Advanced Magnonics

Burkard Hillebrands

Fachbereich Physik and Landesforschungszentrum OPTIMAS,
Technische Universität Kaiserslautern, Germany

Leibniz Institute for Solid State and Materials Research (IFW),
Dresden, Germany

SFB/Transregio 49 Frankfurt-Kaiserslautern-Mainz

MATERIALS SCIENCE IN MAINZ

OPTIMAS light-spin-matter

DFG

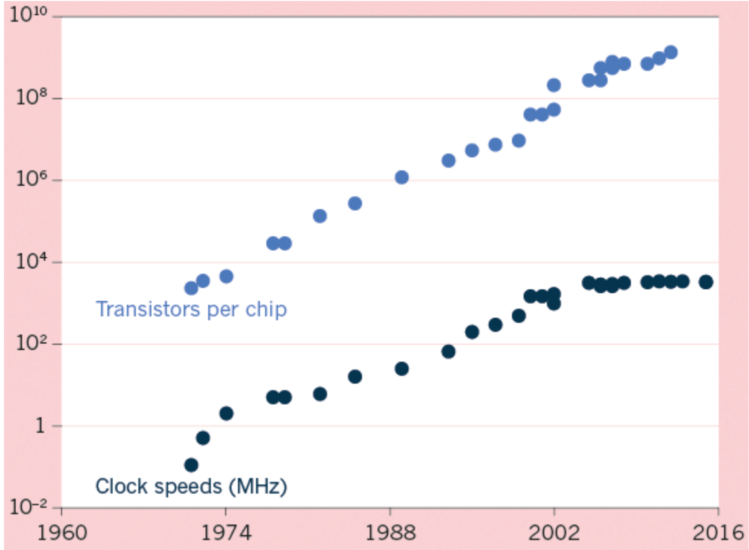
erc

Post CMOS?

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

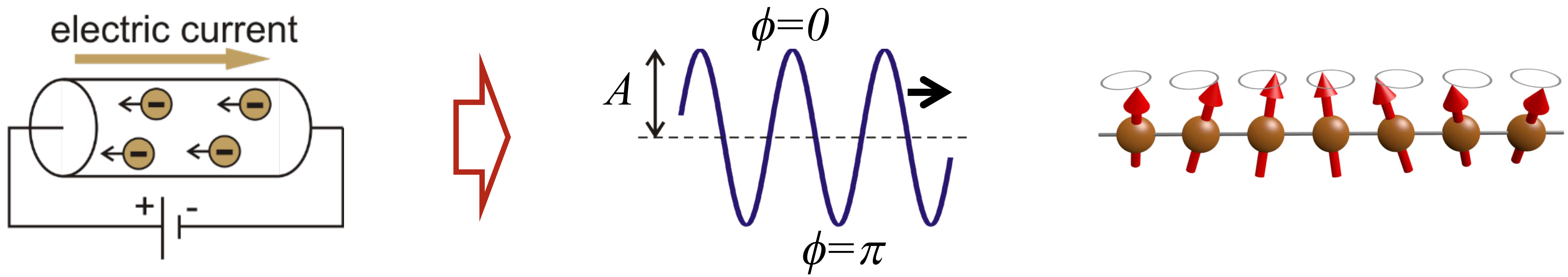
Beyond current CMOS:
- Faster computing, less energy consumption
- Same technology for logic and data
- Logic circuits with reduced footprint and/or 3D

Novel paradigm: wave computing

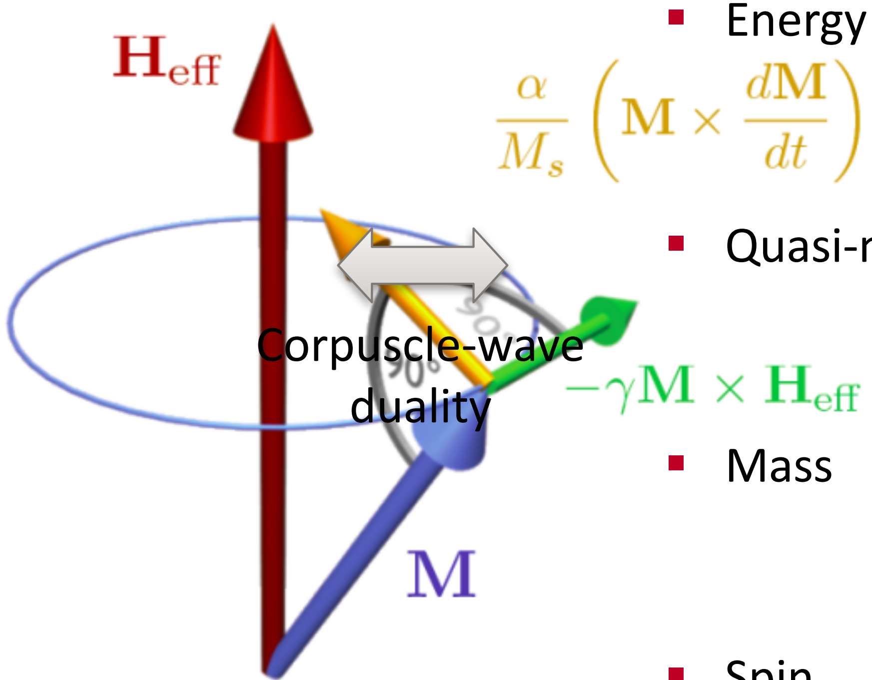


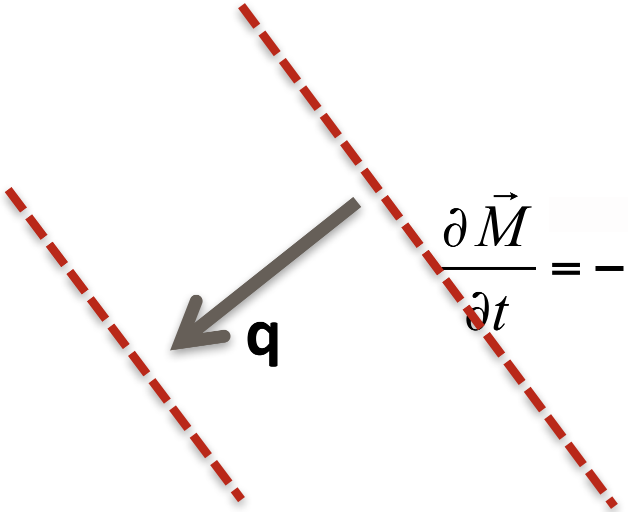
M. Mitchell, Nature **530**, 144 (2016)

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



Coherent dynamics: spin waves and magnons





$$\frac{\partial\vec{M}}{\partial t} = -\gamma\left(\vec{M}\times\vec{B}_{\mathrm{eff}}\right) + \frac{\alpha\mu_0}{M_s}\left(\vec{M}\times\frac{\partial\vec{M}}{\partial t}\right)$$

MAGNON quasi-particle :

- Energy

$$\varepsilon = \hbar\omega = \frac{\eta}{\hbar}p^2$$

- Quasi-momentum

$$\vec{p} = \hbar\vec{q}$$

- Mass

$$m = \hbar M_S/(4J_{ex})$$

- Spin

$$s = 1$$

- Lifetime
  (Yttrium Iron Garnet, $Y_3Fe_5O_{12}$)
  ~ 700 ns !

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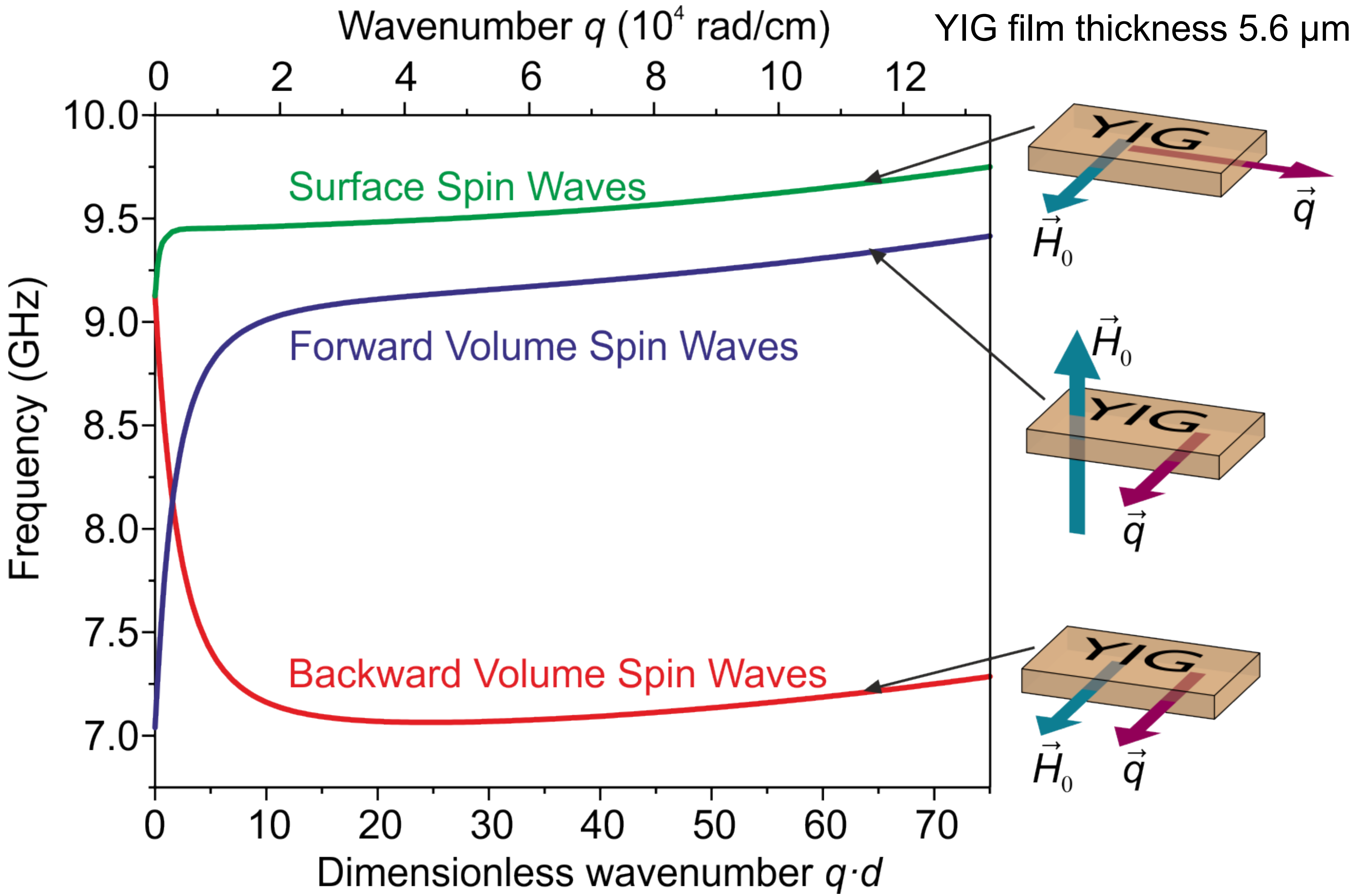
Spin waves spectra of a YIG film



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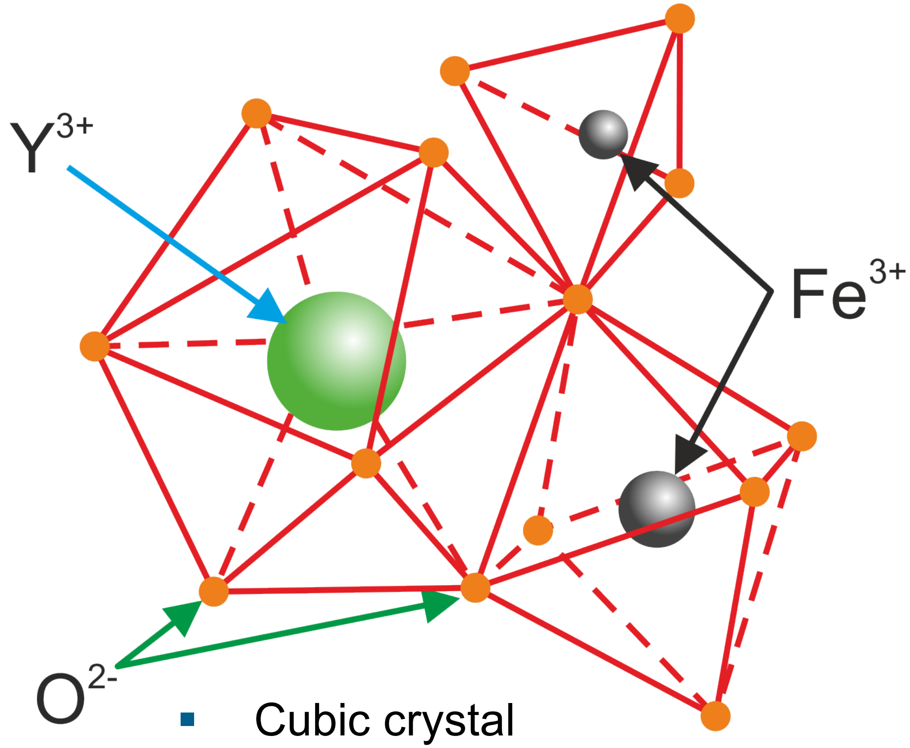
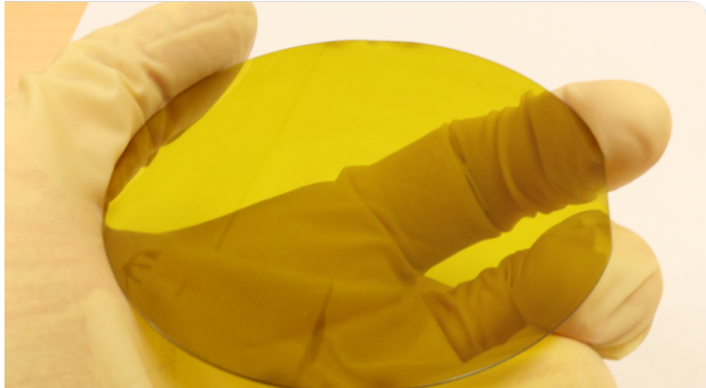
Yttrium Iron Garnet (YIG, $Y_3Fe_5O_{12}$)

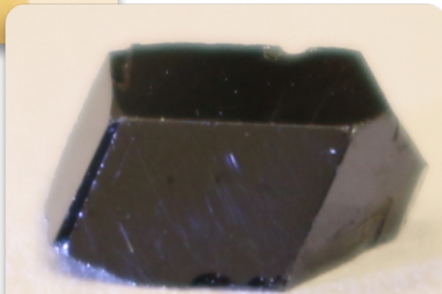
- Room temperature ferrimagnet (T_C = 560 K)
- Low phonon damping
- Magnon lifetime up to 700 ns !



