Chiral and quantum magnons

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- Intro: Cavity magnonics
- Chiral interactions in magnetic arrays
- Analog control of quantum states

Cavity magnonics

Delft University of Technology

- Sanchar Sharma
- Xiang Zhang
- Tao Yu
- Marios Kounalakis

- Artem Bondarenko
- Enes Ilbuga
- YMB

- Toeno van der Sar and van der Sar Lab
- Slava Dobrovitski

Tohoku University

- Mehrdad Elyasi
- Gerrit Bauer

Cambridge University

- James Haigh

Beijing Normal University

- Chuanpu Liu
- Haiming Yu

University of Manitoba

- Bimu Yao
- Can-Min Hu

Iran University of Science and Technology

- Babak Zare Rameshti

Magnons

Magnons are elementary excitations of magnetic structure

Classical limit (large occupation numbers): spin waves

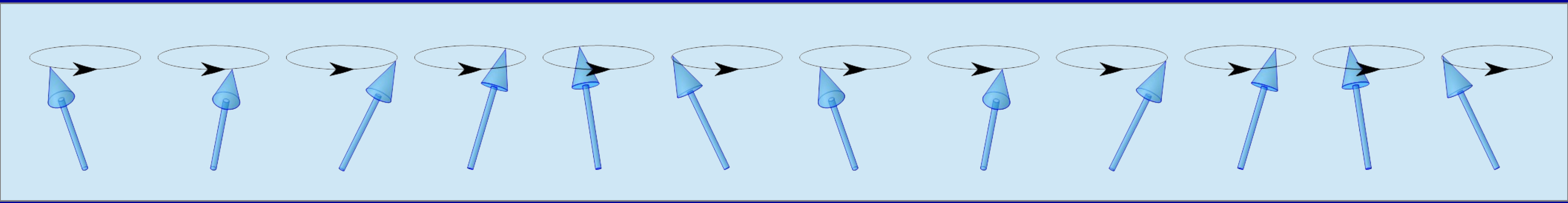
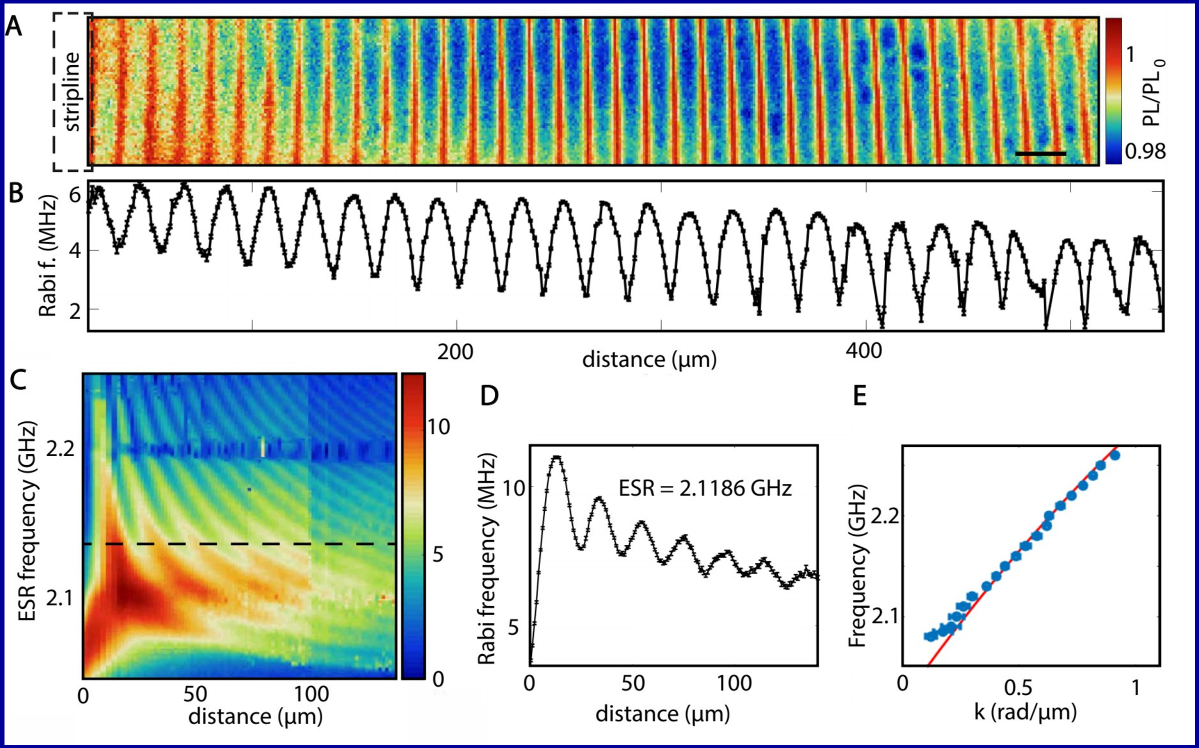


Image credit: Jens Böning, Wikimedia Commons

Imaging of spin waves

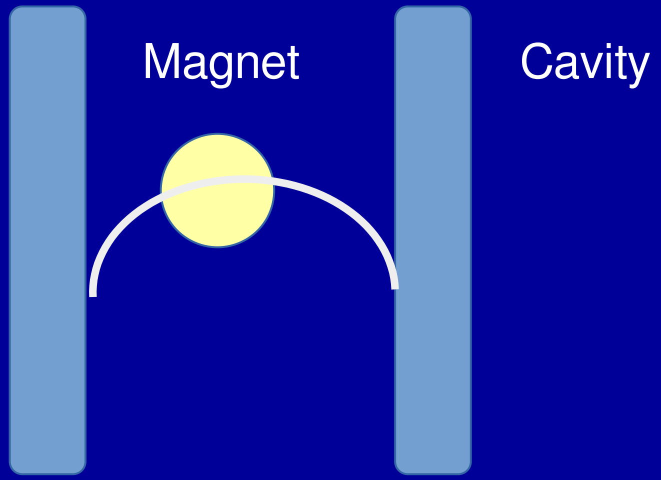
Spin waves in YIG films imaged by NV center magnetometry



I. Bertelli, J. J. Carmiggelt, T. Yu, B. G. Simon, C. C. Pothoven, G. E. W. Bauer, YMB, J. Aarts, and T. van der Sar, Science Adv. **6**, eabd3556 (2020).

