Colour Centers for Quantum Technologies

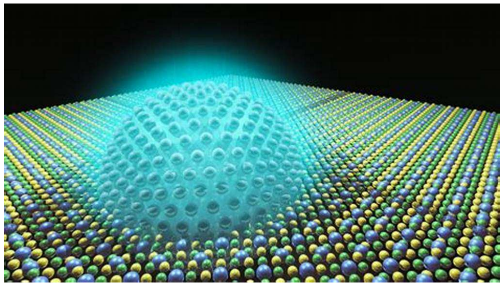
Martin B Plenio

Institute of Theoretical Physics
&
Center for Quantum-BioSciences

Ulm University

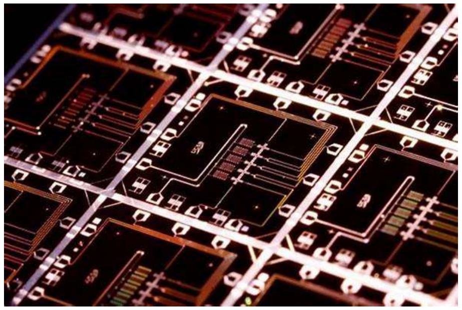
Qubits

Quantum Dots



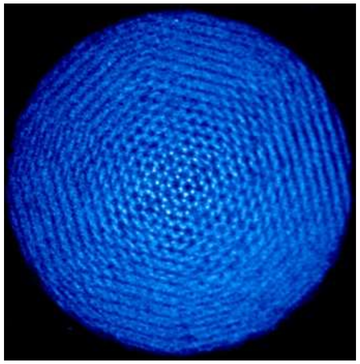
JQI Maryland

Superconductors



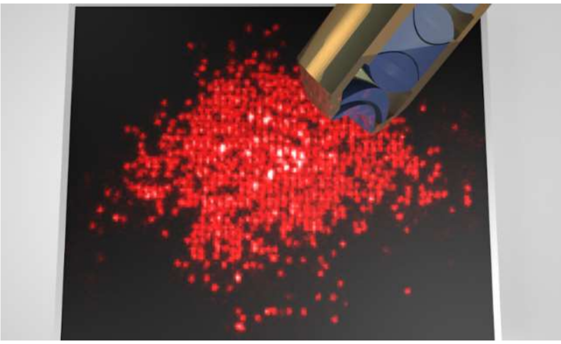
Martinis @ UCSB

2-D Trapped Ion Coulomb Crystal



John Bollinger @ NIST

2-D Neutral Atom Optical Lattice



Immanuel Bloch @ MPQ Garching

Quantum Hardware Shop

Quantum Hardware Shop

A perfect diamond is transparent !

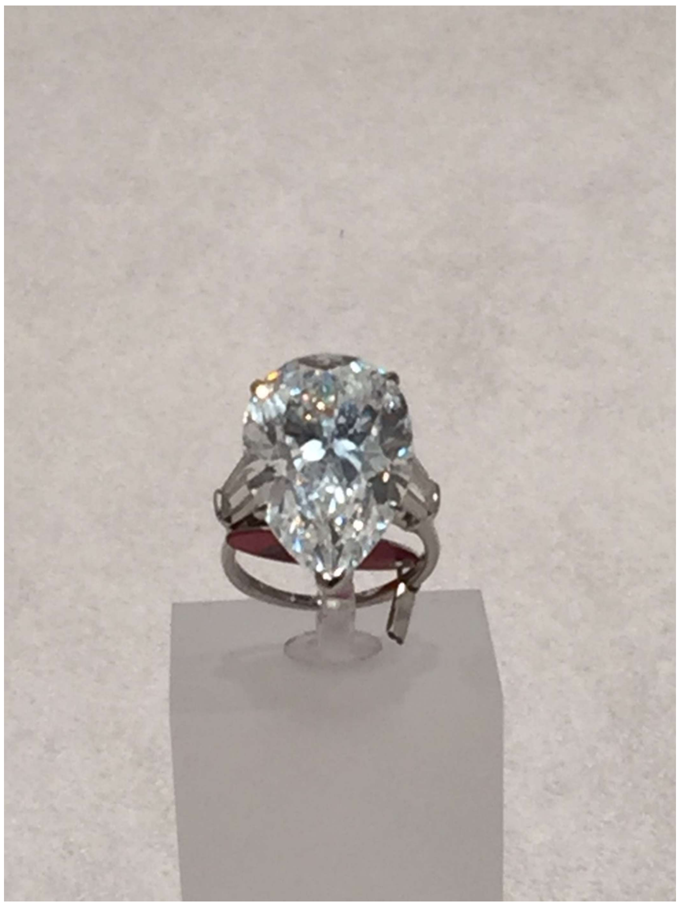
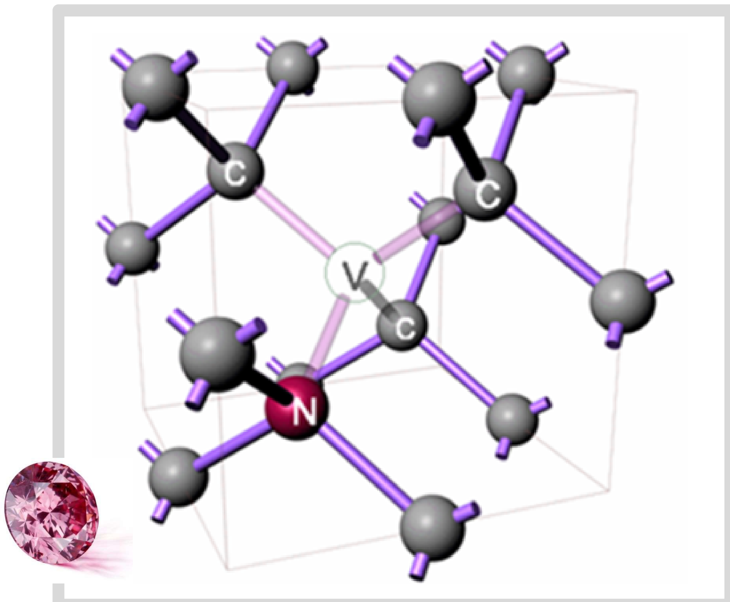


Photo taken at Sotheby's London October 2016

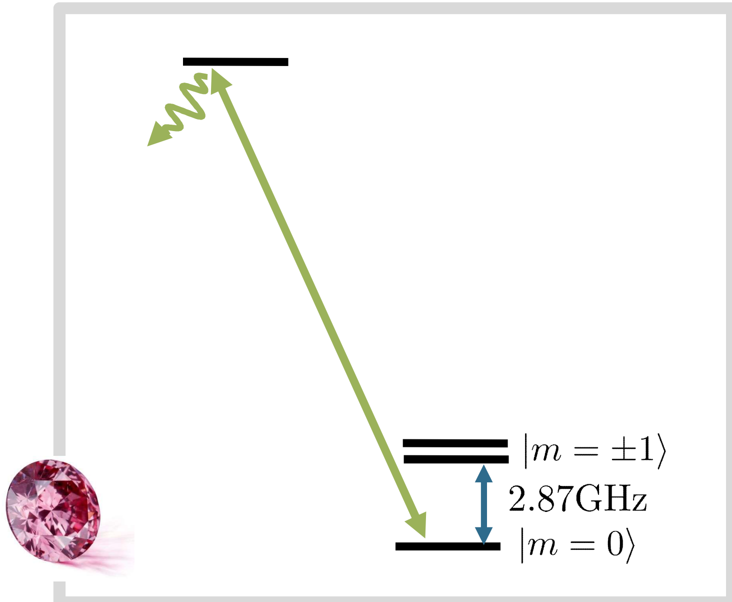
Some diamonds have colour

Principles

Principles



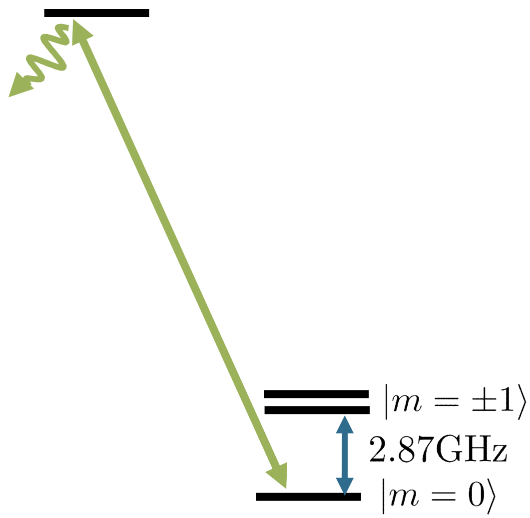
Principles

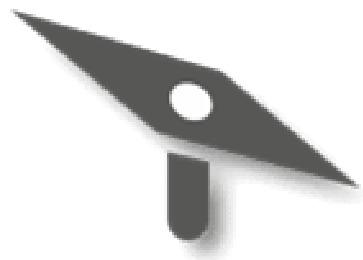


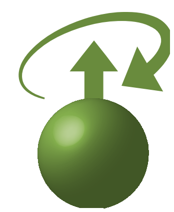
Optically Detected Magnetic Resonance

- Fast state initialisation
- Optical readout by state dependent fluorescence

Principles







Nuclear Spin

Optically Detected Magnetic Resonance

- Fast state initialisation
- Phase induced by magnetic signal
- Optical readout by state dependent fluorescence

Principles

The Electronic Spin Hamiltonian

Magnetic Field

Temperature

$$\hat{V}_{gs} = \mu_B g_{gs}^{\parallel} \hat{S}_z B_z + \mu_B g_{gs}^{\perp} \left(\hat{S}_x B_x + \hat{S}_y B_y\right) + \mu_N g_N \vec{I} \cdot \vec{B} + D(T) S_z^2$$
$$+ d_{gs}^{\parallel}(E_z + \delta_z)\left[\hat{S}_z^2 - S(S+1)/3\right] + d_{gs}^{\perp}(E_x + \delta_x)\left(\hat{S}_y^2 - \hat{S}_x^2\right) + d_{gs}^{\perp}(E_y + \delta_y)\left(\hat{S}_x \hat{S}_y + \hat{S}_y \hat{S}_x\right)$$

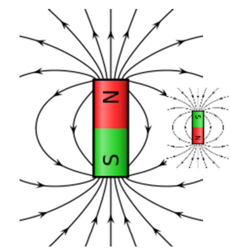
Strain

Electric Field

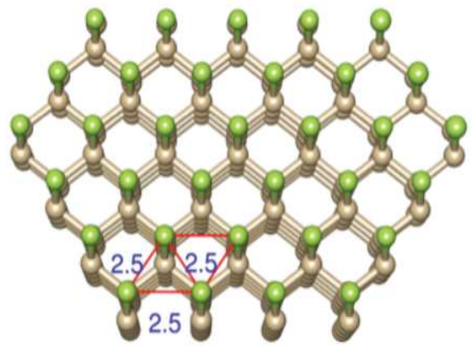
Roadmap

Diamond Quantum Devices for Simulation and Imaging

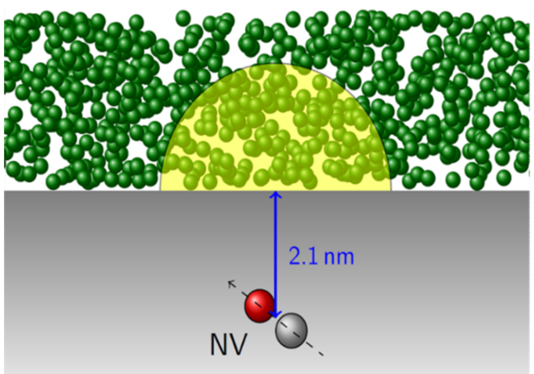
Electrons and Nuclei



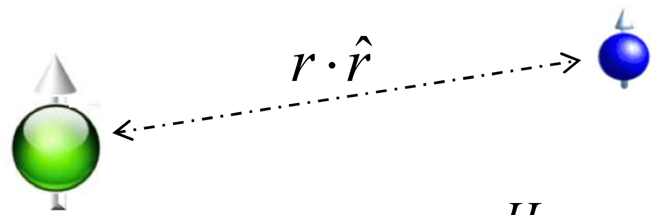
Quantum Simulation



Nanoscale NMR



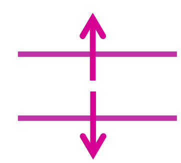
Coupling Electron Spins to Nuclei



$$H_{NV-S} = gS_z\left[3r_x r_z I_N^x + 3r_y r_z I_N^y + \left(3r_z^2 - 1\right) I_N^z\right]$$

$m_s = +1/2$

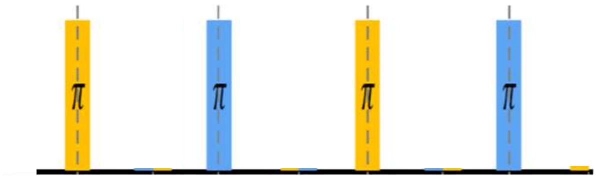
$$H_S = \gamma_N \vec{B} \cdot \vec{I}_N$$

