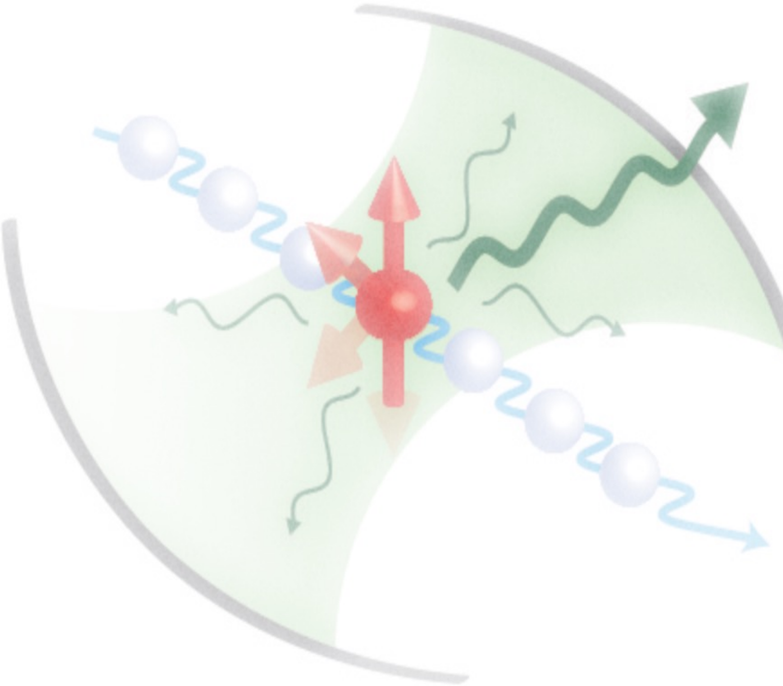
Controlling spin relaxation with a cavity



Audrey BIENFAIT, Xin ZHOU, Philippe CAMPAGNE-IBARCQ, Sebastian PROBST, Denis VION, Daniel ESTEVE, & Patrice BERTET

Quantronics Group, SPEC, CEA-Saclay, France

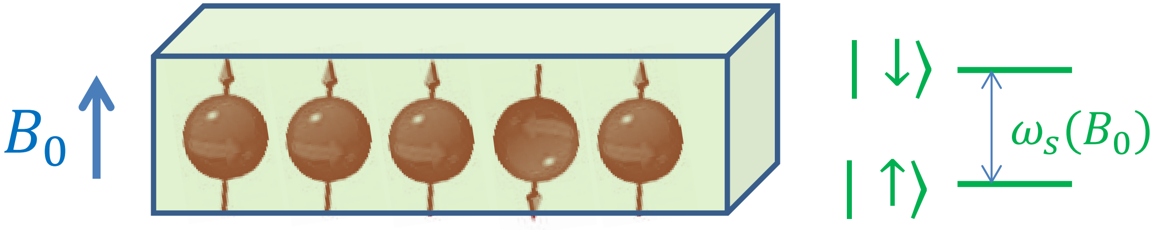
Jarryd J. Pla & John J.L. Morton

London Centre for Nanotechnology, University College of London

Thomas Schenkel

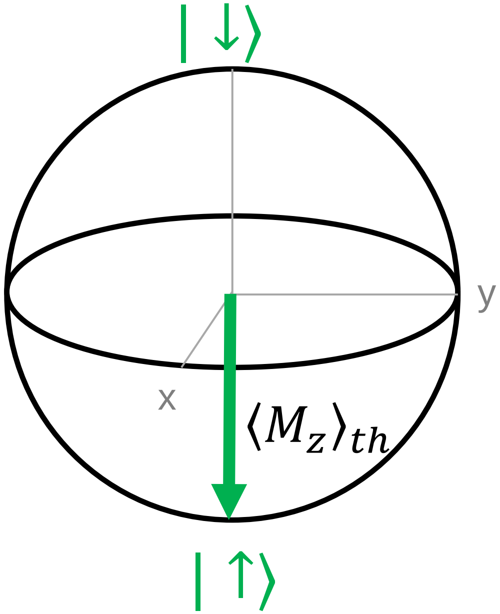
Lawrence Berkeley National Laboratory

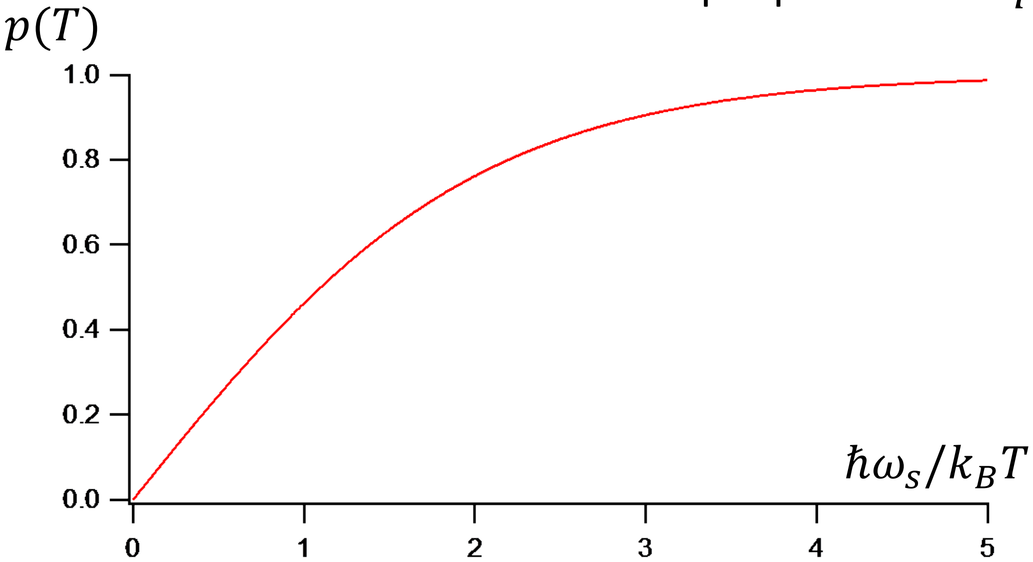
Spin polarization



Ensemble of N spins 1/2
Temperature T

Equilibrium magnetization : $\langle M_z\rangle_{th} = (N_\uparrow - N_\downarrow)(\hbar\gamma/2) = (N\hbar\gamma/2)\underbrace{\tanh \hbar\omega_s/(2k_BT)}_{\text{Spin polarization } p(T)}$

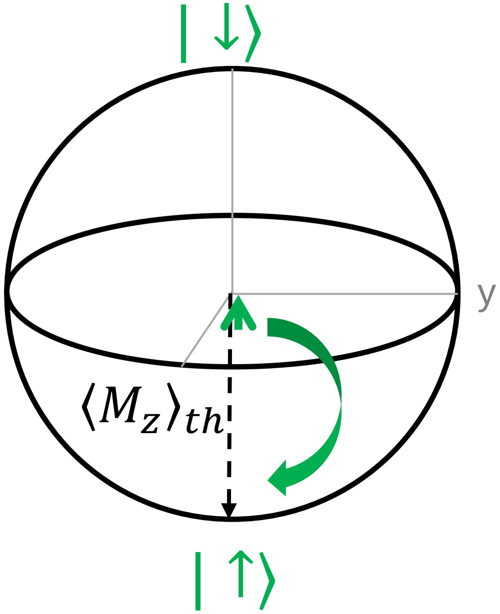




Magnetic resonance signal proportional to $p(T)$

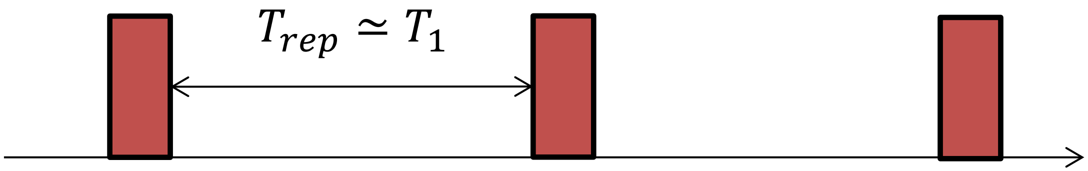
→ Low temperatures $T \ll \hbar\omega_s/k_B$ to maximize signal

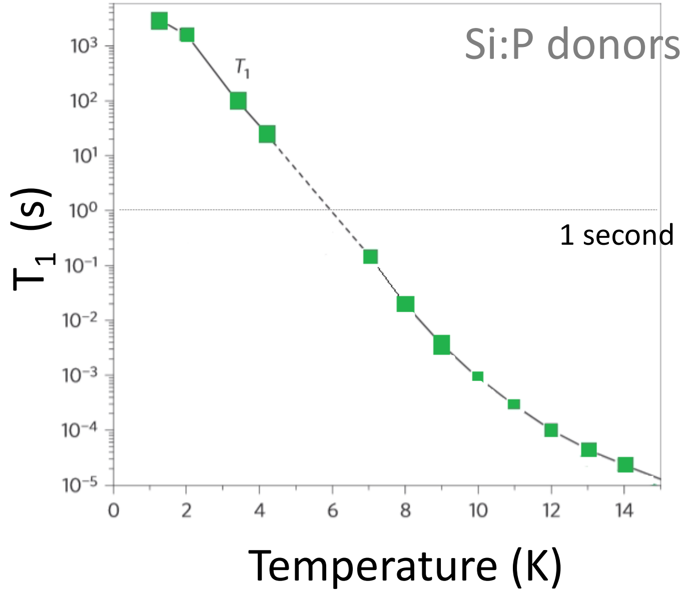
Spin relaxation



How fast do spins return to $\langle M_z \rangle_{th}$ when they are driven out-of-equilibrium ?

Spin relaxation time T_1





Unfortunately …

low temperatures ⟺ long T_1

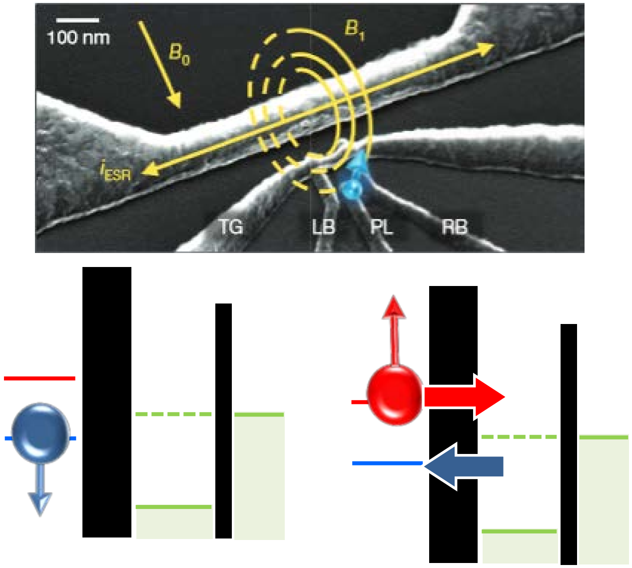
Major issue for magnetic resonance measurements at low temperatures

Need a « spin reset » mechanism

Electron spin initialisation

Electrical reset

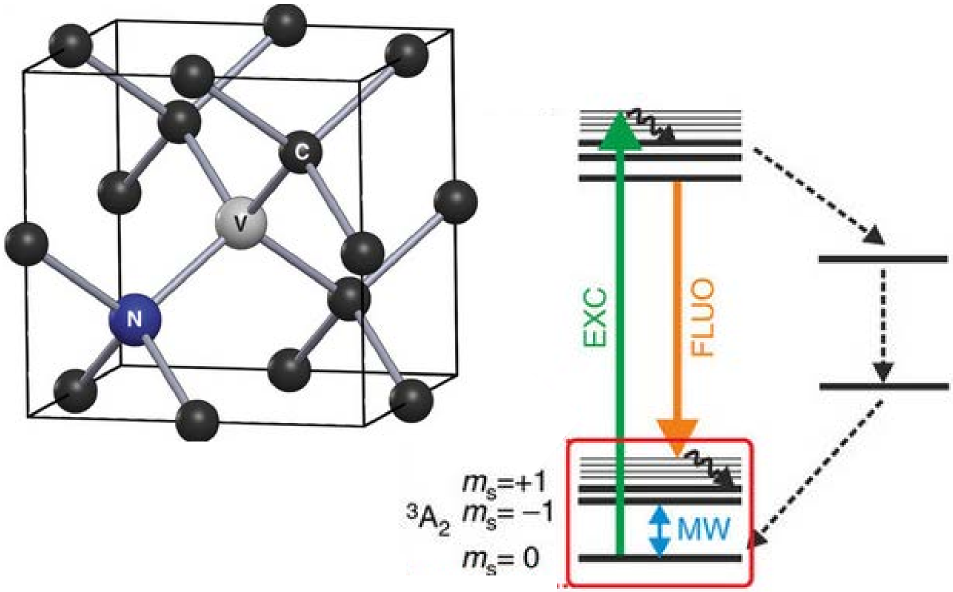
Donors and gate-defined quantum dots in semi-conductors



J. Elzerman, Nature (2010)
A. Morello et al., Nature **467**, 687 (2010)

Optical reset

NV centers
Donors in silicon

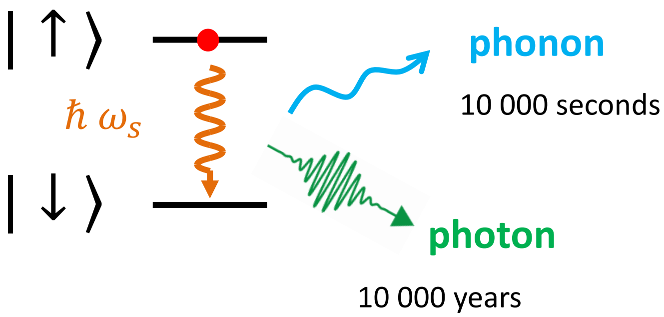


Cf V. Jacques talk !

