Magnetic materials: a platform for quantum technologies

María José (Pepa) Martínez-Pérez

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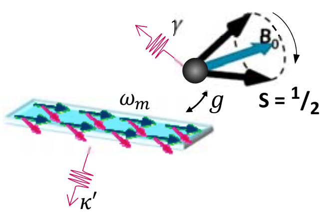
Quantum Materials and Devices
CSIC
Universidad Zaragoza
INMA
INSTITUTO DE NANOCIENCIA Y MATERIALES DE ARAGÓN

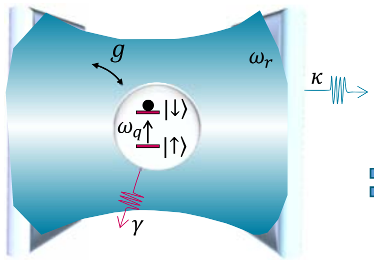
Outline

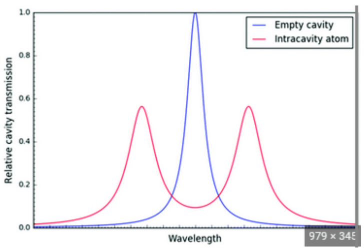
- ❖ Introduction: why do we need cavities in quantum technologies
- ❖ Magnons instead of photons: **does it make sense?**



- ☹ Low damping but this does not affect qubti-qubit interactions
- ☺ Short wavelength -> Ultrasmall cavities (small size and large coupling)
- ☺ Frequency tunable by magnetic field or anisotropy fields (shape…)
- ☺ Good spin qubits candidates to couple to magnons
- ☺ Magnetic textures offer more capabalities

Quantum technologies: electromagnetic cavities and qubits





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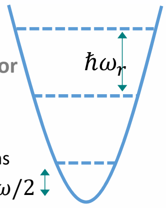
Photons:
Harmonic oscillator



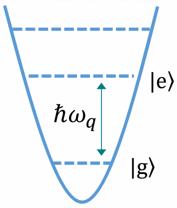
Zero-point fluctuations
$\varepsilon_{rms}=\hbar\omega/2$

In a CPW resonator:

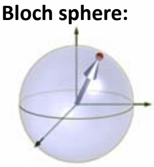
$i_{rms}=\omega_r\sqrt{\hbar\pi/4Z_0}$

+

Atom:
Two level system
Or anharmonic

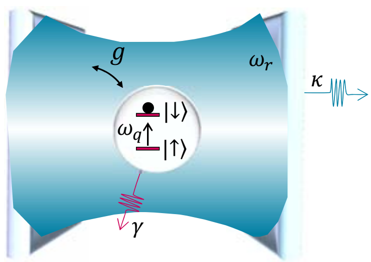


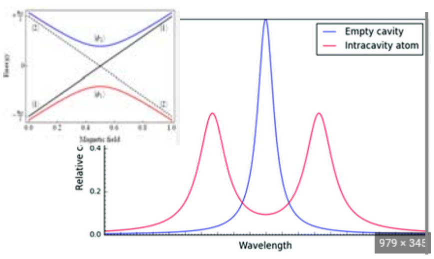
Bloch sphere:



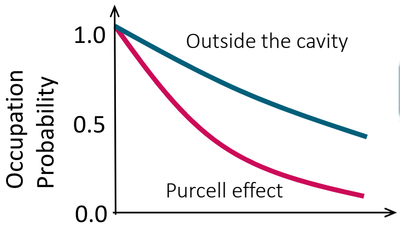
$|\psi\rangle = \cos\frac{\theta}{2}|g\rangle + \sin\frac{\theta}{2}e^{i\phi}|e\rangle$

Quantum technologies: light matter interaction





Weak coupling: $\omega_r = \omega_q$

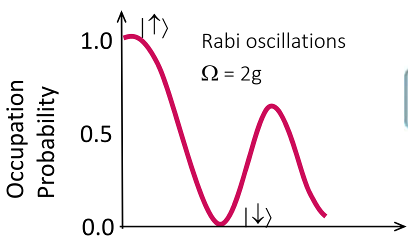


$g < \gamma,\ \kappa$

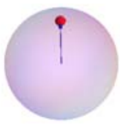
The atom decay rate increases:

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

Strong coupling: $\omega_r = \omega_q$



$g > \gamma,\ \kappa$



Avoided crossing at degeneracy point

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

Quantum technologies: from cavity QED to circuit QED

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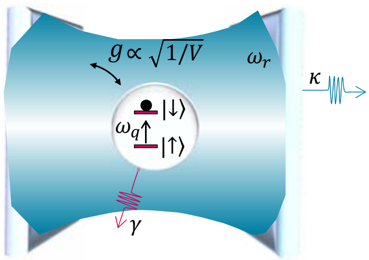
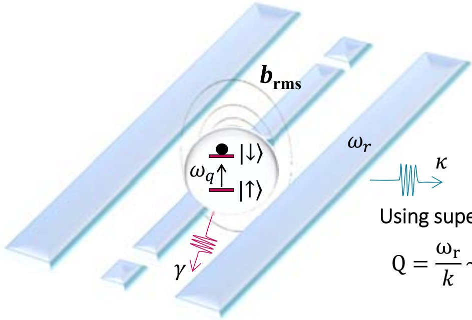
Reducing the mode volume increases the coupling



On-chip version



Using superconductors:

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

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

$$\frac{1}{4}\hbar\omega = \int_V \frac{1}{2}\frac{b_{\mathrm{rms}}^2}{\mu_0} dV$$

$$\boldsymbol{g > \gamma,\ \kappa}$$

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Quantum technologies: circuit QED

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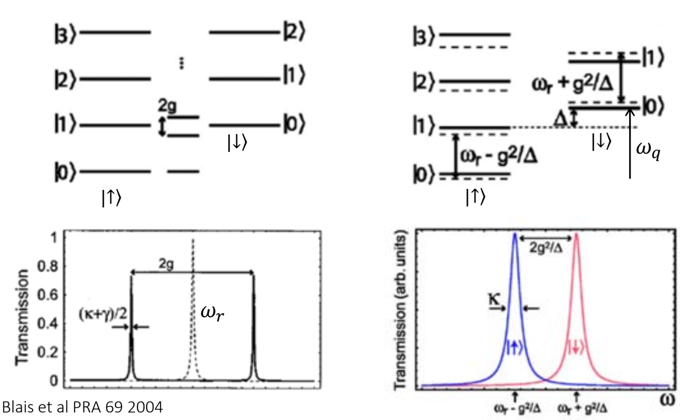
Experimental signatures of strong coupling:

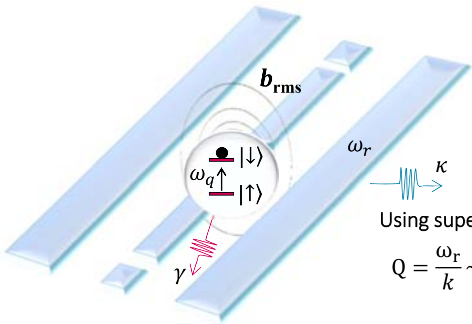
$\Delta = 0$ $\qquad$ $\Delta = \omega_q - \omega_r$



Blais et al PRA 69 2004

Dispersive READOUT of QUBIT states and PHOTON COUNT!

