Bottleneck accumulation of hybrid bosons in a ferrimagnet

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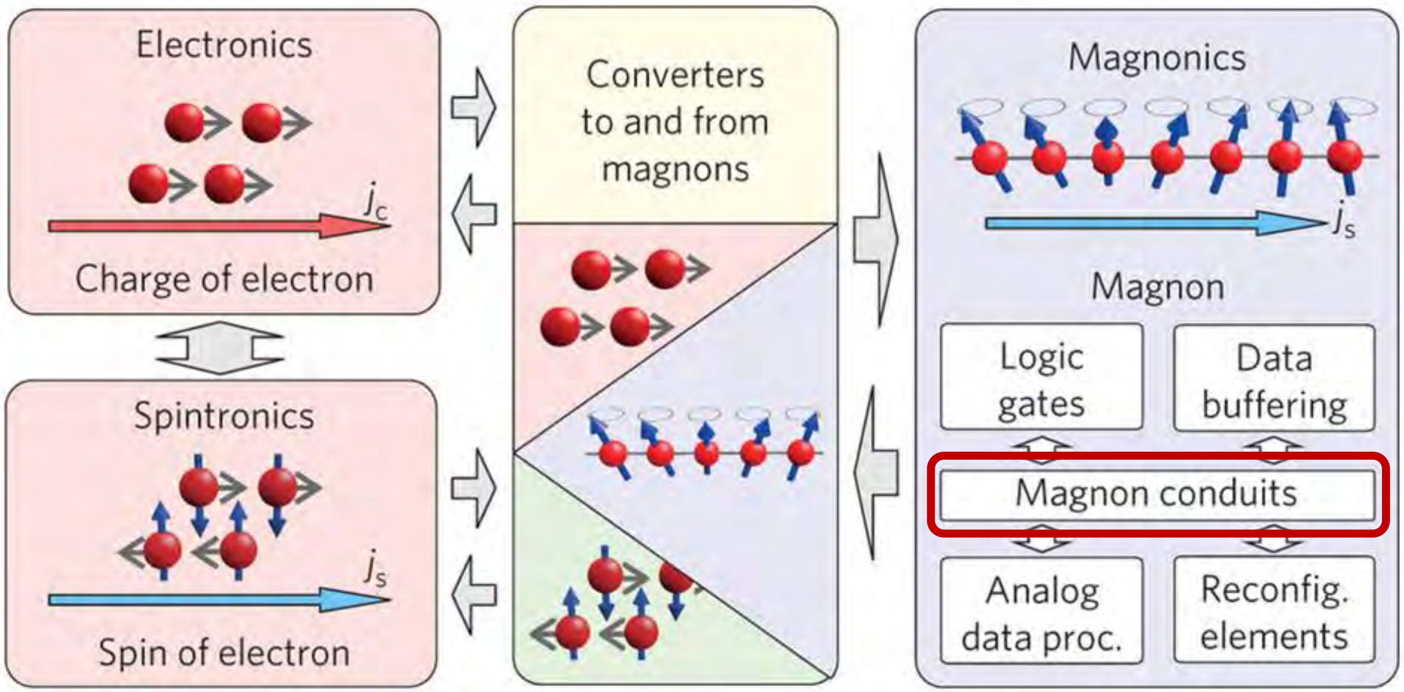
Magnon computing

Concept of magnon spintronics



A.V. Chumak *et al*., Nature Phys. **11**, 453 (2015)

Magnon transport plays a central role in magnonics

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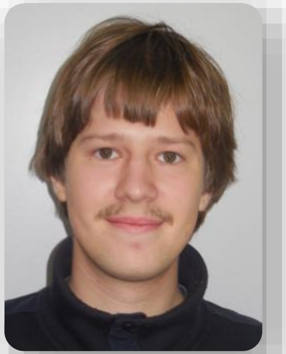
Team

Kaiserslautern University (Germany)



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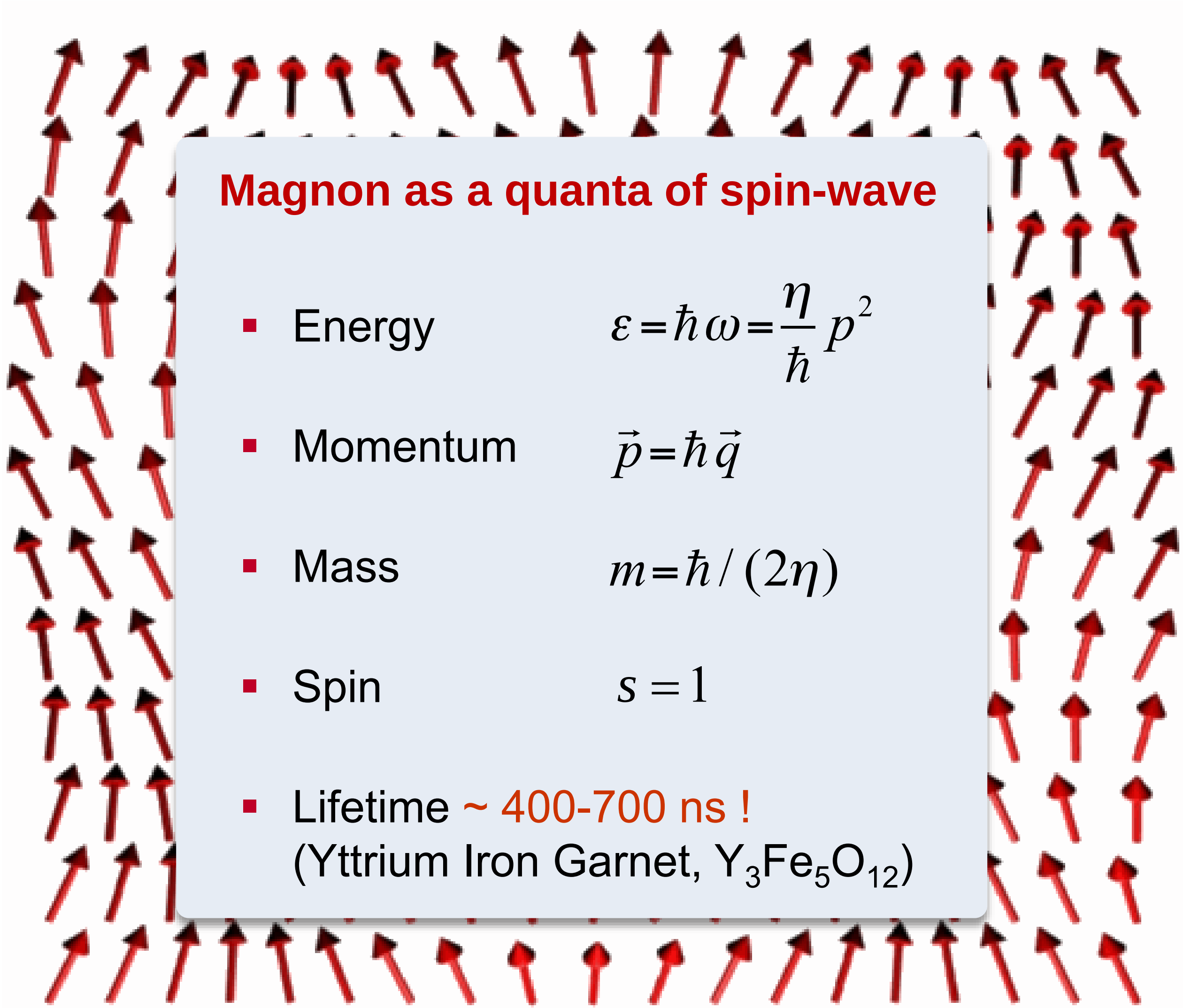
Magnon gas



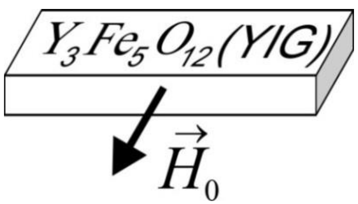
Magnon as a quanta of spin-wave

- Energy $\varepsilon = \hbar\omega = \frac{\eta}{\hbar} p^2$
- Momentum $\vec{p} = \hbar \vec{q}$
- Mass $m = \hbar / (2\eta)$
- Spin $s = 1$
- Lifetime ~ 400-700 ns !
  (Yttrium Iron Garnet, $Y_3Fe_5O_{12}$)

Magnon-phonon spectrum of in-plane magnetized YIG film

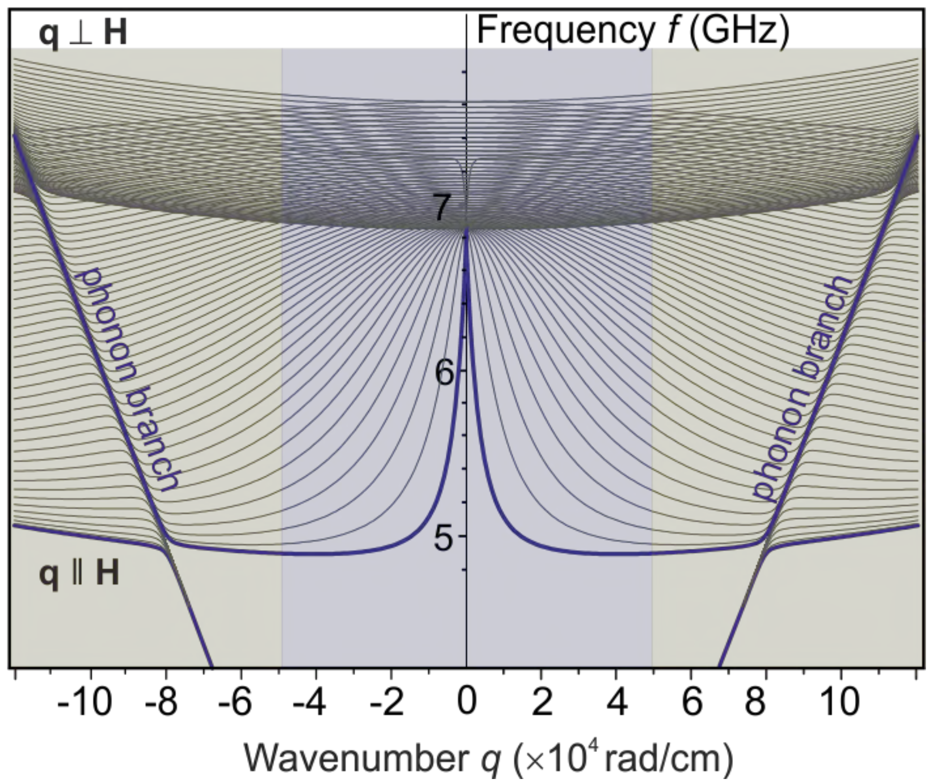
Landau-Lifshitz equation: $$\frac{\partial \vec{M}}{\partial t} = -|\gamma|\vec{M} \times \vec{H}_{\text{eff}}$$

$$\vec{H}_{\text{eff}}(\vec{r}) = \vec{H}_0 + \underbrace{\int_V \tilde{G}(\vec{r},\vec{r}\,') \cdot \vec{M}(\vec{r}\,')\, dr'^3}_{\text{dipolar interaction}} + \underbrace{\frac{\eta}{\gamma M_S}\nabla^2 \vec{M}}_{\text{exchange}} - \underbrace{\frac{\delta U_{\text{mel}}}{\delta \vec{M}}}_{\text{magnetoelastic}} + \ldots$$



