Spin wave resonance techniques

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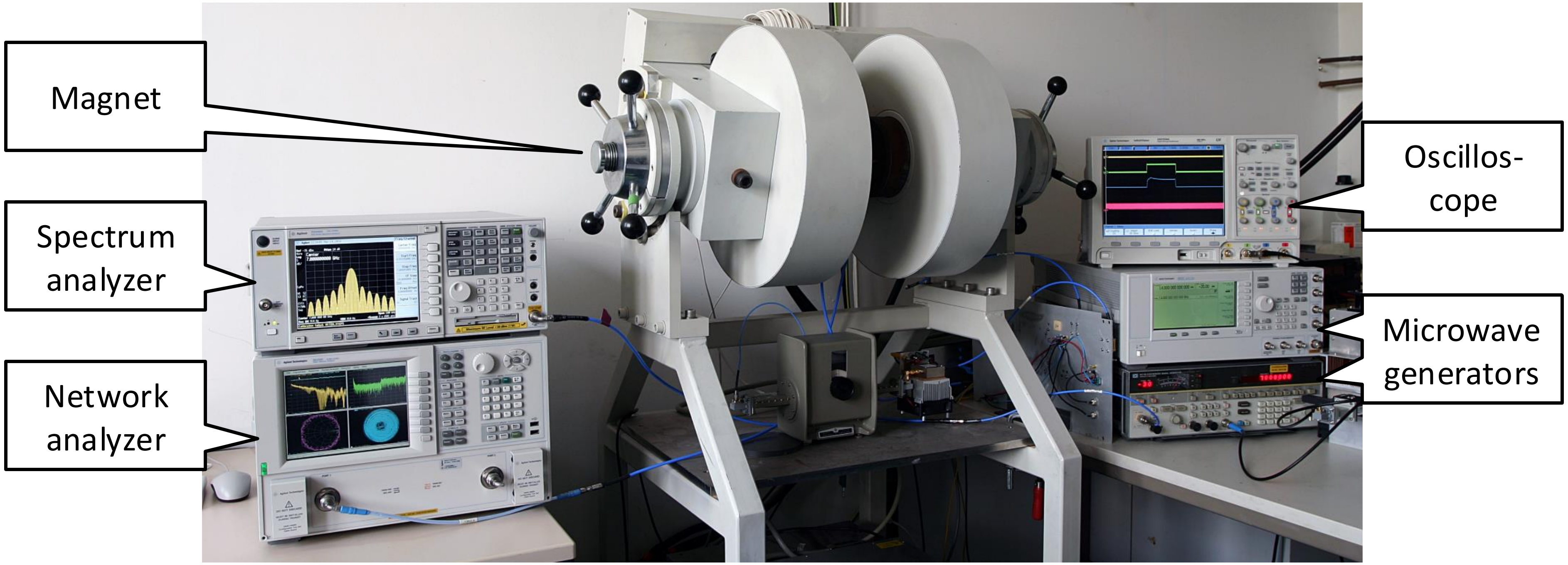
OPTIMAS light-spin-matter

Microwave experiment

What is a microwave experiment with spin waves?

- Microwave excitation of spin waves and detection by other means (e.g. direct current/voltage, BLS, MOKE)
- Microwave input + output experiments $\rightarrow$ transmission and reflection experiments

Microwave technique

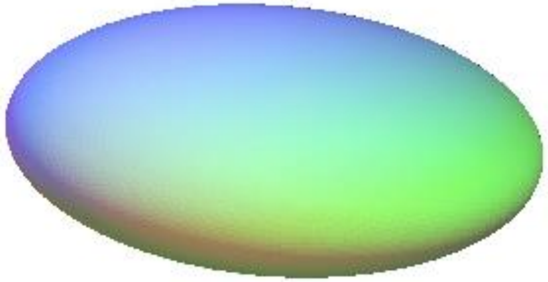


- Continuous and pulsed microwave signals having powers up to ≈100 W in frequency range from 1 to 20 GHz
- Precise spin-wave amplitude and phase measurements in a wide frequency range using spectrum and network analyzers
- Temporal measurements with sub-ns resolution using a broadband oscilloscope
- Microwave characterization: both linear and nonlinear dynamics of magnetization in nano-structured and in macroscopic samples

Uniform resonant oscillation of ellipsoid

Problem: demagnetizing field is most often inhomogeneous.

- only exception: ellipsoid



Magnetic field $\vec{B}_{\text{int}}$ inside ellipsoid as function of external field $\vec{B}_{\text{ext}}$:

$$\vec{B}_{\text{int}} = \vec{B}_{\text{ext}} - \mu_0 \overleftrightarrow{N}\vec{M} = \vec{B}_{\text{ext}} + \vec{B}_{\text{demag}}$$

with $\overleftrightarrow{N}$: demagnetizing tensor, symmetric, $N_{xx} + N_{yy} + N_{zz} = 1$,

$\vec{B}_{\text{demag}}$: demagnetizing field,

$N_{xy} = 0$ for $x \neq y$ if $\vec{B}_{\text{ext}} \parallel$ principal axis of ellipsoid.

Condition of equilibrium for equilibrium saturation magnetization $\vec{M}_0$ in energy minimum:

$$\vec{M}_{\text{S}} \times \left(\vec{B}_{\text{ext}} - \mu_0 \overleftrightarrow{N}\vec{M}_{\text{S}} \right) = 0$$

Equation of motion: $\frac{1}{\gamma}\frac{\partial \vec{M}}{\partial t} = -\vec{M} \times \vec{B}_{\text{int}}$, and, with $\vec{M}(t) = \vec{M}_{\text{S}} + \vec{m}_0 \mathrm{e}^{\mathrm{i}\omega t}$, $\vec{B}_{\text{ext}} \parallel \vec{M}_{\text{S}} \parallel \hat{e}_z$

in linear approximation:

$$\begin{array}{lclcl} (\mathrm{i}\omega + \gamma N_{xy}\mu_0 M_{\text{S}}) m_x & + & \gamma (B_{\text{ext}} - N_{zz}\mu_0 M_{\text{S}} + N_{yy}\mu_0 M_{\text{S}}) m_y & = & 0 \\ -\gamma (B_{\text{ext}} - N_{zz}\mu_0 M_{\text{S}} + N_{xx}\mu_0 M_{\text{S}}) m_x & + & (\mathrm{i}\omega - \gamma N_{xy}\mu_0 M_{\text{S}}) m_y & = & 0 \end{array}$$

Uniform resonant oscillation of ellipsoid in oblique field

Eigen frequencies:

$$\omega_0^2 = \left(\omega_B + \gamma\mu_0 N_{xx} M_S\right)\left(\omega_B + \gamma\mu_0 N_{yy} M_S\right) - \gamma^2\mu_0^2 N_{xy}^2 M_S^2$$

with $\omega_B = \gamma(B_{ext} - \mu_0 N_{zz} M_S)$

Example: $\vec{B}_e$ along one of the principal axes $\Rightarrow$ $\overleftrightarrow{N}$ is diagonal

$$\Rightarrow \quad \omega_0^2 = \gamma^2\left(B_{ext} + \mu_0(N_{xx} - N_{zz})M_S\right)\left(B_{ext} + \mu_0(N_{yy} - N_{zz})M_S\right)$$

Thin film in xy-plane magnetized along $\hat{z}$-axis, i.e., $N_{xx} = N_{yy} = 0, \; N_{zz} = 1$

$\Rightarrow \quad \omega_0 = \gamma\left(B_{ext} - \mu_0 M_S\right)$, i.e. internal field is external field minus saturation magnetization

Thin film in xz-plane magnetized along $\hat{z}$-axis

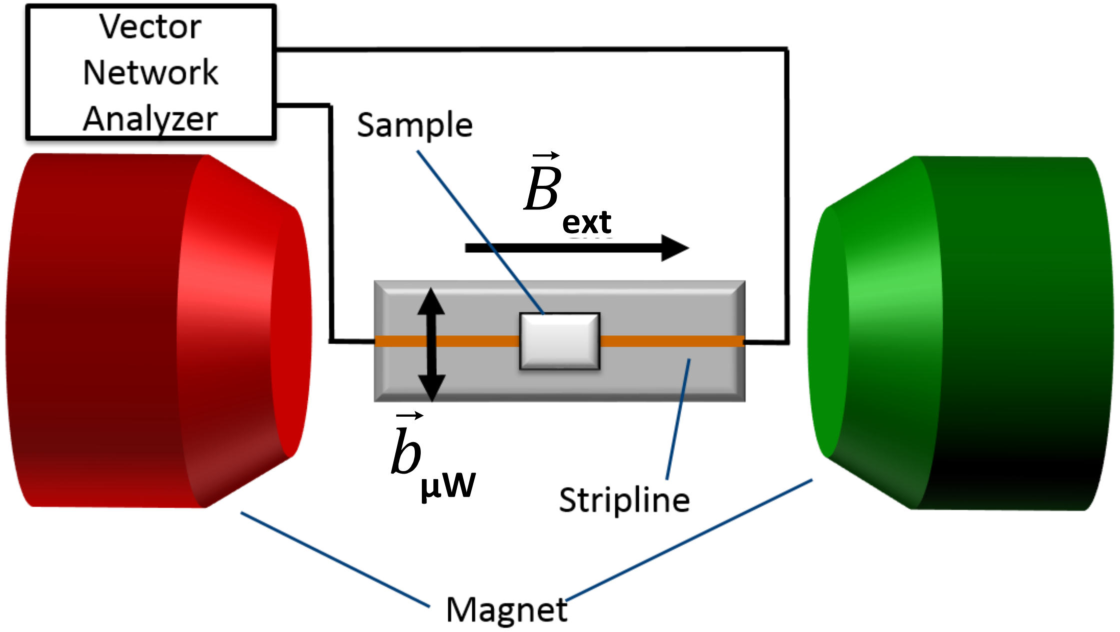
$\Rightarrow \quad \omega_0 = \gamma \sqrt{B_{ext}\left(B_{ext} - \mu_0 M_S\right)}$, i.e., internal field is geometric means of the two field components acting on the magnetization B_{ext} and $B_{ext} - \mu_0 M_S$ (named stiffening fields).

Ferromagnetic Resonance

FMR is a measurement method at microwave frequency

Experiment**:**

- Sample is uniformly magnetized in a static magnetic field $\vec{B}_{\mathrm{ext}}$
- Alternating microwave field $\vec{b}_{\mu\mathrm{W}}$ with fixed frequency is applied to the sample in perpendicular direction to $\vec{B}_{\mathrm{ext}} \rightarrow$ forced precession of magnetization vector
- Sweeping of $\vec{B}_{\mathrm{ext}}$
- Experimental realization:
  Sample
  - in microwave cavity, or
  - on micro-stripline

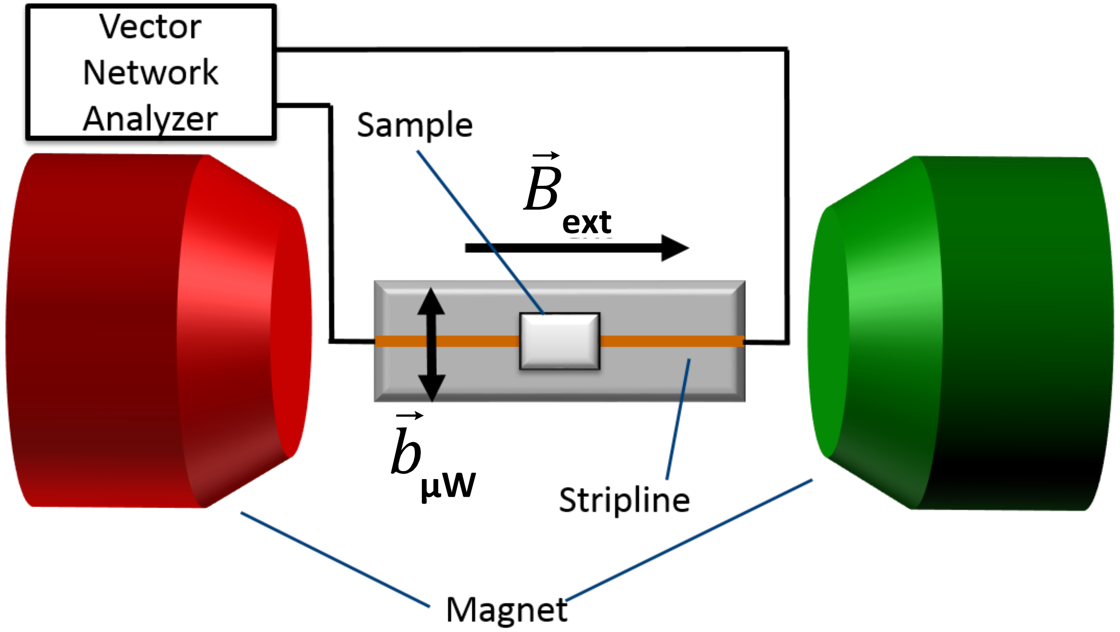


Ferromagnetic Resonance

Resonance frequency:

$$\omega_{\text{res}} = \frac{ge}{2m_e}\sqrt{\left(\frac{2K}{M_\text{S}} + B_\text{ext} + \mu_0 M_\text{S}(N_{yy} - N_{xx})\right)\left(\frac{2K}{M_\text{S}} + B_\text{ext} + \mu_0 M_\text{S}(N_{zz} - N_{xx})\right)}$$

anisotropy field external field demagnetizing field

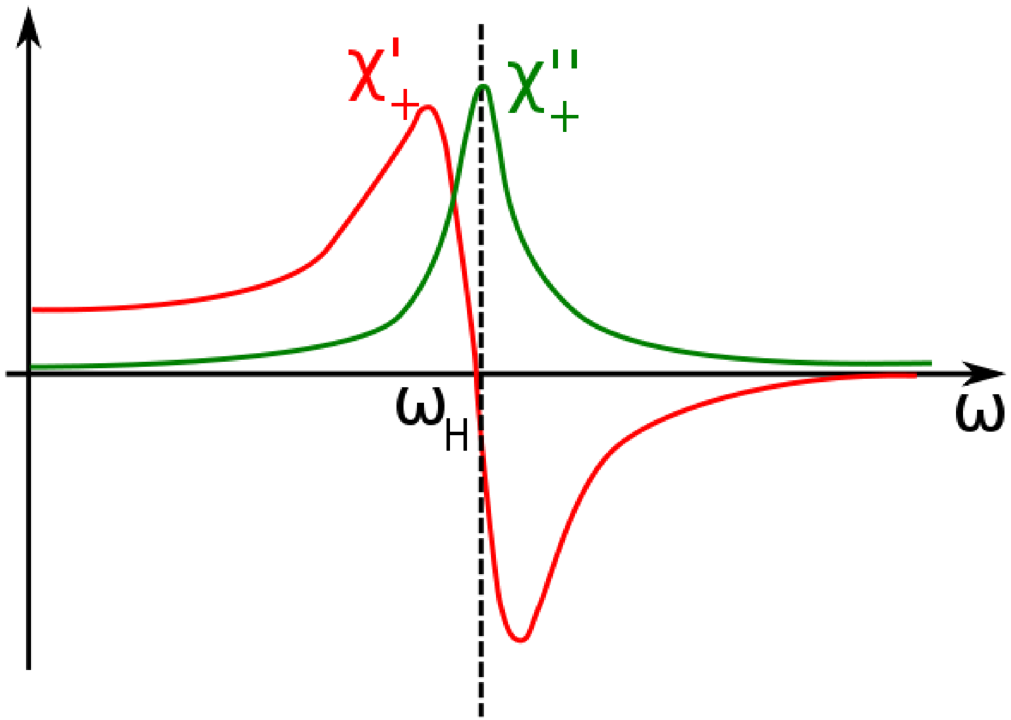


Ferromagnetic Resonance

Measurement:

Change in microwave signal intensity as a function of applied magnetic field $\frac{\mathrm{d}I_{\text{microwave}}}{\mathrm{d}B_{\text{ext}}}$

or microwave frequency $\frac{\mathrm{d}I_{\text{microwave}}}{\mathrm{d}\omega}$ $->$ determination of the complex dynamic susceptibility:



Source: Wikipedia Commons

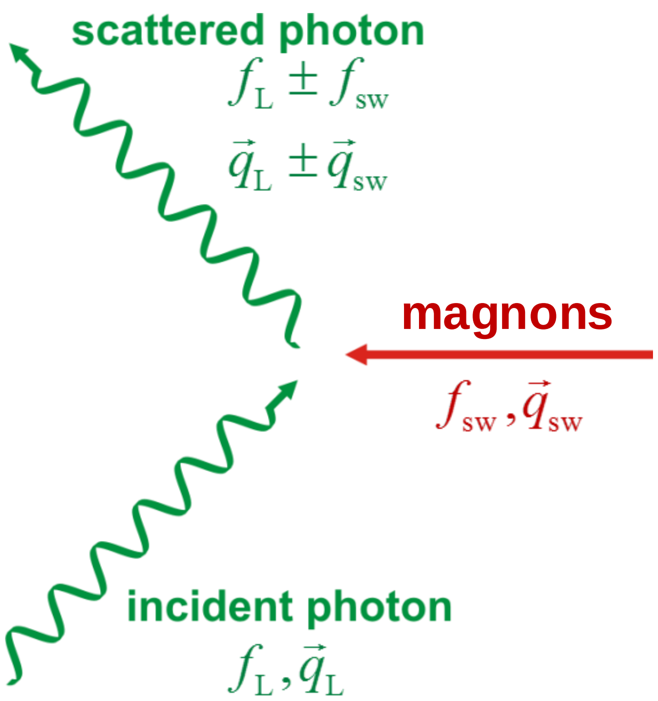
Brillouin light scattering (BLS) spectroscopy

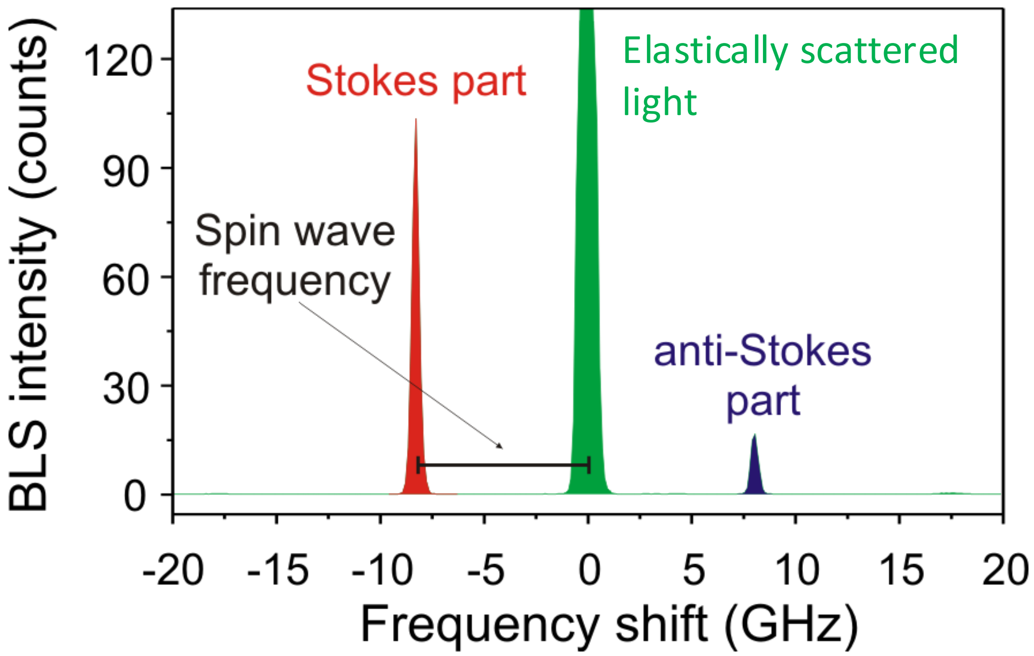
- Inelastic scattering of photons from spin waves:

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

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

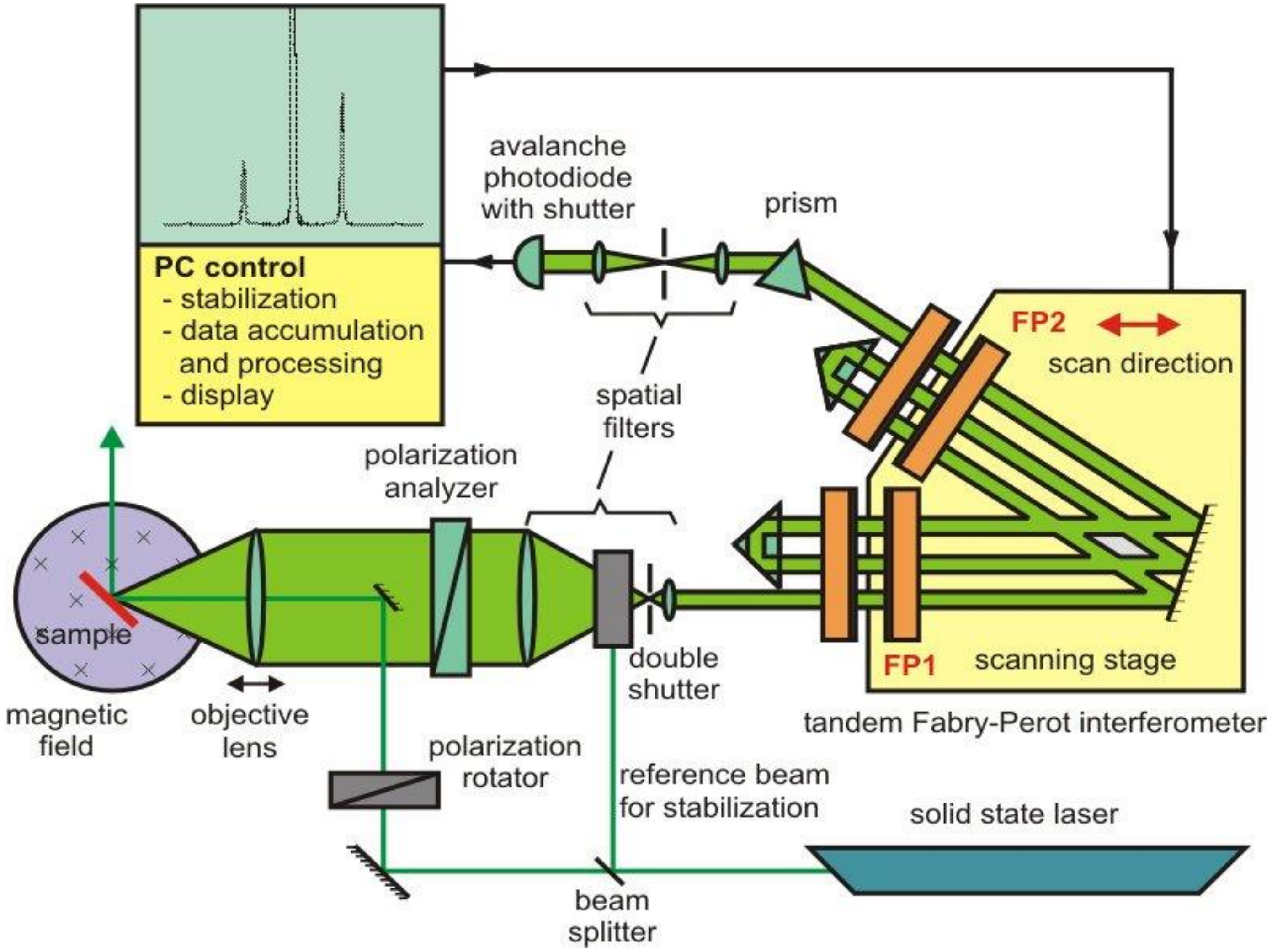
- Intensity of the scattered light is proportional to magnon density