Reducing the mode volume increases the coupling



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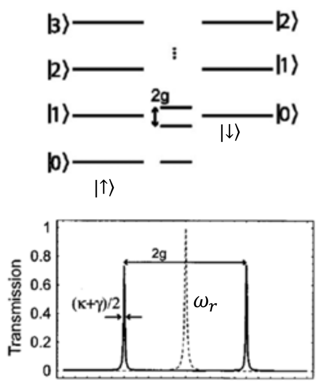

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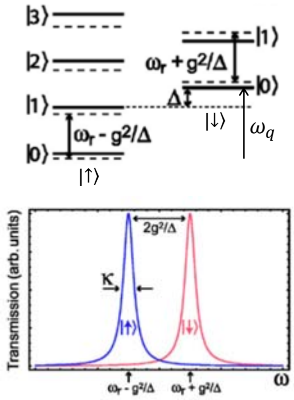

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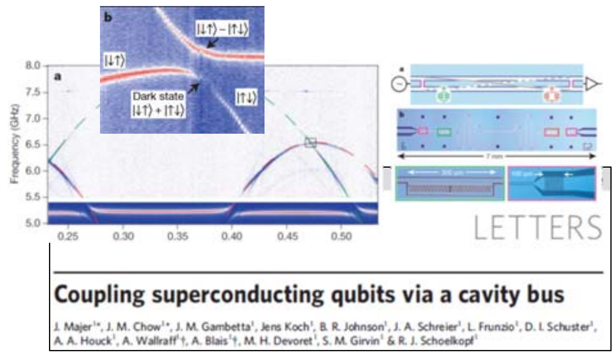
LETTERS

Coupling superconducting qubits via a cavity bus

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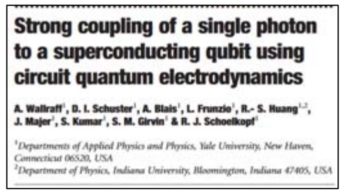
Strong coupling of a single photon to a superconducting qubit using circuit quantum electrodynamics

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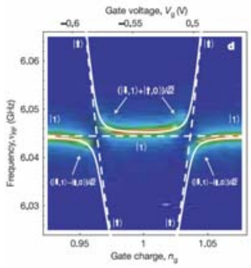
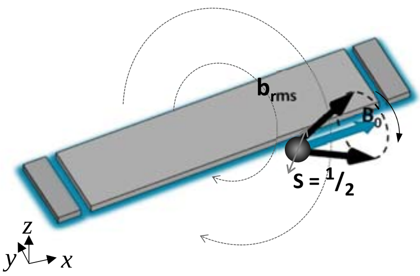
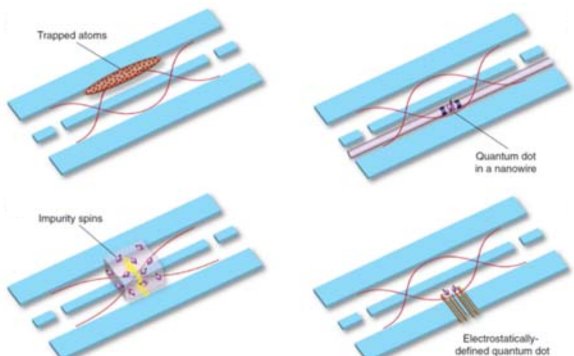
[1]Departments of Applied Physics and Physics, Yale University, New Haven, Connecticut 06520, USA
[2]Department of Physics, Indiana University, Bloomington, Indiana 47405, USA

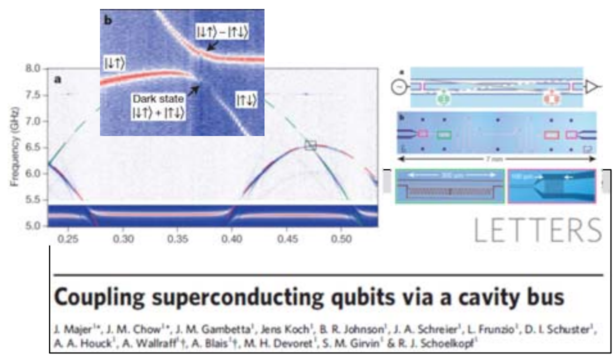


Quantum technologies: circuit QED





Xiang et al Rev Mod Phys 2013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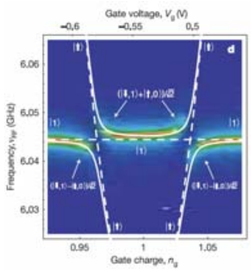
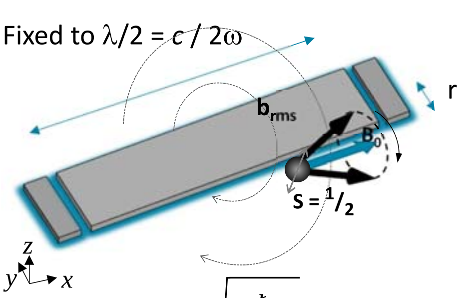
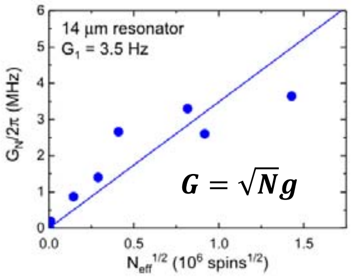


Quantum technologies: the problem to couple to spin qubits



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



$$G = \sqrt{N}g$$

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

Gimeno, MJ M-P et al ACS Nano 2020, 14, 8707–8715

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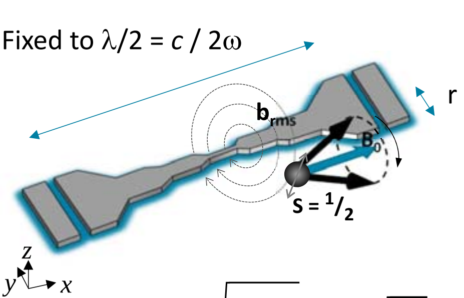
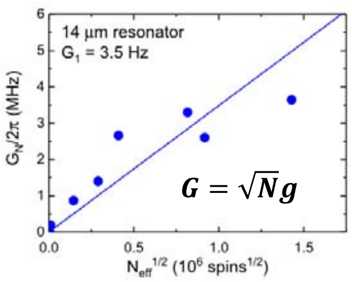


$$g \propto b_{\mathrm{rms}} = \sqrt{\frac{\mu_0 \hbar \omega_r}{2V}} \sim \frac{\omega_r}{r}\sqrt{\frac{2\mu_0}{\pi c}}$$



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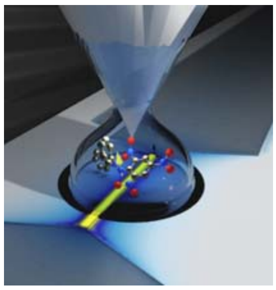
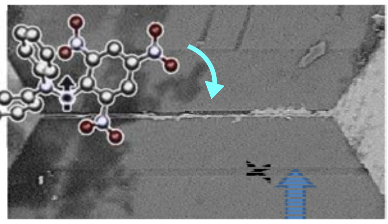
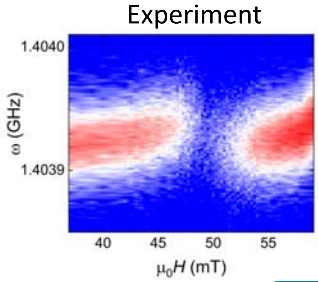
Dip pen distribution of s=1/2 molecules (DPPH)

