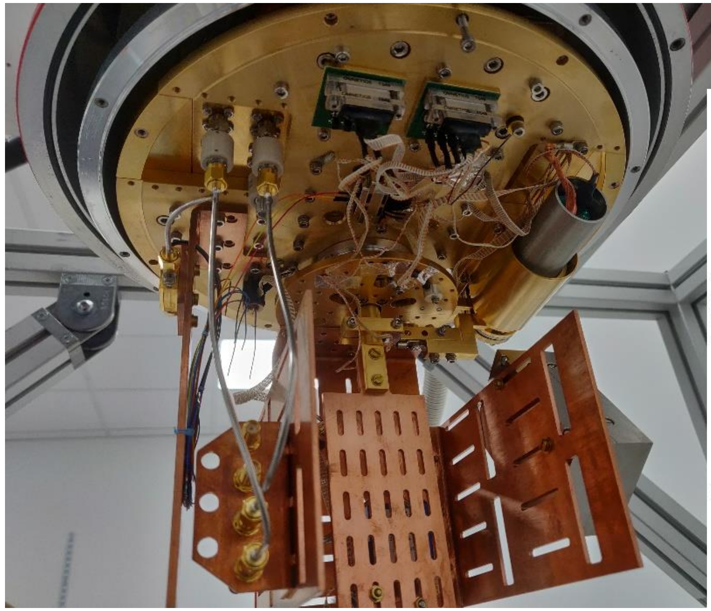
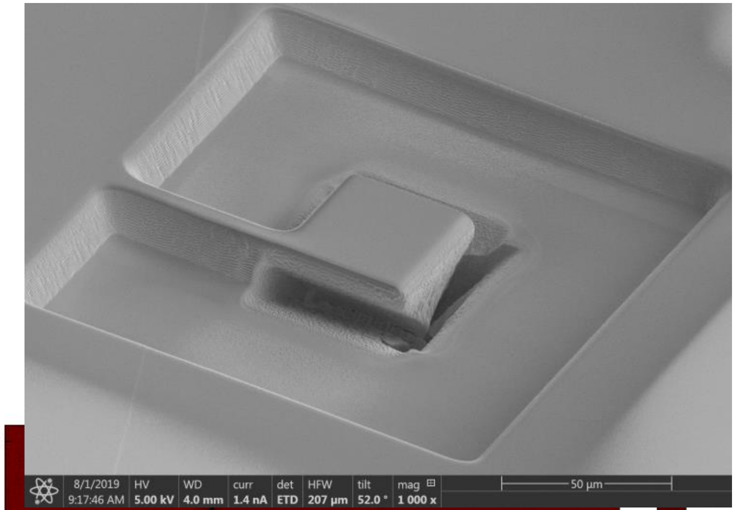
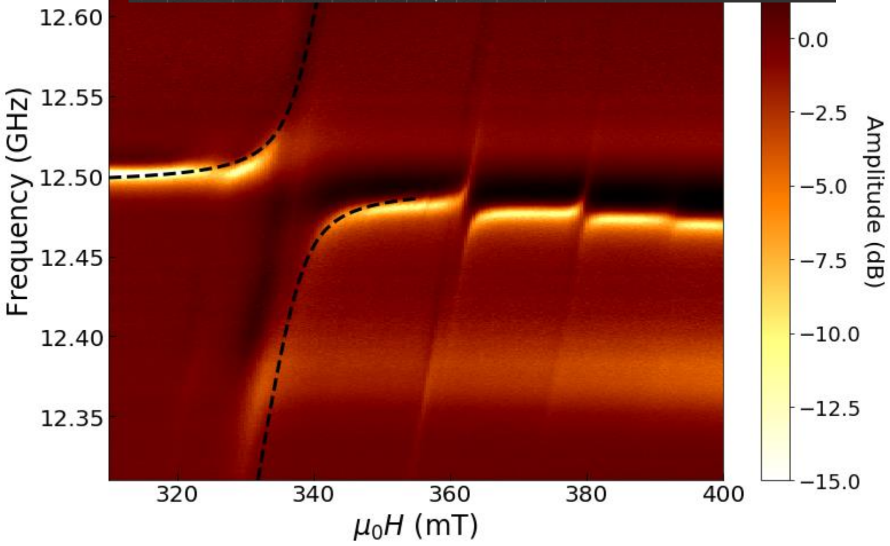
µM-Lab
µ-wave Magnonics Lab

# Yttrium Iron Garnet: the road towards quantum limit

**Dmytro Bozhko**







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CRCW
UCCS Faculty Seed Grants

Department of Physics and Energy Science
University of Colorado Colorado Springs, USA

# My road so far

Feodor Lynen Research Fellow
Alexander von Humboldt foundation

Grad School
MAINZ

Tenure-Track
Assistant Professor
at UCCS

# Computing principles and challenges

- Classical Computing
  - Scalar variable
  - Boolean logic
- Wave Packet Computing
  - Vector variable
  - Special task data processing
- Macroscopic Quantum State Computing
  - Vector state variable
- Quantum Computing
  - Vector state variable
  - Entanglement

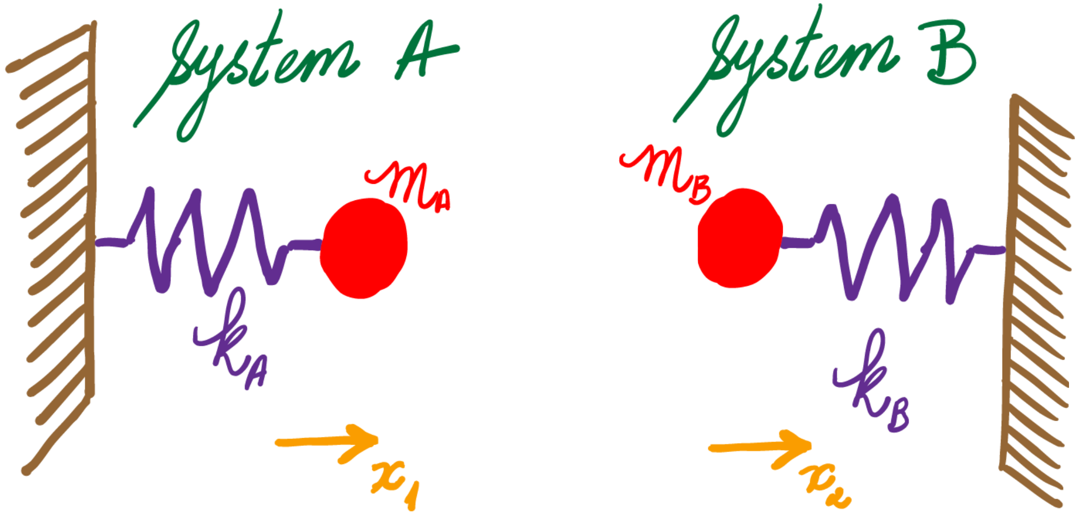
PERFORMANCE INCREASE

Coherent data carriers:
Cooper pairs, phonons, and **magnons**

- Magnon Quantum Computing Challenges
  - Coupling to superconducting quantum systems
  - Implementation of on-chip technology
  - All-magnon quantum computing gates design
  - Sufficiently long magnon lifetime

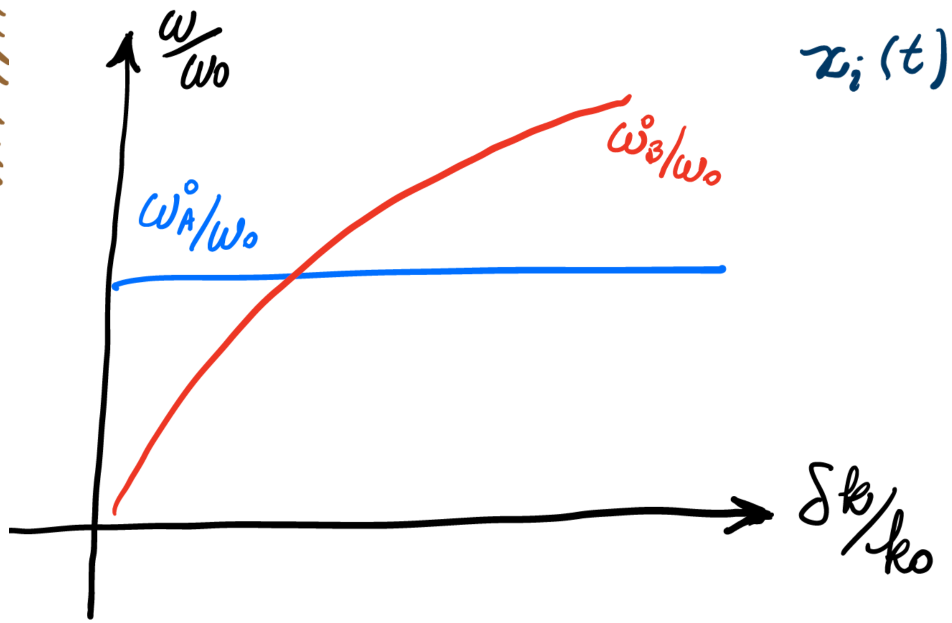
This talk:
I. Coupling
II. YIG on-chip technology

# I. Coupling: two systems



$$\begin{cases} m_A \ddot{x}_A + k_A x_A = 0 \\ m_B \ddot{x}_B + k_B x_B = 0 \end{cases}$$

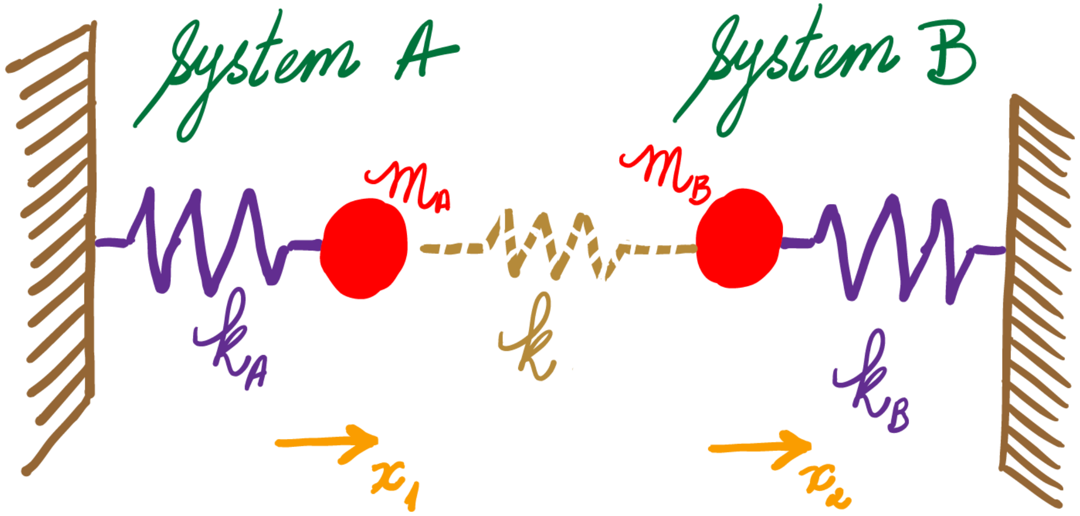
$$x_i(t) = x_i^0 e^{-i\omega_\pm t}$$



To couple two systems, one needs to link them using some physical interaction

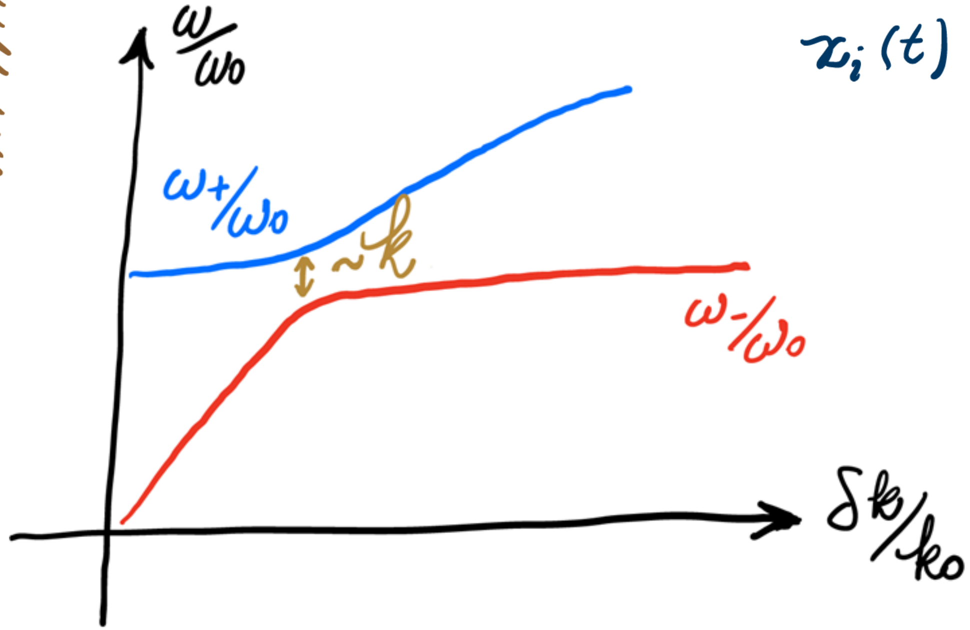
Graphics: Rair Macêdo

# I. Coupling: hybridization



$$\begin{cases} m_A \ddot{x}_A + k_A x_A + k(x_A - x_B) = 0 \\ m_B \ddot{x}_B + k_B x_B + k(x_A - x_B) = 0 \end{cases}$$

$$x_i(t) = x_i^0 e^{-i\omega_\pm t}$$



The stronger the coupling is, the faster one can pass the state from one system to another

Graphics: Rair Macêdo

# I. Coupling: the simplest electromagnetic system

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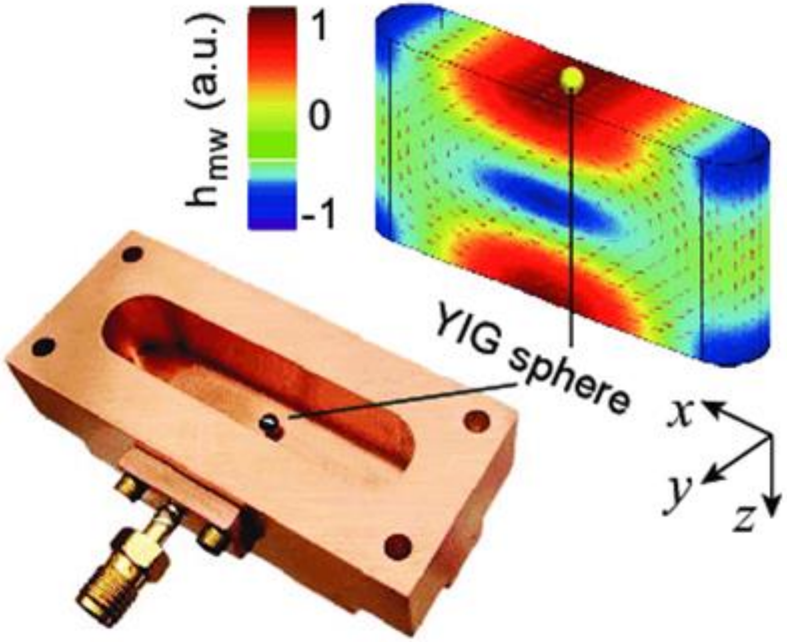
Microwave photon in a cavity and magnon
(cavity magnon polaritons - CMPs):



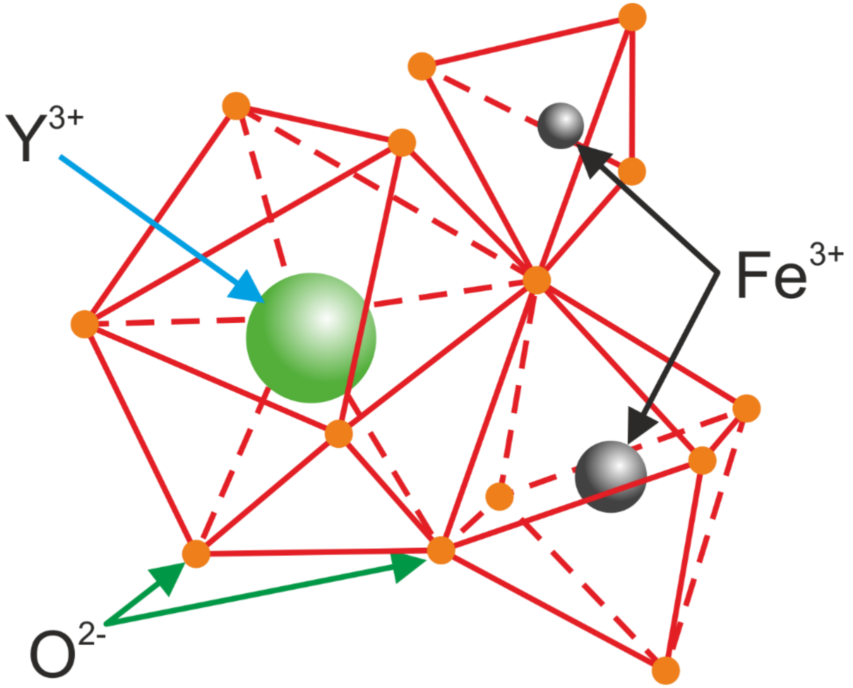
Seems to be a simple system.
Is there a theory around?

Yes and No!