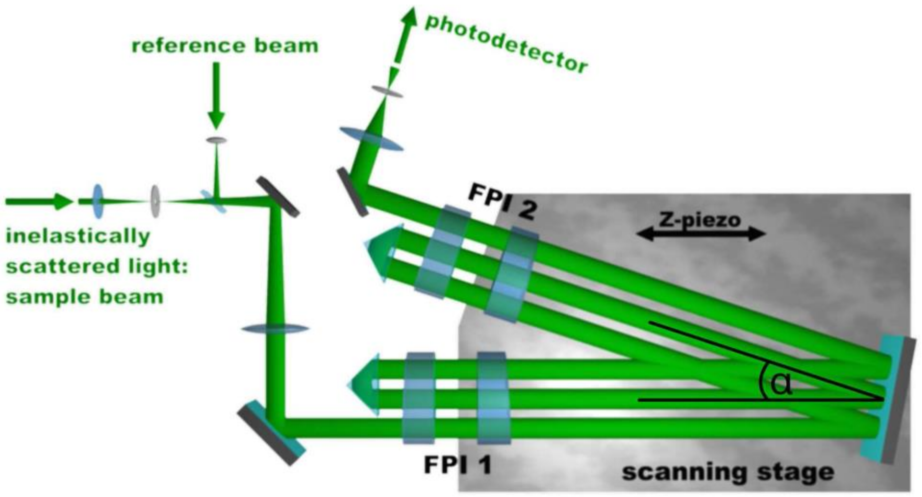


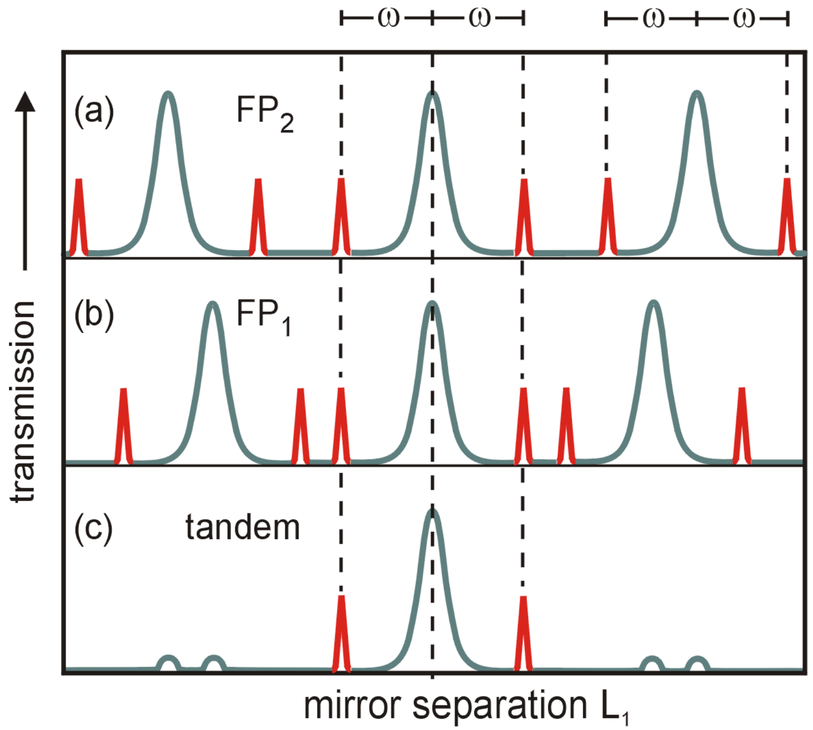
Brillouin light scattering spectrometer

high-resolution interferometry with high contrast
for measurements of acoustic phonons and spin waves



Brillouin light scattering spectrometer





- etalon in transmission if mirror separation L is:

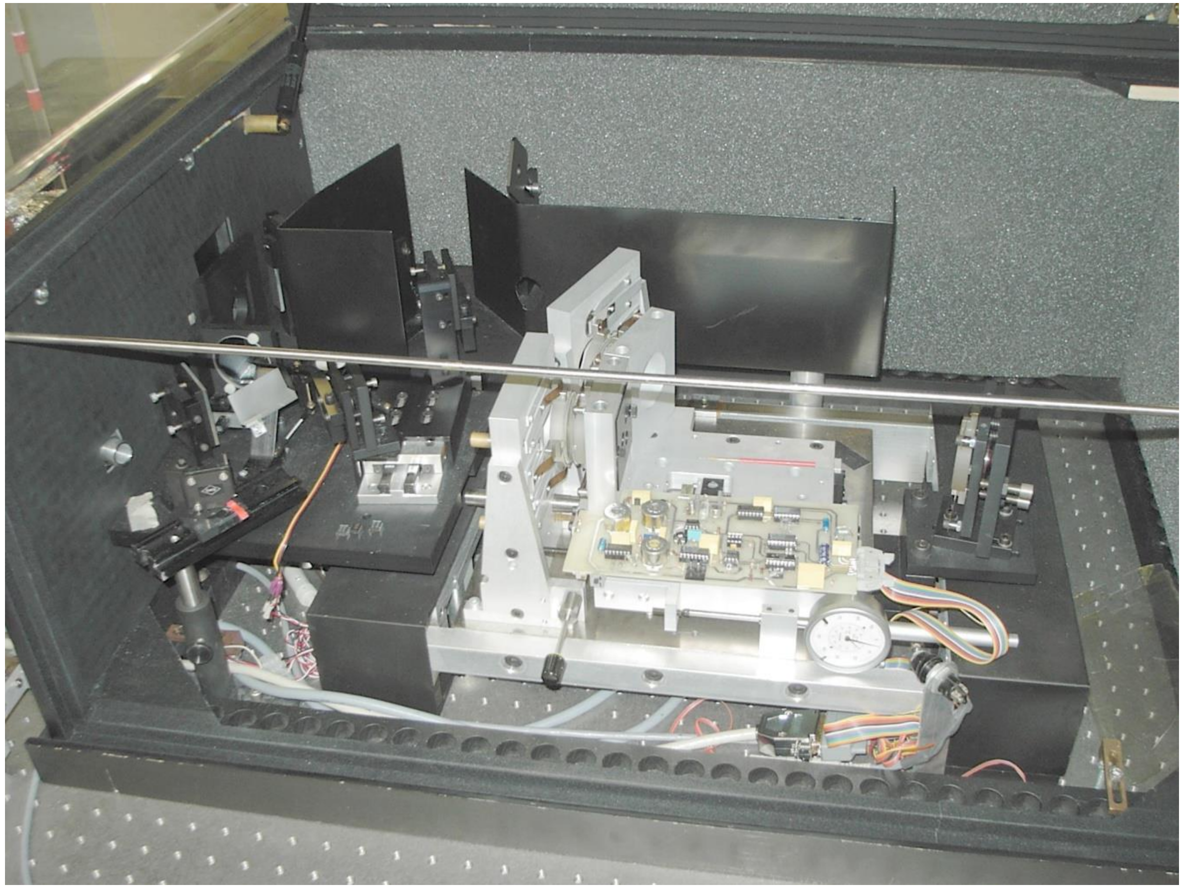
  $L = n\ l_{Laser}/2$

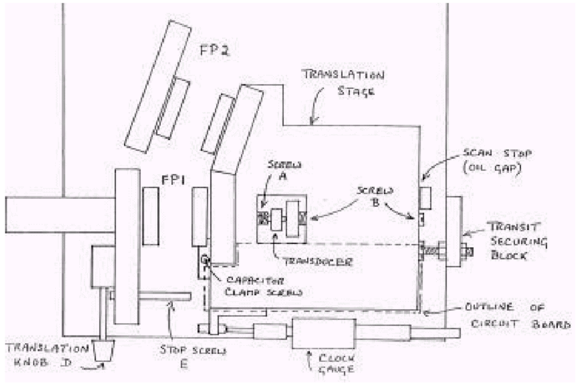
- suppression of neighboring orders if mirror separations L_1, L_2 of both etalons:

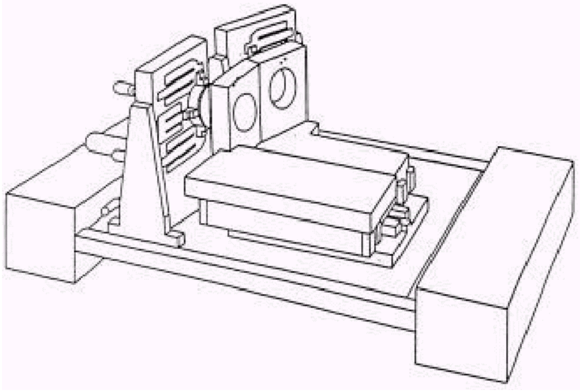
  $L_2 = L_1 \cos a$

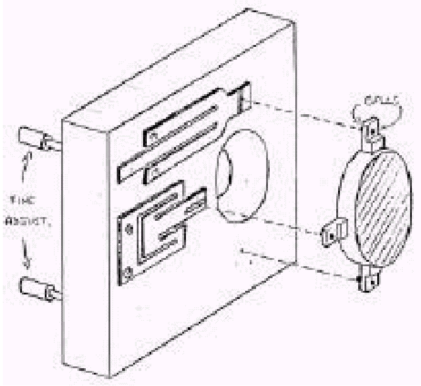
  a : angle between etalon axes

Brillouin light scattering spectrometer









Tandem Fabry-Pérot Interferometer

Sketch of mechanical stage and mirror mounts
(from John Sandercock's 1993 manual)

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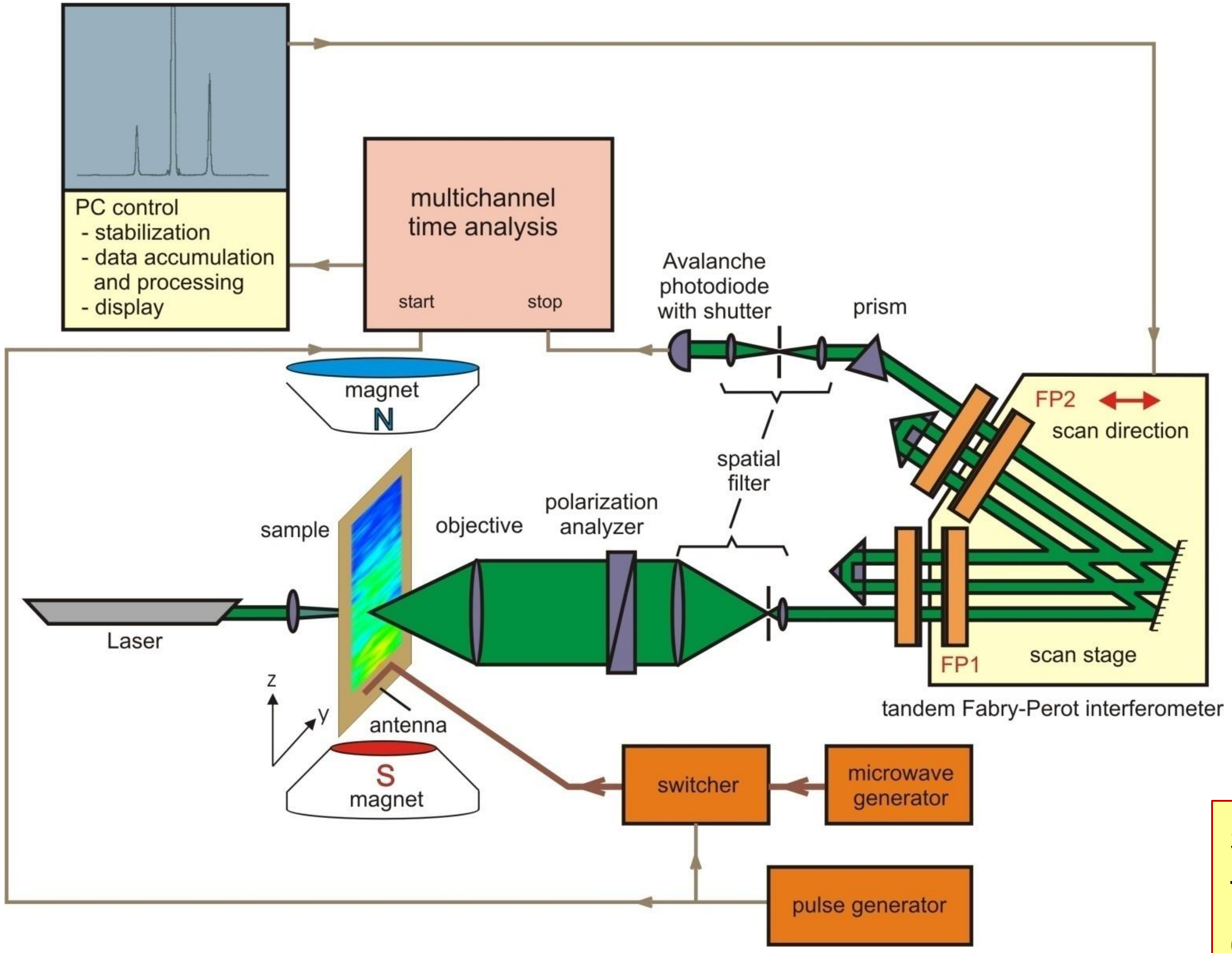
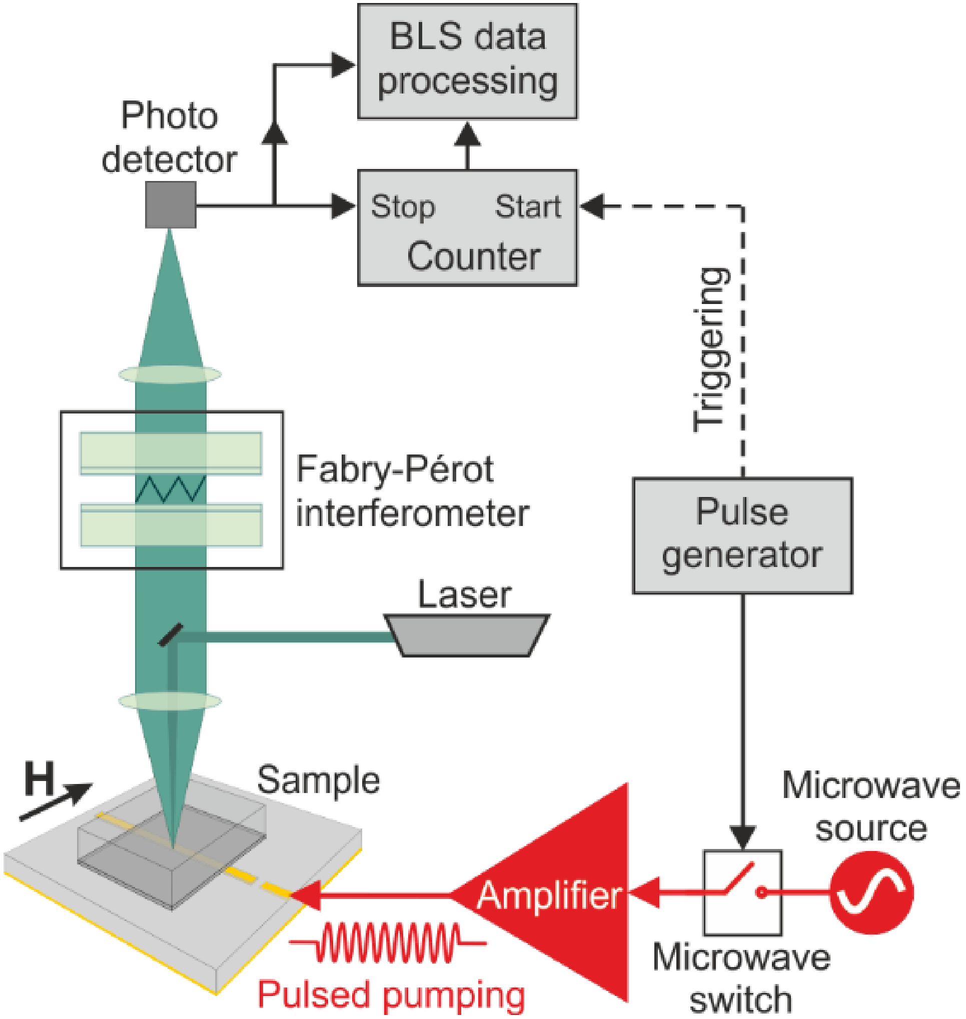
Time- and space-resolved Brillouin light scattering spectroscopy

