Experimental determination and micromagnetic analysis of spin wave modes in cylindrical nanowires

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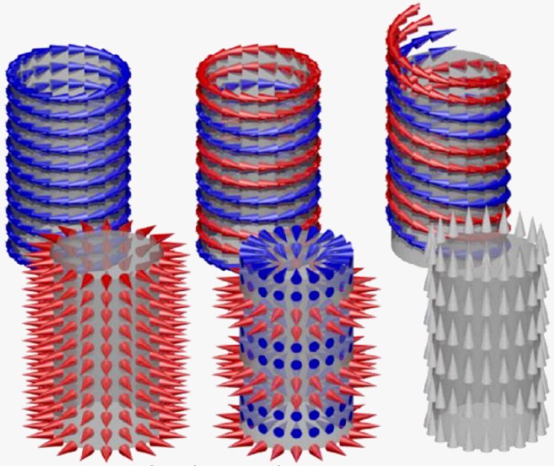
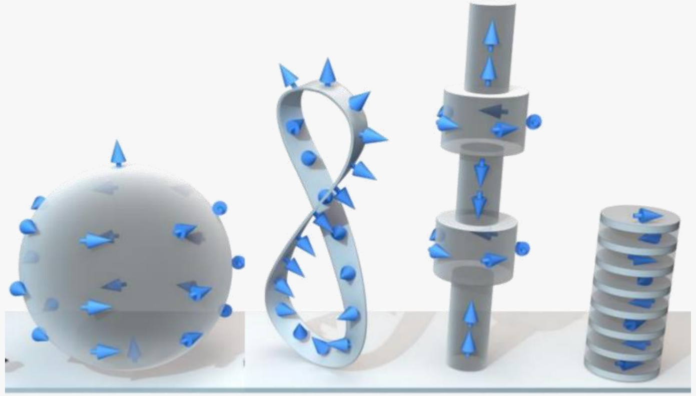
Context (1/2): 3D nanomagnetism

3D nanomagnetism

- **Physical effects**: curvature, topology of geometry and magnetization textures, large magnetostatics
- **Consequences for nanomagnetism**: effective anisotropy and DMI in unwrapped coordinates, chiral textures, topological objects (Bloch points, Hopfions etc.)
- **Numerous predictions, a number of experimental confirmations**



R. Streubel et al., J.Phys.D: Appl.Phys. 49, 363001 (2016)



A. Fernandez-Pacheco et al., Nat. Comm. 8, 15756 (2017)

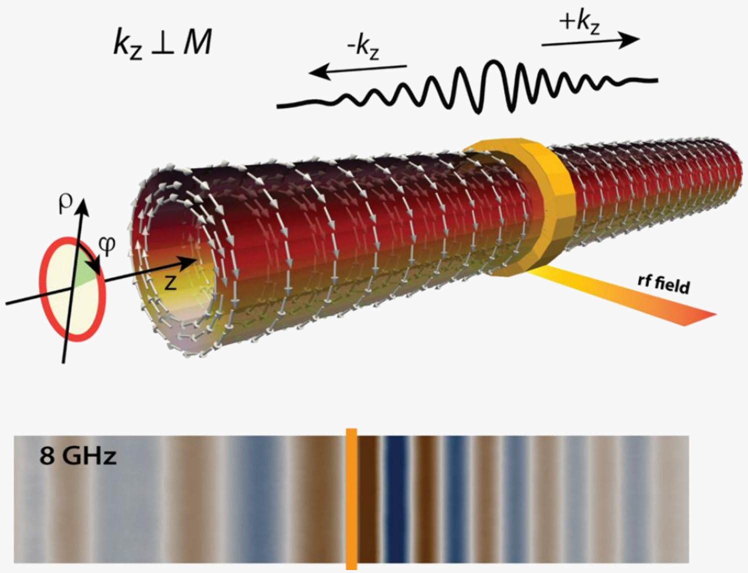
3D spintronics and dynamics

- Numerous predictions on dynamics, less on spintronics
- Experimental realizations are emerging: 3D magnonics, domain-wall motion under current…

Context (2/2): motivation for spin waves

Curvature-induced non-reciprocity

Prediction



J. A. Otálora et al., Phys. Rev. Lett. 117, 227203 (2016)

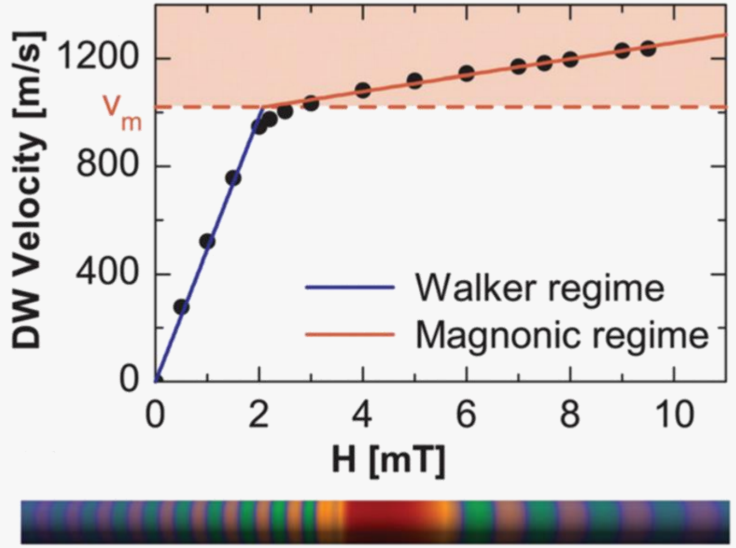
Pioneering experiments

Tubes L. Körber et al., Phys. Rev. B 104, 184429 (2021)

Curved deposits M. Bailleul's group

Interaction with domain walls

Prediction



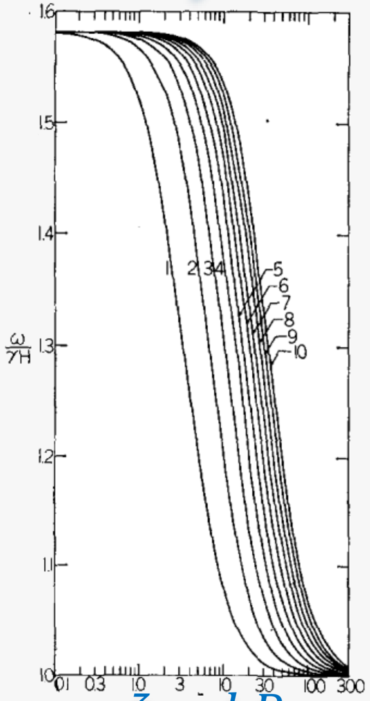
M. Yan, APL 99, 122505 (2011)

- Motivation for techniques for local measurement of spin waves
- Example: time-resolved magnetic microscopy, micro-Brillouin Light Scattering

