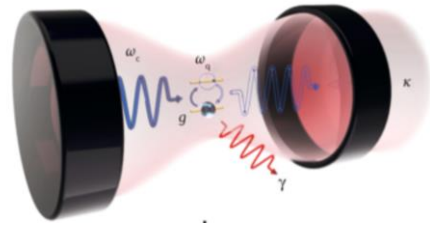
Cavity magnonics in strong coupling regime –

from magnon-polariton hybrid states to perspectives for quantum sensing

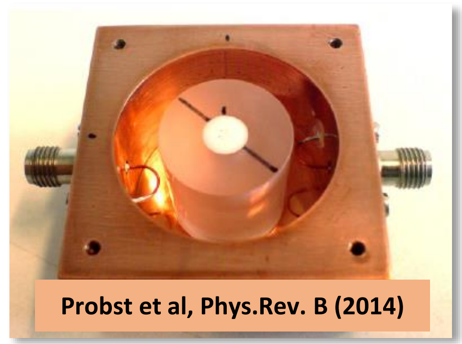
Angelo Leo

Mathematics and Physics Department “E. De Giorgi”, University of Salento, Lecce, Italy
CNR Nanotec – Institute of Nanotechnology, Lecce, Italy
Istituto Nazionale di Fisica Nucleare, Lecce, Italy

Cavity QED and hybrid systems for QC and QS

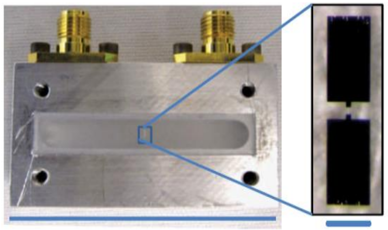


3D MW Cavities



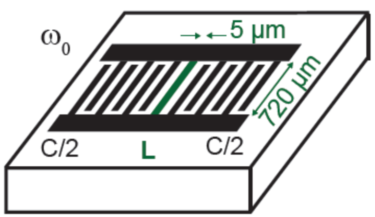
Probst et al, Phys.Rev. B (2014)

ELECTRONS

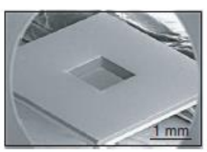


Paik et al, Phys Rev Lett (2011)

PHONONS



Bienfait et al, Nature Lett. (2016)

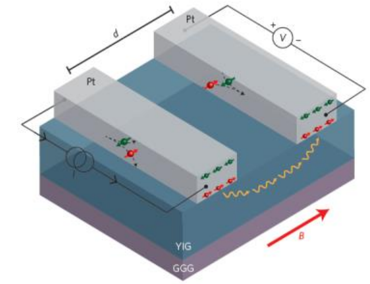


Yuan et al, Nature Comm. (2015)

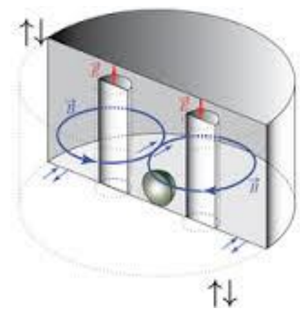
PARAMAGN. SPIN ENSEMBLES

Putz et al, Nature Physics (2014)

FM MATERIALS



Cornelissen et al, Nature Physics (2015)



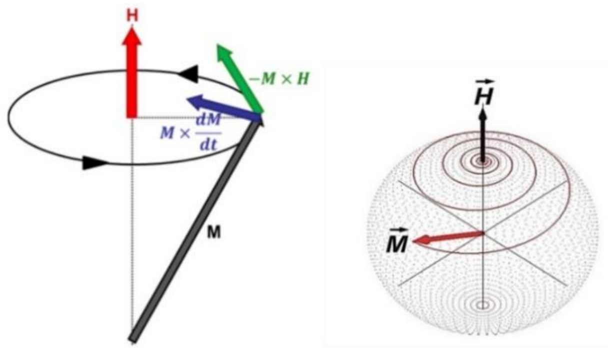
Goryachev et al, Phys Rev App (2014)

Classical approach

Dynamics of Magnetization

Landau – Lifshitz – Gilbert eq.

$$\frac{d\vec{M}}{dt} = \gamma_e \mu_0 (\vec{M} \times \vec{H}_{eff}) + \frac{\alpha}{M_S} \vec{M} \times \frac{d\vec{M}}{dt}$$



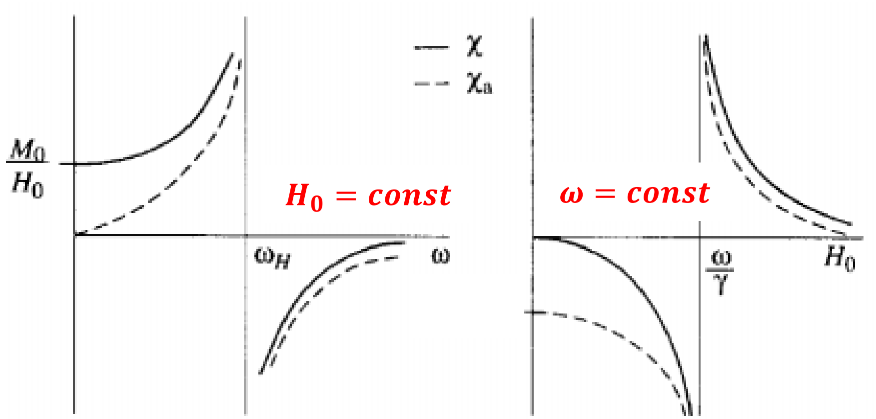
Magnetic susceptivity

$$\overleftrightarrow{\chi} = \begin{pmatrix} \chi & i\chi_a & 0 \\ -i\chi_a & \chi & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\chi_a = \frac{\gamma_e M_0 \omega}{\omega_H^2 - \omega^2}$$

$$\chi = \frac{\gamma_e M_0 \omega_H}{\omega_H^2 - \omega^2}$$

when $\omega = \omega_H = \gamma_e H_0$ **FMR**



Spin waves and magnons – overview

$$\hat{\mathcal{H}} = -2\frac{J}{\hbar^2}\sum_{j,\delta}\hat{\boldsymbol{S}}_j \cdot \hat{\boldsymbol{S}}_{j+\delta} - \frac{g\mu_B H_0}{\hbar}\sum_j \hat{S}_{jz}$$

Exchange among spins of NN sites

with ext. field

Holstein-Primakoff transformations

$$S_j^+|n_j\rangle = \hbar\sqrt{2s}\left(1-\frac{(n_j-1)}{2s}\right)^{1/2}\sqrt{n_j}|n_j-1\rangle$$

$$S_j^+ = \hbar\sqrt{2s}\left(1-\frac{m_j^+ m_j^-}{2s}\right)^{1/2} m_j^-$$

$$S_j^-|n_j\rangle = \hbar\sqrt{2s}\left(1-\frac{(n_j-1)}{2s}\right)^{1/2}\sqrt{n_j+1}|n_j+1\rangle$$

$$S_j^- = \hbar\sqrt{2s}\left(1-\frac{m_j^+ m_j^-}{2s}\right)^{1/2} m_j^+$$

$$\hat{\mathcal{H}} = -2\frac{J}{\hbar^2}\sum_{j,\delta}\hat{\boldsymbol{S}}_j\cdot\hat{\boldsymbol{S}}_{j+\delta} - \frac{g\mu_B H_0}{\hbar}\sum_j \hat{S}_{jz}$$

Exchange among spins of NN sites

with ext. field

At low temperature…

$$m_{\boldsymbol{k}}^{+} = N^{-1/2}\sum_j e^{i\boldsymbol{k}\cdot\boldsymbol{r}_j}\, m_j^{+}$$

$$m_{\boldsymbol{k}} = N^{-1/2}\sum_j e^{-i\boldsymbol{k}\cdot\boldsymbol{r}_j}\, m_j$$

If the j^{th} site has Z nearest neighbours

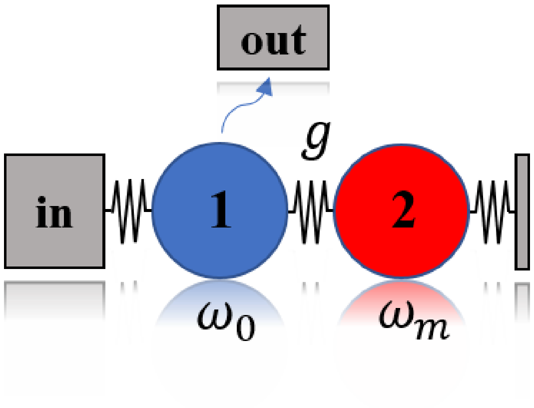
$$\hat{\mathcal{H}} = -2JNZs^2 - g\mu_B H_0 Ns + \hat{\mathcal{H}}_0$$

$$\hat{\mathcal{H}}_0 = \sum_{\boldsymbol{k}}\left(4JaZ(1-\gamma_{\boldsymbol{k}}) + g\mu_B H_0\right) m_{\boldsymbol{k}}^{+} m_{\boldsymbol{k}}$$

n of magnons @ $\boldsymbol{k}$ $\quad \hat{n}_{\boldsymbol{k}} = m_{\boldsymbol{k}}^{+} m_{\boldsymbol{k}}$

$$\hat{\mathcal{H}}_0 = \sum_{\boldsymbol{k}} \hat{n}_{\boldsymbol{k}}\,\hbar\omega_{\boldsymbol{k}} \qquad \hbar\omega_{\boldsymbol{k}} = 4JsZ(1-\gamma_{\boldsymbol{k}}) + g\mu_B H_0$$

$$\varepsilon_{\boldsymbol{k}} = (n_{\boldsymbol{k}} + 1/2)\hbar\omega_{\boldsymbol{k}}$$



Confined EM field $\mathcal{H}_c = \hbar\omega_0\left(a^\dagger a + \frac{1}{2}\right)$

Magnons $\mathcal{H}_m = \hbar\omega_m\left(m^\dagger m + \frac{1}{2}\right)$

only with resonant interactions:

$$\mathcal{H} = \mathcal{H}_c + \mathcal{H}_m + \mathcal{H}_{int}$$

$$\frac{\mathcal{H}}{\hbar} = \omega_0 a^\dagger a + \omega_m m^\dagger m + \underline{g}(a^\dagger m + m^\dagger a)$$

Coupling strength of each spin:

$$\frac{g_{0,i}}{2\pi} = \frac{\left(\eta\gamma_e\sqrt{\frac{(\mu_0\hbar\omega_0)}{V_c}}\right)}{4\pi}$$

As a spin ensemble:

$$g_i = g_{0,i}\sqrt{Ns}$$

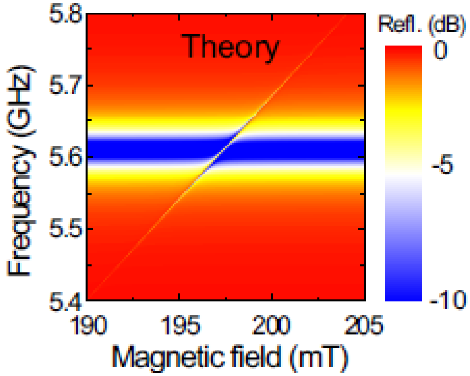
$$g_i \propto \sqrt{\omega_{eff}} = \sqrt{\omega_0\, V_m/V_a}$$

