# Strong Coupling of Hybrid Nuclear-Electron Magnons to a Microwave Resonator

Leonid V. Abdurakhimov[1,*], J. Chen[1], Yu.M. Bunkov[2], D. Konstantinov[1]

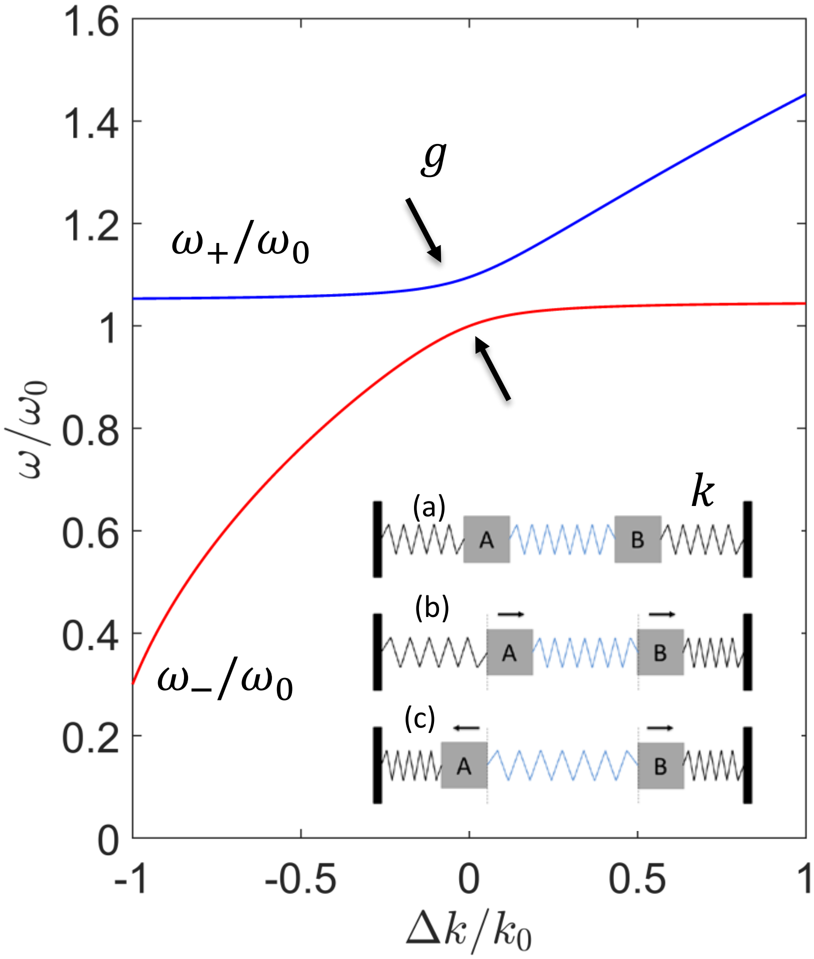
[1]Okinawa Institute of Science and Technology (OIST) Graduate University, Japan
[2]Institute Neel, CNRS, Grenoble, France

[*]Current address: Microelectronics group, Cavendish Laboratory, University of Cambridge, UK

# Strong coupling in classical and quantum systems

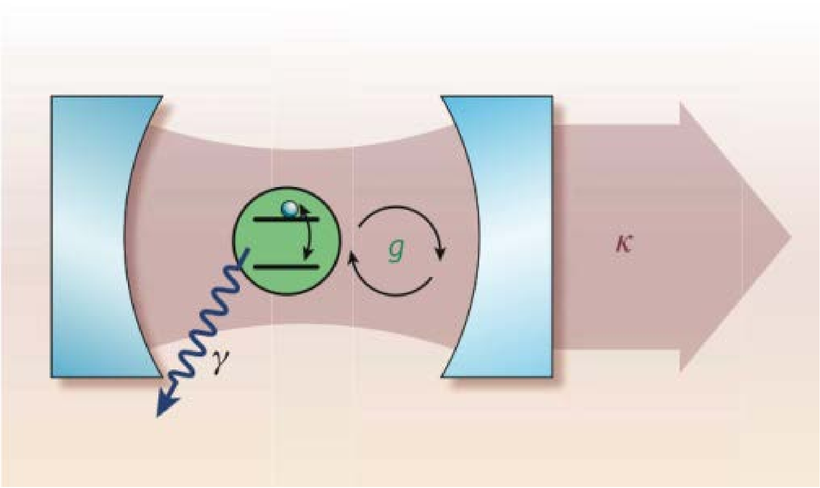
## Classical example

L. Novotny, Am. J. Phys. **78**, 1199 (2010)



## Cavity quantum electrodynamics

$$\boxed{g \gg \gamma, \kappa}$$



Seminal works by Serge Haroche, David J. Wineland, *et al.*

# Cavity QED with spin systems

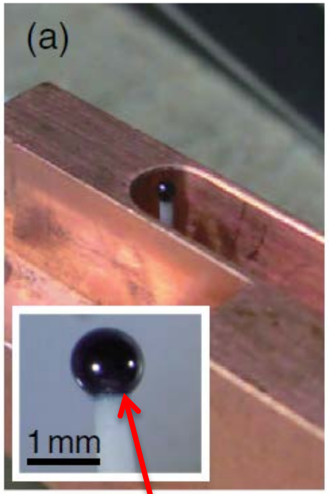
## a) paramagnetic systems

- D. Schuster *et al*, PRL **105**, 140501 (2010)
- Y. Kubo *et al*, PRL **105**, 140502 (2010)
- *etc.*

