Macroscopic magnonic quantum states

Burkard Hillebrands

Fachbereich Physik and Landesforschungszentrum OPTIMAS
Technische Universität Kaiserslautern, Germany

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Team

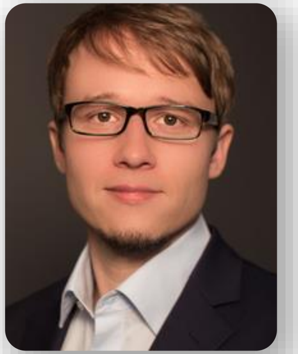
Kaiserslautern

Alexander Kreil

Halyna Musiienko-Shmarova

Morteza Mohseni

Michael Schneider



Philipp Pirro

Vitaliy Vasyuchka

Oleksandr Serha

Dmytro Bozhko
(now Univ. of Colorado)

Andrii Chumak
(now Univ. of Vienna)

Collaborators

- **Victor L'vov** and **Anna Pomyalov**
  (Weizmann Institute of Science, Israel)
- **Gennadii Melkov**
  (Taras Shevchenko National University of Kyiv, Ukraine)
- **Andrei Slavin** and **Vasyl Tiberkevich**
  (Oakland University, USA)

Macroscopic quantum states

Main idea: find macroscopic magnonic quantum states for information transfer and processing

- analogous to superconductivity (Josephson currents)
  and to superfluidity in ^{3}He and ^{4}He
- free of dissipation (apart from magnon-phonon and magnon-electron coupling)

This talk:

- **From magnon Bose-Einstein Condensates (BEC) and supercurrents to Josephson oscillations in a room-temperature magnon BEC**

Why do we name this a „Macroscopic Quantum State“ ?

Microscopic quantum phenomena

Wave–particle duality → Microscopic scale of the system is comparable with the de Broglie wavelength of particles (electrons, Bose atoms, etc.)

Macroscopic quantum phenomena

Wave–particle duality → Macroscopic scale of the system is comparable with the coherence length of the de Broglie wave

- Bose-Einstein condensate (BEC) of particles – spontaneous population by a large number of Bose particles of a single quantum state with macroscopically-large coherence length
- BECs of magnons (quanta of spin waves) – spontaneous formation of a coherent wave in a chaotic magnon system

In **quasi-classical limit** (large number of particles and occupation numbers of magnons) described by the Gross-Pitaevskii equation for de Broglie or spin waves

Properties of both types of condensates are almost identical

⬇

„Macroscopic Quantum Phenomena“

⬇

make use of analogy with numerous phenomena in Bose-Einstein condensates of atoms:
supercurrent, Bogoliubov waves, Josephson effects

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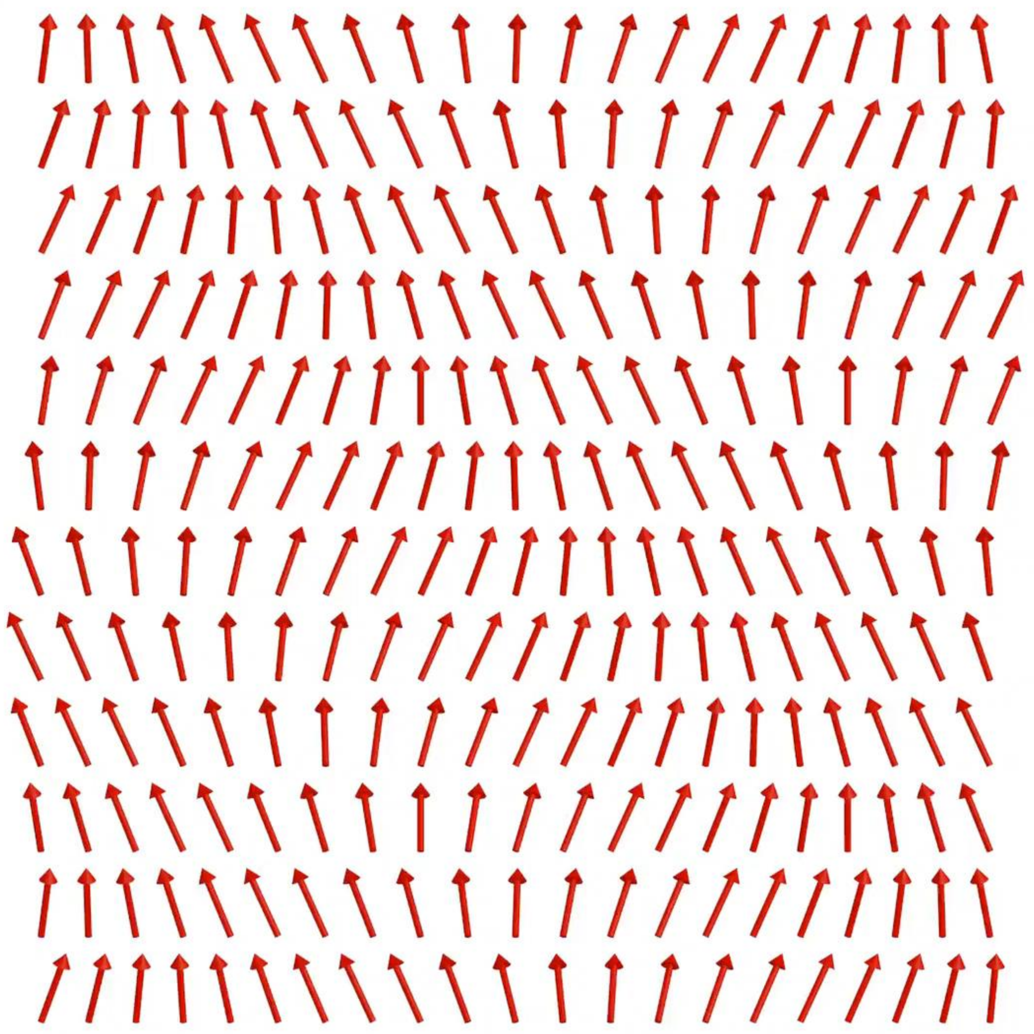
Magnon gas

Magnon as a quanta of spin-wave

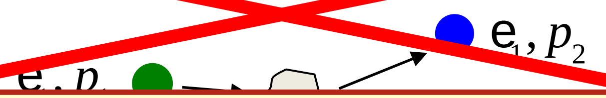
- Energy $\varepsilon = \hbar\omega = \frac{\eta}{\hbar} p^2$
- Momentum $\vec{p} = \hbar\vec{q}$
- Mass $m = \hbar/(2\eta)$
- Spin $s = 1$



(Non-)linear Processes

- **Linear process**

~~Two-magnon scattering~~

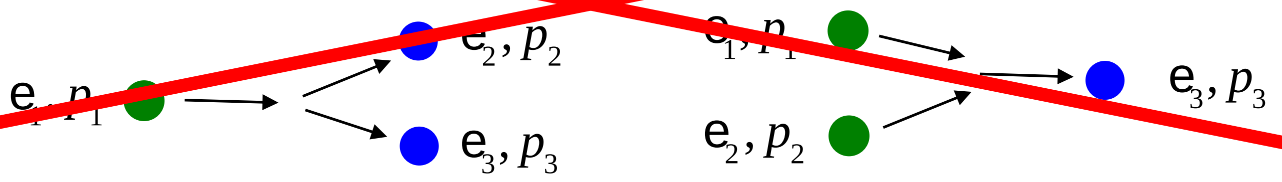


- **Nonlinear pr**

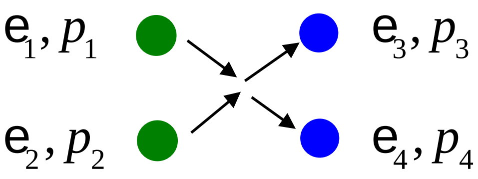
Magnon gas of interacting quasiparticles

Number of particles is conserved

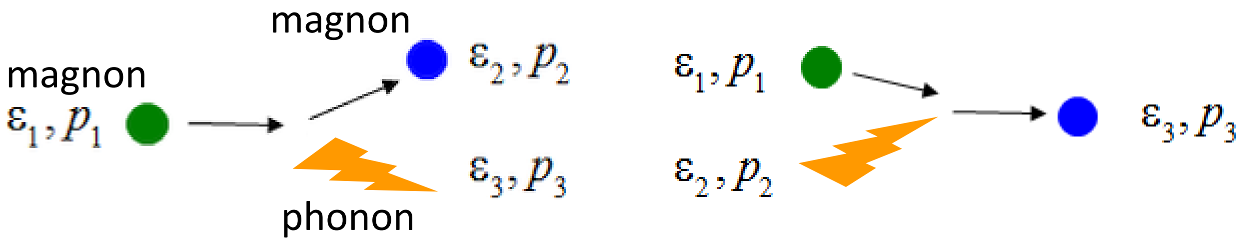
~~Thr~~ ~~nfluence~~



Four-magnon scattering



Cherenkov processes ($v_{\mathrm{gr\ magnon}} > v_{\mathrm{phonon}}$)



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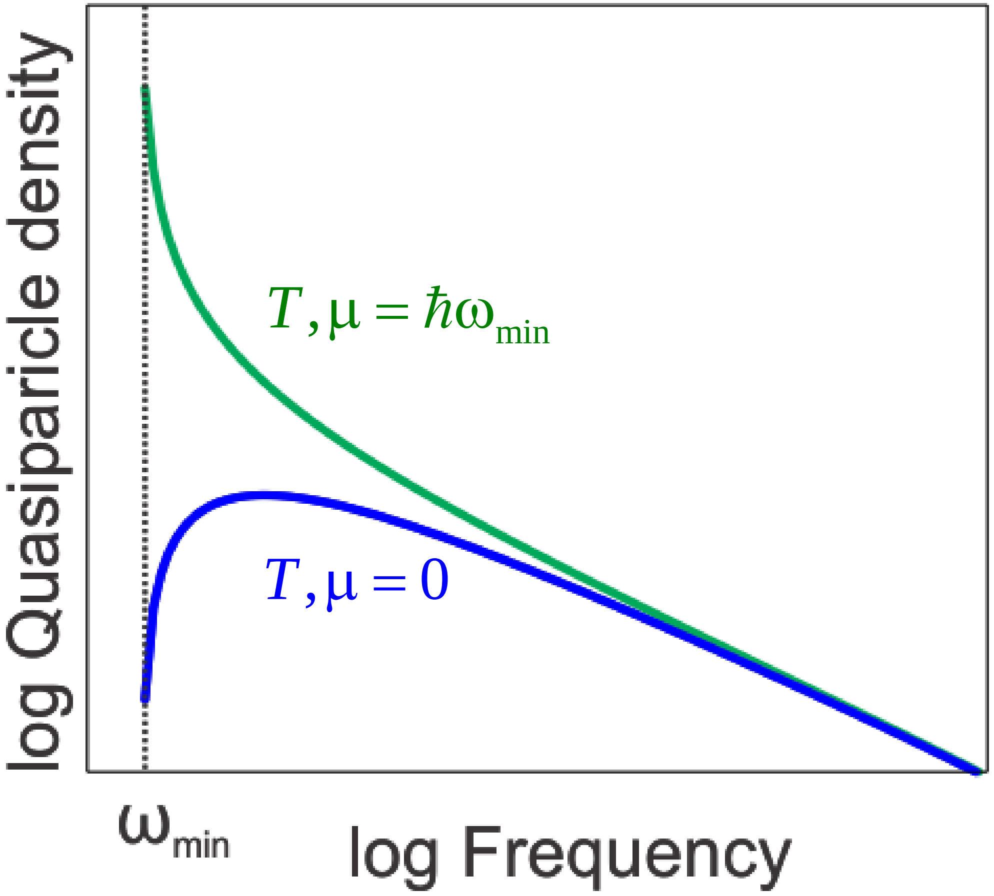
Magnon Bose-Einstein condensation

Bose-Einstein distribution

$$\rho(\omega) = \frac{D(\omega)}{\exp\left(\frac{\hbar\omega - \mu}{k_B T}\right) - 1}$$

μ: chemical potential

External injection of magnons beyond the thermal equilibrium level (about 3%) increases the chemical potential to the bottom of magnon spectrum and leads to Bose-Einstein condensation scenario even at room temperature



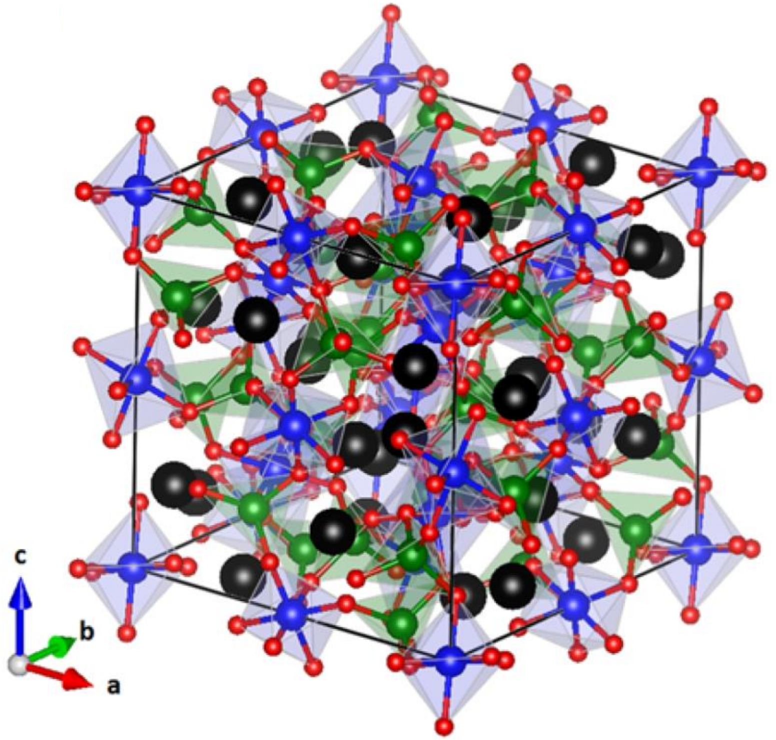
S.O. Demokritov et al., Nature **443**, 430 (2006)

Medium: Yttrium Iron Garnet (YIG, $Y_3Fe_5O_{12}$)

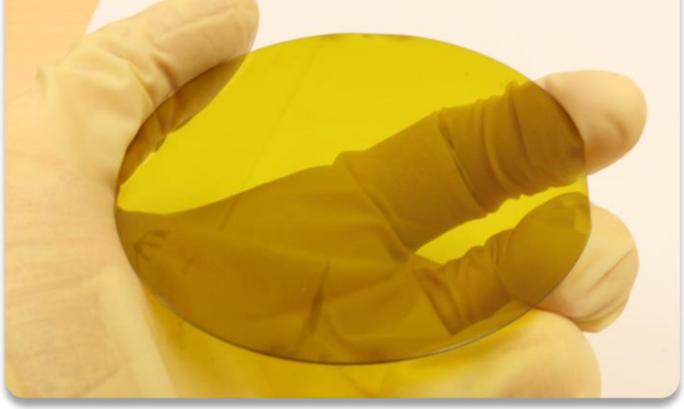
- Room temperature ferrimagnet ($T_C = 560$ K)
- Low phonon damping
- The lowest magnon damping of any known material !

- Cubic crystal
- Lattice constant 12.376 Å
- Unit cell – 80 atoms

V. Cherepanov, I. Kolokolov, and V. L'vov, *The saga of YIG: spectra, thermodynamics, interaction and relaxation of magnons in a complex magnet*
Phys. Rep. **229**, 81–144 (1993)

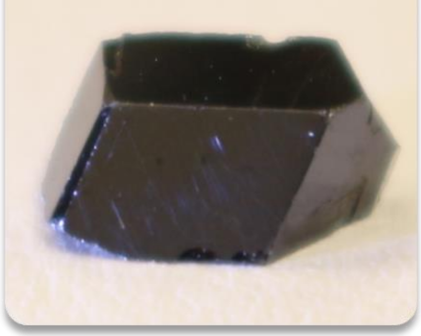


3" YIG wafer



Scientific Research Company "Carat", Lviv, Ukraine

YIG monocrystal



A.J. Princep *et al.*, *The full magnon spectrum of yttrium iron garnet*, npj Quantum Mater. **2**, 63 (2017)

Minority octahedral iron atoms (spin 5/2 down)
Majority tetrahedral iron atoms (spin 5/2 up)

Magnetic moment of a unit cell is 20 Bohr magnetons μ_B at zero temperature

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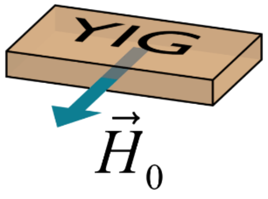
Magnon spectrum of in-plane magnetized YIG film

Landau-Lifshitz equation

$$\frac{\partial \vec{M}}{\partial t} = -|\gamma|\, \vec{M} \times \vec{H}_{\mathrm{eff}}$$

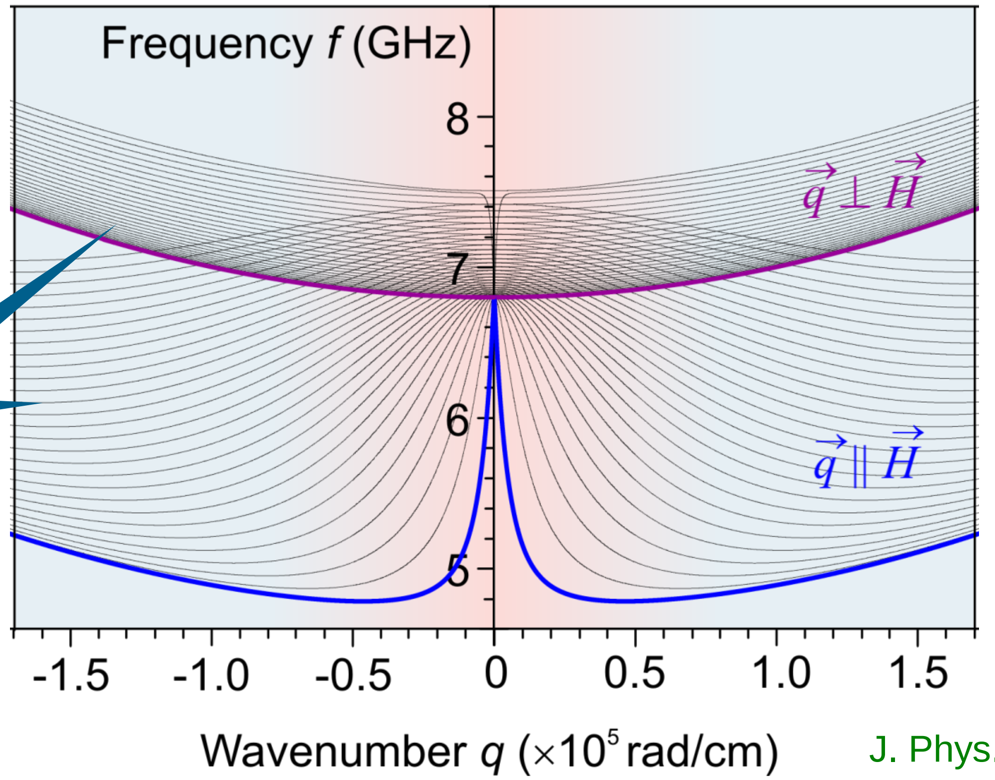
$$\vec{H}_{\mathrm{eff}}(\vec{r}) = \vec{H}_0 + \underbrace{\int_V \tilde{\mathrm{G}}(\vec{r},\vec{r}\,') \cdot \vec{M}(\vec{r}\,')\, dr'^3}_{\text{dipolar interaction}} + \underbrace{\frac{\eta}{\gamma M_S} \nabla^2 \vec{M}}_{\text{exchange interaction}} + \ldots$$

