Light scattering in cavity optomagnonics

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With: Sanchar Sharma, Gerrit Bauer

- Intro: Optomagnonics
- Brillouin scattering of light
- Cooling of magnons

Brillouin scattering: Phys. Rev. B **96**, 094412 (2017)
Cooling: Arxiv:1804.02683

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Cavity optomagnonics

– Magnons interact with electromagnetic radiation (magnetooptical effects)

– The interaction is enhanced in optical or microwave cavities (cavity optomagnonics)

– Interaction with MW is resonant and can be very strong

– Interaction with visible or infrared light is dispersive and weak

A. Osada, R. Hisatomi, A. Noguchi, Y. Tabuchi, R. Yamazaki, K. Usami, M. Sadgrove, R. Yalla, M. Nomura, and Y. Nakamura, Phys. Rev. Lett. **116**, 223601 (2016)

X. Zhang, N. Zhu, C.-L. Zou, and H. X. Tang, Phys. Rev. Lett. **117**, 123605 (2016)

J. A. Haigh, A. Nunnenkamp, A. J. Ramsay, and A. J. Ferguson, Phys. Rev. Lett. **117**, 133602 (2016)

Cavity optomagnonics

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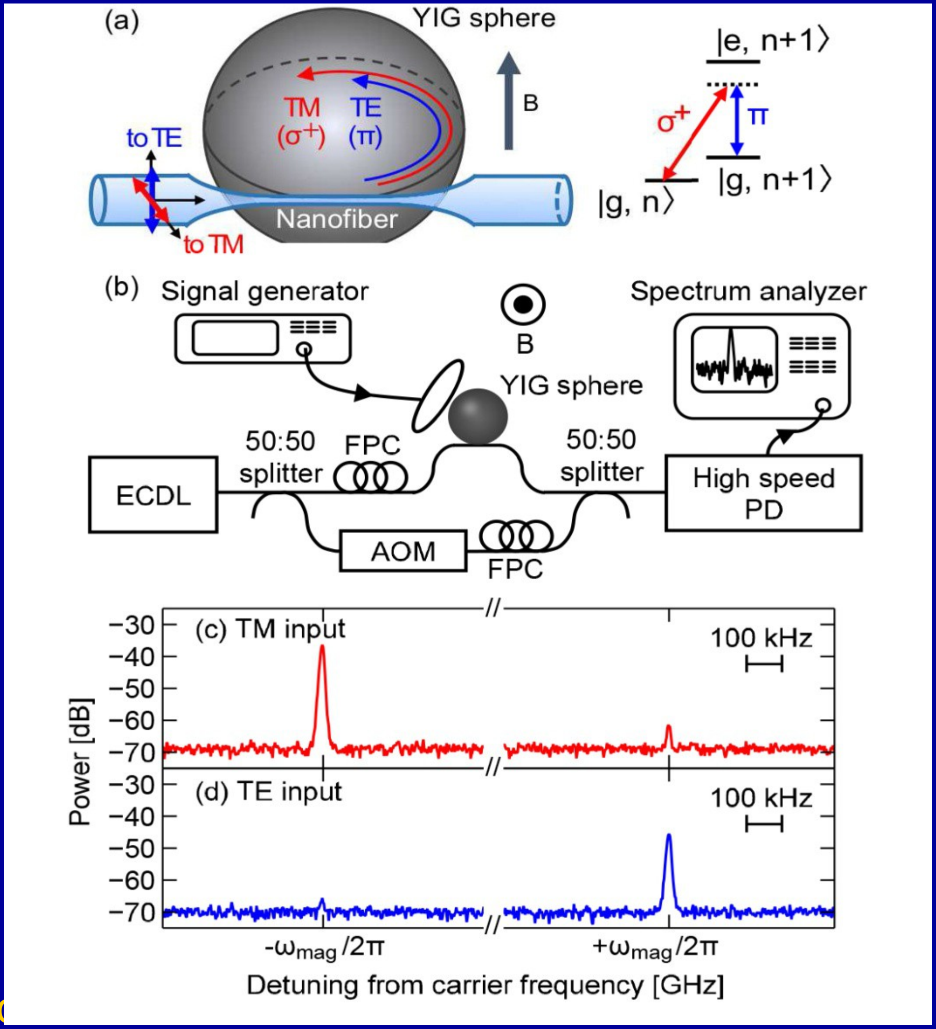
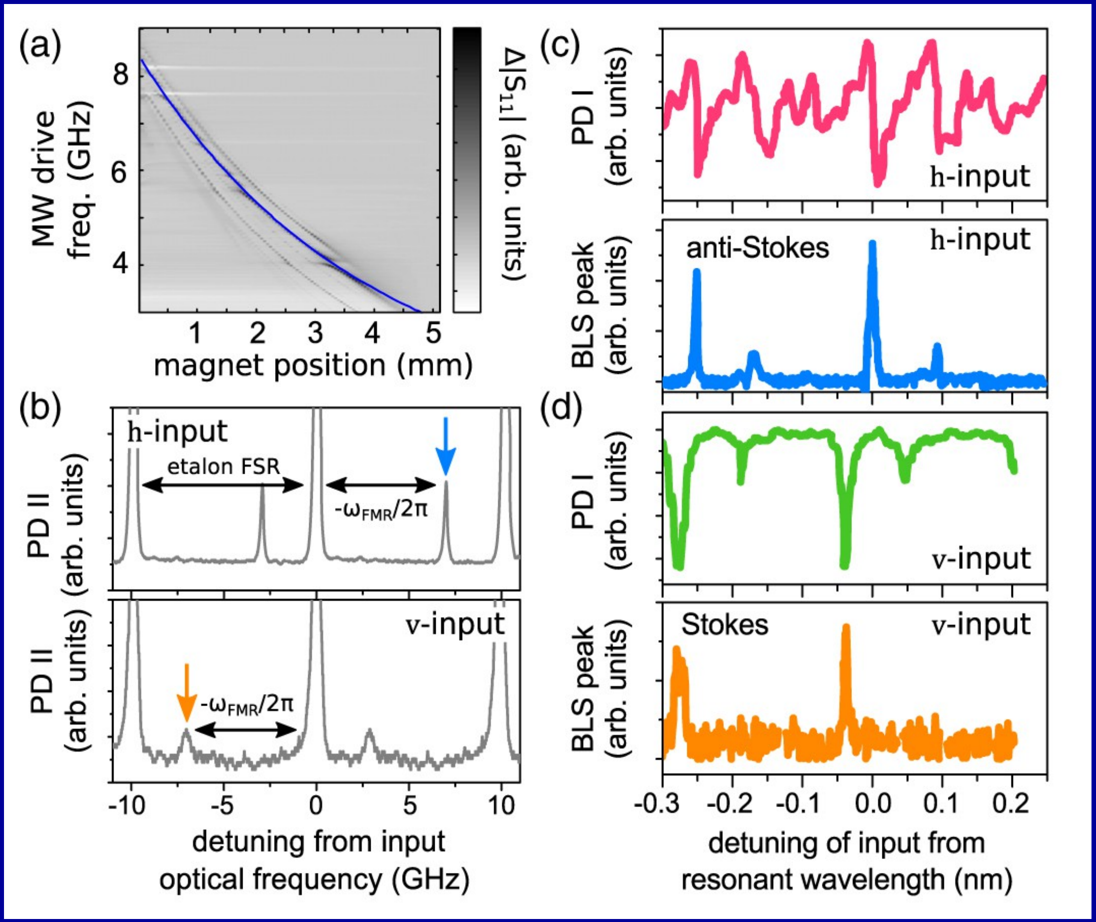


