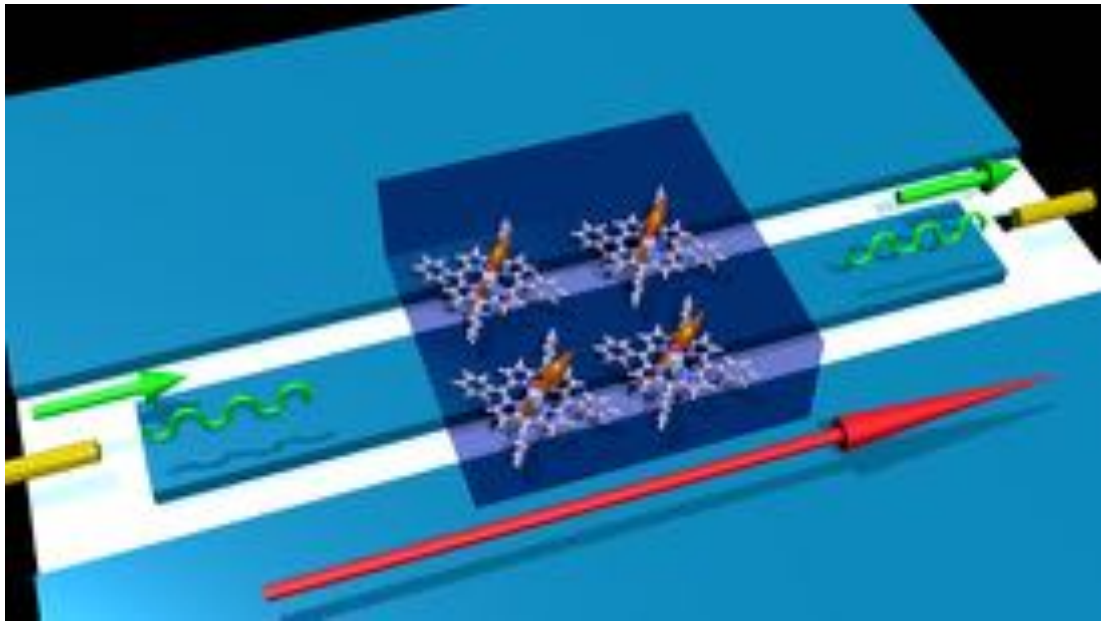
Detection of magnetic excitations for axion's search

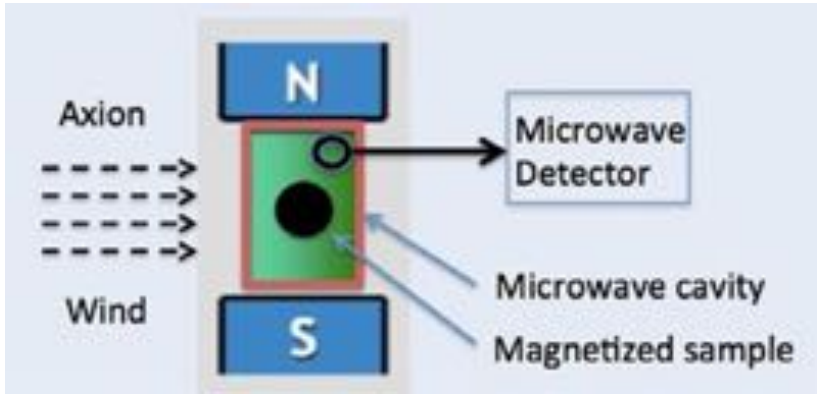




Marco Affronte, Claudio Bonizzoni, Dr. Maksut Maksutoğlu*, Alberto Ghirri
Università di Modena and Reggio Emilia &
CNR Institute Nanoscience S3 Italy
* TUBITAK grant, Gebze T.U.

Basic assumption: Axion to magnon conversion

R. Barbieri, M. Cerdonio, G. Fiorentini, S. Vitale, Phys. Lett B 226, 357 (1989)



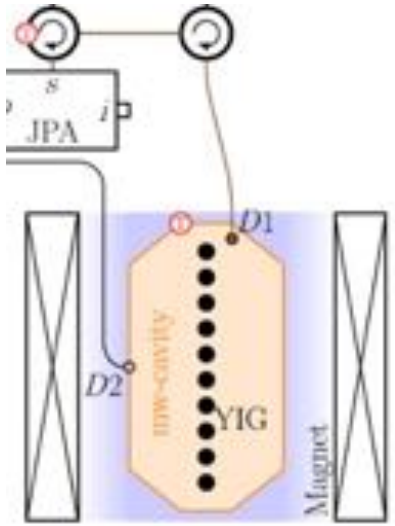
$$\mathcal{L}_{ae} \simeq -2\mu_B \boldsymbol{\sigma} \cdot \left(\frac{g_{aee}}{2e}\right) \nabla a \equiv -2\mu_B \boldsymbol{\sigma} \cdot \mathbf{B}_a.$$

$$B_a = \frac{g_{aee}}{2e} \sqrt{\frac{n_a \hbar}{m_a c}} m_a v_a \simeq 4 \times 10^{-23} \left(\frac{m_a}{42\ \mu\text{eV}}\right)\ \text{T},$$

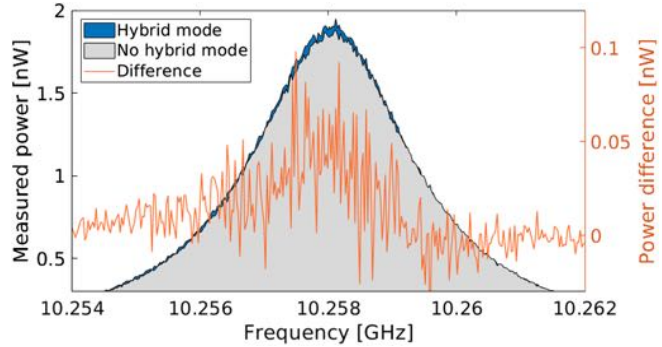
$$P_a = \gamma_e \mu_B N_s \omega_a B_a^2 \tau_s,$$

Axion Search with a Quantum-Limited Ferromagnetic Haloscope

N. Crescini,[1,2,*] D. Alesini,[3] C. Braggio,[2,4] G. Carugno,[2,4] D. D'Agostino,[5] D. Di Gioacchino,[3] P. Falferi,[6] U. Gambardella,[5] C. Gatti,[3] G. Iannone,[5] C. Ligi,[3] A. Lombardi,[1] A. Ortolan,[1] R. Pengo,[1] G. Ruoso,[1,†] and L. Taffarello[4]



QUAX experiment



$$g_{aee} < \frac{e}{\pi m_a v_a} \sqrt{\frac{k_{ac} \times 2\sigma_P}{2\mu_B \gamma_e n_a N_s \tau_s}} \simeq 1.7 \times 10^{-11}.$$

goal (DFSZ model) $g_{aee} = 10^{-15}$

$\gamma_1 \simeq 1.9$ MHz $\tau_s \simeq 84$ ns, $N_s \simeq 1.0 \times 10^{21}$ spins