Cavity magnonics

Optical or microwave cavity: Field is concentrated

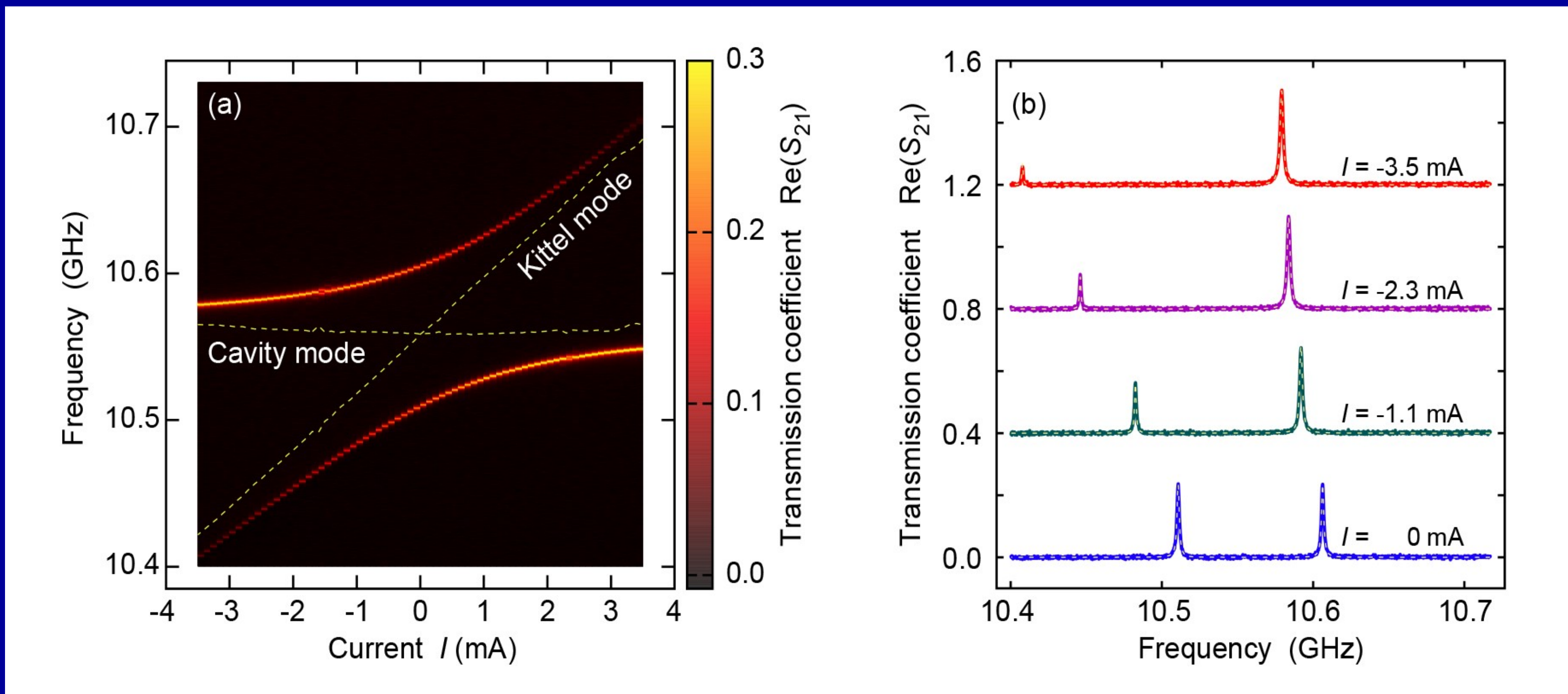


Strong coupling in a cavity predicted by Soykal and Flatte, Phys. Rev. Lett. **104**, 077202 (2010)

Microwave cavities

Mechanism: interaction of $\mathbf{M}$ $\mathbf{B}$
magnetization with the cavity field

Tabuchi et al,
Phys. Rev. Lett. **113**, 083603 (2014)



Normal mode splitting between a magnon (YIG) and a cavity mode

Magnon spintronics

Spin waves can carry information:

Ferromagnetic metals: Spin current is carried by electrons
– Ohmic dissipation

Ferromagnetic insulators: Spin current carried by spin waves
– Weak intrinsic damping of spin waves