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


3” YIG wafer

Scientific Research Company “Carat”, Lviv, Ukraine


YIG monocrystal

8 octahedral iron atoms (spin 5/2 up)
12 tetrahedral iron atoms (spin 5/2 down)

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

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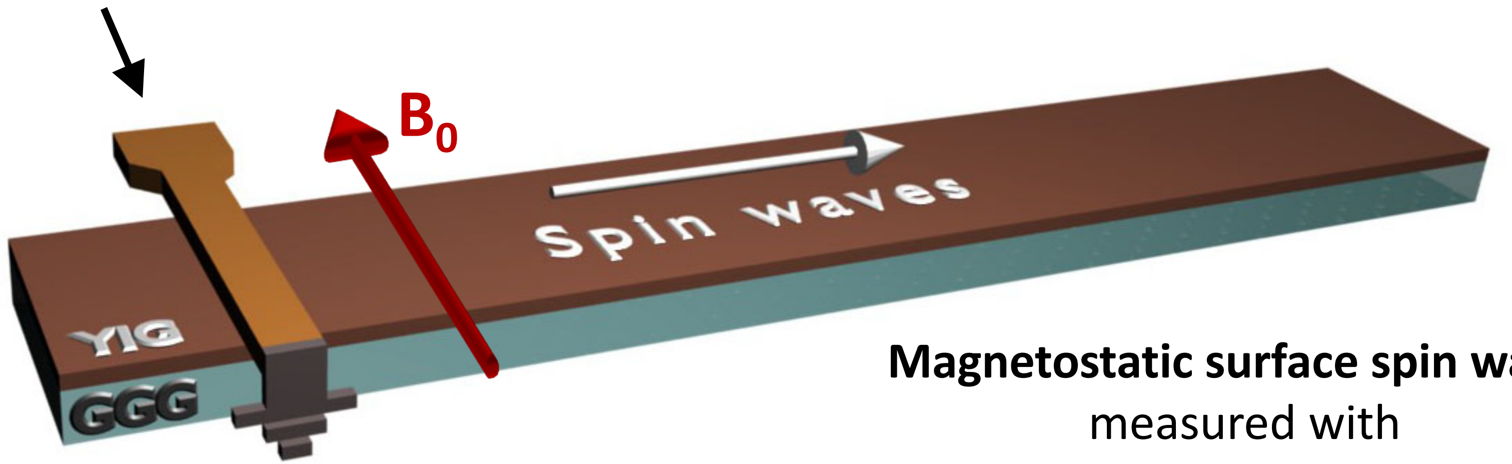
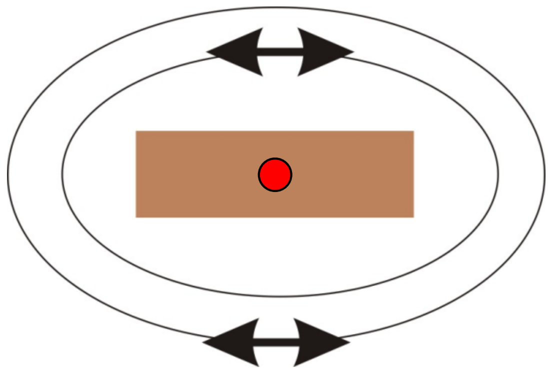
Excitation of dipolar spin waves

Input microwave signal



Magnetostatic surface spin waves
measured with
Brillouin light scattering spectroscopy



Alternating magnetic field

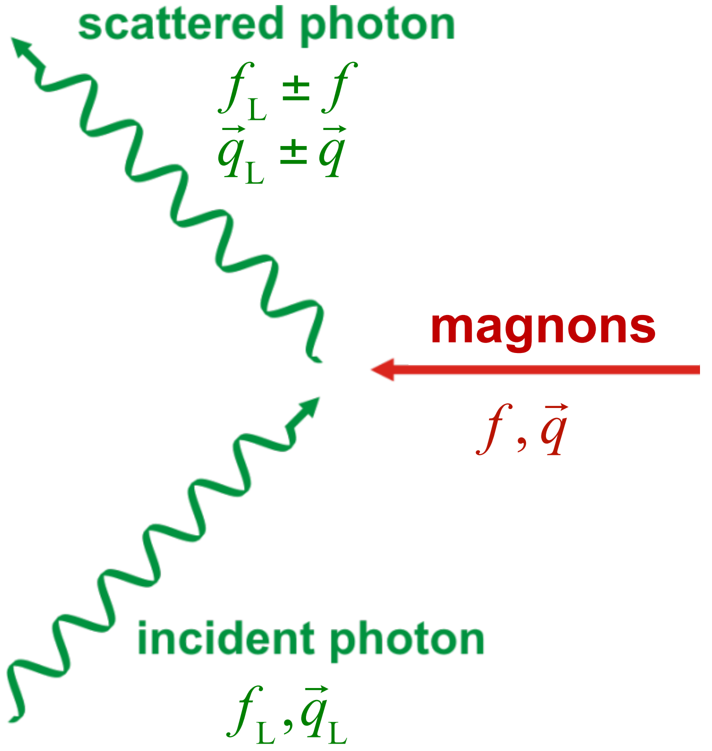
Brillouin light scattering spectroscopy

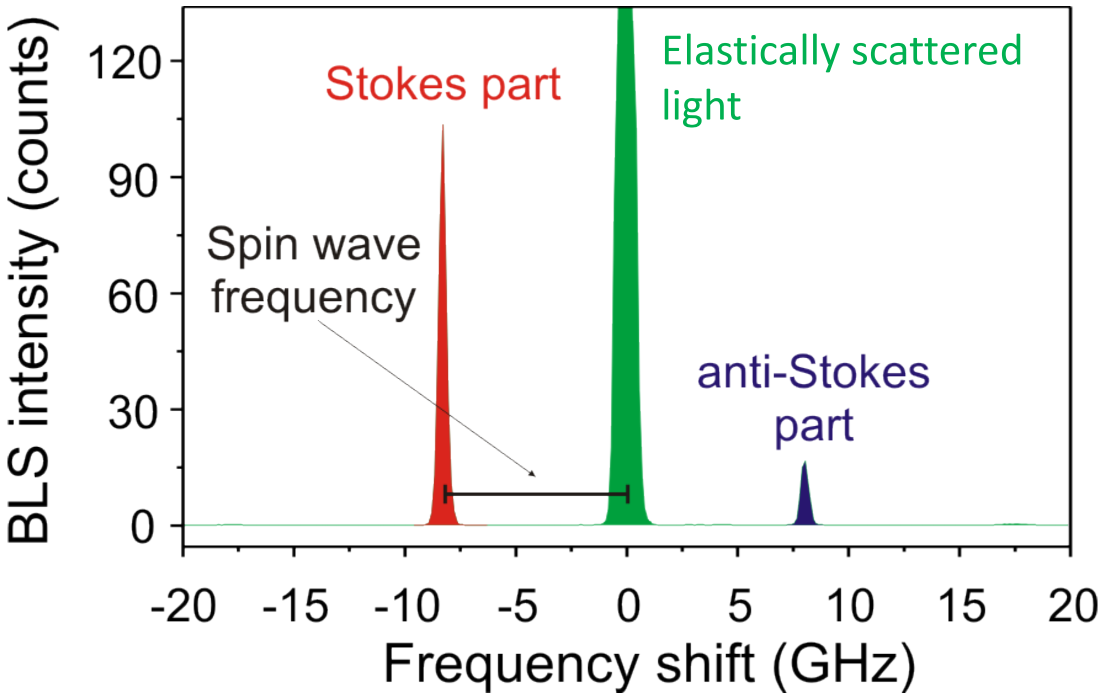
Brillouin light scattering process

= inelastic scattering of photons from spin waves

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

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





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

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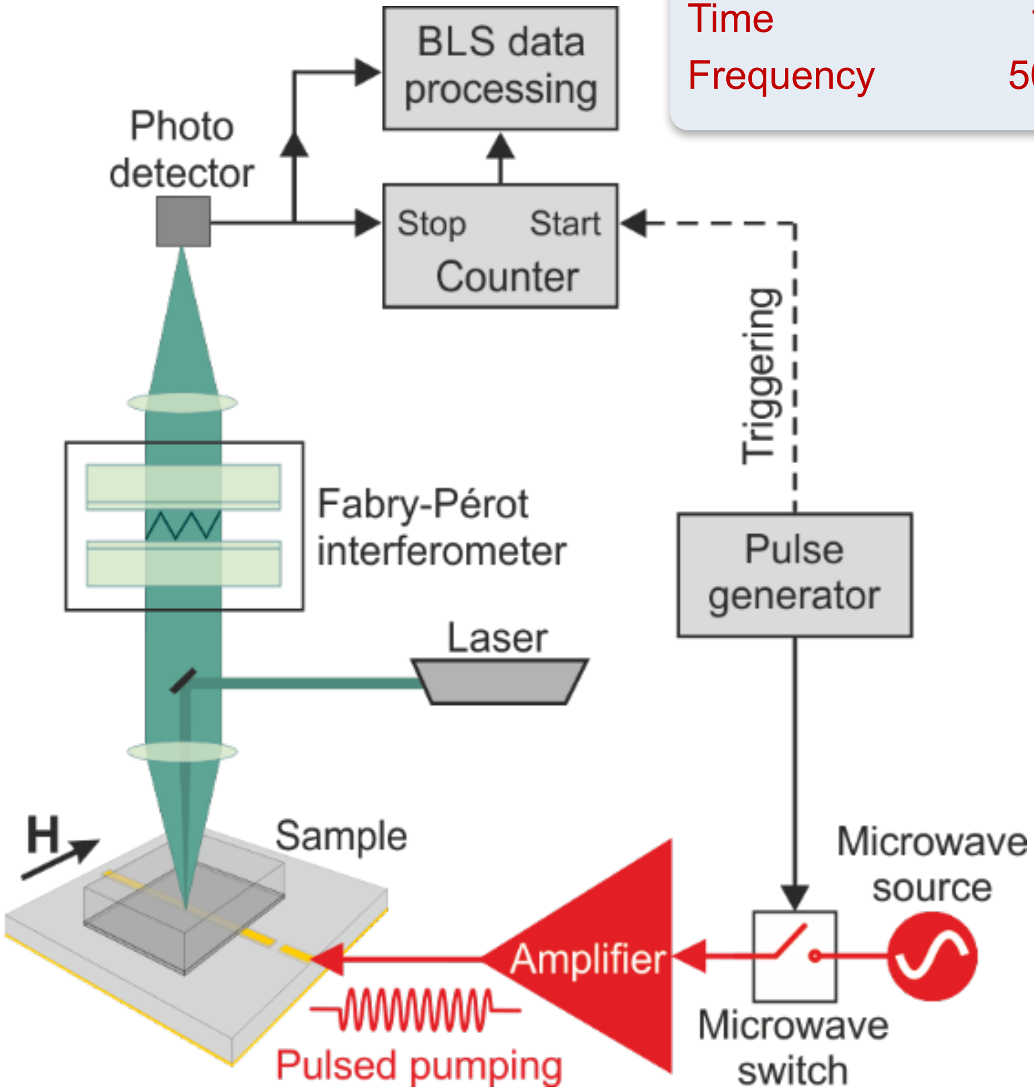
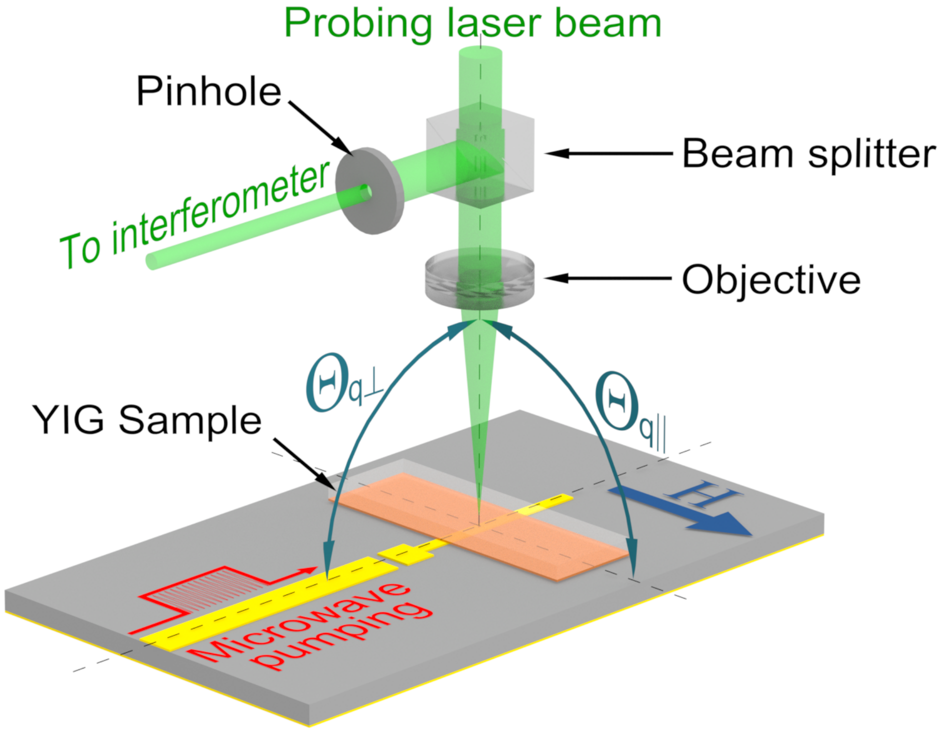


Resolution

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

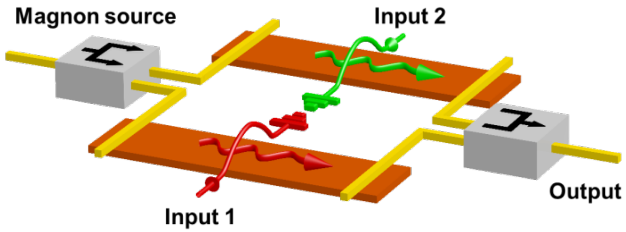
Magnon computing

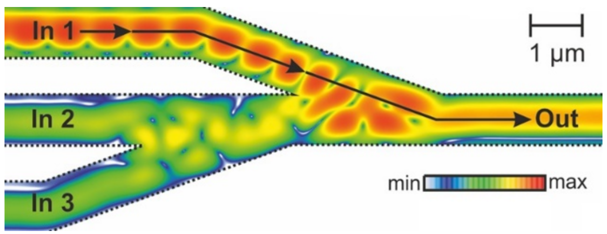
Why spin waves?

- 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”

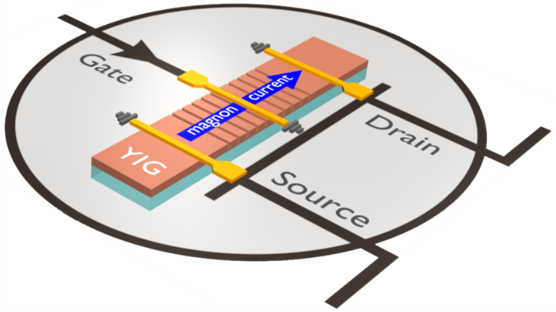
Achievements

Logic gates





Magnon transistor



Andrii Chumak, Kaiserslautern

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Computing principles

- Classical Computing
  - Scalar variable
  - Boolean logic
  - CMOS
- 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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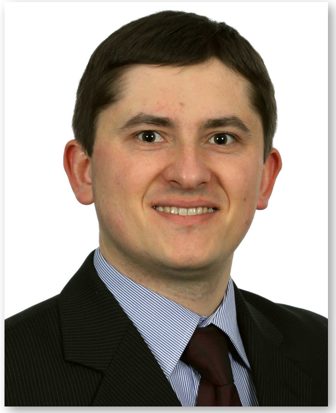
"Magnonics" team

Kaiserslautern PI Team

A. Chumak

P. Pirro



V. Vasyuchka

A. Serga

Main External Collaborators

M.P. Kostylev (University of Western Australia)

V.S. L'vov (Weizmann Institute of Science, Rehovot, Israel)

G.A. Melkov (National Taras Shevchenko University of Kyiv, Ukraine)

E. Saitoh (Tohoku University, Sendai, Japan)

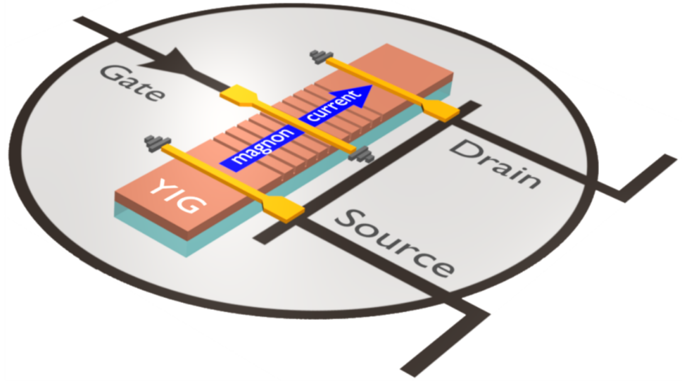
A.N. Slavin (Oakland University, Rochester, USA)

AG Magnetismus

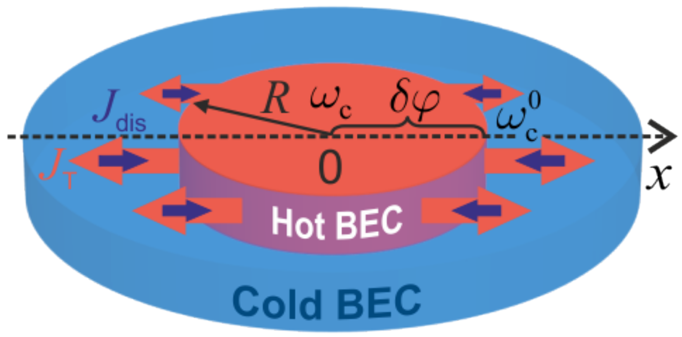
Prof. B. Hillebrands, Jun. Prof. A. V. Chumak, V. Lauer, Q. Wang, P. Frey,
B. Heinz, L. Mihalceanu, M. Kewenig, Dr. D. A. Bozhko, M. Schneider,
Dr. P. Pirro, M. Schweizer, Dr. habil. A. A. Serga, Dr. T. Langner, E. Wiedemann, A. Kreil,
Dr. A. Conca Parra, S. Steinert, M. Geilen, S. Keller, H. Schäfer, T. Noack, T. Fischer, T. Meyer,
Jun. Prof. E. Th. Papaioannou, F. Heussner, J. Greser, K. Fukuda (guest), Dr. V. I. Vasyuchka