$\omega_c = 2\pi$ 1⁄4 10.7 GHz $g_{cm} \simeq 638$ MHz,

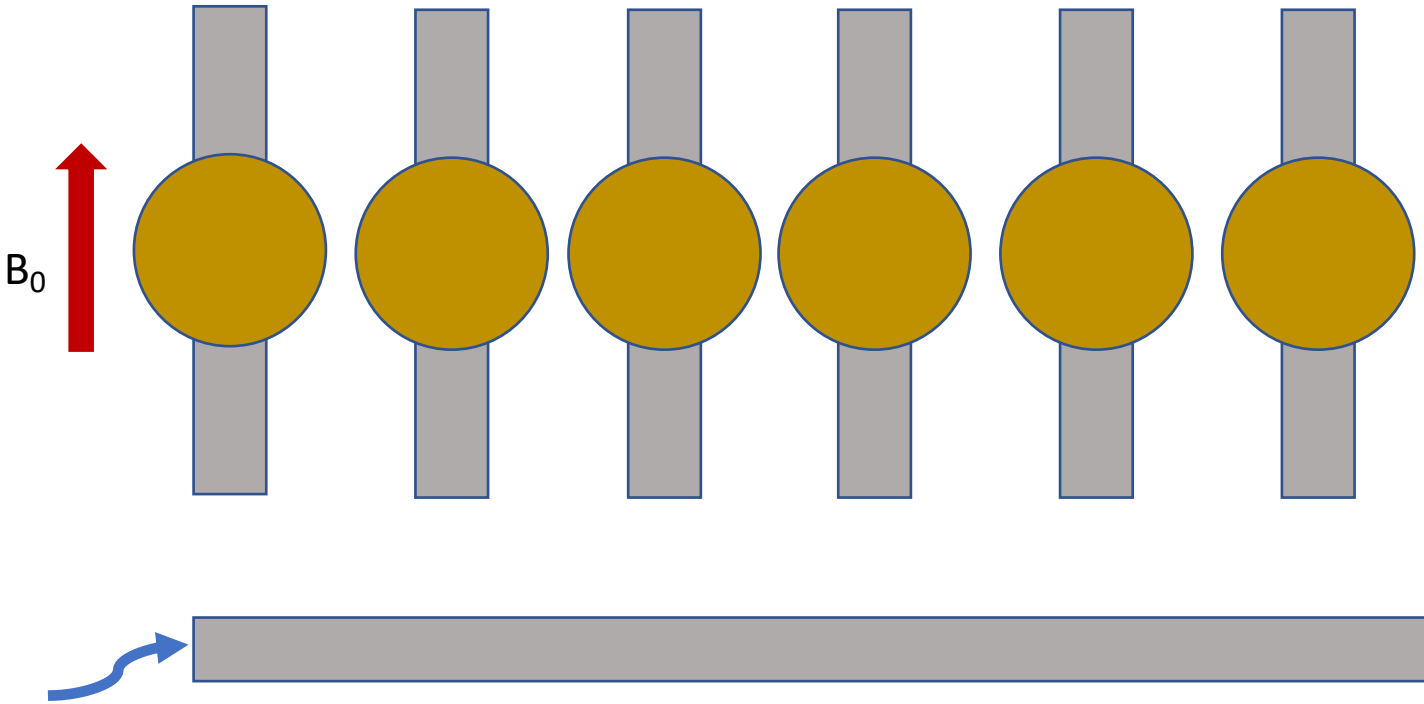
Planar geometry

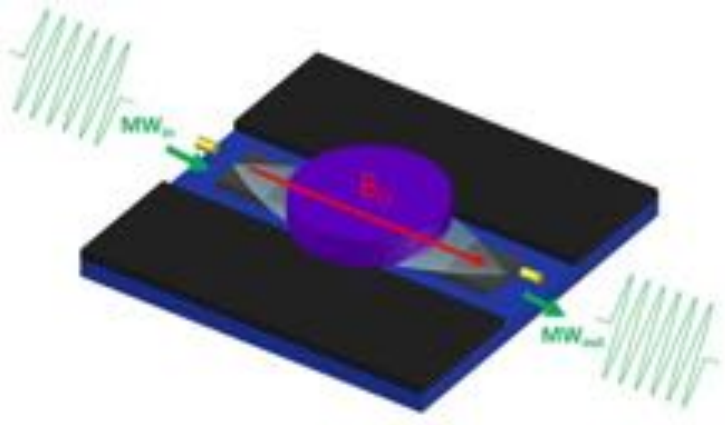
Features & goals:

- Advantages of circuit-QED
- Scalability

Next step:

- Ultra Strong coupling limit
- Avoid magnon to photon conversion
- Dispersive read out



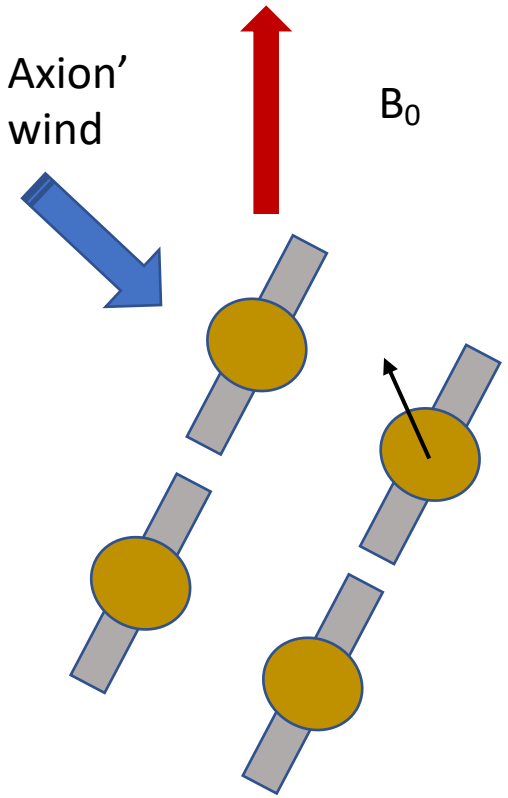


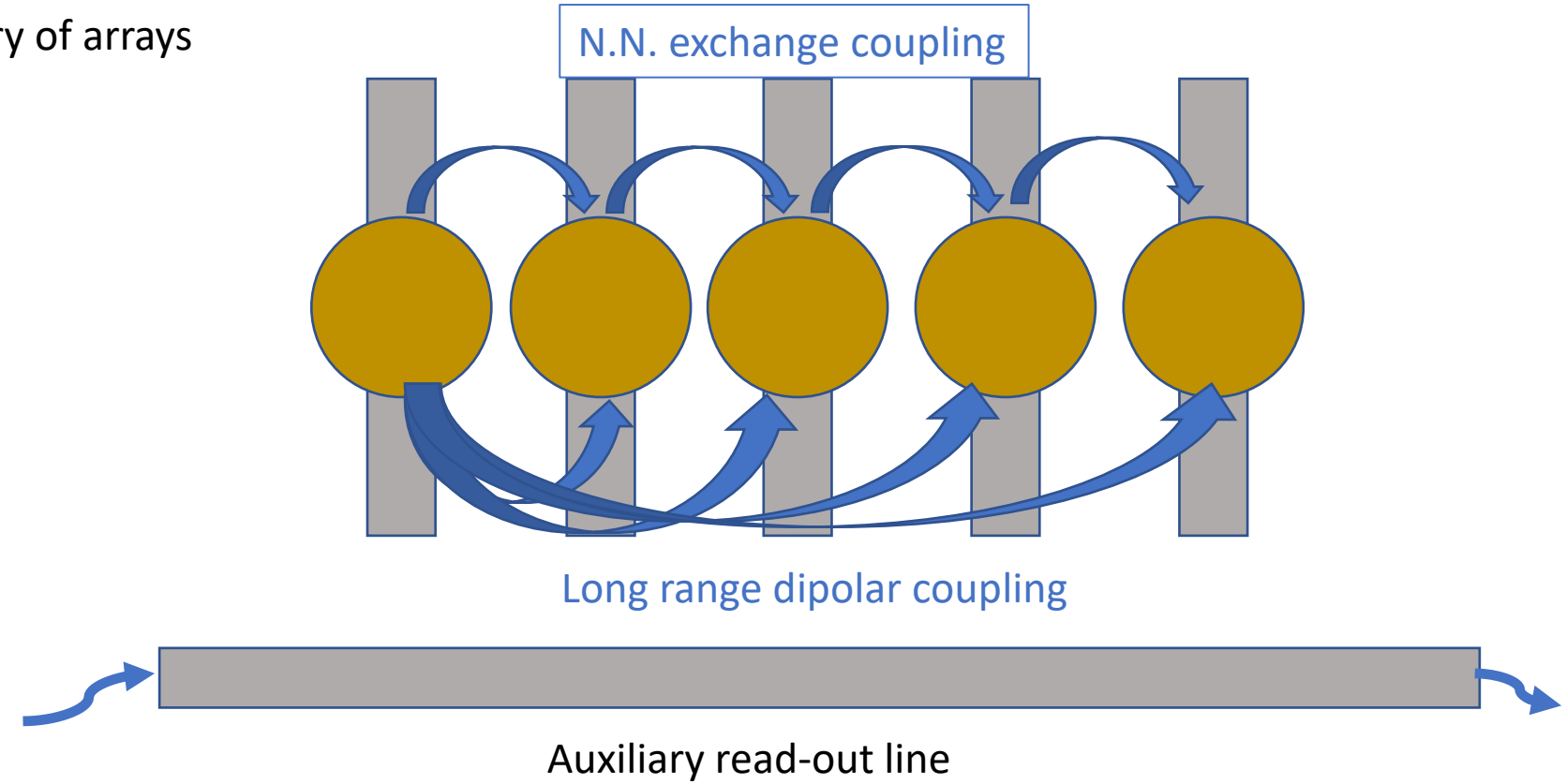
Single magnetic target in a coplanar resonator

Planar arrays of magnetic targets

Features & goals:

- 2D extension & orientation
- Engineering the geometry of arrays
- Coupling engineering



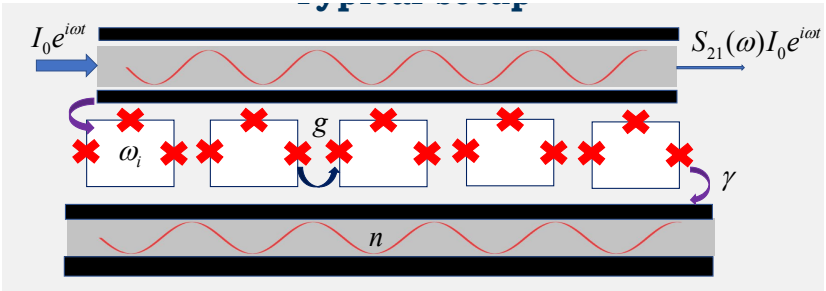


$$H = \sum_i \omega_i \, a^\dagger a + \sum_j \frac{1}{2} \omega_j \, S_z + H_{int}^{Ph-Mag} + H_{int}^{Mag-Mag}$$

Potentialities of qubit arrays

Collective States in Coherent Networks of Interacting Superconducting Qubits

M. V. Fistul[1,2], O. Neyenhuys[1], A.-B. Bastias[1], I. M. Eremin[1]
[1] *Theoretische Physik III, Ruhr-Universität Bochum, Bochum 44801, Germany*
[2] *National University of Science and Technology "MISIS", Moscow 119049, Russia*



Model Hamiltonian

$$\hat{H}_{tot} = \hat{H}_{SQN} - \alpha I_{loc}(t)\sum_i \hat{\sigma}_i^z$$

$$\hat{H}_{SQN} = \hat{H}_{qb} + \hat{H}_{SR\,\mathrm{int}} + \hat{H}_{LR\,\mathrm{int}} + \hat{H}_{ph} + \hat{H}_{qb-ph}$$

$$\hat{H}_{qb} = \sum_i \frac{\Delta_i}{2}\hat{\sigma}_i^x + \frac{\varepsilon_i}{2}\hat{\sigma}_i^z \qquad \hat{H}_{ph} = \hbar\omega_0 \hat{a}^+\hat{a}$$

$$\hat{H}_{SR\,\mathrm{int}} = g_{sr}\sum_{<ij>}\hat{\sigma}_i^z\hat{\sigma}_j^z \qquad \hat{H}_{qb-ph} = \gamma\sum_i \hat{\sigma}_i^z\left(\hat{a}^+ + \hat{a}\right)$$