Dipolar spin waves

- Considers the gain in magnetostatic energy, not the cost in exchange energy

→ Suitable for large-diameter (micro)wires

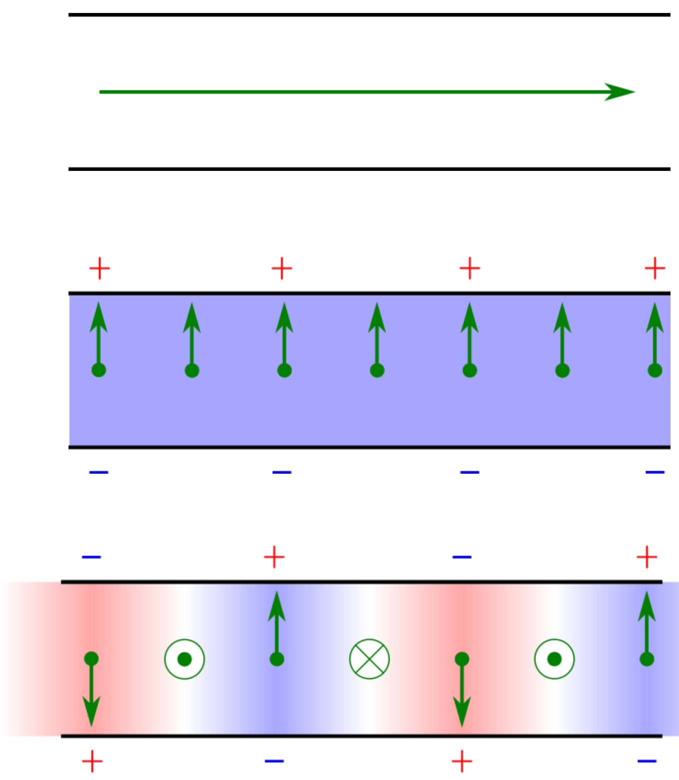


$\zeta = kR$

R. I. Joseph and E. Schlömann, J. Appl. Phys. 32, 1001 (1961)

- Energy decreases with k, similar to backward volume modes
- Energy increases with radial and azimuthal node numbers

Physics of backward volume modes



Statics
no dipolar energy

$k = 0$
Large dipolar energy during precession

$k \neq 0$
Dipolar energy decreased
-> Lower frequency

- Note: similarity with stripe domains in perpendicularly-magnetized films

Spin waves in nanowires – Theory (2/2)

Dipolar/Exchange spin waves

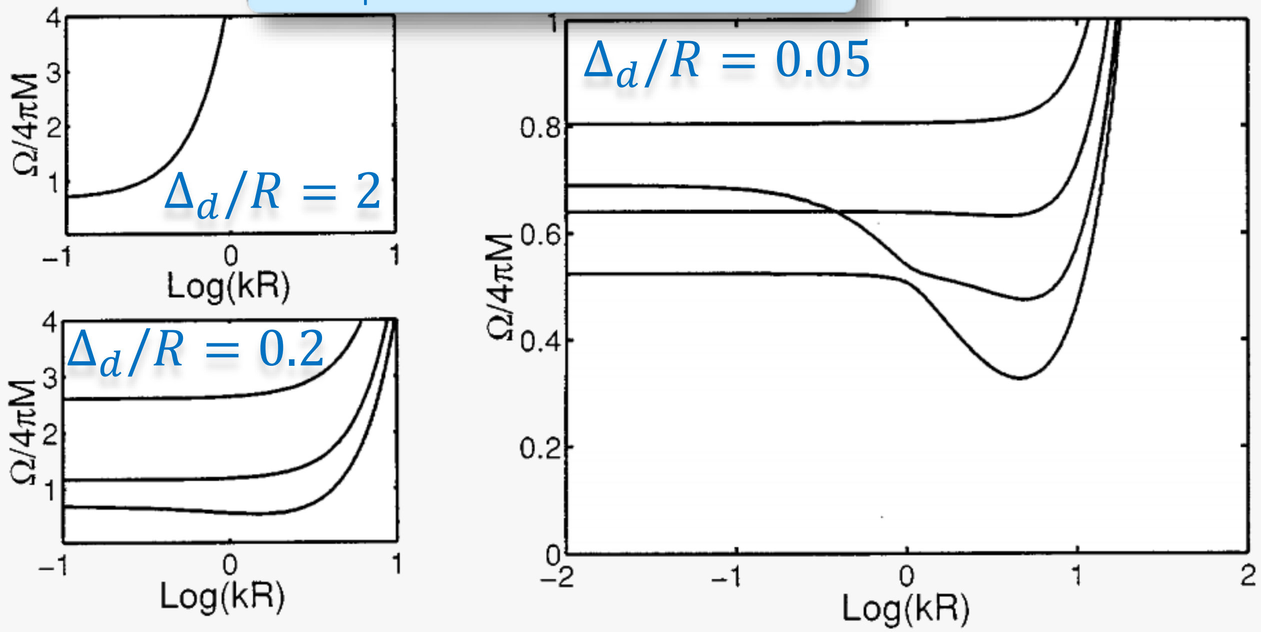
- Considers the gain in magnetostatic energy AND the cost in exchange energy

  ➡ Suitable for nanowires (<few 100nm)

- Describes radial and azimuthal nodes

  $\Phi_M(\rho,\phi,z) = J_m(\kappa\rho)\exp(im\phi + ikz)$

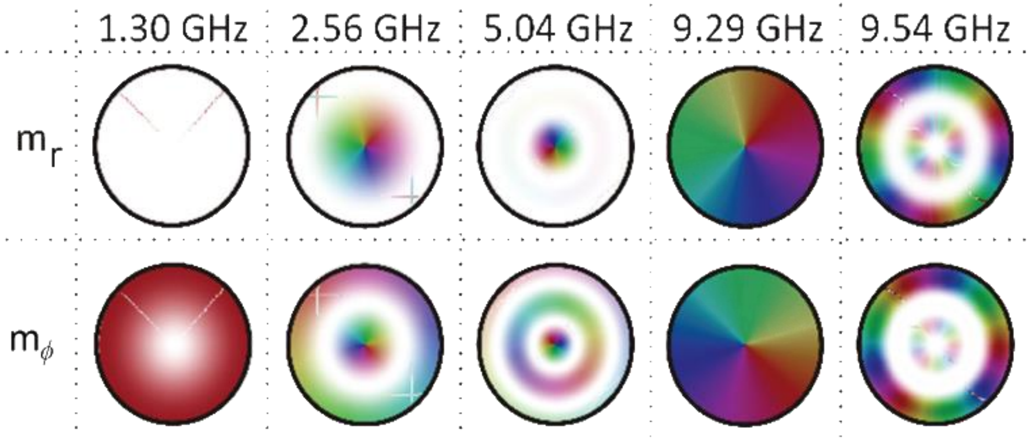
Dispersion curves for m=1



R. Aris, D. L. Mills, Phys. Rev. B 63, 134439 (2001)

Illustration

- Real-space visualization of modes
- Highlight of dipole/exchange energy
- Hybridization of modes

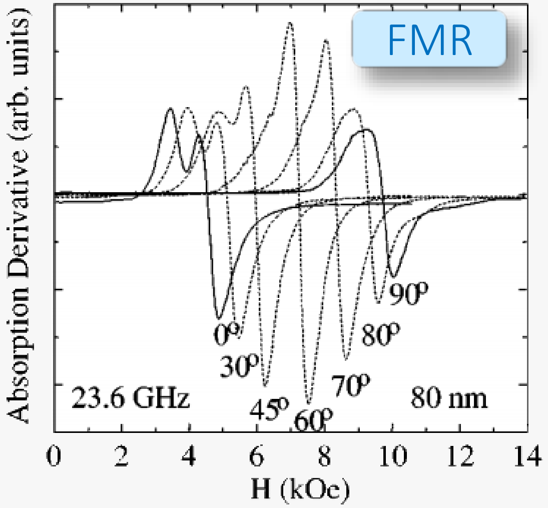


J Rychły et al., J. Phys. D: Appl. Phys. 52, 075003 (2019)