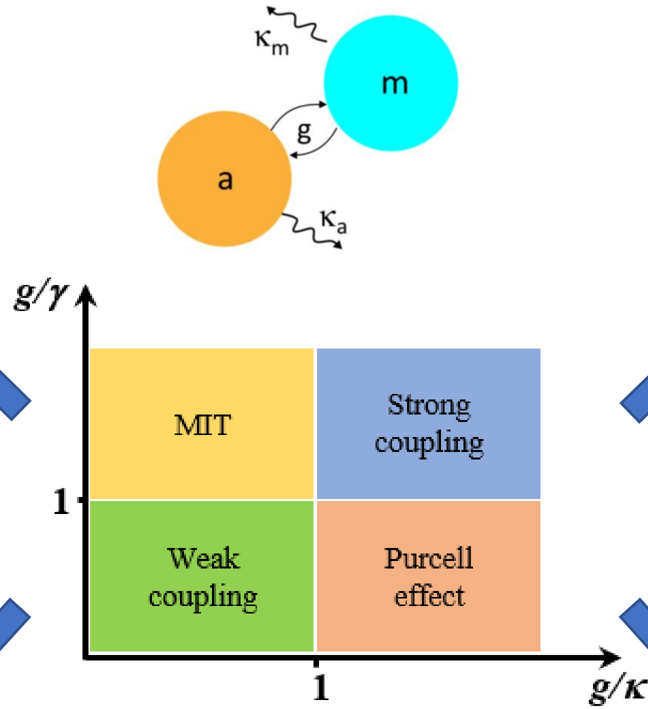
Overlap among subsystems:

$$\eta = \int_{V_m}^{0} \frac{\vec{h}\cdot\vec{M}}{|\vec{h}_{max|}||\vec{M}_{max}|} dV \leq 1$$

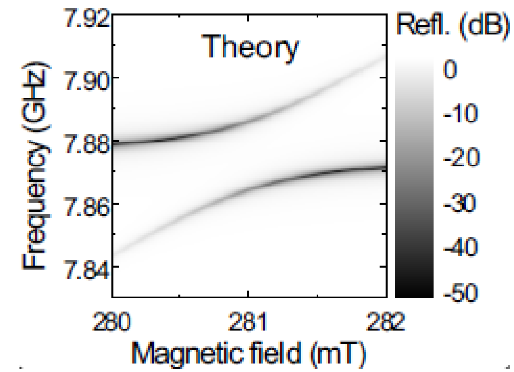
Analogies with quantum systems – cavity magnon polariton systems

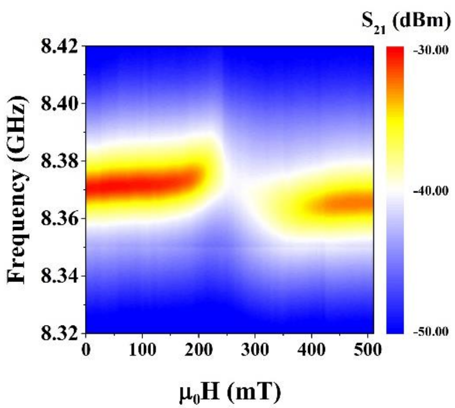
Zhang et al, Phys Rev Lett (2014)



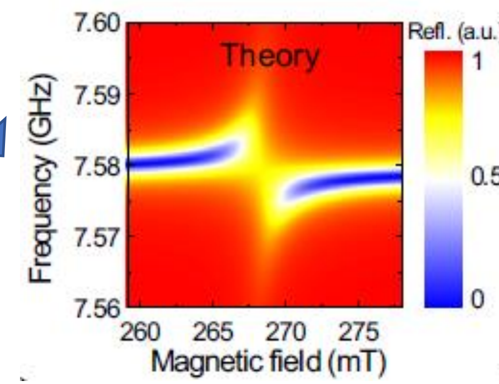


Zhang et al, Phys Rev Lett (2014)



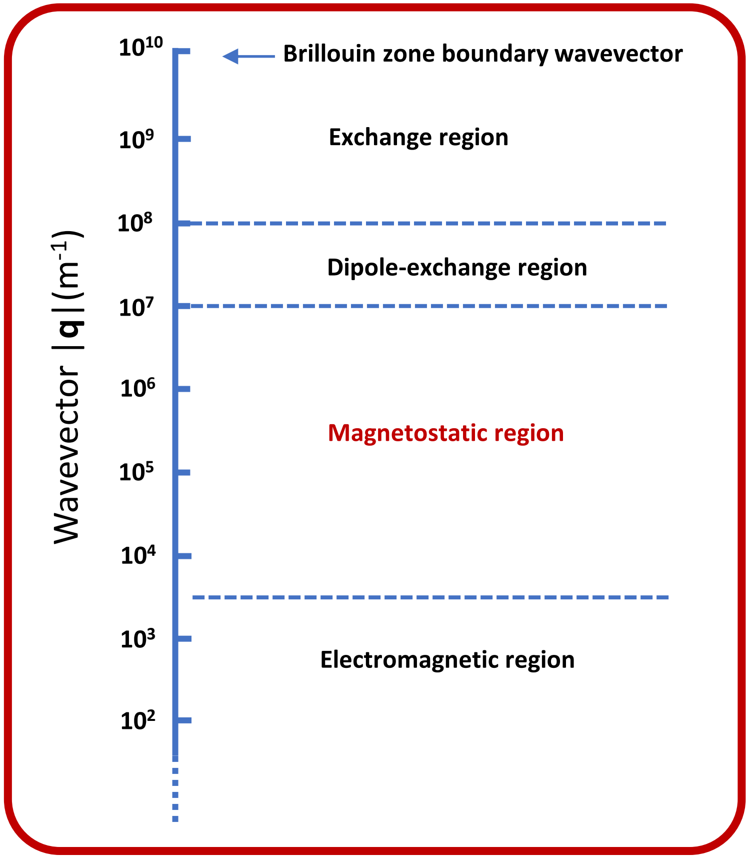


Mn_2FeO_4 NPs in a low Q cavity (Unisalento)



Zhang et al, Phys Rev Lett (2014)

Magnetostatic modes of a magnetic sphere



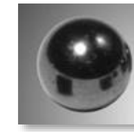
Kittel mode $(m = n = 1)$

$$f = \gamma H_0$$

Magnetic dipolar interaction

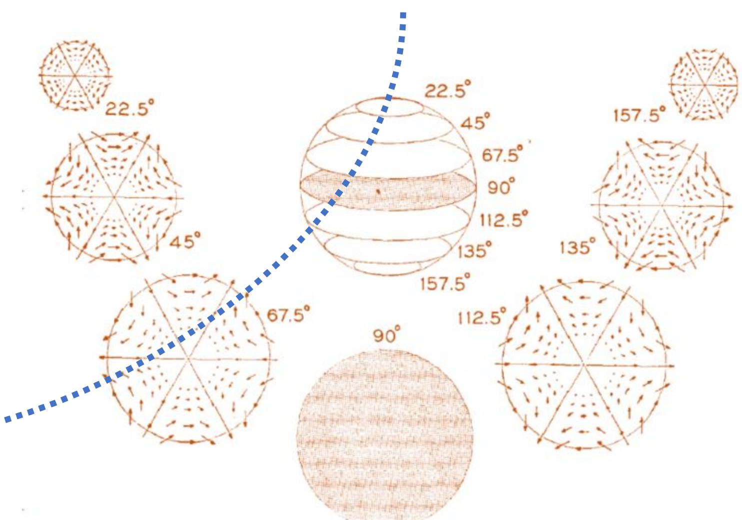
$$\frac{d}{dt}\vec{M} = -\gamma\mu_0\left(\vec{M}\times\vec{H}_{\text{eff}} - \eta\vec{M}\times\frac{d}{dt}\vec{M}\right)$$

+



Indexes of MSMs

$$n + 1 + \xi_0\frac{P_n^{m\prime}(f, H_0)}{P_n^m(f, H_0)} \pm m\frac{\gamma f M_S}{\gamma^2 {H_i}^2 - f^2} = 0$$

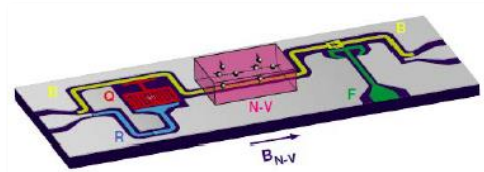


Walker, J.Appl.Phys. (1958)

Yttrium Iron Garnet for cavity magnonics

Paramagnetic spin ensembles

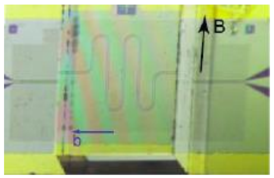
NV- centers in diamond



Putz et al., Nature Physics (2014)

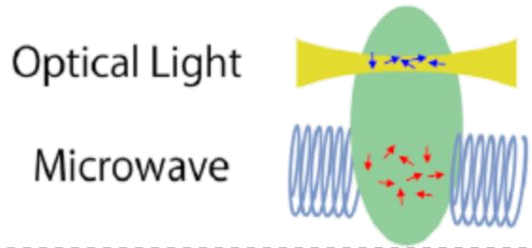
Phys Rev Lett107, 220501 (2011)

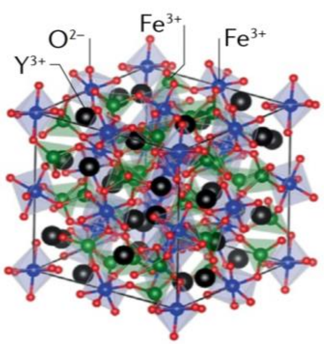
Rare-earth doped crystal



Bushev et al., Phys Rev B (2011)

Low spin density: 10^{12}-10^{18} cm^{-3}

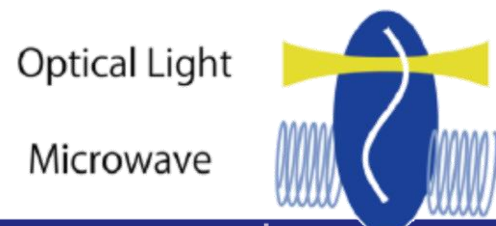




$Y_3Fe_2(FeO_4)_3$

- *High Curie Temperature* — T_C = 560 K
- *Insulator* — BG = 2.68 eV
- *Low magnetic damping* — $\alpha_0 \sim 10^{-5}$
- *Absorption coefficient* — ~10/cm @ 0.8 THz
- *Large Verdet constant* — ~100 °/mm/T
- *large size of the lattice cell* — 1.2376 nm

High net spin density 2.1×10^{22} cm^{-3}

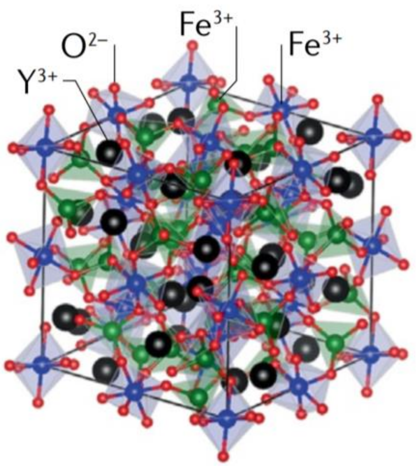


Standard use

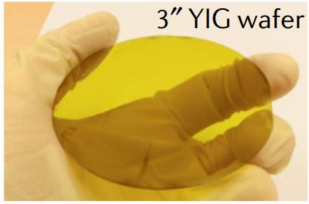
- MW oscillator

- Optical isolator

Yttrium Iron Garnet for coherent cavity magnonics

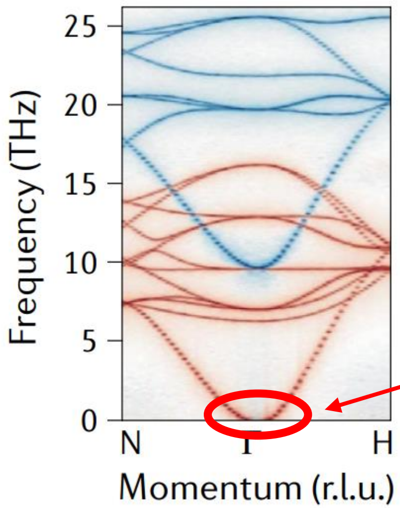


Fabrication



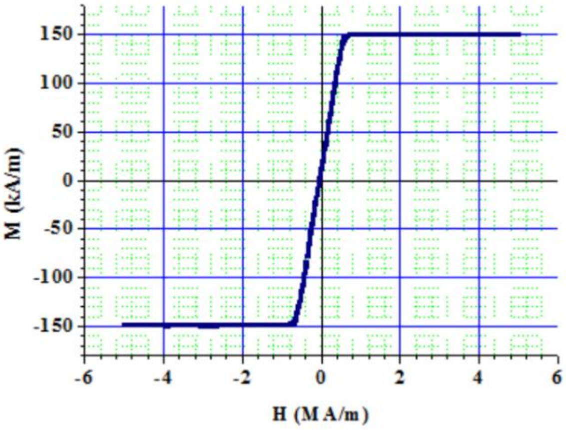
- **LPE**
- **PLD**
- **Magnetron sputtering**

