NV Centers

Decoherence and Noise

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15 May 2014

Outline

- NV Centers
- Decoherence and dynamic decoupling
- Measurement setup
- Decoherence-protected quantum gates
- Outlook

Reference

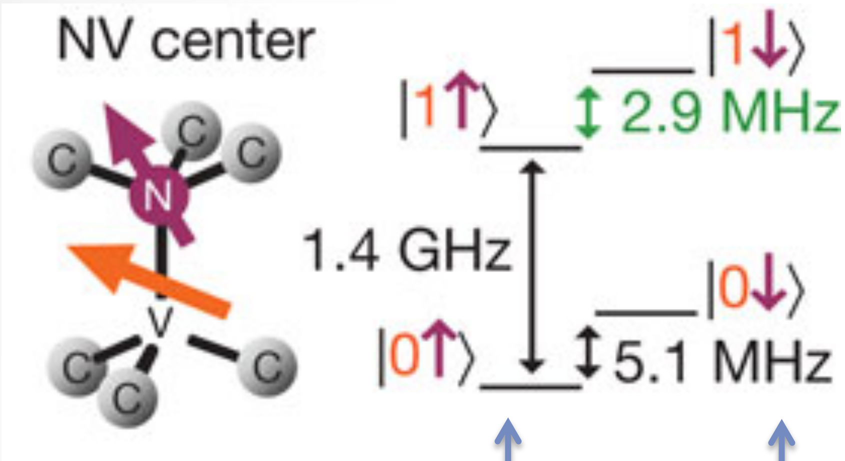
T. van der Sar, Z. H. Wang, M. S. Blok, H. Bernien, T. H. Taminiau, D. M. Toyli, D. A. Lidar, D. D. Awschalom, R. Hanson & V. V. Dobrovitski

Decoherence-protected quantum gates for a hybrid solid-state spin register

5 April 2012

doi:10.1038/nature10900

Diamond defect

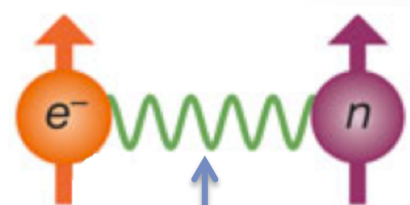


$|m_s\!=\!0> \equiv |0>$
$|m_s\!=\!1> \equiv |1>$ } Electron qubit levels

$|m_I\!=\!0> \equiv |\downarrow>$
$|m_I\!=\!1> \equiv |\uparrow>$ } Nuclear qubit levels

Zeeman interaction

Nuclear quadrupole + Zeeman interaction

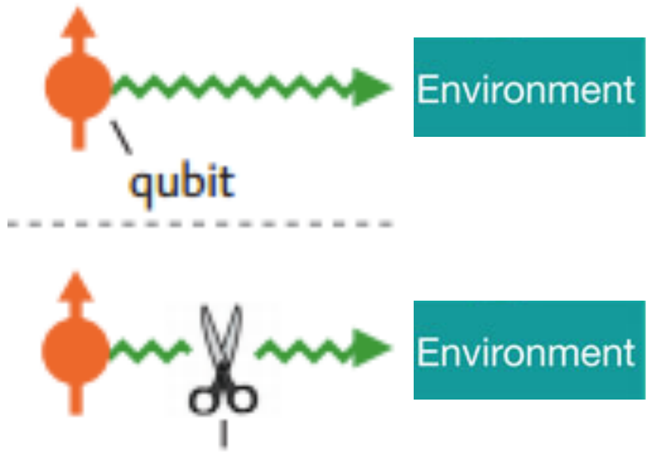


Hyperfine interaction

- **Origin of spin dephasing :**
  - bath of ^{13}C nuclear spins
  - electron spins of other nitrogen atoms

Quantum computation challenge

- **Decoherence** : the loss of information from a system into the environment



Decoupling

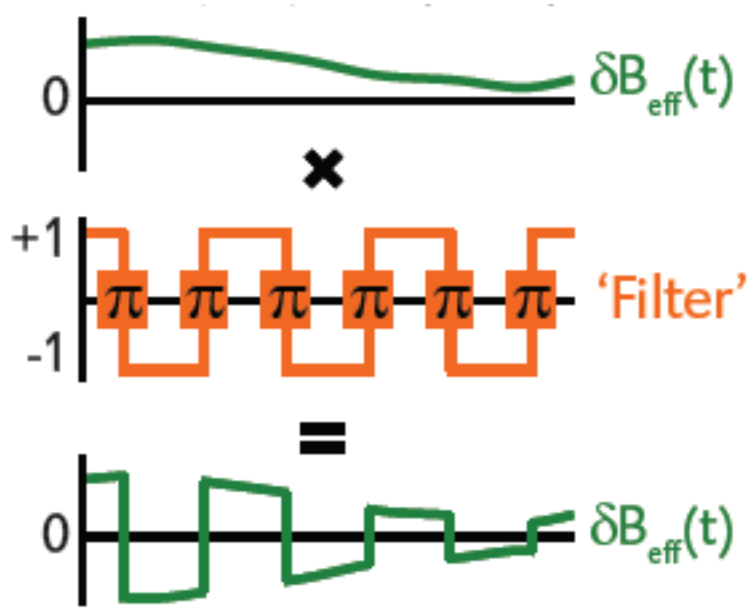
Most promising : dynamic decoupling

G. de Lange *et al. Ned. Tijdschr. v. Na.* **Januari**, 4, (2012)

Dynamic decoupling

- **Dynamic decoupling :** technique that uses <u>fast qubit flips</u> to average out the interactions with the environment