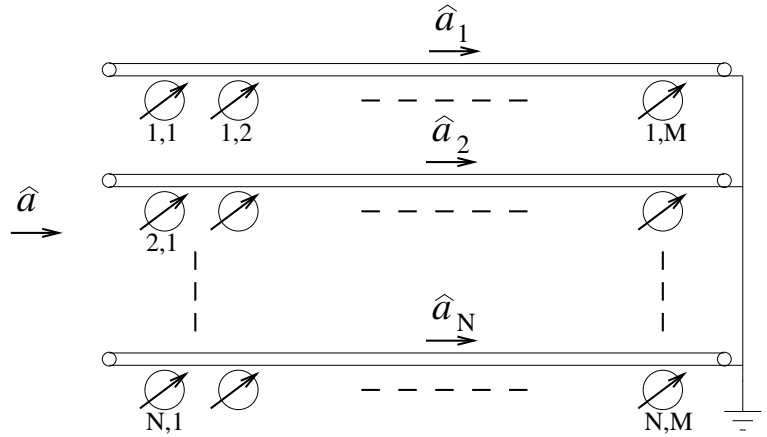
$$\hat{H}_{LR\,\mathrm{int}} = g_{lr}\sum_{i,j}\hat{\sigma}_i^+\hat{\sigma}_j^- + \hat{\sigma}_i^-\hat{\sigma}_j^+$$

- **an amplitude of the main resonance drastically increases** as the interaction overcomes the disorder, and **the collective state is formed**

Towards the Heisenberg limit in microwave photon detection by a qubit array

arXiv:2009.11271v3

P. Navez, A. G. Balanov, S. E. Savel'ev, A. M. Zagoskin
Department of Physics, Loughborough University, Loughborough LE11 3TU, United Kingdom



Arrays of correlated detectors may help to get the quantum (Heisenberg) limits of detection

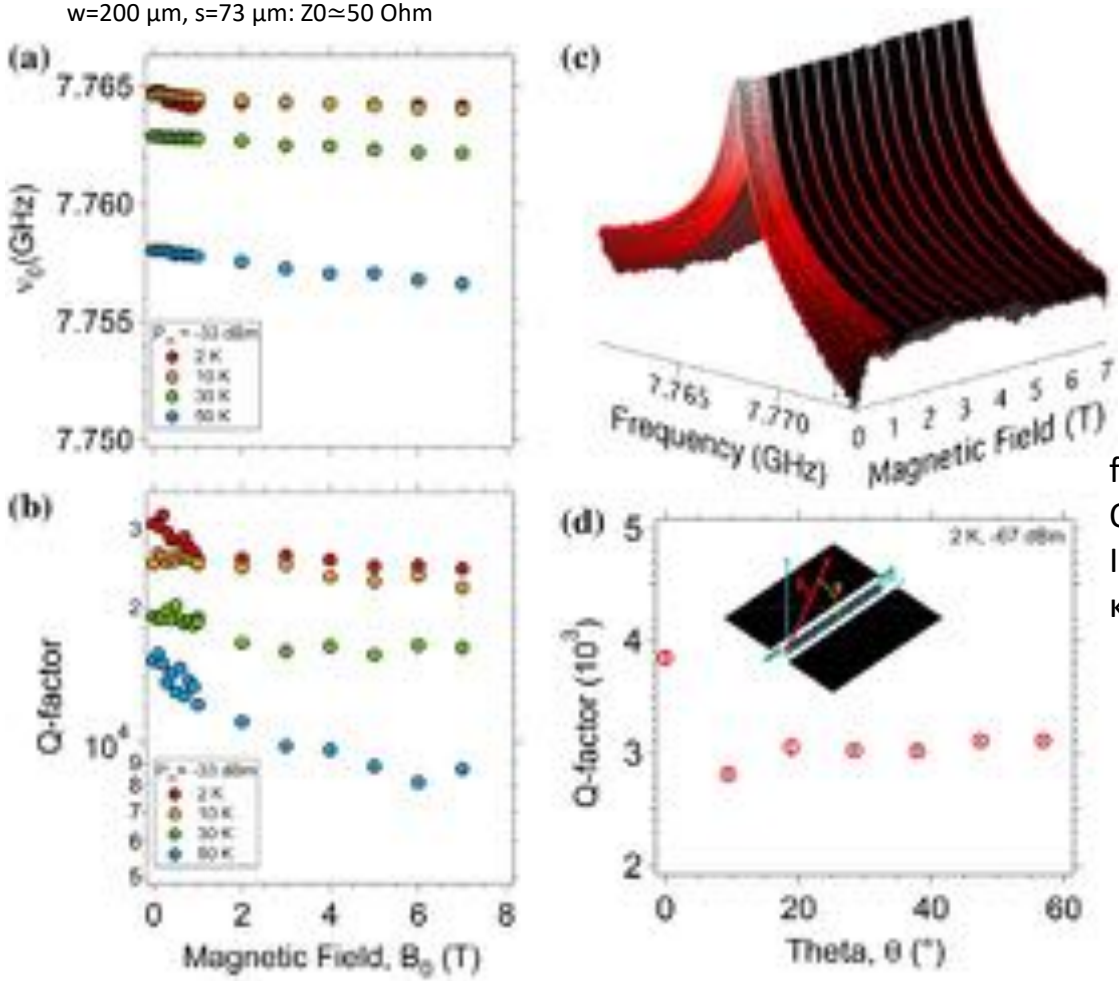
Coplanar resonators resilient to magnetic field

APPLIED PHYSICS LETTERS **106**, 184101 (2015)

$YBa_2Cu_3O_7$ microwave resonators for strong collective coupling with spin ensembles

A. Ghirri,[1,a)] C. Bonizzoni,[2] D. Gerace,[3] S. Sanna,[3] A. Cassinese,[4] and M. Affronte[2]

YBCO coplanar back-plated waveguide resonator
YBCO (330 nm) (Ceraco Gmbh): Tc=87 K
sapphire (430 μm): $\epsilon r \simeq 11$; $\tan(\delta) \sim 10\text{-}6$ at low T
w=200 μm, s=73 μm: Z0≃50 Ohm



f_0=7.7553 GHz
$Q_L \simeq 30000$
IL=-16.5 dB
$\kappa = f_0/Q_L$=0.5 MHz

ADVANCES IN PHYSICS: X, 2018
VOL. 3, NO. 1, 1435305
https://doi.org/10.1080/23746149.2018.1435305

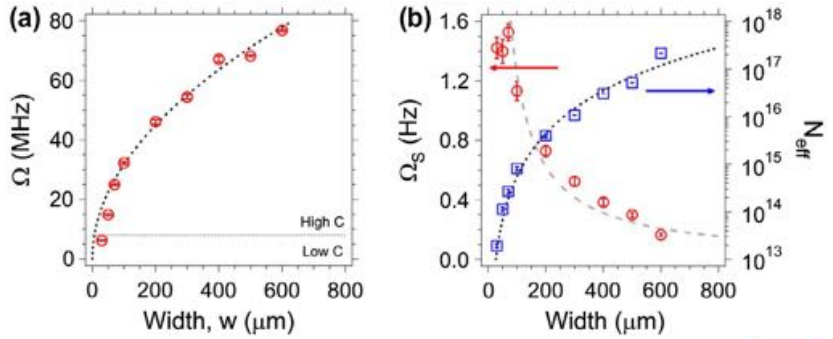
Taylor & Francis
Taylor & Francis Group

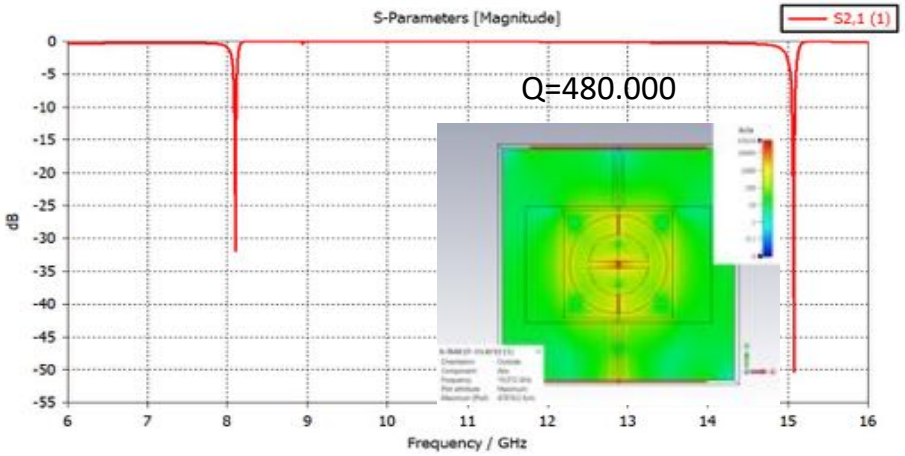
REVIEW ARTICLE

OPEN ACCESS Check for updates

Coherent coupling of molecular spins with microwave photons in planar superconducting resonators

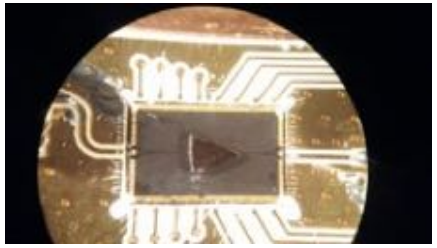
Claudio Bonizzoni[a,b], Alberto Ghirri[b] and Marco Affronte[a,b]