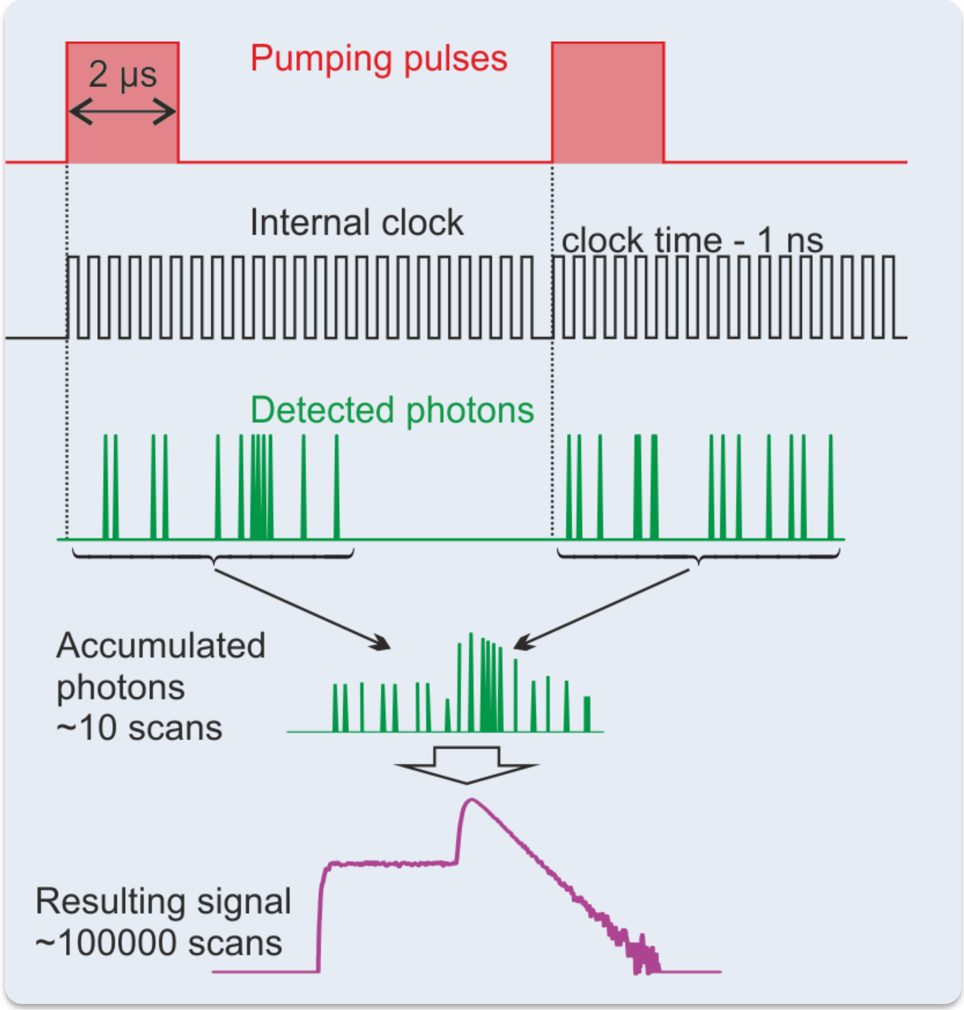


spatial resolution: 40 µm
time resolution: 1 ns
dynamic range: >60 dB

O. Büttner *et al*., Phys. Rev. B **61**, 11576 (2000)

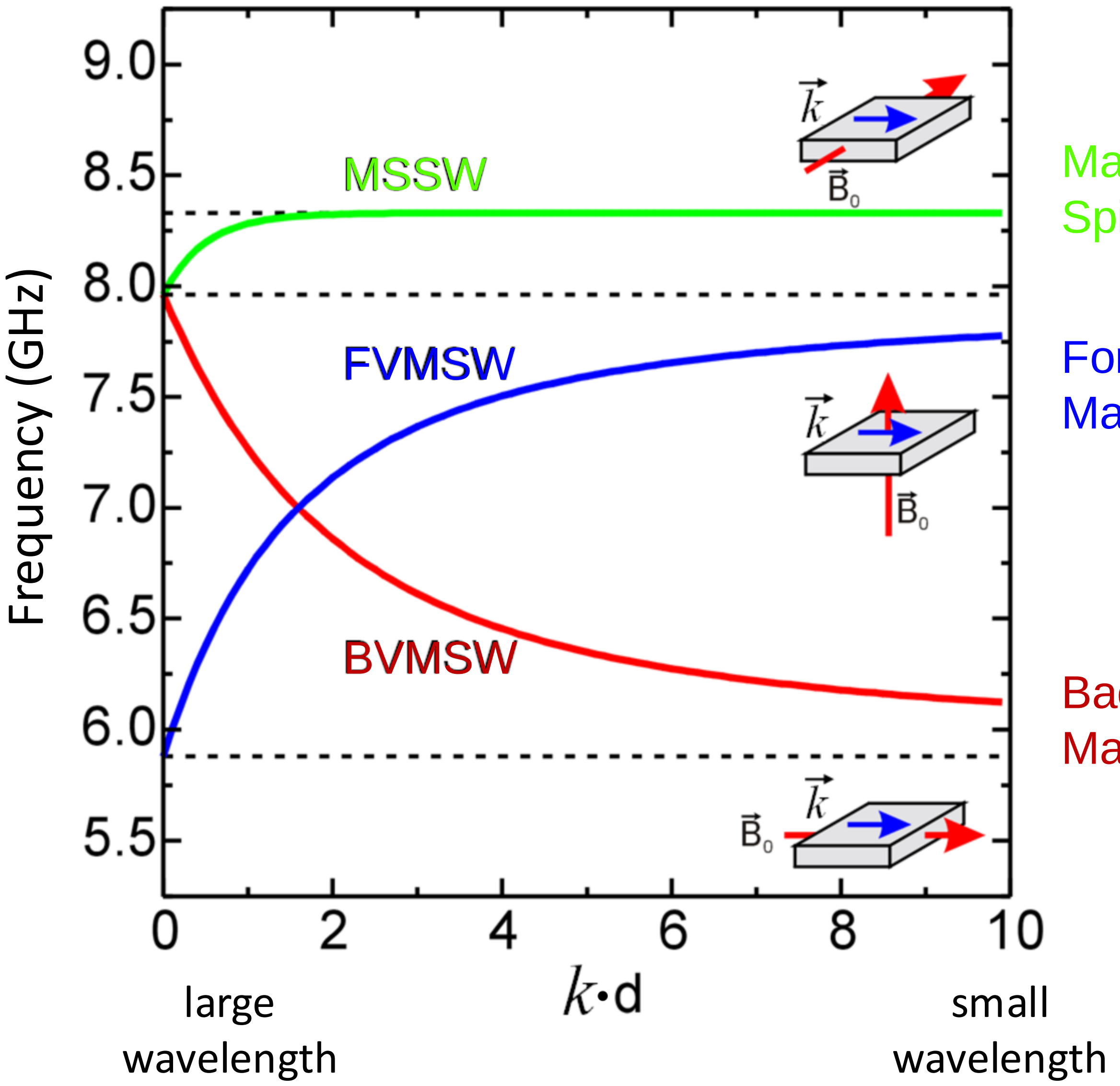
Time-resolved BLS spectroscopy





Time resolution: 1 ns

Dipolar spin waves



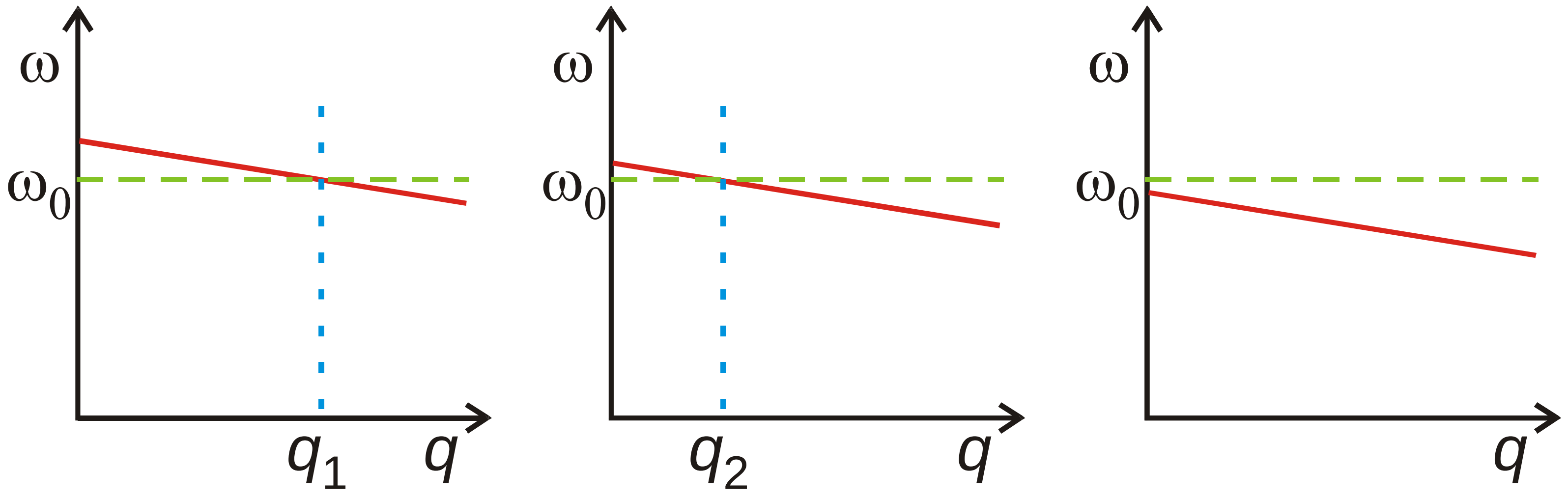
Magnetostatic Surface Spin Waves

Forward Volume Magnetostatic Spin Waves

Backward Volume Magnetostatic Spin Waves

Motion of a spin wave packet in varying field

$H_{int,1}$ > $H_{int,2}$ > $H_{int,3}$



propagation **propagation (q_2<q_1)** **reflection**

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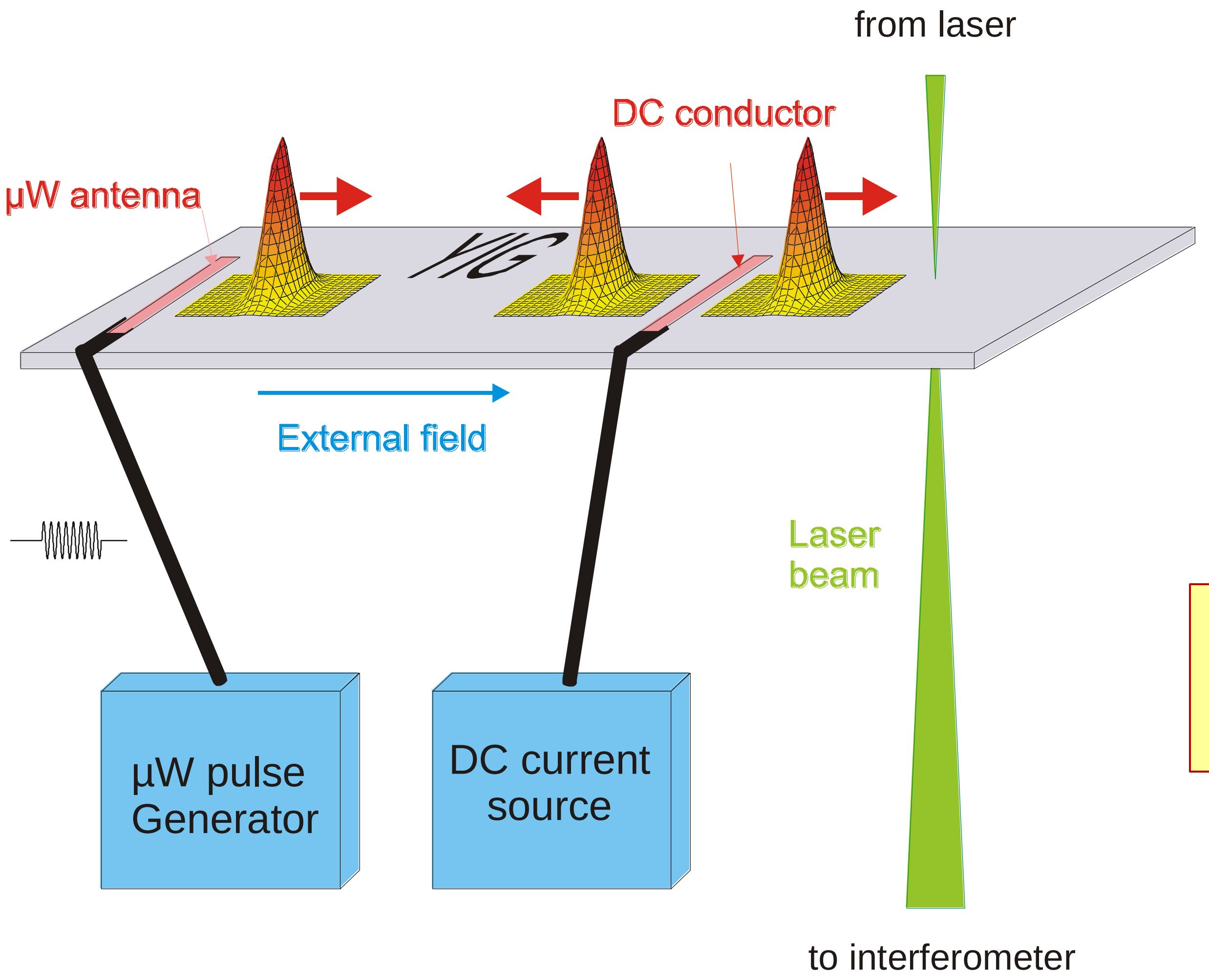
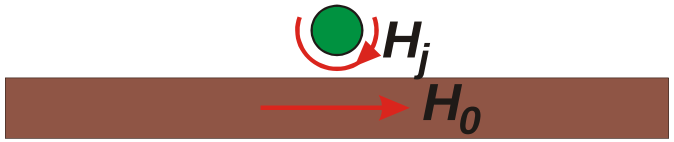
Real-time observation of spin wave propagation



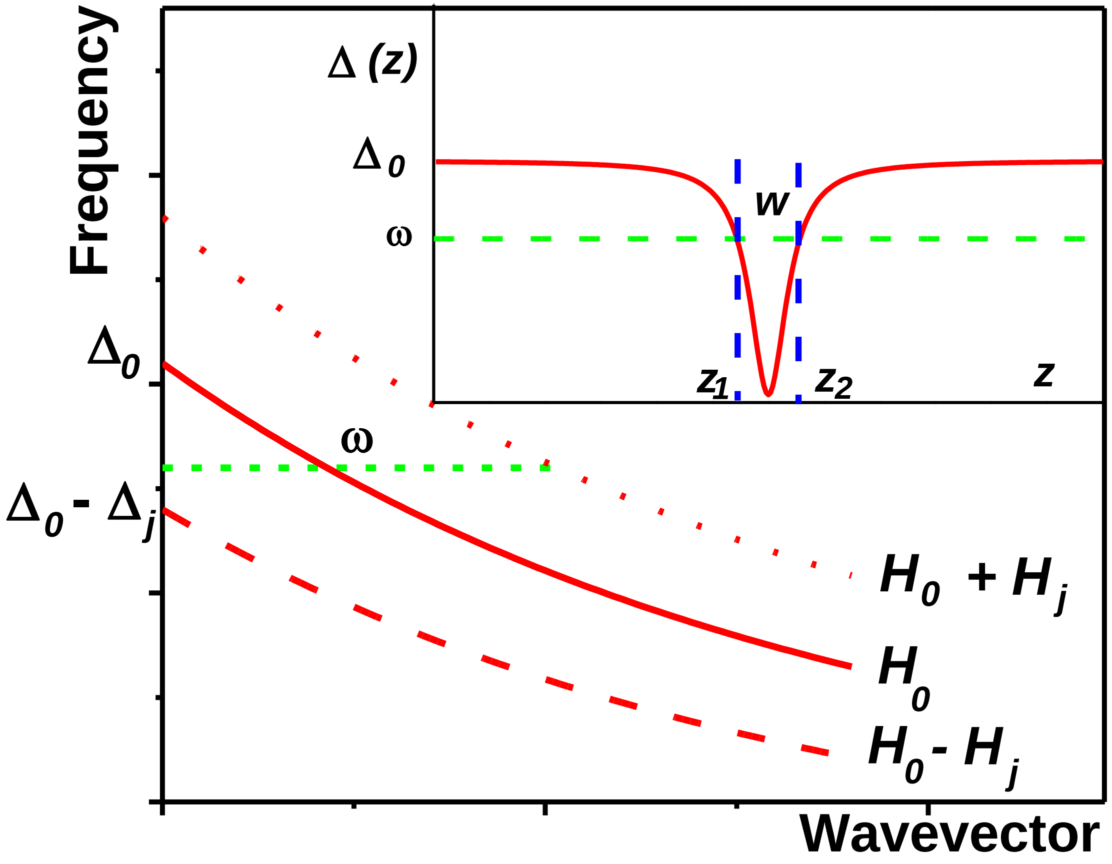
SW-pulses created by microwaves and detected by light scattering with time and space resolution

DC conductor provides a local field inhomogeneity

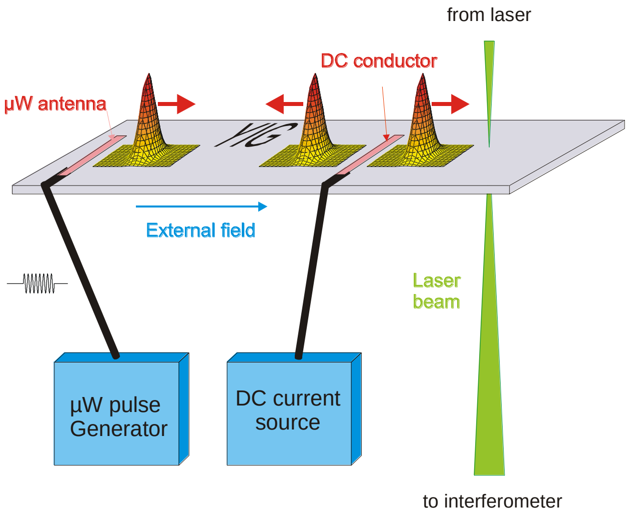
Spin wave tunneling



Δ: zero-wavevector gap

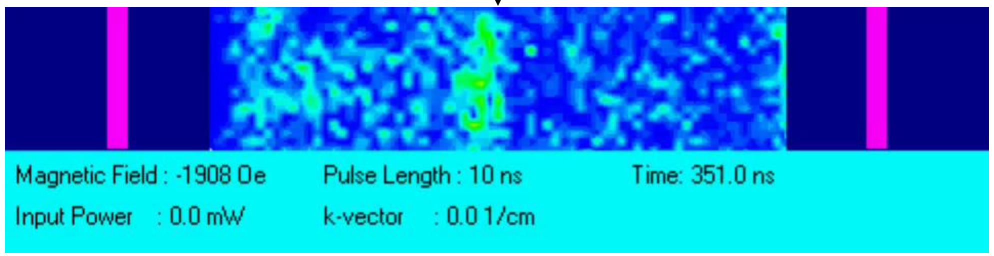


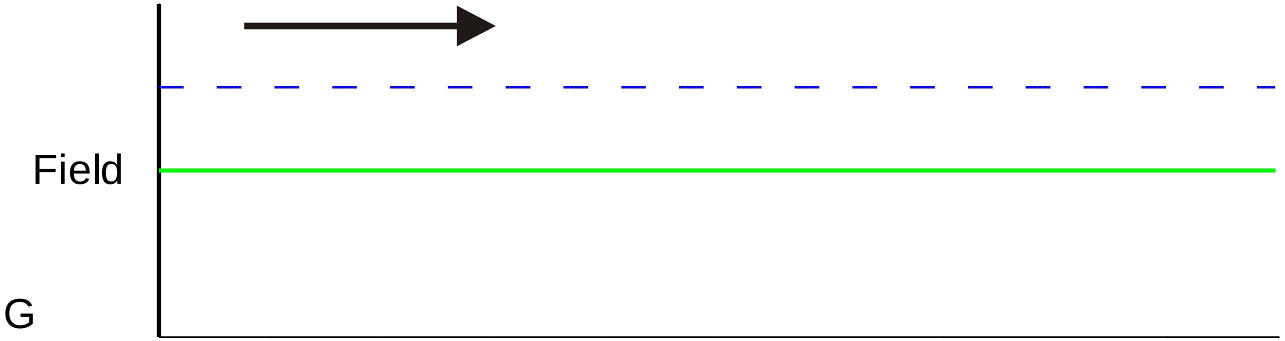
Spin wave pulse propagation



zero current

position of the dc conductor

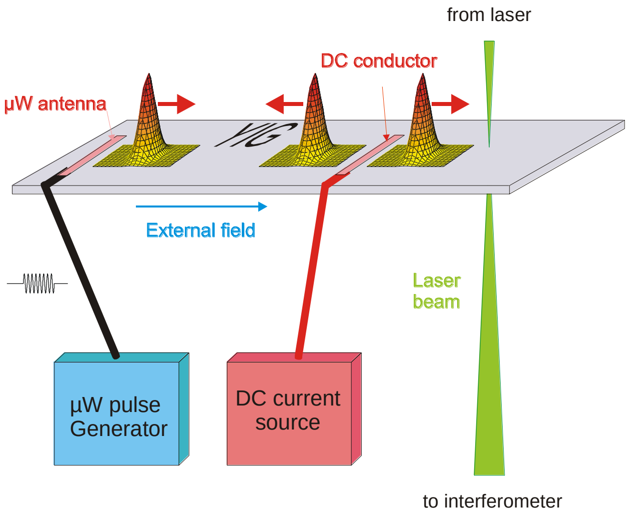




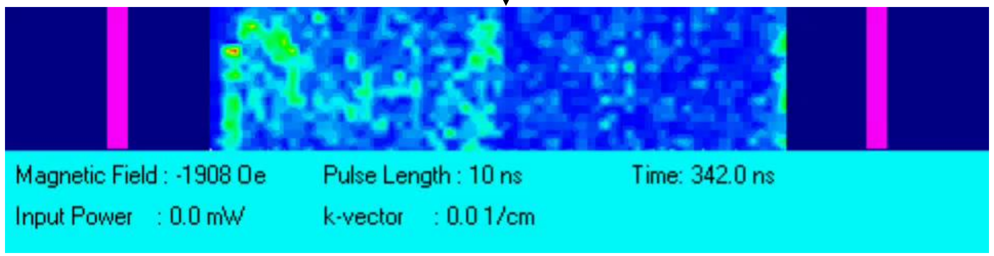
magnetic material: YIG

S.O. Demokritov *et al*., Phys. Rev. Lett. **93**, 047201 (2004)

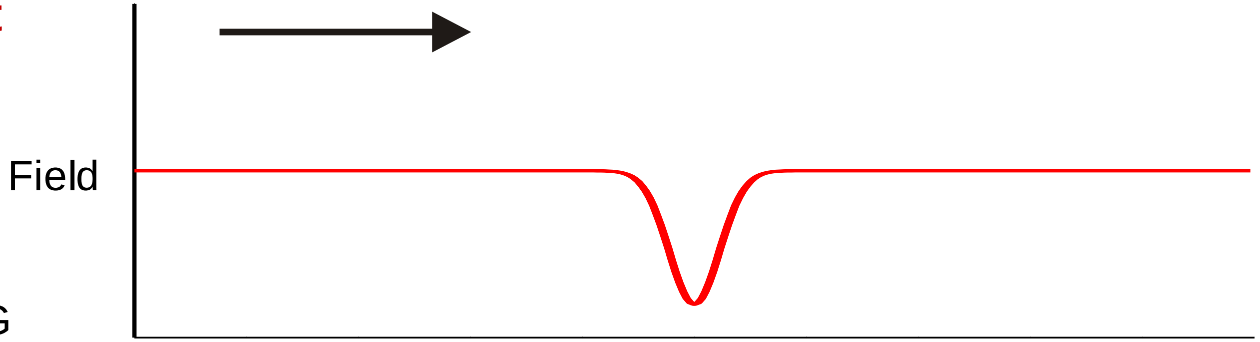
Spin wave pulse propagation



position of the dc conductor



positive current



magnetic material: YIG

dip in field acts like potential barrier

Potential barrier: reflection and tunneling

S.O. Demokritov *et al*., Phys. Rev. Lett. **93**, 047201 (2004)