YIG film: 6 µm

$H_0 = 1710$ Oe

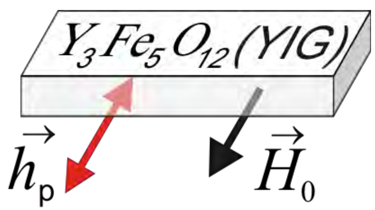


Magnon-phonon spectrum of in-plane magnetized YIG film

Energy and momentum conservation laws

$$\begin{cases} \vec{q}_{sw} + \vec{q}\,'_{sw} = \vec{q}_p \simeq 0 \\ f_{sw} + f'_{sw} = f_p \end{cases}$$

Parametric pumping by electromagnetic wave at microwave frequency



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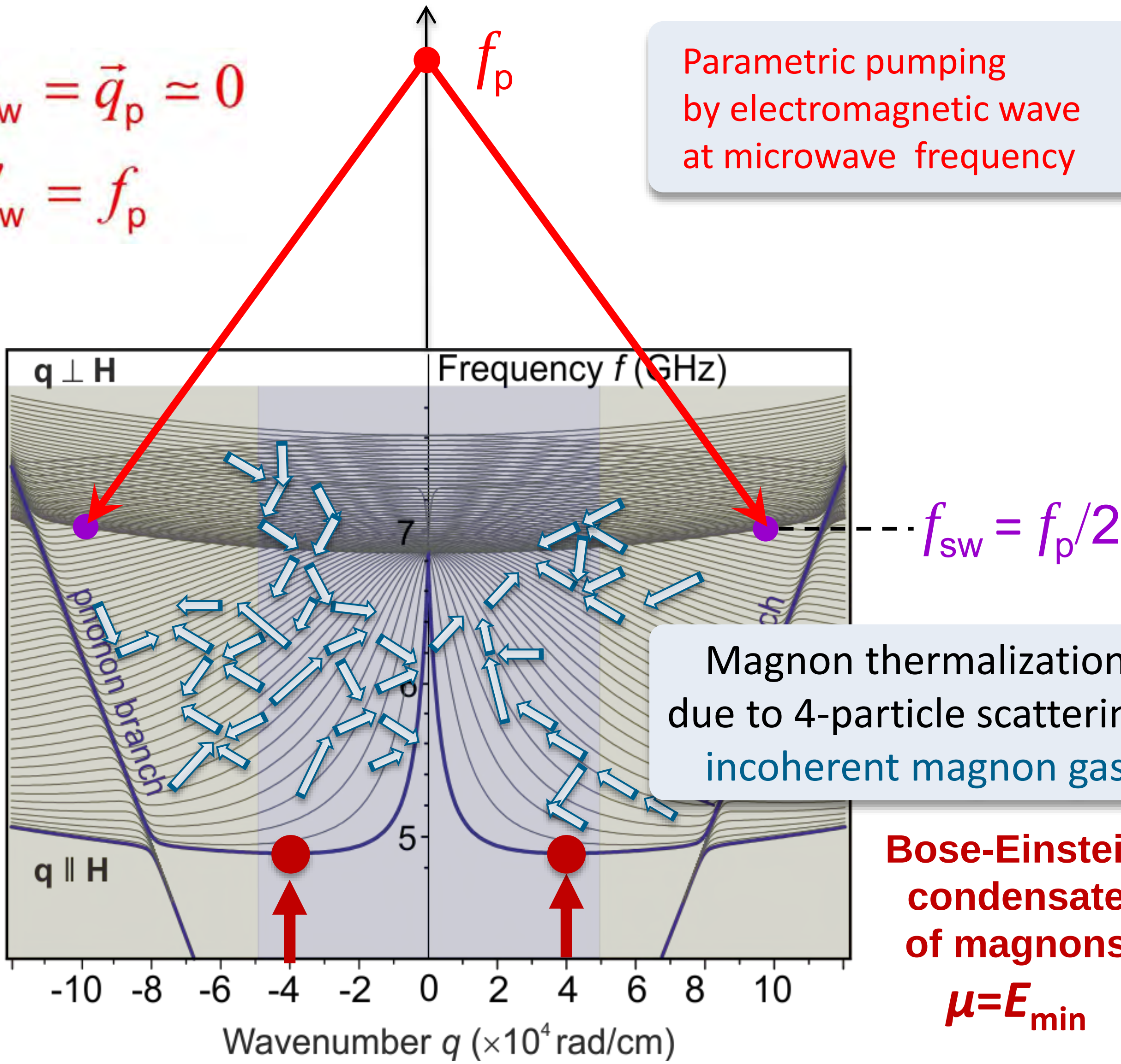

Magnon thermalization due to 4-particle scattering: incoherent magnon gas

Bose-Einstein condensate of magnons

$\mu = E_{min}$

S.O. Demokritov *et al.*, Nature **443**, 430 (2006)

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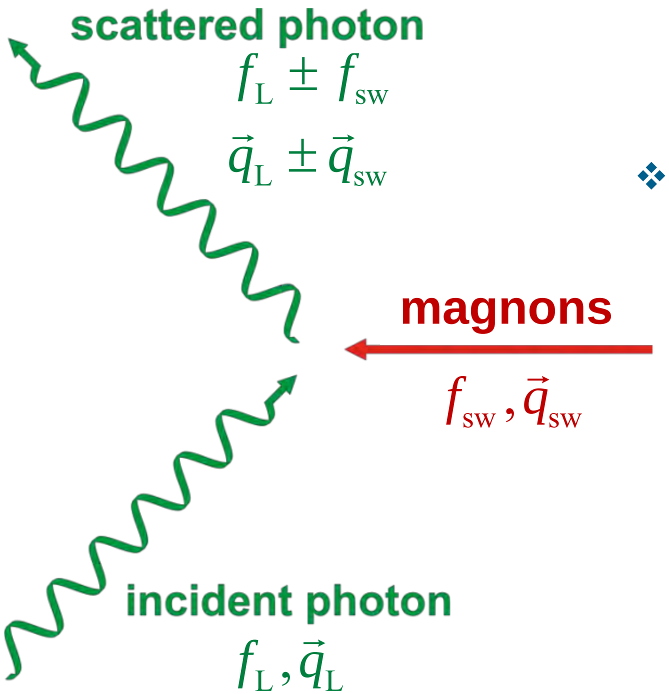
Brillouin light scattering (BLS) spectroscopy

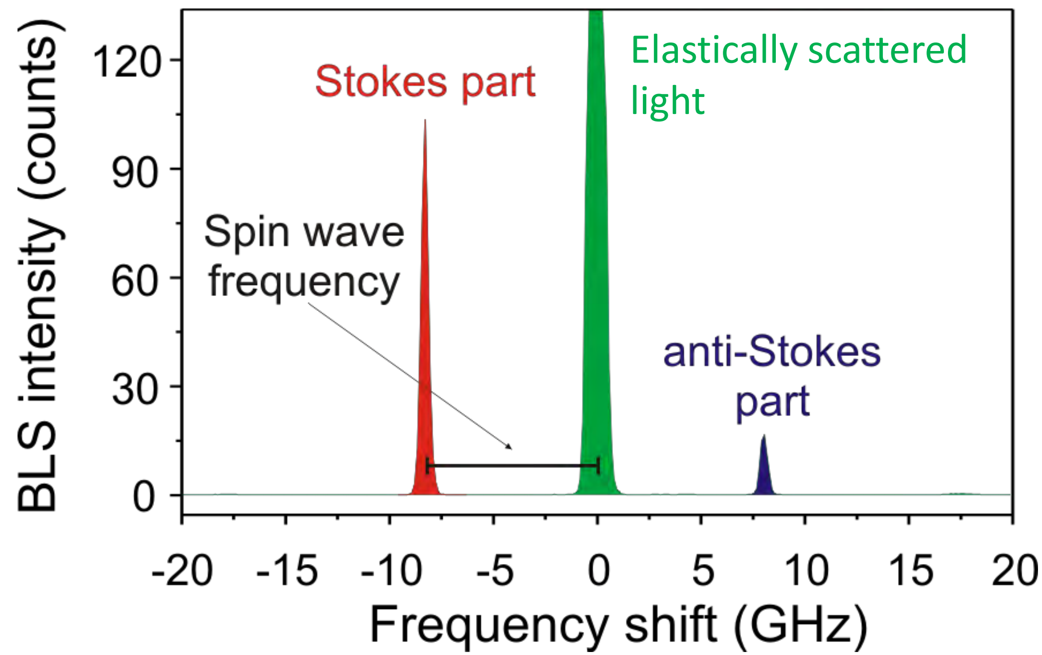
- Inelastic scattering of photons from spin waves

