Magnetization Dynamics II:
Magnonics: Trends and Challenges

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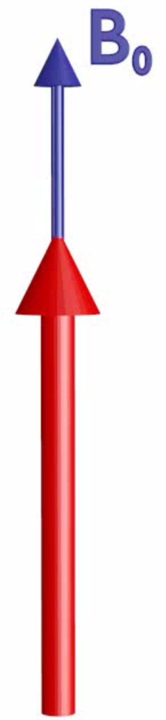
Coherent dynamics: spin waves

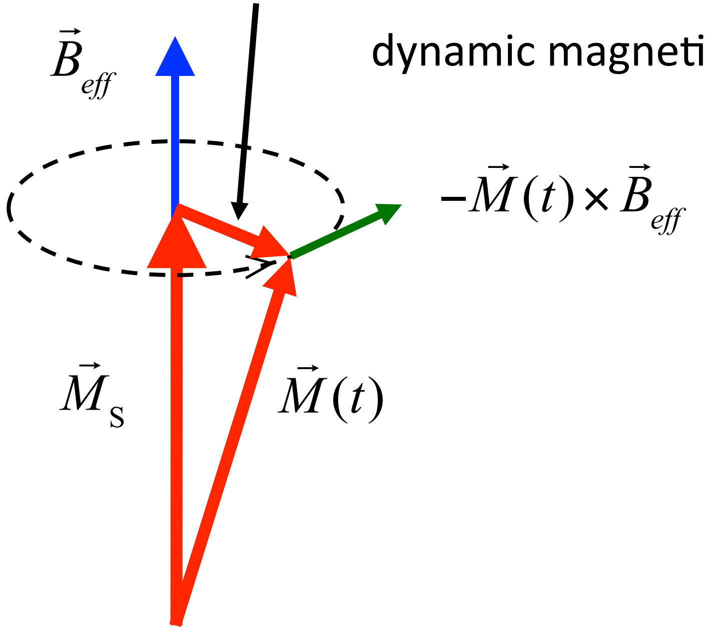
Spin wave: collective motion of magnetic moments



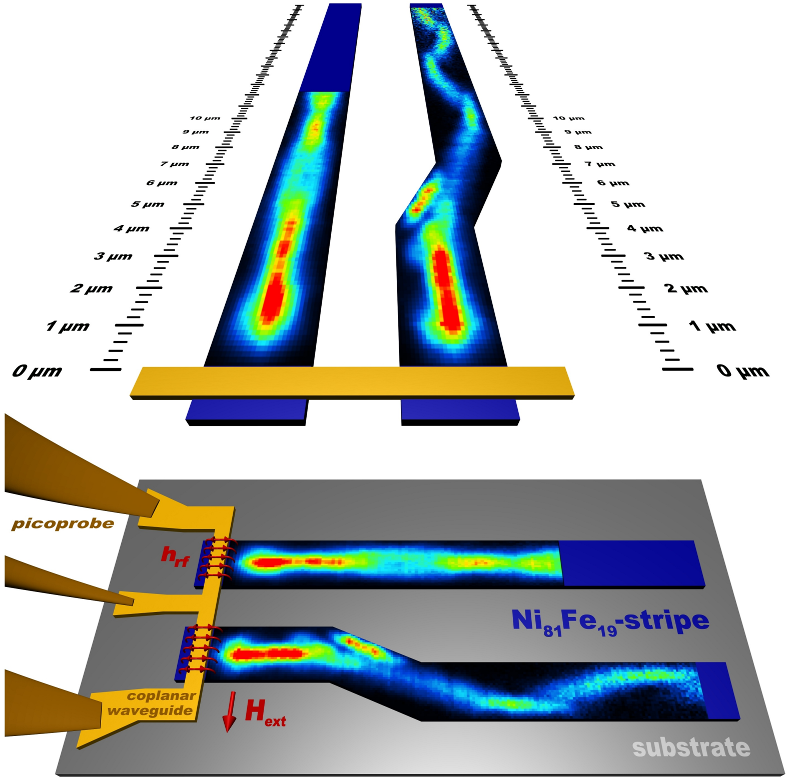
Landau-Lifshitz torque equation

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

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



Spin wave bus



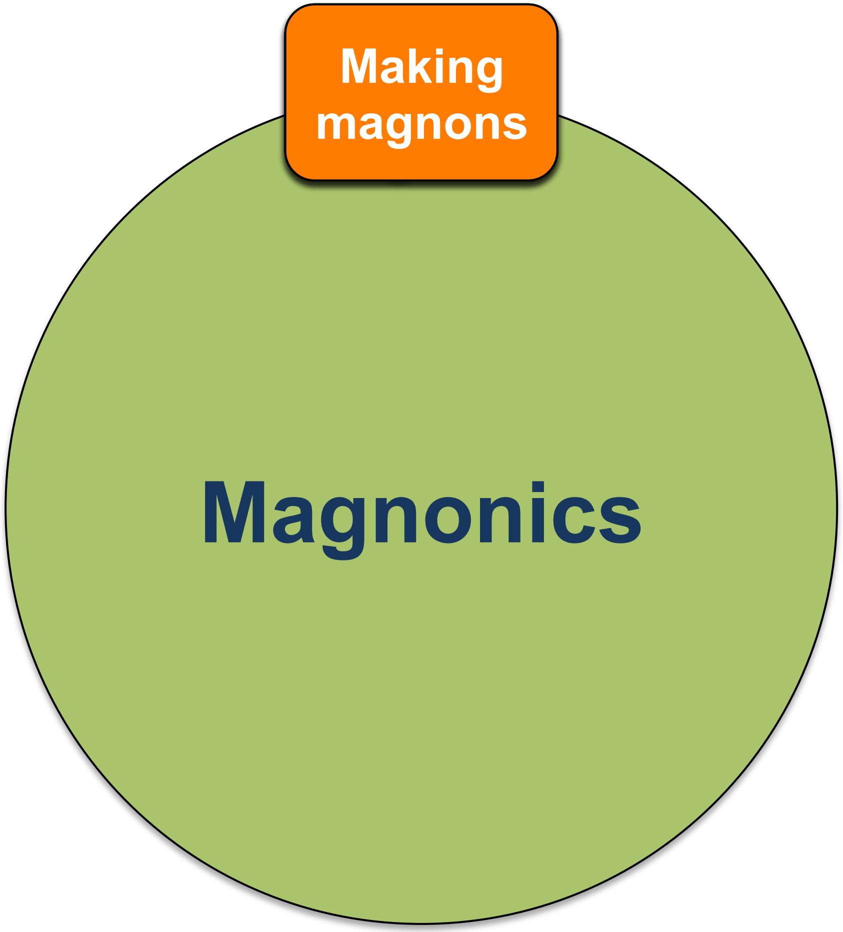
Travelling magnons allow one to:

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

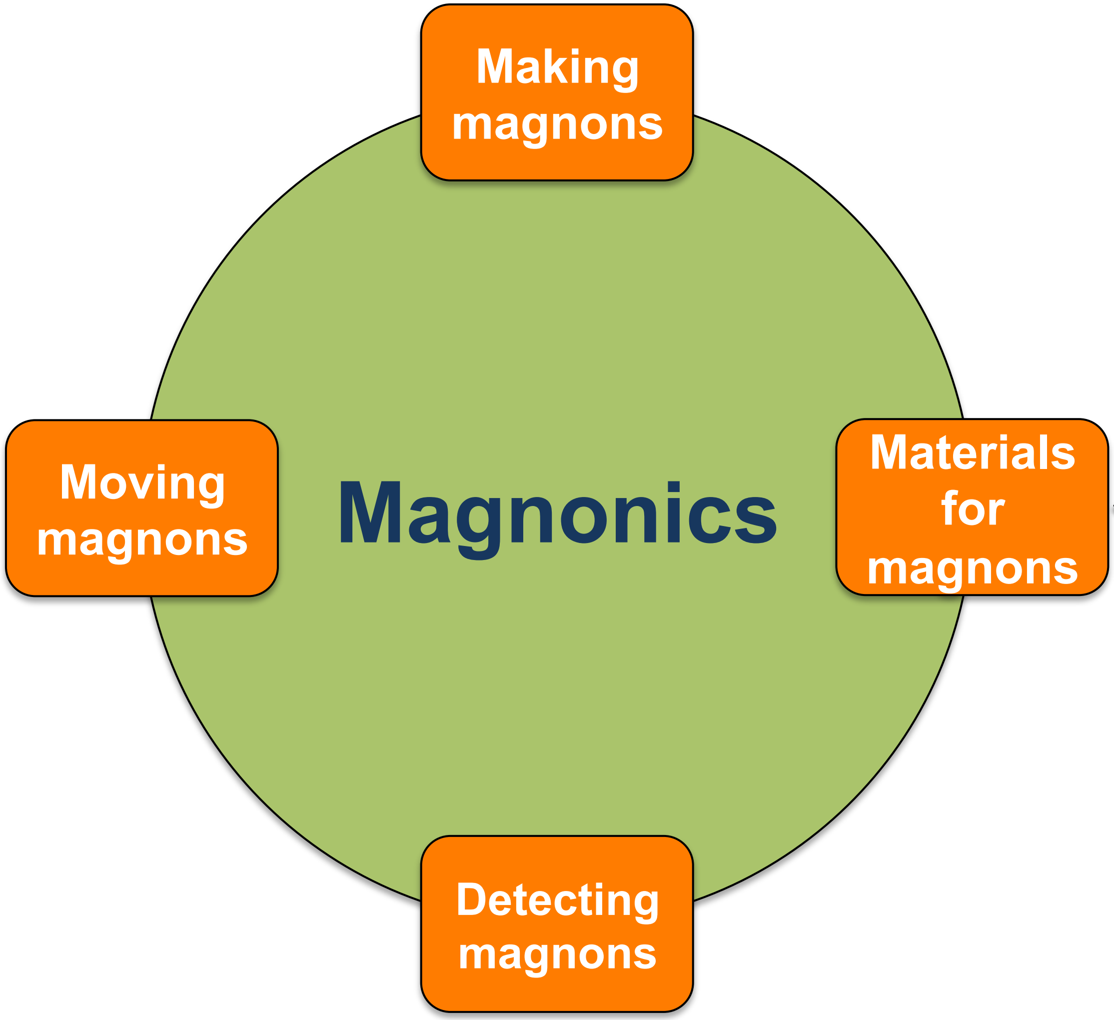
Fundamental properties:

- 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



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.)

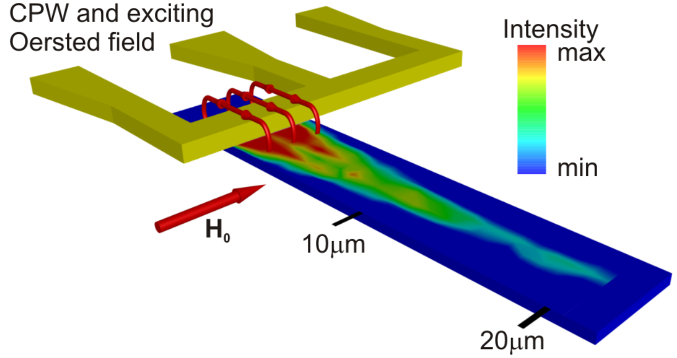
A. Karenowska (Oxford University, U.K.)

M. Kostylev (University of Western Australia)

AG Magnetismus in TU Kaiserslautern

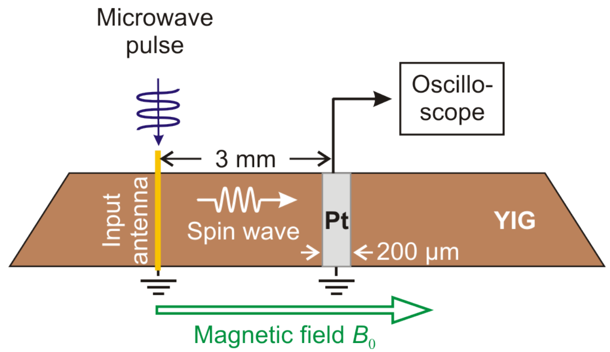
P. Pirro, Dr. A. Conca Parra, Dr. A. Chumak, T. Brächer, D. Pasarello, Prof. Dr. B. Hillebrands, T. Langner, R. Neb, B. Obry, Dr. V. Vasyuchka, M. Agrawal, Dr. B. Leven, P. Clausen, T. Meyer, B. Jungfleisch, T. Sebastian, Dr. E. Papaioannou, A. Kirihara, F. Heussner, V. Lauer, A. Ruiz Calaforra, Dr. F. Ciubotaru (+ Dr. A. Serga).

Magnonics: Main trends



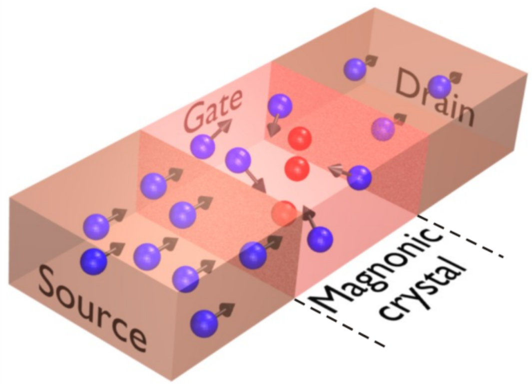
I. New materials for magnonics

II. Novel means for magnon detection



III. Data processing using magnons

IV. Magnonic supercurrents



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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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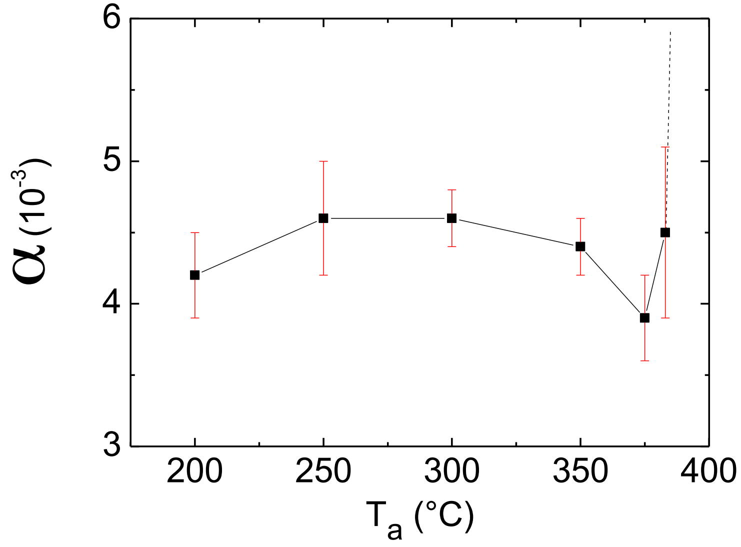
➔ CoFeB: low damping (both am. and crystalline phase): $\alpha = 4 \times 10^{-3}$



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

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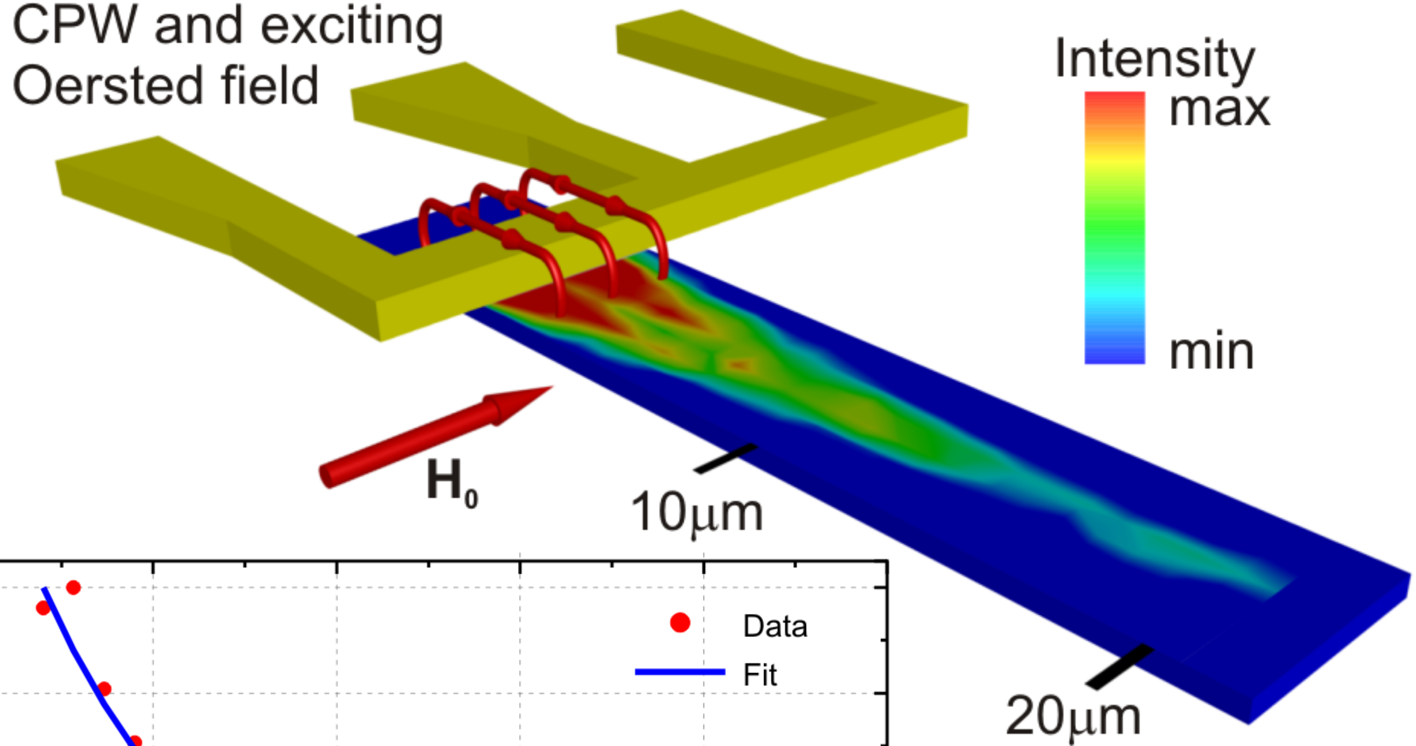
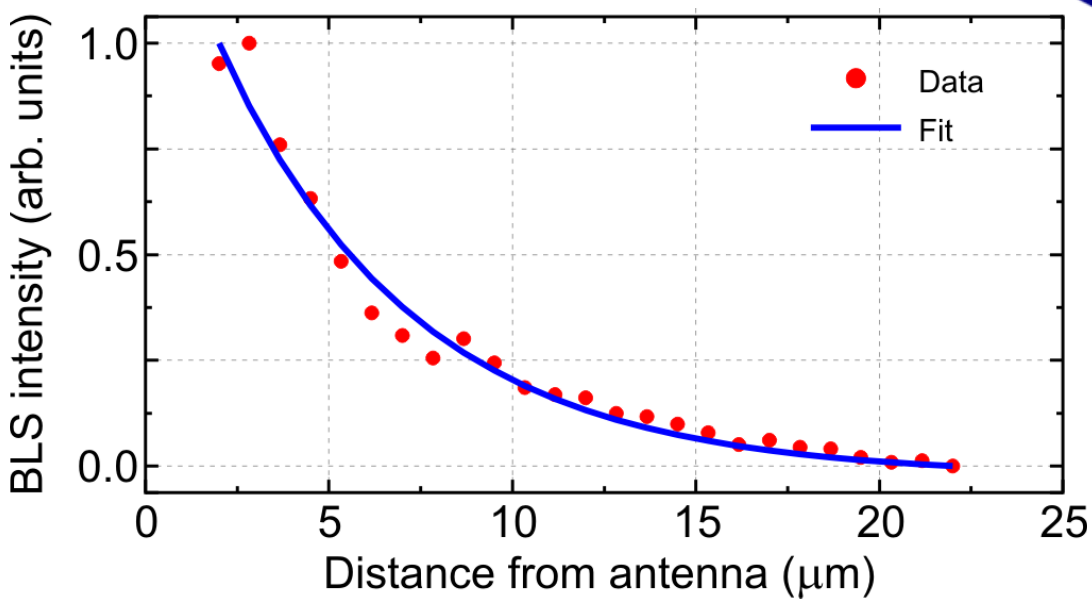
Spin-wave propagation in $Co_2Fe_{0.4}Mn_{0.6}Si$ Heusler waveguides

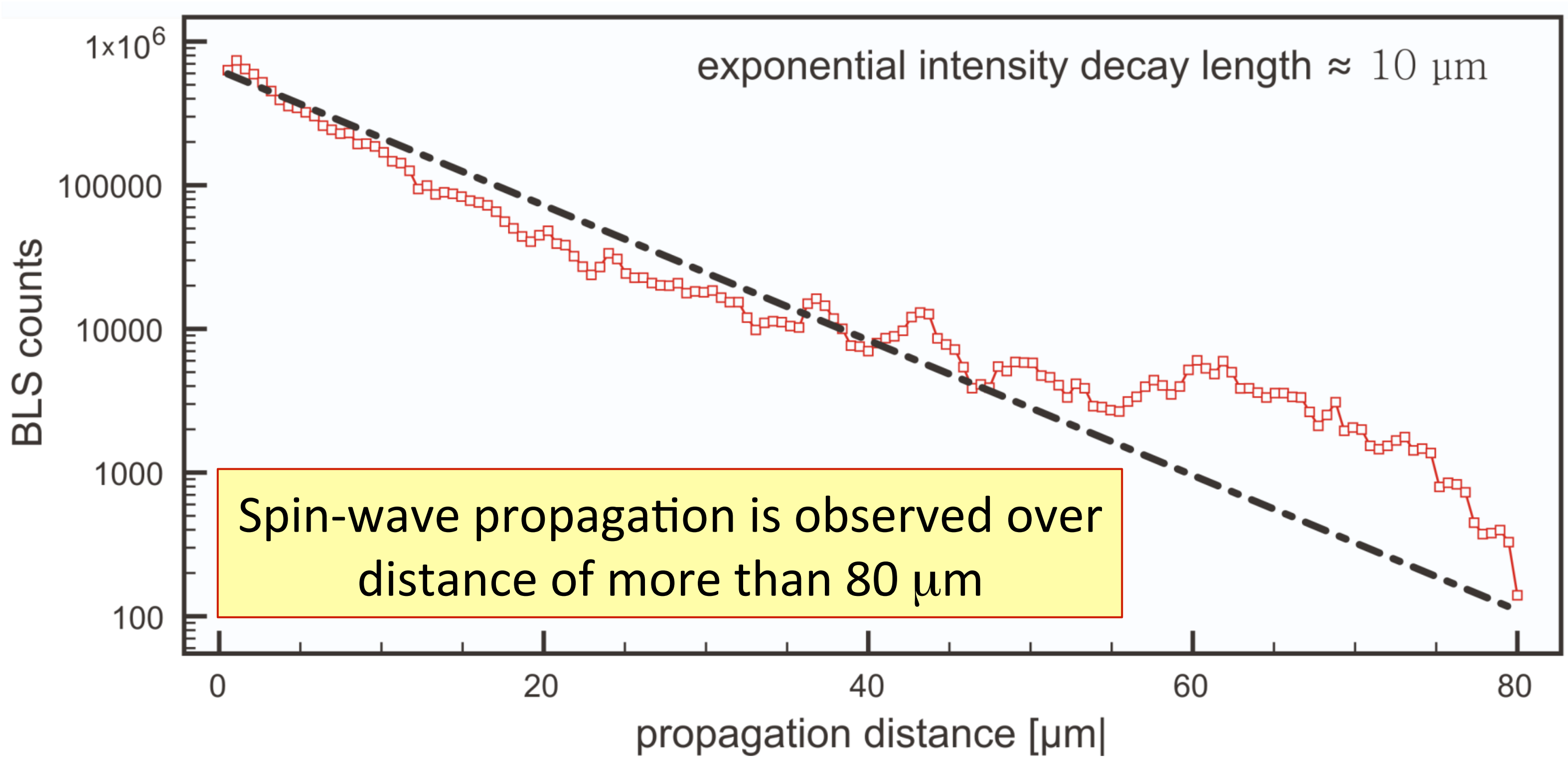




$Co_2Fe_{0.4}Mn_{0.6}Si$
Thickness 30 nm
Stripe width 4 μm
External field: 40 mT
Frequency: 6.2 GHz

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

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



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

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

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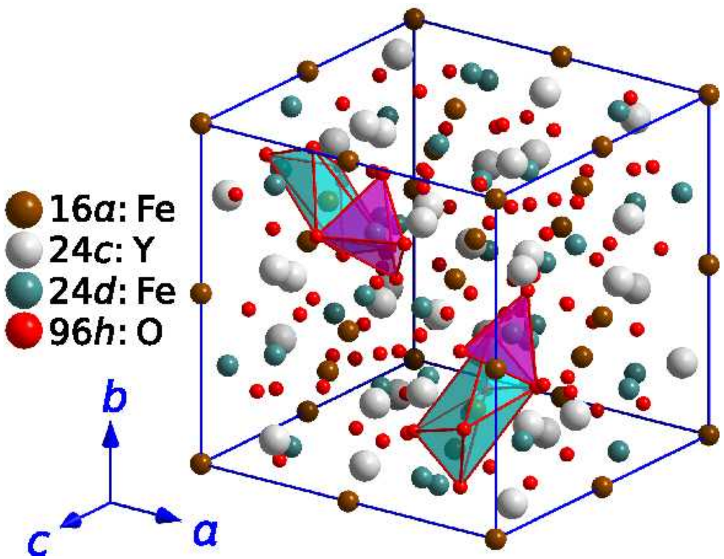
- ⇨ Micro-structured Yttrium Iron Garnet $Y_3Fe_5O_{12}$ (YIG): $\alpha = 4 \times 10^{-5}$

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



YIG:

- magnetic insulator
- smallest spin-wave damping

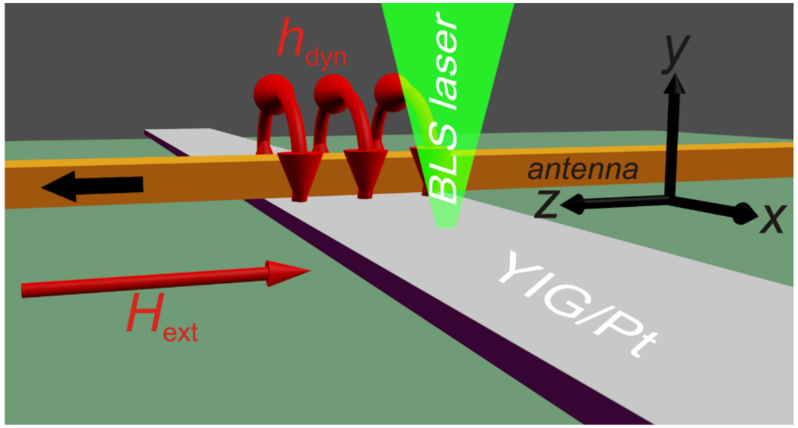
Preparation via:

- liquid phase epitaxy
- sputtering
- pulsed laser deposition

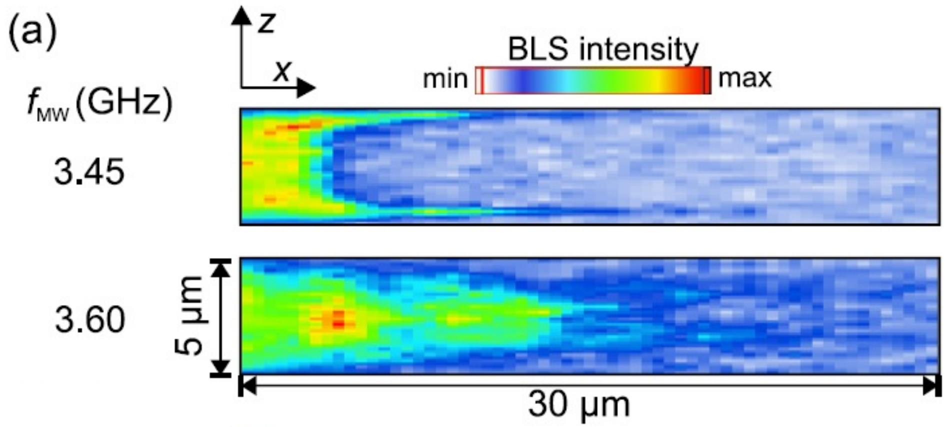
A. Kreisel, Europhysics News (2006)

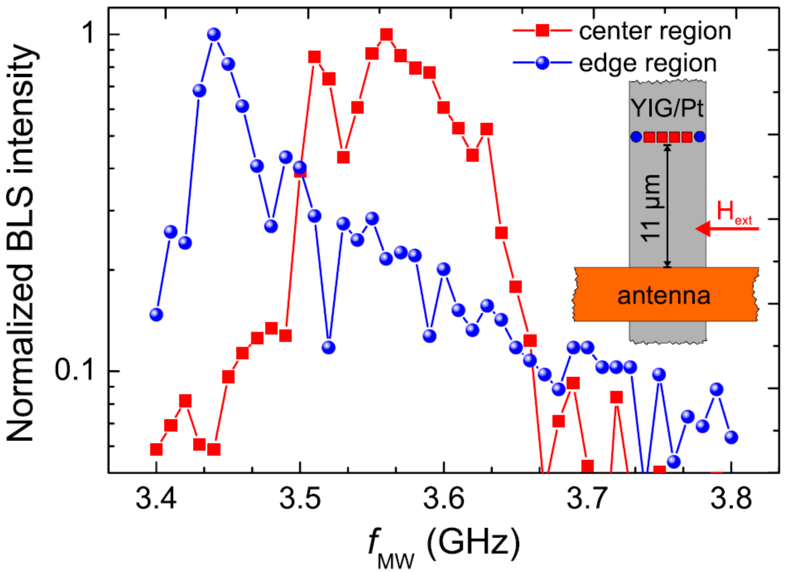
Sample fabrication

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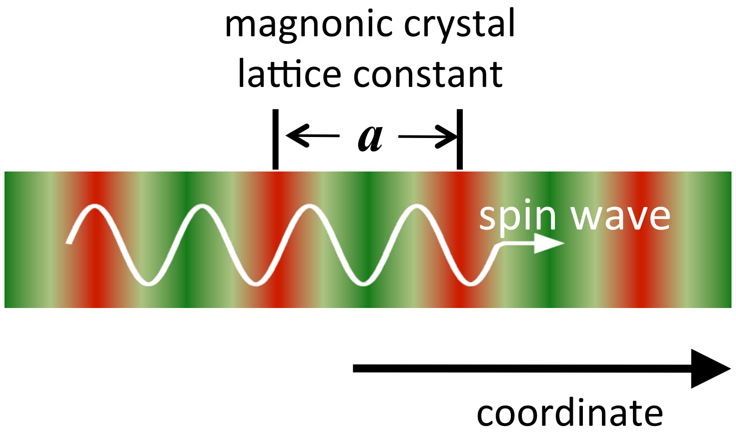
➜ Magnonic crystals: artificial magnetic materials (static and dynamic)

What is a "magnonic crystal"?

