Enhanced Brillouin light scattering in magneto-optical cavities.

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J. A. Haigh,
A. J. Ramsay.

HITACHI Inspire the Next

Brillouin light scattering from magnons

S.O. Demokritov et al. / Physics Reports 348 (2001) 441–489

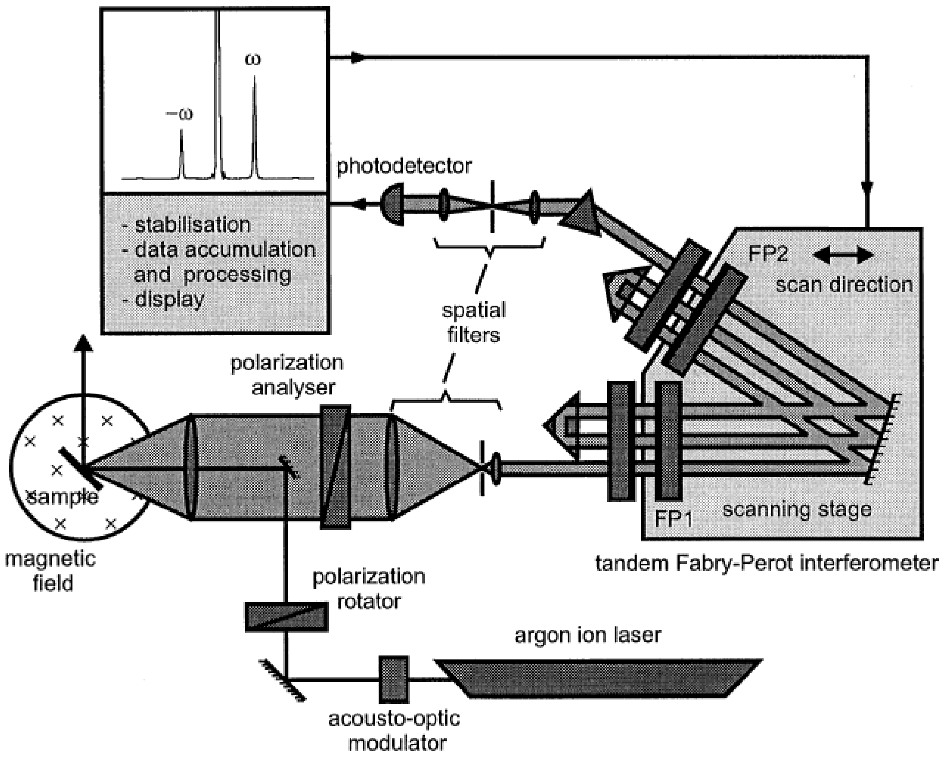


Fig. 8. Schematic view of the Brillouin light scattering setup in the backscattering geometry used for investigation of spin waves in laterally patterned structures. The transferred wavevector is changed by changing the angle between the sample surface and the incident laser beam.

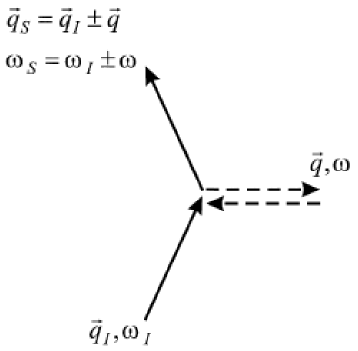
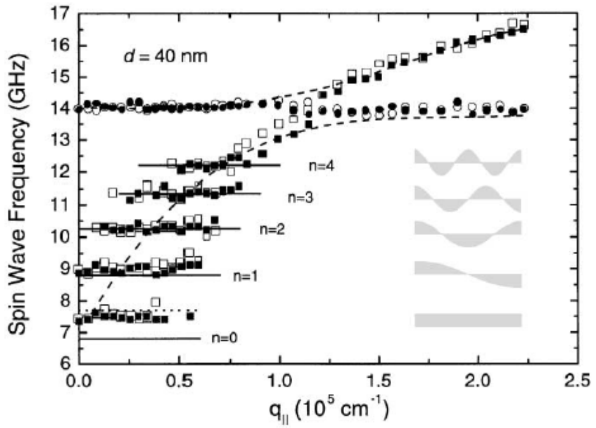


Fig. 4. Scattering process of photons from spin wave excitations.



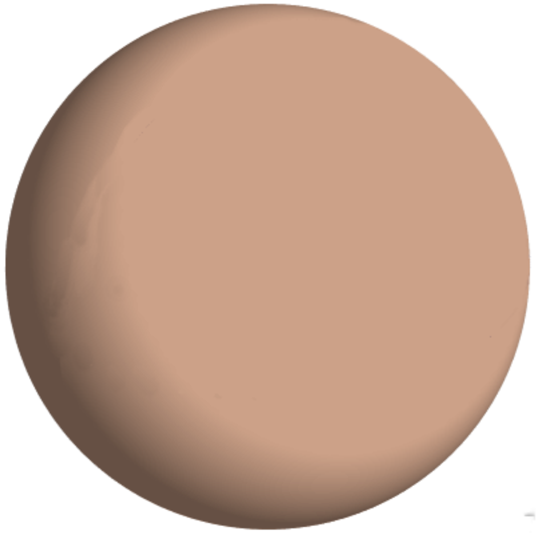
Outline

Can Brillouin light scattering be enhanced using optical cavity modes?

Outline

Yttrium iron garnet sphere

large magneto-optical effects



polished surface

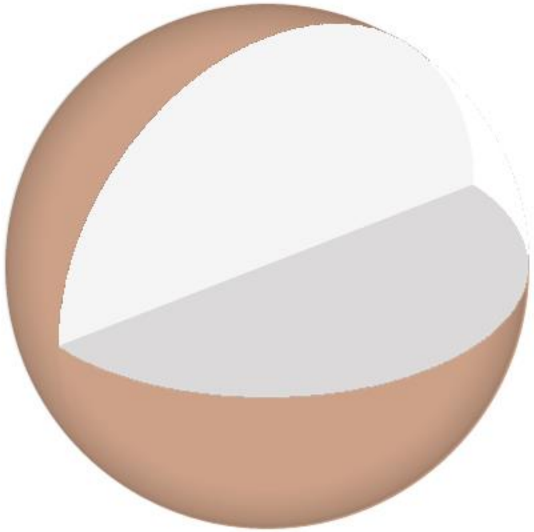
~1mm diameter

transparent in near infrared

ferrimagnetic

Outline

Yttrium iron garnet
sphere



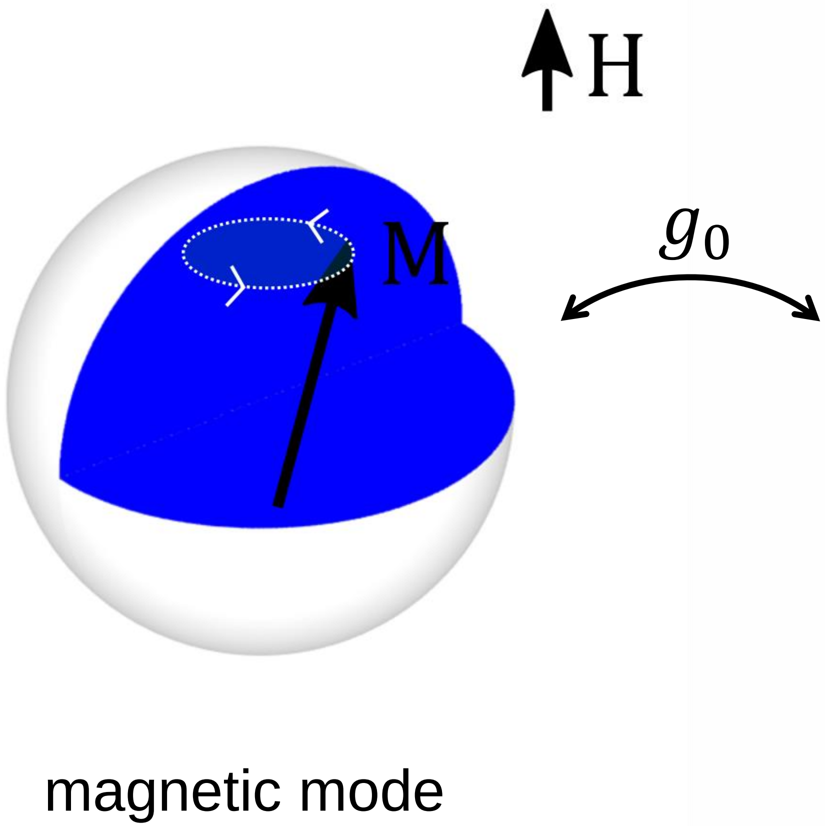
polished surface

~1mm diameter

transparent in
near infrared

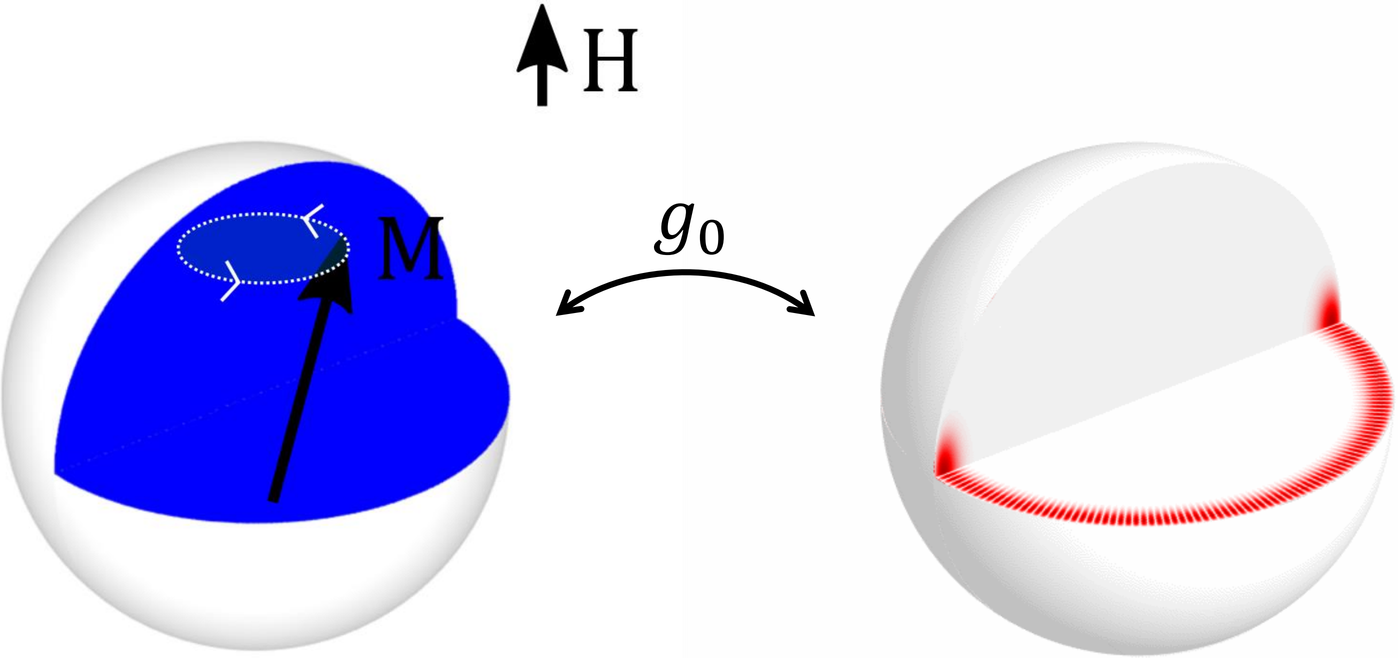
ferrimagnetic

Outline



$$C_0 = \frac{4g_0^2}{\kappa\Gamma}$$

Outline



Cavity Optomagnonics with Spin-Orbit Coupled Photons, A. Osada, R. Hisatomi, A. Noguchi, Y. Tabuchi, R. Yamazaki, **K. Usami**, M. Sadgrove, R. Yalla, M. Nomura, and Y. Nakamura, PRL **116**, 223601 (2016).

Optomagnonic Whispering Gallery Microresonators, X. Zhang, N. Zhu, C.-L. Zou, and **H. X. Tang**, PRL **117**, 123605 (2016).

Triple-Resonant Brillouin Light Scattering in Magneto-Optical Cavities, J. A. Haigh, A. Nunnenkamp, A. J. Ramsay, and A. J. Ferguson, PRL **117**, 133602 (2016).

Outline

- Optical modes
- Magnetic modes
- **Which modes should couple?**

  Light scattering by magnons in whispering gallery mode cavities, S. Sharma, Y. M. Blanter, and G. E. W. Bauer, PRB **96**, 094412 (2017).

- **Which modes we measure..**

  Selection rules for cavity-enhanced Brillouin light scattering from magnetostatic modes, J. A. Haigh, N. J. Lambert, S. Sharma, Y. M. Blanter, G. E. W. Bauer, and A. J. Ramsay, ArXiv:1804.00965 (2018).

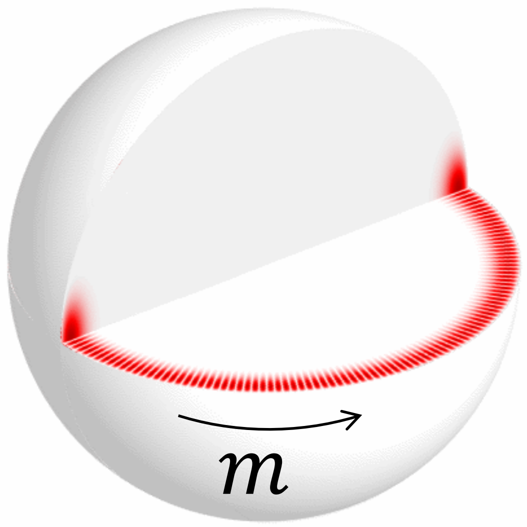
  Brillouin Light Scattering by Magnetic Quasivortices in Cavity Optomagnonics, A. Osada, A. Gloppe, R. Hisatomi, A. Noguchi, R. Yamazaki, M. Nomura, Y. Nakamura, and K. Usami, PRL **120**, 133602 (2018).

Optical modes

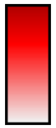
Optical modes: indices

Optical modes labelled by 3 mode indices:

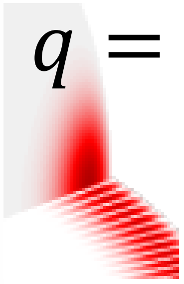
$$\{l, m, q\}$$

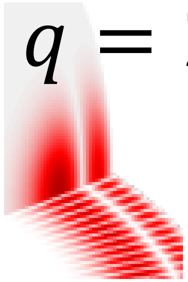


optical mode



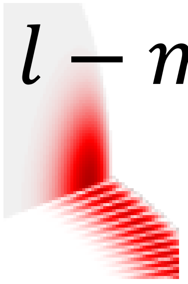
Radial structure

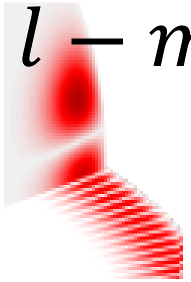




$l = m$

transverse structure





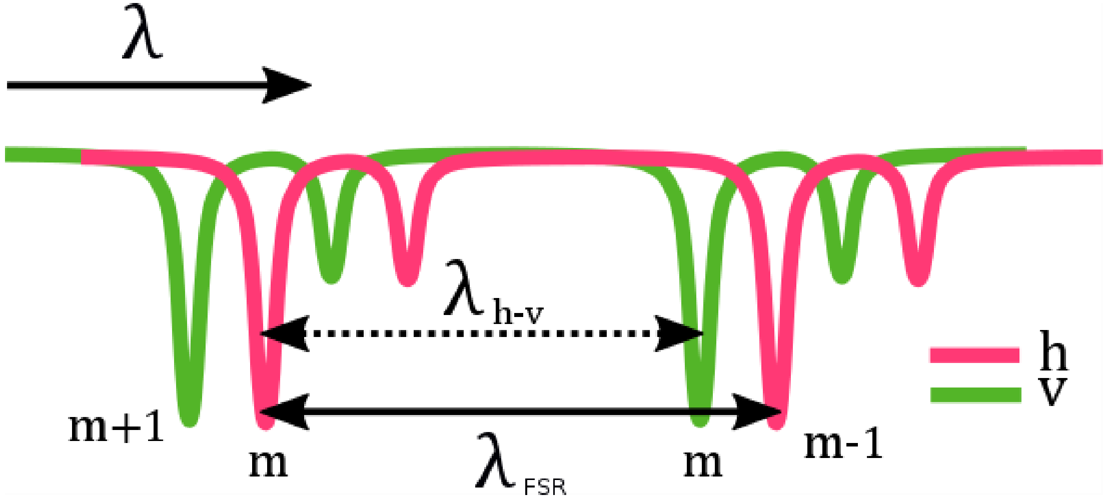
$q = 1$

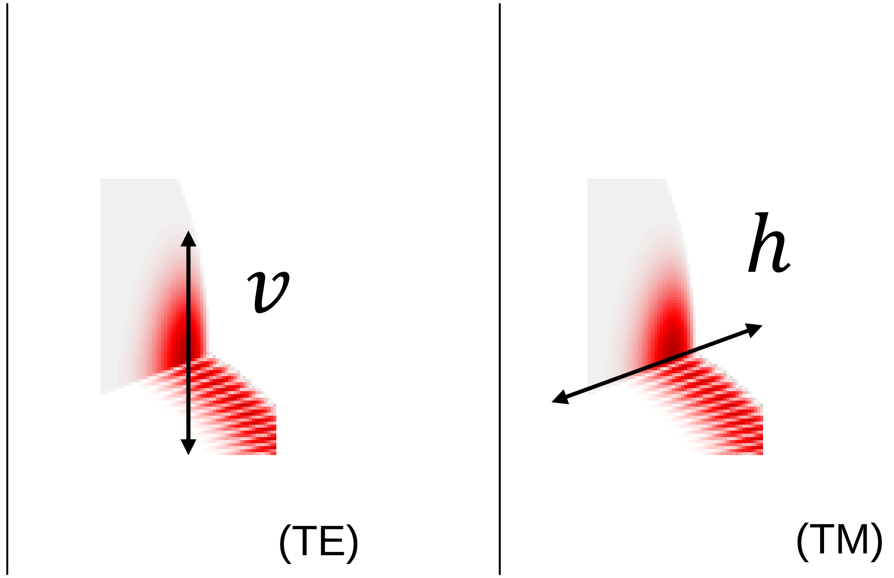
Identifying modes of large whispering-gallery mode resonators from the spectrum and emission pattern, G. Schunk et al., Optics Express **22**, 30795 (2014).