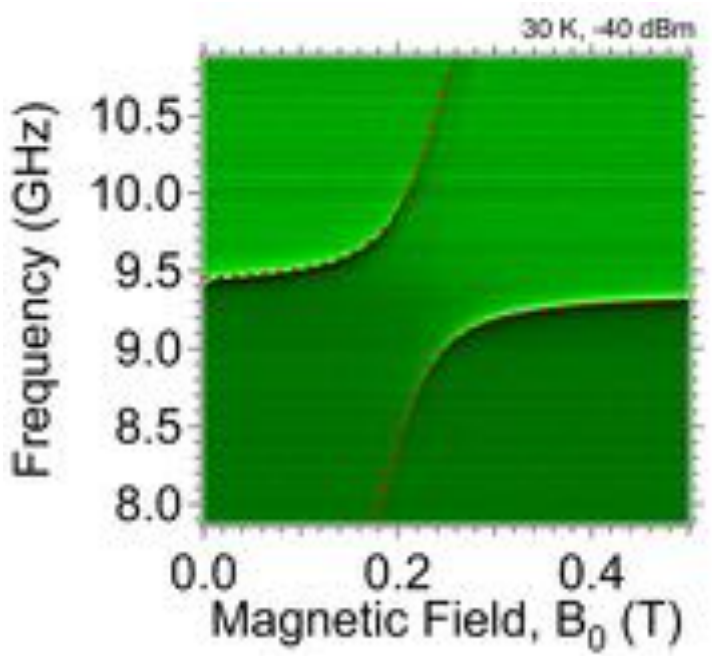


Dense ferro(i)magnetic targets: magnons

Yittrium Iron Garnet

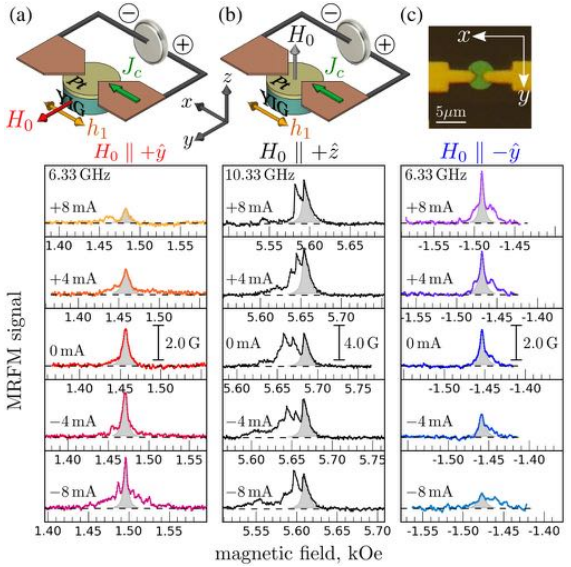


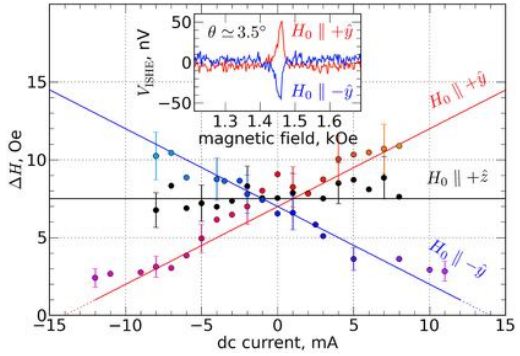
$\Delta f_YIG \approx 5MHz$
$g = 630$ MHz
$c \approx 4000$



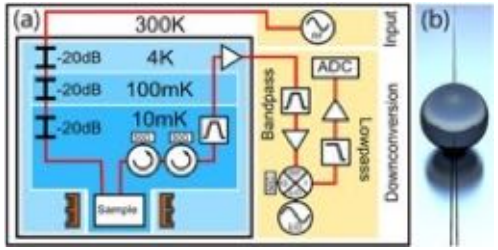
PRL 113, 197203 (2014) PHYSICAL REVIEW LETTERS week ending 7 NOVEMBER 2014

Full Control of the Spin-Wave Damping in a Magnetic Insulator Using Spin-Orbit Torque





Scientific Reports **volume 7**, Article number: 11511 (2017)



$\gamma_m/2\pi = 2.97$ MHz
$g_m/2\pi = 8.17$ MHz

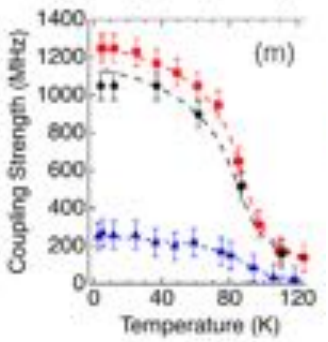
Dense molecular magnetic targets

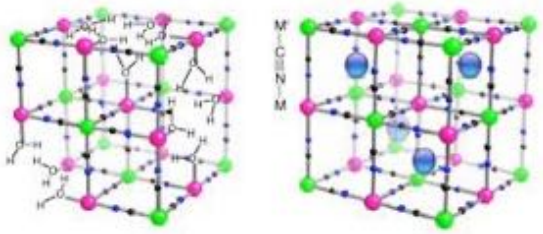
COMMUNICATION

ADVANCED QUANTUM TECHNOLOGIES
www.advquantumtech.com

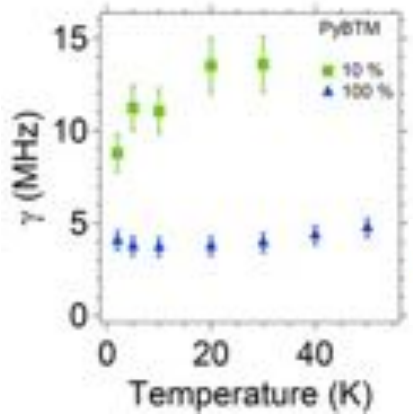
Coupling Nanostructured CsNiCr Prussian Blue Analogue to Resonant Microwave Fields

Alberto Ghirri, Christian Herrero, Sandra Mazérat, Talal Mallah, Oscar Moze, and Marco Affronte*



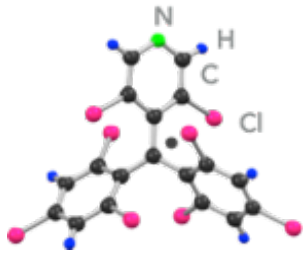


Organic radicals



g=95 MHz
γ=4 MHz
κ_{int}=0.3 MHz

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



(3,5-dichloro-4-pyridyl)bis(2,4,6-trichlorophenyl)methyl

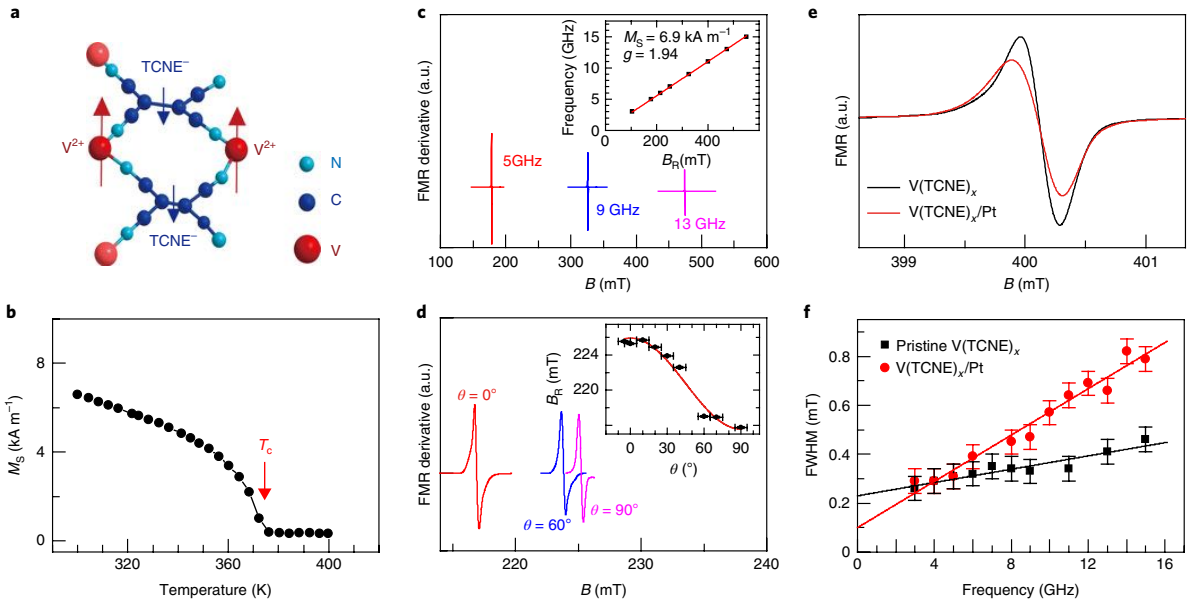
Organic-based magnon spintronics

Haoliang Liu[1,3], Chuang Zhang[1,3], Hans Malissa[1,3], Matthew Groesbeck[1], Marzieh Kavand[1], Ryan McLaughlin[1], Shirin Jamali[1], Jingjun Hao[2], Dali Sun[1], Royce A. Davidson[2], Leonard Wojcik[1], Joel S. Miller[2], Christoph Boehme[1] and Z. Valy Vardeny[1]*

NATURE MATERIALS | VOL 17 | APRIL 2018 | 308–312 |

$\gamma_m/2\pi$= 3.97 MHz

vanadium tetracyanoethylene (V(TCNE)*x* (*x* ≈ 2)),

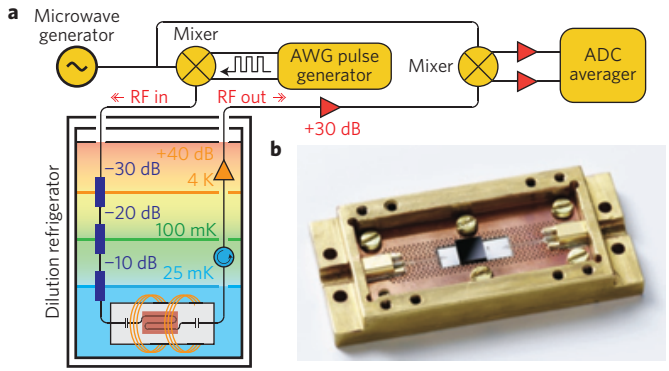


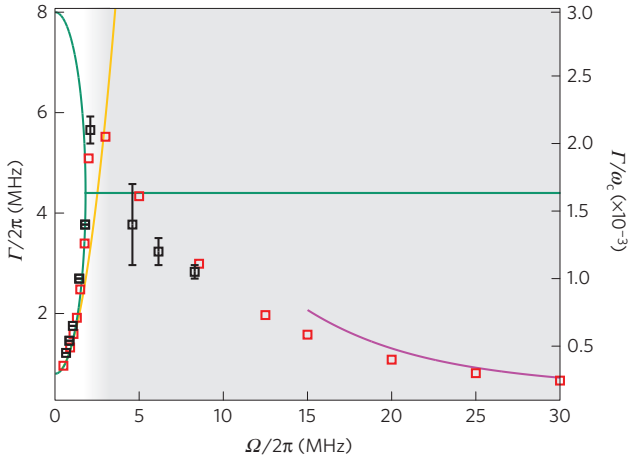
Diluted spin systems

Protecting a spin ensemble against decoherence in the strong-coupling regime of cavity QED