Magnonic crystal – magnetic meta-material:

- artificial medium with periodic lateral variation in magnetic properties

One-dimensional magnonic crystal:

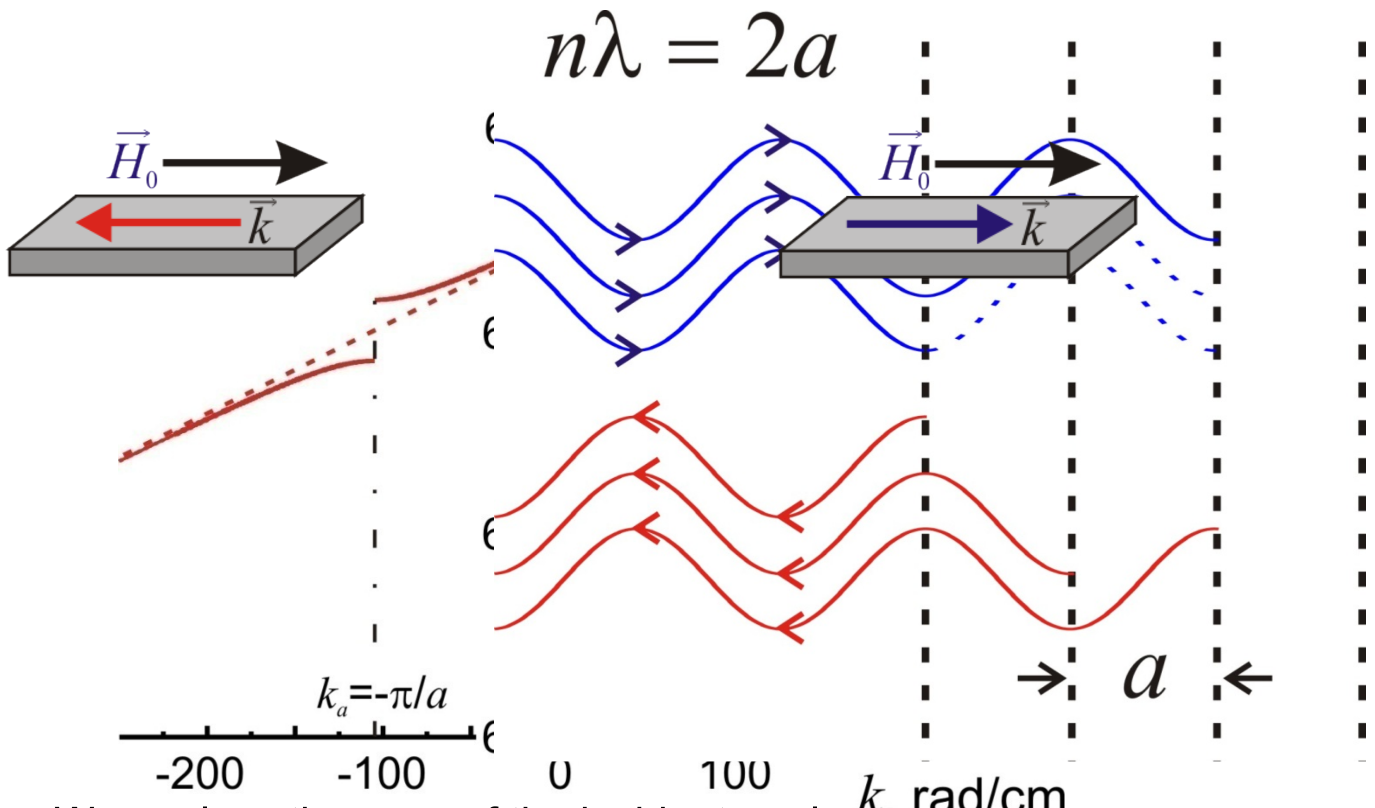


Magnonic-crystal are engineered to have properties that may not be found in nature

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

Band gap

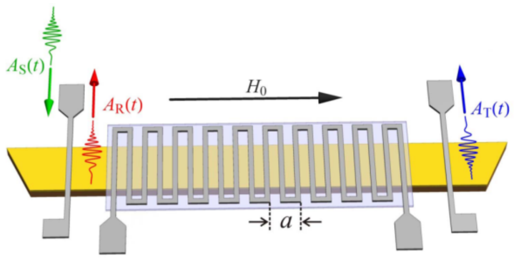
Band gaps – regions of the spectrum over which waves are not allowed to propagate



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

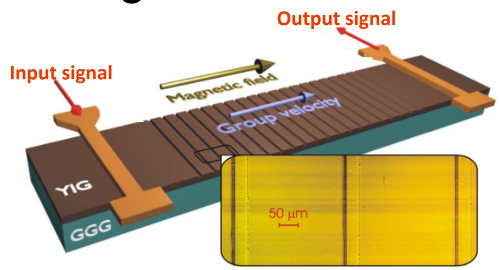
Which magnetic property do we modulate?

Bias magnetic field



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

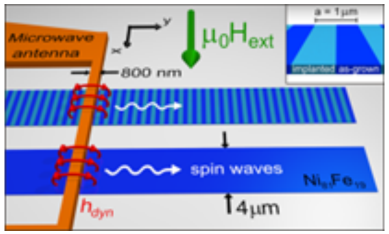
Waveguide thickness



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

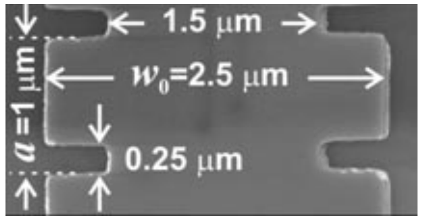
$$f(k) = \gamma\sqrt{H_0\left(H_0 + 4\pi M_0\frac{1-\exp\left\{-\sqrt{(\pi/w)^2+k^2}\,d\right\}}{\sqrt{(\pi/w)^2+k^2}\,d}\right)}$$

Effective saturation magnetization



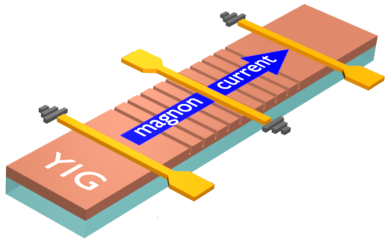
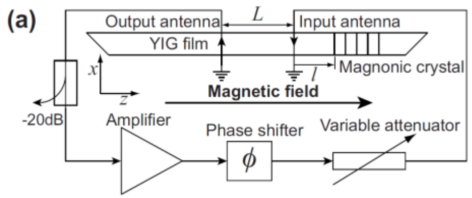
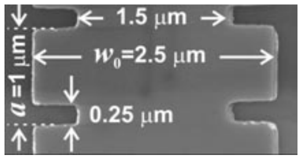
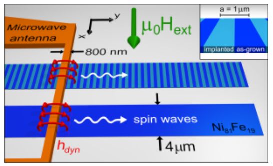
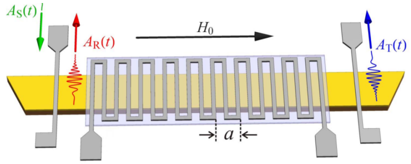
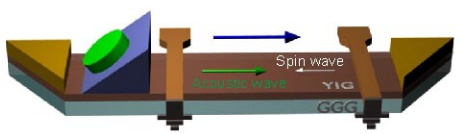
Chumak et al., PRB, **81**, 140404 (2010)
Obry et al., APL, **102**, 202403 (2013)

Waveguide width



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

Magnonic crystals - overview

microwave filter		Chumak et al., APL **93**, 022508 (2008) Chumak et al., APL **94**, 172511 (2009) Chumak et al., JAP **105**, 083906 (2009)
data storage element		Chumak et al., PRL, **108**, 257207 (2012)
stable microwave generator		Karenowska et al., APL 96, 082505 (2010)
micro-sized crystal	 	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)
switchable device		Chumak, et al., J.Phys.D **42,** 205005 (2009) Chumak, et al., Nat. Commun. **1**:141 (2010) Karenowska, et al., PRL **108**, 015505 (2012)
travelling crystal		Chumak et al., PRB, **81**, 140404 (2010)

Localized ion implantation

Localized ion implantation:

- Purely magnetic patterning
- No change in sample topography

State of the art studies (YIG):

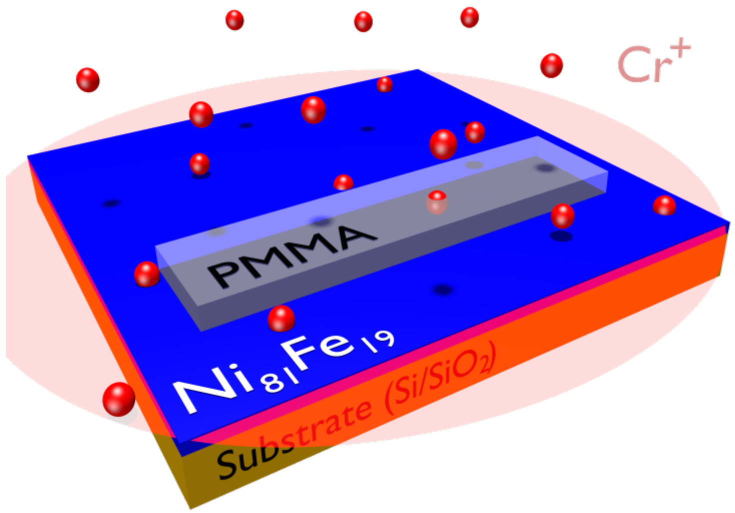
G. Volluet, P. Hartemann,
Reflection of magnetostatic forward volume waves by ion implanted gratings,
Proc. IEEE Ultrasonics Symp., 394 (1981).

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:

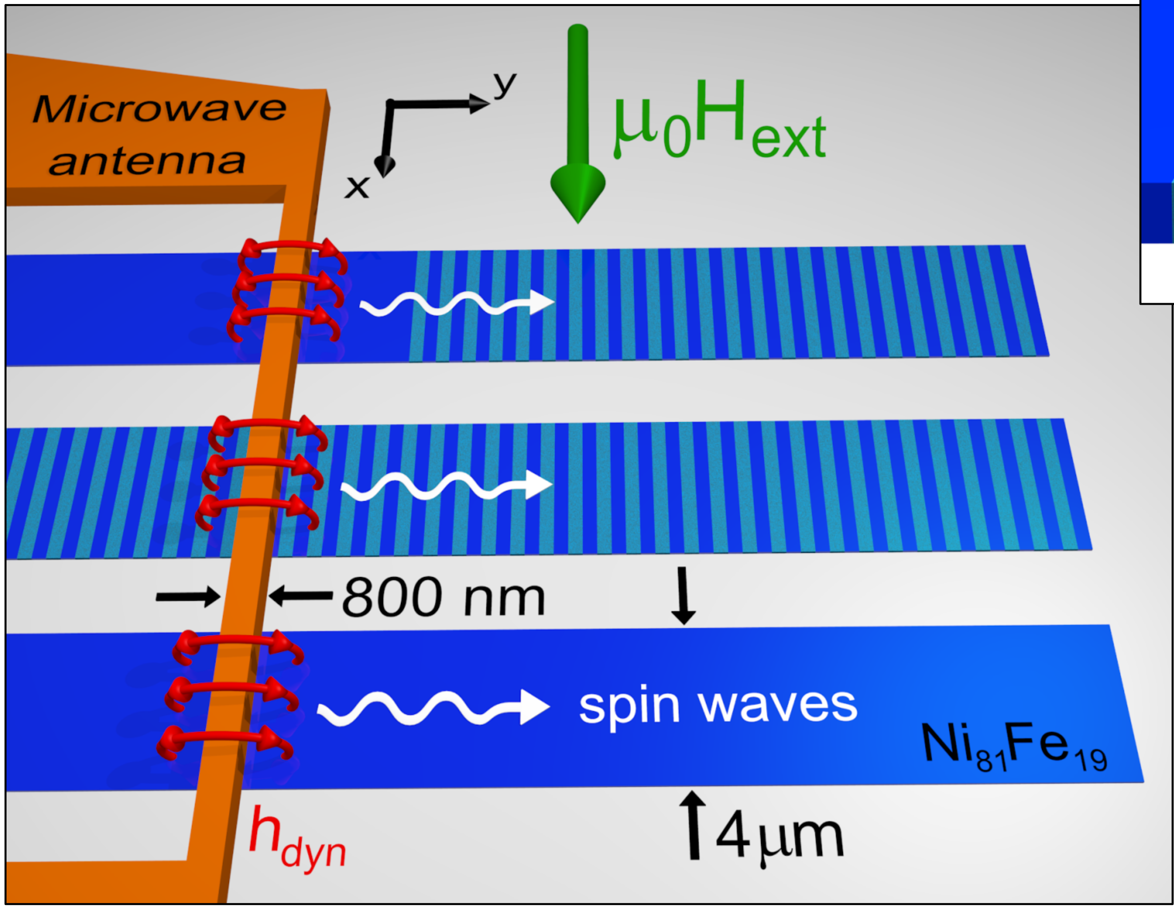
Control saturation magnetization M_S and Gilbert damping α

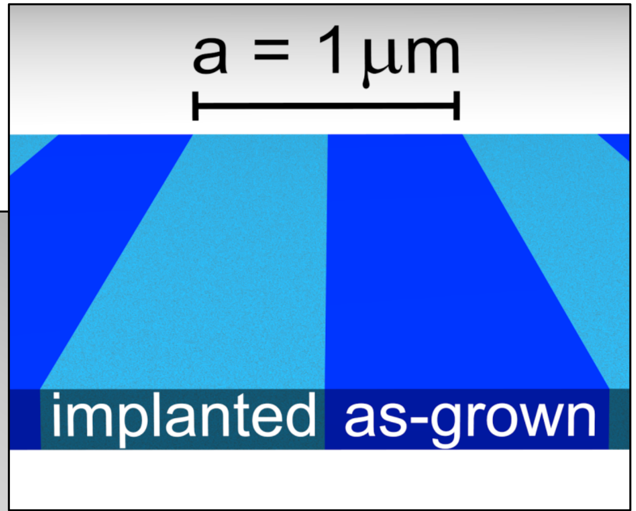
Fassbender *et al.*, PRB **73,** 184410 (2006)



Sample setup

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

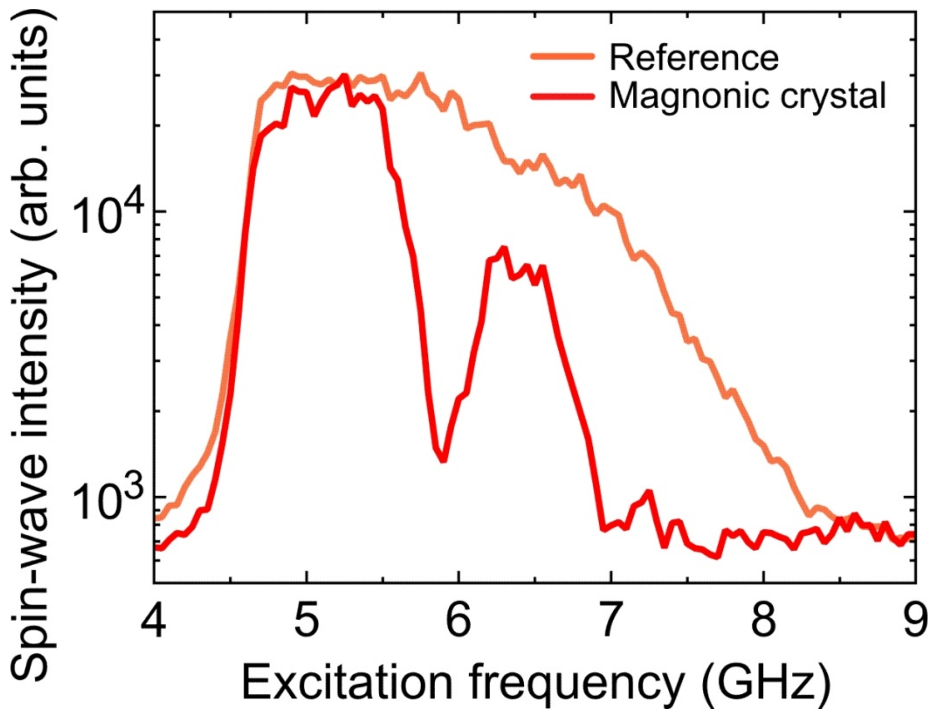


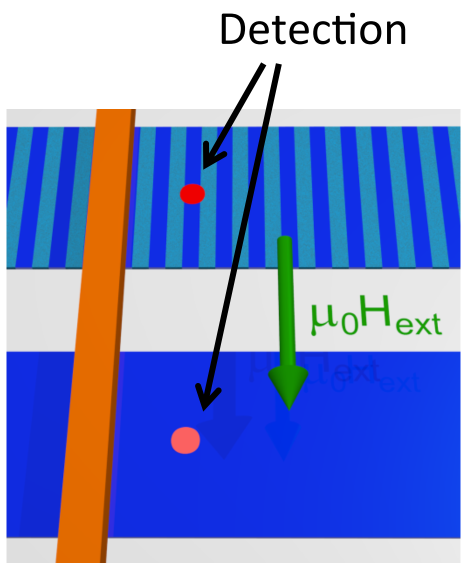


- Waveguides:
  MBE evaporation
  Lift-off techniques

Transmission spectrum

Spin-wave excitation spectra:





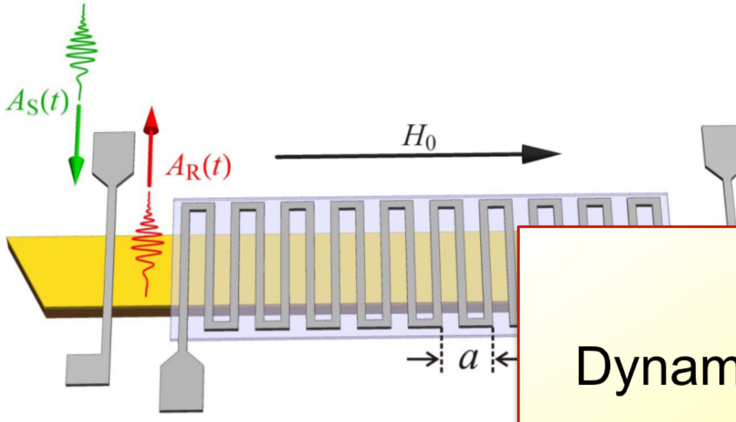
$\mu_0 H_{ext}$ = 27.3 mT

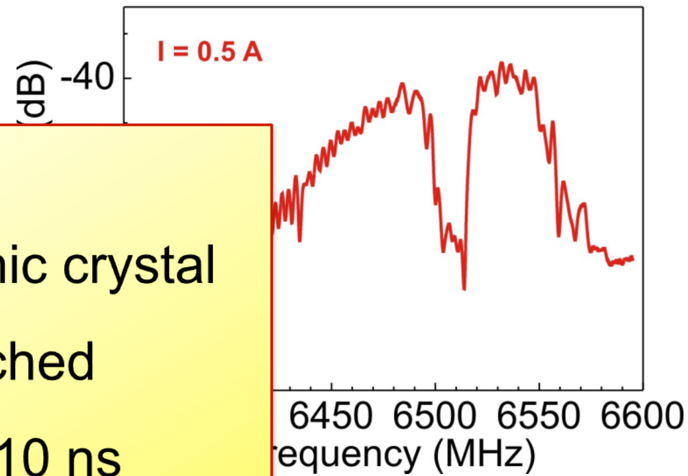
Two pronounced band gaps in transmission spectrum

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

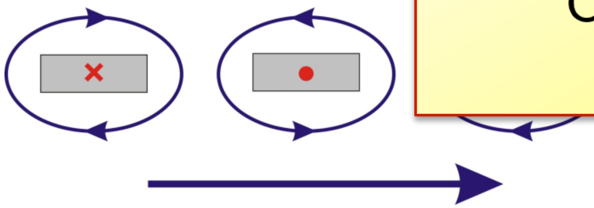


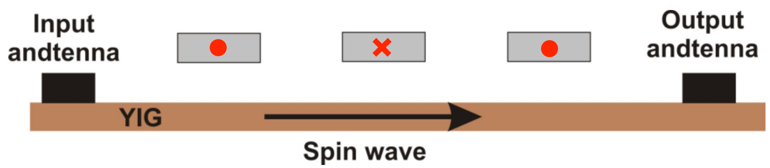


Dynamic magnonic crystal

can be switched

ON/OFF in ~10 ns



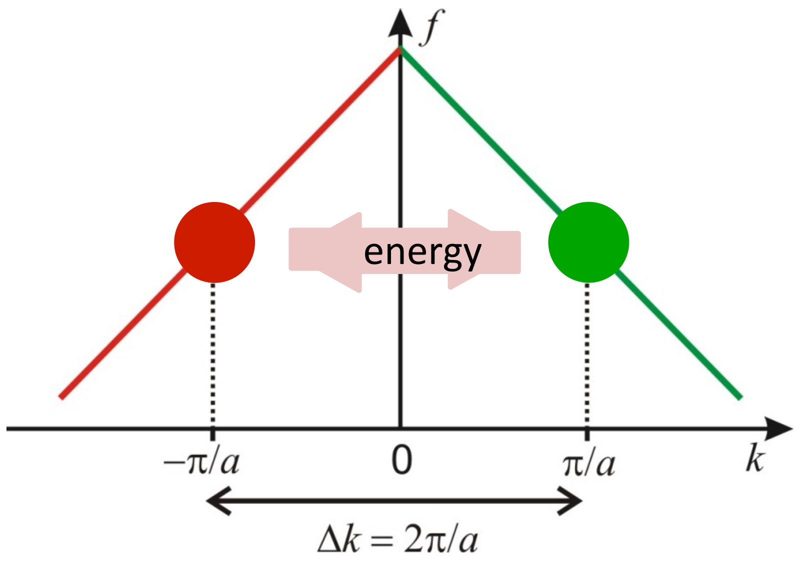


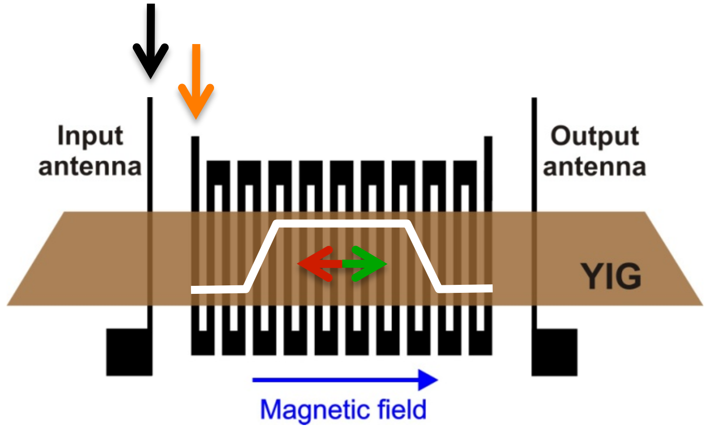
Lattice constant: a = 300 μm

Number of periods: N_g = 20

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

Spin-wave mode coupling by dynamic magnonic crystal

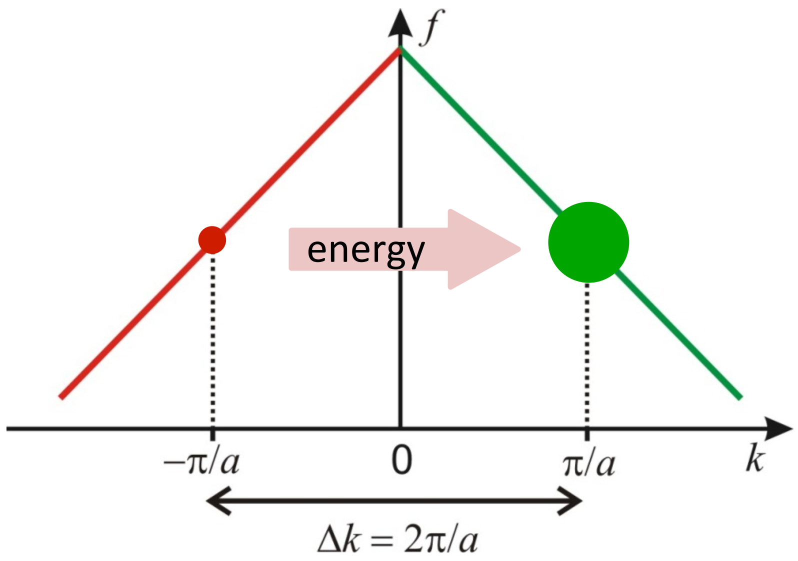


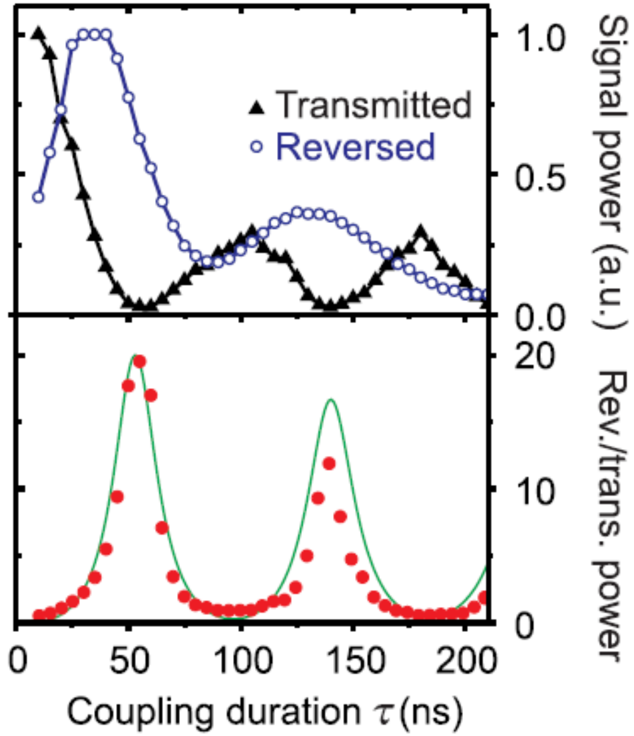


Two modes with $k = \pi/a$ and $k = -\pi/a$ are coupled by periodic variation of field