Optical modes: polarization

Polarization can be

h horizontal or v vertical wrt the WGM plane

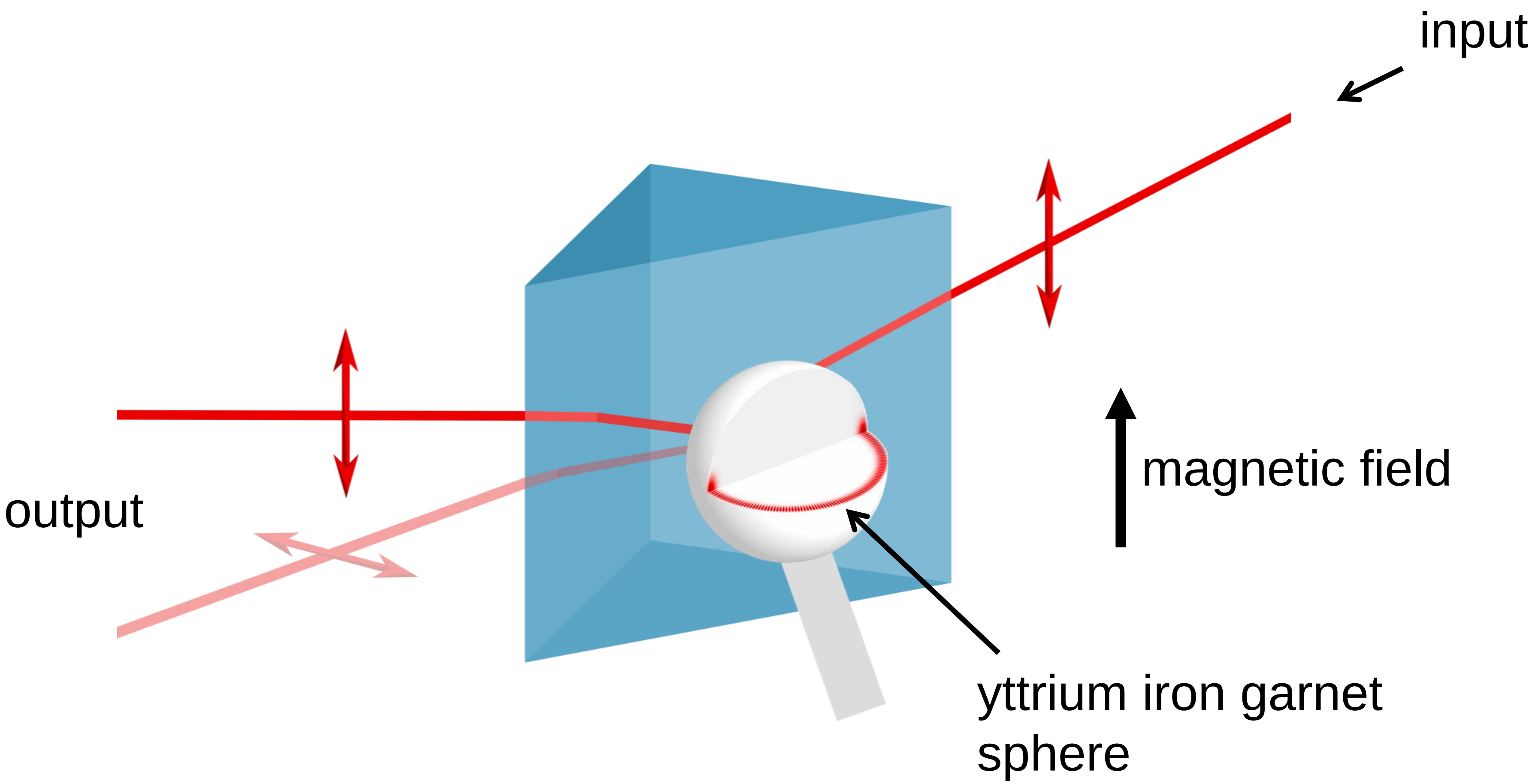




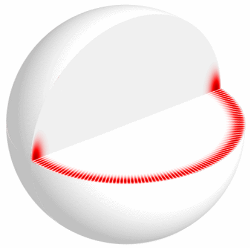
$$\lambda_{h-v} = \lambda_{FSR} \frac{\sqrt{n_{YIG}^2 - 1}}{n_{YIG}}$$

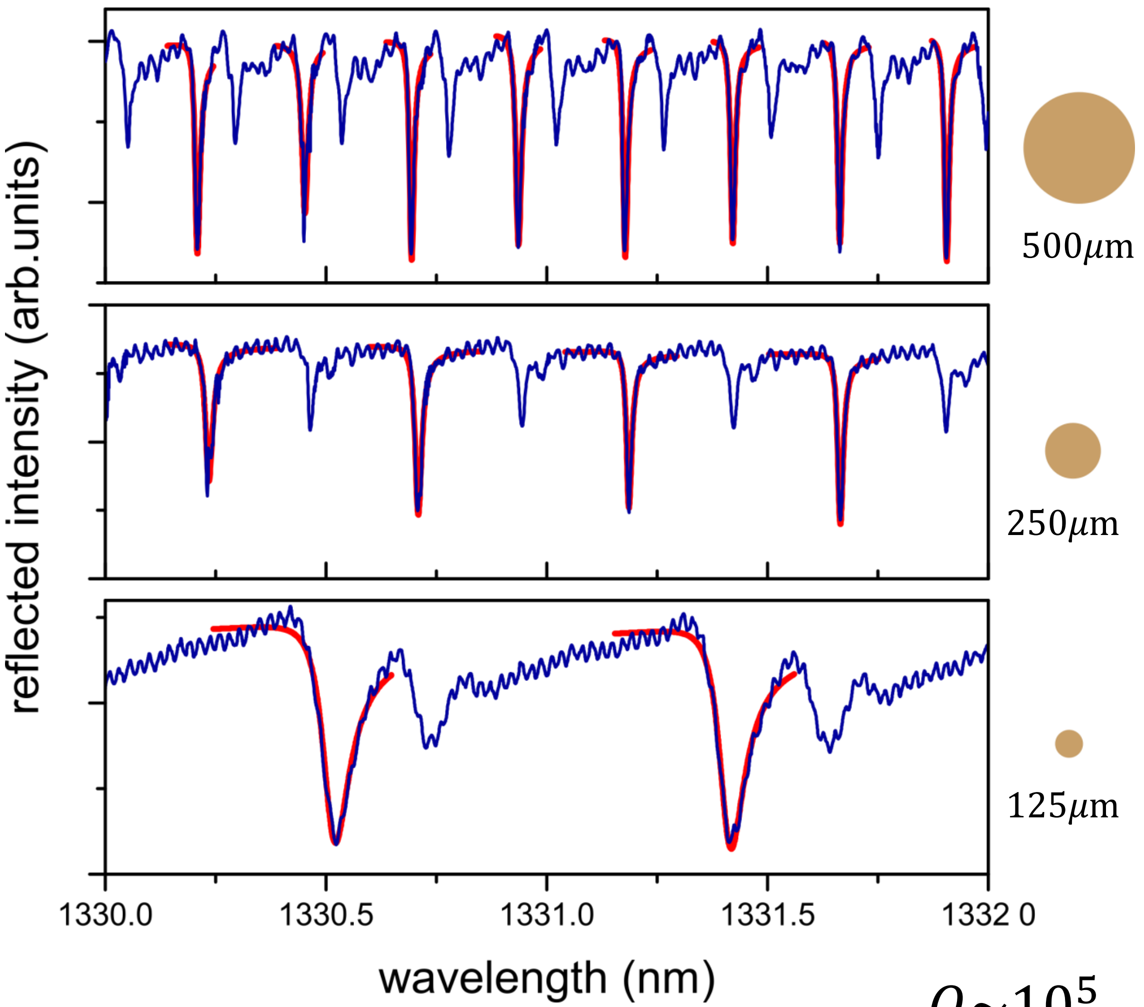
Identifying modes of large whispering-gallery mode resonators from the spectrum and emission pattern, G. Schunk et al., Optics Express **22**, 30795 (2014).

Experimental setup



Optical modes: measurement

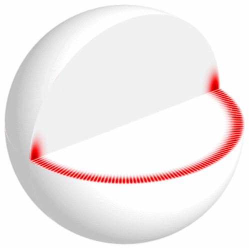


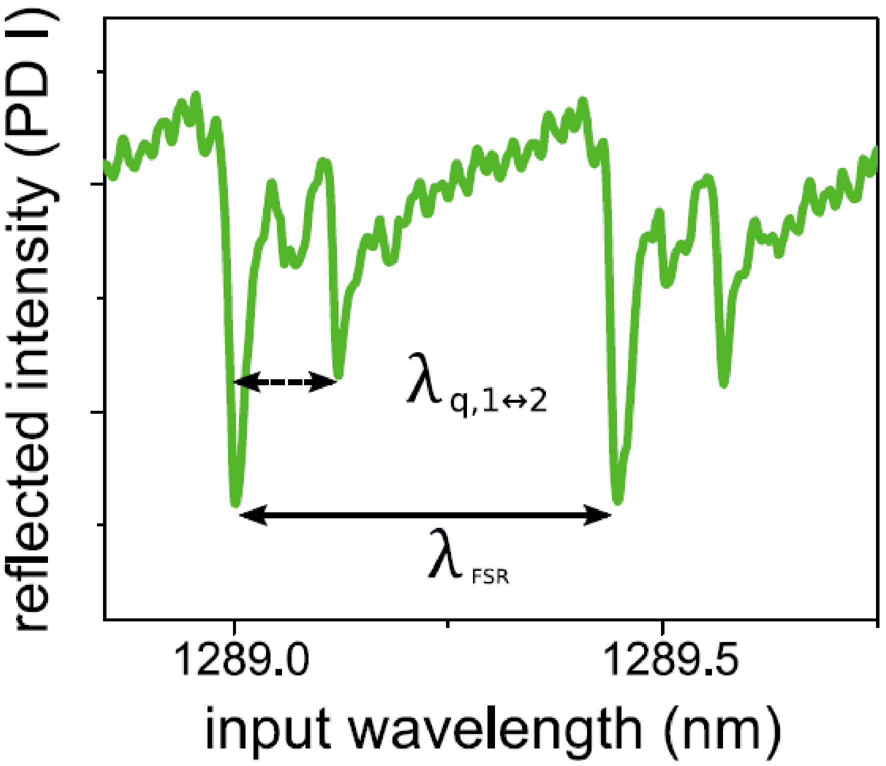


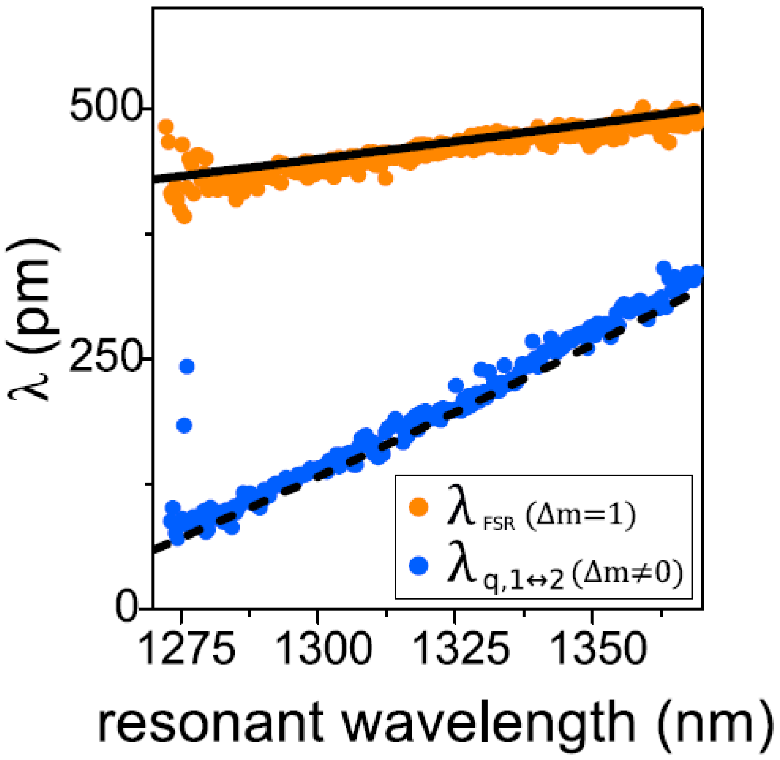
$l \approx m \sim 1000$

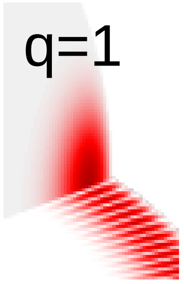
$Q \sim 10^5$

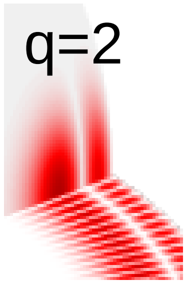
Optical modes: radial mode number





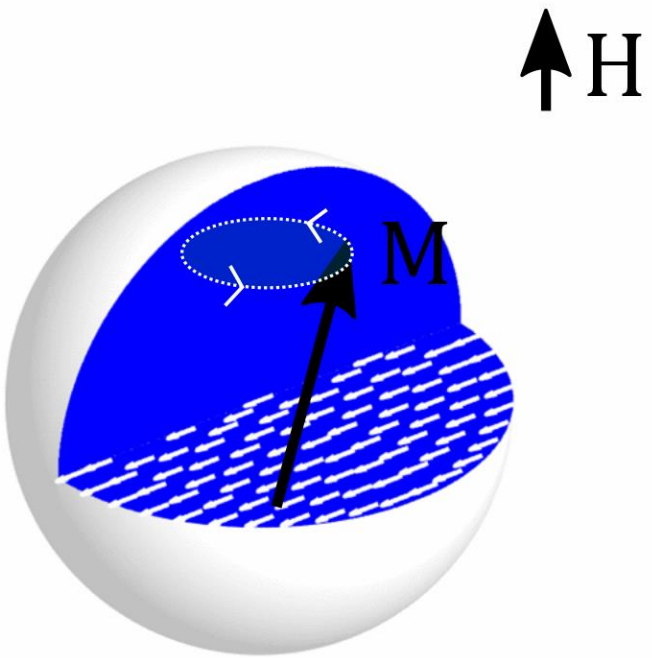






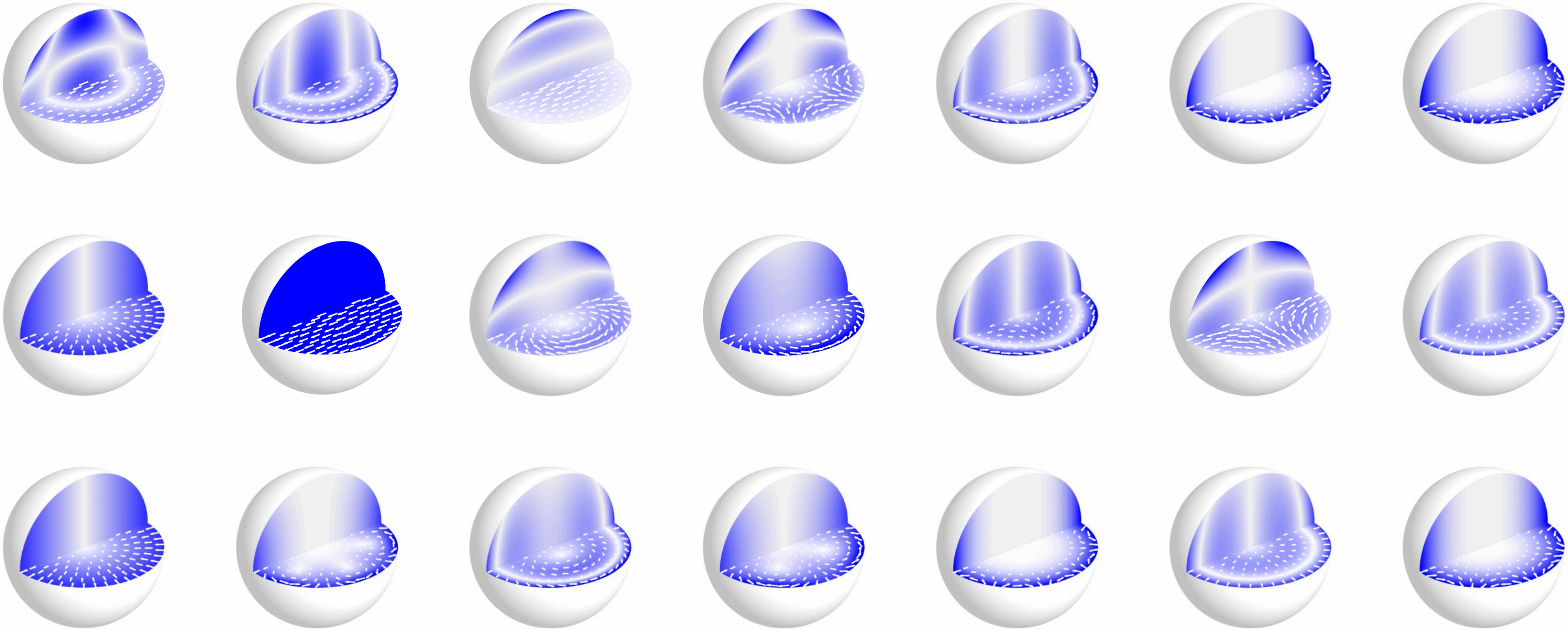
Magnetic modes

Magnetic modes



magnetic mode

Identifying the magneto-static modes



$$\sqrt{\mathrm{Re}(M_x)^2 + \mathrm{Re}(M_y)^2}$$

Ferrimagnetic Resonance Modes in Spheres, P. C. Fletcher and R. O. Bell, Journal of Applied Physics **30**, 687 (1959).

