TATA INSTITUTE OF FUNDAMENTAL RESEARCH

HYDERABAD

Towards a microwave quantum memory based on an ensemble of electron spins

Vishal Ranjan

QEC → practical quantum computing



- Quantum superposition and entanglement are lost due to decoherence
- A quantum state cannot be cloned → QEC

Quantum error correction below the surface code threshold

Google Quantum AI and Collaborators

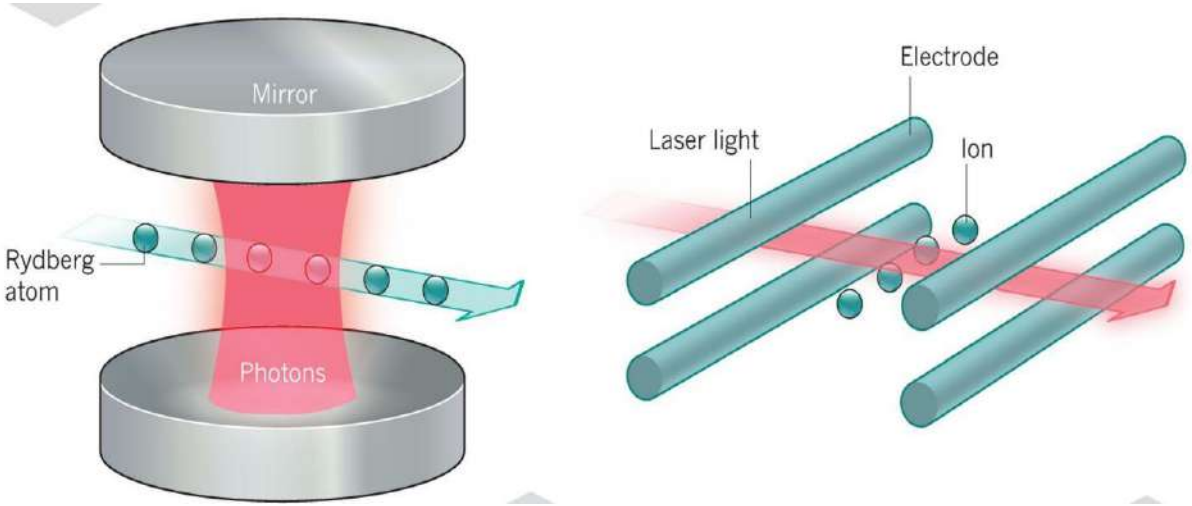
Nature **638**, 920–926 (2025) | Cite this article

Save article

323k Accesses | **1234** Citations | **2471** Altmetric | Metrics

Combining best of two worlds

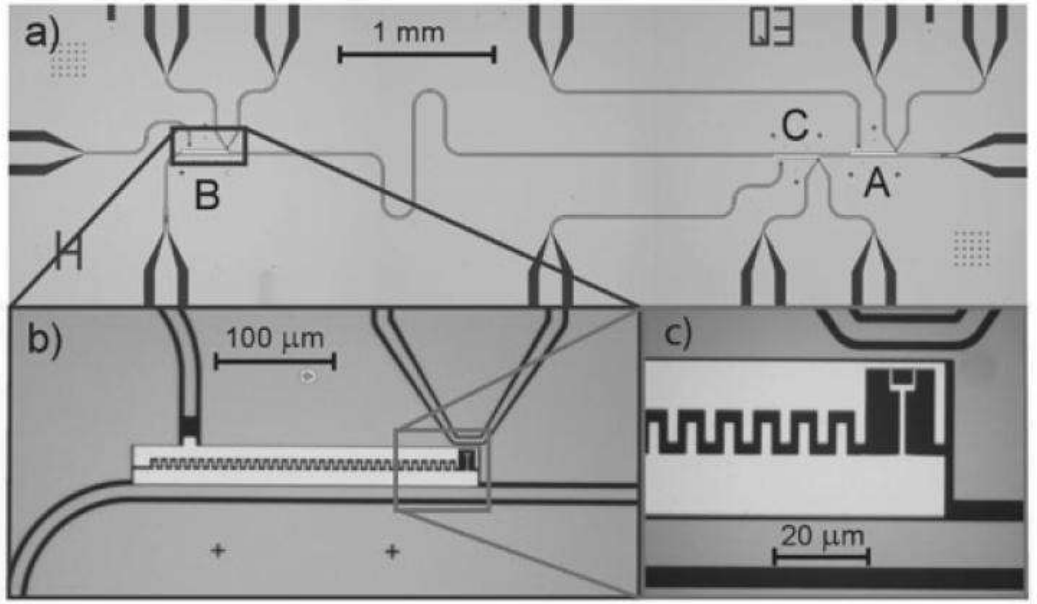
Natural atoms





David Wineland, Serge Haroche
2012

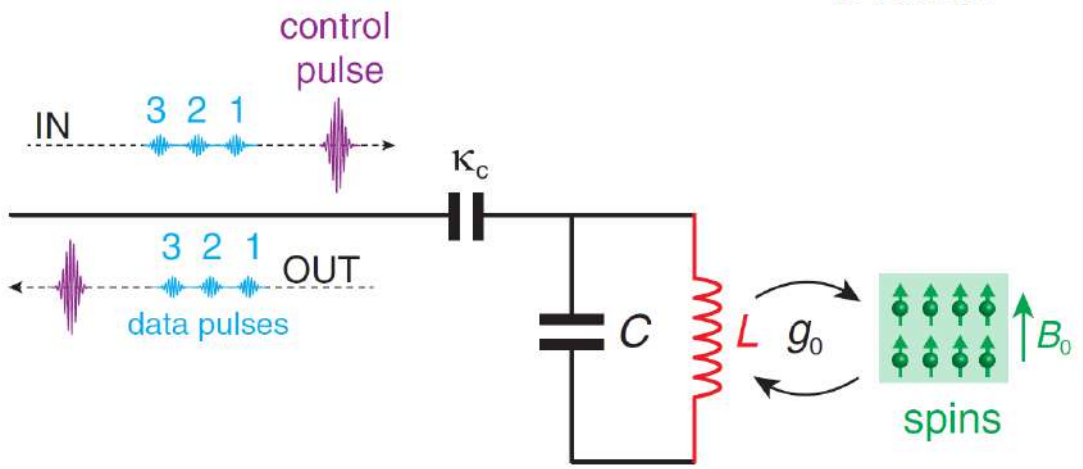
Artificial atoms





John Clarke, Michel Devoret,
John Martinis, 2025

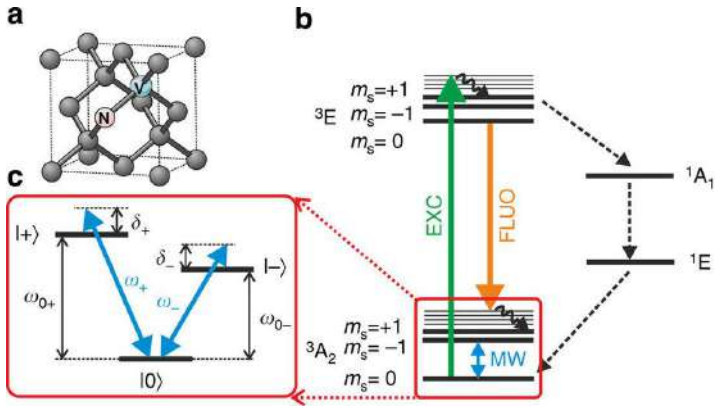
Electron spins based QM – challenges



- Optimal spin readout [1]
- Efficient storage of photons
- Optimal control pulses
- Random access of storage and retrieval [2]
- Unit efficiency of storage and retrieval [3]

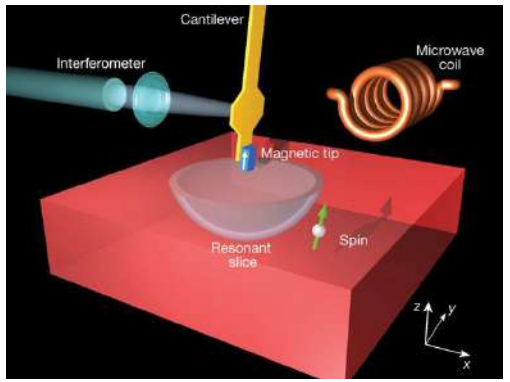
[1] J. Morton and P. Bertet, JMR, **287**, 128 (2018)
[2] O'Sullivan et al, PRX (2022)
[3] Afzelius, New J Physics, **15**, 065008 (2013)

Boosting ESR sensitivity



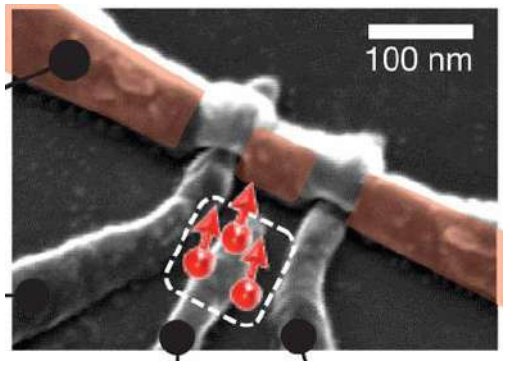
Optically detected ESR

Nature **363**, 244 (1993), Nat. Com. **5**, 4870 (2014)
Nat. Nano. **9**, 279 (2014)



Force detected ESR

Nature **430**, 329 (2004)

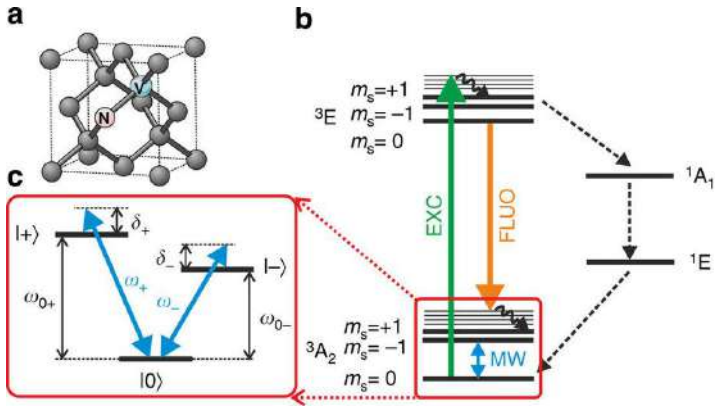


Electrically detected ESR

Rev. Sci. Instr. **83**, 043907 (2012), Nature **467**, 687 (2010)

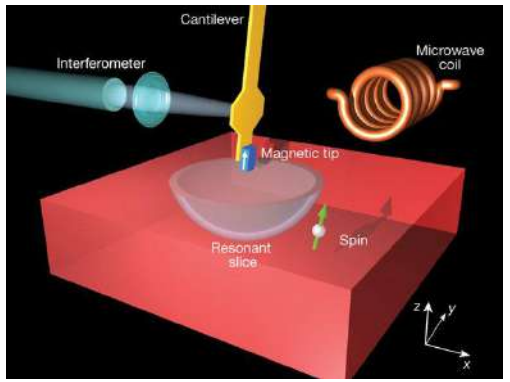
What is common across these readouts?