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

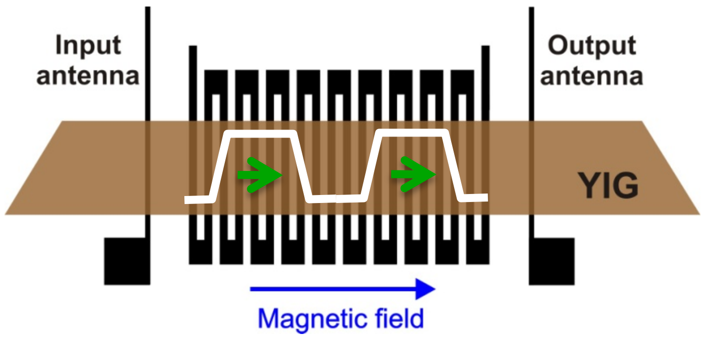
Input signal:

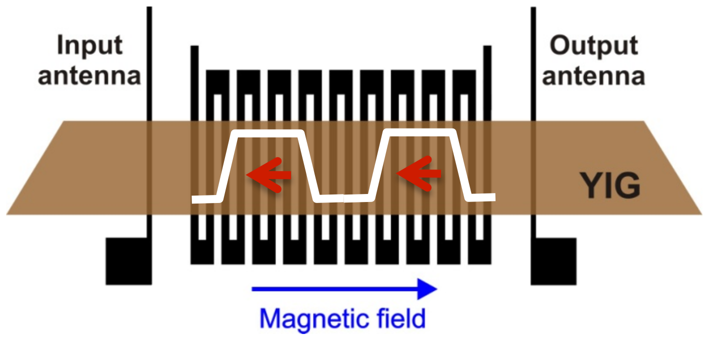
$$A_S(t) \sim \sum_{\Delta f} \exp(-i\,2\pi\,\Delta f\ t)$$

Δf is a frequency shift from the Bragg frequency

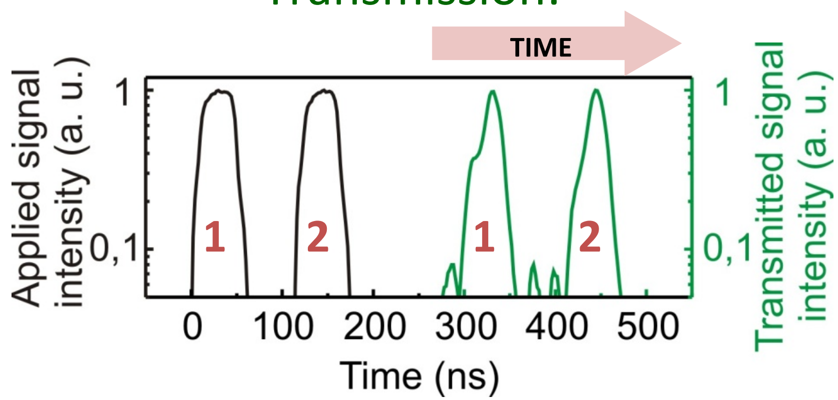
Reflected signal:

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

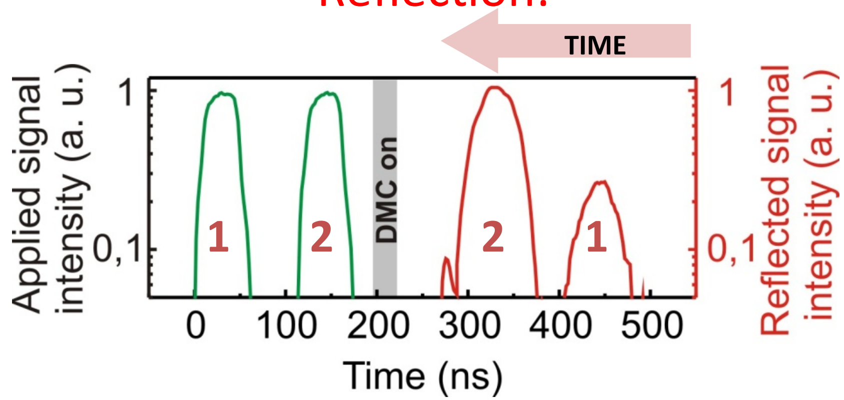




Transmission:



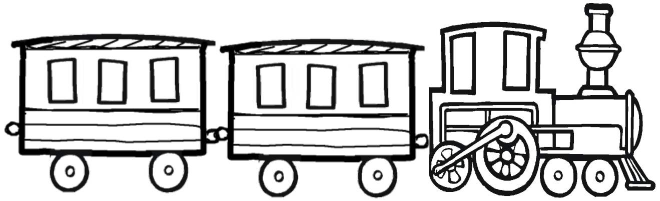
Reflection:

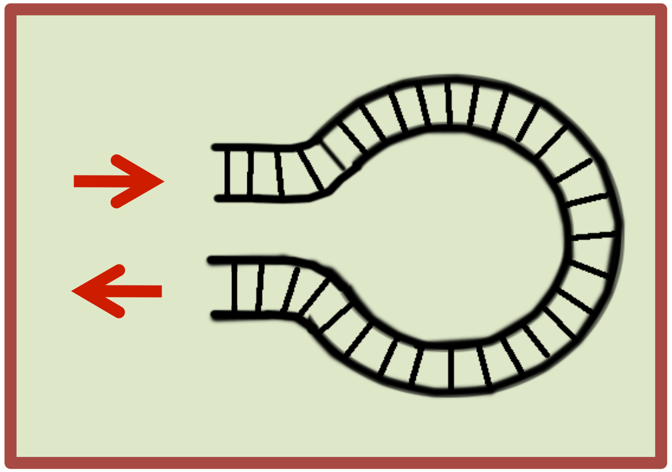


Chumak et al., **Nat. Commun. 1:141** doi: 10.1038/ncomms1142 (2010)

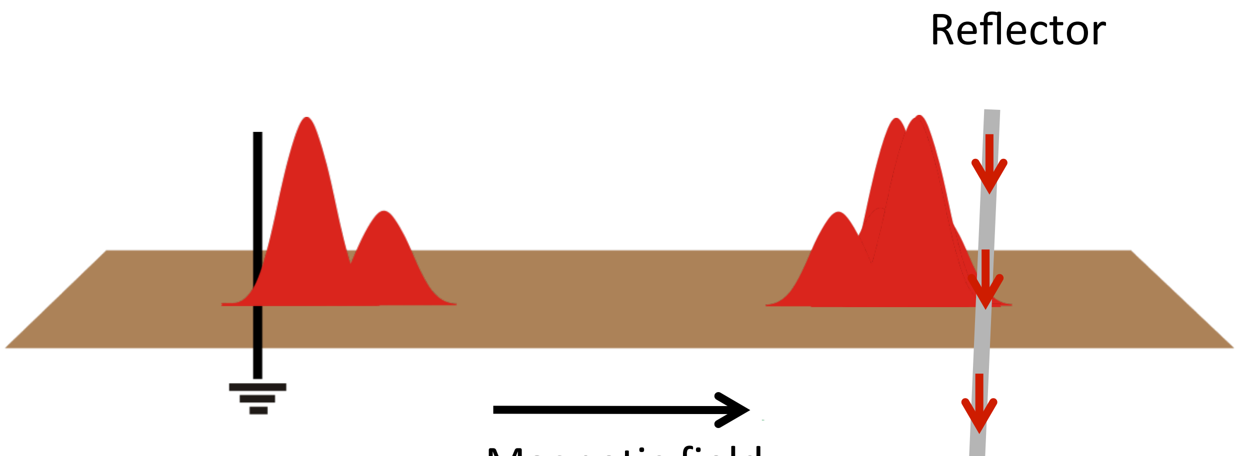
Classical reflection from mirror

Railway analog:



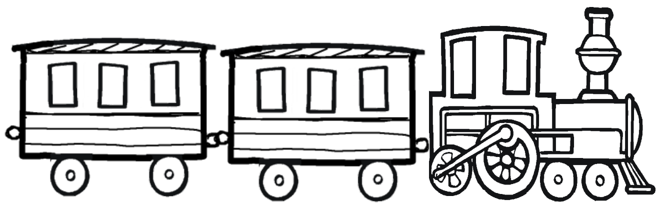


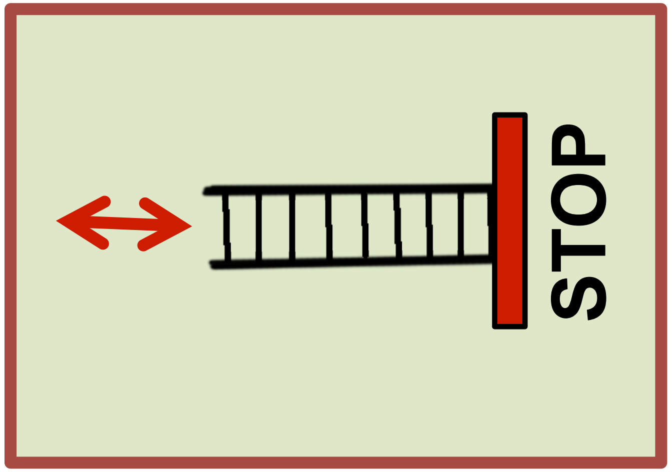
Spin-wave experiment:



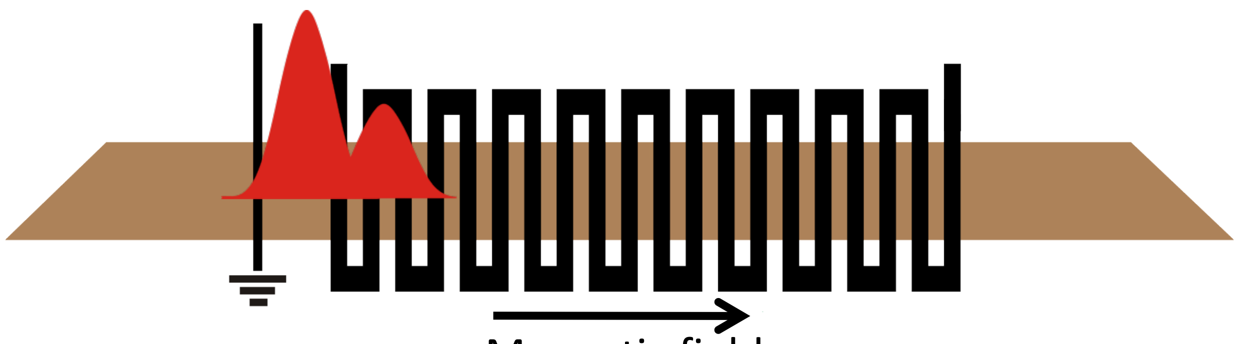
Reflection via time reversal

Railway analog:





Spin-wave experiment:



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

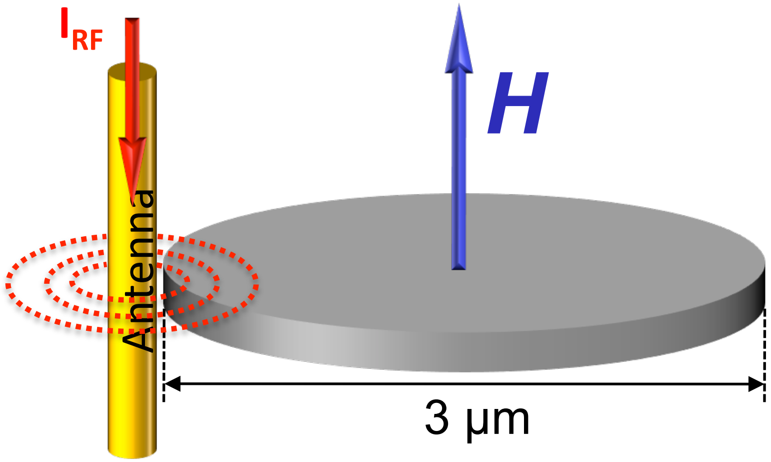
$\mu_0 M_s = 1$ T
$H_k = 0$
$\alpha = 0.007$
$\mu_0 H = 1.050$ T

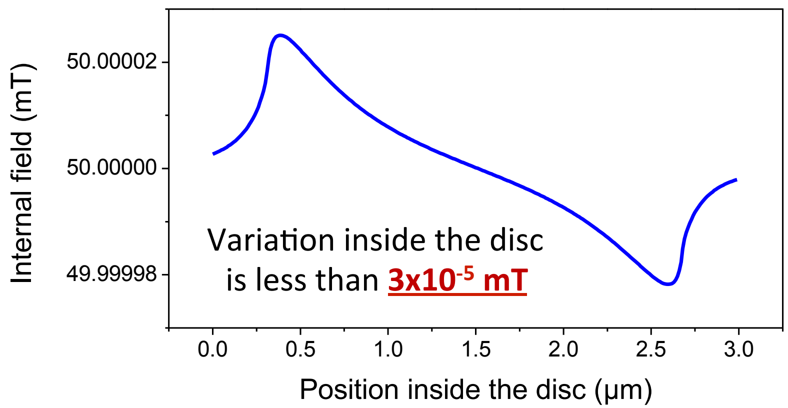
Spin waves are exited by the dynamic Oersted field created by injecting an RF current through antenna.

Diameter of antenna: 500 nm

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

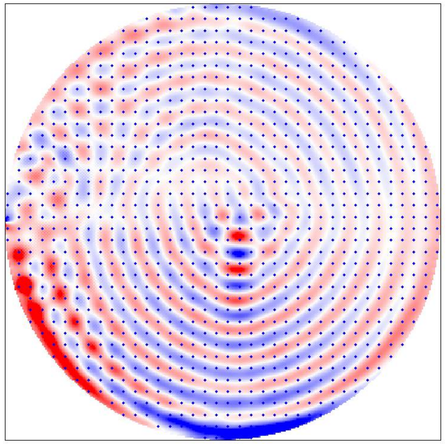
Internal field = 50 mT





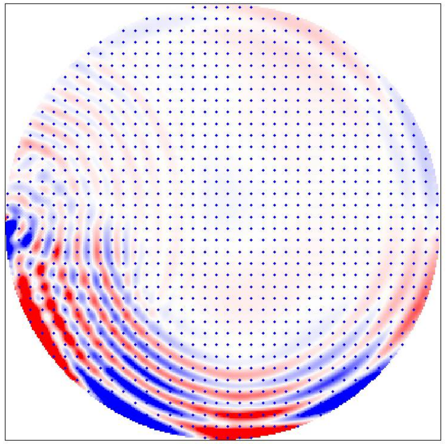
Spin-wave boundary mode

f = 8 GHz



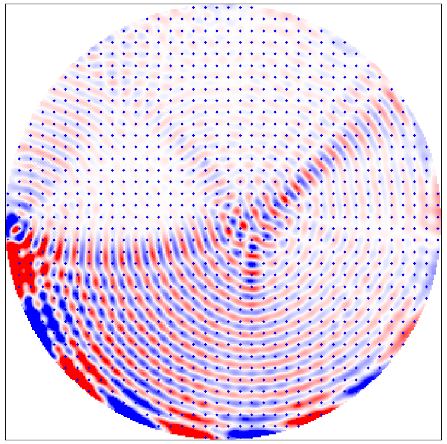
λ_v = 278 nm
λ_e = 3.7 μm

f = 10 GHz

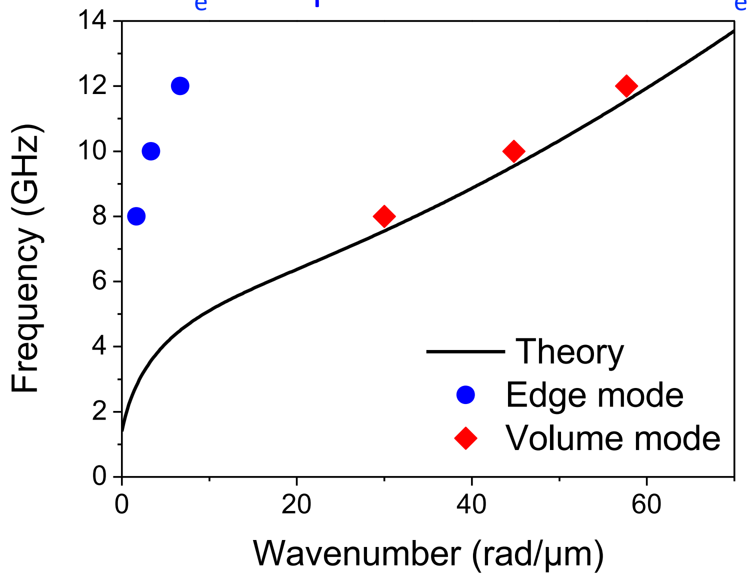


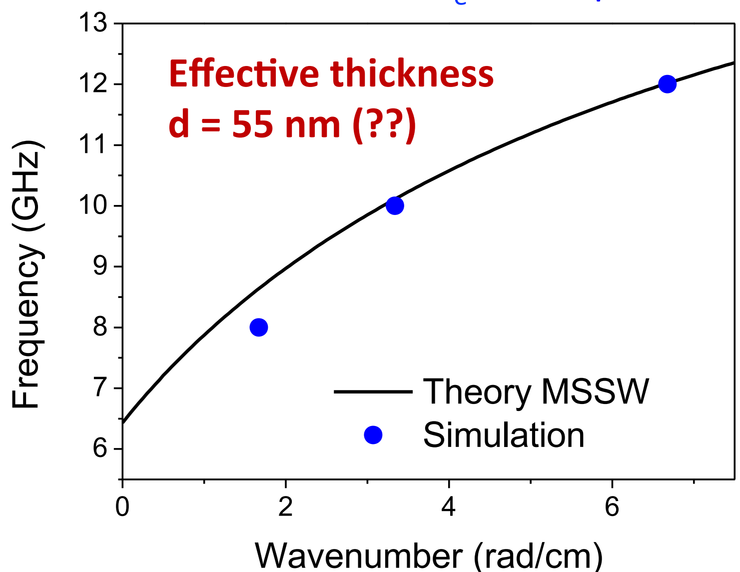
λ_v = 125 nm
λ_e = 1.9 μm

f = 12 GHz



λ_v = 98 nm
λ_e = 0.94 μm

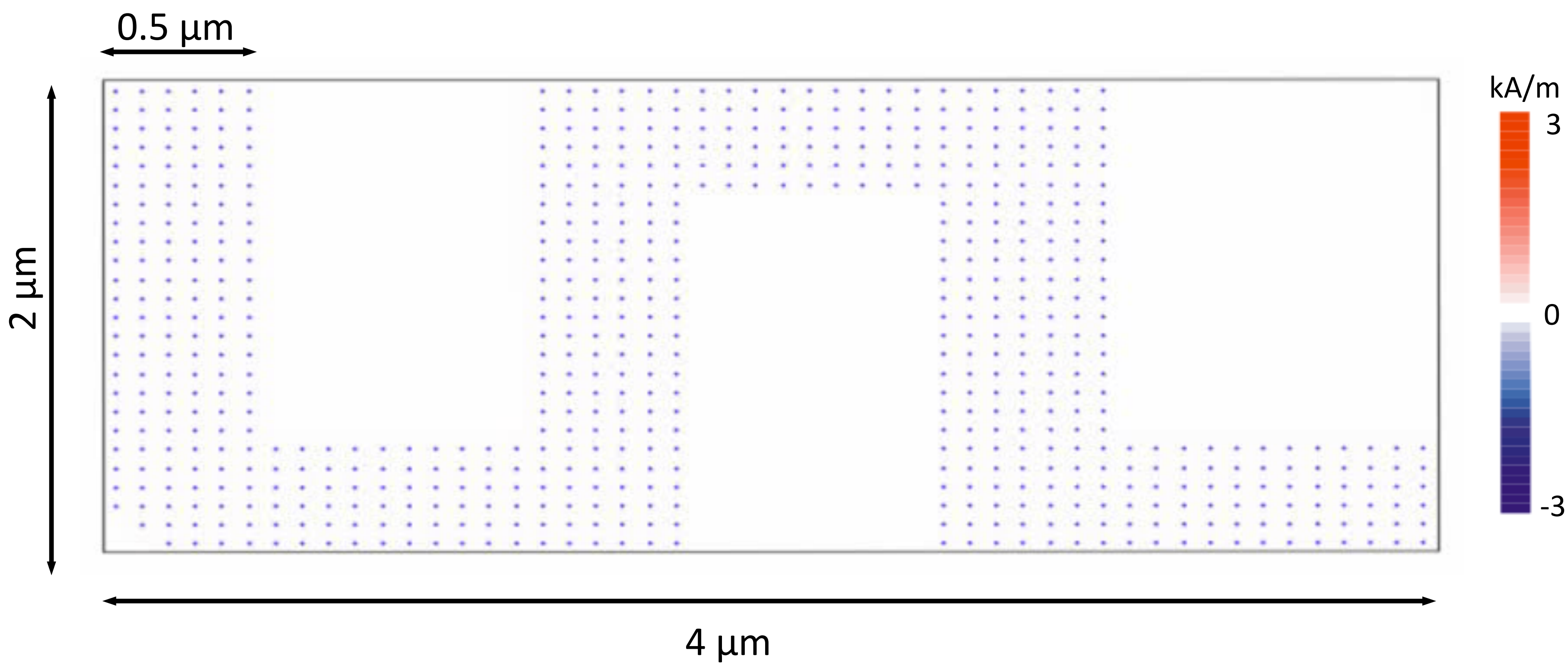




Spin-wave circuit

Thickness = 300 nm

Excitation frequency = 10 GHz



The boundary mode propagates arround the corners without changing its properties

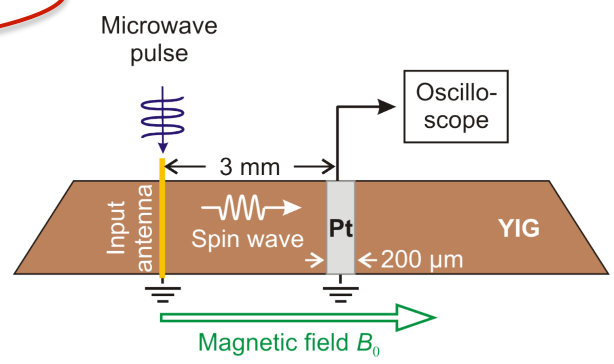
Magnonics: Main trends

I. New materials for magnonics

II. Novel means for magnon detection

III. Data processing using magnons

IV. Magnonic supercurrents



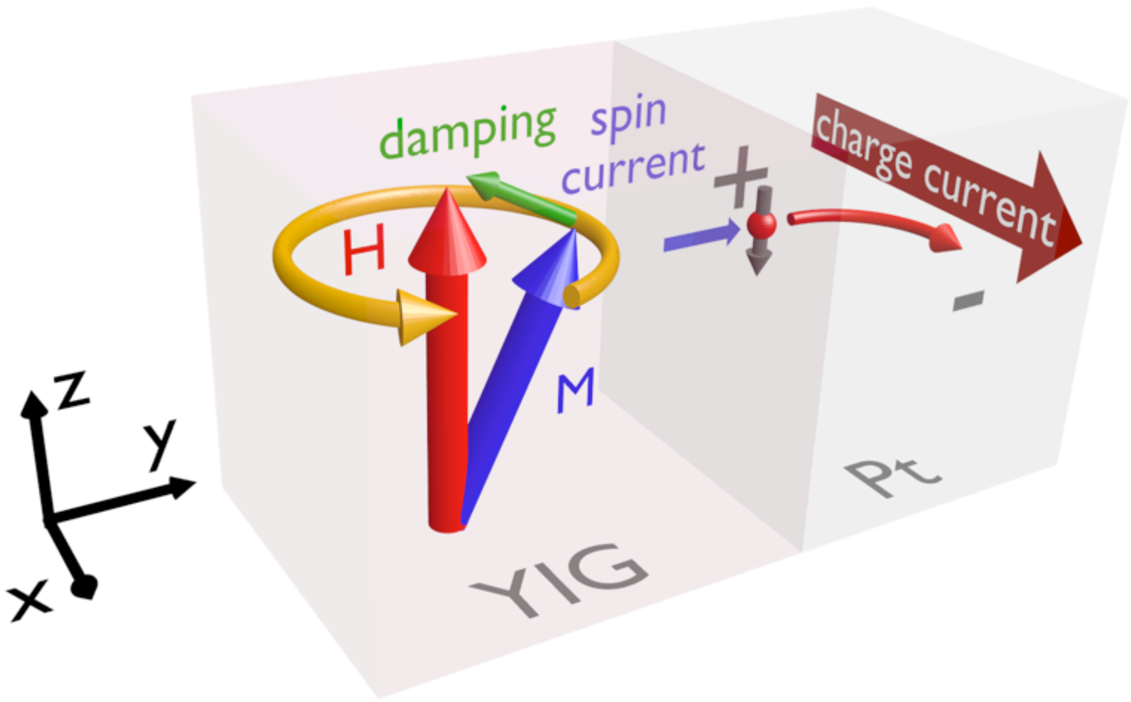
Magnonics: Main trends

II. Novel means for magnon detection

Spin pumping + inverse spin Hall effect

Magnon to charge current conversion

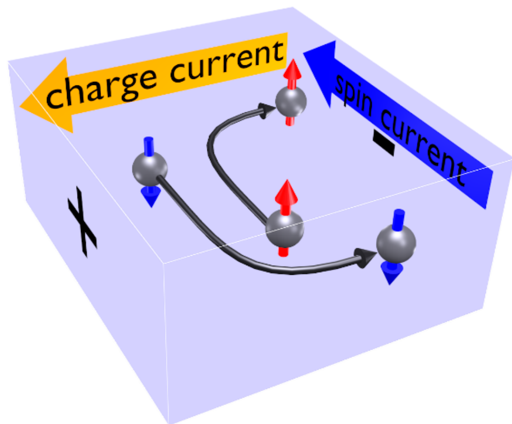
Detection of magnons by a combination of spin pumping and inverse spin Hall effect



Spin pumping

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

Inverse spin Hall effect (ISHE)



