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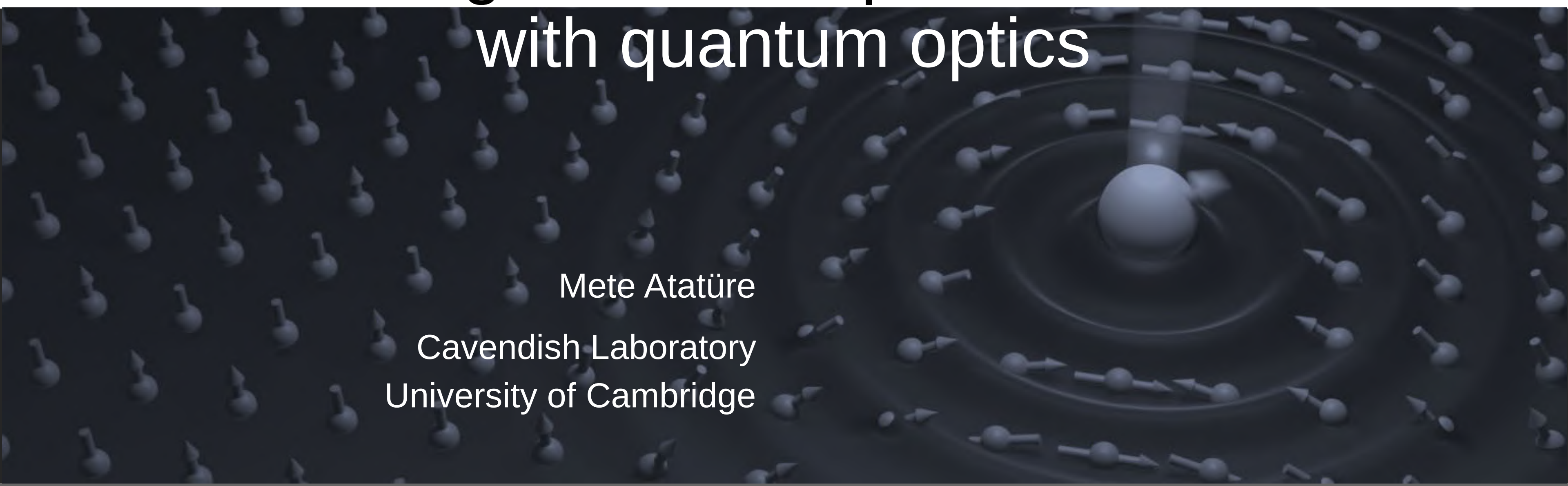
Cavendish Laboratory

taming a nuclear spin ensemble with quantum optics



Mete Atatüre

Cavendish Laboratory
University of Cambridge

College de France

20/01/2026

Quantum Optical Materials and Systems Group, Cambridge UK

QUANTUM FLAGSHIP

Office of Naval Research GLOBAL Science & Technology

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

erc European Research Council

GORDON AND BETTY MOORE FOUNDATION

HENRY ROYCE INSTITUTE

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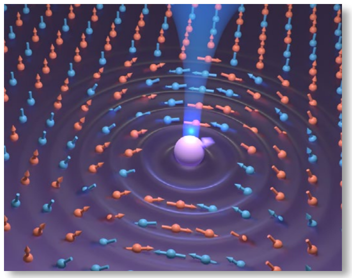
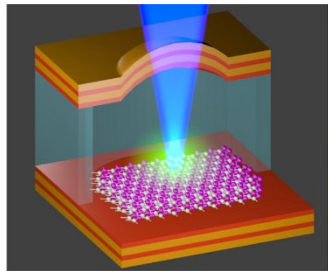
Quantum photonics and spin physics with novel material platforms

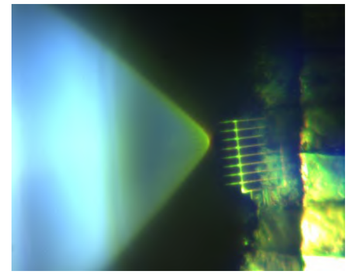
III-Vs



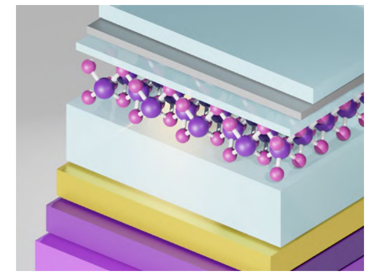
hBN



Diamond

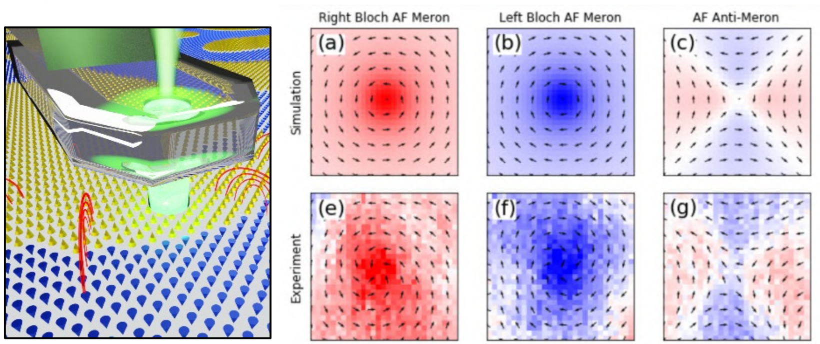


2d vdWs

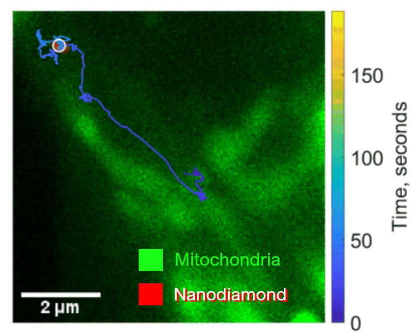


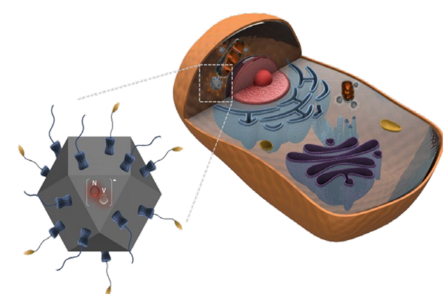
Quantum sensing of emergent magnetism and complexity of life sciences

Diamond magnetometry

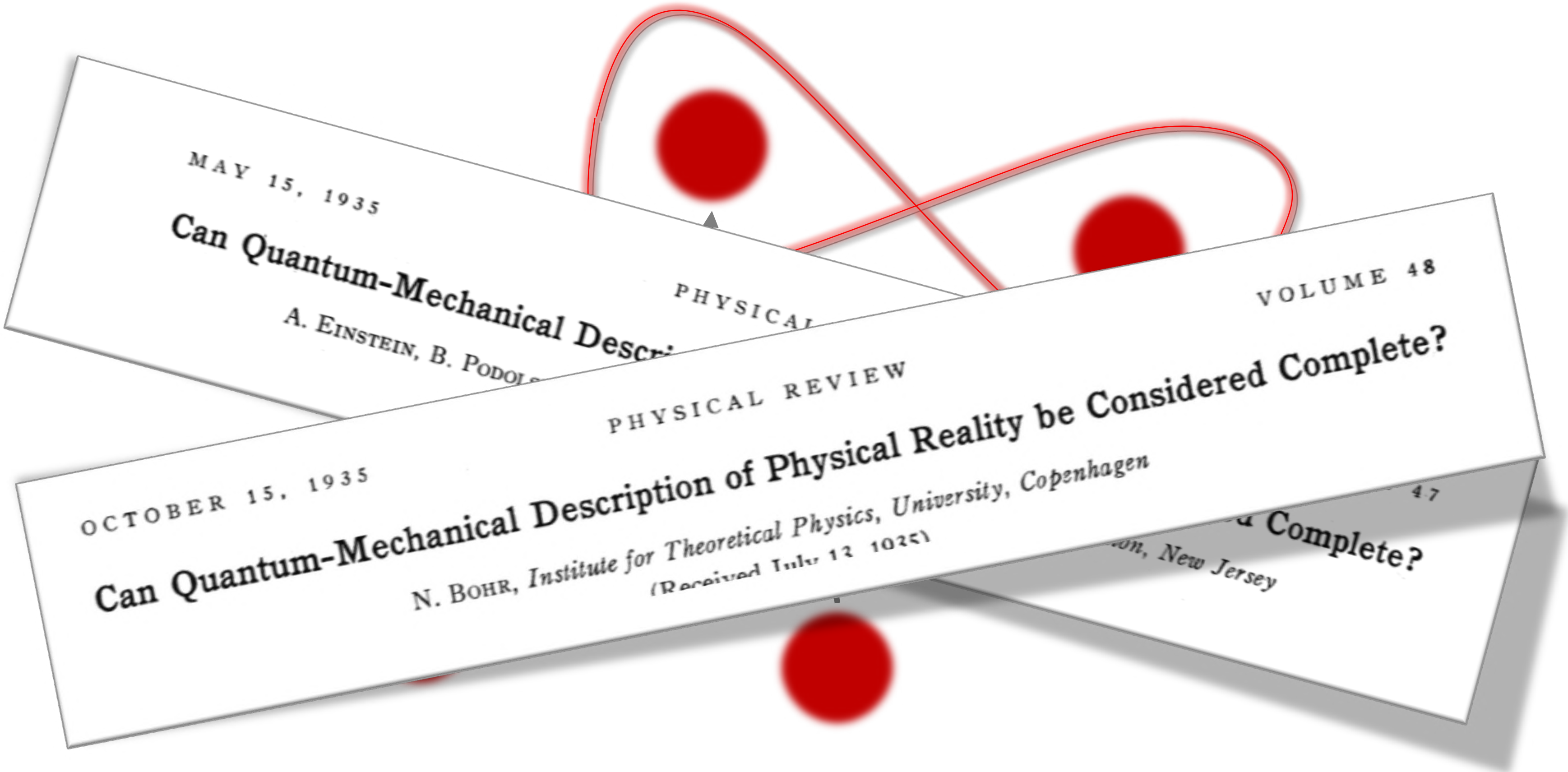


Nanodiamond biosensing

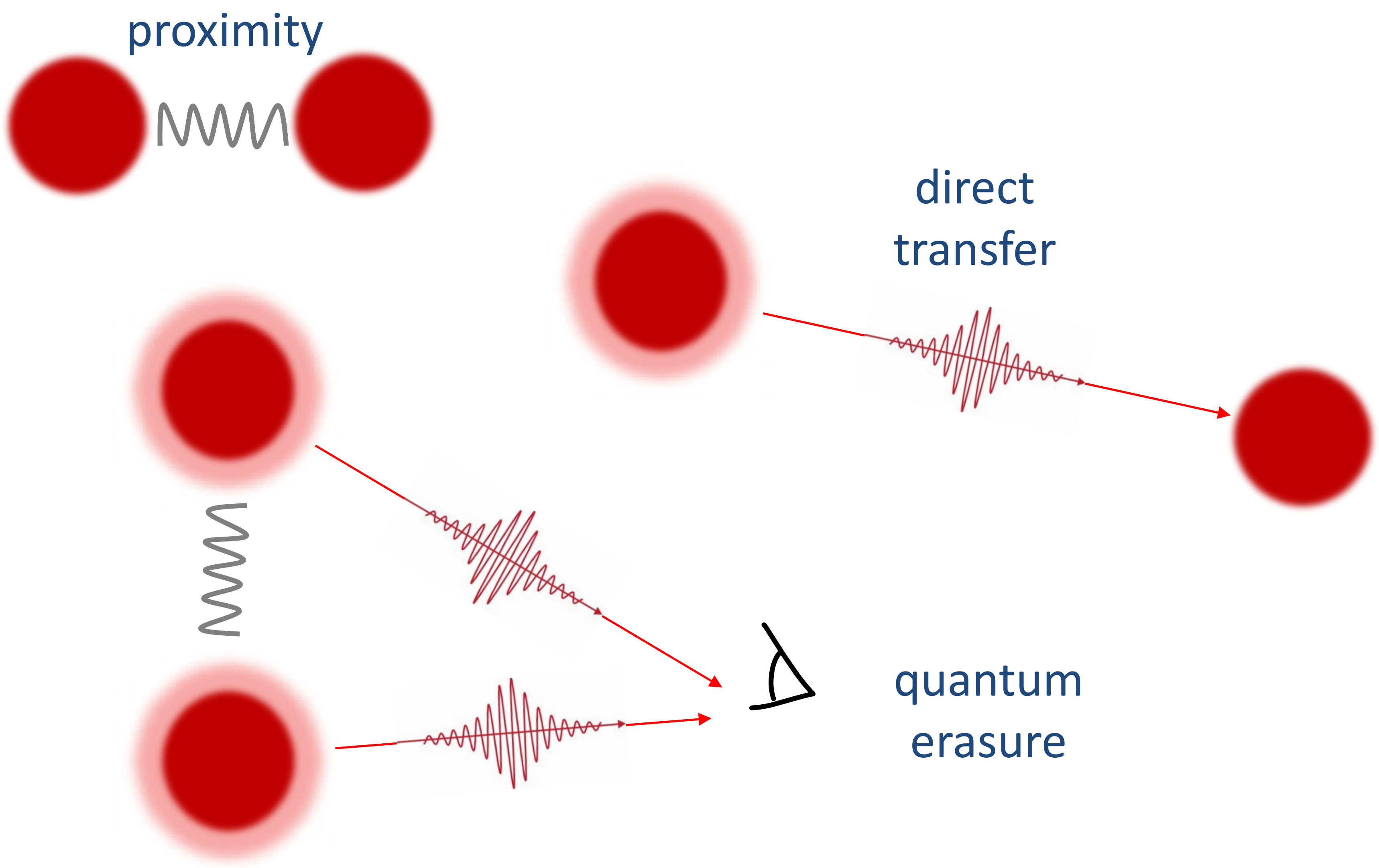




creating correlations

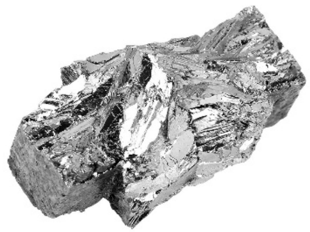


creating correlated particles



creating correlated matter

creating correlated matter – atoms & interactions

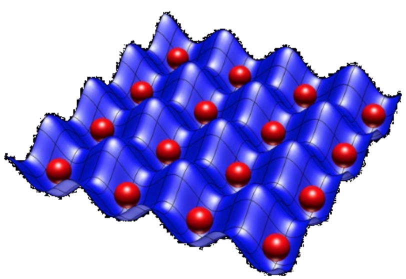


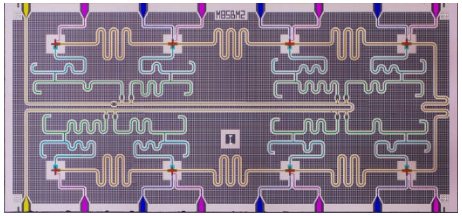
Real atoms
Real matter

Synthetic atoms
Real interactions

Real atoms
Synthetic matter

Synthetic atoms
Synthetic matter

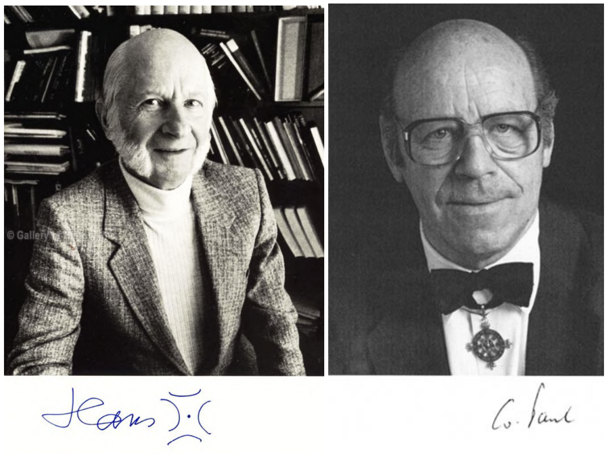




our question…

Can we capitalize on quantum optics, light-matter interaction and engineered material properties to create useful and exotic collective states?

isolating the quantum from the classical



Dehmelt & Paul (Nobel 1989)

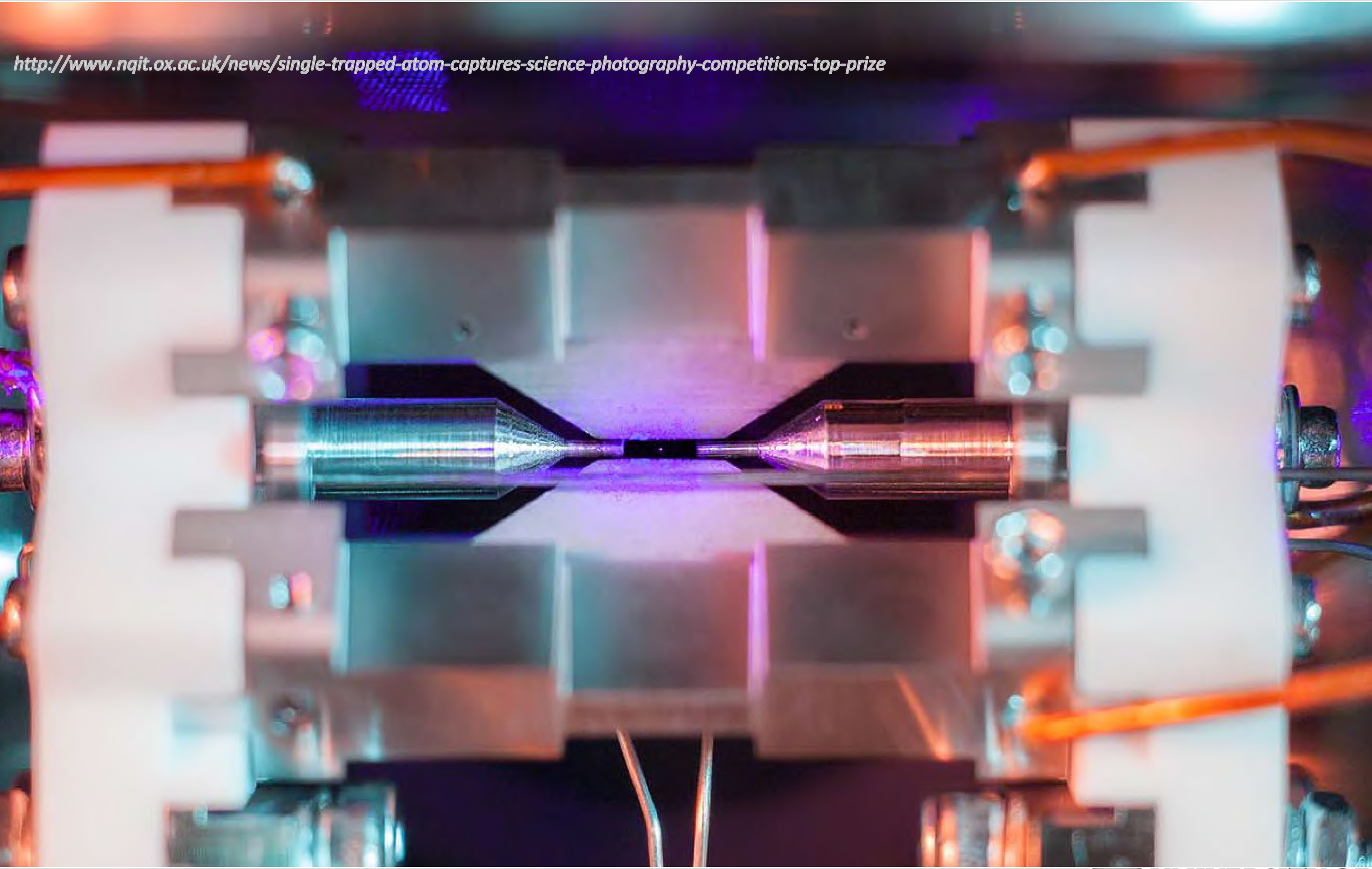
for the development of the ion trap technique"

Wineland & Haroche (Nobel 2012)

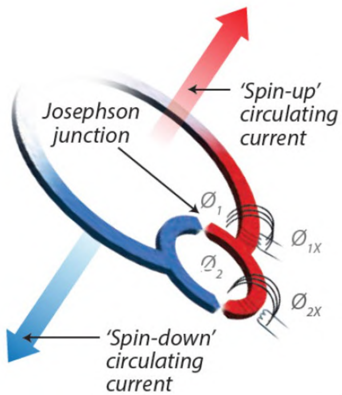
"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"

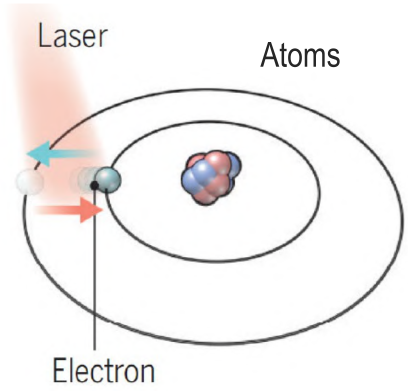
Singular quantum objects & entanglement [quantum 2.0]

