Identification, enhancement and time-resolved study of YIG spin wave modes in a MW cavity in strong coupling regime

Angelo Leo[a], Silvia Rizzato[b], Anna Grazia Monteduro[a,b], Giuseppe Maruccio[a,b]

[a] Mathematics and Physics Department "E. De Giorgi", University of Salento, Lecce, Italy
[b] INFN-Sezione di Lecce, Lecce, Italy

Giuseppe Maruccio
giuseppe.maruccio@unisalento.it

Spintronics Lab

- Cryogenic superconducting magnet (10.5 T, 0.3-300 K)
- Oxford dilution refrigerator (down to 10 mK, vector magnet 6T/1T/1T)
- Cryogenic RF probe station (down to 8 K and up to 0.5 T and 70 GHz).

Italian node of the European Infrastructure on Magnetism (funded within ISABEL project, H2020-INFRADEV-2018-2020, Grant No. 871106).

Giuseppe Maruccio
giuseppe.maruccio@unisalento.it

Magnonics

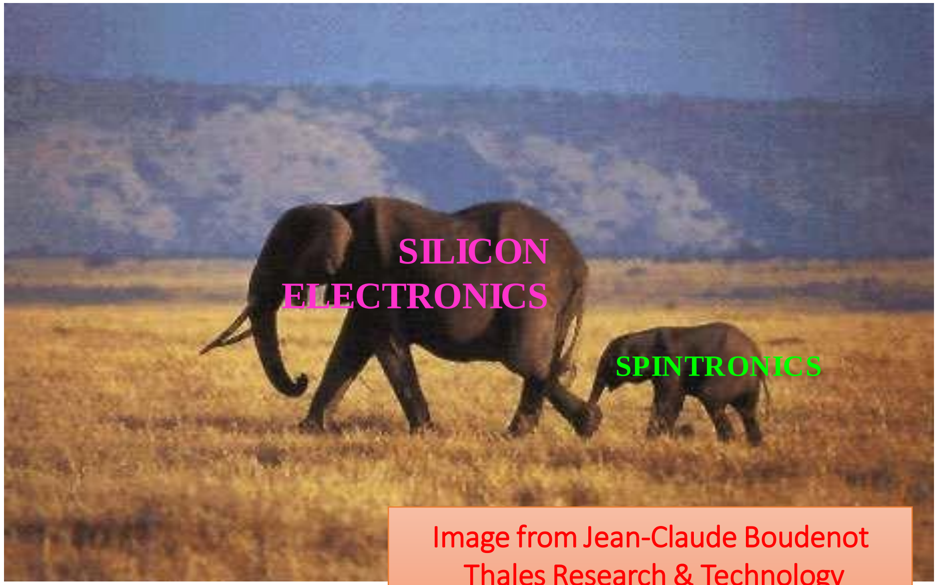
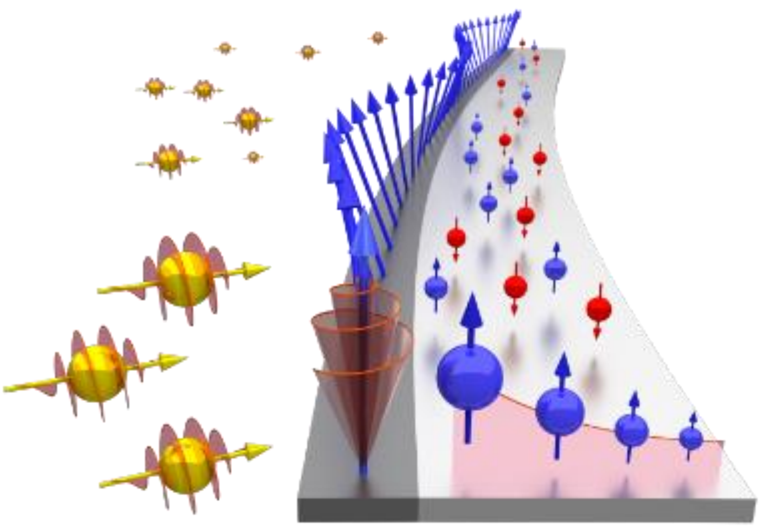
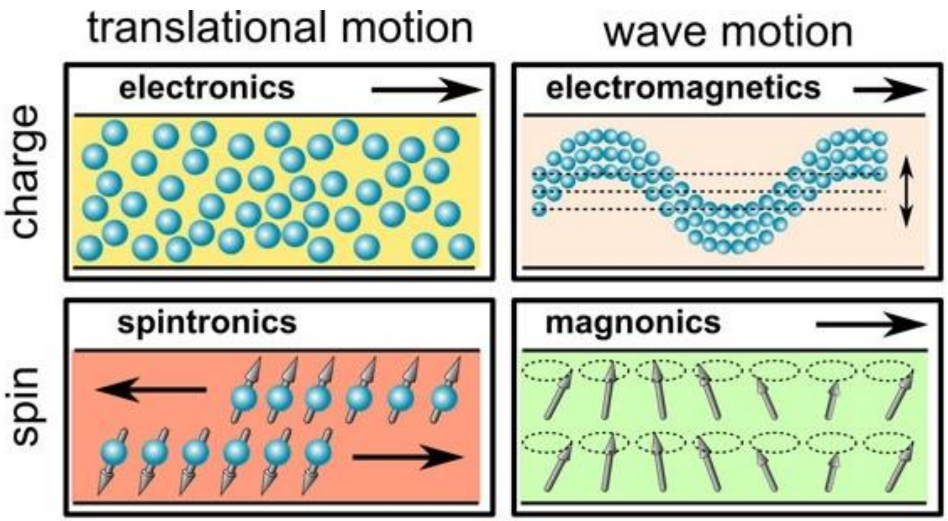


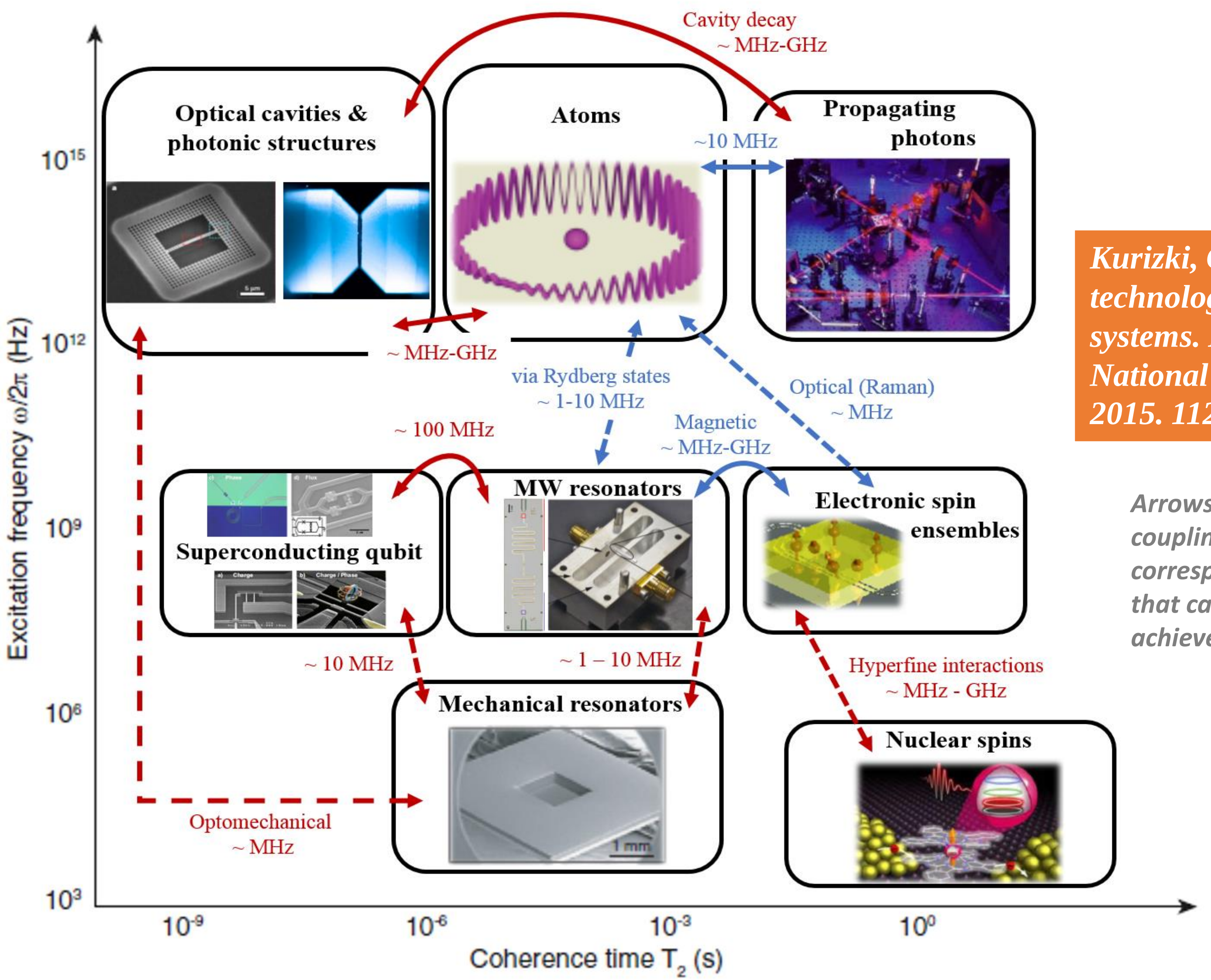
Image from Jean-Claude Boudenot
Thales Research & Technology





Giuseppe Maruccio
giuseppe.maruccio@unisalento.it

Towards quantum technologies with hybrid systems



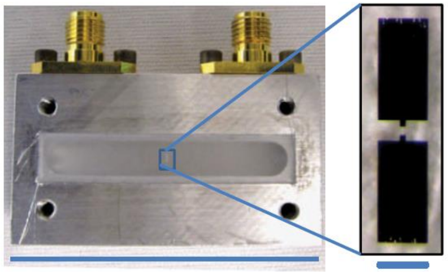
Kurizki, G., et al., Quantum technologies with hybrid systems. Proceedings of the National Academy of Sciences, 2015. 112(13): p. 3866-3873.