$H_0 = 1710$ Oe



Thickness modes having a non-uniform harmonic distribution of dynamic magnetization along the film thickness

6 µm thick YIG film



Calculations based on:
Kalinikos and Slavin,
J. Phys. C: Solid State Phys **19**, 7013 (1986)

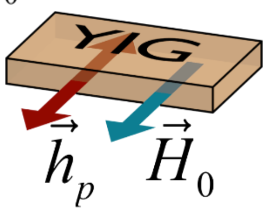
Control of magnon gas density by parametric pumping

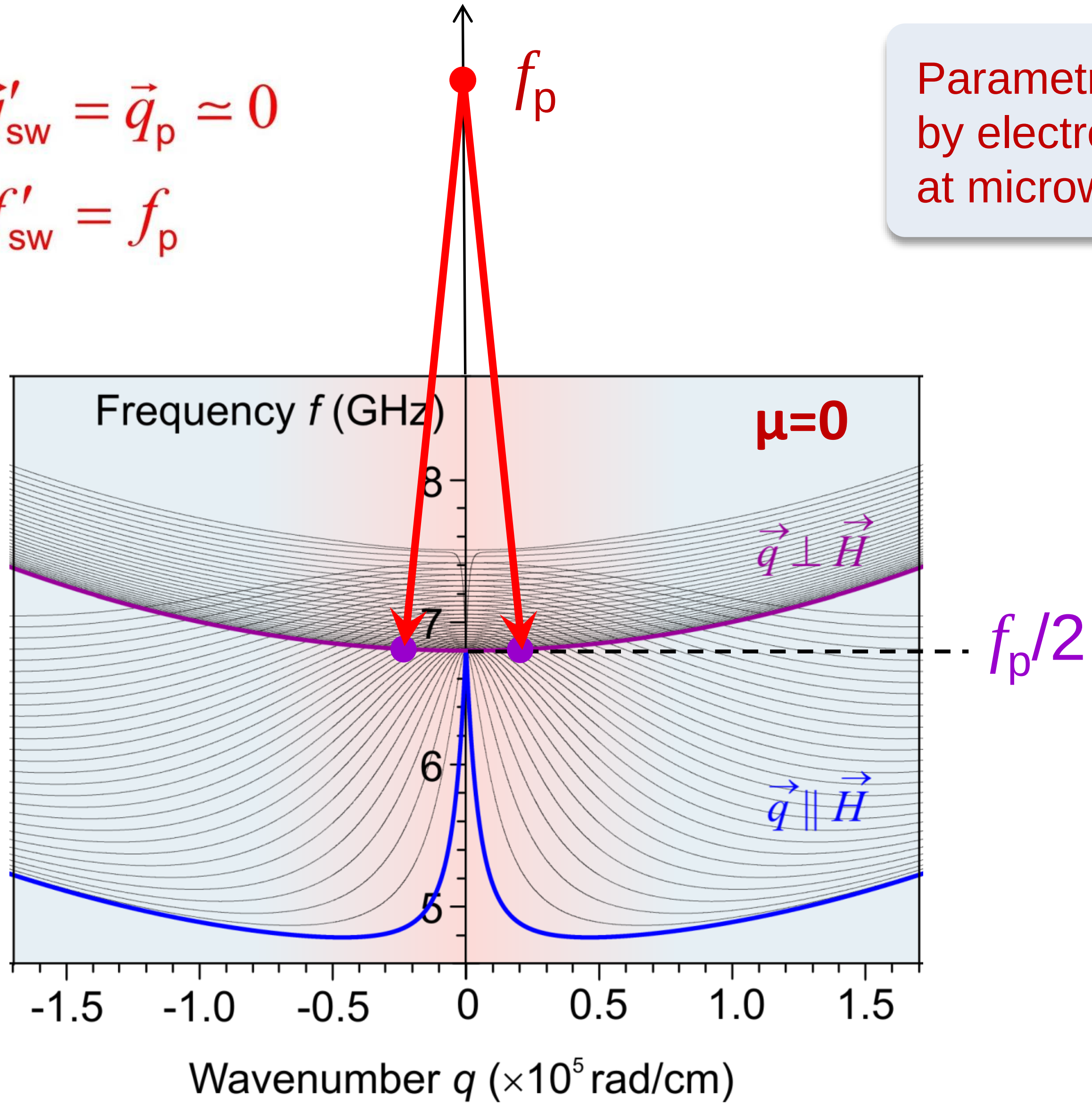
Energy and momentum conservation laws for parametric pumping

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

Parametric pumping by electromagnetic wave at microwave frequency

$H_0 = 1710$ Oe





Bose-Einstein distribution

$$\rho(f) = \frac{D(f)}{\exp\left(\frac{hf - \mu}{k_{\mathrm{B}}T}\right) - 1}$$

μ: chemical potential

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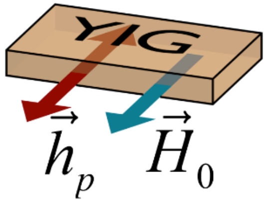

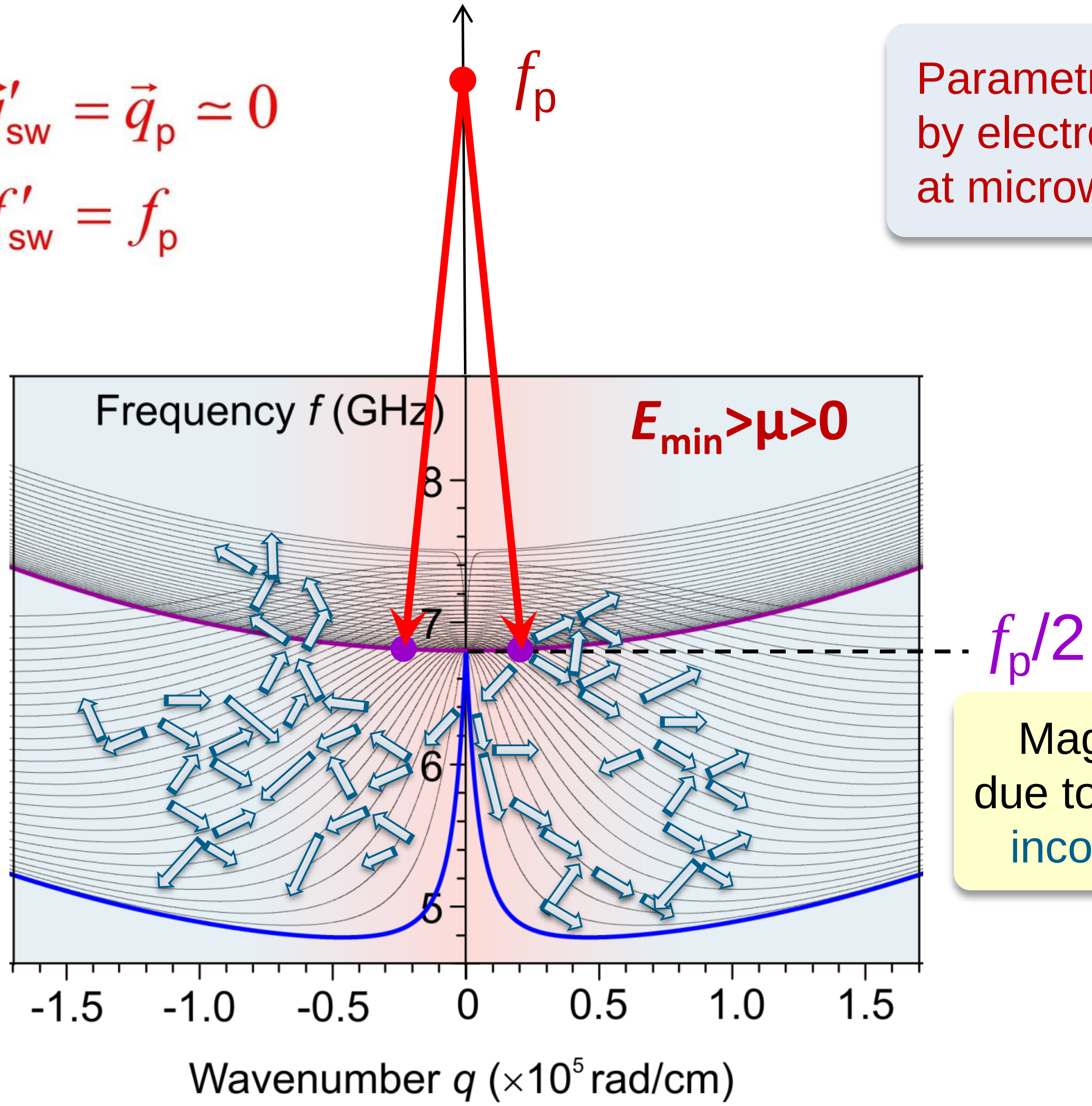

Magnon thermalization due to 4-particle scattering: incoherent magnon gas

Bose-Einstein distribution

$$\rho(f) = \frac{D(f)}{\exp\left(\frac{hf - \mu}{k_{\mathrm{B}} T}\right) - 1}$$

μ: chemical potential

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Bose-Einstein condensation of magnons

Energy and momentum conservation laws for parametric pumping

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

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

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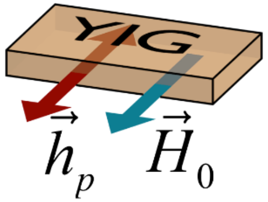

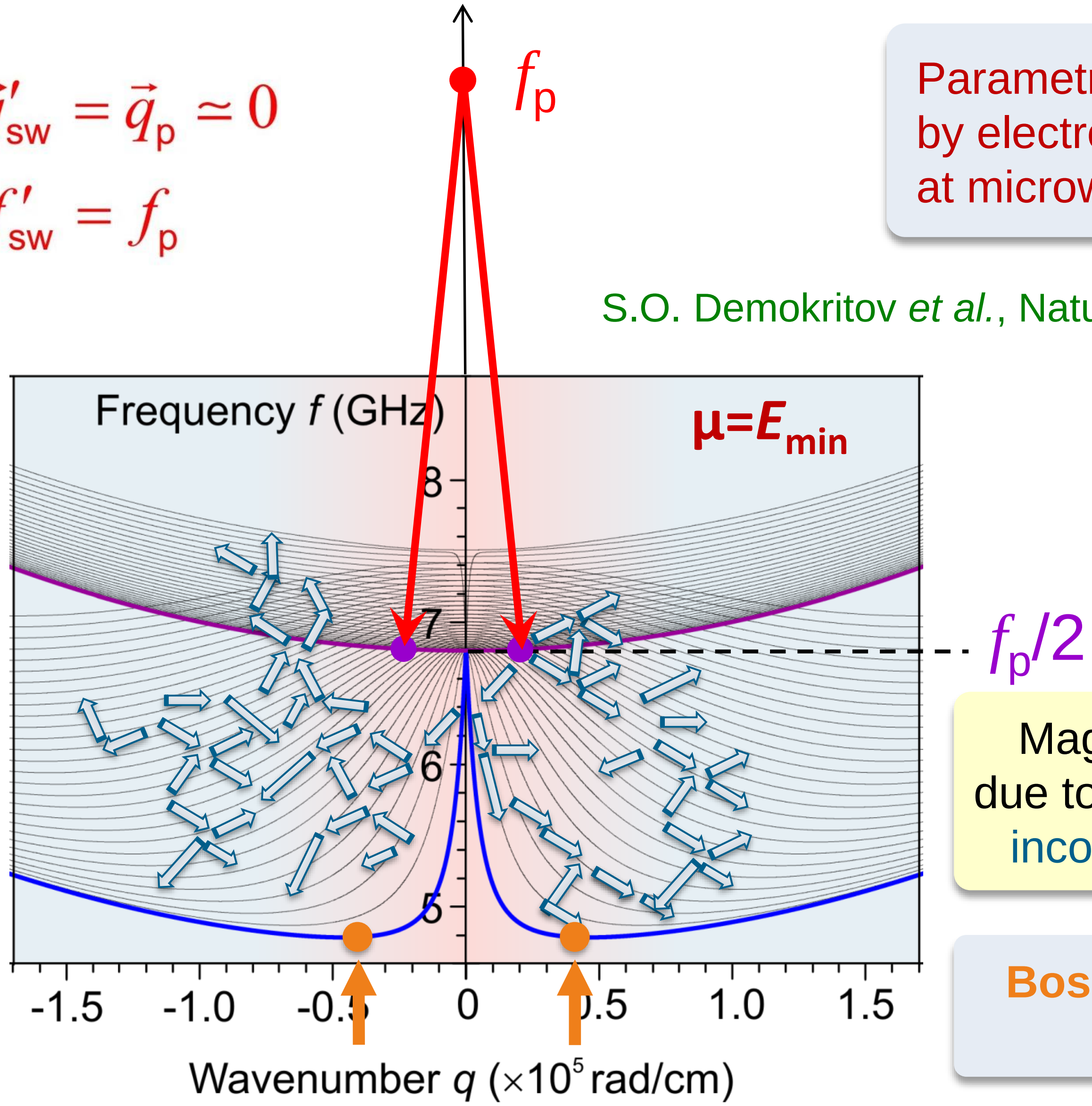

Bose-Einstein distribution

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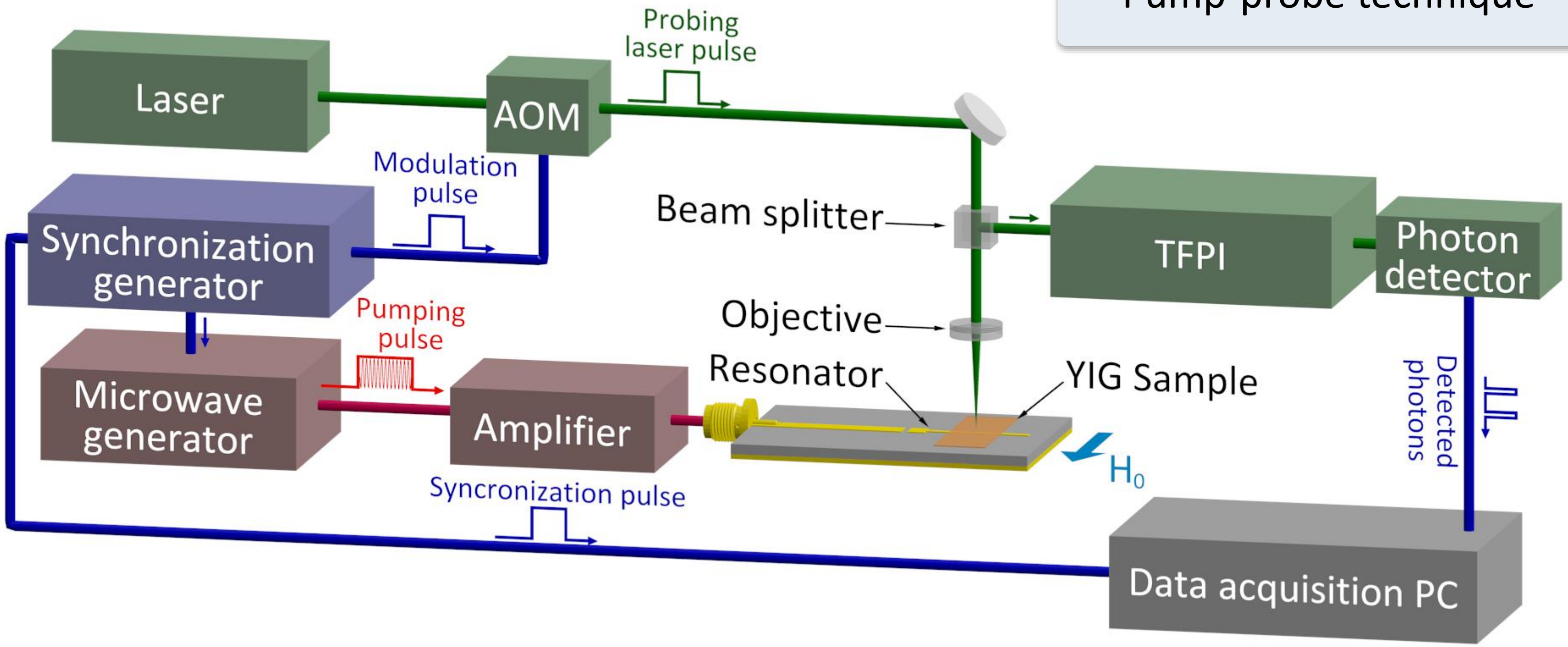
μ: chemical potential

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

Bose-Einstein magnon condensate

Time-, space- and wavevector-resolved pulsed BLS spectroscopy

- Pump-probe technique



Resolution

Time	1 ns
Frequency	50 MHz
Wavenumber	2×10^3 cm^{-1}
Space	5 µm

(111) LPE YIG films	5 - 7 µm
Width of the pumping area	50 and 500 µm
Length of the pumping area	1 mm
Maximum microwave power	100 W

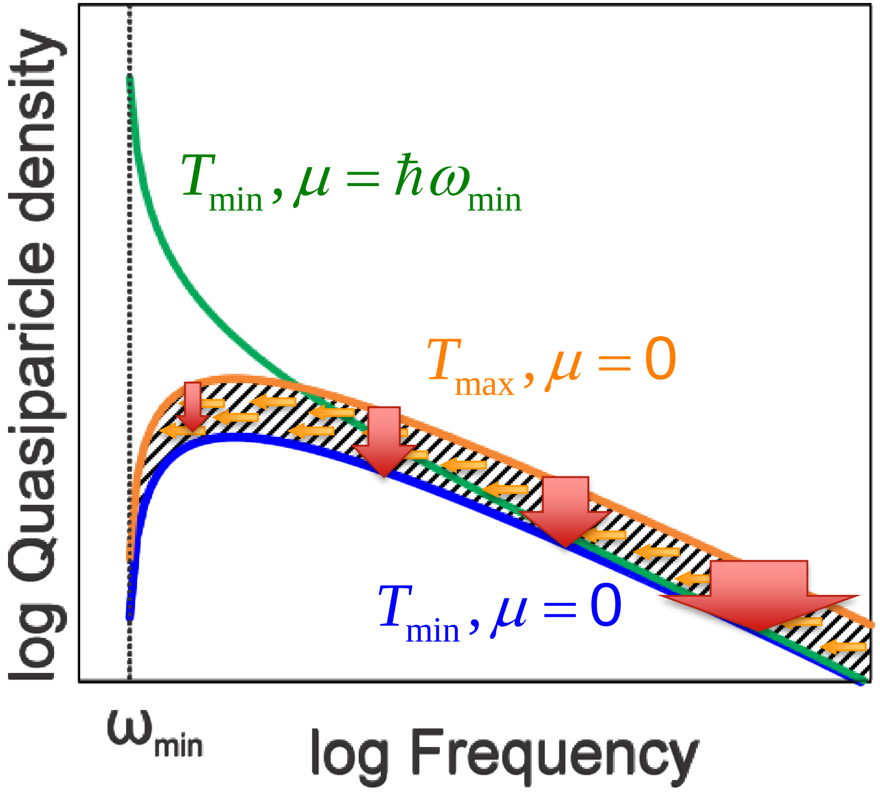
Microwave-free creation of a magnon BEC

Are there other ways how to create a magnon BEC state in YIG?

