Quantum Spintronics

Magnon supercurrents
in a room temperature magnon condensate

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Dresden, Germany

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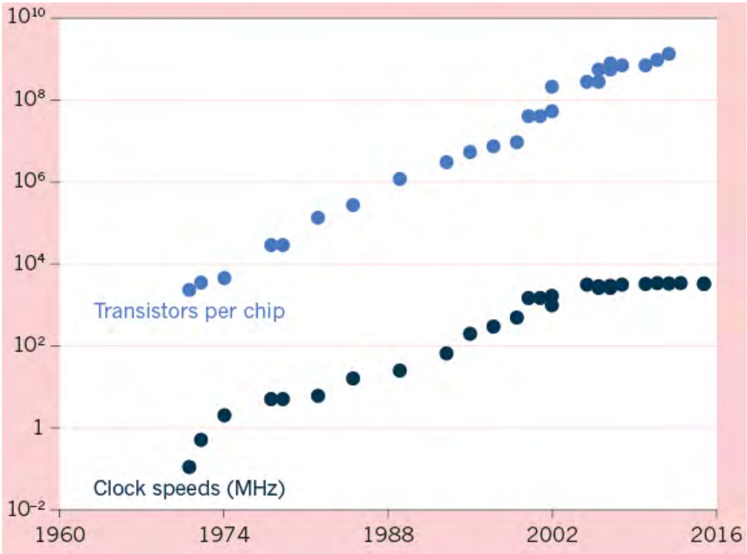
Post CMOS?

CMOS is coming to the end of Moore's law
- Waste energy production
- End of scaling

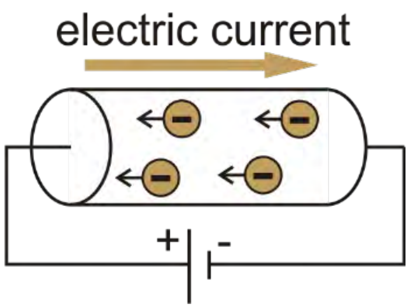
Beyond current CMOS:
- Faster computing, less energy consumption
- Same technology for logic and data
- Logic circuits with reduced footprint and/or 3D

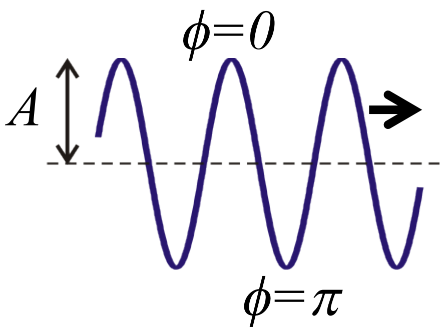
Novel paradigm: wave computing



M. Mitchell, Nature **530**, 144 (2016)

Proposal:
use waves /wave packets instead of particles (electrons) for bit representation





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Magnon computing

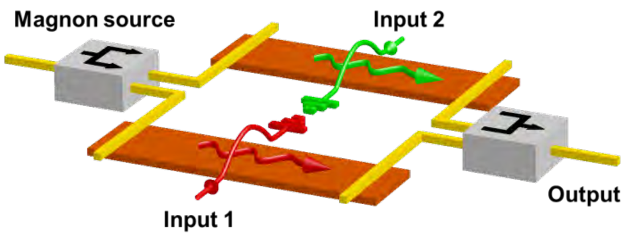
Why spin waves/magnons?

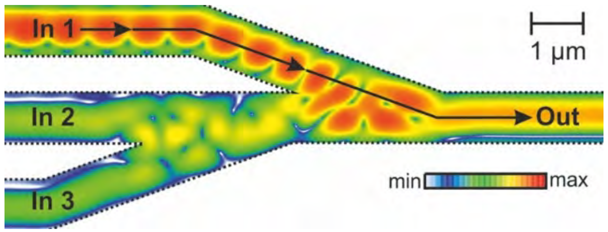
- wavelength down to nanometer, frequency up to several THz
- interference effects easily accessible
- efficient nonlinear effects
- room temperature
- no Joule heat, “insulatronics”
- wave-based computing: smaller footprint, all-wave logic
- good converters to CMOS

→ “magnon spintronics”

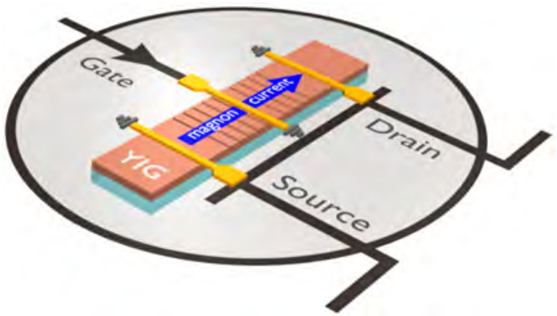
Achievements:

Logic gates





Magnon transistor

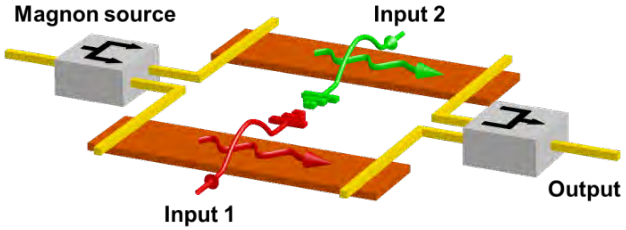


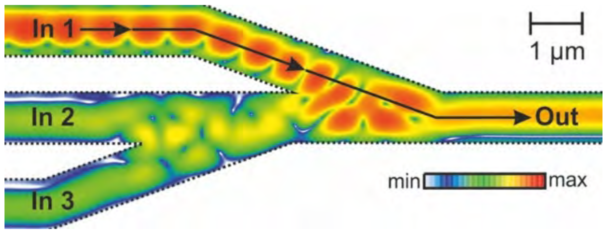
Andrii Chumak, Kaiserslautern

Magnon computing

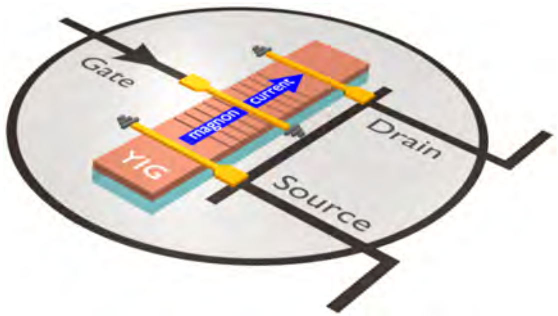
Achievements:

Logic gates





Magnon transistor



Andrii Chumak, Kaiserslautern

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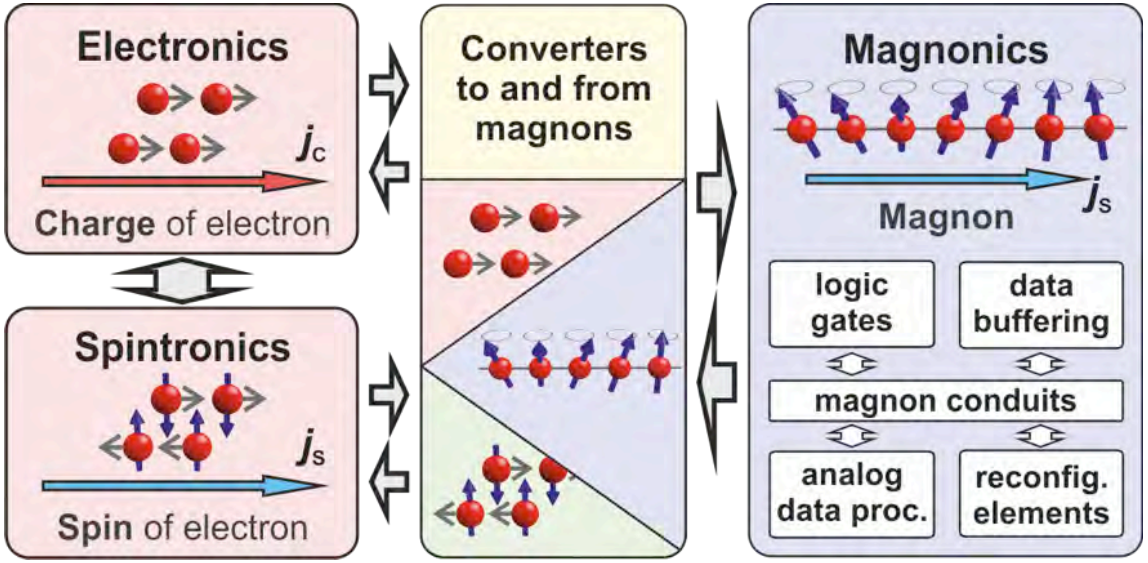
Concept of magnon spintronics



A.V. Chumak, V.I. Vasyuchka, A.A. Serga, B. Hillebrands, *Magnon Spintronics*, Nature Phys. **11**, 453 (2015)

- Magnon packet computing: go to deep exchange regime
  → THz computing, small feature size
- Develop efficient converters
- Engineering of interactions
- New materials
  - low damping
  - compatibility with CMOS
  - compatibility with existing production equipment
- Macroscopic magnonic quantum states computing

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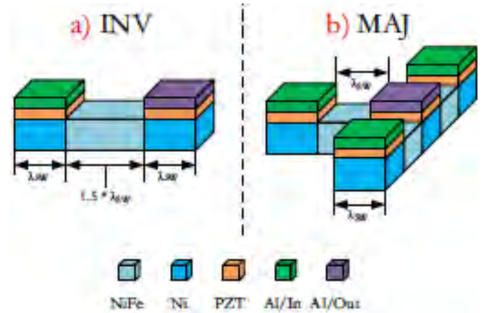
Spin-wave device architectures

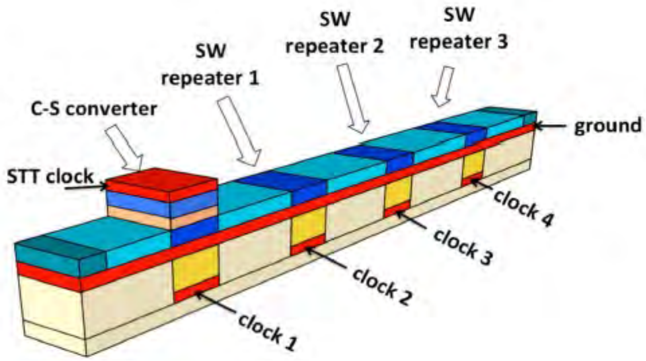
L. Amarú, P.-E. Gaillardon, G. De Micheli
(EPFL,Switzerland)

Majority based synthesis for nanotechnologies



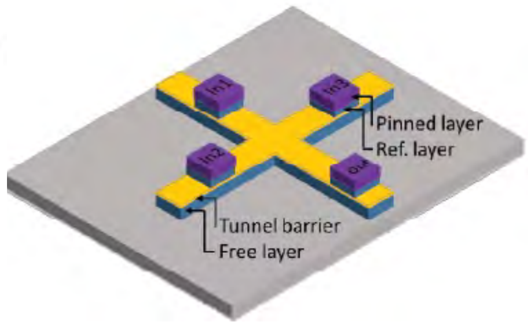
S. Dutta, A. Naeemi
(Georgia Institute of Technology, USA)

Non-volatile clocked spin wave nanomagnet pipelines



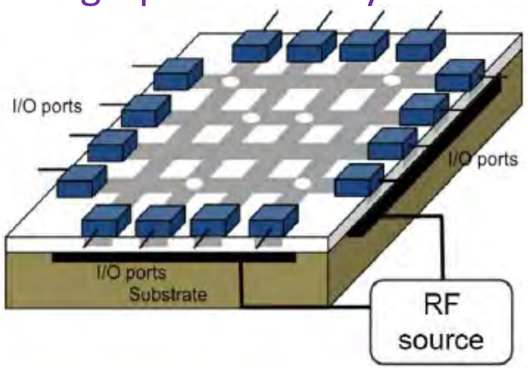
D. E. Nikonov, I. A. Young
(Intel Corp. Hillsboro, Oregon, USA)

Benchmarking,
clocked spin-wave circuits



A. Khitun
(Univ. of California Riverside, USA)

Majority gate,
holographic memory



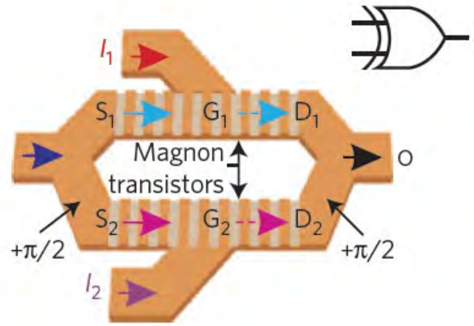
F. Ciubotaru, C. Adelmann
(Imec, Leuven, Belgium)

Magnetoacoustic nanoresonators

(a) ME cell schematic

A. Chumak
(TU Kaiserlautern, Germany)

Magnon transistor,
integrated magnonic circuits



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Benchmarking

Hybrid CMOS-Spin Wave Device Circuits Compared to 10nm CMOS

TABLE IV. SUMMARY OF BENCHMARKING RESULTS

Name	Area (μm^2)				Energy (fJ)	Delay (ns)		Power (μW)		ADPP*		
	SWD core	CMOS SA	SWD Total	10nm Ref.	SWD Total	SWD	10nm Ref.	SWD	10nm Ref.	SWD	10nm Ref.	Impr. (x)
BKA264	36.48	3.12	39.60	118.55	175.50	5.07	0.21	34.62	133.92	$6.95\cdot10^3$	$3.33\cdot10^3$	0.48
HCA464	82.71	3.17	85.88	262.63	178.20	8.01	0.29	22.25	594.28	$1.53\cdot10^4$	$4.53\cdot10^4$	2.96
CSA464	78.42	3.17	81.59	240.26	178.20	7.59	1.78	23.48	663.17	$1.45\cdot10^4$	$2.84\cdot10^5$	19.51
DTM32	326.31	3.07	329.38	1183.64	172.80	14.73	0.52	11.73	3667.50	$5.69\cdot10^4$	$2.26\cdot10^6$	39.66
WTM32	264.96	3.07	268.04	1163.37	172.80	20.61	0.58	8.38	3571.90	$4.63\cdot10^4$	$2.41\cdot10^6$	52.04
DTM64	1192.69	6.14	1198.83	3459.32	345.60	18.09	0.63	19.10	12793.10	$4.14\cdot10^5$	$2.79\cdot10^7$	67.29
GFMUL	44.09	0.82	44.91	162.98	45.90	7.17	0.16	6.40	433.92	$2.06\cdot10^3$	$1.13\cdot10^4$	5.49
MAC32	295.25	3.12	298.37	1372.83	175.50	24.39	0.66	7.20	3872.10	$5.24\cdot10^4$	$3.51\cdot10^6$	67.00
DIV32	899.04	6.14	905.18	3347.73	345.60	117.21	14.00	2.95	5346.10	$3.13\cdot10^5$	$2.51\cdot10^8$	800.94
CRC32	27.61	1.54	29.14	95.88	86.40	5.07	0.22	17.04	304.30	$2.52\cdot10^3$	$6.42\cdot10^3$	2.55
Averages	324.76	3.34	328.09	1140.72	187.65	22.79	1.91	15.31	3138.03	$9.24\cdot10^4$	$2.87\cdot10^7$	105.79

The list includes adders, multipliers,
a divider, and a cyclic redundancy check module

* Area-Delay-Power-Product (ADPP)

Zografos, et al., Proceedings of the 15th IEEE International Conference on Nanotechnology July 27-30, 2015, Rome, Italy

