Bose-Einstein condensation of magnons at RT

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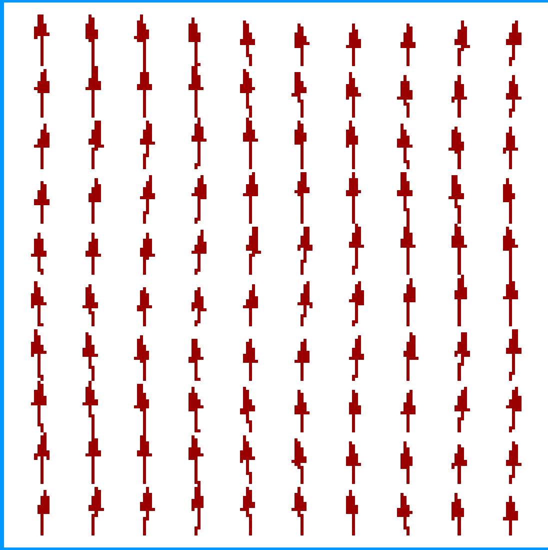
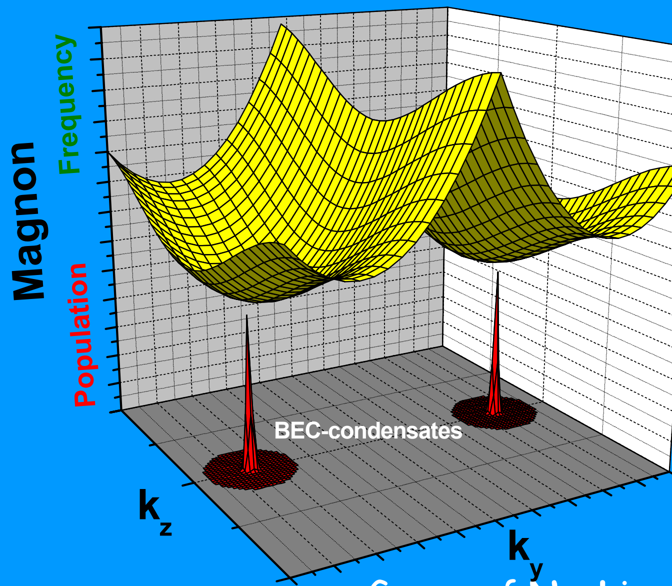


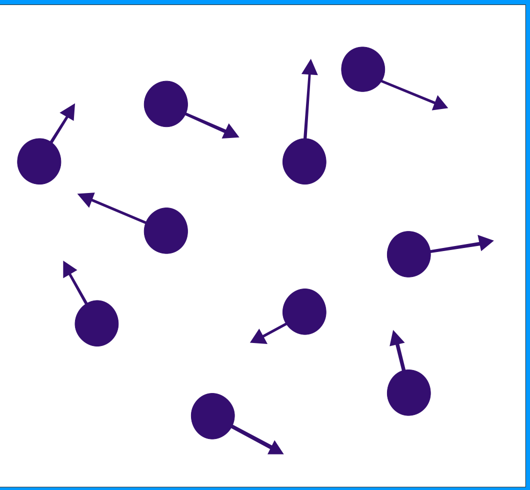
Magnons: quanta of spin waves



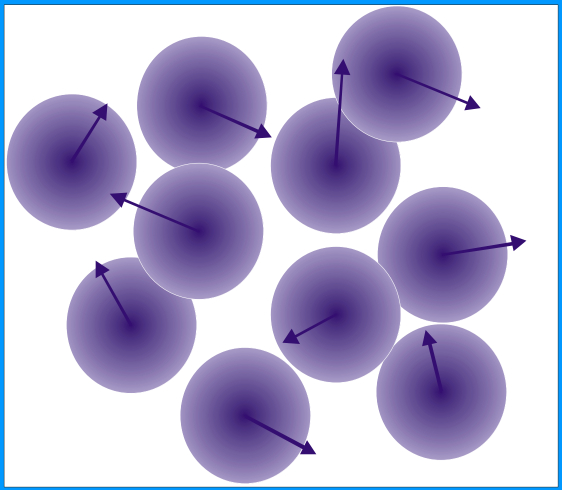
Group of NonLinea
Magnetic Dynami

Bose-Einstein-Condensation

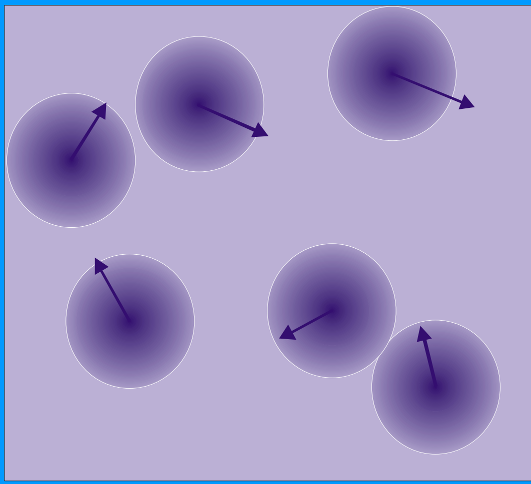
classical gas



quantum gas



BEC



Condition of quantum gas:

$$\lambda = \frac{2\pi\hbar}{p} \approx \sqrt{\langle r^2 \rangle} = N^{-1/3}$$

$$kT \approx \frac{p^2}{2m}$$

$$kT_c = 3.31\frac{\hbar^2}{m}N^{2/3}$$

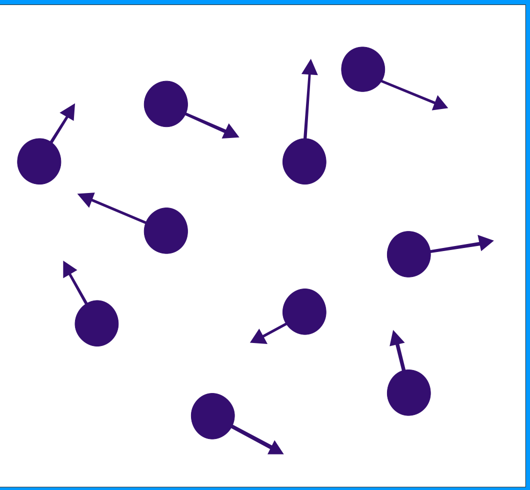
Thermodynamics of BEC:

$$n = \frac{1}{\exp\left(\frac{E-\mu}{kT}\right) - 1}$$

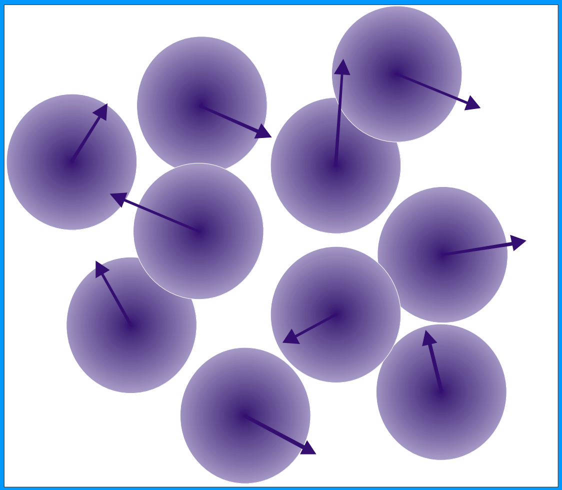
$$\mu = E_{\min}$$

Bose-Einstein-Condensation

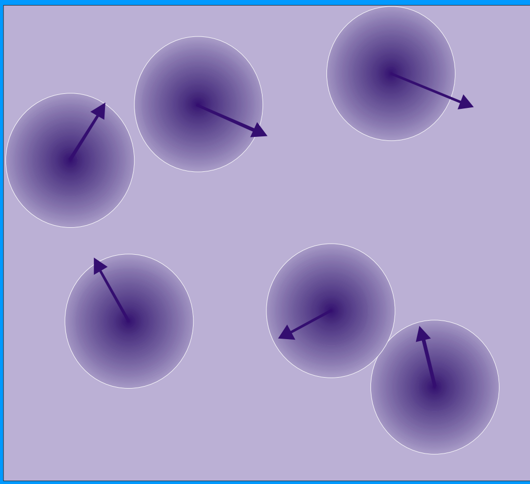
classical gas



quantum gas



BEC



Condition of quantum gas:

$$\langle \lambda \rangle \approx \sqrt{\langle r^2 \rangle} = N^{-1/3}$$

$$\lambda = \frac{2\pi\hbar}{p} \qquad kT \approx \frac{\langle p^2 \rangle}{2m}$$

$$\boxed{\begin{aligned} kT_c &= 3.31\frac{\hbar^2}{m}N^{2/3} \\ N_c^{2/3} &= kT\frac{m}{3.31\hbar^2} \end{aligned}}$$

Thermodynamics of BEC:

$$n = \frac{1}{\exp\left(\frac{E-\mu}{kT}\right)-1}$$

$$\mu = E_{\min}$$

Presented at the PITP/SpinAps Asilomar Conference in June 2007

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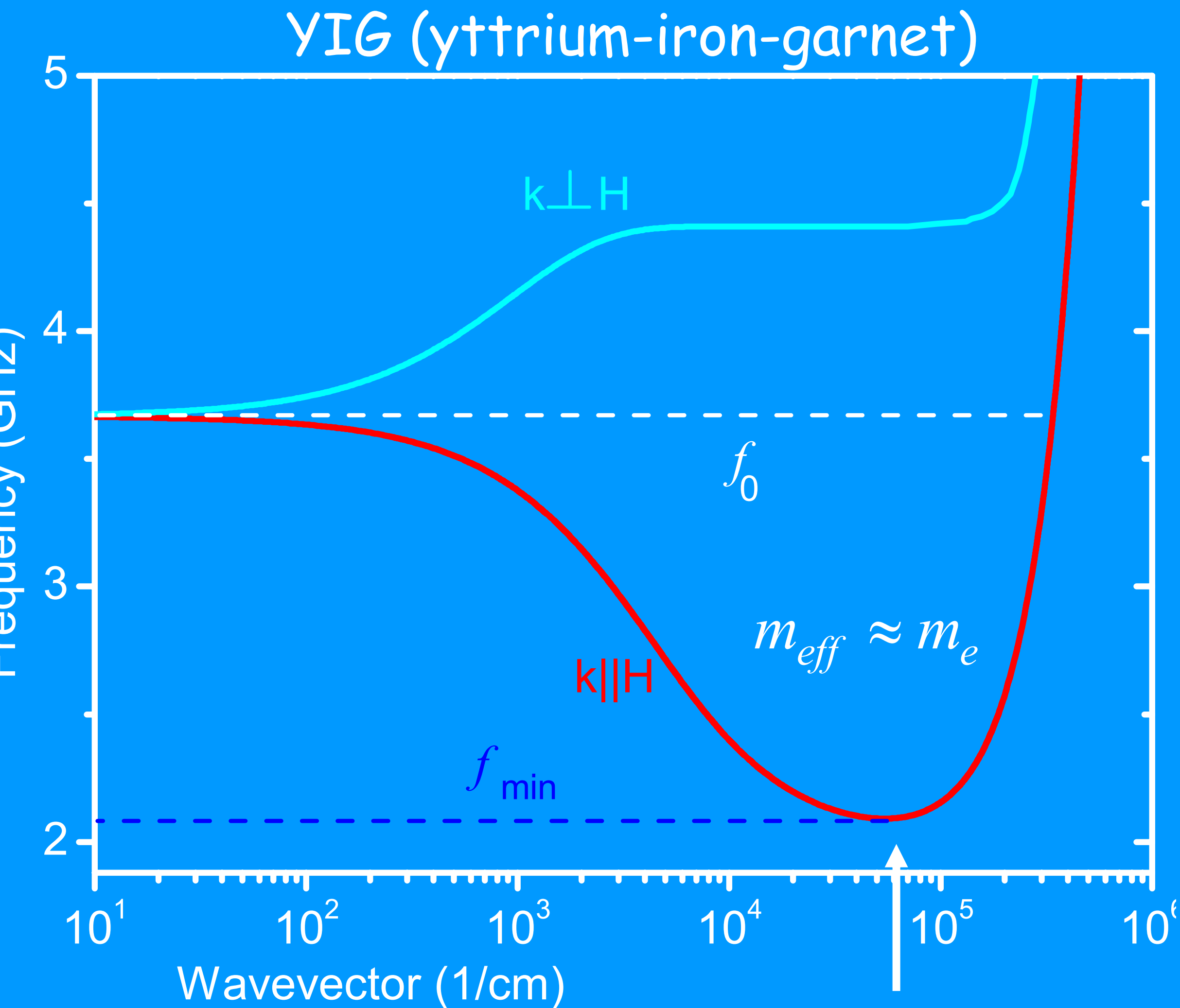
Magnons in ferromagnetic films



$$k_m \approx 0.55\times 10^5\, cm^{-1}$$

Transparen Ferro(i)magn
Films 5 μm thick

$$RT: \quad N \approx 3\cdot 10^{21}\, cm^{-}$$

$$E_{\min} = h\times 2GHz =$$
$$= k_B \times 100mK = 10\mu e$$

In equilibrium:

$$\mu = 0$$

(Thermo)dynamic of magnons

In equilibrium:

Magnons are quasi-particles with variable *N*, therefore the chemical potential is zero $\mu = 0$.

Due to field/dipole-dipole-interection the spectrum has a gap, i.e. $E_{min} > 0$.

No BEC possible.

(Thermo)dynamic of magnons

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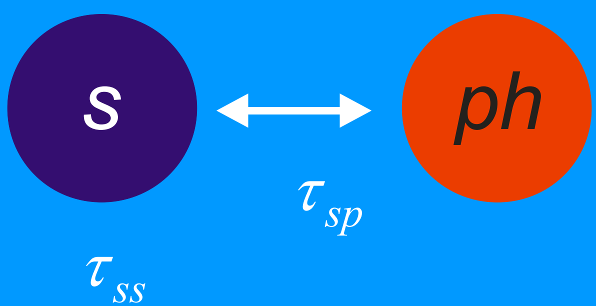
No BEC possible.

In quasi-equilibrium:



Two important time scales.

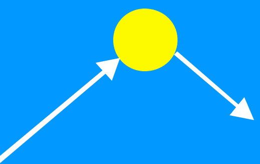
For YIG:

$$\tau_{ss} \approx 10 - 50 ns$$

$$\tau_{sp} \approx 0.3 - 0.5 \mu s$$

For the time scale from 30 ns to 0.3 μs spins are an isolated, thermalized system

Mechanisms of magnon thermalization



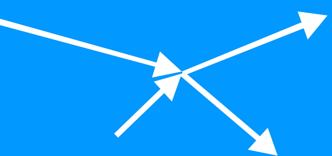
Two-magnon scattering

$$\omega_1 = \omega_2$$

$$k_1 \neq k_2$$

Impurity-scattering, linear effect
(independent of the magnon dens

Elastic, *k*-thermalization



Four-magnon scattering:

$$\omega_1 + \omega_2 = \omega_3 + \omega_4$$

$$k_1 + k_2 = k_3 + k_4$$

Nonlinear effect
(increase with increasing density)

Inelastic, ω,*k*-thermalization

Two- and four-magnon scattering keep the number of magnons CONSTANT!!!