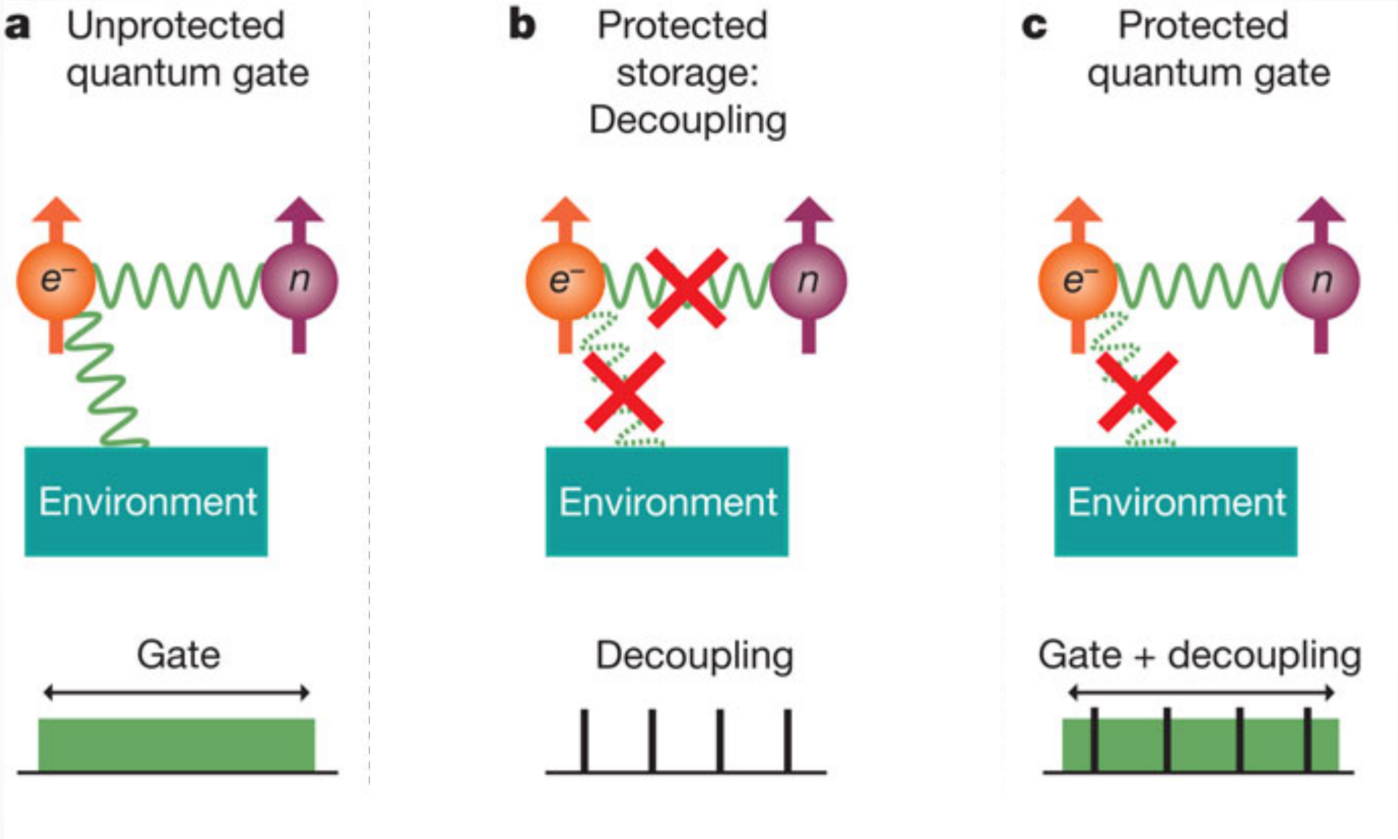
Principle:



From the electron spin's point of view, $\langle B_{eff} \rangle = 0$

G. de Lange *et al. Ned. Tijdschr. v. Na.* **Januari**, 4, (2012)

Hybrid system



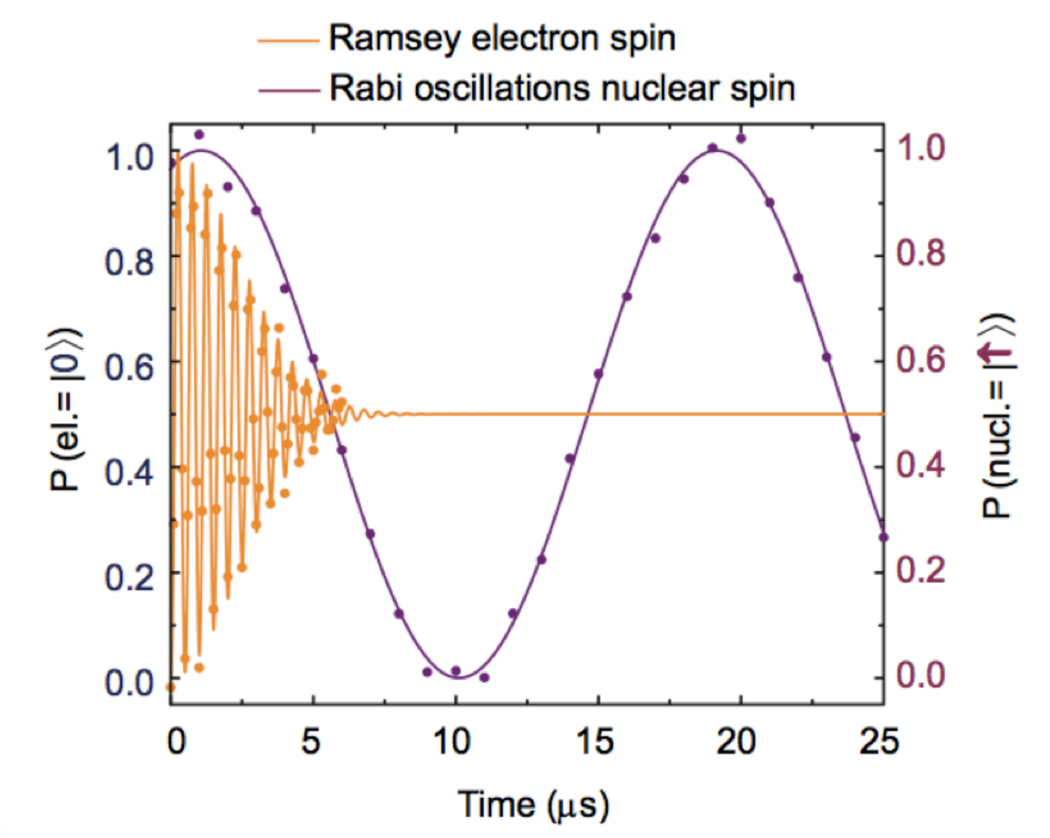
Difficulty

Decoupling spin

➔ supresses decoherence, but disrupts the electron-nucleus coupling

Hybrid system

Comparison between the timescale of the electronic and nuclear spins



Decoupling both electron and nuclear spin

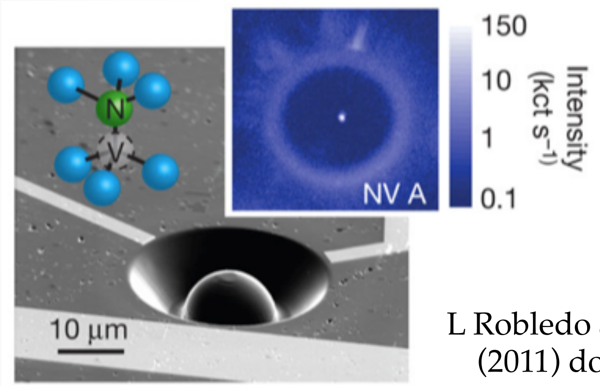
➔ nuclear spin dephasing time > 10 μs, e^- spin dephasing time T_2^*= 0.5-5 μs

Measurement setup

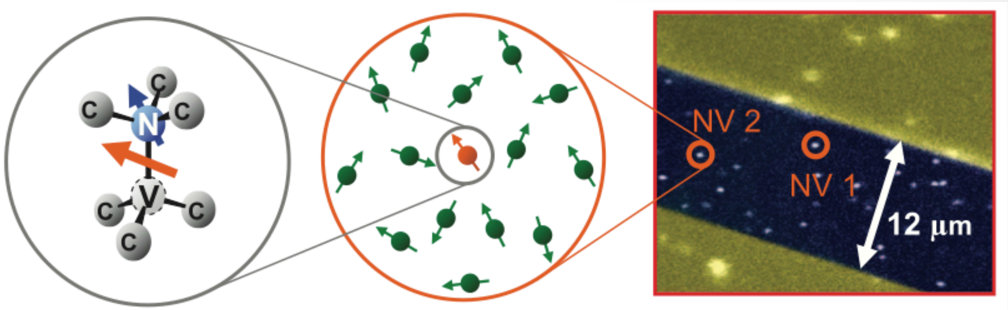
CVD grown diamond

Naturally occuring NV centers located 5-15μm below the surface

- Select NV centers



L Robledo *et al.* *Nature* **477**, 574-578, (2011) doi:10.1038/nature10401

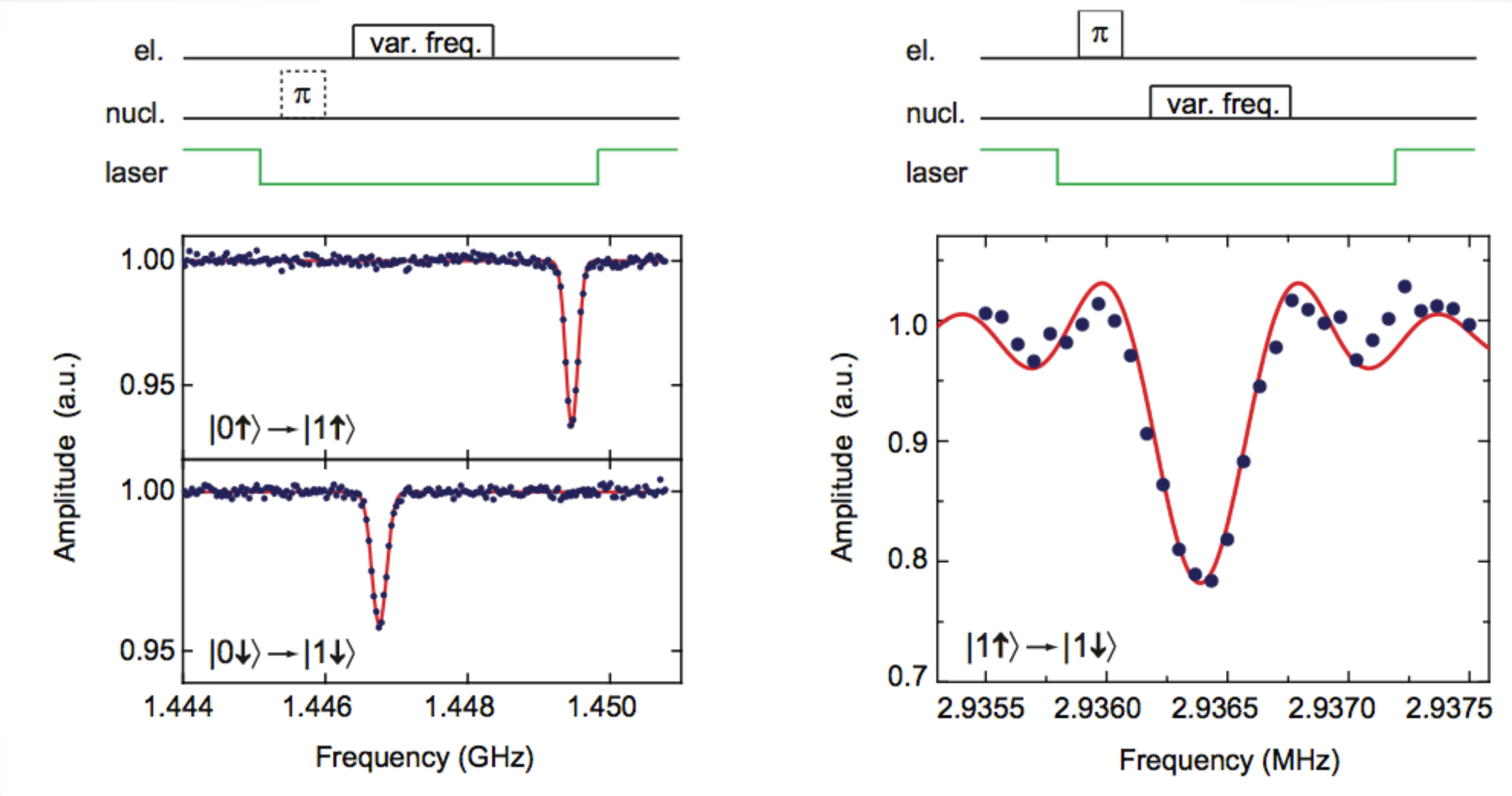


G. de Lange *et al.*, *Science* **330,** 60 (2010) doi: 10.1126/science.1192739

- Mill solid immersion lenses (SILs, 15 μm diameter) into the diamond surface with a focused ion beam
- Apply static magnetic field to lift degeneracy of e^- spin state
- Repeat each measurement typically 10^5-10^6 times to reduce the noise in the data to 1-5%