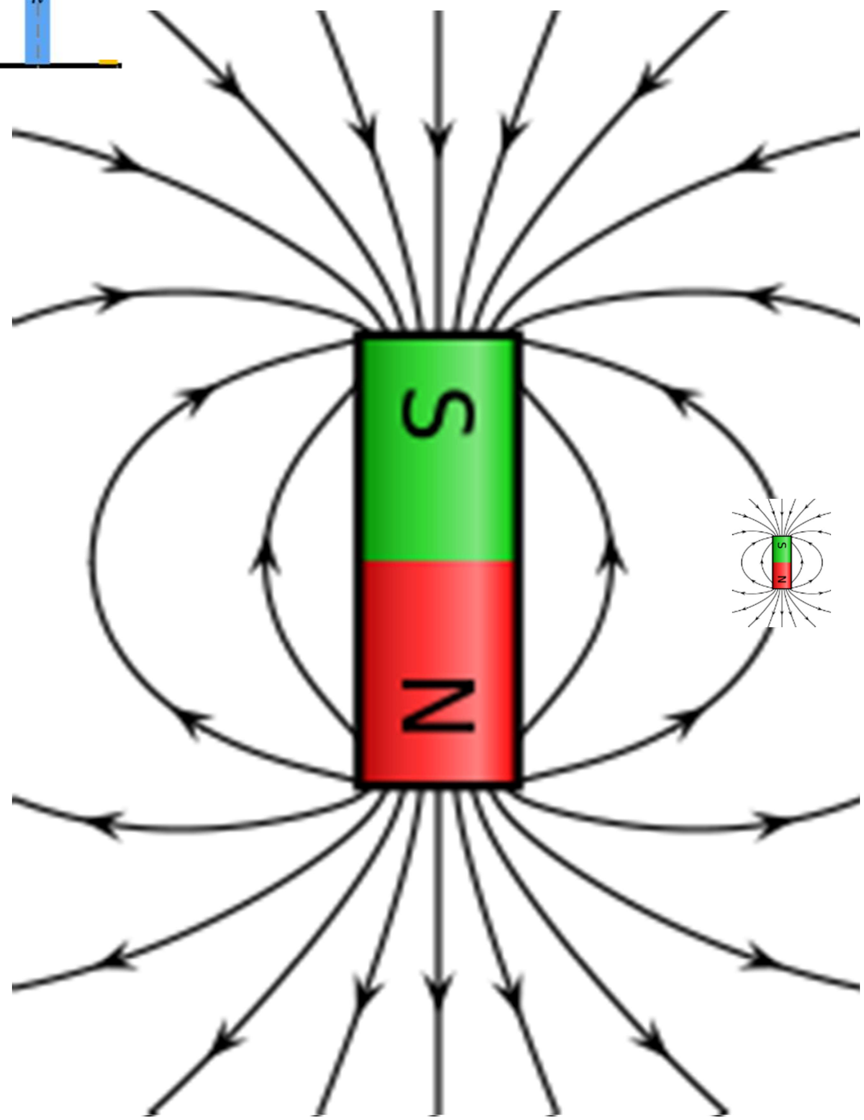


$$H_S = \gamma_E \vec{B} \cdot \vec{S}$$

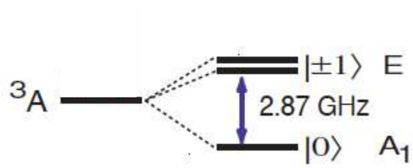
$m_s = -1/2$

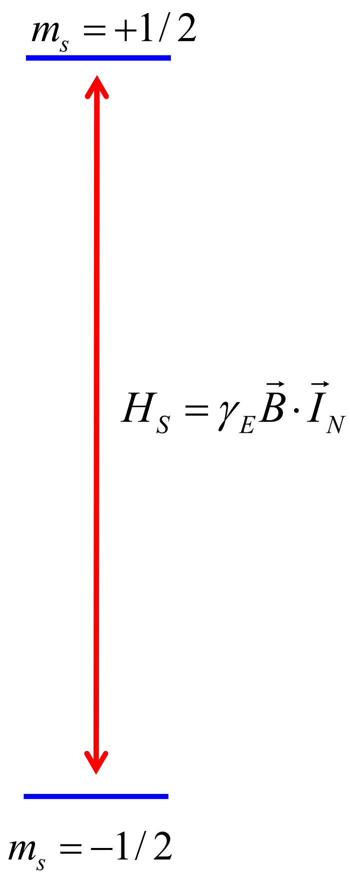
Coupling Electron Spins to Nuclei

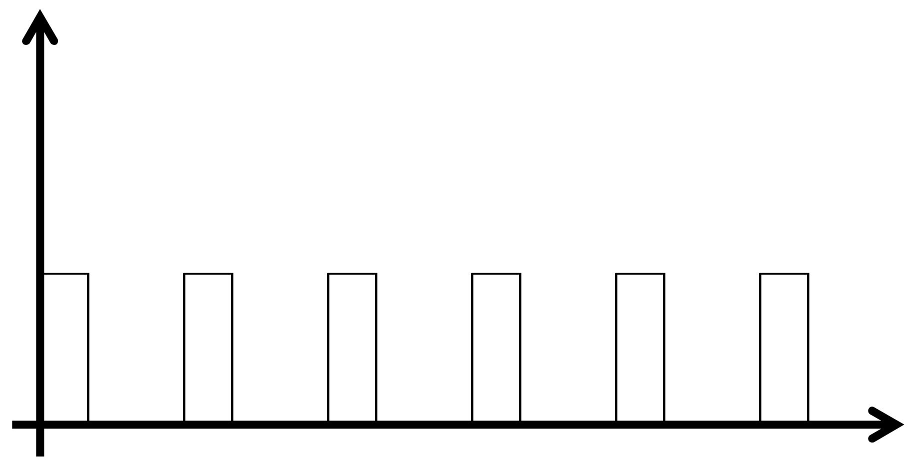




Coupling Electron Spins to Nuclei



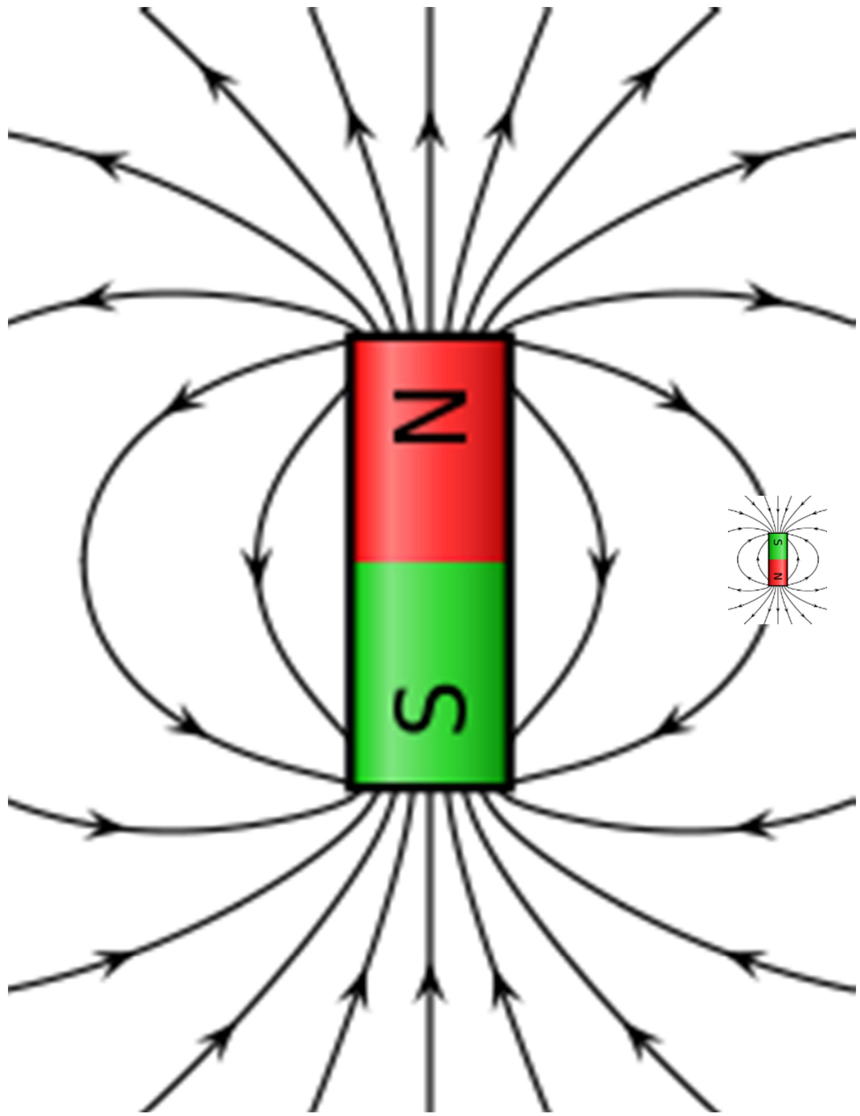




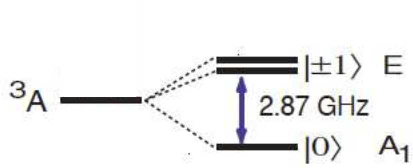
Pulsed decoupling – Induce short π-pulses to flip the electron spin periodically

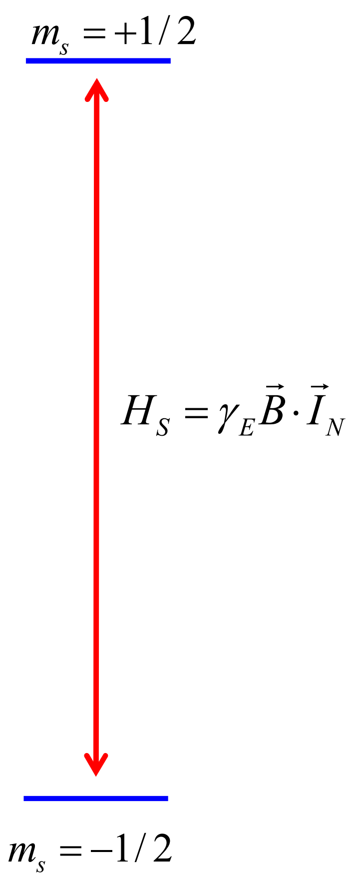
Coupling Electron Spins to Nuclei

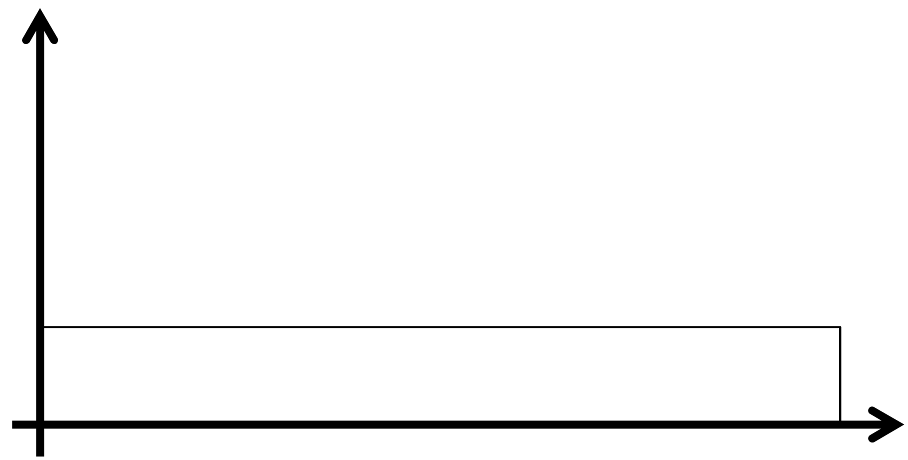
$(\text{Spin locking})_y$



Coupling Electron Spins to Nuclei

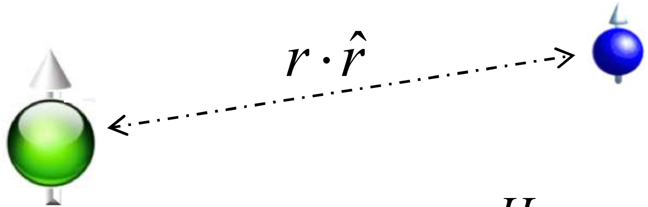






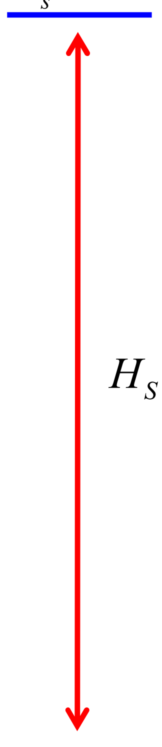
Continuous driving to rotate the electron spin

Coupling Electron Spins to Nuclei



$$H_{NV-S} = gS_z\left[3r_x r_z I_N^x + 3r_y r_z I_N^y + \left(3r_z^2 - 1\right) I_N^z\right]$$

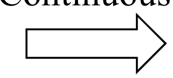
$m_s = +1/2$



$m_s = -1/2$

$$H_S = \gamma_E \vec{B} \cdot \vec{S}$$

Continuous

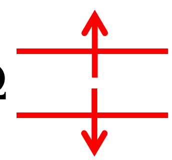


Resonant Drive

$$H_{NV} = \Omega\sigma_x$$

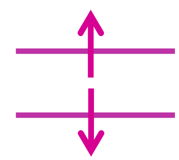
$$\left|+\right\rangle = \left|-1/2\right\rangle + \left|+1/2\right\rangle$$

Ω

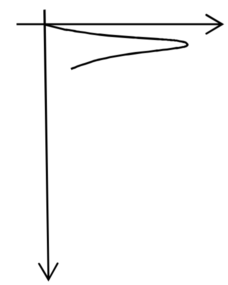


$$\left|-\right\rangle = \left|-1/2\right\rangle - \left|+1/2\right\rangle$$

$$H_S = \gamma_N \vec{B} \cdot \vec{I}_N$$

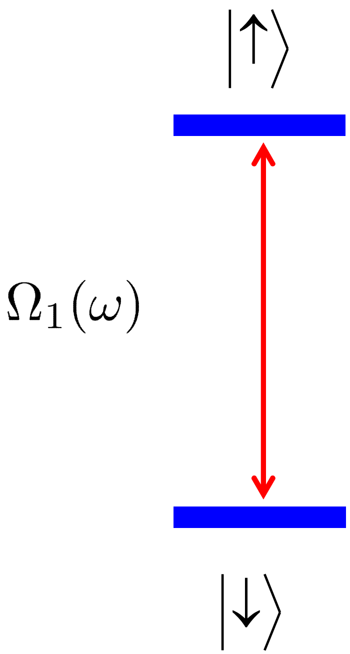


Environment spectral density



Concatenated Continuous Dynamical Decoupling

Robustness Against Driving Field Fluctuations

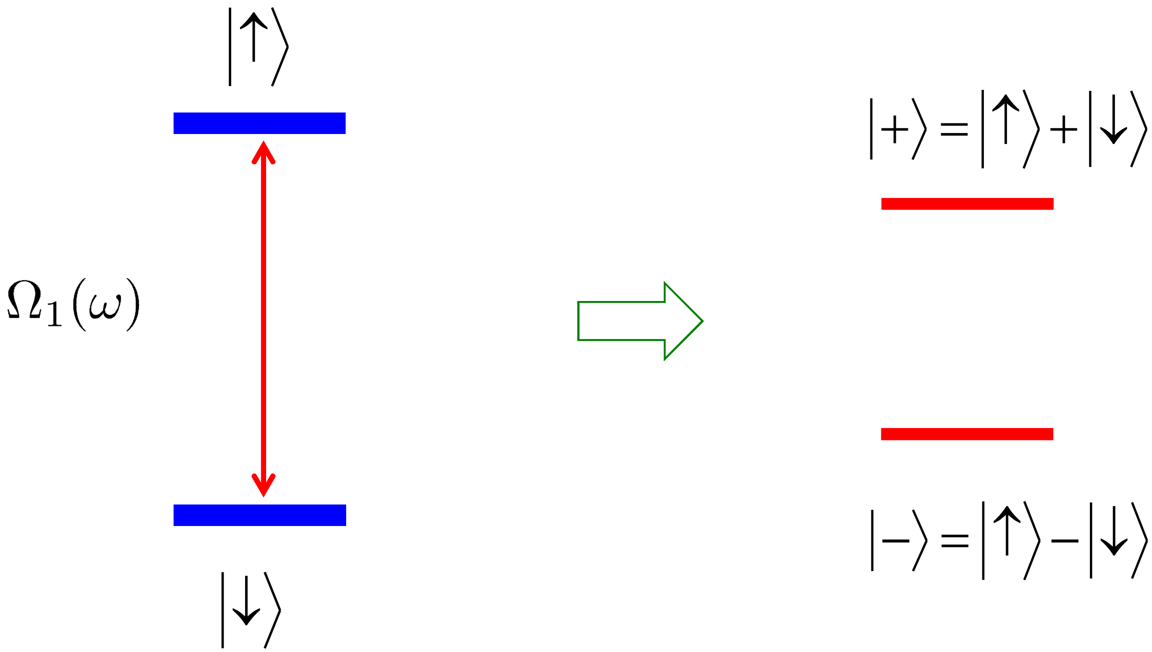


$$H = \hbar\Omega_1 \cos(\omega t)\sigma_x + \frac{\hbar}{2}\omega\sigma_z$$

Theory & Experiment Bulk Diamonds: NJP **14**, 113023 (2012)

