Coherent order and transport in spin-active systems:
Interplay between magnetism and superconductivity

Bose-Einstein condensation of magnons in confined systems

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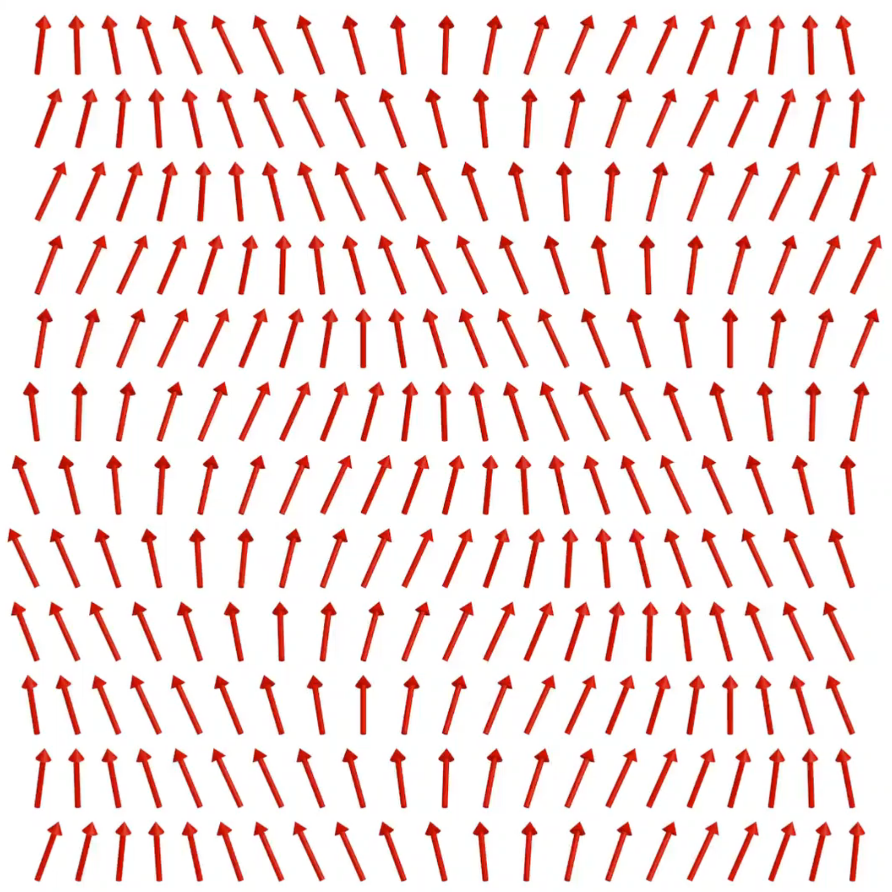
Magnon gas

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 $s = 1$
- Four- and three-magnon scattering



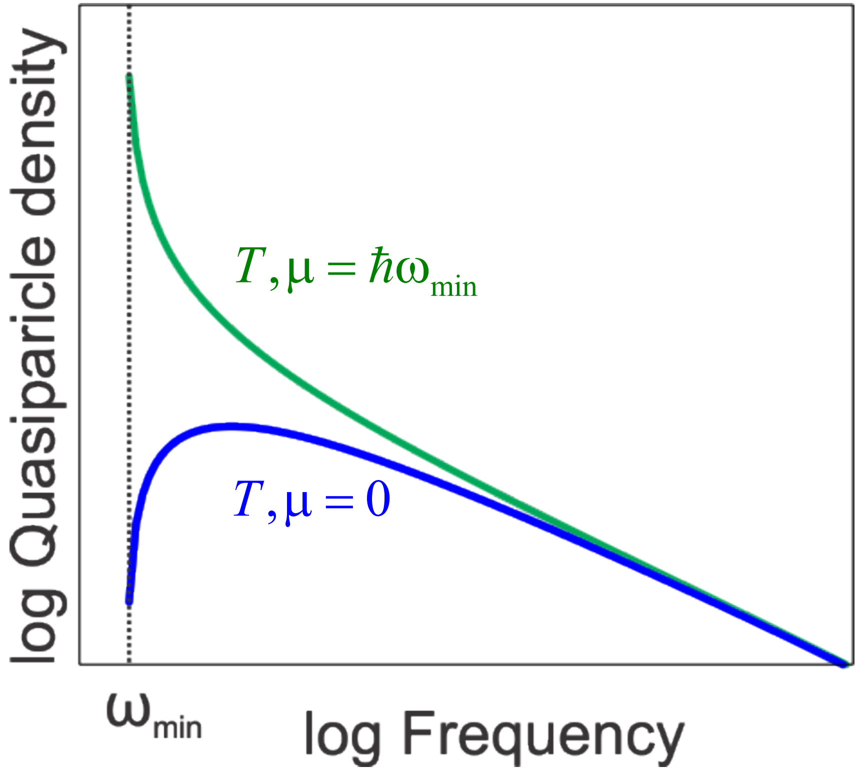
Magnon Bose-Einstein condensation

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)

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Computing principles

PERFORMANCE

- Classical Computing
  - Scalar variable
  - Boolean logic
- Wave Packet Computing
  - Vector variable
  - Special task data processing
- Macroscopic Quantum State Computing
  - Vector state variable
- Quantum Computing
  - Vector state variable
  - Entanglement

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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:

- **Macroscopic magnonic quantum states in confined systems**

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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“

