Circuit-QED-enhanced magnetic resonance

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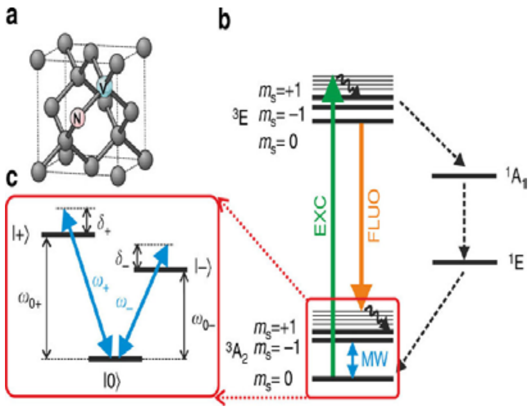
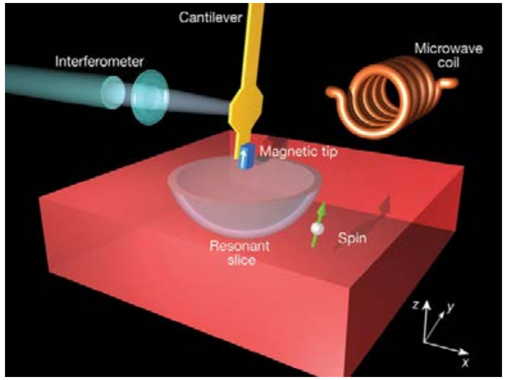
Nanoscale magnetic resonance

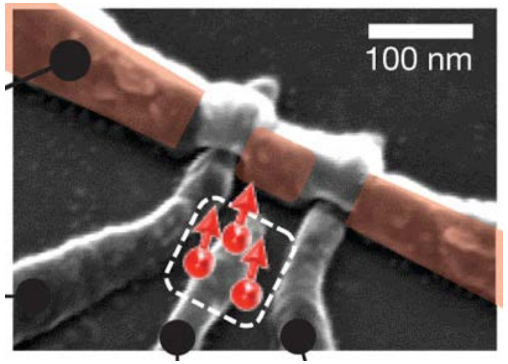
Fantastically useful but
Low sensitivity
Macroscopic samples



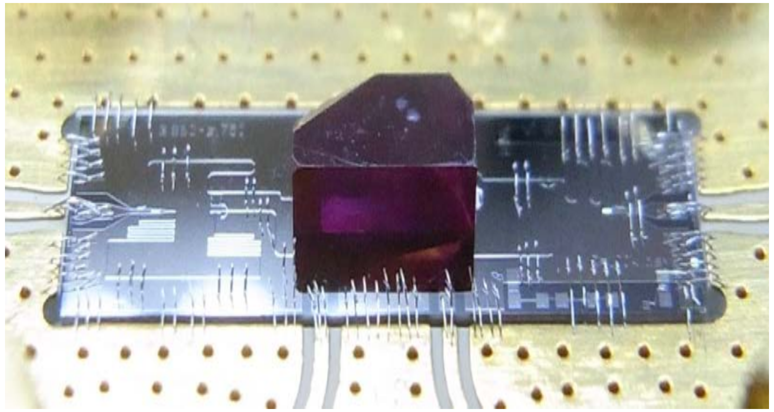
Optical detection
Nature **363**, 244 (1993)
Nat. Com. **5**, 4870 (2014)
Nat. Nano. **9**, 279 (2014)



Scanning probe
Science **350**, 417 (2015)
Nature **430**, 329 (2004)
Phys. Rev. Lett. **62**, 2531 (1989)



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



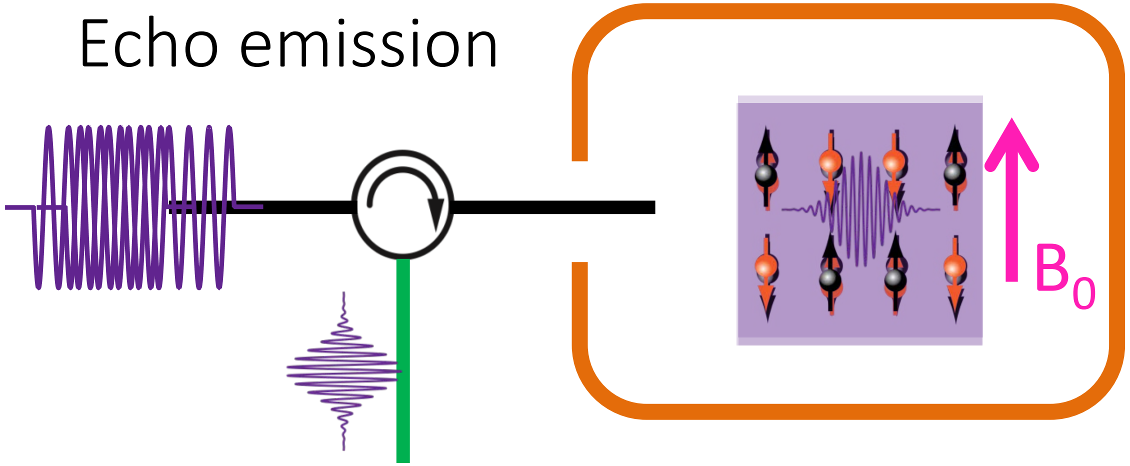
Circuit QED for electron spin resonance detection

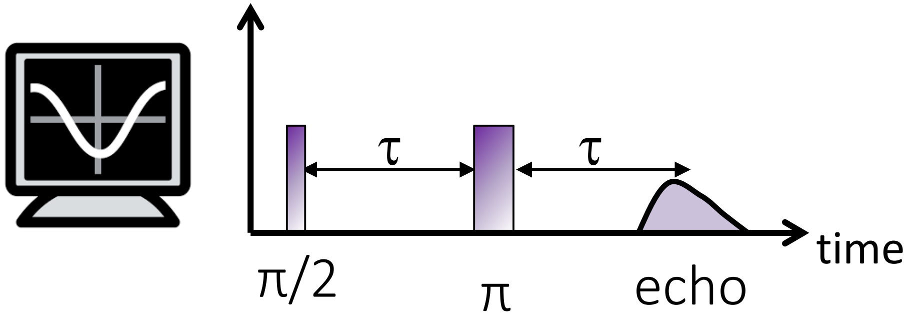
1) Principle
2) Applications :
   - Few-nuclear spin detection
   - Novel e spin hyperpolarization scheme

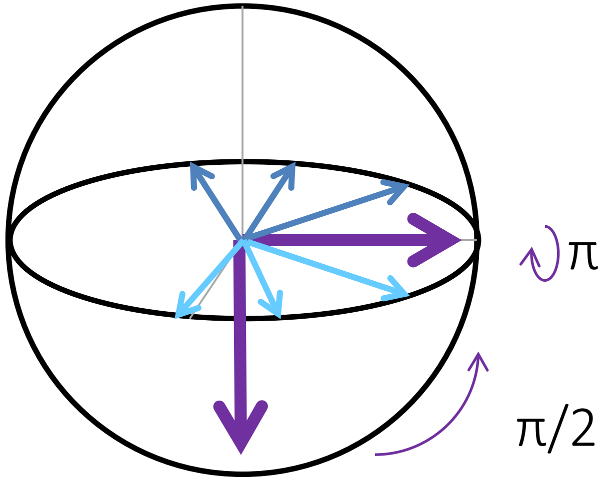
Conventional Pulsed Inductive Detection Electron Spin Resonance (ESR)

Excite spins

Echo emission

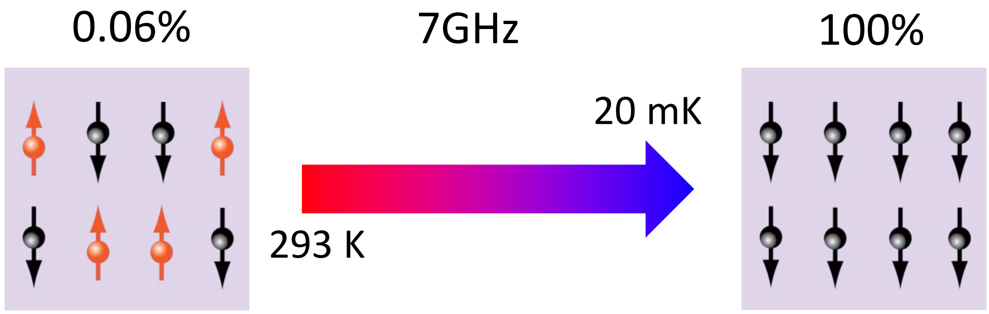




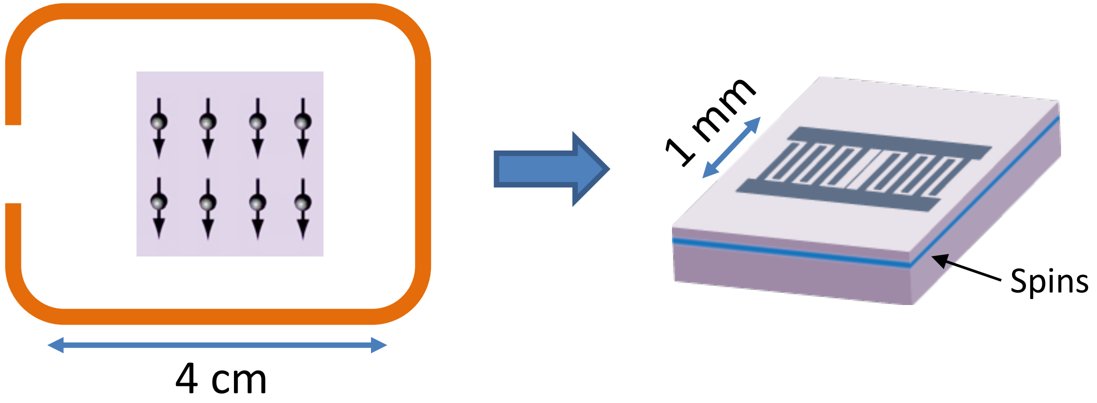


Circuit QED-enhanced ESR

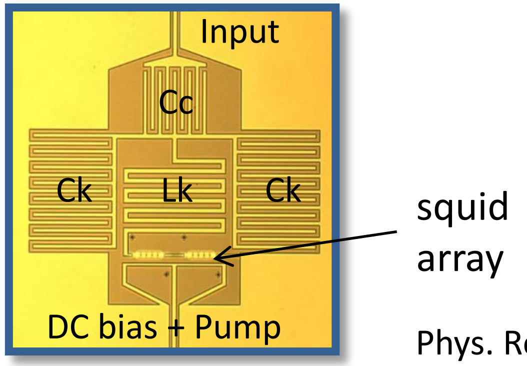
1. Low Temperature
   - *Maximum spin Polarization*
   - *No thermal noise*



2. Superconducting Micro-Resonators
   - *Large spin-MWphoton coupling g*
   - *Large quality factor Q*

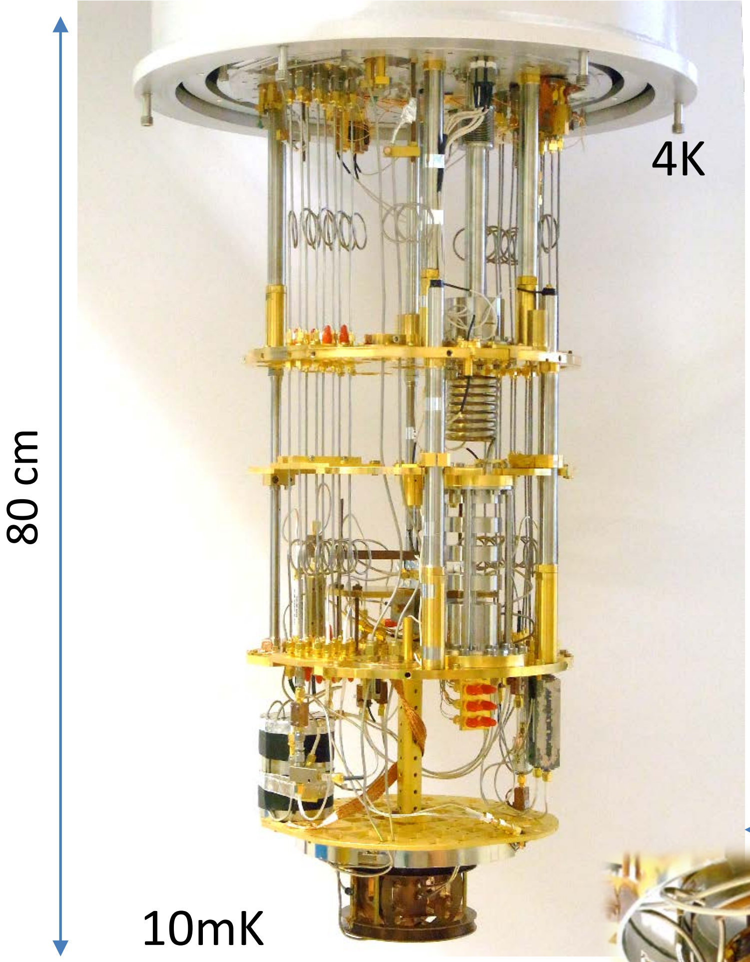


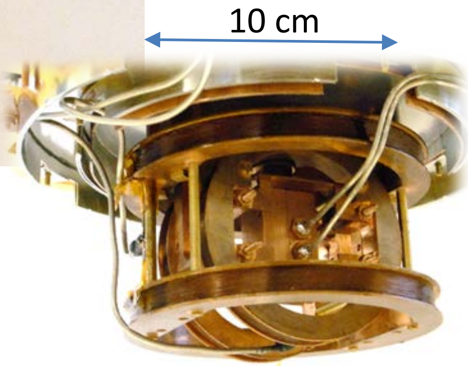
3. Quantum limited detection chain
   - *"Noiseless" amplification by superconducting Josephson Parametric Amplifier (JPA)*

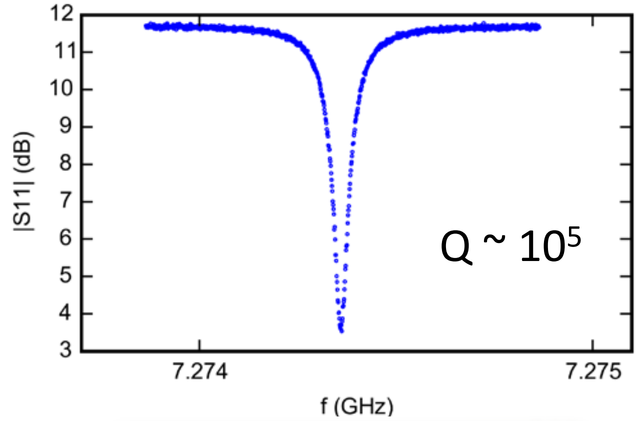


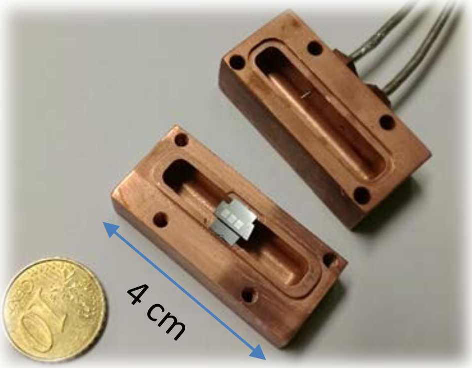
X. Zhou et al.,
Phys. Rev. B **89**, 214517 (2014)