Interaction of magnons (Kittel mode) and whispering gallery modes: Asymmetric Brillouin scattering

Cavity optomagnonics

J. A. Haigh, A. Nunnenkamp, A. J. Ramsay, and A. J. Ferguson
Phys. Rev. Lett. **117**, 133602 (2016)

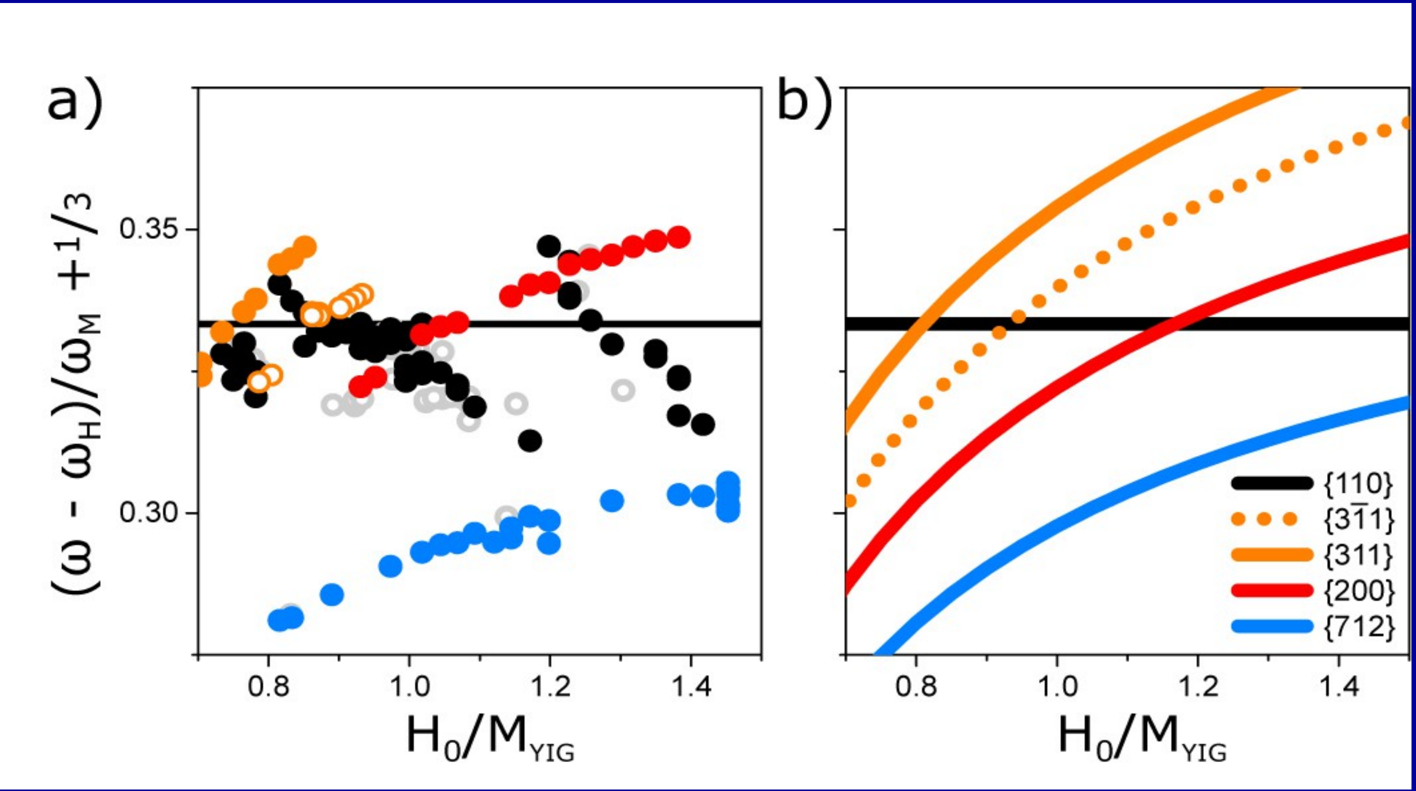


Also the Kittel mode:
Either Stokes or anti-Stokes
(very strong asymmetry, triple resonance)

