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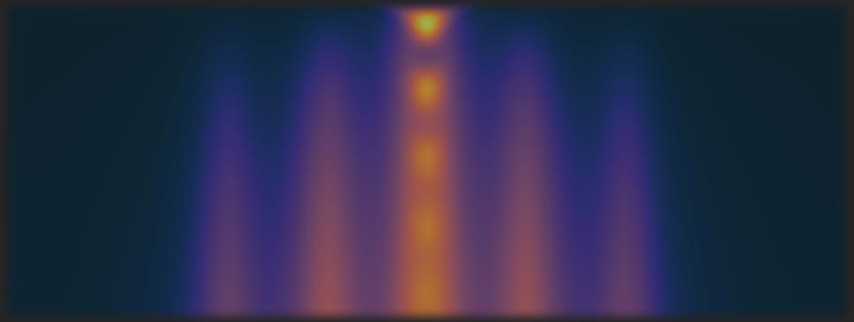
Cavendish Laboratory

nuclear spins in a semiconductor quantum dot: through the looking-glass, and what we found there

Mete Atatüre

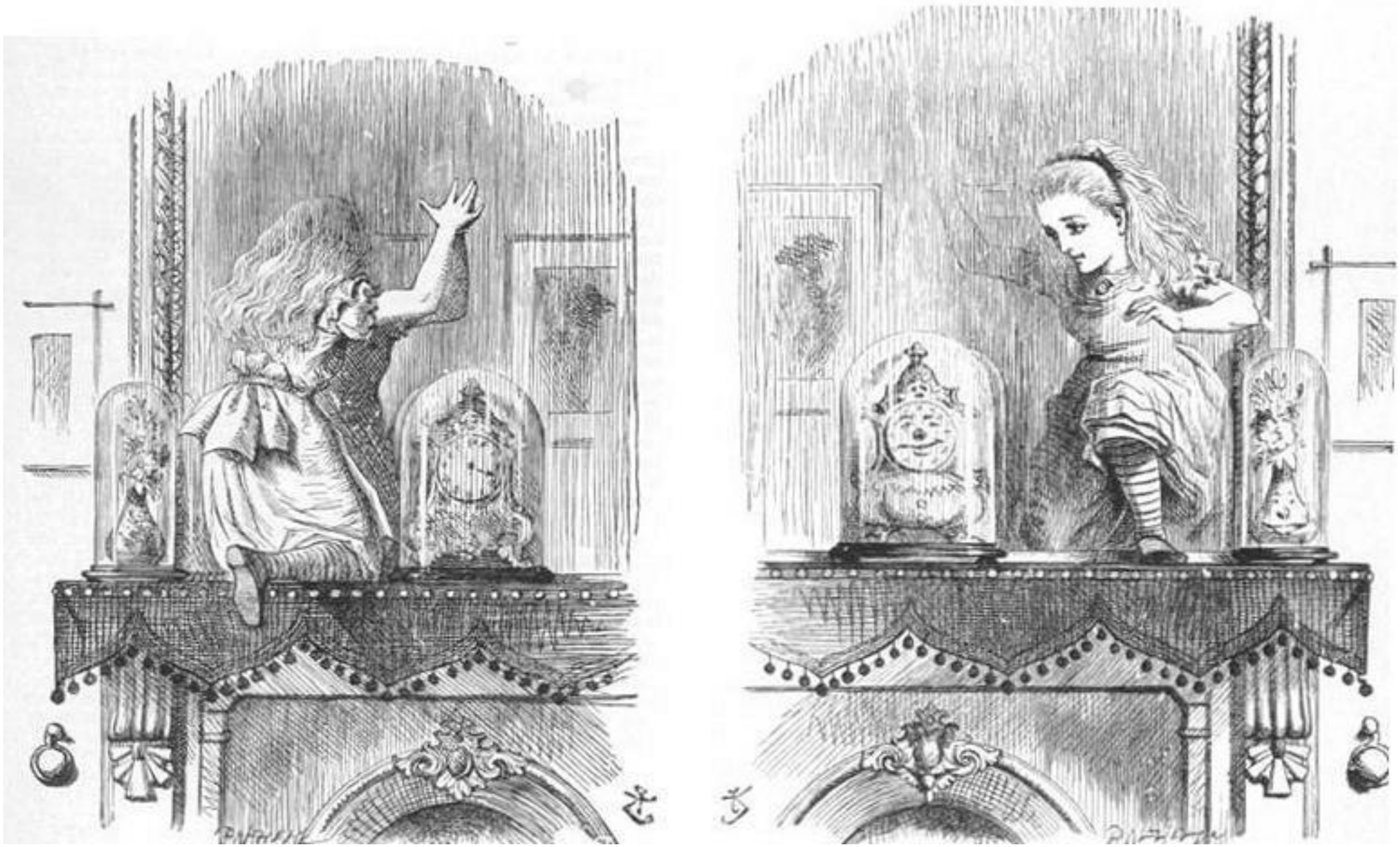
Cavendish Laboratory
University of Cambridge



Quantum Science Seminar

22 July 2021

through the looking-glass…



Through the Looking-Glass, and What Alice Found There ***Lewis Carroll, 1871***

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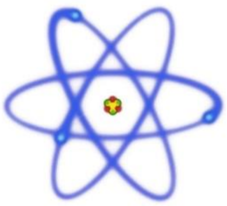
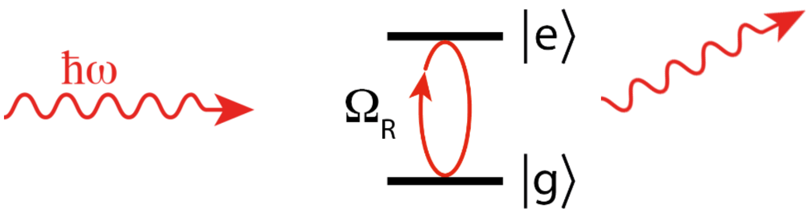
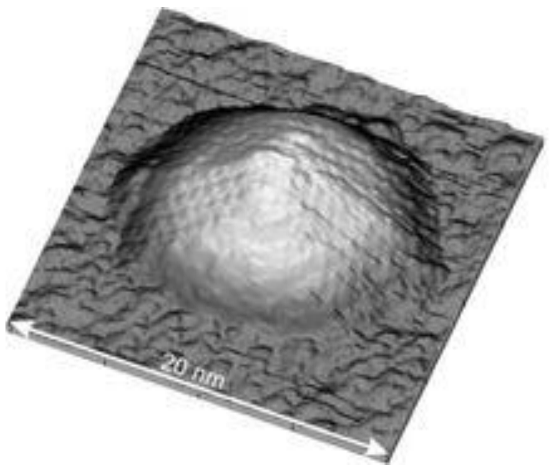
the quest for the ‘artificial’ atom

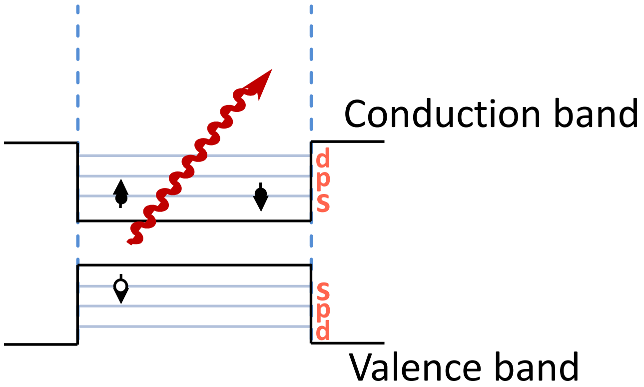
want:





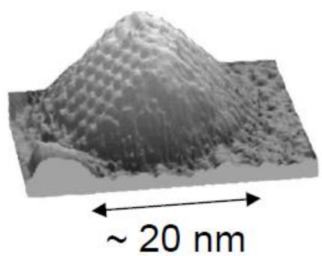
have:

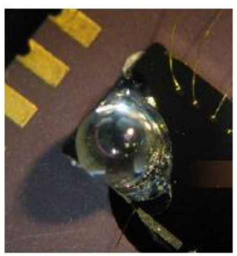




solid-state quantum light sources (w/ spins inside)

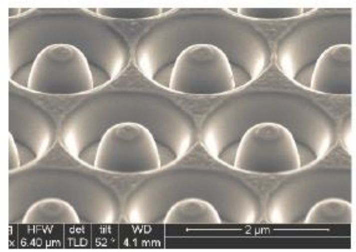
Quantum Dots
(InGaAs)



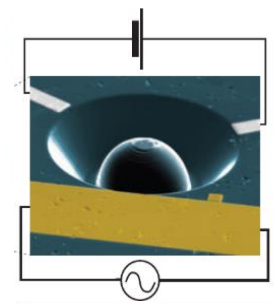


+ GeV, SnV…

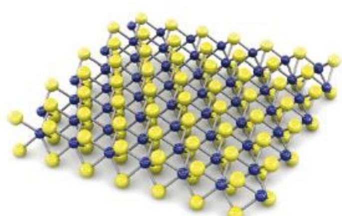
Silicon-vacancy centres
(Diamond)



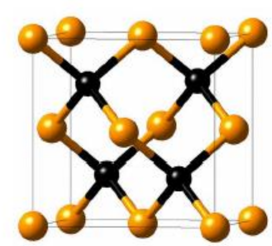
Nitrogen-vacancy centres
(Diamond)



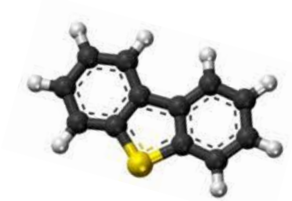
2D materials



Defects in SiC

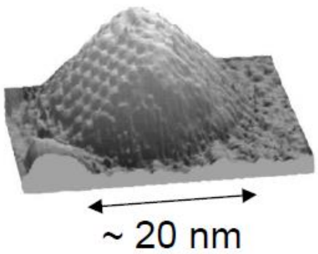


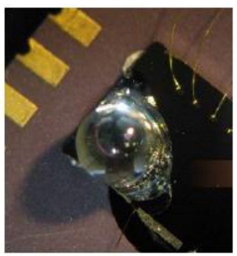
Molecules



solid-state quantum light sources (w/ spins inside)

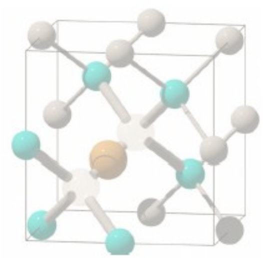
Quantum Dots
(InGaAs)

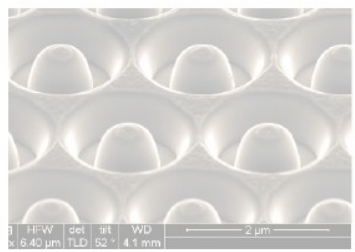




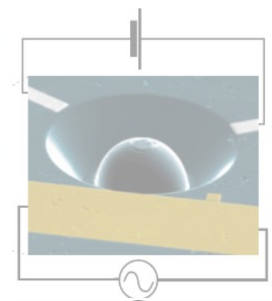
+ GeV, SnV…

Silicon-vacancy centres
(Diamond)

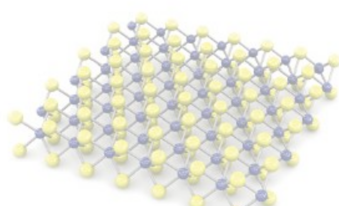




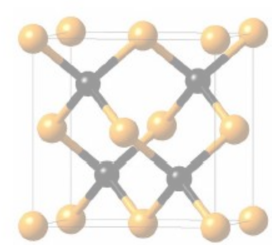
Nitrogen-vacancy centres
(Diamond)



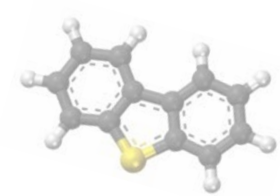
2D materials



Defects in SiC



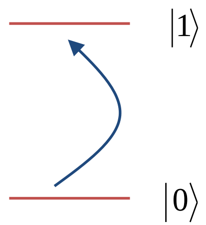
Molecules



M. Atature, D. Englund, N. Vamivakas, S.-Y. Lee, J. Wrachtrup, *Nature Reviews Materials* **3**, 38 (2018)

quantum node ingredients: barley...hops...water

Stationary qubits



$$|\varphi\rangle = c_1|0\rangle + c_2|1\rangle$$

Flying qubits

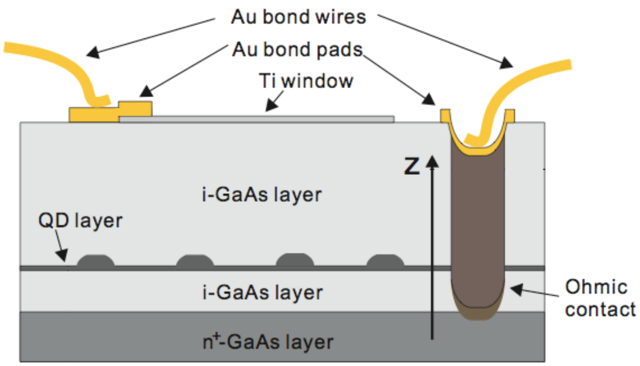
Communication channel

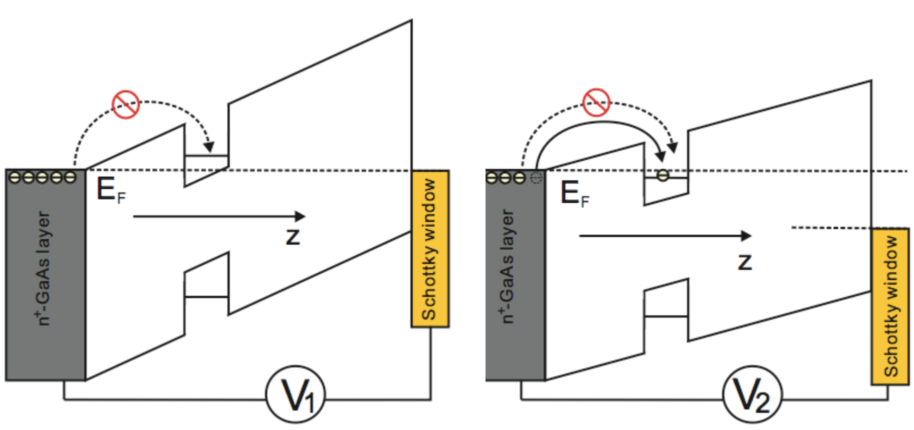
electronic spins

excitonic / optical transitions

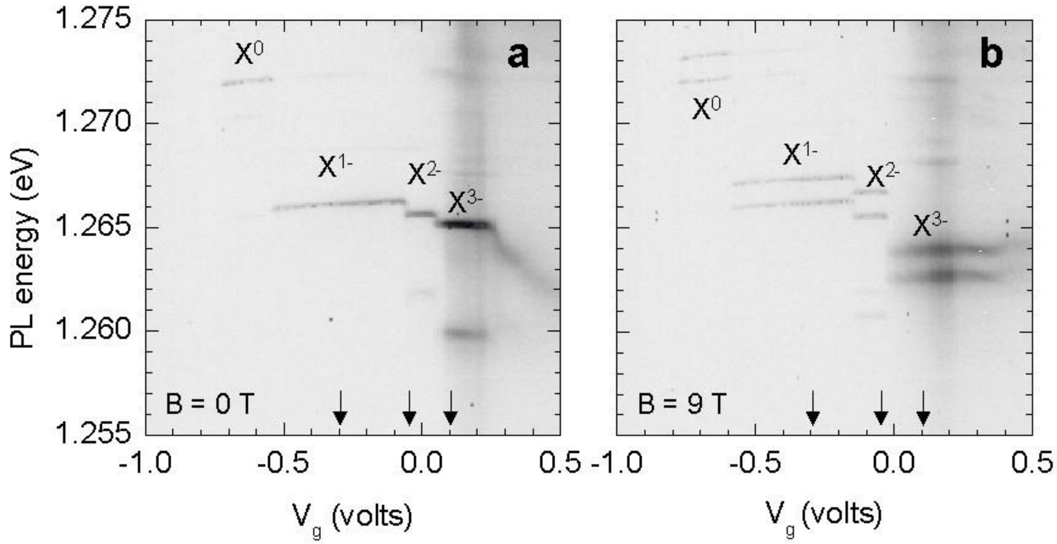
free space / fibers / waveguides

InGaAs quantum dot devices



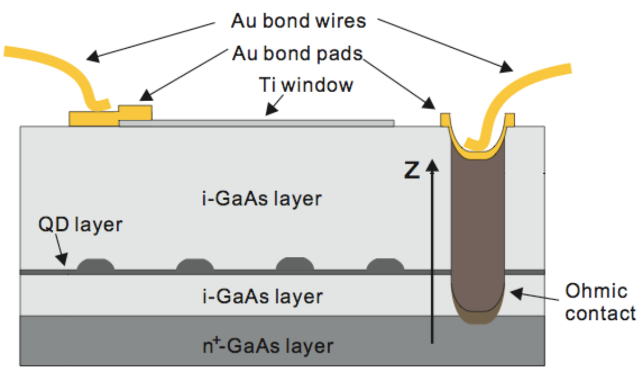


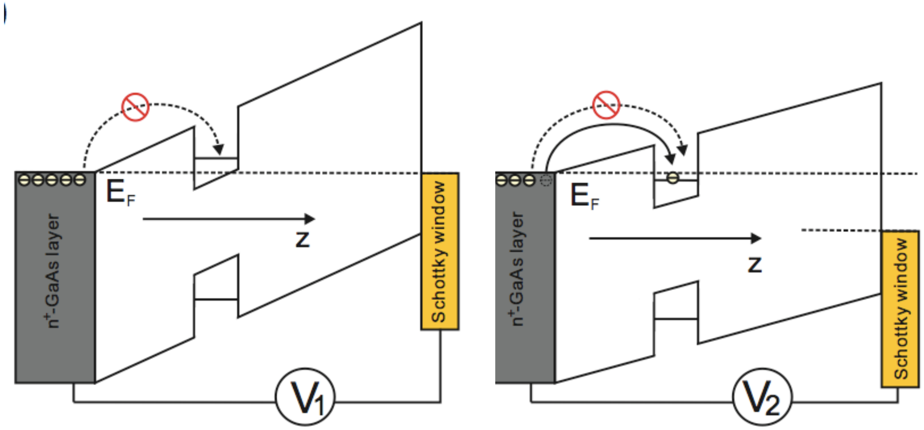
Voltage controlled photoluminescence



Karrai et al. Nature **427**, 135 (2004)