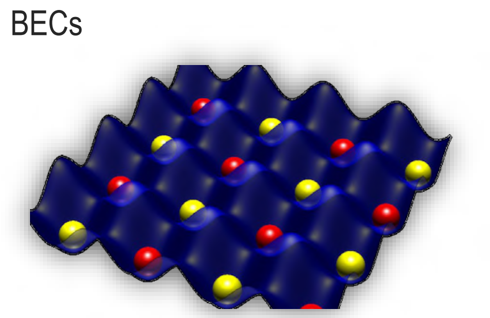
a single ion trapped in vacuum

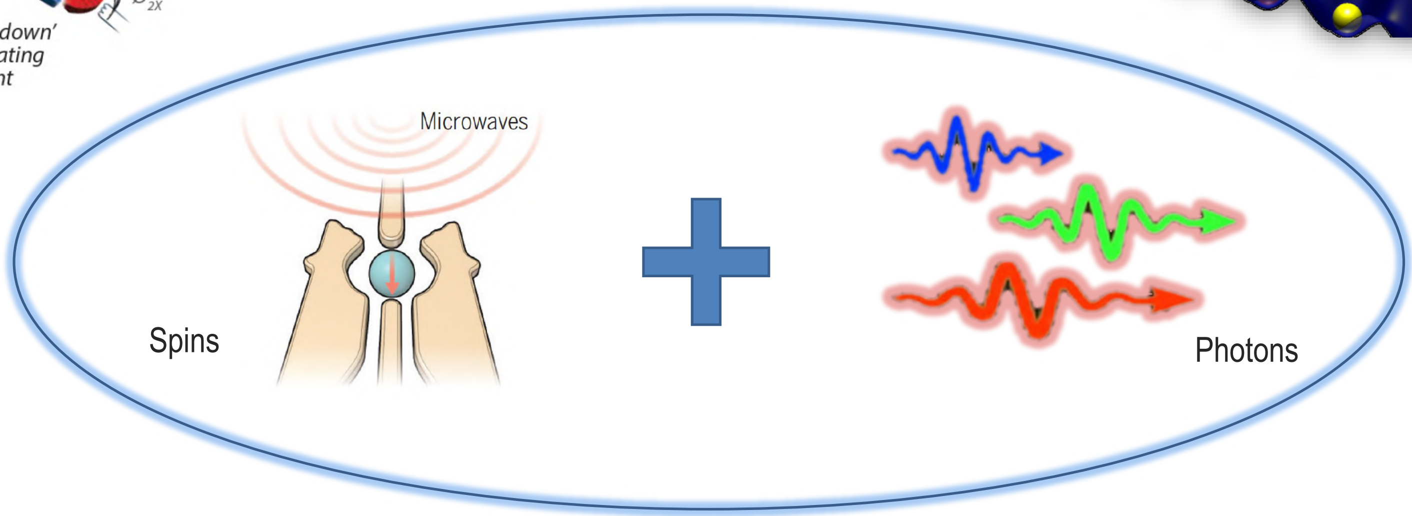


a catalogue of quantum objects

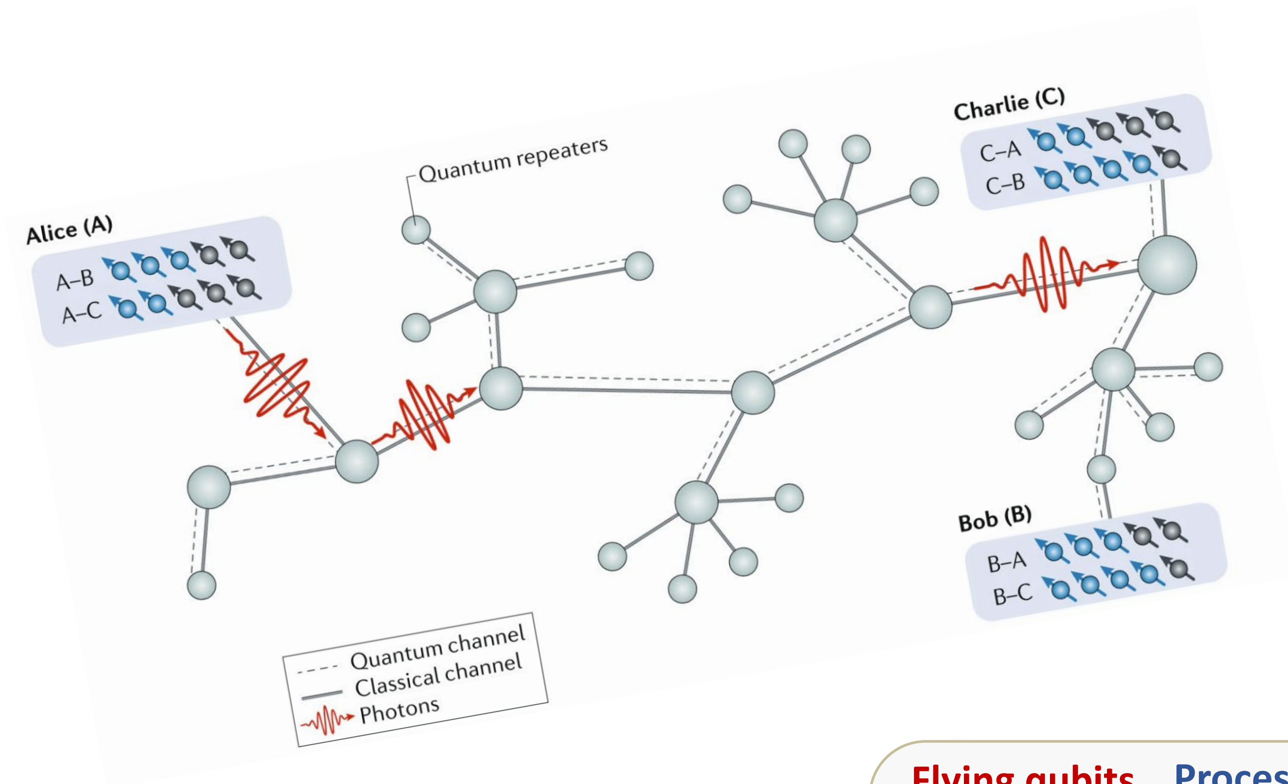


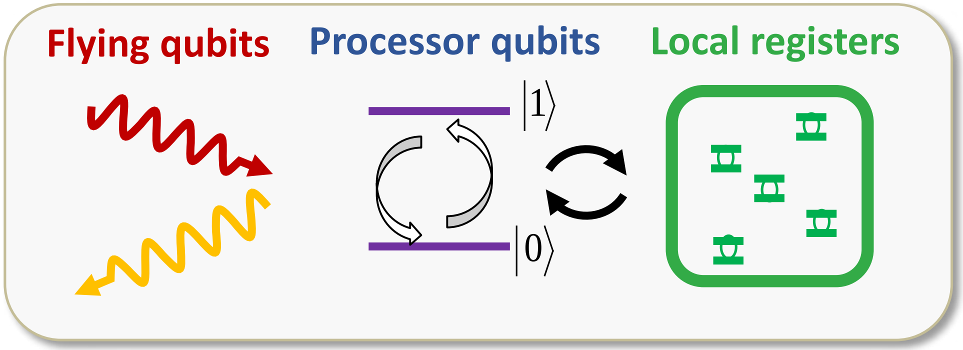




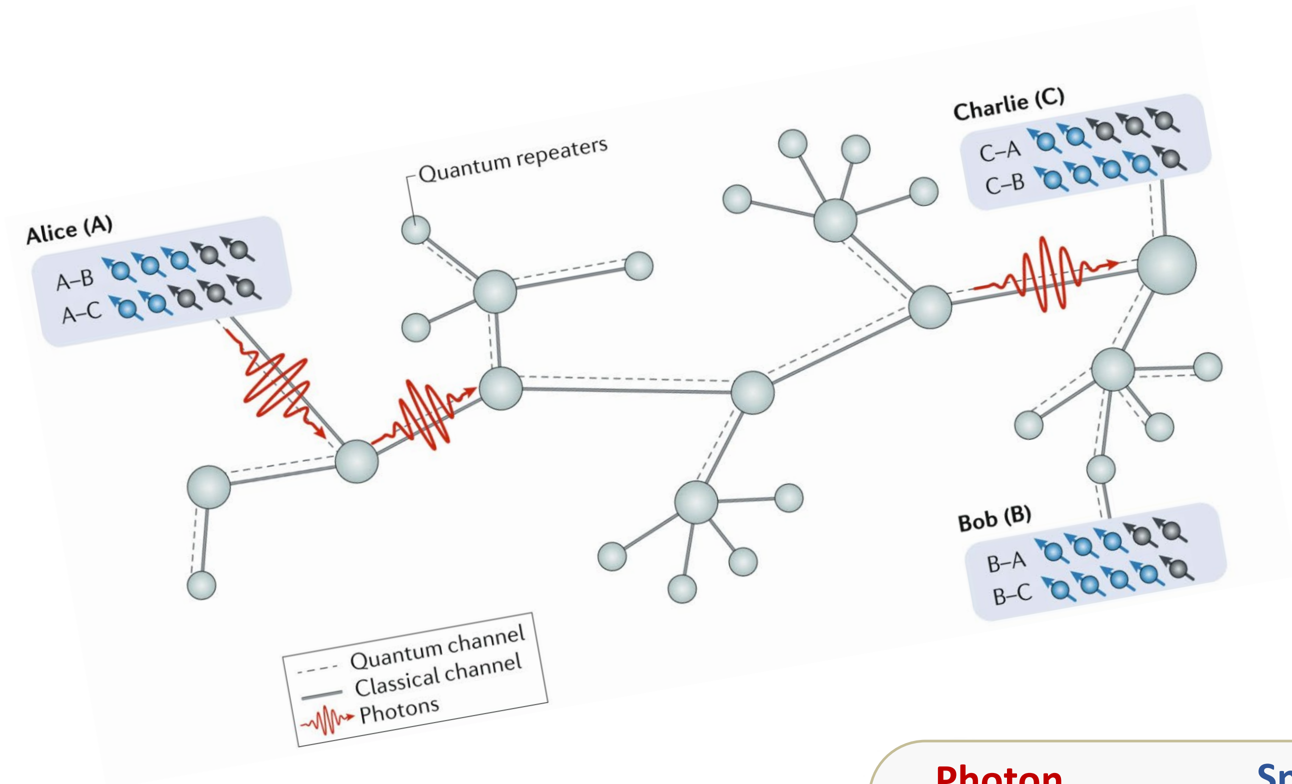


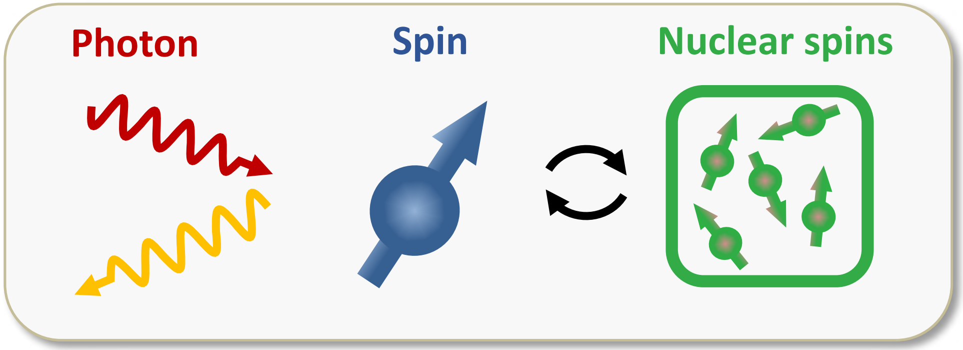
quantum nodes in a network





quantum nodes in a network

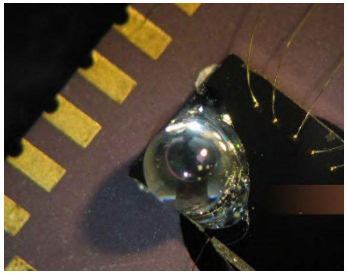




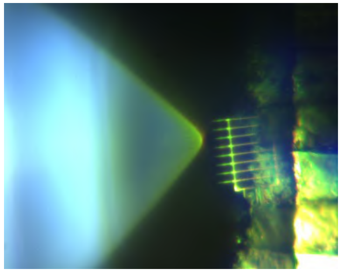
our solid-state sandbox

Quantum photonics and spin physics with many material platforms

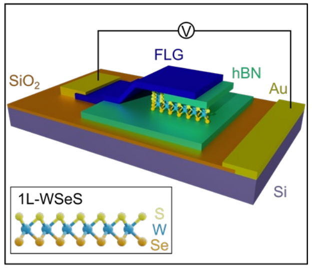
III-Vs



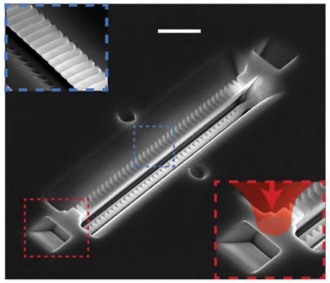
Diamond



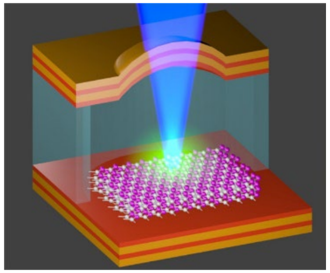
2d vdWs



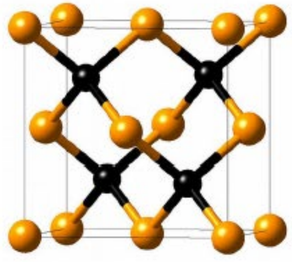
Rare Earth



hBN



SiC



...and more!

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

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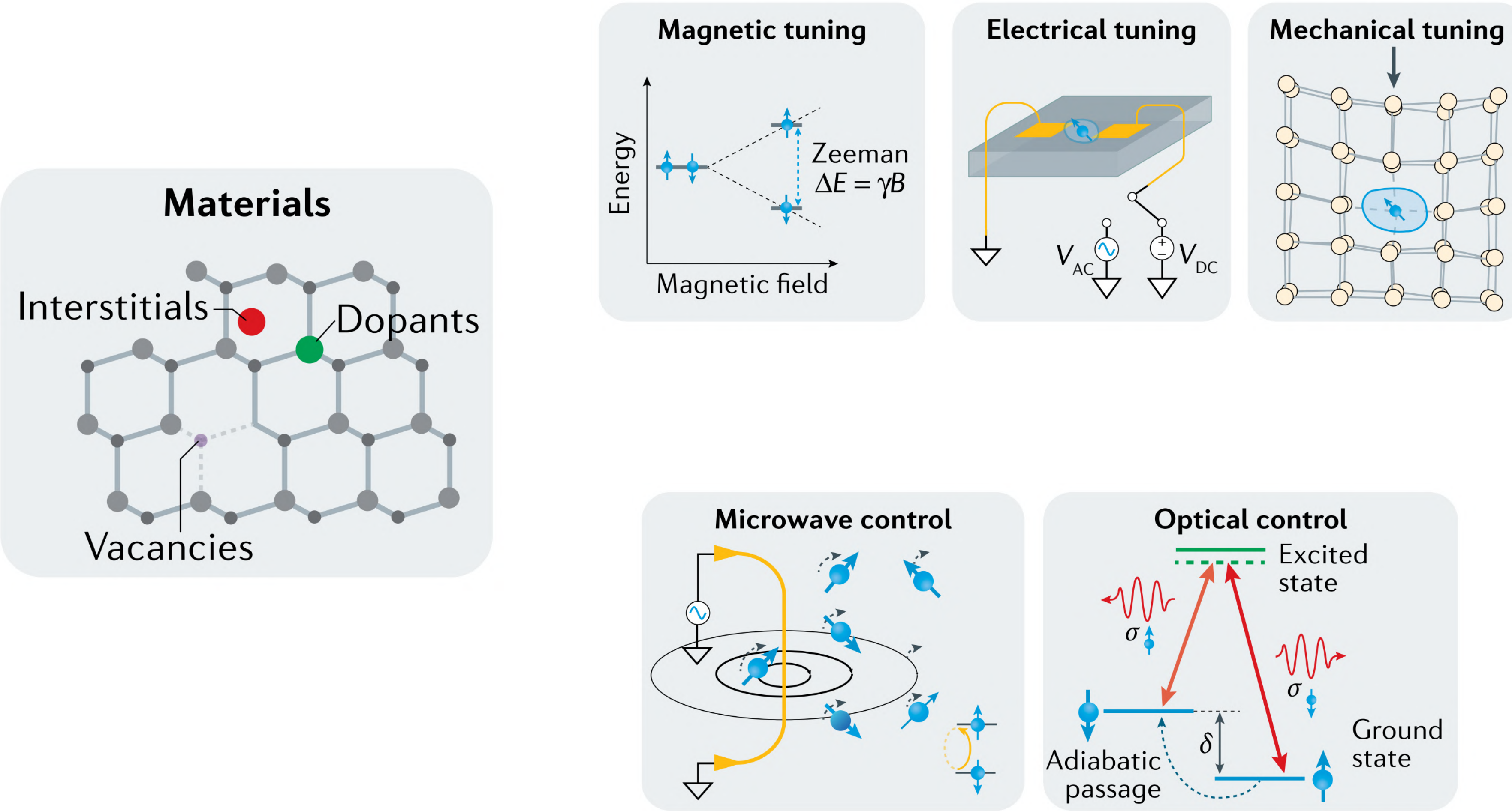
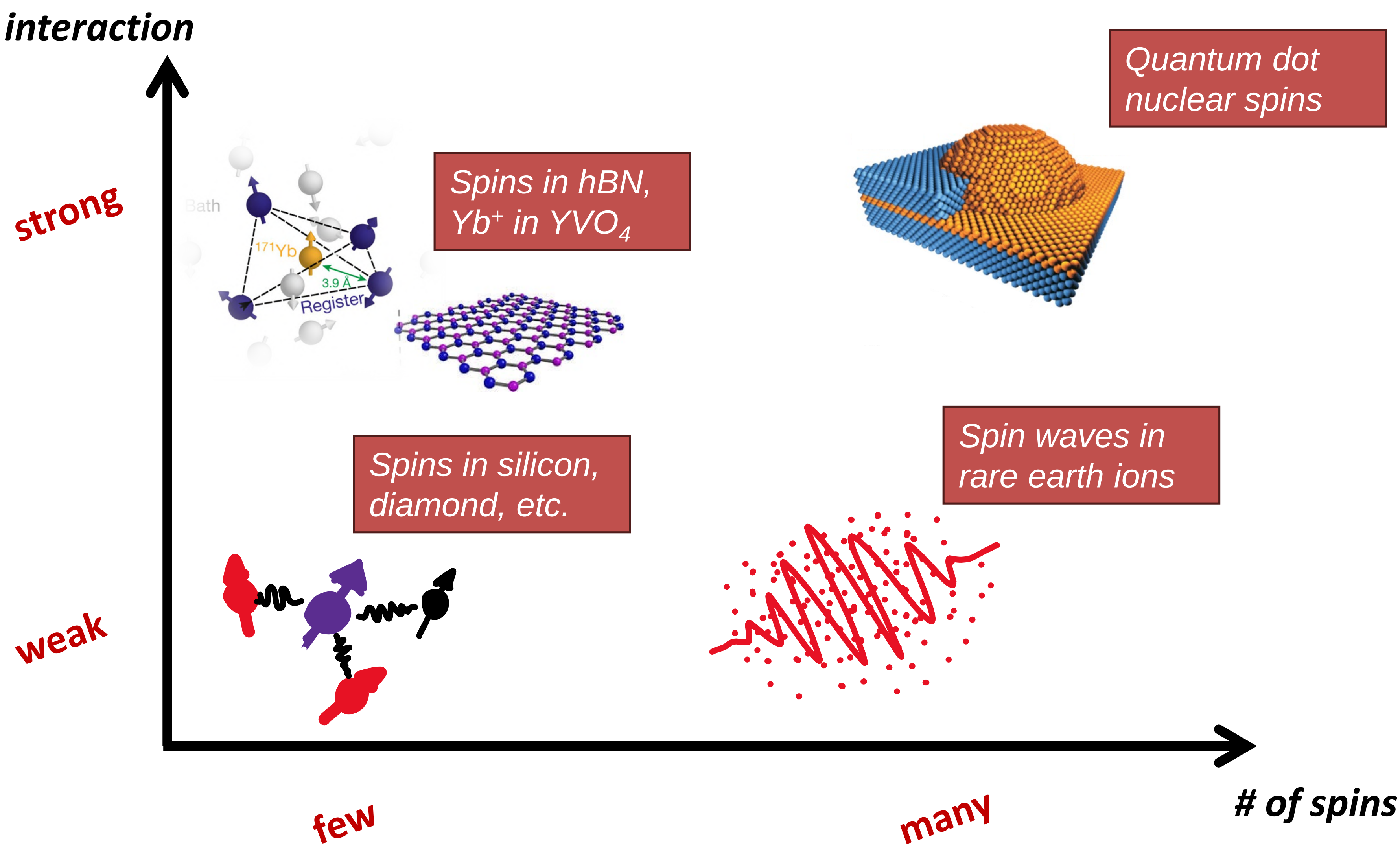
working with optics and spin

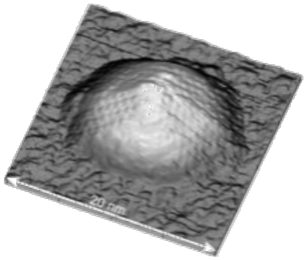


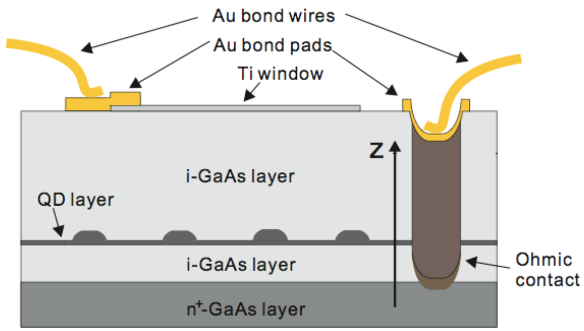
Wolfowicz et al., Nat Rev Mat, 6, 906 (2021)

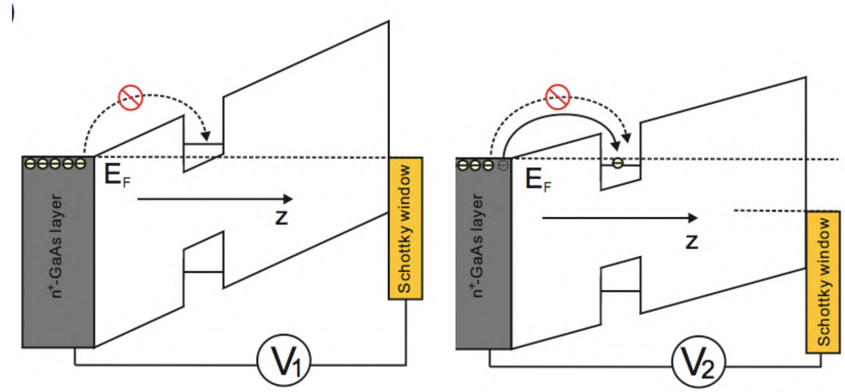
the ‘parameter space’ for central spin

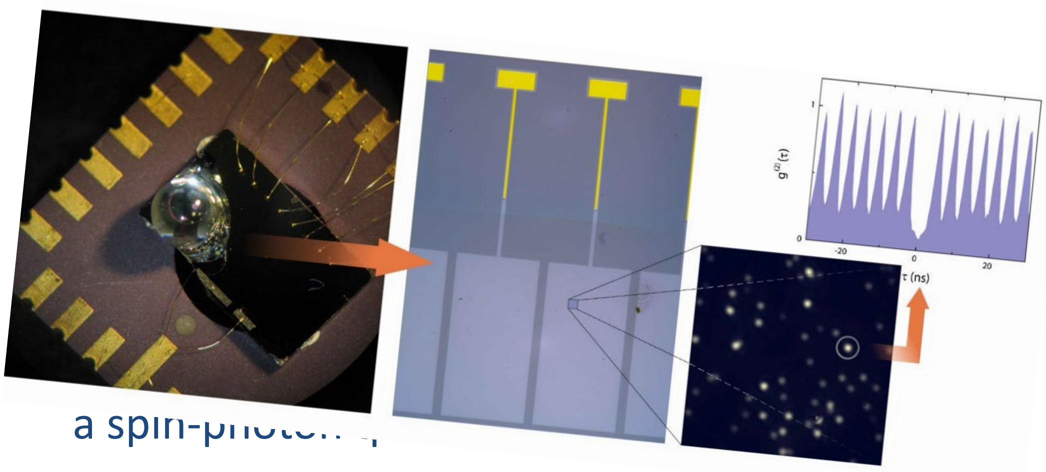


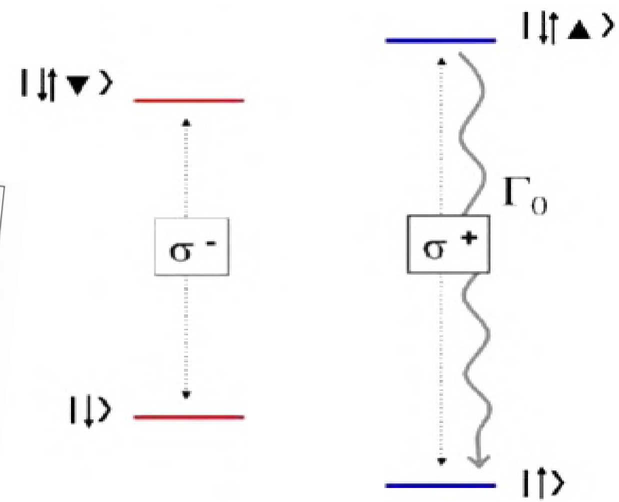
semiconductor quantum dot devices (InGaAs)







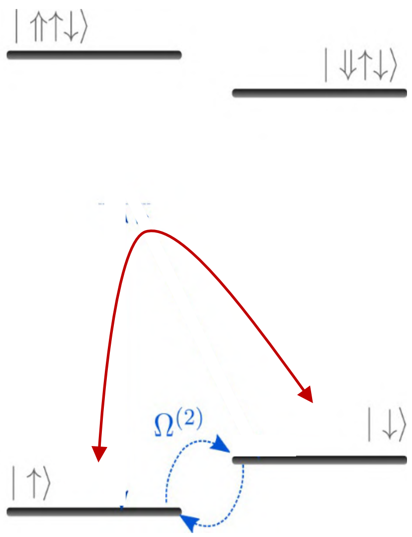


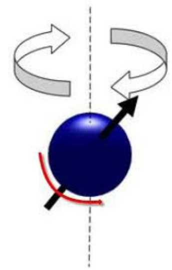


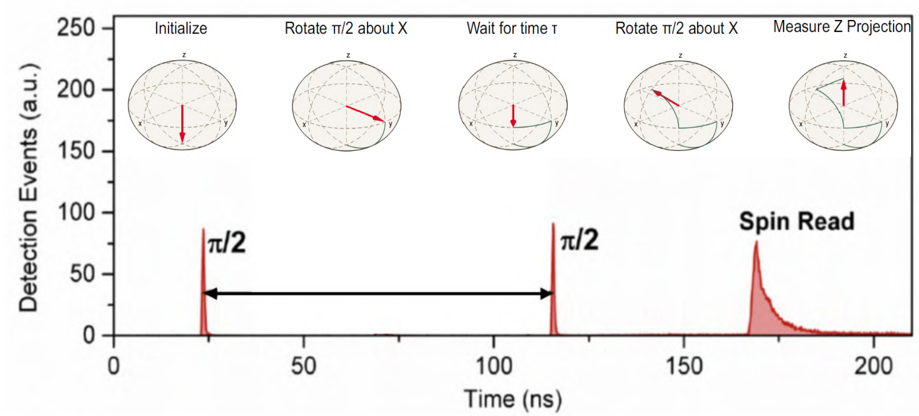
Charged Exciton
(optically accessible spin)

“optics” of semiconductor quantum dots

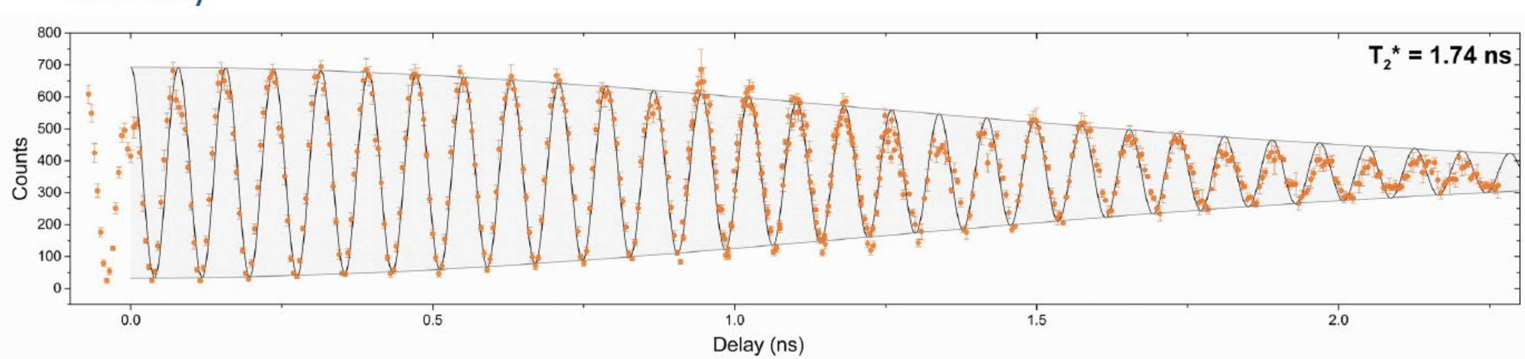
all-optical quantum control and spin coherence