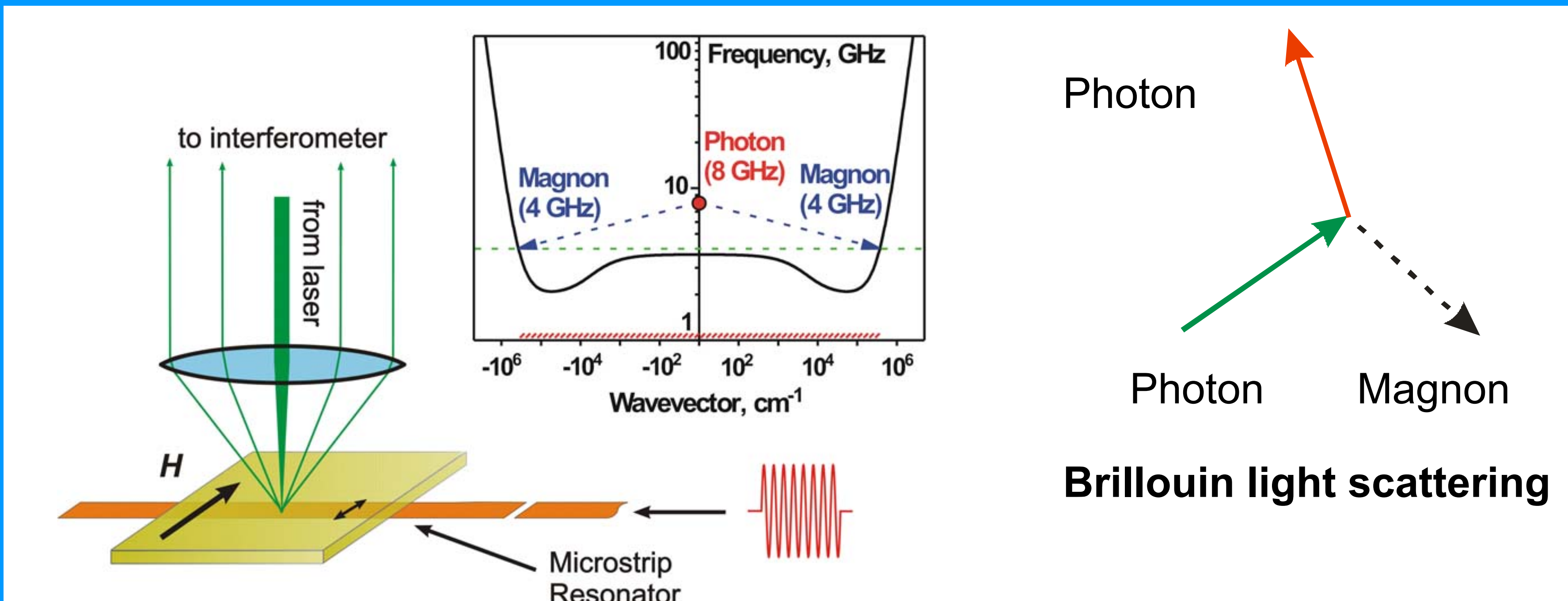
$$\mu \neq 0$$

Strategy to reach BEC of magnons

1. Inject cold magnons (parametric pumping)

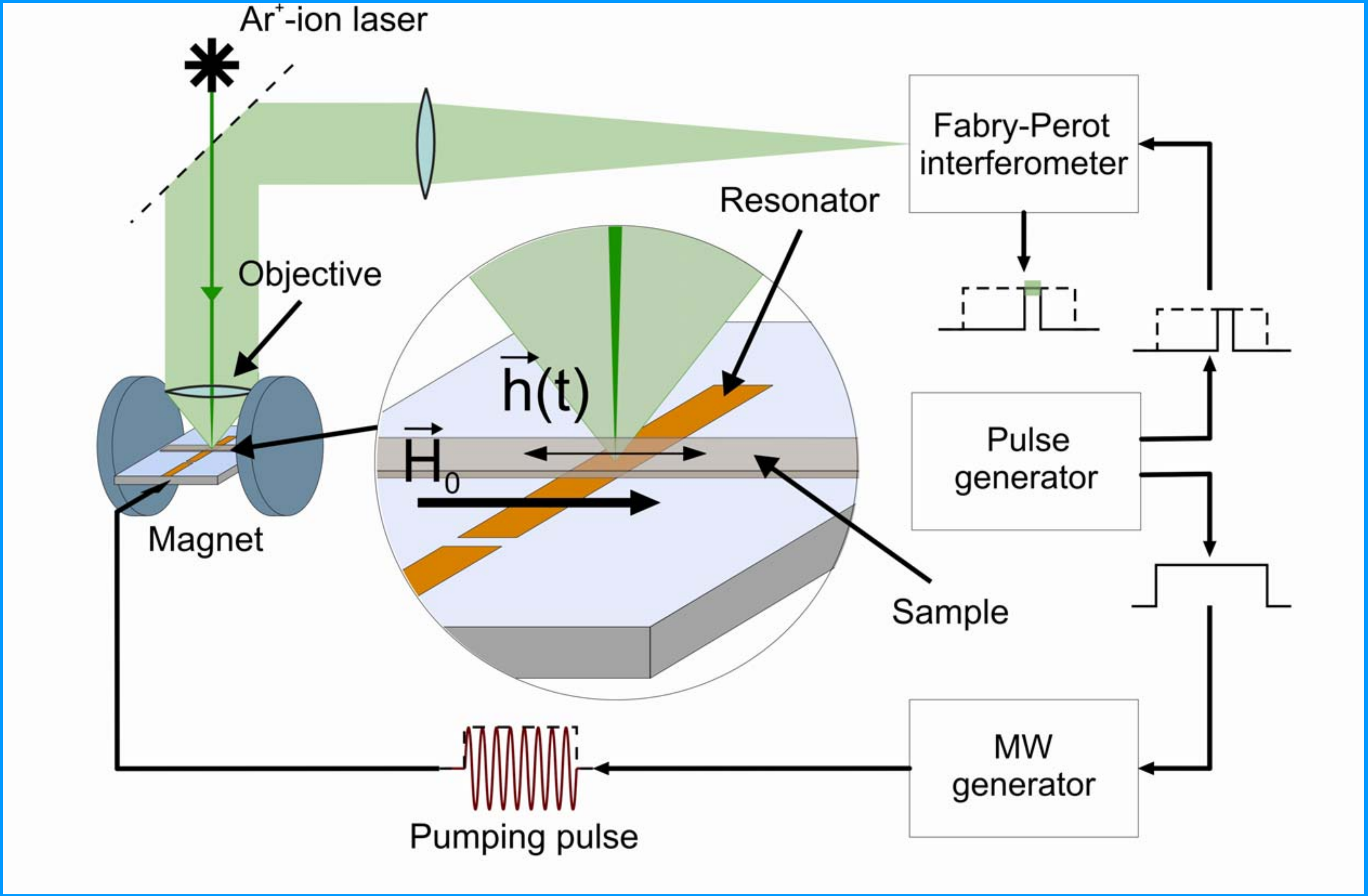
   a) step-like or b) pulse-like pumping