Circuit QED-enhanced ESR : setup

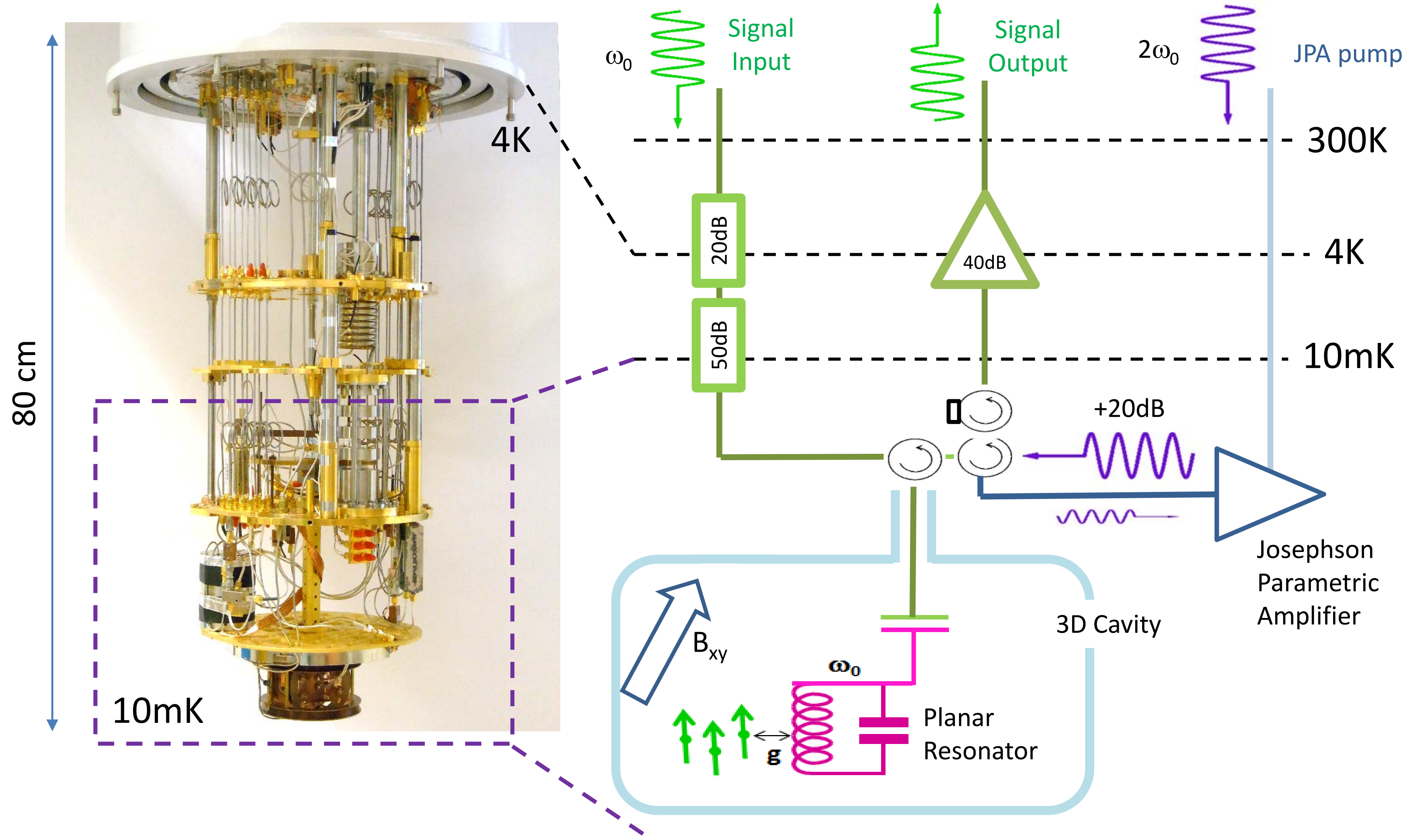




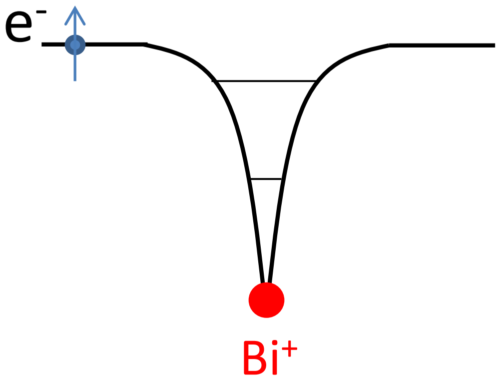


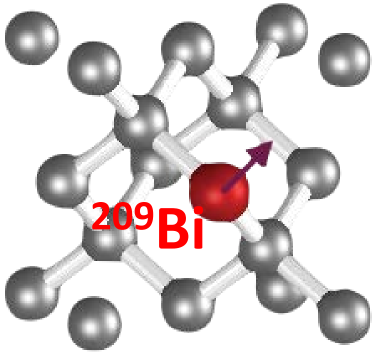


Circuit QED-enhanced ESR : setup



Bismuth donors in silicon





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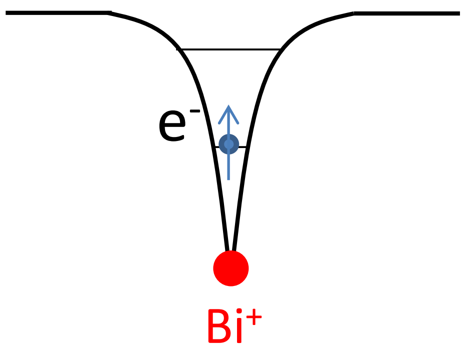
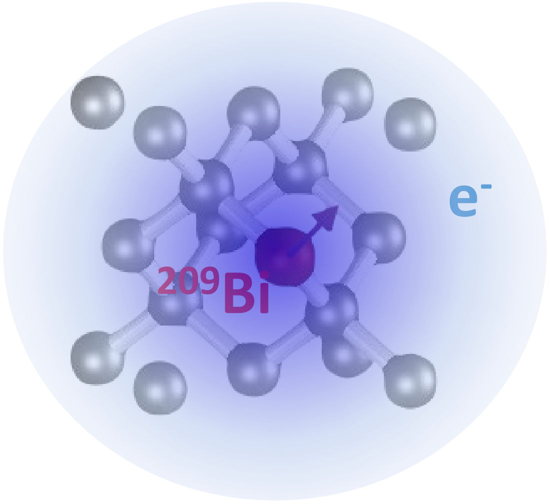




$$\frac{H}{\hbar} = A\boldsymbol{I} \cdot \boldsymbol{S} + \boldsymbol{B_0} \cdot (-\gamma_e \boldsymbol{S} - \gamma_n \boldsymbol{I})$$

HYPERFINE **ZEEMAN EFFECT**

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

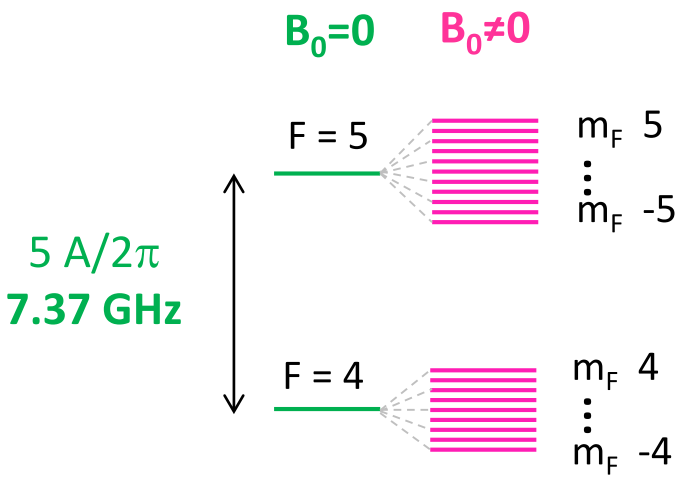
} 20 electro-nuclear states

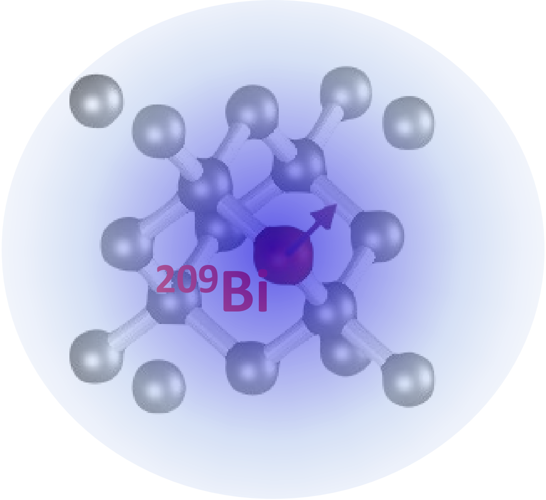
- Large hyperfine coupling $\frac{A}{2\pi} = 1.4754\text{GHz}$

Bismuth donors in silicon

At low-field

$$F = I \pm S$$
$$m_F = m_S + m_I$$
$$m_F = -F \ldots F$$





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

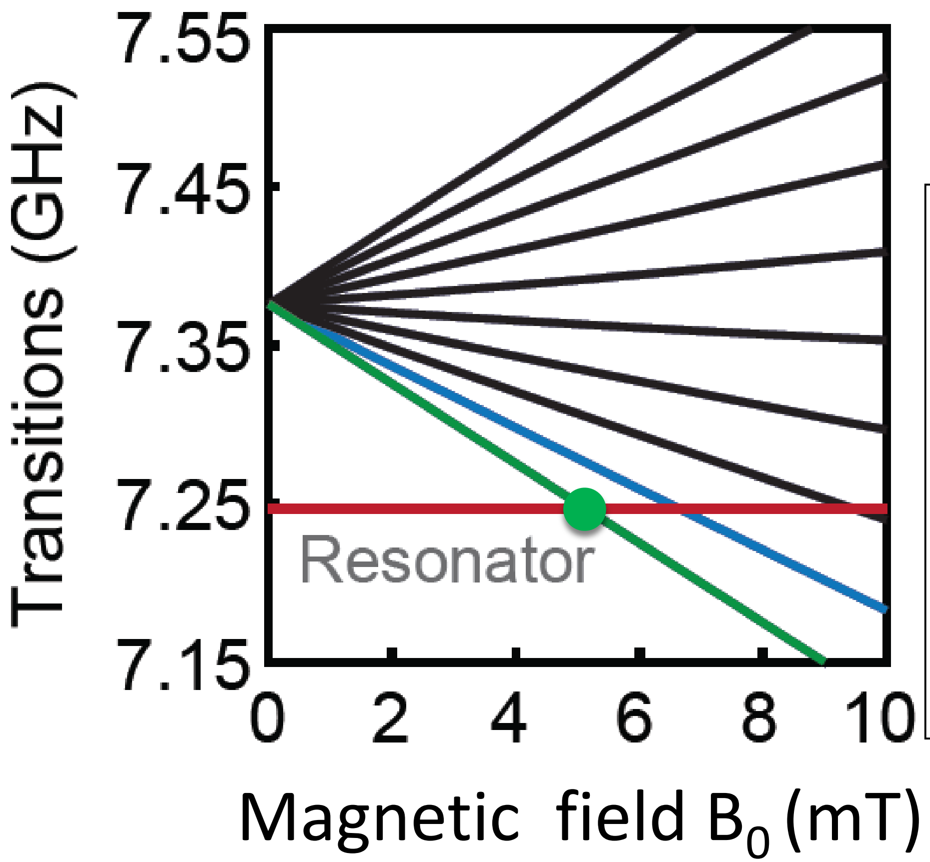
HYPERFINE ZEEMAN EFFECT

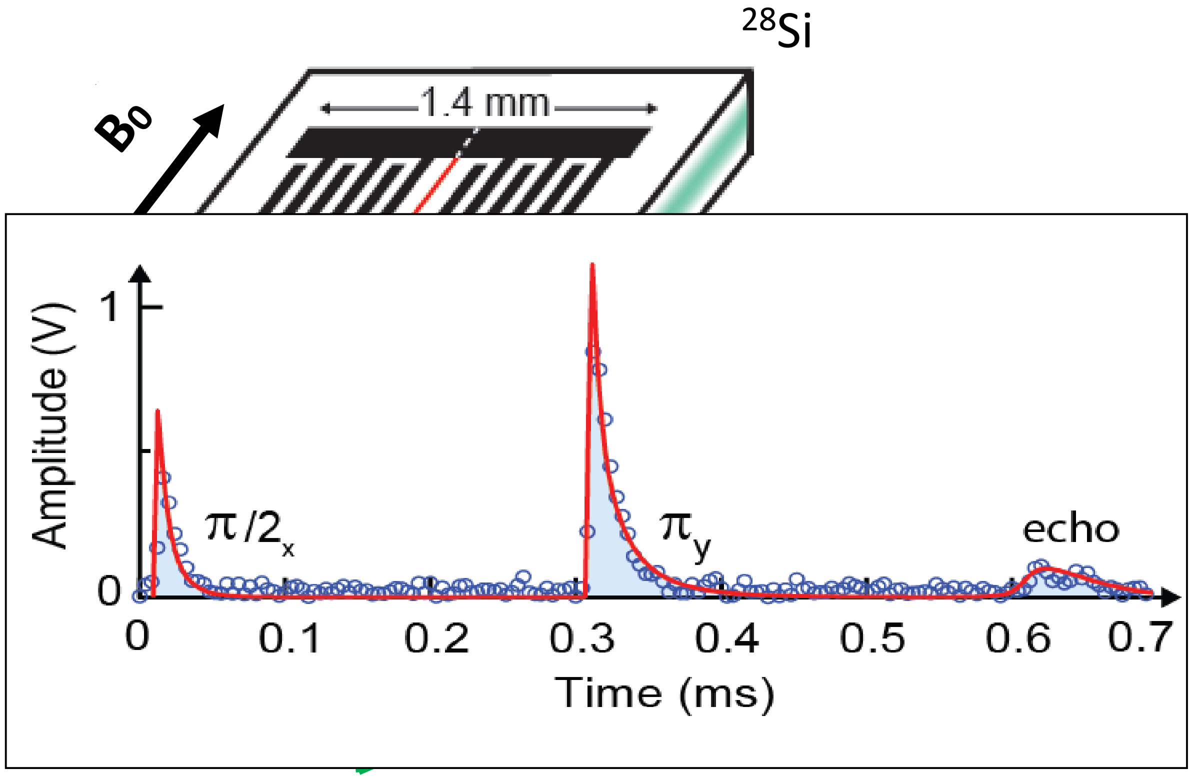
- Nuclear spin I=9/2
- Electronic spin S=1/2
- Large hyperfine coupling $\frac{A}{2\pi} = 1.48$ GHz

RE George *et al.*, Phys Rev Lett **105** 067601 (2010); GW Morley *et al.* Nature Materials **9** 725 (2010)