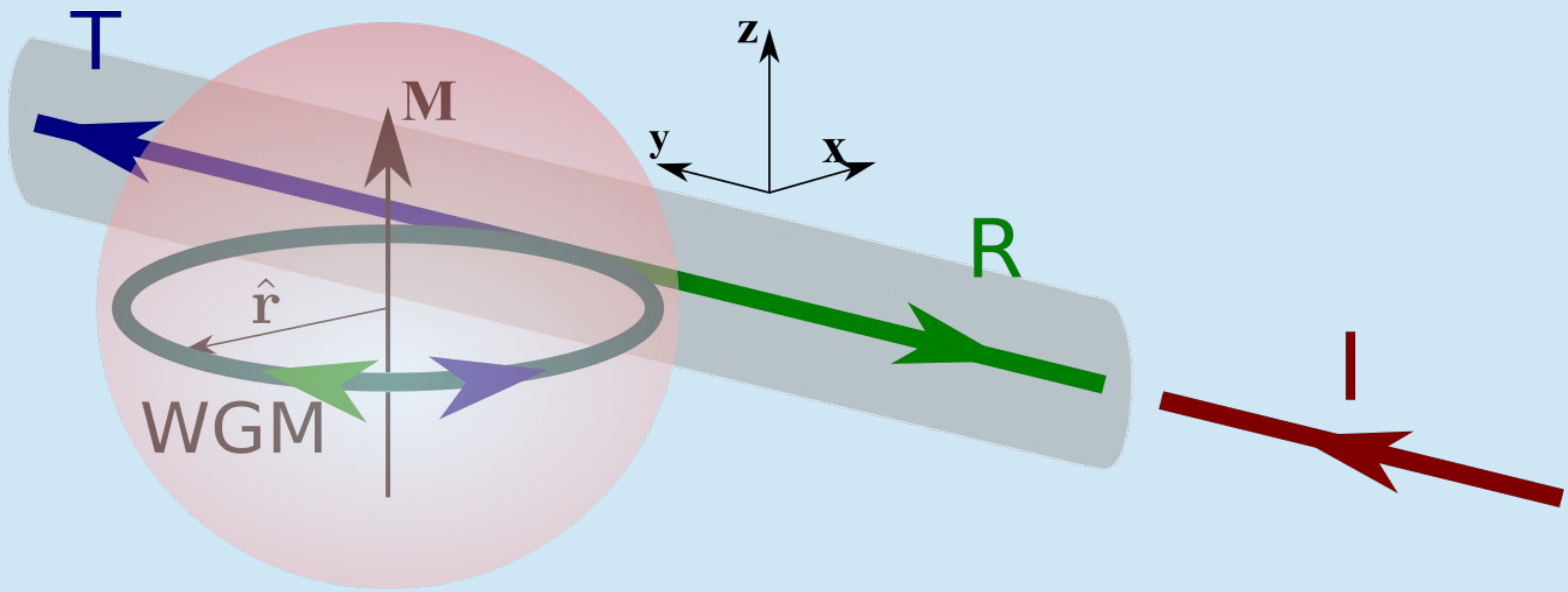
Cavity optomagnonics

J. A. Haigh, N. J. Lambert, S. Sharma, YMB, G. E. W. Bauer, and A. J. Ramsay, arXiv:1804.00965.

Brillouin scattering with higher magnetostatic modes



Light transmission/reflection



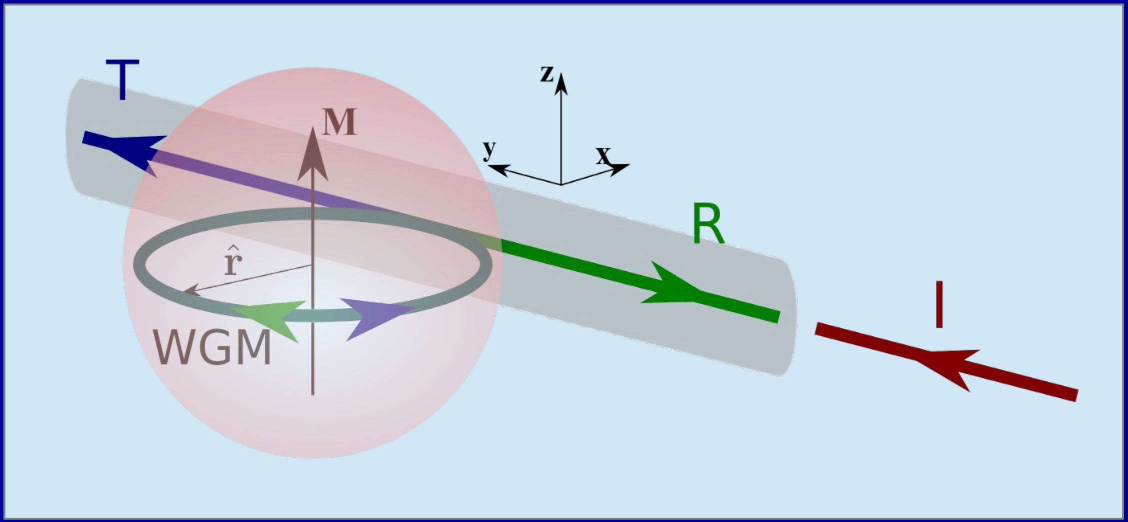
Whispering gallery modes

Characterized by (R, l, m) 	*l* = angular momentum

For large *l*, modes are concentrated around equator
Polarization: Transverse electric (TE) or transverse magnetic (TM)