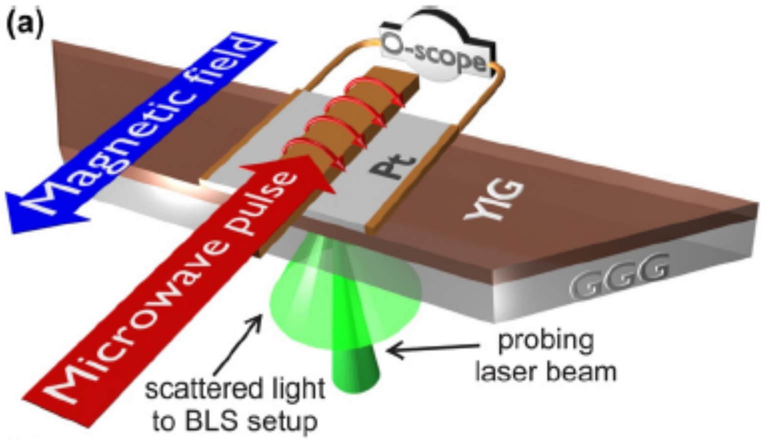
Hirsch, PRL (1999)
Saitoh et al., APL **88** 182509 (2006)

Time resolved ISHE voltage

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

Magnetic field *B* = 0

Microwave frequency 7 GHz

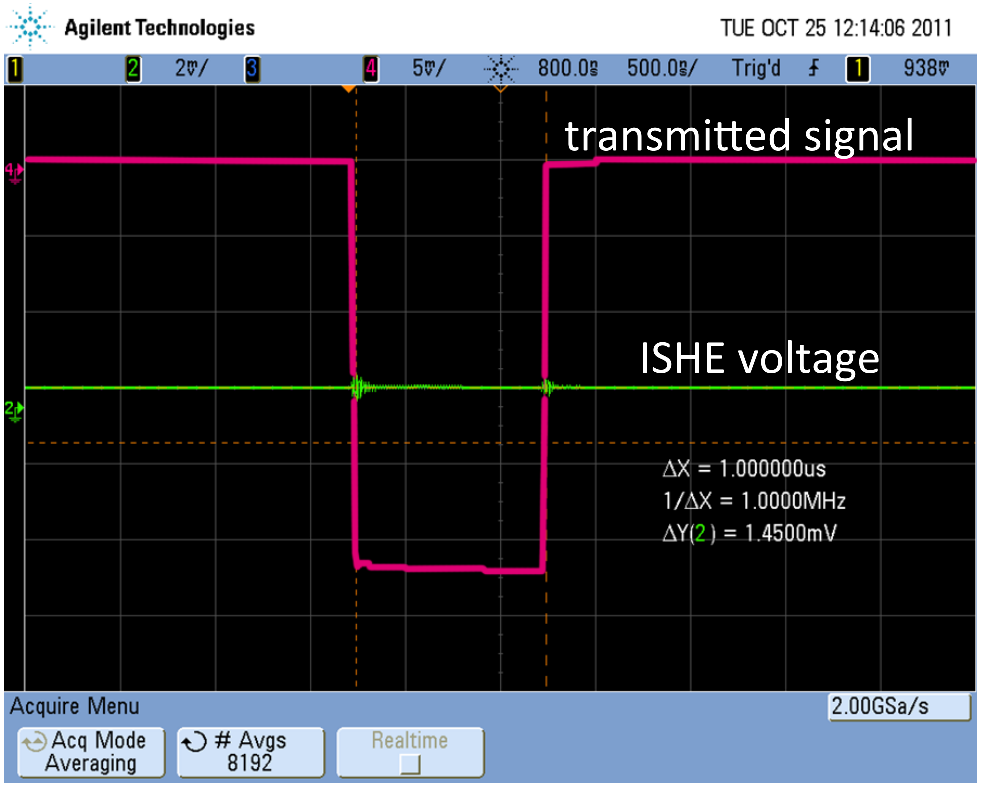


Parameters:

YIG thickness: 2.1 μm

YIG/Pt width: 3 mm

Pt thickness: 10 nm



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

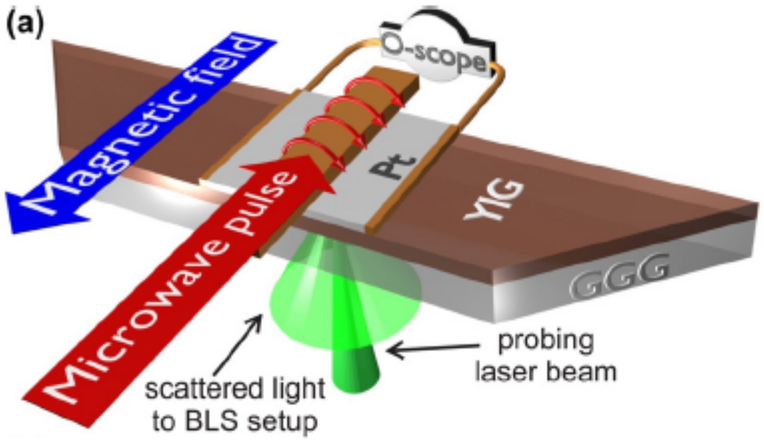
TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

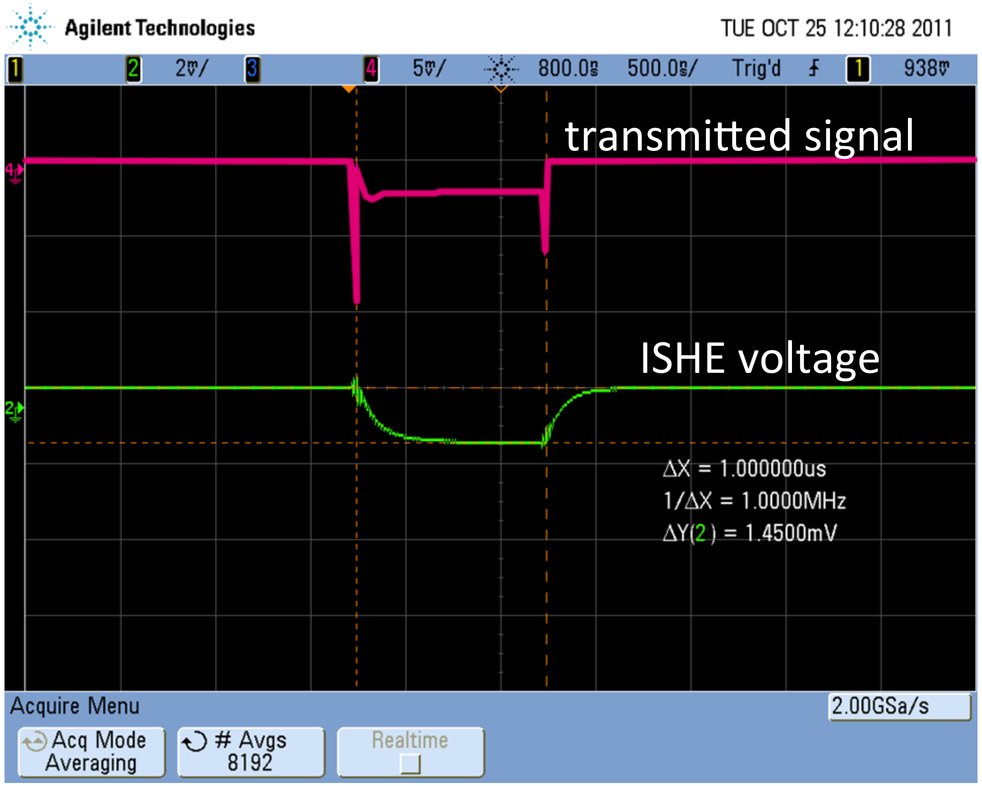
Time resolved ISHE voltage

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

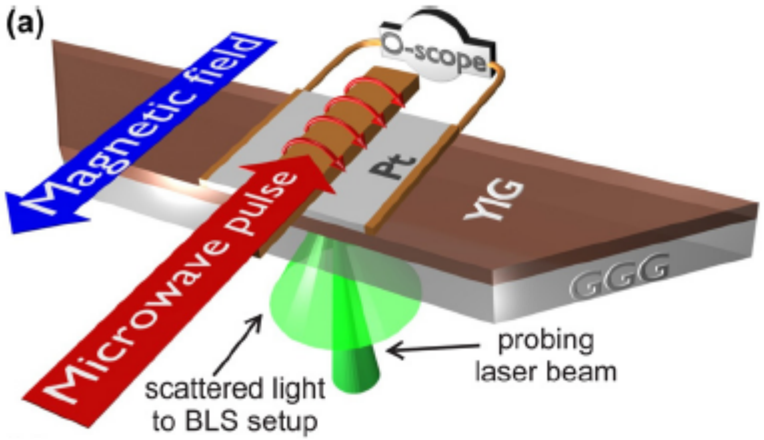
Jungfleisch et al., APL **99**, 182512 (2011)

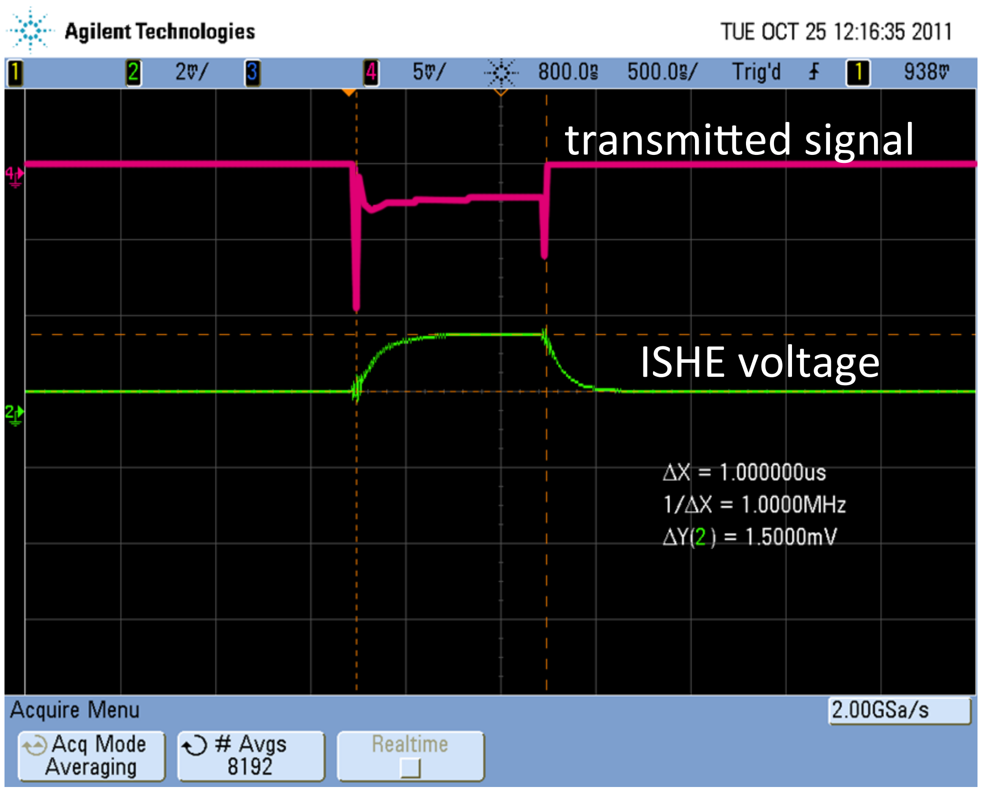
Time resolved ISHE voltage

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

Magnetic field *B* = + 175.5 mT

Microwave frequency 7 GHz





Parameters:

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YIG/Pt width: 3 mm

Pt thickness: 10 nm

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

Time resolved ISHE voltage

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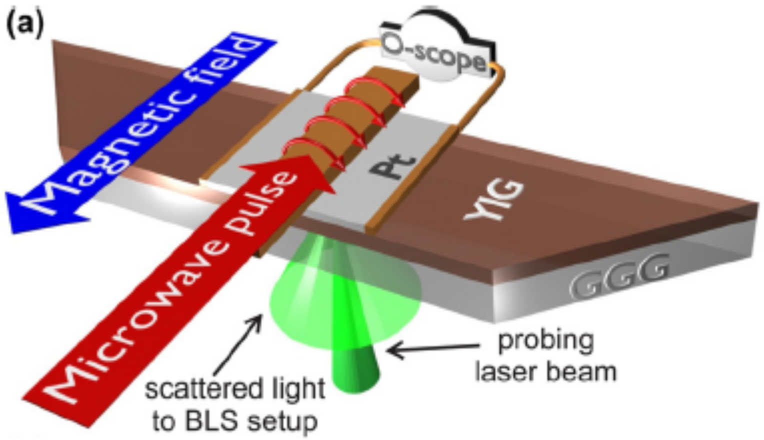
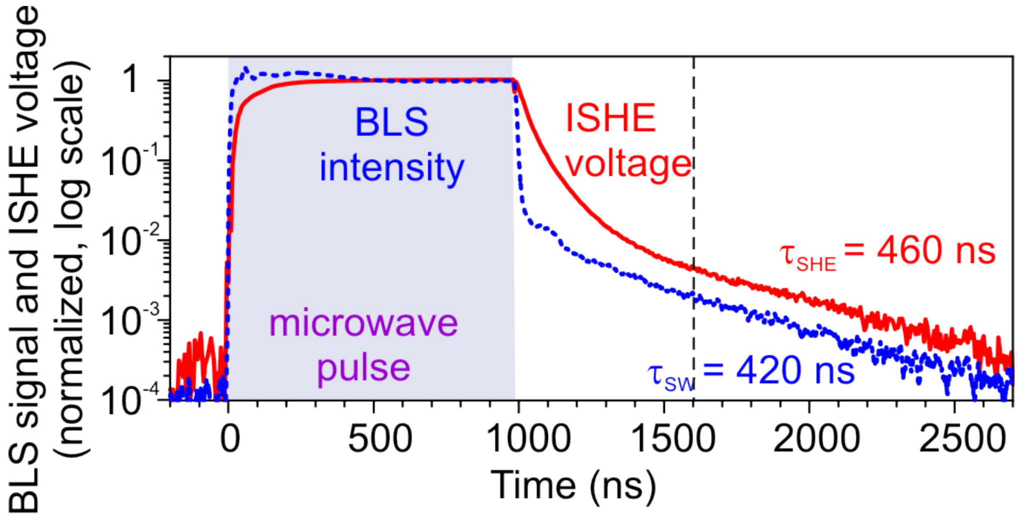




Parameters:

YIG thickness: 2.1 μm

YIG/Pt width: 3 mm

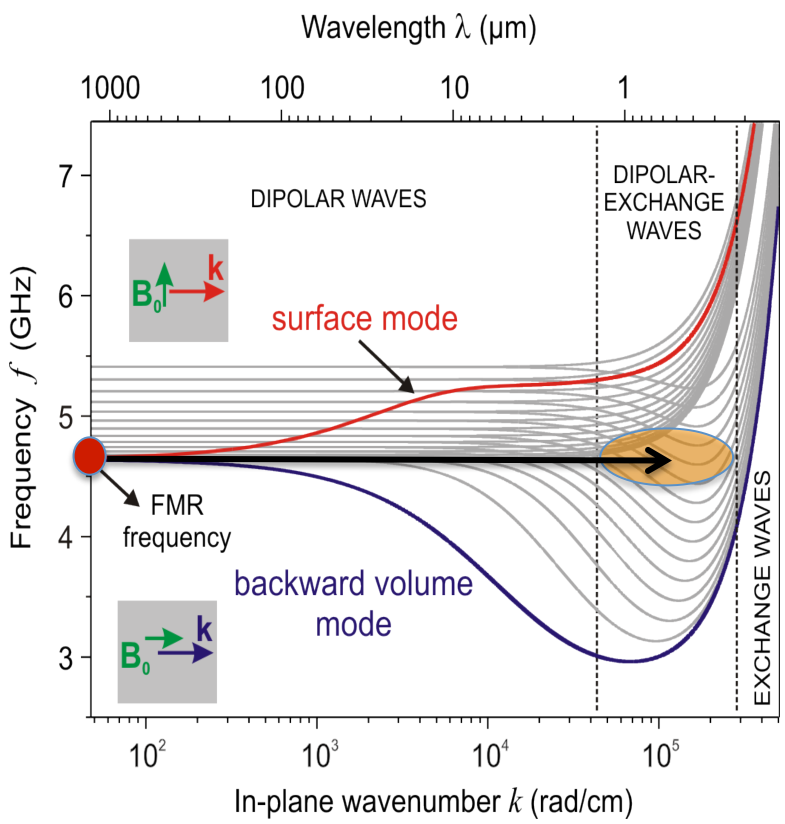
Pt thickness: 10 nm

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

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

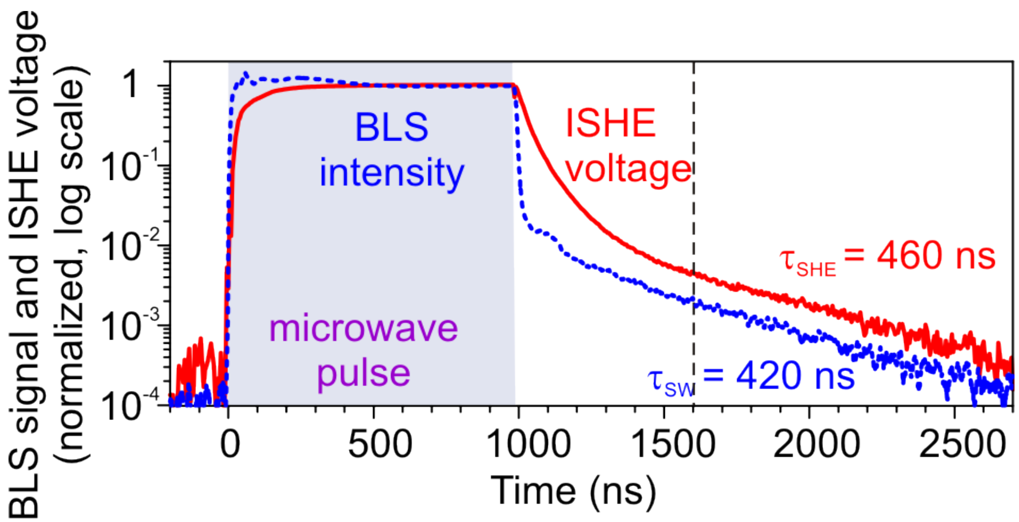
Surface modes contribute to spin pumping

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



Magnetic field B = + 175.5 mT

Dipolar-exchange waves contribute to spin pumping!

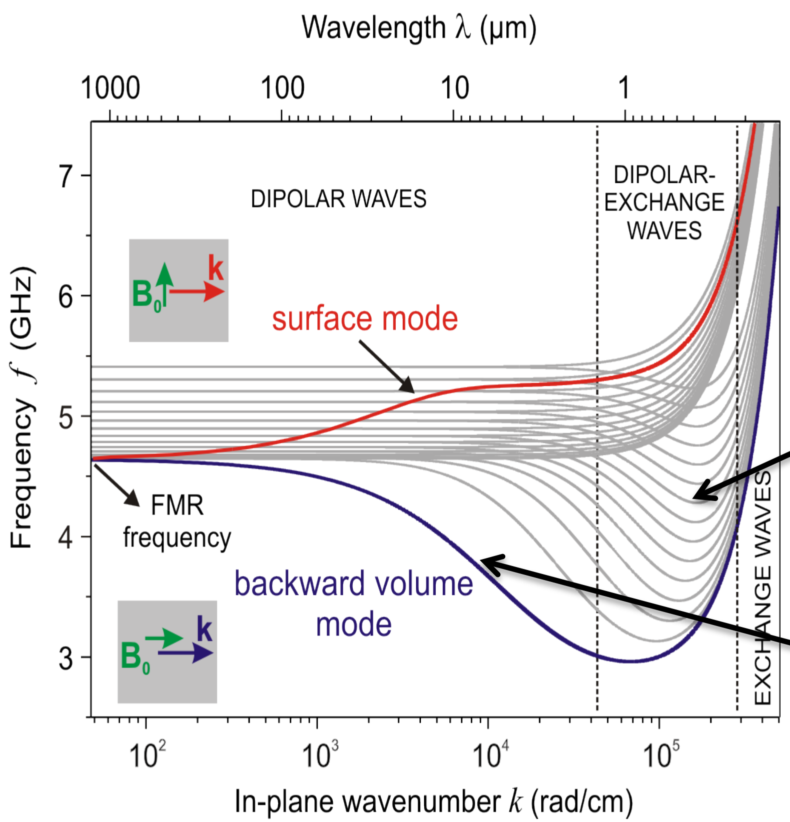


- ISHE pulse has a long rise and fall times
- Secondary magnons contribute to ISHE

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

Surface modes contribute to spin pumping

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

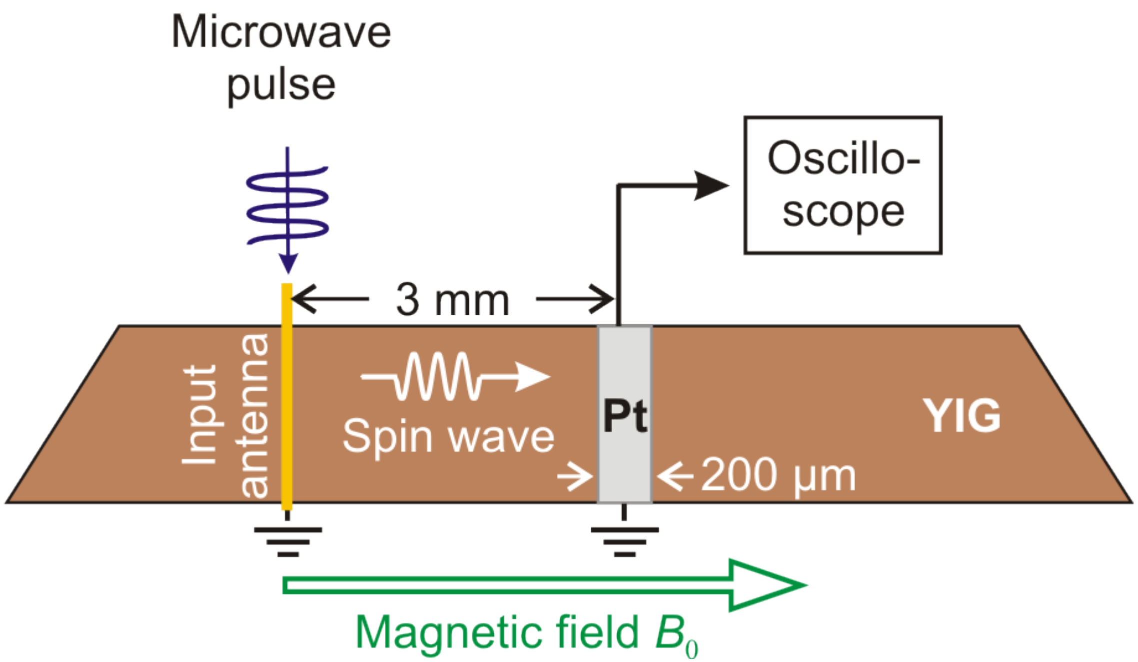


But dipolar-exchange waves have zero velocities → no spin transport

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

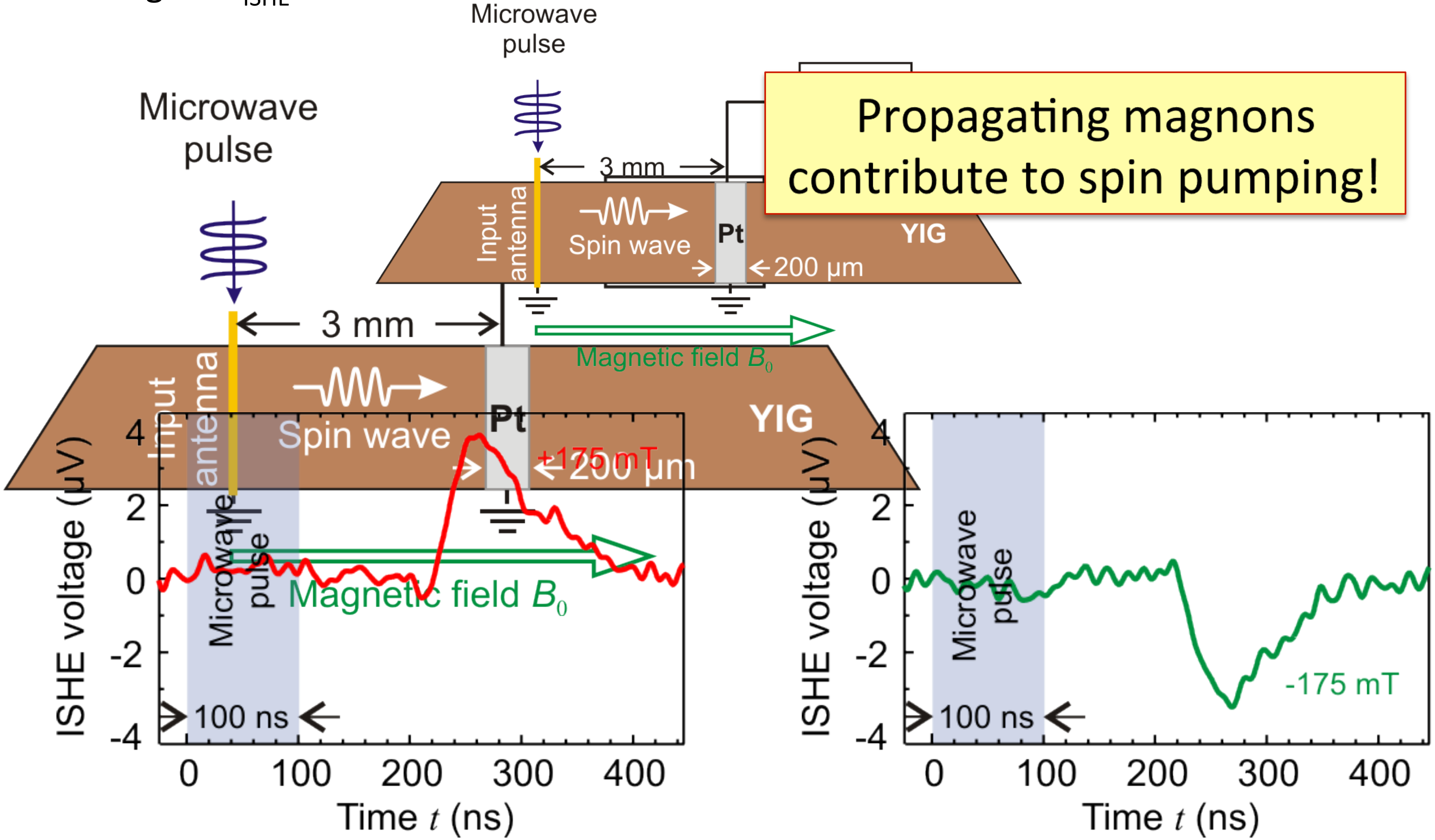
Pt thickness: 10 nm

Signal frequency: 7 GHz

Experimental results

Waveforms of the electromotive force signal V_{ISHE}

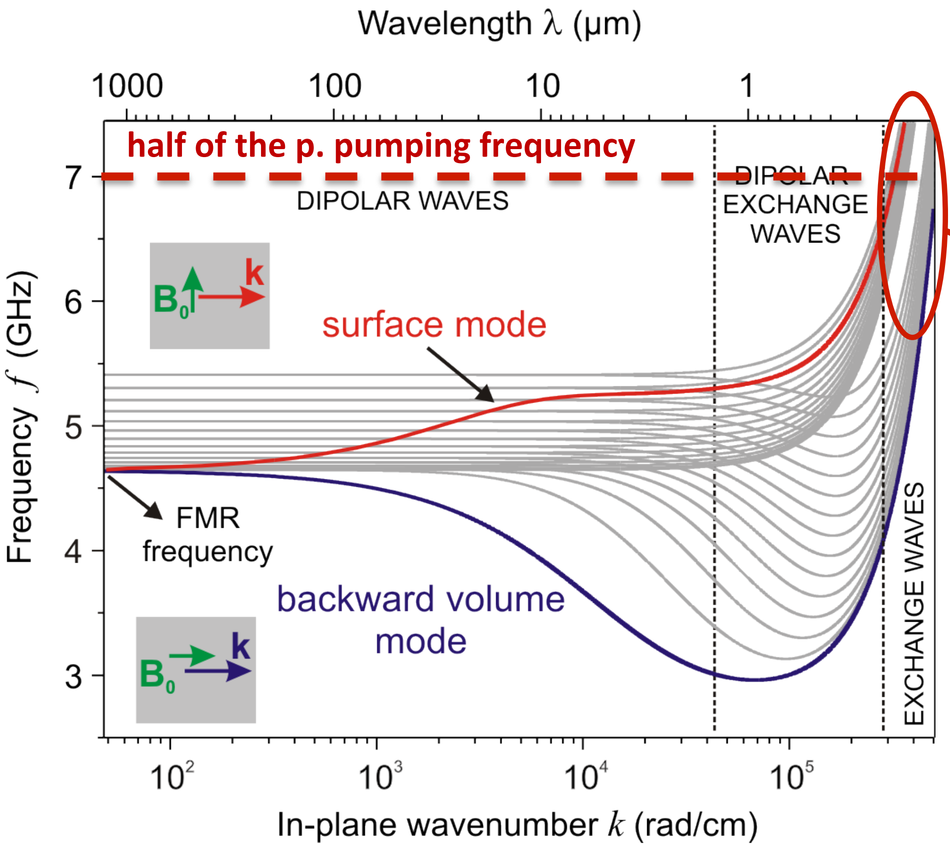
Chumak et al., APL **100**, 082405 (2012)



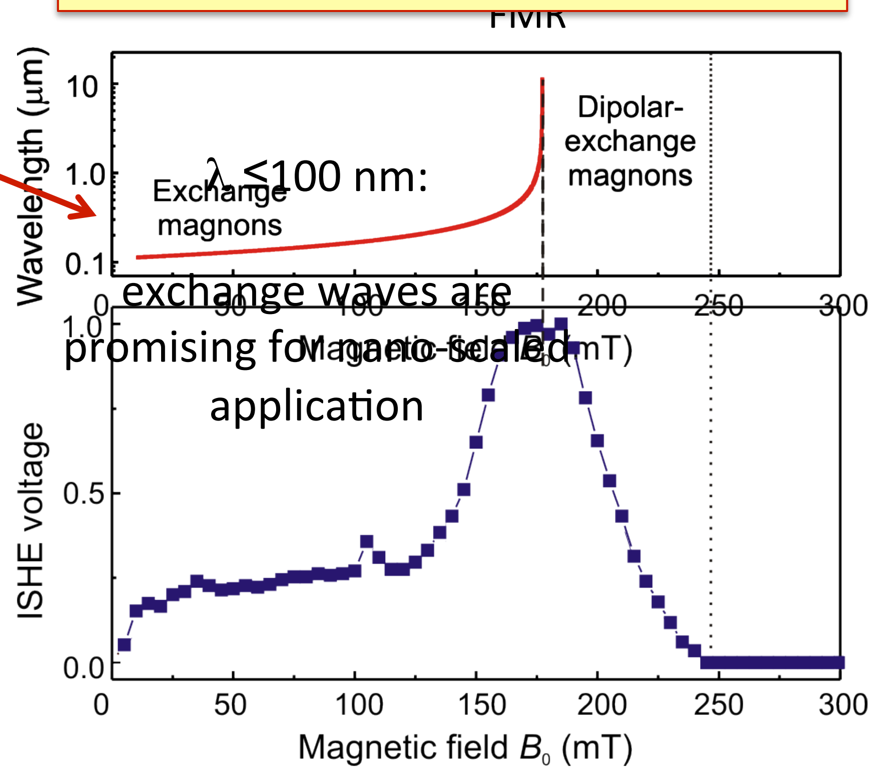
Propagating magnons contribute to spin pumping!