All experiments performed at RT

Electronic resonances



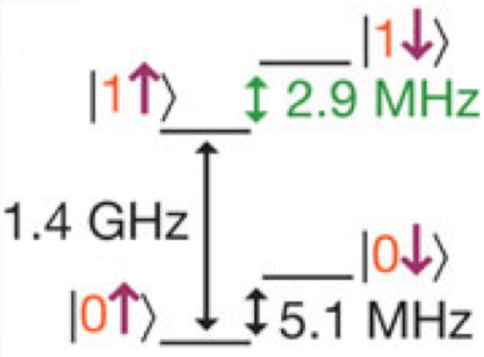
Detuning ➔ Hyperfine coupling constant
$A = 2\pi \cdot 2.16089(9)\ MHz$

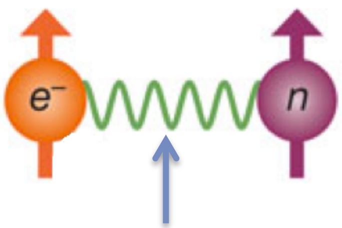
Protected quantum gates

- **Entangling gate between the 2 qubits**
- Decoupling from environment

Protected quantum gates

Entangling gate : Rabi driving at the frequency of the nuclear spin transition, conditioned on the electron spin state





Hyperfine interaction Hamiltonian : $\hat{H}_{\mathrm{hf}} = A\hat{I}_Z\hat{S}_Z$

$A = 2\pi \cdot 2.16\ MHz$

Nuclear and electron spin operators

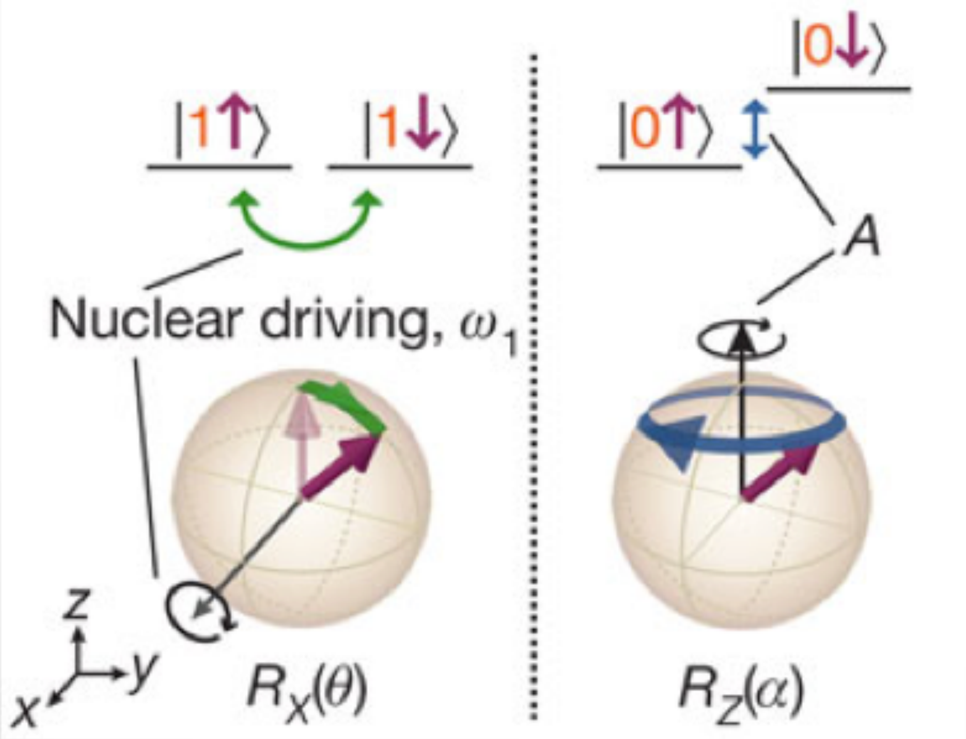
In rotating frame : $\hat{H} = A\hat{I}_Z\hat{S}_Z + \omega_1\hat{I}_X$

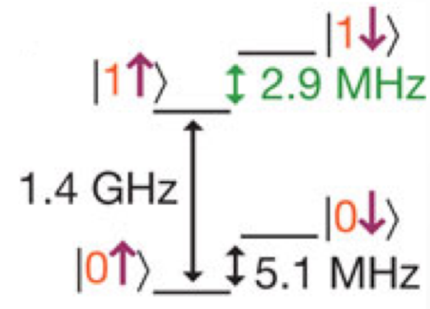
ω_1 : Nuclear Rabi frequency

Protected quantum gates

Entangling gate : Rabi driving at the frequency of the nuclear spin transition, conditioned on the electron spin state

In rotating frame with frequency
- 1.4 *GHz* in the e^- spin subspace
- 2.9 *GHz* in the nuclear spin subspace





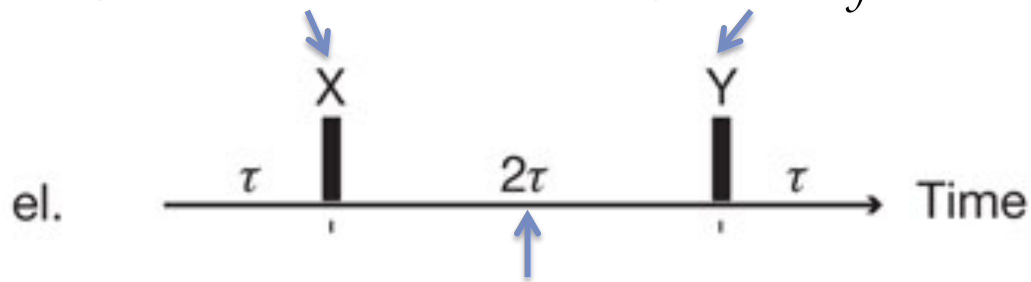
Protected quantum gates

- Entangling gate between the 2 qubits
- **Decoupling from environment**

Protected quantum gates

Decoupling from environment : Short microwave pulses that constantly switch the electron spin between states |0> and |1>