S. Putz[1,2†], D. O. Krimer[3†], R. Amsüss[1], A. Valookaran[1], T. Nöbauer[1,4], J. Schmiedmayer[1], S. Rotter[3*] and J. Majer[1,2*]

DOI: 10.1038/NPHYS3050

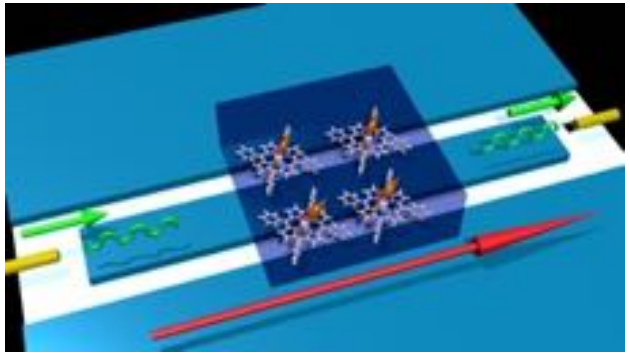


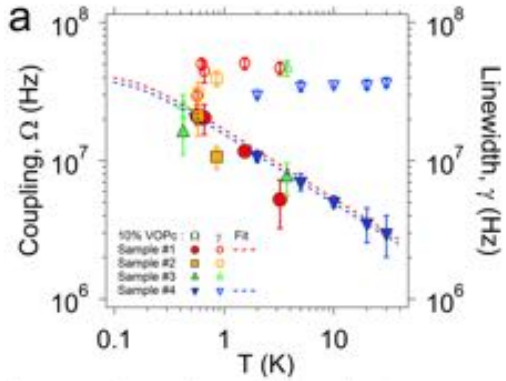


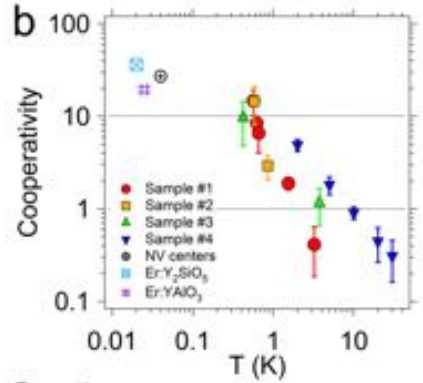
Coherent coupling between Vanadyl Phthalocyanine spin ensemble and microwave photons: towards integration of molecular spin qubits into quantum circuits

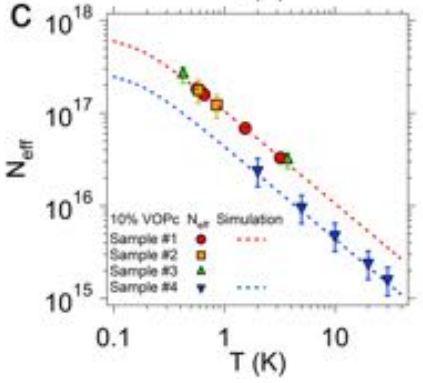
C. Bonizzoni[1,2], A. Ghirri[2], M. Atzori[3], L. Sorace[3], R. Sessoli[3] & M. Affronte[1,2]

SCIENTIFIC REPORTS | 7: 13096 | DOI:10.1038/s41598-017-13271-w



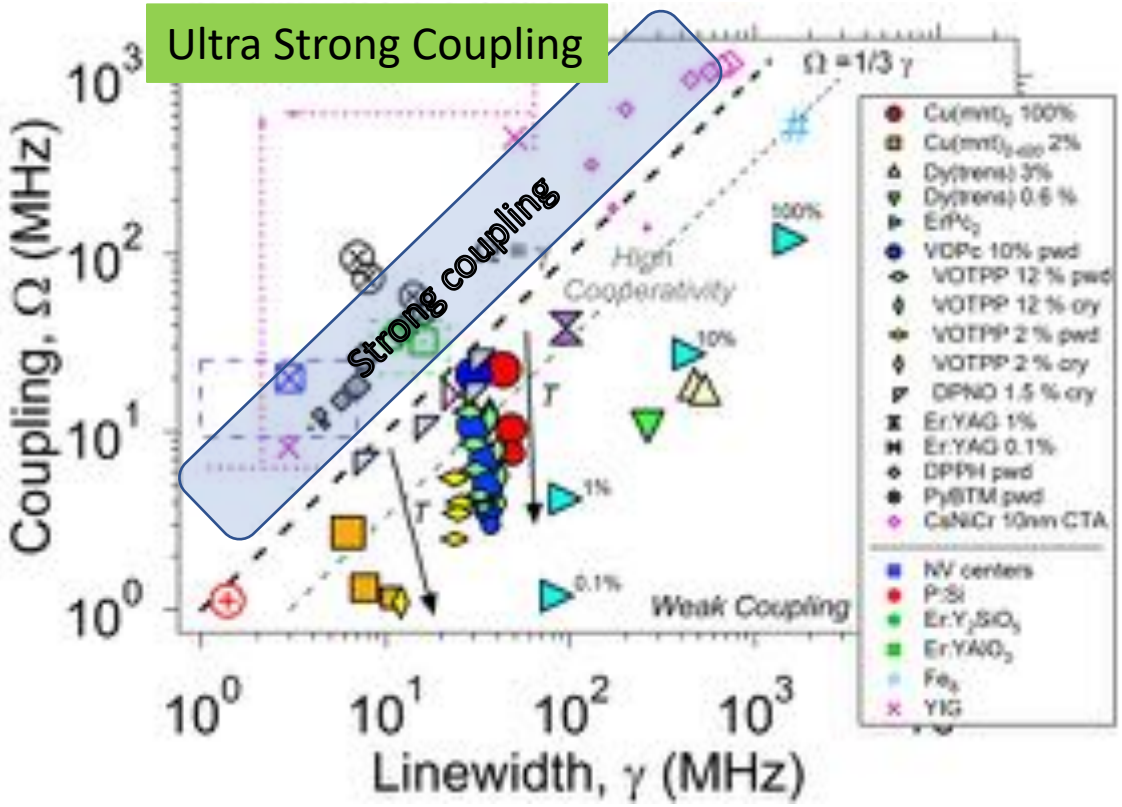






Good candidates as magnetic target

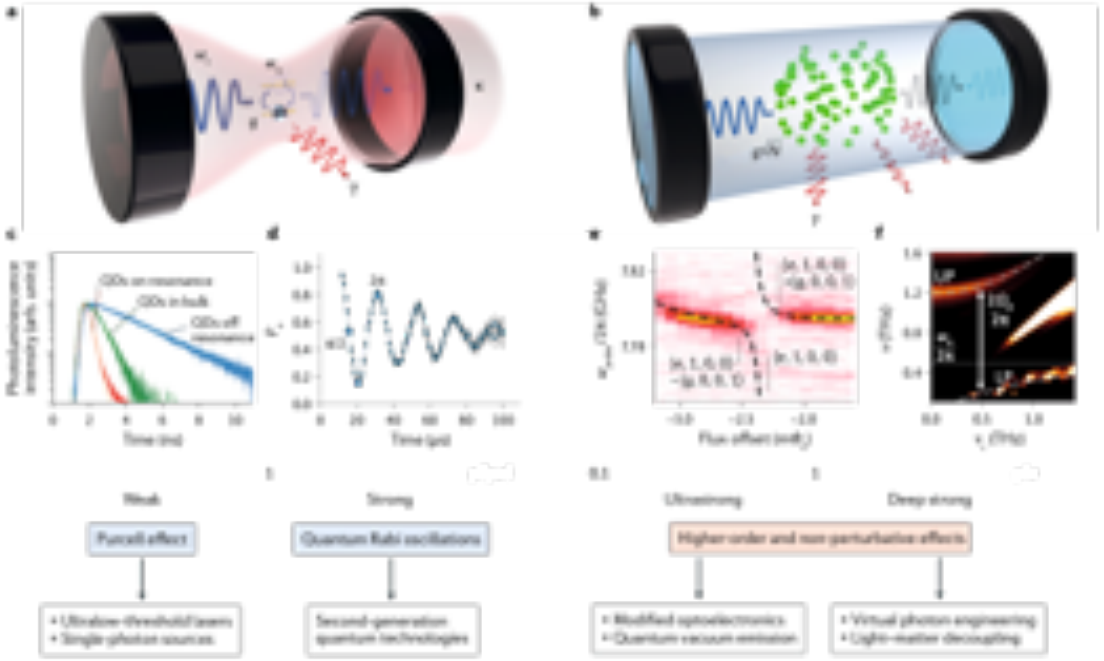
$g > 0.1\ \omega$



Ultrastrong coupling between light and matter

https://doi.org/10.1038/s42254-018-0006-2

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

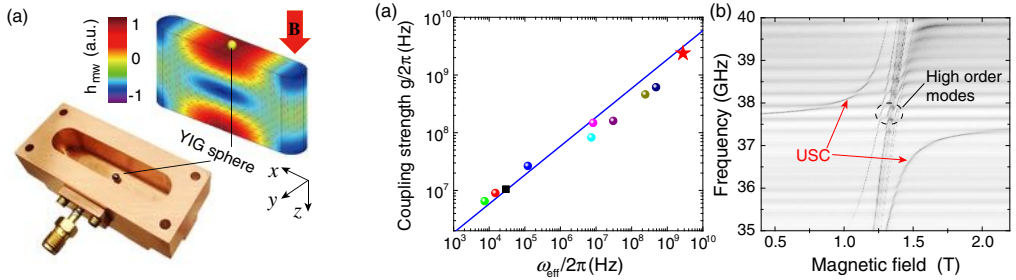


$$\hat{H}_{\text{Rabi}} = \omega_c \hat{a}^\dagger \hat{a} + \frac{1}{2}\omega_q \hat{\sigma}_z + \hat{H}_{\text{int}},$$