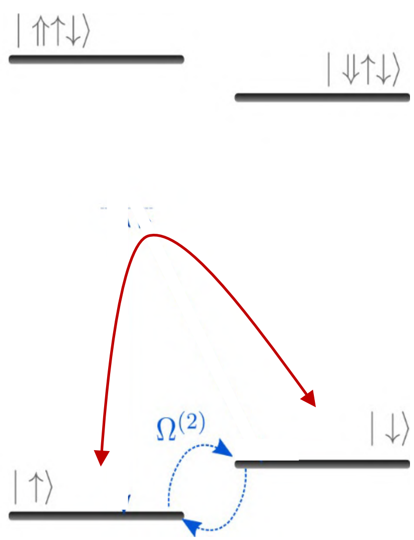


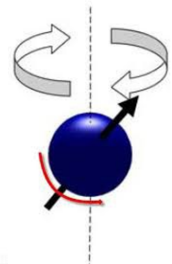


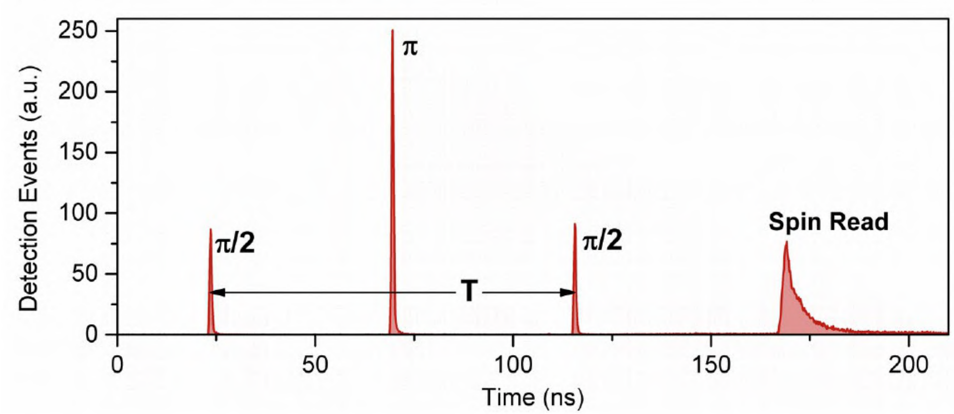
Ramsey

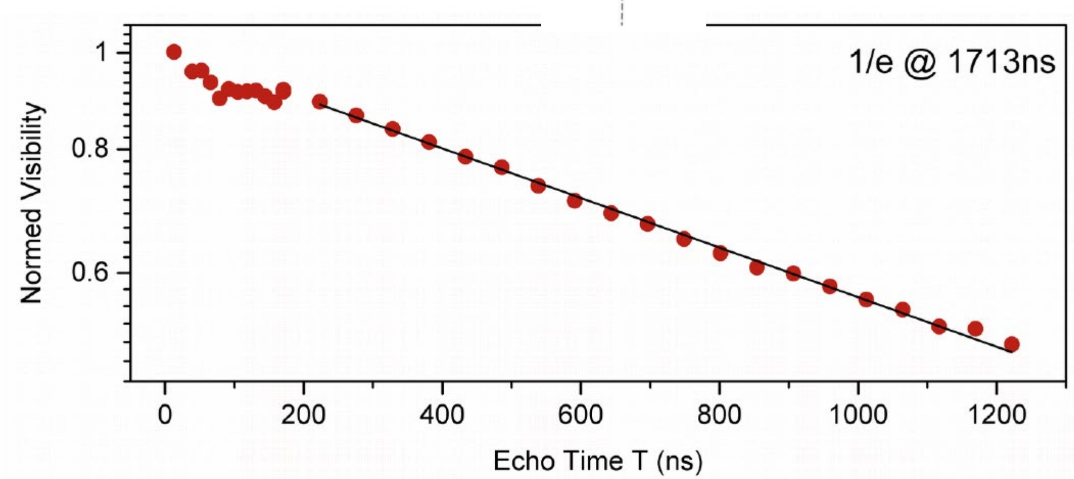


all-optical quantum control and spin coherence









Evidence of slow noise

T_2 limited to ~ a few 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)

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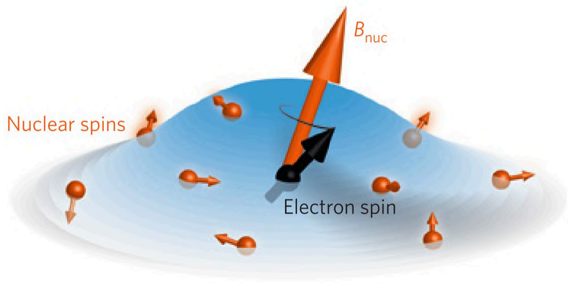
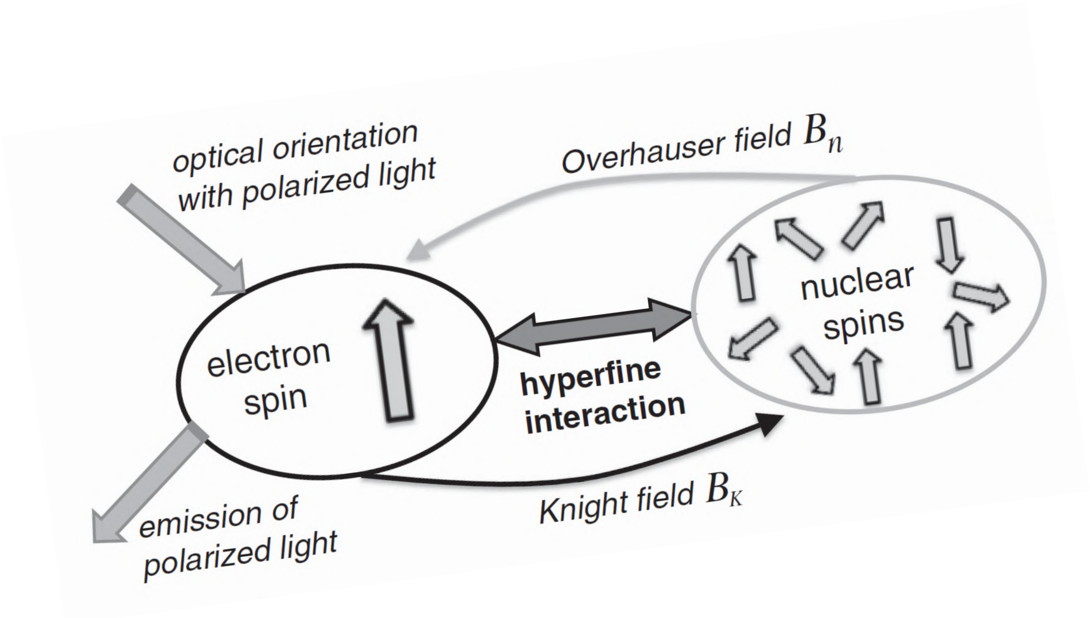
the central spin problem: getting rid of the problem





Dial-up your I_z:

In addition to a quasistatic (classical) magnetic noise,

hyperfine interaction allows Dynamical Nuclear Spin Polarisation!

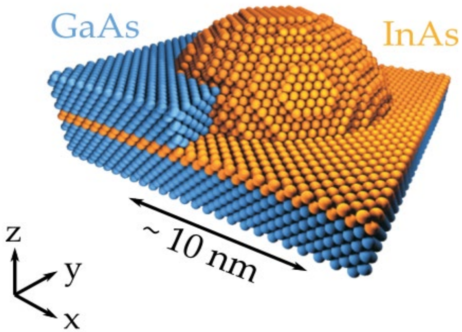
This can polarise nuclear spins! (~70% achieved)

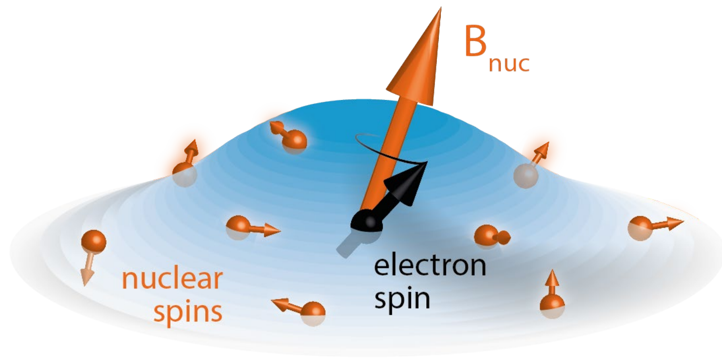
There is an Option B!

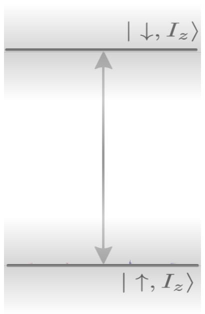
Urbaszek et al., *Reviews of Modern Physics* **85**, 79 (2013)
Chekhovich et al., *Nature Materials* **12**, 494 (2013)

the central spin problem: a many-body physics toolbox

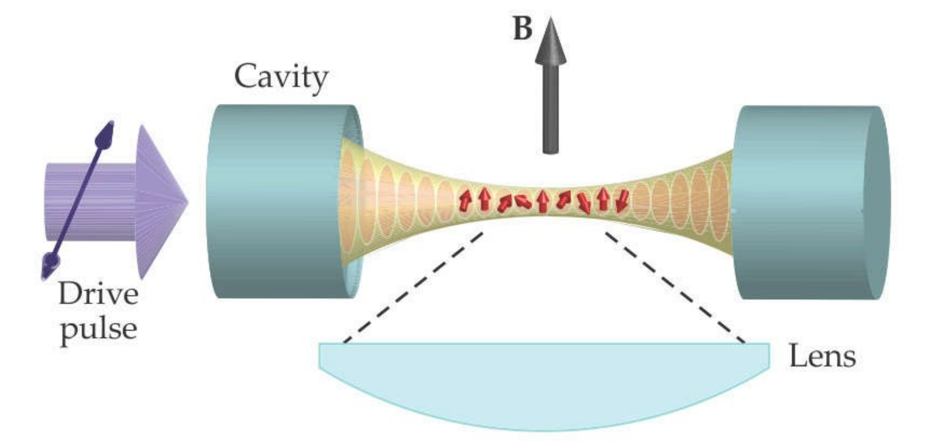
There is strong interaction between the electron and the nuclear spins (~50,000!)







Analogies with an atomic ensemble coupled strongly to a cavity mode



the central spin problem: a many-body physics toolbox

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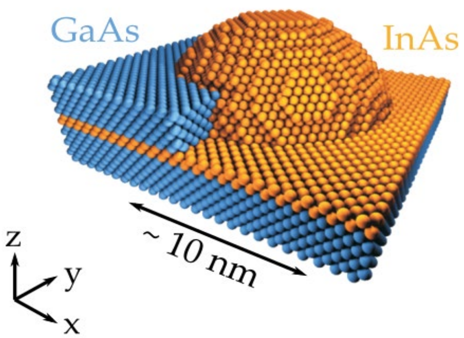
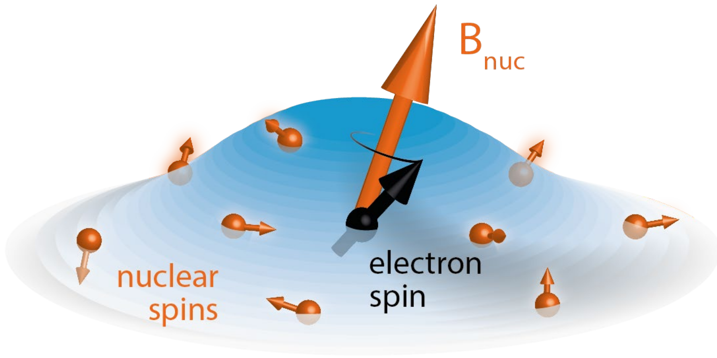
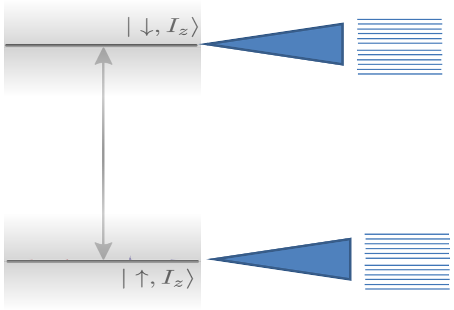




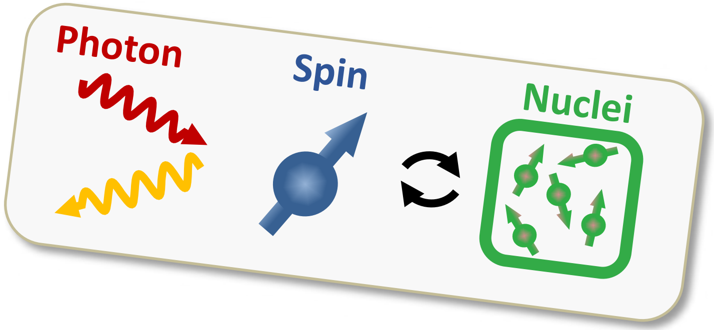


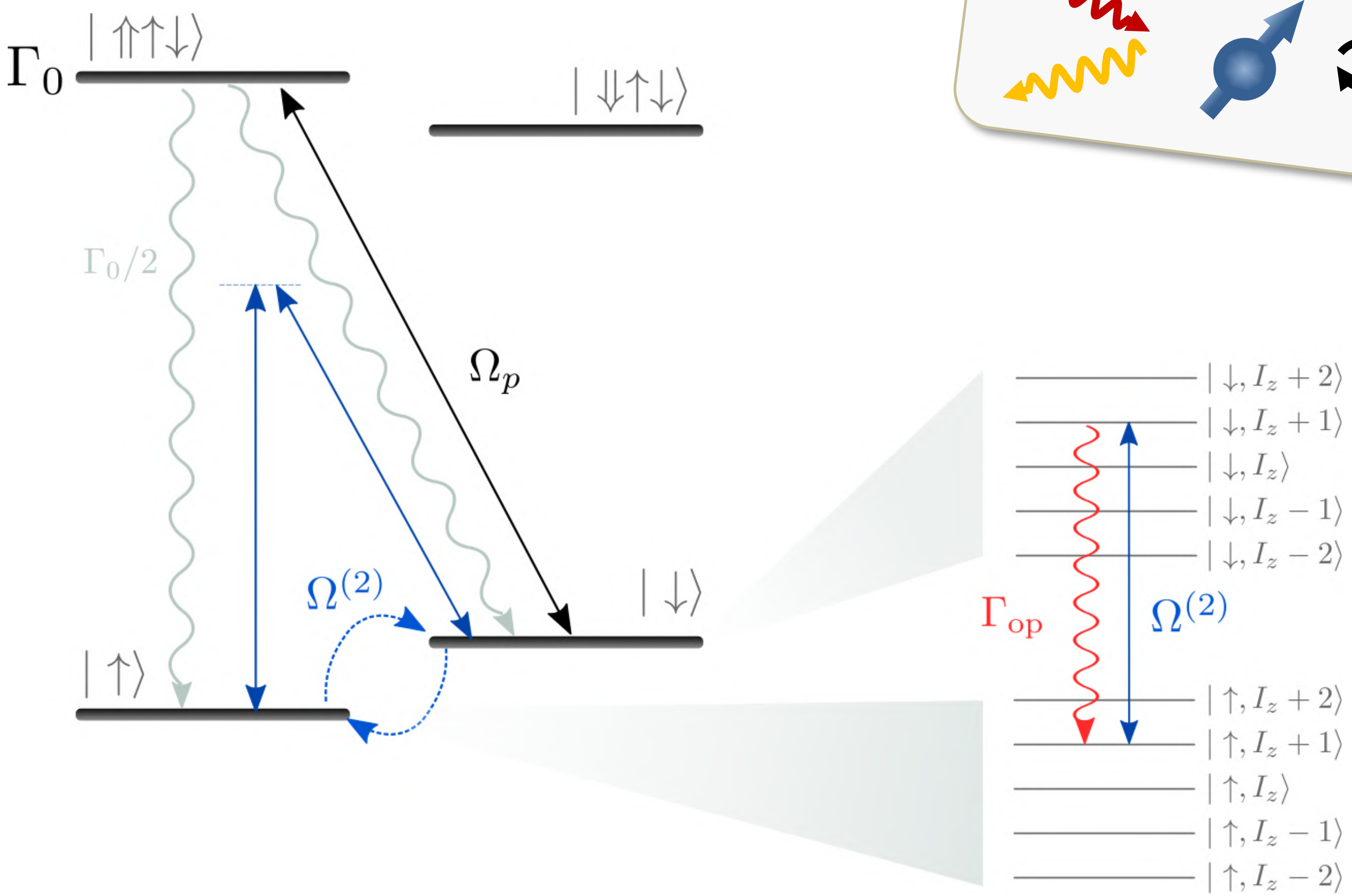
Analogies with an atomic ensemble coupled strongly to a cavity mode

<u>theorists got excited…</u>

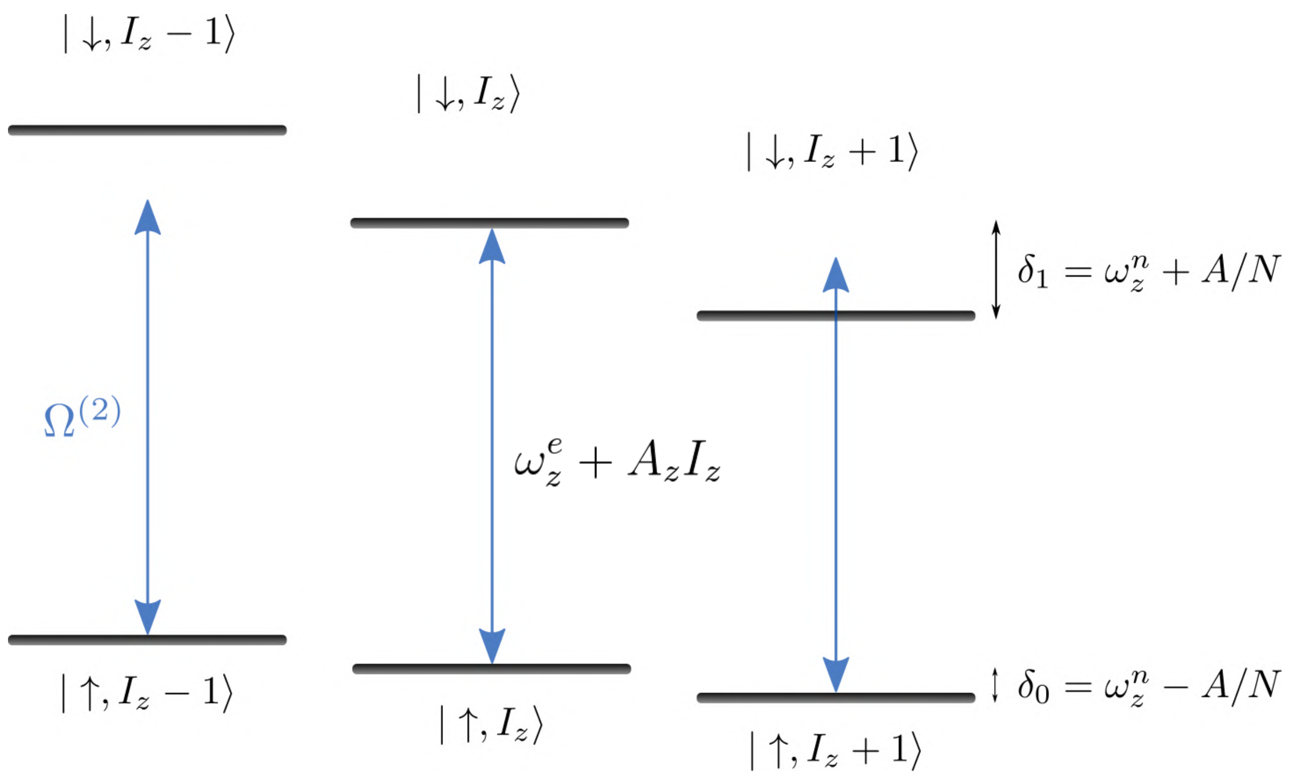
- Robust quantum memory [Taylor et al., PRL **90**, 206803 (2005)]
- Collective dark states [Christ et al., PRB **75**, 155324 (2007)]
- Squeezed nuclear states [Rudner et al., PRL 107, 206806 (2011)]
- Dissipative phase transitions [Kessler et al., PRA **86**, 012116 (2012)]

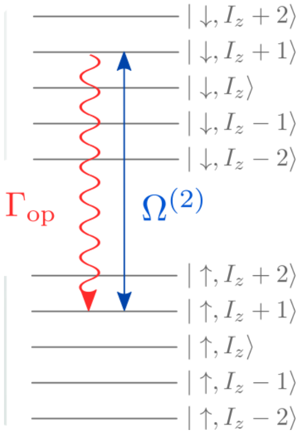
the electronuclear spin-photon coupled system