X. Zhang et. al. Phys, Rev. Lett. **113**, 156401 (2014),
D. Zhang et. al. Nat. Commun. **8**, 1368 (2017)

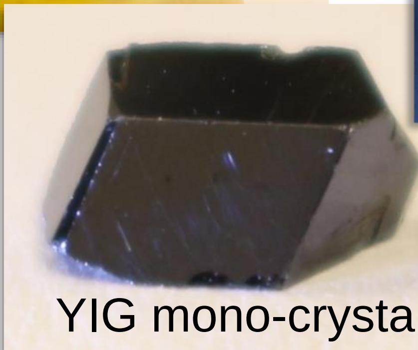
# Yttrium Iron Garnet (YIG, $Y_3Fe_5O_{12}$)

- Room temperature ferrimagnet ($T_C = 560$ K)
- Cubic crystal
- Low phonon damping

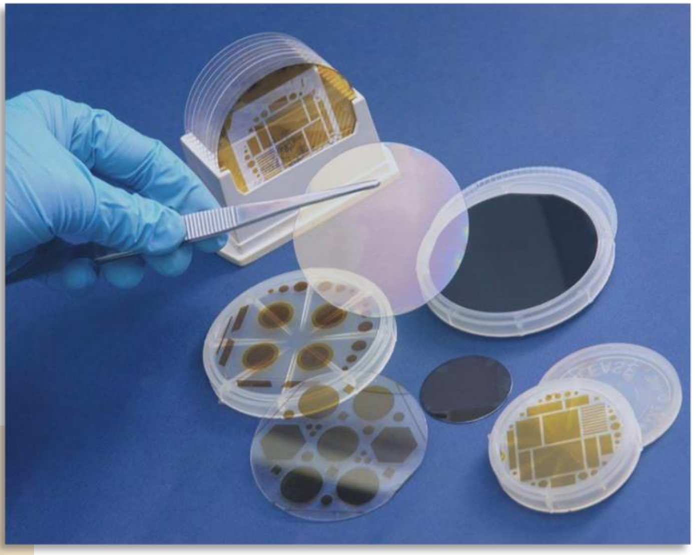


- Lattice constant 12.376 Å
- Unit cell – 80 atoms

3” YIG wafer
SRC “Carat”
I.I. Syvorotka

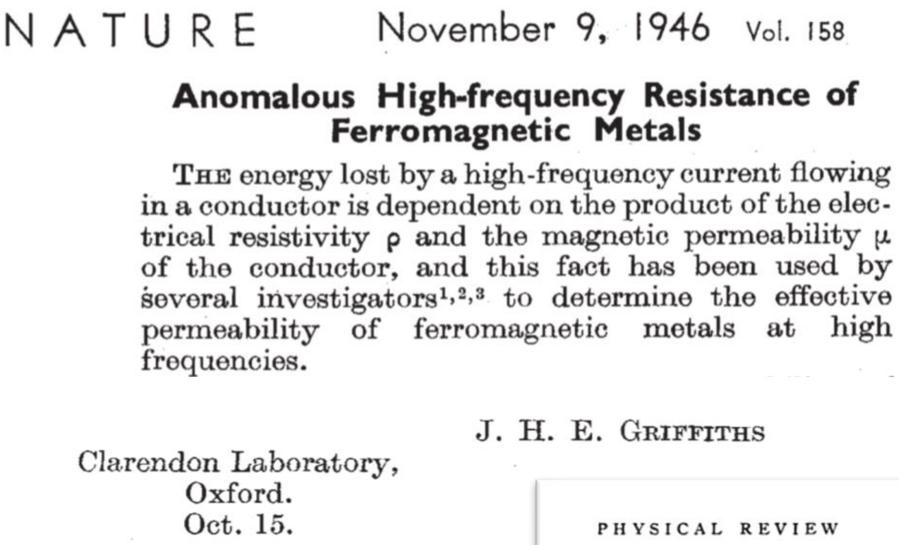


YIG mono-crystal



Longest known spin-wave lifetime (up to 700 ns)

# I. Coupling: CMPs history



NATURE November 9, 1946 Vol. 158

### Anomalous High-frequency Resistance of Ferromagnetic Metals

THE energy lost by a high-frequency current flowing in a conductor is dependent on the product of the electrical resistivity ρ and the magnetic permeability μ of the conductor, and this fact has been used by several investigators[1,2,3] to determine the effective permeability of ferromagnetic metals at high frequencies.

J. H. E. GRIFFITHS

Clarendon Laboratory,
Oxford.
Oct. 15.

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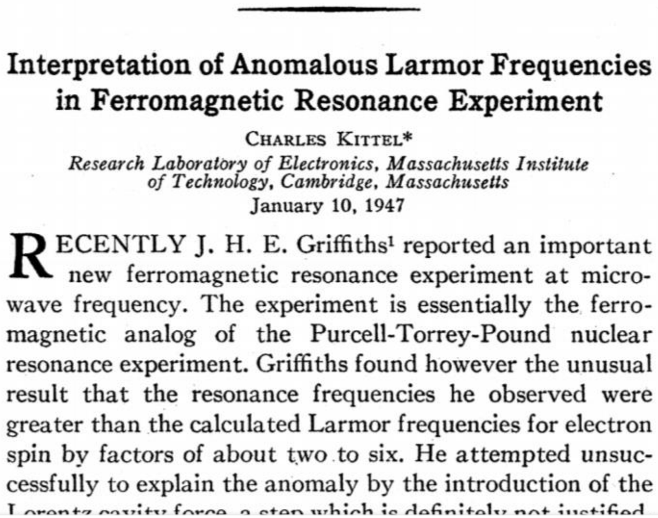

### Interpretation of Anomalous Larmor Frequencies in Ferromagnetic Resonance Experiment

CHARLES KITTEL*
*Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts*
January 10, 1947

RECENTLY J. H. E. Griffiths[1] reported an important new ferromagnetic resonance experiment at microwave frequency. The experiment is essentially the ferromagnetic analog of the Purcell-Torrey-Pound nuclear resonance experiment. Griffiths found however the unusual result that the resonance frequencies he observed were greater than the calculated Larmor frequencies for electron spin by factors of about two to six. He attempted unsuccessfully to explain the anomaly by the introduction of the Lorentz cavity force, a step which is definitely not justified

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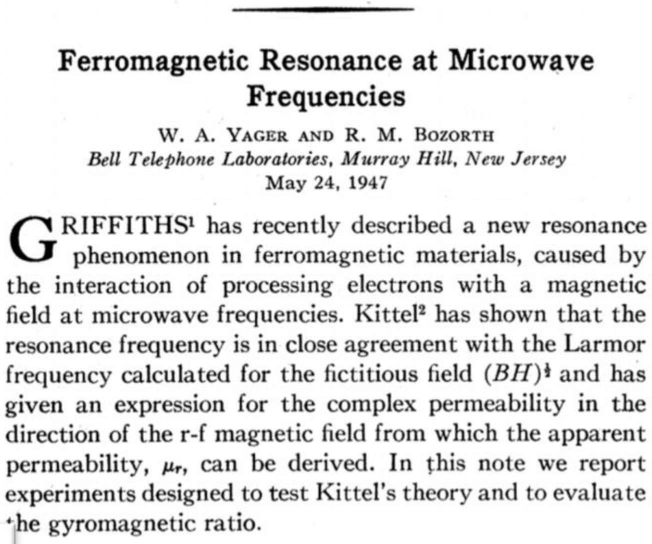

### Ferromagnetic Resonance at Microwave Frequencies

W. A. YAGER AND R. M. BOZORTH
*Bell Telephone Laboratories, Murray Hill, New Jersey*
May 24, 1947

GRIFFITHS[1] has recently described a new resonance phenomenon in ferromagnetic materials, caused by the interaction of processing electrons with a magnetic field at microwave frequencies. Kittel[2] has shown that the resonance frequency is in close agreement with the Larmor frequency calculated for the fictitious field $(BH)^{\frac{1}{2}}$ and has given an expression for the complex permeability in the direction of the r-f magnetic field from which the apparent permeability, $\mu_r$, can be derived. In this note we report experiments designed to test Kittel's theory and to evaluate the gyromagnetic ratio.

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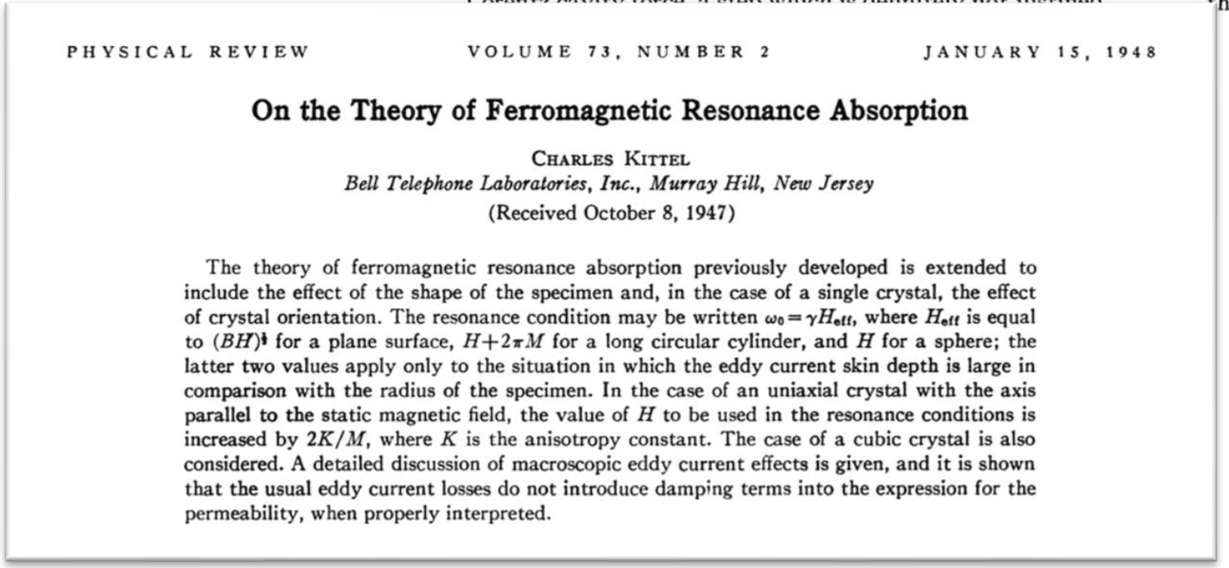


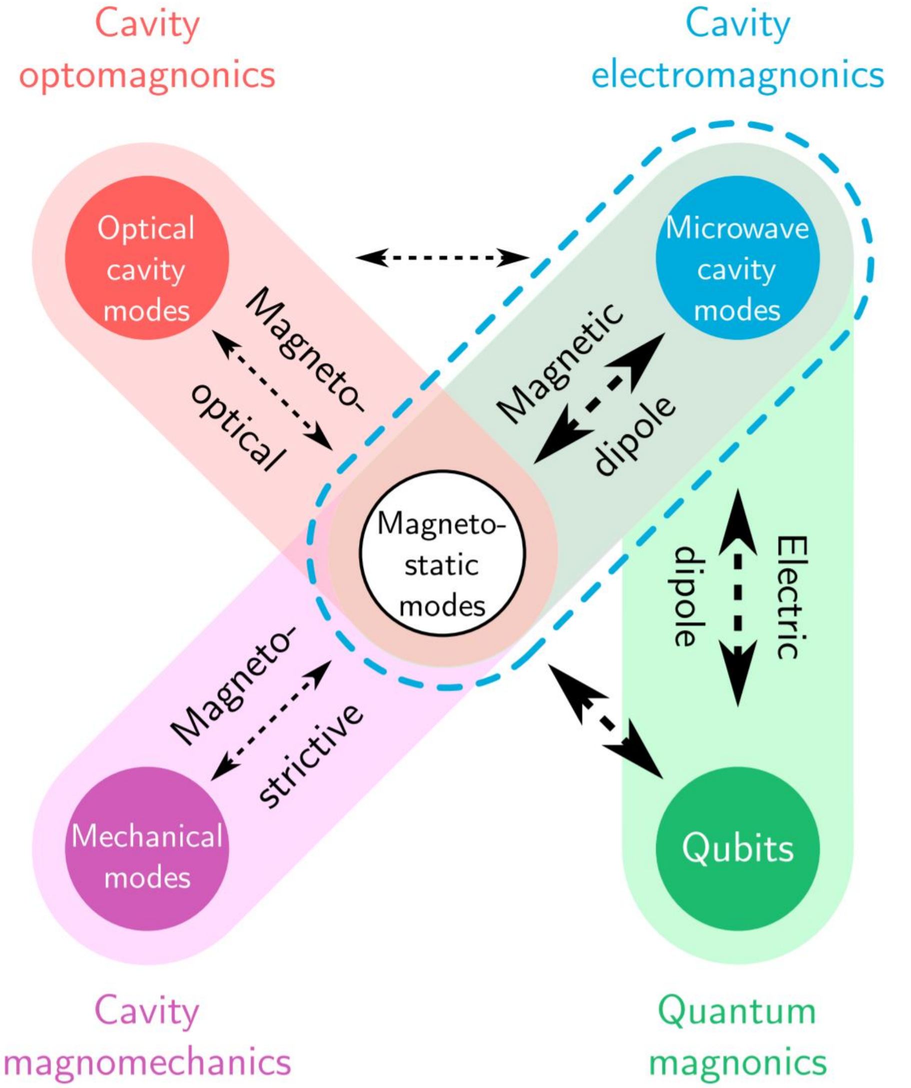
PHYSICAL REVIEW VOLUME 73, NUMBER 2 JANUARY 15, 1948

### On the Theory of Ferromagnetic Resonance Absorption

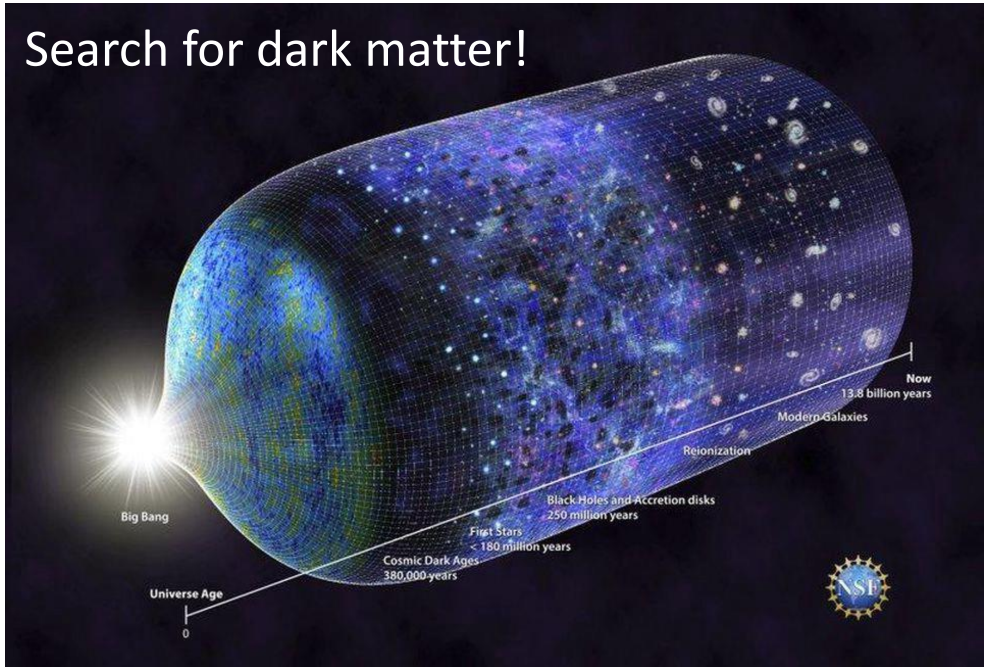
CHARLES KITTEL
*Bell Telephone Laboratories, Inc., Murray Hill, New Jersey*
(Received October 8, 1947)

The theory of ferromagnetic resonance absorption previously developed is extended to include the effect of the shape of the specimen and, in the case of a single crystal, the effect of crystal orientation. The resonance condition may be written $\omega_0=\gamma H_{\text{eff}}$, where $H_{\text{eff}}$ is equal to $(BH)^{\frac{1}{2}}$ for a plane surface, $H+2\pi M$ for a long circular cylinder, and $H$ for a sphere; the latter two values apply only to the situation in which the eddy current skin depth is large in comparison with the radius of the specimen. In the case of an uniaxial crystal with the axis parallel to the static magnetic field, the value of $H$ to be used in the resonance conditions is increased by $2K/M$, where $K$ is the anisotropy constant. The case of a cubic crystal is also considered. A detailed discussion of macroscopic eddy current effects is given, and it is shown that the usual eddy current losses do not introduce damping terms into the expression for the permeability, when properly interpreted.

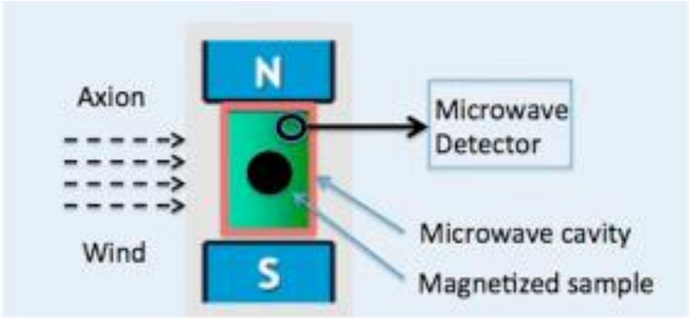
# I. Coupling: what we can couple?