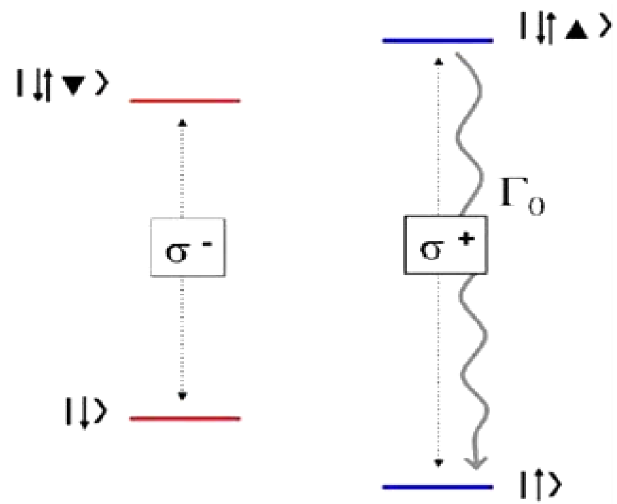
InGaAs quantum dot devices





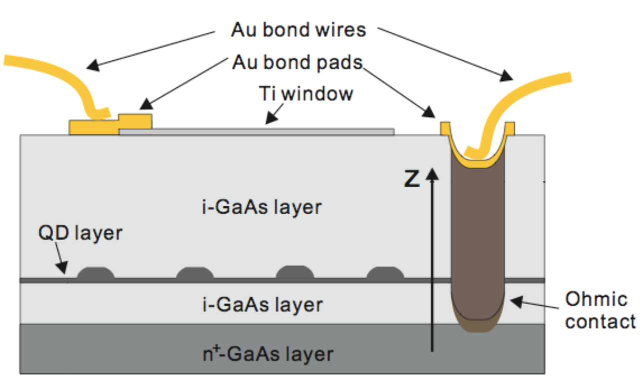
Voltage controlled charged QD:

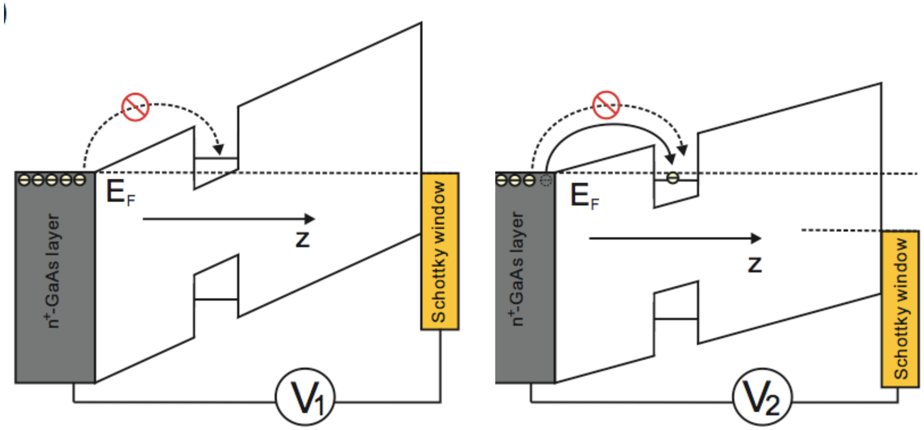
Spin-based ground state,
+
Spin-selective optical transitions.
=
a spin-photon quantum interface.

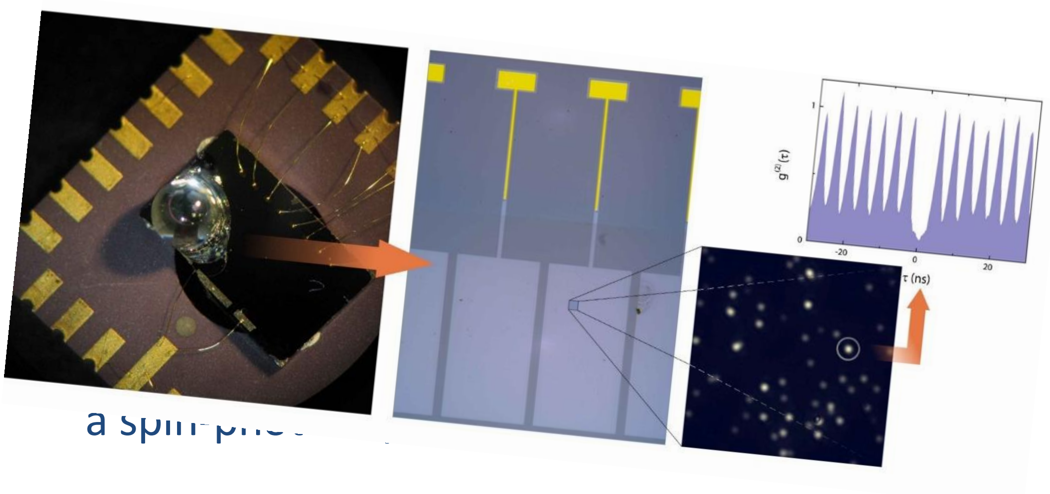


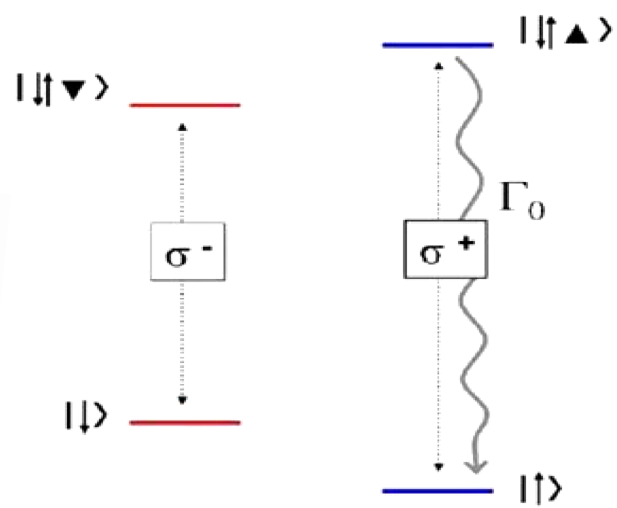
Charged Exciton
(optically accessible spin)

InGaAs quantum dot devices





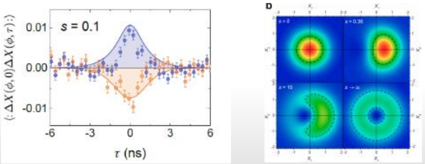




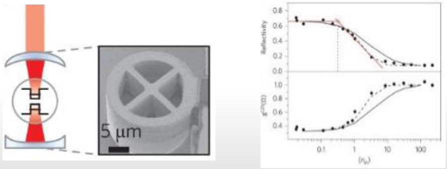
Charged Exciton
(optically accessible spin)

using quantum dots – from fundamentals to applications

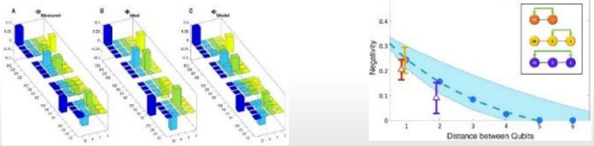
Single-photon quadrature squeezing in the Heitler regime
Schulte et al., Nature **525**, 222 (2015)



Single-photon nonlinearity, Fock-state filter
De Santis et al., Nature Nanotechnology **12**, 663 (2017)

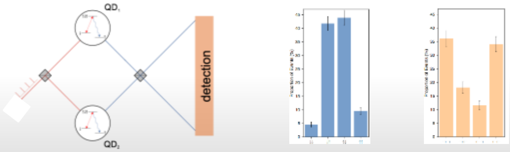


Photonic cluster-state generation
Schwartz et al., Science **354**, 434 (2016)

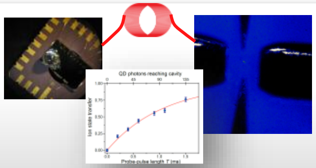


High-efficiency multiphoton boson sampling
Wang et al., Nature Photonics **11**, 361 (2017)

Optically generated spin-spin entanglement
Stockill et al., Phys. Rev. Lett. **119**, 010509 (2017)



Optically linked hybrid system of QD and trapped ion
Meyer et al., Phys. Rev. Lett. **114**, 123001 (2015)



…to list only a few!

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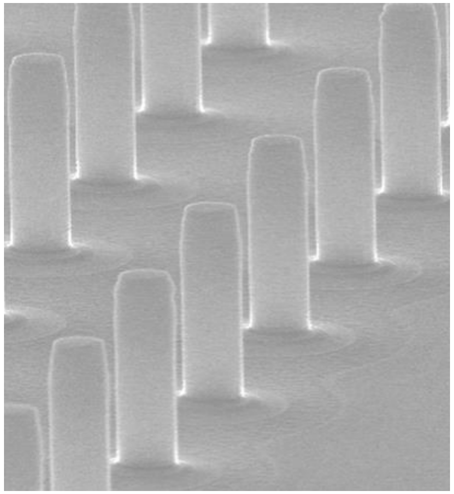
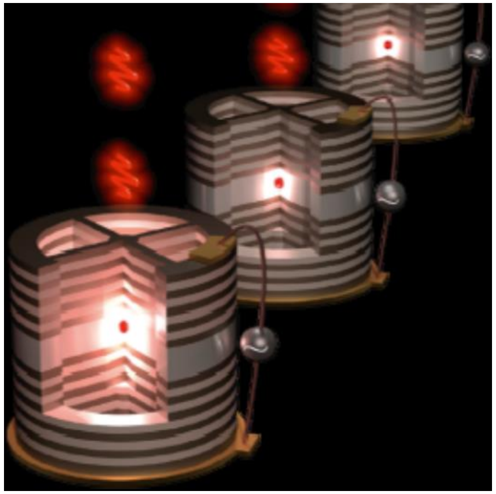
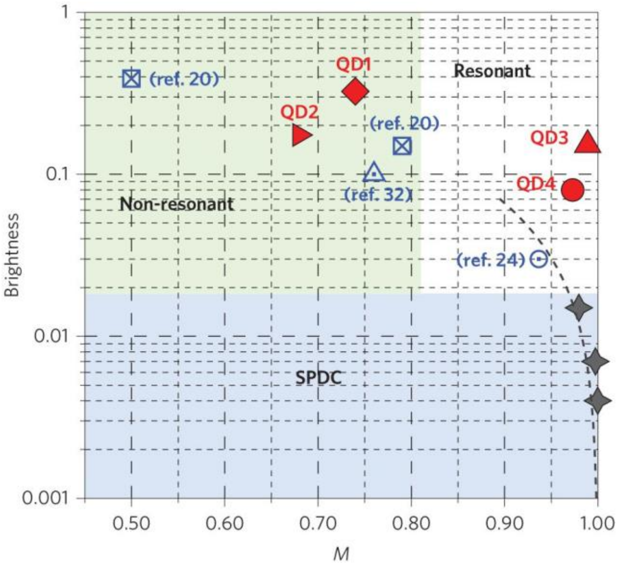
outlook for QDs (photon collection rates)

Optical cavity or waveguide implementations







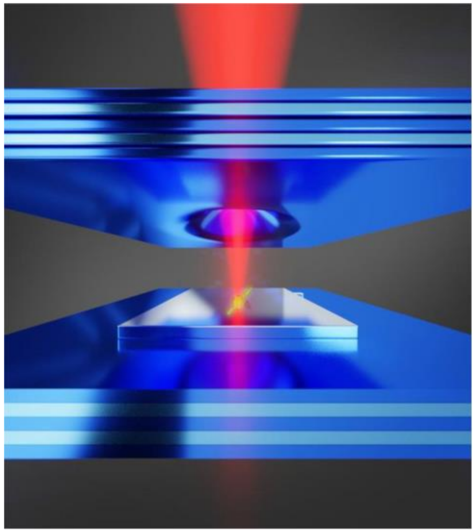
to improve the photon collection efficiency by 10x to 30x!

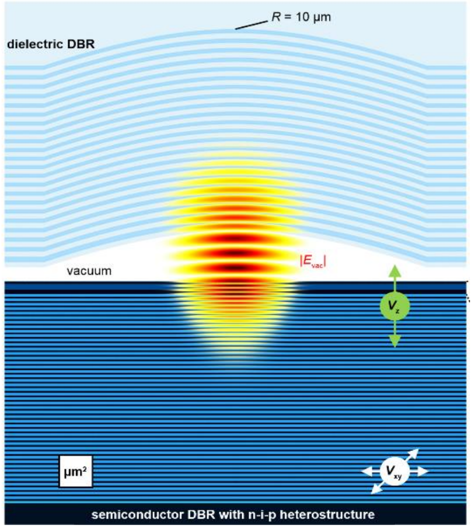
Somaschi et al., *Nature Photonics* **10** 340 (2016)

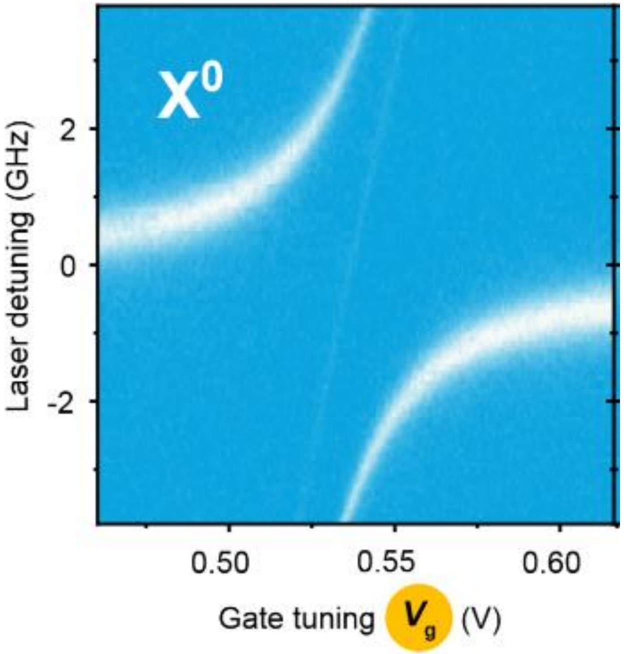
outlook for QDs (photon collection rates)

multiple approaches: photonic crystal cavities, nanopillars, etc.