Spin pumping by exchange magnons

Parametric pumping at 14 GHz



Exchange magnons contribute to spin pumping!



λ ≤100 nm: exchange waves are promising for nano-scaled application

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

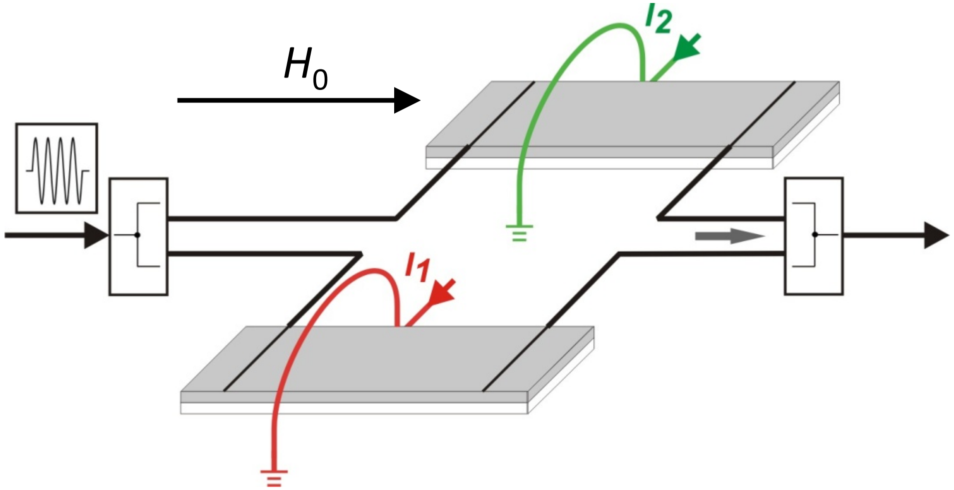
Kurebayashi, Dzyapko et al., APL **99**, 162502 (2011)
Ando et al., APL **99,** 092510 (2011)

Magnonics: Main trends

III. Data processing using magnons

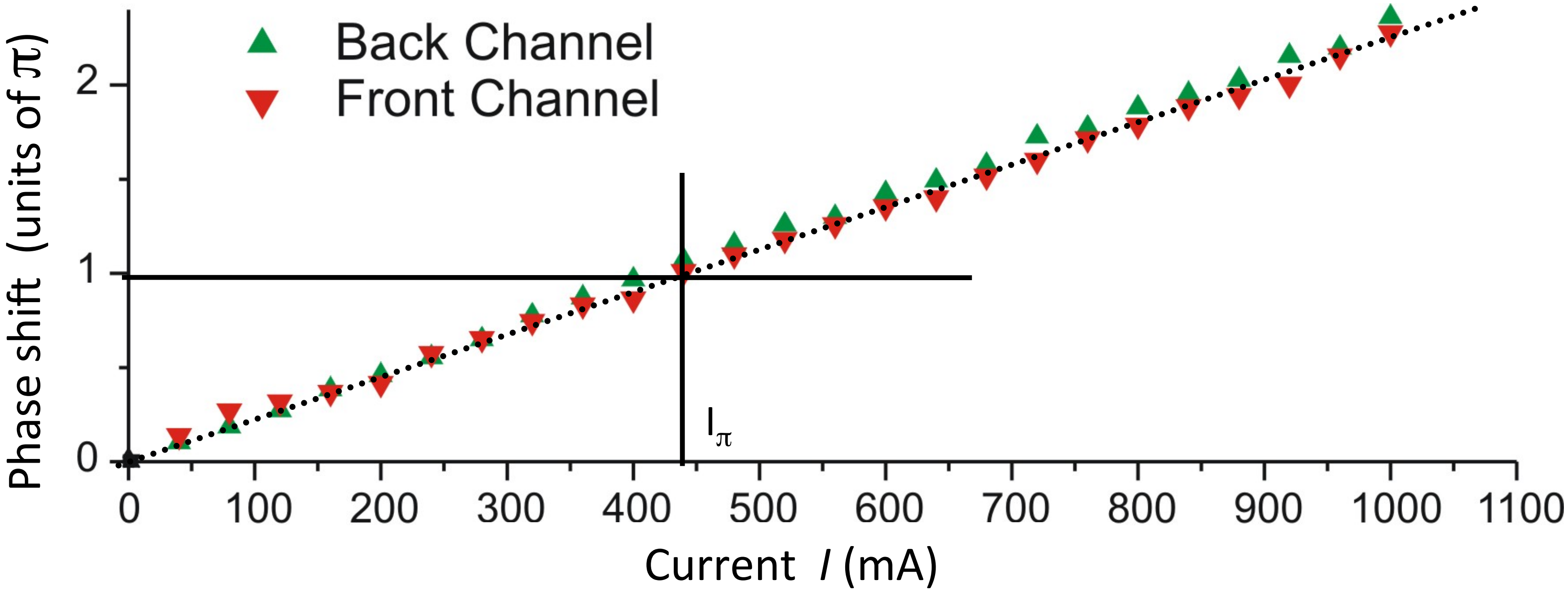
- Spin-wave logic gates

Mach-Zehnder interferometer based spin-wave logic gate

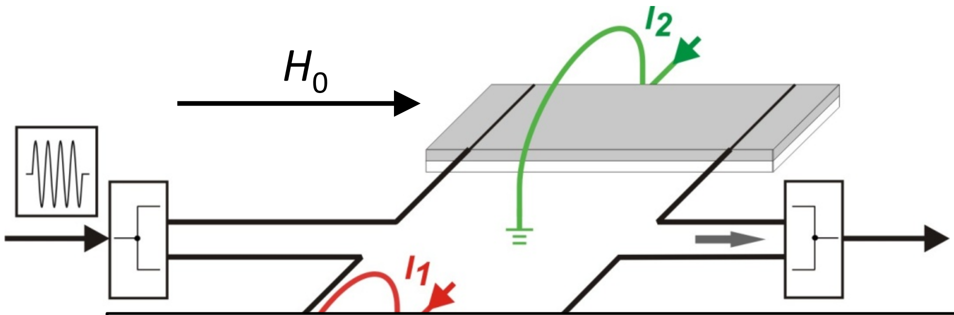


Kostylev et al., **APL 87**, 153501 (2005)

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



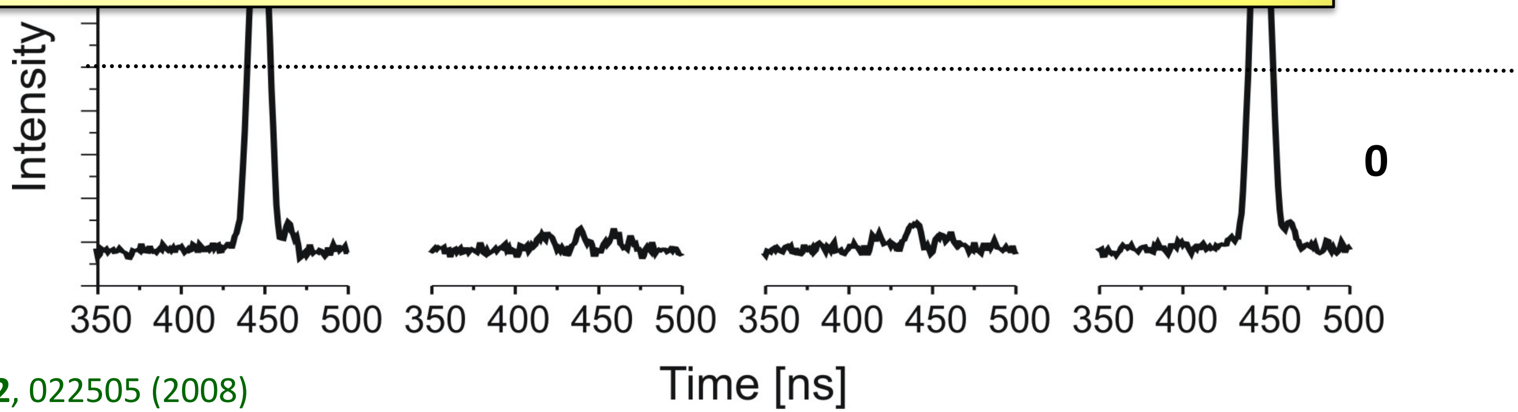
Mach-Zehnder interferometer based spin-wave logic gate



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

Input: DC pulses
Output: magnon packets

How to control one magnon by another?



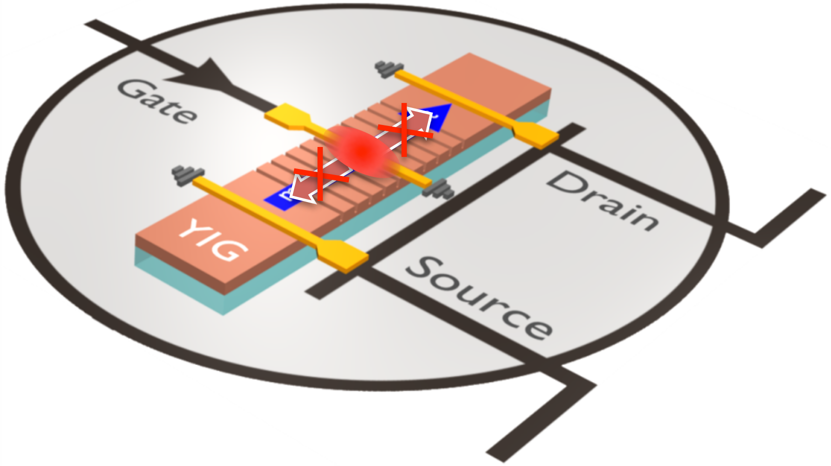
Schneider et al., **APL 92**, 022505 (2008)

Magnonics: Main trends

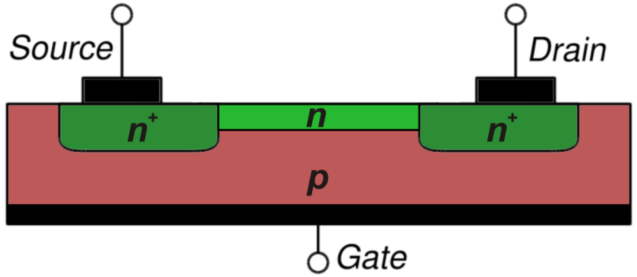
III. Data processing using magnons

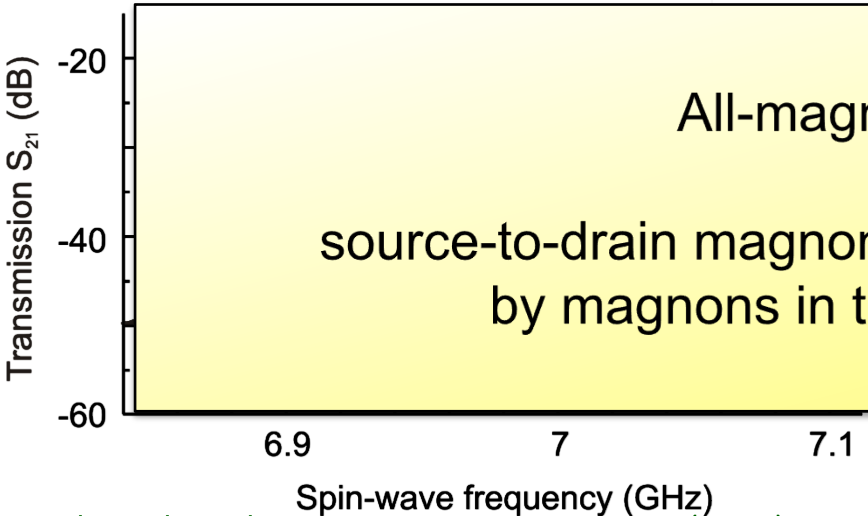
- Spin-wave logic gates
- Magnon transistor

Magnon transistor



Semiconductor field-effect transistor:





All-magnon dev

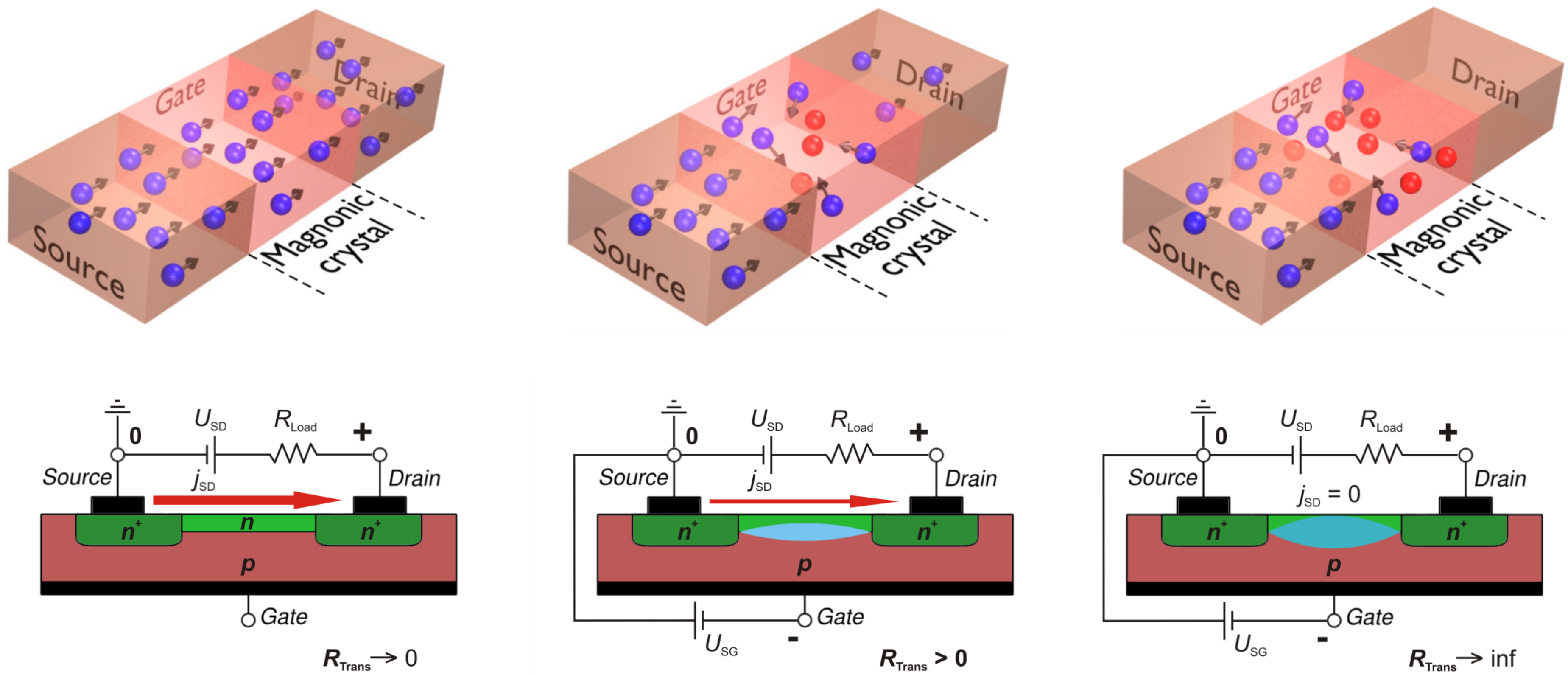
source-to-drain magnon flow sl
by magnons in the trans

Magnonic crystal acts
as an enhancer of
non-linear effects

A.V. Chumak et al., Nature Commun., in press (2014)

Magnon transistor

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



A.V. Chumak et al., Nature Commun., in press (2014)

Magnon transistor

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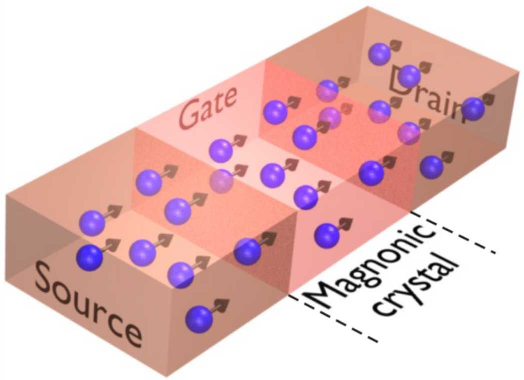
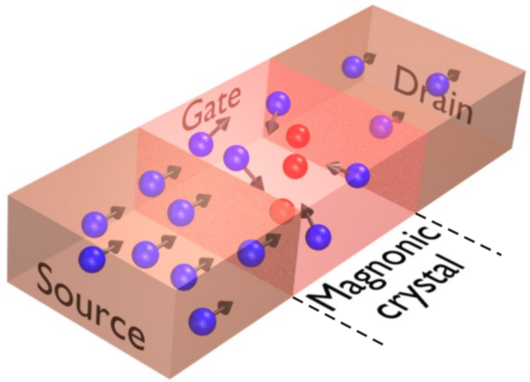
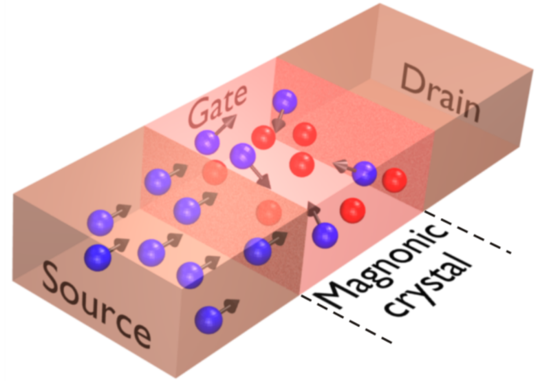
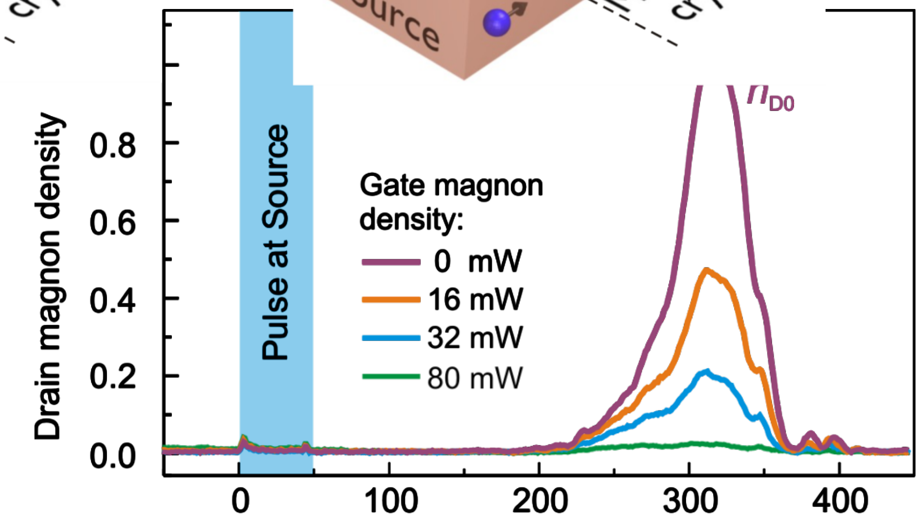
$n_G = 0$	$n_G > 0$	$n_G >> 0$





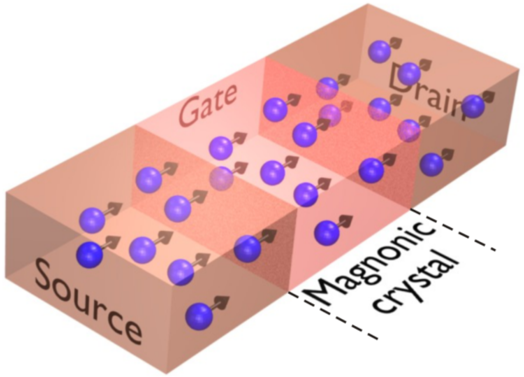


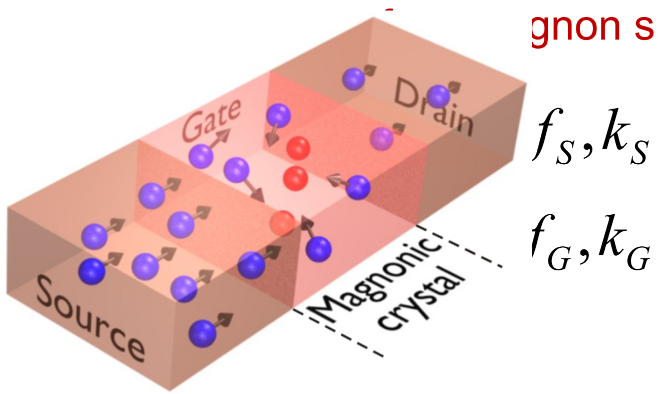


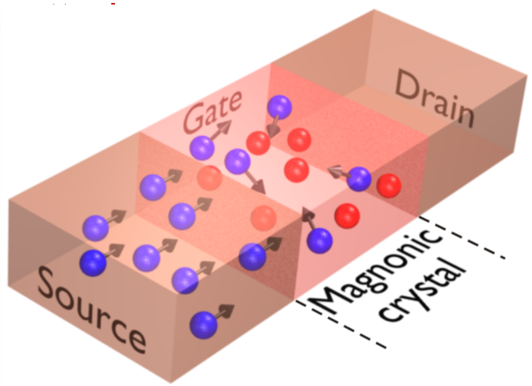
A.V. Chumak et al., Nature Commun., in press (2014)