Arrows indicate possible coupling mechanisms and the corresponding coupling strength that can be realistically achieved.

Giuseppe Maruccio
giuseppe.maruccio@unisalento.it

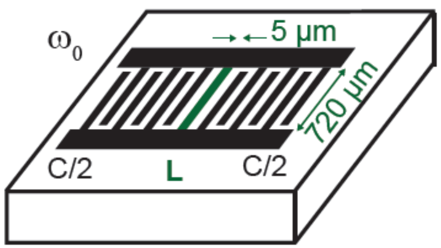
Cavity QED and hybrid systems for QC

SC / TRASMON

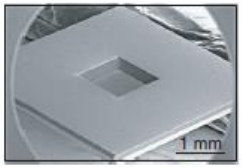


Paik et al, Phys Rev Lett (2011)

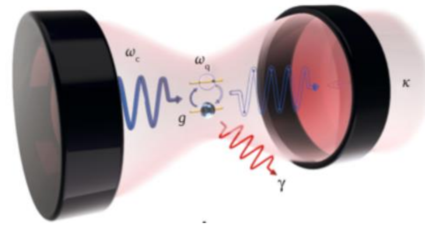
OMR / PHONONS



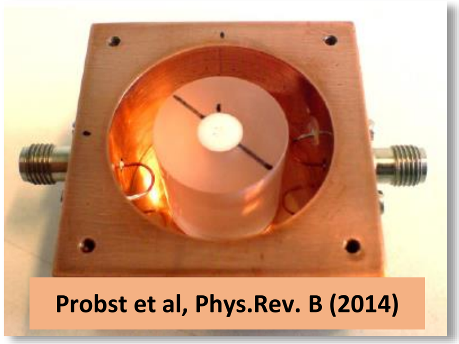
Bienfait et al, Nature Lett. (2016)



Yuan et al, Nature Comm. (2015)



3D MW Cavities

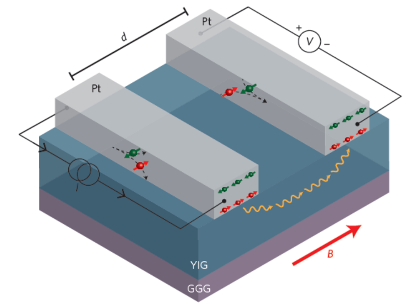


Probst et al, Phys.Rev. B (2014)

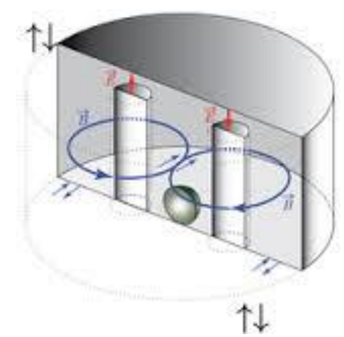
PARAMAGN. SPIN ENSEMBLES

Putz et al, Nature Physics (2014)

FM MATERIALS



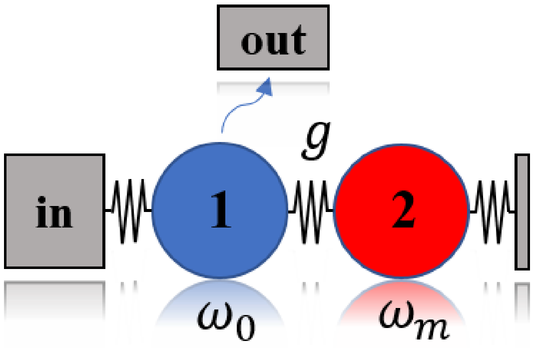
Cornelissen et al, Nature Physics (2015)



Goryachev et al, Phys Rev App (2014)

UNIVERSITÀ DEL SALENTO
CNR NANOTEC
INFN Istituto Nazionale di Fisica Nucleare
OMNICS group
Giuseppe Maruccio
giuseppe.maruccio@unisalento.it

Magnon-Photon coupling



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:

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

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:

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

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

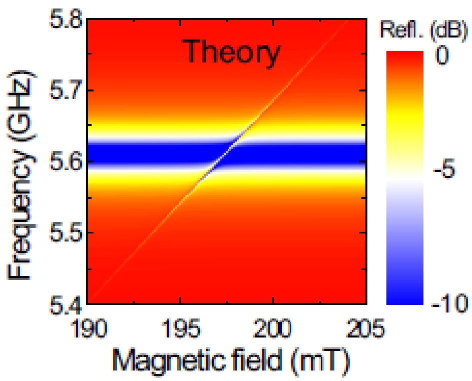
Overlap among subsystems:

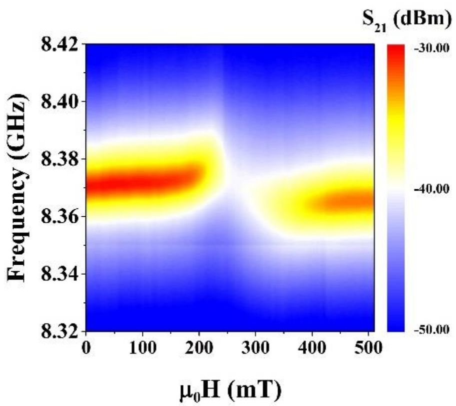
$$\eta = \int_{V_m}^{0} \frac{\vec{h}\cdot\vec{M}}{|\vec{h}_{max}||\vec{M}_{max}|}\, dV \le 1$$

Giuseppe Maruccio
giuseppe.maruccio@unisalento.it

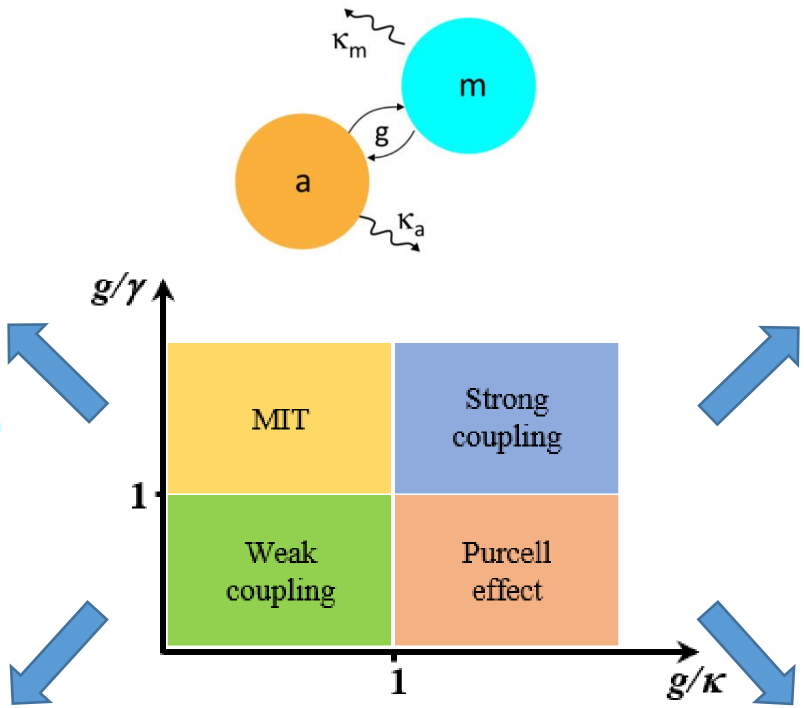
Magnon-Photon Coupling Regimes

Zhang et al, Phys Rev Lett (2014)

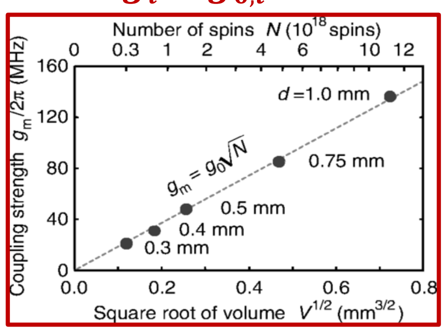




Mn_2FeO_4 NPs in a low Q cavity (Unisalento)

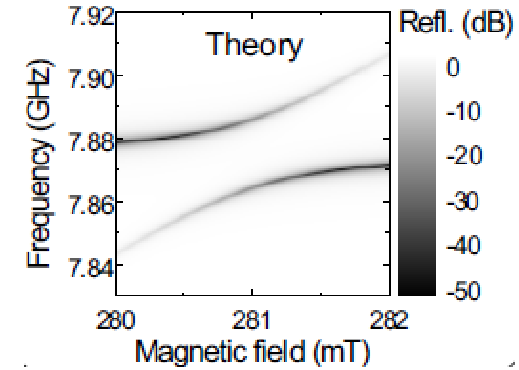


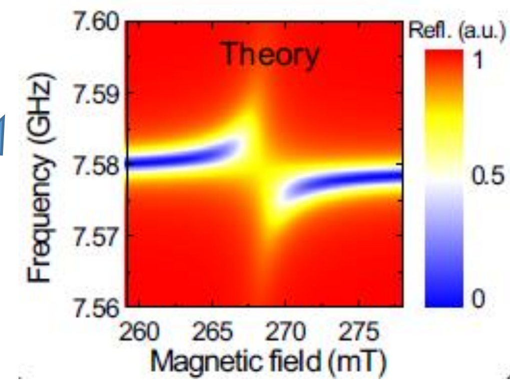
$$g_i = g_{0,i}\sqrt{Ns}$$



Y. Tabuchi et al. PRL (2014)

Zhang et al, Phys Rev Lett (2014)