- Yes, by rapid cooling of a magnon-carrying specimen

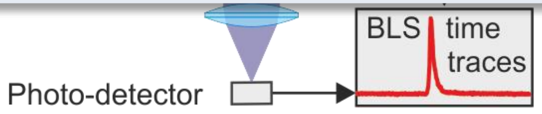
Bose-Einstein distribution

$$\rho(\omega) = \frac{D(\omega)}{\exp\left(\frac{\hbar\omega - \mu}{k_B T}\right) - 1}$$



High-energy magnon states are populated and participate in the BEC formation process

Bose-Einstein distribution function is crucial for the quantitative description of the condensation



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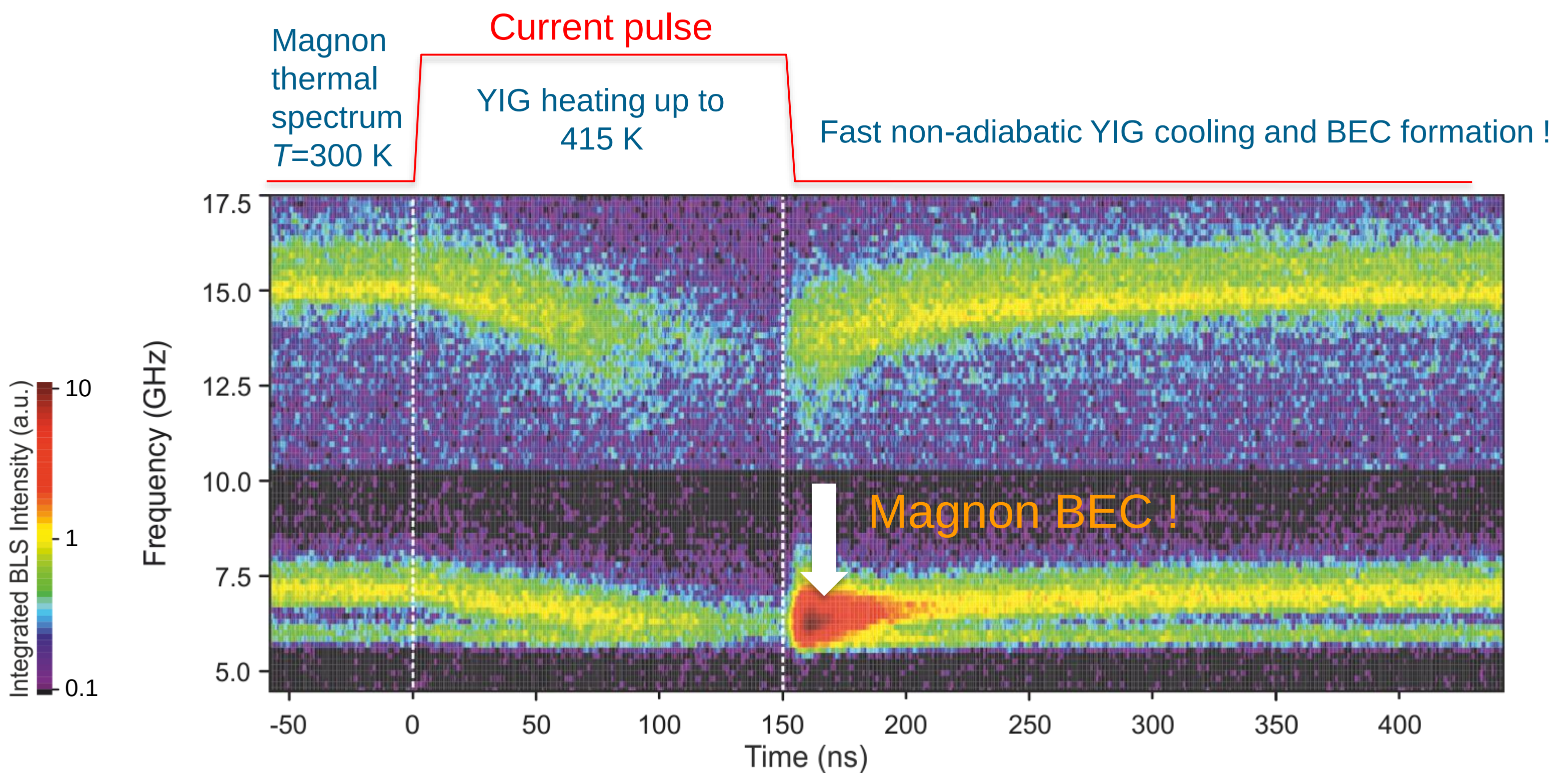
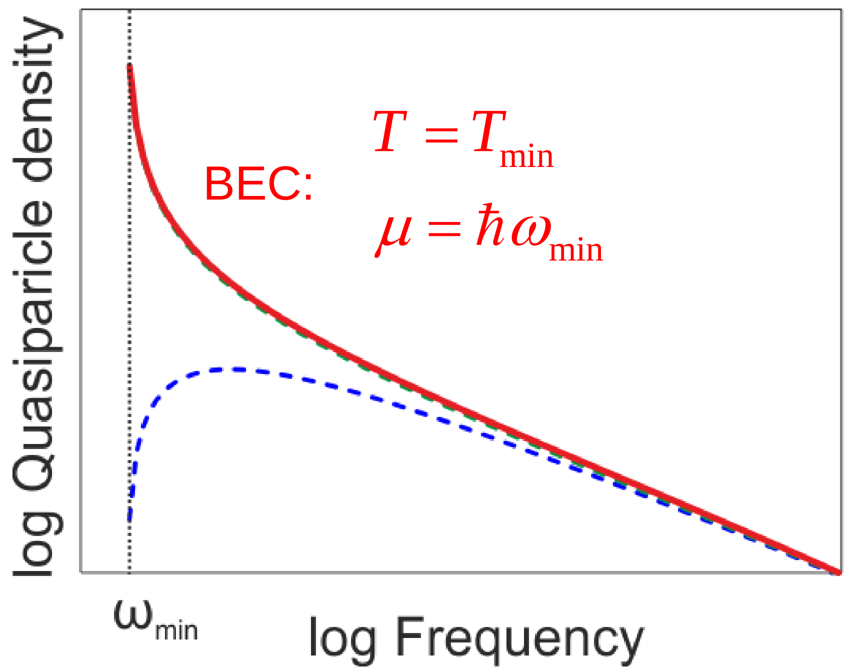
BEC in rapidly cooled magnon gas

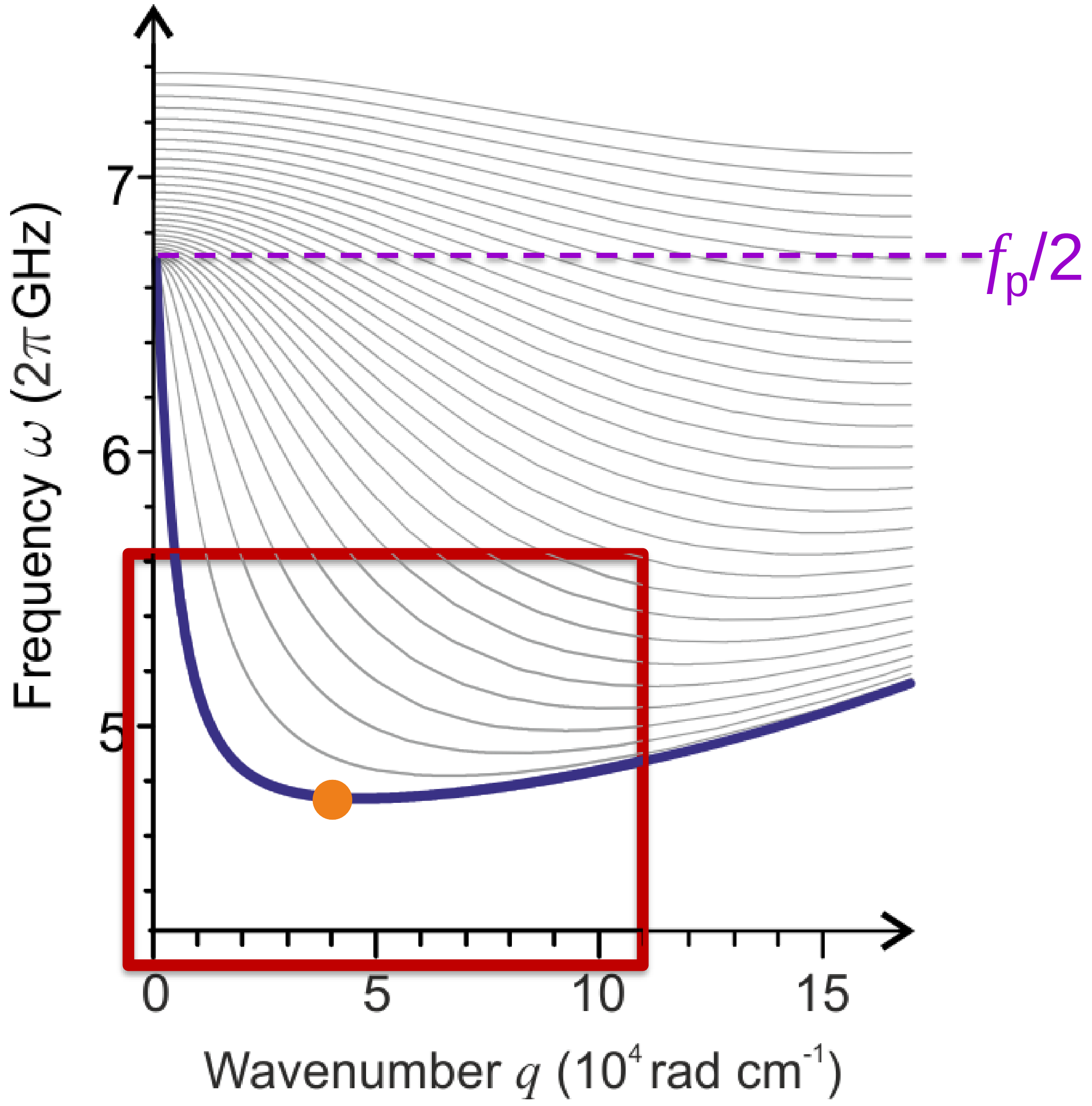


Magnon population distribution



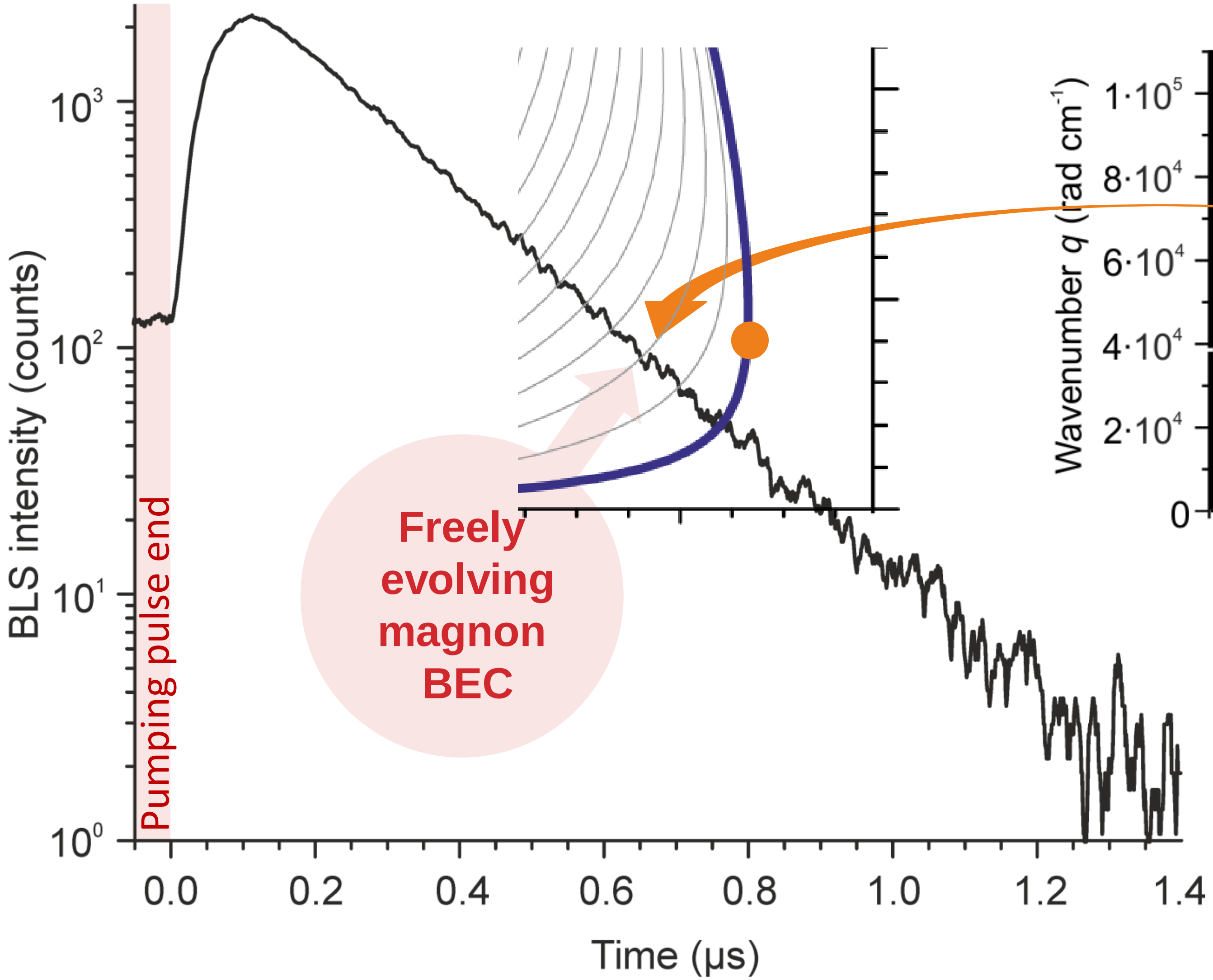
M. Schneider, *et al.*, Nat. Nanotechnol. **15**, 457 (2020)

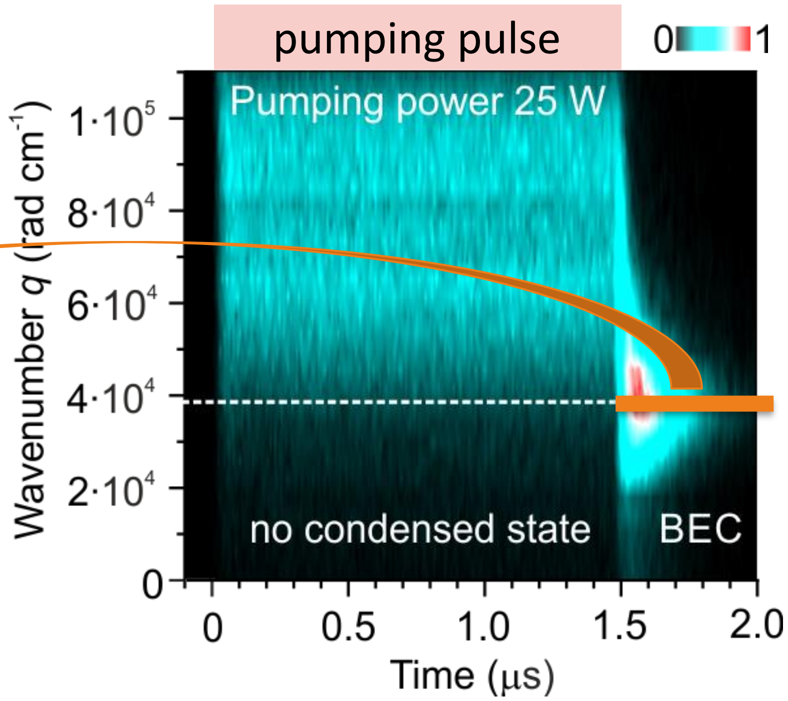
Magnon BEC: Experiment



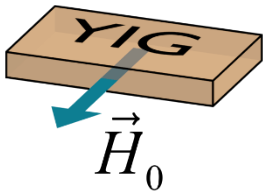
Magnon BEC: Experiment

Magnon BEC: Experiment





BEC is formed **after** the pumping is off



Supercurrent in magnon BEC

Supercurrent: Flow of particles due to **phase gradient** of the **condensate**'s wavefunction

