WMI

Bayerische Akademie der Wissenschaften

Technische Universität München

Non-collinear spin dynamics in magnetic insulators

nanosystems initiative munich

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INNOVENT
Technologieentwicklung Jena

More than Moore

The chips are down for Moore's law

The semiconductor industry will soon abandon its pursuit of Moore's law. Now things could get a lot more interesting.

M. Mitchell Waldrop

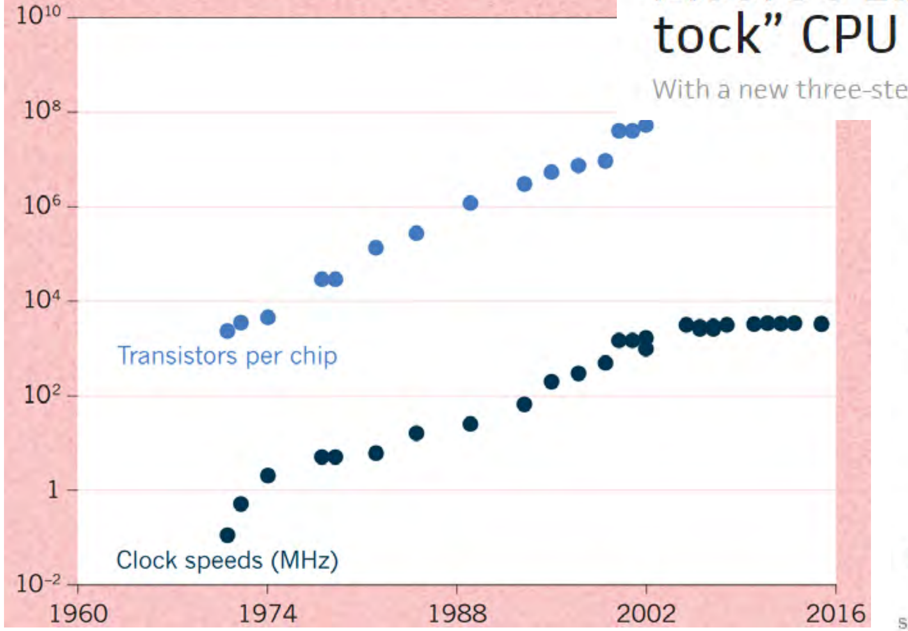
Nature **530,** 144 (2016)

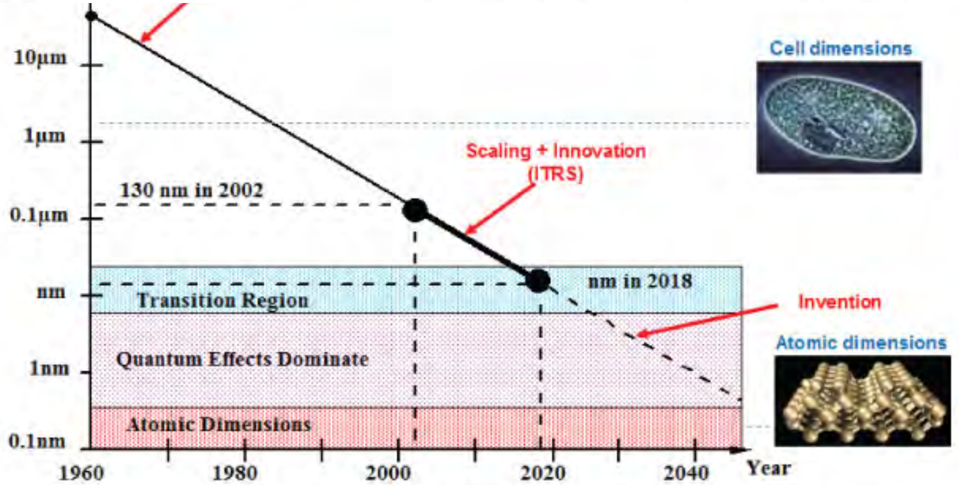
Pcworld, (2016)

NEWS

Moore's Law stutters: Intel officially puts "tick-tock" CPU release cycle on hiatus

With a new three-step manufacturing cadence, Intel takes a break from its typical two-year cycle.





Source: From Silicon VLSI Technology, by professors James D. Plummer, Michael D. Deal, and Peter B. Griffin. Stanford University, 2000.

Heat limit

Size and cost limit

More than Moore

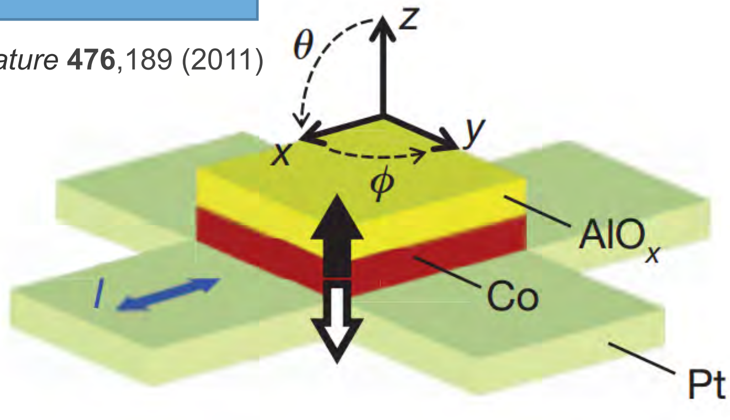
Possible alternatives: "…Spintronic materials that would compute by flipping electron spins rather than by moving electrons."

Nature **530,** 144 (2016)

Spintronics

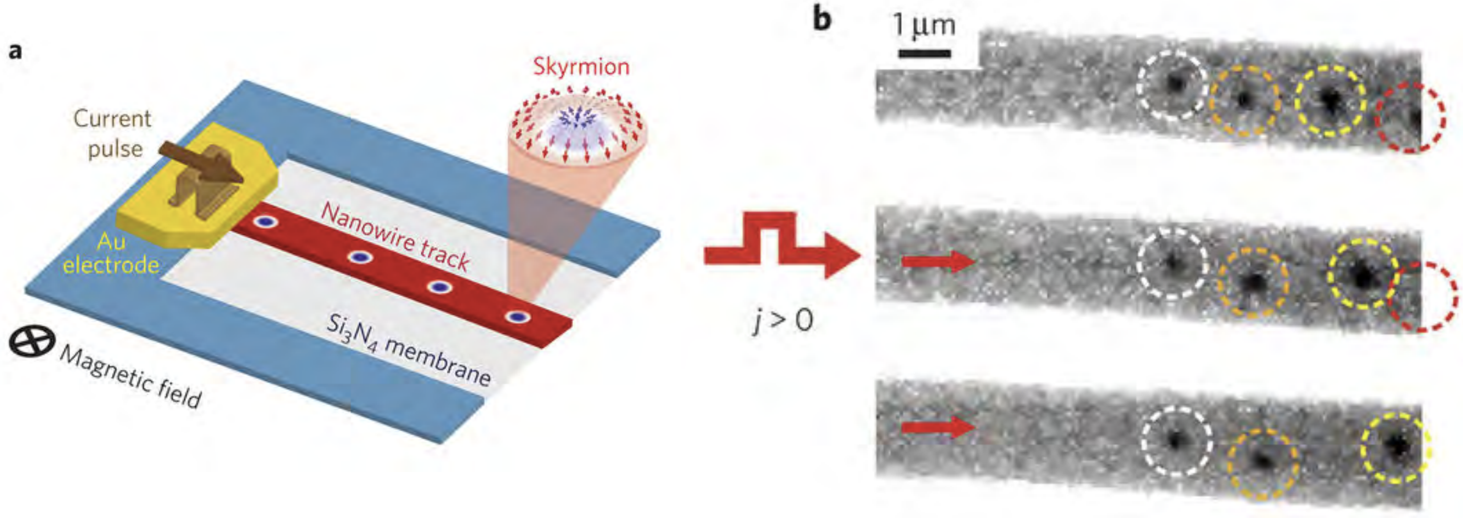
Spin-Orbit-Torques

Miron et al., Nature **476**,189 (2011)

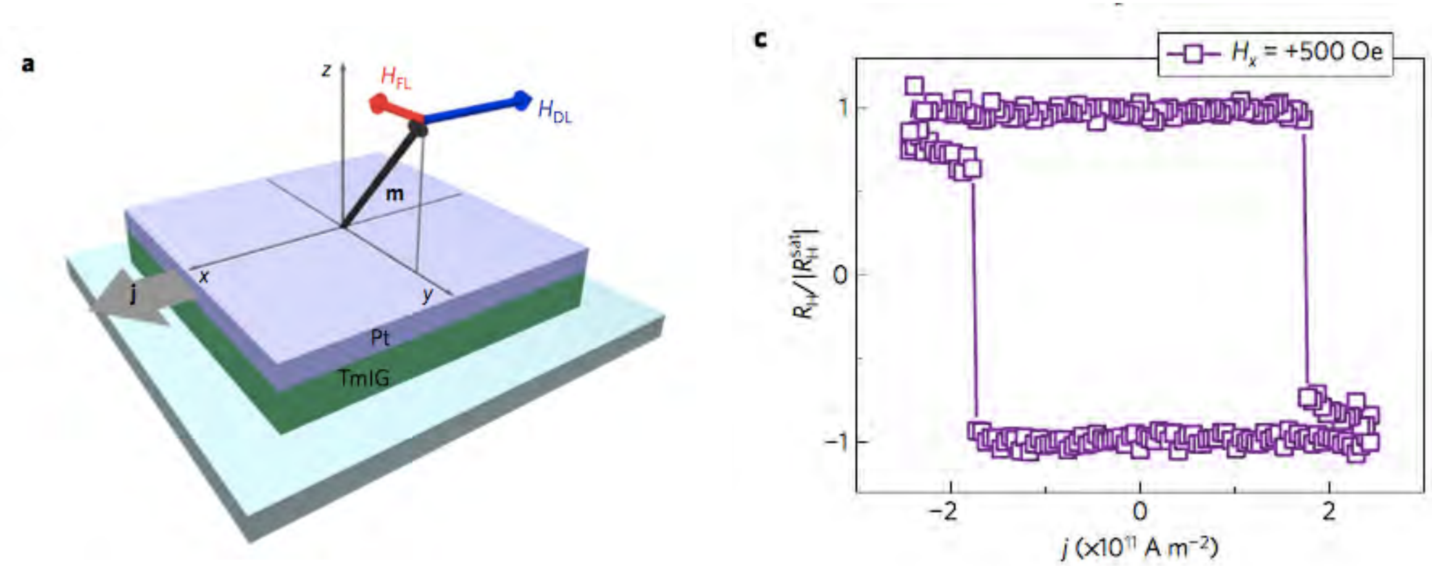


Can we use these concepts for non-collinear magnetic insulators?

Towards insulating Skyrmionics

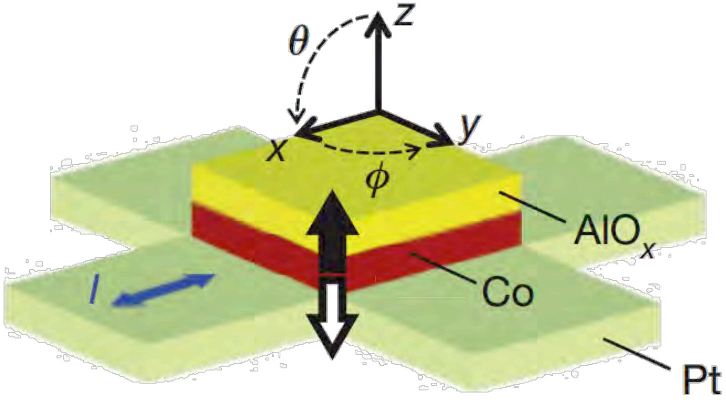


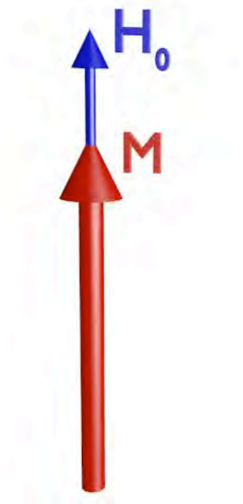
Metallic Skyrmions: Nat Mater **15**, 501 (2016).



Insulating SOTs: Nature Materials **16**, 309 (2017).

Introduction





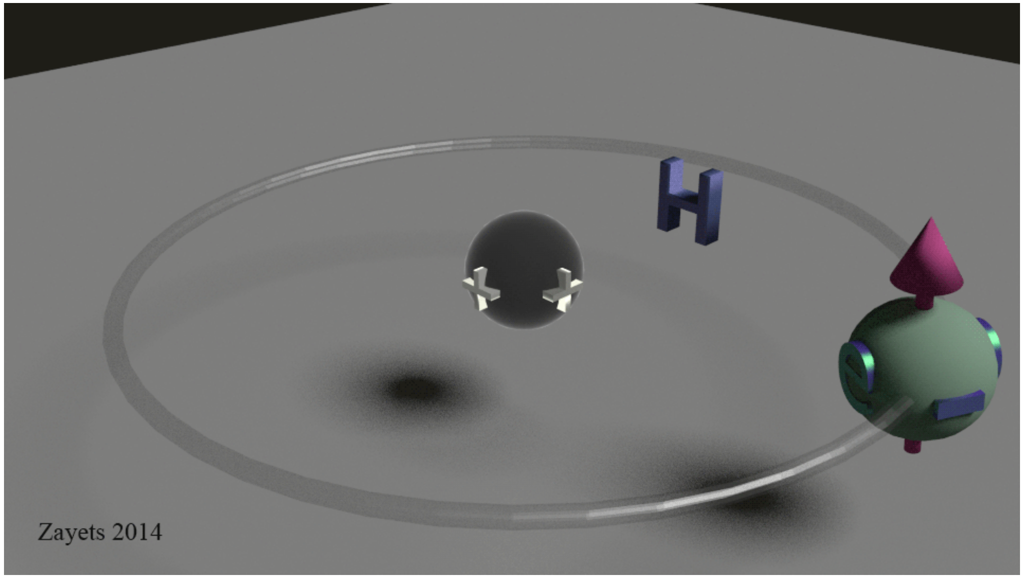
TU Kaiserslautern

Physical mechanisms:

Magnetization dynamics
spin orbit interaction

Spin orbit interaction:

- Electronic configuration
- Magnetic anisotropy
- Magnetoresistance
- Magnetoelasticity
- Skyrmions
- …



Zayets (AIST), Tsukuba, Japan

M-Dynamics at WMI

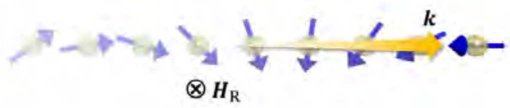
(inverse) Spin-orbit torques

MW et al.,
PRL **113**, 157204 (2014)

Nembach, MW, et al.,
Nat Phys **11**, 825 (2015)

Berger, MW et al.
arXiv:1611.05798 (2016)

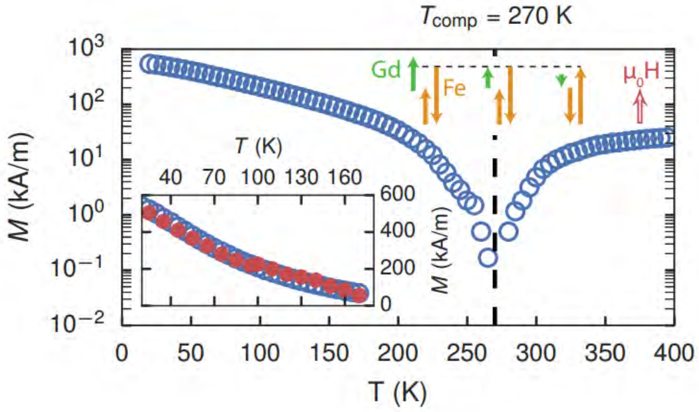
Oshima, MW, et al.,
Nat Mat (2017)



Non-collinear spin dynamics

MW et al., arXiv:
1705.02874 (2017)

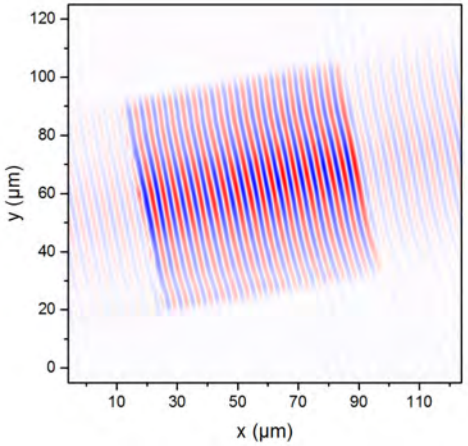
Maier-Flaig, MW et al.,
APL **110**, 132401 (2017).