Zhang et al, Phys Rev Lett (2014)

UNIVERSITÀ DEL SALENTO
CNR NANOTEC
INFN Istituto Nazionale di Fisica Nucleare
OMNICS group
Giuseppe Maruccio
giuseppe.maruccio@unisalento.it

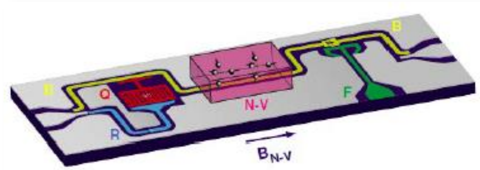
Increasing coupling via spin density (&YIG)

Paramagnetic spin ensembles

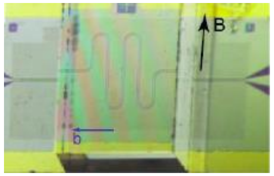
NV- centers in diamond

Rare-earth doped crystal

Putz *et al., Nature Physics* 10, 720–724 (2014)

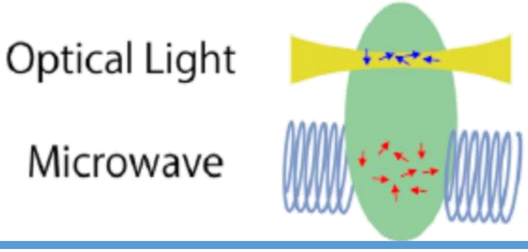


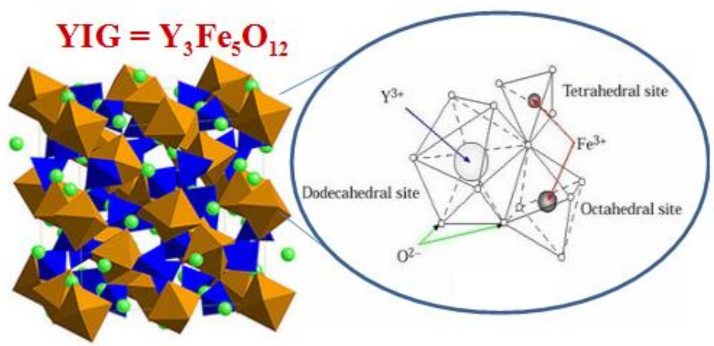
Kubo et al. PRL 107, 220501 (2011)



Bushev et al. PRB 84, 060501(R) (2011)

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





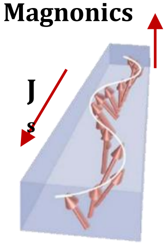
Microwave oscillator

CANDOX Corp.

Optical isolator

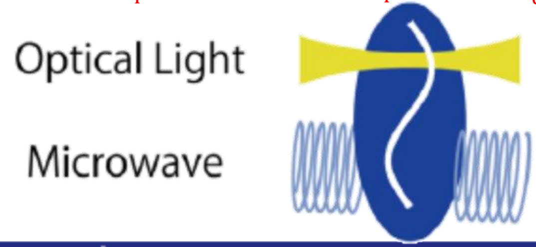
FDK Corp.

Spintronics/ Magnonics



Kajiwara et al. doi:10.1038/nature08876

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

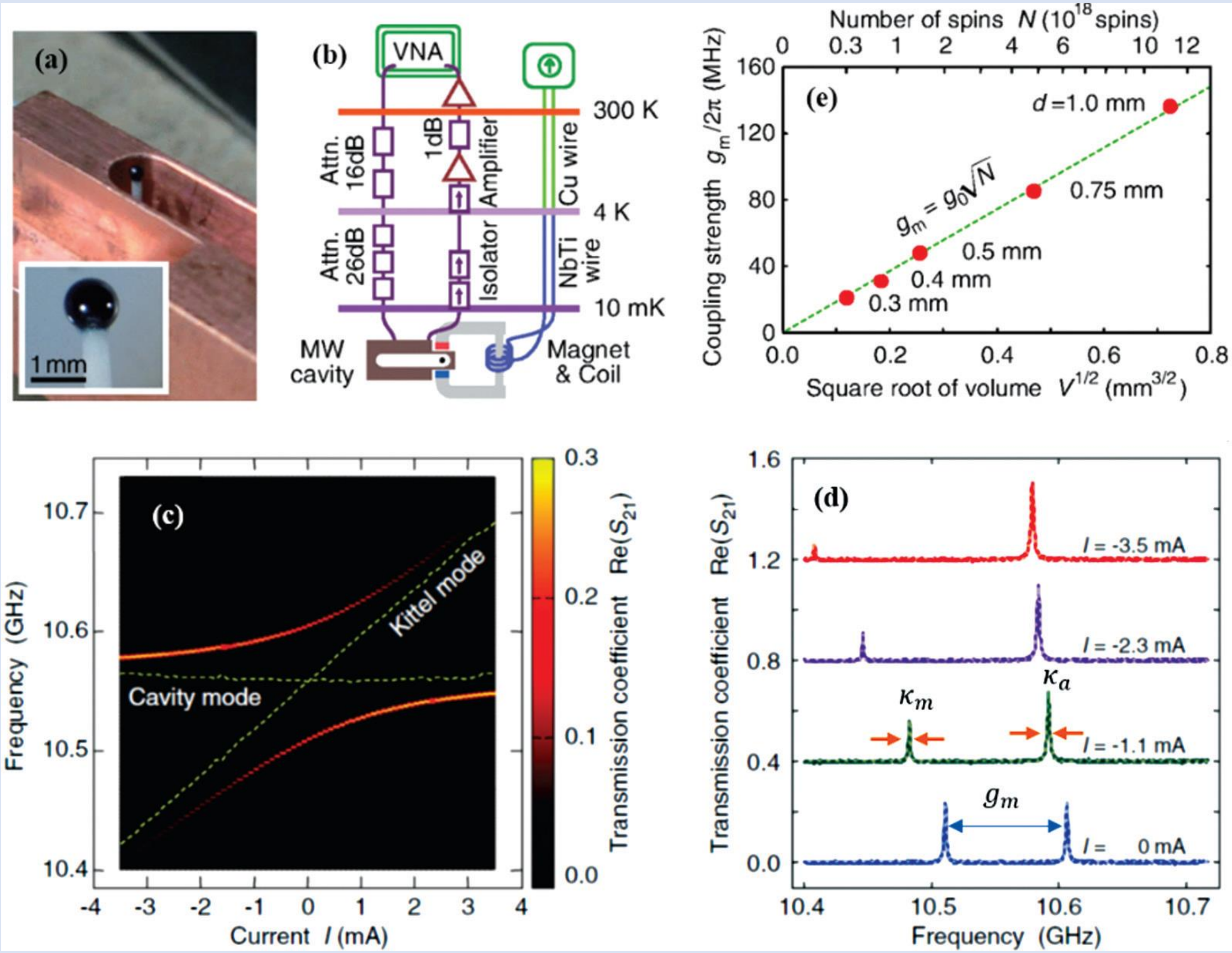


Strong Coupling

& very low damping

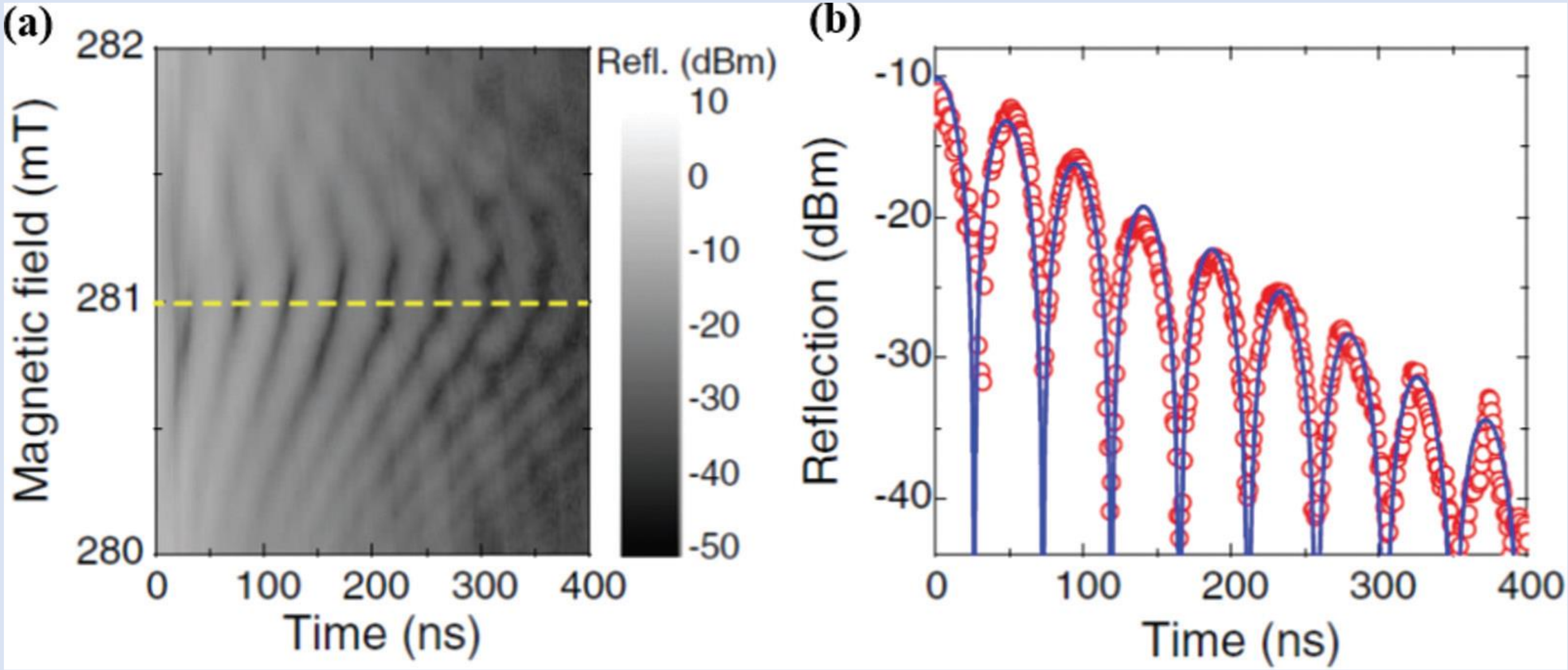
UNIVERSITÀ DEL SALENTO
CNR NANOTEC
INFN Istituto Nazionale di Fisica Nucleare
OMNICS group
Giuseppe Maruccio
giuseppe.maruccio@unisalento.it