Reflection of spin wave at barrier and spin wave tunneling

Carrier frequency:
7.125 GHz

Bias field:
1836 Oe

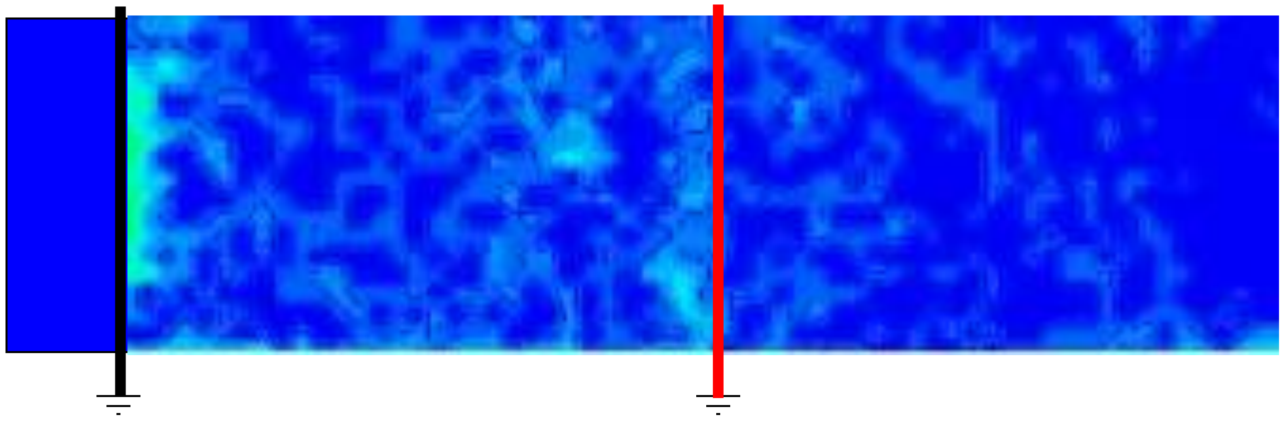
Wave number:
112 rad/cm

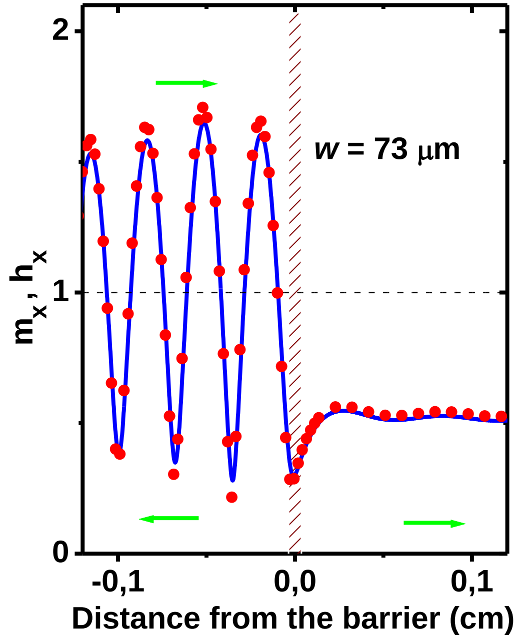
Group velocity:
≈30 km/s

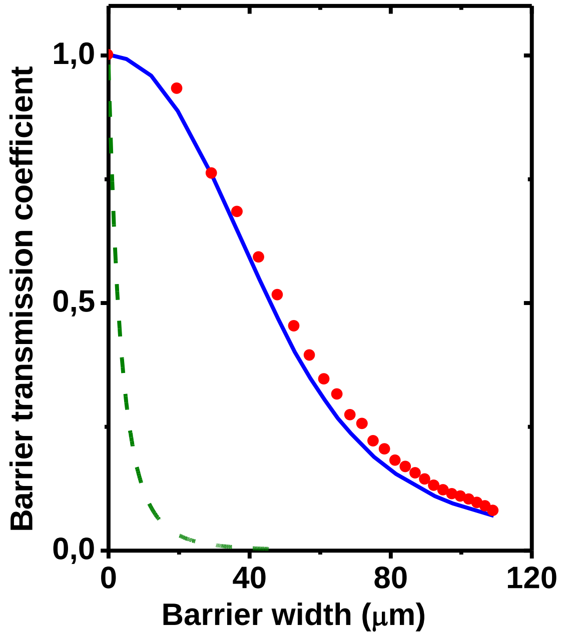
Film thickness:
5.7 µm

Scan region:
6.0 × 1.8 mm²

Logarithmic scale







A. A. Serga *et al*., Appl. Phys. Lett. **94**, 112501 (2009)

Non-exponential decrease of spin wave intensity with barrier size

Spin-wave Fabry-Perot interferometer

Carrier frequency:
7.125 GHz

Bias field:
1836 Oe

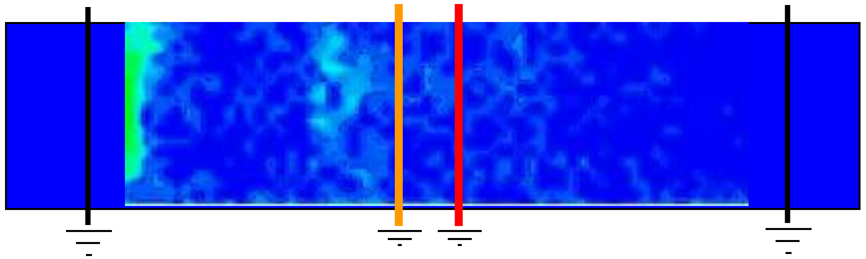
Wave number:
112 rad/cm

Group velocity:
≈30 km/s

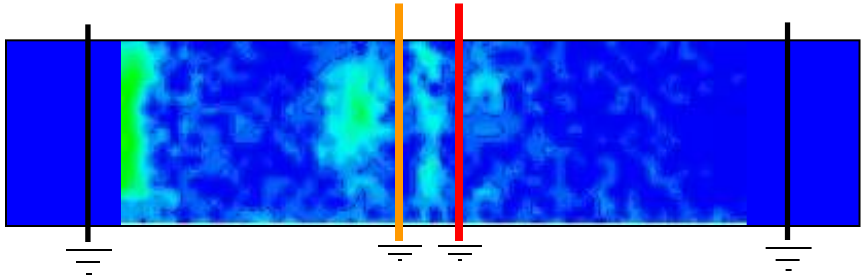
Film thickness:
5.7 µm

Scan region:
$6.0 \times 1.8\ mm^2$

Logarithmic scale



Short SW pulse
18 ns



Long SW pulse
40 ns

A. A. Serga *et al*., Appl. Phys. Lett. **94**, 112501 (2009)

Spin-wave tunneling through mechanical gap

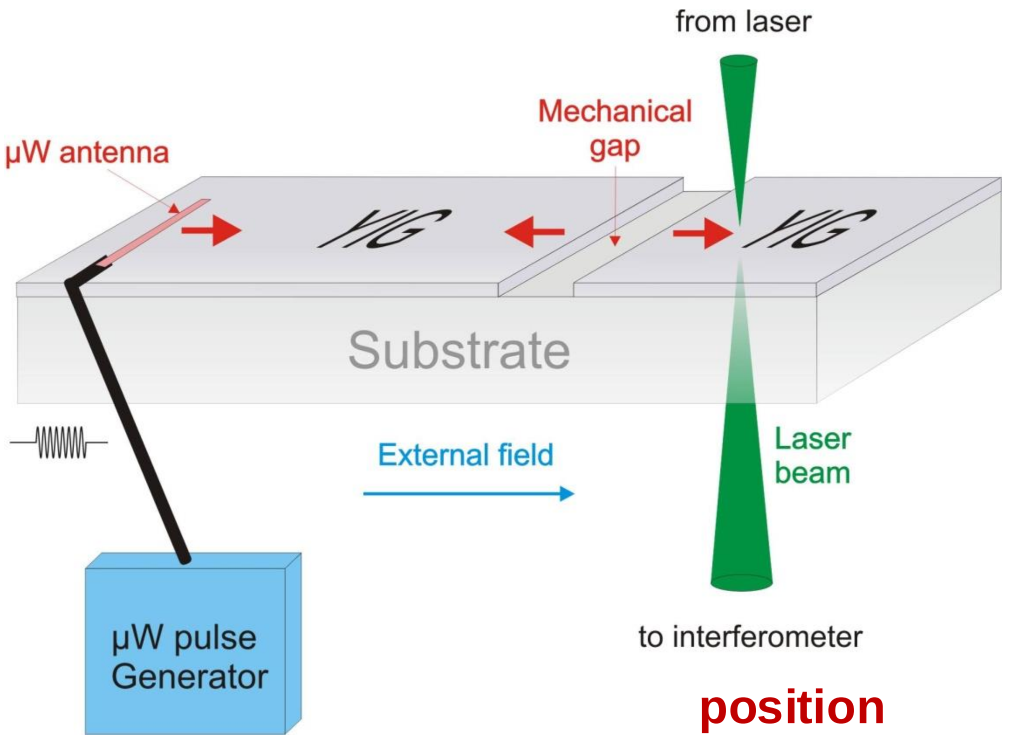
Film thickness:
6 µm

Gap width:
20 µm

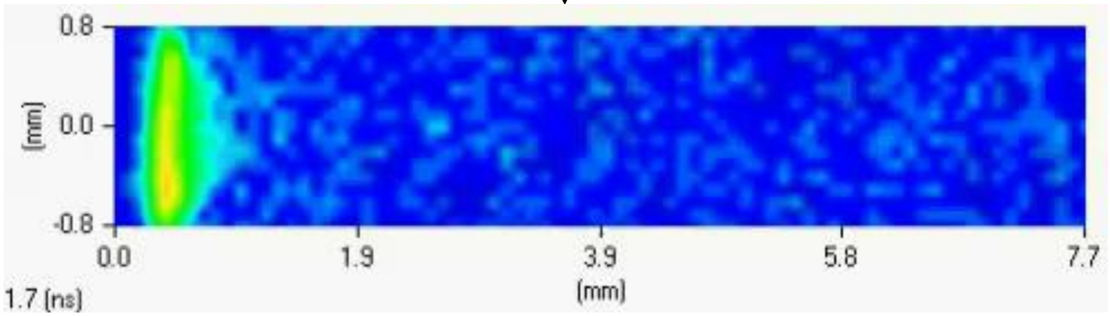
Frequency:
7.125 GHz

Magnetic field:
1835 Oe

Logarithmic scale



position of the gap



T. Schneider *et al*., Europhys. Lett. **90**, 27003 (2010)

Spin wave cavity

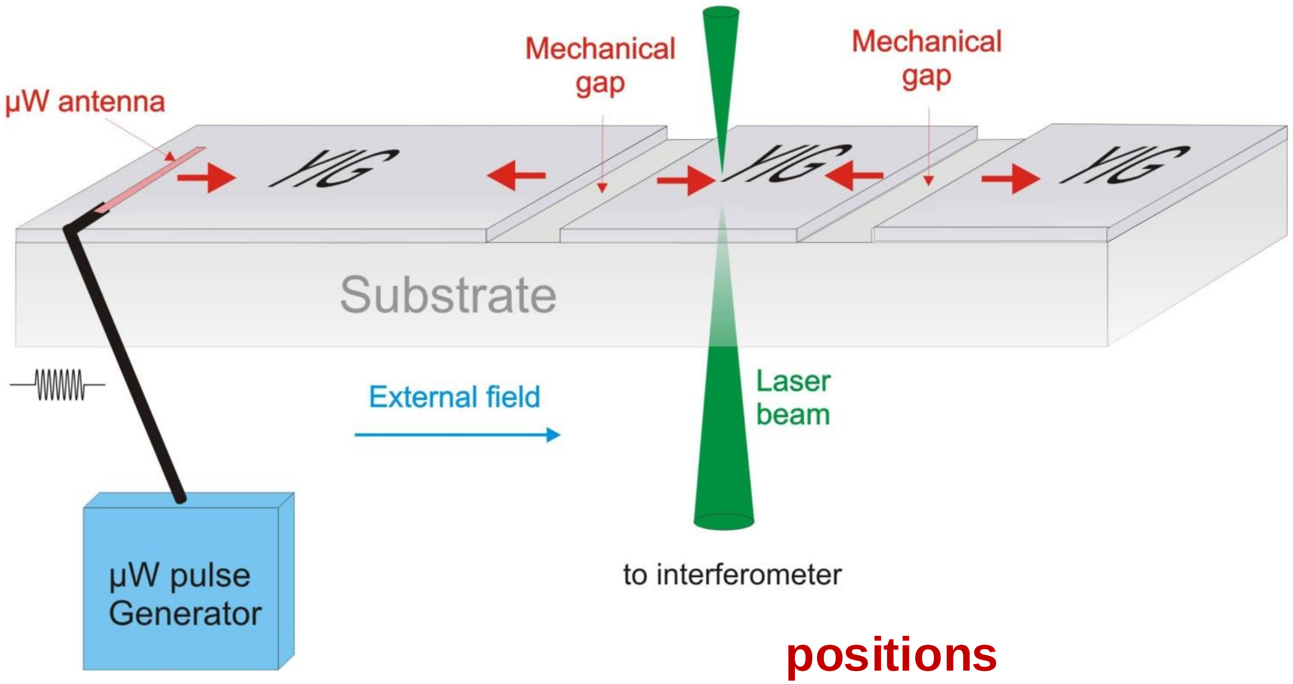
Film thickness:
6 µm

Gap width:
20 µm

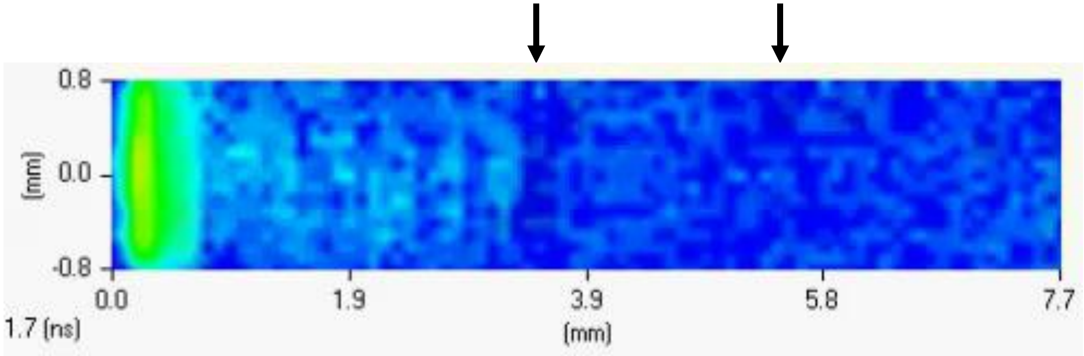
Frequency:
7.125 GHz

Magnetic field:
1839 Oe

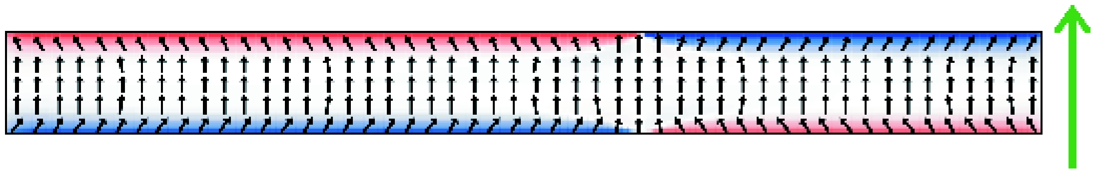
Logarithmic scale

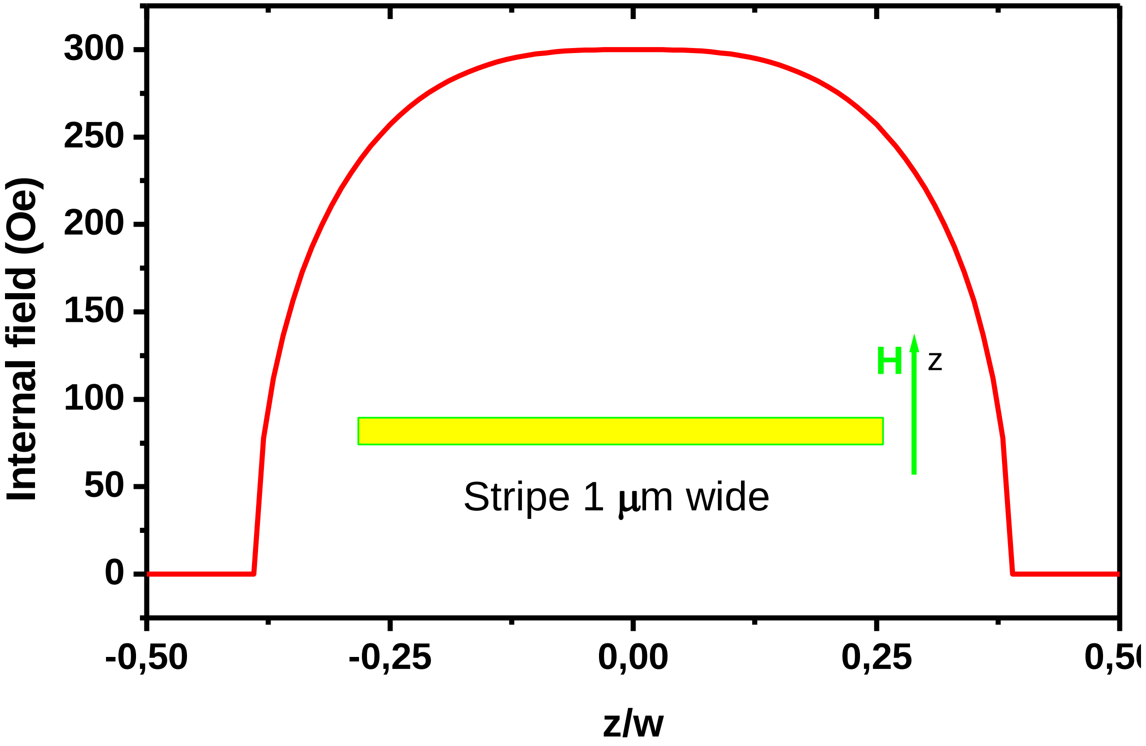


positions of the gaps



Application: Spin waves in films with internal field distribution





Regions with canted magnetization and zero internal field are located near the edges of the stripe

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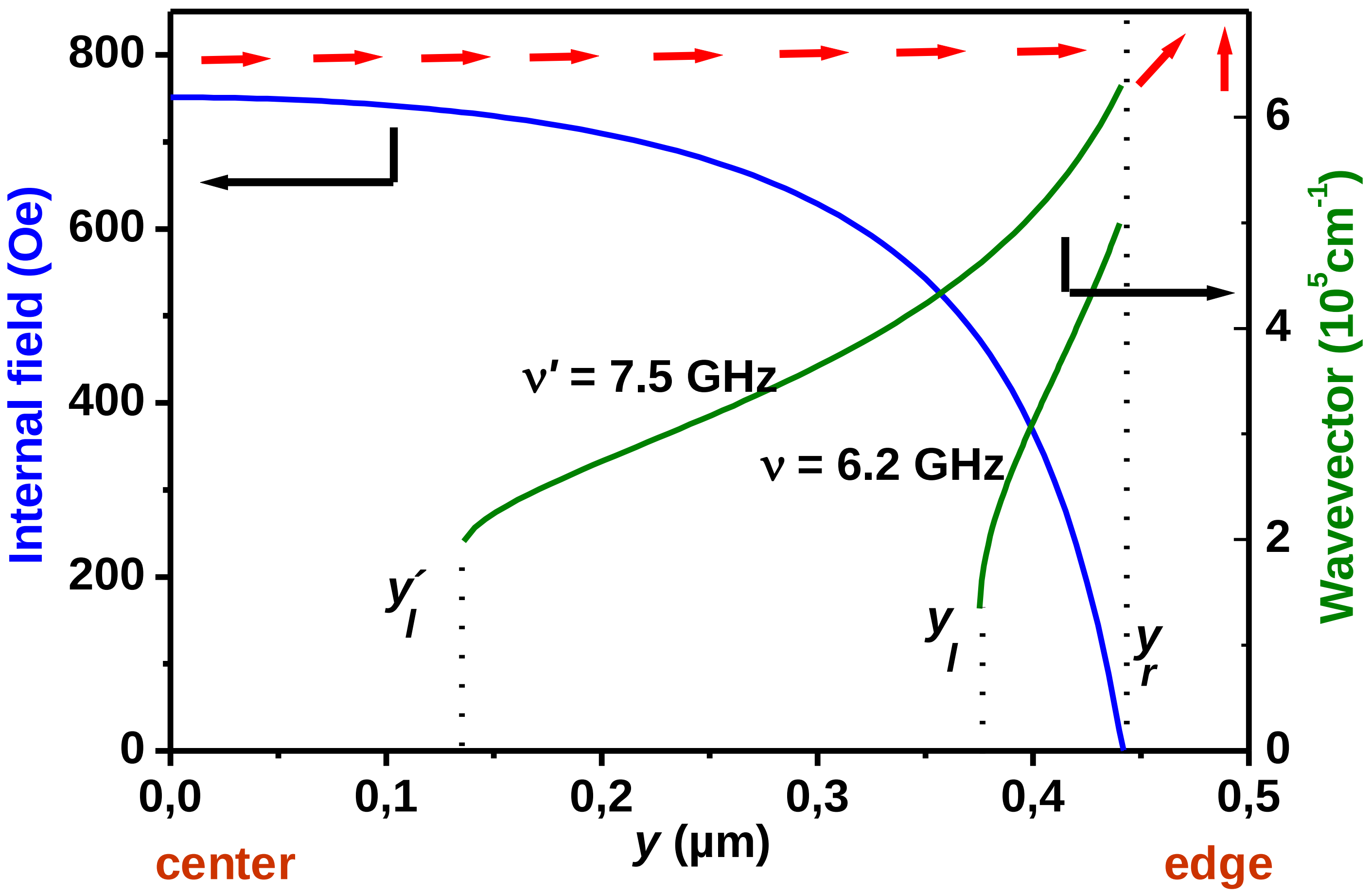
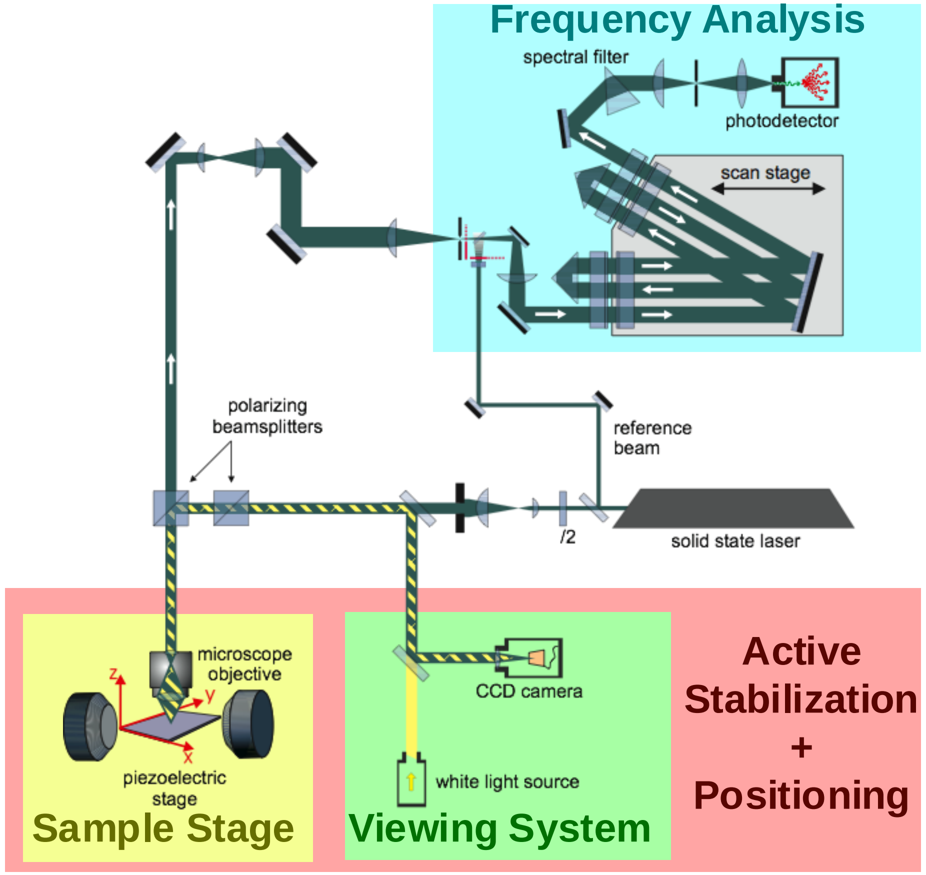
Dynamics in inhomogeneous stripe



y_l , y_l : turning points

y_r- y_l : localization length

BLS microscopy



- optical resolution: 250 nm
- 2D piezo stage

- controlling sample while measuring

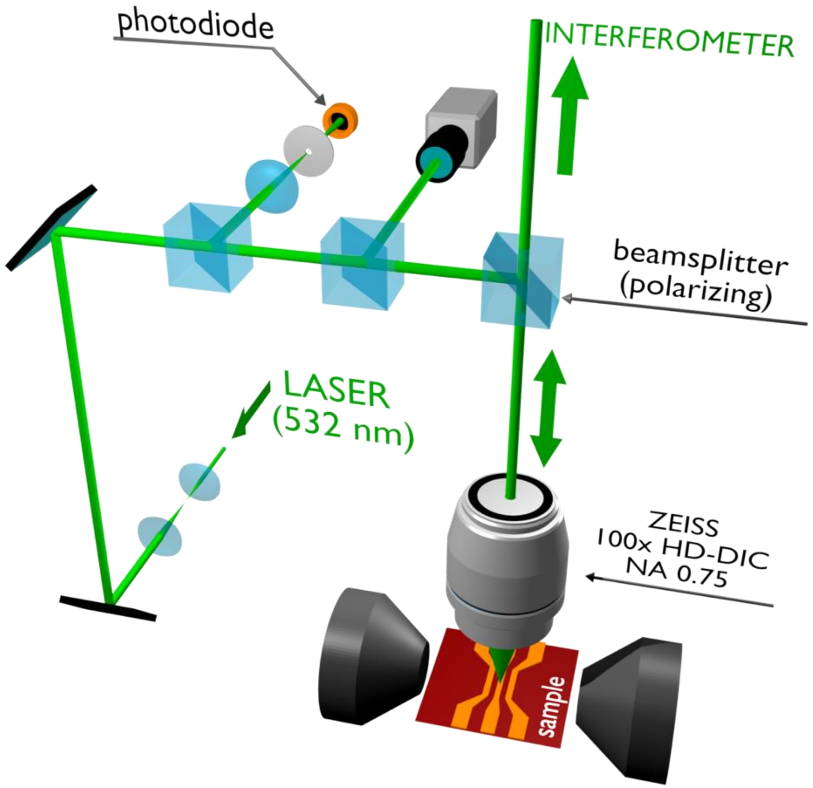
- frequency range: 1 GHz – 1 THz
- spectral resolution: 100 MHz

- position stability: ***infinite***
- accuracy: ***better than 20 nm***
- high reproducibility

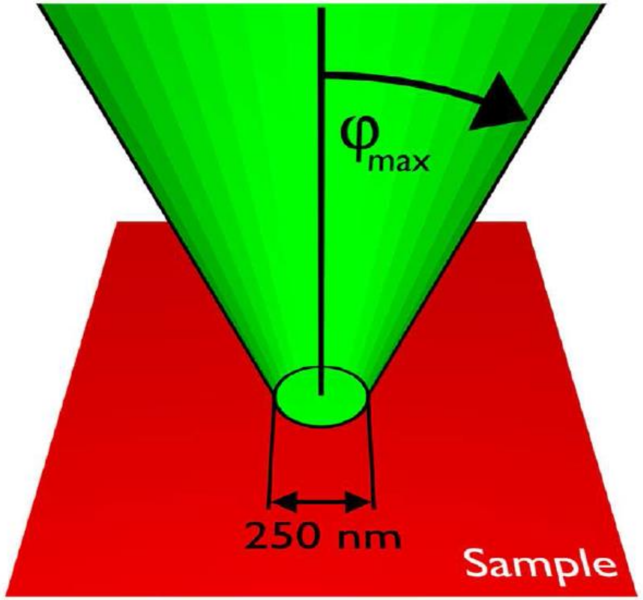
Micro-focused Brillouin light scattering spectroscopy

Experiment:

Brillouin light scattering microscopy



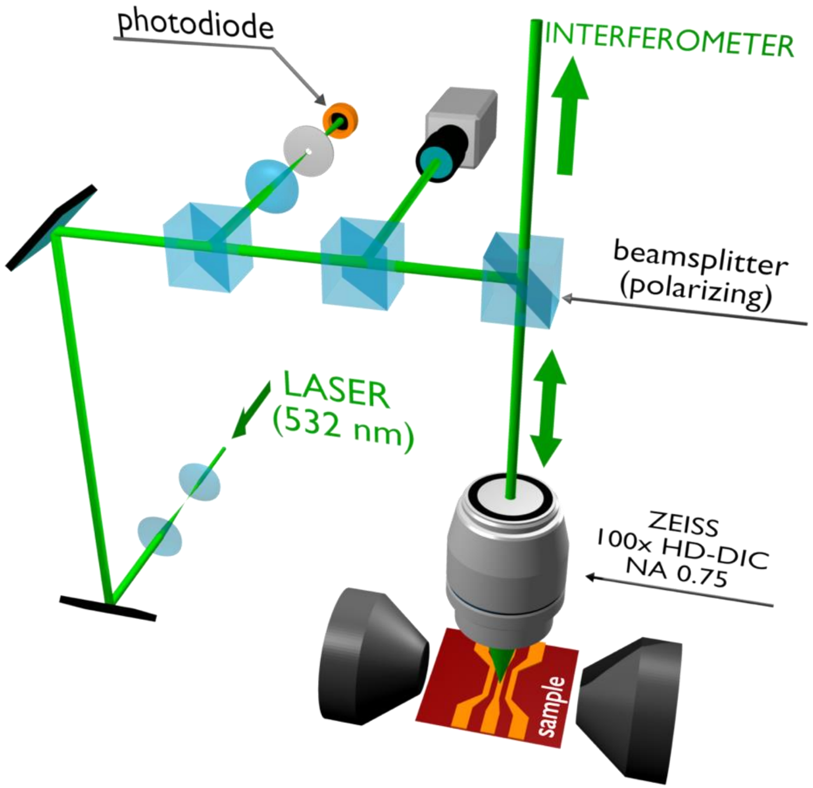
Laser focus on the sample



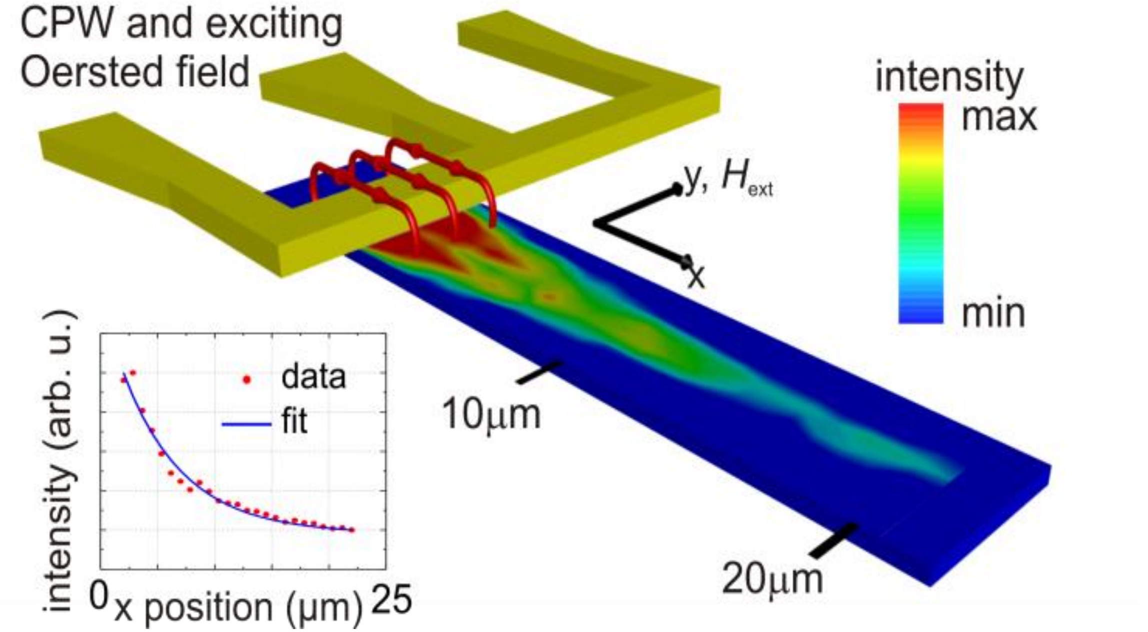
Micro-focused Brillouin light scattering spectroscopy

Experiment:

Brillouin light scattering microscopy



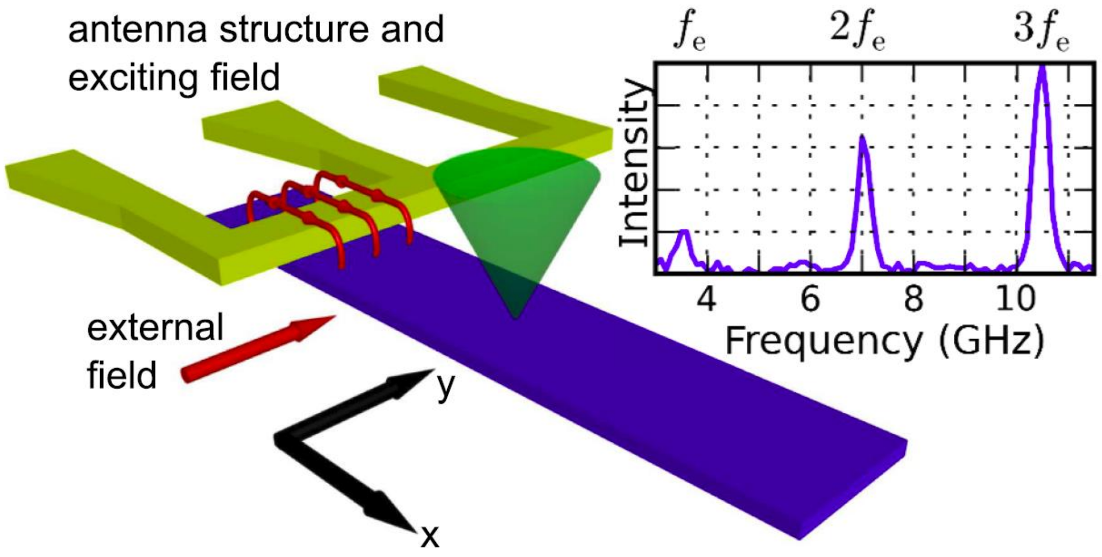
Micro-structured $Co_2Mn_{0.6}Fe_{0.4}Si$ spin-wave conduit