Concatenated Continuous Dynamical Decoupling

Robustness Against Driving Field Fluctuations



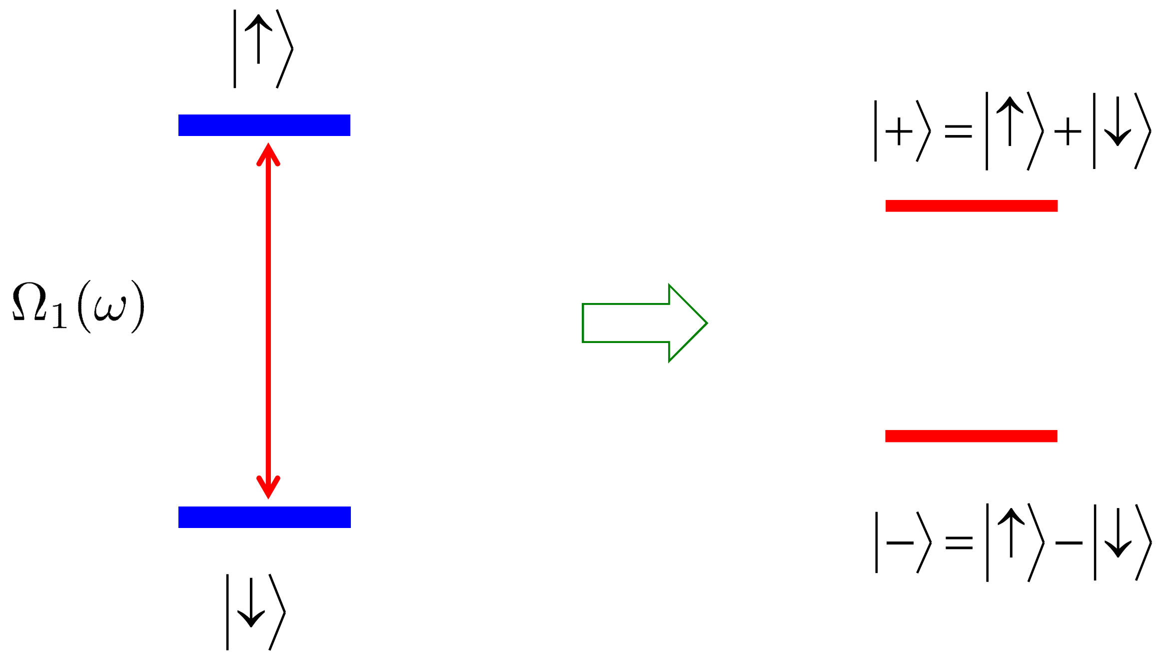
$$H = \hbar\Omega_1 \cos(\omega t)\sigma_x + \frac{\hbar}{2}\omega\sigma_z$$

$$H = \hbar\Omega_1 \cos(\omega t)(\sigma_x \cos(\omega t) + \sigma_y \sin(\omega t))$$
$$\cong \frac{\hbar}{2}\Omega_1\sigma_x$$

Theory & Experiment Bulk Diamonds: NJP **14**, 113023 (2012)

Concatenated Continuous Dynamical Decoupling

Robustness Against Driving Field Fluctuations



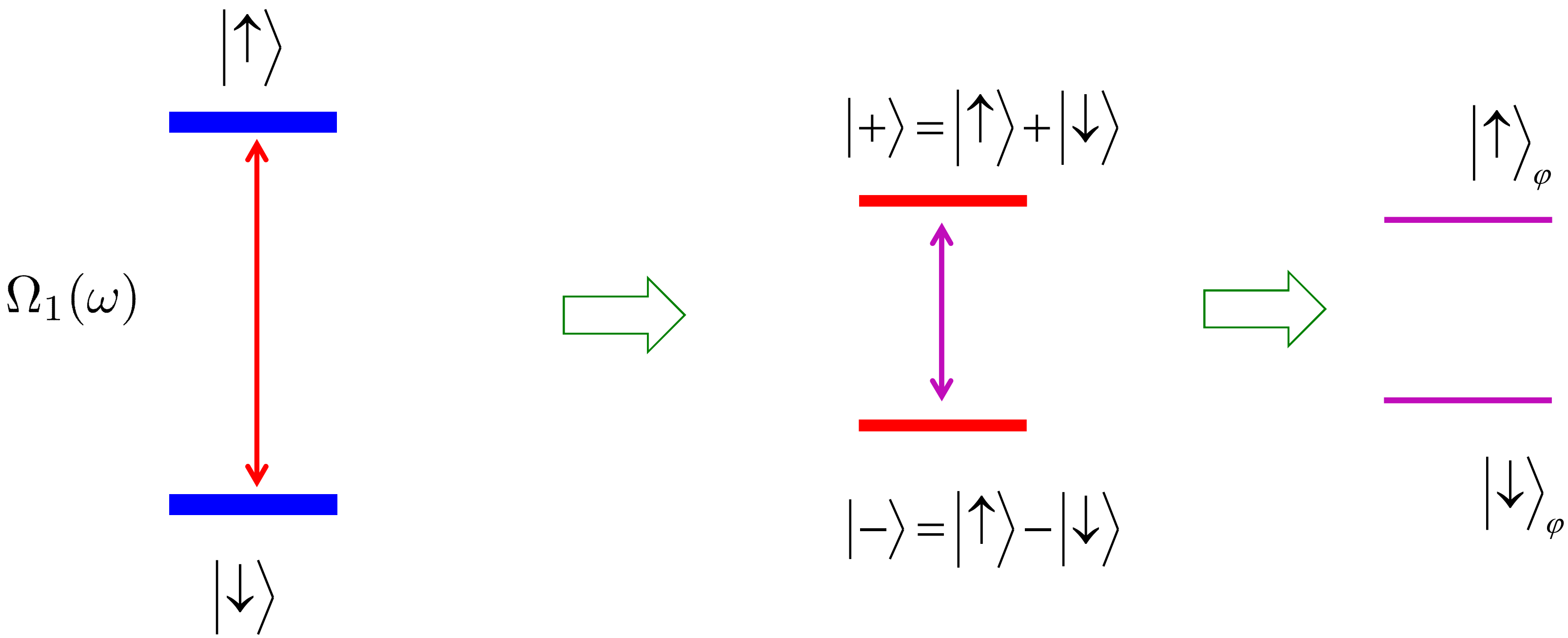
$$H = \hbar\Omega_1 \cos(\omega t)\sigma_x + \frac{\hbar}{2}\omega\sigma_z$$

$$H = \frac{\hbar}{2}\Omega_1\sigma_x$$

Theory & Experiment Bulk Diamonds: NJP **14**, 113023 (2012)

Concatenated Continuous Dynamical Decoupling

Robustness Against Driving Field Fluctuations



$$H = \hbar\Omega_1 \cos(\omega t)\sigma_x + \frac{\hbar}{2}\omega\sigma_z + 2\hbar\Omega_2 \sin(\omega t)\cos(\Omega_1 t)\sigma_x$$

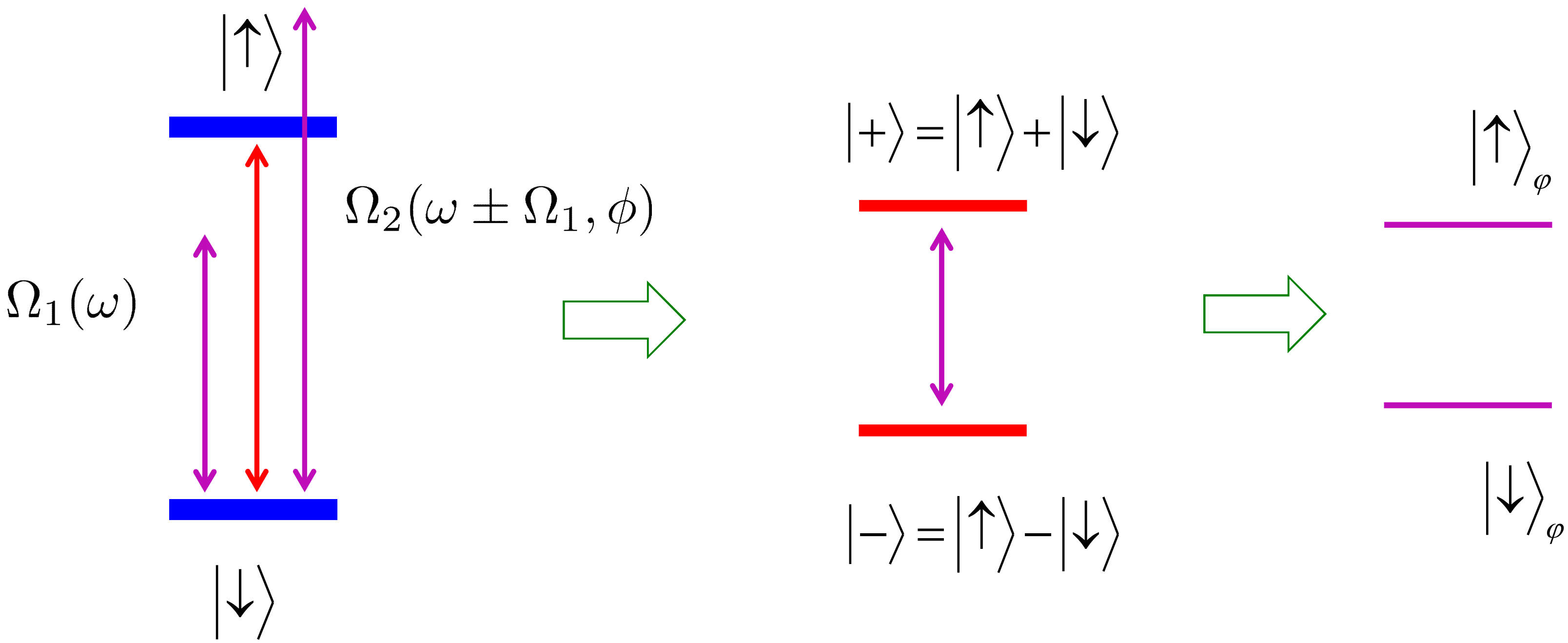
$$H = \frac{\hbar}{2}\Omega_1\sigma_x + \hbar\Omega_2 \cos(\Omega_1 t)\sigma_y$$

$$H = \frac{\hbar}{2}\Omega_2\sigma_y$$

Theory & Experiment Bulk Diamonds: NJP **14**, 113023 (2012)

Concatenated Continuous Dynamical Decoupling

Robustness Against Driving Field Fluctuations



$$H = \hbar\Omega_1 \cos(\omega t)\sigma_x + \frac{\hbar}{2}\omega\sigma_z + 2\hbar\Omega_2 \sin(\omega t)\cos(\Omega_1 t)\sigma_x$$

$$\cong \hbar\Omega_1 \cos(\omega t + \frac{\Omega_2}{\Omega_1}\cos\Omega_1 t)\sigma_x$$

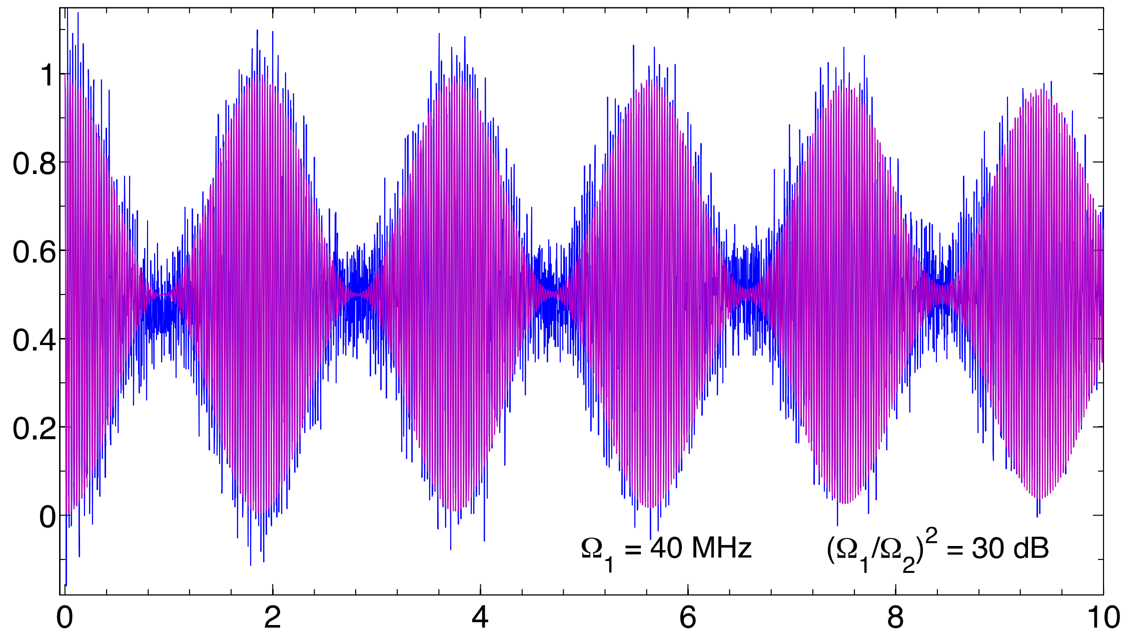
$$H = \frac{\hbar}{2}\Omega_1\sigma_x + \hbar\Omega_2\cos(\Omega_1 t)\sigma_y$$

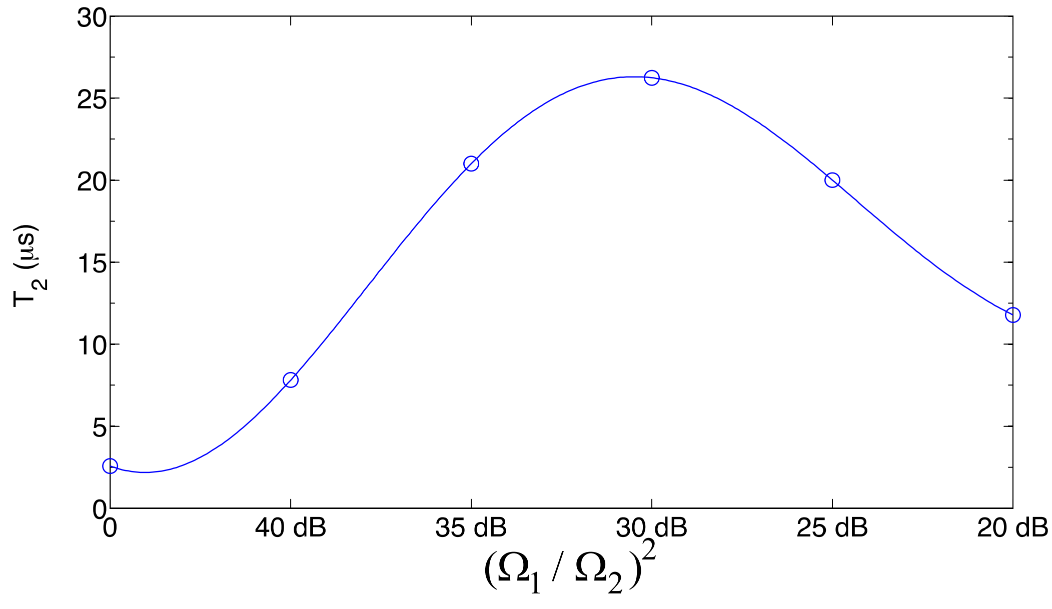
$$H = \frac{\hbar}{2}\Omega_2\sigma_y$$

Theory & Experiment Bulk Diamonds: NJP **14**, 113023 (2012)