$$f_{\text{scattered L}} = f_{\text{L}} \pm f_{\text{sw}}$$

$$\vec{q}_{\text{scattered L}} = \vec{q}_{\text{L}} \pm \vec{q}_{\text{sw}}$$

- Intensity of the scattered light is proportional to magnon density

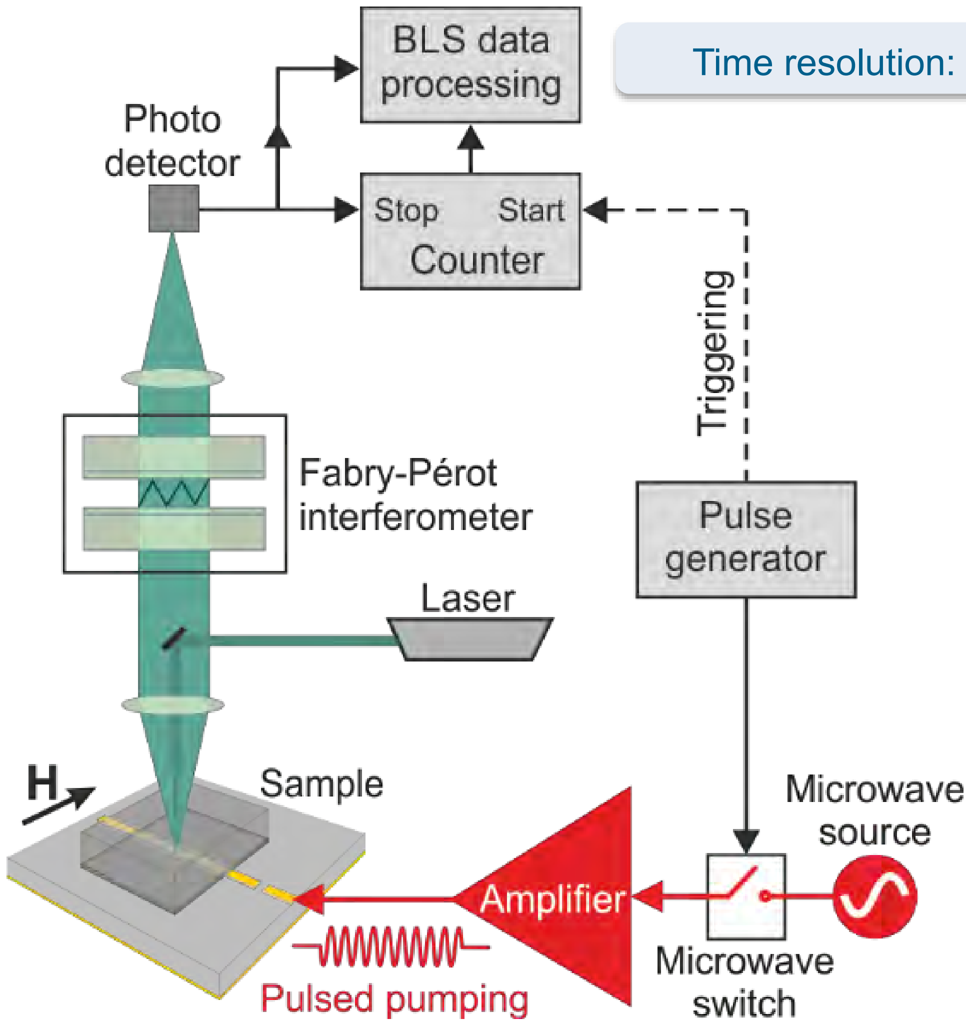




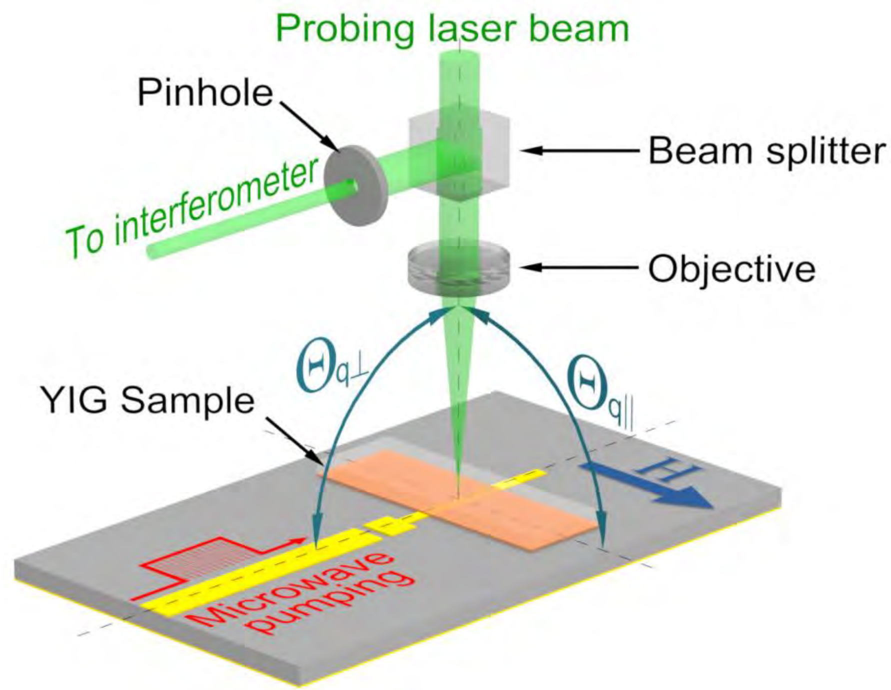
Frequency resolution: 50 MHz

Time- and wavevector-resolved BLS spectroscopy

Time resolution: 1 ns



$$q_{\mathrm{SW}} = 2q_L \cos\left(\Theta_q\right)$$



Max wavenumber:	2.36×10^5 rad/cm
Wavenumber resolution:	2×10^3 rad/cm

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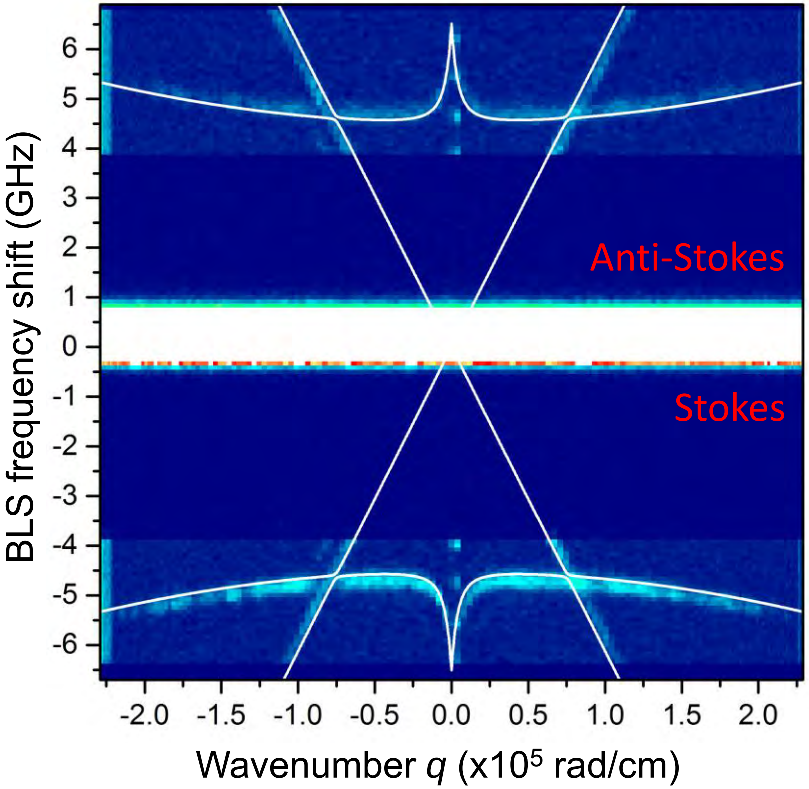
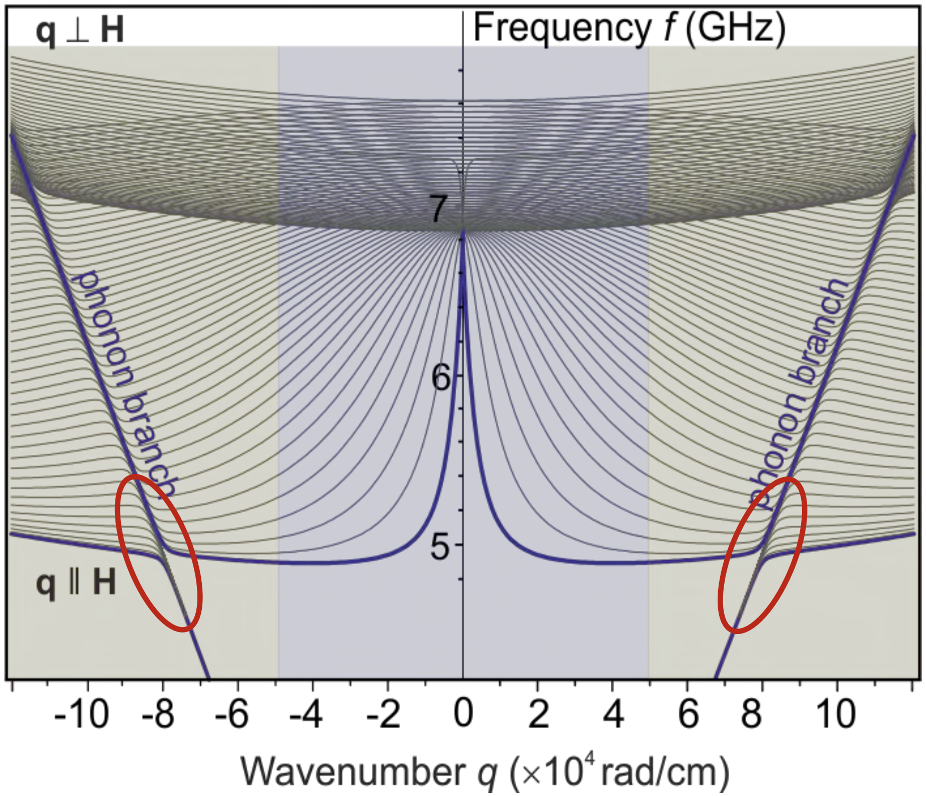
Wavevector-resolved BLS spectroscopy