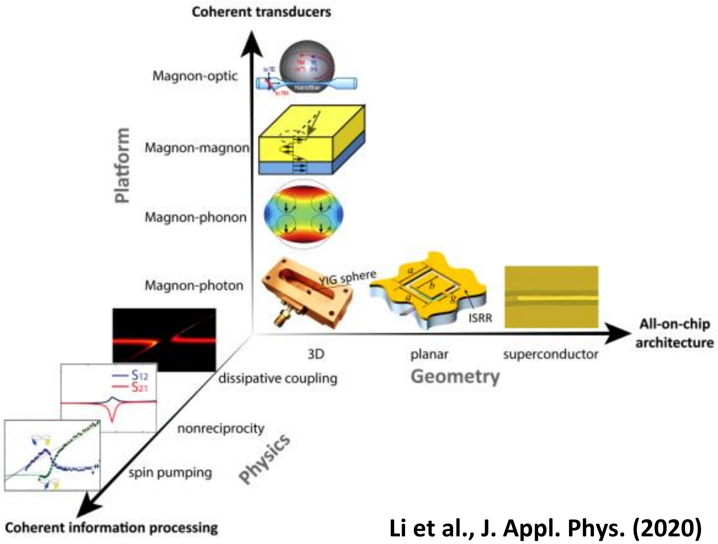
P. Pirro et al., Nature Reviews. (2021)



There are 20 distinct exchange magnon branches but, for cavity (quantum) magnonics, the interest is focused on **Kittel mode**

Vibrating sample magnetometry @ UniSalento

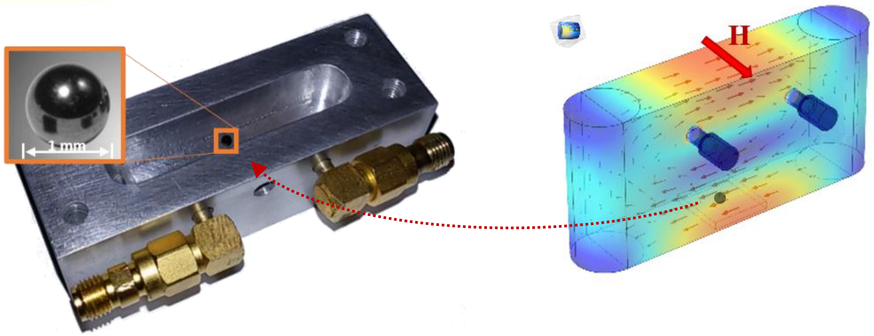


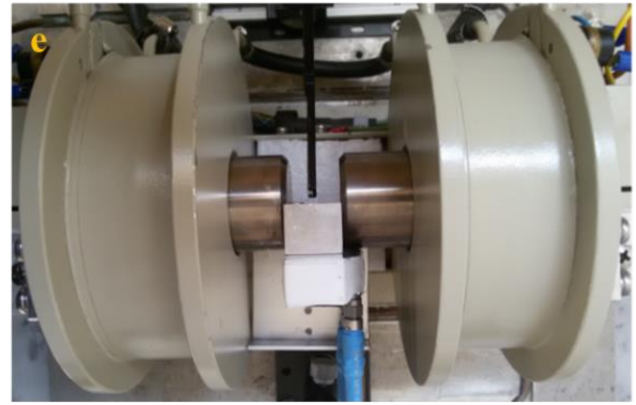


Li et al., J. Appl. Phys. (2020)

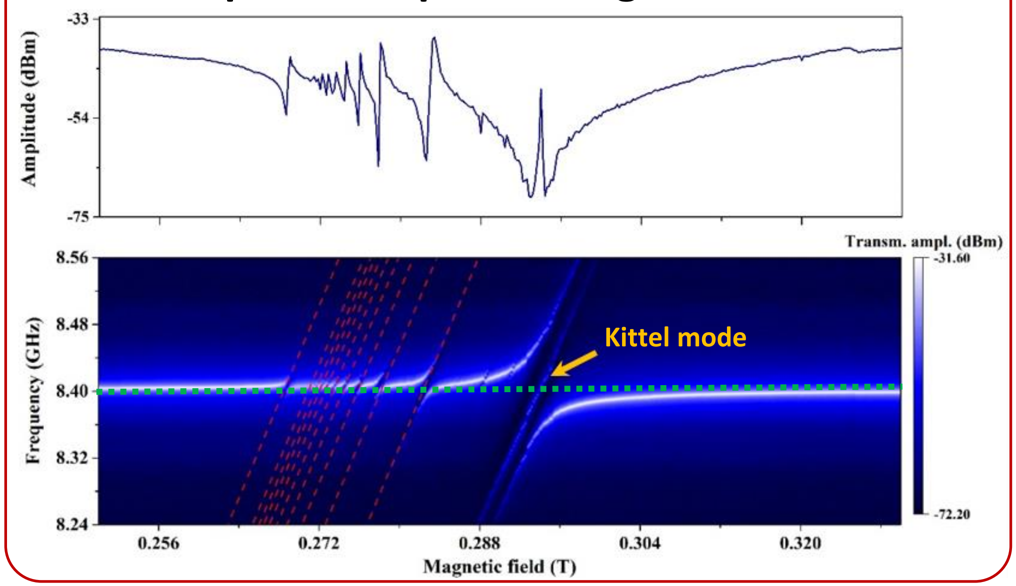
Strong coupling regime

setup





Spectroscopic investigation



Input-output formalism:

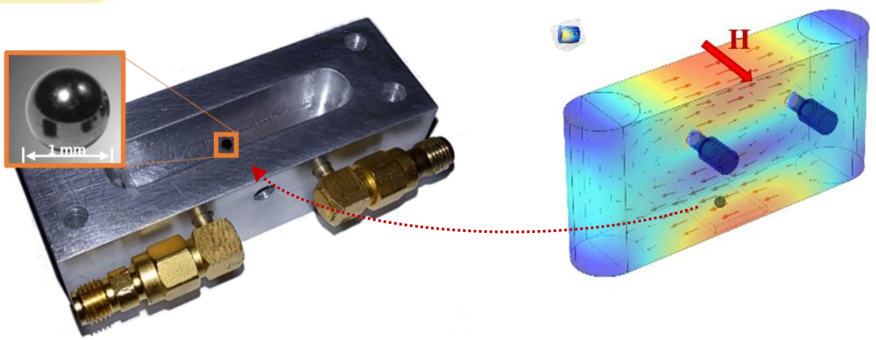
$$T(\omega) = \frac{\kappa_c}{i(\omega - \omega_c) - \kappa_c + \sum_m \frac{|g_m|^2}{-\frac{1}{2}\kappa_m + i(\omega - \omega_m)}}$$

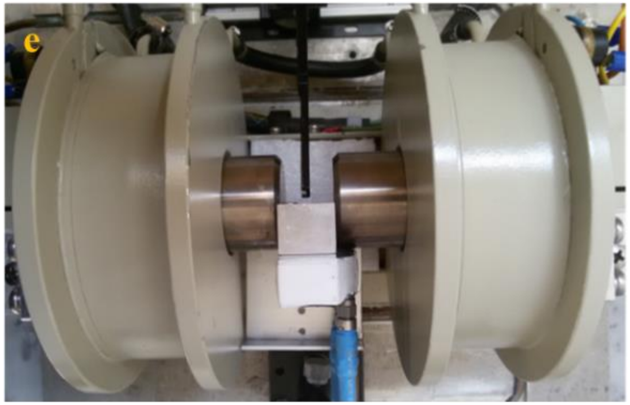
Cavity mode at:	ω_c
Total cavity decay rate:	$\kappa_c = \frac{1}{2}\left(2\kappa_{i,o} + \kappa_{int}\right)$
Magnon mode damping rate:	κ_m (m = FMR, MSMs)
Magnon mode at	ω_m (m = FMR, MSMs)
Coupling strength	g_m (m = FMR, MSMs)

- Leo et al. Phys Rev B (2020)
- *Three-dimensional Magnonics*

Strong coupling regime

setup





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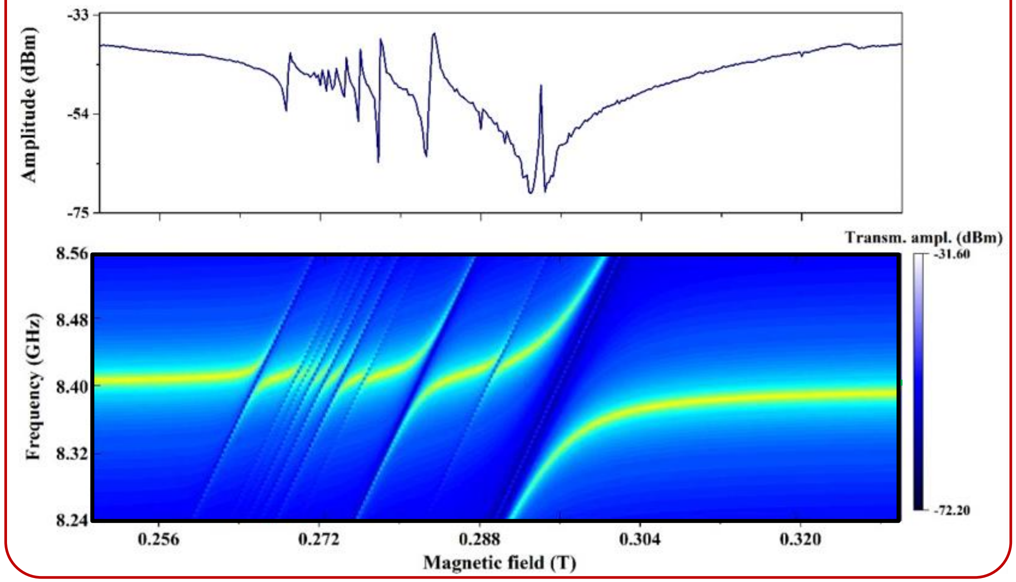

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- Leo et al. Phys Rev B (2020)
- *Three-dimensional Magnonics*

Strong coupling regime

Transmitted signal

$$T(\omega) = \frac{\kappa_c}{i(\omega-\omega_c) - \kappa_c + \sum_m \frac{|g_m|^2}{-\frac{1}{2}\kappa_m + i(\omega-\omega_m)}}$$

