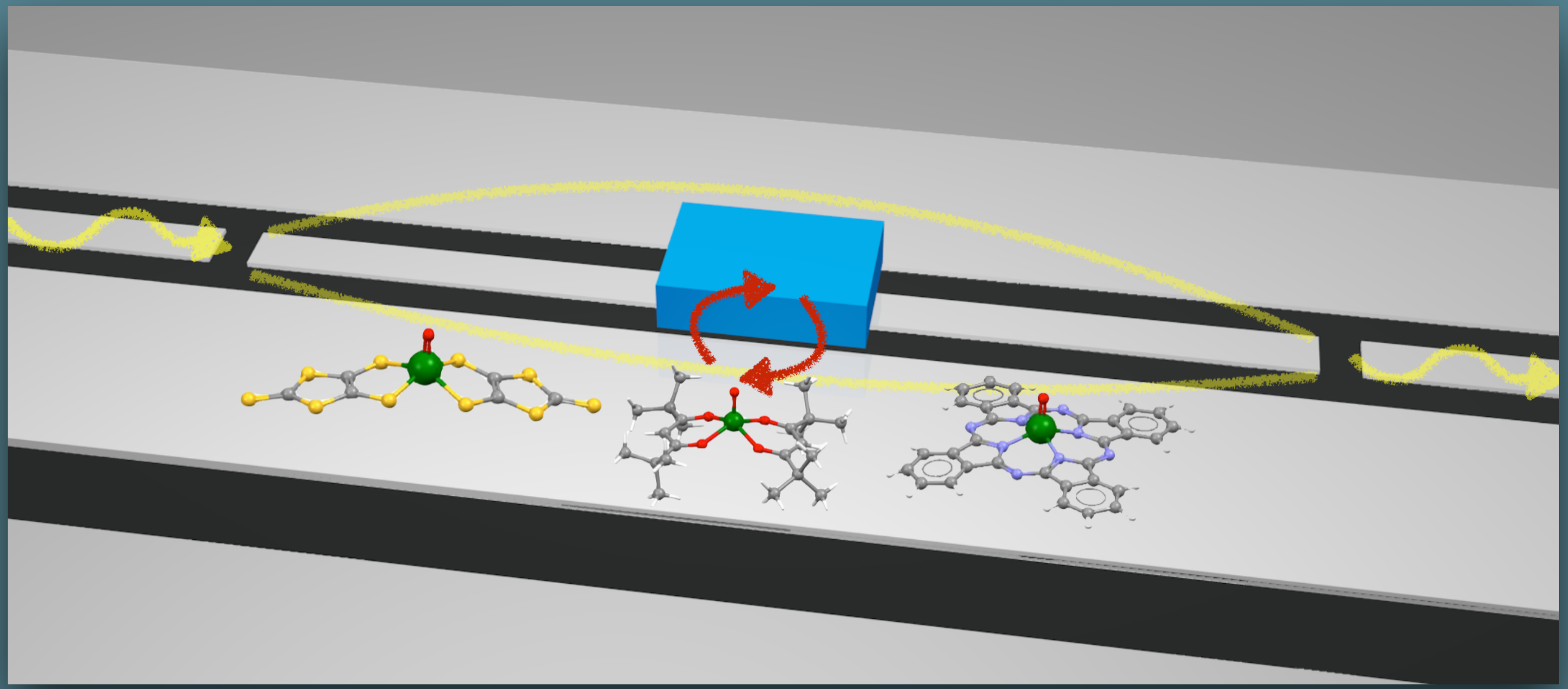
HYBRID SUPERCONDUCTING CIRCUITS WITH SPINS



https://www.lowtlab.unimore.it/

UNIVERSITÀ DI MODENA E REGGIO EMILIA

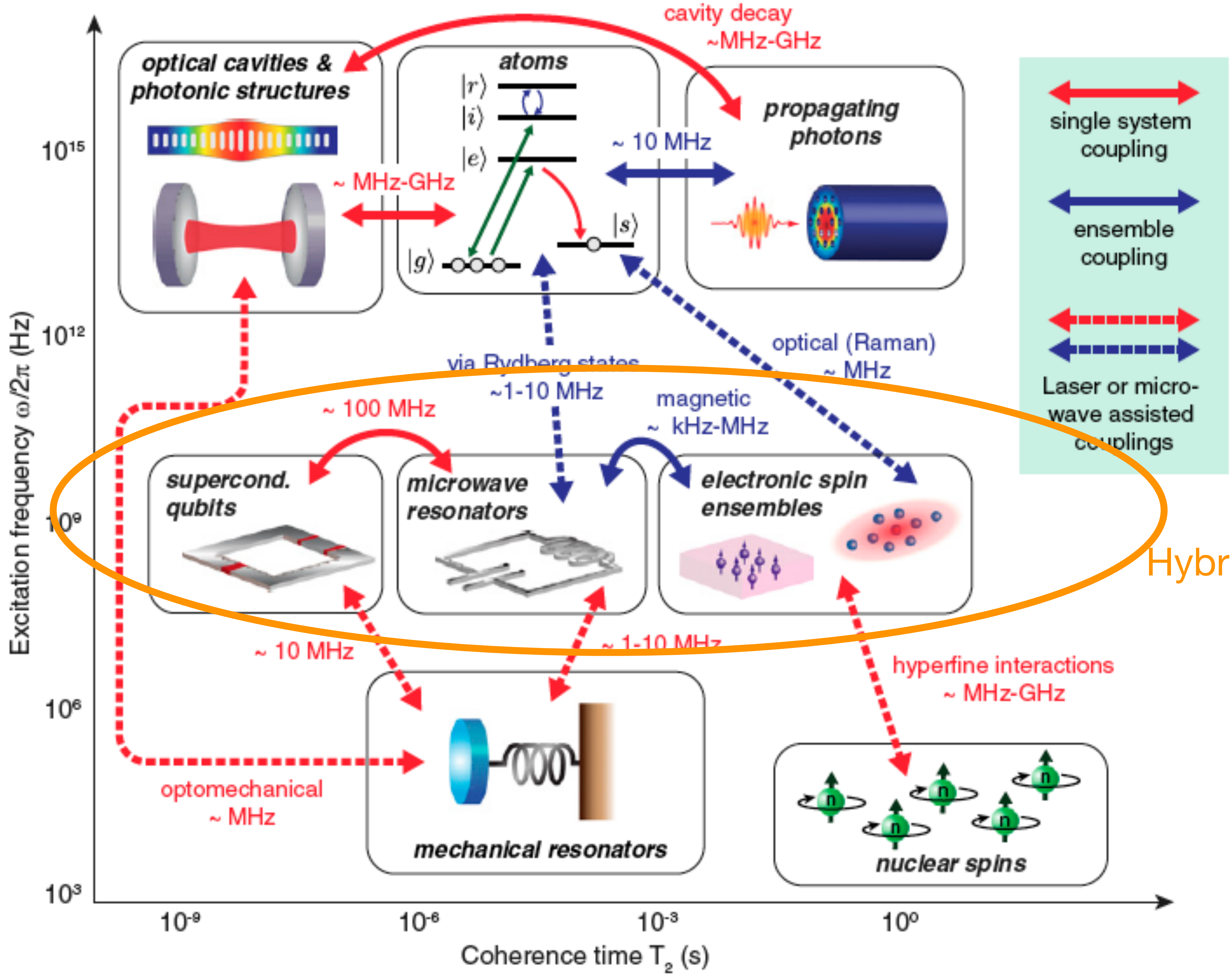
UNIMORE
UNIVERSITÀ DEGLI STUDI DI
MODENA E REGGIO EMILIA

Marco Affronte

CNR-NANO

CNRNANO MODENA S3

Platforms for Solid States Sciences & Technologies

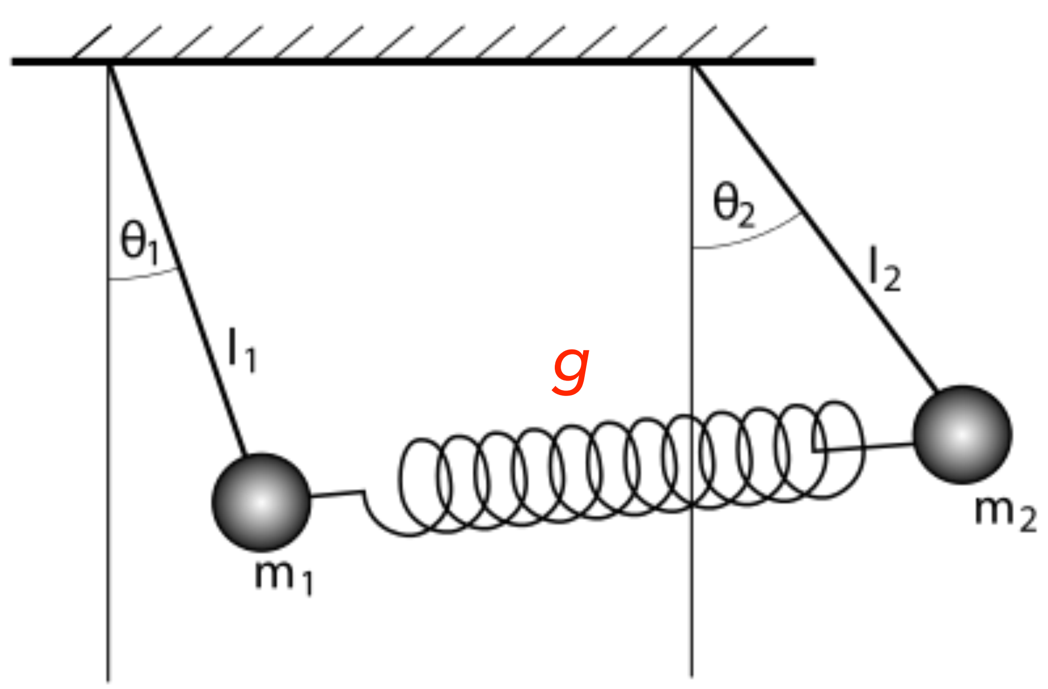


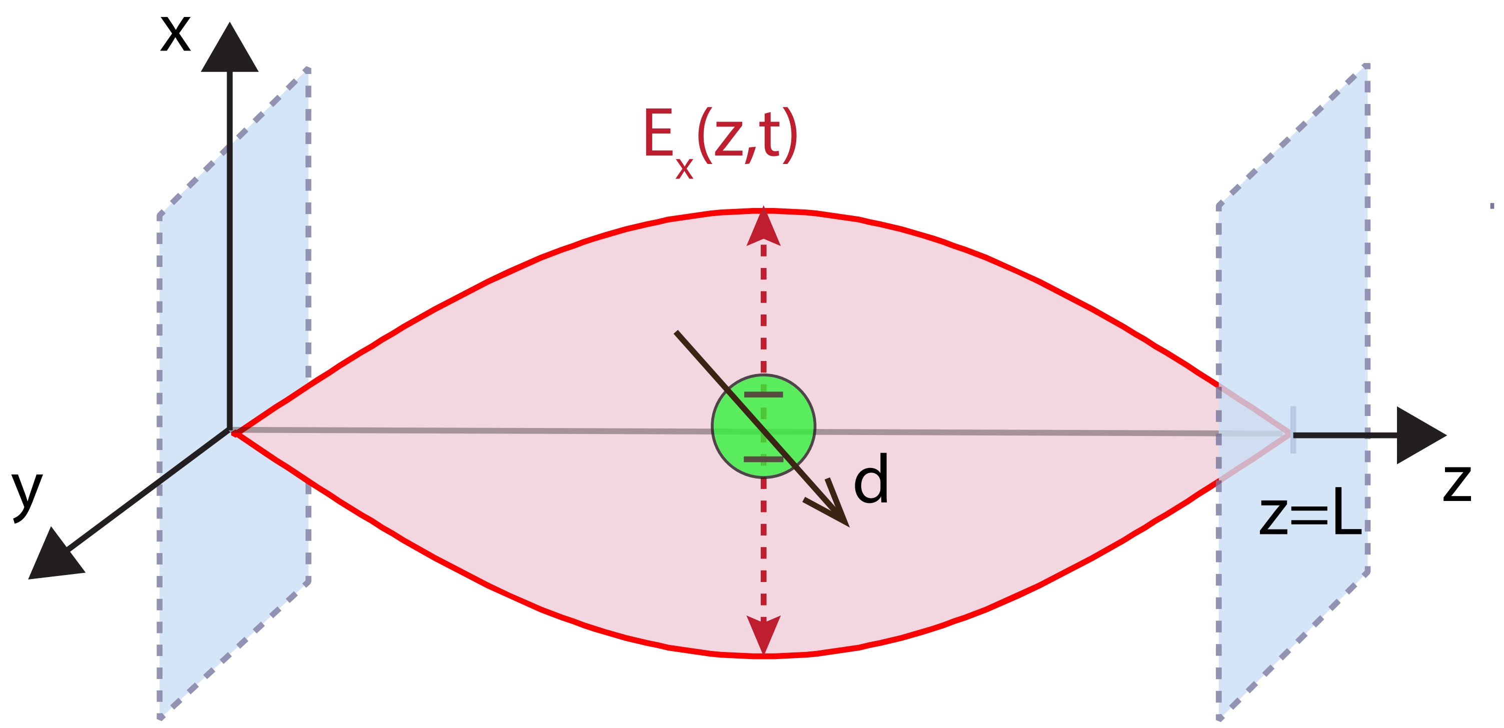
Hybrid solid state-microwaves platform

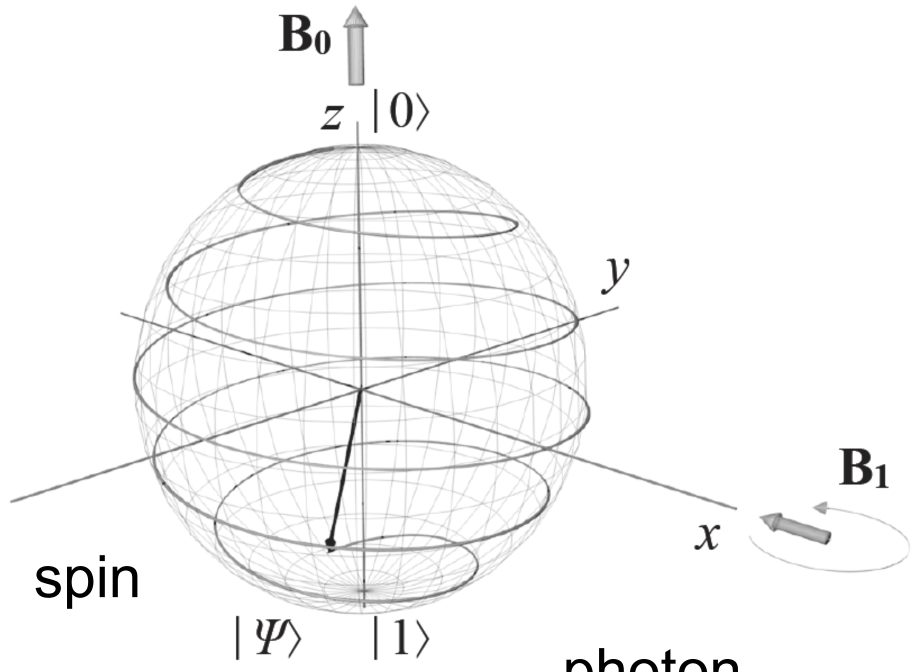
www.pnas.org/cgi/doi/10.1073/pnas.1419326112

two coupled oscillators: the case of spin-photon

classical model for
two coupled oscillators:







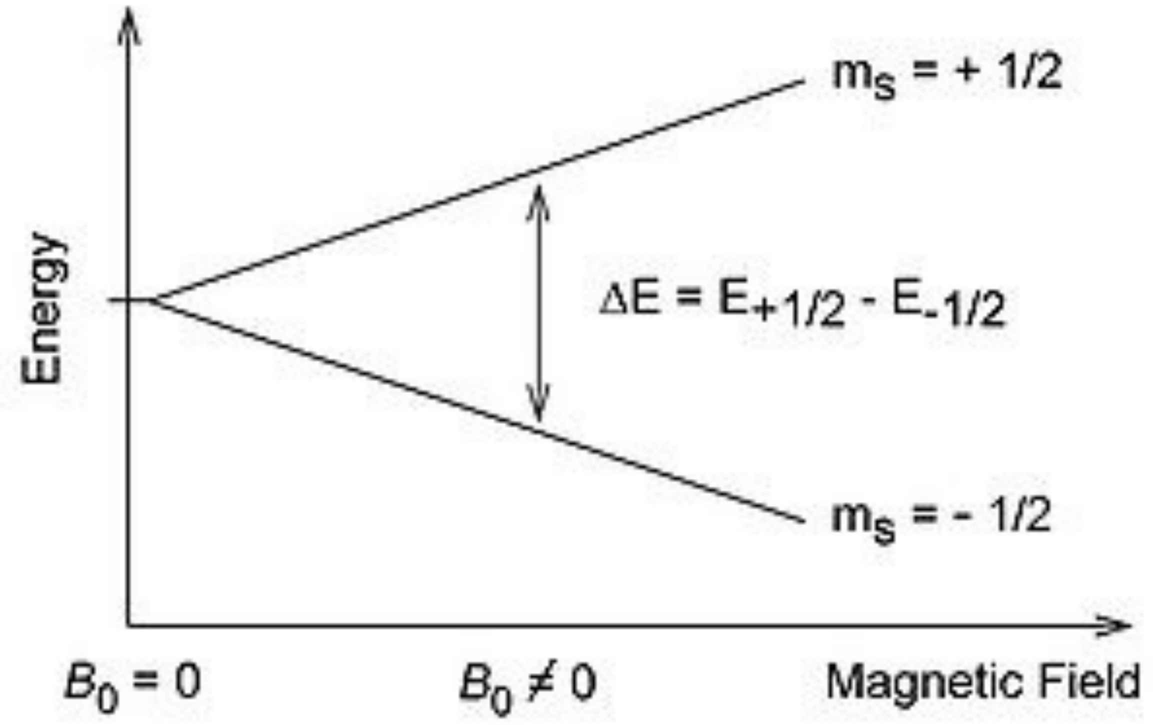
spin

photon

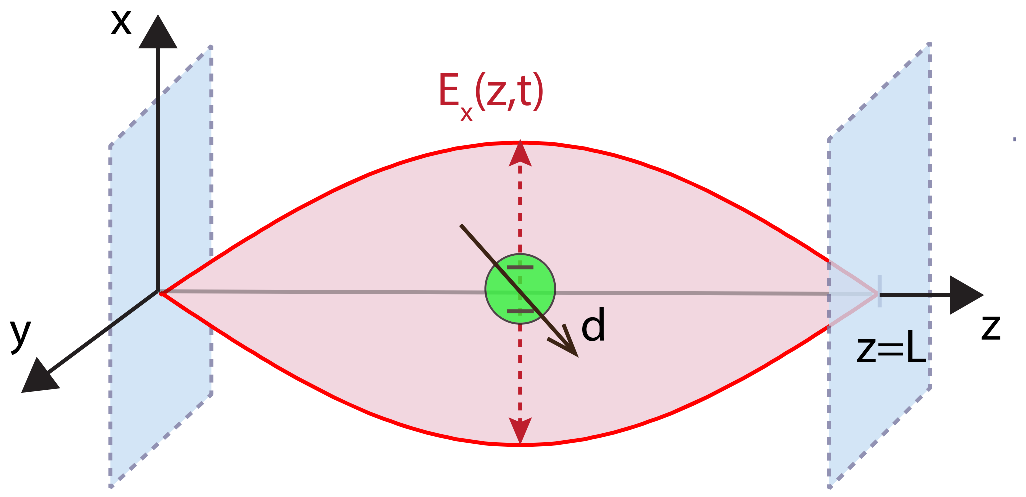
g coupling strength

γ_s (T_1 , T_2)
spin damping

$\kappa = f_0/Q_L$
cavity losses



- The Rabi model



$$H = H_{ph} + H_{TLS} + H_{TLS-ph}$$

$$H_{ph} = h\nu_0 a^\dagger a$$

$$H_{TLS} = h\nu_{TLS}\ \sigma^+_{TLS}\sigma^-_{TLS}$$

$H_{int} = -(\gamma\mu\mathbf{S}) \cdot \mathbf{B}$ *dipole interaction*

$$H_{int} = -g(\hat{a} + \hat{a}^\dagger)(\sigma_+ + \sigma_-),$$

$$H_{\text{Rabi}} = \omega_c(\hat{a}^\dagger\hat{a} + \frac{1}{2}) - \frac{1}{2}\omega_q\sigma_z - g(\hat{a} + \hat{a}^\dagger)(\sigma_- + \sigma_+).$$

$$H_{int} \Rightarrow \hat{a}^\dagger\sigma_- + \hat{a}\sigma_+ + \hat{a}^\dagger\sigma_+ + \hat{a}\sigma_-$$

Rotating Wave Approximation (RWA):

$$g \ll \omega_q, \omega_c, \text{ and also } |\omega_c - \omega_q| \ll |\omega_c + \omega_q|.$$

Janes Cumming hamiltonian in RWA:

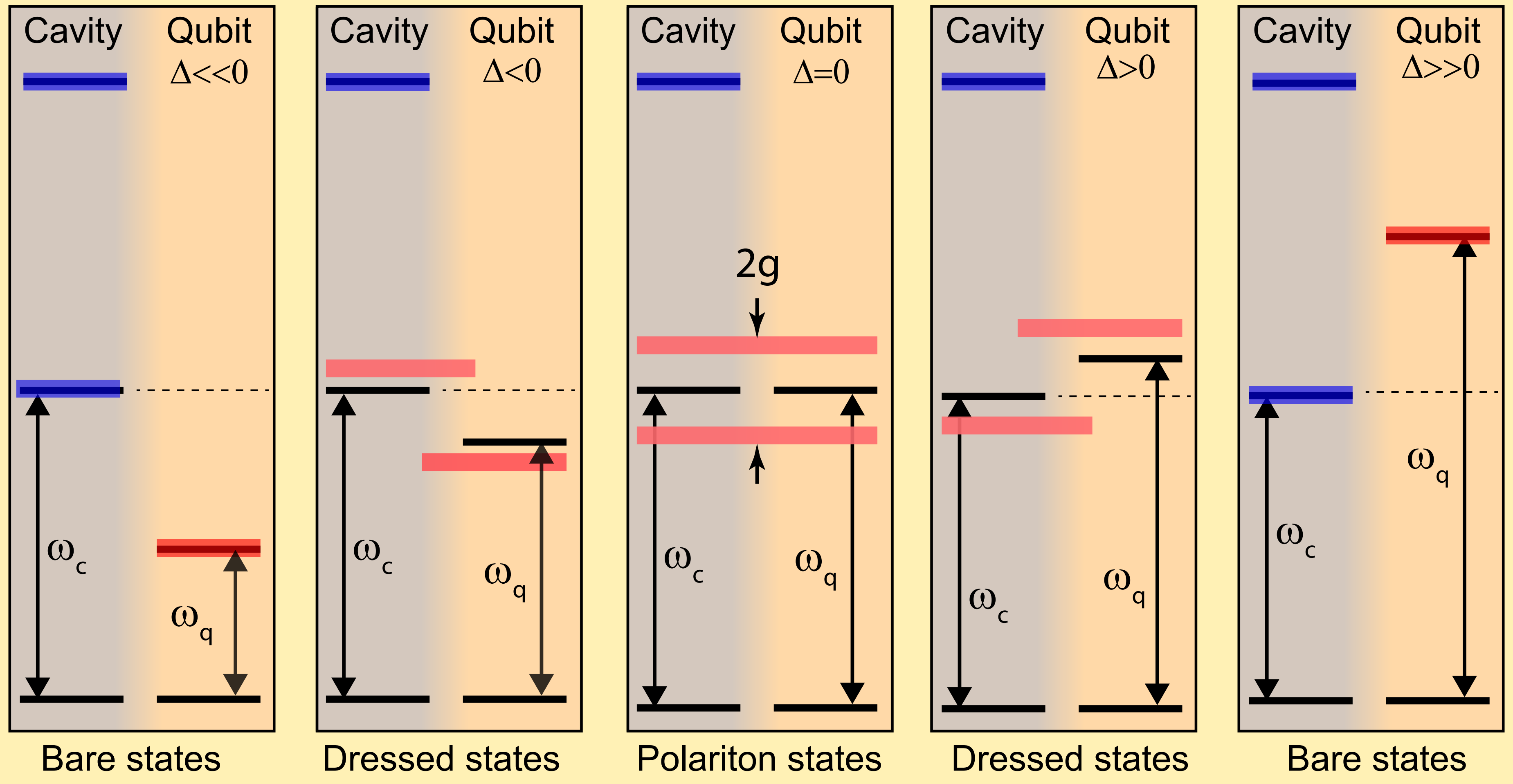
$$H_{\text{JC}} = \omega_c(\hat{a}^\dagger\hat{a} + \frac{1}{2}) - \frac{1}{2}\omega_q\sigma_z - g(\hat{a}^\dagger\sigma_- + \hat{a}\sigma_+).$$

peculiarities of spin systems:

-dipolar coupling with single spin is weak
-diamagnetic term can be neglected (?)
-applications specifically developed for magnetic systems

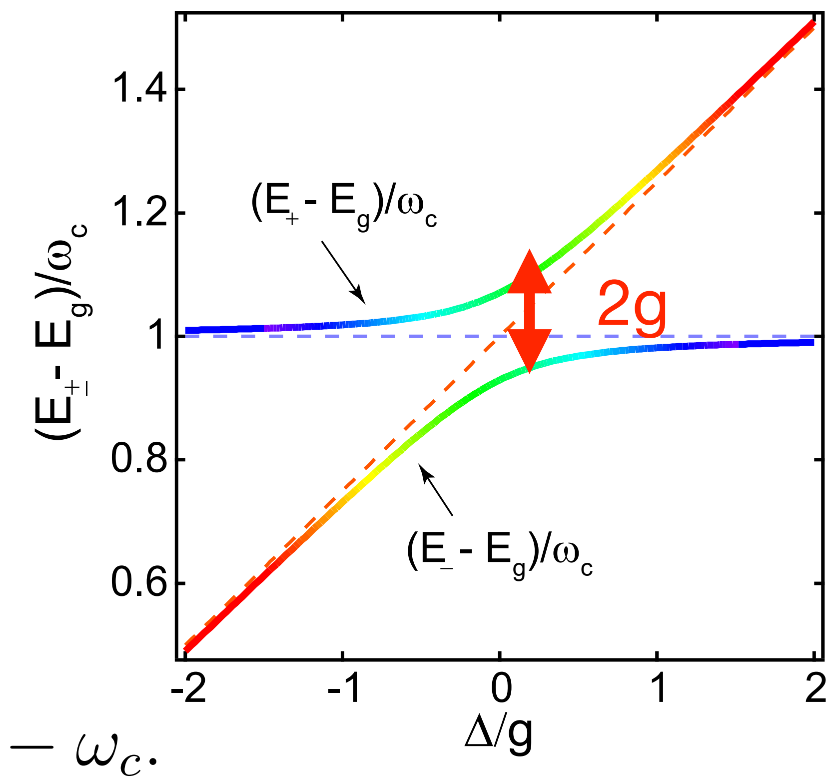
states & energy levels

$|g\rangle|0\rangle \rightarrow$ qubit in ground state, no photons in the cavity
$|g\rangle|n+1\rangle \rightarrow$ qubit in ground state, $n+1$ photons in the cavity
$|e\rangle|n\rangle \rightarrow$ qubit in excited state, n photons in the cavity



polariton-like branches

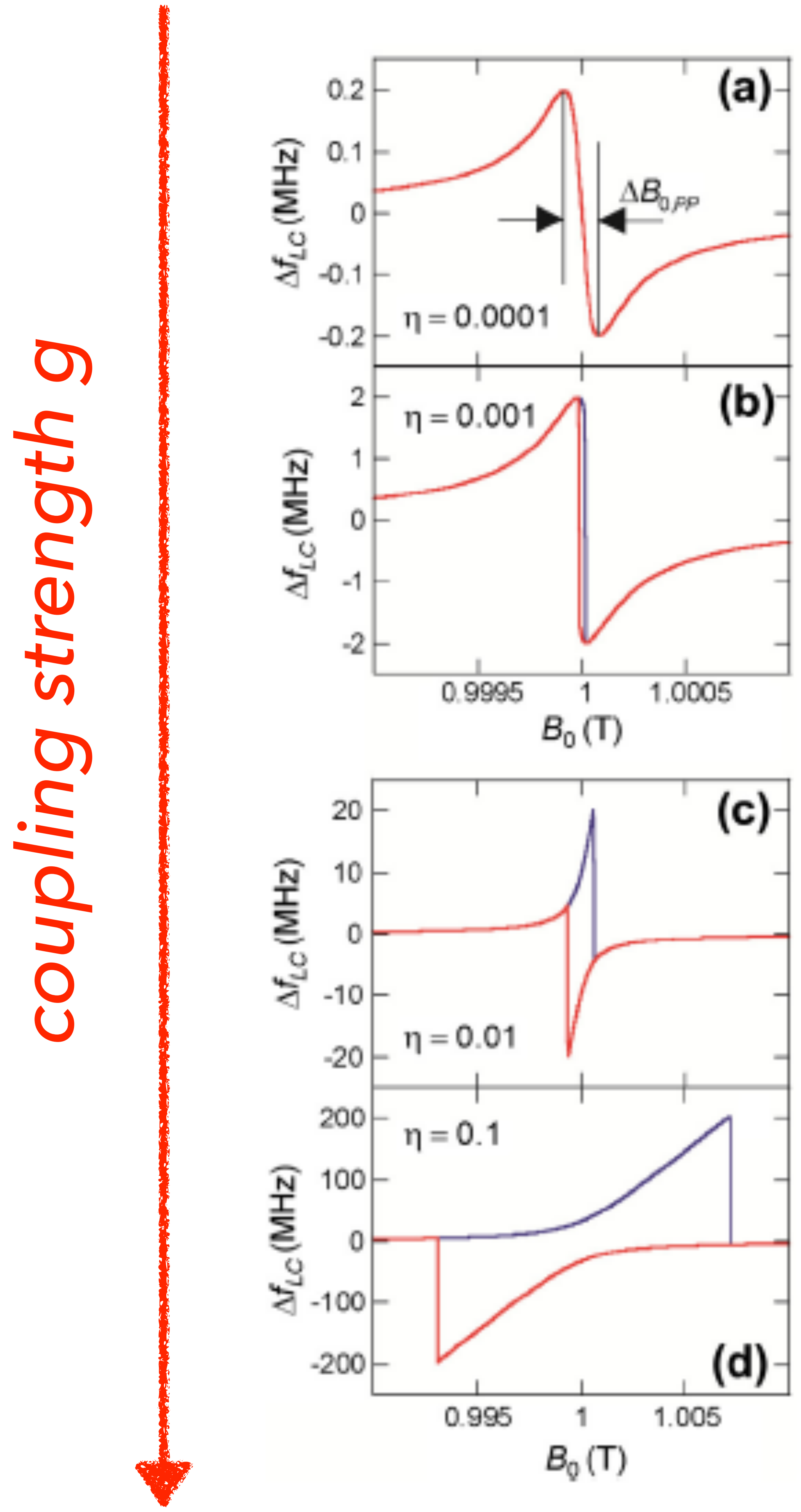
$$E_{\mp} - E_g = \omega_c \mp \frac{1}{2}\sqrt{4g^2+\Delta^2} + \Delta/2.$$



$$\Delta = \omega_q - \omega_c.$$

phenomenology: transmission spectra

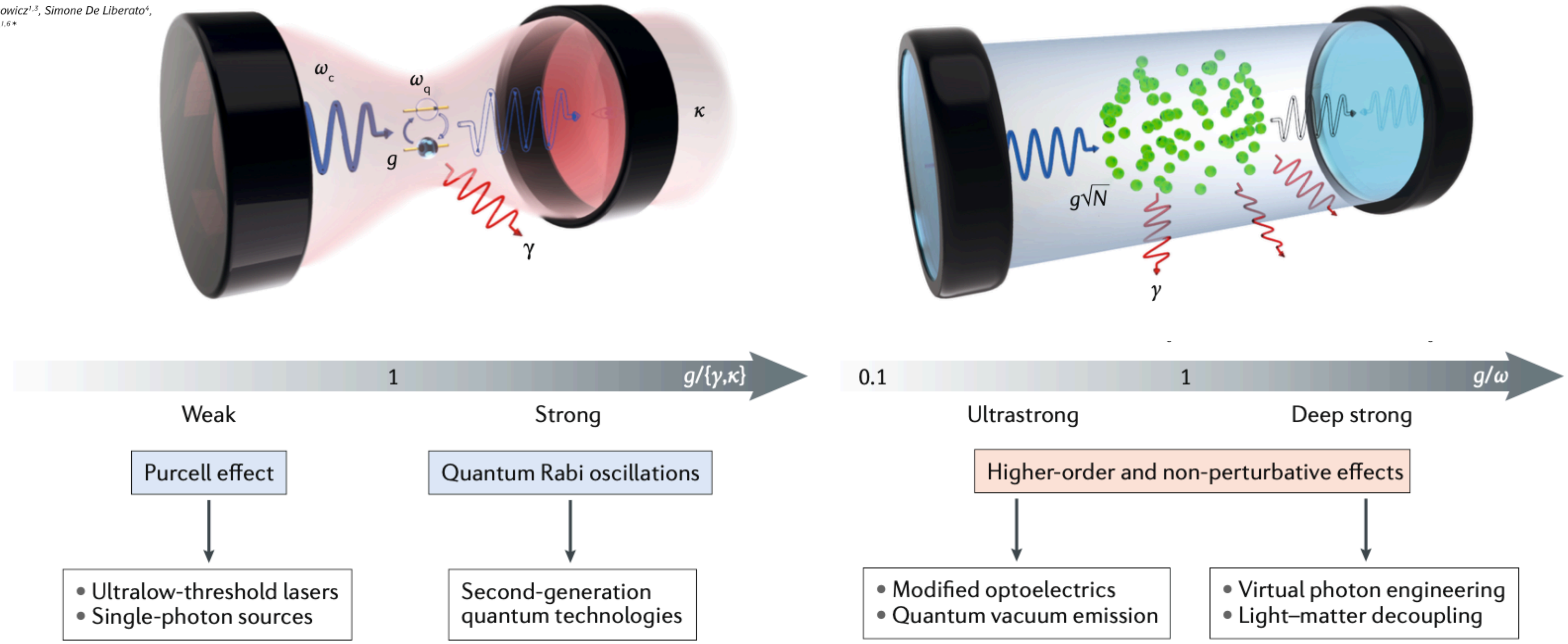
weak coupling: g < γ; k



strong coupling: g > γ; k

Ultrastrong coupling between light and matter

Anton Frisk Kockum[1,2], Adam Miranowicz[1,3], Simone De Liberato[4], Salvatore Savasta[1,5] and Franco Nori[1,6]**



