Integration of Magnons into Superconducting Quantum Circuits

María José (Pepa) Martínez-Pérez

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Plan de Recuperación, Transformación y Resiliencia

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Quantum Materials and Devices

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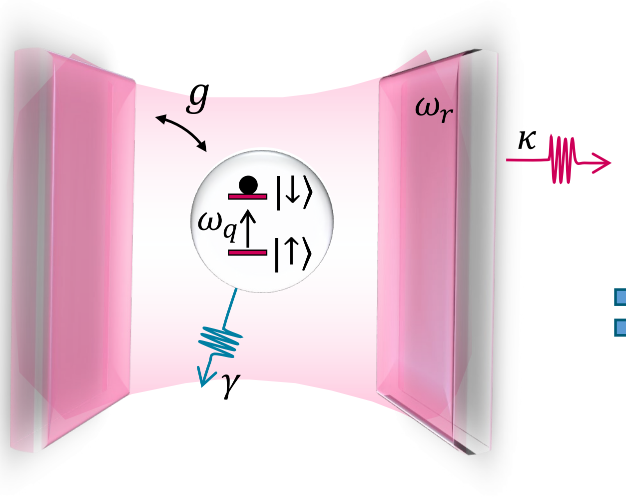
Universidad Zaragoza
1542

INMA
INSTITUTO DE NANOCIENCIA Y MATERIALES DE ARAGÓN

Outline

- Light-matter interaction and circuit QED
- Nanomagnets + **superconducting resonators**
  - ☺ Coupling to spins
  - ☺ Coupling to magnons
- Nanomagnets + **magnonic resonators**
  - ☺ GdW10 as spin qubit
  - ☺ SCB as cavity
  - ☺ Spin – magnon

Cavity QED: electromagnetic cavities and qubits



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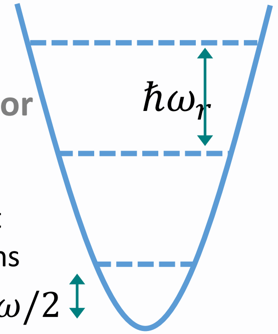
Photons:

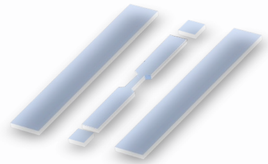
Harmonic oscillator



Zero-point fluctuations

$\varepsilon_{rms} = \hbar\omega/2$

In a CPW resonator:



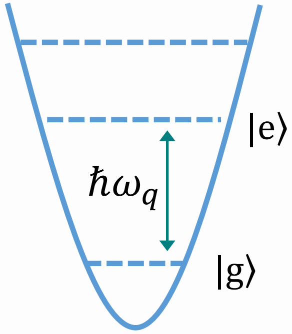
$i_{rms} = \omega_r\sqrt{\hbar\pi/4Z_0}$

+

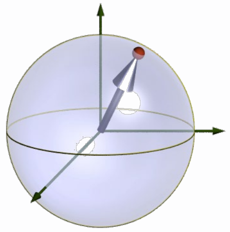
Atom:

Two level system

Or anharmonic

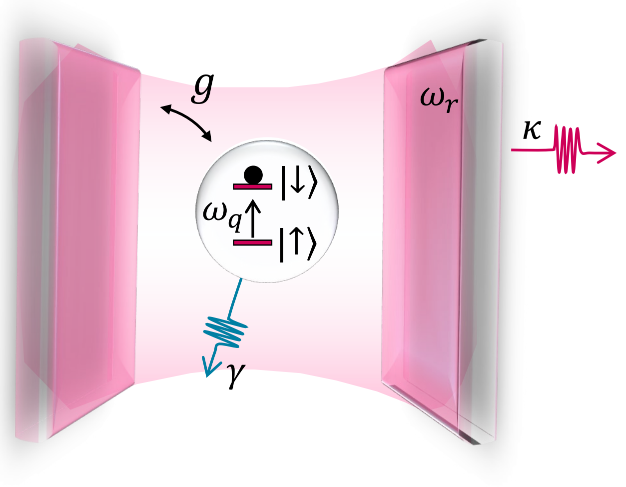


Bloch sphere:

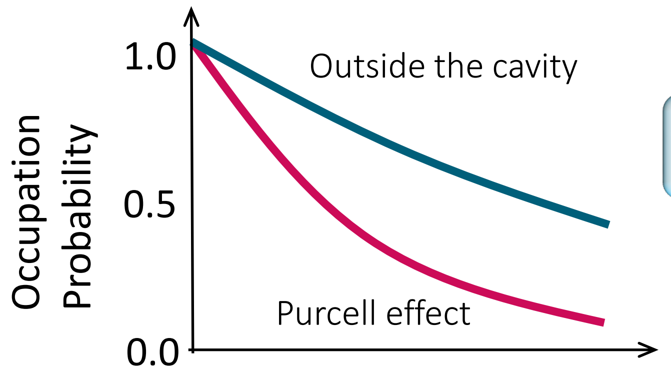


$$|\psi\rangle = \cos\frac{\theta}{2}|g\rangle + \sin\frac{\theta}{2}\, e^{i\phi}\,|e\rangle$$

Cavity QED: electromagnetic cavities and qubits



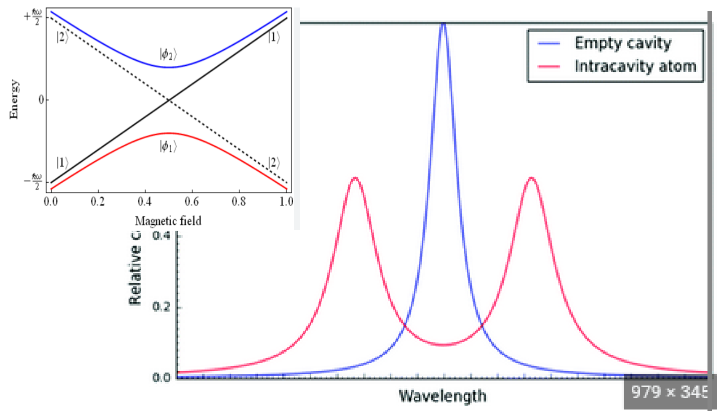
Weak coupling: $\omega_r = \omega_q$



$$g < \gamma,\ \kappa$$

The atom decay rate increases:

$$\tilde{\gamma} = \gamma + \frac{g^2}{\kappa}$$



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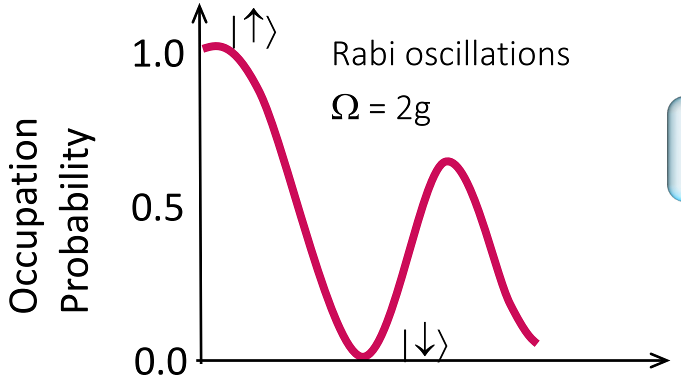
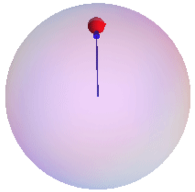


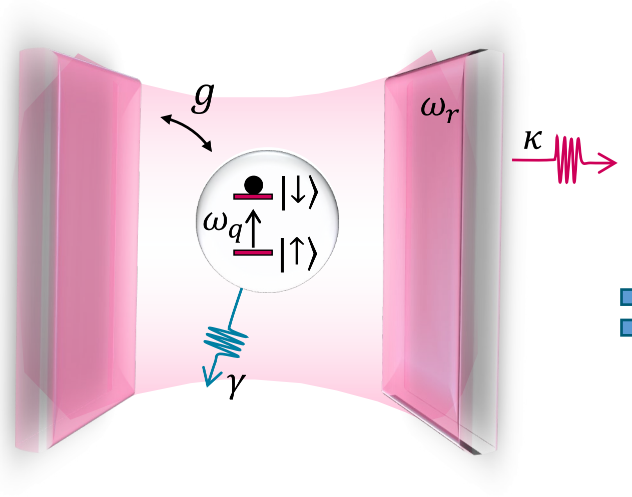
$$g > \gamma,\ \kappa$$



Avoided crossing at degeneracy point

$$\omega_{\pm} = \frac{\omega_r+\omega_q}{2} \pm \frac{\sqrt{4g^2+(\omega_r+\omega_q)^2}}{2}$$

Cavity QED: electromagnetic cavities and qubits



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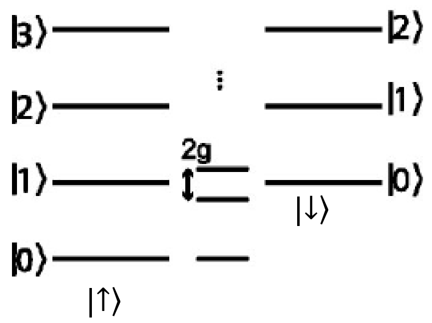
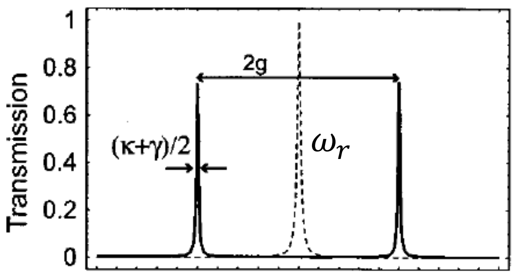
In resonance:

$$\Delta = 0$$

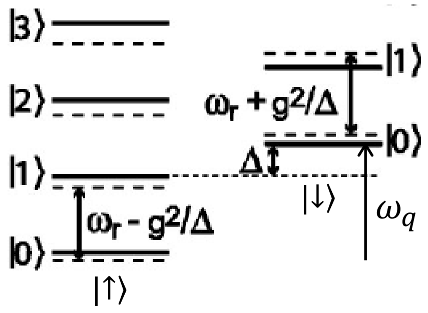


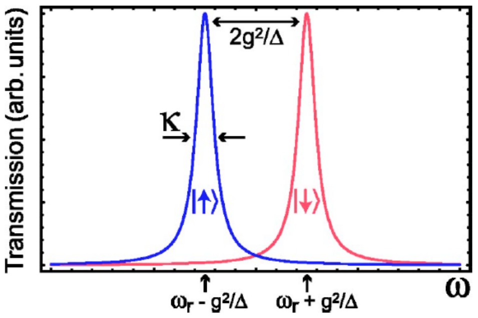


Blais et al PRA 69 2004

Far from resonance:

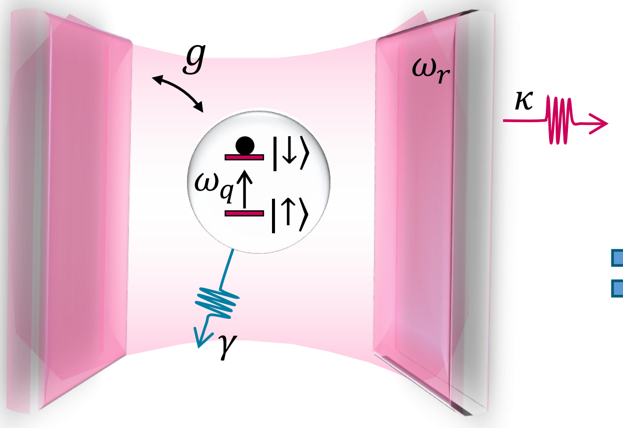
$$\Delta = \omega_q - \omega_r$$





Dispersive READOUT of QUBIT states and PHOTON COUNT!

Cavity QED: electromagnetic cavities and qubits



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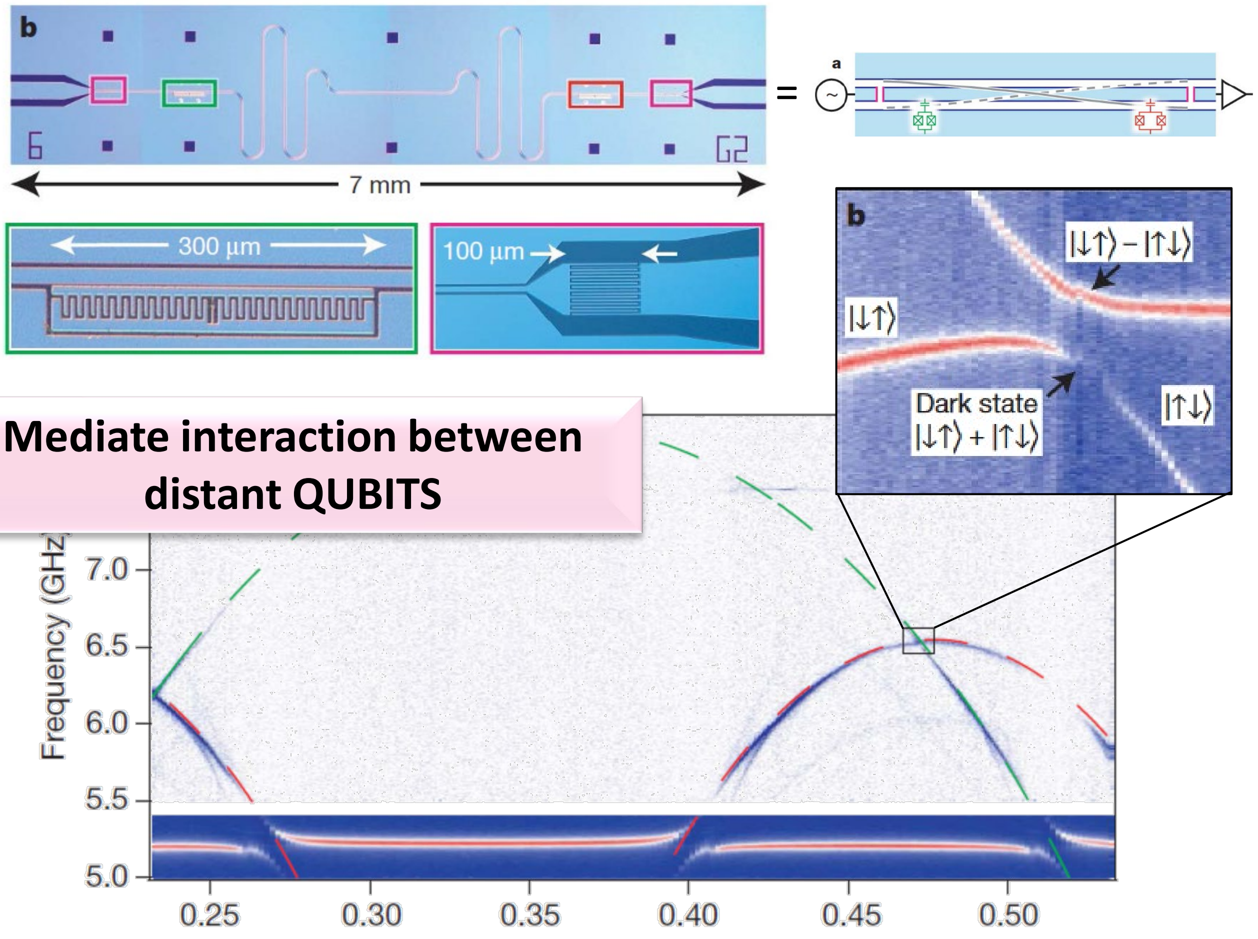
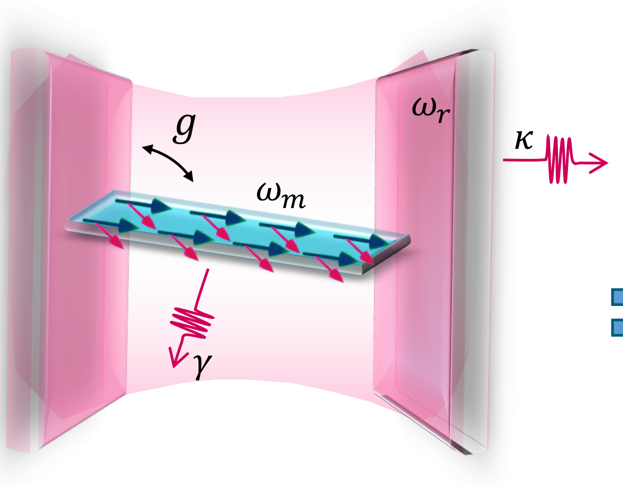
Coupling superconducting qubits via a cavity bus

J. Majer[1*], J. M. Chow[1*], J. M. Gambetta[1], Jens Koch[1], B. R. Johnson[1], J. A. Schreier[1], L. Frunzio[1], D. I. Schuster[1], A. A. Houck[1], A. Wallraff[1]†, A. Blais[1]†, M. H. Devoret[1], S. M. Girvin[1] & R. J. Schoelkopf[1]



Mediate interaction between distant QUBITS

Cavity QED with bosonic excitations: two coupled harmonic oscillators



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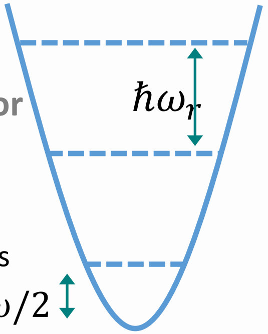
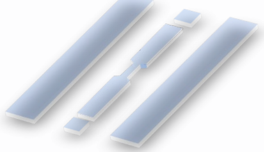
Harmonic oscillator