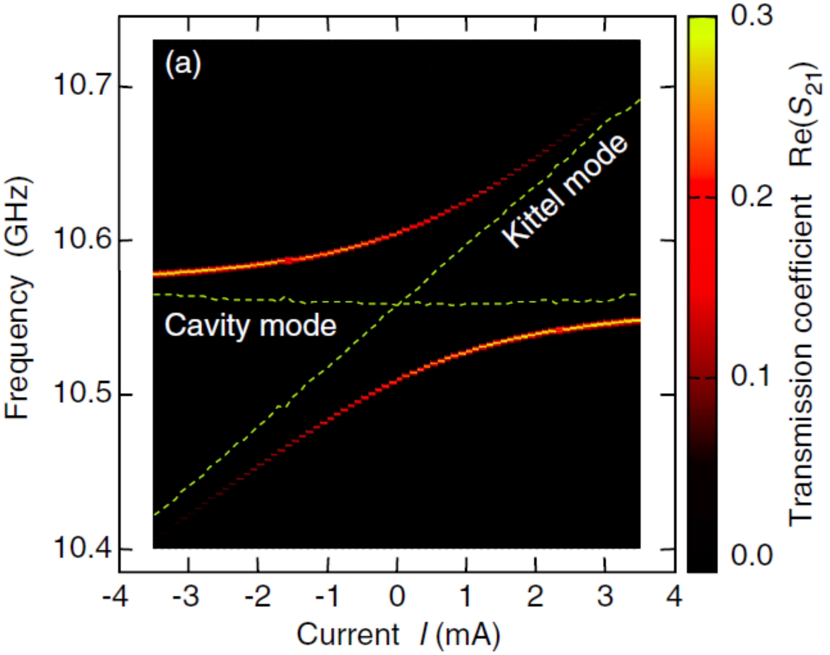
$$g = g_0\sqrt{N}$$

## b) ferrimagnetic YIG

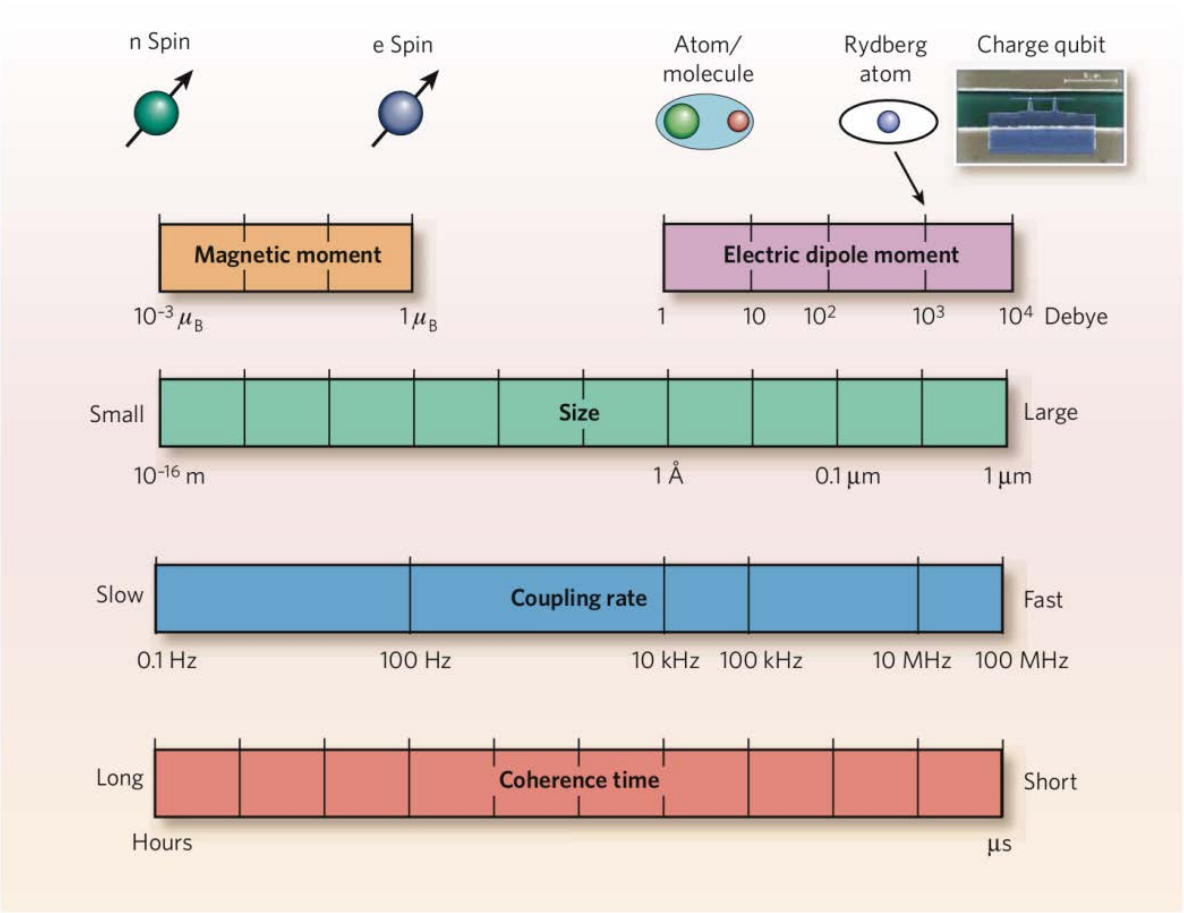
- Y. Tabuchi *et al*, PRL **113**, 083603 (2014)
- X. Zhang *et al*, PRL **113**, 156401 (2014)
- M. Goryachev *et al*, Phys. Rev. Applied **2**, 054002 (2014)
- N.J. Lambert, J.A. Haigh, and A.J. Ferguson, J. Appl. Phys. **117**, 053910 (2015)
- *etc.*



yttrium iron garnet (YIG, $Y_3Fe_5O_{12}$)

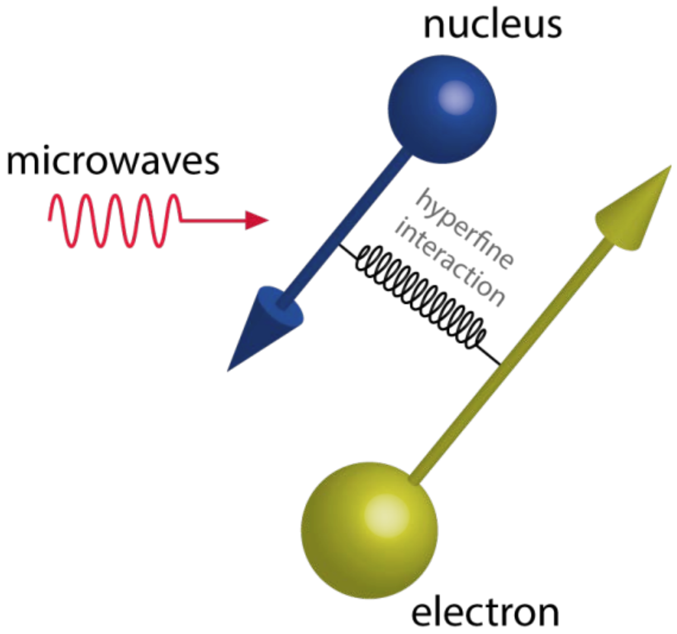


# Coupling rate vs Coherence time. Hybrid quantum computing.



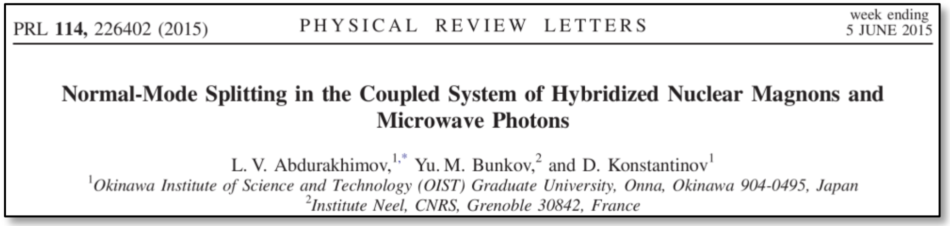
R.J. Schoelkopf and S.M. Girvin, Nature **451**, 664 (2008)

# Strong coupling between hybrid nuclear-electron magnons and a microwave resonator



Outline

1. Strong coupling of hybrid magnons with a split-ring resonator (CW)
    1. Magnetic structure of $MnCO_3$
    2. Experimental setup
    3. Observation of avoided crossing
2. Pulse measurements (new results)
    1. Rabi-like oscillations
    2. Spin echo, measurements of $T_2$