Decoupling pulses that flip the electron spin
around the *x* axis   around the *y* axis



Interpulse delay

Conditional rotation $\tau = (2n+1)\pi / A$

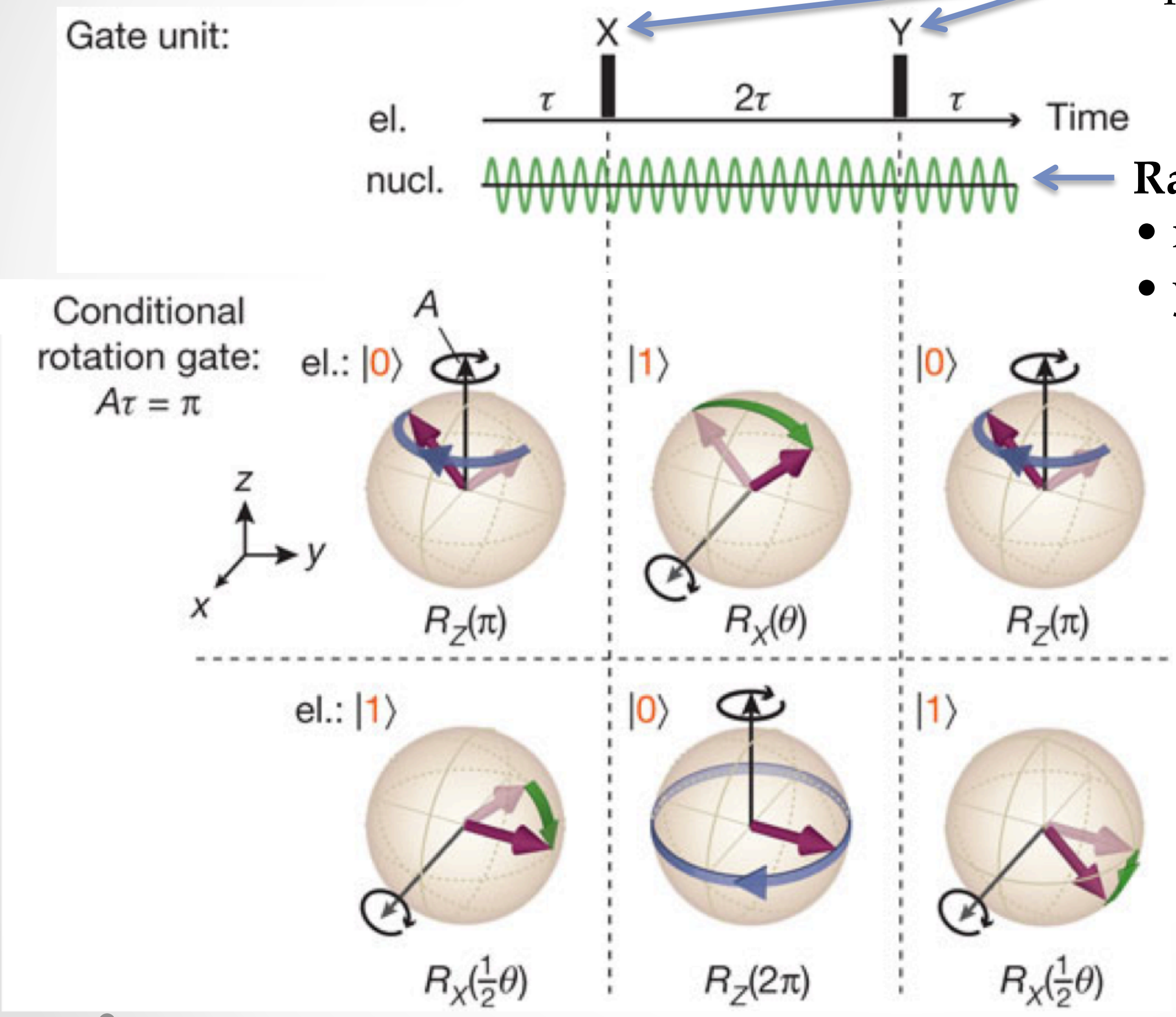
Nuclear spin rotates around the *z*-axis if electron in state |0>

- By 180° during interval τ
- By 360° during interval 2τ ➔ Zero net effect

Unconditional rotation $\tau = 2n\pi / A$

Protected quantum gates

Flipping microwave pulses



Rabi driving (2.9 *MHz*) around :

- x axis if e^- spin in state |1 >
- y axis if e^- spin in state |0 >

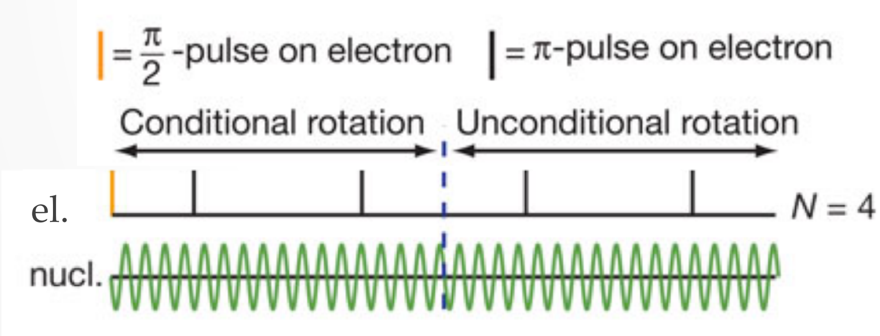
Decoupling pulses applied in resonance with rotation of nuclear spin :