Warburton Group: Gated QDs in an open cavity



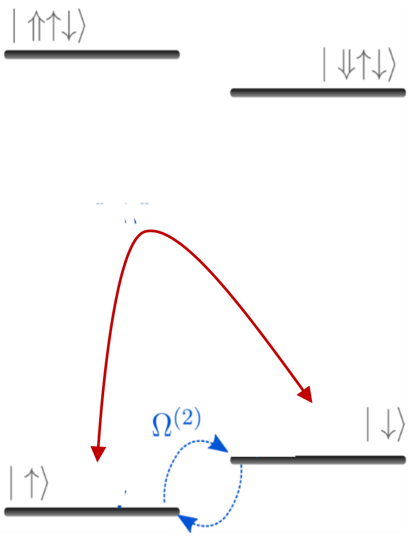


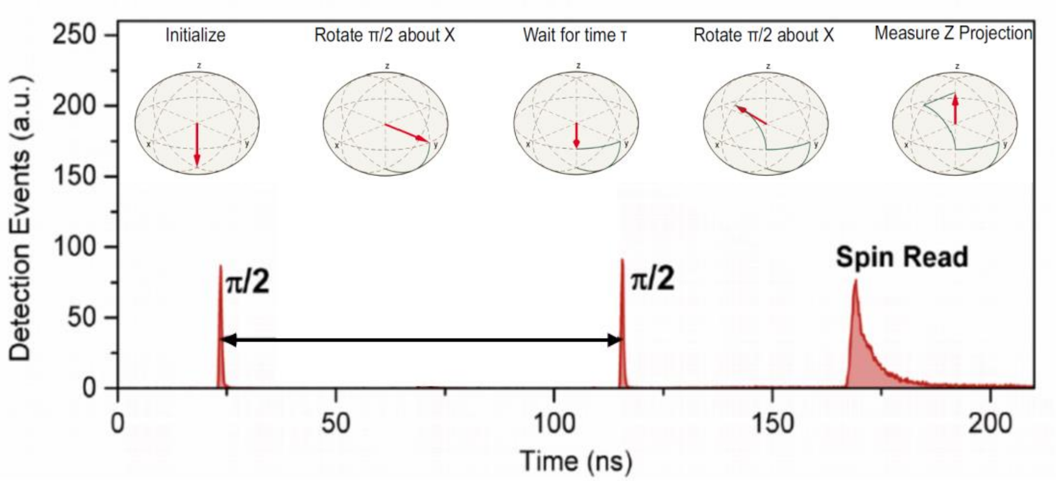


Cooperativity of 150, β-factor of 99.7%

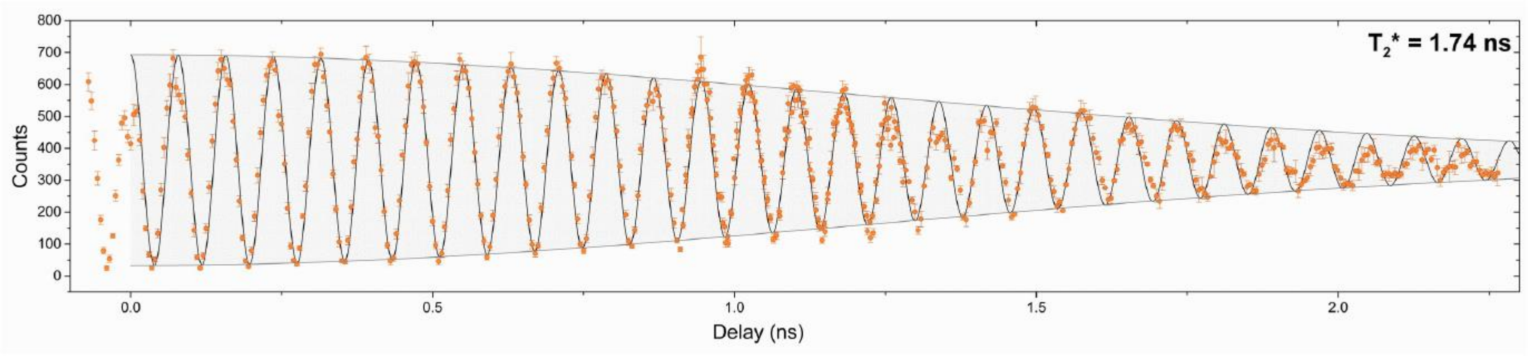
Carter et al., Nat Phys 7, 329 (2013)
Najer et al., Nature 575, 622 (2019)

all-optical ultrafast (broadband) control and spin coherence

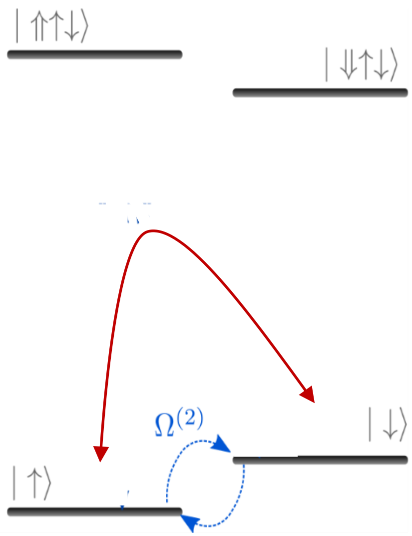


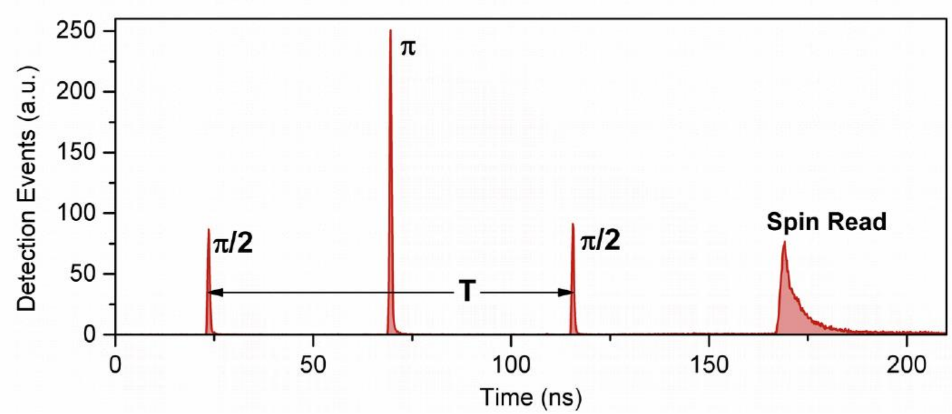


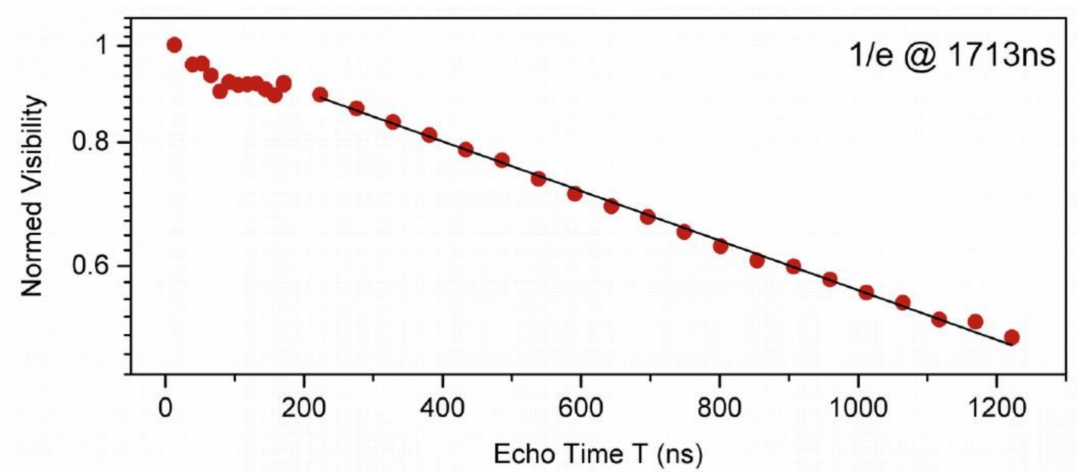
Ramsey



all-optical ultrafast (broadband) control and spin coherence







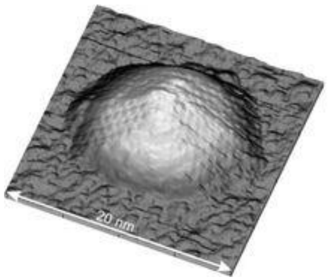
Evidence of slow noise

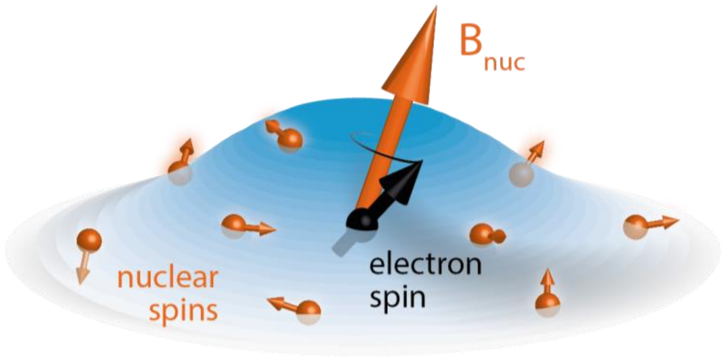
T_2 limit ~10 μs

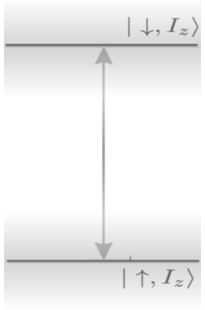
Press et al., Nature Photonics 4, 367 (2010)
Bechtold et al, Nature Physics 11, 1005 (2015)
Stockill et al., Nature Comms 7, 12745 (2016)

the central spin problem: a many-body problem

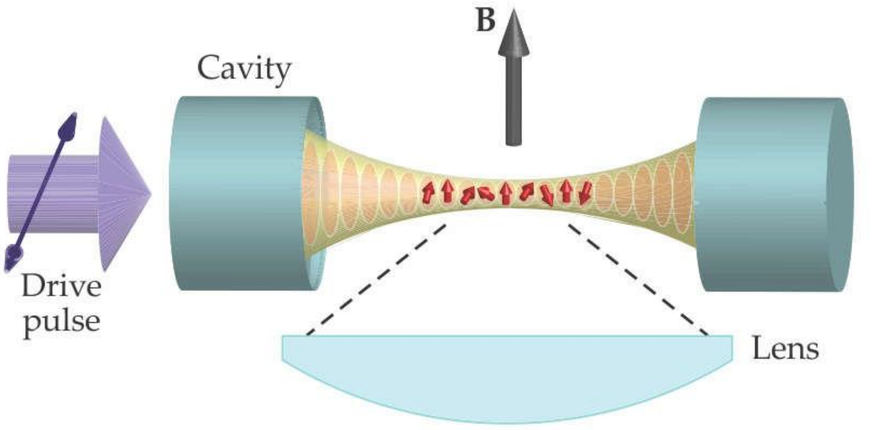
There is strong interaction between an electron and the nuclear spins (~50,000!)



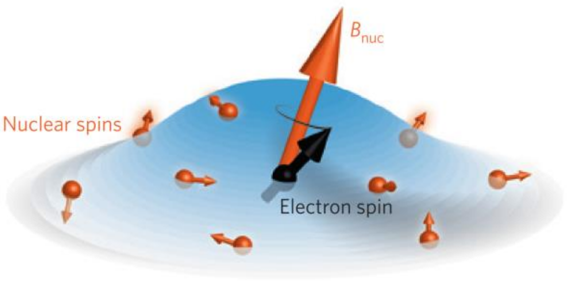


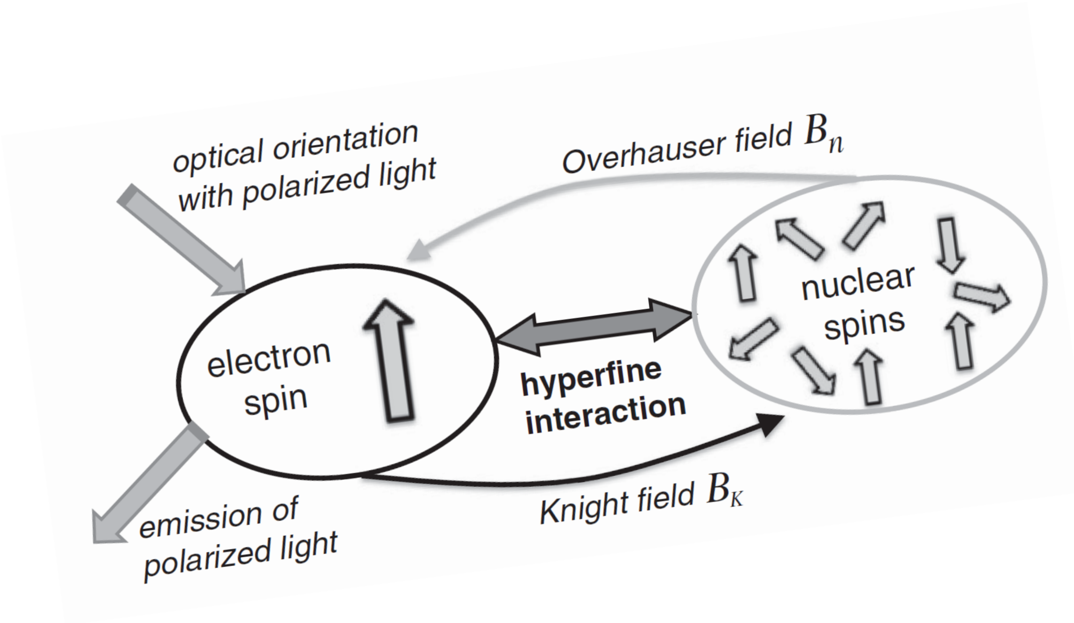


Analogies with an atomic ensemble coupled strongly to a cavity mode



the central spin problem: a many-body problem





Dial-up your I_z:

In addition to a quasistatic (classical) magnetic noise,

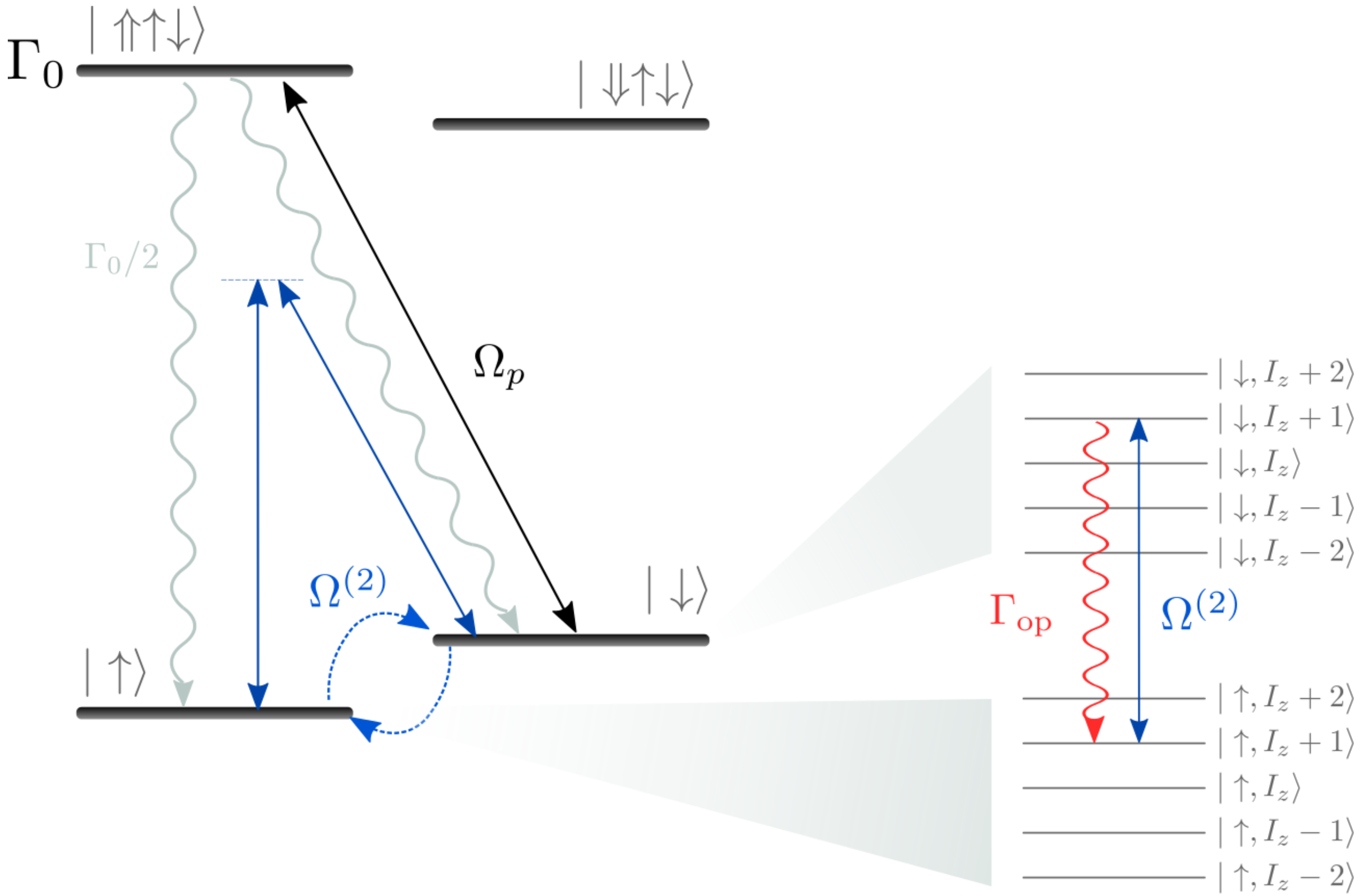
hyperfine interaction allows Dynamical Nuclear Spin Polarisation!