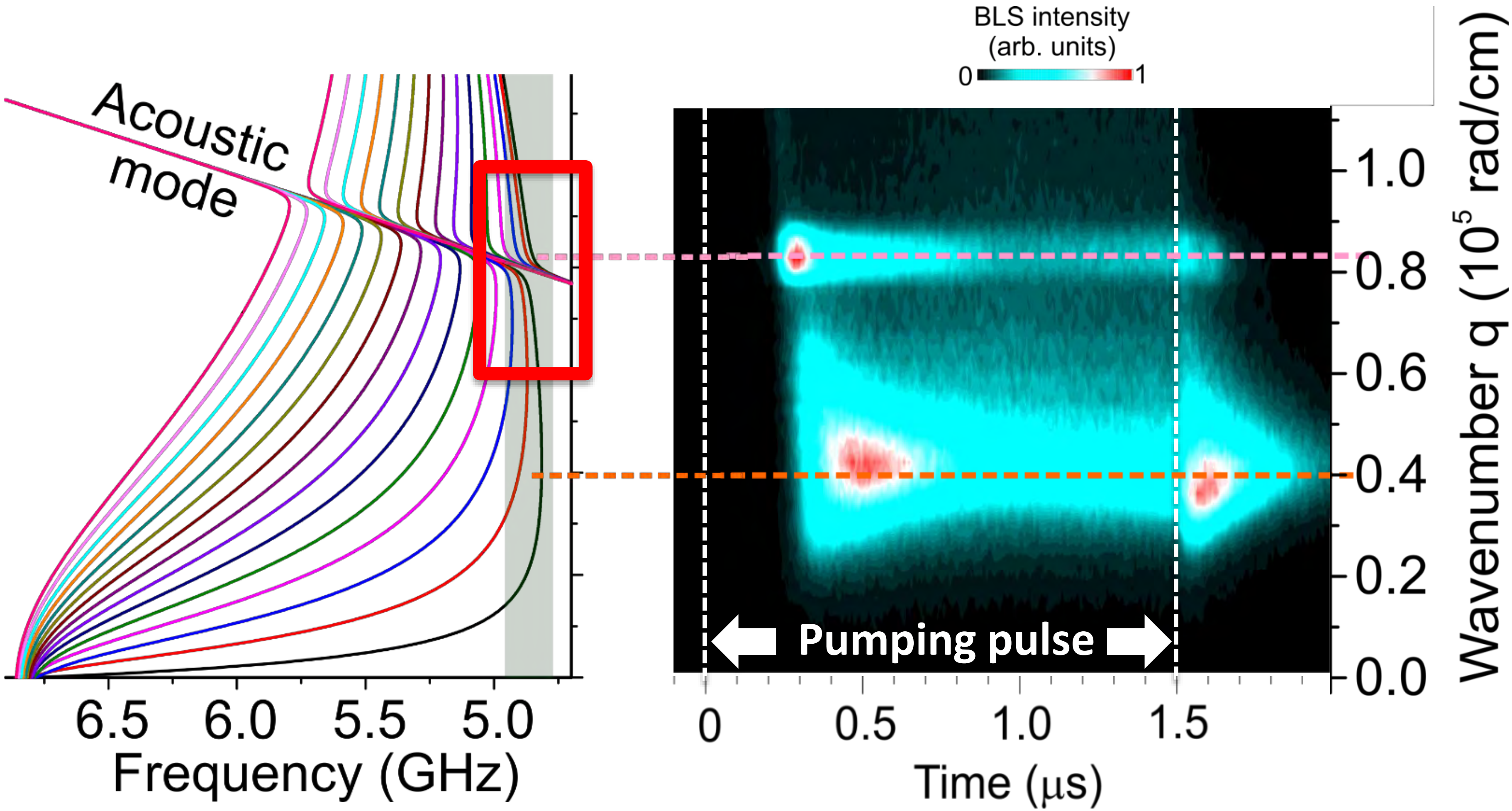
Thermal magnon-phonon spectrum





Hybridization between a phonon mode and magnon modes results in magneto-elastic magnon (MEM) mode

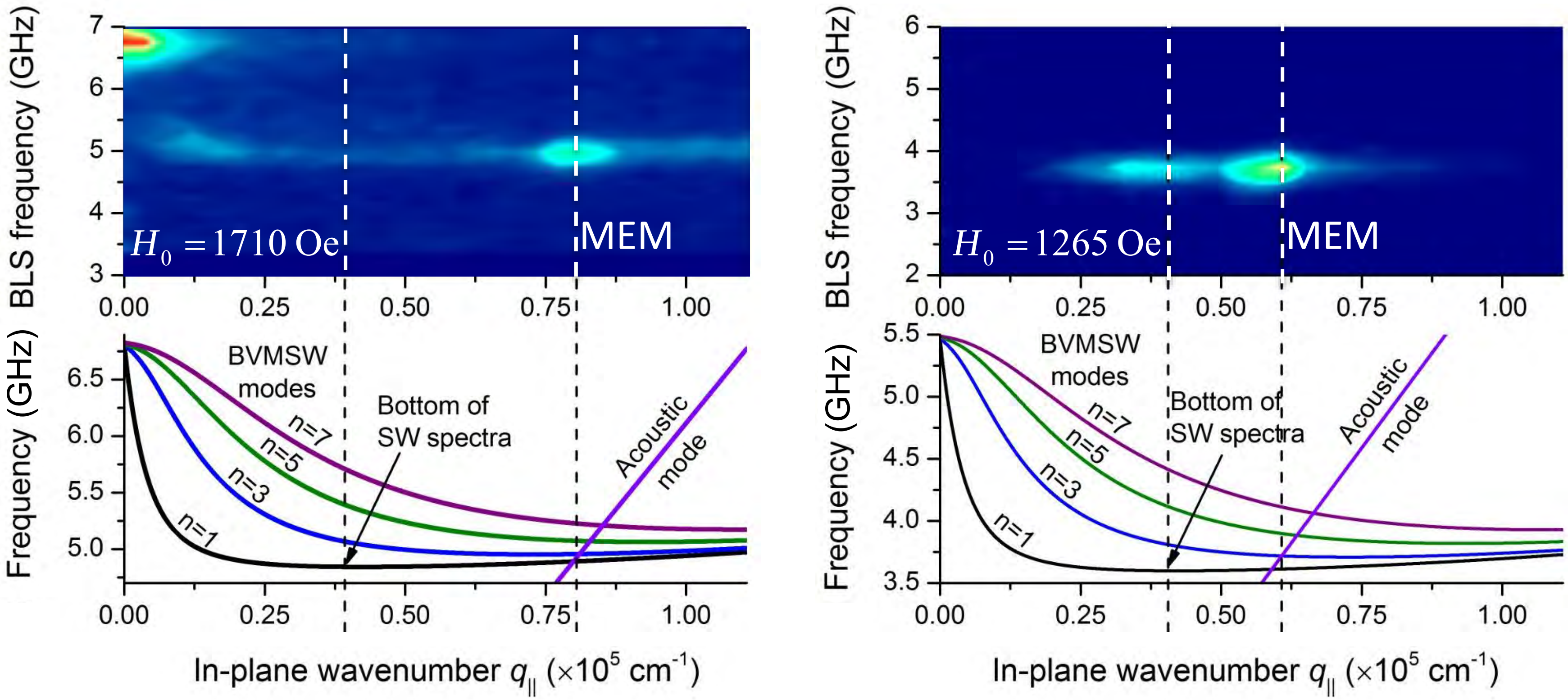
Gaseous phase and magnon BEC at the bottom of spin-wave spectrum



Parametrically injected magnons form Bose-Einstein condensate and accumulate in magneto-elastic magnon (MEM) mode

Magnon accumulation in MEM mode (under parametric pumping conditions)

Shift of the magnon density peak caused by change of the bias magnetic field



How magnons accumulate in the BEC and the MEM mode ?

Intercoupling of BEC and MEM

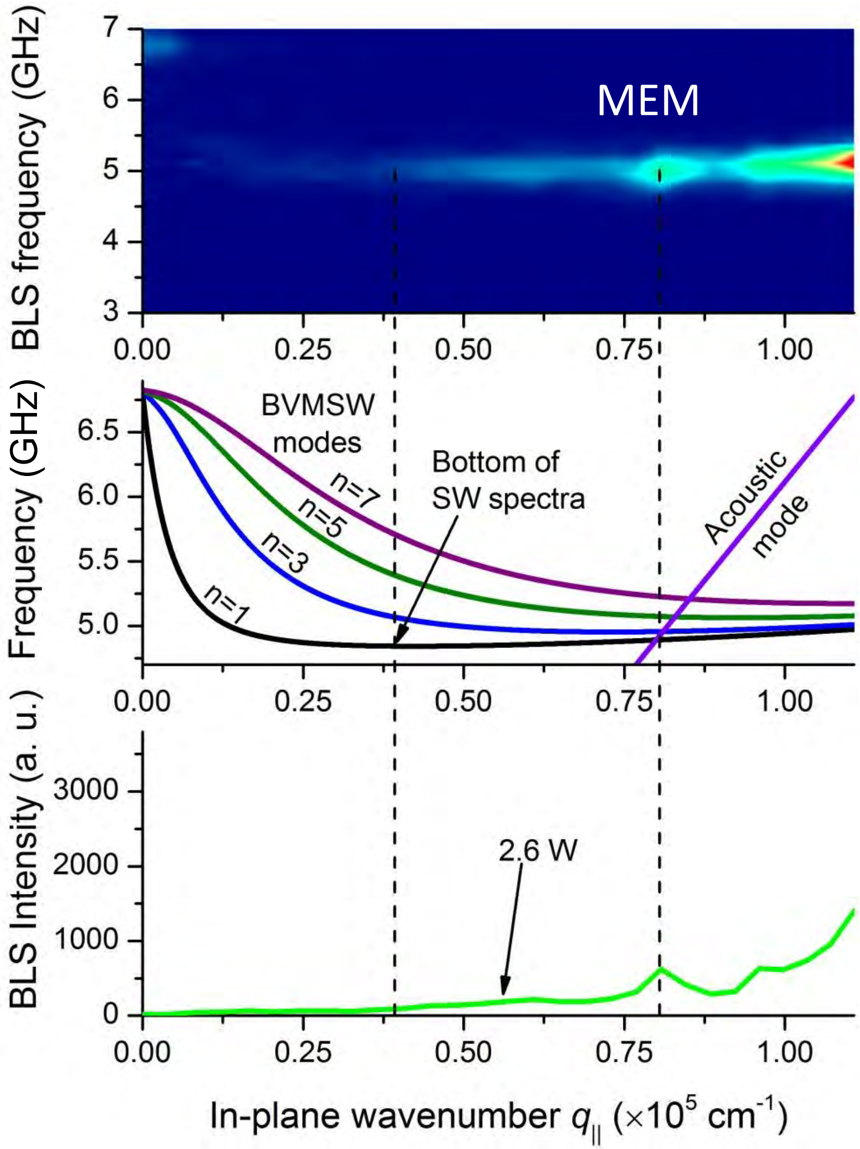
Magnon spectrum population at different pumping powers for

$H_0 = 1710\ \mathrm{Oe}$

$\frac{f_p}{2} = 6810\ \mathrm{MHz}$

Calculated magnon spectrum

Population of the low energy states at different pumping powers



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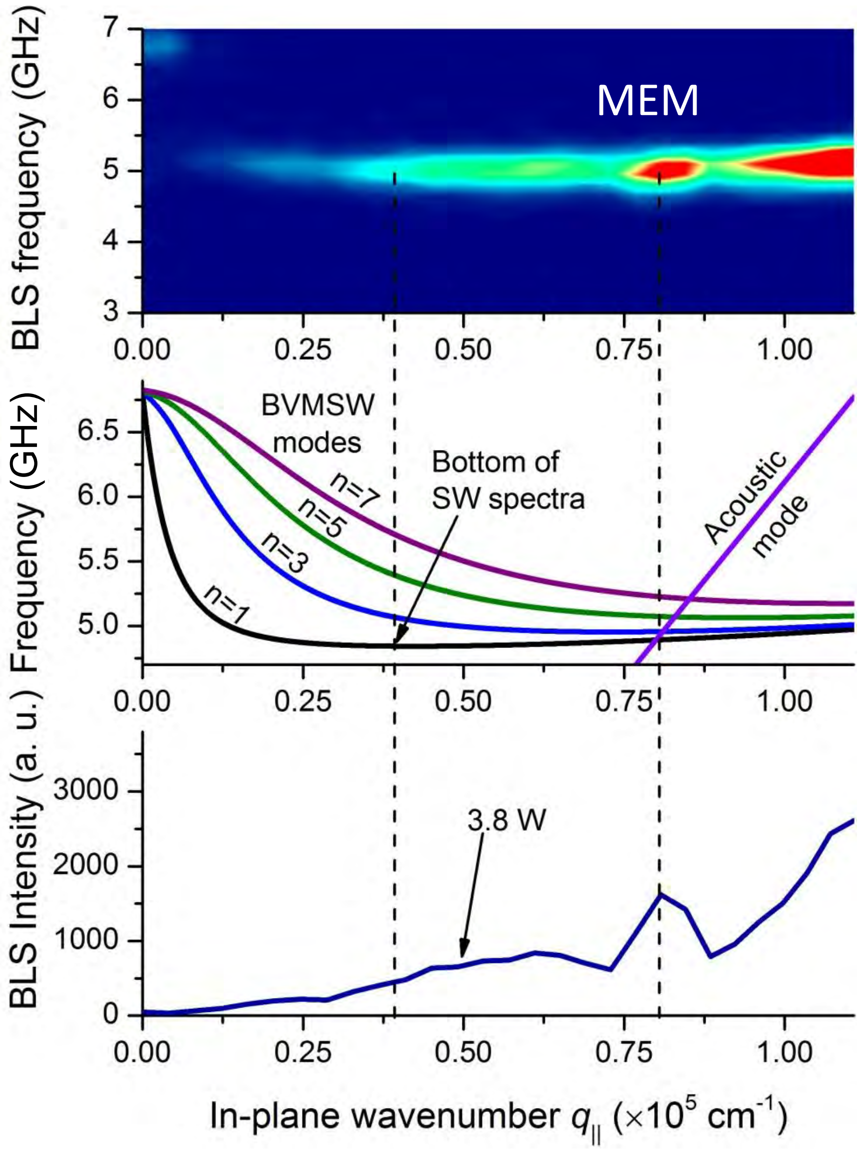