Zero-point fluctuations

$\varepsilon_{rms} = \hbar\omega/2$

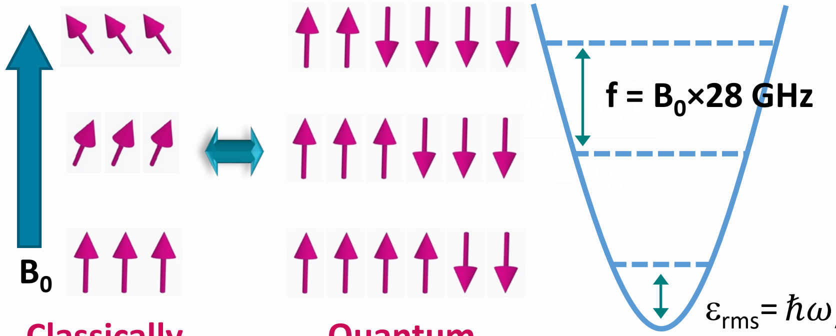
In a CPW resonator:



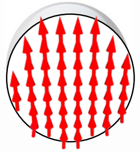
$i_{rms} = \omega_r\sqrt{\hbar\pi/4Z_0}$

+

Magnons: Kittel homogeneous mode



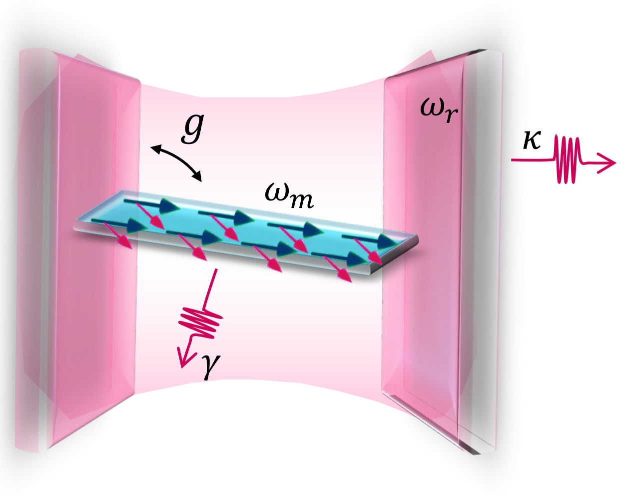
In a sphere:



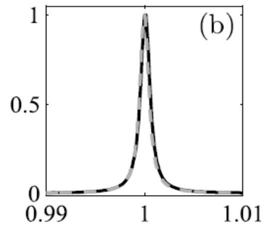
$\mu_{rms} = \sqrt{\frac{g_e M_s V}{2\mu_B}}$

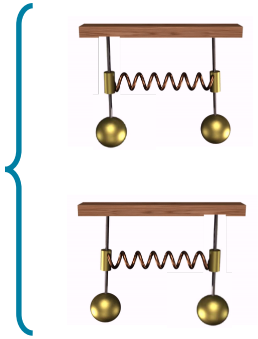
Cavity QED with bosonic excitations: two coupled harmonic oscillators

Two coupled harmonic oscillators with detuning Δk



Weak coupling with no detuning Δk=0





$$\omega_0 = \sqrt{\frac{k_0}{m}}$$

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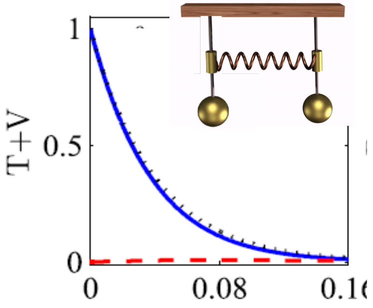
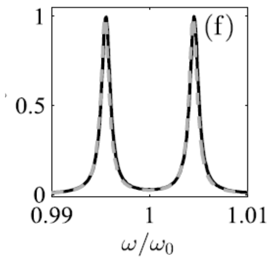
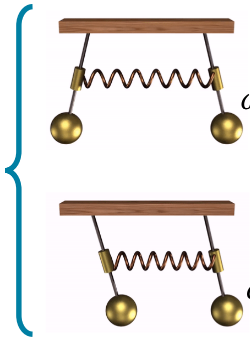


Equivalent to purcell effect!!

$$\kappa = \tilde{\kappa} + \frac{\gamma g^2}{(\omega_p - \omega_m)^2 + \gamma^2}$$

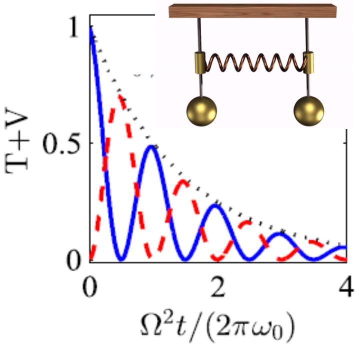
Strong coupling with no detuning Δk=0



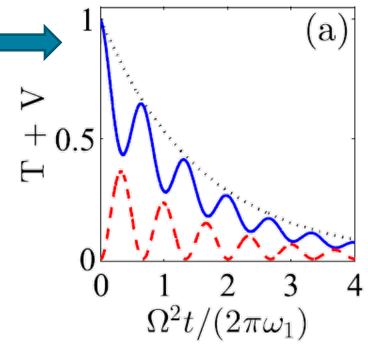


$$\omega_+ = \sqrt{\frac{k_0 + 2g}{m}}$$

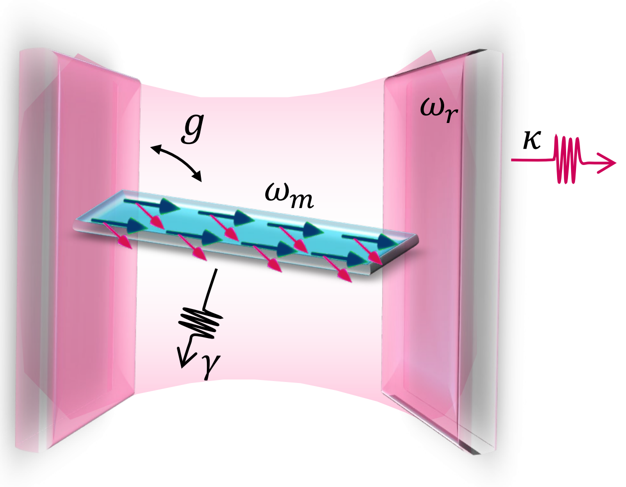
$$\omega_- = \omega_0 = \sqrt{\frac{k_0}{m}}$$

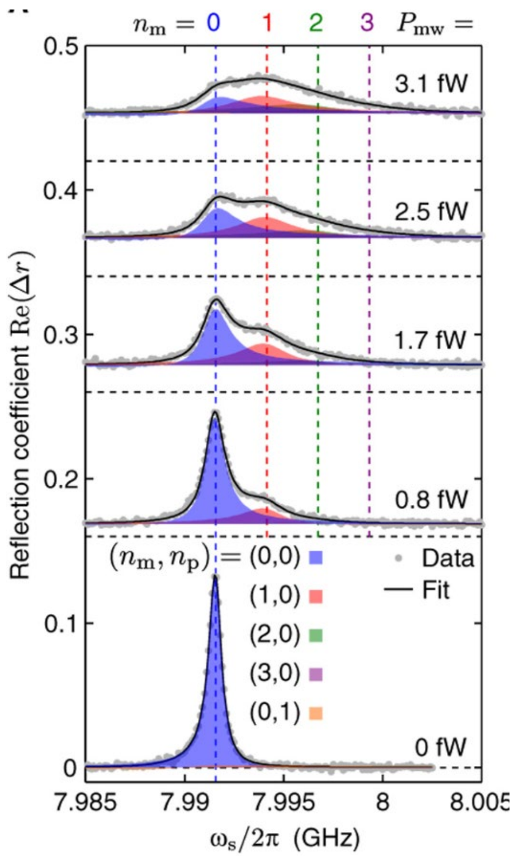


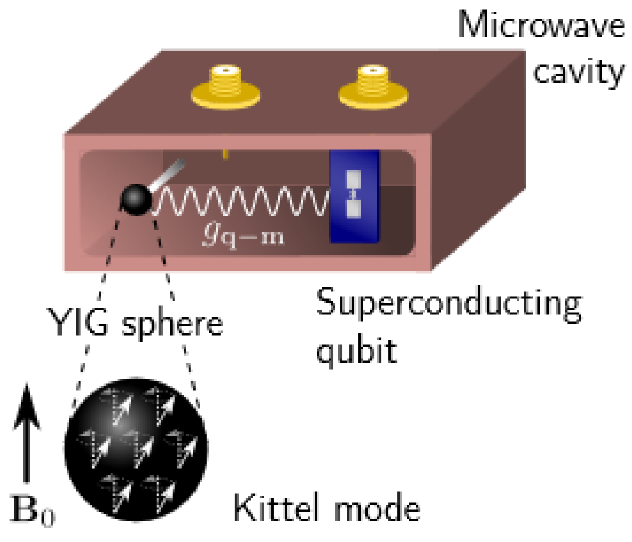
Even detuned Δk≠0



Cavity QED with bosonic excitations: two coupled harmonic oscillators







D. Lachance-Quirion et al, Science Advances 3 (2017)

Counting individual MAGNONS and SENSING!

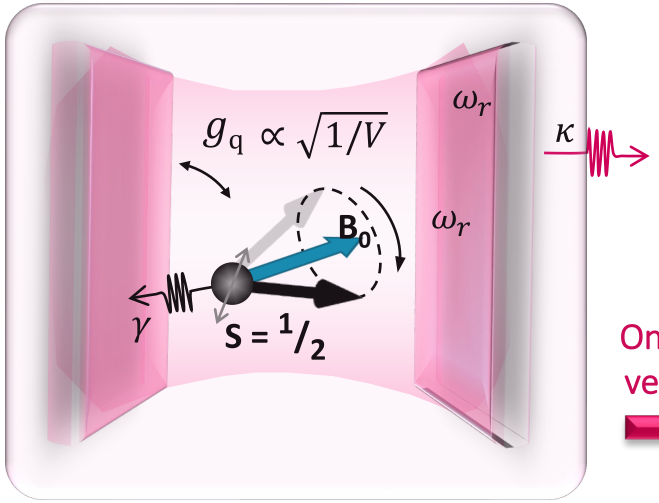
Outline

- Light-matter interaction and circuit QED

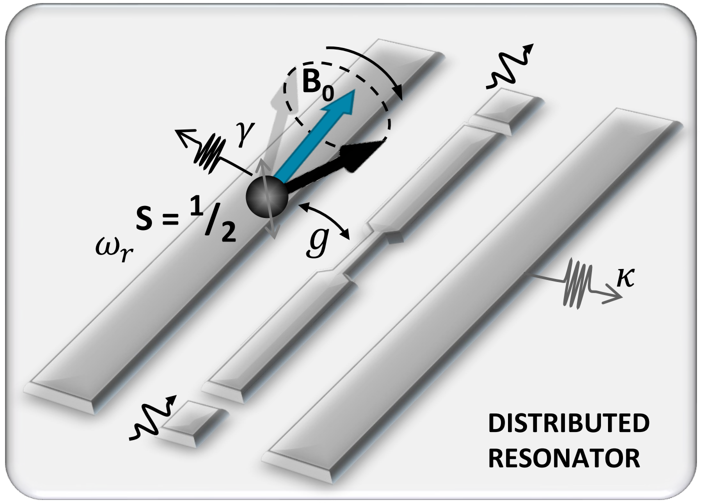
- Nanomagnets + **superconducting resonators**
  - Coupling to spins
  - Coupling to magnons

- Nanomagnets + **magnonic resonators**
  - GdW10 as spin qubit
  - SCB as cavity
  - Spin – magnon

How can we increase the coupling: From superconducting → to magnonic circuits



On-chip version



$$g = |\langle\uparrow|\boldsymbol{\mu}\,\boldsymbol{b}_{\text{rms}}|\downarrow\rangle| \propto b_{\text{rms}} = \sqrt{\frac{\mu_0 \hbar \omega_r}{2V}}$$

$$\frac{1}{4}\hbar\omega = \int_V \frac{1}{2}\frac{b_{\text{rms}}^2}{\mu_0} dV = \frac{1}{2}\frac{L\,i^2}{2}$$

Outline

- Light-matter interaction and circuit QED

- Nanomagnets + **superconducting resonators**

  - ☺ Coupling to spins
  - ☺ Coupling to magnons

- Nanomagnets + **magnonic resonators**

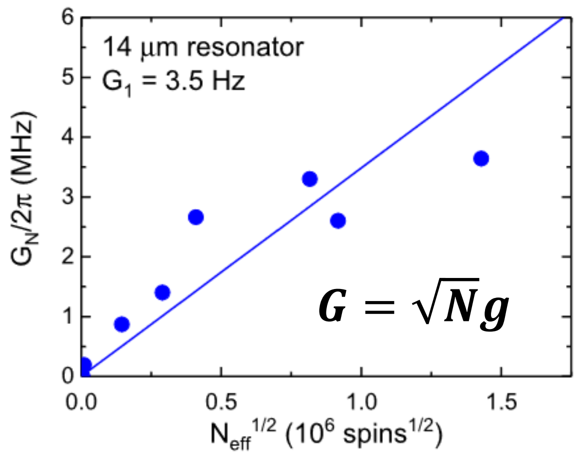
  - ☺ GdW10 as spin qubit
  - ☺ SCB as cavity
  - ☺ Spin – magnon

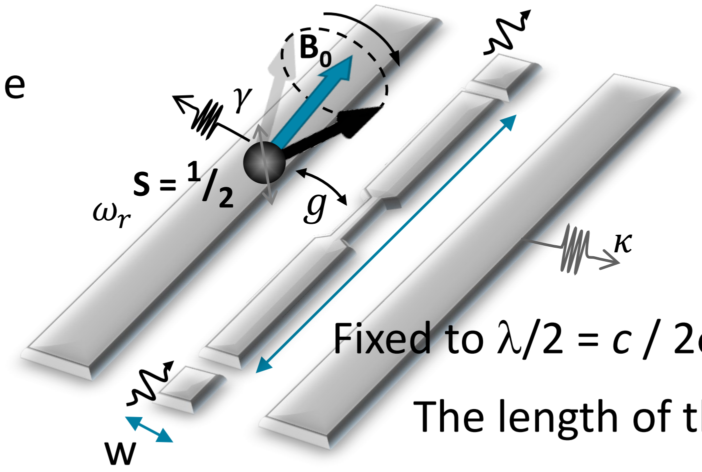
Spin – Photon coupling: the problem to couple to spin qubits

Coupling can be increased by increasing the number of qubits

$$G = \sqrt{\sum_i^N g_i^2}$$

Experimental demonstration





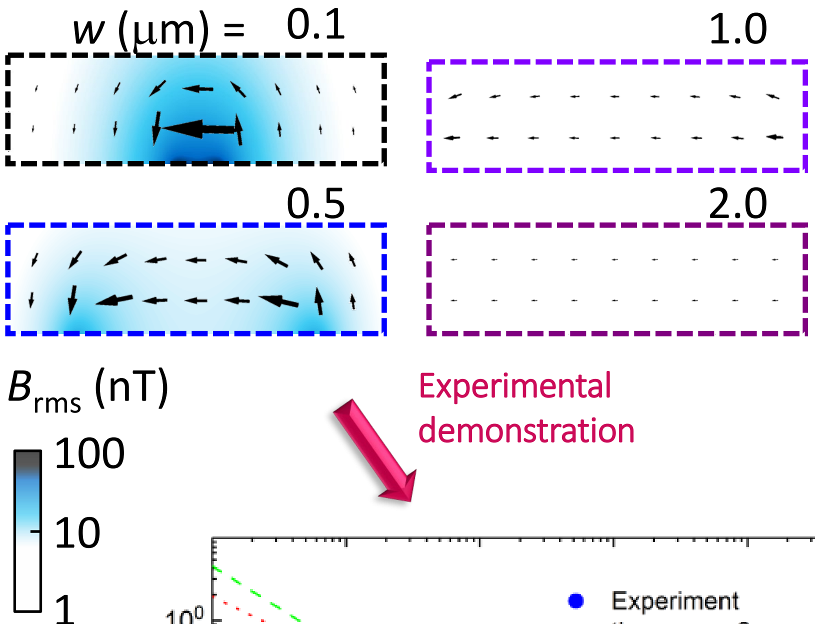
Fixed to $\lambda/2 = c / 2\omega$

The length of the resonator is fixed by frequency

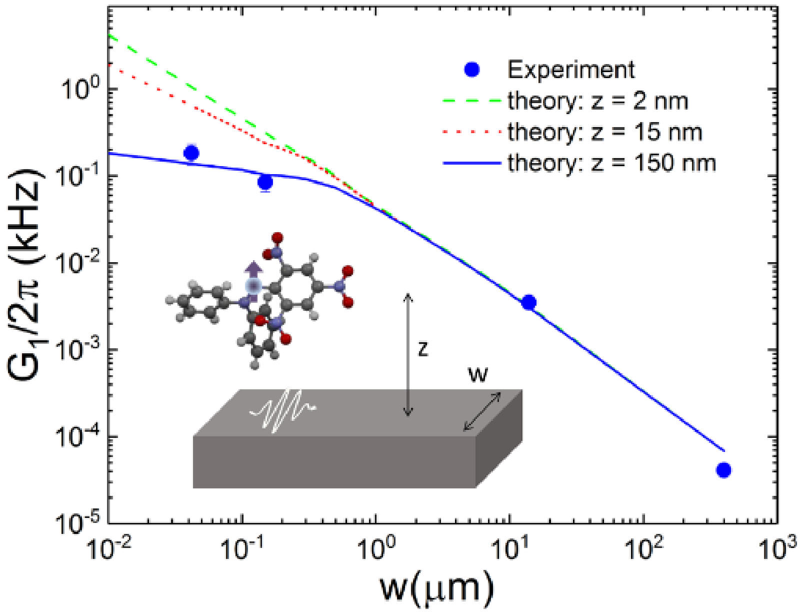
$$g \propto b_{rms} = \sqrt{\frac{\mu_0 \hbar \omega_r}{2V}}$$