Boosting ESR sensitivity



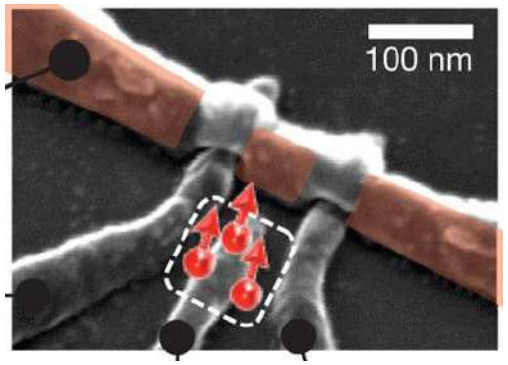
Optically detected ESR

Nature **363**, 244 (1993), Nat. Com. **5**, 4870 (2014)
Nat. Nano. **9**, 279 (2014)



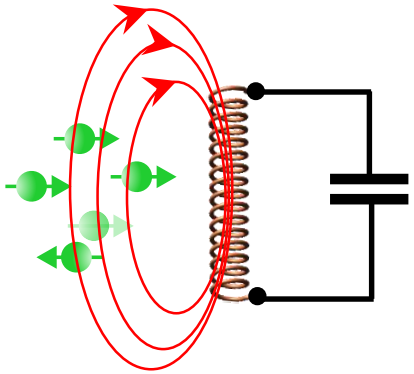
Force detected ESR

Nature **430**, 329 (2004)



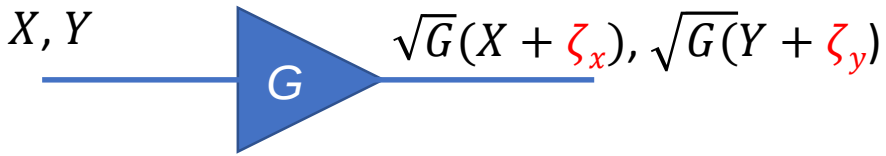
Electrically detected ESR

Rev. Sci. Instr. **83**, 043907 (2012), Nature **467**, 687 (2010)



ESR with cQED, $k_B T << \hbar\omega_0$

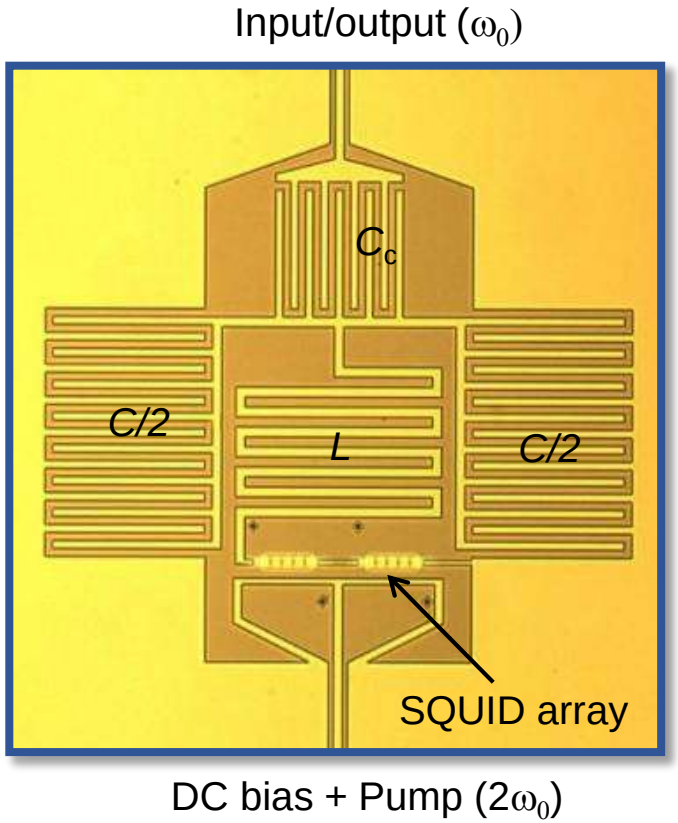
Spin readout: quantum amplifiers



All classical amplifiers (dissipative) add noise ζ to incoming signal

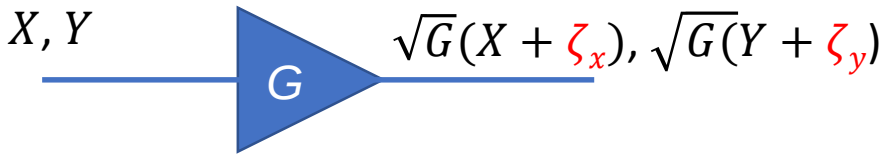
$$X, Y = \text{Real}(Ae^{i\theta}),\ \text{Imag}(Aei^{\theta})$$

Josephson parametric amplifiers use superconducting circuits, are thus are dissipation less, only limited by Heisenberg uncertainty



X. Zhou et al., PRB **89**, 214517 (2014)
A. Roy and M. Devoret, Compte Rendus Physique **17**, 7 (2016)

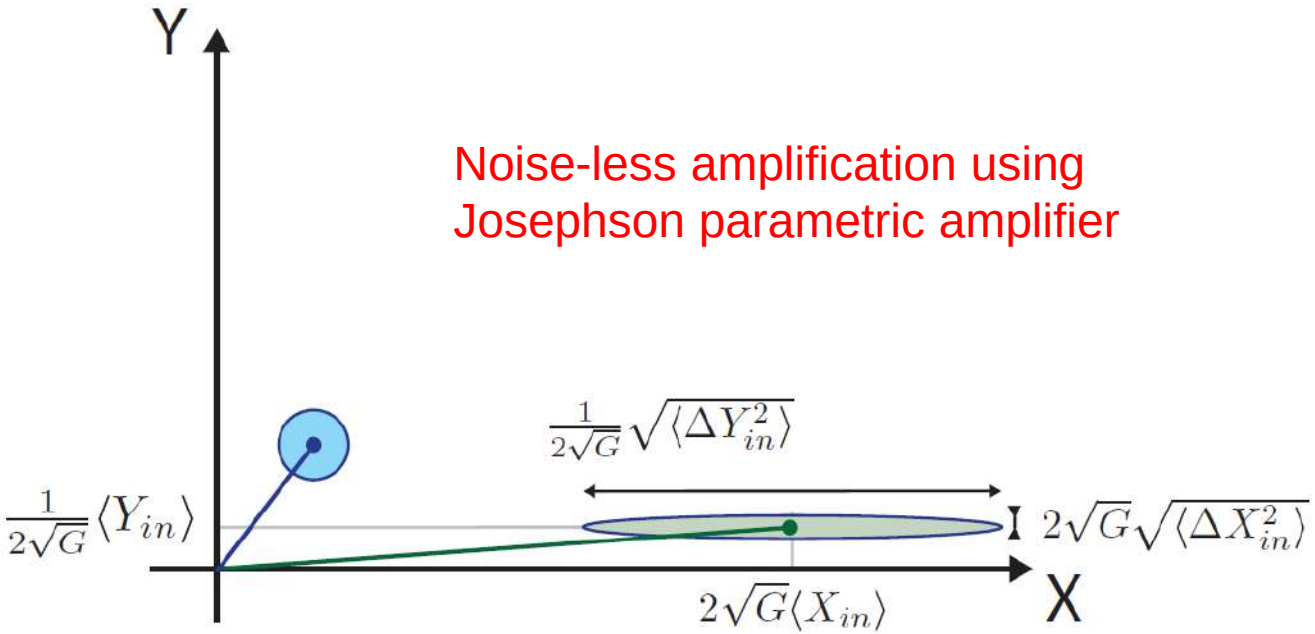
Spin readout: quantum amplifiers



$$X, Y = \text{Real}(Ae^{i\theta}),\ \text{Imag}(Aei^{\theta})$$

Heisenberg's uncertainty principle

$$\langle \Delta \hat{X}^2 \rangle \langle \Delta \hat{Y}^2 \rangle \geqslant \frac{1}{16}$$

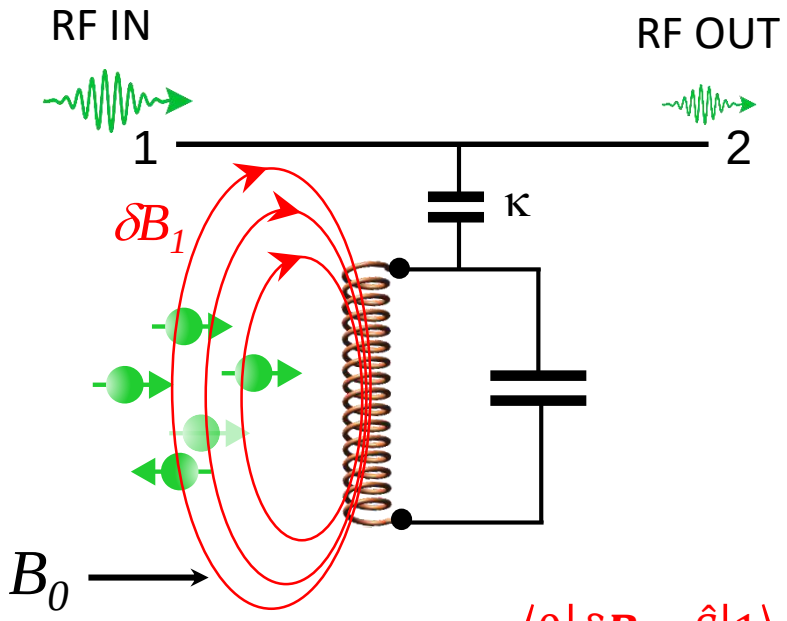


Noise-less amplification using Josephson parametric amplifier

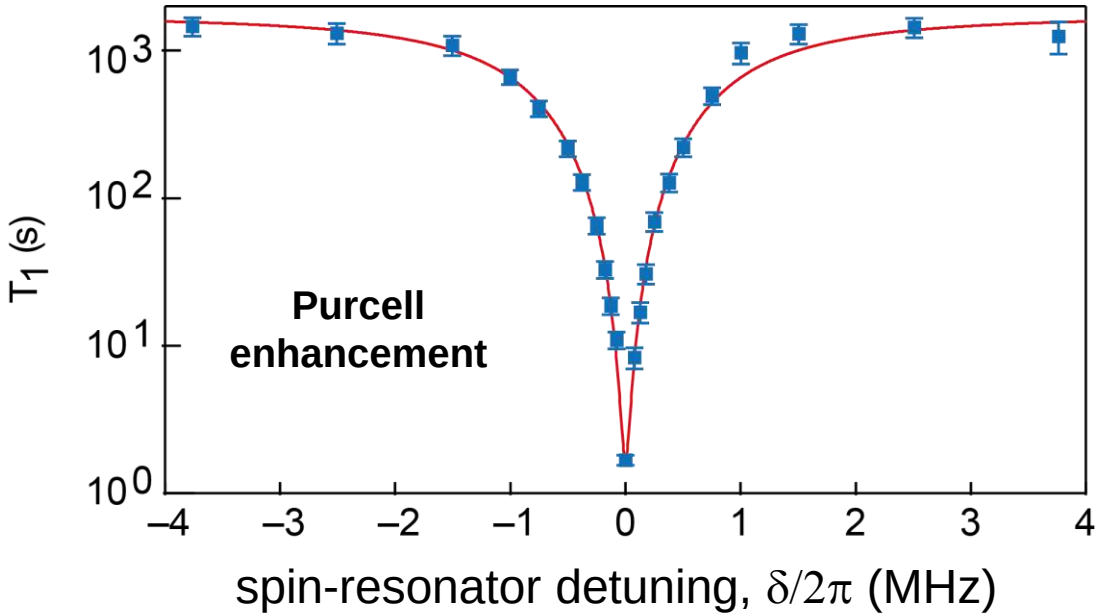
Sensitivity ~ 10 - 100 spins/√Hz [1, 2]