Concatenated Continuous Dynamical Decoupling

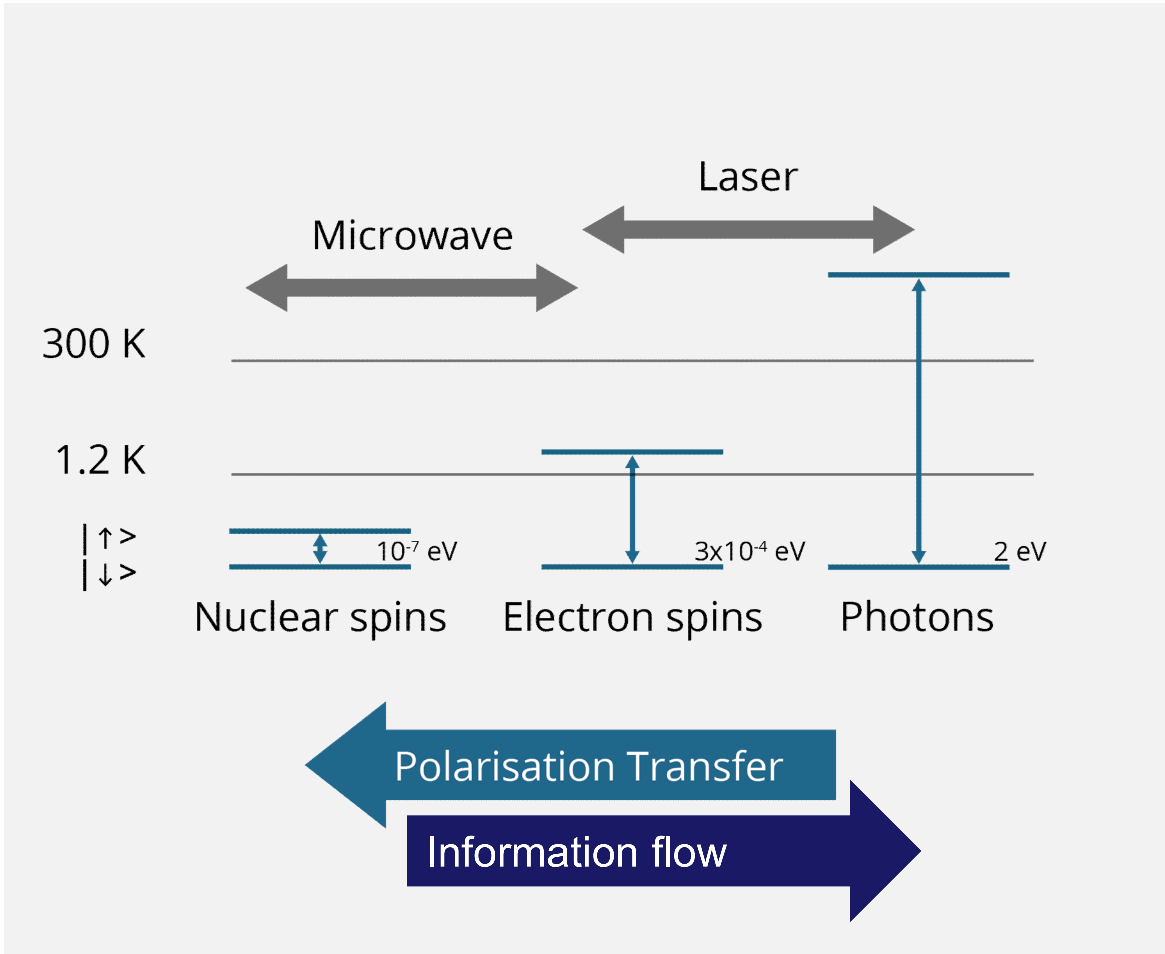
Robustness Against Driving Field Fluctuations





Theory & Experiment: NJP **14**, 113023 (2012).

Principles

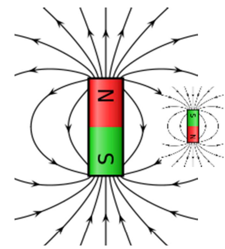


Laser
Microwave
300 K
1.2 K
|↑>
|↓>
10-7 eV
3x10-4 eV
2 eV
Nuclear spins
Electron spins
Photons
Polarisation Transfer
Information flow

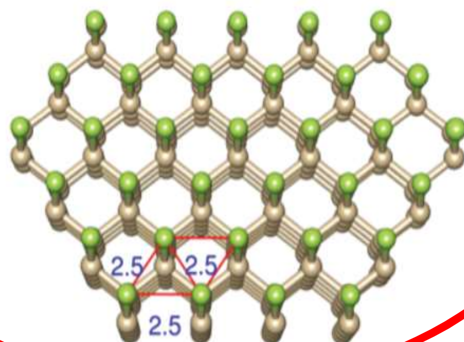
Roadmap

Diamond Quantum Devices for Simulation and Imaging

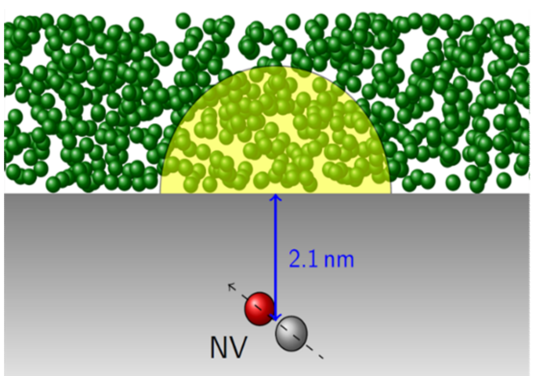
Electrons and Nuclei



Quantum Simulation



Nanoscale NMR



Quantum Simulation for 2-D Systems

Why ?

- Offer unusual physics

  Anyons, Surface codes, Topological phase transitions, Frustration, …

- Difficult to simulate by classical computers

  For 1-D we have (t)-DMRG

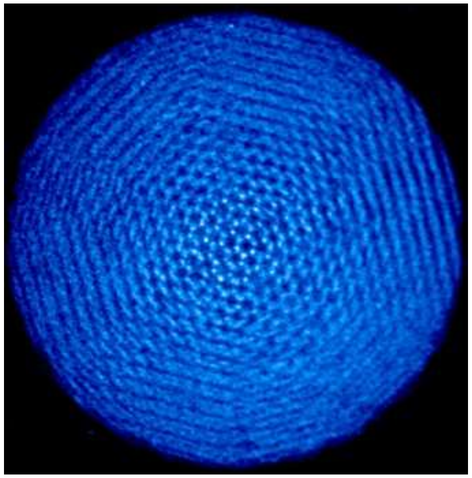
  S.R. White, PRL 1992

  For 2-D …

Systems are really hard to simulate !

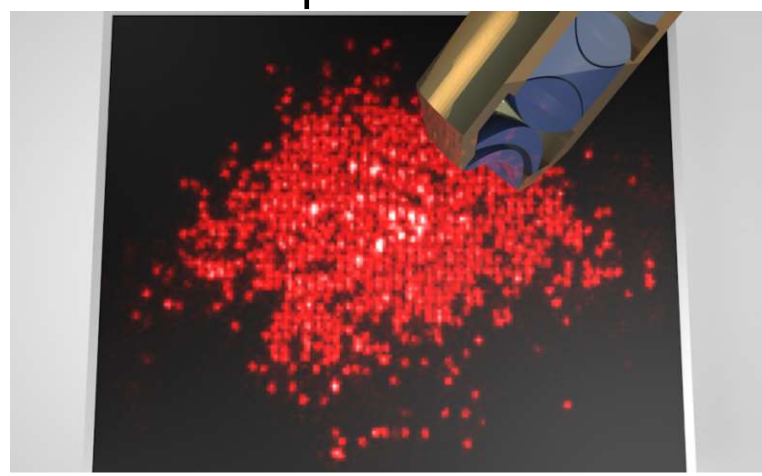
Quantum Simulation for 2-D Systems

2-D Trapped Ion Coulomb Crystal



John Bollinger @ NIST

2-D Neutral Atom Optical Lattice

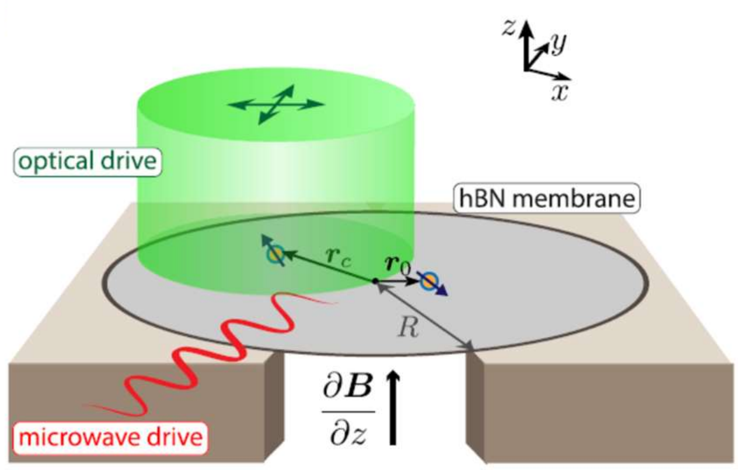


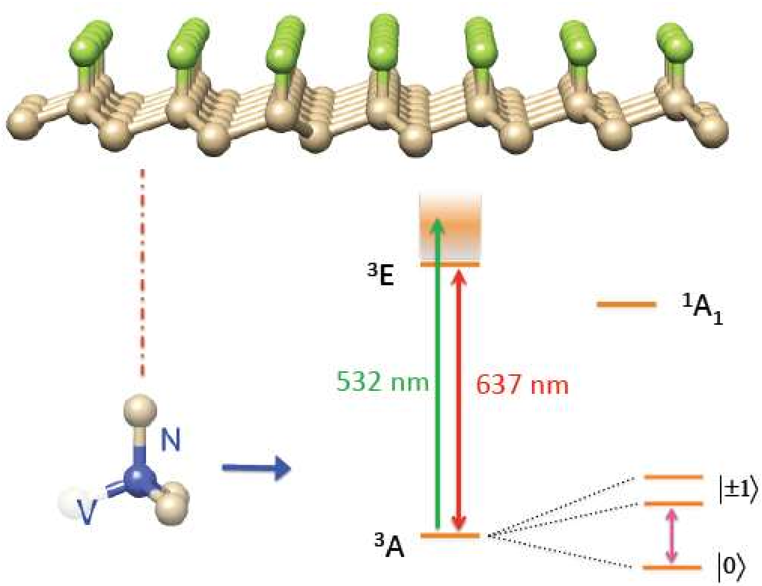
Immanuel Bloch @ MPQ Garching

A Diamond Surface Simulator

Address three main challenges

- Initialization of the nuclear spin lattice
- Control of the Hamiltonian of the nuclear spin lattice
- Readout from the nuclear spin lattice

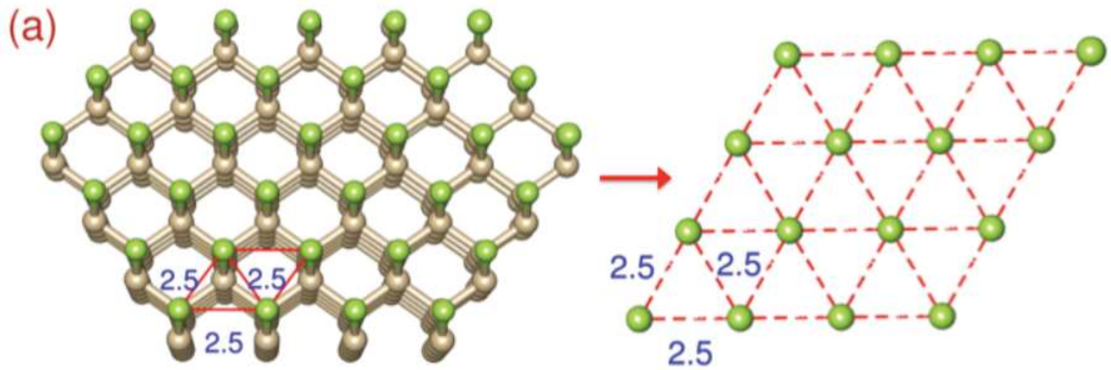




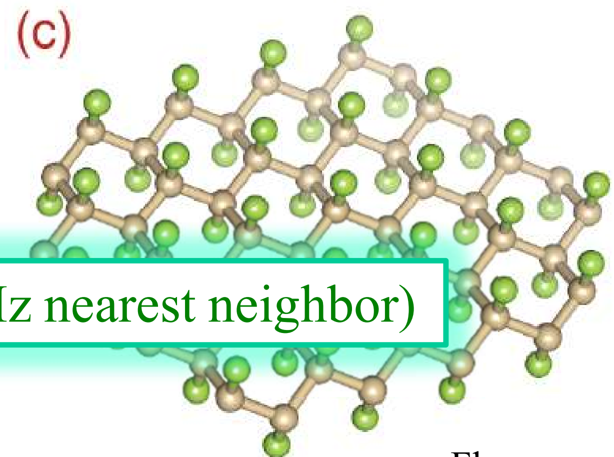
Abdi, Hwang, Aghtar, Plenio, Phys. Rev. Lett. 119, 233602 (2017)

Theory: Cai, Retzker, Jelezko, Plenio, Nature Phys. 2013

A Diamond Surface Simulator

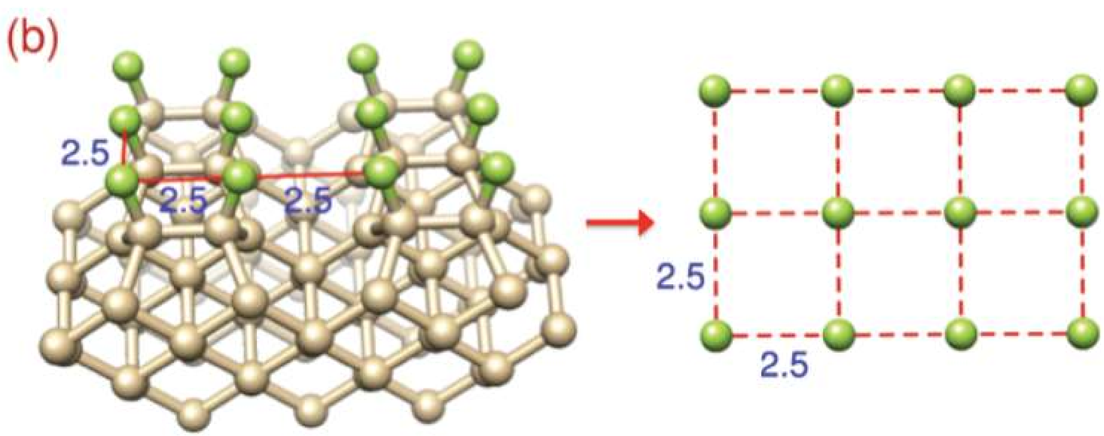


Diamond 111-surface



Fluorographene

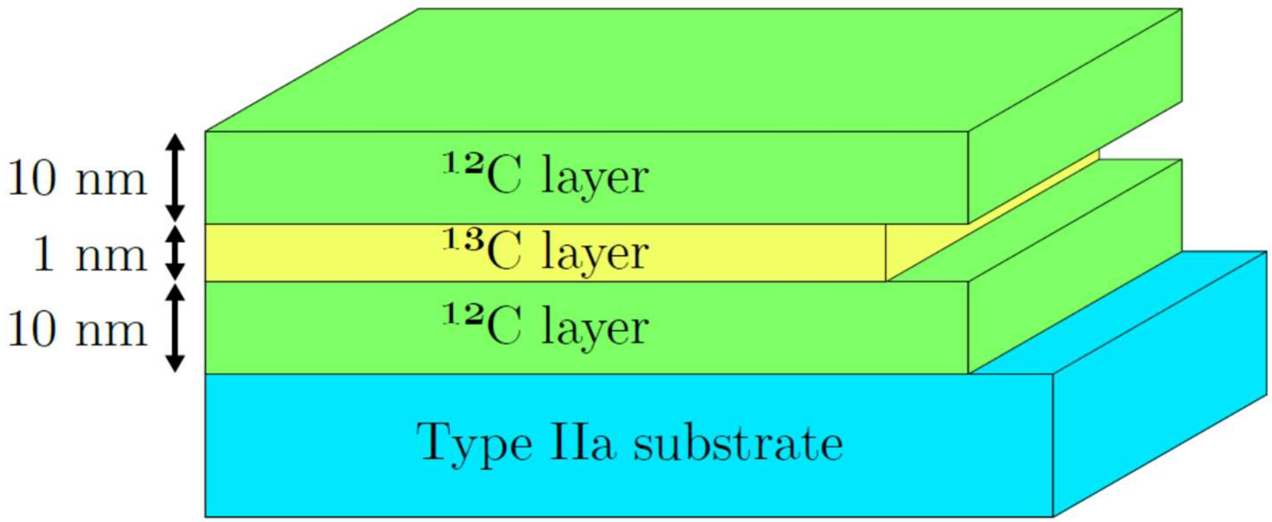
F-F (long range dipole) interaction (6.8kHz nearest neighbor)