$$\omega \propto l, l \gg 1$$

Slightly different dispersions for TE and TM



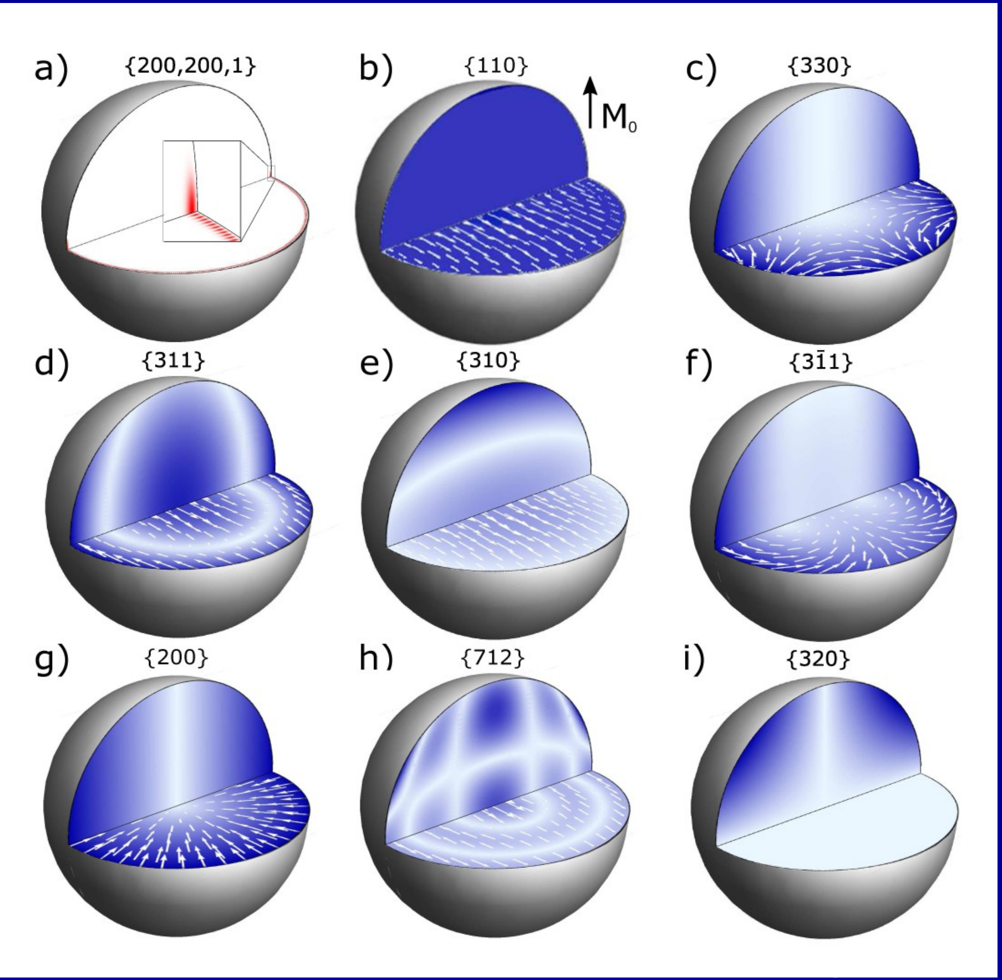
Magnetostatic modes

Solutions of Landau-Lifshitz equation, characterized by (R_s, l_s, m_s)

Kittel mode (011)
– homogeneous precession

Damon-Eshbach modes:

$$l_s \sim m_s \gg 1$$



J. A. Haigh, N. J. Lambert, S. Sharma, YMB, G. E. W. Bauer, and A. J. Ramsay, arxiv:0804.00965

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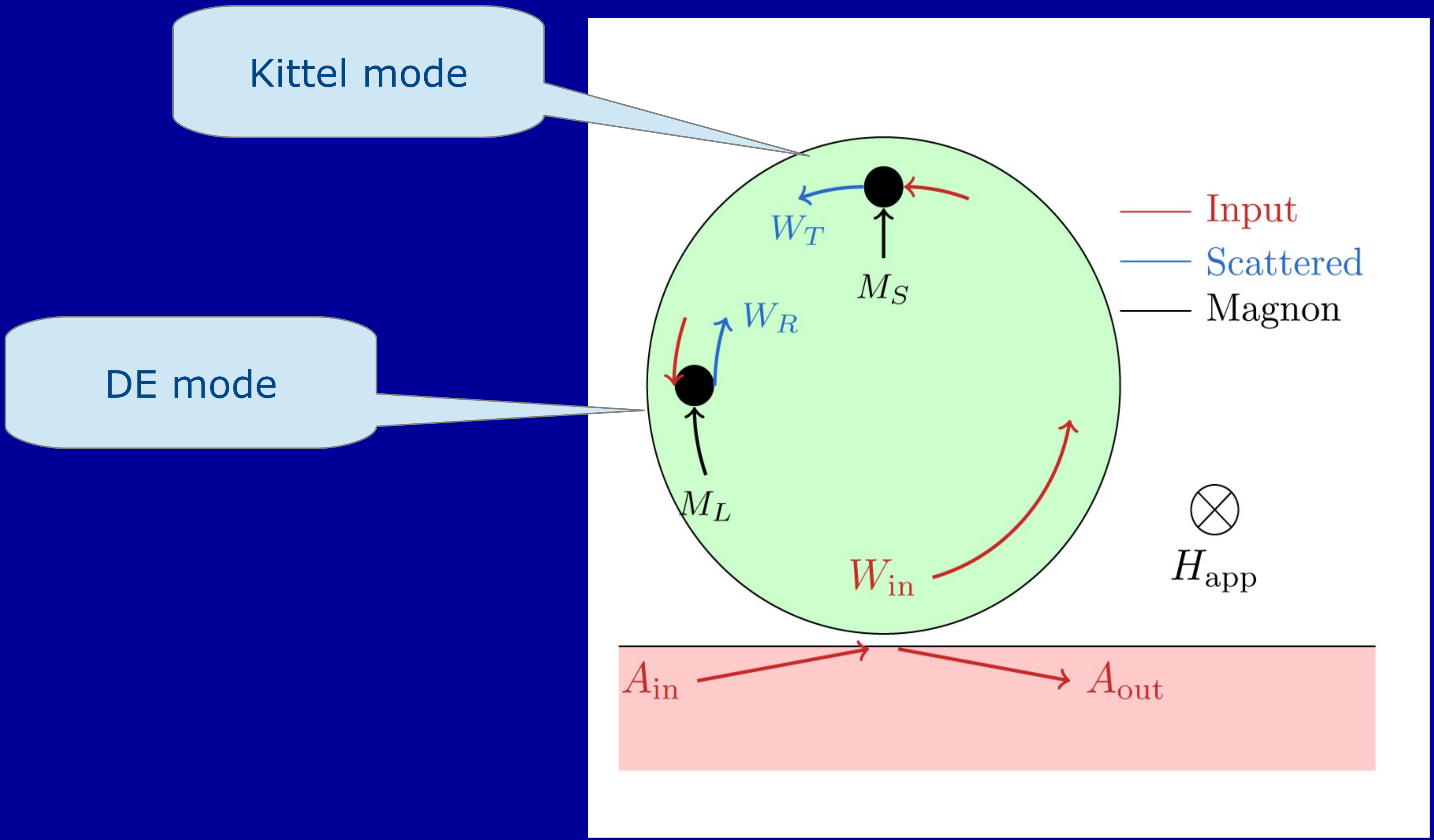
Summary Brillouin scattering



Light-magnon interaction

Magnet in the presence of electric and magnetic field:

$$H = \frac{1}{2}\varepsilon_{ij}(M) E_i E_j^* + \frac{1}{2\mu}|B|^2 - \gamma M \cdot B$$

Interaction – from magnetooptical effects $\hat{\varepsilon} = \hat{\varepsilon}^{el} + \hat{\varepsilon}^{in}$

$$M = M_s \hat{z} + M_x \hat{x} + M_y \hat{y}$$

$$\hat{\varepsilon}^{el} = \begin{pmatrix} \varepsilon_s & -ifM_s & 0 \\ ifM_s & \varepsilon_s & 0 \\ 0 & 0 & \varepsilon_s \end{pmatrix} \qquad \hat{\varepsilon}^{in} = \begin{pmatrix} 0 & 0 & \varepsilon_{xz} \\ 0 & 0 & \varepsilon_{yz} \\ \varepsilon_{xz}^* & \varepsilon_{yz}^* & 0 \end{pmatrix}$$

$$\varepsilon_{xz} = ifM_y + gM_s M_x \qquad \varepsilon_{yz} = -ifM_x + gM_s M_y$$

