Magnon Bose Einstein Condensation

a brief introduction

Dec. 21st 2018

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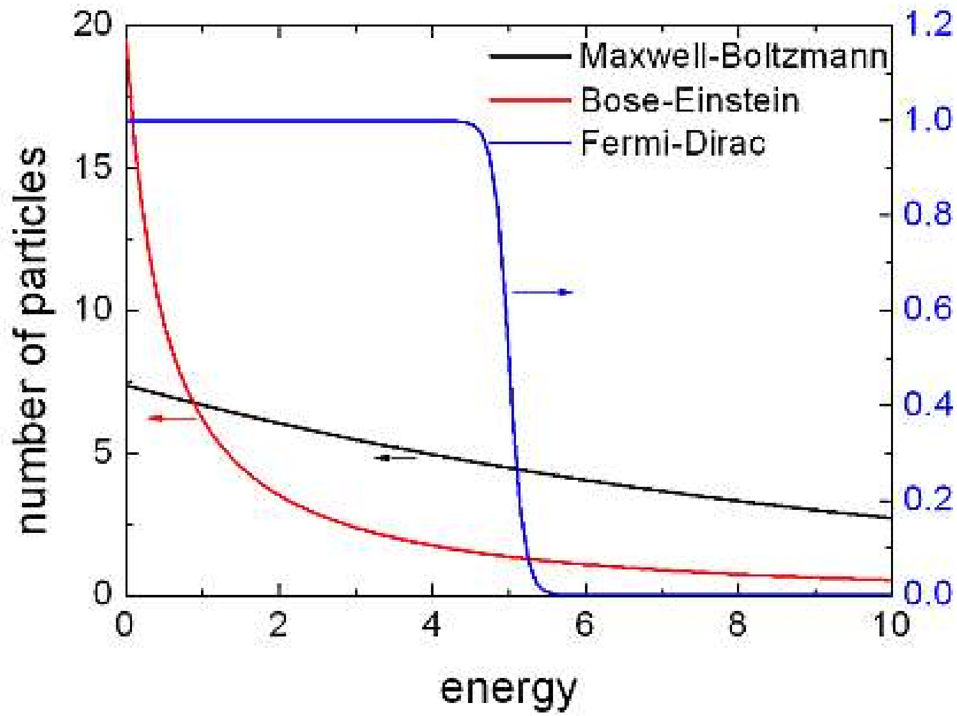
After this presentation, you are supposed to have some basic understanding of:

- What is magnon BEC?
- Why is it so special?
- How to achieve it?
- Several experiments.

Bose Einstein Condensation

$$\boxed{N_{i,BE} = \frac{1}{e^{(\epsilon_i - \mu)/k_B T} - 1}}$$



Bose Einstein Condensation

$$\boxed{N_{i,BE} = \frac{1}{e^{(\epsilon_i - \mu)/k_B T} - 1}}$$

If the total particle number N is fixed,

the chemical potential $\mu = \frac{\partial F}{\partial N}$ has a finite value.

$$\boxed{\epsilon \to \mu \quad \Longrightarrow \quad \text{BEC}}$$

Bose Einstein Condensation

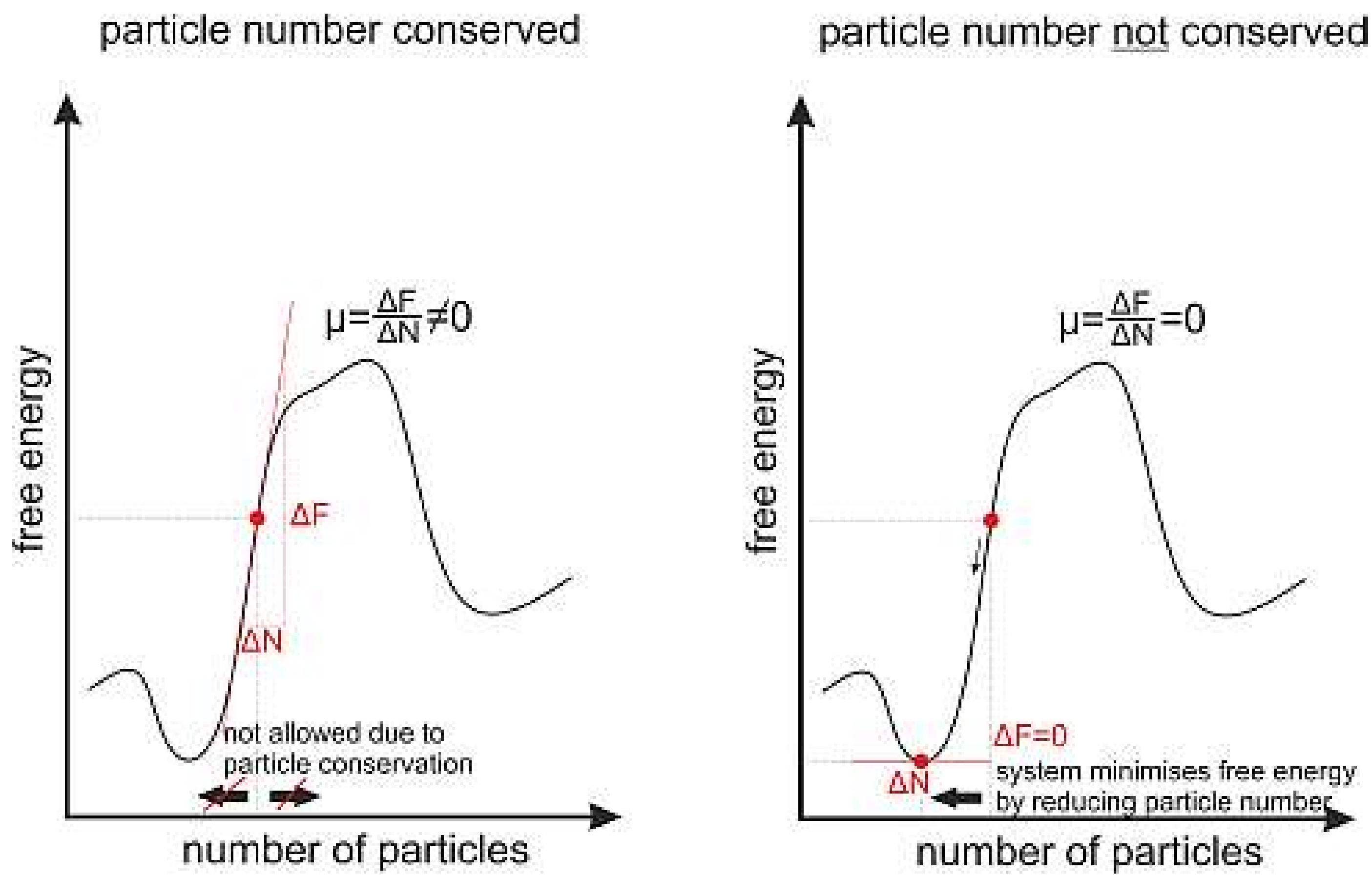
$$\boxed{N_{i,BE} = \frac{1}{e^{(\epsilon_i - \mu)/k_B T} - 1}}$$

If the total particle number N is NOT fixed,

the chemical potential $\mu = \dfrac{\partial F}{\partial N}$ is always zero!

Why?

Bose Einstein Condensation



Bose Einstein Condensation

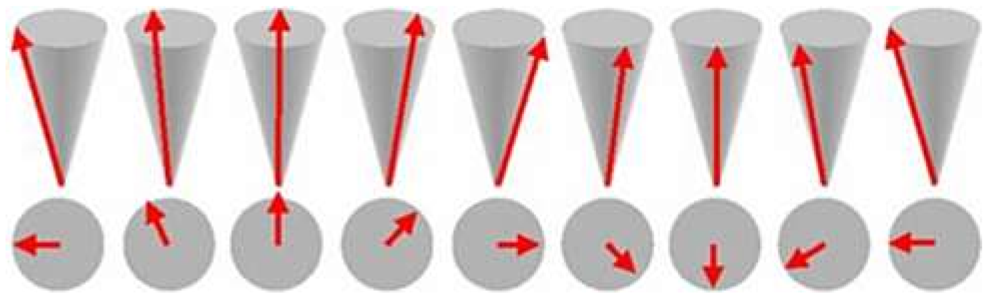
$$\boxed{N_{i,BE} = \frac{1}{e^{(\epsilon_i - \mu)/k_B T} - 1}}$$

If the total particle number N is NOT fixed,

the chemical potential $\mu = \frac{\partial F}{\partial N}$ is always zero!

$$\boxed{\epsilon > \mu \quad \Longrightarrow \quad \text{no BEC}}$$

Magnon



spin wave ⟷ magnon (boson s = 1)

$\mu = 0$ ⟶ no BEC


R.I.P.
magnon
BEC

Magnon BEC

$$\boxed{N_{i,BE} = \frac{1}{e^{(\epsilon_i - \mu)/k_B T} - 1}}$$

Last hope: raise the chemical potential.

But how?

Magnon BEC

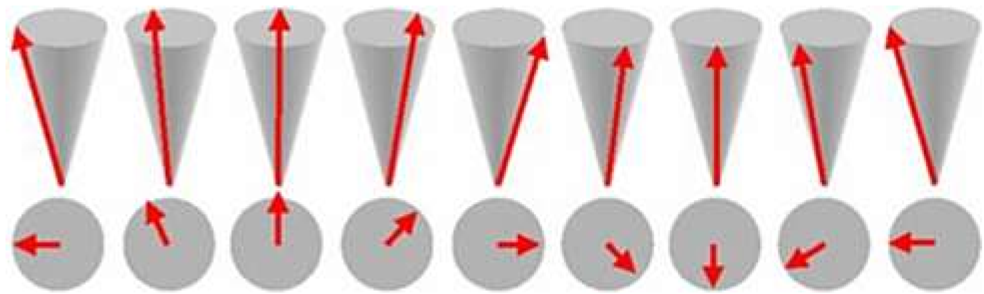
$$\boxed{N_{i,BE} = \frac{1}{e^{(\epsilon_i - \mu)/k_B T} - 1}}$$

Defined at thermal equilibrium,

But at thermal equilibrium …

What happens beyond thermal equilibrium?