Hybrid systems

MW et al.,
PRL **106**, 117601 (2011)

Klingler, MW, et al.
APL **109**, 072402 (2016)



Cavity magnetic resonance

Broadband magnetic resonance

50mK - 300K, up to 17T, up to 50 GHz

Brillouin light scattering

Frequency-resolved MOKE

Spatial resolution < 1µm

Materials for **M**-dynamics

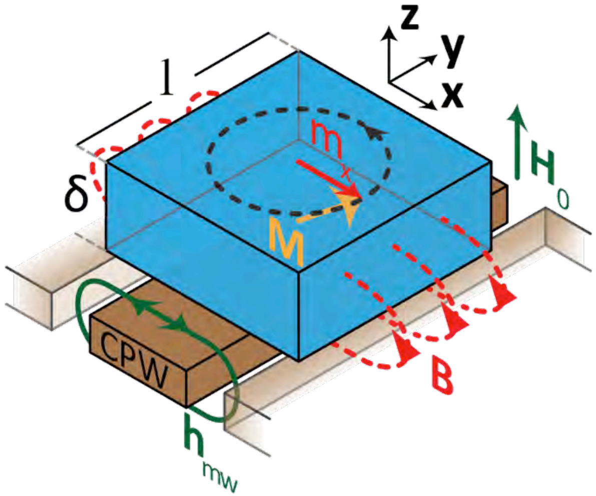
PLD, Evap, Sputter,
E-beam lithography

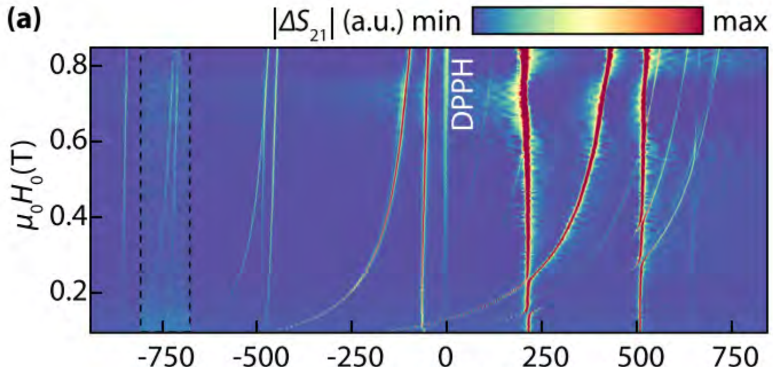
Outline

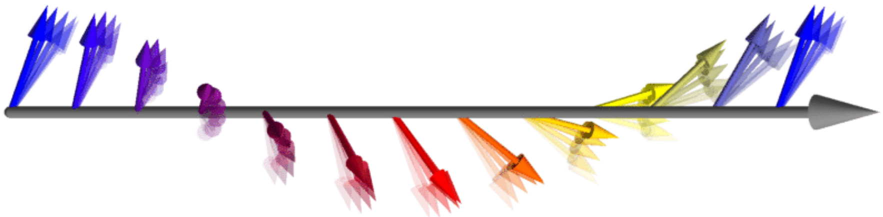
Magnetization dynamics and broadband magnetic resonance spectroscopy

Magnetostatic modes and spin-wave damping in YIG

Cu_2OSeO_3 as a natural helimagnonic crystal







Magnetization dynamics

Landau-Lifshitz-Gilbert equation:

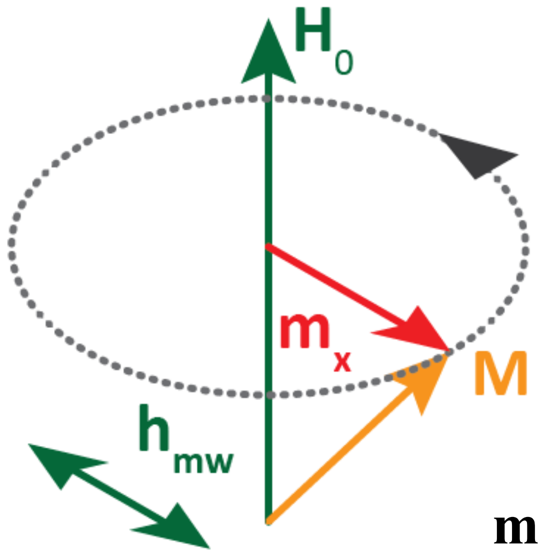
$$\frac{\partial \mathbf{m}}{\partial t} = \underbrace{-\gamma\mu_0 \mathbf{m} \times \mathbf{H}_{\mathrm{eff}}}_{\text{precession}} + \underbrace{\alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t}}_{\text{damping}}$$

M: magnetization vector

γ: gyromagnetic ratio

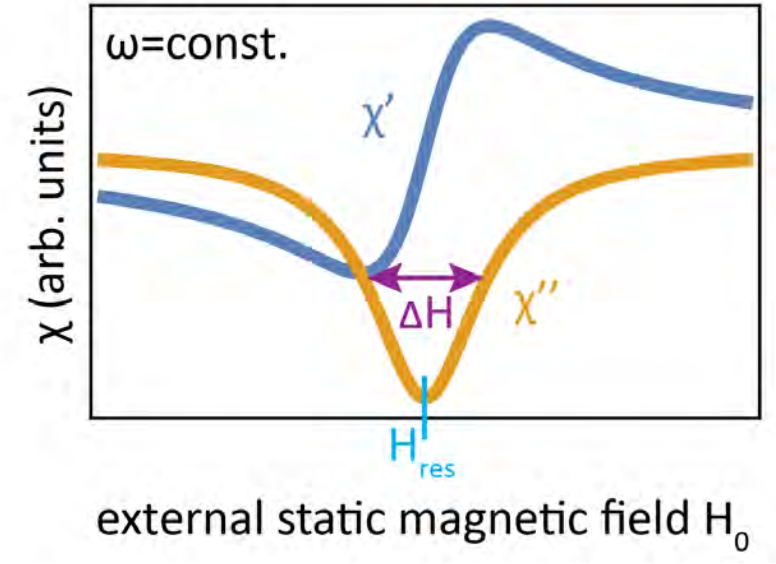
α: damping

M_s: saturation magnetization



$$\mathbf{m} = \mathbf{M} / M_s$$

$$\mathbf{H}_{\mathrm{eff}} = \mathbf{H}_0 + \mathbf{H}_{\mathrm{aniso}} + \mathbf{h}_{\mathrm{mw}}$$



$$m_x = \chi h_{mw}$$

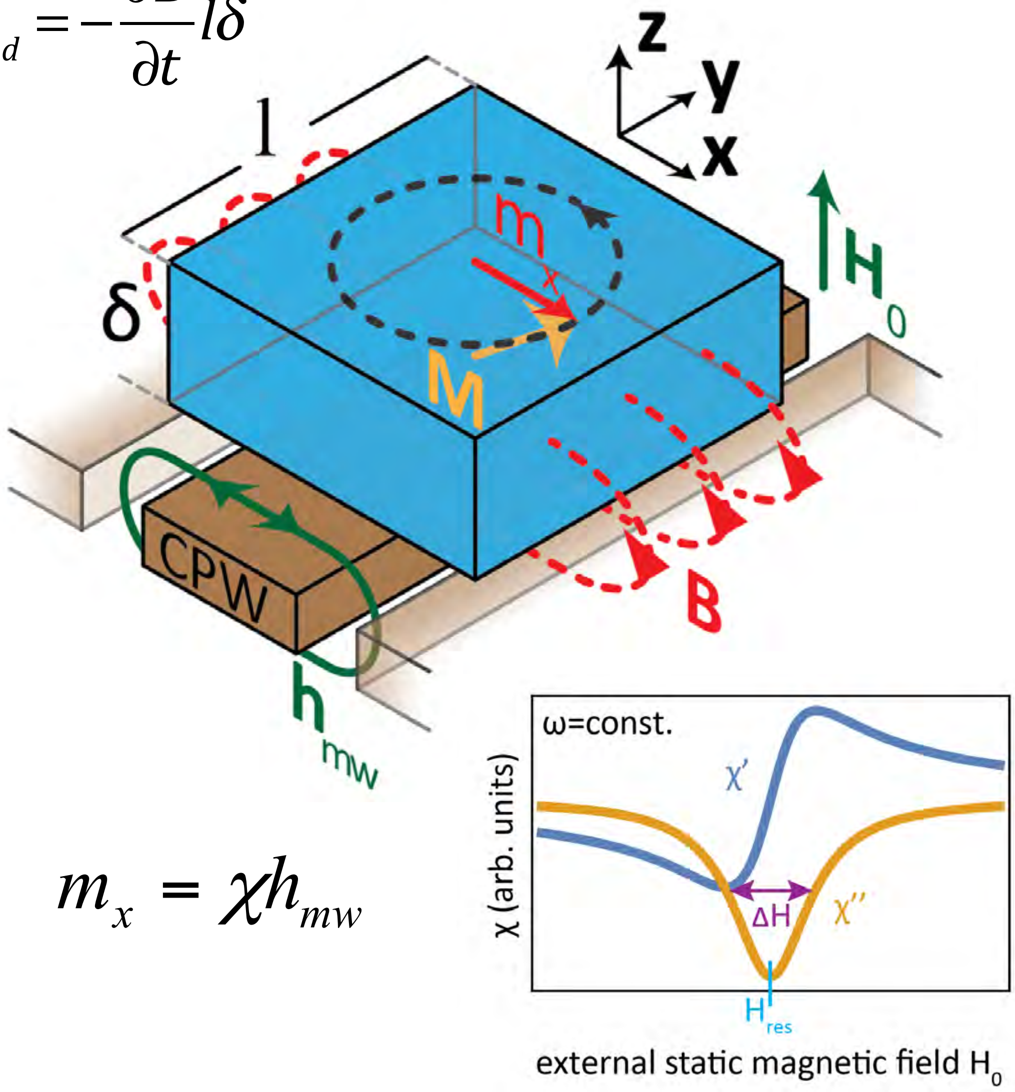
$$\chi = \chi' + i\chi''$$

Polder susceptibility (tensor)

- Damping
- Anisotropies
- g-factor

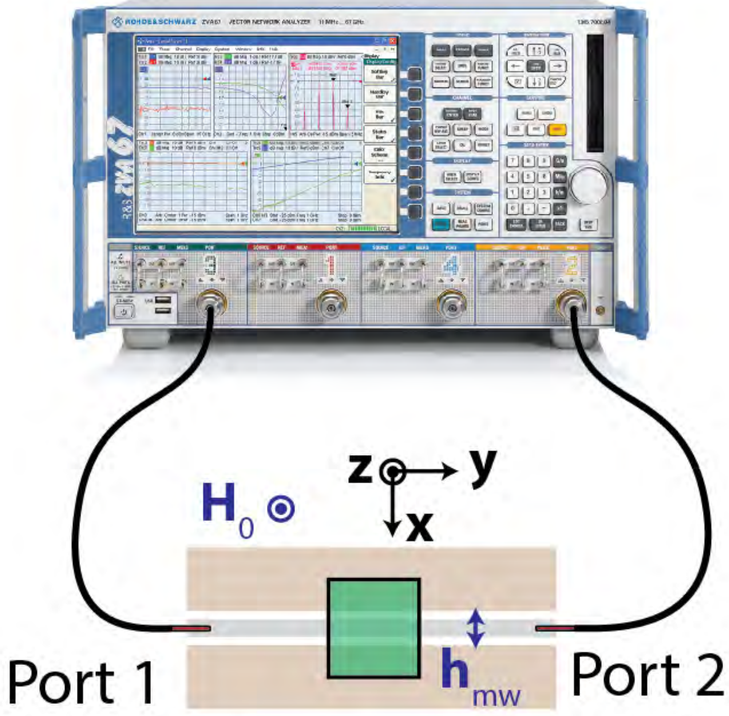
Broadband magnetic resonance spectroscopy

$$V_{ind} = -\frac{\partial B}{\partial t} l\delta$$



$$m_x = \chi h_{mw}$$

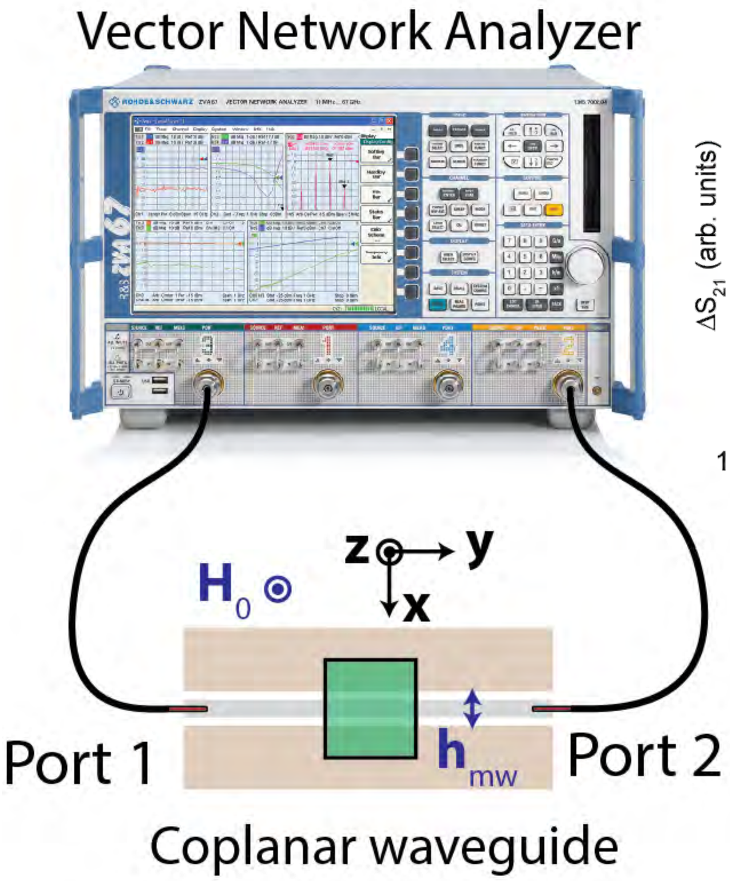
Vector Network Analyzer

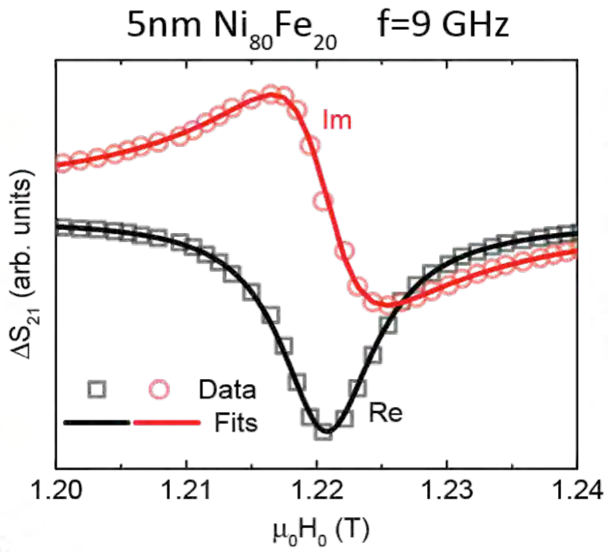


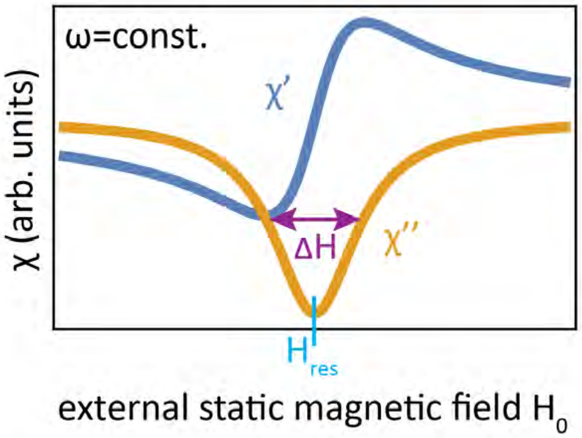
Coplanar waveguide

$$S_{21} = \frac{V_2}{V_1} = \frac{V_{ind}(H_0) + V_1}{V_1}\Gamma$$

Microwave susceptibility measurement







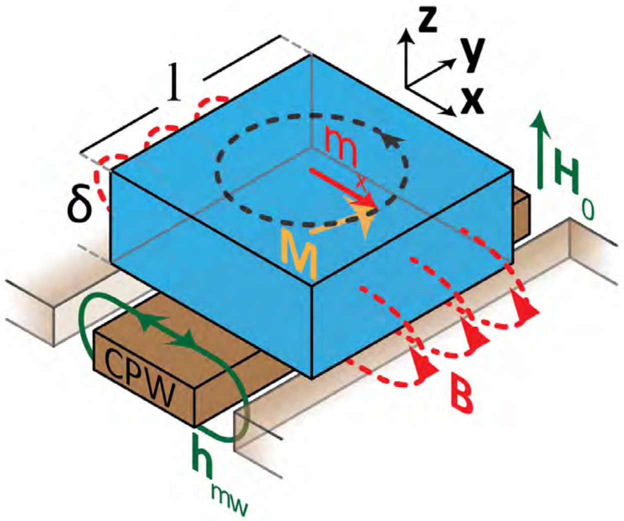
$$\Delta S_{21} = \frac{S_{21}(H_0) - S_{21}^0}{S_{21}^0}$$

$$\text{fit } \Delta S_{21} = -\frac{i\omega\tilde{L}}{2Z_0}\chi$$

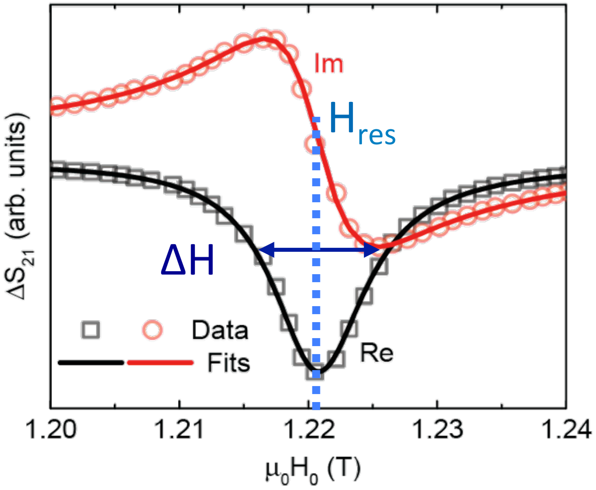
$$\tilde{L} = \mu_0 \frac{l\delta}{4W_{CPW}}$$