Strong Coupling & exp. setup



Y. Tabuchi, S. Ishino, T. Ishikawa, R. Yamazaki, K. Usami and Y. Nakamura (2014). Hybridizing ferromagnetic magnons and microwave photons in the quantum limit, *Physical review letters*, **113**(8): 083603.

Rabi-like oscillations



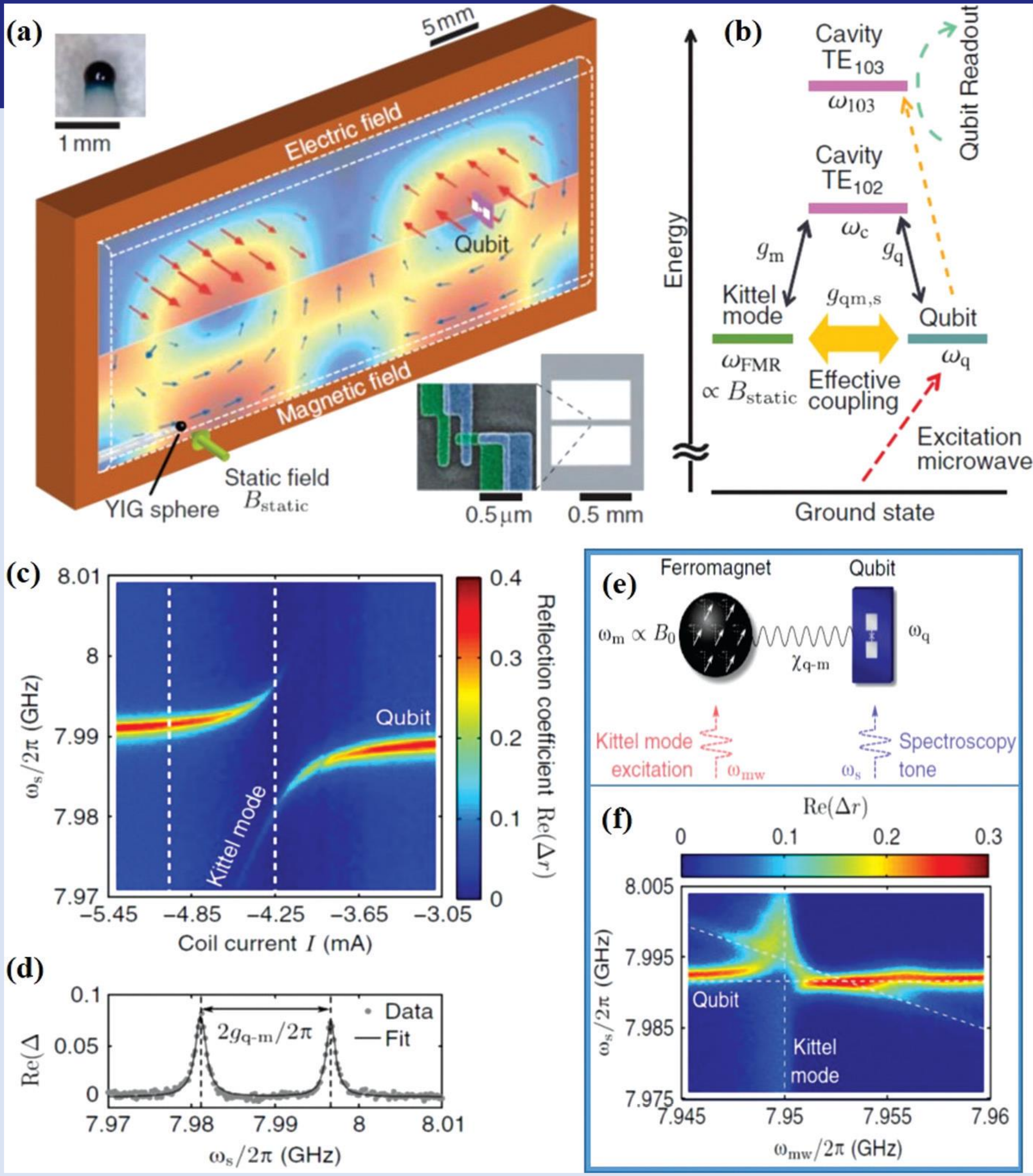
(a) Evolution of the cavity response after a pulsed signal modulated at cavity's eigenfrequency as a function of bias magnetic field. (b) Measured Rabi-like oscillation signal at bias magnetic field such that YIG FMR occurs.

X. Zhang, C.-L. Zou, L. Jiang and H. X. Tang (2014). Strongly coupled magnons and cavity microwave photons, Physical review letters, 113(15): 156401.

Giuseppe Maruccio
giuseppe.maruccio@unisalento.it

Coupling with trasmons

hybrid system in the strong dispersive regime, composed by an FM crystal, a superconducting transmon, and a 3D MW cavity



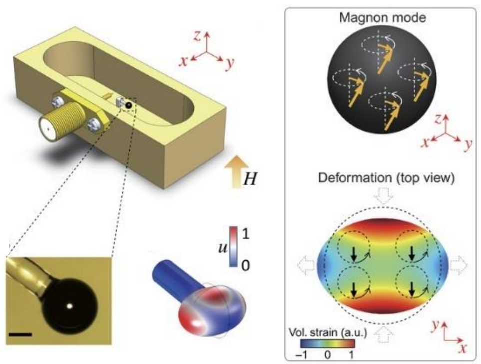
Y. Tabuchi, S. Ishino, A. Noguchi, T. Ishikawa, R. Yamazaki, K. Usami and Y. Nakamura (2015). Coherent coupling between a ferromagnetic magnon and a superconducting qubit, Science, 349(6246): 405–408.

D. Lachance-Quirion, Y. Tabuchi, S. Ishino, A. Noguchi, T. Ishikawa, R. Yamazaki and Y. Nakamura (2017). Resolving quanta of collective spin excitations in a millimeter-sized ferromagnet, Science advances, 3(7): e1603150.

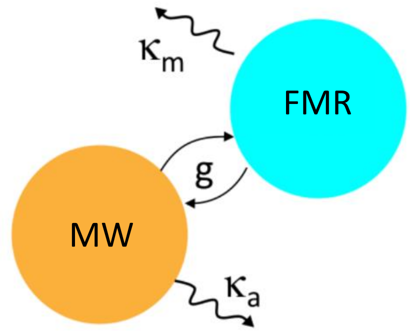
Giuseppe Maruccio
giuseppe.maruccio@unisalento.it

Cavity Magnonics with YIG

Phononic coupling with magnons



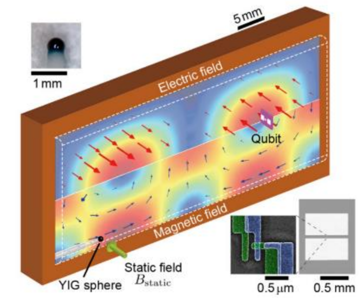
X. Zhang et al, Science Advances (2016)



Room temperature

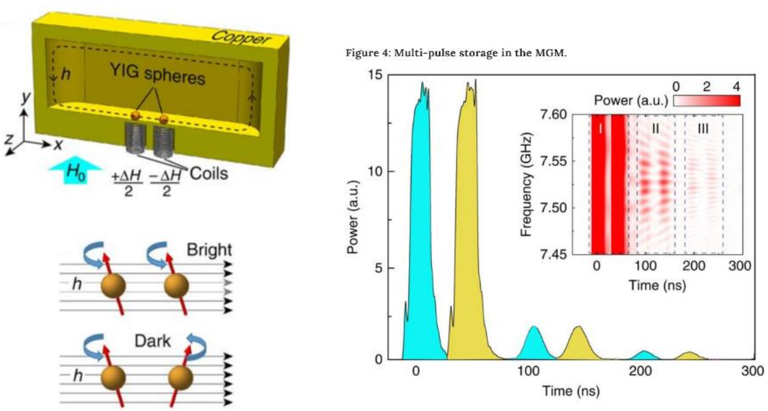
Low temperature

Coupling with transmon



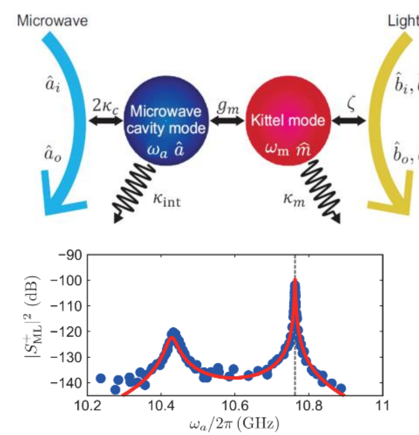
Tabuchi et al, Science (2015)