[1] VR et al., APL **116**, 184002 (2020)
[2] VR *et al*., PRX **11**, 031036 (2021)
[3] A. Bienfait et al, Nat Nanotech **11**, 253 (2016)

Microresonators: Radiative spin relaxation



$$g = \gamma_e \langle 0 | \delta \boldsymbol{B}_1 \cdot \hat{S} | 1 \rangle$$



$$\Gamma_{\mathrm{P}} = \kappa \frac{g^2}{\kappa^2/4 + \delta^2}$$

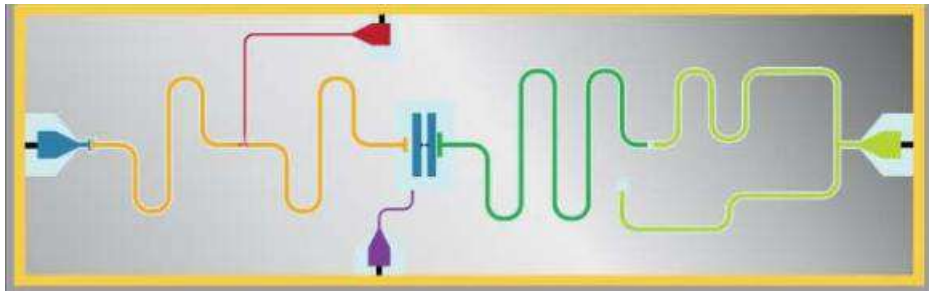
$g/2\pi$ ~ 100 Hz,
ω/κ ~ 10^5
→ $T_1(\delta=0)$ ~ 1s [1]

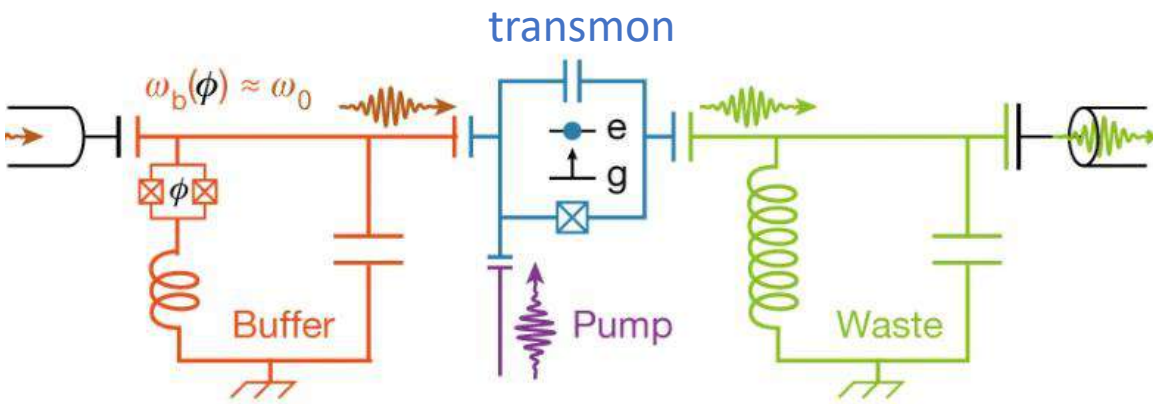
engineered fast repetition rate[1]

→ T_1 as low as 1ms demonstrated [2]

[1] A. Bienfait et al., Nature **531**, 74 (2016)
[2] VR et al., APL **116**, 184002 (2020)

Spin readout: Single photon detectors





$\omega_b + \omega_p \rightarrow \omega_q + \omega_w$

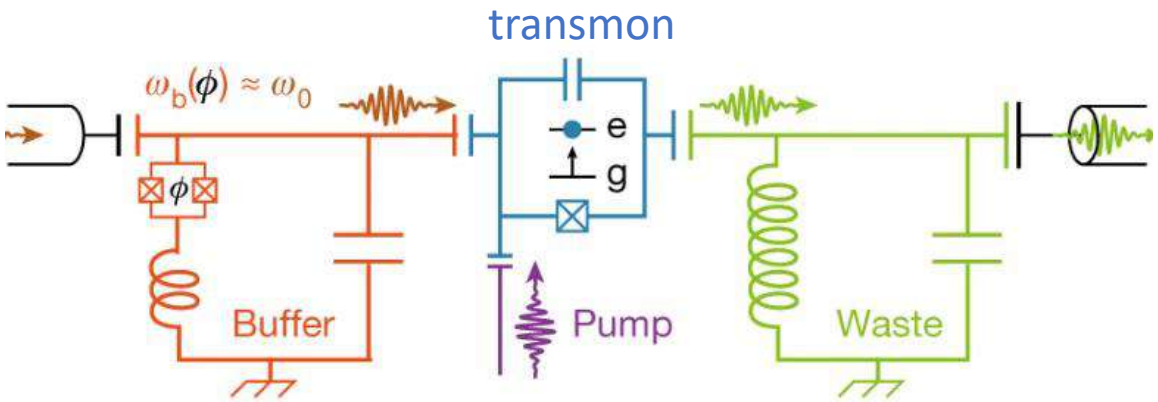
$\omega_b + \omega_p \not\rightarrow \omega_q + \omega_w$

Quickly dissipated

[1] E. Albertinale, … VR et al., Nature **600**, 434 (2021)

Spin readout: Single photon detectors

Fluorescence detected spins at GHz frequencies [1]
→ Single electron detection [2]
→ Single nuclear spin detection [3]

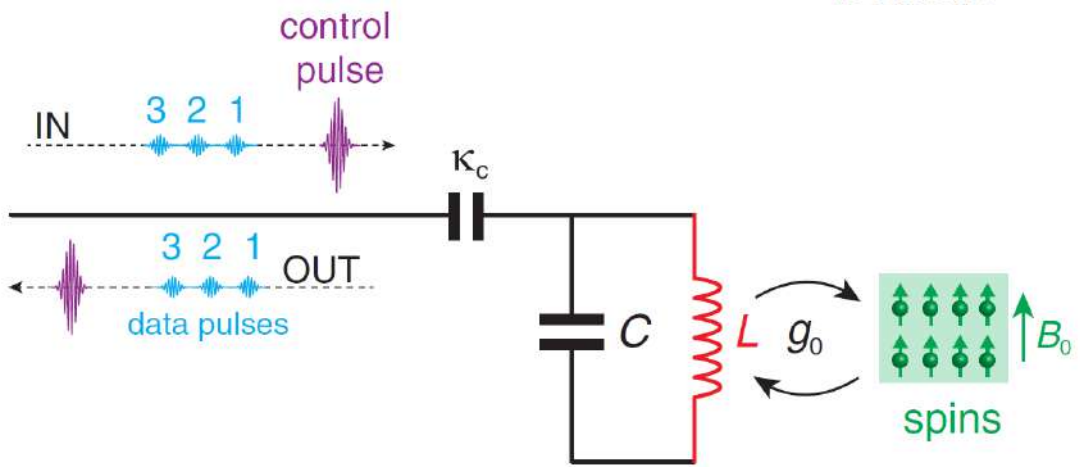


Heisenberg's uncertainty principle

$$\Delta n \Delta \varphi \geq \frac{1}{2}$$

[1] E. Albertinale, … VR et al., Nature **600**, 434 (2021)
[2] Z. Wang et al Nature **619**, 276 (2023)
[3] J. Travesedo et al., Sci. Adv. 11, eadu0581 (2025)

Electron spins based QM – challenges

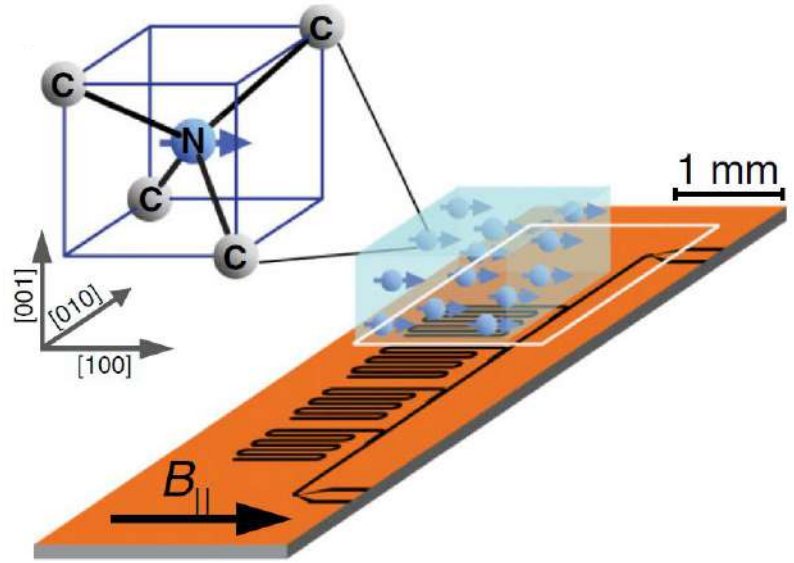


- Optimal spin readout [1]
- Efficient storage of photons
- Optimal control pulses
- Random access of storage and retrieval [2]
- Unit efficiency of storage and retrieval [3]