PRL **114,** 226402 (2015) PHYSICAL REVIEW LETTERS week ending 5 JUNE 2015

**Normal-Mode Splitting in the Coupled System of Hybridized Nuclear Magnons and Microwave Photons**

L. V. Abdurakhimov,[1,*] Yu. M. Bunkov,[2] and D. Konstantinov[1]

[1]*Okinawa Institute of Science and Technology (OIST) Graduate University, Onna, Okinawa 904-0495, Japan*

[2]*Institute Neel, CNRS, Grenoble 30842, France*

Phys. Rev. Lett. **114**, 226402 (2015)

# Materials with strong hyperfine interaction between nuclear and electron spins

$MnCO_3$ crystal

$MnCO_3$, $CsMnF_3$, $RbMnF_3$, $RbMnCl_3$, MnO, $KMnF_3$, $MnF_2$, $MnFe_2O_4$, $FeBO_3$, $CoCO_3$, $He^3$

(A. S. Borovik-Romanov et al., Sov. Phys. Usp. **27**, 235 (1984))

Hyperfine interaction :

$$\mathcal{H}(r) = A\,\boldsymbol{M_e}(r)\cdot\boldsymbol{m_n}(r)$$

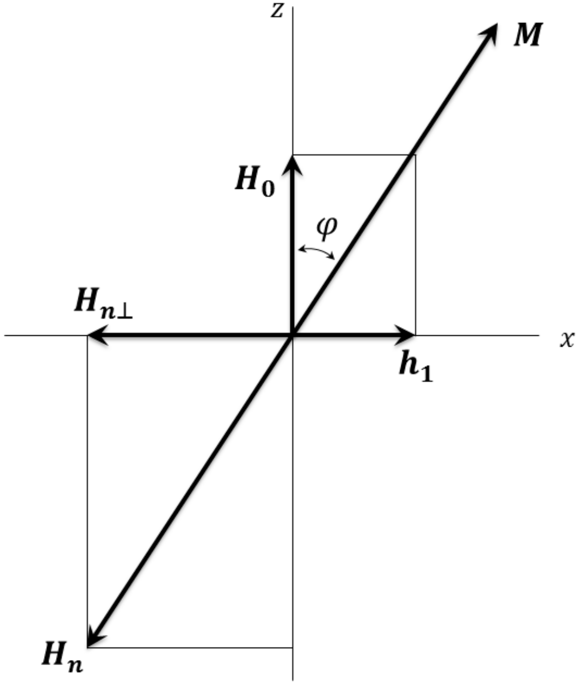
Effective hyperfine magnetic field acting on nuclear spins:

$$\boldsymbol{H_n} = -A\boldsymbol{M_e}(r)$$

Very strong interaction: $\mu_0 H_n \approx 60$ T

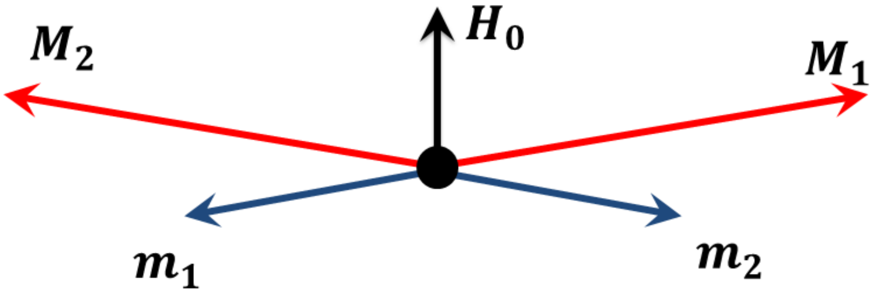
Effect of microwave field enhancement:

$$H_{n\perp} \approx \varphi H_n = \frac{H_n}{H_0} h_1, \quad \eta = \frac{H_n}{H_0} \approx 100$$



# Hybridized nuclear-electron magnons

Magnetic structure of MnCO3



a) canted antiferromagnetism / weak ferromagnetism below $T_n = 32.5$ K :
   - exchange field :

     $$\mu_0 H_E = 34 \text{ T}$$

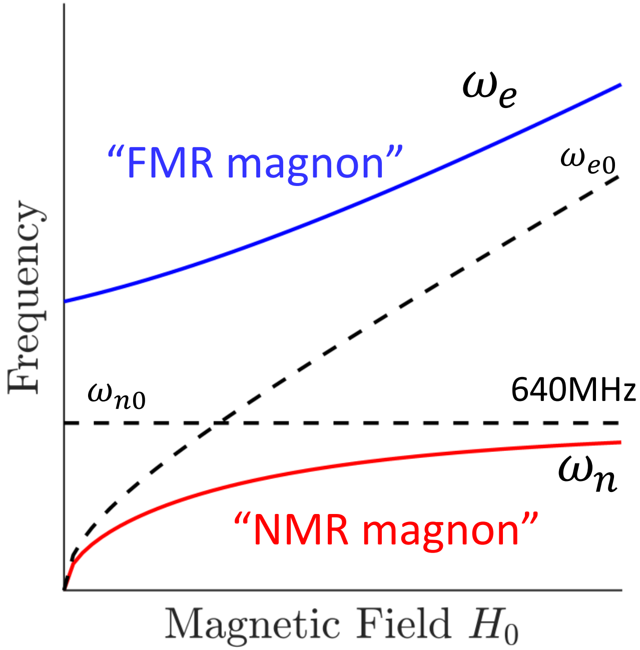
   - Dzyaloshinskii-Morya field :

     $$\mu_0 H_{DM} \approx 0.44 \text{ T}$$

b) hyperfine effective field: $\mu_0 H_n \approx 60$ T

Low-frequency collective spin excitation (magnon) is the hybridized oscillation of nuclear and electron spins

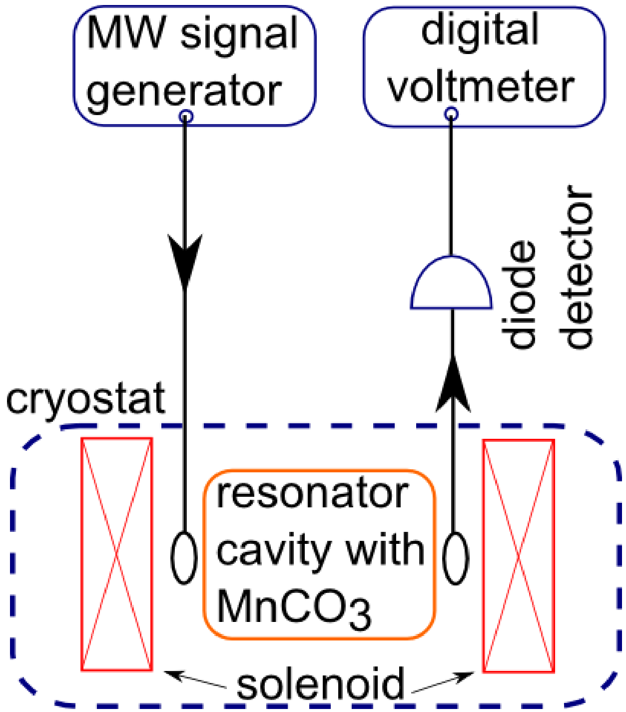
$$\boxed{\omega_n^2 \approx \omega_{n0}^2 \left(1 - \frac{2\, H_E A \langle m_z \rangle}{H_0(H_0 + H_{DM})M}\right)}$$