Advanced magnonics

I. Magnon transistor

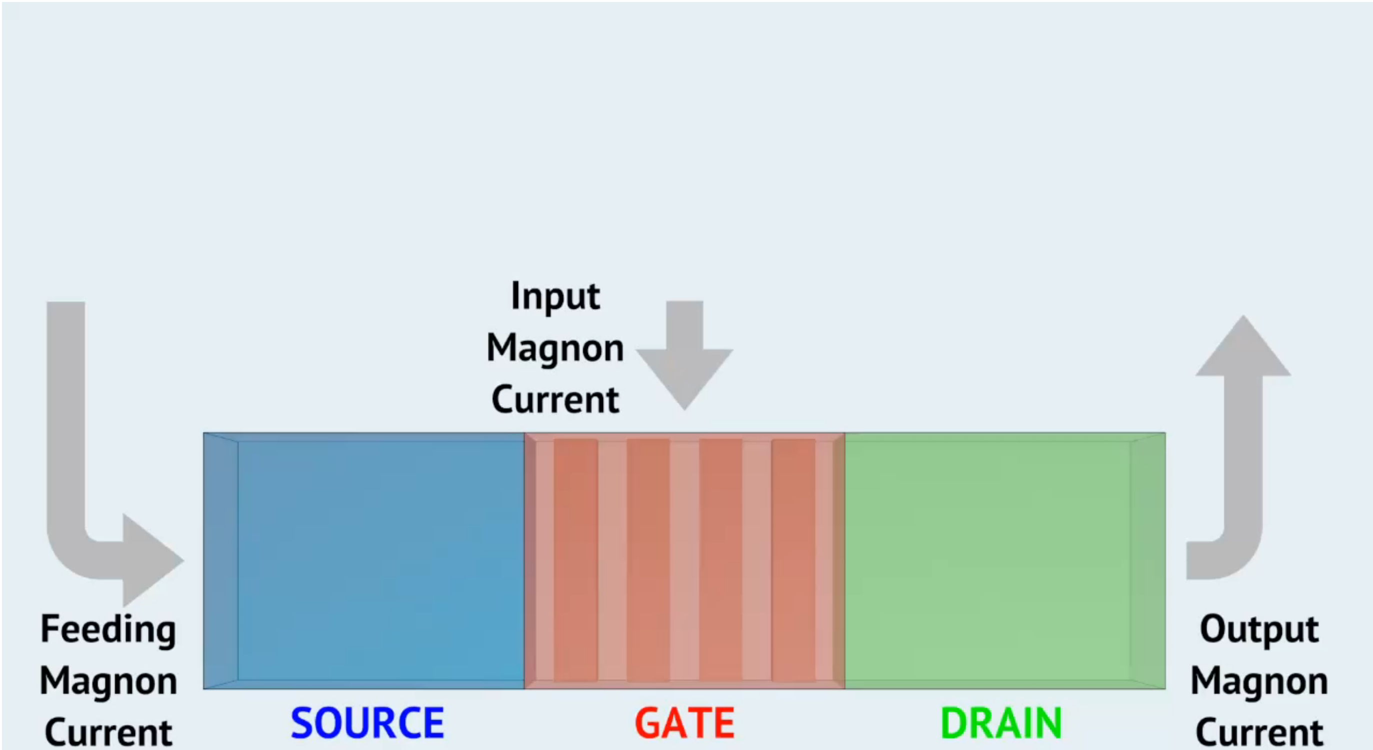


II. Magnonic supercurrents



Magnon transistor

Magnon transistor allows for the control of one magnon current by another



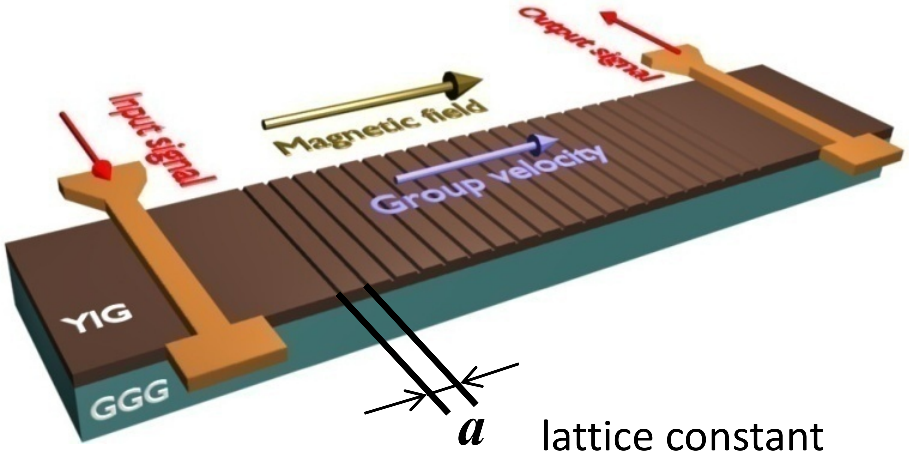
Courtesy: Andrii Chumak
(prepared for Hannovermesse)

What is a “magnonic crystal”?

Magnonic crystal – magnetic meta-material:

- artificial medium with periodic lateral variation in magnetic properties

One-dimensional magnonic crystal:



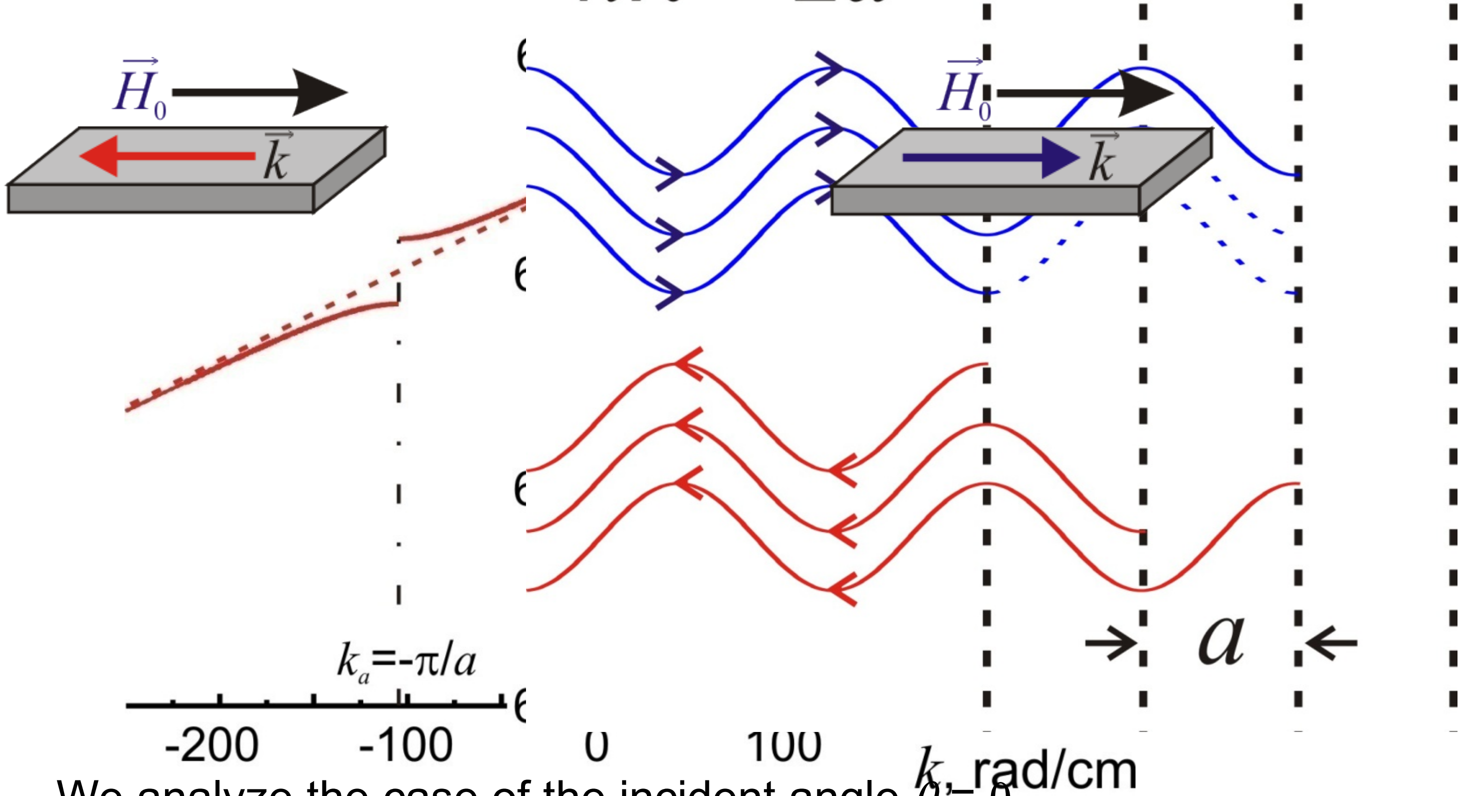
Magnonic-crystal are engineered to have properties that may not be found in nature

- analogous to photonic and sonic crystals but operates with spin waves in the GHz frequency range

Band gap

Band gaps – regions of the spectrum over which waves are not allowed to propagate

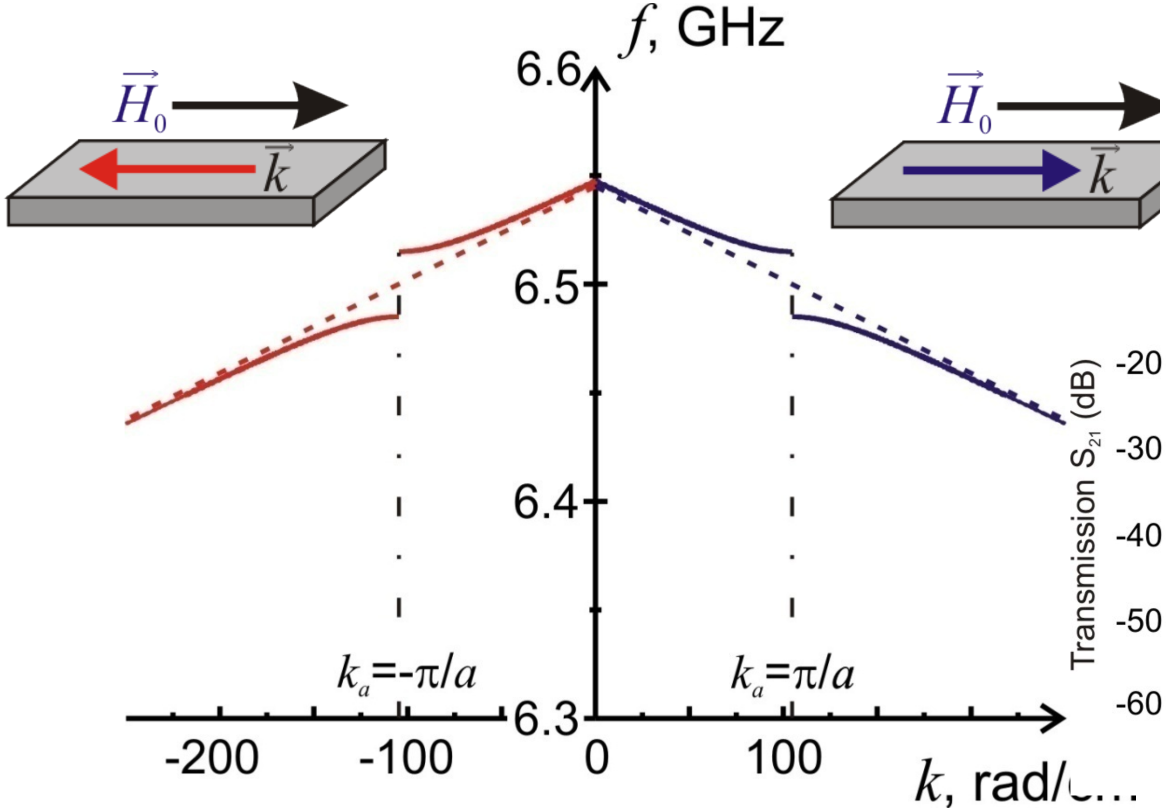
$$n\lambda = 2a$$

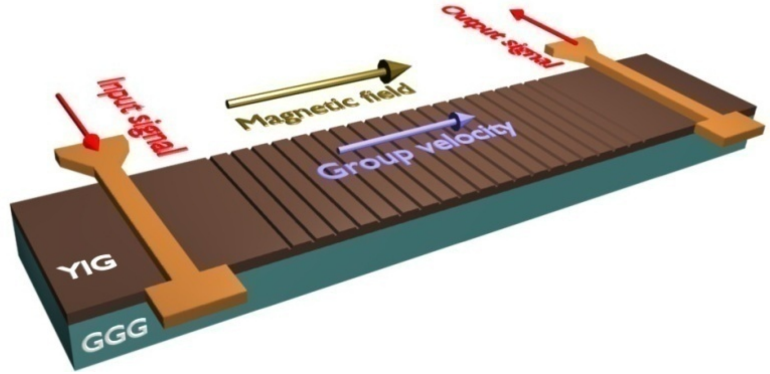


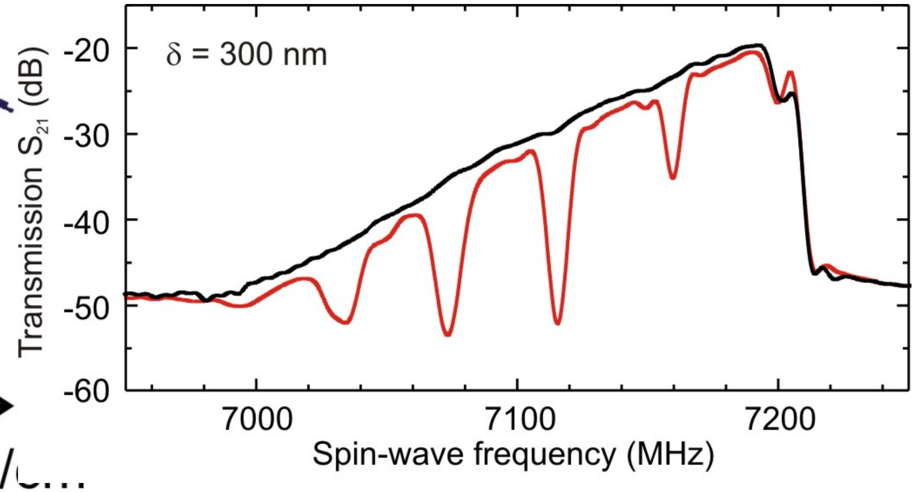
We analyze the case of the incident angle $\theta = 0$

Band gap

Band gaps – regions of the spectrum over which waves are not allowed to propagate

