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AG MAGNETISMUS TU KAISERSLAUTERN

Tutorial: Magnonics

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Frankfurt-Kaiserslautern-Mainz

OPTIMAS light-spin-matter

erc

Tutorial: Magnonics

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Technische Universität Kaiser

Happy Birthday, Jairo

SFB/Transregio 49
Frankfurt-Kaiserslautern-Mainz

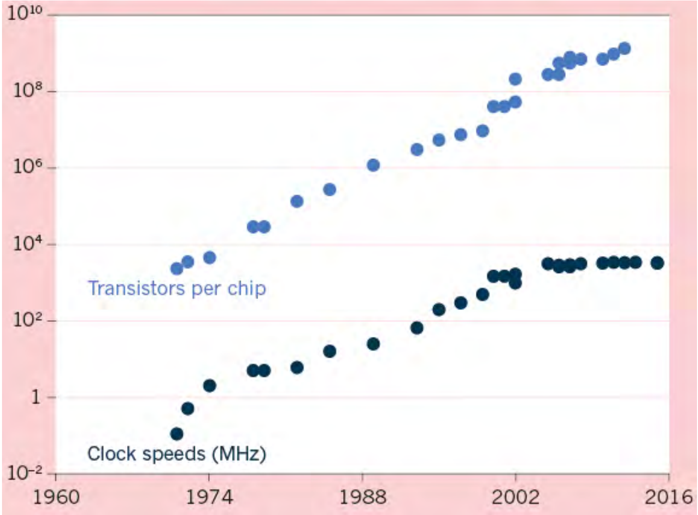
Post CMOS?

CMOS is coming to the end of Moore‘s law

- Waste energy production
- End of scaling

Beyond current CMOS:

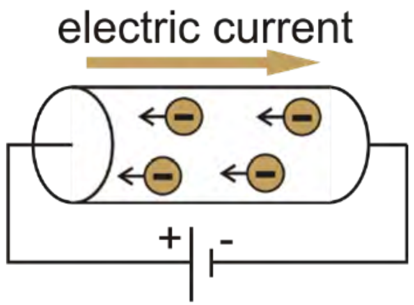
- Faster computing, less energy consumption
- Same technology for logic and data
- Logic circuits with reduced footprint and/or 3D

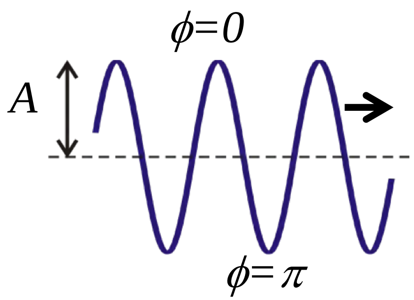


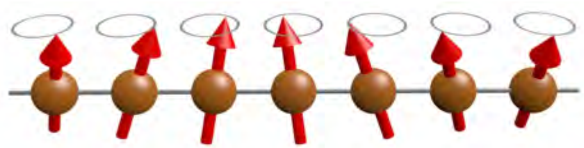
M. Mitchell, Nature **530**, 144 (2016)

Novel paradigm: wave computing

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







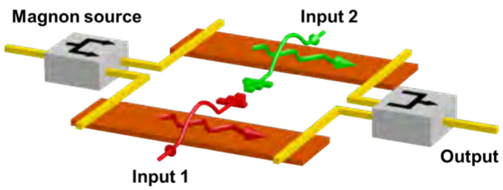
Magnon computing

Why spin waves?

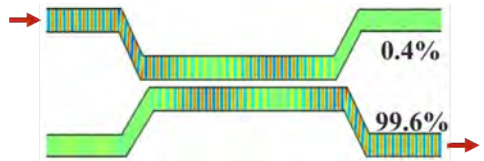
- wavelength down to nanometer, frequency up to several THz
- interference effects easily accessible
- efficient nonlinear effects
- room temperature
- no Joule heat, “insulatronics”
- wave-based computing: smaller footprint, all-wave logic
- good converters to CMOS →“magnon spintronics”

Achievements

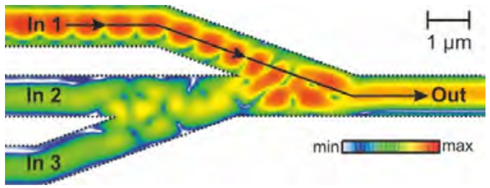
Logic gates



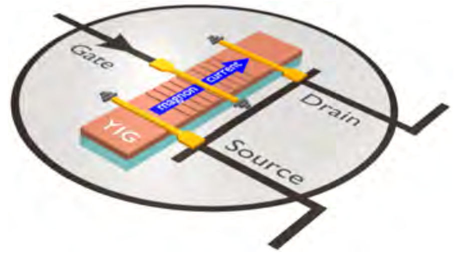
Directional coupler



Majoriy gate



Magnon transistor



Andrii Chumak, Kaiserslautern

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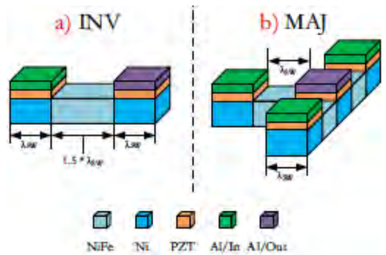
Spin-wave device architectures

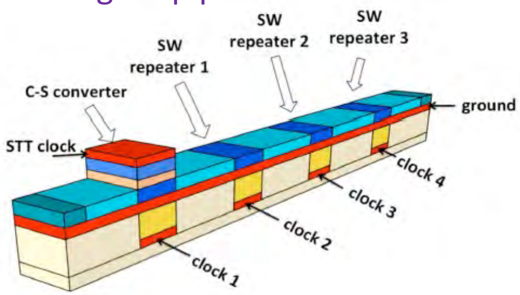
L. Amarú, P.-E. Gaillardon, G. De Micheli
(EPFL,Switzerland)

Majority based synthesis for nanotechnologies



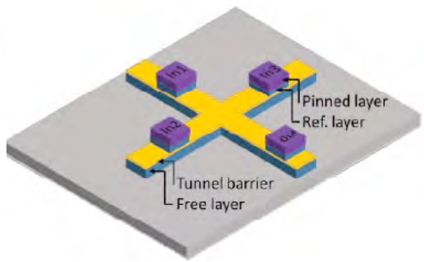
S. Dutta, A. Naeemi
(Georgia Institute of Technology, USA)

Non-volatile clocked spin wave nanomagnet pipelines



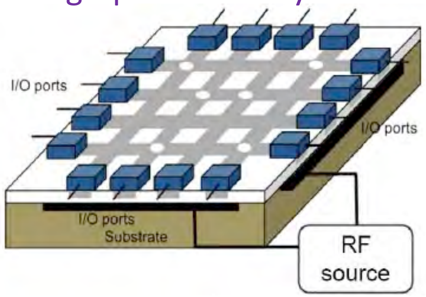
D. E. Nikonov, I. A. Young
(Intel Corp. Hillsboro, Oregon, USA)

Benchmarking, clocked spin-wave circuits



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

Majority gate, holographic memory



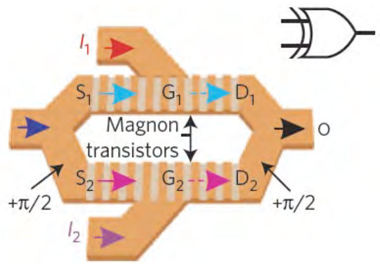
F. Ciubotaru, C. Adelmann
(Imec, Leuven, Belgium)

Magnetoacoustic nanoresonators

(a) ME cell schematic

A. Chumak
(TU Kaiserlautern, Germany)

Magnon transistor, integrated magnonic circuits



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

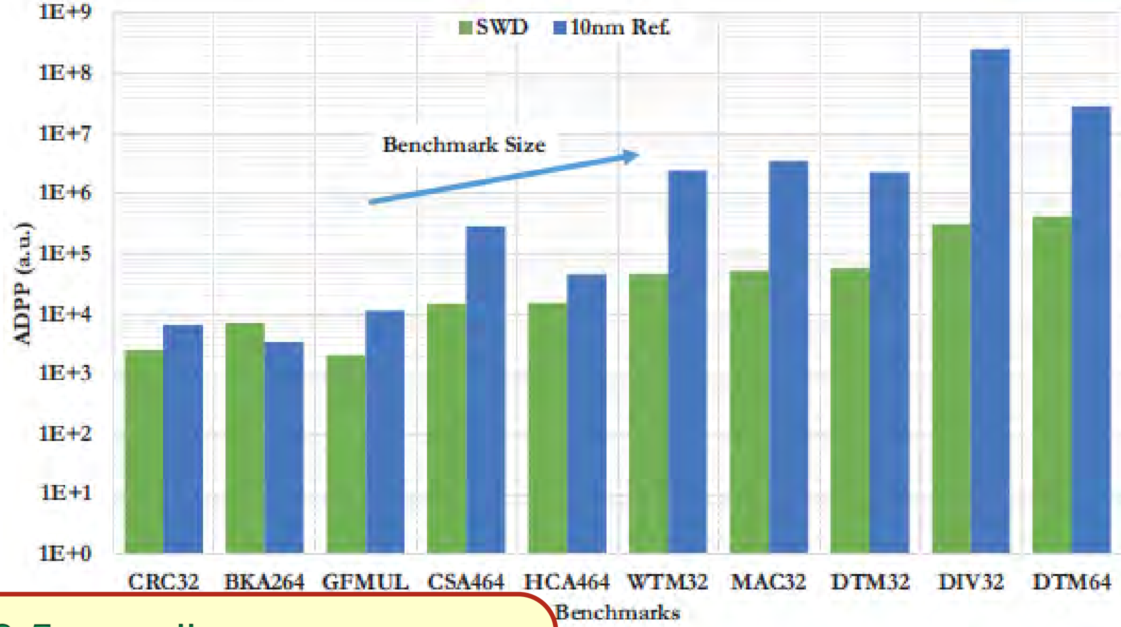
The list includes adders, multipliers,
a divider, and a cyclic redundancy check module

* Area-Delay-Power-Product (ADPP)

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

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

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Computing principles

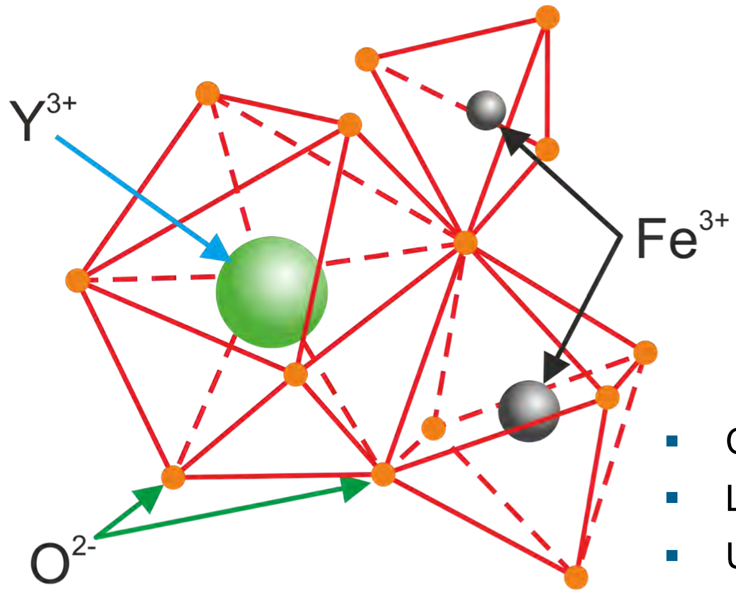
PERFORMANCE

- 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

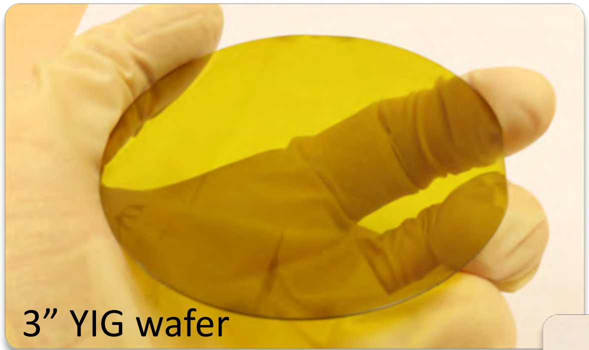
Quantum-Magnonic Analogies

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

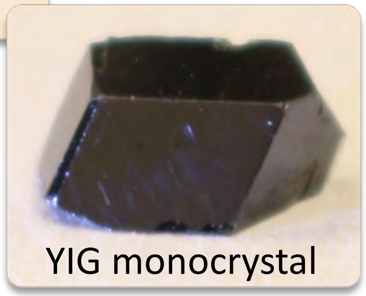
- Room temperature ferrimagnet (T_C = 560 K)
- Low phonon damping
- Magnon lifetime up to 700 ns !



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



Scientific Research Company
“Carat”, Lviv, Ukraine



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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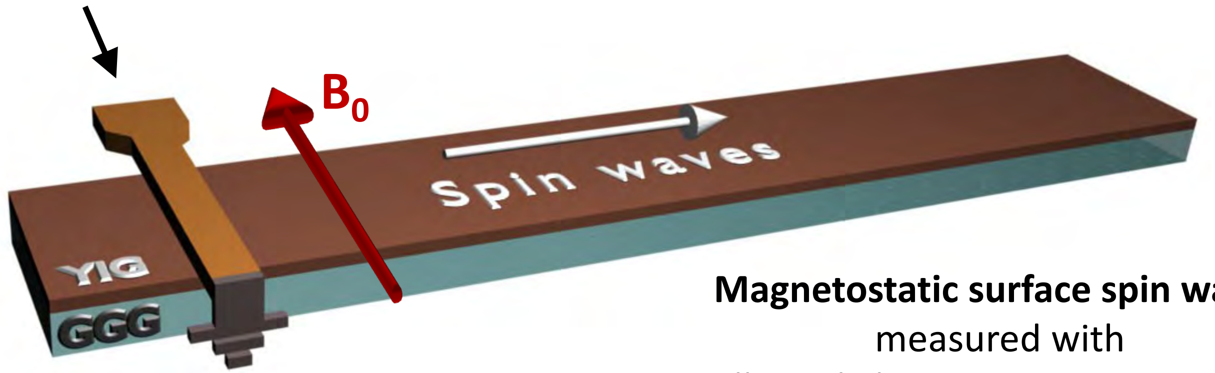
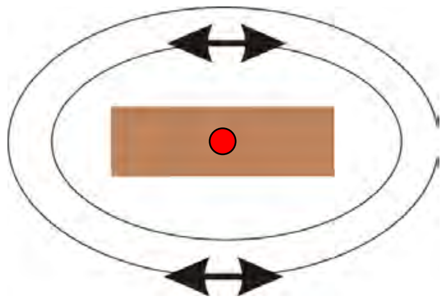
Excitation of dipolar spin waves

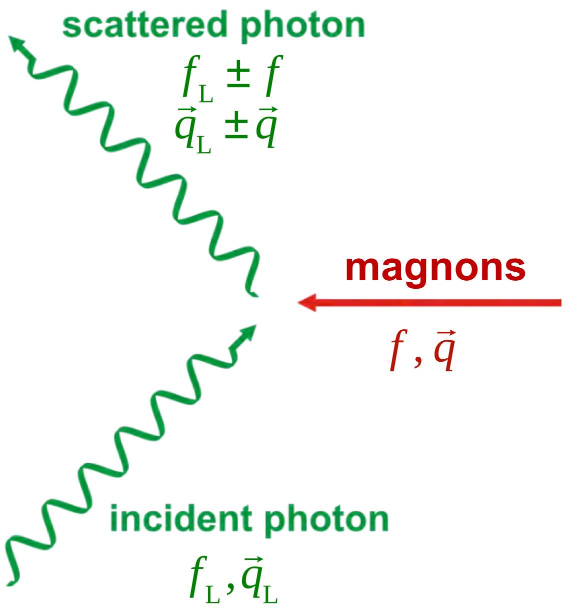


Magnetostatic surface spin waves
measured with
Brillouin light scattering spectroscopy



Alternating magnetic field

Brillouin light scattering spectroscopy

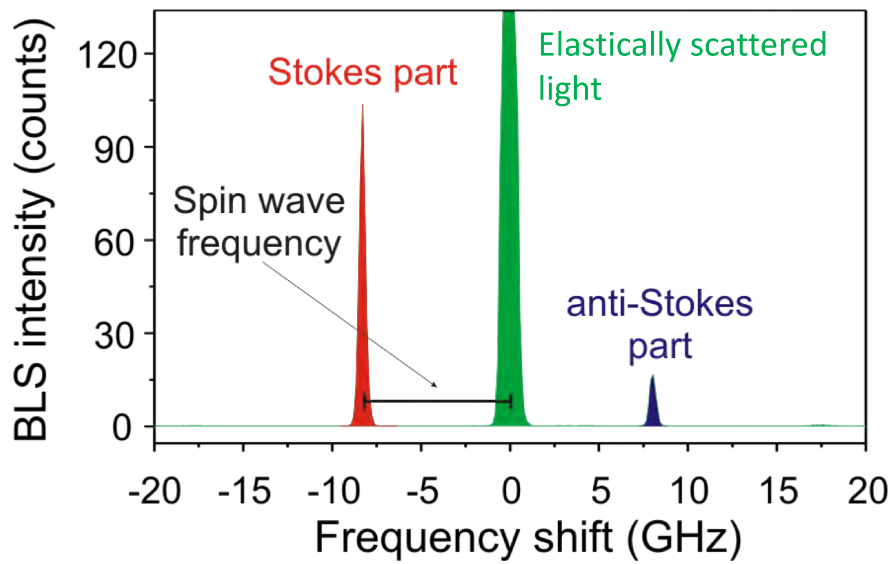


Brillouin light scattering process

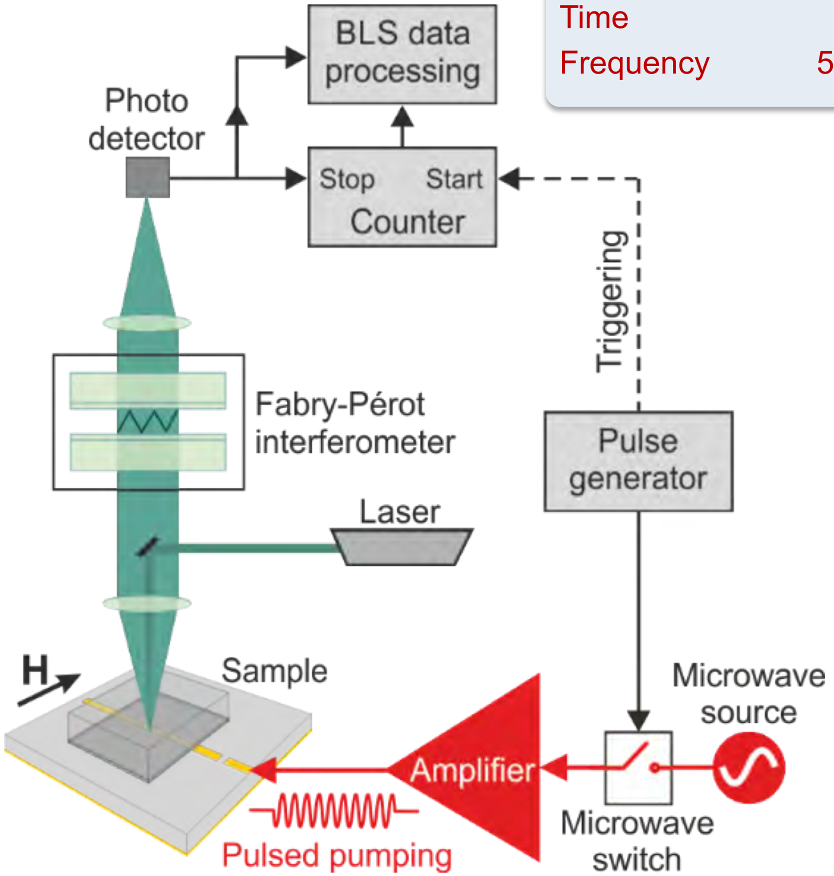
= inelastic scattering of photons from spin waves