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Light-magnon interaction

Fully quantized Hamiltonian:

$$\hat{H} = \hbar \sum_p \omega_p \hat{a}_p^\dagger \hat{a}_p + \hbar \sum_\alpha \omega_\alpha \hat{c}_\alpha^\dagger \hat{c}_\alpha + \hbar \sum_{pq\alpha} \hat{a}_p^\dagger \hat{a}_q \left(G_{pq\alpha}^+ \hat{c}_\alpha + G_{pq\alpha}^- \hat{c}_\alpha^\dagger \right)$$

WGM

Magnons

Interaction

– Polarization switch: Only modes with opposite polarizations are coupled (TE → TM and TM → TE)

– Selection rules, $l_s = 0 : R = R', m' = m \pm 1, l' - m' \approx l - m$

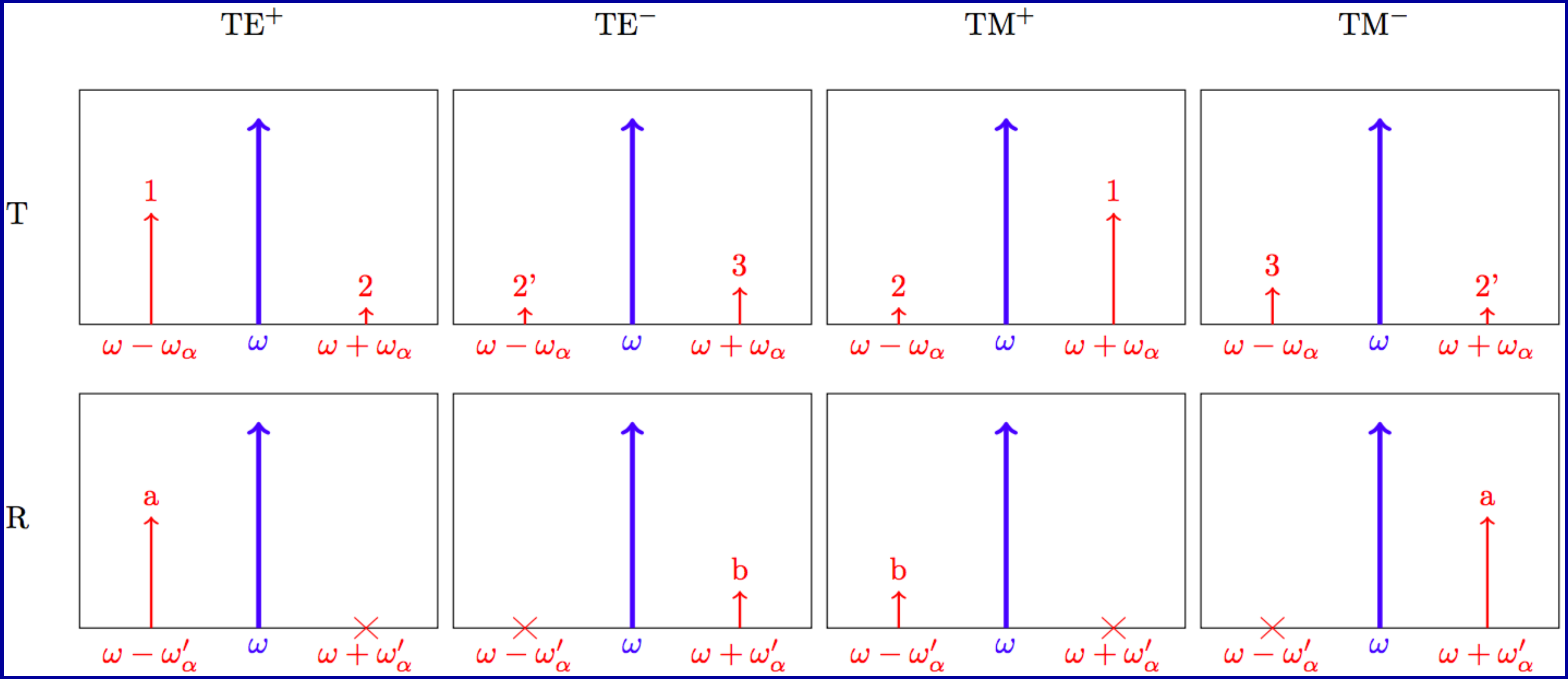
– Selection rules, $l_s \approx m_s \gg 1 :$ $m' \approx -m,\ m = l_s + m'$

Only magnon annihilation, no creation

Light propagation

T

R

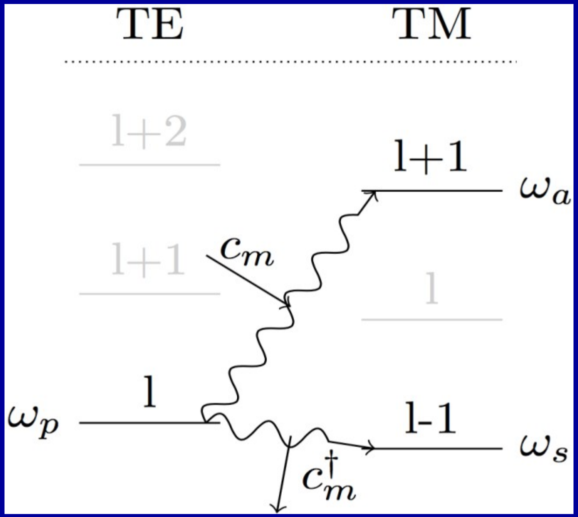


Transmission

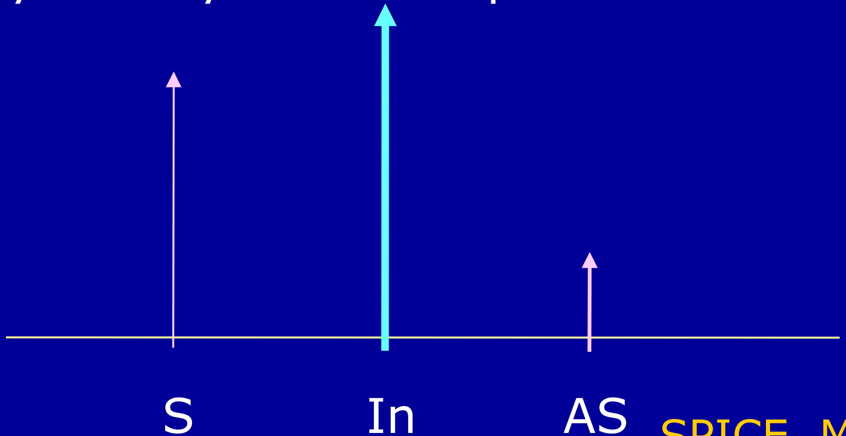
The Kittel mode and other modes with low *l*, *m* are involved

$$\frac{P_S}{P_{in}} = \frac{4\kappa^2}{\kappa_{tot}^2}\left|G_{ps\alpha}^{-}\right|^2 \frac{n_\alpha + 1}{(\omega_p - \omega_s - \omega_\alpha)^2 + \kappa_{tot}^2}$$ – Stokes