Identifying the magneto-static modes

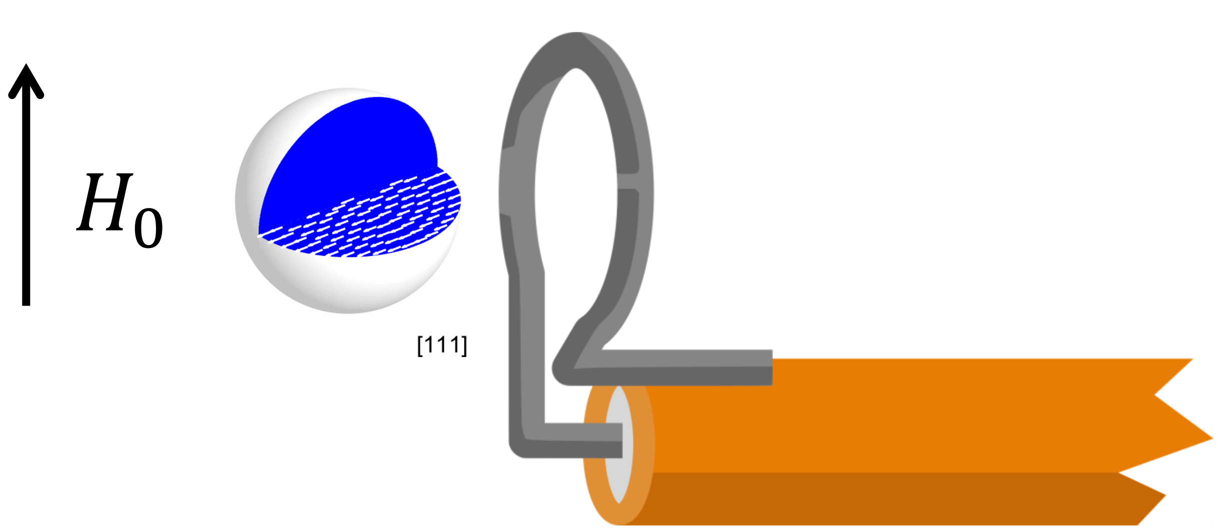
$$\nabla \times \boldsymbol{H} = 0$$
$$\boldsymbol{H} = \nabla \psi$$

$$\psi = A\, P_l^m(\xi) P_l^m(\cos\eta) e^{m\phi}$$

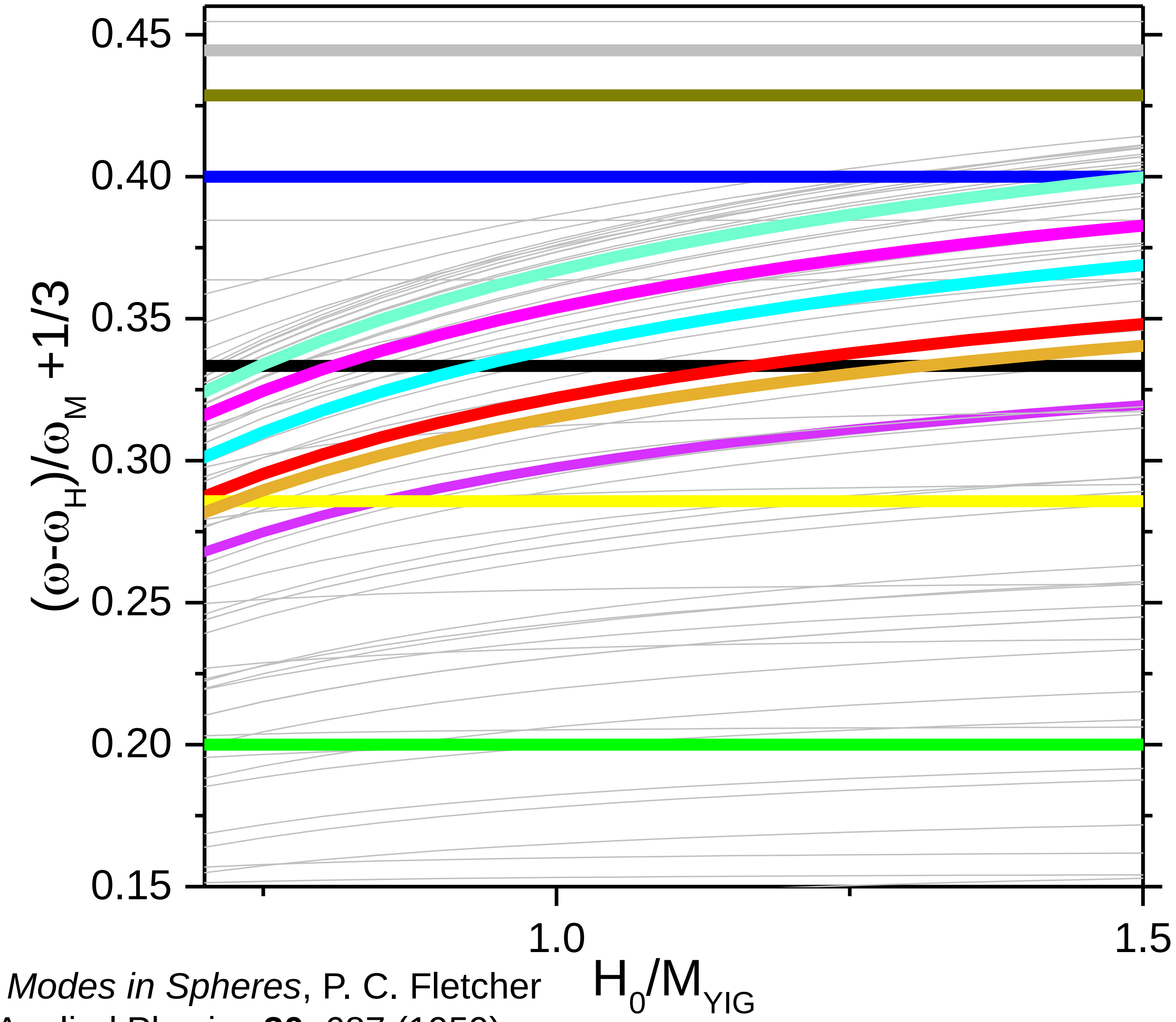
$$\{l_m, m_m, q_m\}$$

Ferrimagnetic Resonance Modes in Spheres, P. C. Fletcher and R. O. Bell, Journal of Applied Physics **30**, 687 (1959).

Outline

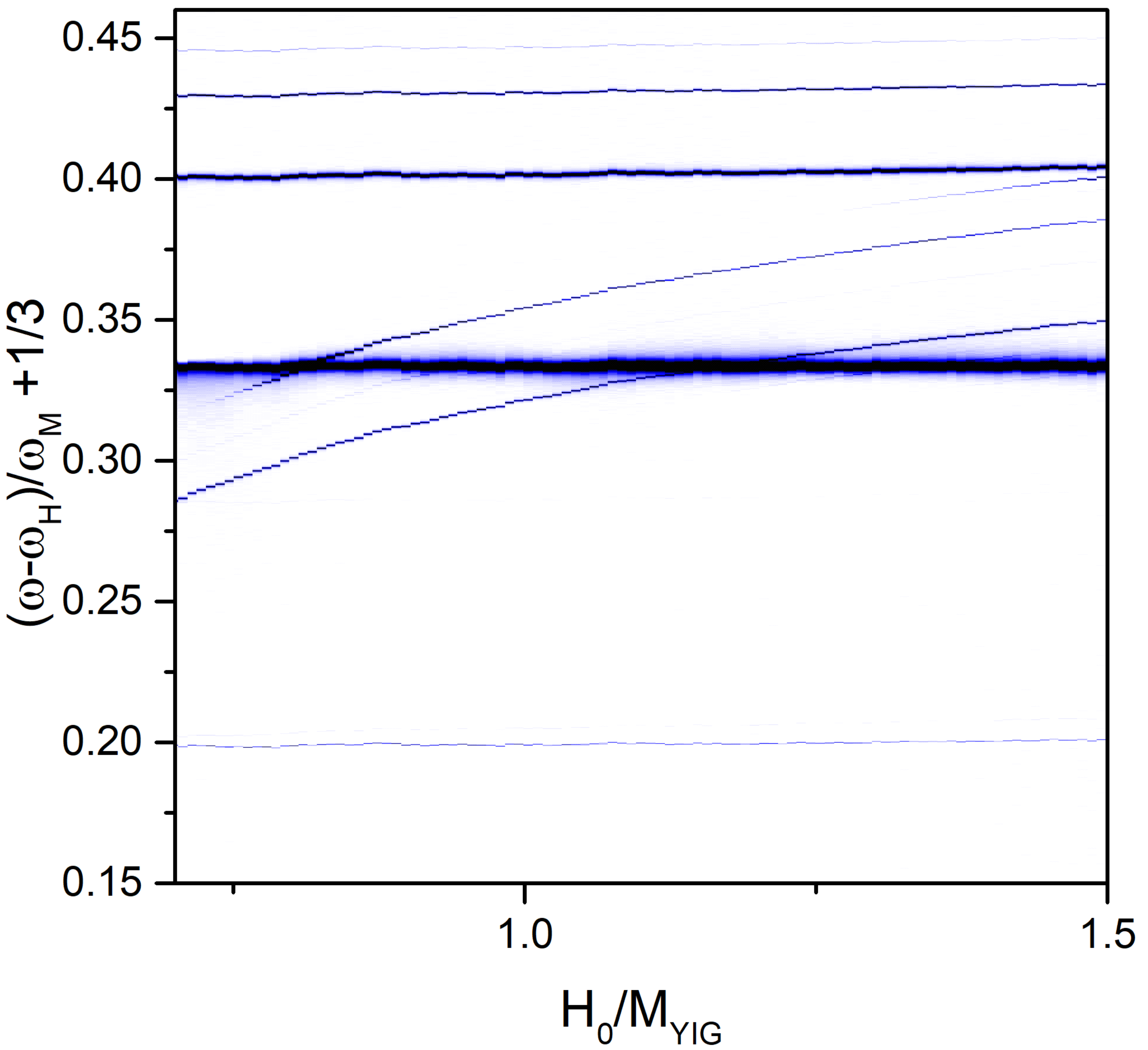


Identifying the magneto-static modes



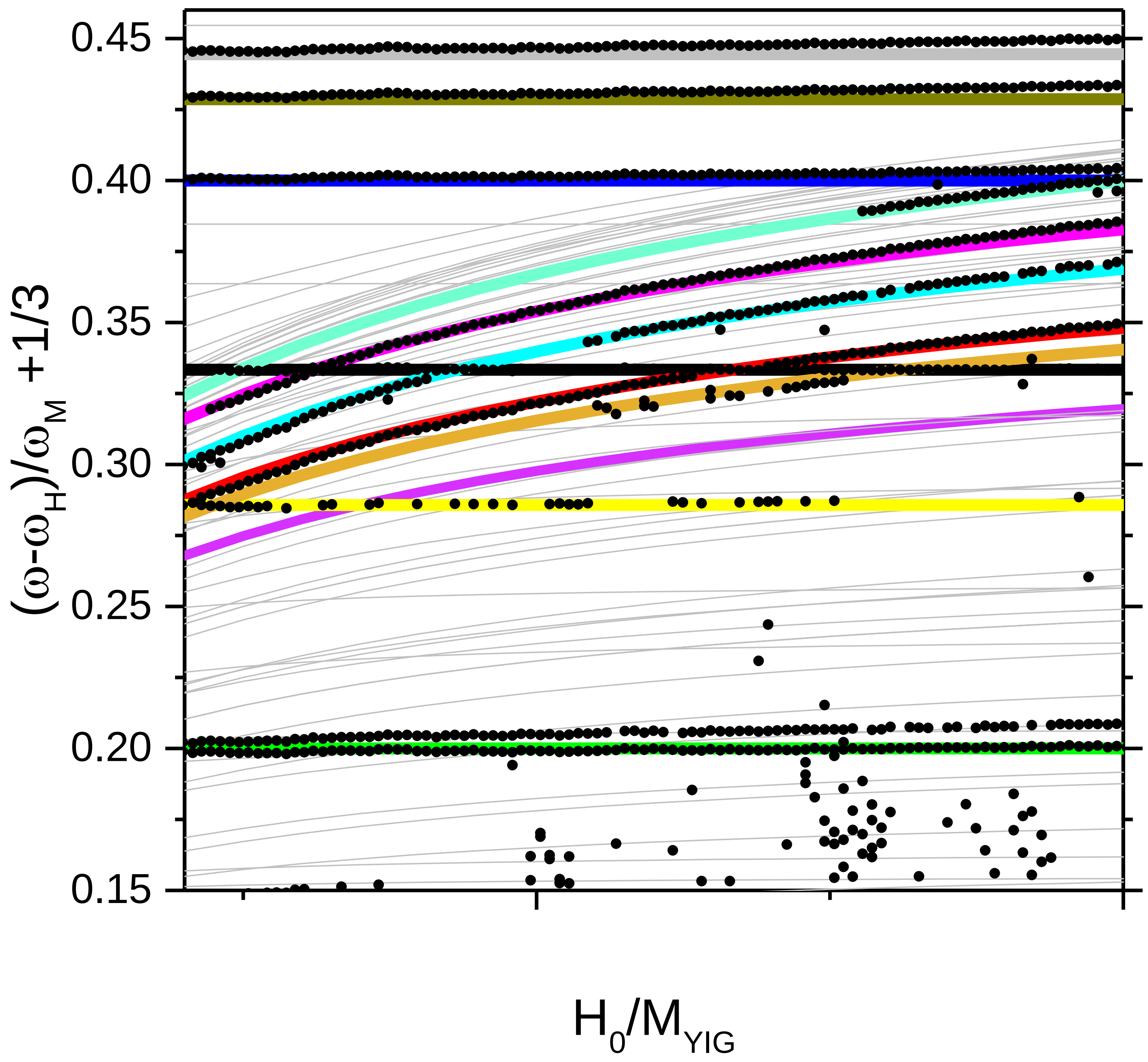
Ferrimagnetic Resonance Modes in Spheres, P. C. Fletcher and R. O. Bell, Journal of Applied Physics **30**, 687 (1959).