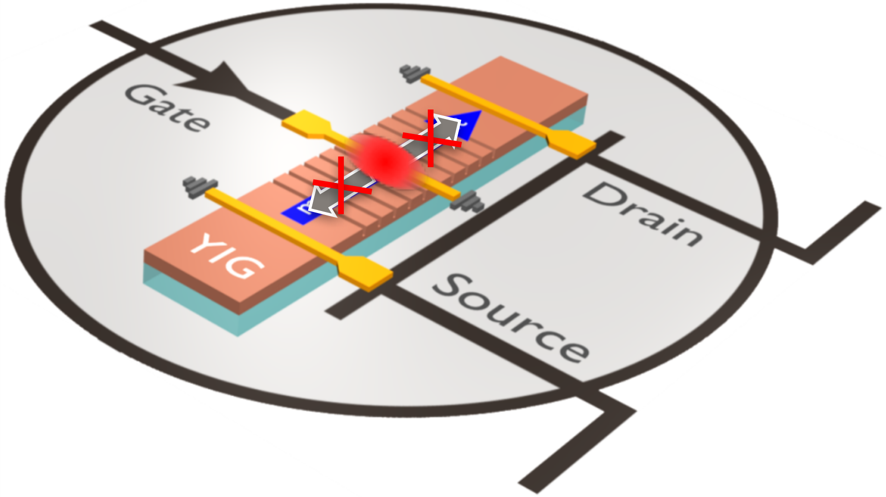




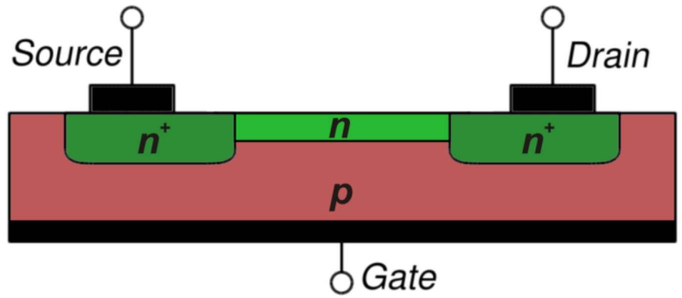


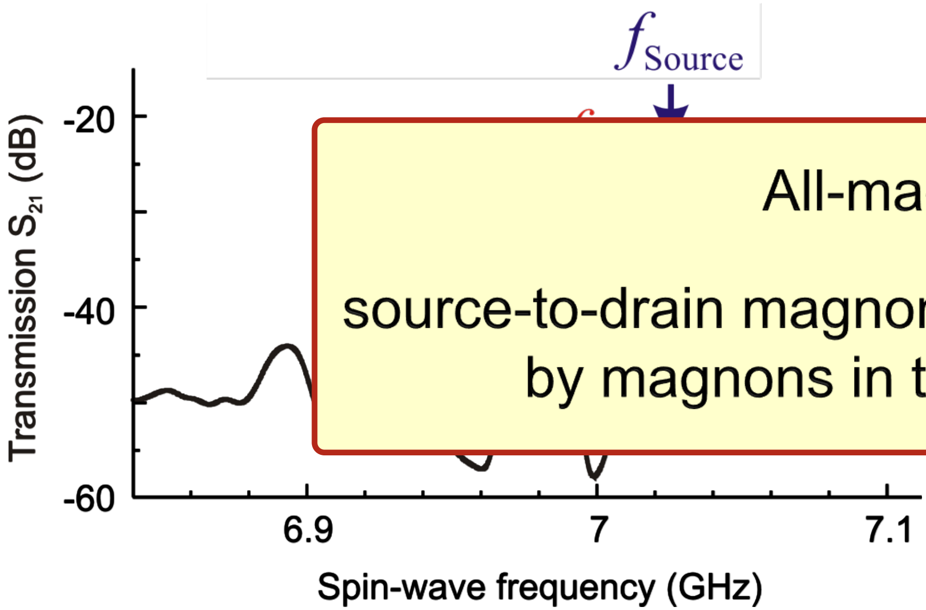
A.V. Chumak et al., Appl. Phys. Lett. **93**, 022508 (2008)

Magnon transistor



Semiconductor field-effect transistor:





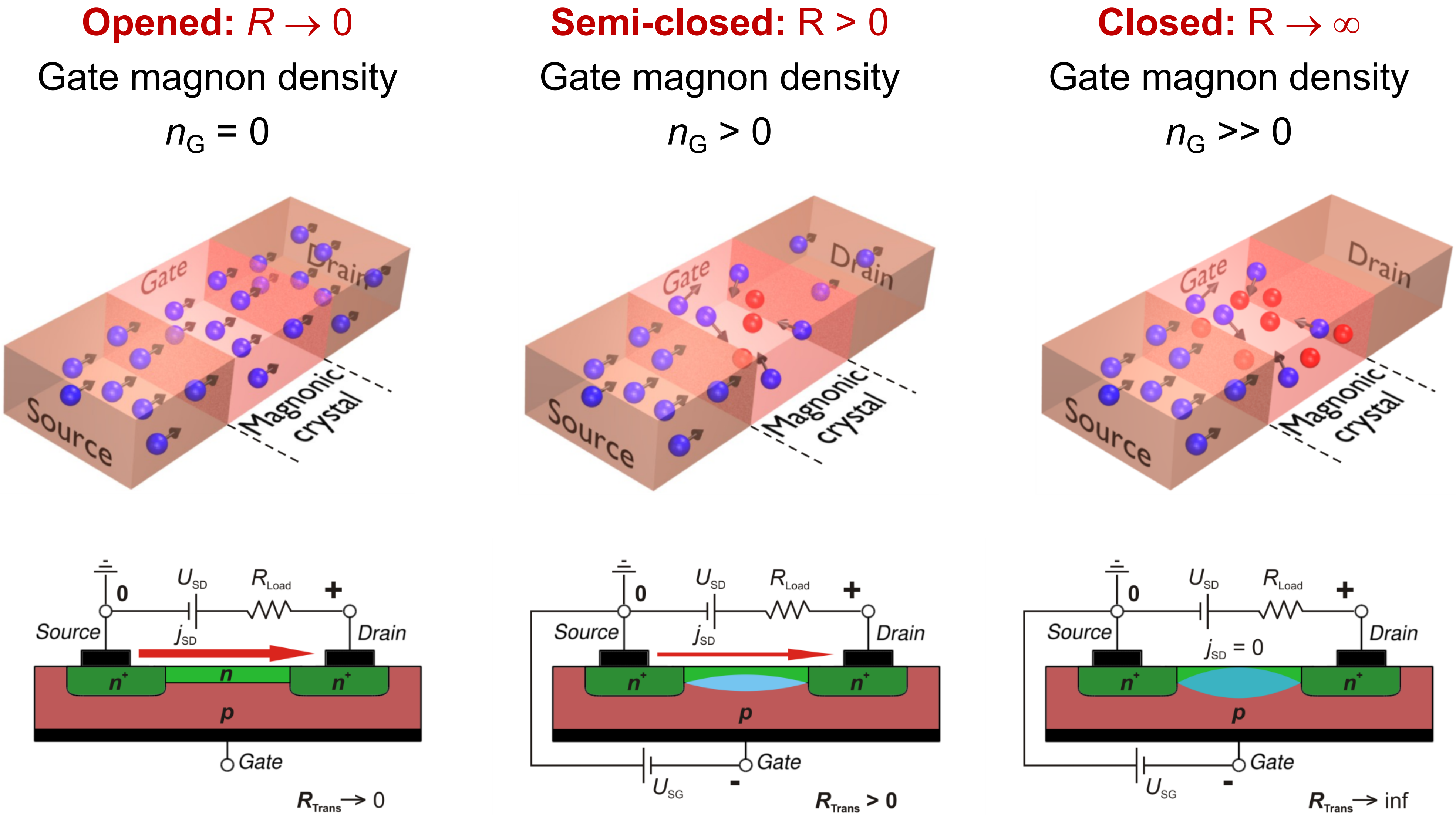
All-magnon dev

source-to-drain magnon flow sho
by magnons in the transis

Magnonic crystal acts
as an enhancer of
non-linear effects

A.V. Chumak et al., Nat. Commun. **5**:4700 (2014)

Magnon transistor



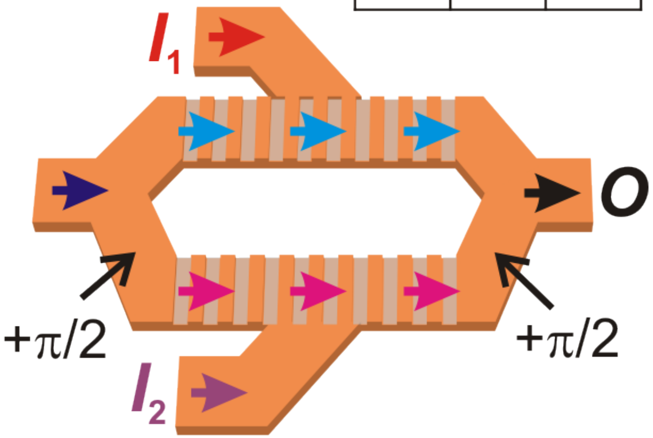
A.V. Chumak et al., Nat. Commun. **5**:4700 (2014)

Logic operations

XOR logic gate

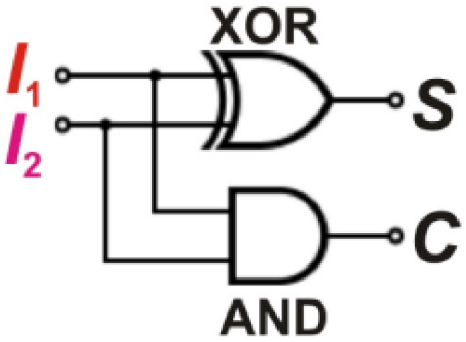
XOR

I_1	I_2	O
0	0	0
0	1	1
1	0	1
1	1	0

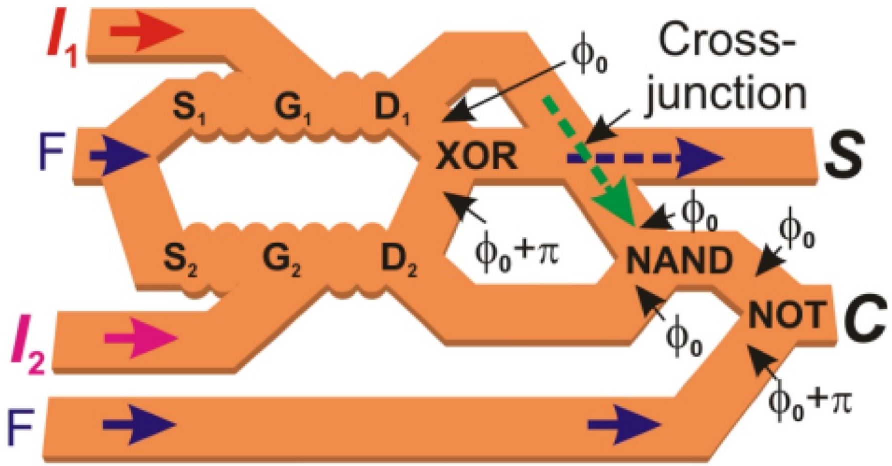


XOR gate requires 2 magnon transistors
instead of 8 FET in CMOS

Half adder



I_1	I_2	C	S
0	0	0	0
1	0	0	1
0	1	0	1
1	1	1	0



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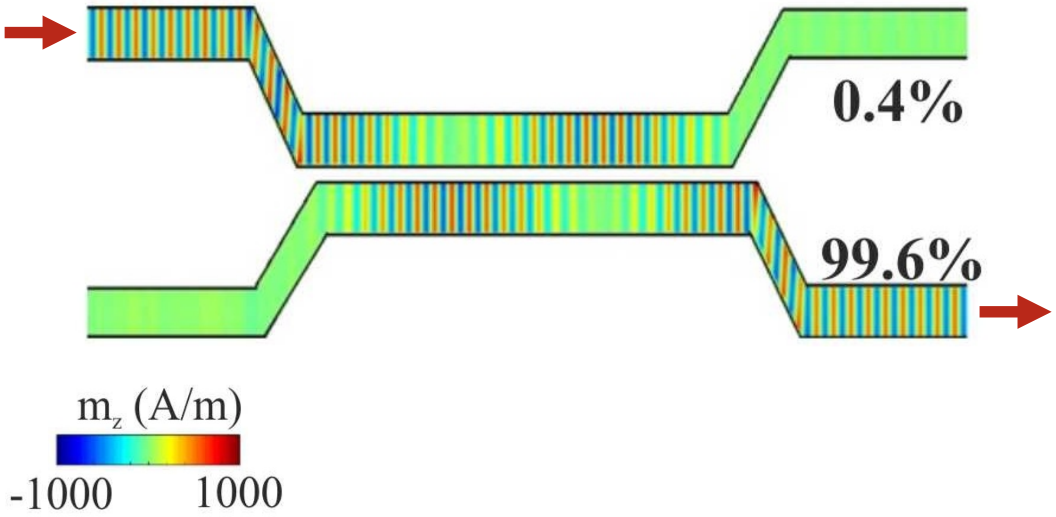
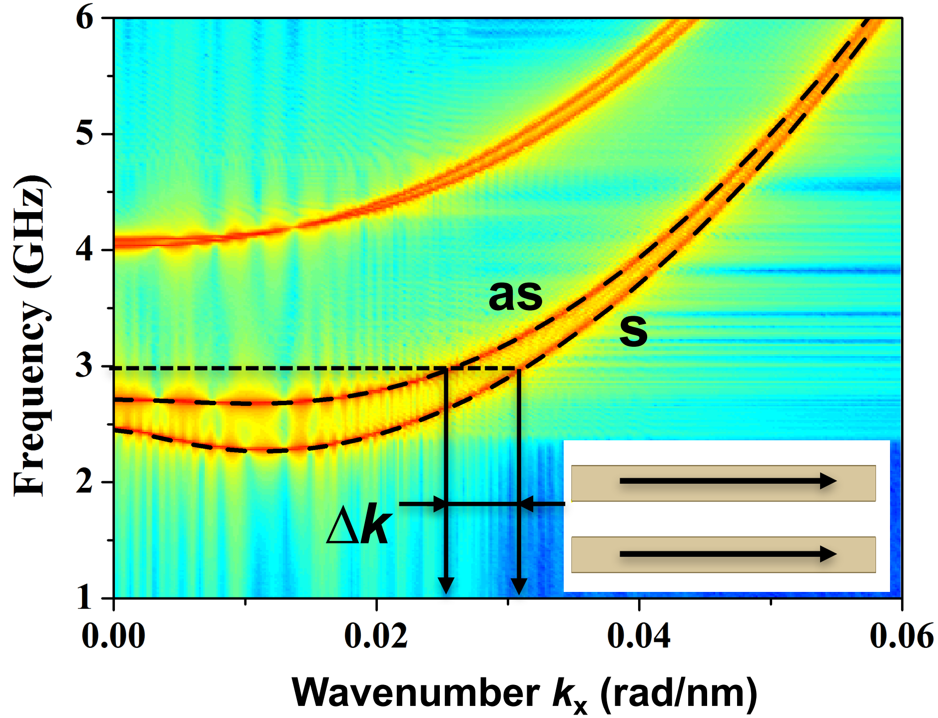
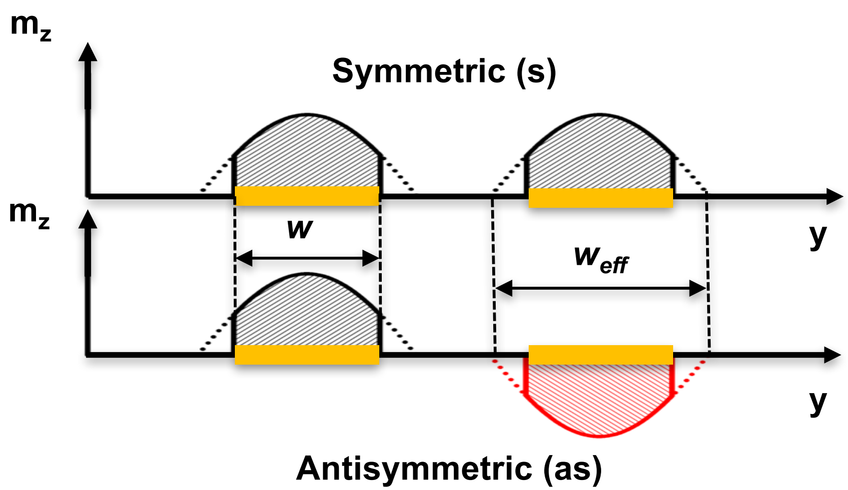
Magnon directional coupler







Magnonic conduits can be connected without a direct contact

Q. Wang et al., arXiv:1704.02255 (2017)

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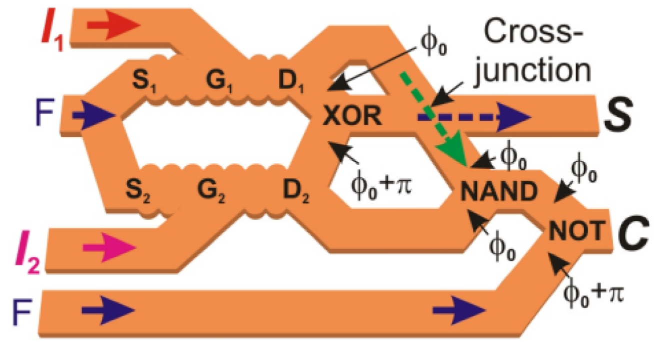
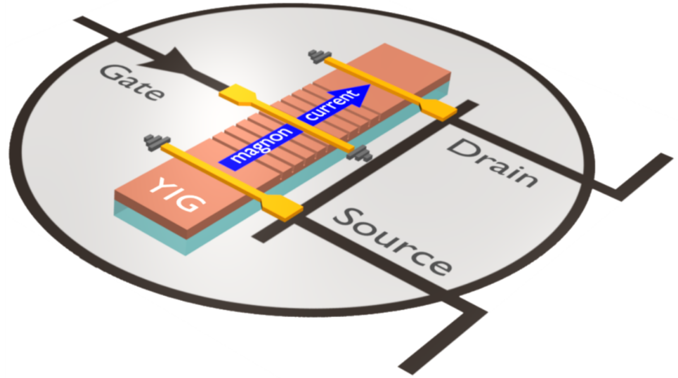
Summary I