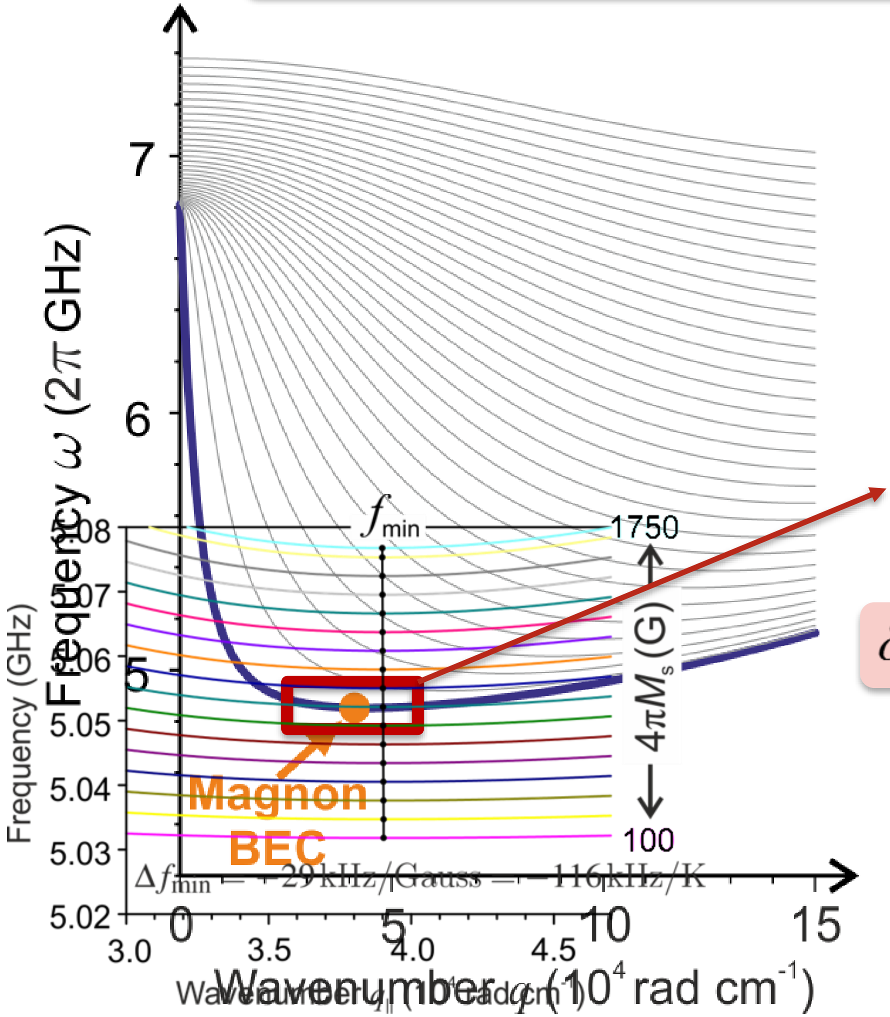
Complex BEC wave function: $\psi(\vec{r},t)$

BEC density: $N_c = |\psi|^2$

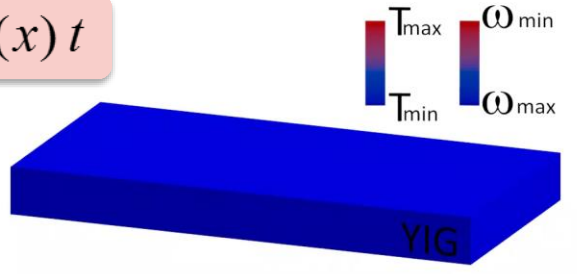
BEC phase: $\varphi = \arg(\psi)$

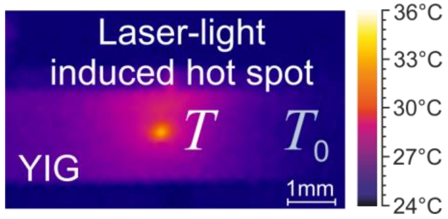
Supercurrent

$$\vec{J}(\vec{r},t) = \frac{\hbar}{m} N_c \nabla\varphi$$



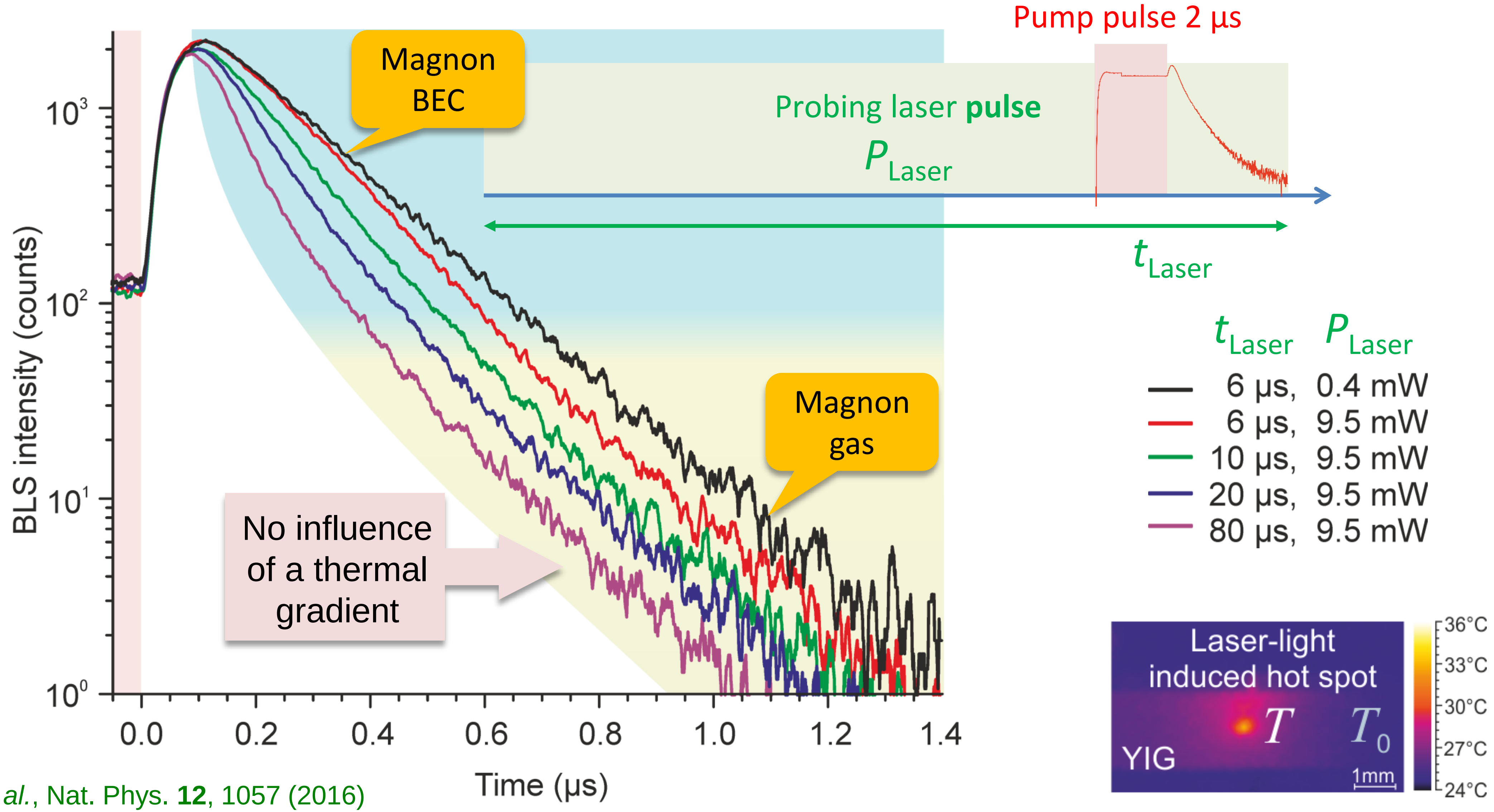
$$\delta\varphi = \delta\omega_c(x)\, t$$





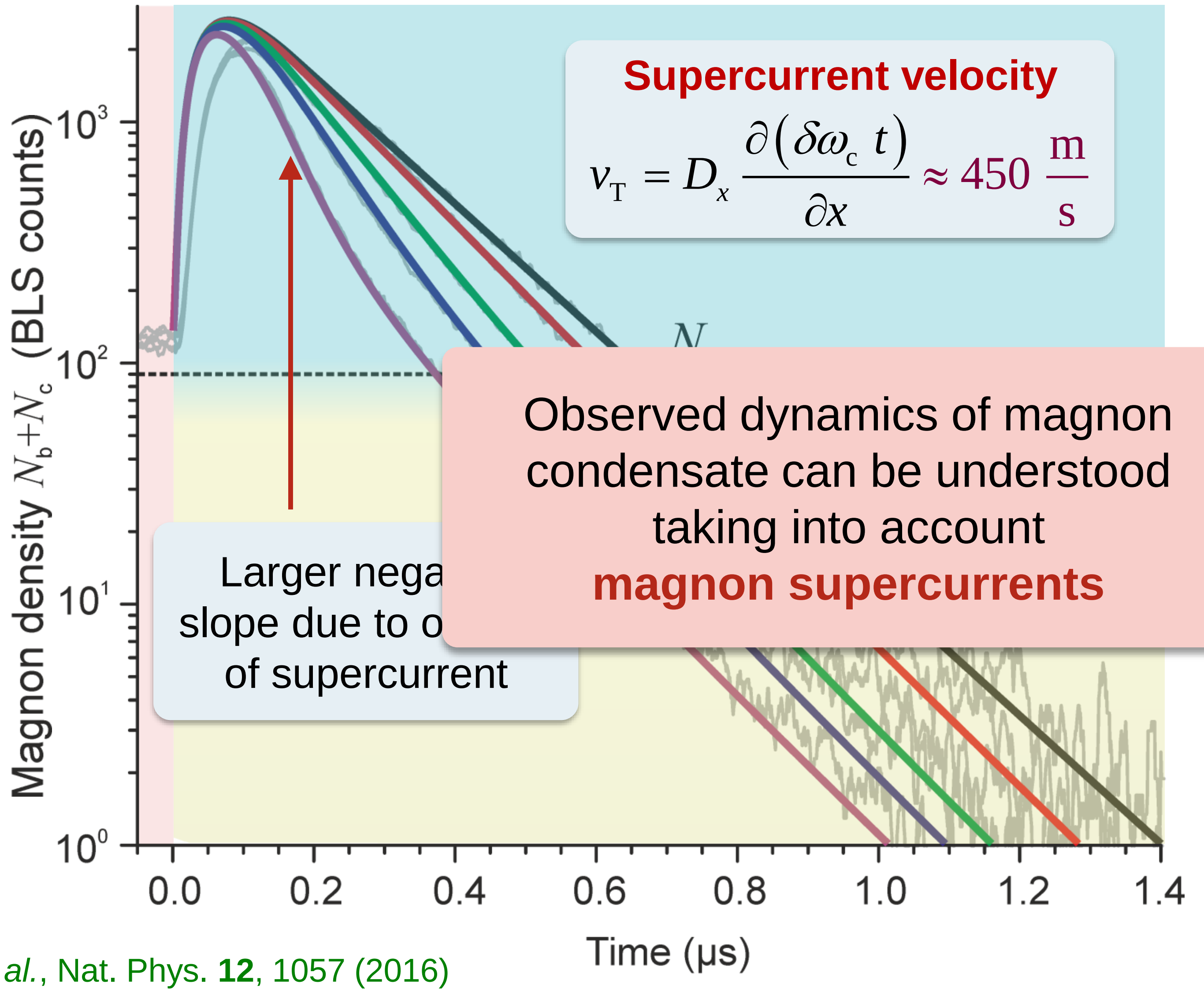
By changing probing laser *power* or laser pulse *duration* it is possible to control the **phase** of the magnon BEC

Dynamics of condensed magnons in thermal gradient



D. A. Bozhko *et al.*, Nat. Phys. **12**, 1057 (2016)

Dynamics of condensed magnons in thermal gradient - comparison with theory



Supercurrent velocity

$$v_T = D_x \frac{\partial(\delta\omega_c\, t)}{\partial x} \approx 450\ \frac{\mathrm{m}}{\mathrm{s}}$$

Larger negative slope due to onset of supercurrent

Observed dynamics of magnon condensate can be understood taking into account **magnon supercurrents**

$$\delta\varphi = \delta\omega_c(T)\,t$$

Thermally induced frequency shift of the magnon BEC $\delta\omega_c(T)/2\pi$

- 0 kHz
- 25 kHz
- 100 kHz
- 198 kHz
- 550 kHz

Corresponding maximal temperature change

4.7 K

D. A. Bozhko *et al.*, Nat. Phys. **12**, 1057 (2016)

Supercurrent and anisotropy of spin-wave spectrum

2D supercurrent

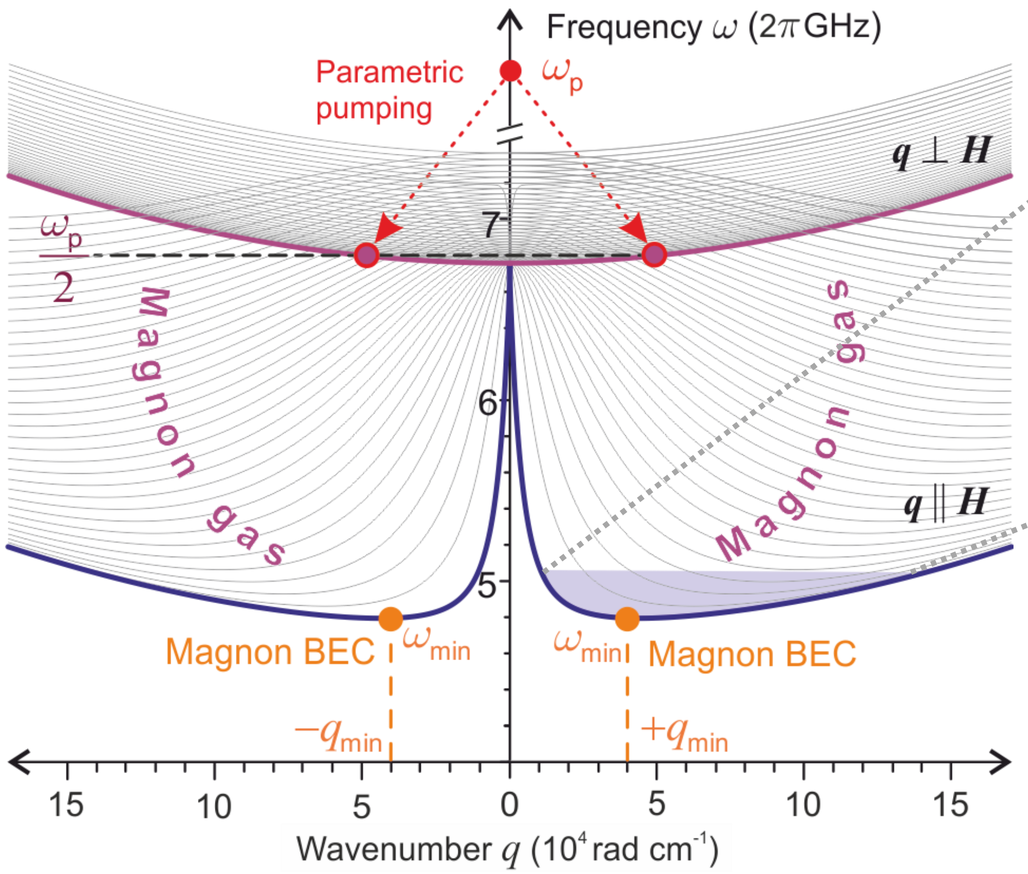
$$J_x = N_c D_x \frac{\partial \varphi}{\partial x}$$

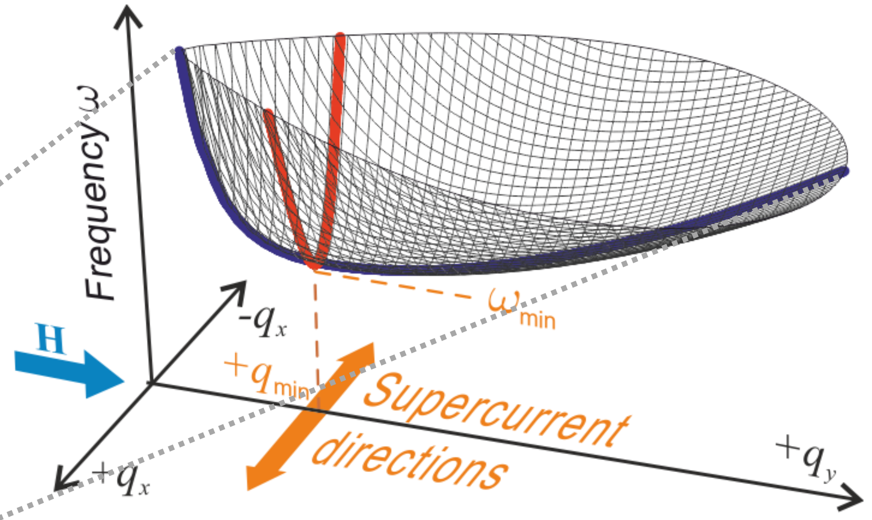
$$J_y = N_c D_y \frac{\partial \varphi}{\partial y}$$