Weak
- Purcell effect
  - Ultralow-threshold lasers
  - Single-photon sources

Strong
- Quantum Rabi oscillations
  - Second-generation quantum technologies

Ultrastrong / Deep strong
- Higher-order and non-perturbative effects
  - Modified optoelectrics
  - Quantum vacuum emission
  - Virtual photon engineering
  - Light–matter decoupling

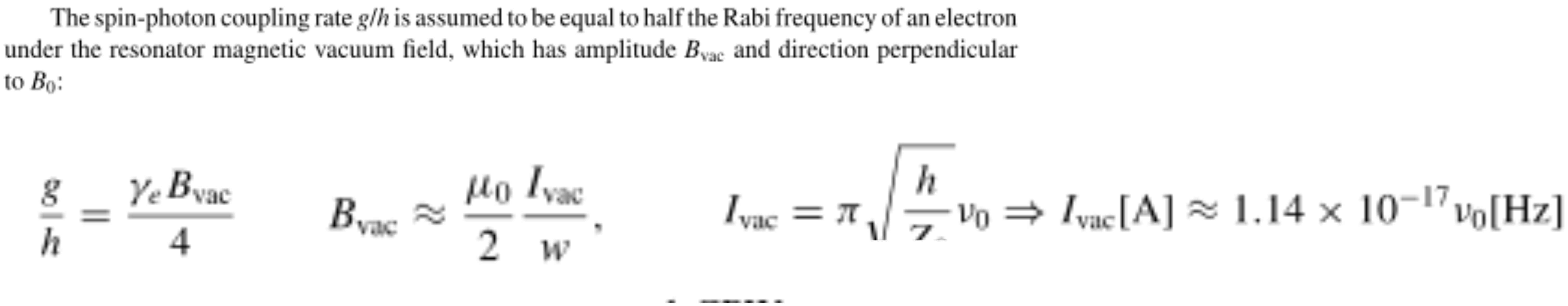
Ultrastrong coupling (USC) and deep strong coupling regimes:
- processes that do not conserve the number of interactions and ground state that contains virtual excitations
- potential applications in quantum technology, nonlinear optics, modified chemical reactions and enhancement of various quantum phenomena

Forn-Diaz et al. Rev. Mod. Phys. 91, 025005 (2019)
Kockum et al. Nat. Rev. Phys. 1, 20 (2019)

Magnetic Coupling strength

how can we increase the magnetic coupling?

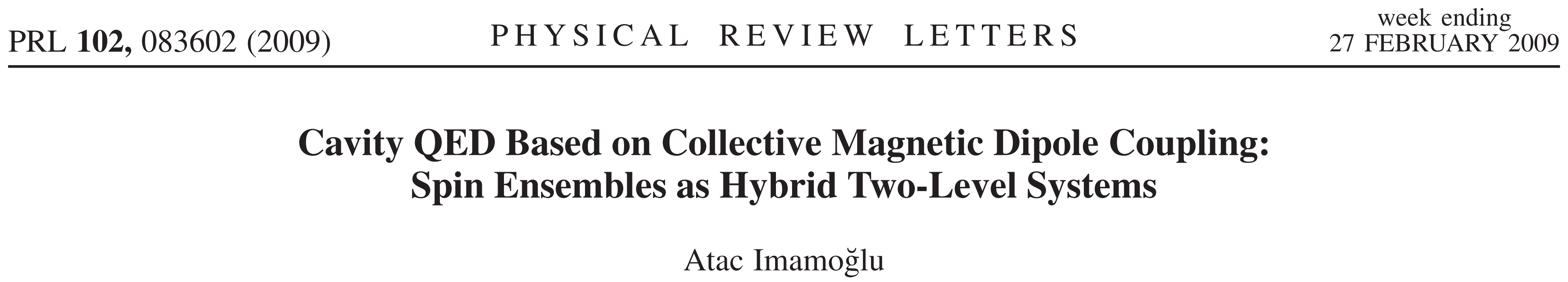
Single spin coupling: $g_s \propto B_{ac}$



The spin-photon coupling rate g/h is assumed to be equal to half the Rabi frequency of an electron under the resonator magnetic vacuum field, which has amplitude $B_{\rm vac}$ and direction perpendicular to B_0:

$$\frac{g}{h} = \frac{\gamma_e B_{\rm vac}}{4} \qquad B_{\rm vac} \approx \frac{\mu_0}{2}\frac{I_{\rm vac}}{w}, \qquad I_{\rm vac} = \pi\sqrt{\frac{h}{Z_0}}\nu_0 \Rightarrow I_{\rm vac}[{\rm A}] \approx 1.14\times 10^{-17}\nu_0[{\rm Hz}]$$

AIP Advances 4, 087122 (2014); https://doi.org/10.1063/1.4893242



PRL **102,** 083602 (2009) PHYSICAL REVIEW LETTERS week ending 27 FEBRUARY 2009

Cavity QED Based on Collective Magnetic Dipole Coupling:
Spin Ensembles as Hybrid Two-Level Systems

Atac Imamoğlu

$g = g_s\sqrt{N}$ collective coupling

g_s ˜ Hz

if N ˜ 10^{12}
$g = g_s\sqrt{N}$ ˜ MHz

if N ˜ 10^{18}
$g = g_s\sqrt{N}$ ˜ GHz

Coupling depends on the effective overlapping of the spin density and the e.m. excitation, that is on the filling factor:

$$g_i^2 = \chi_{\rm eff}\omega^2\xi, \quad \xi = \frac{\int\int\int_{V_{\rm YIG}} \mu_0 \vec{H}^* \vec{H} dV_{\rm YIG}}{\int\int\int_V \mu_0 \vec{H}^* \vec{H} dV}.$$

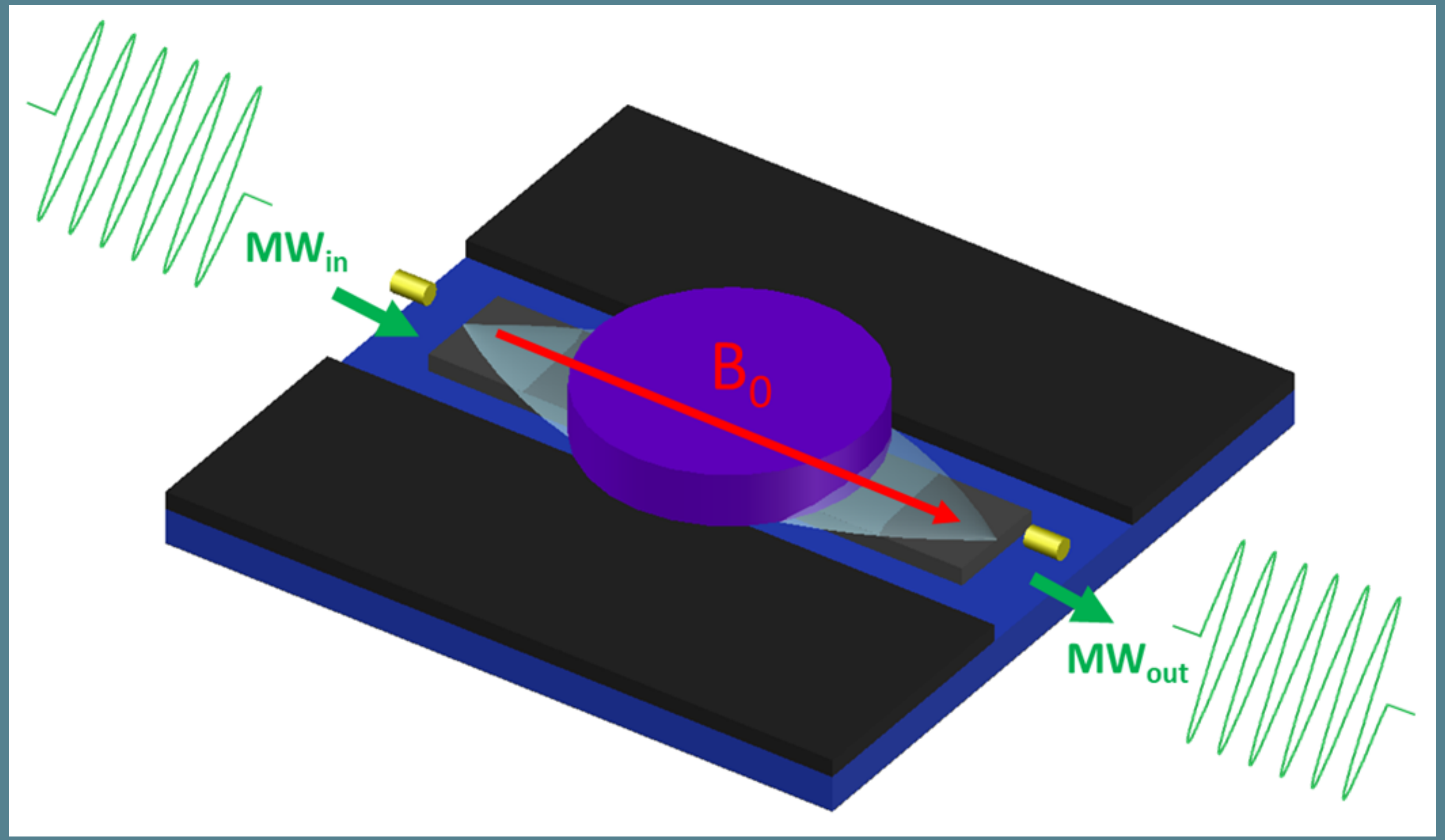
OUTLINE

☑ **GENERAL PROBLEM hybrid circuits (scalability)**

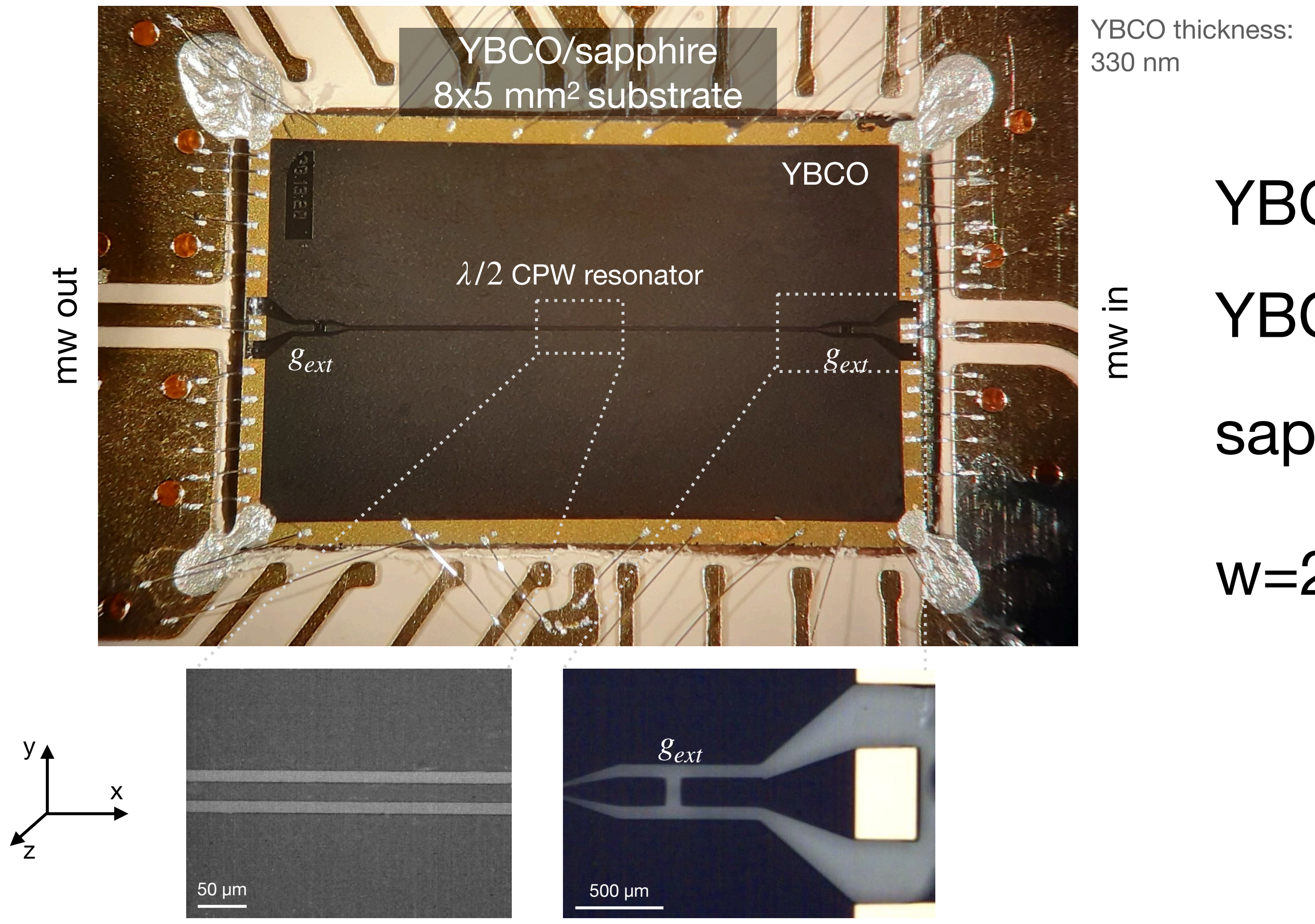
☐ **IMPLEMENTATION**
strategies to enhance the coupling:
resonators: YBCO circuits
spin systems: MolSpin & YIG

☐ **TOWARDS USC**
experiments & model
 CW spectra: examples of S21 dispersion
 data analysis

☐ **PESPECTIVES**
new phenomena
Q-sensing with scalable architectures



Planar superconducting resonators

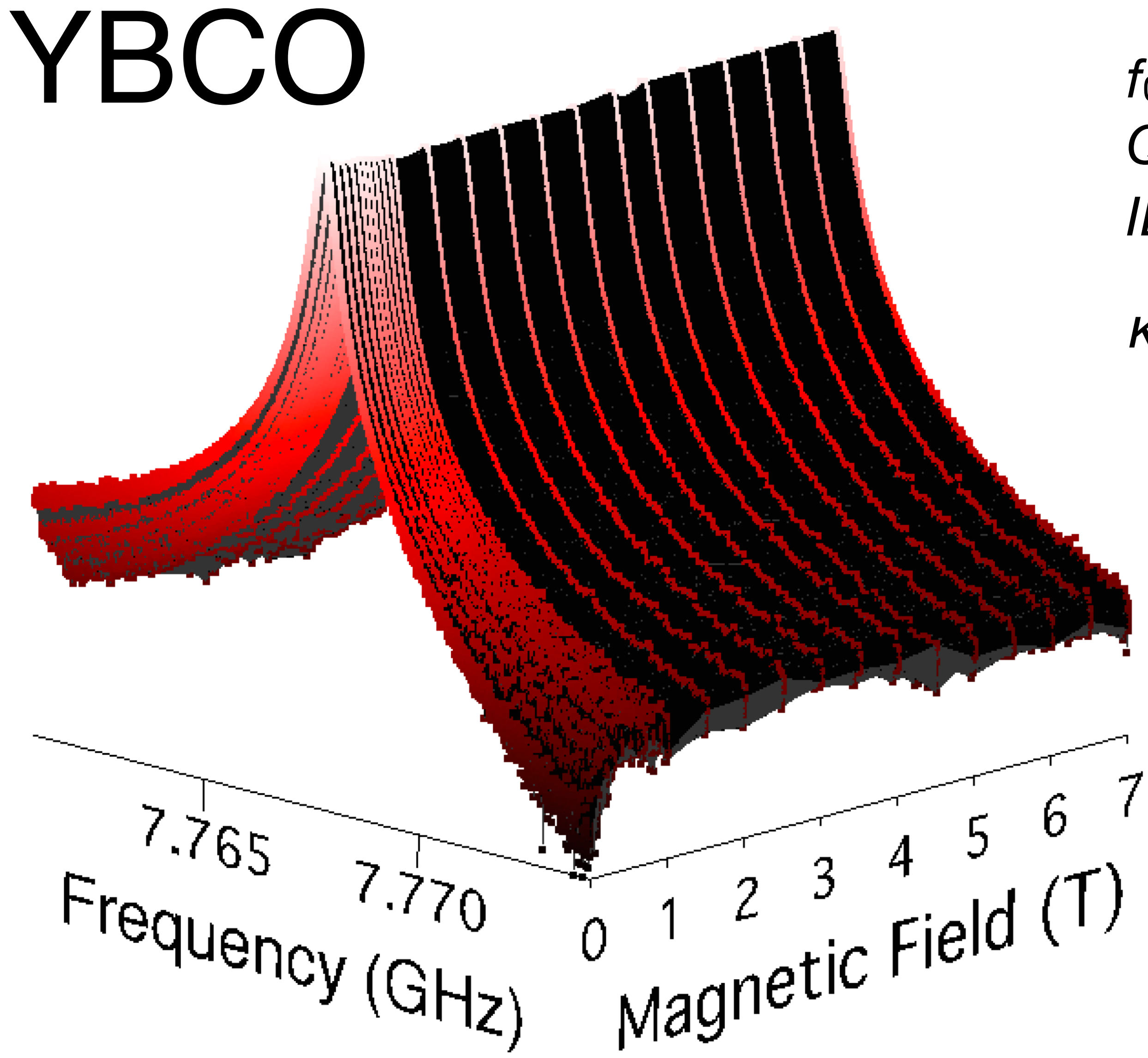


YBCO coplanar back-plated waveguide resonator

YBCO (330 nm) (Ceraco Gmbh): T_c=87 K

sapphire (430 µm): $\epsilon_r \simeq 11$; tan(δ)~10^{-6} at low T

w=200 µm, s=73 µm: $Z_0 \simeq 50$ Ohm

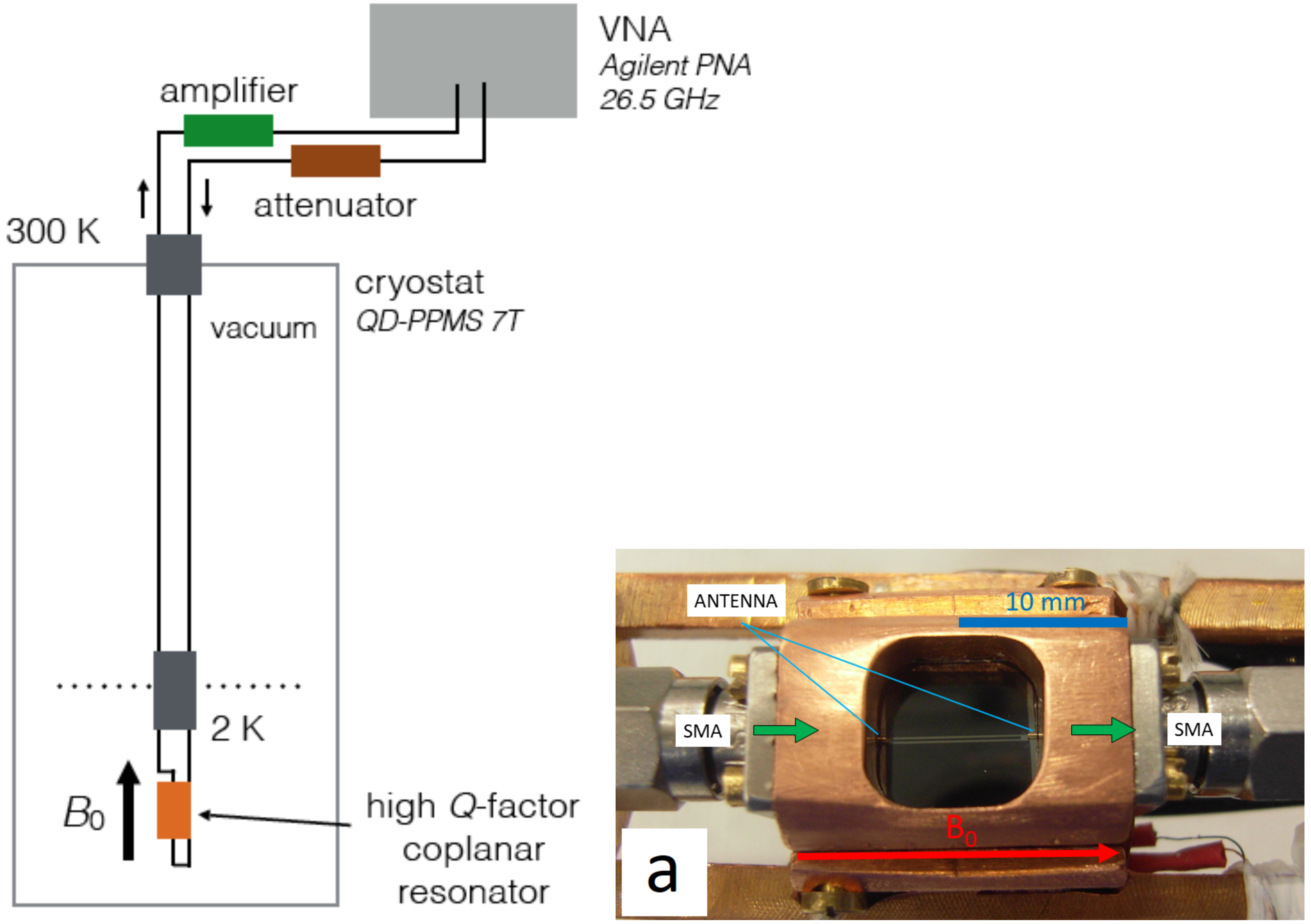


f_0=7.7553 GHz
$Q_L \simeq 30000$
IL=-16.5 dB

$\kappa = f_0/Q_L$=0.5 MHz

A Ghirri, C. Bonizzoni, D. Gerace, S. Sanna, A. Cassinese, and M. Affronte
Applied Physics Letters 106, 184101 (2015); doi: 10.1063/1.4920930

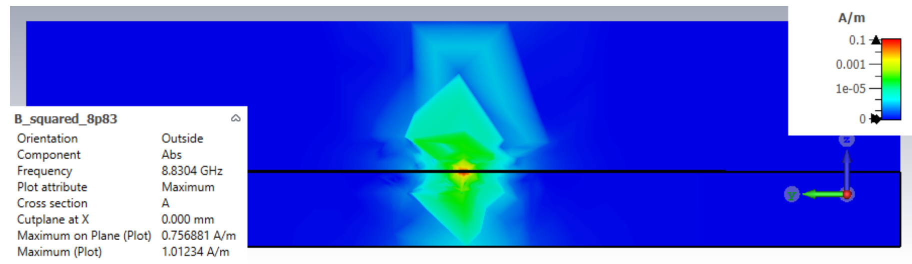
CW spectroscopy



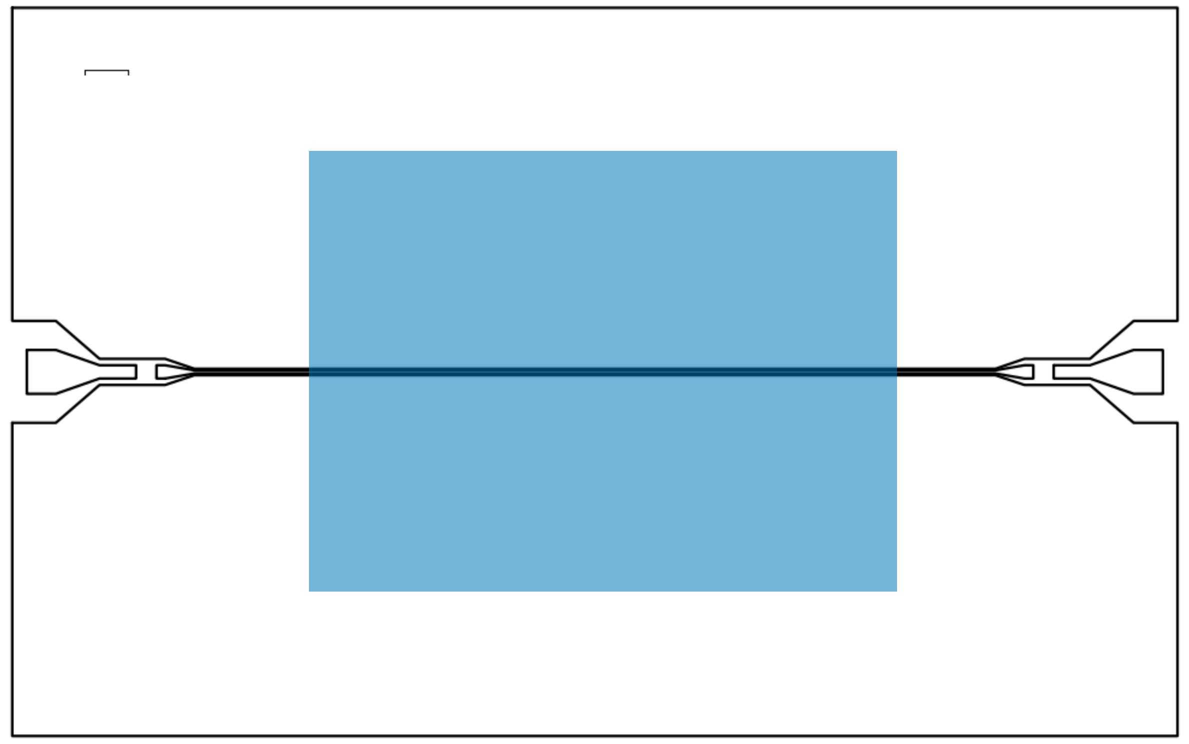
C. Bonizzoni, A. Ghirri, M. Affronte *Advances in Physics X* 3:1, 1435305,
DOI: 10.1080/23746149.2018.1435305 *(2018)*

Optimizing the effective volume & B_{ac} strenght

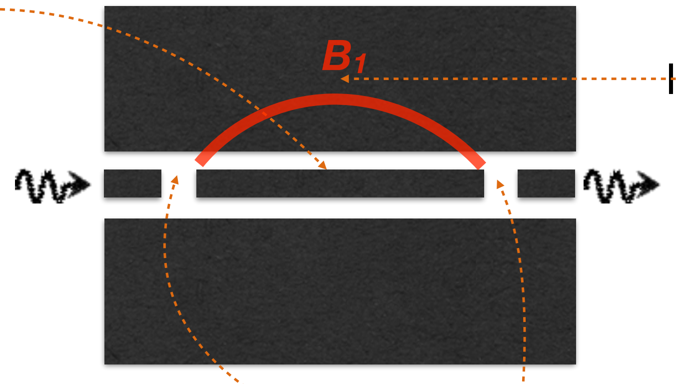
Linear (λ/2)



B_squared_8p83
Orientation Outside
Component Abs
Frequency 8.8304 GHz
Plot attribute Maximum
Cross section A
Cutplane at X 0.000 mm
Maximum on Plane (Plot) 0.756881 A/m
Maximum (Plot) 1.01234 A/m