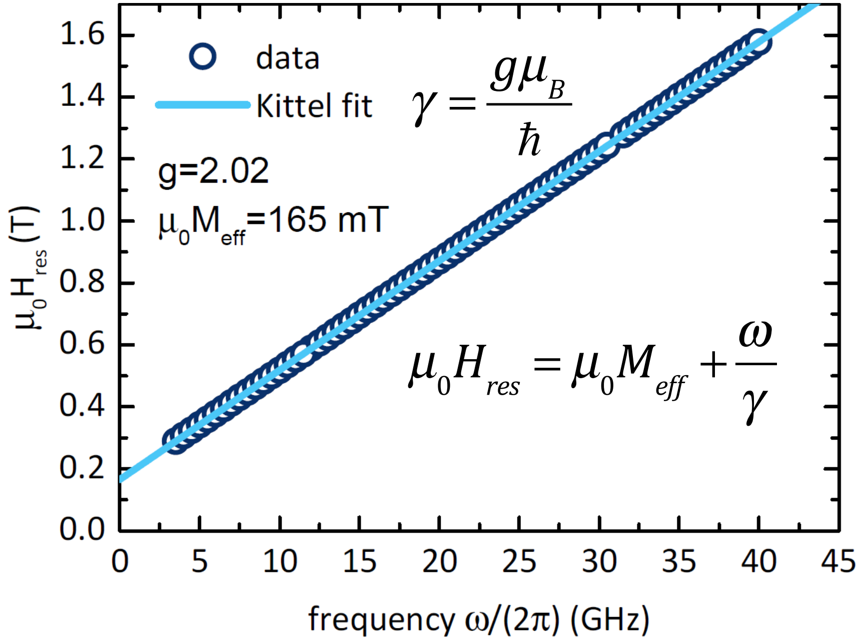
$$Z_0 = 50\Omega$$

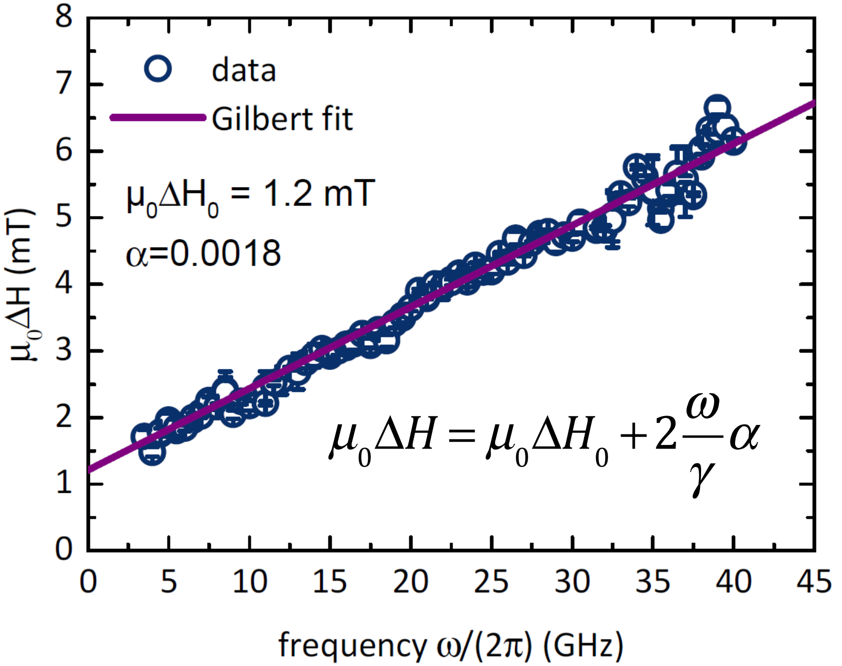
Anisotropy and Damping



Yttrium Iron Garnet
PLD 20nm film







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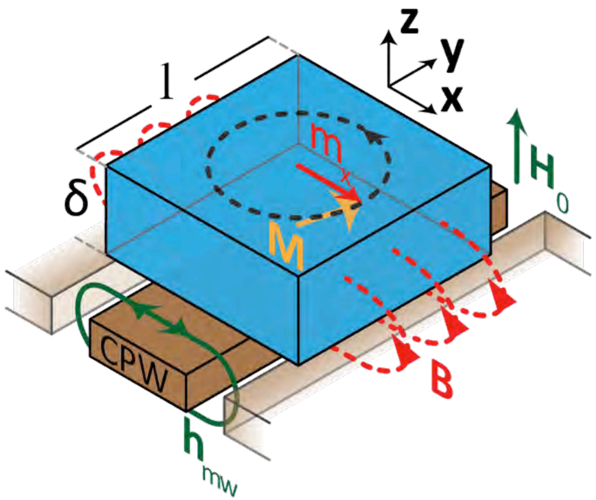
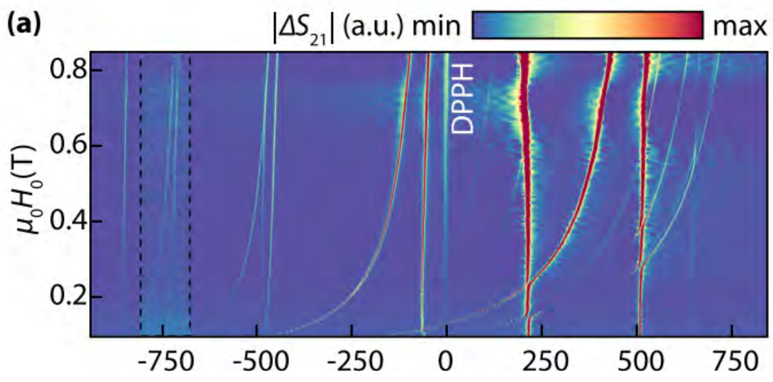
Magnetization dynamics and broadband magnetic resonance spectroscopy

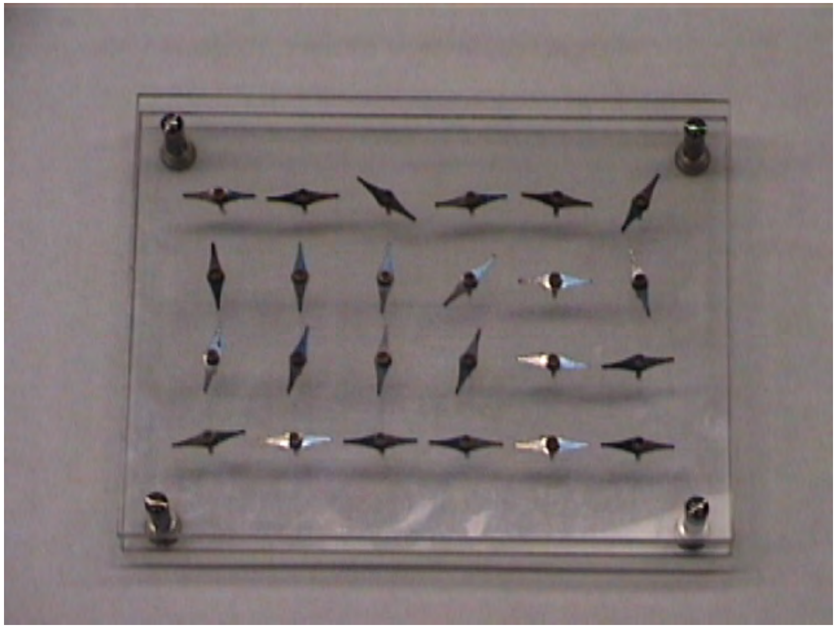
Magnetostatic modes and spin-wave damping in YIG

Cu_2OSeO_3 as a natural helimagnonic crystal





Magnetostatic modes: Theory



- Long-ranged dipolar interaction
- Sample-shape dependend
- Complicated

We are intersted in dynamics with dipolar interactions!

Start with LL equation (no damping):

$$\partial m/\partial t=-\gamma\mu_0\,\mathbf{m}\times\mathbf{H}_{\text{eff}}$$

Linearized LL equation for a spherical sample:

$$i\omega m=-\gamma\mu_0\,[1\times(M_s\,\mathbf{h}-(H_0+M_s N_z)\mathbf{m})$$

$$N_z=1/3$$

Solve with:

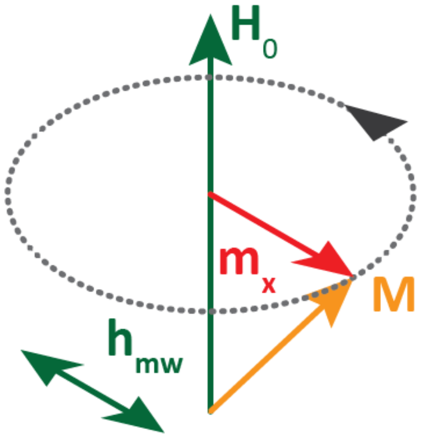
$$\nabla\times\mathbf{h}=0$$

$$\nabla\cdot(\mathbf{h}+\mathbf{m})=0$$

$$n+1+\xi_0\frac{\mathrm{d}P_n^m(\xi_0)/\mathrm{d}\xi_0}{P_n^m(\xi_0)}\pm m\nu=0,$$

L. R. Walker, Phys. Rev. **105**, 390 (1957).

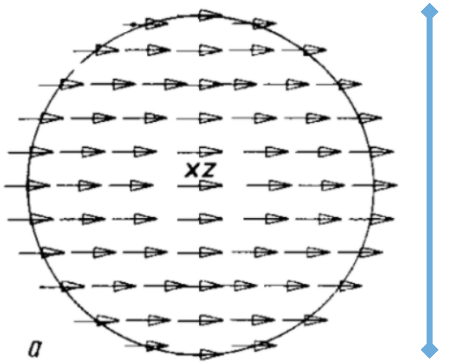
Magnetostatic modes: Theory



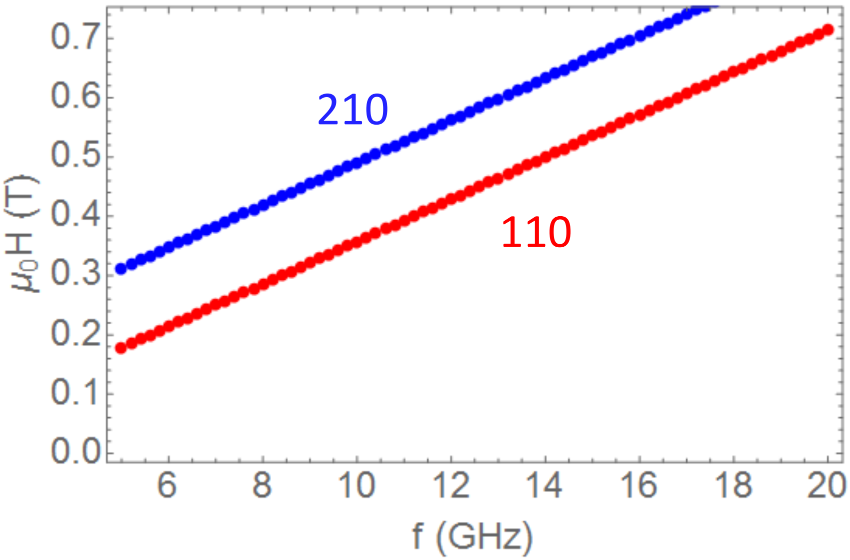
Modes are independent of actual sample size!

Our question:
What about damping?

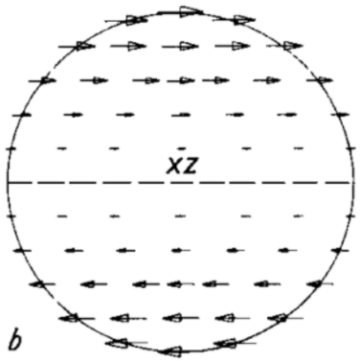
Dynamic m_x



110
„Uniform, Kittel, FMR“



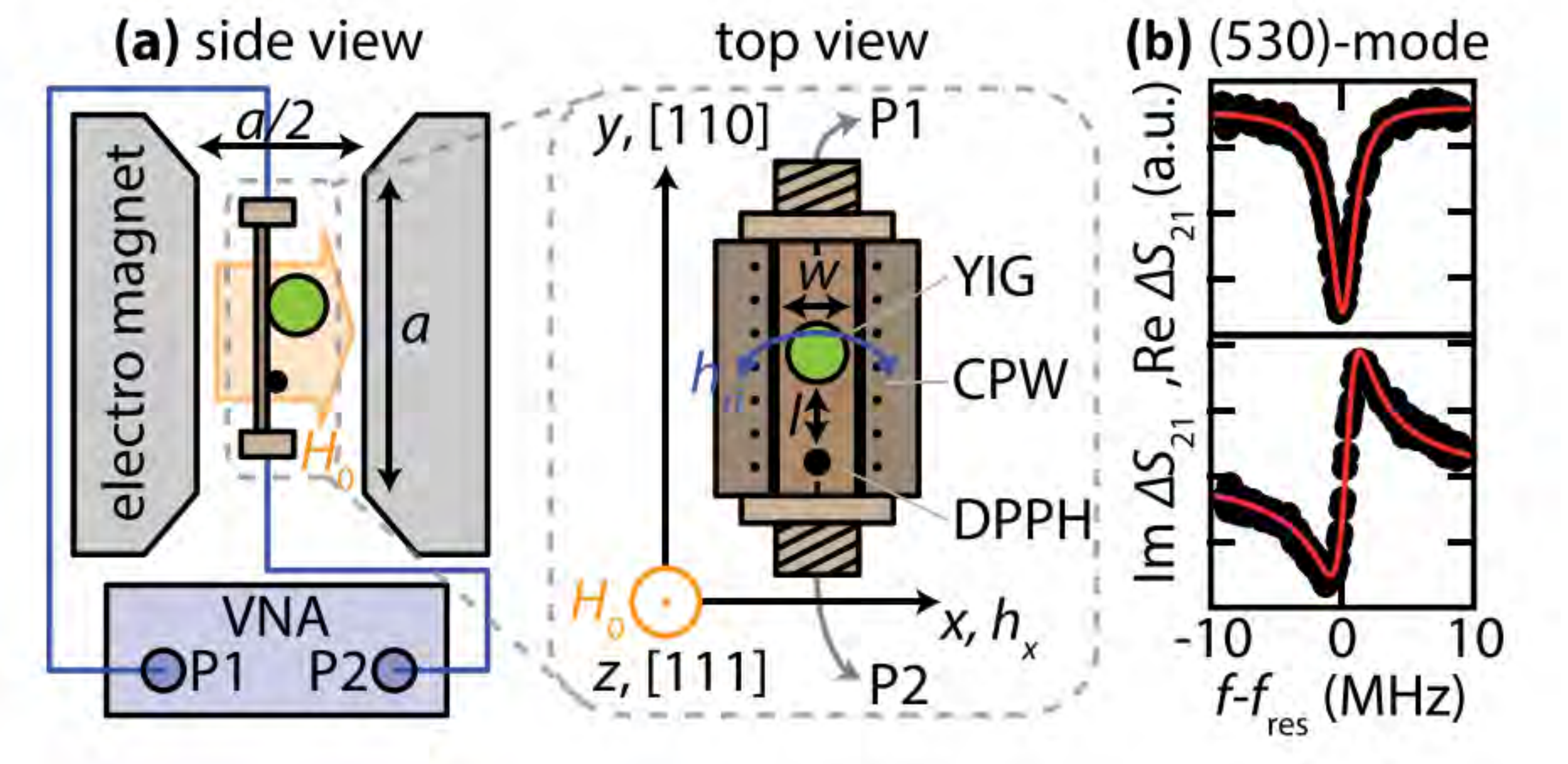
210



Mode numbering *nmr*
n: Surface localization
m: angular-momentun
r: enumerate solutions