Bismuth donors in silicon

10 allowed ESR-like transitions @ low B_0

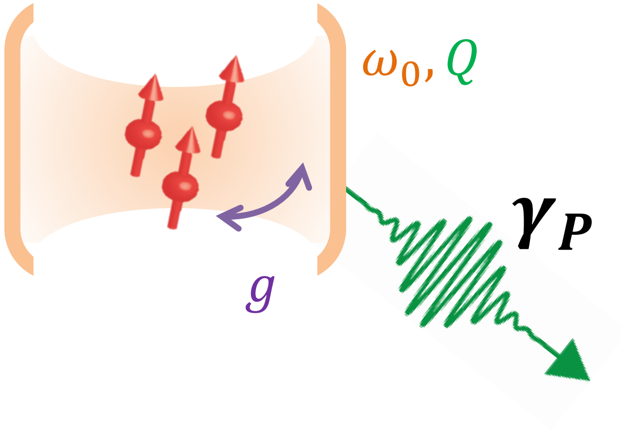




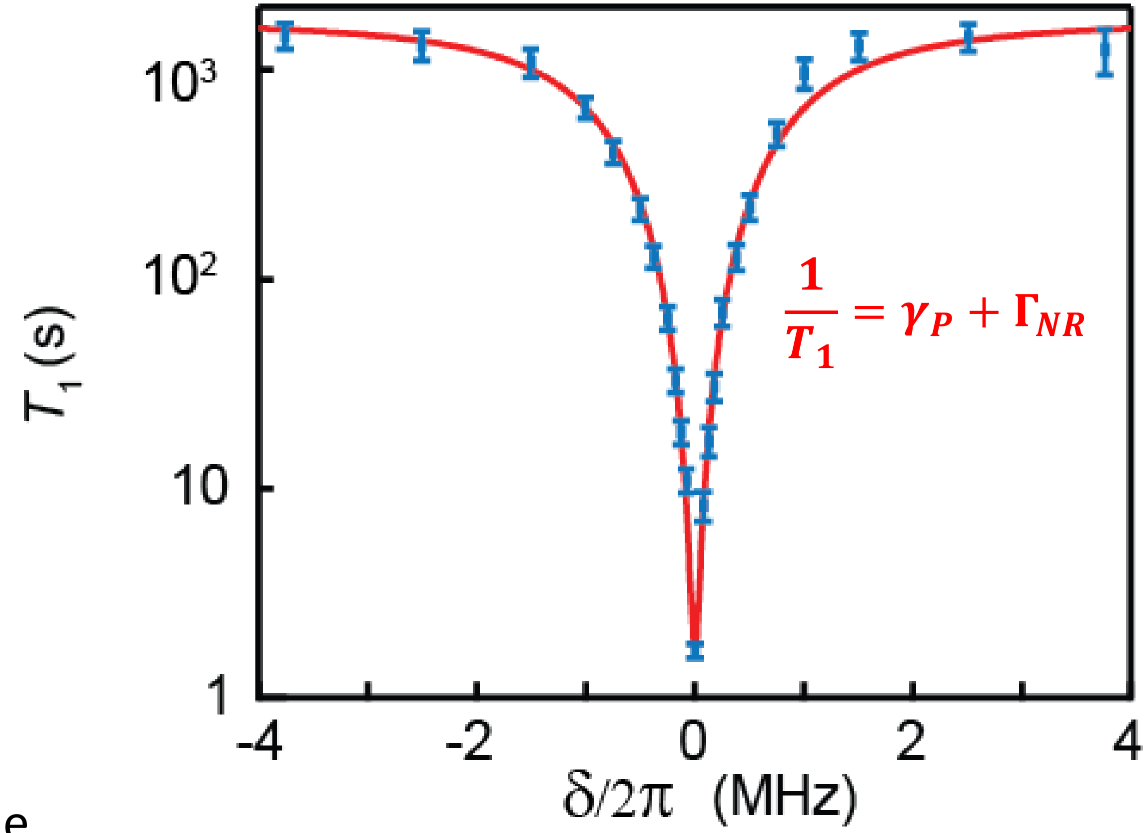
Implanted Bismuth

- $m_F = 4 \rightarrow m_F = 5$, @~5 mT

Spin relaxation by spontaneous emission through the cavity



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



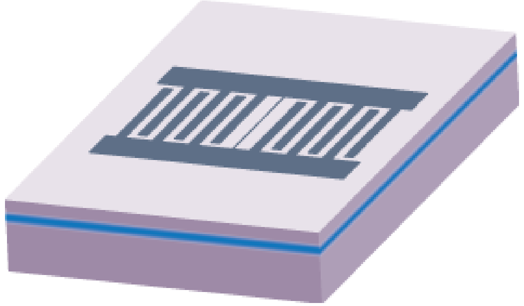
At resonance, $\gamma_P = 4Qg^2/\omega_0$
Direct experimental determination of the spin-photon coupling constant

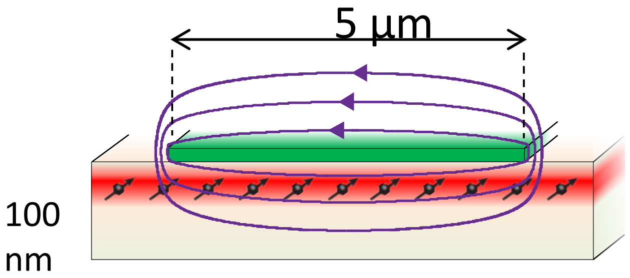
$$\frac{g}{2\pi} = 60 \pm 10\text{Hz}$$

A. Bienfait et al., Nature (2016)

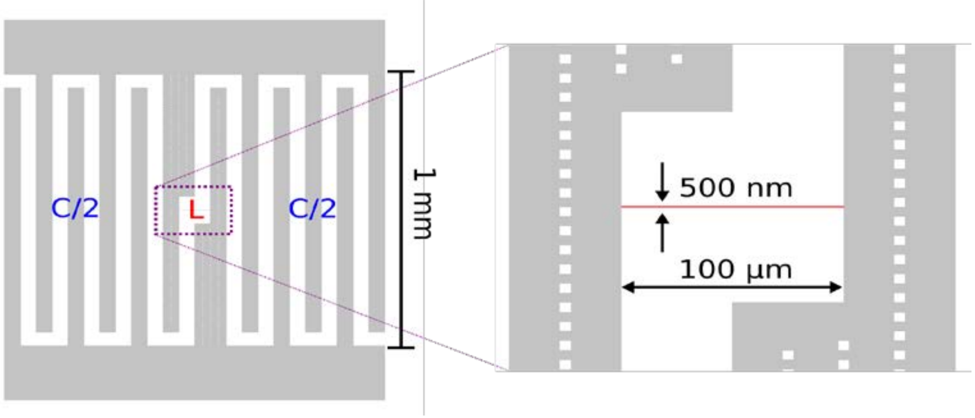
Reducing the magnetic mode volume to enhance the coupling

L=1mm
w=5µm
$V \simeq 20pL$

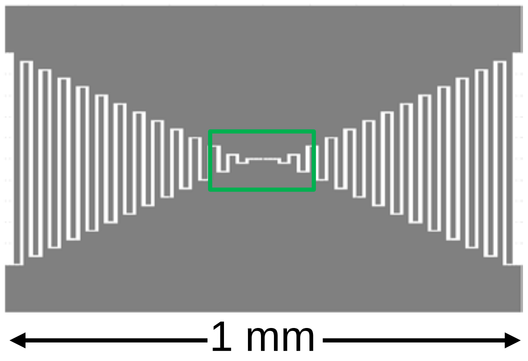


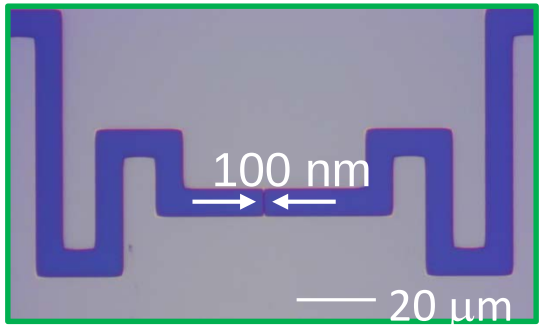


L=0.1mm
w=0.5µm
$V \simeq 200fL$



L=10µm
w=0.1µm
$V \simeq fL$





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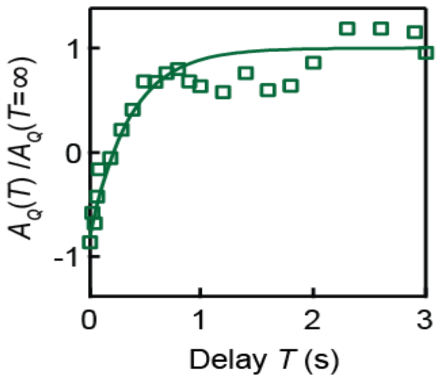
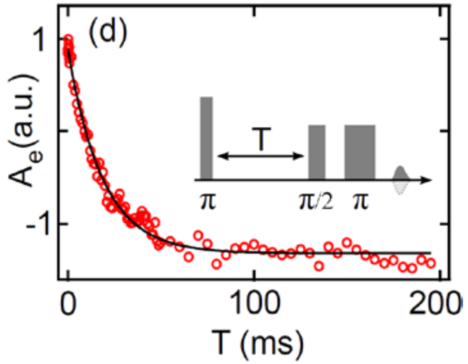


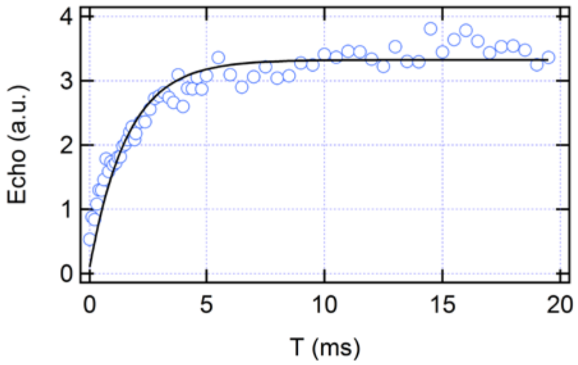
$T_1 = 0.4s$
$\frac{g}{2\pi} = 50Hz$
2000spin/√Hz

L=0.1mm
w=0.5μm
$V \simeq 200fL$



$T_1 = 20ms$
$\frac{g}{2\pi} = 400Hz$
65spin/√Hz

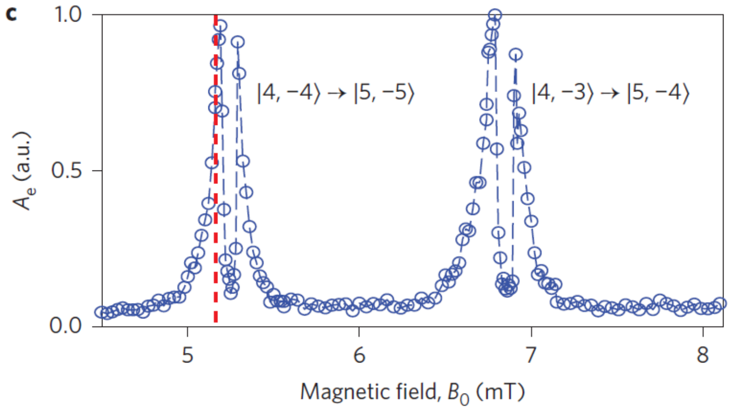
L=10μm
w=0.1μm
$V \simeq fL$

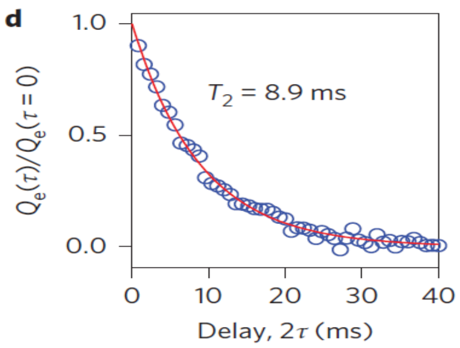


$T_1 = 1.3ms$
$\frac{g}{2\pi} = 3kHz$
10spin/√Hz

Effect on the spin linewidth and coherence time

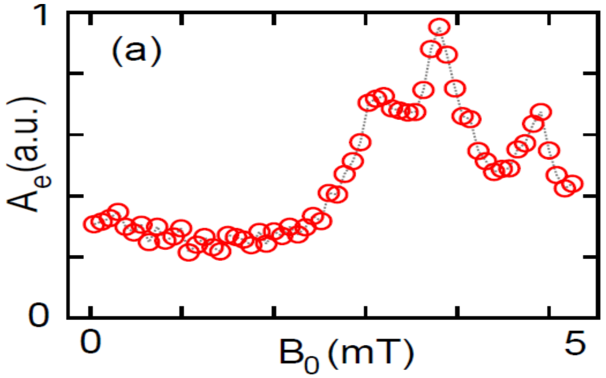
L=1mm
w=5μm
$V \simeq 20pL$

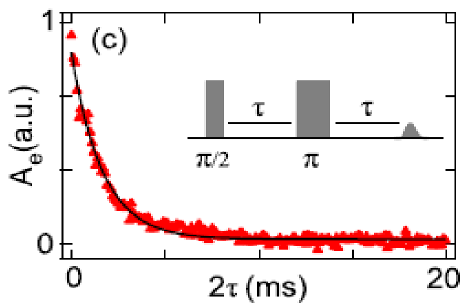




$\Gamma \simeq$ 3MHz
T_2 = 9ms

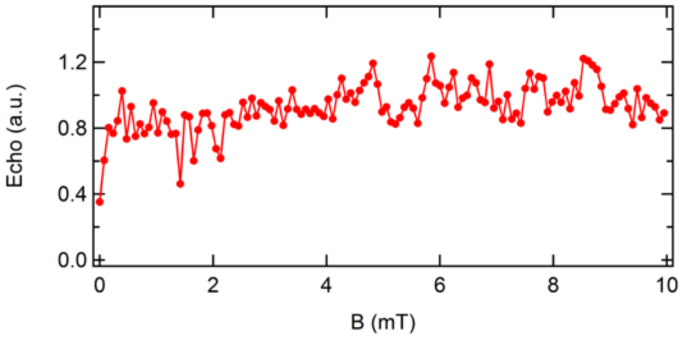
L=0.1mm
w=0.5μm
$V \simeq 200fL$

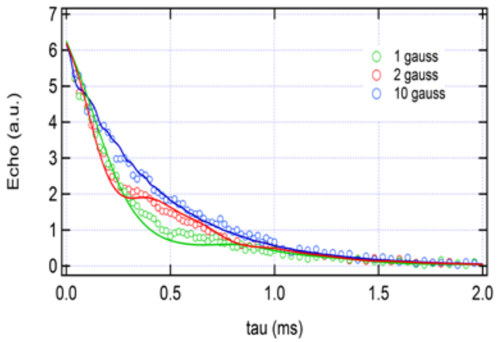




$\Gamma \simeq$ 30MHz
T_2 = 2ms

L=10μm
w=0.1μm
$V \simeq fL$



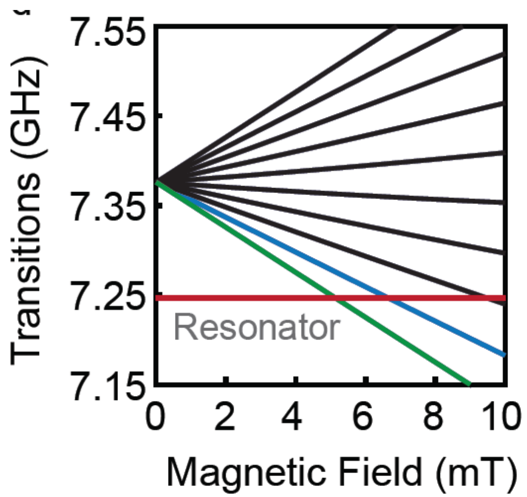


$\Gamma \simeq$ 100MHz ?
T_2 = 0.9ms

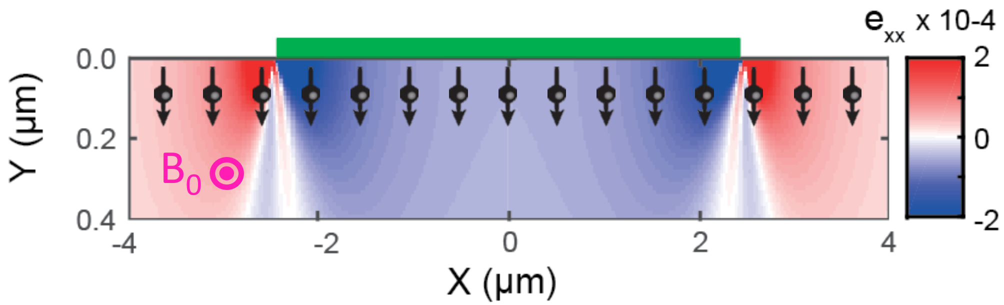
Broadening mechanisms

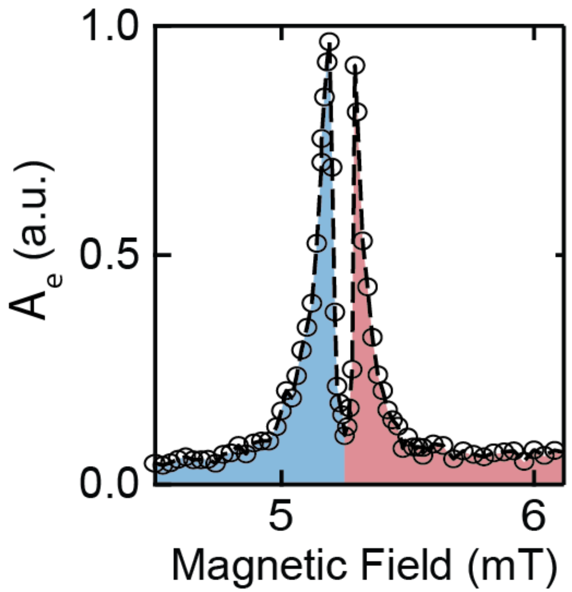
$$\frac{H}{\hbar} = A\boldsymbol{I} \cdot \boldsymbol{S} + \boldsymbol{B_0} \cdot (-\gamma_e \boldsymbol{S} - \gamma_n \boldsymbol{I})$$