P.G. de Gennes et al., Phys. Rev. **129**, 1105 (1963)
D. Shaltiel, Phys. Rev. **142**, 300 (1966)

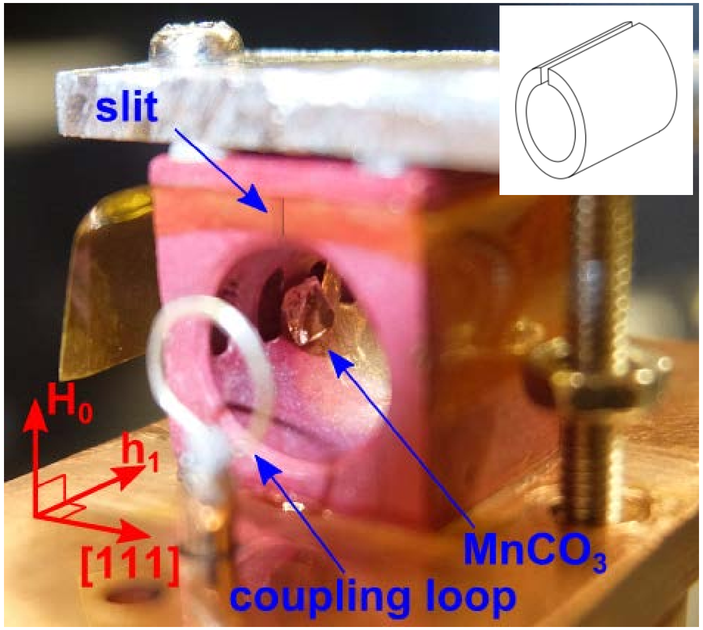
# Experimental setup

## Measurement scheme



## 3D split-ring resonator

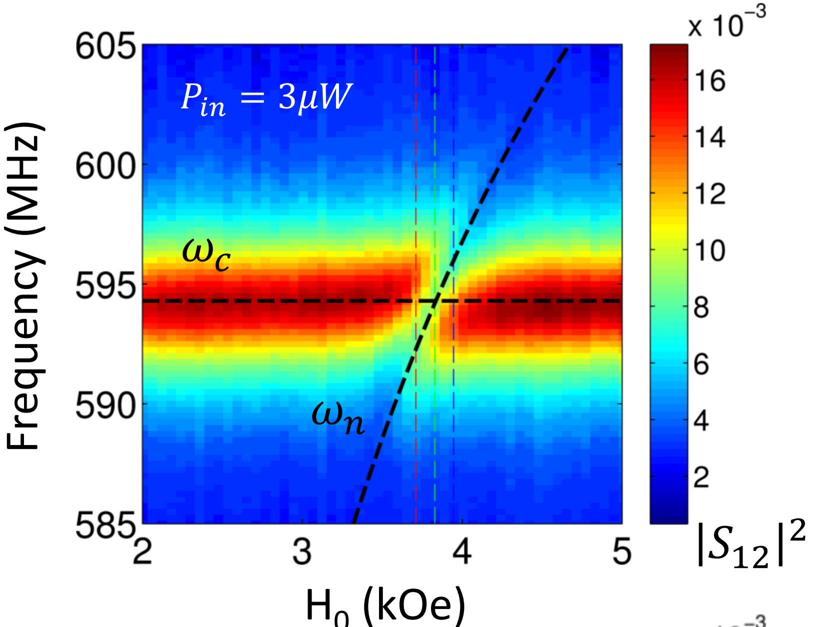
$Q \approx 100$

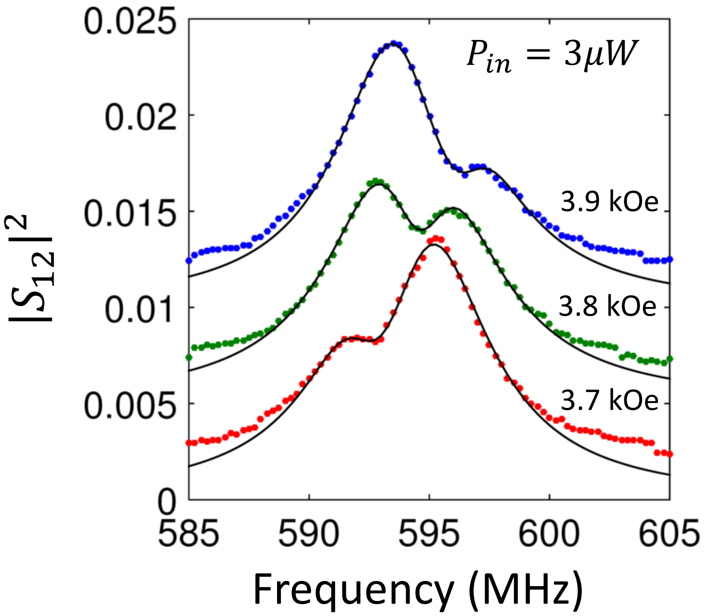


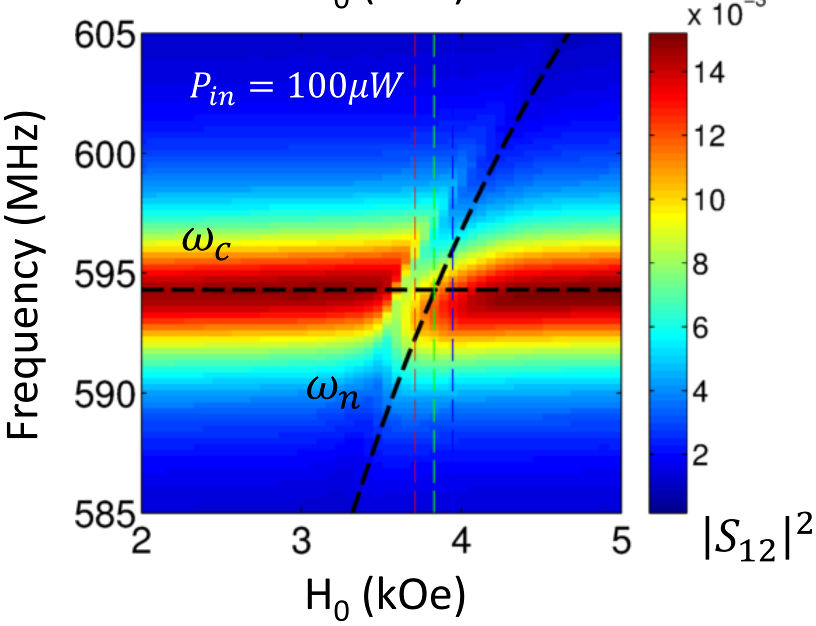
Cavity size: Ø 7 mm x 10 mm

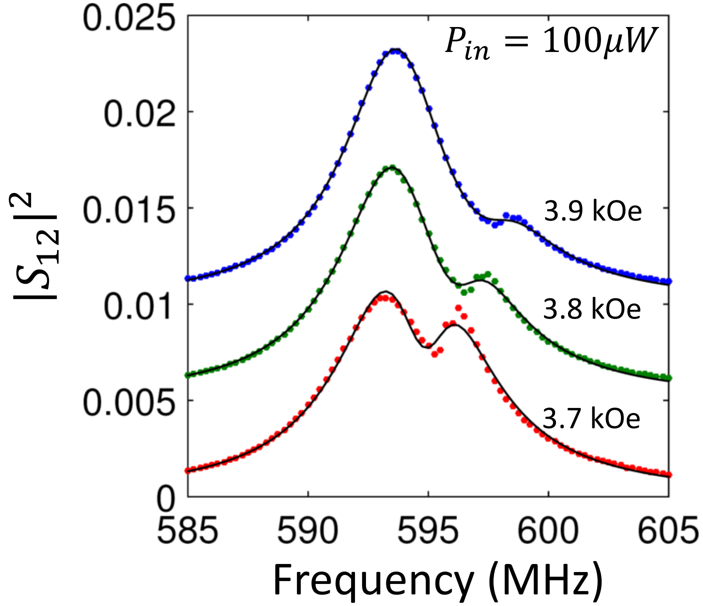
Sample size: 2.4 x 2.7 x 0.7 $mm^3$