This can polarise nuclear spins! (~70% achieved)

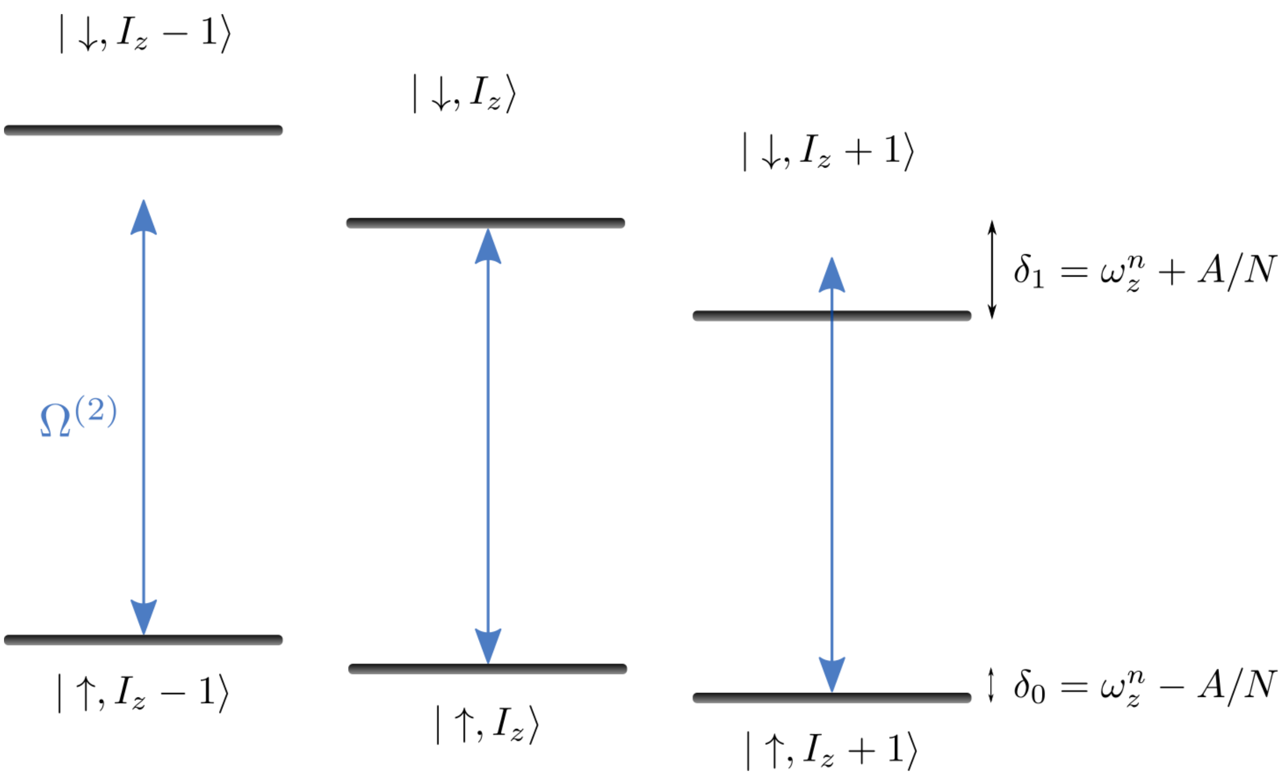
There is an Option B!

Urbaszek et al., *Reviews of Modern Physics* **85**, 79 (2013)

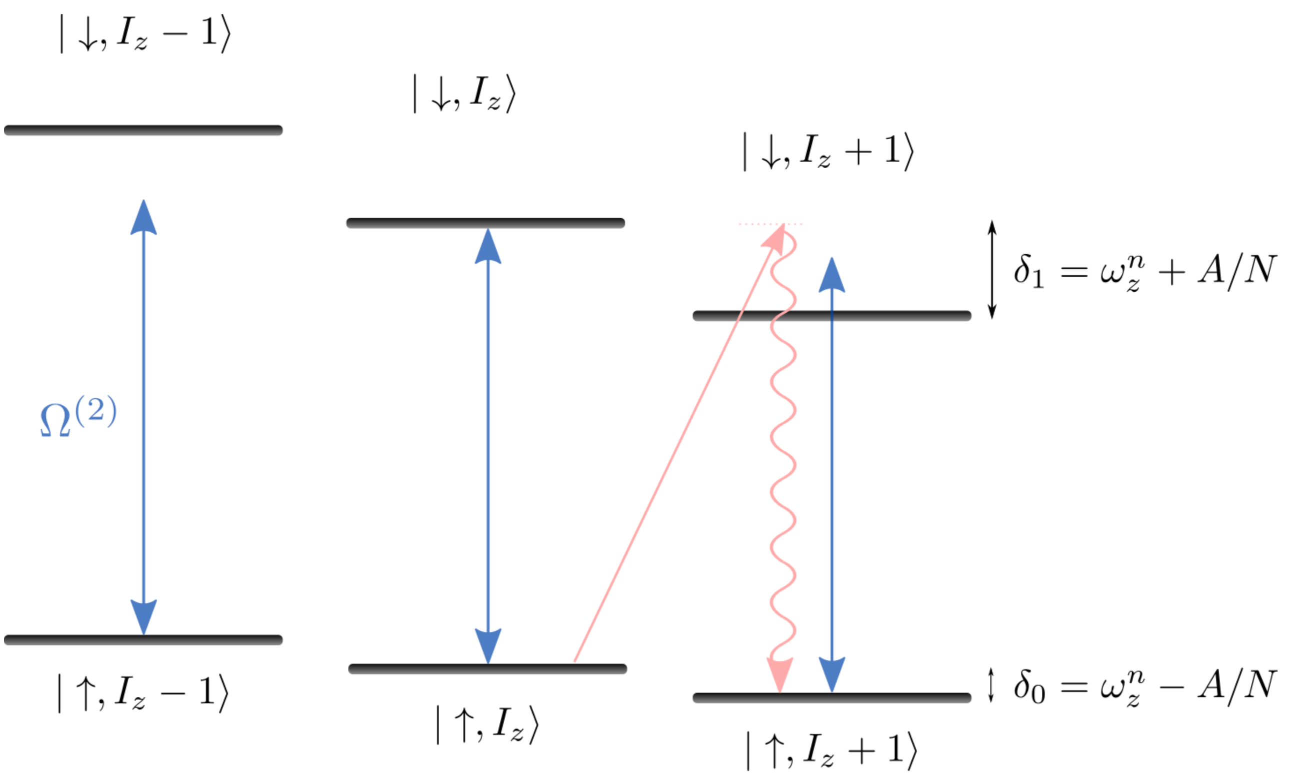
the electron-nuclear coupled system



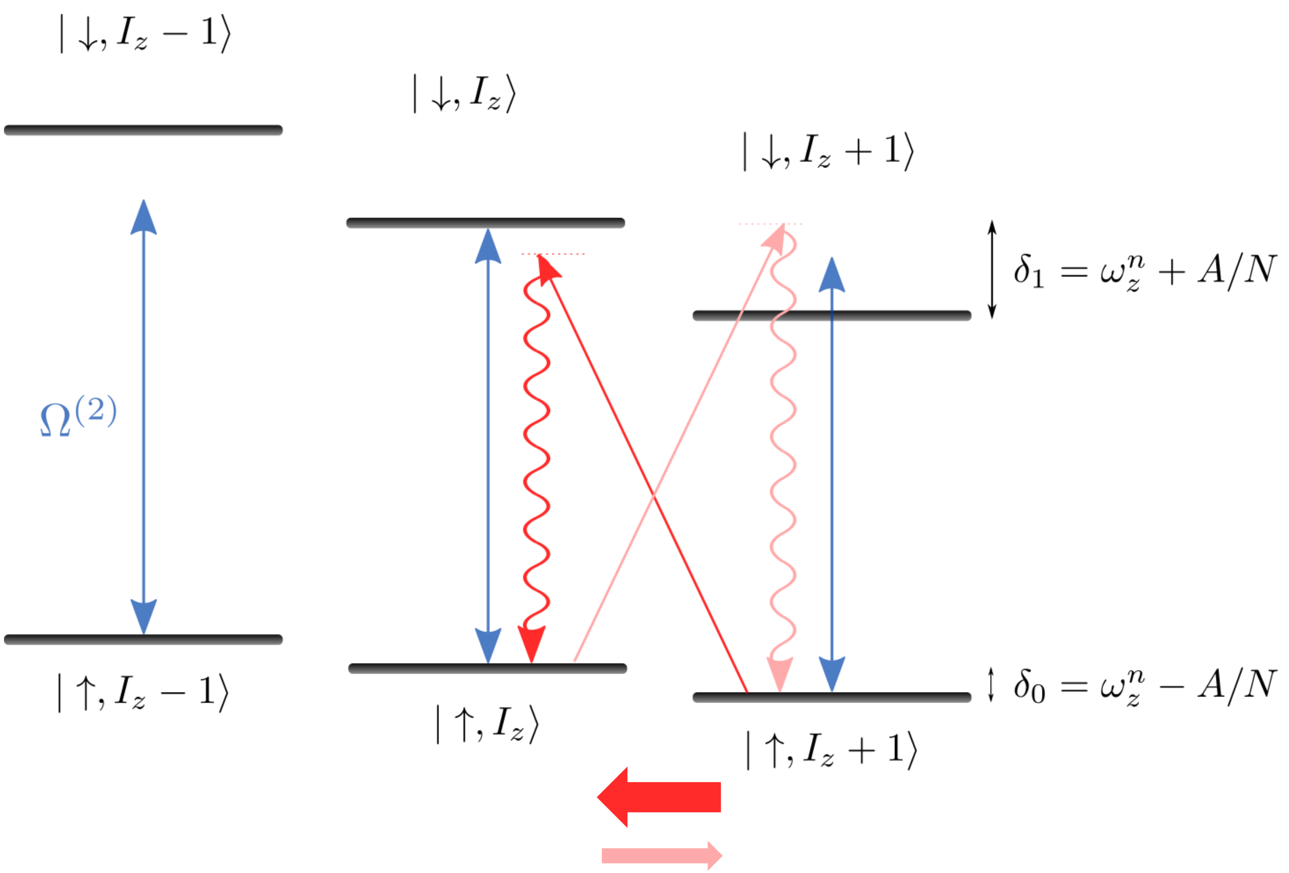
optical orientation of nuclear spins



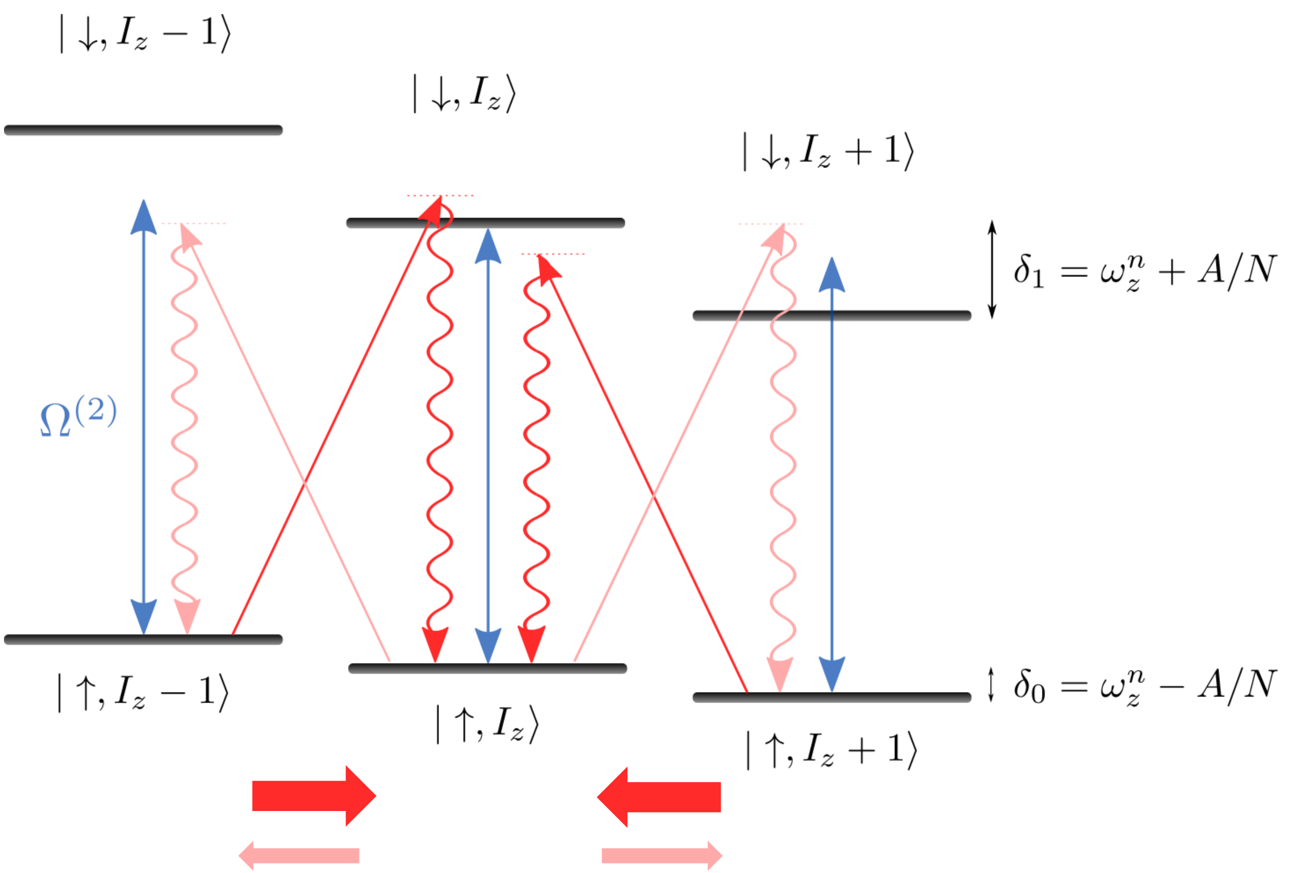
optical orientation of nuclear spins



optical orientation of nuclear spins

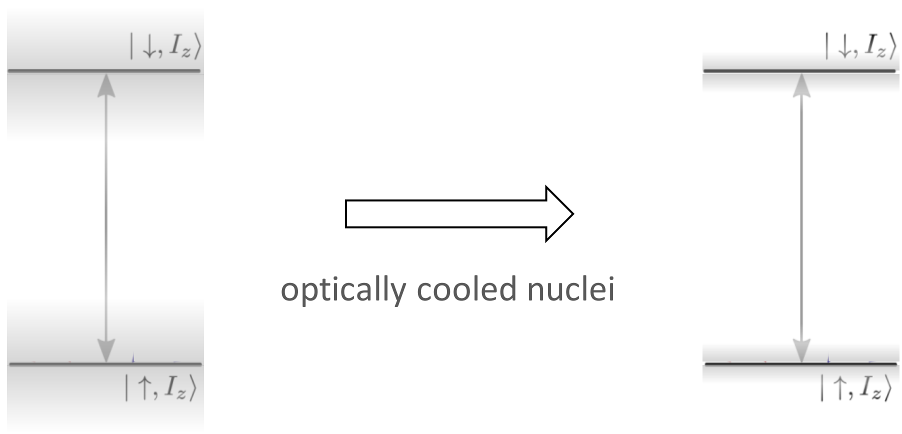


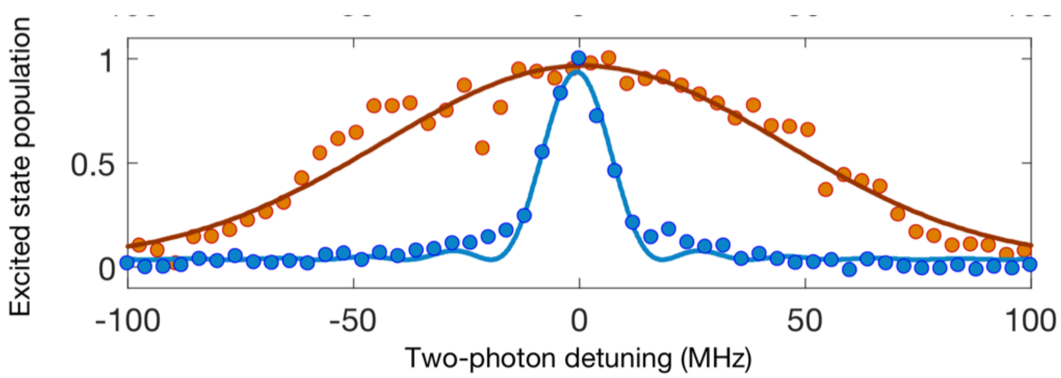
optical orientation of nuclear spins



The anharmonic ladder of states leads to a single I_z determined by two-photon detuning.