Spin system dependent…

$\Rightarrow$ Universal method for spin initialisation ?

Spin relaxation by spontaneous emission



$|\uparrow\rangle$

$\hbar\,\omega_s$

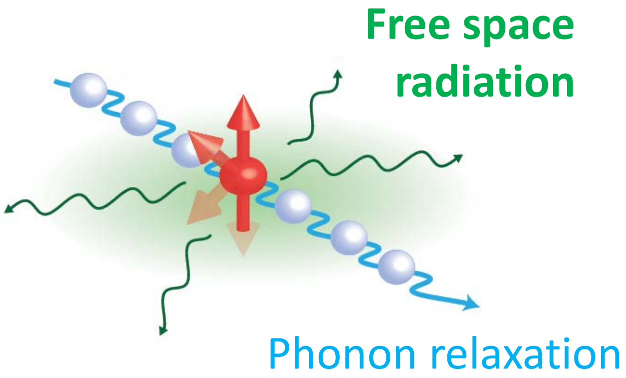
$|\downarrow\rangle$

phonon

10 000 seconds

photon

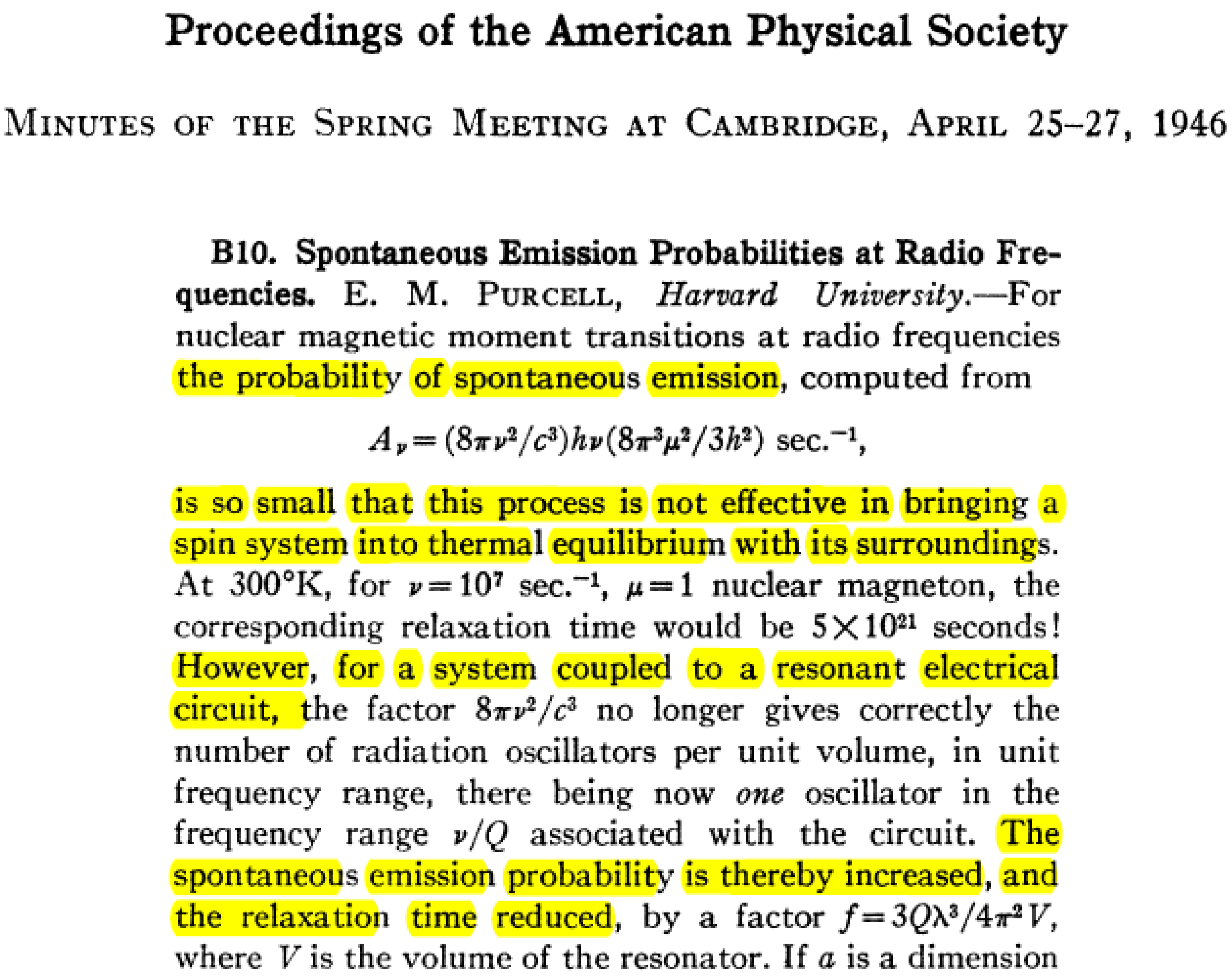
10 000 years



Free space radiation

Phonon relaxation

A « new » phenomenon : the Purcell effect



Proceedings of the American Physical Society

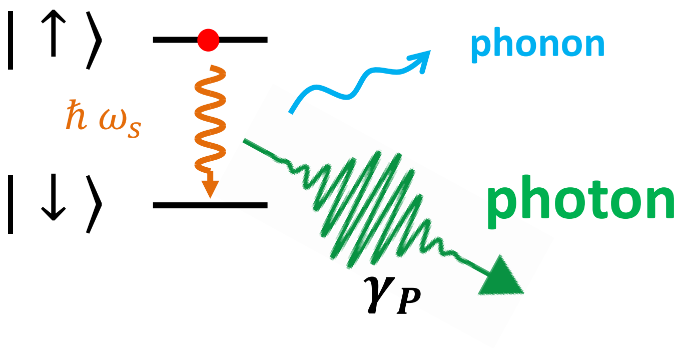
MINUTES OF THE SPRING MEETING AT CAMBRIDGE, APRIL 25–27, 1946

B10. Spontaneous Emission Probabilities at Radio Frequencies. E. M. PURCELL, *Harvard University*.—For nuclear magnetic moment transitions at radio frequencies the probability of spontaneous emission, computed from

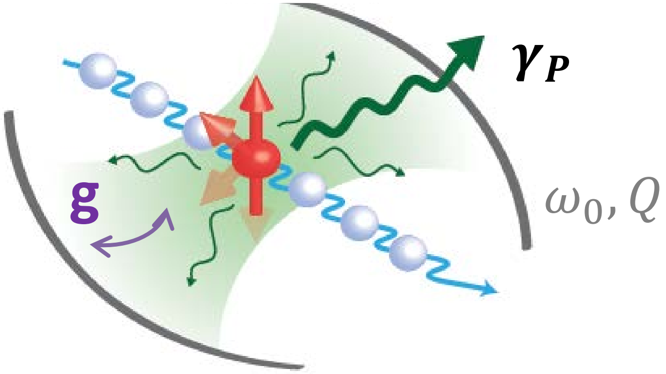
$$A_\nu = (8\pi\nu^2/c^3)h\nu(8\pi^3\mu^2/3h^2)\ \text{sec.}^{-1},$$

is so small that this process is not effective in bringing a spin system into thermal equilibrium with its surroundings. At 300°K, for $\nu = 10^7$ sec.$^{-1}$, $\mu = 1$ nuclear magneton, the corresponding relaxation time would be 5×10^{21} seconds! However, for a system coupled to a resonant electrical circuit, the factor $8\pi\nu^2/c^3$ no longer gives correctly the number of radiation oscillators per unit volume, in unit frequency range, there being now *one* oscillator in the frequency range ν/Q associated with the circuit. The spontaneous emission probability is thereby increased, and the relaxation time reduced, by a factor $f = 3Q\lambda^3/4\pi^2V$, where V is the volume of the resonator. If a is a dimension

Cavity-enhanced spontaneous emission



Cavity-enhanced radiation



Purcell effect

Predicted in 1946 for spins

$$\boxed{\gamma_P = \frac{4Qg^2}{\omega_0}\frac{1}{1+4Q^2\left[\frac{\omega_s-\omega_0}{\omega_0}\right]^2}}$$

Spin-resonator coupling

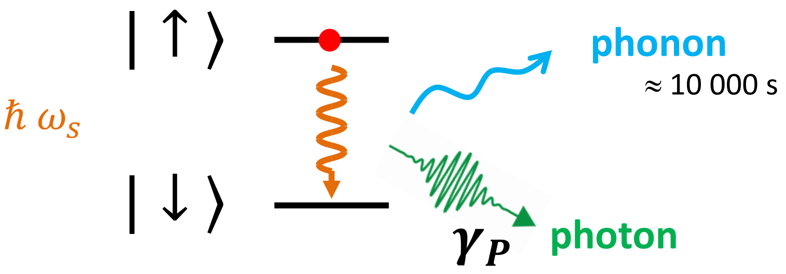
Spin-resonator detuning

Resonator quality factor

Proposals :

M.C. Butler et al, PRA 84, 0634074 (2011)
C.J.Wood et al., PRL 112, 050501 (2014)

Cavity-enhanced spontaneous emission



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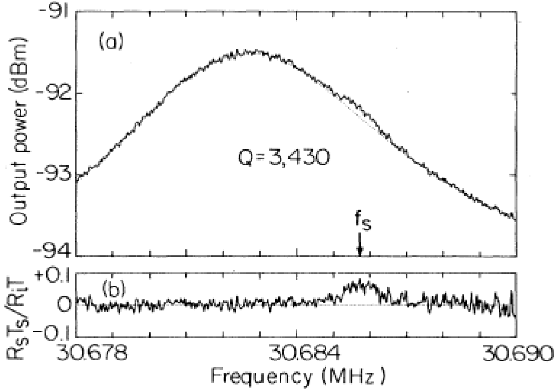
Spin-resonator coupling

Spin-resonator detuning

Resonator Quality factor

Effect already observed for an ensemble of nuclear spins



Sleator et al., PRL 1985

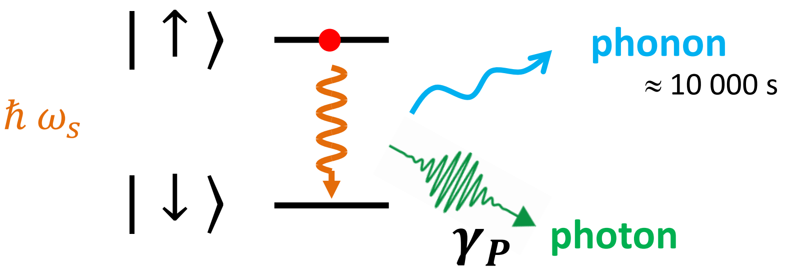
But $\gamma_P \sim 10^{-16}s^{-1}$: negligible compared to non-radiative decay (phonons, …)

Dominant relaxation for systems with an electrical dipole

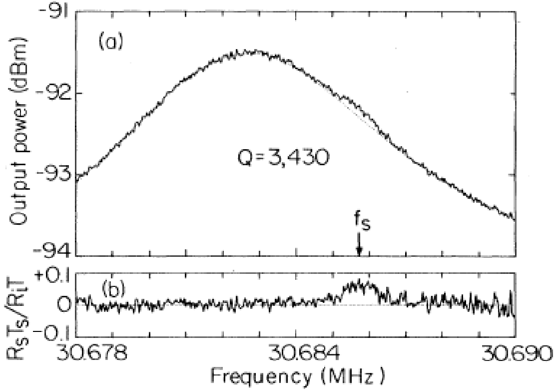
- Atoms in mw / optical cavities
  Goy et al., PRL (1983), Heinzen et al., PRL (1987)
- Semiconducting heterostructures
  Y. Yamamoto, Opics Comm. (1991)