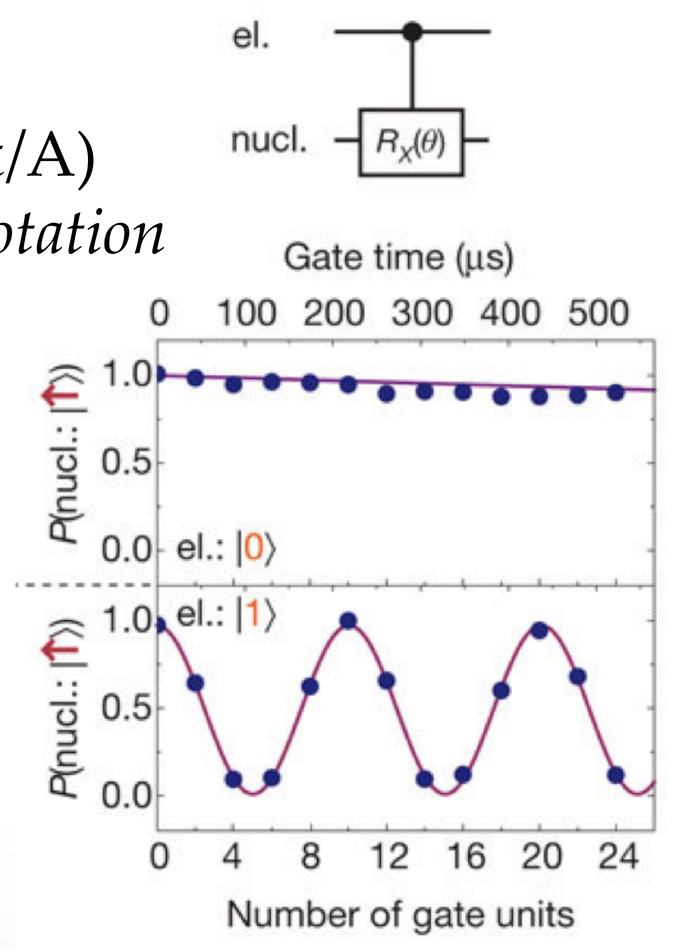
$\tau = (2n + 1)\ \pi/A$

CNOT gate

- From the conditional and unconditional rotations, can construct a complete sets of gates for the two-qubit register

CNOT:
- ***Conditional*** *nuclear spin rotation* (τ = π/A) *followed by* ***unconditional*** **(**τ = 2π/A) *rotation with the same angle around x axis*

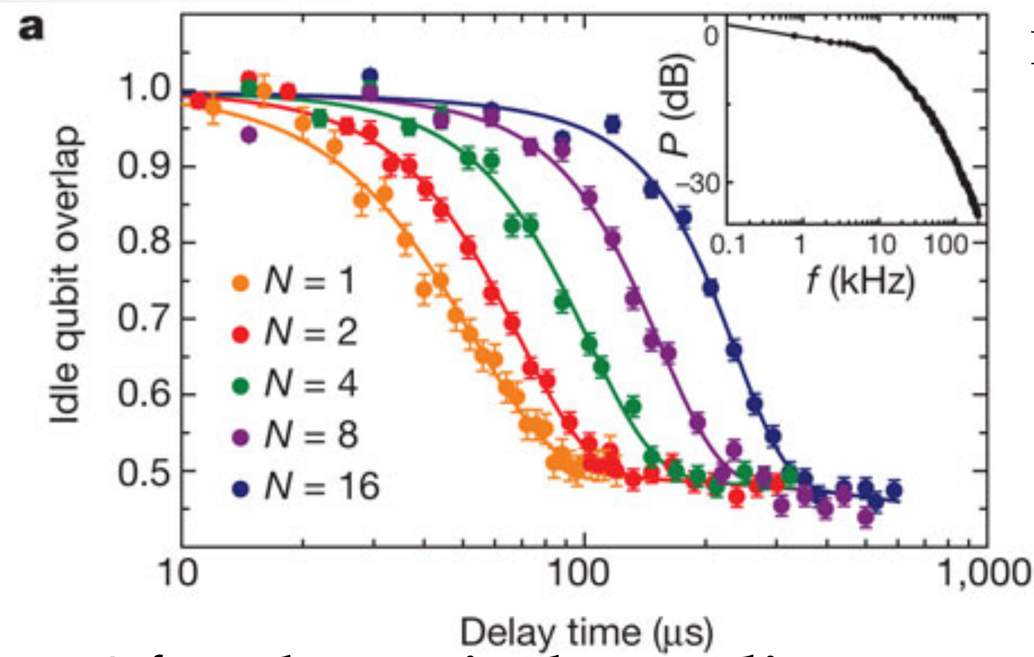




Gate is CNOT when: $\theta_{tot} = 180^{o}$

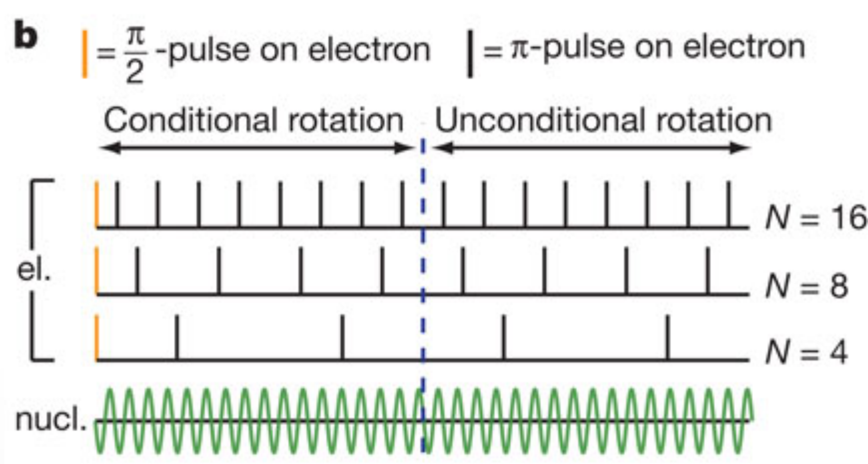
Stronger decoherence

- Inject low-frequency noise into system (electron spin decay time, T_2, shortens: 251(7) to 50(2) μs)
- Reduce nuclear driving power (~$2T_2$)