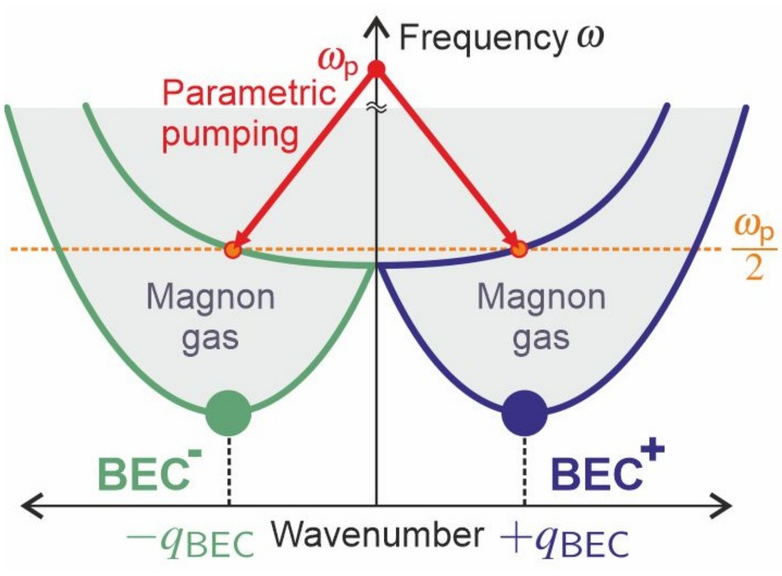
⬇

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

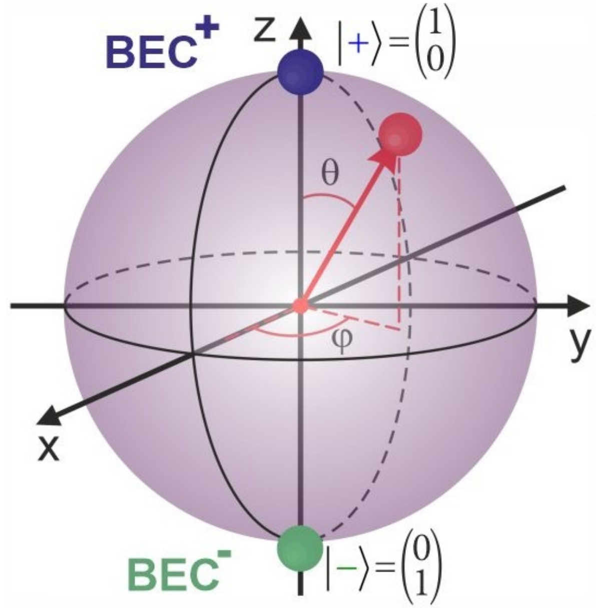
A possible application: magnon BEC qubits

Qubit: we need two states $|+\rangle$ and $|-\rangle$ with well-defined amplitudes and phases to form a qubit state $a|+\rangle + b|-\rangle$

Use magnon Bose-Einstein condensates for representation of the two qubit states:



Representation of qubit state on Bloch sphere:



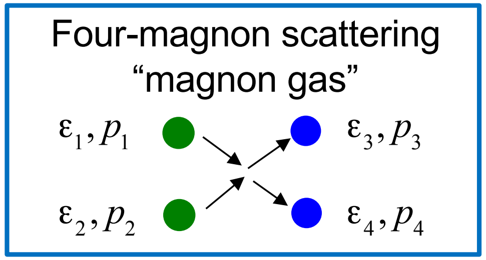
Magnon BEC by microwave excitation

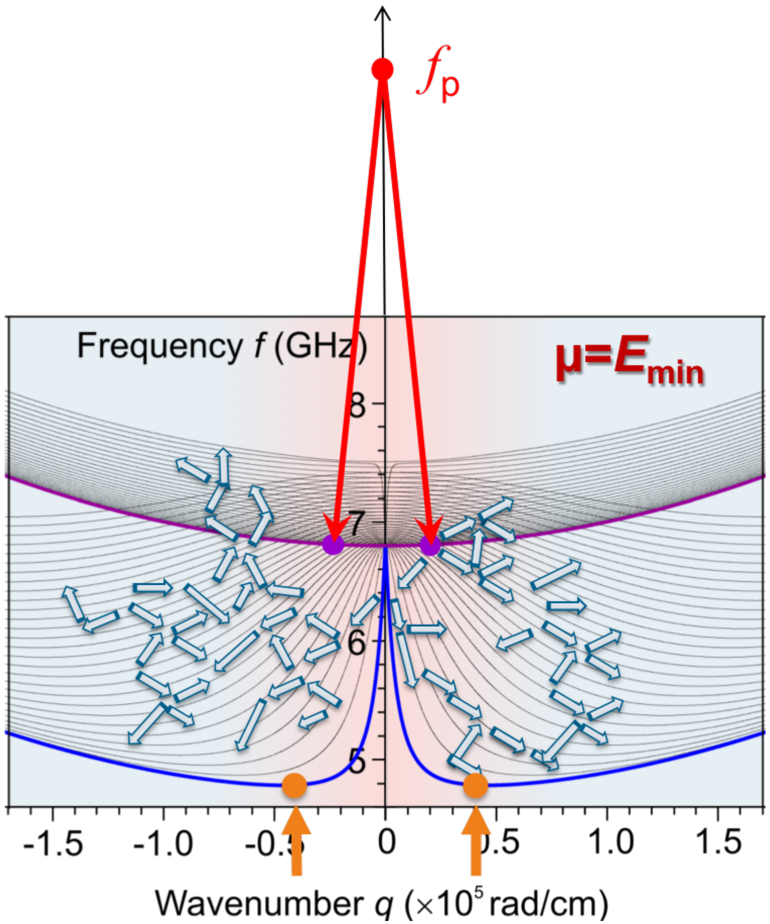
Parametric pumping: Magnon BEC by spacial injection:
⇒ Excess magnon generation via local microwave injection
⇒ thermalization into flow equilibrium, or relaxation into BEC state
via four-magnon scattering events

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

Key element: Excess magnons cannot relax within system relaxation time
→ finite chemical potential μ

New: **BEC by time-scale injection in confined systems**:
⇒ Excess magnon generation via sudden temperature decrease
⇒ relaxation into BEC state
(no microwave generation involved)