D. Lachance-Quirion et. al., Appl. Phys. Express **12**, 070101 (2019)

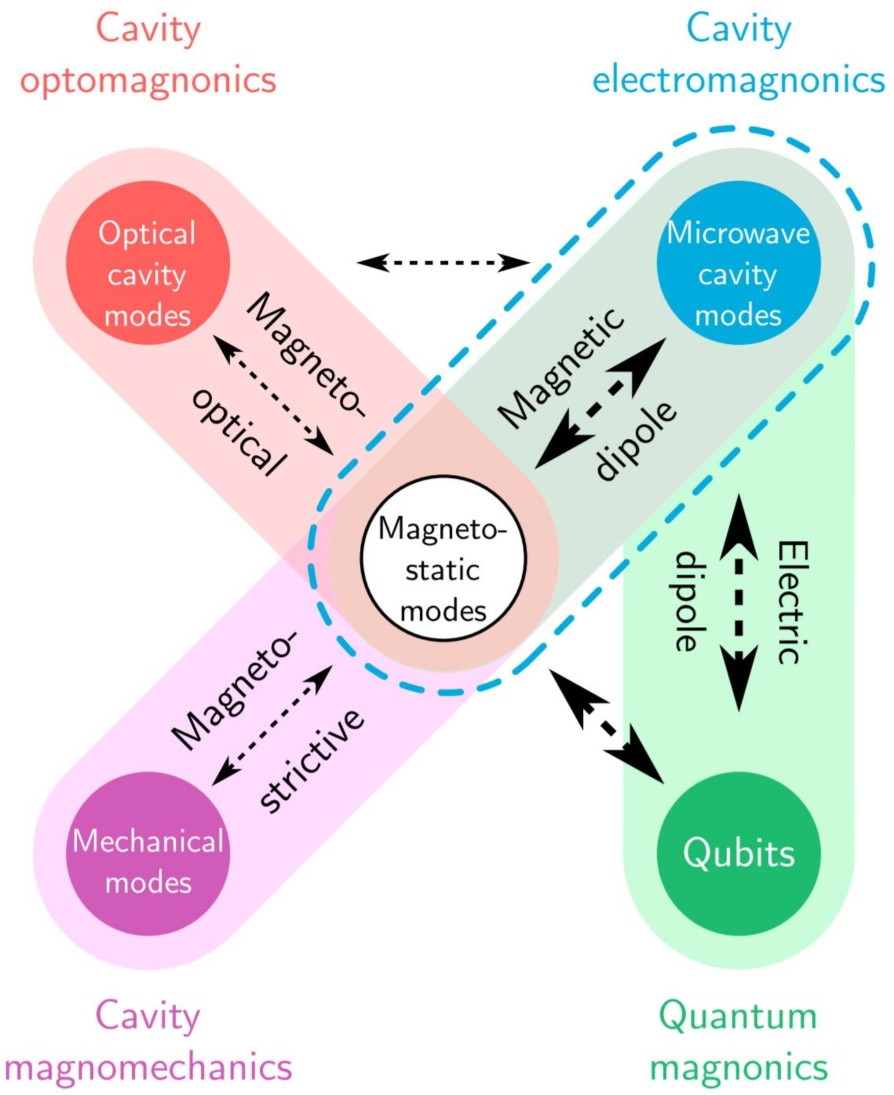

Search for dark matter!

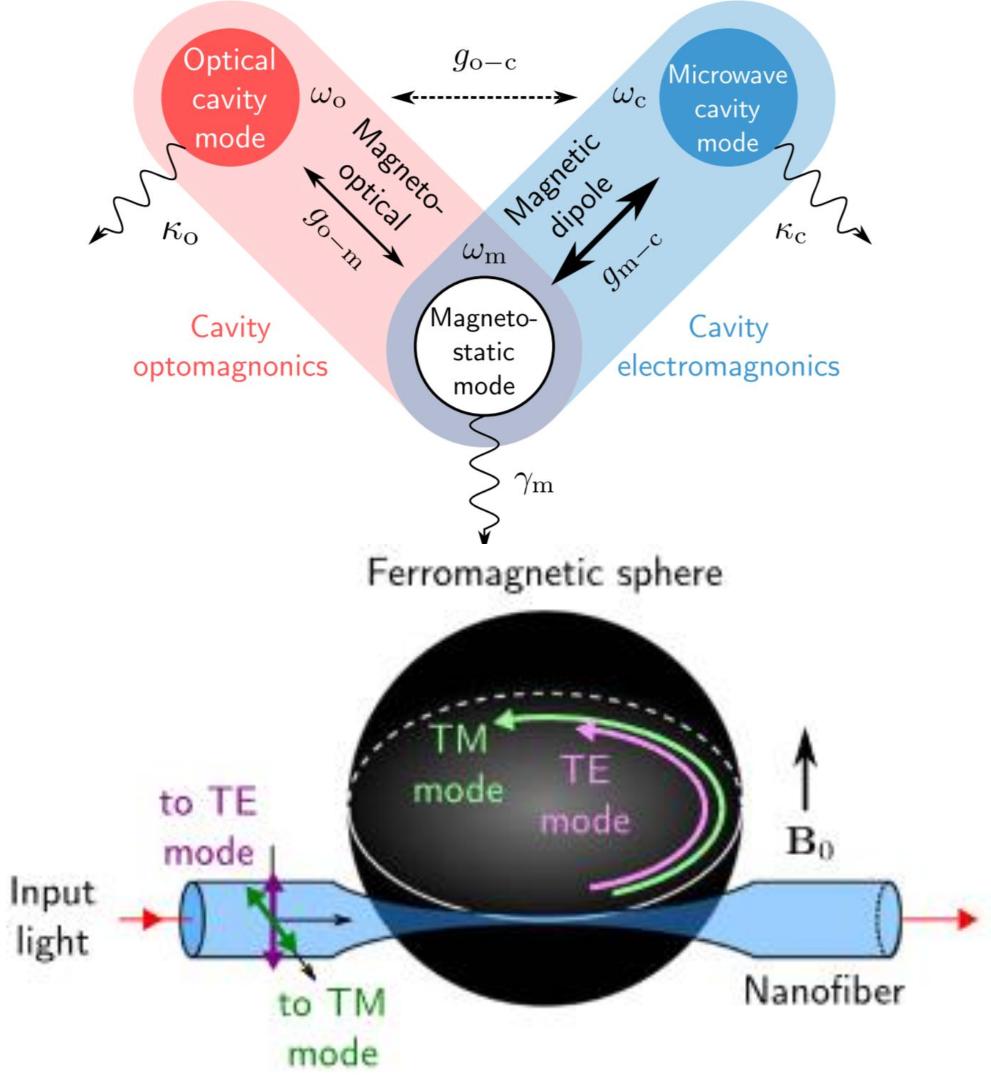
Ferromagnetic axion haloscope:



G. Flower et. al., Physics of the Dark Universe **25** 100306 (2019)

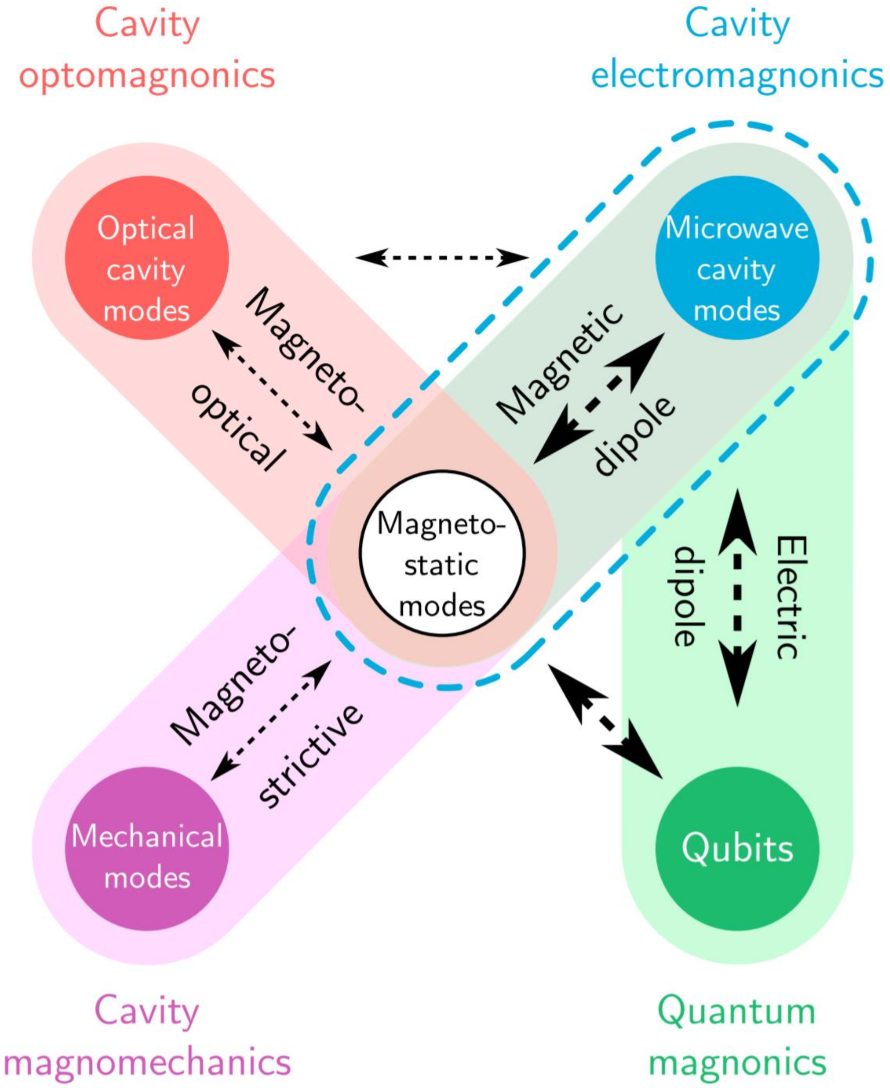
# I. Coupling: what we can couple?

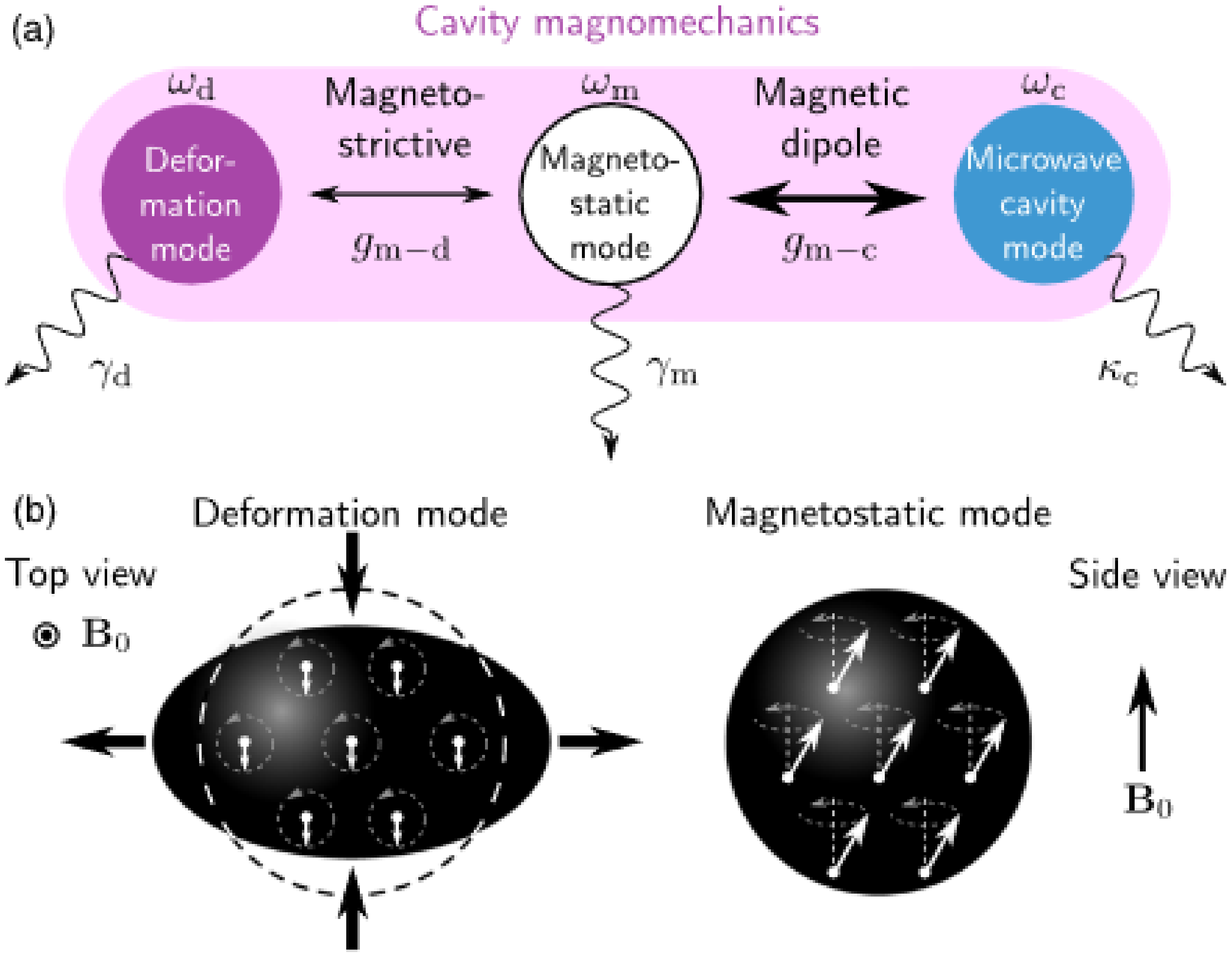




D. Lachance-Quirion et. al., Appl. Phys. Express **12**, 070101 (2019)

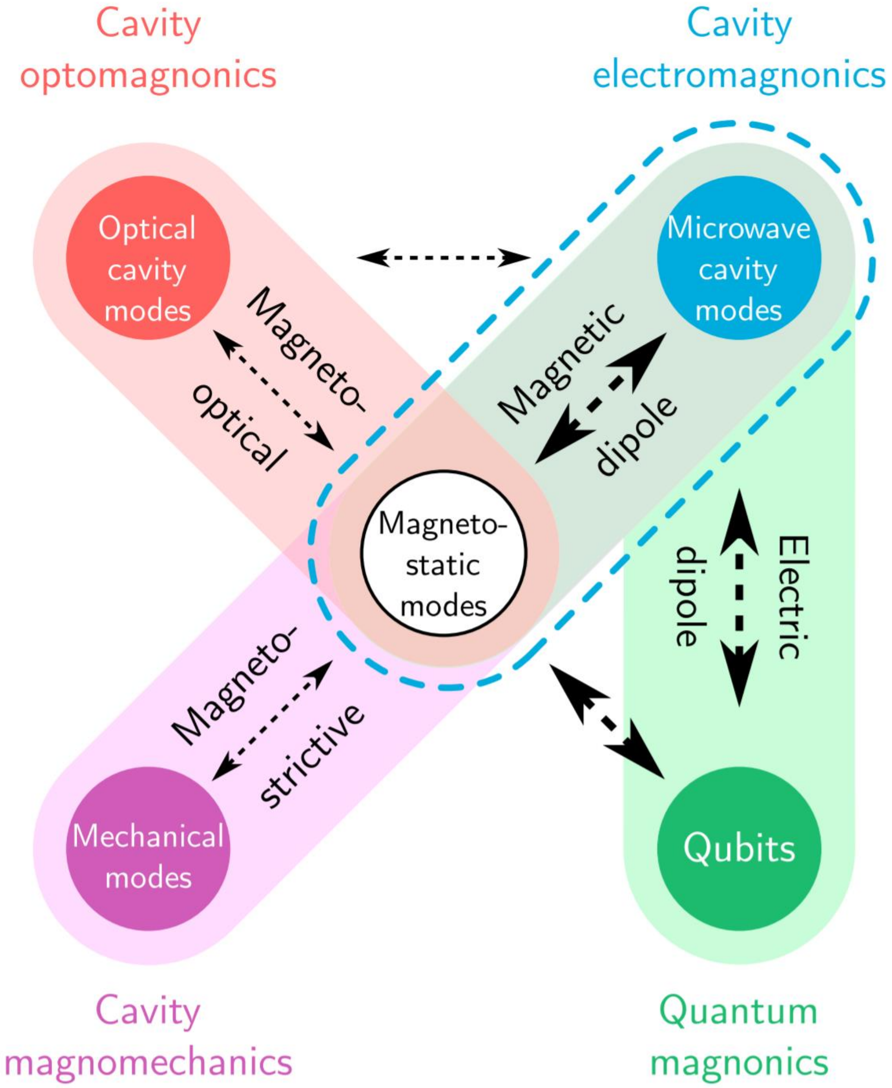
# I. Coupling: what we can couple?