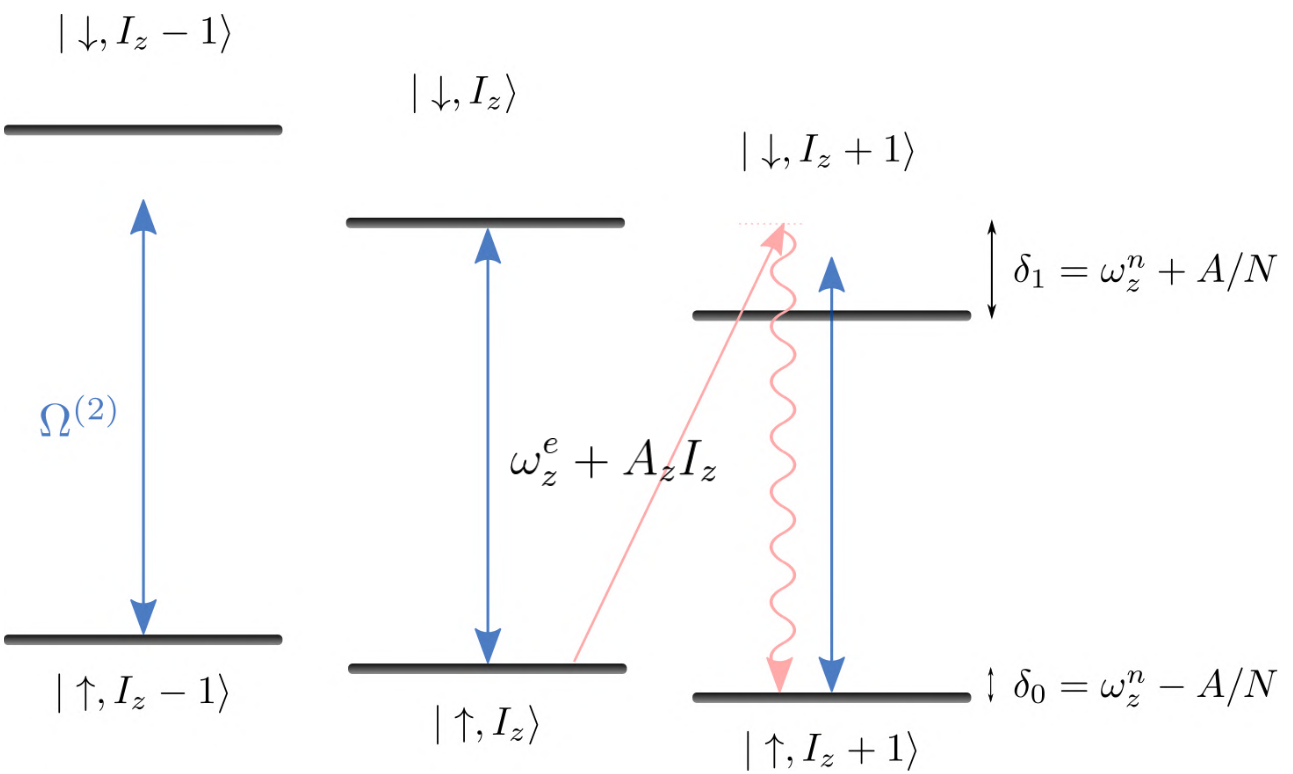


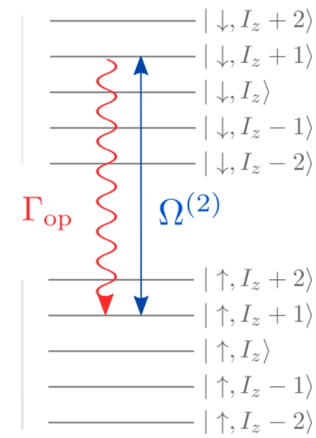
optical orientation of nuclear spins



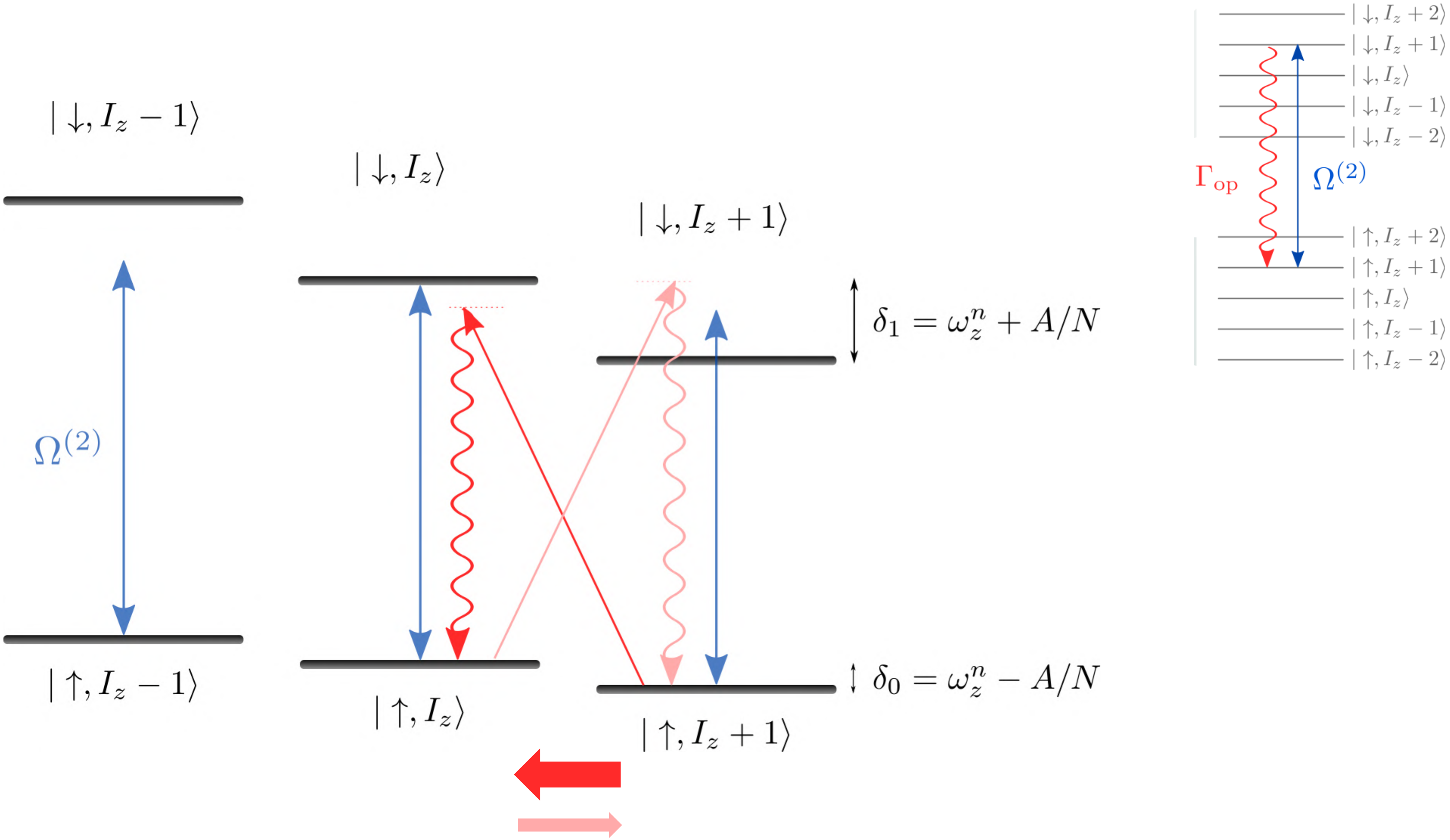


optical orientation of nuclear spins

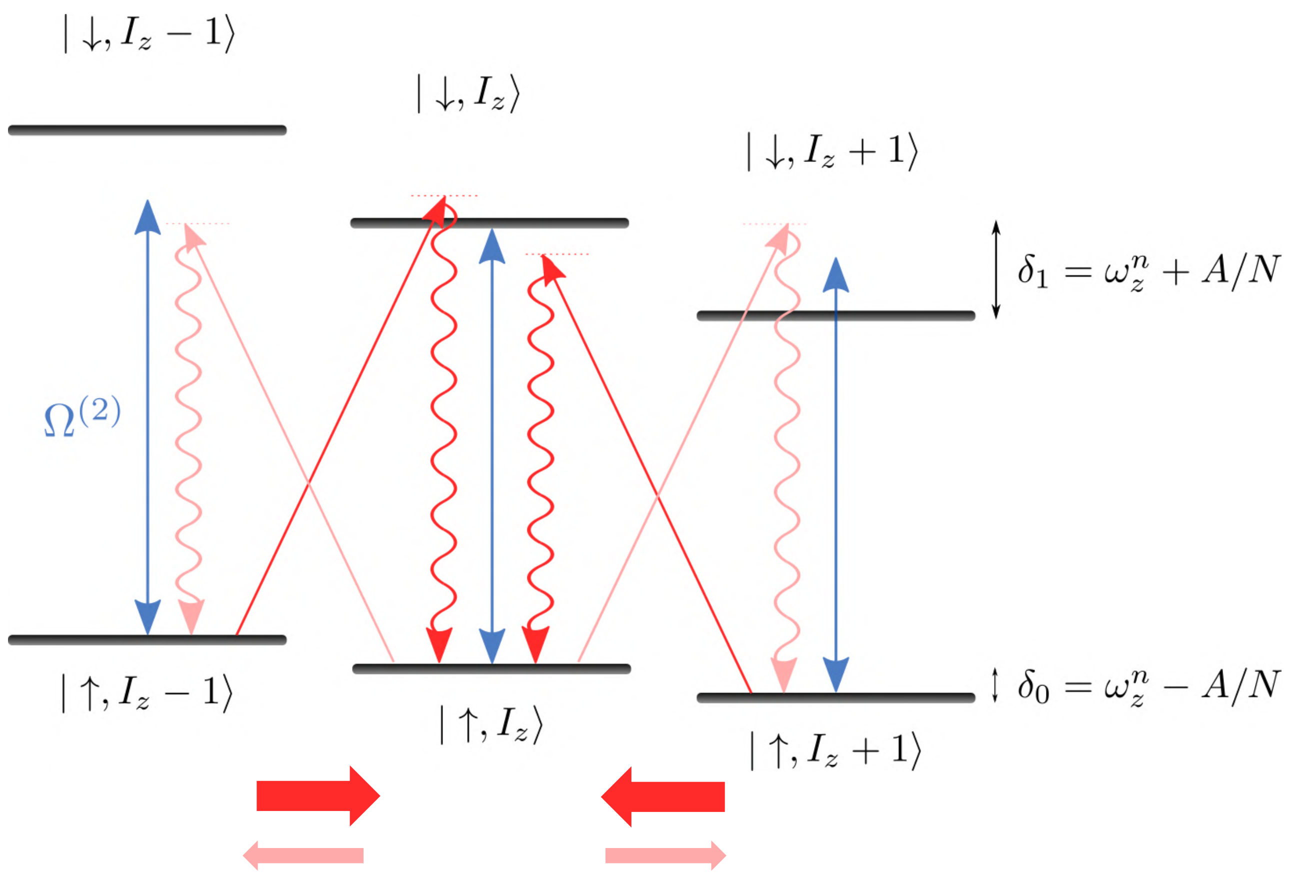


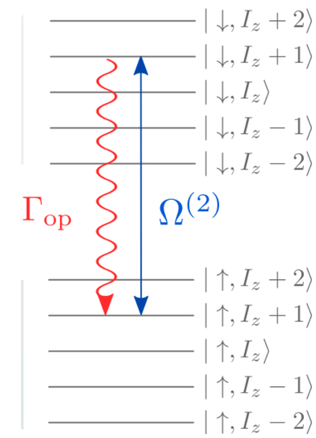


optical orientation of nuclear spins



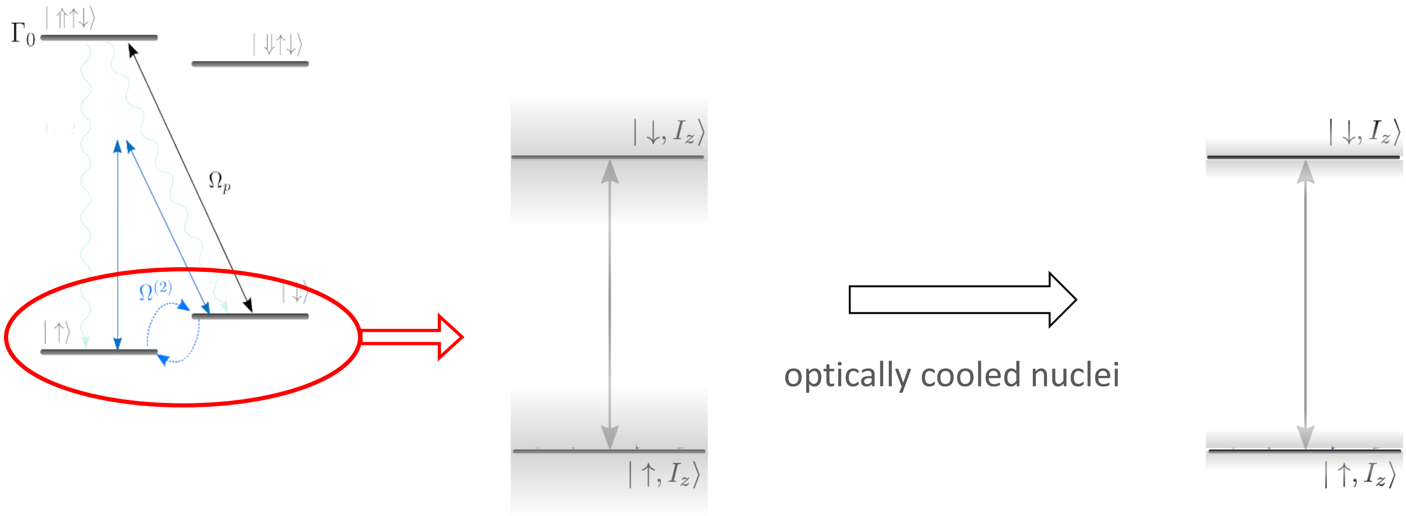
optical orientation of nuclear spins

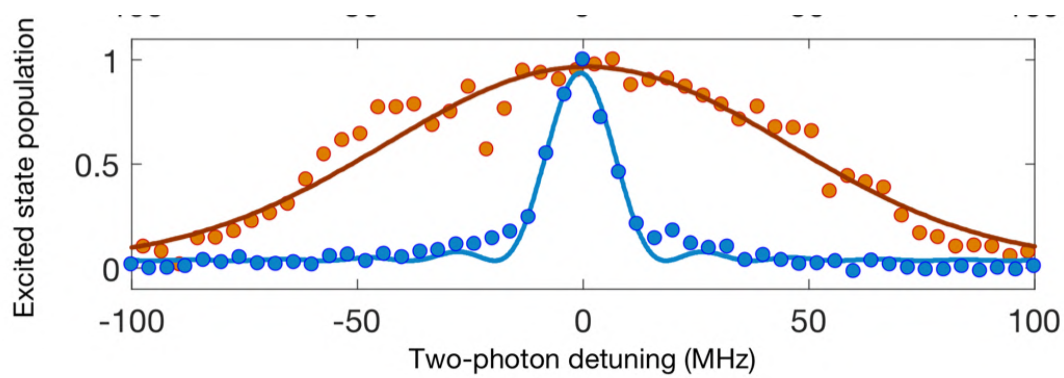




The anharmonic ladder of states leads to a single I_z determined by two-photon detuning.

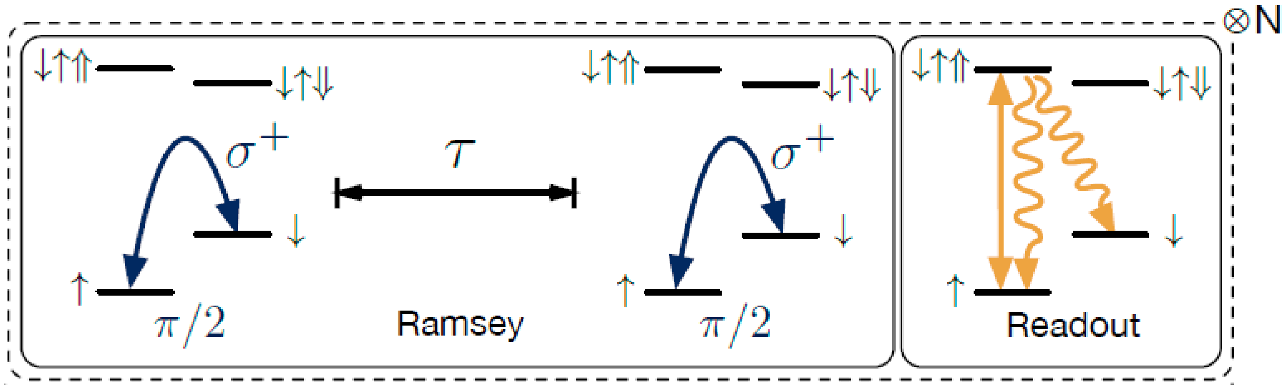
how cool are those cooled nuclei?

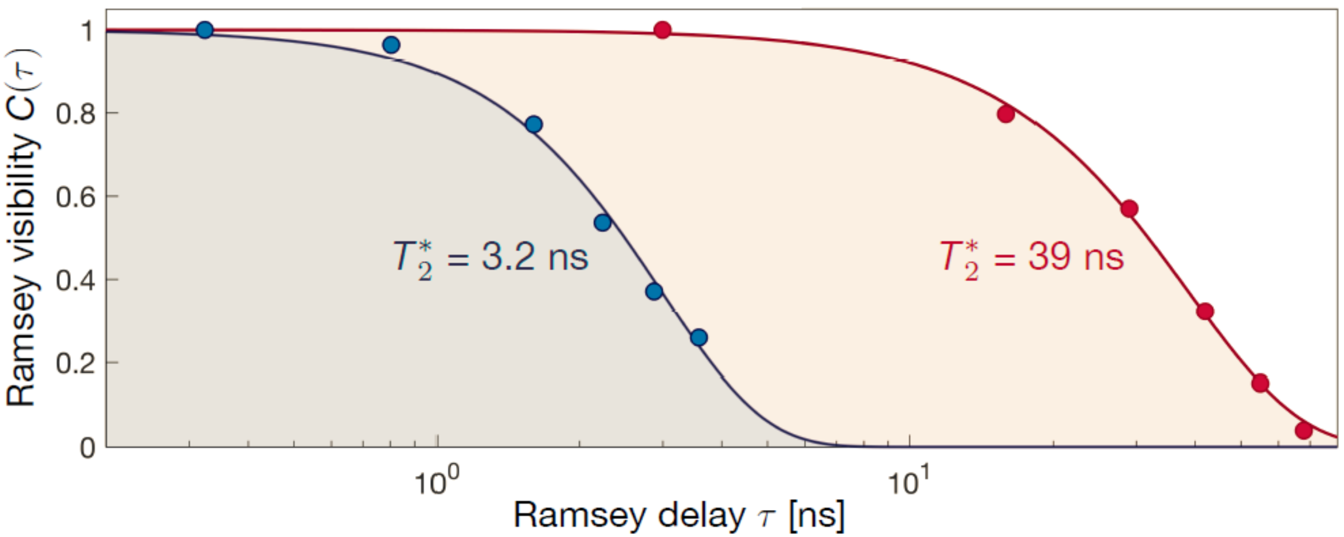




Measured ESR linewidth is ~15 MHz → 400 µK

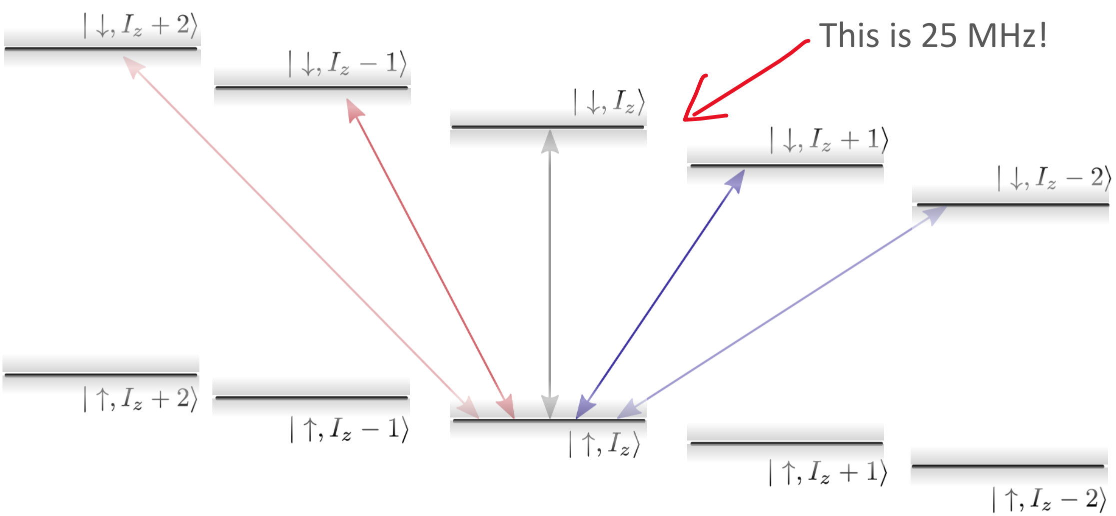
electron coherence after suppressing nuclear magnetic noise

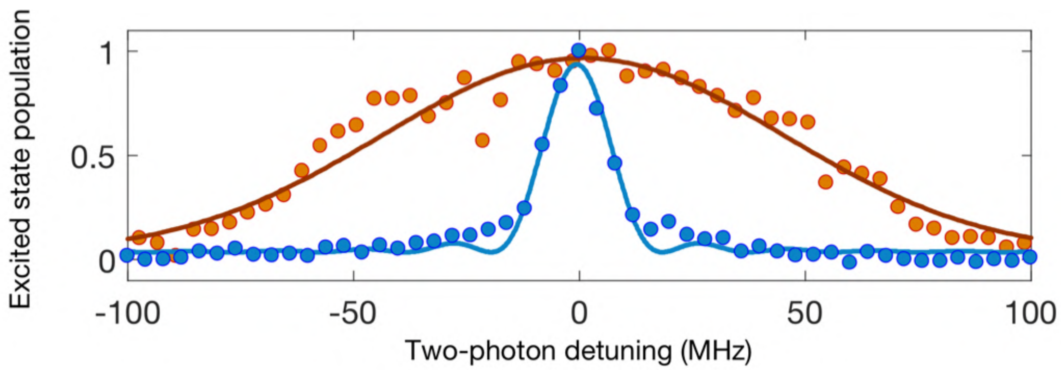




Ethier-Majcher et al., PRL **119** 130503 (2017)

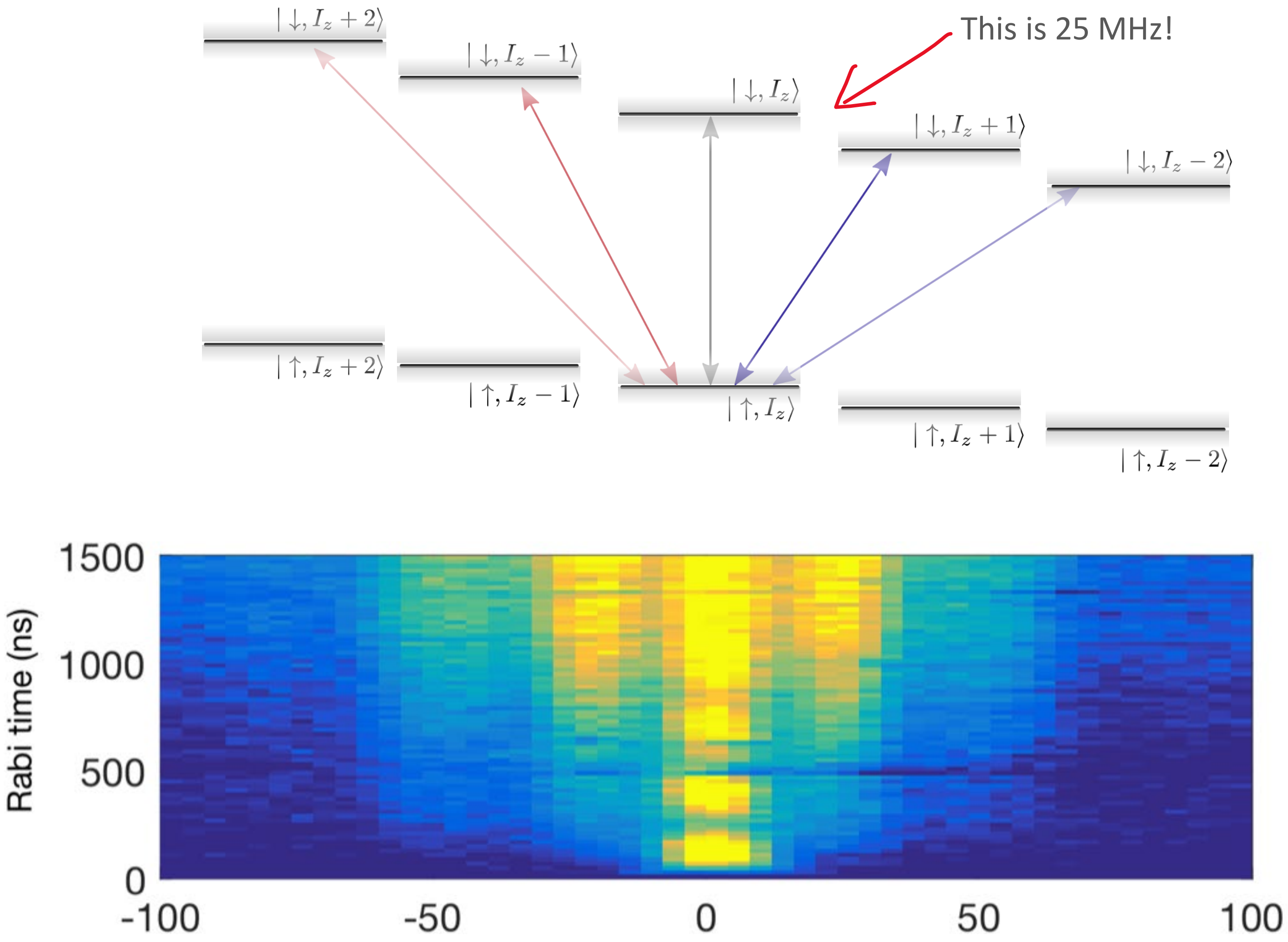
measuring nuclear spin variance via optical ESR