P. Röschmann and H. Dötsch, Phys. Stat. Sol. (B) **82**, 11 (1977).

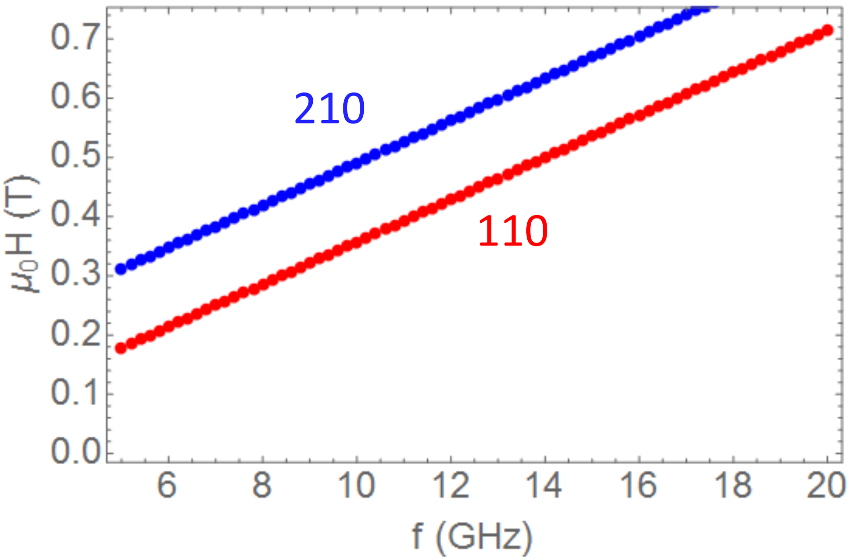
Experimental setup

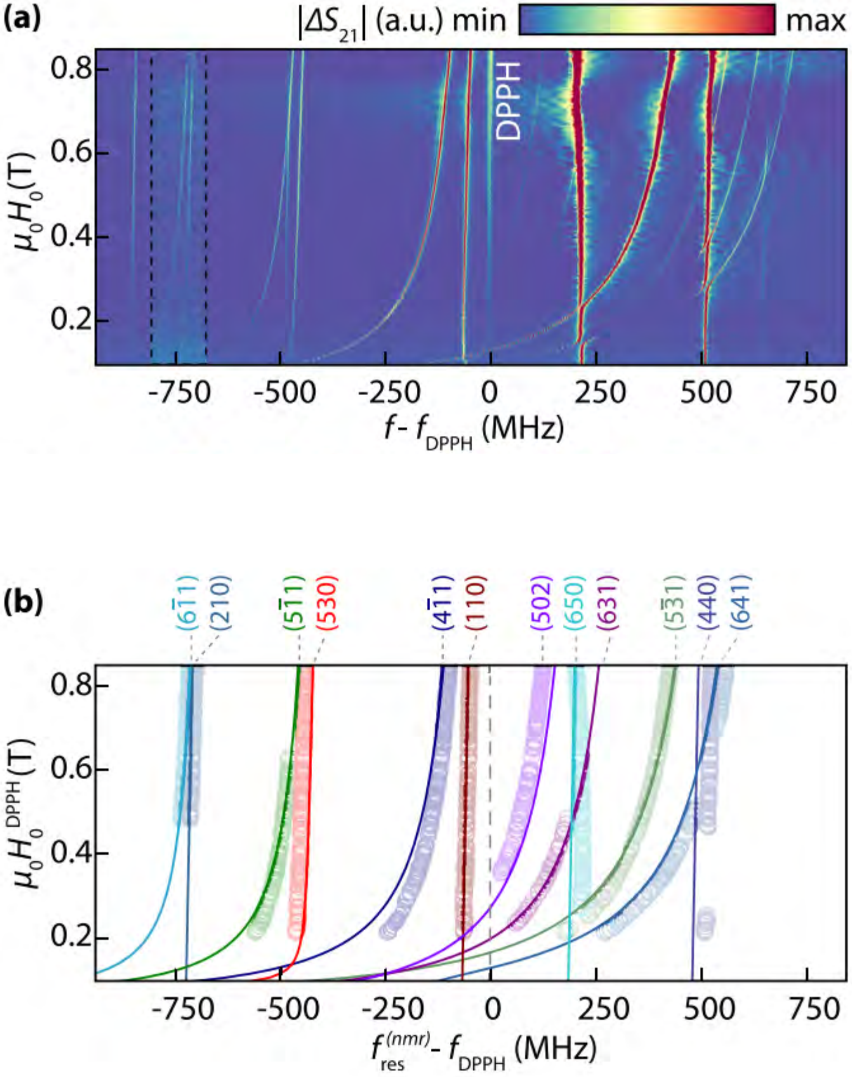


300µm YIG sphere grown by Innovent
300µm center conductor

Non-uniform driving field required for excitation of MSMs

Mode identification



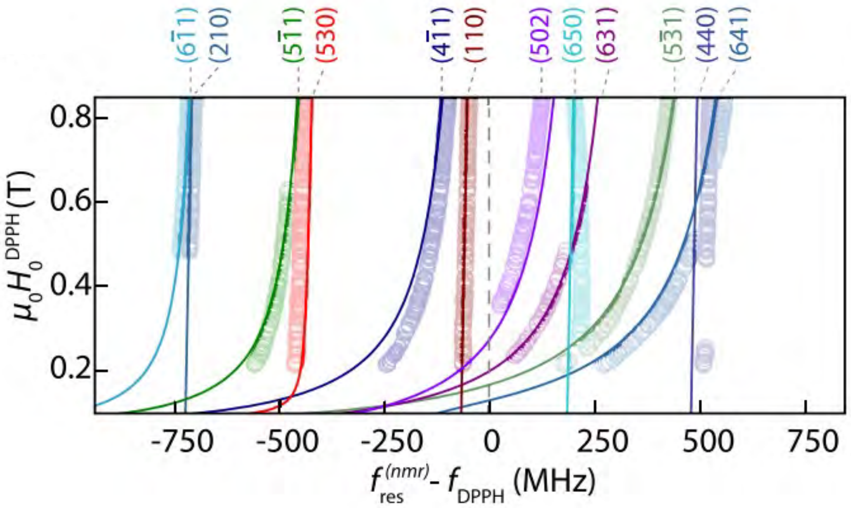


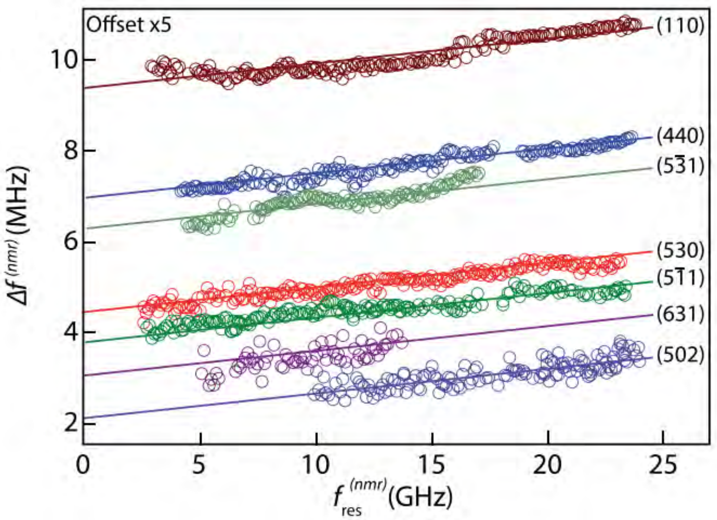
Mode intensity: overlap integral of driving field and MSM

DPPH is used for absolute field calibration

Klingler, MW et al., APL **110**, 092409 (2017).

Linewidth and damping

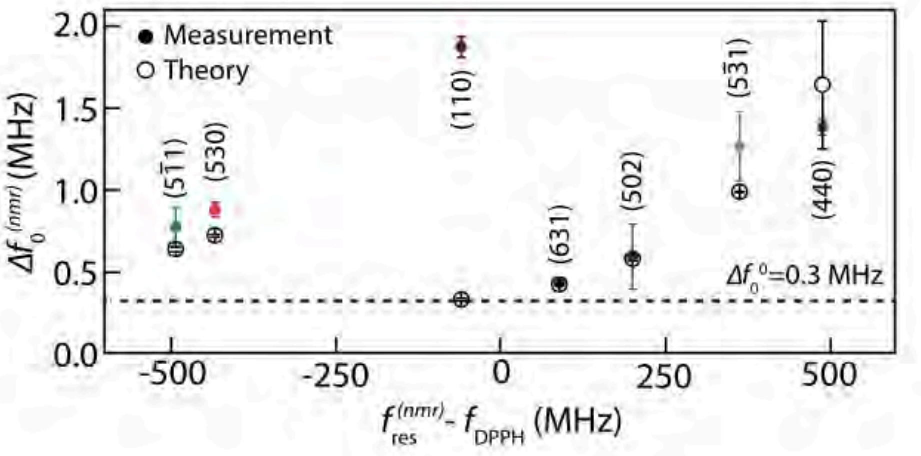




Record-low damping for Yttrium Iron Garnet (or any material)

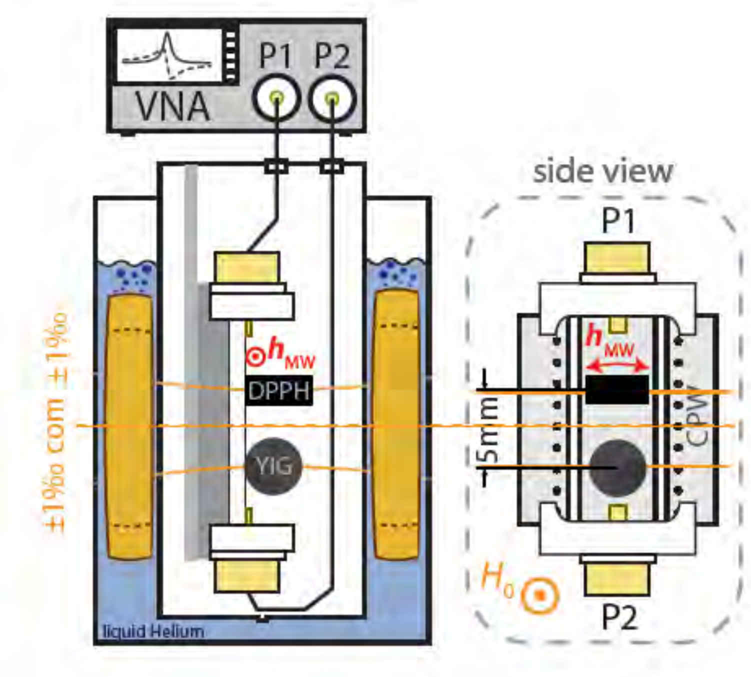
$$\alpha = \frac{\Delta f - \Delta f_0}{2 f_{res}} = 3\times10^{-5}$$

Inhomogeneous broadening from surface pit scattering



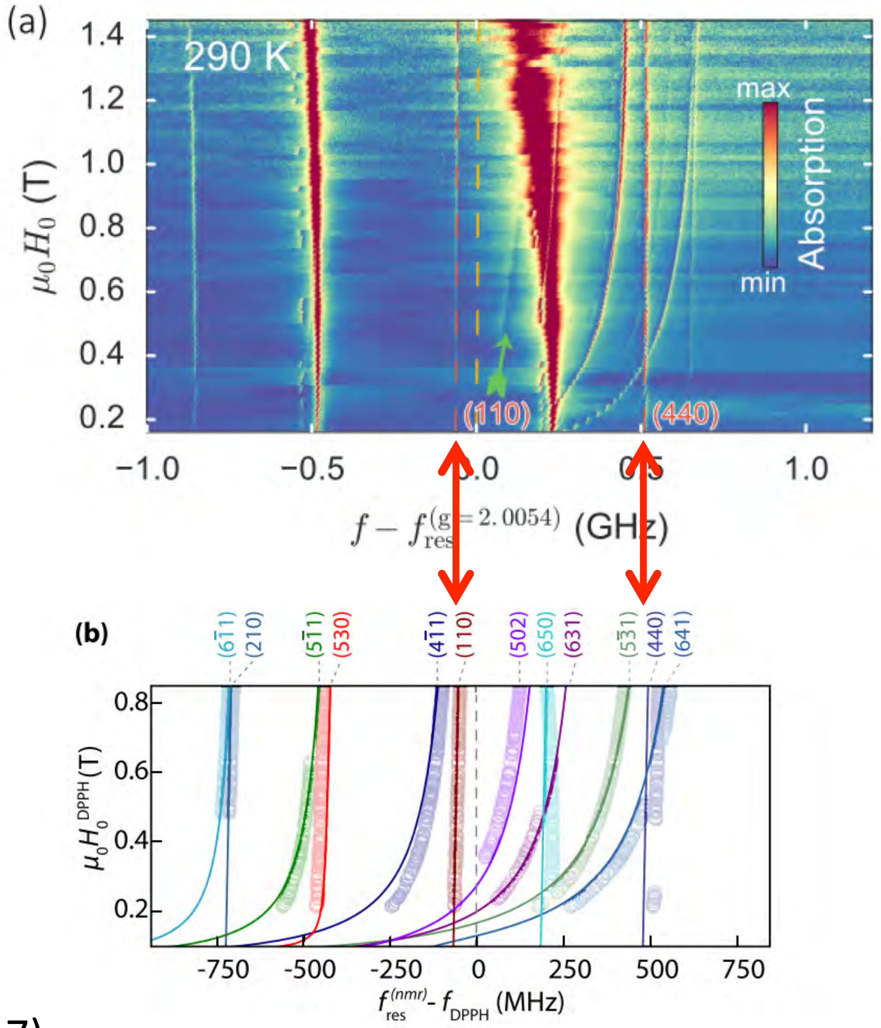
Klingler, MW et al., APL **110**, 092409 (2017).

Temperature-dependent damping in YIG



Maier-Flaig, MW et al., PRB **95**, 214423 (2017).

Same sample: now mounted in magnet cryostat

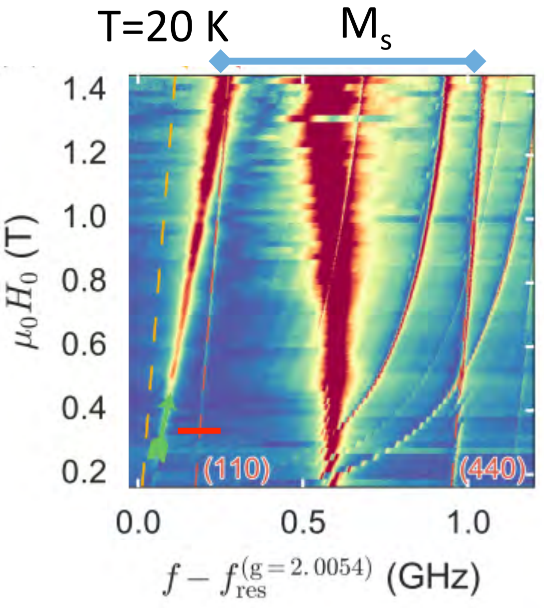


Thin film damping vs temperature:

M. Haidar et al., JAP **117**, 17D119 (2015)

C. L. Jermain et al., Phys. Rev. B **95**, 174411 (2017).

Resonance frequency

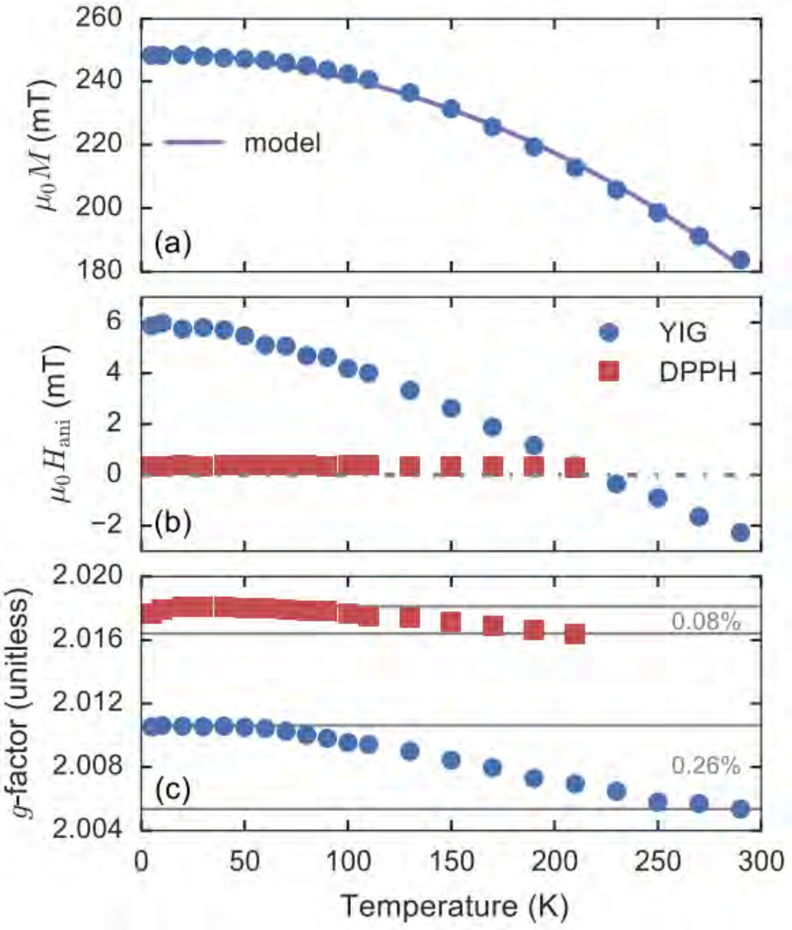


$$\omega_{res}^{110} = \mu_0 \gamma (H_0 + H_{ani})$$

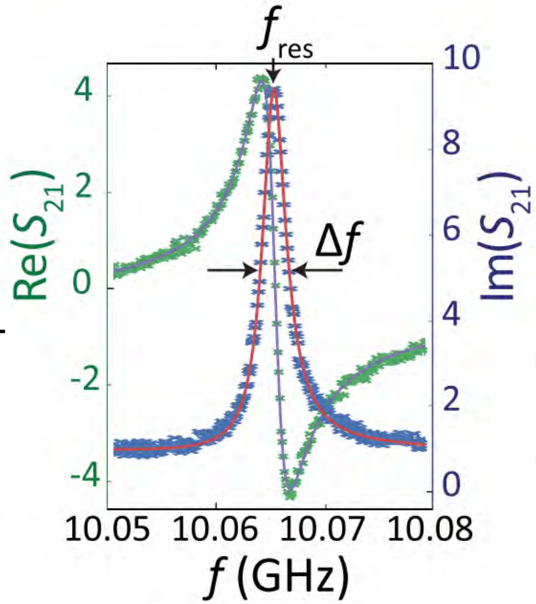
$$\omega_{res}^{440} = \mu_0 \gamma (H_0 + H_{ani} + M_s/9)$$

$$\gamma = g \mu_B /$$

$$\omega_{res}^{DPPH} = \mu_0 \gamma H_0$$

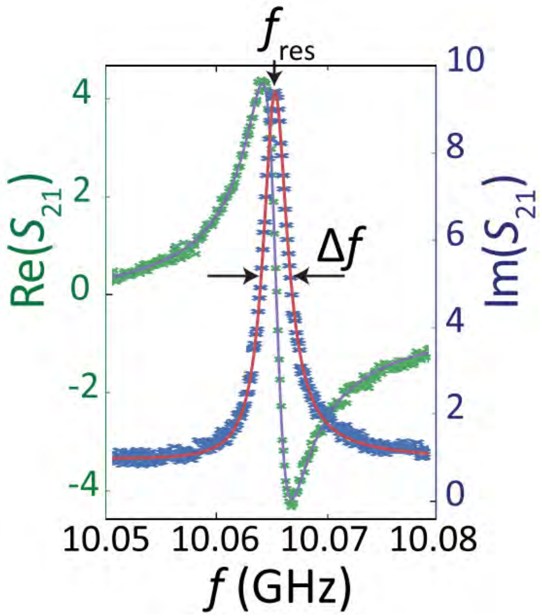


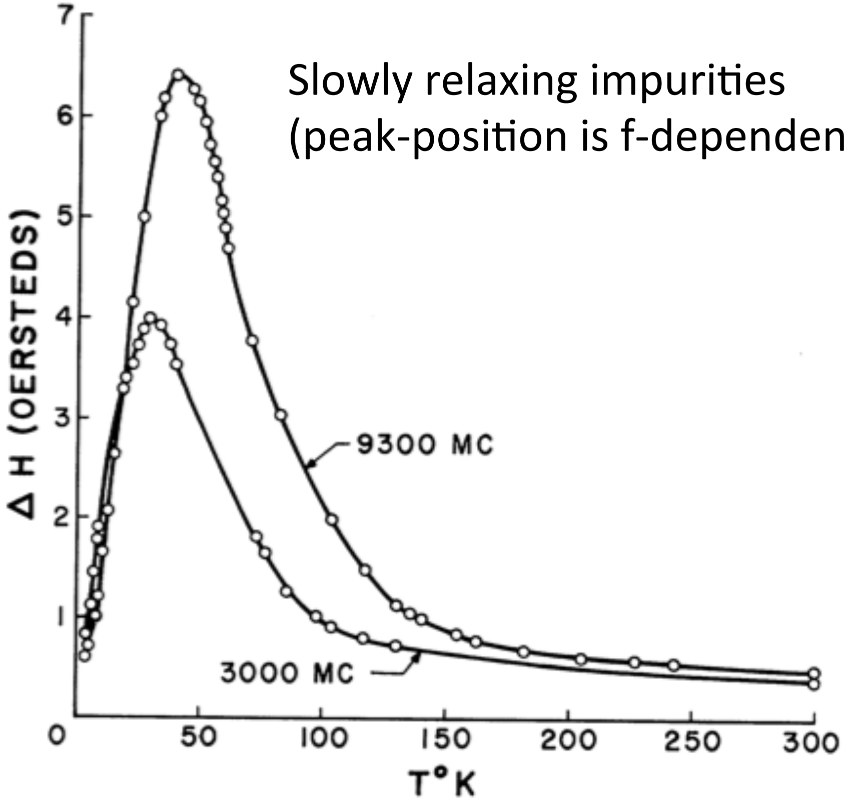
110 mode, $\mu_0 H_0$=321 mT



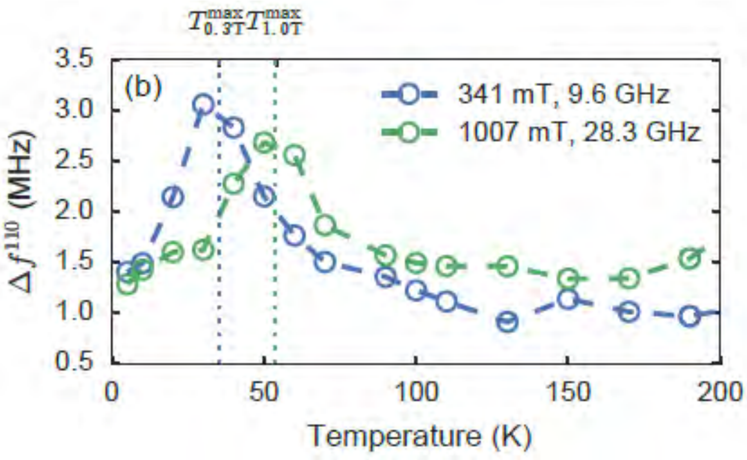
Linewidth

110 mode:





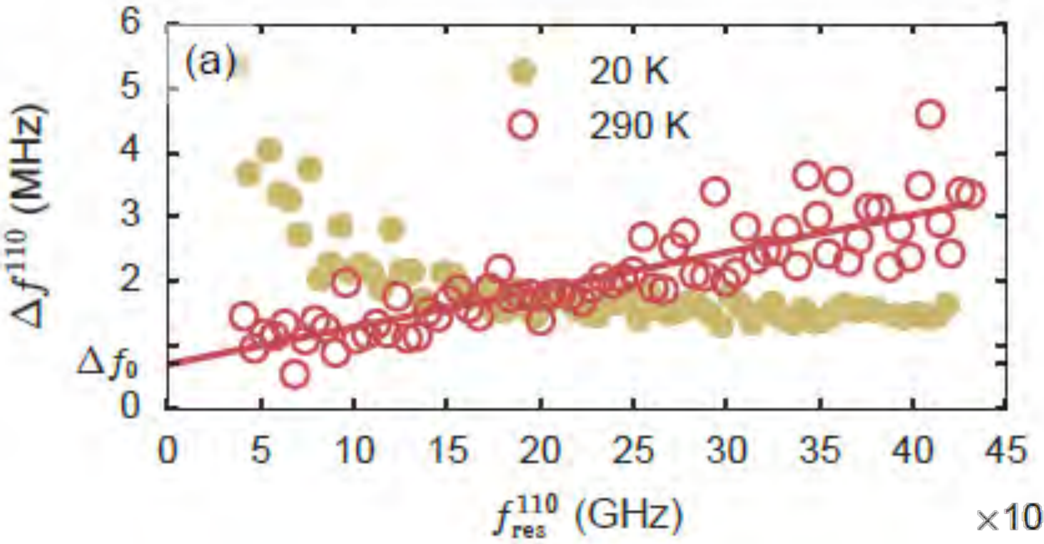
Slowly relaxing impurities (peak-position is f-dependent)



E. G. Spencer, R. C. LeCraw, and A. M. Clogston, Phys. Rev. Lett. **3**, 32 (1959).

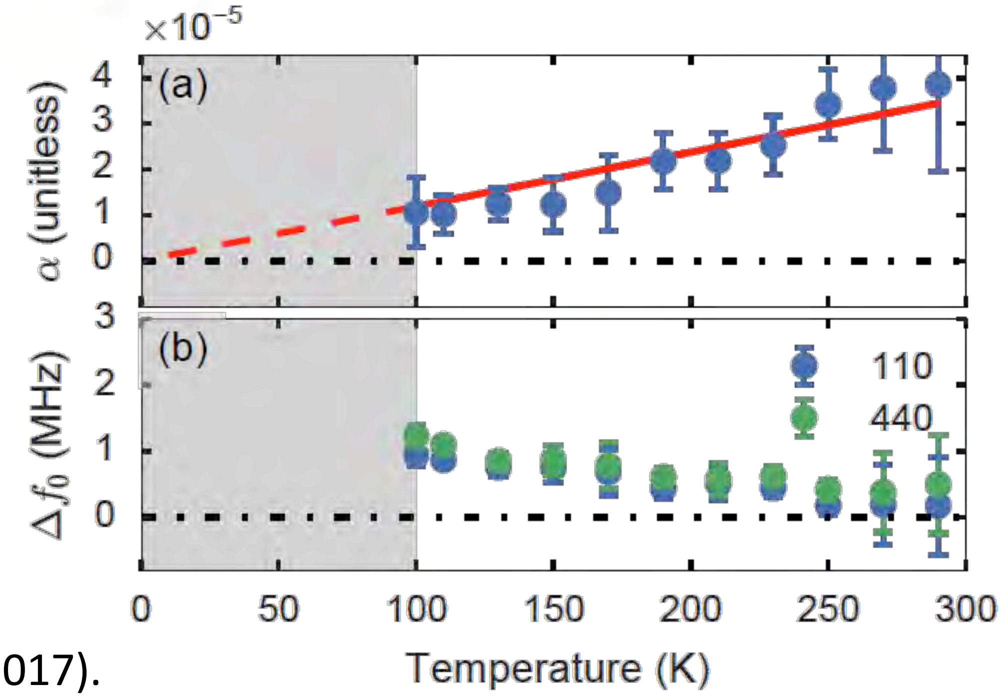
Maier-Flaig, MW et al., PRB **95**, 214423 (2017).

Damping



$$\Delta f = 2\alpha f_{res} + \Delta f_0$$

- Room temperature damping confirmed
- Damping decreases for low T



Maier-Flaig, MW et al., PRB **95**, 214423 (2017).

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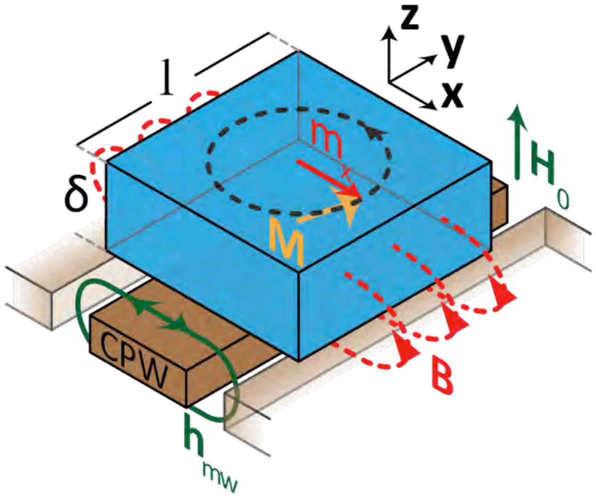
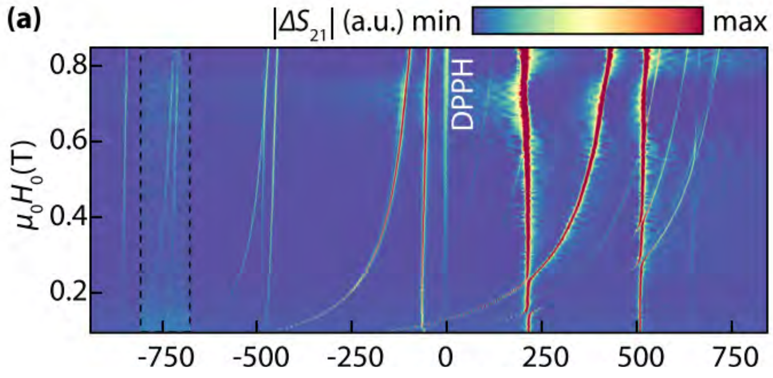
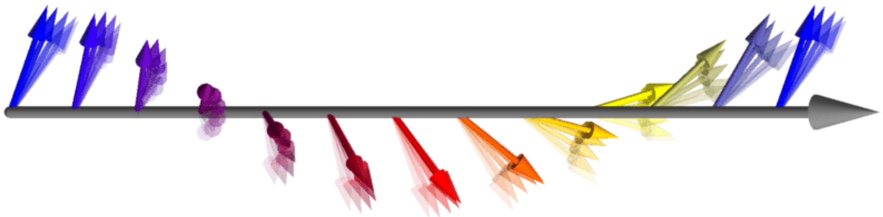






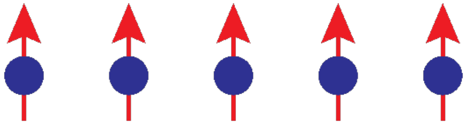
Dzyaloshinskii-Moriya interaction

Heisenberg exchange

$$\boxed{H_H = -J_{ex}\,\mathbf{S}_1\cdot\mathbf{S}_2}$$

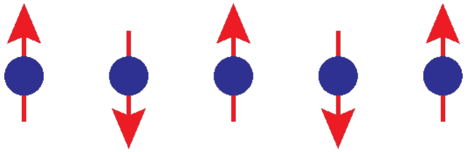
$$J_{ex} \propto A$$

$J_{ex} > 0$



parallel

$J_{ex} < 0$



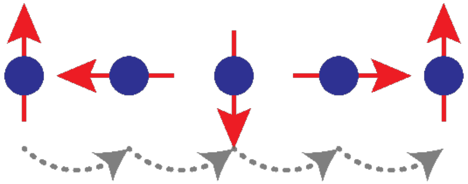
antiparallel

Dzyaloshinskii-Moriya exchange

$$\boxed{H_{DM} = -\mathbf{D}_{DMI}\cdot\left(\mathbf{S}_1\times\mathbf{S}_2\right)}$$

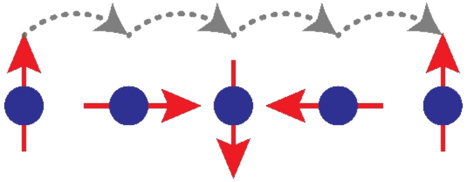
Broken inversion symmetry
Spin-orbit interaction

$\odot$ $\mathbf{D}_{DMI}$



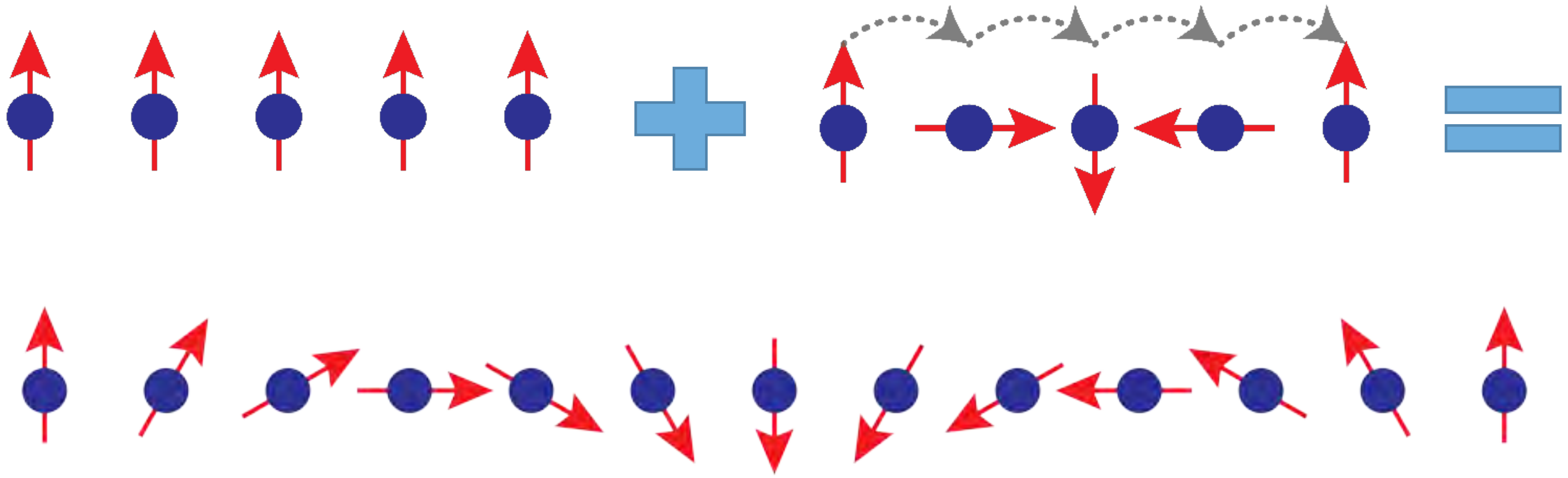
Orthogonal (counterclockwise)