1. Nonlinear magnon scattering opens access to all-magnon circuits



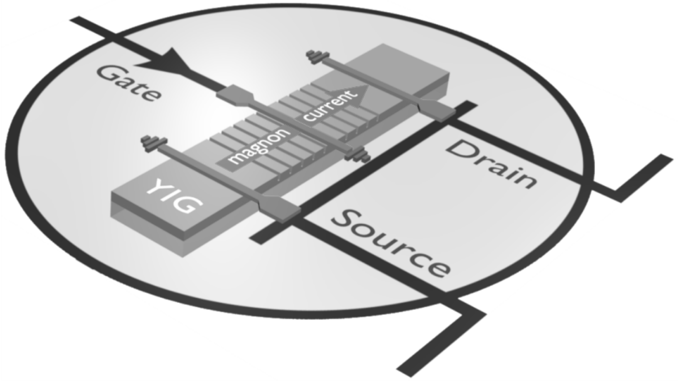
2. Proofs of principle shown for components like magnon transistor and magnon directional coupler



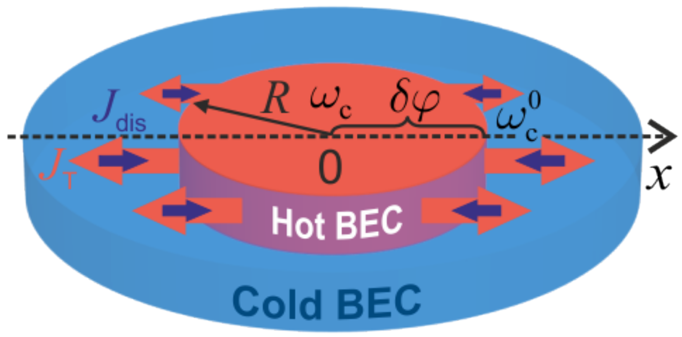
3. Current issues: scaling, nanoscale physics

Advanced magnonics

I. Magnon transistor



II. Magnonic supercurrents



Macroscopic quantum states

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

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

▪ Bose-Einstein Condensate (BEC) of magnons

▪ Supercurrents in magnon condensates

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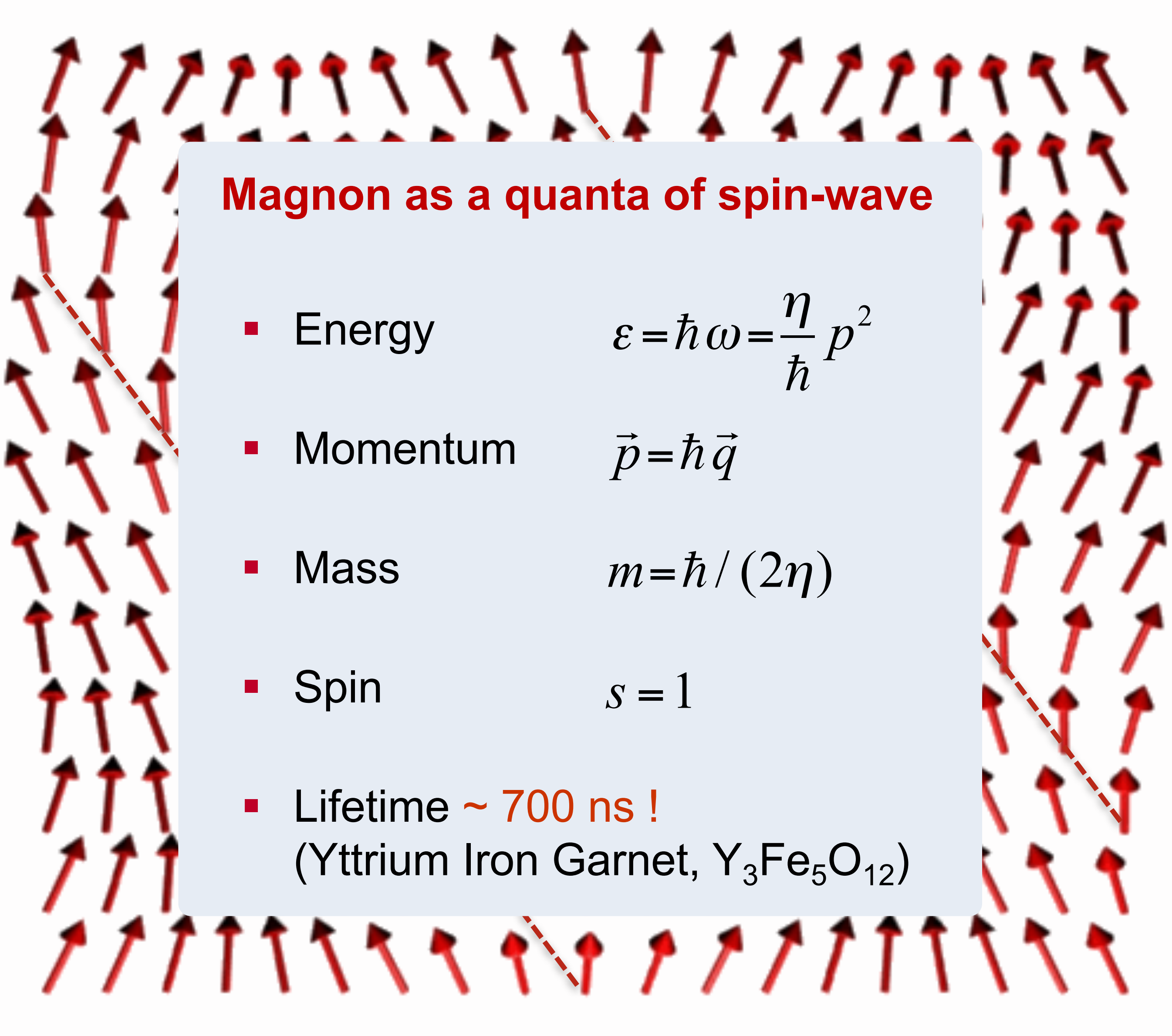
Magnon gas



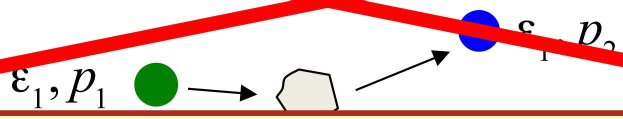
Magnon as a quanta of spin-wave

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

(Non-)linear Processes

- **Linear process**

Two-magnon scattering

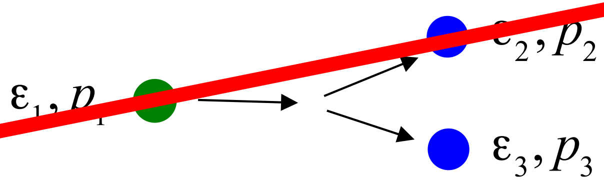


Magnon gas of interacting quasiparticles

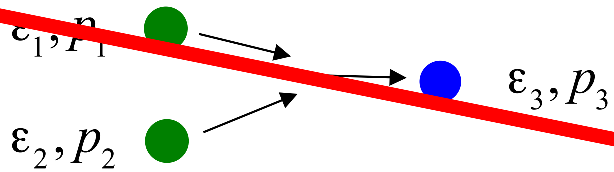
Number of particles is conserved

- **Nonlinear pro**

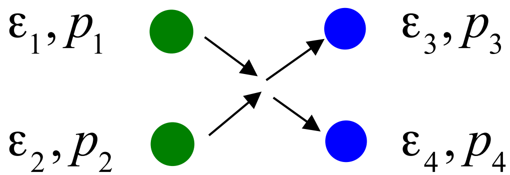
Three-magnon decay



Three-magnon confluence

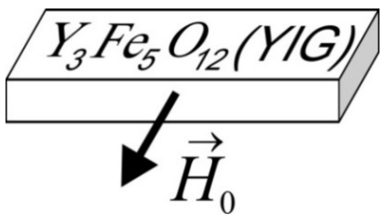


Four-magnon scattering



Magnon distribution

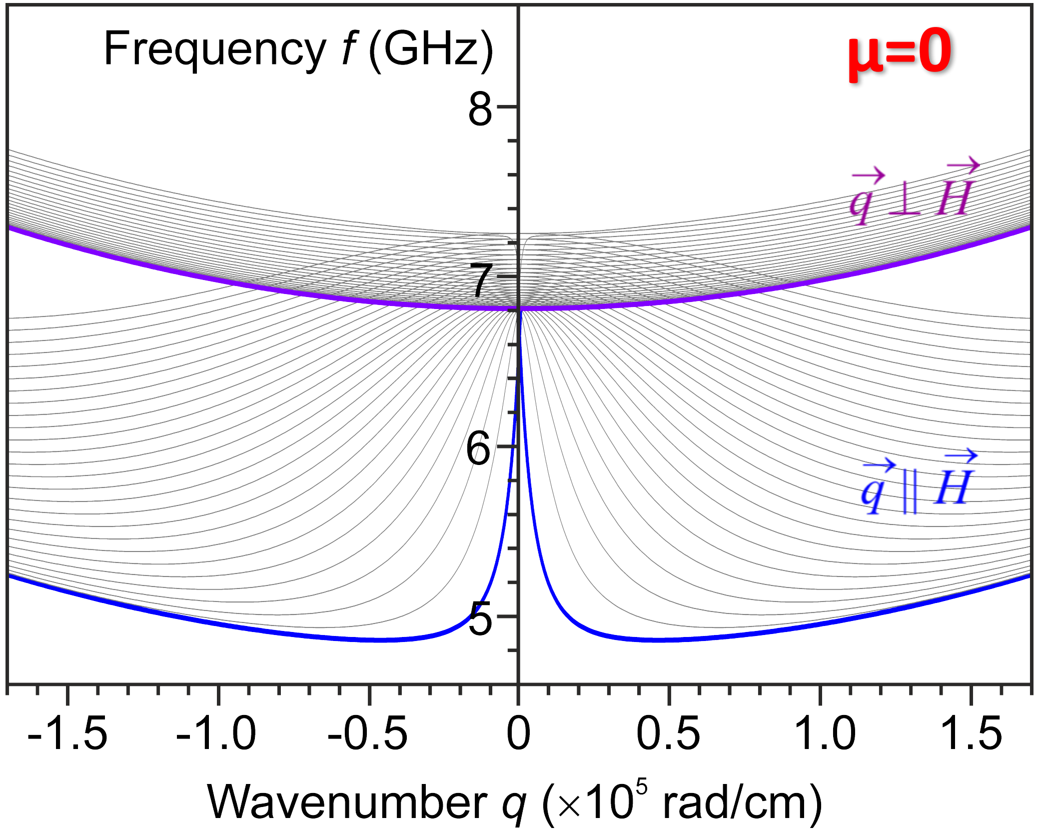
Magnons are bosons (s=1)
and thus as any quasi-particles
are described by Bose-Einstein distribution
with zero chemical potential



Bose-Einstein distribution

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

μ: chemical potential

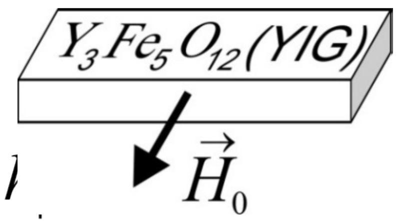


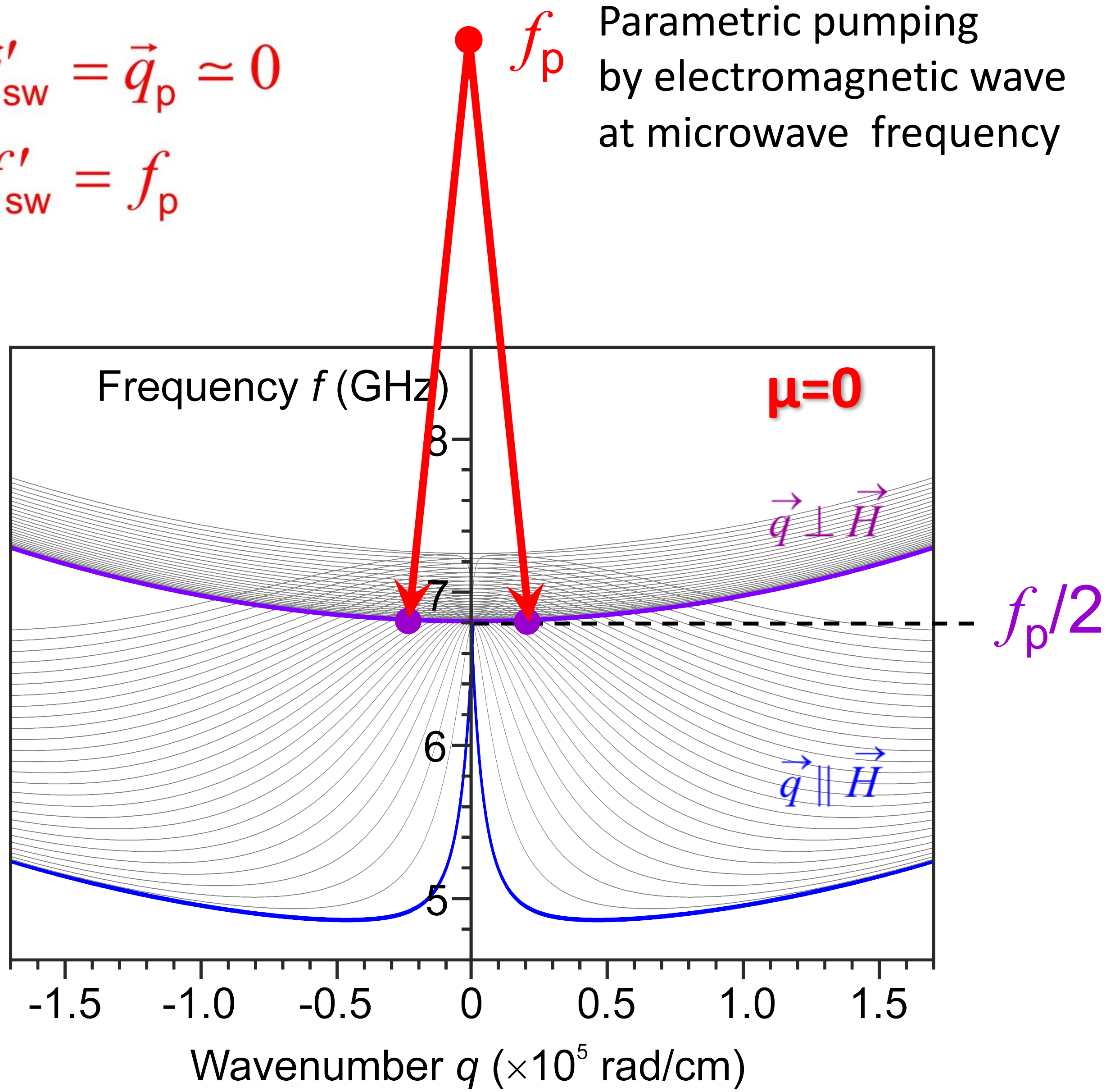
Control of magnon gas density by parametric pumping

Energy and momentum conservation laws

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

Parametric pumping by electromagnetic wave at microwave frequency





Bose-Einstein distribution

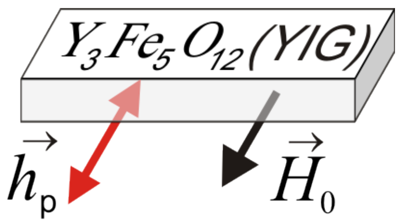
$$\rho(f)=\frac{D(f)}{\exp\left(\frac{hf-\mu}{k_B T}\right)-1}$$

μ: chemical potential

Control of magnon gas density by parametric pumping

Energy and momentum conservation laws
$$\begin{cases} \vec{q}_{\rm sw} + \vec{q}\,'_{\rm sw} = \vec{q}_{\rm p} \simeq 0 \\ f_{\rm sw} + f'_{\rm sw} = f_{\rm p} \end{cases}$$