Diamond 100-surface

Theory: Cai, Retzker, Jelezko, Plenio, Nature Phys. 2013

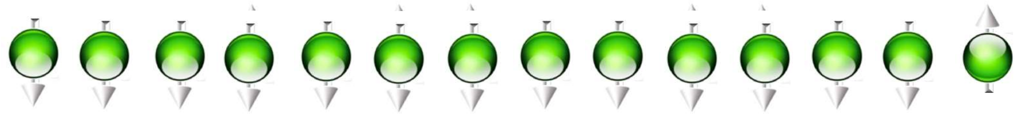
Quasi-2D Spin Layers

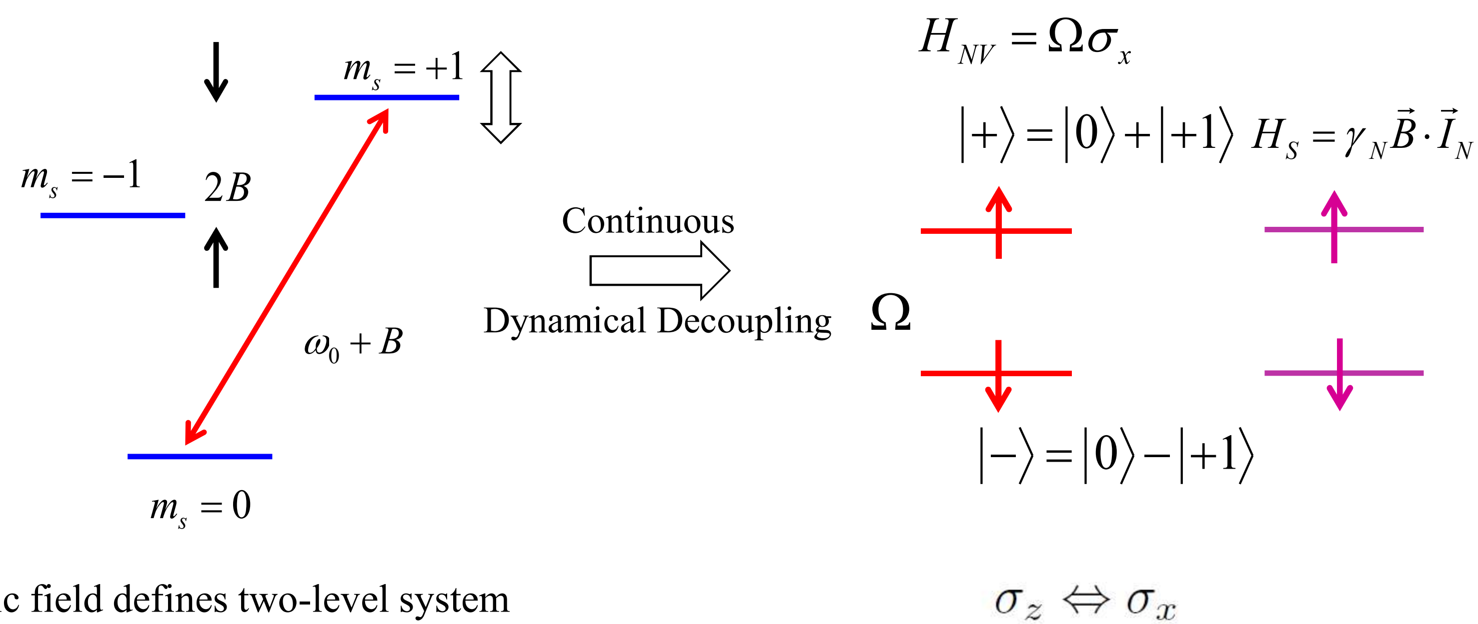


Nitrogen introduced during the growth of the ^{13}C layer, facilitating NV centers in the vicinity of the spin layer.

Unden, Tomek, Weggler, Frank, London, Zopes, Degen, Meijer, Watanabe, Itoh, Plenio, Naydenov & Jelezko. NPJ 2018

Initialising a Nuclear Spin Lattice





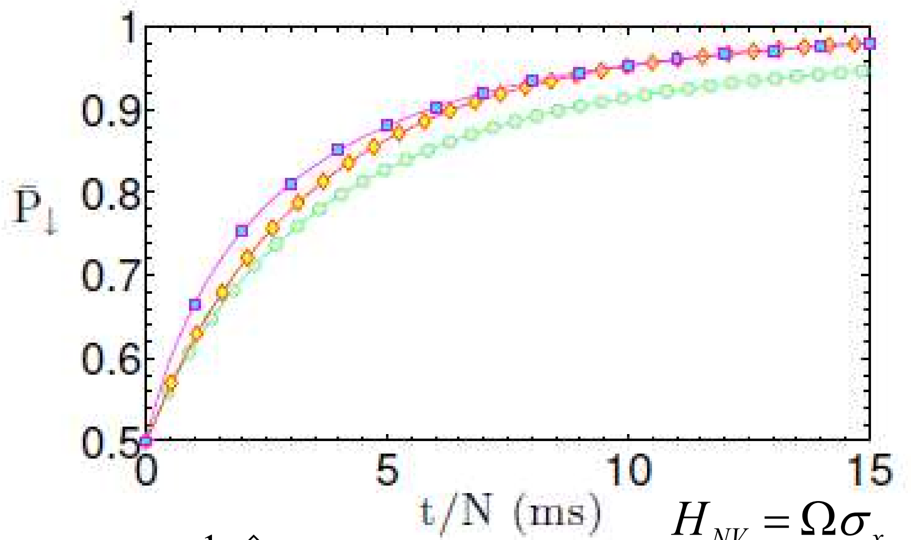
Magnetic field defines two-level system

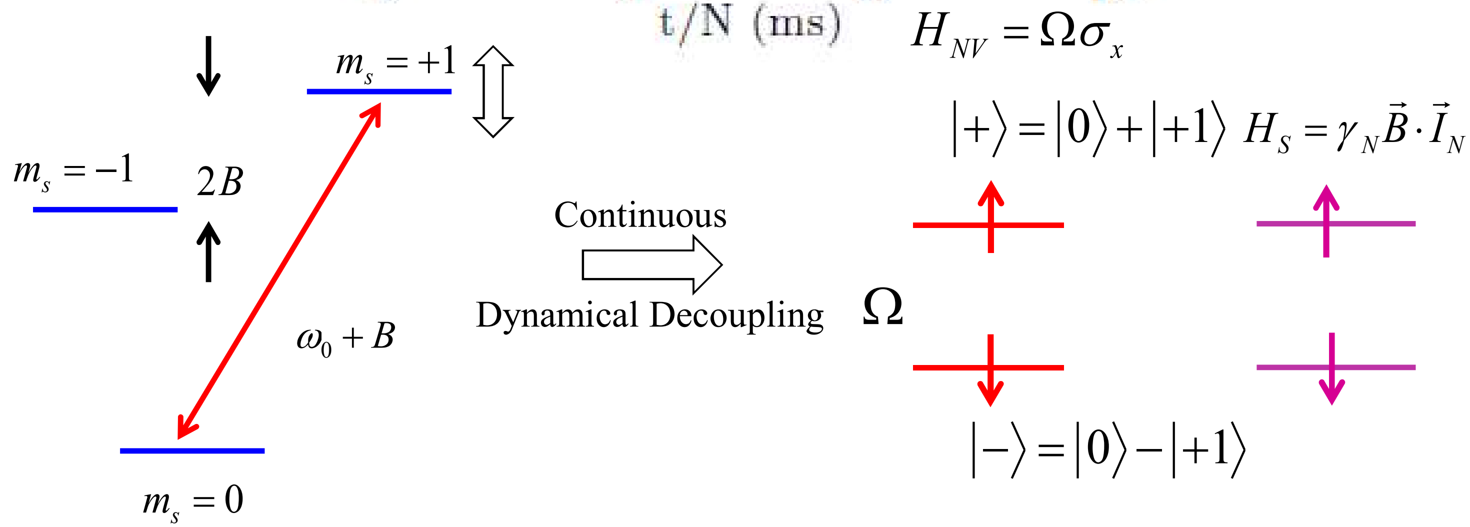
Hartmann-Hahn condition (1962)

Interaction with environment carries energy penalty

Theory: Cai, Retzker, Jelezko, Plenio, Nature Phys. 2013

Initialising a Nuclear Spin Lattice





Magnetic field defines two-level system

$\sigma_z \Leftrightarrow \sigma_x$

Interaction with environment carries energy penalty

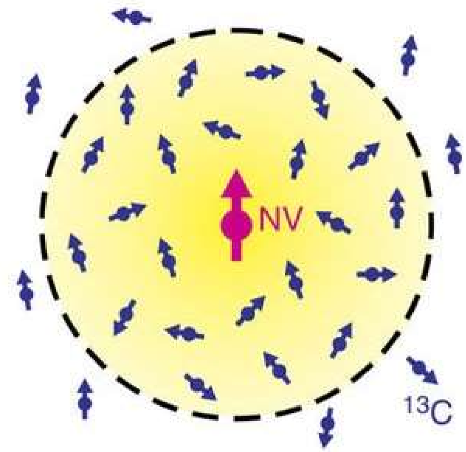
Hartmann-Hahn condition (1962)

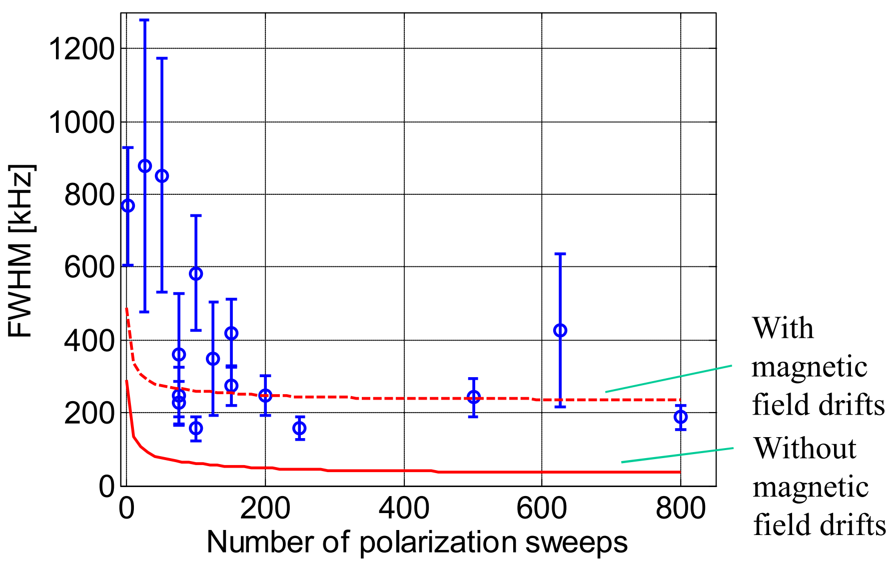
Theory: Cai, Retzker, Jelezko, Plenio, Nature Phys. 2013

Spin Ensemble Initialisation

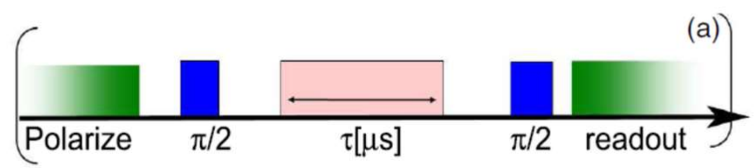
Polarization of nuclear spin bath reduces linewidth due to T2 time

Polarization of nuclear spin bath reduces NV-ESR linewidth





Use continuous microwave drive to establish Hartmann-Hahn resonance.



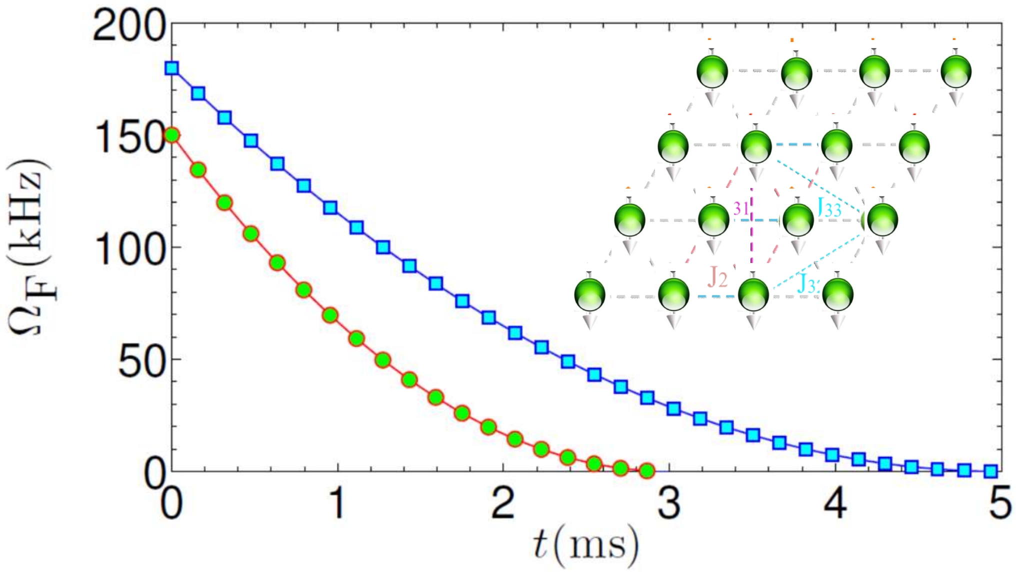
Numerical simulation shows >90% polarization after 500 sweeps of closest 10% of nuclear spins randomly placed in 4nm radius from NV.