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

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



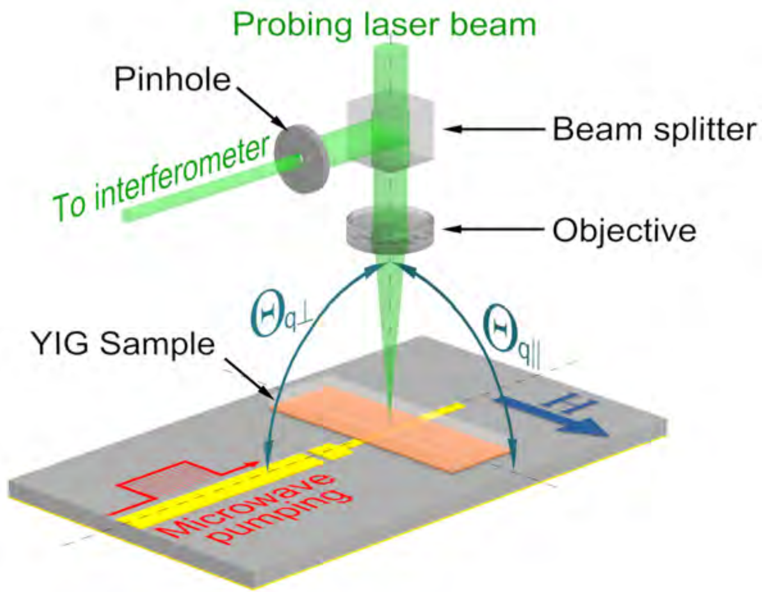
Time-, space- and wavevector-resolved Brillouin light scattering spectroscopy



Resolution

Time	1 ns
Frequency	50 MHz

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



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

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“Magnonics” team

Kaiserslautern PI Team

A. Chumak

P. Pirro

T. Brächer

V. Vasyuchka

A. Serga

Main External Collaborators

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)

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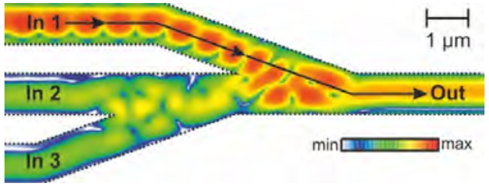
AG Magnetismus

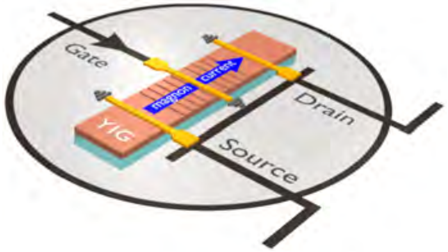
Prof. B. Hillebrands, Jun. Prof. A. V. Chumak, V. Lauer, Q. Wang, P. Frey, B. Heinz, L. Mihalceanu, M. Kewenig, Dr. D. A. Bozhko, M. Schneider, Dr. P. Pirro, M. Schweizer, Dr. habil. A. A. Serga, Dr. T. Langner, E. Wiedemann, A. Kreil, Dr. A. Conca Parra, S. Steinert, M. Geilen, S. Keller, H. Schäfer,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

Advanced magnonics

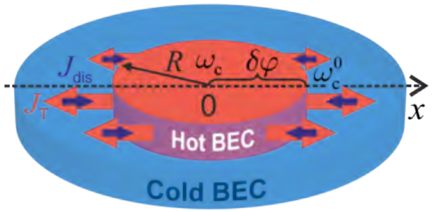
I. Magnon interference logic



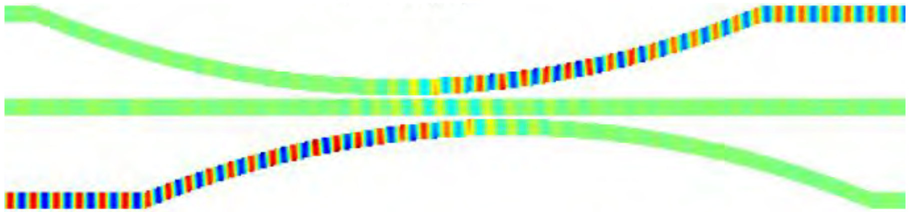
II. Non-linear magnonics: Magnon transistor



III. Magnonic macroscopic quantum state



IV. Quantum-classical analogies in magnonics



Advanced magnonics

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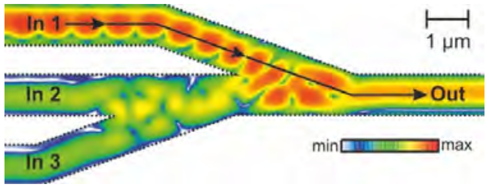

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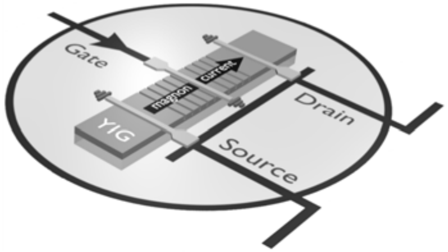

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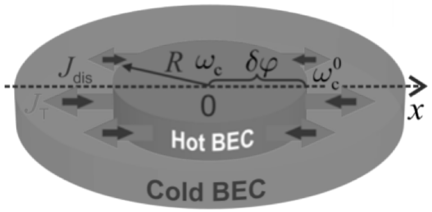
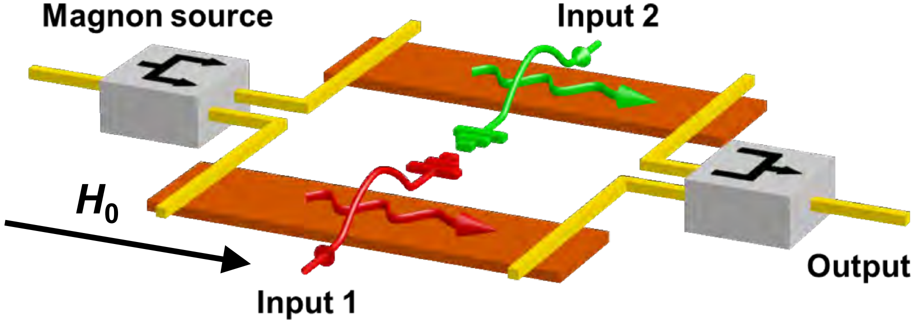


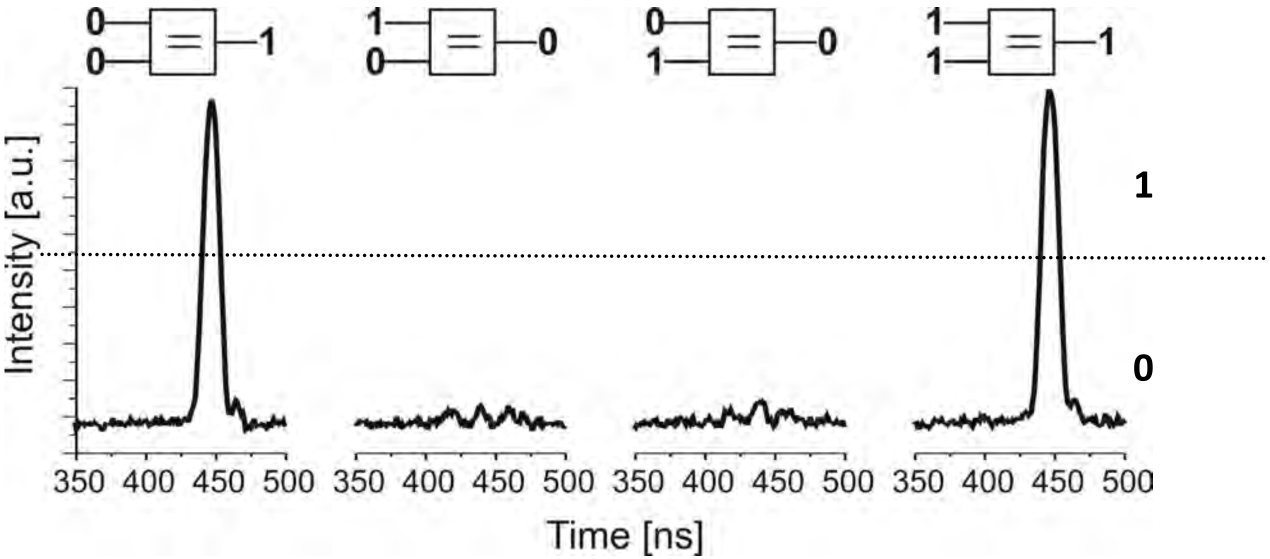
IV. Quantum-classical analogies in magnonics

First prototype Mach-Zehnder interferometer based spin-wave logic gate



Inputs		Output
A (I_1)	B (I_2)	
0 (0)	0 (0)	1
0 (0)	1 (I_π)	0
1 (I_π)	0 (0)	0
1 (I_π)	1 (I_π)	1

Realization of XNOR gate



Kostylev et al., APL **87**, 153501 (2005)

Schneider et al., APL **92**, 022505 (2008)

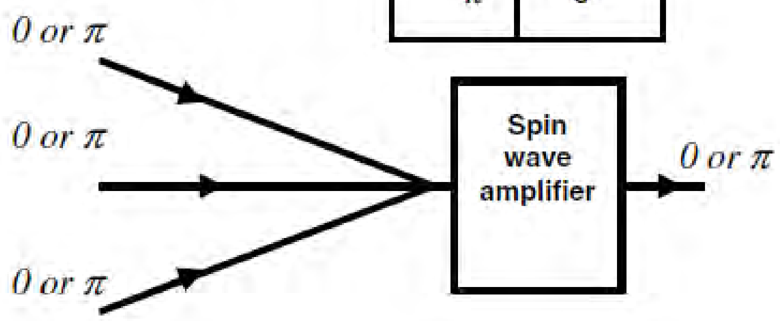
Magnon majority gates: General idea

Data is coded into spin-wave phase

Inverter:

Input	Output
0	π
π	0

Majority Gate:



Majority gate

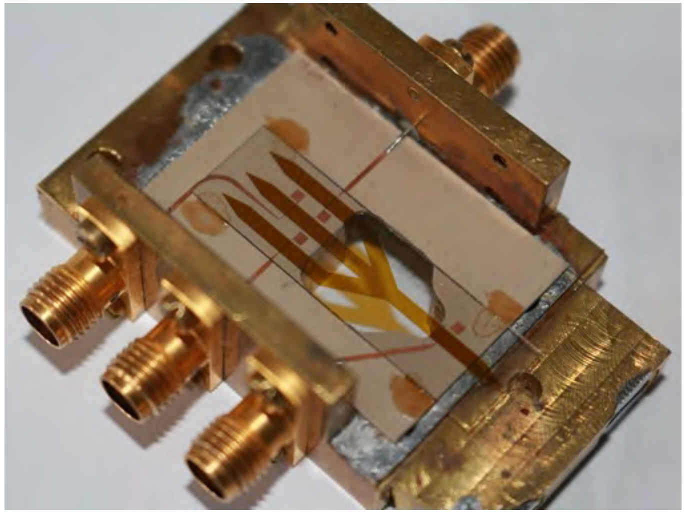
Input			Output
0	0	0	0
0	0	π	0
0	π	0	0
0	π	π	π
π	0	0	0
π	0	π	π
π	π	0	π
π	π	π	π

A. Khitun, et al., J. Phys. D. **43**, 264005 (2010)

- simple realization of majority gate (spin-wave combiner)
- trivial realization of NOT operation (= phase shift during Δx=λ/2 propagation)
- is all-magnonic
- magority gate + inverter are building blocks for full logic functionality

Experimental realization

Macroscopic majority gate

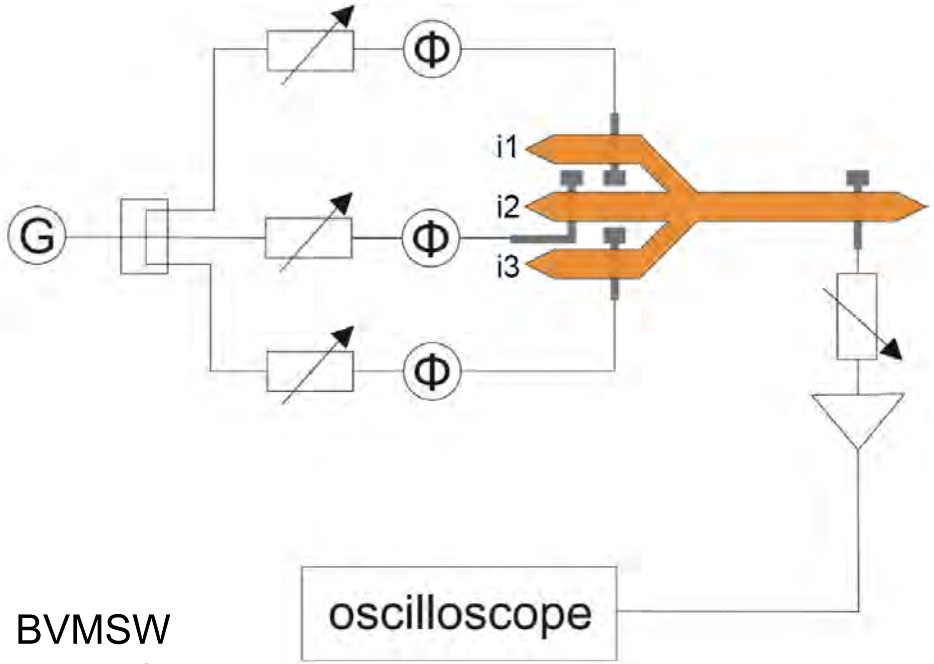


YIG sample:
- thickness 5.4 µm
- waveguide width 1.5 mm

Produced by Scientific Research Company Carat, Lviv, Ukraine

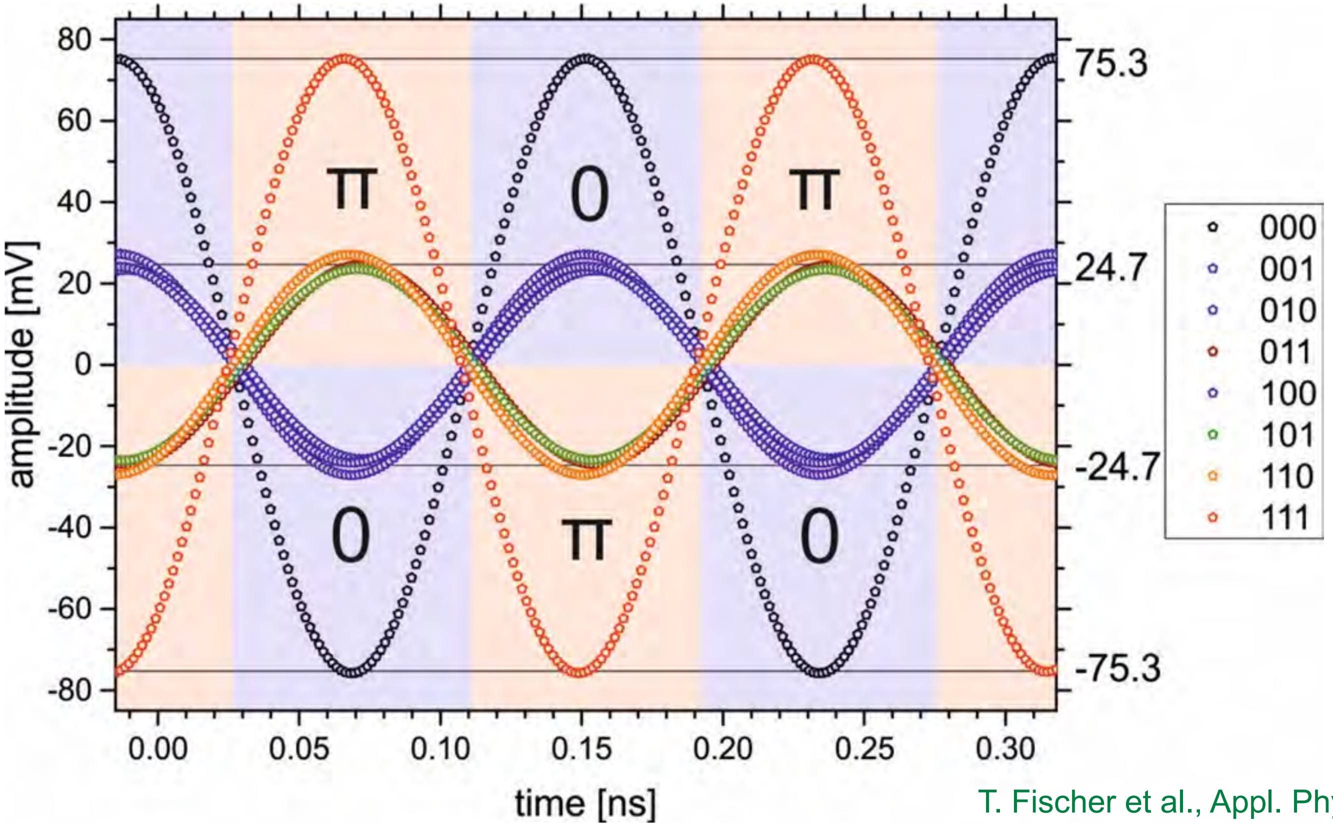
Geometry	BVMSW
Frequency	6.035 GHz
Magnetic field	1429 Oe

Experimental setup



T. Fischer et al., Appl. Phys. Lett. **110**, 152401 (2017)

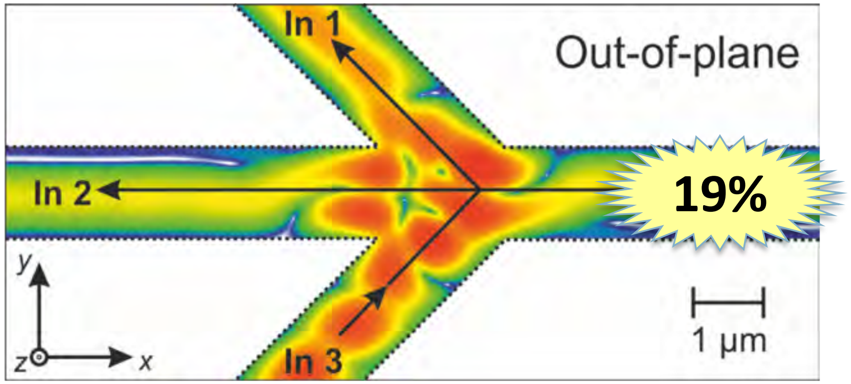
Superposition of all spin-wave channels



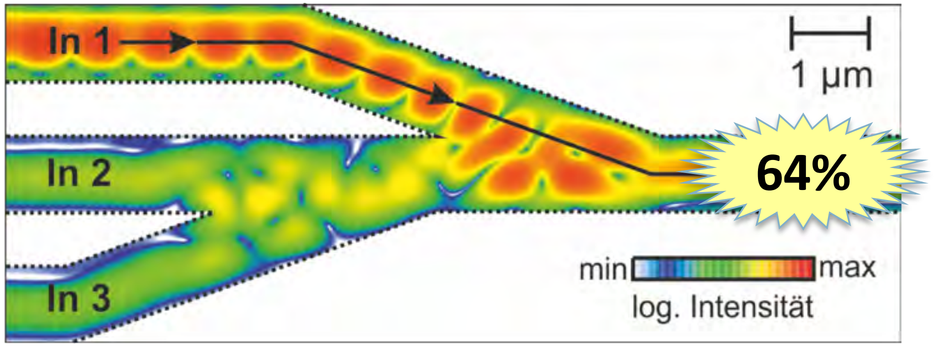
T. Fischer et al., Appl. Phys. Lett. **110**, 152401 (2017)

The output phase of the signal is defined by the majority of the input phases

Majority gates: Out-of-plane magnetization



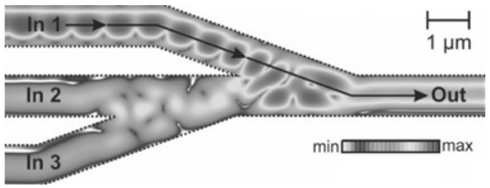
How to increase this value?