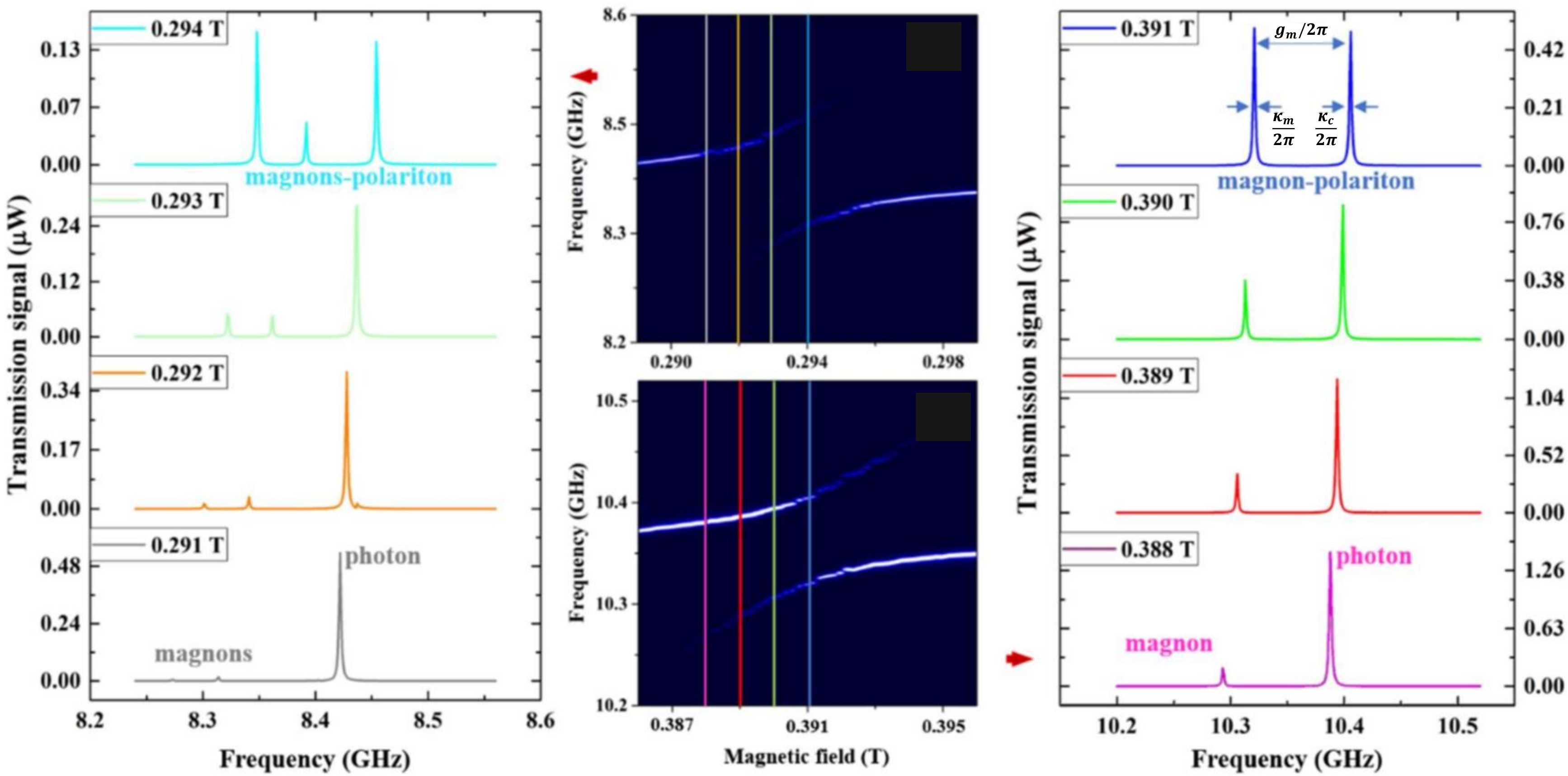
Cavity mode at: ω_c

Total cavity decay rate: $\kappa_c = \frac{1}{2}(2\kappa_{i,o} + \kappa_{int})$

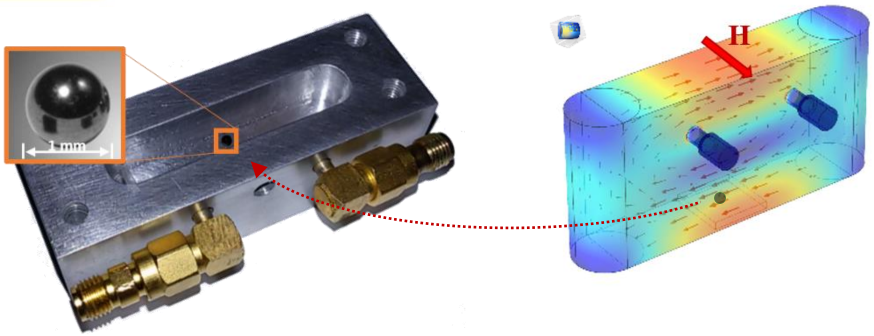
Magnon mode damping rate: κ_m (m = FMR, MSMs)

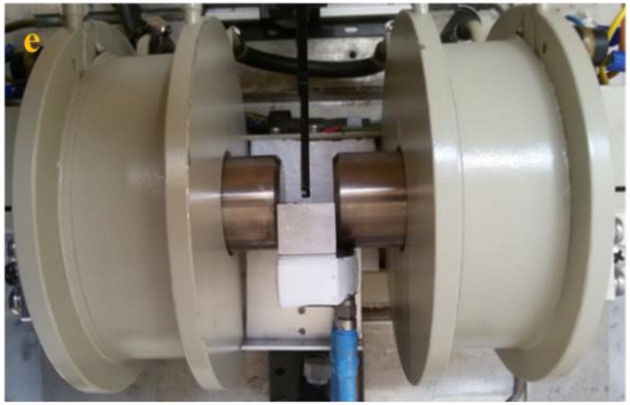
Magnon mode at ω_m (m = FMR, MSMs)

Coupling strength g_m (m = FMR, MSMs)

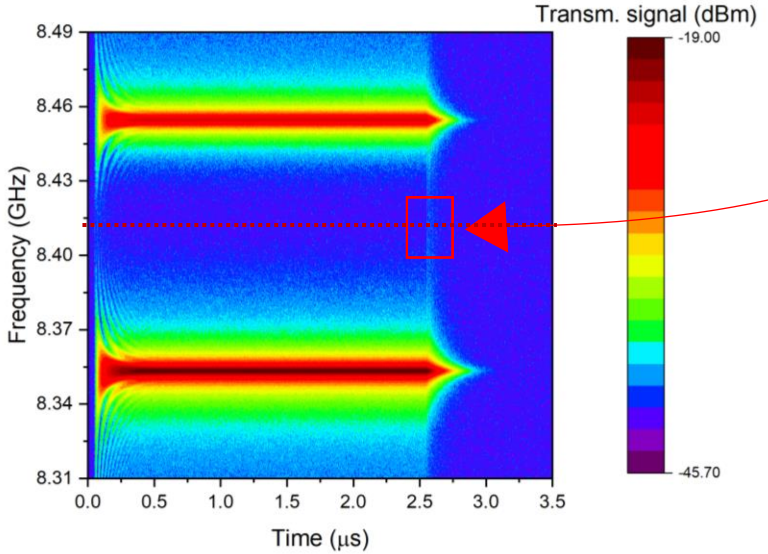


Rabi oscillations





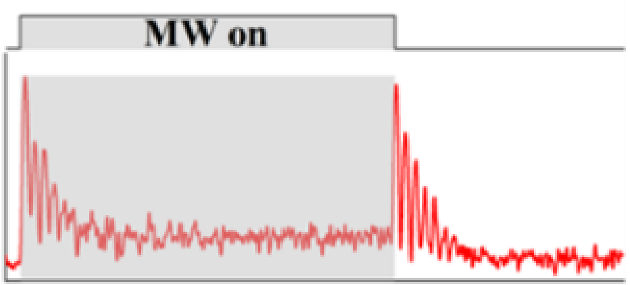
Time-resolved measurements



Rabi oscillations:

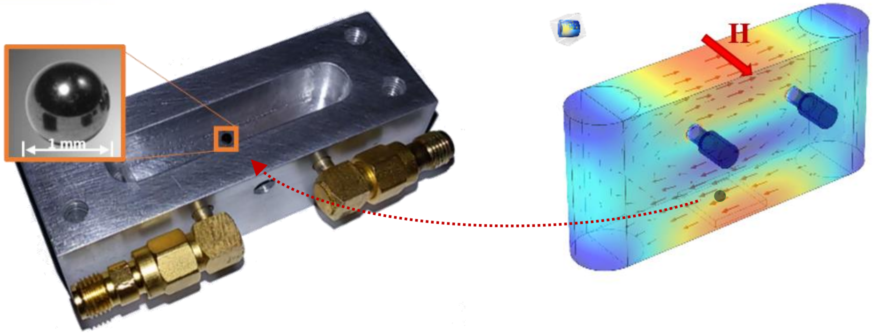
$$P\left(\frac{\omega_i}{2\pi}\right) \propto A_i \cdot log\left[sin^2\left(\frac{g_i}{2\pi}t\right) \cdot exp\left(-\frac{2\kappa_c - \kappa_{int}}{2\pi}t\right)\right]$$

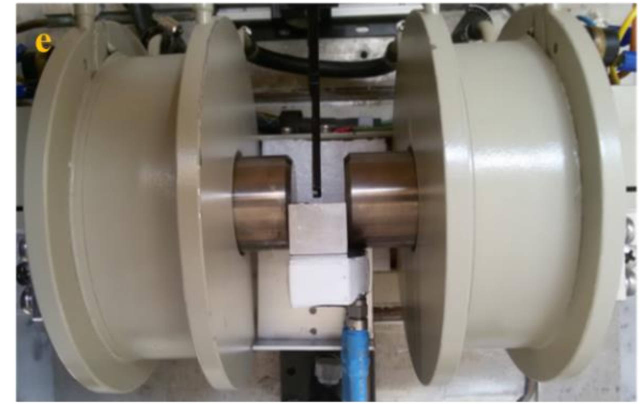
Coupling among resonators — **MW cavity relaxation**



Leo et al. Phys Rev B (2020)

Rabi oscillations





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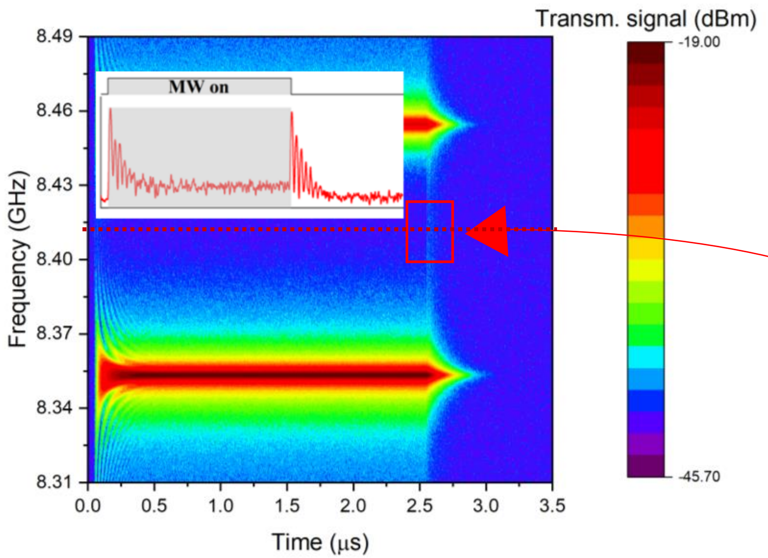