Magnon dark modes and gradient memories



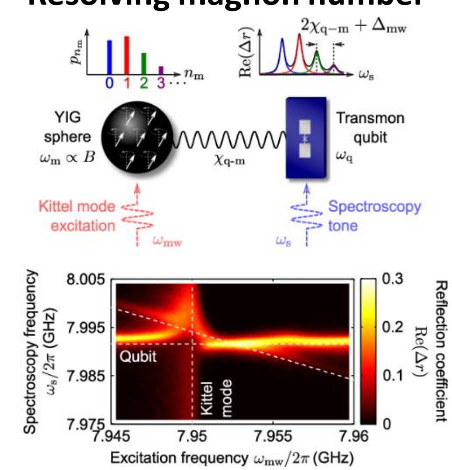
X. Zhang et al, Nature Comms (2015)

MW – opt. conversion



Hisatomi et al, Phys. Rev B (2016)

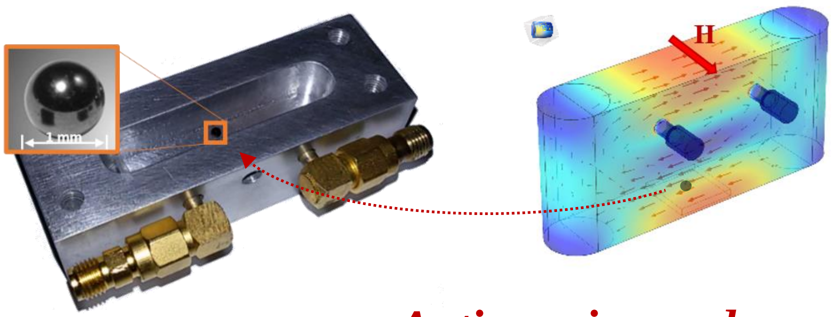
Resolving magnon number

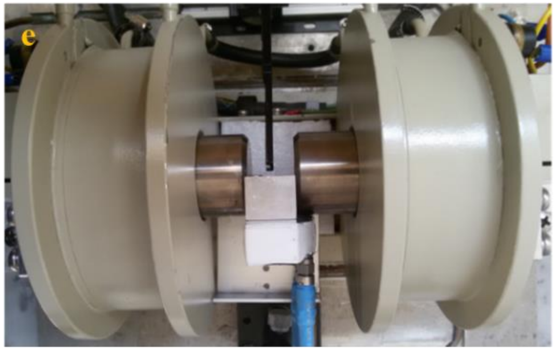


Lalanche-Quirion et al, Science Advances (2017)

A. Leo et al., Strong coupling in Cavity magnonics, in Three-dimensional Magnonics (ed. G. Gubbiotti)
ISBN 9789814800730

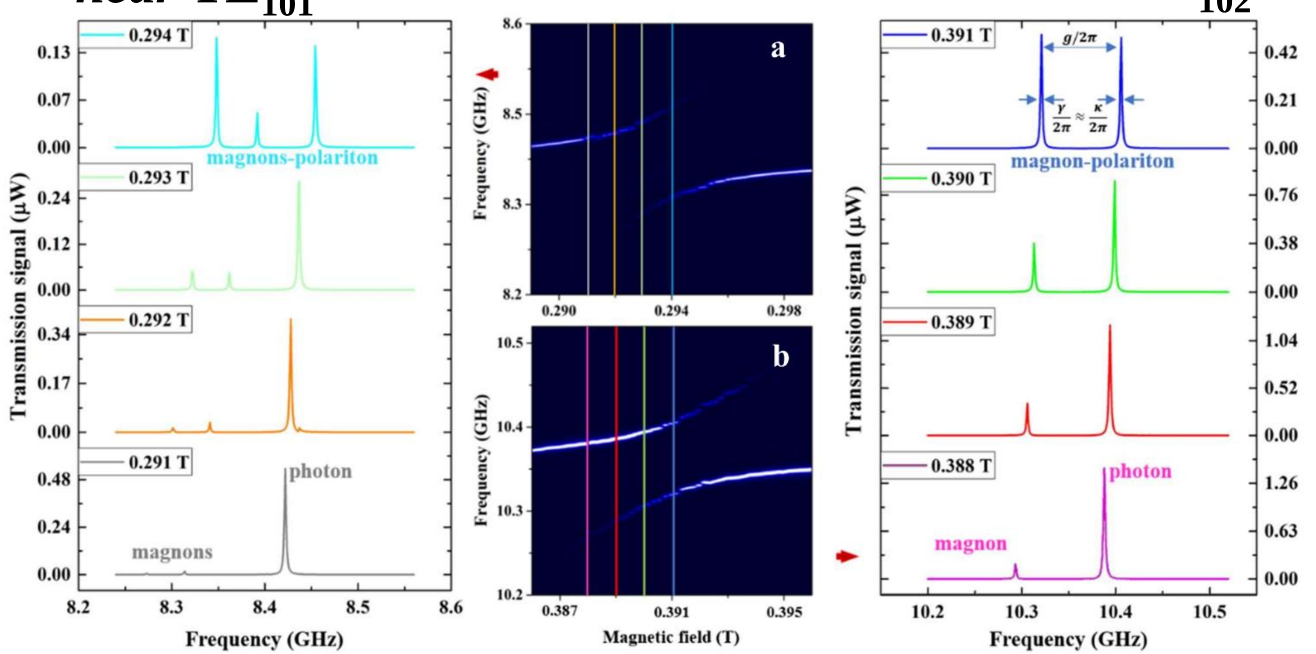
Strong coupling fingerprints (1/2)



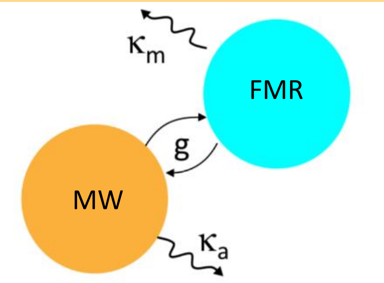


Anticrossing and magnon-polaritons

near **TE_{101}** ***near*** **TE_{102}**



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



Cavity mode at:
ω_c
Total cavity decay rate:
$\kappa_c = \frac{1}{2}\left(2\kappa_{i,o} + \kappa_{int}\right)$

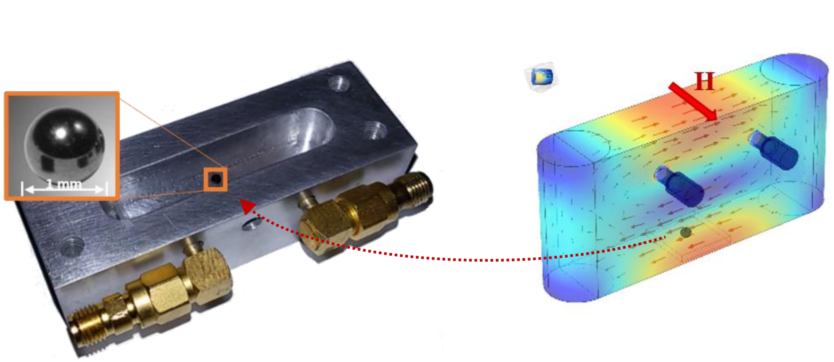
Coupling strength
g_m (m = FMR, MSMs)

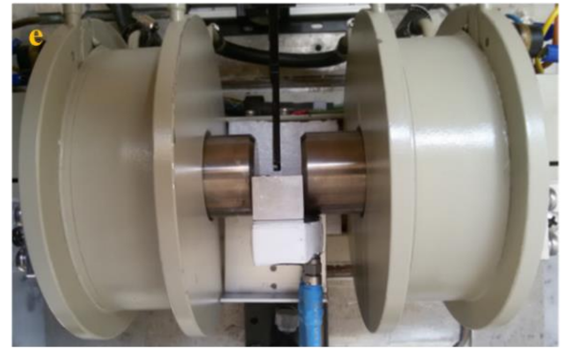
Strong coupling between fundamental mode in the YIG sphere and the TE_{101} and TE_{102} cavity modes.