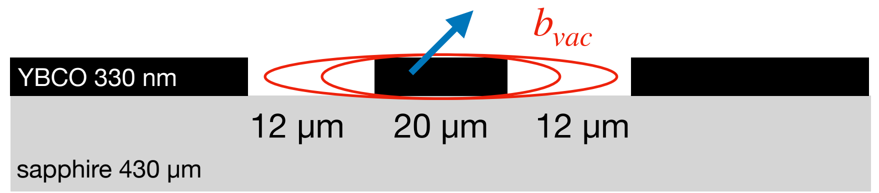


CoPlanar Waveguide (λ/2)



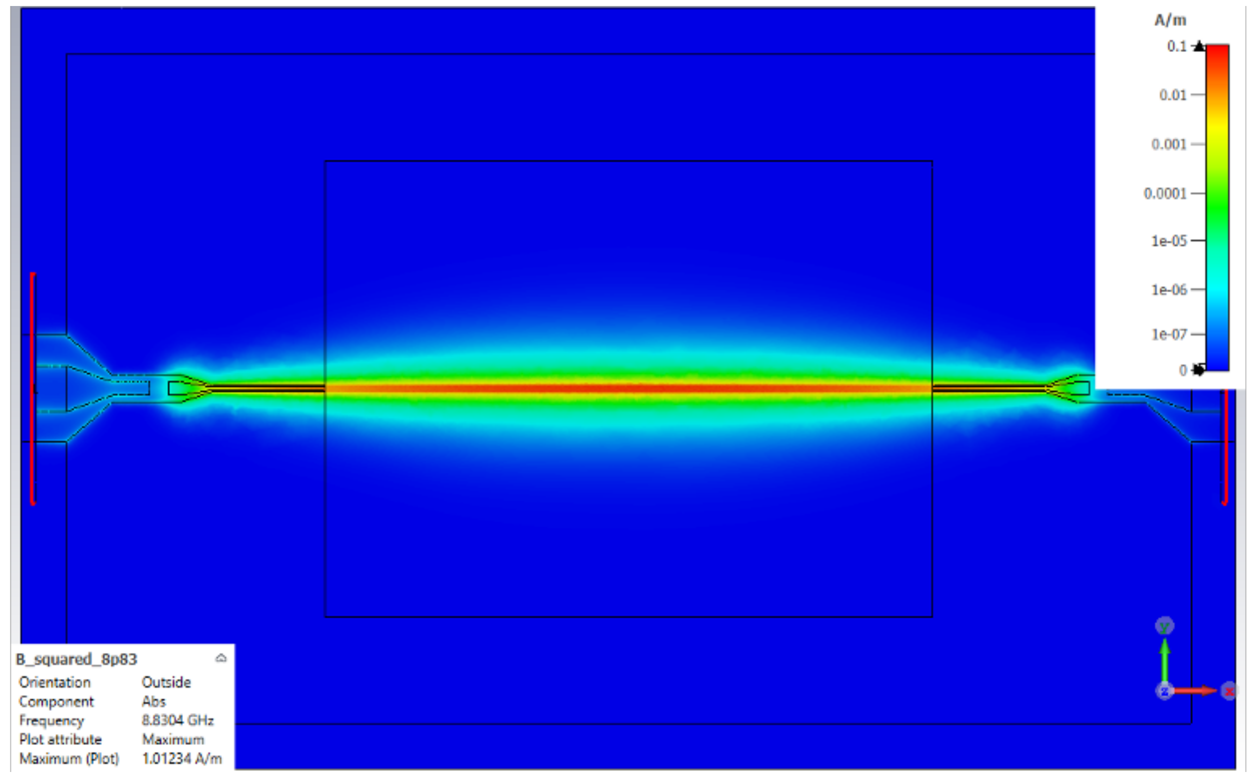
$$f_0 = \frac{c}{\sqrt{\epsilon_{eff}}}\frac{1}{2l}$$

λ/2 resonator

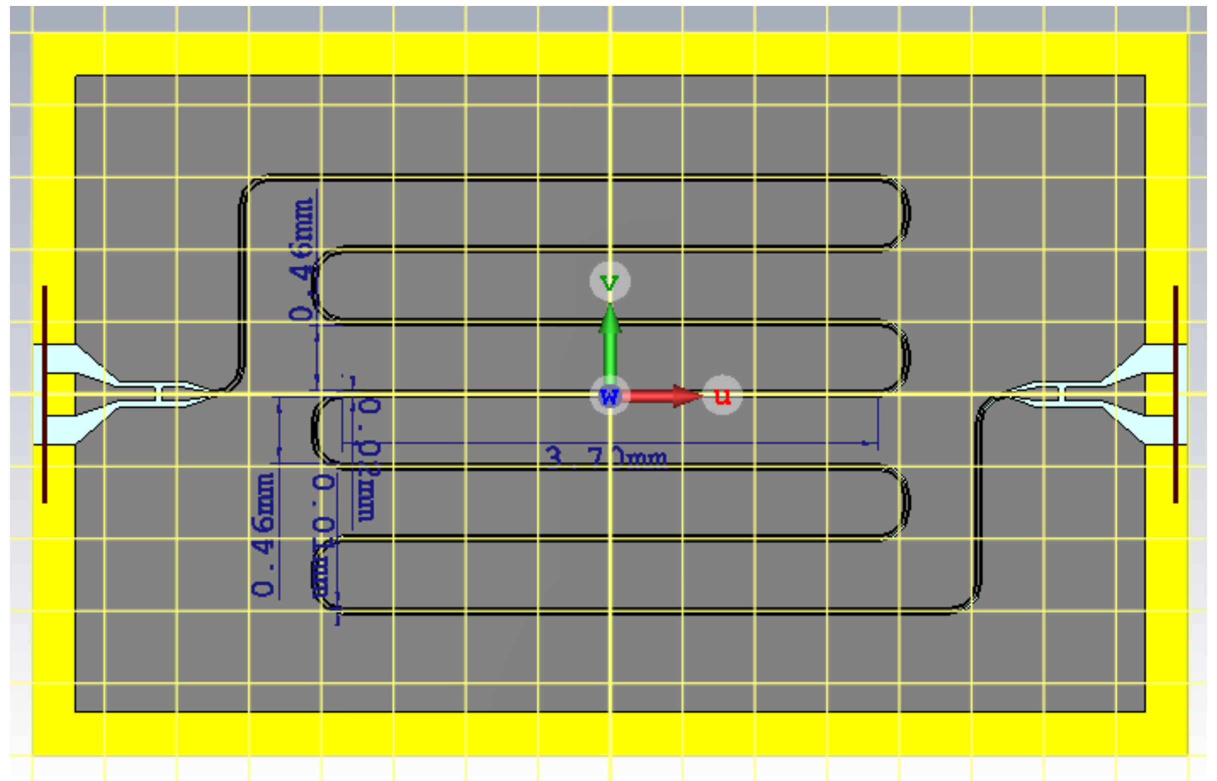


$$g_s/h = \frac{1}{4}\gamma_e b_{vac}$$

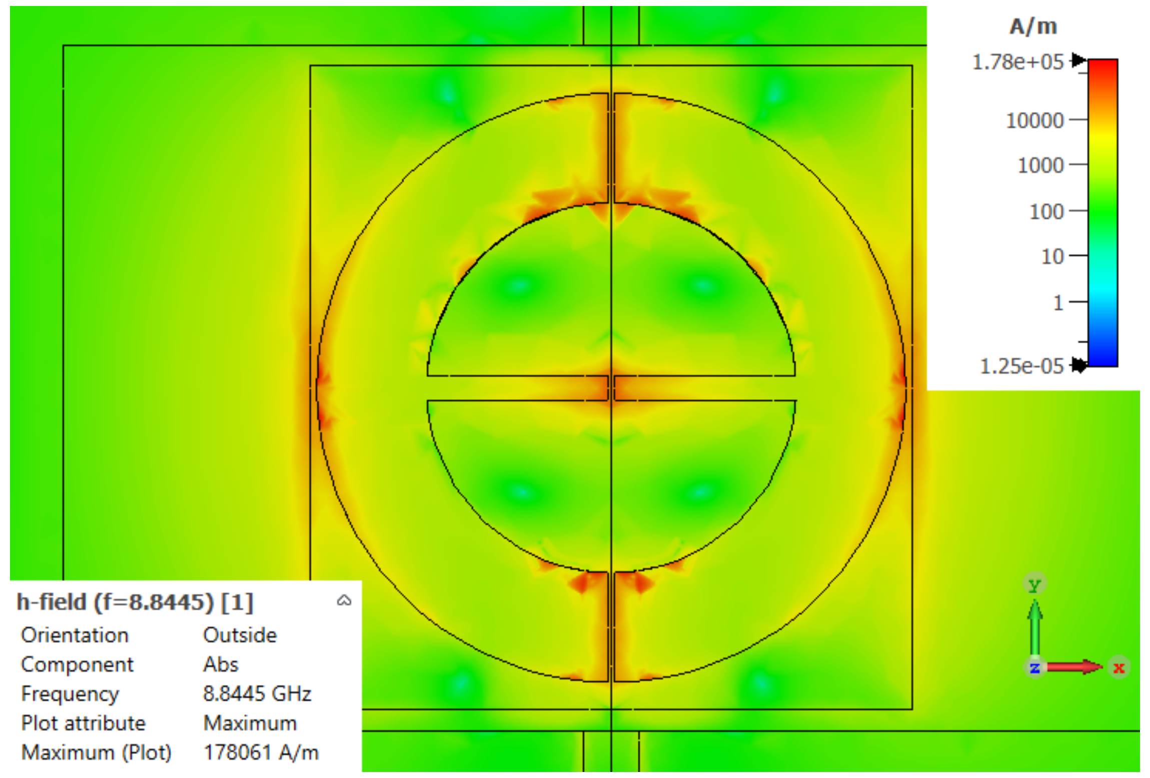
$$g_s \approx 10 \text{ Hz at } 10 \text{ GHz}$$



B_squared_8p83
Orientation Outside
Component Abs
Frequency 8.8304 GHz
Plot attribute Maximum
Maximum (Plot) 1.01234 A/m



Meander [multi-frequency]



h-field (f=8.8445) [1]
Orientation Outside
Component Abs
Frequency 8.8445 GHz
Plot attribute Maximum
Maximum (Plot) 178061 A/m

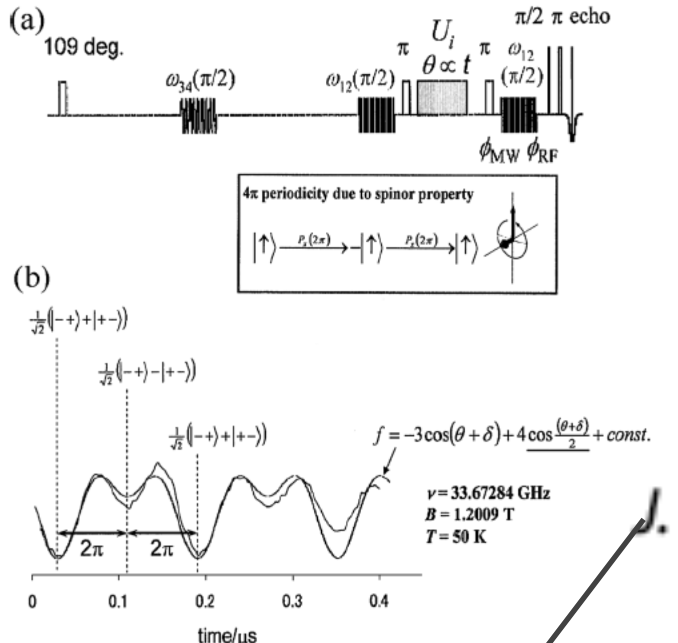
Inverse Anapole

[radiation' field focused on small volume]

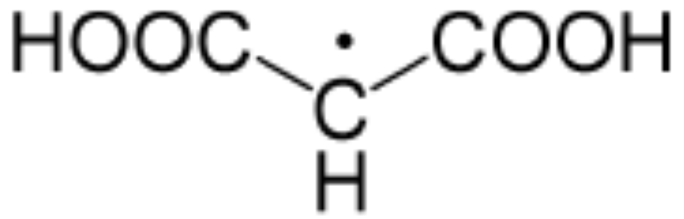
https://doi.org/10.21203/rs.3.rs-1781655/v1

Paramagnetic centers
Molecular spins
electron spin coherence> μs

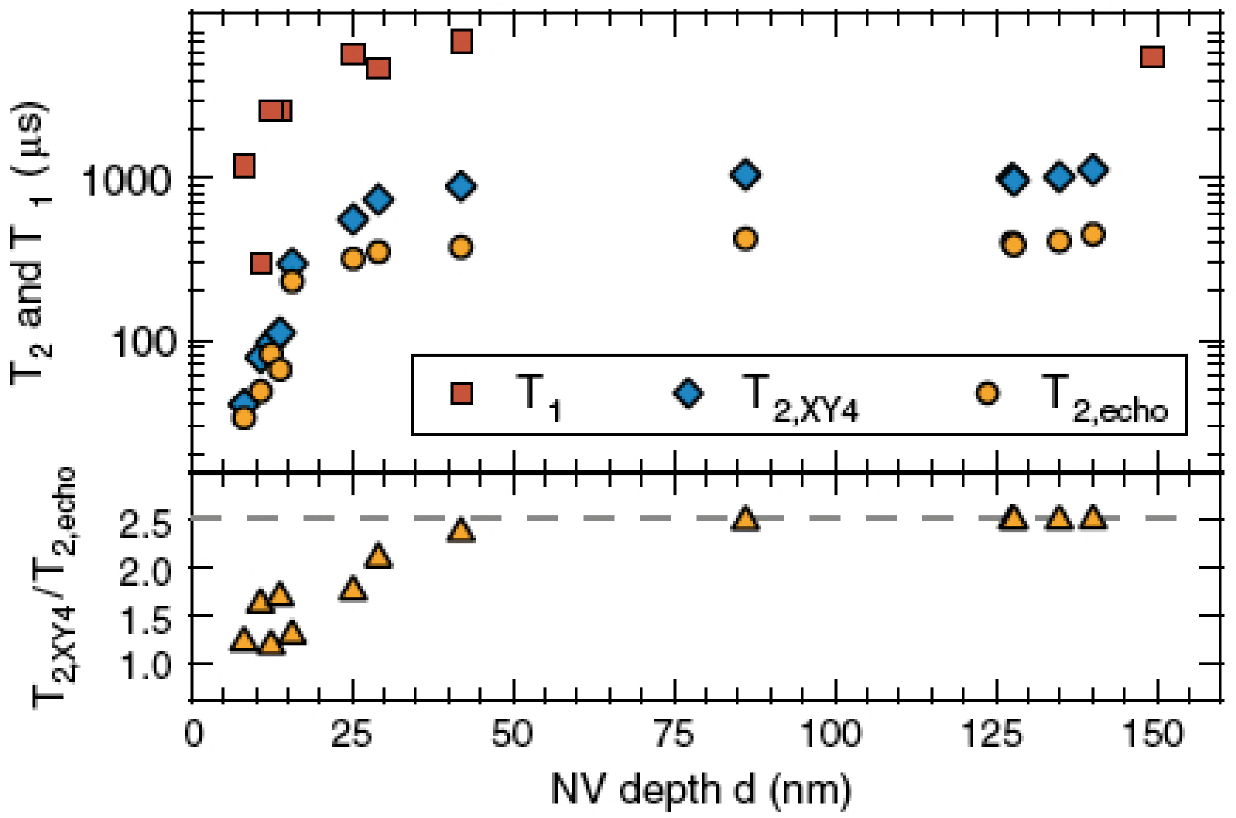
line width ~10MHz



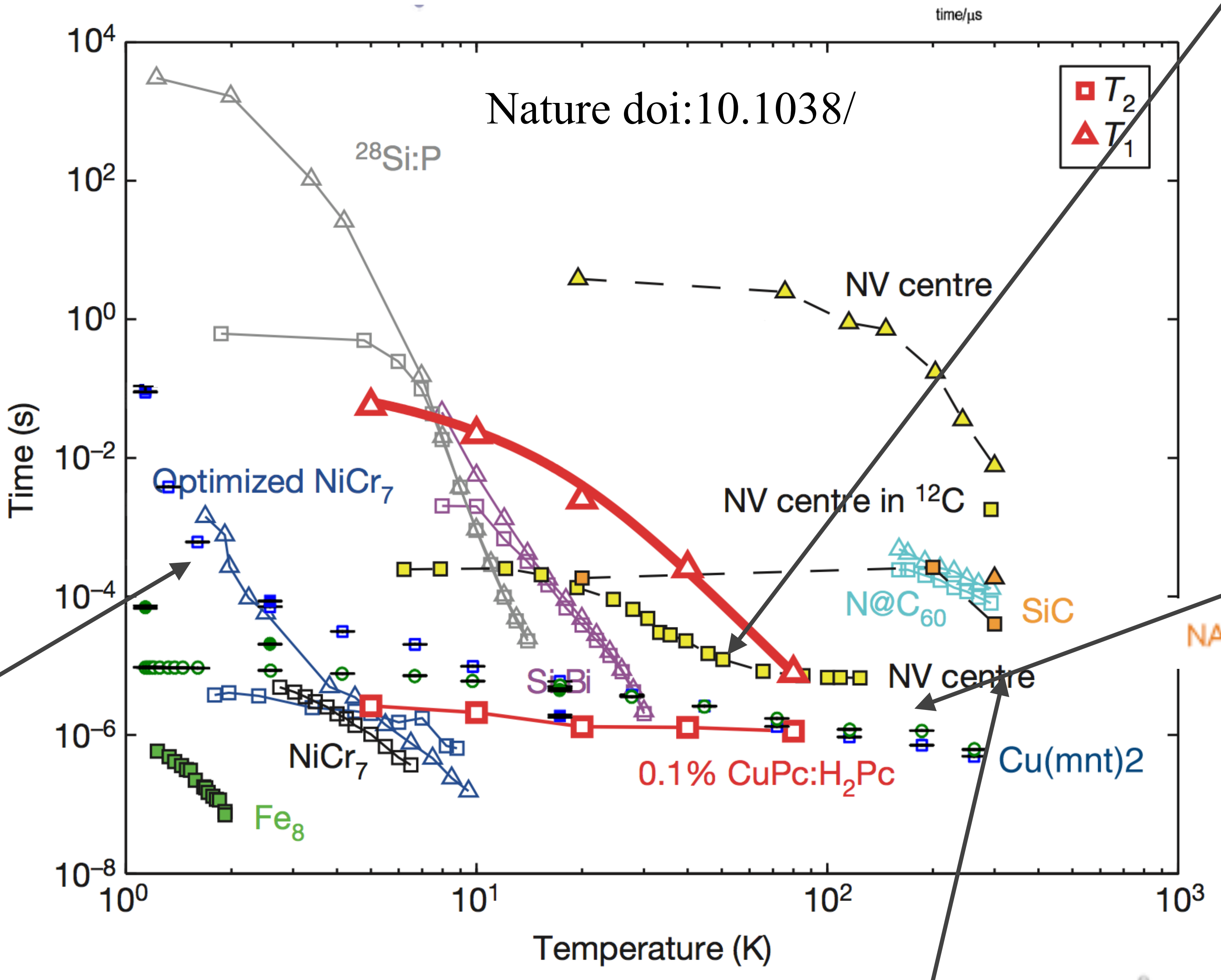
malonyl radical



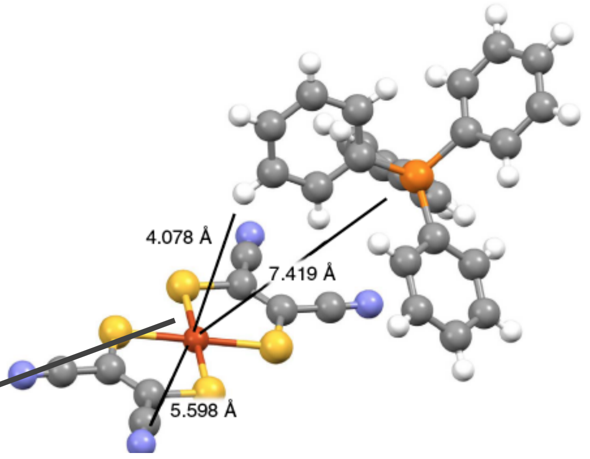
J. Mater. Chem., 2009, **19**, 3739–3754



Molecular Spins in the Context of Quantum Technologies
A. Ghirri, A. Candini, M. Affronte
Magnetochemistry 3(1), 12, (2017)
doi:10.3390/magnetochemistry3010012

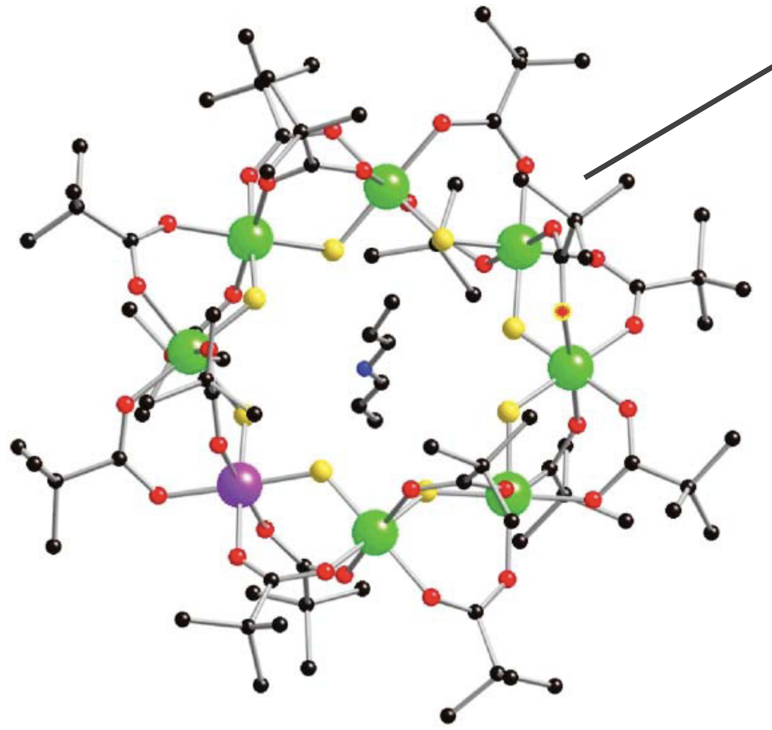

Nature doi:10.1038/

Cu(mnt)$_2$

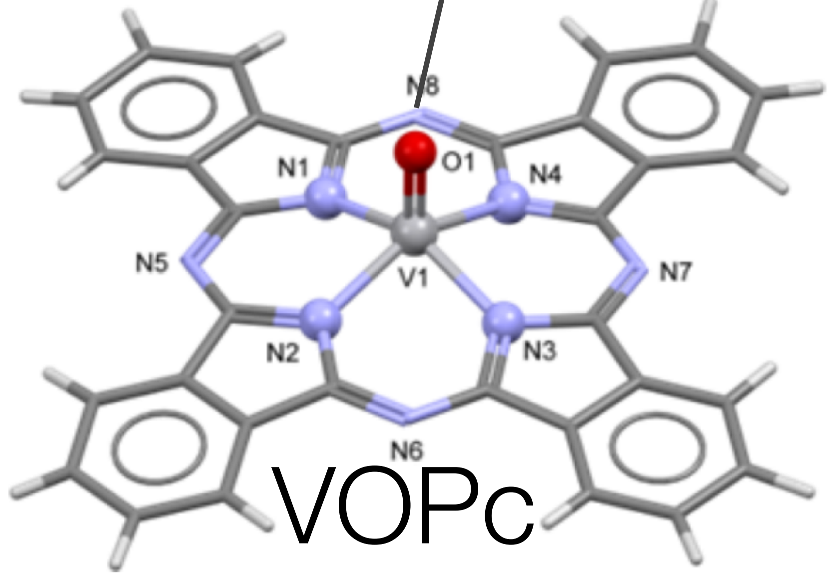


NATURE COMMUNICATIONS | 5:5304 | DOI: 10.1038/ncomms6304

Cr$_7$Ni

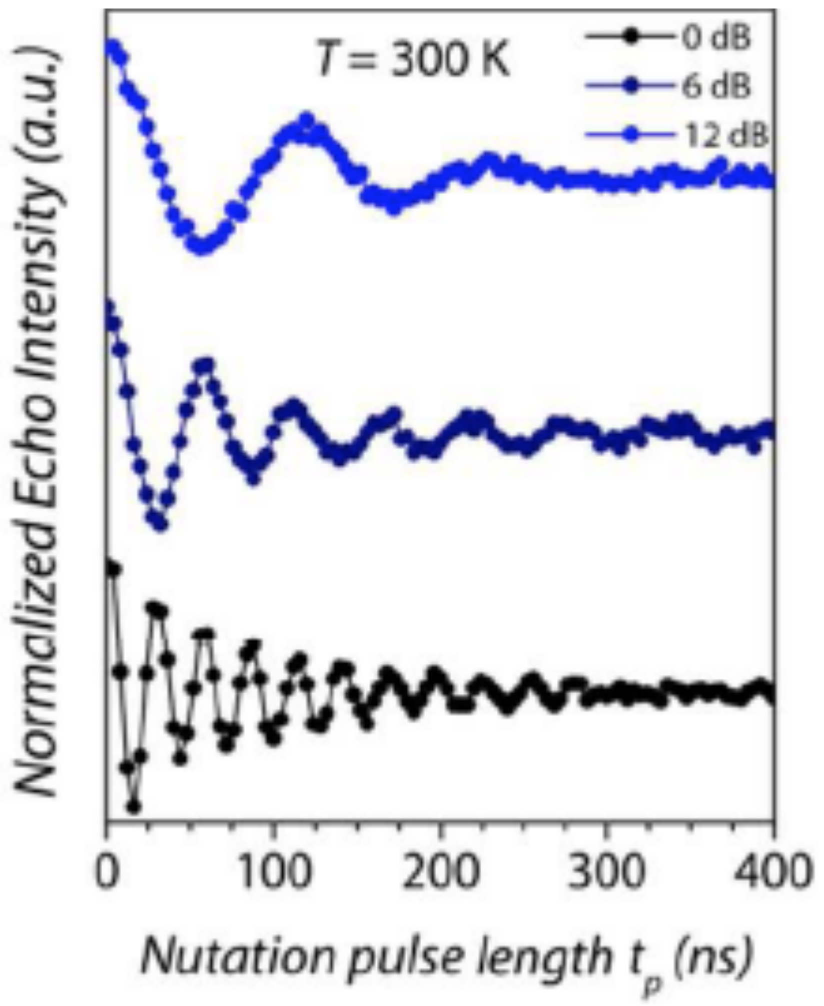


Wedge et al. PRL 108, 107204 (2012)



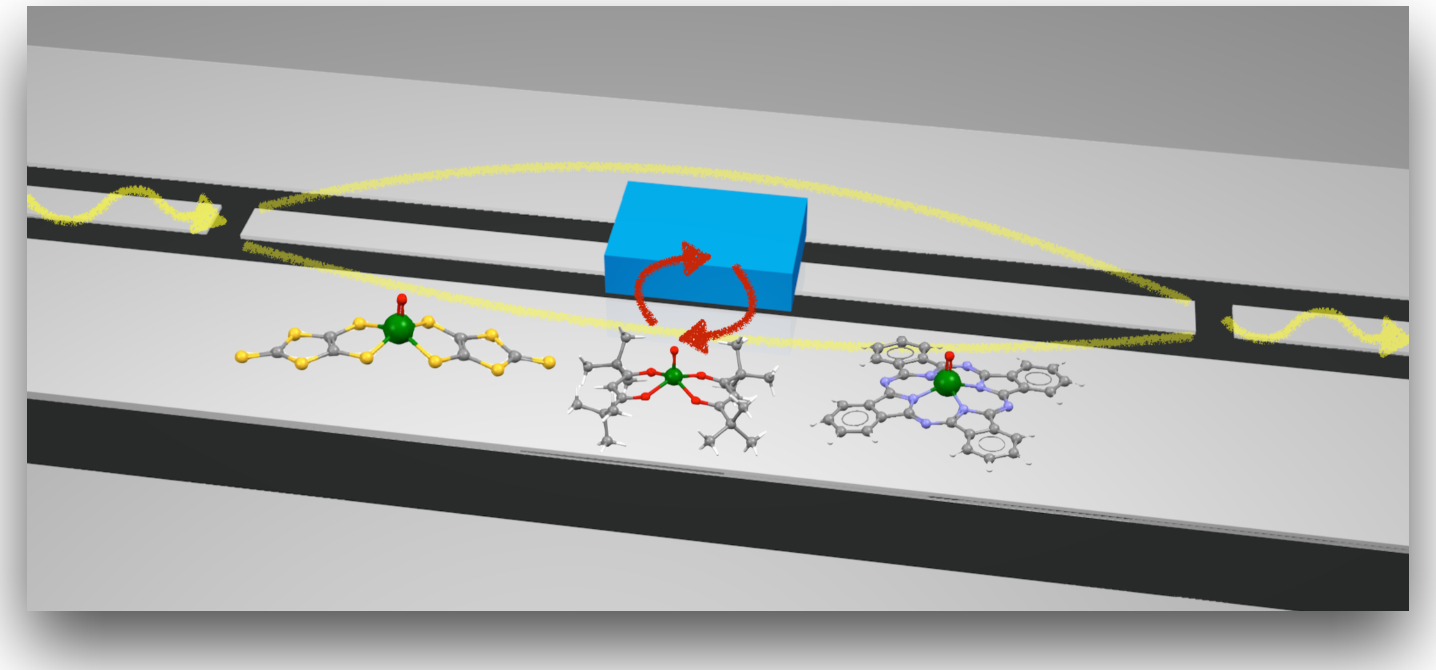
VOPc

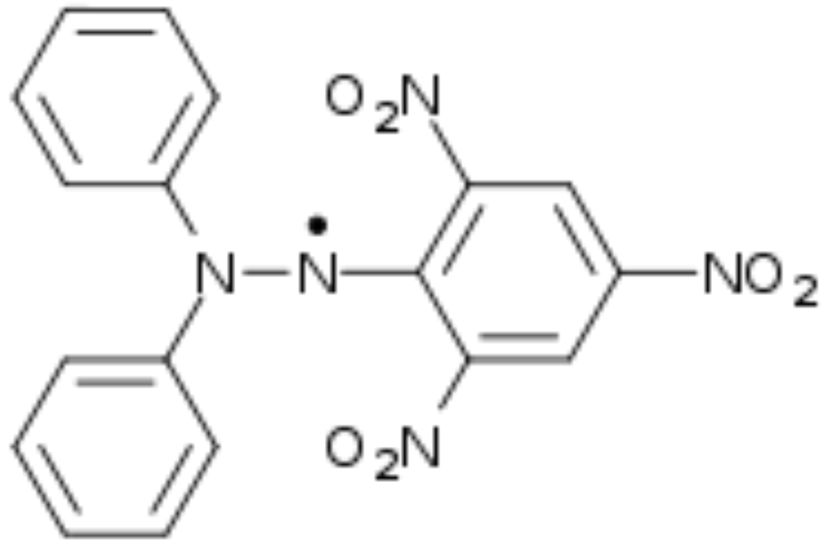
M. Atzori et. al. *JACS 138*, 2154-2157 (2016)