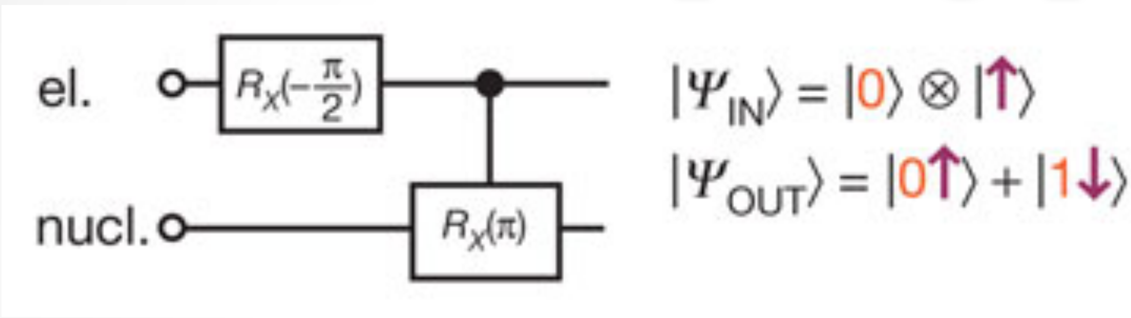
N = number of spin echoes

Total gate time = 120 μs



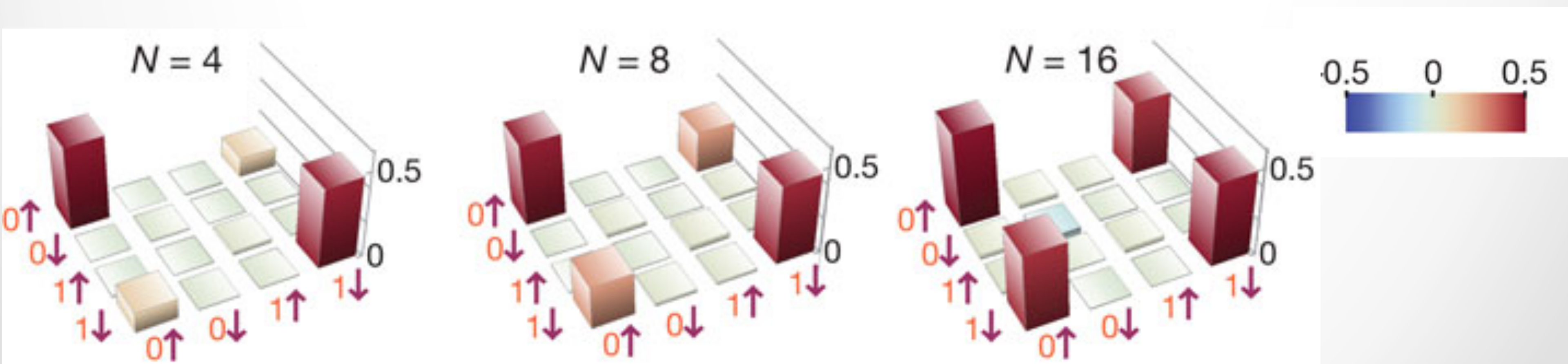
After dynamic decoupling:
Electron spin coherence time increases

Fidelity as function of decoupling pulses



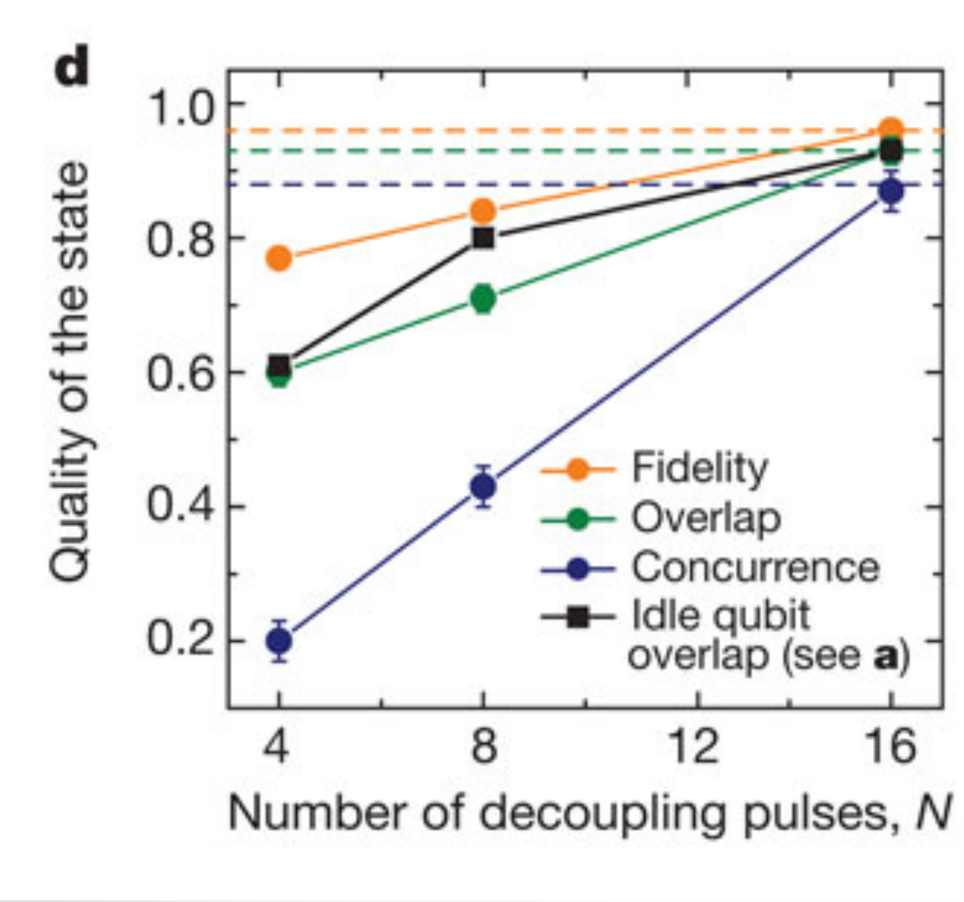
← Ideally

Actual measurement:
Coherence (corresponding to the off-diagonal elements) grows rapidly with number of pulses.