Giuseppe Maruccio
giuseppe.maruccio@unisalento.it

Leo et al.
Phys Rev B, 2020

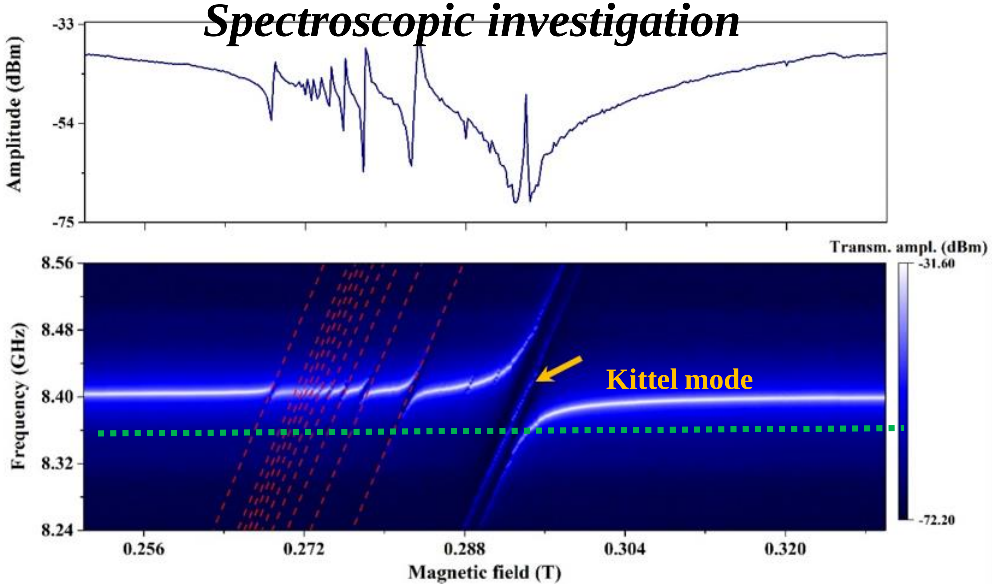
Strong coupling fingerprints and MSMs





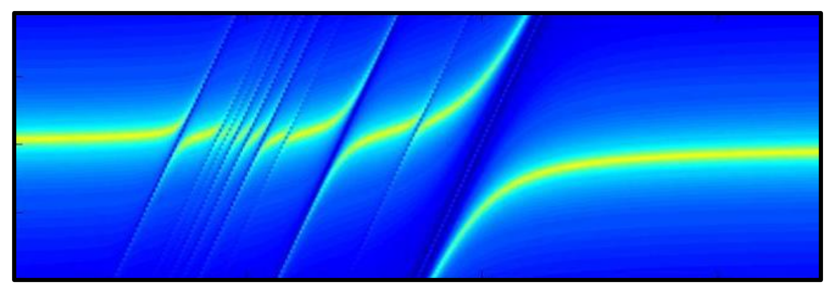
Rich spectrum with MSMs

Spectroscopic investigation



input-output formalism

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



Giuseppe Maruccio
giuseppe.maruccio@unisalento.it

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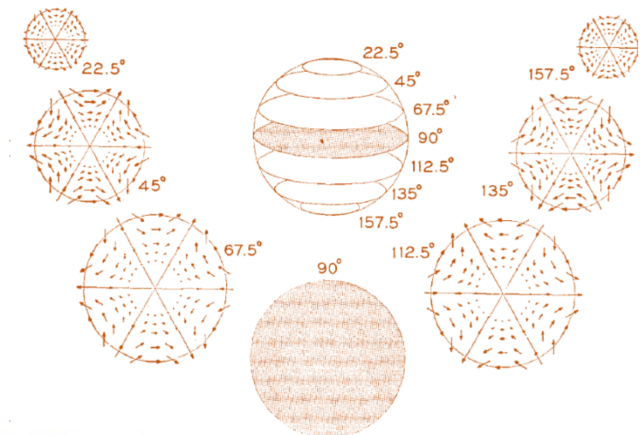
Magnetostatic modes of a sphere

Characteristic equation in associated Legendre functions P_n^m for ***MSMs in spheroids*** within MW cavity working at frequency $f = \omega_c/2\pi$

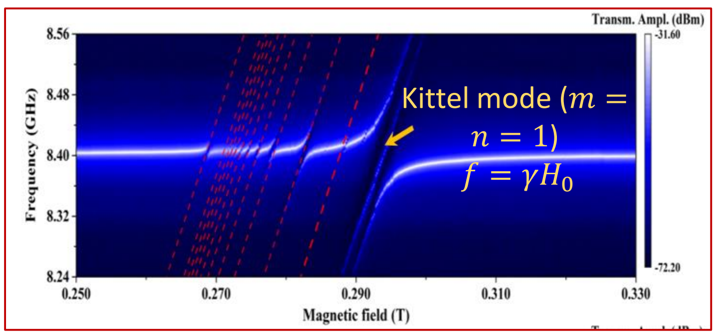
$$n + 1 + \xi_0 \frac{P_n^{m\prime}(f, H_0)}{P_n^m(f, H_0)} \pm m \frac{\gamma f M_S}{\gamma^2 {H_i}^2 - f^2} = 0$$

$$\frac{f}{\gamma M_S} - \frac{H_{0,mm}}{M_S} + \frac{1}{3} = \frac{m}{2m+1} \qquad (n = m)$$

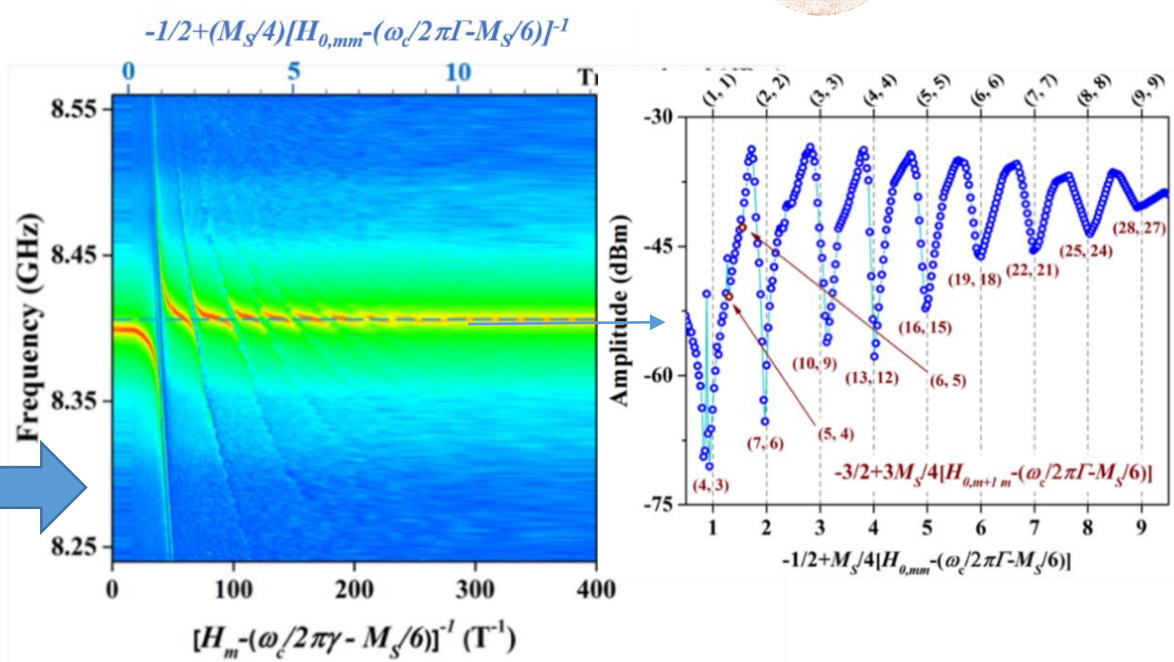
$$\frac{f}{\gamma M_S} - \frac{H_{0,m(m+1)}}{M_S} + \frac{1}{3} = \frac{m}{2m+3} \qquad (n = m + 1)$$



Proposed strategy:
introduce functional plot variable:



rescaled by using: $\gamma \approx 28.76$ GHz/T
$M_S \approx 0.176$ T



Giuseppe Maruccio
giuseppe.maruccio@unisalento.it
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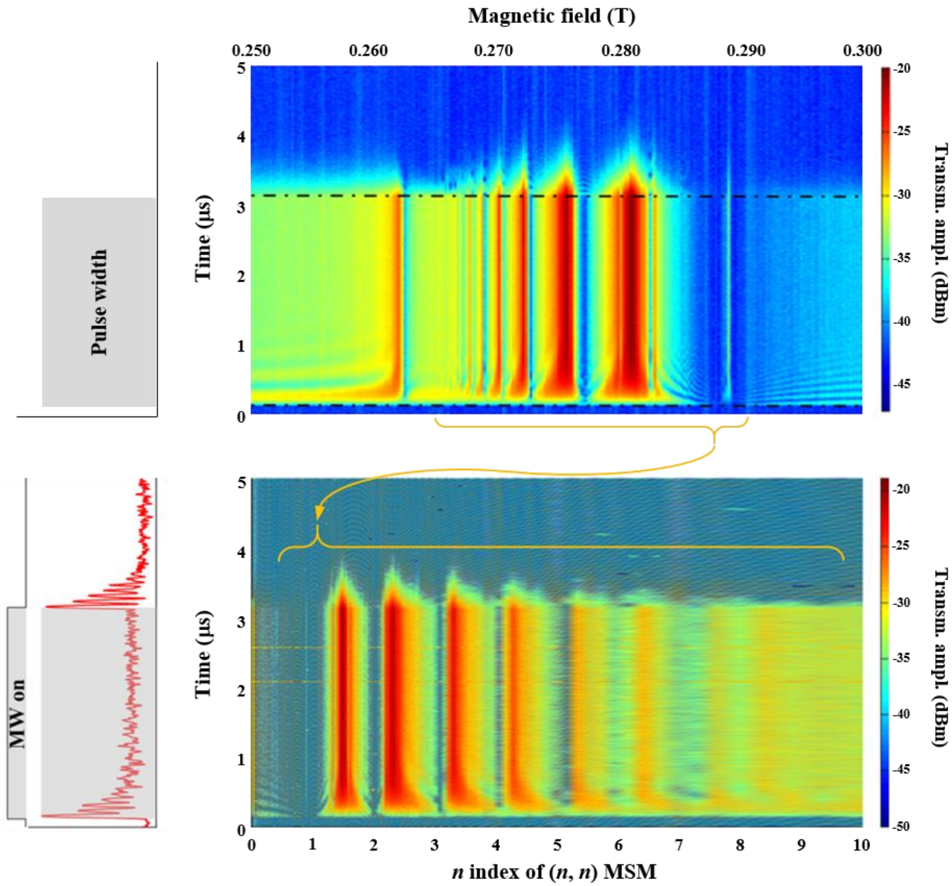
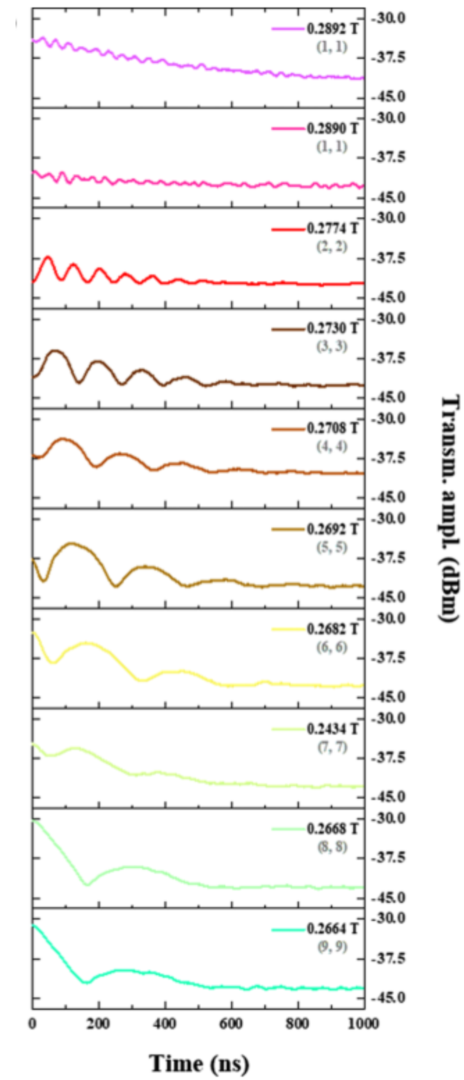
Strong coupling fingerprints (2/2)

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

Coupling among resonators **MW cavity relaxation**



Cavity relaxation @ CMP formation



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CNR NANOTEC
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Giuseppe Maruccio
giuseppe.maruccio@unisalento.it

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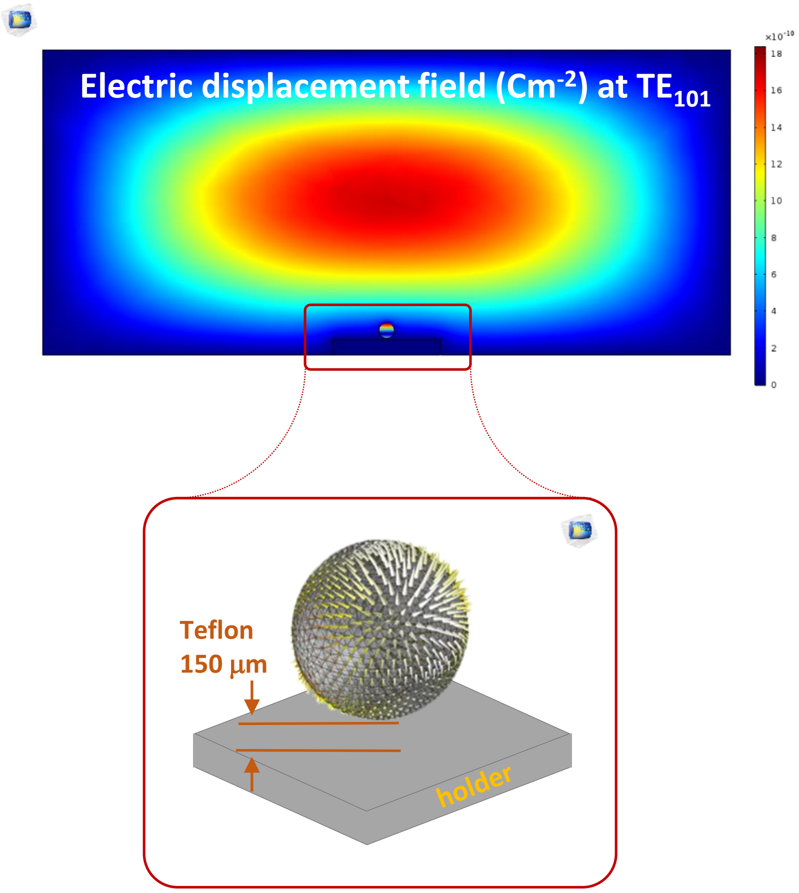
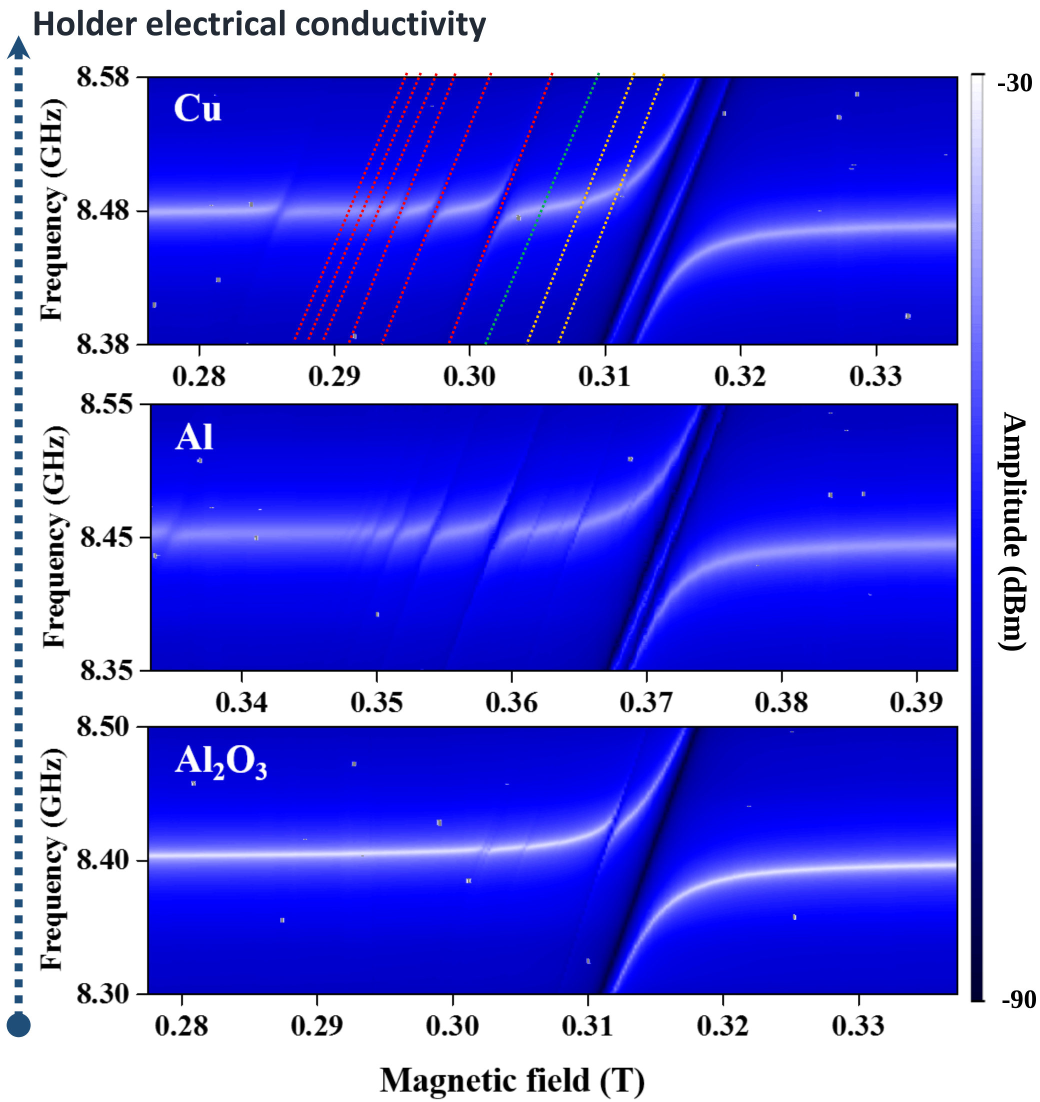
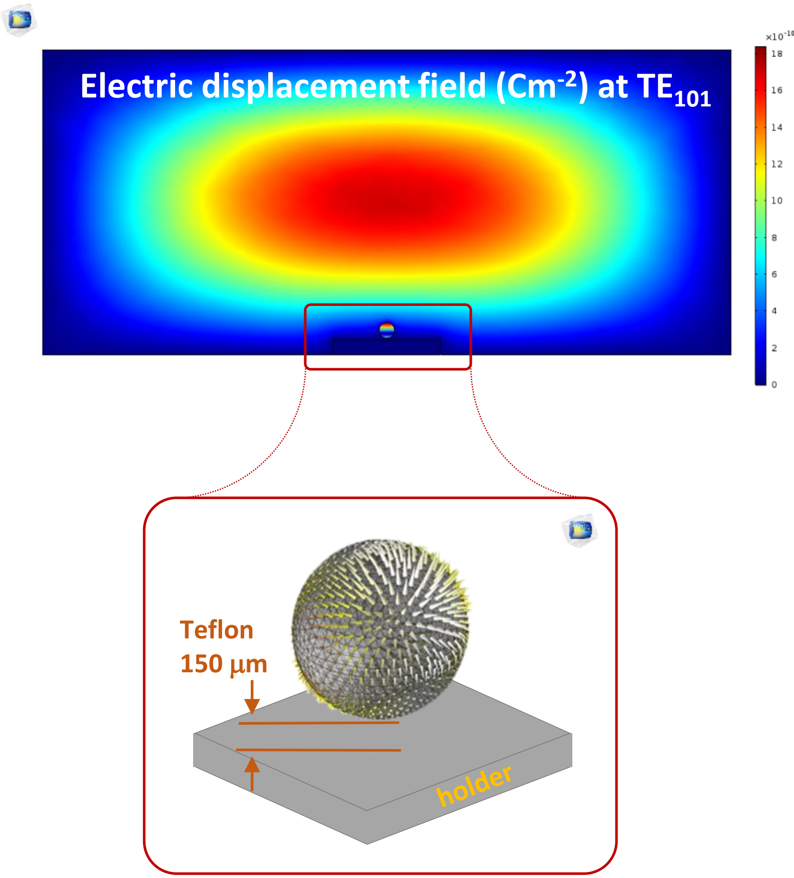
Enhancement of coupling features