Identifying the magneto-static modes



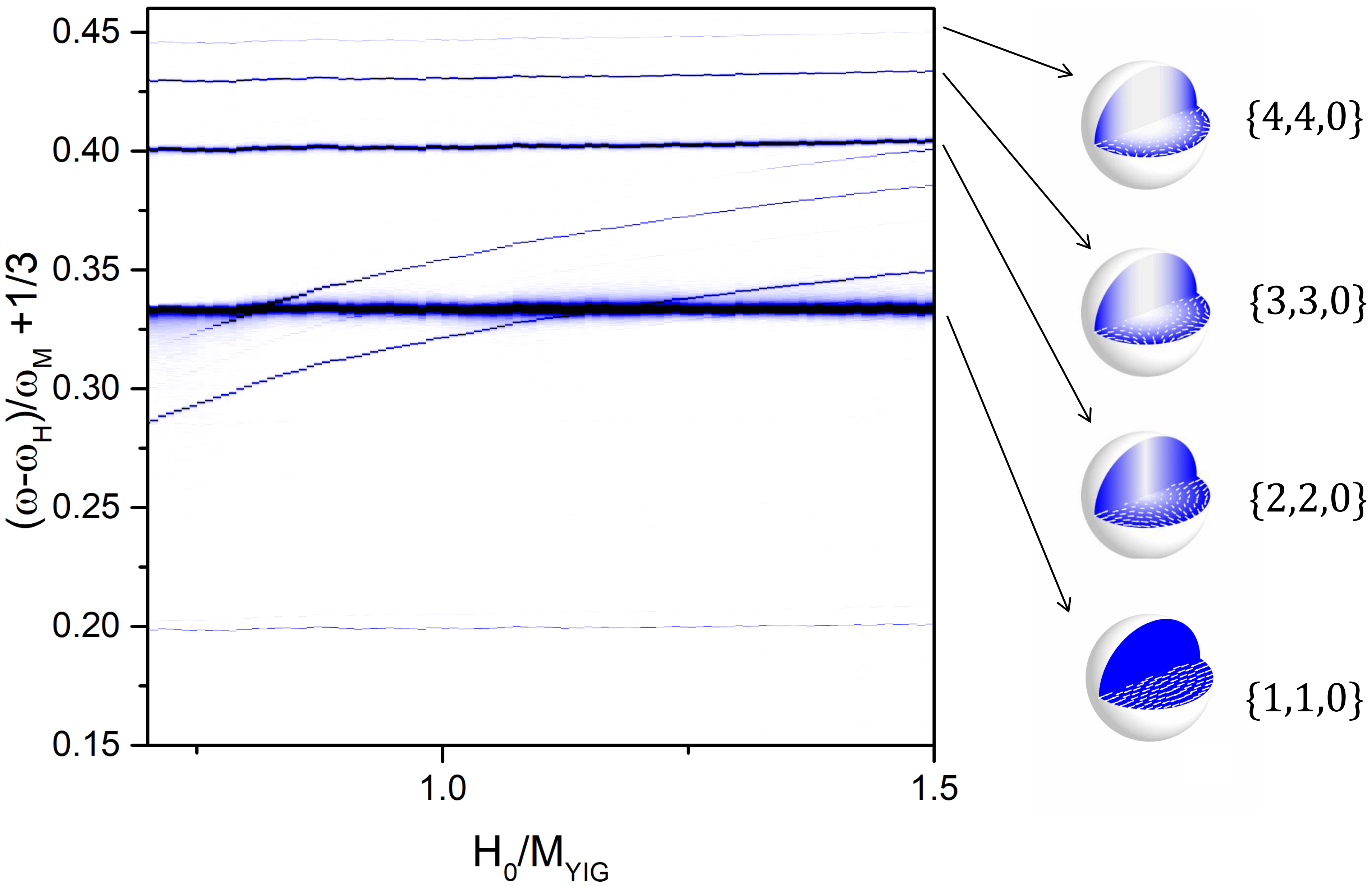
Measured in electromagnet

Identifying the magneto-static modes

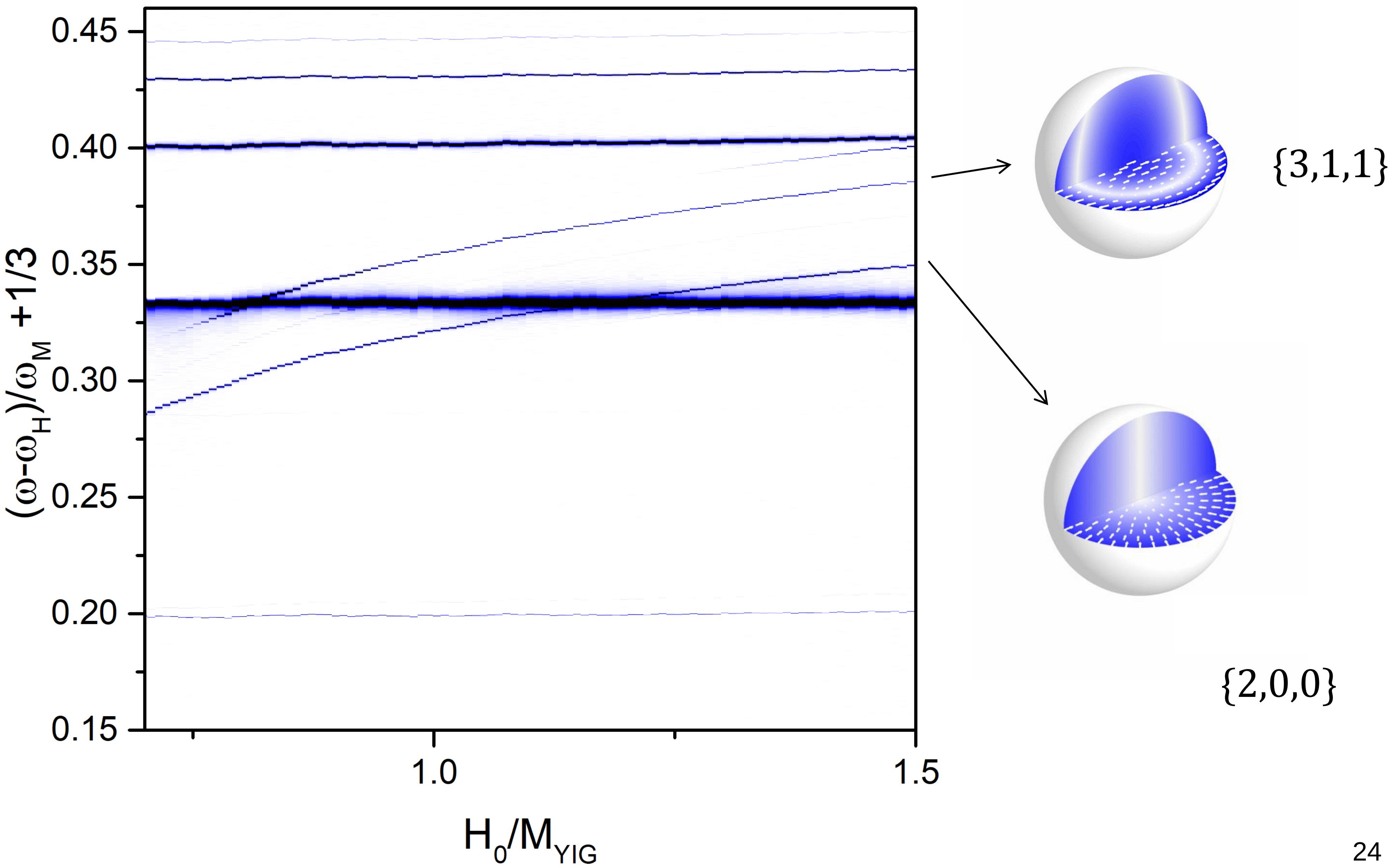


Measured in electromagnet

Identifying the magneto-static modes

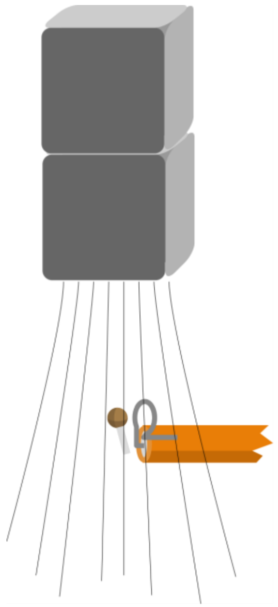


Identifying the magneto-static modes

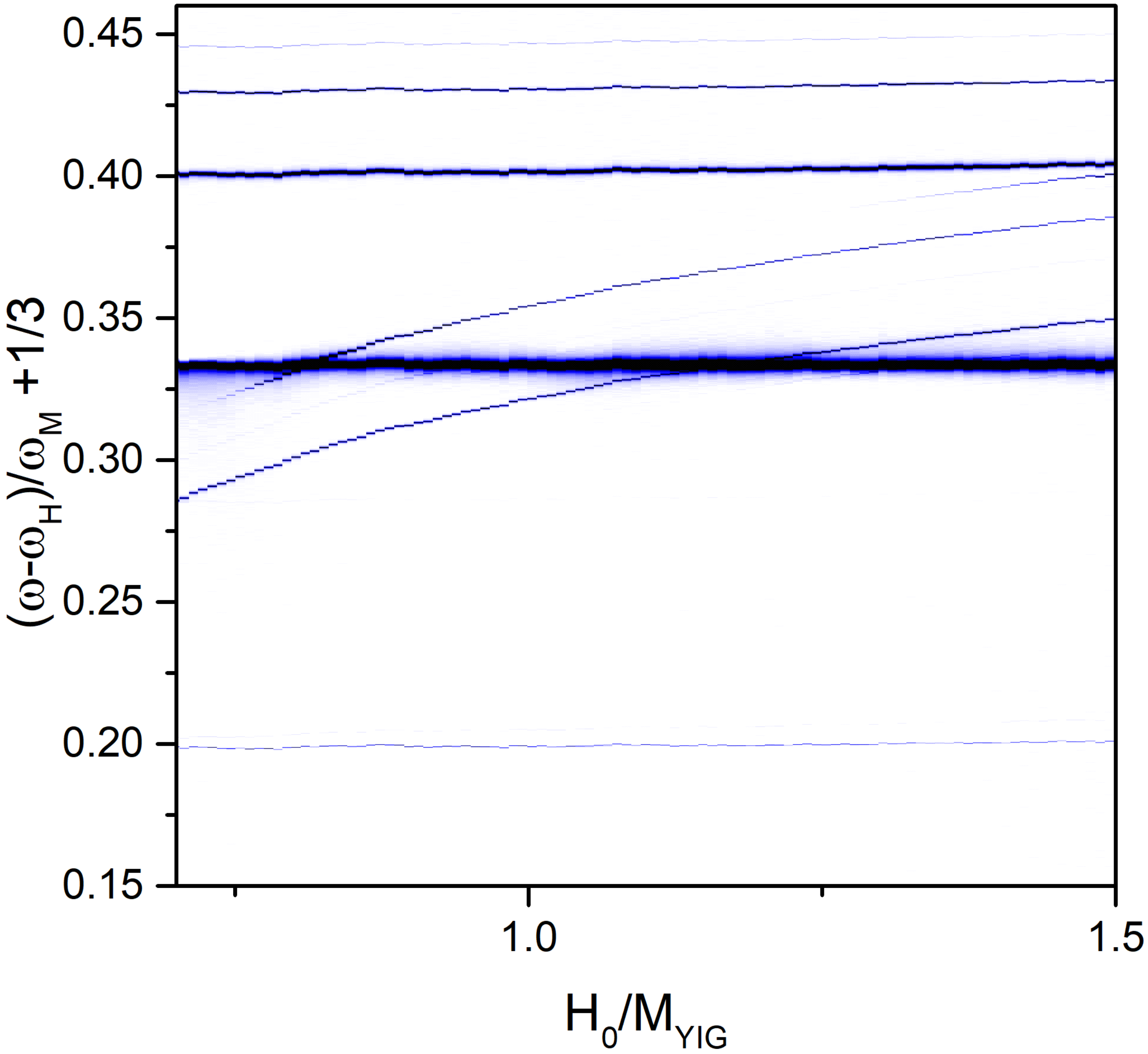


Identifying the magneto-static modes

Complication – in optical setup, static magnetic field applied with permanent magnet

