Magnetization Dynamics II:
Magnonics: Trends and Challenges

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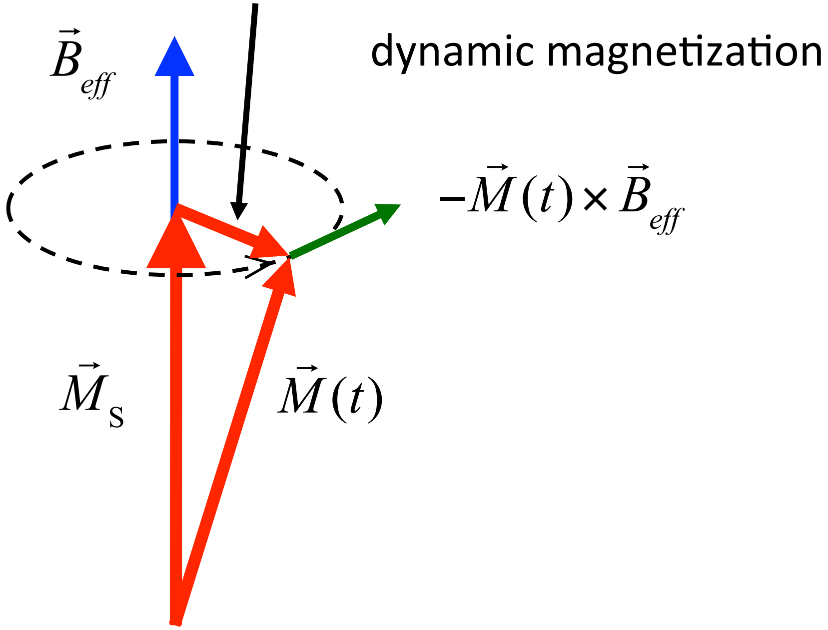
Coherent dynamics: spin waves

Landau-Lifshitz torque equation

$$\frac{1}{|\gamma|}\frac{d\vec{M}(t)}{dt} = -\vec{M}(t)\times\vec{B}_{eff}(t) + \frac{\alpha}{M_s}\vec{M}(t)\times\frac{d\vec{M}(t)}{dt}$$

$$\vec{m}(\vec{r},t) = \vec{m}_0(\vec{r})\times e^{i(\vec{k}\vec{r}-\omega t)}$$



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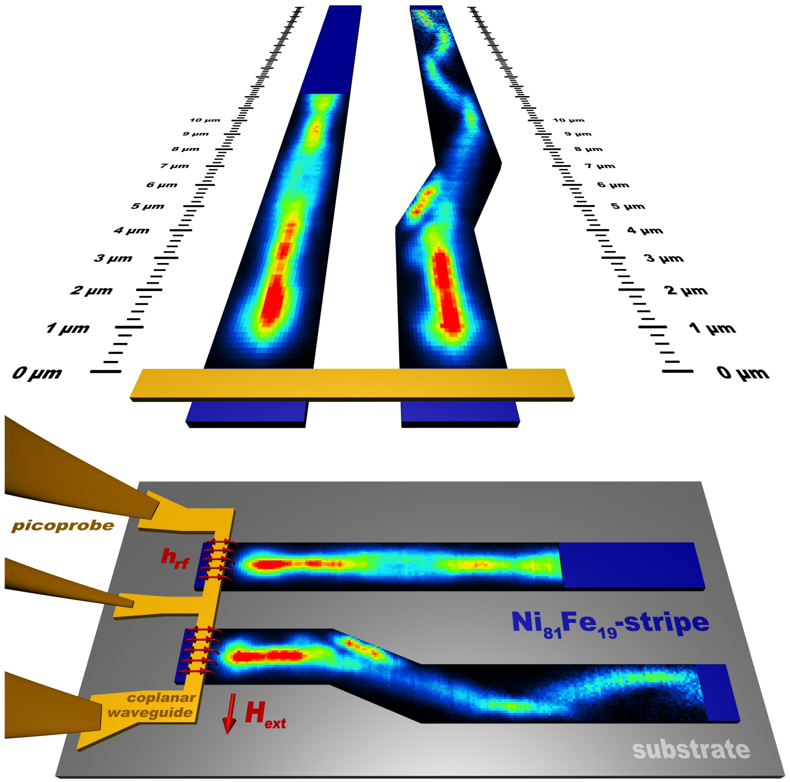
Spin wave bus



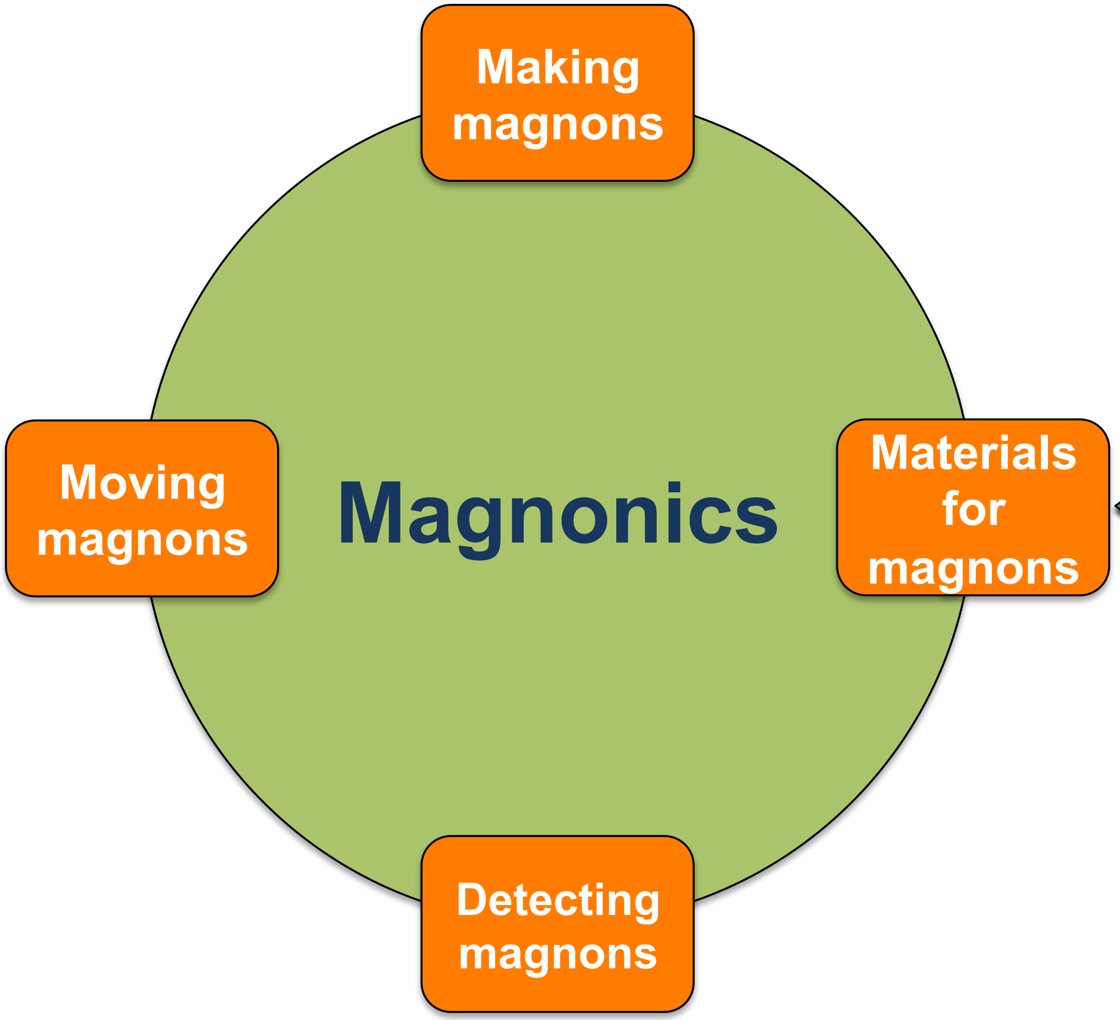
Travelling magnons allow one to:

- **transfer** spin information over centimeter distances
- **process** the information (using wave nature of magnon)
- **operate** in insulator-based technology

Fundamental properties:

- Minimal wavelength is down to several nm
- Frequency is in GHz and up to the THz range
- Energy: $E_{magnon} << k_B T$
- Lifetime: up to several 100 ns

Magnonics: Trends



- Thermal excitation
- Microwave excitation
- Parametric pumping
- Spin Hall effect
- Spin torque oscillator
- Femtosecond laser pulses
- …

“Magnonics” team

Kaiserslautern PI Team

A. Chumak

V. Vasyuchka

A. Serga

B. Leven

Main External Collaborators

Y. Ando, E. Saitoh (Tohoku University, Sendai, Japan)

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

A.N. Slavin (University of Rochester, Michigan, U.S.A.)

A. Karenowska (Oxford University, U.K.)

M. Kostylev (University of Western Australia)

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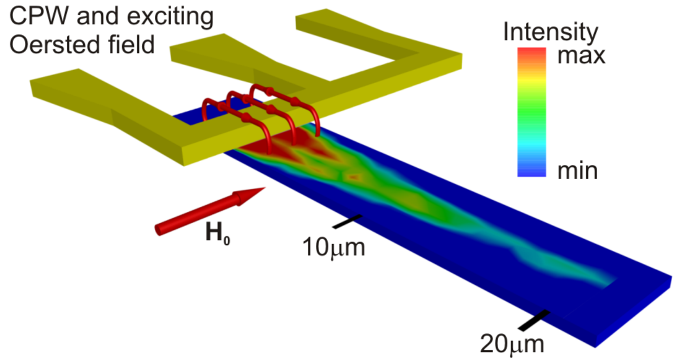
AG Magnetismus in TU Kaiserslautern

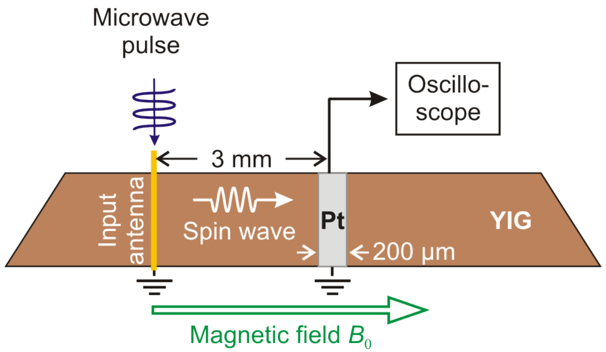
D. A. Bozhko, Dr. M. Agrawal, T. Fischer, S. Klingler, Dr. B. Leven, S. Keller, P. Clausen, L. Mihalceanu, Dr. A. A. Serga, L. Gareis, T. Langner, J. Greser, Dr. P. Pirro, Dr. A. Conca Parra, Jun.-Prof. Dr. E. Th. Papaioannou, Dr. A. Ruiz Calaforra, Dr. T. Brächer, F. Heussner, T. Meyer, Dr. V. I. Vasyuchka, V. Lauer, Prof. Dr. B. Hillebrands + (Dr. A. V. Chumak).

Magnonics: Main trends

I. New materials for magnonics

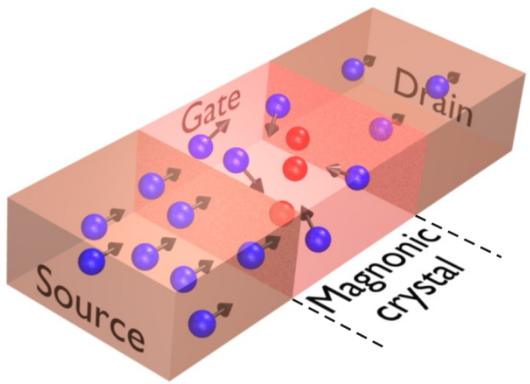


II. Novel means for magnon detection



III. Data processing using magnons

IV. Magnonic supercurrents



Magnonics: Main trends

I. New materials for magnonics

Main requirement: small damping parameter

Commonly used material: Permalloy (Py, NiFe): $\alpha = 8 \times 10^{-3}$

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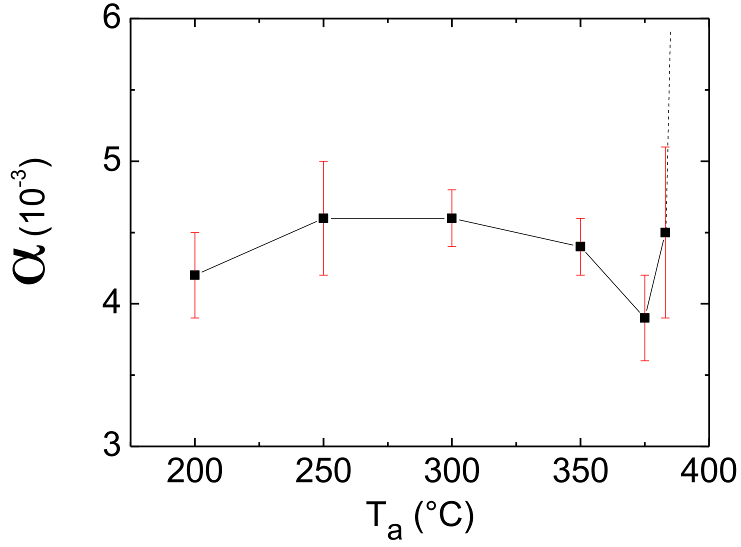

Liu, et al. JAP **110**, 033910 (2011)
Conca, et al. APL **104**, 182407 (2014)

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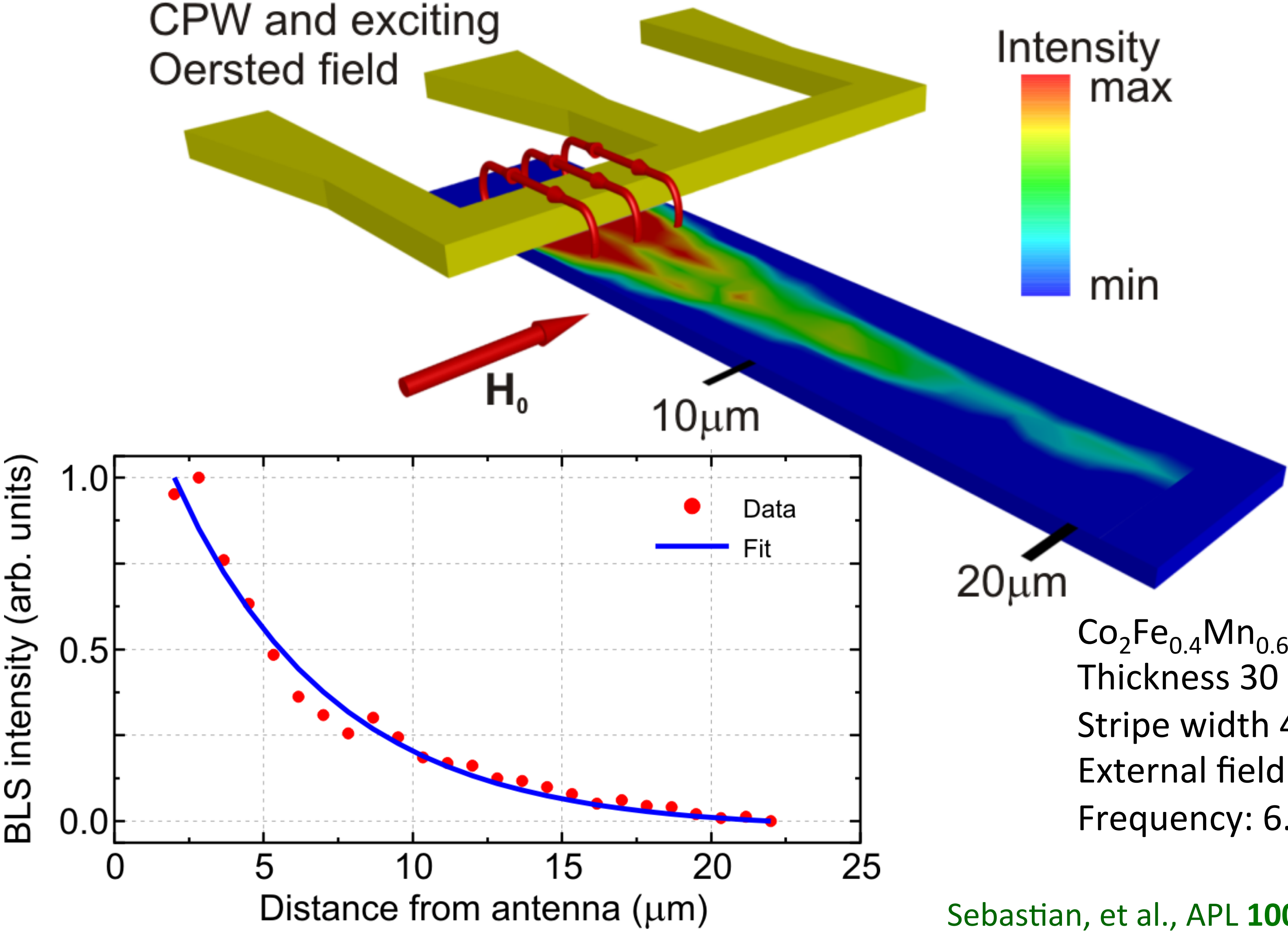
⇨ Novel Heusler compounds: $\alpha = 3 \times 10^{-3}$

Spin-wave propagation in $Co_2Fe_{0.4}Mn_{0.6}Si$ Heusler waveguides



$Co_2Fe_{0.4}Mn_{0.6}Si$
Thickness 30 nm
Stripe width 4 µm
External field: 40 mT
Frequency: 6.2 GHz

Sebastian, et al., APL **100**, 112402 (2012)

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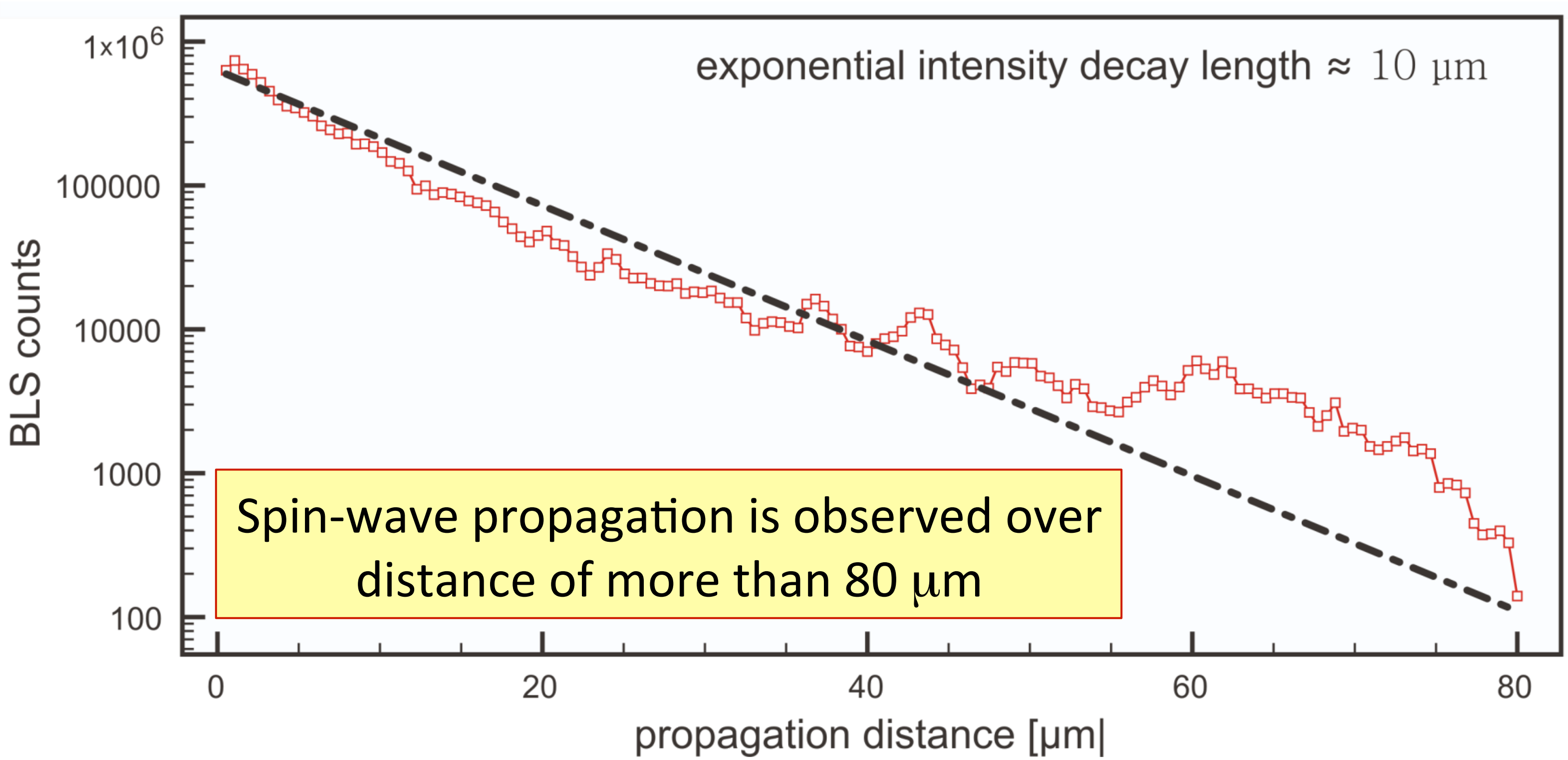

$$I(x) = I_0 \exp\left(-\frac{2x}{\delta}\right) + b$$

$$\alpha = \frac{1}{\tau\gamma\mu_0(H_{eff} + M_s)} \qquad \tau = \delta / v_G$$

Decay length: 10.6 μm

Damping α: 4.7×10^{-3}

Sebastian, et al., APL **100**, 112402 (2012)
Sebastian, et al., PRL **110**, 067201 (2013)

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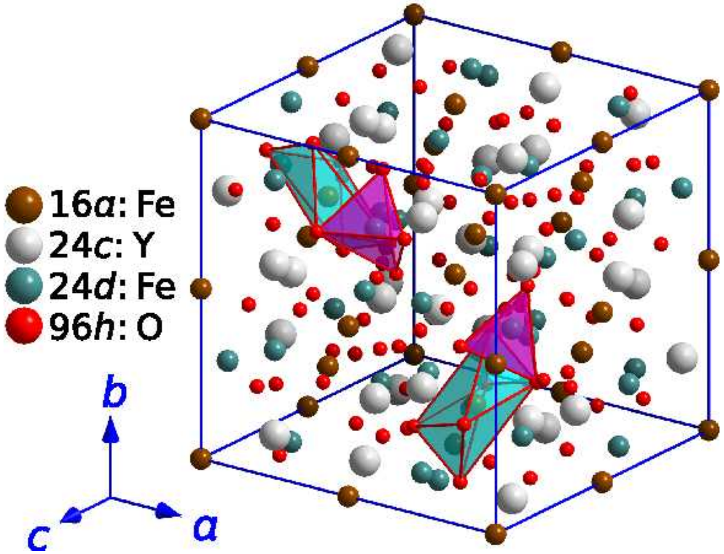
⇨ Micro-structured Yttrium Iron Garnet $Y_3Fe_5O_{12}$ (YIG): $\alpha = 4 \times 10^{-5}$

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



YIG:

- magnetic insulator
- smallest spin-wave damping

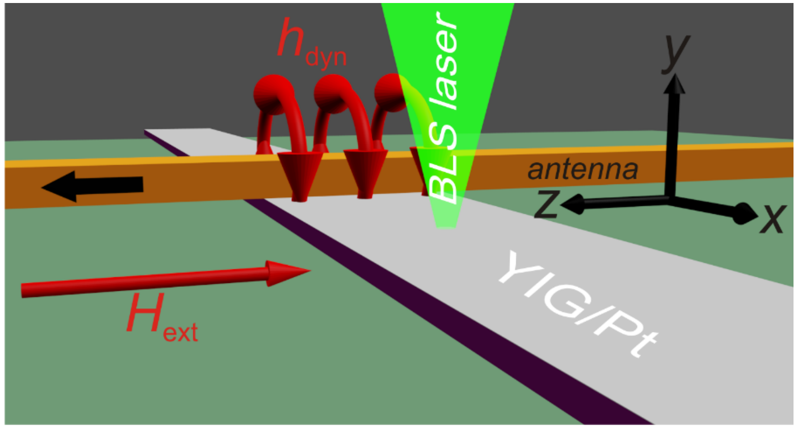
Preparation via:

- liquid phase epitaxy
- sputtering
- pulsed laser deposition

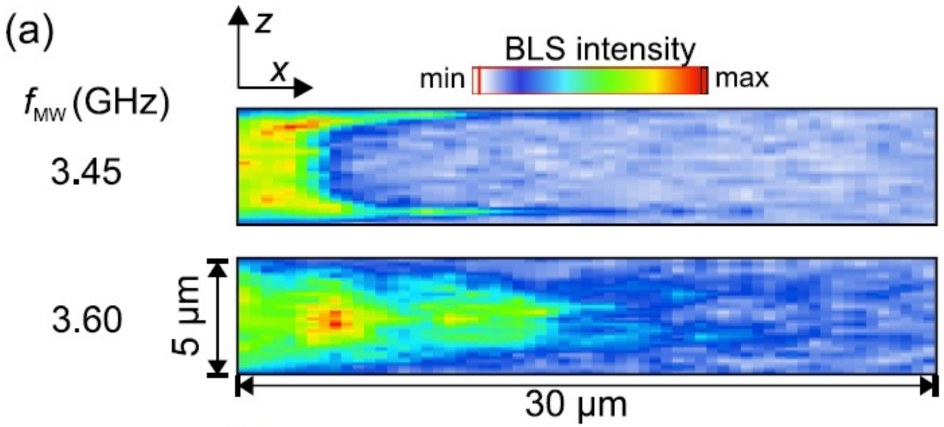
A. Kreisel, Europhysics News (2006)

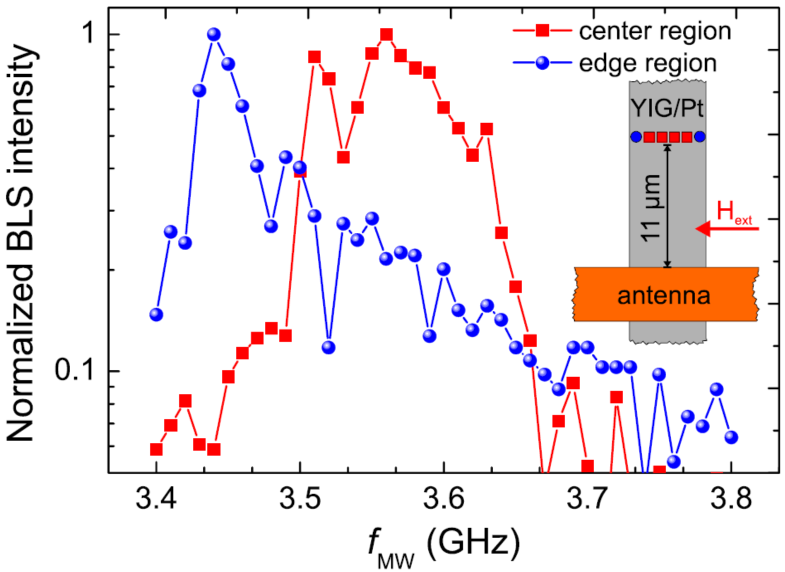
Sample fabrication

Micro-focused Brillouin Light Scattering setup was used for magnon detection



BLS intensity map: YIG thickness: 100 nm
made by liquid phase epitaxy





For standard YIG quality:
free path will be up to 1 mm

P. Pirro, et al., APL **104**, 012402 (2014)

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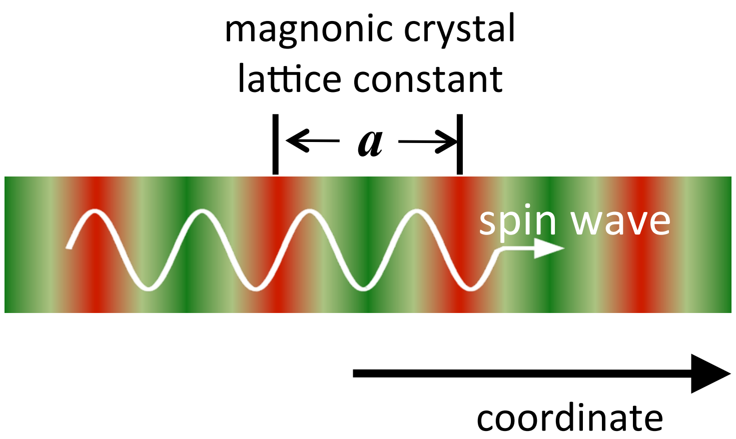
⇒ Magnonic crystals: artificial magnetic materials (static and dynamic)

What is a “magnonic crystal”?

Magnonic crystal – magnetic meta-material:

- artificial medium with periodic lateral variation in magnetic properties

One-dimensional magnonic crystal:

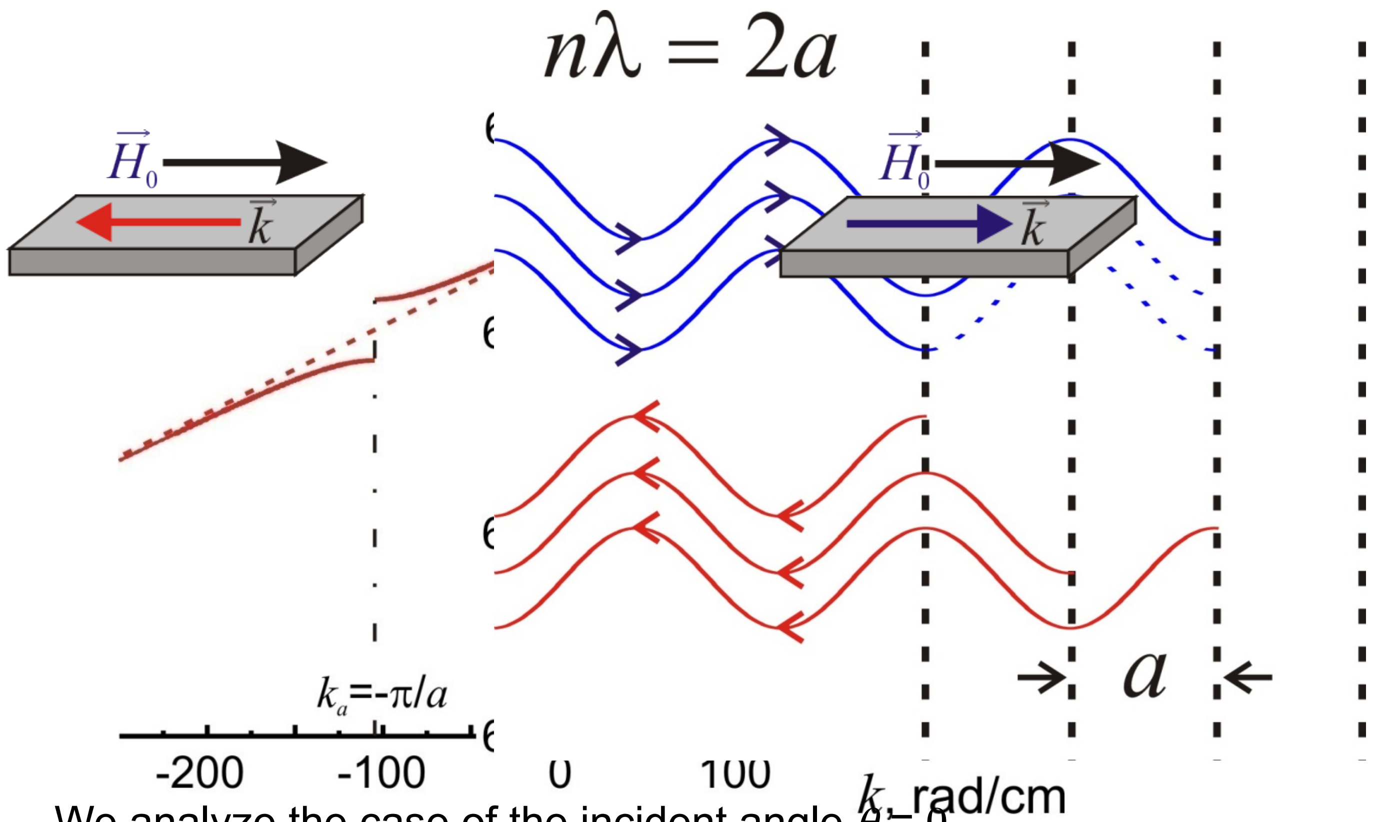


Magnonic-crystal are engineered to have properties that may not be found in nature

- 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



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

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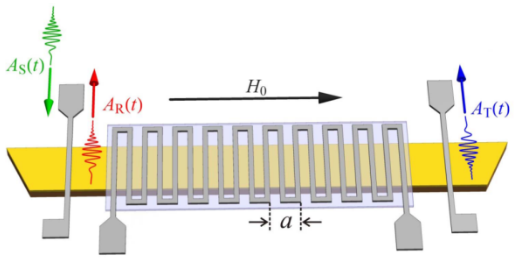
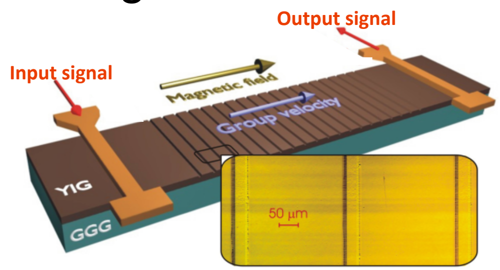
Which magnetic property do we modulate?