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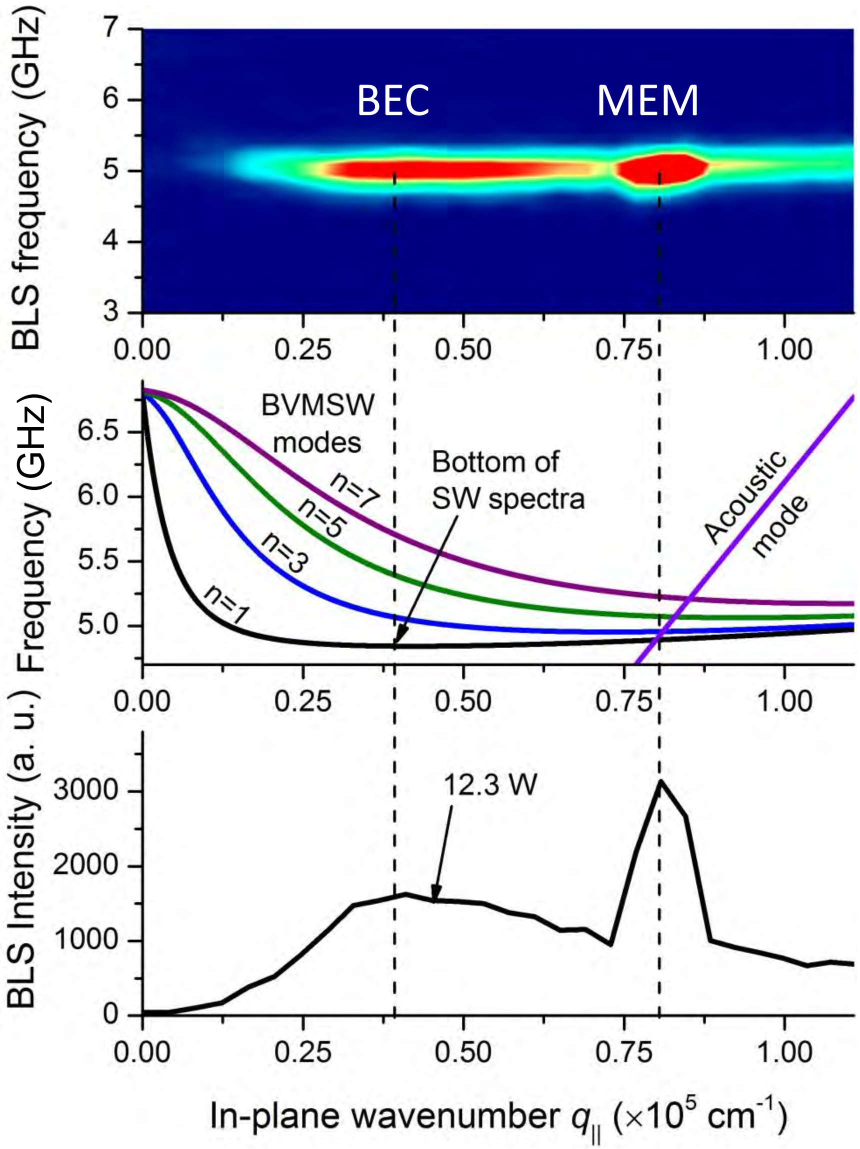

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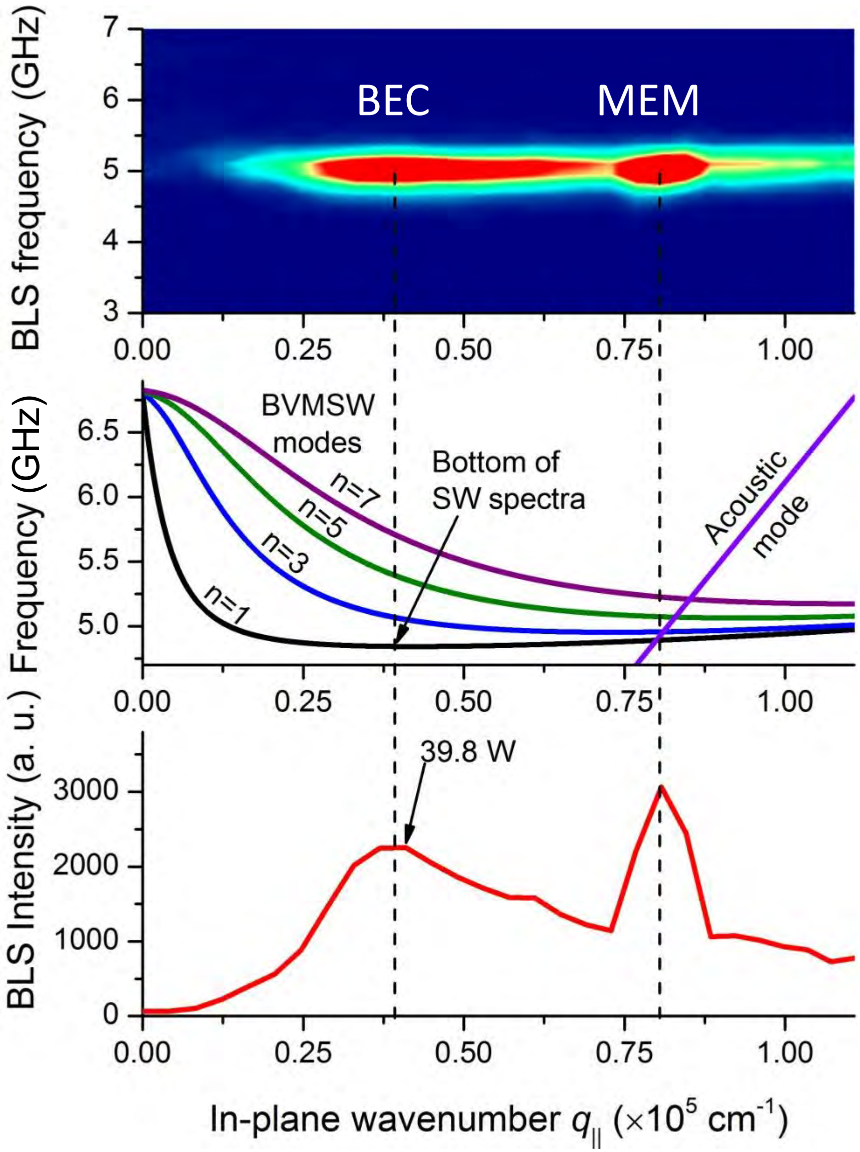

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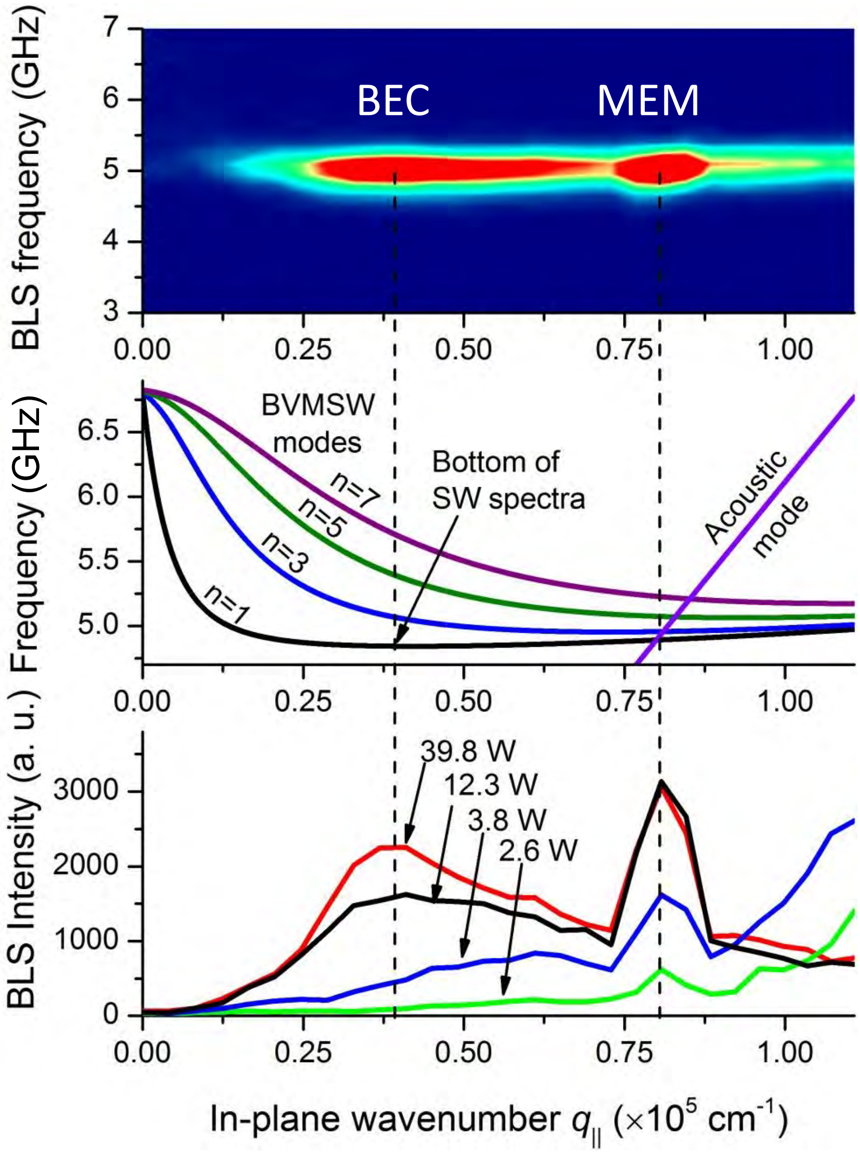