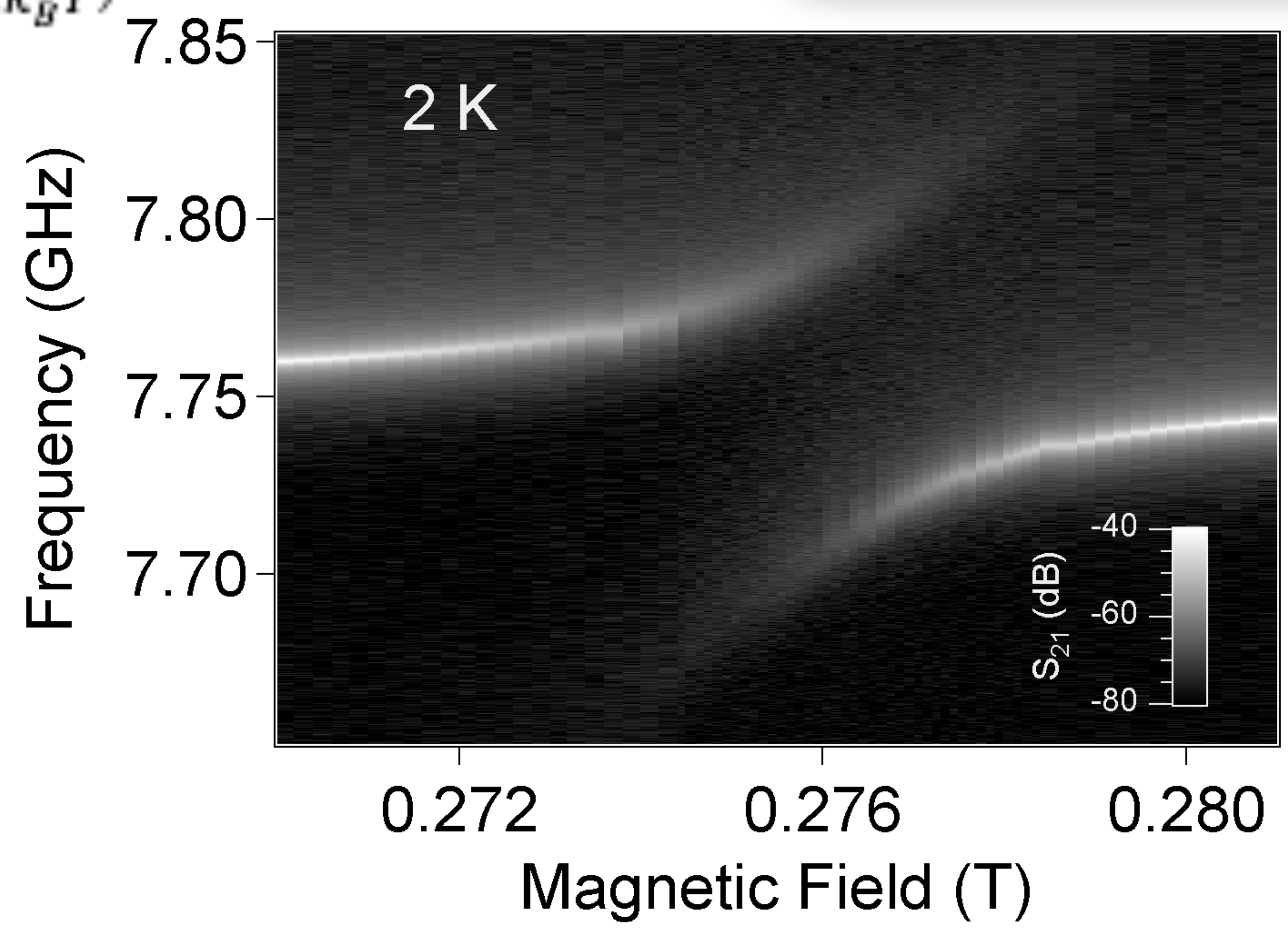
Paramagnetic centres: Radical DPPH

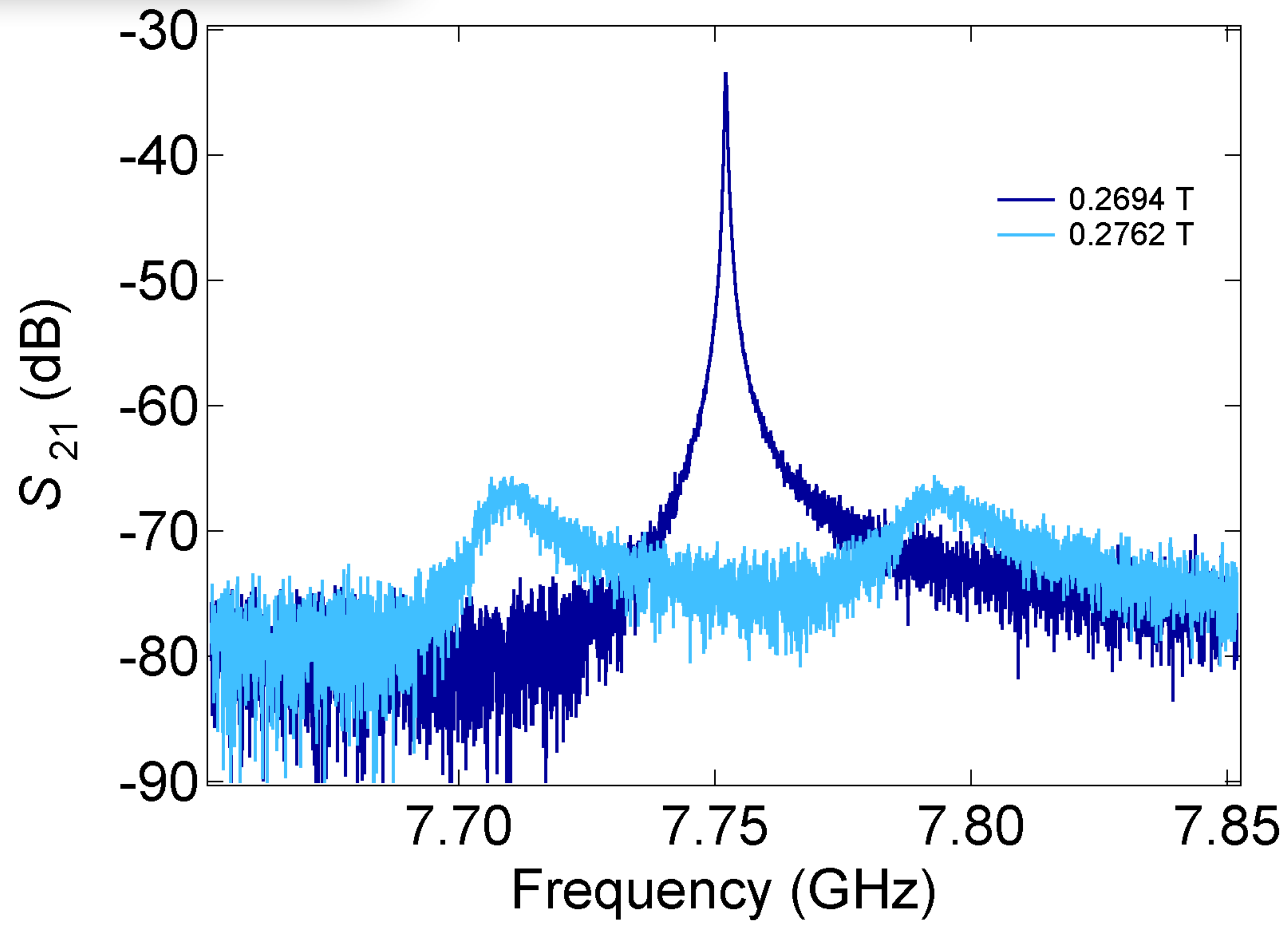
$$N_p = N \tanh\left(\frac{\hbar\omega}{2k_BT}\right)$$





di(phenyl)-(2,4,6-trinitrophenyl)iminoazanium





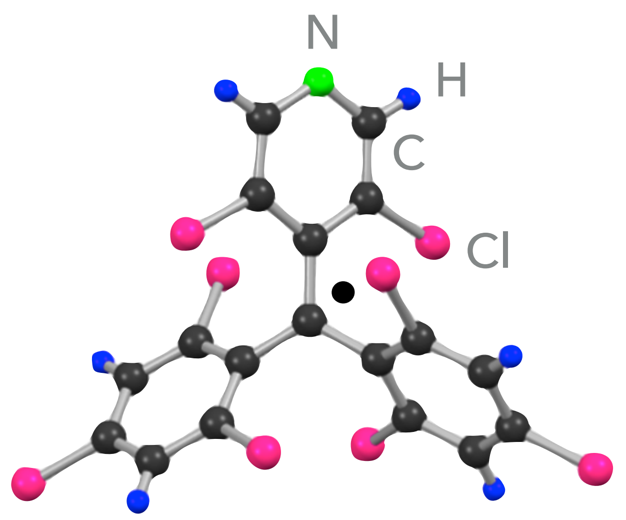
spin ensemble:
γ_s=3 MHz @ 77 K, γ_s=14 MHz @ 2 K

resonator: Q_L=20000; $\kappa \simeq 0.5$ MHz

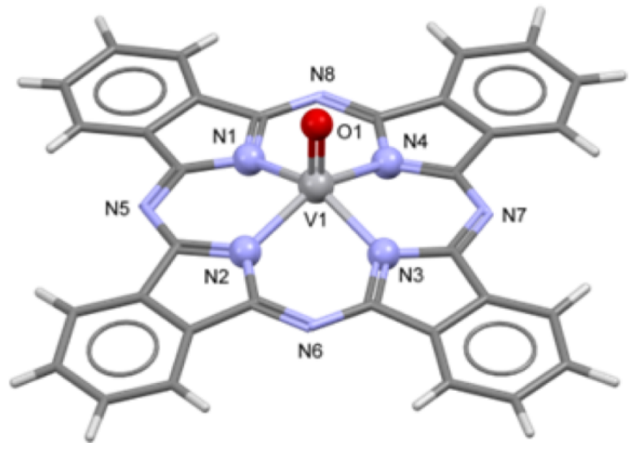
Applied Physics Letters 106, 184101 (2015); doi: 10.1063/1.4920930

$$g_c >> \kappa,\ \gamma_s$$

Py-BTM



$$C = \frac{g^2}{\gamma\kappa} = 4300$$

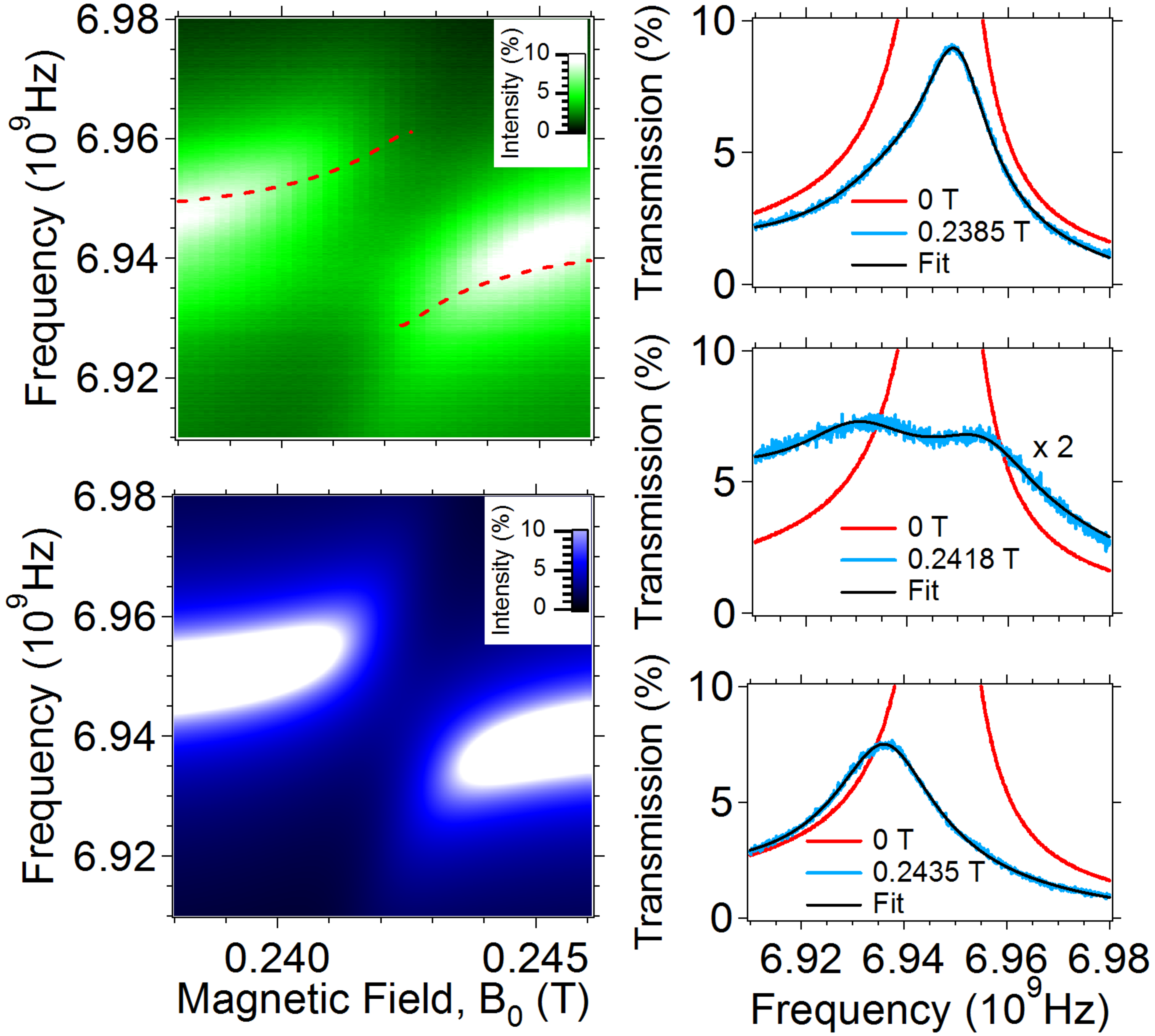


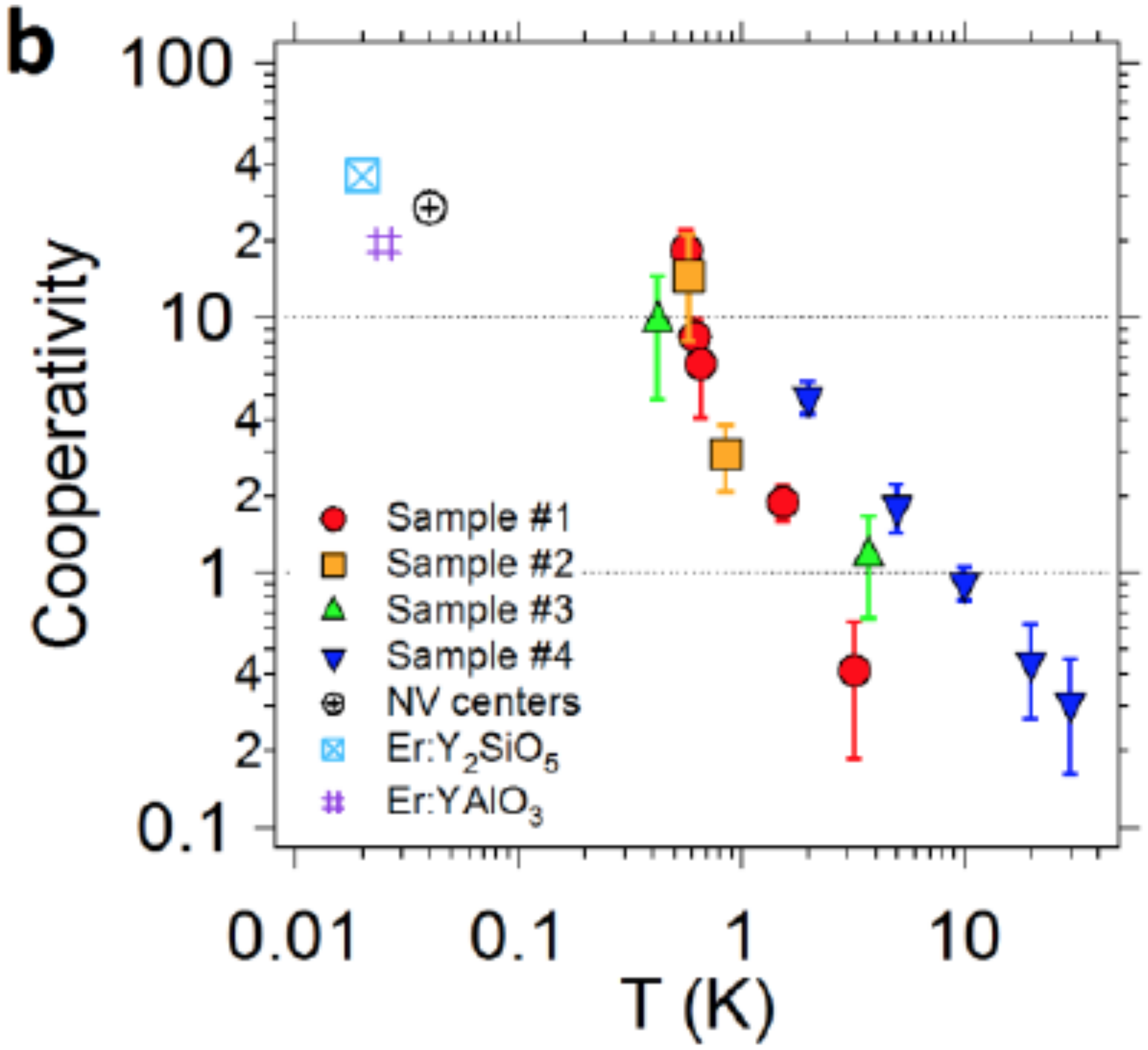
S = ½ system (VO^{+2})

10% PELLETS VOPc:TiOPc

M. Atzori et. al. *JACS 138*, 2154-2157 (2016)

VOPc





Ω = 25 ± 4 MHz

γ = 32 ± 5 MHz

κ ≈ 1.0 ± 0.2 MHz

$$C = \frac{\Omega^2}{\gamma\kappa} \approx 18 \gg 1$$

HIGH COOPERATIVITY

$\Omega = g_s\sqrt{N}$ collective coupling

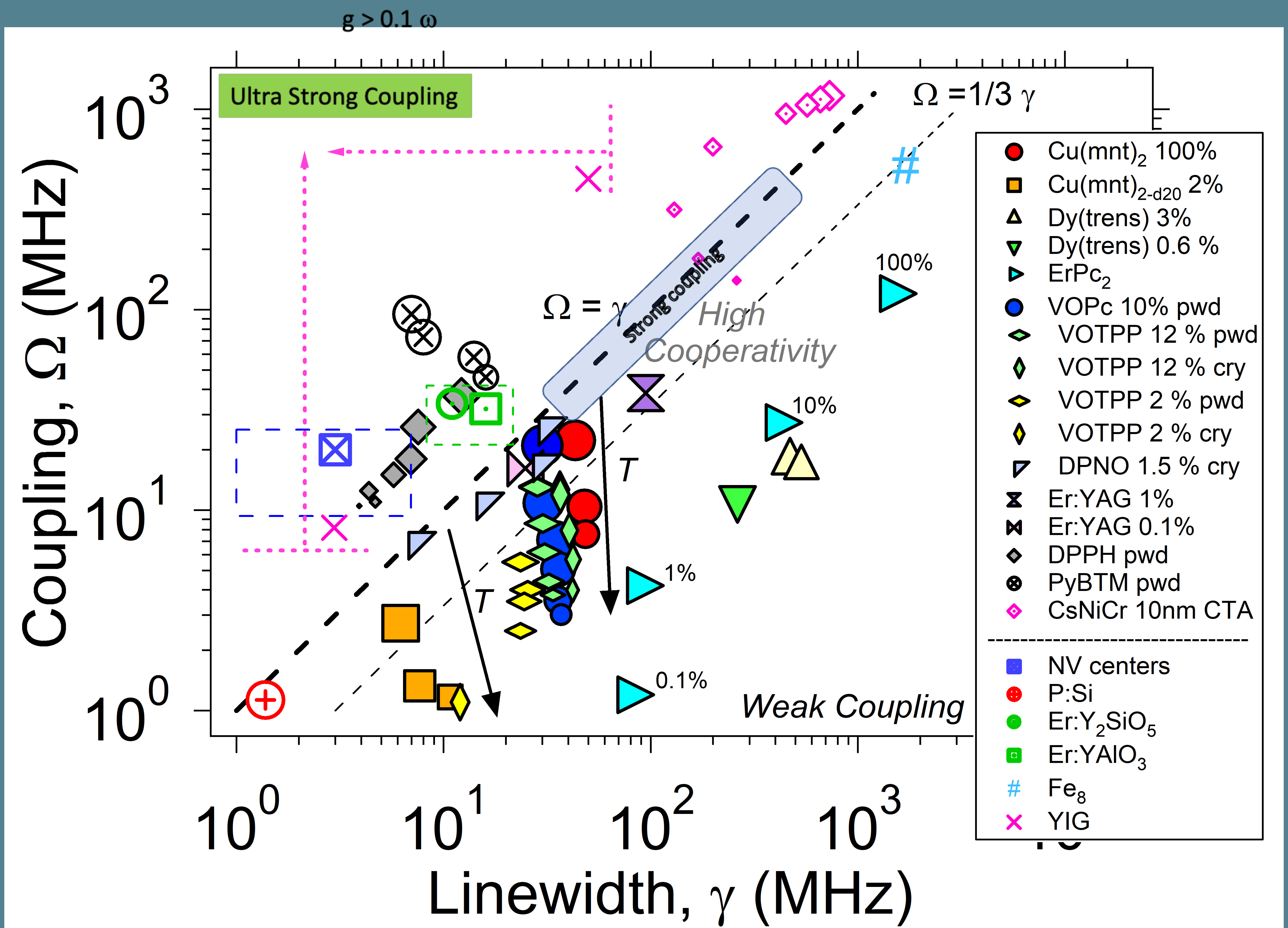
Ω_s = 0.05 ± 0.01 Hz $\quad N_{eff} \approx 2\cdot10^{17}$

C. Bonizzoni et al. Scientific Reports 7, (2017) *13096*

MOLECULAR SPINS EMBEDDED IN SUPERCONDUCTING CIRCUITS

long coherence time

strong el-ph coupling



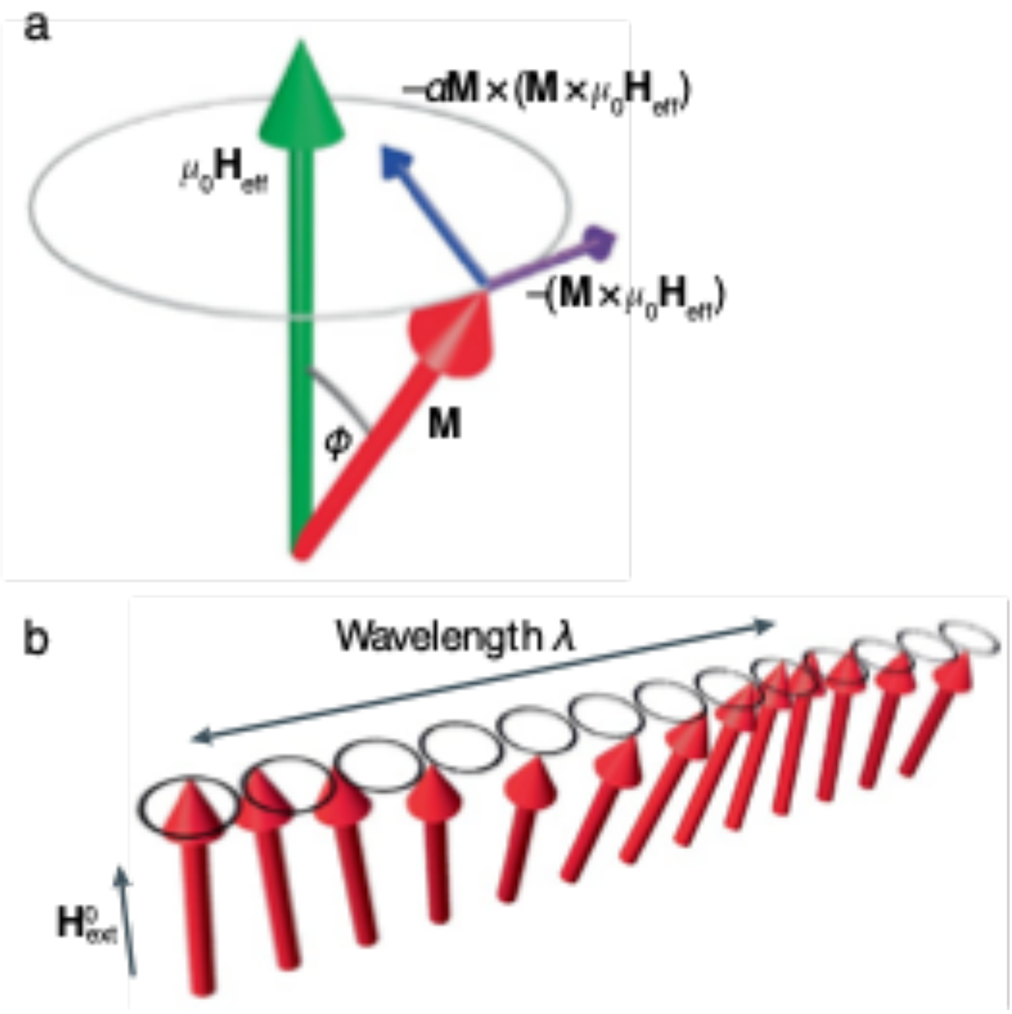
C. Bonizzoni, A. Ghirri, M. Affronte *Advances in Physics X* 3:1, 1435305,
DOI: 10.1080/23746149.2018.1435305 *(2018)*

spin waves in ordered magnets

For a mono domain sample and uniform mode we can use **Landau-Liftshitz-Gilbert Eq.** as a macroscopic description of ***precession*** of uniform magnetization vector:

$$\frac{dM}{dt} = \gamma\vec{M}\times\vec{H}_{eff} - \frac{\lambda}{M_s}\vec{M}\times(\vec{M}\times\vec{H}_{eff})$$

$$H_{eff}=H_{magnst}+H_{exch}+H_{anis}+H_{ext}$$



Shape effects are taken into account by the demagnetization factor:

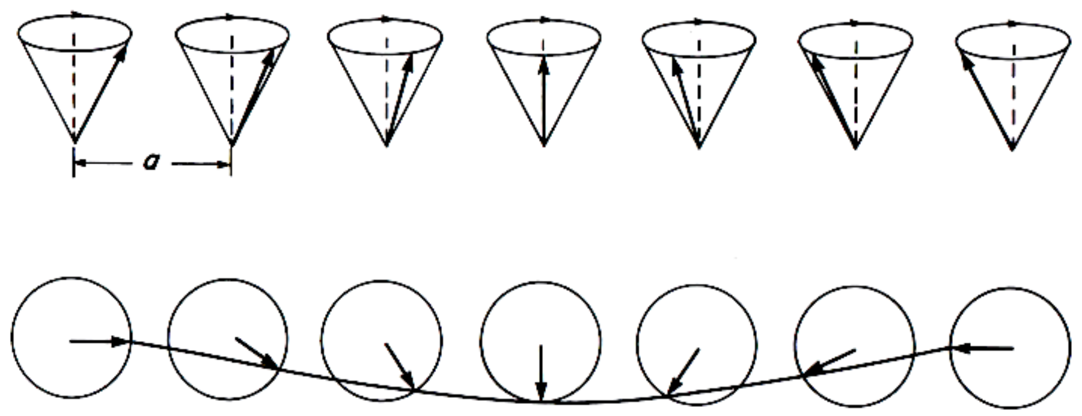
$$B_x^i = B_x^0 - N_x M_x\ ; \quad B_y^i = B_y^0 - N_y M_y\ ; \quad B_z^i = B_z^0 - N_z M_z\ .$$

$$\text{(CGS)} \qquad \omega_0^2 = \gamma^2[B_0 + (N_y - N_z)M][B_0 + (N_x - N_z)M]\ ;$$

$$\text{(SI)} \qquad \omega_0^2 = \gamma^2[B_0 + (N_y - N_z)\mu_0 M][B_0 + (N_x - N_z)\mu_0 M]\ .$$

Equivalently, a **microscopic description of spin waves** an be obtained by considering both N.N. exchange and dipole-dipole interactions:

$$\hat{H} = -\frac{1}{2}\sum_{ij} J_{ij}\boldsymbol{S}_i\cdot\boldsymbol{S}_j - \mu\boldsymbol{H}_e\cdot\sum_i \boldsymbol{S}_i$$
$$-\frac{1}{2}\sum_{ij,i\neq j}\frac{\mu^2}{|\boldsymbol{R}_{ij}|^3}\left[3(\boldsymbol{S}_i\cdot\hat{\boldsymbol{R}}_{ij})(\boldsymbol{S}_j\cdot\hat{\boldsymbol{R}}_{ij}) - \boldsymbol{S}_i\cdot\boldsymbol{S}_j\right],$$



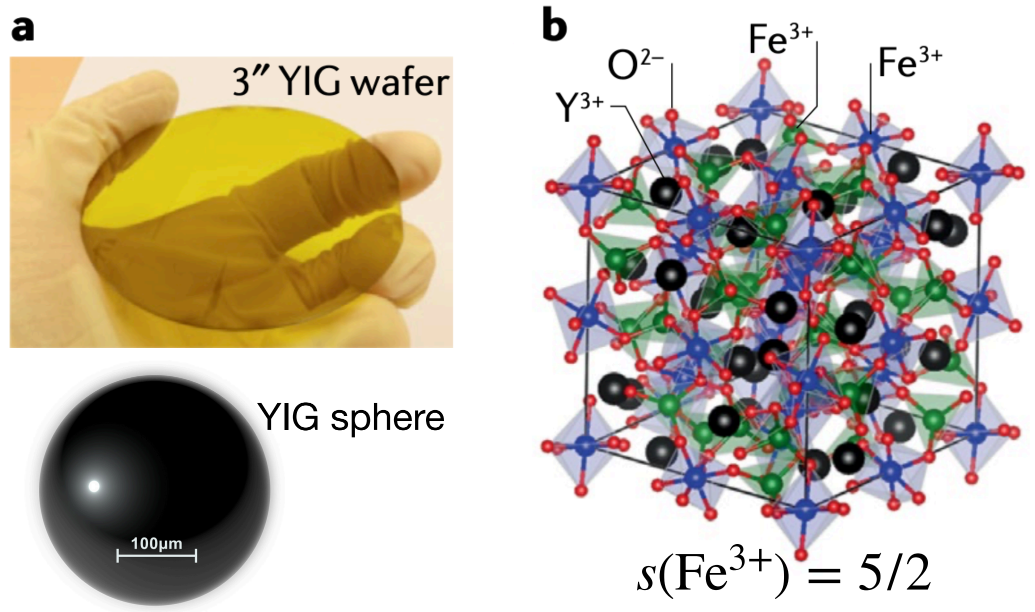
Eur. Phys. J. B **71**, 59–68 (2009)
DOI: 10.1140/epjb/e2009-00279-y