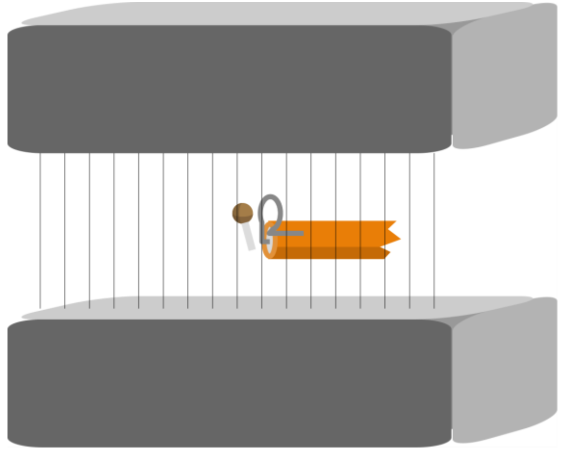


Identifying the magneto-static modes

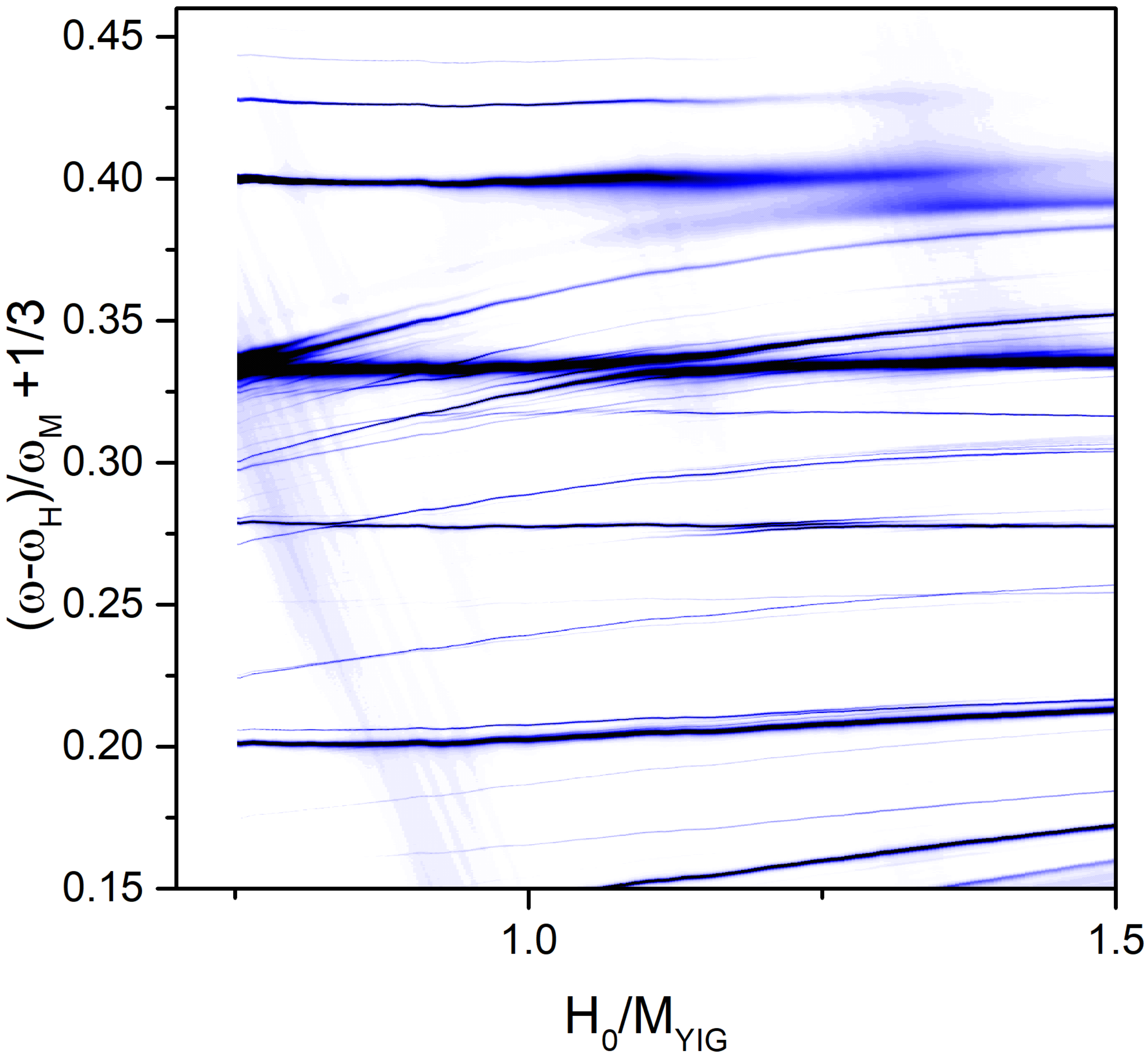


Measured in electromagnet

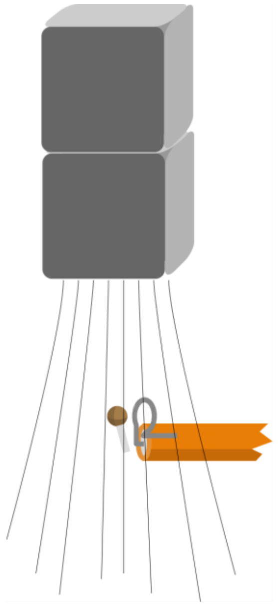
Uniform field



Identifying the magneto-static modes



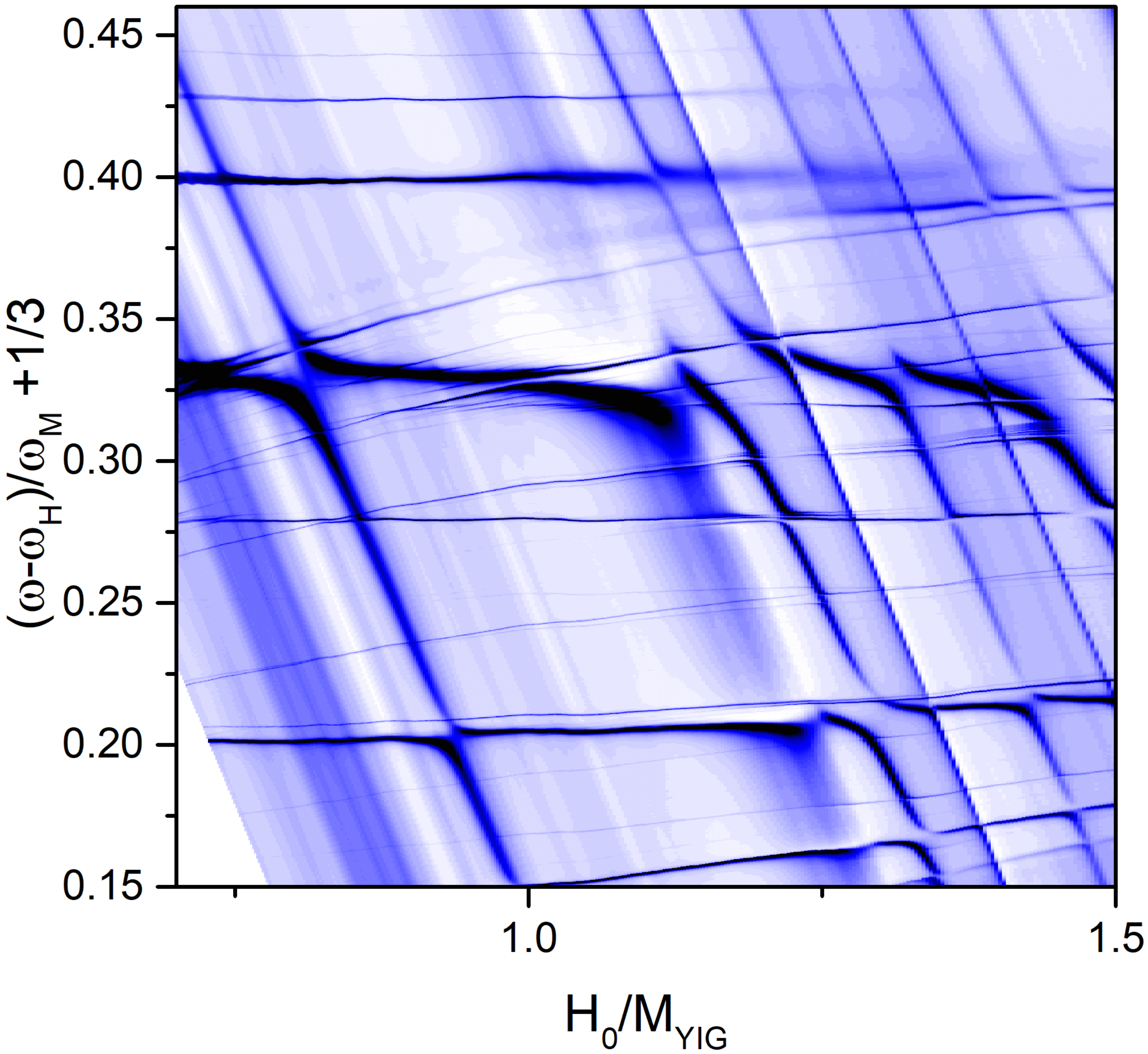
Measured in optical setup



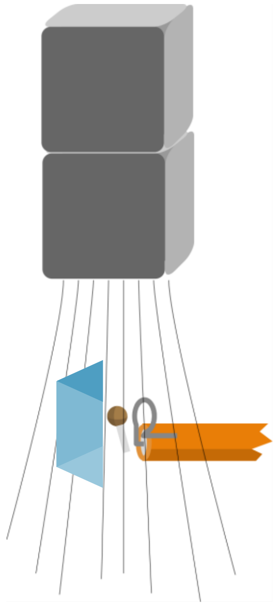
Non-uniform field

Identifying the magneto-static modes

Rutile coupling prism supports microwave resonances

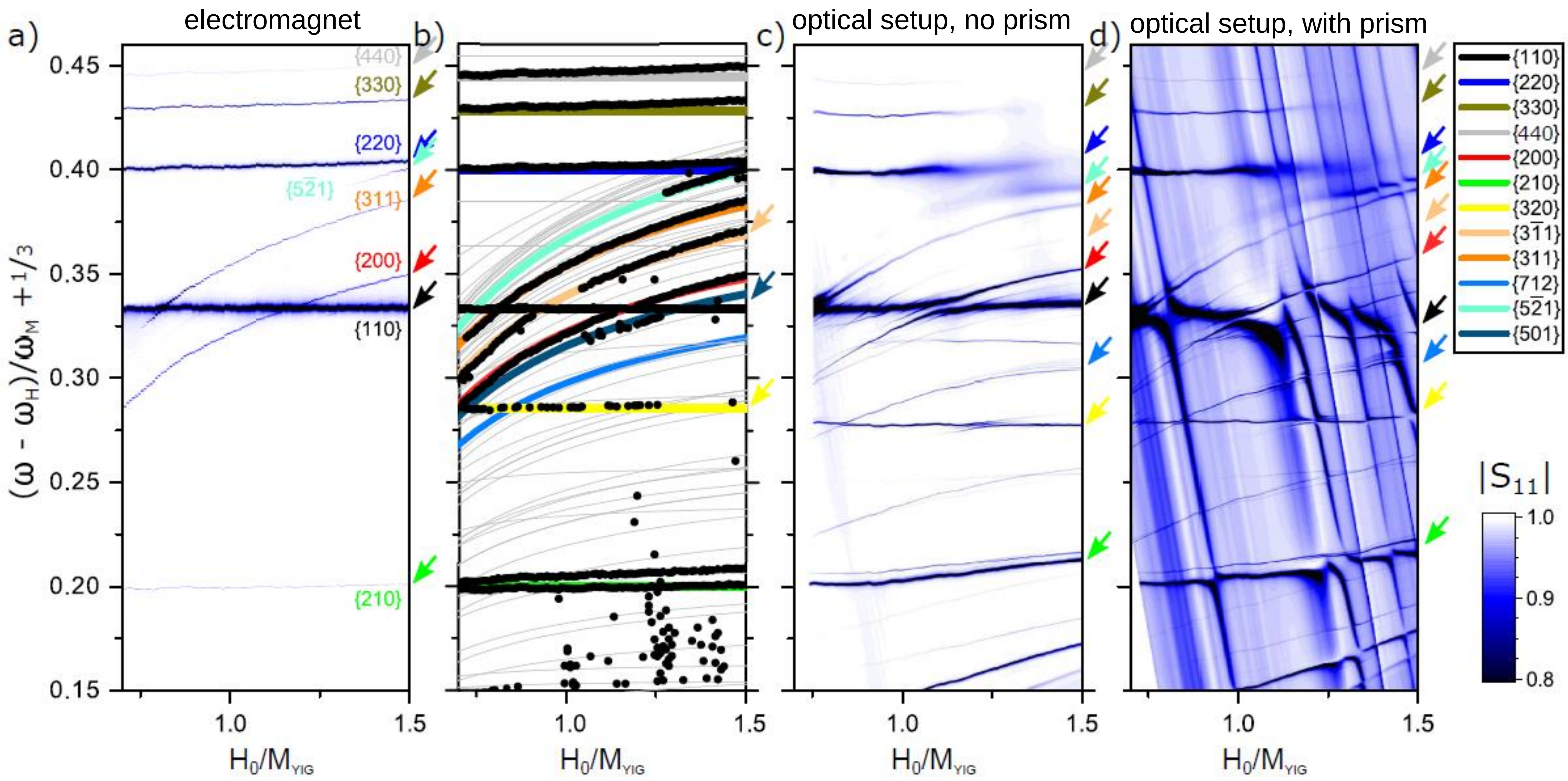


Measured in optical setup



Non-uniform field

Identifying the magneto-static modes

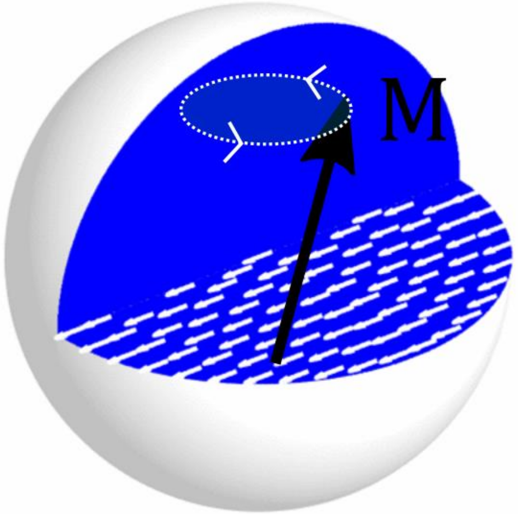


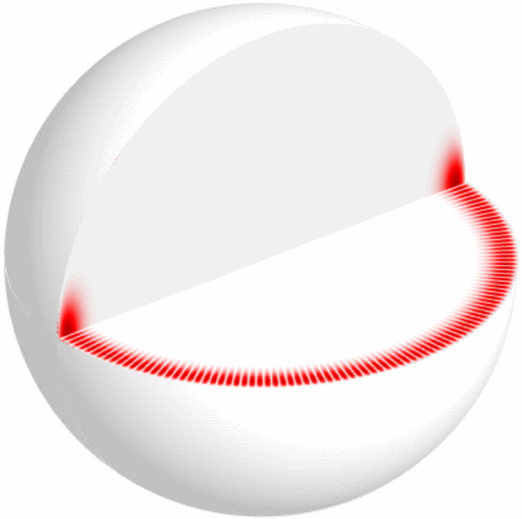
Which modes should couple?

Which modes should couple?

$\{l_m, m_m, q_m\}$

$\{l, m, q\}$





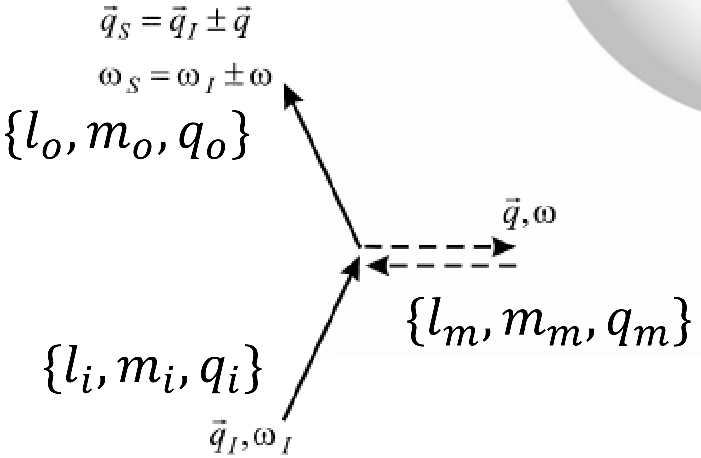


Fig. 4. Scattering process of photons from spin wave excitations.

$$\varepsilon_{ij} = \varepsilon_{ij}^{(0)} + K_{ijk}M_k + G_{ijkl}M_kM_l$$

magneto-optical interaction

Faraday

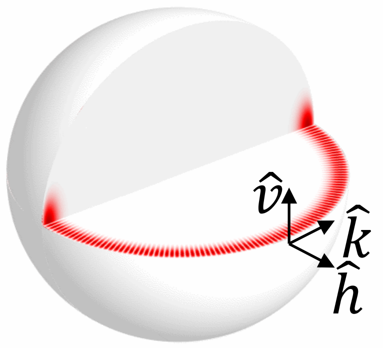
Voigt

(Cotton-Mouton)

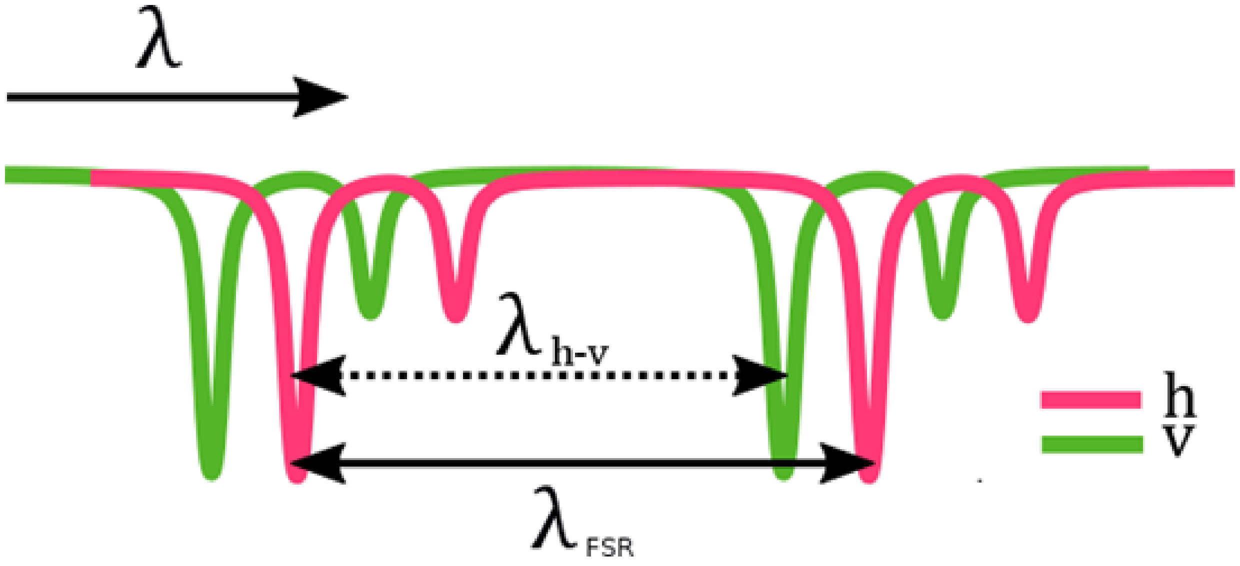
Selection rules for Brillouin light scattering

- Due to angular momentum conservation, BLS from magnons is forbidden between modes with equal polarization.

=> as the WGMs modes are linearly polarized, scattering is always between orthogonal polarizations $h \leftrightarrow v$.



$$M.E_i \times E_o^*$$

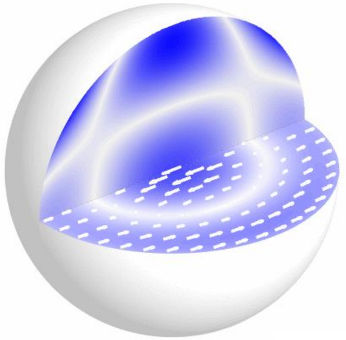


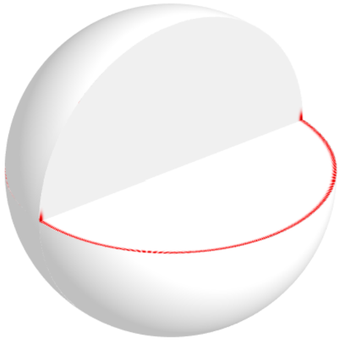
Selection rules for Brillouin light scattering

❶

Because we are only looking at low l_m magnons, transverse structure of optical modes is conserved =>

$$l_i - m_i \; = \; l_o - m_o$$
$$\Delta q = 0$$

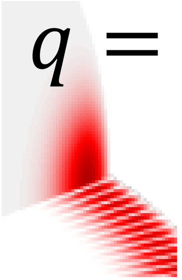




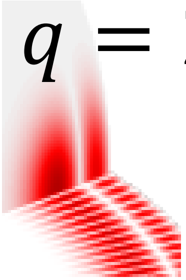
{5,1,1}

Radial structure

$q = 1$



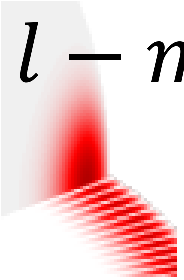
$q = 2$



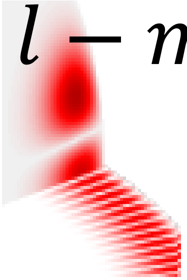
$l = m$

transverse structure

$l - m = 0$



$l - m = 2$



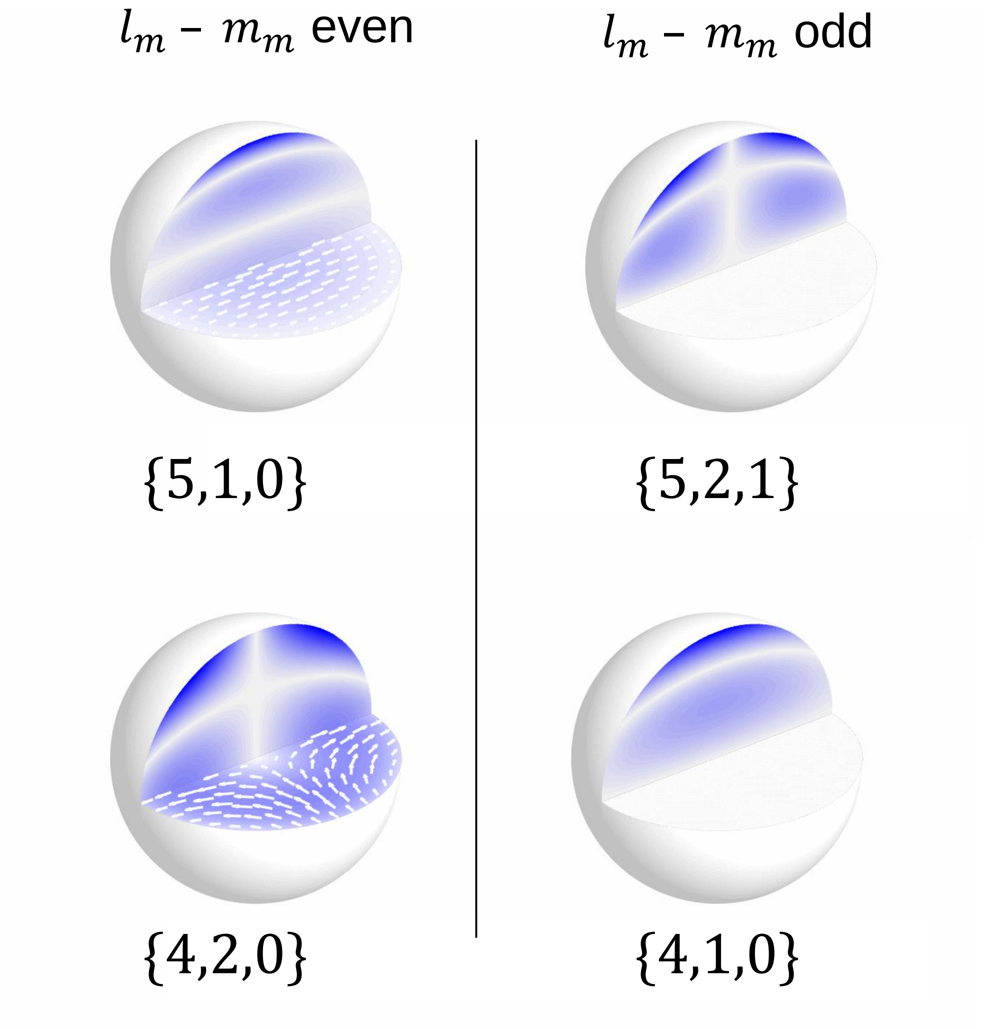
$q = 1$

Selection rules for Brillouin light scattering

❷

Magnons with l_m – m_m odd have a node at the equator.

=> l_m – m_m must be **even**



Selection rules for Brillouin light scattering

❸

The wave-matching conditions in the azimuthal direction =>

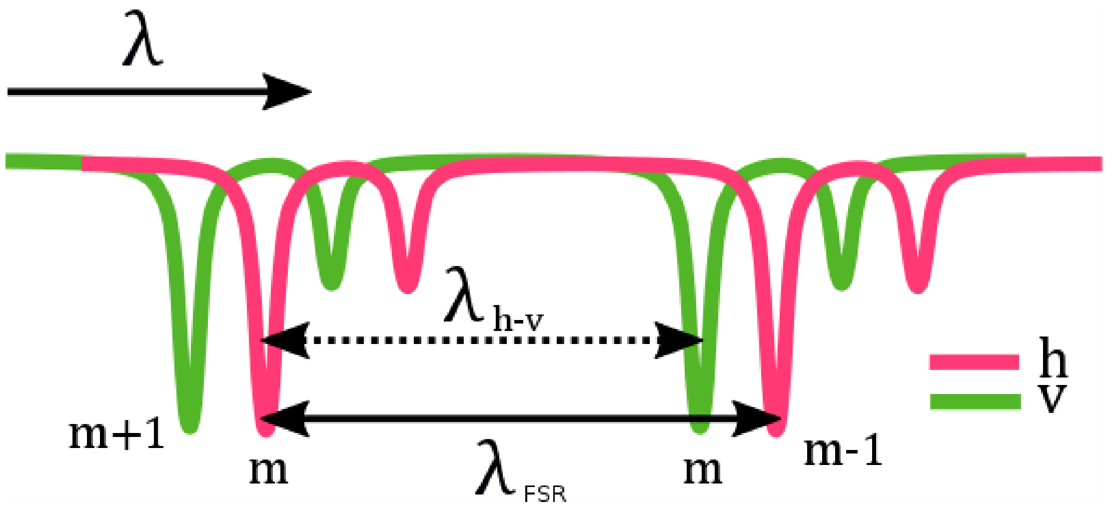
$$m_o = m_m + m_i$$

Selection rules for Brillouin light scattering

4

Due to the magnon frequency, and geometrical birefringence, the relevant two optical modes have

$$m_i - m_o = \pm 1$$



Selection rules for Brillouin light scattering

❹

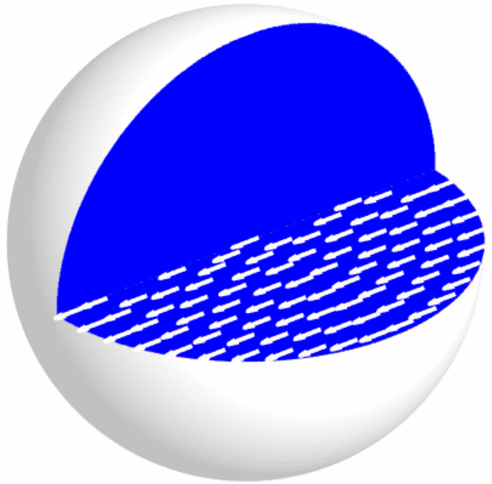
What do $m_m = \pm 1$ magnetic modes look like?

Selection rules for Brillouin light scattering

❹

What do $m_m = \pm 1$ magnetic modes look like?

{1,1,0}



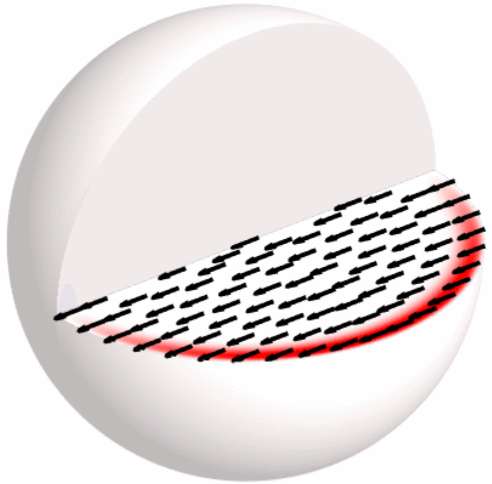
Selection rules for Brillouin light scattering

❹

What do $m_m = \pm 1$ magnetic modes look like?

$$M_k . E_i \times E_o^*$$

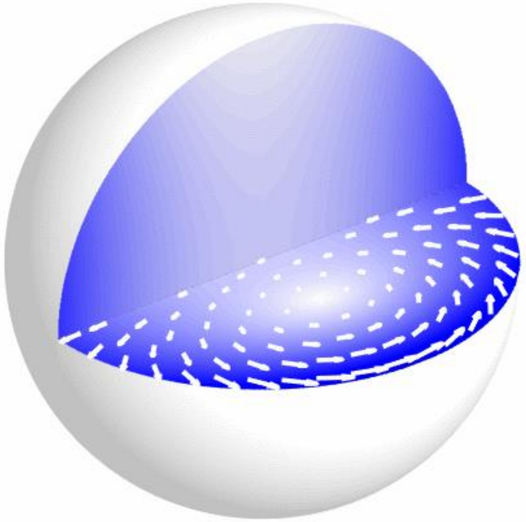
{1,1,0}



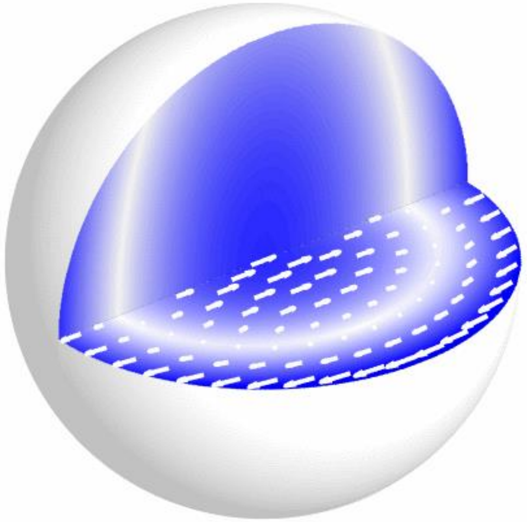
Selection rules for Brillouin light scattering

❹

What do $m_m = \pm 1$ magnetic modes look like?