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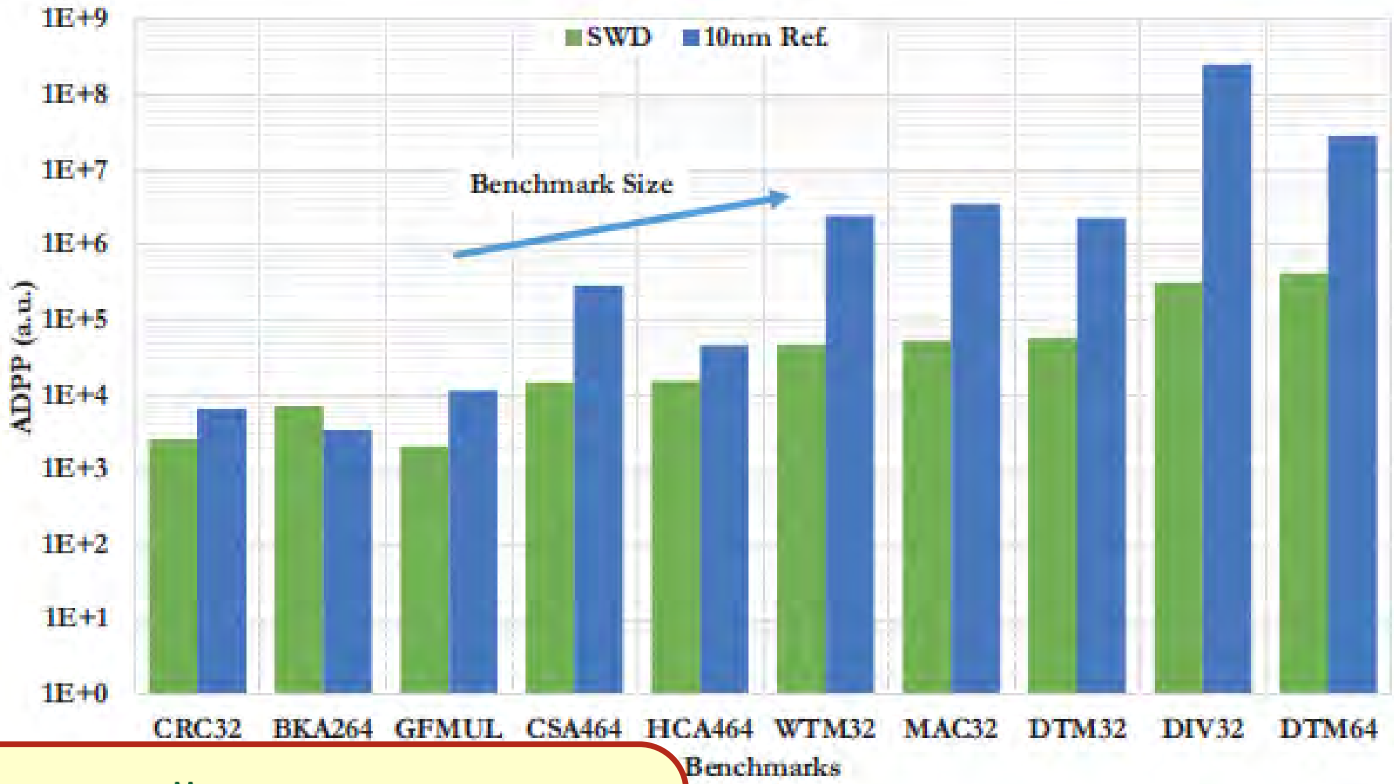
Benchmarking

Hybrid CMOS-Spin Wave Device Circuits Compared to 10nm CMOS



Area: 3.5x smaller

Delay: 10-20x slower

Power consumption: 100x lower

ADPP: 50-100x better!

* Area-Delay-Power-Product (ADPP)

Zografos, et al., Proceedings of the 15th IEEE International Conference on Nanotechnology July 27-30, 2015, Rome, Italy

Novel magnon states

Main idea:

find novel magnon states useful for information transfer and processing

Here:

- macroscopic magnonic quantum states for information transfer and processing

A. Serga upcoming talk:

- magnon-phonon states at minimum energy and with large group velocity

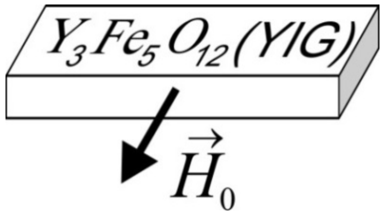
Macroscopic magnonic quantum states:

- 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)
- prominent example: magnonic Bose Einstein condensate

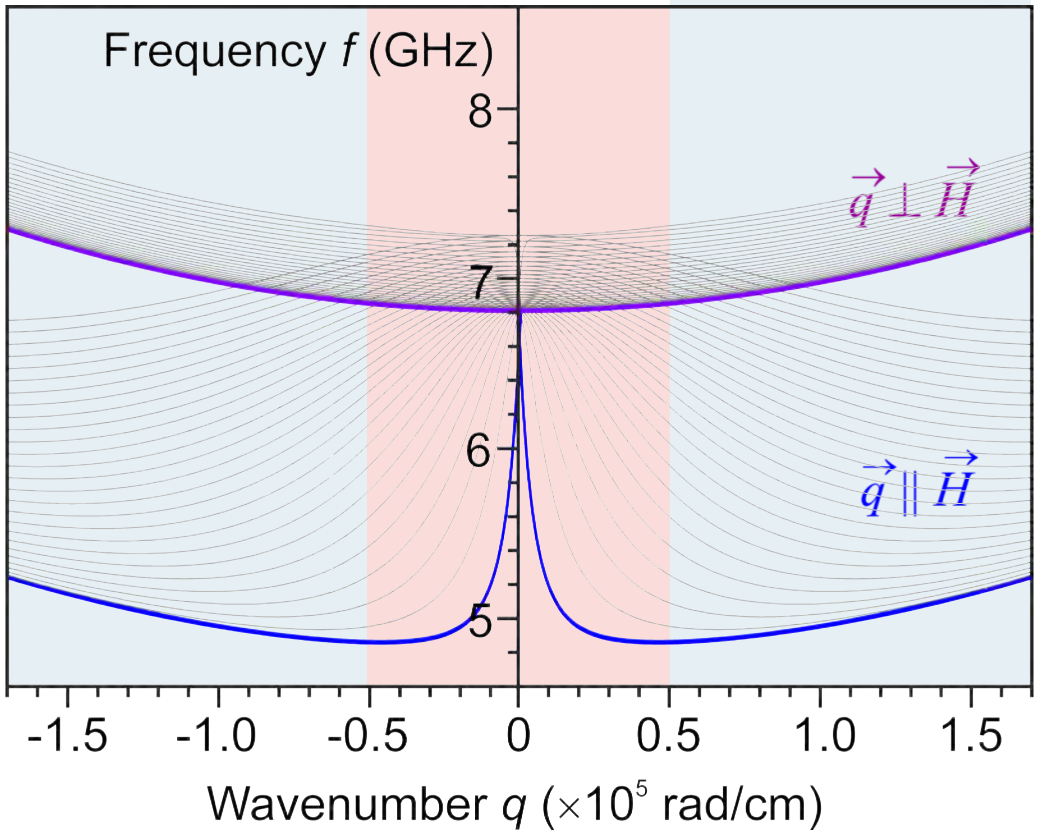
Magnon spectrum of in-plane magnetized ferrimagnetic YIG film

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

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



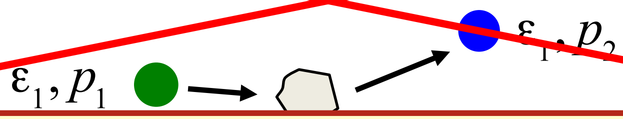
$H_0 = 1710$ Oe



(Non-)linear Processes

- **Linear process**

Two-magnon scattering

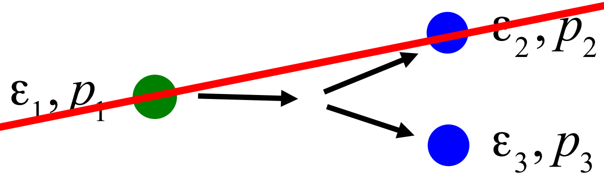


- **Nonlinear pr**

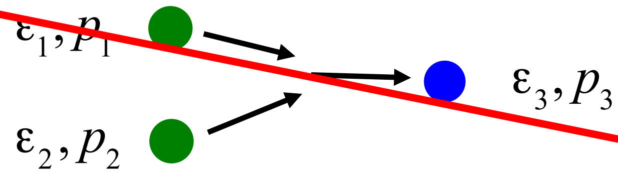
Magnon gas of interacting quasiparticles

Number of particles is conserved

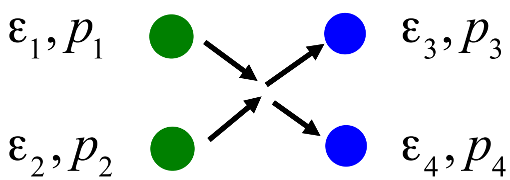
Three-magnon decay



Three-magnon confluence

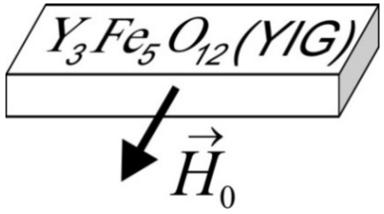


Four-magnon scattering



Magnon distribution

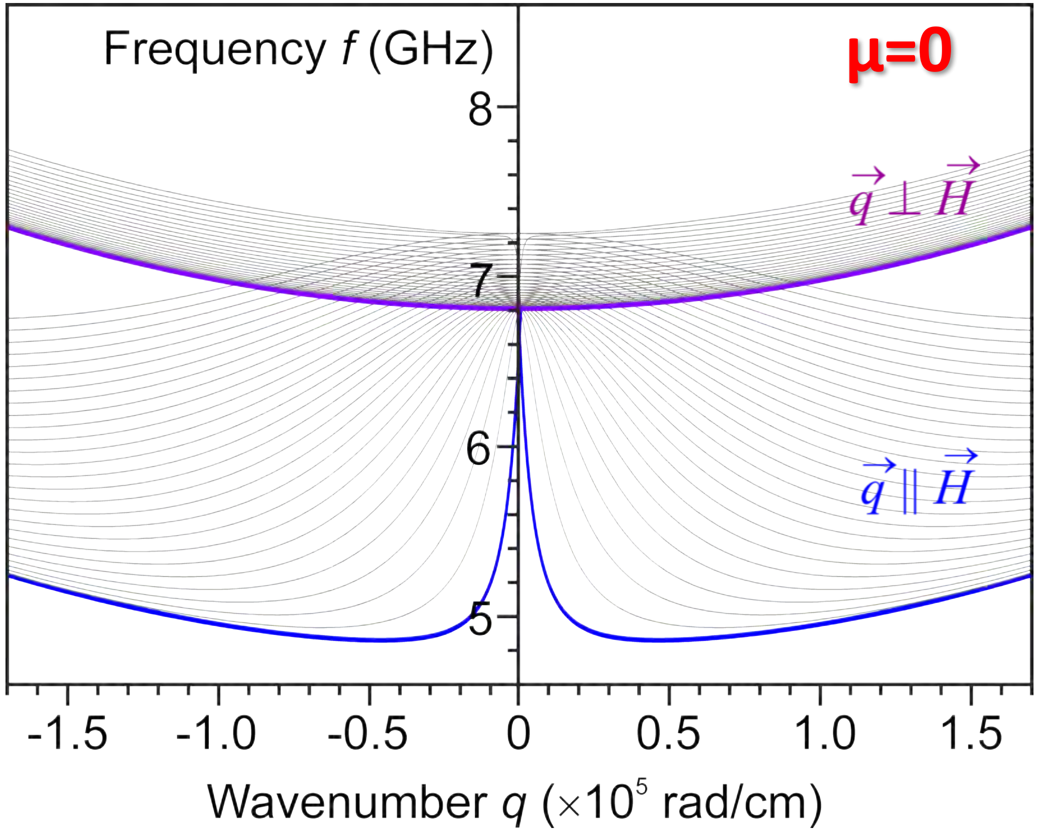
Magnons are bosons (s=1)
and thus, as any quasi-particles,
described by a Bose-Einstein distribution
with zero chemical potential



Bose-Einstein distribution

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

μ: chemical potential

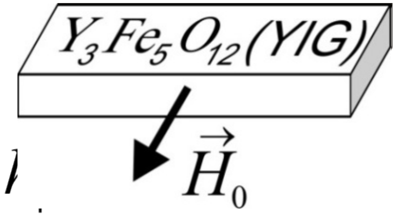


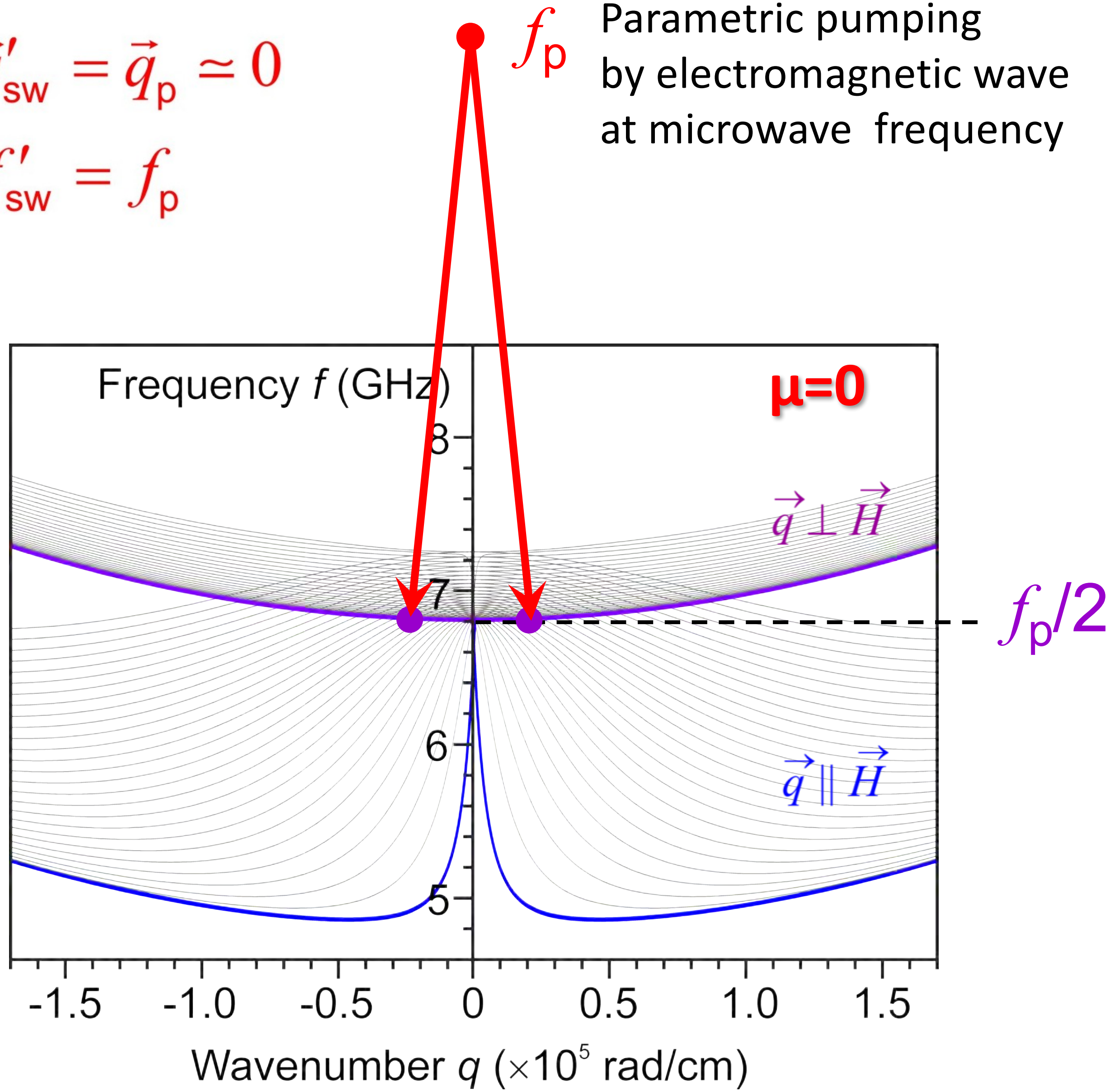
Control of magnon gas density by parametric pumping

