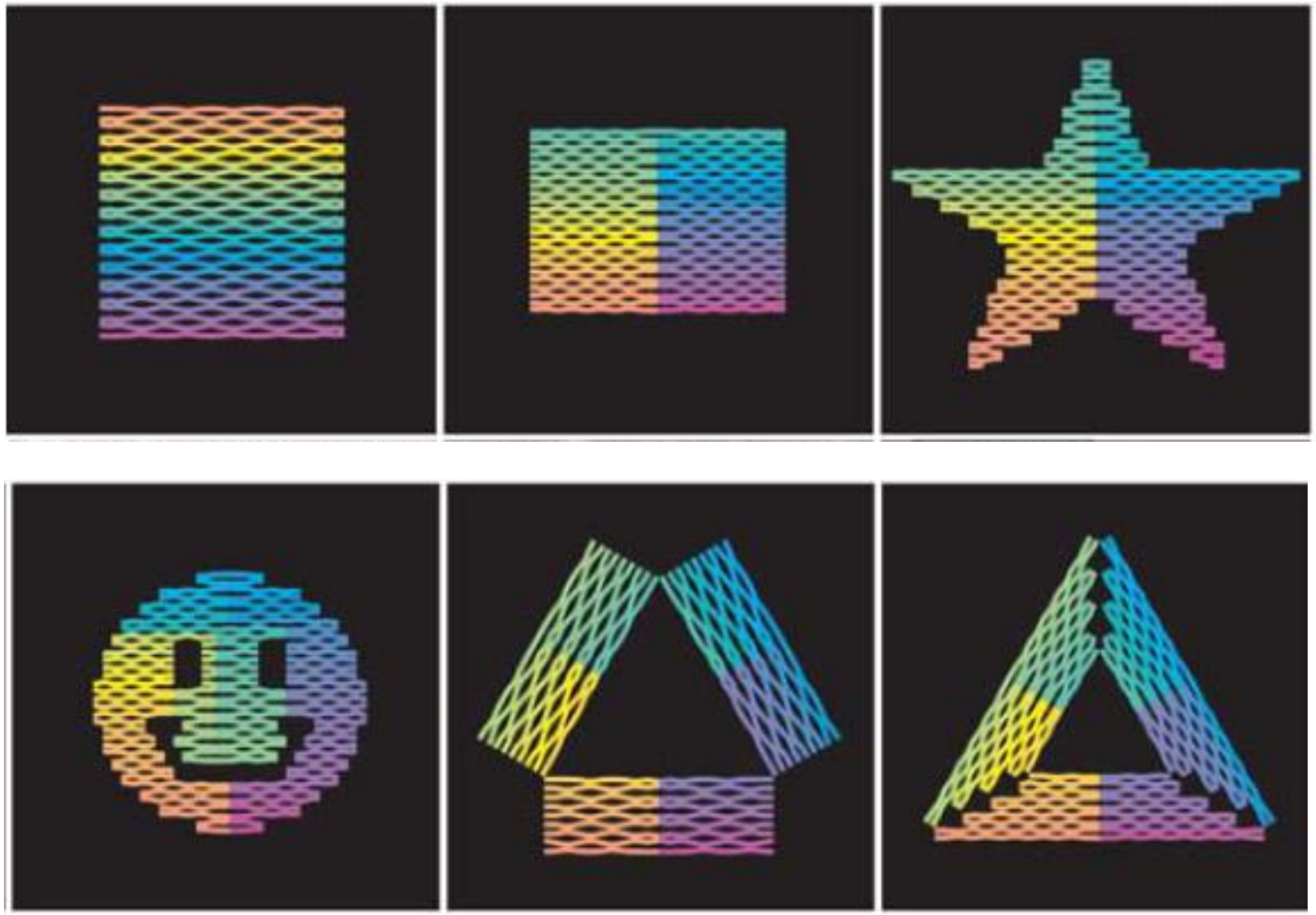
$$H_{\mathrm{F}} = \sum_i \gamma_N \mathrm{B} \mathbf{s}_i^z + \frac{\mu_0}{4\pi} \sum_{i,j} \frac{\gamma_N^2}{r_{ij}^3} \left[\mathbf{s}_i \cdot \mathbf{s}_j - 3 \left(\mathbf{s}_i \cdot \hat{\mathbf{r}}_{ij} \right) \left(\mathbf{s}_j \cdot \hat{\mathbf{r}}_{ij} \right) \right] + 2\Omega_F \cos\left[(\gamma_N \mathrm{B} - \omega_F) t \right] \sum_i \mathbf{s}_i^x$$

$$H_{\mathrm{F}} = \sum_i \left(\omega_F \mathbf{s}_i^z + \Omega_F \mathbf{s}_i^x \right) + \sum_{i,j} g_{ij} \left[\mathbf{s}_i^z \cdot \mathbf{s}_j^z - \Delta \left(\mathbf{s}_i^x \cdot \mathbf{s}_j^x + \mathbf{s}_i^y \cdot \mathbf{s}_j^y \right) \right]$$