The MEM density peak appears before the magnon BEC

Formation of the magnon BEC is accompanied by **saturation** of the MEM peak

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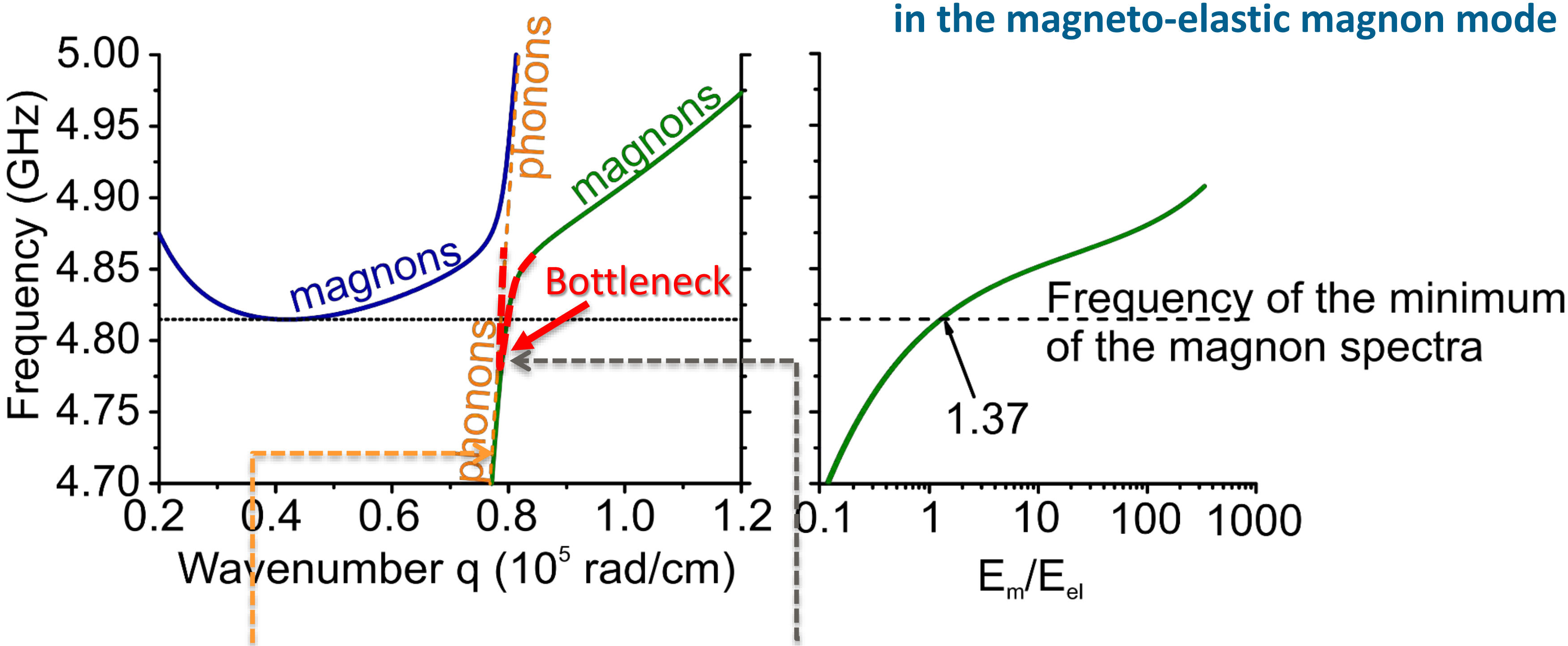
Accumulation of magnon-phonon hybrid particles

Magnon-phonon hybridization area

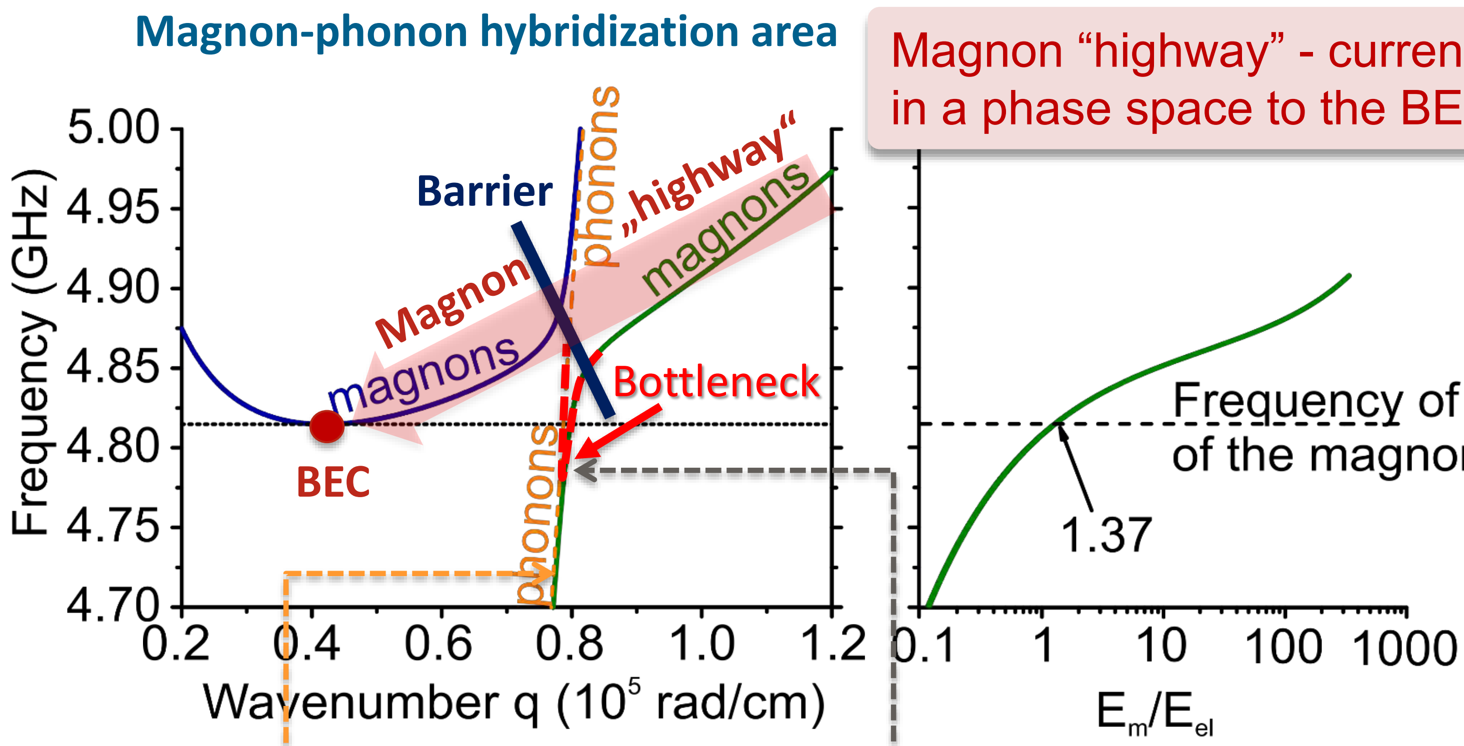
Ratio of magnetic E_m and elastic E_{el} energies in the magneto-elastic magnon mode



Pure phonon states -
no non-linear scattering and thus
no connection with upper
magnon states

Accumulation of the
hybridized magnon-phonon states
at the bottom of the magnon spectrum

Accumulation of magnon-phonon hybrid particles



Magnon “highway” - current of magnons in a phase space to the BEC state

Pure phonon states - no non-linear scattering and thus no connection with upper magnon states

Accumulation of the hybridized magnon-phonon states at the bottom of the magnon spectrum

Hamiltonian approach to magnon-phonon hybridization

Hamiltonian equation of motion:

$$i\frac{\partial a_q}{\partial t} = \frac{\partial \mathcal{H}}{\partial a_q^*} \qquad i\frac{\partial b_q}{\partial t} = \frac{\partial \mathcal{H}}{\partial b_q^*}$$

Magnon – phonon hybridization Hamiltonian

$$\mathcal{H} = \mathcal{H}_2 + \mathcal{H}_4$$

$$\mathcal{H}_2 = \sum_q \left[\omega_q^{\mathrm{m}} a_q a_q^* + \omega_q^{\mathrm{p}} b_q b_q^* + \frac{\Delta}{2}\left(a_q b_q^* + a_q^* b_q\right) \right]$$

magnons, phonons, hybridization

Δ - magnetoelastic coupling amplitude

$$\mathcal{H}_4 = \frac{1}{4} \sum_{q_1+q_2=q_3+q_4} T_{12,34} a_1^* a_2^* a_3 a_4$$

$T_{12,34}$ - Interaction amplitudes

Interaction Hamiltonian of 2↔2 magnon scattering

V. L'vov and A. Pomyalov, unpublished

Magnon-phonon hybridization

Linear canonical Bogoliubov transformation for transition to hybridized MEM modes $c_q^{\pm}$

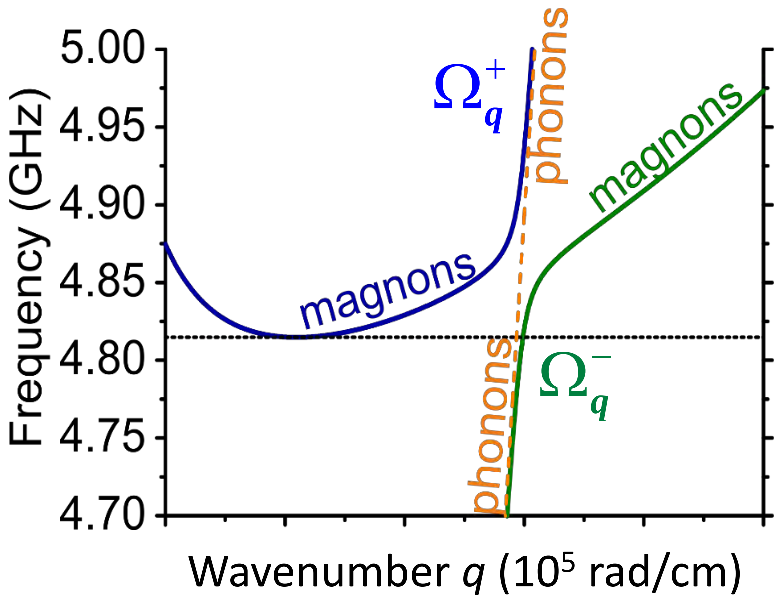
$$\begin{cases} a_q = \cos(\varphi_q) c_q^- + \sin(\varphi_q) c_q^+ \\ b_q = -\sin(\varphi_q) c_q^- + \cos(\varphi_q) c_q^+ \end{cases}$$

Rotation in the (a_q, b_q) plane allows us to obtain the diagonal quadratic Hamiltonian