$\Rightarrow$ Reach regime of Purcell-enhanced relaxation for electronic spins

Cavity-enhanced spontaneous emission



Effect already observed
for an ensemble of nuclear spins



Sleator et al., PRL 1985

Purcell effect

Predicted in 1946 for spins

$$\boxed{\gamma_P = \frac{4Q\boldsymbol{g}^2}{\omega_0}\frac{1}{1+4Q^2\left[\frac{\omega_s-\omega_0}{\omega_0}\right]^2}}$$

Spin-resonator coupling

Spin-resonator detuning

Resonator Quality factor

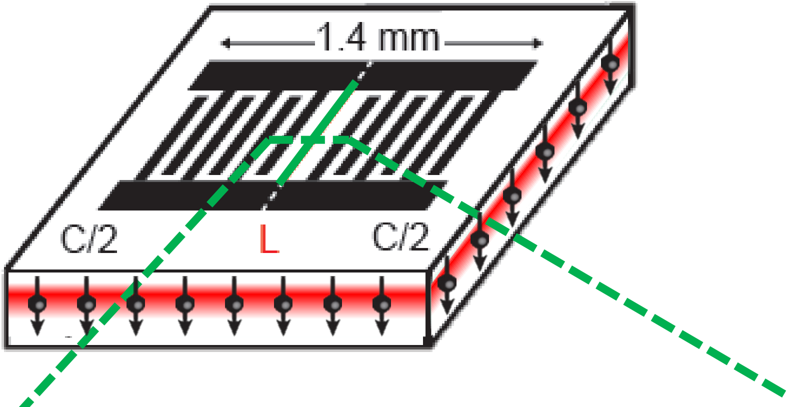
But $\gamma_P \sim 10^{-16} s^{-1}$: negligible compared to non-radiative decay (phonons, …)

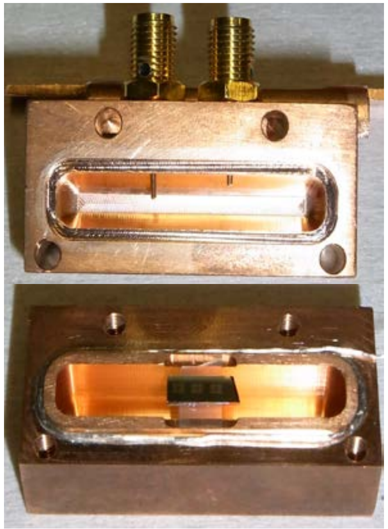
Cavity with small mode volume

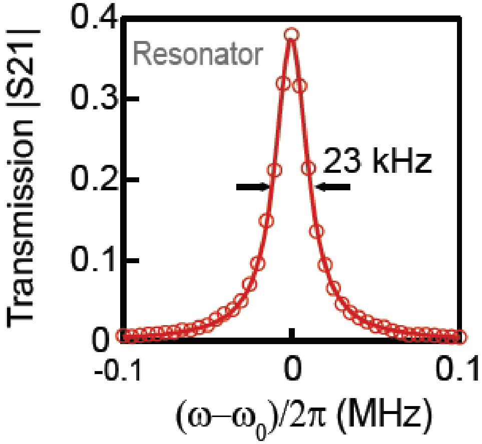
High quality factor cavity

⇒ Reach regime of Purcell-enhanced relaxation for electronic spins

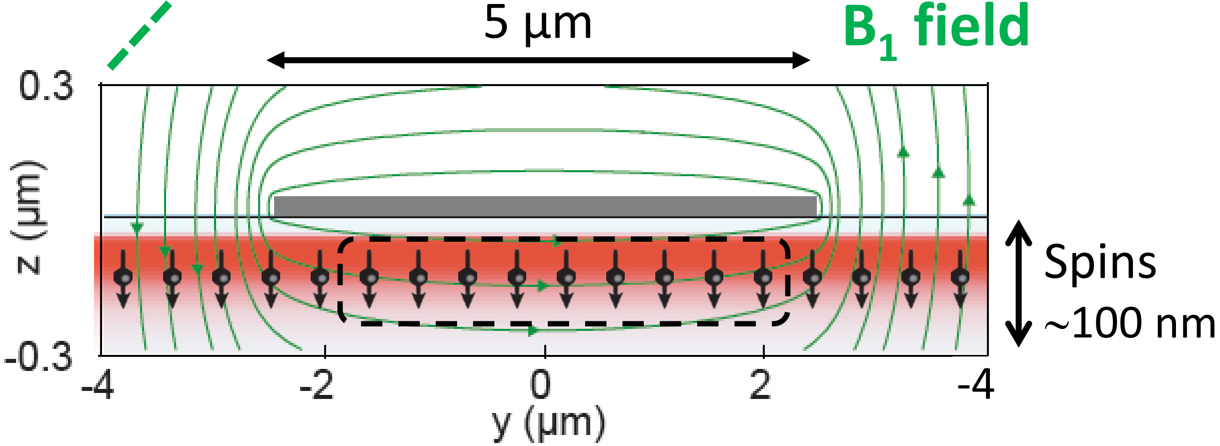
Experimental setup







$\omega_0/2\pi$ = 7.24 GHz, Q = 3 10^5

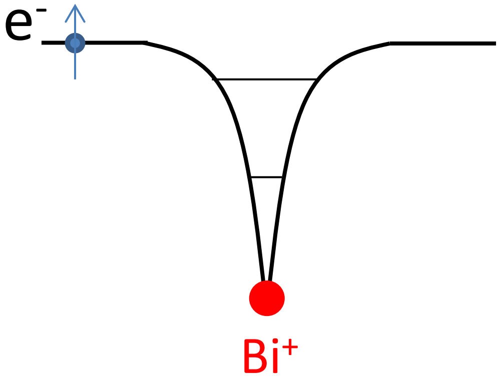


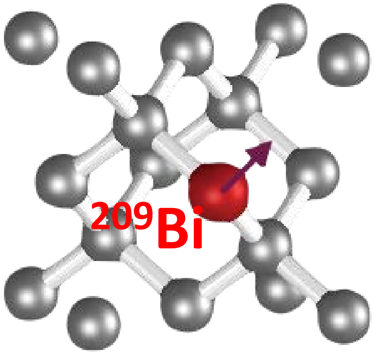
Spin-resonator coupling $\frac{g}{2\pi} = 55 Hz$

Expected Purcell rate at resonance

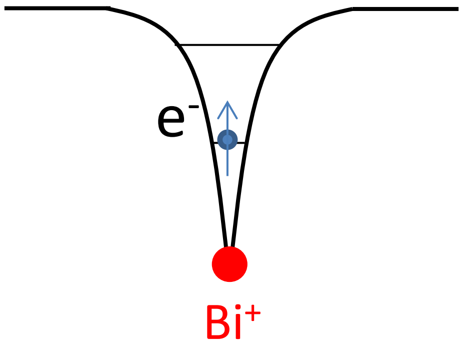
$\Gamma_P = 4g^2Q/\omega_0 \approx 3\ \text{s}^{-1}$

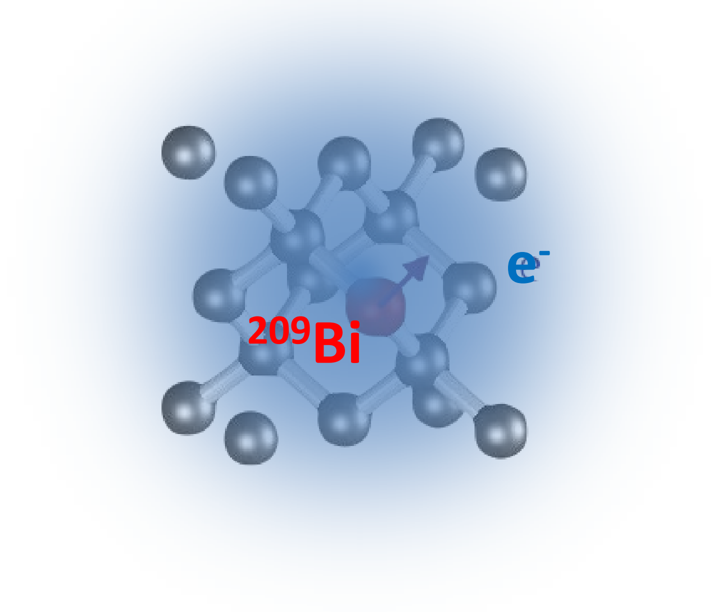
The Spins: Bi donors in silicon





The Spins: Bi donors in in silicon





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

ZEEMAN EFFECT HYPERFINE

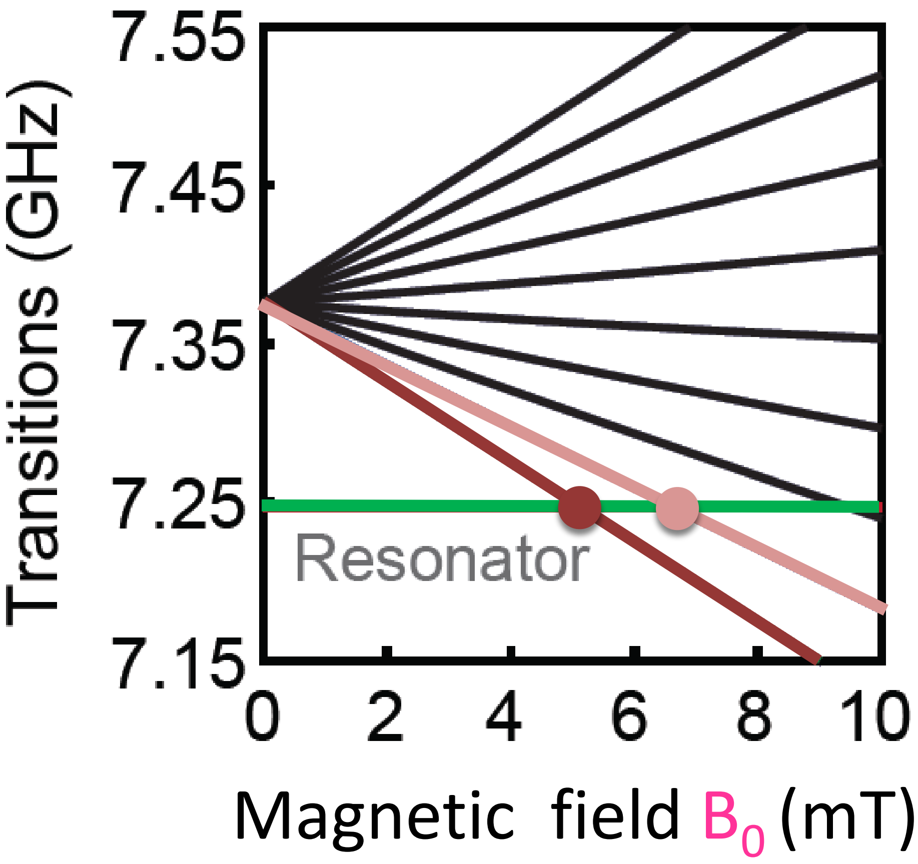
- Electronic spin = 1/2
- Nuclear spin I=9/2

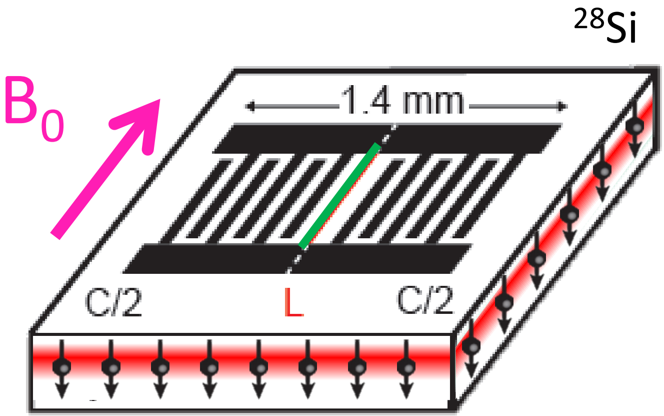
20 electro-nuclear states !