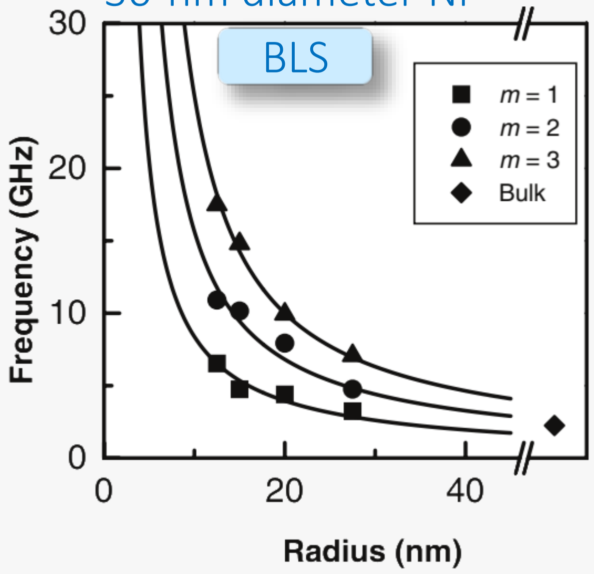
spintec
SPIN IN ELECTRONICS

Investigations of arrays of nanowires

80-nm diameter Ni



30-nm diameter Ni



- Multiple peaks observed on Kittel mode
- Dipolar/Exchange spin waves mentioned but not analyzed

U. Ebels et al., Phys. Rev. B 64, 144421 (2001)

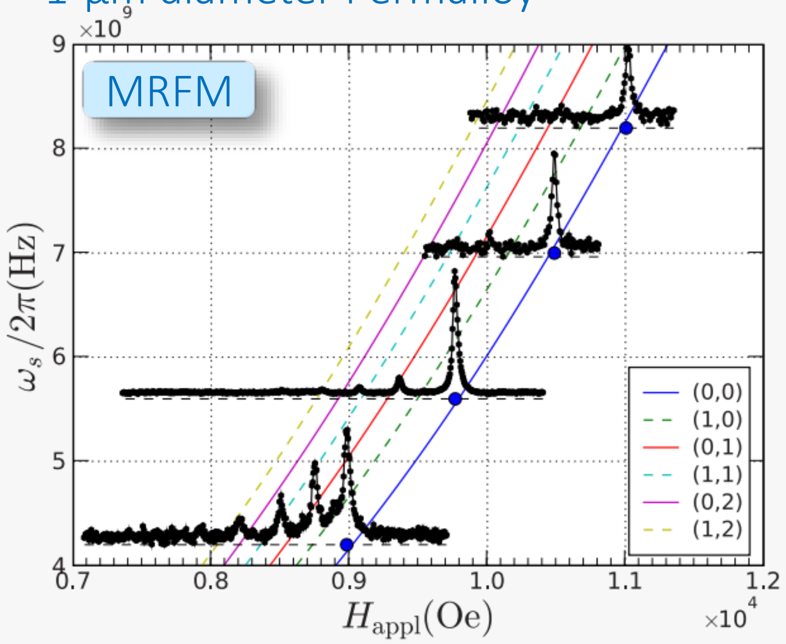
- Multiple peaks observed on Kittel mode
- Frequency shift increases at smaller radius: exchange
- Good fitting only for anomalously-low exchange stiffness

Z. K. Wang et al., Phys. Rev. Lett. 027201 (2002)

Single isolated flat disks

- Rotational invariance but flat (weak dipolar energy)

1-µm diameter Permalloy



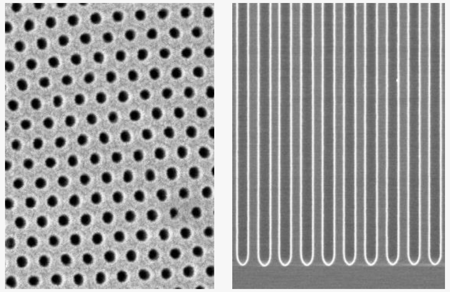
Absence of dipolar interactions and distributions allows the unambiguous identification of modes

O. Klein et al., Phys. Rev. B 78, 144410 (2008)

Methods

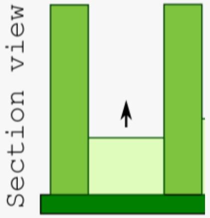
Electroplated nanowires

- Template: anodized aluminum



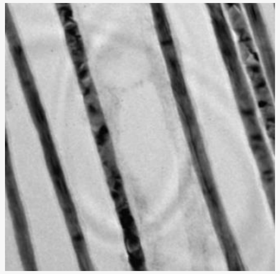
H. Masuda, Science 268, 1466 (1995)

- Filling with electroplating



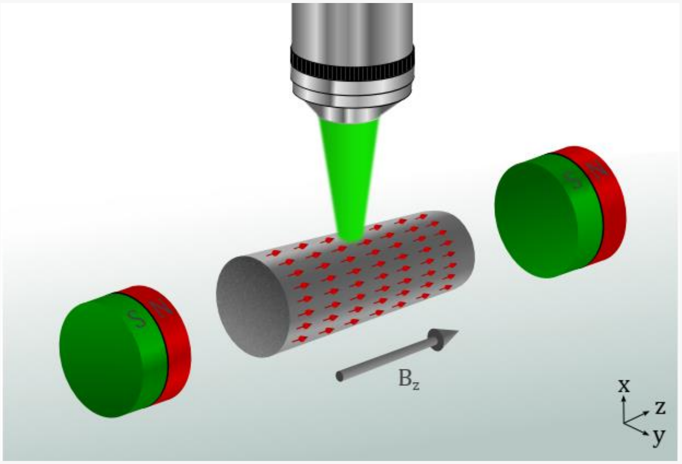
115-nm diameter Permalloy

- Dissolve matrix: single wires



S. Ruiz et al., Sci. Rep. 8, 16695 (2018)

Micro Brillouin Light Scattering

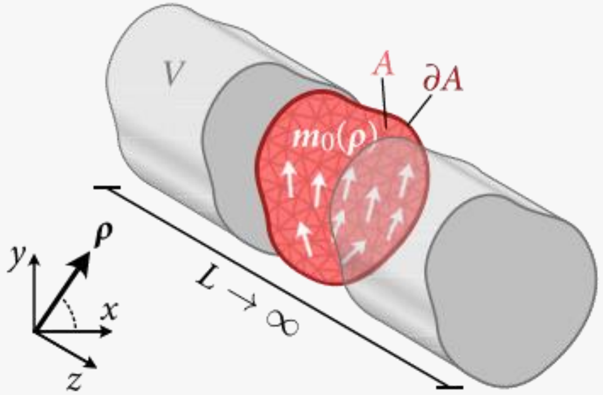


- BLS probes energy gain and loss in scattered light. **k** vector selected by incidence angle.
- µBLS, focus few 100nm: probes single wires with high sensitivity
- Loss of **k** resolution due to large numerical aperture
- Longitudinal applied field with permanent magnets

T. Sebastian et al., Front. Phys. 3, 35 (2015)

TetraX simulation software

- Computes resonance modes and their frequency
- 2D-like, fast: arbitrary cross-section + translational geometrical invariance
- Open source and freeware