$A(E, e)$: spin line broadening if inhomogeneous electric or strain fields



Strain induced by the aluminum wire on the underlying silicon substrate due to differential thermal contraction during cooldown

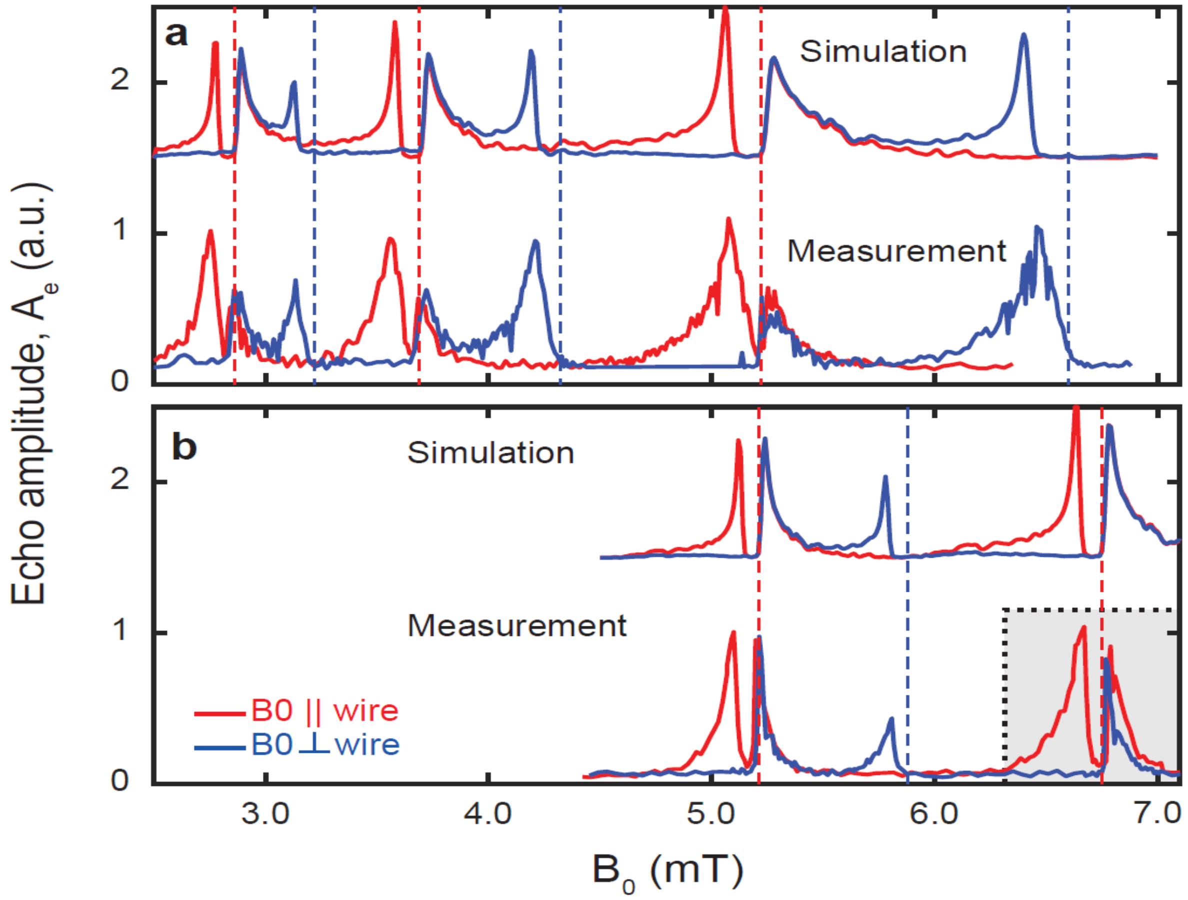




At low strain, $A = K/3\ (e_{xx} + e_{yy} + e_{zz})$ with $K = 19\text{GHz}$

J. Mansir et al., arxiv (2017)

Understanding lineshapes



Strain profile

⇩

Hyperfine shift

⇩

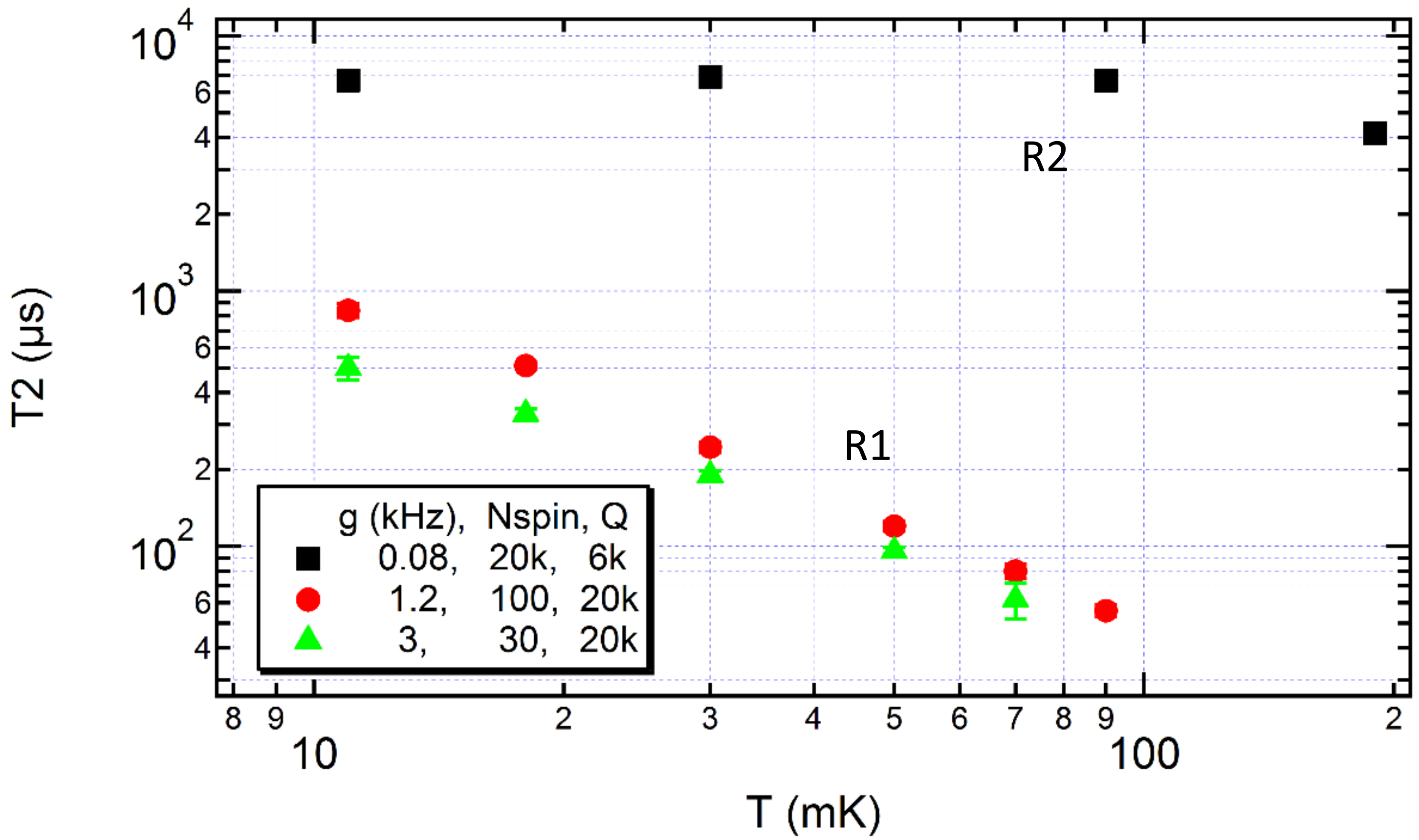
Simulated spectrum
w/o adjustable parameter (J. Pla)

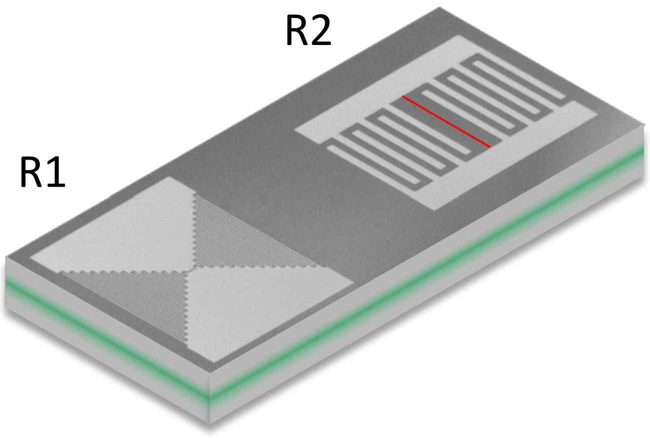
J. Pla et al.,
Phys. Rev Appl. (2018)

- Strain broadening : quantitative understanding for 5μm-wide wires
  ....but only qualitative for narrower wires. Extra shifts due to stray electric fields ?

- Observed reduction in T_2 for increased spin-resonator coupling ??

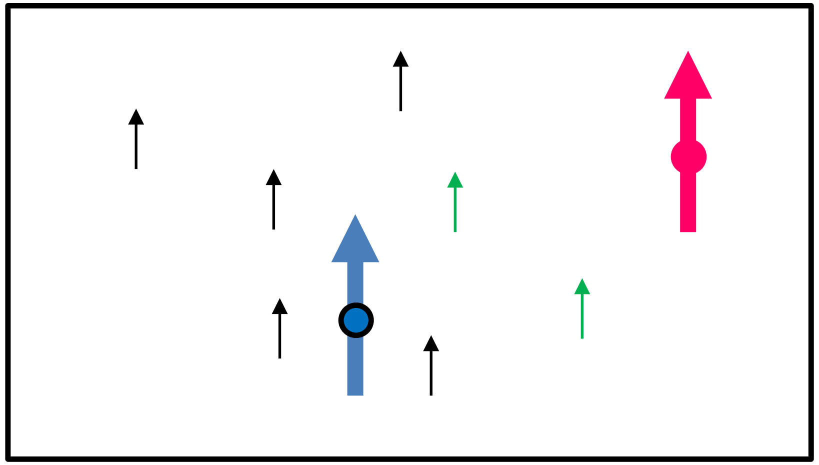
Temperature dependence of T2





- Unexplained temperature dependence of T2. Similar data obtained by H. Huebl's group (TUMunchen)
- Non-trivial resonator-induced decoherence mechanism ?

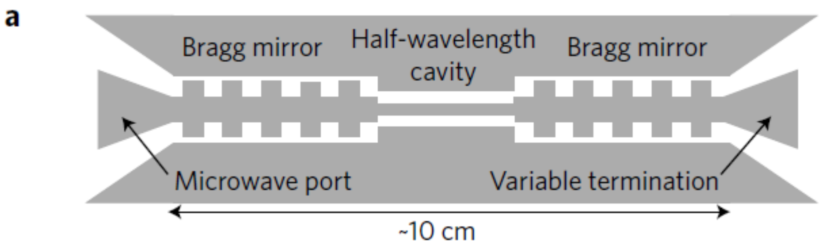
Accessing the electron spin magnetic environment

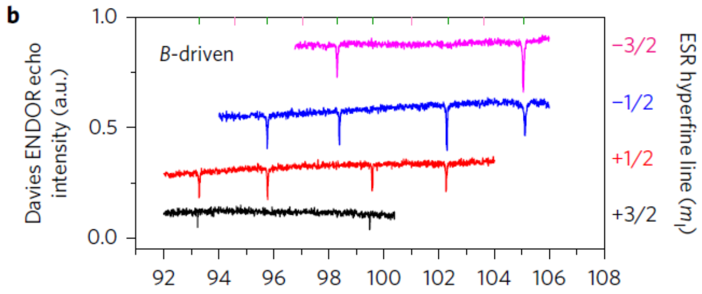


EPR spectroscopy gives acess to electron spin environment

using pulse sequences such as ENDOR, ELDOR, DEER, ESEEM, …

Can we do this with quantum-limited spectrometer ?