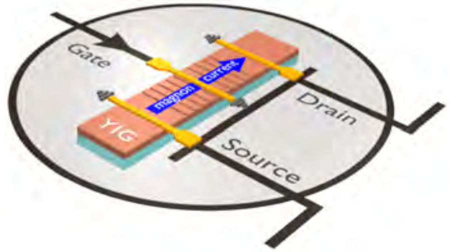
S. Klingler et al., Appl. Phys. Lett. **106**, 212406 (2015)

Advanced magnonics

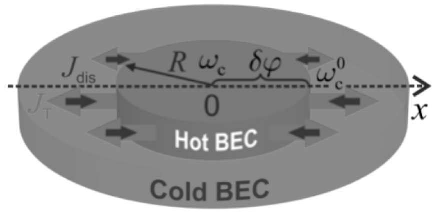
I. Magnon interference logic



II. Non-linear magnonics: Magnon transistor



III. Magnonic macroscopic quantum state



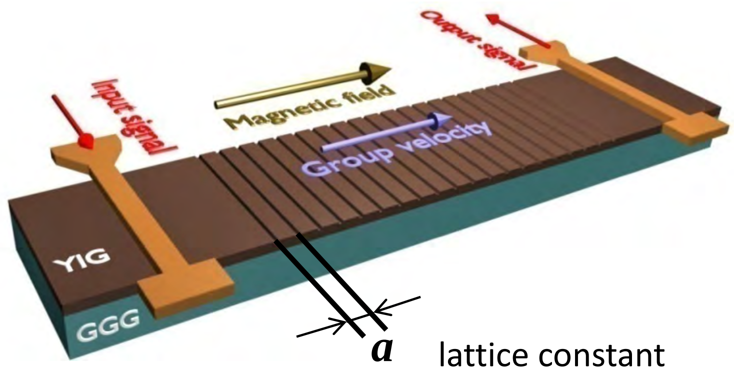
IV. Quantum-classical analogies in magnonics

Magnonic crystal

Magnonic crystal – magnetic meta-material:

- artificial medium with periodic lateral variation in magnetic properties
- Acts like magnonic Fabry-Pérot cavity characterized by quality factor

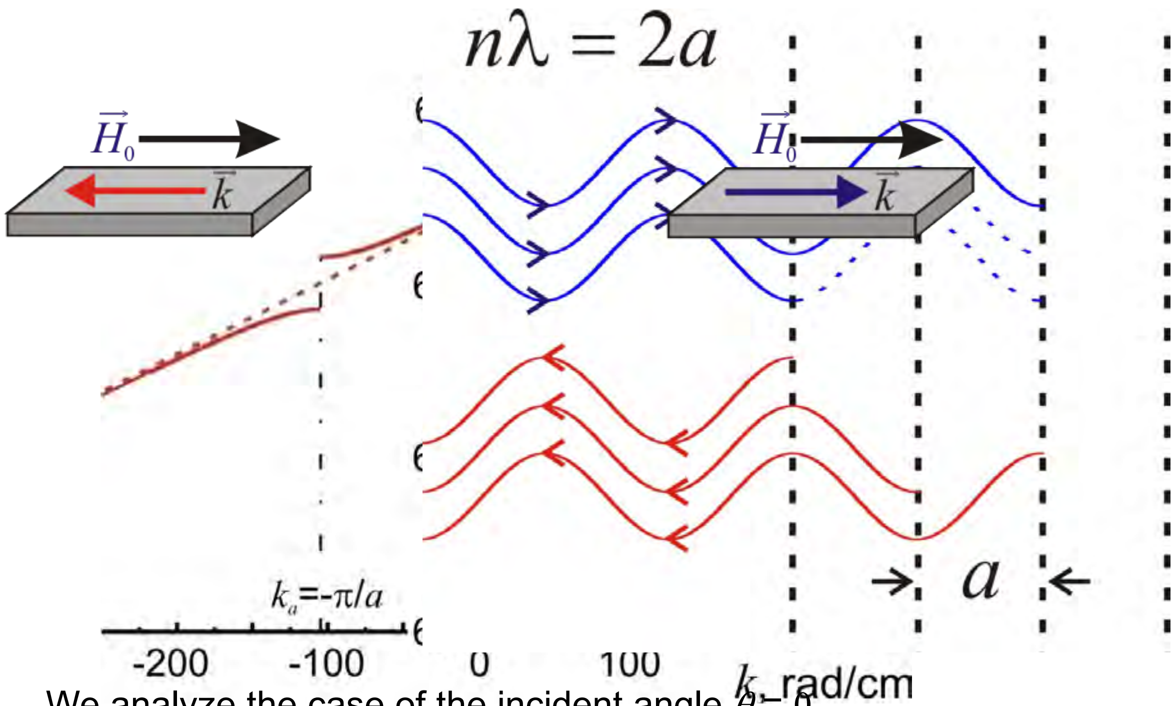
One-dimensional magnonic crystal:



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

Band gap

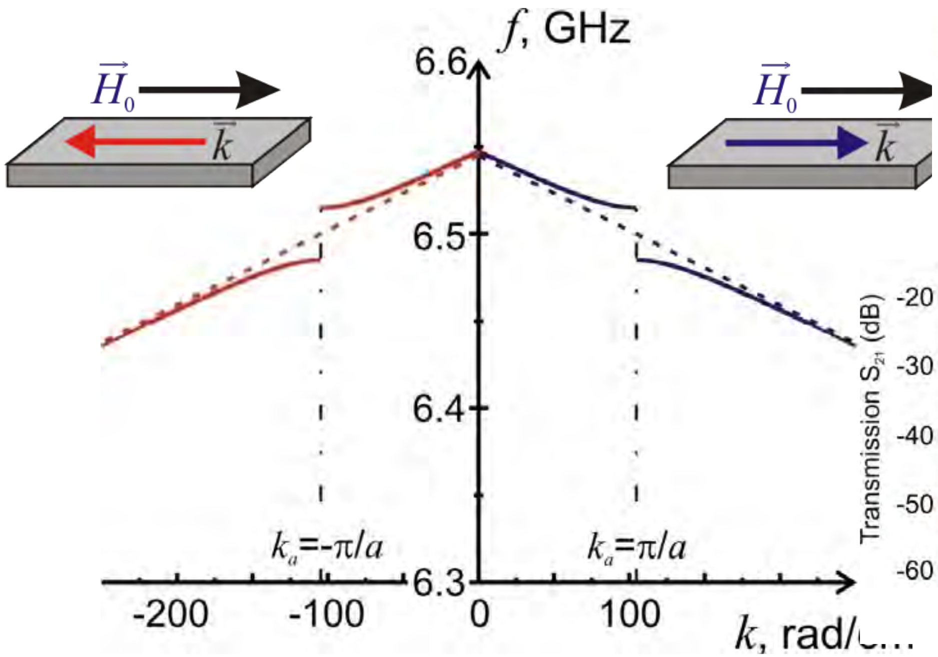
Band gaps – regions of the spectrum over which waves are not allowed to propagate

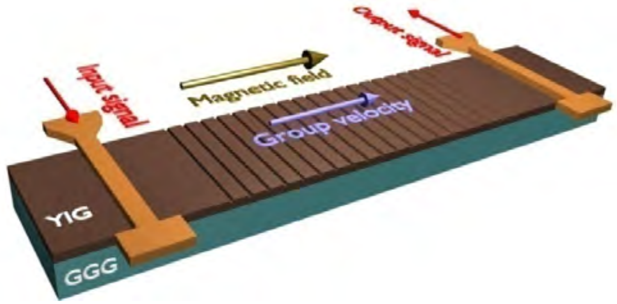


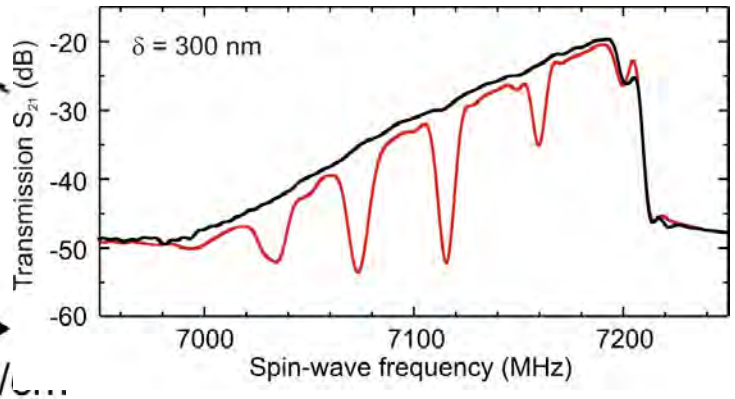
We analyze the case of the incident angle $\theta = 0$

Band gap

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

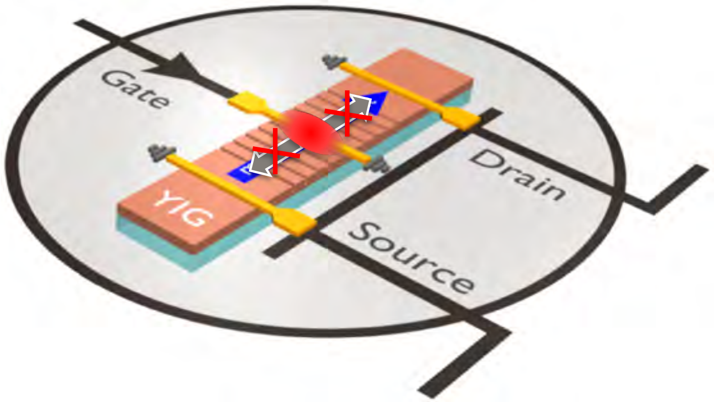




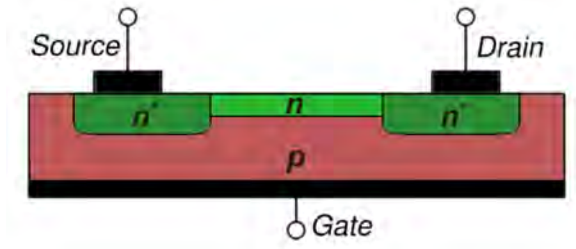


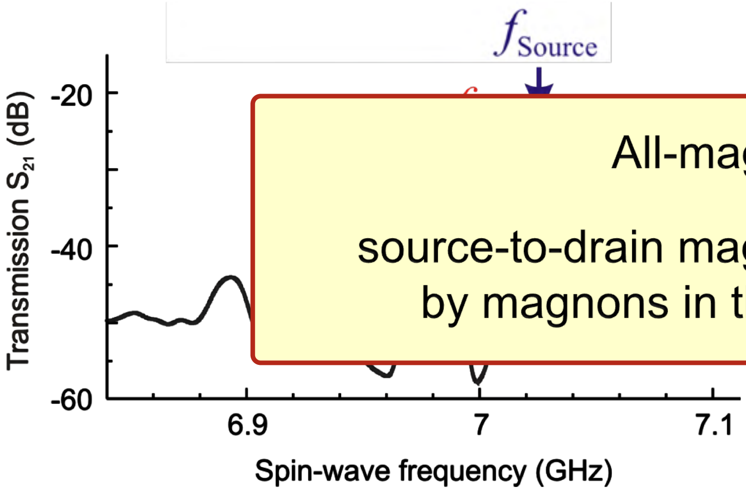
A.V. Chumak et al., Appl. Phys. Lett. **93**, 022508 (2008)

Magnon transistor



Semiconductor field-effect transistor:





All-magnon dev

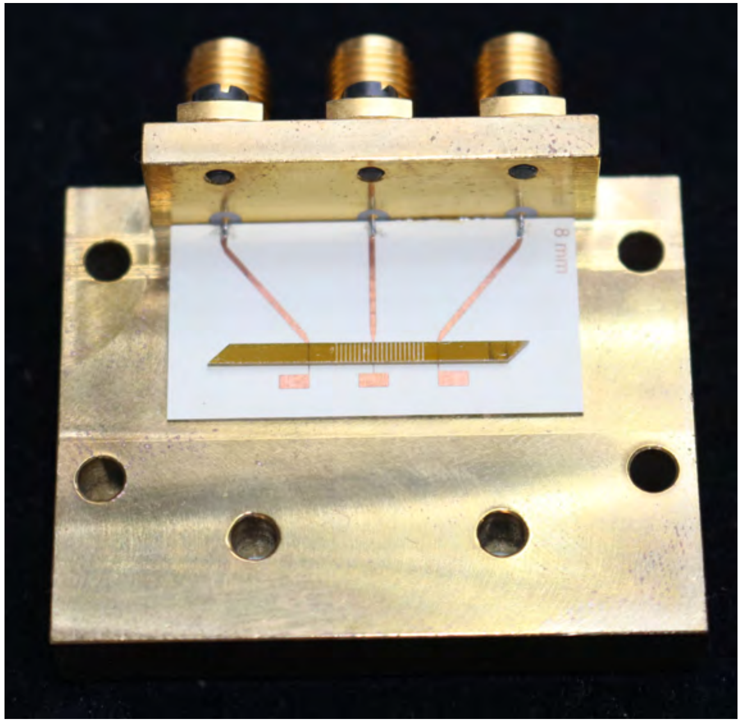
source-to-drain magnon flow
by magnons in the transis

Magnonic crystal acts as an enhancer of non-linear effects

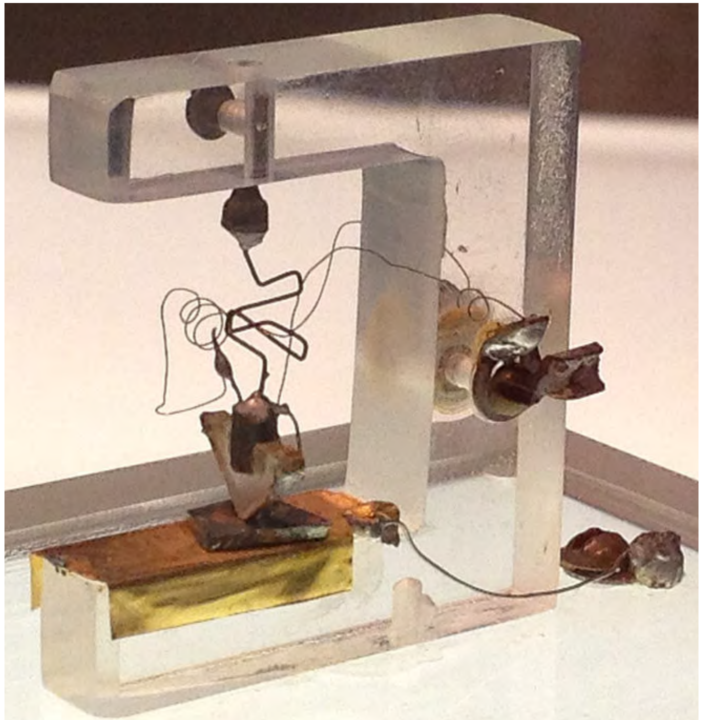
A.V. Chumak et al., Nat. Commun. **5**:4700 (2014)

First transistors

Magnon transistor prototype, 2014



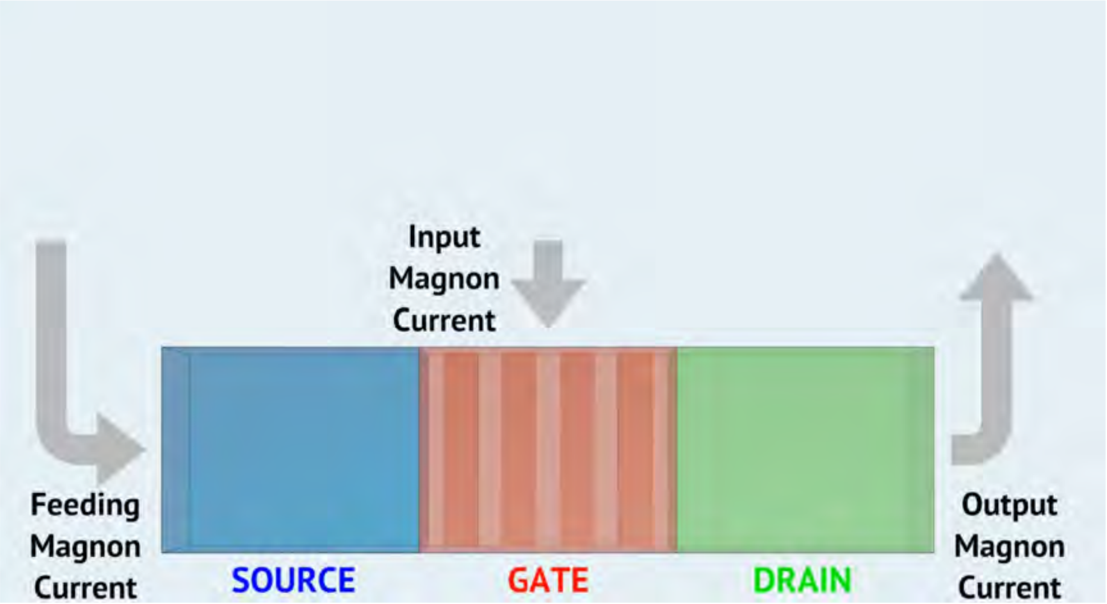
First transistor, 1947



https://de.wikipedia.org

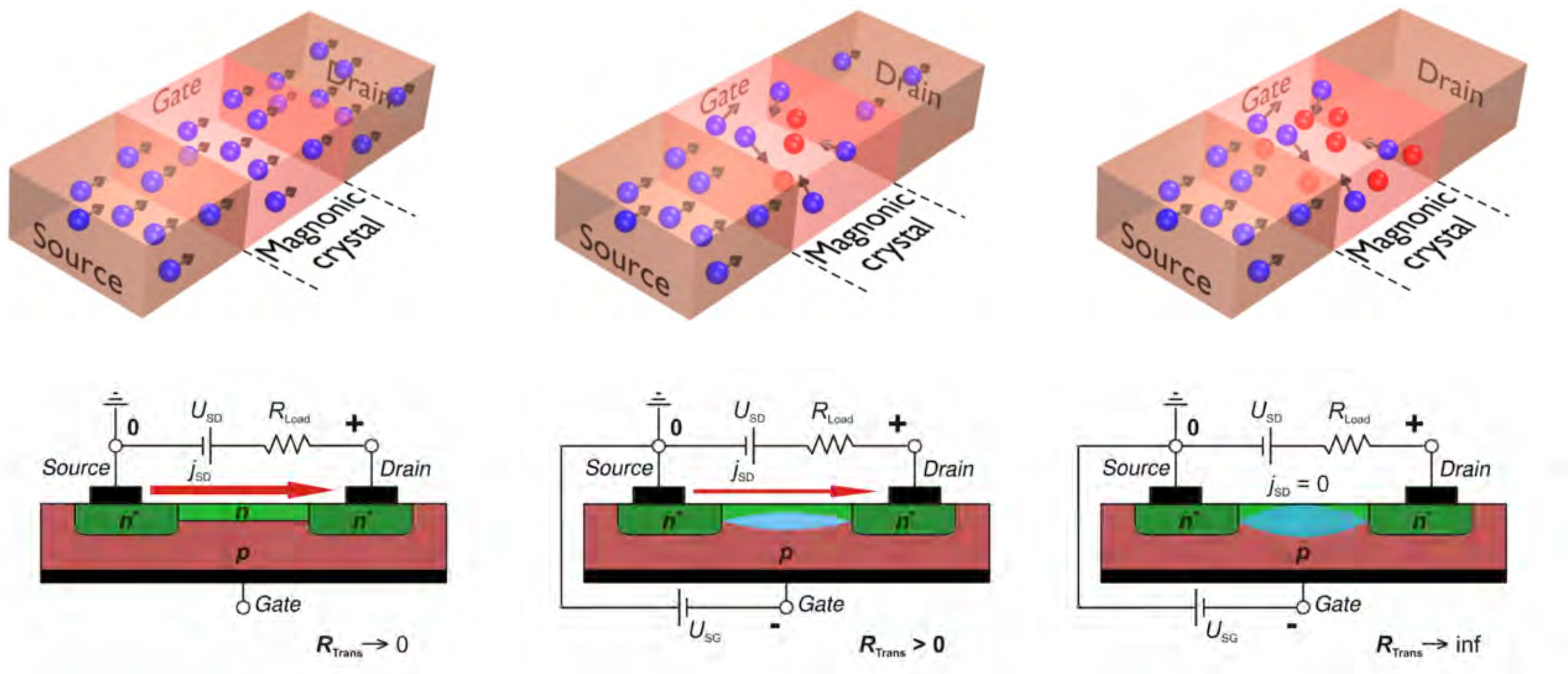
Magnon transistor

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



Magnon transistor

Opened: $R \rightarrow 0$	**Semi-closed:** R > 0	**Closed:** $R \rightarrow \infty$
Gate magnon density	Gate magnon density	Gate magnon density
$n_G = 0$	$n_G > 0$	$n_G >> 0$