YIG samples

$Y_3Fe_5O_{12}$ (YIG)

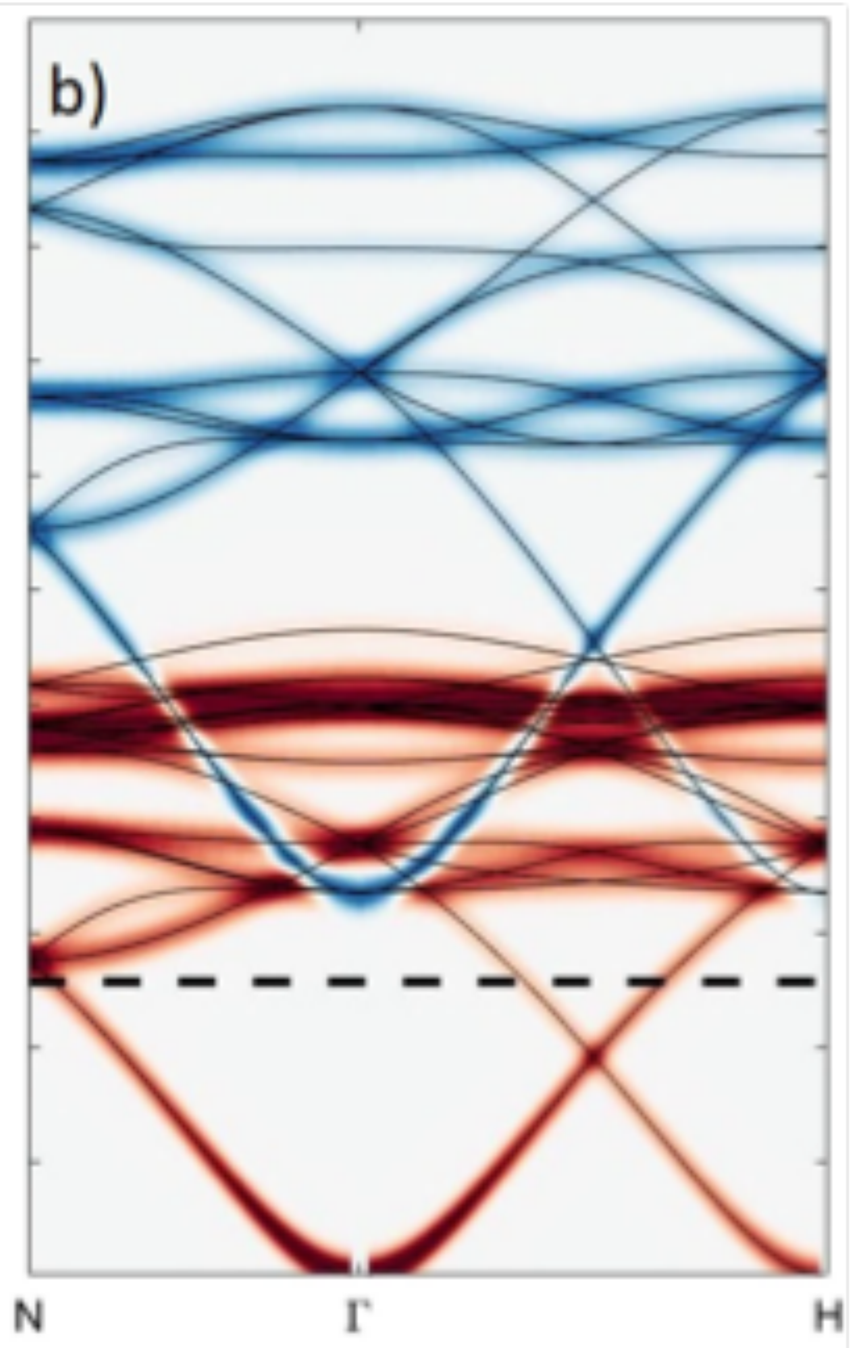
- Ferrimagnetic
- $\rho_s = 4.22 \times 10^{27}\ \mathrm{m}^{-3}$
- Low Gilbert damping:

$\alpha \sim 10^{-4} - 10^{-5}$

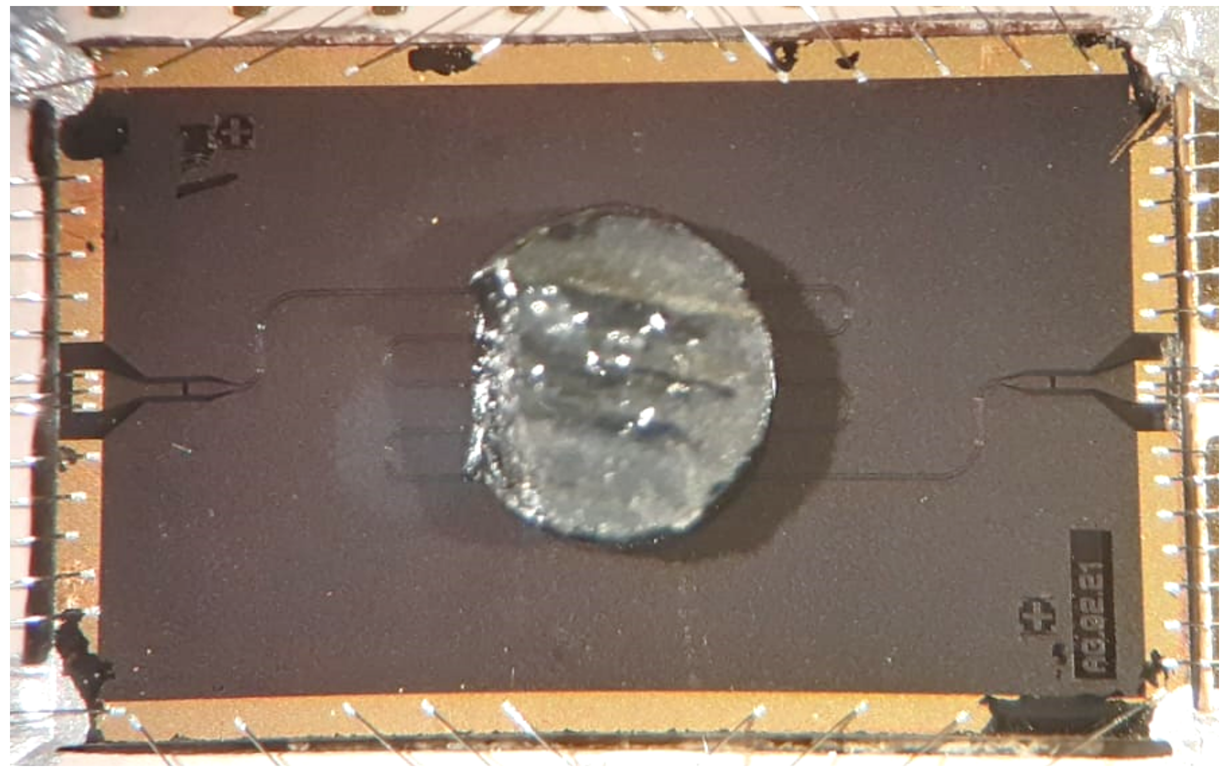


$s(\mathrm{Fe}^{3+}) = 5/2$

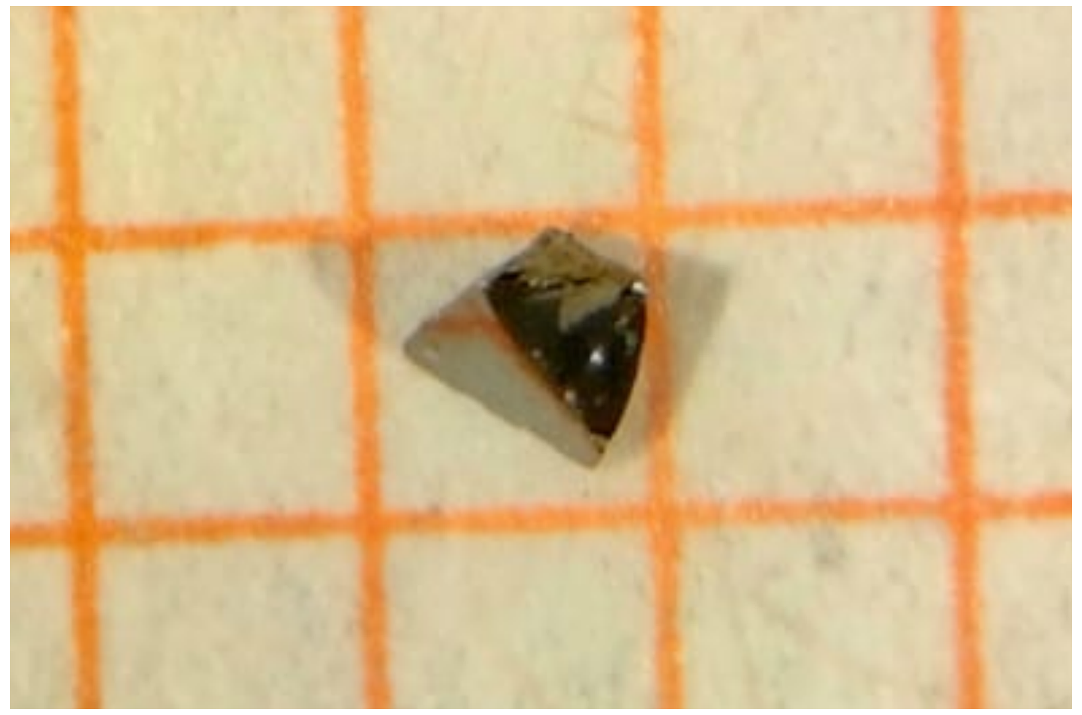
spin wave dispersion in bulk



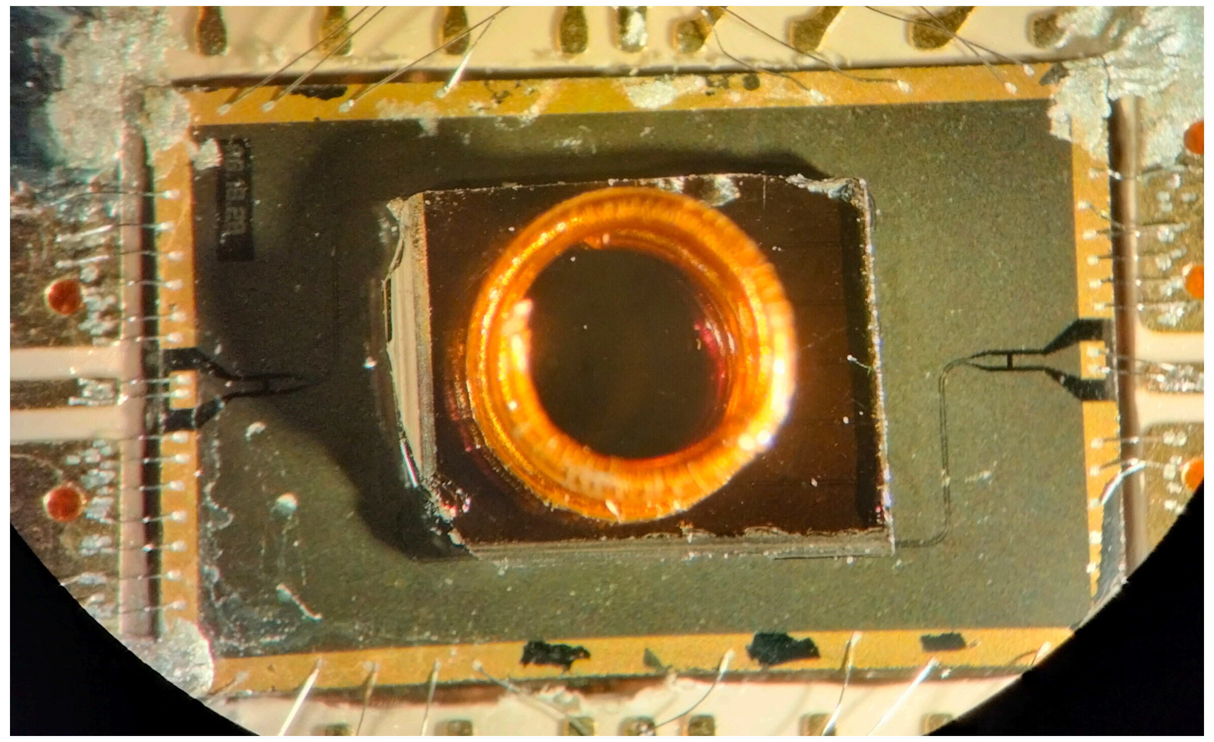
npj Quantum Materials (2017)2:63 ; doi:10.1038/s41535-017-0067-y



Sample #1: Bulk YIG Crystal,
from Istambul kindly provided by R. Bulat



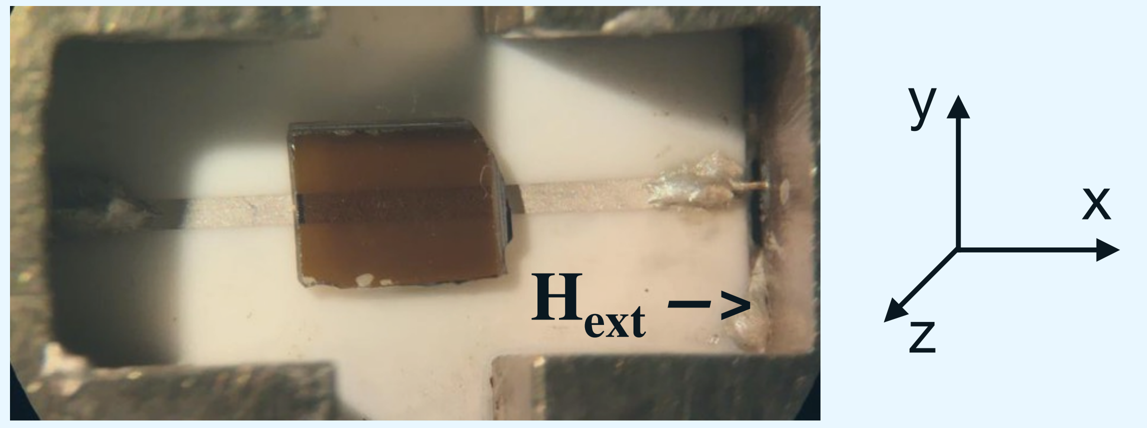
from Japan, kindly provided by G. Ruoso INFN

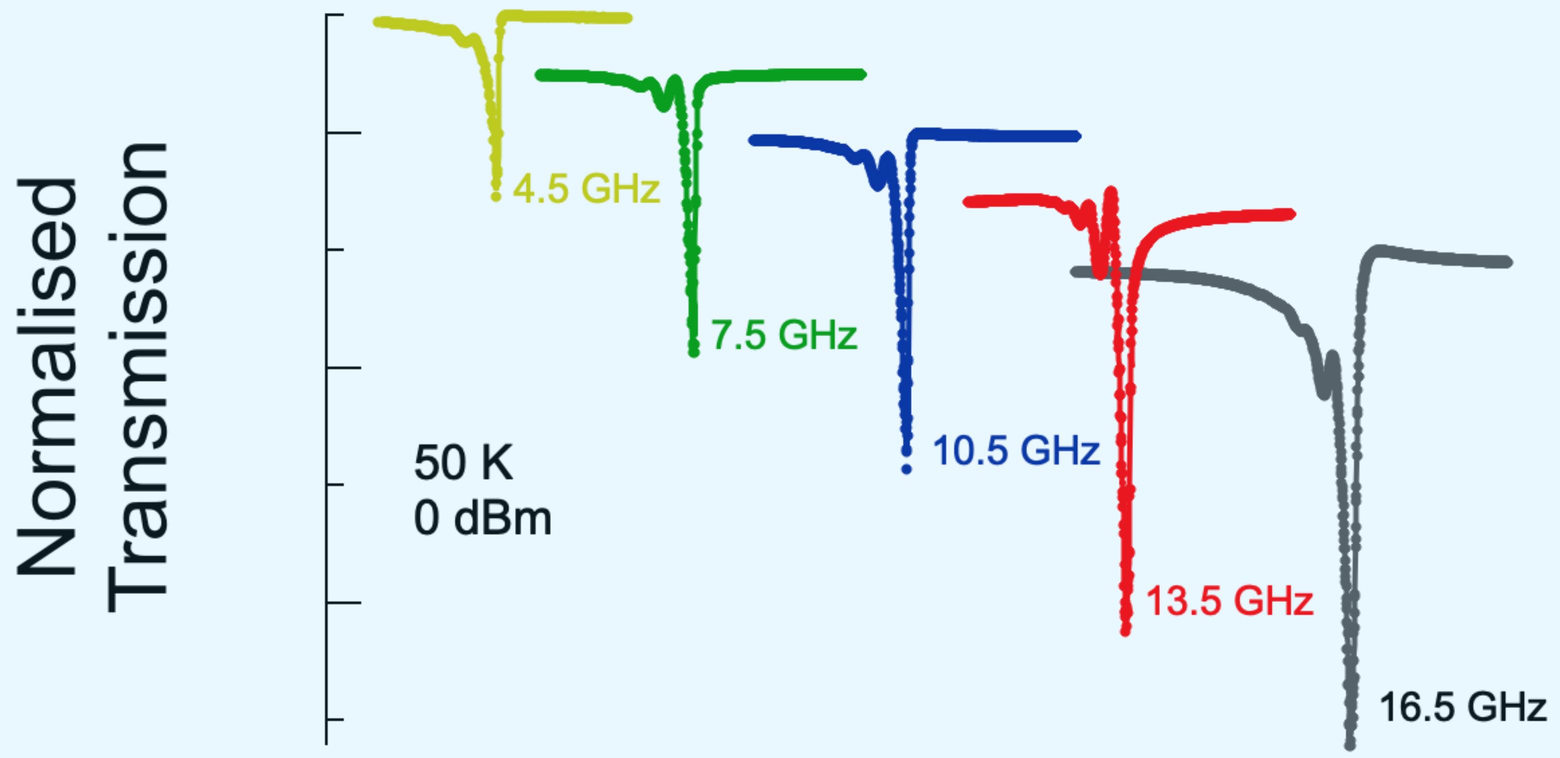


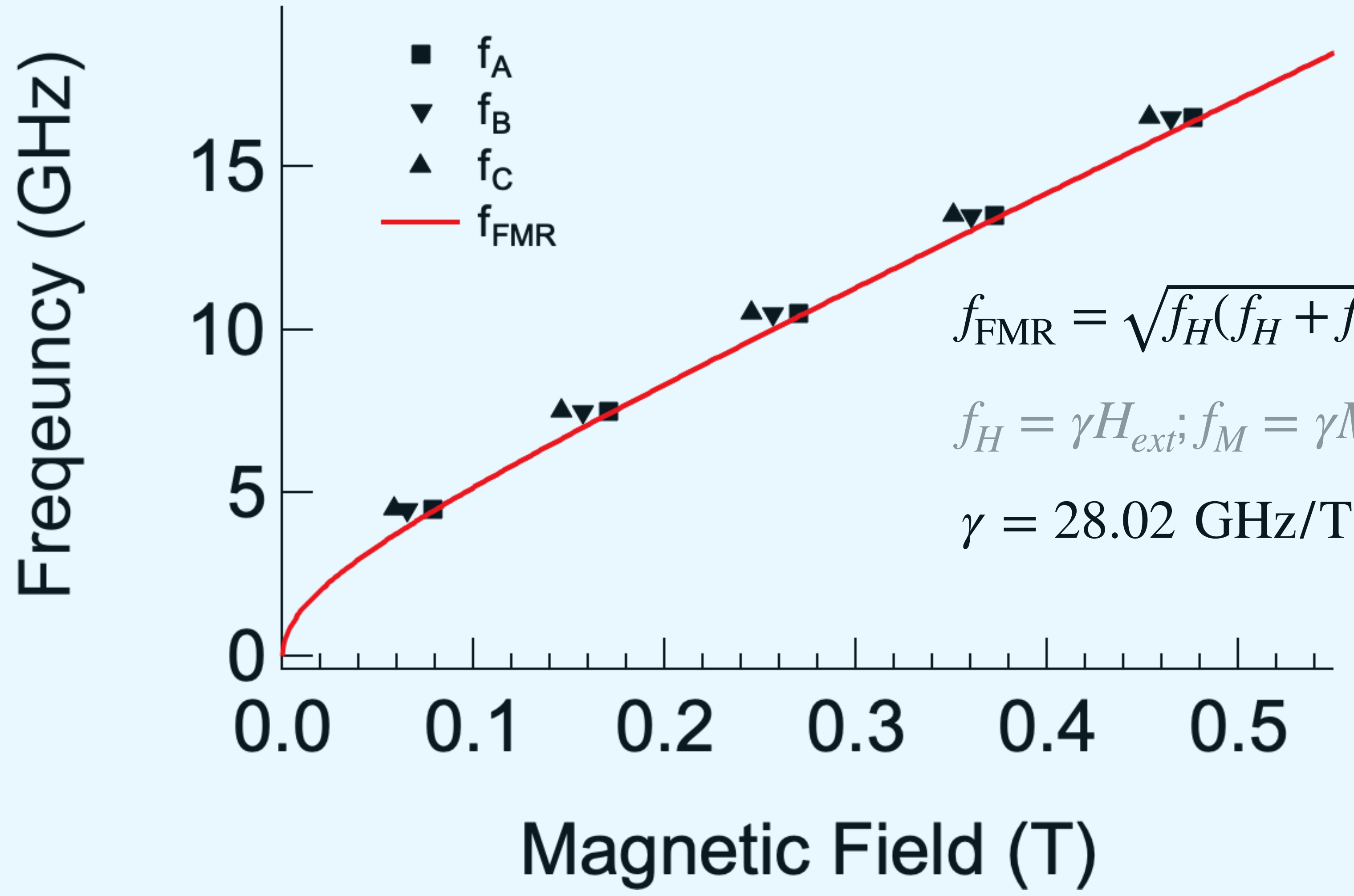
Sample #2: **YIG/GGG film** with dimension $\approx 4x3mm^2$; *w*= (5 & 20 μm)
commercial from Matesi

Spin waves in YIG film: characterisation by broadband stripline

Metallic (Ag) broadband Microstrip line
lateral width 500 µm







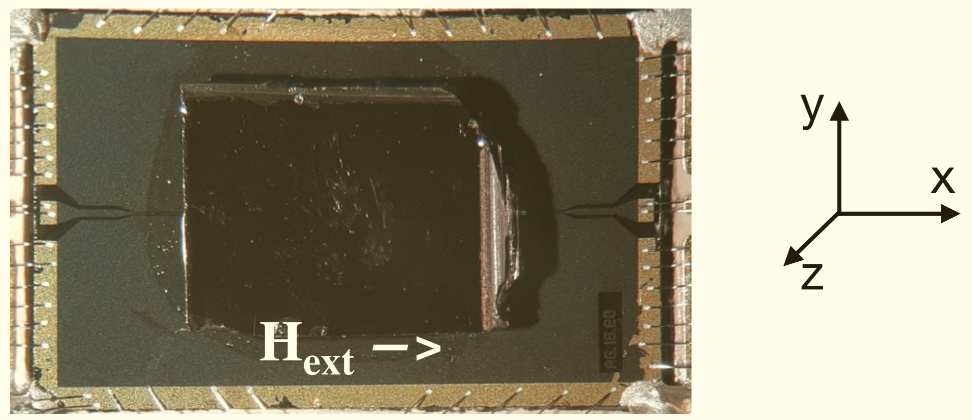
$$f_{\mathrm{FMR}} = \sqrt{f_H(f_H + f_M)}$$

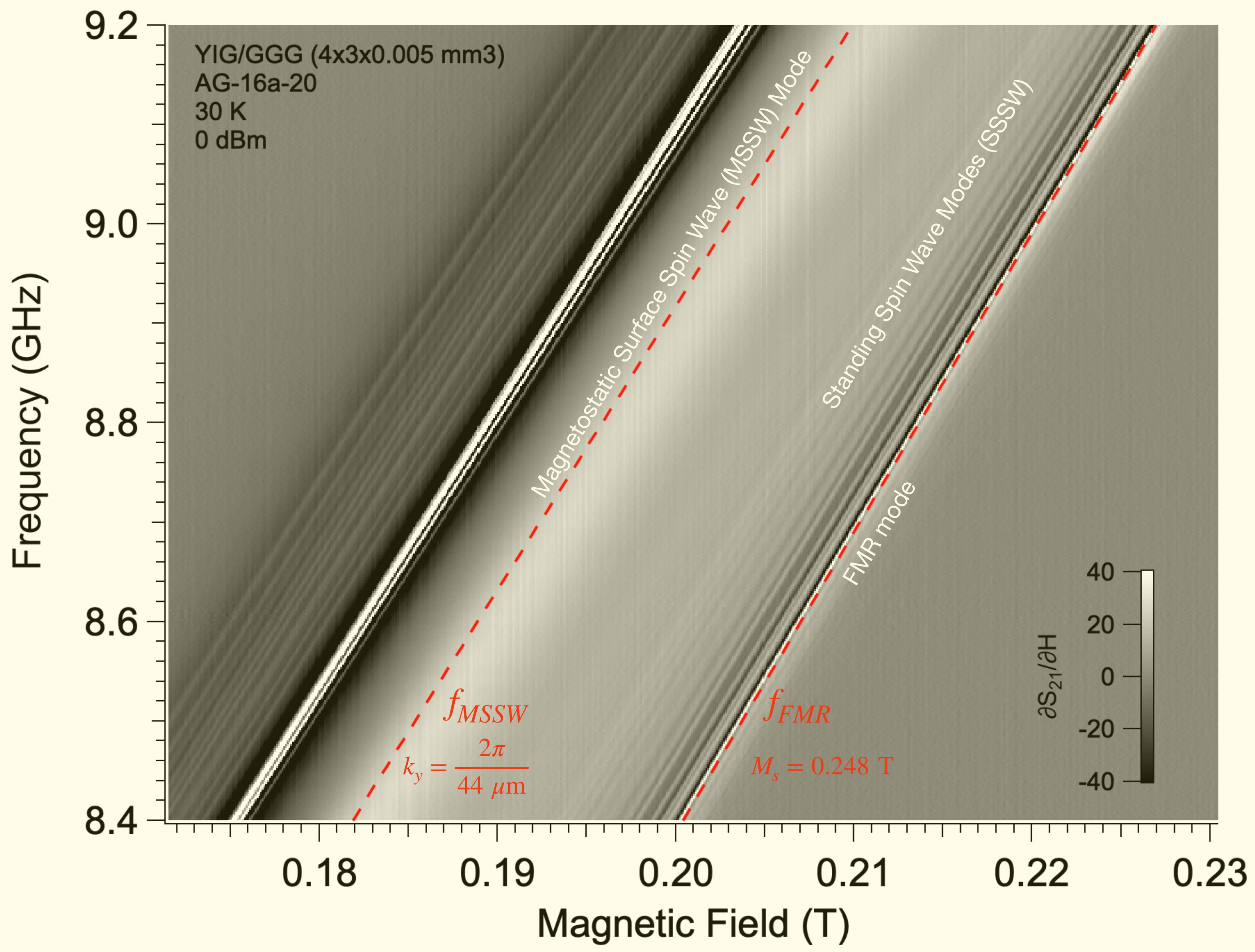
$$f_H = \gamma H_{ext}; f_M = \gamma M_s$$