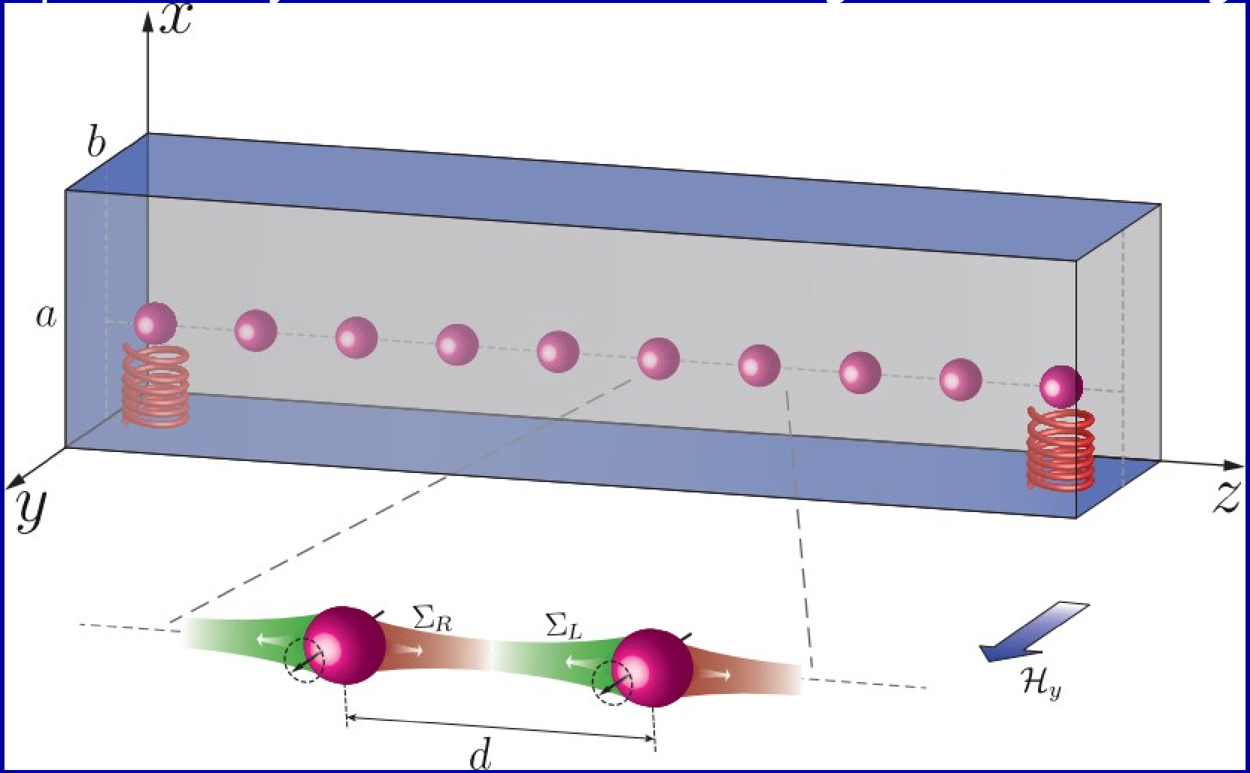
We want to be able to excite, manipulate, and read out spin waves

Cavity Magnonics, Babak Zare Rameshti, Silvia Viola Kusminskiy, James A. Haigh, Koji Usami, Dany Lachance-Quirion, Yasunobu Nakamura, Can-Ming Hu, Hong X. Tang, Gerrit E. W. Bauer, and YMB, Physics Reports **979**, 1 (2022).

Quantum magnonics: When magnon spintronics meets quantum information science, H. Y. Yuan, Yunshan Cao, Akashdeep Kamra, Rembert A. Duine, and Peng Yan, Physics Reports **965**, 1 (2022).

Chiral interaction

Many identical magnetic spheres in a waveguide: Positions can be engineered so that every sphere only interacts with the neighbors on the right



T. Yu, Y.-X. Zhang, S. Sharma, X. Zhang, YMB, and G. E. W. Bauer, Phys. Rev. Lett **124,** 107202 (2020)

T. Yu, X. Zhang, S. Sharma, YMB, and G. E. W. Bauer, Phys. Rev. B **101,** 094414 (2020)

Quantization of spin waves

Holstein-Primakoff transformation

$$\hat{S}_+ = \hbar\sqrt{2S}\sqrt{1 - \frac{\hat{m}^\dagger \hat{m}}{2S}}\hat{m}$$

$$\hat{S}_- = \hbar\sqrt{2S}m^\dagger\sqrt{1 - \frac{\hat{m}^\dagger \hat{m}}{2S}}$$

$$\hat{S}_z = \hbar\left(S - \hat{m}^\dagger \hat{m}\right)$$

Linearized transformation:

$$\hat{m}^\dagger \hat{m} \ll S$$

One-mode linear Hamiltonian:

$$\hat{H} = \hbar\omega_m \hat{m}^\dagger \hat{m}$$

Magnetic array in a waveguide

Hamiltonian: $\hat{H} = \hat{H}_{ph} + \hat{H}_m + \hat{H}_{int}$

Photons: $\hat{H}_{ph} = \sum_k \hbar\omega_k \hat{a}_k^\dagger \hat{a}_k \ , \ \omega_k^2 = c^2 \left(k^2 + (\pi m/a)^2 + (\pi n/b)^2\right)$