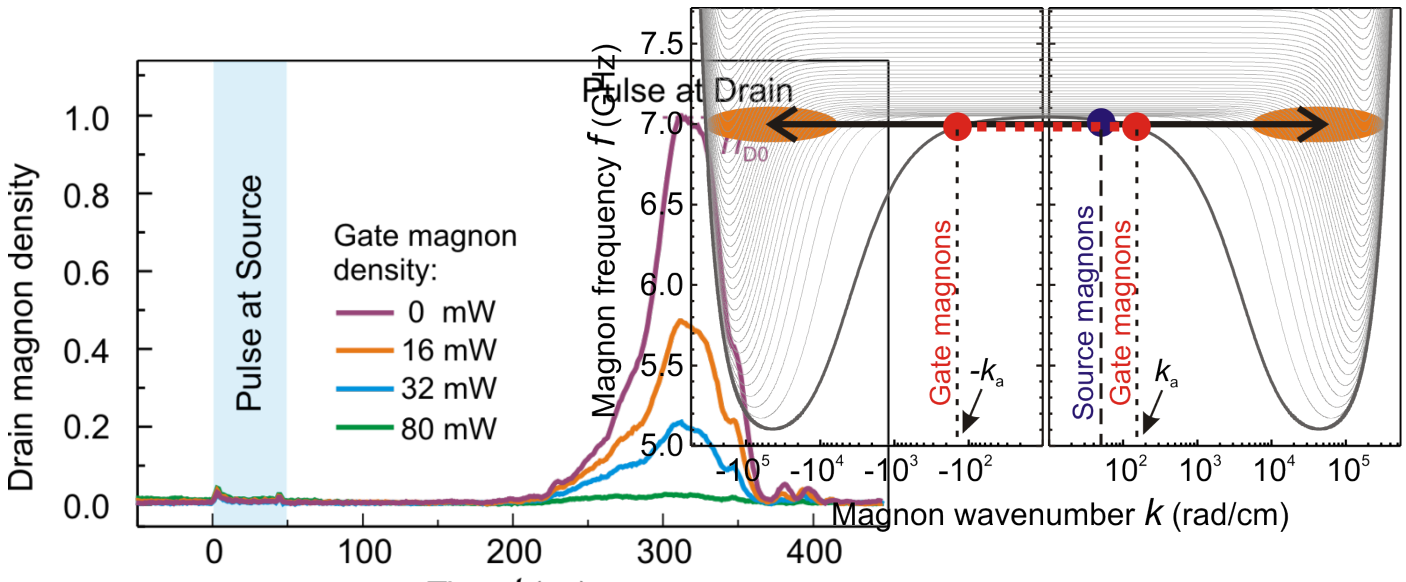
Magnon transistor

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



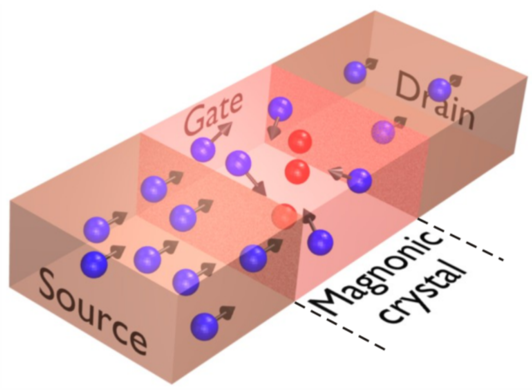


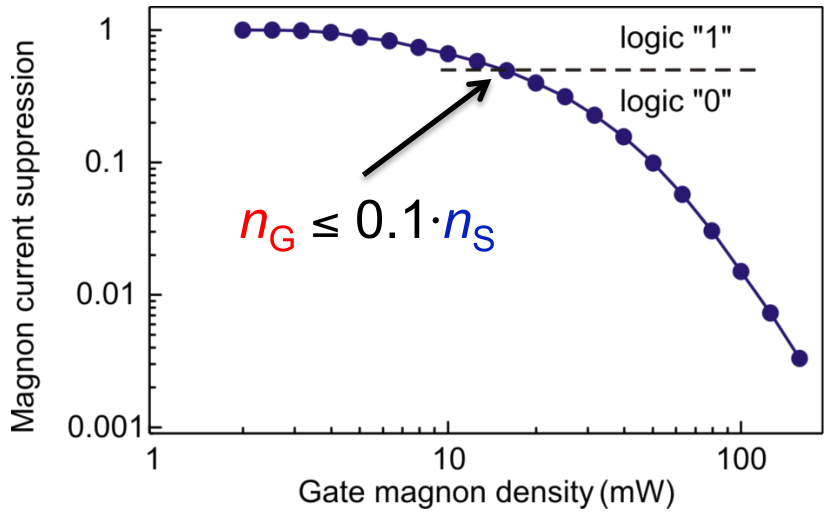


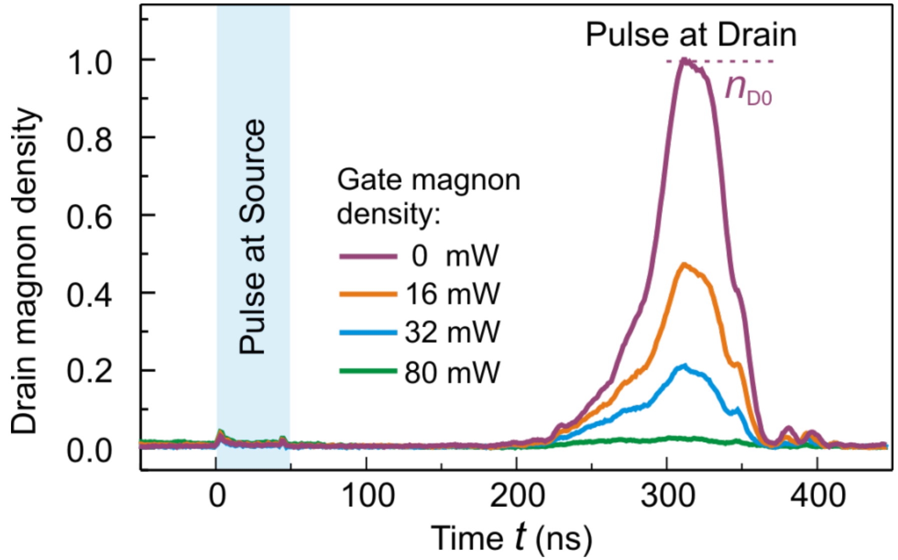


A.V. Chumak et al., Nature Commun., in press (2014)

Magnon transistor







“magnon control by magnon“ principle was realized:

data can be processed on the same magnetic chip

A.V. Chumak et al., Nature Commun., in press (2014)

Magnonics: Main trends

III. Data processing using magnons

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

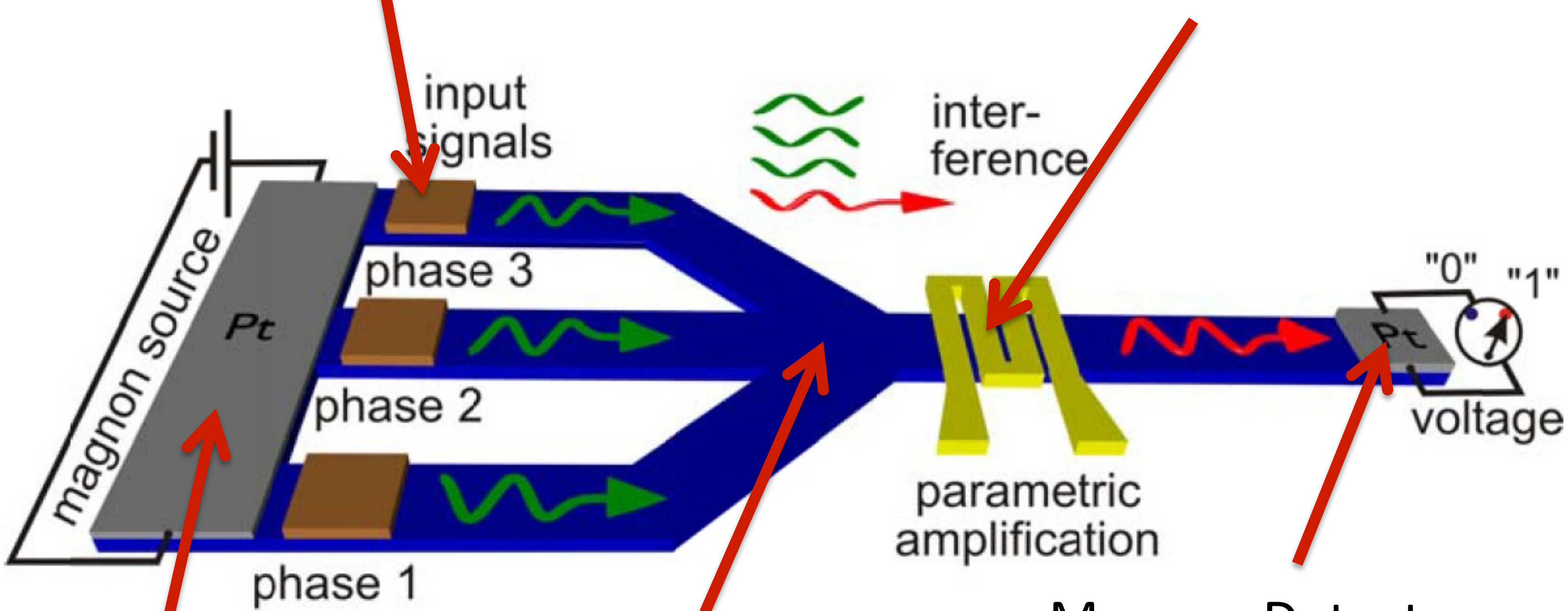
Majority gate

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)



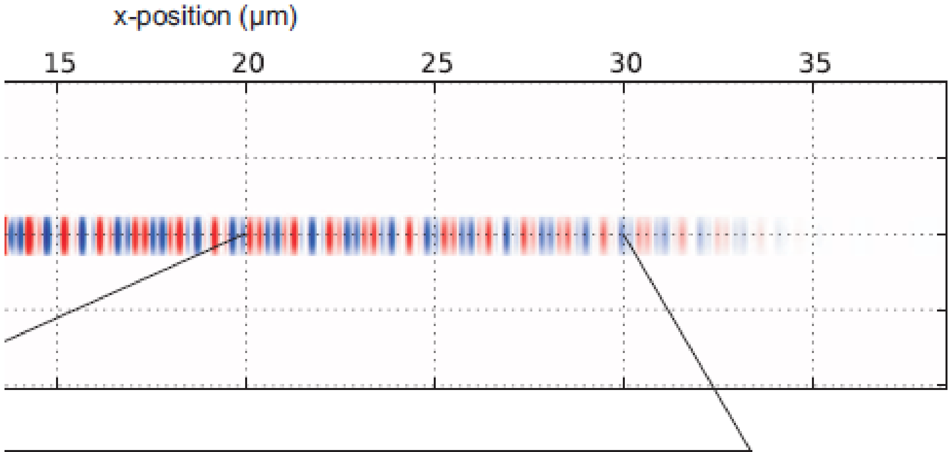
Magnon Source

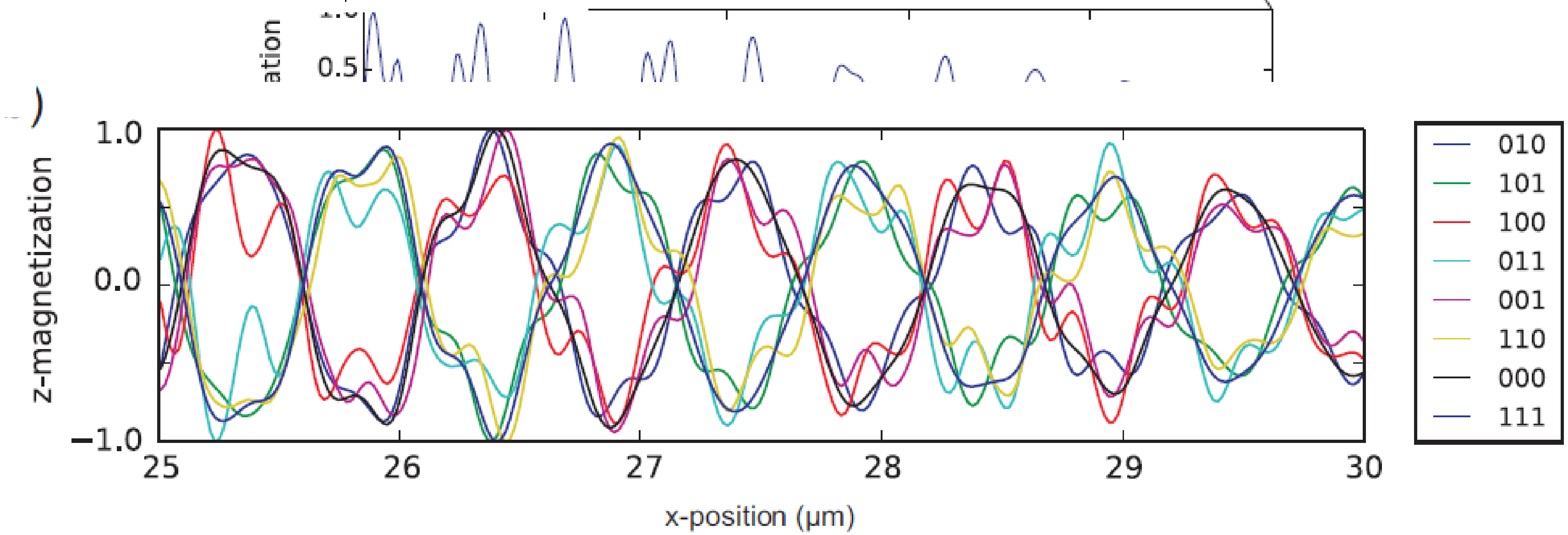
Magnon Processor

Magnon Detector

Majority gates: Simulations

Input 1	Input 2	Input 3	Output	
Signal	Signal	Control		
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	



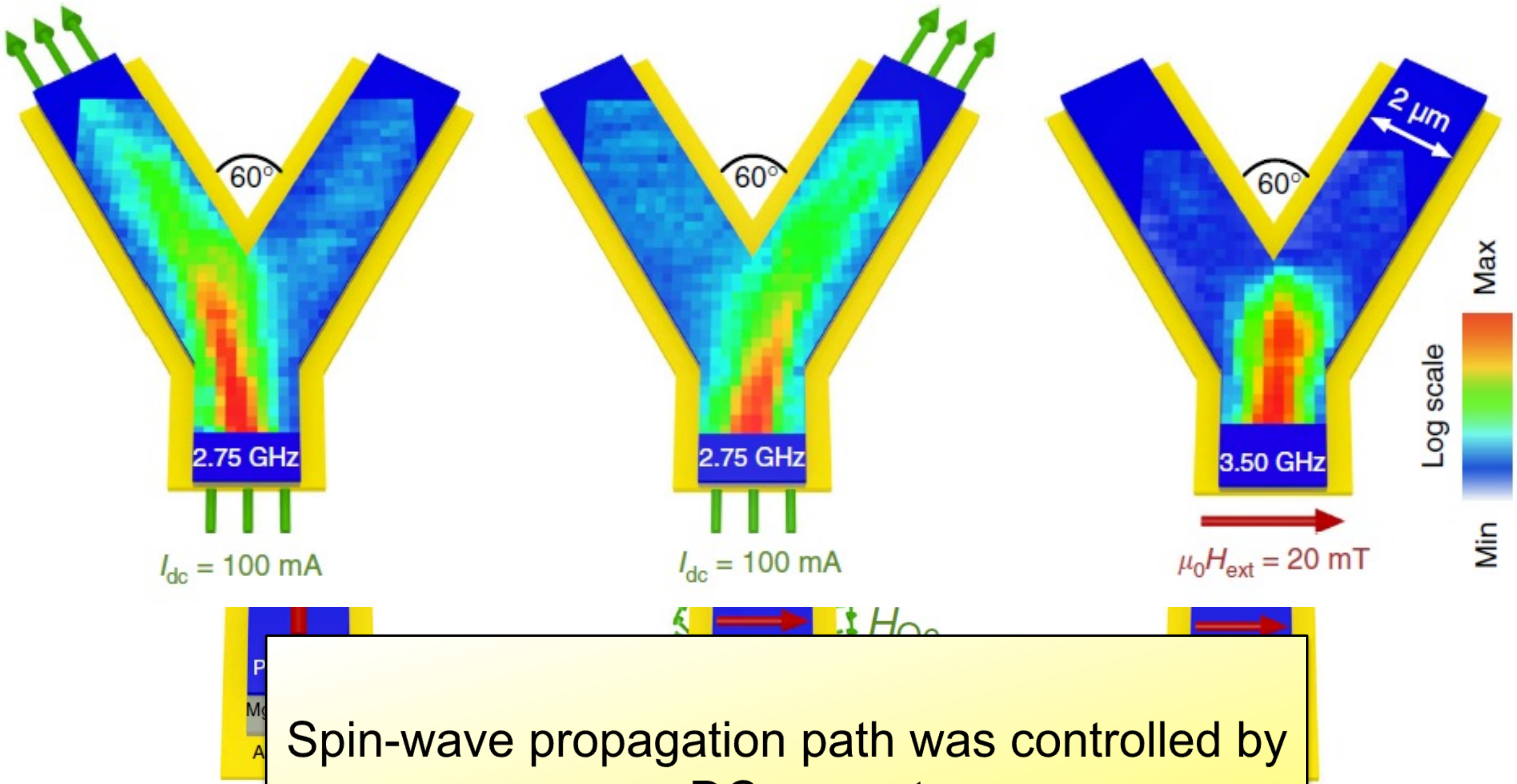


Magnonics: Main trends

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

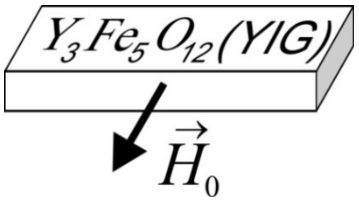
Main idea: find coherent, propagating modes for information transfer, which are free of dissipation (apart from magnon-phonon and magnon-electron coupling)

- No two-magnon, three-magnon, four-magnon scattering etc.

- Bose-Einstein Condensation (BEC) of magnons
- Phonon-coupled BEC of magnons

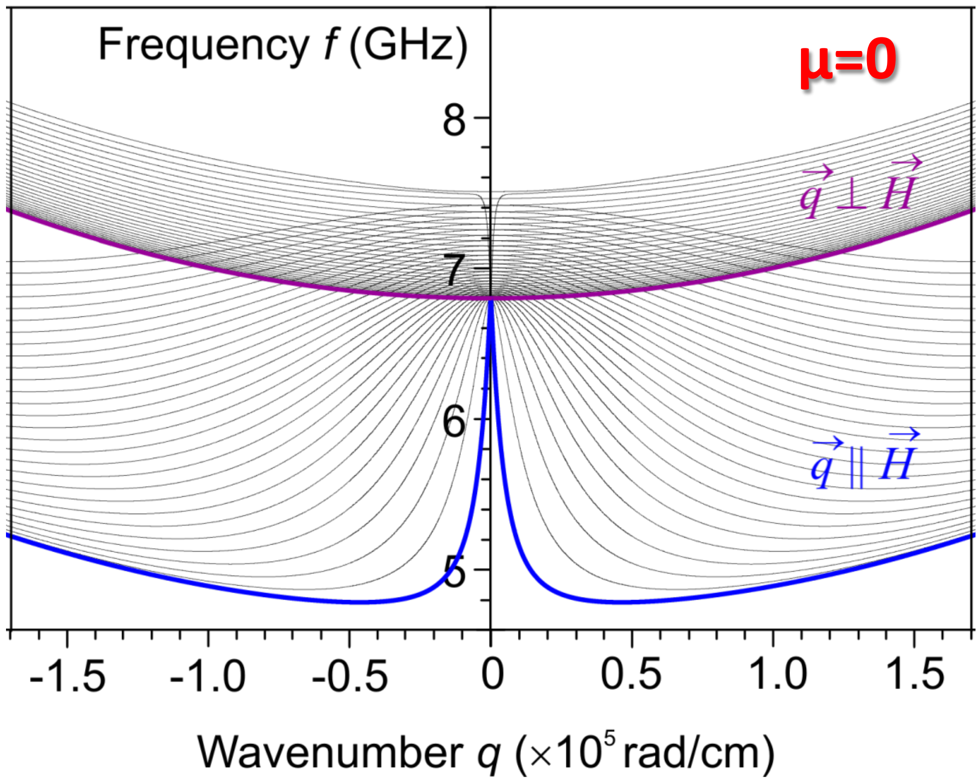
Magnon distribution

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



Bose-Einstein distribution

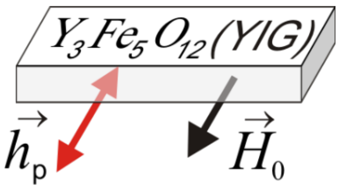
$$\rho(f) = \frac{D(f)}{\exp\left(\frac{hf - \mu}{k_B T}\right) - 1}$$



Control of magnon gas density by parametric pumping

Energy and momentum conservation laws

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



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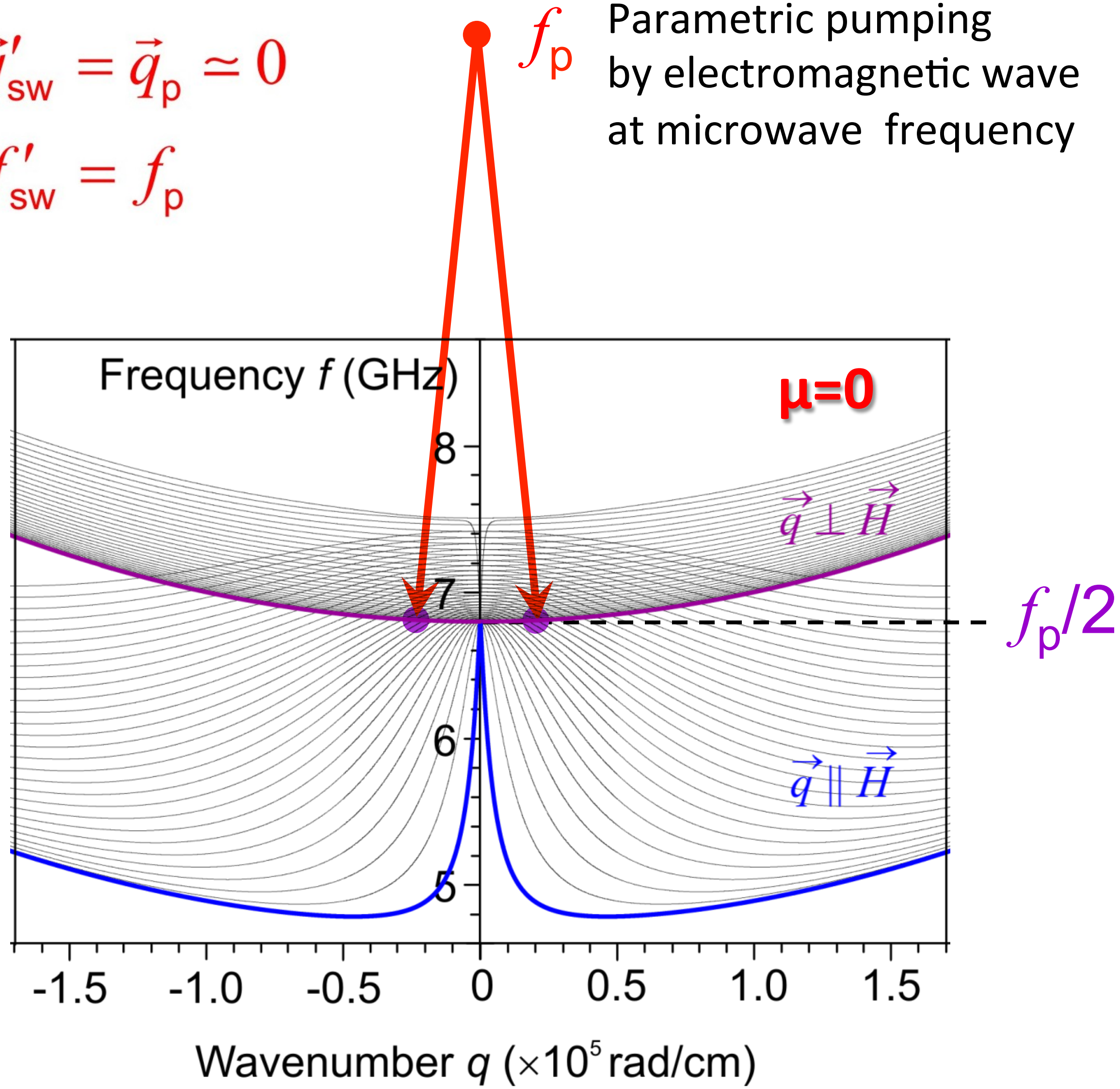
f_p Parametric pumping by electromagnetic wave at microwave frequency



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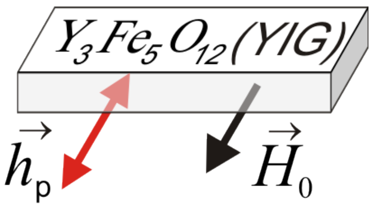

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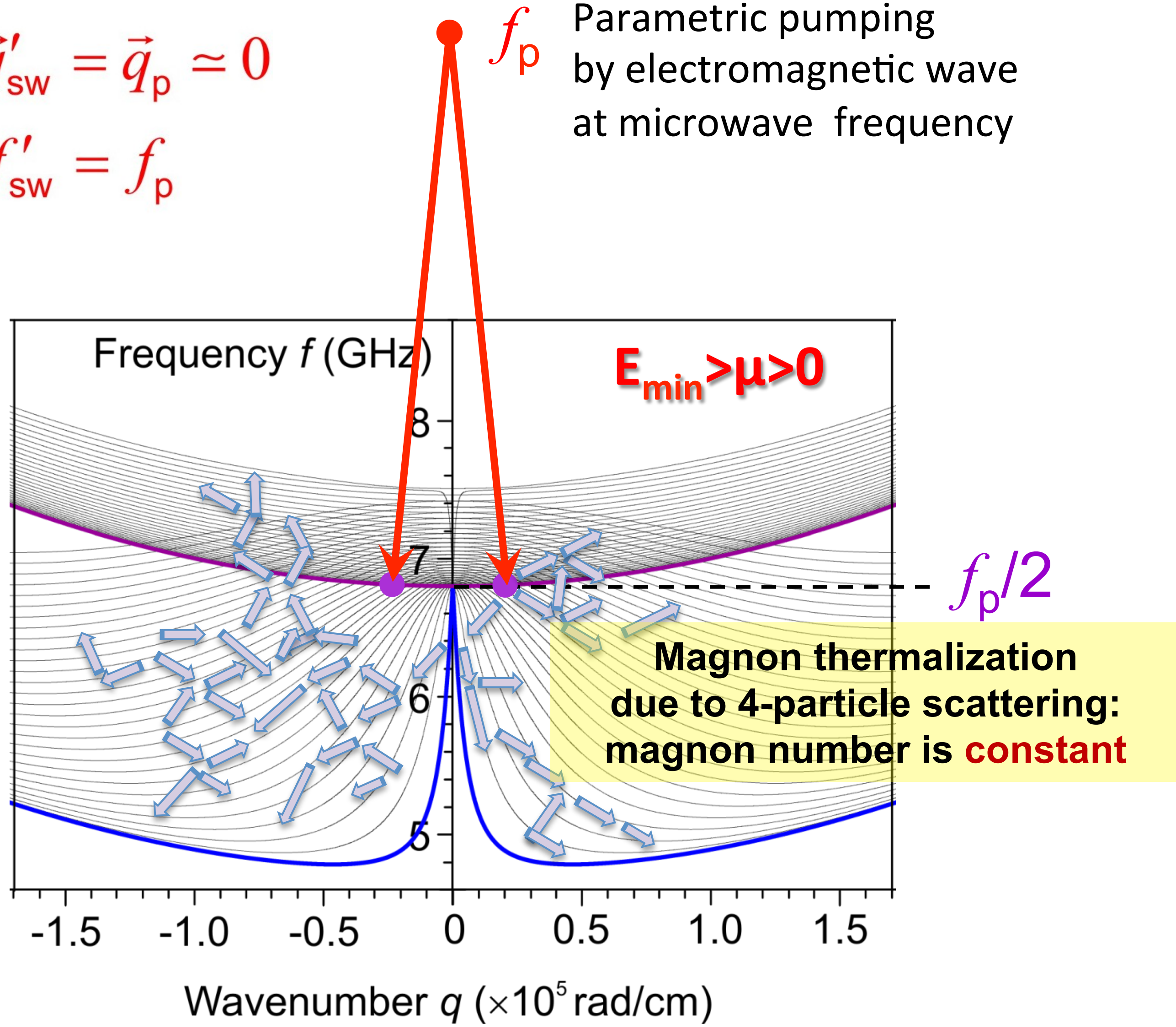

Bose-Einstein condensate of magnons

Technische Universität Kaiserslautern

Energy and momentum conservation laws

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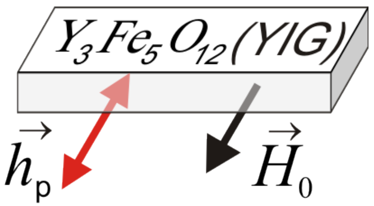