Bose-Einstein condensation of magnons by rapid cooling

Michael Schneider

Oleksandr Serha

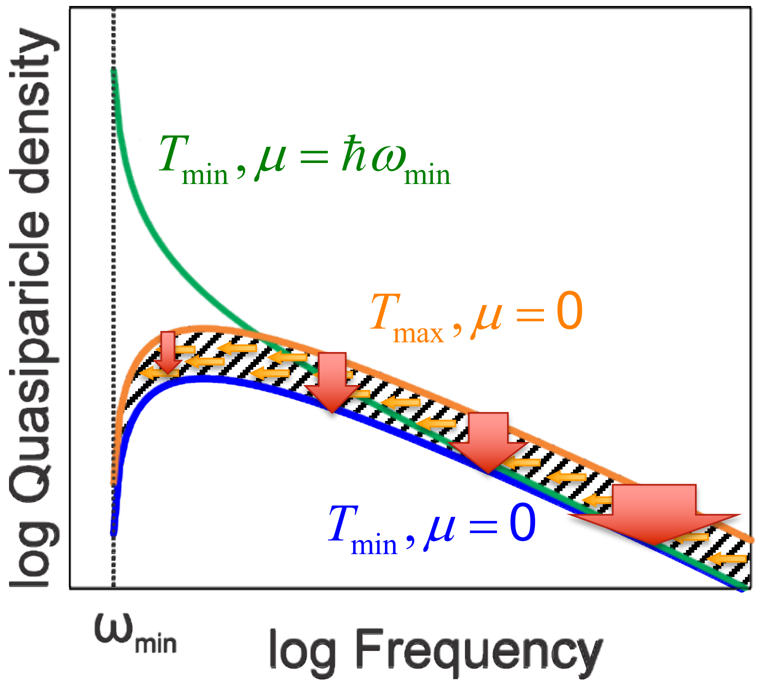
Andrii Chumak
(now University of Vienna)

Magnon BEC via time-scale injection

- 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

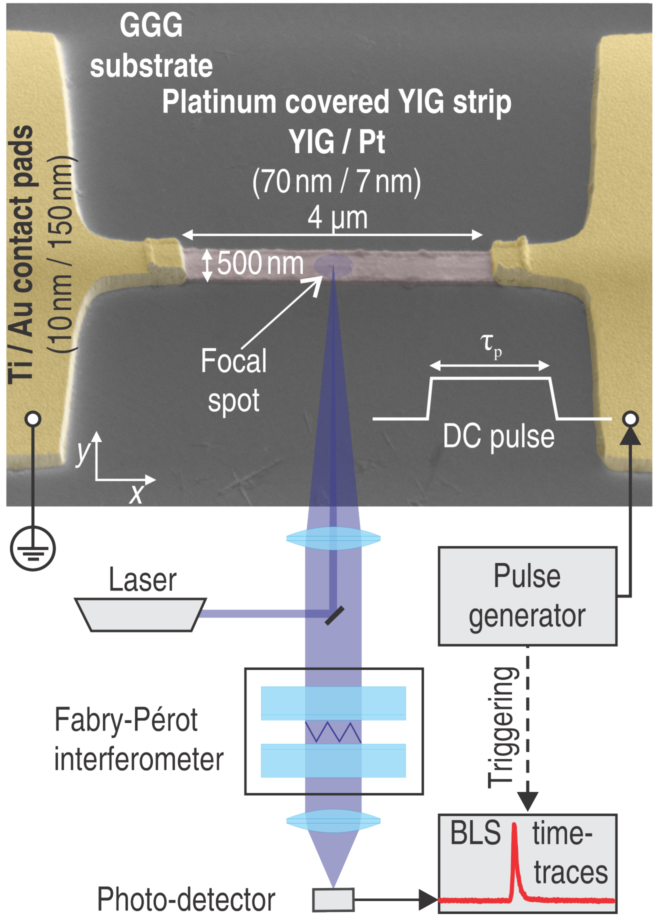
Experimental setup

LPE YIG film from Innovent e.V., Jena

C. Dubs, et al., *J. Phys. D:* **50**, 204005 (2017)

- YIG film thickness : 70 nm
- 7 nm Pt film deposited via MBE
- Damping YIG : $\alpha = 2.6\times10^{-4}$
- Damping YIG/Pt : $\alpha = 1.2\times10^{-3}$
- Dual angle etching of microstructures
- Deposition of Au contacts

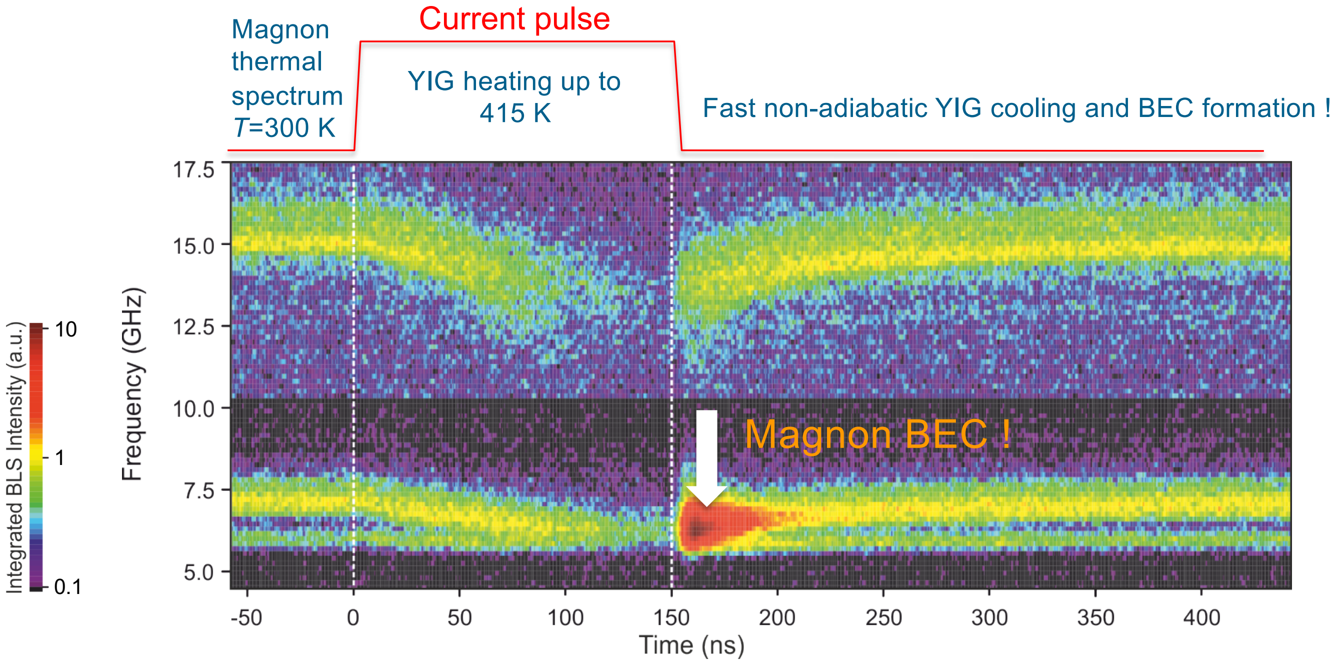
Time-resolved microfocused BLS setup without wavenumber resolution