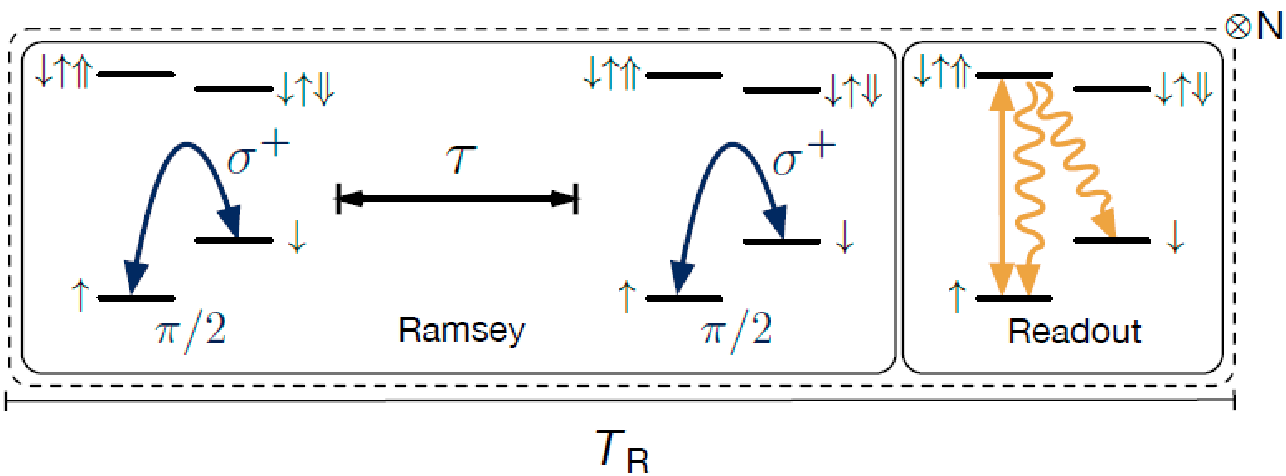
how cool are those cooled nuclei?

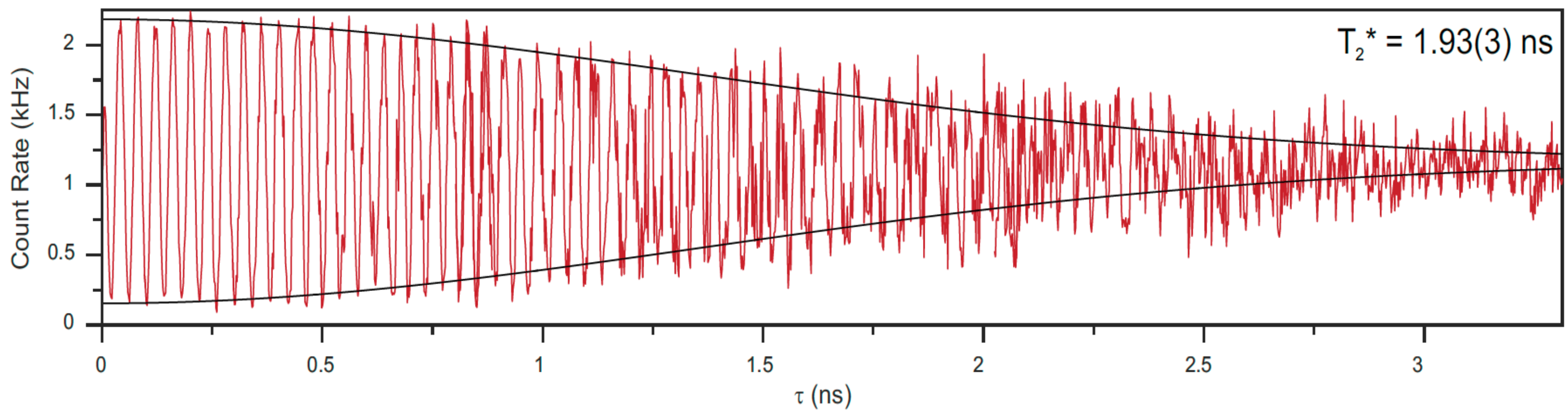




Measured ESR linewidth is ~15 MHz → 400 μK

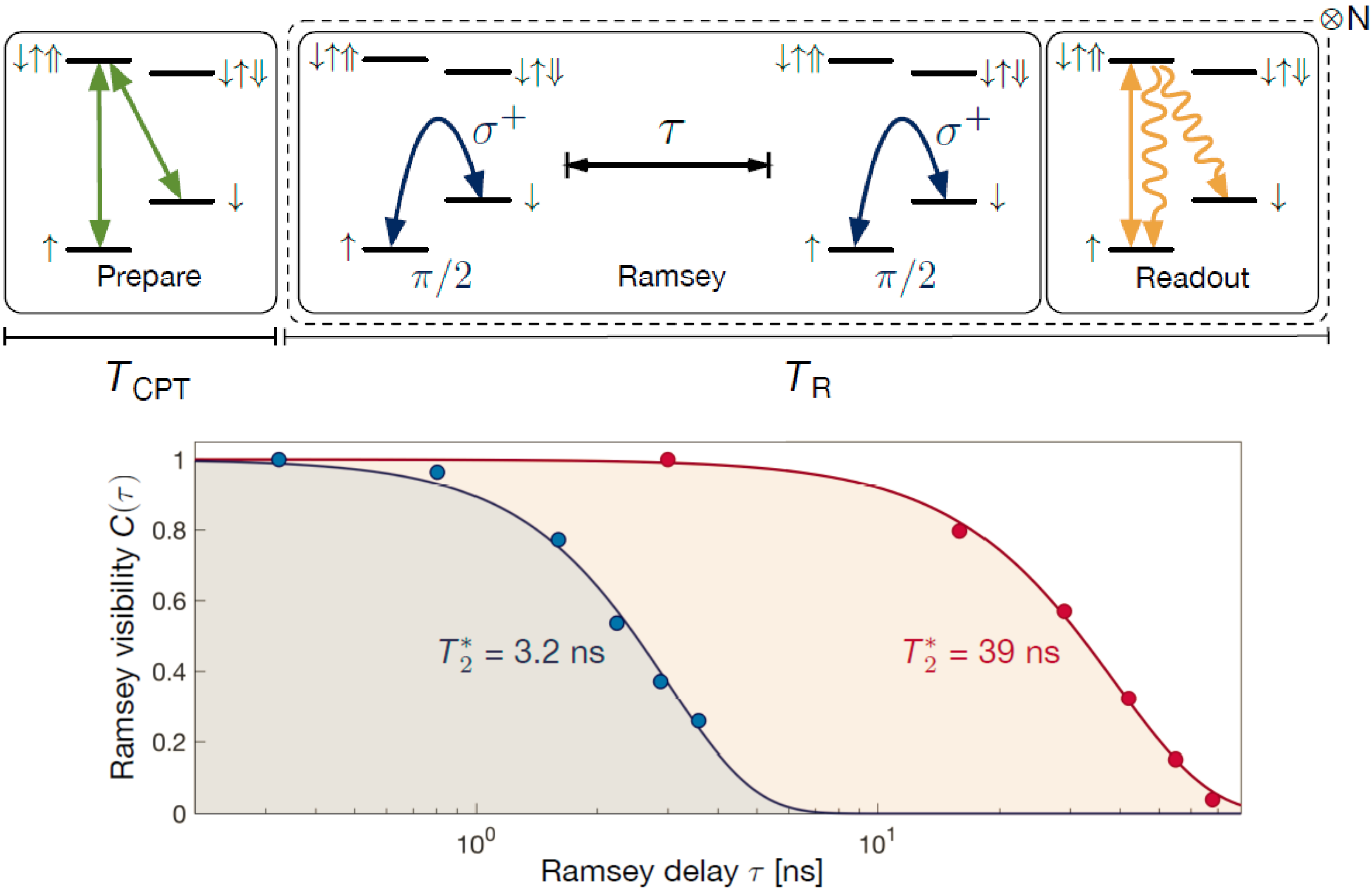
electron coherence after the suppressing nuclear magnetic noise





Ethier-Majcher et al., PRL **119** 130503 (2017)

electron coherence after the suppressing nuclear magnetic noise



Ethier-Majcher et al., PRL **119** 130503 (2017)

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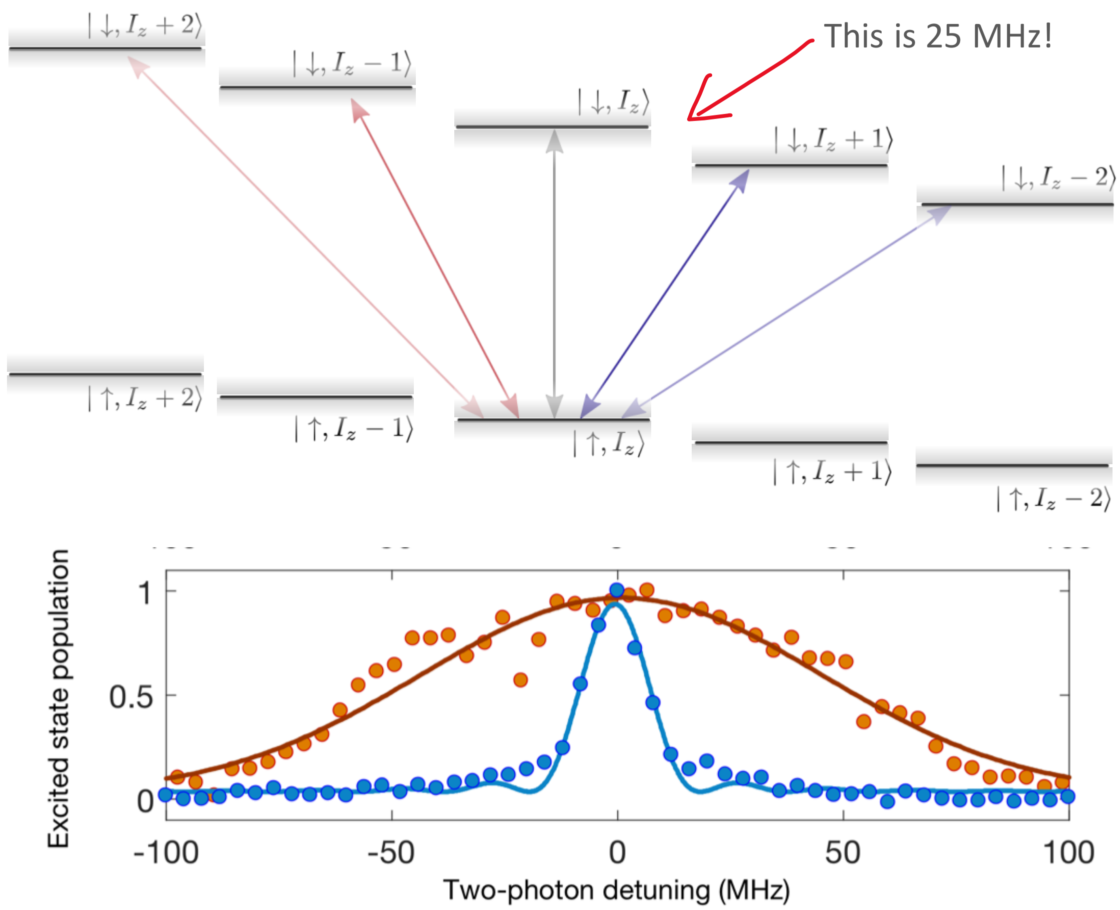
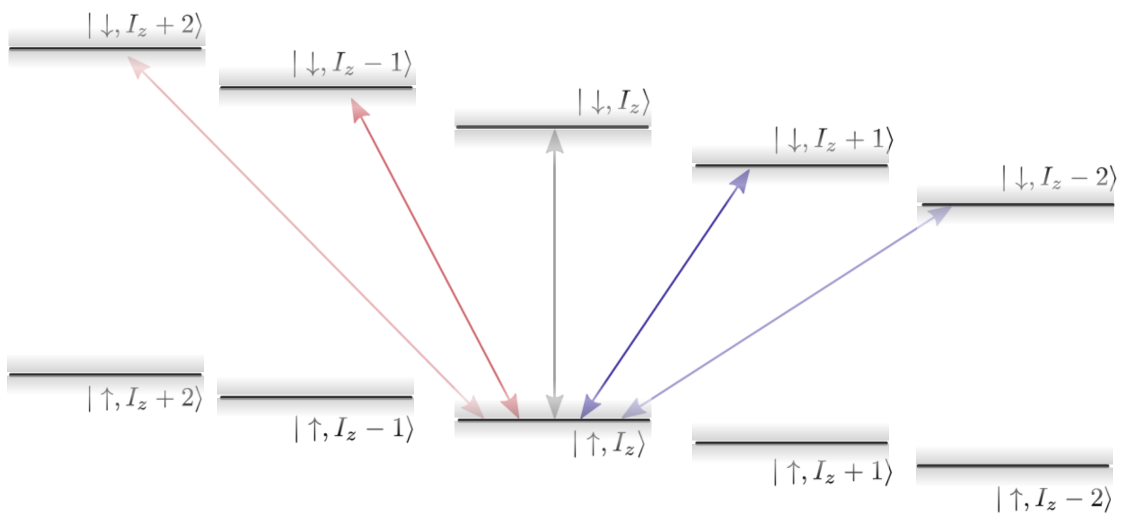
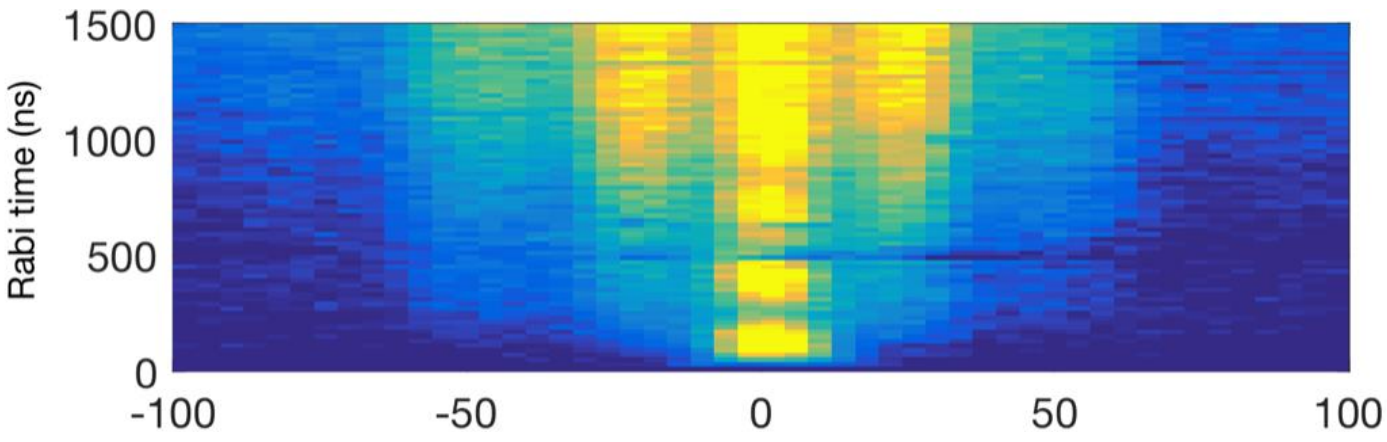
measuring nuclear spin variance via optical ESR



Measured ESR linewith is ~15 MHz → 400 µK
Single nuclear spin Zeeman energy is 25 MHz.

probing the single-spin excitation spectrum of the nuclei





Gangloff *et al.*, Science 364, 62 (2019).