Magnon



create magnons

heating

oscillating magnetic field

scattering

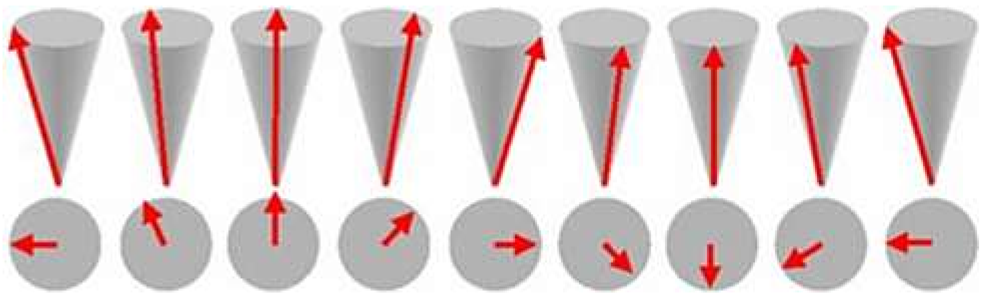
magnon's life

destroy magnons

cooling

dissipation into lattice

Magnon



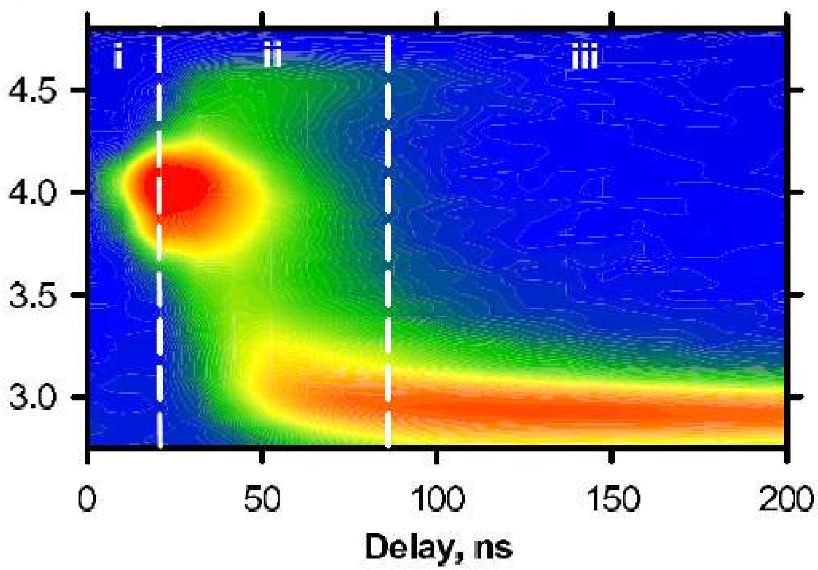
dissipation into lattice : μs

scattering into equilibrium : ns

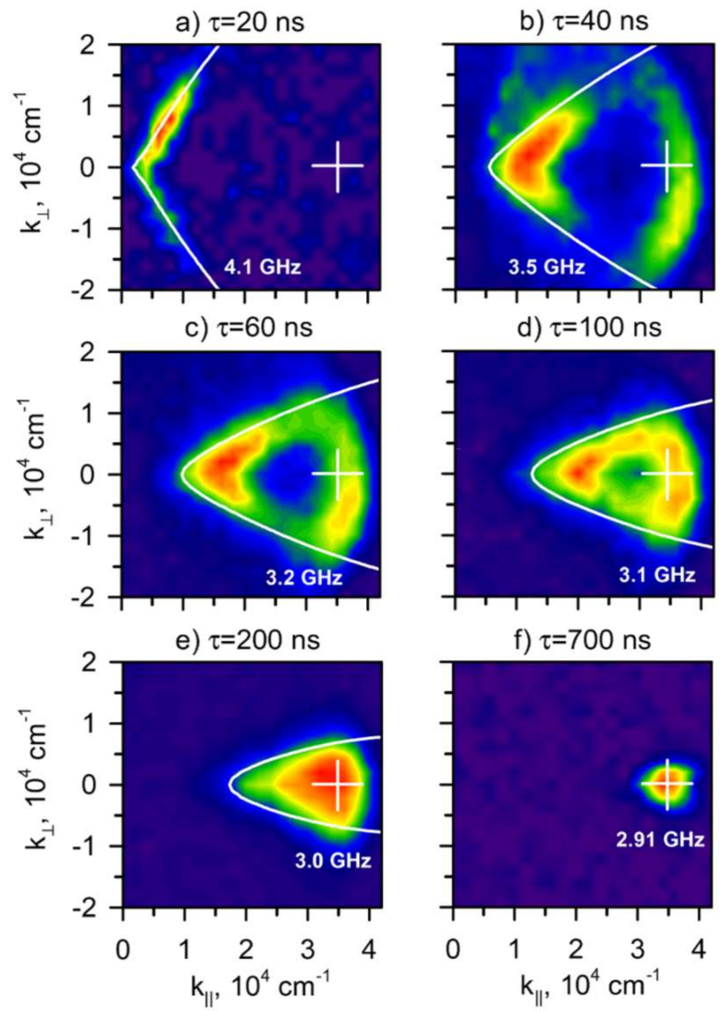
→ **quasi-equilibrium**

Magnon BEC

YIG film



V. E. Demidov *et al*., *Phys. Rev. Lett.* **100**, 047205 (2008).



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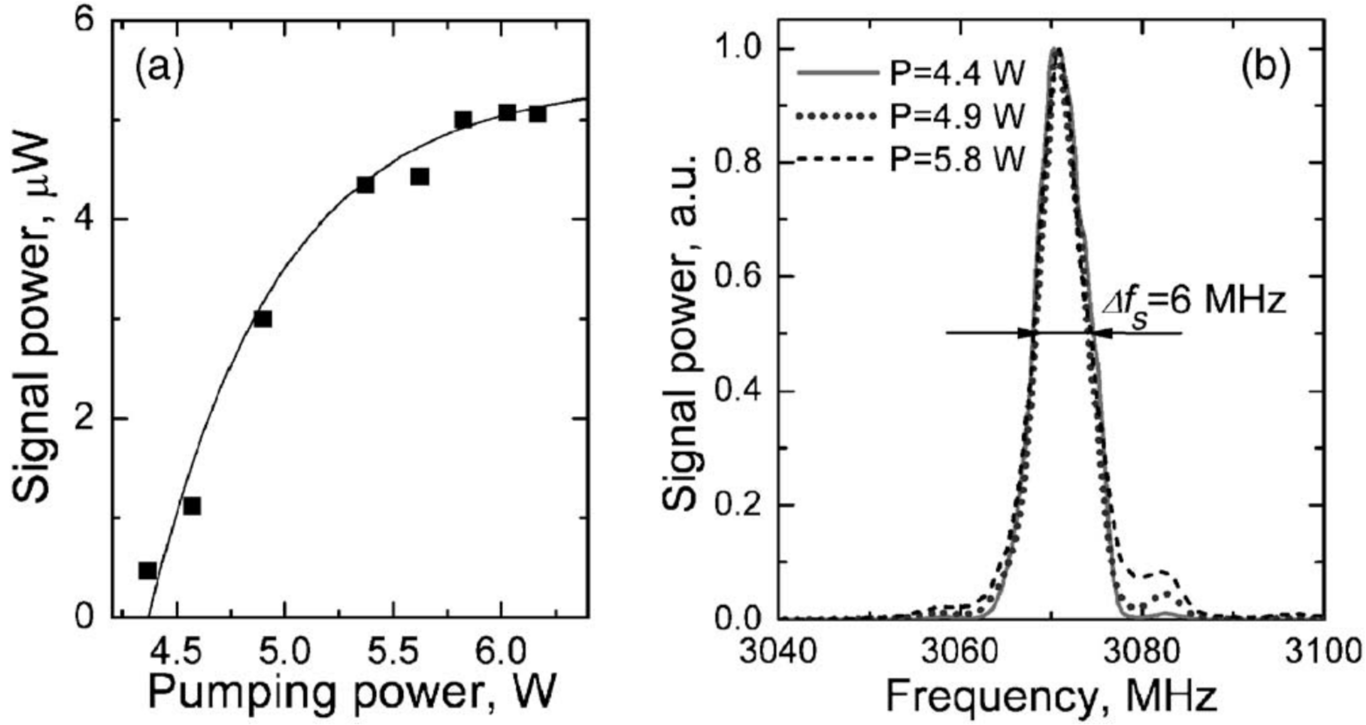
Magnon BEC