- Large hyperfine coupling $\frac{A}{2\pi} = 1.4754\mathrm{GHz}$

The Spins: bismuth donors in silicon

10 allowed ESR-like transitions @ low B_0

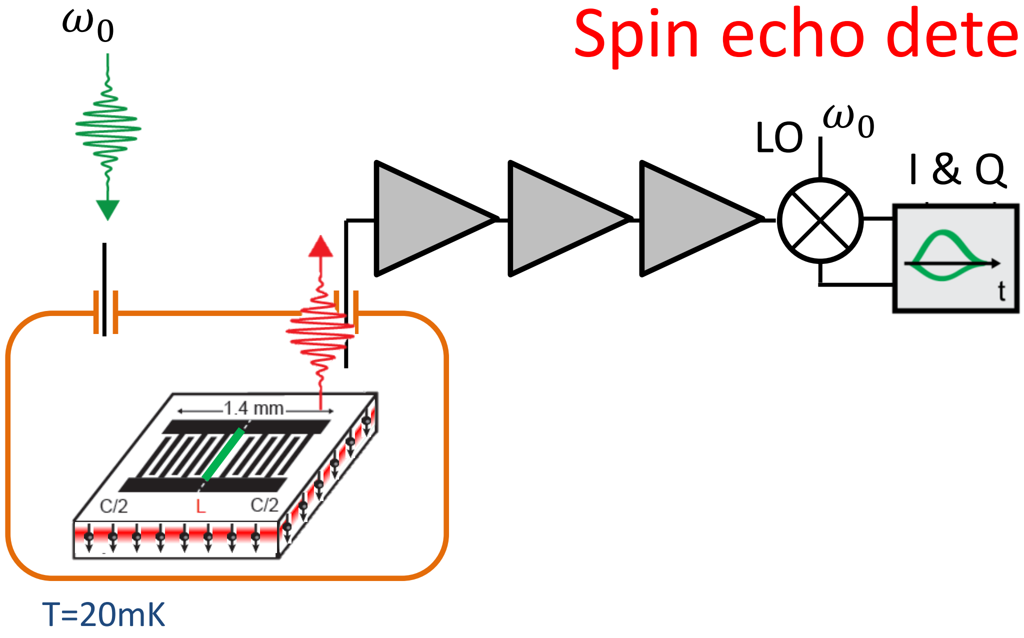


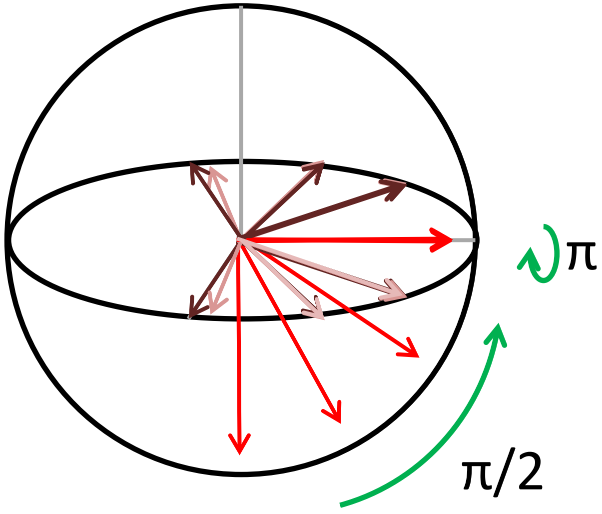


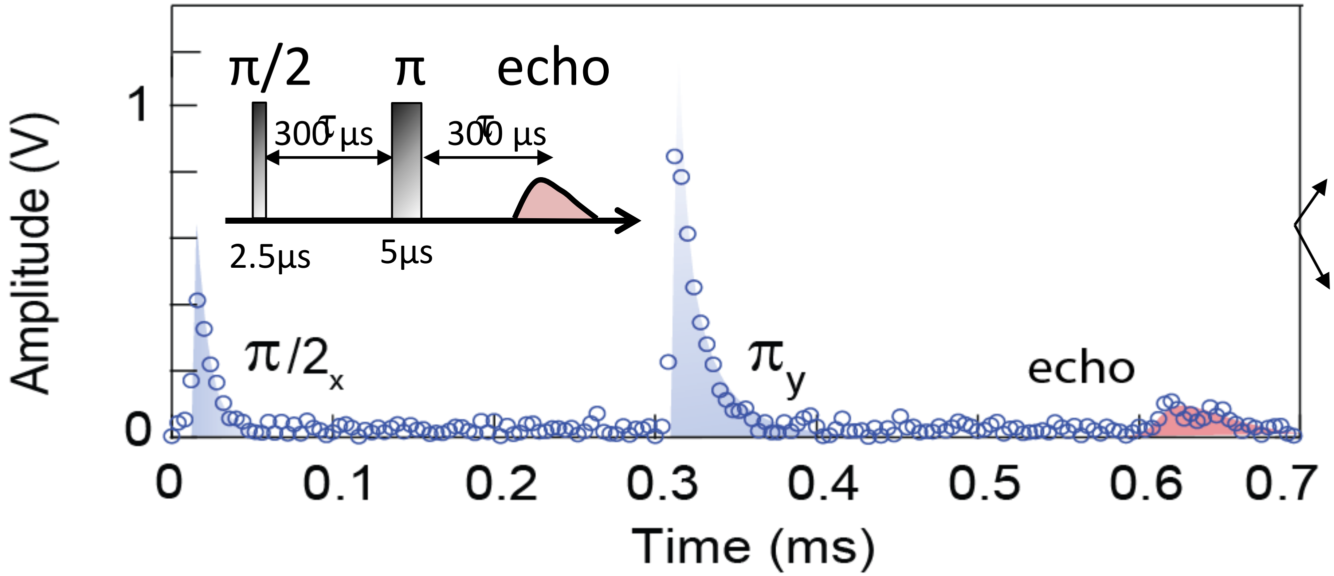
≈ 5.2 mT

≈ 6.8 mT

Spin echo detection



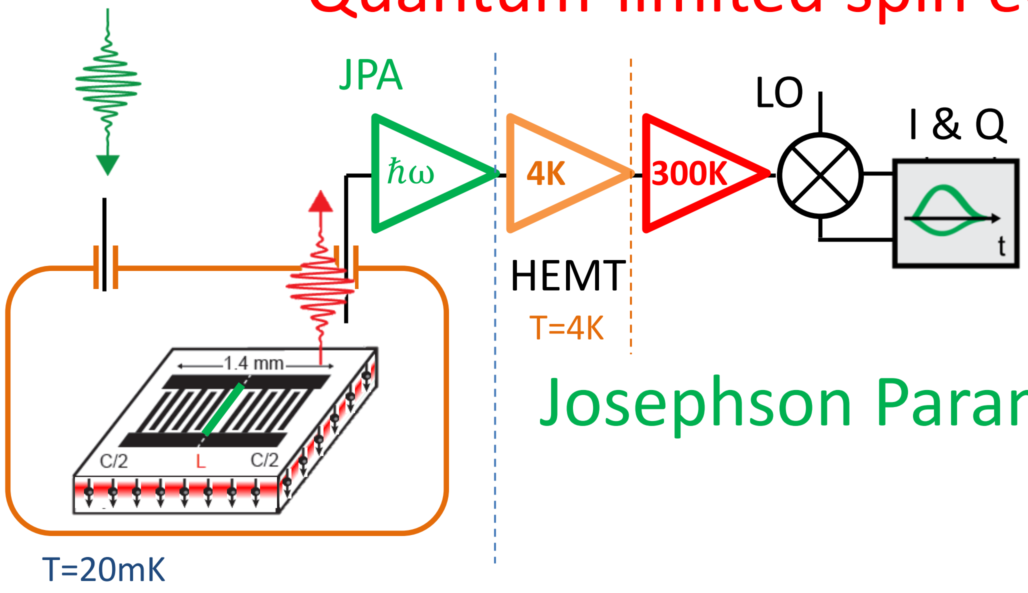




$$A_e = \frac{1}{T_E}\int A(t)dt$$

$$A_Q = \frac{1}{T_E}\int Q(t)dt$$

Quantum-limited spin echo detection

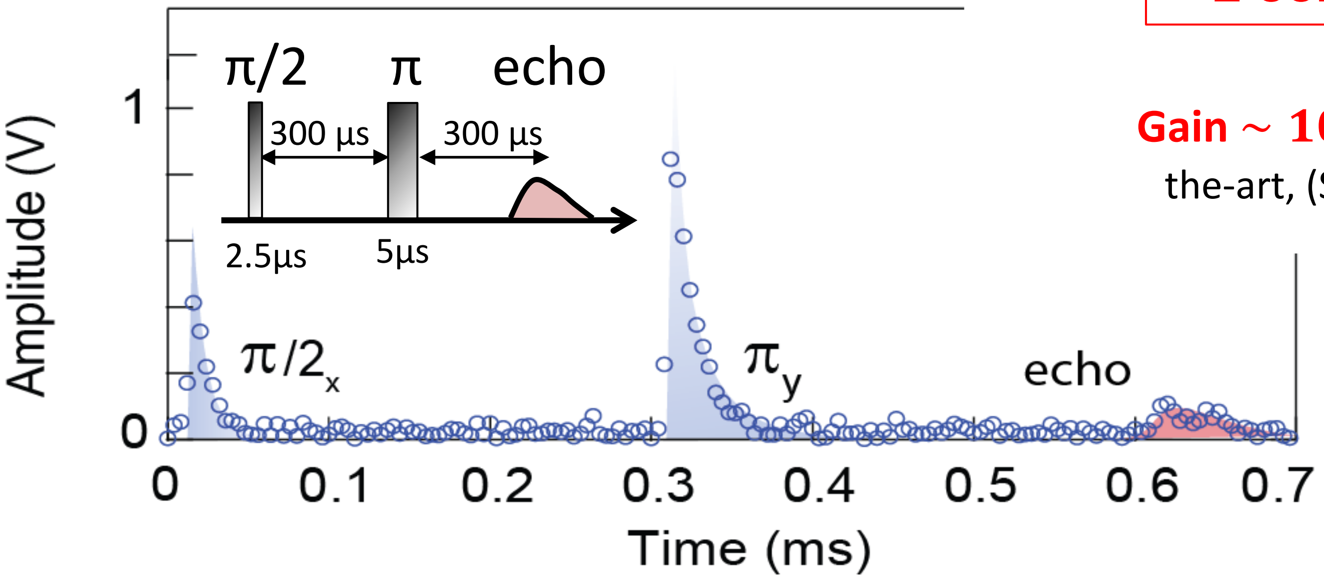


Josephson Parametric Amplifier

X. Zhou et al., PRB (2014)

Quantum limited ESR
1 echo: 1700 spins

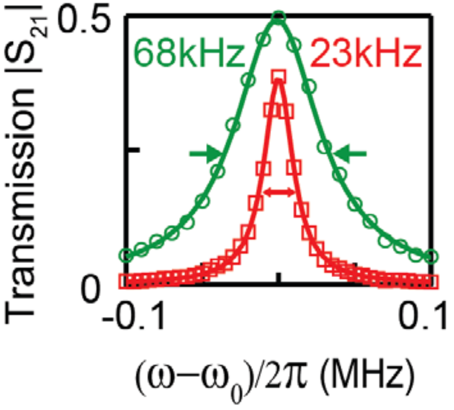
Gain ~ 10^4 compared to state-of-the-art, (Sigillito et al., APL 2014)



A.Bienfait et al, Nature Nanotechnology (2016)