Bias magnetic field



Chumak et al., J. Phys. D **42**, 205005 (2009)

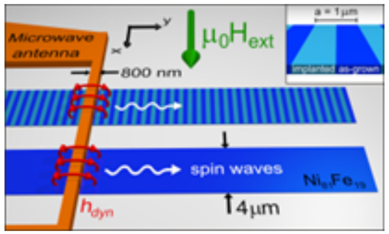
Waveguide thickness



Sykes et al., APL **29**, 388 (1976)
Chumak et al., APL **93**, (2008)

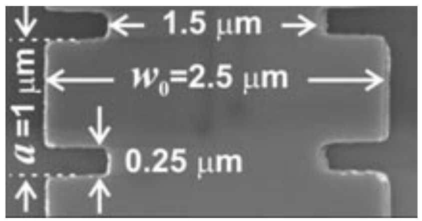
$$f(k) = \gamma \sqrt{H_0 \left(H_0 + 4\pi M_0 \frac{1 - \exp\left\{-\sqrt{(\pi/w)^2 + k^2}\, d\right\}}{\sqrt{(\pi/w)^2 + k^2}\, d} \right)}$$

Effective saturation magnetization



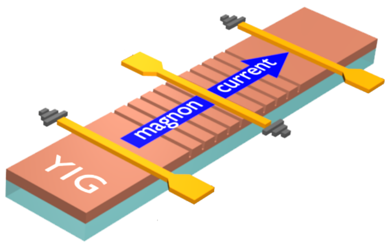
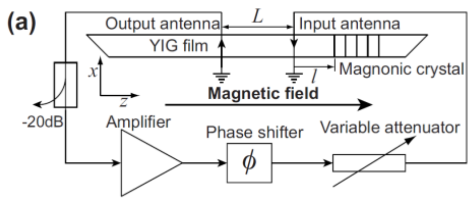
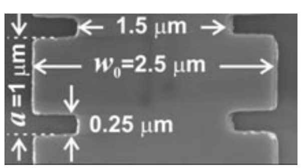
Chumak et al., PRB, **81**, 140404 (2010)
Obry et al., APL, **102**, 202403 (2013)

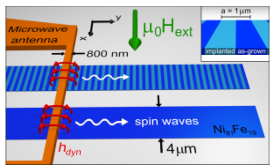
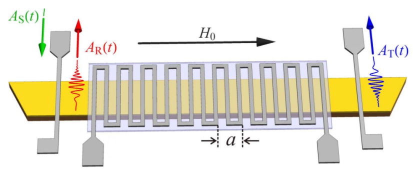
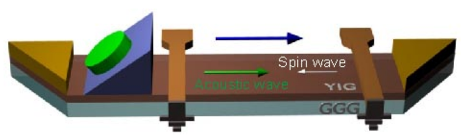
Waveguide width



Chumak et al., APL **95**, (2009)
Lee et al., PRL **102**, 127202 (2009)

Magnonic crystals - overview

<table>
<tr><td>microwave filter</td><td>
</td><td>Chumak et al., APL 93, 022508 (2008)
Chumak et al., APL 94, 172511 (2009)
Chumak et al., JAP 105, 083906 (2009)</td></tr>
<tr><td>data storage element</td><td></td><td>Chumak et al., PRL, 108, 257207 (2012)</td></tr>
<tr><td>stable microwave generator</td><td>
</td><td>Karenowska et al., APL 96, 082505 (2010)</td></tr>
<tr><td>micro-sized crystal</td><td>


</td><td>Chumak et al., APL 95, 262508 (2009)
Ciubotaru et al., J.Phys.D 45, 255002 (2012)
Obry et al., APL, 102, 202403 (2013)
Ciubotaru, et al. PRB 88, 134406 (2013)</td></tr>
<tr><td>switchable device</td><td>
</td><td>Chumak, et al., J.Phys.D 42, 205005 (2009)
Chumak, et al., Nat. Commun. 1:141 (2010)
Karenowska, et al., PRL 108, 015505 (2012)</td></tr>
<tr><td>travelling crystal</td><td>
</td><td>Chumak et al., PRB, 81, 140404 (2010)</td></tr>
</table>

Localized ion implantation

Localized ion implantation:

- Purely magnetic patterning
- No change in sample topography

State of the art studies (YIG):

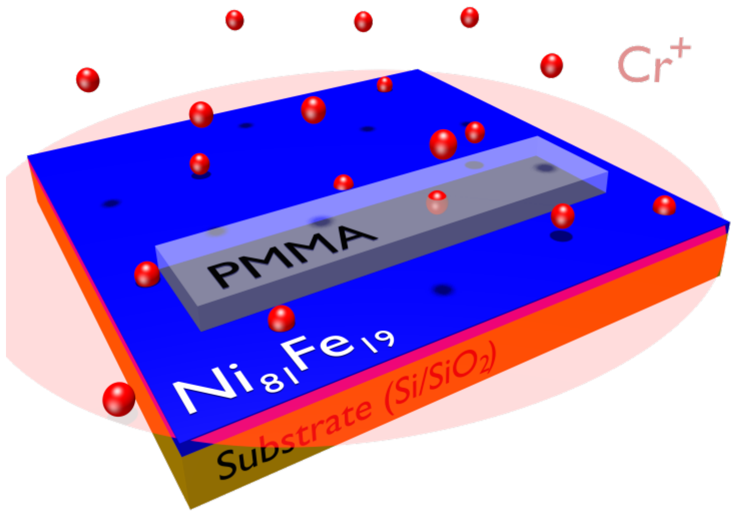
G. Volluet, P. Hartemann,
Reflection of magnetostatic forward volume waves by ion implanted gratings,
Proc. IEEE Ultrasonics Symp., 394 (1981).

R. L. Carter, J. M. Owens, C. V. Smith, Jr., K. W. Reed,
Ion-implanted magnetostatic wave reflective array filters,
J. Appl. Phys. 53 (1982), 2655.

Irradiation of $Ni_{81}Fe_{19}$ films with 30 keV Cr^+ ions:

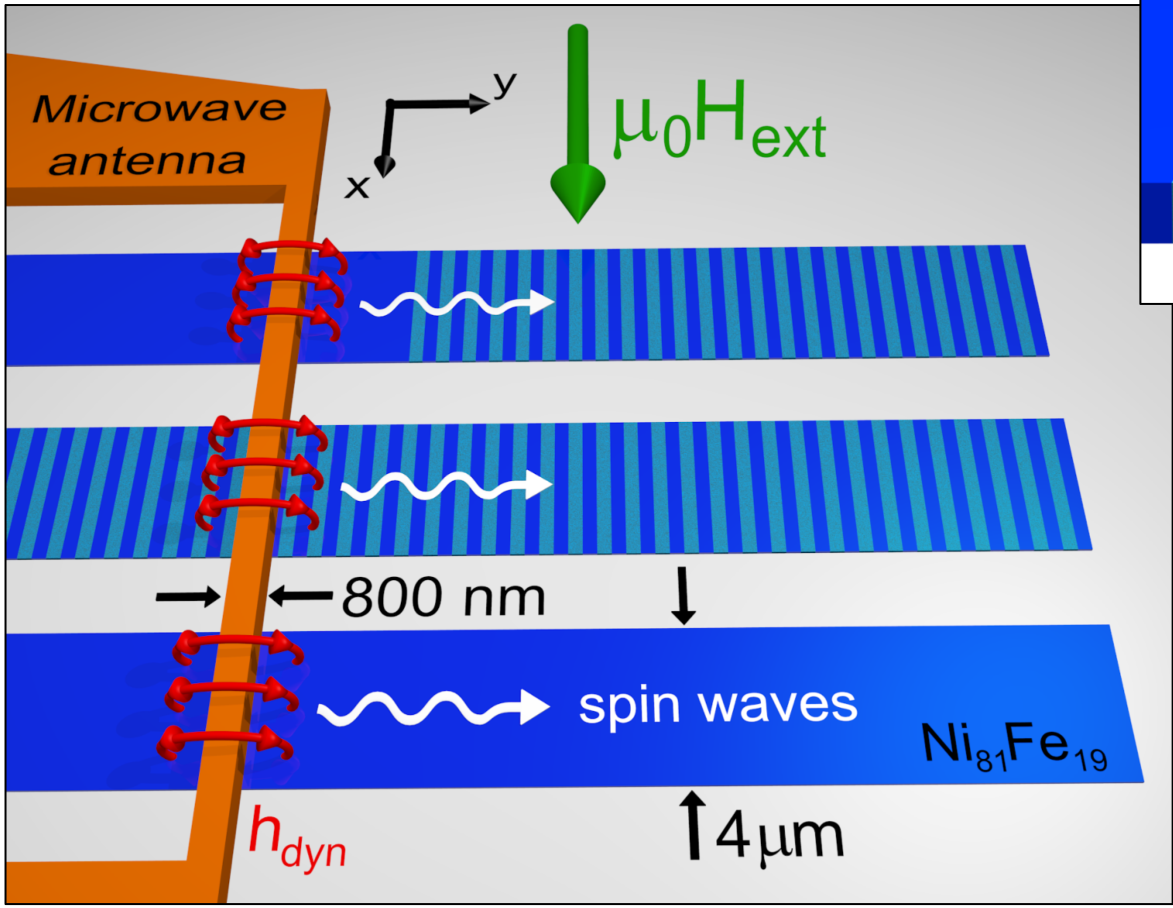
Control saturation magnetization M_S and Gilbert damping α

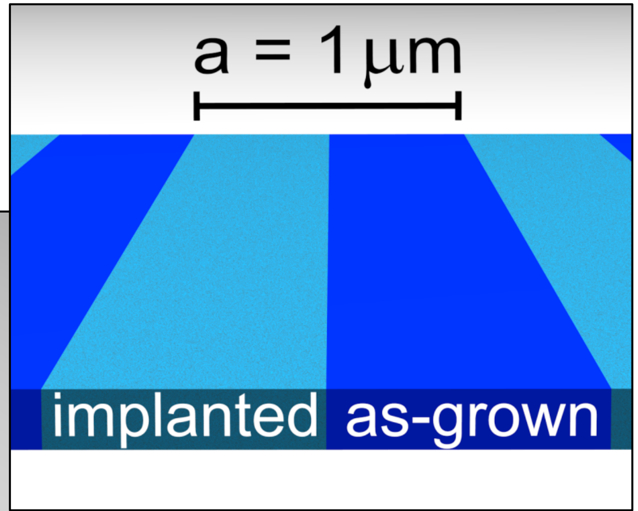
Fassbender *et al.*, PRB **73,** 184410 (2006)



Sample setup

Fabrication of microscopic metallic magnonic crystal with periodic change in saturation magnetization M_S

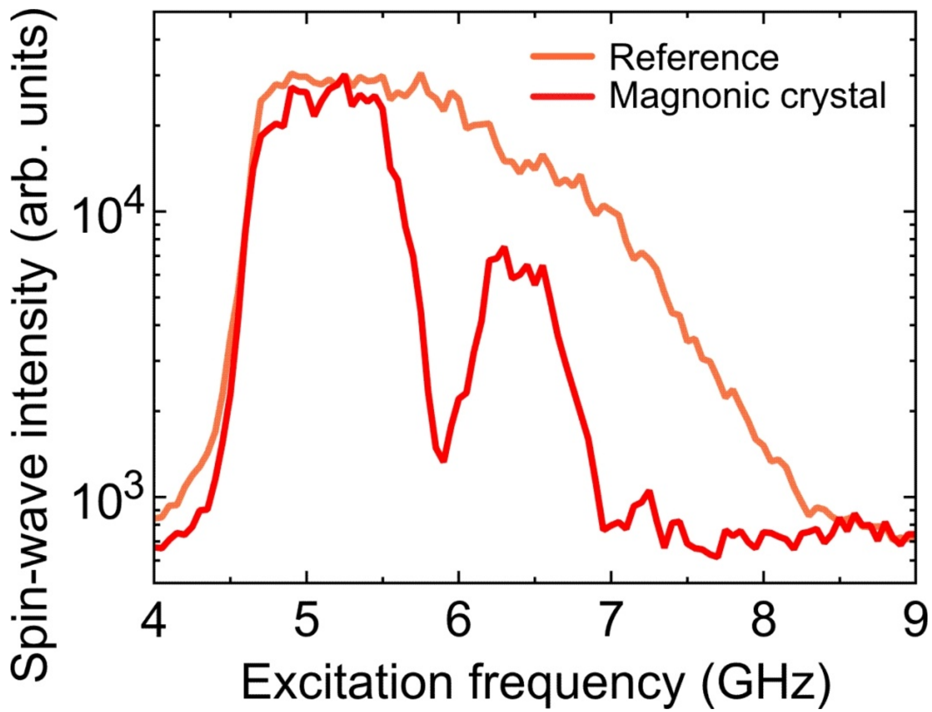


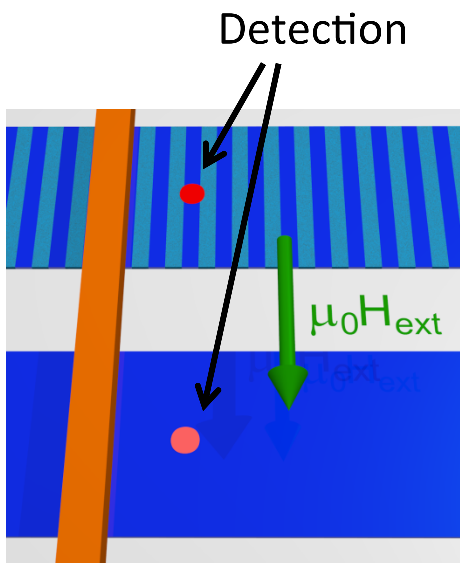


- Waveguides:
  MBE evaporation
  Lift-off techniques

Transmission spectrum

Spin-wave excitation spectra:





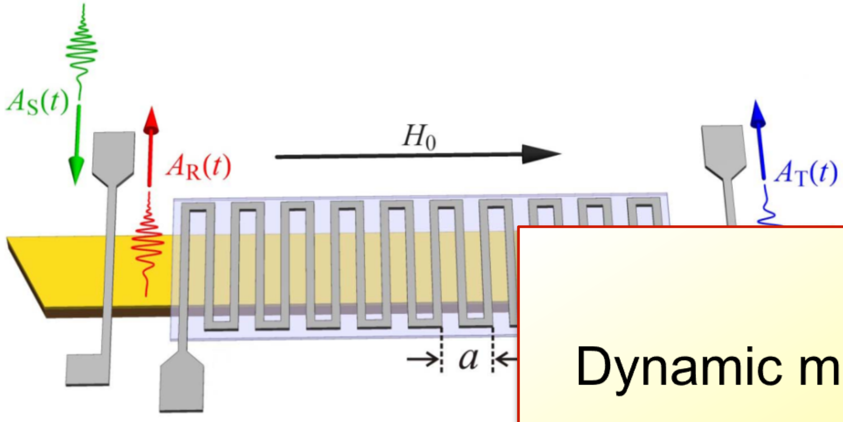
$\mu_0 H_{ext}$ = 27.3 mT

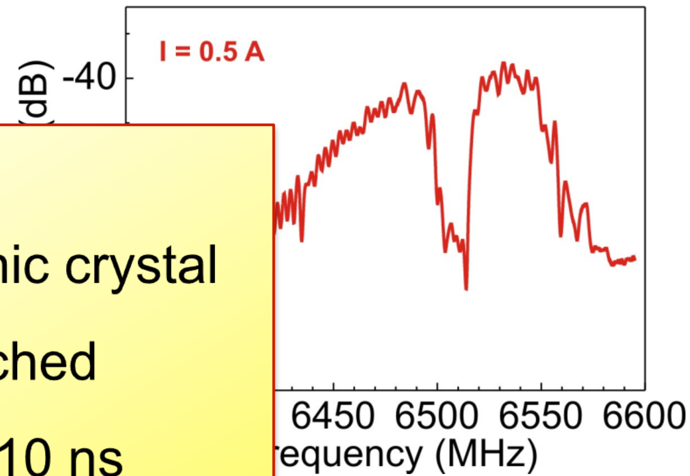
Two pronounced band gaps in transmission spectrum

Obry *et al.*, APL **102**, 202403 (2013)
Ciubotaru, et al. PRB **88**, 134406 (2013)

Dynamic magnonic crystal

Periodic modulation of the bias magnetic field by current-carrying wires

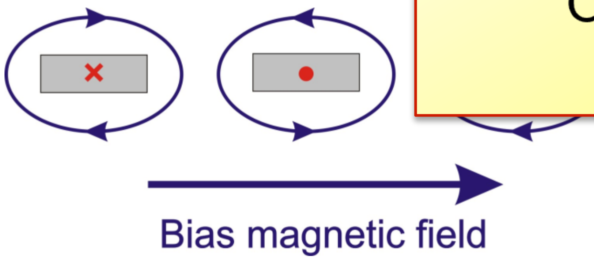


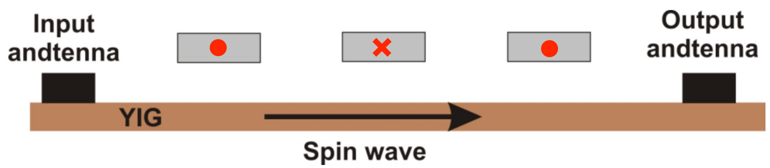


Dynamic magnonic crystal

can be switched

ON/OFF in ~10 ns



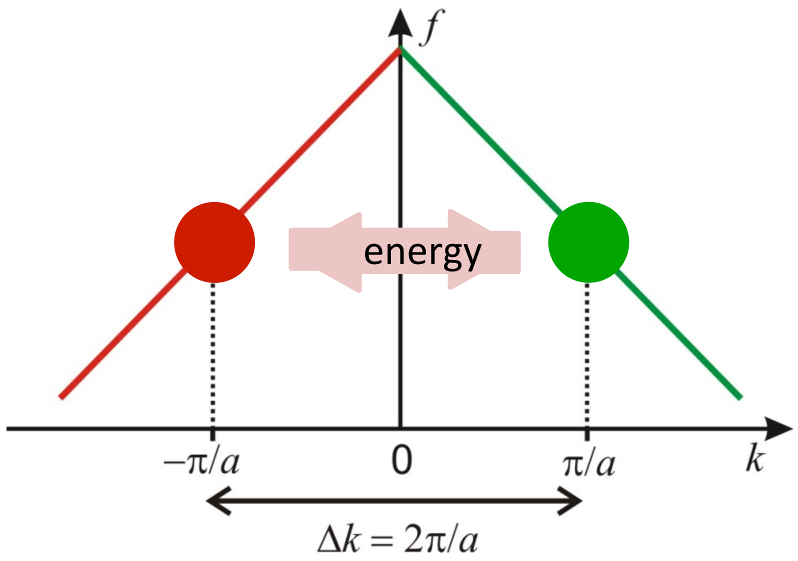


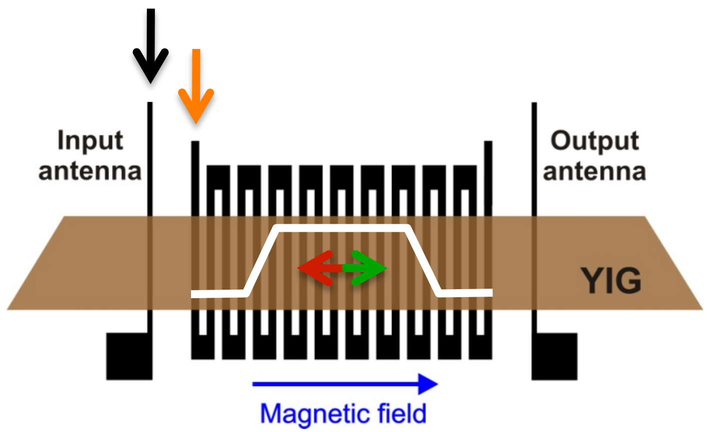
Lattice constant: a = 300 μm

Number of periods: N_g = 20

Chumak, et al., J. Phys. D **42,** 205005 (2009)

Spin-wave mode coupling by dynamic magnonic crystal

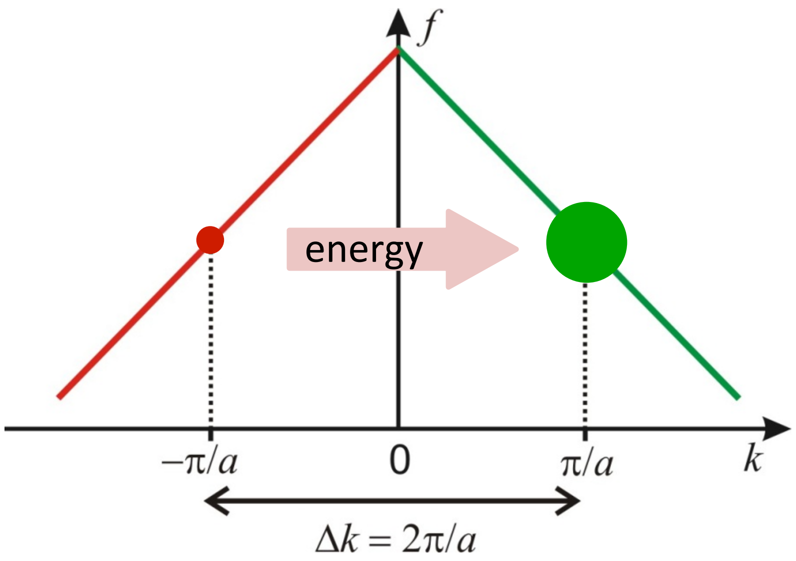


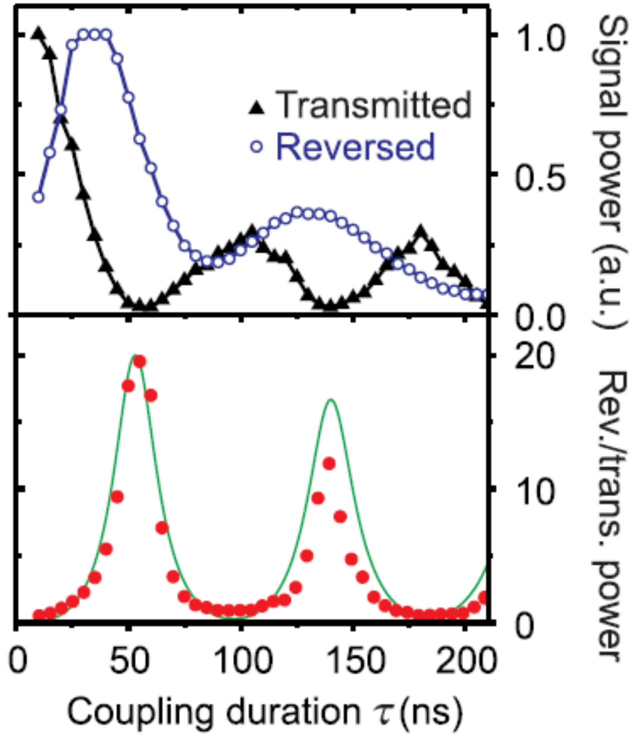


Two modes with $k = \pi/a$ and $k = -\pi/a$ are coupled by periodic variation of field

Coupling provides a mechanism for energy transfer

Spin-wave mode coupling by dynamic magnonic crystal





Chumak, et al., Nat. Commun. **1**:141 (2010)
Karenowska, et al., PRL **108**, 015505 (2012)

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Coupling provides a mechanism for energy transfer

All-linear time reversal by DMC

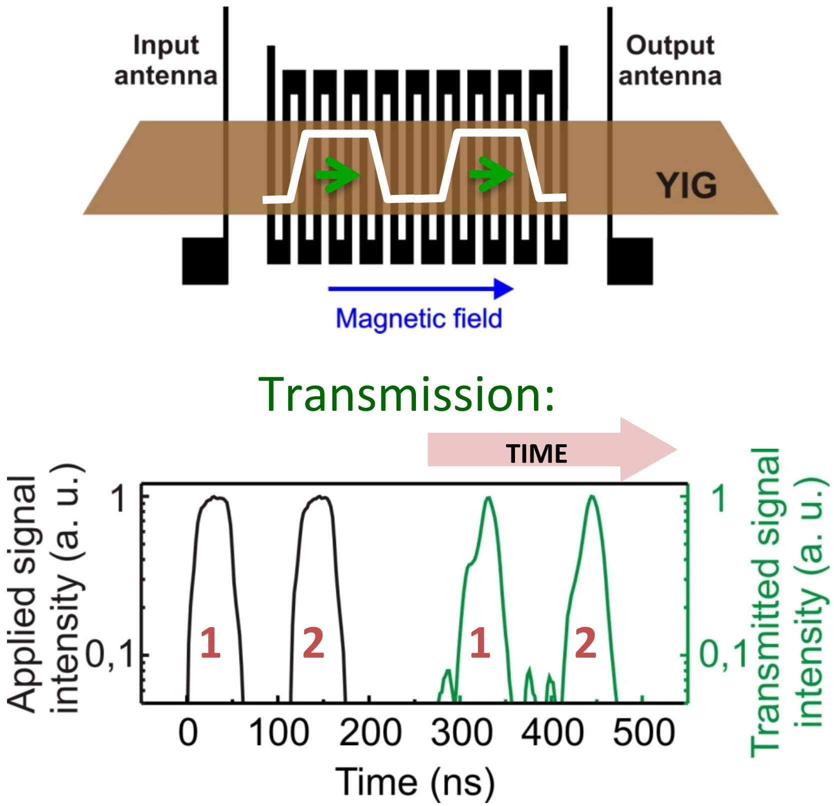
Input signal:

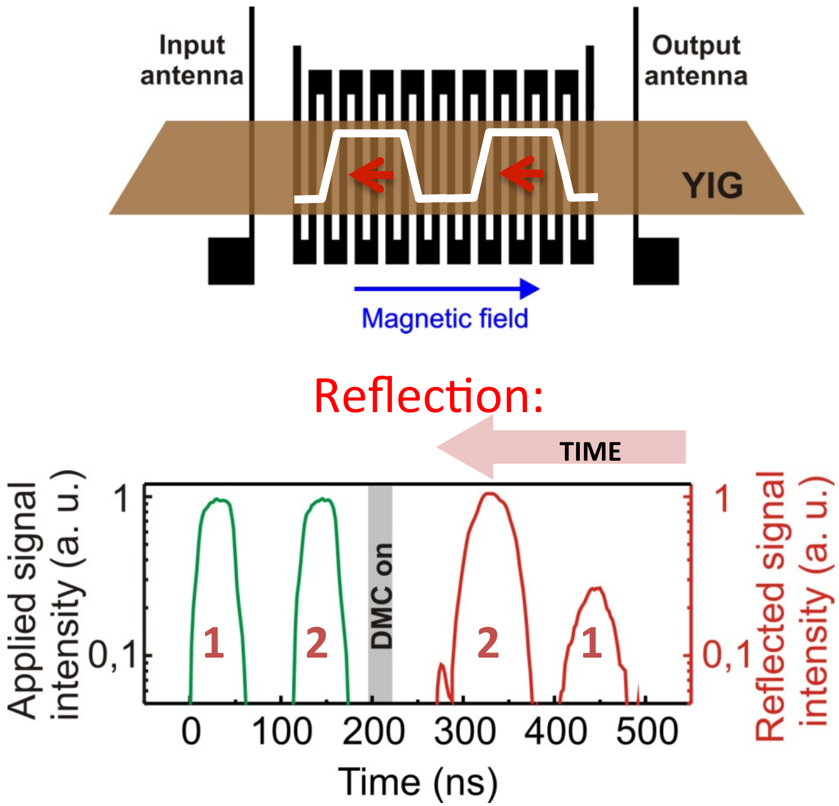
$$A_S(t) \sim \sum_{\Delta f} \exp(-i\,2\pi\,\Delta f\,t)$$

Δf is a frequency shift from the Bragg frequency

Reflected signal:

$$A_R(t) \sim \sum_{\Delta f} \exp(i\,2\pi\,\Delta f\,t) \sim A_S(-t)$$

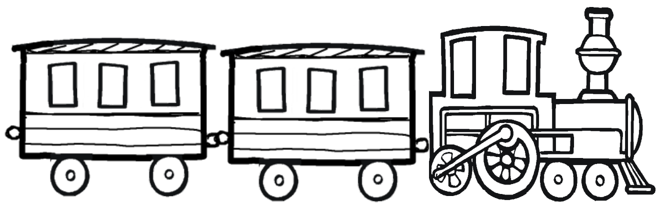


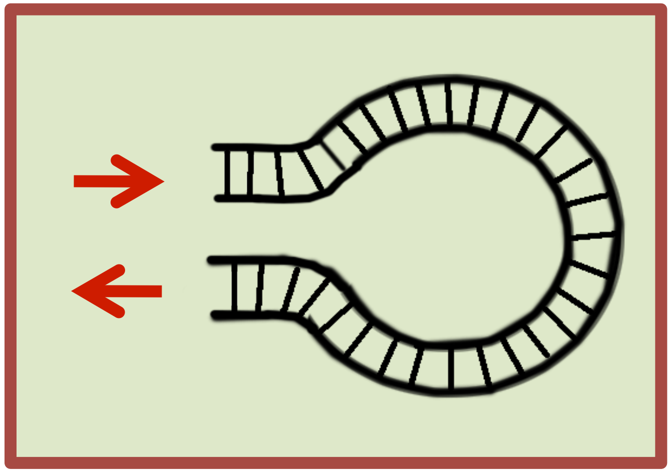


Chumak et al., **Nat. Commun. 1:141** doi: 10.1038/ncomms1142 (2010)