Energy and momentum conservation laws

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

f_{p} Parametric pumping by electromagnetic wave at microwave frequency





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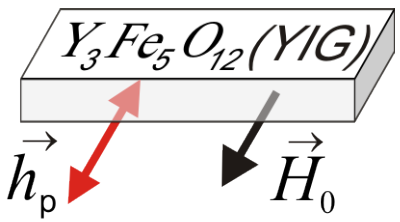

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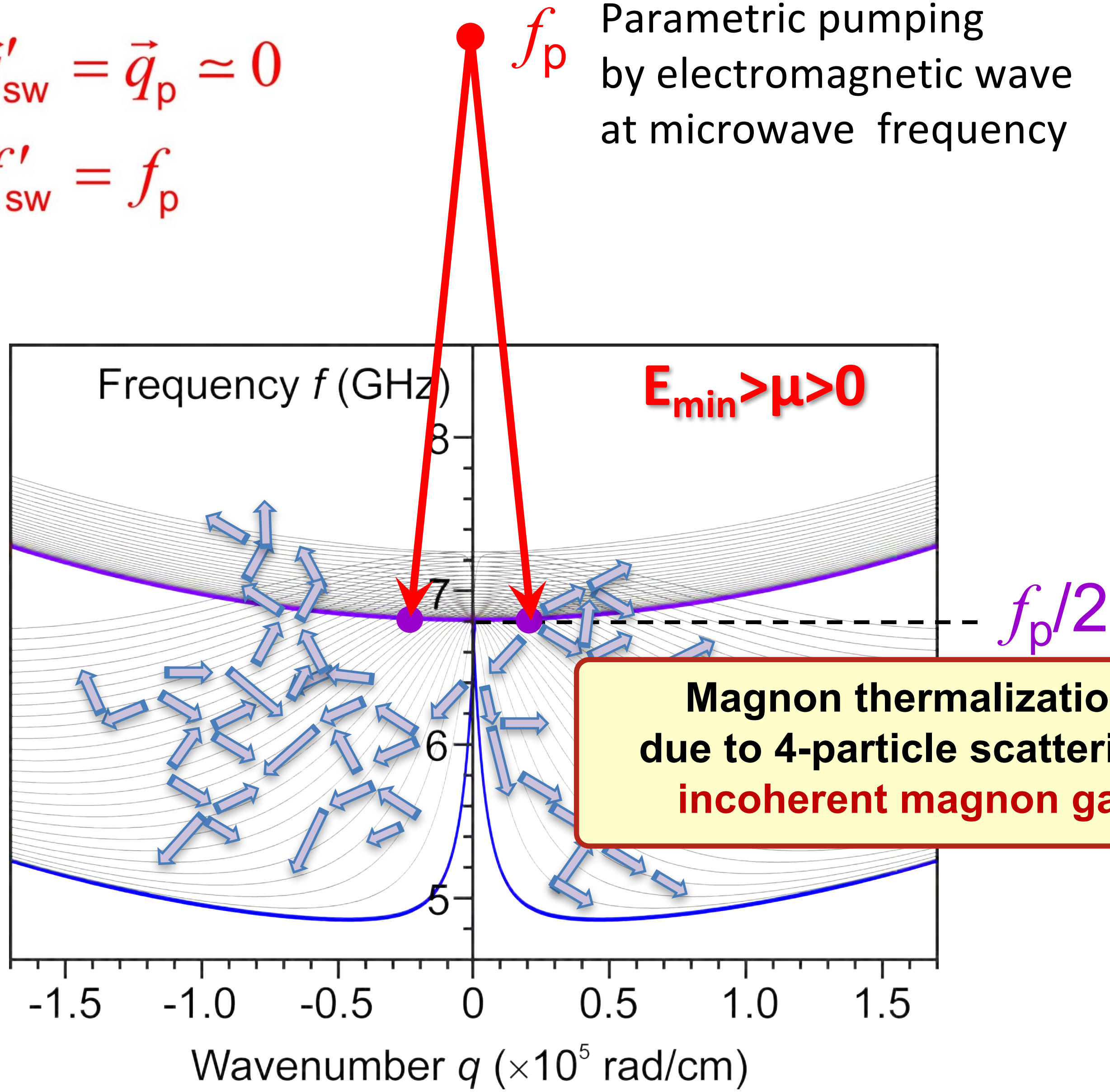

Magnon thermalization due to 4-particle scattering: incoherent magnon gas

Control of magnon gas density by parametric pumping

Energy and momentum conservation laws

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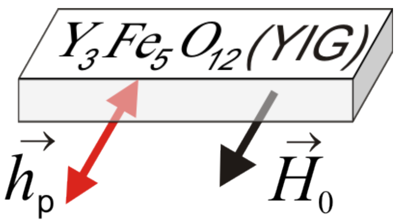
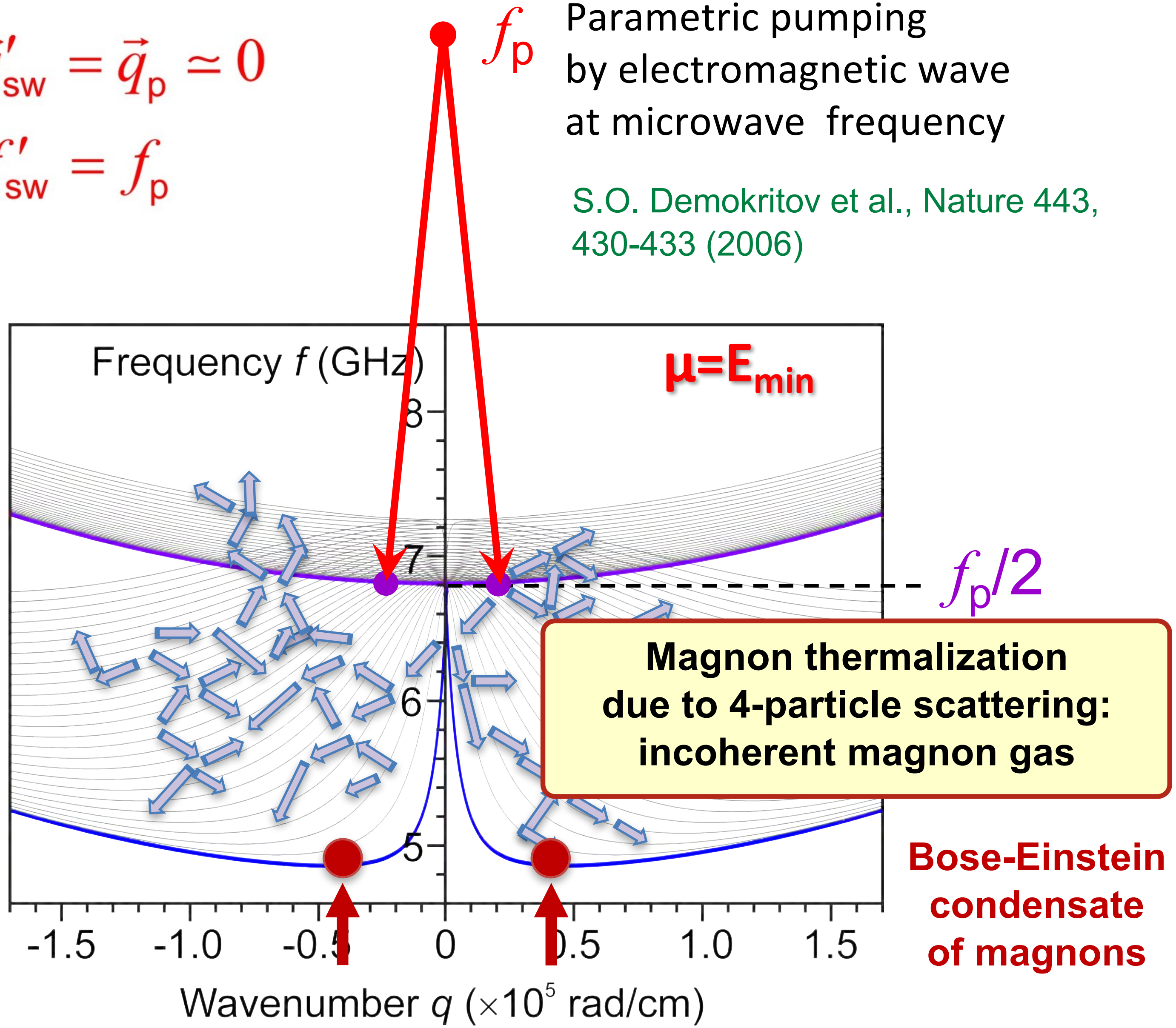
Parametric pumping by electromagnetic wave at microwave frequency

S.O. Demokritov et al., Nature 443, 430-433 (2006)





Bose-Einstein distribution

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μ: chemical potential

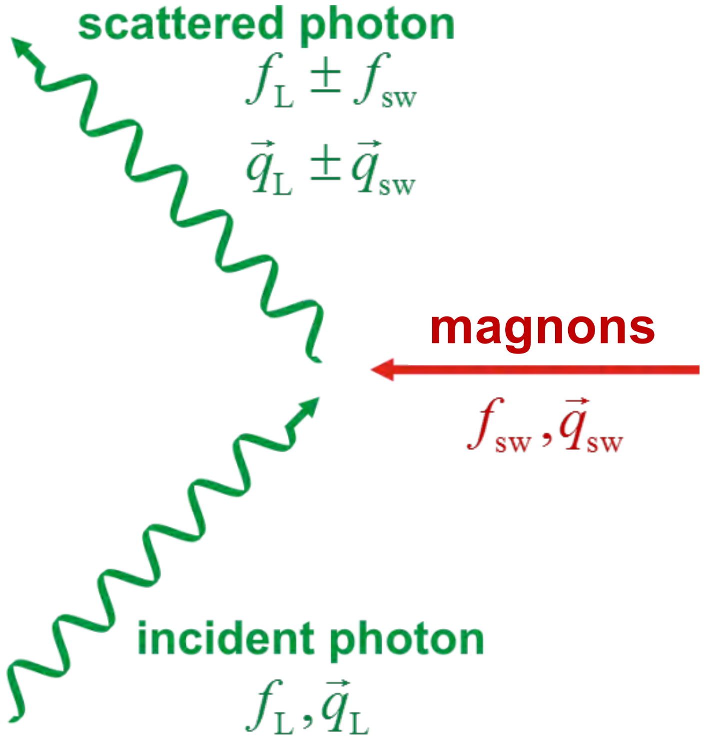
Brillouin light scattering (BLS) spectroscopy

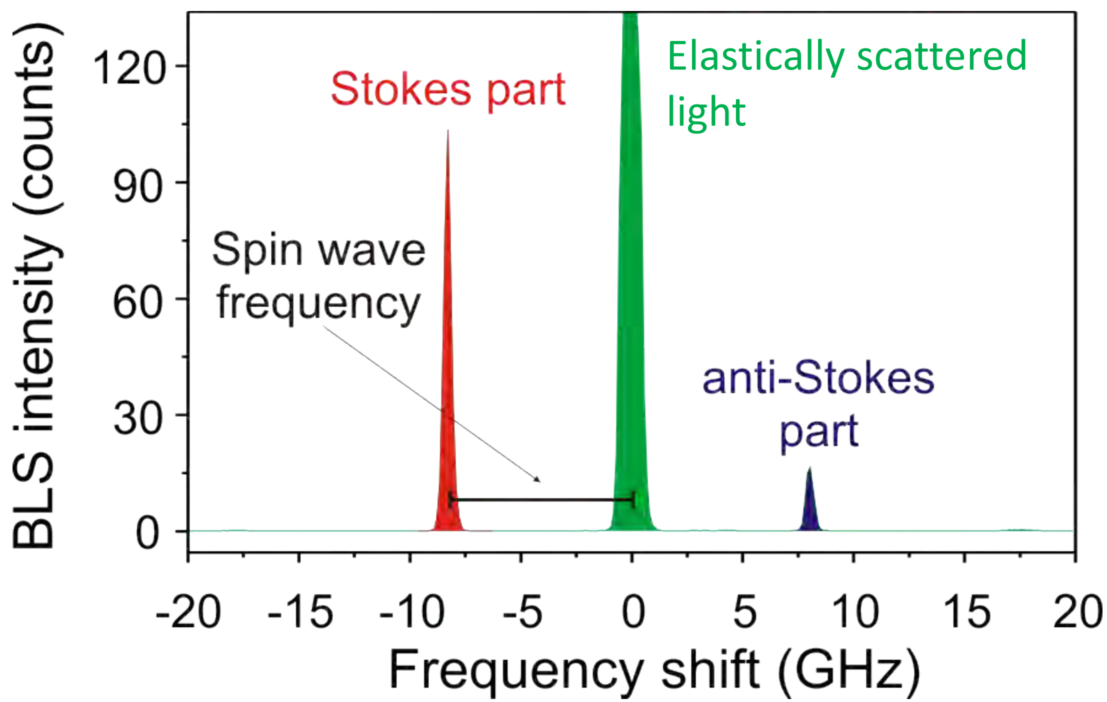
- Inelastic scattering of photons from spin waves:

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

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

- Intensity of the scattered light is proportional to magnon density





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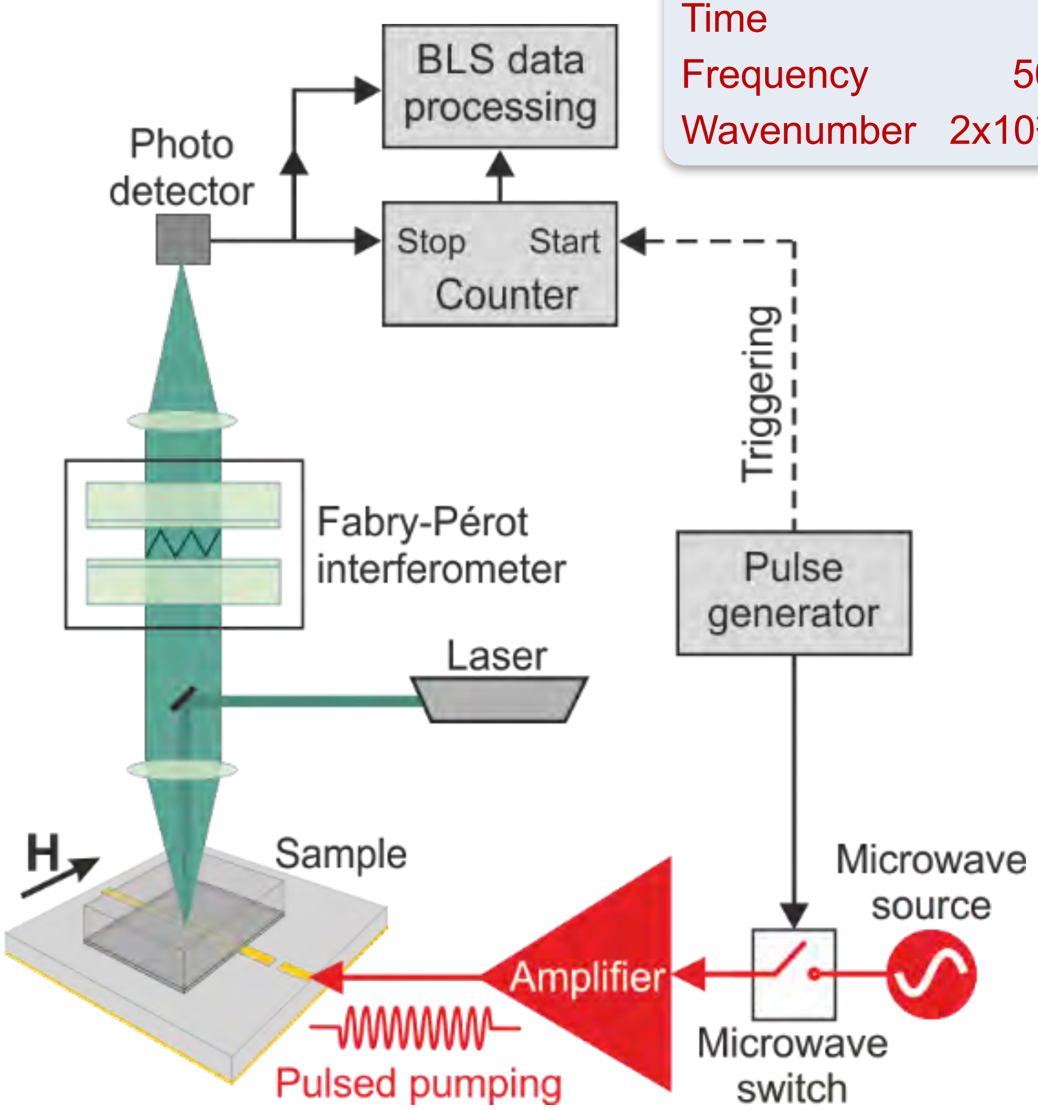
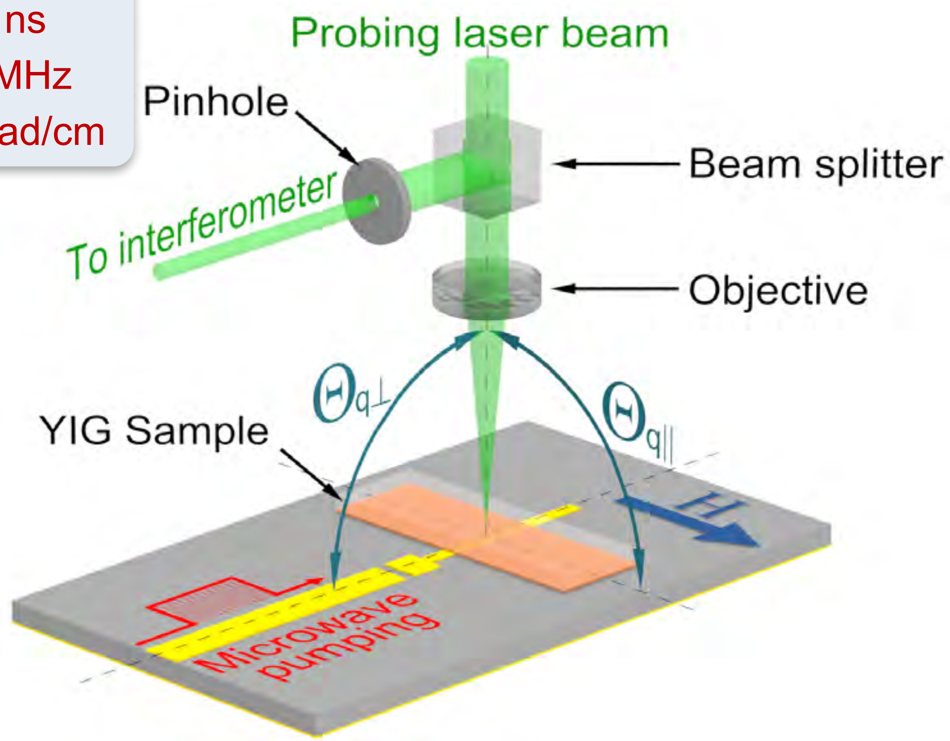
Time- and wavevector-resolved Brillouin light scattering spectroscopy

Resolution

Time	1 ns
Frequency	50 MHz
Wavenumber	2×10^3 rad/cm





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

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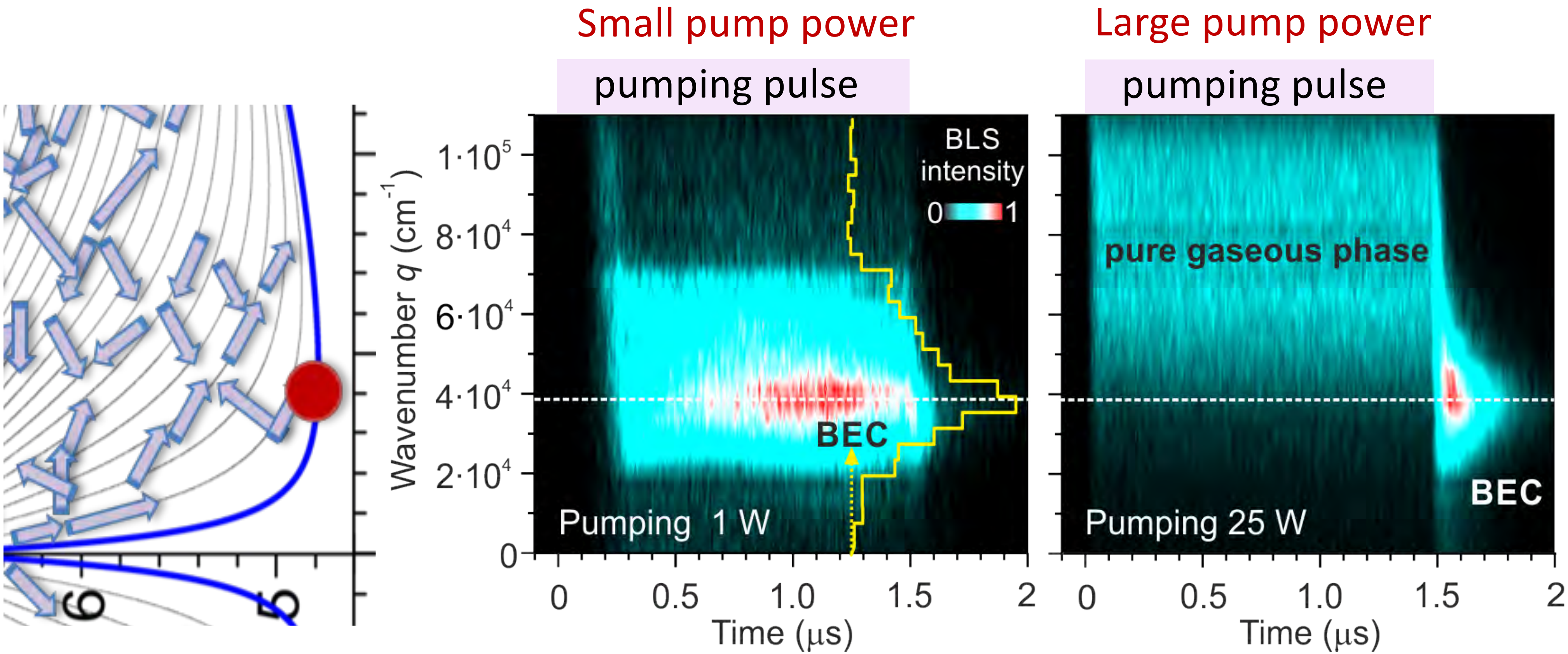
Time- and wavenumber-resolved BLS measurements of magnon BEC



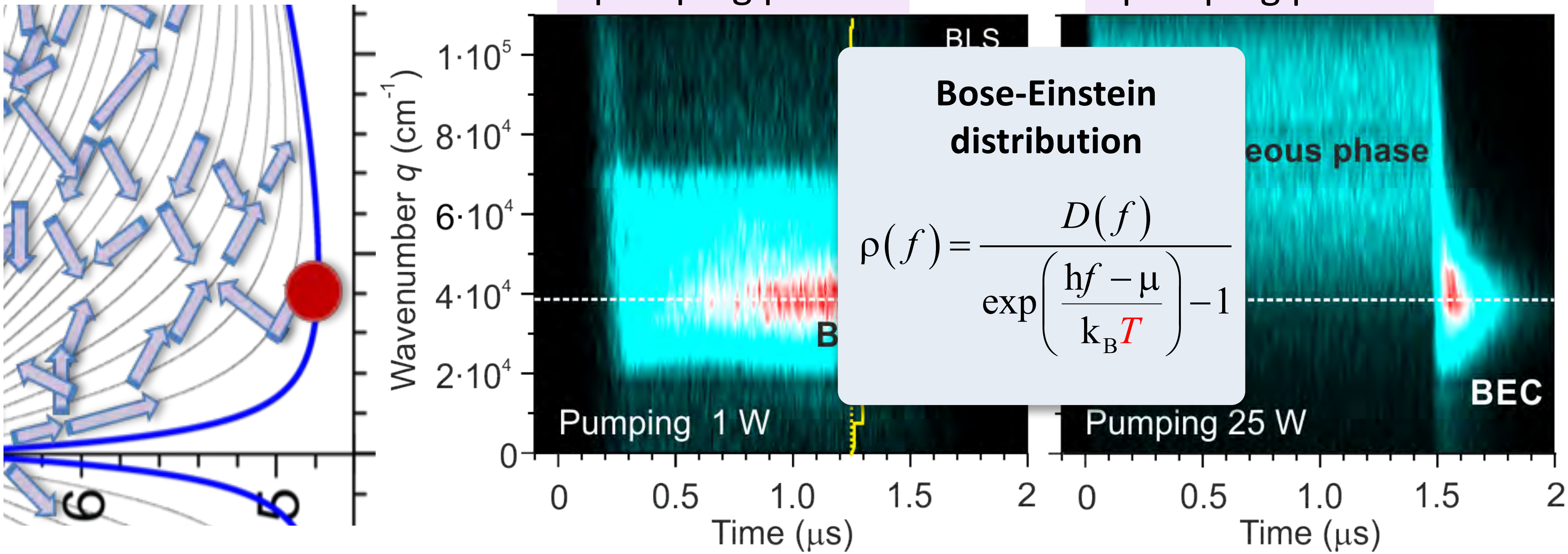
BEC is formed during
the pumping pulse is on

A. A. Serga *et al.*, Nat. Commun. **5**, 4452 (2014)

Time- and wavenumber-resolved BLS measurements of magnon BEC

Small pump power | Large pump power

pumping pulse | pumping pulse



Bose-Einstein distribution

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

BEC is formed during the pumping pulse is on

BEC is formed **after** the pumping pulse is switched off due to decrease of effective temperature of a magnon gas

A. A. Serga *et al.*, Nat. Commun. **5**, 4452 (2014)

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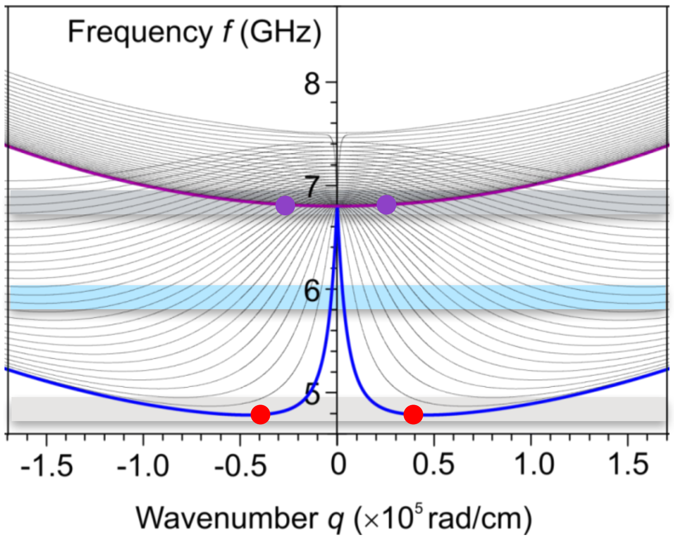
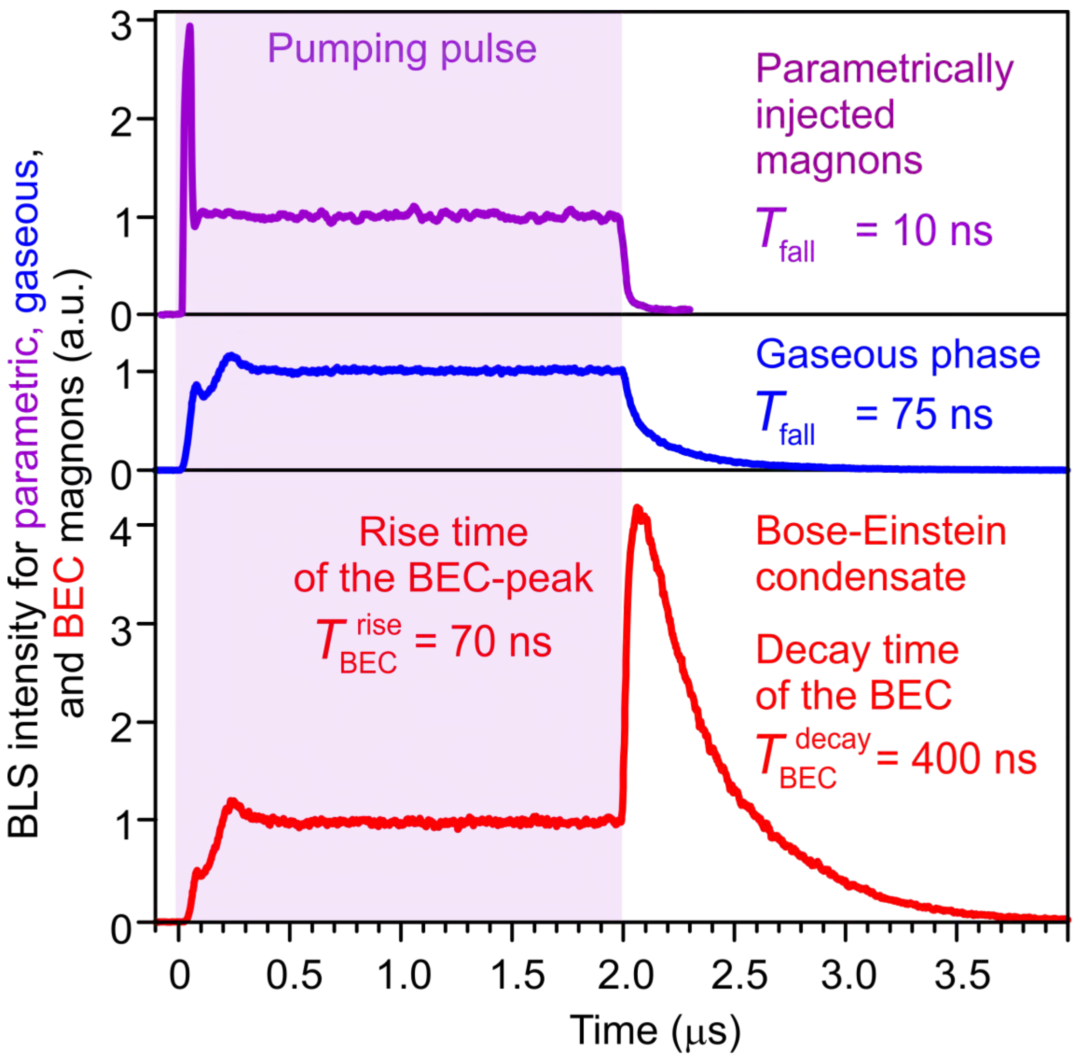
Time-resolved measurements of parametric magnons, gaseous phase, and magnon BEC