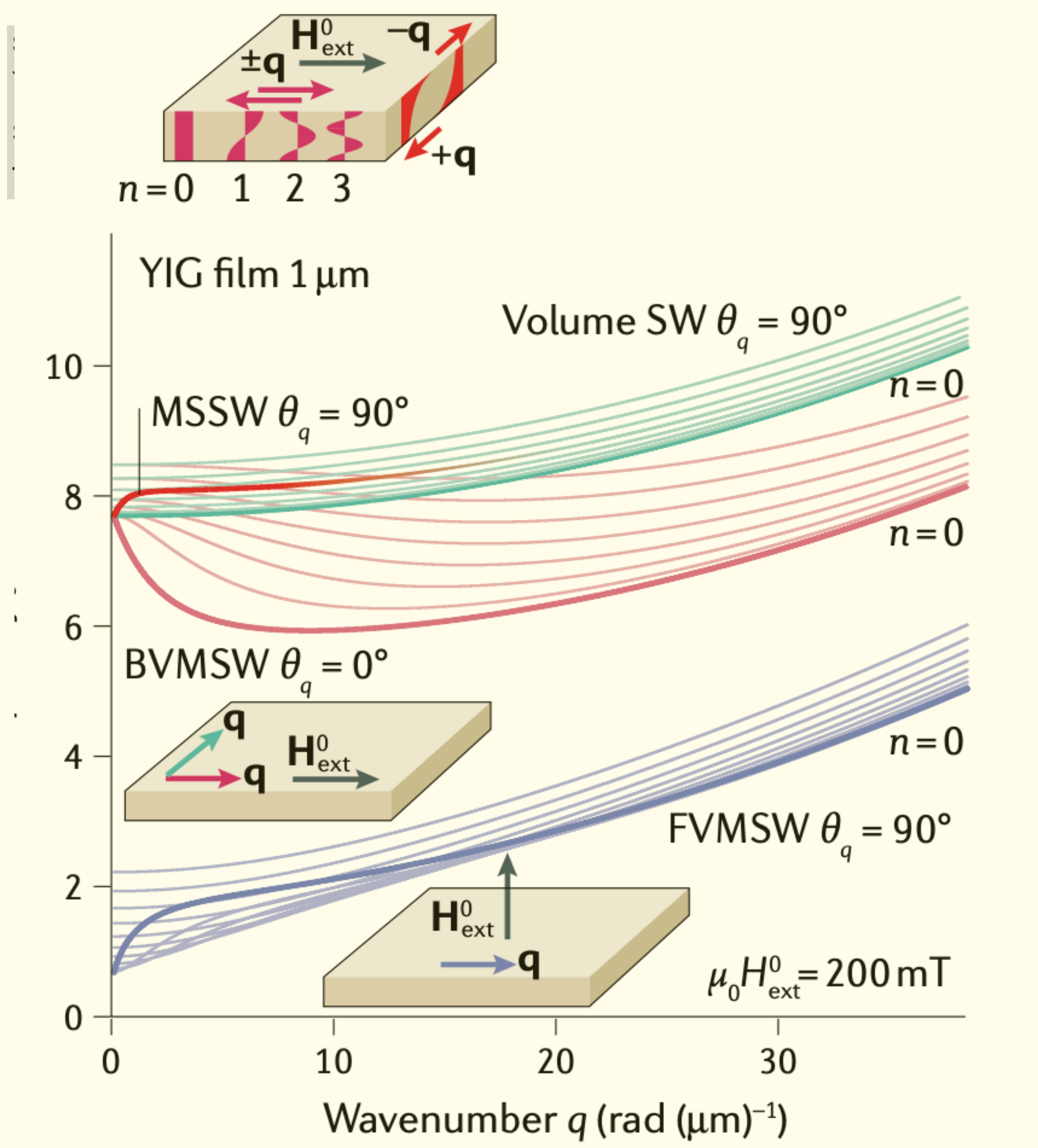
$$\gamma = 28.02\ \mathrm{GHz/T}; M_s = 0.24\ \mathrm{T}$$

central conductor lateral width 20 µm

sample #1
YIG/GGG film
size: 4x3 mm²
thickness: 5 µm







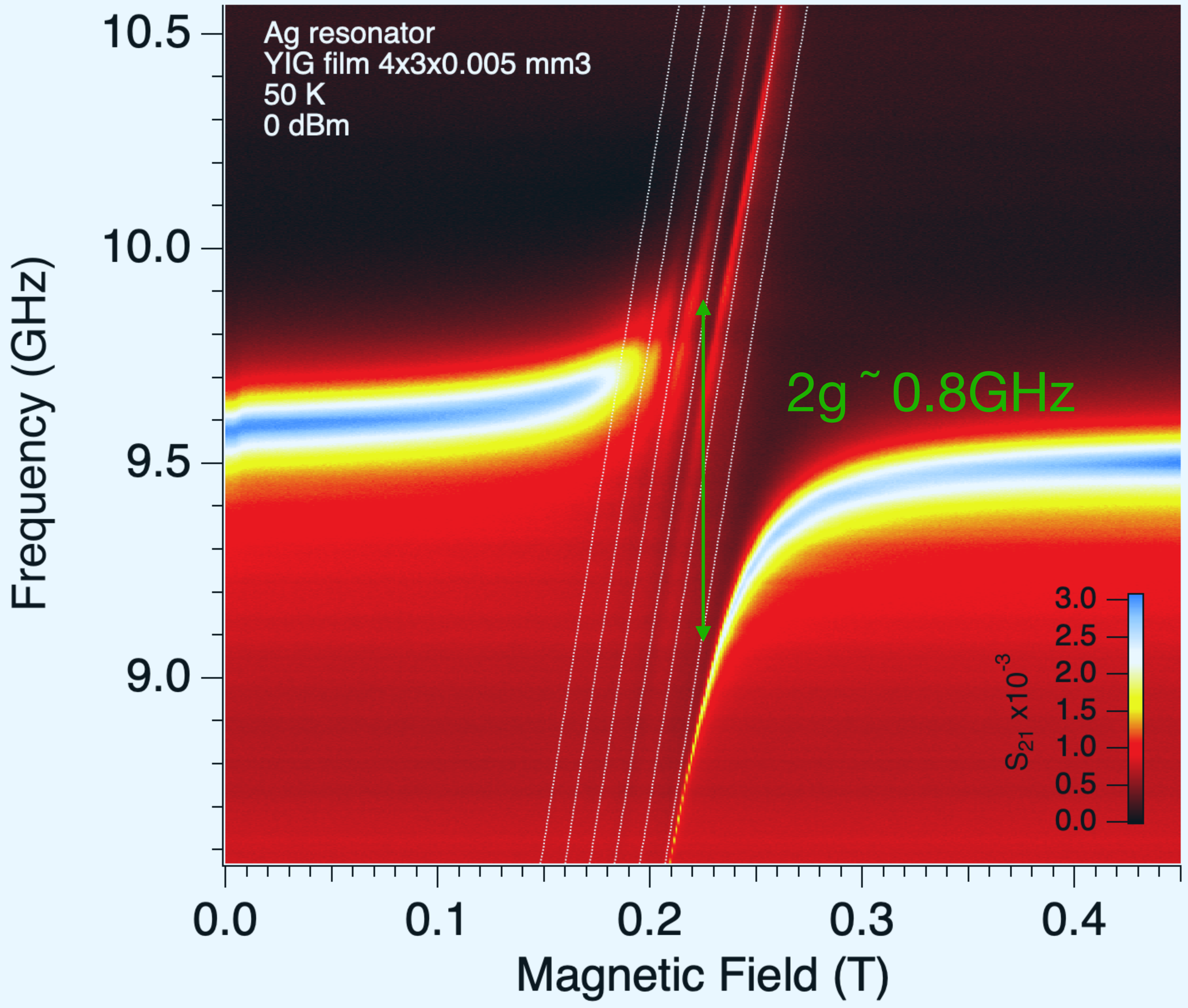
Pirro et al. Nat. Rev. Mater. 6, 1114 (2021)

$$\omega_n(\mathbf{k} = 0) = \omega_{\mathrm{FMR}} + \gamma D \left(\frac{\pi n}{d}\right)^2$$

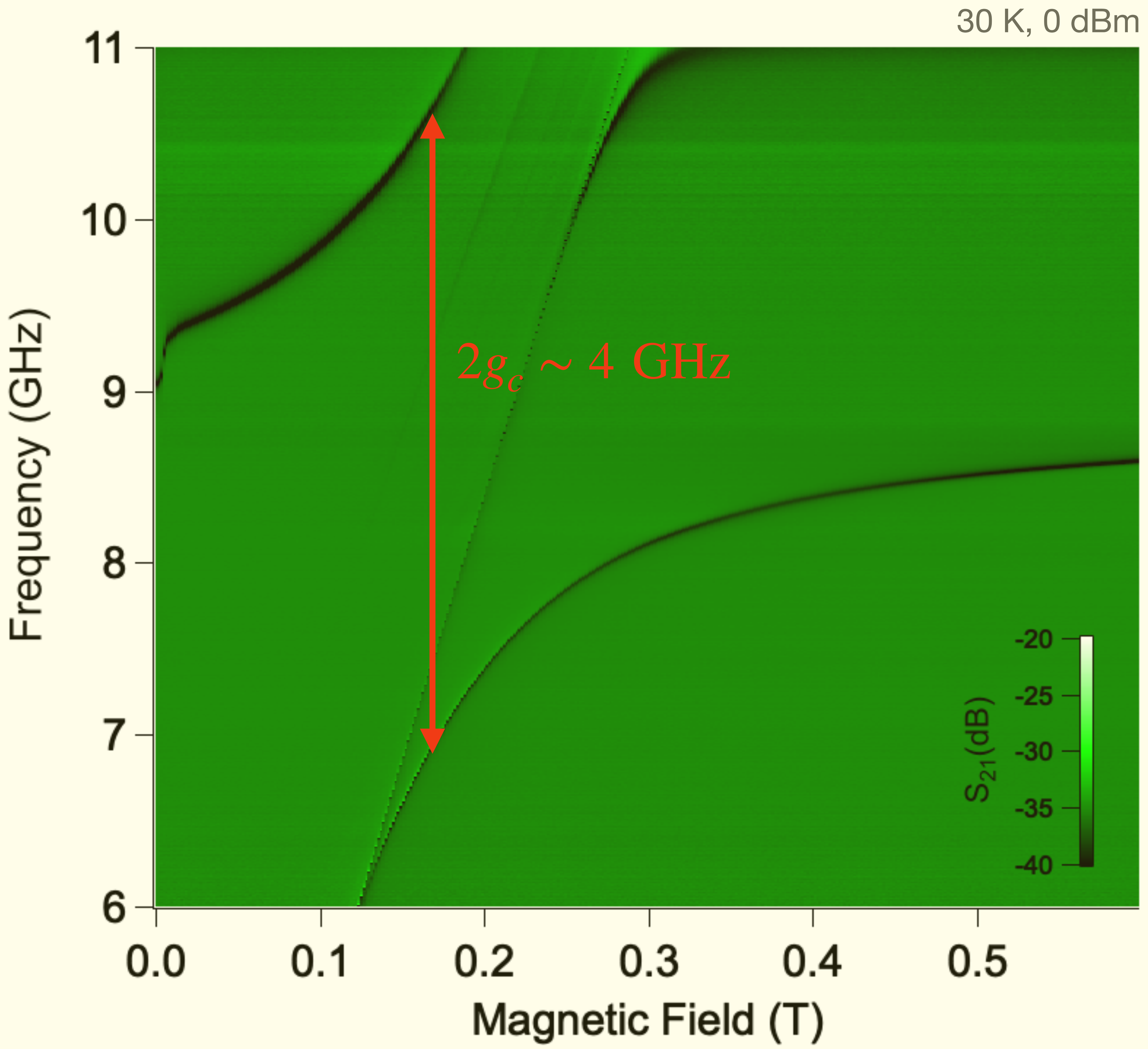
Film thickness $d = 5\ \mu m$
Exchange stiffness: $D = 5.29 \times 10^{-17}\ \mathrm{T\ m^2}$
Saturation magnetisation $M_s = 0.24\ \mathrm{T}$

Damon Eshbach, J. Phys.Chem. Solidi 19,308 (1961)
Kalinikos, Sov. Phys. J. 24, 718 (1981)
Harms and Duine, J. Magn. Magn. Mater. 567, 169426 (2022)
Kreisel et l., Eur. Phys. J. B 71, 59 (2009)
Klinger et al., J. Phys. D: Appl. Phys. 48 015001 (2015)

Increasing coupling strength through the effective Volume



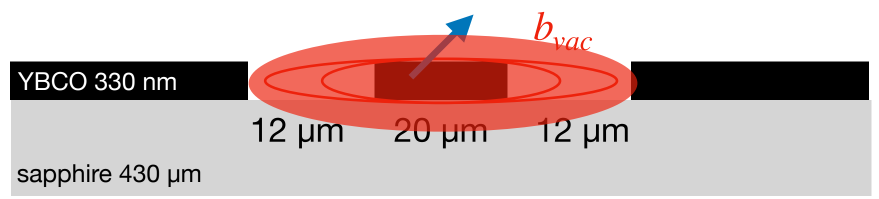
linear resonator, lateral size 500µm
YIG/GGG film
thickness 5µm
area 12mm²



CPW resonator, lateral size 20 µm

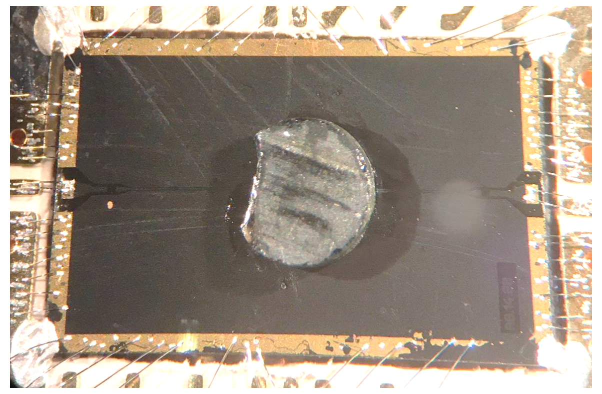
YIG/GGG film
thickness 5 µm
area 12 mm²

further tests with bulk samples

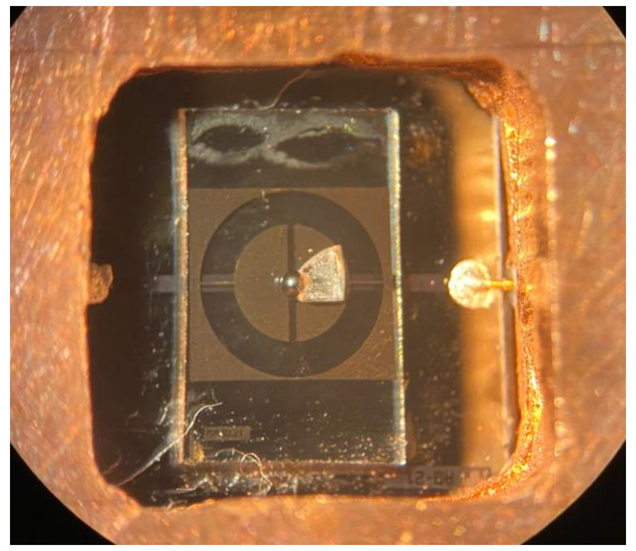


$$g_s/h = \frac{1}{4}\gamma_e b_{vac}$$

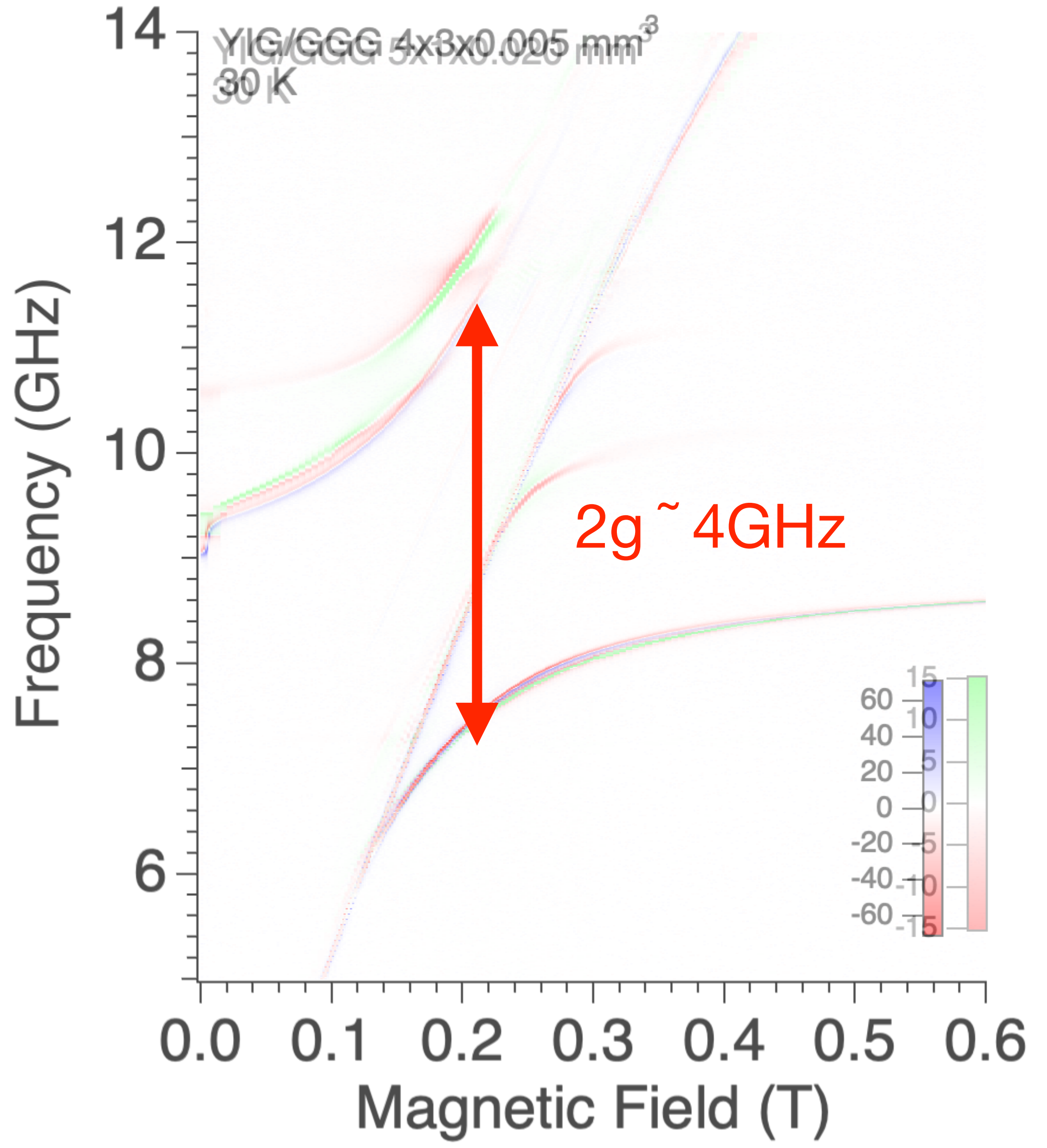
$$g_s \approx 10 \text{ Hz at } 10 \text{ GHz}$$



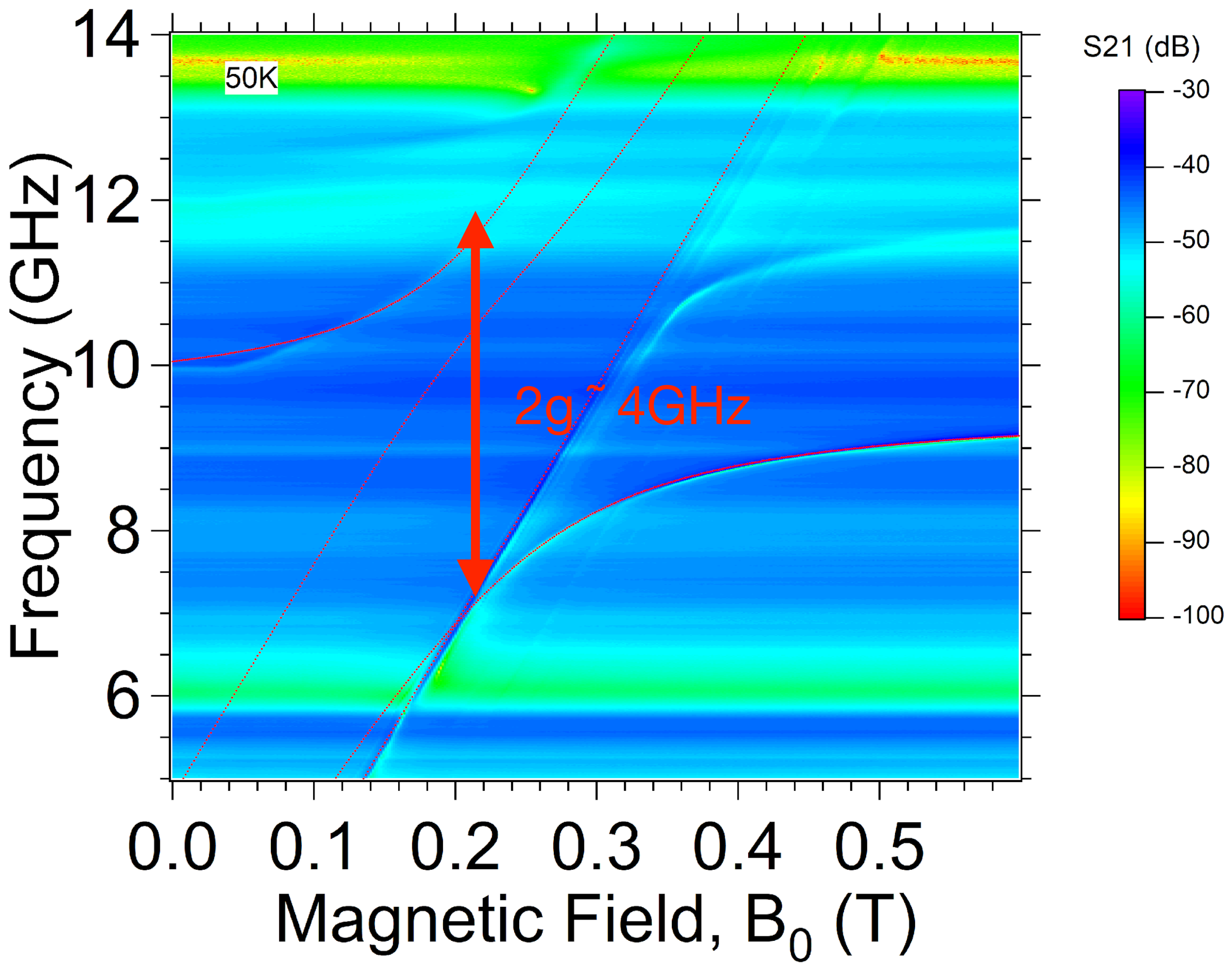
linear Resonator+ YIG disk



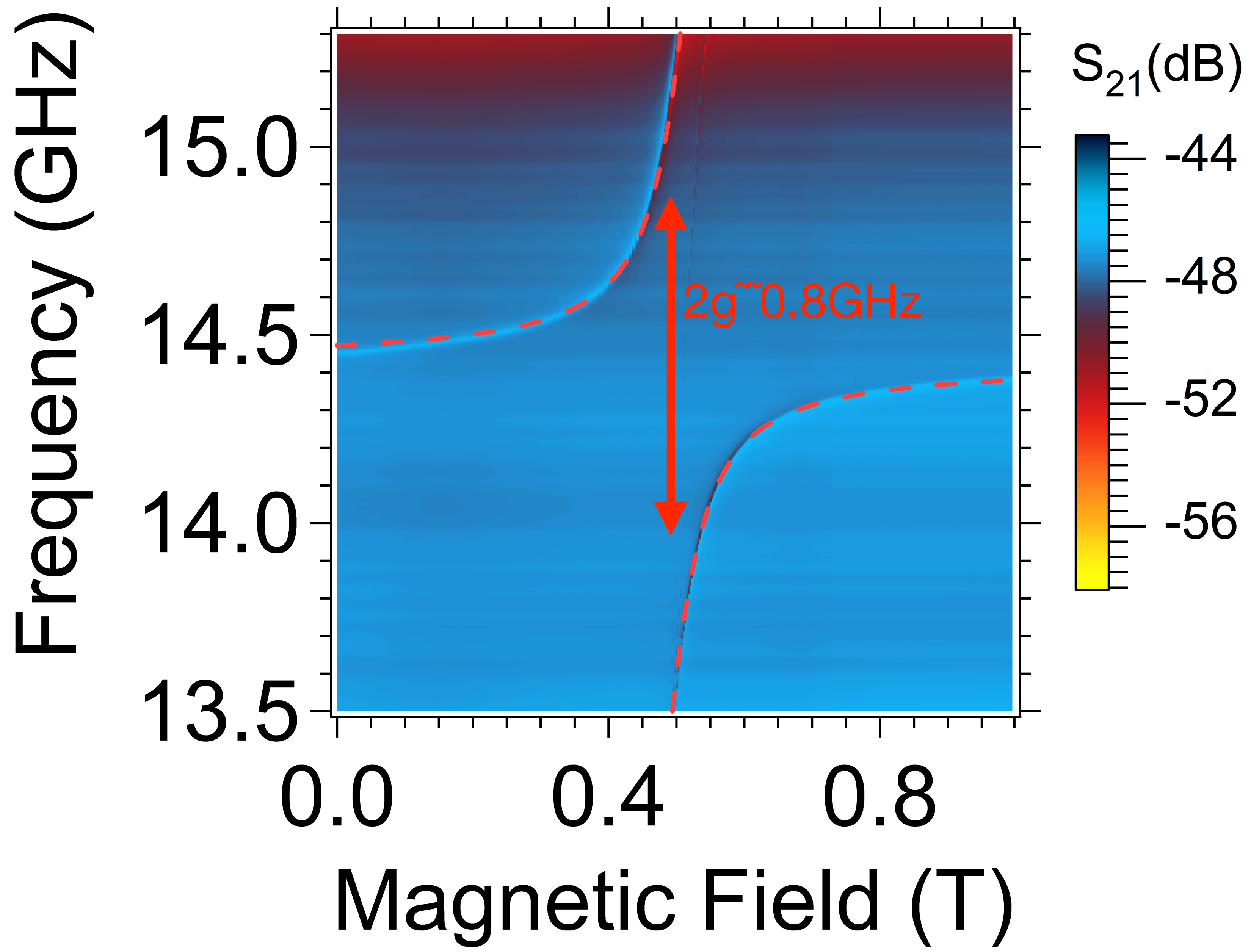
Inv. Anapole Resonator+ YIG sphere



USC achieved with thicker film (20µm)
but significant increase of the coupling

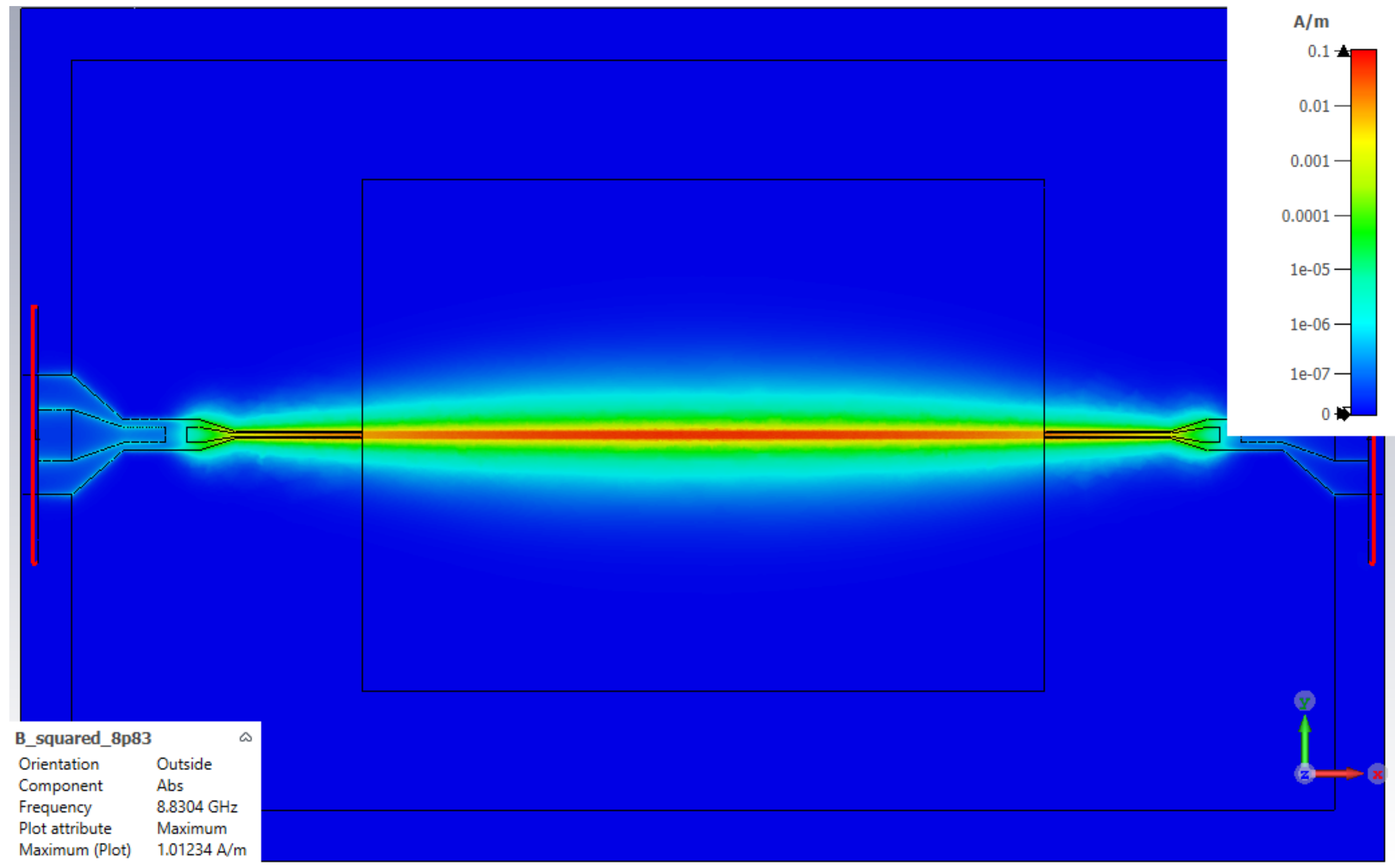


radiation field as CPW
-> USC achieved but not larger than film



radiation field focused in small volume (5µm)³
-> USC not achieved

ESTIMATION OF NUMBER OF COUPLED SPINS



B_squared_8p83
Orientation Outside
Component Abs
Frequency 8.8304 GHz
Plot attribute Maximum
Maximum (Plot) 1.01234 A/m

Number of spins is estimated starting from CST simulation of the resonant mode volume, using a 1:1 scale model filled with vacuum and with same sample dimension and position.

$$N_{eff} = N_0 p(T) = \rho V_{eff} P(T) \approx \rho V_{eff} \qquad \rho = 4.22 \bullet 10^{27} spin/m^3$$

From effective number of spins it is also possible to estimate the single spin coupling

Diameter (mm)	Resonator	ν_0 (GHz)	V_{eff} (m^3)	g_s (Hz)	$g=g_s\sqrt{N}$ (GHz)
#1	Meander	8.7	$2.2 \cdot 10^{-12}$ ↓	↑ 11	1.0
	Copl. 20 μm	9.55	$9.3 \cdot 10^{-11}$	6.7	4.2
	Copl. 600 μm	7.08	$3.97 \cdot 10^{-10}$	1.1	1.4
#2	Meander	8.7	$7.9 \cdot 10^{-12}$	11	2.0
	Copl. 20 μm	9.55	$1.9 \cdot 10^{-10}$	6.7	5.9
	Copl. 600 μm	7.08	$1.5 \cdot 10^{-9}$	1.1	2.8

Modelling.