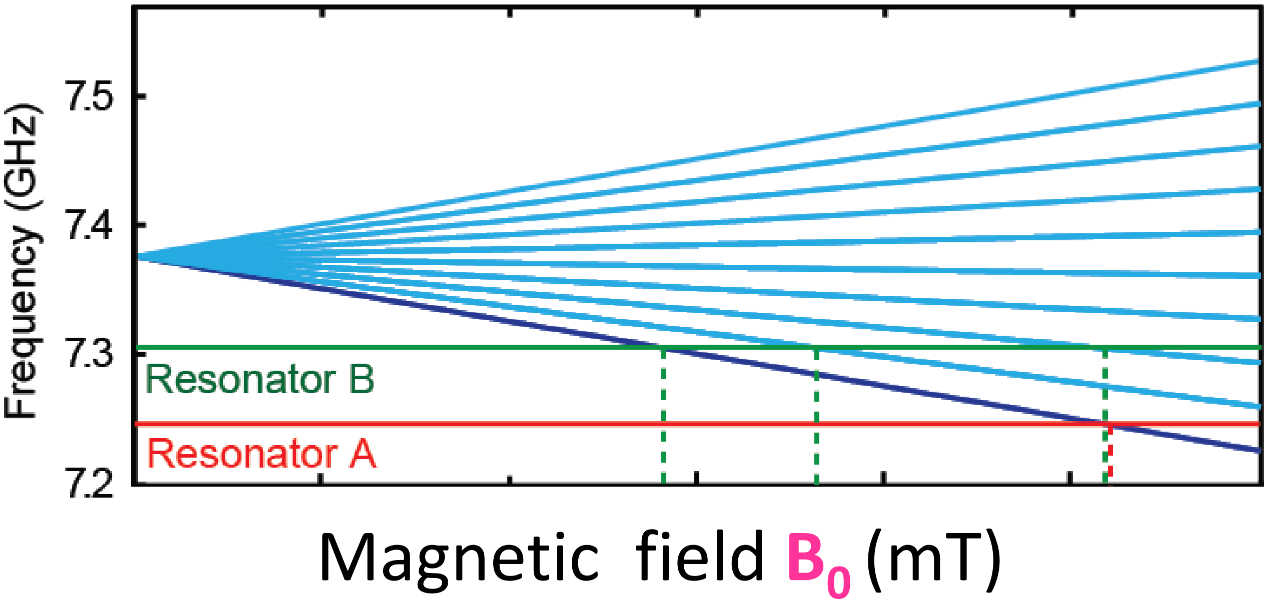
Hahn-echo detected ESR Spectroscopy

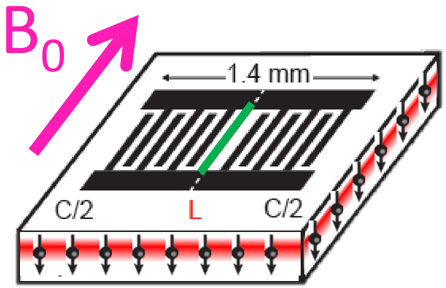
Two resonators



$Q_A = 3.2\ 10^5$

$Q_B = 1.1\ 10^5$





Hahn-echo detected ESR Spectroscopy

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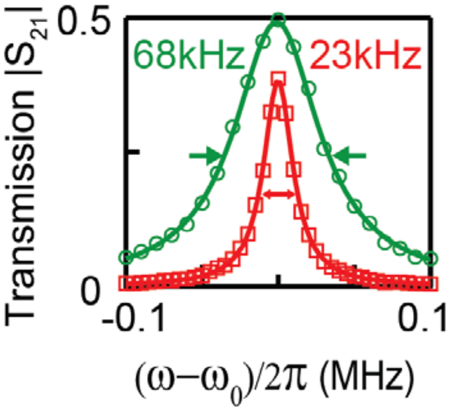
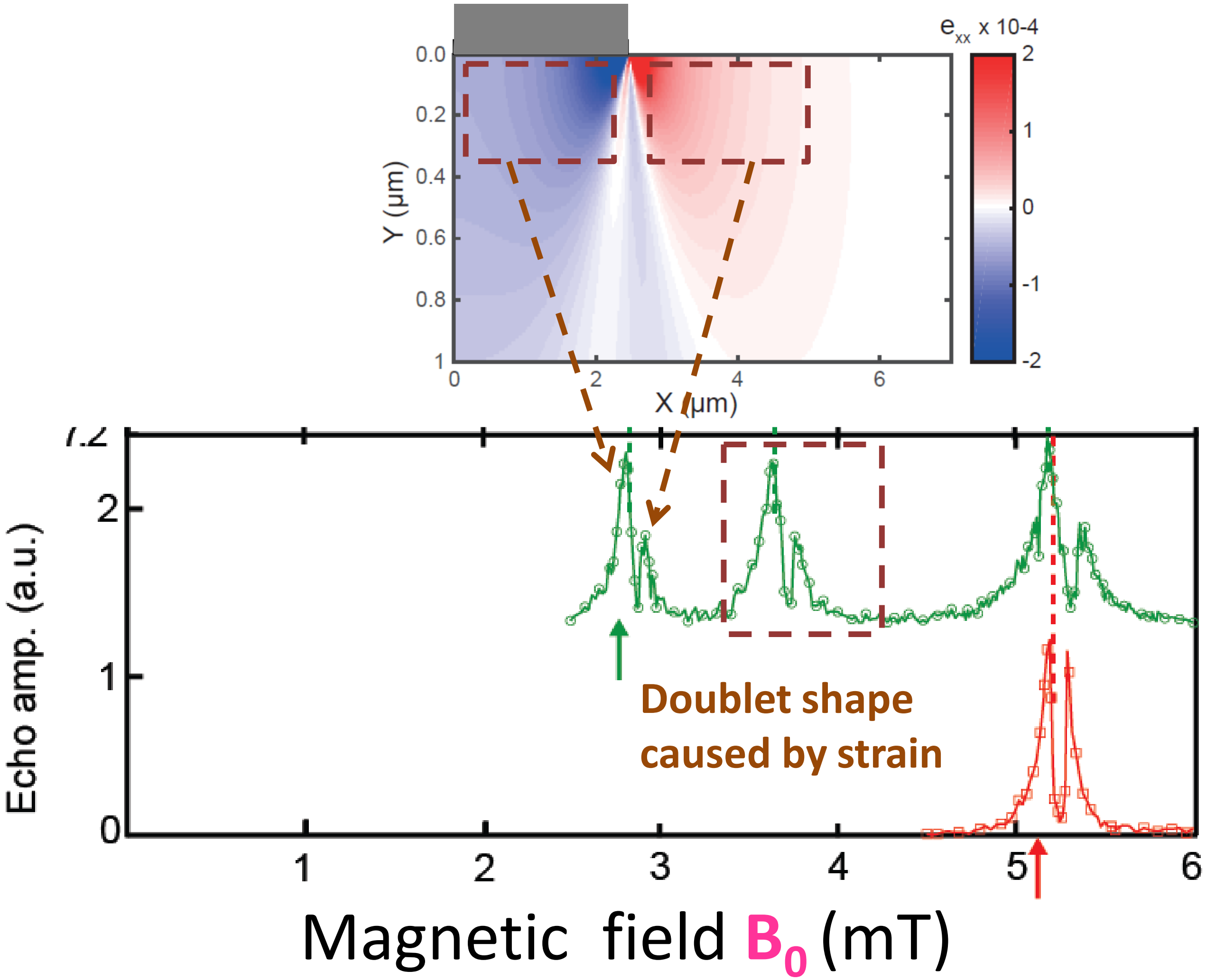
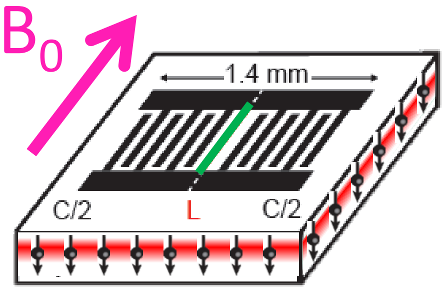


$Q_A = 3.2\ 10^5$

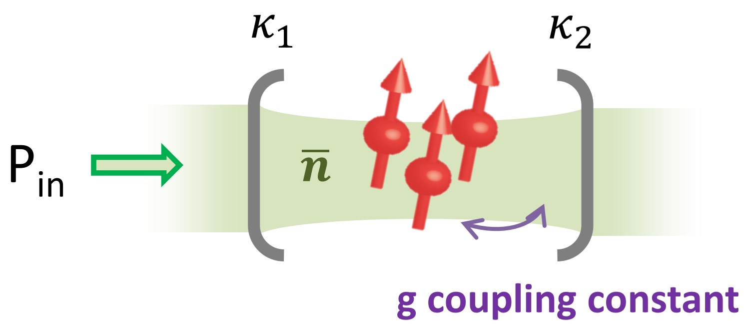
$Q_B = 1.1\ 10^5$

Aluminium wire



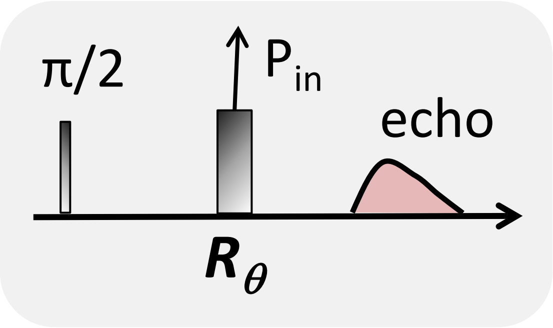


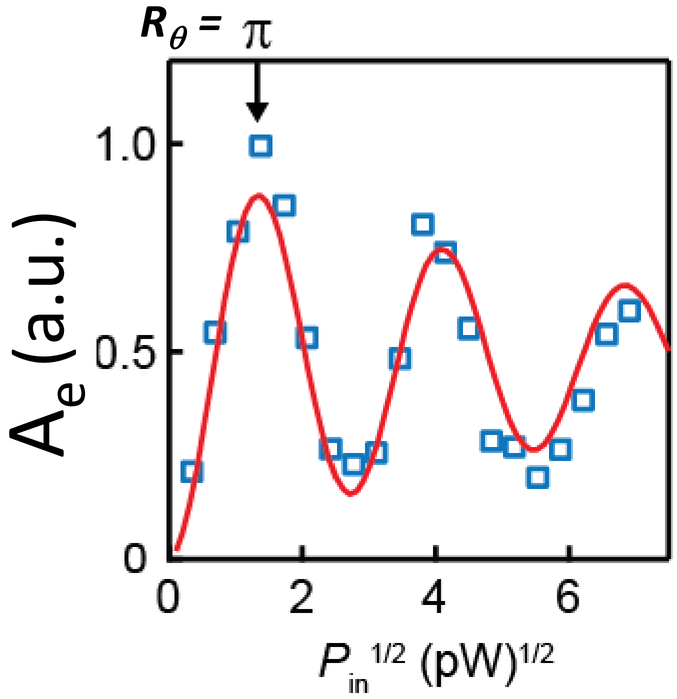
Rabi oscillations – g calibration



$\bar{n} = 4\frac{\kappa_1}{(\kappa_1+\kappa_2)^2}P_{in}$ intra-resonator photon number

$$\boldsymbol{\Omega_R = 2\sqrt{\bar{n}}g}$$

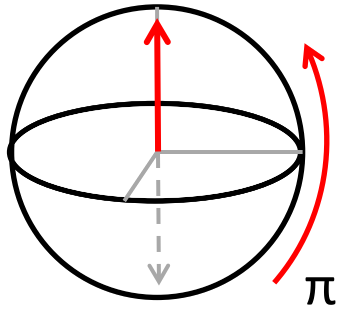


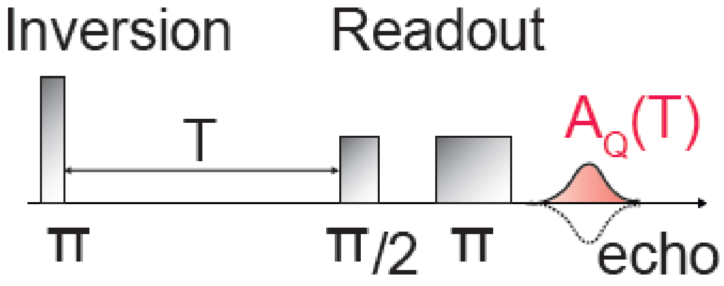


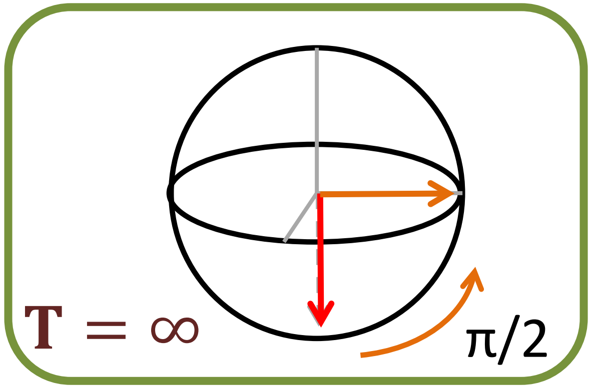
$$\boxed{\frac{g}{2\pi} = 50 \pm 10\text{Hz}}$$