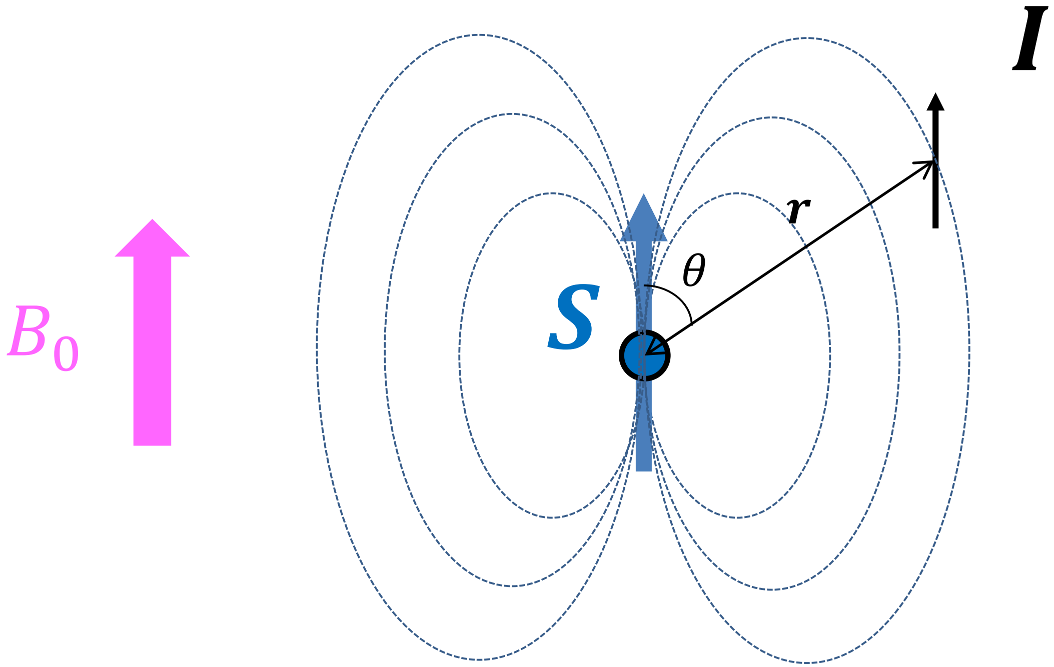




Davies ENDOR with superc. μresonator

Sigillito et al., Nature Nano (2017)

Electron Spin Echo Envelope Modulation (ESEEM)



Electron spin S=1/2
Nuclear spin I=1/2

Dipolar Hyperfine Constant

$$T = \frac{\mu_0}{4\pi} \frac{g_e g_n \beta_e \beta_n}{h r^3}$$

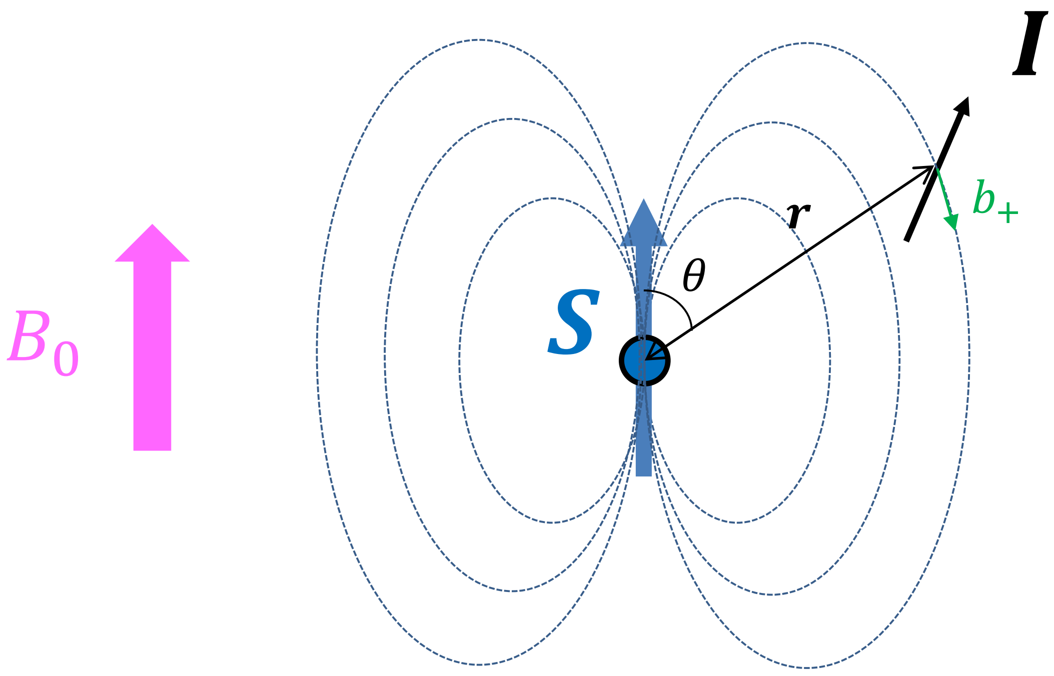
$$A = T(3\cos^2\theta - 1)$$
$$B = 3T \sin\theta \cos\theta$$

Dipolar hyperfine Hamiltonian

$$H = \omega_e S_z + \omega_n I_z + A\, S_z I_z + B\, S_z I_x$$

Rowan, Hahn, Mims, Phys. Rev. A (1965)
W.B. Mims, Phys. Rev. B (1972)

Electron Spin Echo Envelope Modulation (ESEEM)



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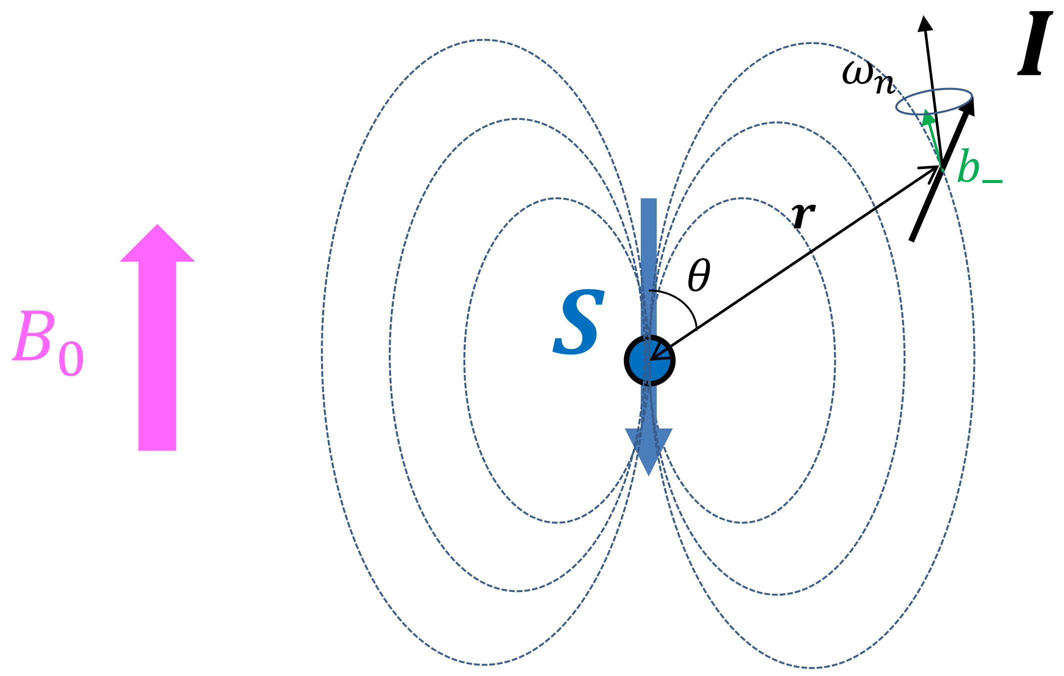

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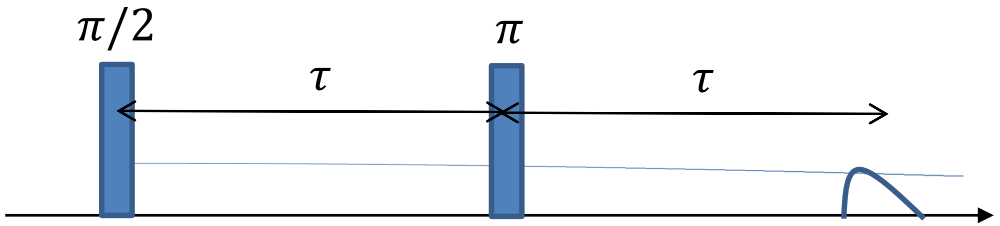
Dipolar hyperfine Hamiltonian

$$H = \omega_e S_z + \omega_n I_z + A\,S_z I_z + B\,S_z I_x$$

$\tau \ll 2\pi/\omega_n$



Rowan, Hahn, Mims, Phys. Rev. A (1965)
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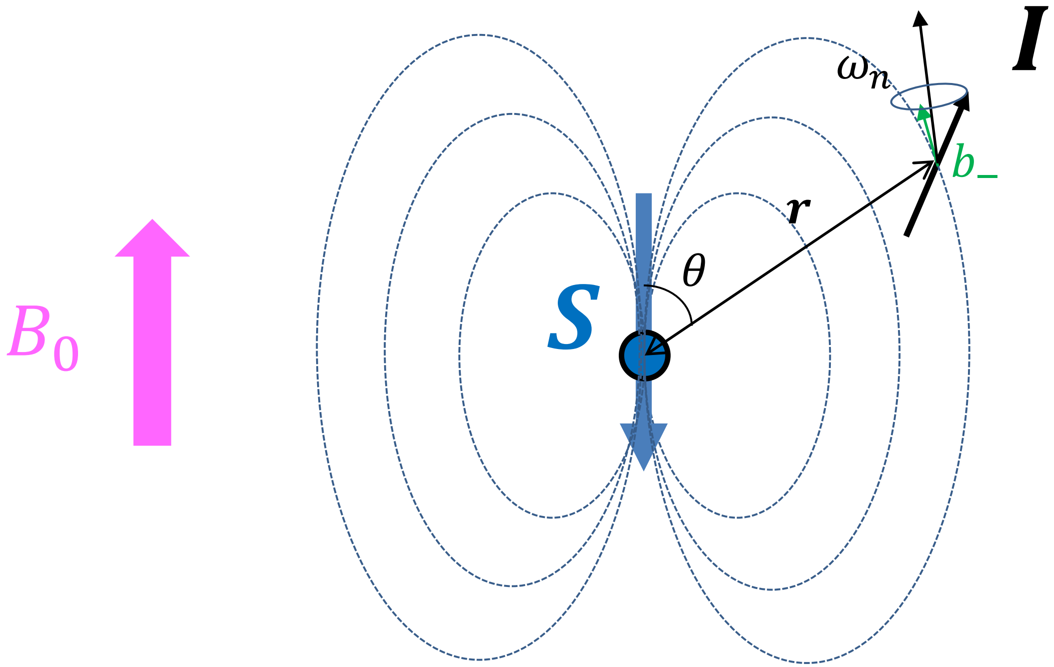

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Nuclear spin I=1/2

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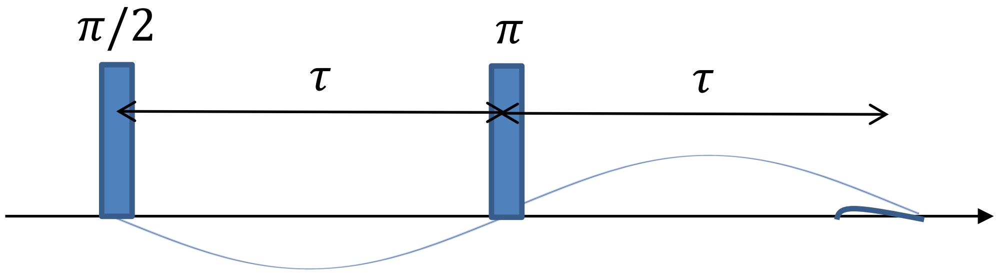
Dipolar hyperfine Hamiltonian

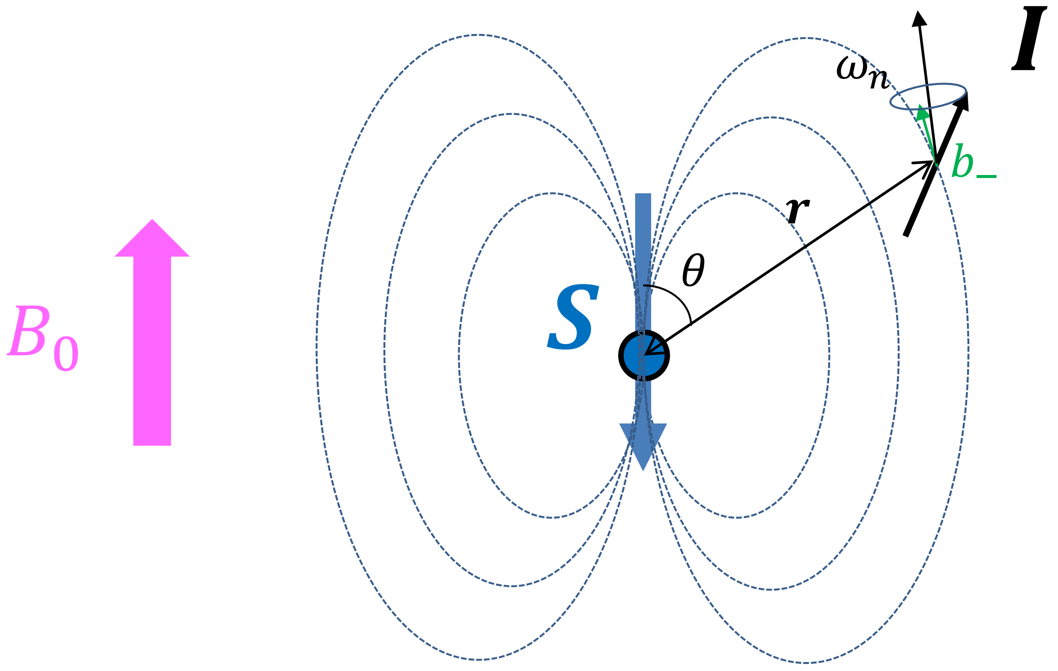
$$H = \omega_e S_z + \omega_n I_z + A\, S_z I_z + B\, S_z I_x$$

$\tau = \pi/\omega_n$ Suppressed echo

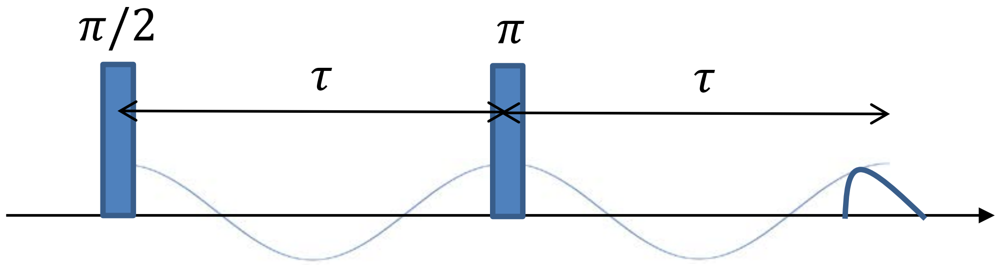


Rowan, Hahn, Mims, Phys. Rev. A (1965)
W.B. Mims, Phys. Rev. B (1972)

Electron Spin Echo Envelope Modulation (ESEEM)



$\tau = 2\pi/\omega_n$ Echo recovery



Electron spin S=1/2
Nuclear spin I=1/2

Dipolar Hyperfine Constant

$$T = \frac{\mu_0}{4\pi}\frac{g_e g_n \beta_e \beta_n}{h r^3}$$

$$A = T(3\cos^2\theta - 1)$$
$$B = 3T\sin\theta\cos\theta$$

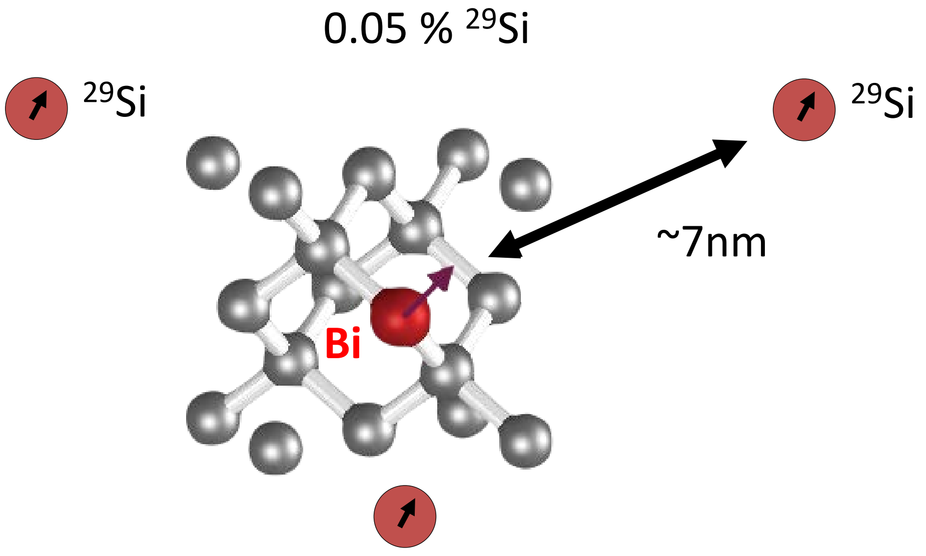
Dipolar hyperfine Hamiltonian

$$H = \omega_e S_z + \omega_n I_z + A\, S_z I_z + B\, S_z I_x$$

- Modulation of spin-echo envelope at $\approx \omega_n$
- Modulation amplitude $\sim \left(\frac{B(\theta)}{\omega_n}\right)^2$