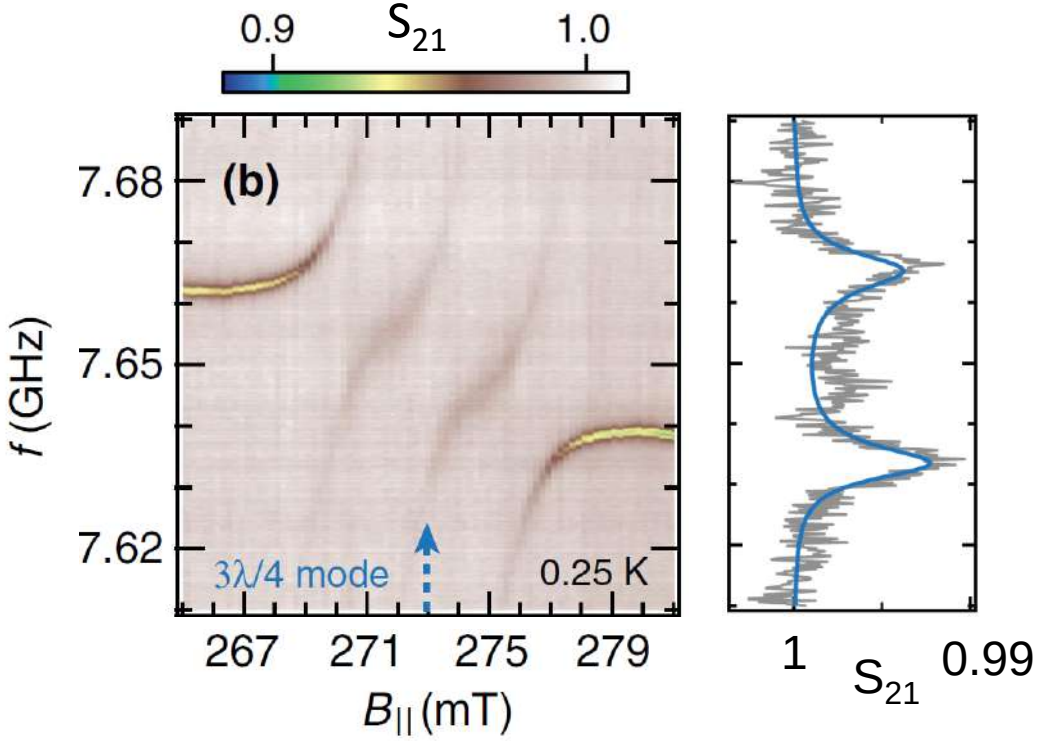
[1] J. Morton and P. Bertet, JMR, **287**, 128 (2018)
[2] O'Sullivan et al, PRX (2022)
[3] Afzelius, New J Physics, **15**, 065008 (2013)

Strong coupling

200 ppm P1 centres



NbTiN resonators



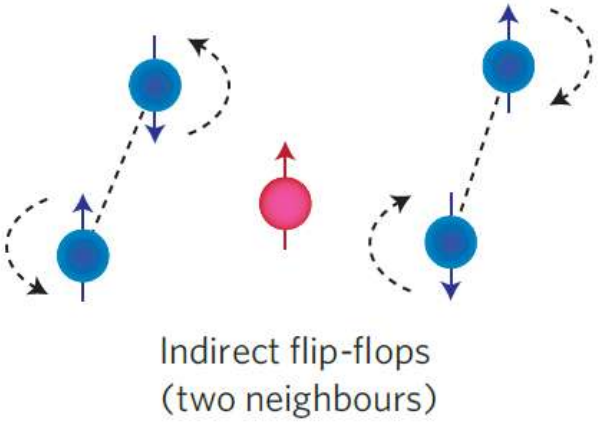
$$|\mathrm{W}\rangle = \frac{1}{\sqrt{n}}(|100...0\rangle + |010...0\rangle + \ldots + |00...01\rangle)$$

→ g√n scaling

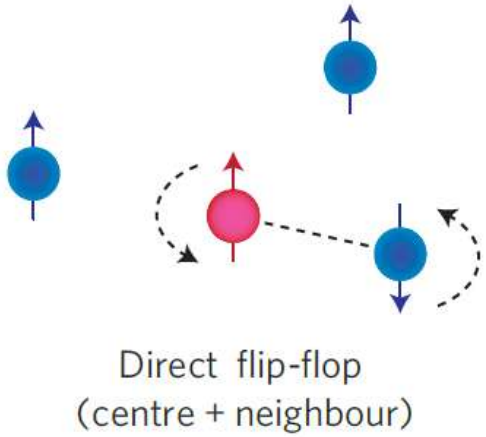
$g_{ens}/2\pi$ = 24 MHz, $\Gamma/2\pi$ = 12 MHz

VR et al., PRL **110**, 067004 (2013)

Spin concentration and coherence



any spin species



same spin species

Flip-flops→ fluctuating field → low T_2

Tyryshkin et al., Nature materials **11**, 143 (2012)

Suppressing magnetic noise: clock transitions

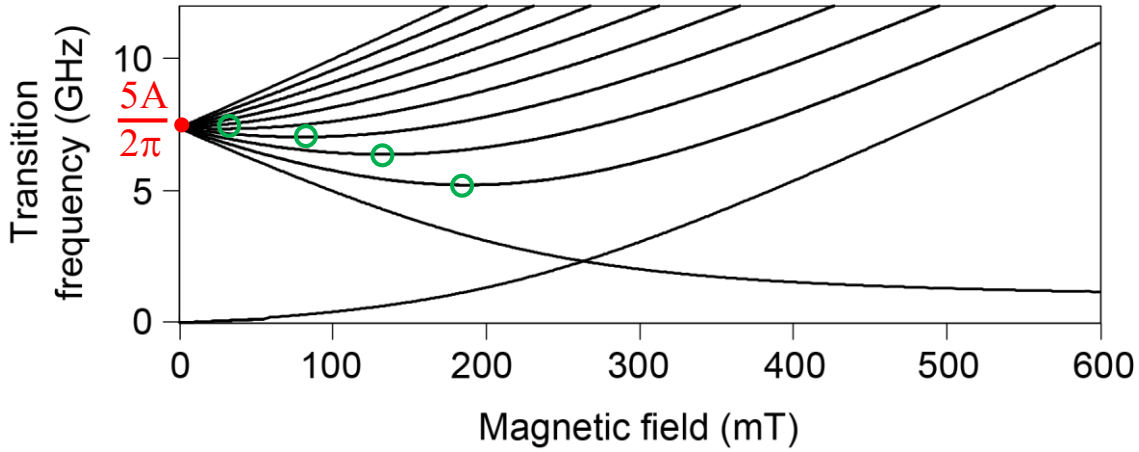


$$H/\hbar = -\boldsymbol{B}_0 \cdot (\gamma_e \boldsymbol{S} + \gamma_n \boldsymbol{I}) + A\, \boldsymbol{S} \cdot \boldsymbol{I}$$

Zeeman hyperfine

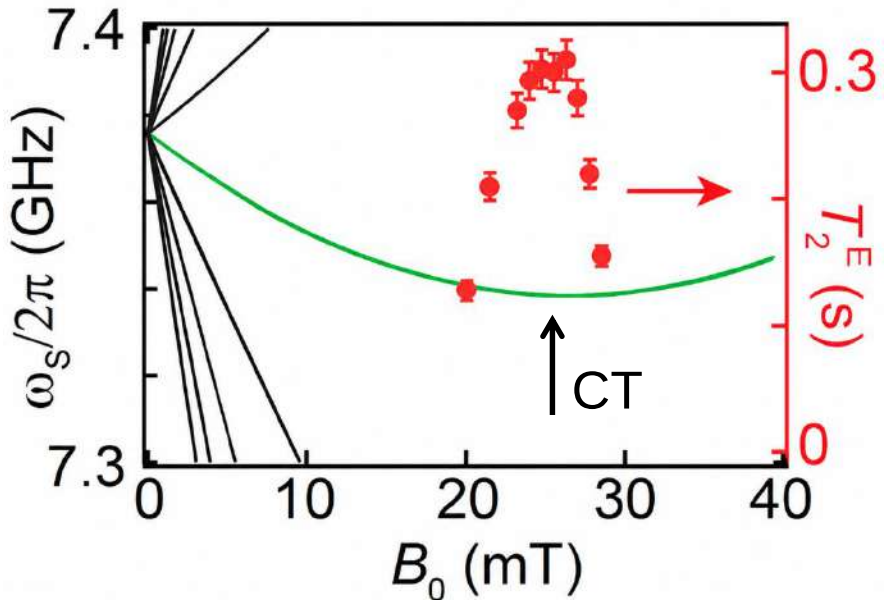
$$S = 1/2,\ I = 9/2$$
$$F = |S \pm I|$$

$A/2\pi$ = 1.47 GHz



G. Feher, Phys. Rev. **114**, 1219 (1959).

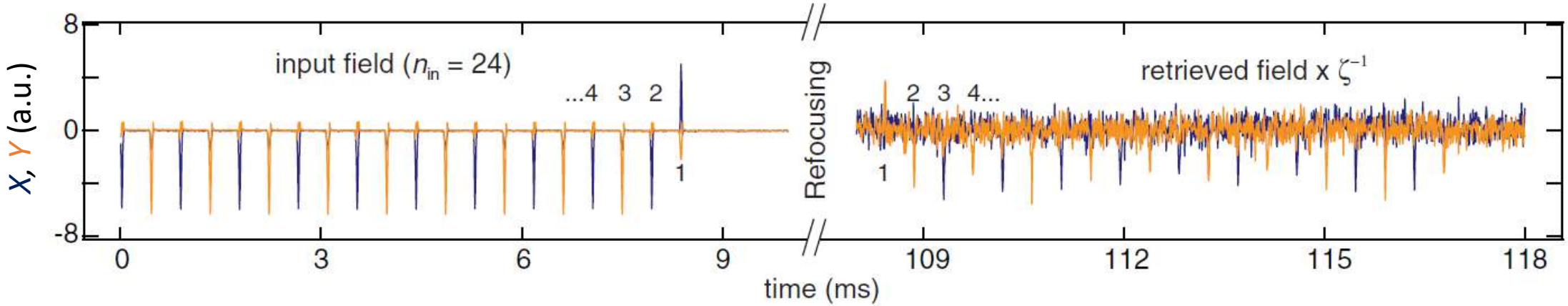
Clock transition in Bi:Si



- Clock transition (CT) → insensitive to indirect flip-flops and instantaneous diffusion
- T2 extended to ~1 second using 8 CPMG π pulses

VR et al., PRL **125**, 210505 (2020)
G. Wolfowicz et al, Nature Nano **8**, 561 (2013)