$$\hat{H}_{\text{int}} = g\hat{X}\hat{\sigma}_x = g_1(\hat{a}\hat{\sigma}_+ + \hat{a}^\dagger\hat{\sigma}_-) + g_2(\hat{a}\hat{\sigma}_- + \hat{a}^\dagger\hat{\sigma}_+),$$

where $\hat{a}$ and $\hat{a}^\dagger$ are the annihilation and creation operators of the cavity mode, respectively; $\hat{\sigma}_- = |g\rangle\langle e|$ and $\hat{\sigma}_+ = |e\rangle\langle g$ are the lowering and raising operators between the ground ($|g\rangle$) and excited ($|e\rangle$) states of a given two-level system $\hat{\sigma}_x = \hat{\sigma}_- + \hat{\sigma}_+$ and $\hat{\sigma}_z = |e\rangle\langle e| - |g\rangle\langle g|$ are Pauli operators; and $\hat{X} = \hat{a} + \hat{a}^\dagger$ is the canonical position operator of the electric of the cavity mode. For simplicity, we ignore the vacuum-field energy in the free Hamiltonian in equation B1.1. g, g_1 ... g_2 denote light–matter coupling strengths. In the quantum Rabi model, $g = g_1 = g_2$, but this condition can be relaxed[221]. Setting $g_2 = 0$ gives the Jaynes–Cummings model[39]. The extensions of the quantum Rabi model and the Jaynes–Cummings

YIG@ 3D copper box



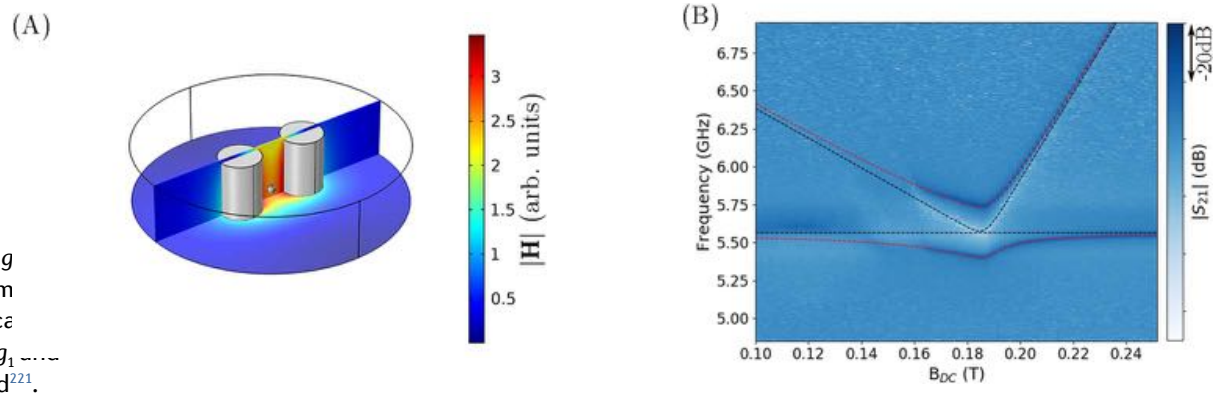
PRL **113,** 156401 (2014)

Experimental implementations of cavity-magnon systems: from ultra strong coupling to applications in precision measurement

YIG or LiFe

Graeme Flower[1], **Maxim Goryachev**, **Jeremy Bourhill and Michael E Tobar**

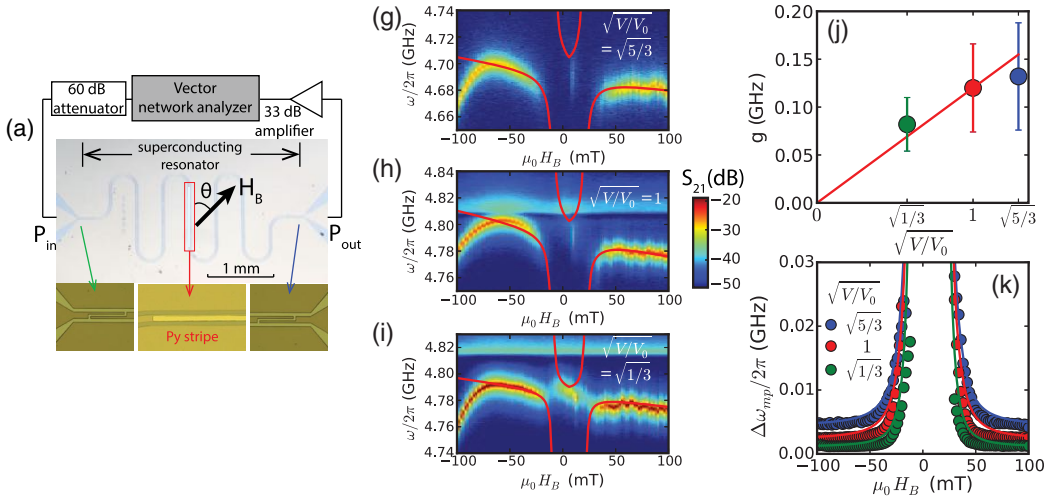
New J. Phys. **21** (2019) 095004 https://doi.org/10.1088/1367-2630/ab3e1c

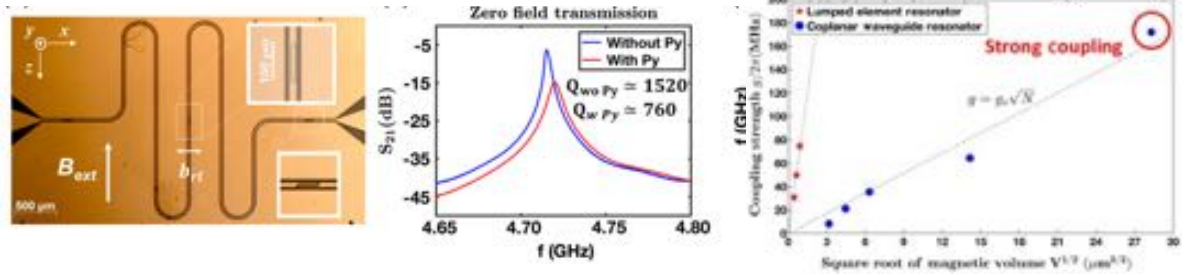


(Ultra) Strong Coupling

Permalloy @ superconducting cpw

PHYSICAL REVIEW LETTERS **123,** 107701 (2019)





PHYSICAL REVIEW LETTERS **123,** 107702 (2019)

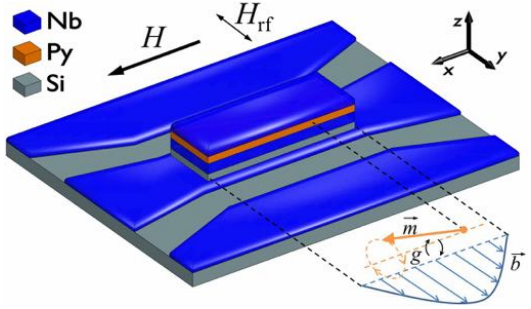
SCIENCE ADVANCES | RESEARCH ARTICLE

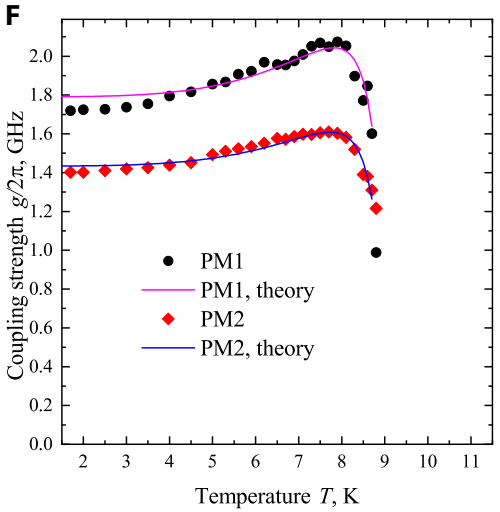
PHYSICS

Golovchanskiy *et al., Sci. Adv.* 2021; **7** : eabe8638 18 June 2021

Ultrastrong photon-to-magnon coupling in multilayered heterostructures involving superconducting coherence via ferromagnetic layers

Igor A. Golovchanskiy[1,2]*, Nikolay N. Abramov[2], Vasily S. Stolyarov[1,3], Martin Weides[4], Valery V. Ryazanov[2,5], Alexander A. Golubov[1,6], Alexey V. Ustinov[2,7,8], Mikhail Yu. Kupriyanov[1,9]



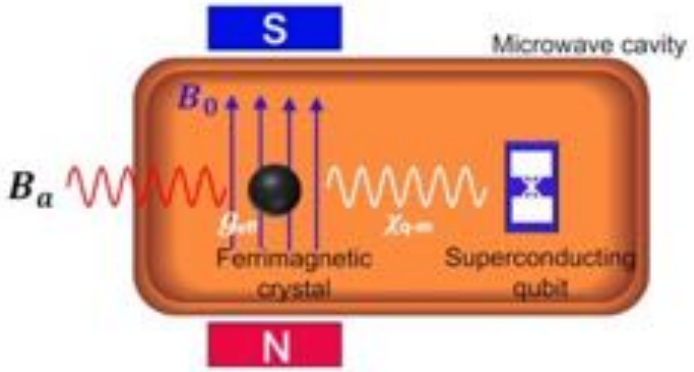


$frS = \bar{c}/2L \approx 17$ GHz for a $\lambda/2$ resonator

QUANTUM MAGNETISM

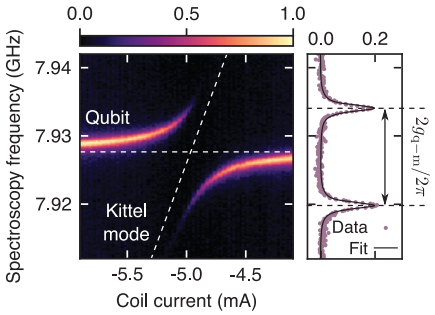
Resolving quanta of collective spin excitations in a millimeter-sized ferromagnet