Theory: Cai, Retzker, Jelezko, Plenio, Nature Phys. 2013
Experiment: Unden, … Plenio, Naydenov, and Jelezko, npj Quant. Inf. 2018

Experiment: London, …, Plenio, Jelezko, PRL 2013

A Diamond Surface Simulator

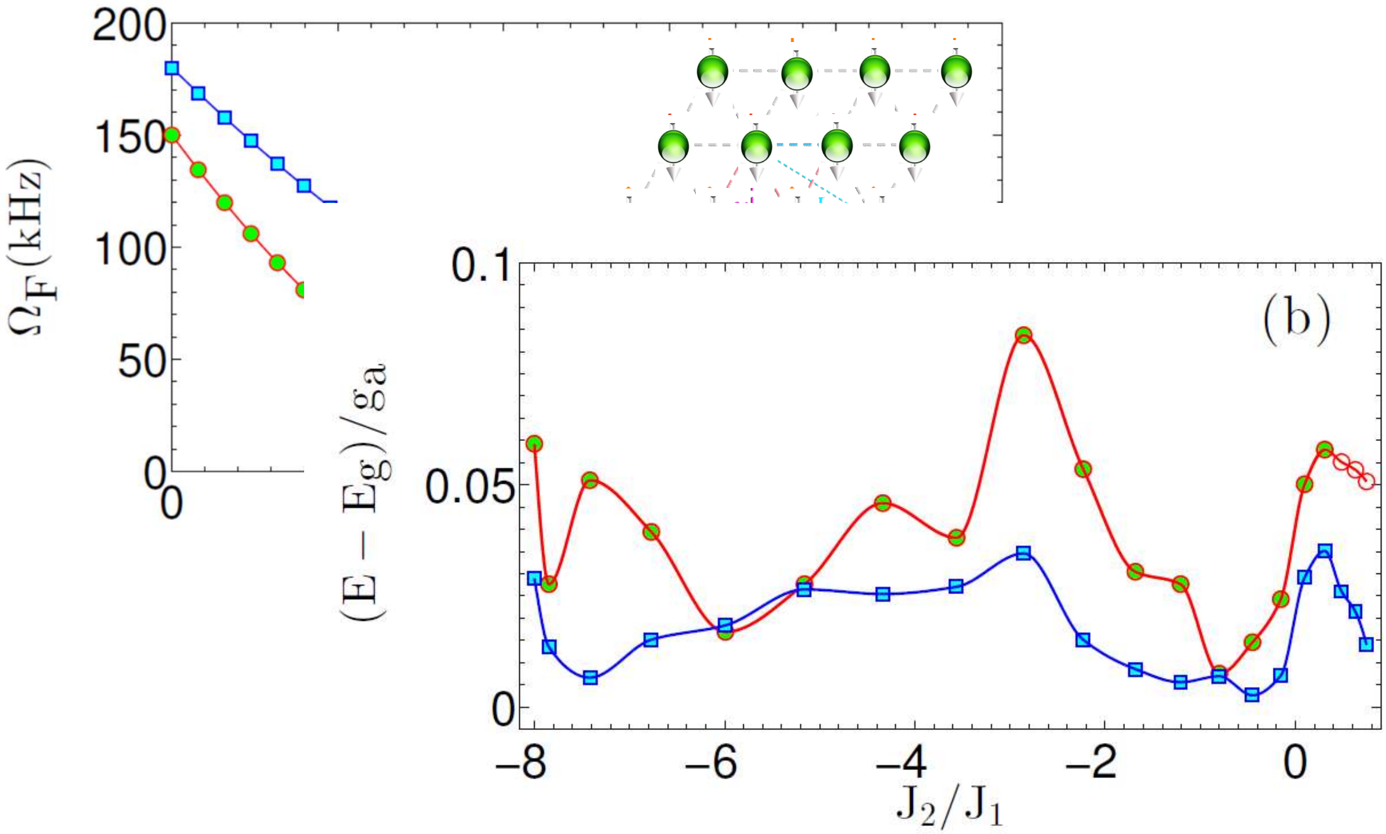
Ground State Preparation & Detecting Quantum Phases



Theory: Cai, Retzker, Jelezko, Plenio, Nat. Phys. 9, 168 (2013)

A Diamond Surface Simulator

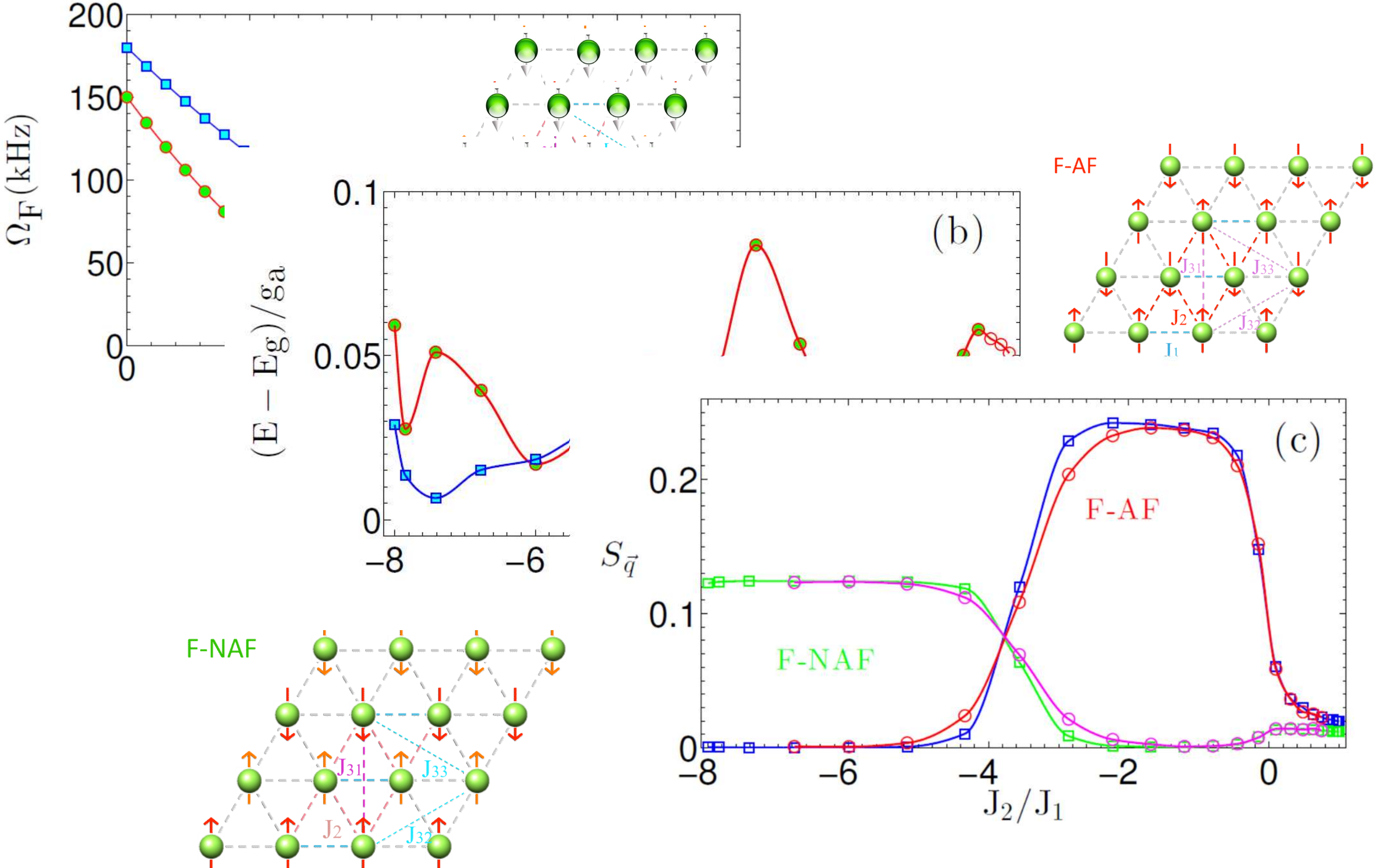
Ground State Preparation & Detecting Quantum Phases



Theory: Cai, Retzker, Jelezko, Plenio, Nat. Phys. 9, 168 (2013)

A Diamond Surface Simulator

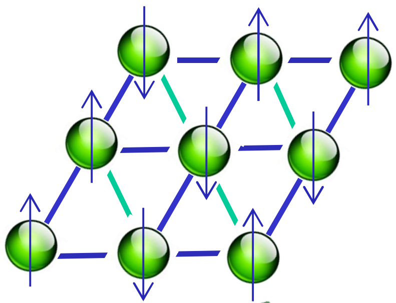
Ground State Preparation & Detecting Quantum Phases



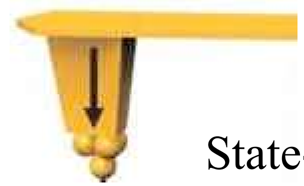
Theory: Cai, Retzker, Jelezko, Plenio, Nat. Phys. 9, 168 (2013)

Readout of Nuclear Spin Lattice

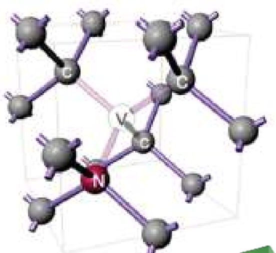
Measurement with NV: $P_{\downarrow}^{\uparrow}(\tau) - P_{\uparrow}^{\downarrow}(\tau) = 2\tau^2 \sum_i g_i^2 I_i^z$ → Spin magnetization $\langle S_z \rangle = \sum_i \langle I_i^z \rangle$



Magnetic gradient: magnetic tip



State-of-art: 7 Gauss per Å



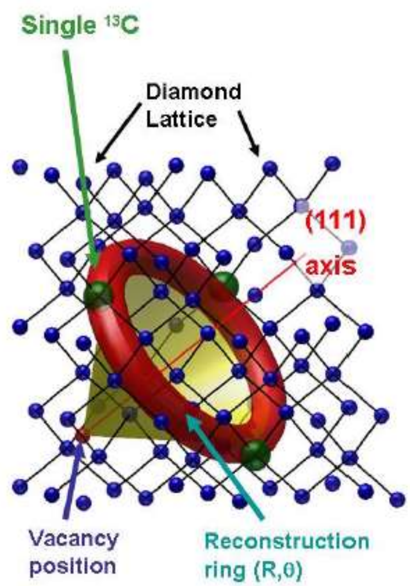
Spin structure factor: ↓ Various tricks

$$S(Q) = \sum_{(i,j)} \left\langle e^{i\vec{q}\cdot(\vec{r}_i - \vec{r}_j)} I_i^z I_j^z + e^{i\vec{q}\cdot(\vec{r}_j - \vec{r}_i)} I_j^z I_i^z \right\rangle$$

Theory: Cai … Plenio, Nat. Phys. 9, 168 (2013)

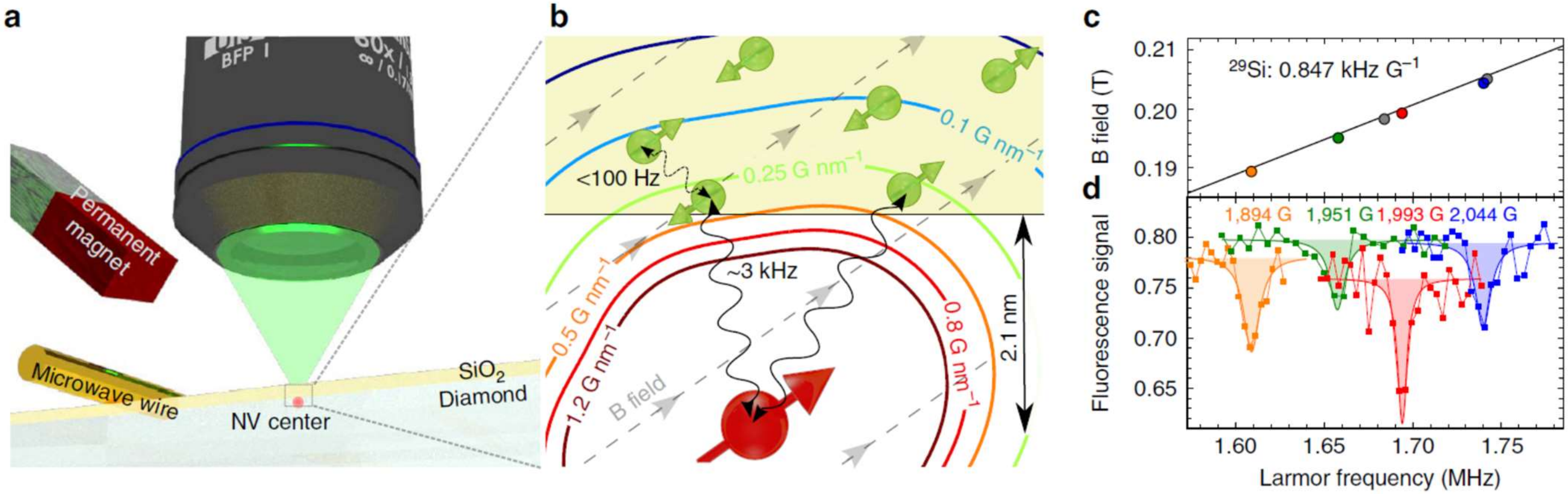
Sufficient to lower bound entanglement:
Cramer, Plenio, Wunderlich, PRL 2013

Exploit Hartmann-Hahn condition



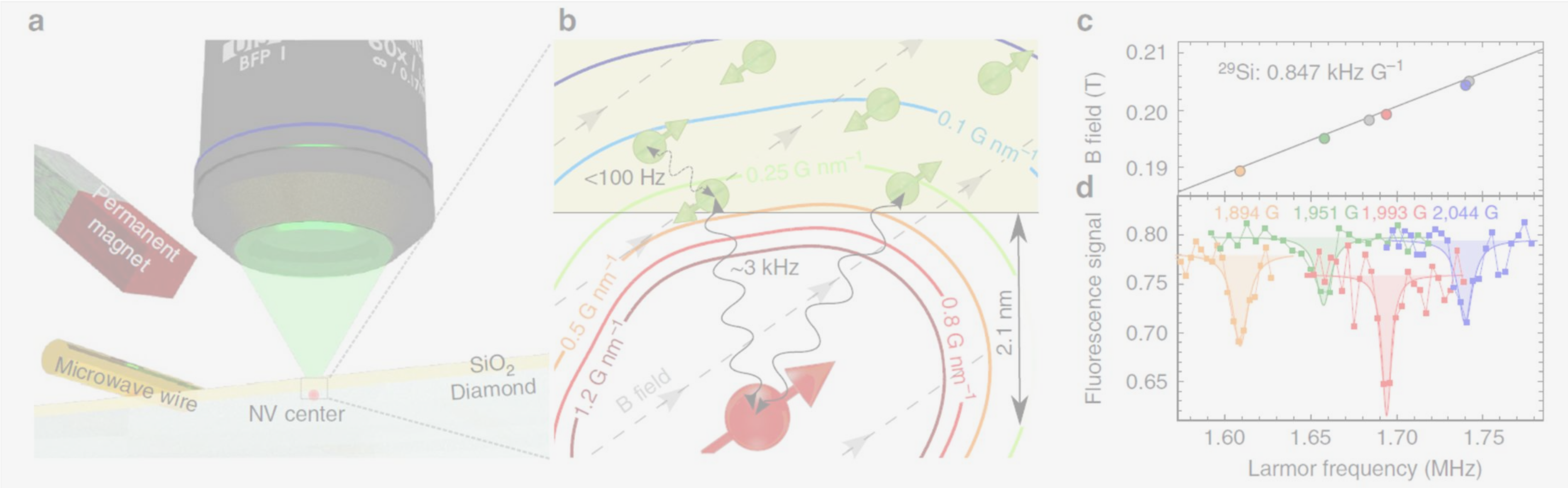
Theory: Cai, Retzker, Jelezko, Plenio, Nature Phys. **9**, 168 (2013)