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

TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

Magnon transistor

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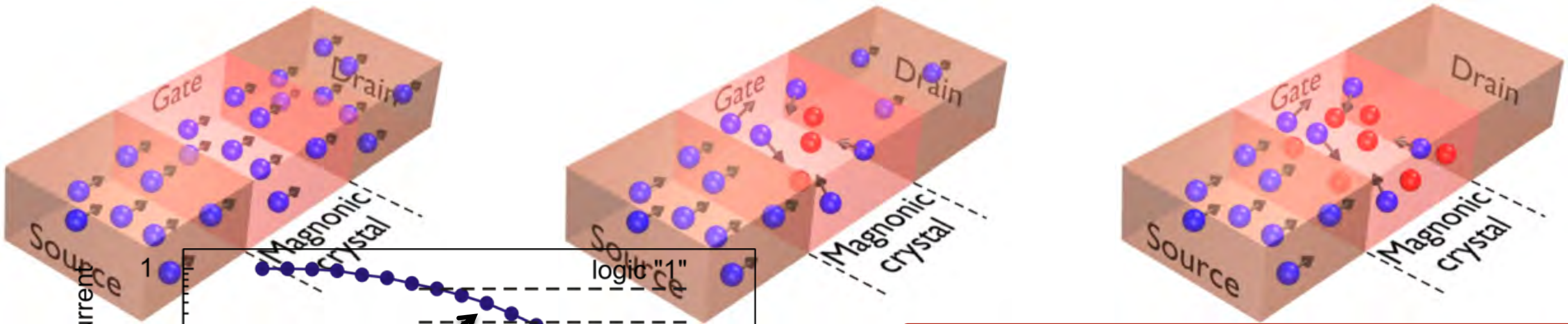
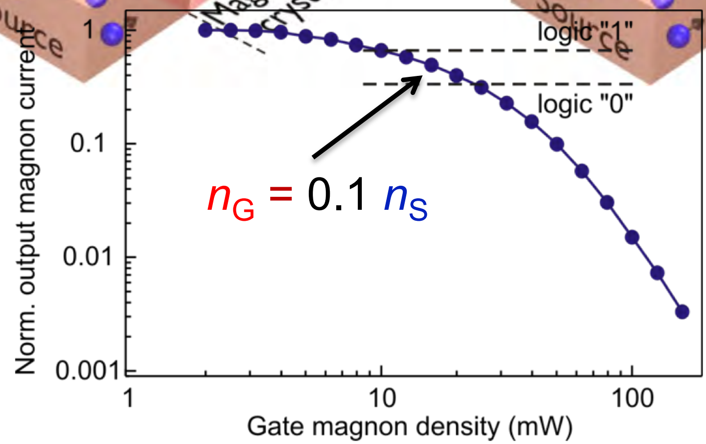


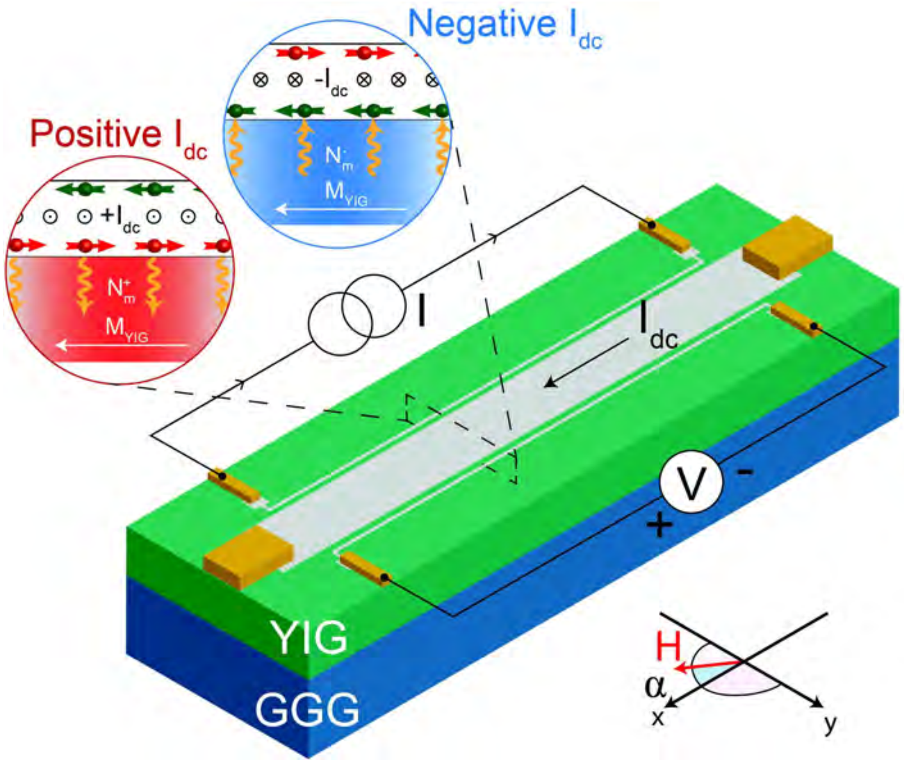


“magnon control by magnon“ principle was realized: data can be processed on the same magnetic chip

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

Magnon transistor based on the diffusive transport of thermal magnons

Proof of principle of a method for modulating the diffusive transport of thermal magnons



L. J. Cornelissen et al., Phys. Rev. Lett. **120**, 097702 (2018)

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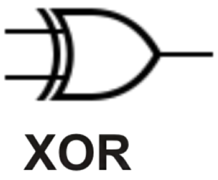
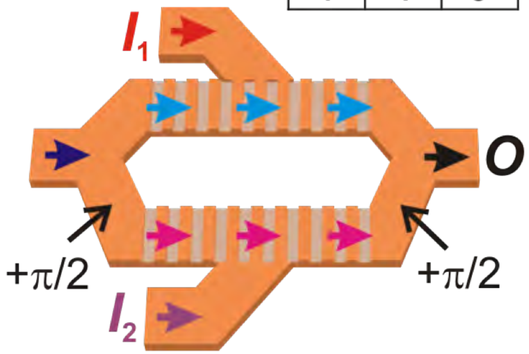
Logic operations

XOR logic gate

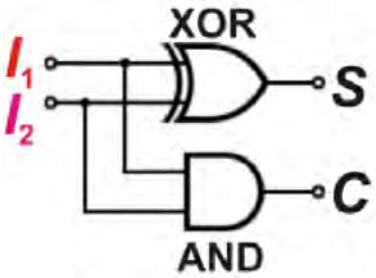


I_1	I_2	O
0	0	0
0	1	1
1	0	1
1	1	0

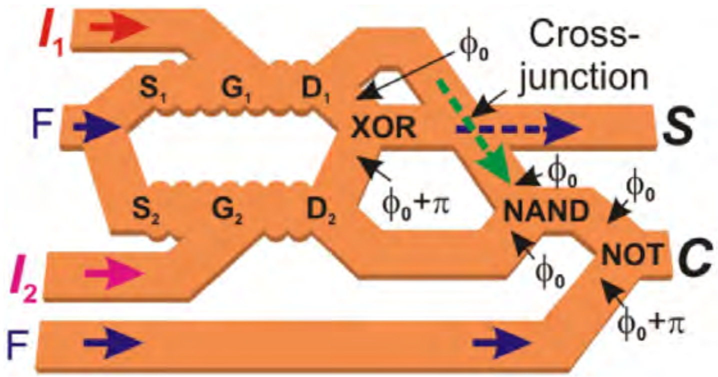


XOR gate requires 2 magnon transistors instead of 8 FET in CMOS

Half adder

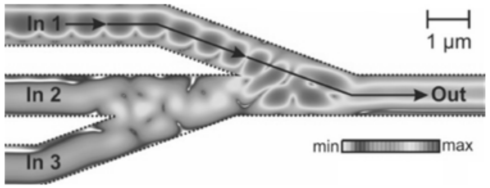


I_1	I_2	C	S
0	0	0	0
1	0	0	1
0	1	0	1
1	1	1	0

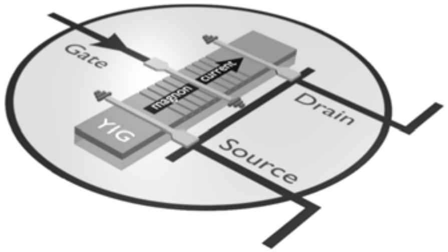


Advanced magnonics

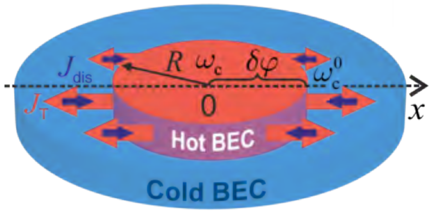
I. Magnon interference logic



II. Non-linear magnonics: Magnon transistor



III. Magnonic macroscopic quantum state



IV. Quantum-classical analogies in magnonics

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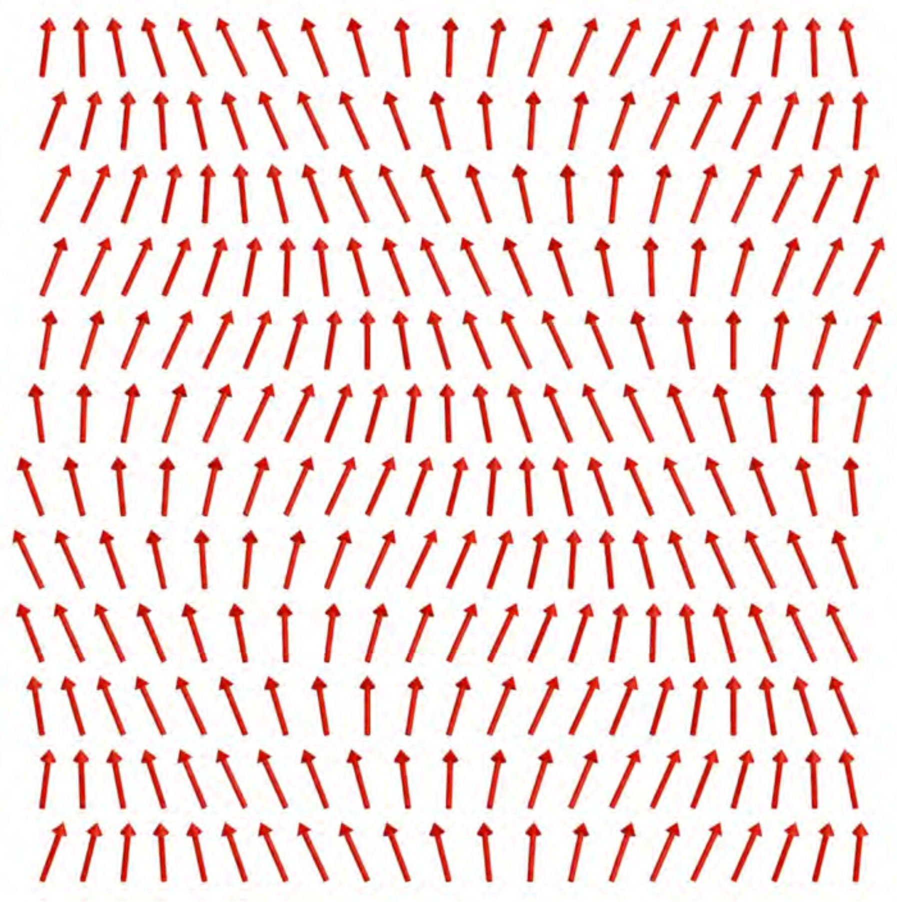
Magnon gas

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 distribution

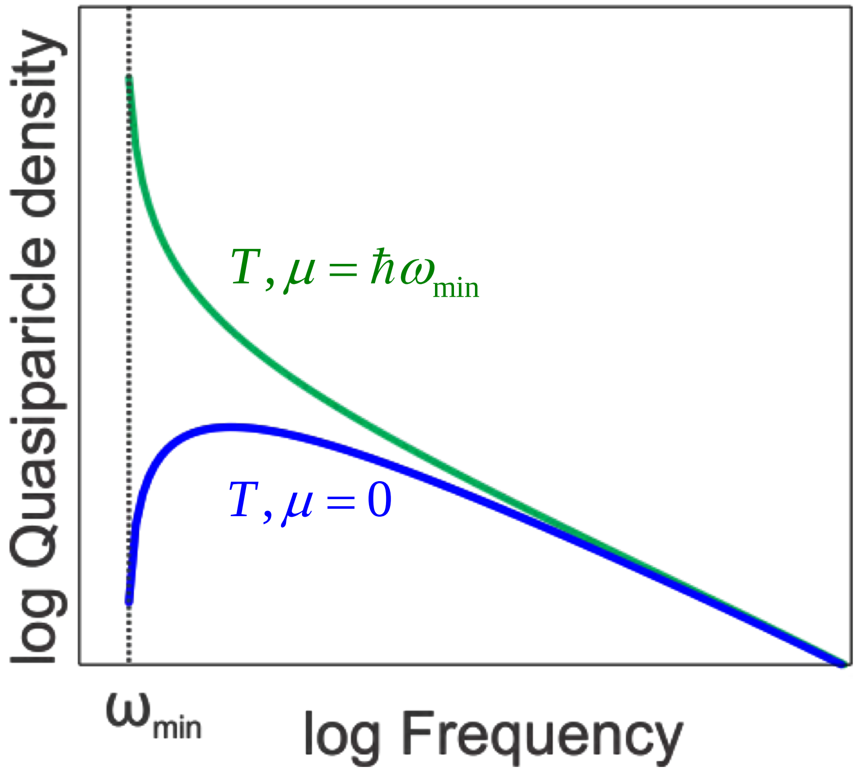
Magnon distribution

Bose-Einstein distribution

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

μ: chemical potential

Magnons are bosons (s=1) and similar to other quasi-particles are described in thermal equilibrium by Bose-Einstein distribution with zero chemical potential



Magnon spectrum of in-plane magnetized YIG film

Landau-Lifshitz equation

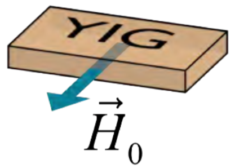
$$\frac{\partial \vec{M}}{\partial t} = -|\gamma|\, \vec{M} \times \vec{H}_{\text{eff}}$$

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

dipolar interaction

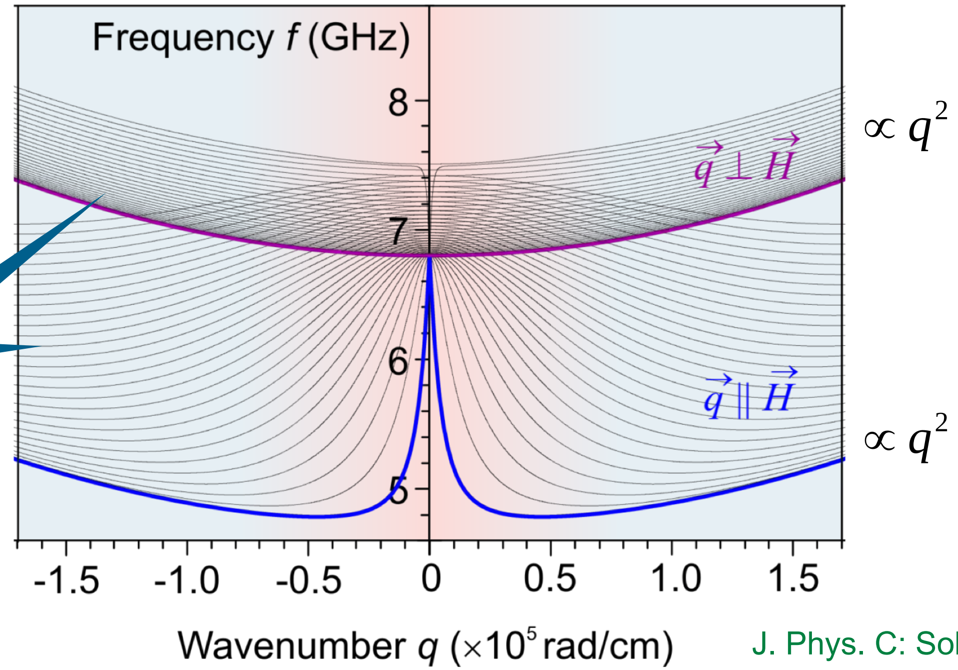
exchange interaction

$H_0 = 1710$ 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)

Technische Universität Kaiserslautern

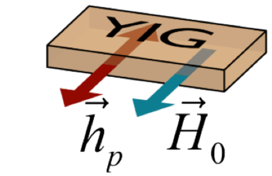
Control of magnon gas density by parametric pumping

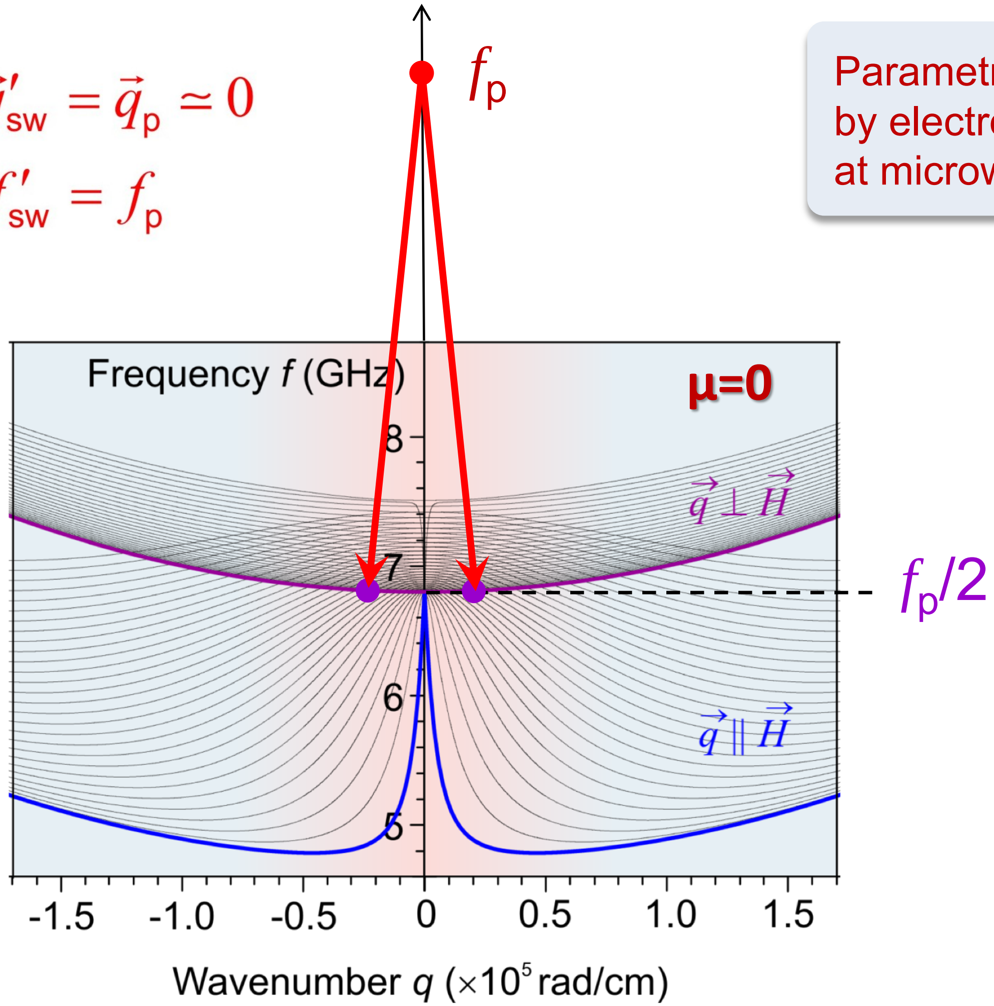
Energy and momentum conservation laws for parametric pumping

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

Parametric pumping by electromagnetic wave at microwave frequency

$H_0 = 1710$ Oe





Bose-Einstein distribution

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μ: chemical potential

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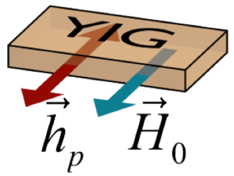