$\otimes$ $\mathbf{D}_{DMI}$



Orthogonal (clockwise)

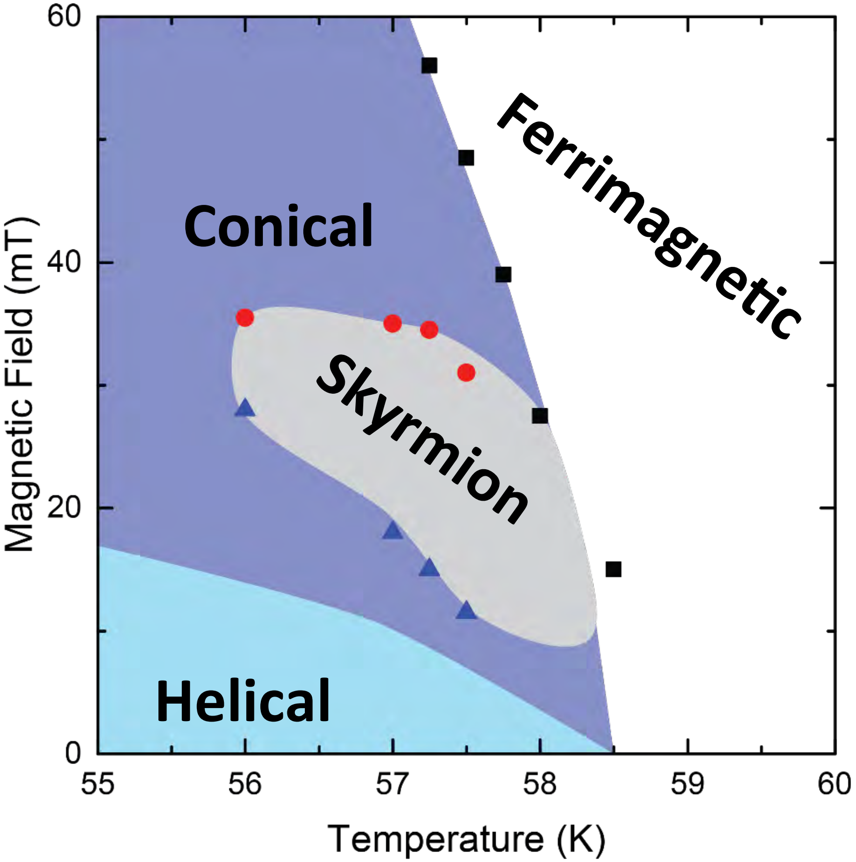
Chiral magnetic ordering



Non-collinear equilibrium spin ordering!

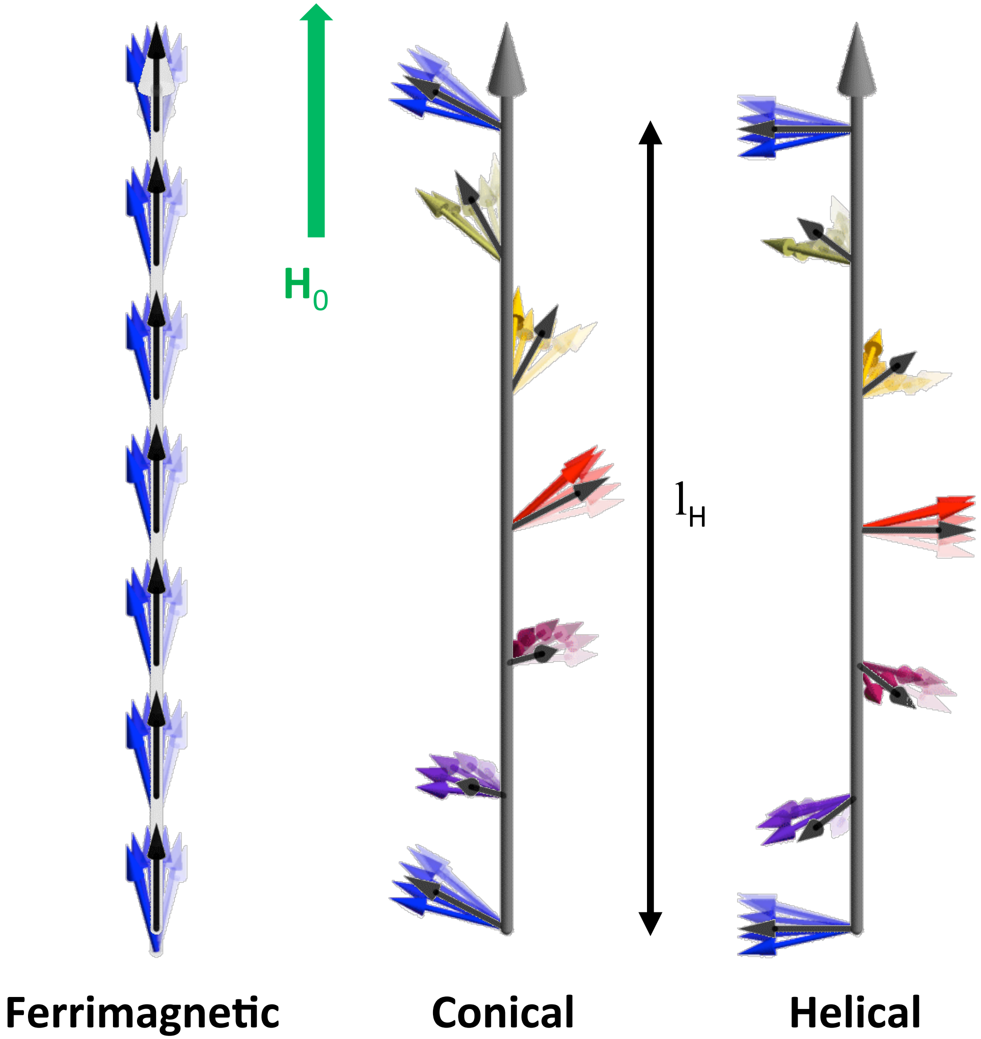
Lengthscale about 10nm-100nm

Dynamics of the chiral magnet Cu_2OSeO_3



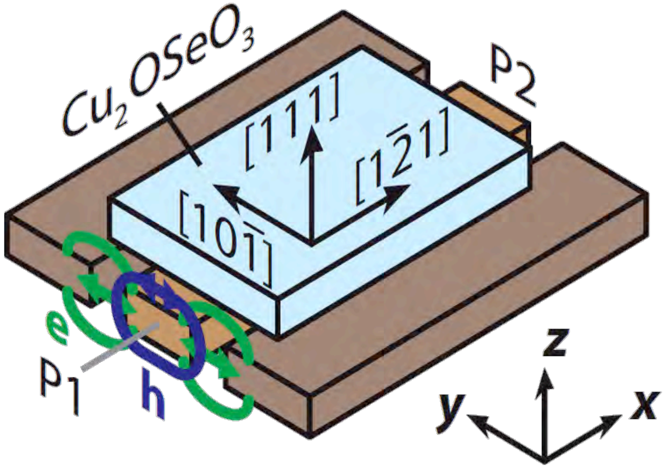
Skyrmion

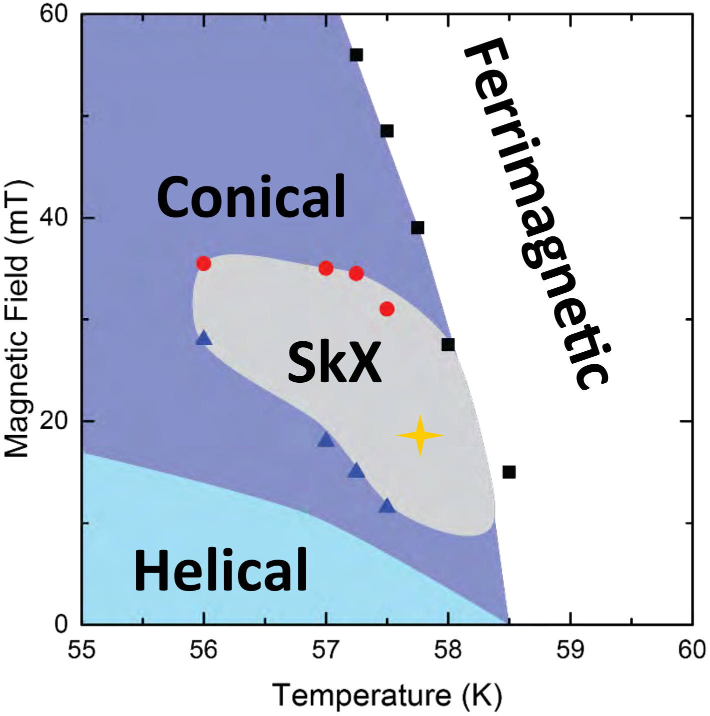
Image: K. Everschorr-Sitte



See also: Schwarze et al., Nat. Mat. 14, 478 (2015)

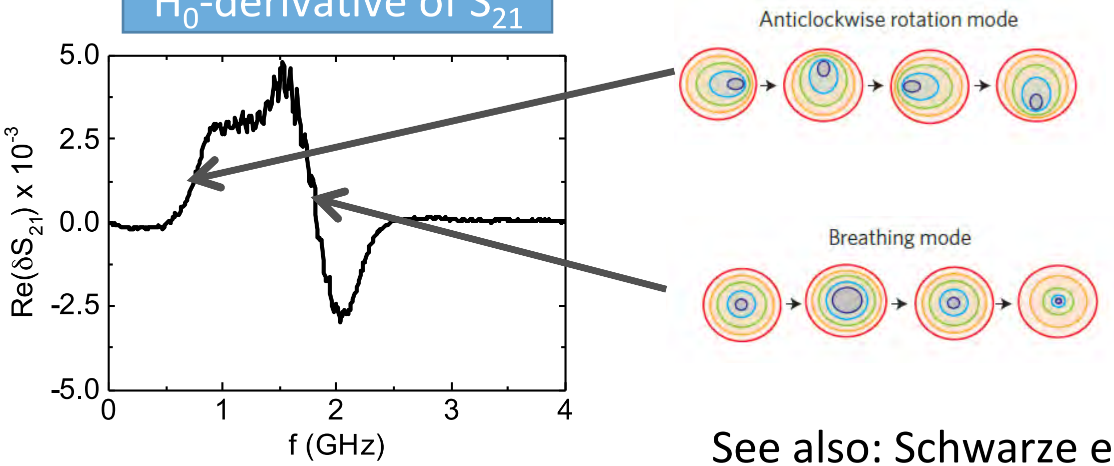
Skyrmion resonance at T=57K

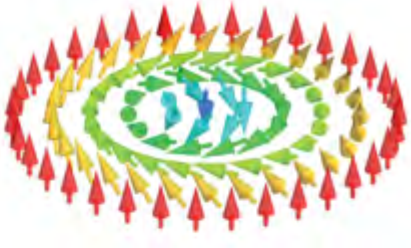




$$\delta S_{21}(f,H_0) \equiv \frac{S_{21}(f,H_0+\delta H_0) - S_{21}(f,H_0-\delta H_0)}{S_{21}(f,H_0)}$$

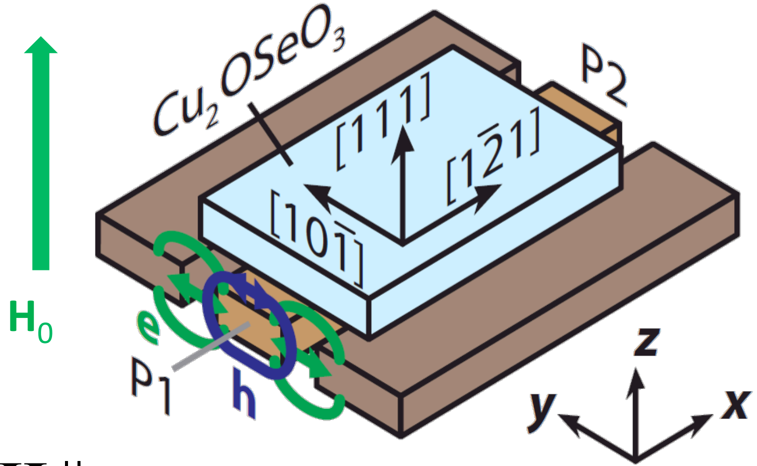
H_0-derivative of S_{21}





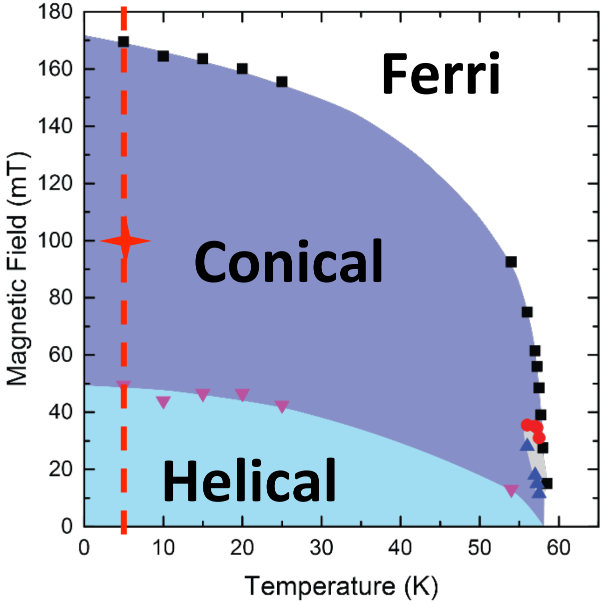
See also: Schwarze et al., Nat. Mat. 14, 478 (2015)