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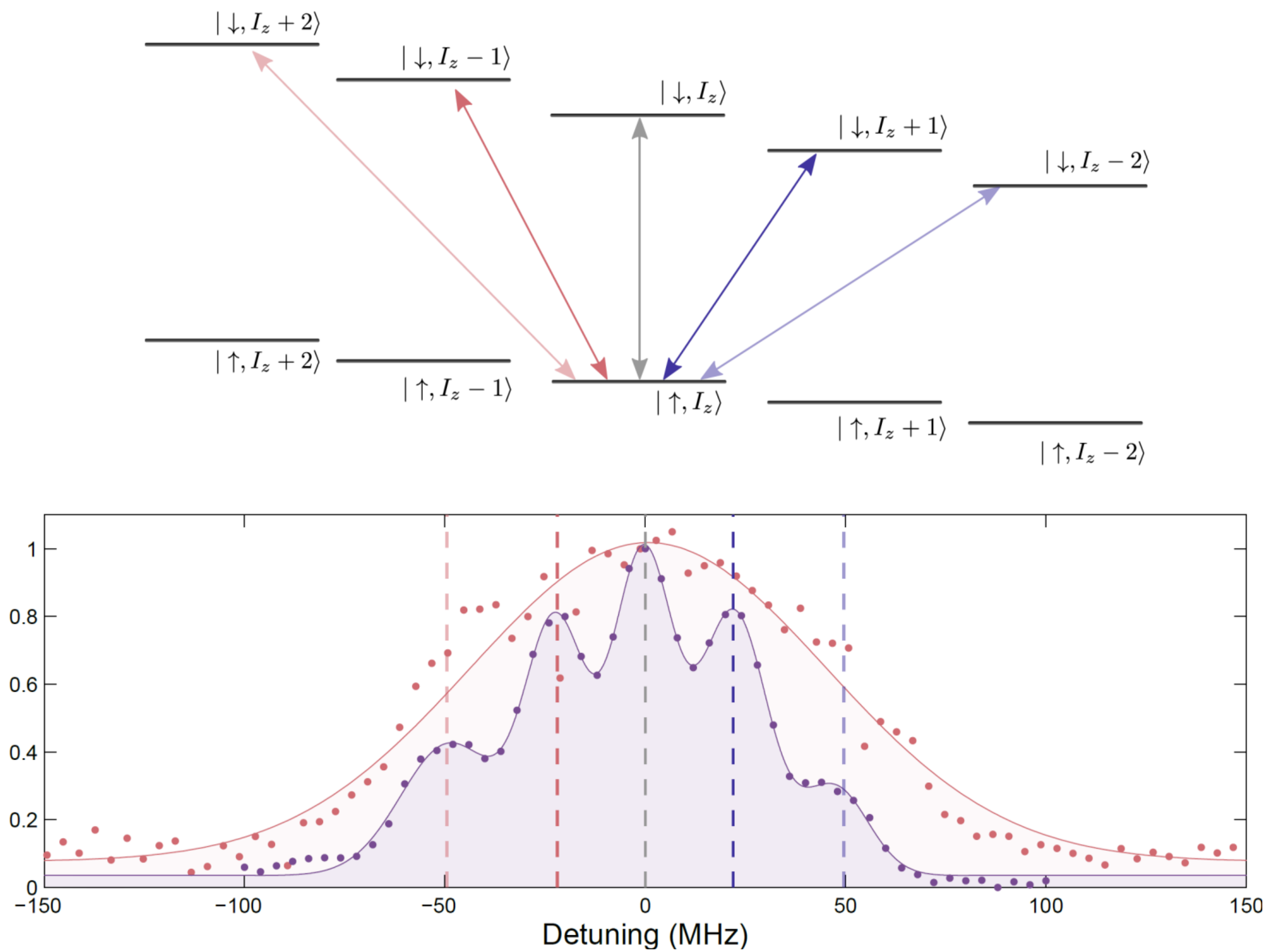
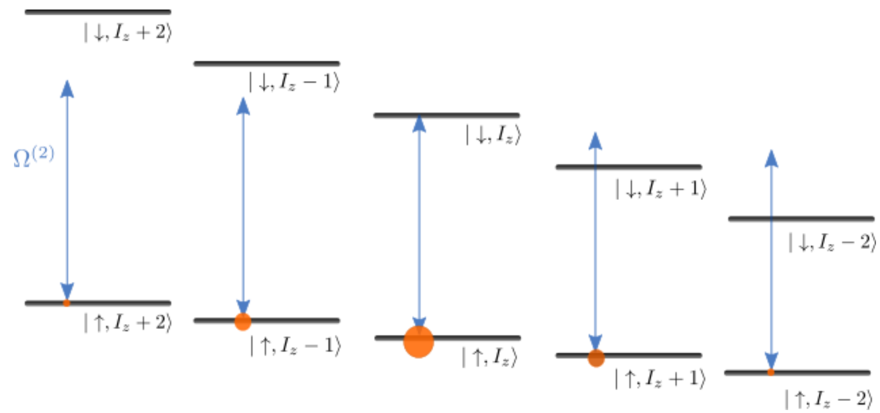
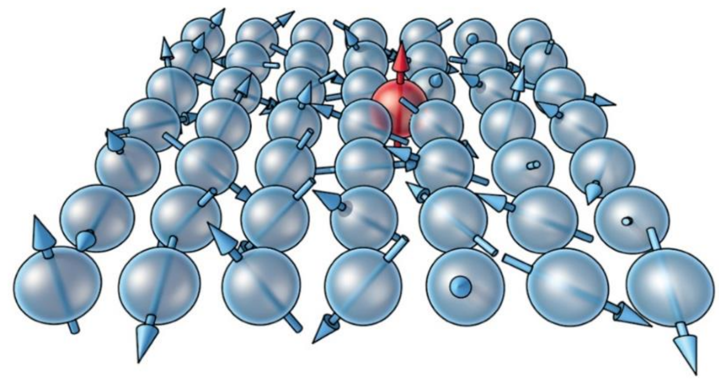


Gangloff *et al.*, Science 364, 62 (2019).

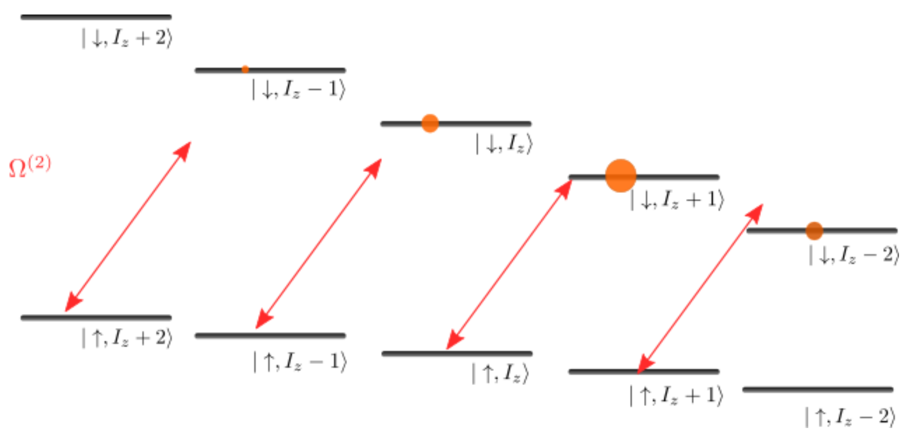
driving of a collective nuclear excitation

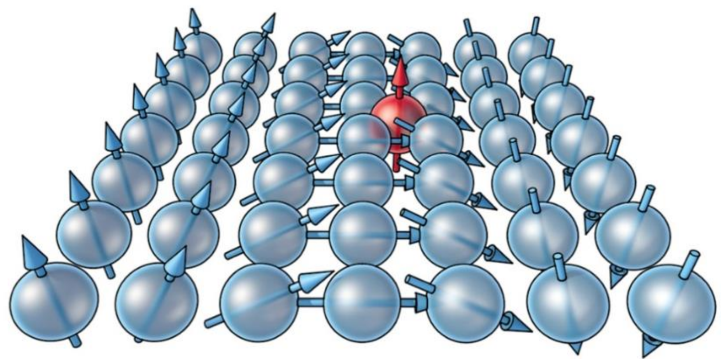
1. Prepare the nuclear bath in a cooled state



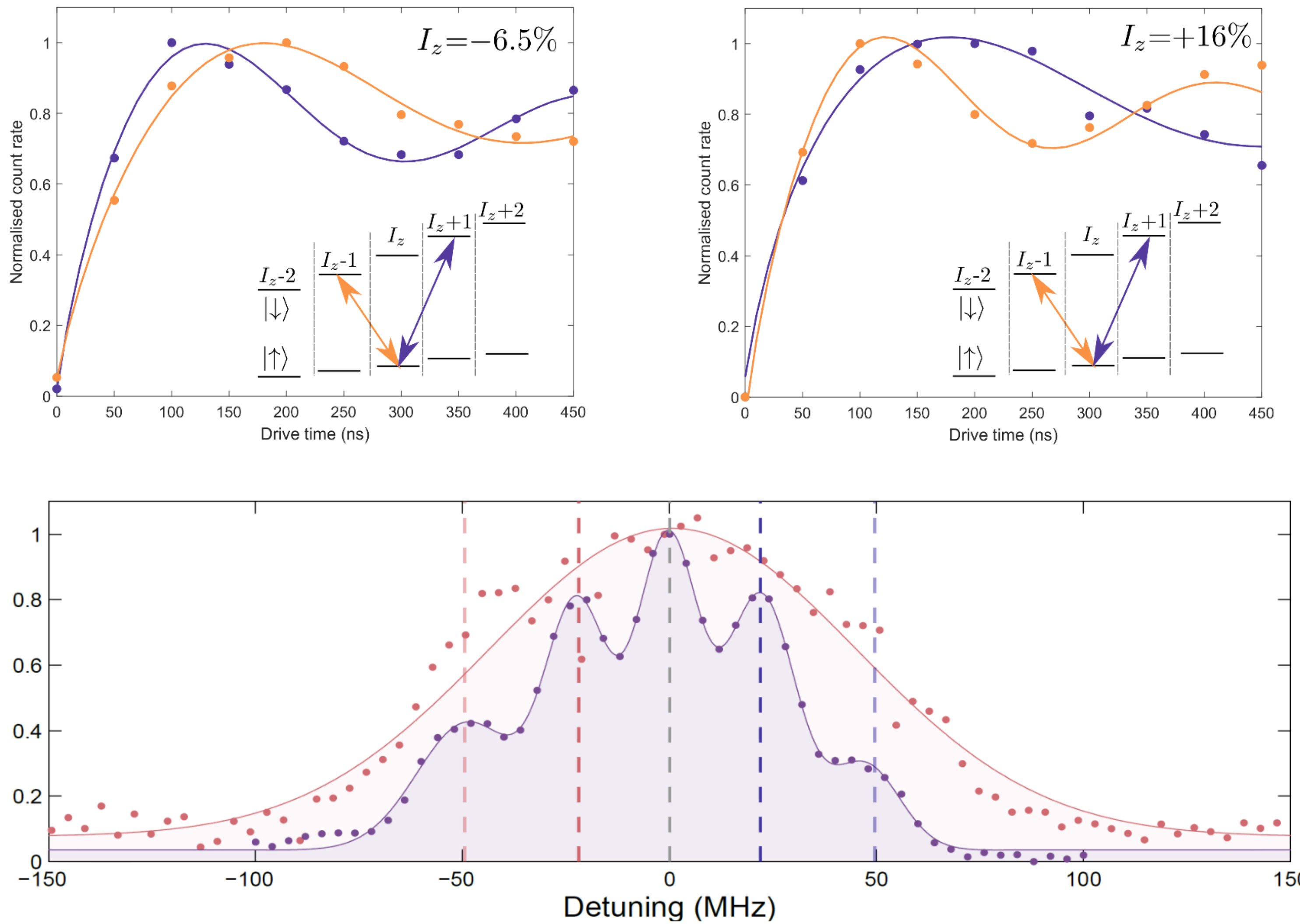


2. Coherently drive a nuclear excitation sideband





driving of a collective nuclear excitation (a nuclear magnon)



Gangloff *et al.*, Science 364, 62 (2019).

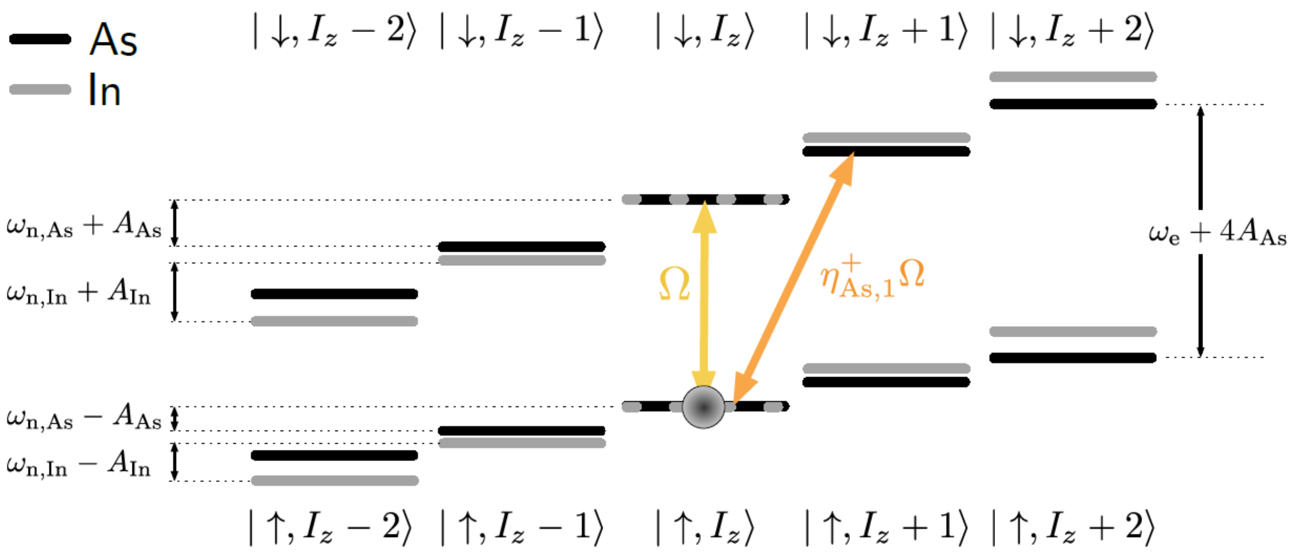
an inhomogeneous ensemble of species (^{113}In, ^{115}In, ^{69}Ga, ^{71}Ga, ^{75}As)

Strain is good!
(quadrupolar enhancement)

Species have slightly different gyromagnetic ratios

Strain dispersion is bad!
(inhomogeneity of nuclei)

Heterogeneity contributes to the modest Rabi curve



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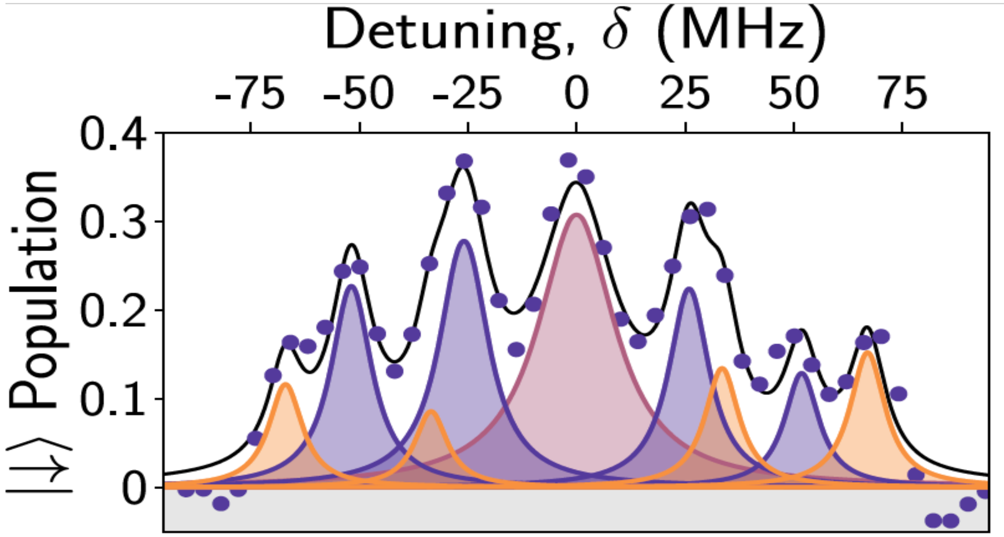
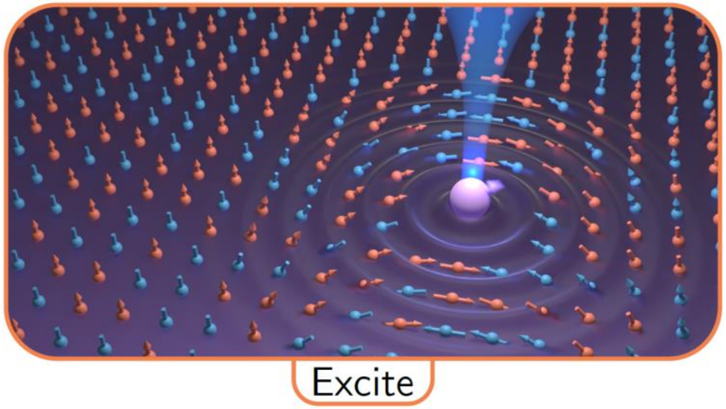
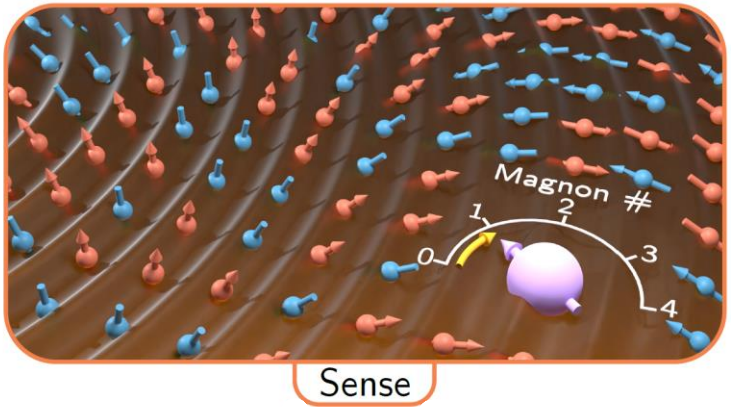


detecting a nuclear spin wave…via an electron spin…optically



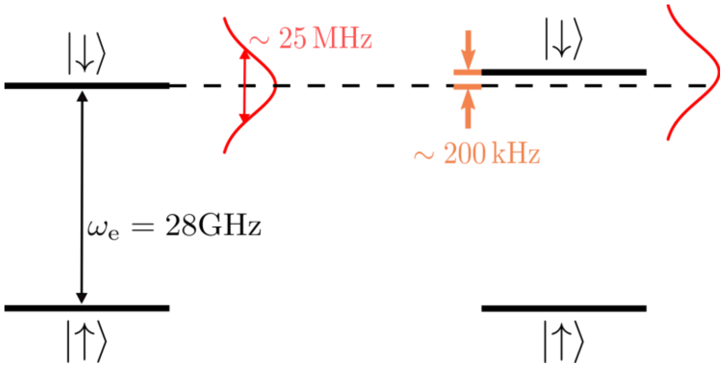


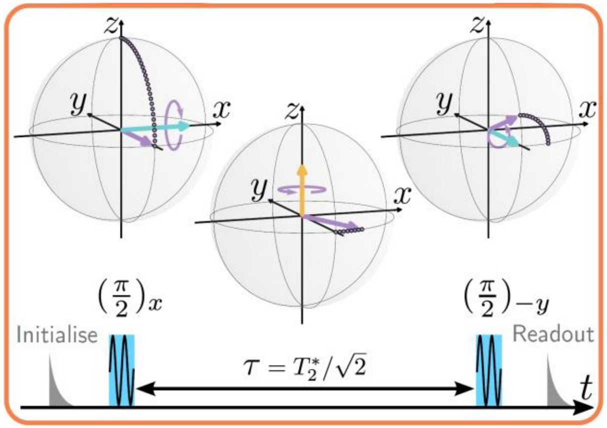
The electron-nuclear coupling is used to excite magnons deterministically

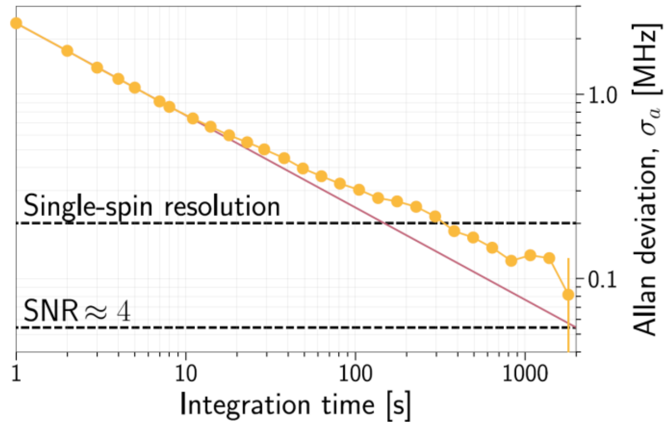
Can the same electron detect/sense a single nuclear spin in a dense ensemble?