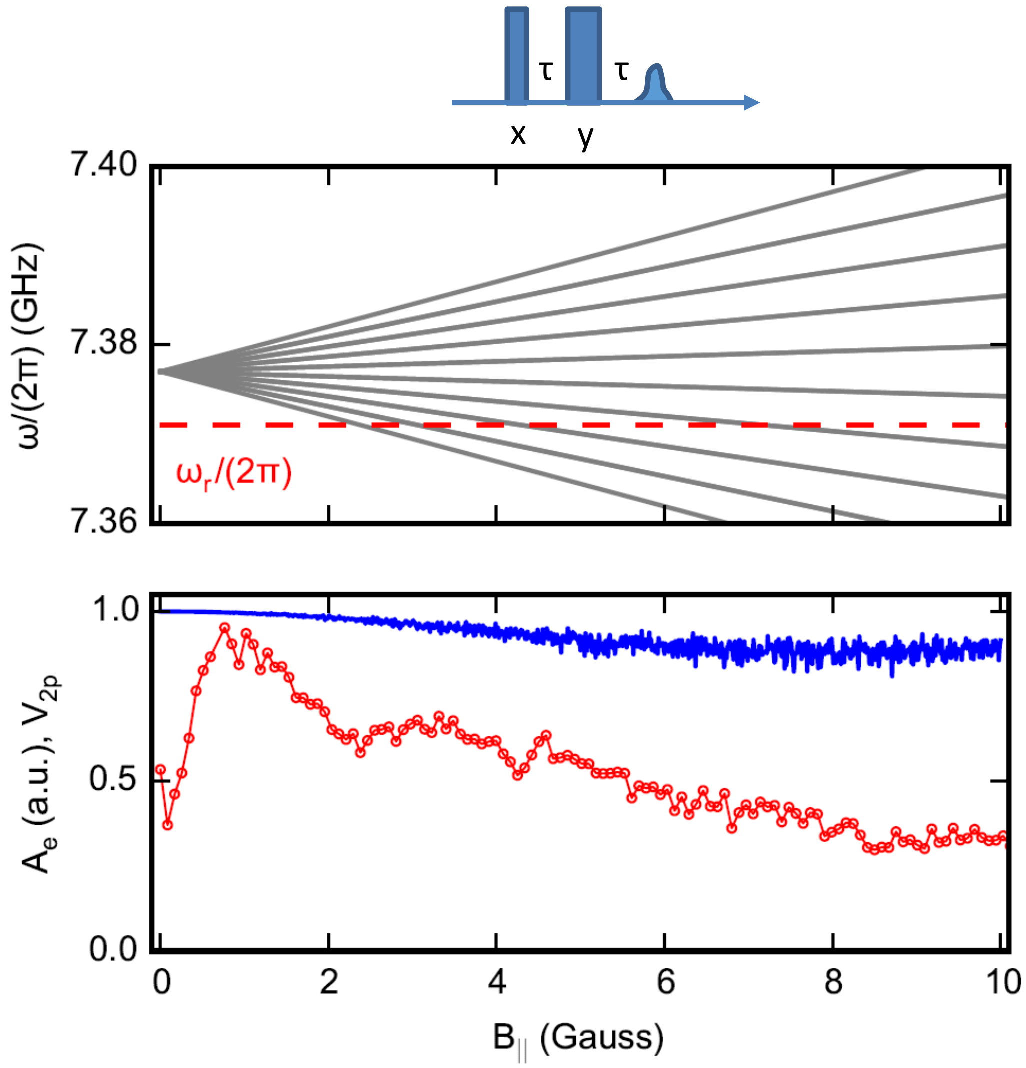
Rowan, Hahn, Mims, Phys. Rev. A (1965)
W.B. Mims, Phys. Rev. B (1972)

Detecting residual ^{29}Si nuclear spins through ESEEM

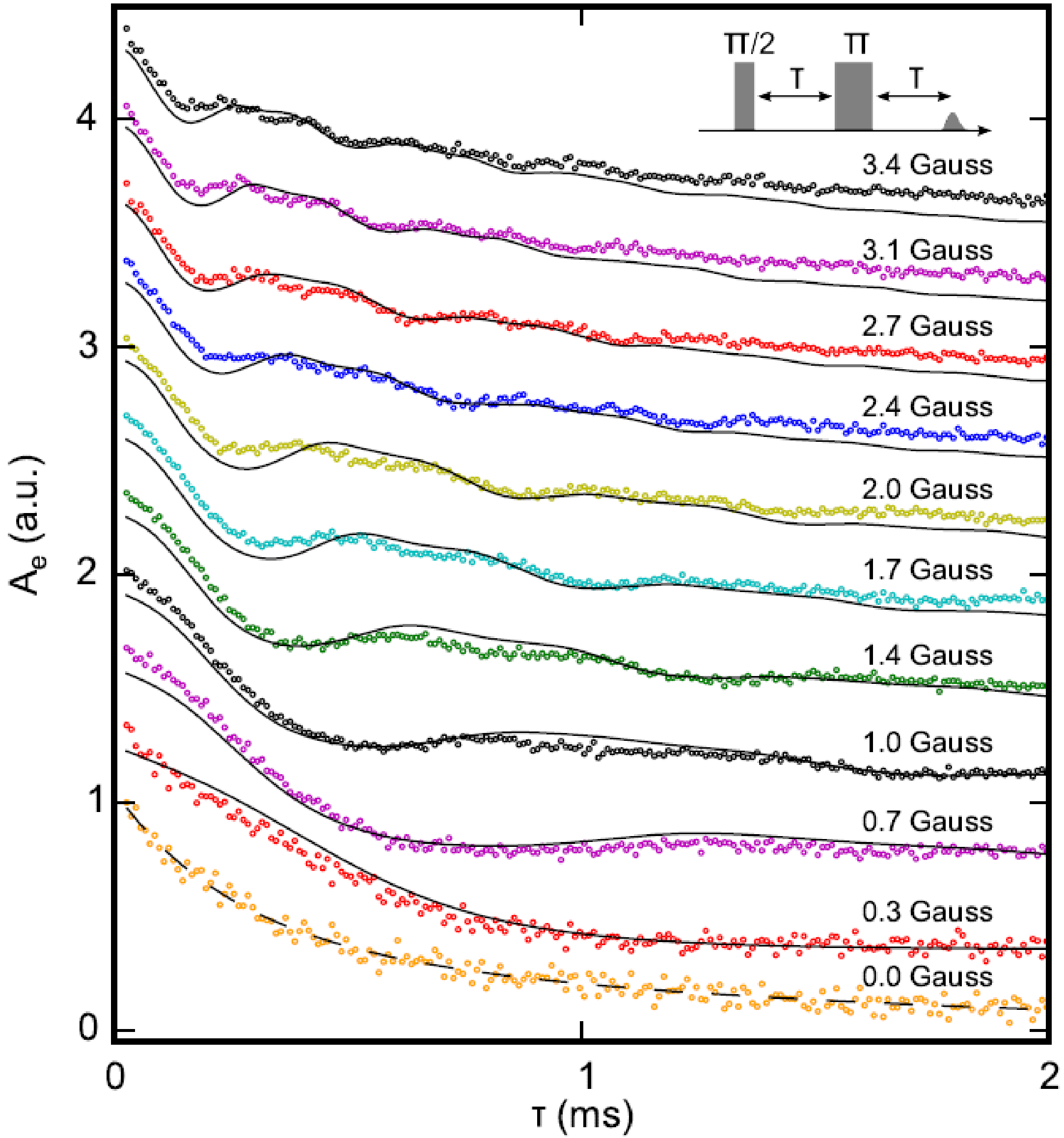


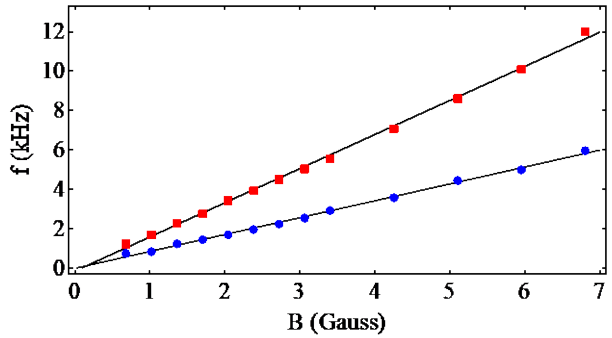
Typical $\frac{T}{2\pi} \simeq 1kHz$

Need to measure at very low B_0



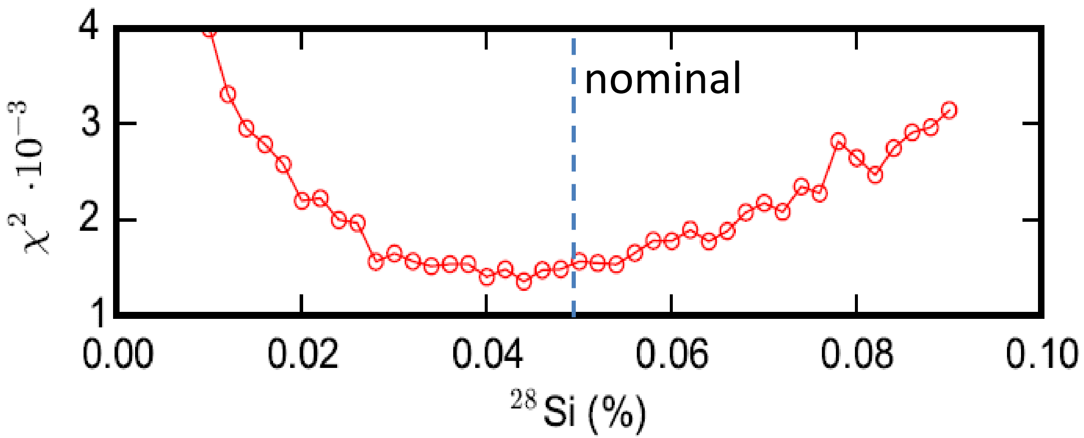
Sensing ^{29}Si nuclear spins through ESEEM





Oscillation 8.5MHz/T corresponds to ^{29}Si gyromagnetic ratio

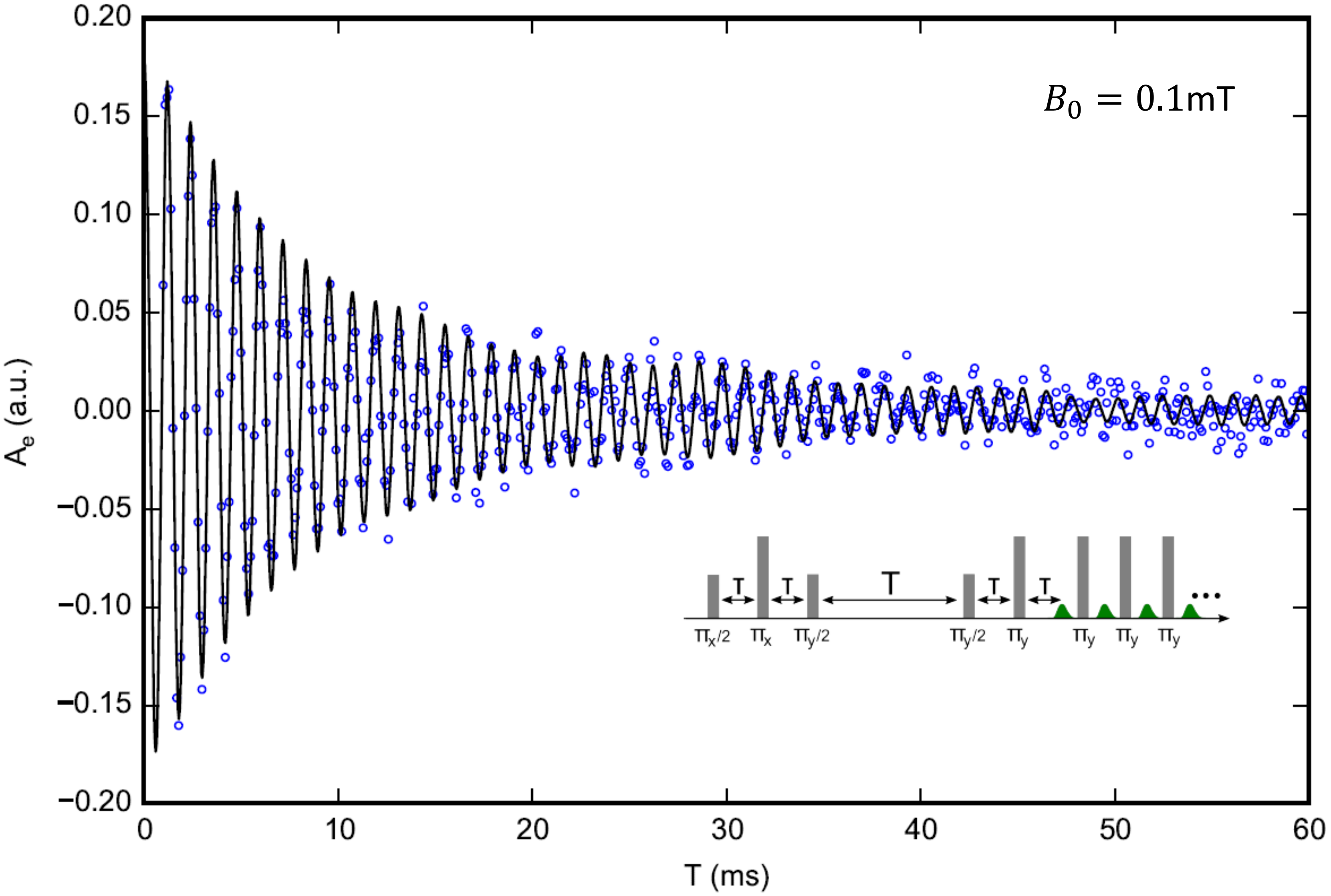
Independent confirmation of ^{29}Si concentration