Dany Lachance-Quirion,[1,2] Yutaka Tabuchi,[2] Seiichiro Ishino,[2] Atsushi Noguchi,[2] Toyofumi Ishikawa,[2] Rekishu Yamazaki,[2] Yasunobu Nakamura[2,3*]



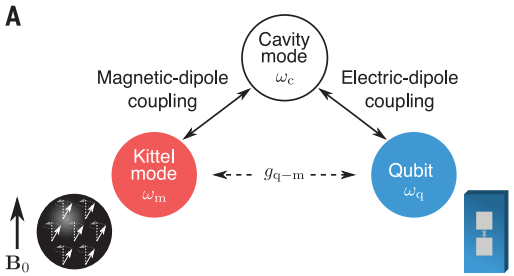
Lachance-Quirion et al. Sci. Adv. 3, e1603150 (2017)

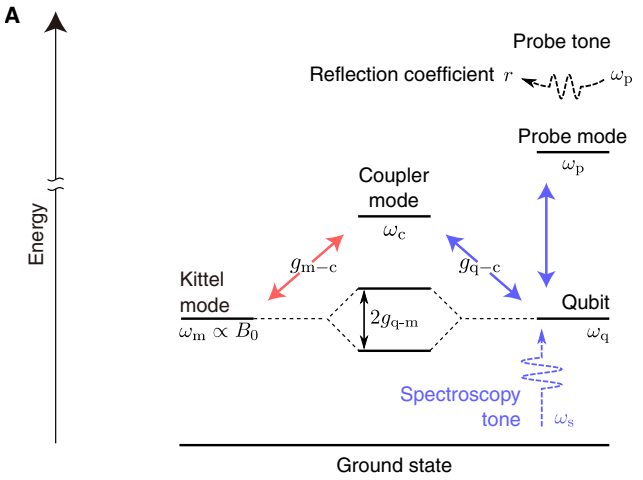
Lachance-Quirion et al. Sciece 367, 425 (2020)

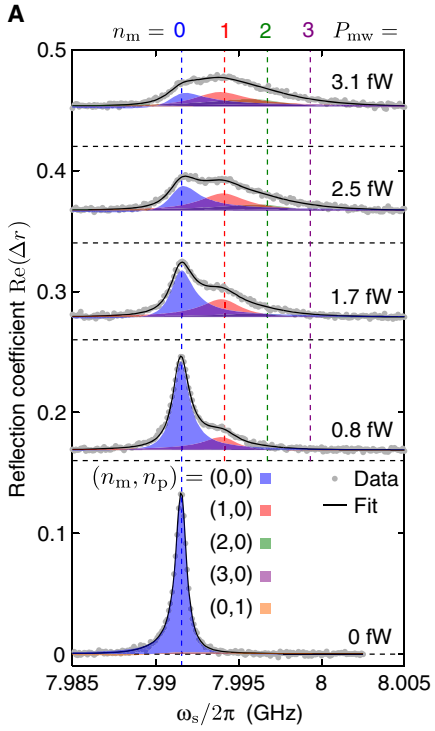


$g_{m\text{-}c}/2p$ = 22.5 MHz is much larger than both the cavity ($\kappa_c/2\pi$ = 2.08 MHz) and magnon ($\gamma m/2\pi$ = 1.3 MHz) linewidths.

Dispersive detection of single magnetic excitation



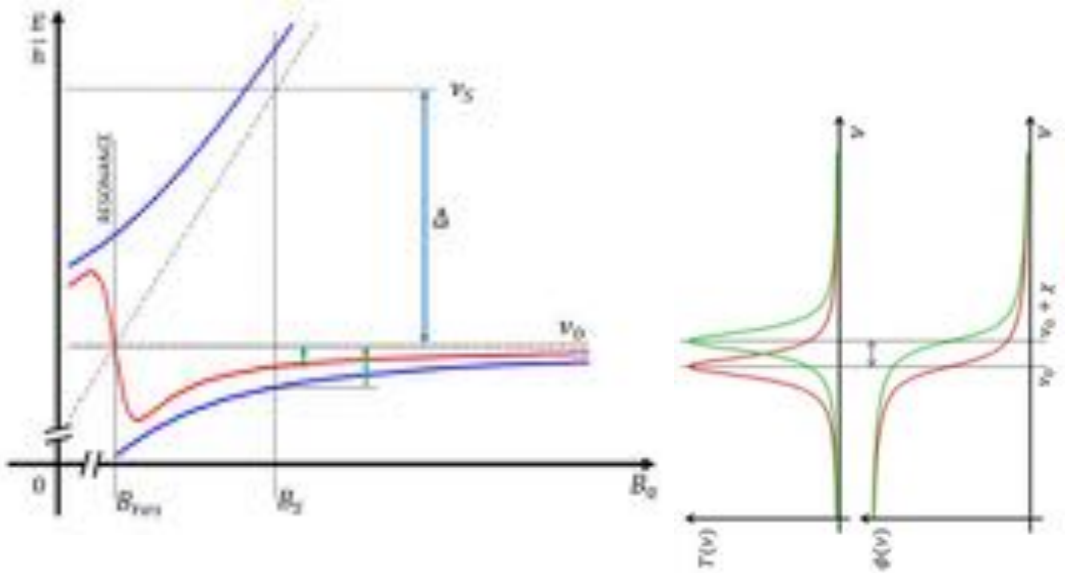




Non demolitive measurement of single magnetic excitation

Transmission Spectroscopy of Molecular Spin Ensembles in the Dispersive Regime

Claudio Bonizzoni, Alberto Ghirri, Shigeaki Nakazawa, Shinsuke Nishida, Kazunobu Sato, Takeji Takui, and Marco Affronte*

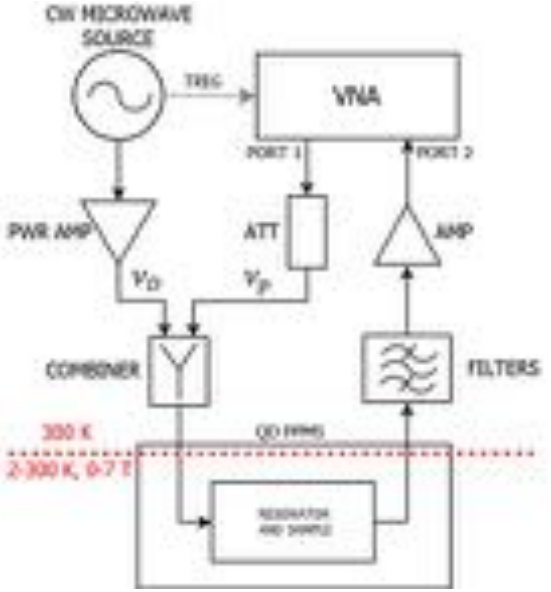


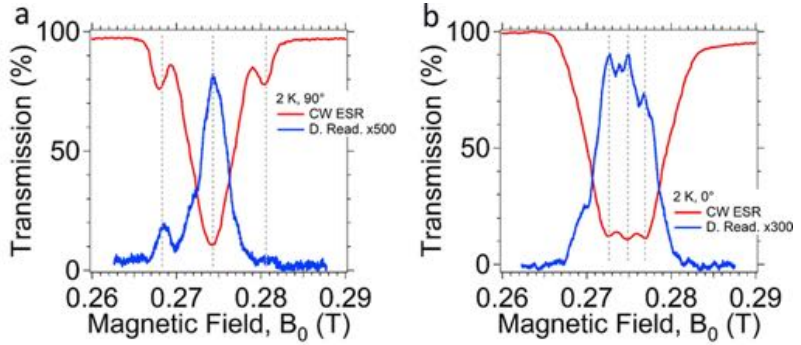
$$H \approx \hbar\omega_r a^\dagger a + \hbar\omega_a \frac{S_z}{2} + \hbar\chi\left(a^\dagger a + \frac{1}{2}\right)S_z$$

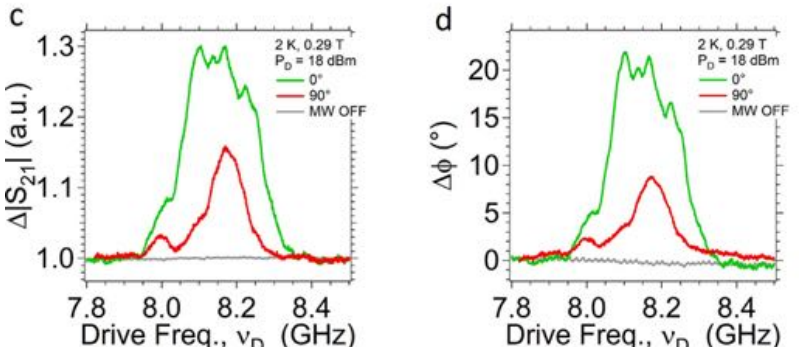
$$\chi = \frac{\Omega^2}{\Delta} \qquad \Omega = \Omega_S\sqrt{N}$$