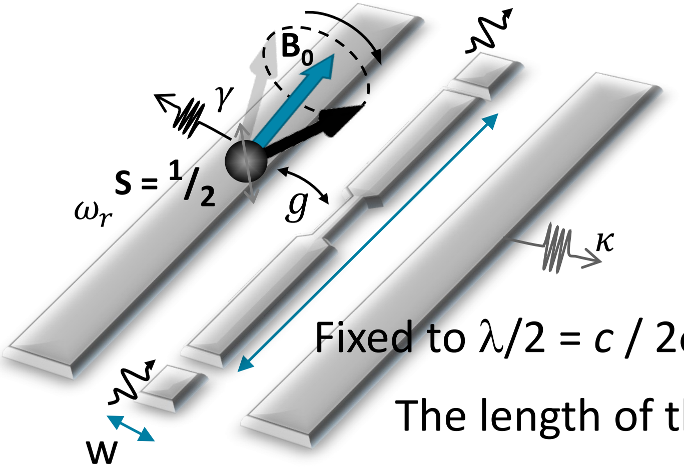
Gimeno, MJ M-P (...) F. Luis ACS Nano 2020, 14, 8707–8715

Spin – Photon coupling: the problem to couple to spin qubits



Experimental demonstration





Fixed to λ/2 = c / 2ω

The length of the resonator is fixed by frequency

The width can be decreased reducing the mode volume

$$g \propto b_{\rm rms} = \sqrt{\frac{\mu_0 \hbar \omega_r}{2V}} \sim \frac{\boldsymbol{\omega_r}}{\boldsymbol{r}} \sqrt{\frac{\boldsymbol{2\mu_0}}{\boldsymbol{\pi c}}}$$

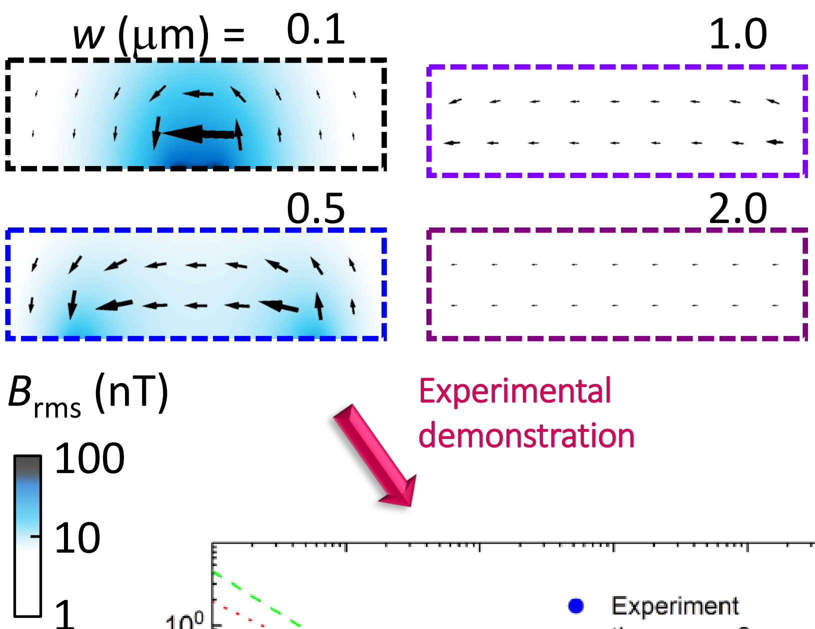
How can we estimate the z.p.f. field

$$\frac{1}{4}\hbar\omega = \int_V \frac{1}{2}\frac{b_{\rm rms}^2}{\mu_0} dV = \frac{1}{2}\frac{L\, i_{\rm rms}^2}{2} \quad \Rightarrow \quad i_{\rm rms} = \boldsymbol{\omega_r}\sqrt{\frac{\hbar\pi}{4Z_0}}$$

$$Z_0 = \frac{\pi}{2} L \omega_r$$

Gimeno, MJ M-P (...) F. Luis ACS Nano 2020, 14, 8707–8715

Spin – Photon coupling: the problem to couple to spin qubits



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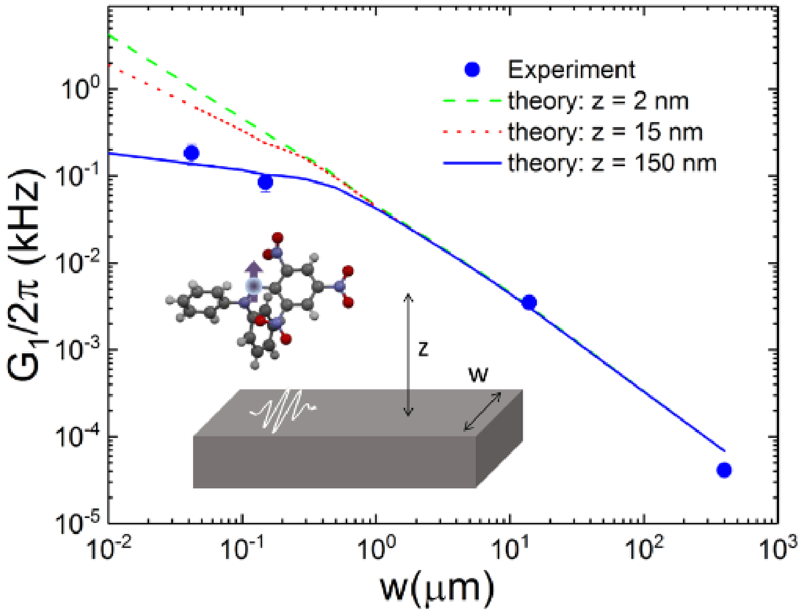
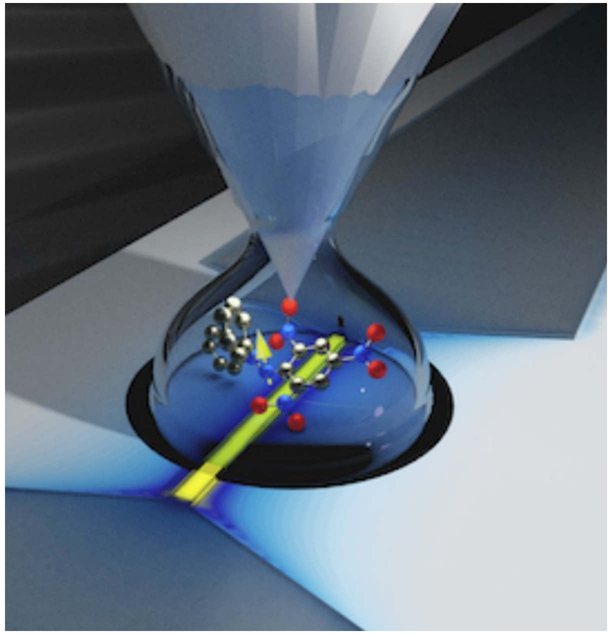
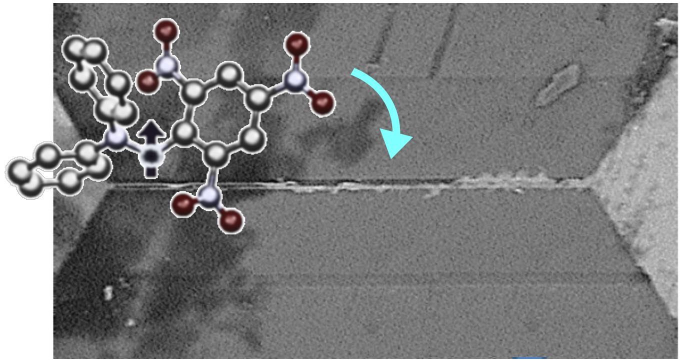
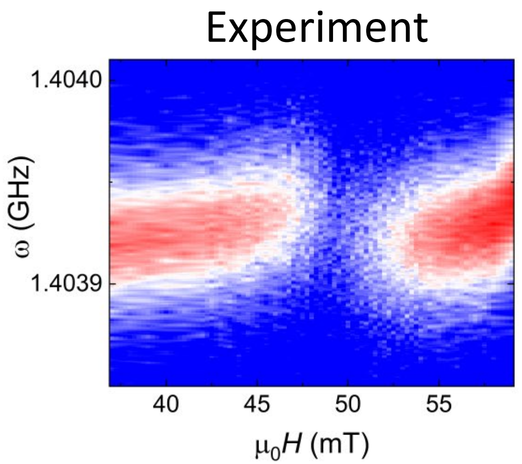
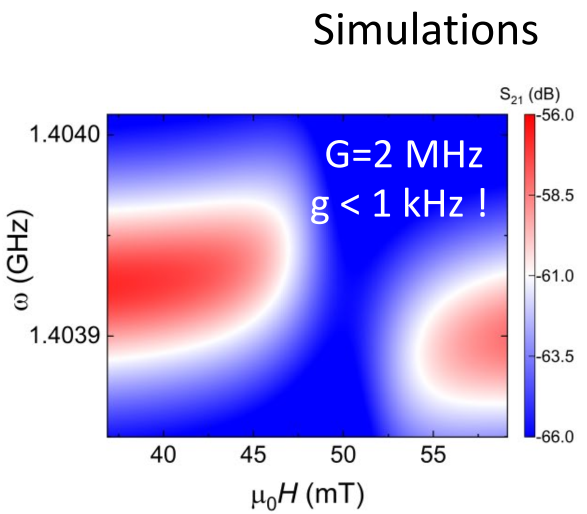


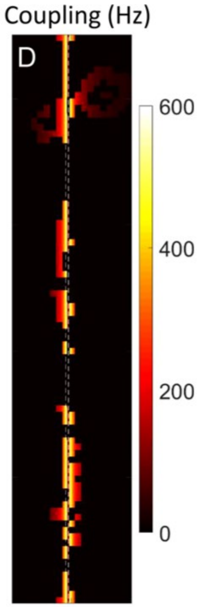


Dip pen distribution of s=1/2 molecules (DPPH)



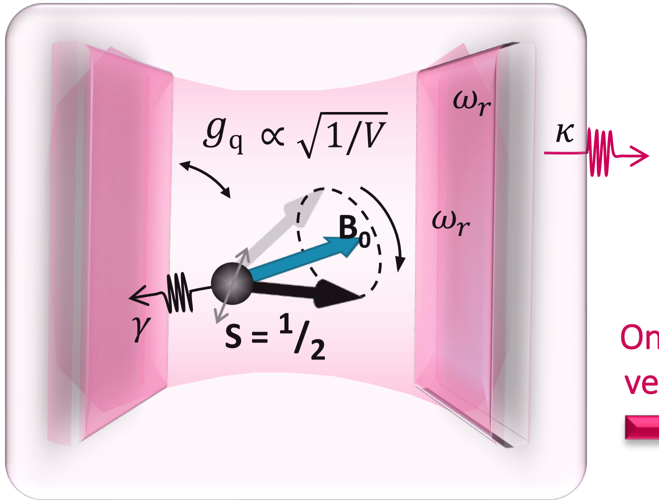




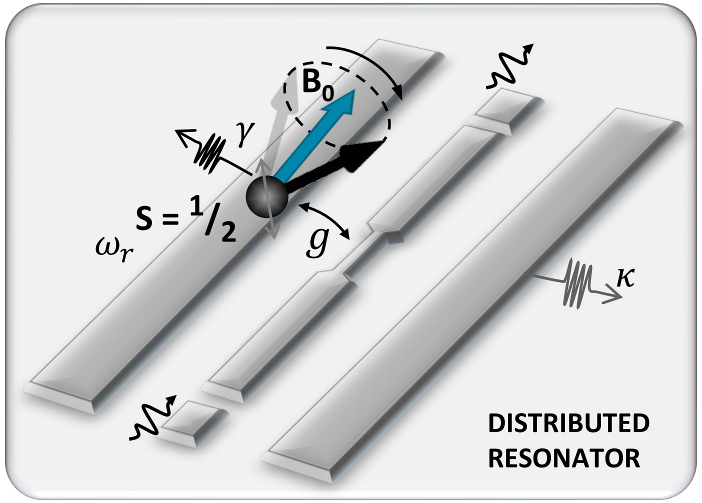


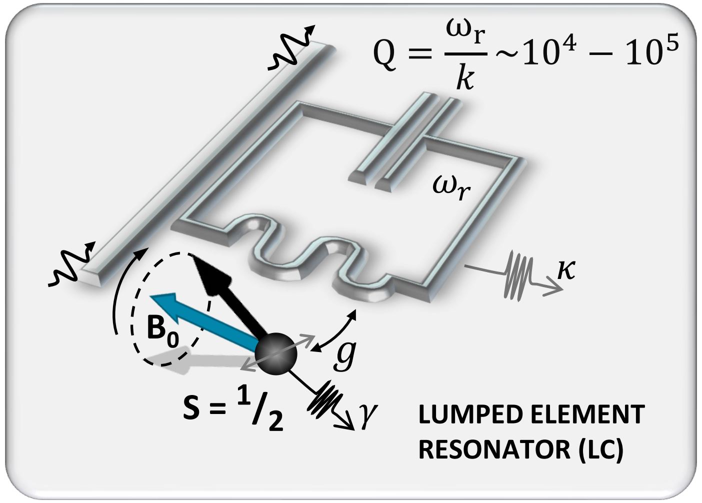
Gimeno, MJ M-P (...) F. Luis ACS Nano 2020, 14, 8707–8715

How can we increase the coupling: From superconducting → to magnonic circuits



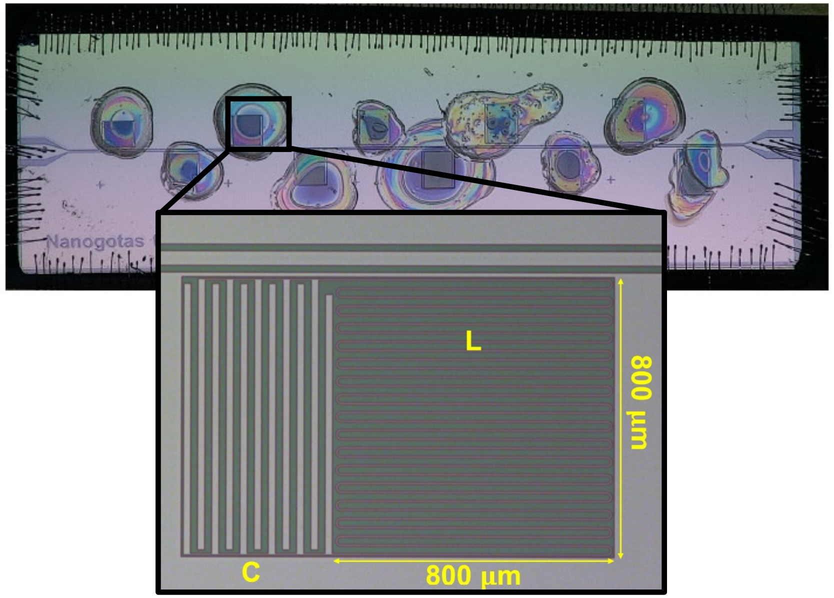
On-chip version





How can we increase the coupling: From superconducting → to magnonic circuits

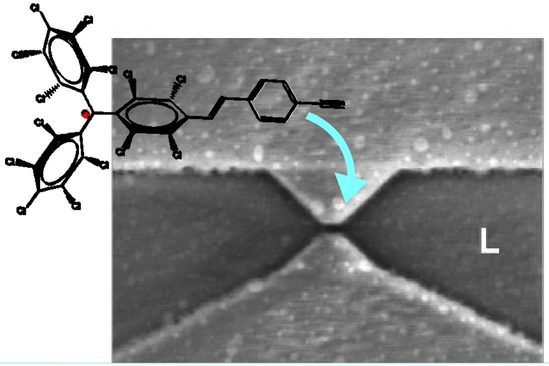
INMA



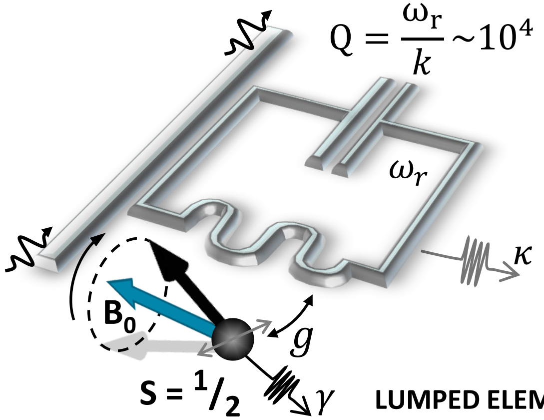
How can we estimate the z.p.f. field

$$\frac{1}{4}\hbar\omega = \int_V \frac{1}{2}\frac{b_{\rm rms}^2}{\mu_0}dV = \frac{1}{2}\frac{L\,i_{\rm rms}^2}{2} \quad \xrightarrow{Z_0 = L\omega_r} \quad i_{\rm rms} = \omega_r\sqrt{\frac{\hbar}{Z_0}} = \sqrt{\frac{\hbar\omega_r}{L}}$$

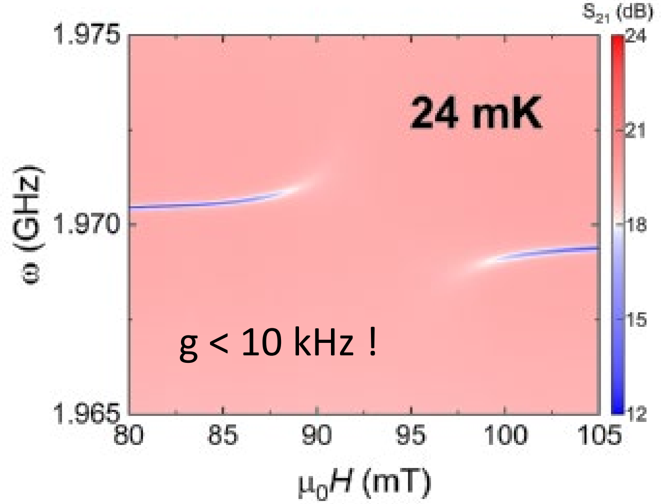
Coupling increases by one order of magnitude !!!