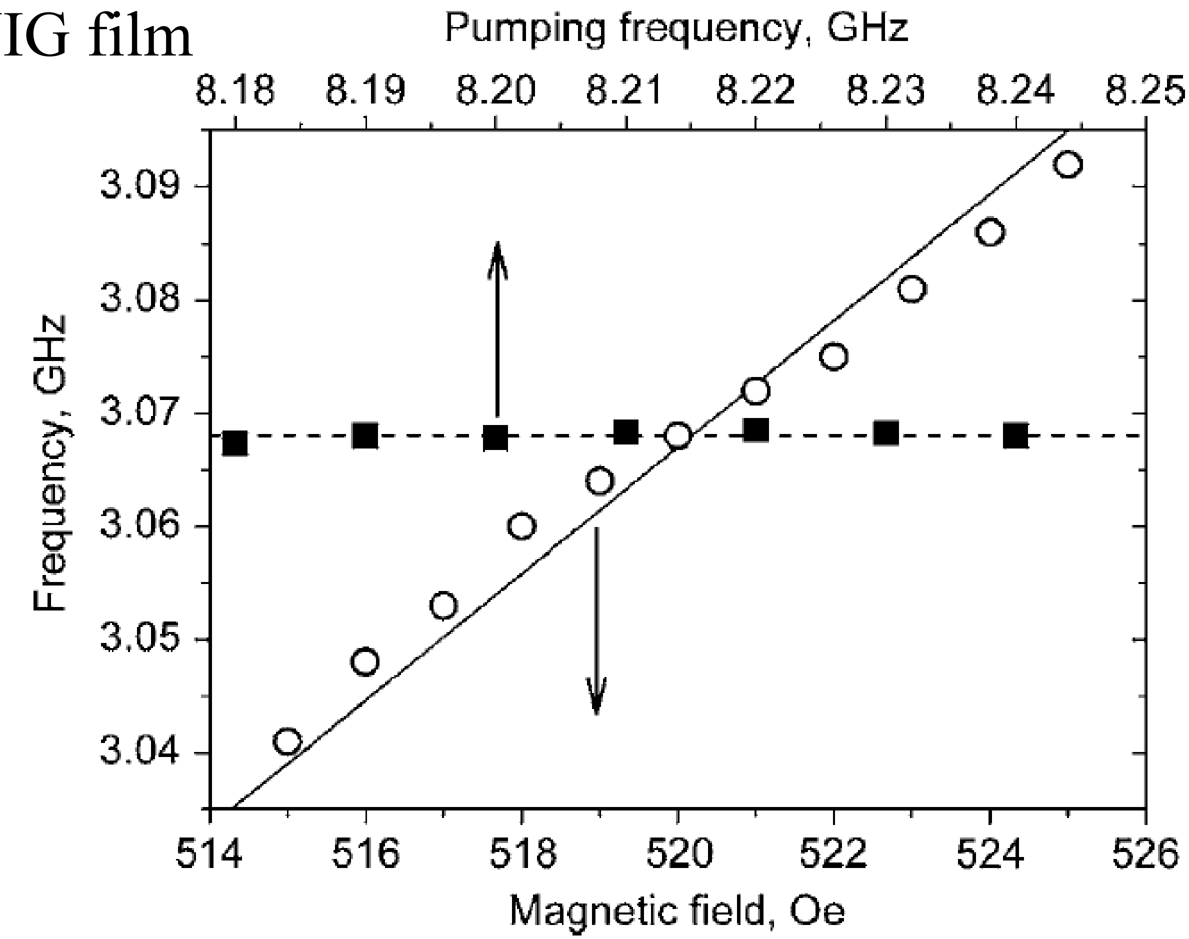
YIG film



O. Dzyapko *et al*., *Appl. Phys. Lett.* **92**, 162510 (2008).

Magnon BEC

YIG film



O. Dzyapko *et al*., *Appl. Phys. Lett.* **92**, 162510 (2008).

First experimental discovery of mBEC

nature Vol 443|28 September 2006|doi:10.1038/nature05117

LETTERS

Bose–Einstein condensation of quasi-equilibrium magnons at room temperature under pumping

S. O. Demokritov[1], V. E. Demidov[1], O. Dzyapko[1], G. A. Melkov[2], A. A. Serga[3], B. Hillebrands[3] & A. N. Slavin[4]

New Journal of Physics
The open-access journal for physics

Direct observation of Bose–Einstein condensation in a parametrically driven gas of magnons

O Dzyapko[1], V E Demidov[1], S O Demokritov[1,4], G A Melkov[2] and A N Slavin[3]

Magnon BEC

FM material + $\vec{\boldsymbol{H}}$ + pumping $\rightarrow$ magnons

$N(\nu_{\min}) = N_{max}$ $\rightarrow$ BEC

YIG

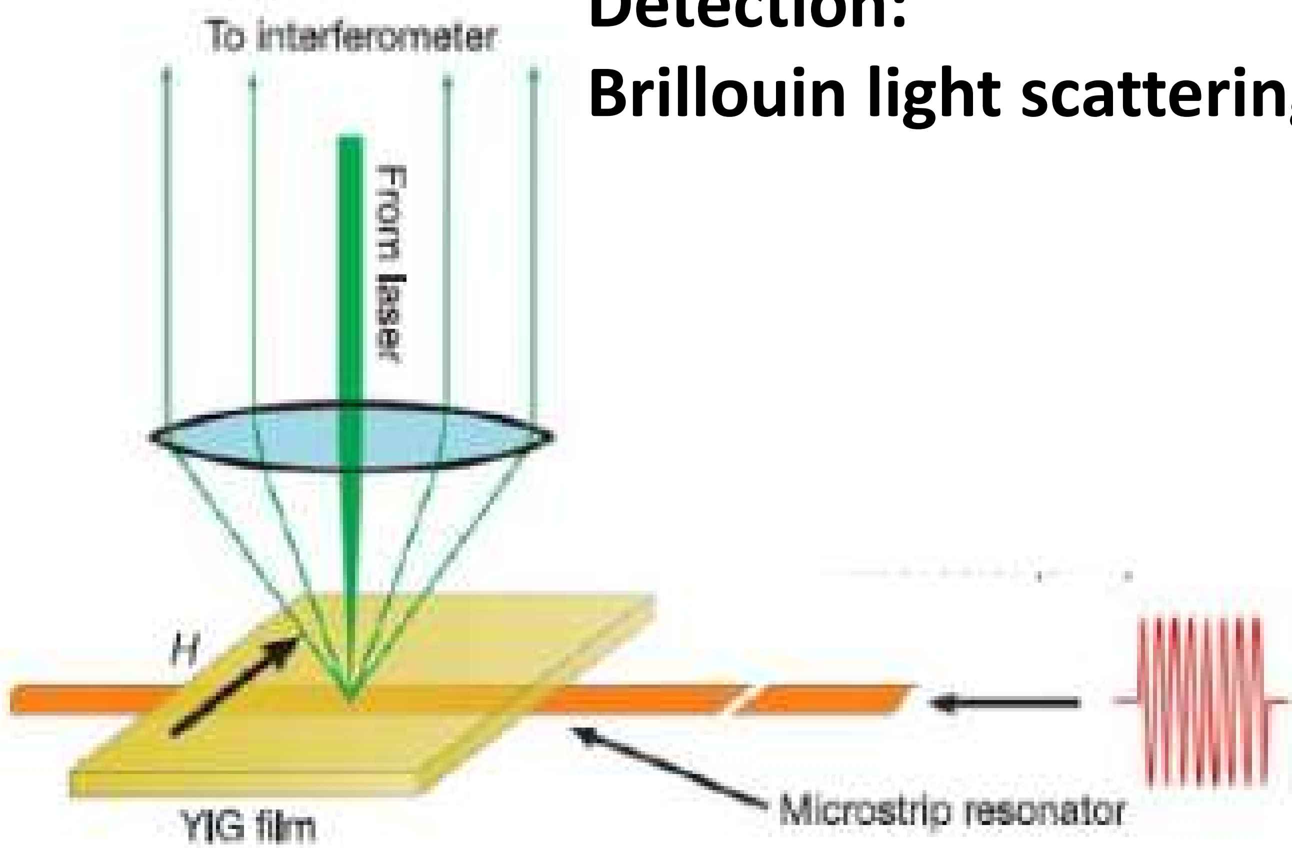
①microwave electromagnetic field—density of magnon

② $\tau_{sl} > 1\mu s$, $\tau_{ss} < 100ns$—**quasi-equilibrium**

③transparent for visible light

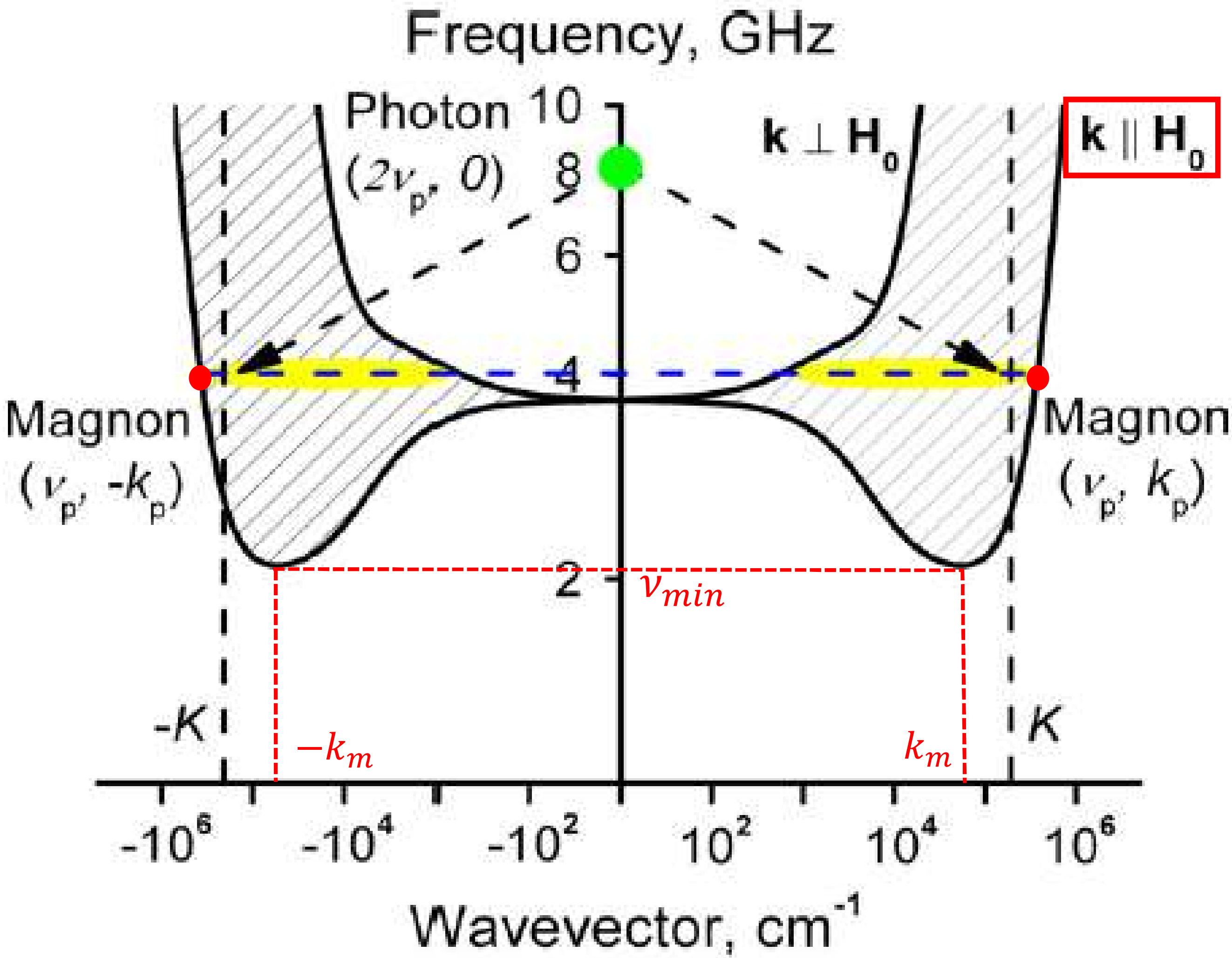
Experimental set-up

Detection:
Brillouin light scattering (BLS)