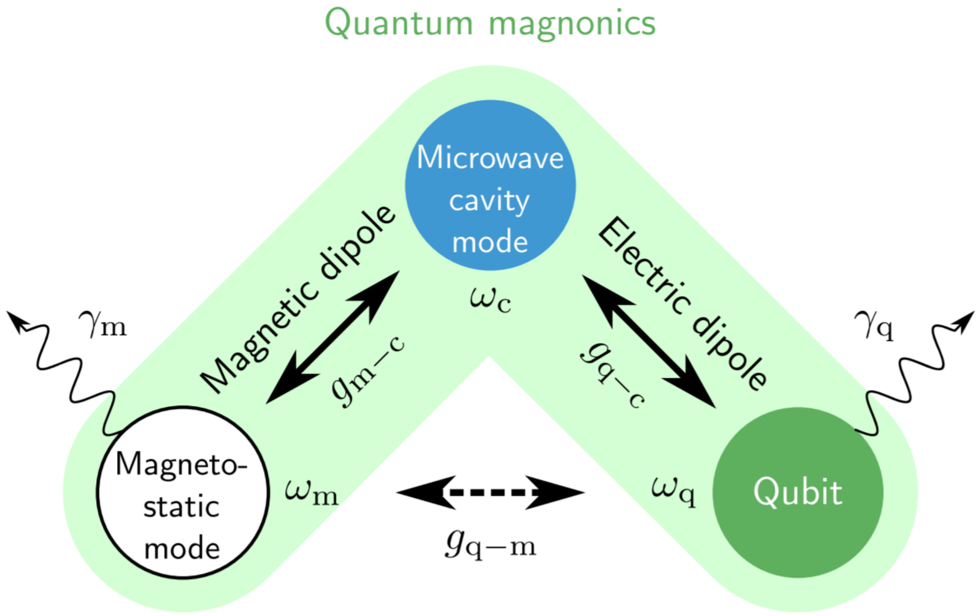


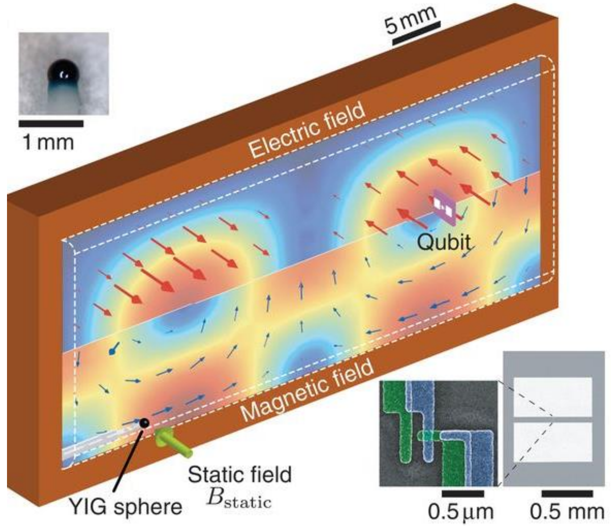
D. Lachance-Quirion et. al., Appl. Phys. Express **12**, 070101 (2019)

# I. Coupling: what we can couple?



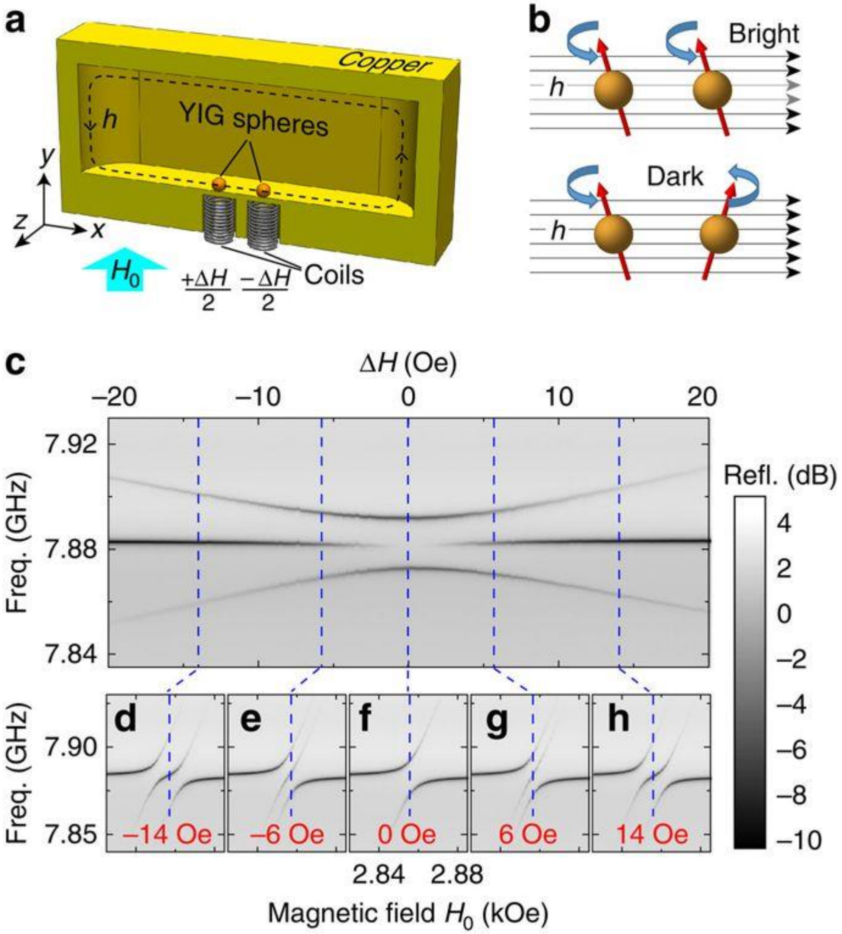
D. Lachance-Quirion et. al., Appl. Phys. Express **12**, 070101 (2019)





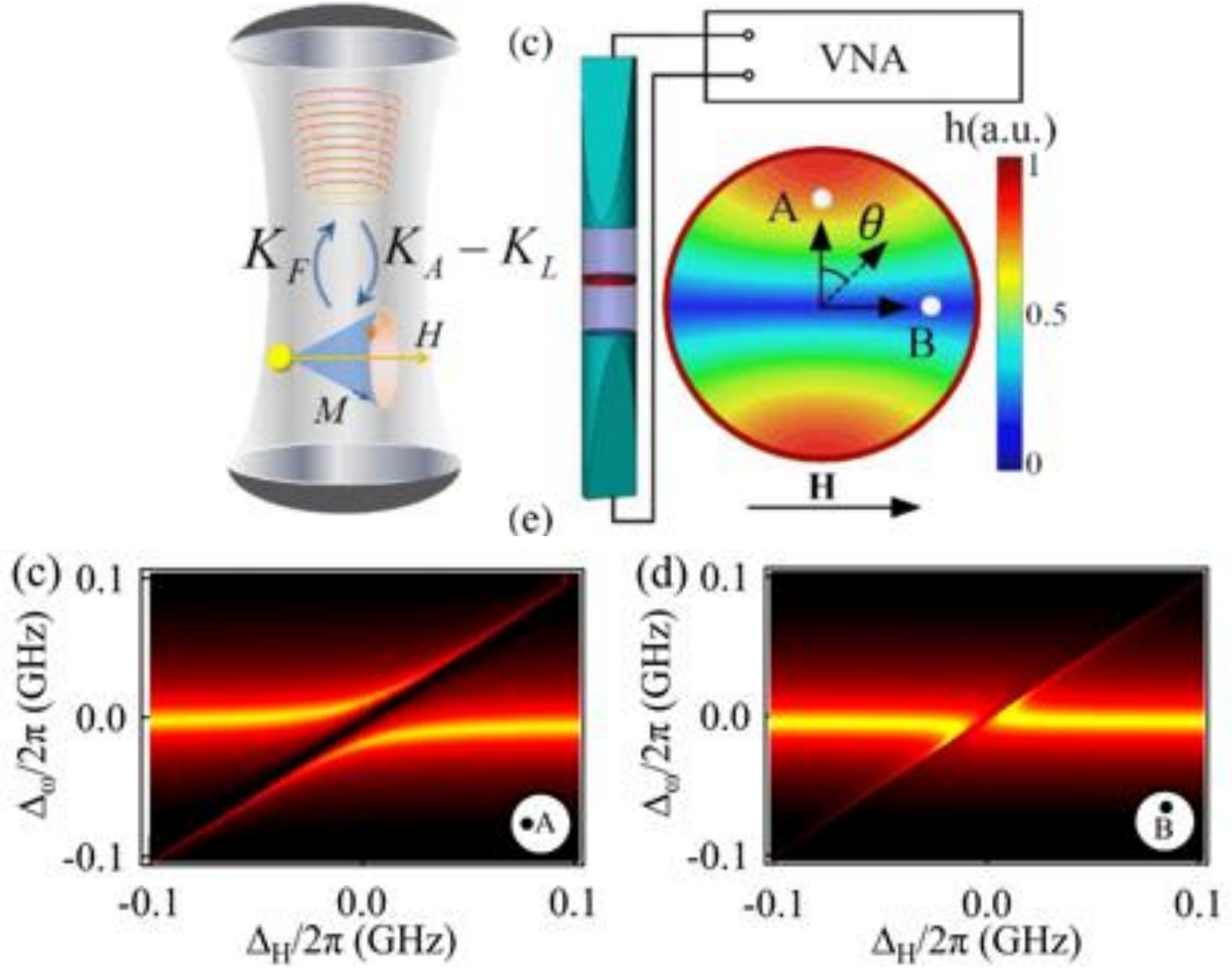
# I. Coupling: control

## Magnetic bias field:



X. Zhang et. al. Nat. Commun. **6**, 8914 (2015)

## Position of the sample:

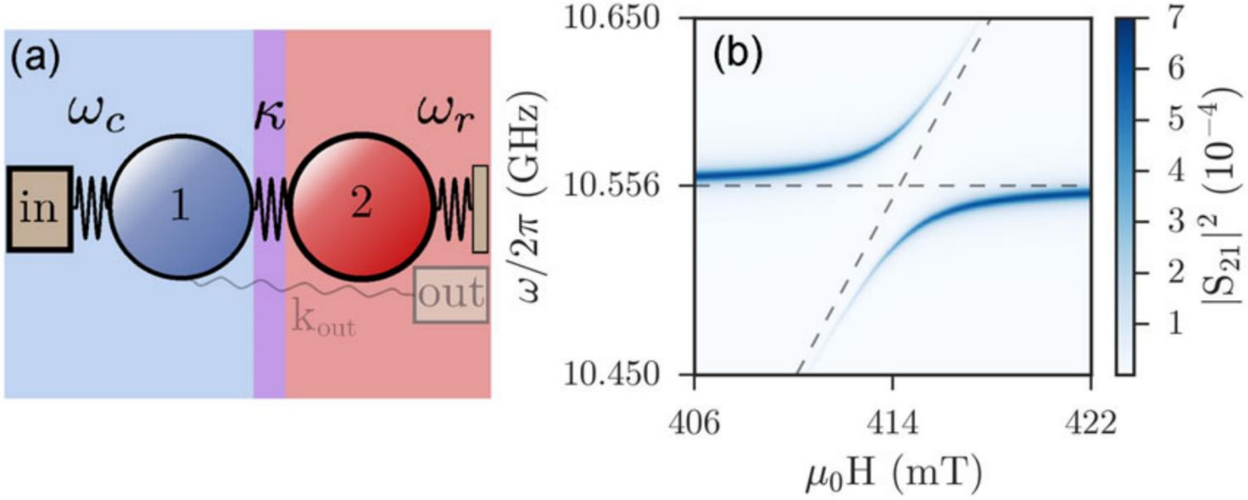


M. Harder Phys. Rev. Lett. **121**, 137203 (2018)

# I. Coupling: theory

## Harmonic coupling:

$$\ddot{x}_1 + \omega_c^2 x_1 + 2\beta\omega_c\dot{x}_1 - \kappa^2\omega_c^2 x_2 = f\mathrm{e}^{-\mathrm{i}\omega t},$$
$$\ddot{x}_2 + \omega_r^2 x_2 + 2\alpha\omega_c\dot{x}_2 - \kappa^2\omega_c^2 x_1 = 0,$$
$$\ddot{x}_{\mathrm{out}} - k_{\mathrm{out}}^2\omega_c^2 x_1 = 0,$$



**Unknown!!!**

$$\boldsymbol{\Omega} = \begin{pmatrix} \omega^2 - \omega_c^2 + 2\mathrm{i}\beta\omega_c\omega & \boxed{\kappa^2}\omega_c^2 \\ \boxed{\kappa^2}\omega_c^2 & \omega^2 - \omega_r^2 + 2\mathrm{i}\alpha\omega_c\omega \end{pmatrix},$$

$$|S_{21}|^2 = \frac{E_{\mathrm{out}}}{E_{\mathrm{in}}}$$

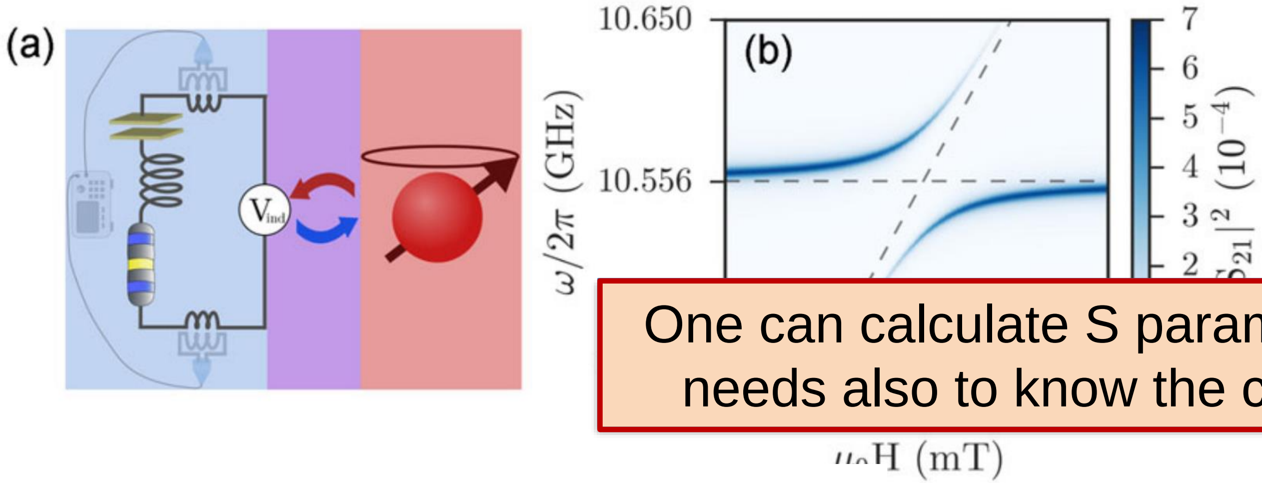
$$\boxed{|S_{21}|^2 = \frac{E_{\mathrm{out}}}{E_{\mathrm{in}}} = \eta\frac{\omega_c^8}{\omega^4}\frac{|\omega^2 - \omega_r^2 + 2\mathrm{i}\alpha\omega\omega_c|^2}{|\det(\boldsymbol{\Omega})|^2},}$$

M. Harder et al, Sci. China-Phys. Mech. Astron. **59**, 117511 (2016)

# I. Coupling: theory

## Dynamic Phase Correlation:

$$Rj^+(t) + \frac{1}{C}\int j^+(t)dt + L\frac{dj^+(t)}{dt} = V^+(t)$$



$$V^+(t) = iK_cL\frac{dm^+(t)}{dt}$$

One can calculate S parameters but needs also to know the coupling!

$$dt \qquad \gamma\mathbf{M}\times\mathbf{H}_f - \frac{\alpha}{M}\left(\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right)$$

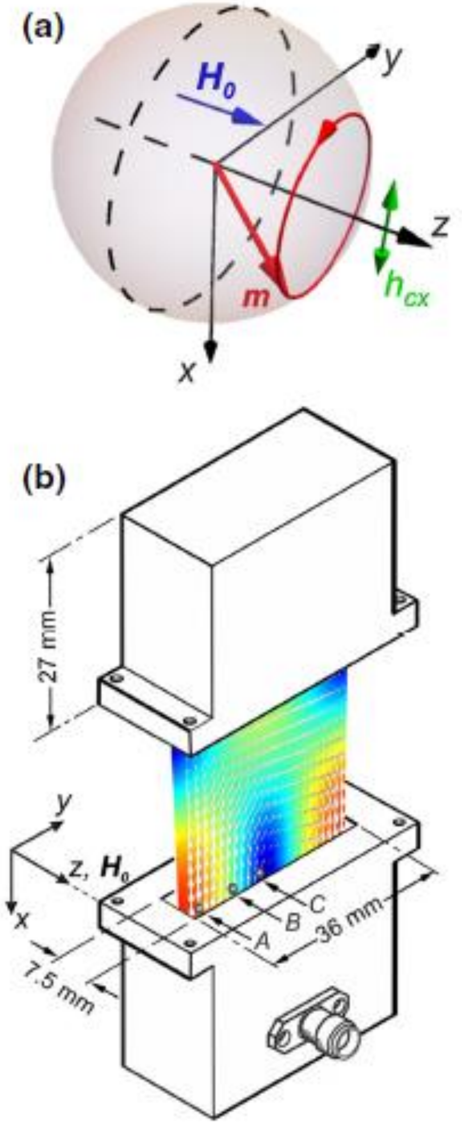
$$Z_c = -i\frac{L}{\omega}\left(\omega^2 - \omega_c^2 + 2i\beta_{\text{int}}\omega_c\omega\right).$$

$$Z_m = \frac{i\omega_c K_c K_m L\omega}{\omega - \omega_r + i\alpha\omega}$$

$$\mathrm{S}_{21} = \frac{2\left(Z_{01}Z_{02}\right)^{1/2}}{AZ_{02} + B + CZ_{01}Z_{02} + DZ_{01}}$$