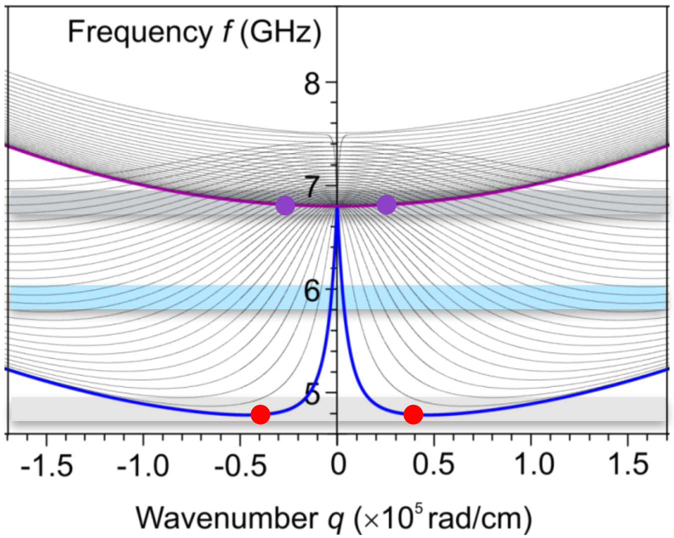


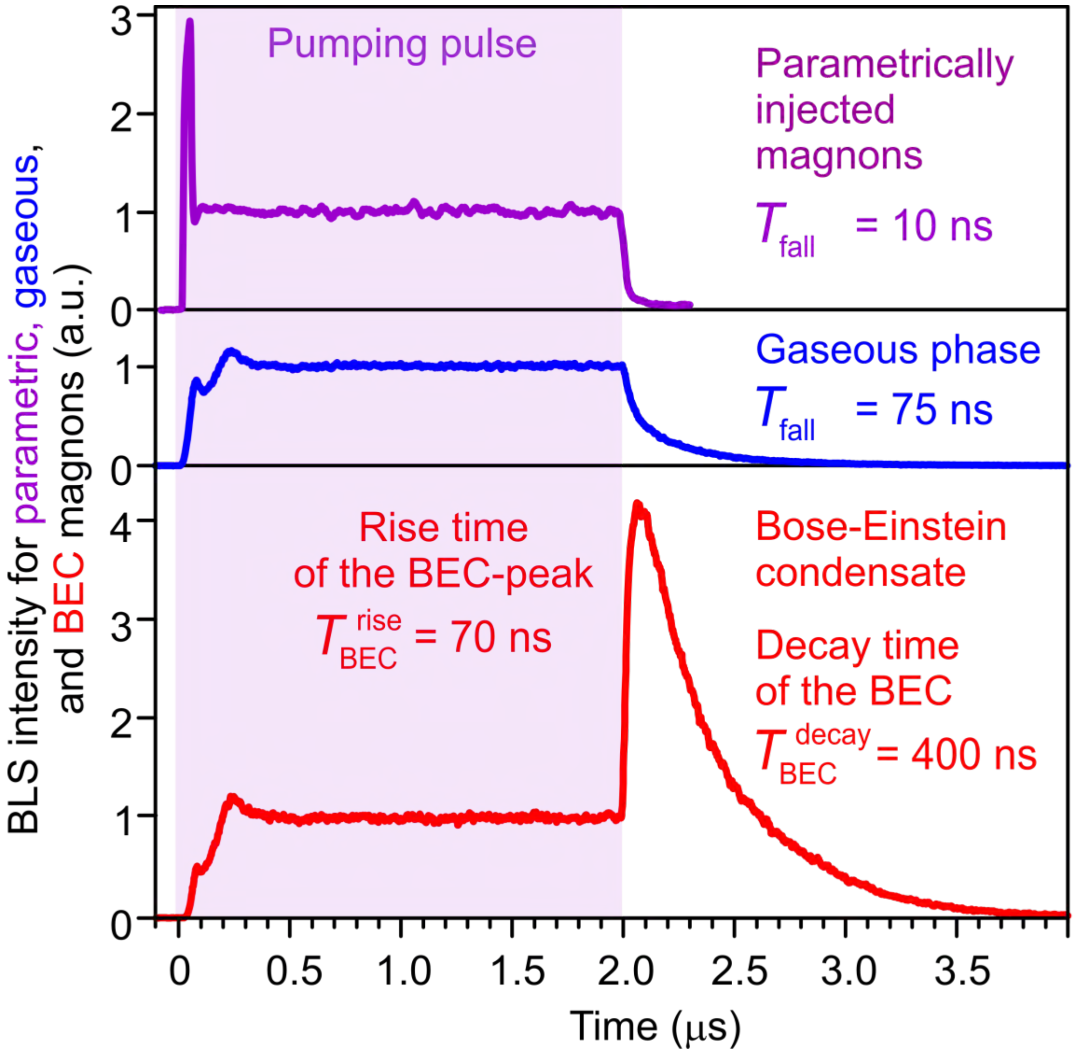
Decrease of density of
parametric magnons
and
gaseous magnon phase

⬇

Sharp increase of intensity of **pumping free** BEC of magnons

Parametric magnons, gaseous phase, and magnon BEC





Cooling of strongly overheated low energy area of the magnon gas

A. A. Serga *et al.*, Nat. Commun. **5**, 4452 (2014)

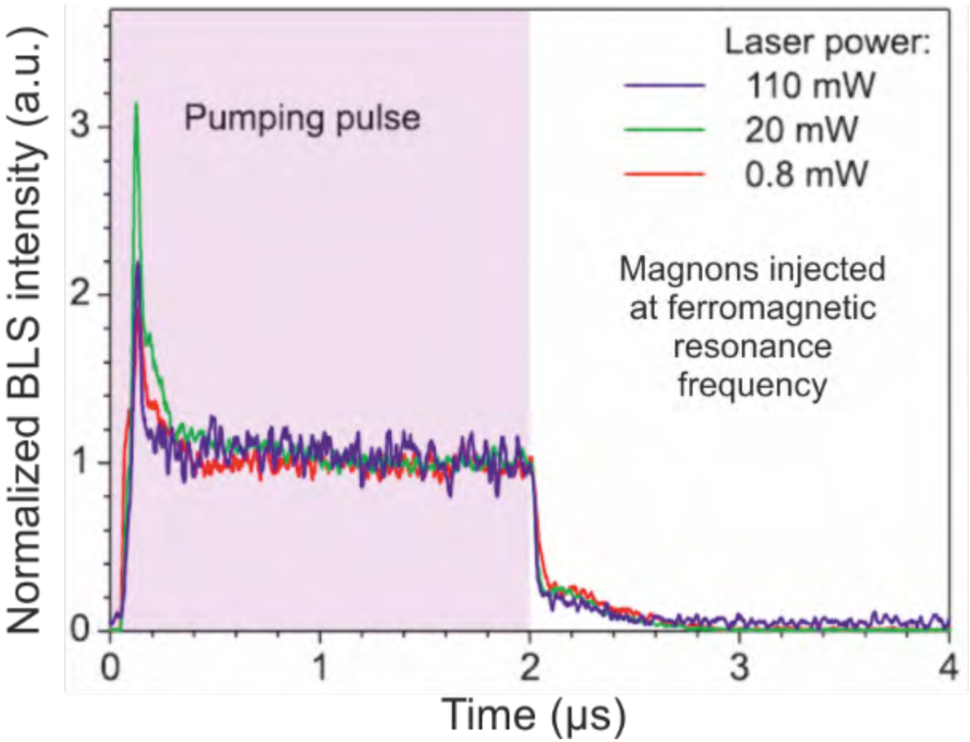
Influence of power of probing laser beam

Parametrically injected magnons

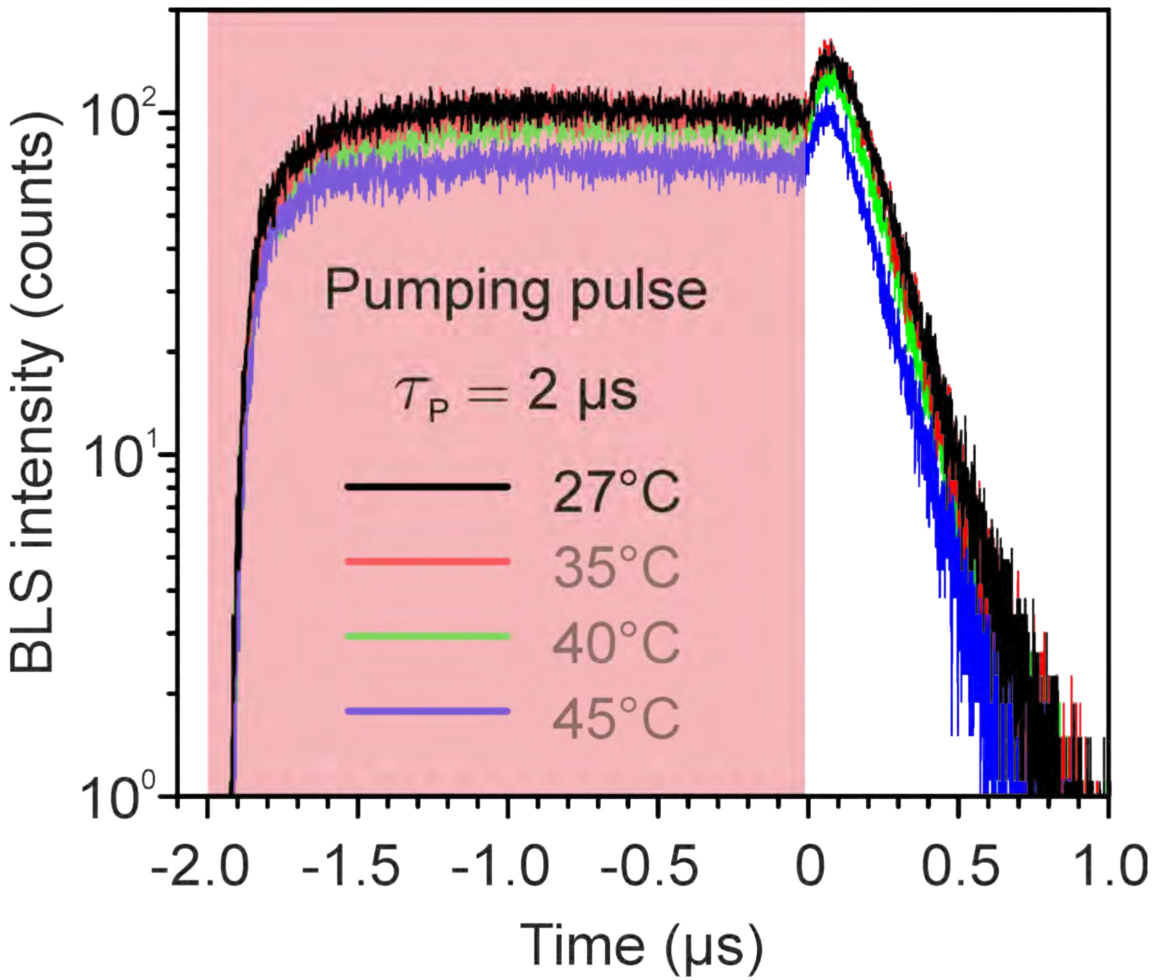
- No influence from laser power on temporal dynamics !
- Laser heating decreases magnetization and thus might shift down the magnon dispersion curves

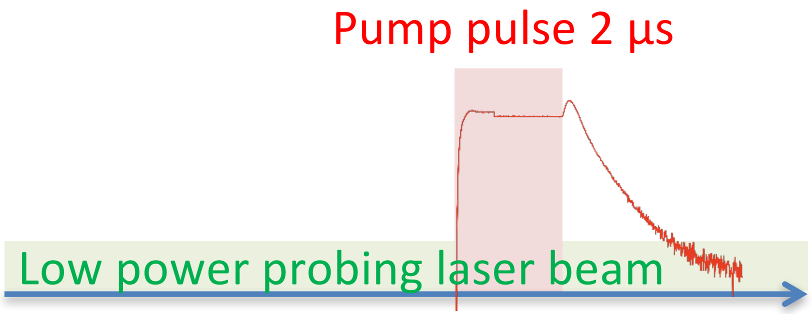
Bose-Einstein condensate

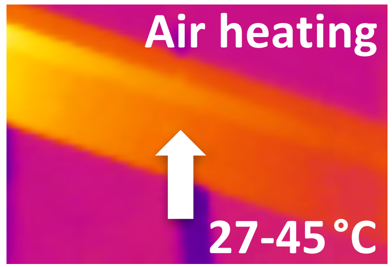
- Increasing laser power results in significant decrease of the BEC‘s lifetime and amplitude !
- Only weak frequency shift of BEC due to temperature change