Chiral magnetic excitations



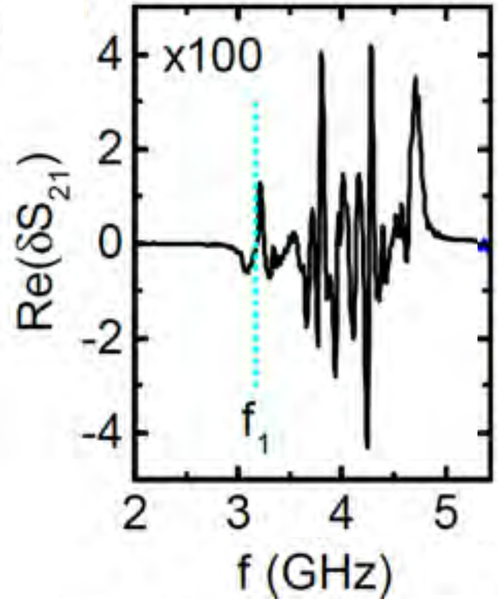
$$T = 5\mathrm{K}$$

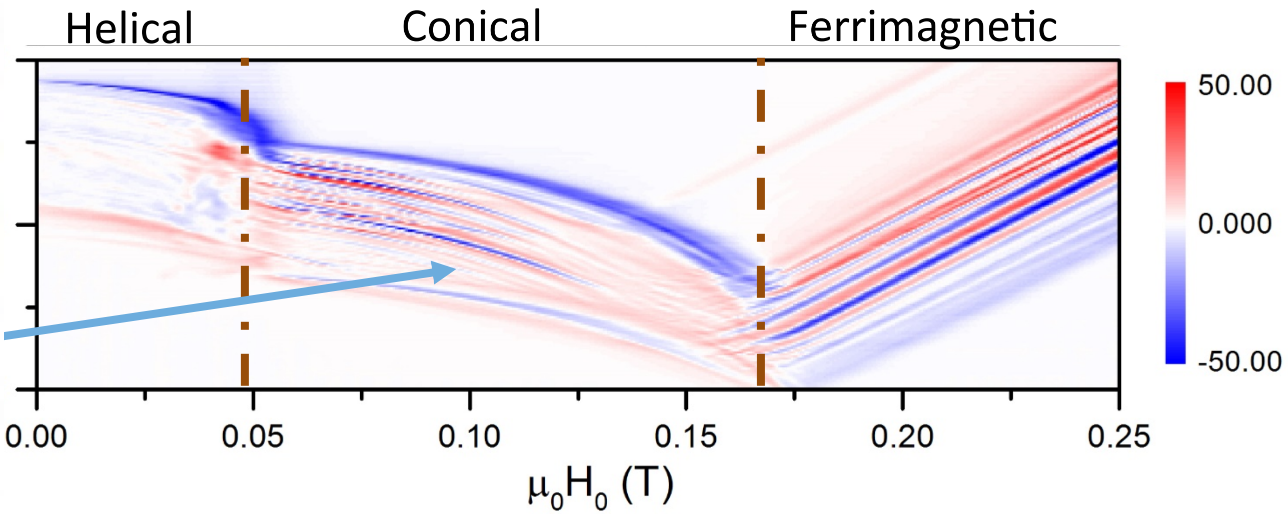
$$\mu_0 H = 100\mathrm{mT}$$



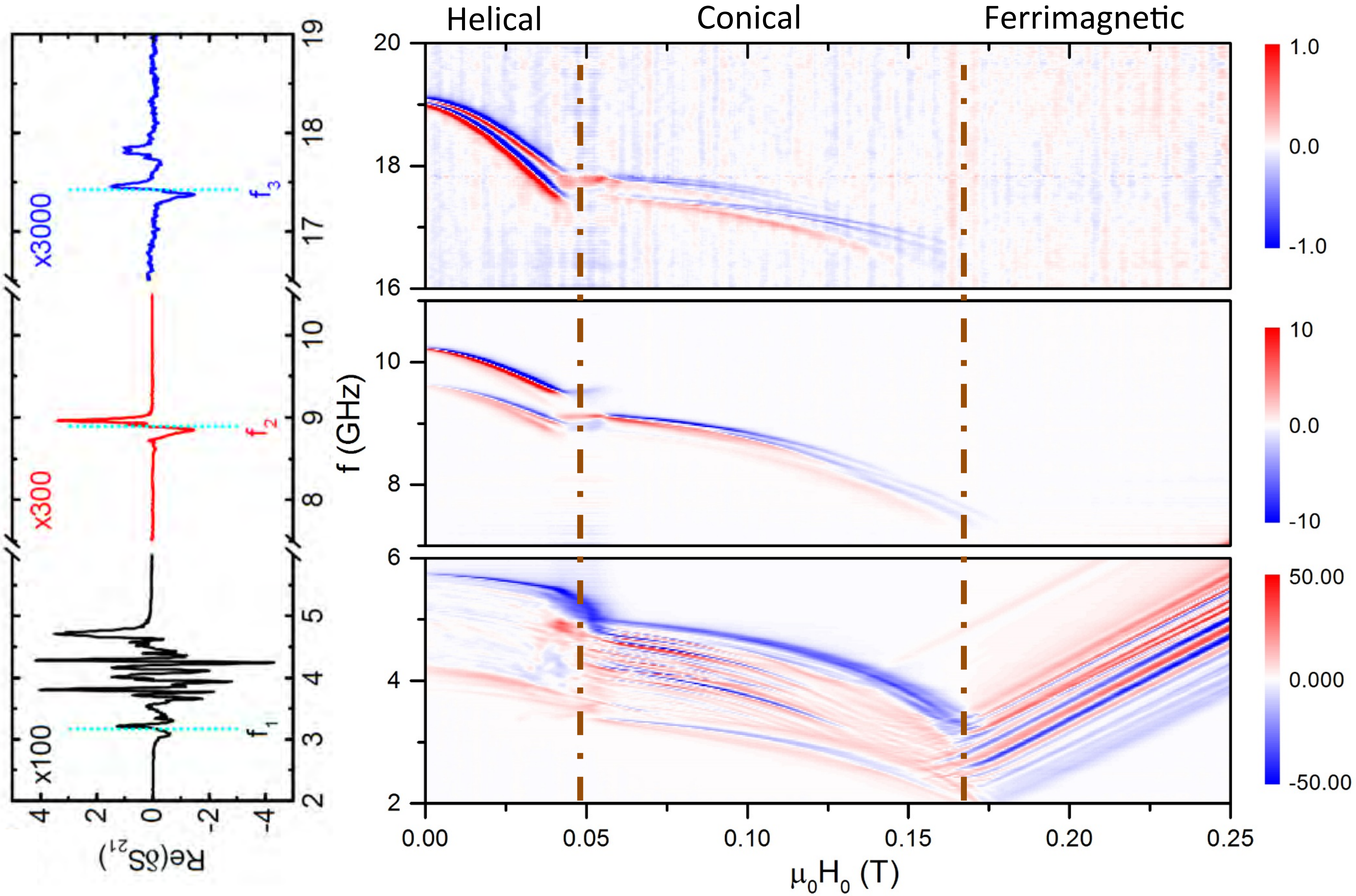
$\mathbf{H} \parallel \mathbf{z}$

See also: Schwarze et al., Nat. Mat. 14, 478 (2015)

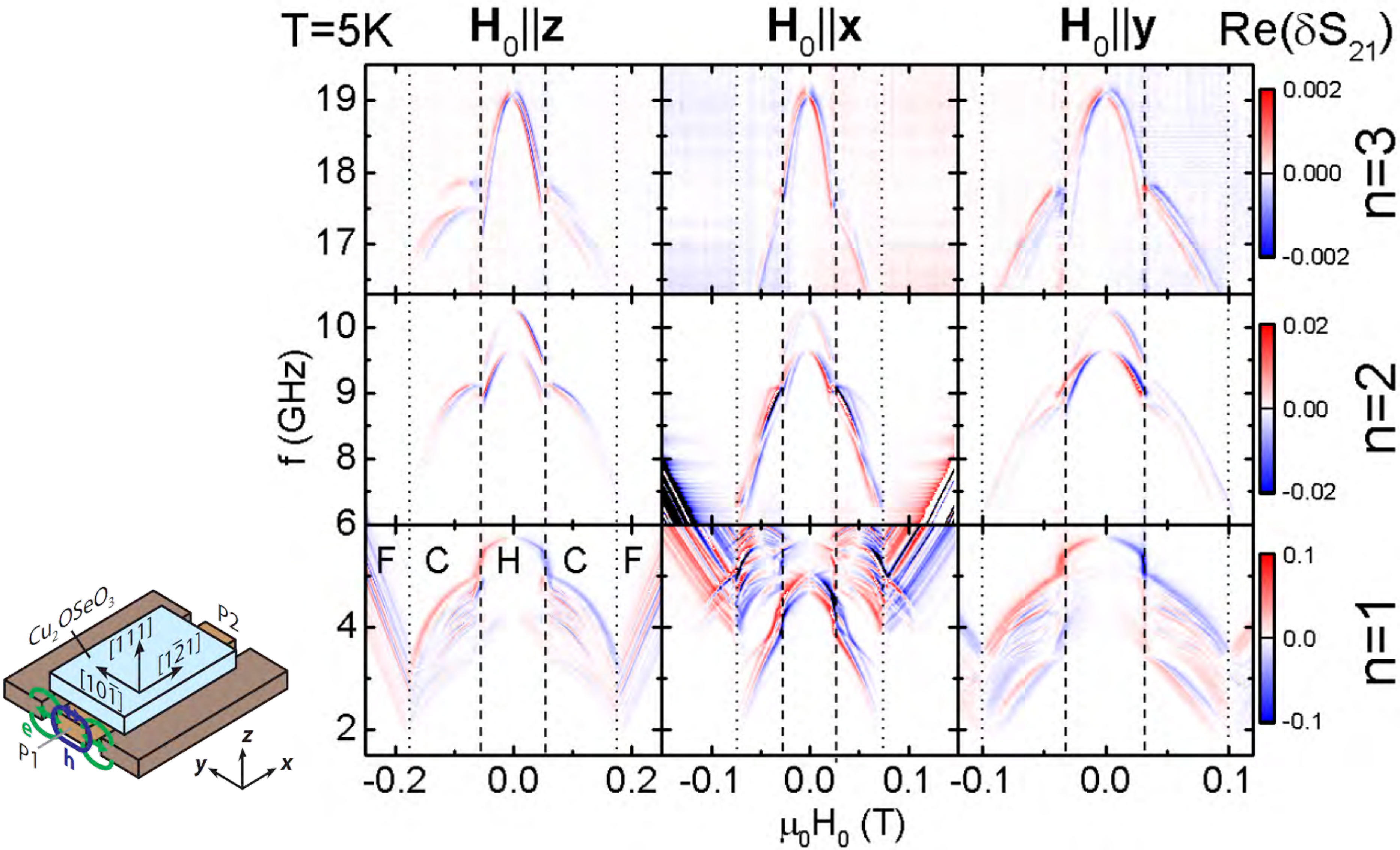




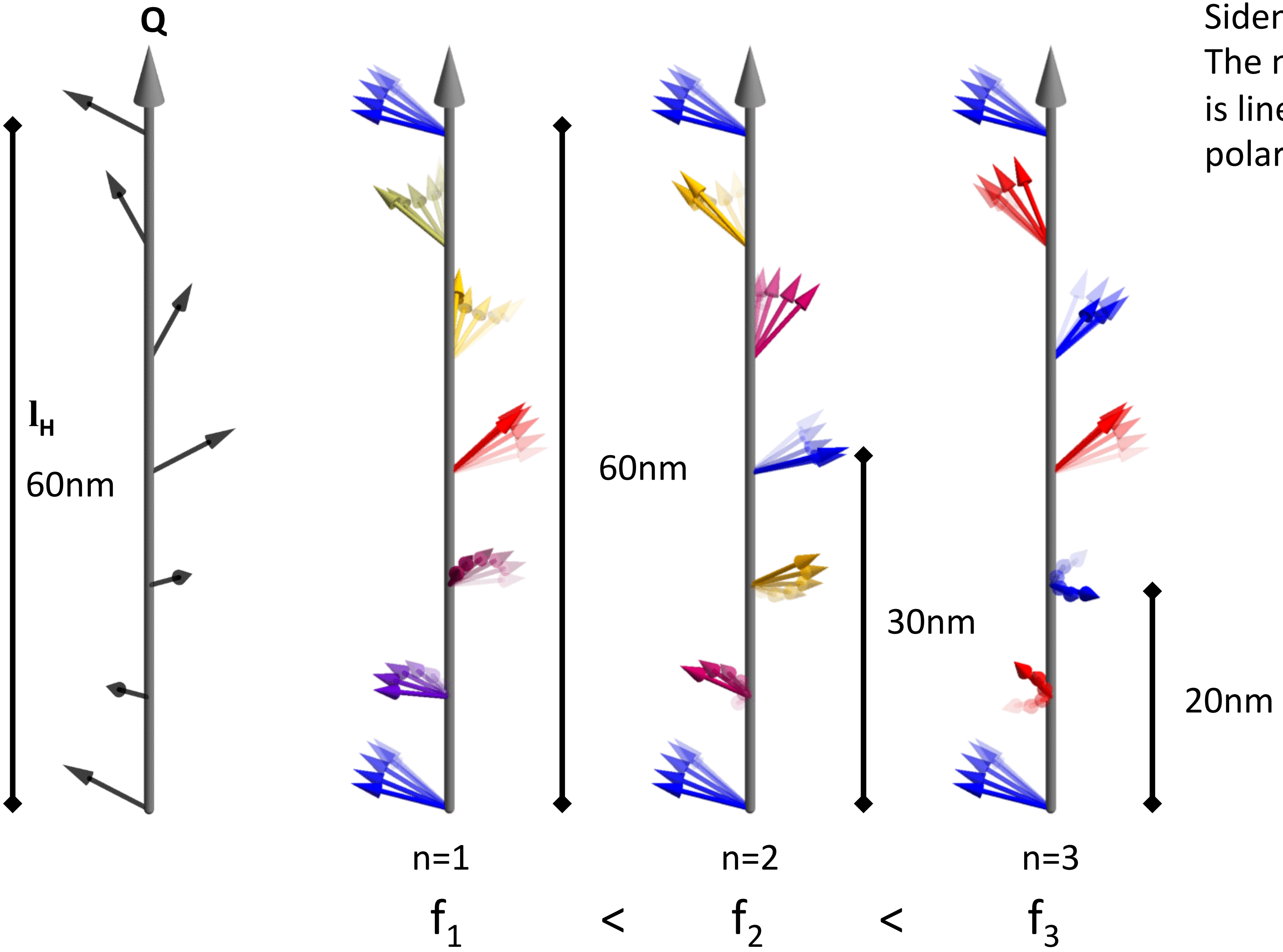
Chiral magnetic excitations



Excitation spectrum

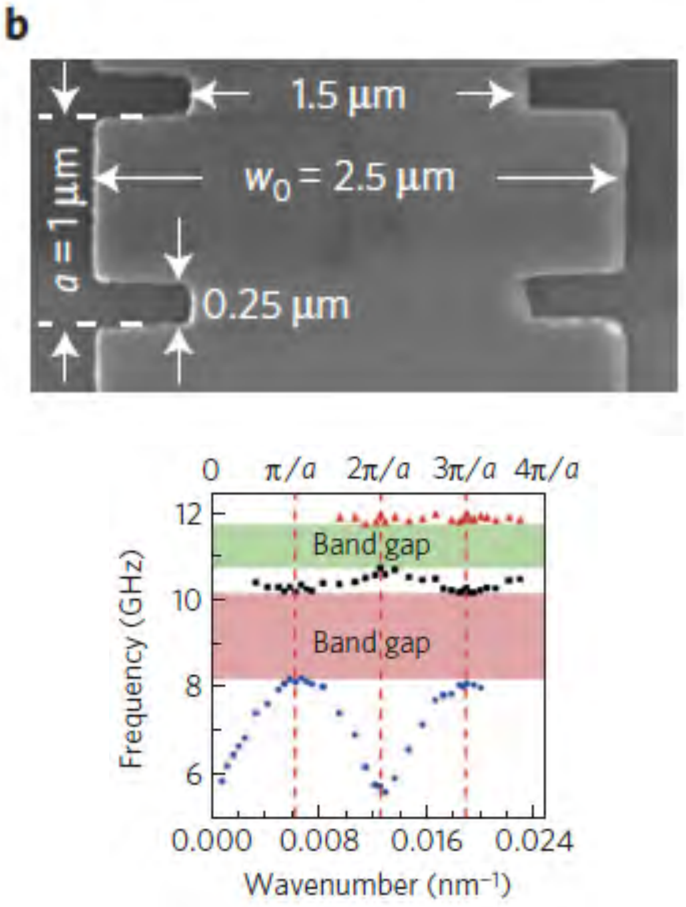


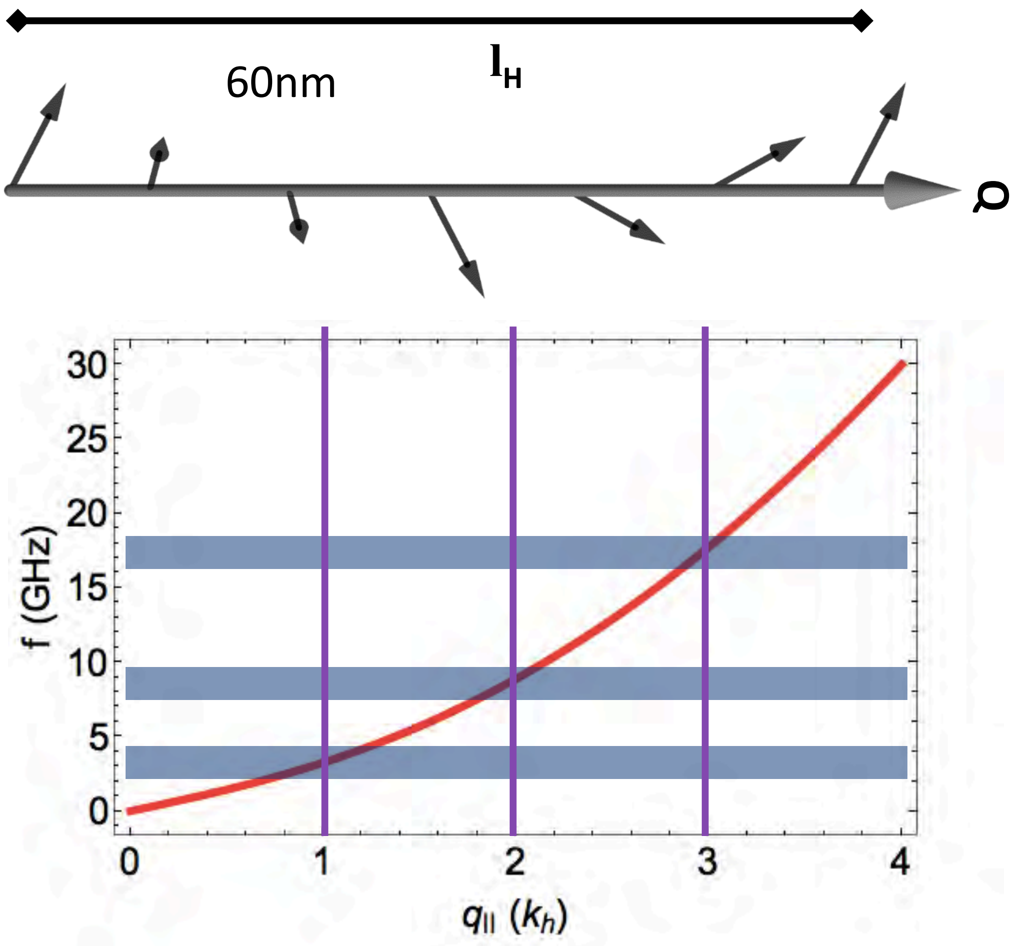
Helimagnon modes



Sidenote:
The n=1 mode
is linearly
polarized

An intrinsic, chiral magnonic crystal





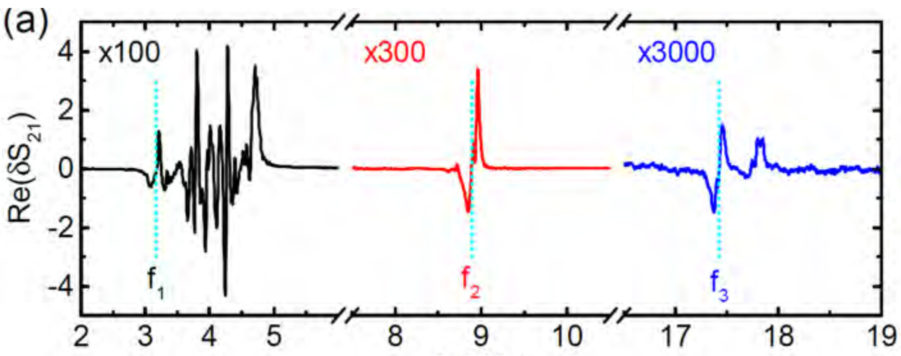
Conventional Magnonic Crystal:
Bandstructure from extrinsic, periodic modulation

Chumak, et al., Nat Phys **11**, 453 (2015).