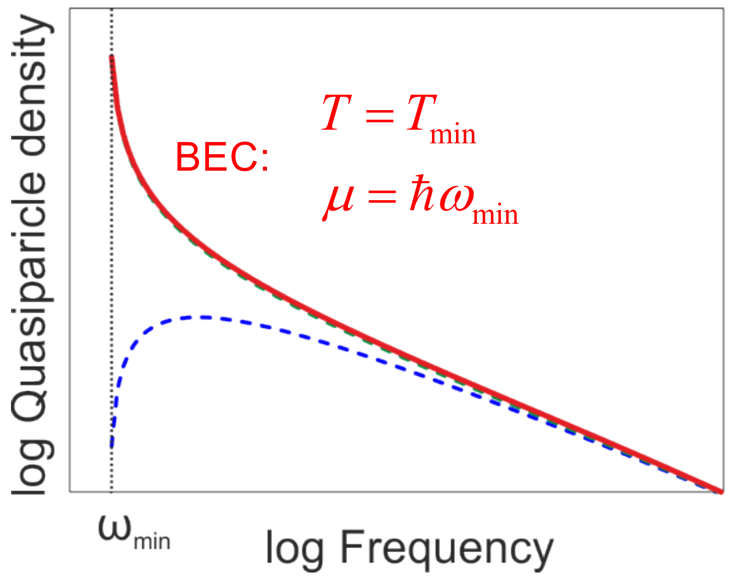
M. Schneider, *et al.*, Nat. Nanotechnol. **15**, 457 (2020)

BEC in rapidly cooled magnon gas

Damon-Eshbach geometry

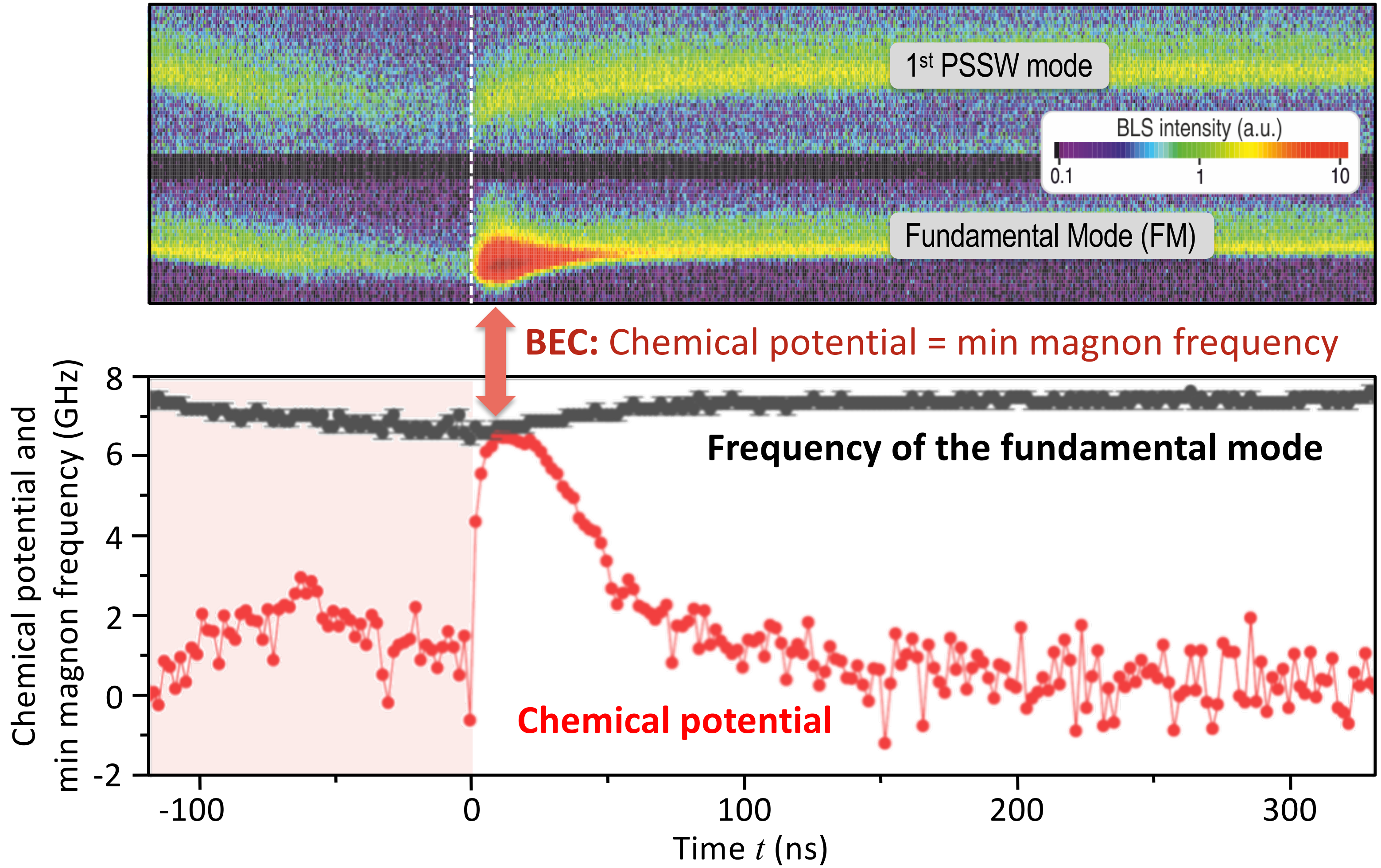


Magnon population distribution



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

Temporal dynamics of chemical potential and minimal magnon frequency



Rayleigh–Jeans distribution

$$n(f) = \frac{k_B T}{h(f - \mu)}$$

n – magnon density ∝ BLS intensity

f – magnon frequency

μ – chemical potential

Chemical potential

$$\mu(t) = \frac{A_{\mathrm{PSSW}} f_{\mathrm{PSSW}} - A_{\mathrm{FM}} f_{\mathrm{FM}}}{A_{\mathrm{PSSW}} - A_{\mathrm{FM}}}$$