Signal comes from ≈100 Bi donor spins each coupled to ≈10 nuclear spins

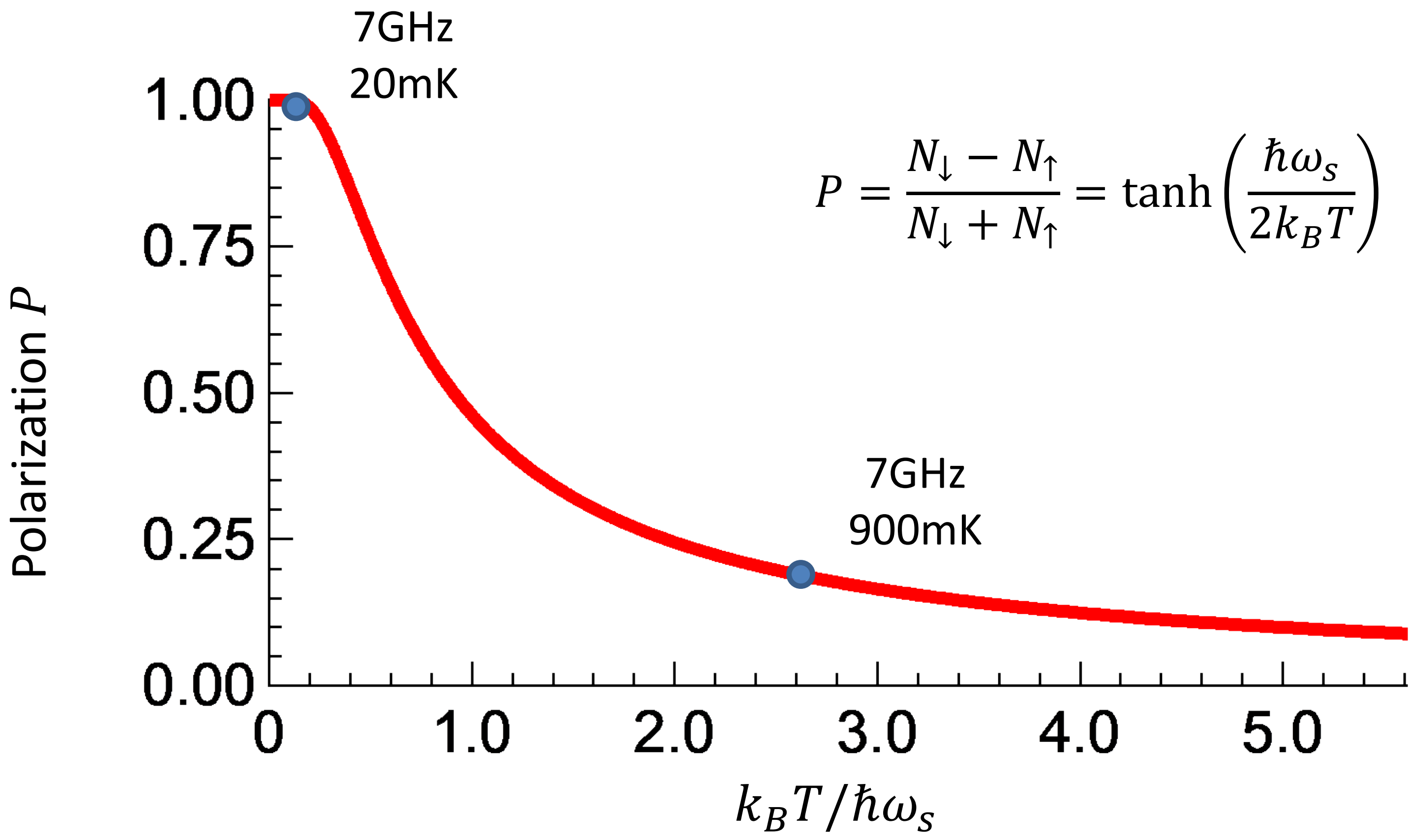
S. Probst, G. Zhang et al., in preparation

Beyond T2 limitation : 5-pulse ESEEM



S. Probst, G. Zhang et al., in preparation

Circuit-QED-enhanced electron spin hyperpolarization



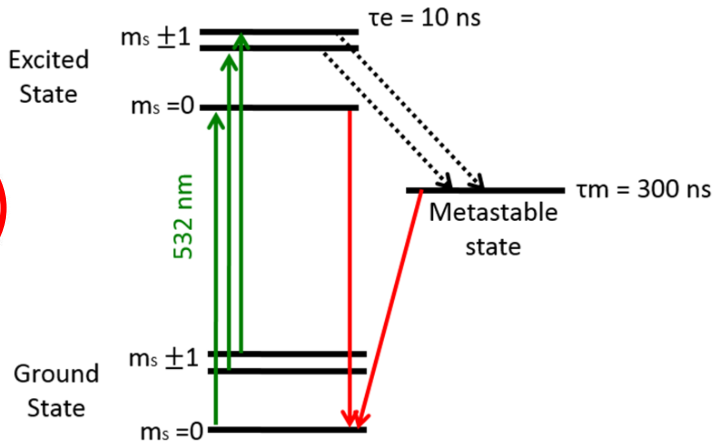
How to polarize spins beyond the Boltzmann distribution at the sample temperature T ?

Hyperpolarization techniques

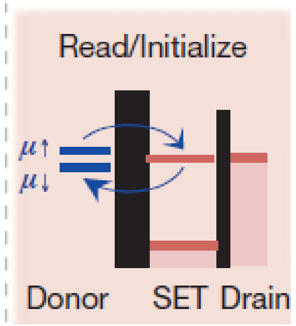
For electron spins

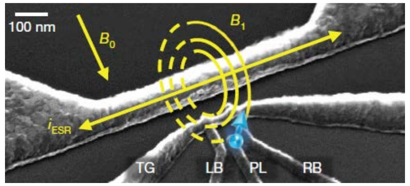
- Optical pumping

  Ex: NV centers in diamond



- Spin-dependent tunneling





Elzerman et al. Nature (2004)
Pla et al., Nature (2010)

Hyperpolarization techniques

For electron spins

- Optical pumping

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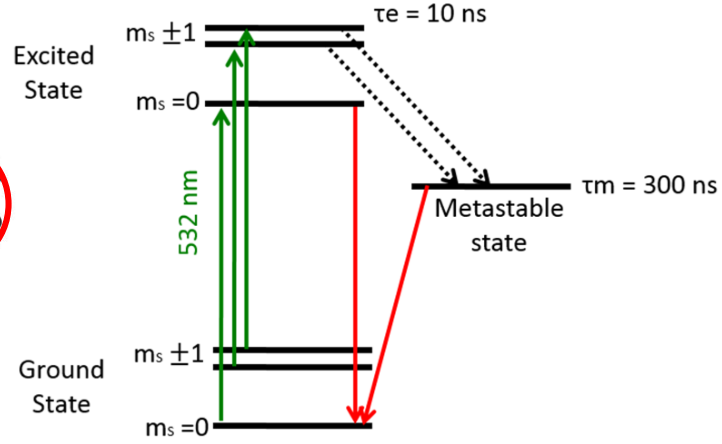
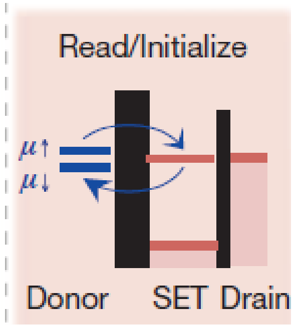
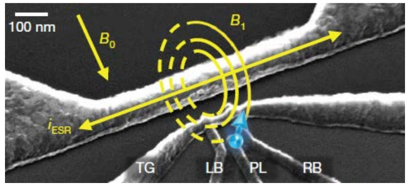


- Spin-dependent tunneling

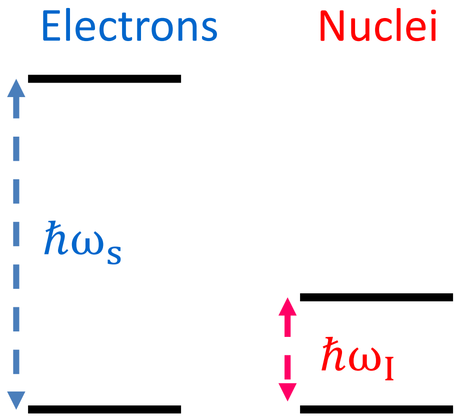




Elzerman et al. Nature (2004)
Pla et al., Nature (2010)

For nuclear spins

- Dynamical Nuclear Polarization

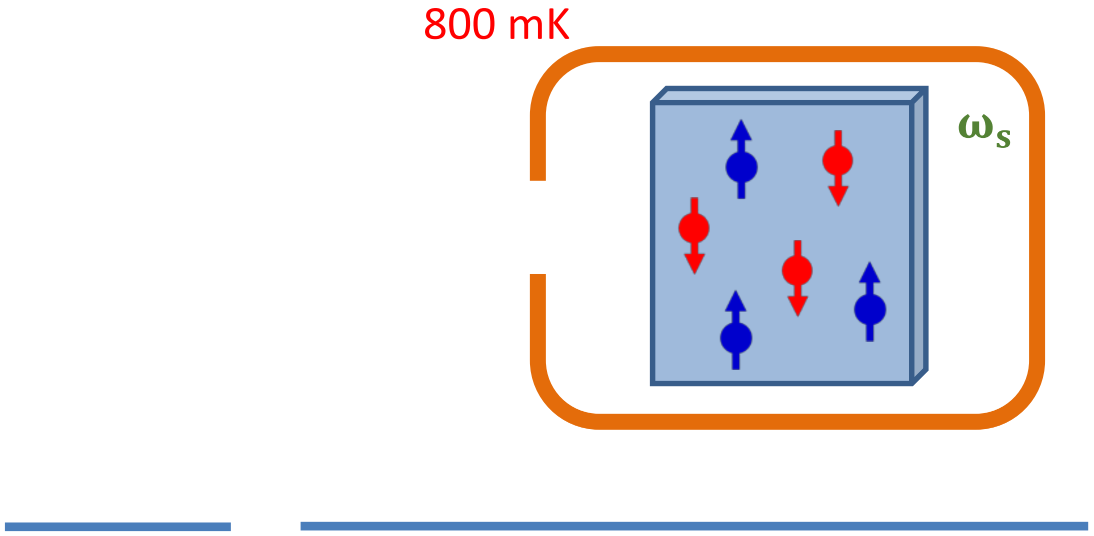


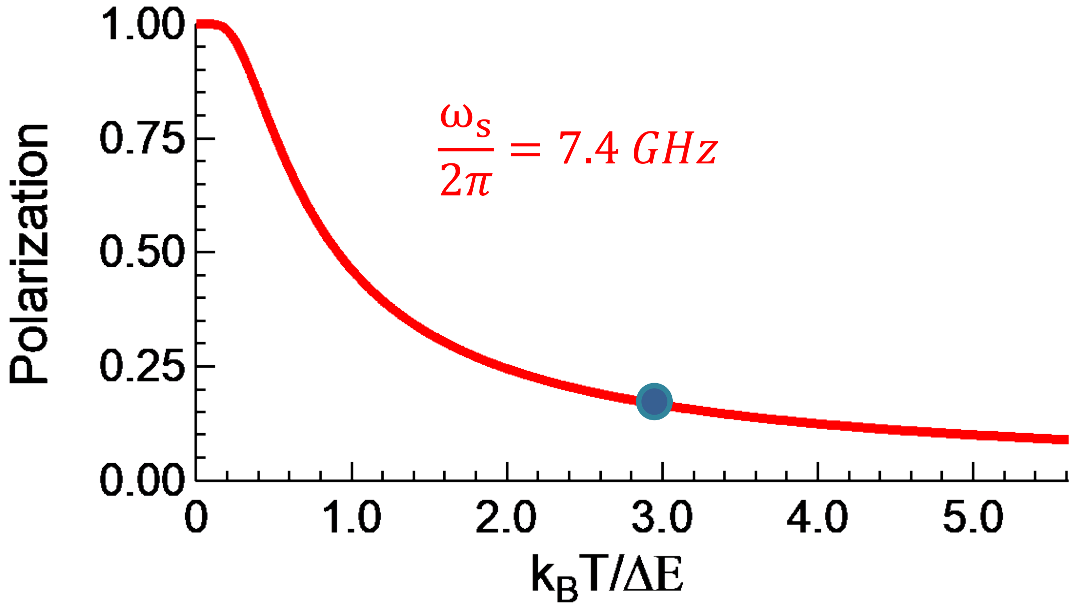
$\mathbf{P_n} \ll \mathbf{P_e}$

MW drive at $\simeq \omega_S - \omega_I$ → $\mathbf{P_n} \cong \mathbf{P_e}$

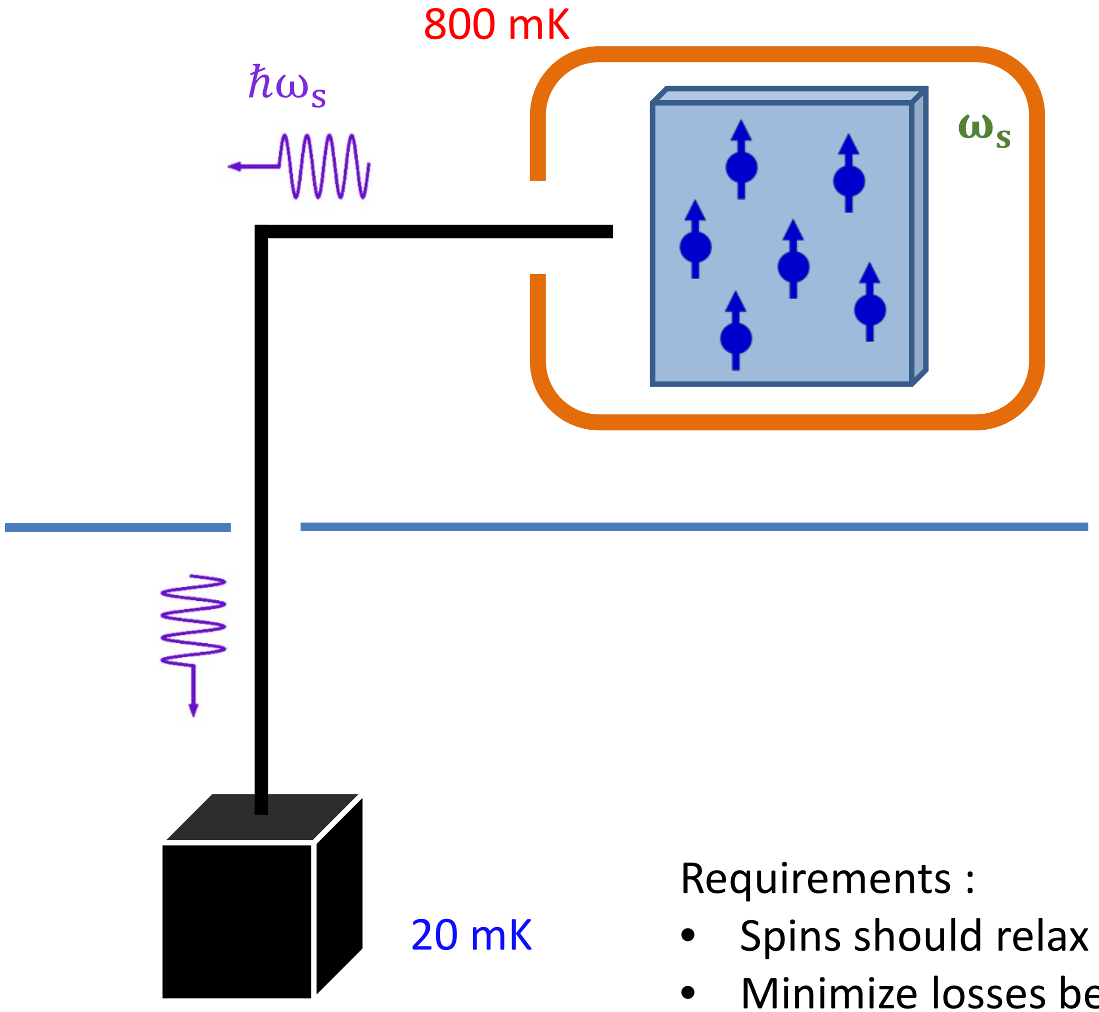
Interest for a more general hyperpolarization scheme for electron spins