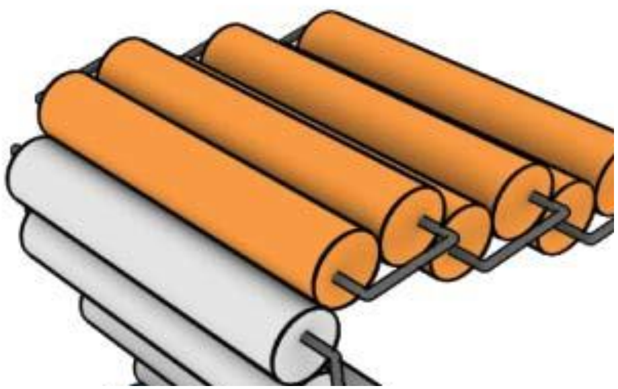


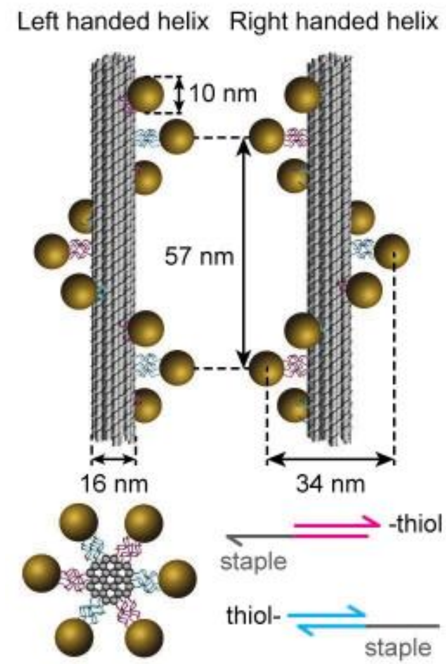
$$H_{\mathrm{NV-F}} = \frac{\mu_0}{4\pi} \sum_i \frac{\gamma_e \gamma_N}{r_i^3} \left[\mathbf{S} \cdot \mathbf{s}_i - 3 \left(\mathbf{S} \cdot \hat{r} \right) \left(\mathbf{s}_i \cdot \hat{r} \right) \right].$$

Rothemund's idea: DNA origami
Nature, 440, (2006)