Magnons: $\hat{H}_m = \sum_i \hbar\omega_i \hat{m}_i^\dagger \hat{m}_i$

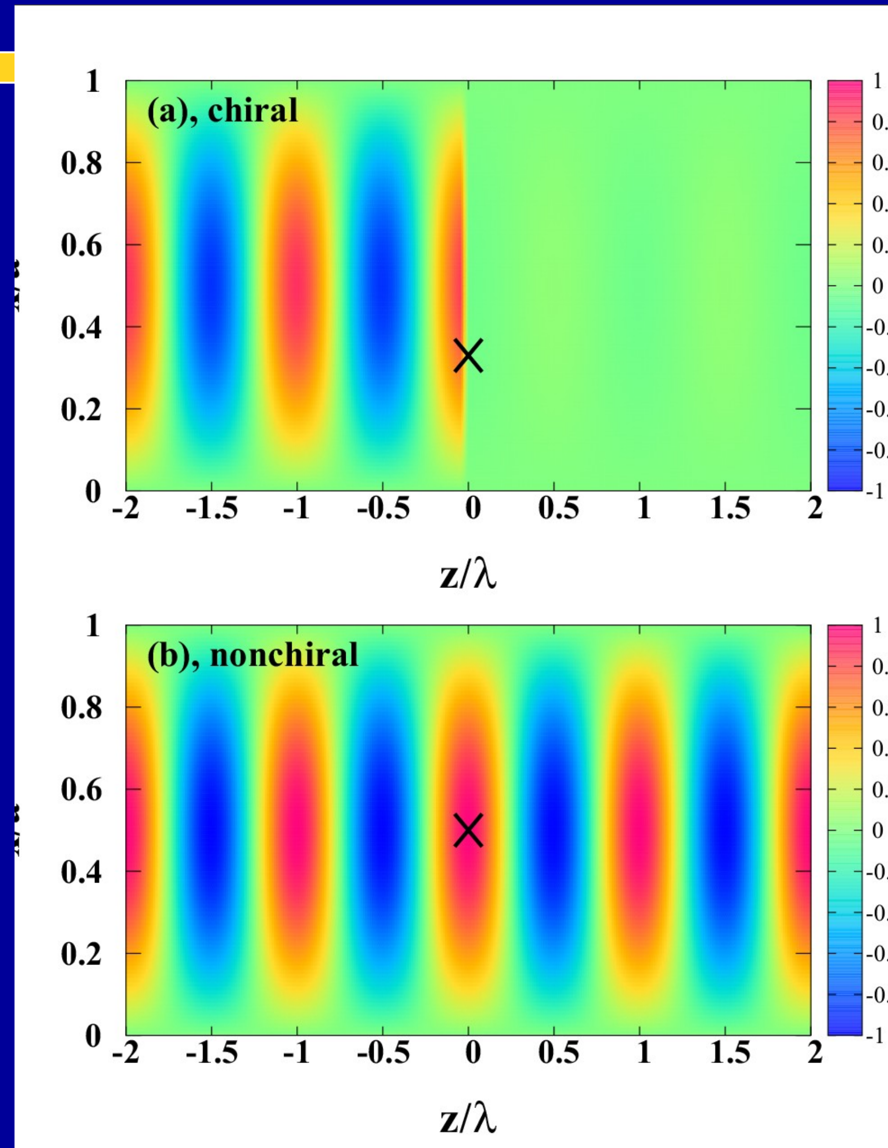
$$H_{int} = \sum_{jk} \left(g_{jk} \hat{m}_j^\dagger \hat{a}_k + H.c.\right) \ ; \ g_{jk} = \tilde{g}_k e^{ik(j-1)d}$$

Proportional to the transverse magnetic field

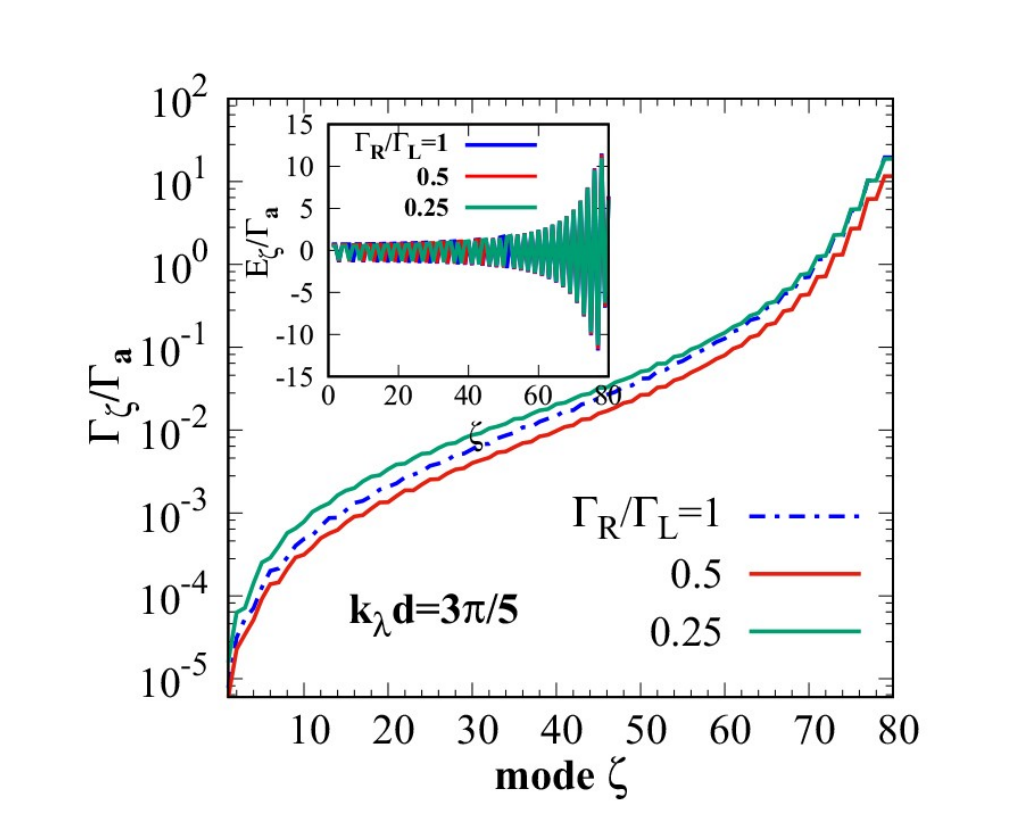
Resonant interaction for TE (1,0) mode:

$$k_0 = \sqrt{\omega_m^2/c^2 - \pi^2/a^2}$$

Field distribution



Collective states



Superradiant states

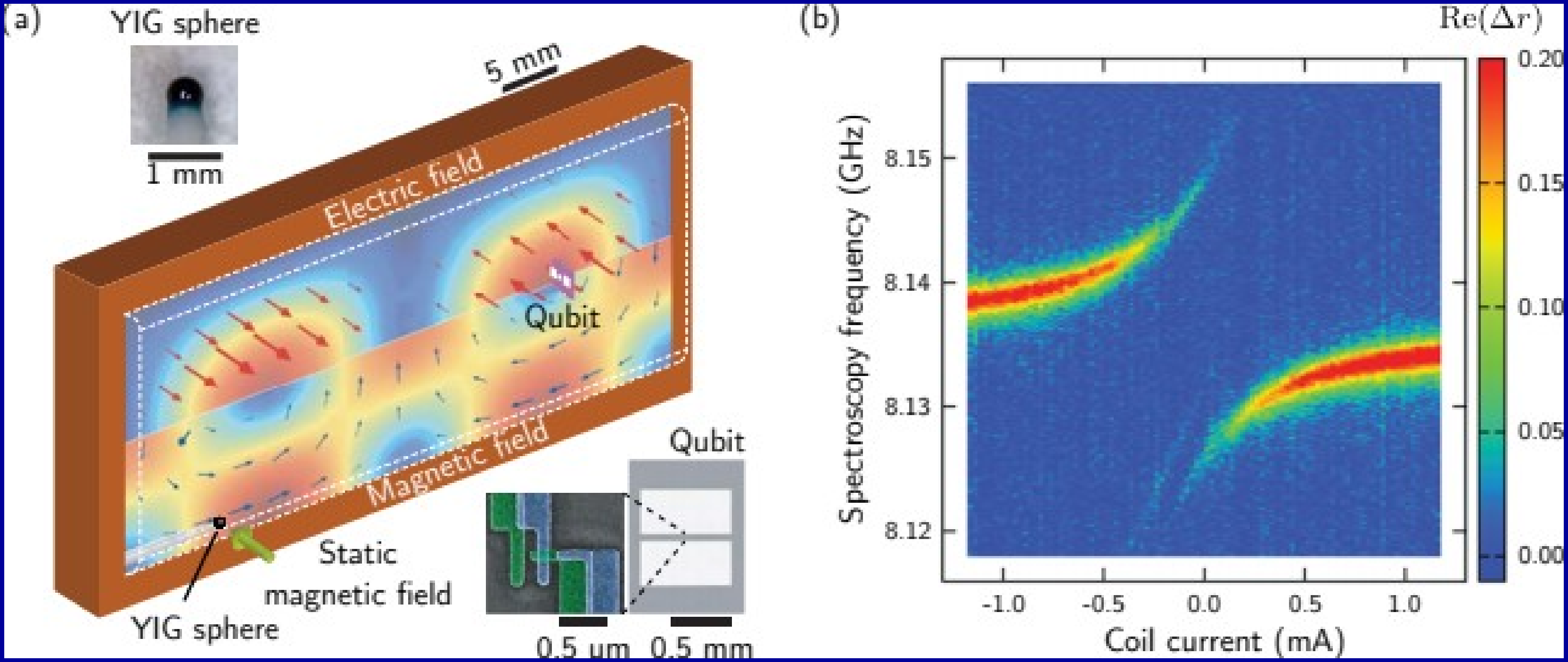
$$\Gamma \propto N$$

Subradiant states

$$\Gamma \propto N^{-3}$$

Quantum magnonics

Coherent coupling of a magnon to a qubit via a cavity

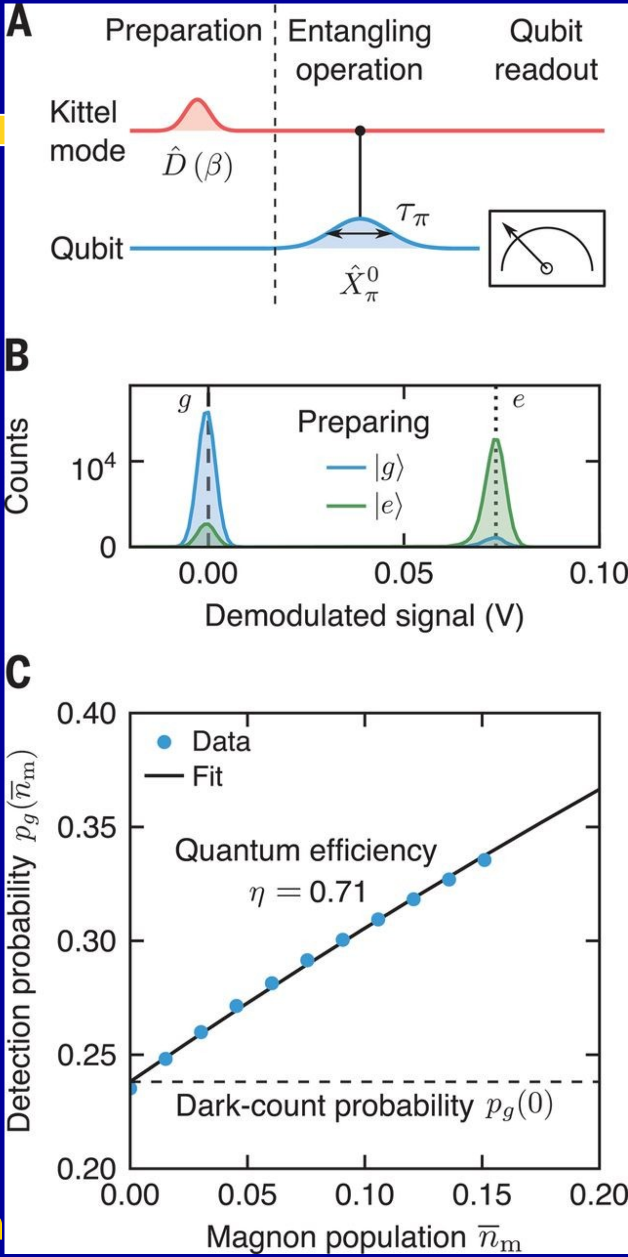


Y. Tabuchi, S. Ishino, A. Noguchi, T. Ishikawa, R. Yamazaki, K. Usami, and Y. Nakamura, Science **349**, 405 (2015)

Quantum magnonics

Single-magnon readout

- Preparation: a coherent magnon state by the cavity
- Entanglement: Using cavity-mediated interaction between the magnon and the qubit
- Detection: by the qubit



D. Lachance-Quirion, S. P. Volski, Y. Tabuchi, S. Kono, K. Usami, and Y. Nakamura, Science **367**, 425 (2020)

Magnons for quantum circuits?