Kugler et al., PRL **115**, 097203 (2015).

Spin Helix:
Intrinsic, 60-nm periodicity

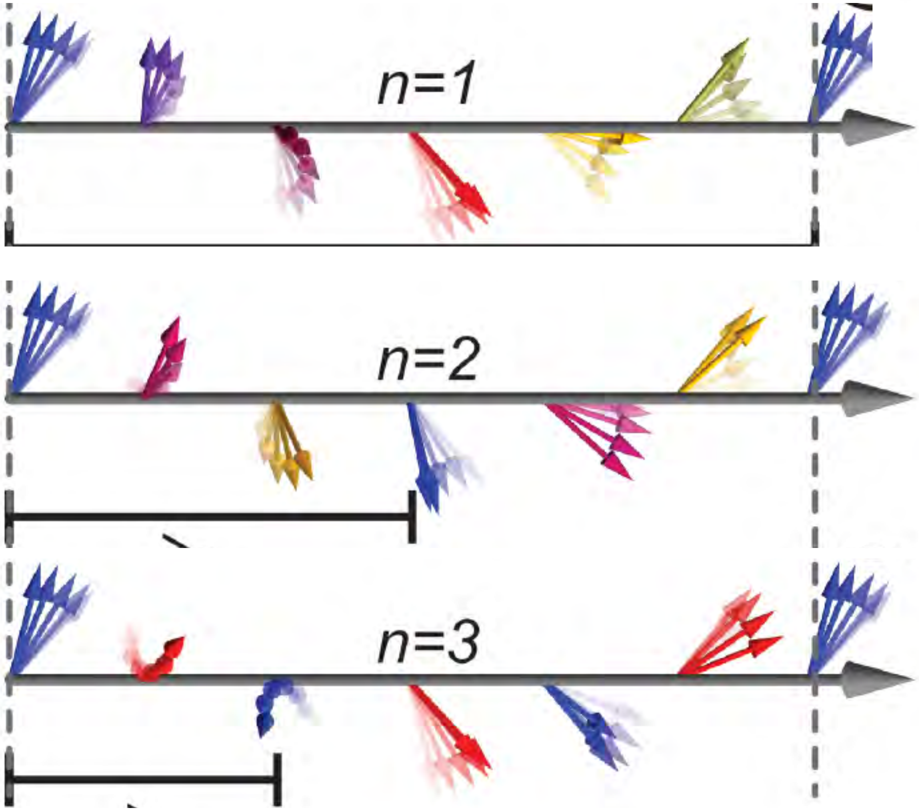
Analytical model

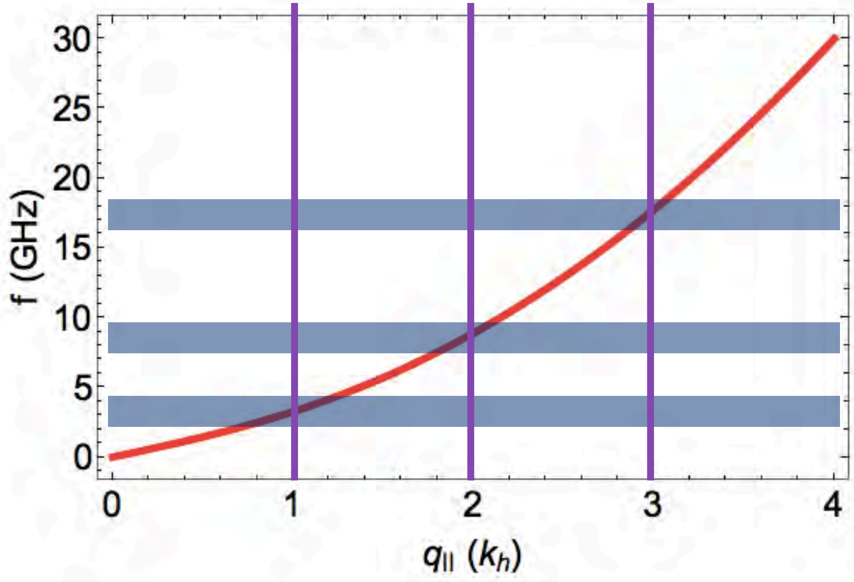


$$\hbar\omega_n = n\frac{g\mu_{\mathrm{B}}B_{\mathrm{c2}}}{1+N\chi}\sqrt{n^2+(1+\chi)\sin^2\Theta}$$

$$\chi = \mu_0\frac{M_{\mathrm{s}}^2}{DQ}$$

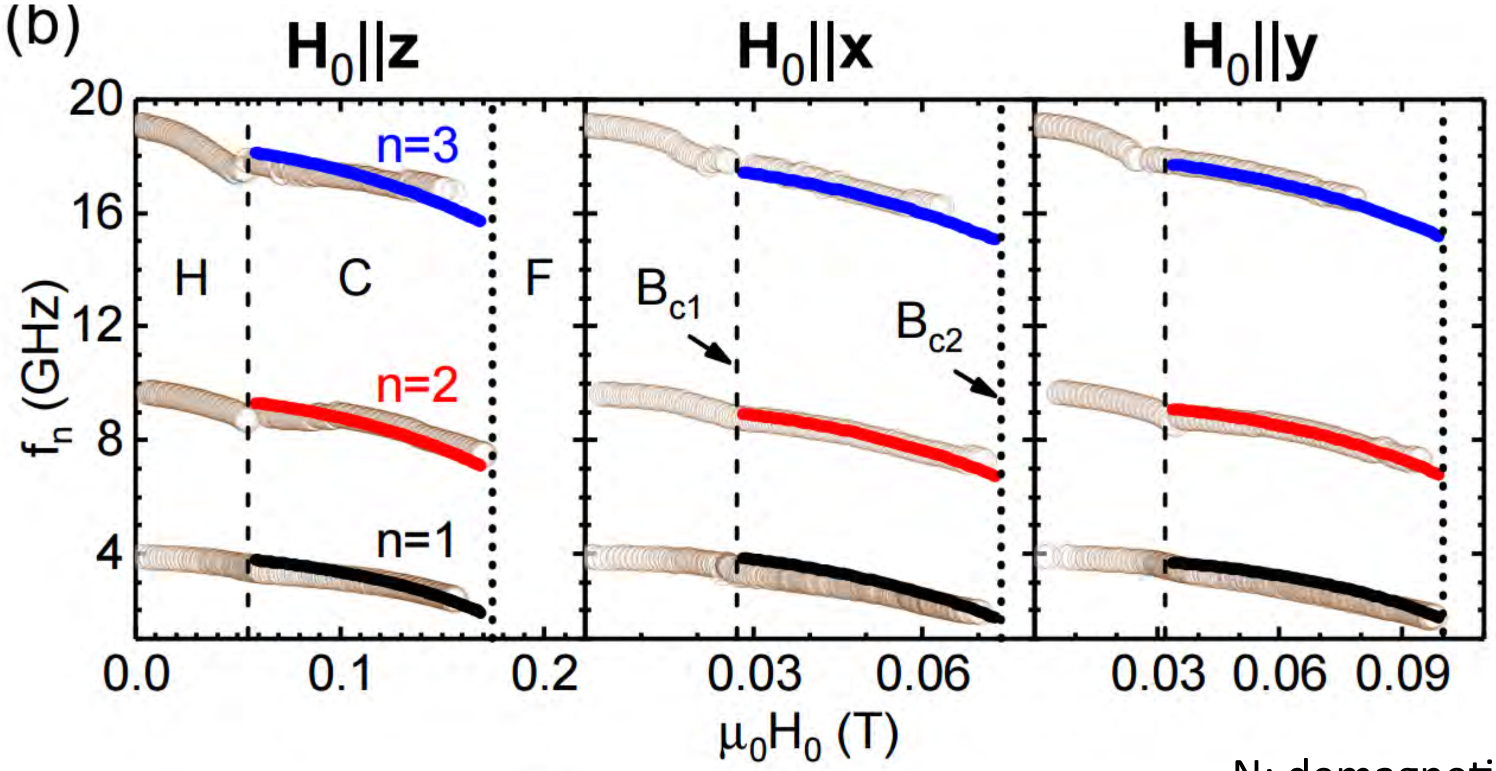
$$\cos\Theta = \frac{\mu_0 H_0}{B_{c2}}$$





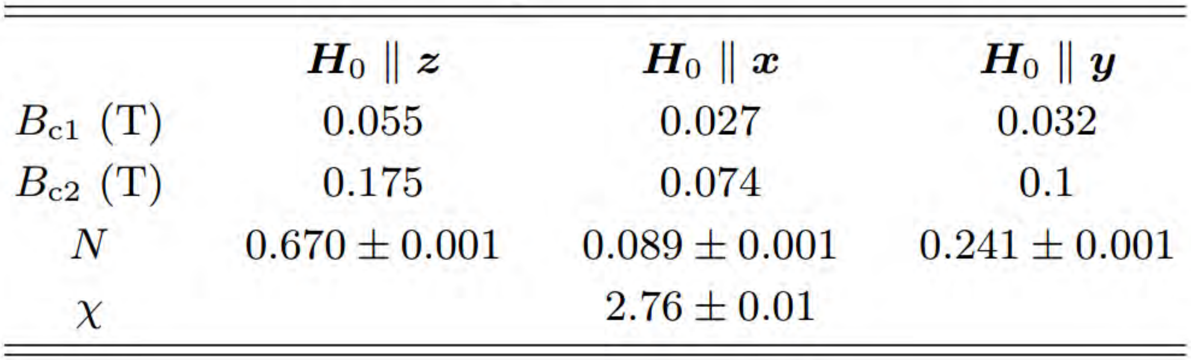
MW et al., arXiv:1705.02874 (2017).

Fits to the conical resonance frequencies



T=5K

N: demagnetization



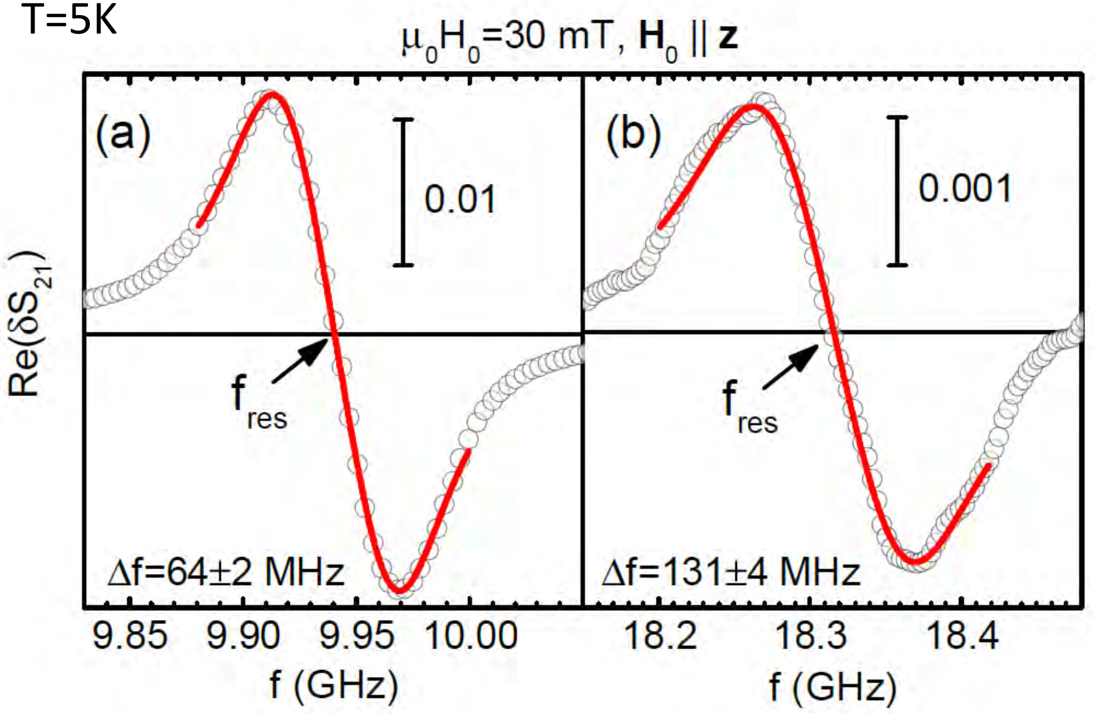
	$H_0 \parallel z$	$H_0 \parallel x$	$H_0 \parallel y$
B_{c1} (T)	0.055	0.027	0.032
B_{c2} (T)	0.175	0.074	0.1
N	0.670 ± 0.001	0.089 ± 0.001	0.241 ± 0.001
χ		2.76 ± 0.01	

$$\chi = \mu_0 \frac{M_s^2}{DQ}$$

$$Q = D / J$$

Low damping in Cu_2OSeO_3

T=5K



n=2

n=3

$$\alpha = \frac{\Delta f}{2f} \leq 0.003$$

In ferrimagnetic phase at T=5K:
α=0.001

arXiv:1705.03416 (2017).

$$\delta S_{21} = \chi(f - \delta f) - \chi(f + \delta f)$$

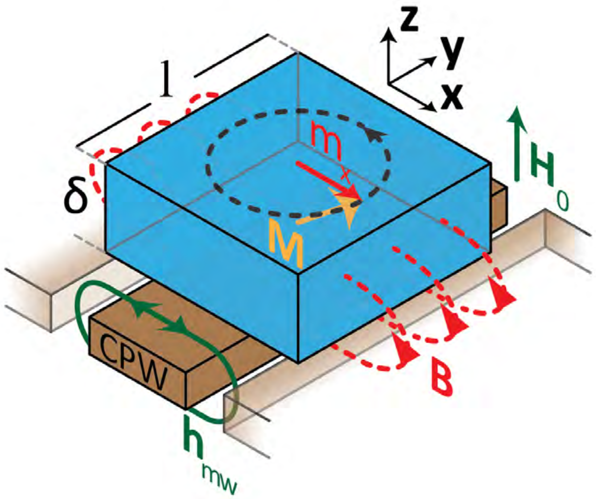
$$\chi(f) = \frac{C_0}{f_{\text{res}}^2 - f^2 - i f \Delta f}$$

Lowest magnetic damping for helimagnons reported so far

Summary

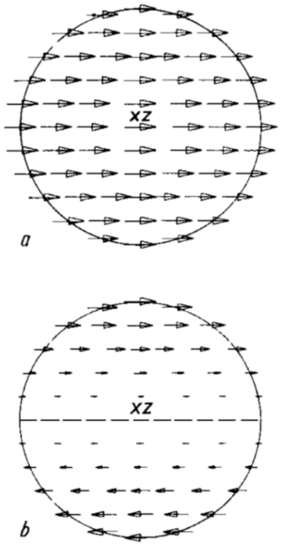
Non-collinear magnetization dynamics

Broadband spectroscopy



Magnetostatic Modes

Helimagnons



- Uniform equilibrium spin alignment
- Long-ranged dipolar interaction
- Very small damping in YIG spheres, independent of MSM mode number
- Damping decreases for low T

- Spiral equilibrium spin alignment
- Exchange and DMI
- Low damping at T=5 K
- Natural magnonic crystals