2. Wait and see what happens with magnon distribution

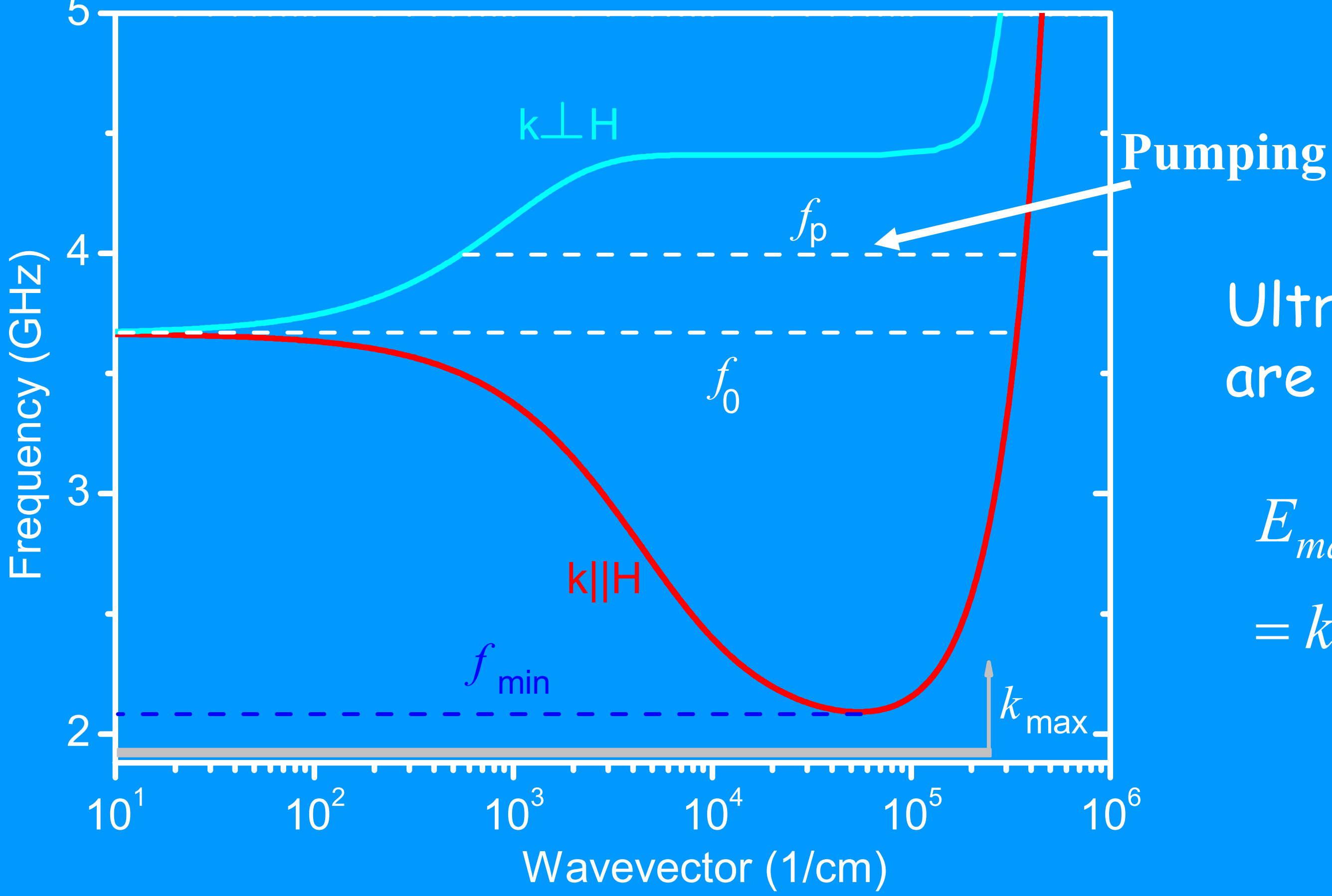


Magnons created by microwaves and detected by light scattering with time (and space) resolution