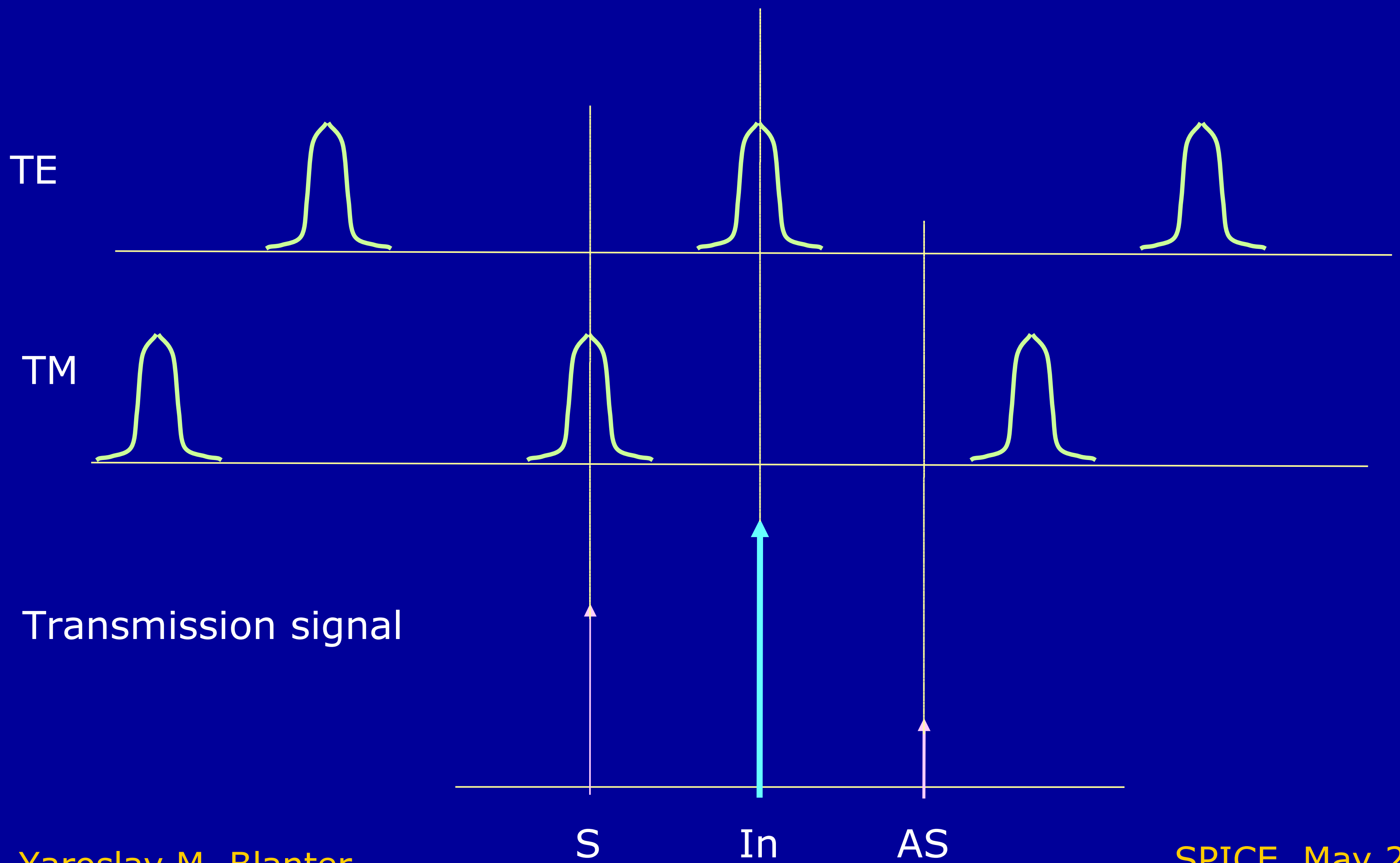
$$\frac{P_{AS}}{P_{in}} = \frac{4\kappa^2}{\kappa_{tot}^2}\left|G_{pa\alpha}^{+}\right|^2 \frac{n_\alpha}{(\omega_p - \omega_a - \omega_\alpha)^2 + \kappa_{tot}^2}$$ – anti-Stokes



Asymmetry for TE+ input:



Transmission



Reflection

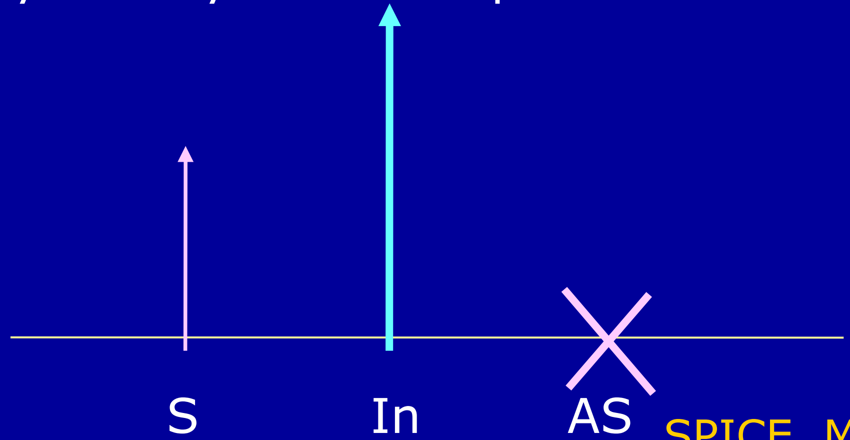
A large shift of angular momentum involved → DE modes → chiral