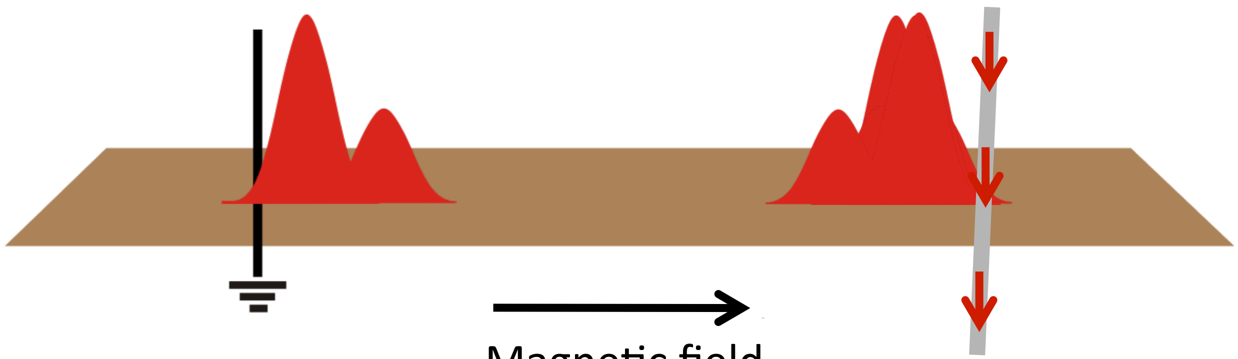
Classical reflection from mirror

Railway analog:



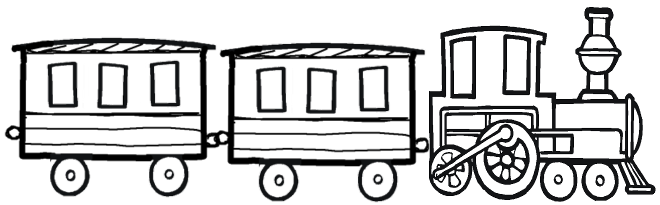


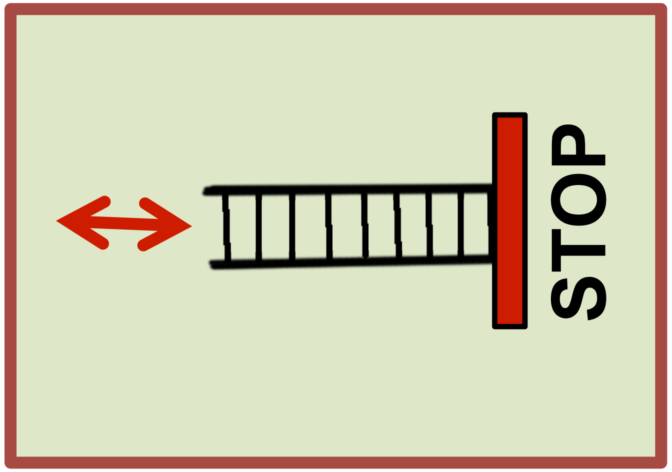
Spin-wave experiment:



Reflection via time reversal

Railway analog:





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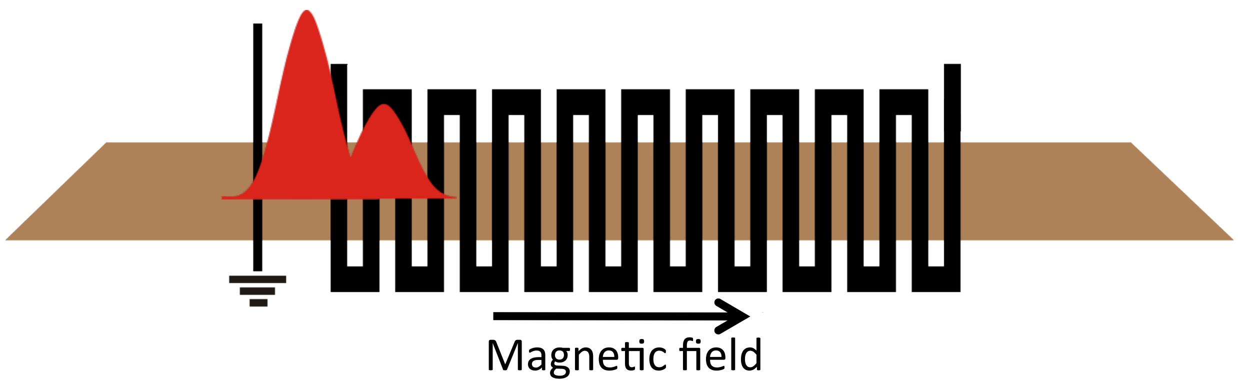
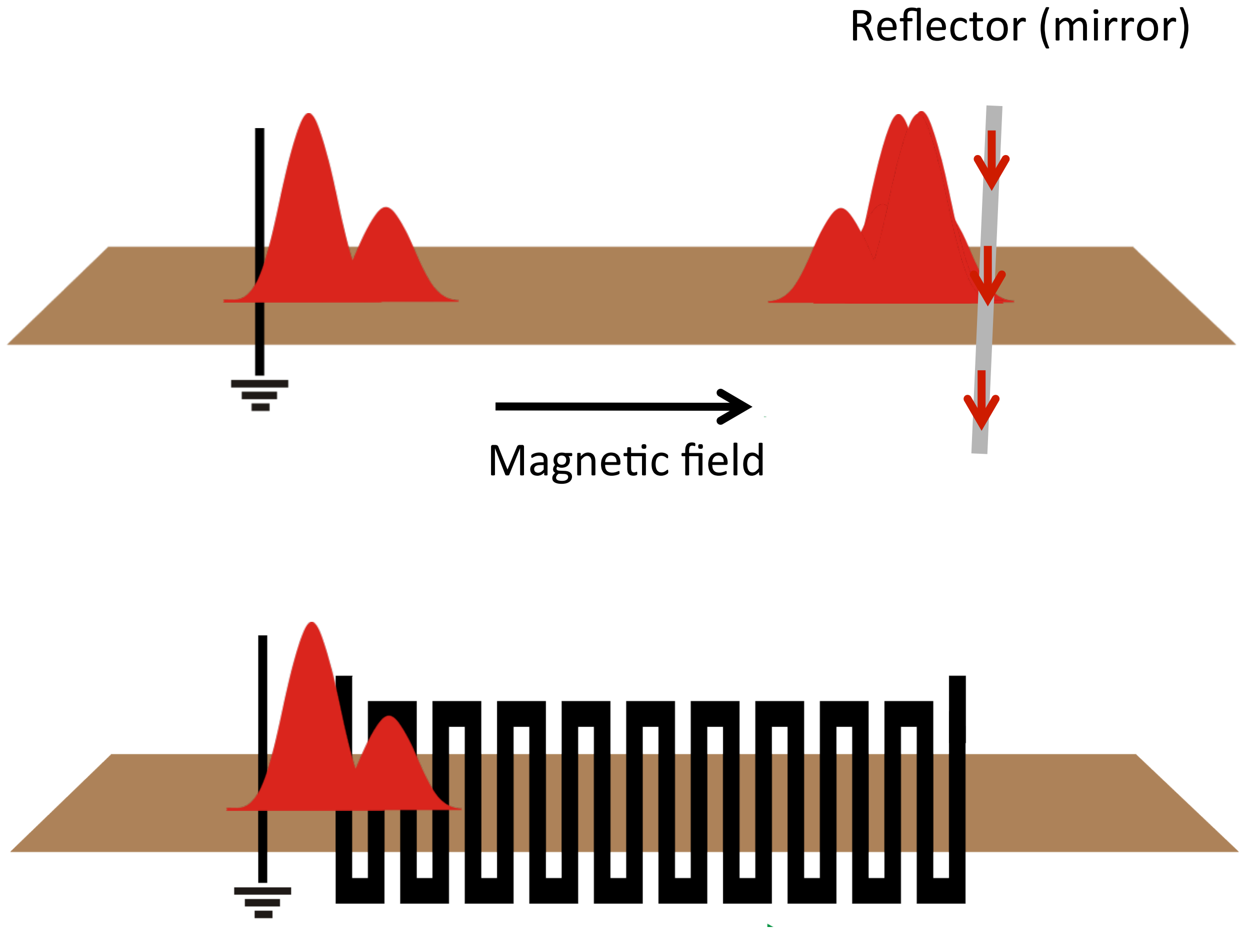


Reflection from a mirror



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Karenowska, et al., PRL **108**, 015505 (2012)

Magnonics: Main trends

I. New materials for magnonics

- Commonly used material: Permalloy (Py, NiFe): $\alpha = 8 \times 10^{-3}$
- CoFeB: low damping (both am. and crystalline phase): $\alpha = 4 \times 10^{-3}$
- Novel Heusler compounds: $\alpha = 3 \times 10^{-3}$
- Micro-structured Yttrium Iron Garnet $Y_3Fe_5O_{12}$ (YIG): $\alpha = 4 \times 10^{-5}$
- Magnonic crystals: artificial magnetic materials (static and dynamic)

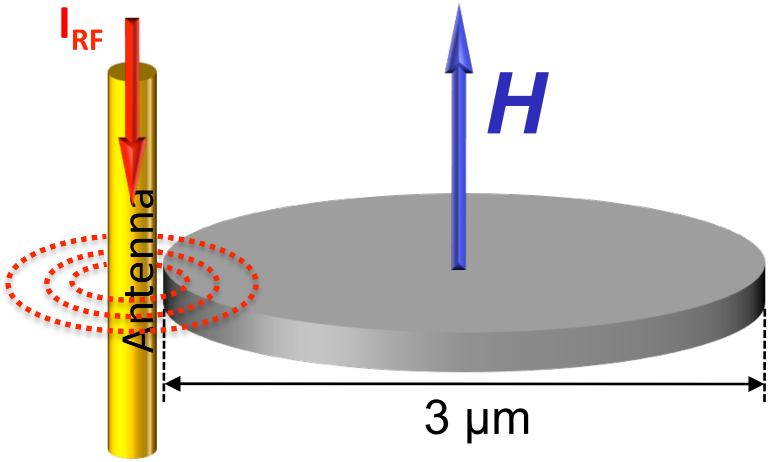
⇨ Normally magnetized non-reciprocal materials

Sample configuration

Simulation of a perpendicular magnetized Permalloy discs (OOMMF)

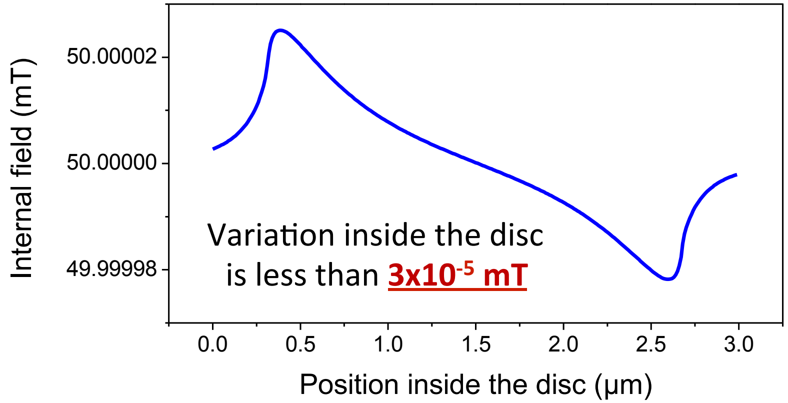
Parameters

$\mu_0 M_s = 1$ T
$H_k = 0$
$\alpha = 0.007$
$\mu_0 H = 1.050$ T



Spin waves are exited by the dynamic Oersted field created by injecting an RF current through antenna.

Diameter of antenna: 500 nm



Side charges were added in order to have an uniform distribution of the internal field.

Internal field = 50 mT

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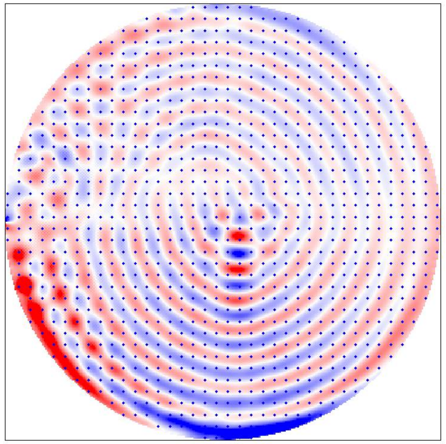
Spin-wave boundary mode

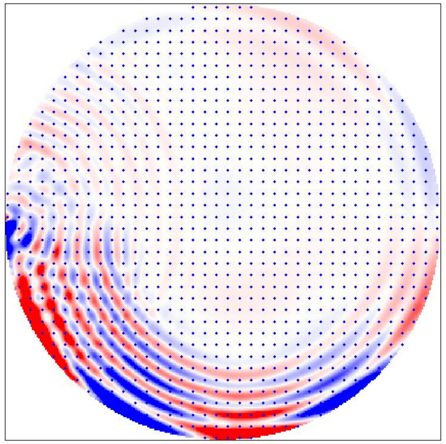
f = 8 GHz



λ_v = 278 nm

λ_e = 3.7 µm

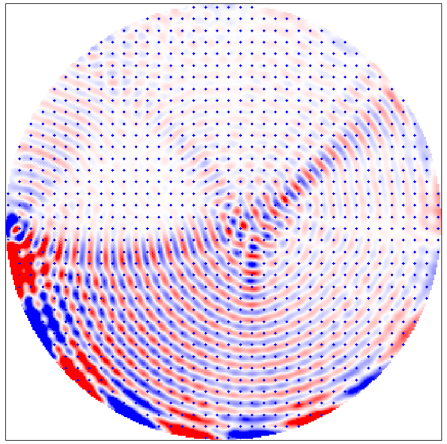
f = 10 GHz



λ_v = 125 nm

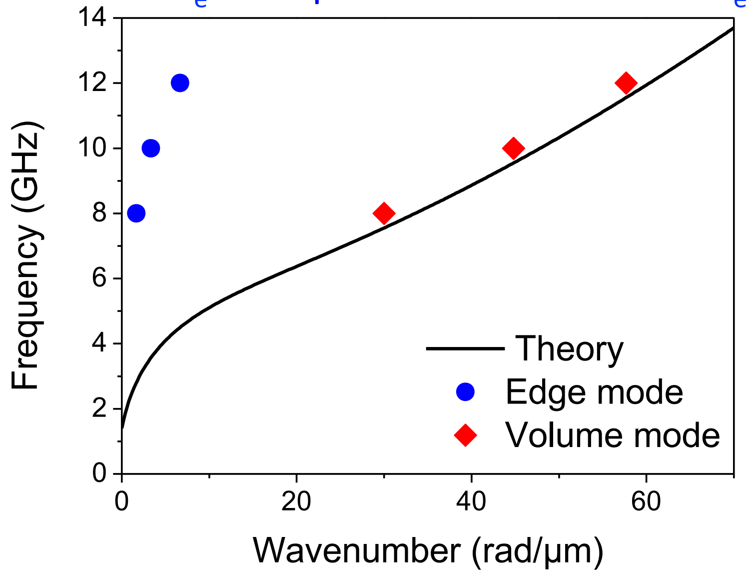
λ_e = 1.9 µm

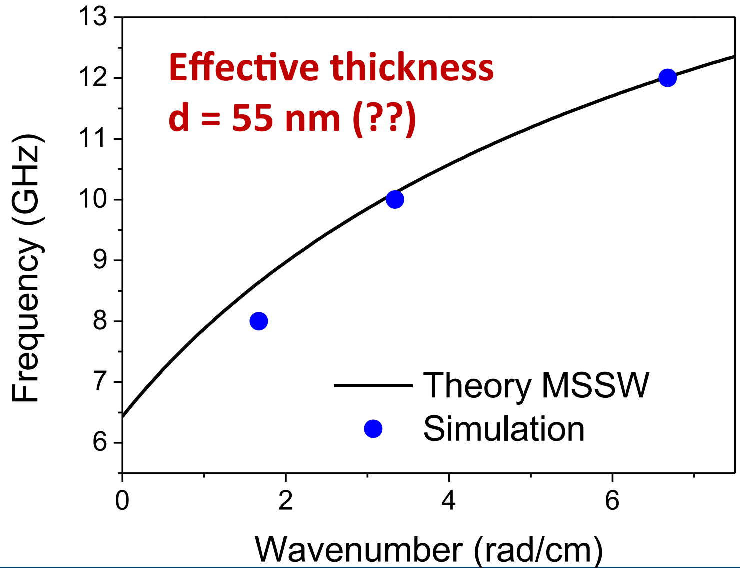
f = 12 GHz



λ_v = 98 nm

λ_e = 0.94 µm

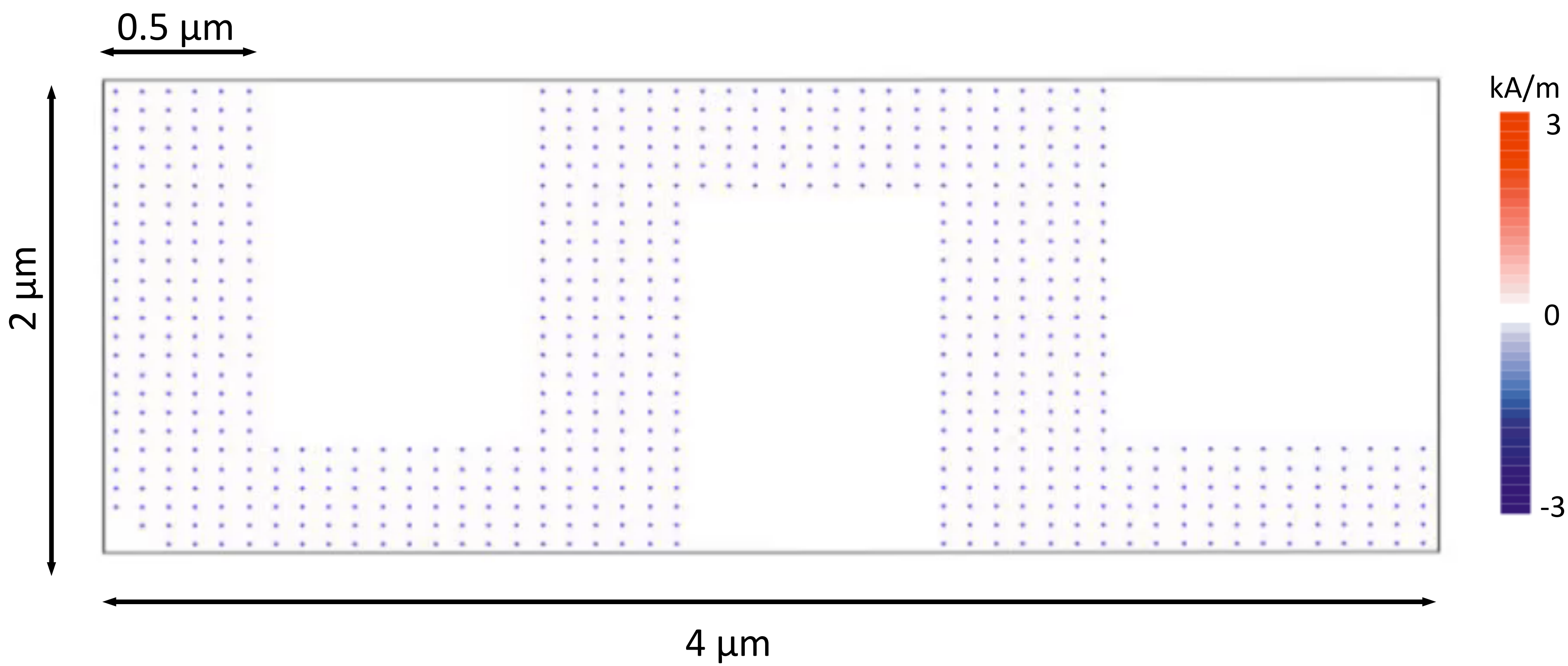




Spin-wave circuit

Thickness = 300 nm

Excitation frequency = 10 GHz



The boundary mode propagates arround the corners without changing its properties

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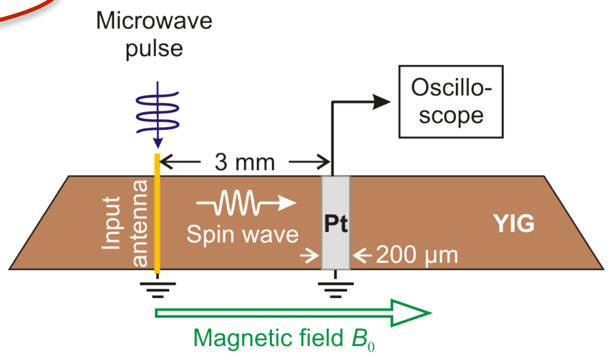
Magnonics: Main trends

I. New materials for magnonics

II. Novel means for magnon detection

III. Data processing using magnons

IV. Magnonic supercurrents

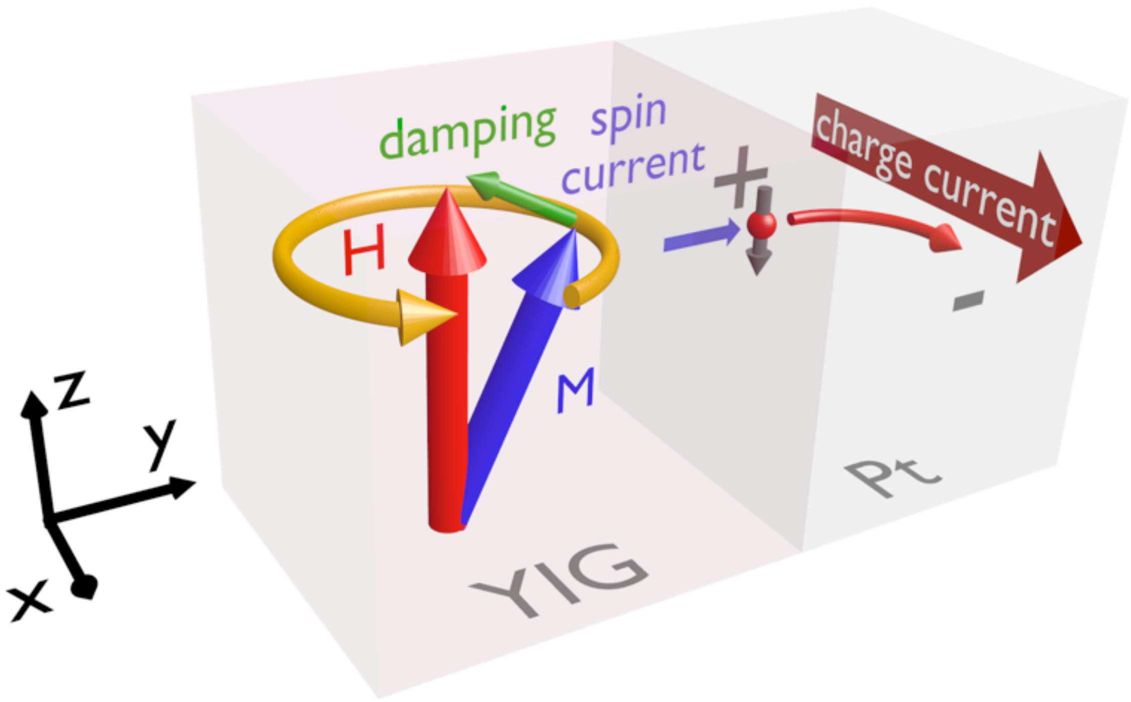


II. Novel means for magnon detection

- Spin pumping + inverse spin Hall effect

Magnon to charge current conversion

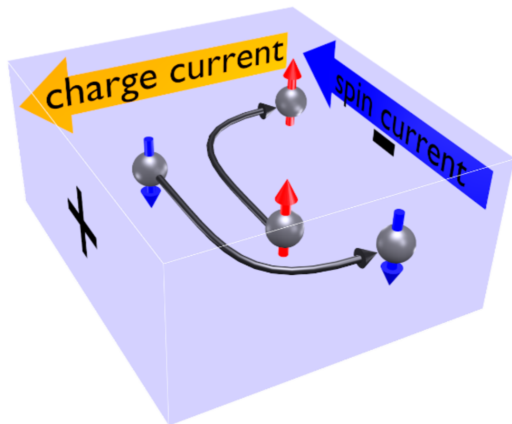
Detection of magnons by a combination of spin pumping and inverse spin Hall effect



Spin pumping

Tserkovnyak et al., PRL (2002)
Costache et al., PRL (2006)

Inverse spin Hall effect (ISHE)



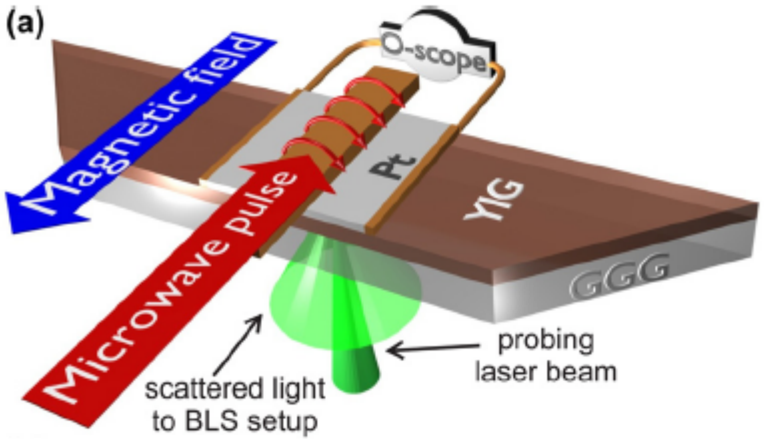
Hirsch, PRL (1999)
Saitoh et al., APL **88** 182509 (2006)

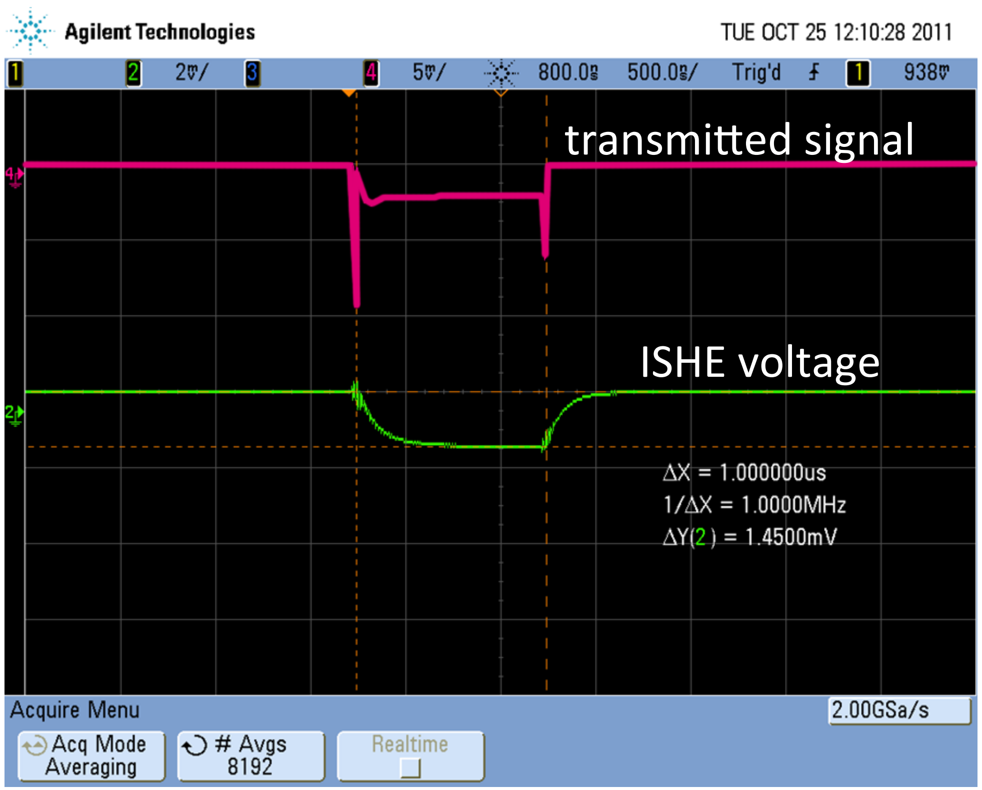
Time resolved ISHE voltage

Yttrium iron garnet (YIG) / platinum (Pt) bilayer was used

Magnetic field *B* = – 175.5 mT

Microwave frequency 7 GHz





Parameters:

YIG thickness: 2.1 μm

YIG/Pt width: 3 mm

Pt thickness: 10 nm

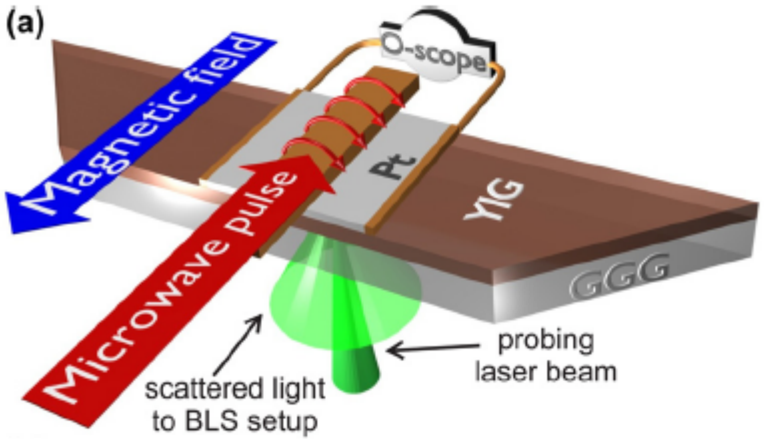
Jungfleisch et al., APL **99**, 182512 (2011)