$\{3, -1, 1\}$

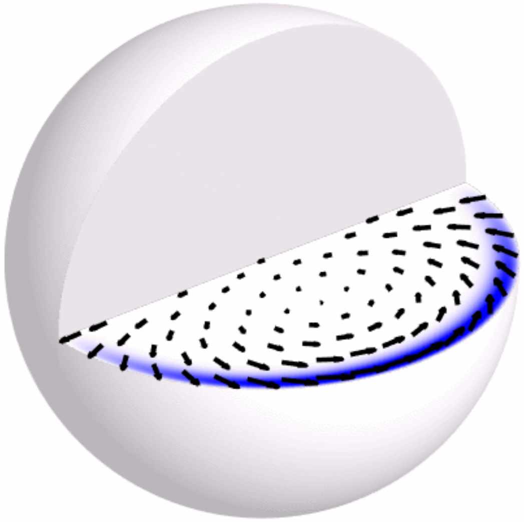


$\{3, 1, 1\}$

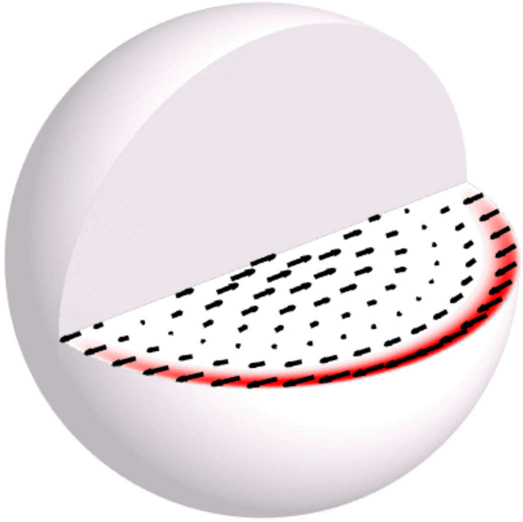
Selection rules for Brillouin light scattering

❹

What do $m_m = \pm 1$ magnetic modes look like?



$\{3, -1, 1\}$



$\{3, 1, 1\}$

Selection rules for Brillouin light scattering

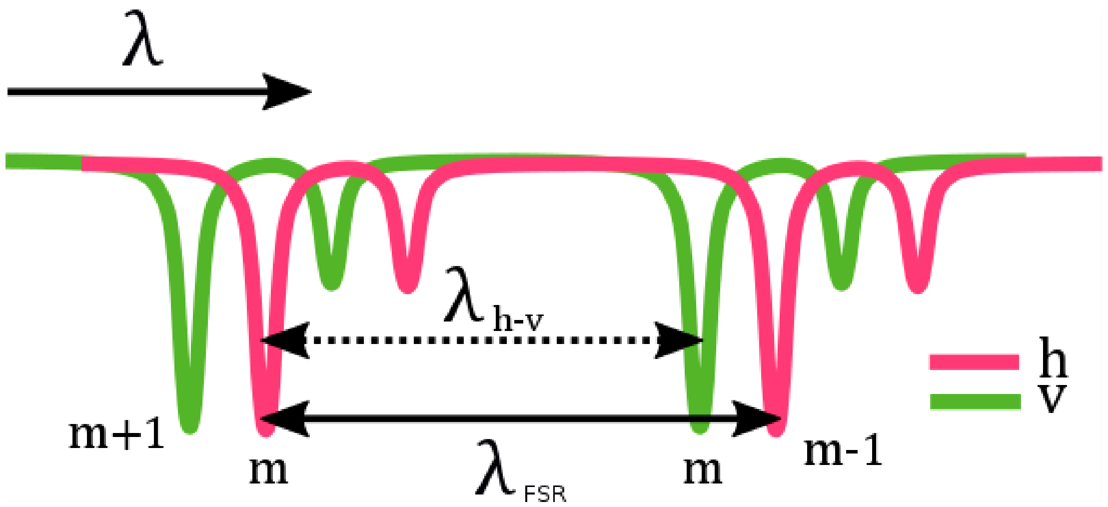
5

Energy conservation:

$$\omega_i - \omega_o = \pm\omega_m$$

Due to mode structure:

$$\omega_v - \omega_h = +\omega_m$$



⇒ **For $\omega_i = \omega_v$, only Stokes scattering**

⇒ **For $\omega_i = \omega_h$, only anti-Stokes scattering**

Selection rules for Brillouin light scattering

❶+❷+❸+❹

$l_i - m_i \ = \ l_o - m_o$

l_m – m_m must be **even**

$m_o \ = \ m_m + m_i$

m_i – $m_o \ = \ \pm 1$

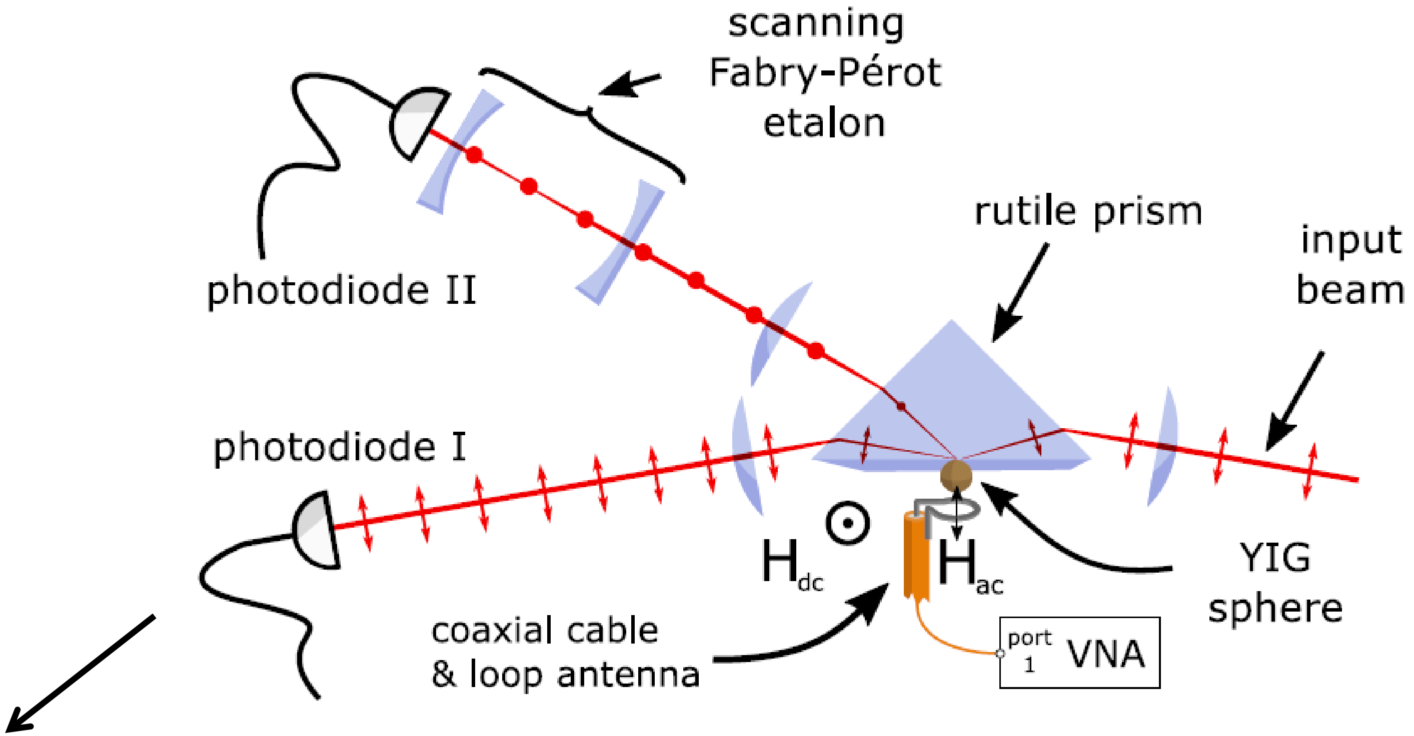
$$l_m = 1,2,3, \ldots$$

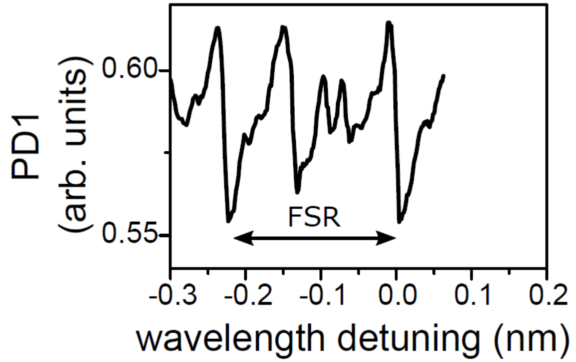
$$m_m = \pm 1$$

Depends on magnetic field sign and wgm circulation direction

Which modes we measure?

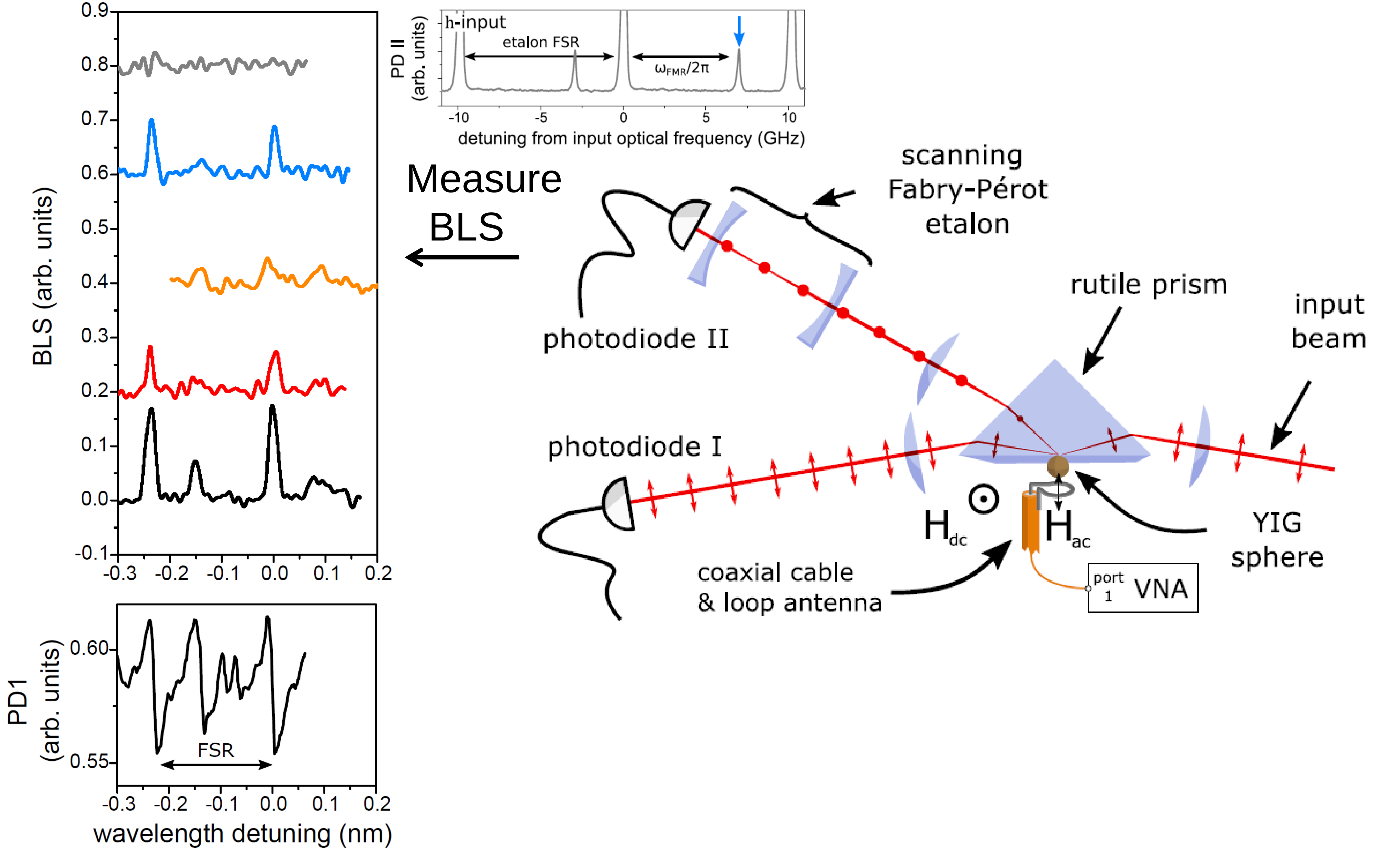
Which modes we measure?



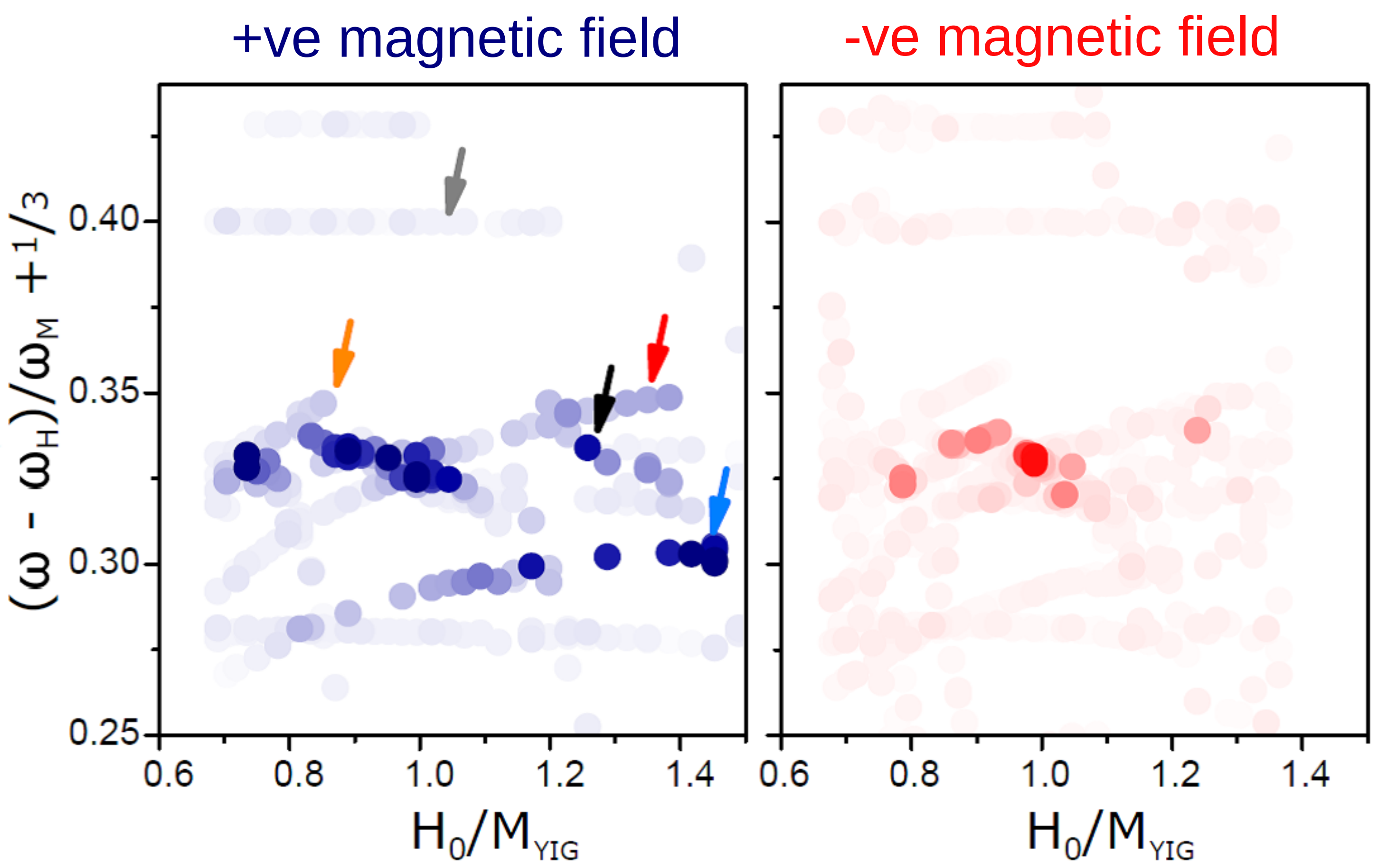


Identify WGM

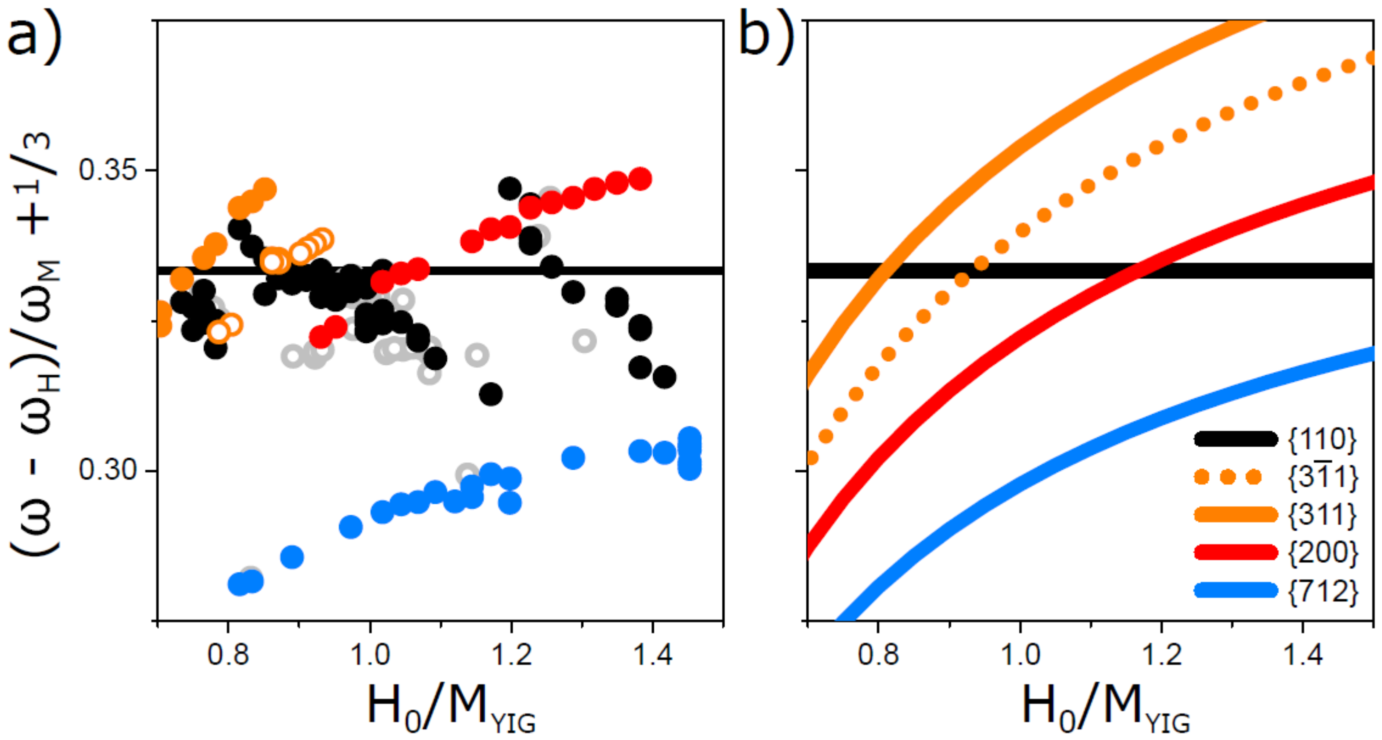
Which modes we measure?