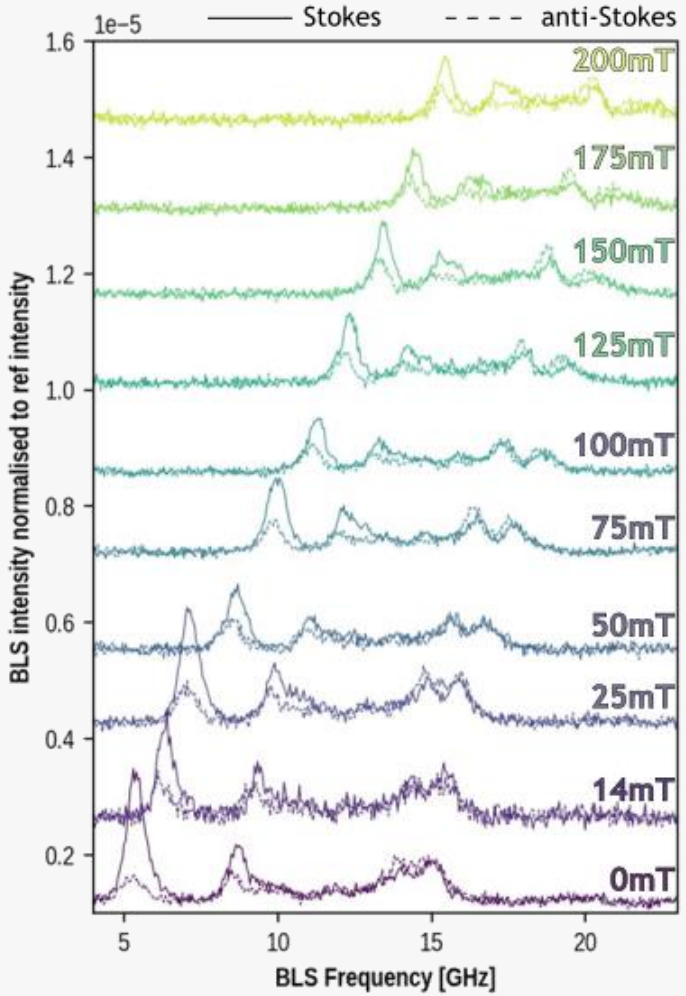


L. Körber, AIP Adv. 11, 095006 (2021)

DOI: 10.14278/rodare.1418

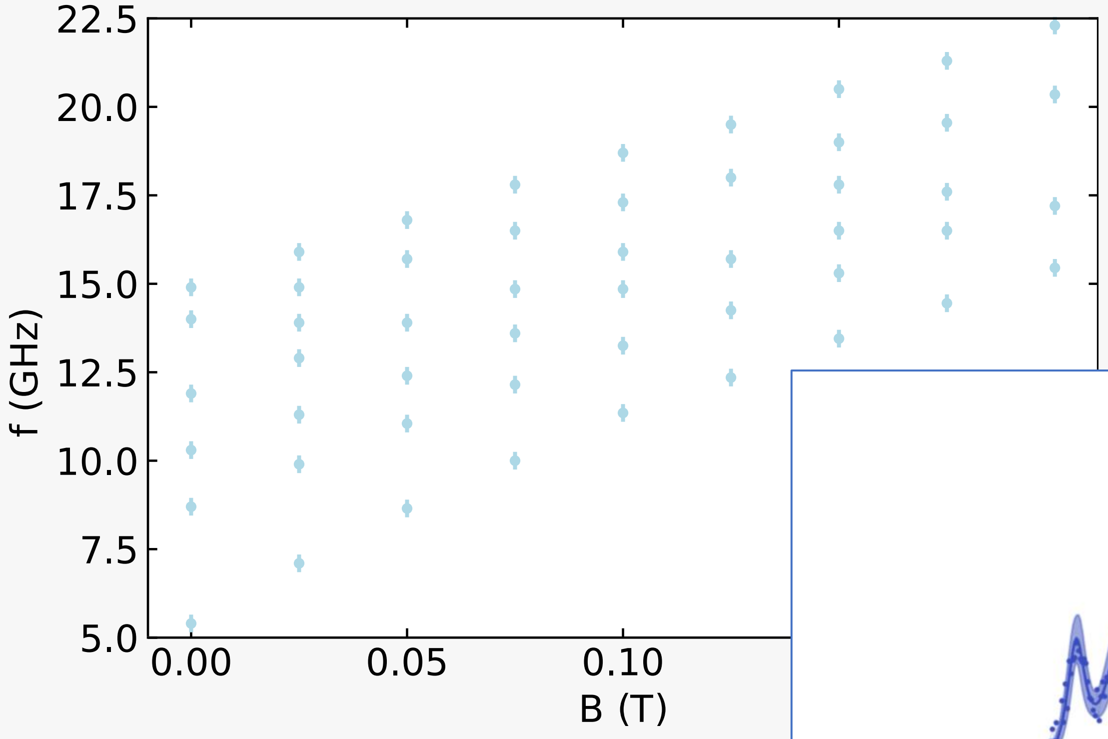
Experimental µBLS spectra

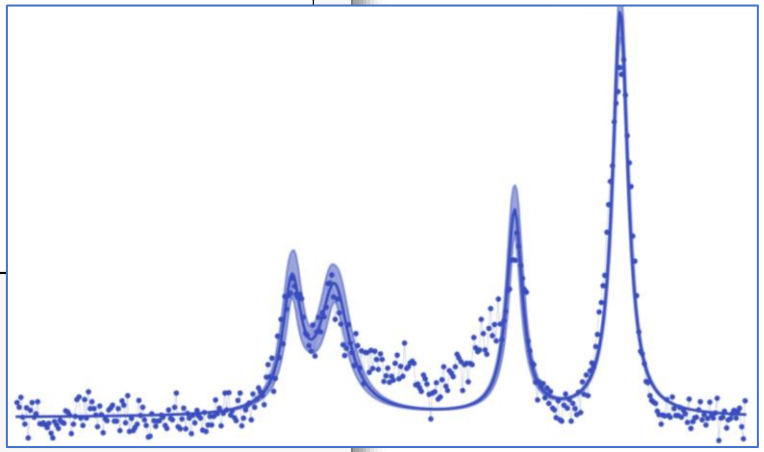
Measured spectra



- Stokes (magnon emission) and anti-Stokes (magnon absorbtion) folded

Peak fitting

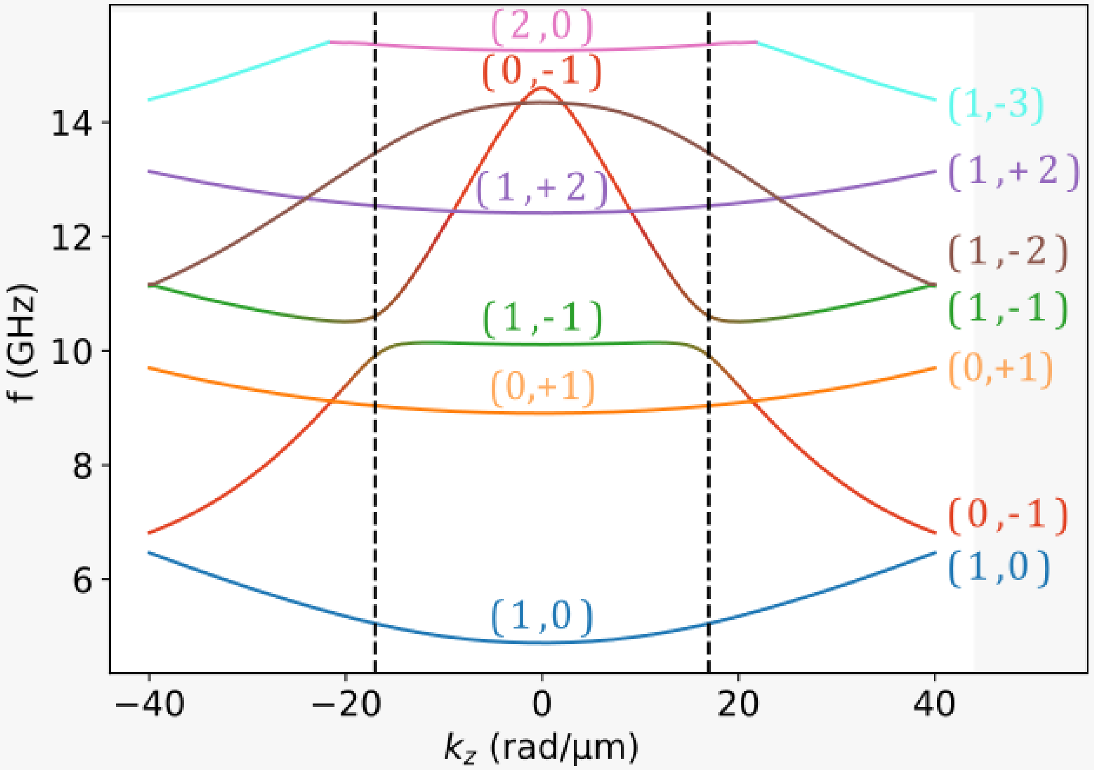




- Seven peaks identified and followed
- Lorentz-peak fitting
- Error bars 250 MHz
- Energy increases with applied field, as expected

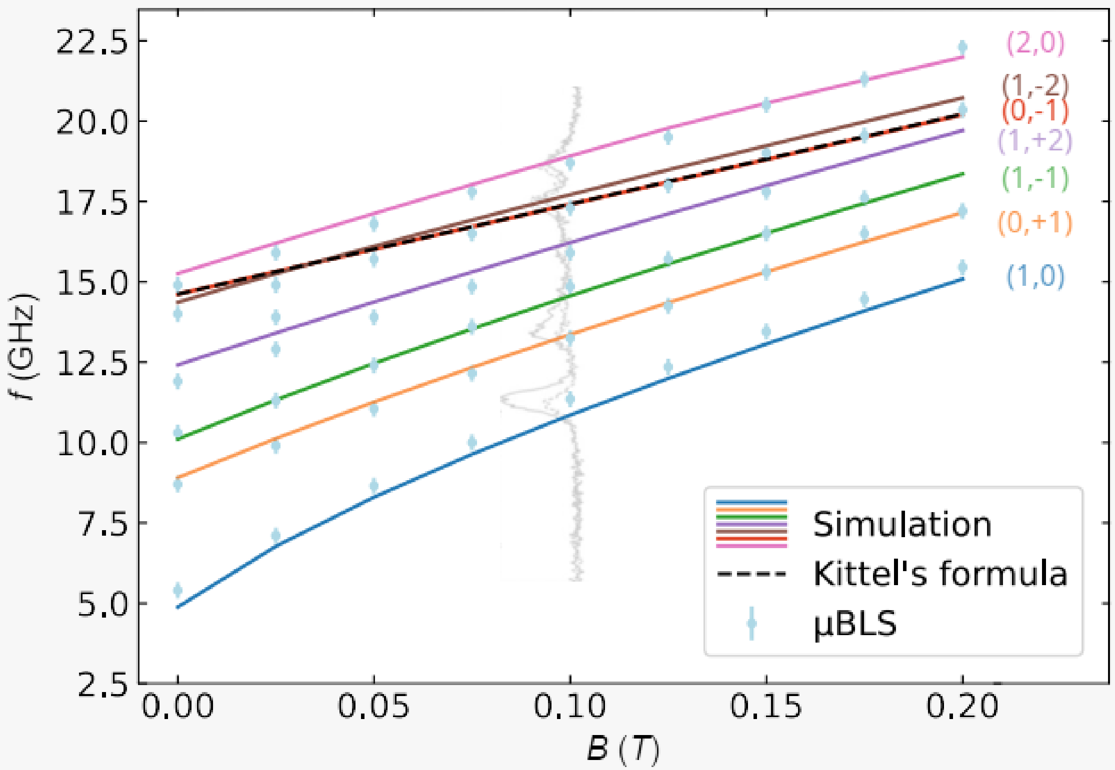
Mode identification

Simulated dispersion curves



- Software: TetraX DOI: 10.14278/rodare.1418
- Consider $k(\omega = 0)$ owing to greater µBLS sensitivity for this value