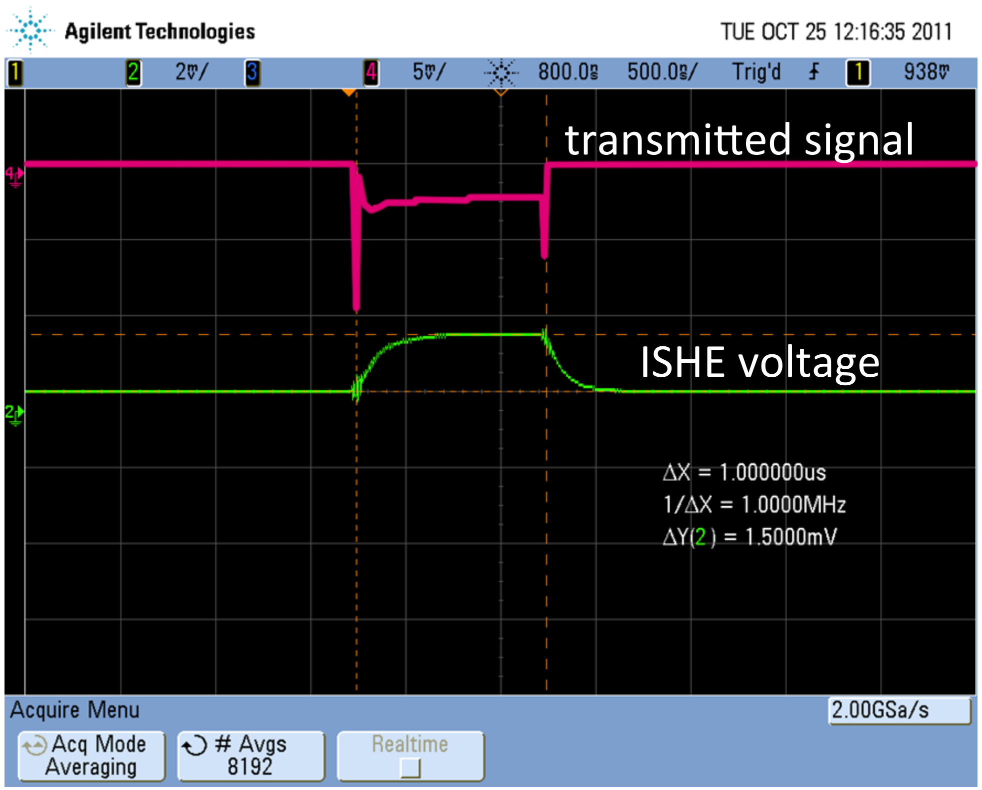
Time resolved ISHE voltage

Yttrium iron garnet (YIG) / platinum (Pt) bilayer was used

Magnetic field B = + 175.5 mT

Microwave frequency 7 GHz





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Time resolved ISHE voltage

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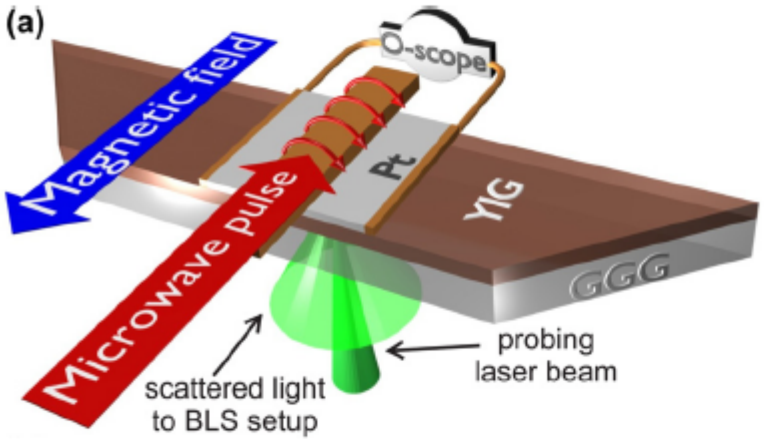
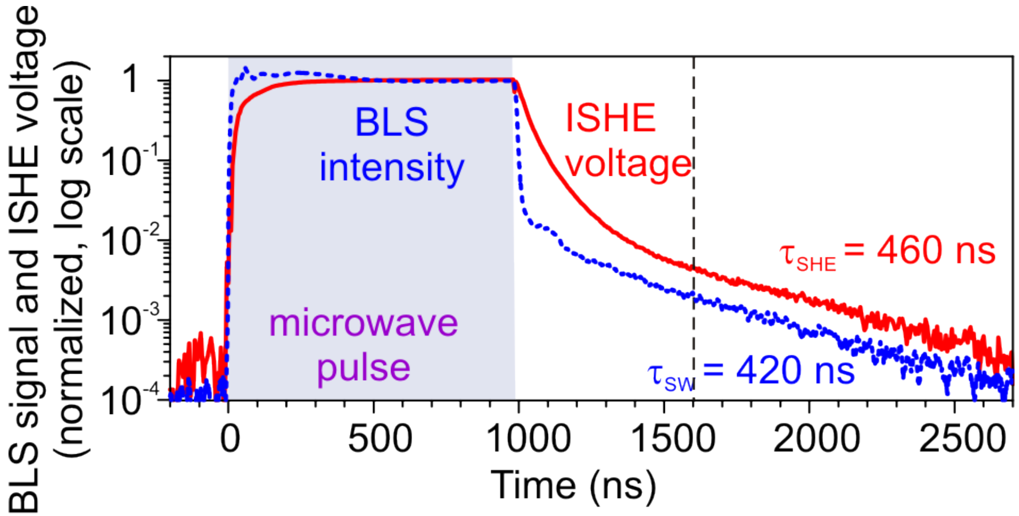




Parameters:

YIG thickness: 2.1 μm

YIG/Pt width: 3 mm

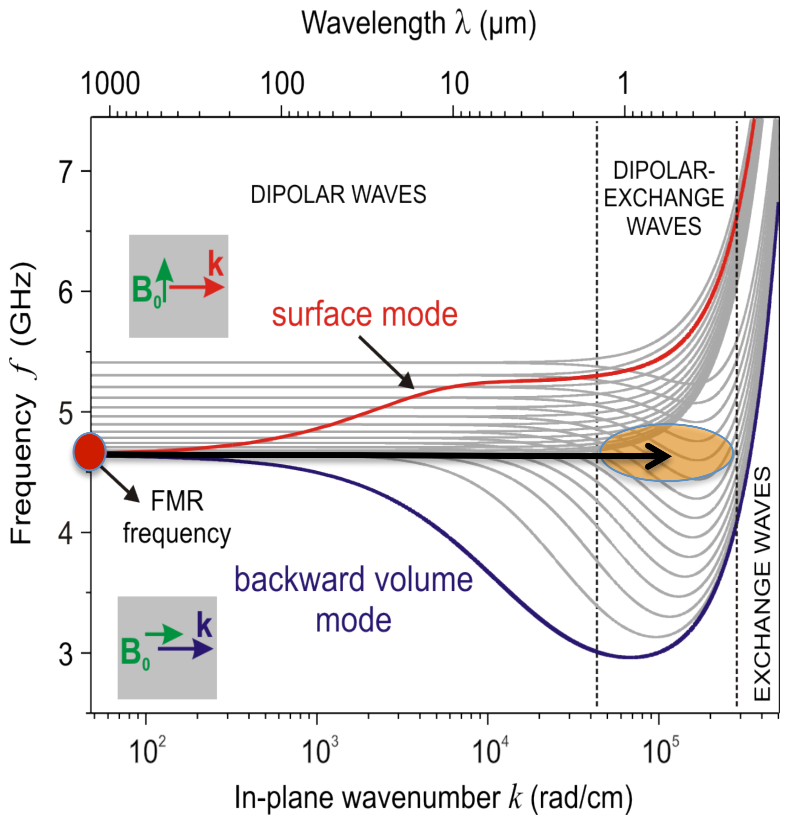
Pt thickness: 10 nm

- ISHE pulse has a long rise and fall times
- Secondary magnons contribute to ISHE

Jungfleisch et al., APL 99, 182512 (2011)

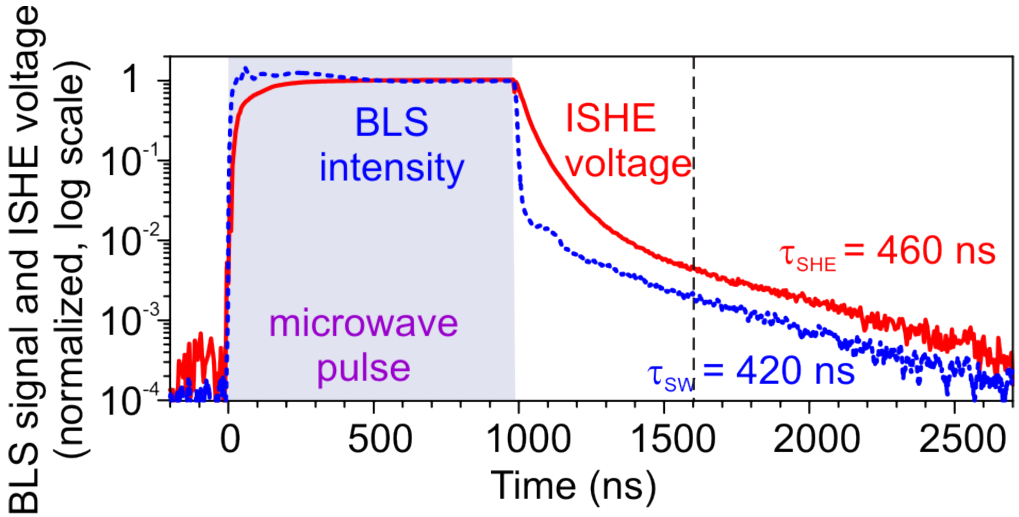
Surface modes contribute to spin pumping

Yttrium iron garnet (YIG) / platinum (Pt) bilayer was used



Magnetic field $B = + 175.5$ mT

Dipolar-exchange waves contribute to spin pumping!

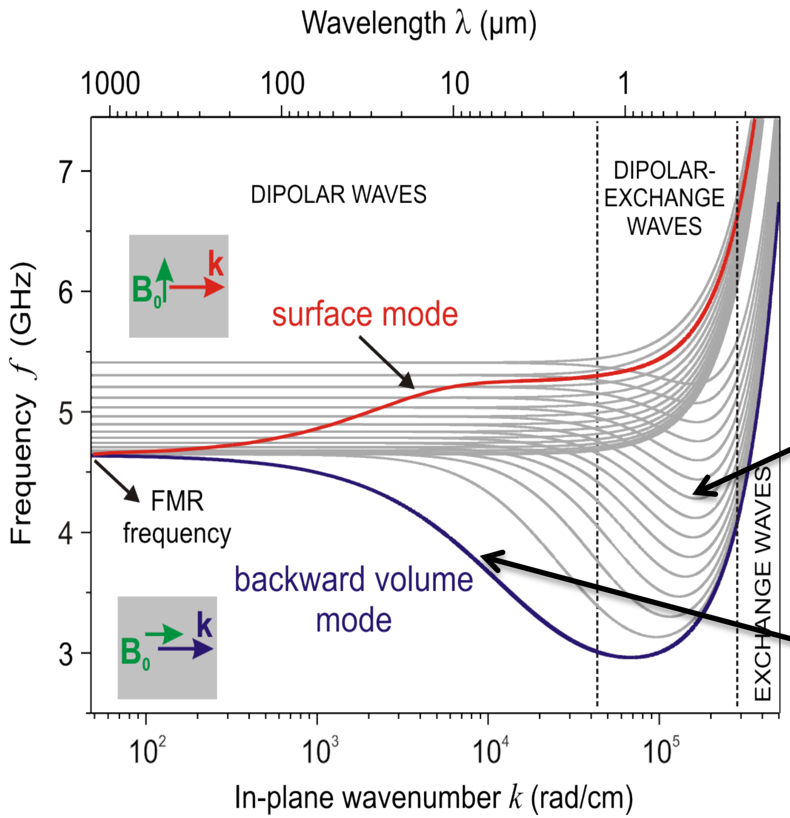


- ISHE pulse has a long rise and fall times
- Secondary magnons contribute to ISHE

Jungfleisch et al., APL 99, 182512 (2011)

Surface modes contribute to spin pumping

Yttrium iron garnet (YIG) / platinum (Pt) bilayer was used

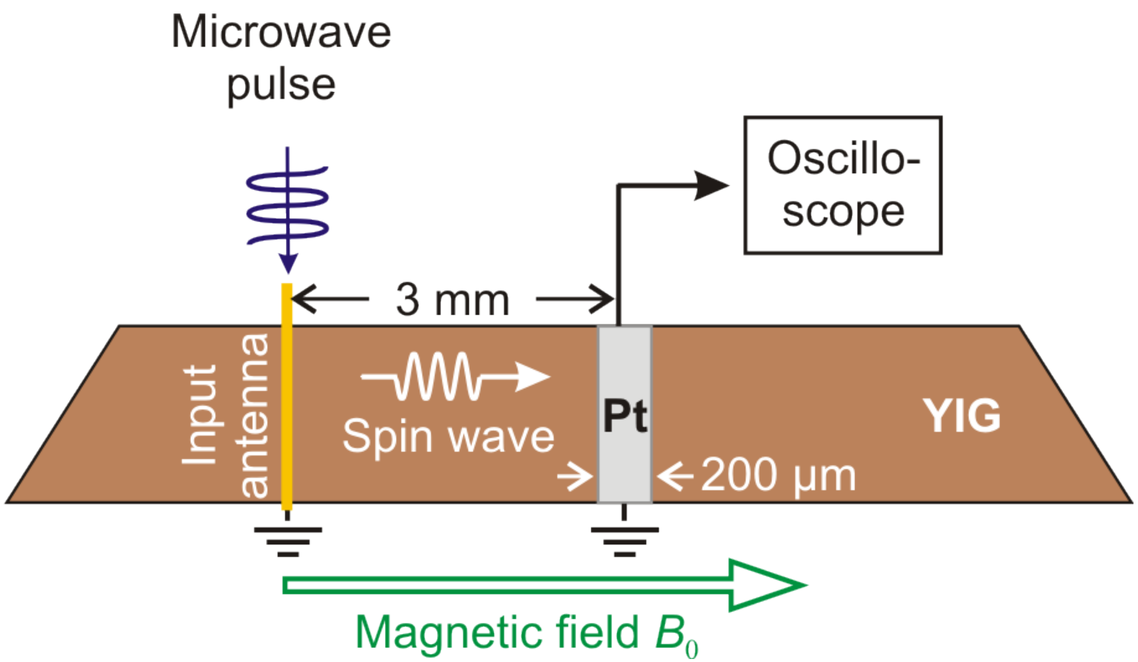


But dipolar-exchange waves have zero velocities → no spin transport

Spin pumping by propagating magnons?

ISHE detection of propagating spin waves

Spin-wave source and Pt detector are separated in space



Parameters:

YIG thickness: 2.1 μm

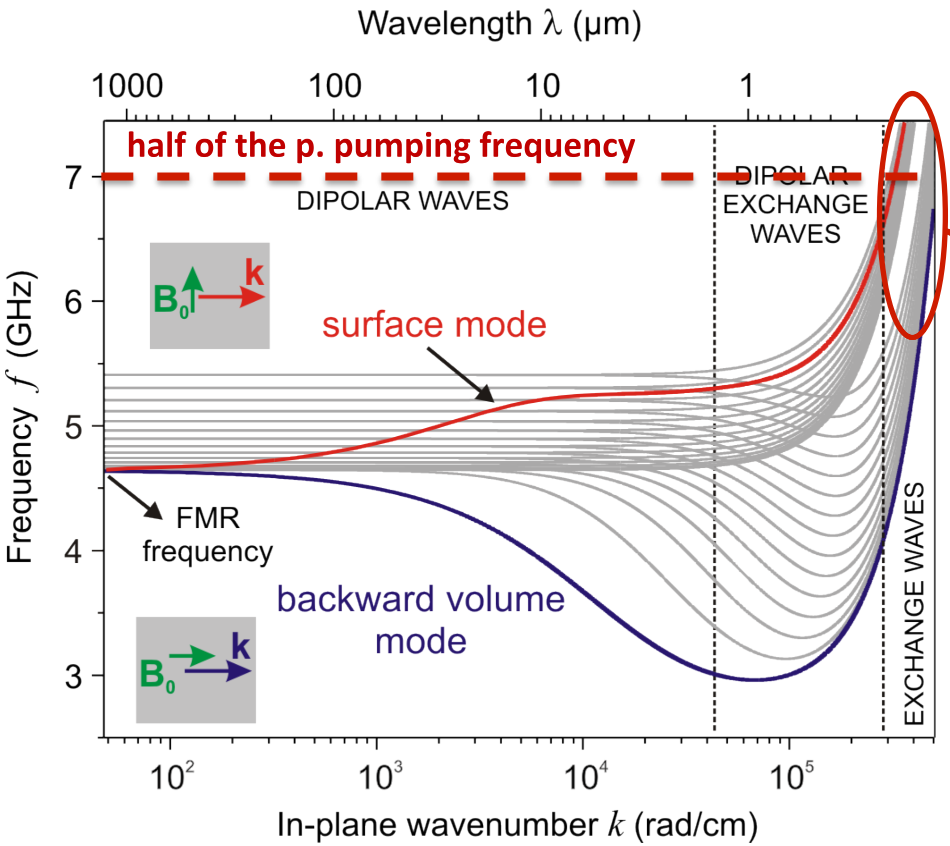
Pt size: 3 x 0.2 mm

Pt thickness: 10 nm

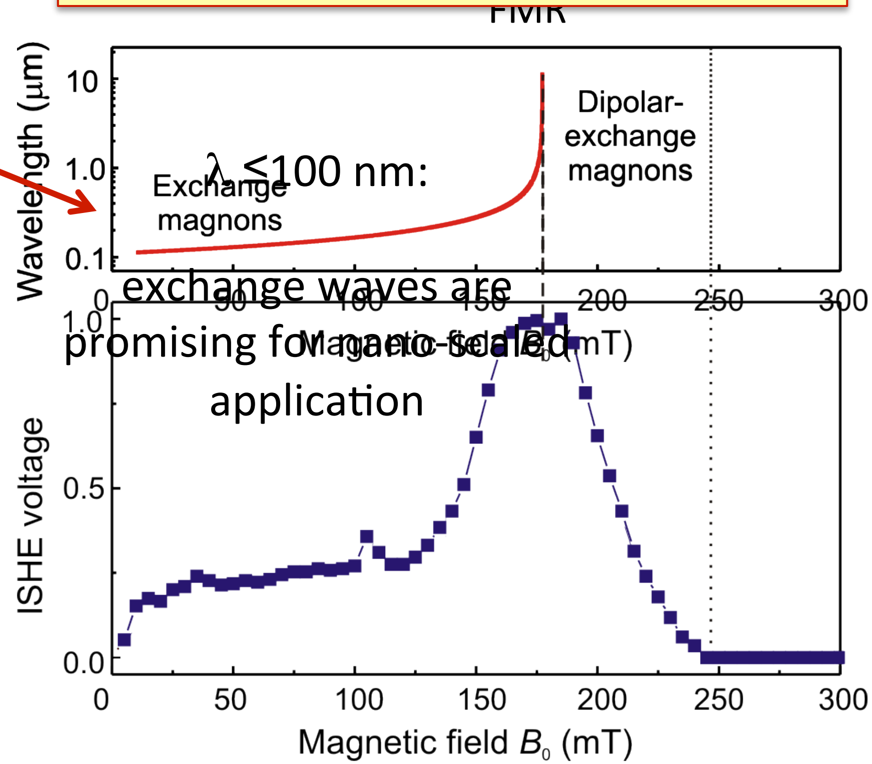
Signal frequency: 7 GHz

Spin pumping by exchange magnons

Parametric pumping at 14 GHz



Exchange magnons contribute to spin pumping!



Sandweg et al., PRL **106**, 216601 (2011)

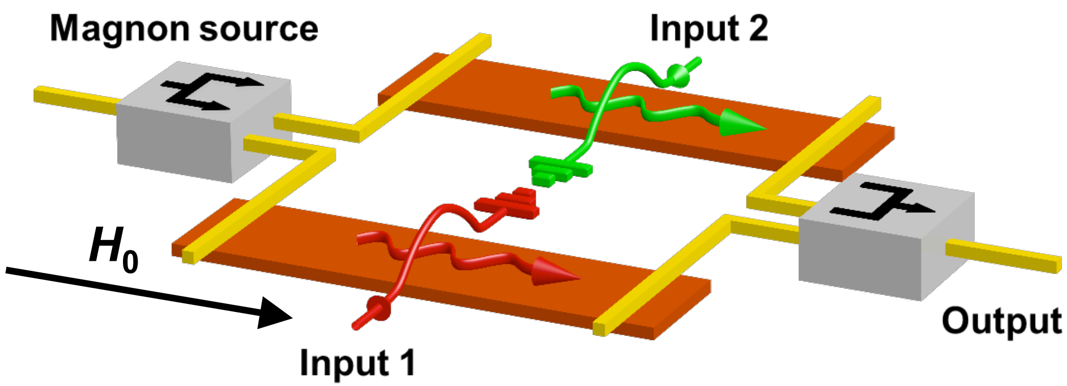
Kurebayashi, Dzyapko et al., APL **99**, 162502 (2011)
Ando et al., APL **99,** 092510 (2011)

Magnonics: Main trends

III. Data processing using magnons

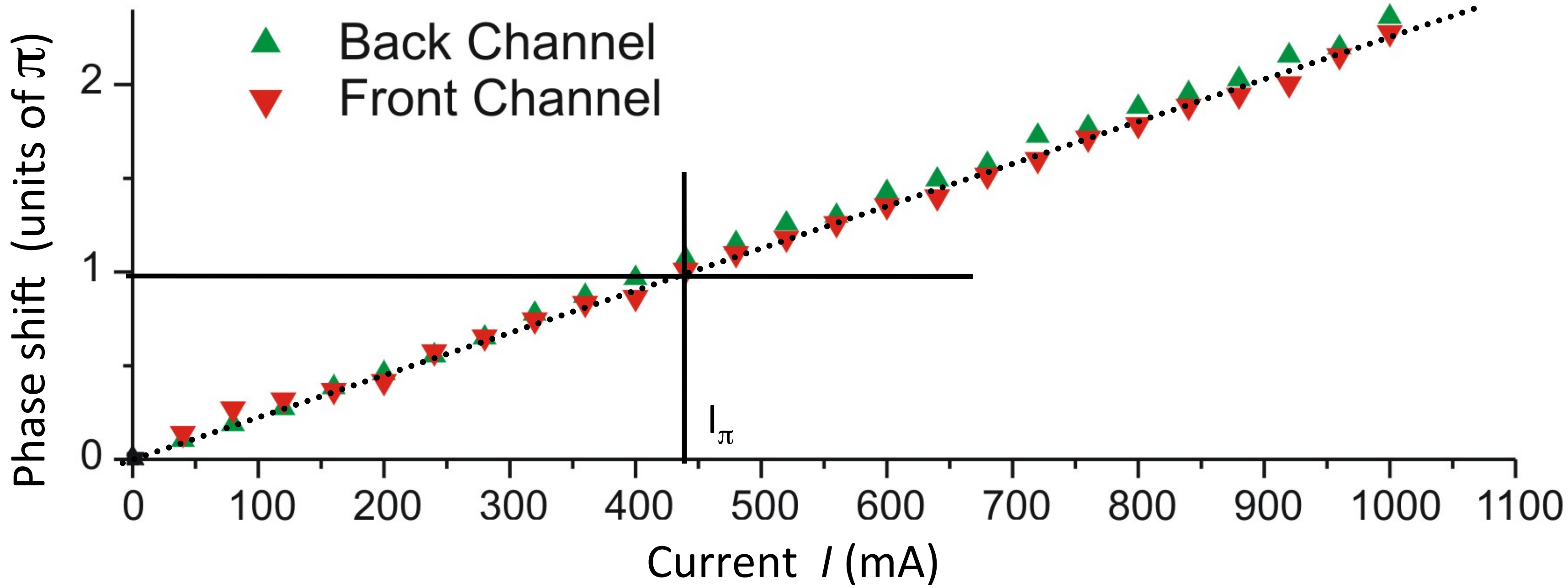
- Spin-wave logic gates

Mach-Zehnder interferometer based spin-wave logic gate

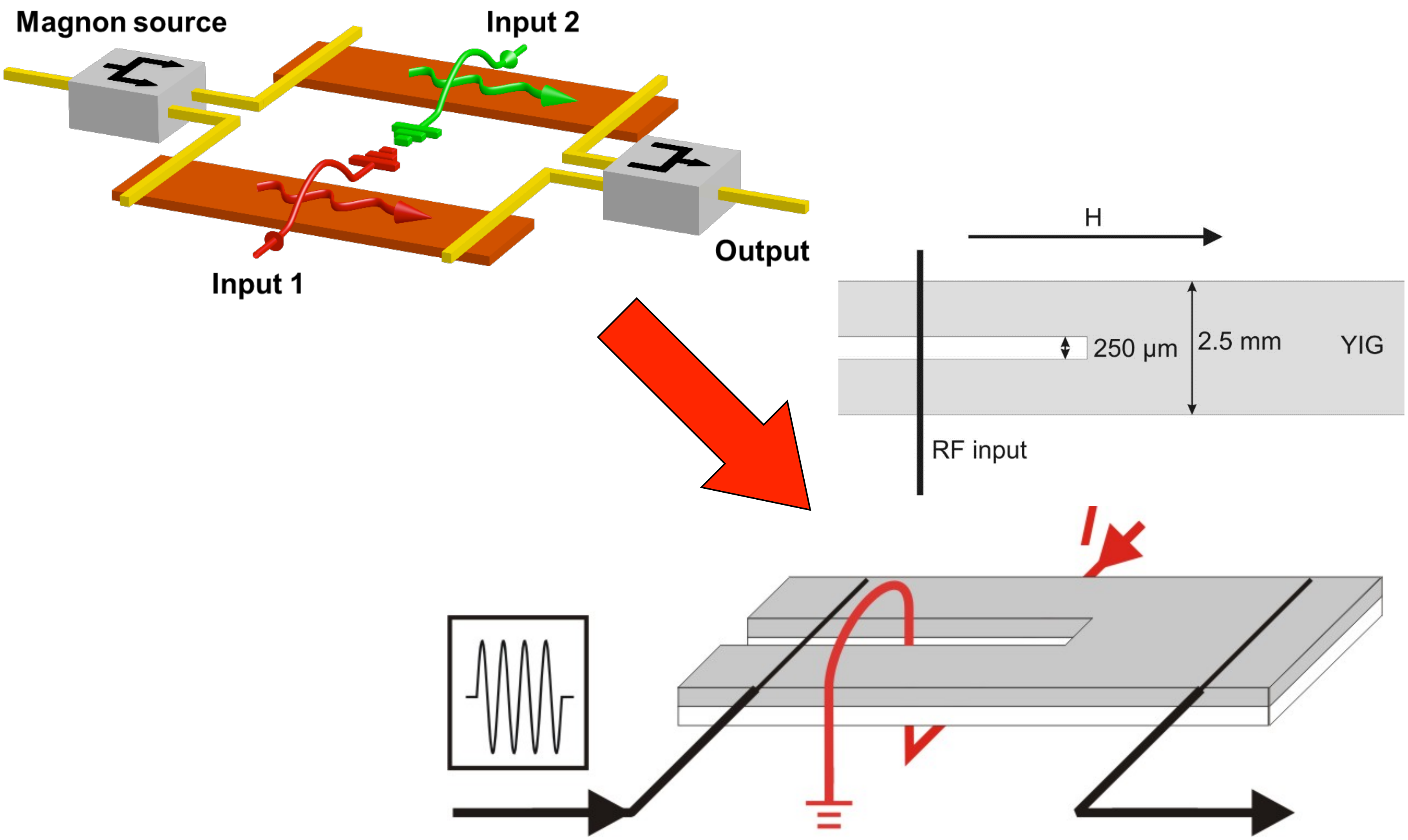


Kostylev et al., **APL 87**, 153501 (2005)

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

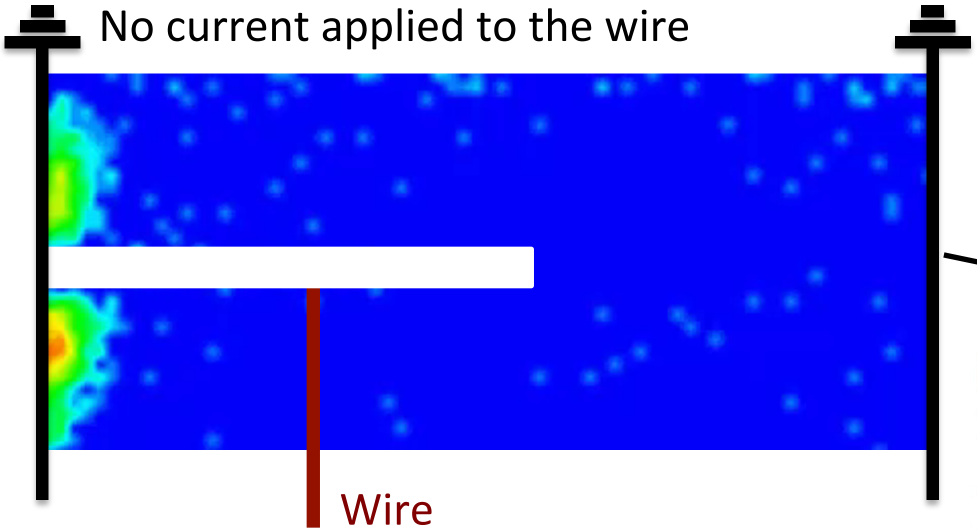


“Interferometer on a waveguide“

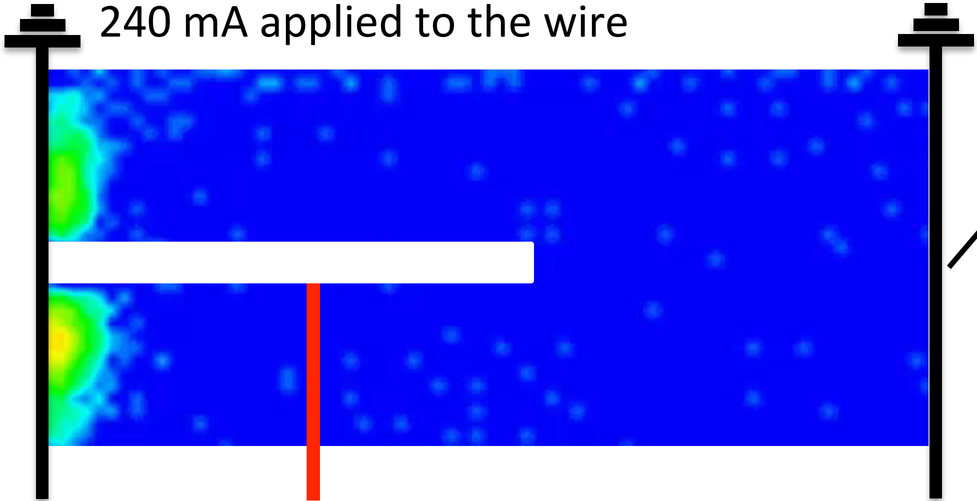


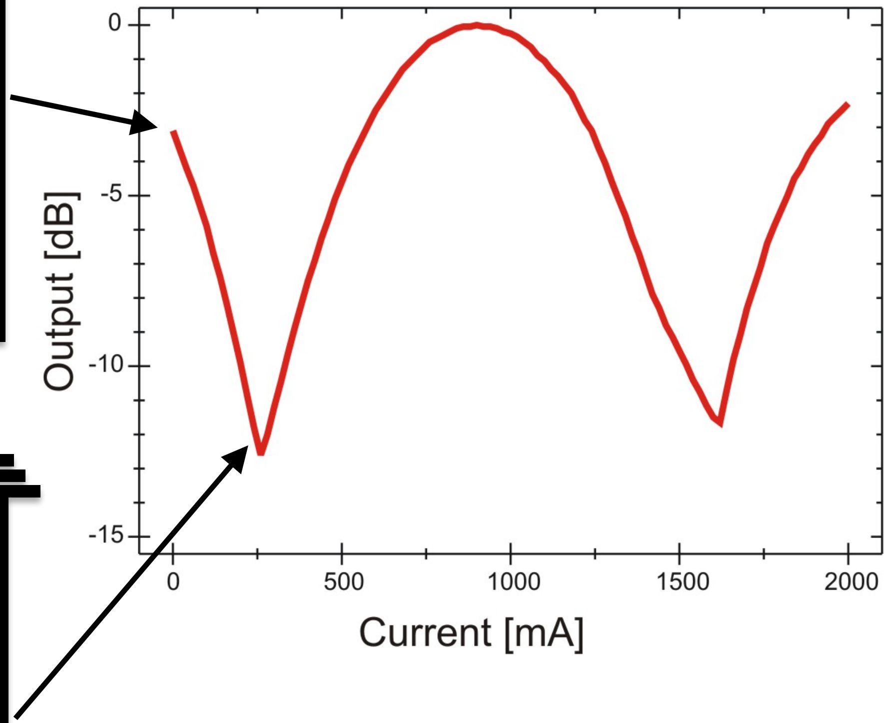
"Interferometer on a waveguide" – BLS measurement

No current applied to the wire



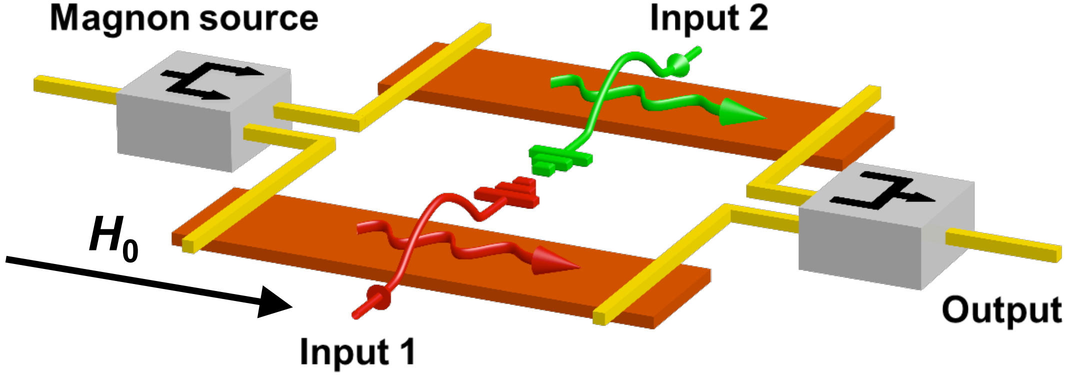
240 mA applied to the wire





Schneider et al., J. of Nanoelectronics and Optoelectronics **3**, 69 (2008)

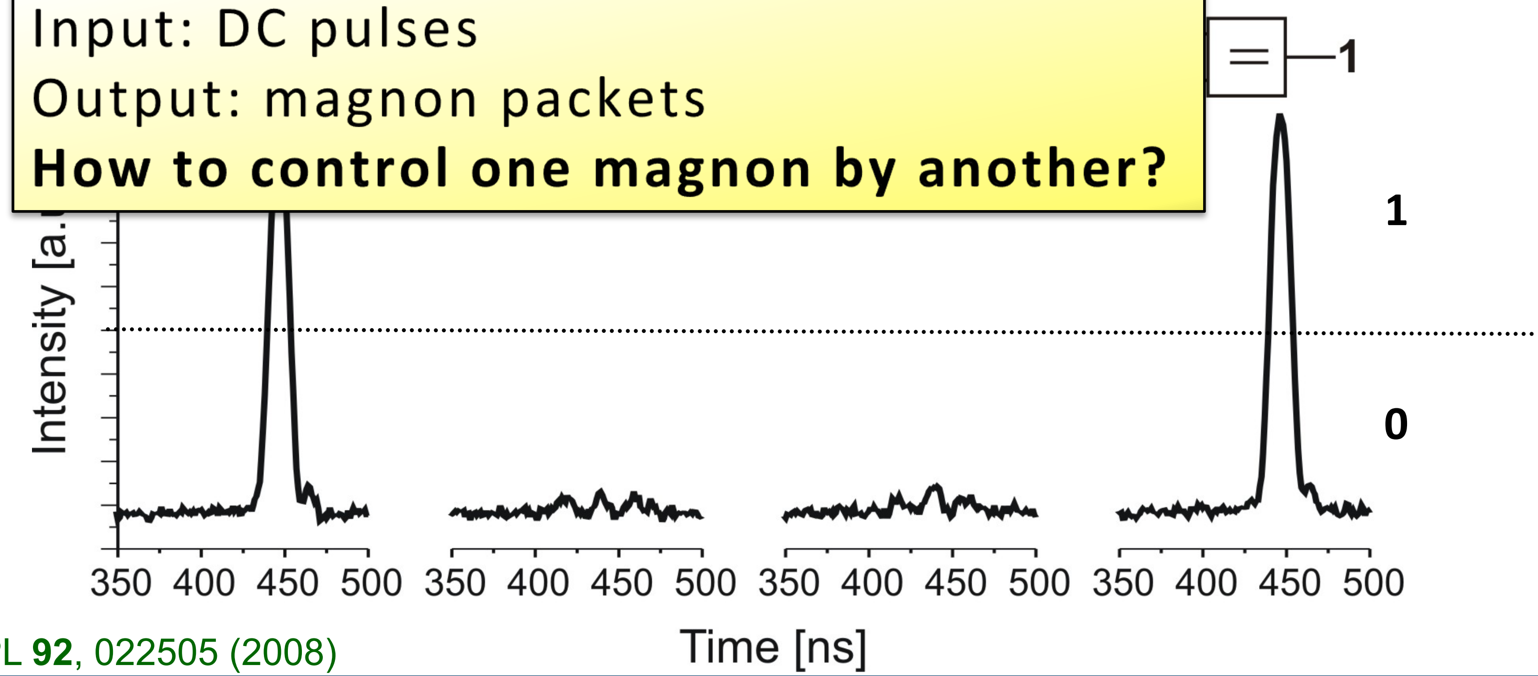
Mach-Zehnder interferometer based spin-wave logic gate



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

Input: DC pulses
Output: magnon packets
How to control one magnon by another?