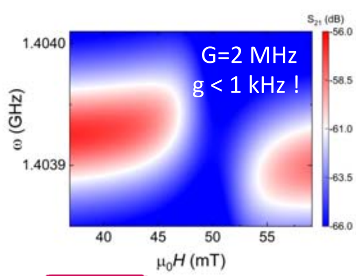


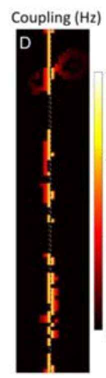


Experiment

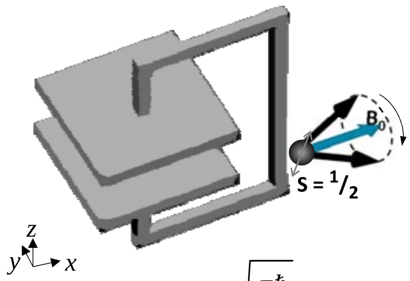


Simulations



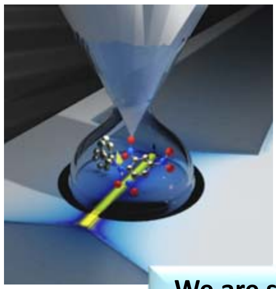


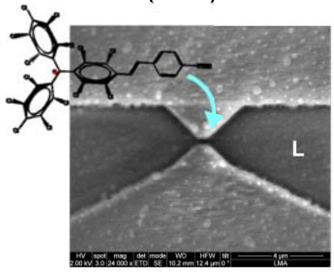
Quantum technologies: the problem to couple to spin qubits



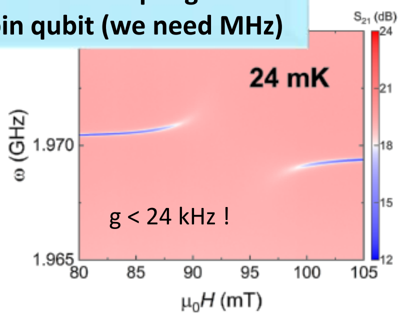
$$g \propto i_{\mathrm{rms}} = \omega_r \sqrt{\frac{\pi\hbar}{4Z_0}}$$

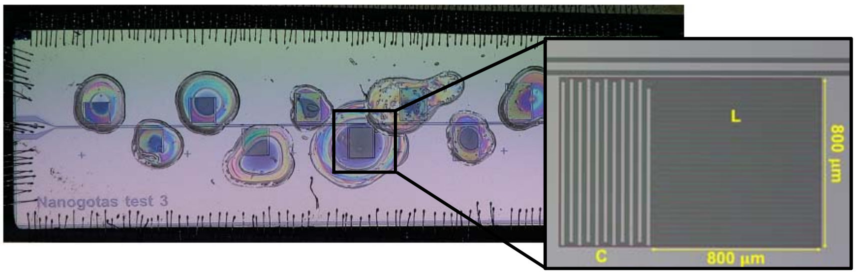
Dip pen distribution of s=1/2 molecules (PTM)





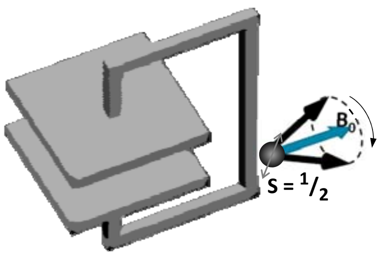
We are still far from coupling to one individual spin qubit (we need MHz)

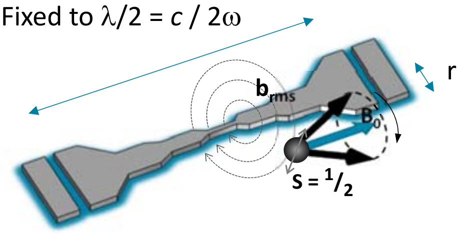




Gimeno, PhD Thesis

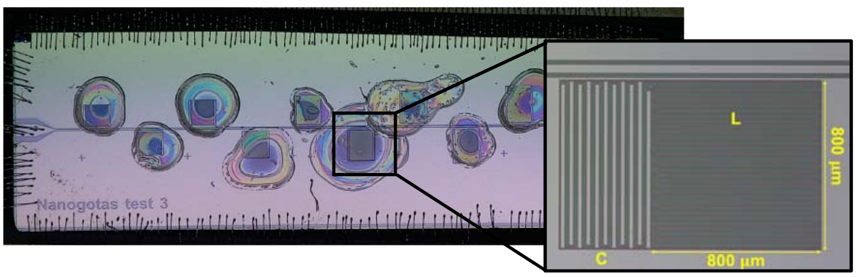
Quantum technologies: the problem to couple to spin qubits





Superconducting cavities

- ☺ Quality factors (> 10^5)
- ☹ Mode volumen depends on frequency
- ☹ Micrometric (several hundred µm)



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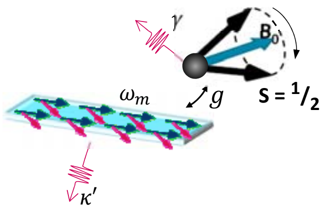

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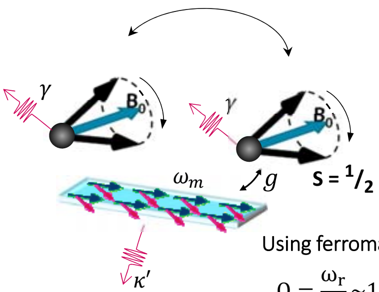
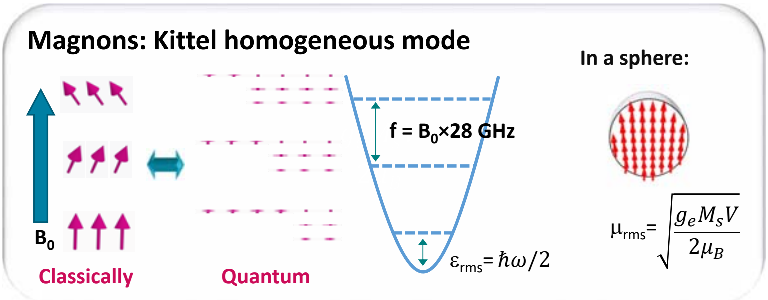
Magnon cavities

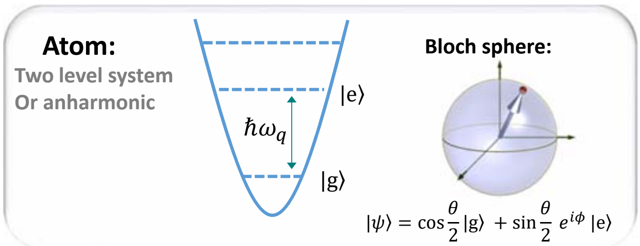
Virtual magnon Exchange, INDEPENDENT OF DAMPING!



Using ferromagnets:

$$Q = \frac{\omega_r}{k} \sim 10^2 - 10^4$$





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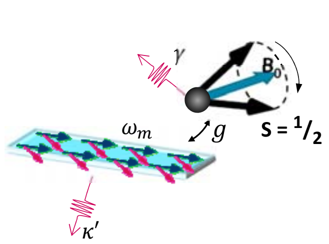

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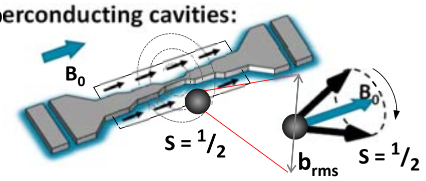
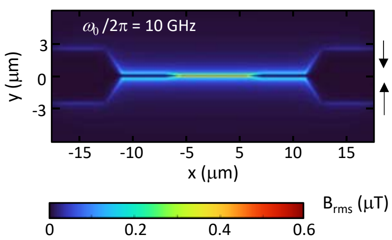
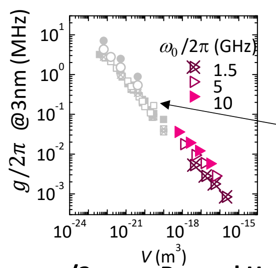
Magnon nanocavities

Superconducting cavities:

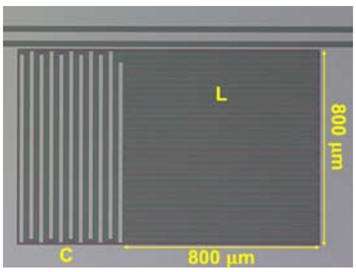






$g_{max}/2\pi = \mu_B B_{rms}$ ~ kHz

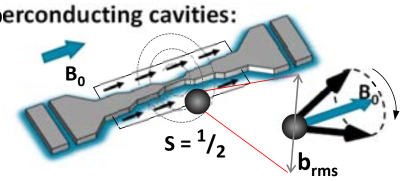
Superconducting LC resonators:

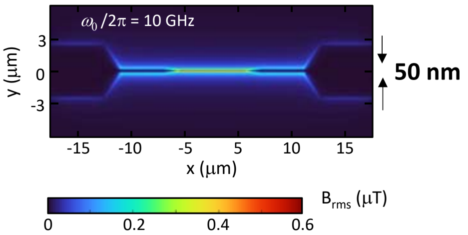


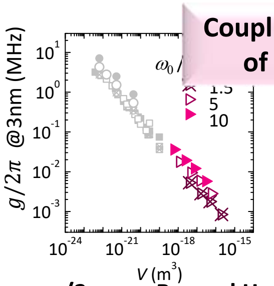
$g_{max}/2\pi = \mu_B B_{rms}$ ~ 10-100 kHz

Magnon nanocavities

Superconducting cavities:



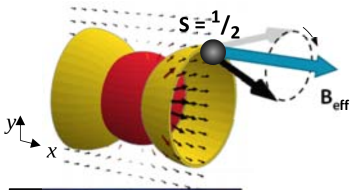


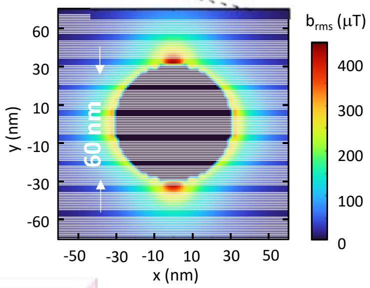


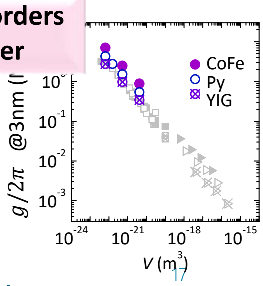
Couplings are three orders of magnitude larger

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

Spheres:





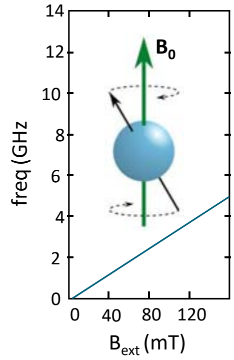


$g_{max}/2\pi = \mu_B B_{rms}$ ~ MHz for S=1/2 !!!

Spheres:

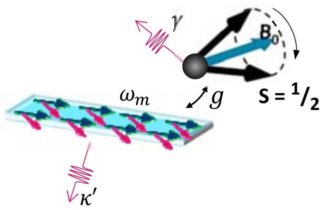
- Not optimally coupled to planar superconducting circuits for readout
- Only tunable via magnetic field:

$\gamma_e/2\pi$ = 28 GHz/T



Outline

- ❖ Introduction: why do we need cavities in quantum technologies
- ❖ Magnons instead of photons: **does it make sense?**



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Magnon nanocavities: tuning of the resonance frequency

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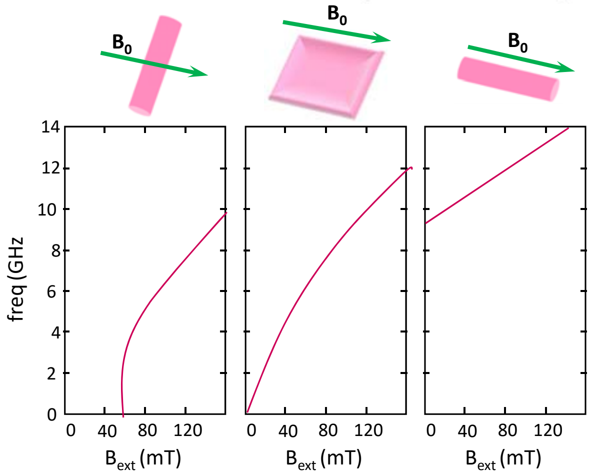
Arbitrary shapes:

$$\omega_m^2 = \gamma_e^2\left[B_{ext} + (N_y - N_x)\mu_0 M_s\right] \times \left[B_{ext} + (N_z - N_x)\mu_0 M_s\right]$$



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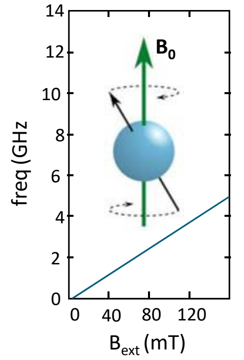
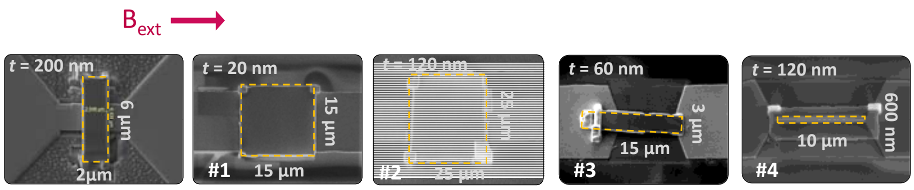
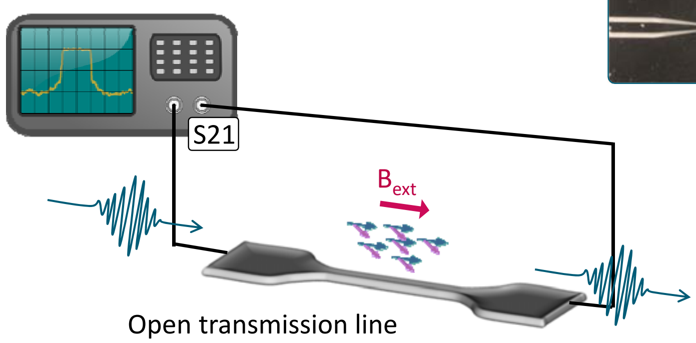
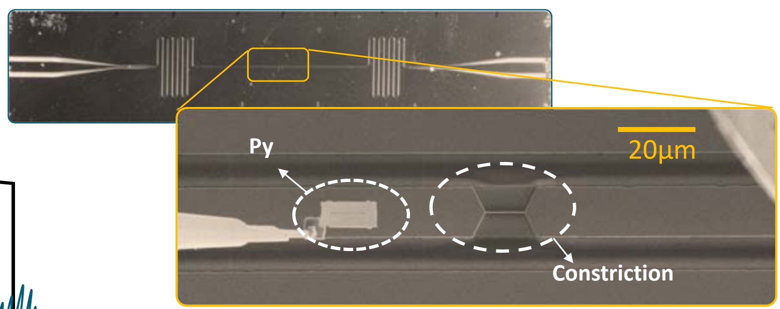