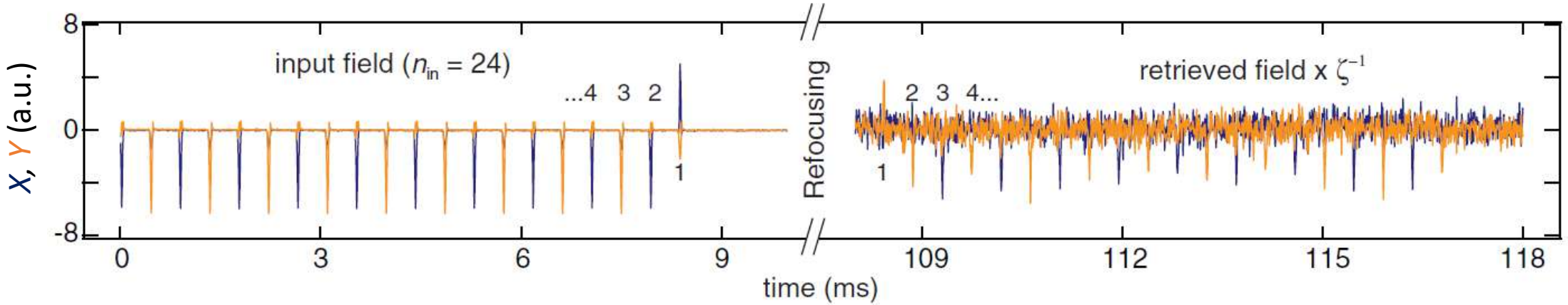
Hahn echo based QM



- ζ = 0.04 [field retrieval efficiency]
- 0.03 photons per echo

VR et al., PRL **125**, 210505 (2020)

Hahn echo based QM

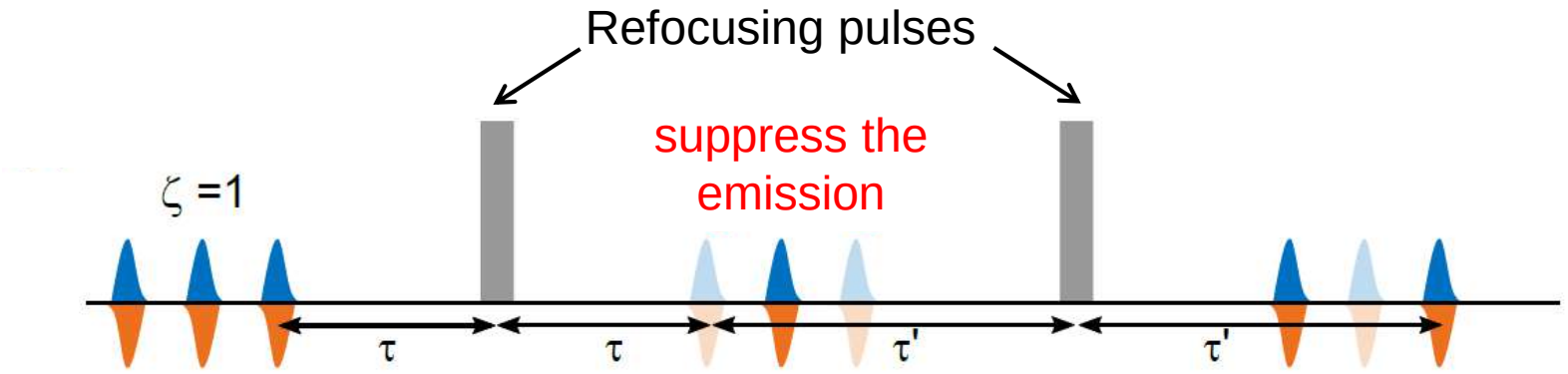


Problems:

1) All states retrieved as first-in/last-out
2) Refocusing pulse inverts the population of the spins → noise on the retrieved states

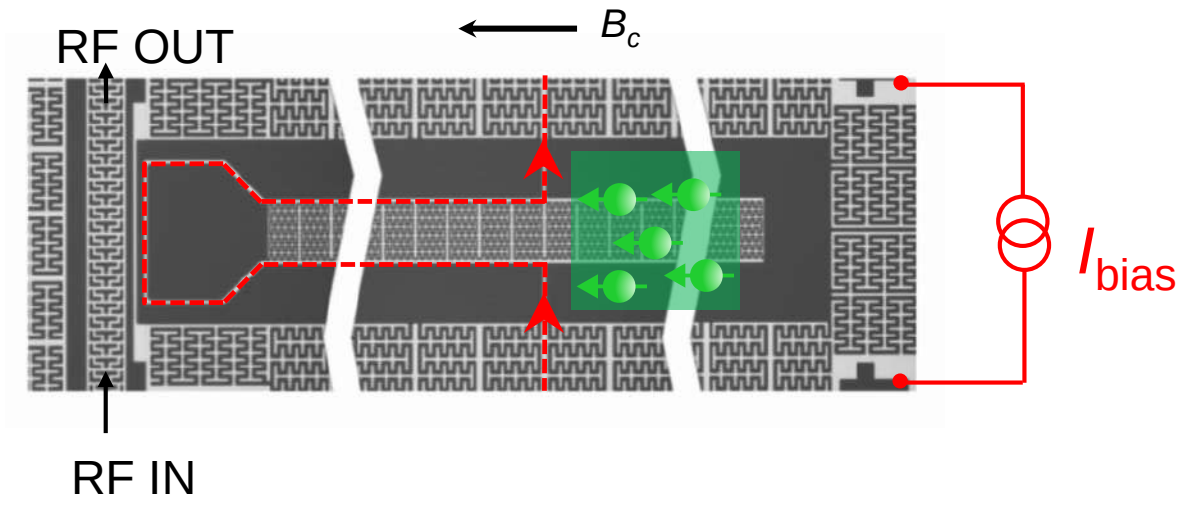
Damon et al., New J. Phys. **13**, 093031 (2011)
Afzelius at al., New J Phys, **15**, 065008 (2013)

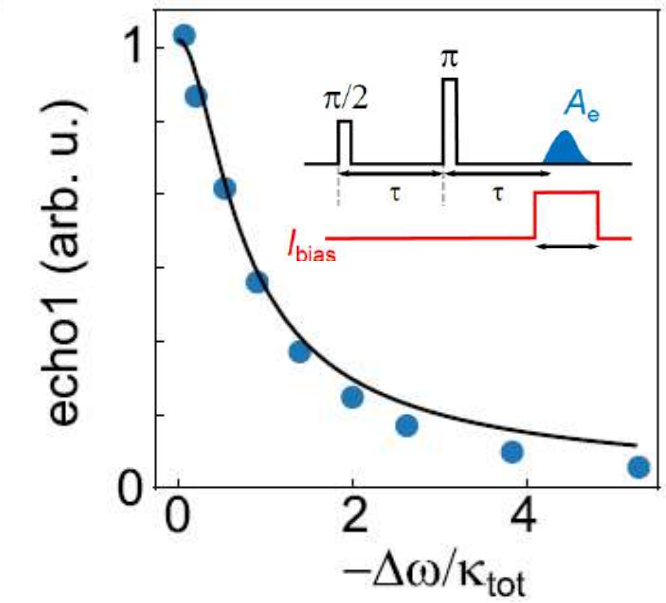
Random access with 100% efficiency



Unit efficiency → cooperativity $= \frac{4g_{ens}^2}{\kappa\Gamma} = 1$

Echo silencing with resonator tuning





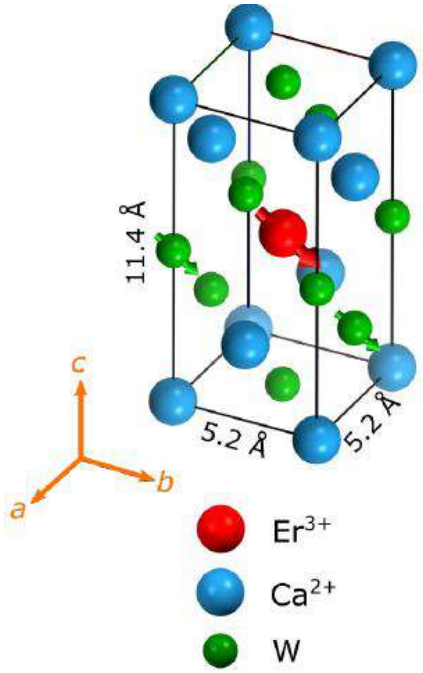
different I_{bias} → different kinetic inductance of the superconductor
→ different resonance frequency

100% efficiency not reached in this sample

VR *et al*, PRL **129**, 180504 (2022).

Interlude: move to TIFRH

Present lab: Er^{3+} in $CaWO_4$



- Presence of clock transitions at ~3.5 GHz
- Microwave to optical conversion in the telecom band [1]
- T_2 approaching 20 ms in natural crystals: 1ppb concentration[2]

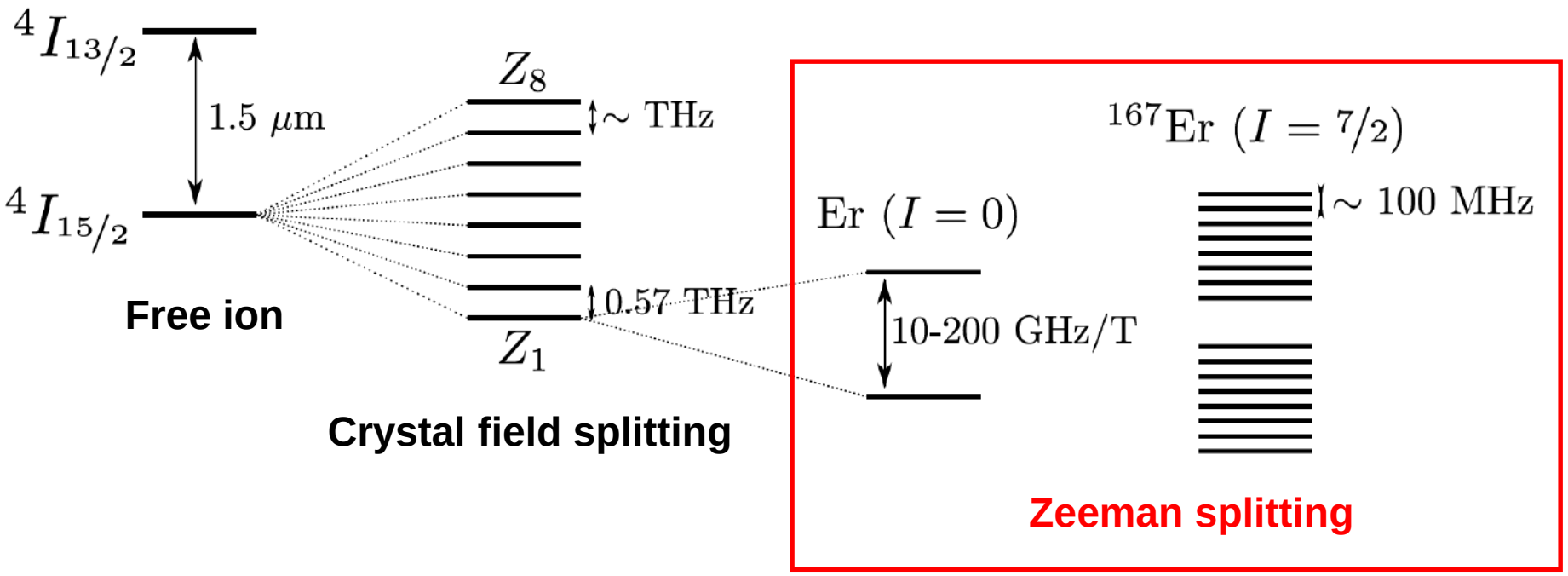
Er: [Kr] $4d^{10}\ 5s^2\ 5p^6\ 4f^{12}\ 6s^2$