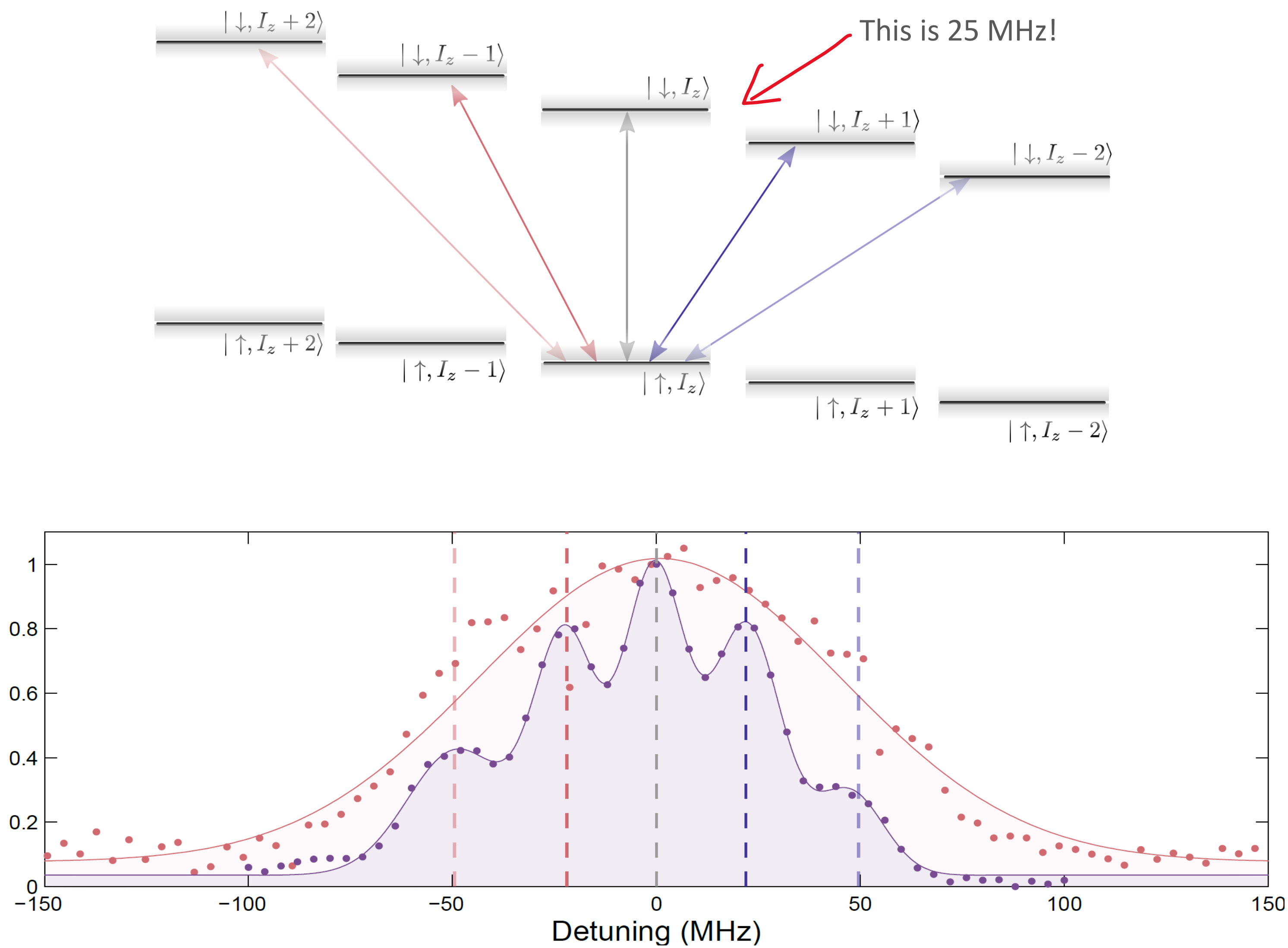


Measured ESR linewith is ~15 MHz → 400 μK

entering the sideband-resolved regime

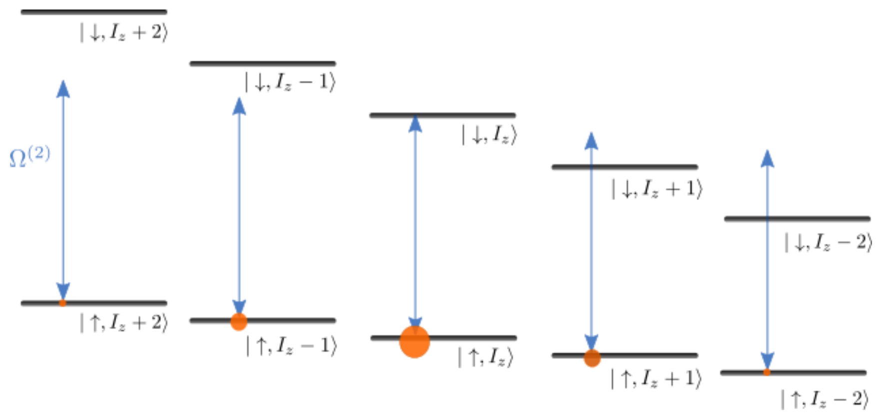


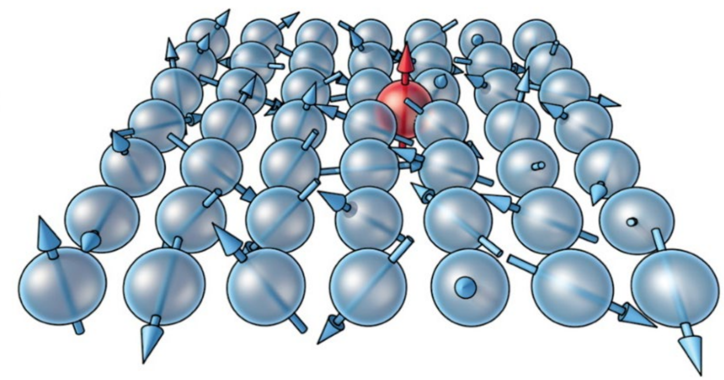
entering the sideband-resolved regime



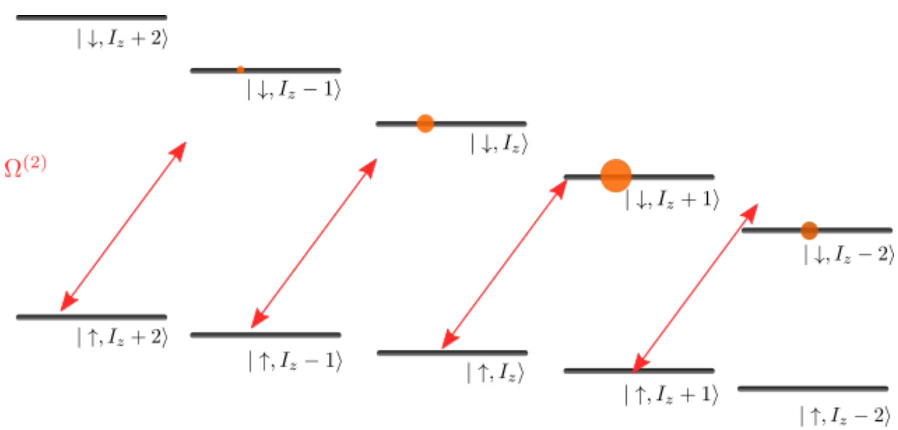
driving of a collective nuclear excitation

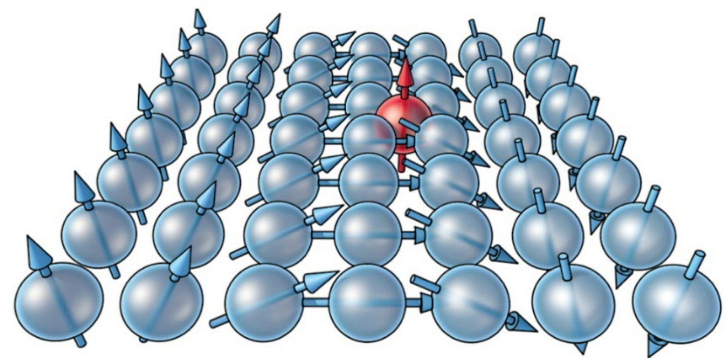
1. Prepare the nuclear bath in a cooled state





2. Coherently drive a nuclear excitation sideband





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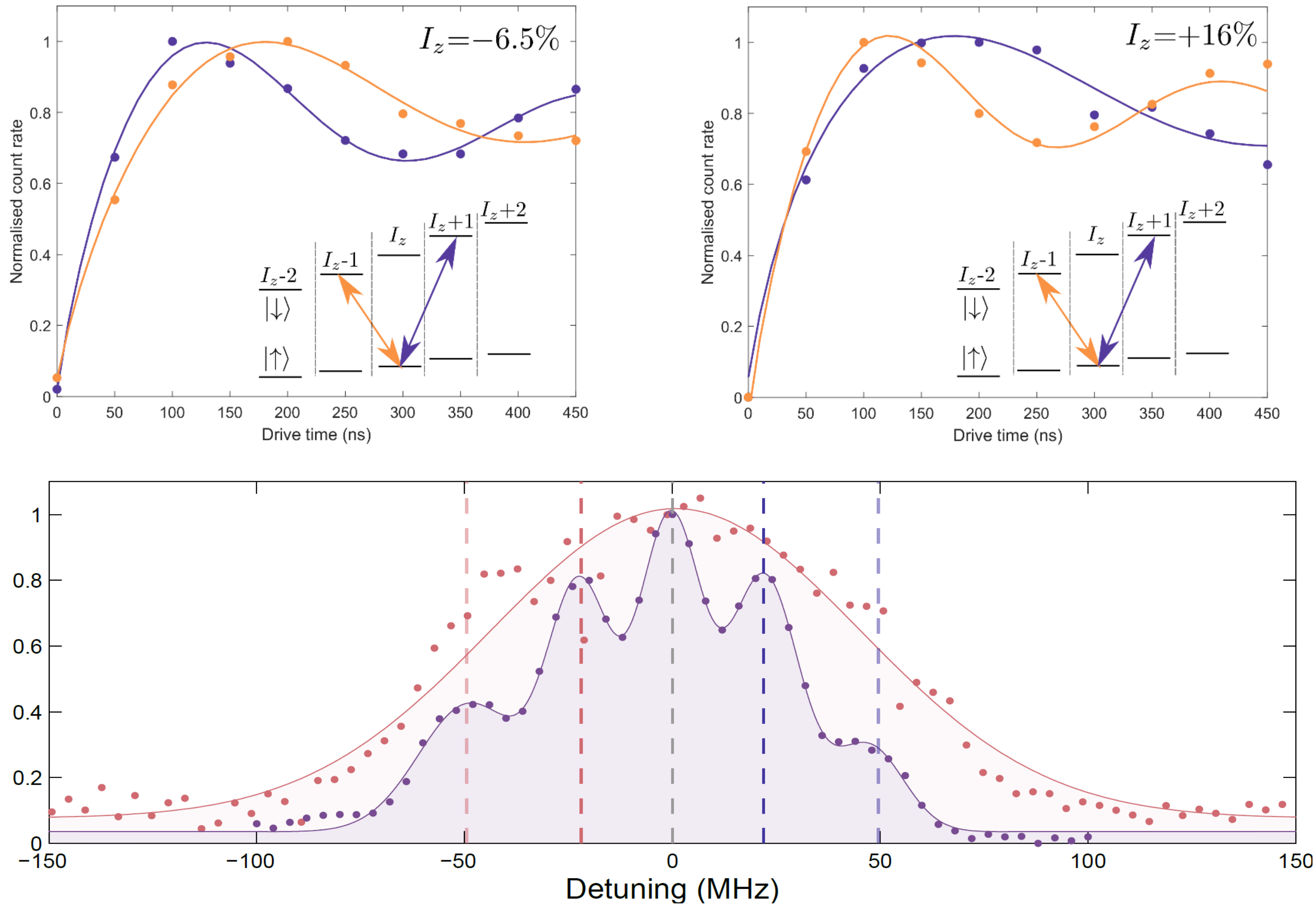
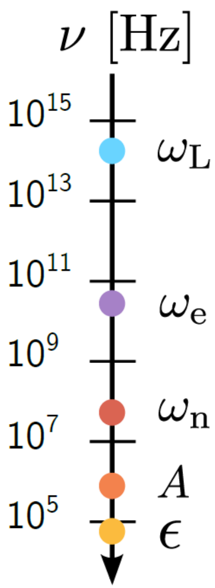
collective coherence of nuclear magnons

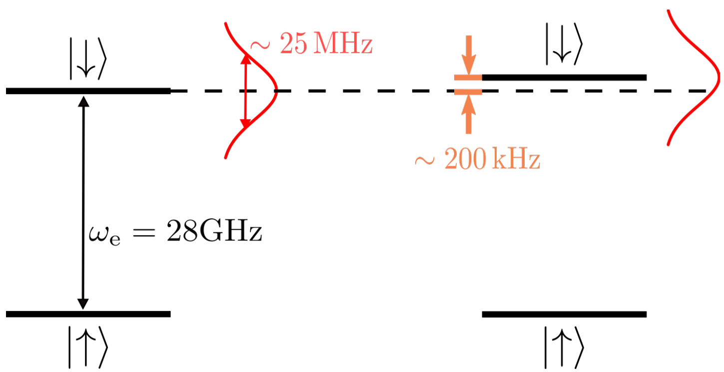
Collectively enhanced spin-excitation: $\Omega_{e-nuc} \propto \sqrt{\mathrm{N}}\, A_i^{nc}$

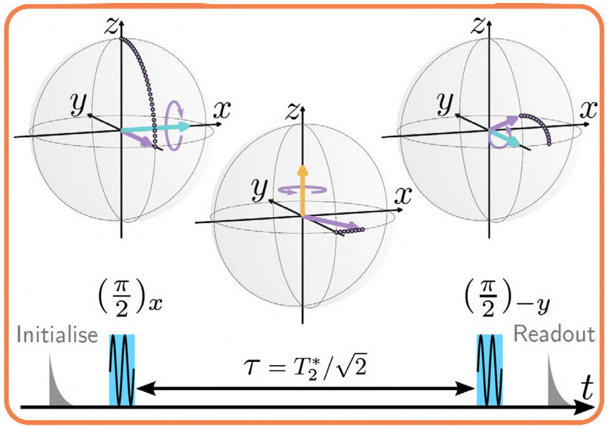


Gangloff *et al*., Science 364, 62 (2019).

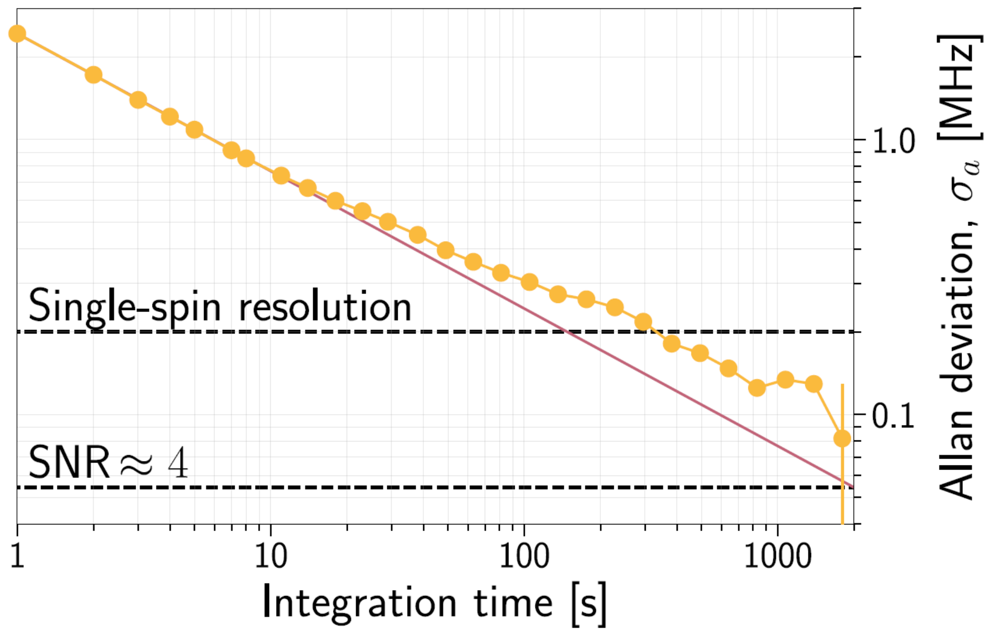
Sensing: full experimental sequence

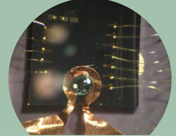




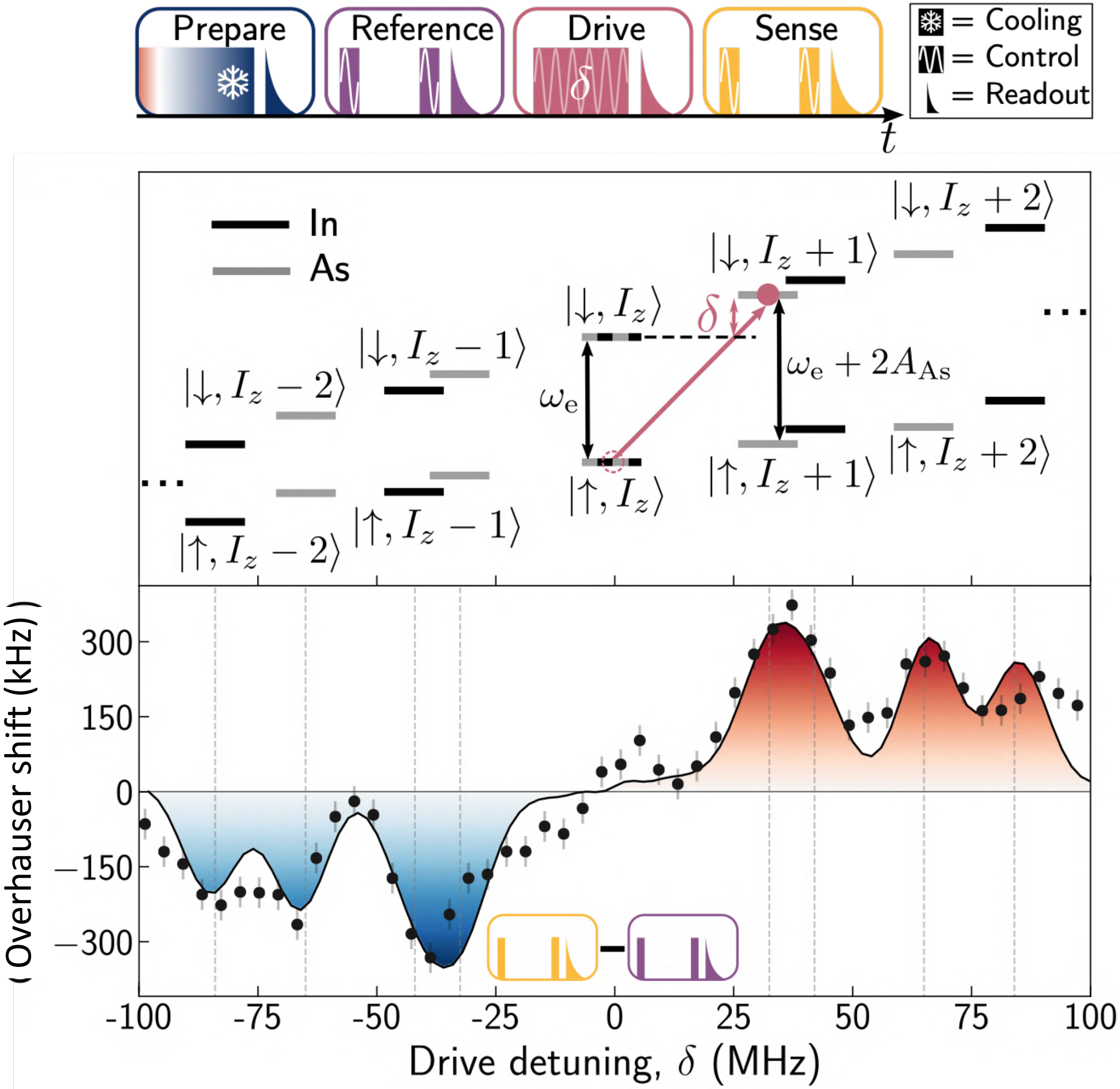


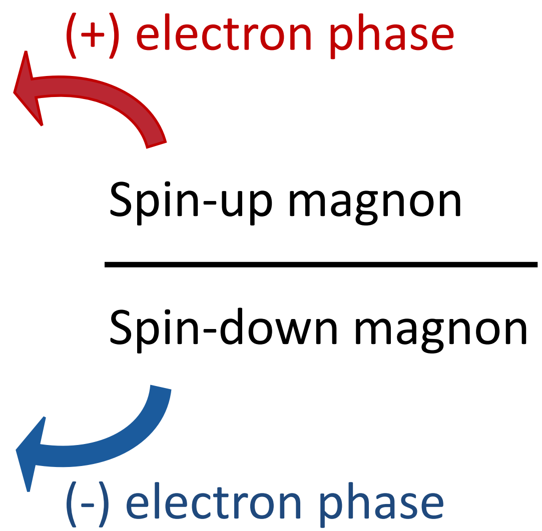
Frequency shift detected via Ramsey Interferometry



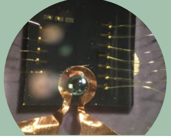


Magnon sensing: Spectrum





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



Pushing the limits of cooling

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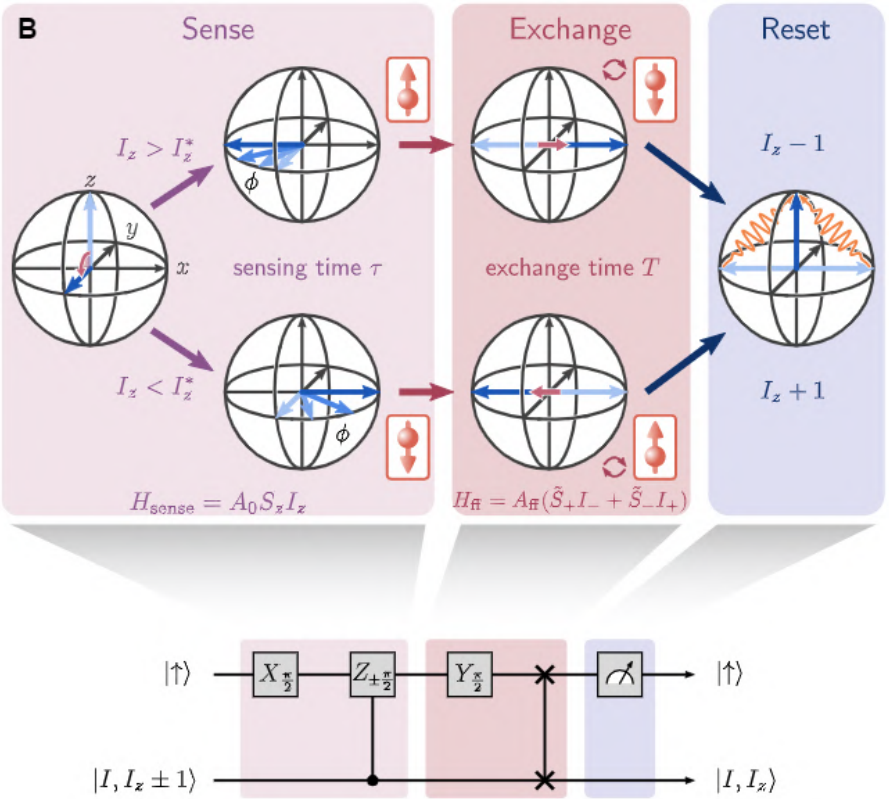
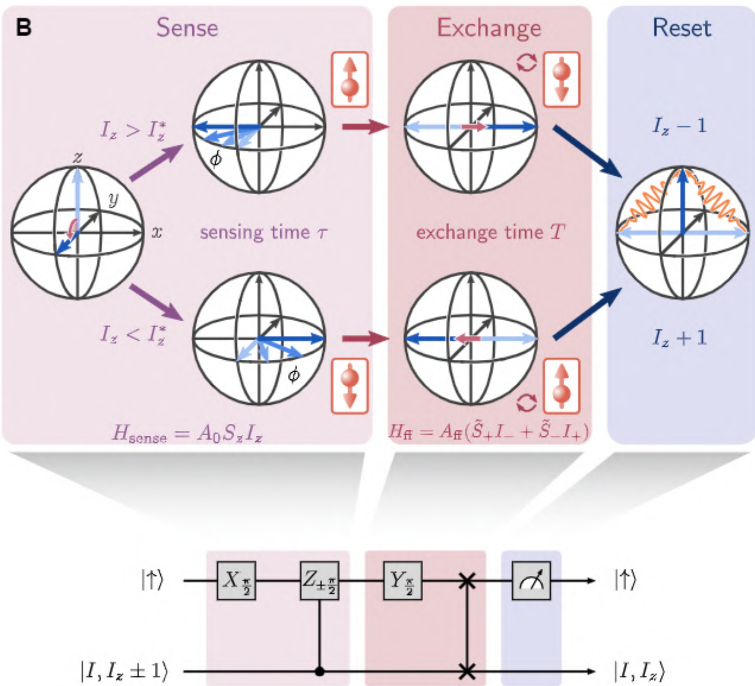
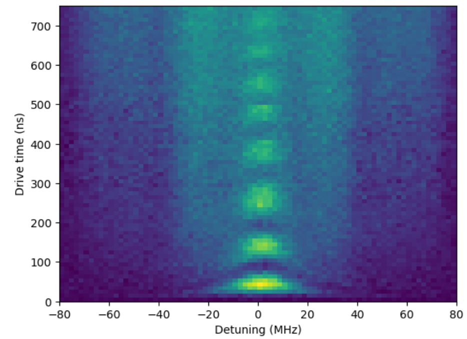
Cooling the nuclei via electro-nuclear coupling in the steady-state

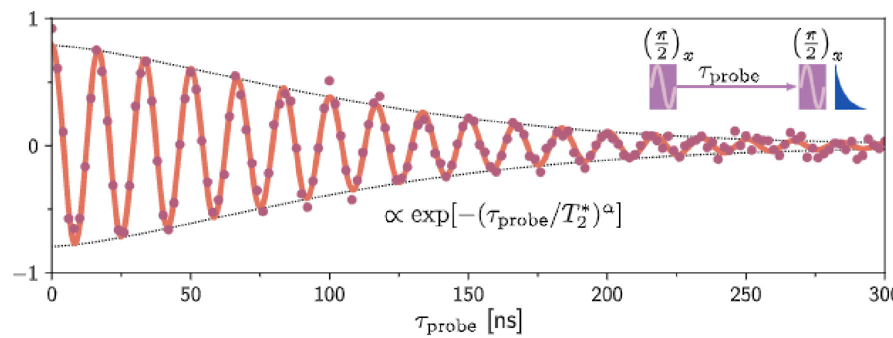
Sensing the writing of a single magnon into the nuclei





Raman cooling





Jackson *et* al., PRX **12**, 031014 (2022)