$$Q = \frac{\omega_r}{k} \sim 10^4 - 10^5$$



LUMPED ELEMENT RESONATOR (LC)



We are still far from coupling to one individual spin qubit (we need MHz)

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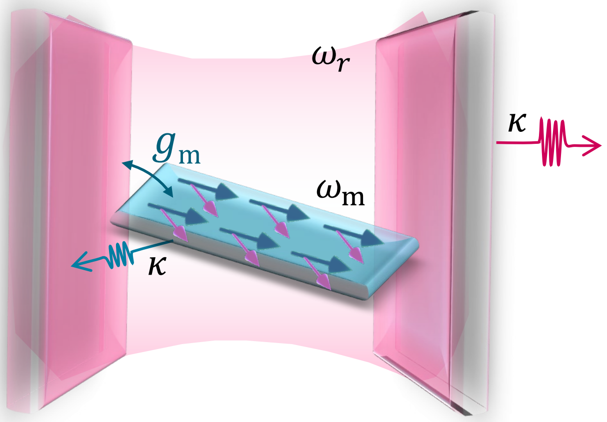
Magnon nanocavities: how can we estimate the magnon-photon coupling



The hamiltonian, harmonic magnon mode:

$$H = \underbrace{\hbar\omega_c a_c^+ a_c}_{H_{\text{cavity}}} + \underbrace{\hbar\omega_v a_m^+ a_m}_{H_{\text{vortex}}} + \underbrace{\hbar g\,(a_c^+ + a_m)(a_m^+ + a_c)}_{H_{\text{coupling}}}$$

Zeeman magnon-cavity coupling: $H_{\text{coupling}} = \sum_j \mu_j B(r_j) = V M_j B(r_j)$

cavity quant: $\hat{B} = b(a_c^+ + a_c)$

magnon quant: $\hat{M} = m\,(a_m^+ + a_m)$

→ $\hbar g = Vmb$

Classical driving feld: $H_{\text{coupling}} = \hbar g 2\alpha \cos\omega t\,(a_m^+ + a_m)$

Response of the driven HO: $M(t) = m\langle a_m^+ + a_m\rangle = \underbrace{\frac{\hbar g}{Vb}\frac{\hbar g 2\alpha}{\hbar\Delta\omega/2}}_{\Delta M}\sin\omega t$

one photon → $$g = \frac{b_{\text{rms}}}{2}\sqrt{\frac{V\chi\Delta f_m}{\hbar}}$$

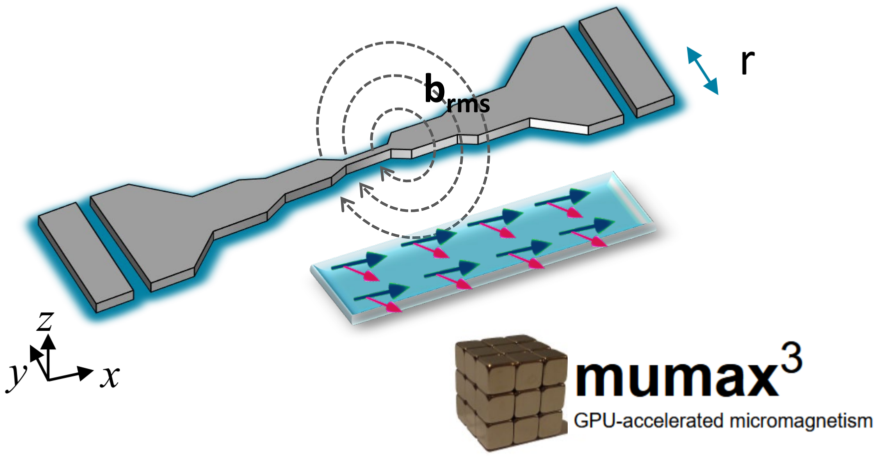
$\chi(f_m) = \Delta M/b$

One needs to know the susceptibility of the mode

MJ M-P & D Zueco, ACS photonics 2019

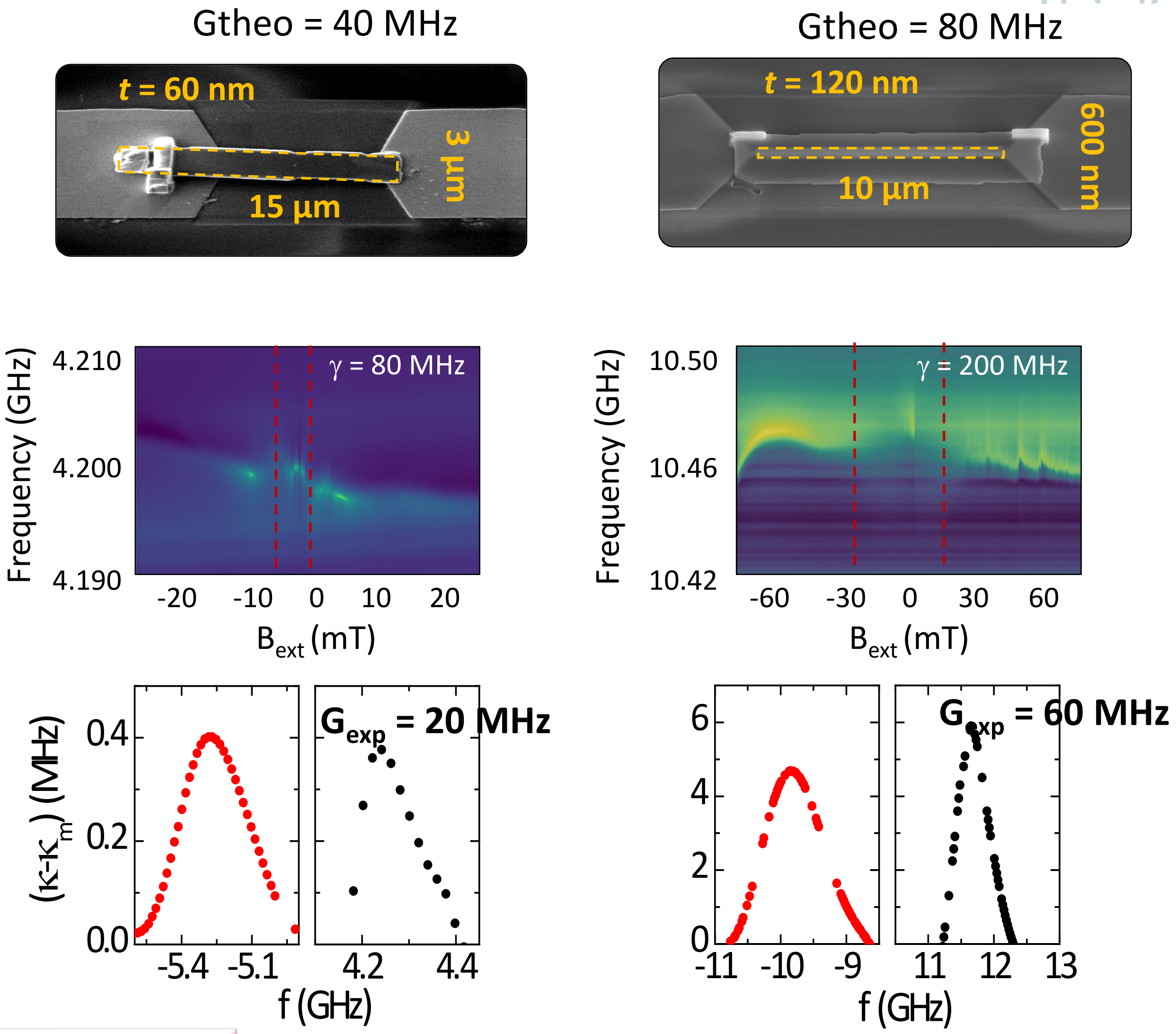
Spin – Photon coupling: Coupling to ferromagnetic spins

Fixed to $\lambda/2 = c / 2\omega$



Coupled spins

$$G = \sqrt{\frac{\gamma\, v_{cell}}{4\hbar} \sum_{j}^{N_{cell}} \Delta \boldsymbol{M}_j \cdot \boldsymbol{b}_{rms}(r_j)}$$



Not in strong coupling

Martinez-Losa, (...) MJ M-P Phys Rev Appl, 2022

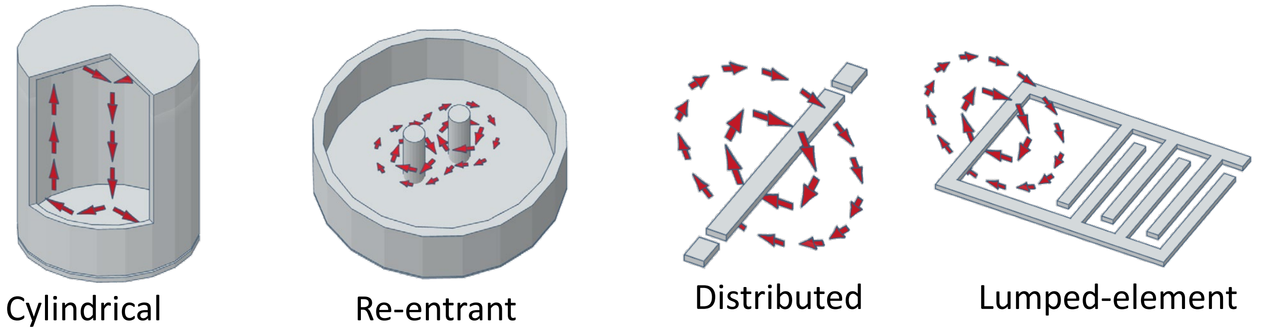
$$\kappa = \tilde{\kappa} + \frac{\gamma g^2}{(\omega_p - \omega_m)^2 + \gamma^2}$$

In the weak coupling regime:

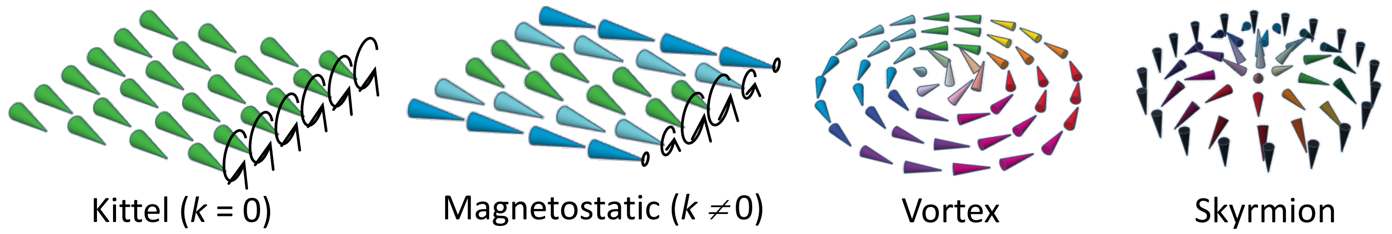
MJ M-P & D Zueco, ACS photonics 2019

Magnon nanocavities: how can we estimate the magnon-photon coupling

Real cavities yield strongly non-homogeneous profiles…



That excite non homogeneous magnon modes. Also magnetic textures can be stabilized



Spin – Photon coupling: cavity quantum electrodynamics with MUMAX3-cQED

available on GitHub

Heisenberg equation of motion for spin:

$$\dot{\hat{\boldsymbol{S}}}_i = \frac{i}{\hbar}[\hat{H}, \hat{\boldsymbol{S}}_i] \quad \xrightarrow{\text{Large spin limit}} \quad \dot{\boldsymbol{m}}_i = -\gamma \boldsymbol{m}_i \times \boldsymbol{B}_{\text{eff}}(\boldsymbol{r}_i) \quad + \text{DAMPING}$$

We can now simulate the response of M upon the action of a cavity field B_{rms}. Hamiltonian:

$$\hat{H} = \gamma \sum_i \hat{\boldsymbol{S}}_i \cdot \boldsymbol{B}_{\text{eff}}(\boldsymbol{r}_i) + \gamma \sum_i \hat{\boldsymbol{S}}_i \cdot \boldsymbol{B}_{\text{rms}}(\boldsymbol{r}_i)\left(\hat{a} + \hat{a}^\dagger\right) + \hbar\omega_c \hat{a}^\dagger \hat{a}$$

Corresponding Heisenberg eq. of motion

$$\begin{cases} \dot{\hat{\boldsymbol{S}}}_i = -\gamma \hat{\boldsymbol{S}}_i \times \boldsymbol{B}_{\text{eff}}(\boldsymbol{r}_i) - \gamma\left(\hat{\boldsymbol{S}}_i \times \boldsymbol{B}_{\text{rms}}(\boldsymbol{r}_i)\right)\left(\hat{a} + \hat{a}^\dagger\right), \\ \dot{\hat{a}} = -i\omega_c \hat{a} - i\frac{\gamma}{\hbar}\sum_i \hat{\boldsymbol{S}}_i \cdot \boldsymbol{B}_{\text{rms}}(\boldsymbol{r}_i). \end{cases}$$

Expectation value

$$\begin{cases} \dot{\boldsymbol{S}}_i = -\gamma \boldsymbol{S}_i \times \boldsymbol{B}'_{\text{eff}}(\boldsymbol{r}_i), \\ \dot{\alpha} = -i\omega_c \alpha - i\frac{\gamma}{\hbar}\sum_i \boldsymbol{S}_i \cdot \boldsymbol{B}_{\text{rms}}(\boldsymbol{r}_i), \end{cases}$$

$$\boldsymbol{B}'_{\text{eff}}(\boldsymbol{r}_i) = \boldsymbol{B}_{\text{eff}}(\boldsymbol{r}_i) + \boldsymbol{B}_{\text{rms}}\Gamma(t)$$

Memory term

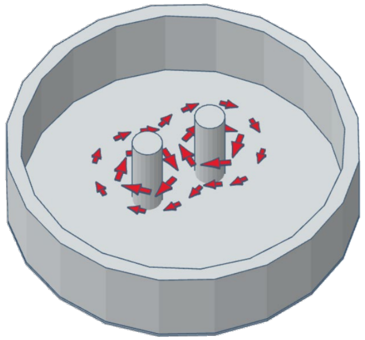
$$\Gamma(t) = -\frac{2M_s V_c}{\hbar}\boldsymbol{B}_{\text{rms}}\int_0^t e^{-\kappa(\tau-t)}\sin(\omega_c(\tau-t))\boldsymbol{m}(\tau)d\tau$$

Martinez-Losa, (...) MJ M-P sumbitted to Computer Physics Commun.

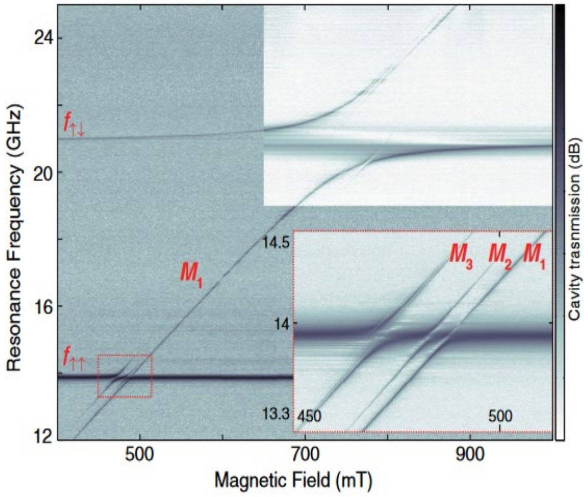
Spin – Photon coupling: cavity quantum electrodynamics with MUMAX3-cQED

Soon available on GitHub

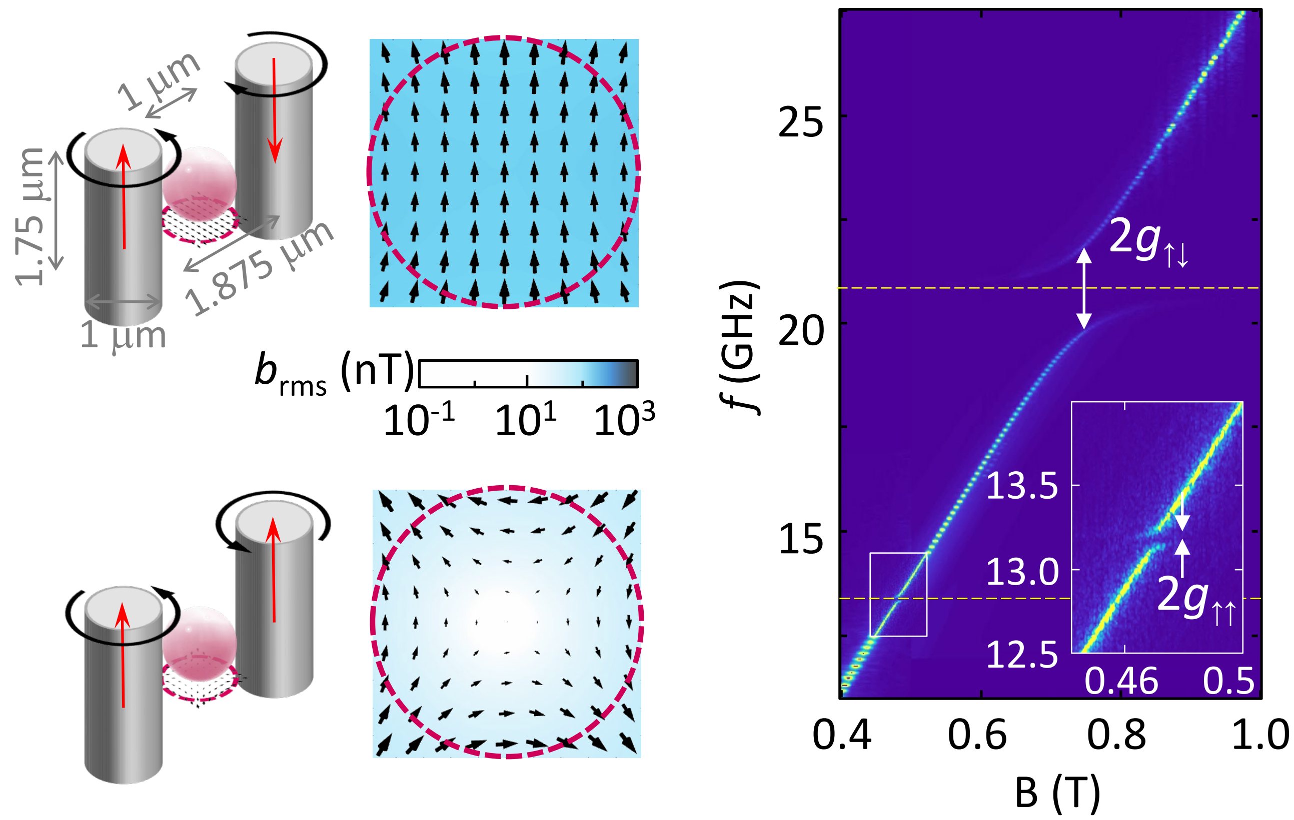
Reproduce EXPERIMENT by:



M. Goryachev,, Physical Review Applied 2 (5) (2014)



NUMERICAL RESULTS:

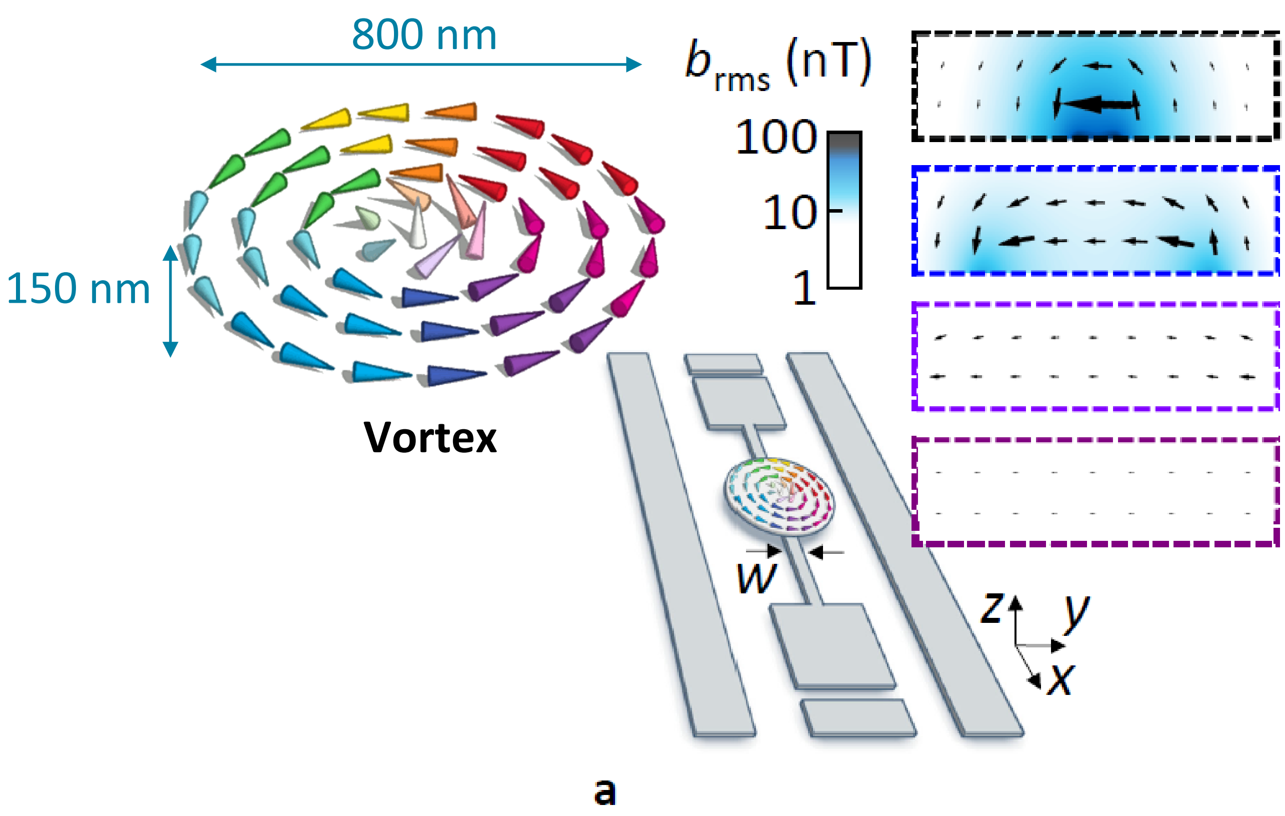


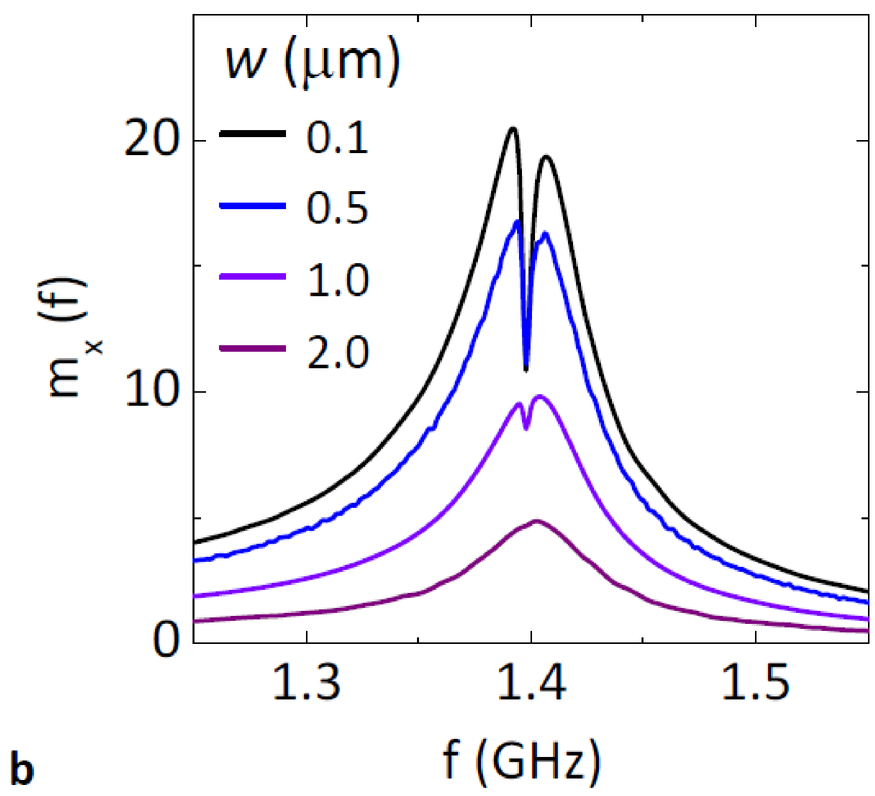
Martinez-Losa, (...) MJ M-P SUBMITTED TO Computer Physics Commun.

Spin – Photon coupling: cavity quantum electrodynamics with MUMAX3-cQED

Soon available on GitHub

Magnetic textures + non-homogeneous magnetic profile





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Outline

INMA

❖ Light-matter interaction and circuit QED

❖ Nanomagnets + **superconducting resonators**

- ☺ Coupling to spins
- ☺ Coupling to magnons

❖ Nanomagnets + **magnonic resonators**

- ☺ GdW10 as spin qubit
- ☺ SCB as cavity
- ☺ Spin – magnon

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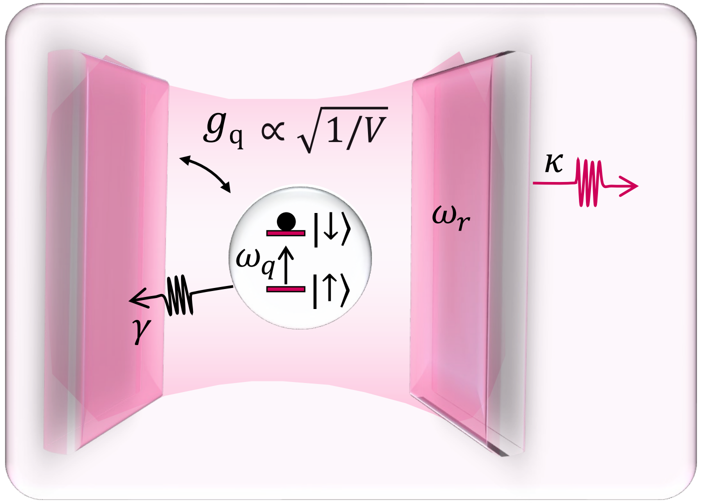
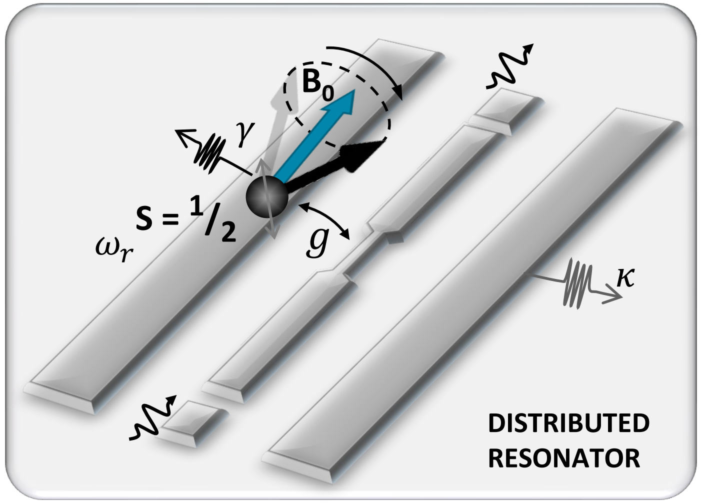
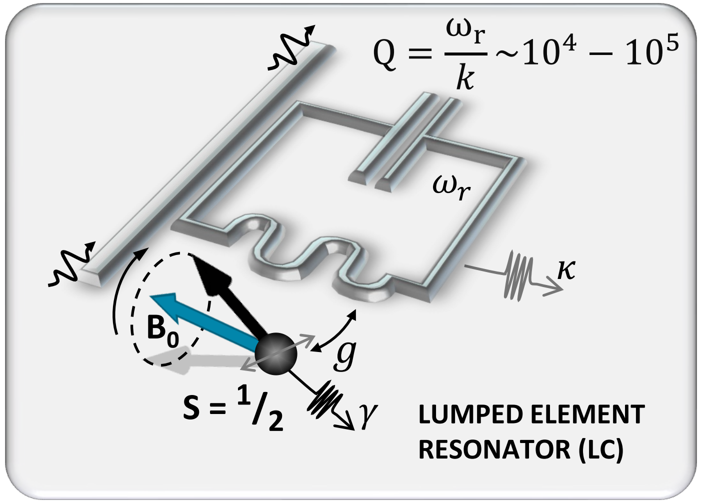
How can we increase the coupling: From superconducting → to magnonic circuits



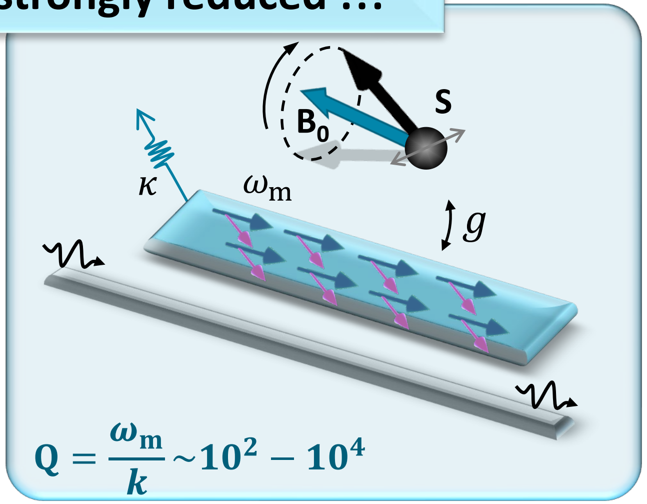
On-chip version





Magnon version

Mode volumen can be strongly reduced !!!



Magnon nanocavities

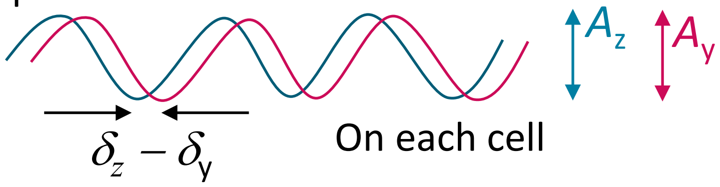
mumax^3

GPU-accelerated micromagnetism

Use excitation field $B = \beta \sin(\omega t)$

$$\Lambda(\beta) = \sqrt{\frac{2 g_e \mu_B M_z}{v_{\text{cell}} \sum_n A_z(\mathbf{r}_n) A_y(\mathbf{r}_n) |\sin(\delta_z(\mathbf{r}_n) - \delta_y(\mathbf{r}_n))|}}$$

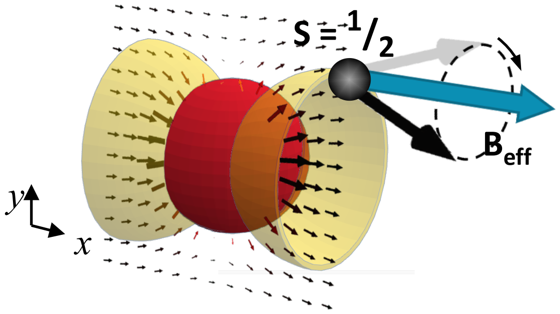
Response:

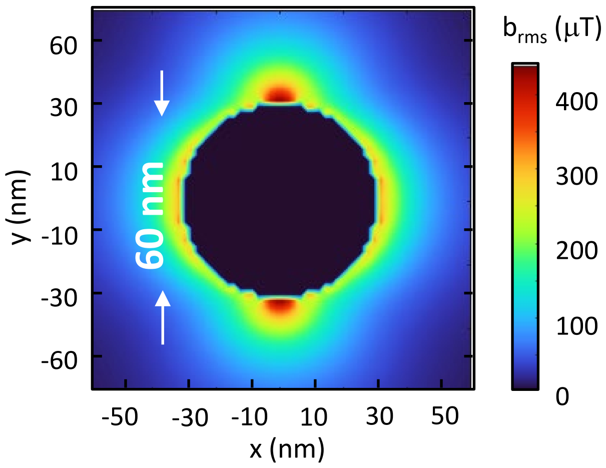


On each cell

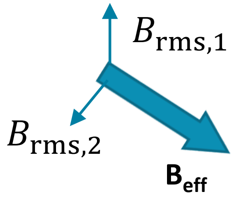
$$\rightarrow \; \boldsymbol{B}_{\text{rms}} = \Lambda(\beta)\, \boldsymbol{B}^{\text{ac}}_{\text{stray}}(\beta)$$

Ferromagnetic spheres:





Relevant zpf to calculate coupling to ½ spin:

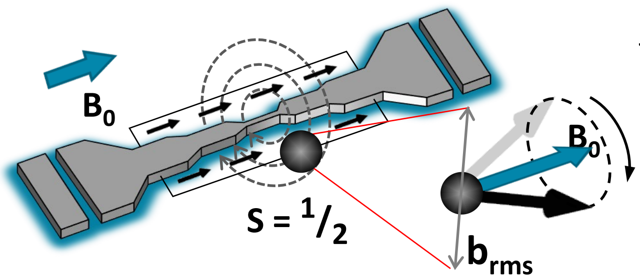


$$B_{\text{rms}} = \sqrt{B^2_{\text{rms},1} + B^2_{\text{rms},2}}$$

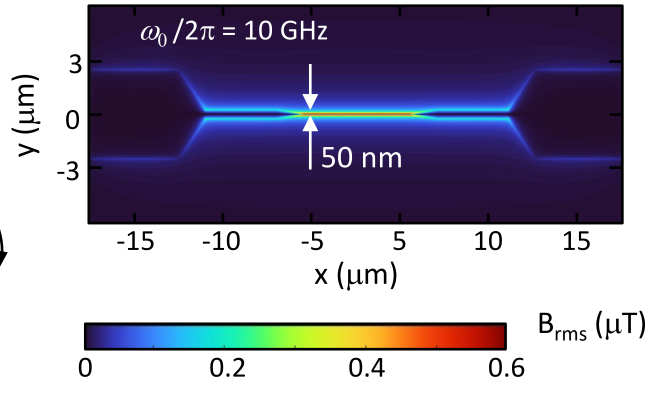
Gonzalez-Gutierrez, MJ M-P ACS Nano 2023

Magnon nanocavities

Superconducting cavities:

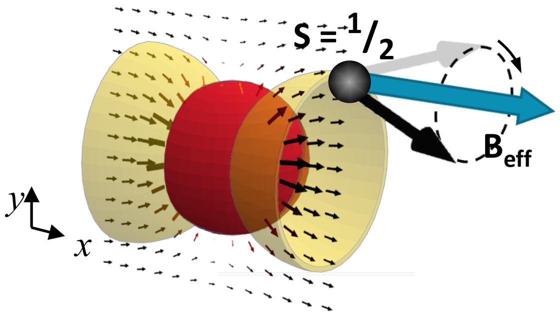


$g_{max}/2\pi = \mu_B B_{rms} \leq 10$ kHz

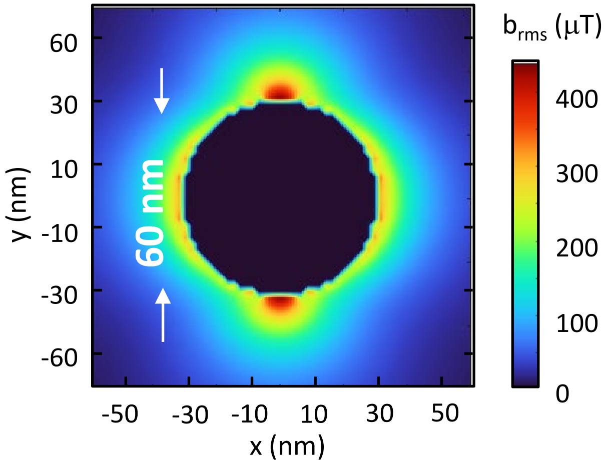


$$g \propto b_{rms} = \sqrt{\frac{\mu_0 \hbar \omega_r}{2V}}$$

Ferromagnetic spheres:

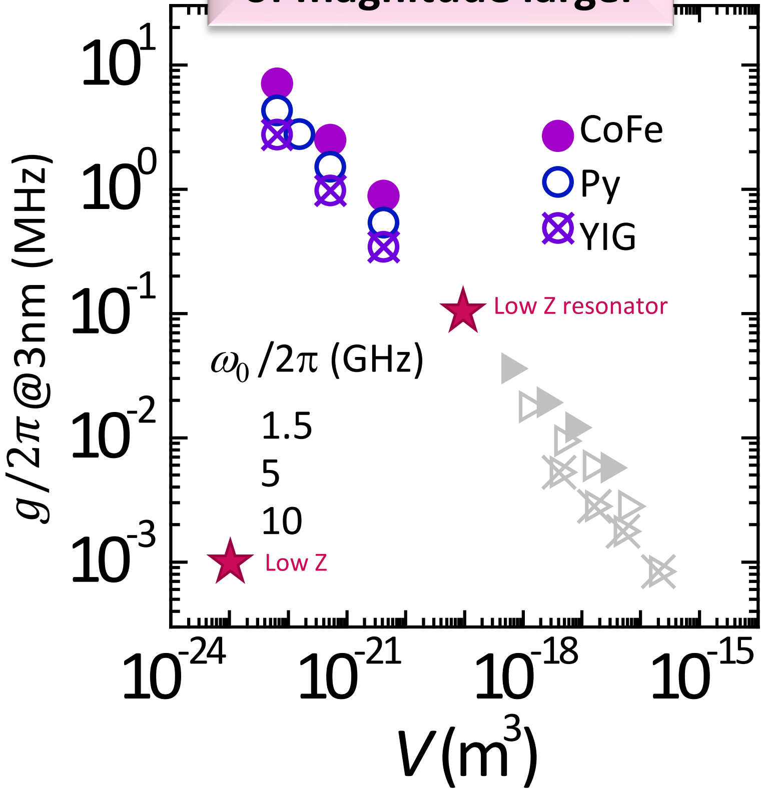


$g_{max}/2\pi = \mu_B B_{rms}$ ~ MHz for S=1/2 !!!



$$g \propto M_{rms} = \sqrt{\frac{g_e M_s}{2\mu_B V}}$$

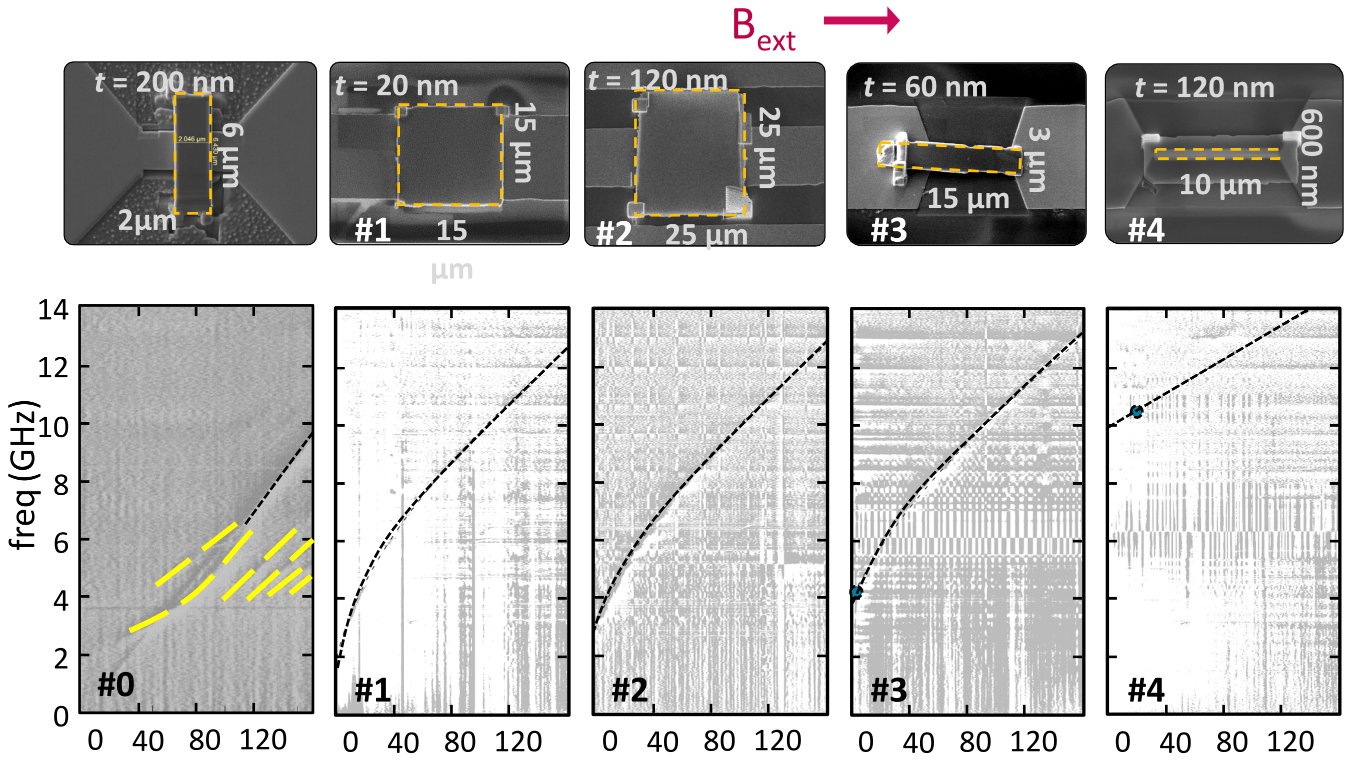
g can be three orders of magnitude larger

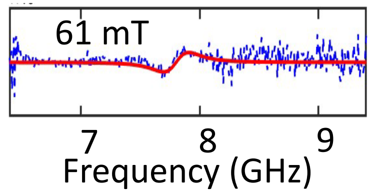


Gonzalez-Gutierrez, MJ M-P ACS Nano 2023

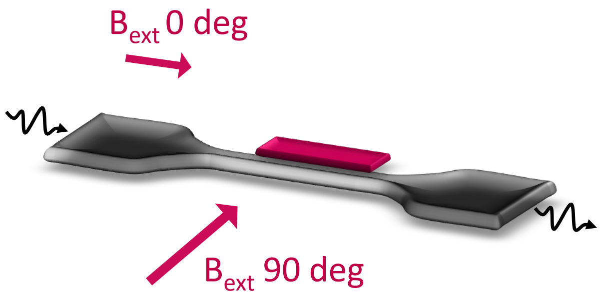
Metallic ferromagnets: permalloy and FeCo

Broad band ferromagnetic resonance at mK temperatures

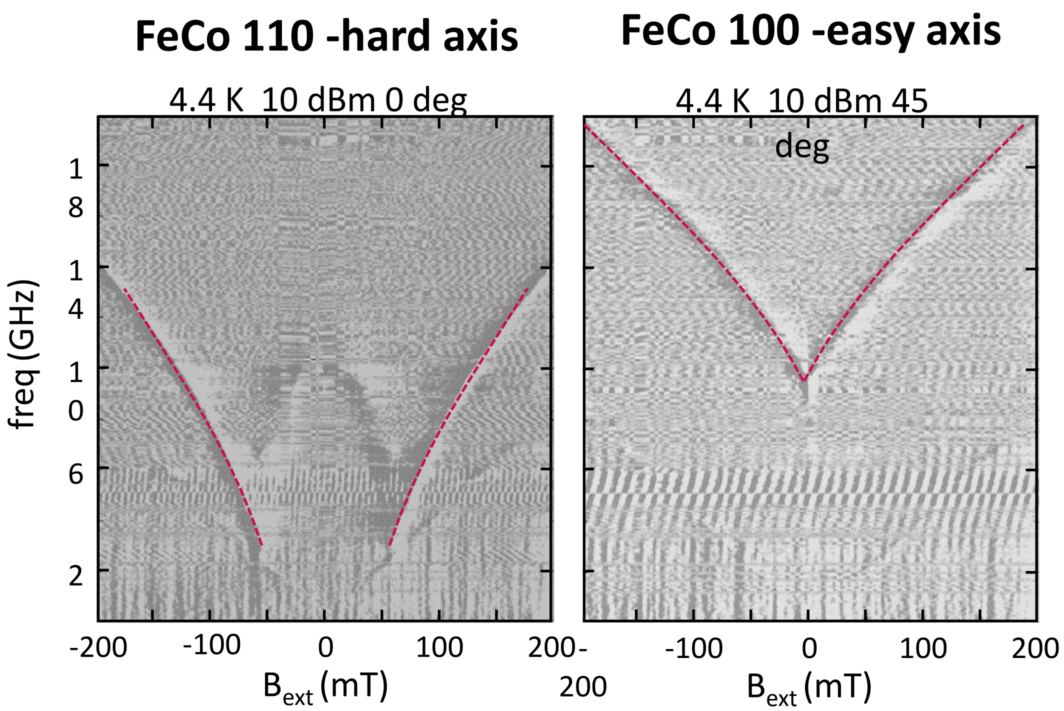


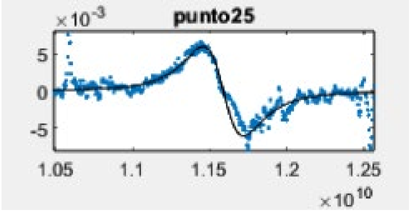


$\alpha \sim 0.01$ **Q~50**



(collaboration with A. Butera (Bariloche))





$\alpha \sim 0.01$ **Q~50**

Shape and magnetocrystallyne anisotropy allows to tune the resonance frequency !!

Martinez-Losa, (...) MJ M-P Phys Rev Appl 2023

Insulating ferrimagnets: Yttrium Iron Garnet at mK temperatures with no GGG

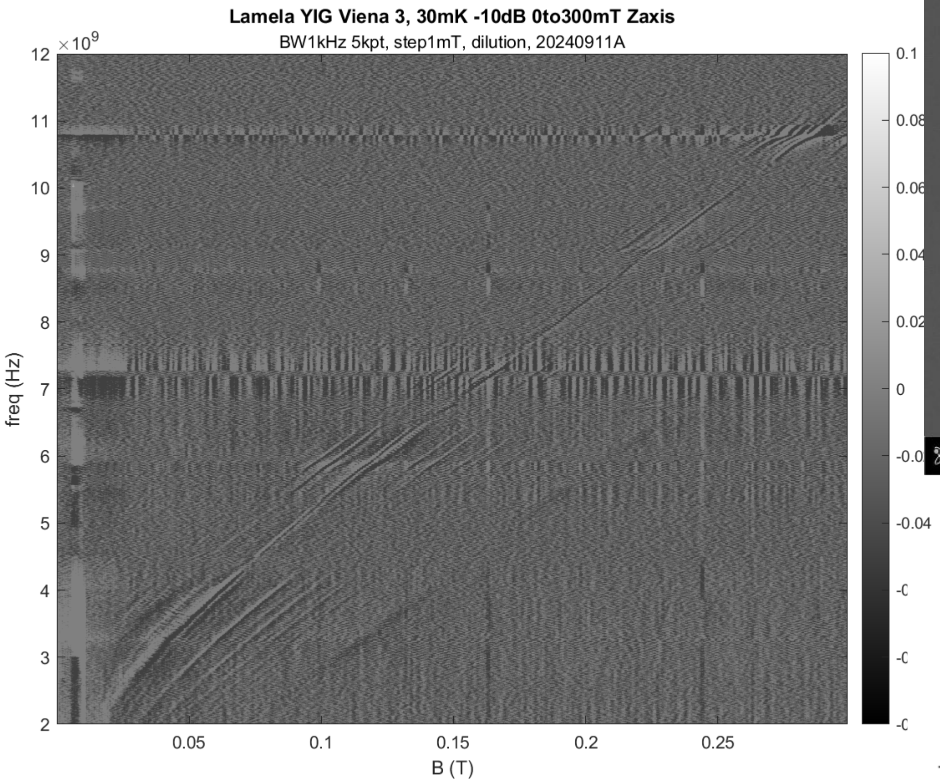
Using YIG at Room temperature: $\alpha \sim 0.0001$ **Q~5000**

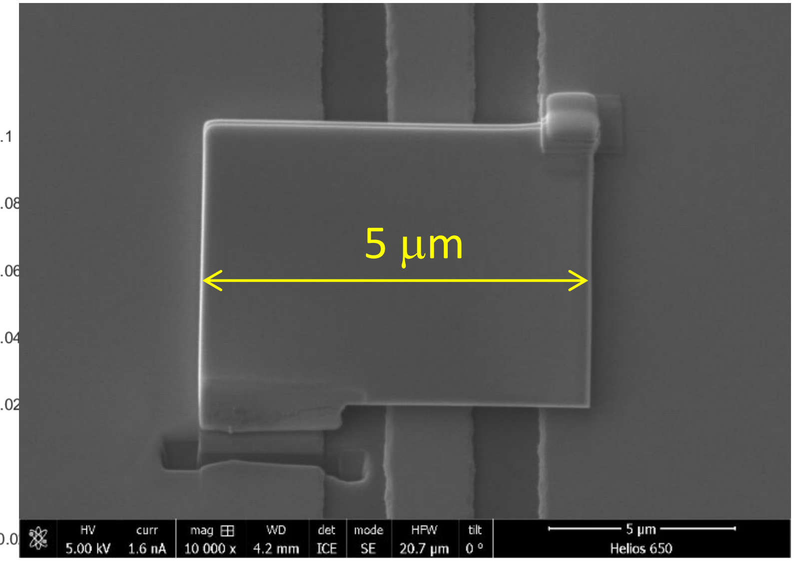
Using nanopatterned YIG at 30 mK:

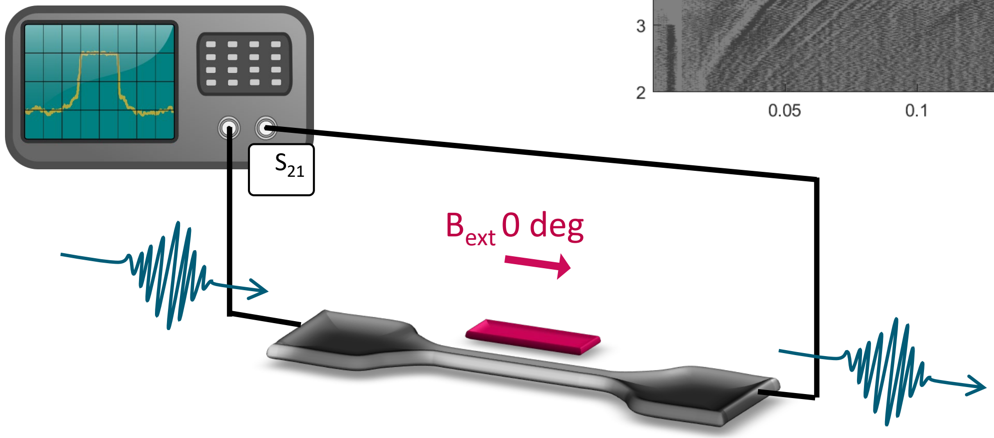
$\alpha \sim 0.0007$

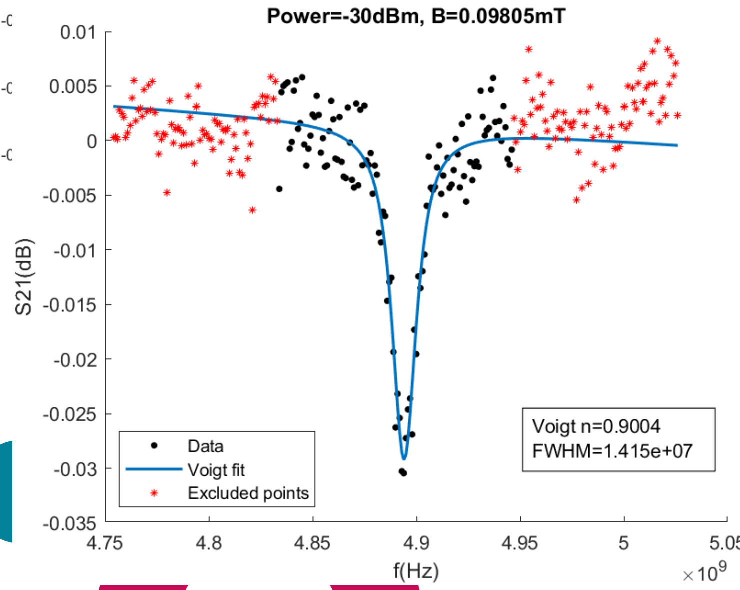
Q~700

Very encouraging !!