Observed modes for BLS



Observed modes for BLS



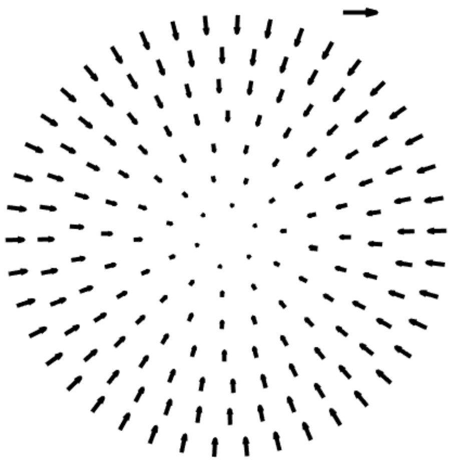
- Pair of modes {3,±1,1} for opposite magnetic fields
- Higher order odd l_m, $m_m = 1$
- Unexpected {2,0,0} mode

Unexpected {200} mode

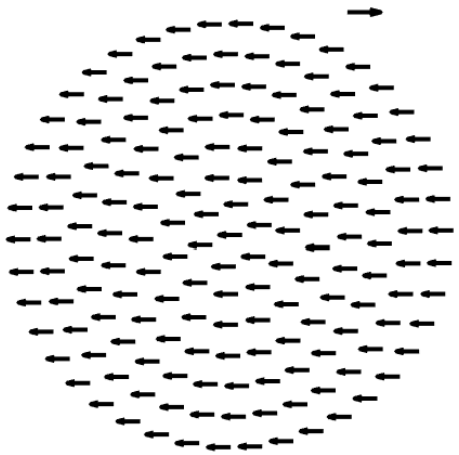
We know the applied field from the permanent magnet is slightly nonuniform

The solutions of (17) in terms of $(\cos^2 \theta_0)_{n0r}$ are independent of Ω_H. Therefore, the dispersion of the $n0r$-modes is identical with that of spinwaves having $\theta_0 = \theta_{n0r}$ and F_{n0r} can be derived from (11). This interesting property seems to play a role for the coupling process between the UPR mode and $n0r$-modes caused by inhomogeneities of the ferrite sphere. This coupling is very often observed between the UPR mode and the 200-mode and occasionally with other $m = 0$ modes (e.g. 401, 501, 602, 702) in single-crystal YIG spheres and partly also in polycrystalline low linewidth spheres.

{2,0,0}



{1,1,0}



Properties of Magnetostatic Modes in Ferrimagnetic Spheroids, P. Röschmann and H. Dötsch, Phys. Stat. Sol. (B) **82**, 11 (1977).

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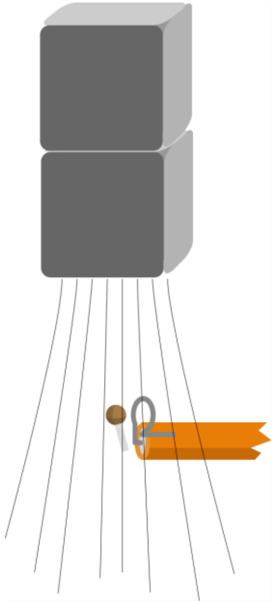
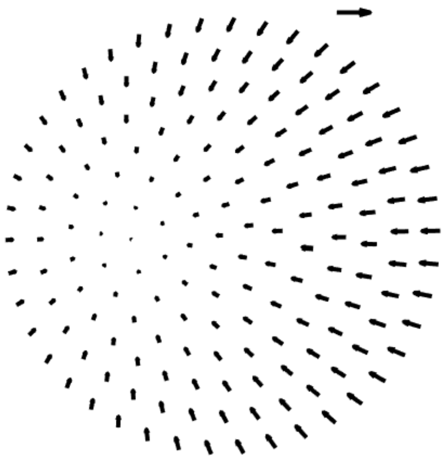
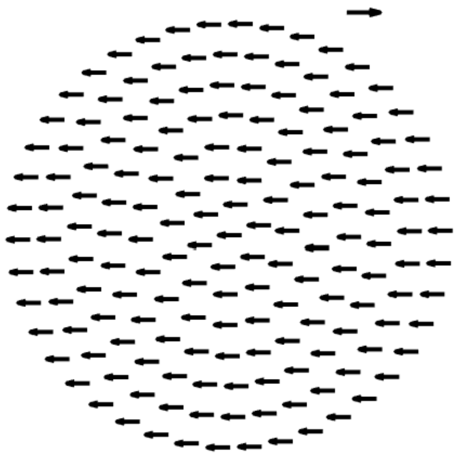


{2,0,0}



{1,1,0}



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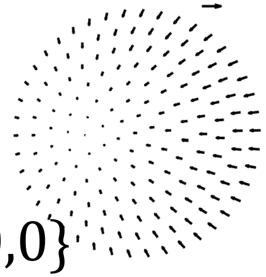
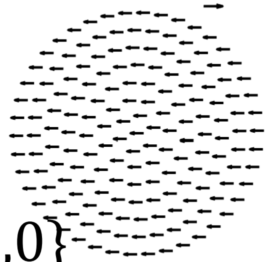
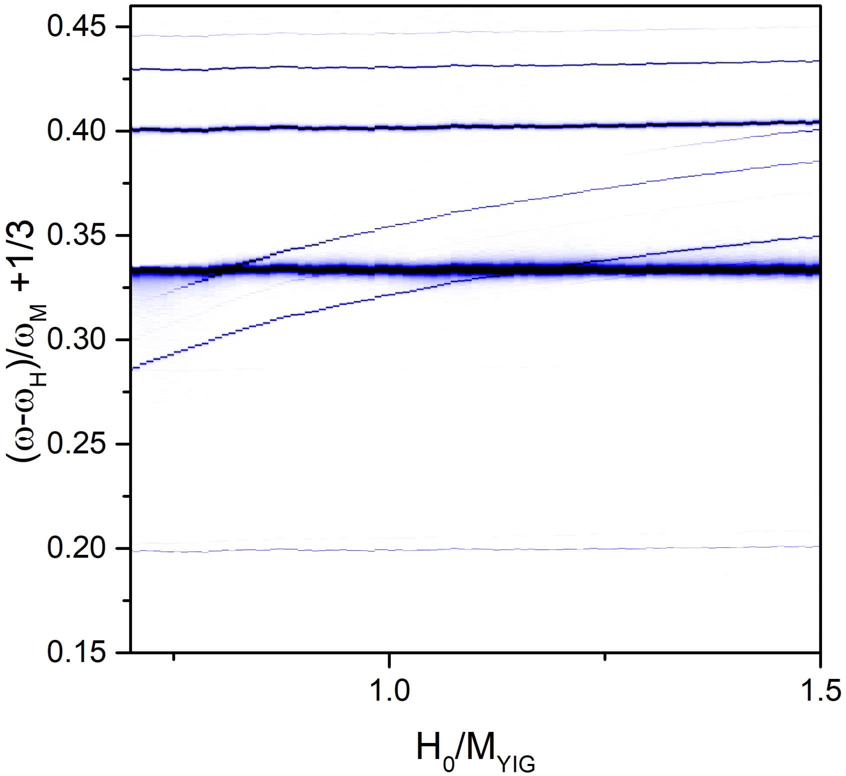
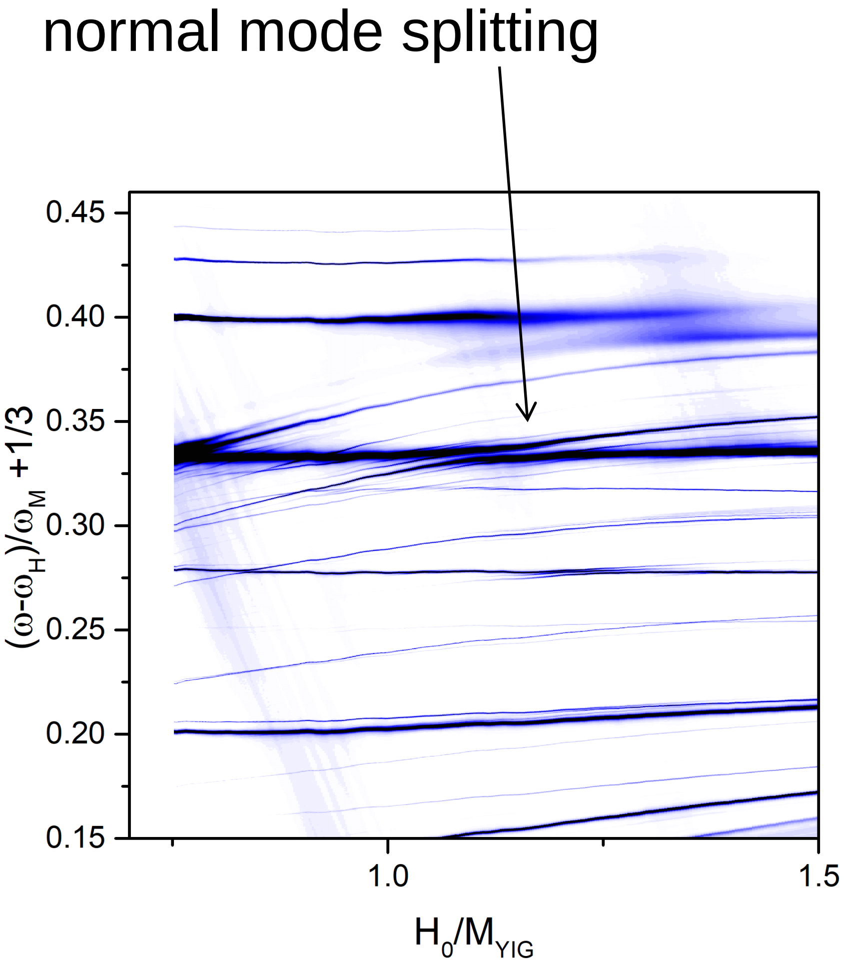


{2,0,0}



{1,1,0}



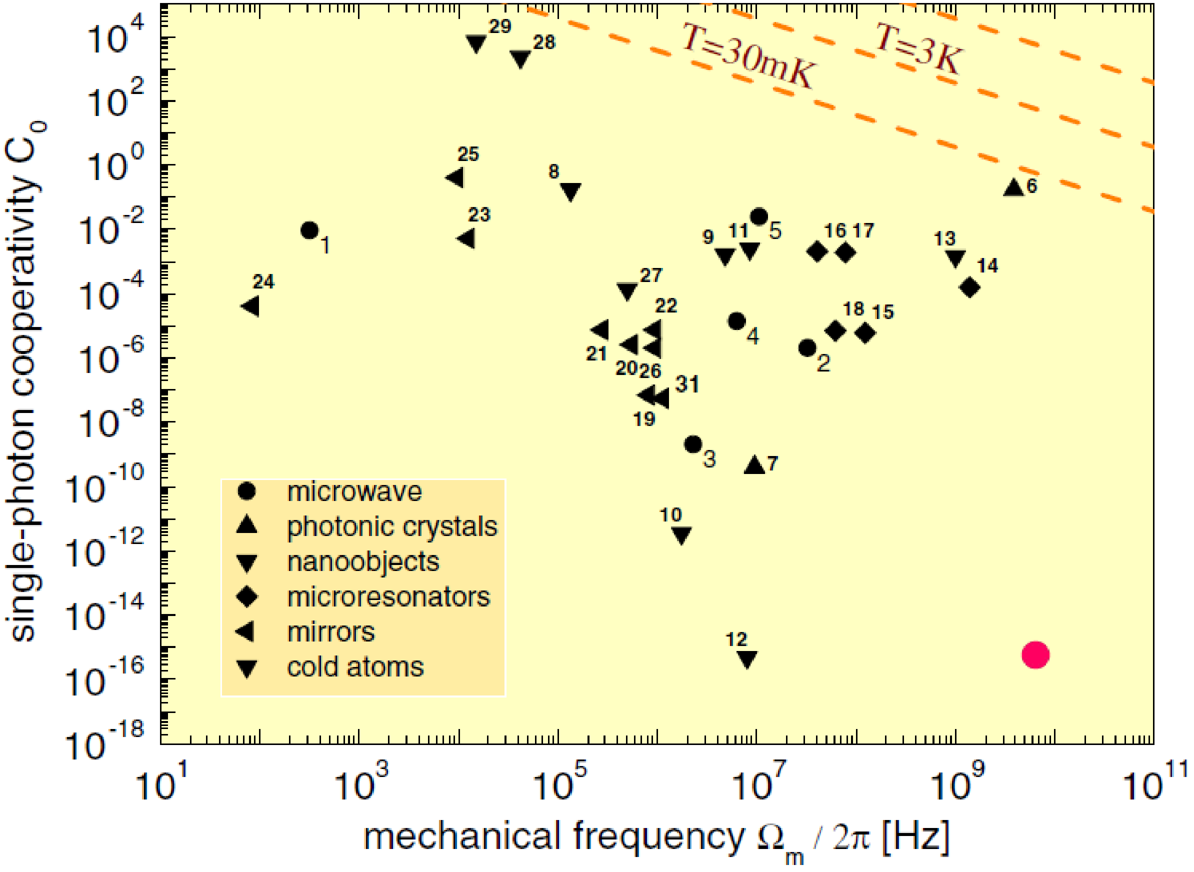


Same symmetry breaking also means that BLS is allowed

Properties of Magnetostatic Modes in Ferrimagnetic Spheroids, P. Röschmann and H. Dötsch, Phys. Stat. Sol. (B) **82**, 11 (1977).

Comparison with opto-mechanics

Single photon cooperativity



$$C_0 = \frac{4g_0^2}{\kappa\Gamma}$$

M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, “Cavity optomechanics,” *Rev. Mod. Phys.* **86** 1391 (2014)

Summary

Brillouin light scattering can be enhanced via optical cavity modes

We can understand and observe the selection rules for BLS from different magnetic modes.

Some (small) enhancement of the coupling constant by going to higher order magnetic modes.

Selection rules for Brillouin light scattering

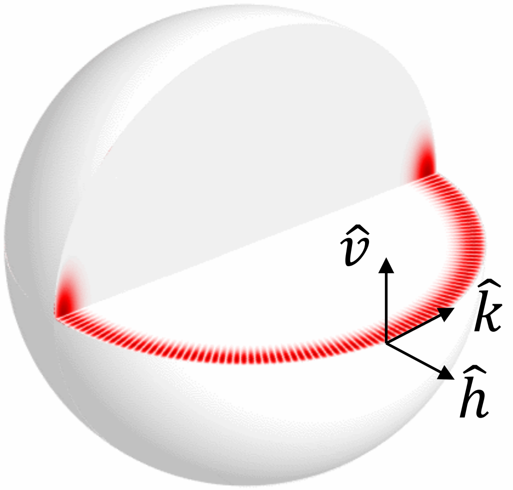
❸

The wave-matching conditions in the azimuthal direction =>

$$m_o = m_m + m_i$$

Interaction energy ∝ $\epsilon(M) E_i E_o^*$

$$M_k . E_i \times E_o^*$$



Can we improve the coupling rate?

Can we improve the coupling rate?

$$C_0 = \frac{4g_0^2}{\kappa\Gamma}$$

coupling rate $\quad g_0 =$ 1 Hz

$$g_0 = \frac{\mathcal{V}c'}{4}\sqrt{\frac{1}{N_{\text{spins}}}}$$

$\mathcal{V}$ is Verdet constant: material parameter
c' is speed of light in YIG: material parameter

"This provides a strong incentive for designing small magnetic structures"

S. Viola Kusminskiy, H. X. Tang, and F. Marquardt, "Coupled spin-light dynamics in cavity optomagnonics," *PRA* **94** 033821 (2016).

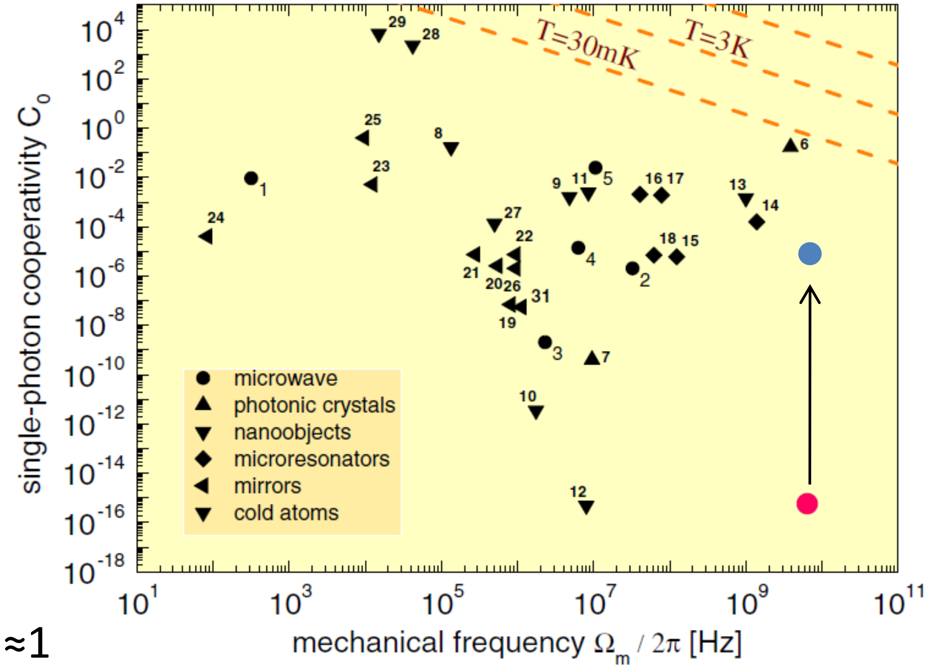
Is it possible to get to an interesting regime?

$$C_0 = \frac{4g_0^2}{\kappa\Gamma}$$

- Volume decrease gives factor 10^5 in coupling constant $g_0 = 0.1$ MHz (currently 1 Hz).
- Decrease in magnetic linewidth gives factor 10
- Decrease in internal optical dissipation doesn't seem to matter as the maximum Q is about the same.