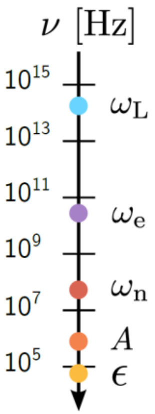
We will need to detect 200 kHz shift of a 28 GHz ESR resonance!

detecting qubit frequency shift due to a single nuclear magnon





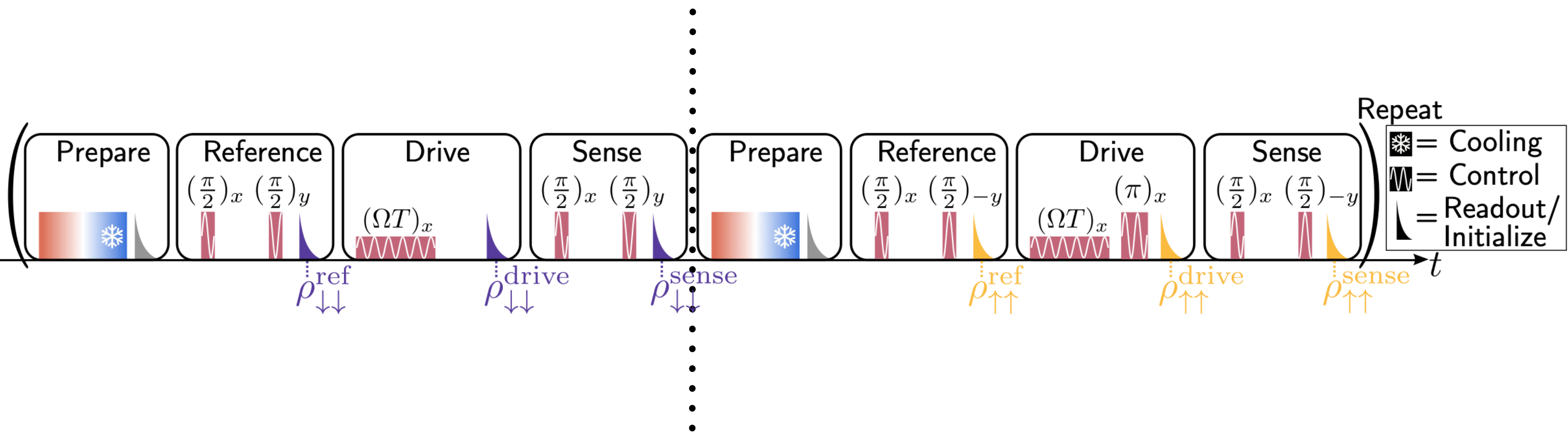




Frequency-shift detection via Ramsey Interferometry

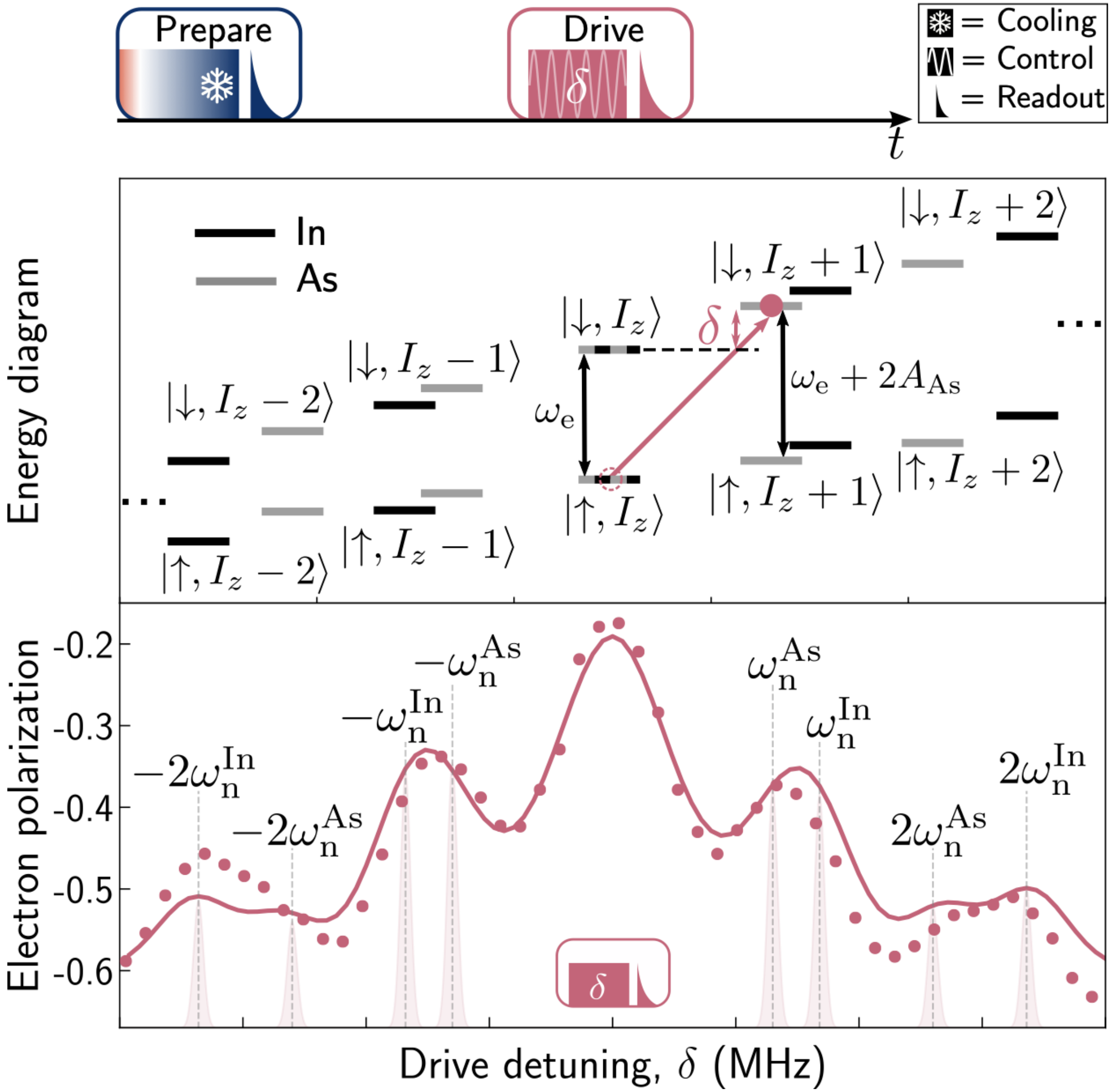
Our electron spin qubit operates as a sensor at 1.9 ppm sensitivity

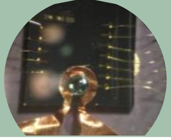
Sensing: Full experimental sequence



$$\Delta\omega_D = \Delta\omega_{\mathrm{sense}} - \Delta\omega_{\mathrm{ref}}$$

Magnon sensing: Spectrum





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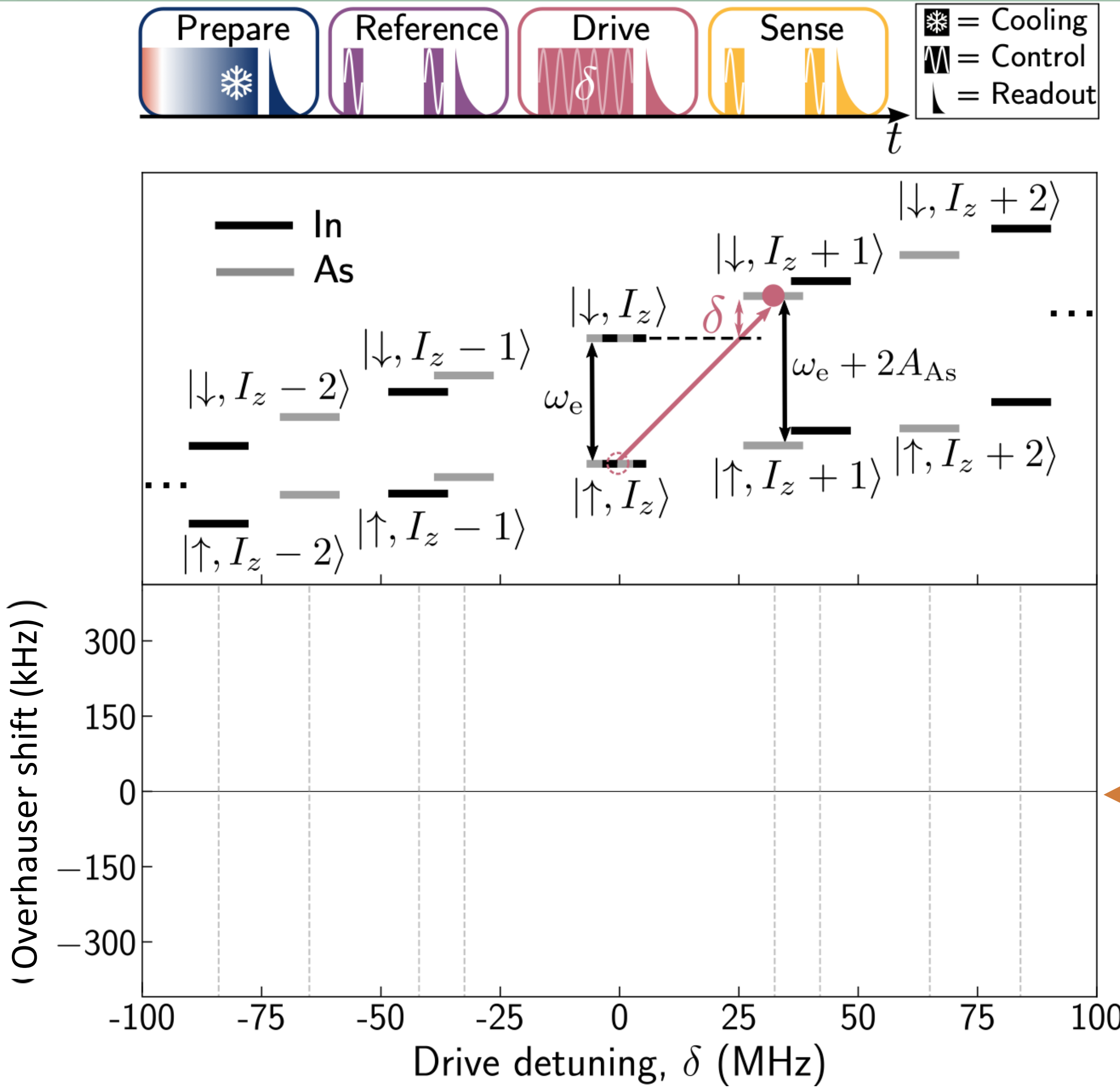

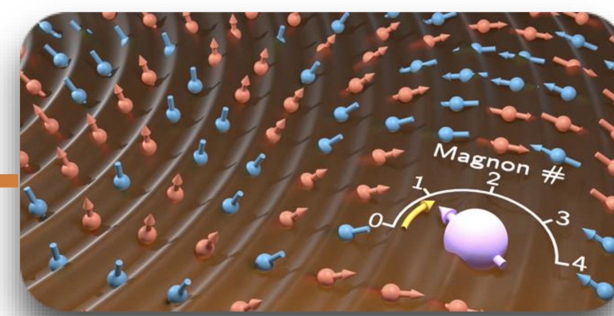

D. M. Jackson, at al. *Nature Physics* **17**, 585 (2021)

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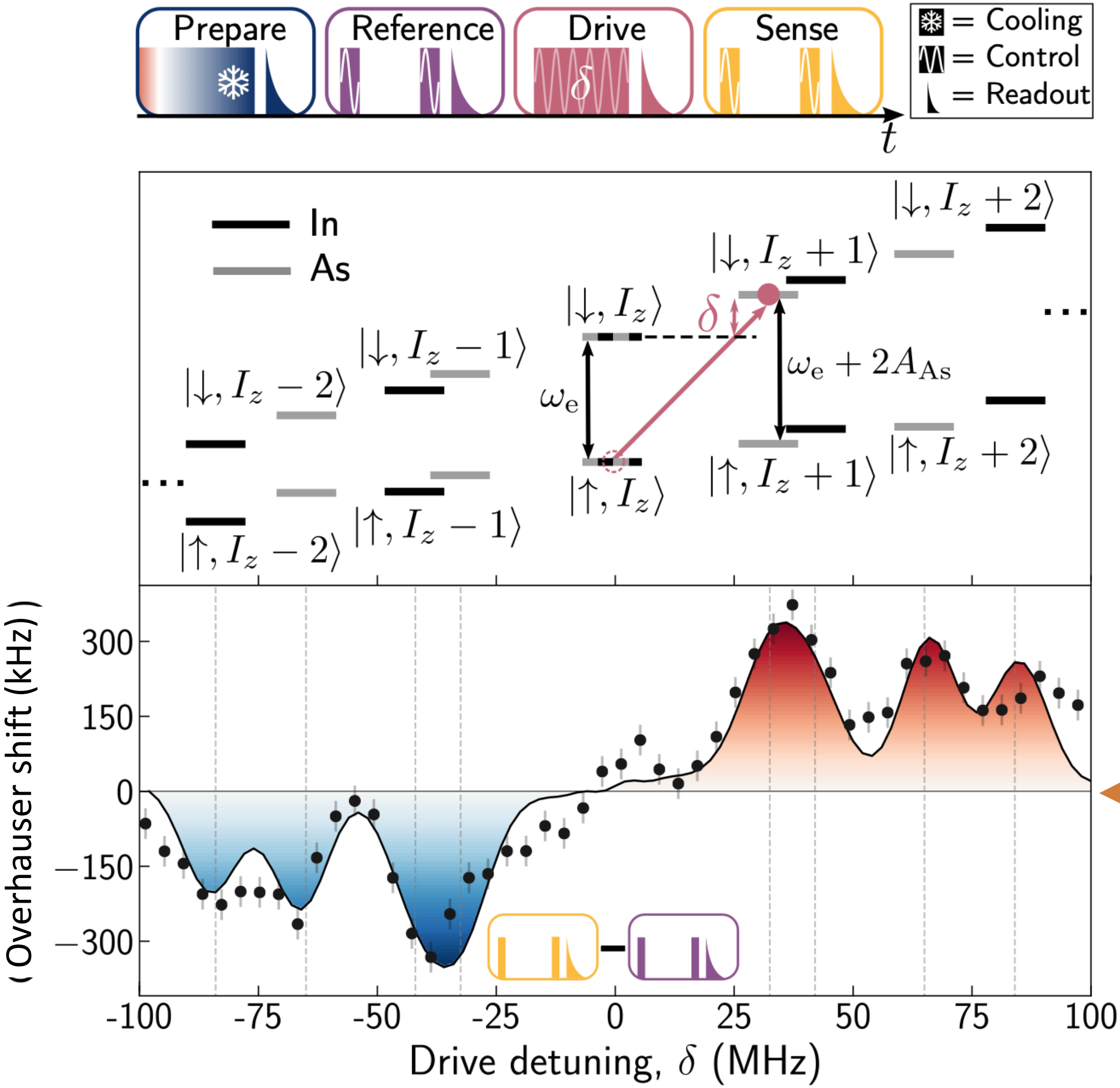

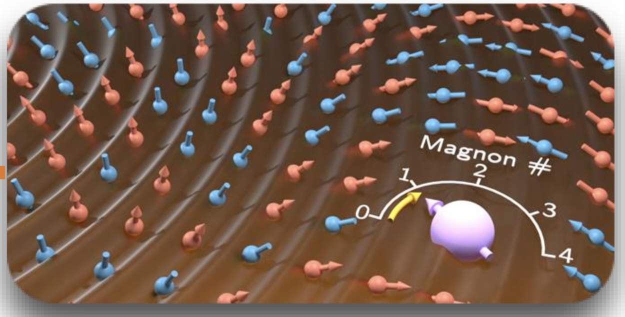

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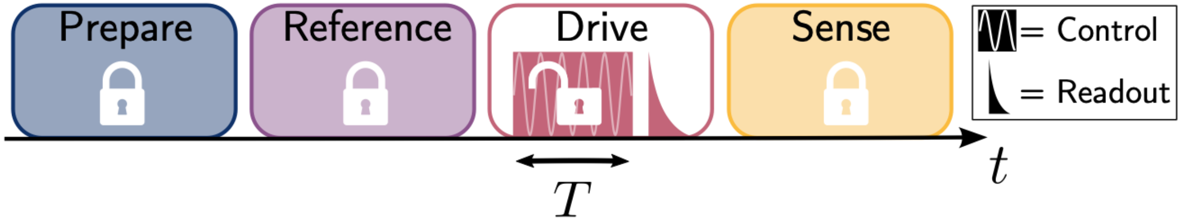
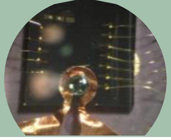
Magnon sensing: Dynamics

- Monitor coherent dynamics of a single magnon.