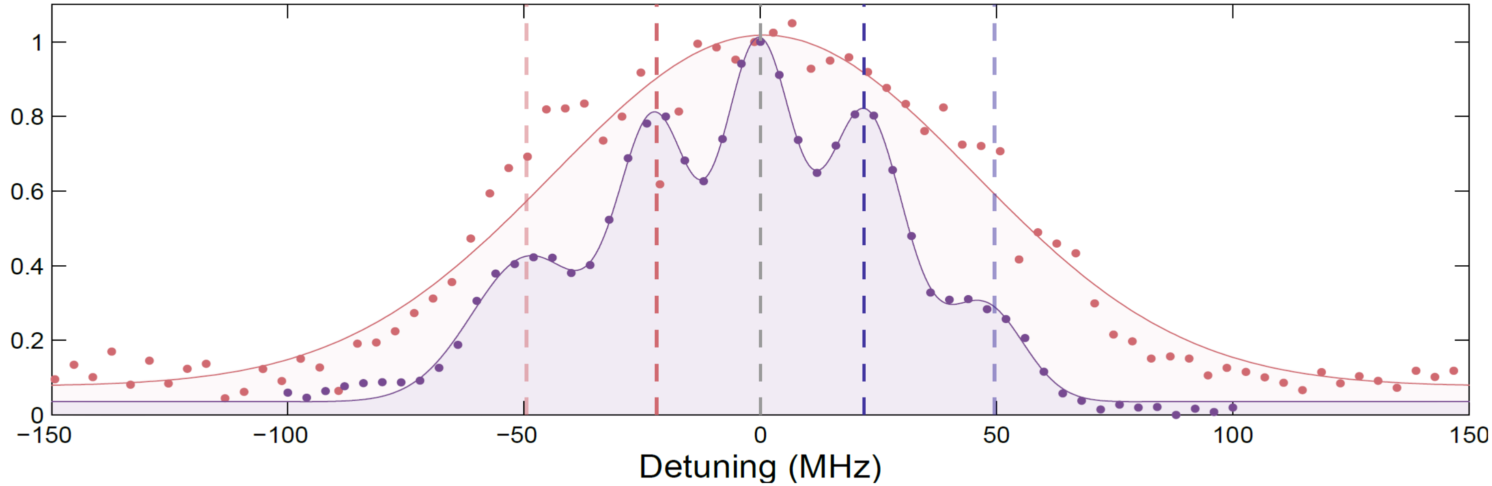
an inhomogeneous ensemble of species (^{113}In, ^{115}In, ^{69}Ga, ^{71}Ga, ^{75}As)

Strain is good!
(quadrupolar enhancement)

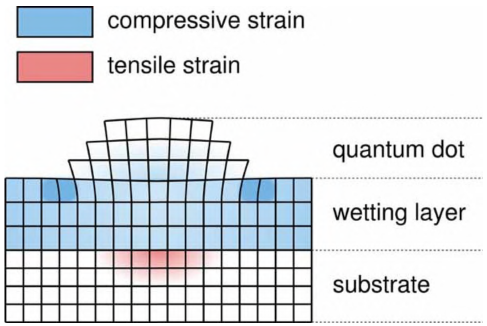
Species have slightly different gyromagnetic ratios

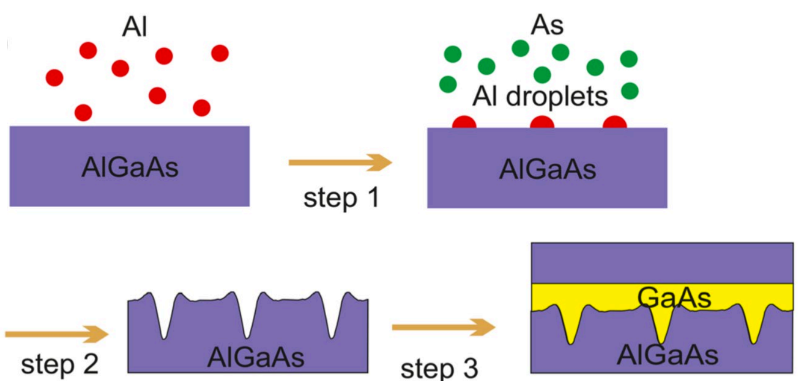
Strain *dispersion* is bad!
(inhomogeneity of nuclei)

Heterogeneity contributes to the modest magnon coherence



next generation quantum-dot devices

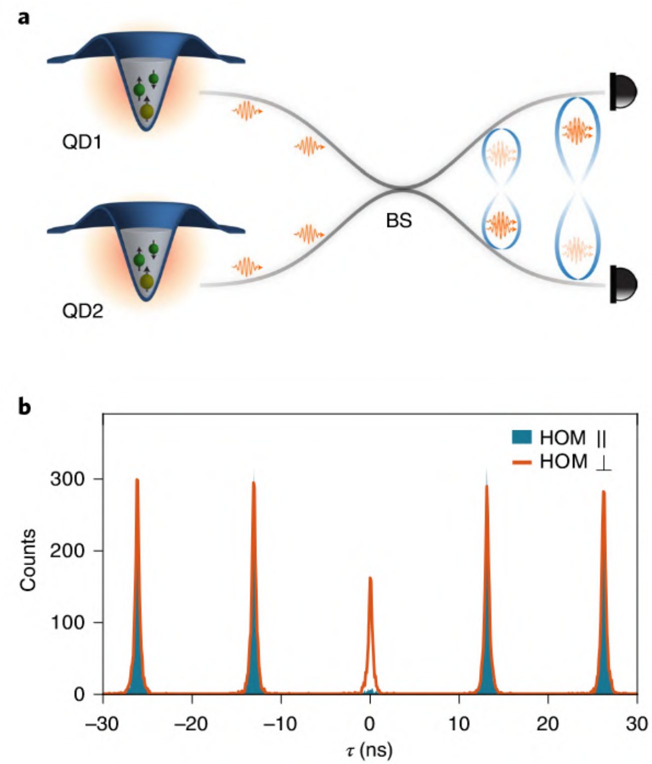




Negligible difference in lattice constant

Quantum interference of identical photons from remote GaAs quantum dots

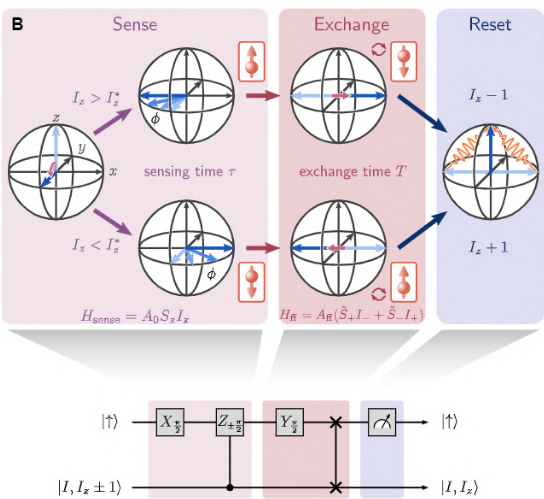
Liang Zhai[1]✉, Giang N. Nguyen[1], Clemens Spinnler[1], Julian Ritzmann[2], Matthias C. Löbl[1], Andreas D. Wieck[2], Arne Ludwig[2], Alisa Javadi[1] and Richard J. Warburton[1]

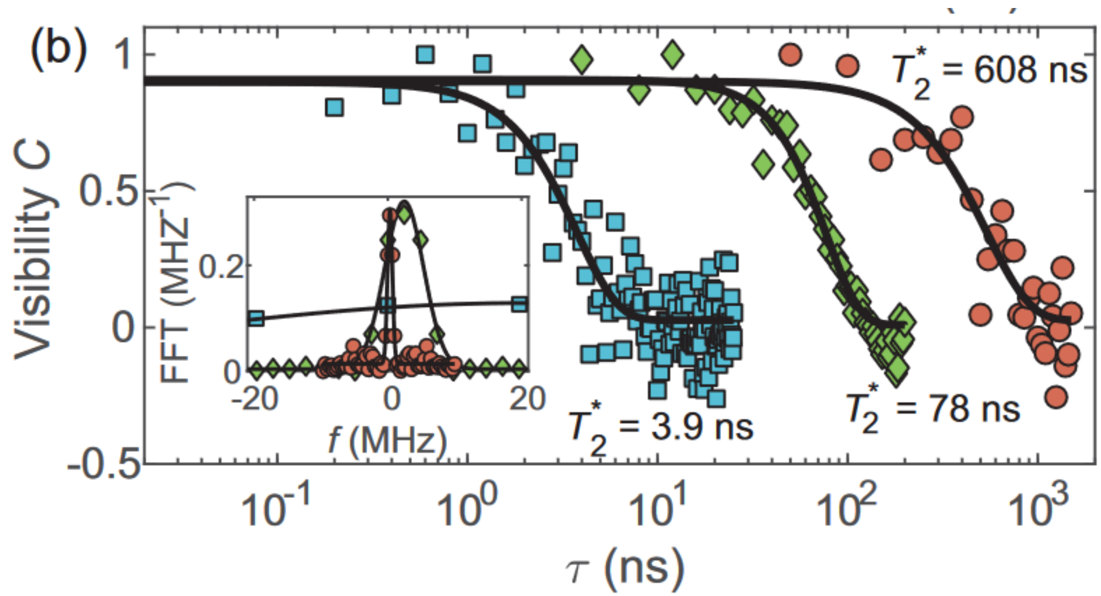


93% remote HOM visibility

Covre da Silva et al., Appl. Phys. Lett. **119**, 120502 (2021)
Zhai et al., Nature Nanotechnol. **17**, 829 (2022)

first evidence of optically cooled nuclei in GaAs QDs





150-fold improvement from 4 ns

Nguyen et al., PRL **131**, 210805 (2023)

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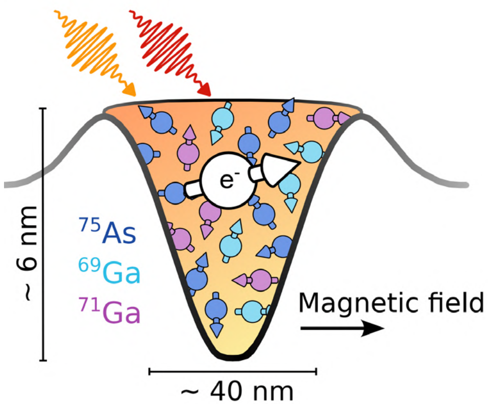
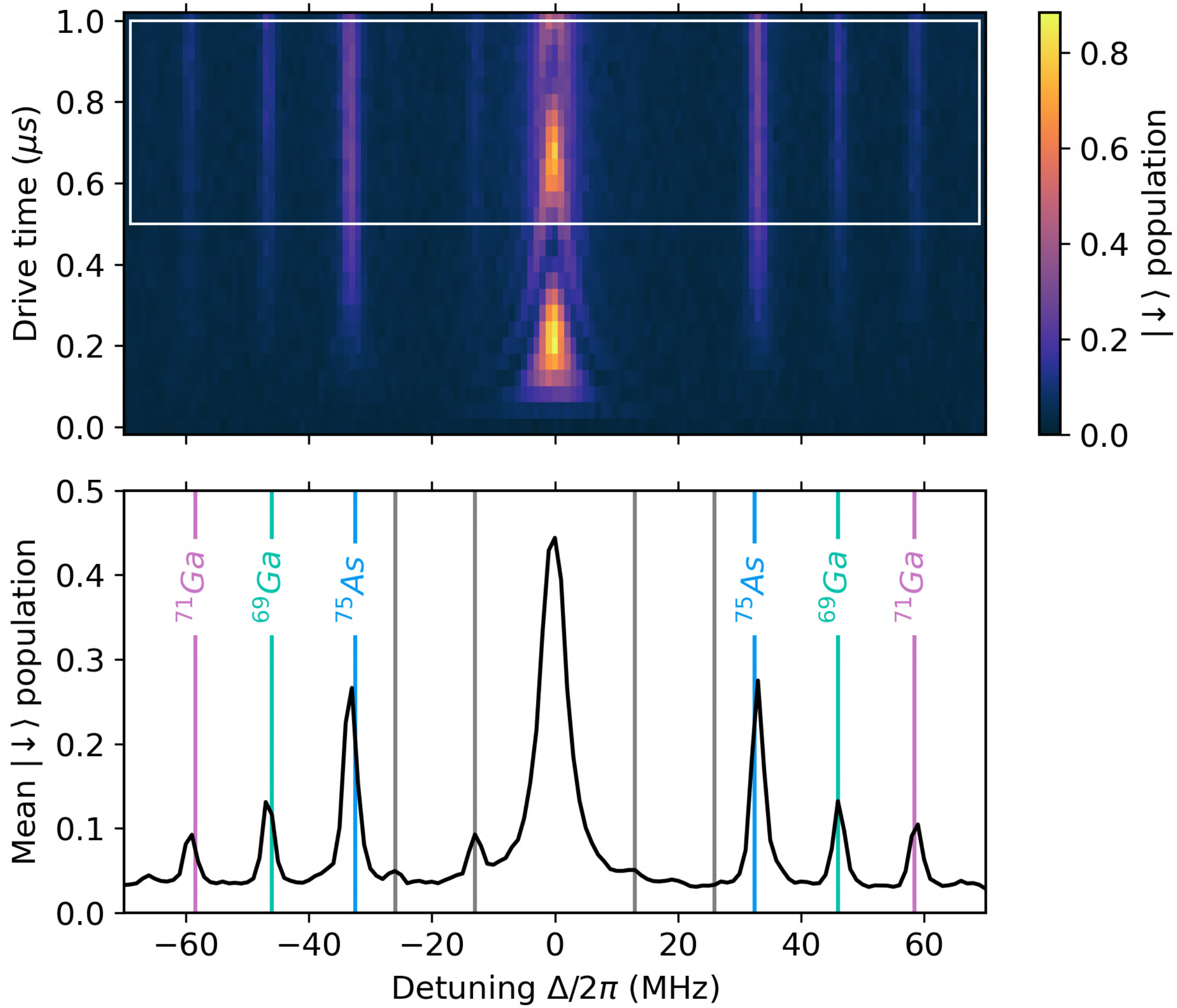
nuclear magnon spectrum for GaAs QD spins





Appel et al. *Nat. Phys*. **21**, 368 (2025)

a many-body quantum register

VOLUME 90, NUMBER 20 PHYSICAL REVIEW LETTERS week ending 23 MAY 2003

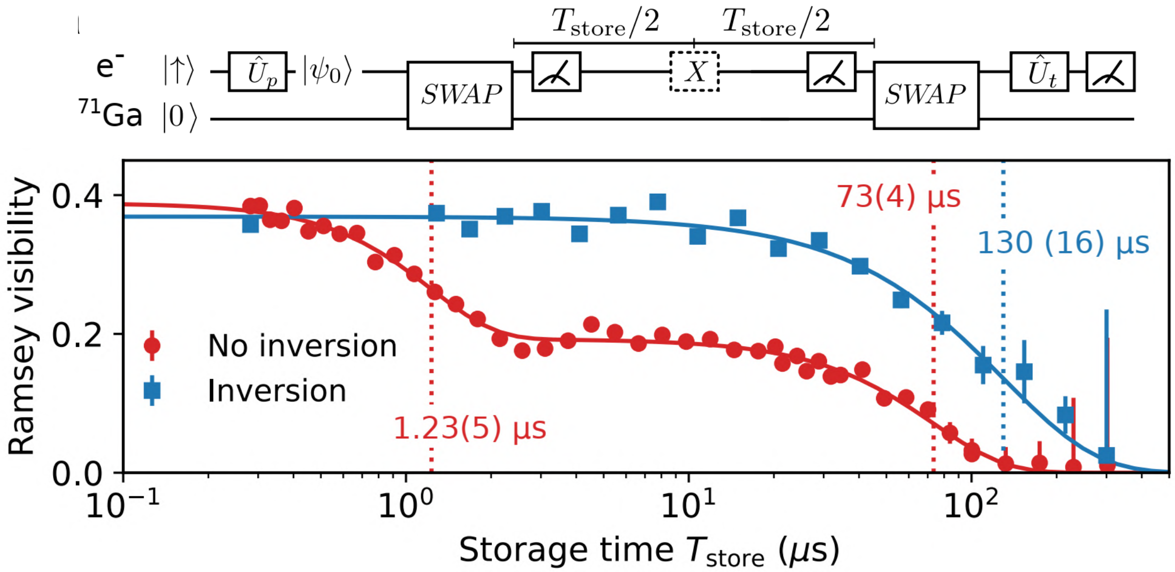
Long-Lived Memory for Mesoscopic Quantum Bits

J. M. Taylor, C. M. Marcus, and M. D. Lukin

Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

(Received 17 January 2003; published 20 May 2003)

We describe a technique to create long-lived quantum memory for quantum bits in mesoscopic systems. Specifically we show that electronic spin coherence can be reversibly mapped onto the collective state of the surrounding nuclei. The coherent transfer can be efficient and fast and it can be used, when combined with standard resonance techniques, to reversibly store coherent superpositions on the time scale of seconds. This method can also allow for "engineering" entangled states of nuclear ensembles and efficiently manipulating the stored states. We investigate the feasibility of this method through a detailed analysis of the coherence properties of the system.



Appel et al. *Nat. Phys*. **21**, 368 (2025)

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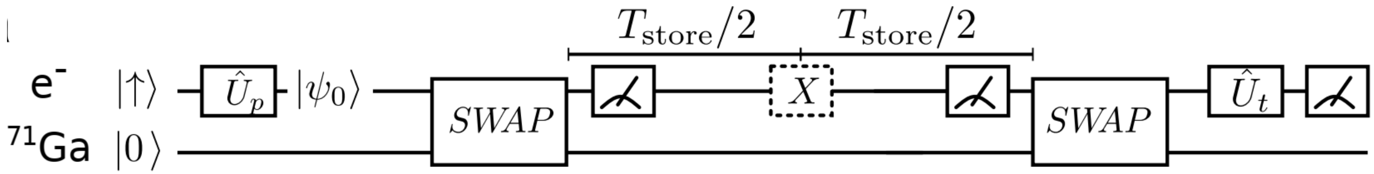
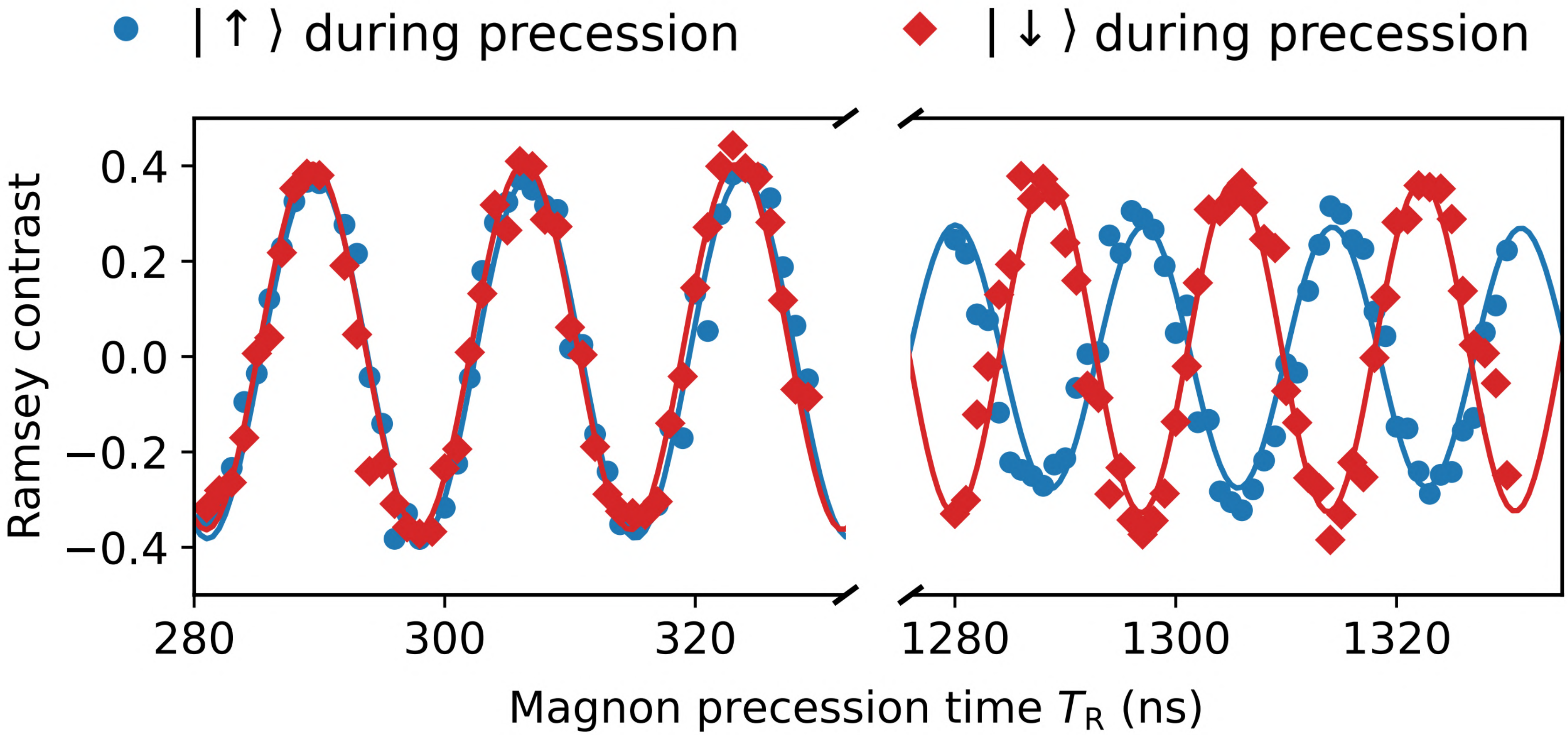
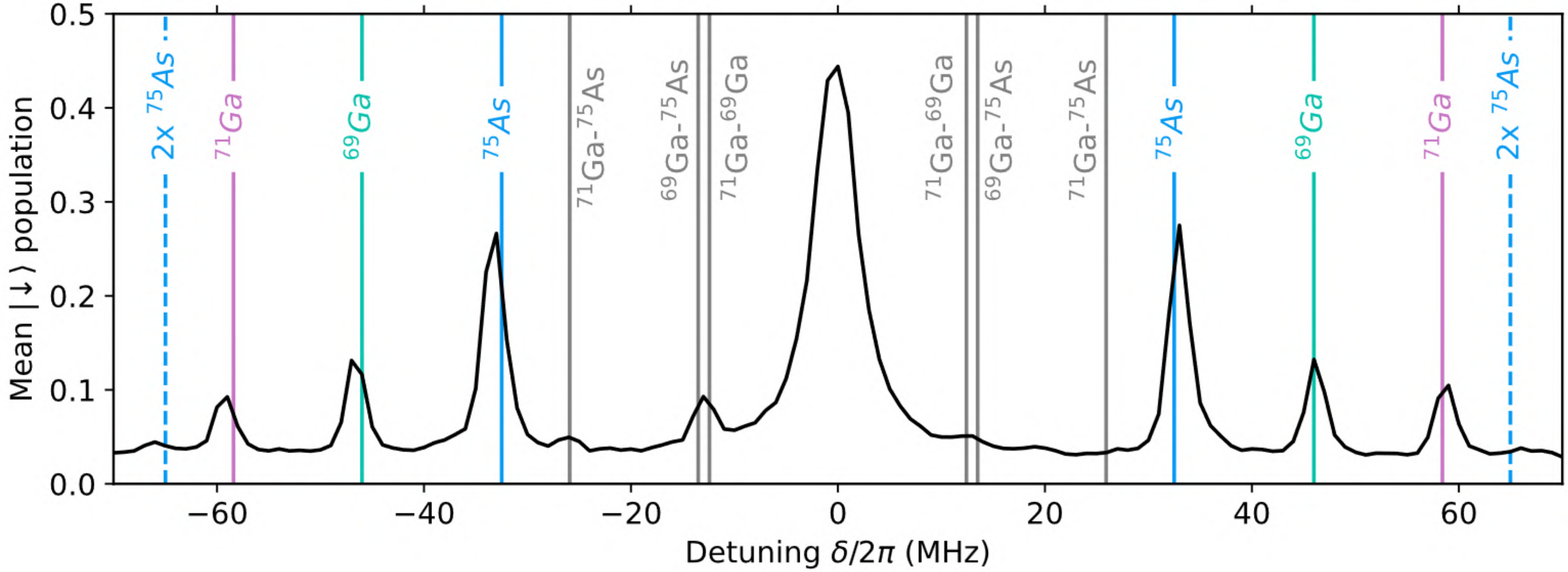
A nuclear magnon spin sensor (roles reversed…)





Appel et al. *Nat. Phys.* **21**, 368 (2025)

closer look at the magnon spectrum…3-body interactions



Three-body interactions at nuclear difference frequencies

A direct route to creating correlations

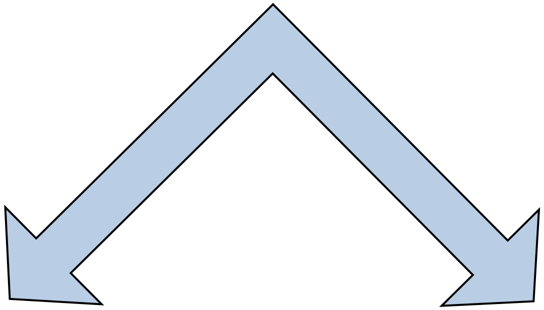
Appel et al. *Nat. Phys*. **21**, 368 (2025)

our storyline in the last decade (building on almost two decades)

a coherent ensemble…to play with

A long-lived coherent spin ensemble

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



the team (and friends)

QD team:

Martin Appel
Clara Bachorz
Jonny Bodey
Gabriel Ethier-Majcher
Dorian Gangloff
Claire Le Gall
Alex Ghorbal
Urs Haeusler
Lukas Huthmacher
Daniel Jackson
Constantin Lang
Clemens Matthiesen
Noah Shofer
Megan Stanley
Rob Stockill
Leon Zaporski
Christian Schrimpf
Isabel Parke
Yusuf Karli
...