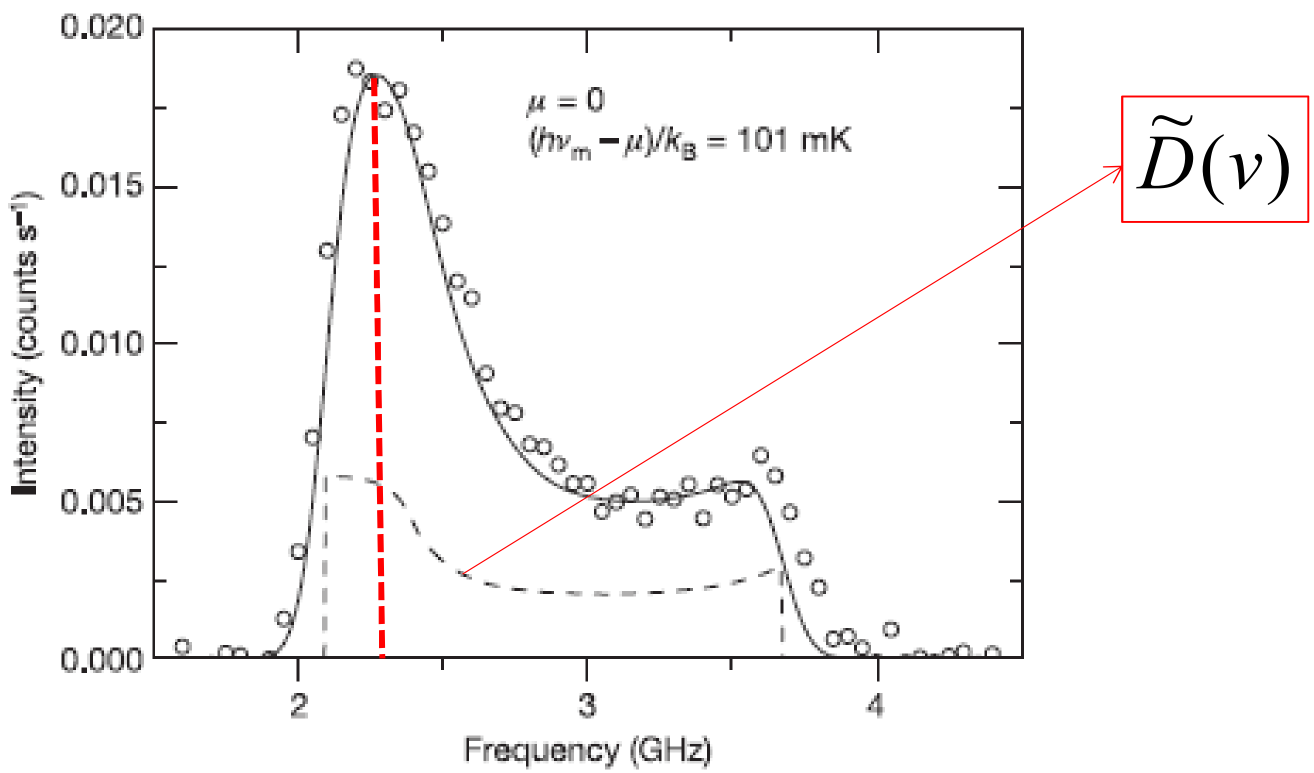
Demokritov S O. et al. Nature, 2006, 443(7110):430-433.
Dzyapko O. et al. New Journal of Physics, 2007, 9(3):64.

Dispersion curve



Dzyapko O. et al. New Journal of Physics, 2007, 9(3):64.

BLS spectrum **without** pumping



$$\rho(\nu) = D(\nu)n(\nu) = \frac{D(\nu)}{e^{\frac{h\nu-\mu}{k_B T_0}} - 1} \overset{\mu=0}{\Longleftrightarrow} \frac{\widetilde{D}(\nu)}{e^{\frac{h\nu}{k_B T_0}} - 1}$$

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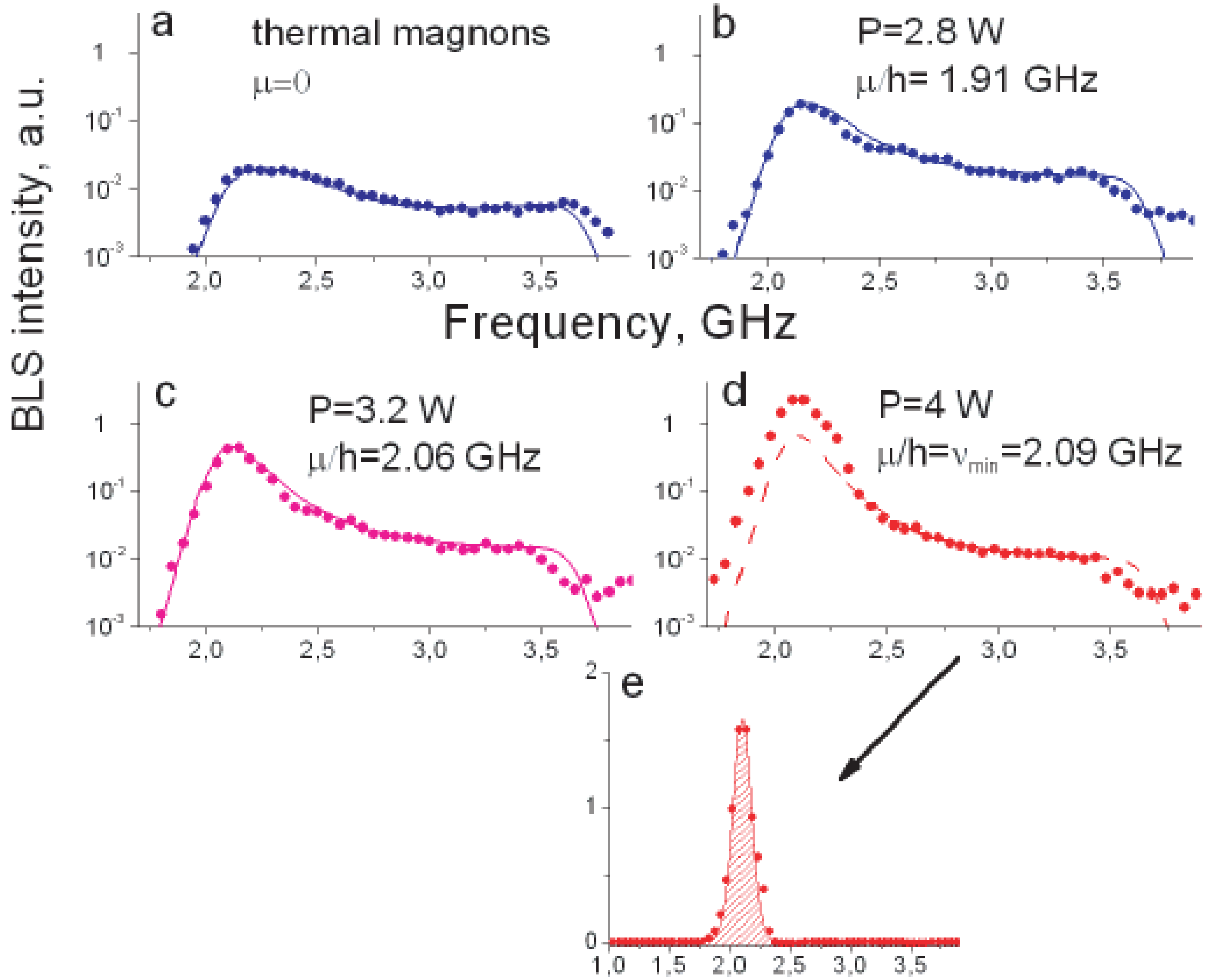
BLS spectrum **with** pumping