- Note: quantitative µBLS theory exists at present only for multilayers
  O. Wojewoda, Phys. Rev. B110, 224428 (2024)

Fitting of measured spectra



- Diameter set to 115nm, $\gamma = 28$ GHz/T
- Simultaneous fit of all branches gives high confidence

$$M_s = 830 \text{ kA/m}$$

$$A_{ex} = 1.15 \times 10^{-11} \text{ J/m}$$

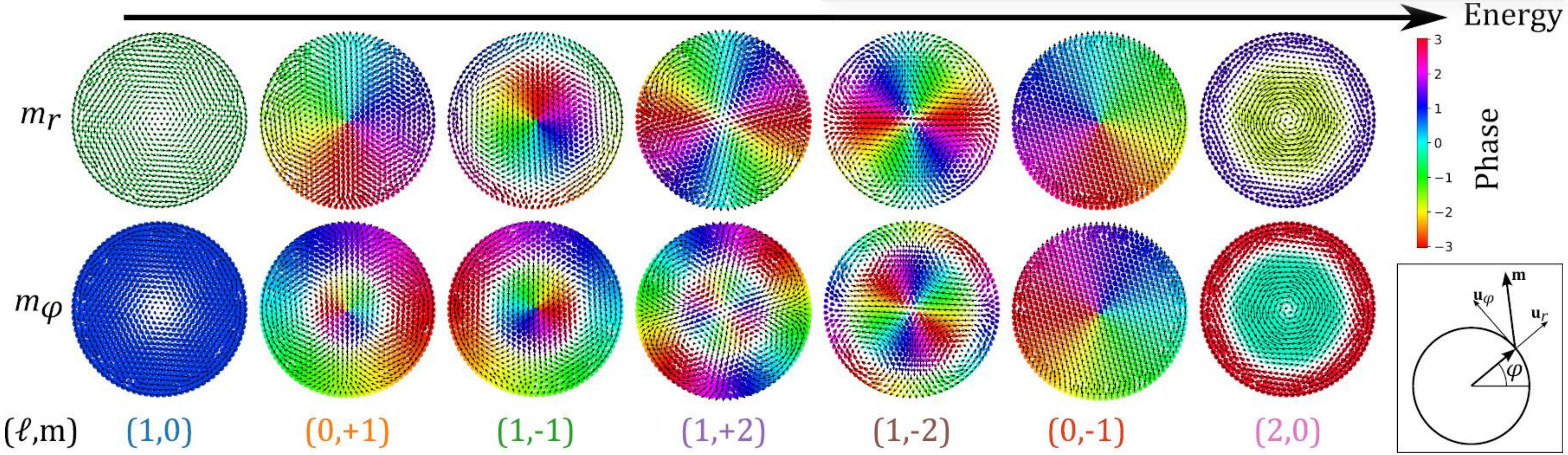
Mode inspection (1/4)

Representation of the dynamical magnetization

- Use cylindrical coordinates to match the geometrical rotational invariance (m_r, m_φ)
- The color codes the phase of the dynamical response
- The intensity of the color codes the magnitude of the dynamics response