- Extension of circuit QED
- Non-trivial quantum states of magnon/magnon-qubit can be prepared by using pulse sequences
- (Short lifetime for magnons: $Q \sim 10^4$)

Digital quantum computing

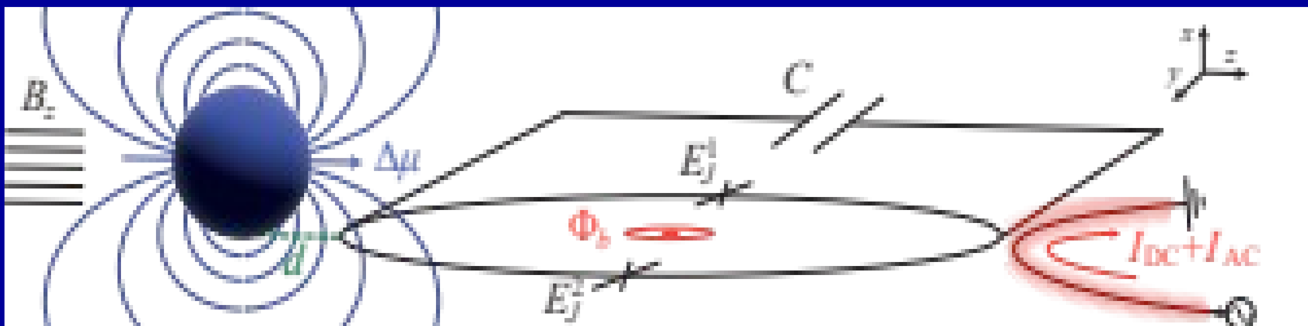
Can we also have analog quantum computing?

- Using natural interactions?

Magnon-qubit coupling

Superconducting qubit (transmon) feels the flux produced by the dipolar field of the mag

(n



$$\hat{H}_q = \hbar\omega_q \hat{c}^\dagger \hat{c} - \frac{E_C}{2} \hat{c}^\dagger \hat{c}^\dagger \hat{c}\hat{c} \; ; \quad \hat{H}_m = \hbar\omega_m \hat{m}^\dagger \hat{m} \; ;$$

$$\hat{H}_{int} = \hbar J \left(\hat{c}^\dagger \hat{m} + \hat{c}\hat{m}^\dagger\right) + g_{rp} \hat{c}^\dagger \hat{c} \left(\hat{m}^\dagger + \hat{m}\right)$$

"Jaynes-Cummings" coupling

"Magnon radiation pressure" coupling

Classical: C. C. Rusconi, M. J. A. Schuetz, J. Gieseler, M. D. Lukin, and O. Romero-Isart, Phys. Rev. A 100, 022343 (2019)

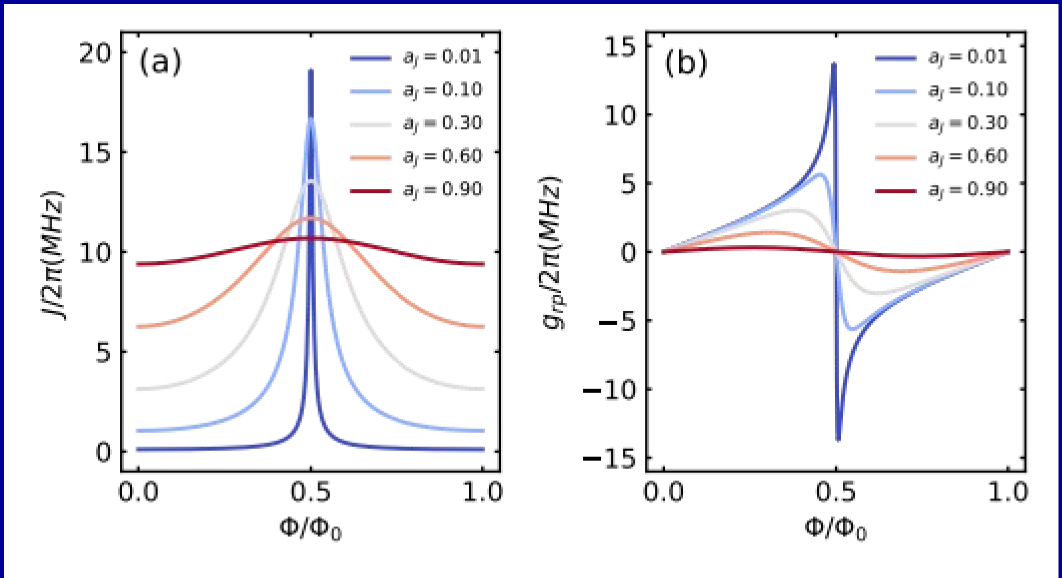
Quantum: M. Kounalakis, G. E. W. Bauer, and YMB, Phys. Rev. Lett. **109**, 037205 (2022)

Magnon-qubit coupling

$$H_{int} = \hbar J \left(\hat{c}^\dagger \hat{m} + \hat{c}\hat{m}^\dagger\right) + g_{rp}\hat{c}^\dagger \hat{c}\left(\hat{m}^\dagger + \hat{m}\right)$$