↓ 3+

Er^{3+}: [Kr] $4d^{10}\ 5s^2\ 5p^6\ 4f^{11}$

[1] E. Saglamyurek et al., Nat Phot, 9, 83 (2015)
[2] M. Le Dantec et al., Science Adv, abj9786 (2021)

Er^{3+} in $CaWO_4$



$^{2S+1}L_J$ = Russell Saunders notation

[1] E. Saglamyurek et al., Nat Phot, 9, 83 (2015)
[2] M. Le Dantec et al., PhD Thesis 2021

Spin eigenstates

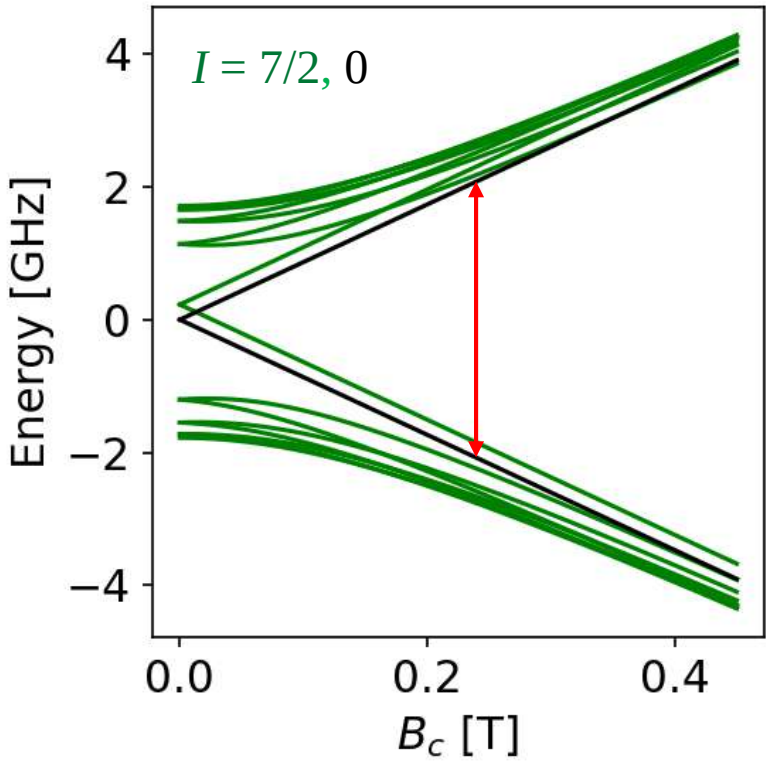
$$H/\hbar = -\boldsymbol{B_0}\cdot(\gamma_e \boldsymbol{S} + \gamma_n \boldsymbol{I}) + A\, \boldsymbol{S}\cdot\boldsymbol{I}$$

Zeeman hyperfine

$S_{\text{eff}} = 1/2, \quad I = 0 \text{ or } 7/2$

$A_{ab} = 0.87$ GHz, $A_c = 0.13$ GHz

$g_{ab} = 8.38$, $g_c = 1.25$



g-factor anisotropy

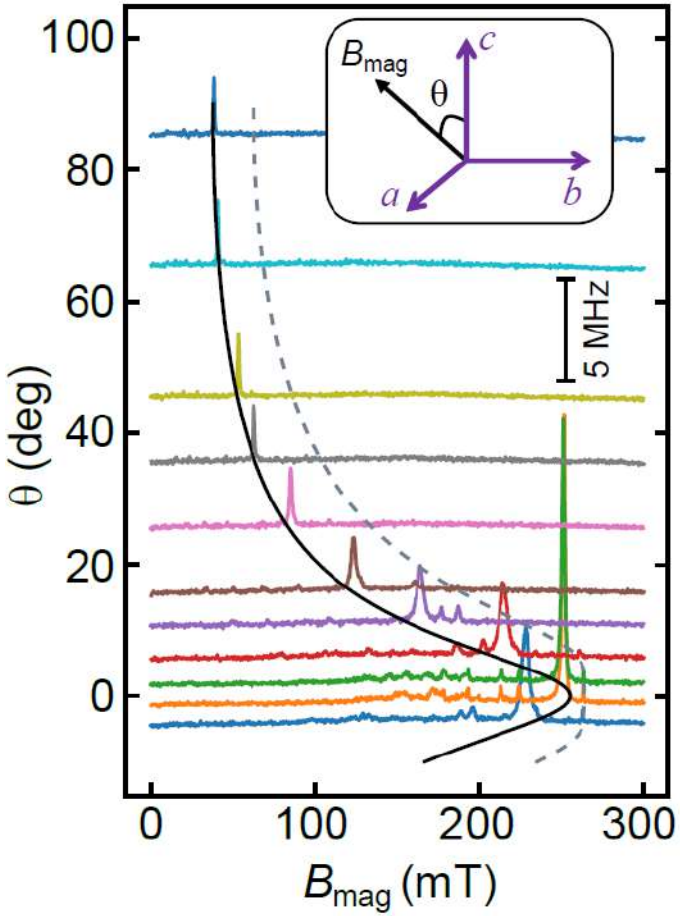
$$H/\hbar = -\boldsymbol{B_0}\cdot(\gamma_e \boldsymbol{S} + \gamma_n \boldsymbol{I}) + A\,\boldsymbol{S}\cdot\boldsymbol{I}$$

Zeeman hyperfine

$S_{\text{eff}} = 1/2, \quad I = 0$ or $7/2$

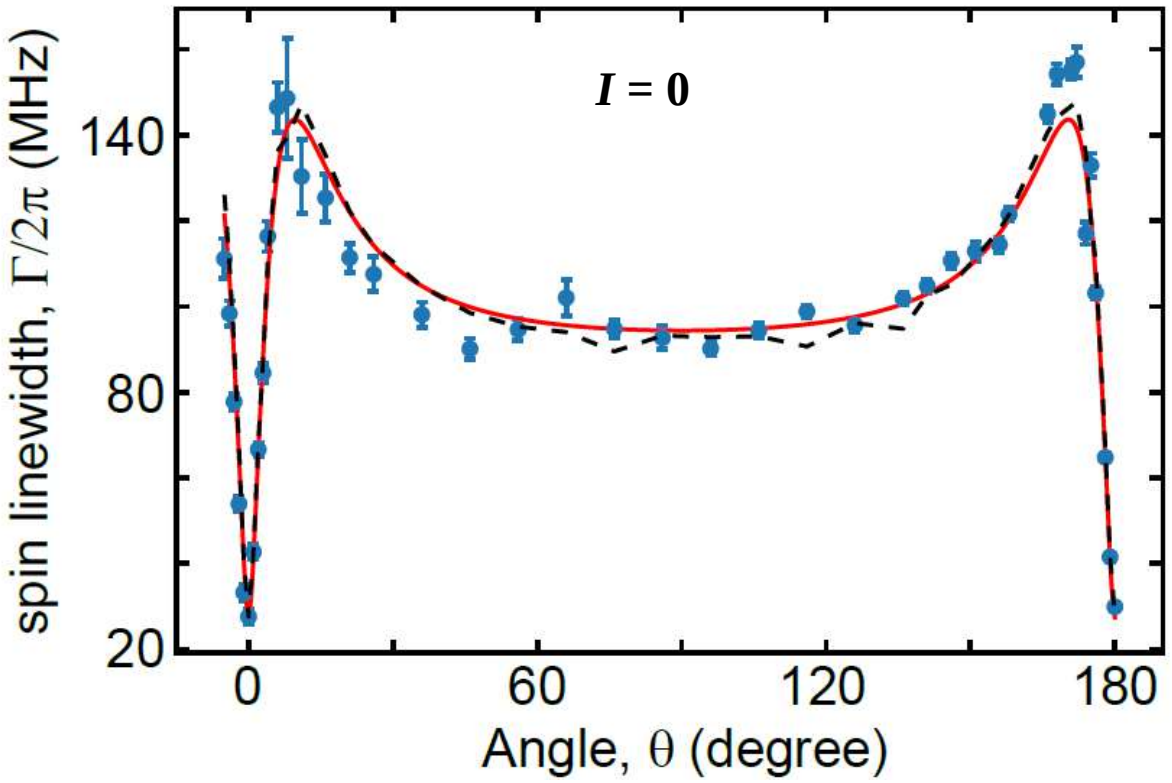
$A_{\text{ab}} = 0.87$ GHz, $A_{\text{c}} = 0.13$ GHz

$g_{\text{ab}} = 8.38$, $g_{\text{c}} = 1.25$



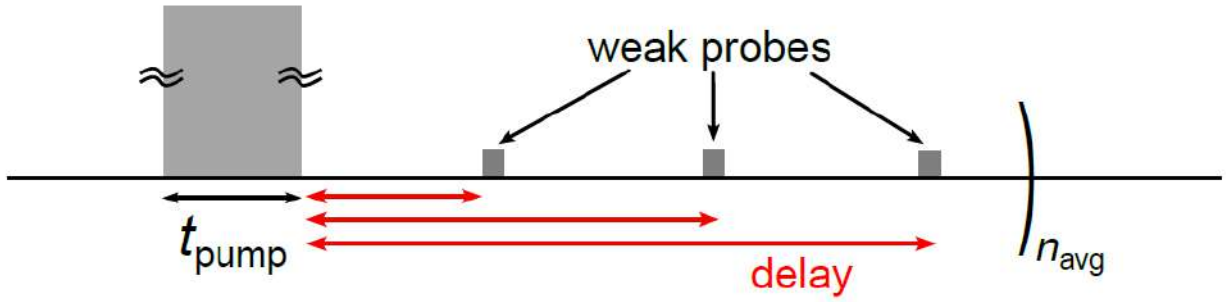
Spin linewidth

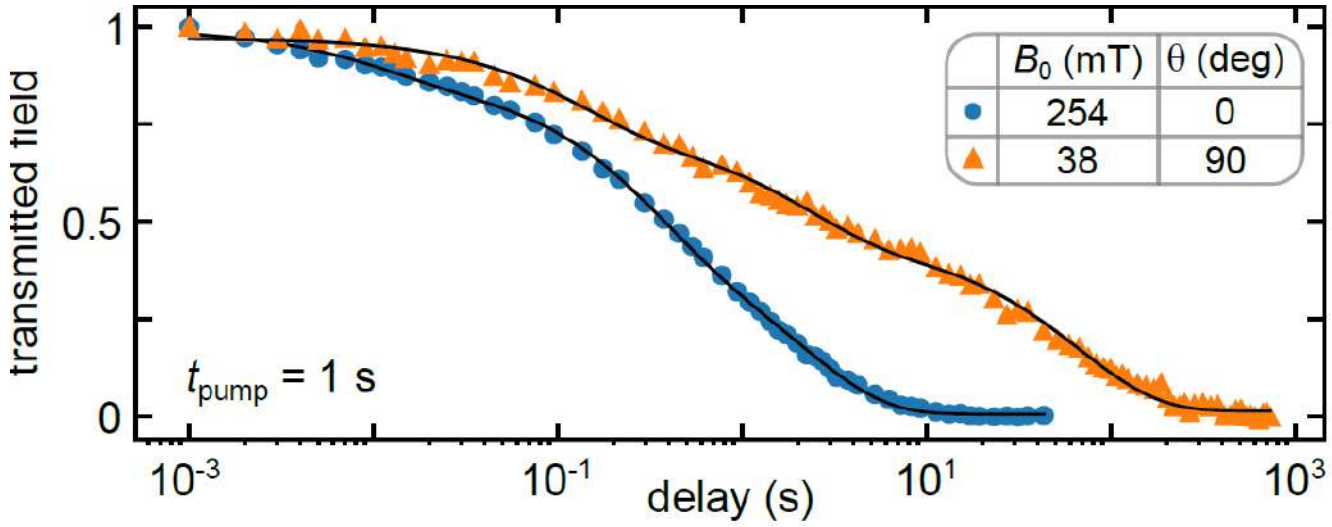
Er3+ replaces Ca2+ sites → charge defects