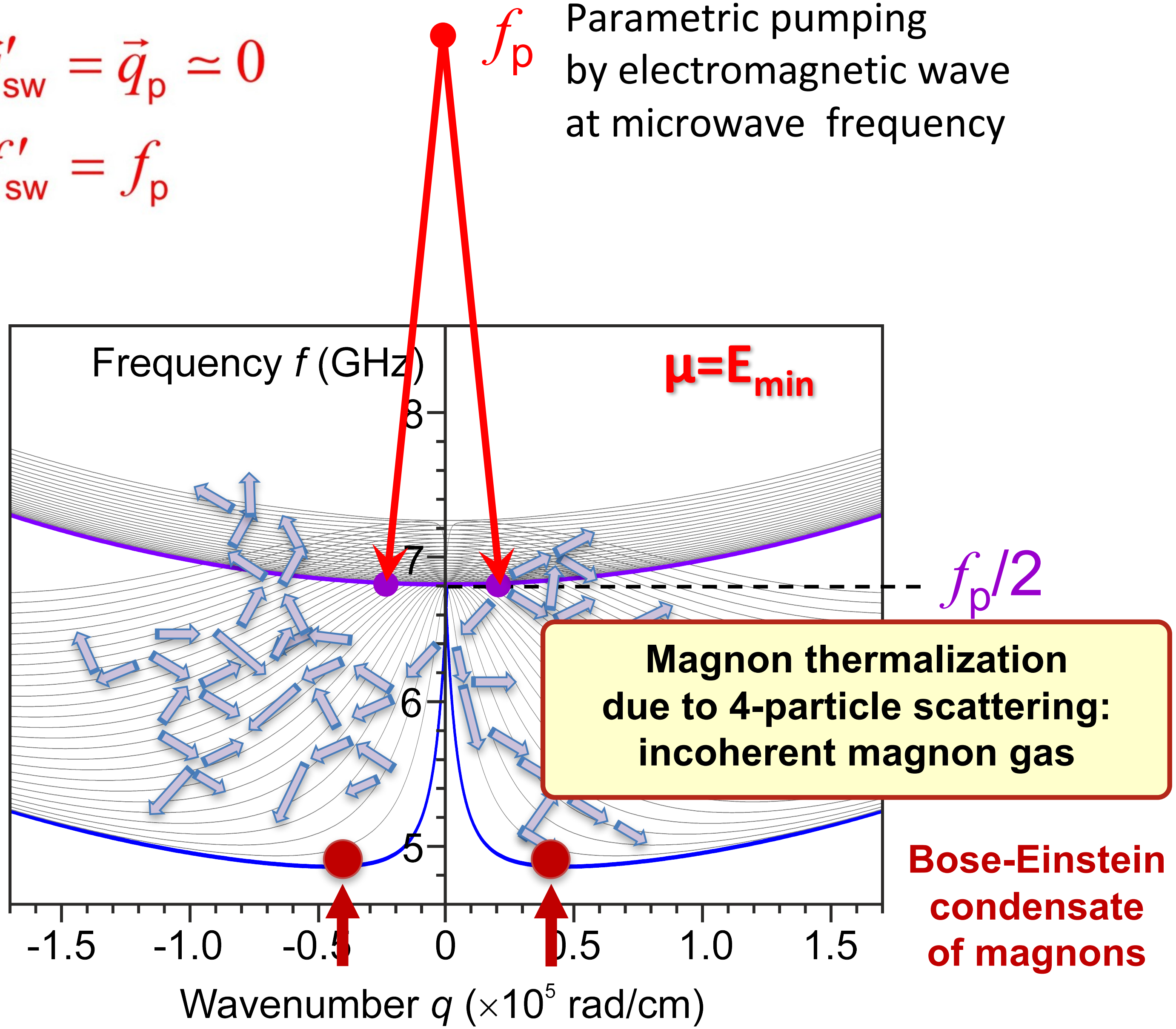
$f_{\rm p}$ Parametric pumping by electromagnetic wave at microwave frequency



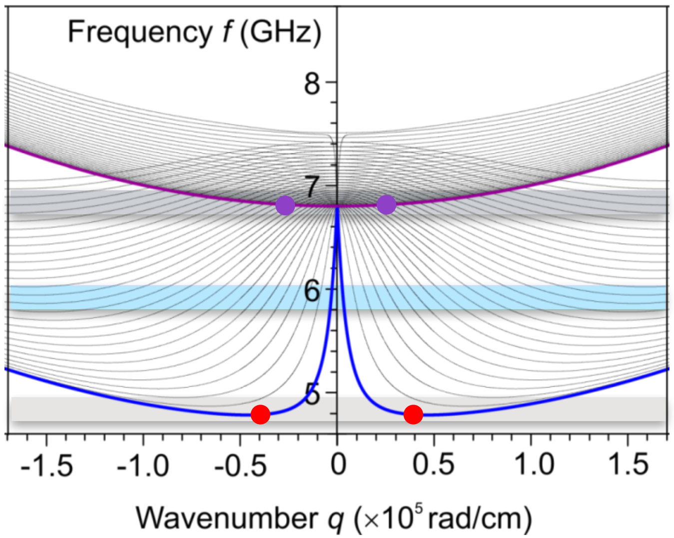
Bose-Einstein distribution

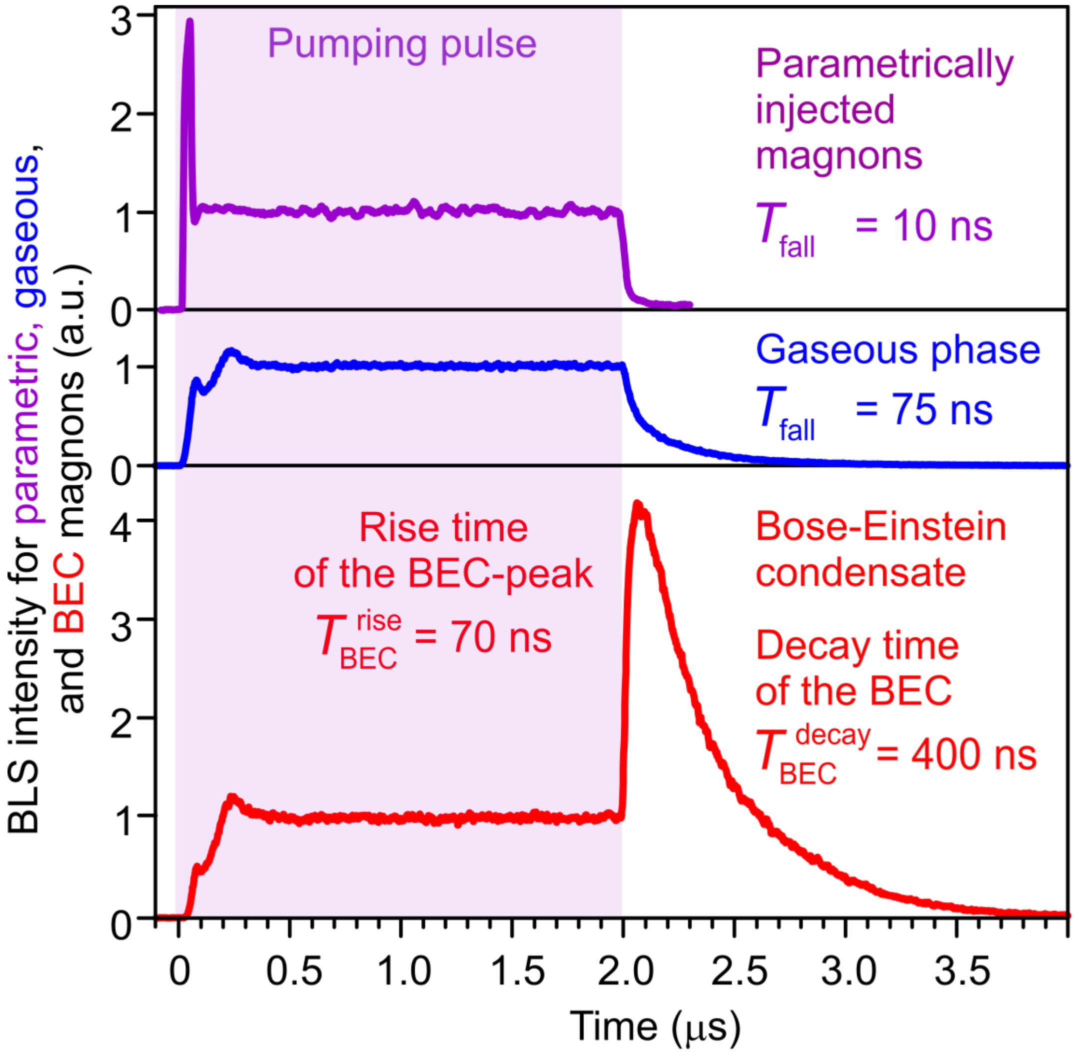
$$\rho(f) = \frac{D(f)}{\exp\left(\frac{hf - \mu}{k_B T}\right) - 1}$$

μ: chemical potential



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

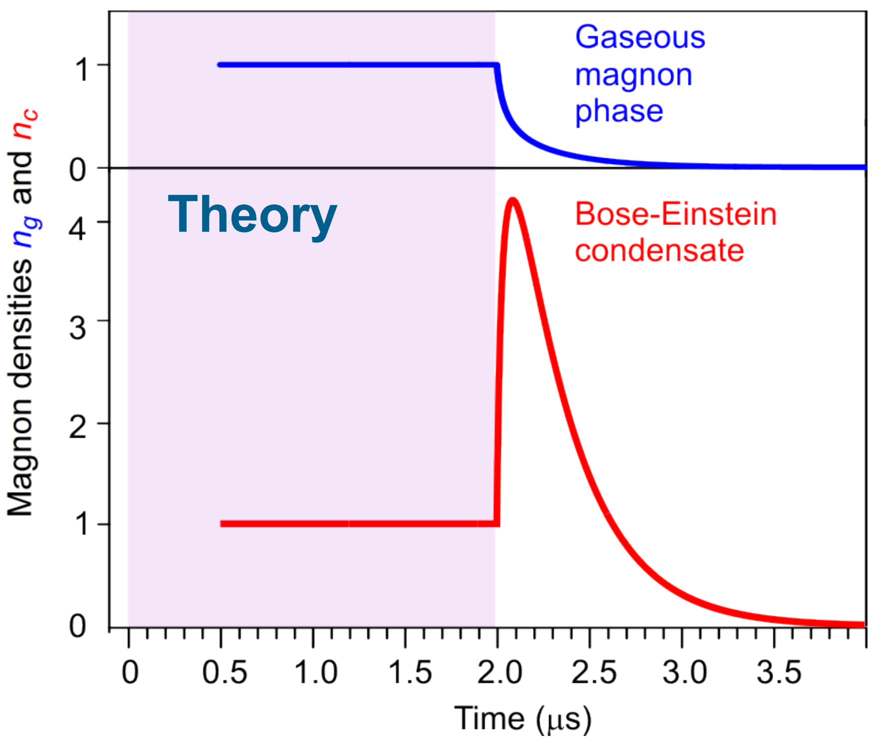
Temporal profiles of the magnon densities

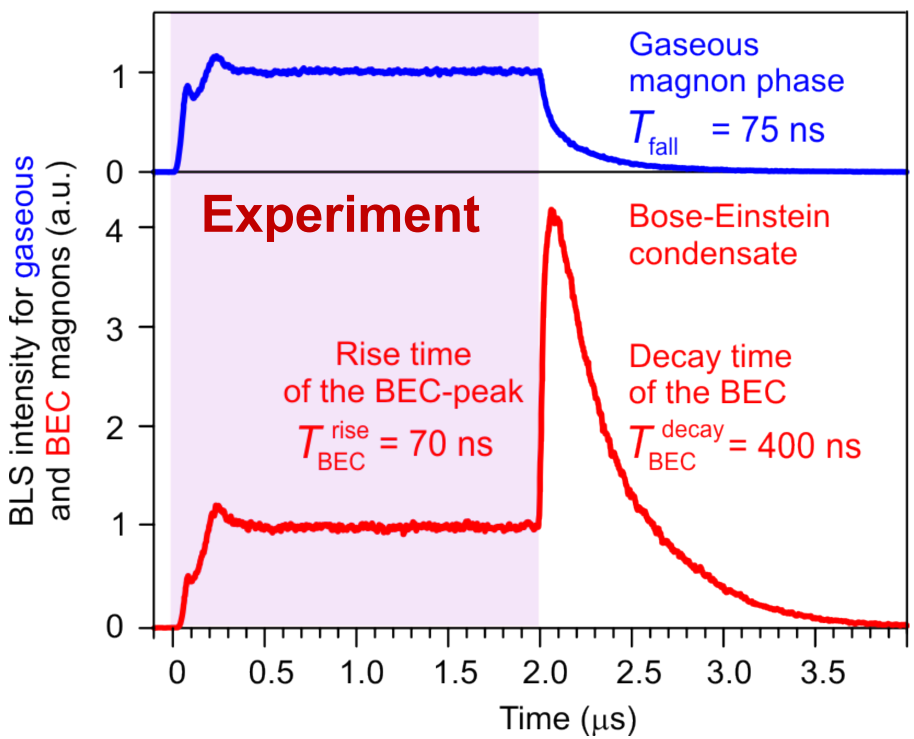
Dynamics of condensed magnons n_c, magnons in gaseous states n_g

$$\frac{1}{\Gamma}\frac{dn_c}{dt} = -\lambda n_{in}(t) - n_c + n_g^3$$

$$\frac{1}{\Gamma}\frac{dn_g}{dt} = n_{in}(t) - n_g - n_g^3$$

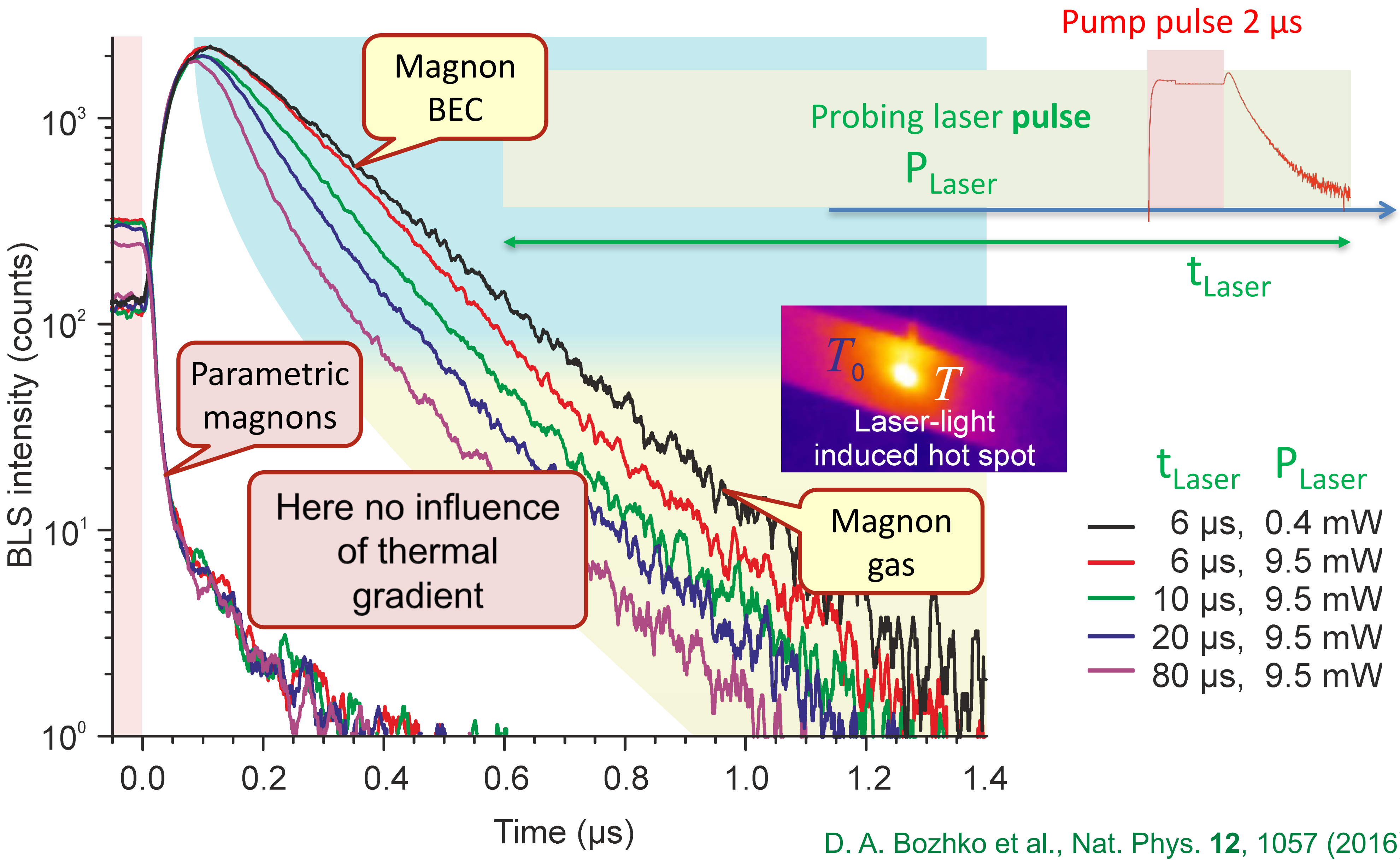
$n_{\mathrm{in}}(t)$: magnons injected by pumping
Γ : relaxation frequency
λ : supercooling process intensity coefficient