"Jaynes-Cummings" coupling

"Magnon radiation pressure" coupling



$$a_J = \frac{E_{J1} - E_{J2}}{E_J^{\max}}$$

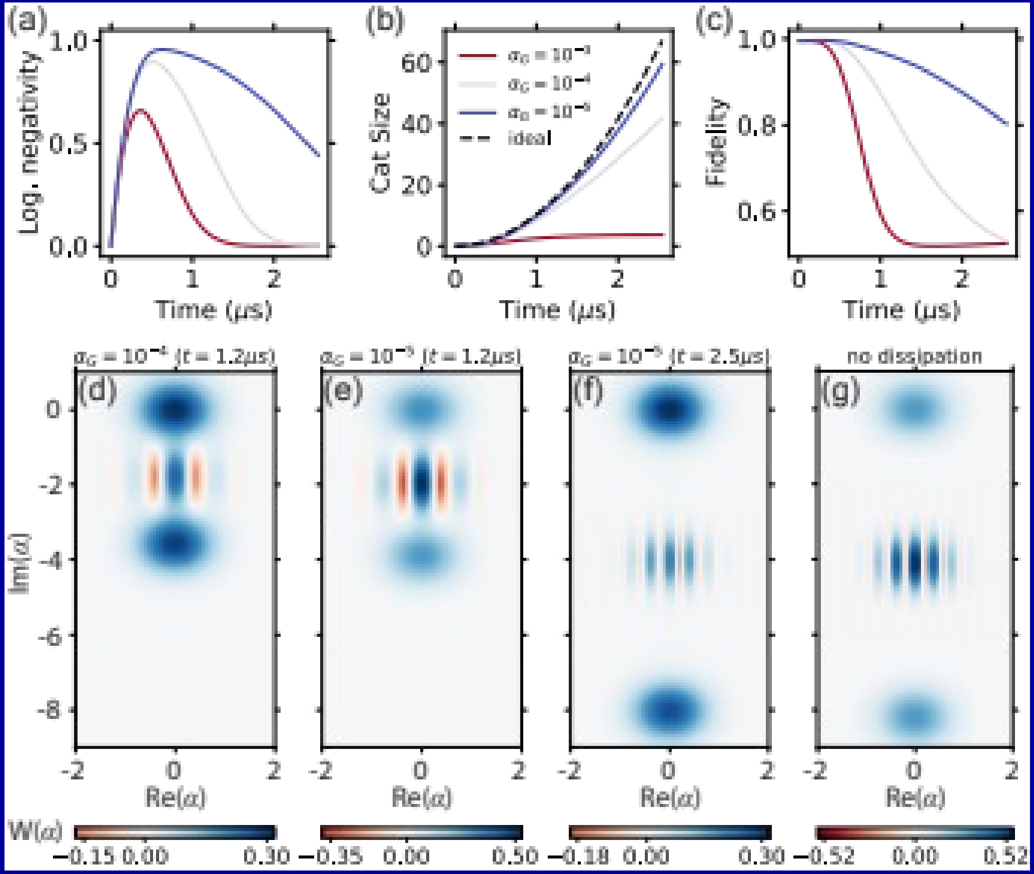
- asymmetry parameter of the transmon

$J \propto a_J$

$$g_{rp} \propto \left(1 - a_J^2\right)\sin\left(2\pi\Phi_b/\Phi_0\right)$$

M. Kounalakis, G. E. W. Bauer, and YMB, Phys. Rev. Lett. **109**, 037205 (2022)

Generation of cat states



Protocol:

1) Prepare qubit and magnon in the ground states
2) $R_{y,\pi/2}$ on the qubit

3) Time-dependent resonant flux modulation
4) $R_{y,\pi/2}$ on the qubit

5) Projective measurement of the qubit

If |0> is measured the state of the

$$\Psi_{even}\rangle = \frac{1}{N} \, |0\rangle + \; -ig_{rp}\tau\rangle$$

(even cat state)

If |1> is measured the magnon is in the odd cat state

M. Kounalakis, G. E. W. Bauer, and YMB, Phys. Rev. Lett. **109**, 037205 (2022)

Conclusions

➢ Dipolar fields generated by spin waves can be strongly anisotropic:

- Unidirectional excitation
- Strong coupling and chiral interactions between magnets

➢ Natural interactions between a magnet and a qubit can be used to facilitate quantum manipulation of magnons