Magnon-photon coupling: broadband ferromagnetic resonance

INMA







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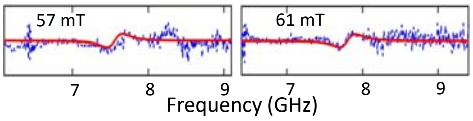
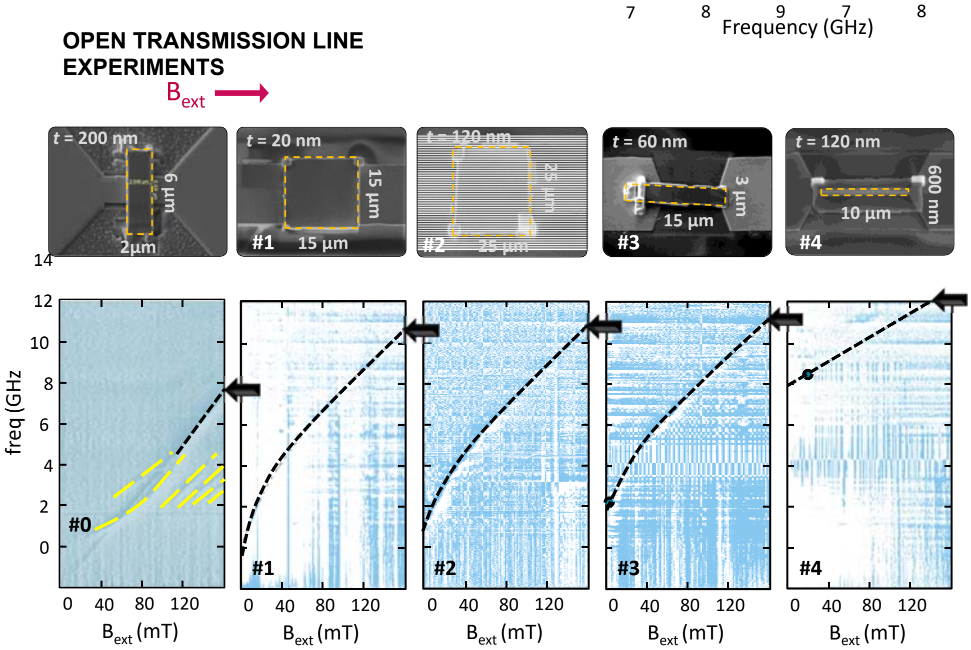
Shape anisotropy

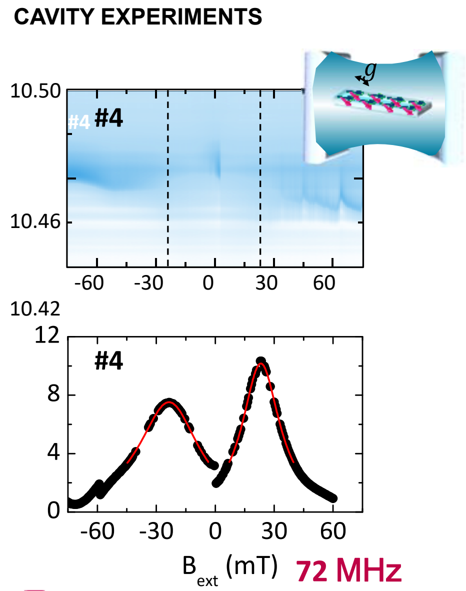
$\alpha \sim 0.01$



Using Permalloy:

$$Q = \frac{\omega_r}{k} \sim 10^2$$





72 MHz

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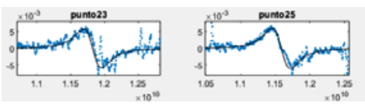
Magnetocrystalline anisotropy

Using FeCo:

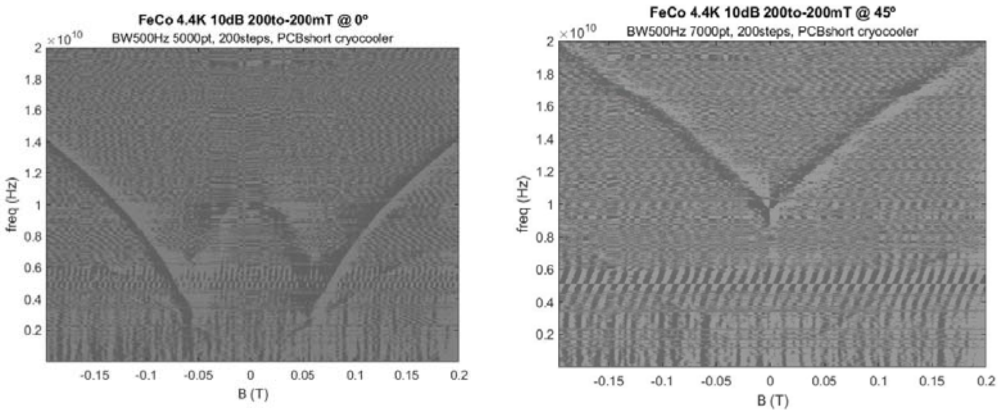
$$Q = \frac{\omega_r}{k} \sim 10^3$$

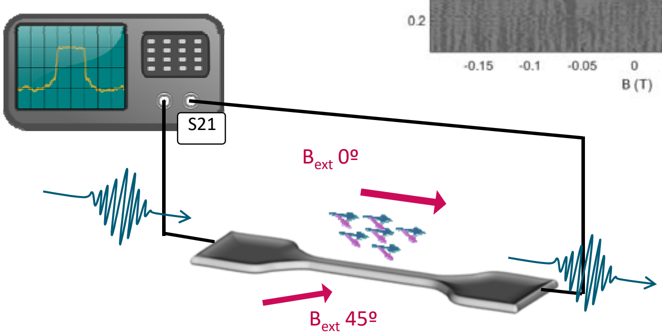


$\alpha \sim 0.001$

FeCo 110 -hard axis

FeCo 100 -easy axis





these MODES can COUPLE to SPIN QUBITS and also MEDIATE SPIN-SPIN INTERACTIONS !

Pons, MJ M-P et al in preparation

Outline

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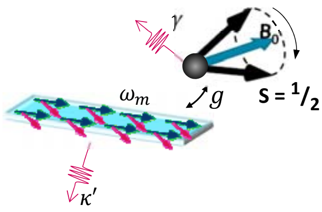

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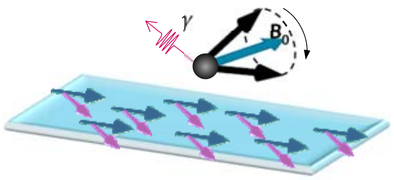
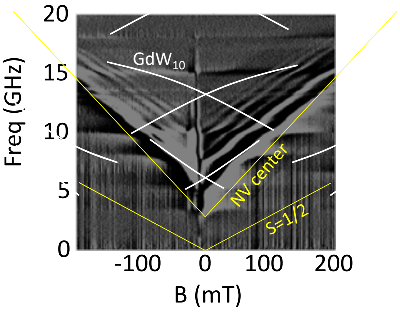
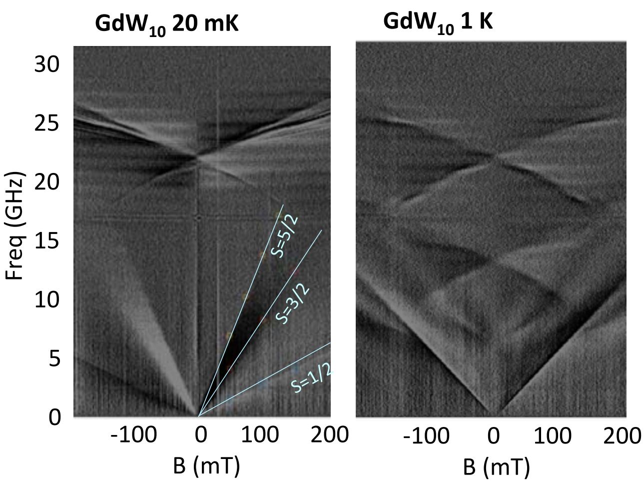
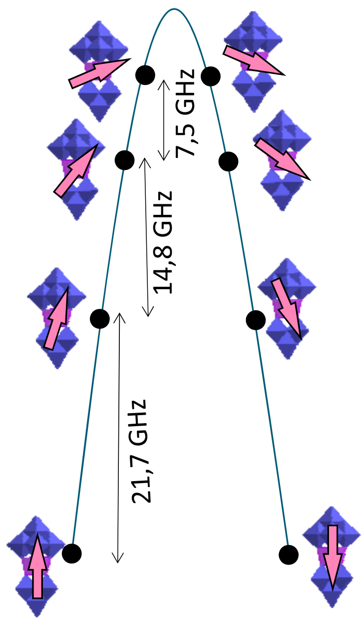
Spin qubits candidates: NV centers, single ion magnets



Spin qubit Coupling to magnons?