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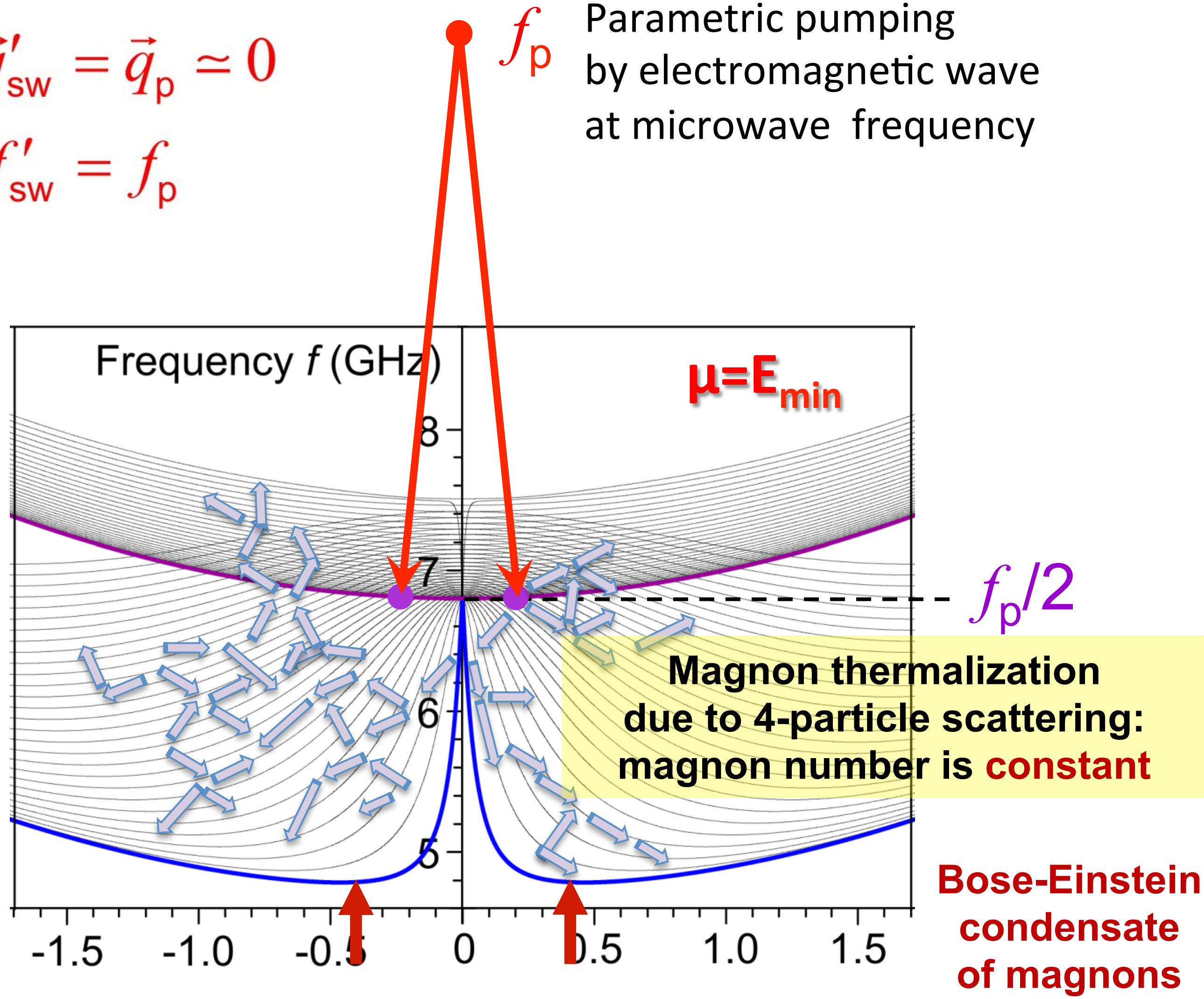
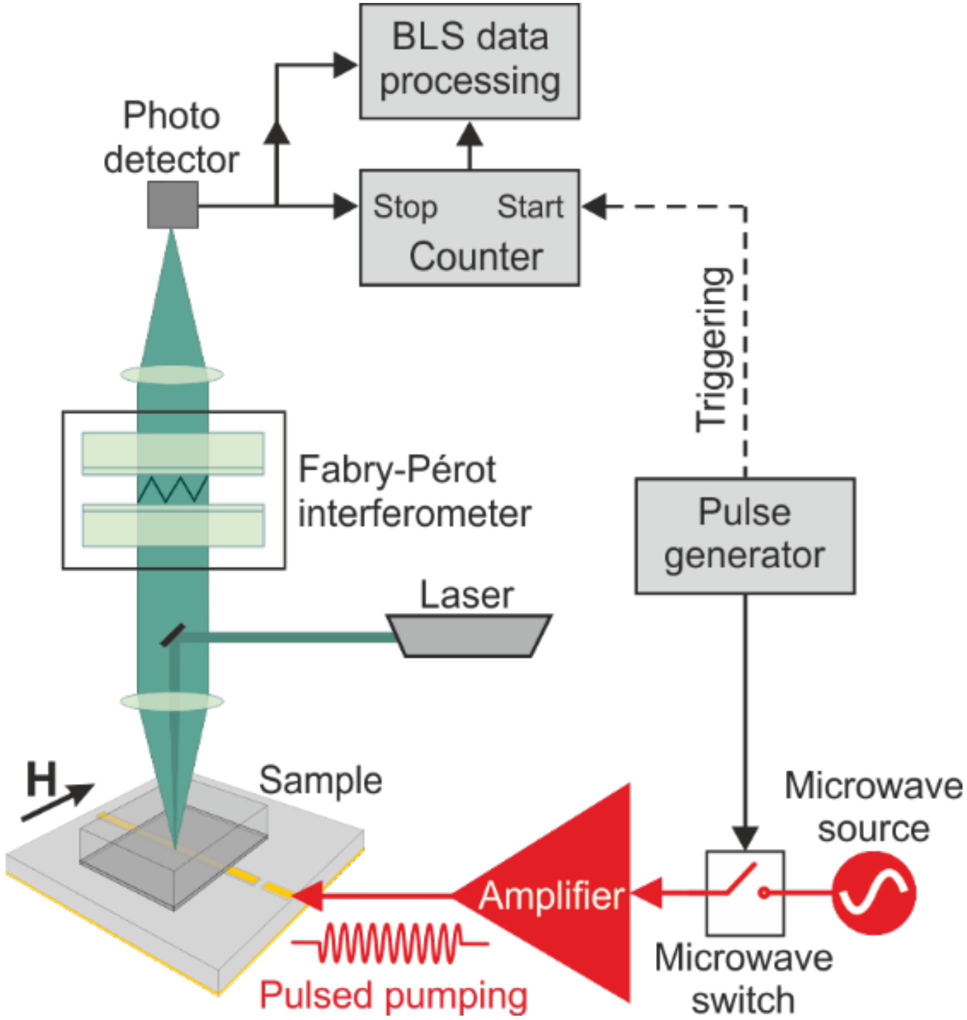
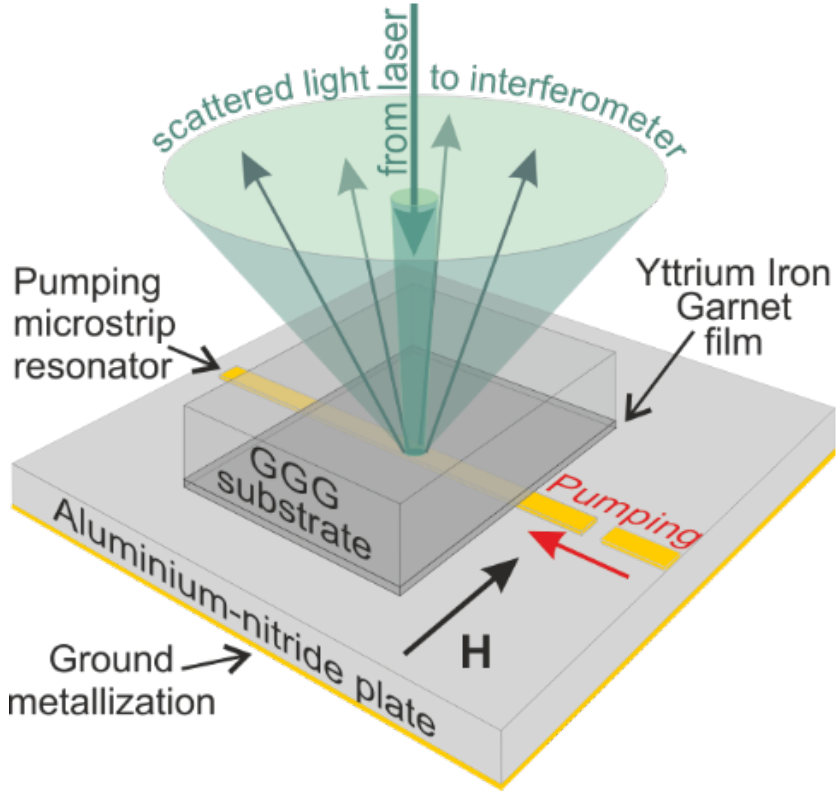


Bose-Einstein condensate of magnons

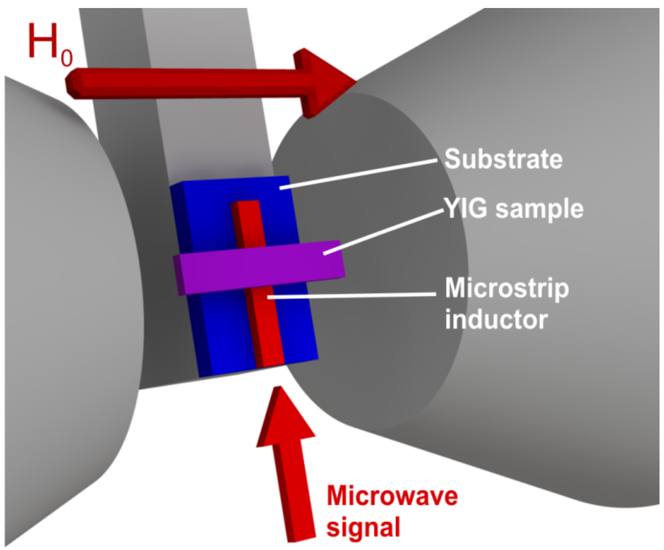
Demokritov et al., Nature **443**, 430 (2006)

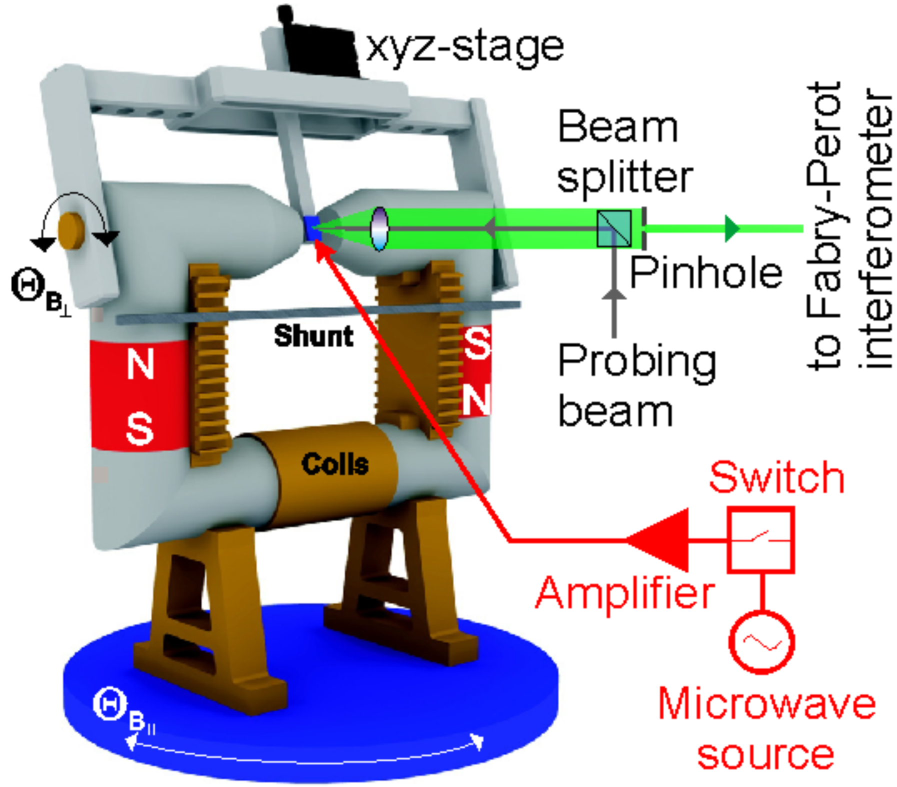
Time-resolved Brillouin light scattering spectroscopy



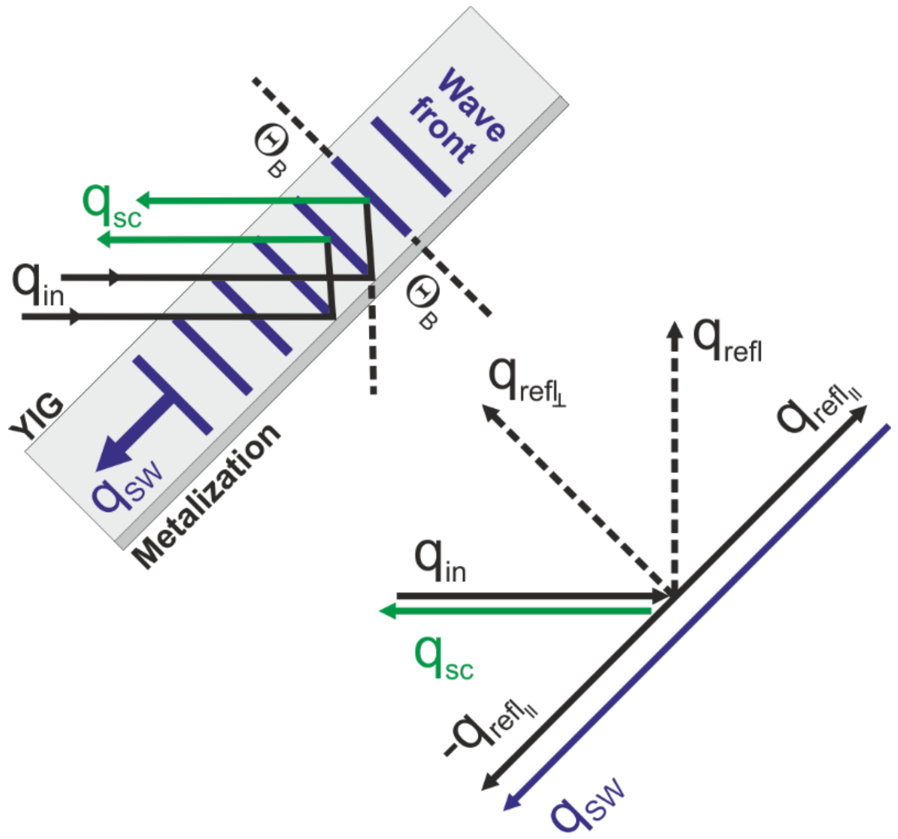


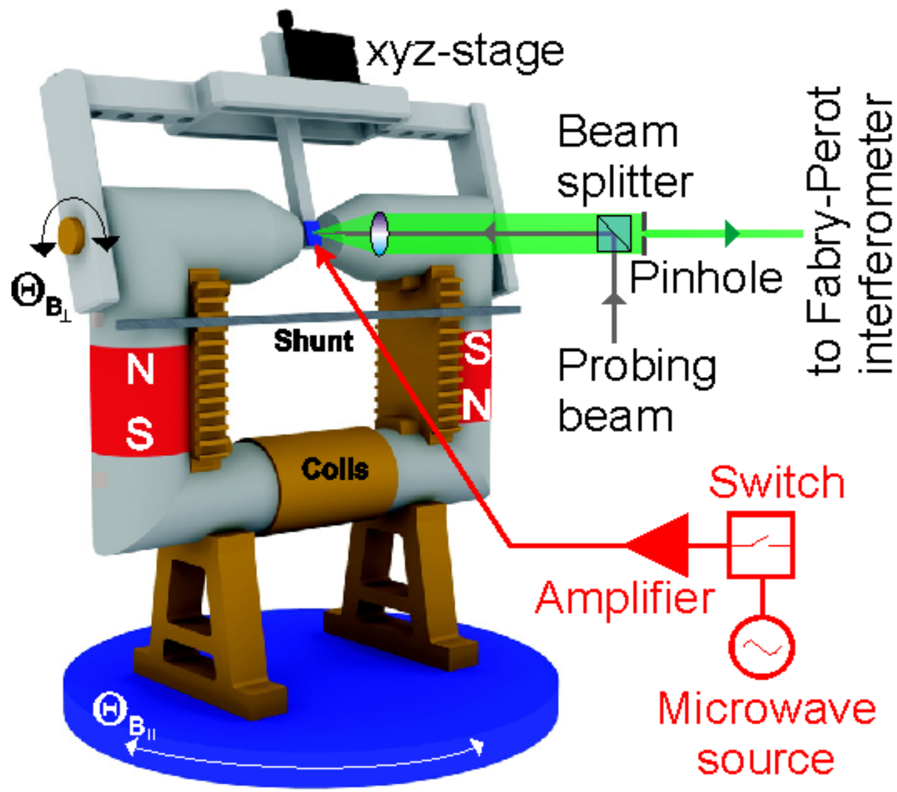
Wave-vector resolved BLS setup





Wave-vector resolved BLS setup

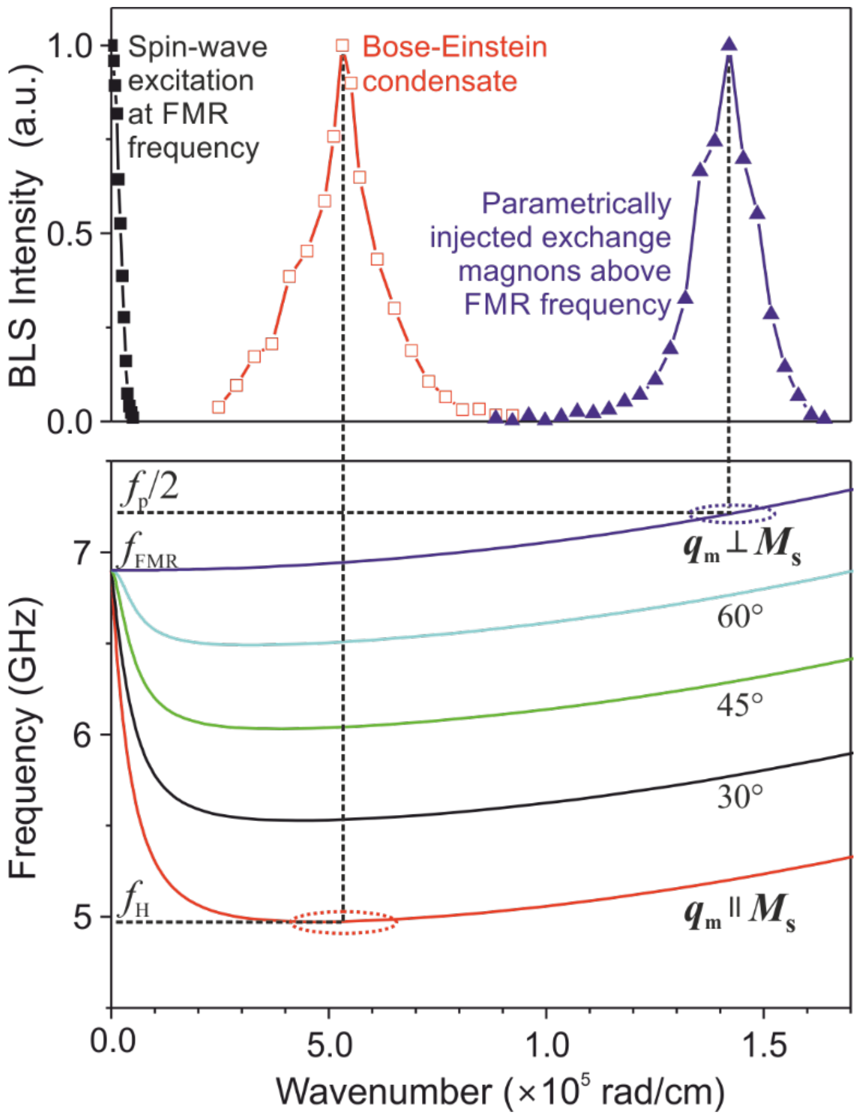




Detection of wave numbers	≤ 2.36×10^5 rad/cm
Wavenumber resolution	4.1×10^3 rad/cm

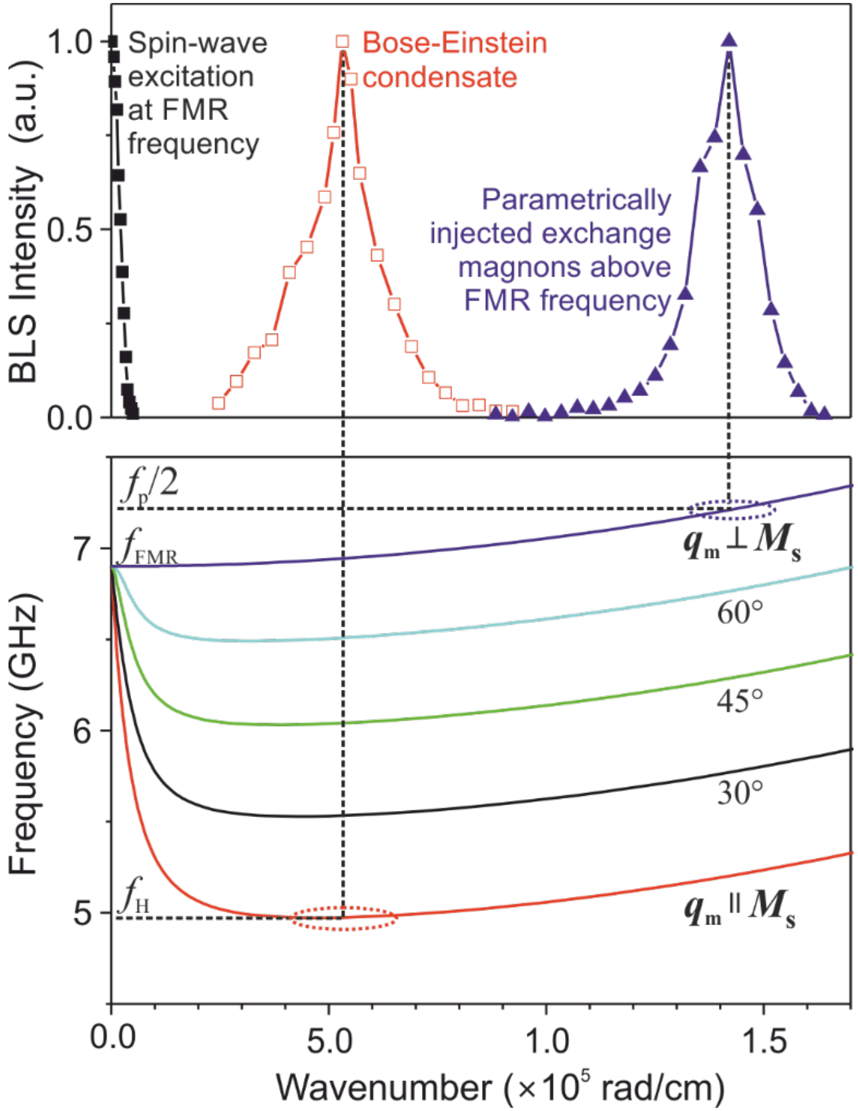
Time resolution	250 ps
Frequency resolution	150 MHz
Spatial resolution	25 µm

Wave-vector resolved BLS setup

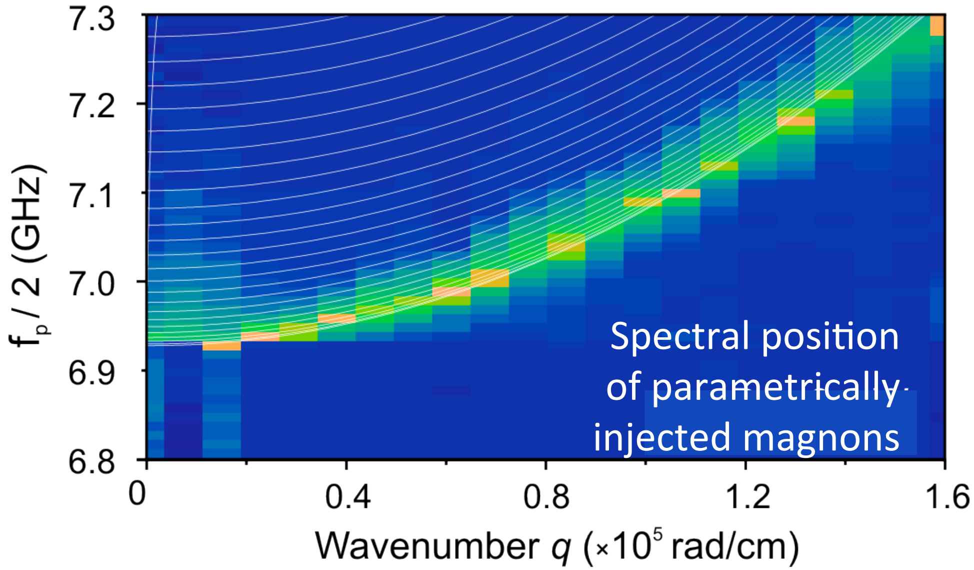


Sandweg *et al.*, Rev. Scientific Instr. **81**, 073902 (2010)

Wave-vector resolved BLS setup



Serga *et al*., Phys. Rev. B **86**, 134403 (2012)

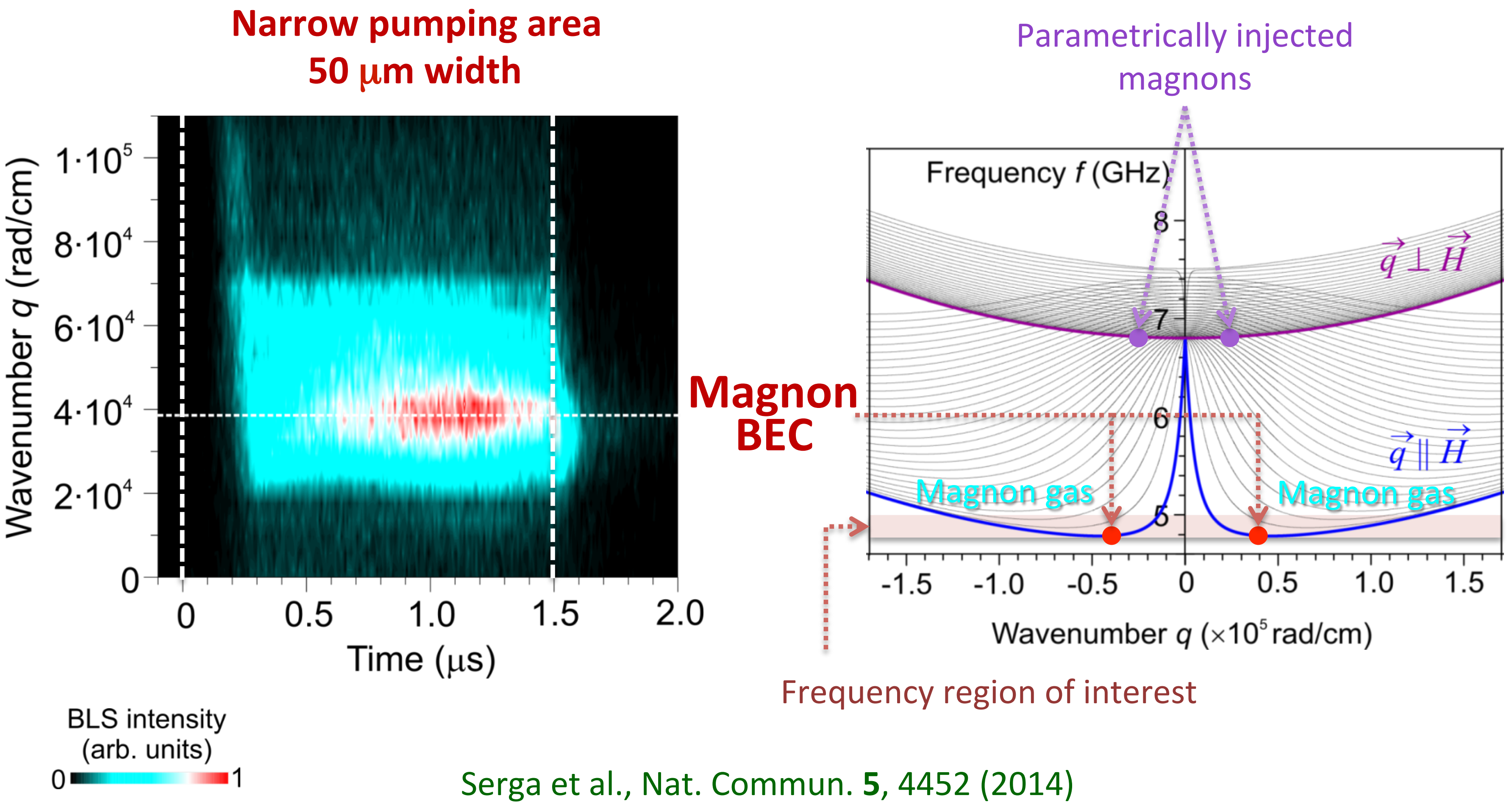


Sandweg *et al*., Rev. Scientific Instr. **81**, 073902 (2010)