and special thanks to:

Rastelli Group (GaAs QD growth – Linz)
National III-V Centre (InAs QD growth – Sheffield)

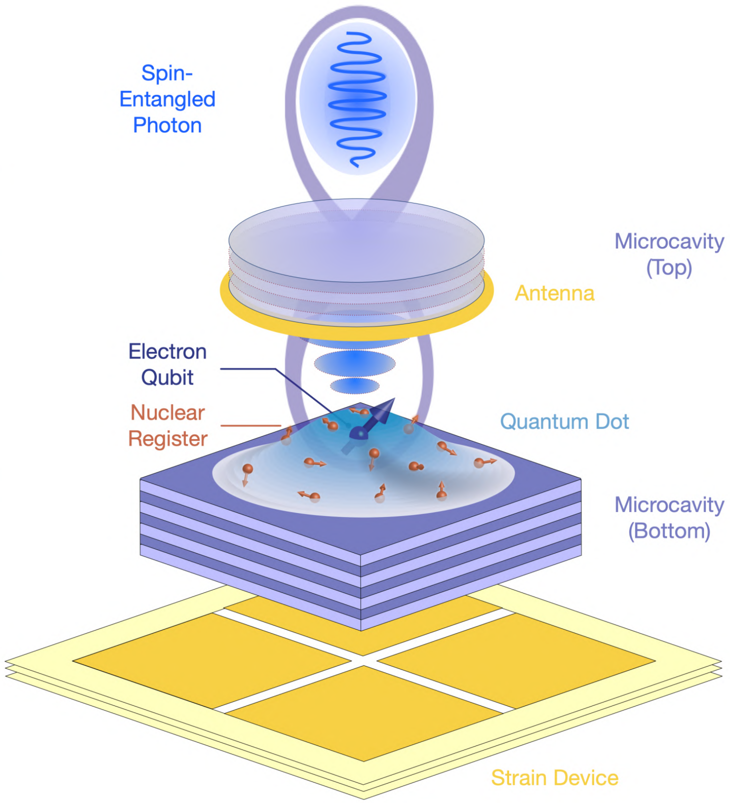
EPSRC (NQIT, QUES^{2}T), EU (S^{3}NANO, spinNANO, QLUSTER, QUDOT-TECH, Quantum Flagship, MEEDGARD), ERC, ONRG

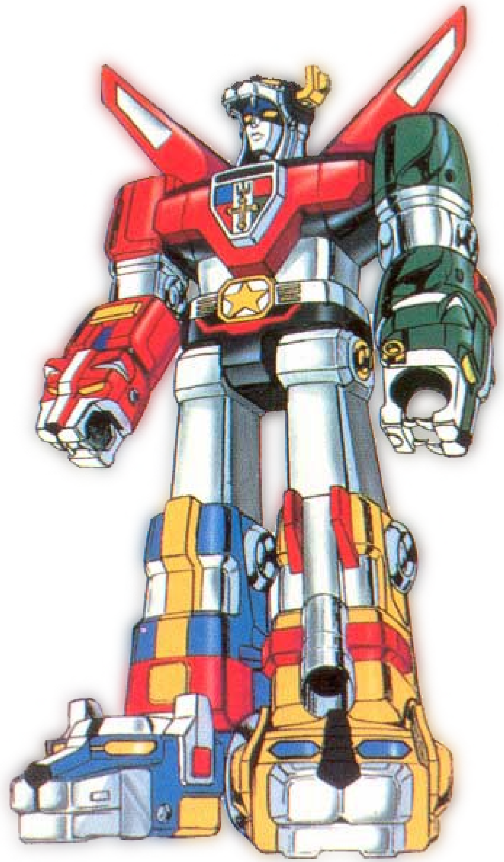
MEEDGARD – a 'Voltron' of quantum-dot devices

https://meedgard.phy.cam.ac.uk

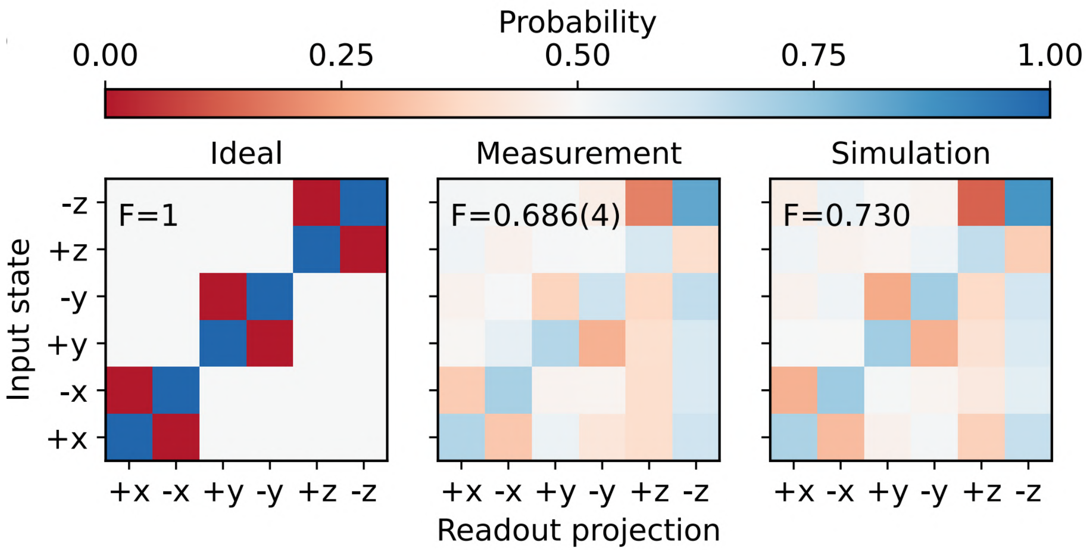
Exciton-polaritons
(charged and neutral)

Electro-nuclear magnons
(anisotropy or strain activated)





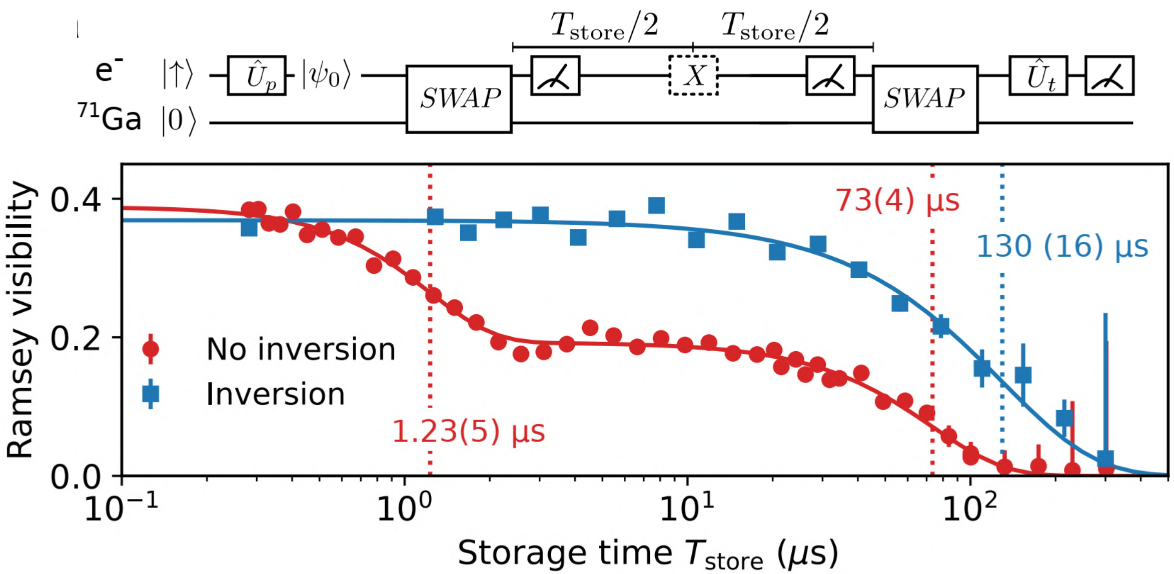
a many-body quantum register



$F = (1 + \langle C \rangle) / 2$

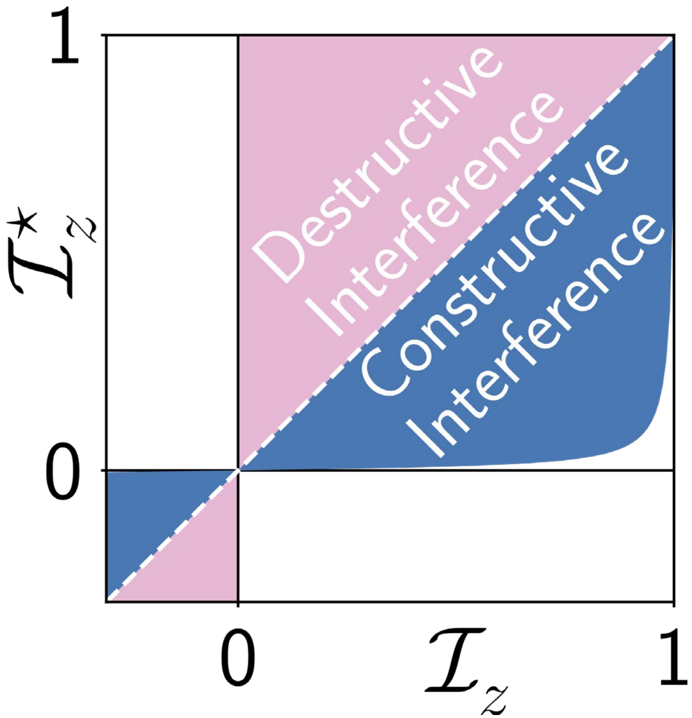
$F_{limit} = 2/3$

$F_{exp} = 0.69$



Appel et al. *Nat. Phys*. **21**, 368 (2025)

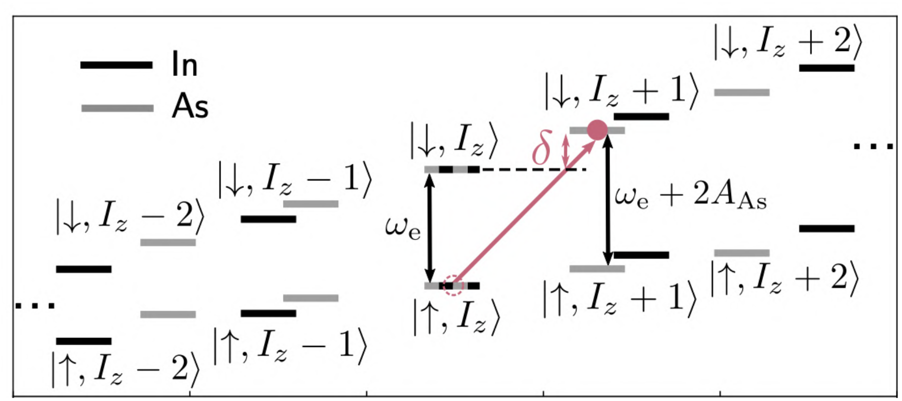
Compare $\mathcal{I}_z$ from Overhauser shift to $\mathcal{I}_z^\star$ from sideband asymmetry

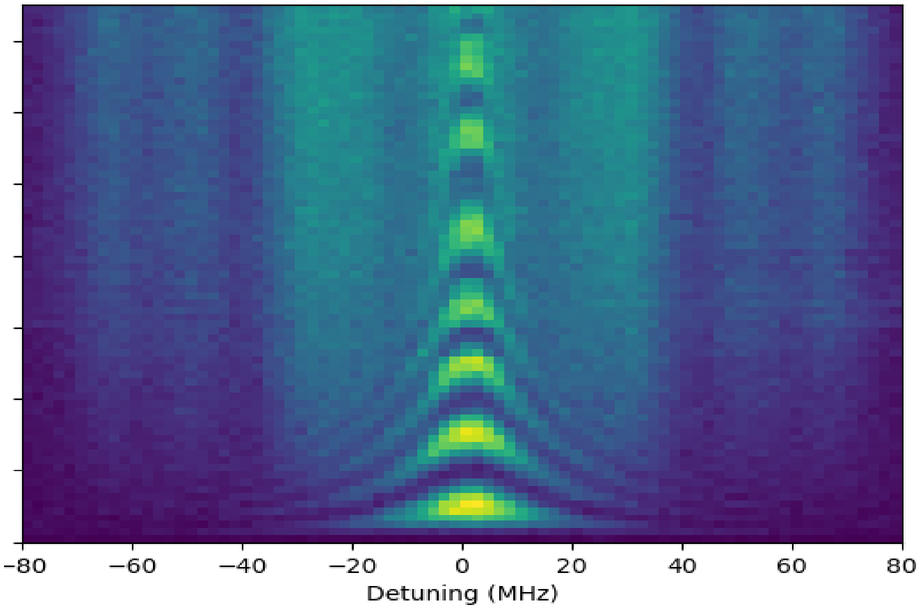


Christ et al., PRB **75**, 155324 (2007)
Taylor et a., PRL, 91, 246802 (2003)

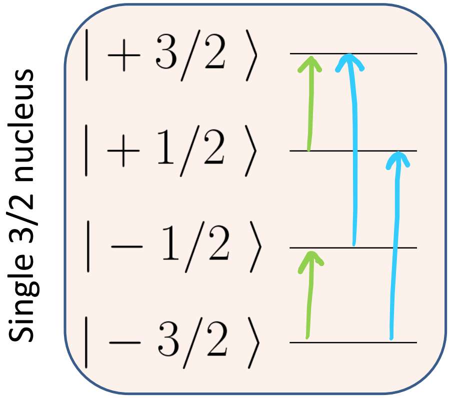
D.A. Gangloff et al., *Nature Physics*, 17, 1247 (2021)

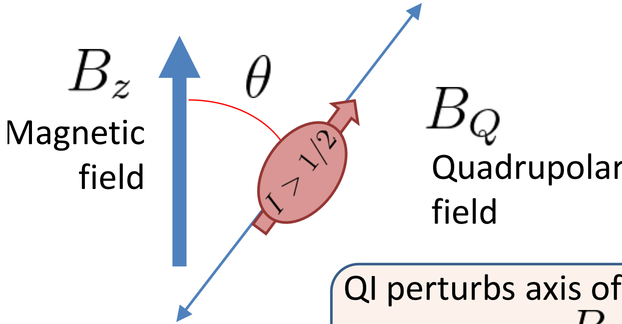
resolving nuclear species via magnons





$$H^{nc}_{e-nuc} = \sum_i A_1^{nc}(S_z(I_x^i I_z^i + I_z^i I_x^i)) + \sum_i A_2^{nc}(S_z(I_x^{i2} - I_y^{i2}))$$



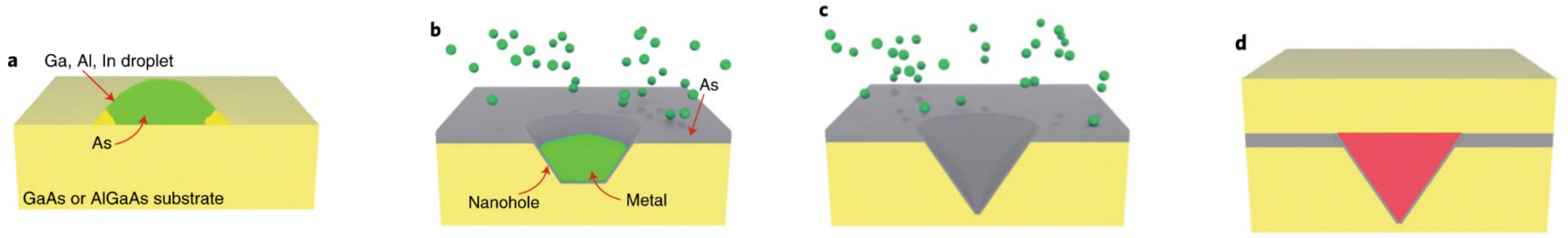


QI perturbs axis of the e-nuc HI

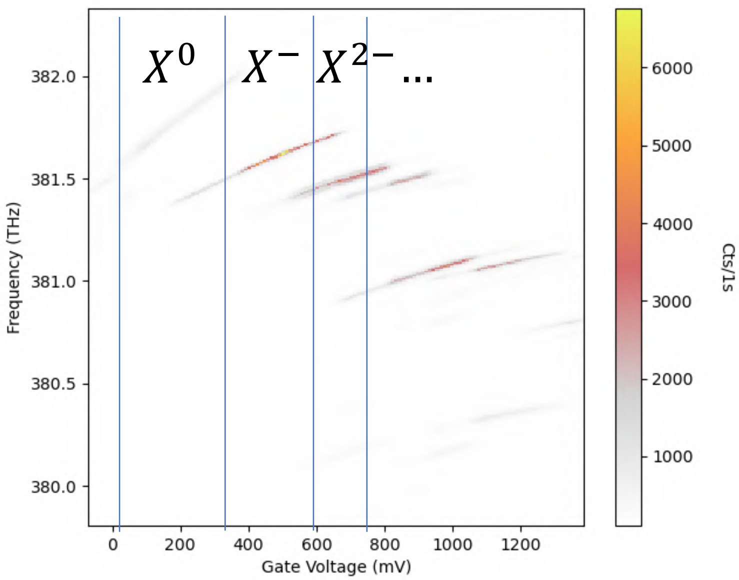
$$A_1^{nc} = A_z \frac{B_Q}{B_z}\sin(2\theta)$$

how to avoid the strain dispersion problem (avoid dispersion!)

Strain-free GaAs QDs



Gate controlled GaAs QDs



JOHANNES KEPLER UNIVERSITÄT LINZ

in collaboration with Rastelli Group

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The problem with InGaAs

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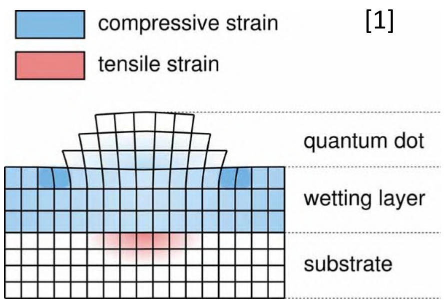
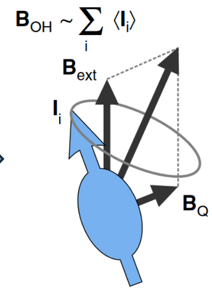
Stranski-Krastanow growth:

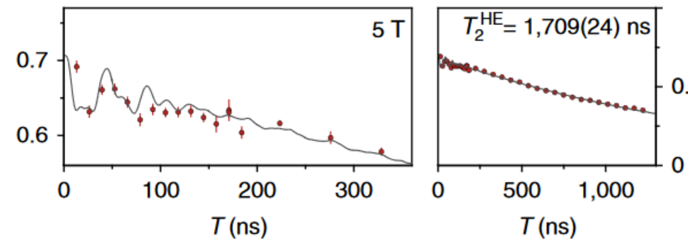


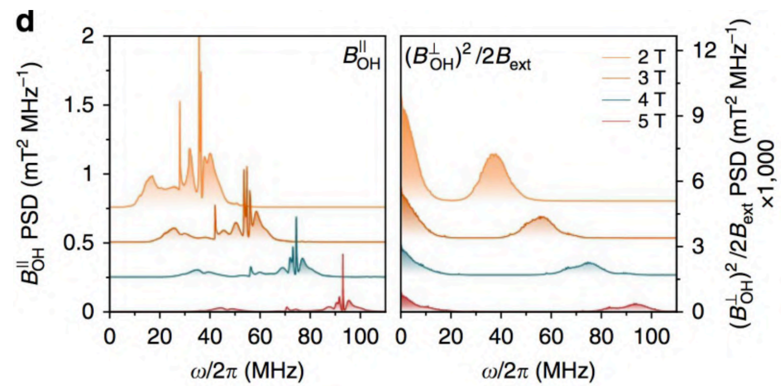
7% lattice mismatch



Spin echo [2]:

Limited spin coherence: T_2





- Strain: Non-collinear coupling
- Strain dispersion: 5 MHz nuclear broadening
- Broadening limits electron coherence, electro-nuclear coupling, NMR control, etc…

[1] Figge et al., Phys. Status Solidi B 248, 8 (2011)
[2] Stockill et al, Nat. Commun., 7, 12745 (2016)

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GaAs droplet quantum dots

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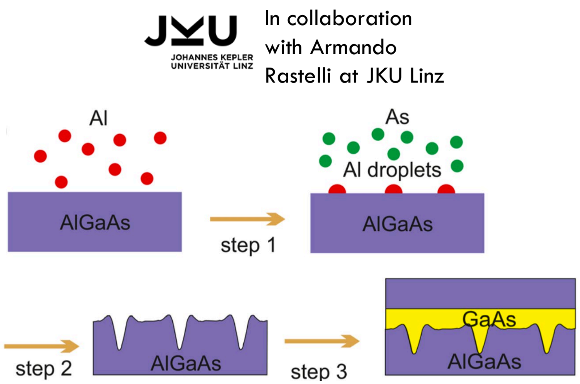
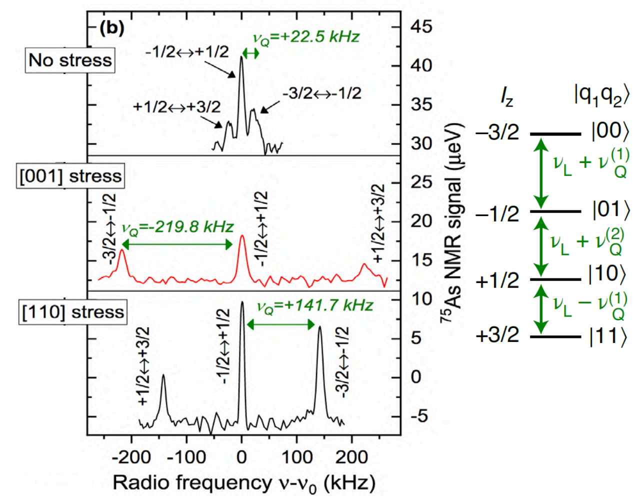
Droplet epitaxy growth[1]:



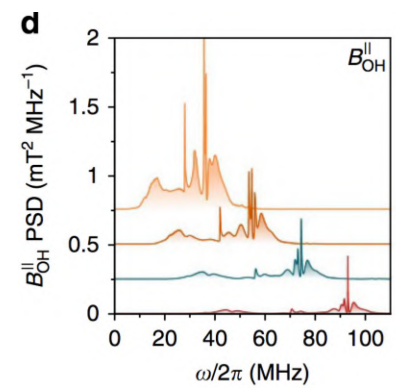
Negligible difference in lattice constant

QD detected NMR on 75Ga



10-100 KHz broadening [2]

Comparison with InGaAs



~ **10 MHz** broadening

How often do you win two orders of magnitude?!?