Next candidates: GdW30…
(collaboration with E. Coronado ICMOL)

Outline

INMA

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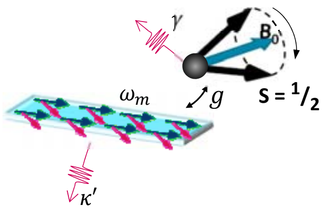

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Inhomogeneous magnon modes: defects

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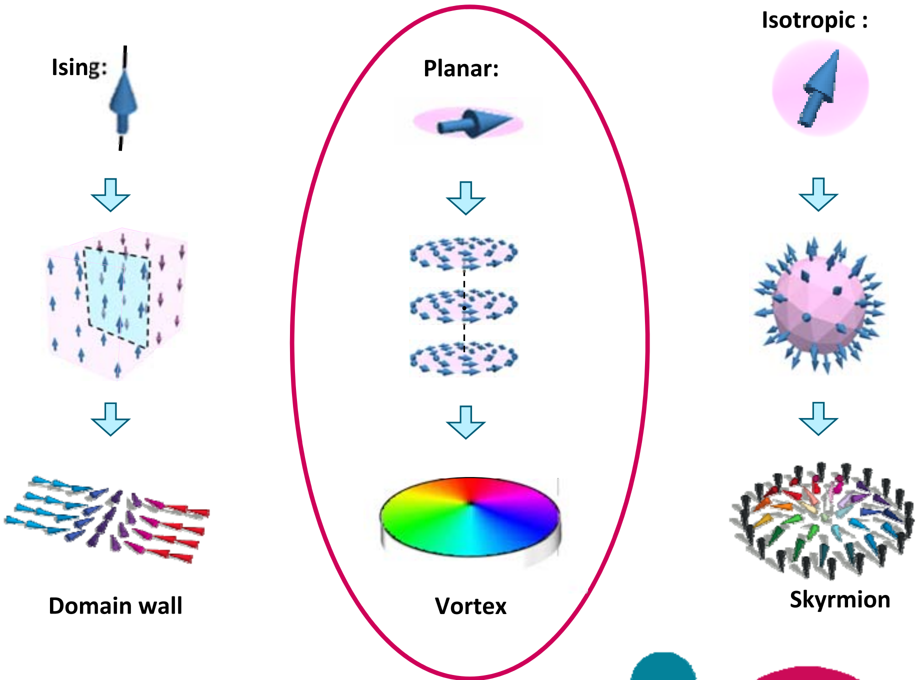

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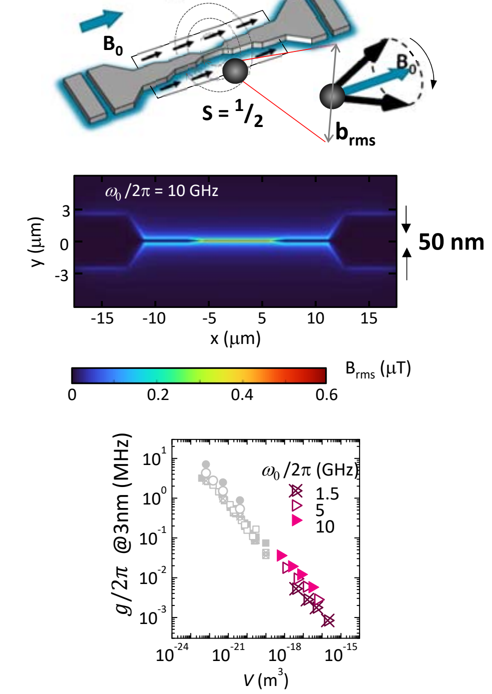
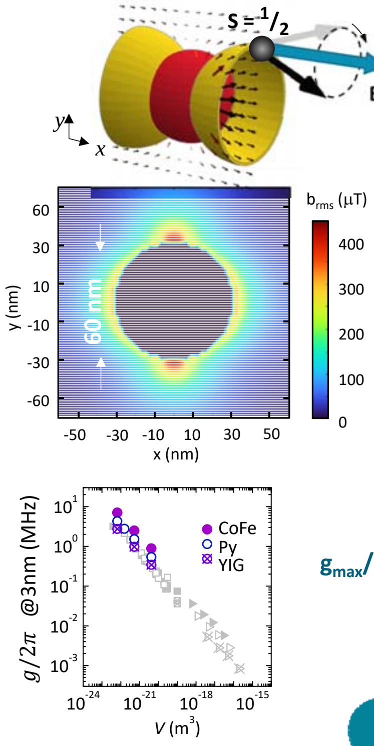
Vortex nanocavities: properties

Superconducting cavities:

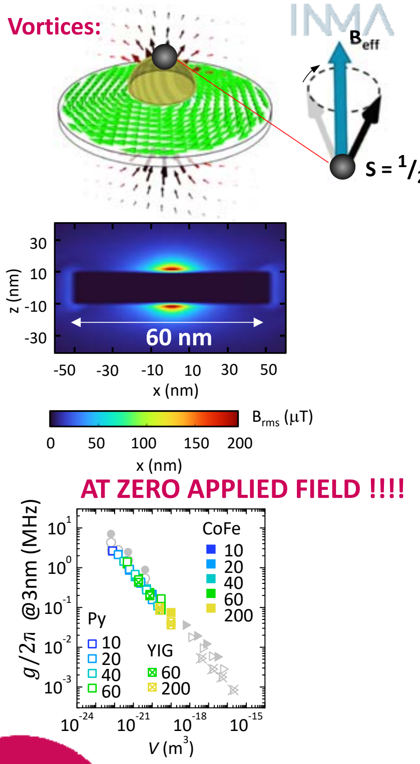


Spheres:



$g_{max}/2\pi$ ~ MH !!!

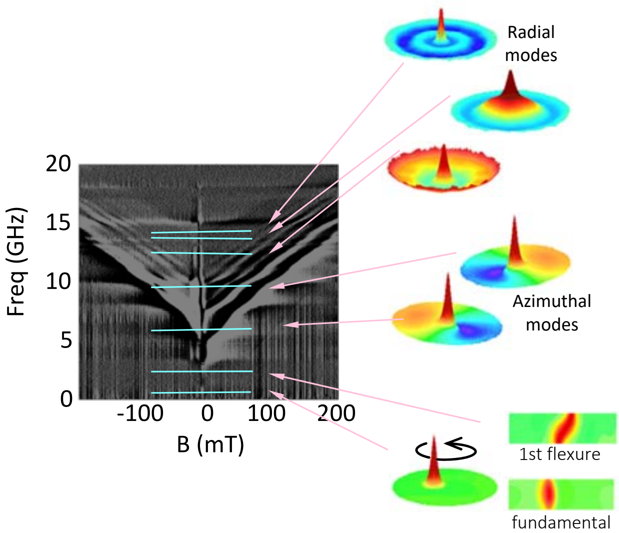
Vortices:



AT ZERO APPLIED FIELD !!!!