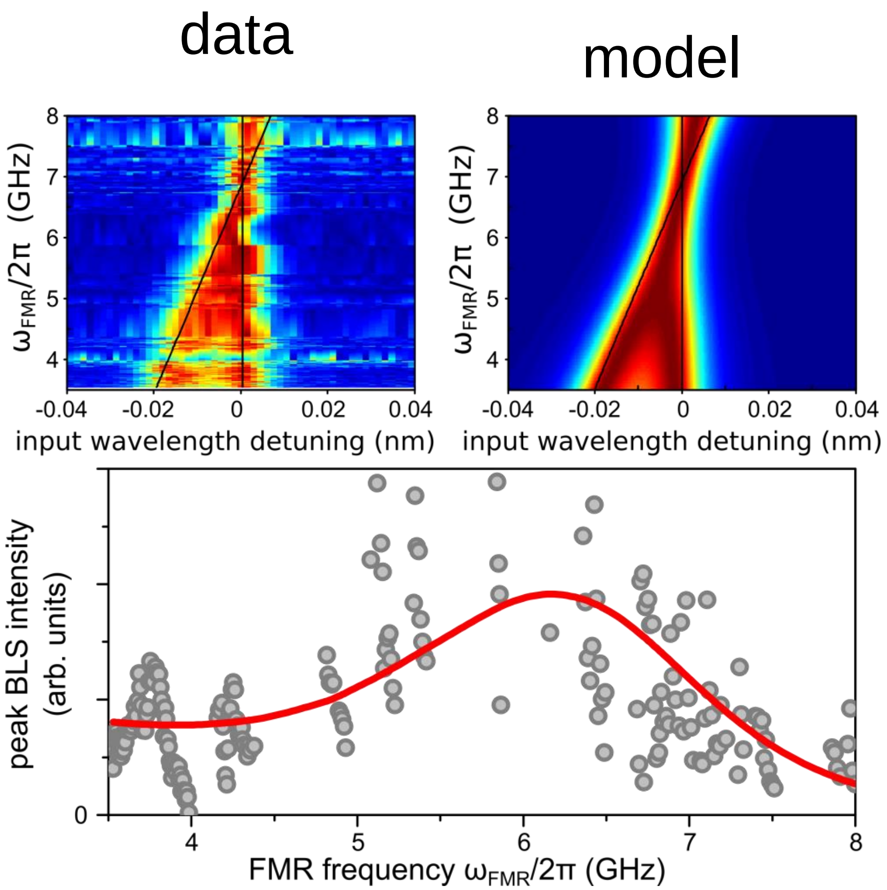
$\Rightarrow$ At most 10^{11} increase in cooperativity.

$$C_0 = \frac{g_0^2}{\kappa\Gamma}$$



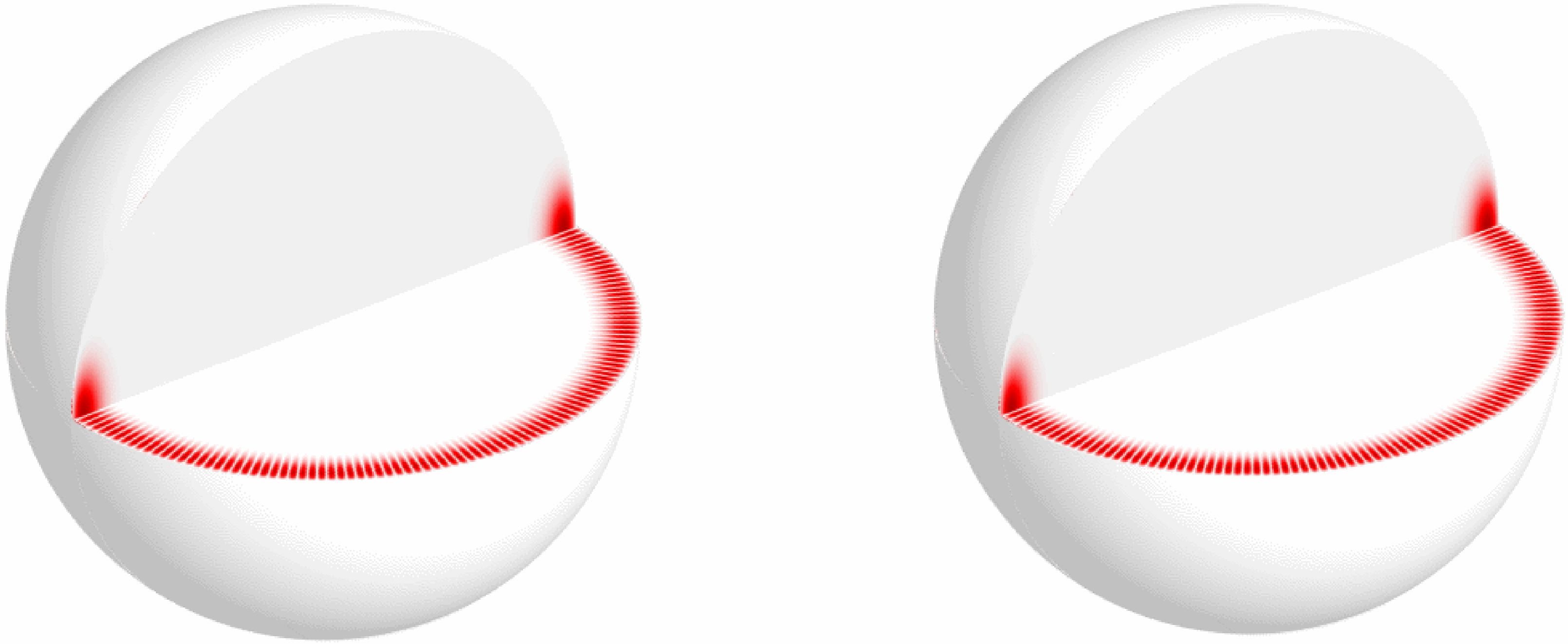
=> With optical pumping, in principle ≈1

Triple resonant condition

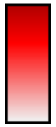


$$|\langle \hat{d}_v \rangle|^2 = \frac{4\bar{G}^2 |\bar{m}_{\text{in}}|^2 \kappa_v |\bar{a}_{\text{in}}|^2 / \Gamma}{\left[\frac{\kappa_h^2}{4} + (\omega_h - \omega_L)^2\right] \left[\frac{\kappa_v^2}{4} + (\omega_{\text{FMR}} - \omega_v + \omega_L)^2\right]}$$

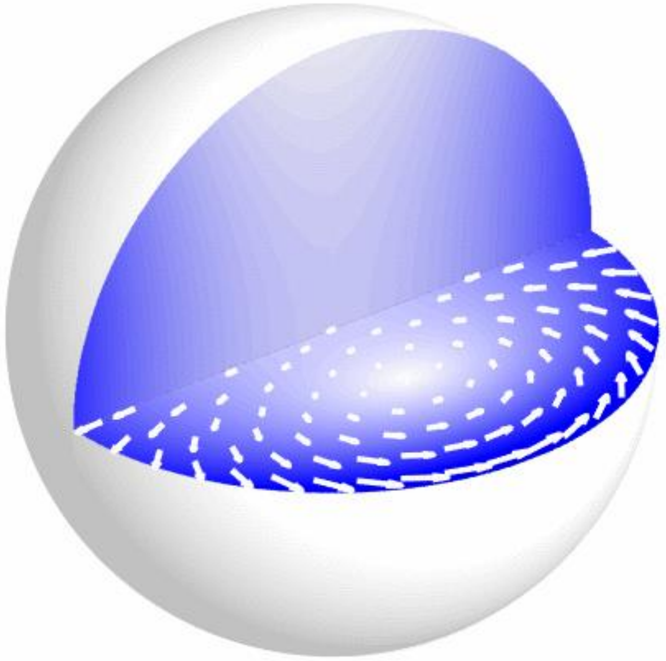
Negative angular momentum modes



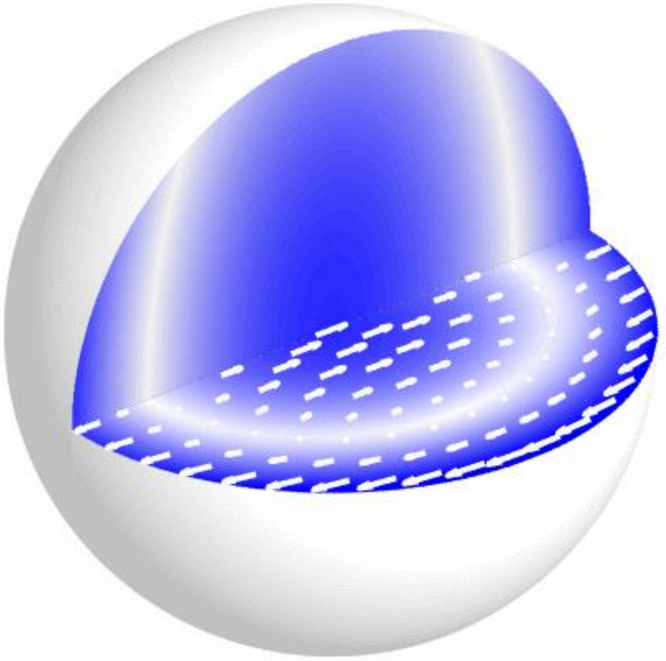
$\{100, -100, 1\}$ $\{100, 100, 1\}$



Negative angular momentum modes

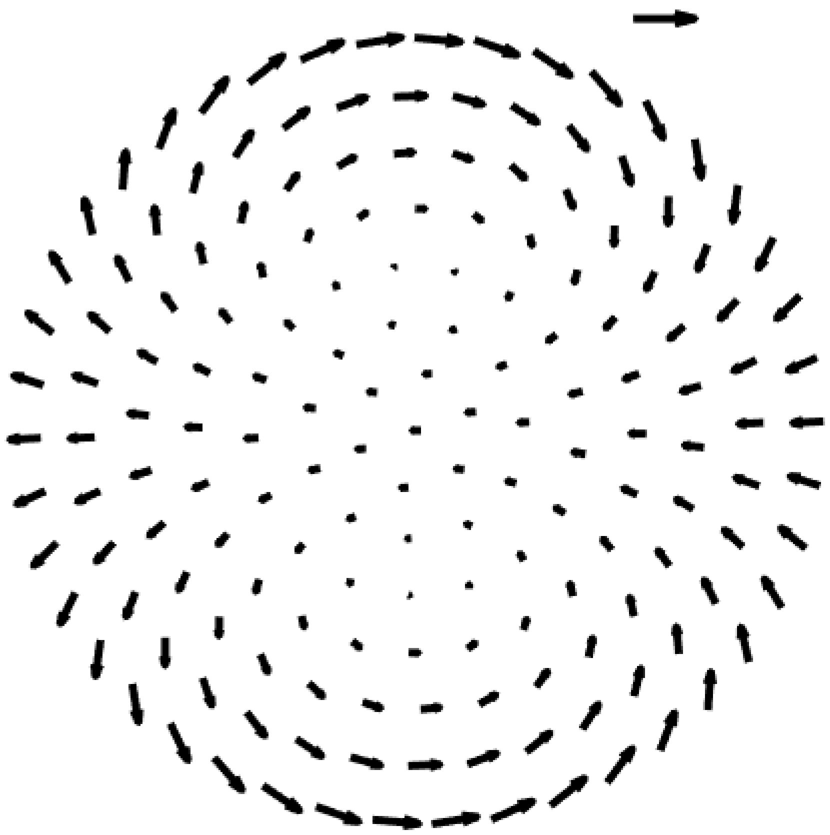


$\{3,-1,1\}$



$\{3,1,1\}$

Negative angular momentum modes



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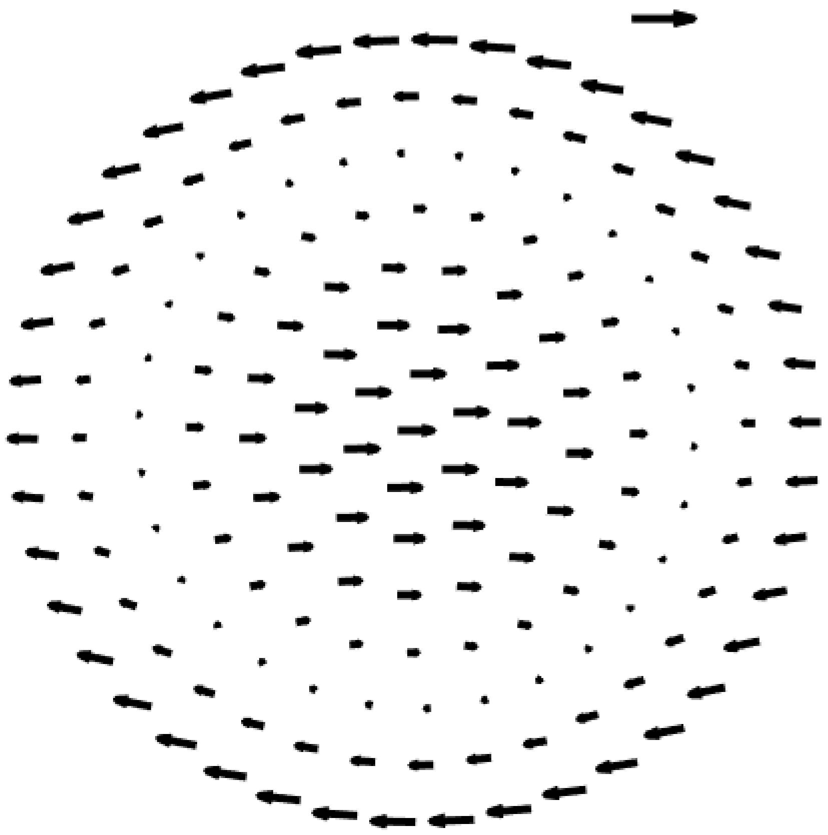
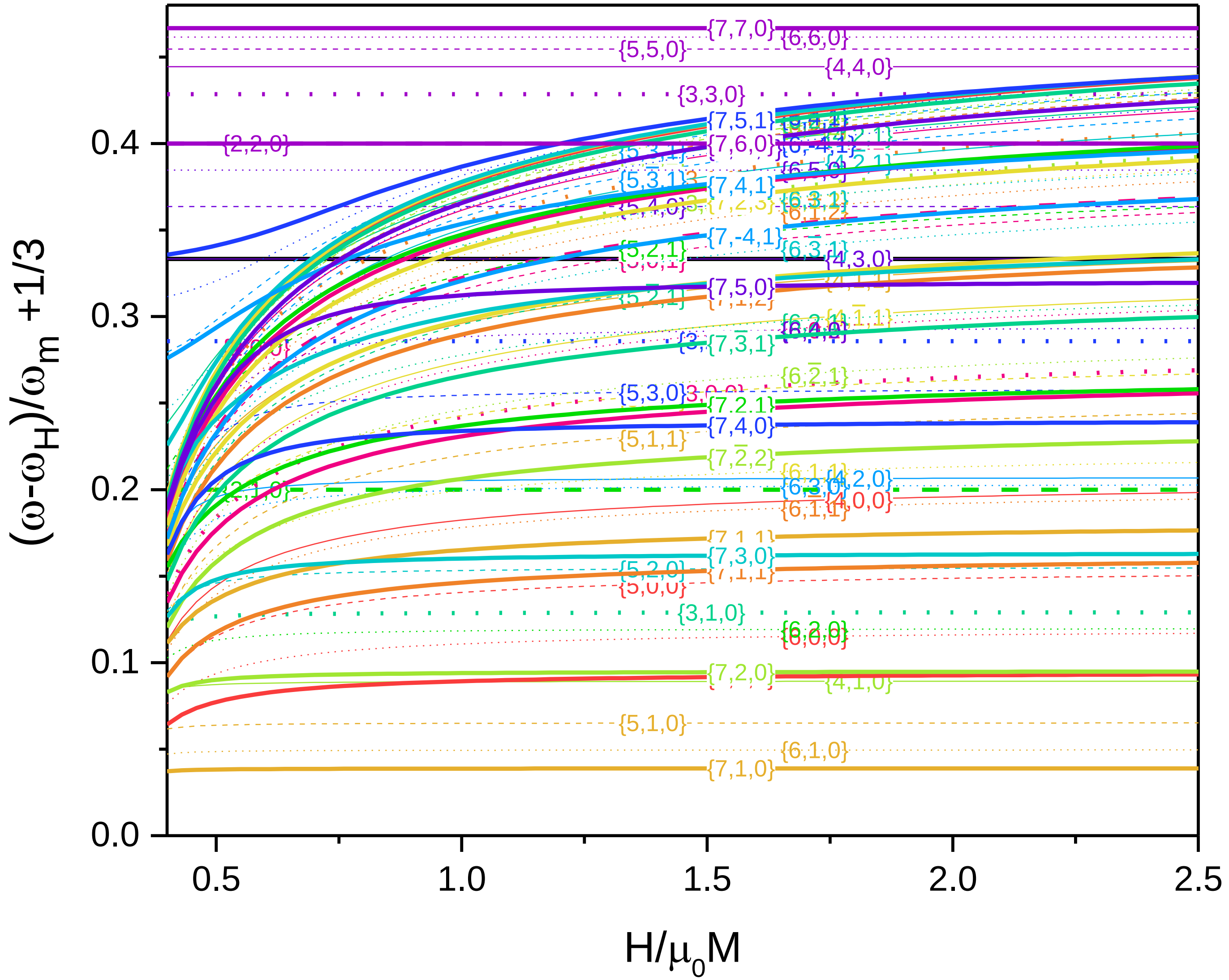


$\{3,1,1\}$

Identifying the magneto-static modes



Ferrimagnetic Resonance Modes in Spheres, P. C. Fletcher and R. O. Bell, Journal of Applied Physics **30**, 687 (1959).