M. Harder et al, Sci. China-Phys. Mech. Astron. **59**, 117511 (2016)

# Perturbation theory



$$\left.\begin{aligned}\nabla\times\boldsymbol{h}_0 &= i\omega_c\varepsilon_0\boldsymbol{E}_0\\ \nabla\times\boldsymbol{E}_0 &= -i\omega_c\mu_0\boldsymbol{h}_0.\end{aligned}\right\}\ \textbf{Empty cavity}$$

$$\left.\begin{aligned}\nabla\times\boldsymbol{h} &= i\omega\varepsilon_0\boldsymbol{E}+\boldsymbol{J}_e\\ \nabla\times\boldsymbol{E} &= -i\omega\mu_0\boldsymbol{h}+\boldsymbol{J}_m.\end{aligned}\right\}\ \textbf{At the sample}$$

$$\begin{aligned}\boldsymbol{J}_e &= i\omega\varepsilon_0\chi_e(\omega)\cdot\boldsymbol{E} = i\omega[\varepsilon(\omega)-\varepsilon_0]\cdot\boldsymbol{E}\\ \boldsymbol{J}_m &= -i\omega\mu_0\chi_m(\omega)\cdot\boldsymbol{h} = -i\omega[\mu(\omega)-\mu_0]\cdot\boldsymbol{h}.\end{aligned}$$

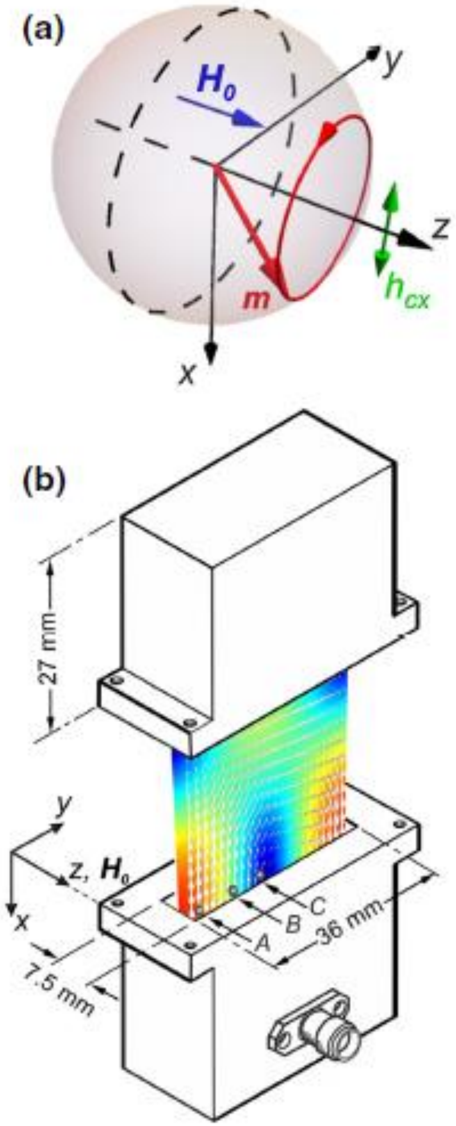
$$\omega-\omega_c = i\frac{\int_{\Delta v}(\boldsymbol{J}_e\cdot\boldsymbol{E}_0^*-\boldsymbol{J}_m\cdot\boldsymbol{h}_0^*)dv}{\int_v(\varepsilon_0\boldsymbol{E}_0^*\cdot\boldsymbol{E}+\mu_0\boldsymbol{h}_0^*\cdot\boldsymbol{h})dv}$$

**If disturbance to the cavity mode due to dielectric part of the sample is small:**

$$\boxed{\omega-\omega_c = -\omega_c\frac{\displaystyle\int_{\delta v}\mu_0\left[\overleftrightarrow{\chi}_m(\omega)\cdot\mathbf{h}_c\right]\cdot\mathbf{h}_c^*\,dv}{\displaystyle 2\int_v\mu_0\mathbf{h}_c^*\cdot\mathbf{h}_c\,dv}}$$

R. Macedo et al, Phys. Rev. Applied **15**, 024065 (2021)

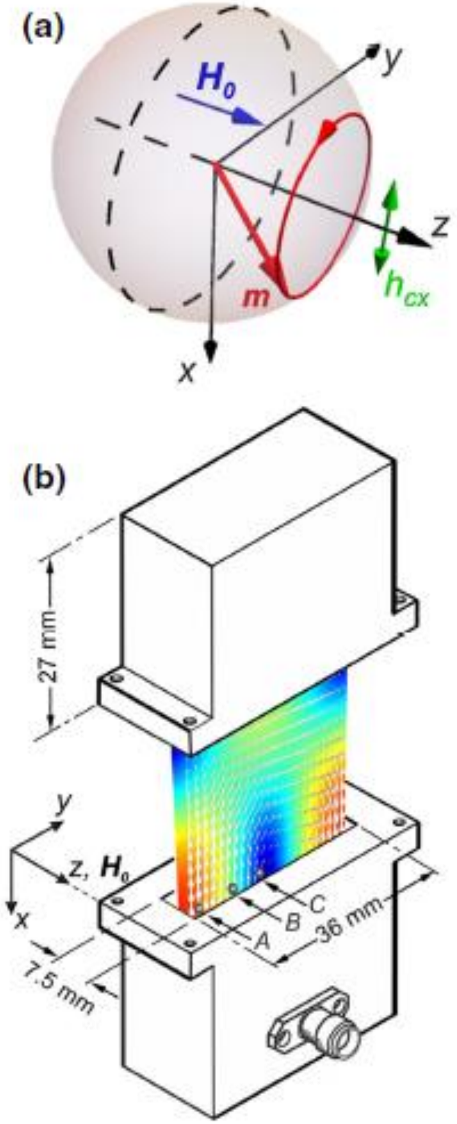
# Perturbation theory



R. Macedo et al, Phys. Rev. Applied **15**, 024065 (2021)

$$\omega - \omega_c = -\omega_c \frac{\int_{\delta v} \mu_0 \left[\overleftrightarrow{\chi}_m(\omega) \cdot \mathbf{h}_c\right] \cdot \mathbf{h}_c^* \, dv}{2 \int_v \mu_0 \mathbf{h}_c^* \cdot \mathbf{h}_c \, dv}$$

# Perturbation theory



$$\boxed{\omega - \omega_c = -\omega_c \frac{\int_{\delta v} \mu_0 \left[ \overleftrightarrow{\chi}_m(\omega) \cdot \mathbf{h}_c \right] \cdot \mathbf{h}_c^* \, dv}{2 \int_v \mu_0 \mathbf{h}_c^* \cdot \mathbf{h}_c \, dv}}$$

Now calculating the susceptibility tensor:

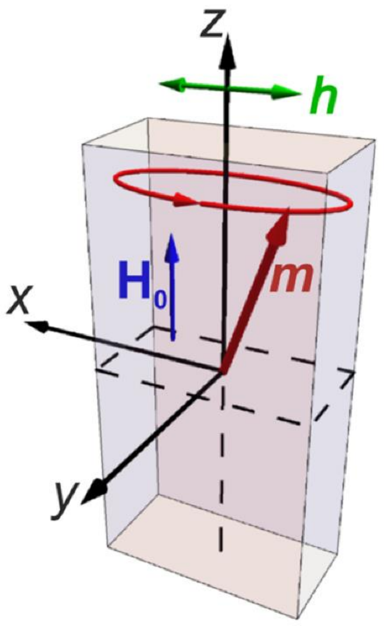
$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mu_0 (\mathbf{M} \times \mathbf{H}_{\text{eff}}).$$

Any sample shape can be accounted for:

$$\omega_0^2 = \gamma^2 \mu_0^2 [H_0 + (D_y - D_z) M_s] \times [H_0 + (D_x - D_z) M_s].$$

$$\begin{bmatrix} m_x \\ m_y \end{bmatrix} = \underbrace{\begin{bmatrix} \chi_{xx} & \chi_{xy} \\ \chi_{yx} & \chi_{yy} \end{bmatrix}}_{\overleftrightarrow{\chi}_m(\omega)} \begin{bmatrix} h_x \\ h_y \end{bmatrix}$$

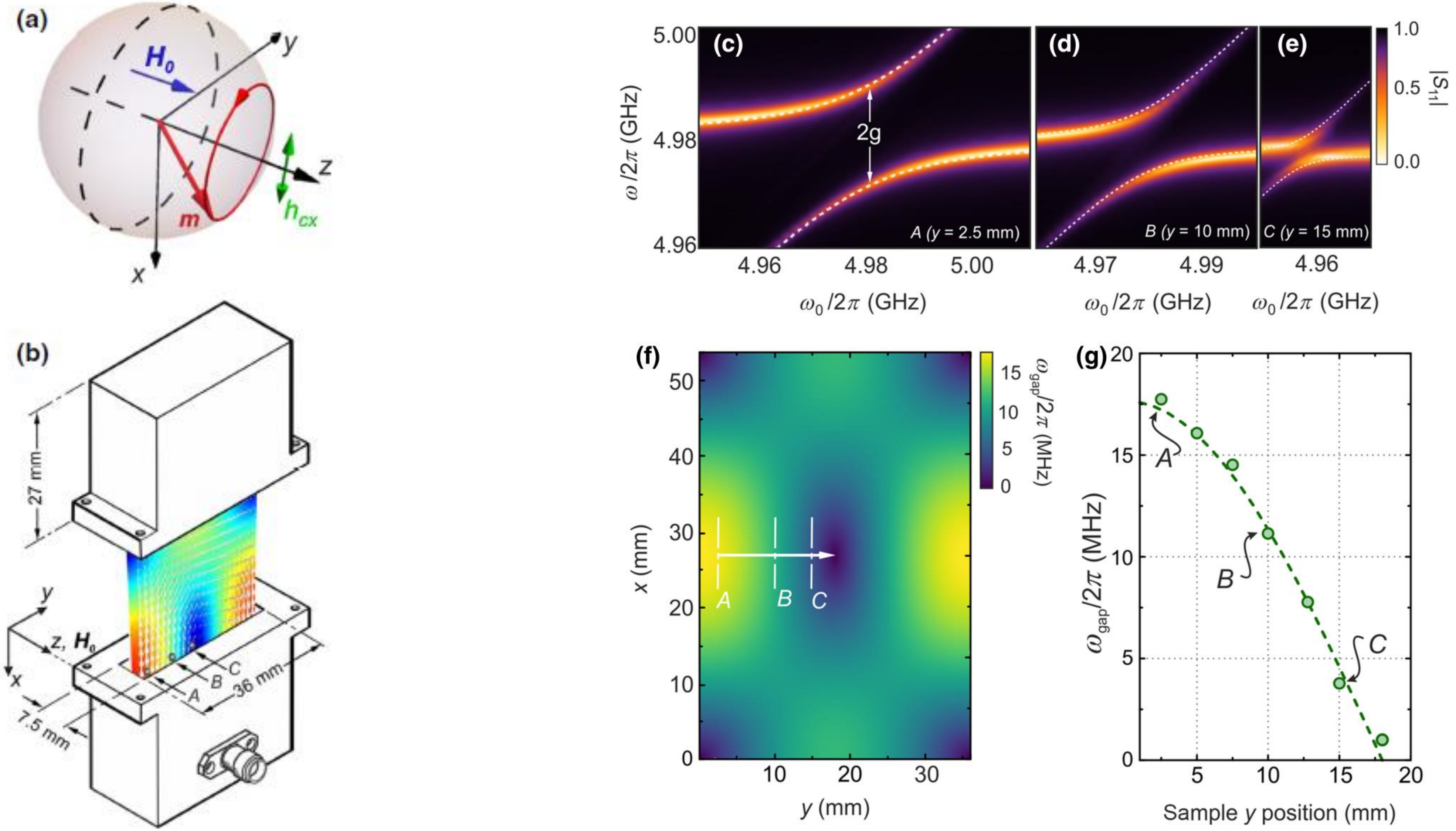
$$\chi_{xx}(\omega) = \frac{\chi_a}{1 - (\omega/\omega_0)^2}, \quad \chi_a = \frac{M_s}{H_0 + (D_x - D_z) M_s}.$$



If the sample’s shape is more complicated ⇨ Micromagnetics

R. Macedo et al, Phys. Rev. Applied **15**, 024065 (2021)

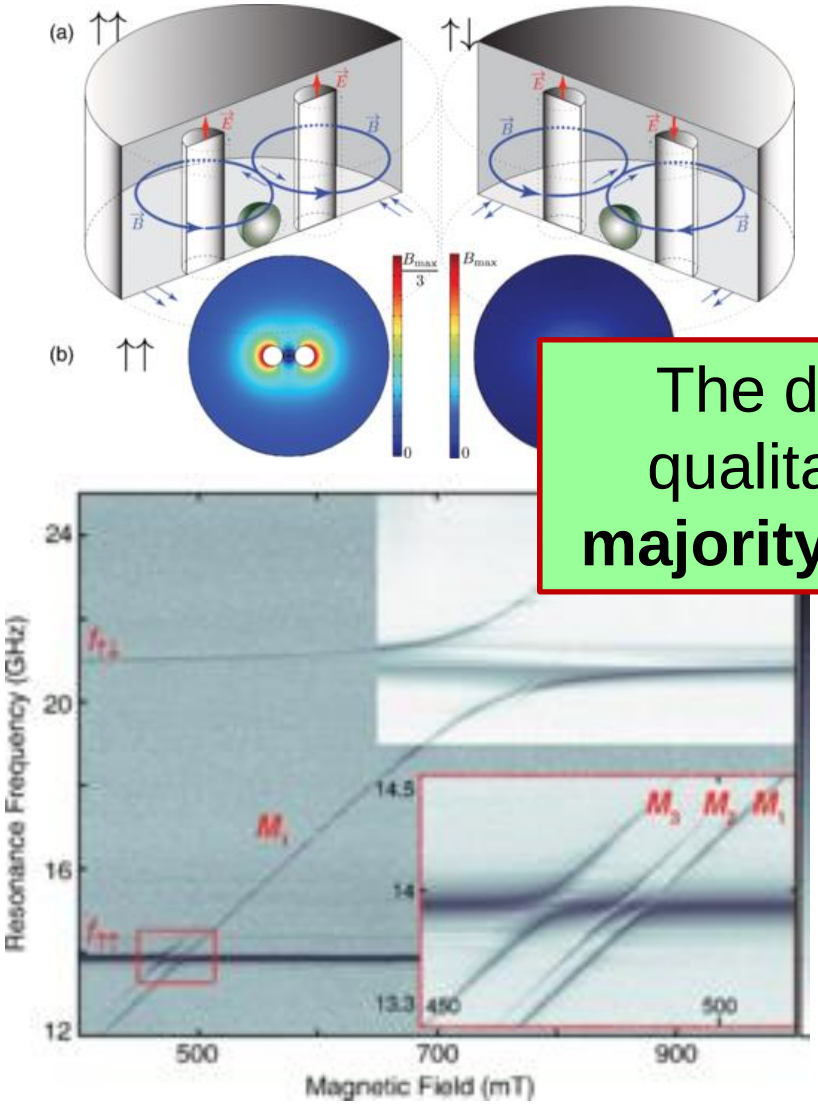
# Perturbation theory: results



R. Macedo et al, Phys. Rev. Applied **15**, 024065 (2021)

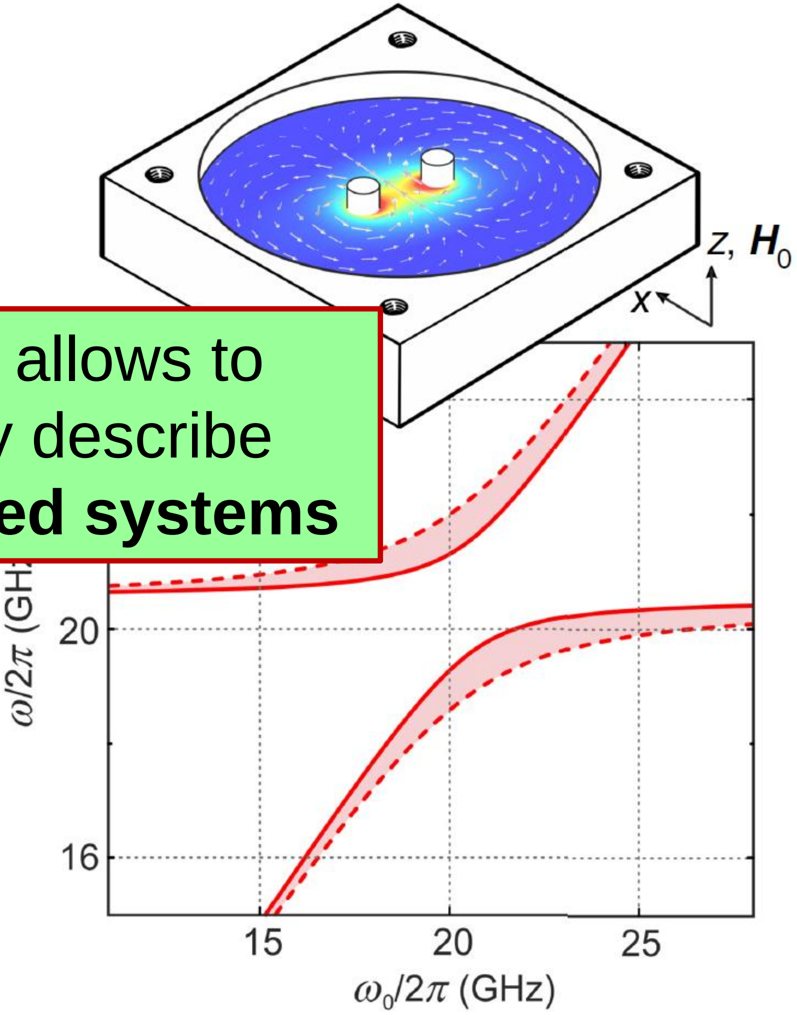
# Perturbation theory: ultra-strong coupling