Only either Stokes or anti-Stokes peak present!!

$$\frac{P_S}{P_{in}} = \frac{4\kappa^2}{\kappa_{tot}^2}\left|G_{ps\alpha}^{-}\right|^2 \frac{n_\alpha + 1}{(\omega_p - \omega_s - \omega_\alpha)^2 + \kappa_{tot}^2}$$ – Stokes

$$\frac{P_{AS}}{P_{in}} = \frac{4\kappa^2}{\kappa_{tot}^2}\left|G_{pa\alpha}^{+}\right|^2 \frac{n_\alpha}{(\omega_p - \omega_a - \omega_\alpha)^2 + \kappa_{tot}^2}$$ – anti-Stokes

Asymmetry for TE+ input:



Magnon cooling

Asymmetry between Stokes and anti-Stokes scattering

↓

Magnons can easier lose energy than gein energy, or vice versa

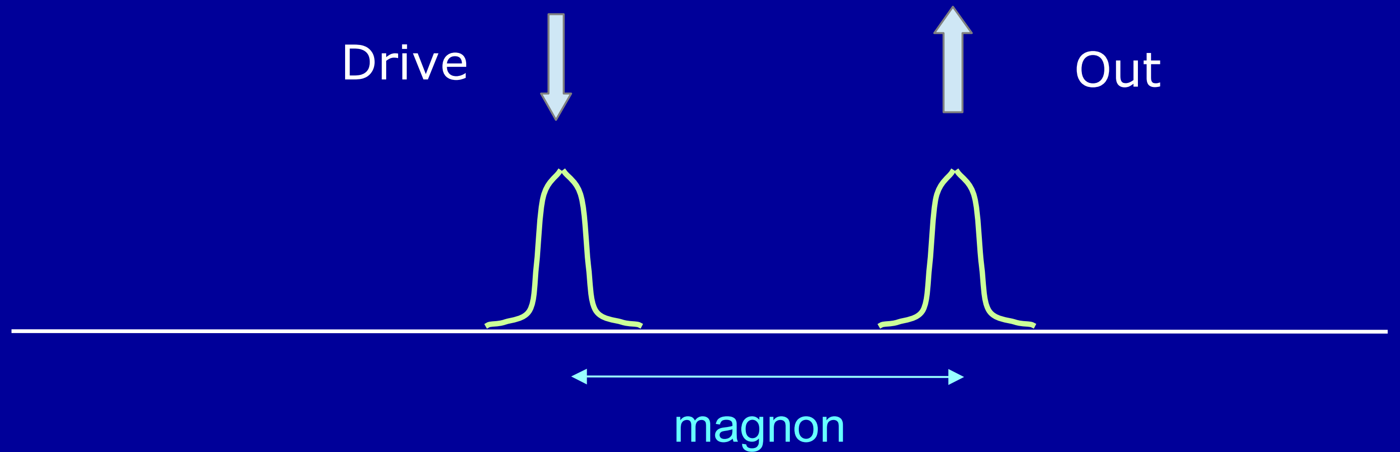
↓

Cooling of magnons (both Kittel mode or DE modes)

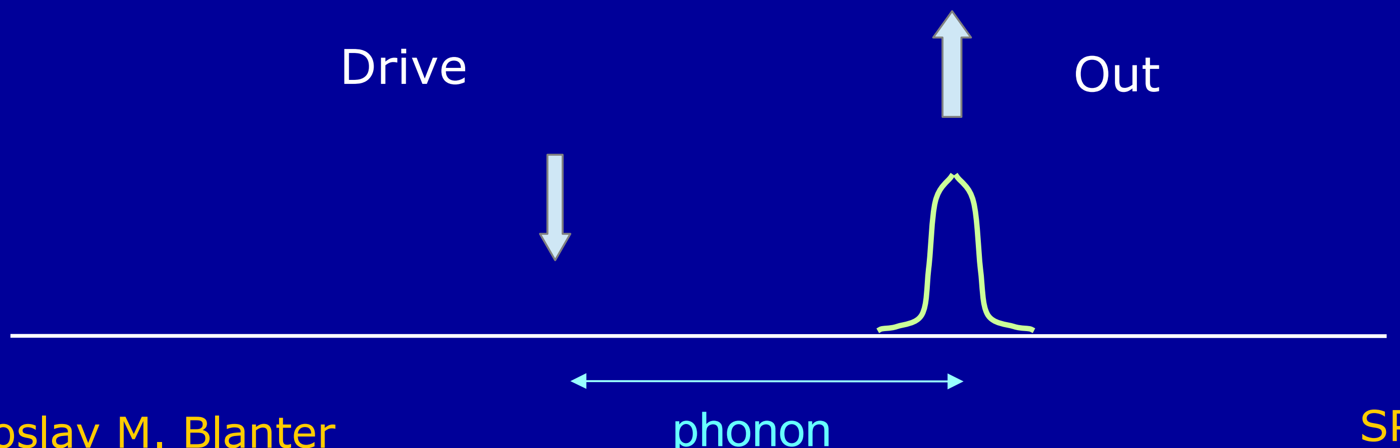
- What is the cooling temperature?
- What is the needed intensity?