[1] Covre da Silva et al., Appl. Phys. Lett. 119, 120502 (2021)
[2] Chekhovich et al, Phys. Rev. B 97, 235311 (2018)

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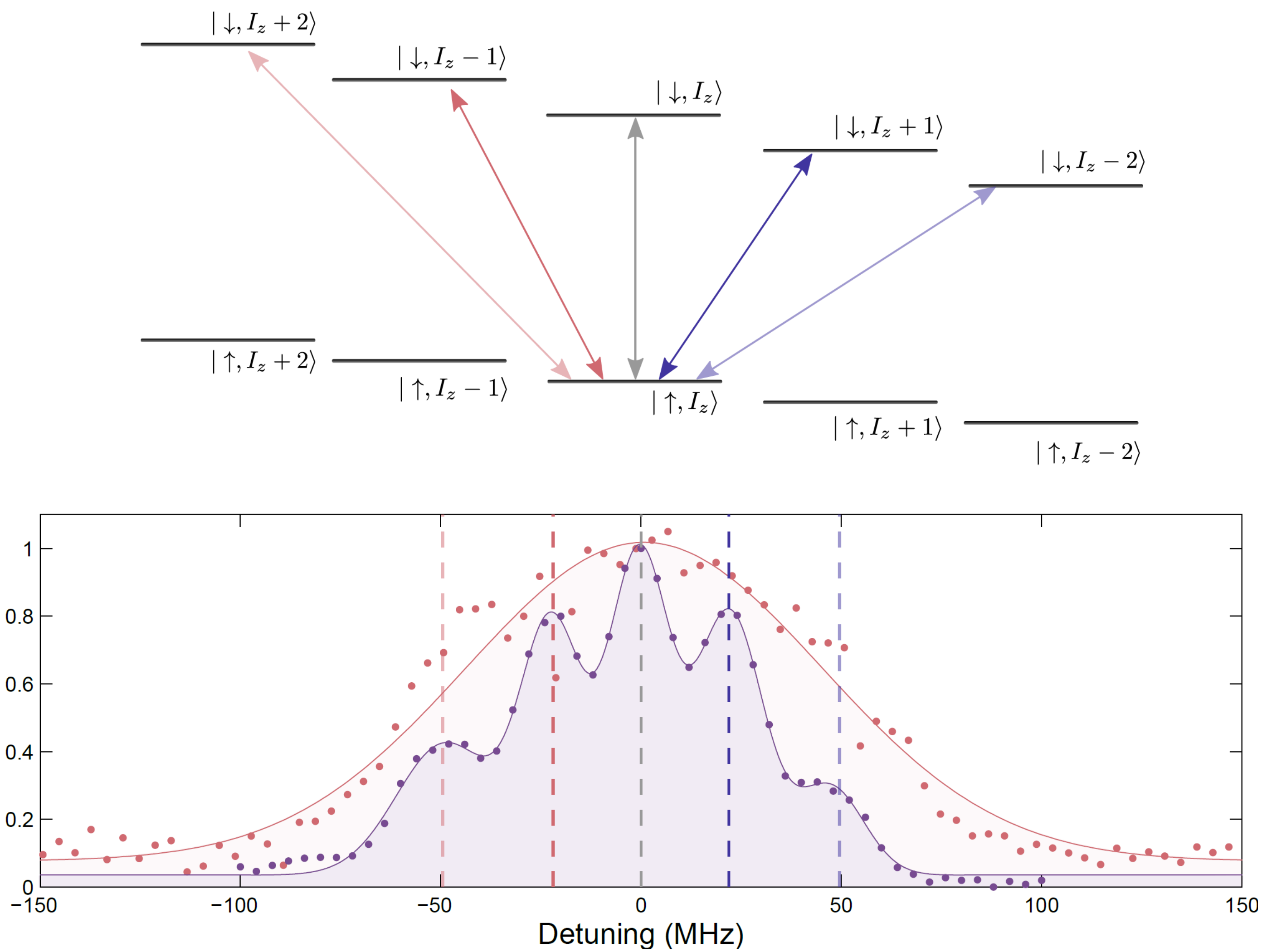
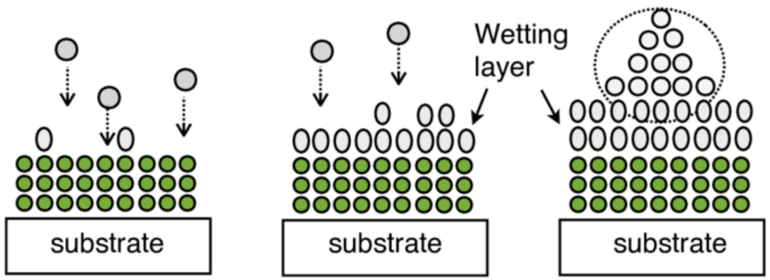
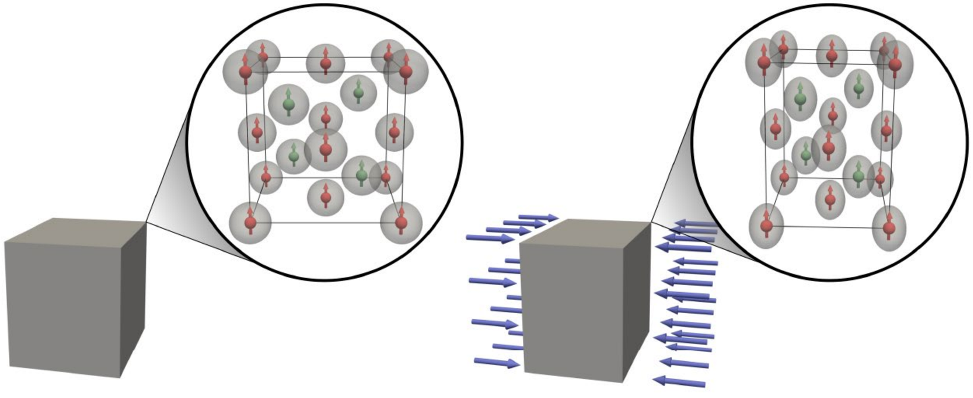
probing the single-spin excitation spectrum of the nuclei

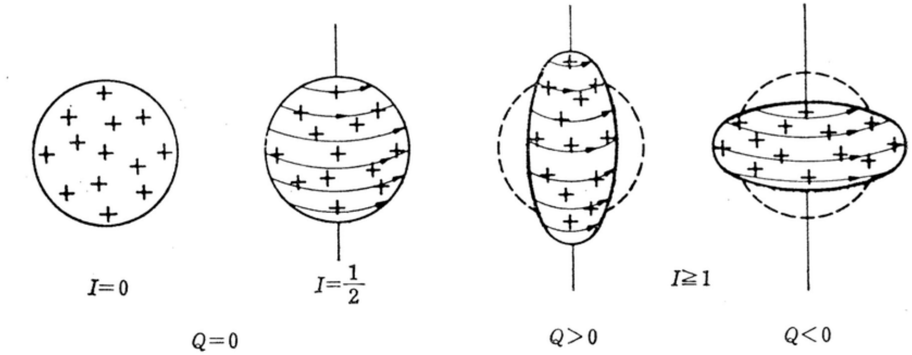


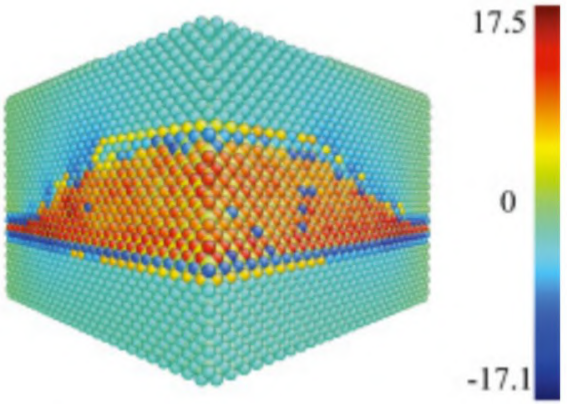
Gangloff *et al.*, Science 364, 62 (2019).

the role of strain on electro-nuclear interactions

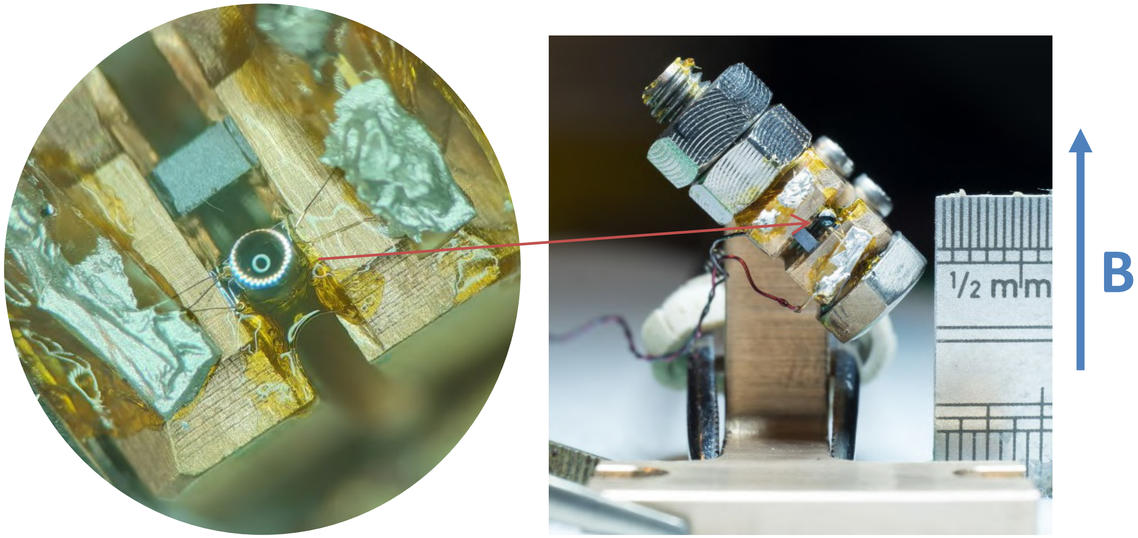








first optical cooling of the nuclei in GaAs QDs

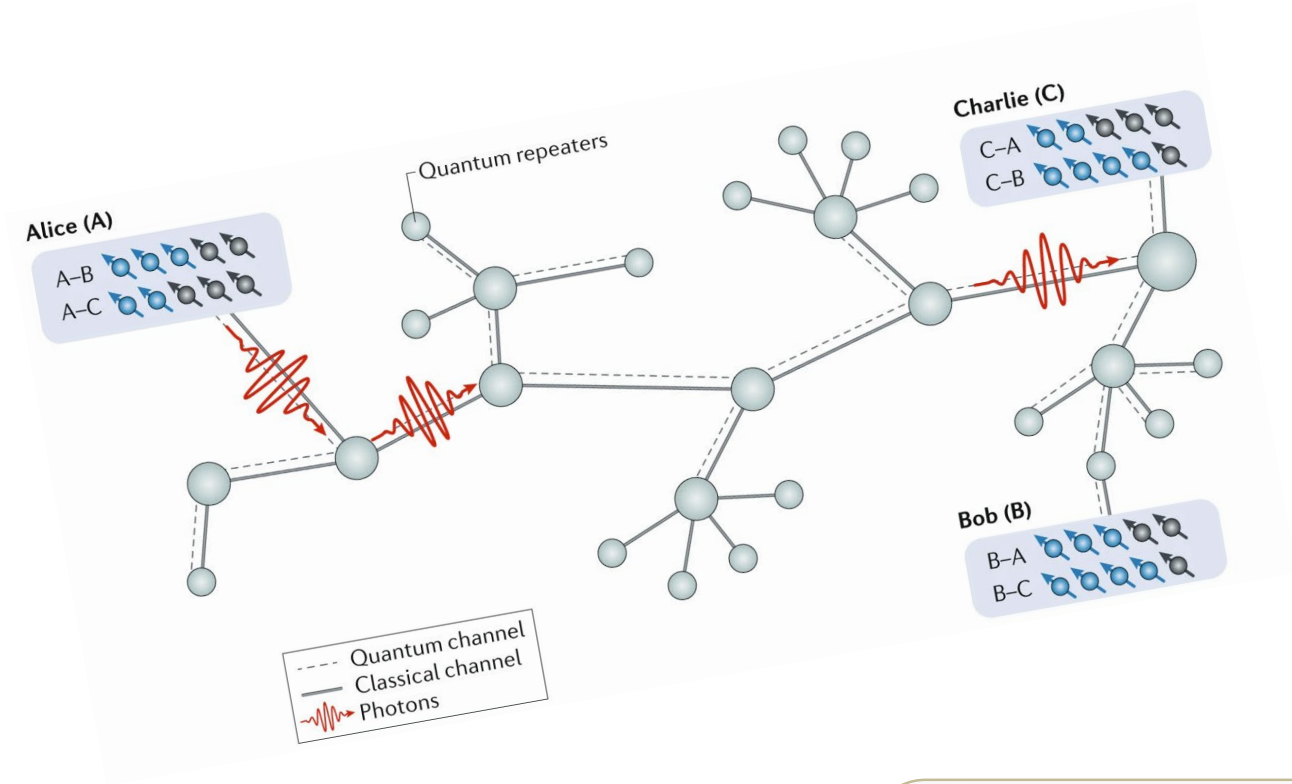


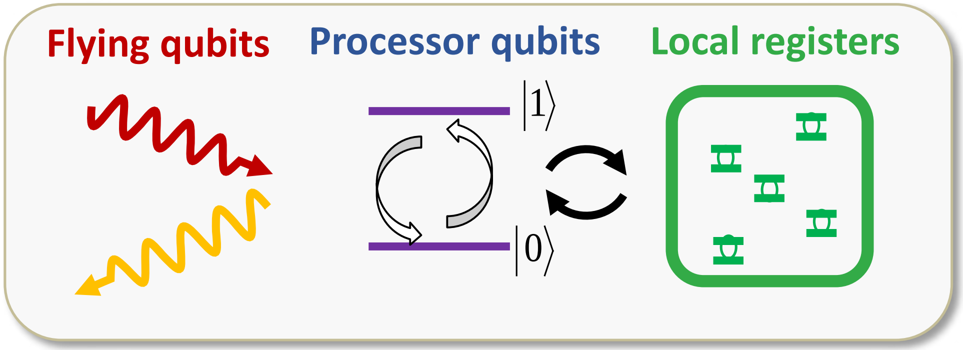
Attempt to induce homogeneous strain.

Up to 120 kHz quadrupolar shift

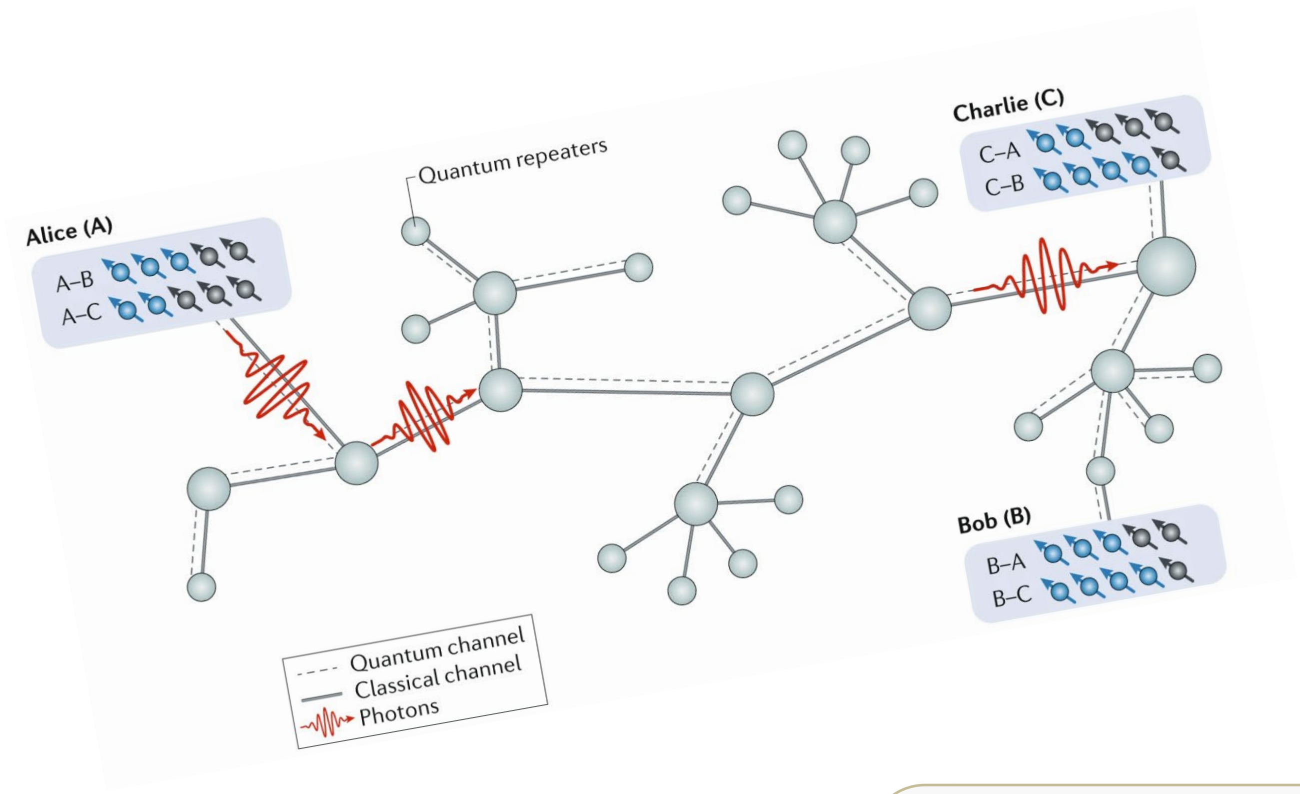
(many GaAs QD devices were harmed in the making of this research)

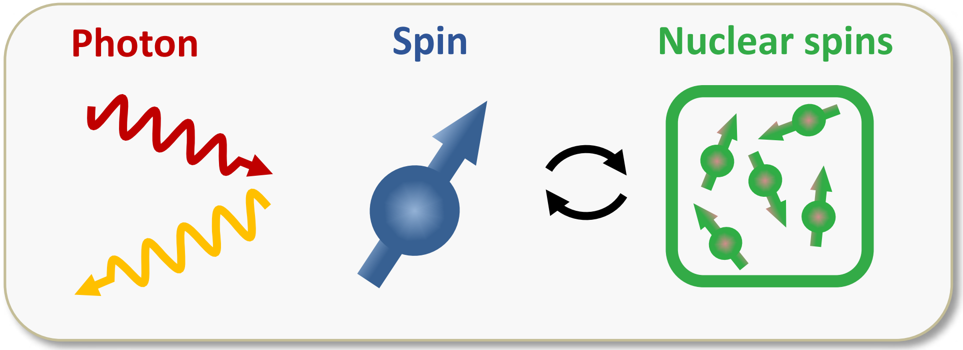
quantum nodes in a network



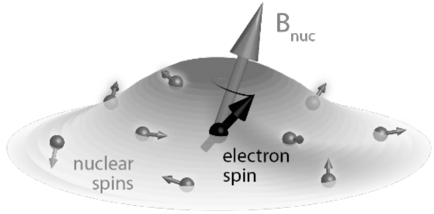


quantum nodes in a network





electronuclear interactions



Zeeman

$$\hat{H} = \underline{\omega_e \hat{S}_z} + \sum_i \omega_i \hat{I}_z^{(i)}$$

Collinear hyperfine

$$+ \underline{\hat{S}_z \sum_i a_\parallel^{(i)} \hat{I}_z^{(i)}}$$

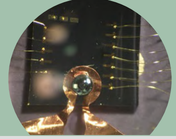
(T2* limit)

Non-collinear hyperfine

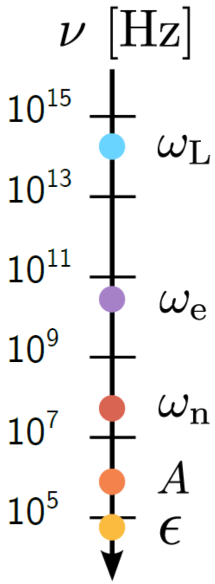
$$+ \hat{S}_z \sum_i a_\perp^{(i)} \hat{I}_x^{(i)} = \hat{S}_z \sum_i \underline{a_\perp^{(i)} (\hat{I}_+^{(i)} + \hat{I}_-^{(i)})/2}$$

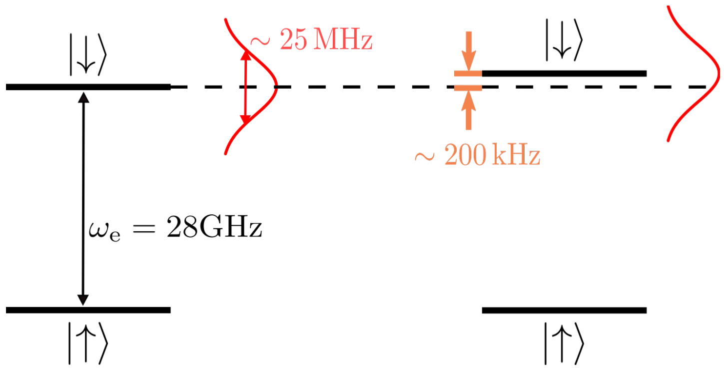
Three-body interaction

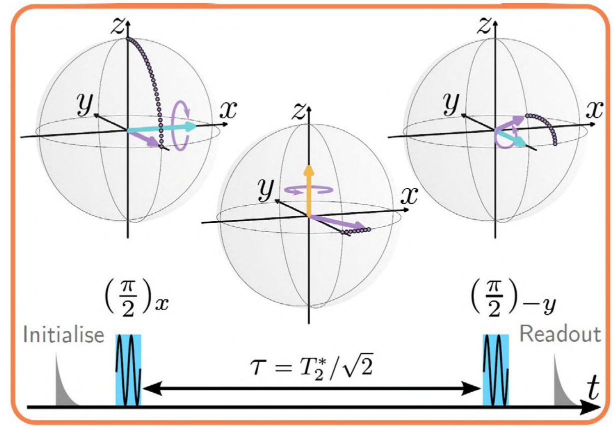
$$+ \hat{S}_z \sum_{i,j} \frac{a_i a_j}{2\omega_e} \underline{\left(\hat{I}_x^{(i)} \hat{I}_x^{(j)} + \hat{I}_y^{(i)} \hat{I}_x^{(j)} \right)} = \hat{S}_z \sum_{i,j} \frac{a_i a_j}{4\omega_e} \left(\hat{I}_+^{(i)} \hat{I}_-^{(j)} + \hat{I}_-^{(i)} \hat{I}_+^{(j)} \right)$$



Sensing: Full experimental sequence

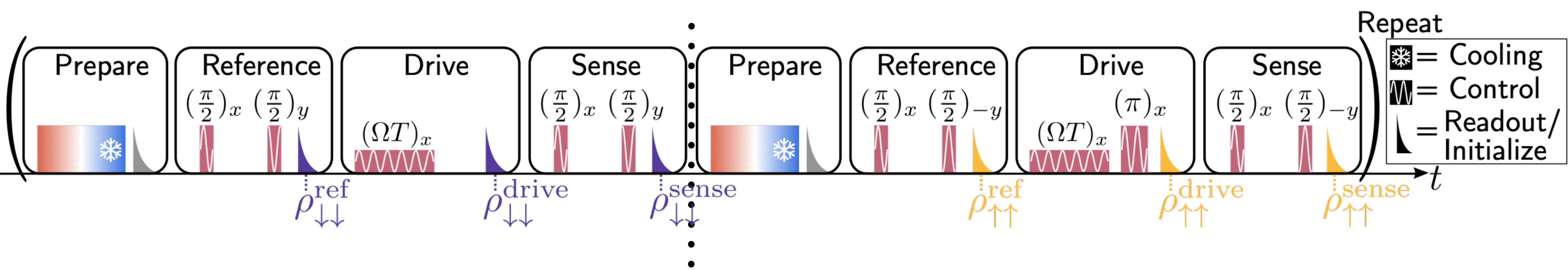






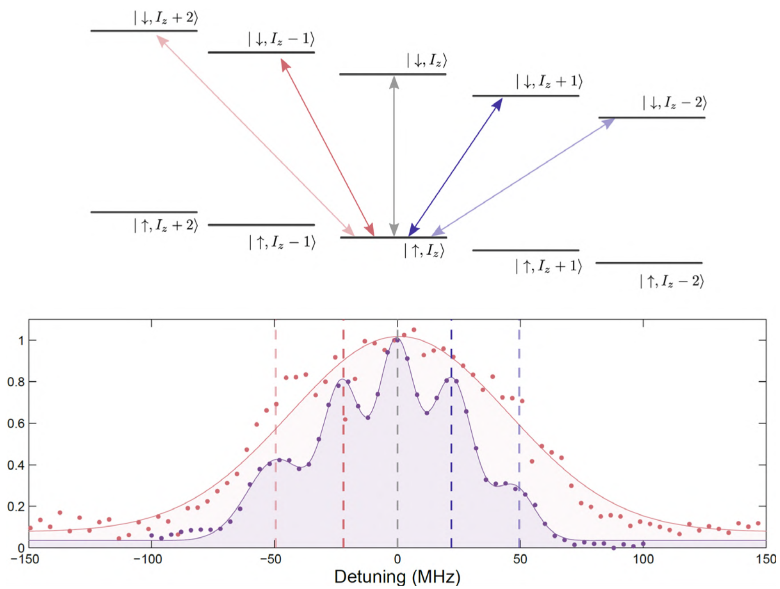
Frequency shift detected via Ramsey Interferometry

Electron spin becomes a sensor with 1.9 ppm sensitivity

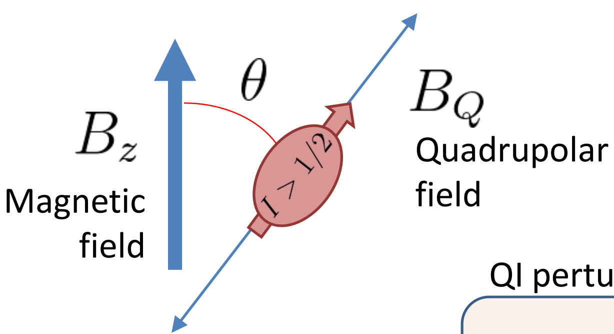


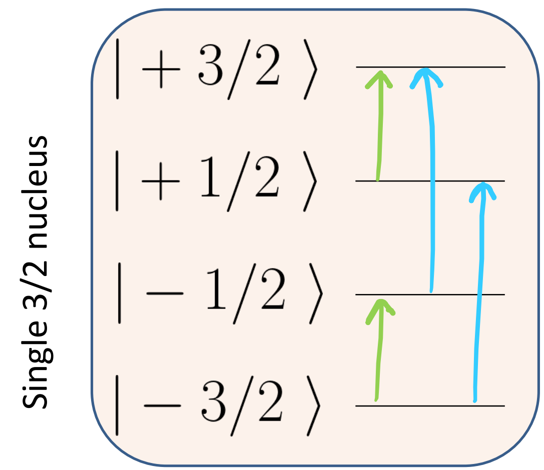
$$\Delta\omega_D = \Delta\omega_{\mathrm{sense}} - \Delta\omega_{\mathrm{ref}}$$

strain-enabled non-colinear hyperfine interaction



$$H^{nc}_{\mathrm{e-nuc}} = \sum_i A^{nc}_1 (S_z (I^i_x I^i_z + I^i_z I^i_x)) + \sum_i A^{nc}_2 (S_z (I^{i2}_x - I^{i2}_y))$$





QI perturbs axis of the e-nuc HI

$$A^{nc}_1 = A_z \frac{B_Q}{B_z} \sin(2\theta)$$