T. Sebastian *et al*., Appl. Phys. Lett. **100**, 112402 (2012)

Four-magnon interactions in a spin-wave waveguide

High frequency harmonic generation

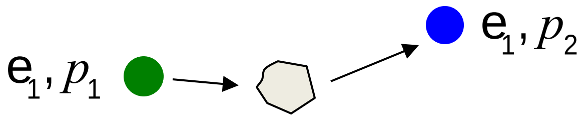


T. Sebastian et al., Phys. Rev. Lett. **110**, 067201 (2013)

(Non-)linear Processes

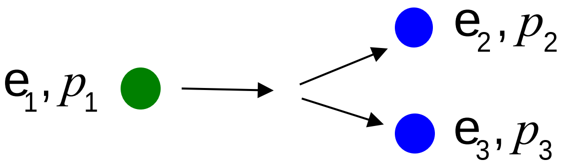
- **Linear process**

Two-magnon scattering

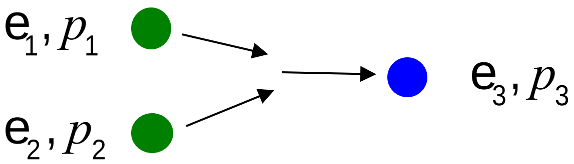


- **Nonlinear processes**

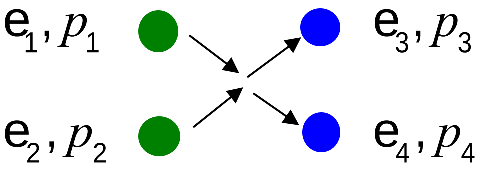
Three-magnon decay



Three-magnon confluence

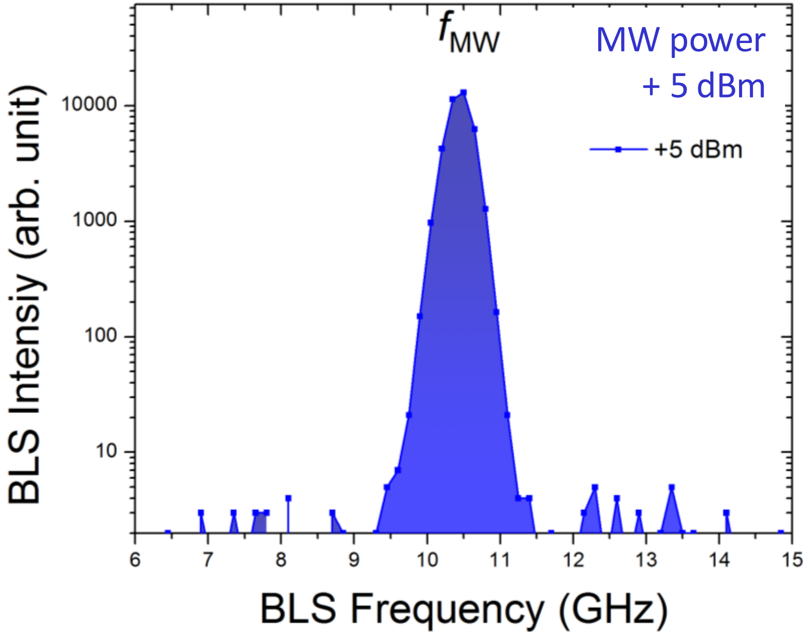


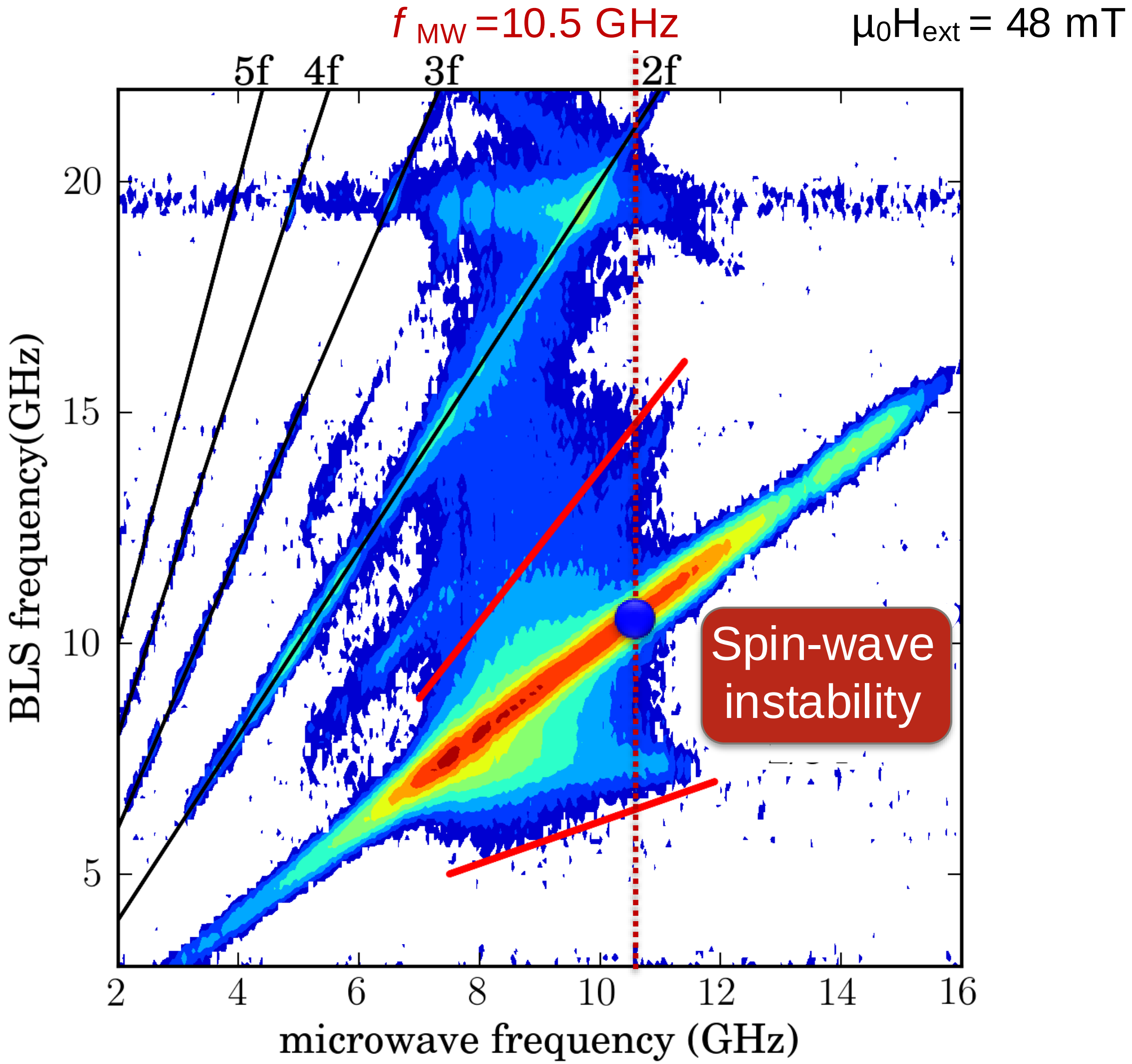
Four-magnon scattering



Four-magnon interactions in a spin-wave waveguide

Linear regime



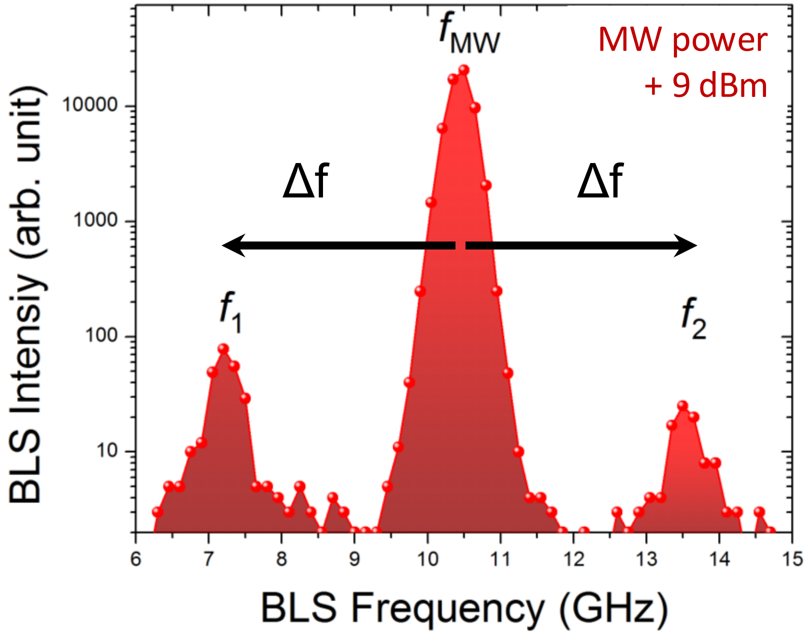


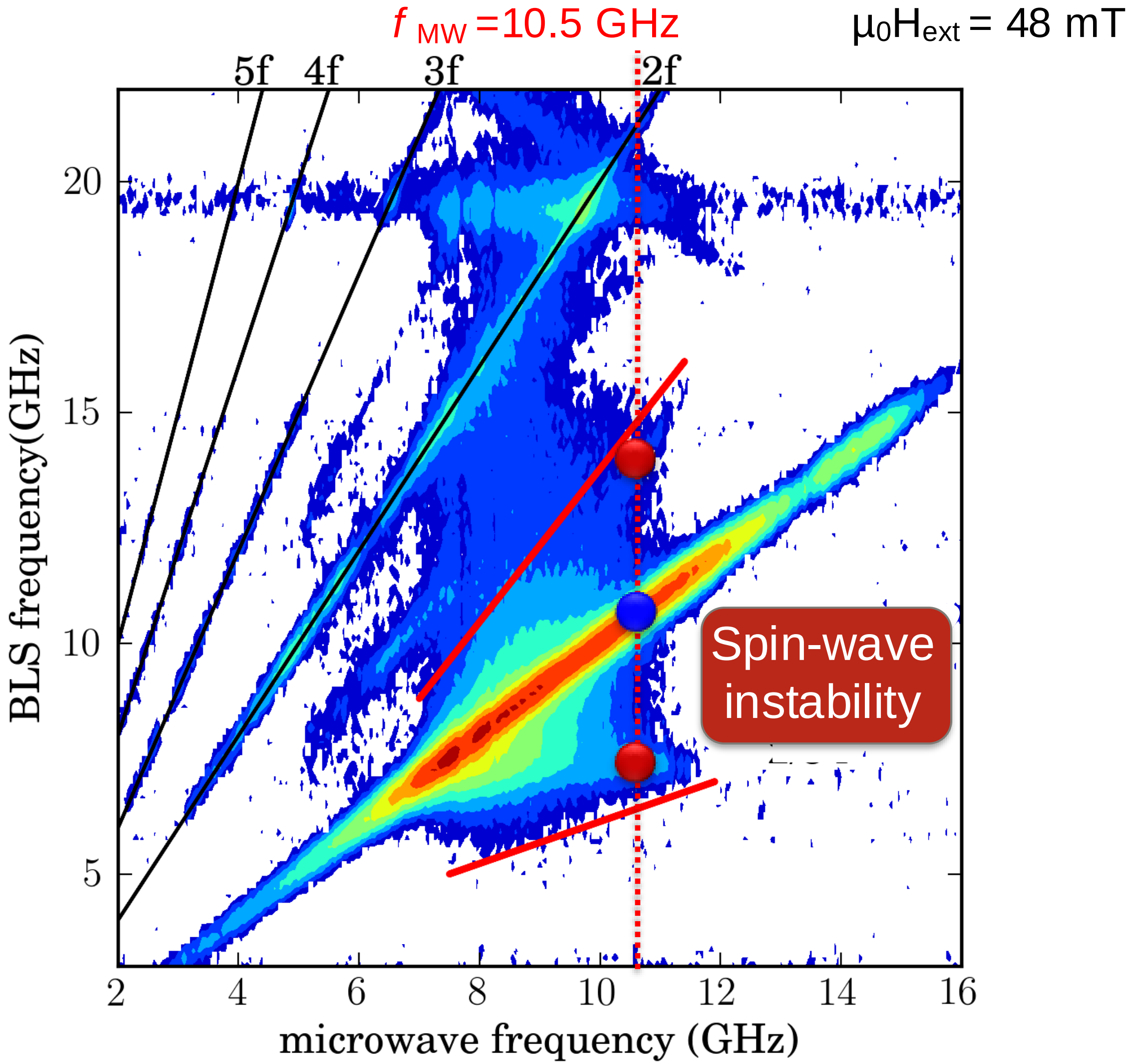
P. Pirro *et al.*, Phys. Rev. Lett. **113**, 227601 (2014)

Four-magnon interactions in a spin-wave waveguide

Nonlinear regime

f_1, f_2 : unstable modes





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Four-magnon interactions in a spin-wave waveguide

Nonlinear regime

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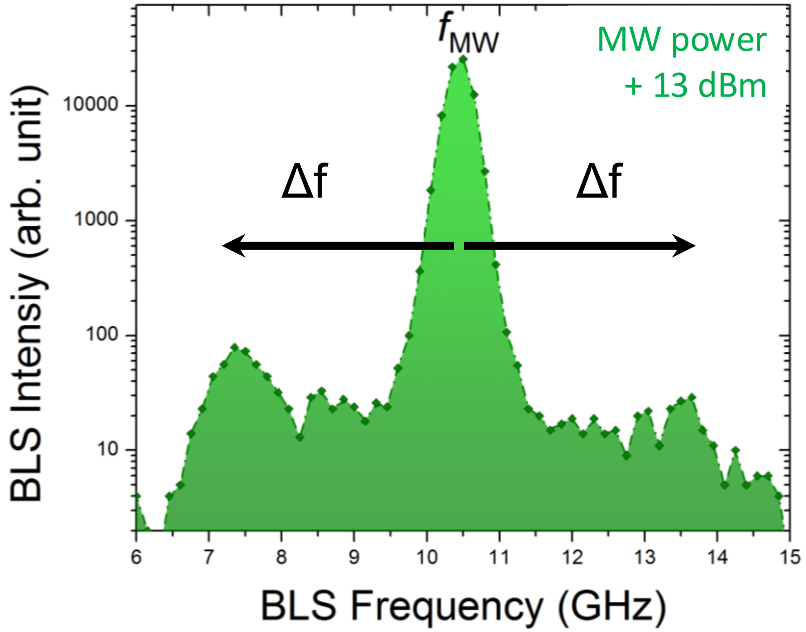
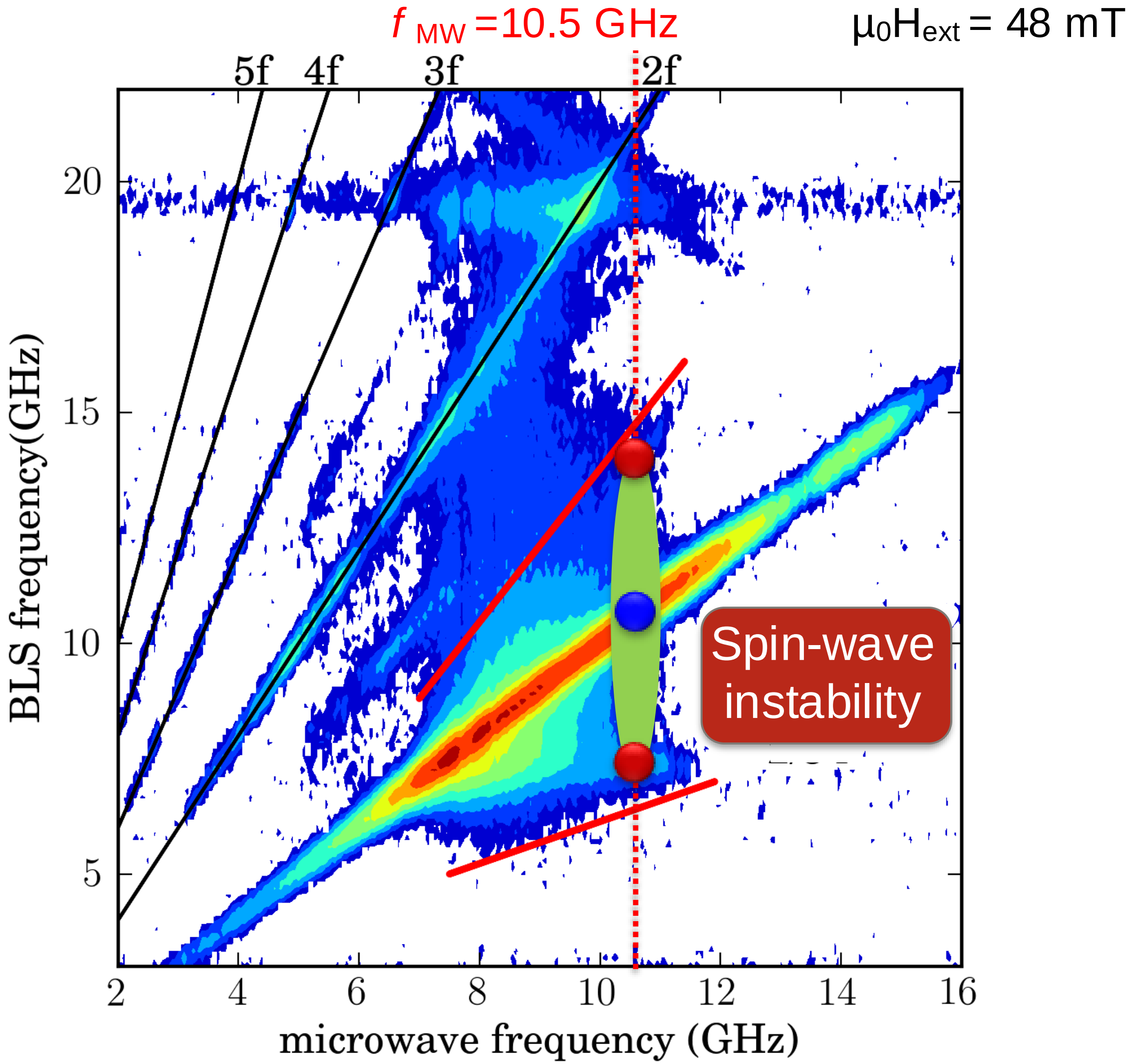
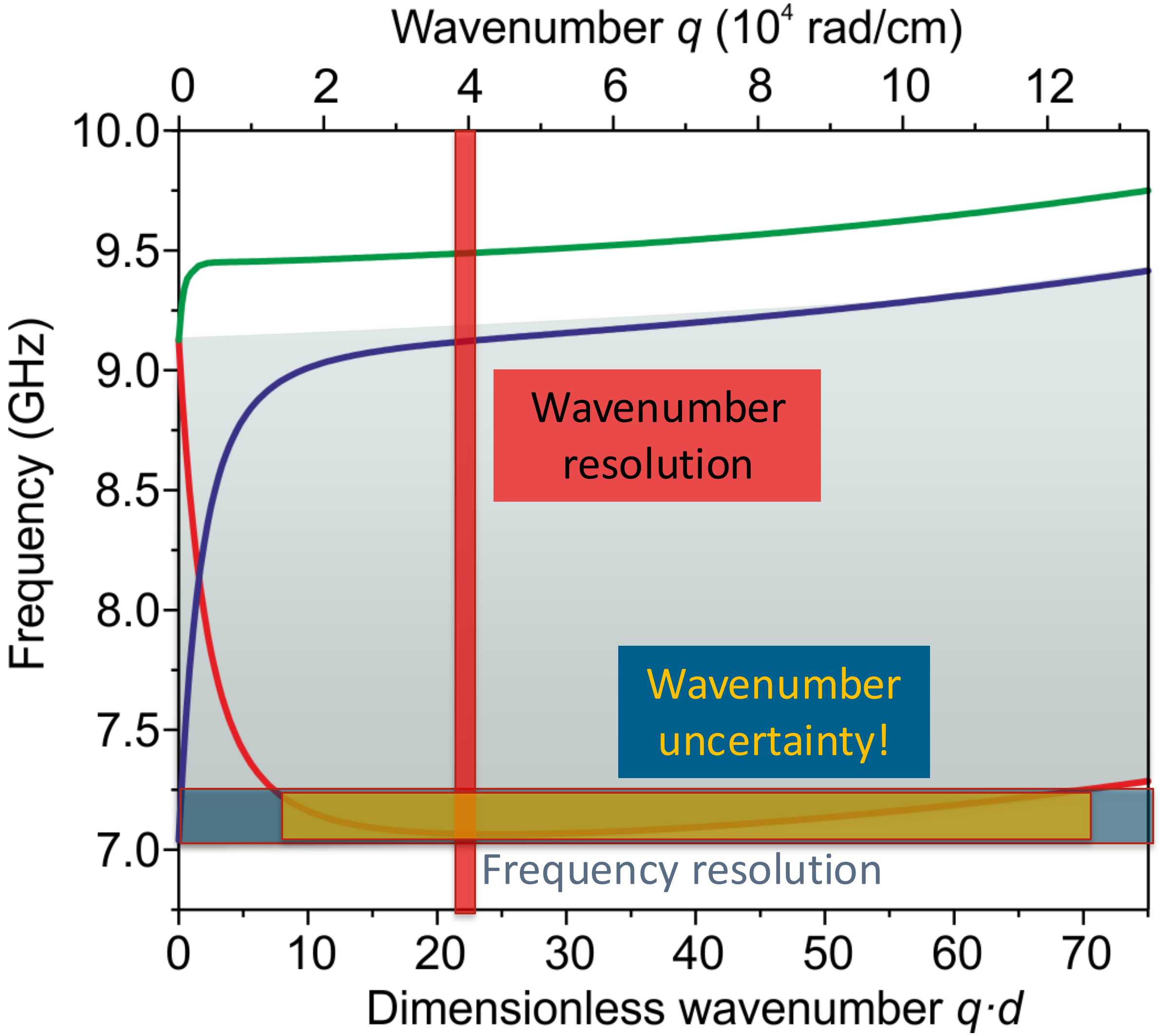