Vortex nanocavities: properties

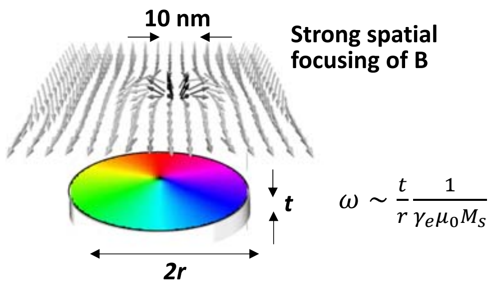
Vortices:



Very rich excitation spectrum

ALSO AT ZERO APPLIED FIELD !!!!

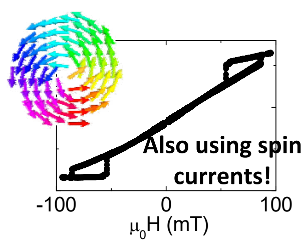
(unlike Kittel modes or standing waves)



Strong spatial focusing of B

$$\omega \sim \frac{t}{r}\frac{1}{\gamma_e \mu_0 M_s}$$

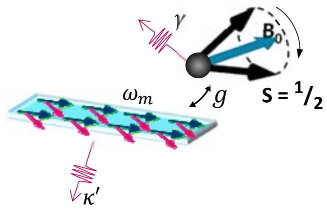
Frequency tunable and mobile



Summary

INMA

❖ Magnons can be used to mediate qubit – qubit interactions



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☺ Magnetic textures offer more capabalities

Great challenge for Advanced Material science: fabrication of magnetic materials with lower damping !!!

V[TCNE]x, YIG, FeGo, Heusler alloys…

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Acknowledgements

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Quantum Materials and Devices

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erc European Research Council

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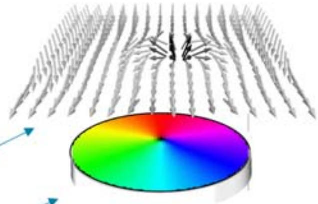
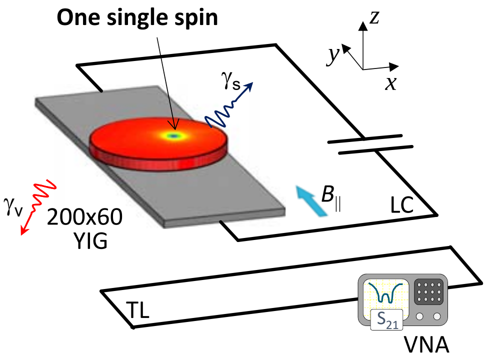
Vortex nanocavities: sensing applications

INMA

Electron Spin Resonance
AT ZERO APPLIED FIELD !!!!

- Magnetic fields gradients (polarize spins)
- Radiofrequency field (induce spin transitions)
- Spectroscopy absorption (detection)

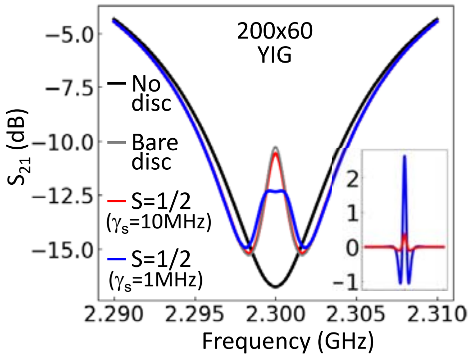




Strong coupling

$g > \gamma, \gamma_s$

Double peak



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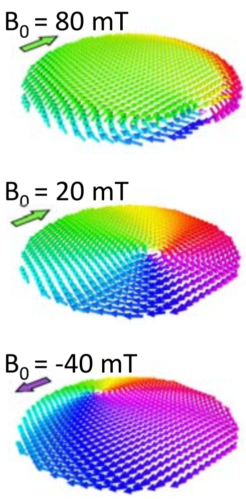
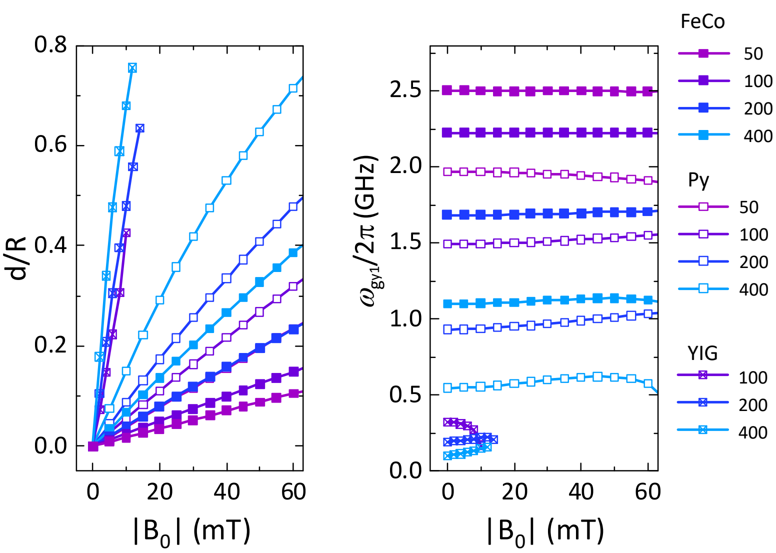
(...) MJ M-P submitted ACS Nano

(...) MJ M-P submitted ACS Nano

Vortex nanocavities: scanning vortex

INMA





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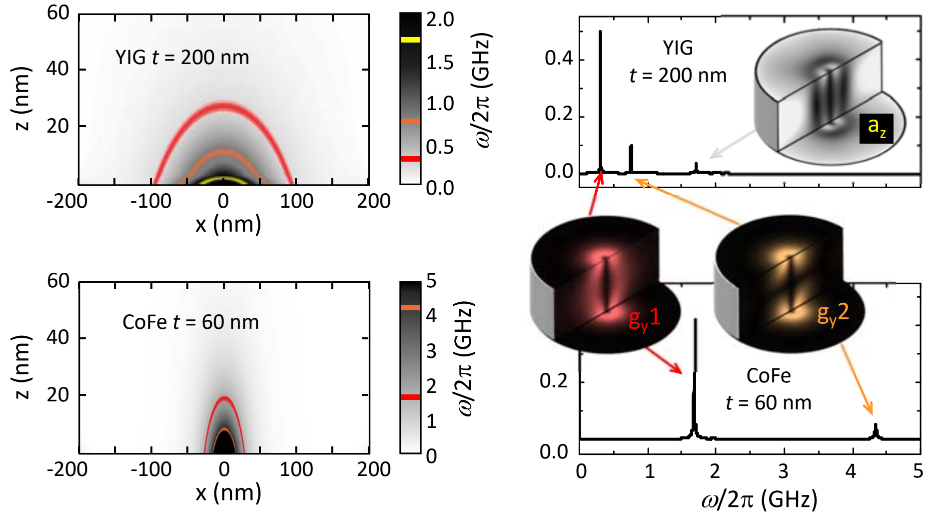
(...) MJ M-P submitted ACS Nano

Vortex nanocavities: high frequency modes

INMA



(...) MJ M-P submitted ACS Nano

Vortex nanocavities: sensing applications

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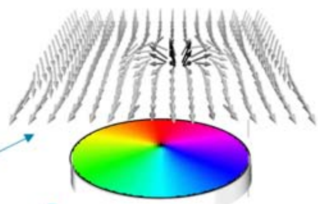
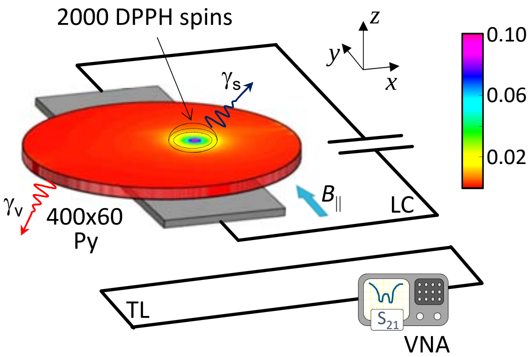
Electron Spin Resonance
AT ZERO APPLIED FIELD !!!!