# Avoided crossing (at T=1.15K)









# Results of fitting

Fitting equation (input-output formalism theory):

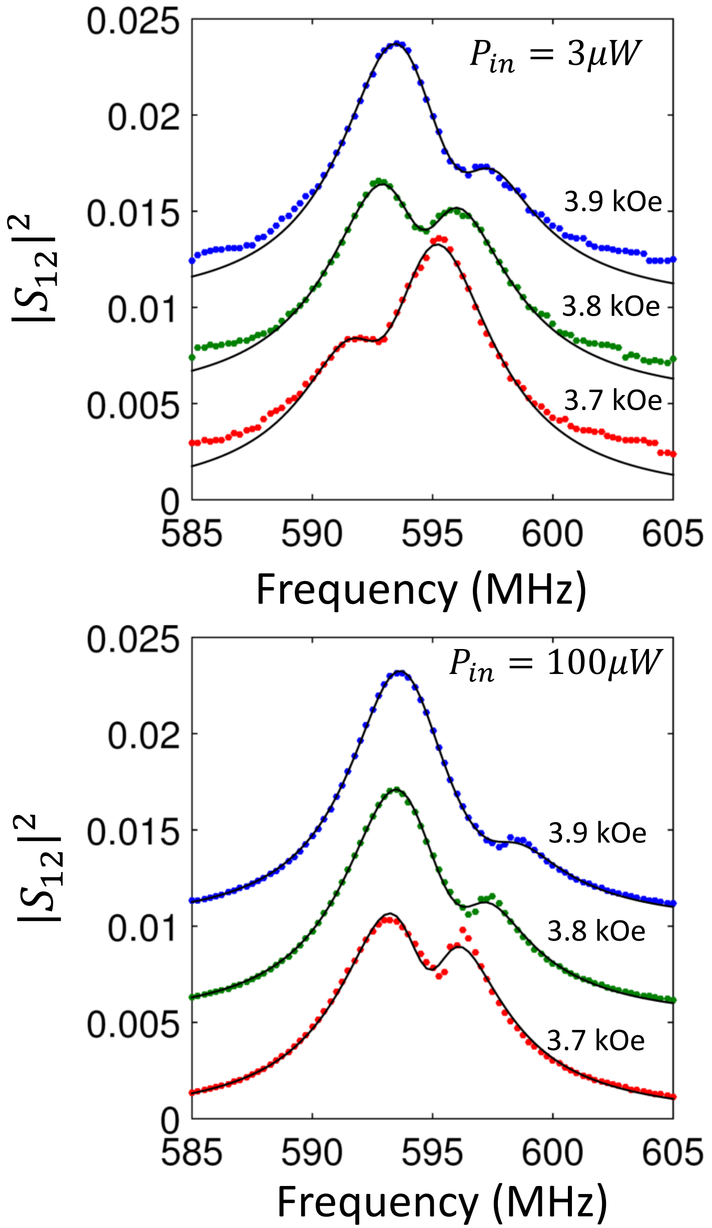
$$|S_{12}|^2 = \left| \frac{\sqrt{\kappa_1 \kappa_2}}{i(\omega - \omega_c) - \frac{\kappa_1 + \kappa_2 + \kappa_i}{2} + \frac{g_m^2}{i(\omega - \omega_m) - \frac{\gamma_m}{2}}} \right|^2$$

- coupling strength
  $g_m/2\pi \approx 1$ MHz

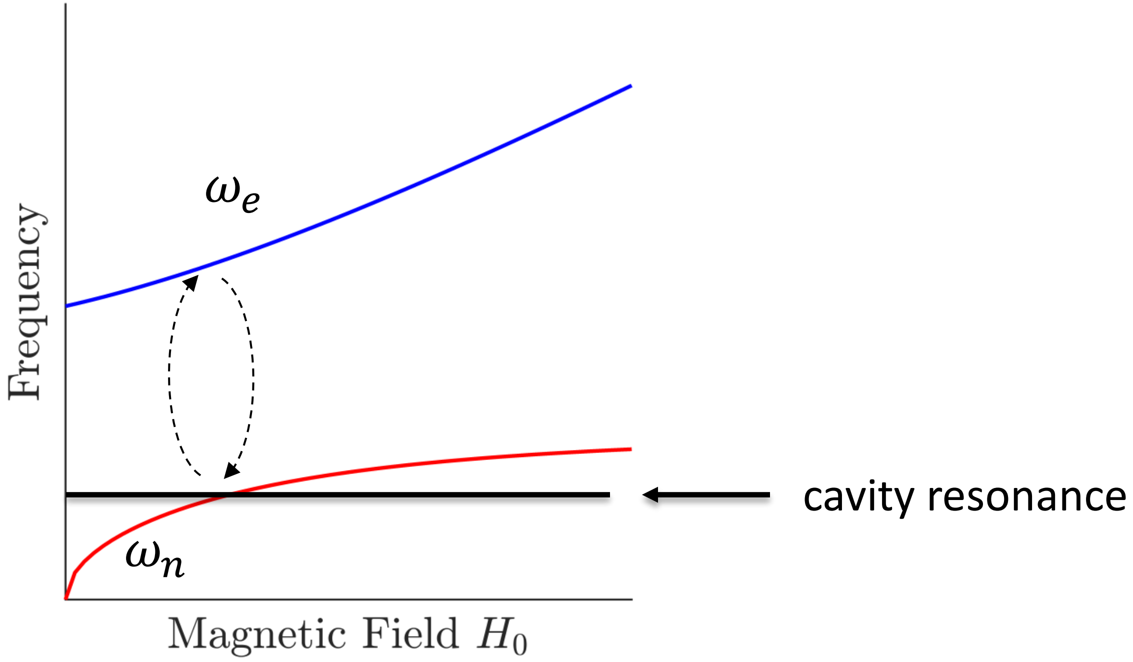
- magnon mode linewidth
  $\gamma_m/2\pi \approx 3$ MHz