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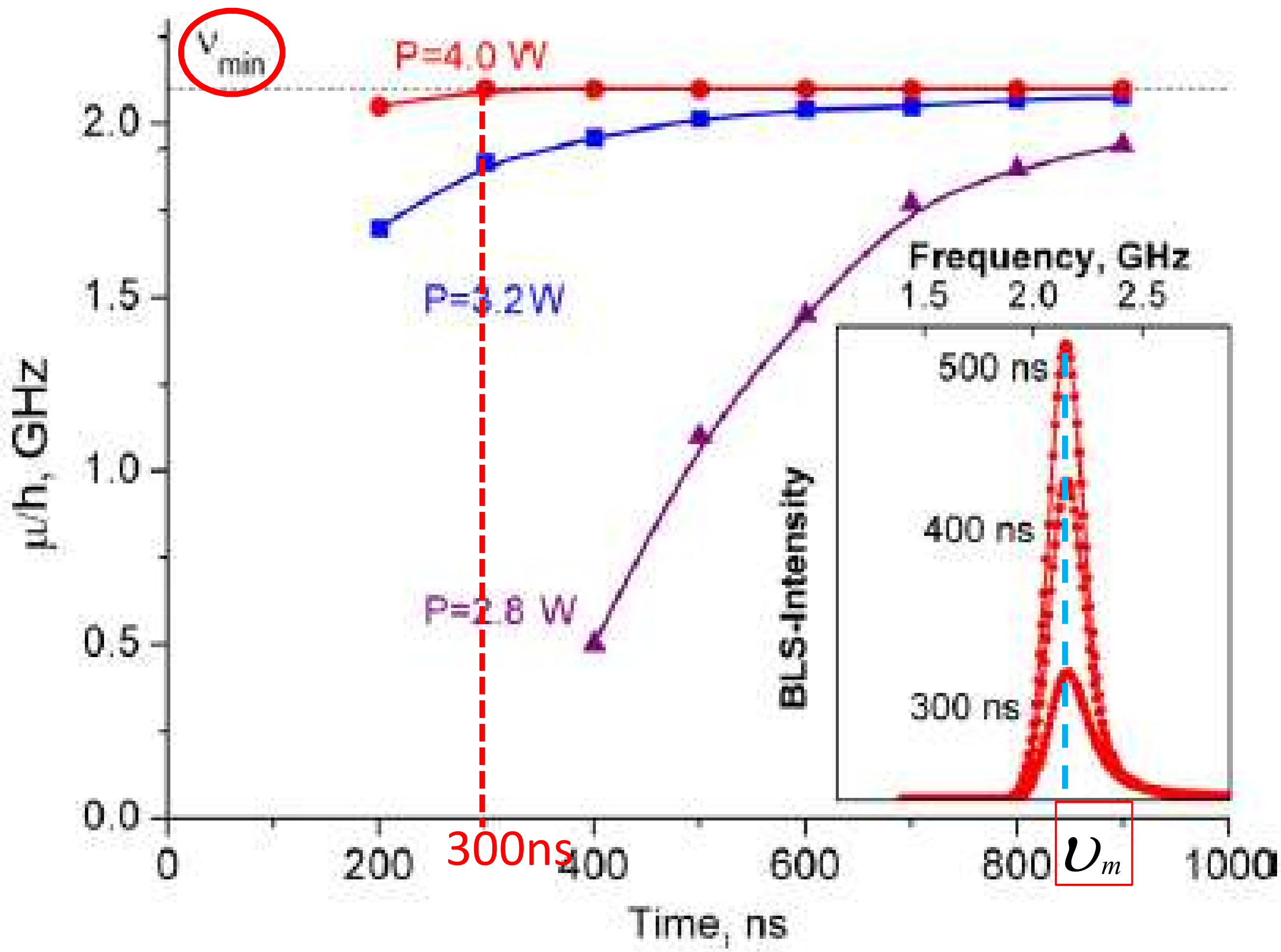
BLS spectrum **with** pumping



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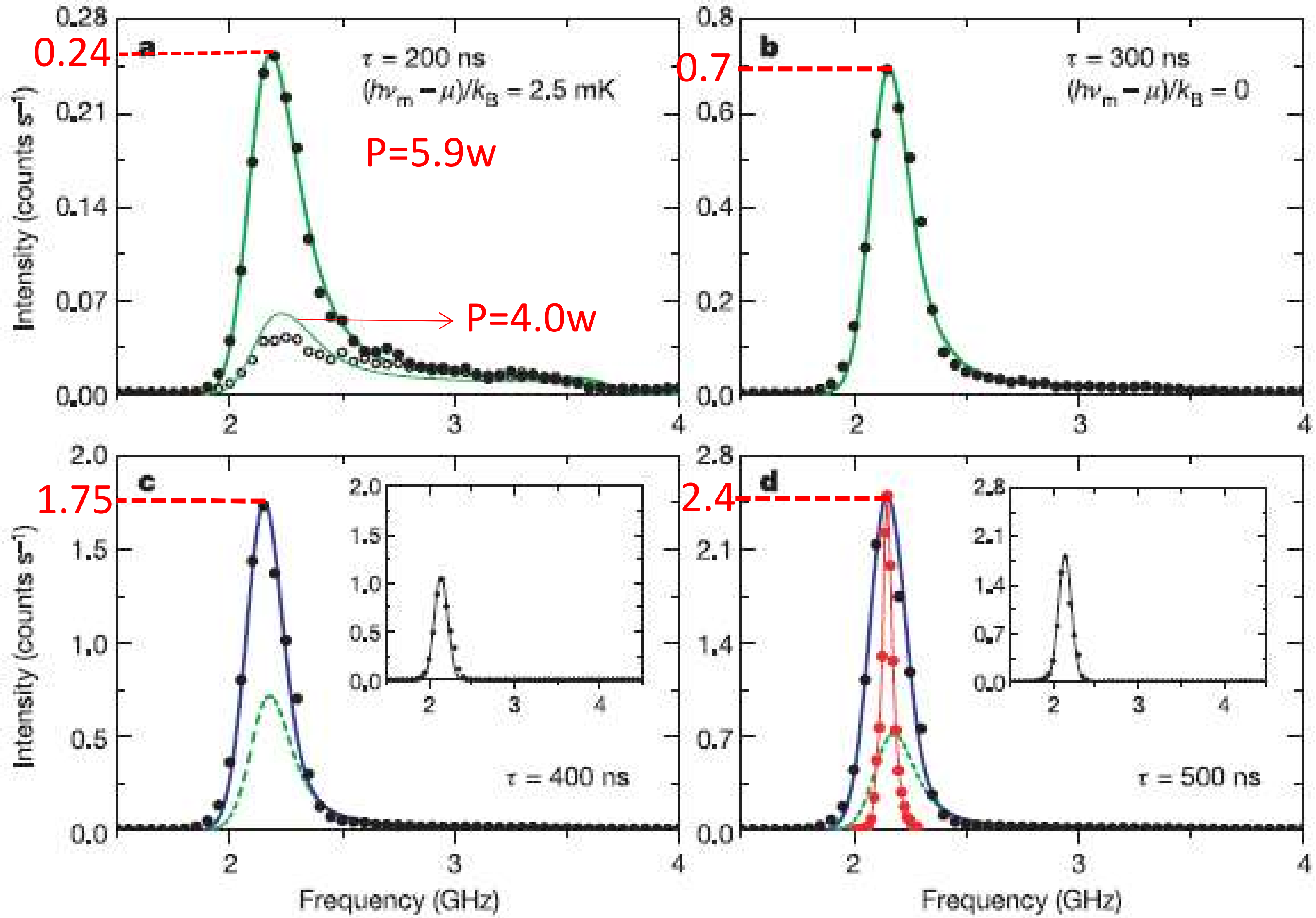
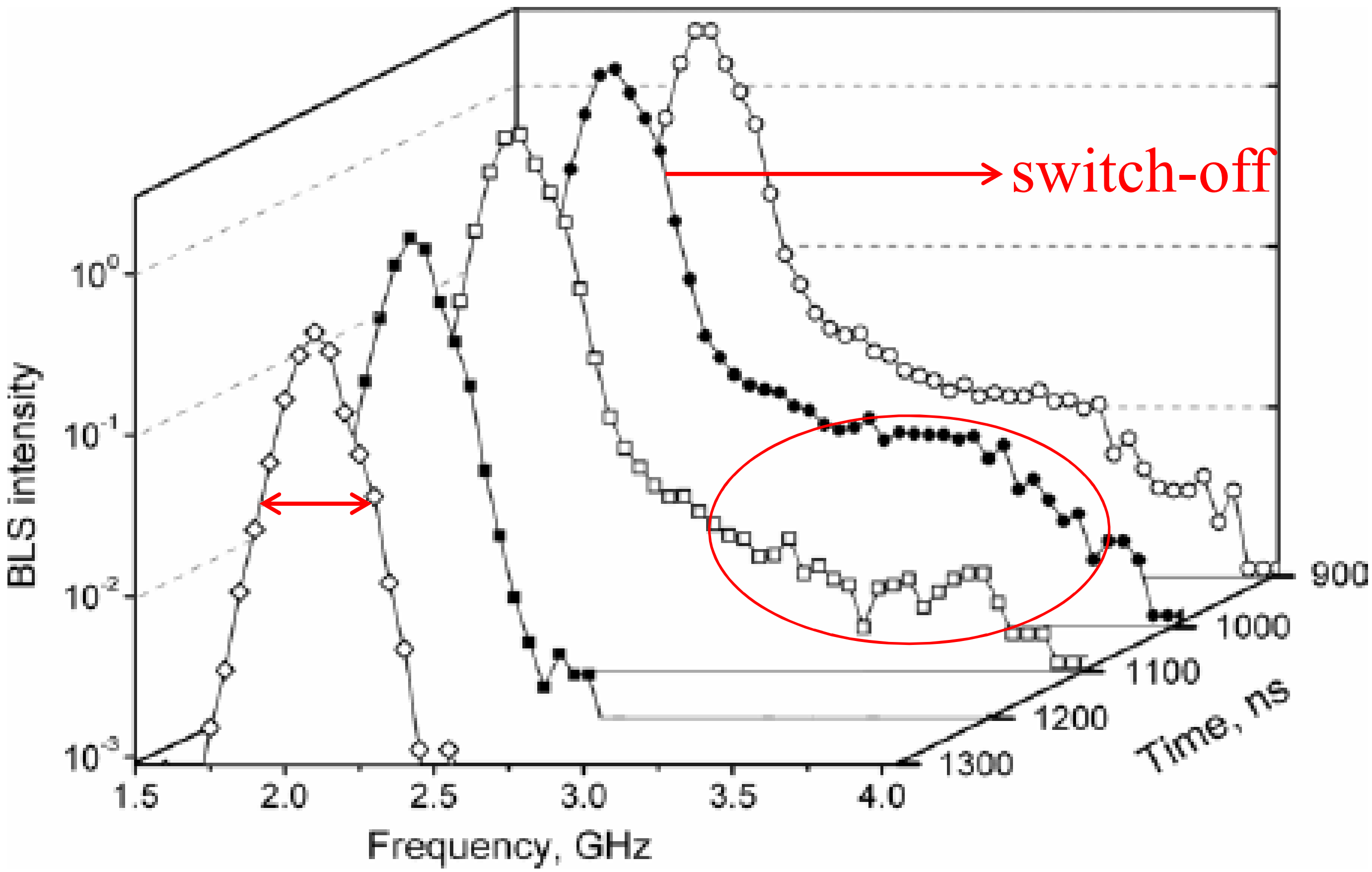
BLS spectrum **with** pumping



Demokritov S O. et al. Nature, 2006, 443(7110):430-433.