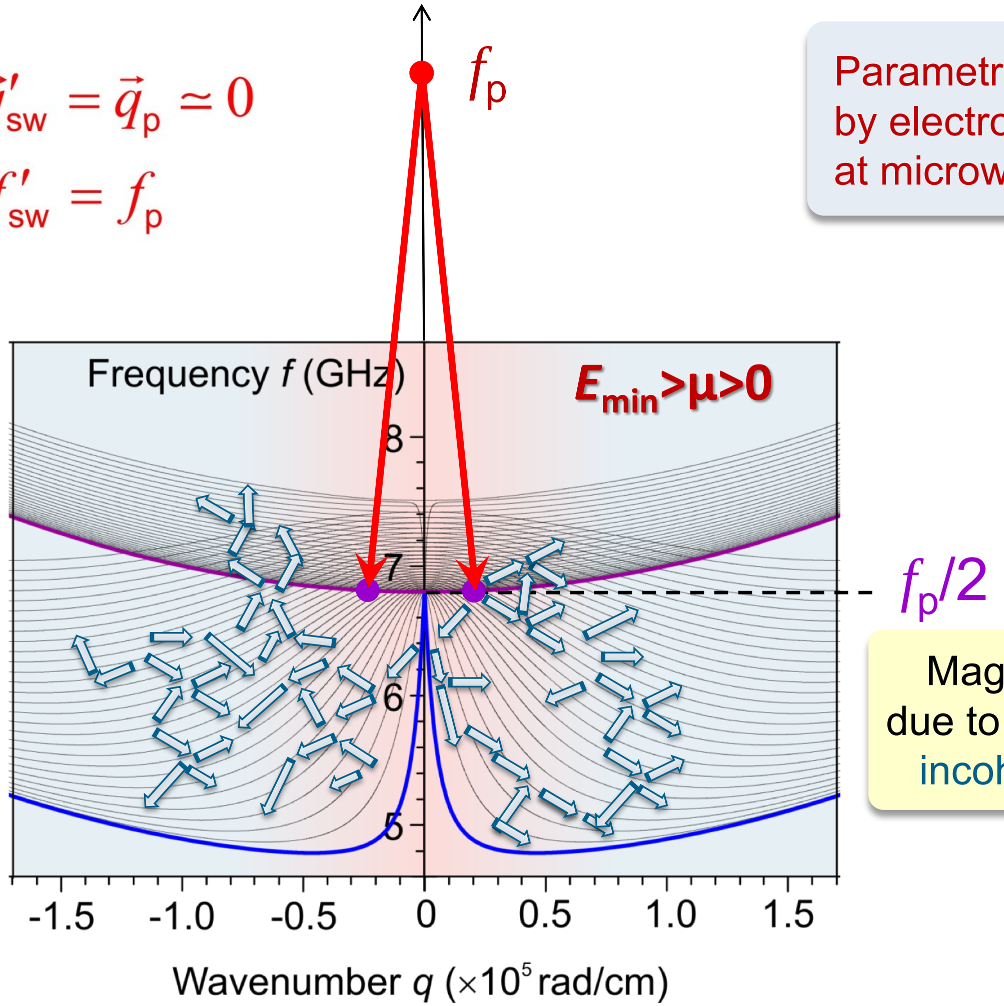

Magnon thermalization due to 4-particle scattering: incoherent magnon gas

Bose-Einstein distribution

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μ: chemical potential

Bose-Einstein condensation of magnons

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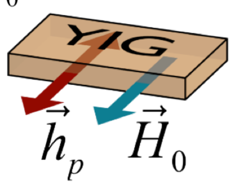
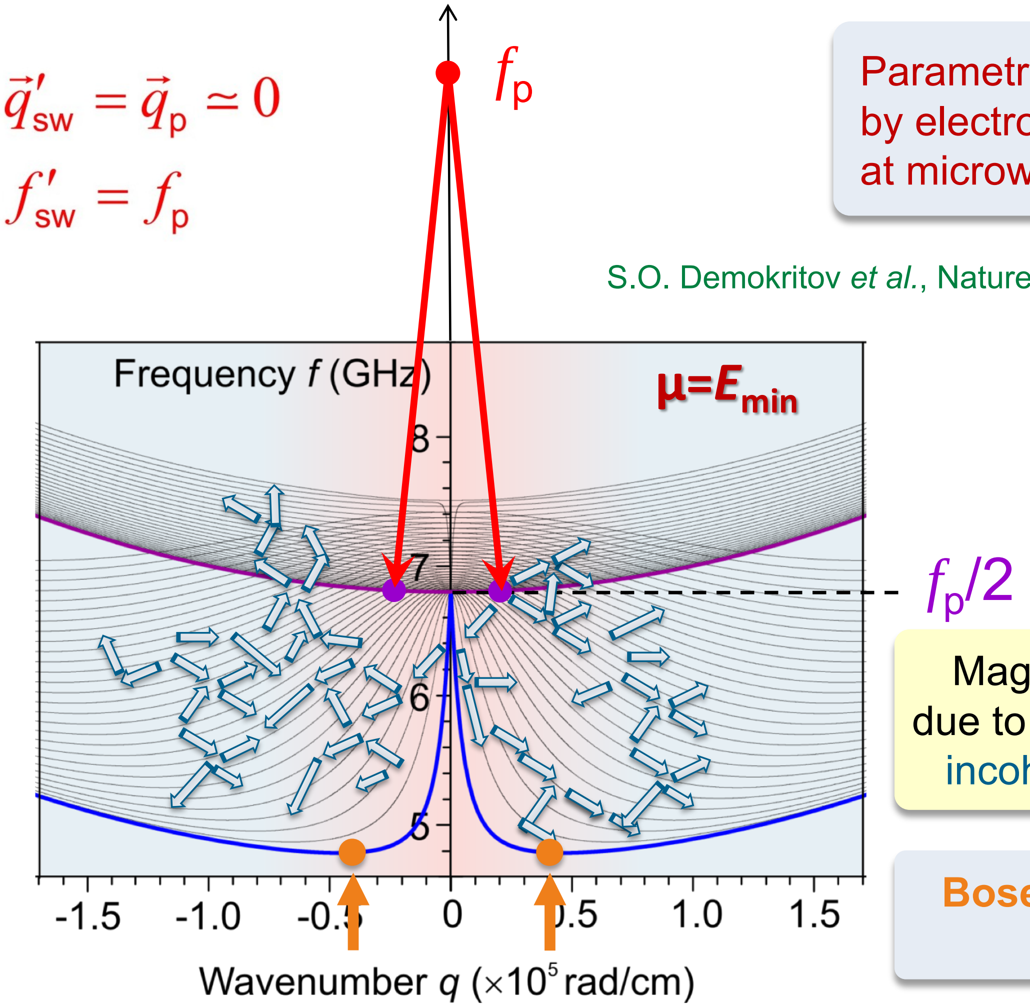
$$\begin{cases} \vec{q}_{sw} + \vec{q}\,'_{sw} = \vec{q}_p \simeq 0 \\ f_{sw} + f'_{sw} = f_p \end{cases}$$

Parametric pumping by electromagnetic wave at microwave frequency

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

$H_0 = 1710$ Oe





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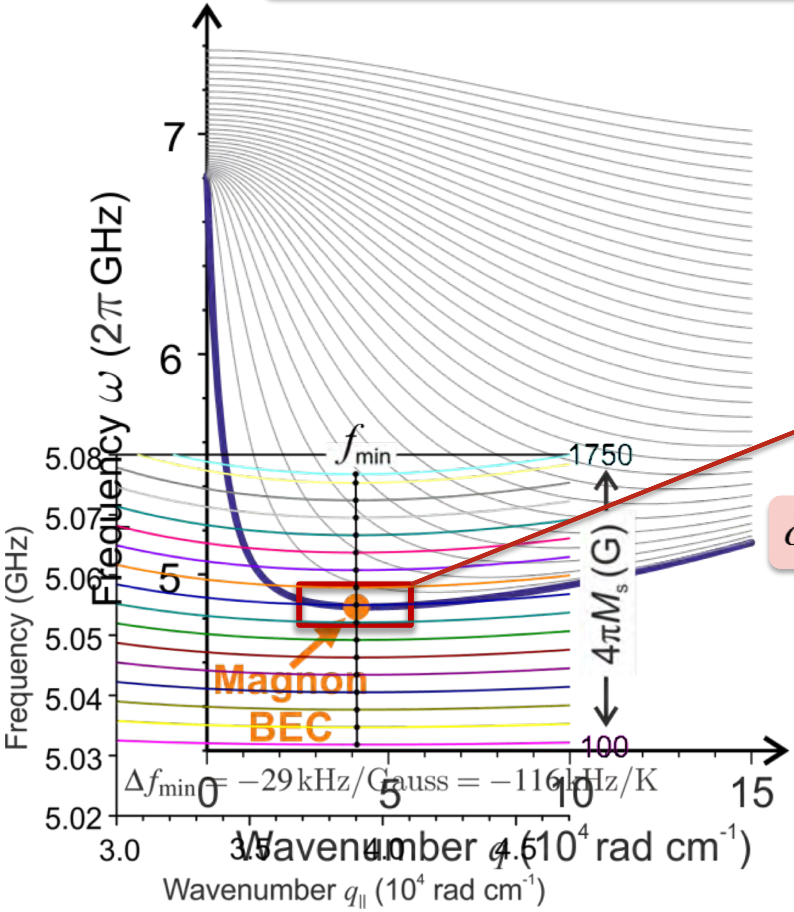
μ: chemical potential

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

Bose-Einstein magnon condensate

Supercurrent in magnon BEC

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



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

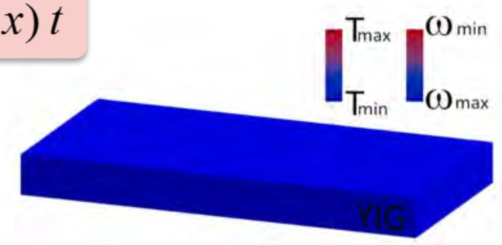
BEC density: $N_c = |\psi|^2$

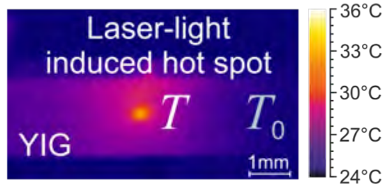
BEC phase: $\varphi = \arg(\psi)$

Supercurrent

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

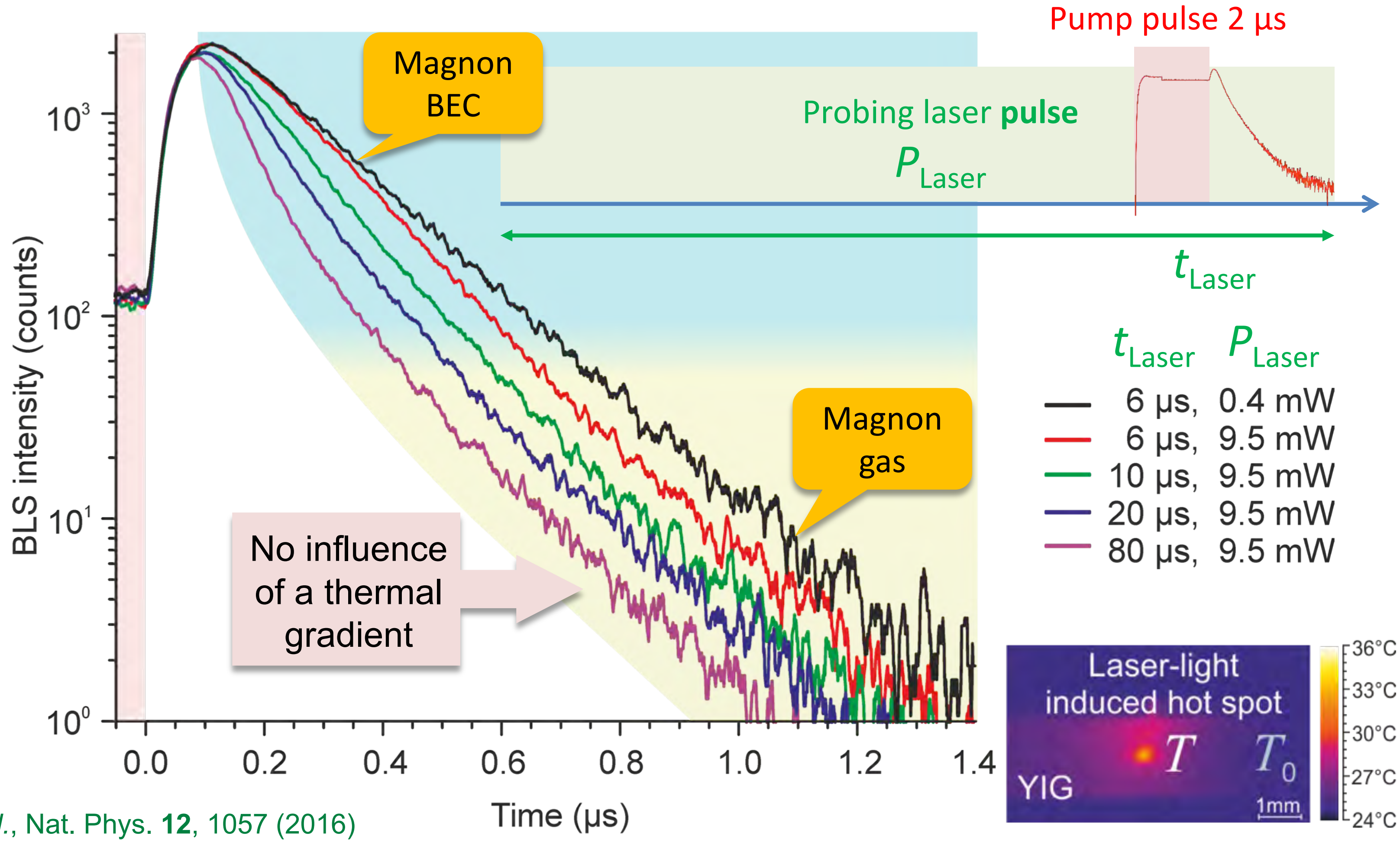
$$\delta\varphi = \delta\omega_c(x)\,t$$





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)

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Dynamics of condensed magnons in thermal gradient - theory

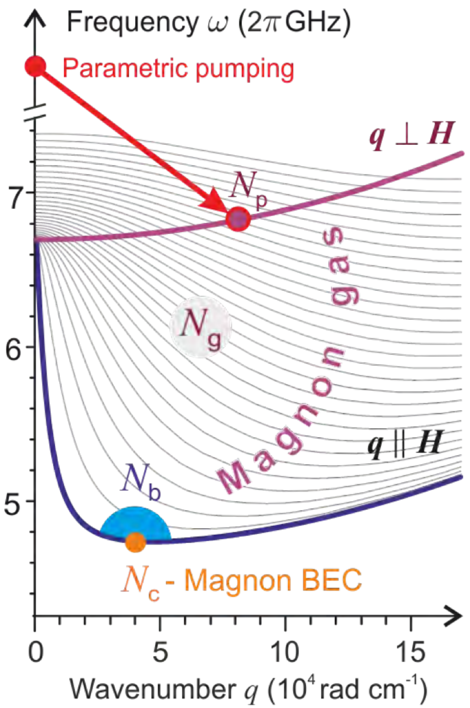
Dynamics of condensed magnons $N_c(t)$, magnons in gaseous states $N_g(t)$ and gaseous magnons at the bottom of SW spectrum $N_b(t)$ described using rate equations

Without thermal gradient

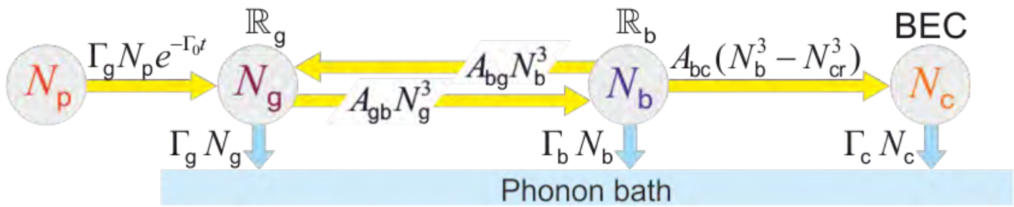
$$\frac{\partial N_g}{\partial t} = -\Gamma_g N_g + \Gamma_g N_p e^{-\Gamma_0 t} - A_{gb} N_g^3 + A_{bg} N_b^3$$

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

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



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

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

Phase gradient

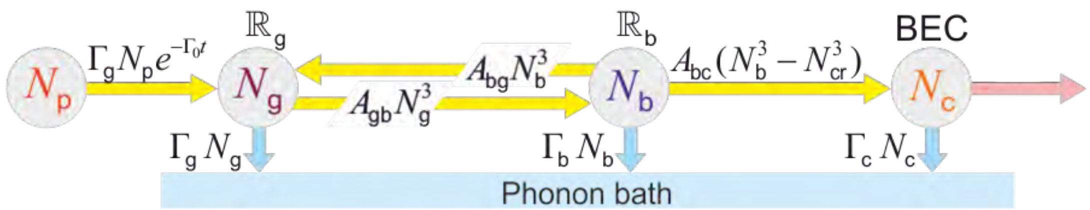
Additional decrease of population of condensed magnons $N_c(t)$ due to magnon supercurrent $\vec{J}(\vec{r},t)$

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

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

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

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



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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

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

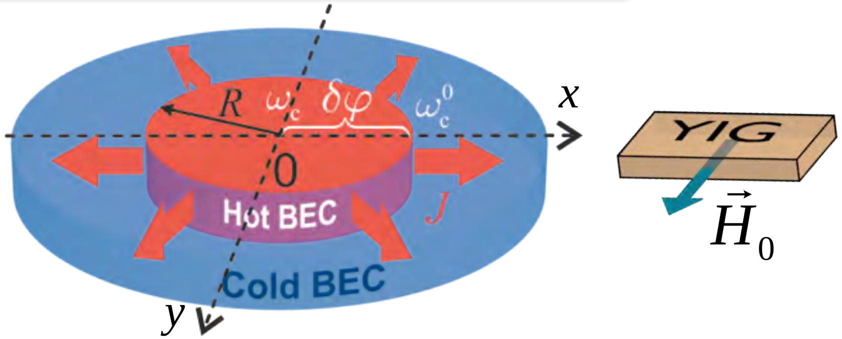
$$J_y = N_c D_y \frac{\partial \varphi}{\partial y}$$

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

Anisotropic dispersion coefficients

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

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



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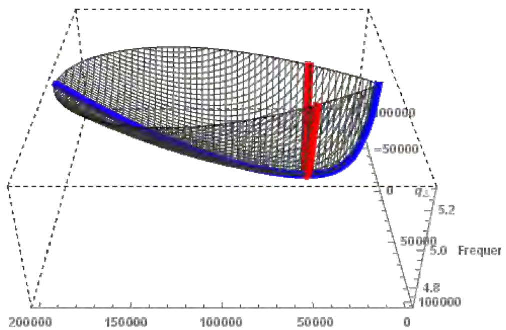
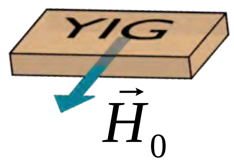
In experiment:

$$D_x \simeq 21 D_y$$

$$J_T = J_x \gg J_y$$





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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

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

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

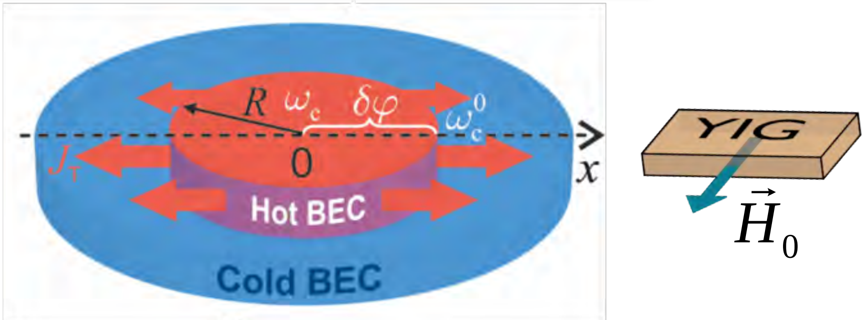
a weak frequency shift of the BEC wave function due to temperature change