$$|\Delta| = |\omega_a - \omega_r| \gg \Omega$$

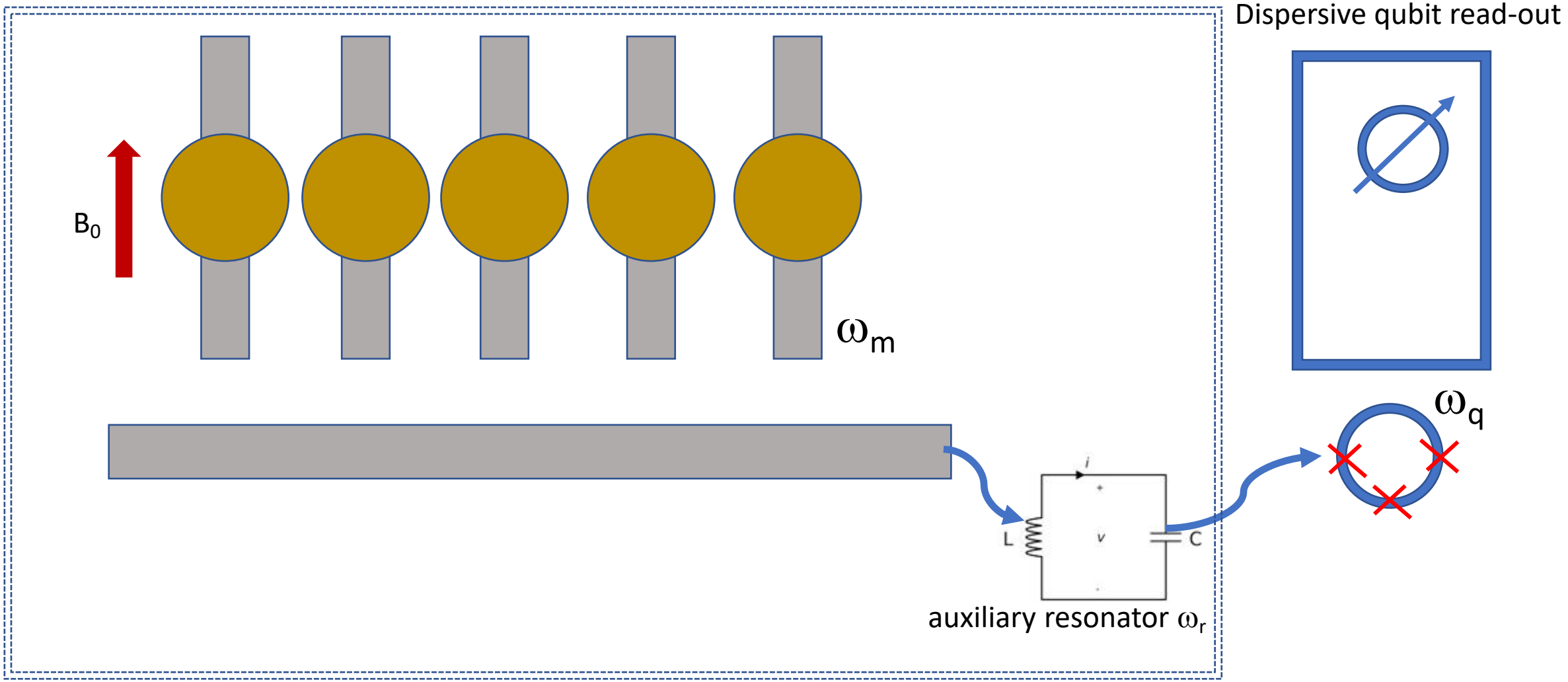








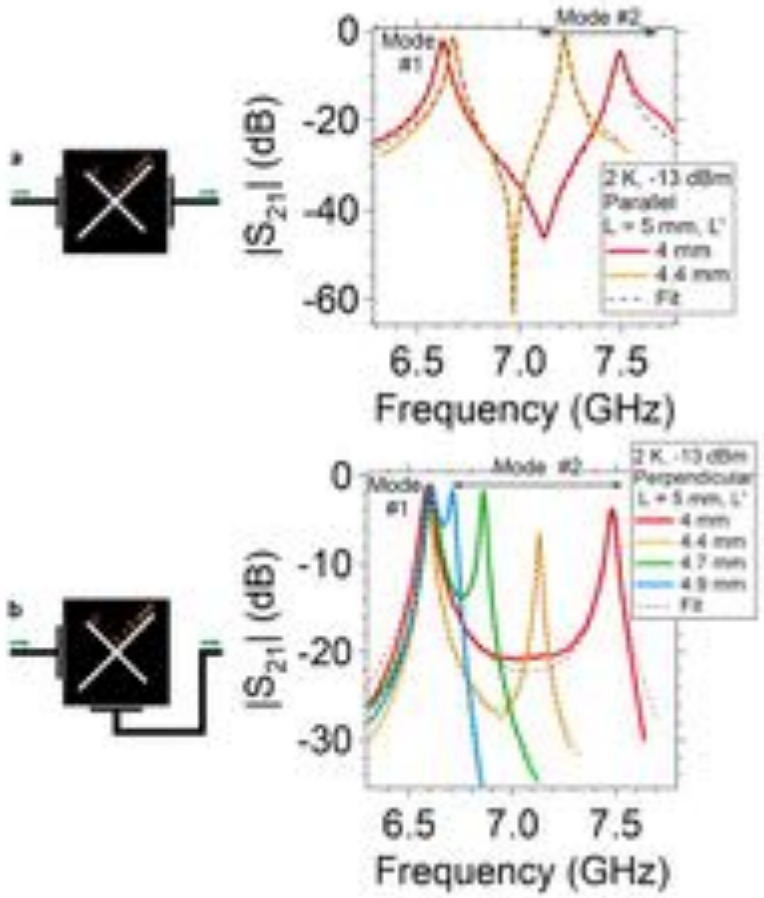
Possible cQED scheme for dispersive read out of single magnetic excitation with planar architectures

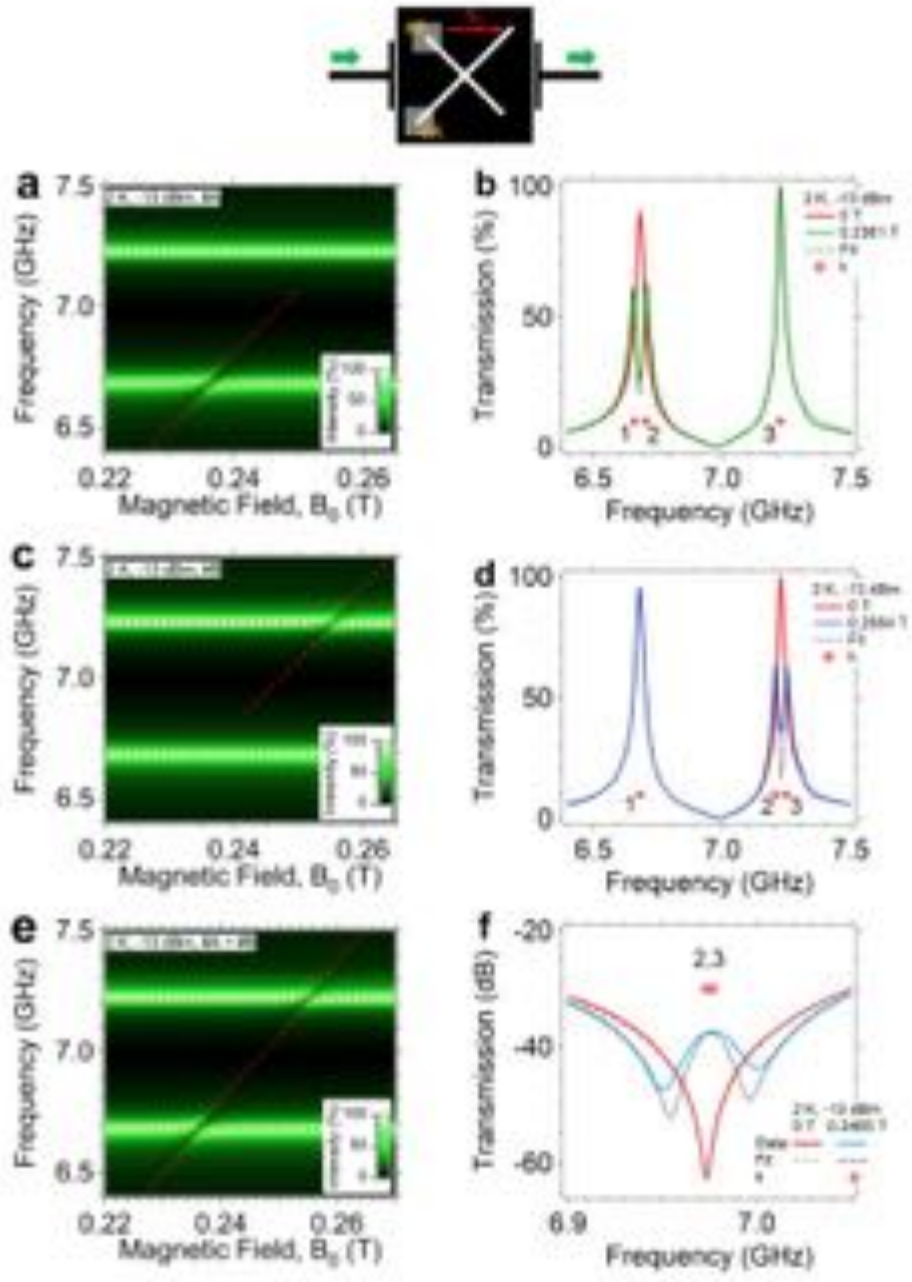


JOURNAL OF APPLIED PHYSICS **124**, 194501 (2018)

Microwave dual-mode resonators for coherent spin-photon coupling

C. Bonizzoni,[1,a)] F. Troiani,[2] A. Ghirri,[2] and M. Affronte[1,2]





Conclusions

- Planar circuit QED hybrid magnetic superconducting architectures can work in magnetic filed and strong coupling regime with high cooperativity.
- Planar Arrays of magnetic detectors offer scalability and possibility to profit for collective benefits.
- Ultra strong coupling between magnetic and superconducting resonators can be achived. If combined with dispersive read out, enhanched quantum effects may allow to achive unprecedented quantum limits for axion's detection.

Thanks to:

Alberto Ghirri
Claudio Bonizzoni
Samuele Cornia



For discussion and €€€ support