BLS spectrum **after** pumping



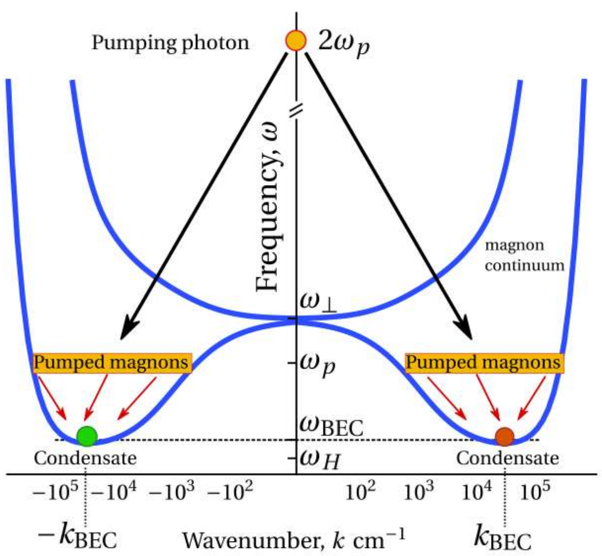
Dzyapko O. et al. New Journal of Physics, 2007, 9(3):64.

Research about magnon-magnon interaction

Magnon-magnon interactions in a room-temperature magnonic Bose-Einstein condensate

2017

Oleksandr Dzyapko,[1] Ivan Lisenkov,[2,3,*] Patrik Nowik-Boltyk,[1] Vladislav E. Demidov,[1] Sergej O. Demokritov,[1,4] Benny Koene,[5] Andrei Kirilyuk,[5] Theo Rasing,[5] Vasyl Tiberkevich,[6] and Andrei Slavin[6]



- Parametric pumping
- Doubly degenerate mBEC

$$W_{\text{int}}(r'-r)=\frac{4\pi\hbar^2 a}{m}\delta(r'-r)=g\delta(r'-r)$$

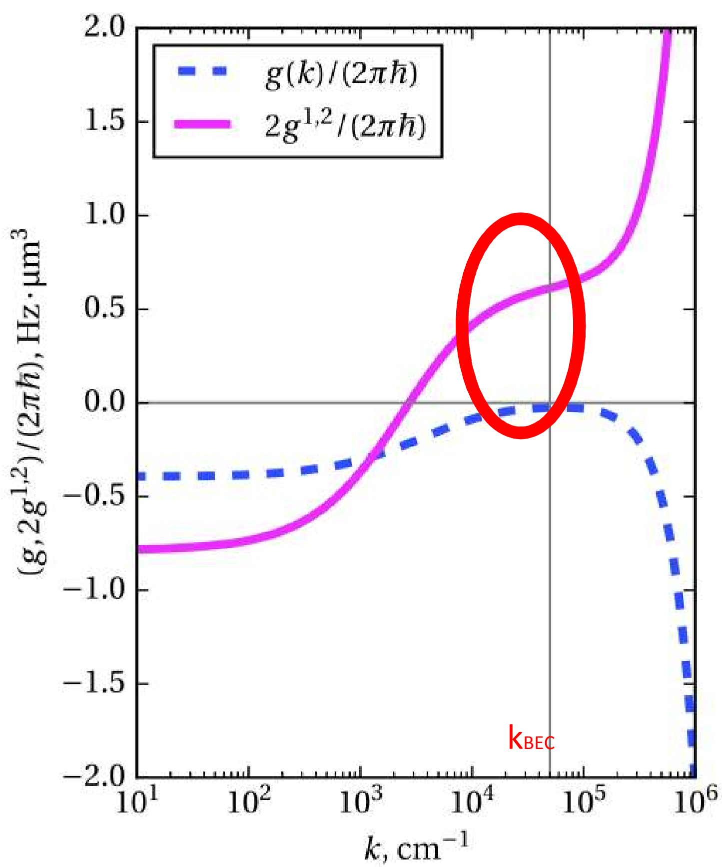
g>0, repulsive interaction;
g<0, attractive interaction

$$i\hbar\dot{b}_1=(\hbar\omega_0+g\frac{b_1^*b_1}{V}+2g^{12}\frac{b_2^*b_2}{V})b_1$$

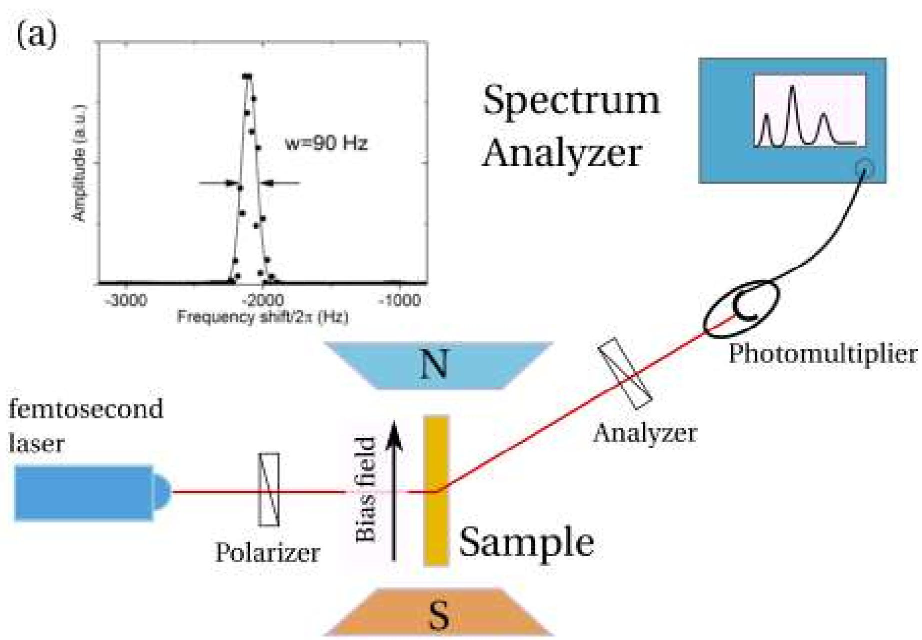
$$i\hbar\dot{b}_2=(\hbar\omega_0+g\frac{b_2^*b_2}{V}+2g^{12}\frac{b_1^*b_1}{V})b_2$$

$$\delta\omega=\omega-\omega_0=(g/\hbar)\rho+(2g^{12}/\hbar)\rho$$

Research about magnon-magnon interaction

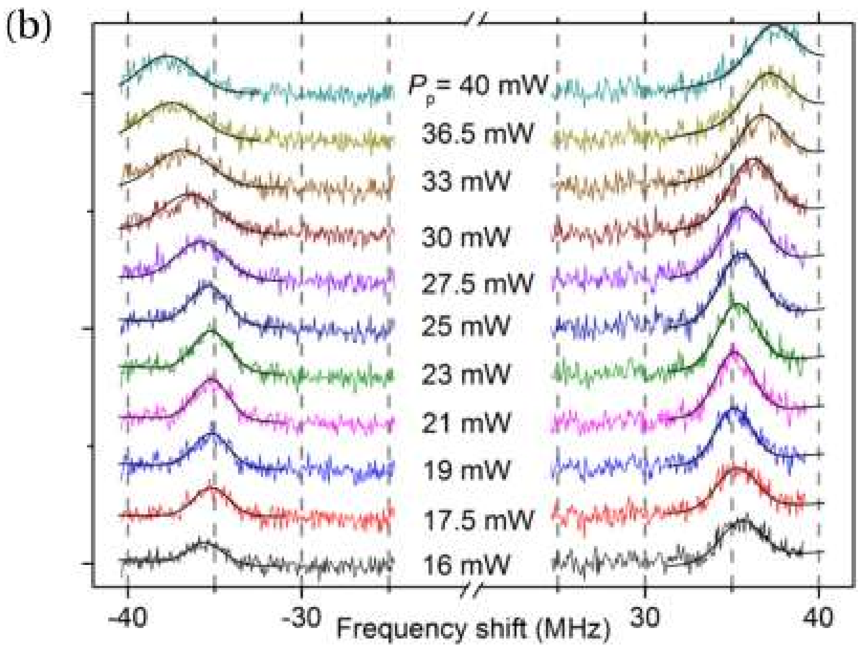


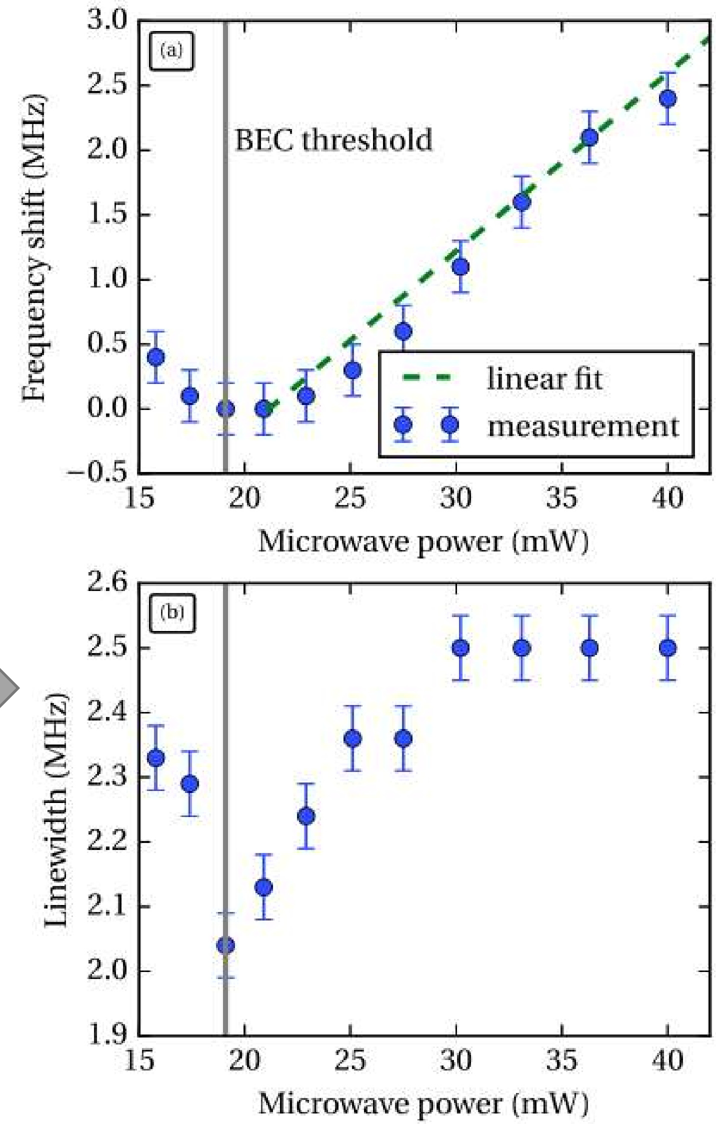
- MOKE
- Wavelength: 490nm
- Duration: 100 fs
- Repetition frequency ωL/(2π)=82.379MHz