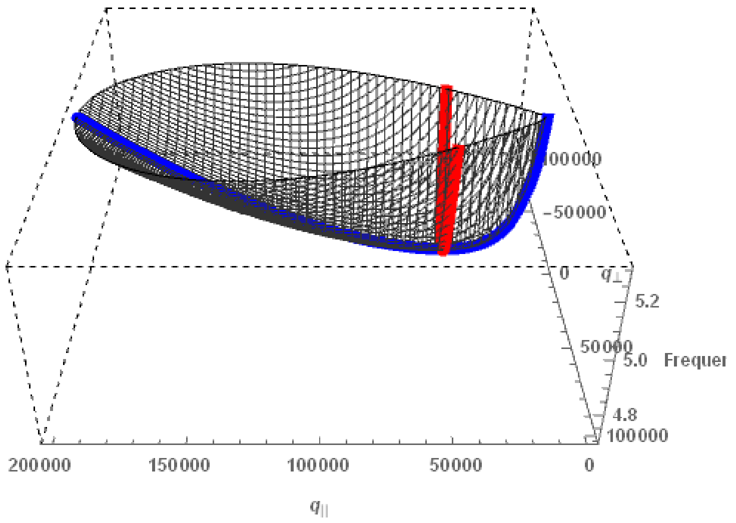
Dispersion coefficients

$$D_x = \frac{1}{2}\frac{\partial^2 \omega(\vec{q})}{\partial q_x^2}$$

$$D_y = \frac{1}{2}\frac{\partial^2 \omega(\vec{q})}{\partial q_y^2}$$

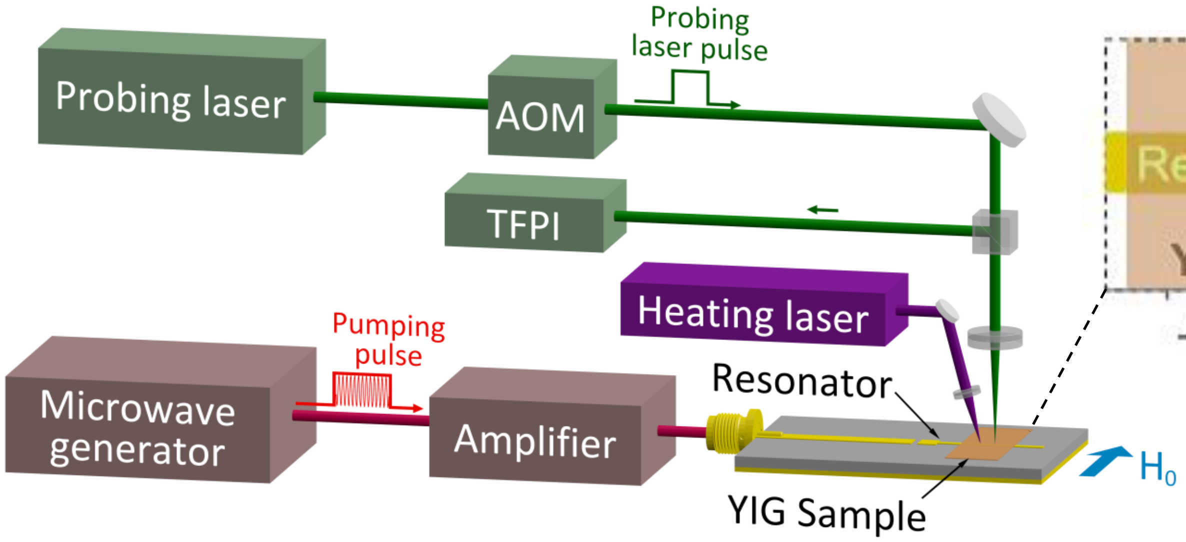


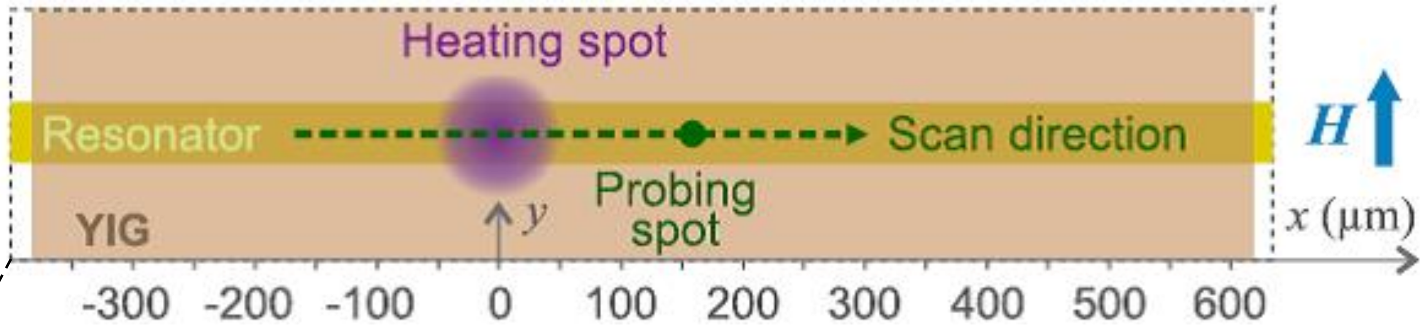


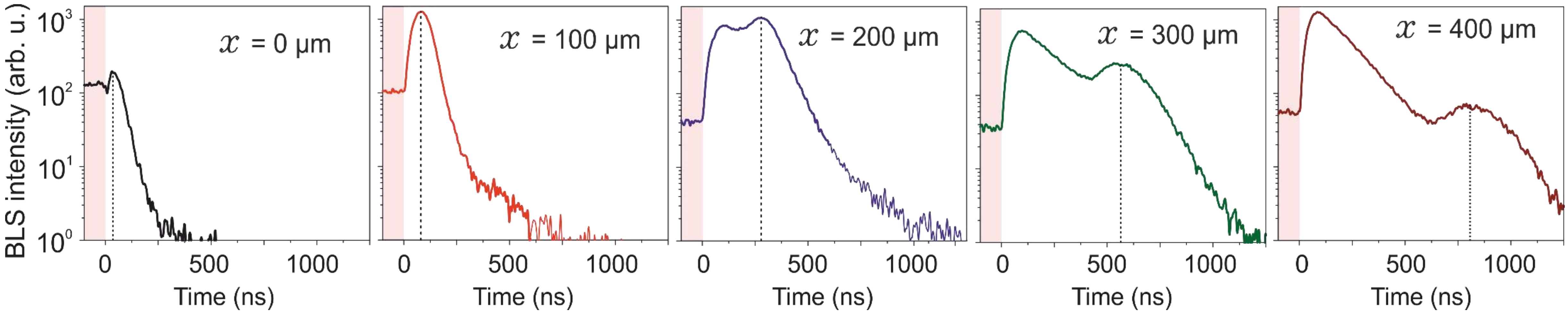


$D_x \simeq 21 D_y$ → $J_s = J_x \gg J_y$ → **1D supercurrent**

Non-local measurement: Supercurrent magnon transport







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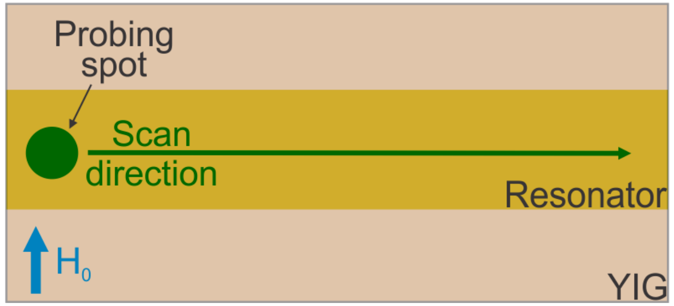
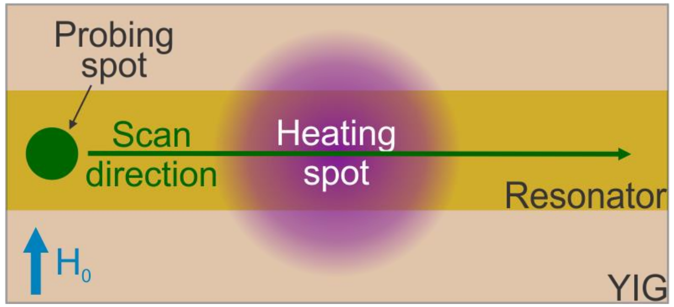
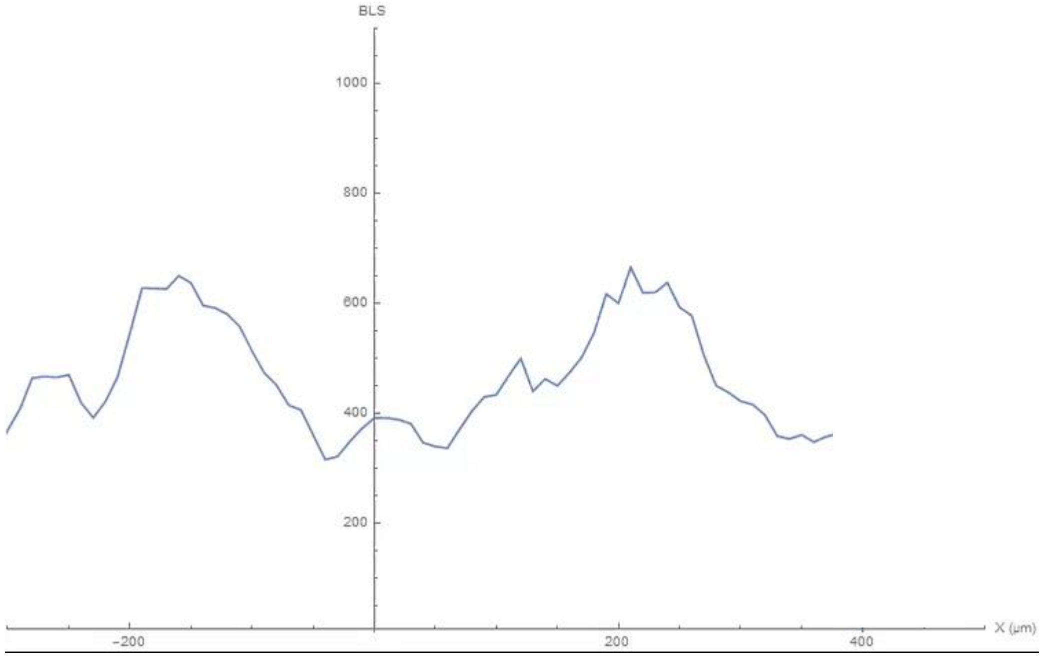
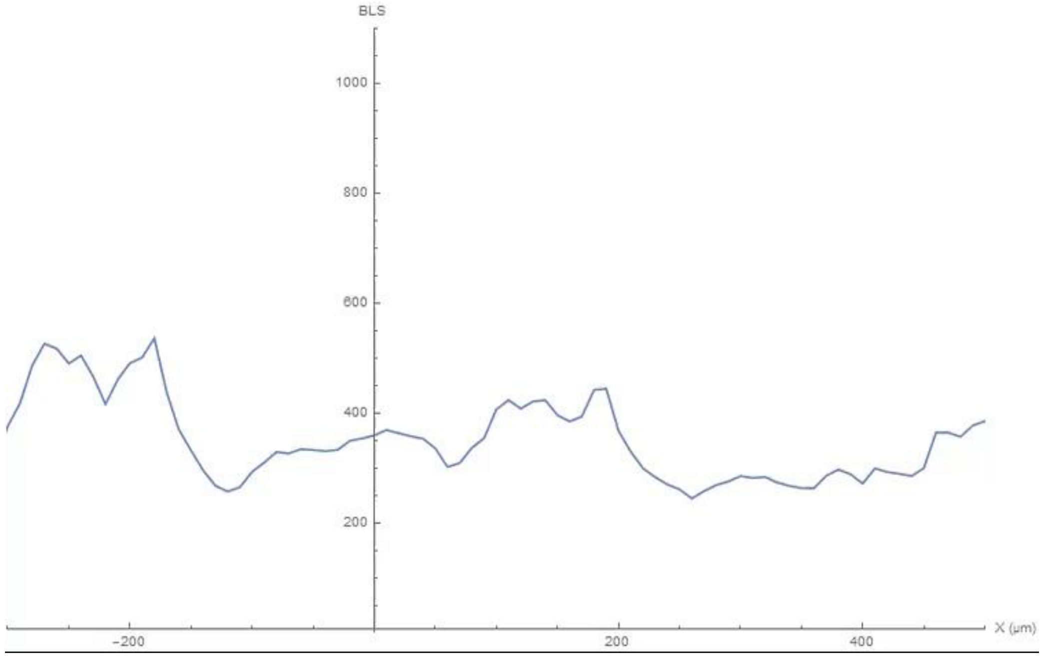




Heating laser switched off

Heating laser power 116 mW





Second sound scenario

Framework: Gross-Pitaevskii equation

$$\left[i\frac{\partial}{\partial t} + D_x \frac{\partial^2}{\partial x^2} - W\,|\psi|^2 \right]\psi = 0$$

Dispersion coefficient $$D_x = \frac{1}{2}\frac{\partial^2 \omega(\vec{q})}{\partial q_x^2}$$

Amplitude of four-wave **repulsive** interaction $$W > 0$$

Dzyapko *et al.*, Phys. Rev. B **96**, 064438 (2017)

Stationary solution: $\psi(x,t) = \sqrt{N_\mathrm{c}}\exp(-iWN_\mathrm{c}t)$

Magnon BEC density: N_c

Second sound scenario

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Stationary solution: $\psi(x,t) = \sqrt{N_c}\exp(-iWN_c t)$

Magnon BEC density: N_c

Solution: Bogoliubov waves $\Omega(k)$ (second sound)

$$\Omega(k) = c_s k \sqrt{1 + D_x k^2 / 2WN_c}$$

Long-wavelength limit $$D_x k^2 \ll 2WN_c$$

$$\Downarrow$$

Linear dispersion $$\Omega(k) = c_s k$$

$$\Downarrow$$

Second sound velocity

$$\boxed{c_s = \sqrt{2D_x W N_c}}$$

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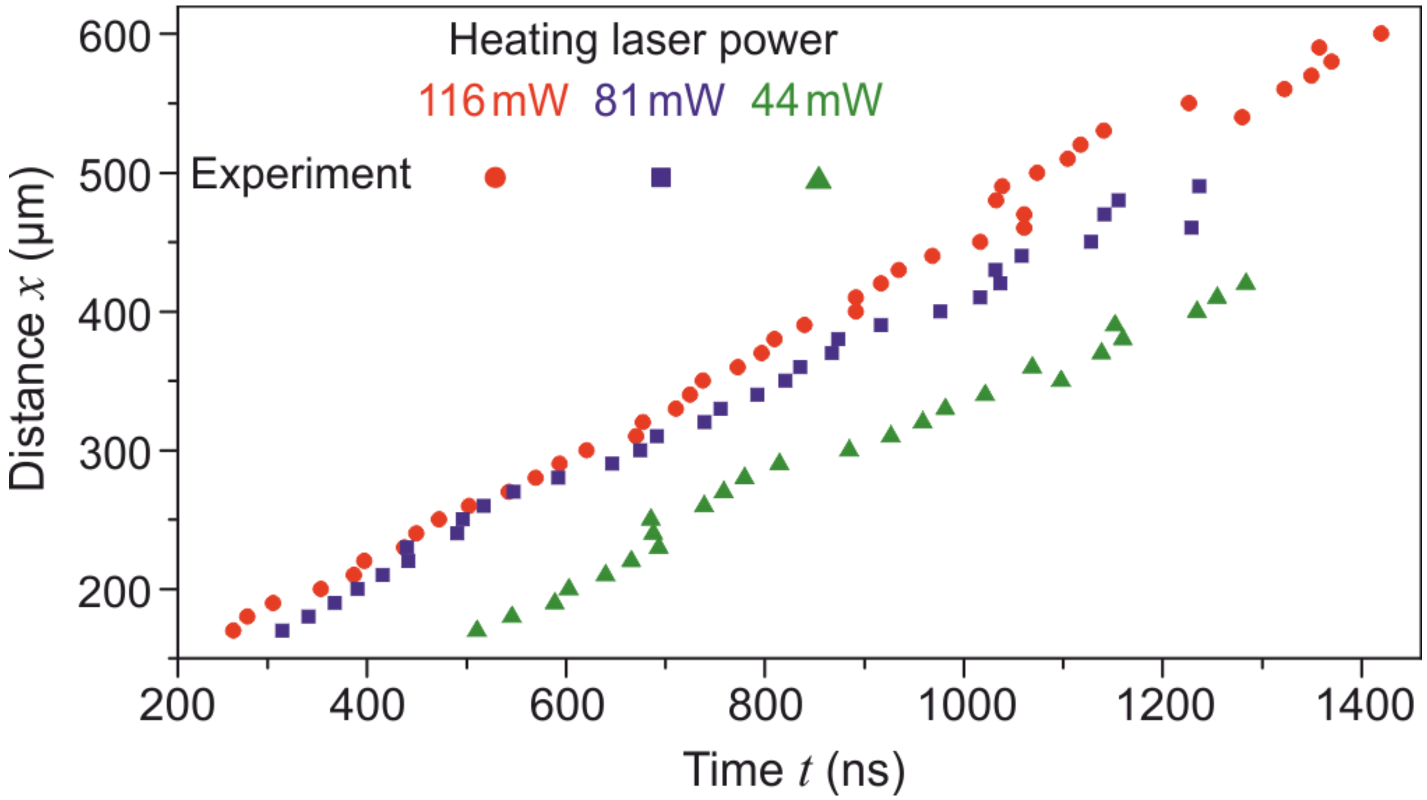
Second sound scenario

$$\Omega(k) = c_s k, \qquad c_s = \sqrt{2 D_x W N_c}$$

- The sound velocity c_s must be **independent** on the excitation conditions i.e. the heating laser power, which determine the BEC pulse width



D. A. Bozhko *et al.*, Nat. Commun. **10**:2460 (2019)

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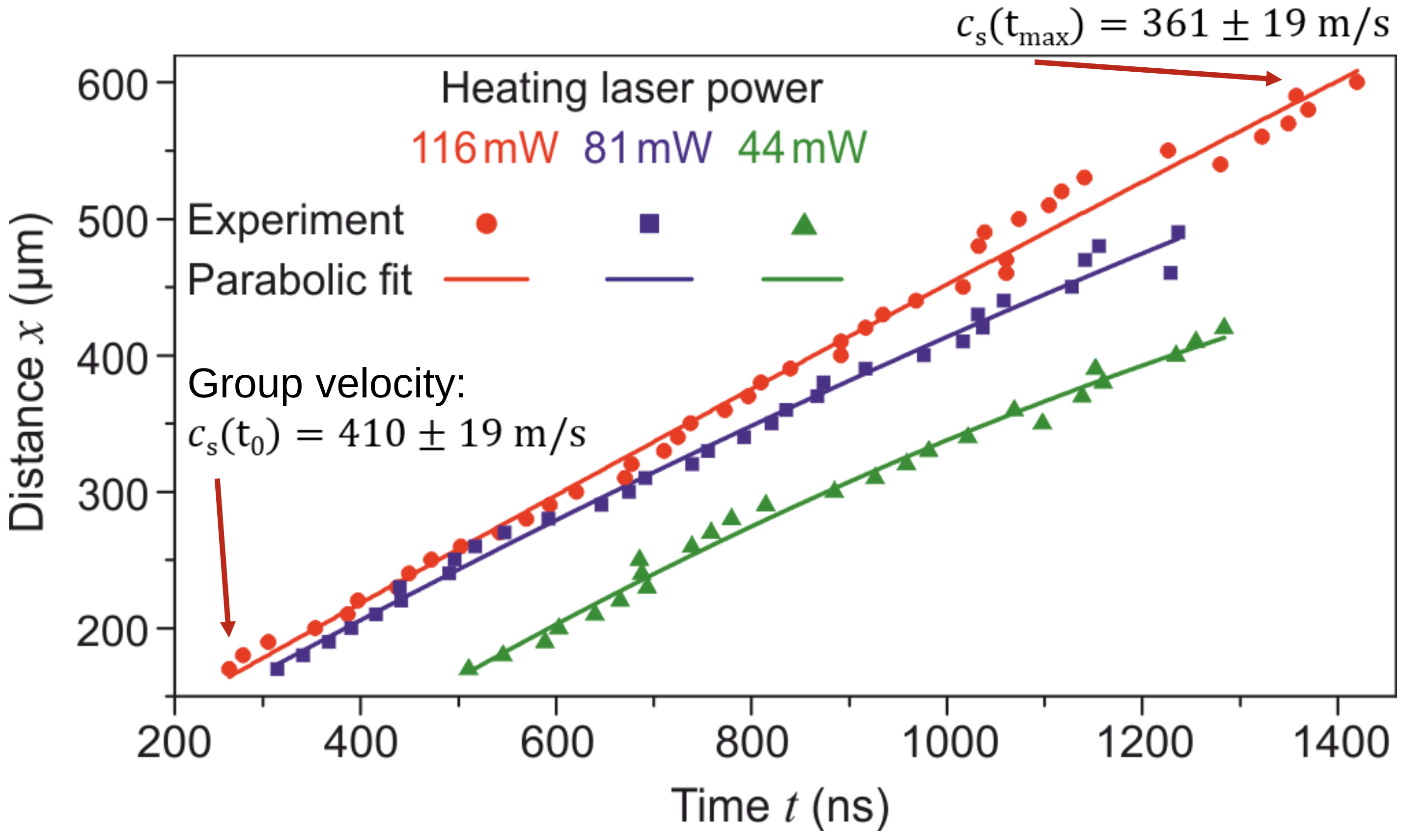
Second sound scenario

$$\Omega(k) = c_s k, \quad c_s = \sqrt{2 D_x W N_c}$$

- The sound velocity c_s must be **independent** on the excitation conditions i.e. the heating laser power, which determine the BEC pulse width
- During the pulse propagation, the amplitude of the background condensate decays and the sound velocity also has to decay

  The sound velocity decrease is clear visible from parabolic fits !