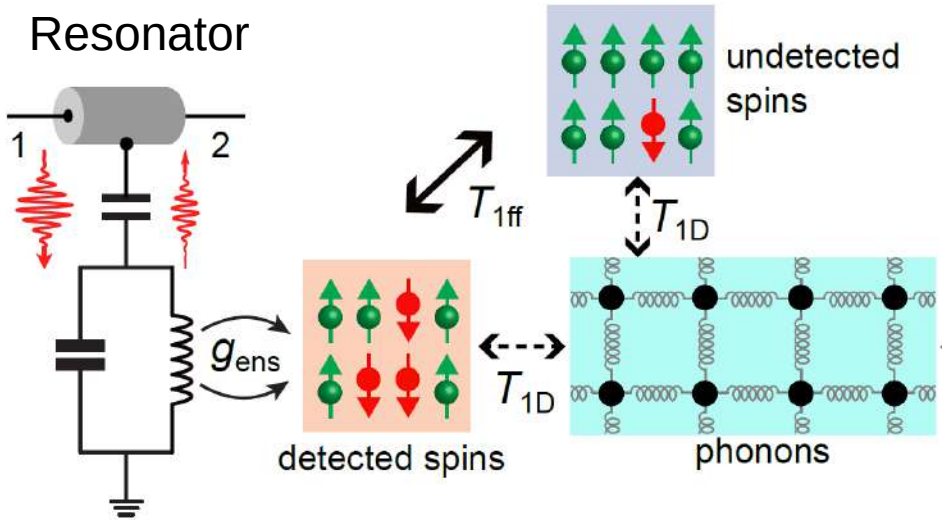
R. Shaik et al, in preparation
W. B. Mims and R. Gillen, Physical Review 148, 438 (1966).

Spin relaxation





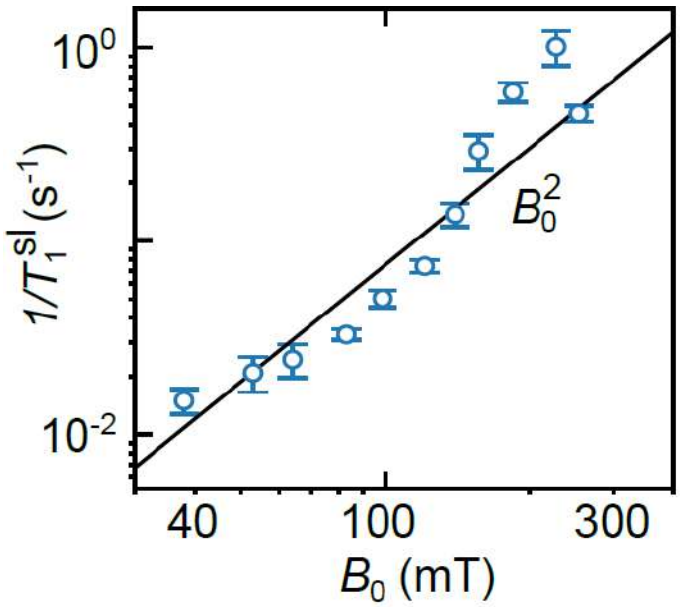
Non exponential decay: Spin diffusion



Finite saturation and detection bandwidth

→ diffusion in both spatial and frequency domains

Direct-phonon relaxation

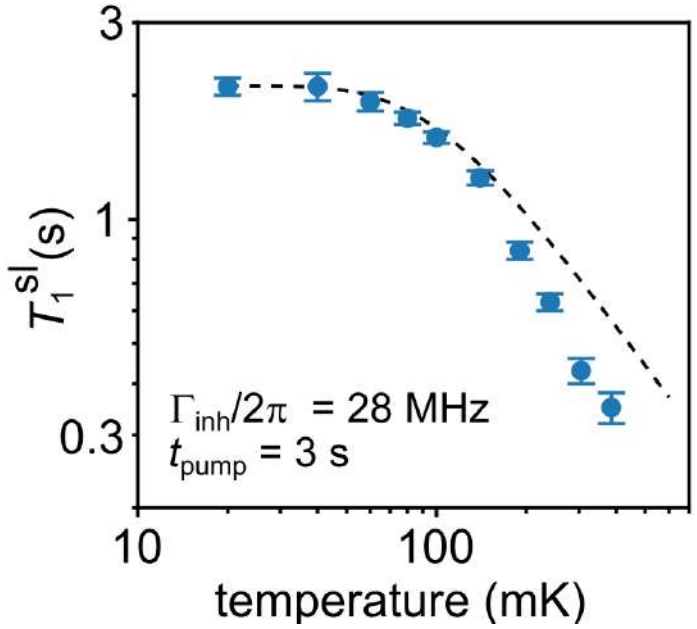


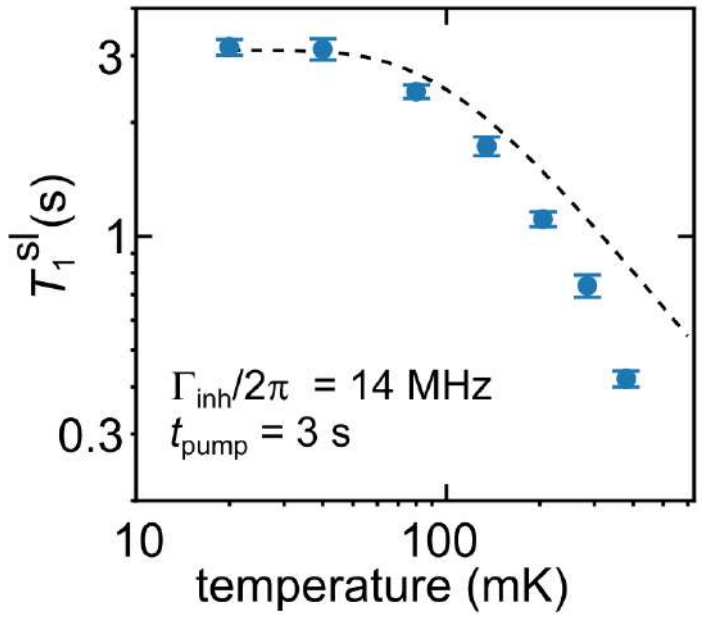
$$1/T_{1\mathrm{D}} = \alpha_{\mathrm{D}}\omega_s^3 B_0^2 \coth\left(\frac{\hbar\omega_0}{2k_{\mathrm{B}}T}\right)$$

Spin-lattice coupling anisotropy is also expected, contained in α_D

P. L. Scott and C. D. Jeffries, Physical Review 127, 32 (1962).

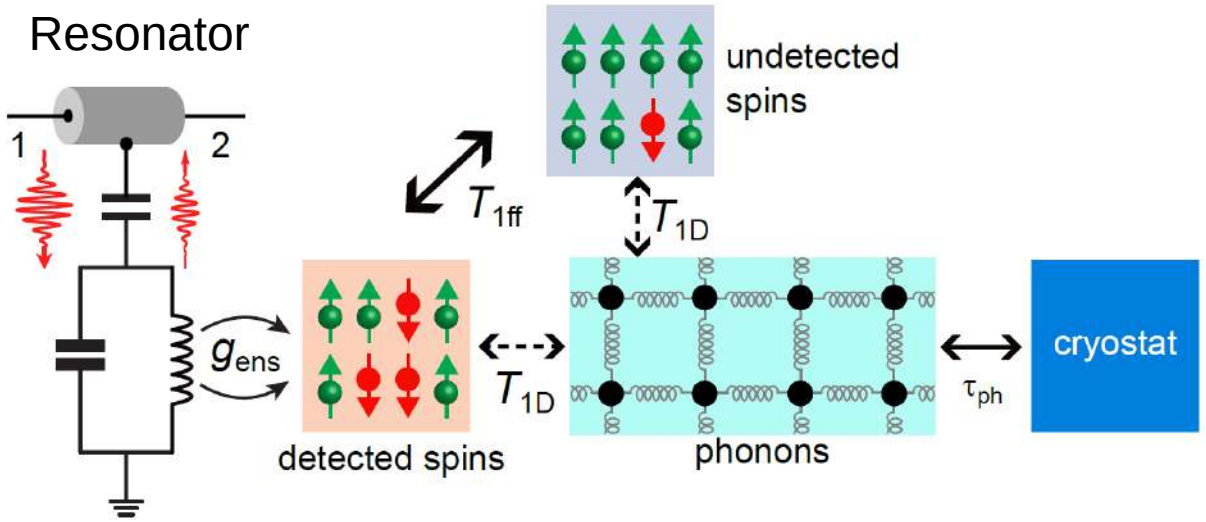
Direct-phonon relaxation





--- $1/T_{1\mathrm{D}} = \alpha_{\mathrm{D}}\omega_s^3 B_0^2 \coth\left(\dfrac{\hbar\omega_0}{2k_{\mathrm{B}}T}\right)$