Comparison

- Gate performs similarly to how it does without introduced decoherence for N=16

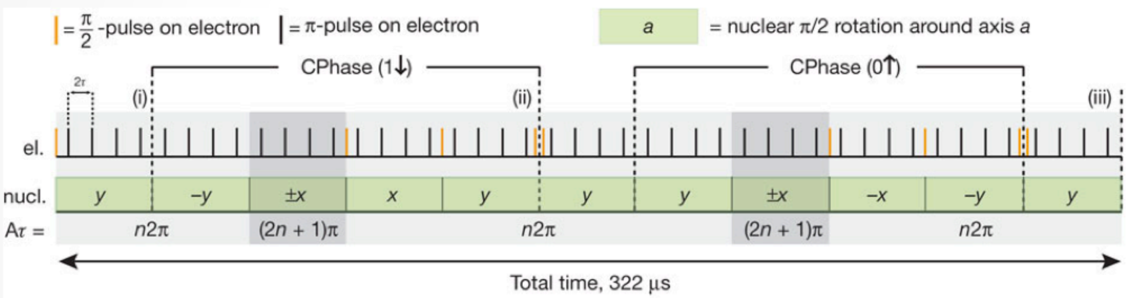


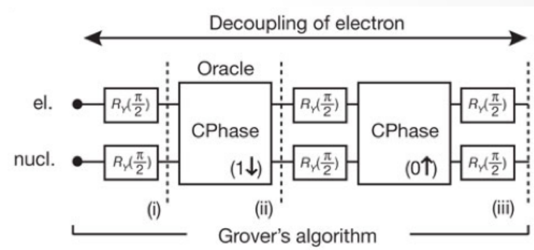
} Absence of induced decoherence

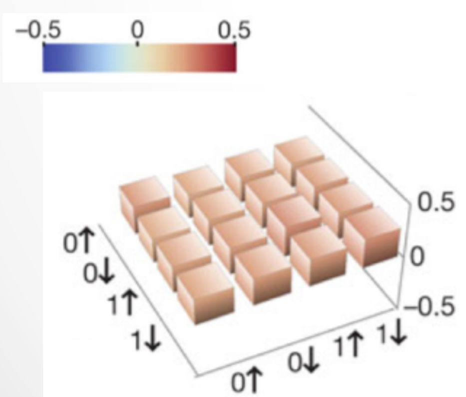
Grover's algorithm

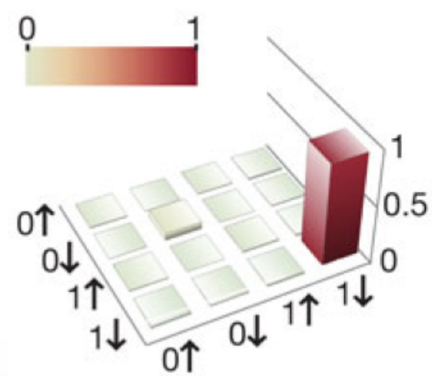
Electron spin's dephasing time : $T_2^* =$ **0.5-5 μs**
Total execution time : T = **332 μs**
} Need decoherence protection

Target state |1↓>





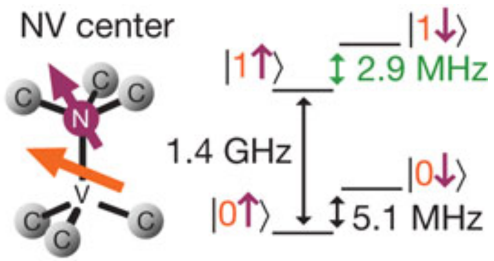




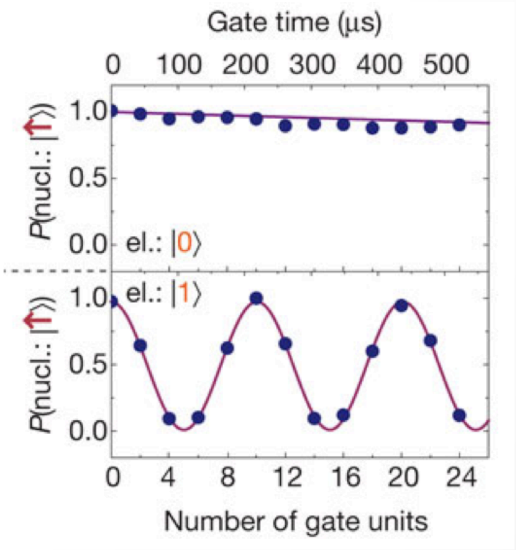
Target state	Fidelity of resulting state [%]
|1↓>	95 (1)
|1↑>	92 (1)
|0↓>	91 (2)
|0↑>	91 (1)

Conclusion

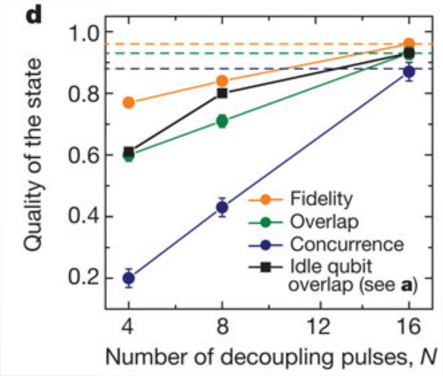
- Hybrid system
  - *Electron spin*
  - *^{14}N nuclear spin*



- Perform dynamical decoupling during gate operation
  - *High-fidelity gates*
  - *High-fidelity algorithm execution*



- Induced stronger decoherence
  - *Effects canceled after sufficient decoupling*



Outlook

- Quantum error correction
  - G. Waldherr, Y. Wang, S. Zaiser, M. Jamali, T. Schulte-Herbrüggen, H. Abe, T. Ohshima, J. Isoya, J. F. Du, P. Neumann & J. Wrachtrup
    Quantum error correction in a solid-state hybrid spin register
  - T. H. Taminiau, J. Cramer, T. van der Sar, V. V. Dobrovitski & R. Hanson
    Universal control and error correction in multi-qubit spin registers in diamond

- Quantum-information processor
  - A. Bermudez, F. Jelezko, M.B. Plenio & A. Retzker
    Electron-mediated nuclear-spin interactions between distant Nitrogen-Vacancy centers

Thank you for your attention !