- Magnetic fields gradients (polarize spins)
- Radiofrequency field (induce spin transitions)
- Spectroscopy absorption (detection)

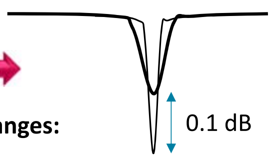


Weak coupling

$$g < \gamma, \gamma_s$$

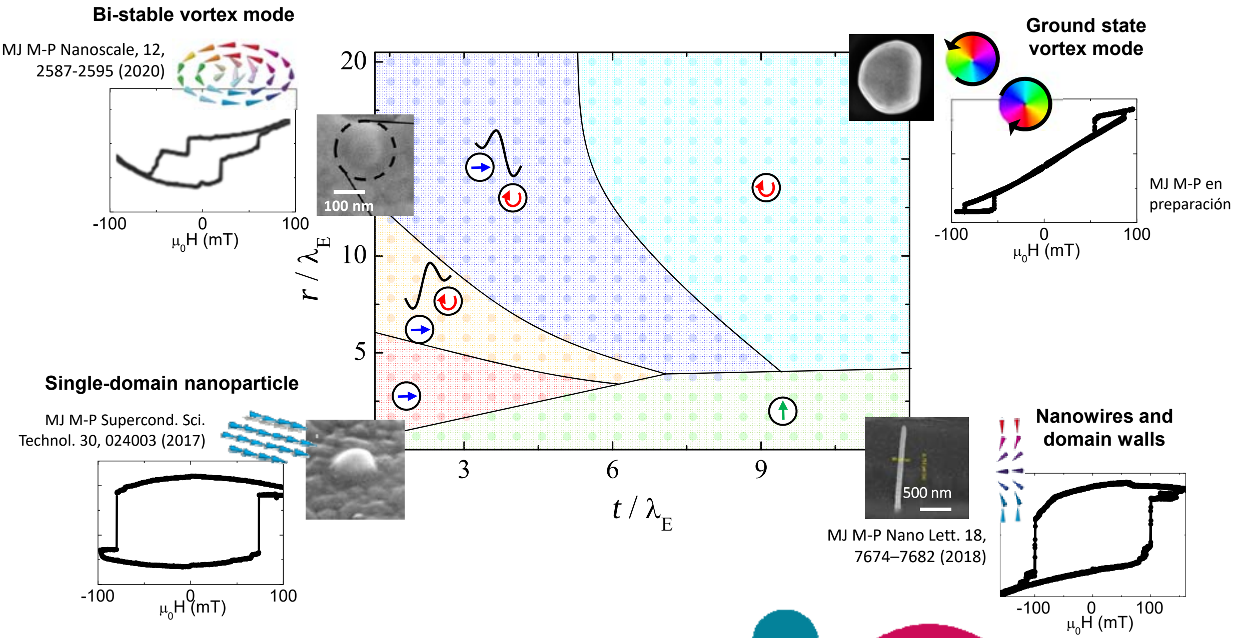
The vortex linewidth changes:

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



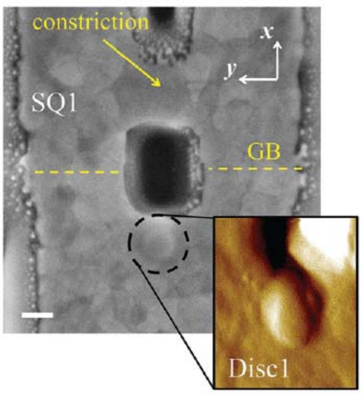
(...) MJ M-P submitted ACS Nano

Stabilization and control of small vortices

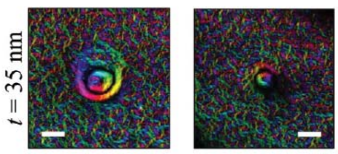


λ_E (Fe) ~ 3 nm
λ_E (Py) ~ 6 nm
λ_E (YIG) ~ 17 nm

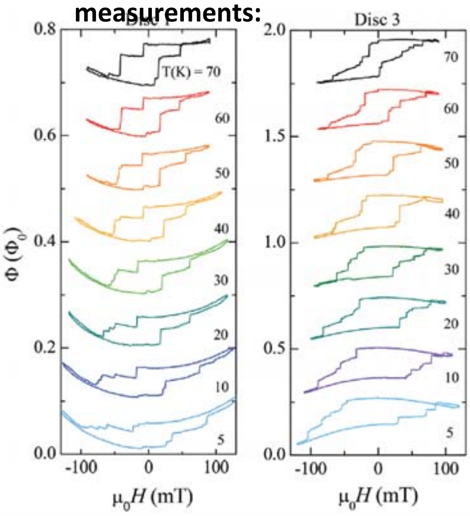
Smallest magnetic vortices



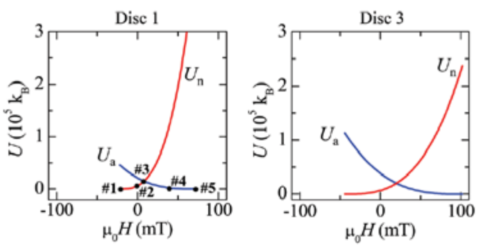
Electron holography:

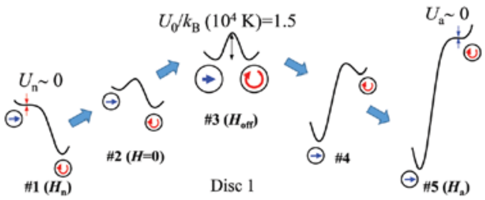


NanoSQUID measurements:



From fittings:

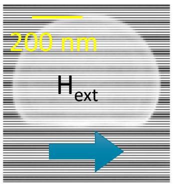




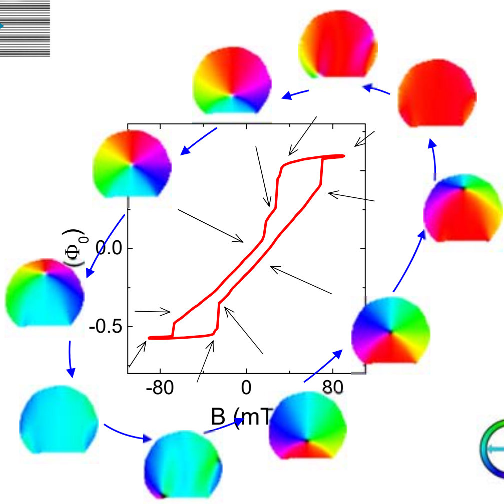
Ground state!

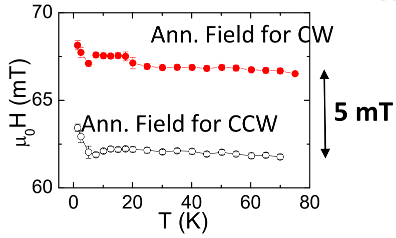
MJ M-P et al. Nanoscale., **12**, 2587-2595 (2020)

Magnetic vortex control

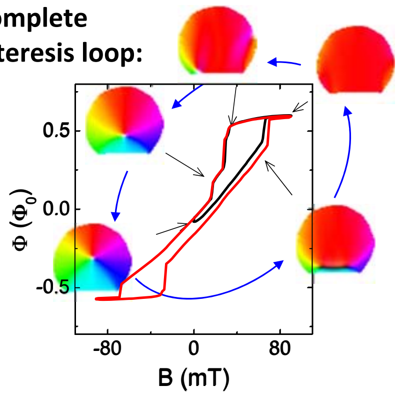


Complete Hysteresis loop:





Incomplete Hysteresis loop:



MJ M-P et al. In preparation