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

In experiment:

$$D_x \simeq 21 D_y$$

$$J_T = J_x \gg J_y$$



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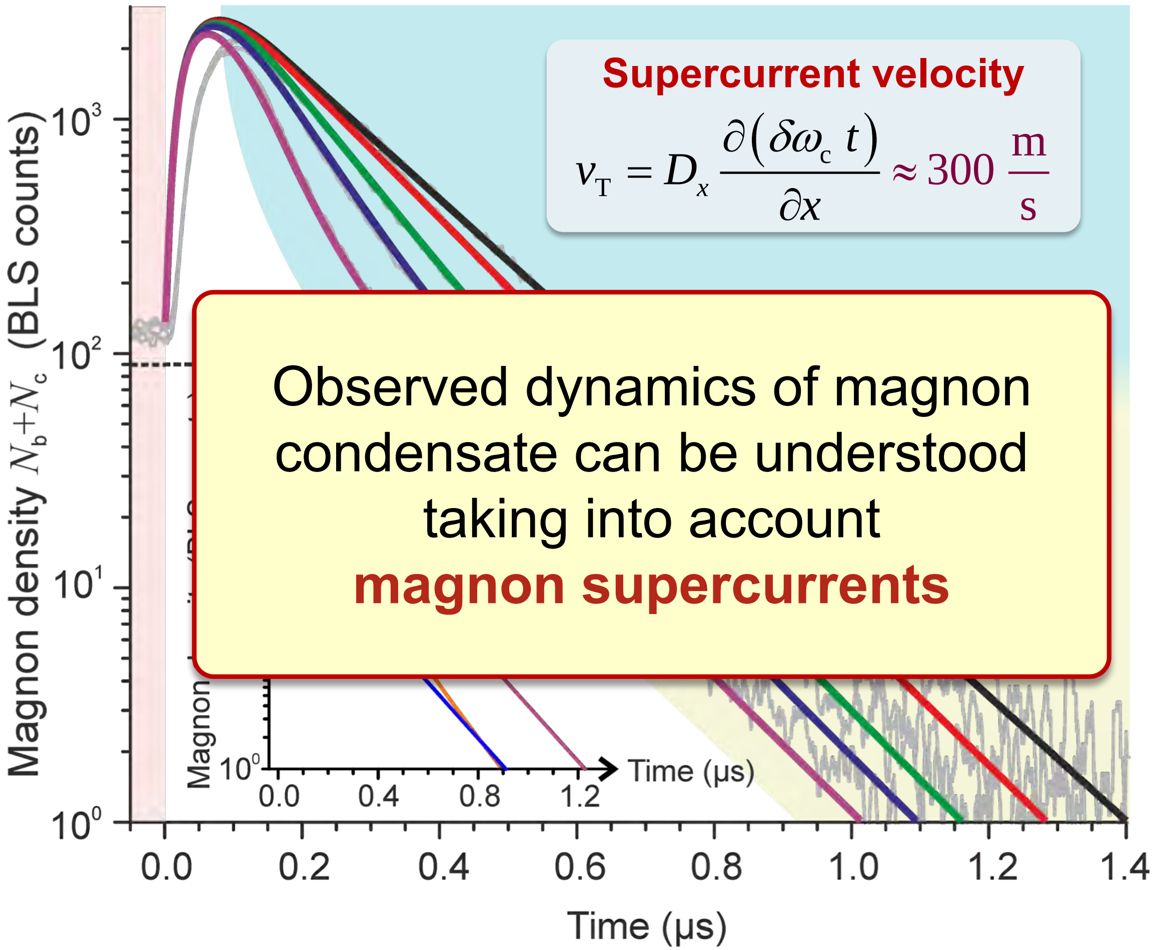
Dynamics of condensed magnons in thermal gradient - comparison with theory



Supercurrent velocity

$$v_T = D_x \frac{\partial(\delta\omega_c t)}{\partial x} \approx 300 \frac{m}{s}$$

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 $\delta\omega_c(T)/2\pi$

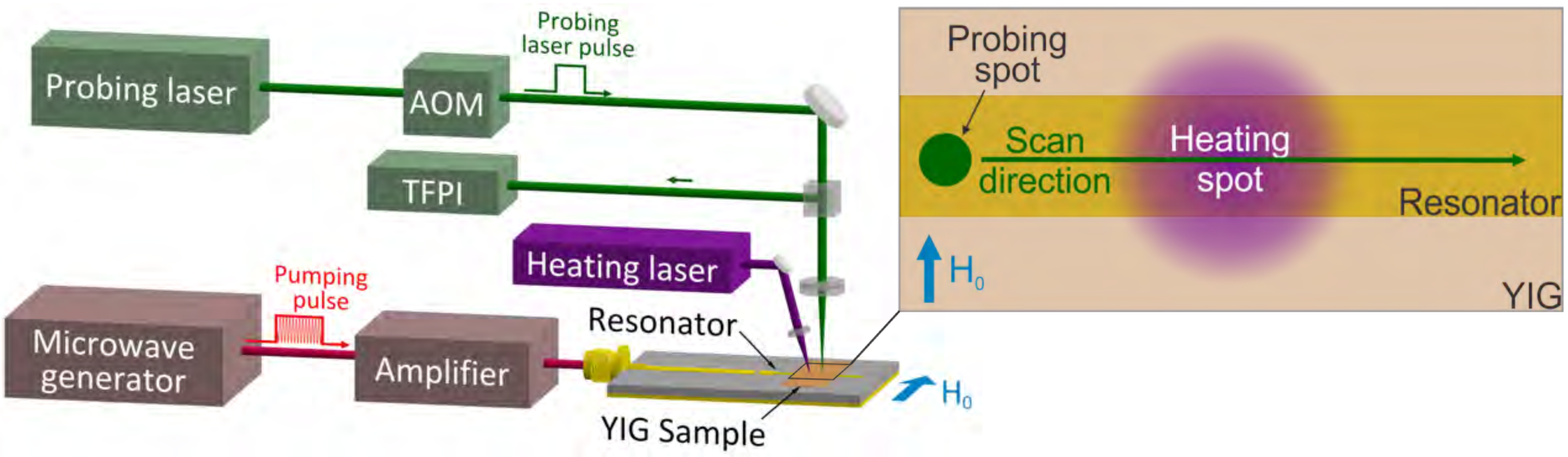
- 0 kHz
- 25 kHz
- 100 kHz
- 198 kHz
- 550 kHz

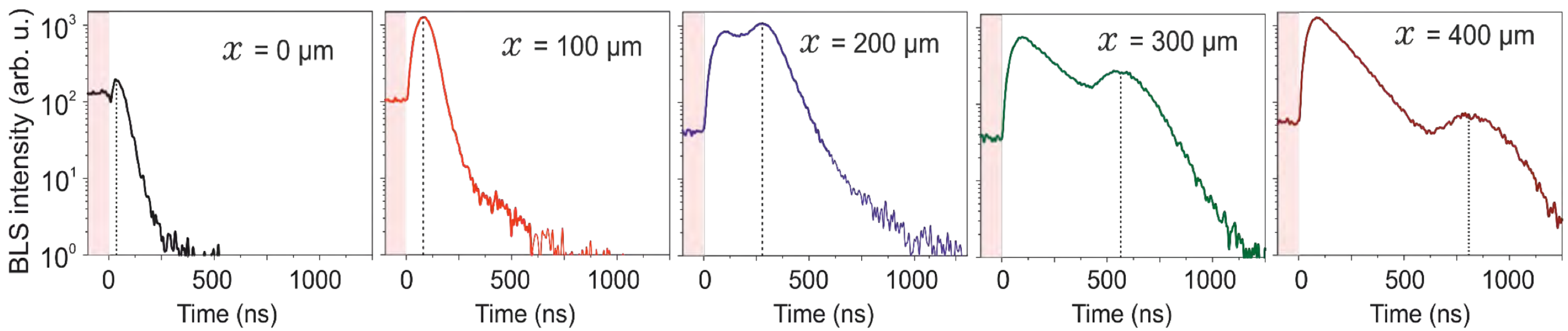
Corresponding maximal temperature change

4.7 K

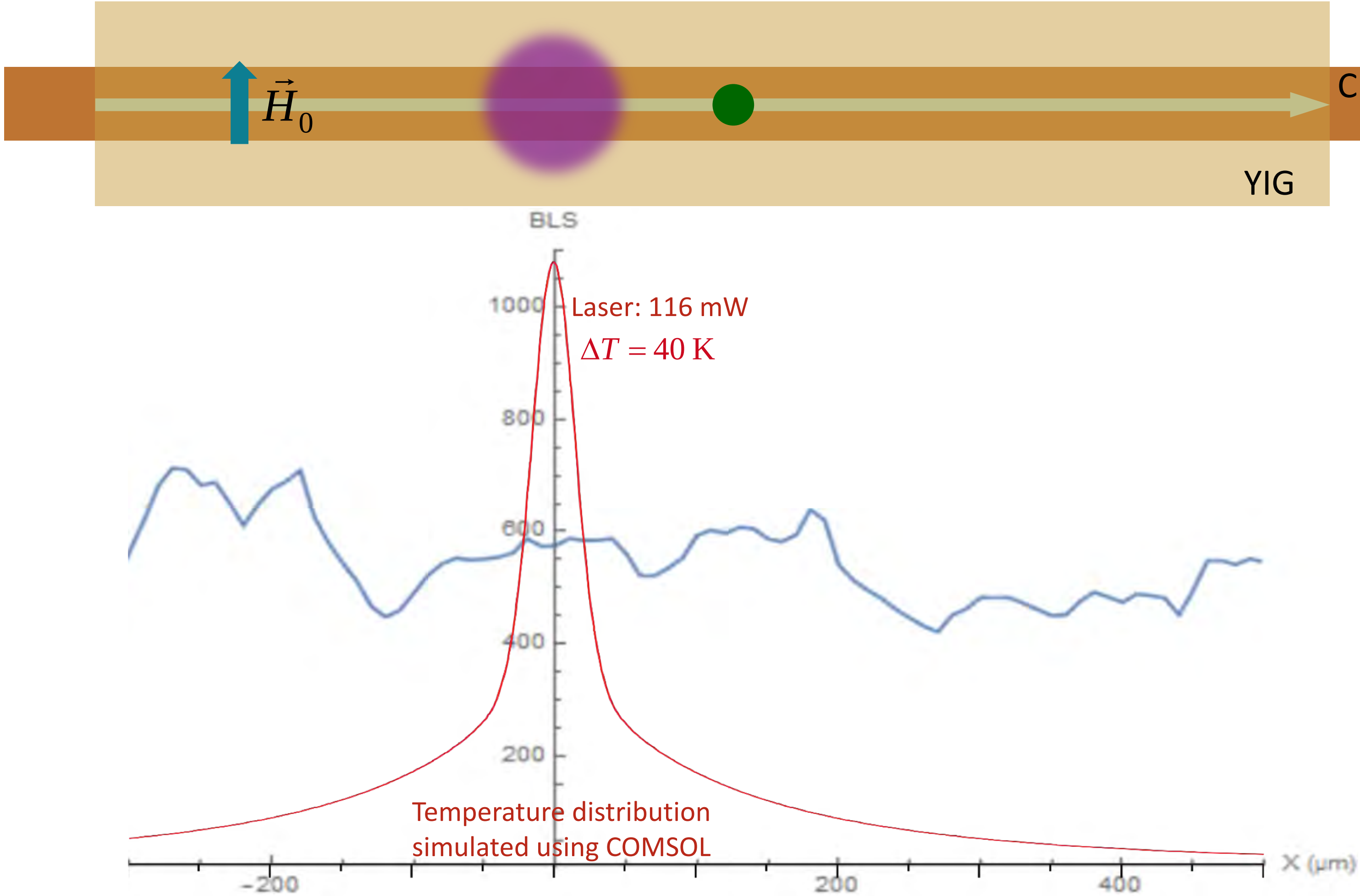
D. A. Bozhko *et al.*, Nat. Phys. **12**, 1057 (2016)

Non-local measurement: Supercurrent magnon transport





Non-local measurement: Supercurrent magnon transport



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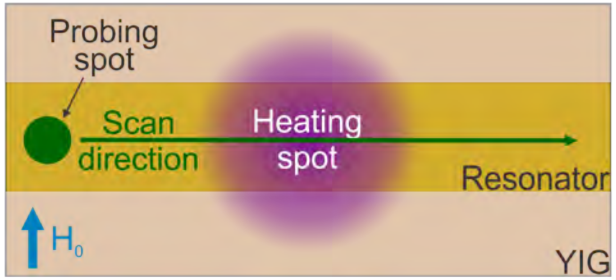
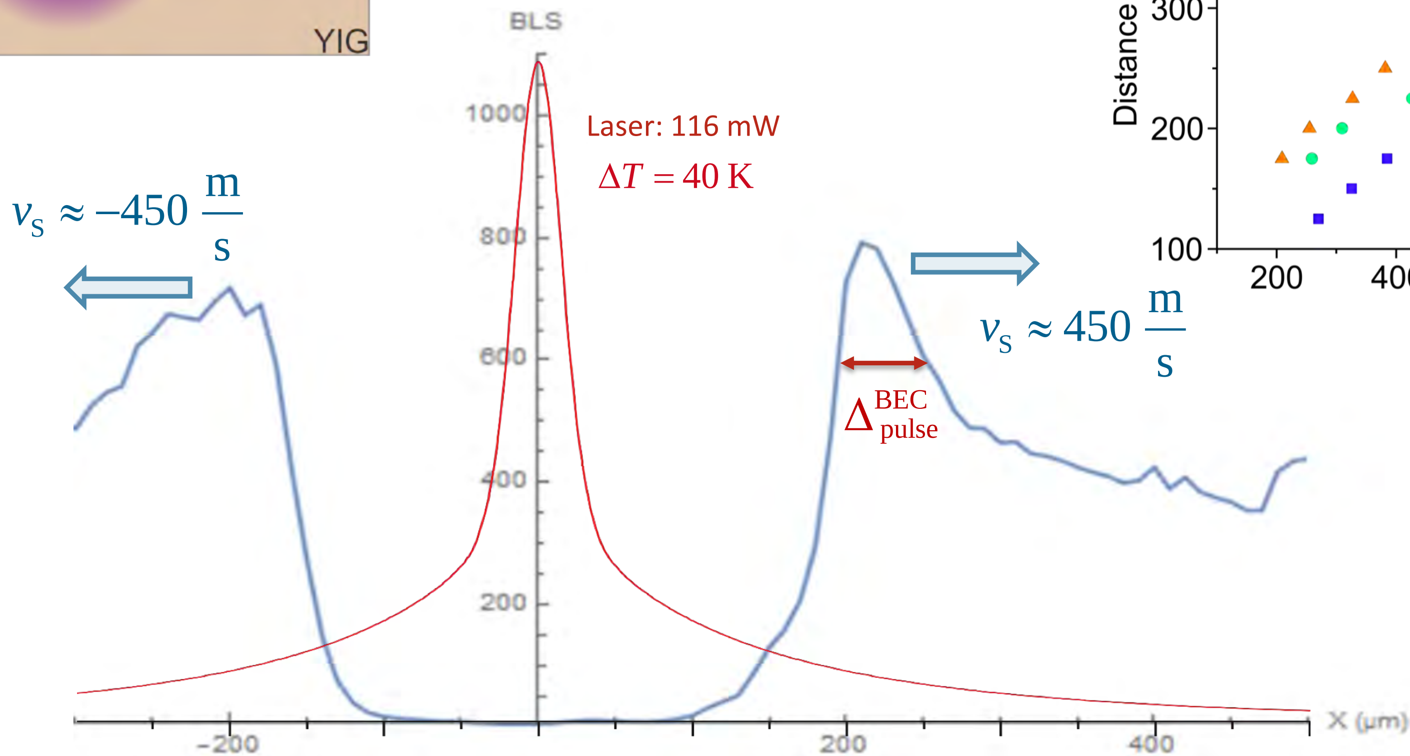
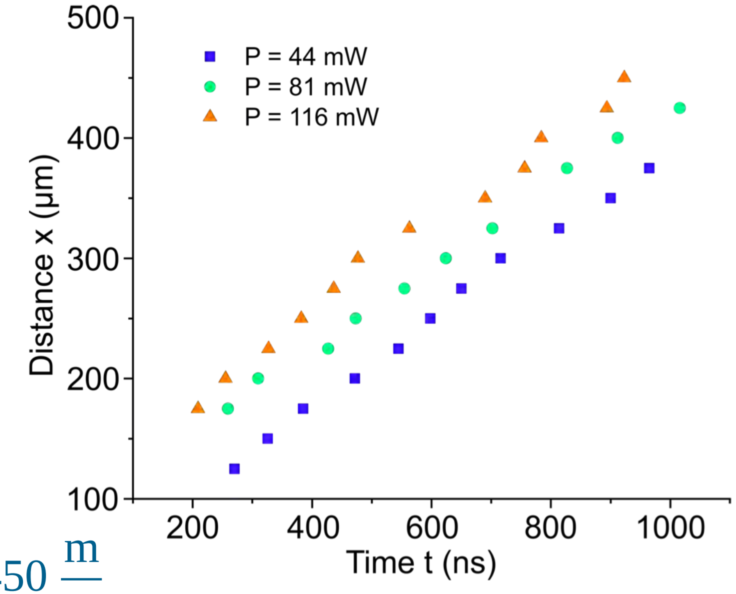
Non-local measurement: Supercurrent magnon transport







Non-local measurement: Second magnonic sound scenario

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Gross-Pitaevskii equation for dynamic behavior of the magnon BEC

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

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

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

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

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

Magnon BEC density N_c

Bogoliubov dispersion law for small perturbations on the background of the stationary solution (**second sound**)

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

$D_x q^2 \ll 2WN_c$:

$$\omega(q) = c_s q$$

second sound velocity

$$c_s = \sqrt{2D_x WN_c}$$

$D_x q^2 \gg 2WN_c$:

$$\omega(q) = D_x q^2$$

Estimations for $c_s = v_s \approx 450\,\mathrm{m/s}$ and $D_x \approx 7.45\,\mathrm{cm^2/s}$

Nonlinear frequency shift: $2WN_c \approx 2\pi \cdot 44\ \mathrm{MHz}$

For 116 mW laser power the BEC pulse width $\Delta_{\mathrm{pulse}}^{\mathrm{BEC}} \approx 44\ \mu\mathrm{m}$

$q = \pi / \Delta_{\mathrm{pulse}}^{\mathrm{BEC}} \approx 720\ \mathrm{rad/cm}$ $D_x q^2 \approx 2\pi \cdot 0.52\ \mathrm{MHz}$

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Non-local measurement: Second magnonic sound scenario

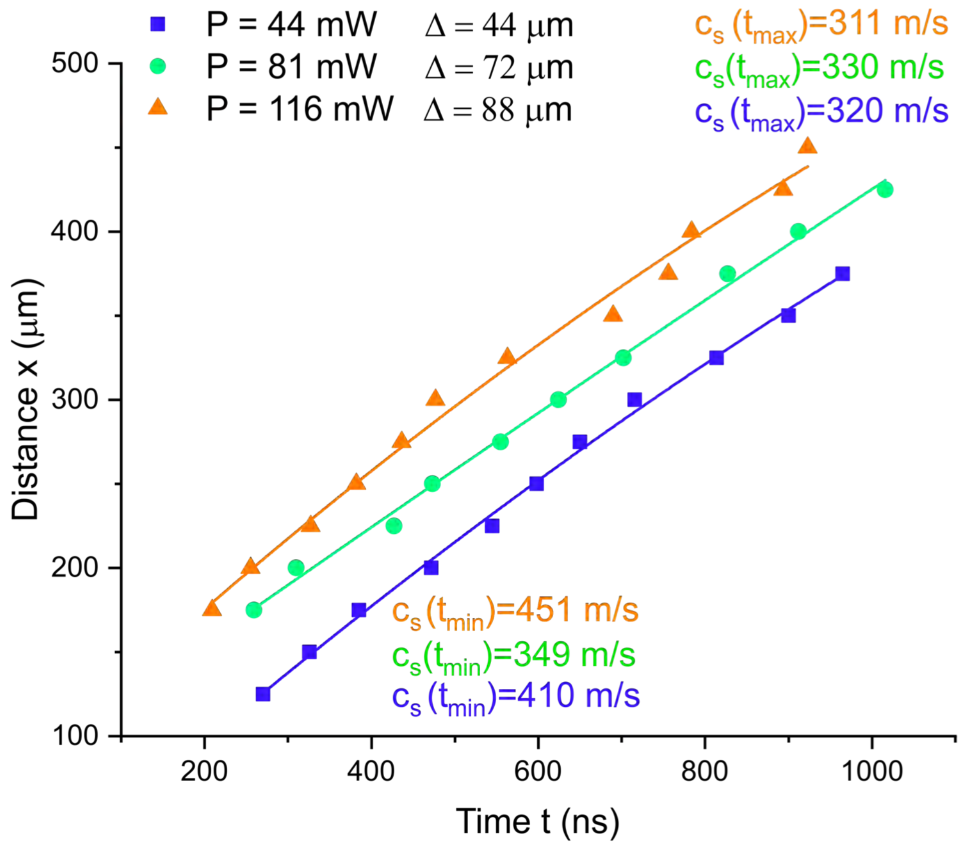
$$\omega(q) = c_s q, \quad c_s = \sqrt{2 D_x W N_c}$$

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

100% change in Δ^{BEC}_{pulse} ⇔ 9% change in c_s

- 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 !