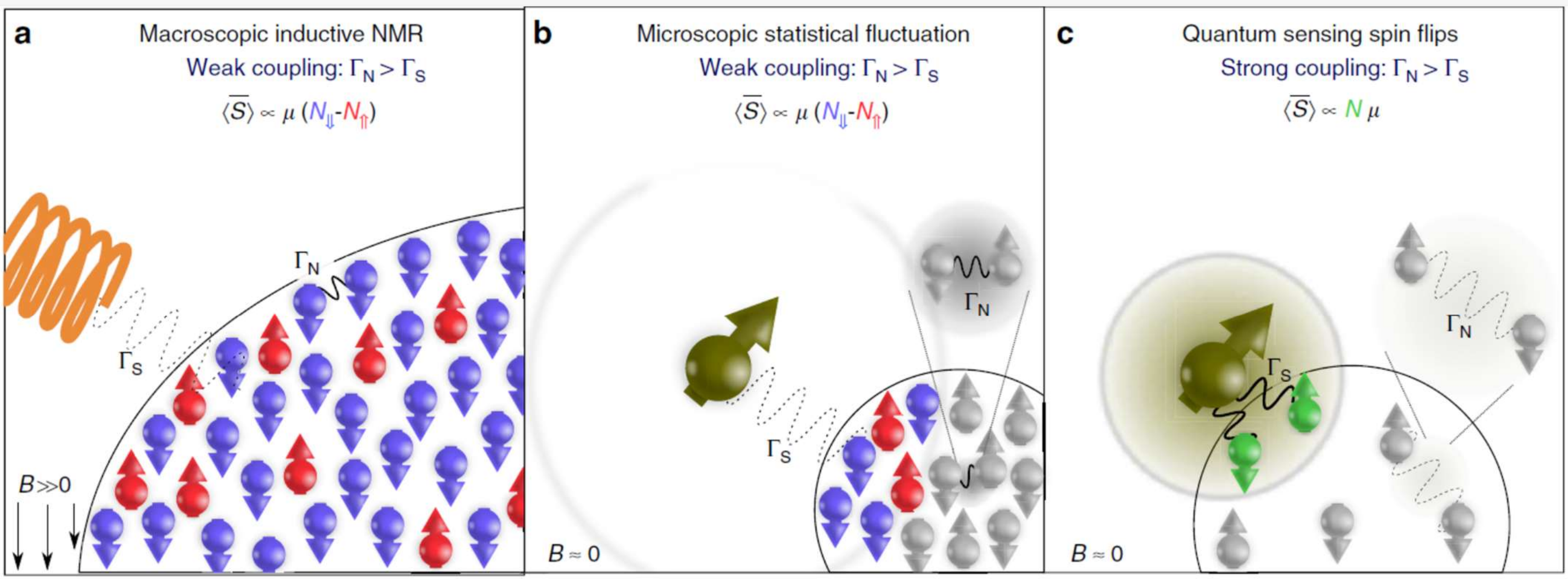
Sensing Silicon Nuclear Spins above Diamond Surface



Experiment & Theory: Müller, Kong, Cai, Melentijevic, Stacey, Markham, Isoya, Pezzagna, Meijer, Du, Plenio, Naydenov, McGuinness & Jelezko., Nat. Comm. (2014)

Sensing Silicon Nuclear Spins above Diamond Surface



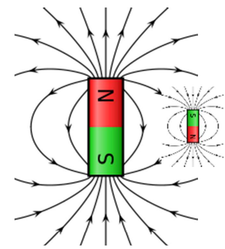


Experiment & Theory: Müller, Kong, Cai, Melentijevic, Stacey, Markham, Isoya, Pezzagna, Meijer, Du, Plenio, Naydenov, McGuinness & Jelezko., Nat. Comm. (2014)

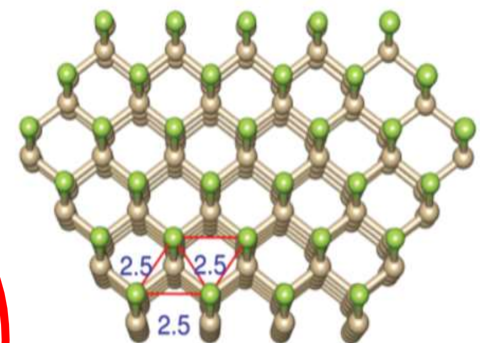
Roadmap

Diamond Quantum Devices for Simulation and Imaging

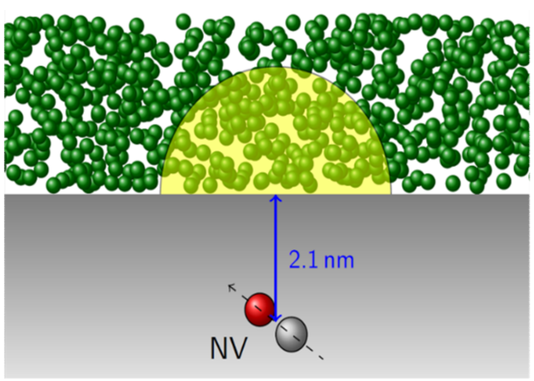
Electrons and Nuclei



Quantum Simulation



Nanoscale NMR



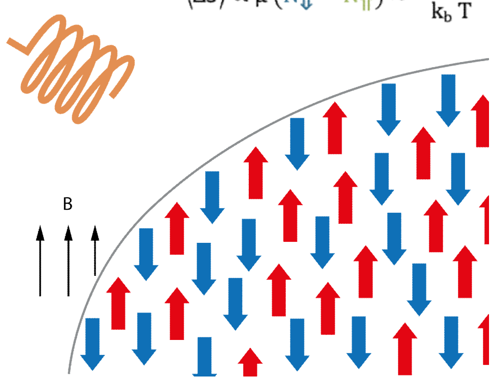
The Sensitivity Challenge of NMR

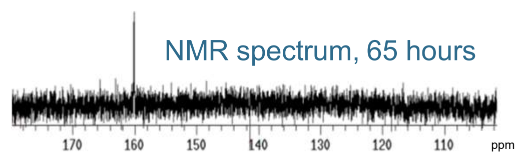
Classical NMR

- Inductive detector has high electronic noise
- Weak magnetisation – only one spin out of 1,000,000 polarised
- Typical sensitivity – 10^{18} spins (volume ~ millimeter scale)

Macroscopic – Inductive NMR

$$\langle \Delta S \rangle \propto \mu \left(N_{\Downarrow} - N_{\Uparrow} \right) \approx \frac{N \mu^2 B}{k_b T}$$





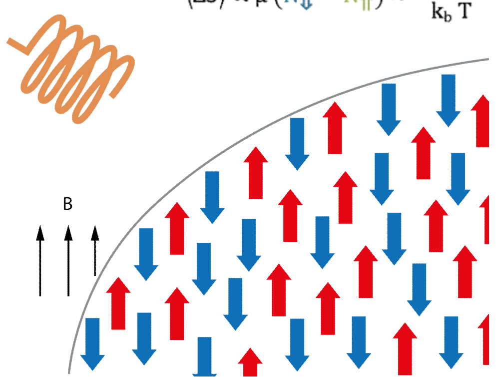
The Sensitivity Challenge of NMR

Hyperpolarised Classical NMR

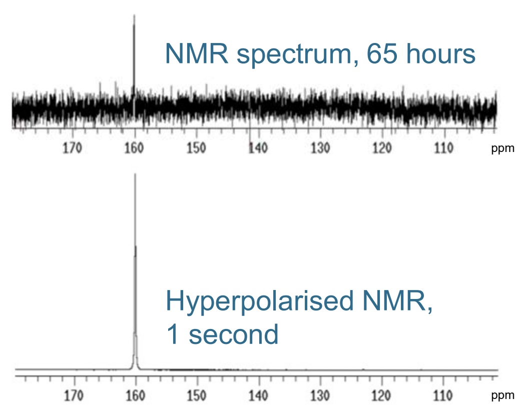
- Inductive detector has high electronic noise
- Hyperpolarisation – one spin out of 10 polarised
- Typical sensitivity – 10^{13} spins (volume ~ 100 micron scale)

Macroscopic – Inductive NMR

$$\langle \Delta S \rangle \propto \mu \,(N_{\Downarrow} - N_{\Uparrow}) \approx \frac{N\,\mu^2\,B}{k_b\,T}$$



Hyperpolarisation



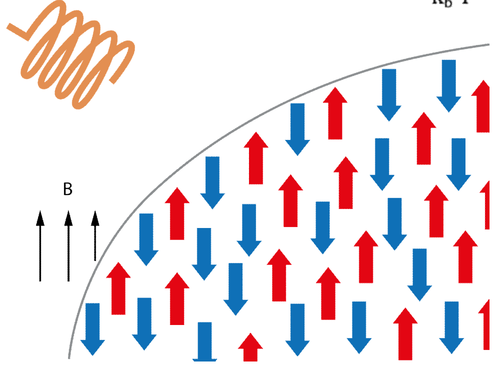
The Sensitivity Challenge of NMR

Hyperpolarised Quantum NMR

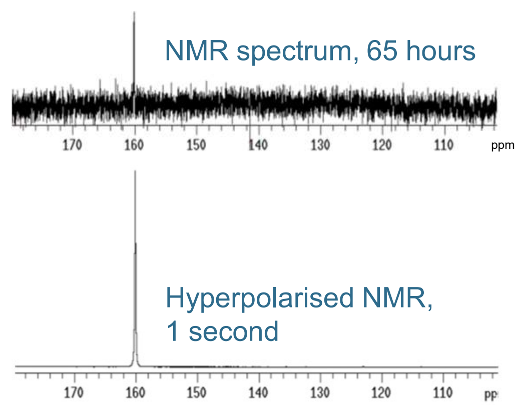
- Optically detected magnetic resonance
- Hyperpolarisation – one spin out of 10 polarised
- Detection volume – (sub)micron scale

Macroscopic – Inductive NMR

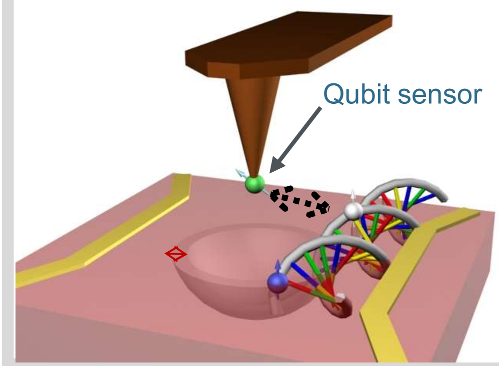
$$\langle \Delta S \rangle \propto \mu \left(N_{\Downarrow} - N_{\Uparrow} \right) \approx \frac{N \mu^2 B}{k_b T}$$