Experimental setup for time-resolved measurement



Pumped magnons

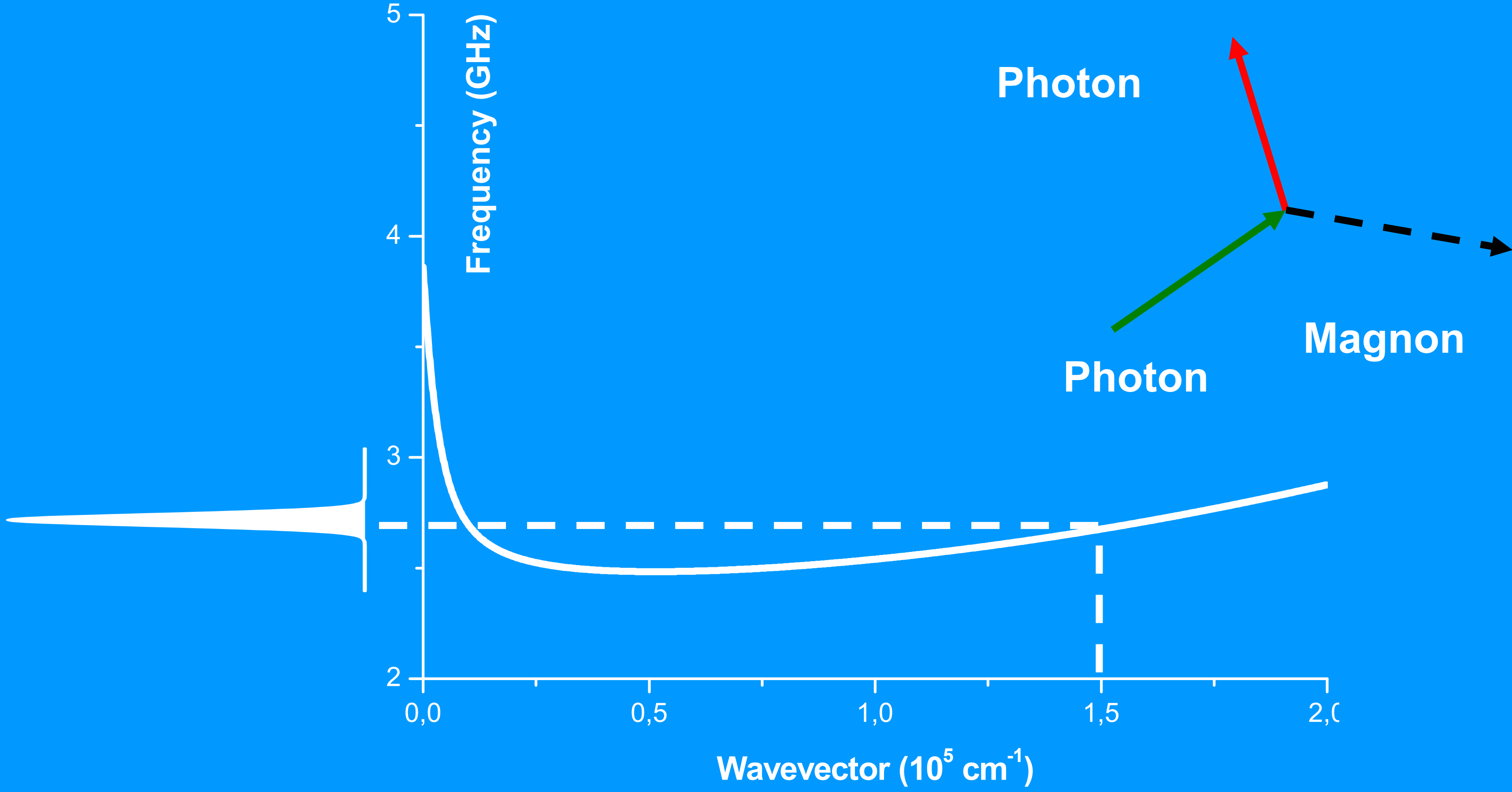


Ultra-cold magnons are pumped

$$E_{magnon} = h \times 4GHz =$$
$$= k_B \times 200mK$$

BLS spectroscopy

A well defined wavevecto



BLS spectroscopy

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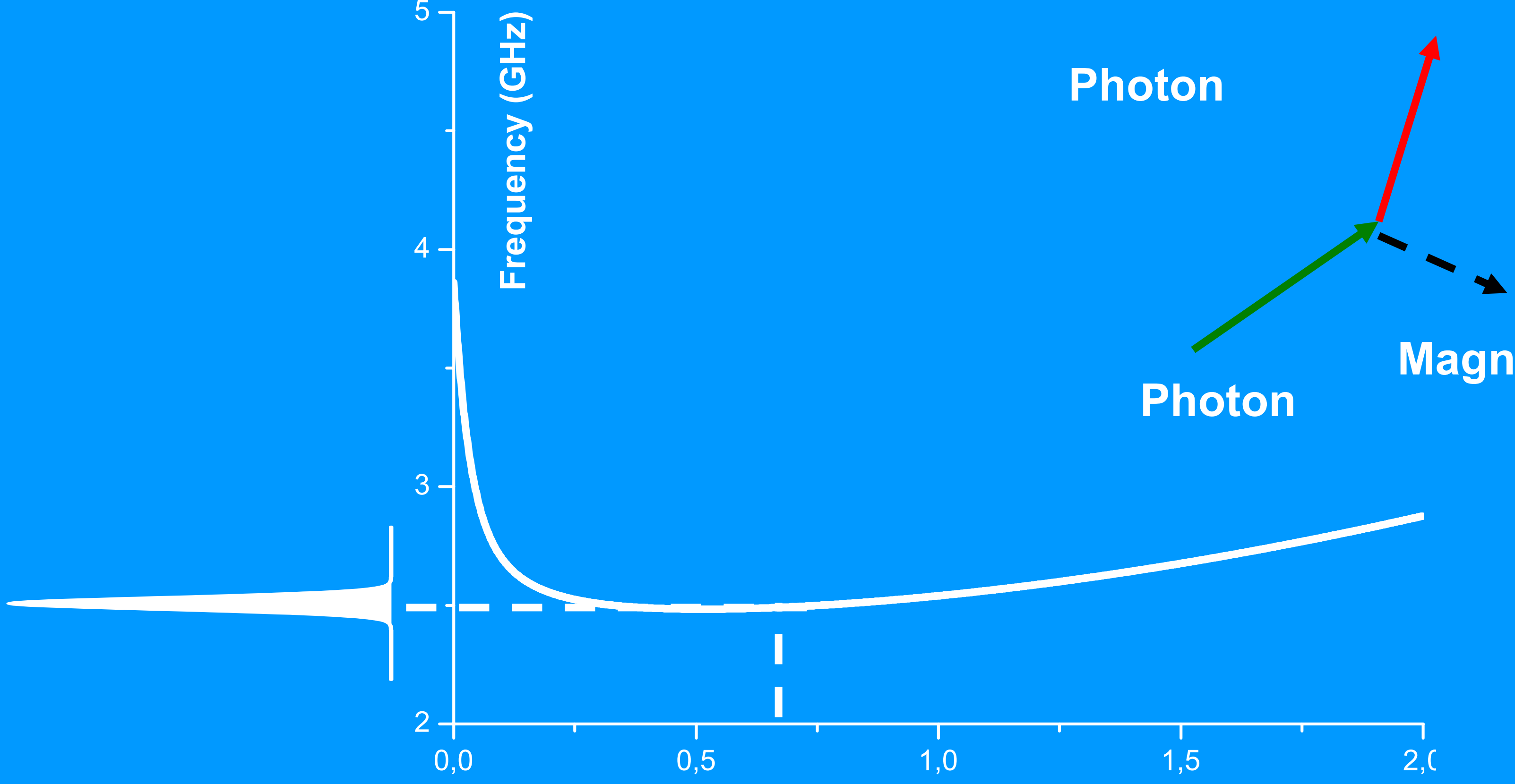
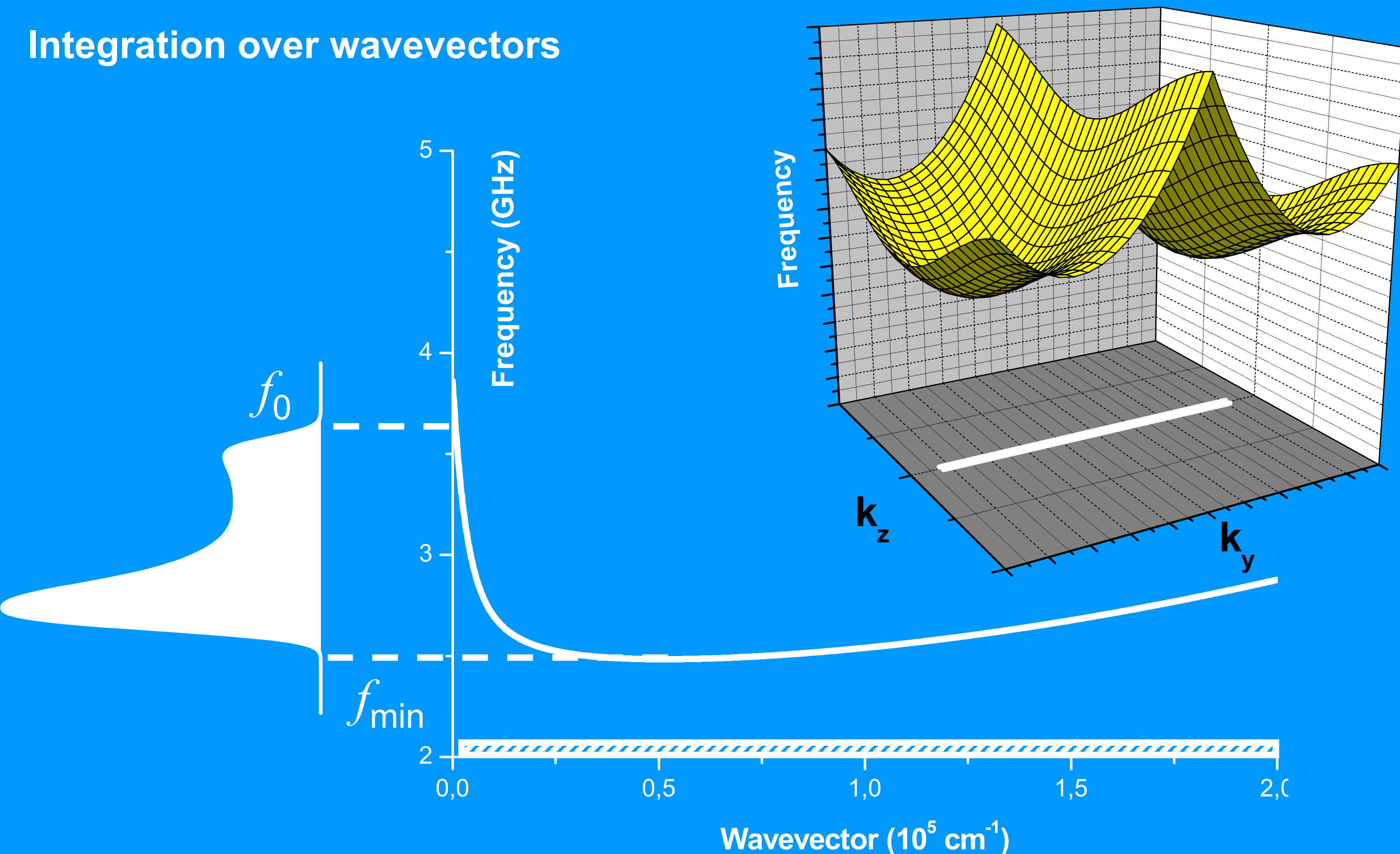
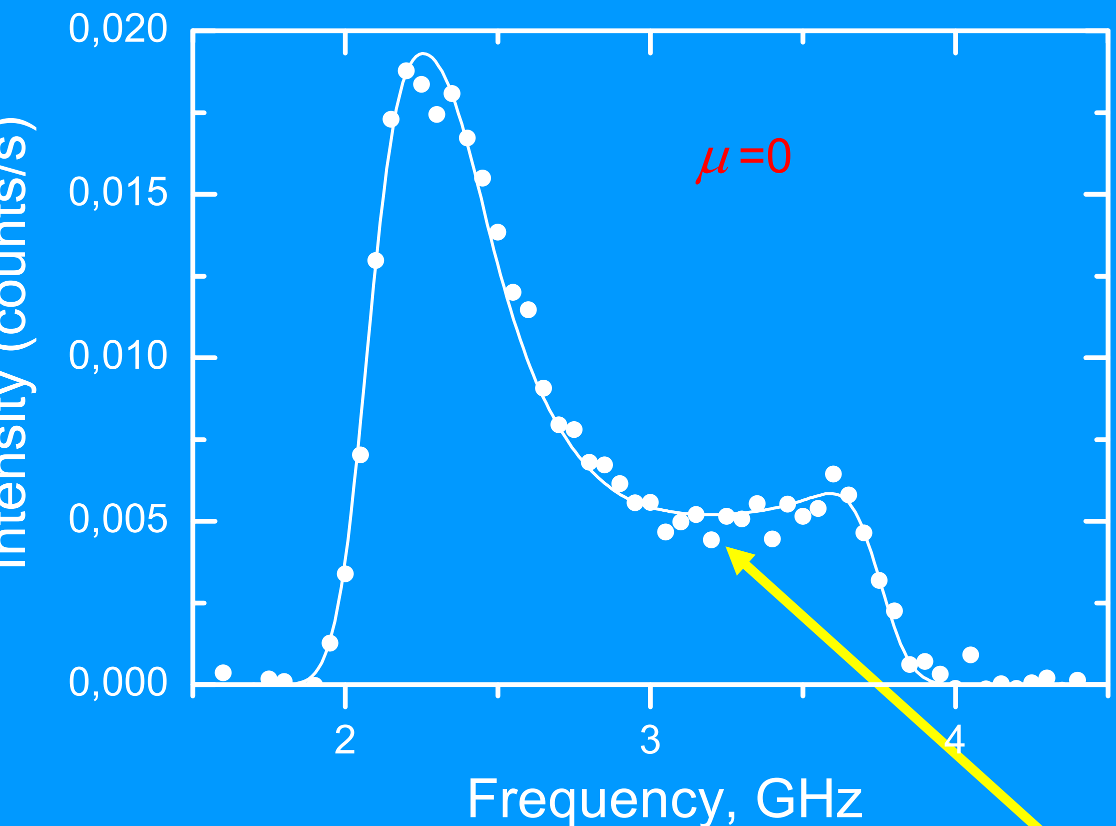