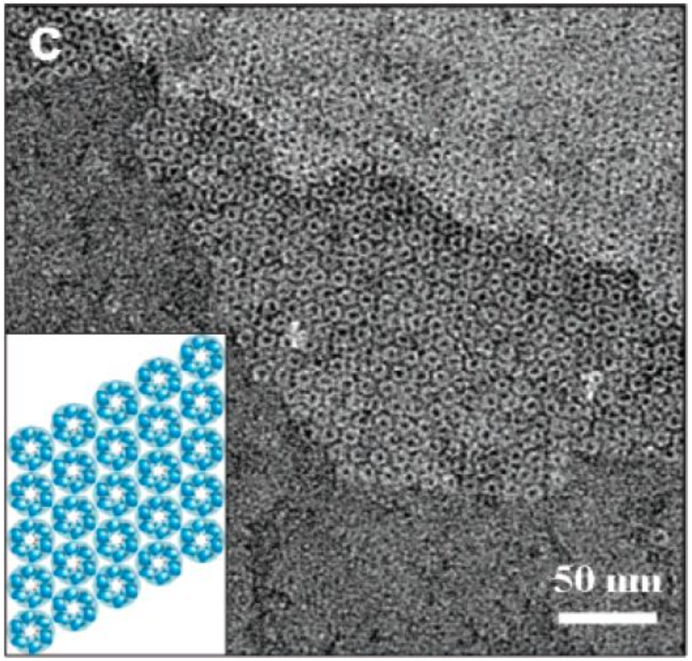


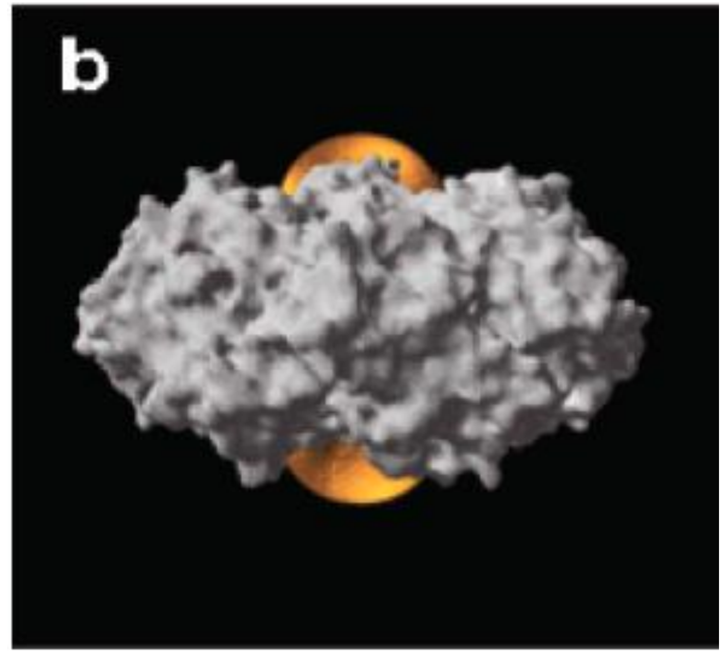
DNA origami and gold





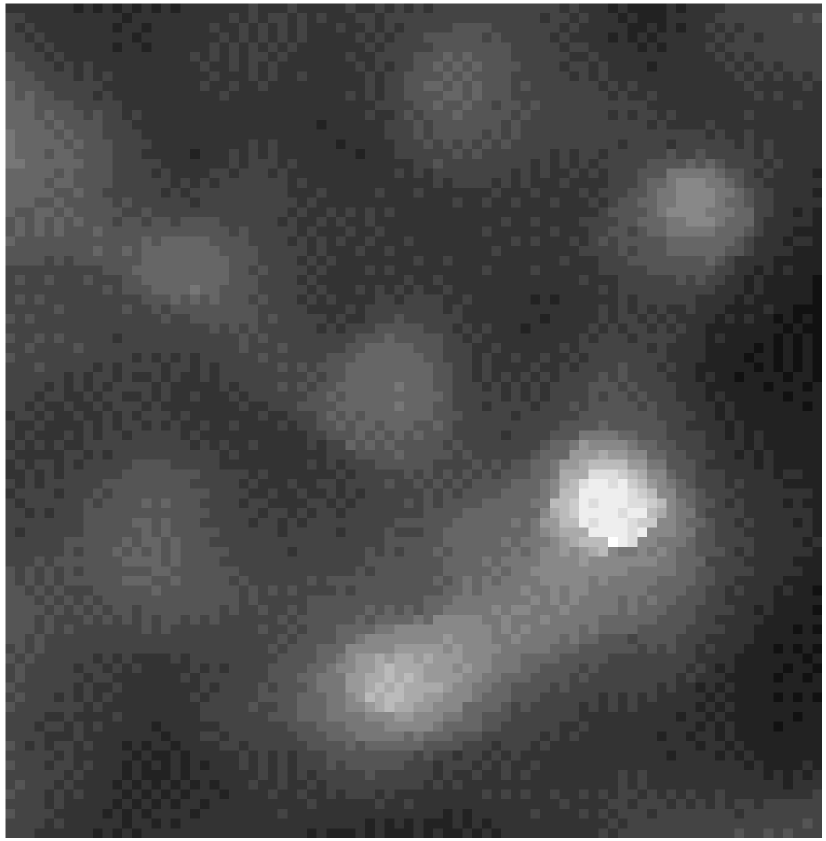
SP1 and gold





Oded Shoseyov and Danny Porath

SP1 and NV

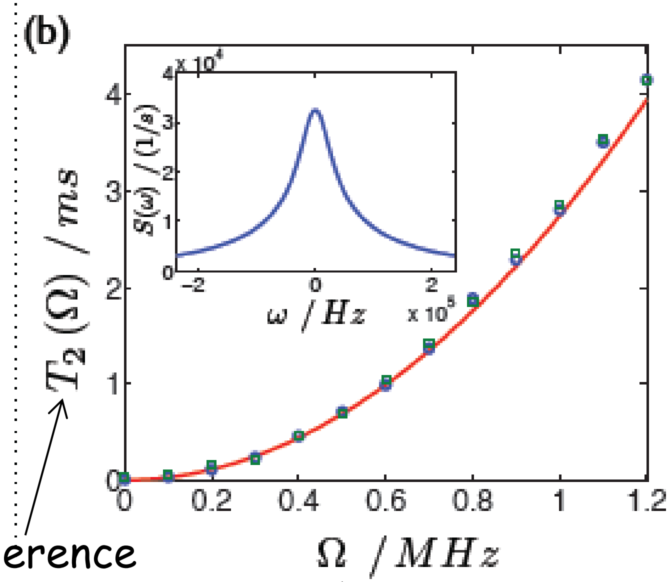


Andreas Albrecht, AR, Guy Koplovitz, Fedor Jelezko, Shira Yochelis, Danny Porath, Yuval Nevo, Oded Shoseyov, Yossi Paltiel, and Martin B Plenio arxiv:1301.1871

The Spin lattice

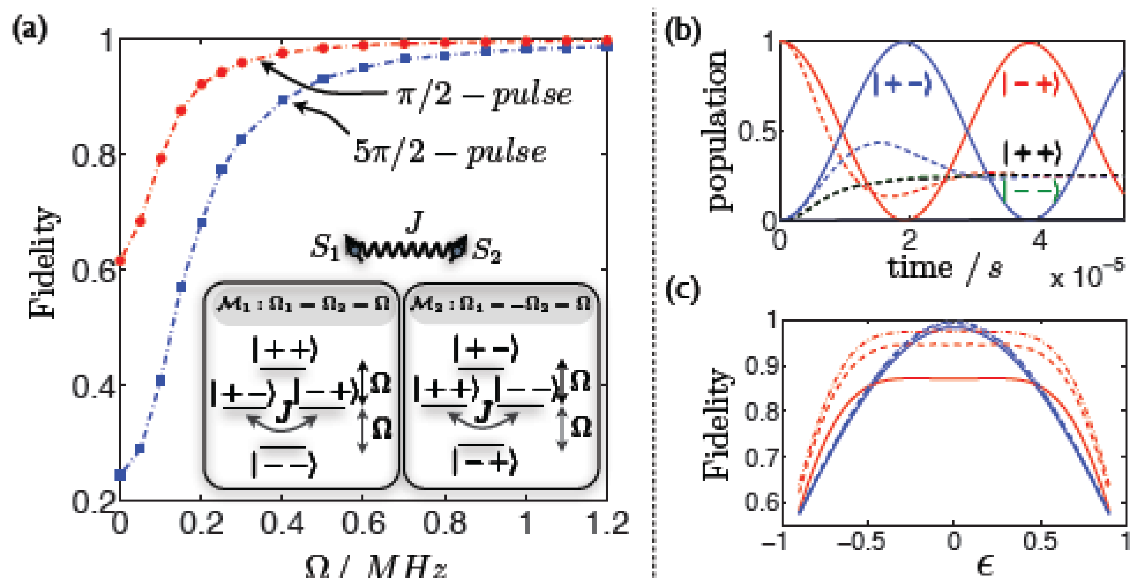
noise decoupling Dipolar coupling

$$H' \simeq \sum_i \frac{b_i(t)}{2}\,\sigma_z^i + \sum_i \frac{\Omega_i}{2}\,\sigma_x^i + \sum_{i>j} \frac{J_{ij}}{2}\,\sigma_z^i\,\sigma_z^j\,.$$



Coherence time

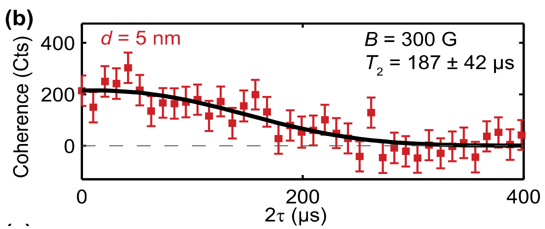
Rabi frequency of driving/ decoupling



In principle very versatile as a large set of Hamiltonians could be created digitally

Summary

- NV probe for measuring nuclear spin states – Quantum microscope
  - ☞ Readout a single nuclear (electron) spin state: quantum information processing
    - Ψ Selective coupling
    - Ψ Sensitivity limit : approaching to T_1
  - ☞ Probe many-body physics: towards a large-scale quantum simulator
    - Ψ A new platform based on NVs for quantum simulations
    - Ψ Complementary advantages to the other physical systems




Thank you!