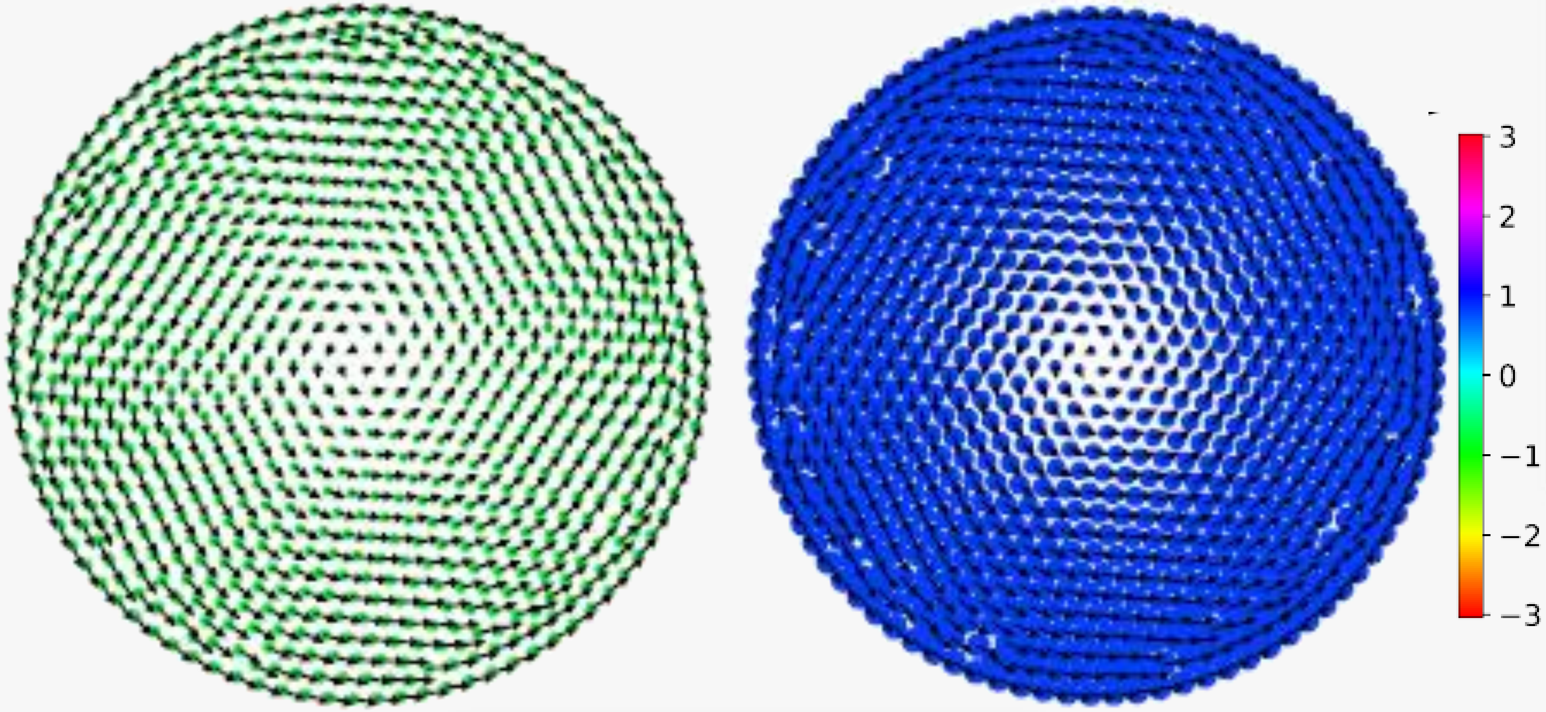
Note

- $(\boldsymbol{m_r}, \boldsymbol{m_\varphi})$ are $\boldsymbol{\pi/2}$-shifted anywhere/anytime
- Magnitude car be different in both components: ellipitical trajectories
- Index ℓ : the number of nodes in $\boldsymbol{m_r}$
- Index $\boldsymbol{m}$: number of $\boldsymbol{2\pi}$ turns (winding) along periphery



Mode inspection (2/4)