Smaller decrease of the sound velocity than expected from the decay of the condensate

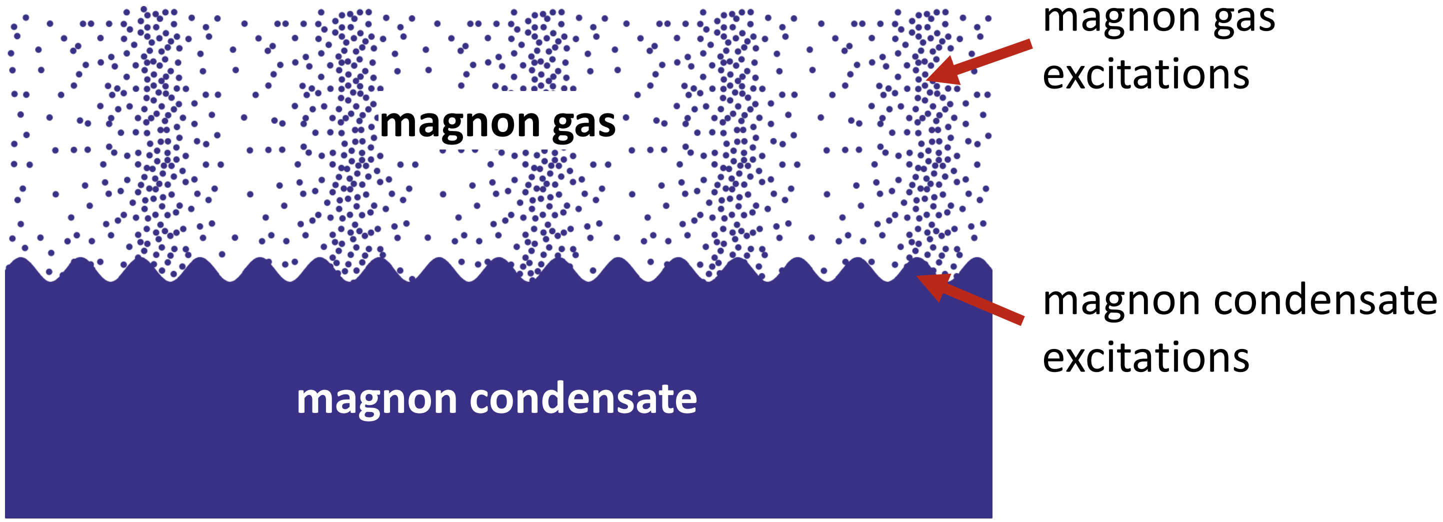
⇨

Low decay of the propagating BEC pulse due to an efficient gathering of surrounding magnons

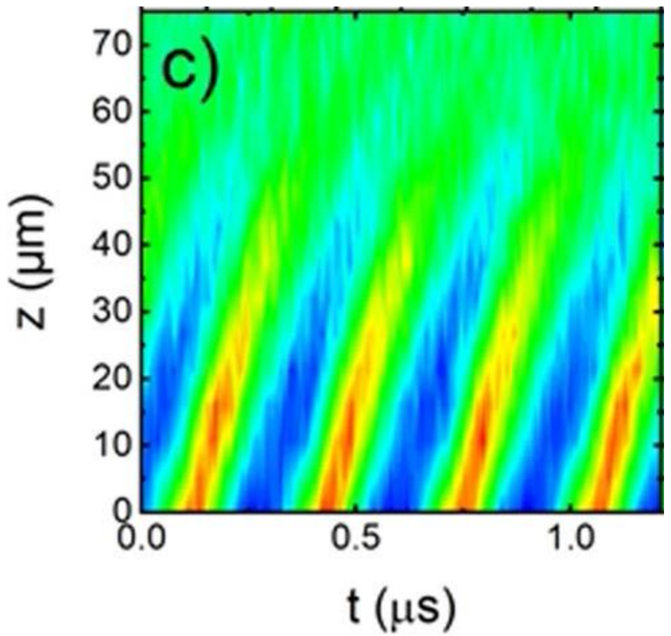
D. A. Bozhko *et al.*, Nat. Commun. **10**:2460 (2019)

Second sound in an incoherent magnon gas

Excitation of coherent waves in a magnon condensate and in a magnon gas



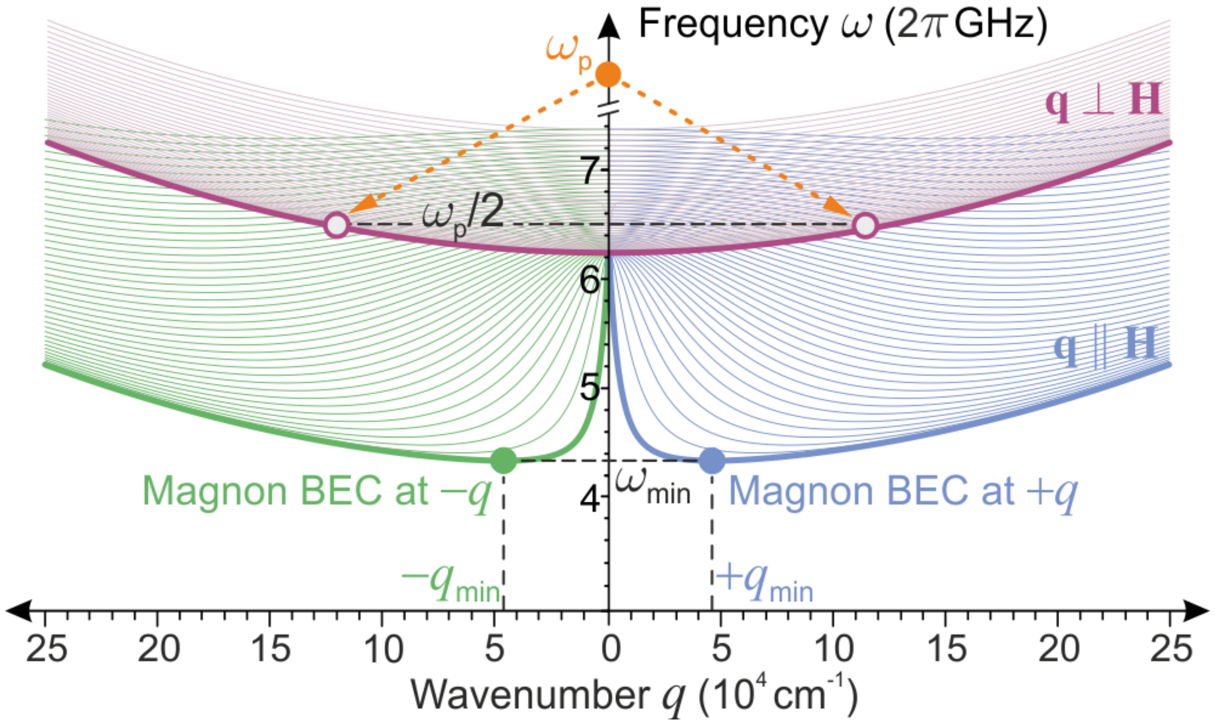
Second sound waves in a dense magnon gas



V. S. Tiberkevich *et al.*, Sci. Rep. **9**:9063 (2019)

General two-fluid model of a magnon gas combined with the Gross-Pitaevskii equation for the magnon BEC needs to be developed

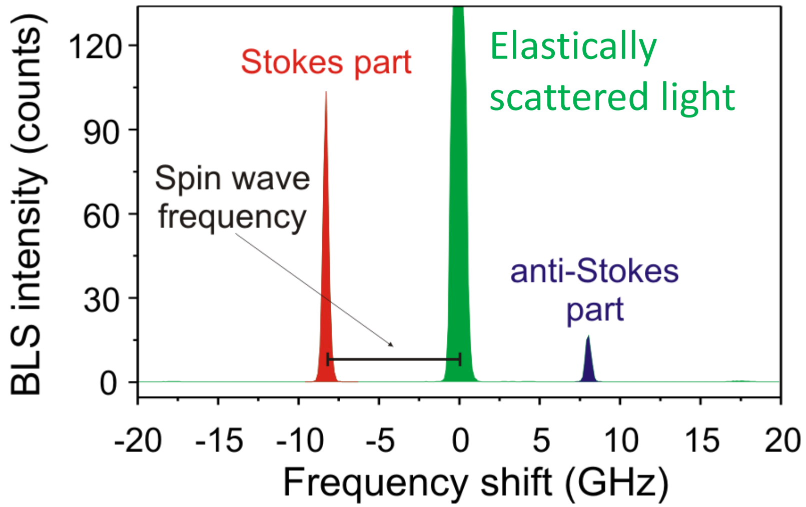
Two-component magnon BEC



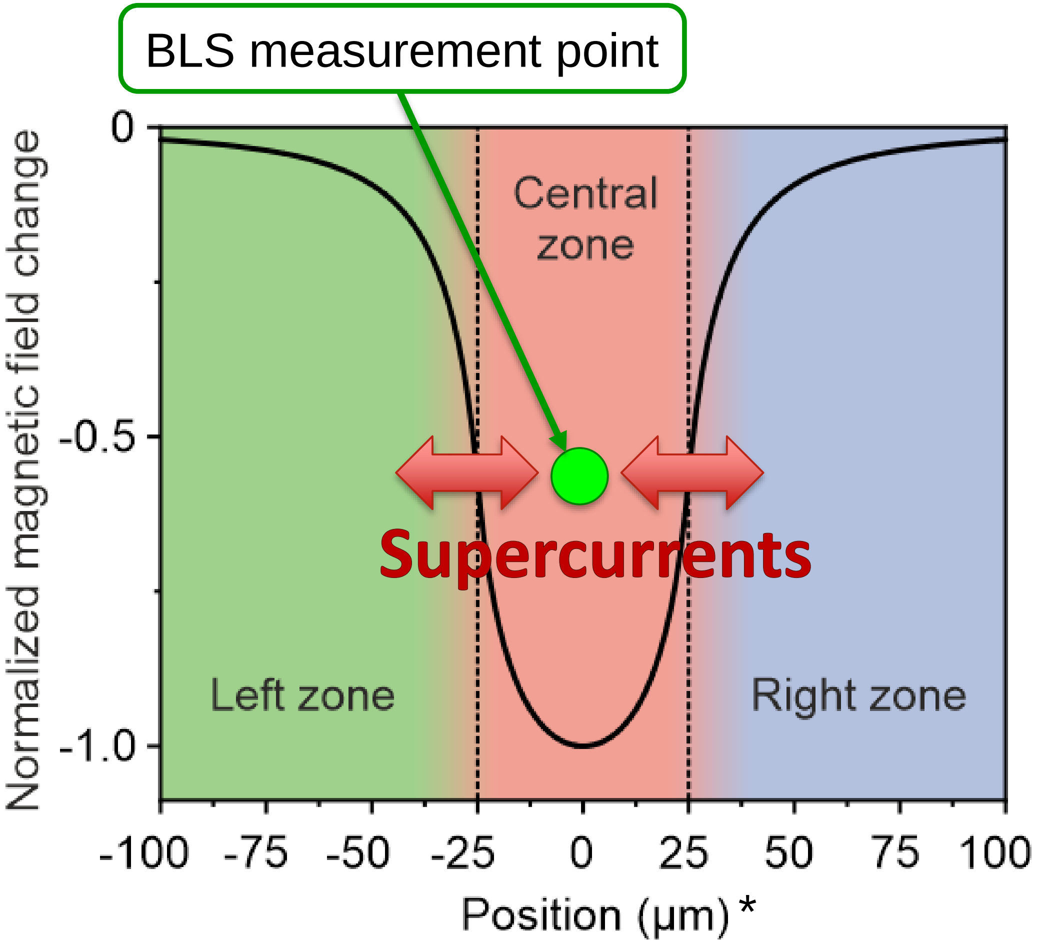
BLS intensities of the Stokes and anti-Stokes spectral peaks are related to the densities of magnons with wavenumbers $+q_{min}$ and $-q_{min}$ (for fixed angle of wavevector-resolved BLS setup)

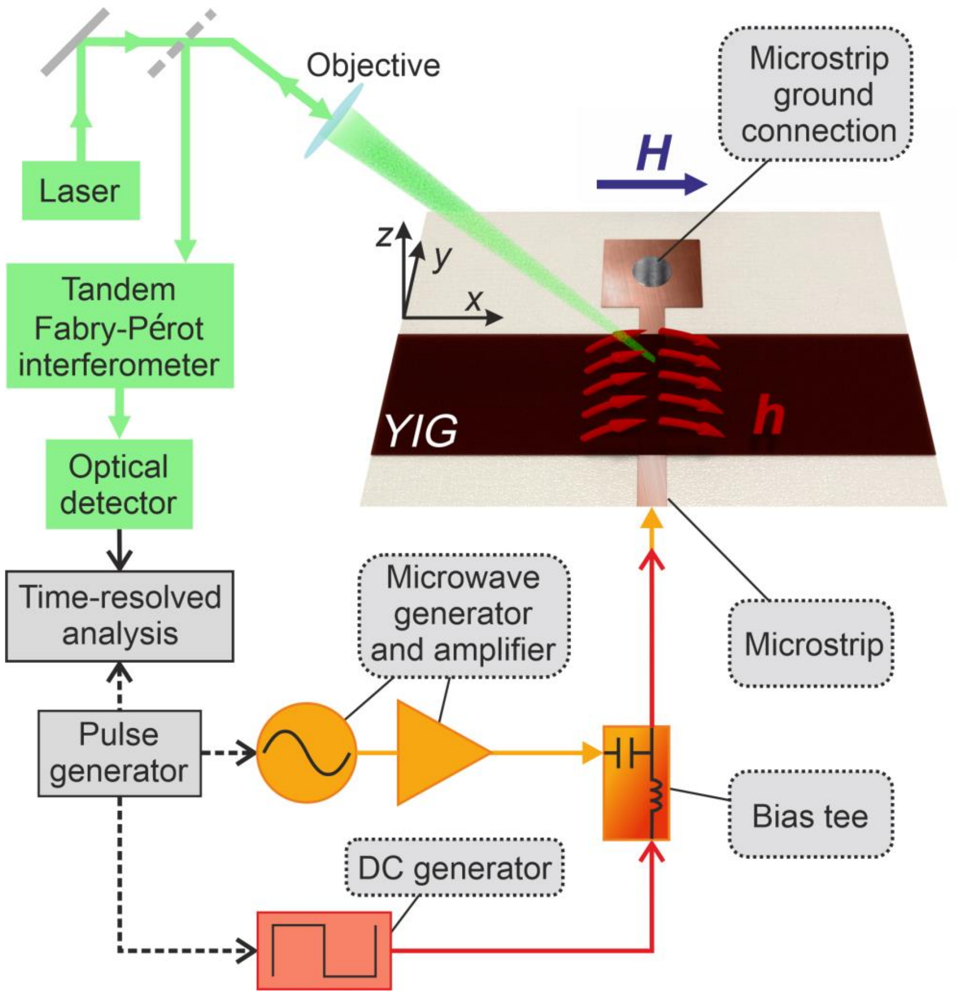
$$\omega_{\text{scattered L}} = \omega_L \mp \omega_{min}$$

$$\vec{q}_{\text{scattered L}} = \vec{q}_L \mp \vec{q}_{min}$$



Magnon condensate density in a magnetic trench

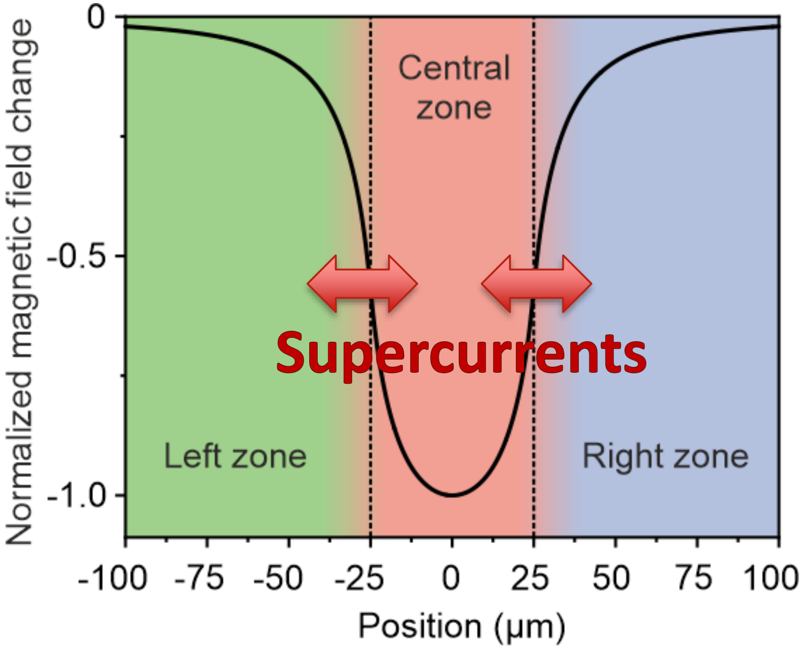


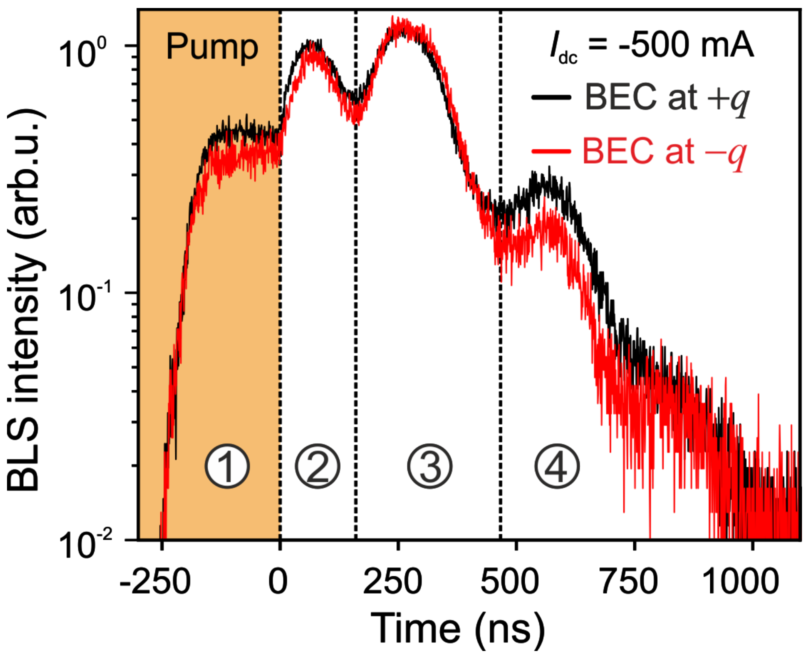


(* Position relative to the antenna)