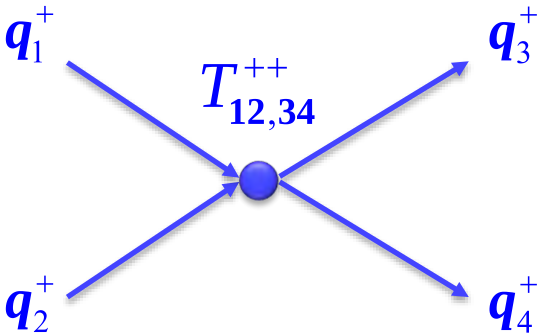
$$\mathcal{H}_2 = \sum_q \left[\Omega_q^+ c_q^+ c_q^{+*} + \Omega_q^- c_q^- c_q^{-*} \right]$$

$$\Omega_q^{\pm} = \frac{1}{2} \left\{ \omega_q^{\mathrm{m}} + \omega_q^{\mathrm{p}} \pm \sqrt{\left[\omega_q^{\mathrm{m}} - \omega_q^{\mathrm{p}} \right]^2 + \Delta^2} \right\}$$

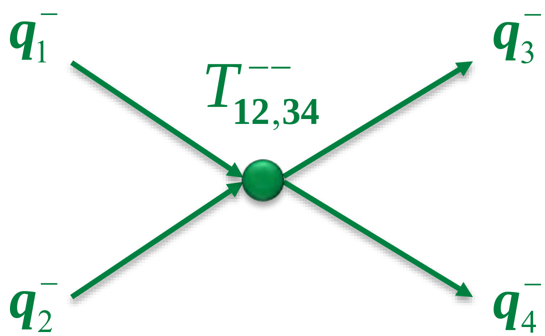
for the upper and lower MEM modes



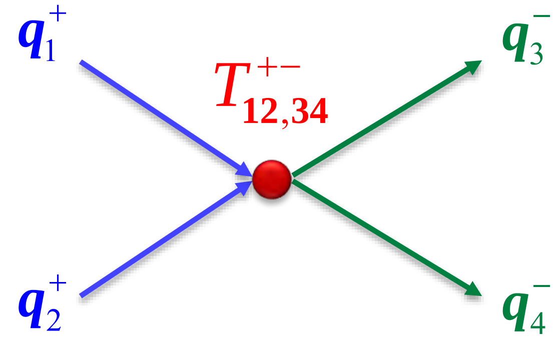
Interaction amplitudes T of the upper and lower MEMs



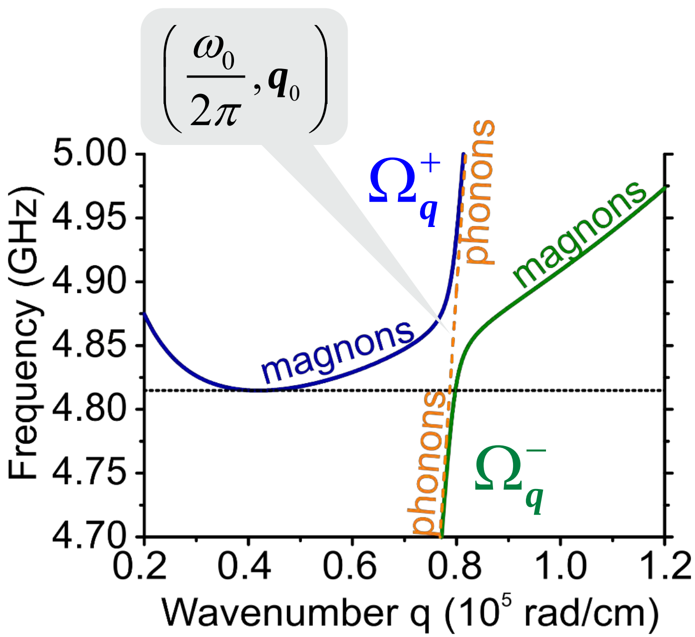
Upper-Upper interaction



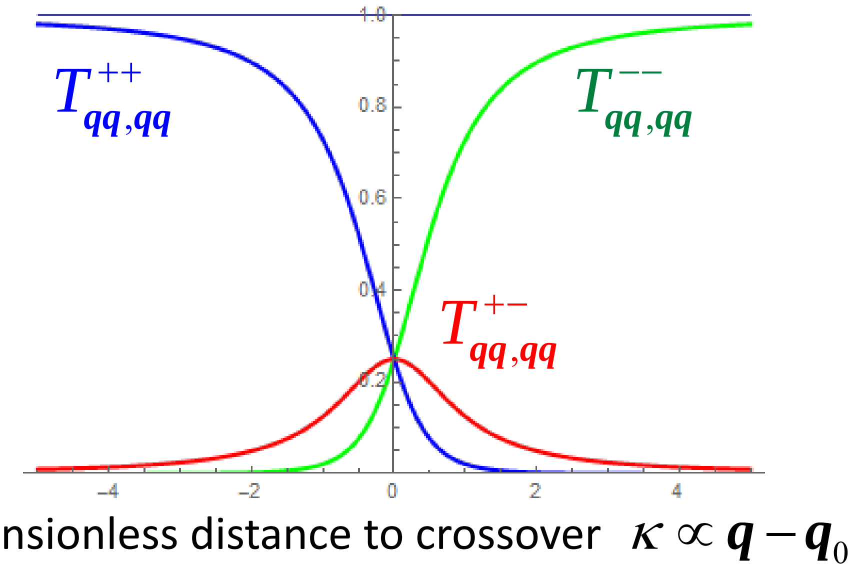
Lower-Lower interaction



Cross Upper-Lower MEMs interaction



Wavenumber dependence of interaction amplitudes



Statistical description

$$\frac{\partial \mathcal{N}_q^-}{\partial t} = \frac{d\mu_q}{dq} - F_q^{-+}$$

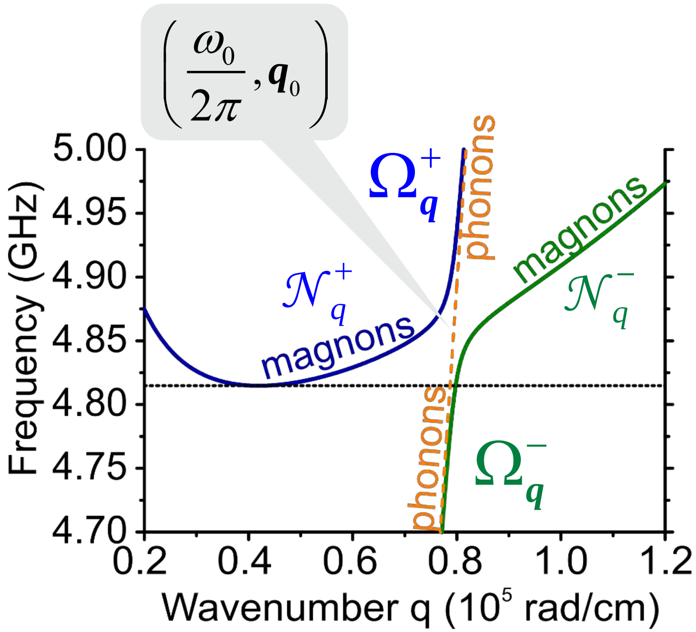
- Kinetic Equation for the lower MEM mode occupation numbers $\mathcal{N}^-$

$$\mu_q \propto \left|T_q^{--}\right|^2 \left(\mathcal{N}_q^-\right)^3$$

- flux of $\mathcal{N}^-$ towards the hybridization region

$$F_q^{-+} \propto \left|T_q^{-+}\right|^2 \left(\mathcal{N}_q^-\right)^2 \mathcal{N}_q^+$$

- transition rate $\mathcal{N}^- \rightarrow \mathcal{N}^+$ in the hybridization region



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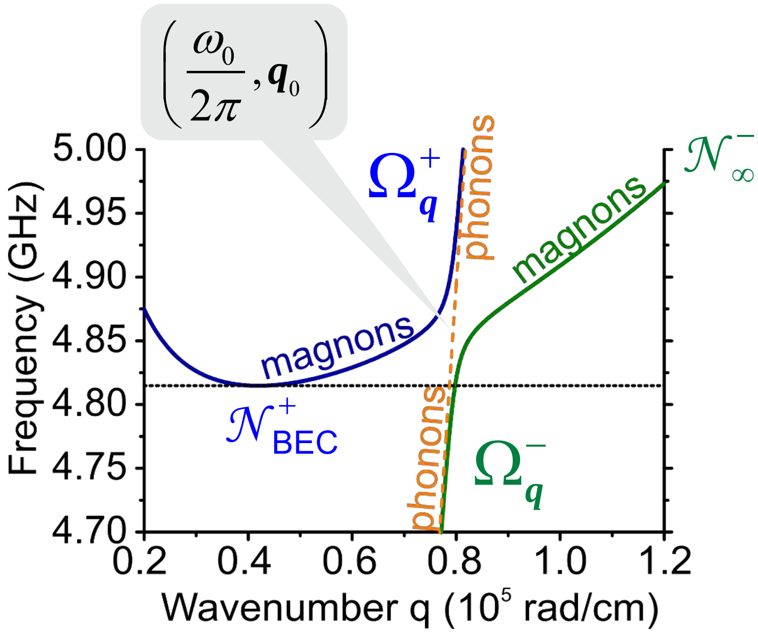
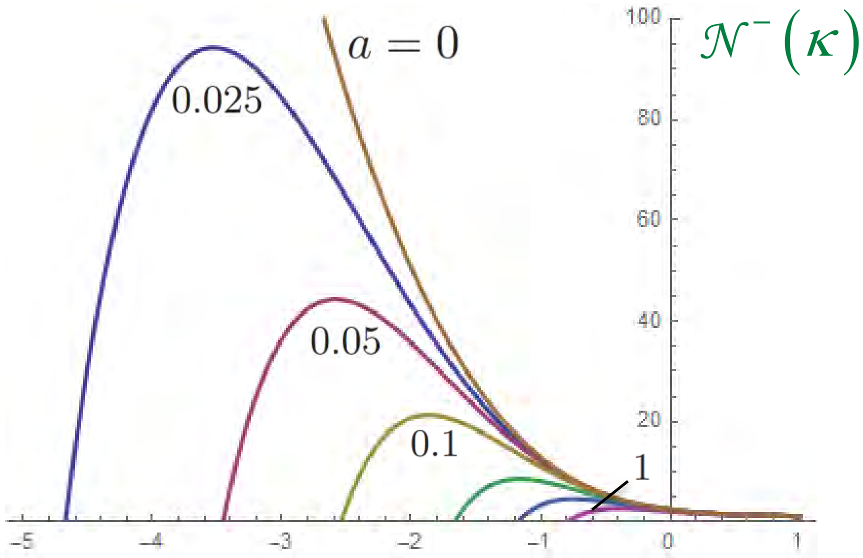
$$F_q^{-+} \propto \left|T_q^{-+}\right|^2 \left(\mathcal{N}_q^-\right)^2 \mathcal{N}_q^+$$