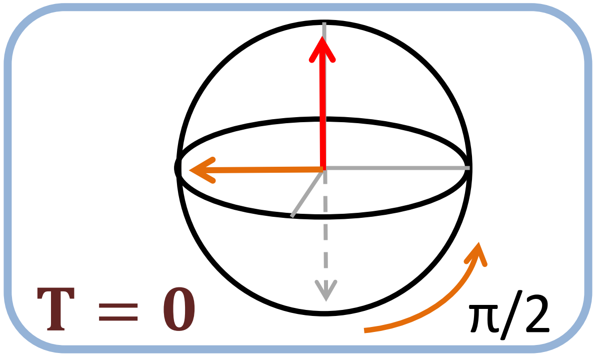
as determined numerically

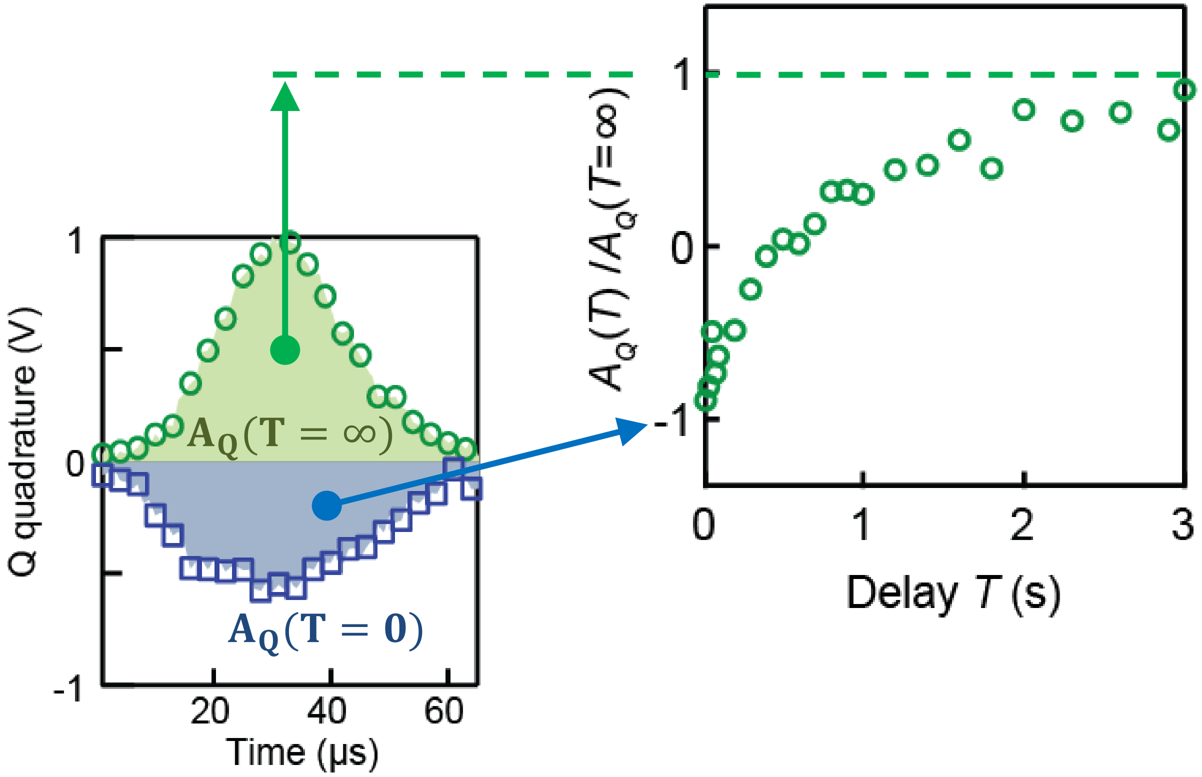
T_1 – Inversion recovery











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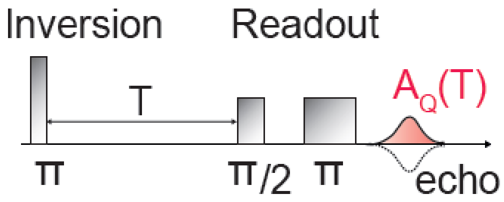

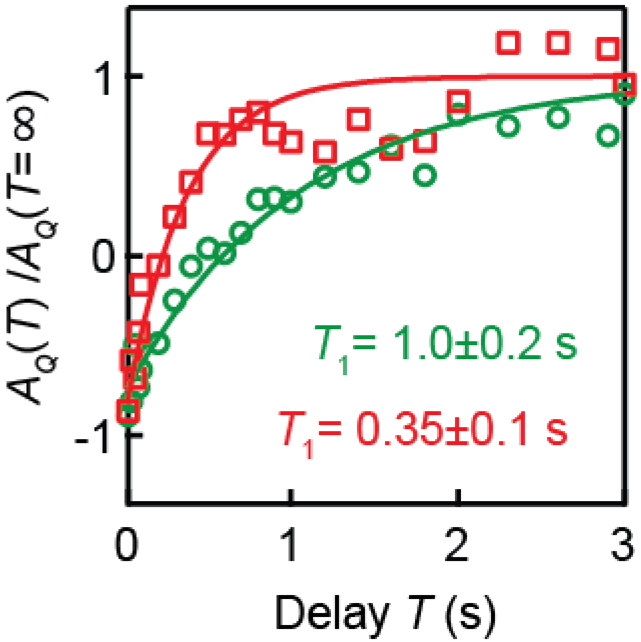

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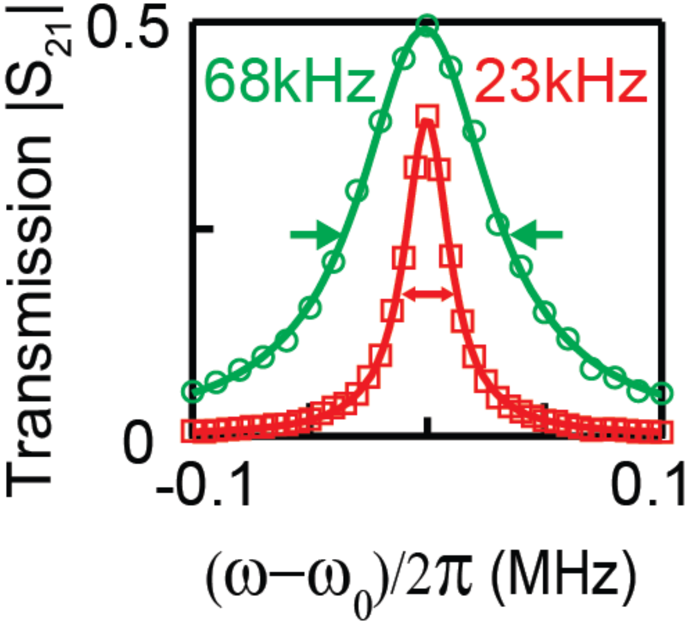


At resonance : $\Gamma_P = 4g^2Q/\omega_0$

Good agreement with predicted $T_{1A} = 0.3s$ and $T_{1B} = 1s$

Control of the spin relaxation

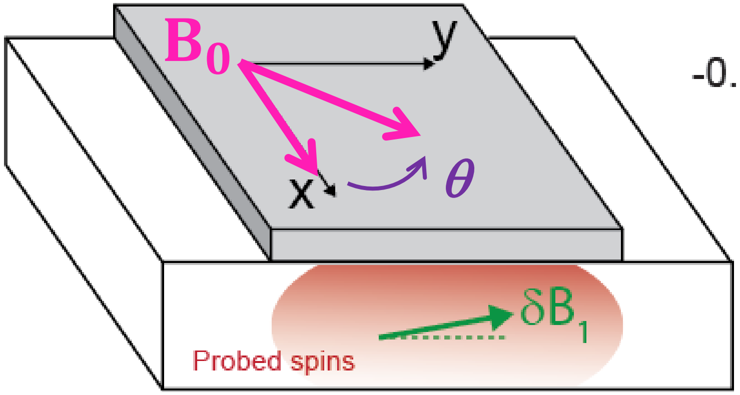
1) Spin-resonator coupling

At resonance, $\gamma_P = \frac{4Q\boldsymbol{g}^2}{\omega_0}$

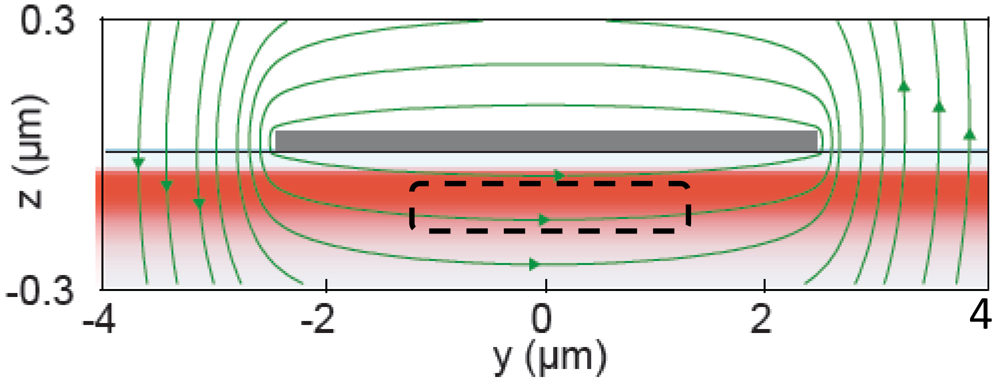
2) Spin-resonator detuning

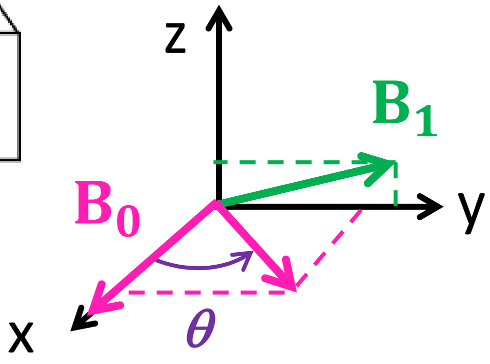
$$\gamma_P = \frac{\gamma_P(\omega_s = \omega_0)}{1 + 4Q^2\left[\frac{\omega_s - \omega_0}{\omega_0}\right]^2}$$

Control by tuning the spin-resonator coupling



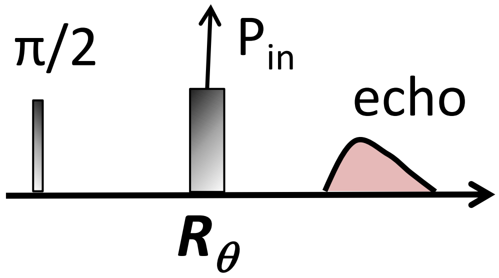
B$_1$ field

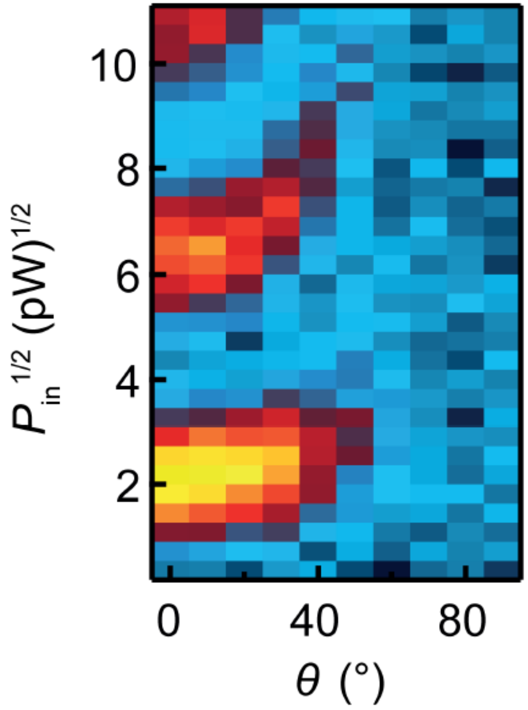




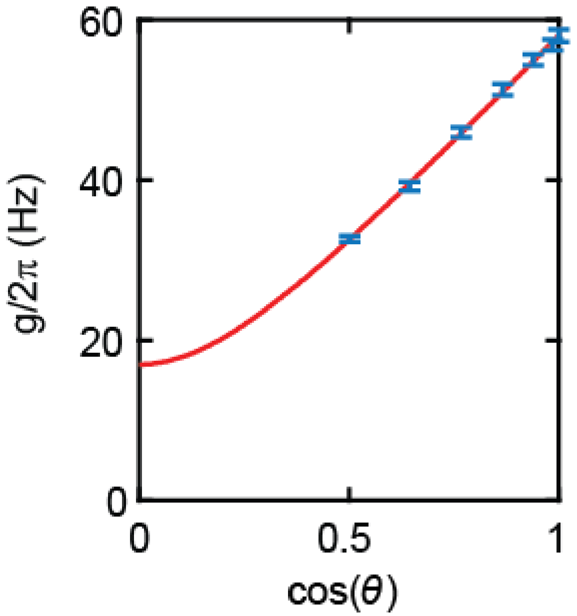
$$g = -\gamma_e \langle 1|S_x|0\rangle \delta B_{1,\perp} \quad \Longrightarrow \quad g(\theta)\ \alpha\ \sqrt{\delta B_{1y}^2 \cos^2\theta + \delta B_{1z}^2}$$