Magnon sensing: Dynamics

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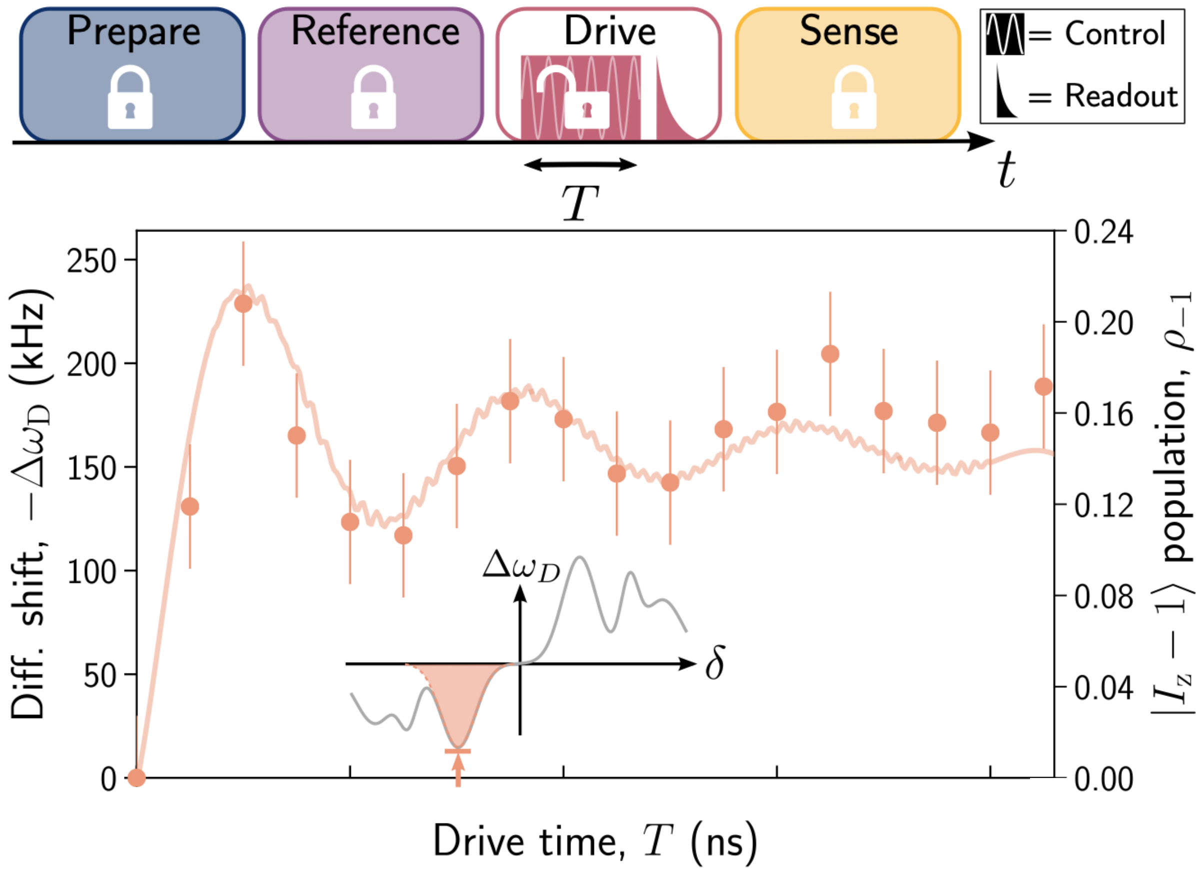

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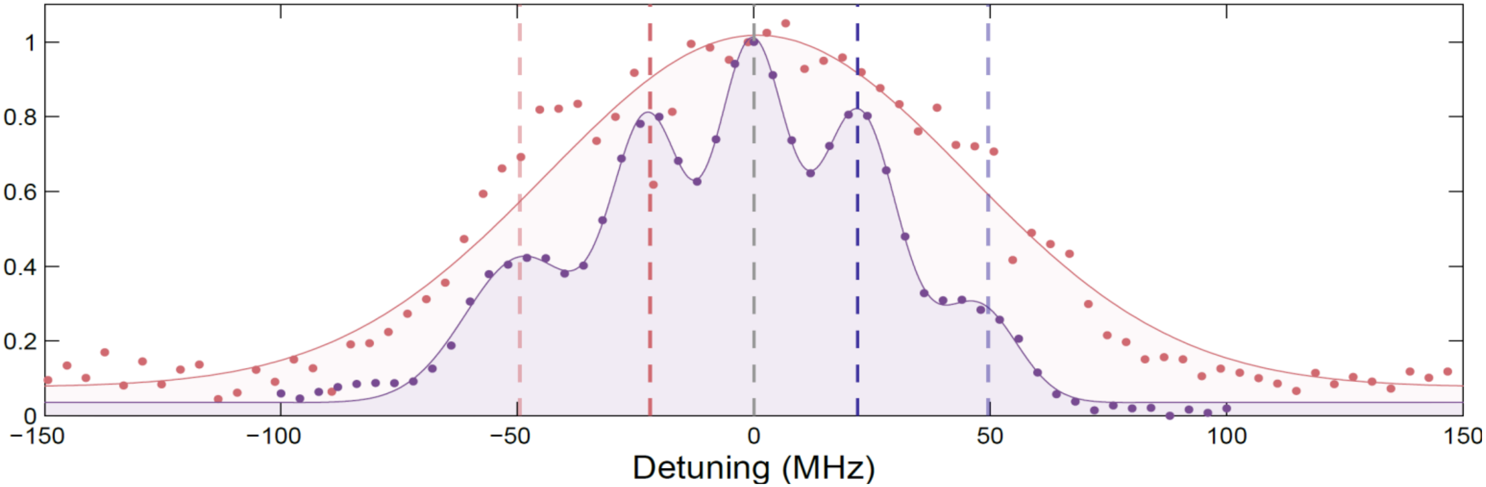
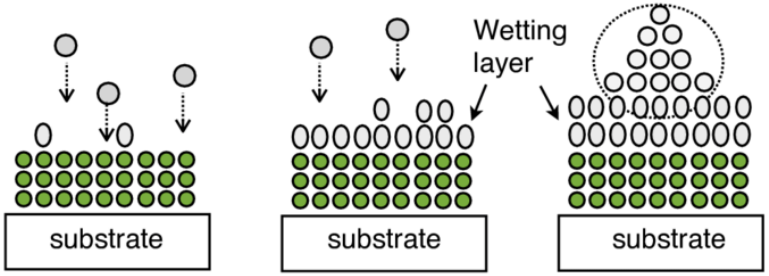
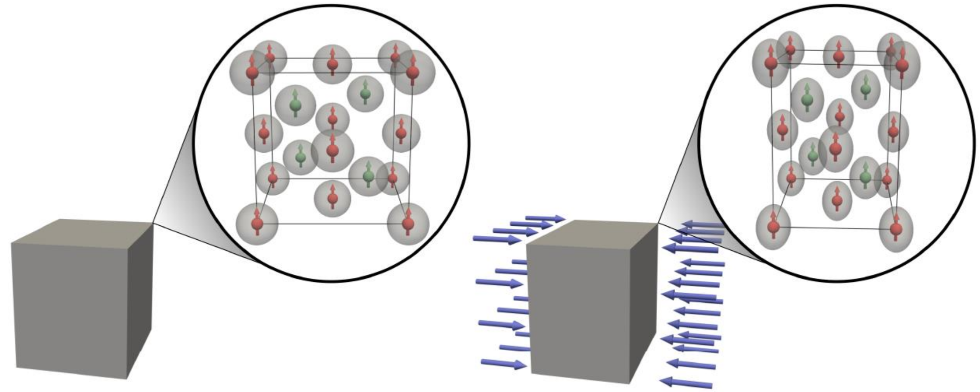
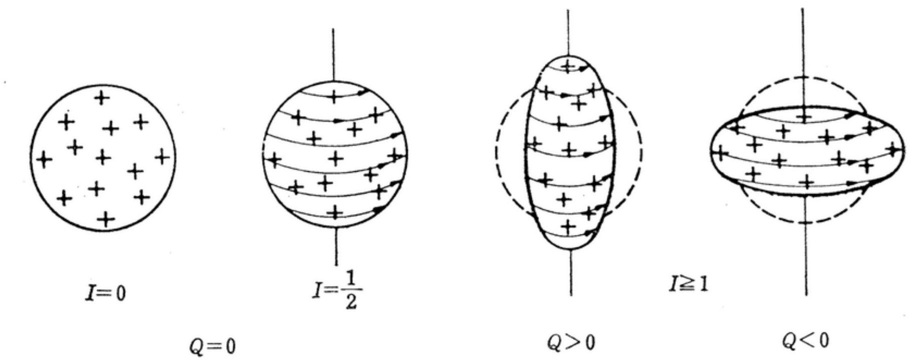
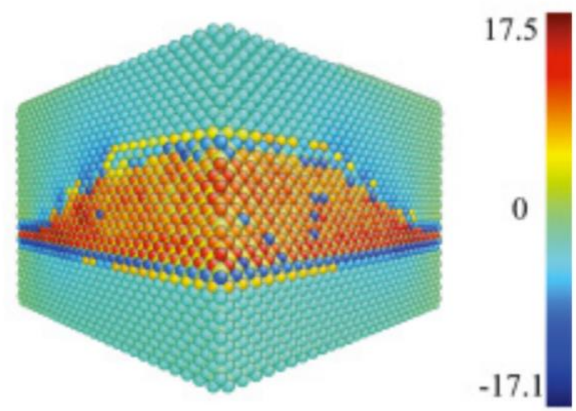


strain dispersion problem





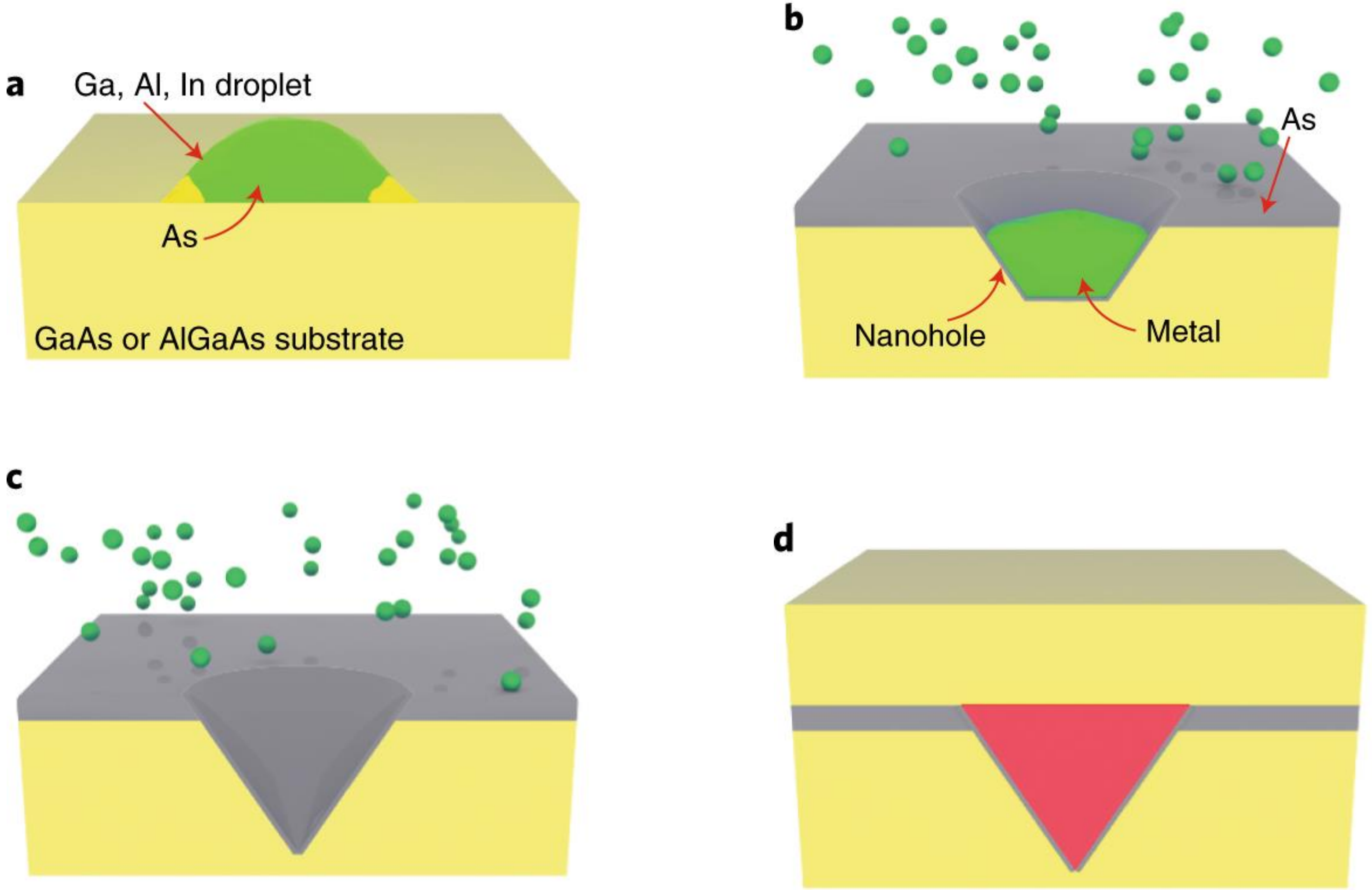




$$\hat{H}_Q = 2\pi \times \frac{eQ}{6hI(2I-1)} \sum_{i,j} \frac{\partial^2 V}{\partial r_i \partial r_j} \left[\frac{3}{2}(\hat{I}_i \hat{I}_j - \hat{I}_j \hat{I}_i) - \delta_{ij} I^2 \right]$$

how to avoid the strain dispersion problem

Strain-free GaAs QDs



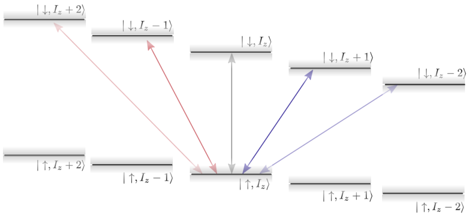
a coherent nuclear ensemble

A long-lived far from equilibrium spin ensemble

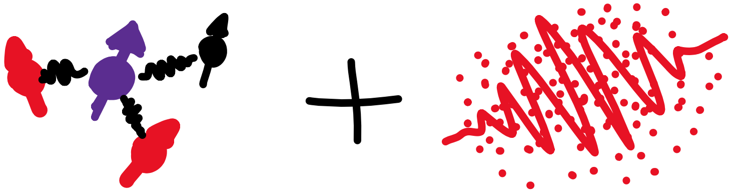
with independently tuneable $\langle I_z \rangle$ and ΔI_z

Optical coherent control of nuclear spin waves using sideband transitions

an isolated many-body system
(cats, random walks, synchronisation…)



a deterministic quantum memory
(efficient, collectively enhanced)



Also see: arXiv:2012.11279 (2021)

Denning *et al*., PR, 123 140502 (2019).

the team (and friends)

InAs QD team:

Clara Bachorz
Jonny Bodey
Claire Le Gall
Gabriel Ethier-Majcher
Dorian Gangloff
Lukas Huthmacher
Daniel Jackson
Constantin Lang
Clemens Matthiesen
Megan Stanley
Rob Stockill
Leon Zaporski

Join us!

and special thanks to:

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