Volterra equation

$$a(t) = \int_0^t d\tau \mathcal{K}(t-\tau) a(\tau) + \mathcal{F}(t)$$

$$\mathcal{F}(t) = -\int_0^t d\tau \cdot \eta(\tau) e^{-\kappa(t-\tau)}$$

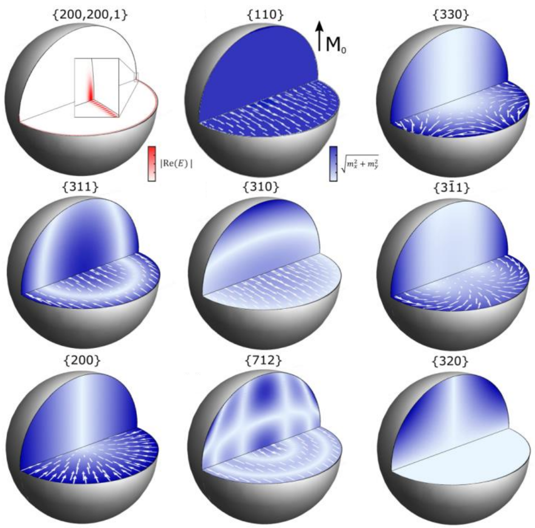
$$\mathcal{K}(t-\tau) = g_m^2 \int d\omega\, \rho(\omega) \frac{\left[e^{-i(\omega-\omega_c-i(\kappa_m-\kappa_c))(t-\tau)} - 1\right]}{-i(\omega-\omega_c-i(\kappa_m-\kappa_c))} \cdot e^{-\kappa(t-\tau)}$$

Rabi oscillations:

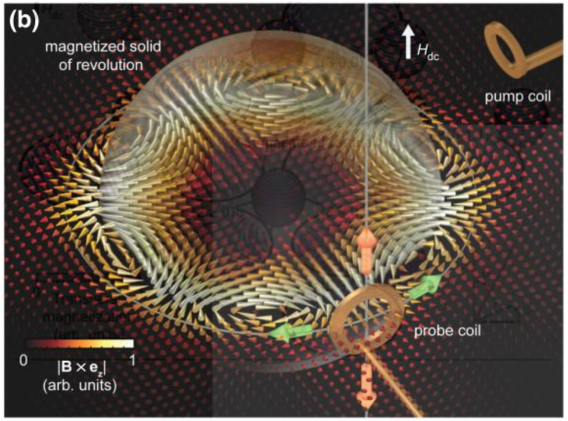
$$P\left(\frac{\omega_i}{2\pi}\right) \propto A_i \cdot log\left[sin^2\left(\frac{g_i}{2\pi}t\right) \cdot exp\left(-\frac{2\kappa_c - \kappa_{int}}{2\pi}t\right)\right]$$

Coupling among resonators **MW cavity relaxation**

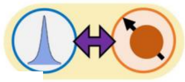
Effect of reservoir on MSMs visualization

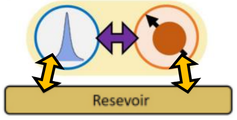


J.A. Haigh Phys Rev B (2018)



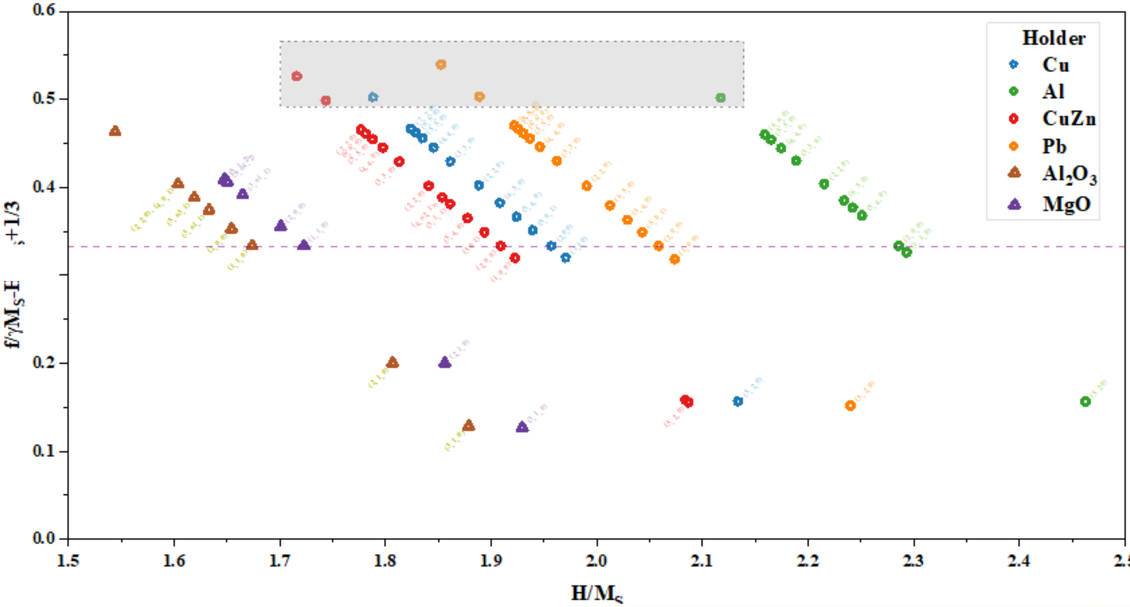
A. Gloppe, Phys Rev Appl (2018)

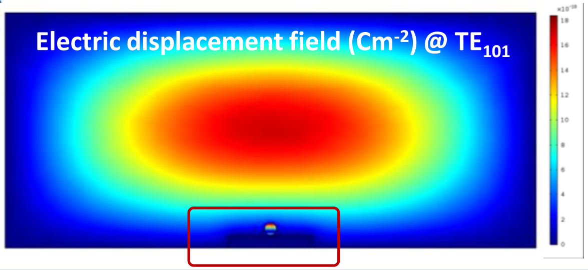




Holder electrical conductivity

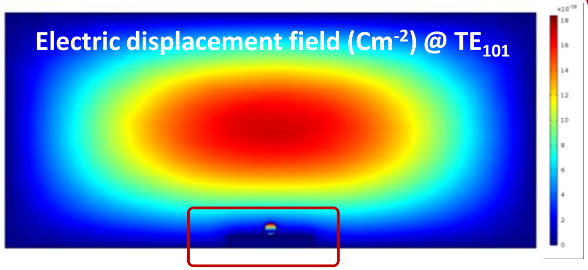
MSMs identification based on: $$n + 1 + \xi_0 \frac{P_n^{m\prime}(f, H_0)}{P_n^m(f, H_0)} \pm m \frac{\gamma f M_S}{\gamma^2 {H_i}^2 - f^2} = 0$$

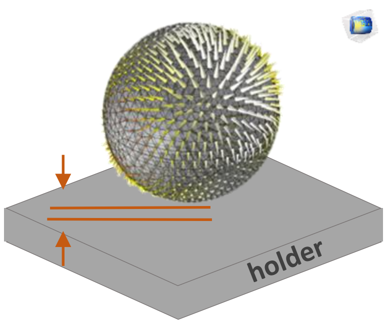




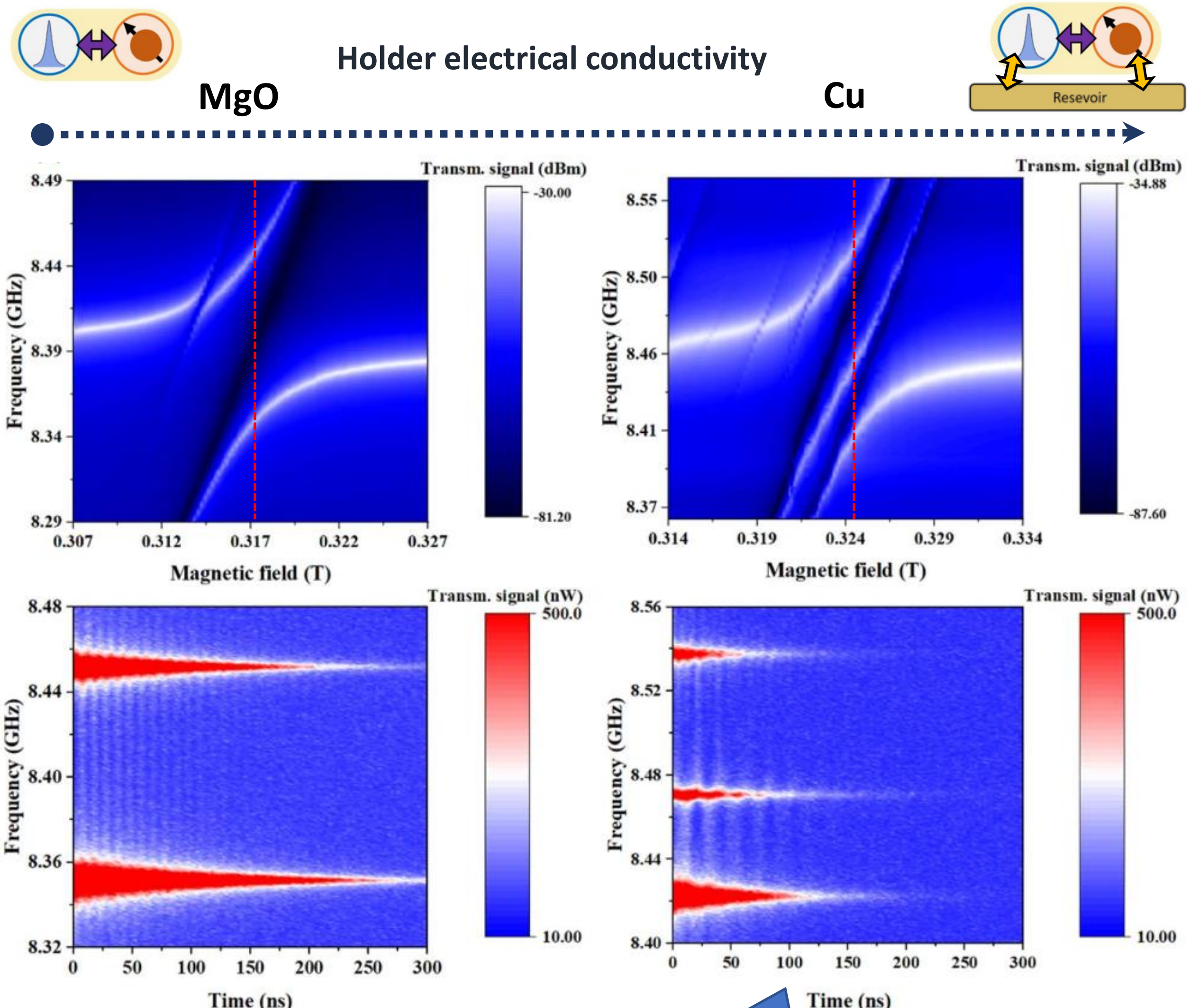
Effect of reservoir on MSMs visualization

RF electric field @ TE101

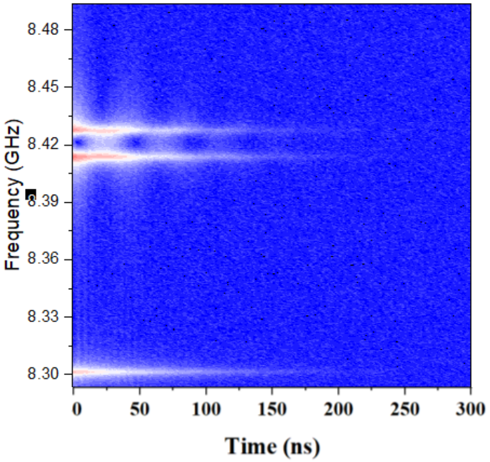


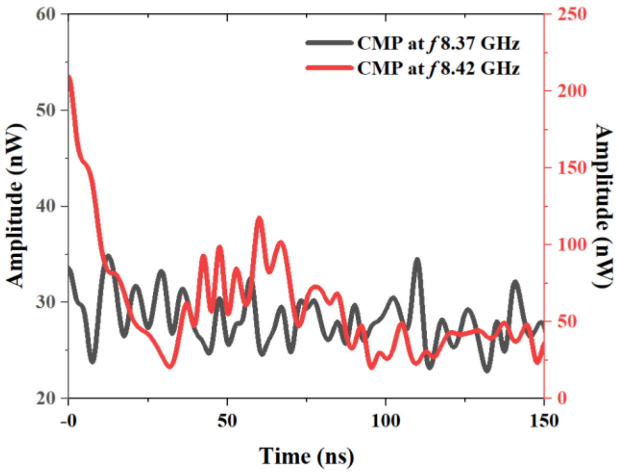


Surf. electric currents on YIG sphere at cavity working frequency



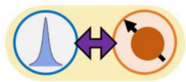
multimode hybridization mediated by cavity photons