Research about magnon-magnon interaction

- H_0=113.91kA/m
- A threshold
- $P<P_{th}$, before the condensation of magnons





Spin current induced magnons

Chemical potential of quasi-equilibrium magnon gas driven by pure spin current

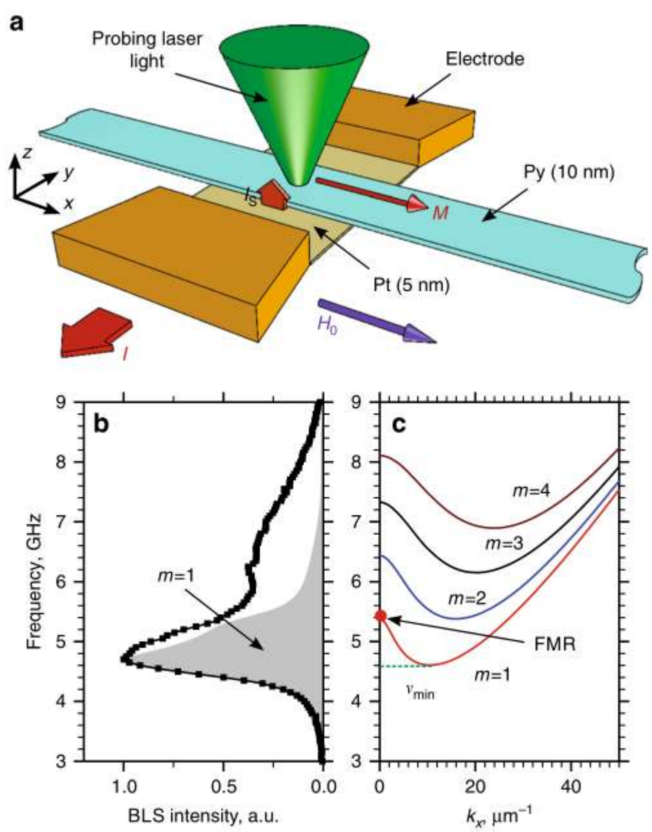
V.E. Demidov[1], S. Urazhdin[2], B. Divinskiy[1], V.D. Bessonov[3], A.B. Rinkevich[3], V.V. Ustinov[3,4] & S.O. Demokritov[1,3] 2017

- Spin-Hall effect
- Ferromagnetic Permalloy (Py) strip+Pt
- Magnetization of Py: 10.2KG
- Spin current//M
- Microfocus Brillouin light scattering (BLS) technique

  $\rho(\nu) = D(\nu)n(\nu)$

  ρ: spectral density of magnons

- $k_y = \pi m/w$



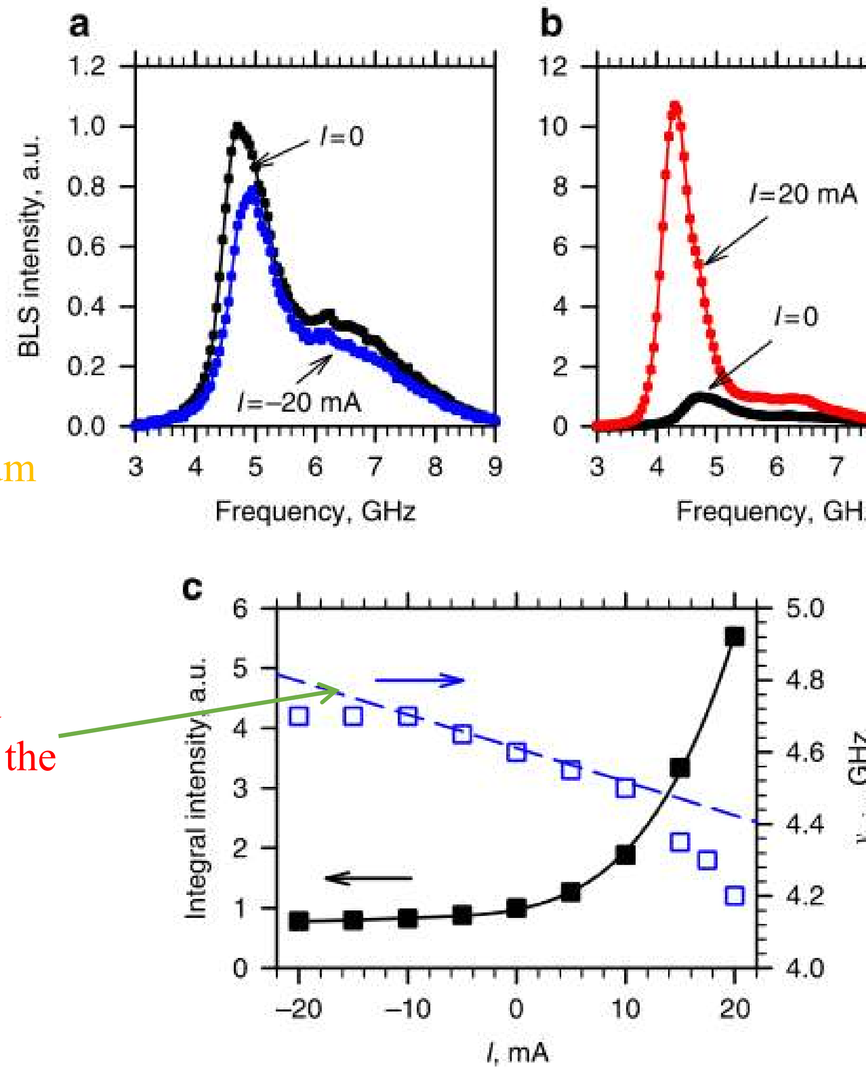
Spin current induced magnons

- H_0=200Oe

$$\rho_0(\nu) = D(\nu)n_0(\nu)$$

thermal equilibrium

$$\rho_I(\nu) = D(\nu)n_I(\nu)$$

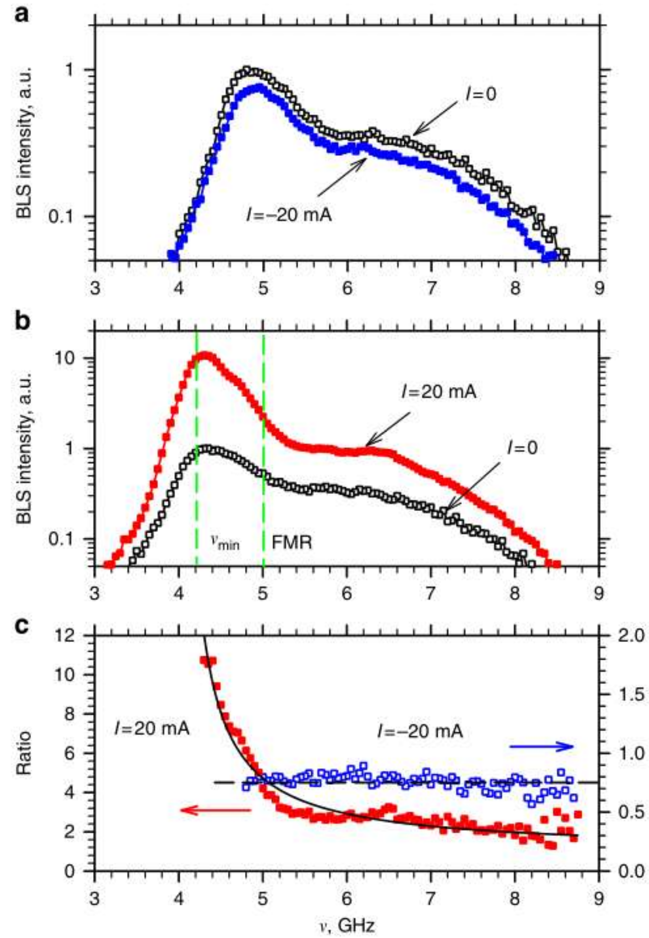


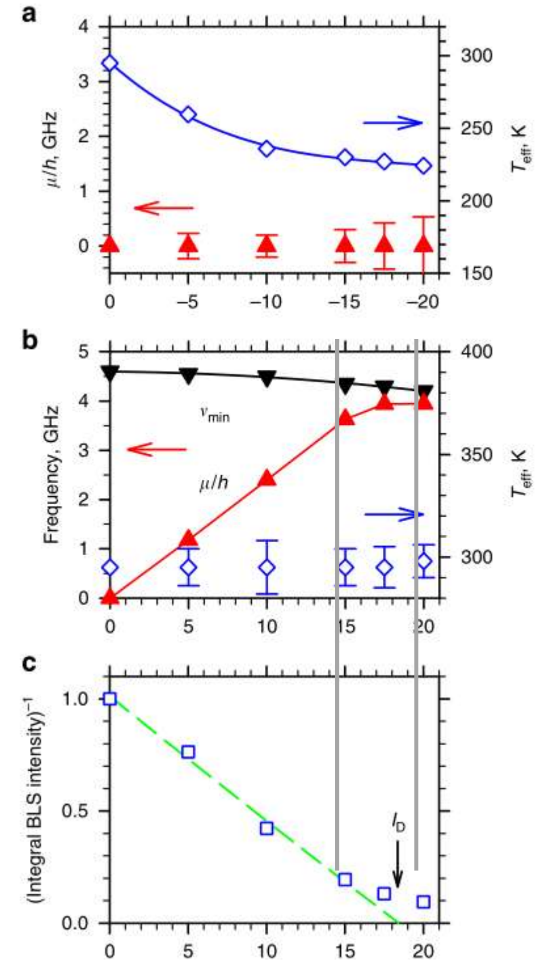
Oersted field of the current

Spin current induced magnons

$$n_0(\nu) = k_B T_0 / h\nu$$
$$n_I(\nu) = k_B T_{eff} / (h\nu - \mu)$$
$$R(\nu) = \frac{n_I(\nu)}{n_0(\nu)} = \frac{T_{eff}}{T_0} \frac{\nu}{\nu - \mu / h}$$