$A_{\mathrm{PSSW}}, f_{\mathrm{PSSW}}$ - BLS intensity and frequency of the 1st PSSW mode

$A_{\mathrm{FM}}, f_{\mathrm{FM}}$ - BLS intensity and frequency of the fundamental mode

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Magnon condensates in confined systems

Morteza Mohseni

Philipp Pirro

+

Arne Brataas

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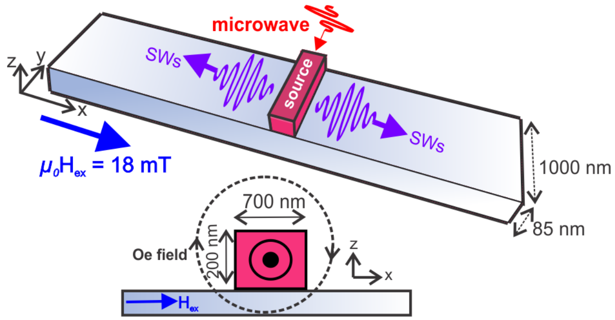
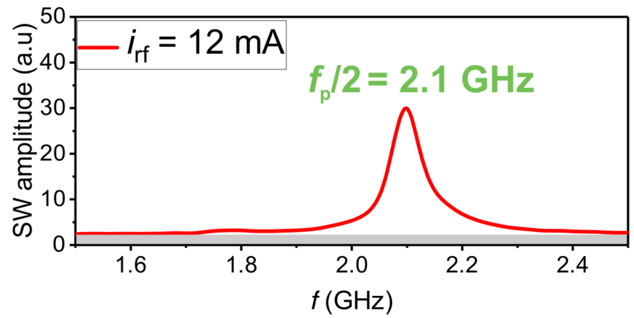
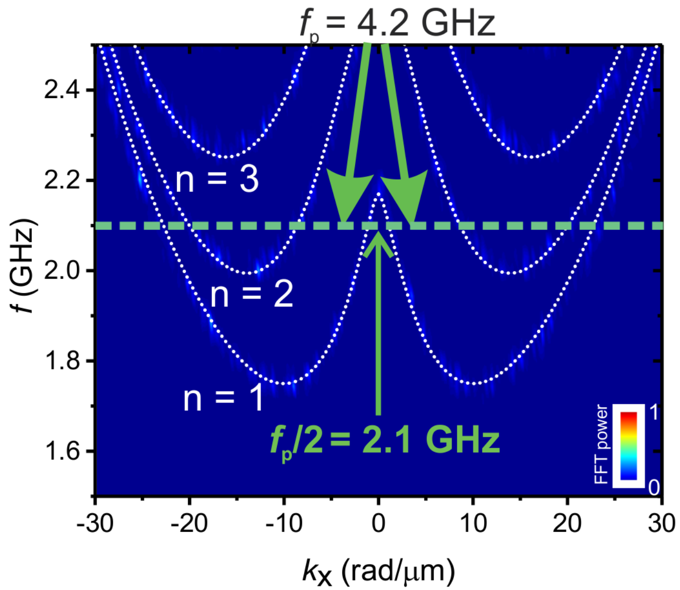
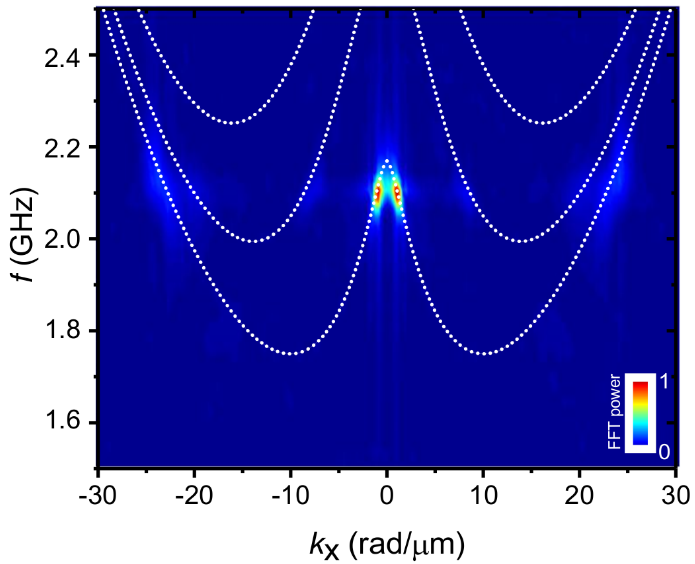
Parametric excitation of magnons in a YIG microconduit