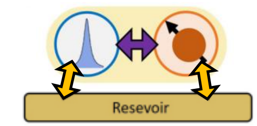


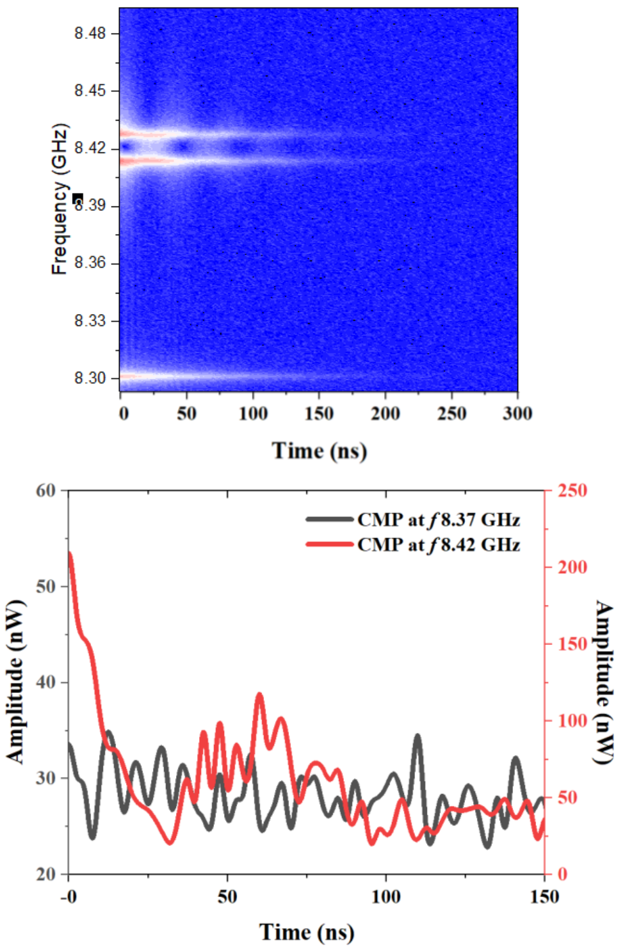
multimode hybridization mediated by cavity photons

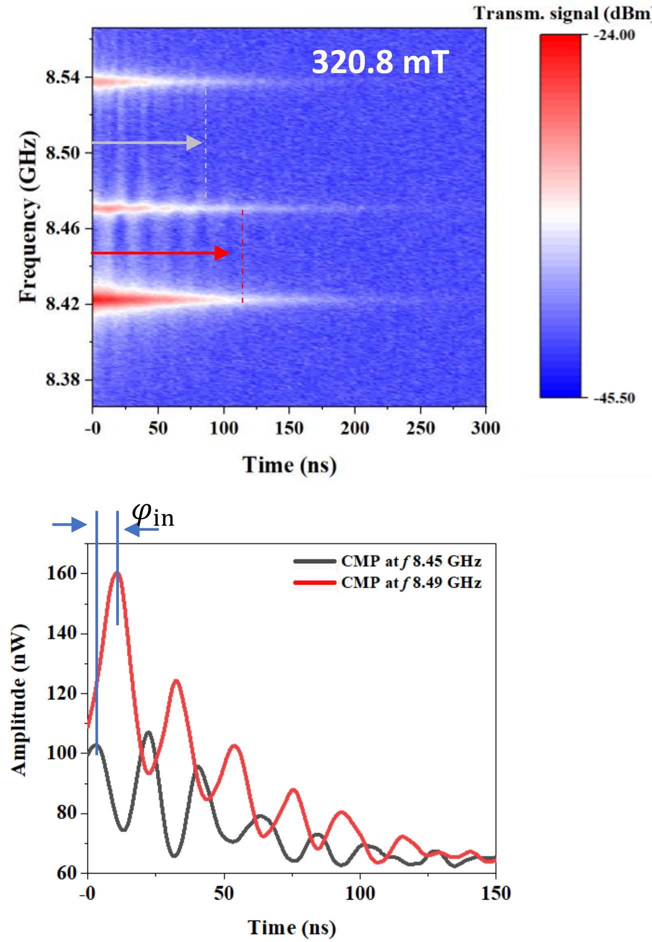
$$\frac{1}{4\pi^2}\begin{pmatrix} \omega^2-\omega_{FMR}^2+i2\alpha\omega_{FMR}\omega & g_1^2\omega_{FMR}^2 & 0 \\ g_1^2\omega_{FMR}^2 & \omega^2-\omega_C^2+i2\alpha\omega_C\omega & g_2^2\omega_{(2,0,0)}^2 \\ 0 & g_2^2\omega_{(2,0,0)}^2 & \omega^2-\omega_{(2,0,0)}^2+i2\alpha\omega_{(2,0,0)}\omega \end{pmatrix}\begin{pmatrix} m_{FMR} \\ h_\omega \\ m_{(2,0,0)} \end{pmatrix} = \omega^2\begin{pmatrix} 0 \\ \Gamma \\ 0 \end{pmatrix} h_0$$

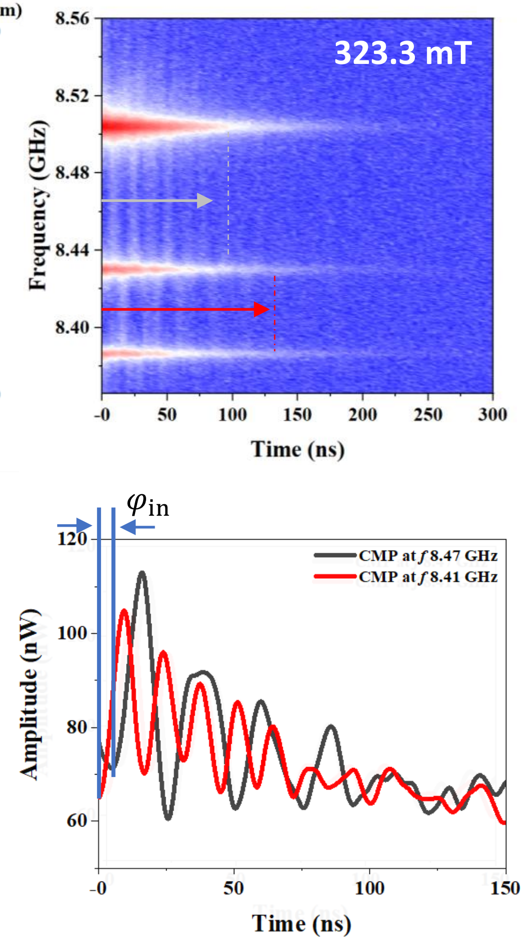


Nonreciprocity









multimode hybridization mediated by cavity photons

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“quantum unidirectional processing of information”

C. Zhang et al., PRB (2021)

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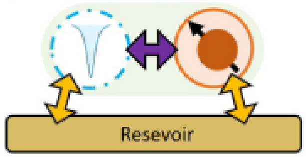
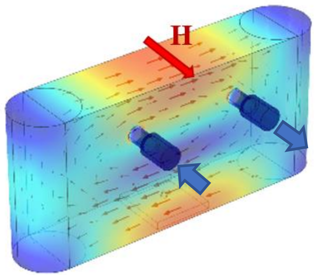
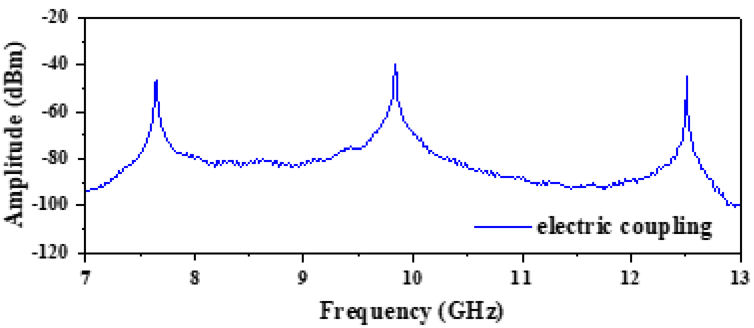
Leo et al. - *submitted*

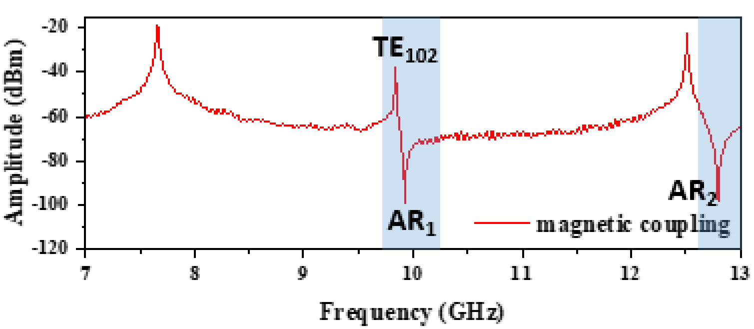
Investigation in dissipative regime of CMP hybrid system







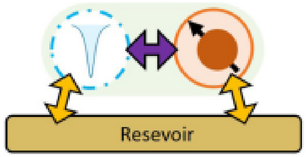
Switch of antennas/probes

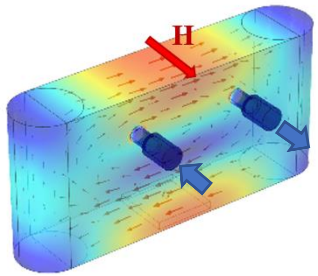


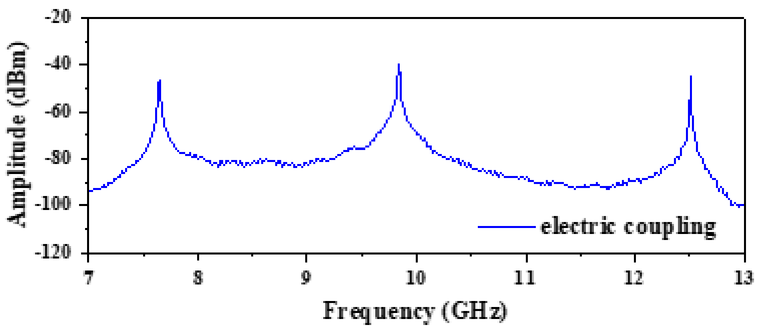
Cavity Lenz effect

$$\begin{pmatrix} \omega^2 - \omega_c^2 + i2\kappa_a\omega_c\omega & i\omega^2 K_F \\ -i\omega_m(K_A - K_L) & \omega - \omega_r + i\kappa_m\omega \end{pmatrix}\begin{pmatrix} I \\ M \end{pmatrix} = 0$$

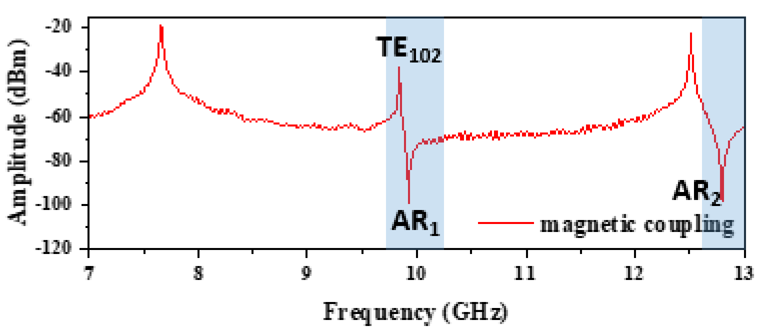
Investigation in dissipative regime of CMP hybrid system