Control by tuning the spin-resonator coupling

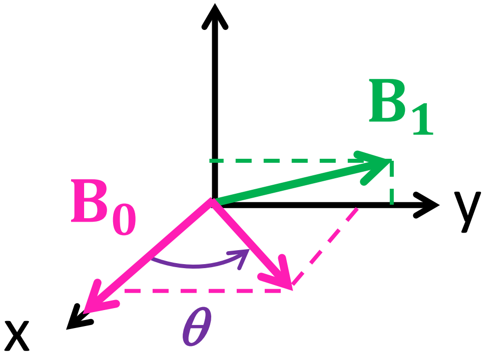




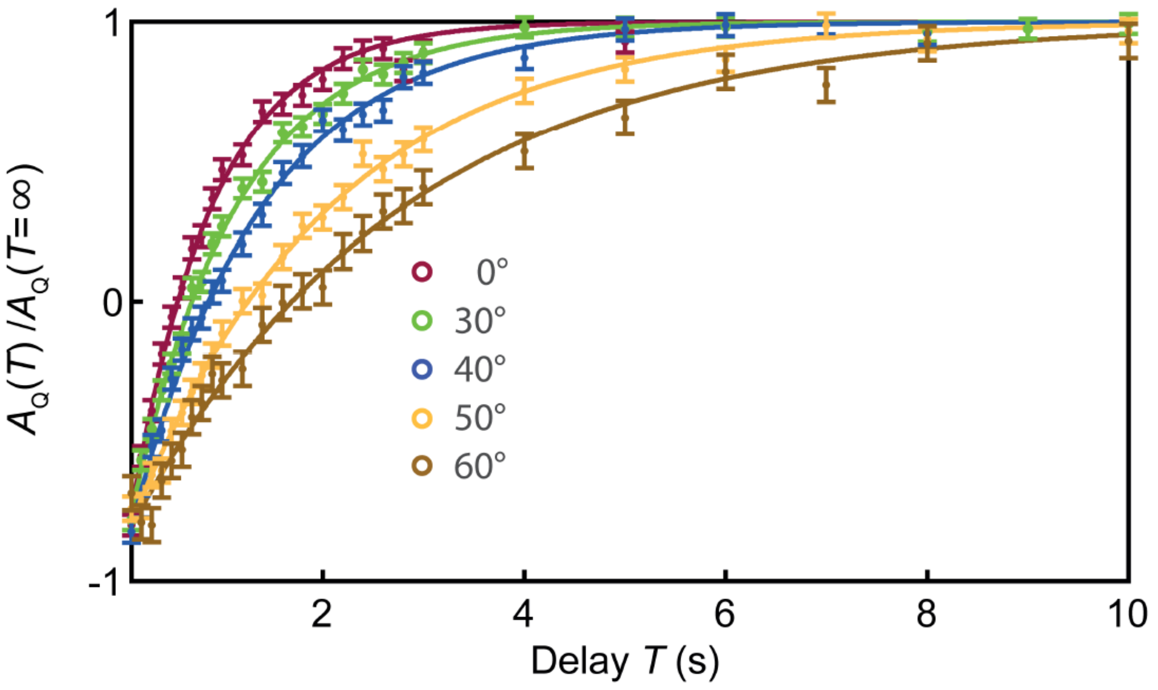
$$\Omega_R(\theta) = 2g(\theta)\sqrt{\bar{n}}$$