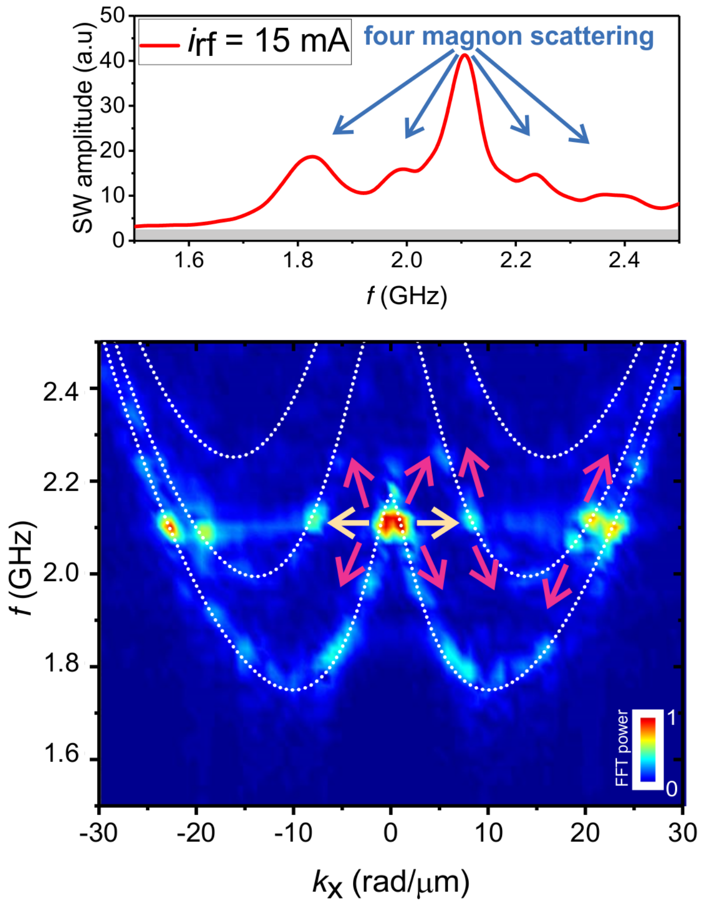




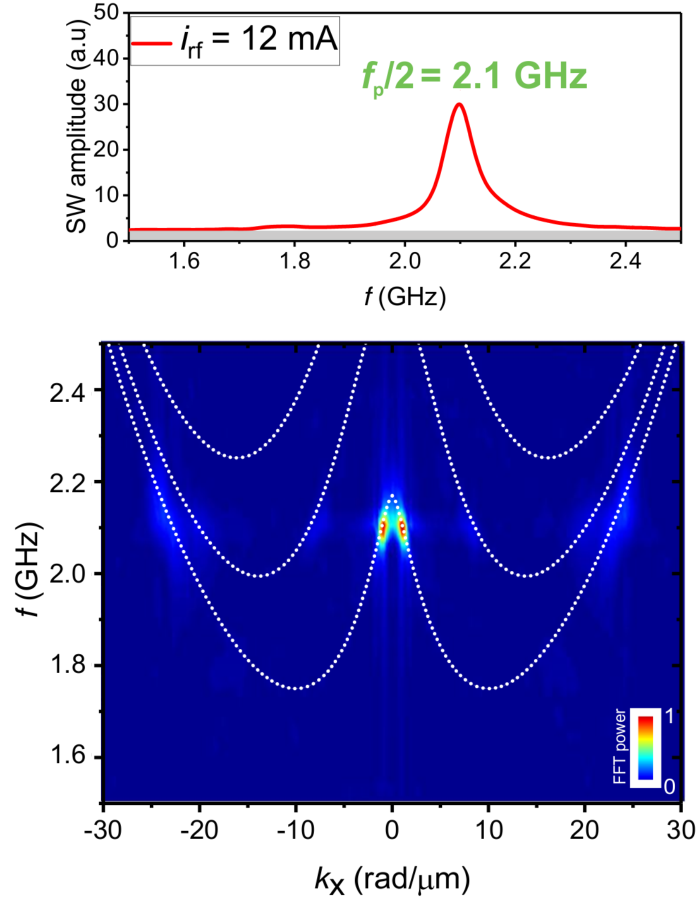
MuMax 3.0 numerical calculations

Onset of four-magnon scattering

Four-magnon scattering enabled

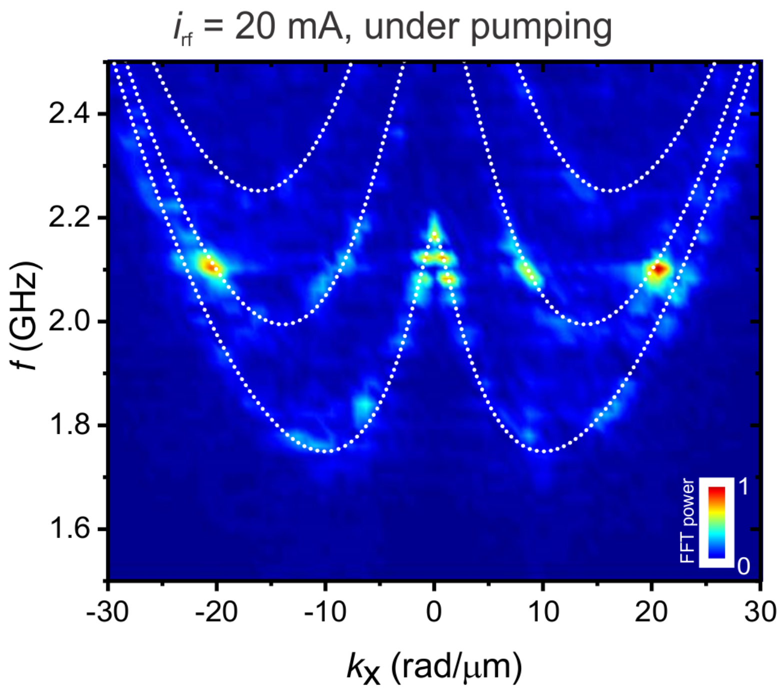


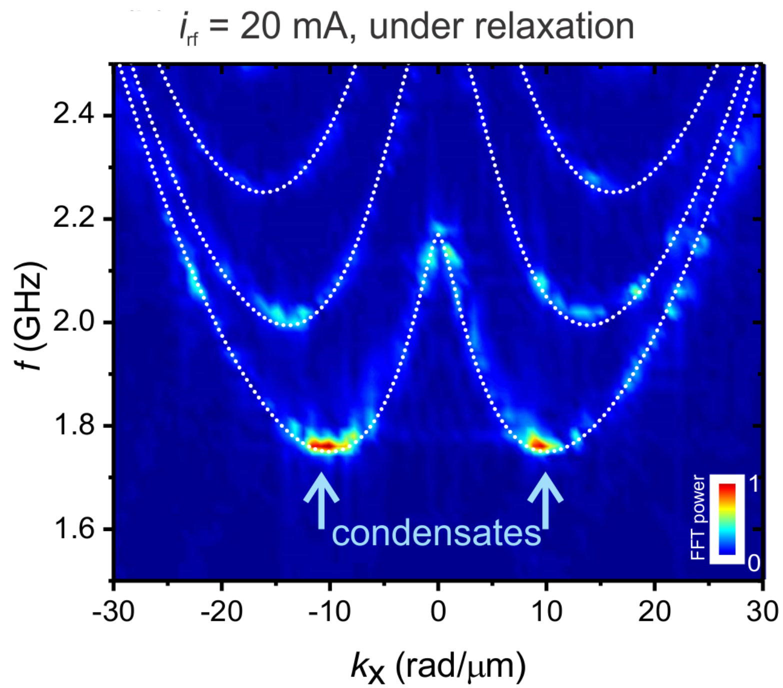
Four-magnon scattering threshold is not overcome