Solution of the kinetic equation

$$\mathcal{N}_q^- = \frac{1}{(\cos\varphi_q)^{8/3}}\left[1 - a\int_q^\infty \frac{(\sin\varphi_p)^4\,dp}{(\cos\varphi_p)^{4/3}}\right]$$

$$a \simeq \frac{\mathcal{N}_{\mathrm{BEC}}^+}{\mathcal{N}_\infty^-}$$





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Statistical description

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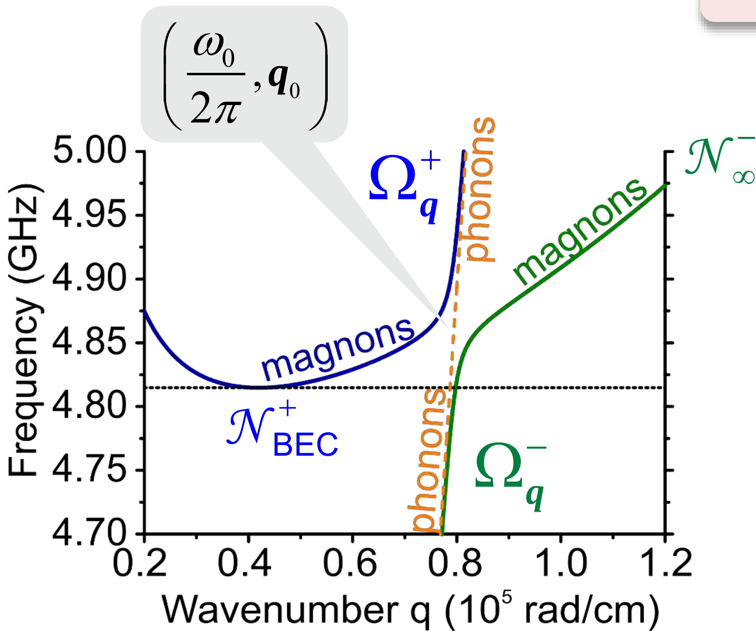
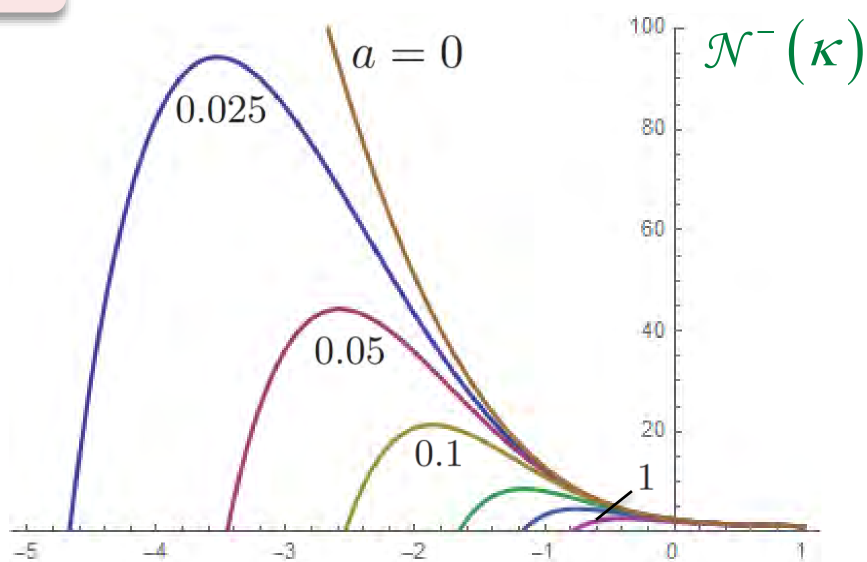
$$F_q^{-+} \propto \left|T_q^{-+}\right|^2 \left(\mathcal{N}_q^-\right)^2 \mathcal{N}_q^+$$

Increase in the magnon BEC population $\mathcal{N}_{\text{BEC}}^+$
decreases bottleneck effect
and explains the saturation phenomenon

$$a \simeq \frac{\mathcal{N}_{\text{BEC}}^+}{\mathcal{N}_\infty^-}$$





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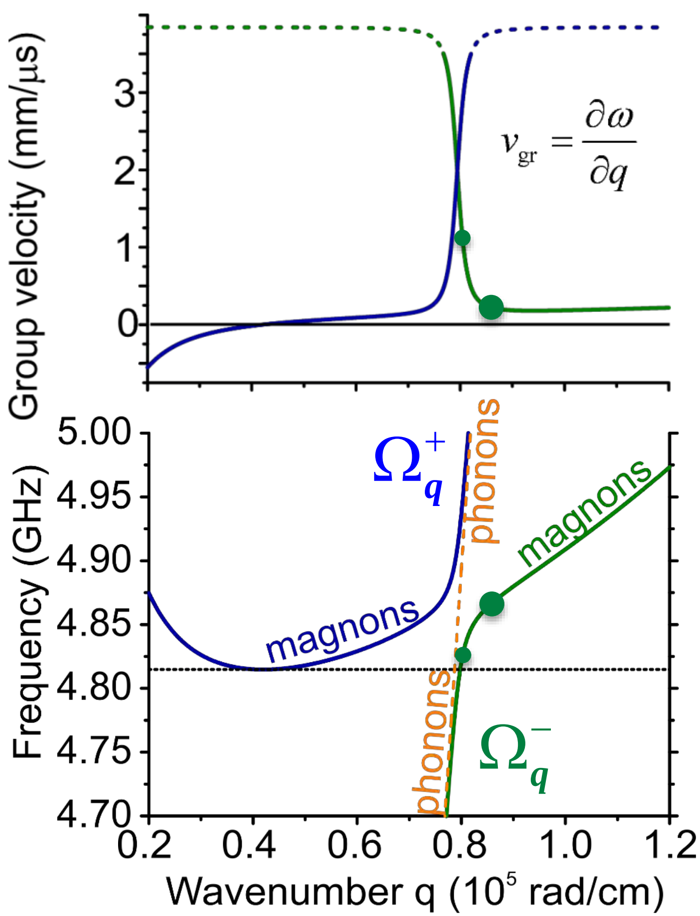
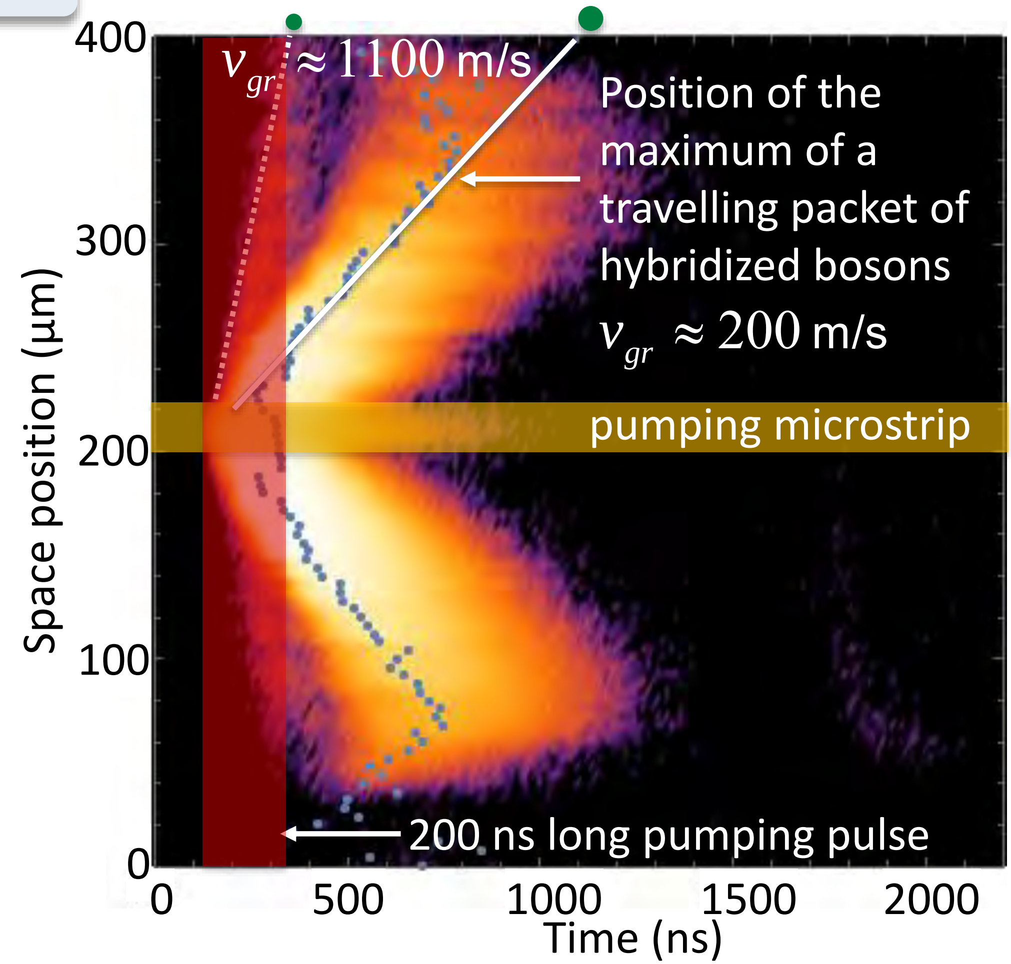
Transport measurements of accumulated hybridized bosons

Accumulation of hybridized bosons with non-zero group velocity can be used for spin transport

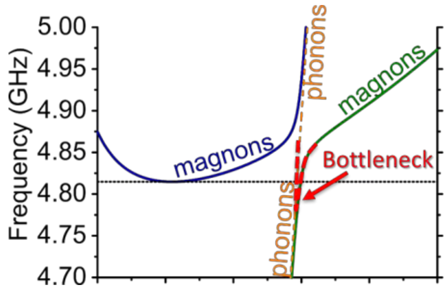


Experimental time-space diagram for MEM mode

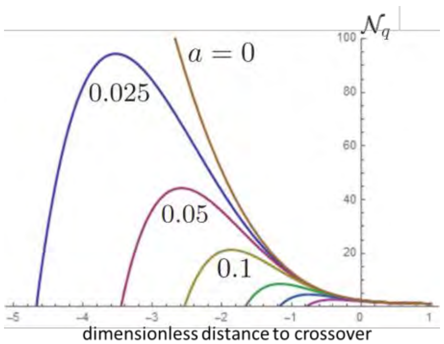


Summary

- Hybridization between magnons and phonons creates a spectral bottleneck in the system



- The effects evidence the bottleneck accumulation of the hybridized magnon-phonon bosons at the bottom of the magnon spectrum



- Developed minimal model describes observed phenomenon of the hybrid bosons accumulation

- Accumulation of hybridized bosons with non-zero group velocity can be used for spin transport