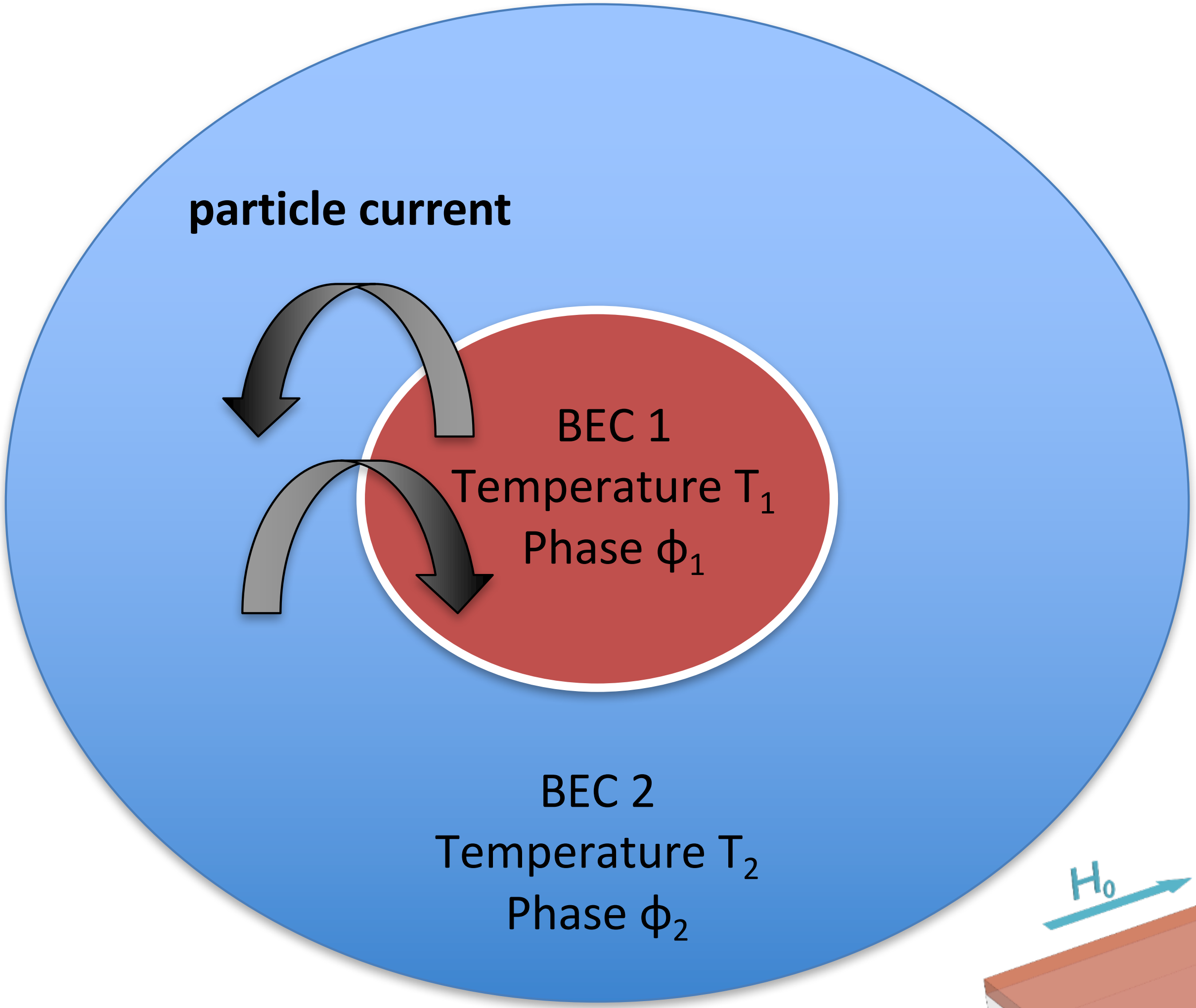
A. A. Serga *et al.*, Nat. Commun. **5**, 4452 (2014)

Dynamics of condensed magnons in thermal gradient



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

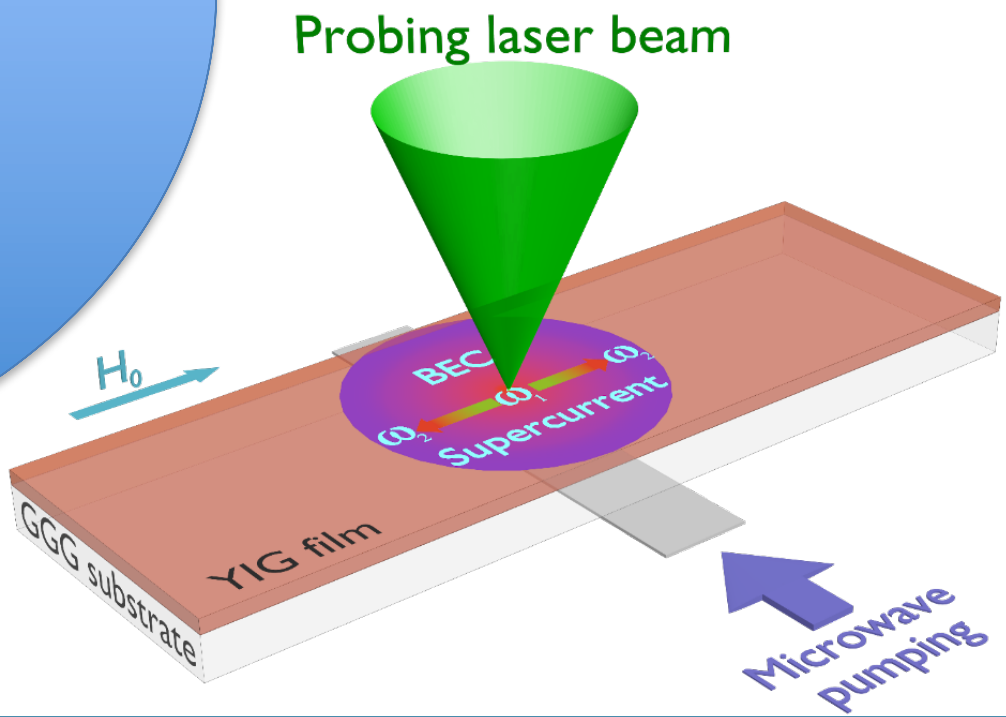
Magnonic supercurrents



$T_1 > T_2$

$\rightarrow \phi_1 \neq \phi_2$

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 equations

Without thermal gradient

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

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

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

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 equations

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

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

With thermal gradient

Additional decrease of population of condensed magnons $N_c(t)$ due to magnonic supercurrent

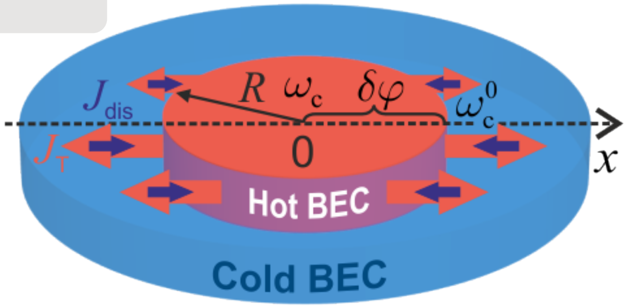
Flow of condensed magnons

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

$J_T = -B_s N_c \delta\omega_c t$ - Flow of condensed magnons due to the phase gradient

$J_{dis} = B_{dis}(N_c^0 - N_c)$ - Dispersive flow of condensed magnons

Phase gradient



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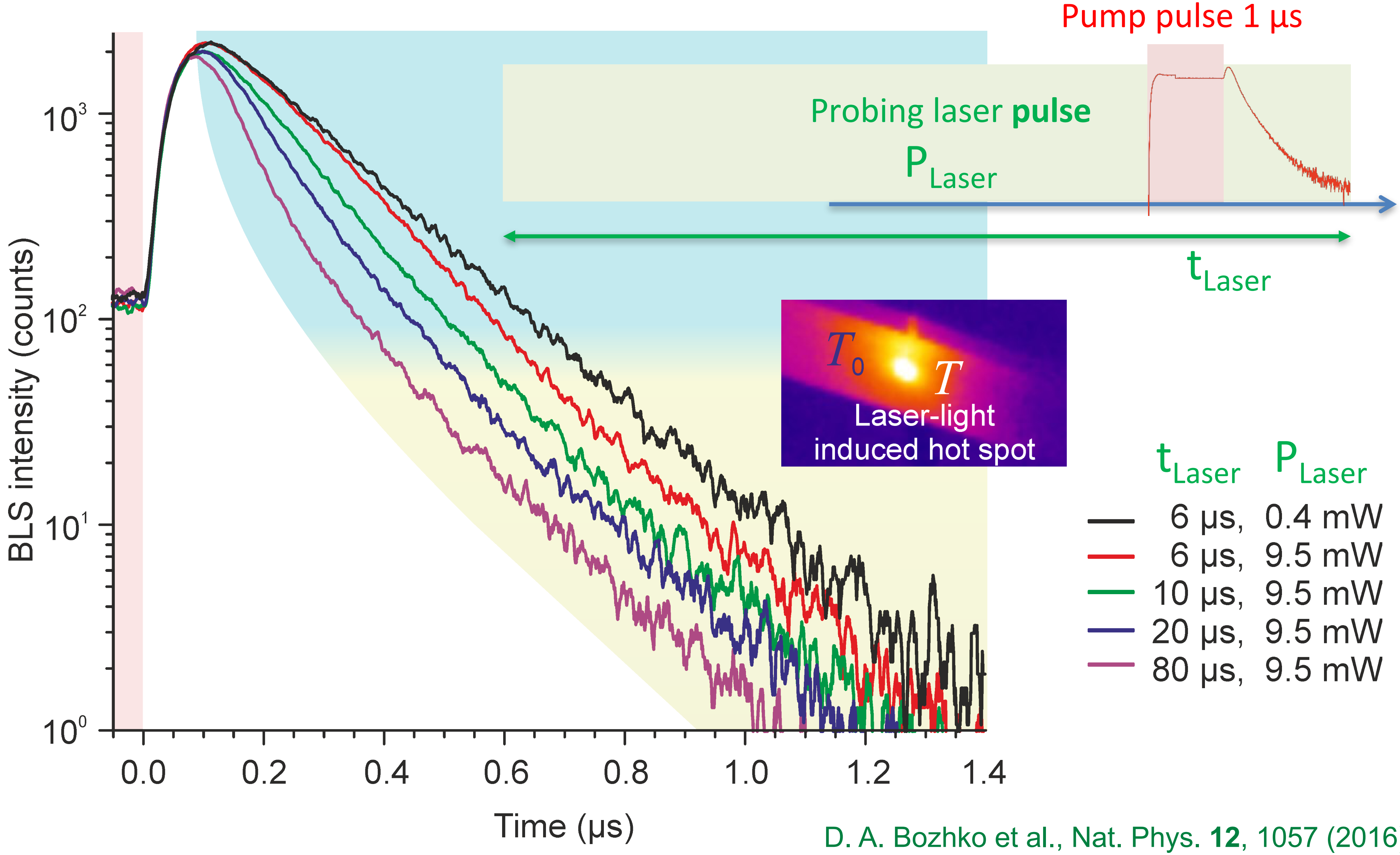
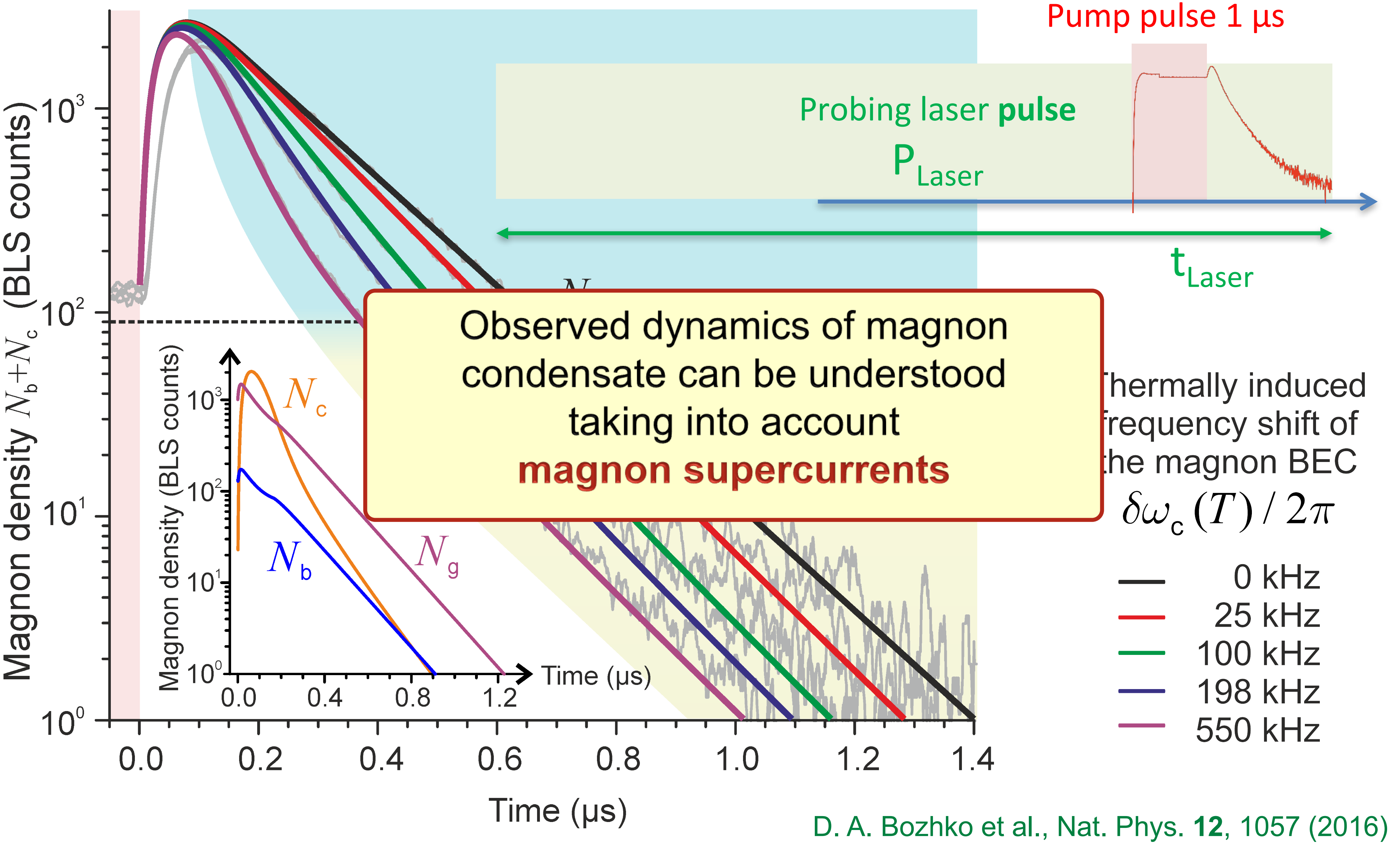
Dynamics of condensed magnons in thermal gradient - comparison with theory



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

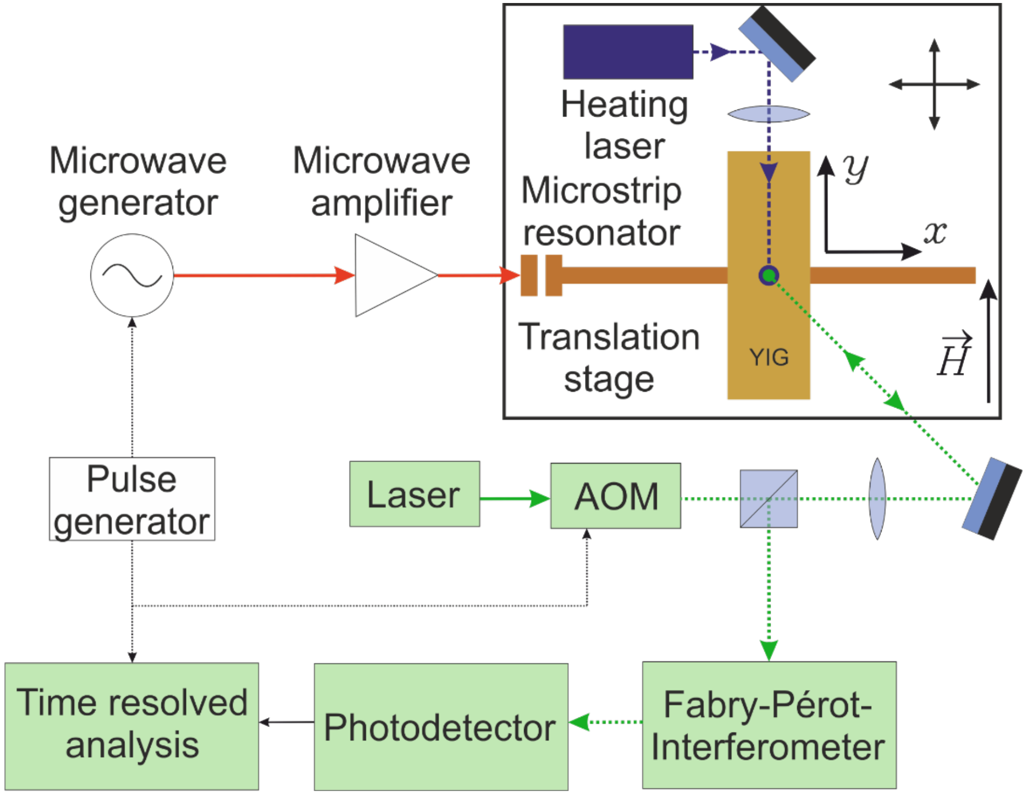
Dynamics of condensed magnons in thermal gradient - comparison with theory