**Experiment:**



M. Goryachev et al, Phys. Rev. Applied **2**, 054002 (2014)

**Our theory:**



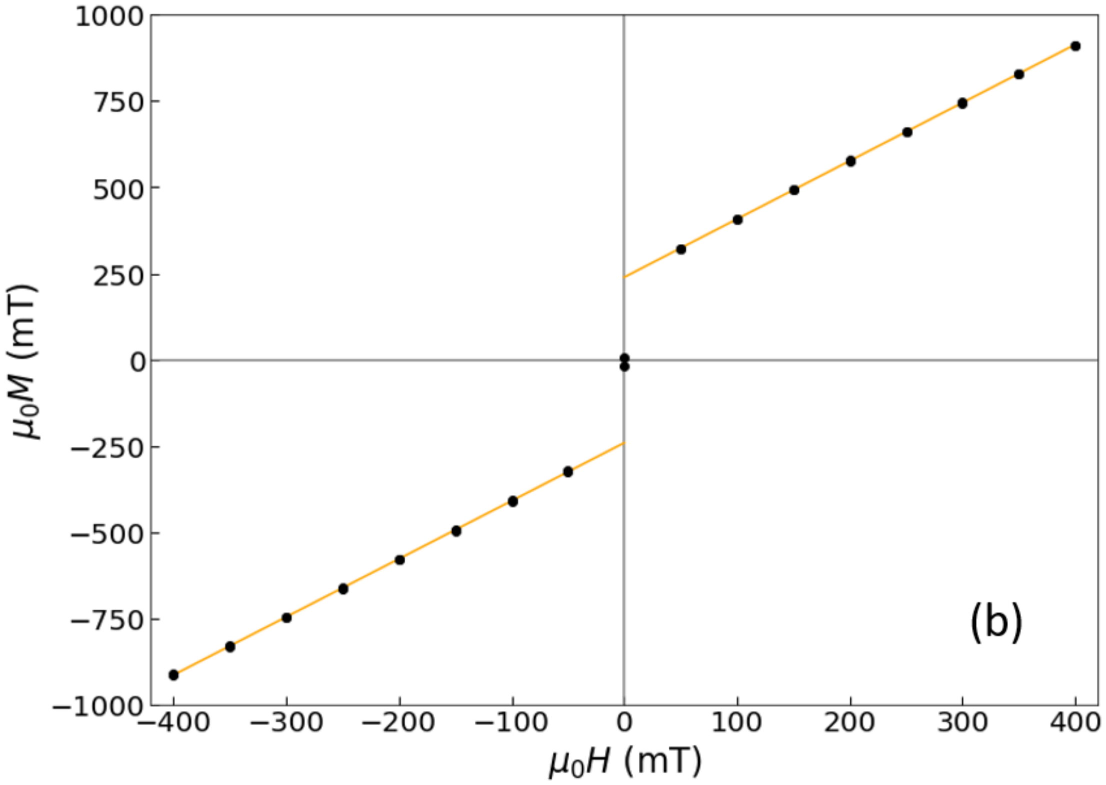
R. Macedo et al, Phys. Rev. Applied **15**, 024065 (2021)

The developed theory allows to qualitatively accurately describe **majority of so far studied systems**

# II. YIG on-chip technology - problems

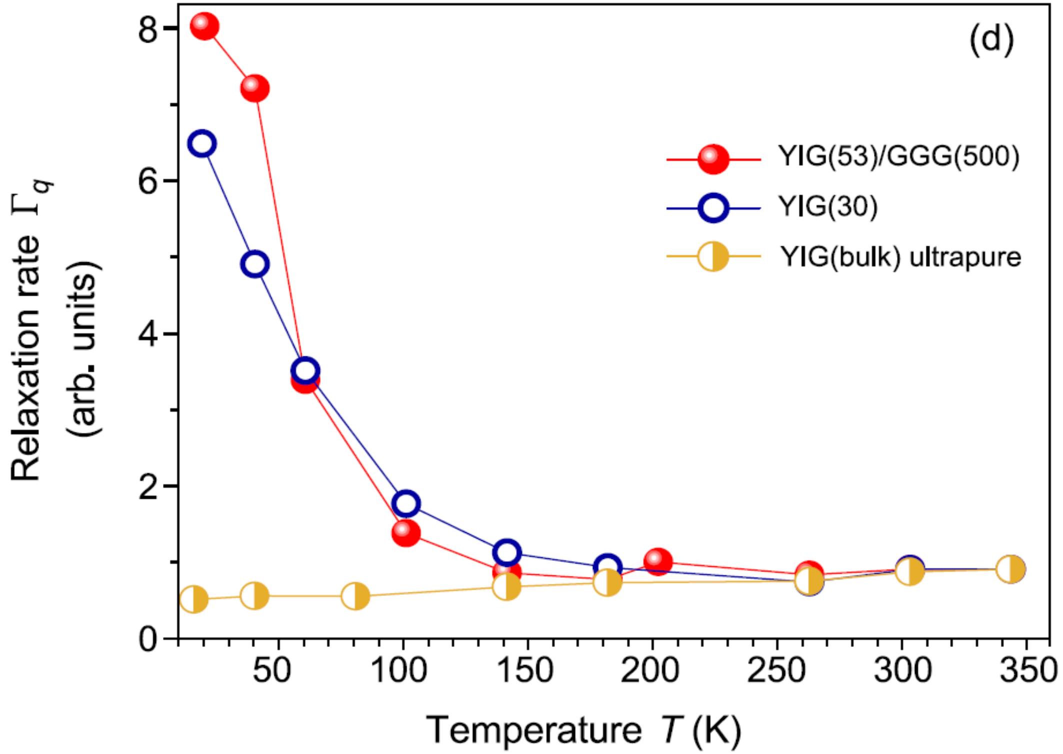
Bulk YIG samples are great, but what about thin films?

Magnetization of YIG/GGG sample at 4K:



Baity et al., arXiv:2104.08068v2 (2021)

YIG/GGG sample damping above 10K:



L. Mihalceanu *et al*., Phys. Rev. B **97**, 214405 (2018)

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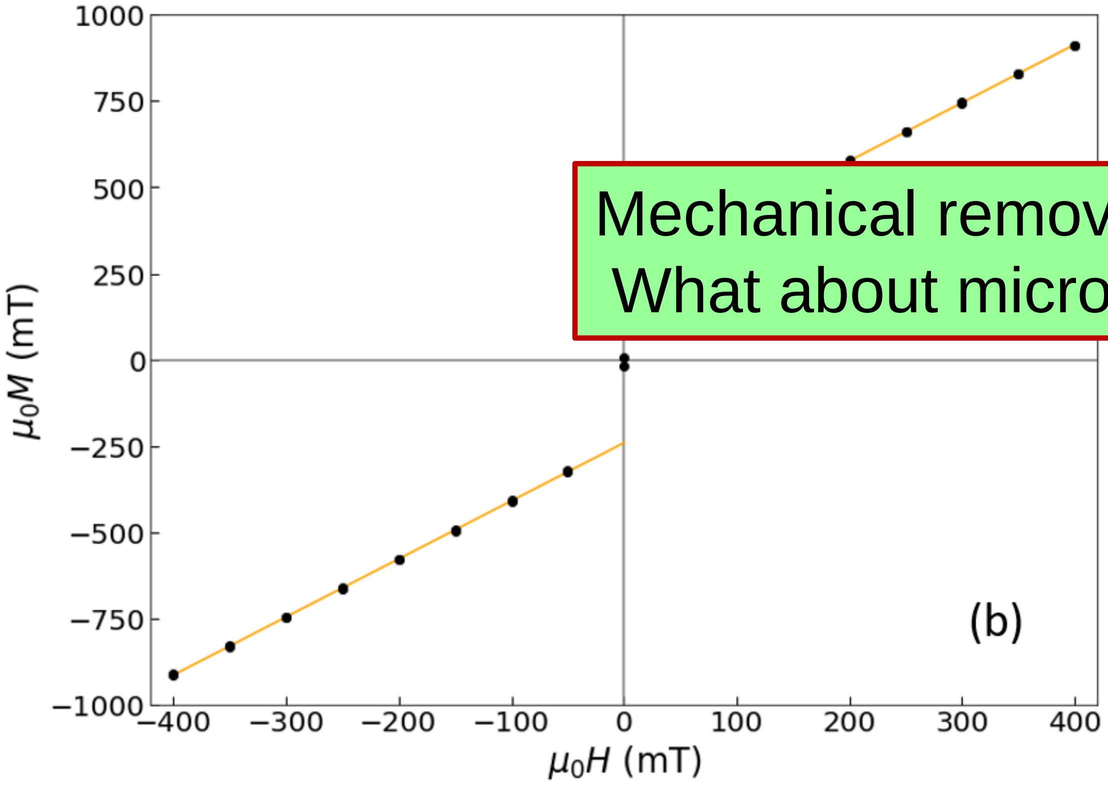
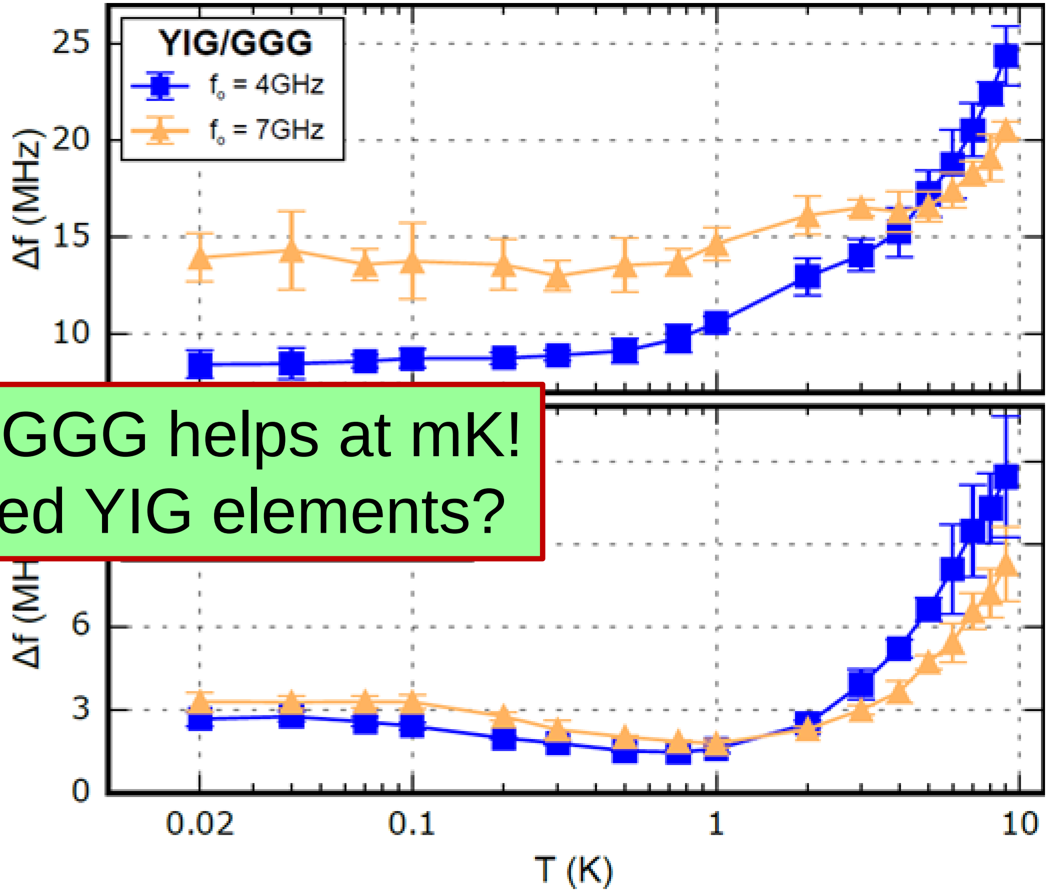


Baity et al., arXiv:2104.08068v2 (2021)

YIG/GGG sample damping below 10K:



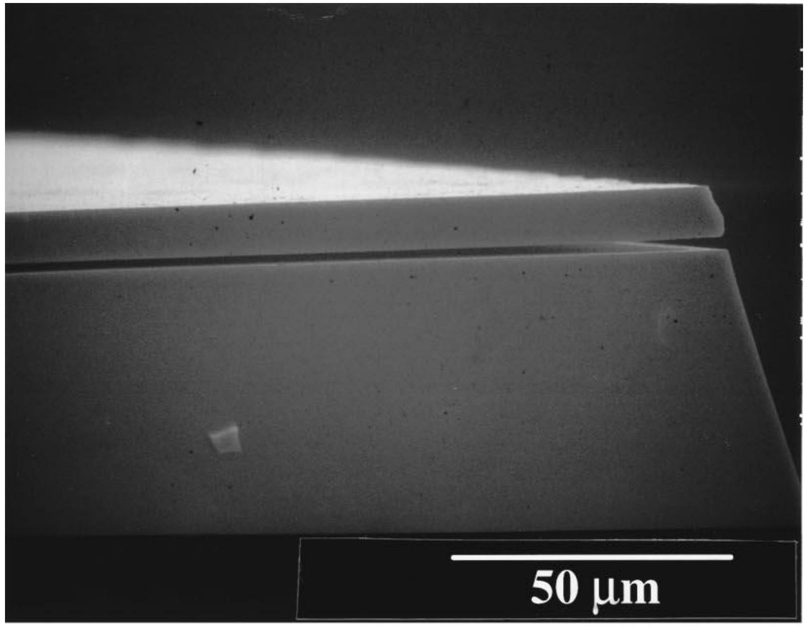
Kosen et al., APL Mater. **7**, 101120 (2019)

Mechanical removal of GGG helps at mK!
What about micron-sized YIG elements?

Magnon damping in YIG/GGG is due to magnetization of GGG and impurities in YIG

# II. YIG on-chip technology - solutions

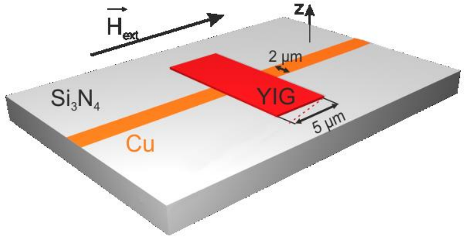
## Epitaxial liftoff

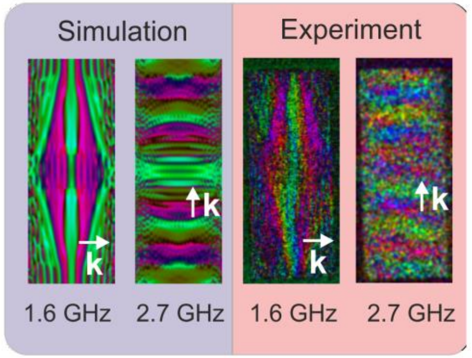


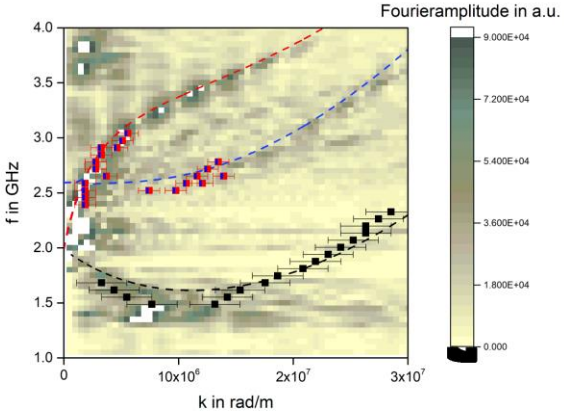
Levy *et al*., Appl. Phys. Lett. **71**, 2618 (1997)

## Ga⁺ Focused Ion Beam

Time-resolved scanning transmission x-ray microscopy:







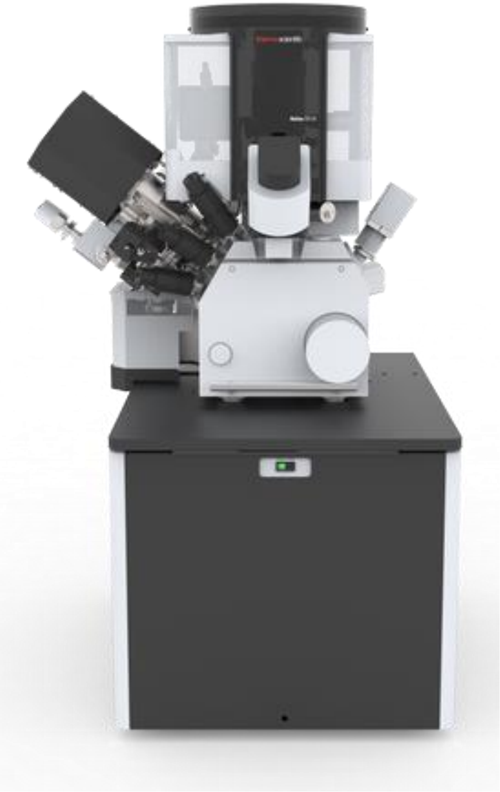
J. Förster *et al*., J. Appl. Phys. **126**, 173909 (2019)