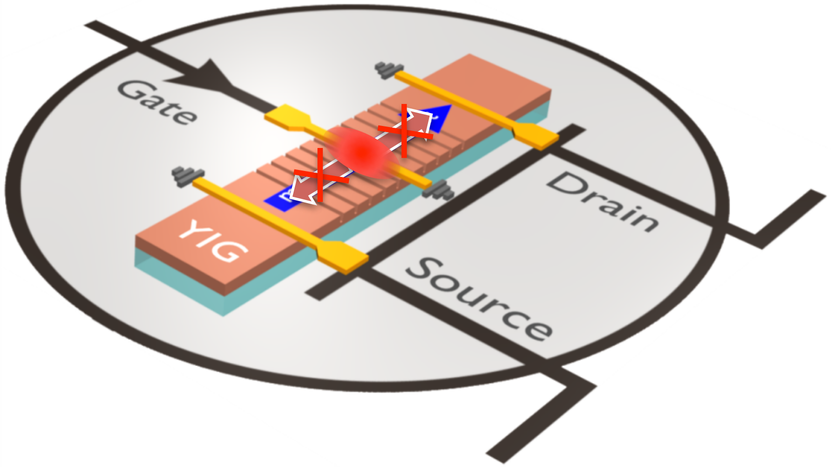
Schneider et al., APL **92**, 022505 (2008)

Magnonics: Main trends

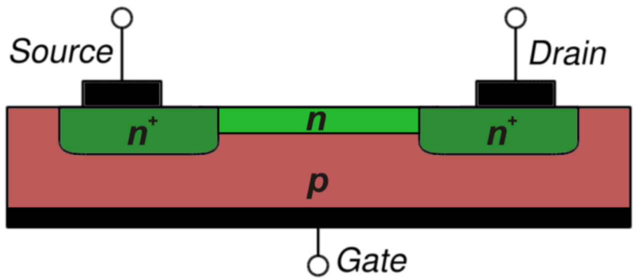
III. Data processing using magnons

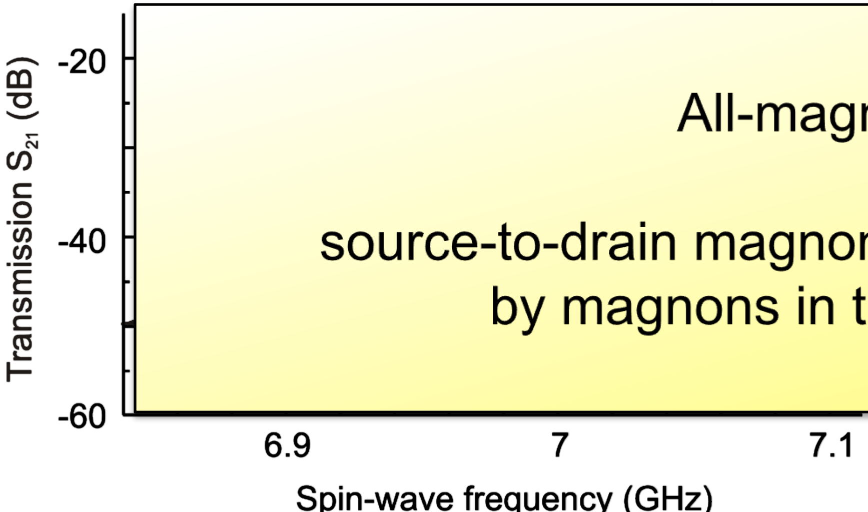
- Spin-wave logic gates
- Magnon transistor

Magnon transistor



Semiconductor field-effect transistor:





All-magnon dev

source-to-drain magnon flow sh
by magnons in the trans

Magnonic crystal acts
as an enhancer of
non-linear effects

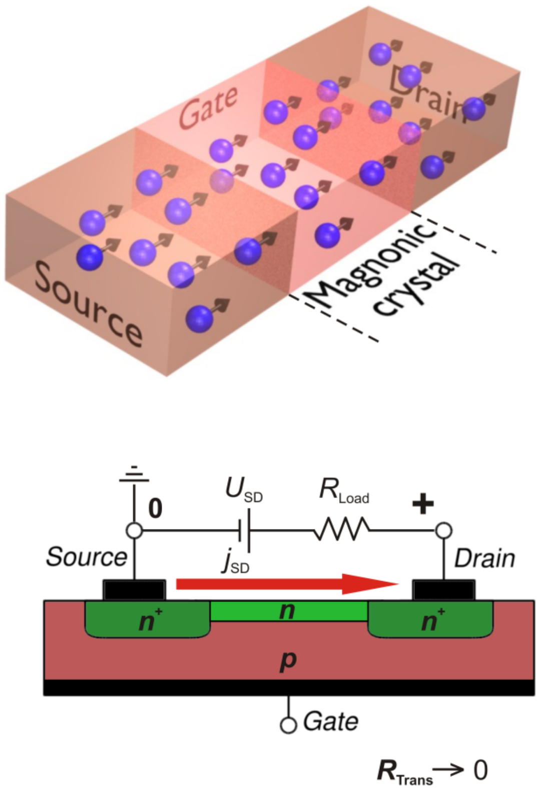
A.V. Chumak et al., Nat. Commun. **5**:4700 (2014)

Magnon transistor

Opened: $R \to 0$

Gate magnon density

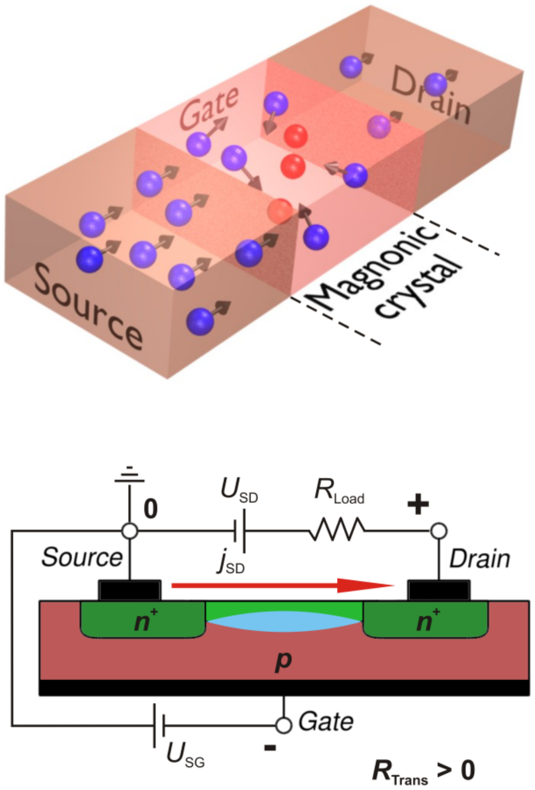
$n_G = 0$



Semi-closed: R > 0

Gate magnon density

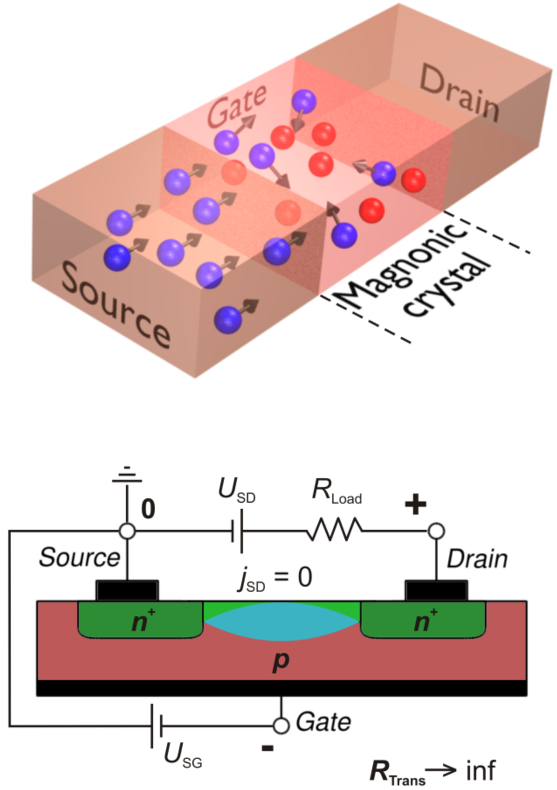
$n_G > 0$



Closed: $R \to \infty$

Gate magnon density

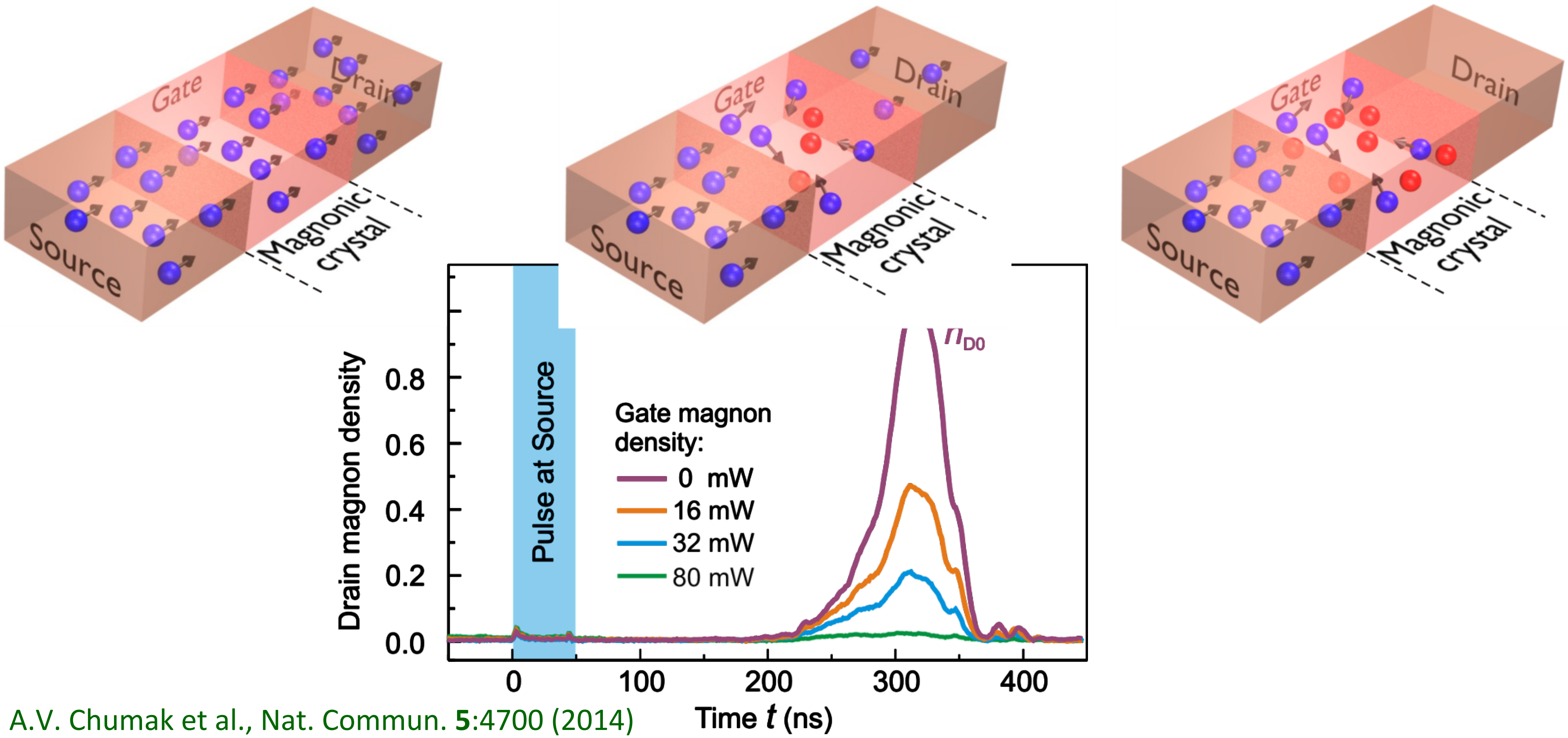
$n_G >> 0$



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

Magnon transistor

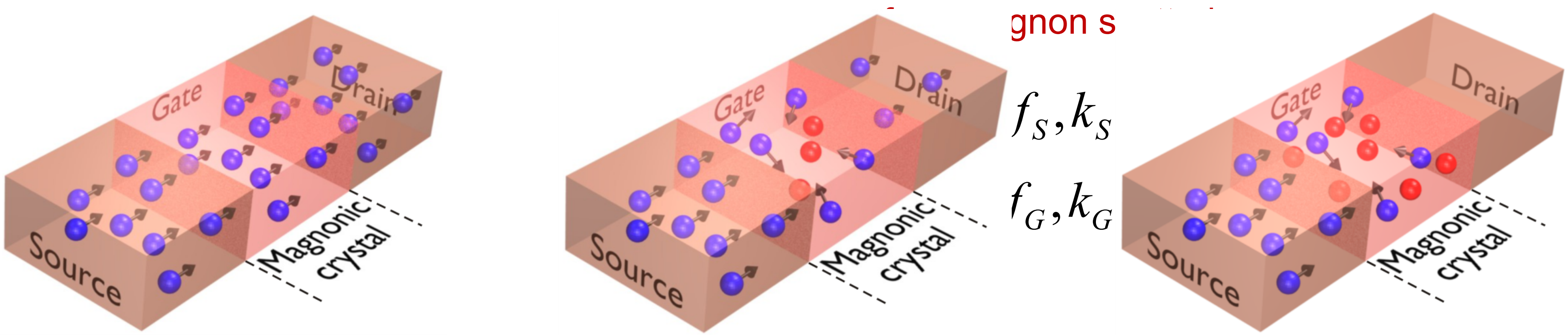
Opened: $R \rightarrow 0$	**Semi-closed:** R > 0	**Closed:** $R \rightarrow \infty$
Gate magnon density	Gate magnon density	Gate magnon density
$n_G = 0$	$n_G > 0$	$n_G >> 0$

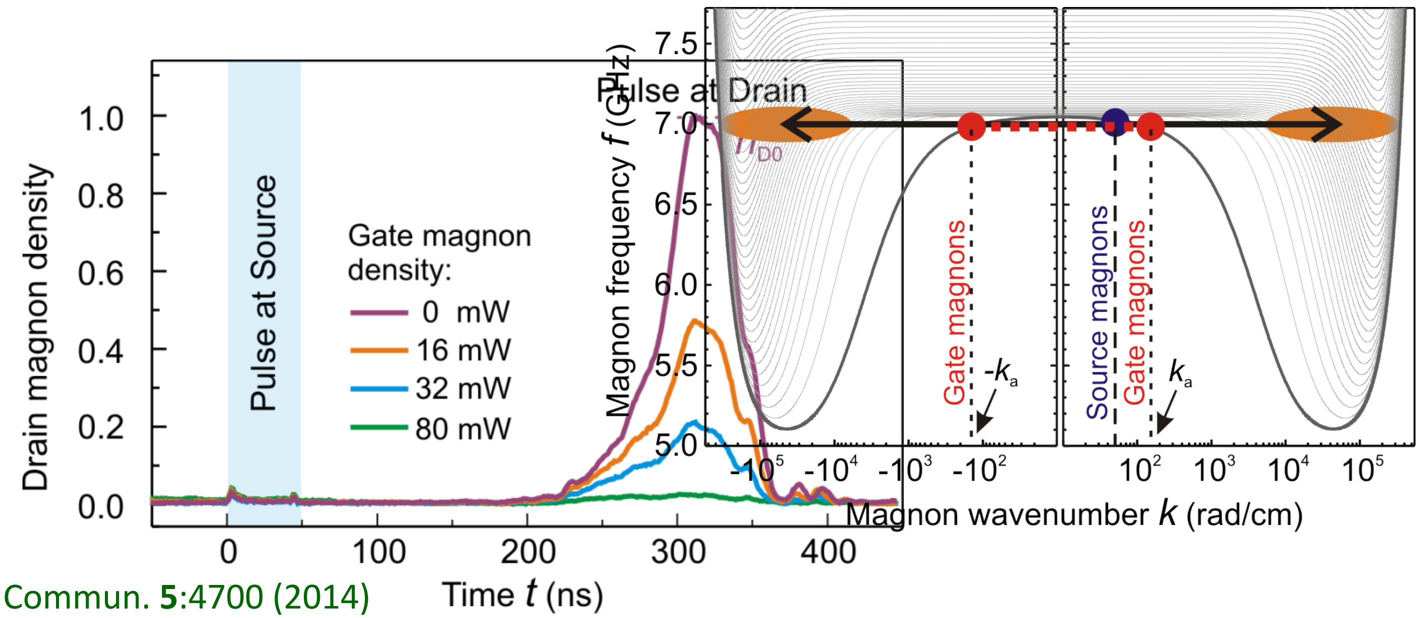


A.V. Chumak et al., Nat. Commun. **5**:4700 (2014)

Magnon transistor

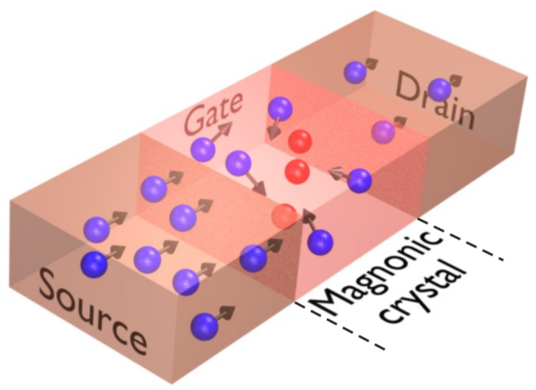
Opened: $R \to 0$ **Semi-closed:** $R > 0$ **Closed:** $R \to \infty$

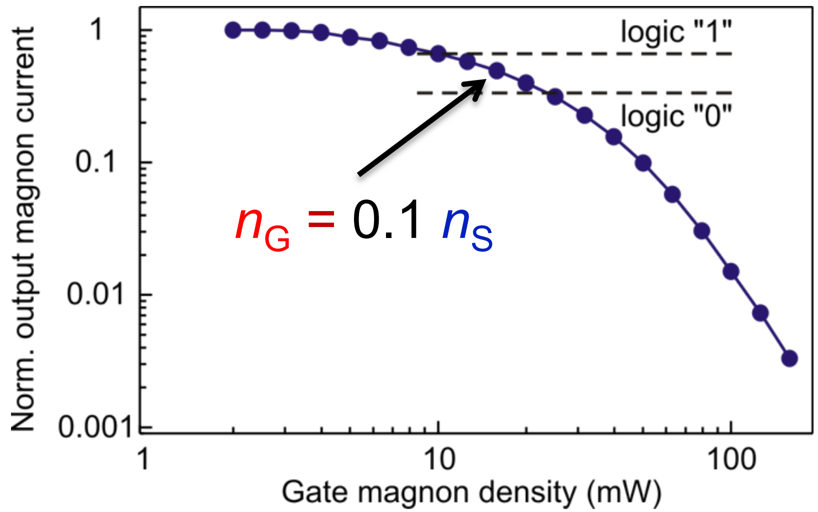


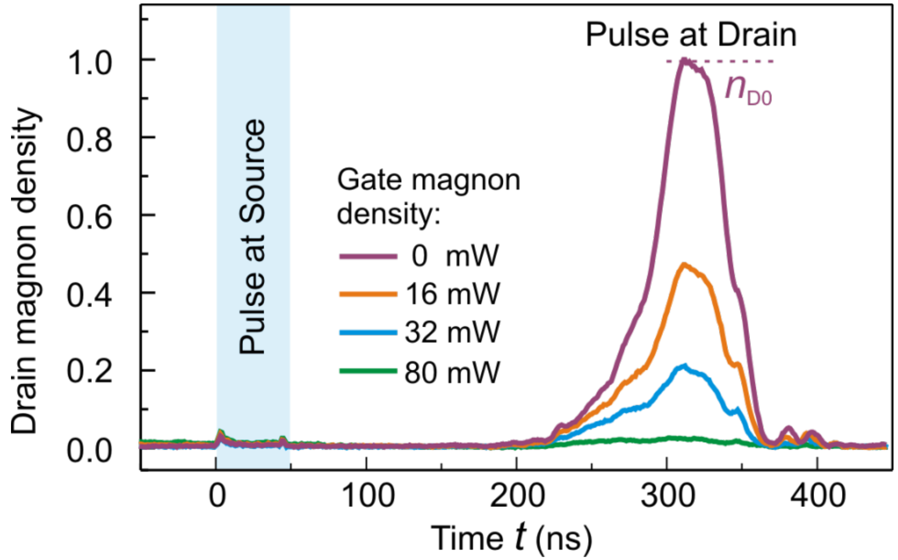


A.V. Chumak et al., Nat. Commun. **5**:4700 (2014)

Magnon transistor







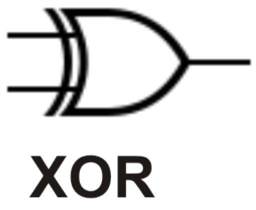
“magnon control by magnon“ principle was realized:

data can be processed on the same magnetic chip

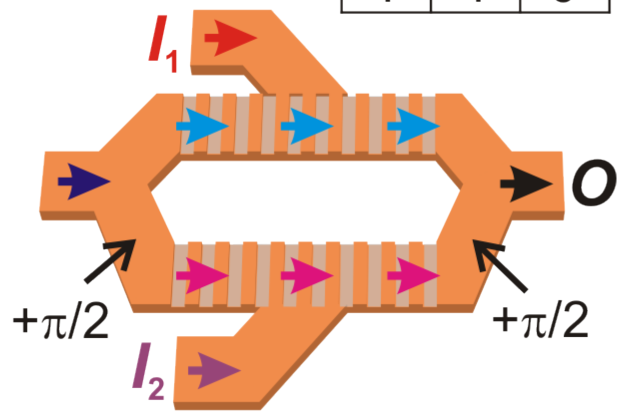
A.V. Chumak et al., Nat. Commun. **5**:4700 (2014)

Logic operations

XOR logic gate

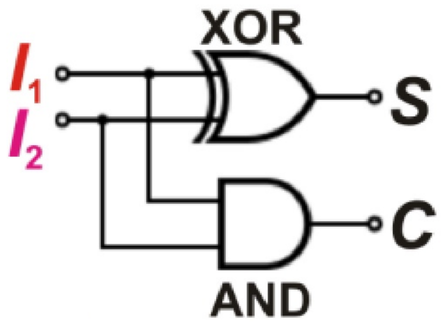


I_1	I_2	O
0	0	0
0	1	1
1	0	1
1	1	0

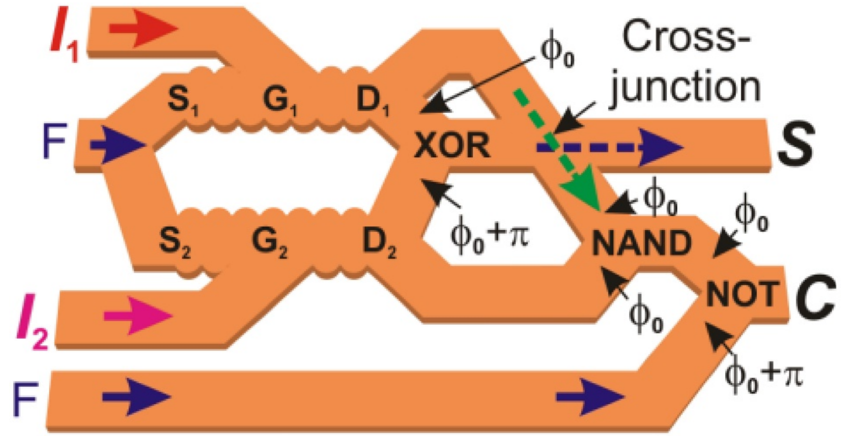


XOR gate requires 2 transistors instead of 8 FET in CMOS

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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Magnonics: Main trends

III. Data processing using magnons

- Spin-wave logic gates
- Magnon transistor
- Magnon majority gate

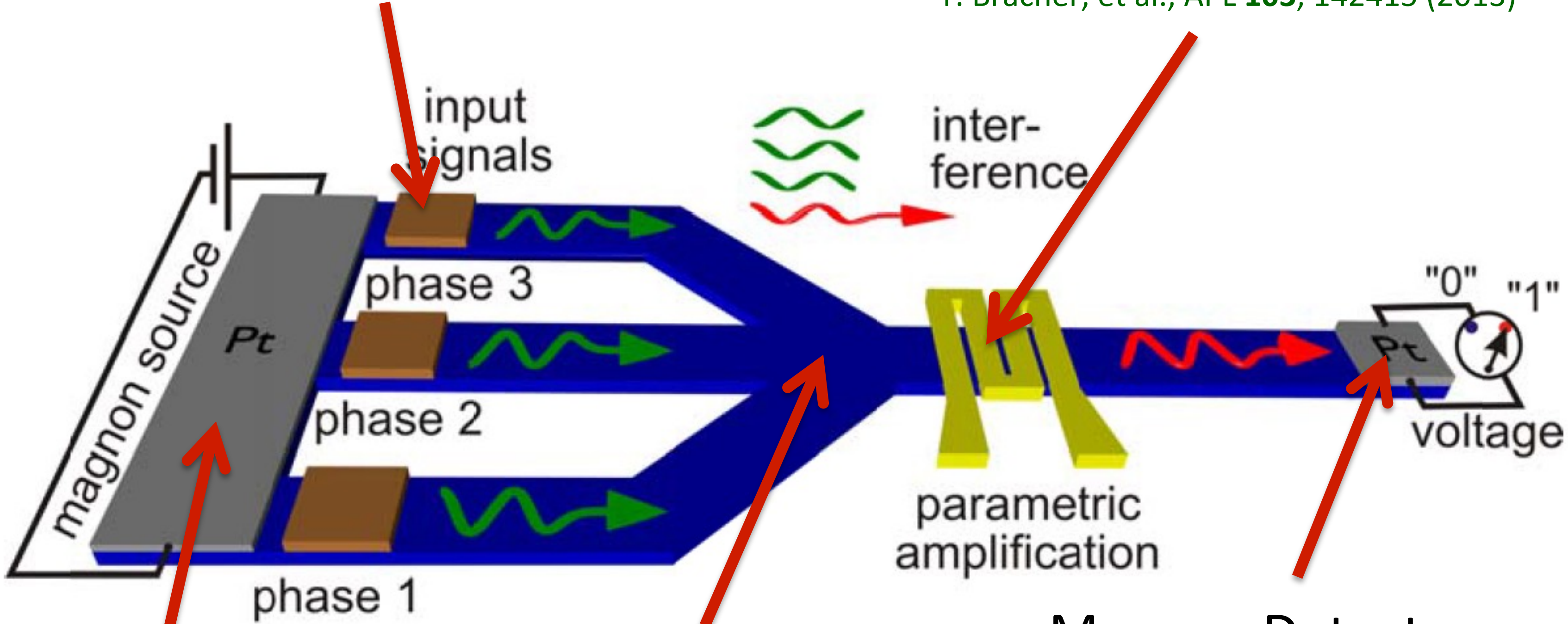
Majority gate

Phase Shifter

T. Neumann, et al. APL **94**, 042503 (2009)
M.P. Kostylev, et al., PRB **76**, 184419 (2007)

Parametric Amplifier

T. Brächer, et al. APL **104**, 092418 (2014)
T. Brächer, et al., APL **103**, 142415 (2013)



Magnon Source

Magnon Processor

Magnon Detector

Technische Universität Kaiserslautern

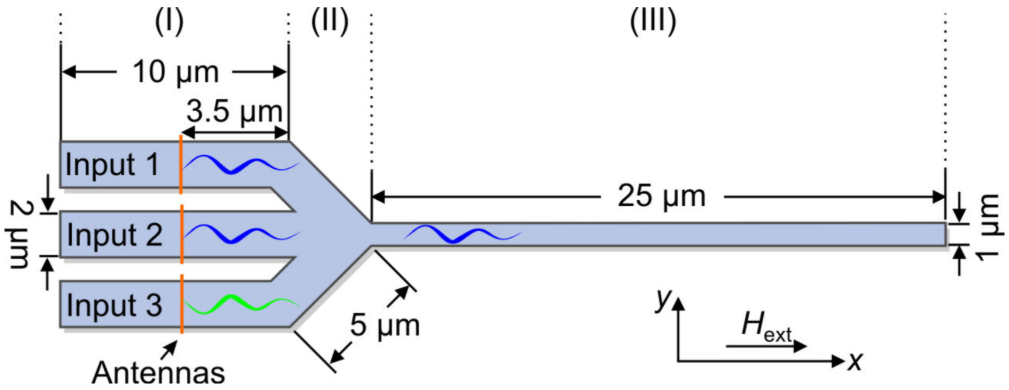
Majority gates: Design

Design of a spin-wave majority gate employing mode selection

S. Klingler,[1,*] P. Pirro,[1] T. Brächer,[1] B. Leven,[1] B. Hillebrands,[1] and A. V. Chumak[1]
[1] *Fachbereich Physik and Landesforschungszentrum OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany*
(Dated: August 15, 2014)