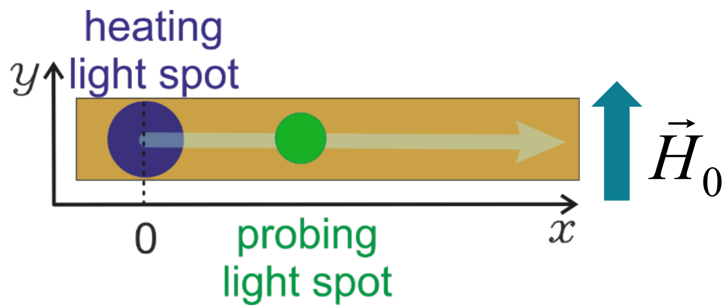


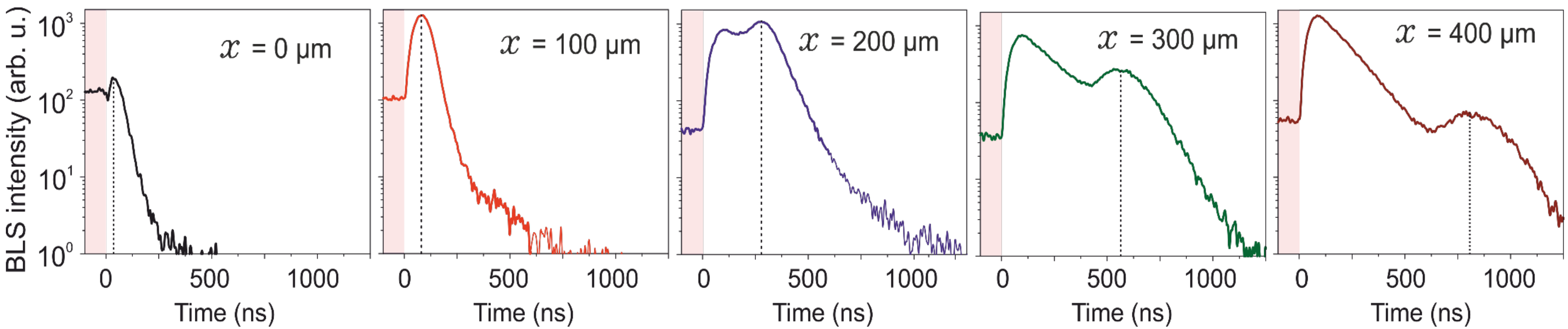
Observed dynamics of magnon condensate can be understood taking into account **magnon supercurrents**

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

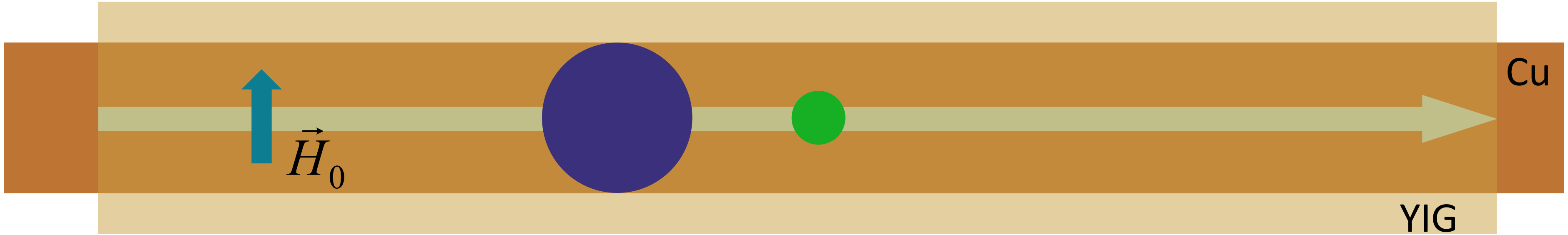
Non-local measurements: supercurrent magnon transport

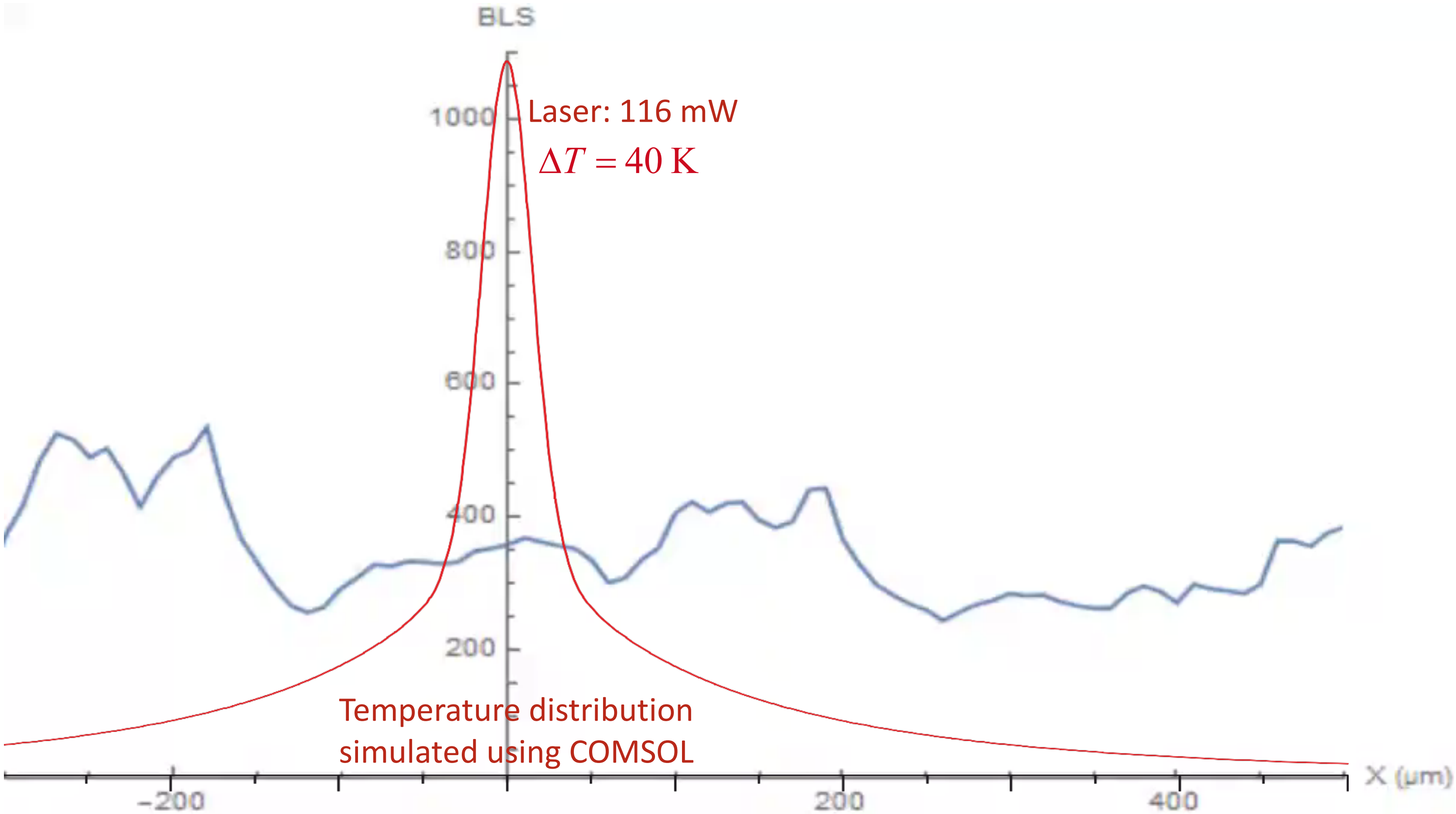




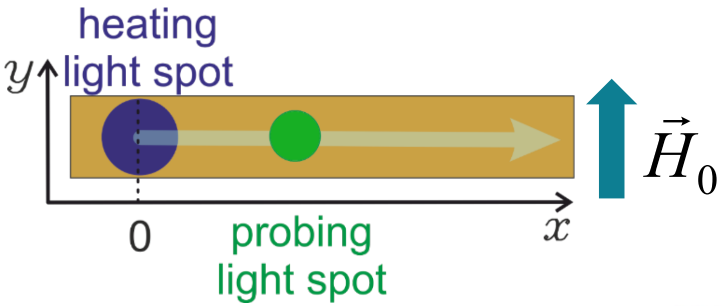


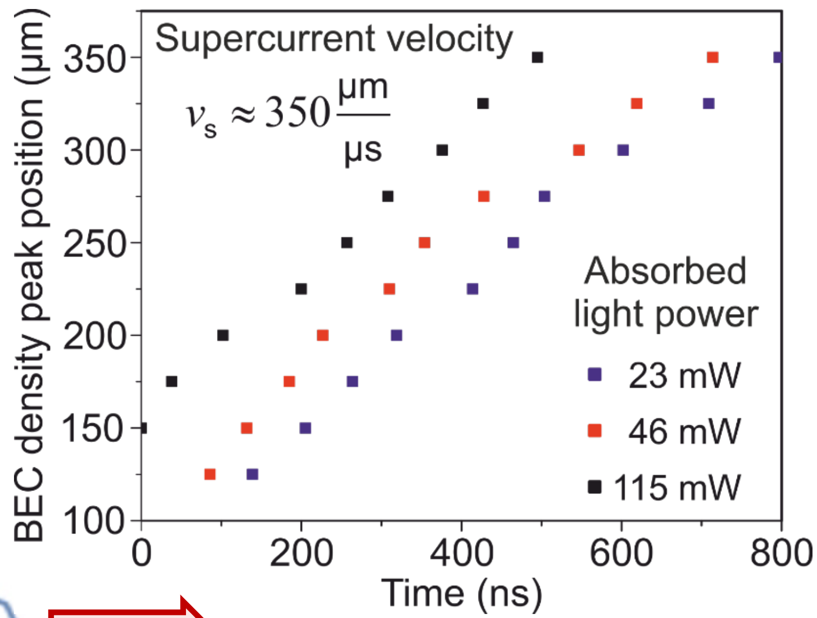
Non-local measurements: supercurrent magnon transport

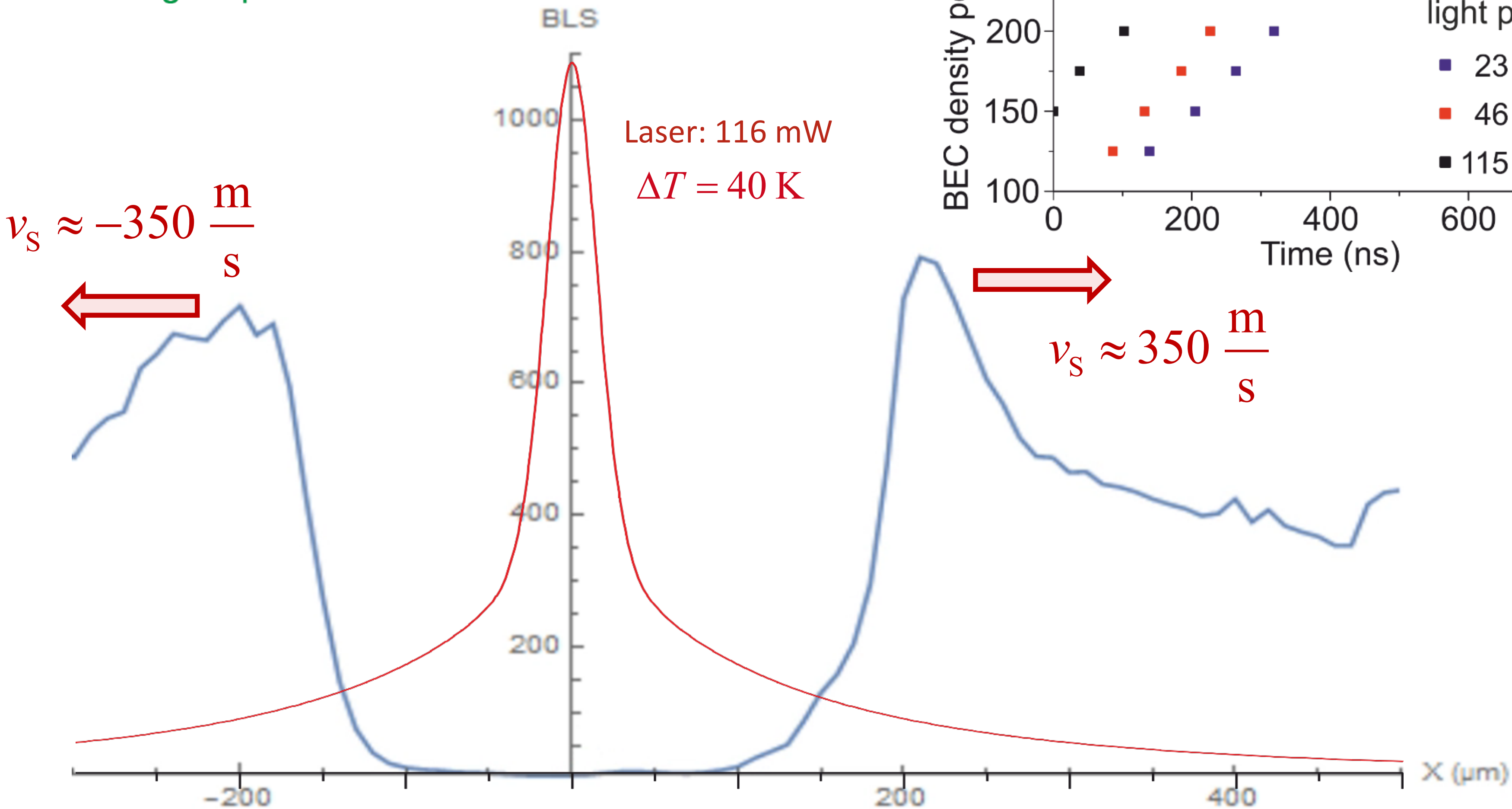




Non-local measurements: supercurrent magnon transport







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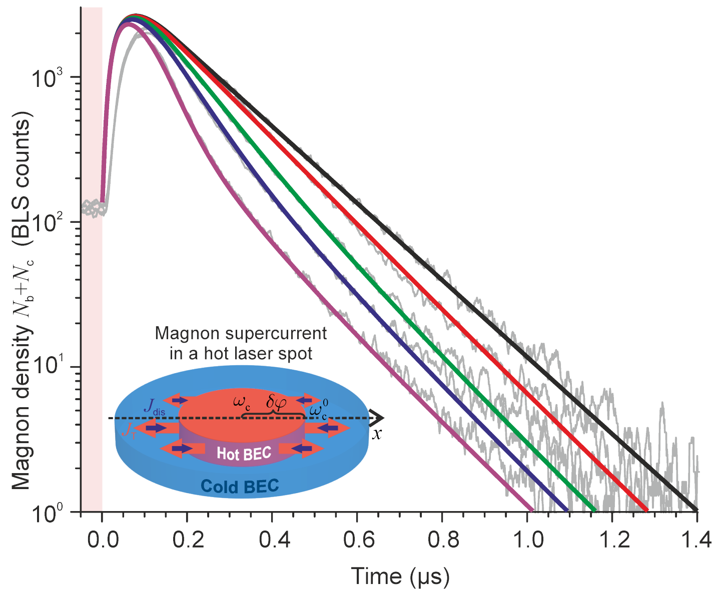
Summary II

1. Magnonics provides model system for macroscopic quantum phenomena
   - Room temperature experiments
   - Tool: Brillouin light scattering

2. First evidence for magnon supercurrent in a room-temperature magnonic Bose Einstein condensate found



3. Supercurrent depends on phase gradient induced by lateral temperature gradient

4. Bose Einstein magnon condensate with zero group velocity can be used for spin transport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