MuMax 3.0 numerical calculations

Magnon condensation in microconduits





- No condensation during the pumping

- **Condensation of magnons in two global minima**

M. Mohseni, *et al*, New J. Phys. **22**, 083080 (2020)

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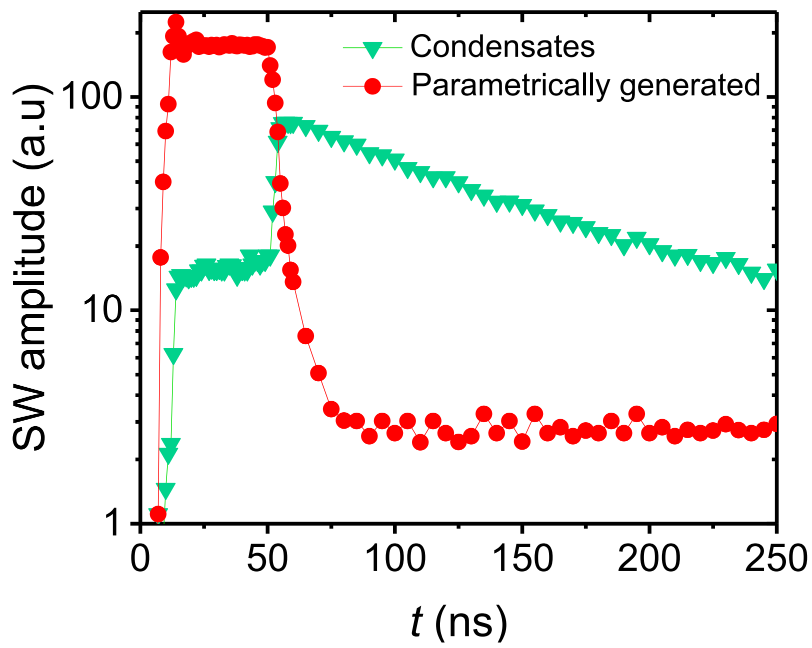
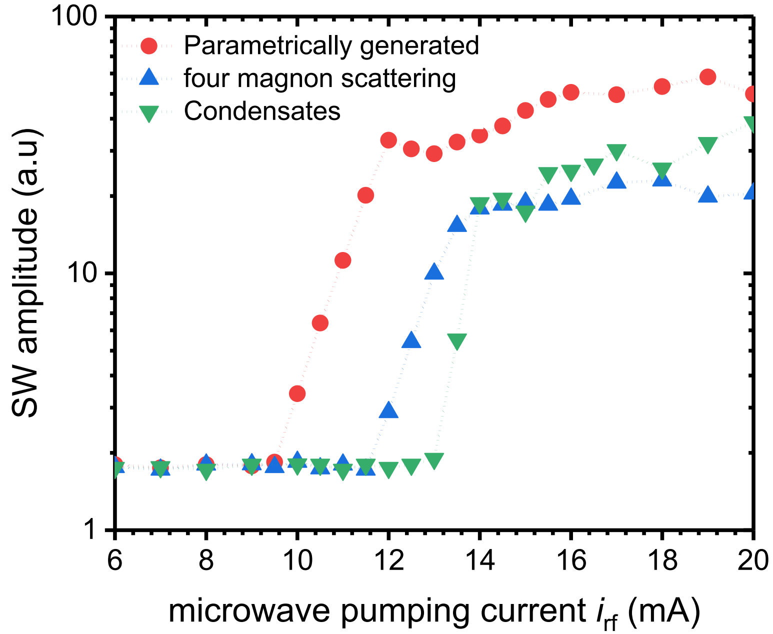
Relaxation and thresholds





- Decay time of parametrically excited magnons: 5ns
- Decay time of condensed magnons: 100ns

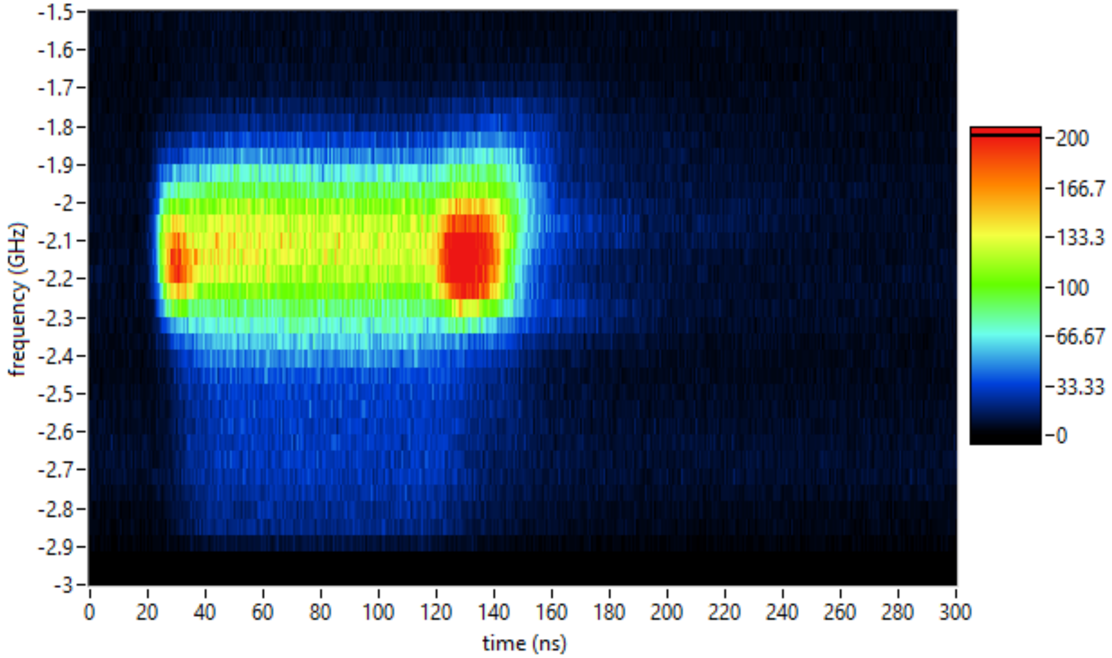
- Parametric generation threshold
- Four-magnon scattering
- Magnon condensation