Majority gate design:

100 nm YIG, Pirro et al., APL **104**, 012402 (2014)



In CMOS **56 transistors** (3 NOT, 4 AND, 3 OR) are needed for majority gate

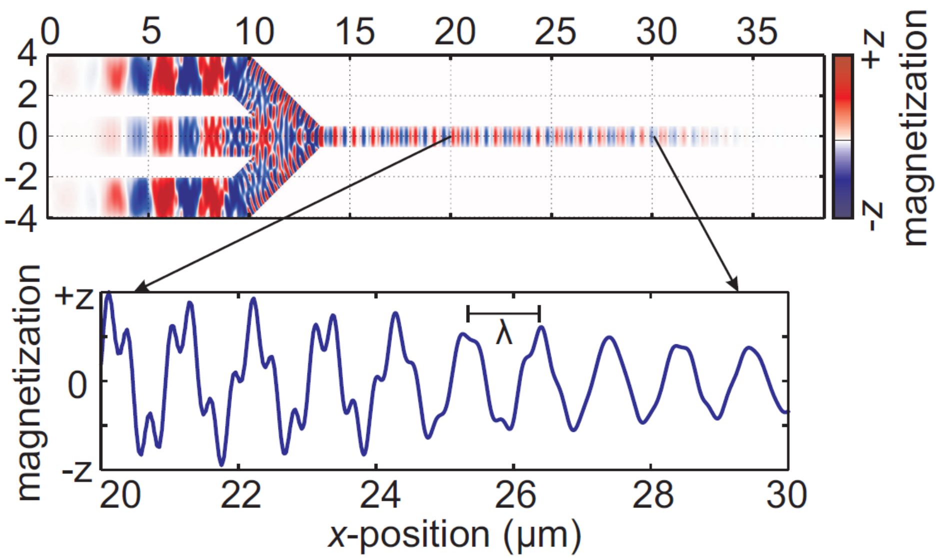
S. Klinger et al., arXiv: 1408.3235

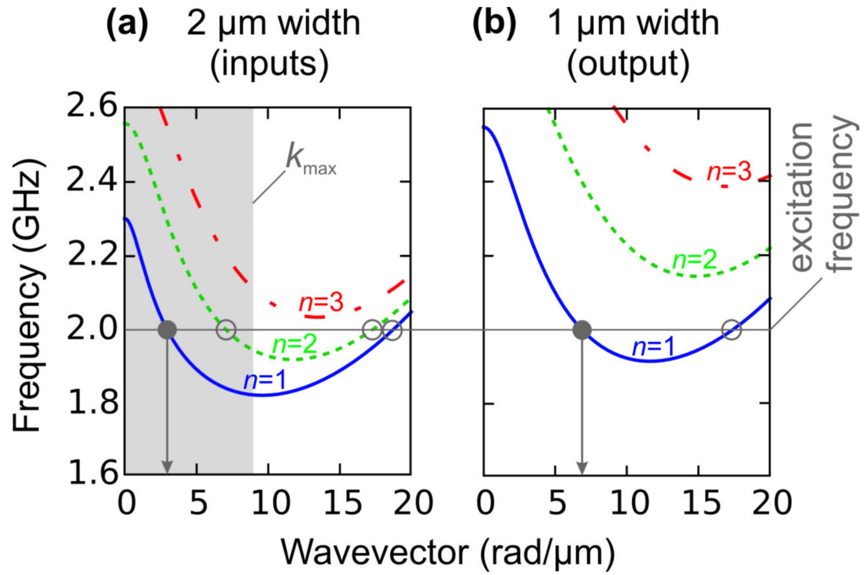
Truth-table:

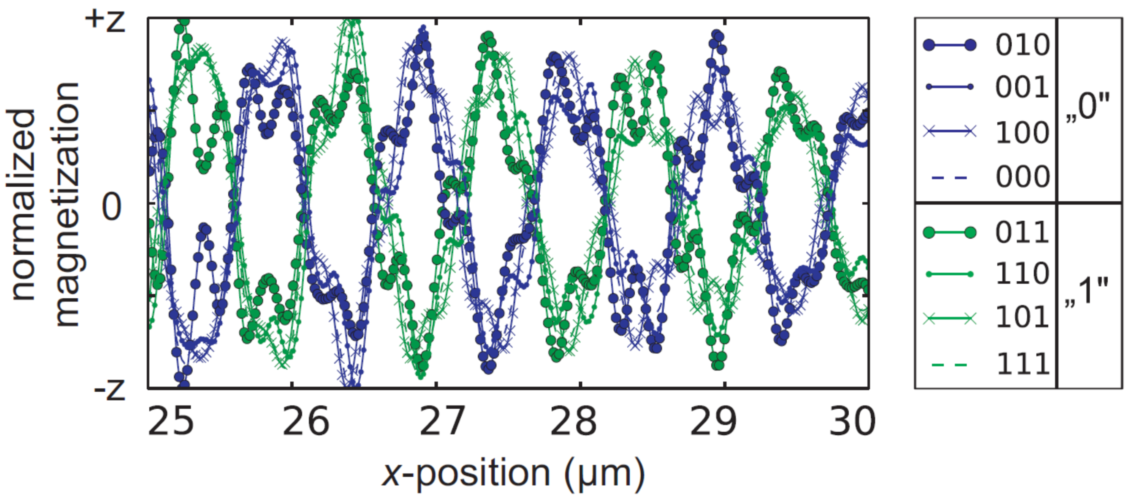
Input 1 Signal	Input 2 Signal	Input 3 Control	Output	
0	0	0	0	AND
1	0	0	0	
0	1	0	0	
1	1	0	1	
0	0	1	0	OR
1	0	1	1	
0	1	1	1	
1	1	1	1	

Data is coded into spin-wave phase

Majority gates: Simulations



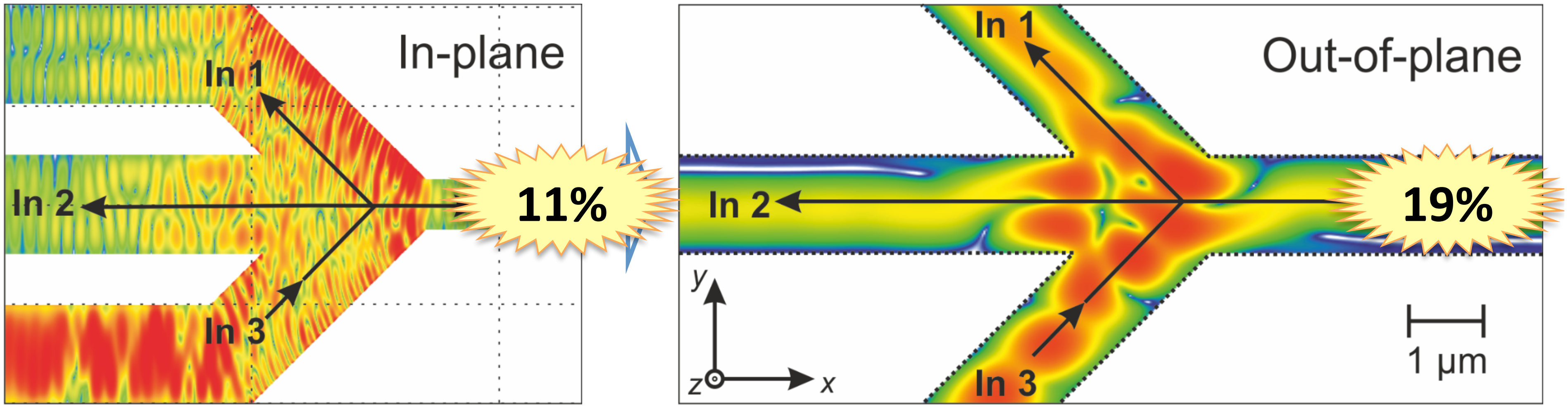




Majority gates: Out-of-plane magnetization

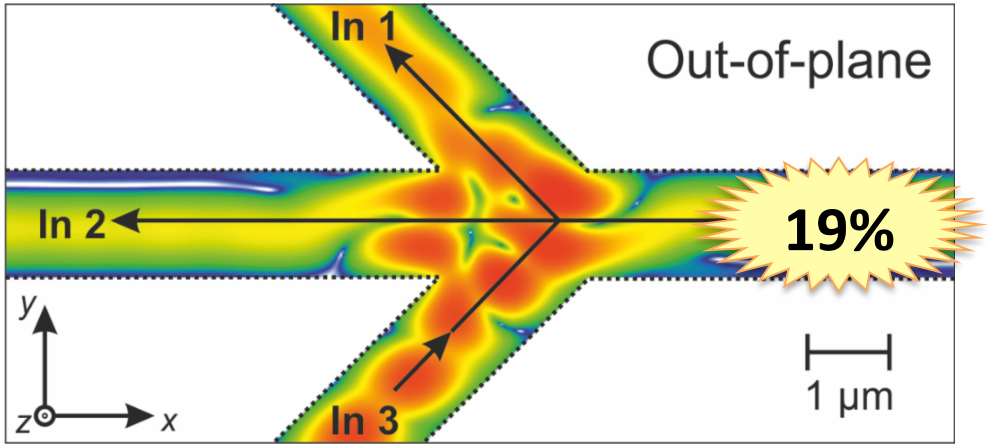
Switch from the in-plane magnetization to the out-of-plane
(see e.g. T. Schwarze, et al., Phys. Rev. B 85, 134448 (2012))

Forward volume spin waves are isotropic (always transverse to field)

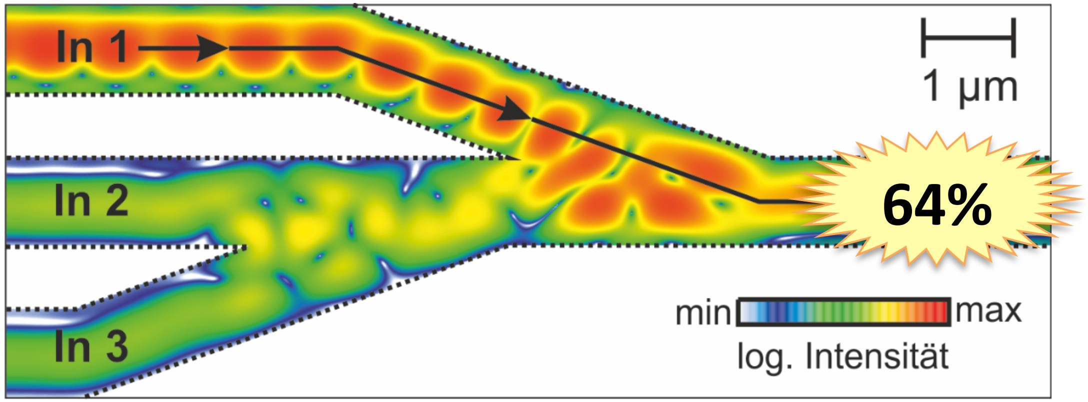


but no parasitic generation of high-wavenumber magnons

Majority gates: Out-of-plane magnetization

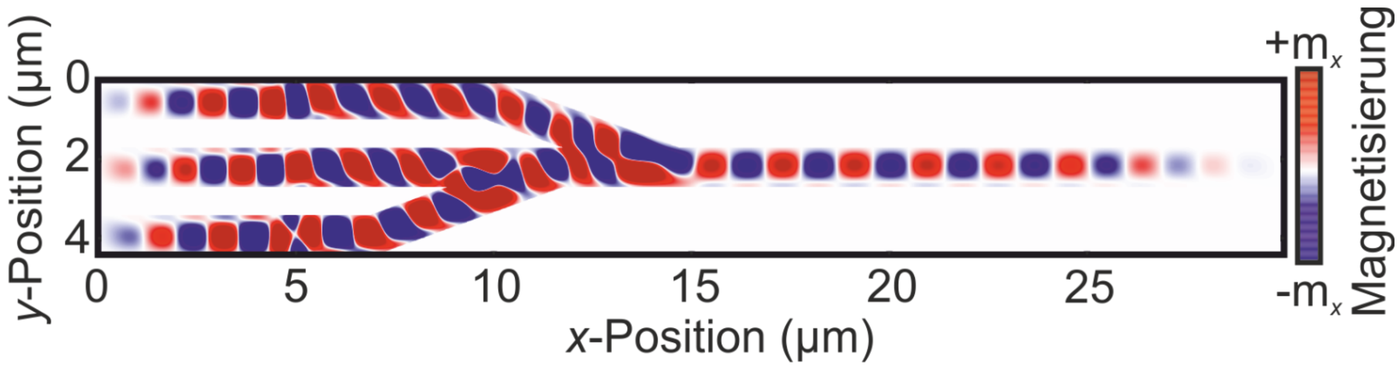


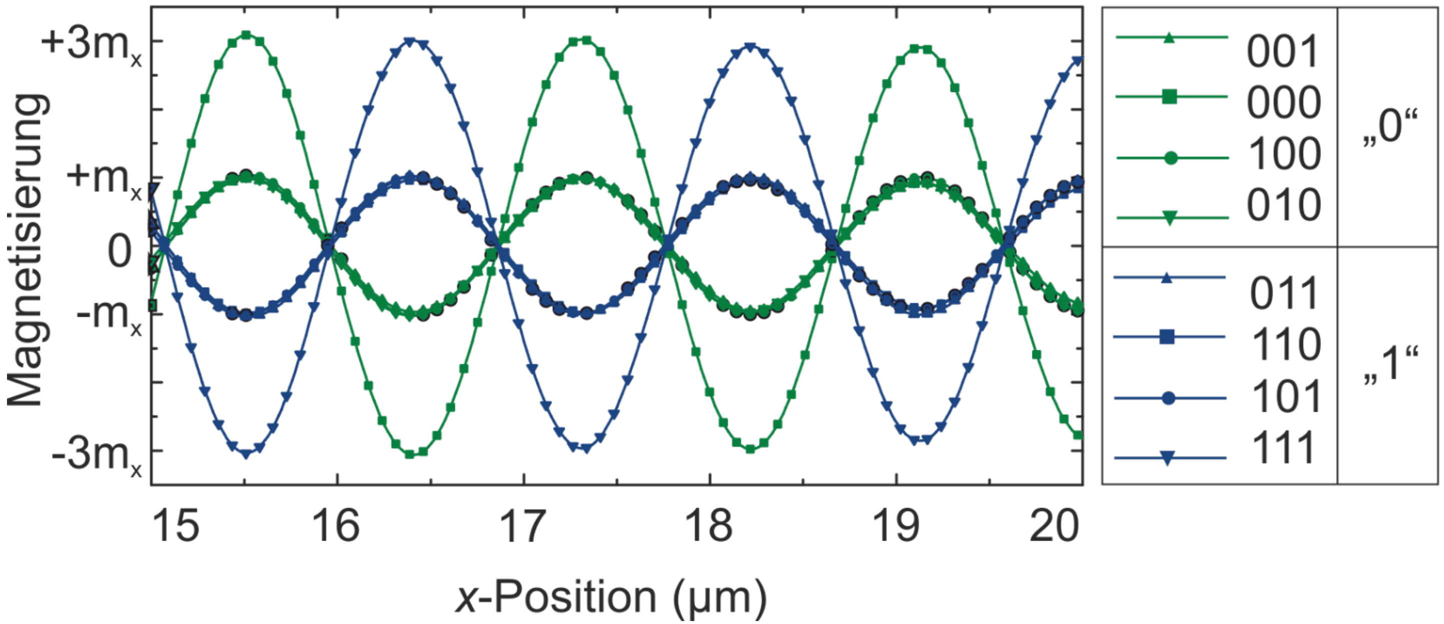
How to increase this value?



Majority gates: Out-of-plane magnetization

Results of numerical simulation (MuMax 2)





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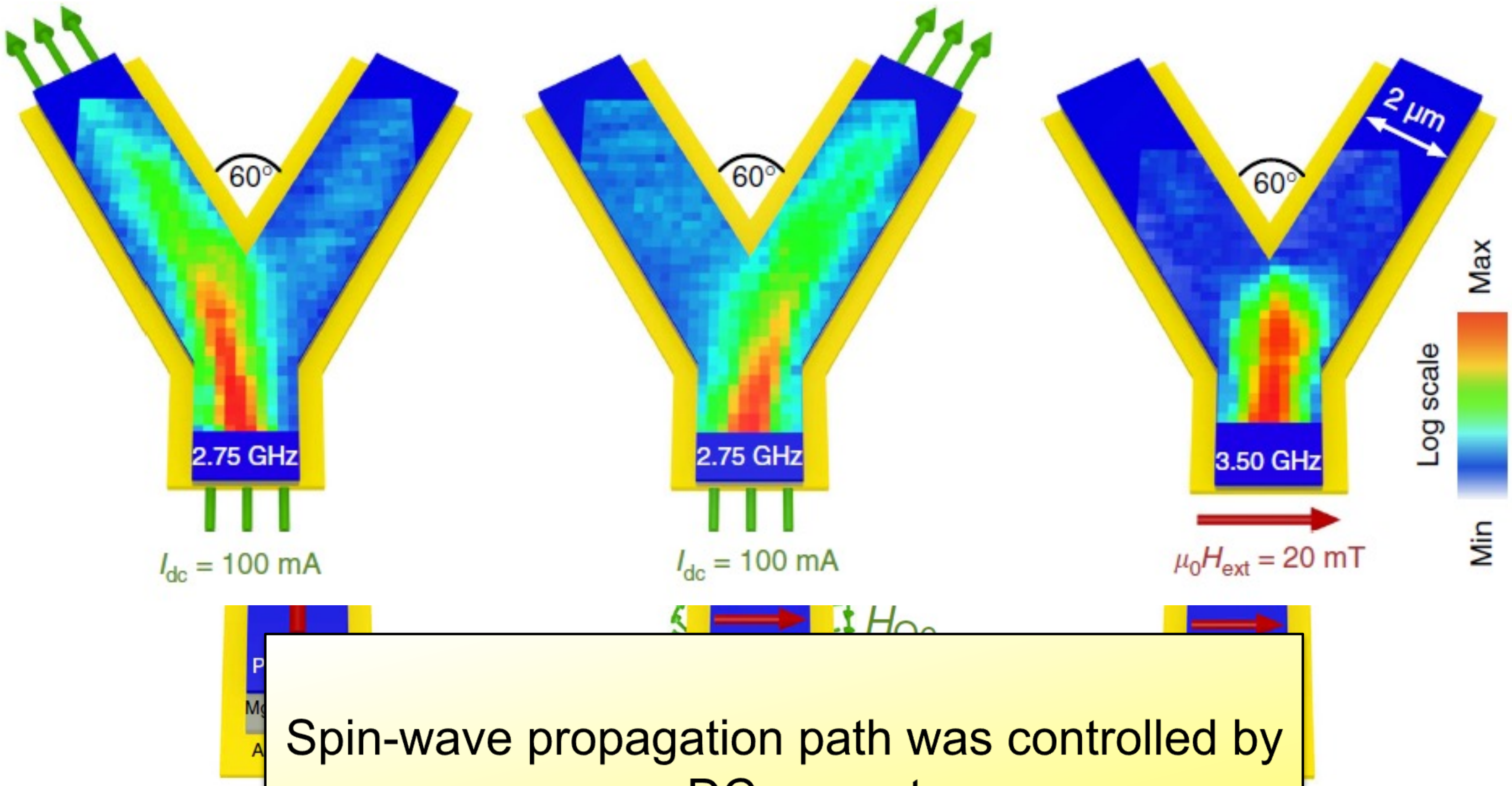
Magnonics: Main trends

III. Data processing using magnons

- Spin-wave logic gates
- Magnon transistor
- Magnon majority gate
- ➔ Magnon multiplexer

Magnon multiplexer



Spin-wave propagation path was controlled by a DC current

Vogt, et al., Nat. Commun. **5**:3727 (2014)

Computing principles

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

Magnonics: Main trends

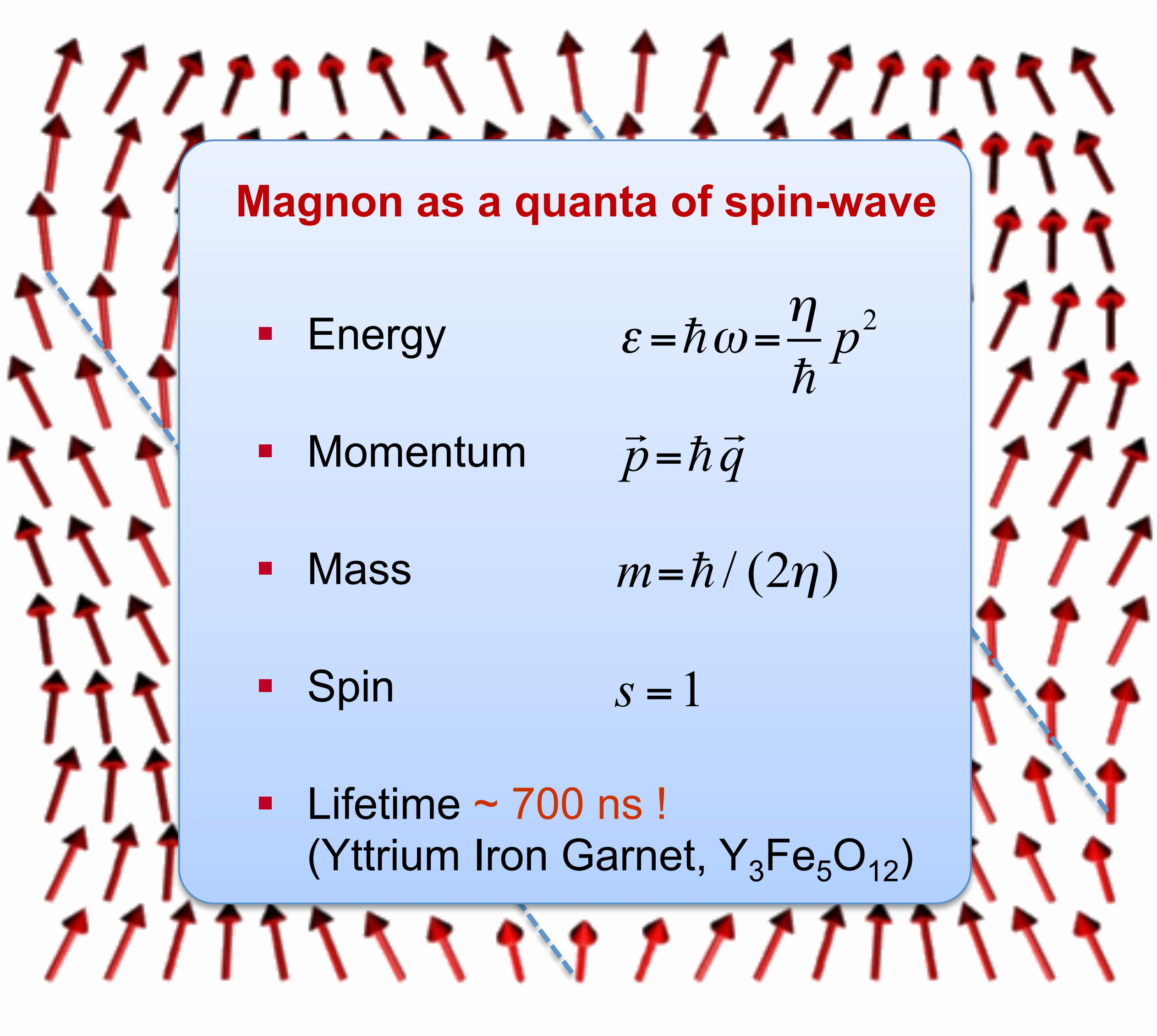
IV. Magnonic supercurrents

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

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

- Bose-Einstein Condensation (BEC) of magnons
- Supercurrents in magnon condensates

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, $Y_3Fe_5O_{12}$)

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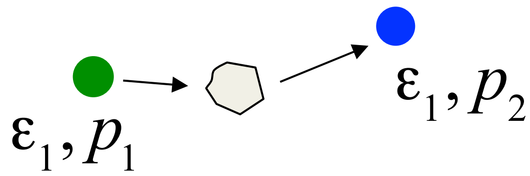
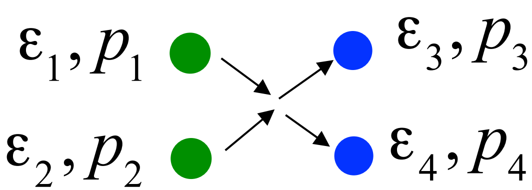
Magnon scattering

TWO-MAGNON SCATTERING



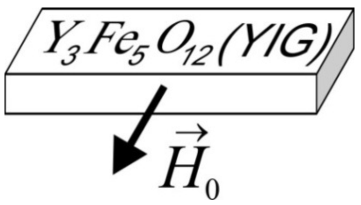
Magnon gas of interacting quasiparticles
Number of particles is conserved

FOUR-MAGNON SCATTERING



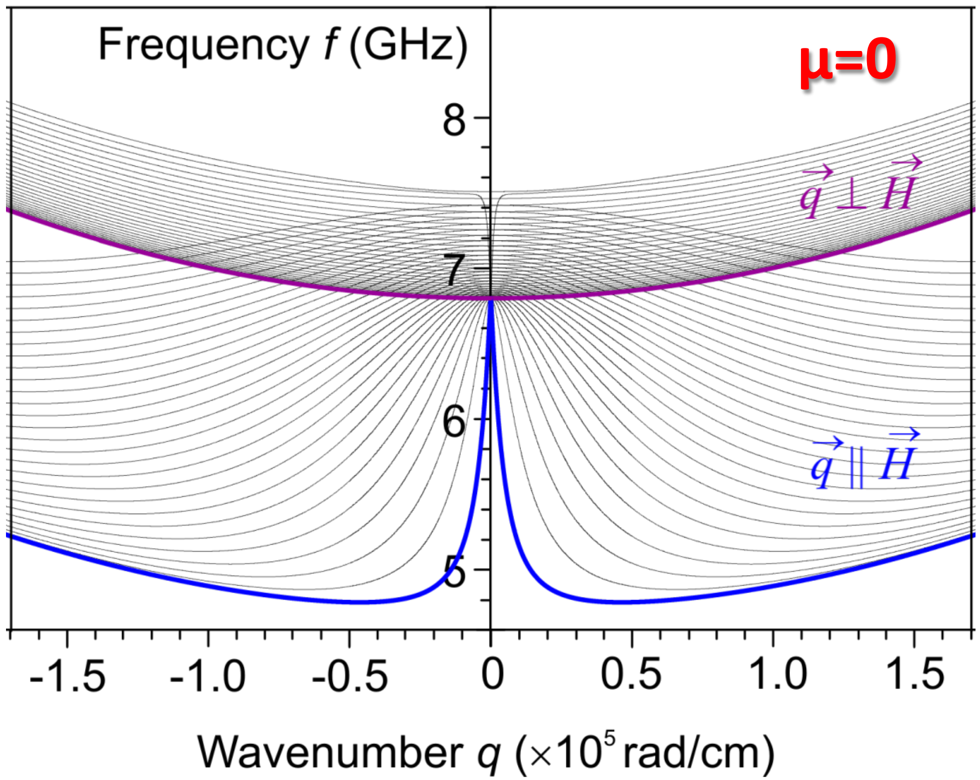
Magnon distribution

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



Bose-Einstein distribution

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

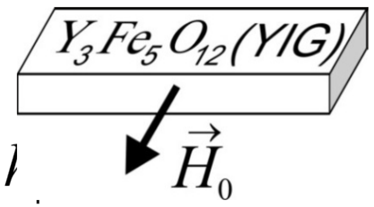


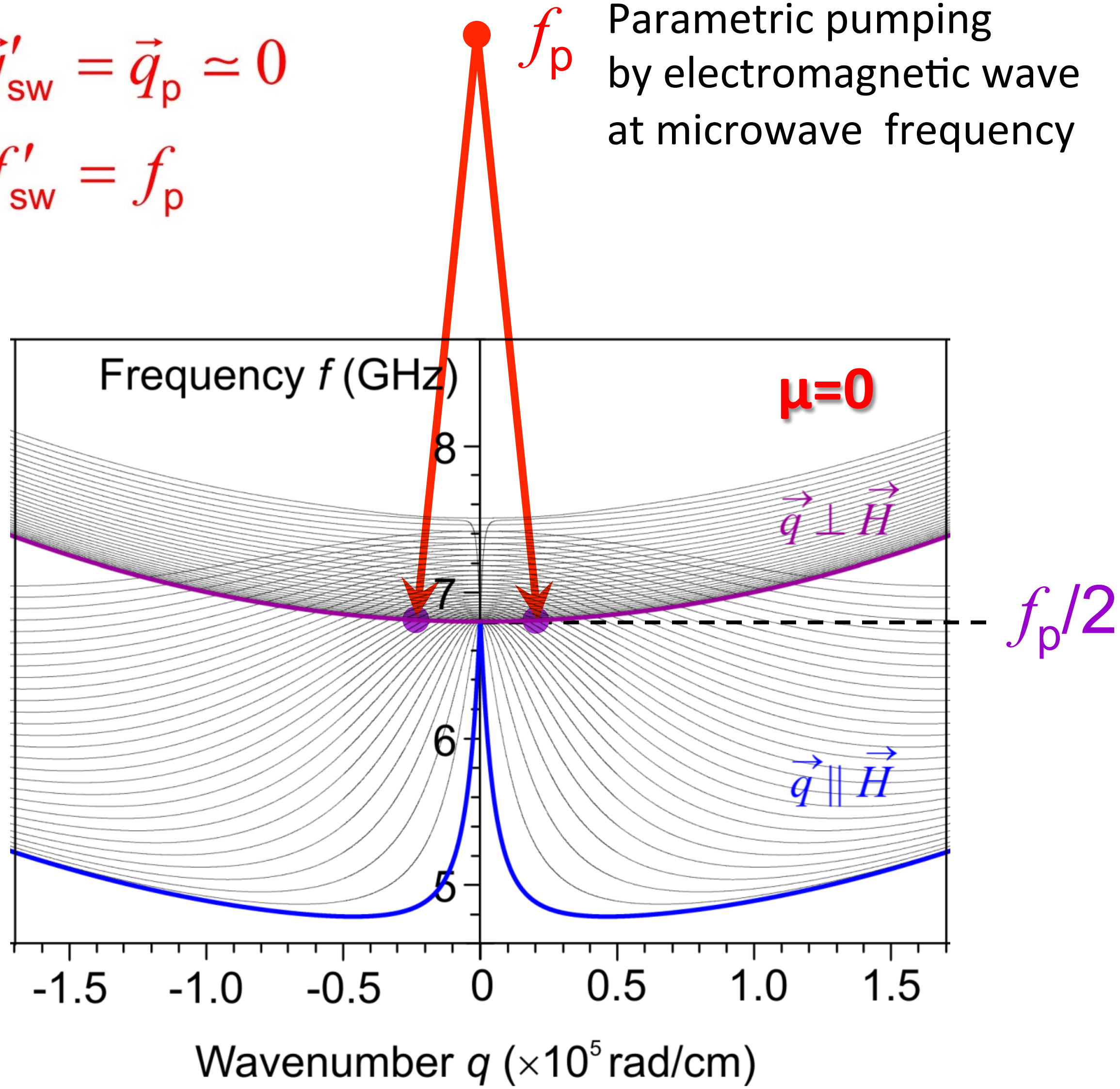
Control of magnon gas density by parametric pumping