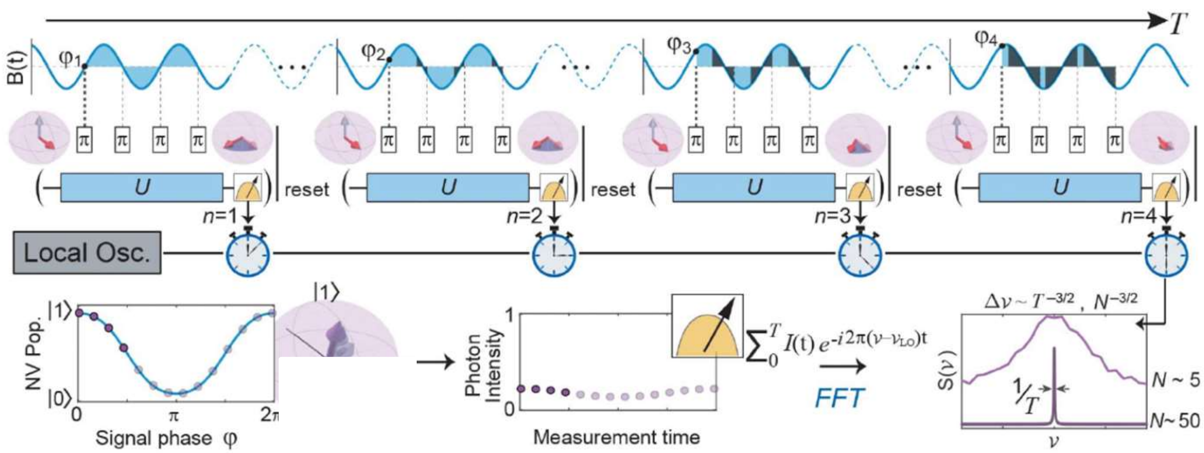
Hyperpolarisation



Diamond quantum sensing



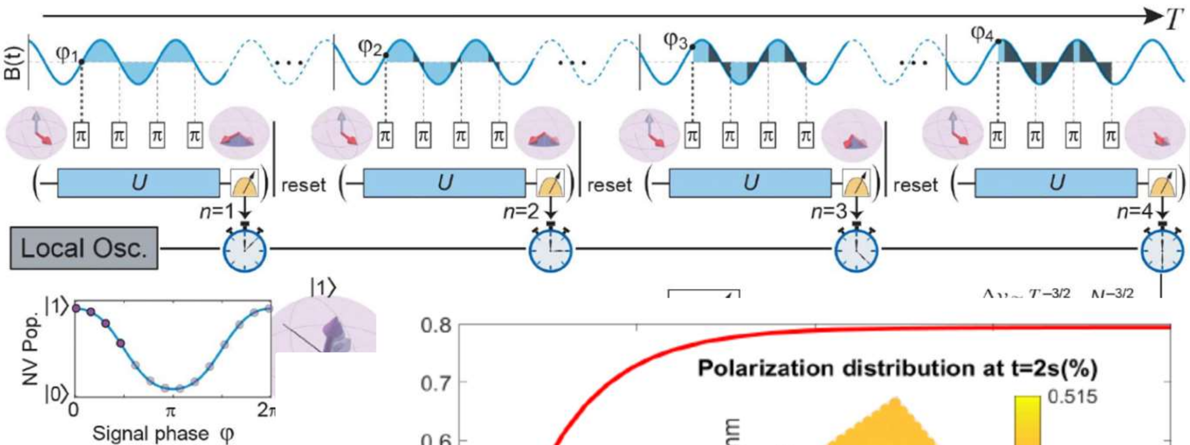
Nanoscale NMR



Qdyne

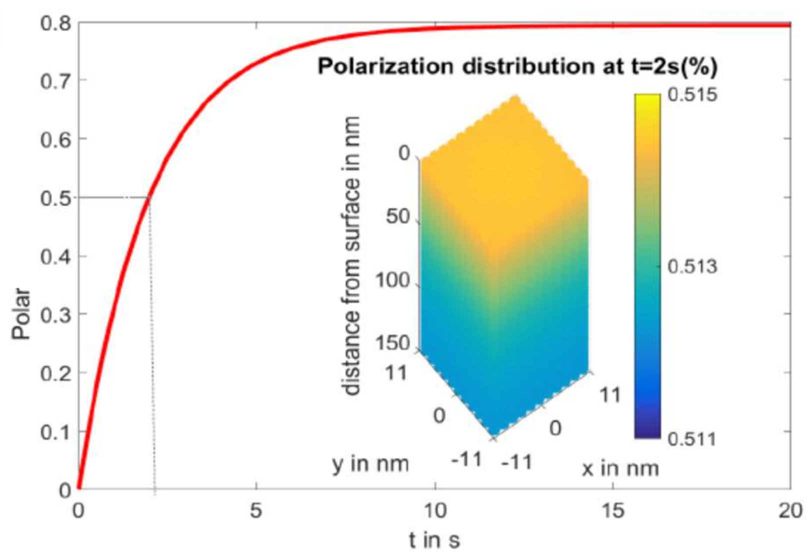
Science 356, 832 (201

Nanoscale NMR



Qdyne

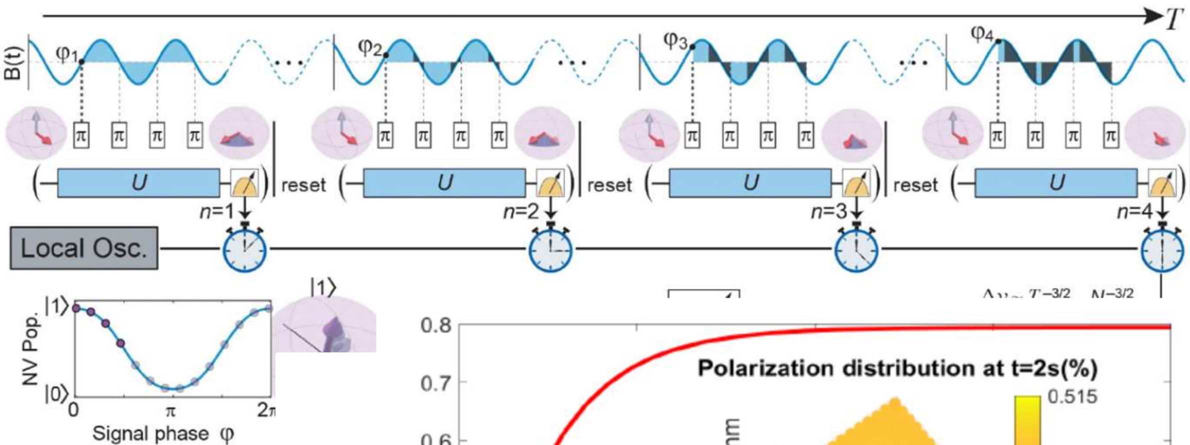
Science 356, 832 (201



Hyperpolarisation

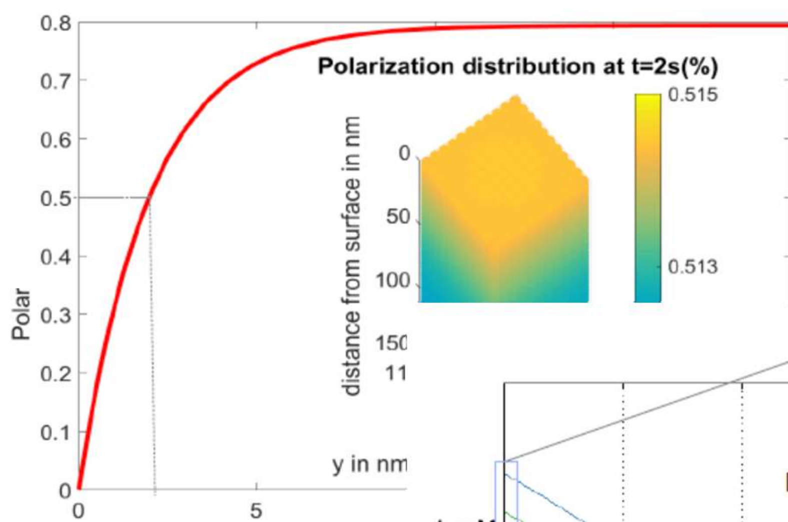
Nat. Phys. 9, 168 (2013)
Phys. Rev. Lett. 111, 067601 (2013)
Sci. Reports 9, 6938 (2019)

Nanoscale NMR



Qdyne

Science 356, 832 (201



Hyperpolarisation

Nat. Phys. 9, 168 (2013)
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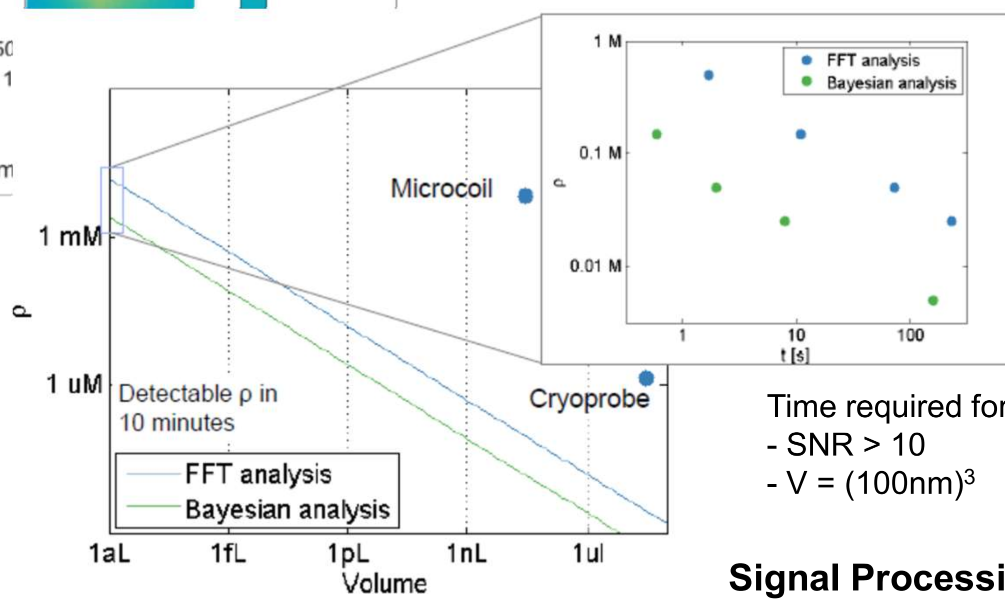
Sci. Reports 9, 6938 (2019)

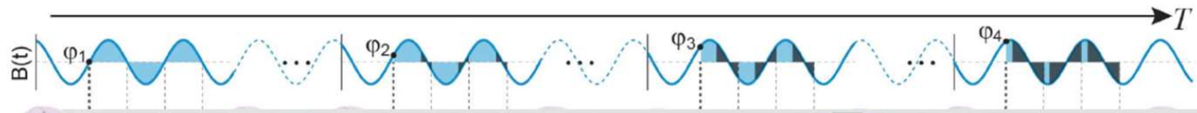


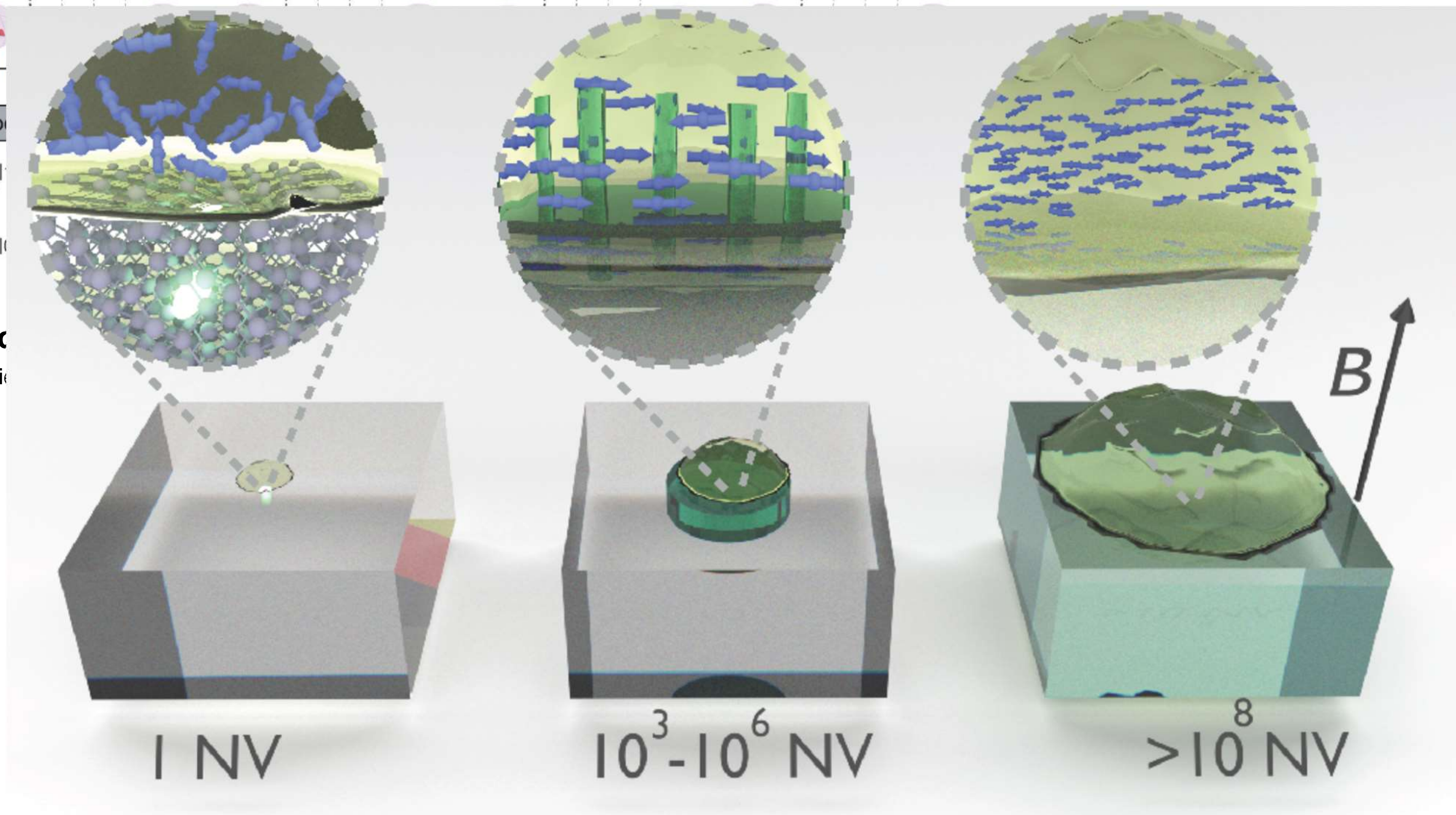
Time required for
- SNR > 10
- V = $(100nm)^3$

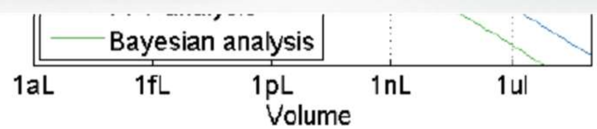
Signal Processing

Sci. Reports 9, 6938 (2019)

Nanoscale NMR





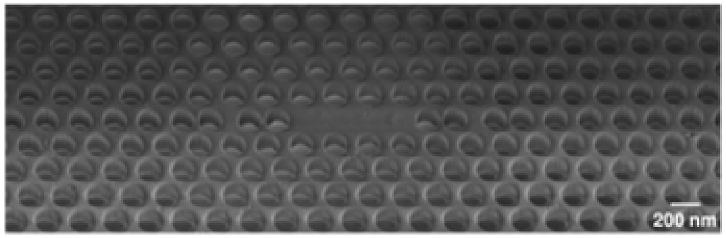


Signal Processing

Sci. Reports 9, 6938 (2019)

Colour Centers for Quantum Technologies

Optical Interface, Repeater, Computer

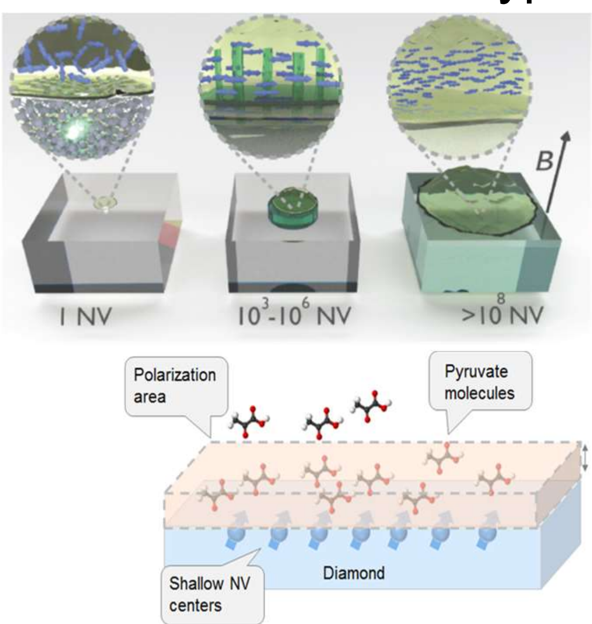


Englund et al, arXiv:1801.01151

Quantum Sensor

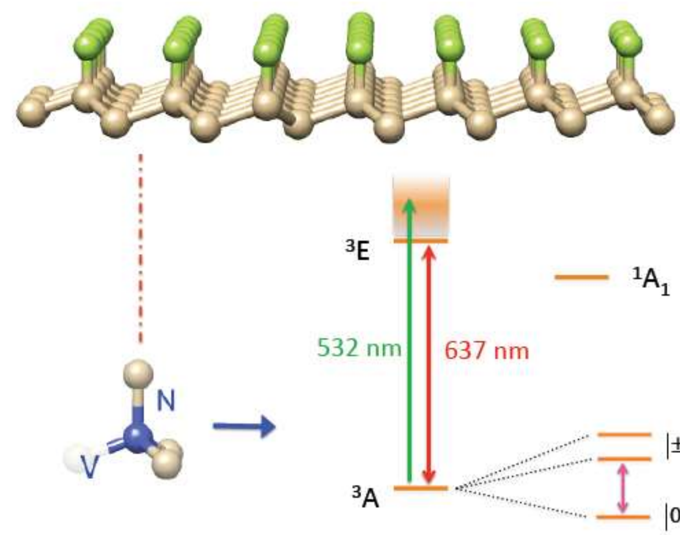
NJP 15, 013020 (2013); Nature Comm. **5**, 4703 (2014); …

Nanoscale NMR & Hyperpolarisation



PRL 111, 067601 (2013); Sci. Adv. 4, eaat8978 (2018); Science 356, 832 (2017)

Quantum Simulator



Nature Phys. 9, 168 (2013)

Institute of Theoretical Physics & Center for Quantum Biosciences

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Susana Huelga

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Raphael Weber

Alexander von Humboldt Stiftung / Foundation

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Synergy Grant: Diamond Quantum Devices and Biology & Proof of Concept Grant (BioQ) 2013 -2019

Synergy Grant: Quantum hyperpolarisatio
for ultrasensitive NMR and MRI
(HyperQ) 2020 - 2026

HYPERDIAMOND

Bundesministerium für Bildung und Forschung

NanoSpin
DiaPol

DFG Deutsche Forschungsgemeinschaft

SFB TRR-21 & SPP 1601
Reinhart Koselleck Award