Gaseous magnons and magnon BEC in a phase space

Technische Universität Kaiserslautern

Bose-Einstein magnon condensate

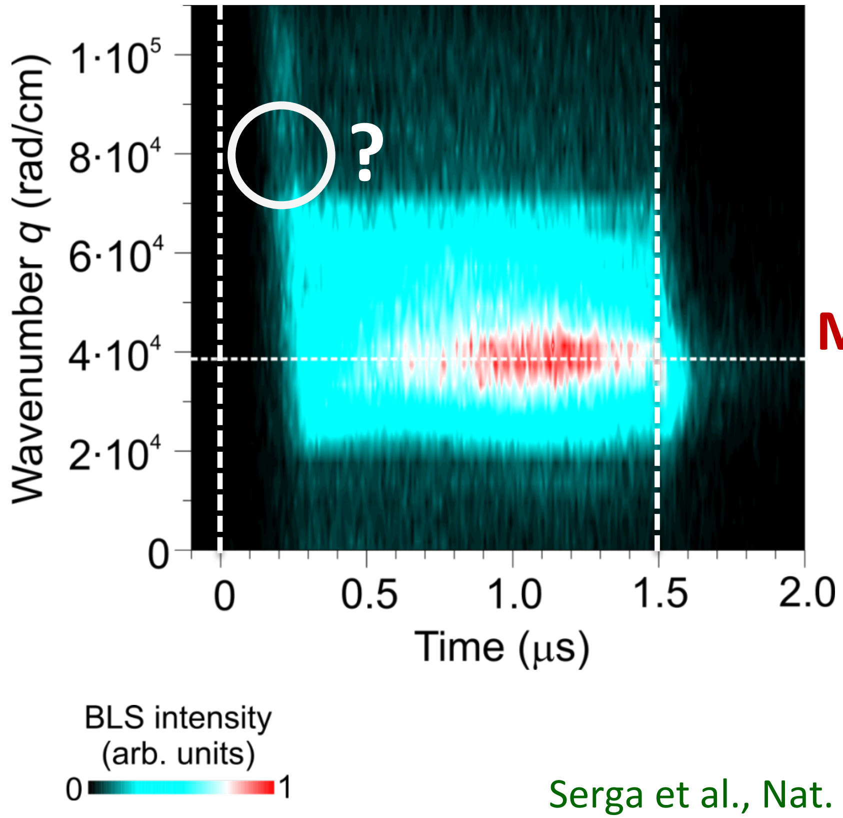


Serga et al., Nat. Commun. **5**, 4452 (2014)

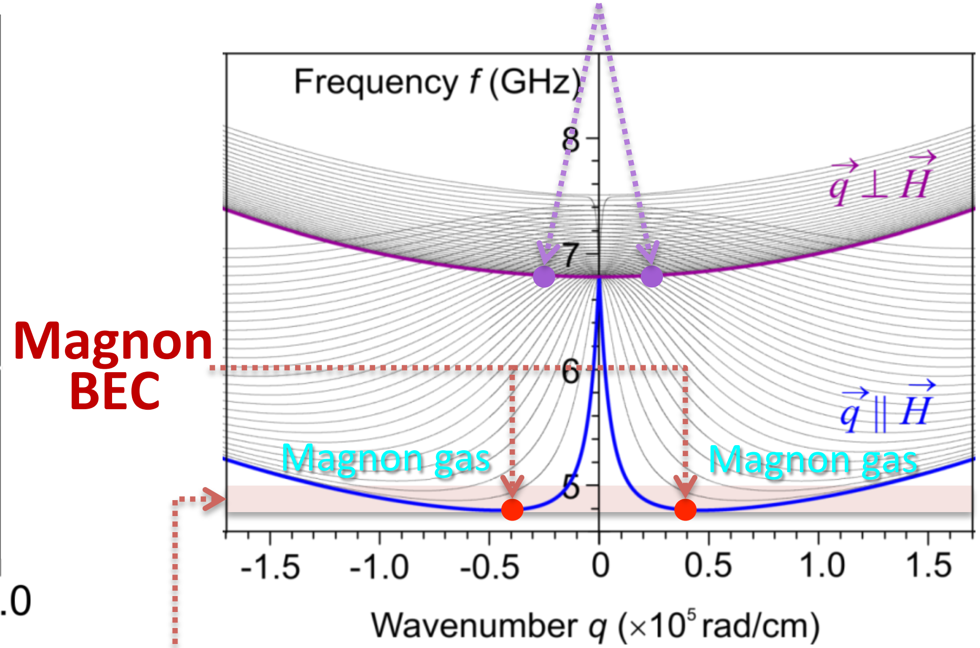
Gaseous magnons and magnon BEC in a phase space

Bose-Einstein magnon condensate

Narrow pumping area
50 μm width



Parametrically injected magnons

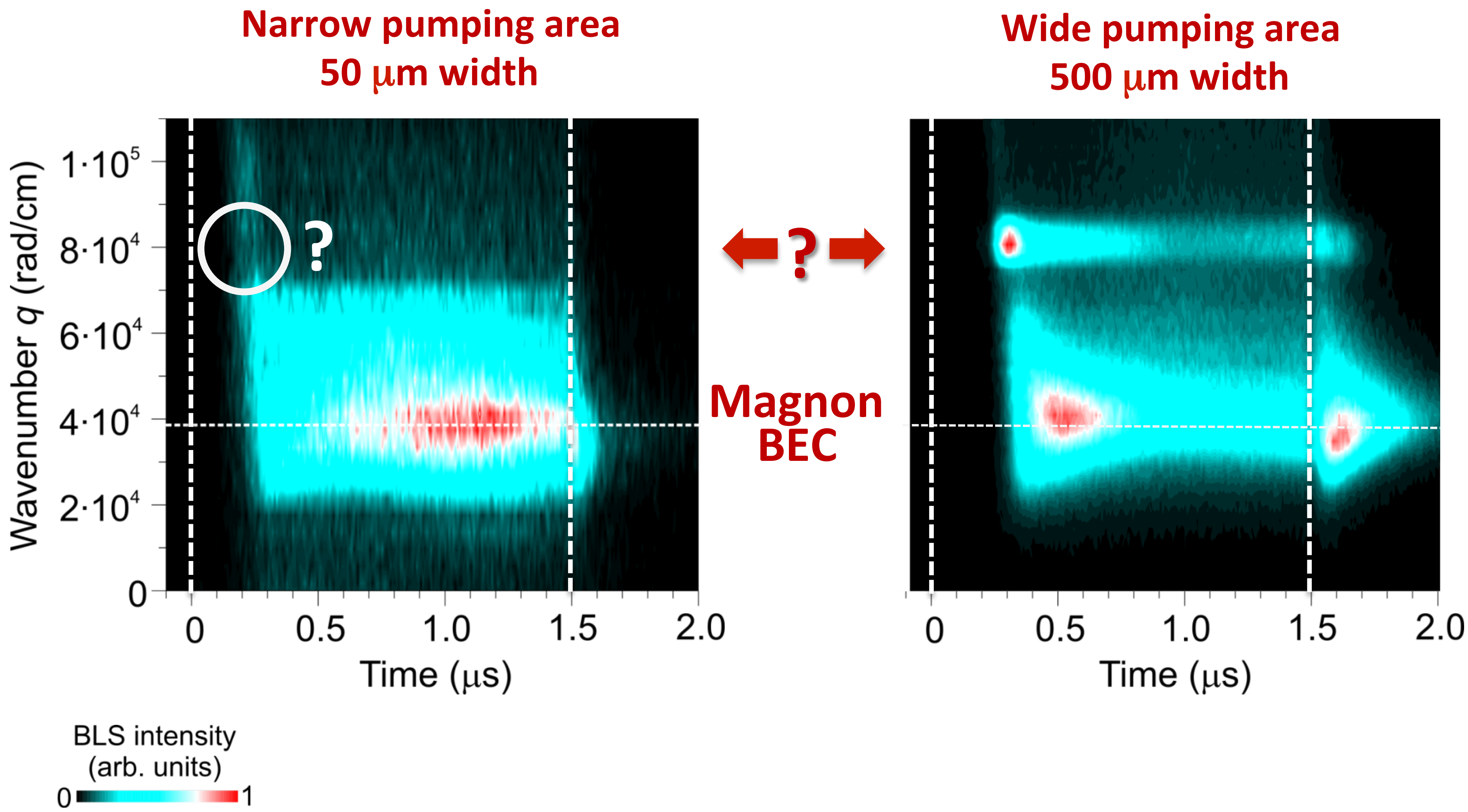


Frequency region of interest

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

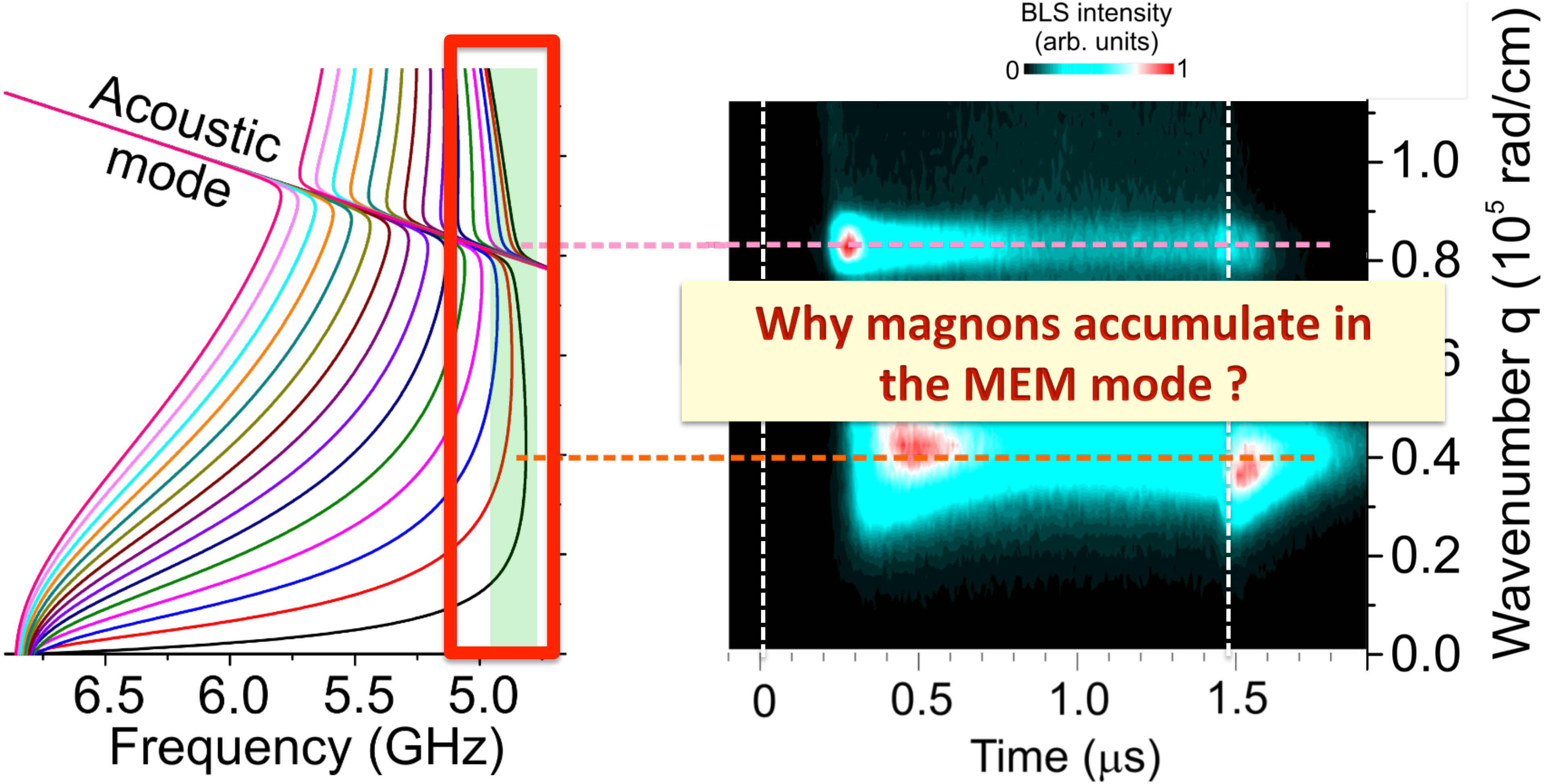
Gaseous magnons and magnon BEC in a phase space

Bose-Einstein magnon condensate



Gaseous phase and magnon BEC at the bottom of spin-wave spectrum

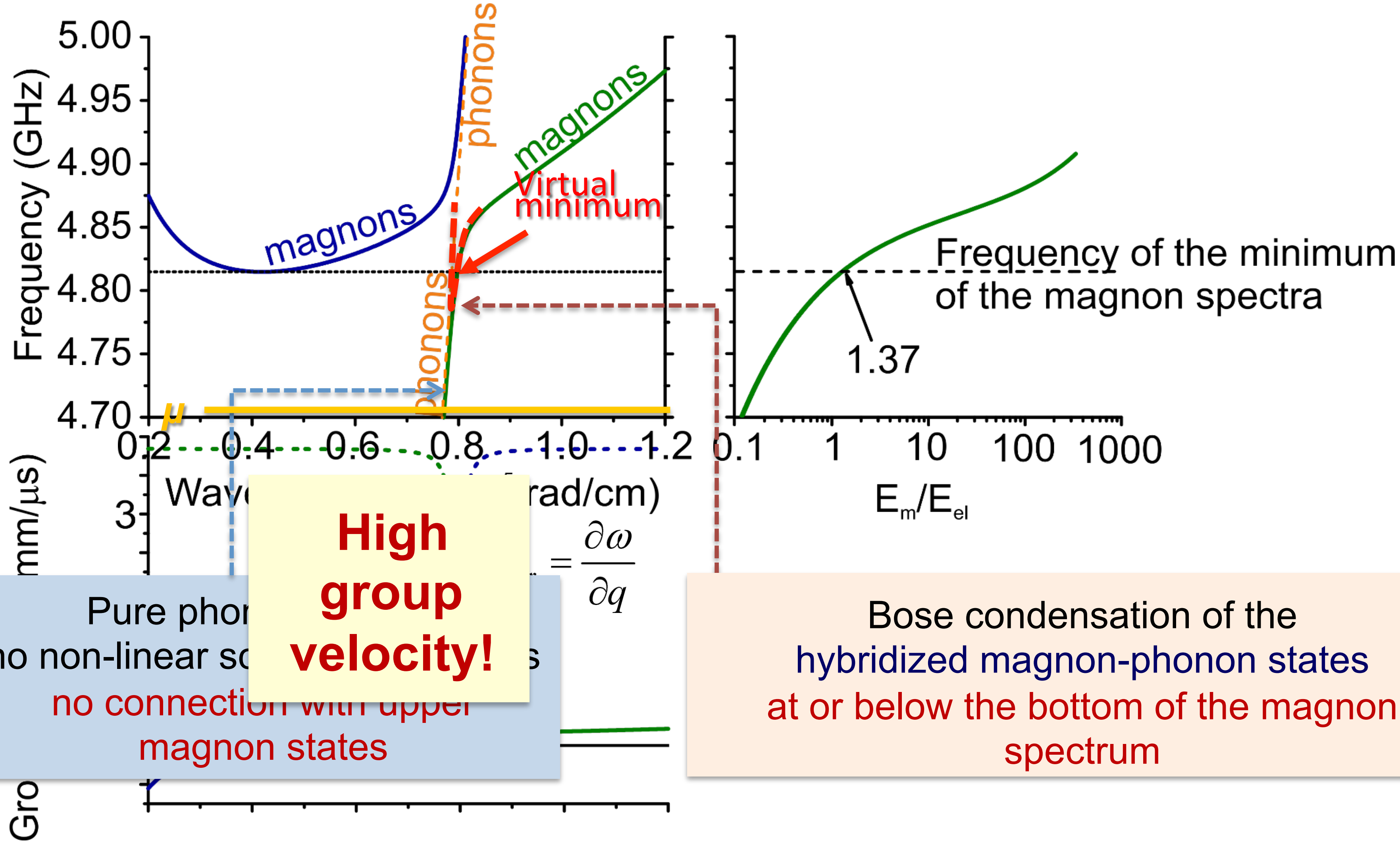
TECHNISCHE UNIVERSITÄT KAISERSLAUTERN



Why magnons accumulate in the MEM mode ?

Hybridization between a phonon mode and magnon modes results in magneto-elastic magnon (MEM) mode

Condensation of magnon-phonon hybrid particles



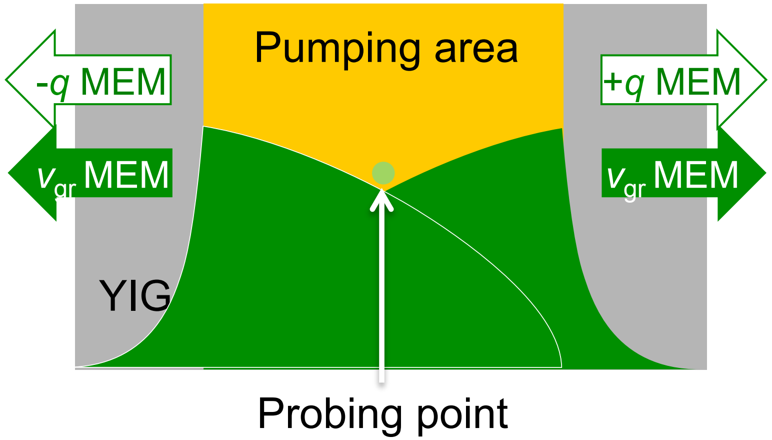
High group velocity!

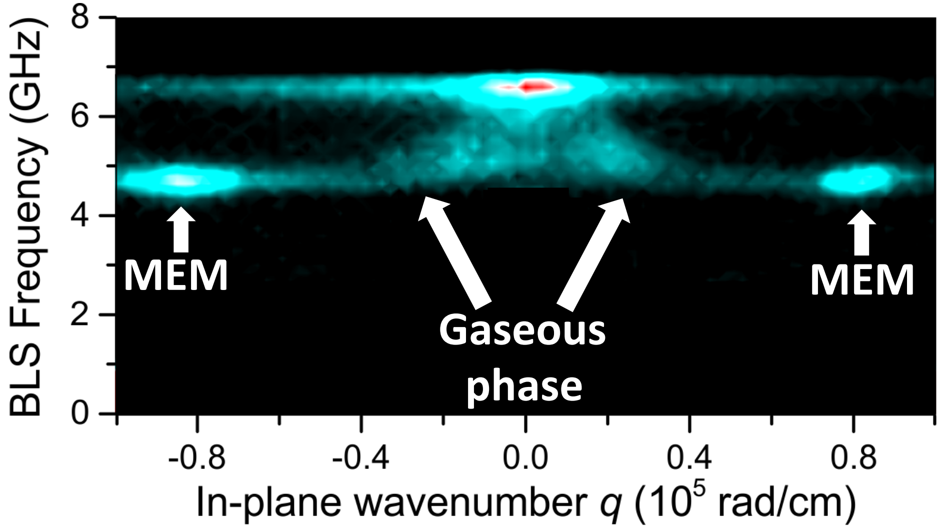
Pure phon... no non-linear sc... s
no connection with upper magnon states

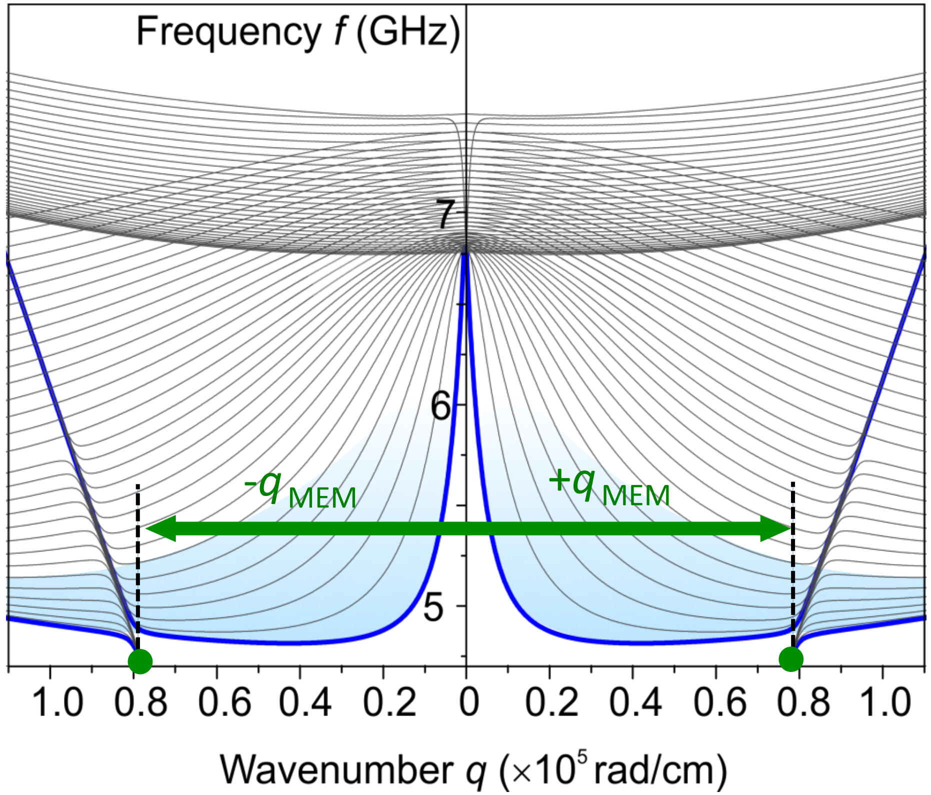
Bose condensation of the hybridized magnon-phonon states at or below the bottom of the magnon spectrum

Asymmetry of MEM mode

Amplification of the travelling MEM mode







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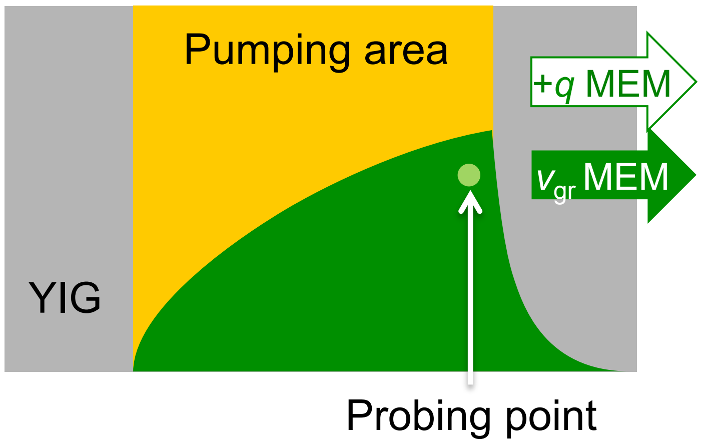

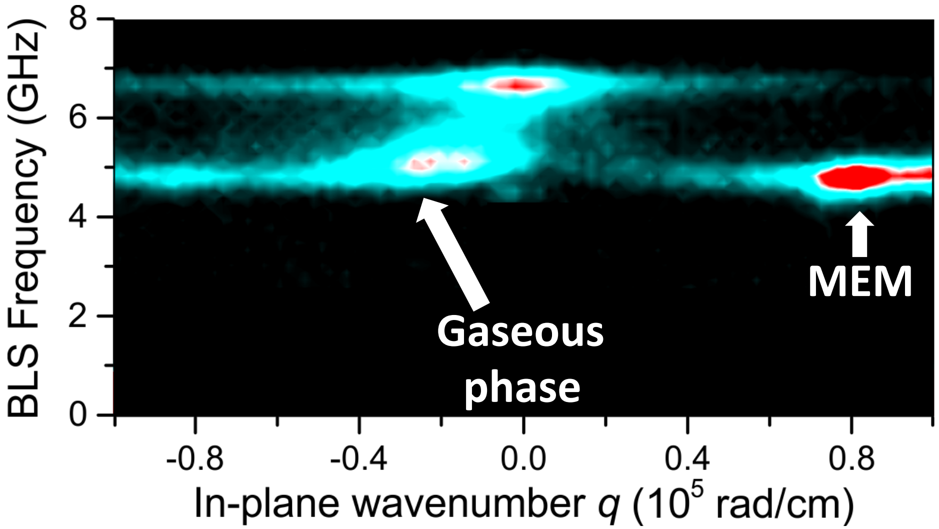

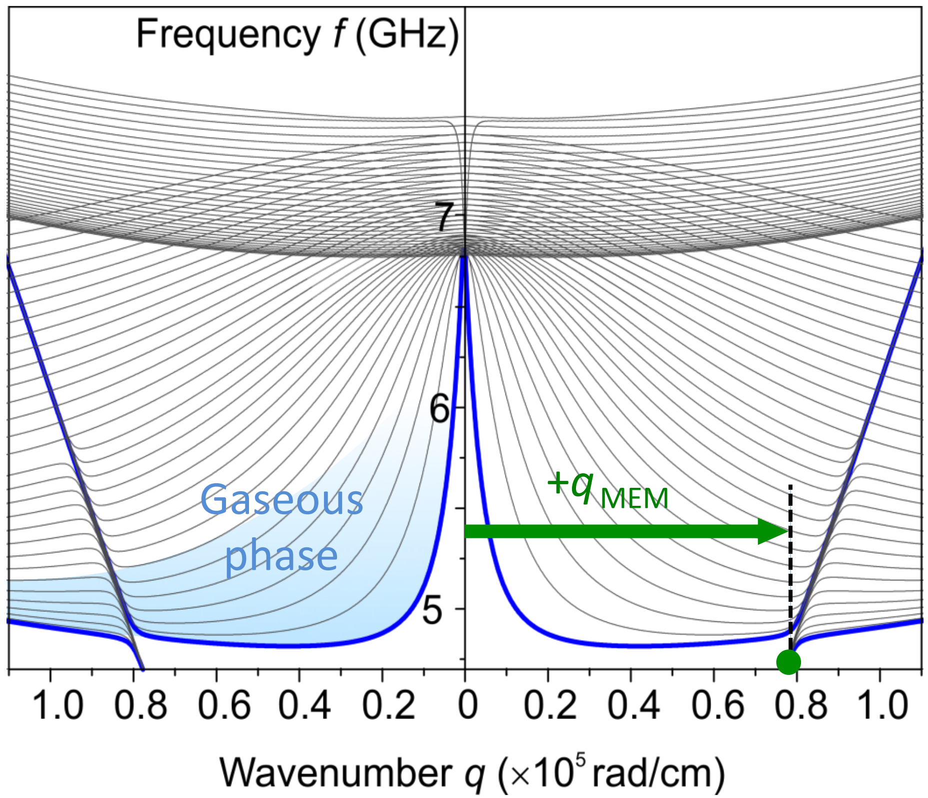

Magnonics: Challenges

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