Energy and momentum conservation laws

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

f_p Parametric pumping by electromagnetic wave at microwave frequency





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μ: chemical potential

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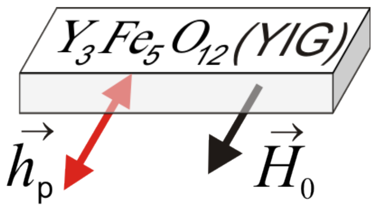

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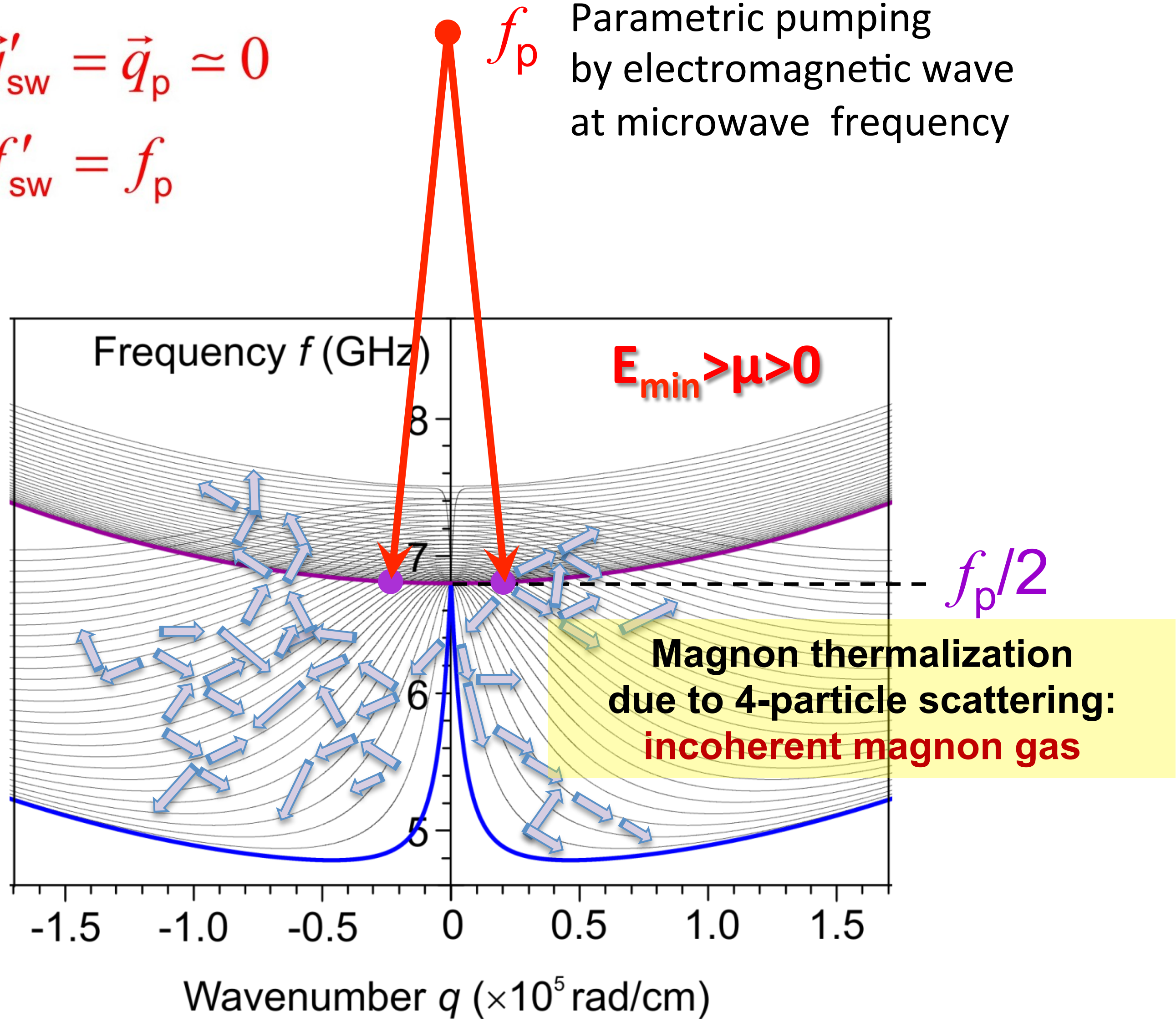

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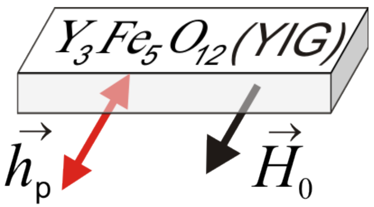

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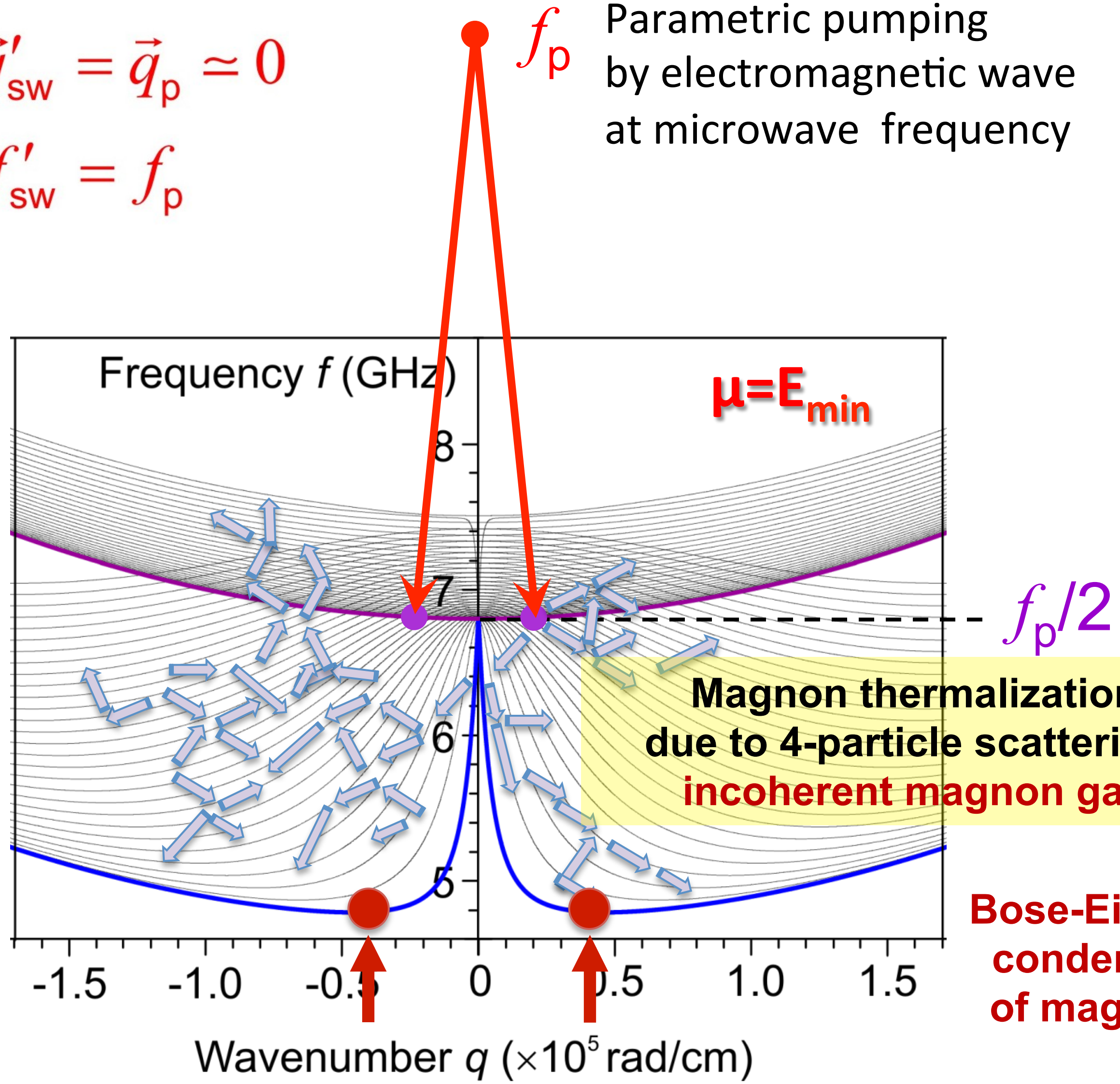


Magnon thermalization due to 4-particle scattering: incoherent magnon gas

Bose-Einstein condensate of magnons

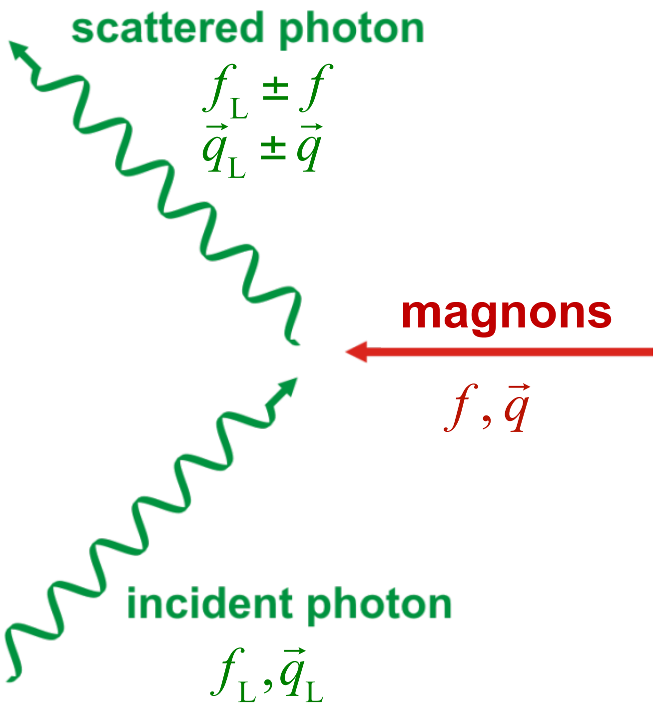
Brillouin light scattering spectroscopy

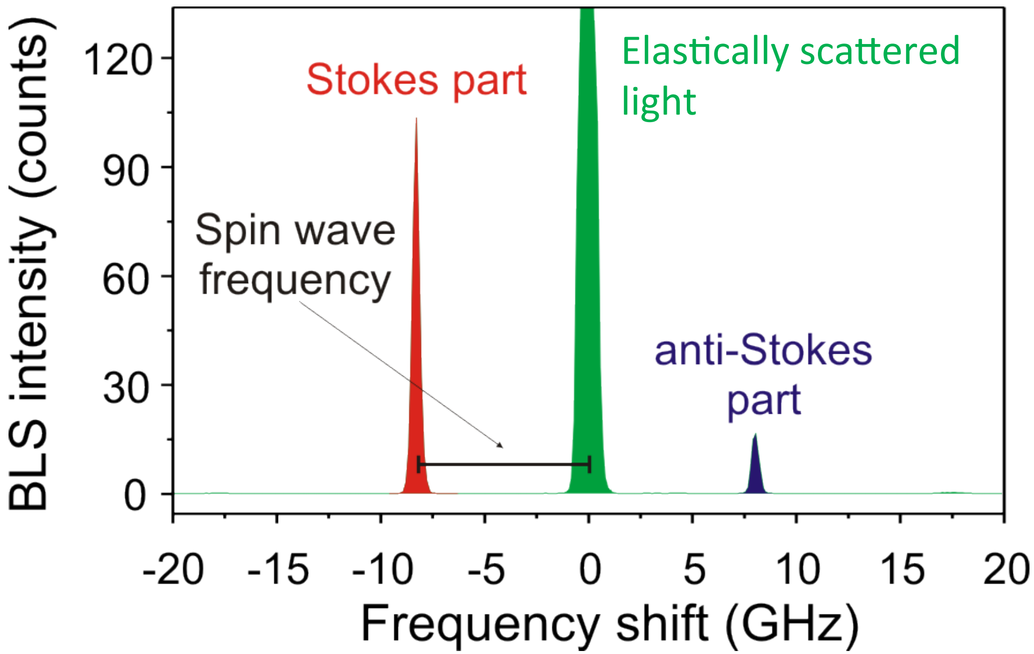
Brillouin light scattering process

= inelastic scattering of photons from spin waves

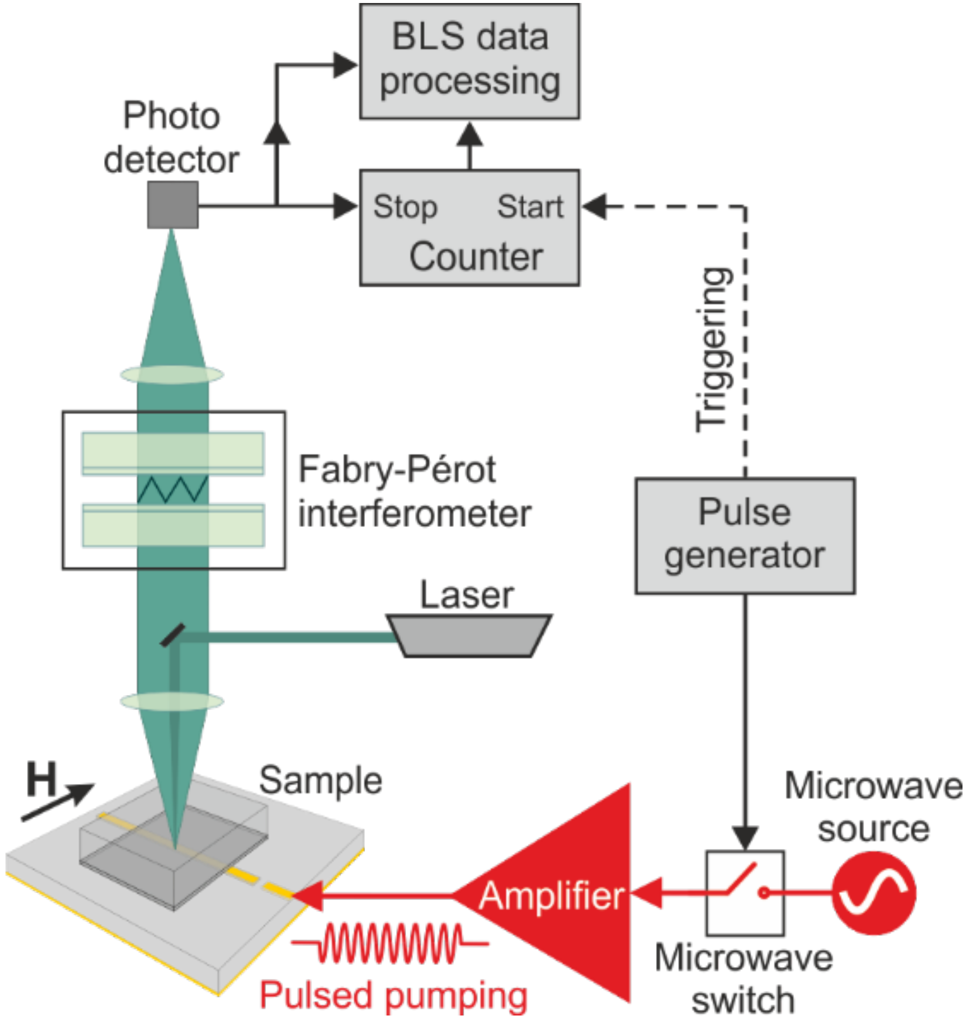
$$f_{\text{scattered L}} = f_L \pm f$$

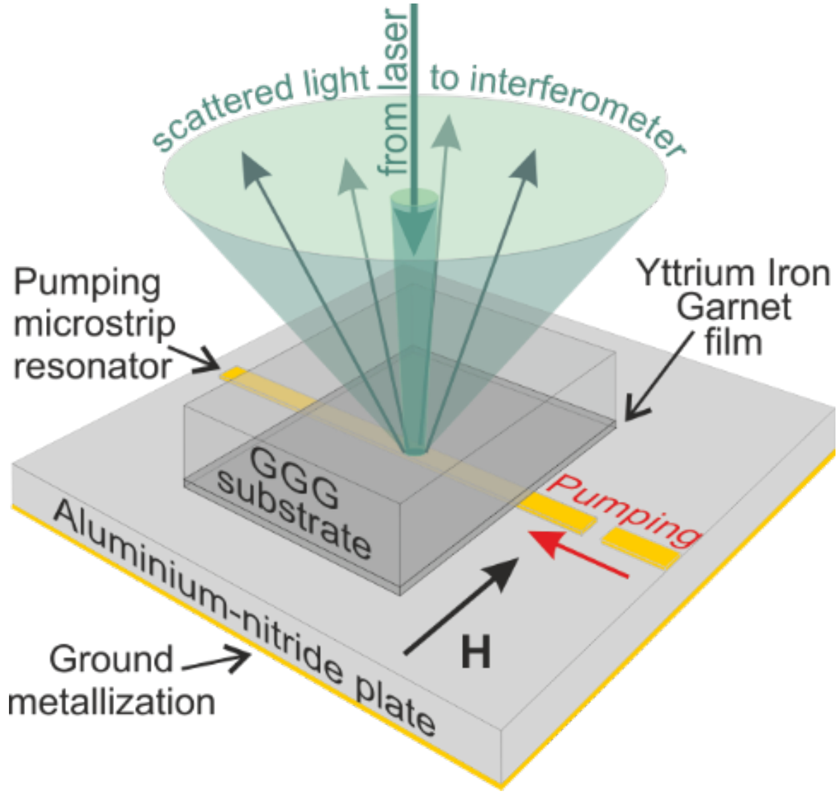
$$\vec{q}_{\text{scattered L}} = \vec{q}_L \pm \vec{q}$$



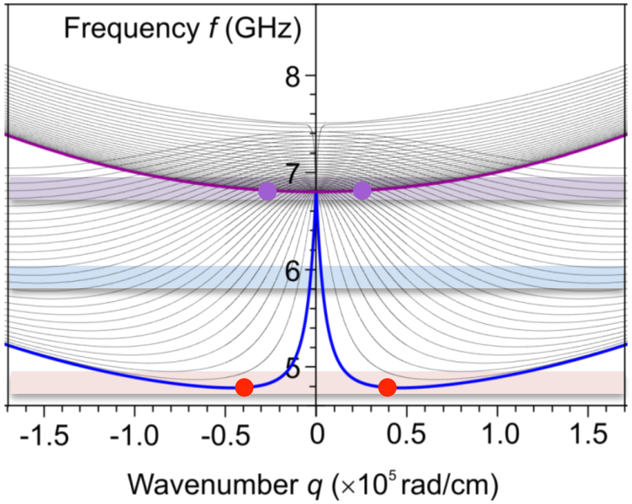


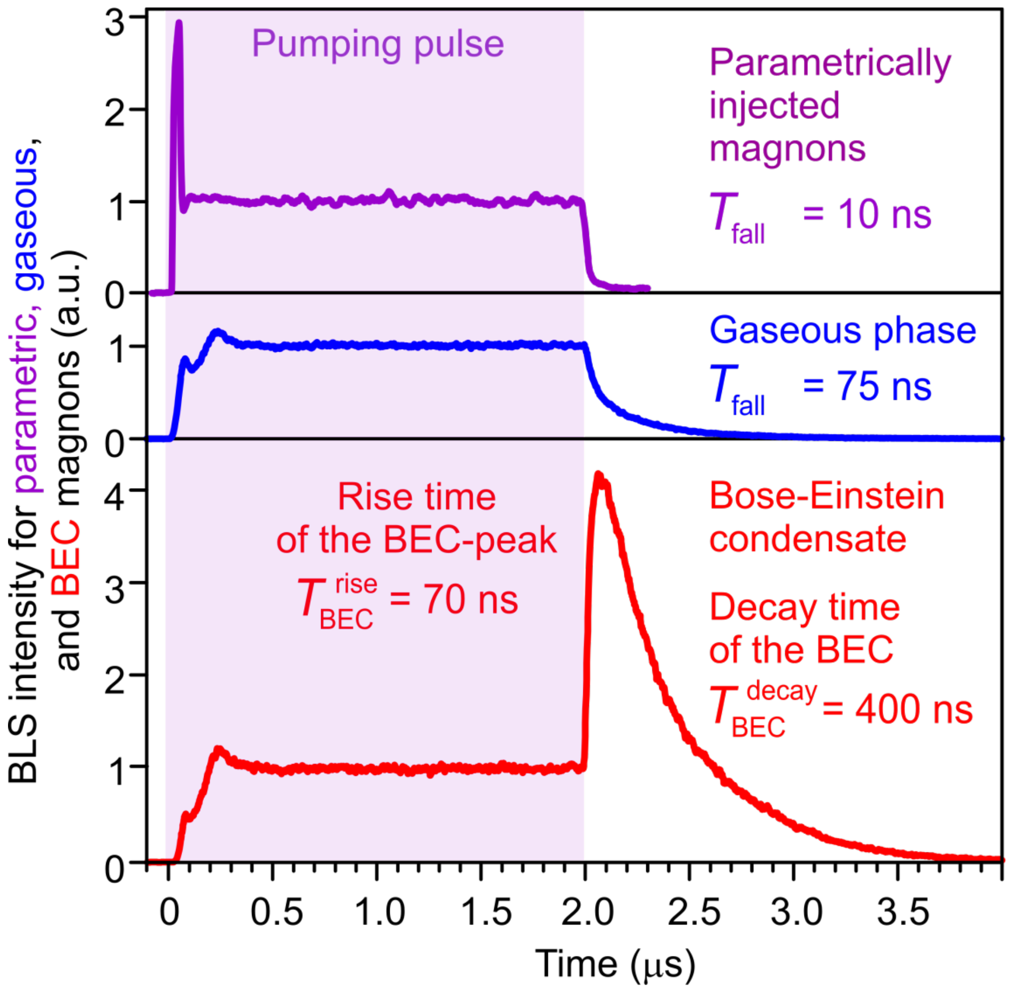
Time-resolved
Brillouin light scattering spectroscopy





Parametric magnons, gaseous phase, and magnon BEC



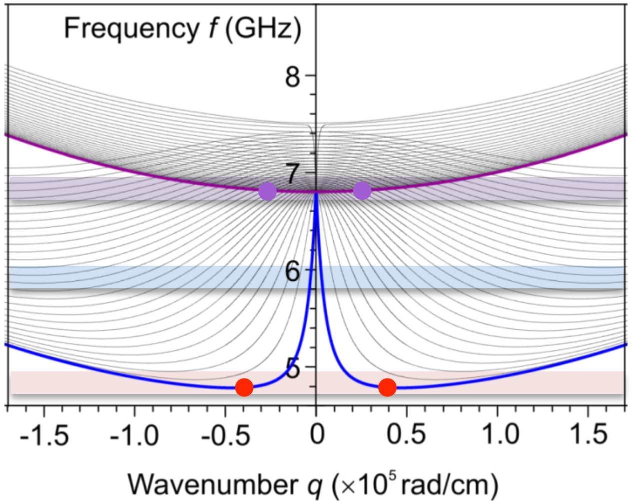


Decrease of density of
parametric magnons
and
gaseous magnon phase

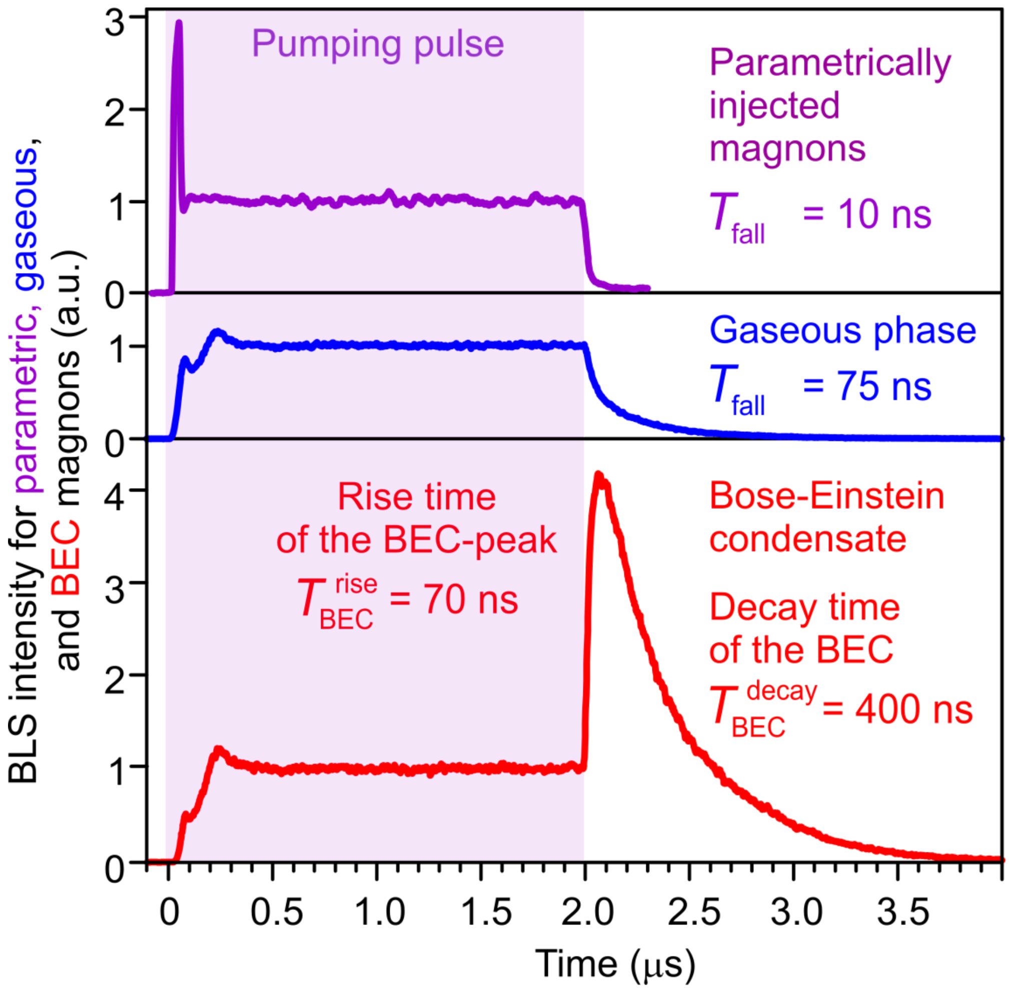
↓

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

Parametric magnons, gaseous phase, and magnon BEC



Evaporative supercooling of strongly overheated low energy area of the magnon gas



Serga et al., Nature Communications **5**, 4452 (2014)

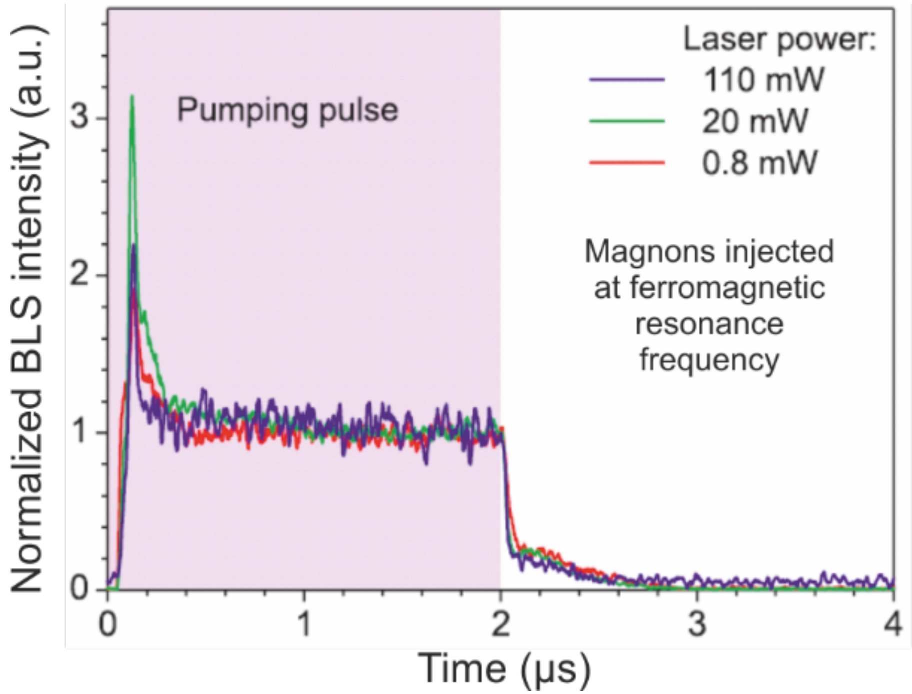
Influence of power of probing laser beam

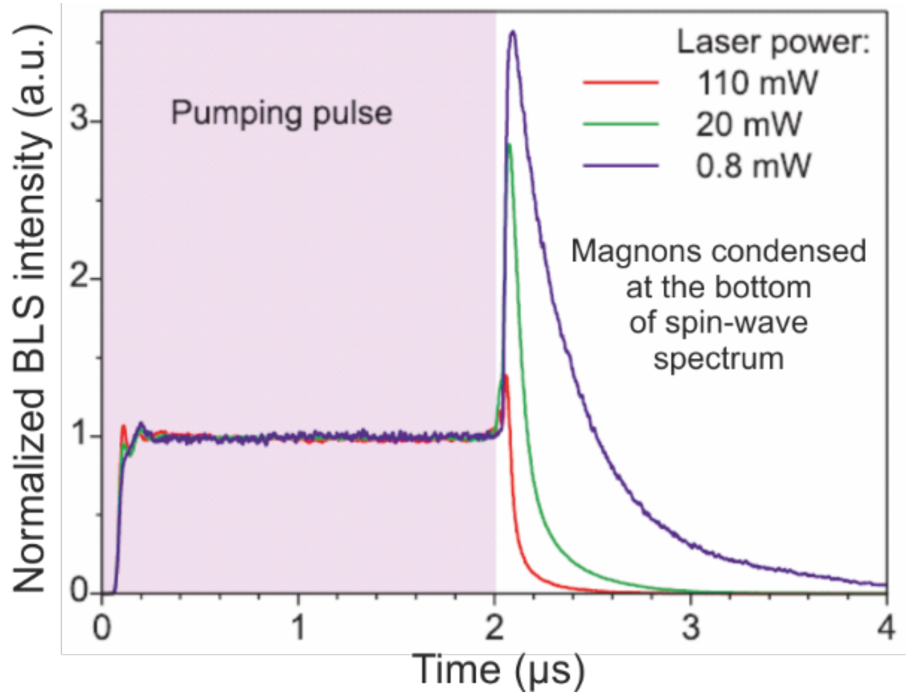
Parametrically injected magnons

- No influence from laser power on temporal dynamics !
- Laser heating decreases magnetization and thus strongly shifts down the magnon dispersion branch