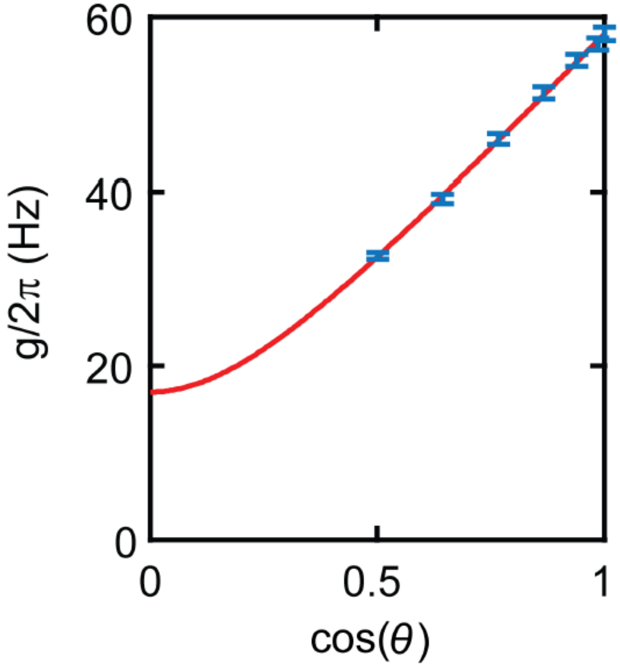


with $g(\theta) = \sqrt{g_y^2 \cos^2\theta + g_z^2}$



Control by tuning the spin-resonator coupling

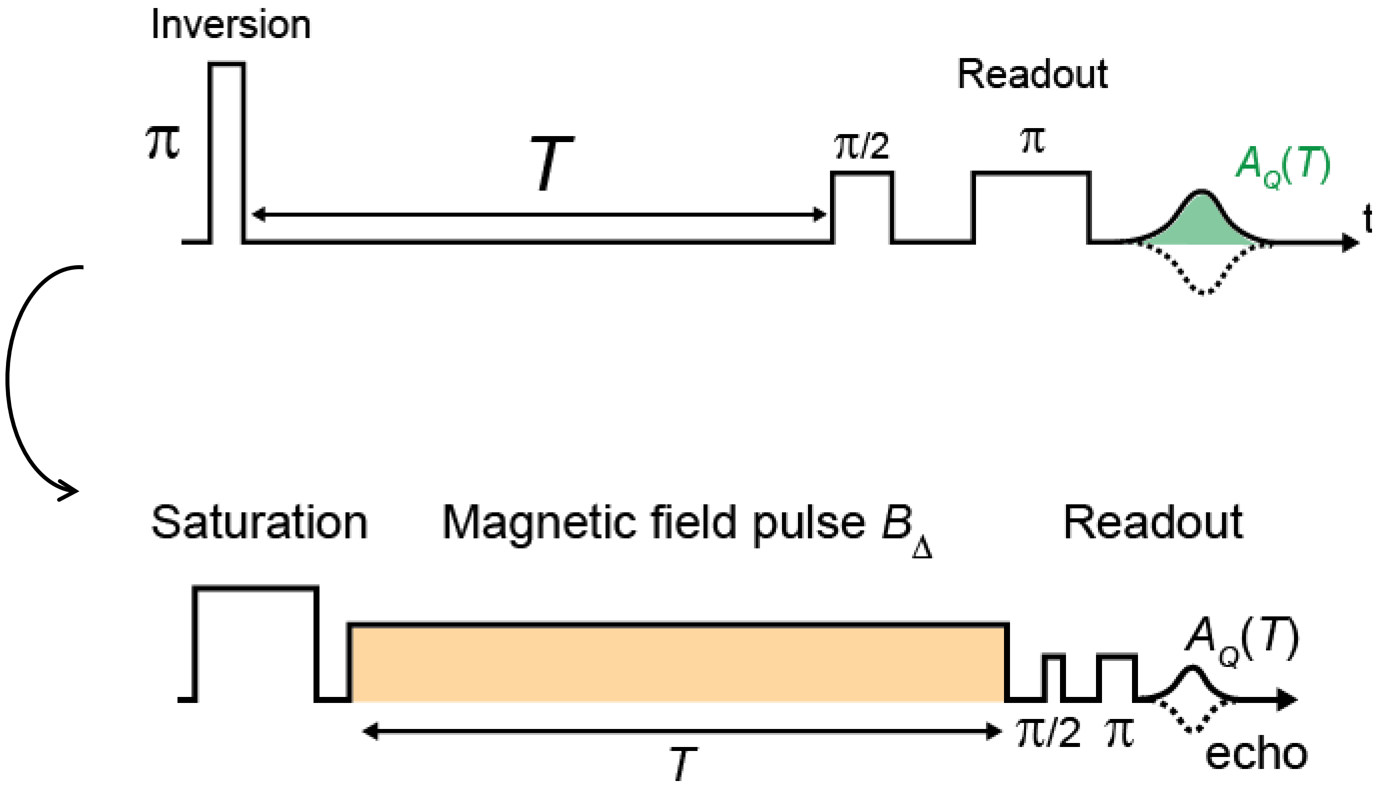




with $g(\theta) = \sqrt{g_y^2 \cos^2 \theta + g_z^2}$

and as expected from formula $\Gamma(\theta) = \dfrac{4g^2(\theta)}{\kappa}$

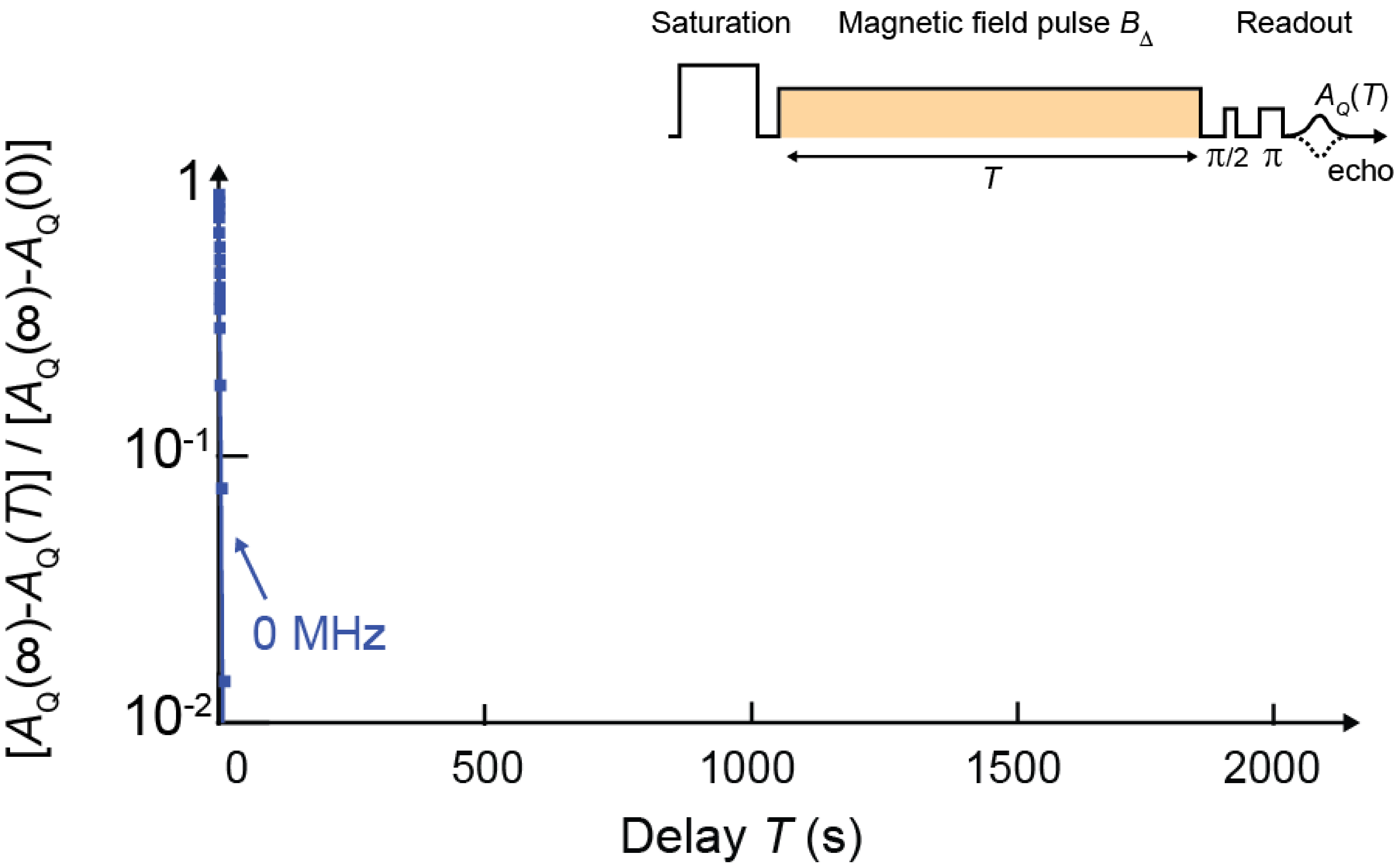
Control by spin-resonator detuning



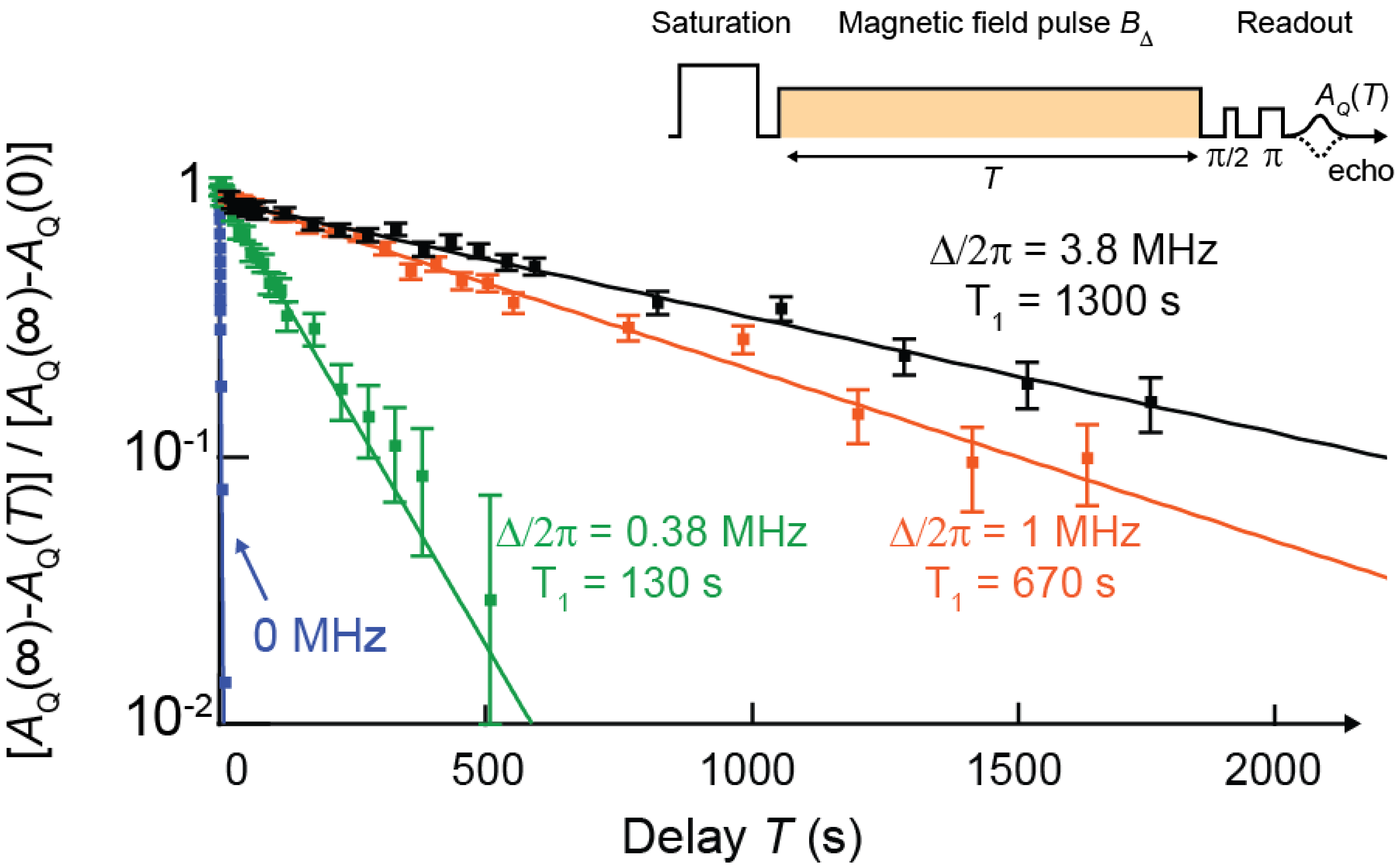
Total magnetic field $B_0 + B_\Delta$

Spins detuned during T from cavity by $\Delta = B_\Delta \times \left|\frac{\partial \omega_s}{\partial B}\right|$

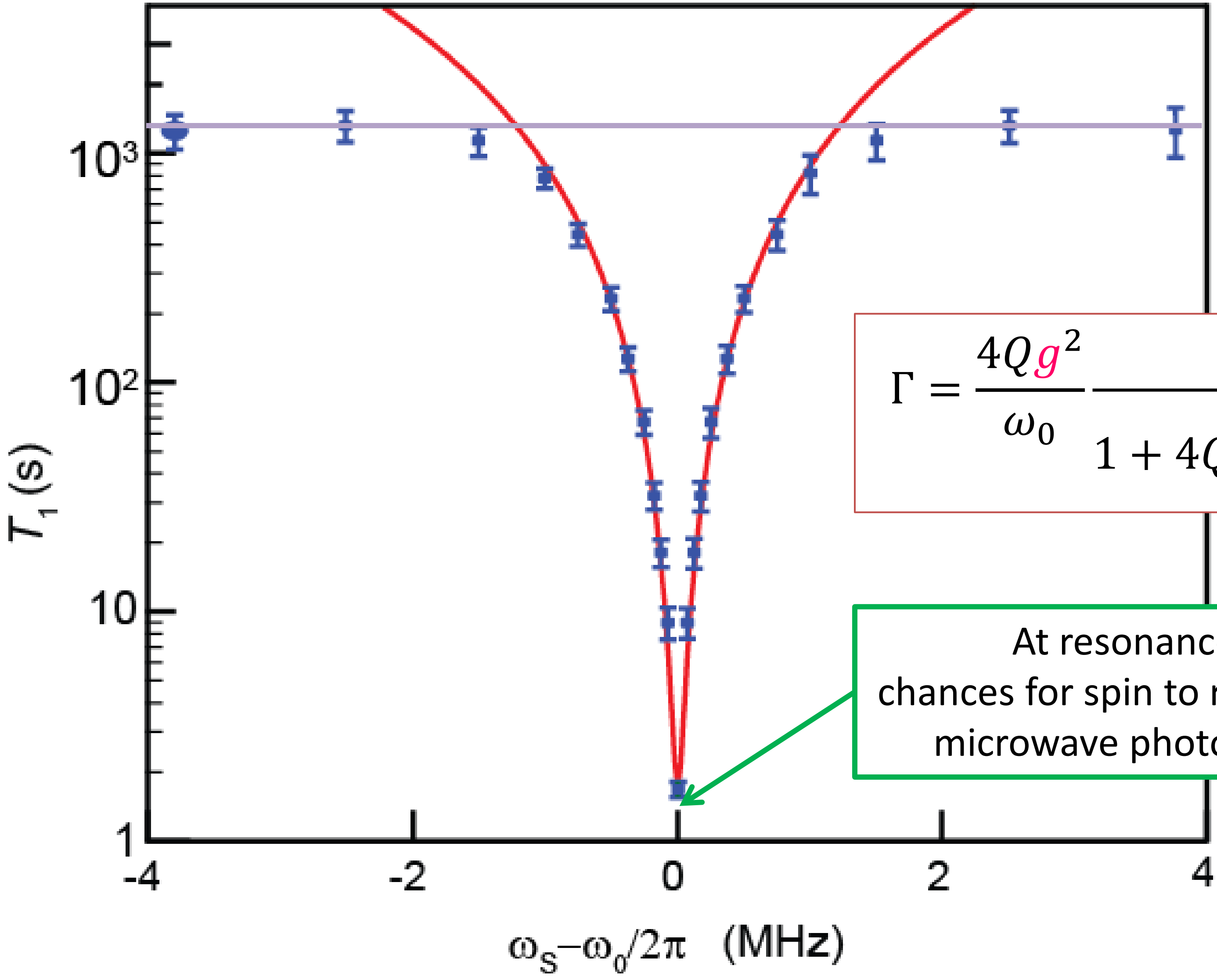
Control by spin-resonator detuning



Control by spin-resonator detuning



Detuning dependence of relaxation time



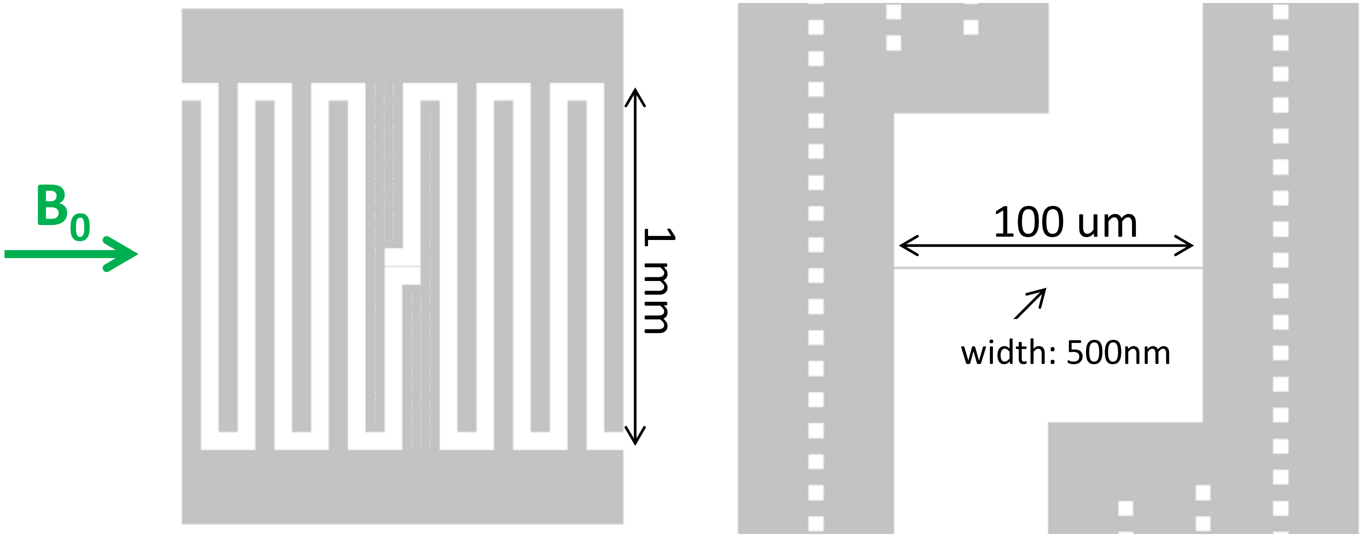
$$\Gamma_{NR} = (1500s)^{-1}$$

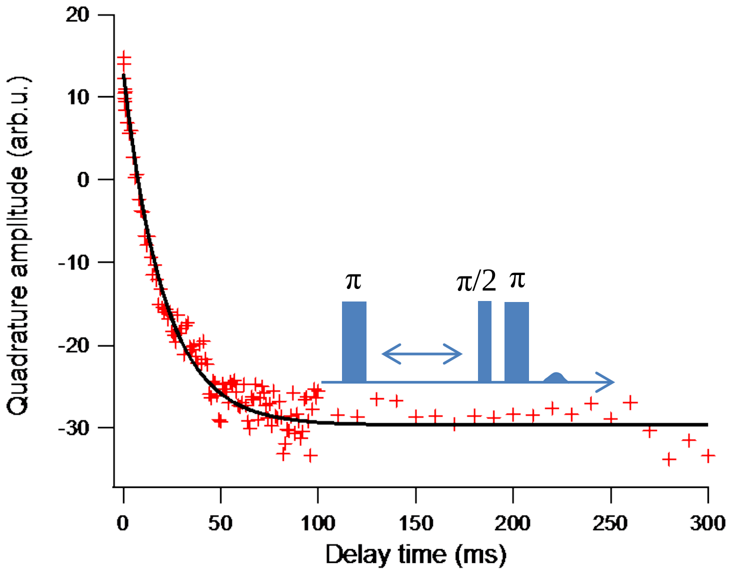
$$\Gamma = \frac{4Qg^2}{\omega_0}\frac{1}{1+4Q^2\left[\frac{\omega_s-\omega_0}{\omega_0}\right]^2}$$

At resonance, 99.9% chances for spin to relax by emitting microwave photon into cavity

A. Bienfait et al., Nature (2016)

Larger coupling, shorter T1





T_1 = 21 ms
$g/2\pi$ = 440 Hz

S. Probst et al. (2016)

Conclusions & Perspectives

First observation of Purcell-enhanced relaxation for electronic spins

- Universal initialization for electronics spins
- Tunable over three orders of magnitude

$\Rightarrow$ with a 30nm wire, $g/2\pi$ = 4kHz could be reached, yielding $T_1 \approx$ 200 μs. Sufficient sensitivity for single-spin detection

A. Bienfait et al., Controlling spin relaxation with a cavity, Nature (2016)

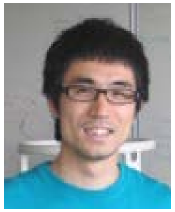
Acknowledgements

Quantronics group, CEA Saclay

D. ESTEVE

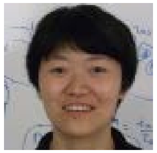
D. VION

A. BIENFAIT



Y. KUBO

S. PROBST



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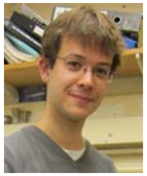

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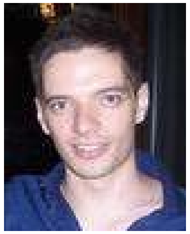
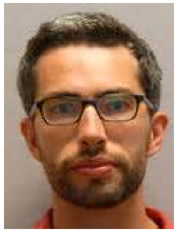


J. PLA



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POSITIONS OPEN