Representation of the mode $(\ell, m) = (1,0)$



m_r

Black arrows: magnetization at a given time

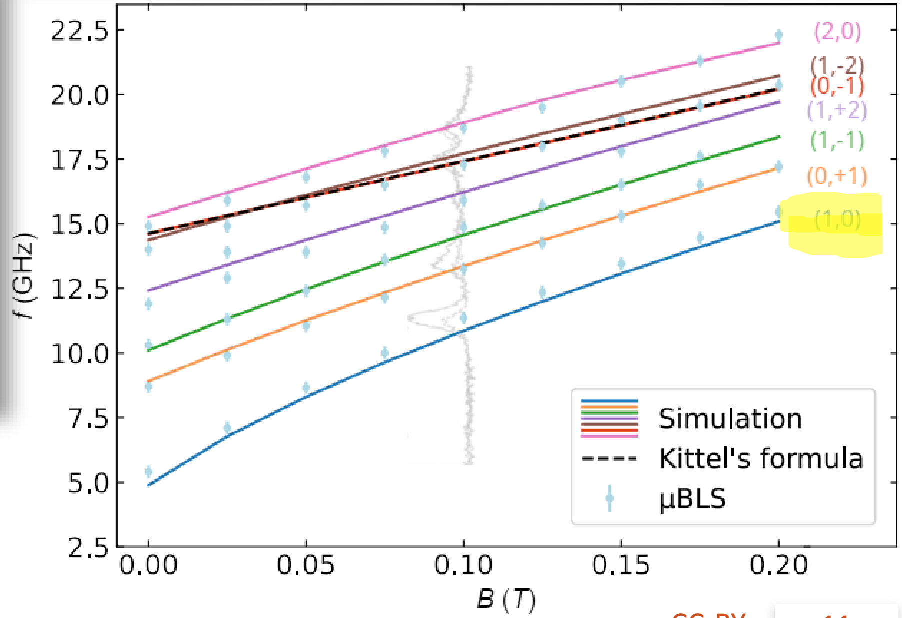
m_φ

- Lowest-energy mode
- Energy determined by azimuthal/radial exchange

Note

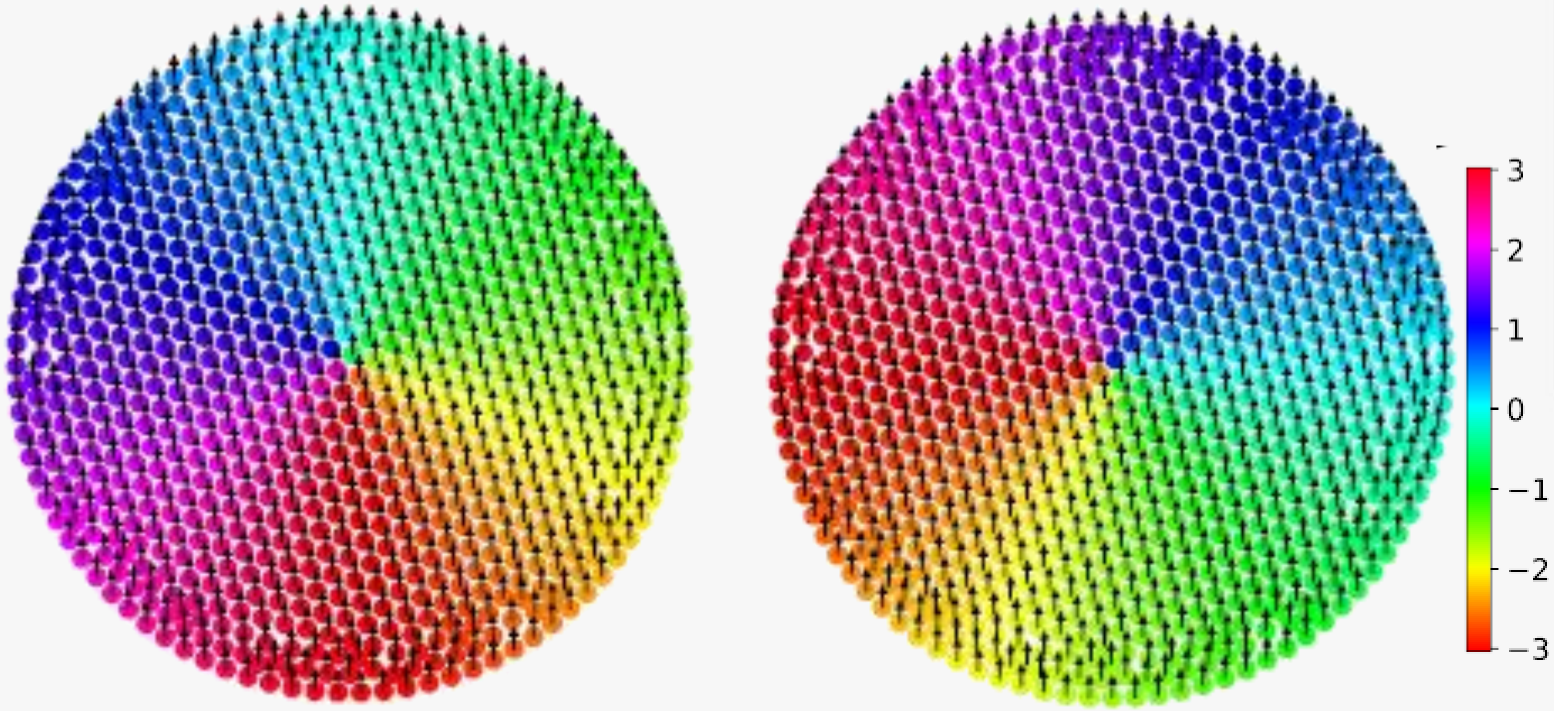
- Uniform color -> Rotational invariance
- Node of both components at center
- Azimuthal component larger than radial component, for the sake of magnetostatics

-> Similarity with Kittel mode for in-plane thin film



Mode inspection (3/4)

Representation of the mode $(\ell, m) = (0, -1)$



m_r

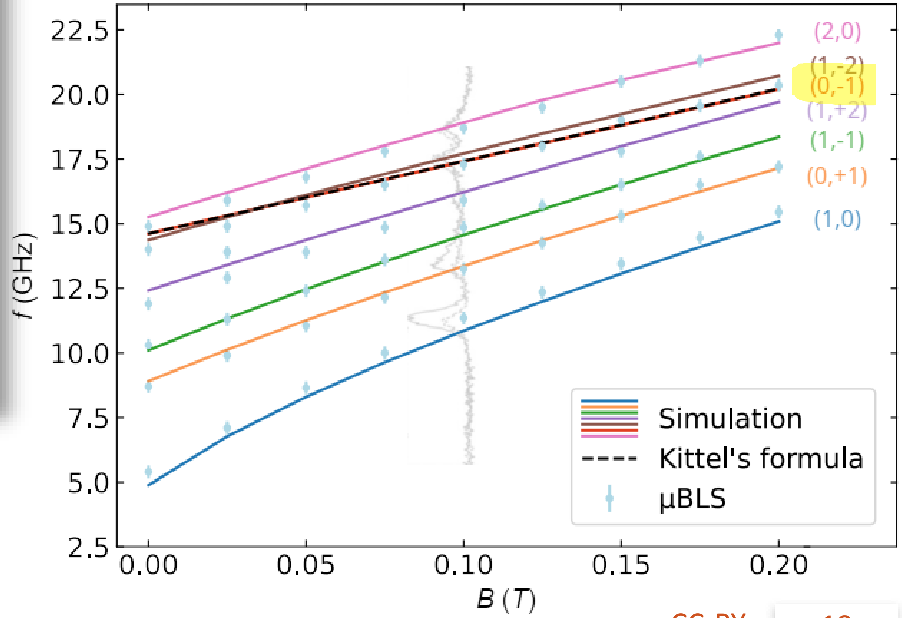
Black arrows: magnetization at a given time

m_φ

Note

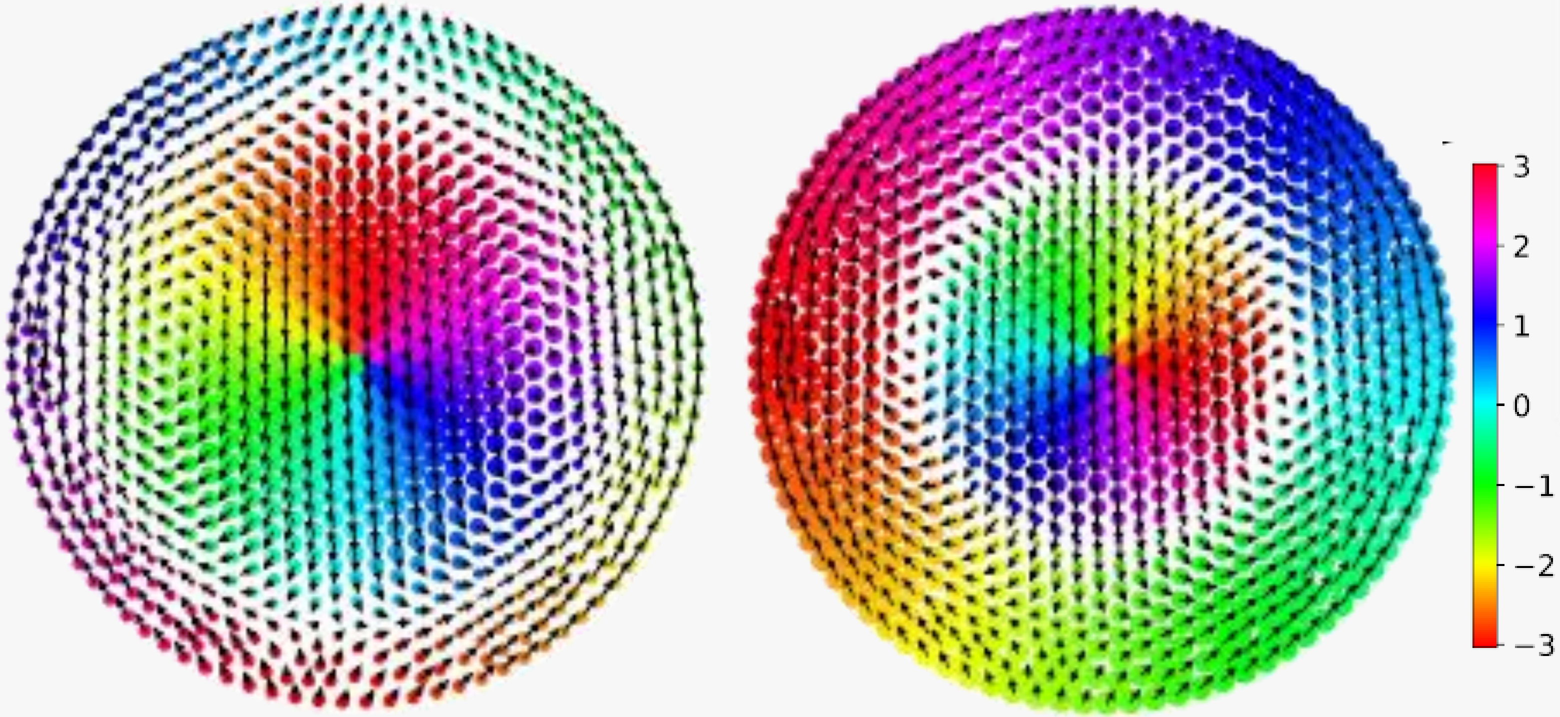
- Uniform magnetization
- The phase rotates opposite to m_r and m_φ along the periphery
- Same magnitude of the two components : circular trajectories