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





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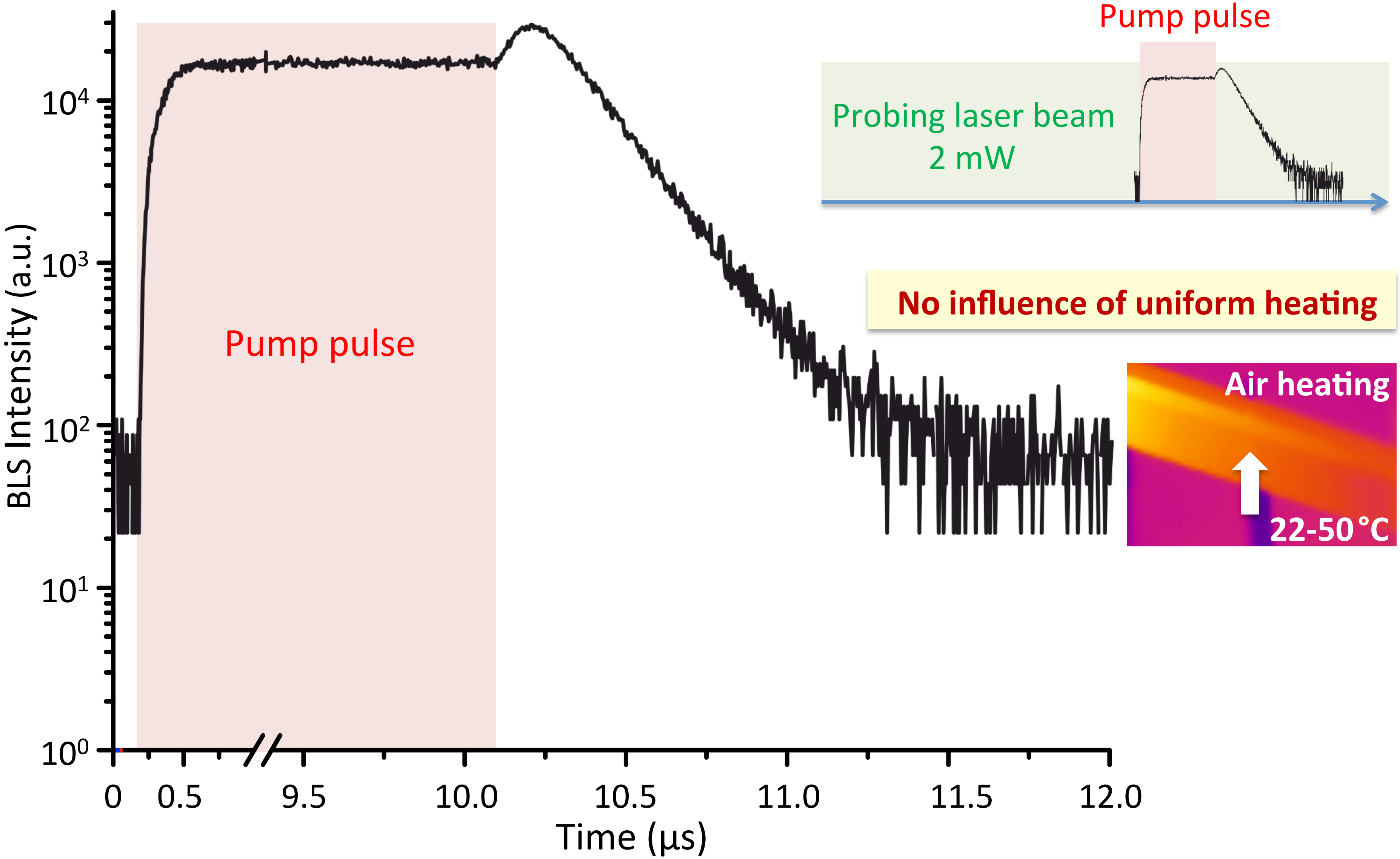
Magnon supercurrents – magnon BEC dynamics in thermal gradient



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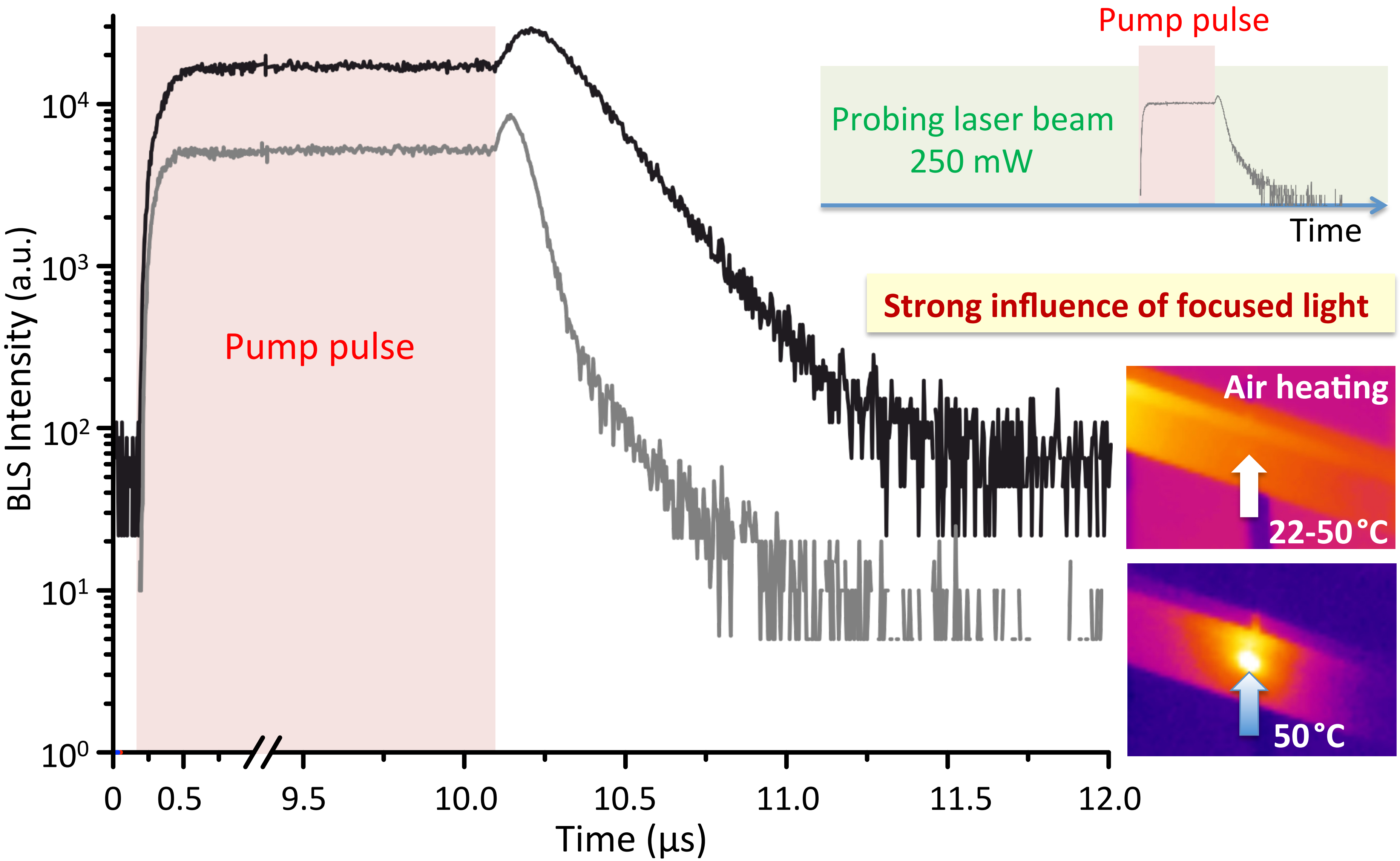

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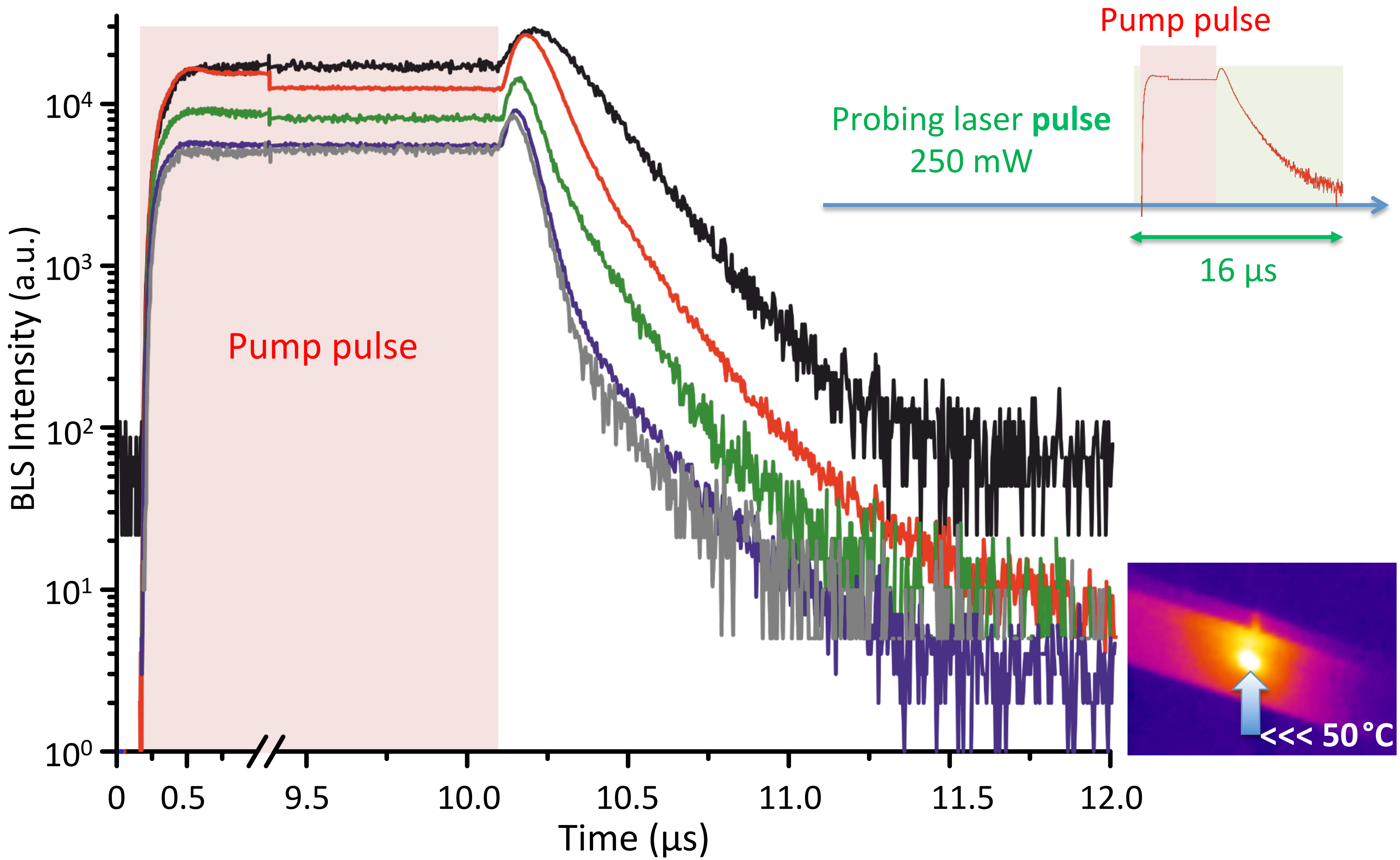

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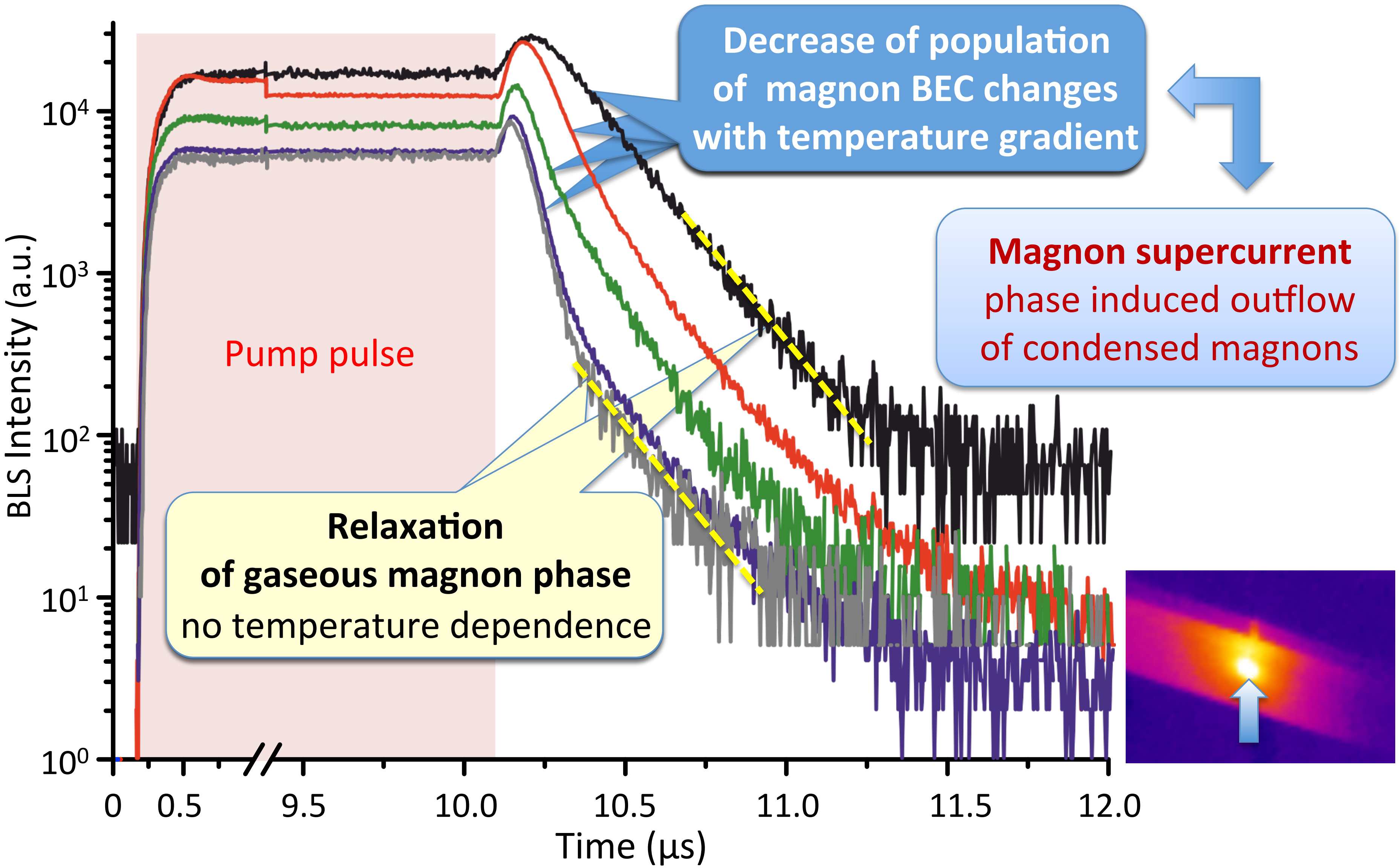
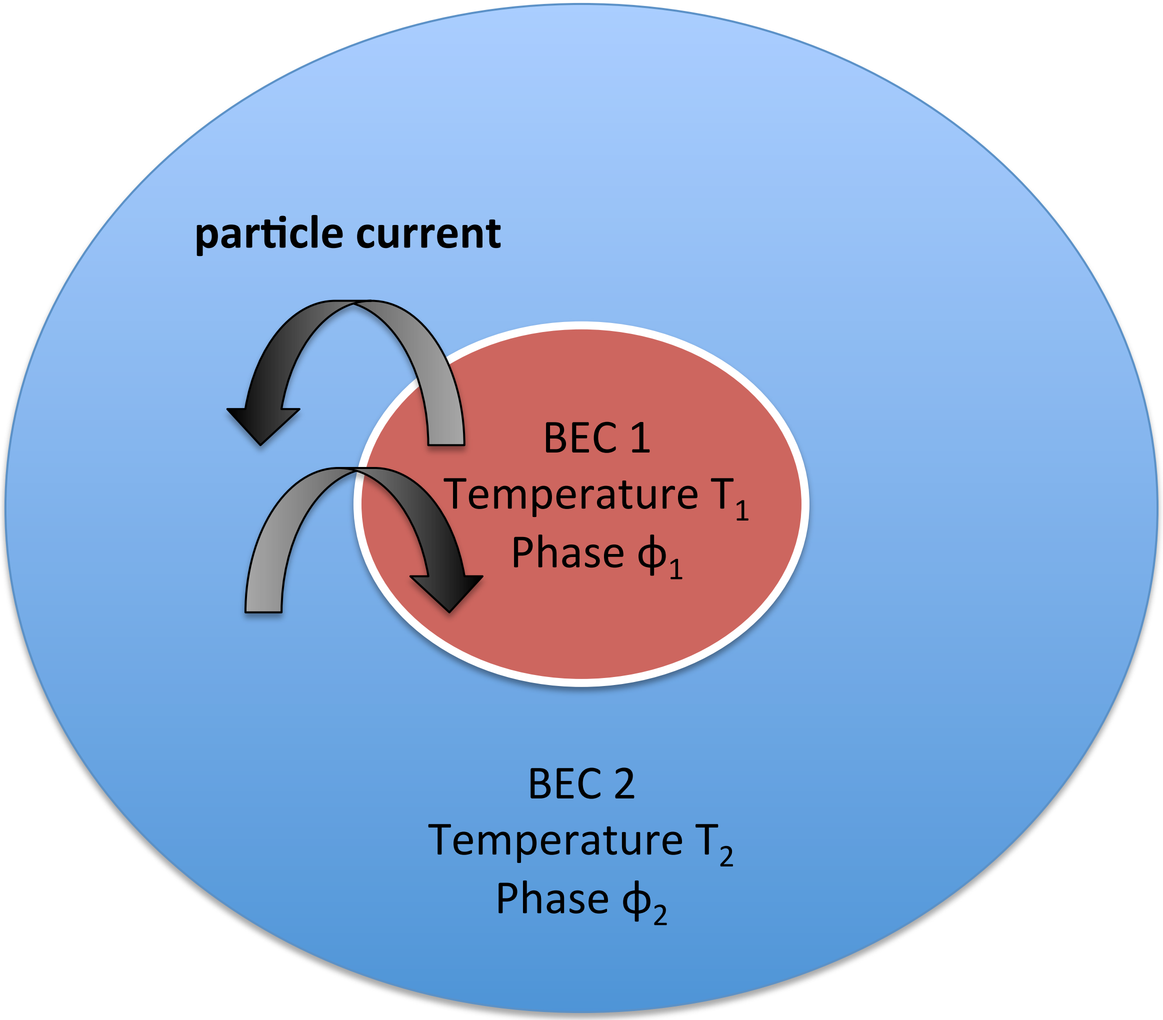


Magnonic supercurrents



$T_1 > T_2$

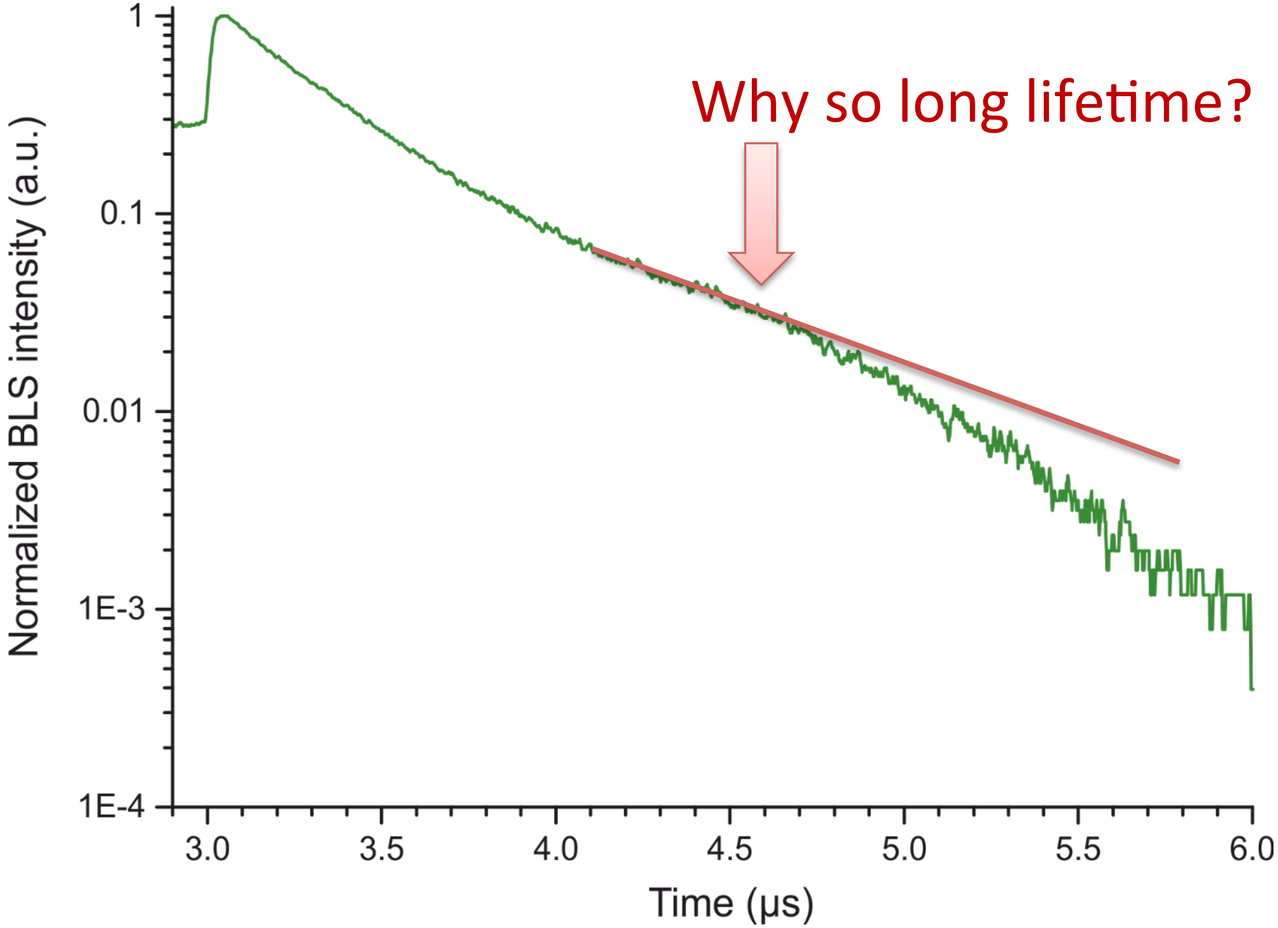
$\rightarrow \Phi_1 \neq \Phi_2$

Long-lifetime BEC in thermal gradient

Sample of better quality: Magnon lifetime 700 ns

Probing laser power 0.8 mW ensures small BEC outflow

Long existence time of the magnon BEC in the probing point



Oscillations of the BEC lifetime

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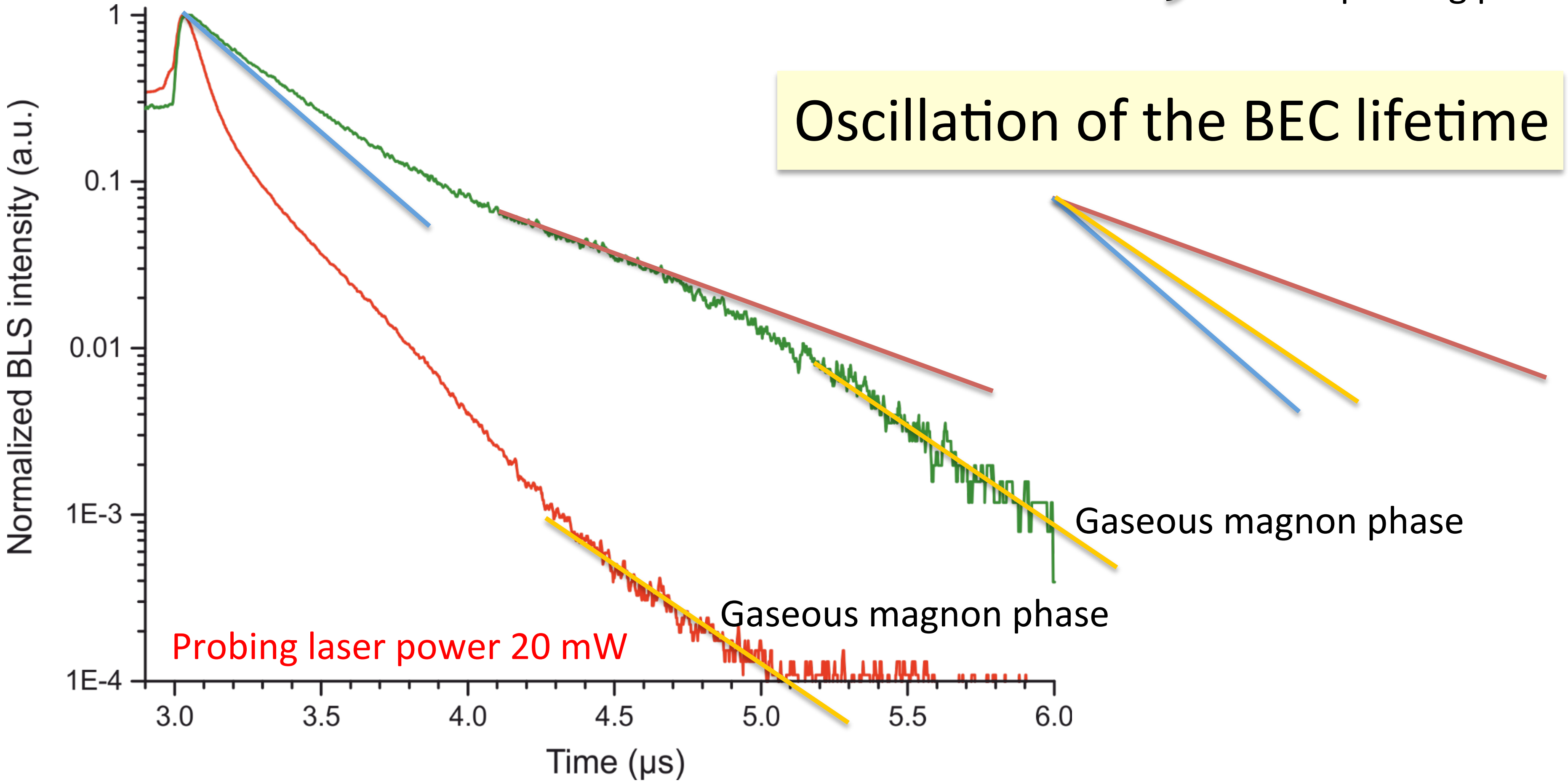
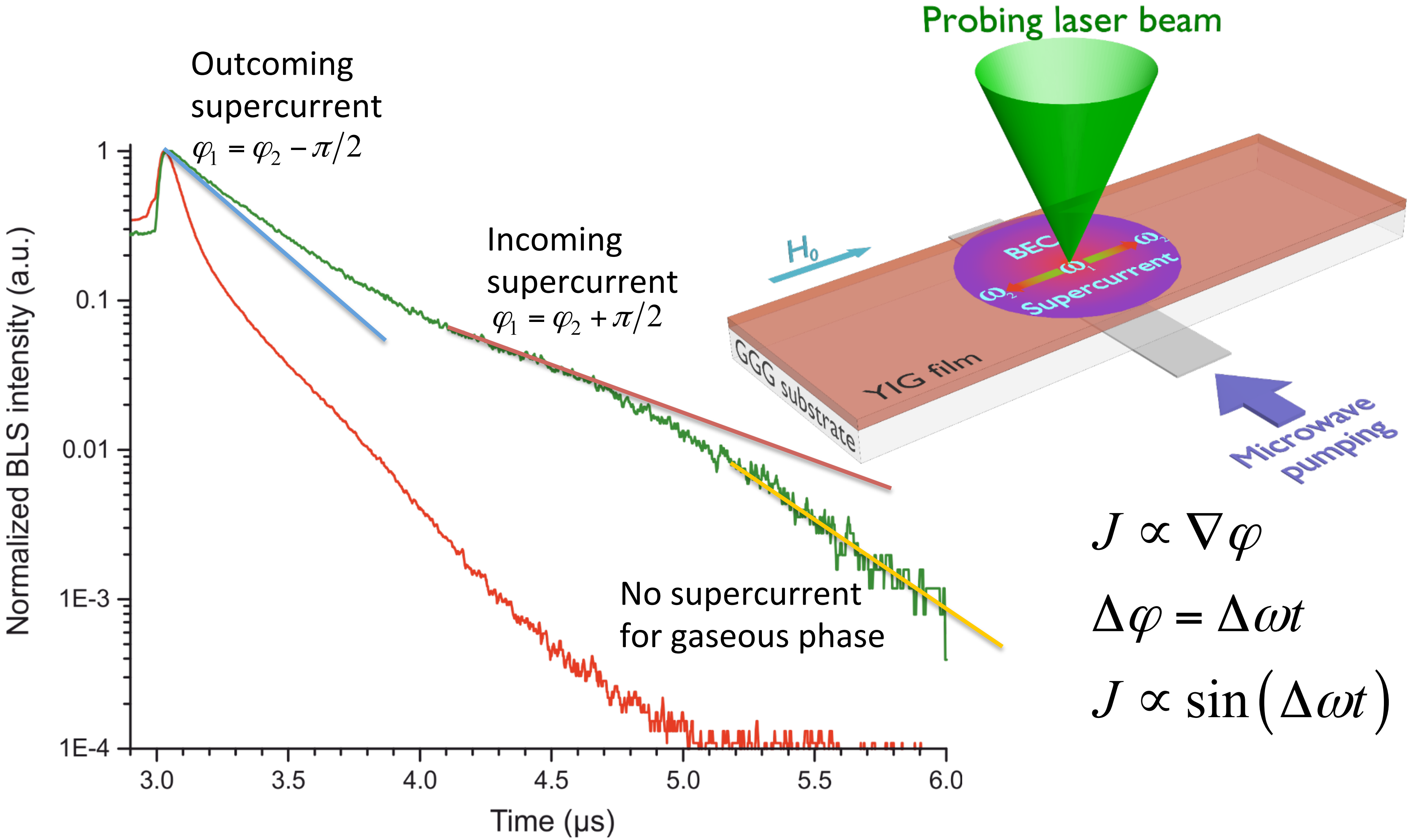


BEC in gradient of saturation magnetization



$$J \propto \nabla \varphi$$

$$\Delta\varphi = \Delta\omega t$$

$$J \propto \sin(\Delta\omega t)$$

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Magnonics: Challenges

Materials for magnons

- New insulators
- Materials with controlled damping
- Novel artificial materials
- Materials with controlled spin-orbit coupling

Making magnons

- Magnon Bose (Einstein) condensates
- Spin Transfer Torque effect in insulators
- Miniaturization
- THz magnonics
- Single magnon gener. and detection

Moving magnons

- Magnon supercurrents
- Dzyaloshinskii-Moria interactions
- Electric field effects

Detecting magnons

- Enhancement of existing techniques
- TMR
- Quantum effects