Switch of antennas/probes



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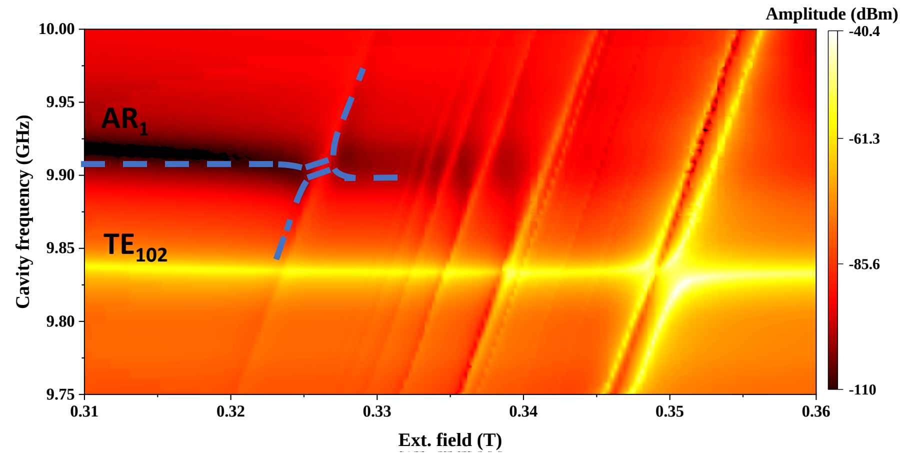

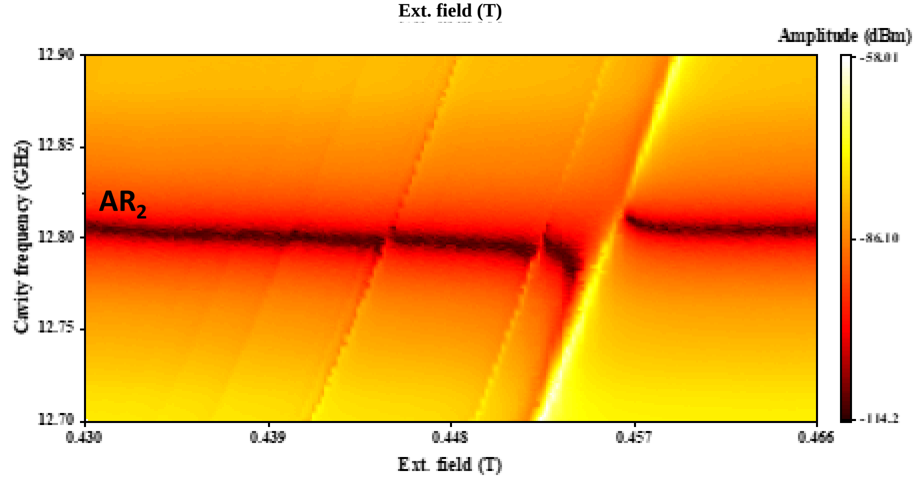

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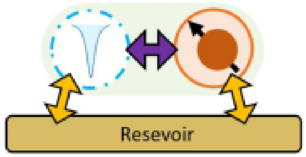
Leo et al. – *in preparation*

Investigation in dissipative regime of CMP hybrid system



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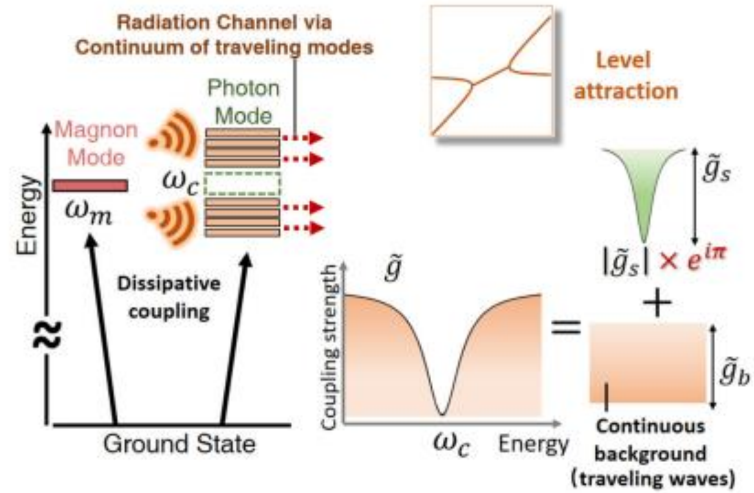
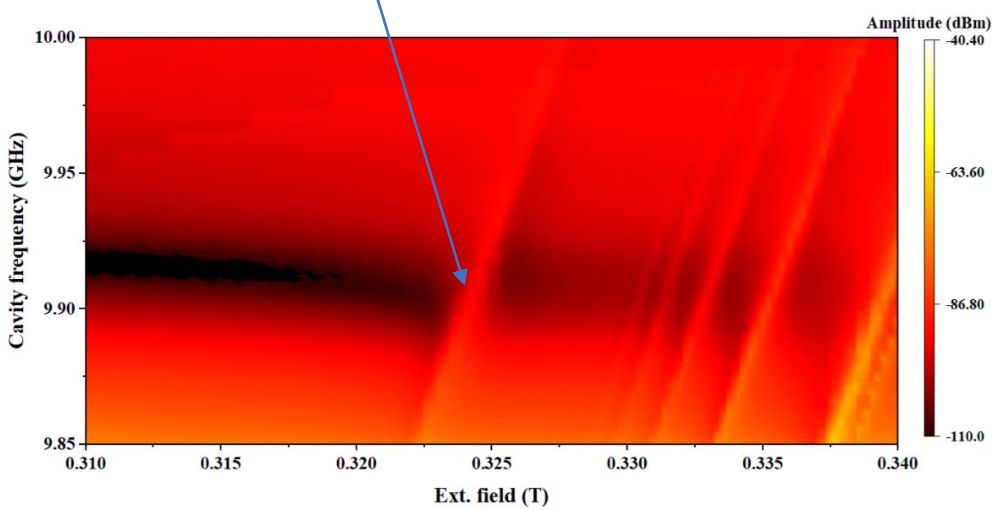
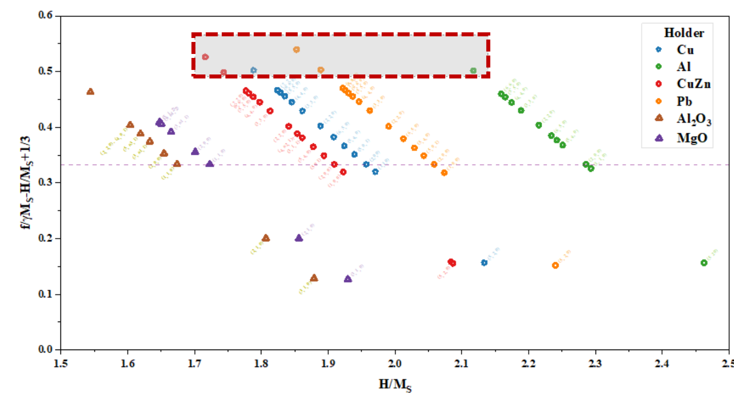


B. Yao et al., PRB (2019)

«Exceptional point»





«Topological energy transfer»

H. Xu et al., Nature 2016

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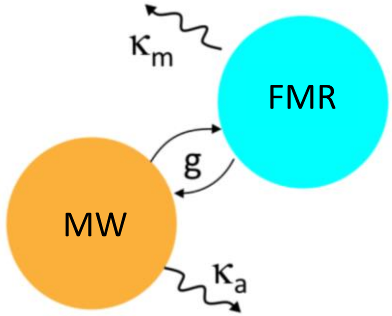
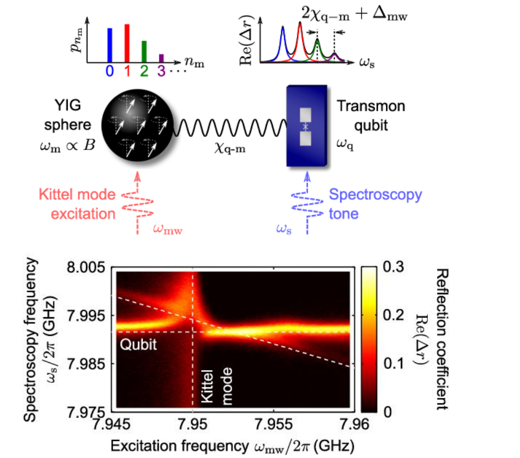
Leo et al. – *in preparation*

FMR-based information transducer and pespectives for QS



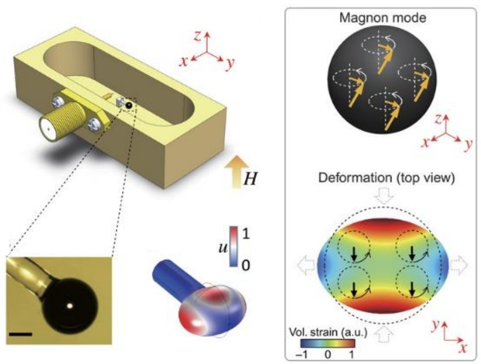
Low temperature



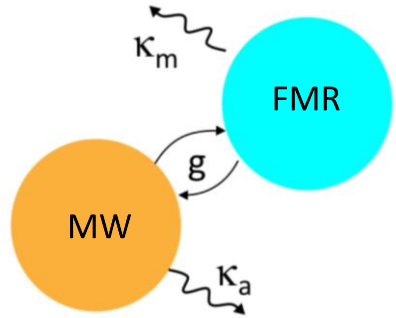
Lachance-Quirion et al., Science (2020)

FMR-based information transducer and pespectives for QS

Phononic coupling with magnons

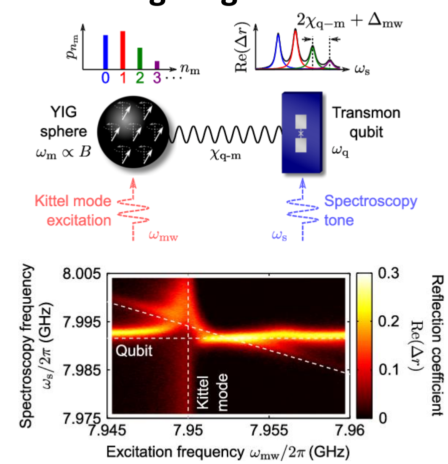


X. Zhang et al., Science Advances (2016)



Low temperature

Resolving magnon number



Lachance-Quirion et al., Science (2020)

FMR-based information transducer and pespectives for QS

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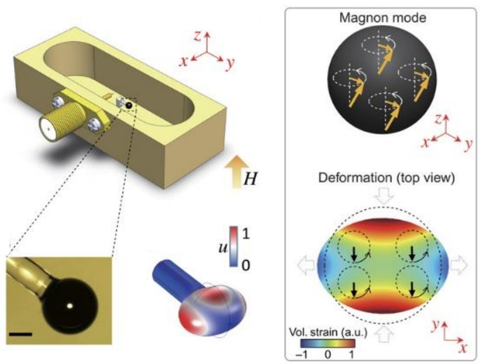
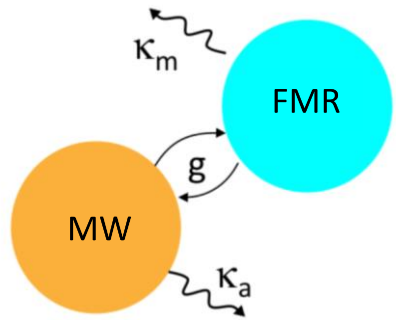