Integrated BLS spectrum

Integration over wavevectors



Thermal magnons



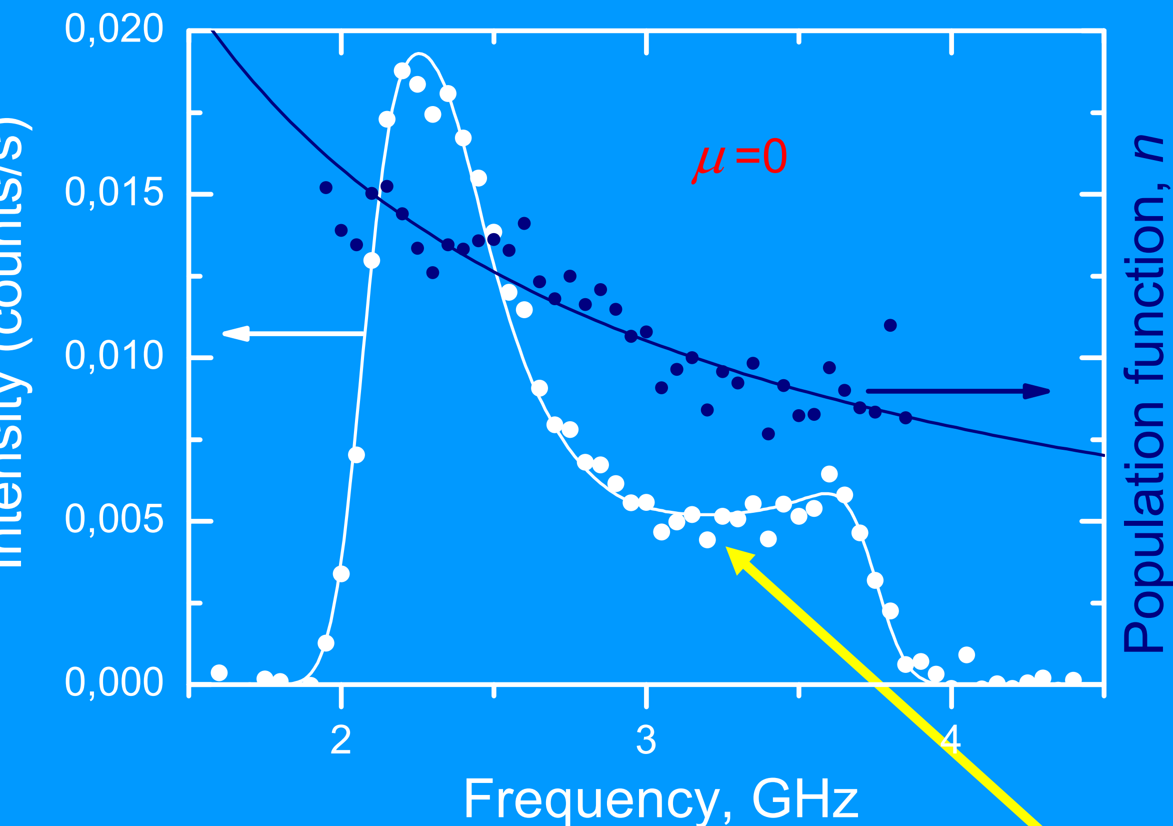
Thermally excited magnons are measured to determine DOS