M. Mohseni, *et al*, New J. Phys. **22**, 083080 (2020)

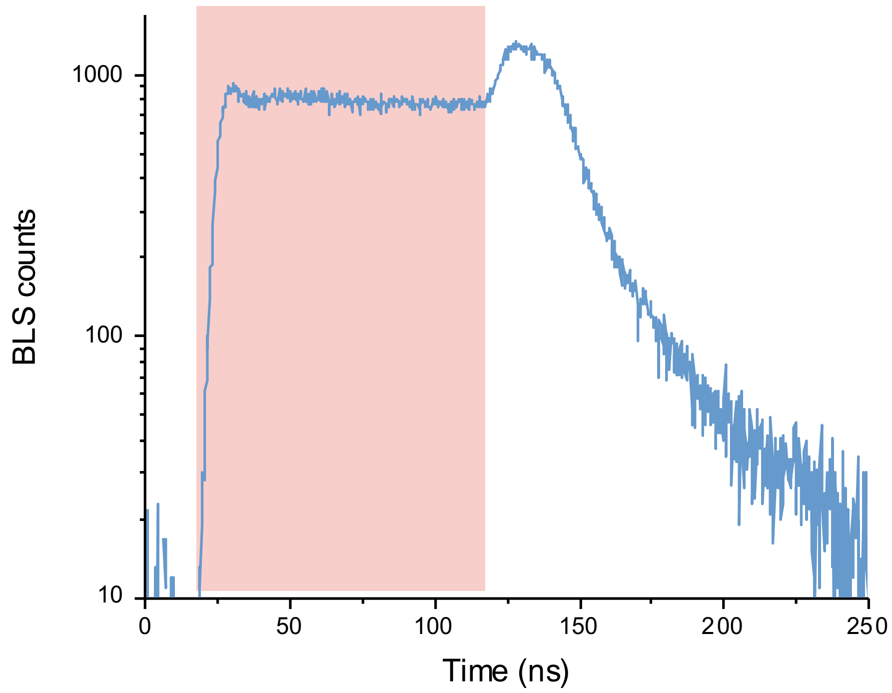
Experimental investigations of BEC in a waveguide

- 1µm-wide YIG waveguide, 85nm thickness, Backward Volume Mode geometry
- Microwave pumping frequency f_p = 4.2 GHz
- Pumping power P_p = 20 dBm

Time-resolved BLS signal

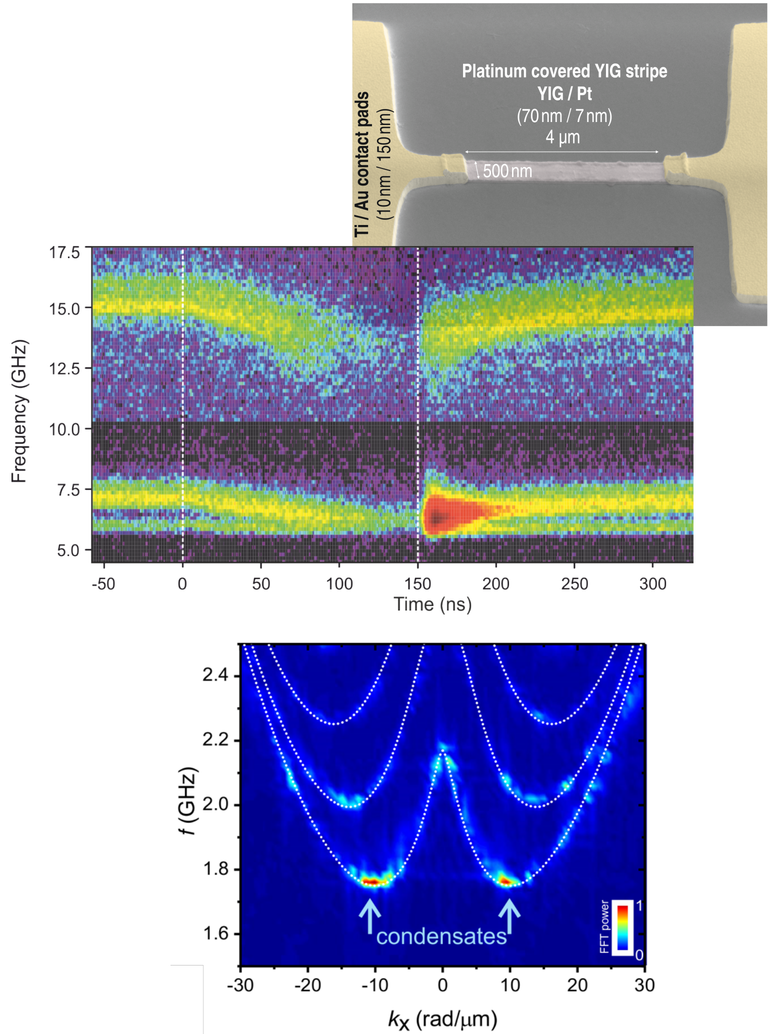


Pumping pulse



Summary

- First experimental evidence of a magnon BEC caused by rapid cooling of a magnetic nano-structure (magnon injection on time scale)
- The injection mechanism is originally incoherent and can be applied to other bosonic systems
- Magnon condensation in microconduits is demonstrated using micromagnetic simulations and confirmed by the first experimental investigations



Outlook

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