- total resonator linewidth
  $\kappa\ /\ 2\pi = (\kappa_1 + \kappa_2 + \kappa_i)/2\pi \approx 6$ MHz

Cooperativity $C = 4g_m^2/\kappa\gamma_m \approx 0.2$



# Theoretical estimations of coupling strength



$$g = \frac{\mu_d}{\hbar} \times B_{photon} \times \sqrt{N} =$$

$$= \frac{\gamma_n}{2}\sqrt{2p_n I N} \times (H_n/H_0)\sqrt{\hbar\omega_c\mu_0/V_c} \approx 1\text{ MHz}$$

gyromagnetic ratio $\gamma_n = 2\pi \times 11\text{ MHz/T}$

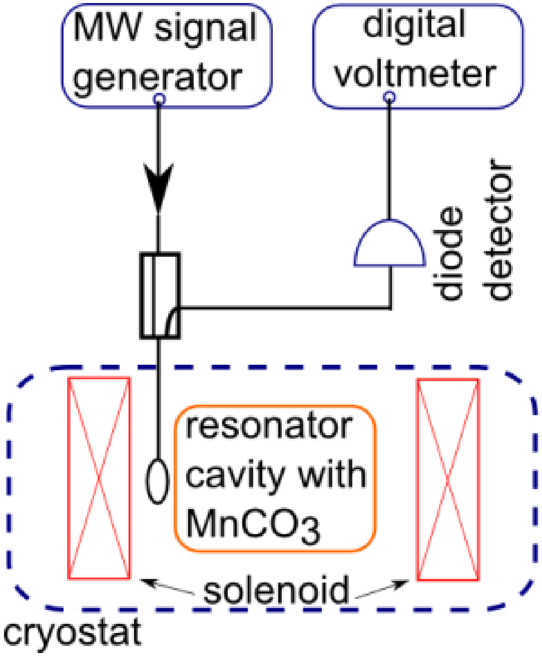
spin polarization $p_n = \frac{\gamma_n \hbar (I+1) H_n}{3 k_b T_n} \approx 0.005$

nuclear spin $I = \frac{5}{2}$

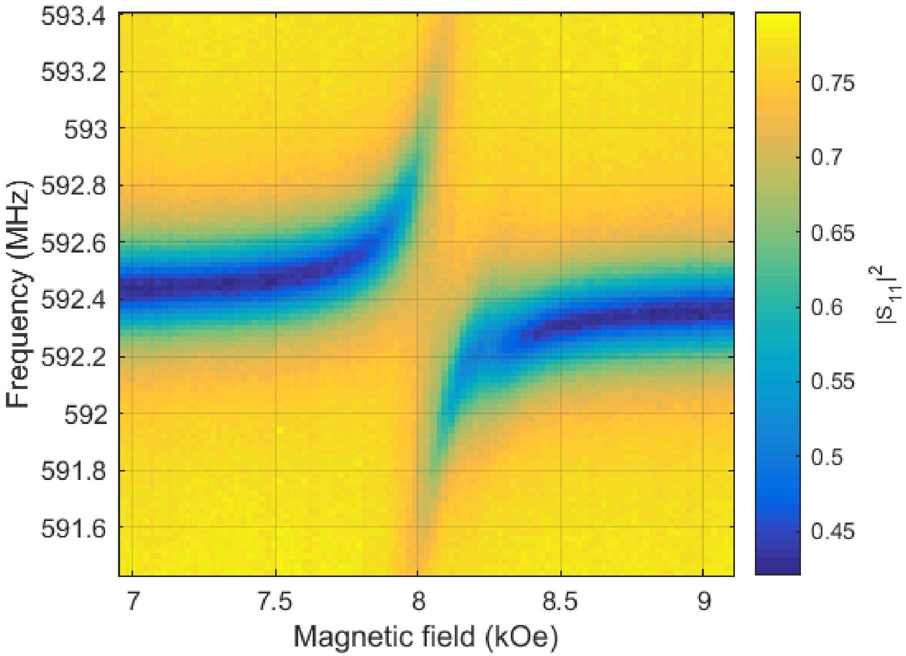
number of spins $N \approx 4 \times 10^{19}$