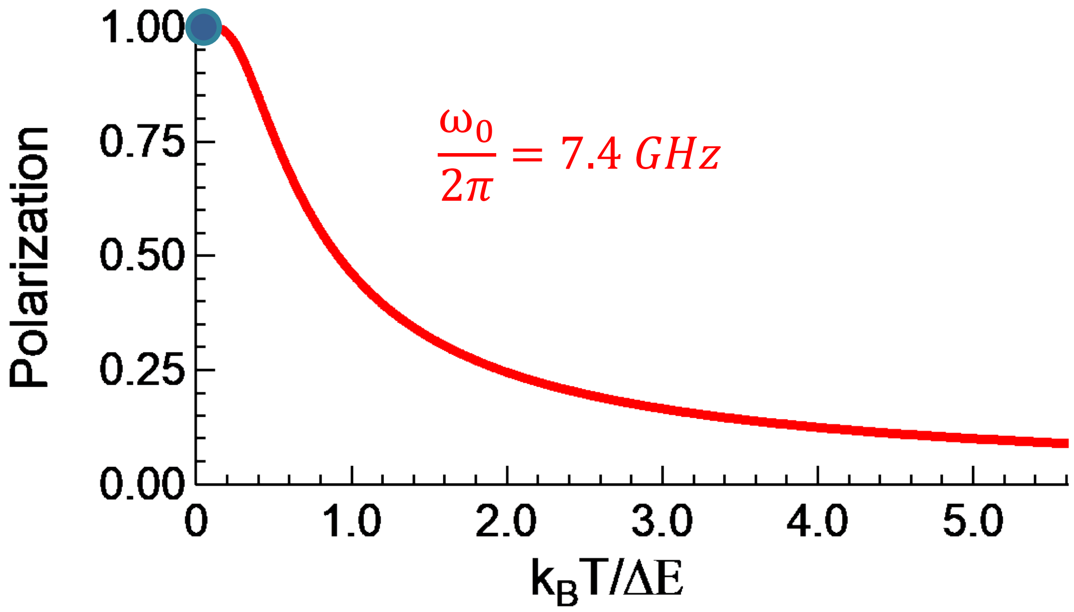
Hyperpolarization via radiative cooling





Hyperpolarization via radiative cooling





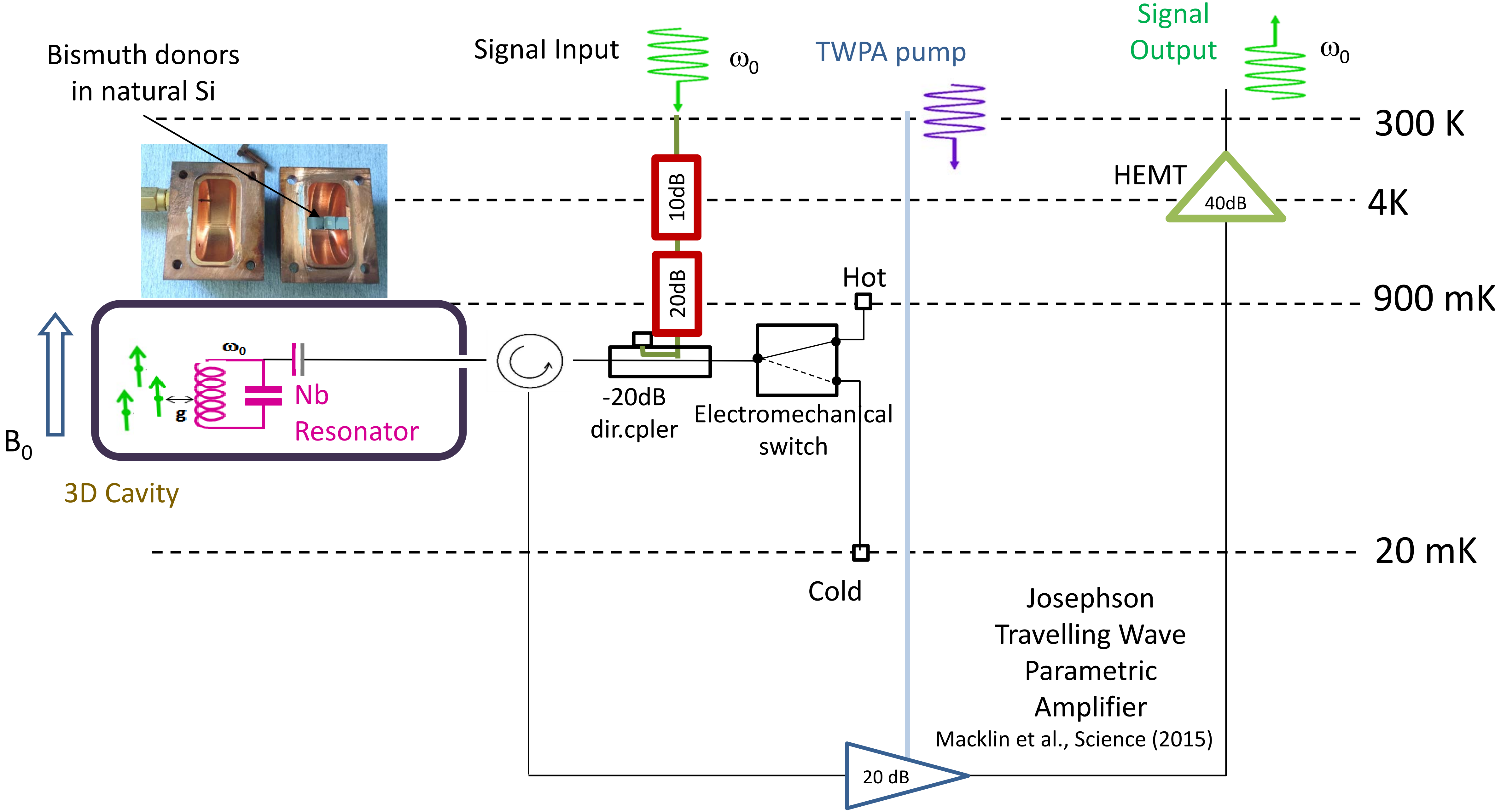
$$\frac{P_{cold}}{P_{hot}} = \frac{2\bar{n}_{800mK} + 1}{2\bar{n}_{20mK} + 1} = 4.5$$

Requirements :

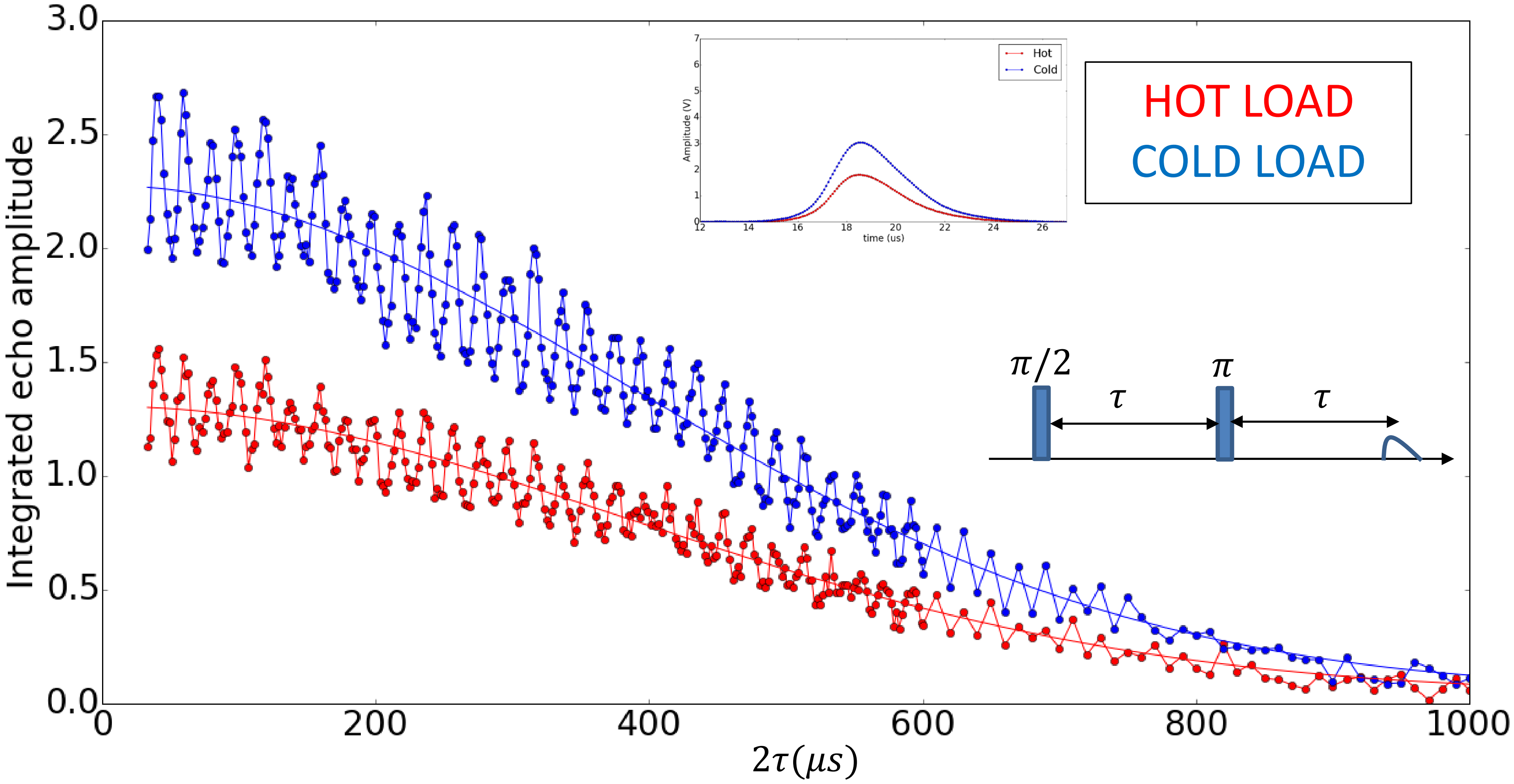
- Spins should relax radiatively (i.e. Purcell regime)
- Minimize losses between cold load and spins

Enabled by Circuit QED

Hyperpolarization by radiative cooling : implementation

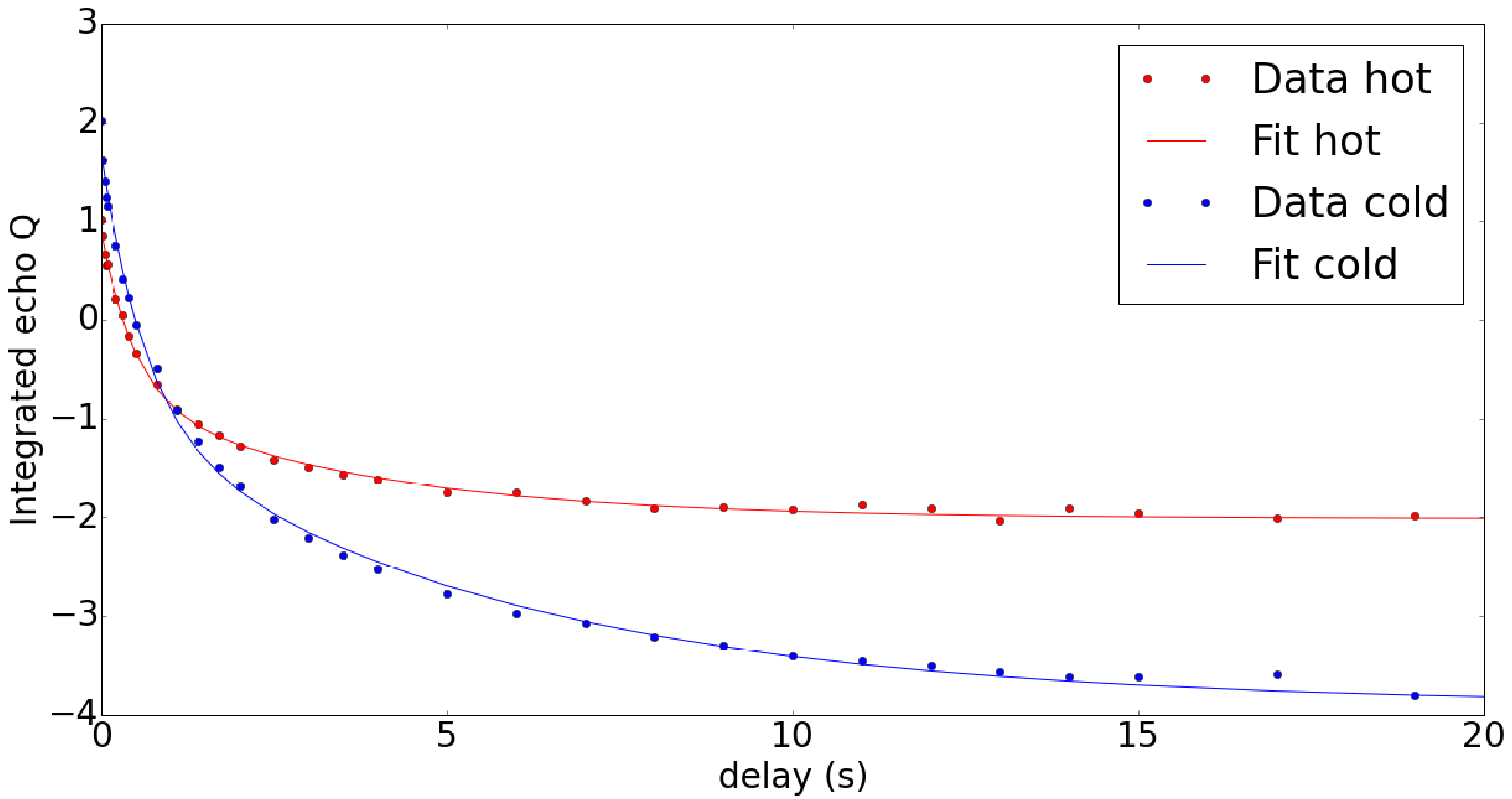


Hyperpolarization by radiative cooling : results



- Strong ESEEM (natural abundance ^{29}Si)
- Polarization increase by factor 1.9 – 2.1 when cold load connected. Less than expected due to unwanted losses

Hyperpolarization by radiative cooling : results



- Spin relaxation time reduced by the same factor as polarization as expected

Conclusion

- Circuit-QED-based EPR spectroscopy enables unprecedented sensitivity for inductive detection
  Demonstrated spin sensitivity of 10spin/√Hz, entering the few-spin regime
  Bienfait et al., Nature Nano (2016)
  Probst et al., APL (2017)

- Response to strain and electric field, resonator-induced decoherence, …need to be better understood
  Mansir et al., to appear in PRL (2018)
  Pla et al., PRAppl (2018)

- Spectrometer can be used to probe electron spin environment using standard pulse EPR techniques
  Probst et al., in preparation (2018)

- The Purcell regime offers novel schemes for electron spin hyperpolarization

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Y. Kubo (OIST)
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