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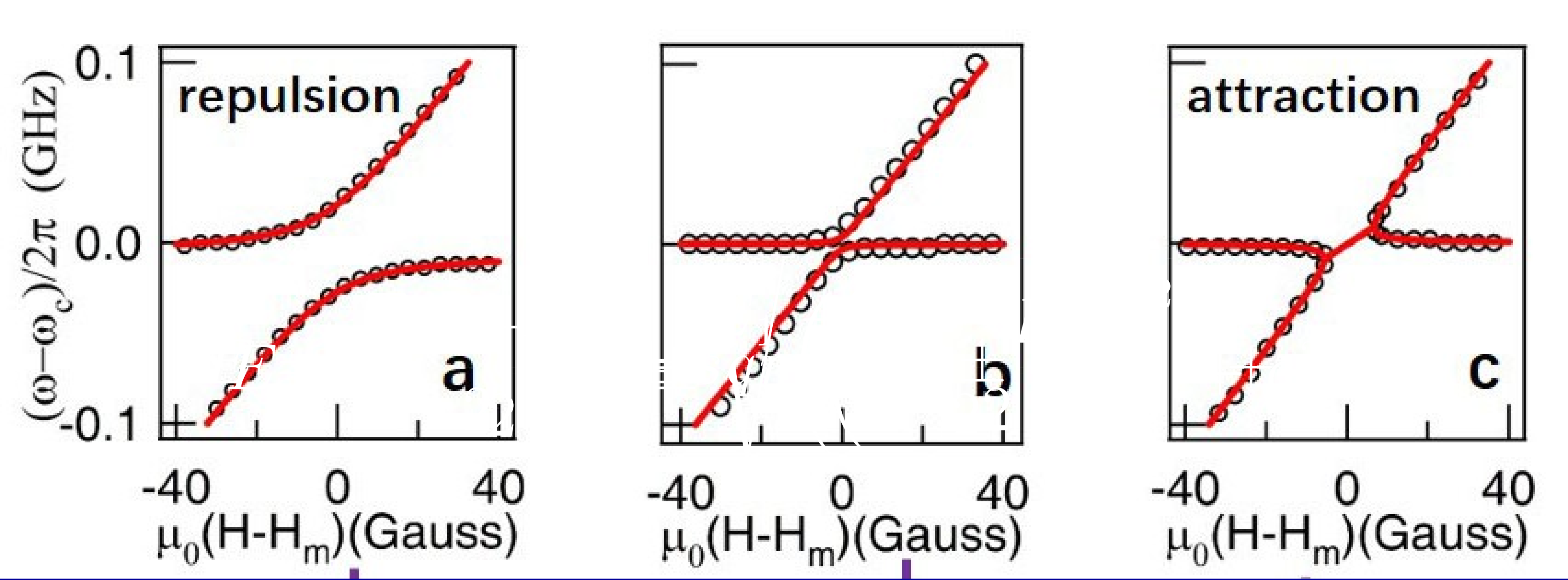
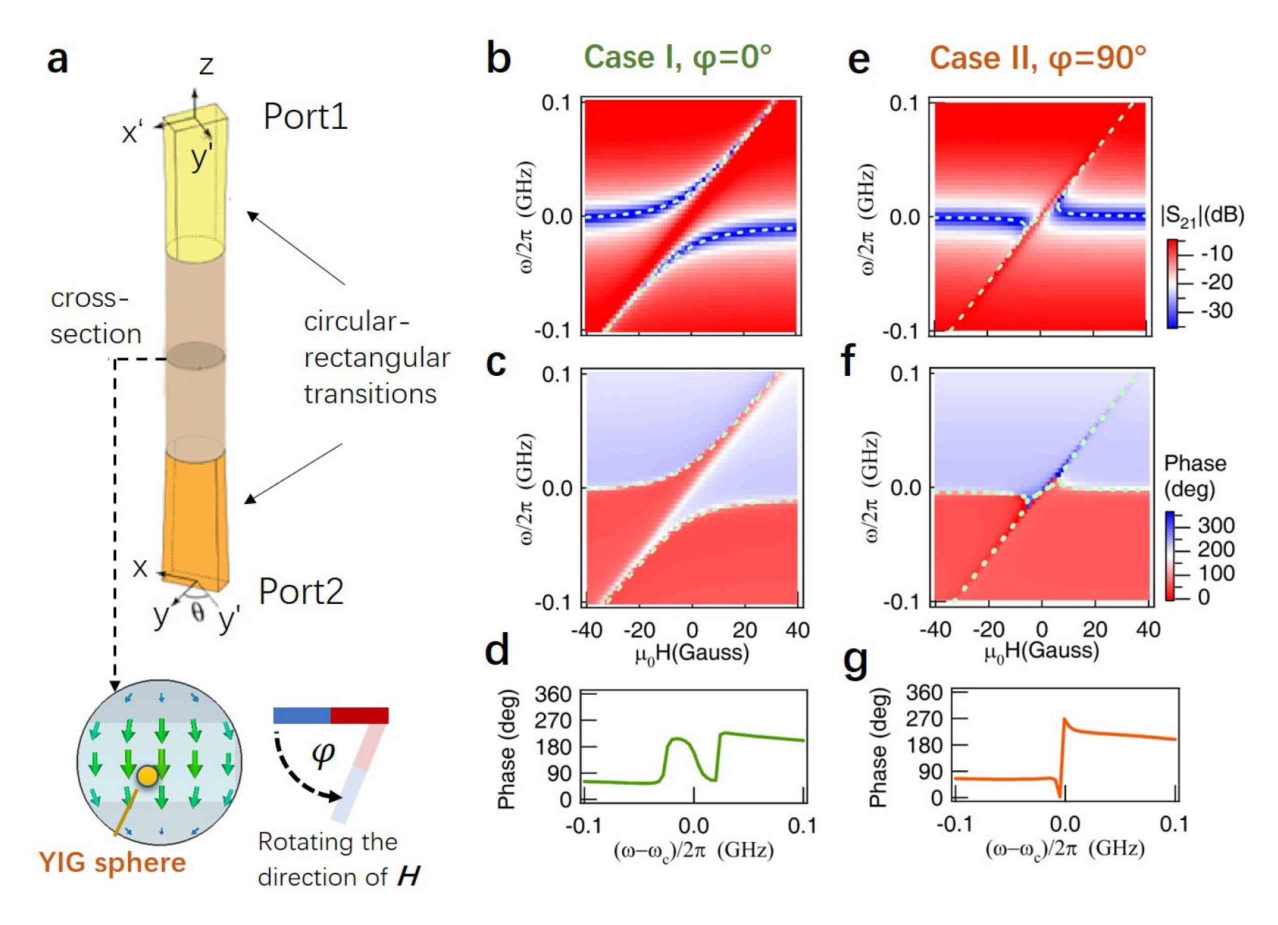
Level repulsion and attraction



$$E = \frac{E_1 + E_2}{2} \pm \sqrt{\left(\frac{E_1 - E_2}{2}\right)^2 + g^2}$$

Level attraction

A magnetic sphere in a lossy Fabry-Perot cavity



B. Yao, T. Yu, X. Zhang, W. Lu, Y. Gui, C.-M. Hu, and YMB, Phys. Rev. B **100,** 214426 (20

Dissipative coupling

Cavity photon spectrum:
- Localized waves at resonances
- Continuous travelling waves away from resonances

Coherent coupling to resonant modes – leads to level repulsion

Coupling to travelling modes – dissipative, leads to level attraction
- Non-Hermitian Hamiltonian
- Competition between level repulsion and attraction

Dissipative coupling