Magnon cooling

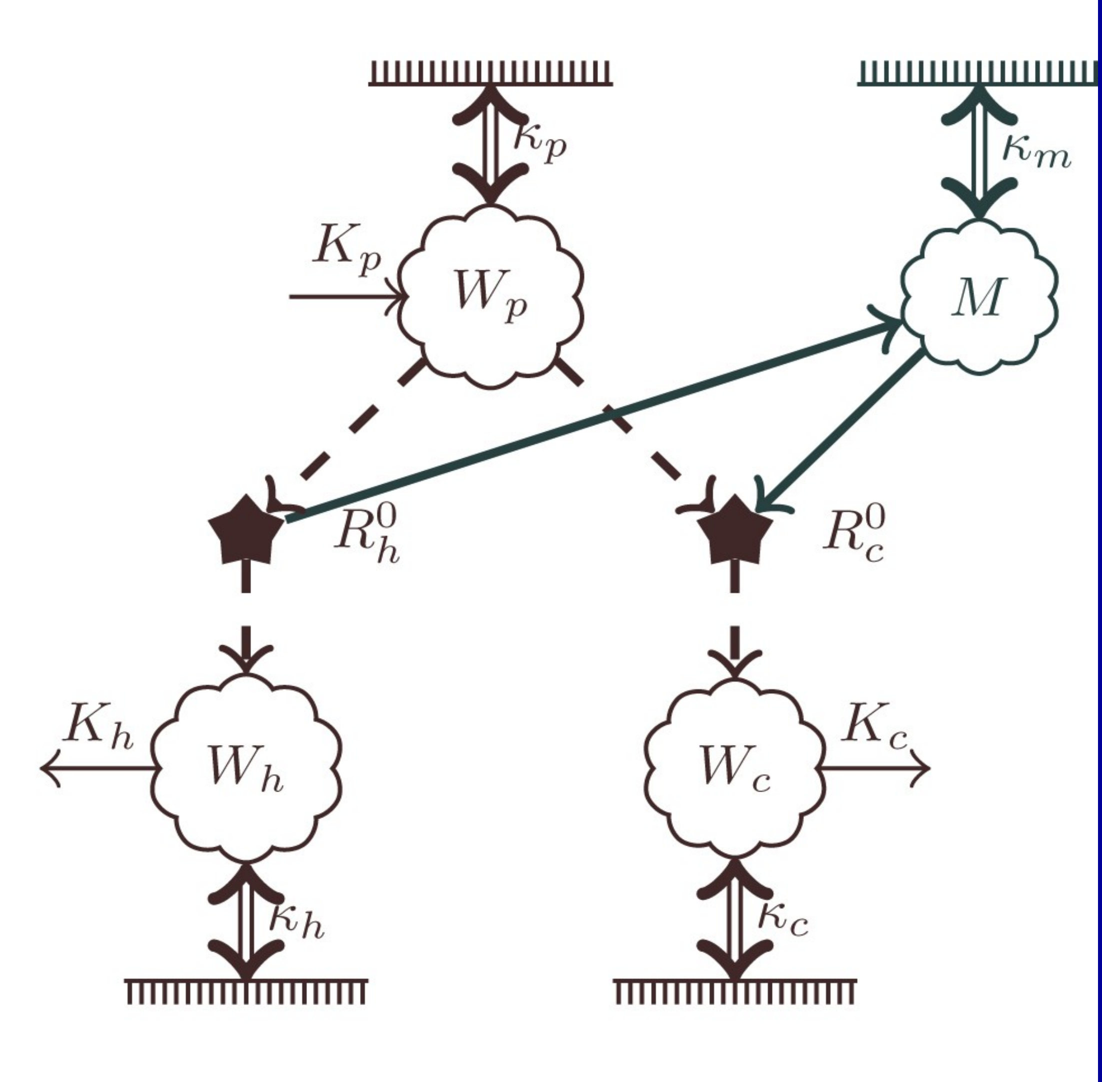
Magnon cooling: Use triple resonance



Optomechanical cooling: Drive at a sideband



Rate equations



$$W_p + M \to W_c$$

$$W_p \to M + W_h$$

Number of magnons:

$$n_m = \frac{\kappa_m n_{th} + R_h^0 n_p}{\kappa_m + \left(R_c^0 - R_h^0\right) n_p}$$

$$n_{th} = \left[1 + \exp\left(-\frac{\hbar\omega_m}{k_B T}\right)\right]^{-1}$$

$$R_{c,h}^0 = \frac{\left|g_{c,h}\right|^2 \left(\kappa_{c,h} + K_{c,h}\right)}{\left(\omega_p \pm \omega_m - \omega_{c,h}\right)^2 + \left(\kappa_{c,h} + K_{c,h}\right)^2 / 4}$$

Quantum treatment

$$W_p + M \rightarrow W_c$$

$$W_p \rightarrow M + W_h$$

- Input-output relations for photons
- Heisenberg equation (with dissipation) for magnons
- Disregard back-action of magnons on photons
- Solve for photons treating magnons as slow
- Solve for magnons assuming weak coupling and using mean-field

Quantum treatment

$$\frac{d\hat{M}}{dt} = -i\left(\tilde{\omega}_c + \tilde{\omega}_h\right)\hat{M} - \frac{\kappa_{tot}}{2}\hat{M} - \sqrt{\kappa_{tot}}\,\hat{b}(t)$$

$$\left\langle \hat{b}(t) \right\rangle = 0; \left\langle \hat{b}^{\dagger}(t)\hat{b}(t') \right\rangle = n_m \delta\left(t - t'\right)$$

Occupation number of magnons defines the magnon temperature

$$n_m = \frac{\kappa_m n_{th} + \bar{\kappa}_h}{\kappa_m + \bar{\kappa}_c - \bar{\kappa}_h} \qquad \bar{\kappa}_{c,h} = \frac{\left|g_{c,h}\right|^2 \left(\kappa_{c,h} + K_{c,h}\right)}{\left(\omega_p \pm \omega_m - \omega_{c,h}\right)^2 + \left(\kappa_{c,h} + K_{c,h}\right)^2 / 4} n_p$$

(same as from the rate equations:) $\bar{\kappa}_{c,h} = R_{c,h}^{(0)} n_p$

Magnon cooling

$$n_m = \frac{\kappa_m n_{th} + \bar{\kappa}_h}{\kappa_m + \bar{\kappa}_c - \bar{\kappa}_h}$$

– Can be both higher or lower than the thermal occupation

– Instability at $\kappa_m < \bar{\kappa}_h - \bar{\kappa}_c$

– Experimental evidence for cooling: Output power saturates as a function of input power

Magnon cooling

$$n_m = \frac{\kappa_m n_{th} + \bar{\kappa}_h}{\kappa_m + \bar{\kappa}_c - \bar{\kappa}_h}$$

Example: $\omega_p = 2\pi \times 300\text{THz}; Q_p = 10^6;$ $\kappa_m = 2\pi \times 1\text{MHz}; g_c = 2\pi \times 10\text{Hz}$ → $P_S = 140\text{W}$

Way too much; can be optimized by engineering magnon-photon overlap and increasing the coupling: we hope for 10 mW

– Cooling is experimentally observable even at low powers $P_S / 20$

$T = 1K, P = P_S$ Magnons get cooled down from 1.62 to 0.81 (0.6K)

Conclusions

➢ Transmission and reflection of light are qualitatively different and involve different magnon modes

➢ Asymmetry of Stokes and anti-Stokes peaks in transmission: due to the mode structure of WGM's

➢ Reflection: either Stokes or anti-Stokes present

➢ Cooling of magnons: different from optomechanical cooling; can be achieved with the current technology