(collaboration with A. Chumak, Vienna)

Outline

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    - Coupling to magnons
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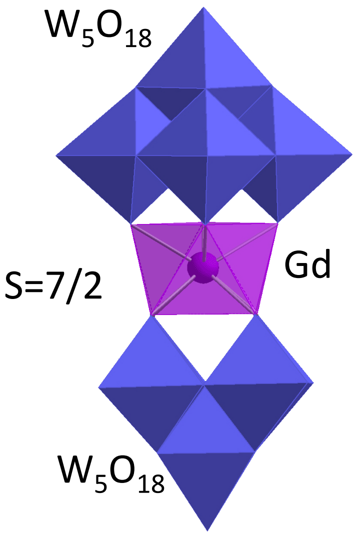
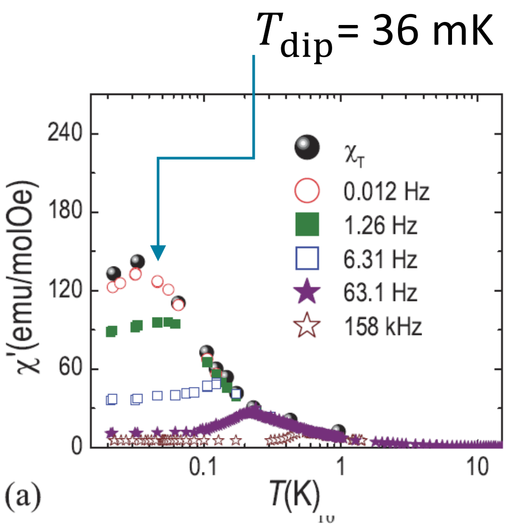
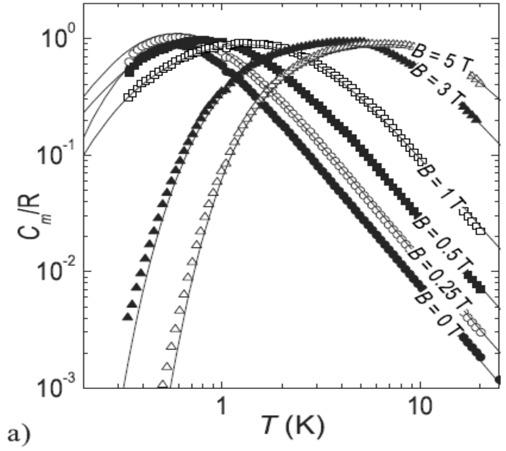
GdW10 a prototype spin qubit

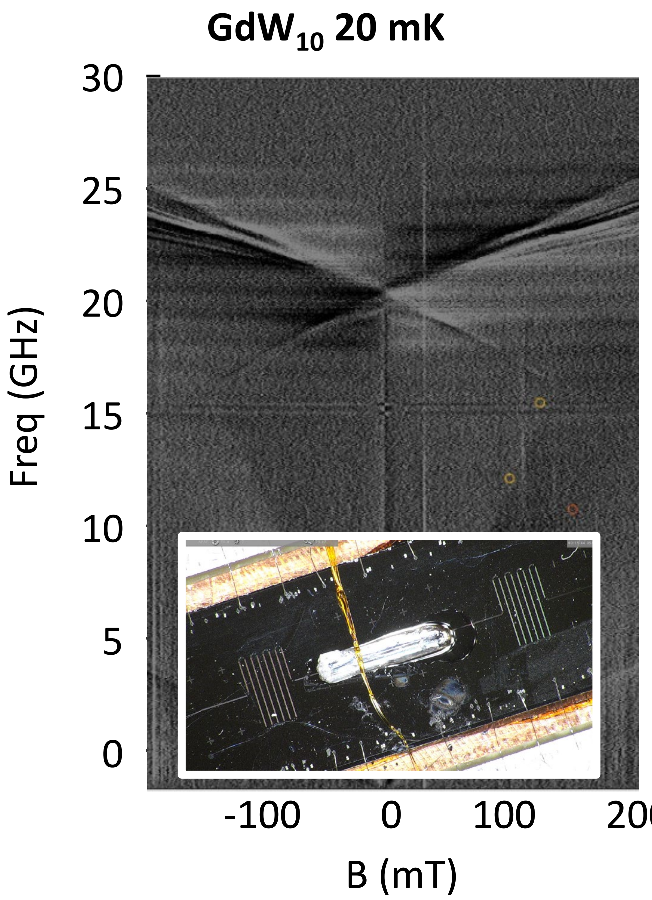
GdW10 has a well defined easy axis. Hamiltonian: $\mathrm{H} = B_2^0\mathbf{O}_2^0 + B_4^4\mathbf{O}_4^4 - g\mu_B\left[\frac{1}{2}(S_+ + S_-)(H_x + iH_y) + S_zH_z\right]$

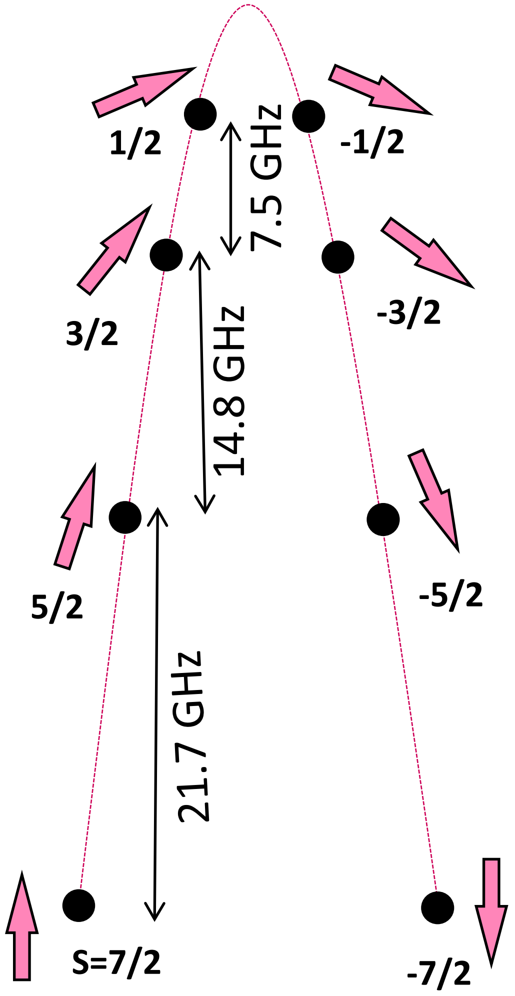
B_2^0=-0.059 K B_4^4= 4e-4 K











- Relatively large Zero Field Spliting of ~40 GHz (2 K)
- Diplar order at 36 mK (very weak dipolar interactions)

(collaboration with E. Coronado ICMOL)

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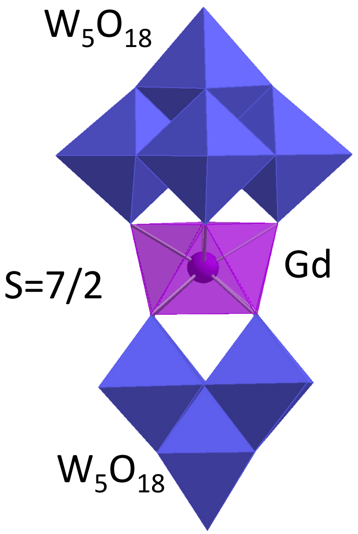

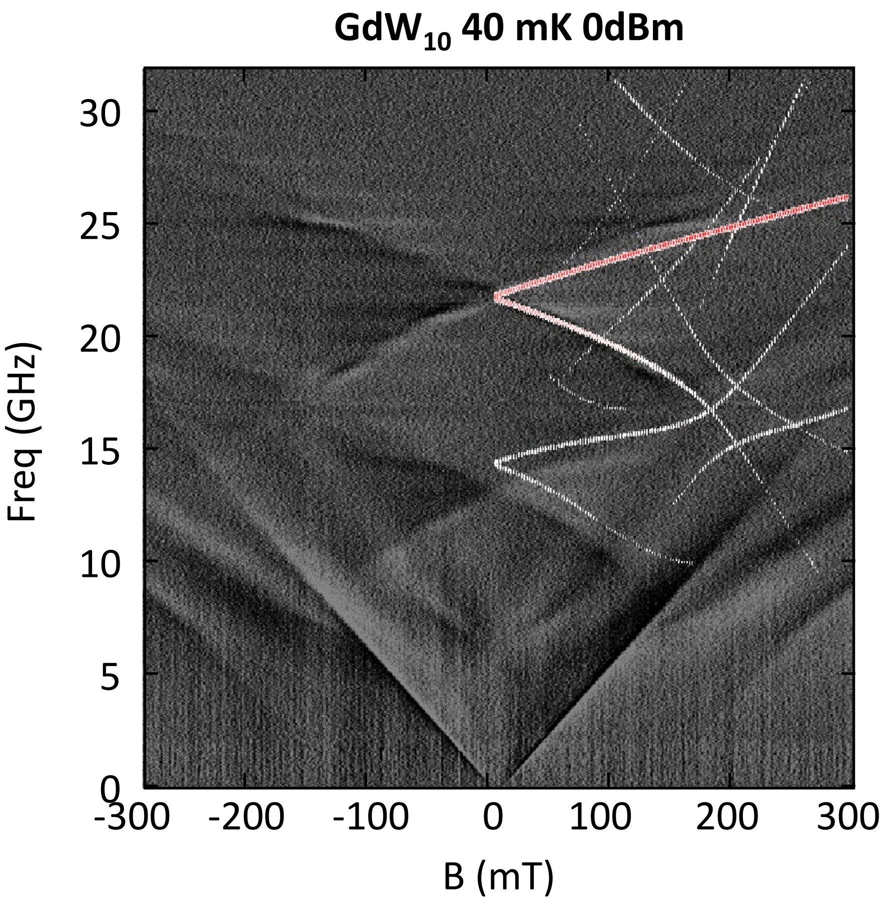

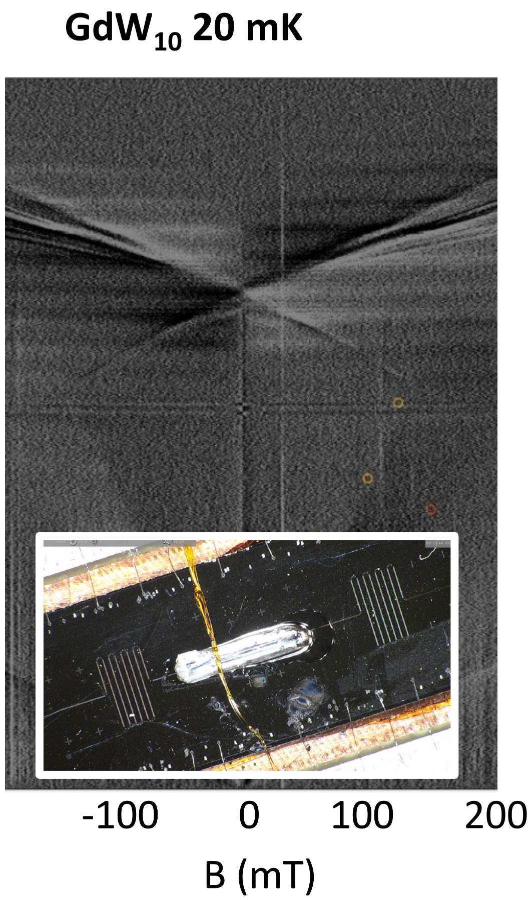

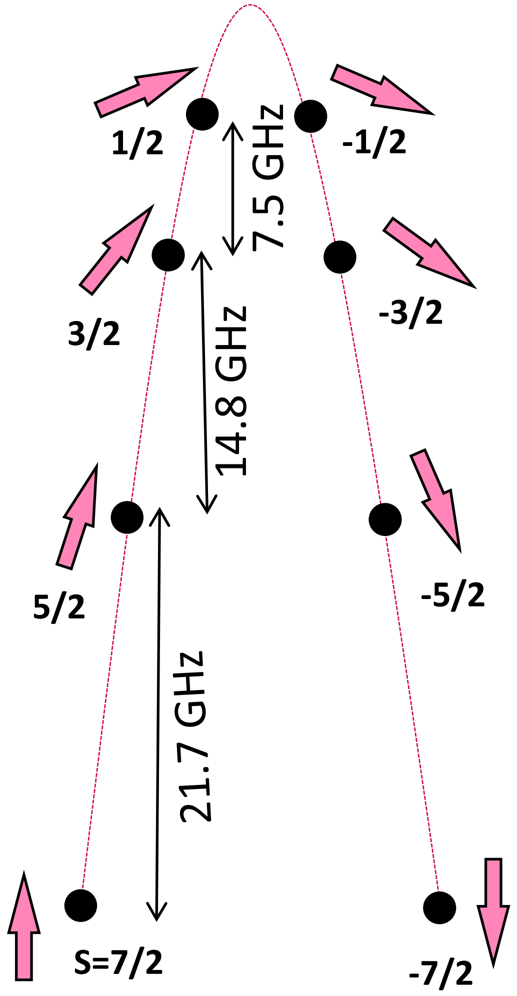

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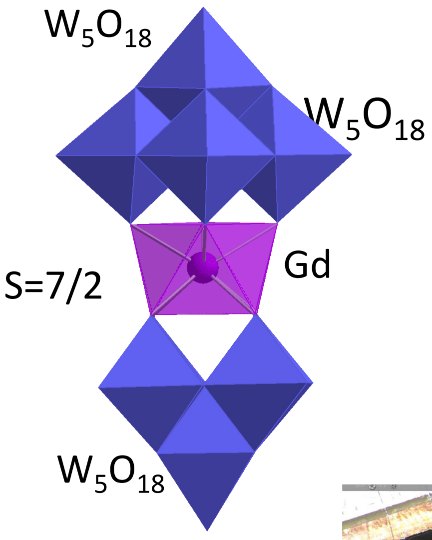
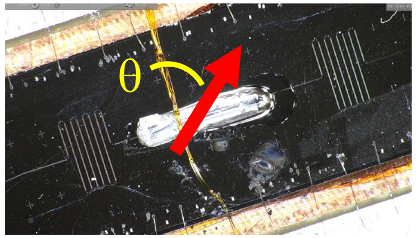
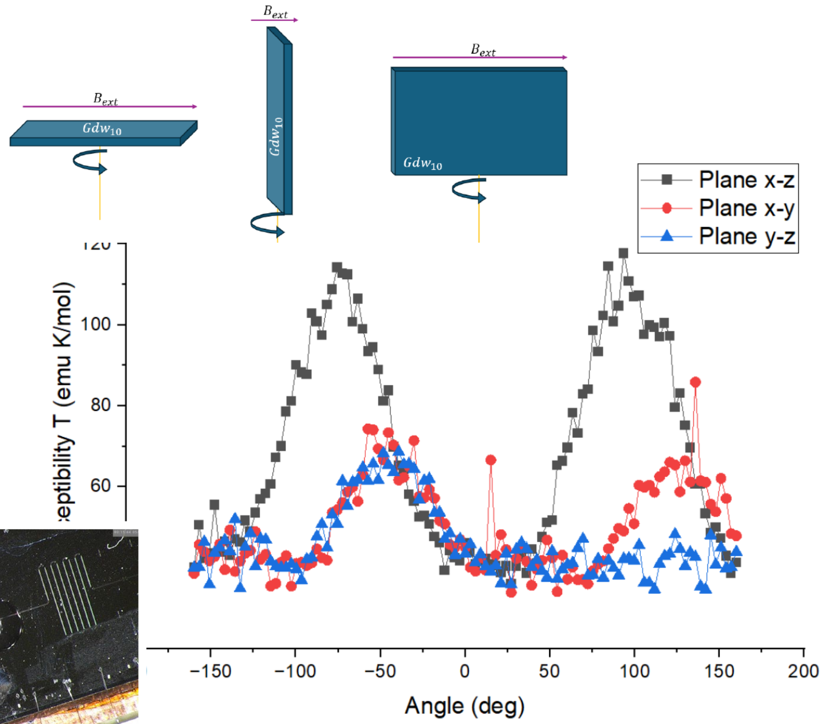
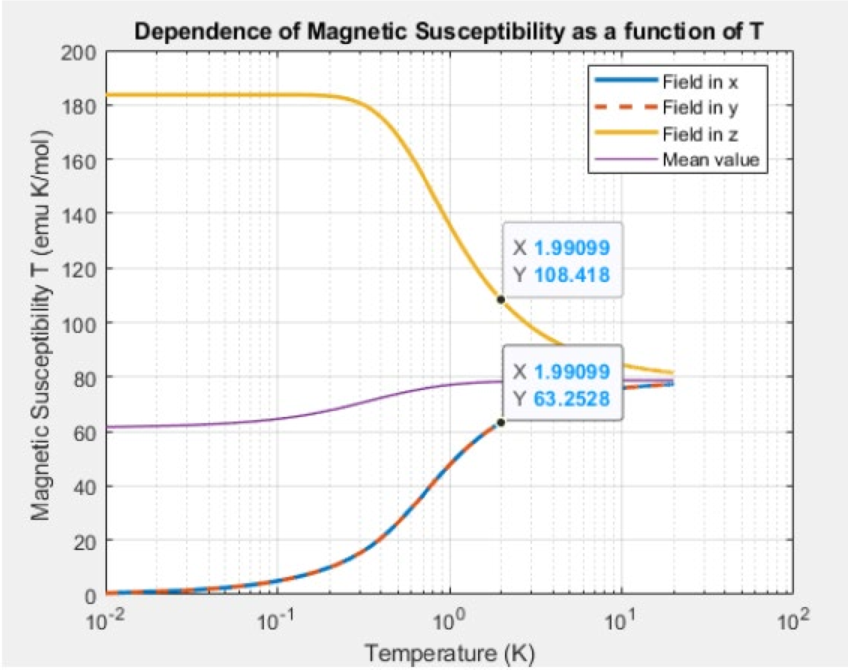
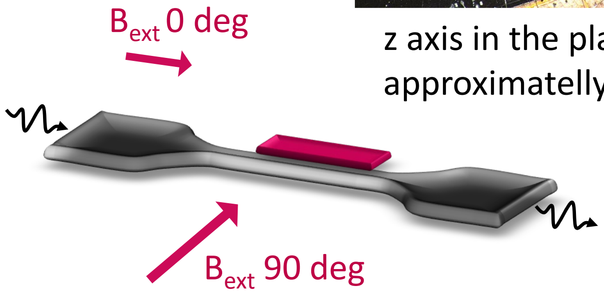