- Energy determined by transverse demag coefficient 1/2
- Rather high-energy mode



Mode inspection (4/4)

Representation of the mode $(\ell, m) = (1, -1)$



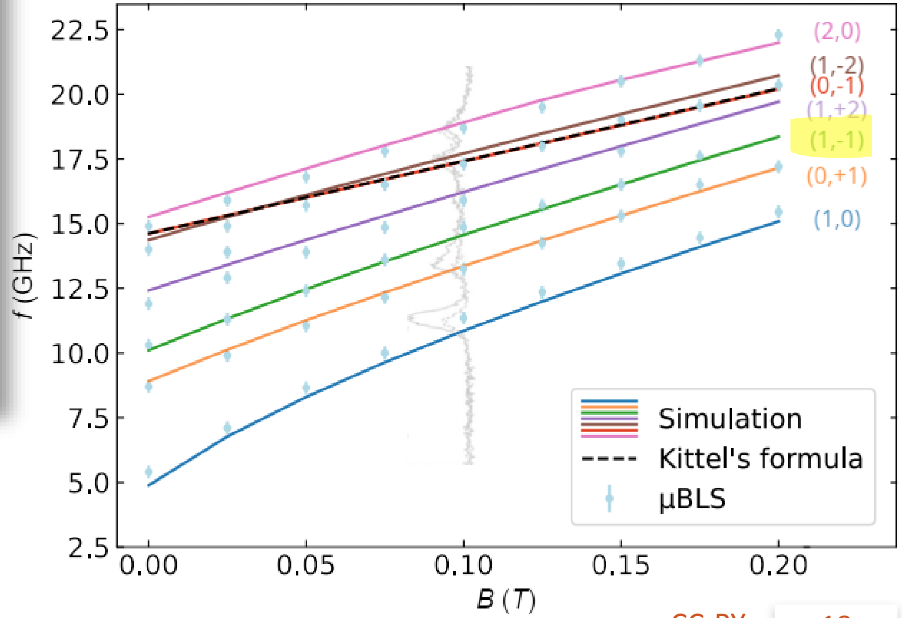
m_r

Black arrows: magnetization at a given time

m_φ

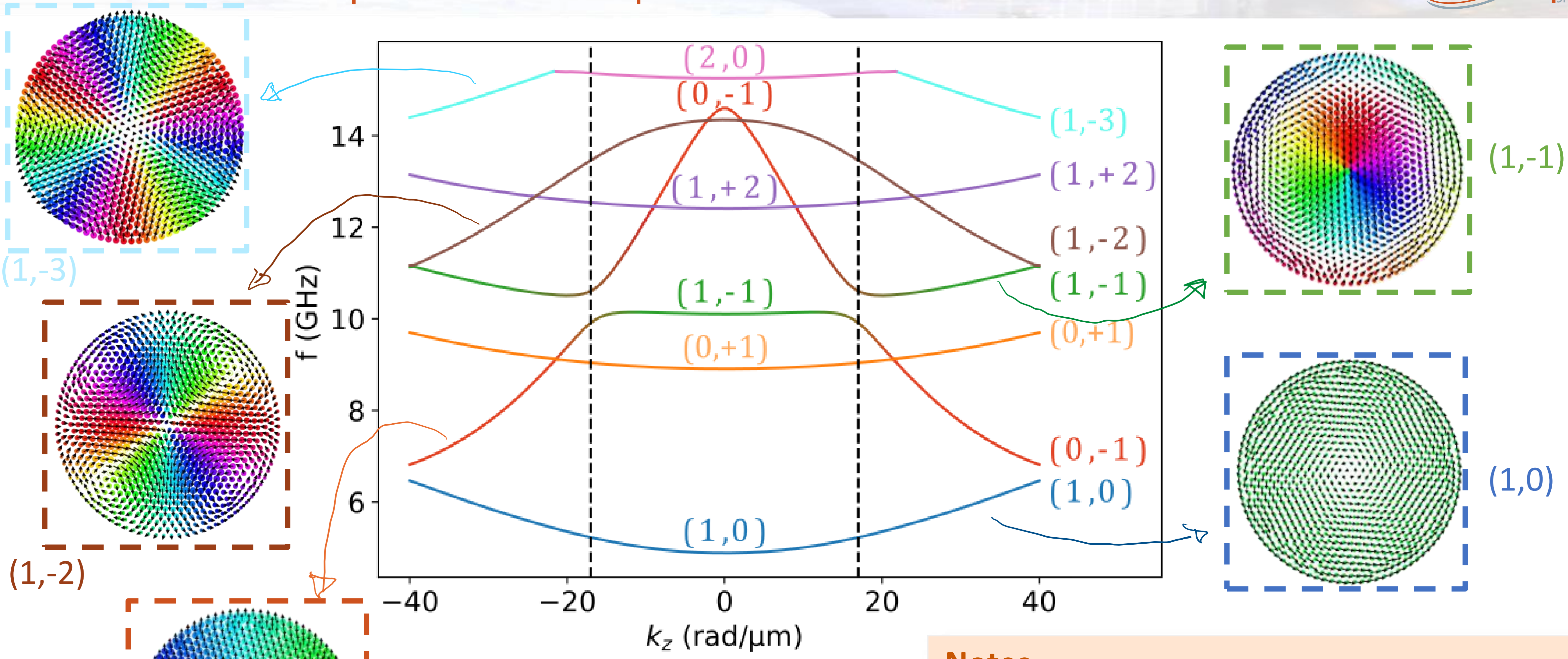
Note

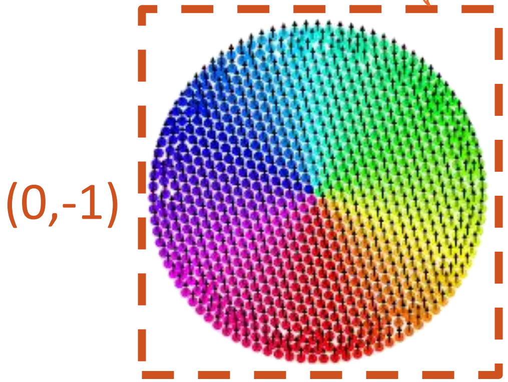
- Similar to uniform magnetization but with a radial node (π-phased)
- Flux-closure state with two vortices circulating azimuthally



- Energy determined by demag and radial exchange
- Energy decreased compared to uniform mode

Mode versus spin-wave dispersion





Notes

- Flux-closure dynamic states give rise to positive group velocity
- Dynamic states with significant stray/internal field give rise to negative group velocity

Take-away message

- Thermal spin waves measured locally in a single cylindrical nanowire
- Absence of interactions/distributions facilitates analysis
- Seek richer physics, e.g., non-reciprocity and interaction with domain walls

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arXiv: 2508:15591

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