Università
degli Studi di
Messina

Salvatore Savasta
Omar Di Stefano
Alberto Mercurio

- Q-Rabi hamiltonian:

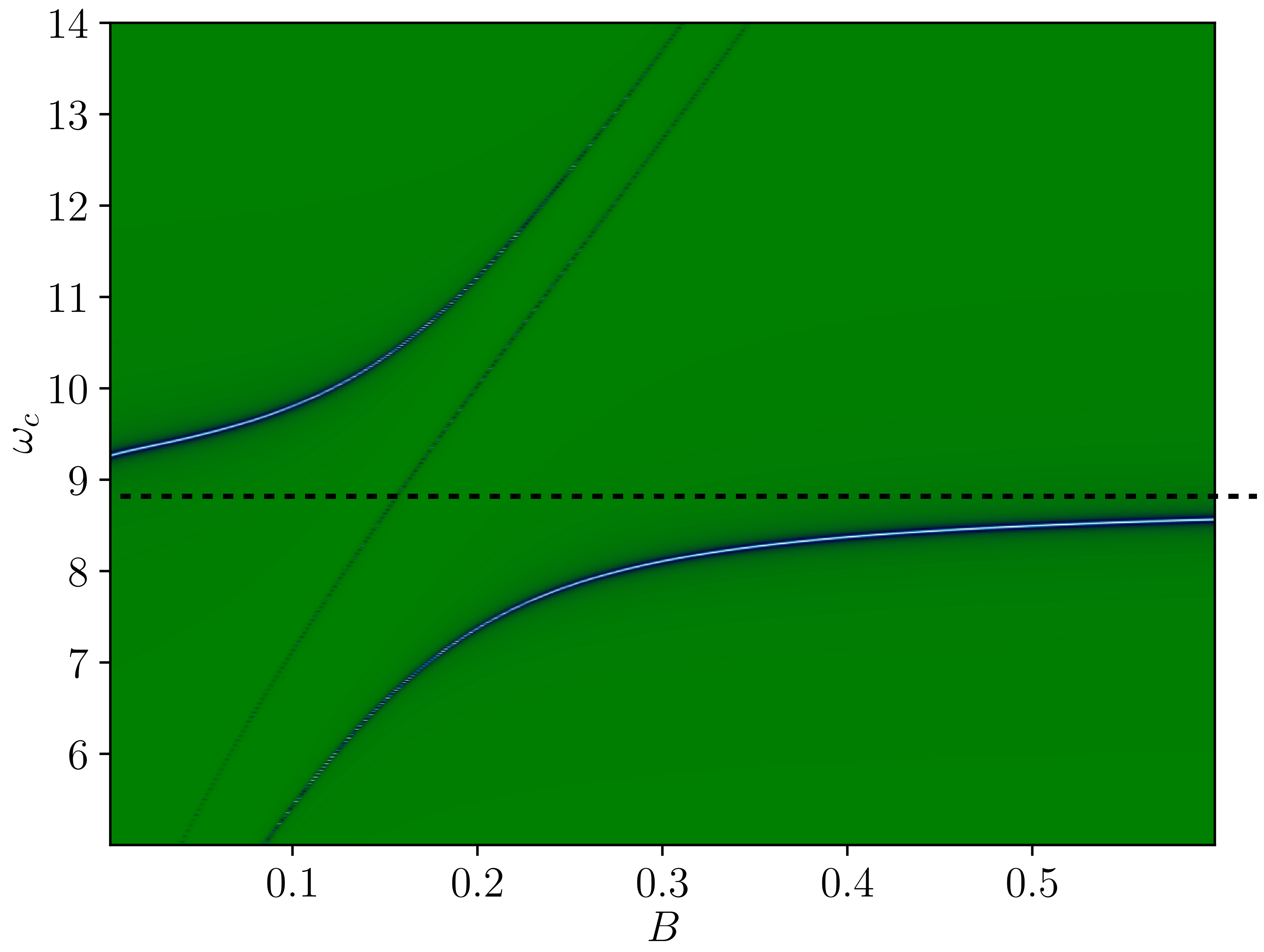
$$H = \omega_c \hat{a}^\dagger \hat{a} + \omega_1 \hat{b}_1^\dagger \hat{b}_1 + \omega_2 \hat{b}_2^\dagger \hat{b}_2 + g_1 (\hat{b}_1 + \hat{b}_1^\dagger)(\hat{a} + \hat{a}^\dagger) + g_2 (\hat{b}_2 + \hat{b}_2^\dagger)(\hat{a} + \hat{a}^\dagger) + \alpha (\hat{a} + \hat{a}^\dagger)^2$$

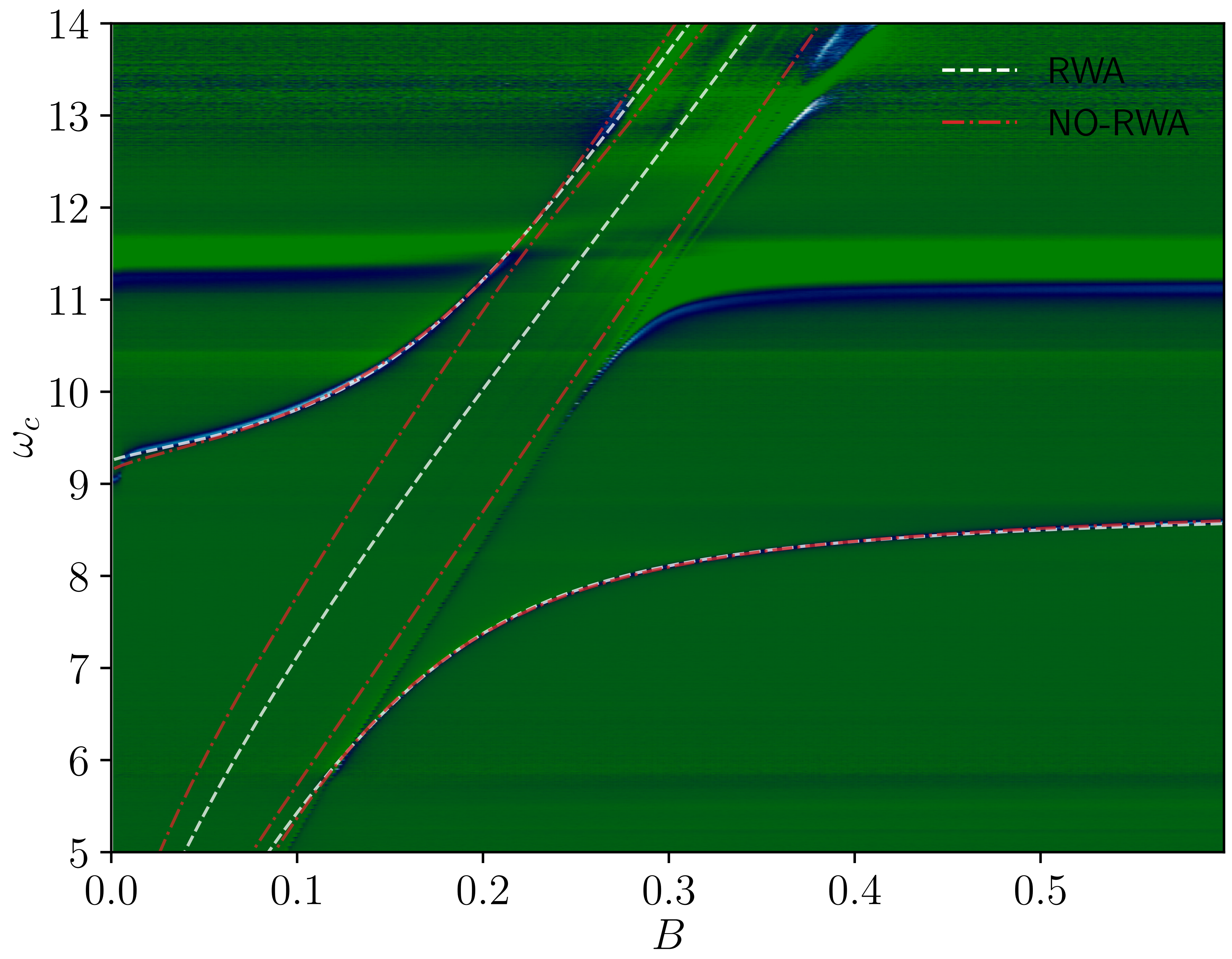
- direct numerical diagonalization with *n* magnetic modes

- Analytical solution without RWA:

$$\omega_\pm = \frac{\sqrt{\omega b^2 + 4\,\alpha\,\omega c + \omega c^2 \pm \sqrt{\omega b^4 + 16\,\lambda^2\,\omega b\,\omega c - 2\,\omega b^2\,\omega c\,(4\,\alpha + \omega c) + \omega c^2\,(4\,\alpha + \omega c)^2}}}{\sqrt{2}}$$

transmission spectra & best fit





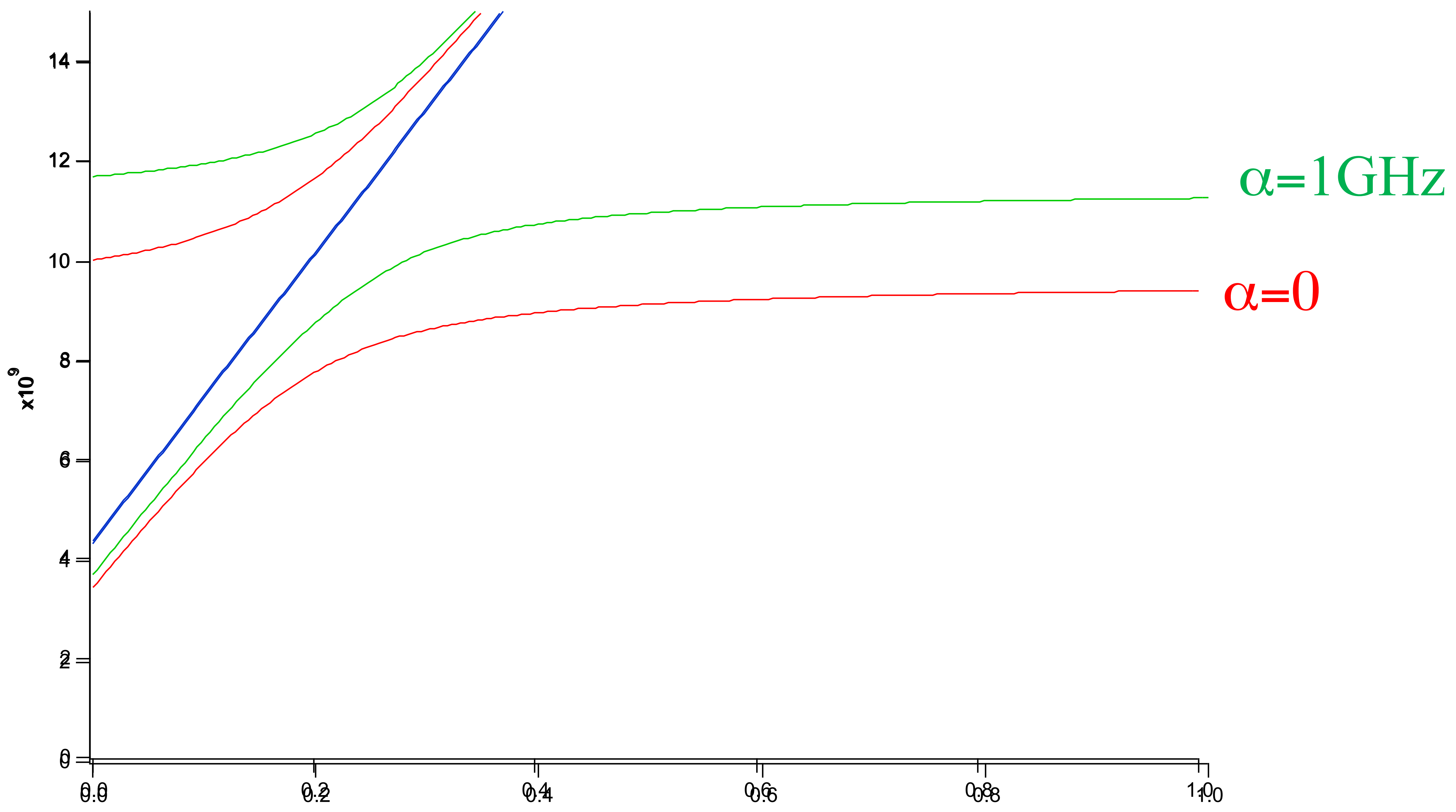
RWA:			
\Delta_1	=	0.99	GHz
\Delta_2	=	2.13	GHz
g_1	1,51	GHz	
g_2	0,946	GHz	
ω_c	=	8.818	GHz

$g_1/\omega_c > 0.1$

USC achieved!

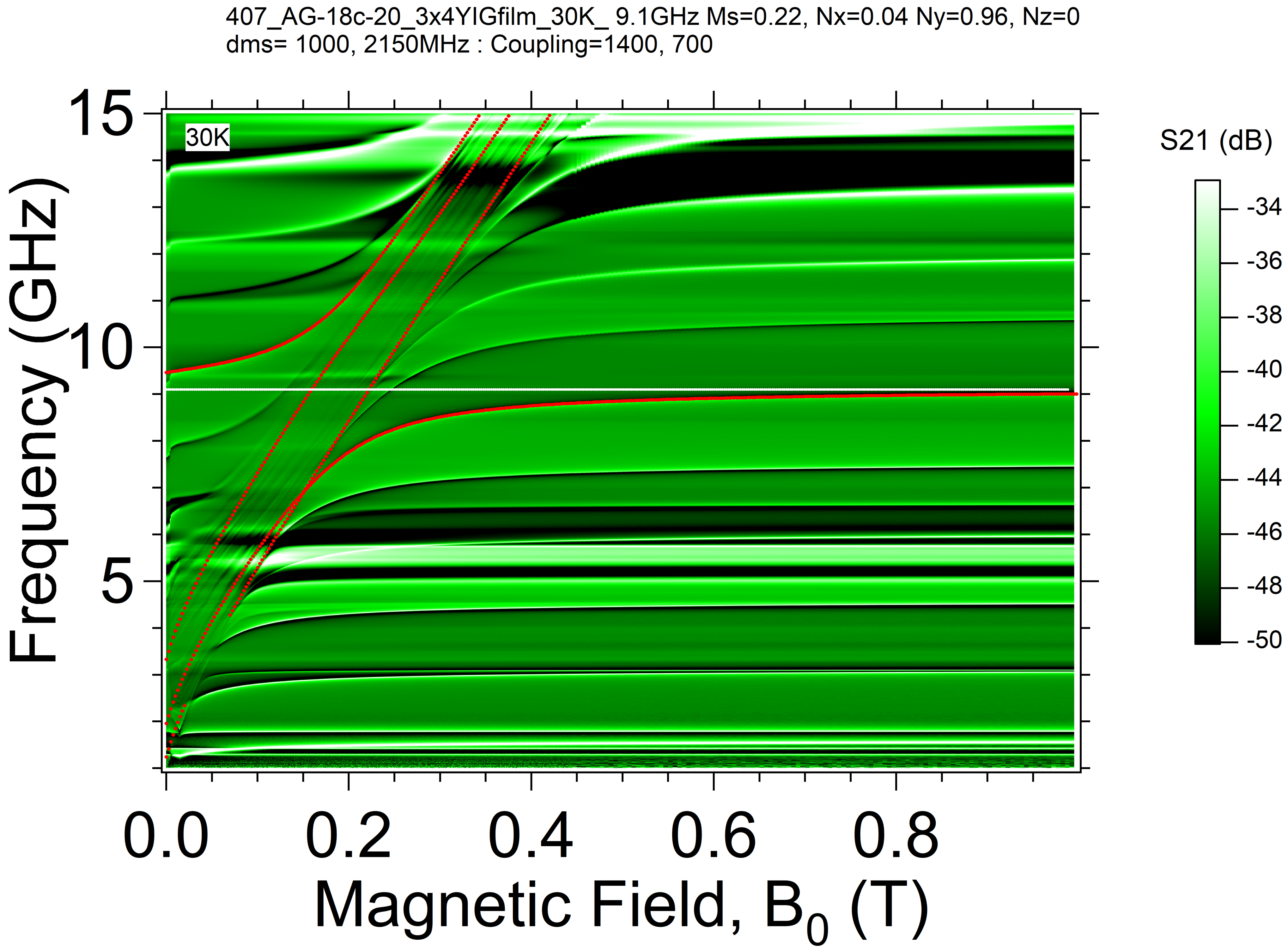
NO-RWA:			
\Delta_1	=	0.33	GHz
\Delta_2	=	1.63	GHz
\Delta_3	=	2.58	GHz
g_1	0,283	GHz	
g_2	1.76	GHz	
g_3	0,283	GHz	
ω_c	=	8.963	GHz

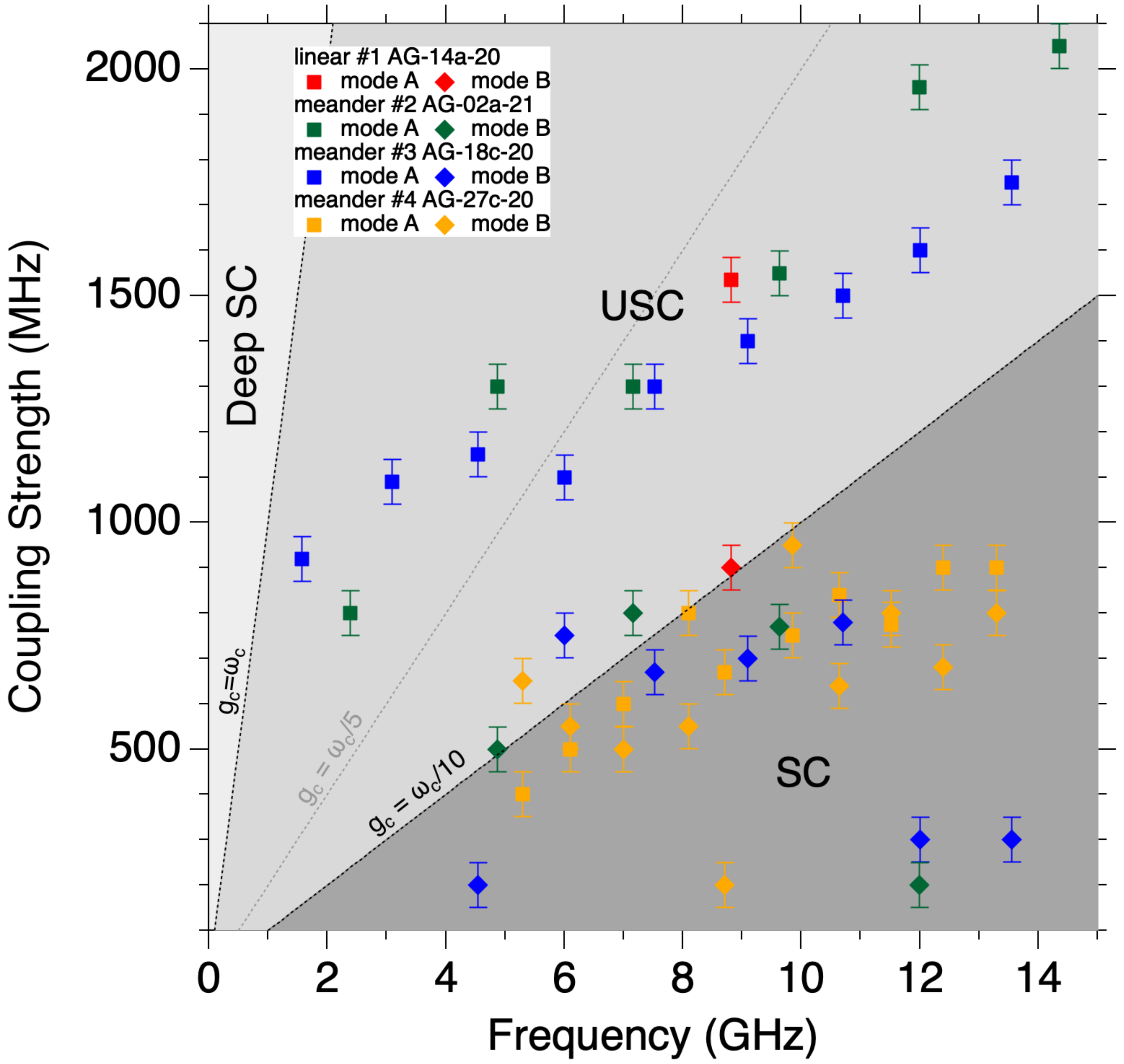
Effect of diamagnetic term



Ag14Op4x2 (omega_c=9.65GHz) with YIGfilm 20micron on top
Rabi(gamma=0.24, Nxx=0,Nyy=1-0.4,Nzz=0.4, Delta= 1GHz, 0, lambda=1.9e9)

Multi-mode coupling using meander resonator

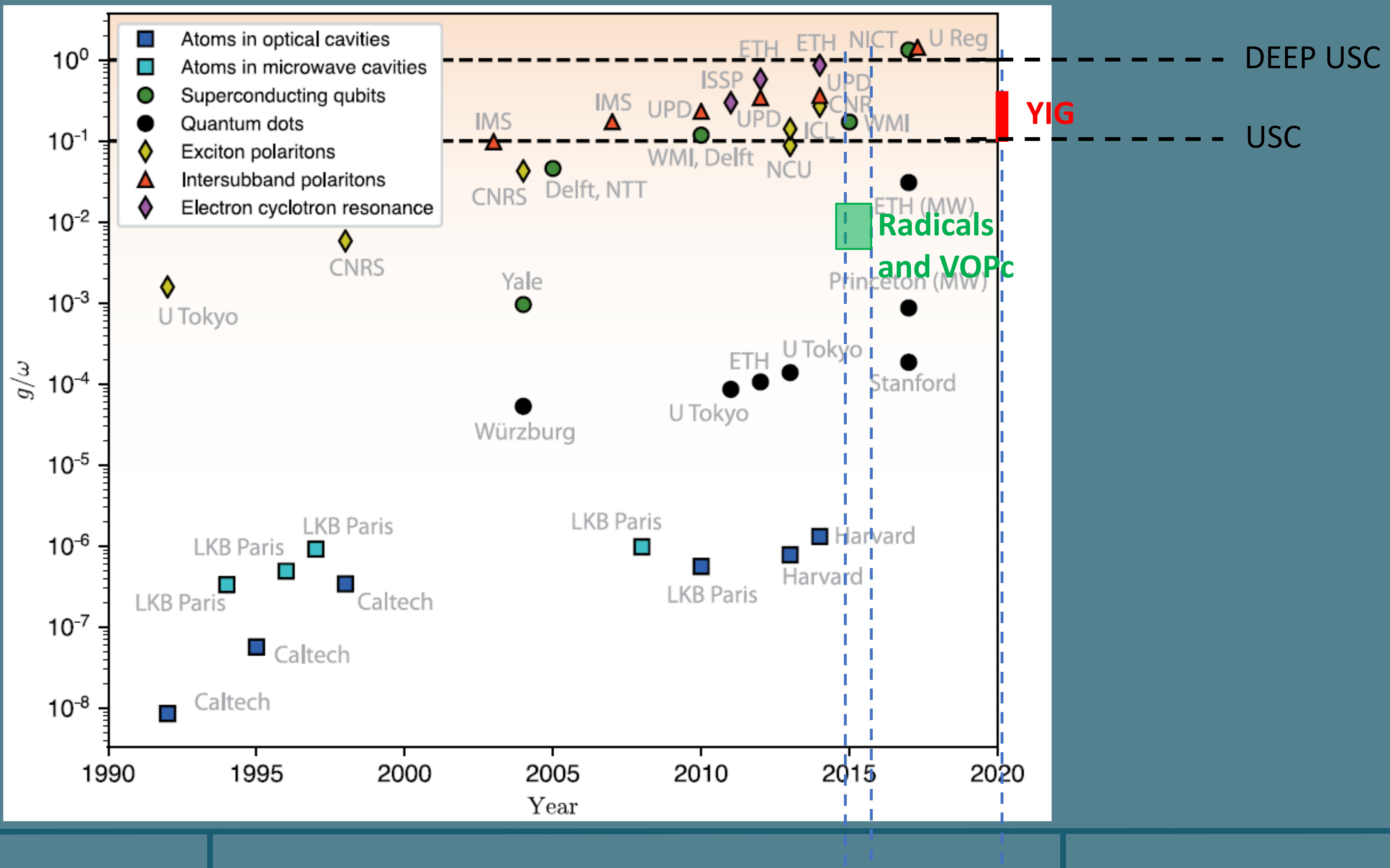




- Input-output formalism:

$$S21 = \frac{\kappa_c}{i(\omega-\omega_c) - \frac{1}{2}(2\kappa_c+\kappa_{\mathrm{int}}) + \sum_j \frac{|g_j|^2}{-\frac{1}{2}\gamma_j + i(\omega-\omega_j)}},$$

Evolution of g/ω over last 20 years



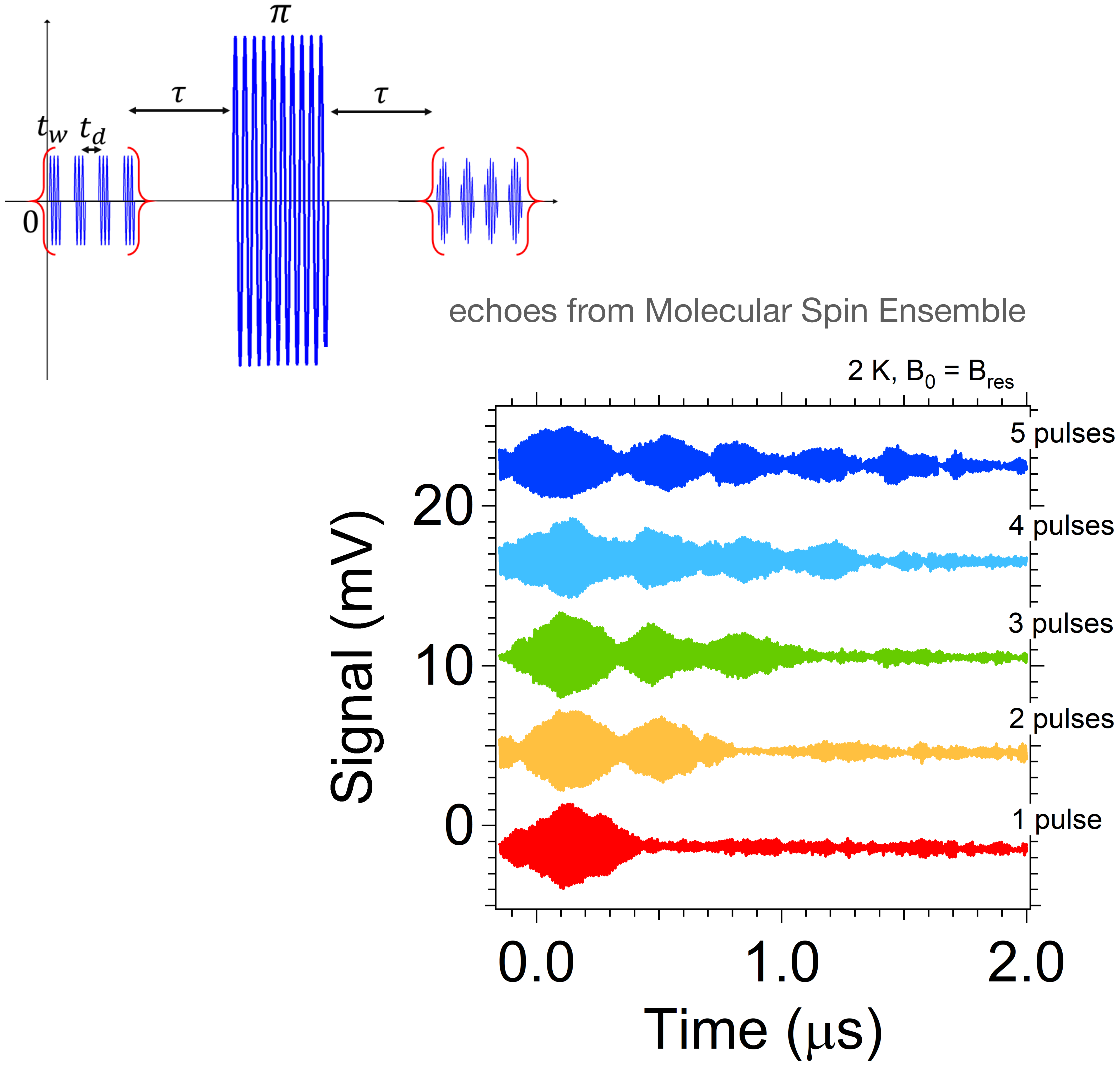
adapted from Forn-Diaz et al Rev. Mod. Phys. 91, 025005 (2019)

New Phenomena & Applications in USC regime

- fast and protected QIP
- nonlinear optics
- superradiance
- enhancement of quantum phenomena

New Phenomena & Applications

- fast and protected QIP
  - storage & retrieval of MW pulses
- nonlinear optics
- superradiance
- enhancement of quantum phenomena