Potentially good and robust method, but:
Requires a few MeV He ion source

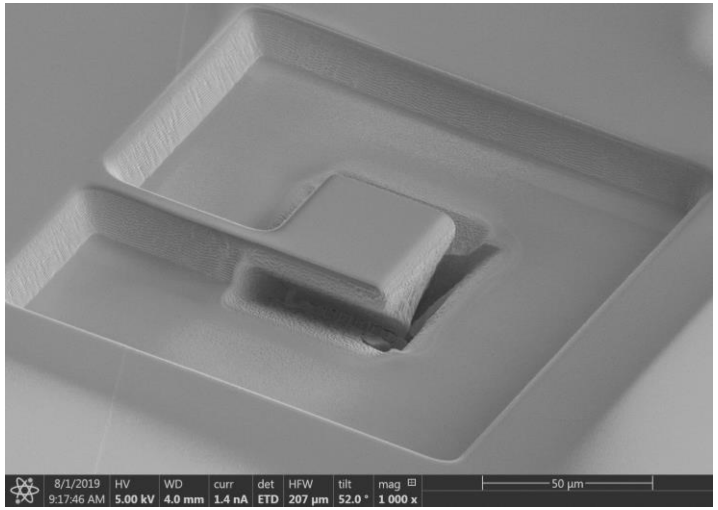
Robust and available in most of labs, but:
Implantation of Ga ions ruins YIG

# II. YIG on-chip technology - solutions

## Xenon Plasma Focused Ion Beam tool



## Fabrication (starting from 100µm YIG on GGG):

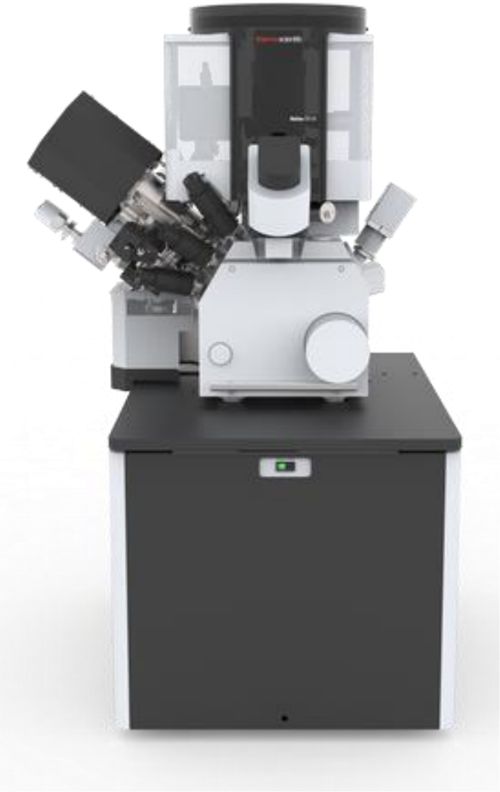


Robust and available in some labs,
No implantation of noble gas ions

Baity et al., arXiv:2104.08068v2 (2021)

# II. YIG on-chip technology - solutions

## Xenon Plasma Focused Ion Beam tool



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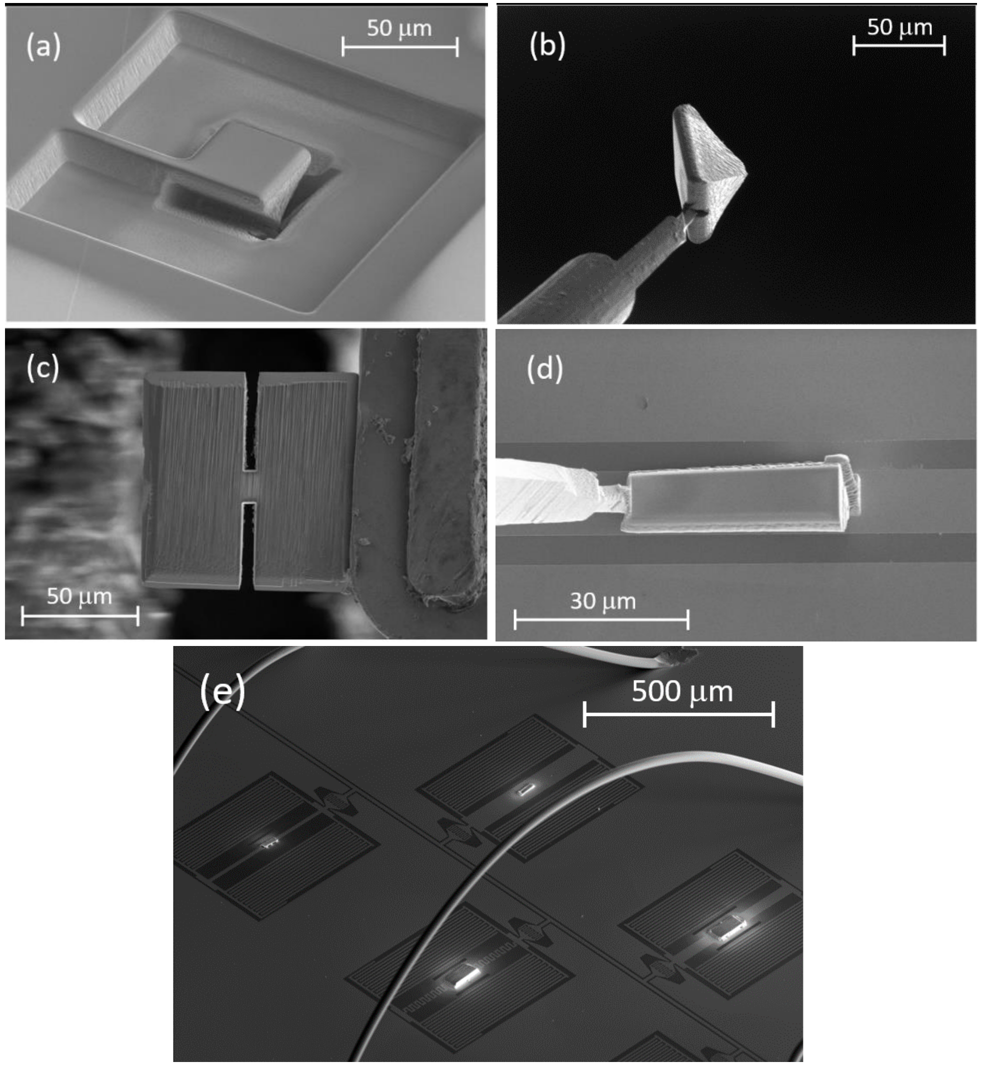
Baity et al., arXiv:2104.08068v2 (2021)

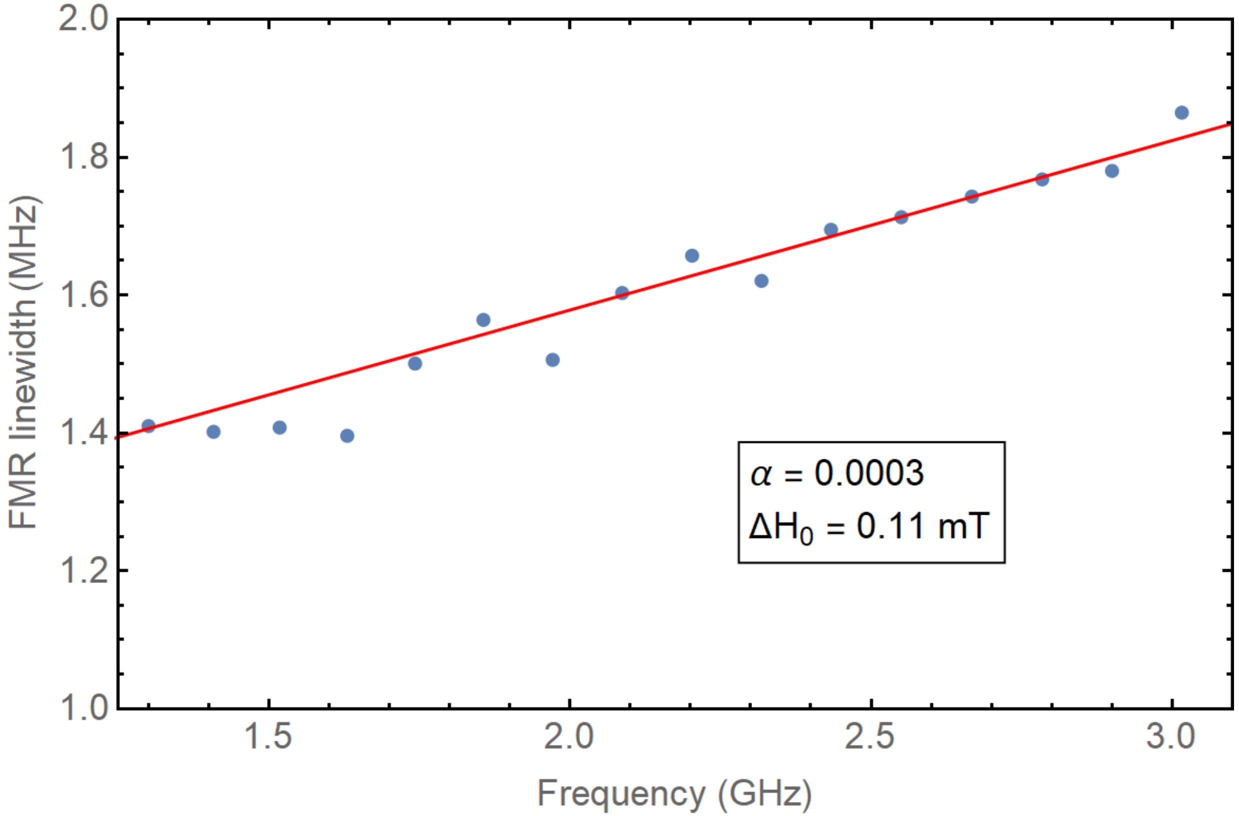
## Fabrication:



# II. YIG on-chip technology: measurements

µM-Lab
µ-wave Magnonics Lab

FMR of unstructured 100µm thick YIG on GGG at RT

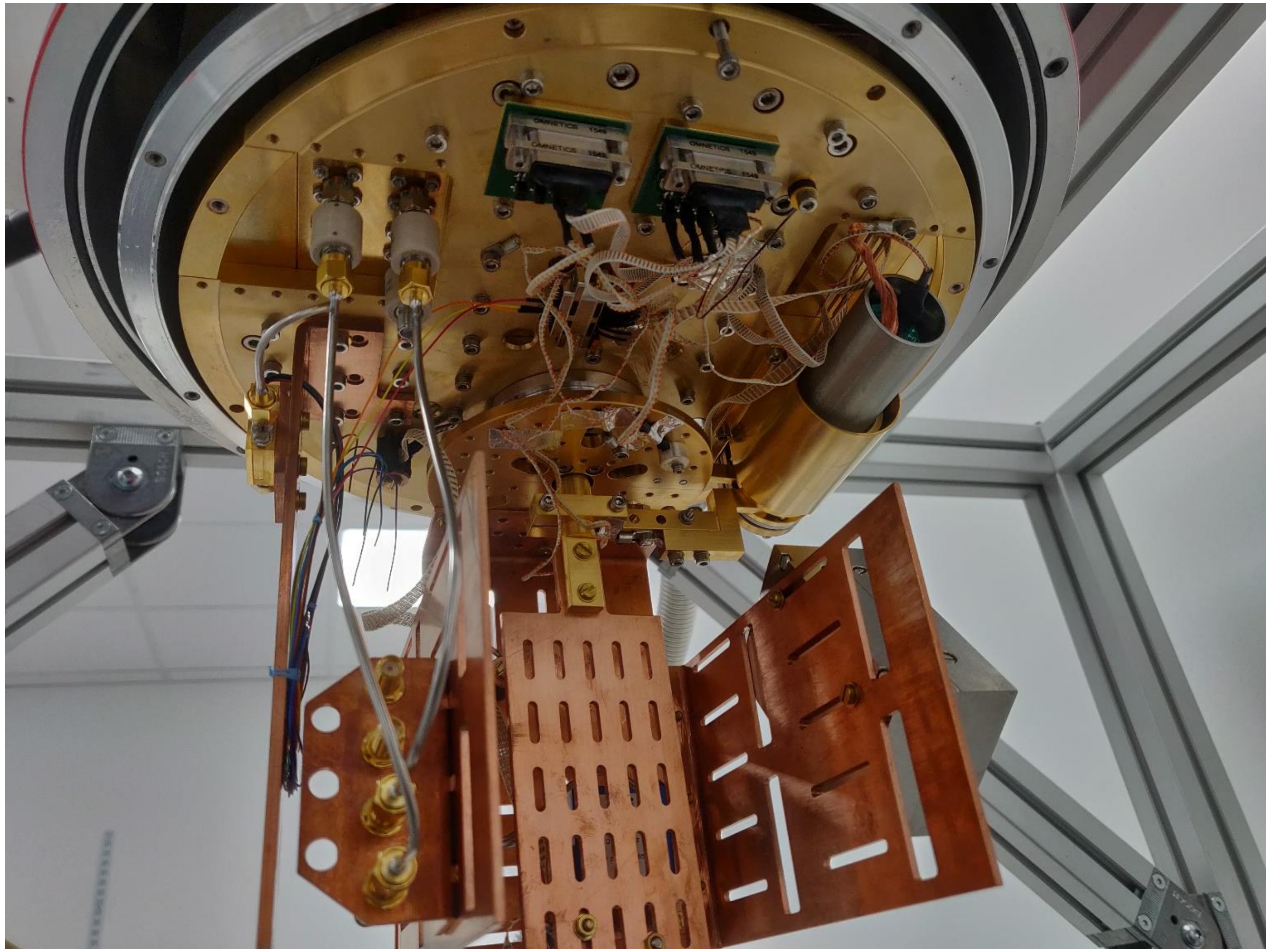


Not the best YIG to start from,
but good to test the technology

Baity et al., arXiv:2104.08068v2 (2021)

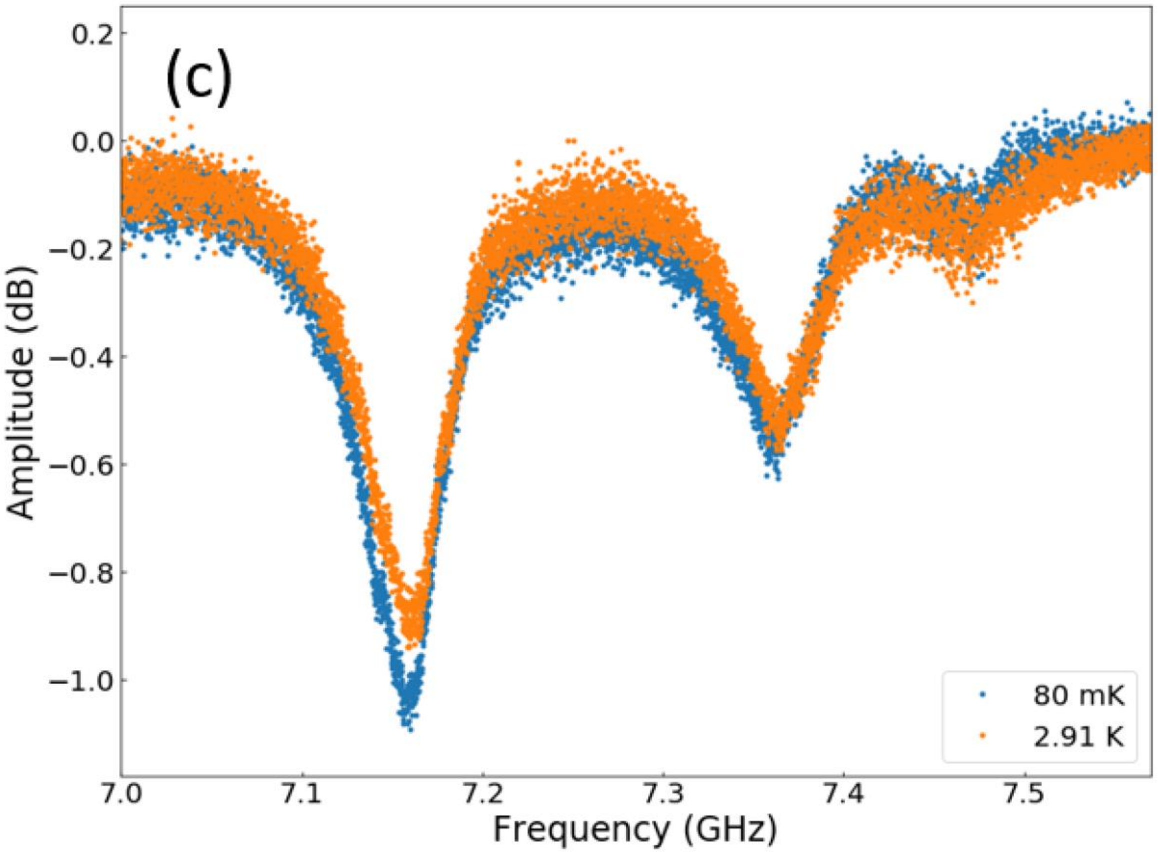
# II. YIG on-chip technology: mK measurements