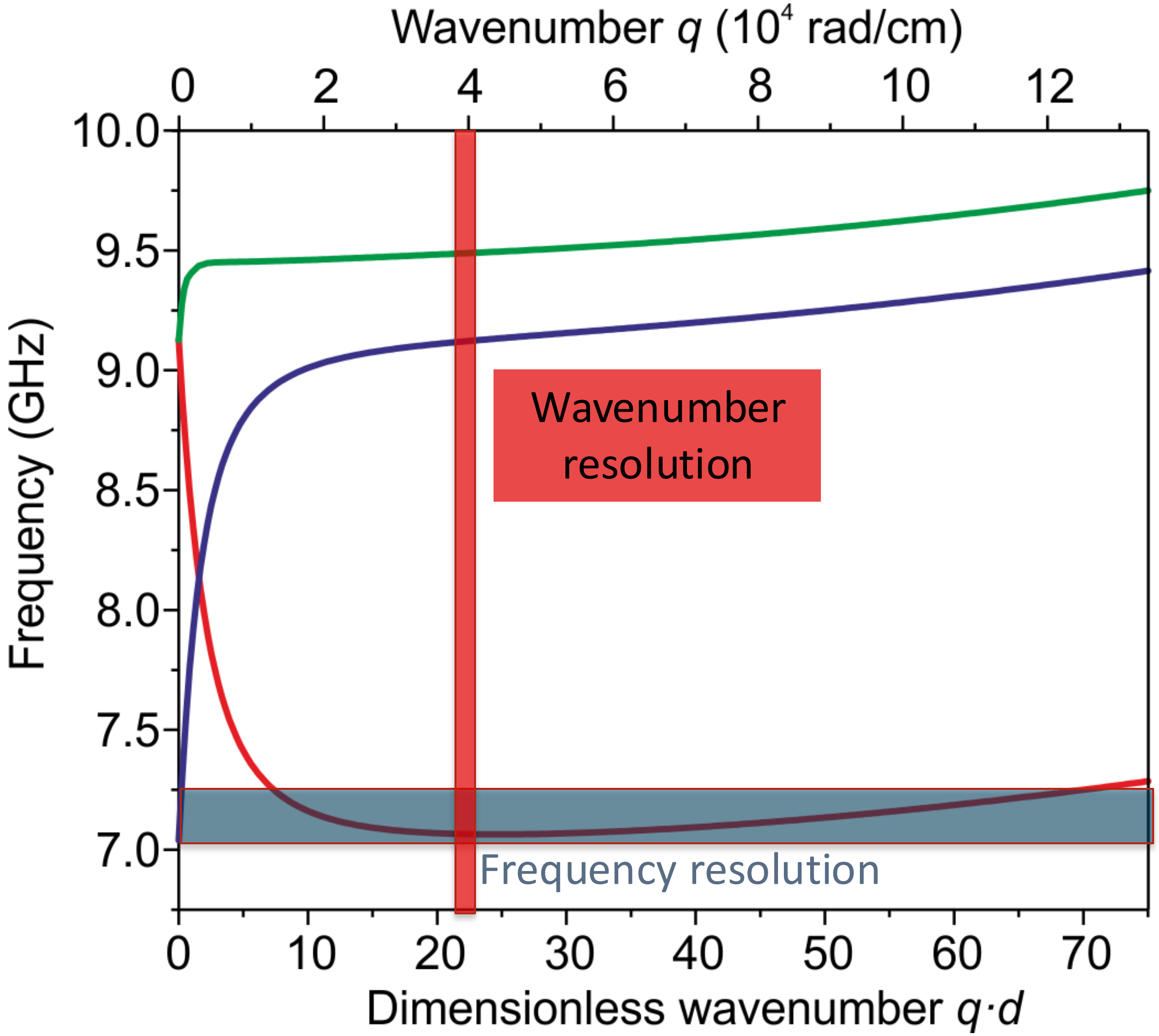


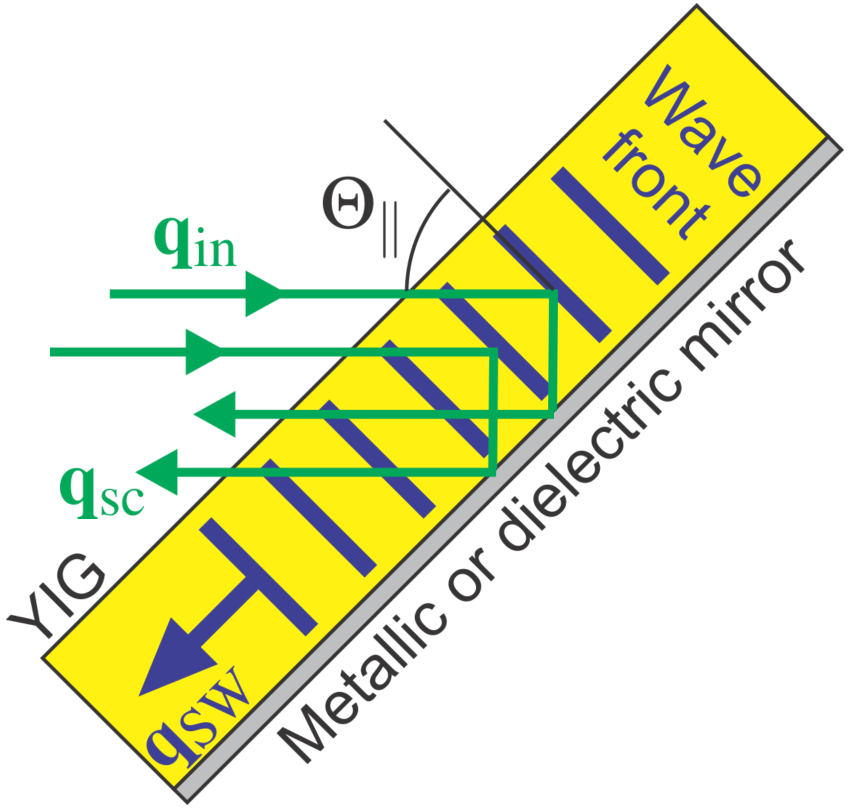
P. Pirro *et al*., Phys. Rev. Lett. **113**, 227601 (2014)

Wavenumber resolution principle



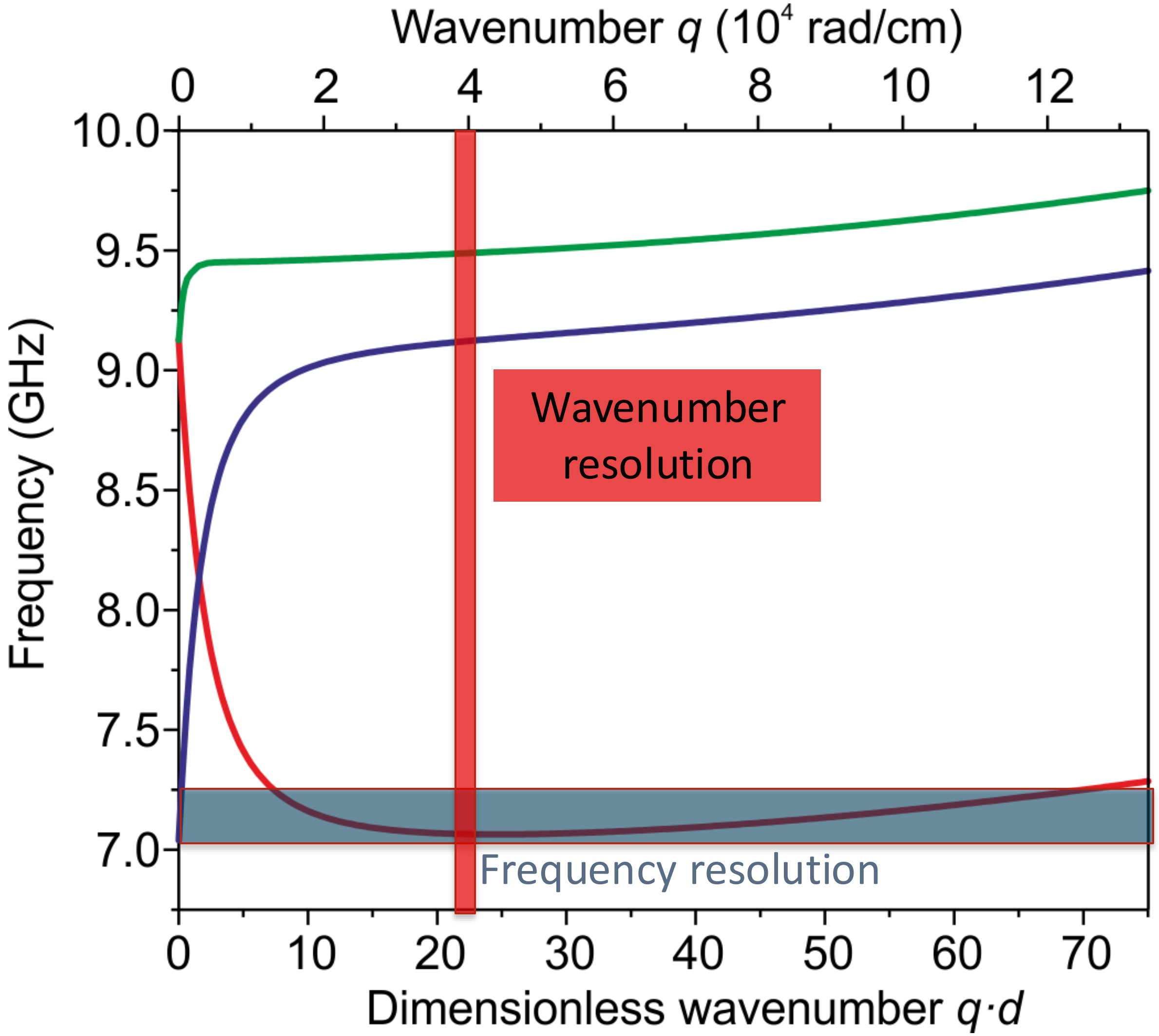
Wavenumber resolution principle

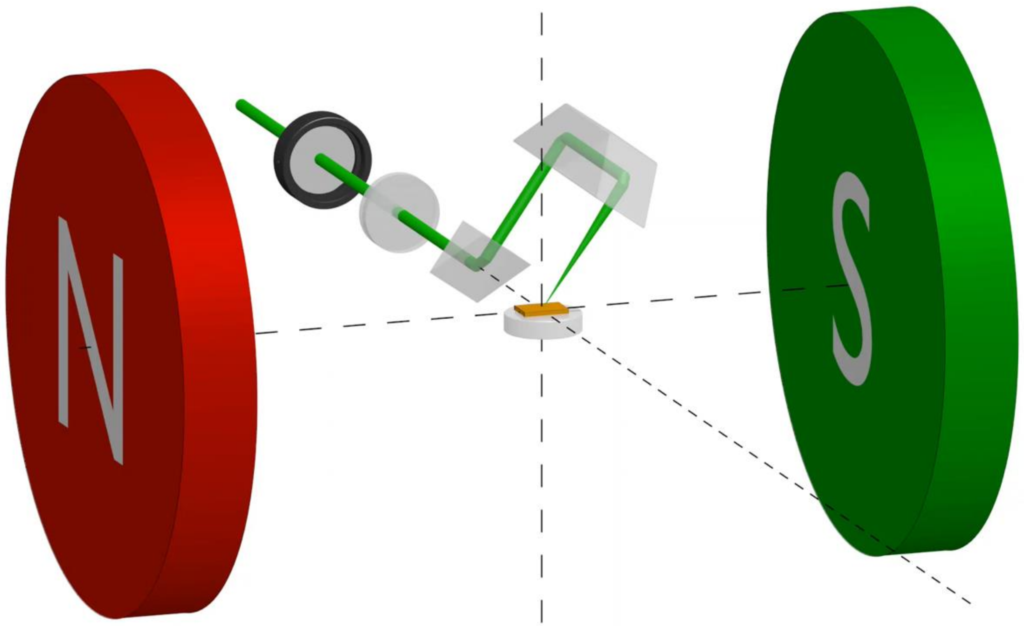




$$q_{\text{Spin wave}} = 2q_{\text{Laser}} \sin(\Theta_{\|})$$

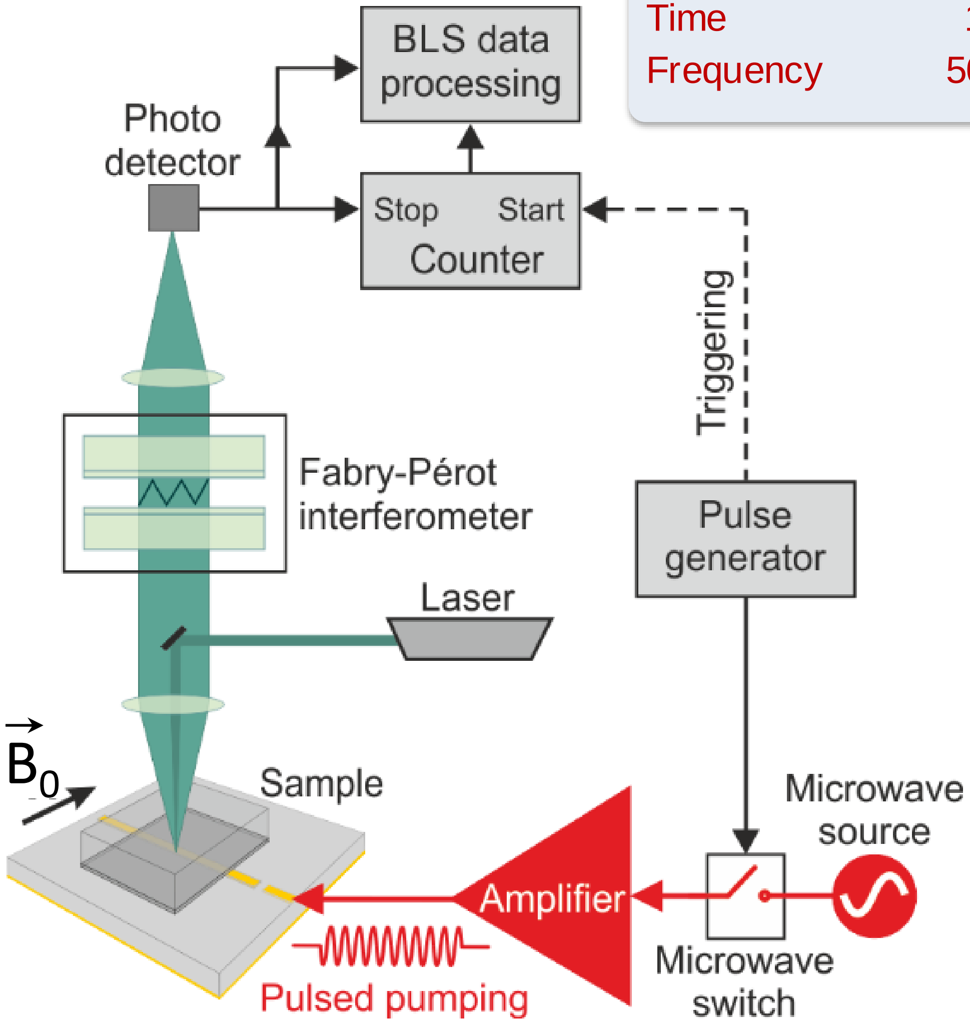
Wavenumber resolution experiment





Max wavenumber	2.36×10^5 rad/cm
Wavenumber resolution	0.02×10^5 rad/cm

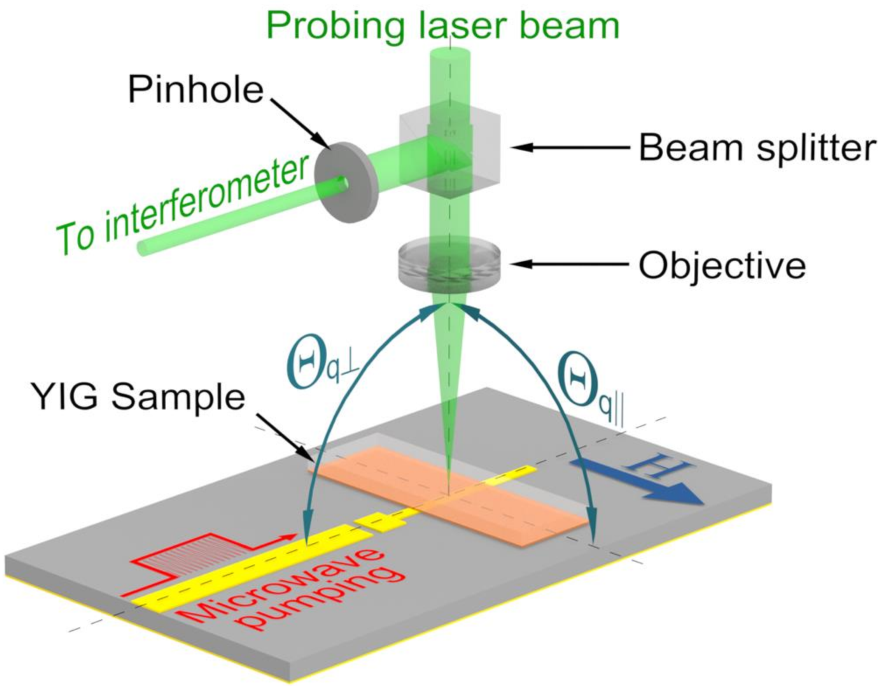
Time-, space- and wavevector-resolved Brillouin light scattering spectroscopy



Resolution

Time	1 ns
Frequency	50 MHz

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



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

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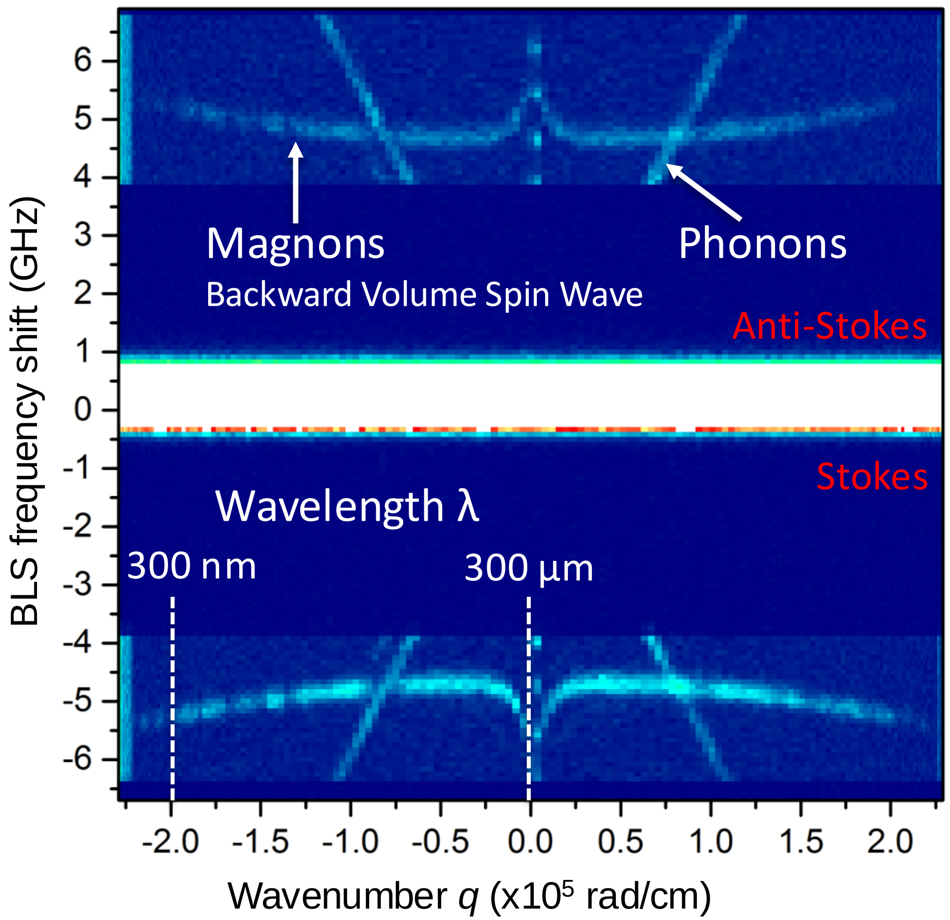
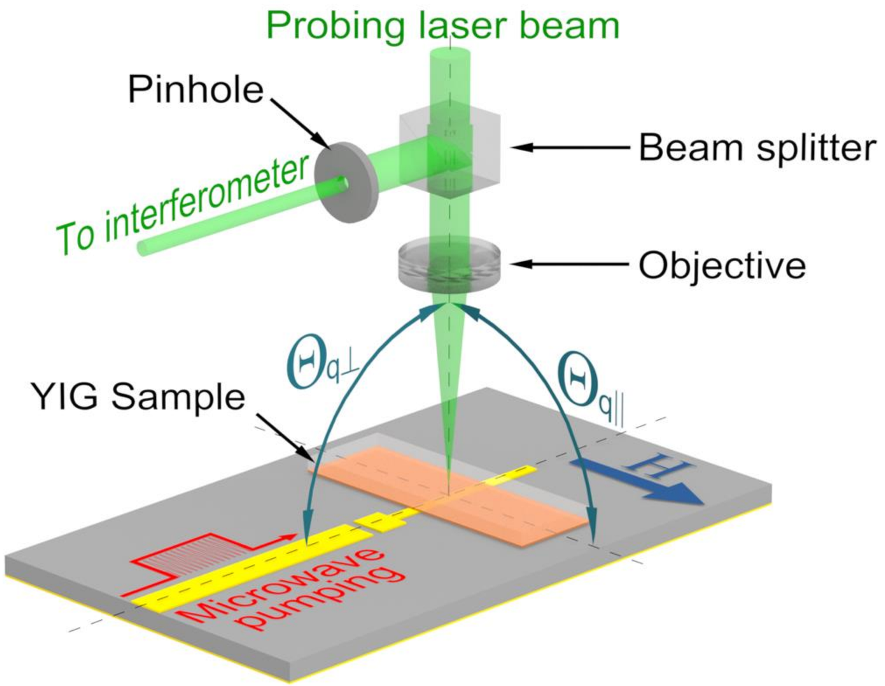
Wavevector-resolved BLS spectroscopy

Thermal spectrum of 6 µm thick YIG film



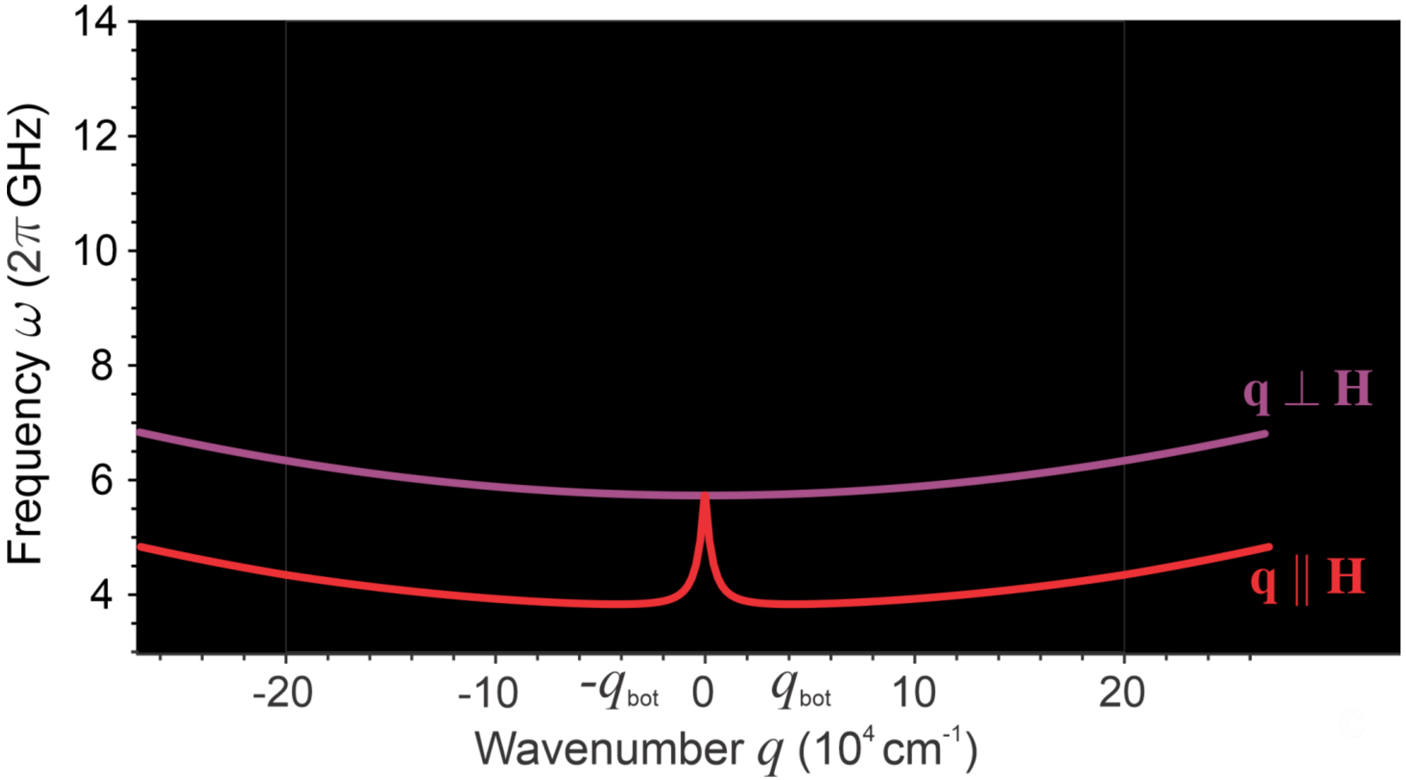
$$q_{SW} = 2q_L \cos\left(\Theta_q\right)$$