# Measurements of microwave reflection (at 300mK)
## + new resonator

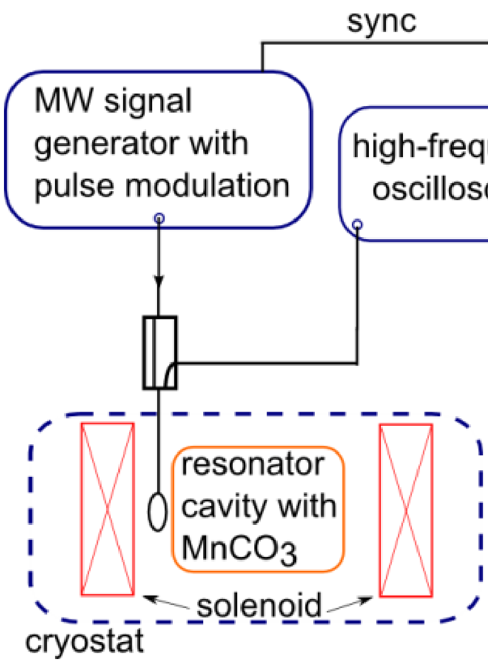
Q-factor was improved from 100 to 1000



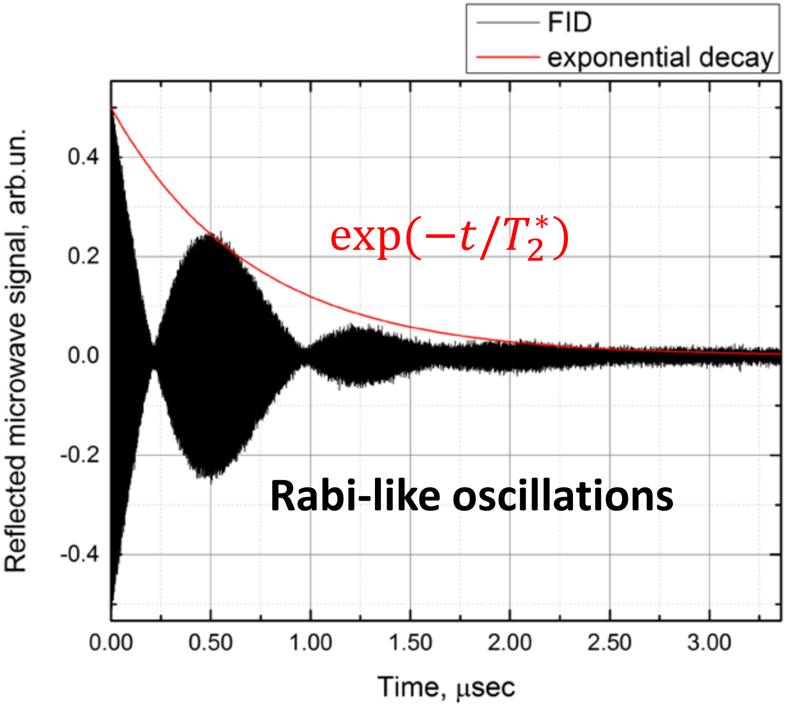
$P_{in} \approx -70$ dBm



# Pulse measurements.
# Free induction decay after single pulse.



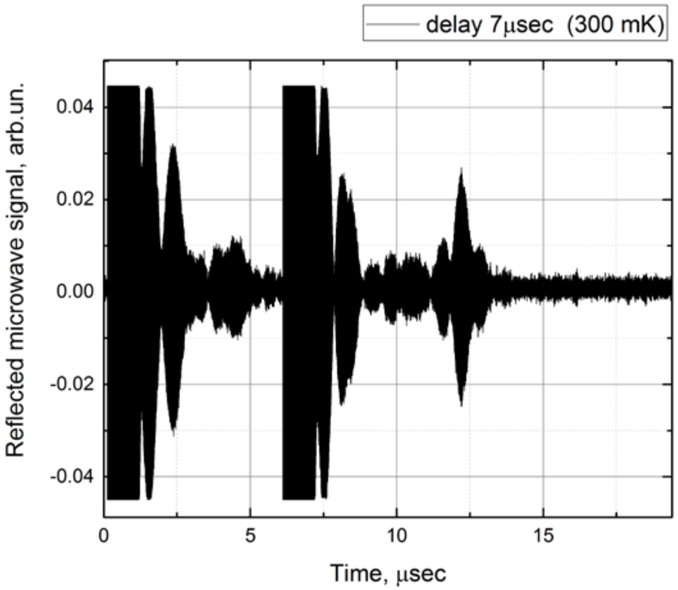
pulse duration 240 ns, $P_{in} \approx 5\text{dBm}$



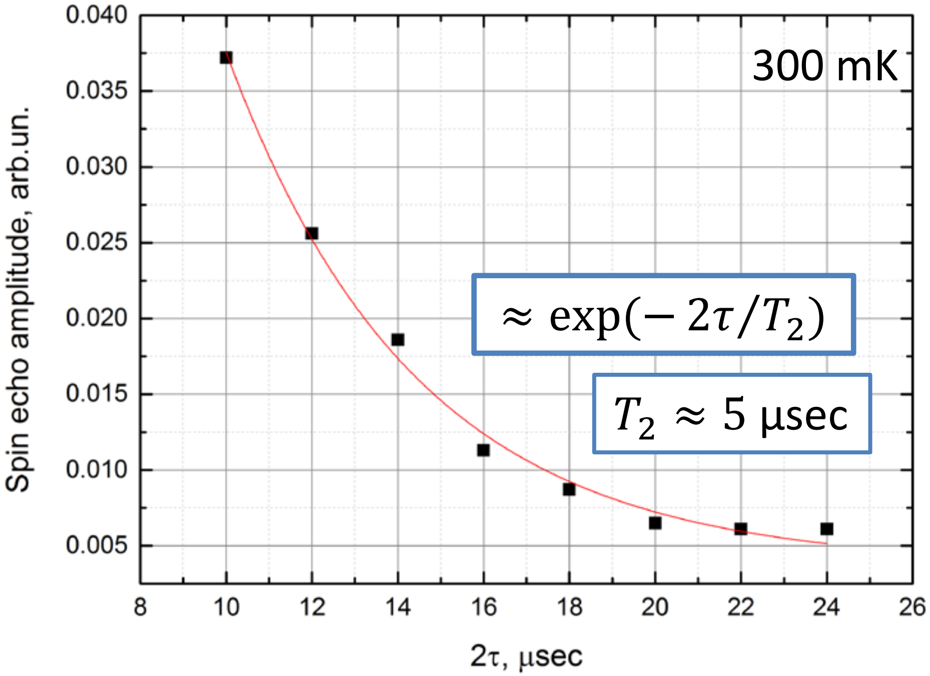
$T_{Rabi} \approx 0.75\mu\text{sec} \longrightarrow g \approx 1\text{MHz}$