z axis in the plane at approximatelly 45 deg







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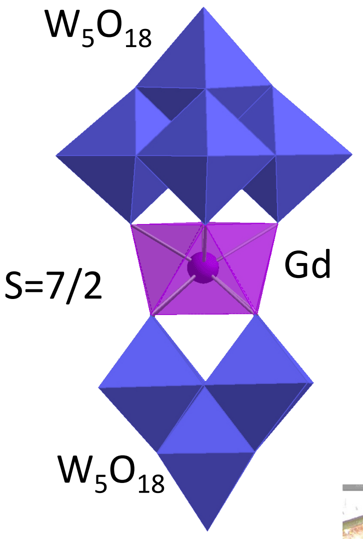
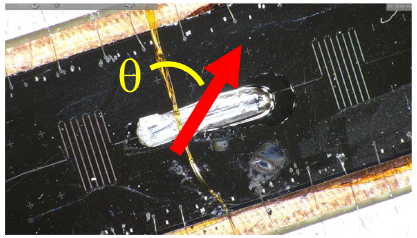
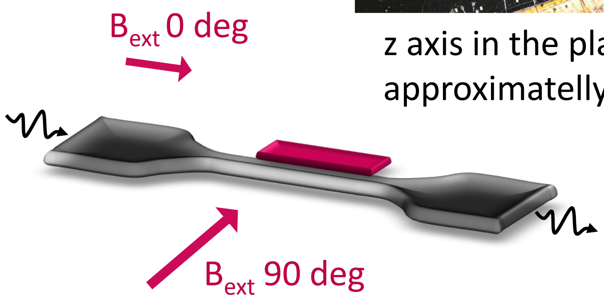
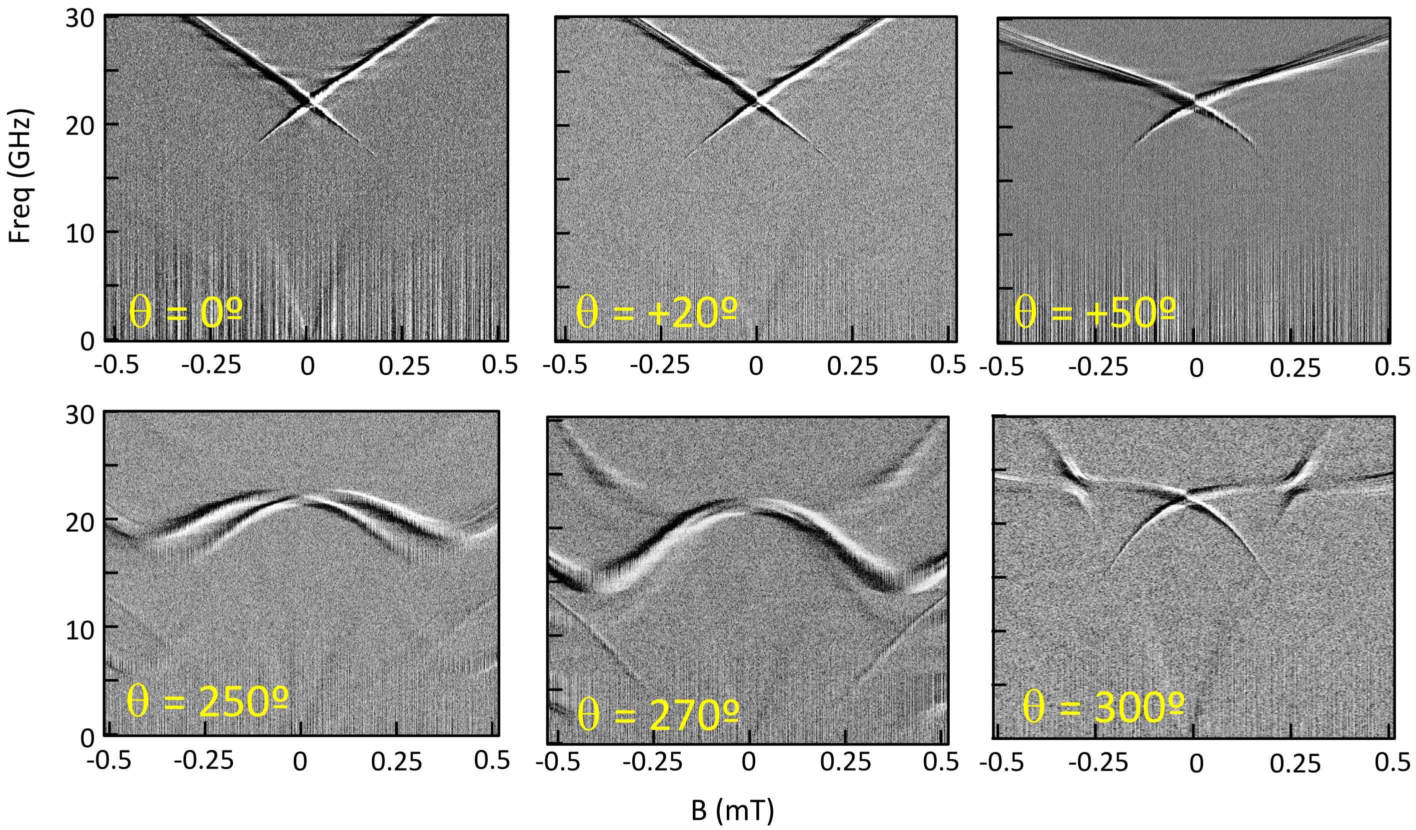




z axis in the plane at approximatelly 45 deg



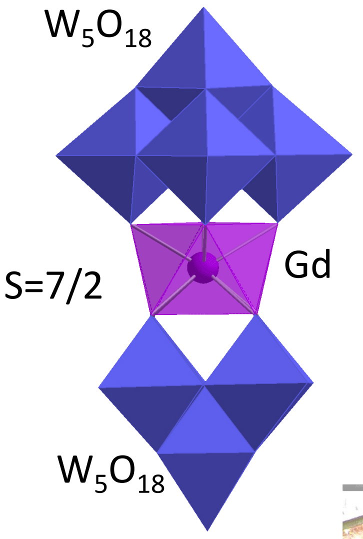


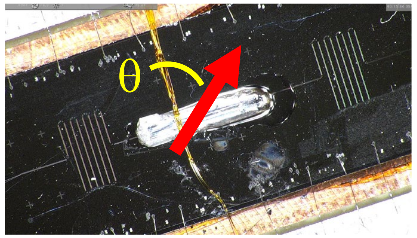
(collaboration with E. Coronado ICMOL)

GdW10 a prototype spin qubit

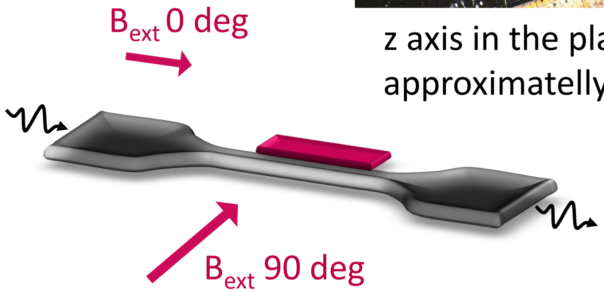
GdW10 has a well defined easy axis. Hamiltonian: $\mathrm{H} = B_2^0\mathbf{O}_2^0 + B_4^4\mathbf{O}_4^4 - g\mu_B\left[\frac{1}{2}(S_+ + S_-)(H_x + iH_y) + S_zH_z\right]$

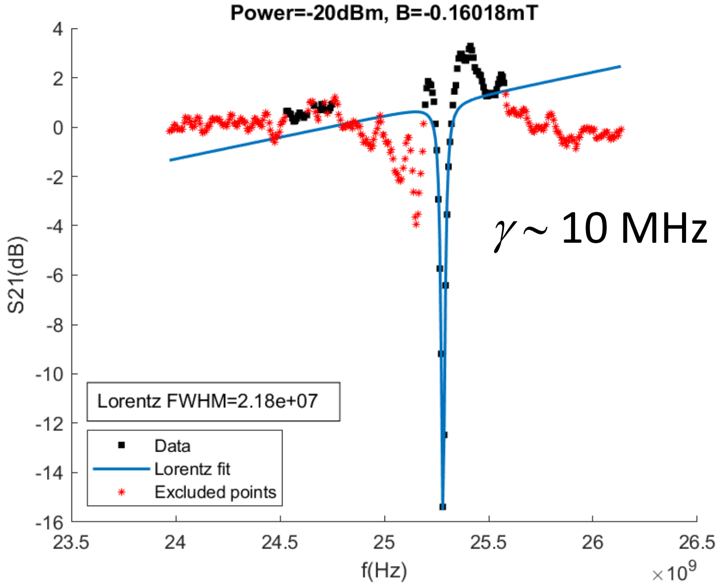
B_2^0=-0.059 K B_4^4= 4e-4 K



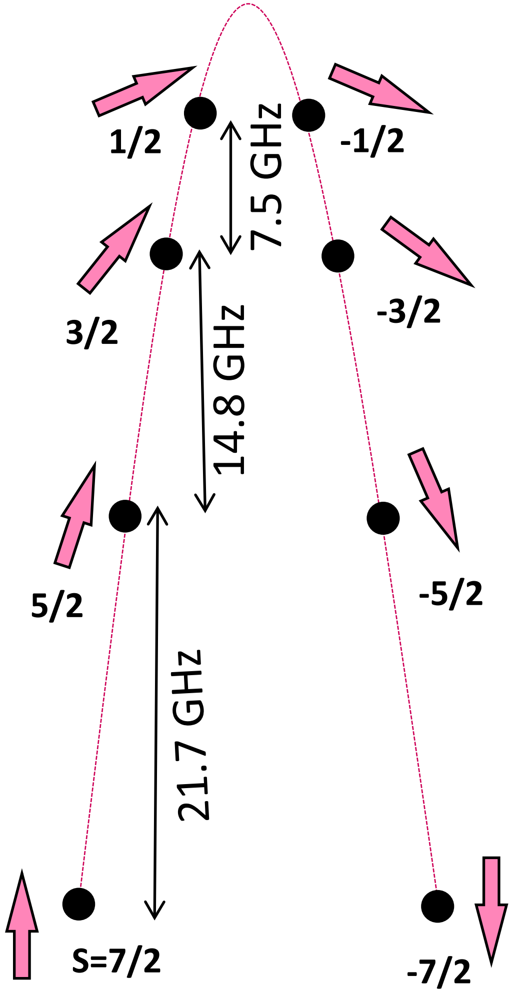


z axis in the plane at approximatelly 45 deg





$\tau \sim$ 100 ns



(collaboration with E. Coronado ICMOL)

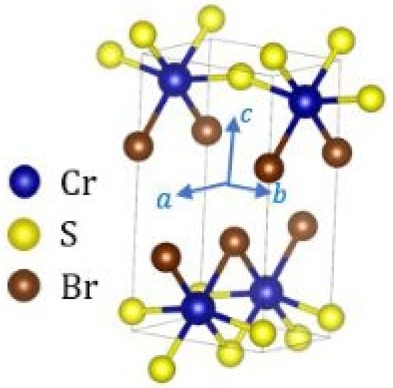
Outline

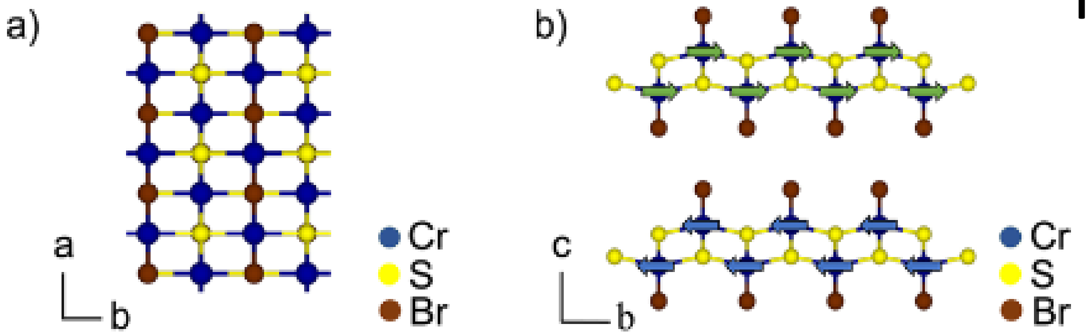
- Light-matter interaction and circuit QED

- Nanomagnets + **superconducting resonators**
  - ☺ Coupling to spins
  - ☺ Coupling to magnons

- Nanomagnets + **magnonic resonators**
  - ☺ GdW10 as spin qubit
  - ☺ SCB as cavity
  - ☺ Spin – magnon

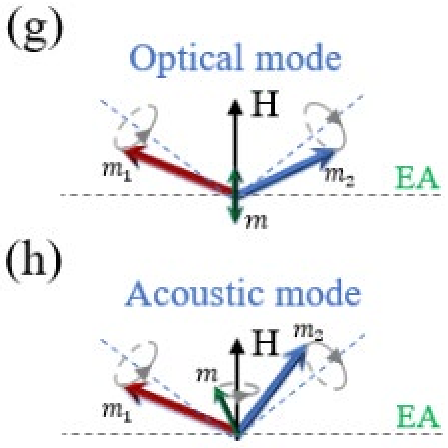
Van der Waals antiferromagnet: Chromium Sulfide Bromide





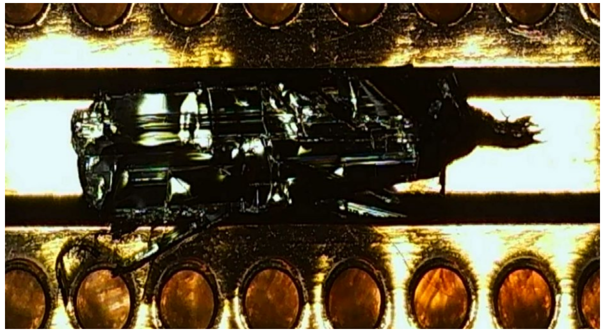
T_N = 132 K

c axis is hard, the b axis is easy, a axis is intermediate



Bex=0.395 T

Bk,c=1.30 T Bk,a=0.383 T



Two coupled LLG equations

$$\frac{d\hat{\mathbf{m}}_{1(2)}}{dt} = -\mu_0\gamma\hat{\mathbf{m}}_{1(2)} \times \left(\mathbf{H} - H_E\hat{\mathbf{m}}_{2(1)} - H_c(\hat{\mathbf{m}}_{1(2)}\cdot\hat{c})\hat{c} - H_a(\hat{\mathbf{m}}_{1(2)}\cdot\hat{a})\hat{a}\right)$$

Hongyue Xu et al arXiv:2409.12501
Cham et al Nano Lett. 2022, 22

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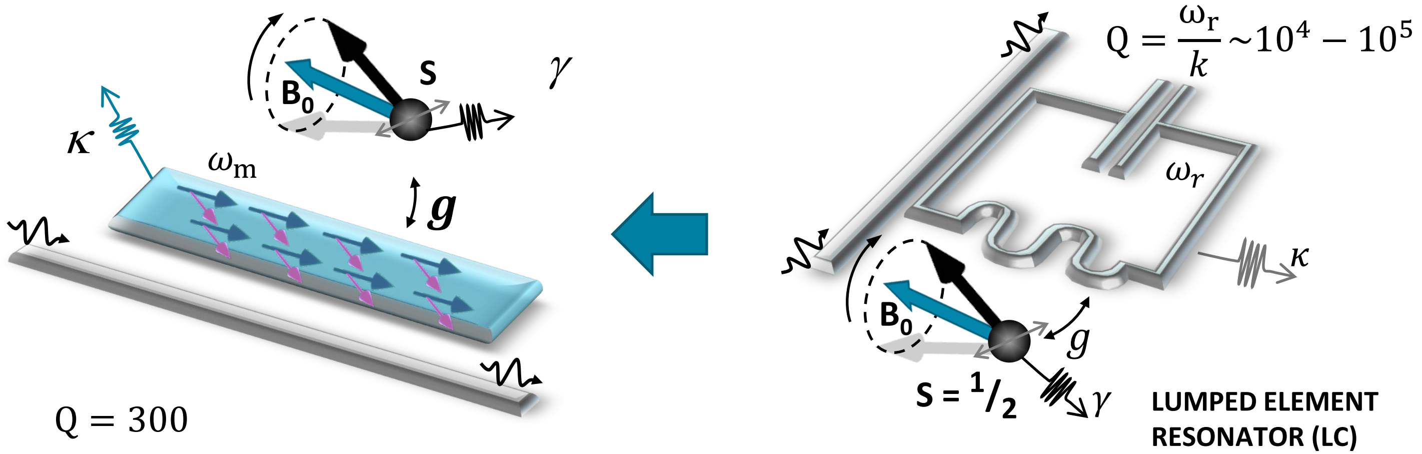
  - Spin – magnon

Spin – magnon coupling: GdW_{10} - CrSBr



Pérez-Bailón, (...) MJ M-P in preparation

Acknowledgements

Quantum Materials and Devices

INMA

F. Luis
J. Sesé
D. Zueco
A. Camón
C. Pobes

V. Rollano
I Gimeno
M. Rubín
C. del Río
P. Strichovanec
C. Andres Gonzalez

J. Pérez-Bailón
S. Martinez-Losa
D. García Pons
X. Del Arco

INMA INSTITUTO DE NANOCIENCIA Y MATERIALES DE ARAGÓN

R. Alicante
A. Lostao
M.C. Pallarés
P. Alonso
J. Martínez
C. Sanchez-Azqueta

ICMOL INSTITUTO DE CIENCIA MOLECULAR

E. Coronado
S. Mañas Valero
C. Boix
I. Gómez Muñoz

CENTRO DE ASTROBIOLOGÍA CAB
ASOCIADO AL NASA ASTROBIOLOGY PROGRAM

A. Gómez
M. Calero

instituto imdea nanociencia

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