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

Outlook: Pumped magnon spectra

Calculated magnon dispersion branches



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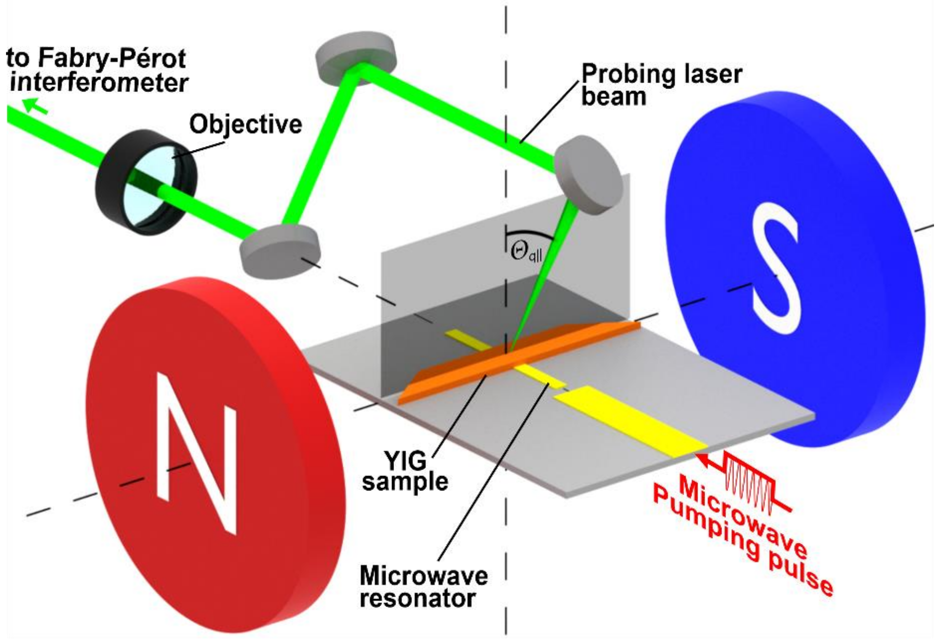
BLS setup + microwave pumping circuit



(111) LPE-grown YIG film:	6.7 µm
Width of the pumping area:	50 µm
Microwave power:	20 W
Pumping pulse:	1 µs
Pumping frequency:	13.2 GHz

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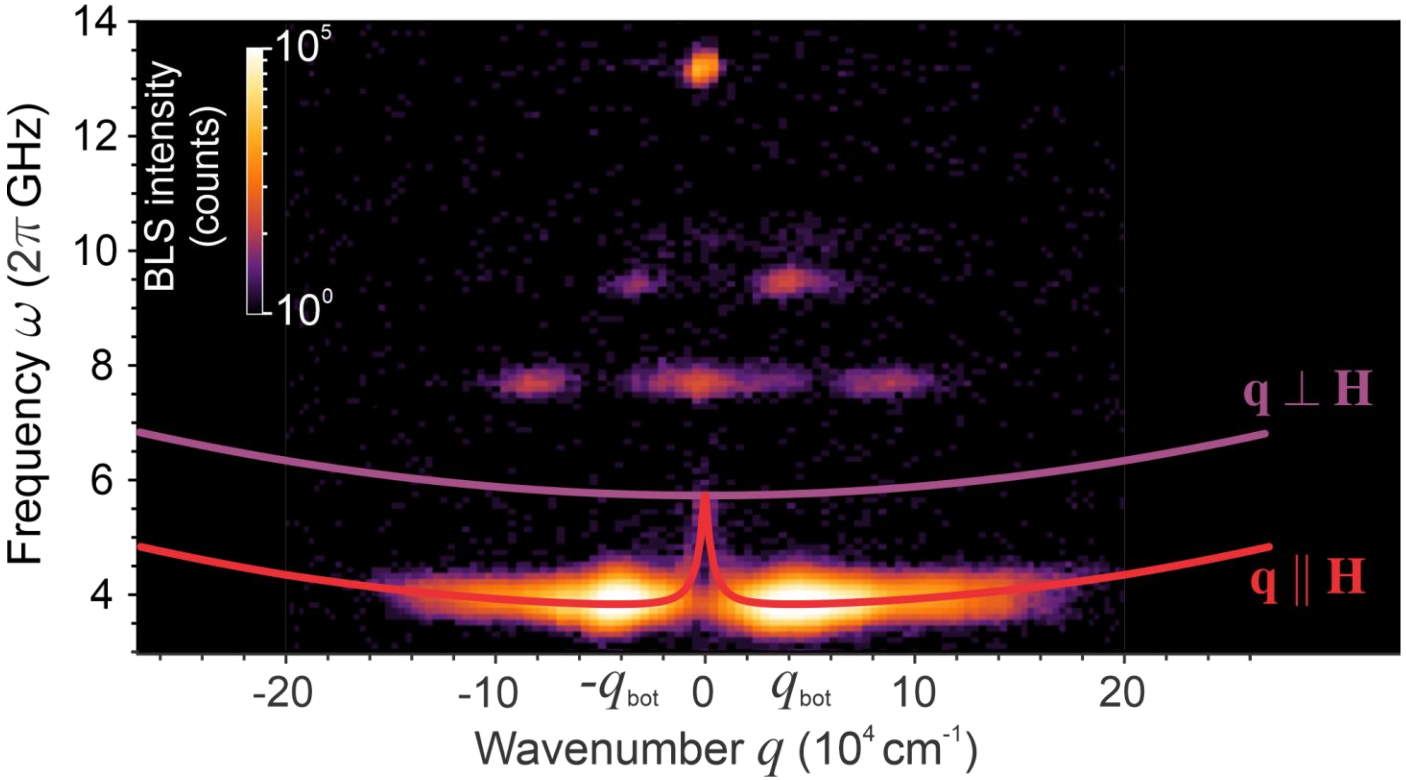
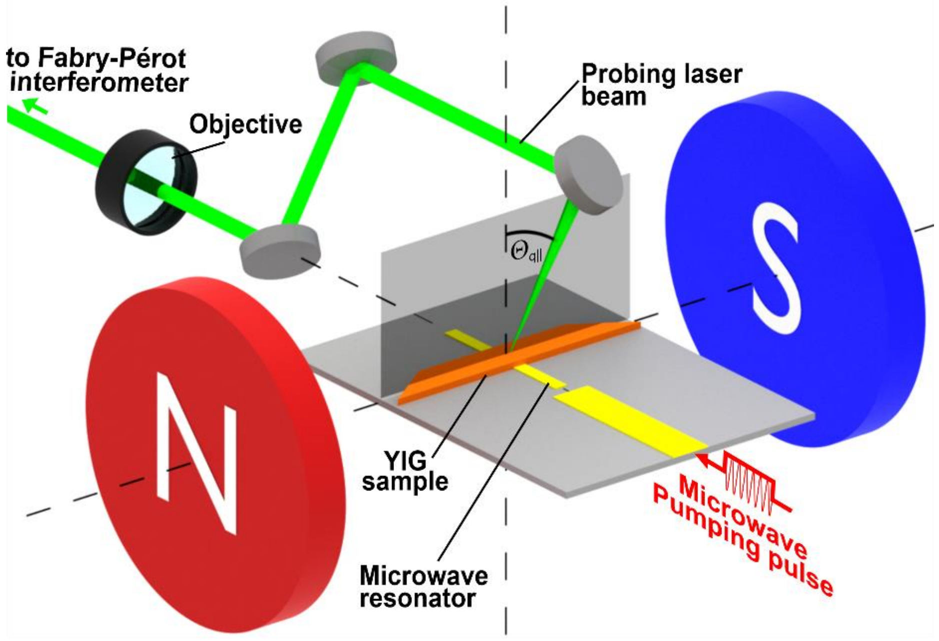
Outlook: Pumped magnon spectra

BLS wavevector-resolved spectra (time integrated)



BLS setup + microwave pumping circuit



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Outlook: Pumped magnon spectra

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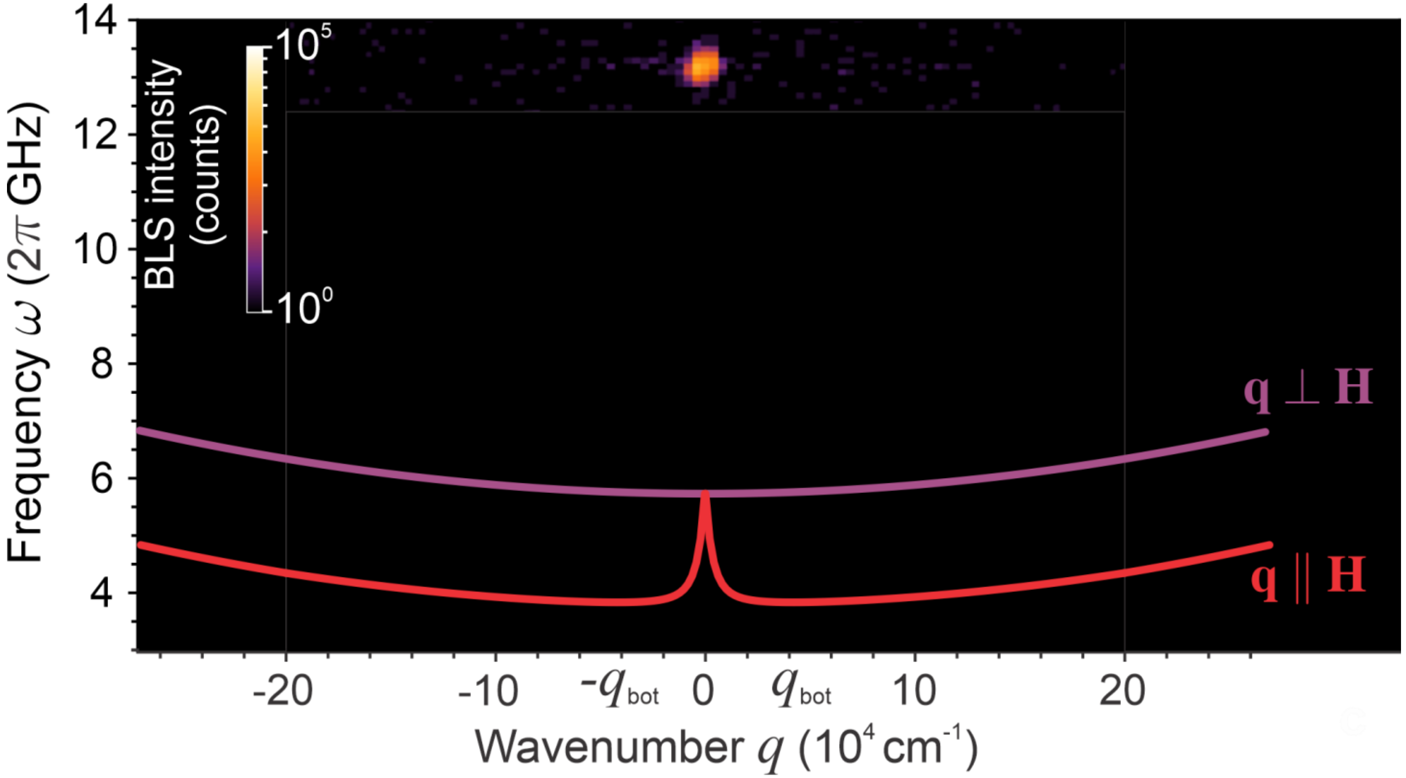

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Outlook: Pumped magnon spectra

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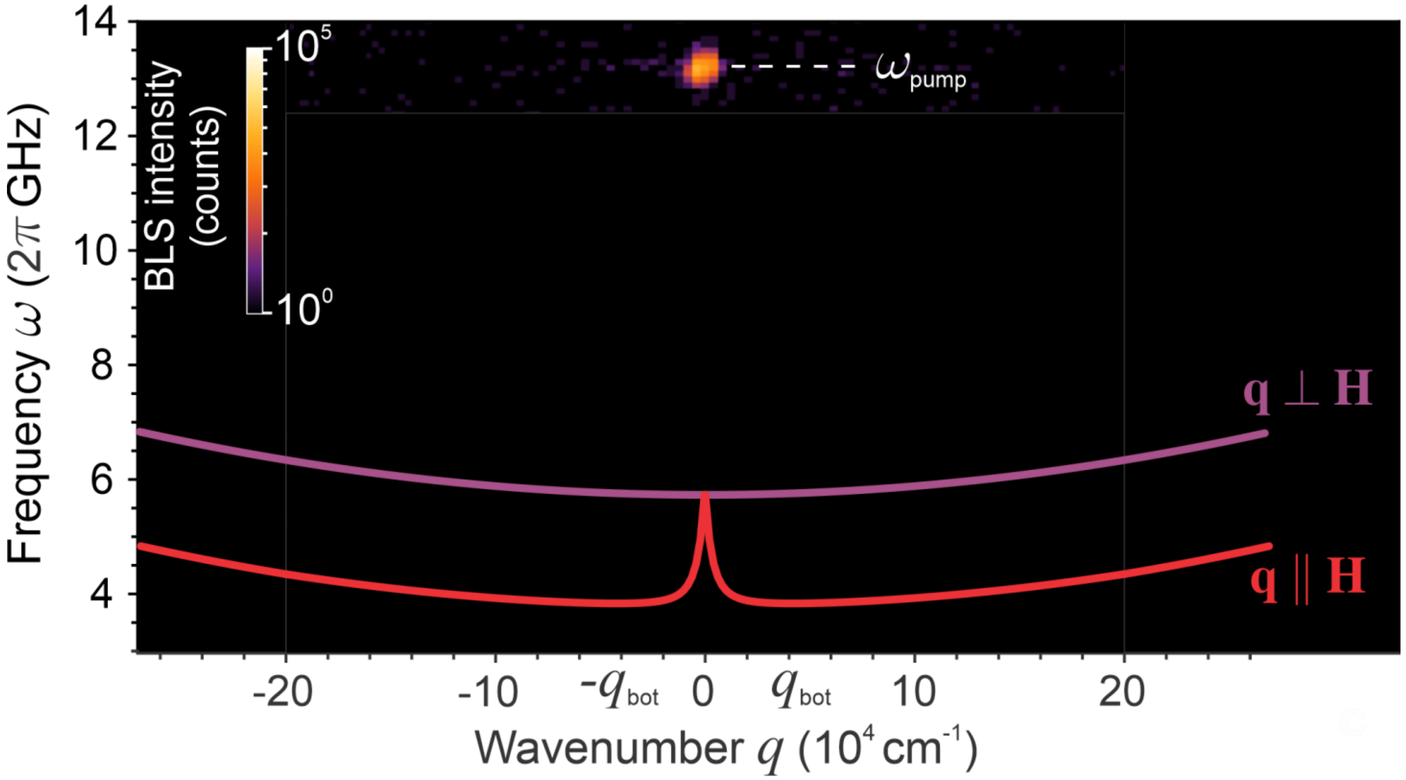

"Virtual" pumped, forced magnons

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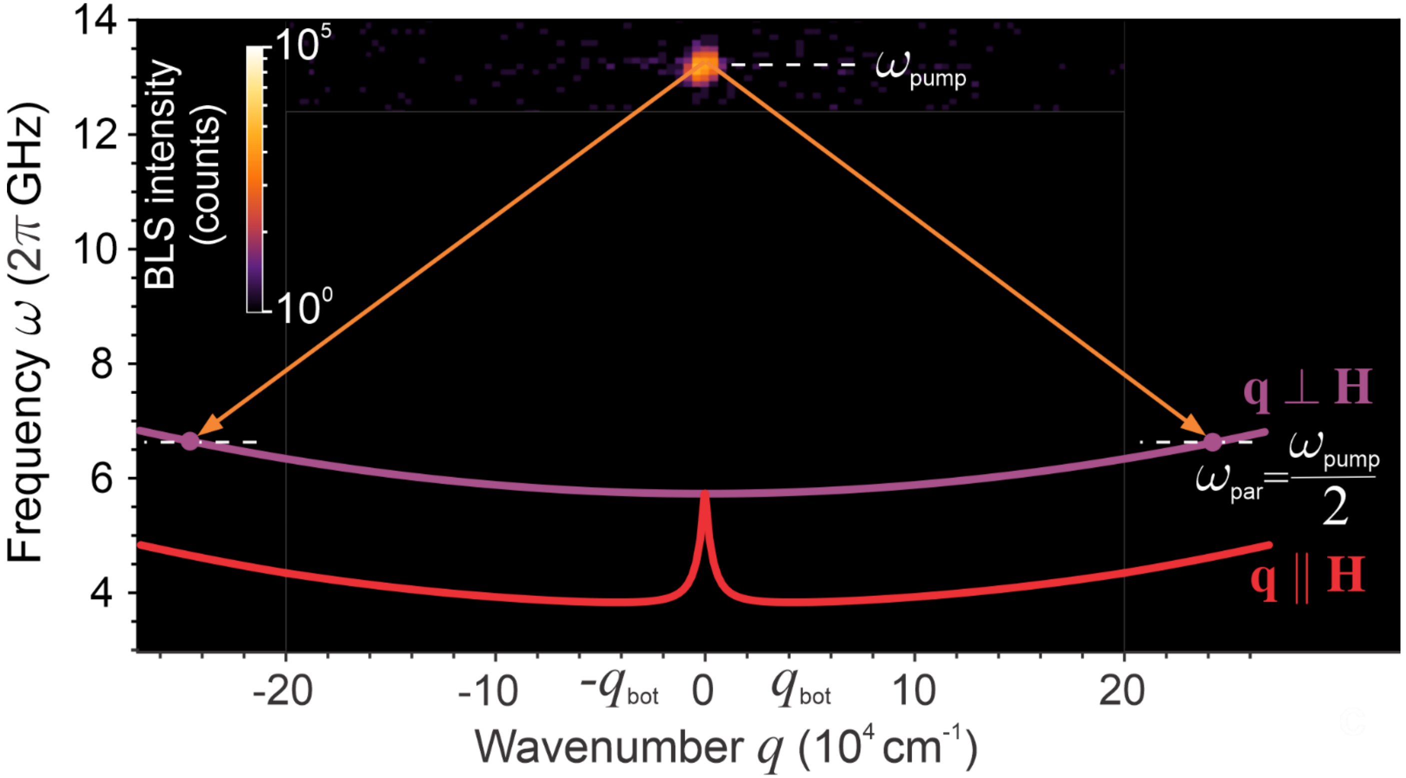
Outlook: Pumped magnon spectra

BLS wavevector-resolved spectra (time integrated)



"Real" parametric magnons

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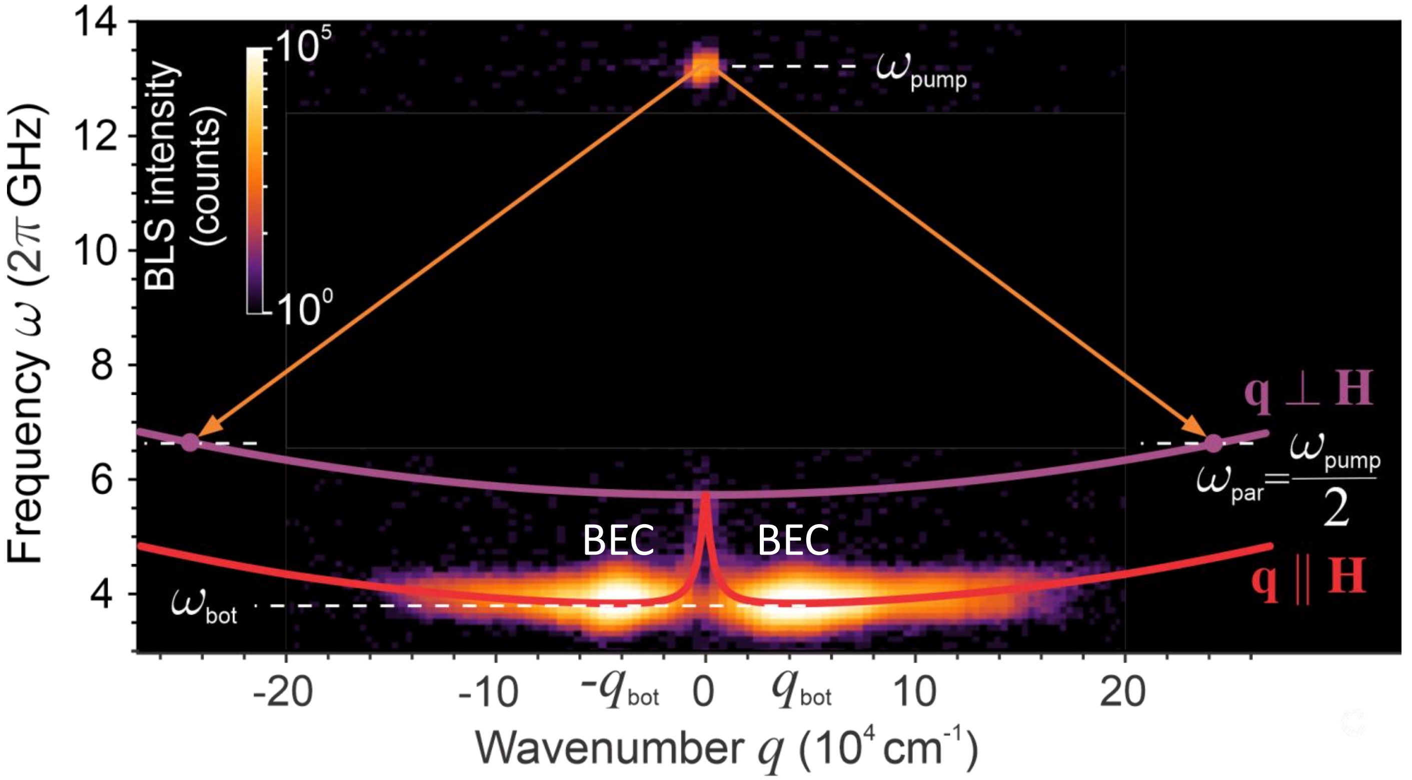
Outlook: Pumped magnon spectra

BLS wavevector-resolved spectra (time integrated)



Magnon BEC
and magnon gas

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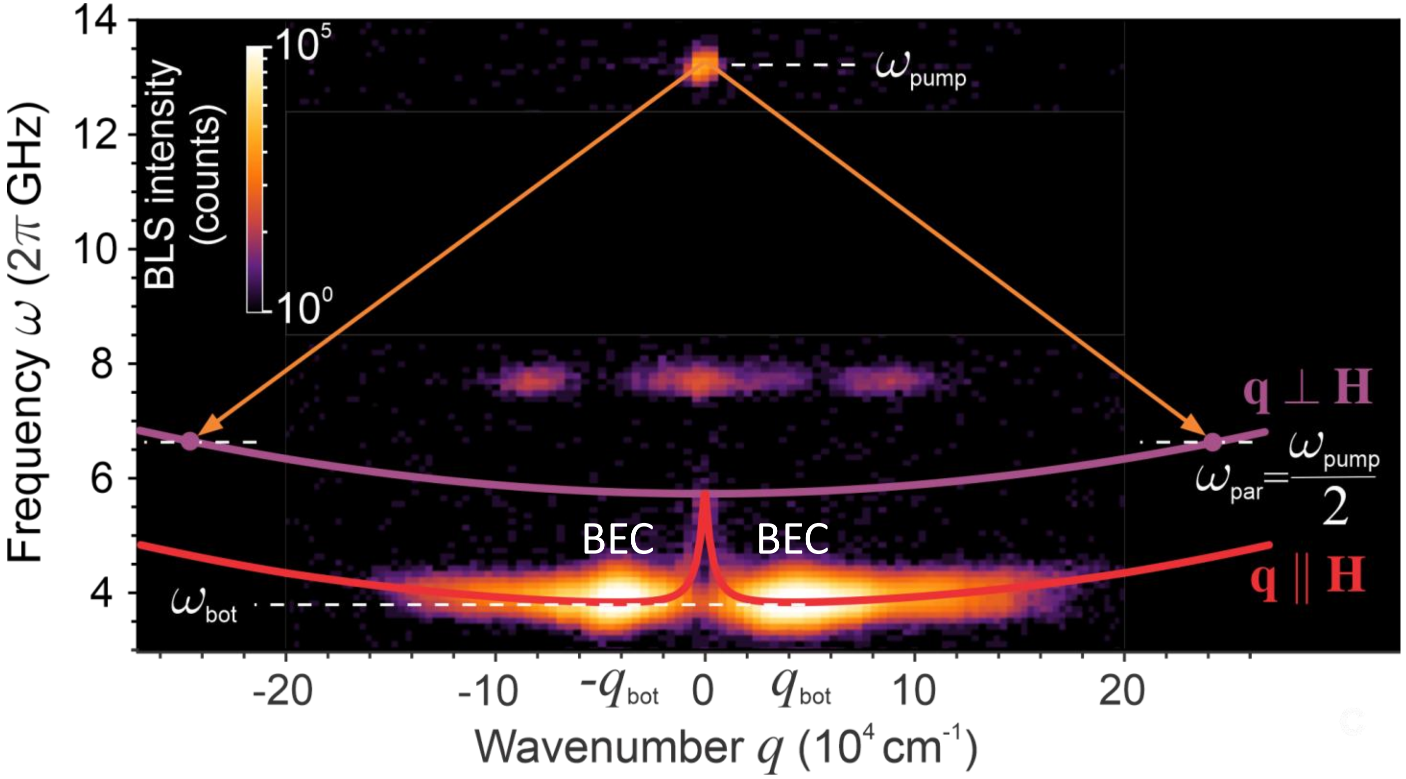
Outlook: Pumped magnon spectra