(Magnetic trench formation for negative DC current)

Josephson oscillations in magnon condensate





(1) time, when magnons are excited by parametric pumping

(2) time interval during which the BEC forms

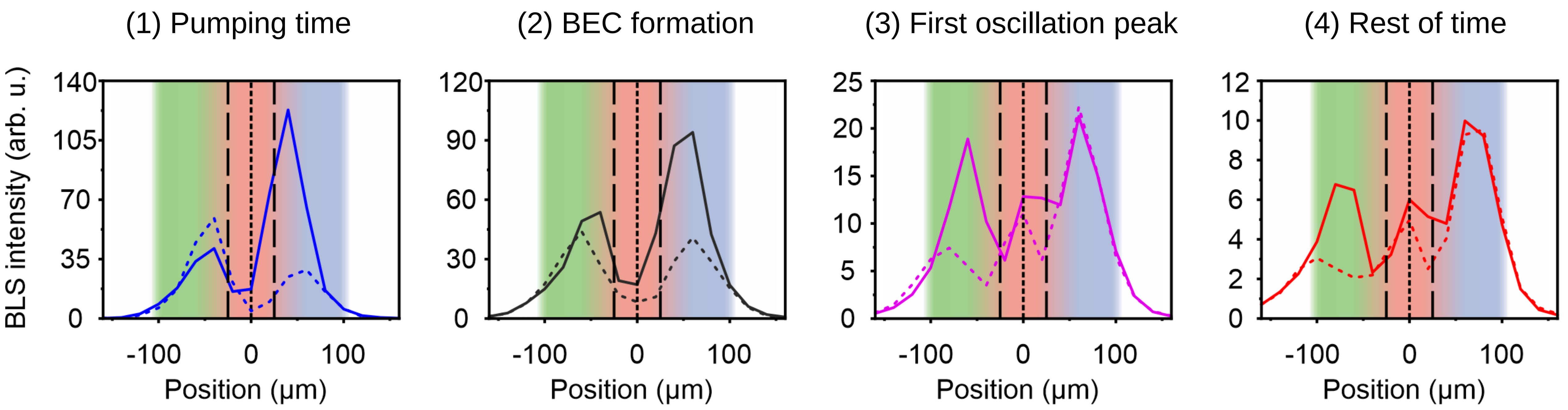
(3) time interval during which the first oscillation appears

(4) the rest of the observation time

A.J.E. Kreil *et al.*, arXiv:1911.07802v1 (2019)

Time-dependence of spatial magnon distributions in magnetic trench

Time intervals

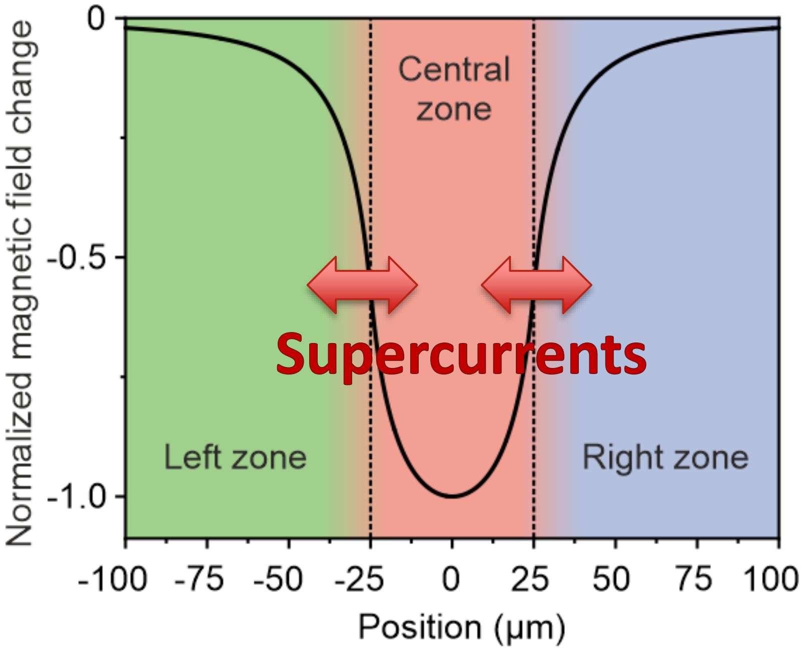


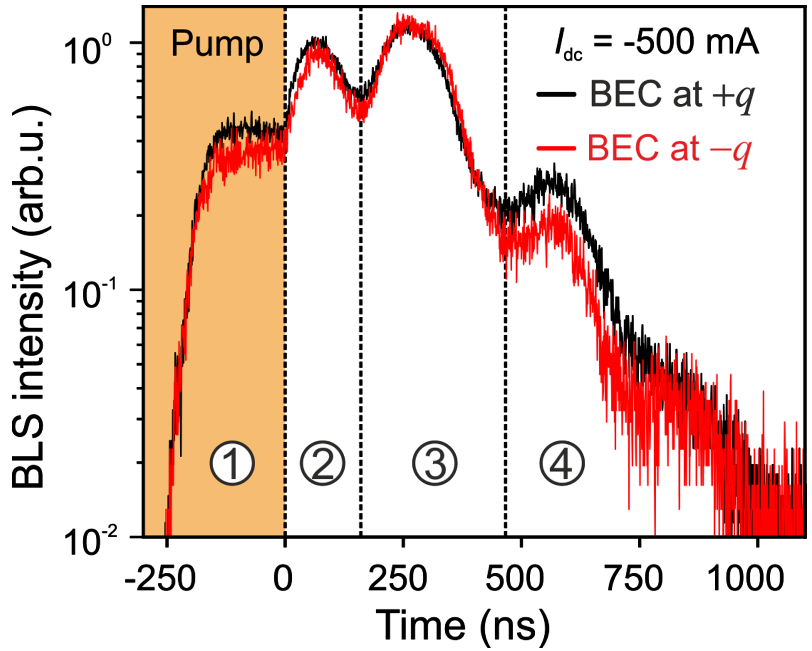
Full lines: BEC at +*q*
Dashed lines: BEC at -*q*

I = - 500 mA

A.J.E. Kreil *et al.*, arXiv:1911.07802v1 (2019)

Josephson oscillations in magnon condensate





(1) time, when magnons are excited by parametric pumping

(2) time interval during which the BEC forms

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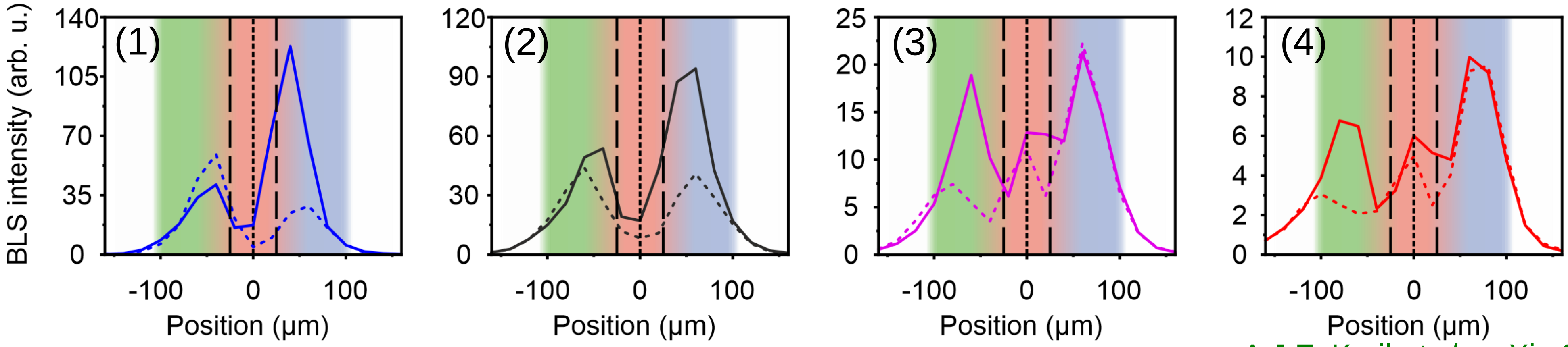
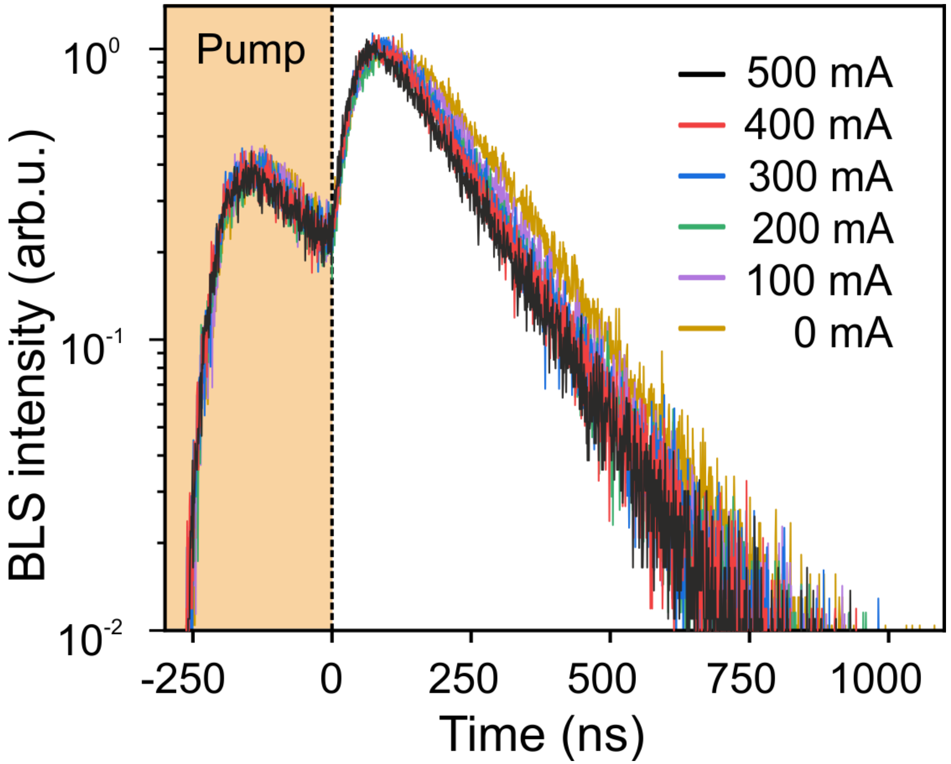
(4) the rest of the observation time



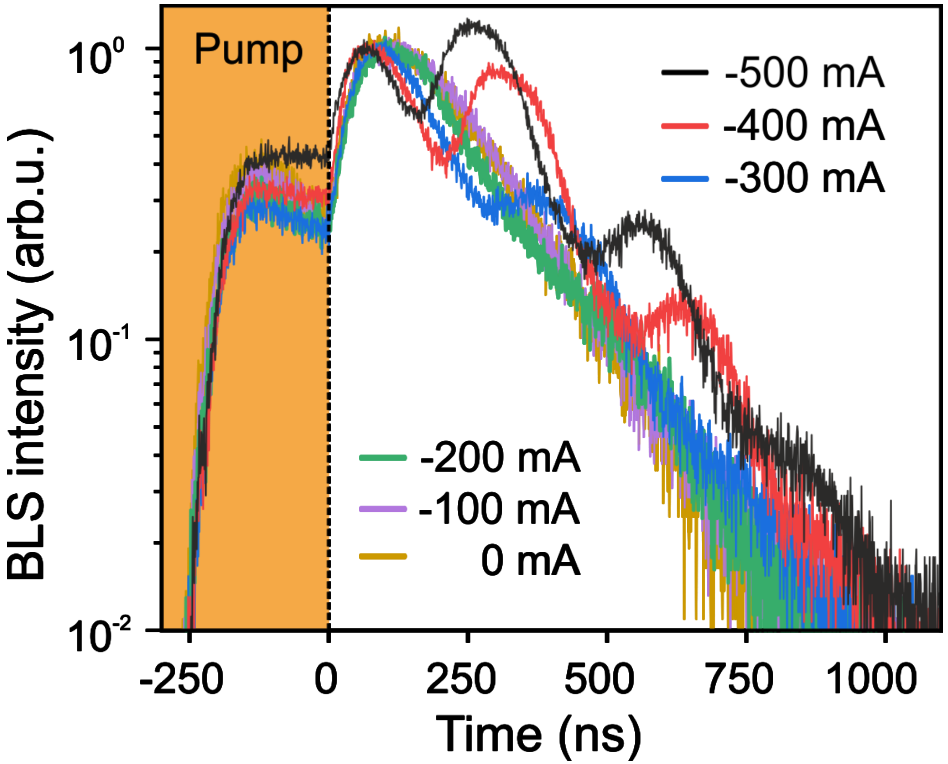
A.J.E. Kreil *et al.*, arXiv:1911.07802v1 (2019)

Josephson oscillations in magnon condensate

Potential barrier formed by dc current



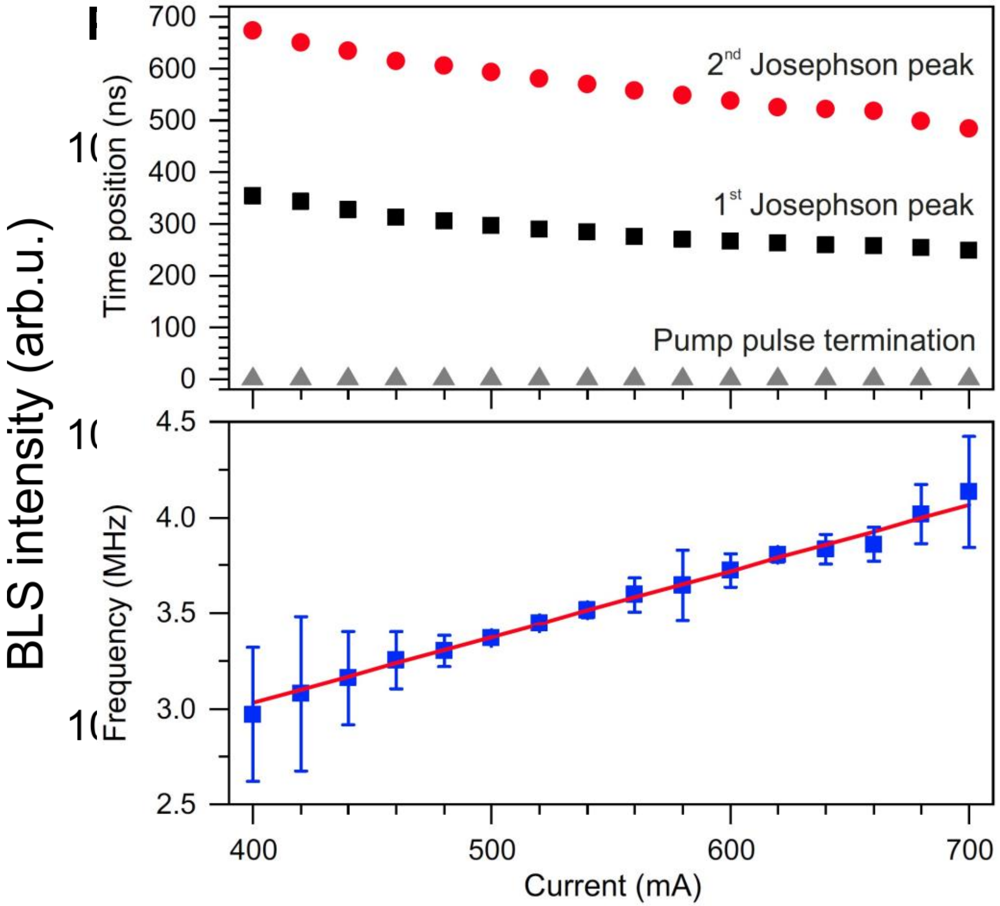
Potential trench formed by dc current



ac Josephson effect in a magnon BEC
carried by a room-temperature ferrimagnetic film

A.J.E. Kreil *et al.*, arXiv:1911.07802v1 (2019)

Josephson oscillations in magnon condensate

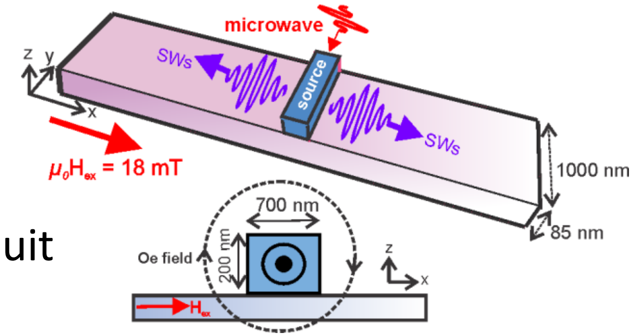


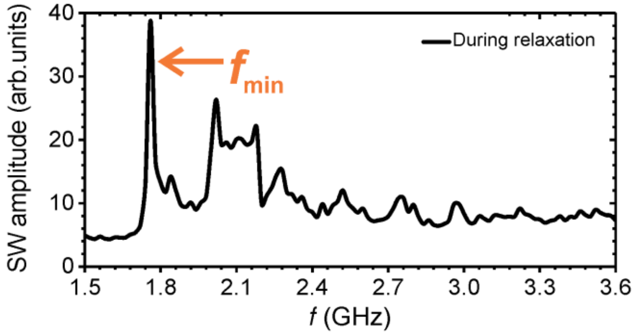
Frequency of the Josephson oscillations is in semi-quantitative agreement with the prediction of theory