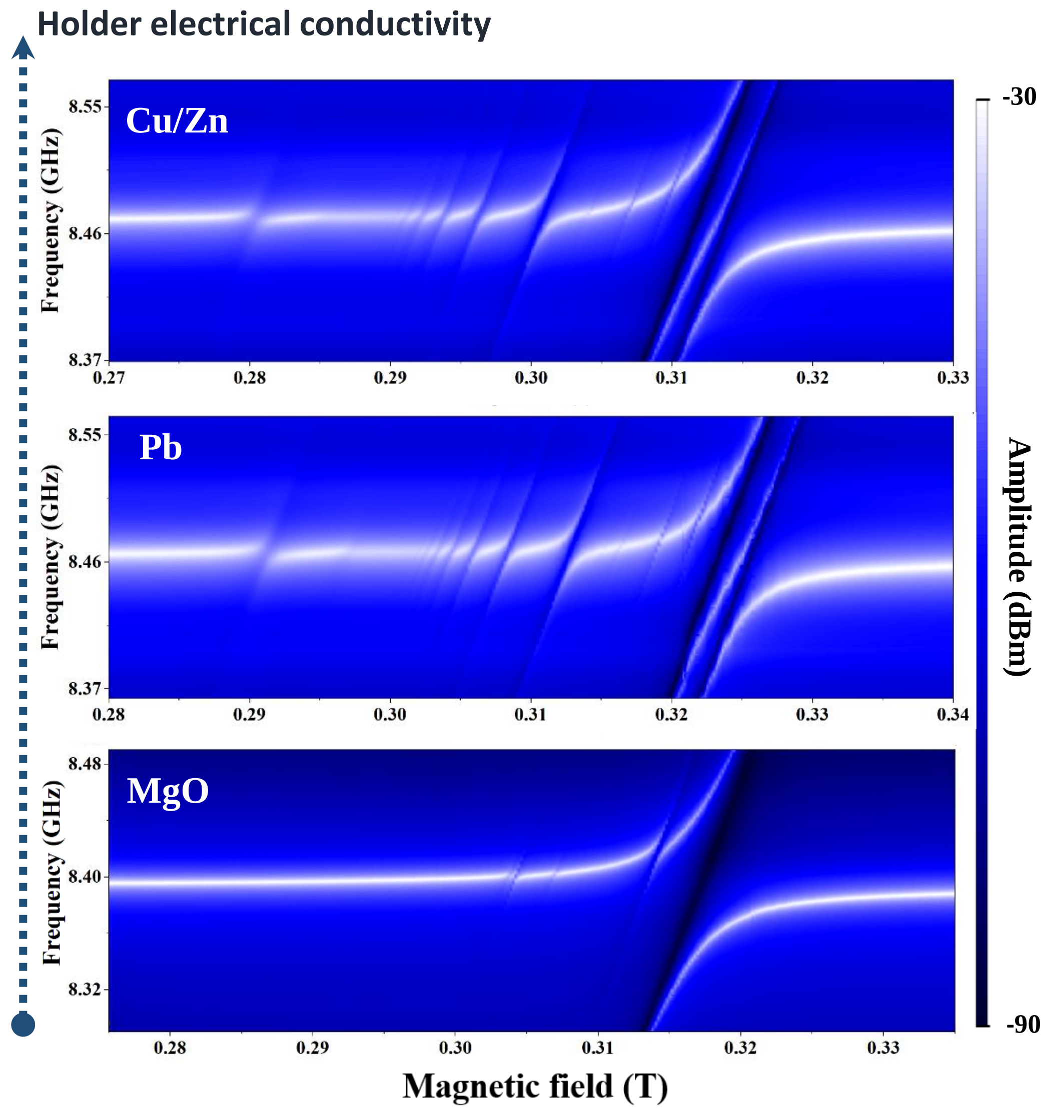




Giuseppe Maruccio
giuseppe.maruccio@unisalento.it

Enhancement of coupling features





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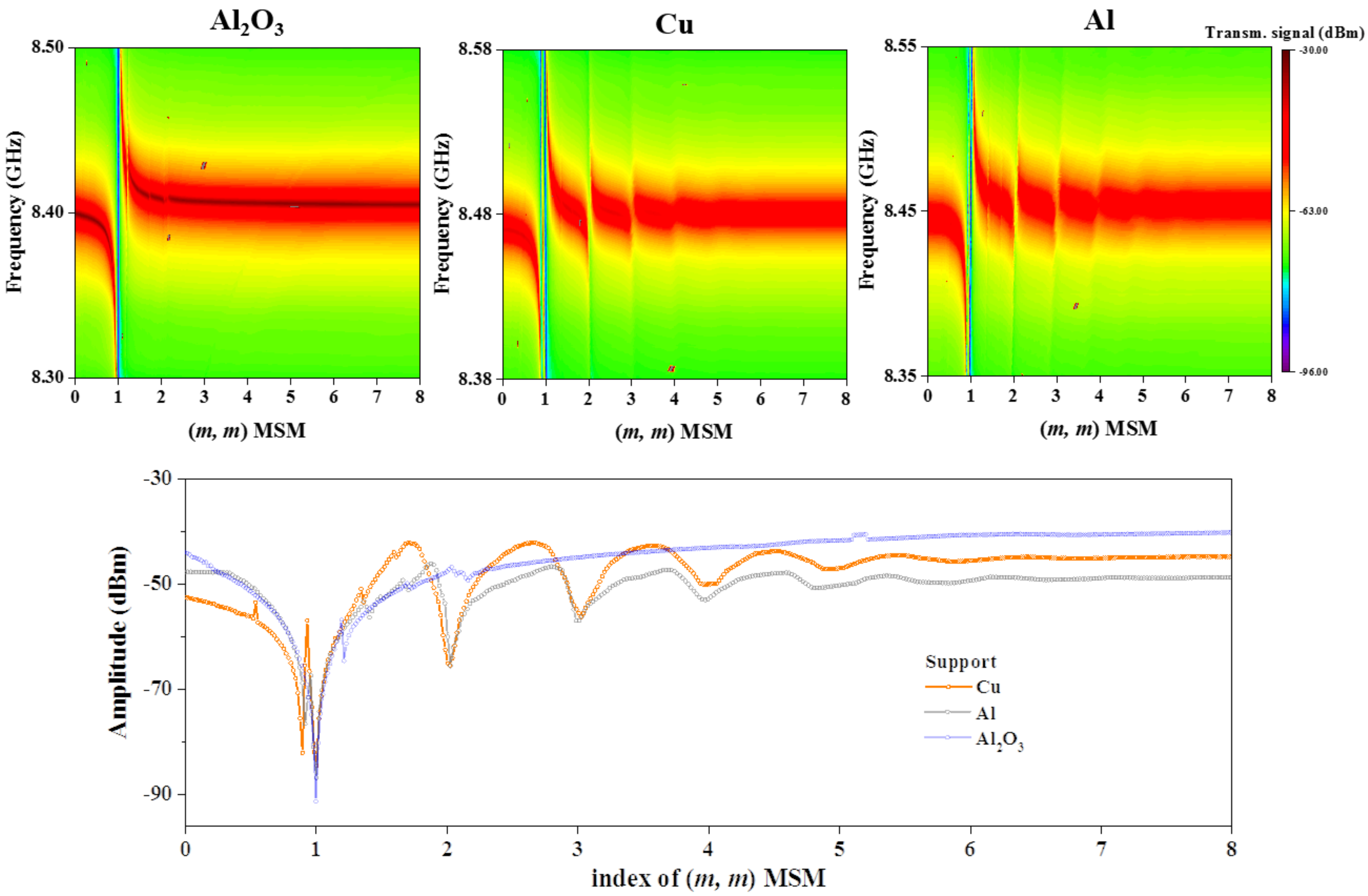
giuseppe.maruccio@unisalento.it

Enhancement of coupling features



Giuseppe Maruccio
giuseppe.maruccio@unisalento.it