X. Zhang et al., Science Advances (2016)



Low temperature

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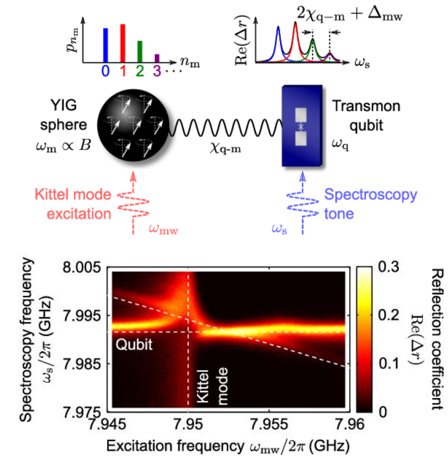
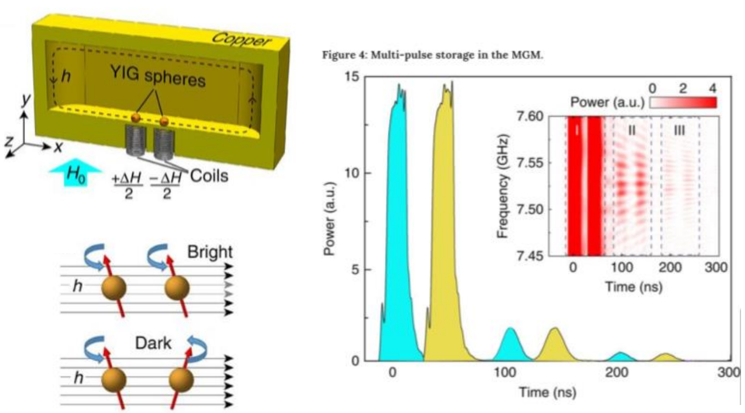


Lachance-Quirion et al., Science (2020)

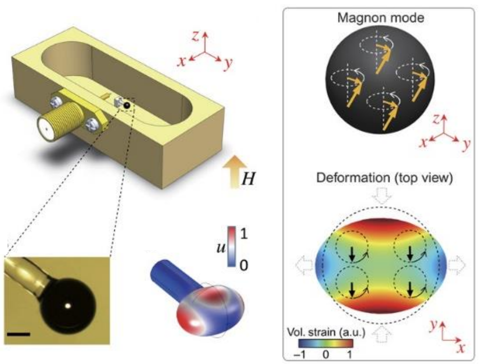
Magnon dark modes and gradient memories



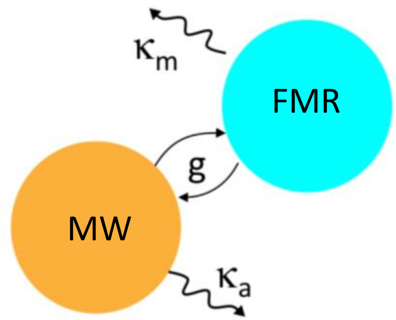
X. Zhang et al., Nature Comms (2015)

FMR-based information transducer and pespectives for QS

Phononic coupling with magnons

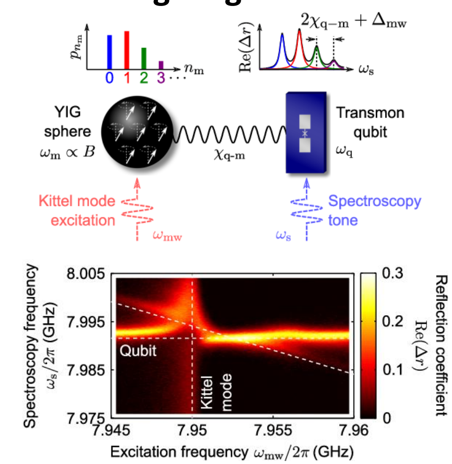


X. Zhang et al., Science Advances (2016)



Low temperature

Resolving magnon number



Lachance-Quirion et al., Science (2020)

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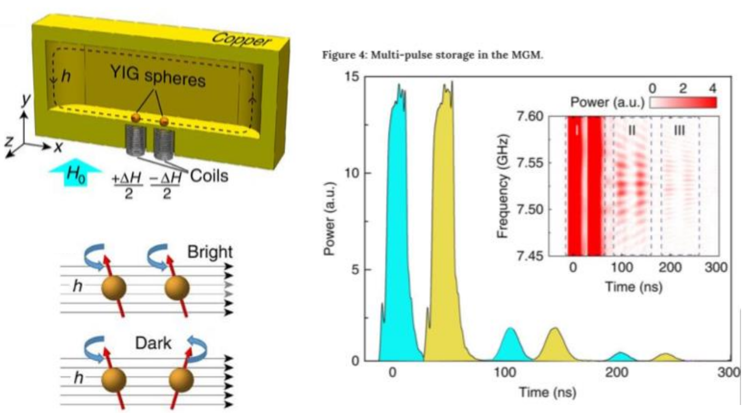
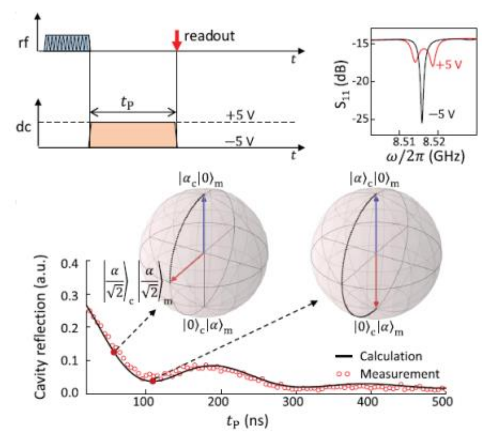


X. Zhang et al., Nature Comms (2015)

Gate operations



Xu et al, Phys. Rev. Lett. (2021)

FMR-based information transducer and pespectives for QS

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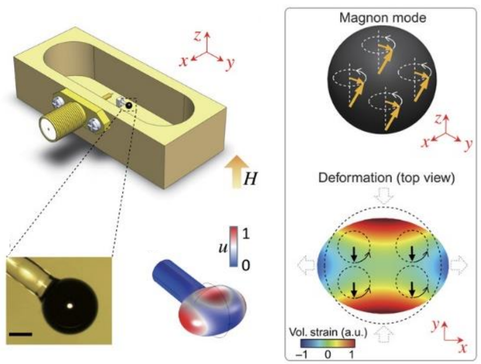
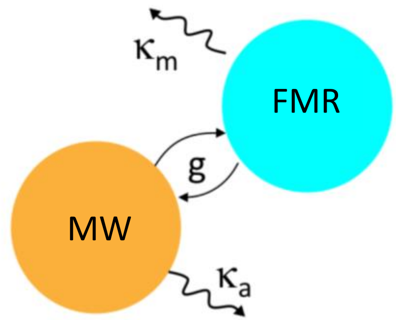


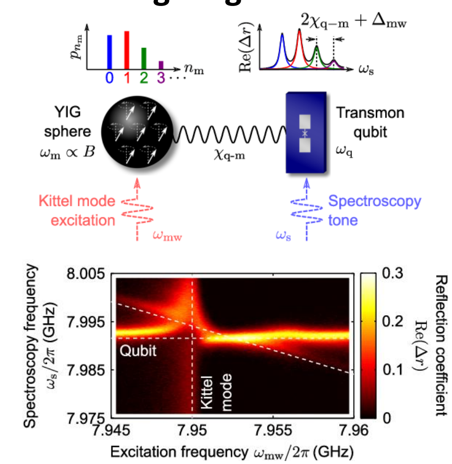
X. Zhang et al., Science Advances (2016)



Low temperature

Room temperature

Resolving magnon number



Lachance-Quirion et al., Science (2020)

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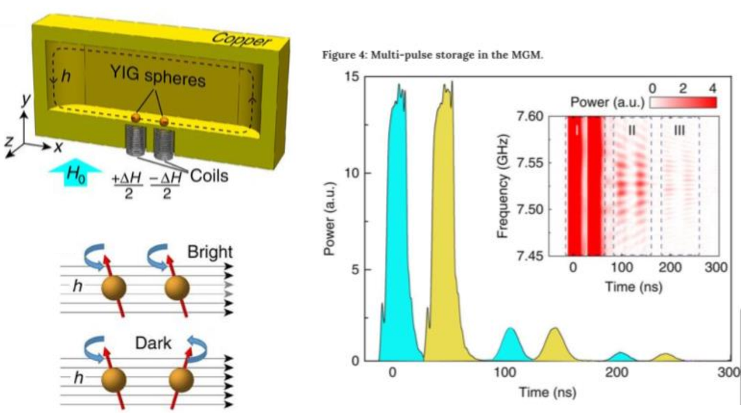

X. Zhang et al., Nature Comms (2015)

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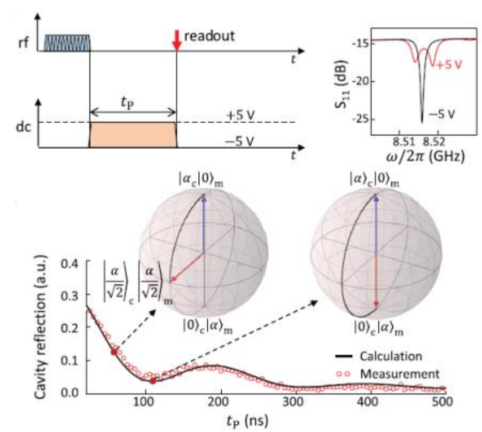
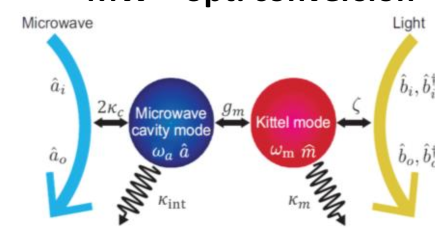
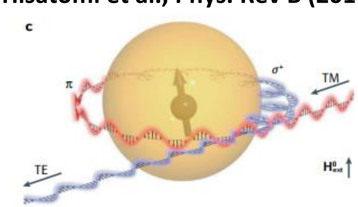


Xu et al, Phys. Rev. Lett. (2021)

MW – opt. conversion



Hisatomi et al., Phys. Rev B (2016)



Zhang et al., Phys. Rev Lett (2016)

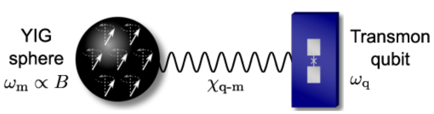
DARTWARS: Detector Array Readout with Traveling Wave AmplifieRS

DARTWARS project [INFN]:

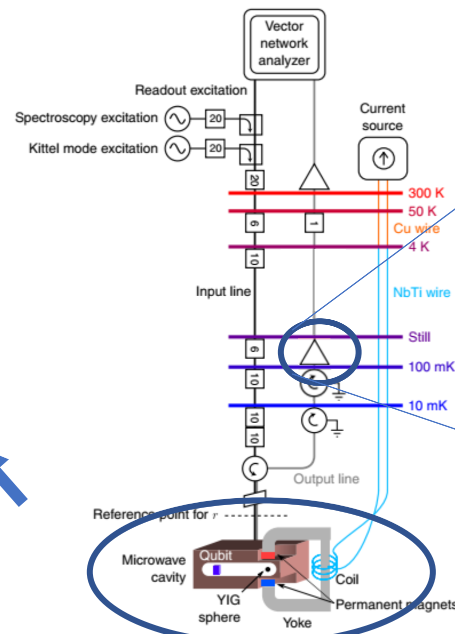
1. development of high-performance amplifiers – both KIT and TWJPA – optimizing design, new materials and fabrication processes

2. demonstration of readout of various detectors/devices with improved performances thanks to the amplification with added noise at the quantum level

[LE] higher-level investigation of cavity-magnon polaritons using DARTWARS KIT and TWJPA amplifiers



D. Lachance-Quirion et al., Science (2020)



Picture courtesy of INRiM

From **D. Lachance-Quirion et al., SciAdv (2018)**

UNIVERSITÀ DEL SALENTO INFN DART WARS DETECTOR ARRAY READOUT WITH TRAVELING WAVE AMPLIFIERS

Dilution Fridge – 10 mK