- T_{eff}: frequency independent scaling of R
- μ: a comprehensive modulation on R(ν)



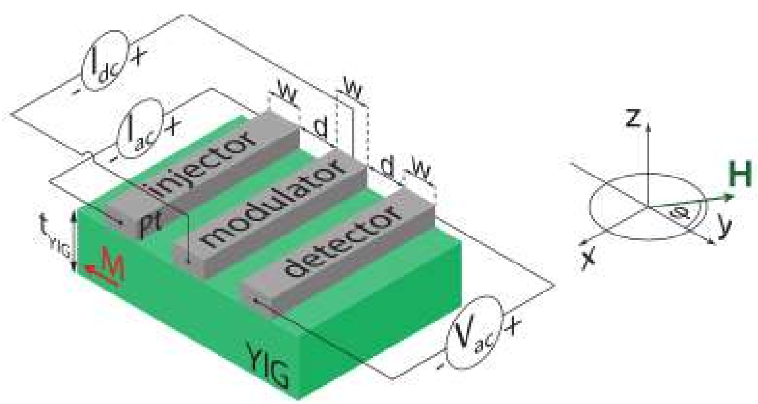


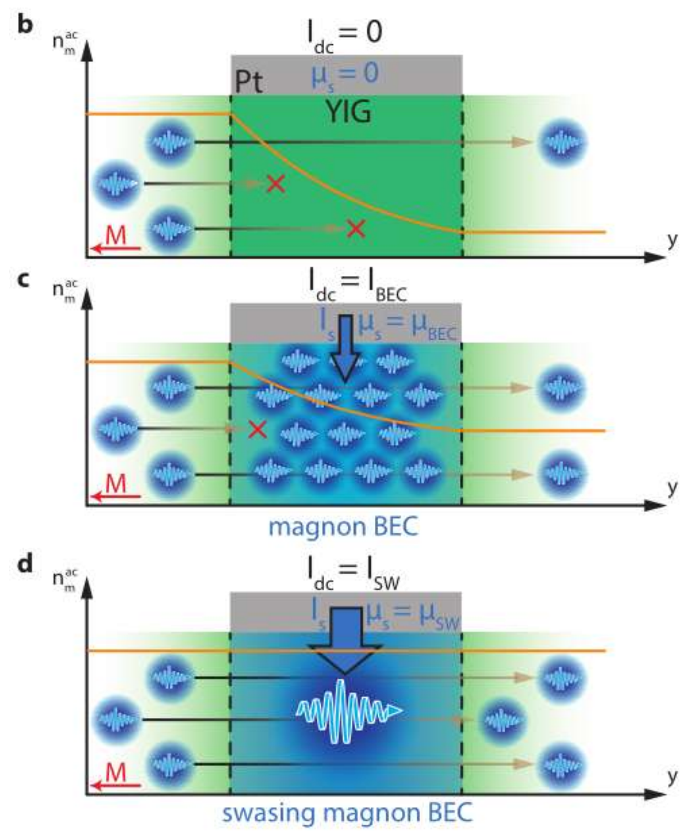
Current induced and detected mBEC

Spin transport in a charge current induced magnon Bose-Einstein condensate at room temperature

T. Wimmer,[1,2,*] M. Althammer,[1,2,†] L. Liensberger,[1,2] N. Vlietstra,[1]
S. Geprägs,[1] M. Weiler,[1,2] R. Gross,[1,2,3] and H. Huebl[1,2,3,‡]

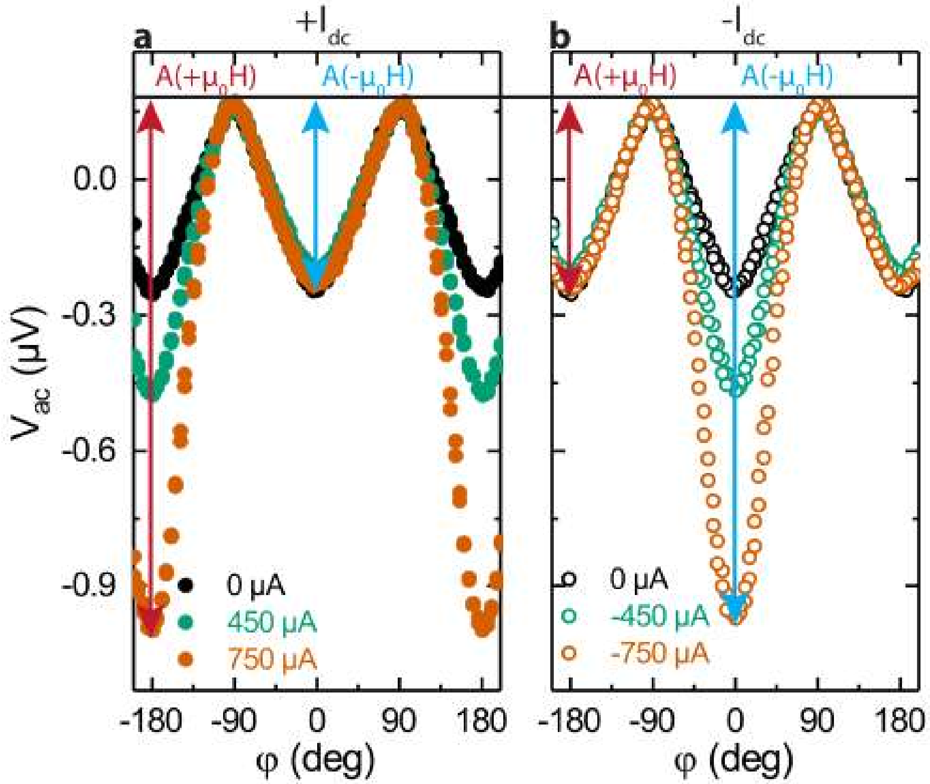
- Dissipationless magnon transport
- $I_{dc} = 0$, nac from the injector decays exponentially
- $I_{dc} = I_{BEC}$, formation of magnon BEC
- $I_{dc} = I_{SW}$, magnon damping is completely compensated





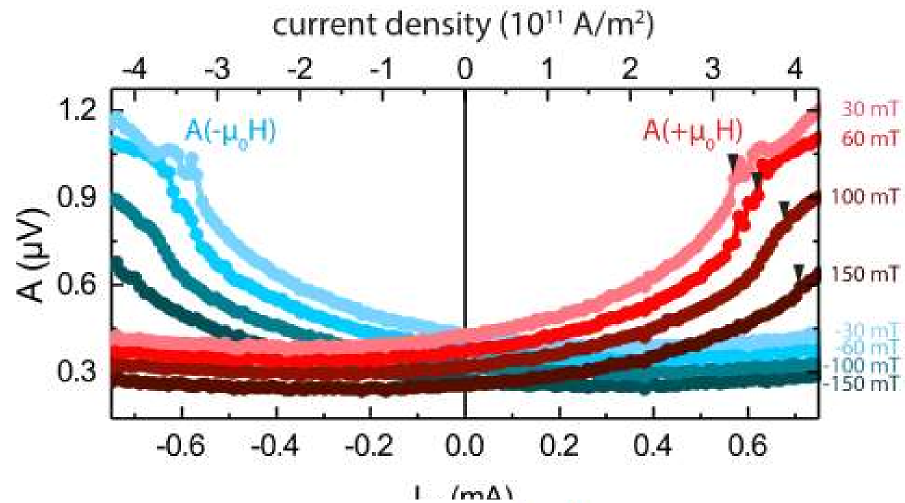
Current induced and detected mBEC

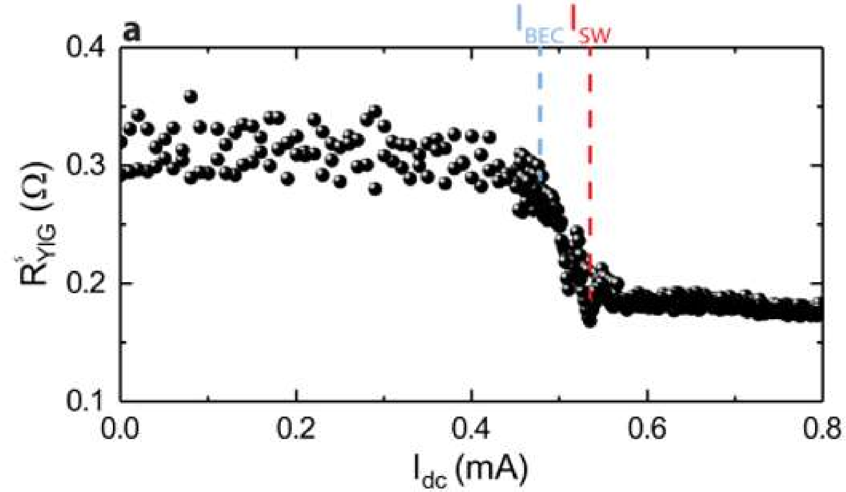
- μ_0H = 50mT, T = 280K
- ϕ=±180 ◦ , magnon accumulation underneath the modulator
- ϕ=0 ◦, magnon depletion obtained in this configuration



Current induced and detected mBEC

- Linear dependence: SHE induced injection effects
- Quadratic dependence: thermal activation





Thank you for your attentions!