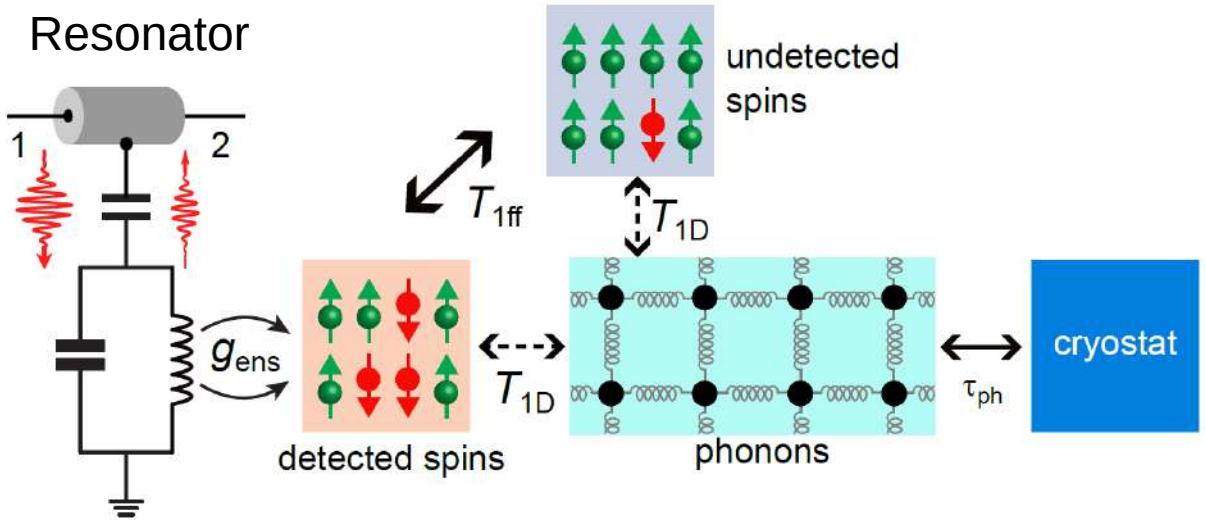
Phonon bottleneck



at mK temperature,
→ thermal occupation per mode n_{BE} ~ 0,
→ Quantum occupation per mode = 1/2
→ number of phonons per spin = 10^{-6}

J. H. Van Vleck, Physical Review 59, 724 (1941).
P. L. Scott and C. D. Jeffries, Physical Review 127, 32 (1962).

Phonon bottleneck

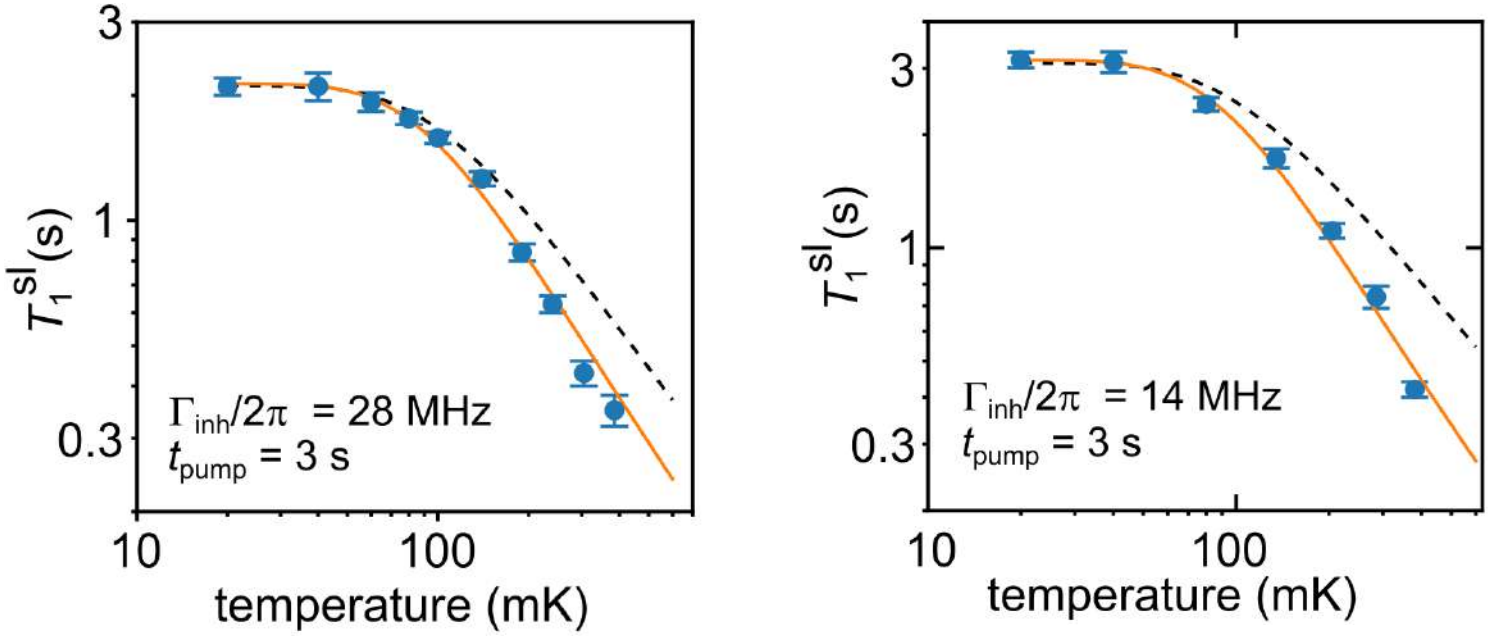


$$T_{1D} \rightarrow T_{1D}(1+b), \qquad b = \frac{\tau_{\mathrm{ph}}}{T_{1D}} \frac{2\pi^2 c v^3}{3\omega_0^2 \Gamma_{\mathrm{inh}}} \left[\tanh\left(\frac{\hbar\omega}{2k_B T}\right)\right]^2$$

Bottleneck parameter,
b = (E_s/T_{1D}) / (E_p/τ_{ph})

J. H. Van Vleck, Physical Review 59, 724 (1941).
P. L. Scott and C. D. Jeffries, Physical Review 127, 32 (1962).

Direct-phonon relaxation



$$T_{1D} \rightarrow T_{1D}(1+b), \qquad b = \frac{2\pi^2 c v^3}{3\omega_0^2 \Gamma_{\text{inh}}} \left[\tanh\left(\frac{\hbar\omega}{2k_B T}\right)\right]^2$$

Bottleneck parameter, *b* = [0.9, 1.95]

S. Rajendran et al., Phys. Rev. Lett. (in press)

Summary

- Low-mode volume (fL) + cQED + Purcell effect
  → Large spin detection sensitivity

- Large spin concentration
  → Low coherence times
  → Phonon bottleneck

- Clock transition in Bi:Si
  → Long storage times in a spin ensemble

- Fast Tunable resonators
  → Echo silencing, selective state retrieval

Efficiency of storage/retrieval

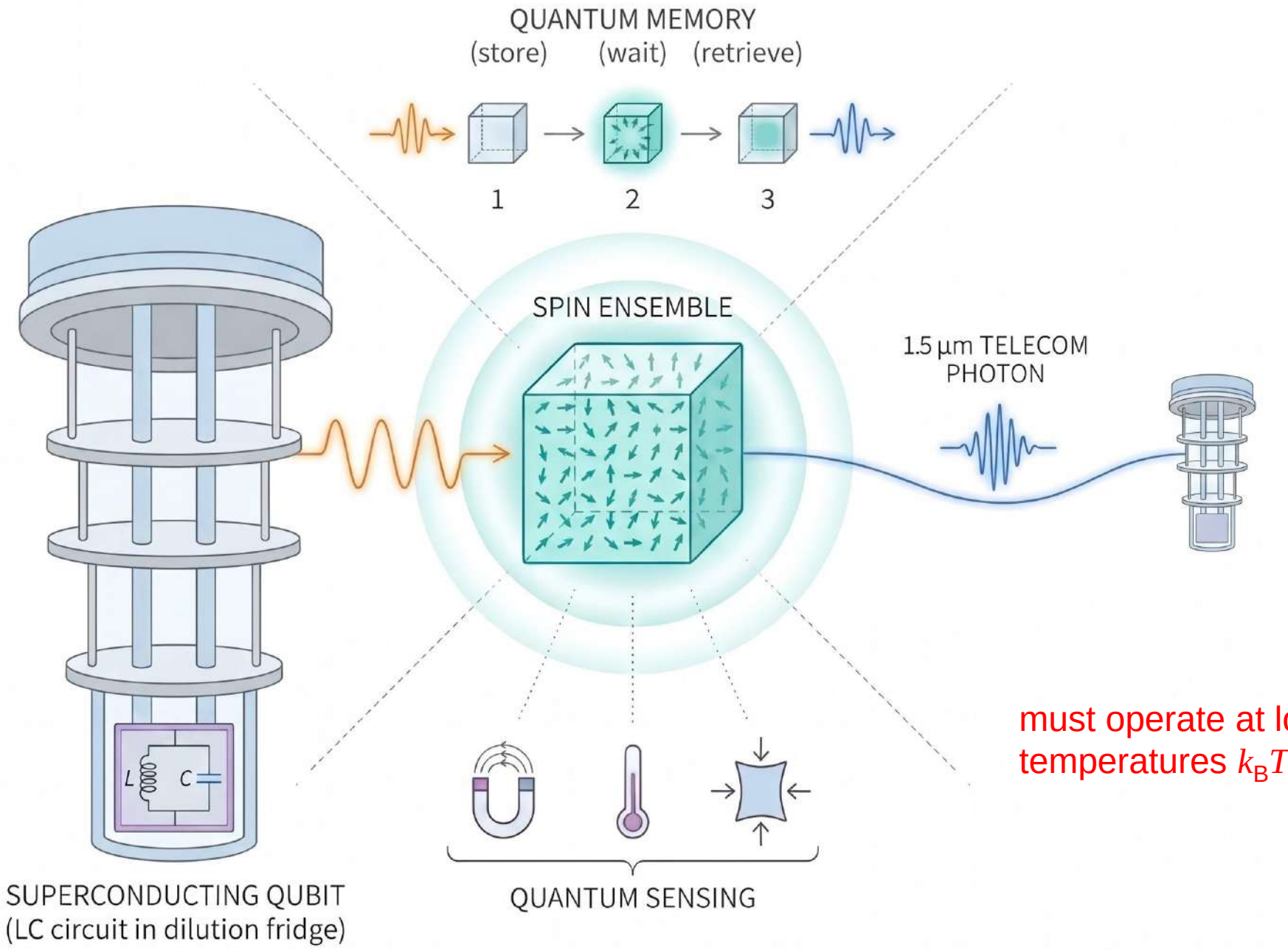
- tunable across the spin resonance to some extent
- Hyperpolarization by driving nuclear transitions

Unit efficiency → cooperativity $= \frac{4g_{ens}^2}{\kappa\Gamma} = 1$

- kappa tuning can be dynamical for catch and release, and for suppressing super-radiance and stimulated emissions

- Rotation of field axis for anisotropic g-tensor spin species

Electron spin ensembles for quantum technologies



must operate at low temperatures $k_B T << \hbar\omega_0$

Image source: Basanta

Acknowledgement



Aathif

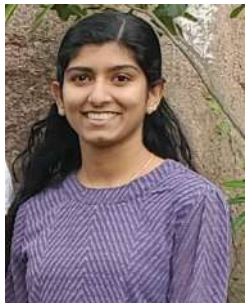


Prof. KV Raman





Bhargava (now at Uppsala University)



Anusree (now at Max Planck Institute)

Thank you