A.J.E. Kreil *et al.*, arXiv:1911.07802v1 (2019)

Magnon BEC in confined systems

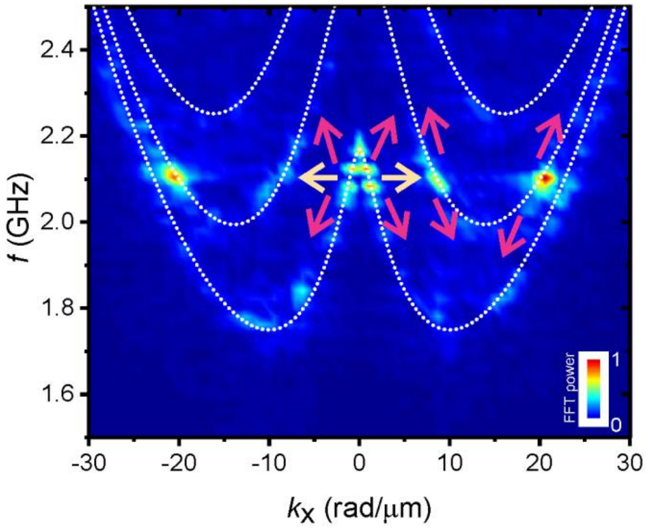
YIG microconduit



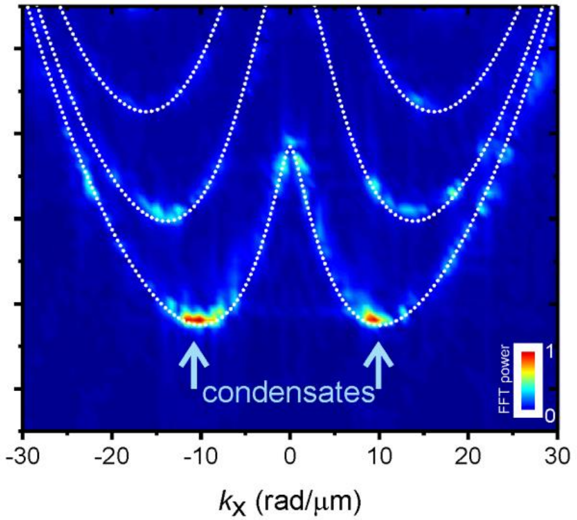


MuMax 3.0 numerical calculations

During pumping



During relaxation

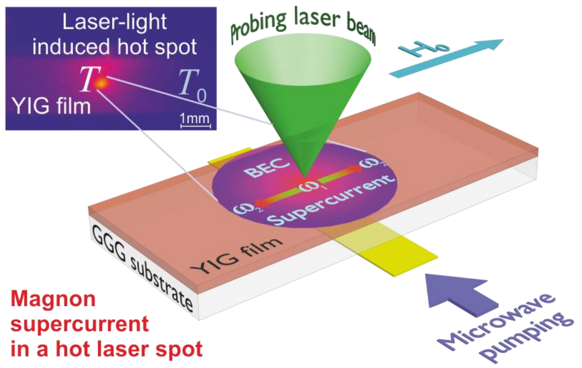


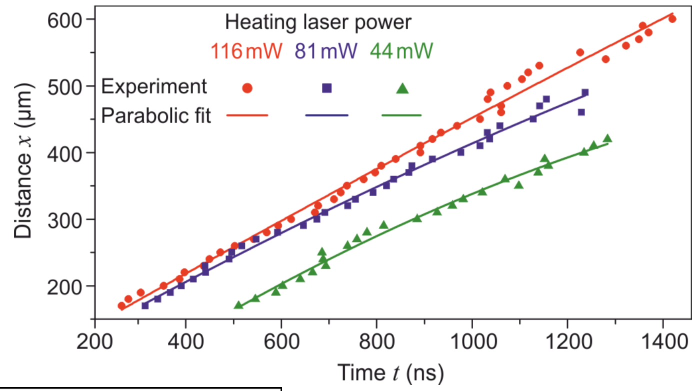
- Parallel pumping and magnon scattering processes
- Magnon BEC during relaxation

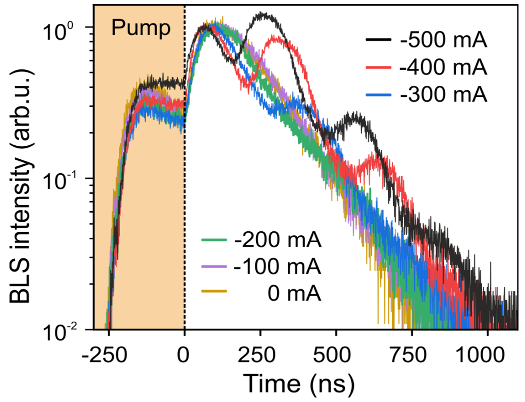
M. Mohseni, *et al*, New J. Phys., In press (2020)

Summary

- Non-local spin transport by magnon supercurrent in a room-temperature magnon BEC
- Bogoliubov second sound scenario for the distant supercurrent propagation
- Josephson oscillations in a room-temperature Bose-Einstein magnon condensate observed
- Advancing of the physics of room-temperature macroscopic quantum phenomena for their application in magnon spintronics devices

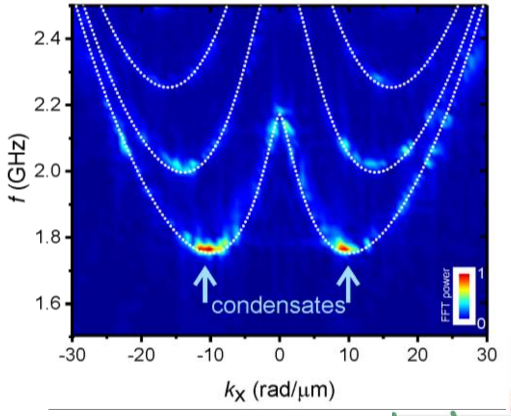


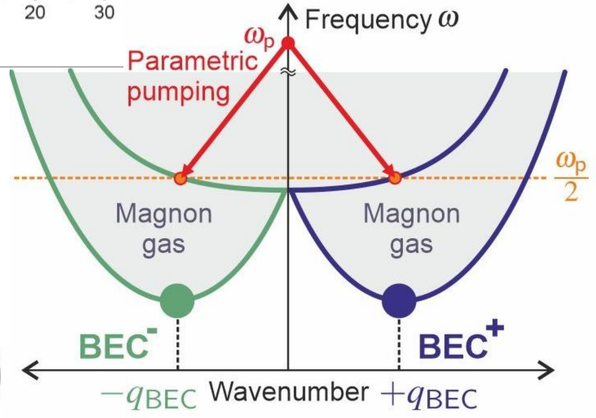


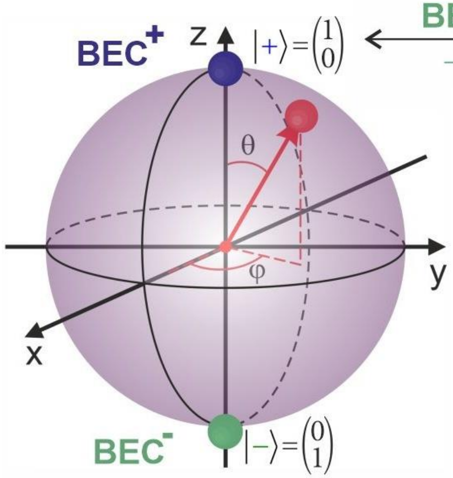


Outlook

- Spin transport by magnon supercurrent in 2D magnetic landscapes
- New ways to create the magnon BEC (rapid cooling, spin pumping)
- Non-viscose propagation of the magnon BEC
- Interference of Bogoliubov waves
- Computing with two-component magnon condensates
- Qubit representation using macroscopic magnonic quantum states

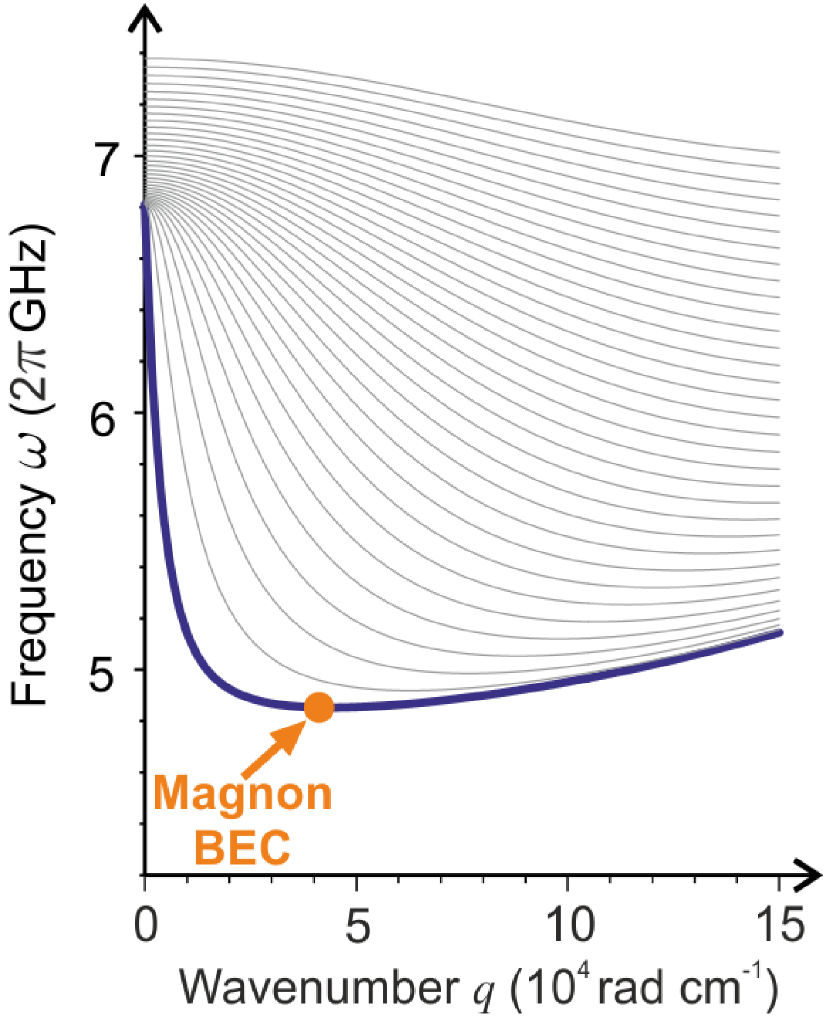






Appendix: phase of supercurrent in magnon BEC

Supercurrent: Flow of particles due to phase gradient of the condensate's wave function



Complex BEC wave function of particles: $\Psi_\mathrm{p}(\boldsymbol{r},t)$

Particle BEC density: $N_\mathrm{p} = |\Psi_\mathrm{p}|^2$

Particle BEC phase: $\varphi_\mathrm{p} = \arg \Psi_\mathrm{p}$

Supercurrent of particles

$$\boldsymbol{J}_\mathrm{p}(\boldsymbol{r},t) = \frac{\hbar}{M_\mathrm{p}} N_\mathrm{p} \nabla\varphi_\mathrm{p}$$

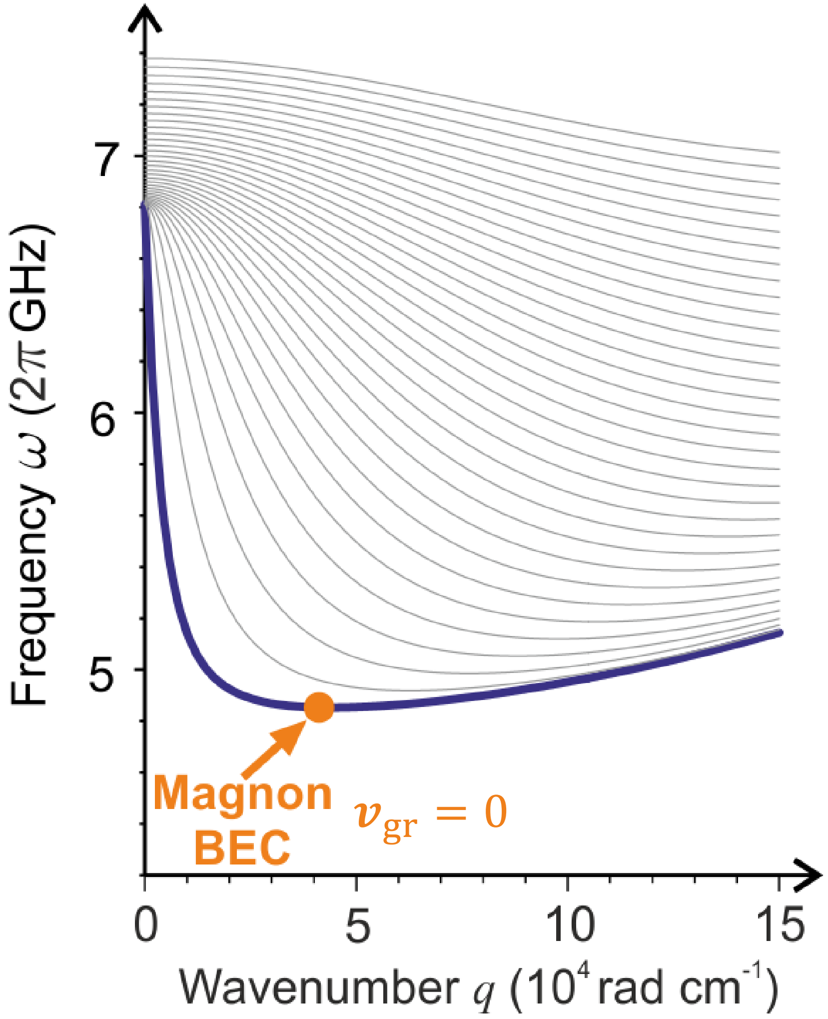
Complex BEC wave function of magnons: $\Psi_\mathrm{m}(\boldsymbol{r},t) = C_\mathrm{m}(\boldsymbol{r},t)\exp[i(\boldsymbol{q}_0 \cdot \boldsymbol{r} - \omega_0 t)]$

Magnon BEC density N_m and phase φ_m: $C_\mathrm{m}(\boldsymbol{r},t) = \sqrt{N_\mathrm{m}}\exp(i\varphi_\mathrm{m})$

Phase φ_m of a spatially heterogeneous condensate at position $\boldsymbol{r}$: we take the deviation of the angle of rotation of the spin at this position from the rotation for the case of a fully monochromatic spatially coherent spin wave.
Thus, the phase of a spatially homogeneous condensate is zero.

Appendix: phase of supercurrent in magnon BEC

Supercurrent: Flow of particles due to phase gradient of the condensate's wave function



Complex BEC wave function of particles: $\Psi_{\mathrm{p}}(\boldsymbol{r},t)$

Particle BEC density: $N_{\mathrm{p}} = |\Psi_{\mathrm{p}}|^2$

Particle BEC phase: $\varphi_{\mathrm{p}} = \arg \Psi_{\mathrm{p}}$

Supercurrent of particles

$$\boldsymbol{J}_{\mathrm{p}}(\boldsymbol{r},t) = \frac{\hbar}{M_{\mathrm{p}}} N_{\mathrm{p}} \nabla\varphi_{\mathrm{p}}$$

Complex BEC wave function of magnons: $\Psi_{\mathrm{m}}(\boldsymbol{r},t) = C_{\mathrm{m}}(\boldsymbol{r},t)\exp[i(\boldsymbol{q}_0\cdot\boldsymbol{r} - \omega_0 t)]$

Magnon BEC density N_{m} and phase φ_{m}: $C_{\mathrm{m}}(\boldsymbol{r},t) = \sqrt{N_{\mathrm{m}}}\exp(i\varphi_{\mathrm{m}})$

$$\begin{cases} \dfrac{\partial N_{\mathrm{m}}(\boldsymbol{r},t)}{\partial t} \approx \dfrac{\partial |C_{\mathrm{m}}(\boldsymbol{r},t)|^2}{\partial t} = \dfrac{\partial C_{\mathrm{m}}(\boldsymbol{r},t)}{\partial t} C^*_{\mathrm{m}}(\boldsymbol{r},t) + C_{\mathrm{m}}(\boldsymbol{r},t)\dfrac{\partial C^*_{\mathrm{m}}(\boldsymbol{r},t)}{\partial t} \\ \left[i\dfrac{\partial}{\partial t} + i v_{\mathrm{gr}}\nabla + \dfrac{1}{2}\omega''_{ij}\nabla_i\nabla_j - T|C_{\mathrm{m}}(\boldsymbol{r},t)|^2 \right] C_{\mathrm{m}}(\boldsymbol{r},t) = 0 \end{cases}$$

← **Gross-Pitaevskii equation**

Continuity equation:

$$\frac{\partial N_{\mathrm{m}}(\boldsymbol{r},t)}{\partial t} + \nabla \boldsymbol{J}_{\mathrm{m}} = 0$$

$$v_{\mathrm{gr}} = \left.\frac{d\omega(\boldsymbol{q})}{d\boldsymbol{q}}\right|_{\boldsymbol{q}=\boldsymbol{q}_0} \qquad \omega''_{ij} = \left.\frac{d^2\omega(\boldsymbol{q})}{d\boldsymbol{q}_i d\boldsymbol{q}_j}\right|_{\boldsymbol{q}=\boldsymbol{q}_0}$$

Magnon supercurrent:

$$J_{\mathrm{m}i} = \cancel{v_{\mathrm{gr}i}|C_{\mathrm{m}}|^2} + \frac{i\omega''_{ij}}{2}\left[C_{\mathrm{m}}\nabla_j C^*_{\mathrm{m}} - C^*_{\mathrm{m}}\nabla_j C_{\mathrm{m}}\right]$$

$$J_{\mathrm{m}i} = \frac{\omega''_{ij}}{2} N_{\mathrm{m}} \frac{\partial\varphi_{\mathrm{m}}}{\partial r_j}$$