BLS wavevector-resolved spectra (time integrated)



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Outlook: Pumped magnon spectra

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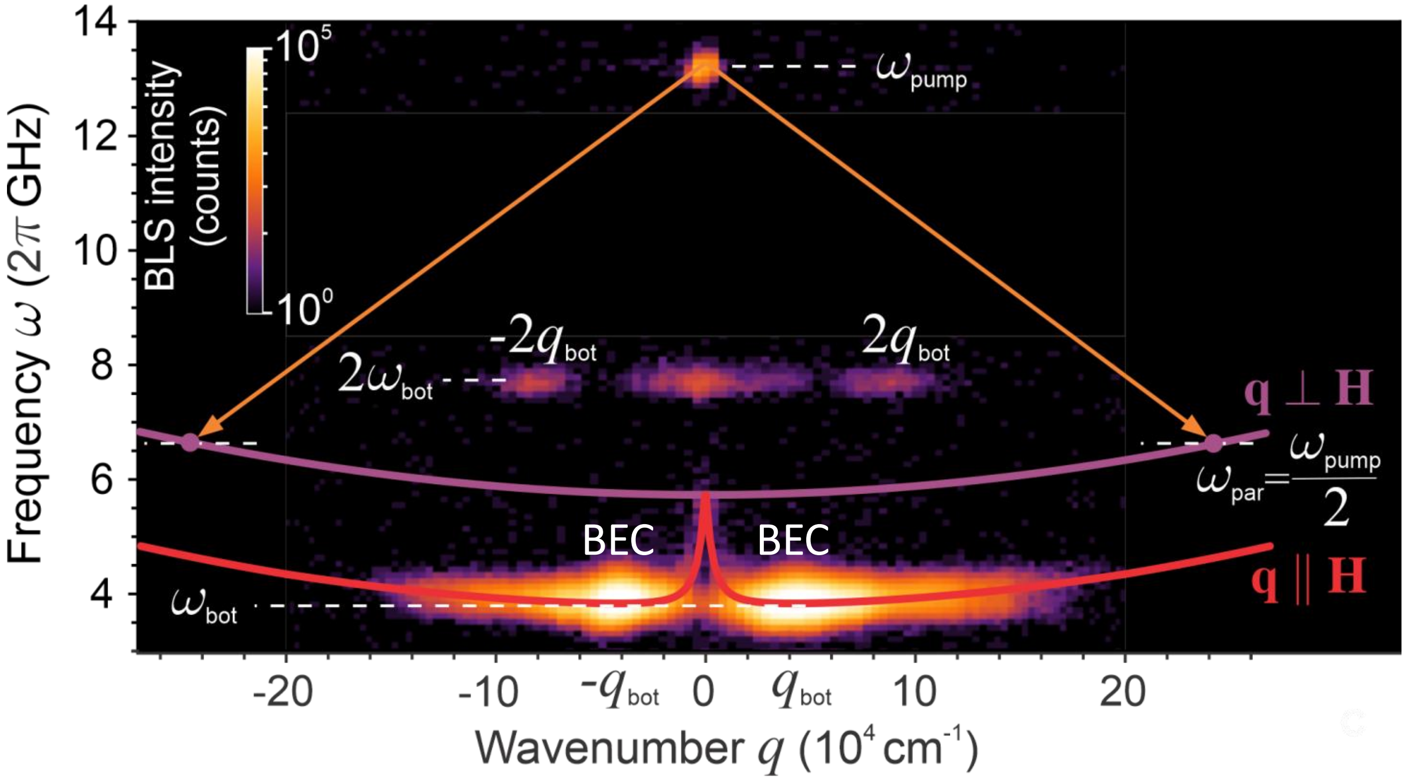

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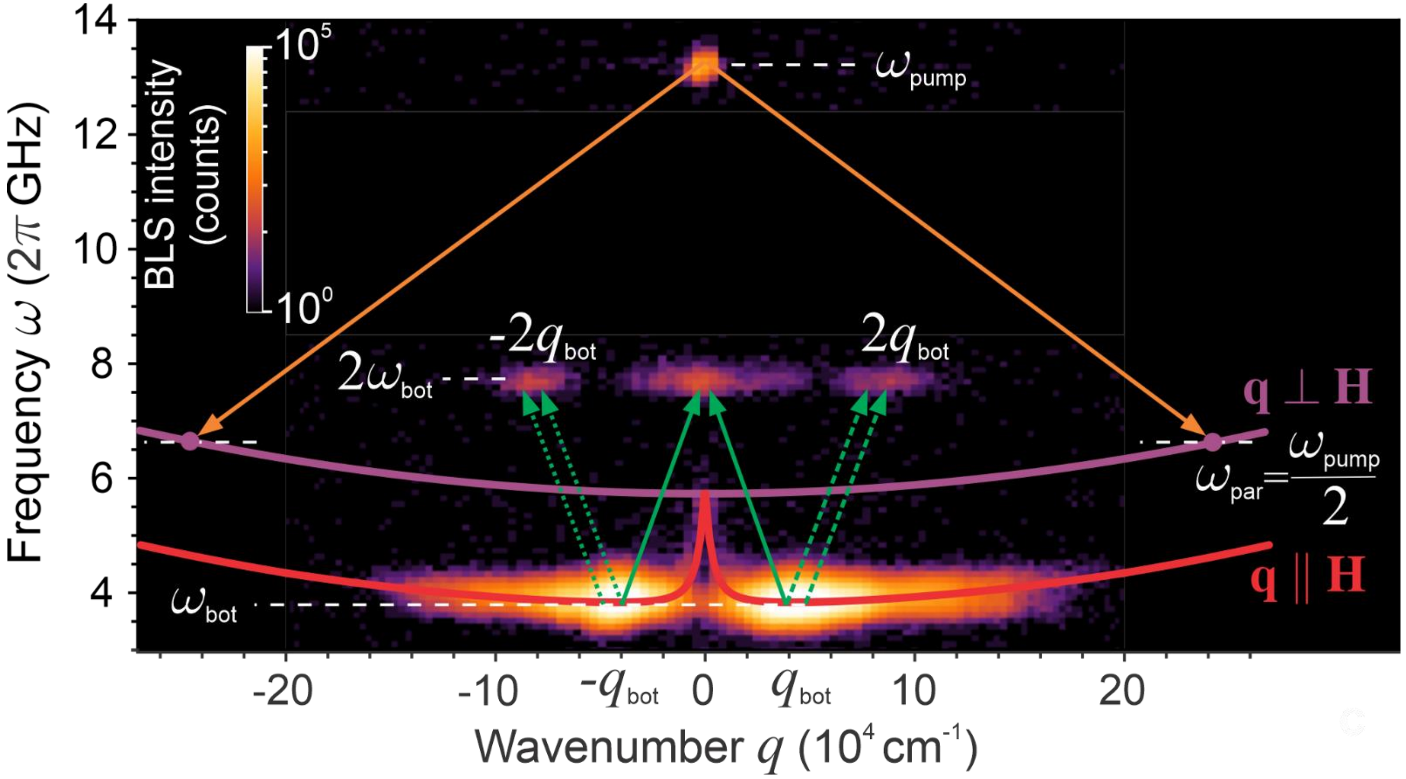
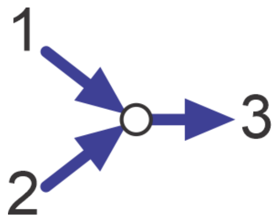
Outlook: Pumped magnon spectra

BLS wavevector-resolved spectra (time integrated)



Confluence processes:



Central spot:

$$\omega_{-q_{\parallel}} + \omega_{+q_{\parallel}} \Rightarrow 2\omega_{\text{bot}} \text{ and } q = 0$$

Left spot:

$$\omega_{-q_{\parallel}} + \omega_{-q_{\parallel}} \Rightarrow 2\omega_{\text{bot}} \text{ and } q = -2q_{\text{bot}}$$

Right spot:

$$\omega_{+q_{\parallel}} + \omega_{+q_{\parallel}} \Rightarrow 2\omega_{\text{bot}} \text{ and } q = 2q_{\text{bot}}$$

"Double-bottom virtual" magnons

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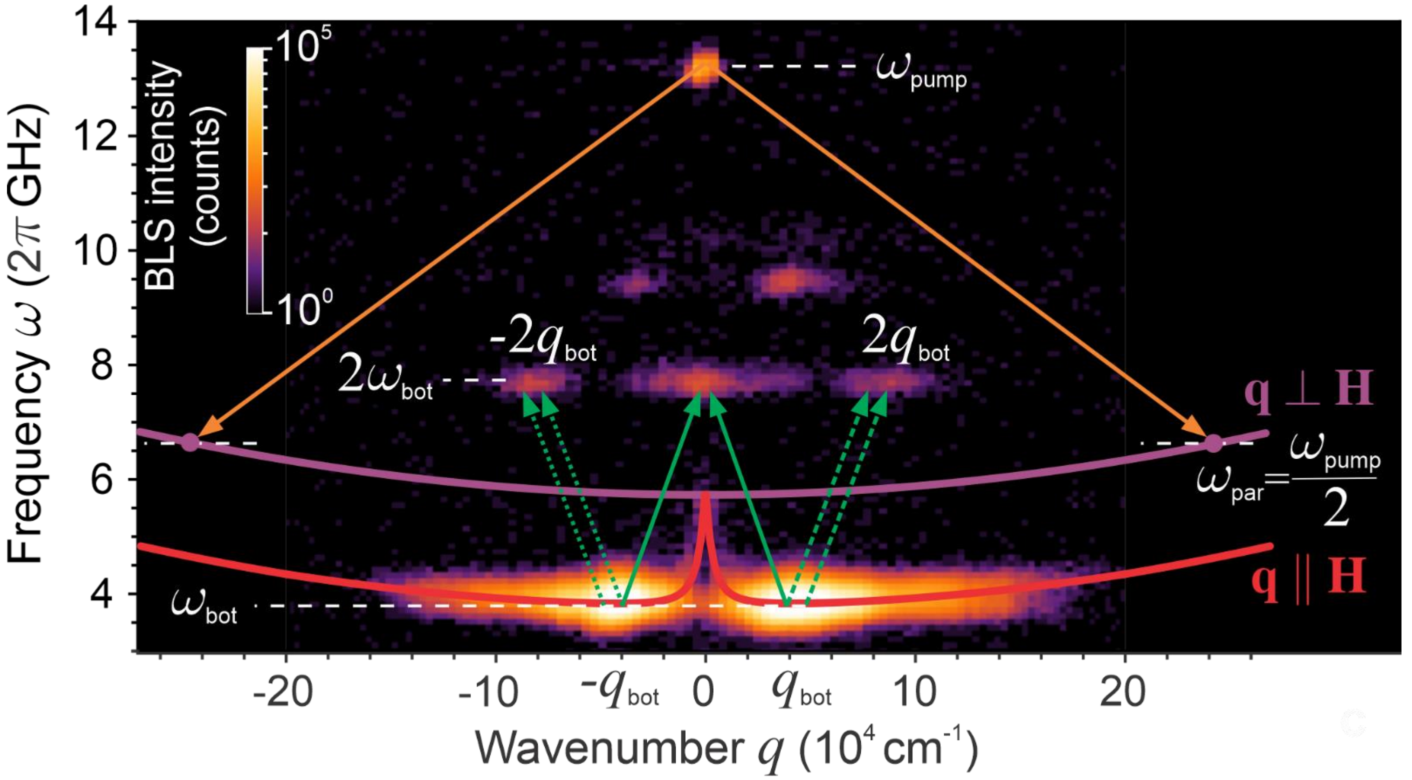
Outlook: Pumped magnon spectra

BLS wavevector-resolved spectra (time integrated)



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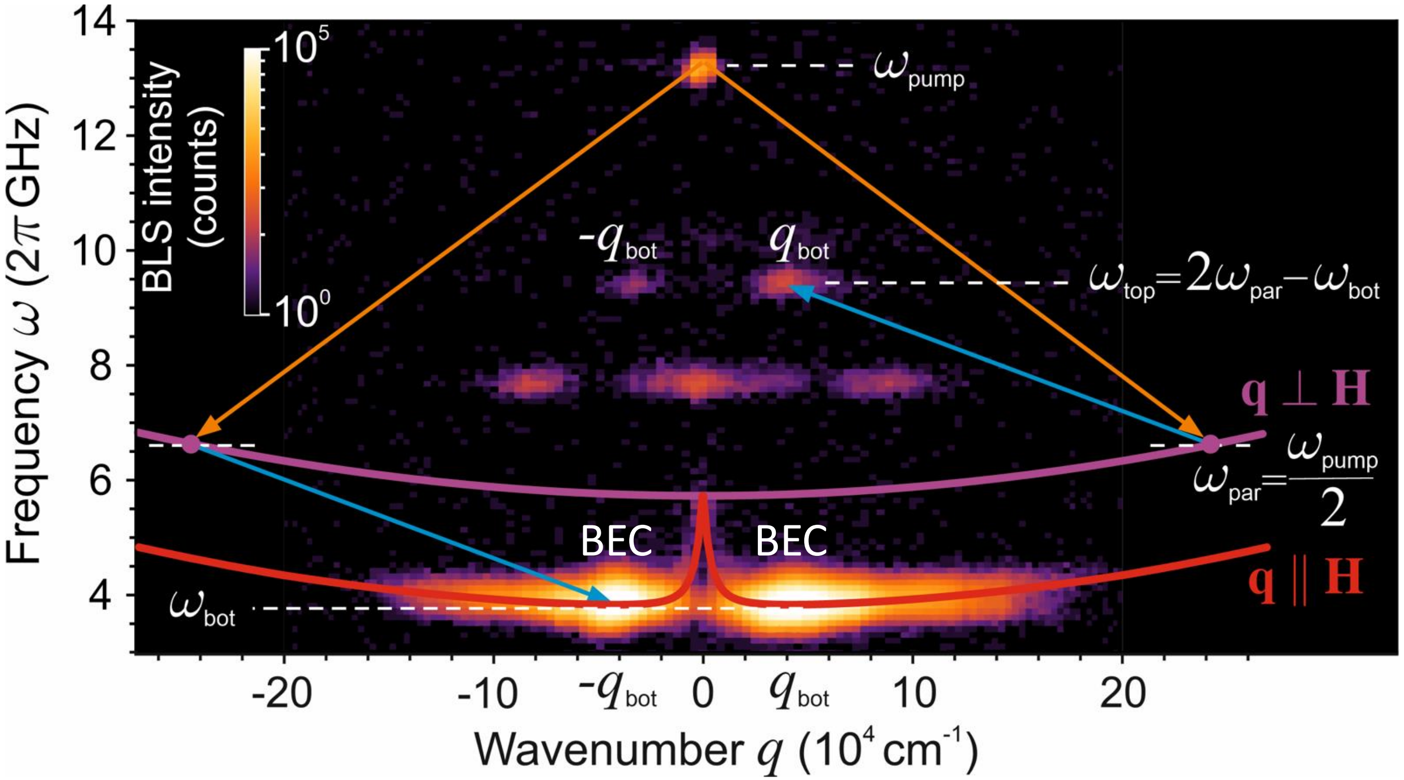
Outlook: Pumped magnon spectra

BLS wavevector-resolved spectra (time integrated)



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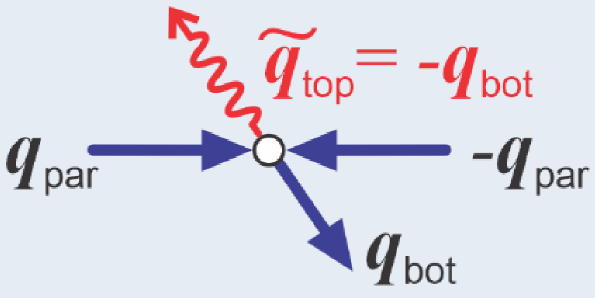
4-magnon scattering process similar to the kinetic instability



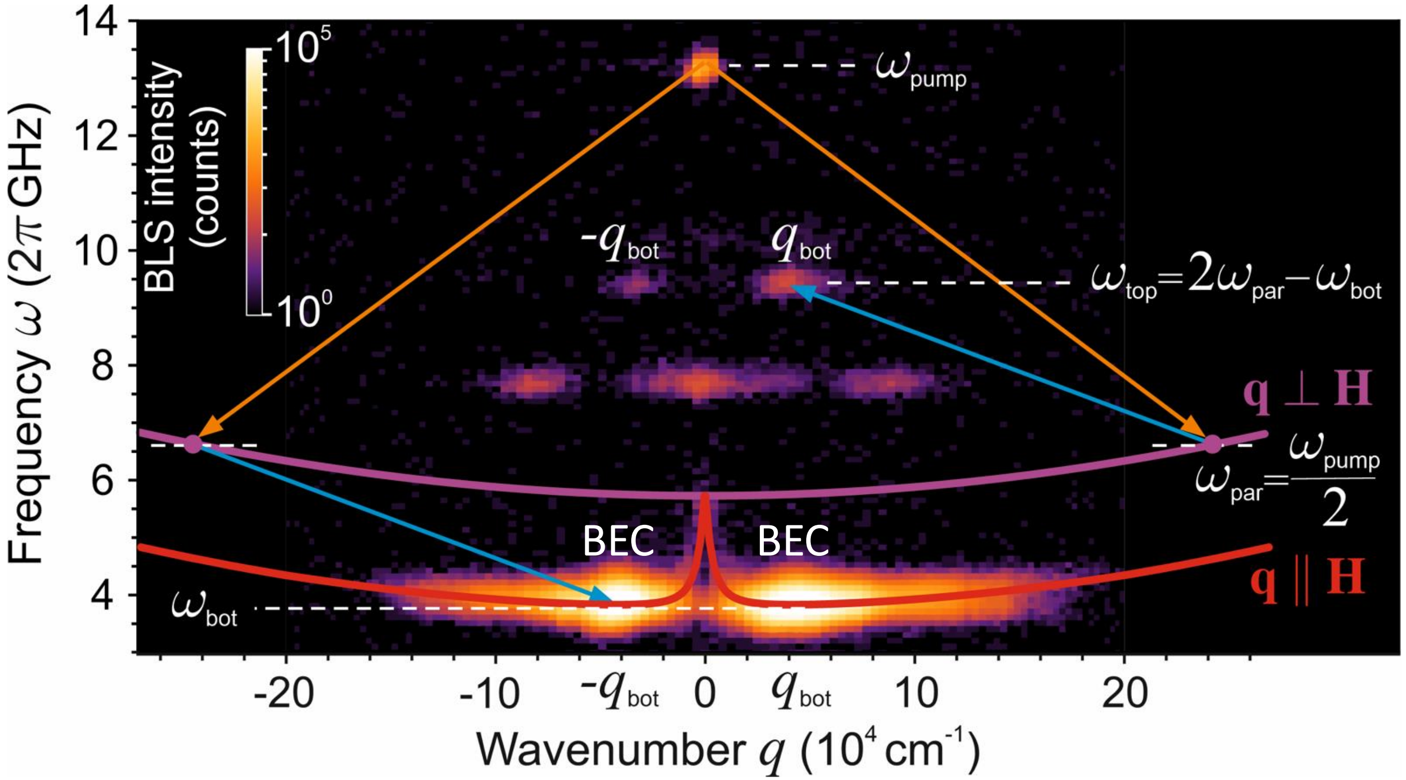
No magnon states with $(\omega_{top}, \pm q_{bot})$

⇩

negligibly weak process!

Outlook: Pumped magnon spectra

BLS wavevector-resolved spectra (time integrated)



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- Full phase correlation in the pairs of parametric waves with $\pm q_{par}$

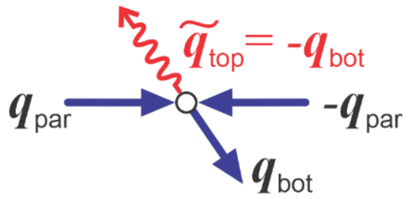
⇩

- Consider a pair of parametric magnons as a coherent wave object

⇩

- Therefore, such a four-magnon scattering process is phase enhanced

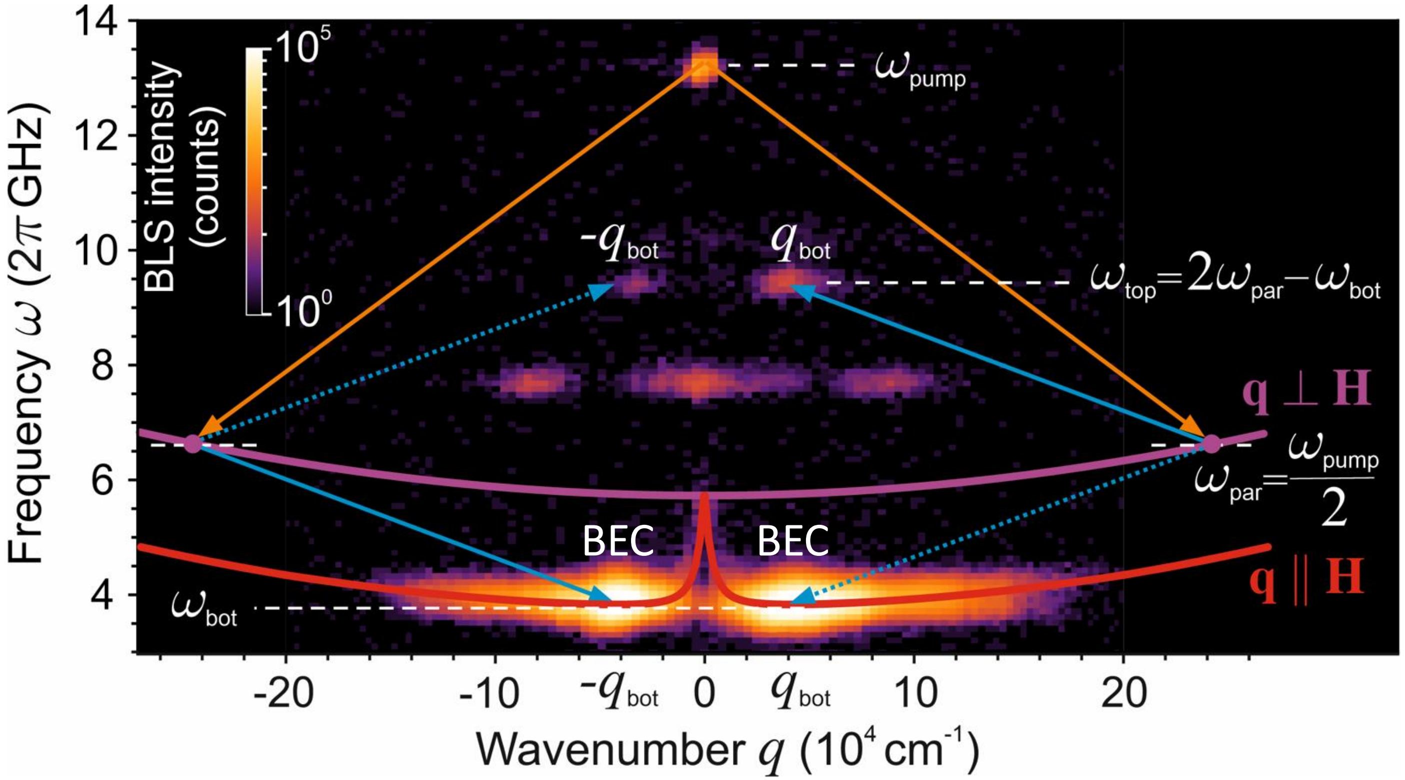
In quantum optics:
nonlinear processes with quantum-correlated input have higher efficiency



Classical version of quantum enhancement

Outlook: Pumped magnon spectra

BLS wavevector-resolved spectra (time integrated)



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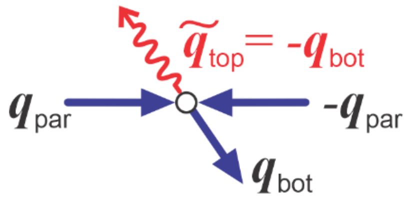

Classical version of quantum enhancement

Summary: What we leaned in this lecture:

- Ferromagnetic resonance and basics of microwave experiment with spin waves
- Brillouin light scattering (BLS) spectroscopy
- Time- and space-resolved BLS
- BLS microscopy
- Wavevector-resolved BLS
- Nonlinear processes
- Coherency might enlarge four-magnon processes – classical version of quantum enhancement