## Adiabatic demagnetization refrigerator experimental setup



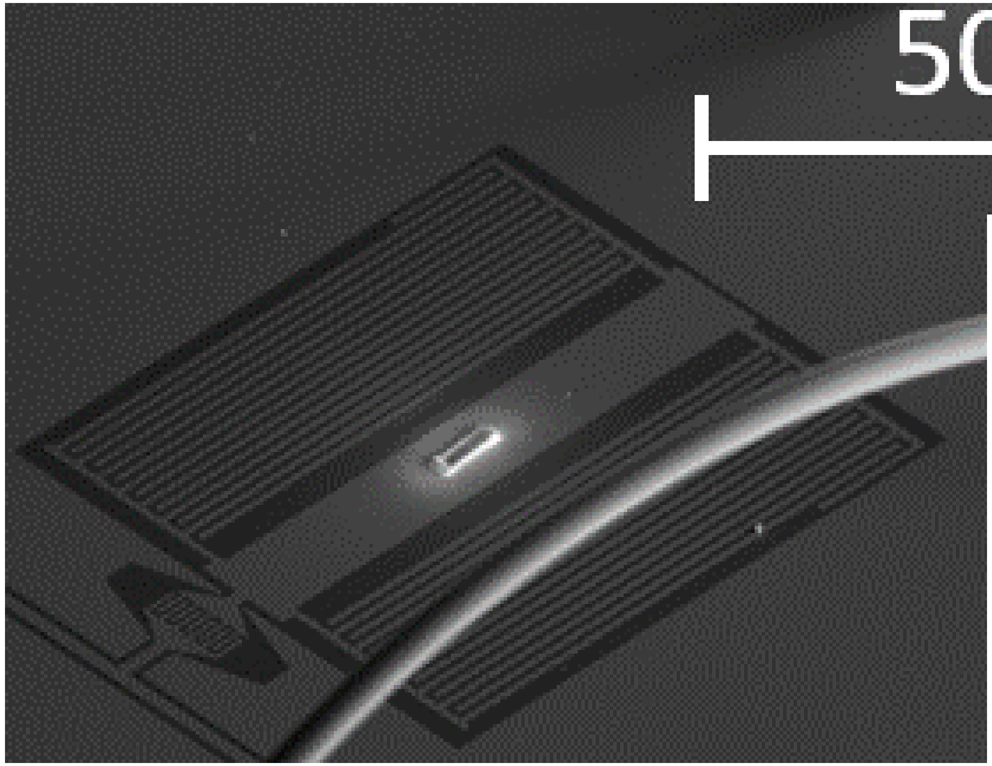
Baity et al., arXiv:2104.08068v2 (2021)

## Simple CPW measurement



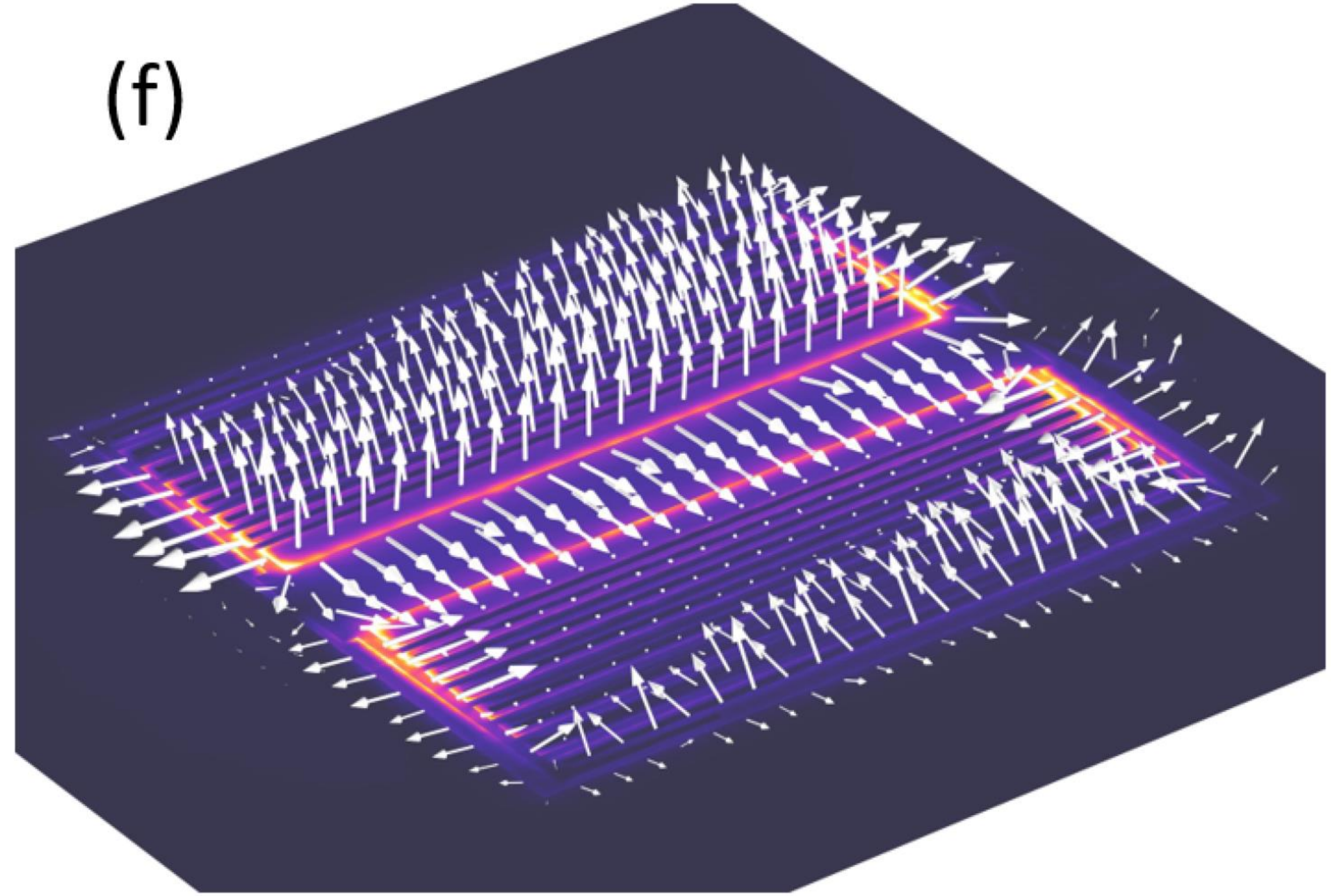
Measured FMR linewidth – 15MHz
Sample is strongly overcoupled!

# II. YIG on-chip technology: mK measurements



Resonator with YIG sample

COMSOL simulation of resonator fields:

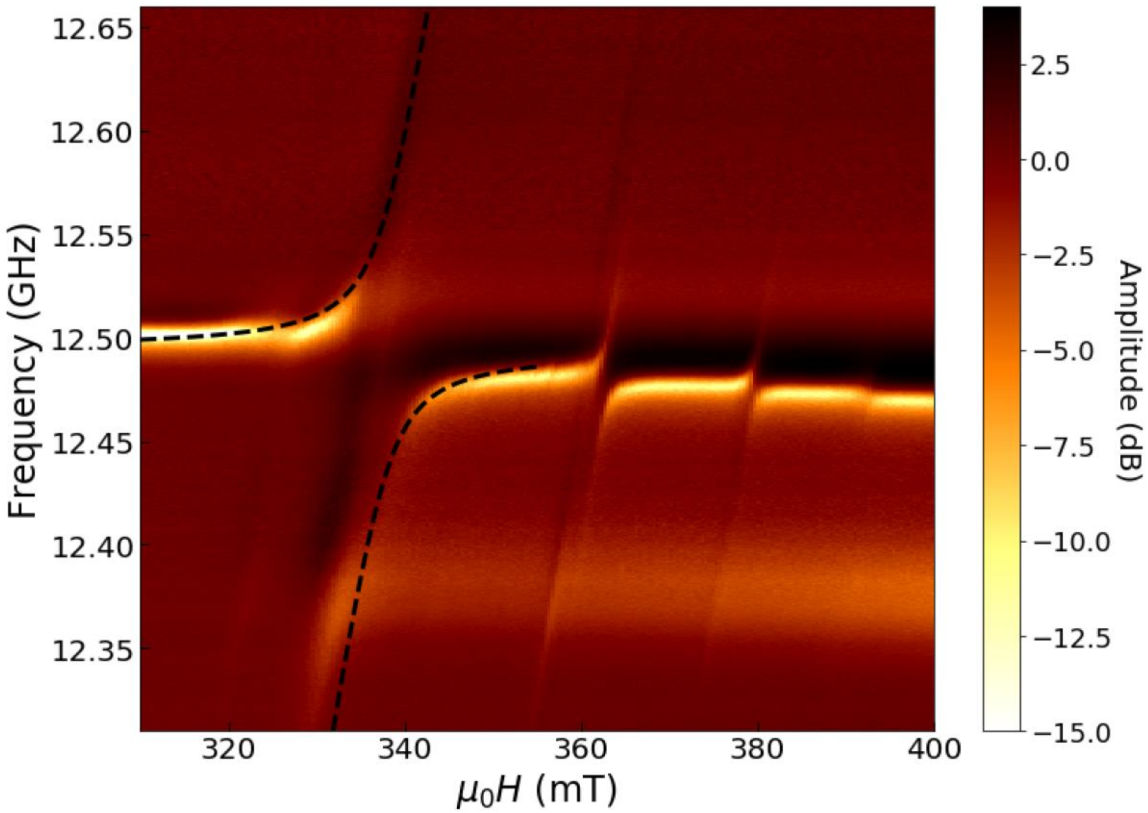


Baity et al., arXiv:2104.08068v2 (2021)

# II. YIG on-chip technology: mK measurements

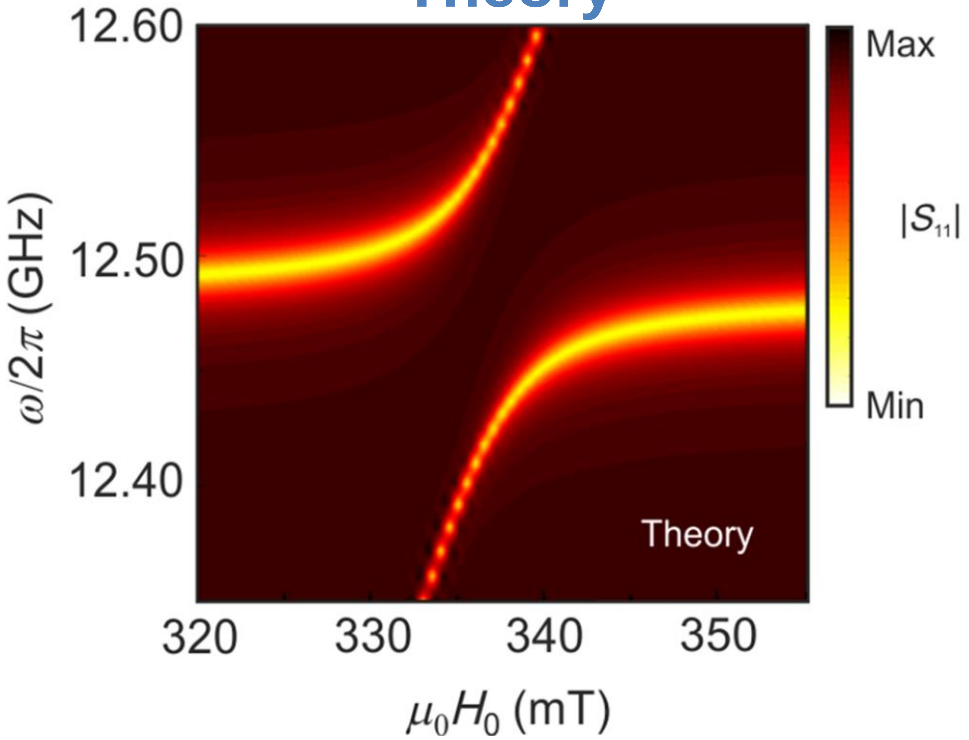
µM-Lab
µ-wave Magnonics Lab

## Measurement



$$g/2\pi = 63 \pm 3\ \mathrm{MHz}$$

## Theory



$$g = 68 \pm 3\ \mathrm{MHz}$$

R. Macedo et al, Phys. Rev. Applied **15**, 024065 (2021)

Baity et al., arXiv:2104.08068v2 (2021)

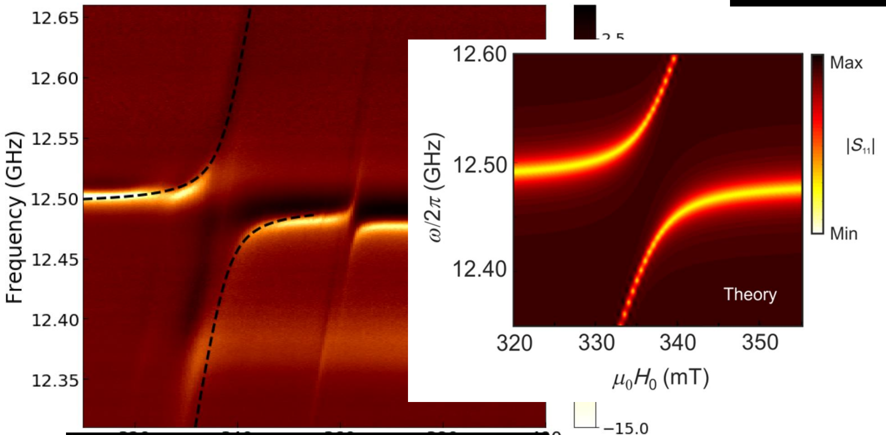
Strong coupling regime ($g^2/(\Gamma_{YIG}\Gamma_{resonator})$>>1) achieved as well as good agreement between experiment and theory

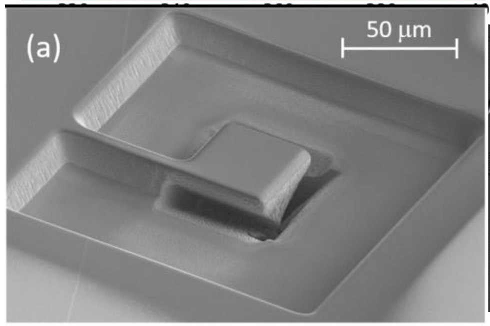
# Conclusions

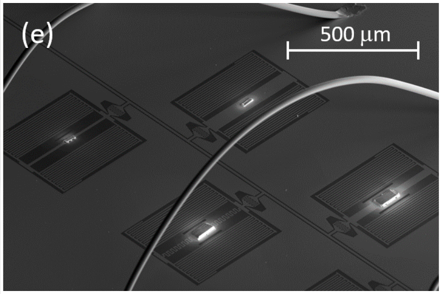
- Theory of coupling of a ferromagnetic element to an electromagnetic resonator has been developed and proven to be accurate (even in the case of strong coupling)

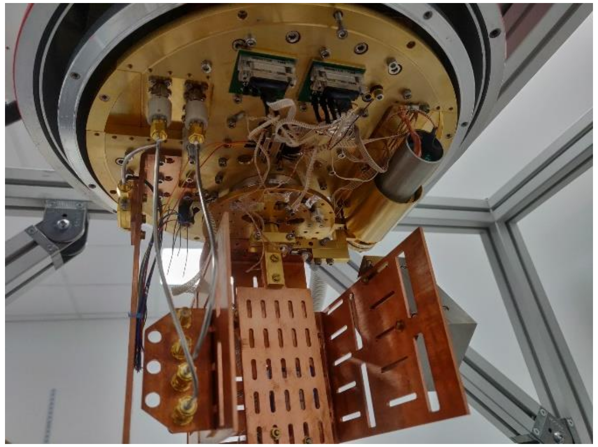
- Basics of the YIG on-chip technology were developed but require further investigations

- Despite relatively large obtained linewidth, the obtained planar YIG/superconducting elements hybrids are much better than other magnetic materials for quantum computing applications









# Team and acknowledgements

## University of Glasgow

## Oakland University (USA)

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Slavin

Vasyl
Tiberkevich

## University of Newcastle (Australia)

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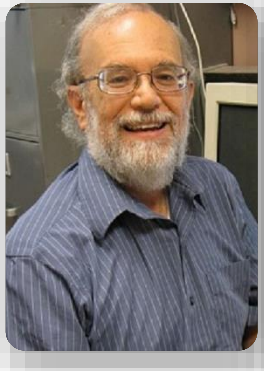
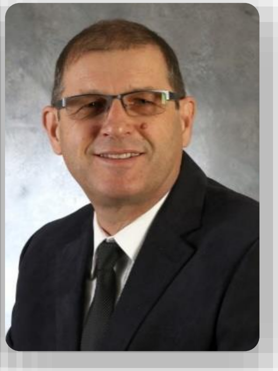
Livesey

## University of Colorado Colorado Springs



Robert
Camley



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Celinski

## Funding sources:

Unterstützt von / Supported by
Alexander von Humboldt
Stiftung / Foundation

CRCW
UCCS Faculty Seed Grants