$T_2^* \approx 0.5\ \mu\text{sec}$

# Spin echo measurements. Two-pulse echo.



pulse duration 240 ns, $P_{in} \approx 30$ dBm

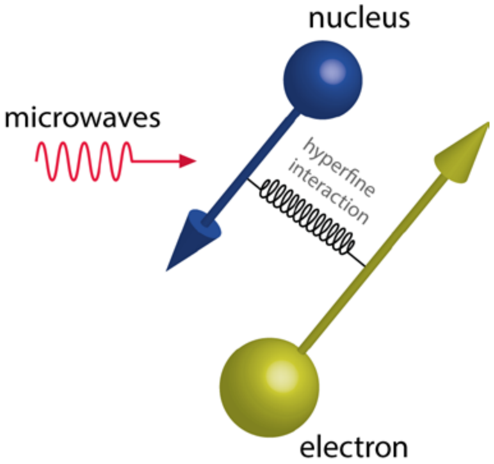


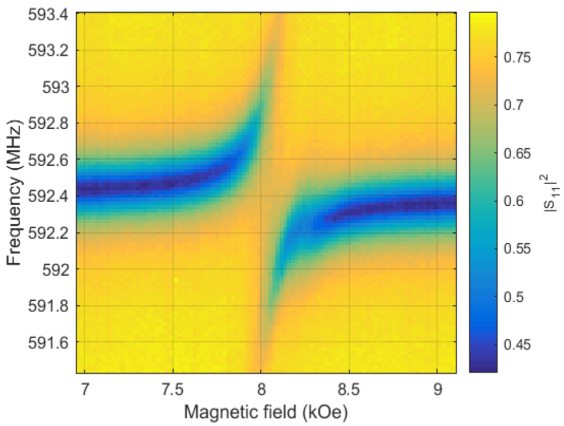
$\approx \exp(-2\tau/T_2)$

$T_2 \approx 5$ μsec

# Conclusions

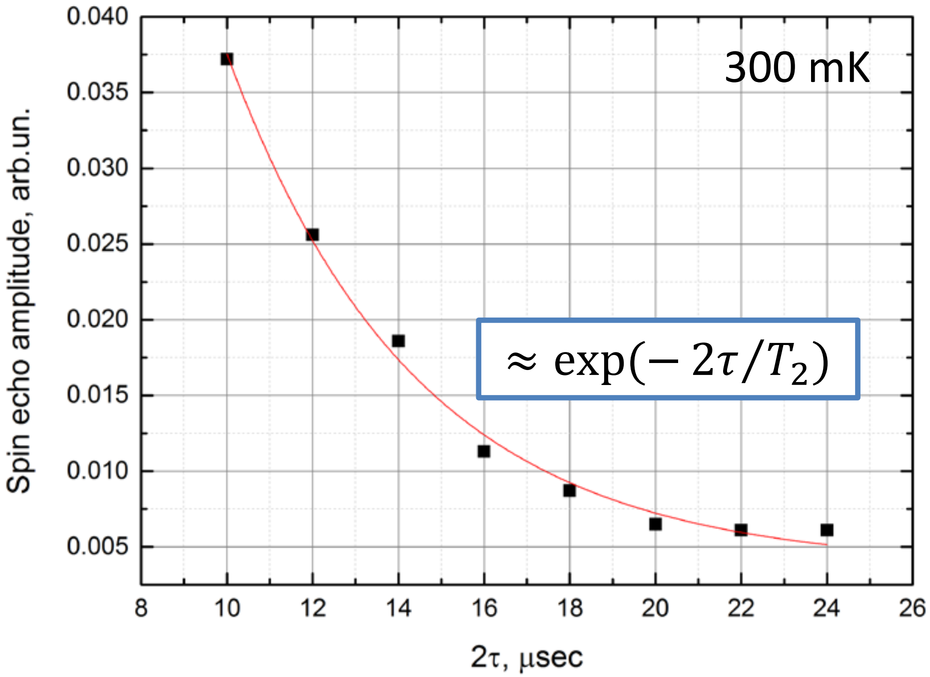
- strong coupling between nuclear spins and photons is mediated by electron spins via the hyperfine interaction (“double hybridization”)
- $T_2$ is quite long, but not as long as was expected. More systematic studies are required.
- similar strong coupling phenomena could be realized in other systems with strong hyperfine interaction





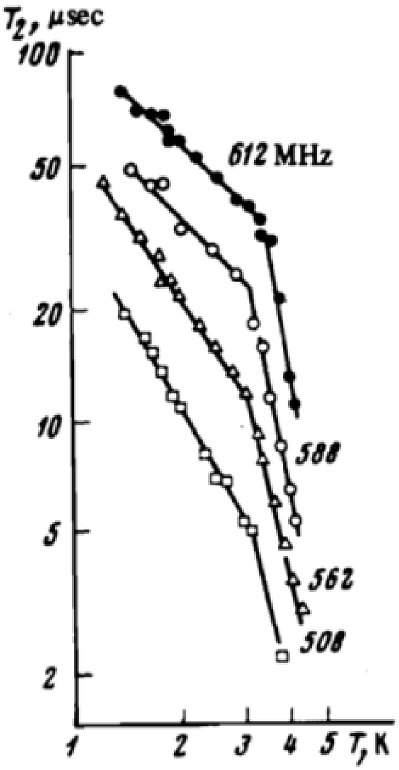
# Appendix

# Estimation of $T_2$



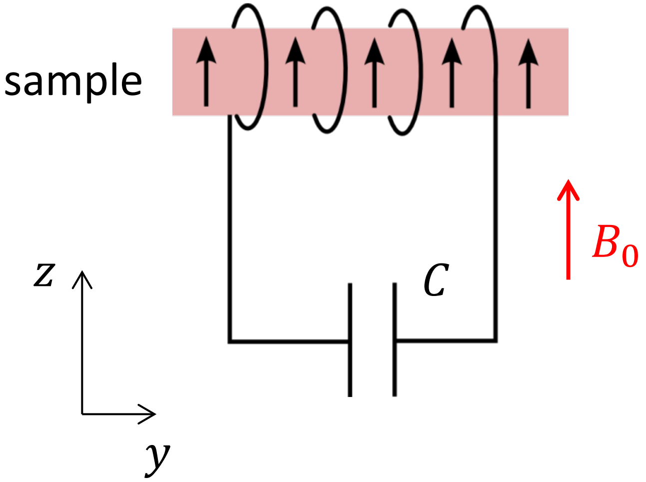
$$\approx \exp(-2\tau/T_2)$$

$$T_2 \approx 5\ \mu\text{sec}$$



Y. M. Bunkov and B. S. Dumesh
*Sov. Phys. JETP* **41**, 576 (1975)

# Classical model



Bloch equation: $d\vec{M}/dt = \gamma[\vec{M} \times \vec{B}]$

Magnetic flux through the coil:

$$\Phi = B_y(t) \times A = \mu_0\big(H_y + \eta M_y\big)A$$

Faraday's law: $\varepsilon = -\mathrm{d}\Phi/dt$

LC-circuit equation: $I = -C\ddot{\Phi} = -C(L\ddot{I} + \mu_0 \eta A \ddot{M}_y)$

$\omega_m = \gamma B_0$

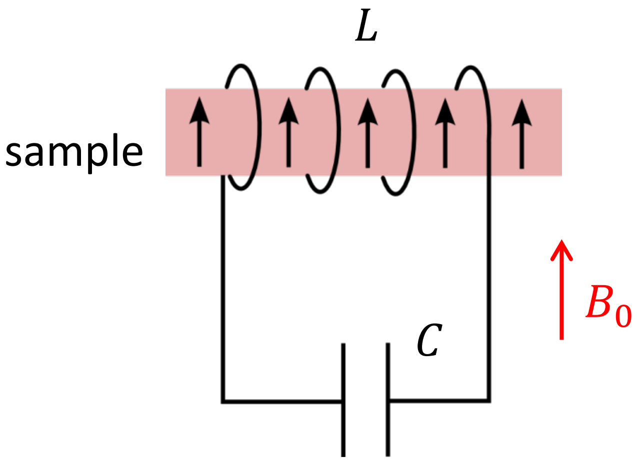
$\omega_c = 1/\sqrt{LC}$

Eigenmodes equation: $\omega^4 - \omega^2(\omega_m^2(1 + \eta\chi_0) + \omega_c^2) + \omega_c^2\omega_m^2 = 0$

static susceptibility $M_0 = \chi_0 H_0$

Solution ($\omega_m \approx \omega_c \approx \omega_0, \eta\chi_0 \ll 1$): $\omega_{1,2}^2 = \omega_0^2(1 \pm \sqrt{\eta\chi_0})$

Splitting value: $\Delta\omega = \omega_0\sqrt{\eta\chi_0}$



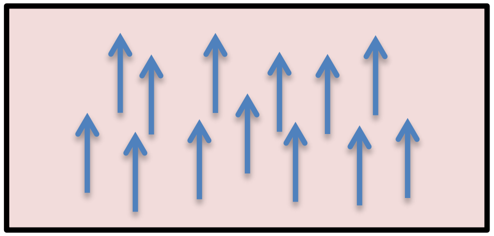
Classical model: $\Delta\omega = \omega_0\sqrt{\eta\chi_0}$

But $\eta = V/V_c$, $\chi_0 = \frac{M}{H_0} = \frac{N\mu_B}{H_0 V} = \frac{N(\hbar\gamma\backslash g)}{\left(\frac{\omega_0}{\gamma\mu_0}\right)V}$

Thus $\Delta\omega = 2g_{eff} = \omega_0\sqrt{\frac{V}{V_c}\frac{N\hbar\mu_0\gamma^2}{\omega_0 V}} =$

$= \gamma\sqrt{\mu_0\hbar\omega_c/2V_c}\sqrt{N}$

N spins in a cavity



Quantum model:

$$g_{eff} = g_0\sqrt{N} = \frac{\gamma}{2}\sqrt{\mu_0\hbar\omega_c/V_c}\sqrt{N}$$