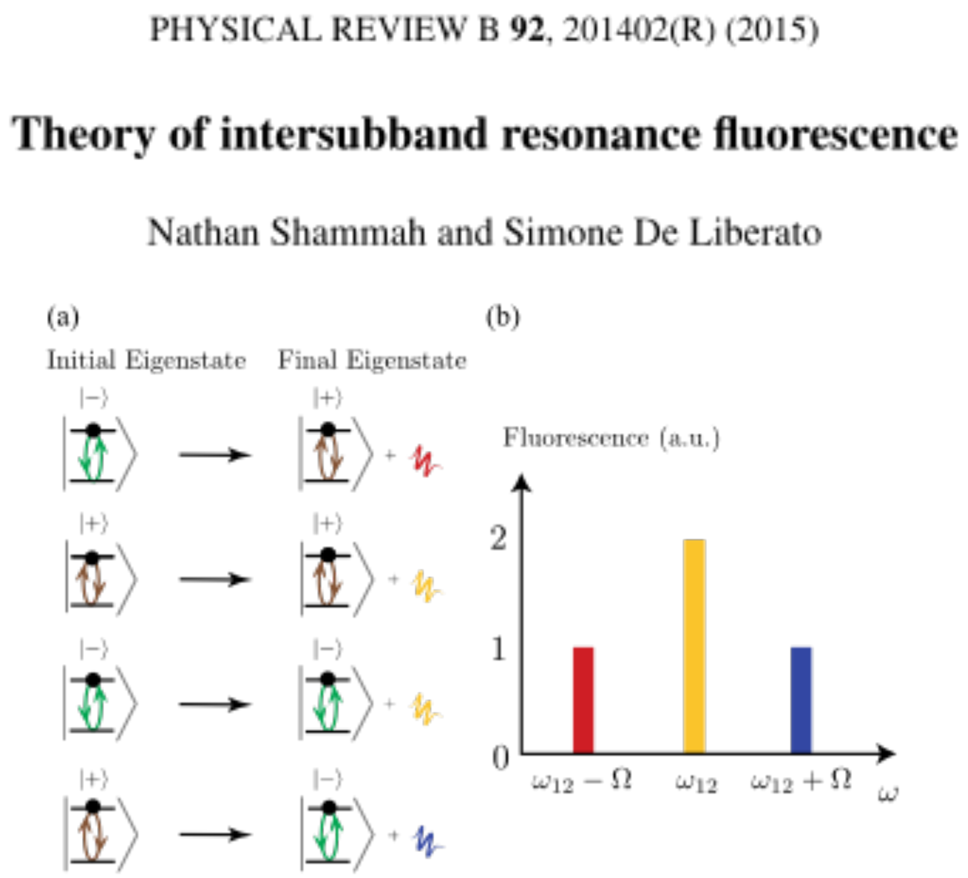


echoes from Molecular Spin Ensemble

C. Bonizzoni et al. *NPJ Quantum Inf. 6, 68 (2020)*

New Phenomena & Applications

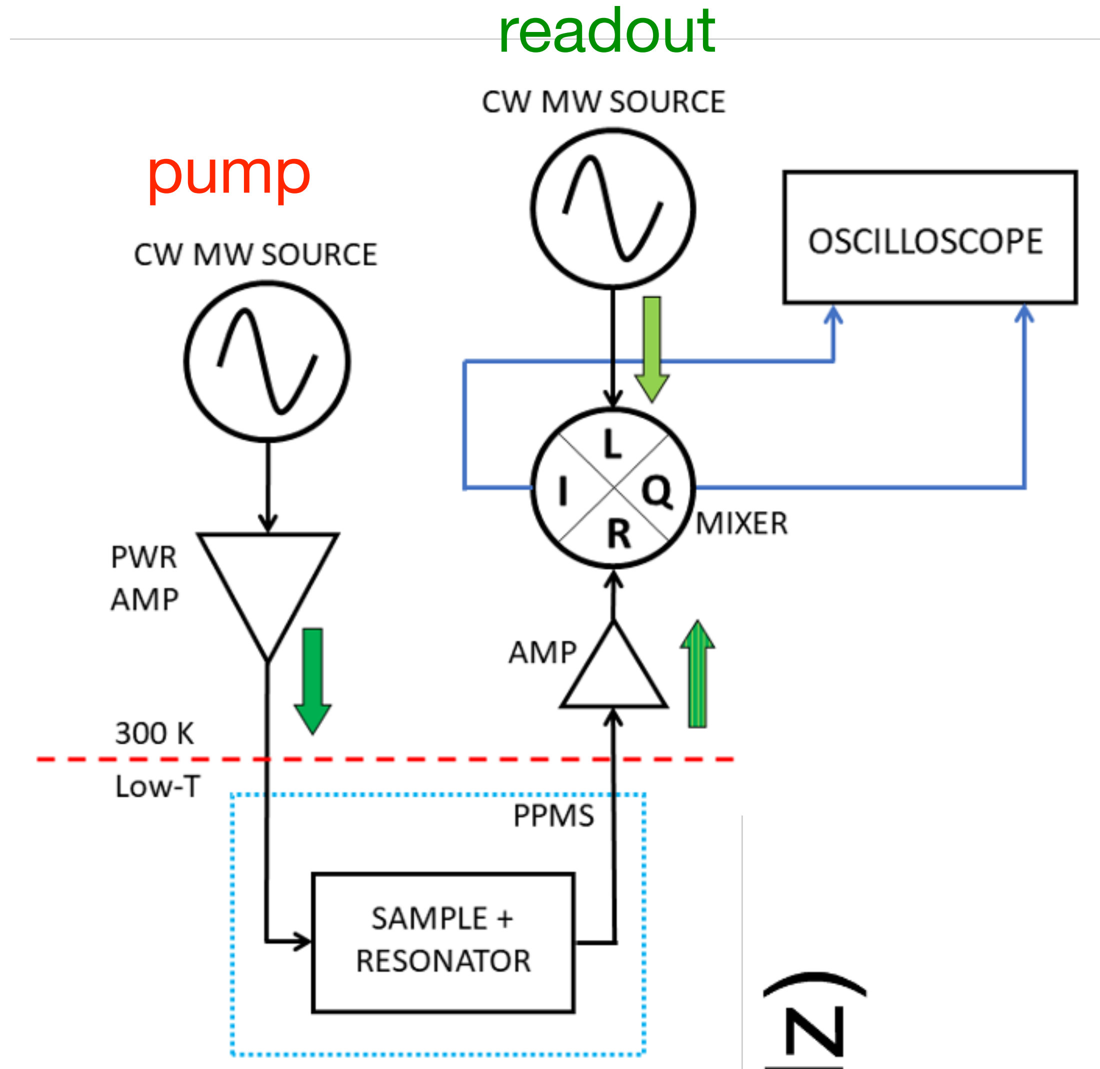
- fast and protected QIP
- nonlinear optics
  - fluorescence
- superradiance
- enhancement of quantum phenomena

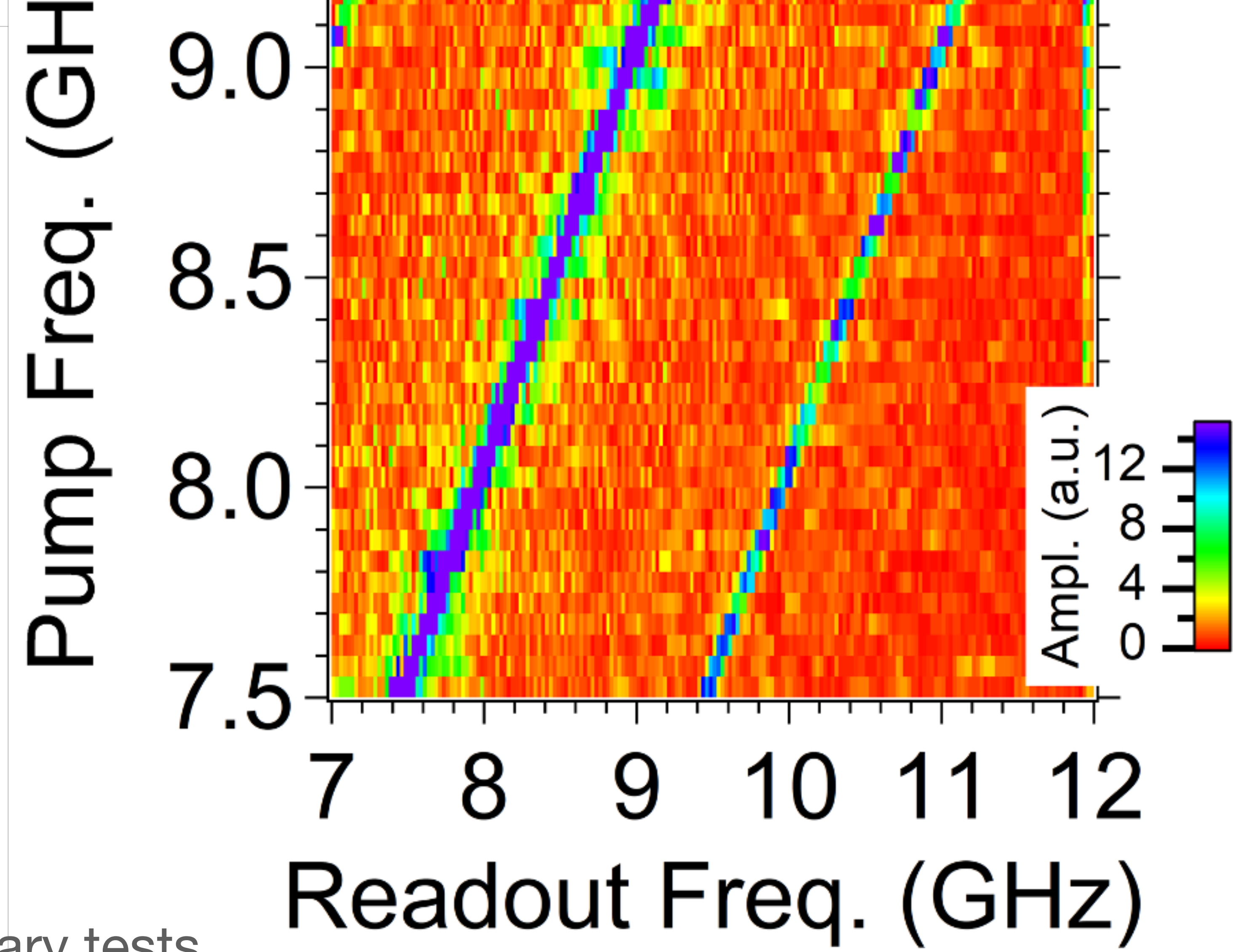


PHYSICAL REVIEW B **92**, 201402(R) (2015)

Theory of intersubband resonance fluorescence

Nathan Shammah and Simone De Liberato



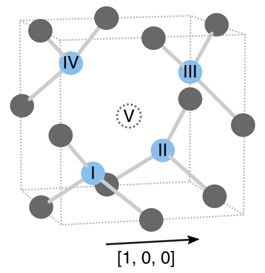


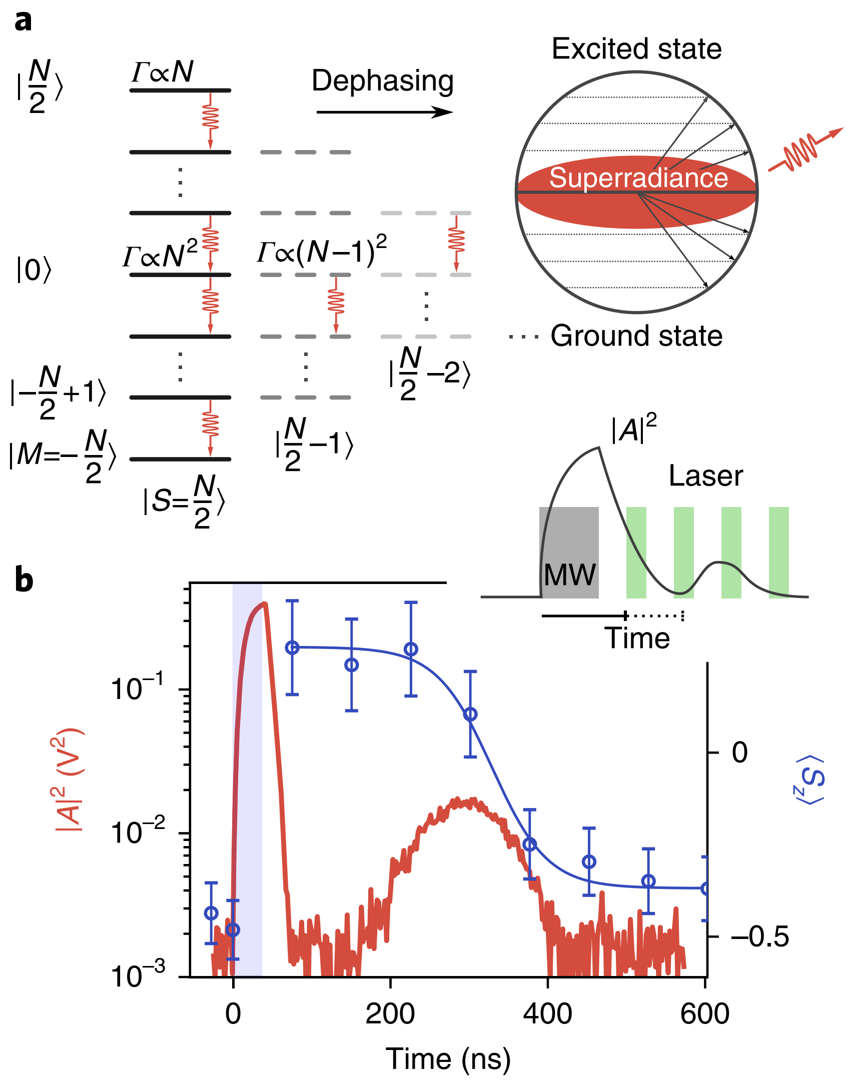
preliminary tests

(C. Bonizzoni, A. Ghirri, M. Maksutoglu, M. Affronte)

New Phenomena & Applications

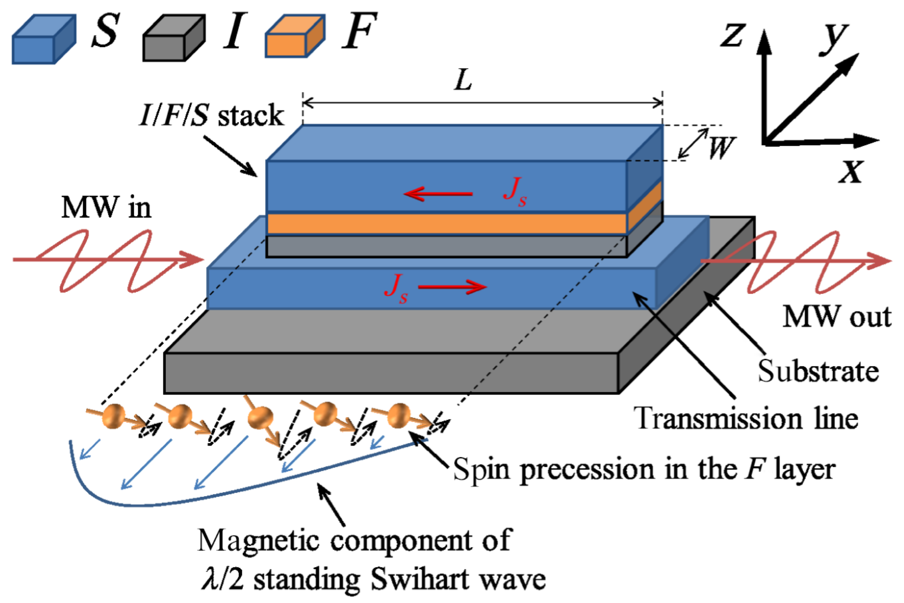
- fast and protected QIP
- nonlinear optics
- superradiance
- enhancement of quantum phenomena

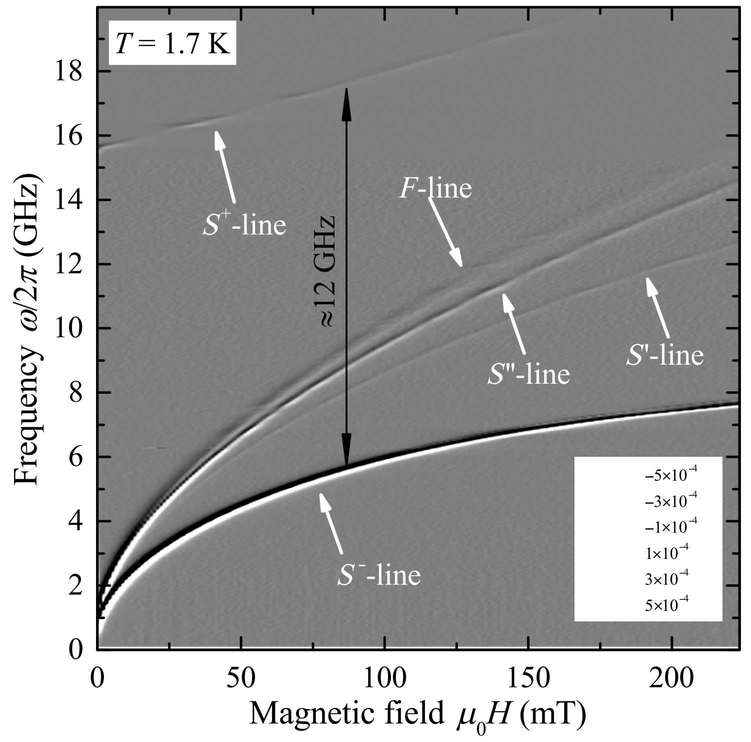




NATURE PHYSICS | VOL 14 | DECEMBER 2018 | 1168–1172 |

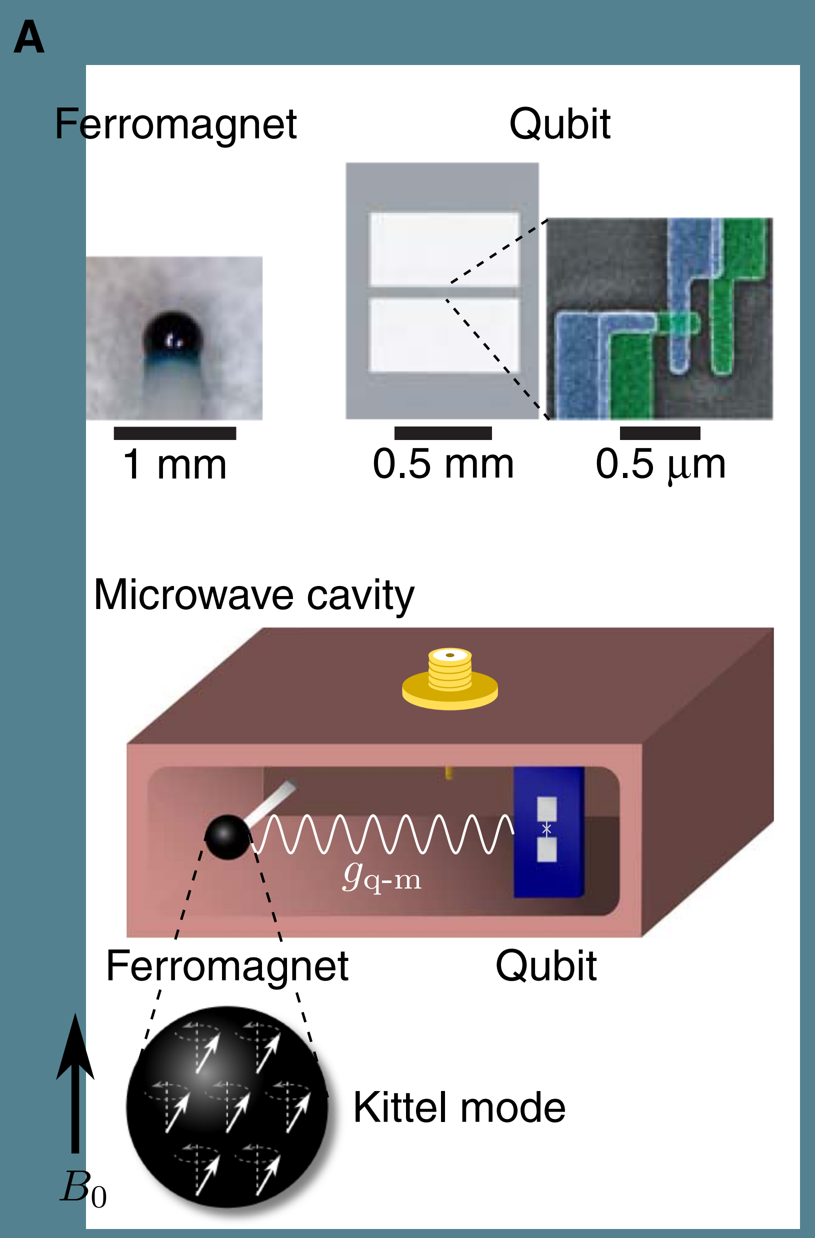
PHYS. REV. APPLIED **16,** 034029 (2021)



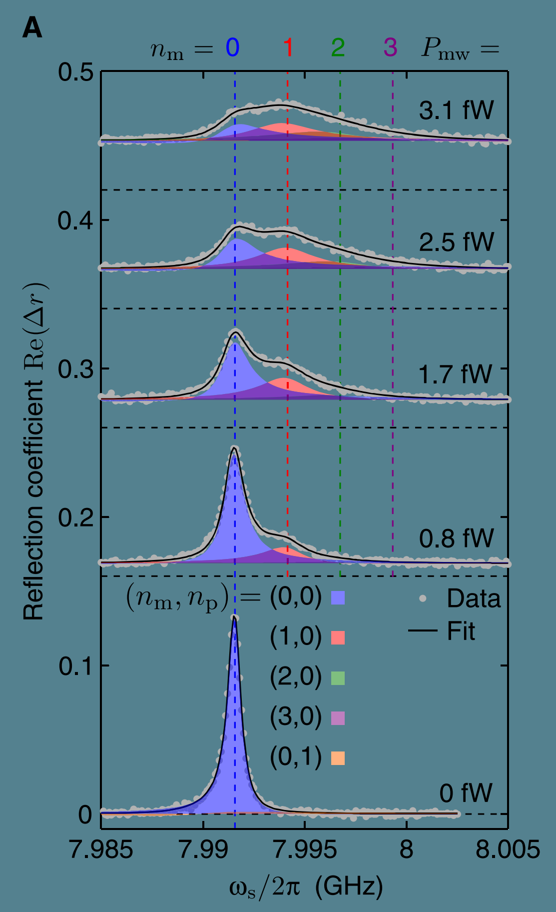


g/ω = 0.6 !

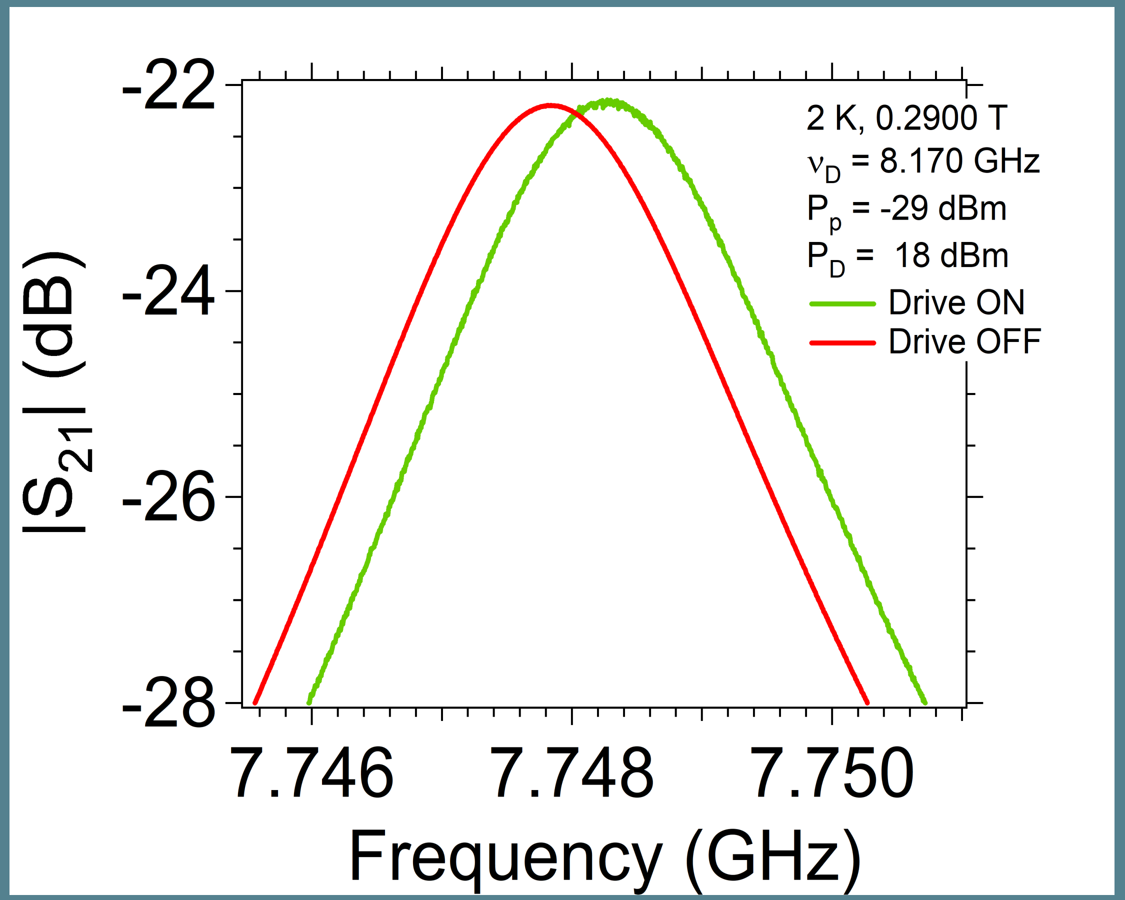
PERSPECTIVES FOR QUANTUM SENSING



Dispersive Read out of spin states



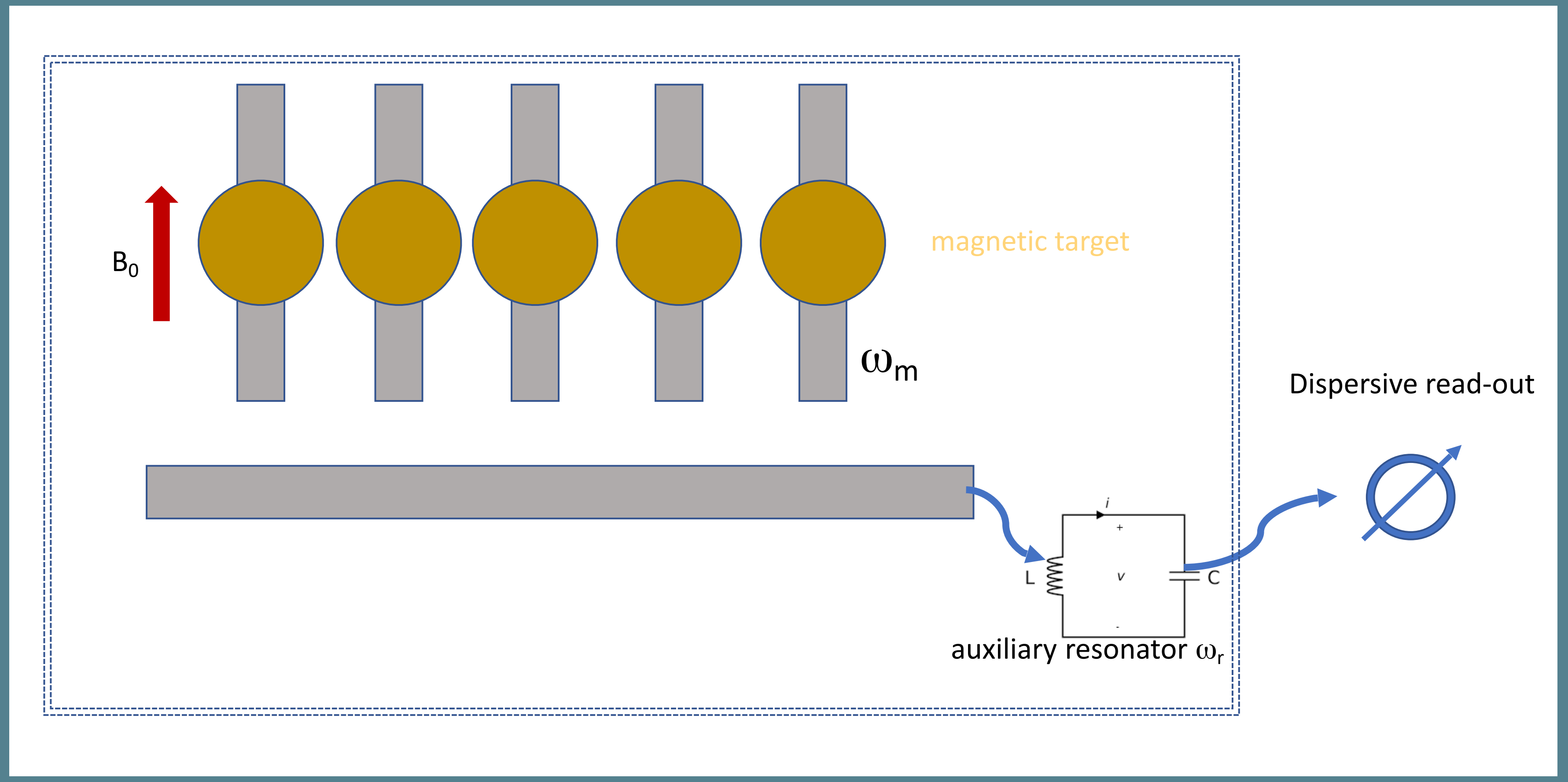
Lachance-Quirion *et al*., *Sci. Adv.* 2017;**3**:e1603150



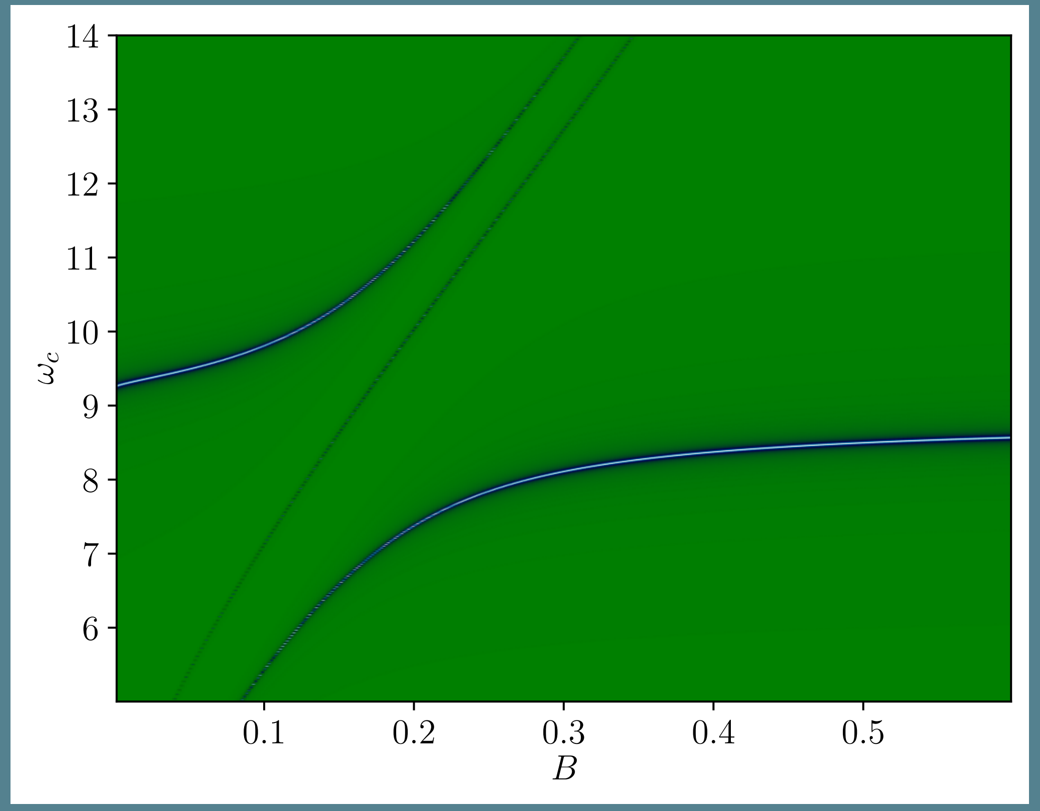
C. Bonizzoni et al. *Adv. Quantum Tech.* 4, 2100039 (2021)

Scalability of hybrid s/c-spin architectures

Possible cQED scheme for dispersive read out of single magnetic excitation with planar architectures



Ultra-Strong spin-photon coupling

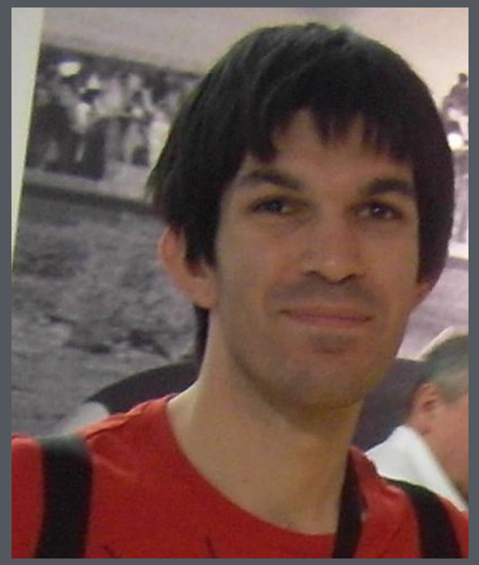


Acknoledgments:

CNRNANO MODENA S3

Experiments:

Alberto Ghirri



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Università degli Studi di Messina

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SUPERGALAX

Mikhail Lisitskiy
Claudio Gatti
Giuseppe Ruoso

thank you !