Both statements are well satisfied

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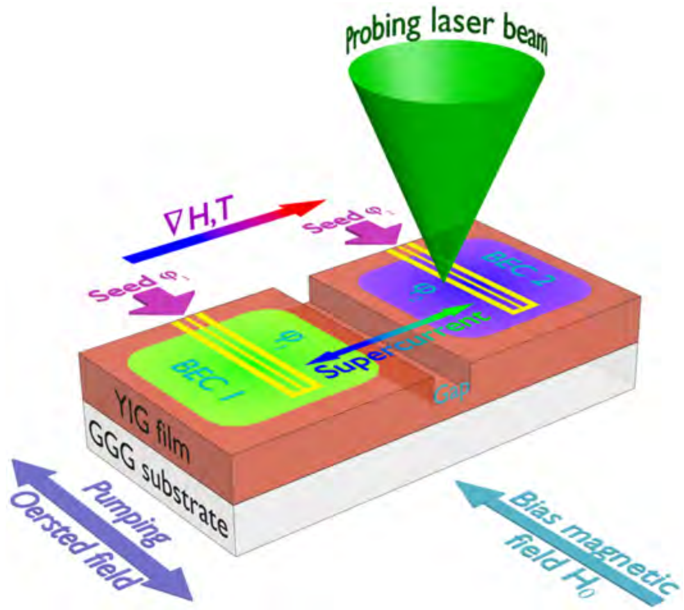
Outlook 1: AC/DC magnon Josephson effect



1. Use of magnon supercurrent for applications

Magnon supercurrent between two spatially separated condensates

- Phase difference is realized using initial seeding of each condensate
- Coupling strength of BECs can be varied by changing the size of the gap between the condensates
- Additional gradients of magnetic field or temperature can be applied to induce time-dependent phase shift

Modified complex Ginzburg-Landau equation

Phase accumulation from external potential | Condensate motion | Nonlinear phase accumulation | Magnon damping | BEC seeding

$$i\hbar\frac{\partial\psi}{\partial t}=\left(\hbar\omega_0(x,T,H)-\frac{\hbar^2}{2m}\nabla^2+\hbar N|\psi|^2\right)\psi+i\hbar(\eta-\beta|\psi|^2)\psi+if(\mathbf{r},t)$$

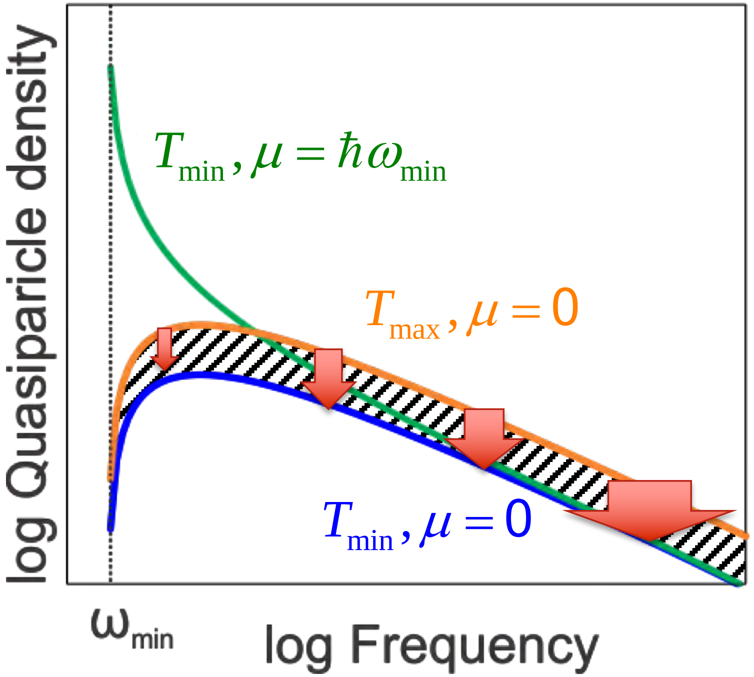
Outlook 2: Microwave-free creation of a magnon BEC

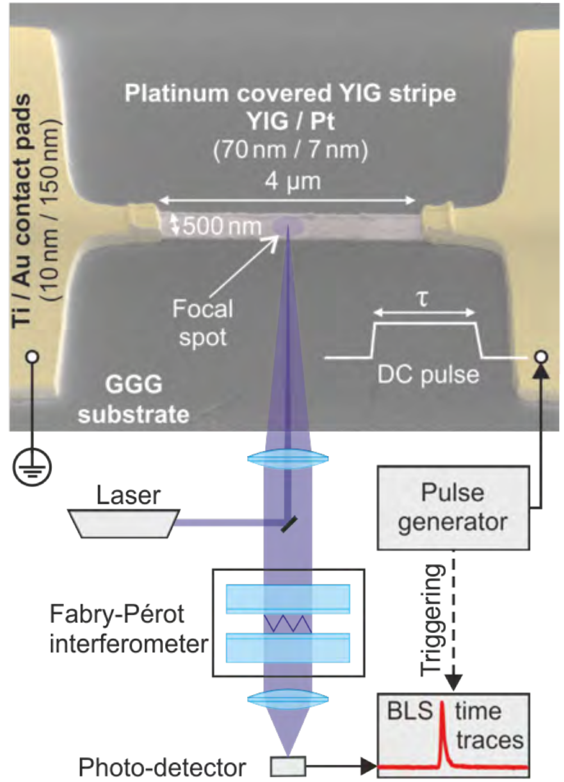
2. Are there other ways how to create a magnon BEC state in YIG?

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

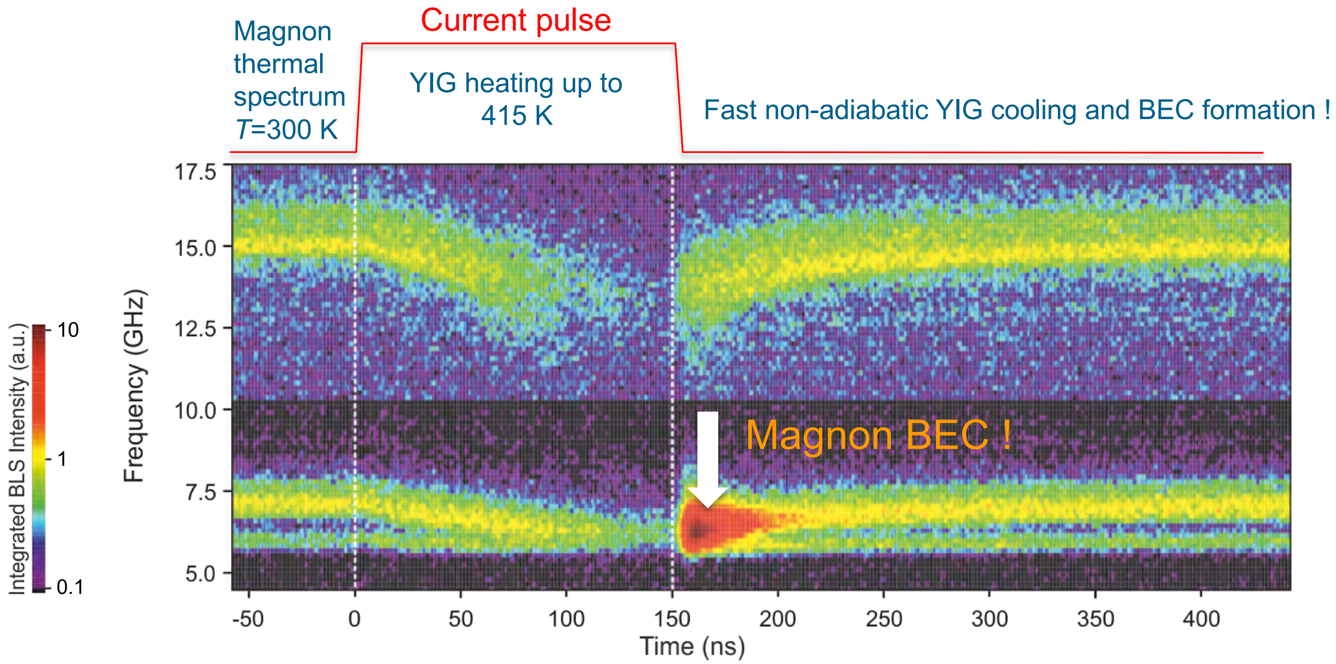
Bose-Einstein distribution

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

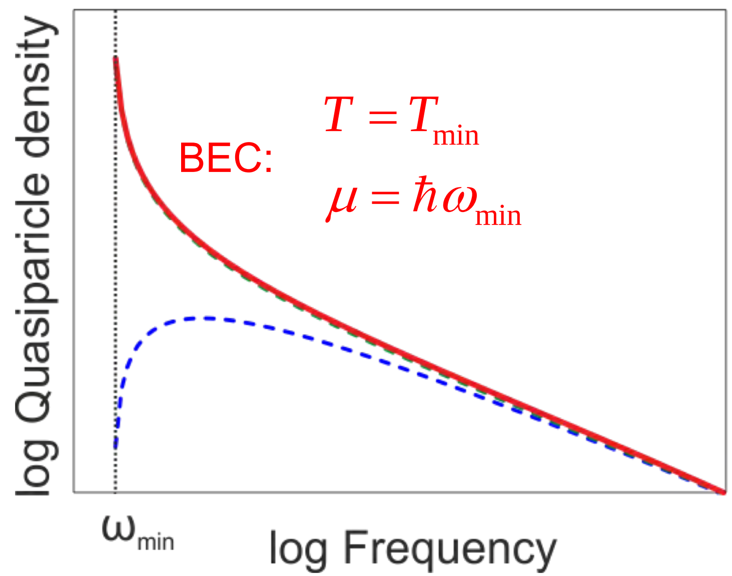




BEC in rapidly cooled magnon gas



Magnon population distribution



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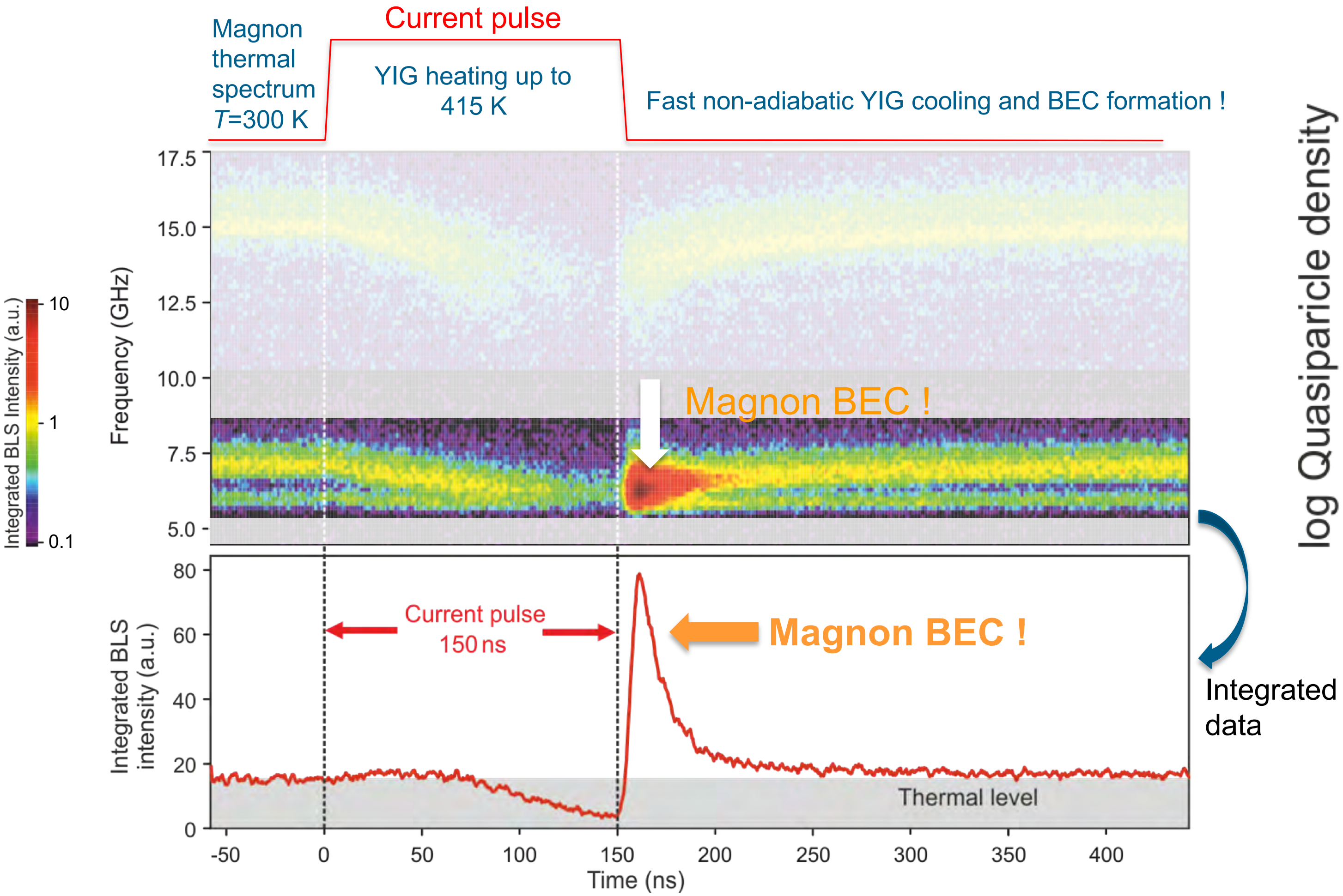
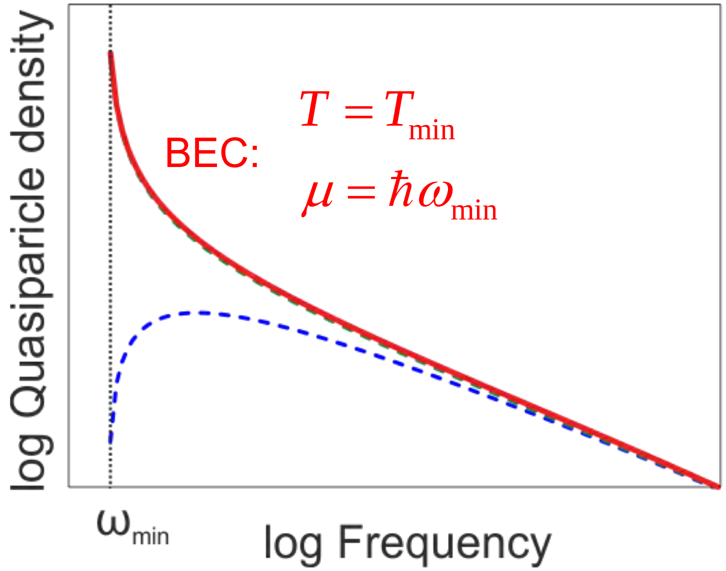
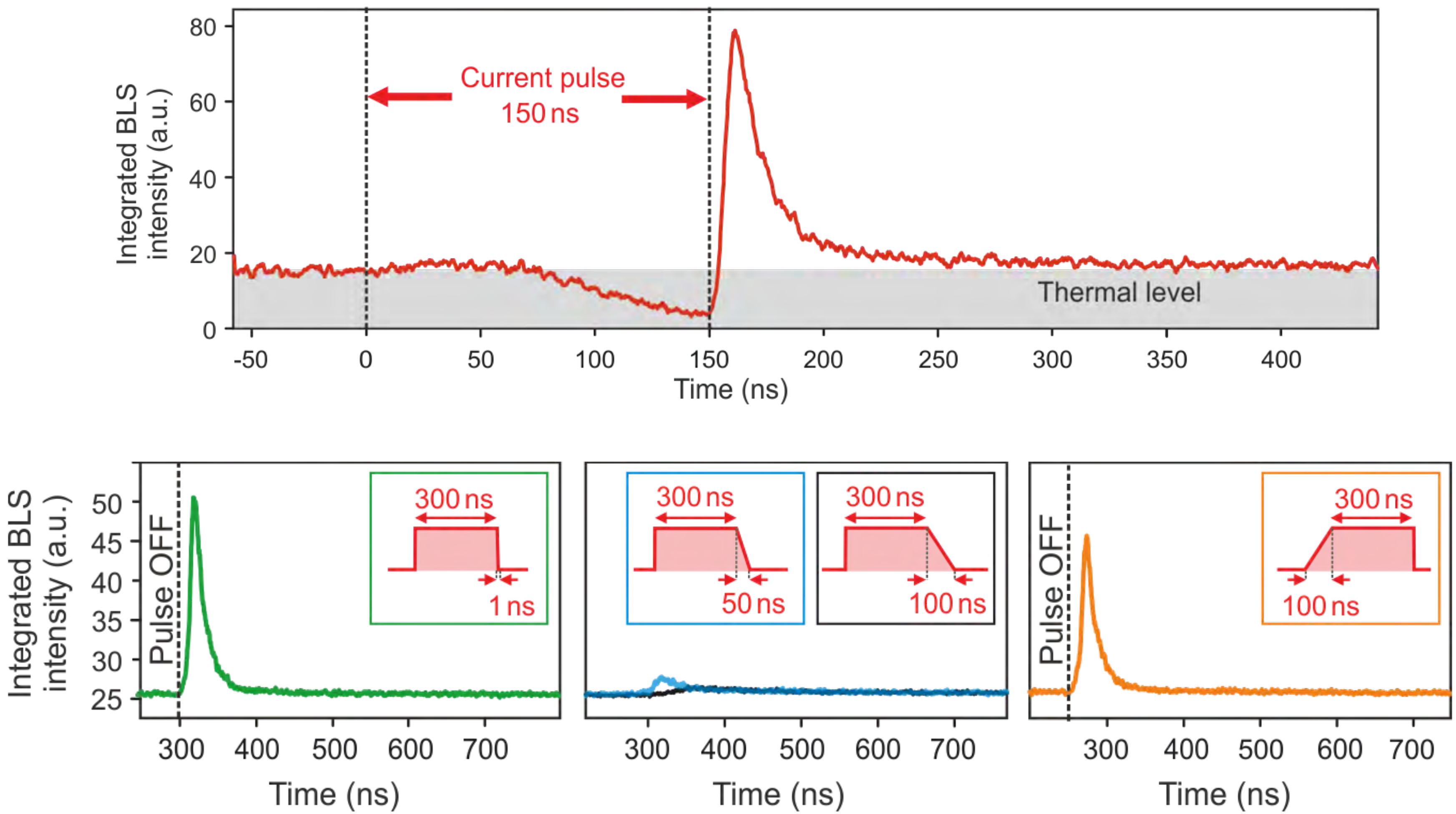
BEC in rapidly cooled magnon gas



Magnon population distribution



Magnon BEC intensity and cooling rate



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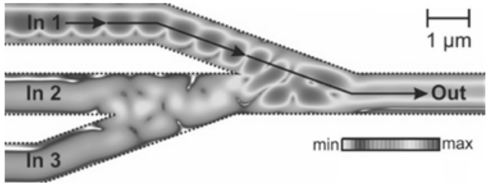
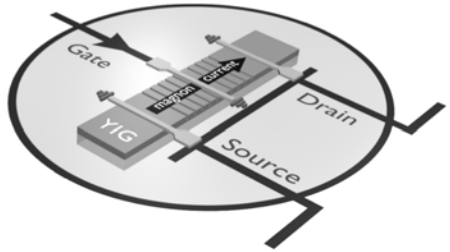
Advanced magnonics