Magnon BEC dynamics for uniform temperatures







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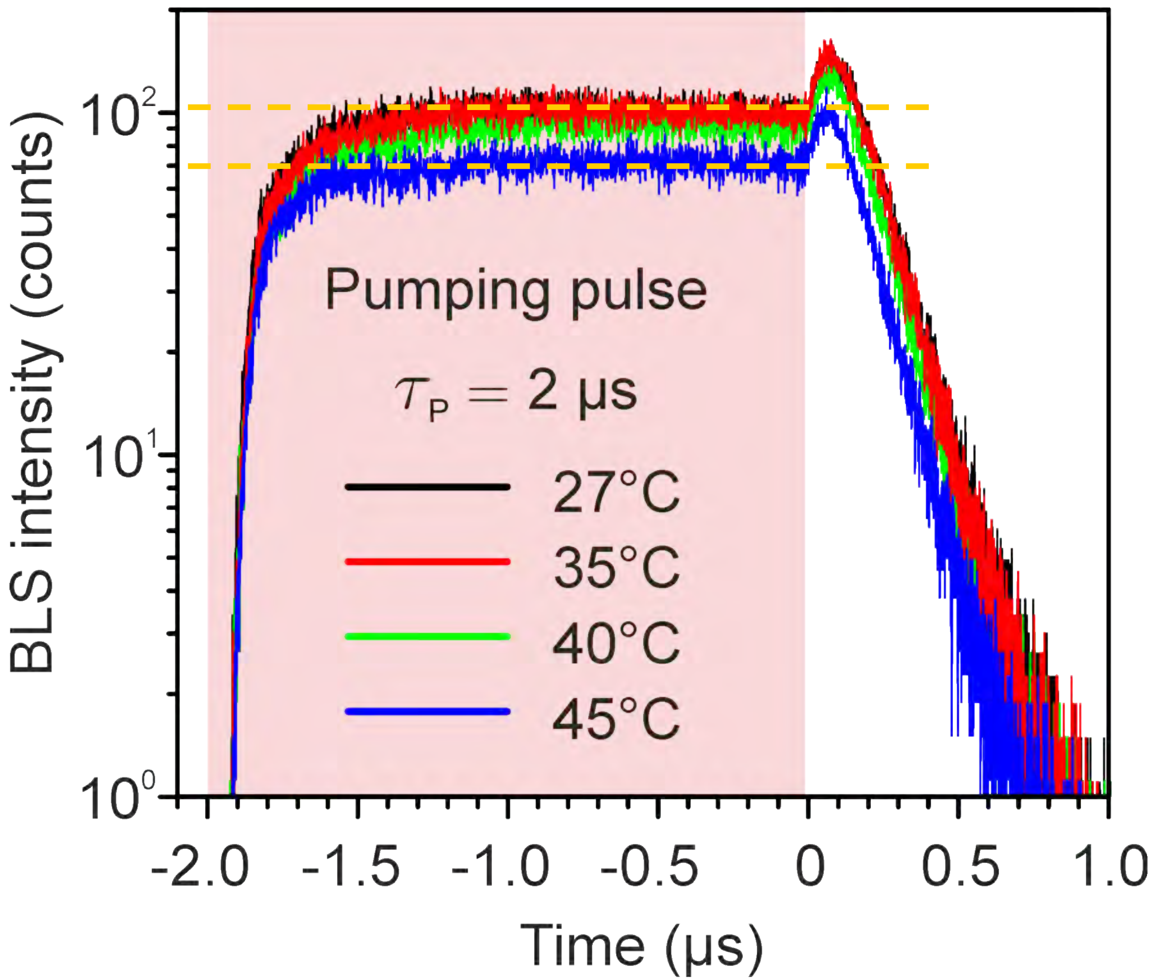
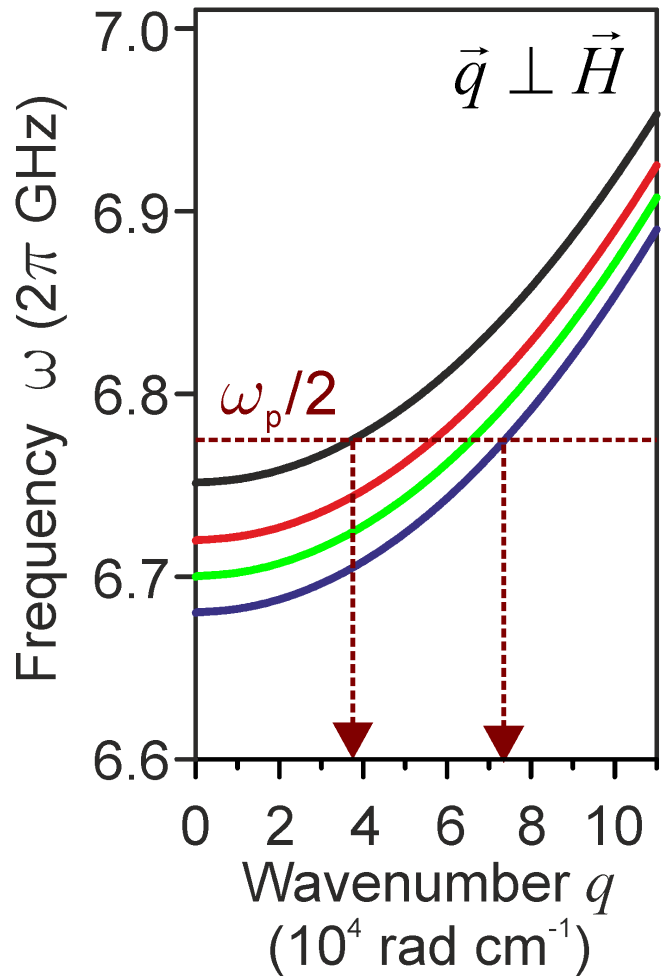
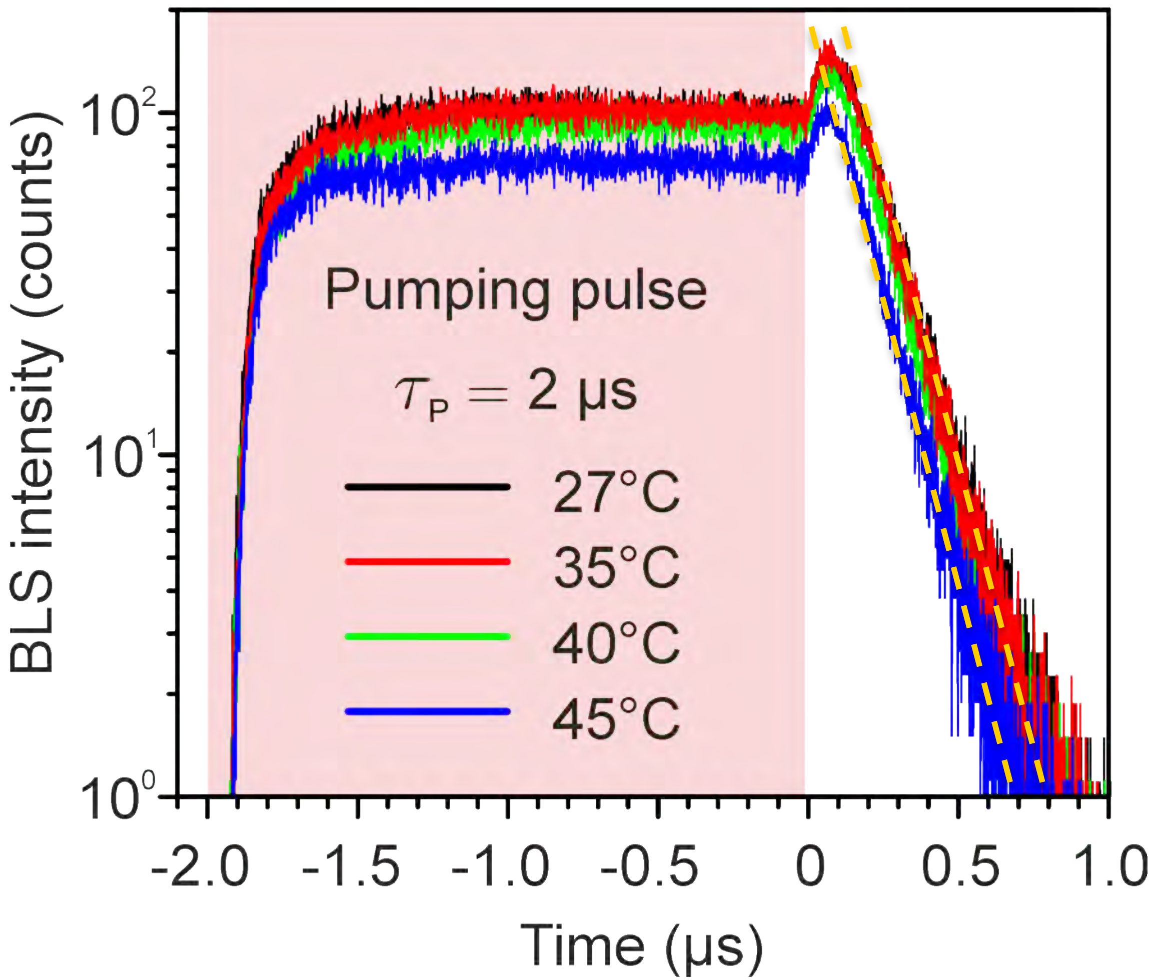
Magnon BEC dynamics for uniform temperatures

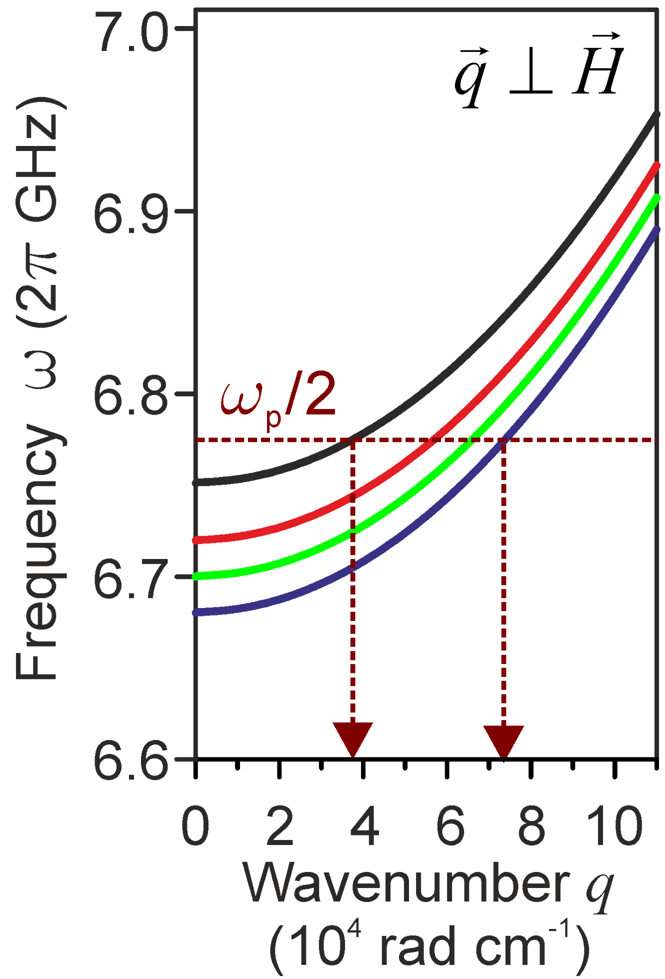




Decrease in the steady-state magnon density due to higher magnon damping and lower efficiency of the parametric pumping

Magnon BEC dynamics for uniform temperatures





No influence of uniform heating on the decrease of population of magnon BEC

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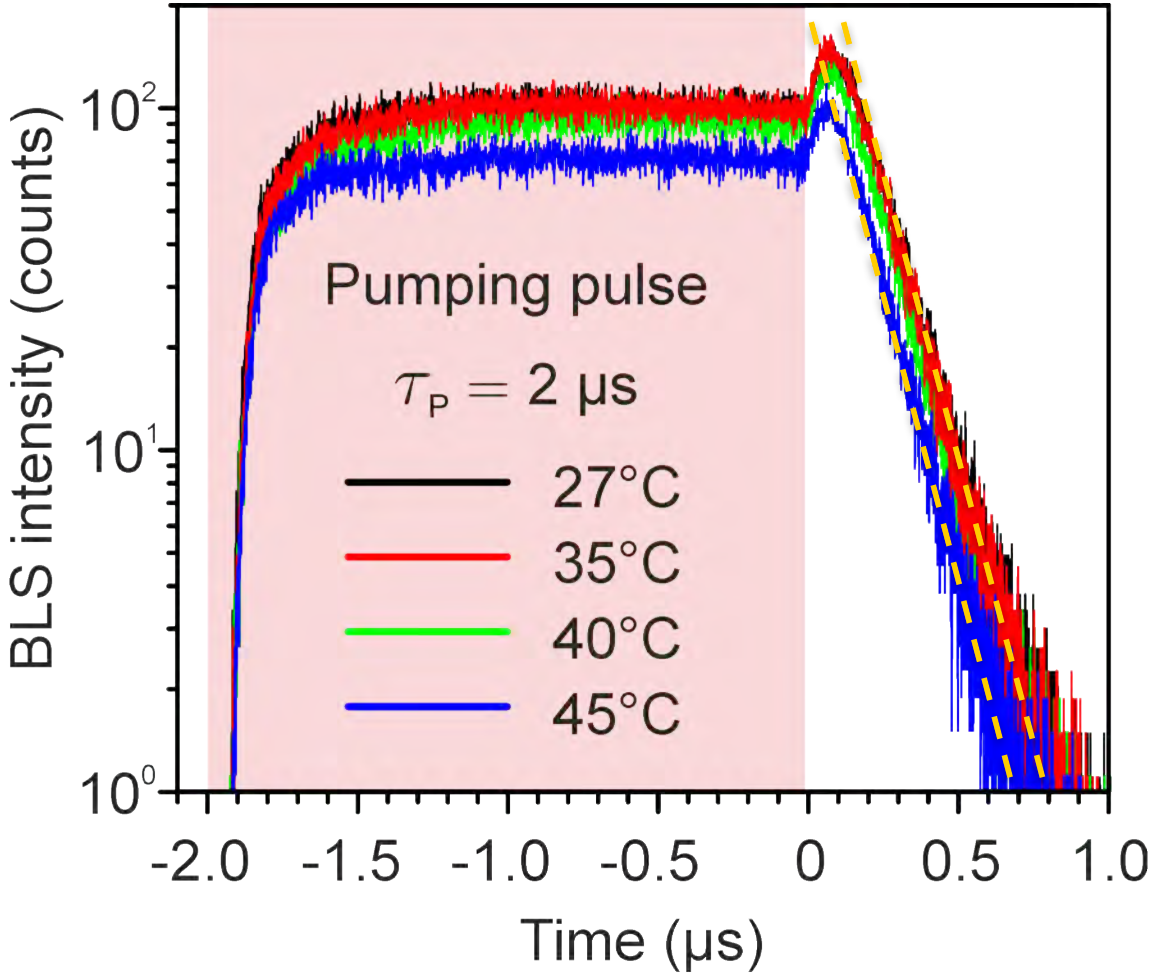

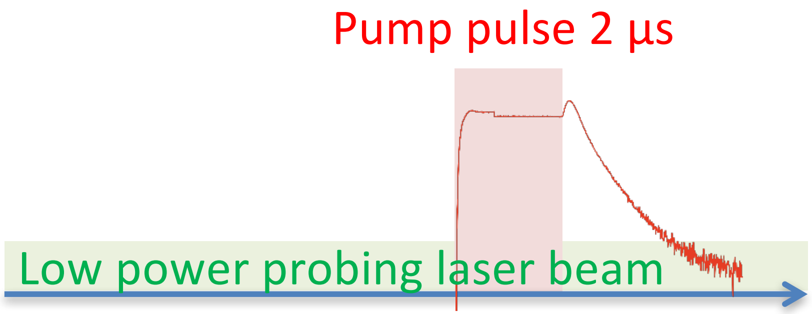

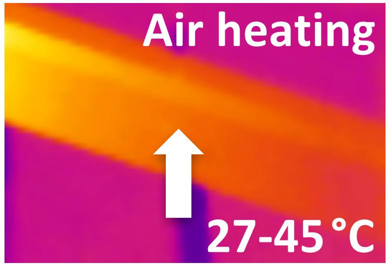

No influence of uniform heating
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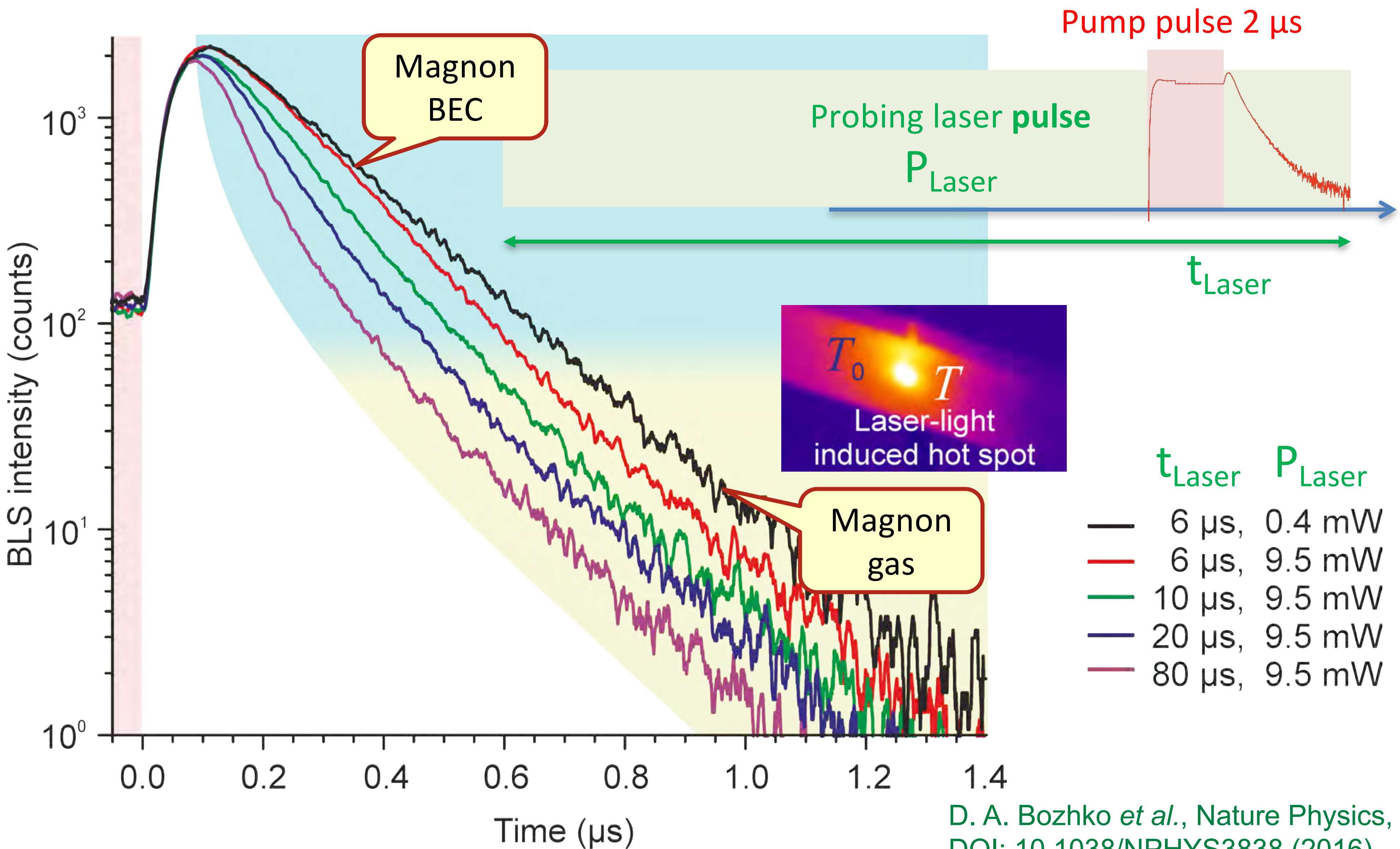
Dynamics of condensed magnons in thermal gradient