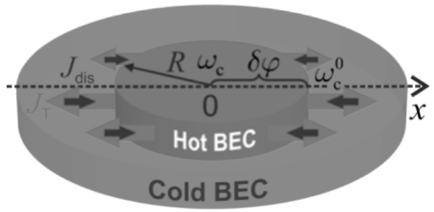
I. Magnon interference logic



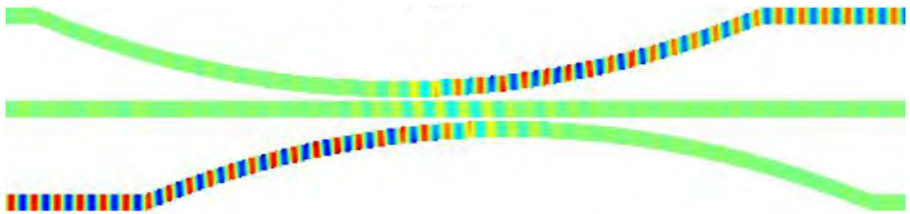
II. Non-linear magnonics: Magnon transistor



III. Magnonic macroscopic quantum state

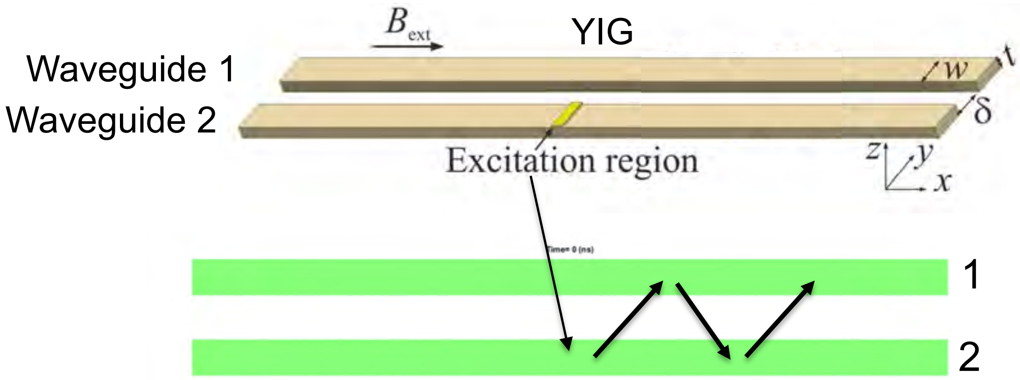


IV. Quantum-classical analogies in magnonics



Coupled waveguides

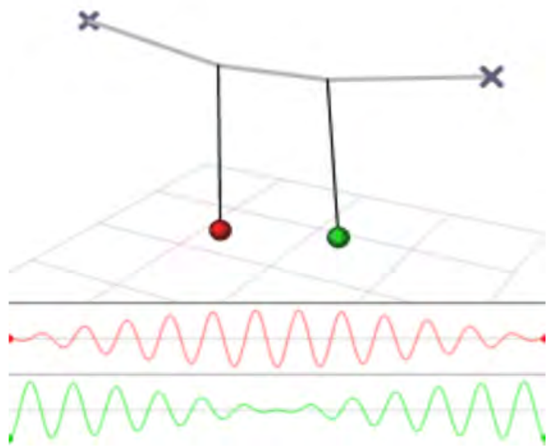
Micromagnetic simulation:



Yttrium Iron Garnet (YIG):

$M_s = 1.4\times10^5$ A/m	t = 50 nm
A = 3.5 pJ	w = 100 nm
$\alpha = 2\times10^{-4}$	δ = 100 nm

Coupled oscillators



Simulation package Mumax3: A. Vansteenkiste, et al., *AIP Advance* **4**, 107113 (2014)

Source: Wikipedia

Coupled waveguides

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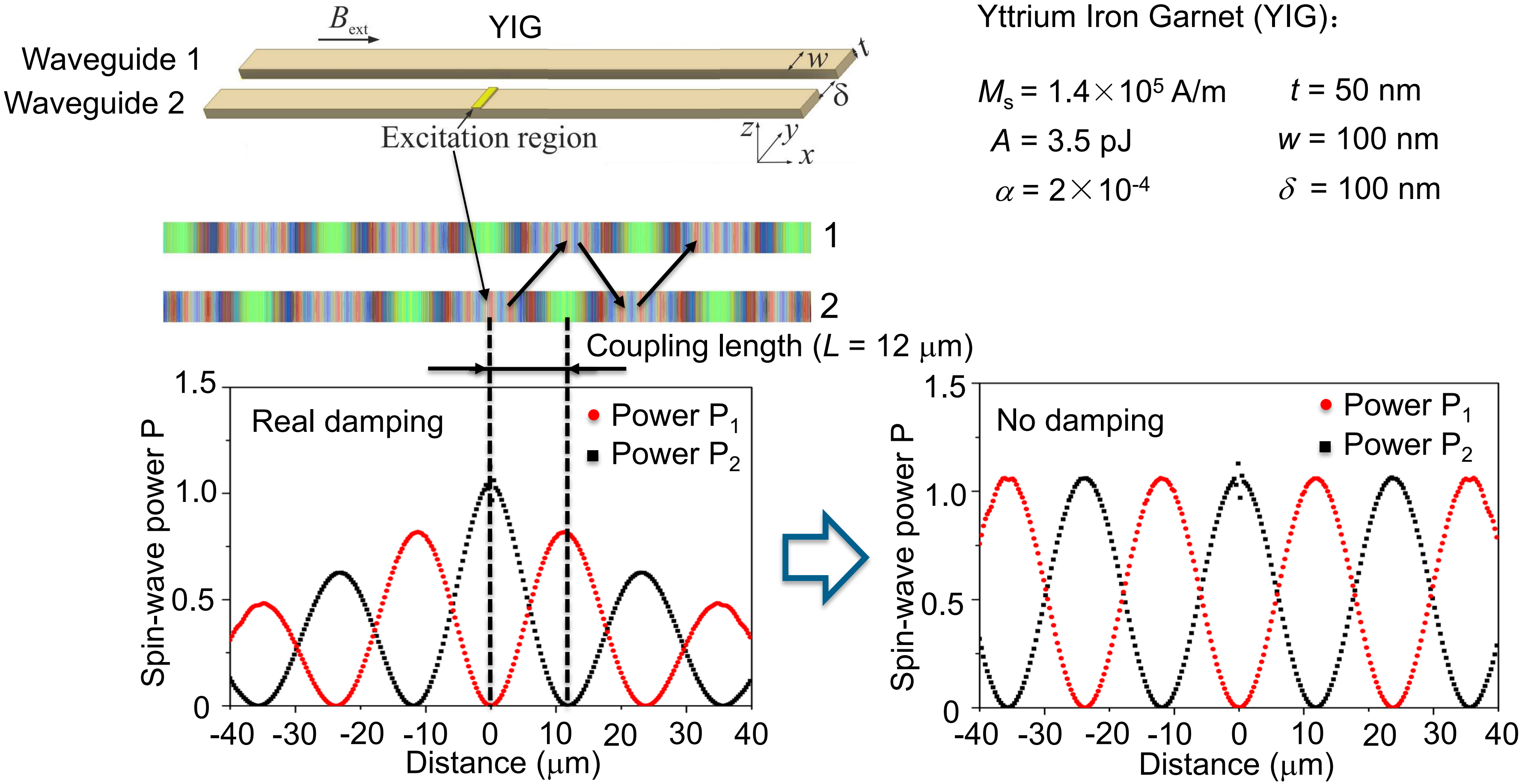
Micromagnetic simulation:



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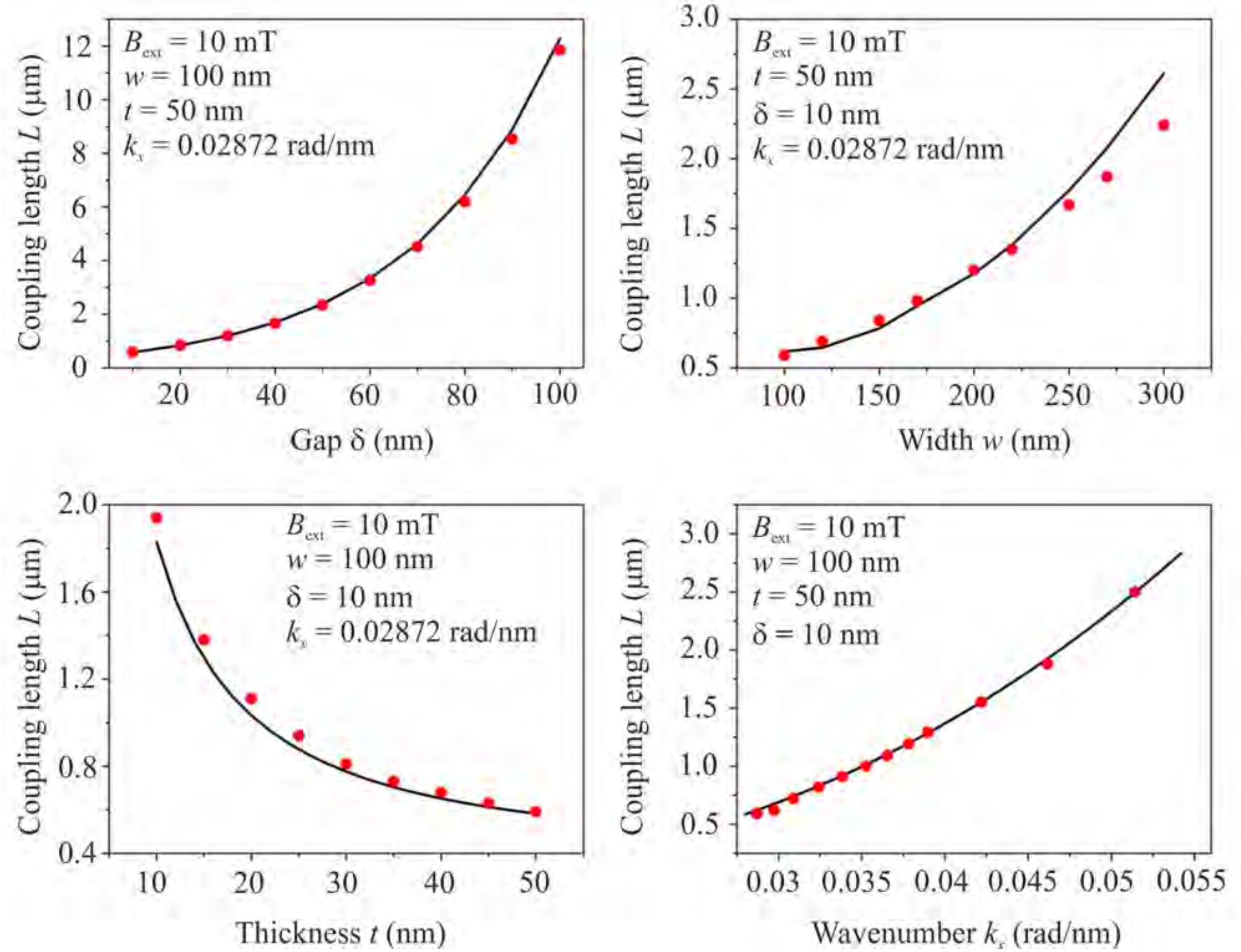
Coupling length as a function of system parameters



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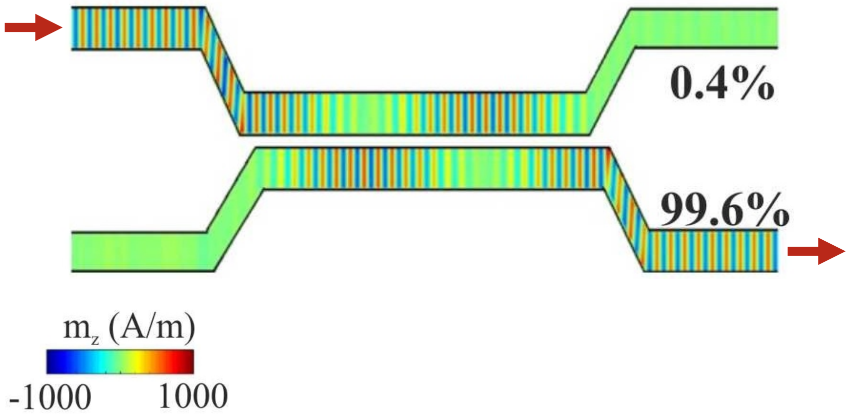
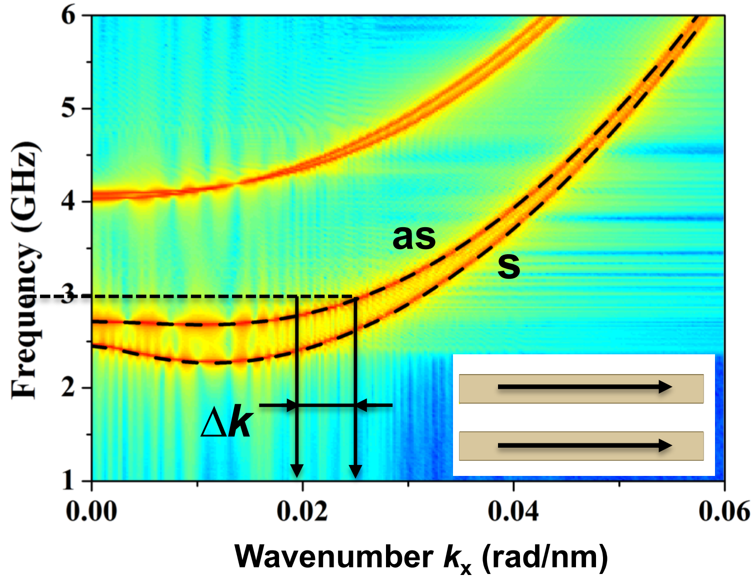
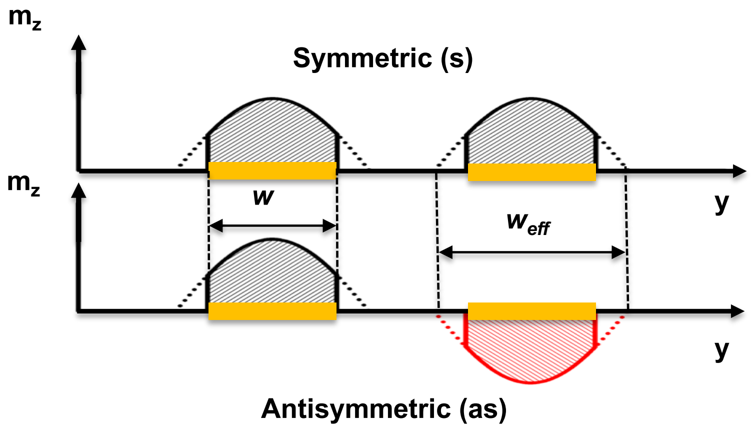
Magnon directional coupler







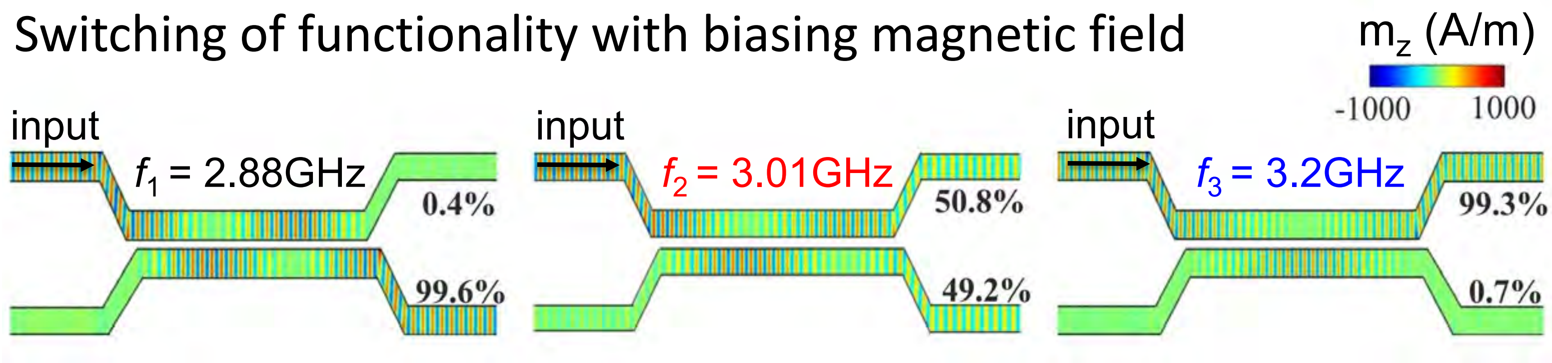
Coupling length: $$L = \frac{\pi}{\Delta k}$$

Coupling strength: $$\kappa = \frac{1}{L}$$

Q. Wang, et al., Sci. Adv. **4**, e1701517 (2018)

Functionalities of directional coupler

Switching of functionality with biasing magnetic field



Q. Wang, et al., Sci. Adv. **4**, e1701517 (2018)

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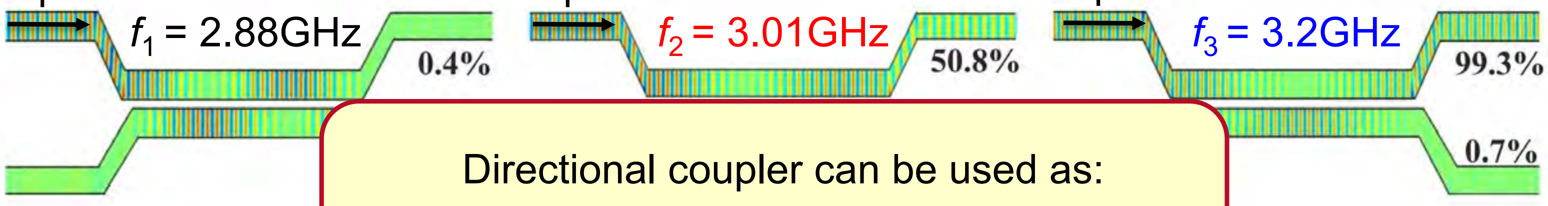
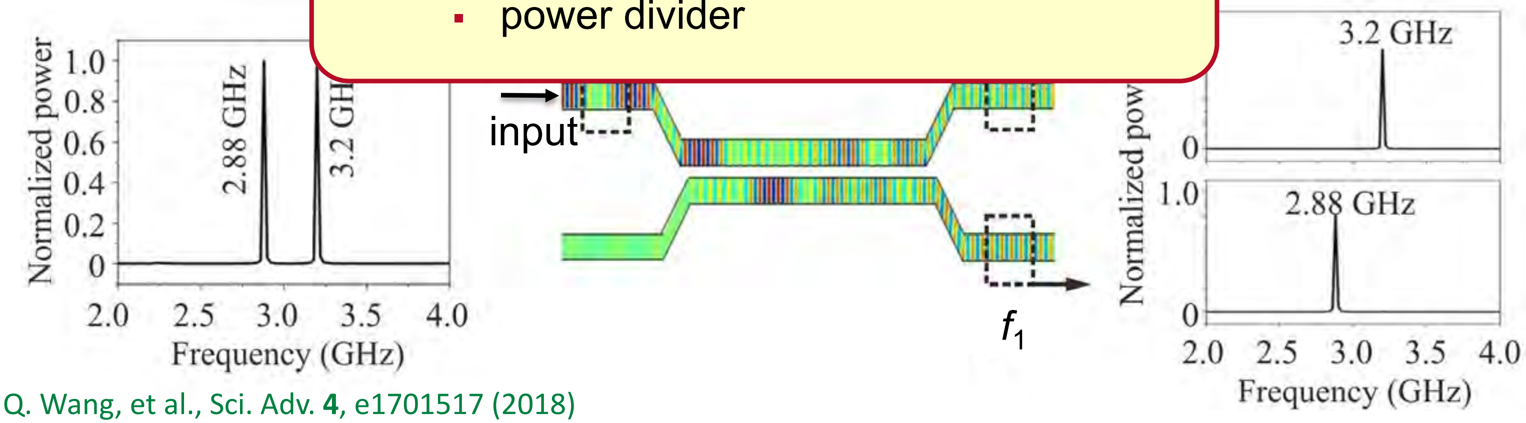


Directional coupler can be used as:

- interconnector
- multiplexer
- power divider

Utilization of t ltiplexer



Q. Wang, et al., Sci. Adv. **4**, e1701517 (2018)

Summary

- Magnon interference logic allows for data processing fully in the magnonic system
- Magnon transistor is an important nonlinear building block of magnonics for future wave-based technology
- Magnon Bose-Einstein condensate (BEC) with zero group velocity can be used for coherent spin transport
- First experimental evidence of creation of a magnon BEC by rapid cooling of a micro-scale YIG/Pt structure
- A magnonic quantum-classical analogy device has been demonstrated (magnonic STIRAP process)