D. A. Bozhko *et al.*, Nature Physics, DOI: 10.1038/NPHYS3838 (2016)

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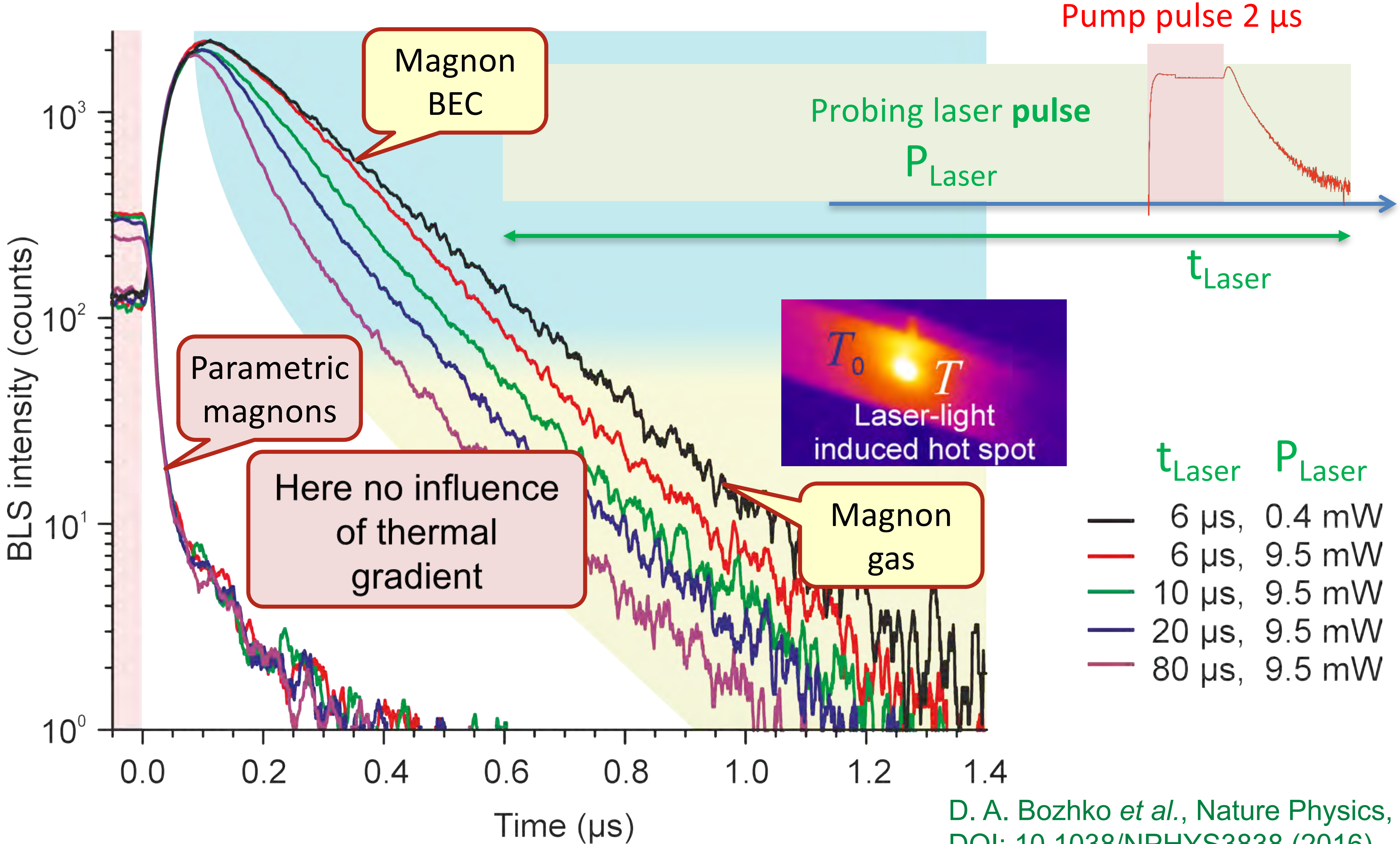

D. A. Bozhko *et al.*, Nature Physics,
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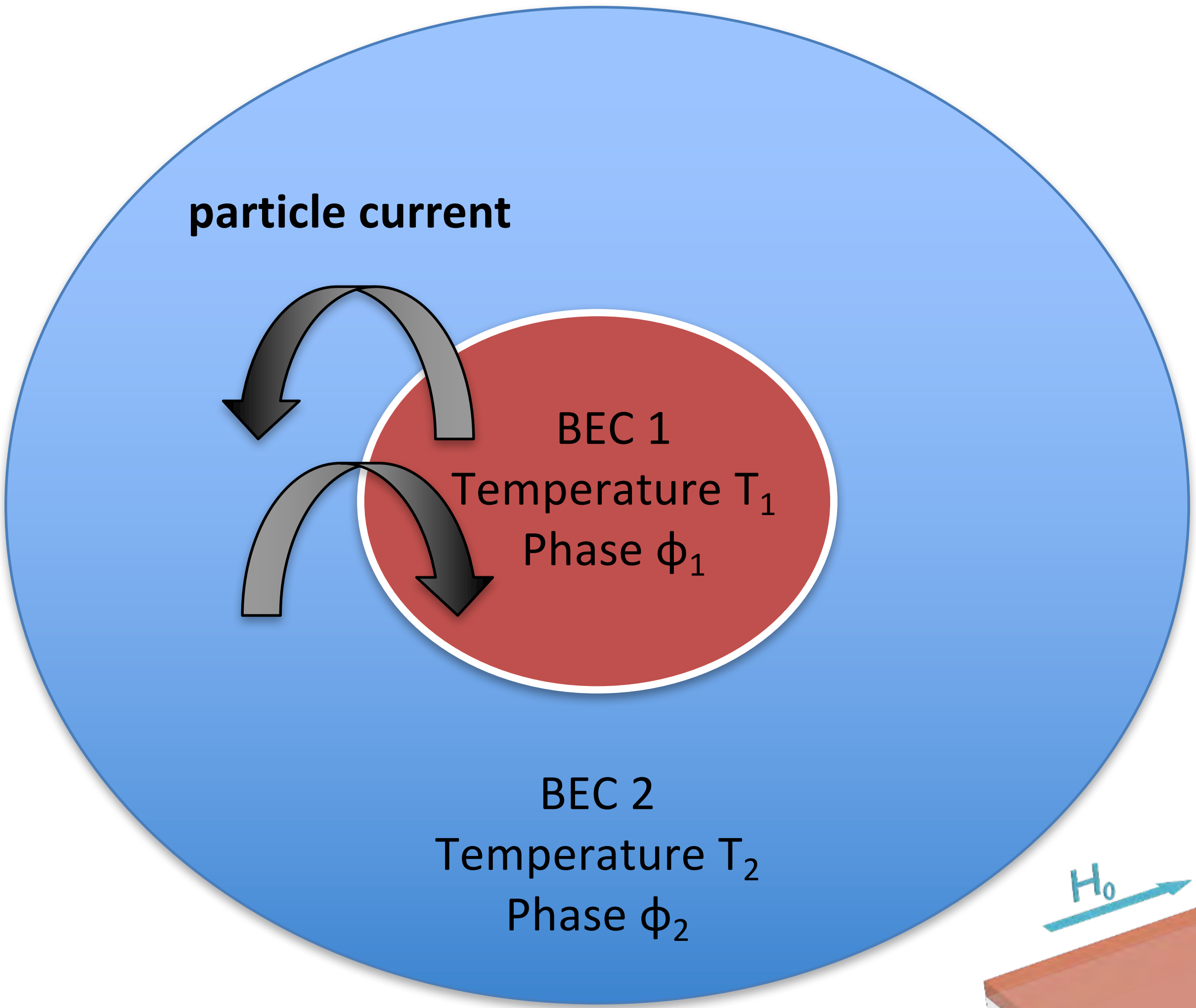
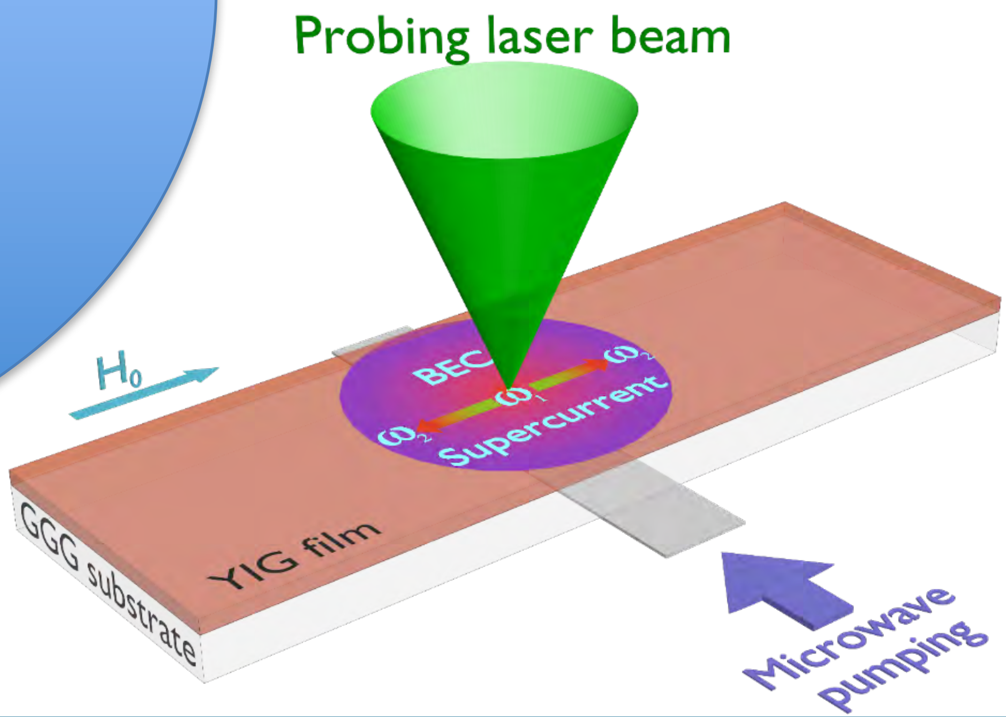
Magnonic supercurrents



$T_1 > T_2$

$\rightarrow \phi_1 \neq \phi_2$

Phase gradient leads to the formation of magnonic supercurrents



Dynamics of condensed magnons in thermal gradient - theory

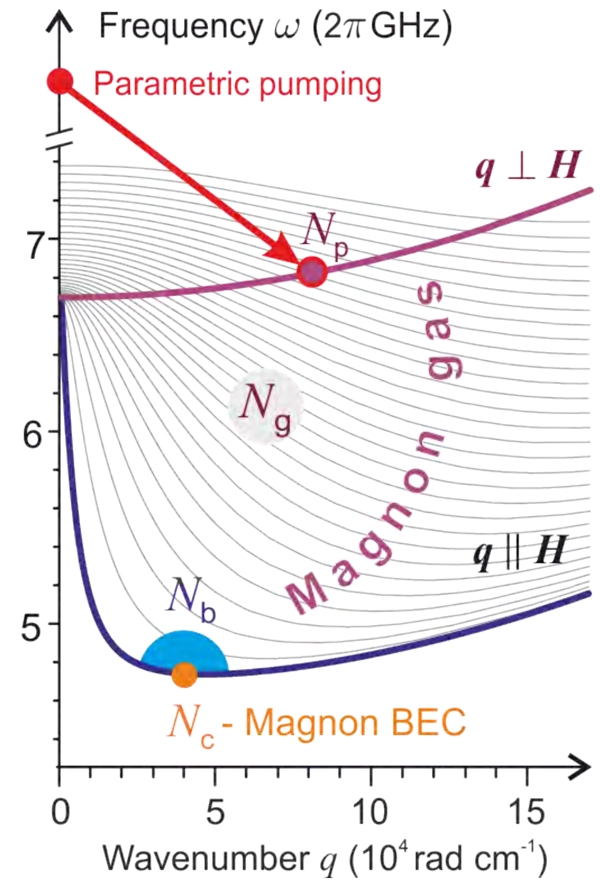
Dynamics of condensed magnons $N_c(t)$, magnons in gaseous states $N_g(t)$ and gaseous magnons at the bottom of SW spectrum $N_b(t)$ was described using balance equations

Without thermal gradient

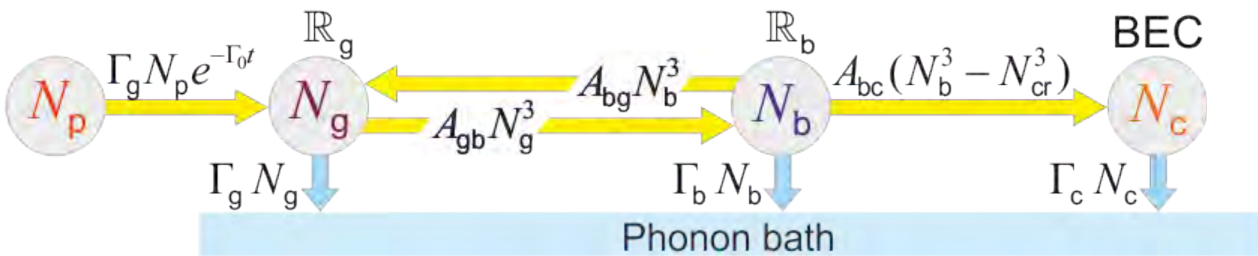
$$\frac{\partial N_g}{\partial t} = -\Gamma_g N_g + \Gamma_g N_p e^{-\Gamma_0 t} - A_{gb} N_g^3 + A_{bg} N_b^3$$

$$\frac{\partial N_b}{\partial t} = -\Gamma_b N_b + A_{gb} N_g^3 - A_{bg} N_b^3 - A_{bc}(N_b^3 - N_{cr}^3)\Theta(N_b - N_{cr})$$

$$\frac{\partial N_c}{\partial t} = -\Gamma_c N_c + A_{bc}(N_b^3 - N_{cr}^3)\Theta(N_b - N_{cr})$$



N_{cr} – a critical number of magnons at which the chemical potential μ of the magnon gas reaches ω_{min}



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$$\frac{\partial N_c}{\partial t} = -\Gamma_c N_c + A_{bc}(N_b^3 - N_{cr}^3)\Theta(N_b - N_{cr}) - \frac{\partial J(\vec{r},t)}{\partial \vec{r}}$$

Supercurrent

Phase

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

gradient

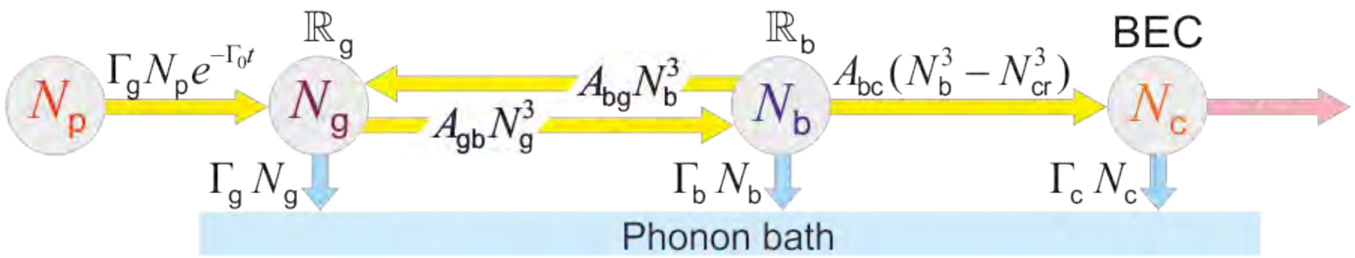
BEC density: $N_c = |\psi|^2$

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

Magnon mass: $m = \hbar \Big/ \dfrac{\partial^2 \omega(q)}{\partial q^2}$

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

Additional decrease of population of condensed magnons $N_c(t)$ due to magnon supercurrent $\vec{J}(\vec{r},t)$



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$$\frac{\partial N_c}{\partial t} = -\Gamma_c N_c + A_{bc}(N_b^3 - N_{cr}^3)\Theta(N_b - N_{cr}) - \frac{\partial J_x}{\partial x} - \frac{\partial J_y}{\partial y}$$

2D supercurrent

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

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

Additional decrease of population of condensed magnons $N_c(t)$ due to magnon supercurrent $\vec{J}(x,y,t)$

Anisotropic dispersion coefficients:

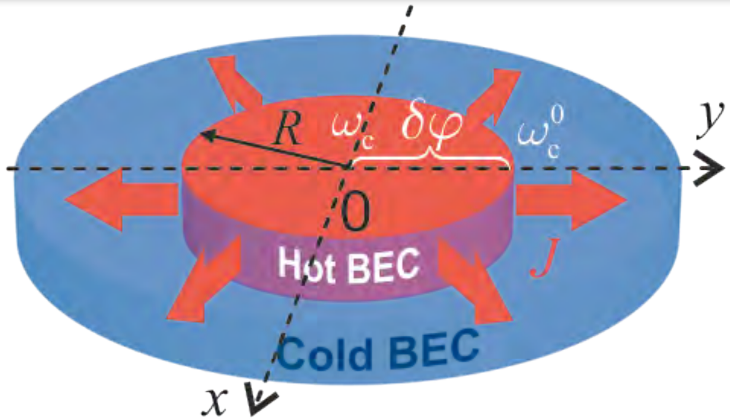
$$D_x = \frac{1}{2}\frac{d^2\omega(\vec{q})}{dq_x^2}$$

$$D_y = \frac{1}{2}\frac{d^2\omega(\vec{q})}{dq_y^2}$$

In experiment:

$$D_x \simeq 21 D_y$$

$$J_T = J_x \gg J_y$$



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$$\frac{\partial N_c}{\partial t} = -\Gamma_c N_c + A_{bc}(N_b^3 - N_{cr}^3)\Theta(N_b - N_{cr}) - \frac{\partial J_T}{\partial x}$$

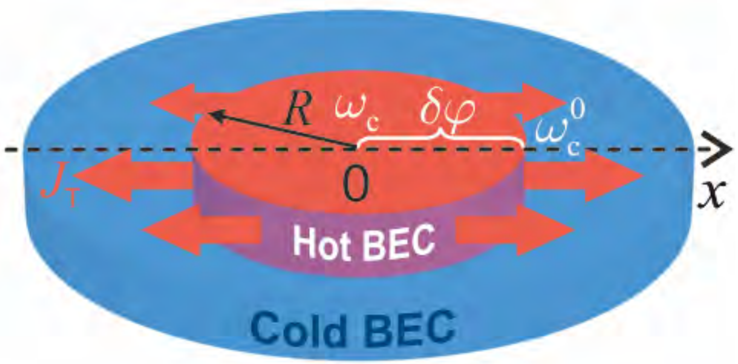
1D thermally driven supercurrent

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

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

weak frequency shift of the magnon BEC due to temperature change

Additional decrease of population of condensed magnons $N_c(t)$ due to magnon supercurrent $J_T(x,t)$



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$$\frac{\partial N_c}{\partial t} = -\Gamma_c N_c + A_{bc}(N_b^3 - N_{cr}^3)\Theta(N_b - N_{cr}) - \frac{\partial J_T}{\partial x} + \frac{\partial J_{dis}}{\partial x}$$

1D thermally driven supercurrent

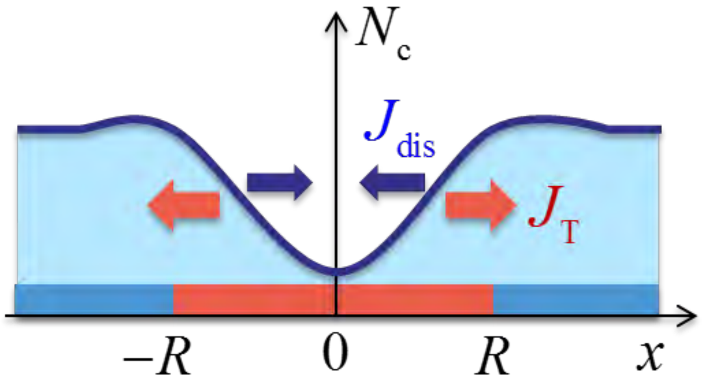
$$J_T = N_c D_x \frac{\partial \varphi}{\partial x}$$

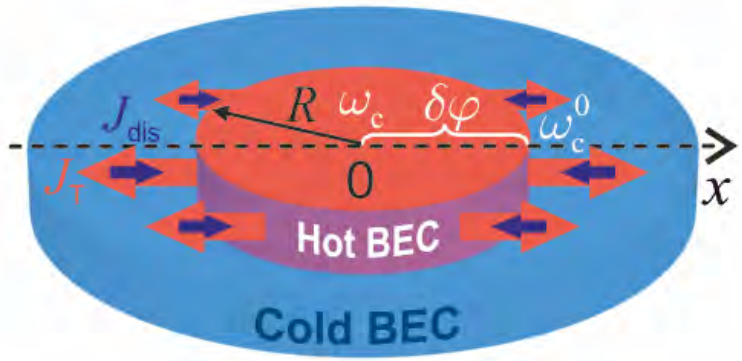
$$\delta\varphi = \delta\omega_c(x)\, t$$

Additional decrease of population of condensed magnons $N_c(t)$ due to magnon supercurrent $J_x(x)$

1D dispersive supercurrent

$$J_{dis} = -D_x \frac{\partial N_c}{\partial x}$$





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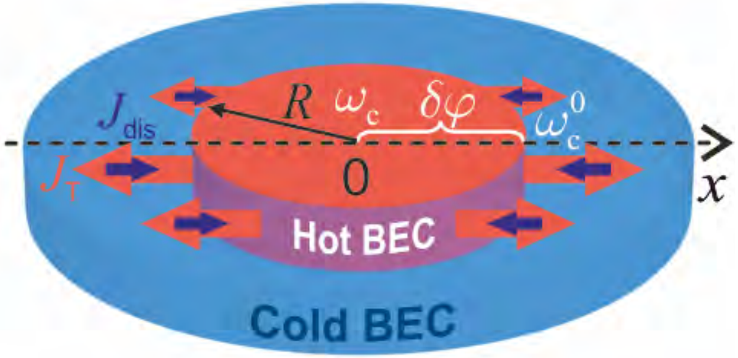
1D dispersive supercurrent

$$J_{dis} = -D_x \frac{\partial N_c}{\partial x}$$

Total supercurrent

$$J = -B_s N_c \delta\omega_c t + B_{dis}(N_c^0 - N_c)$$

$$B_s \sim B_{dis} \sim -\frac{D_x}{R}$$



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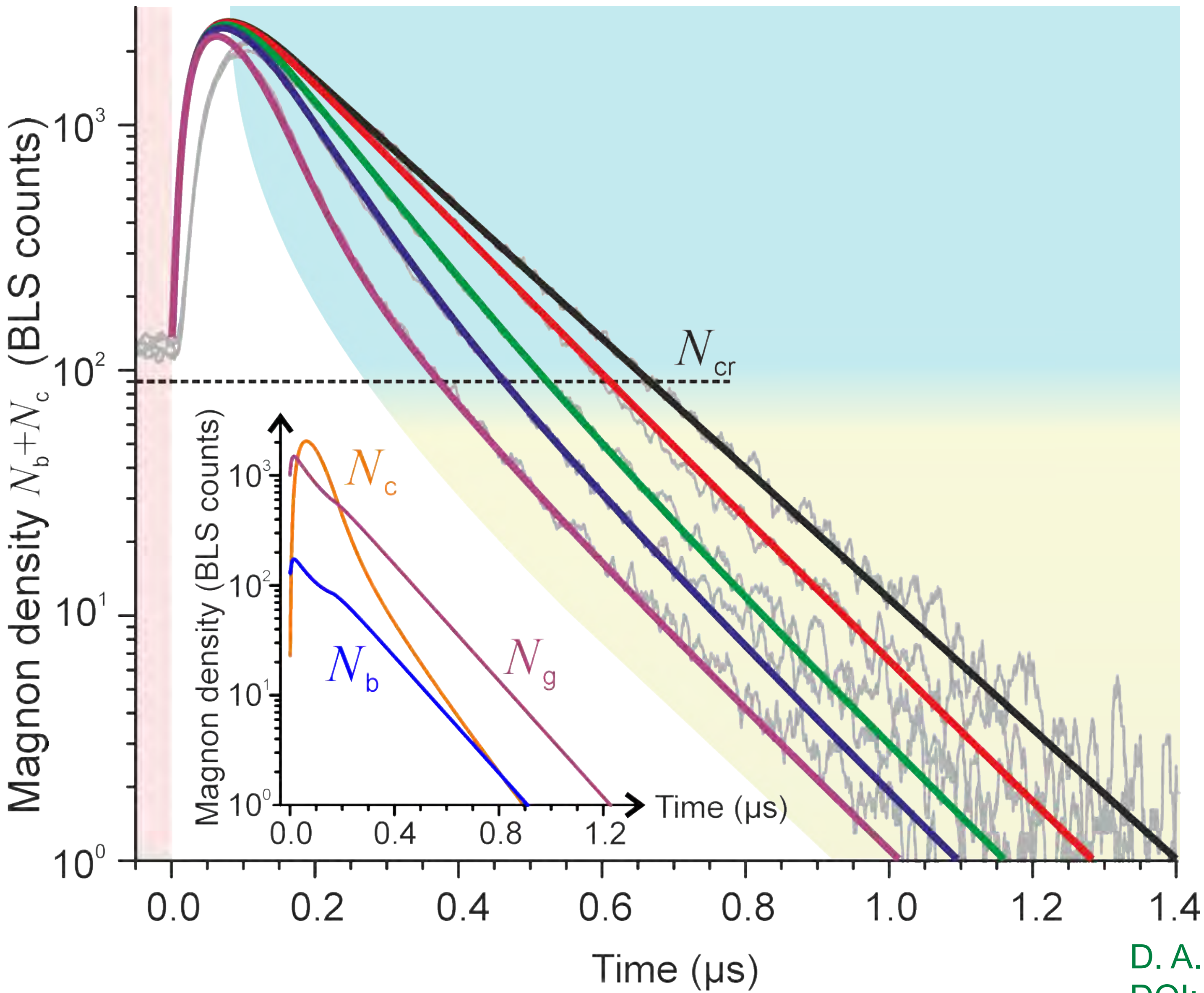
Dynamics of condensed magnons in thermal gradient - comparison with theory



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

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.*, Nature Physics, DOI: 10.1038/NPHYS3838 (2016)

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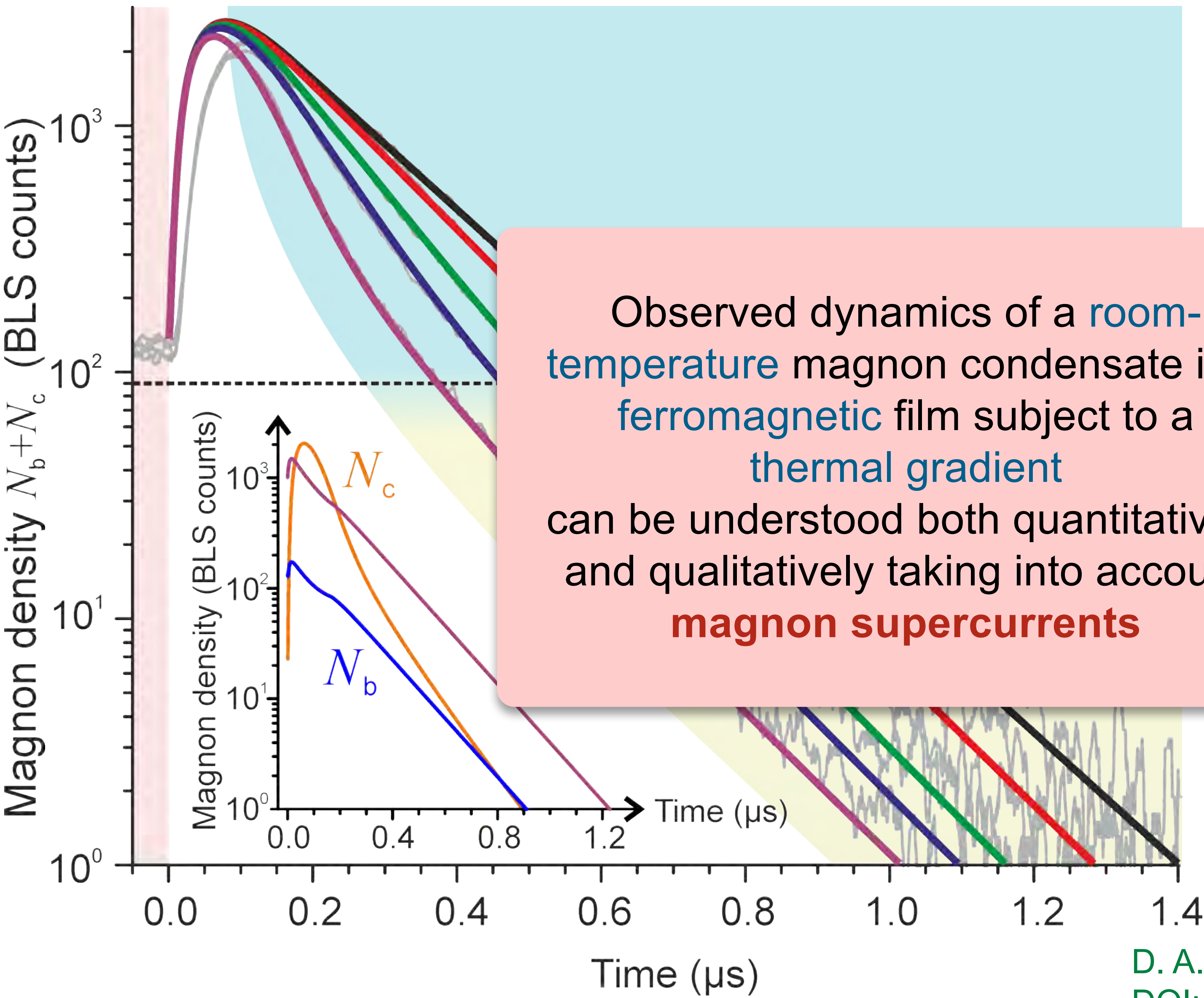
Dynamics of condensed magnons in thermal gradient - comparison with theory



Observed dynamics of a room-temperature magnon condensate in a ferromagnetic film subject to a thermal gradient can be understood both quantitatively and qualitatively 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

COMSOL simulation using 3D heat-transfer model

5.7 K

D. A. Bozhko *et al.*, Nature Physics, DOI: 10.1038/NPHYS3838 (2016)

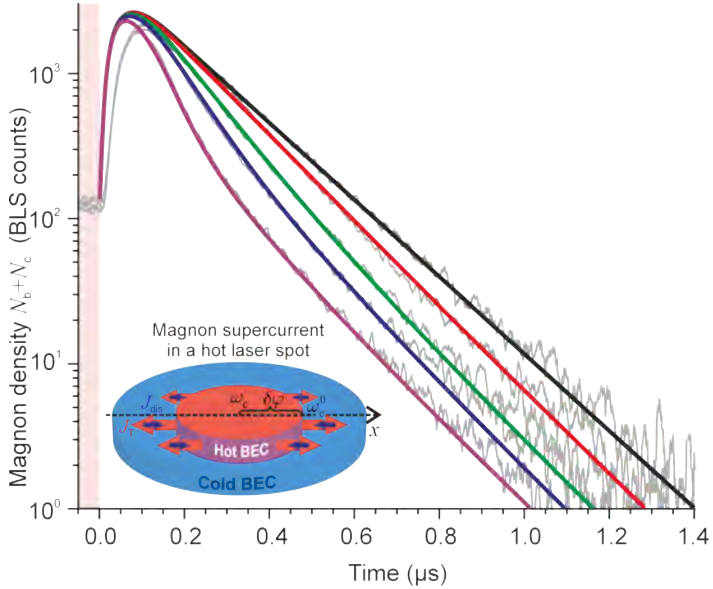
Summary

1. Magnonics provides model system for macroscopic quantum phenomena

   – Room temperature experiments

   – Tool: Brillouin light scattering

2. First evidence for magnon supercurrent in magnonic Bose Einstein condensate found



3. Supercurrent depends on phase gradient

4. Phase gradient induced by lateral temperature gradient