Equilibrium: $\mu = 0$

$$n = \frac{1}{\exp\left(\frac{\hbar\omega}{kT}\right) - 1} \approx \frac{kT}{\hbar\omega}$$

BLS-intensity ~ $n \times DOS$

Thermal magnons



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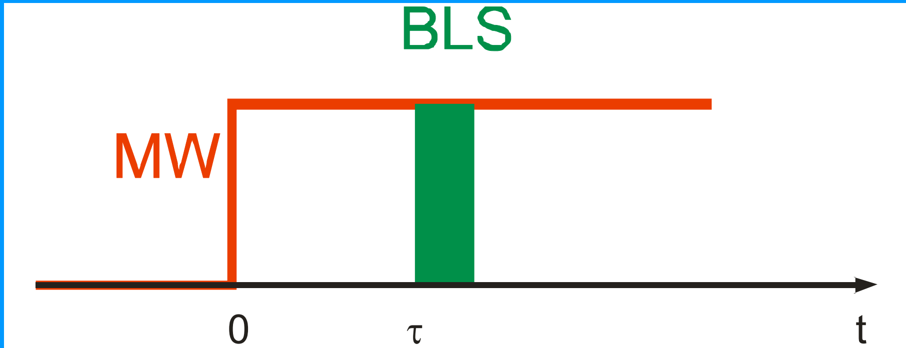
Equilibrium: $\mu = 0$

$$n = \frac{1}{\exp\left(\frac{\hbar\omega}{kT}\right) - 1} \approx \frac{kT}{\hbar\omega}$$

BLS-intensity ~ n×*DOS*

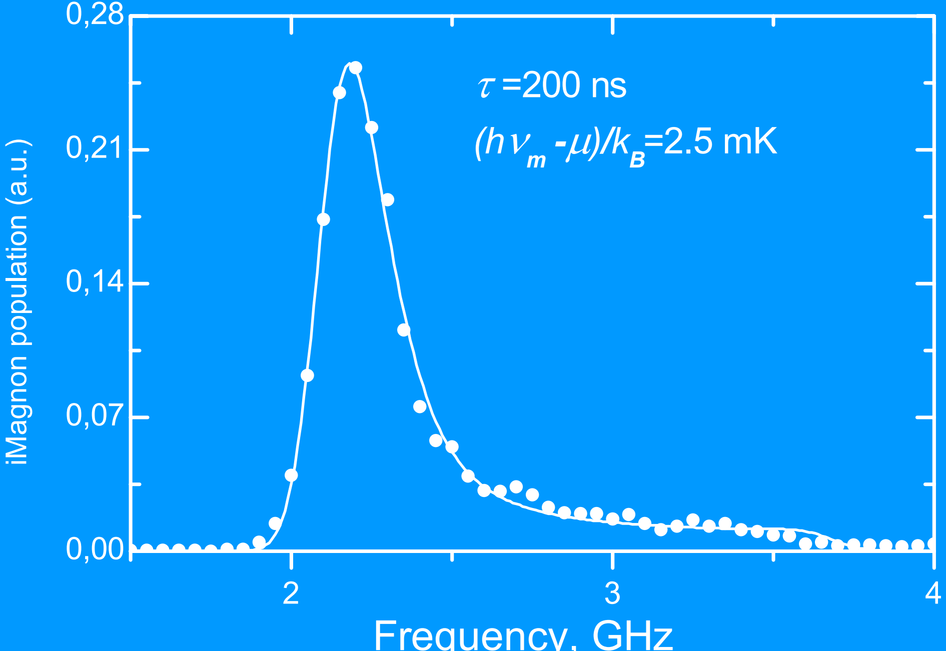
Pumped magnons (step-like pumping)

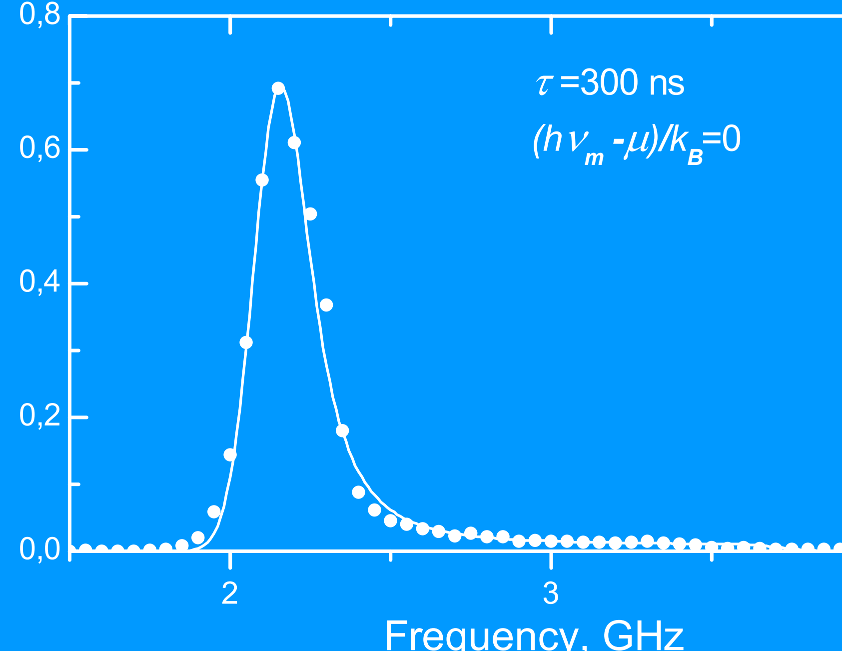


Time development of magnon distribution

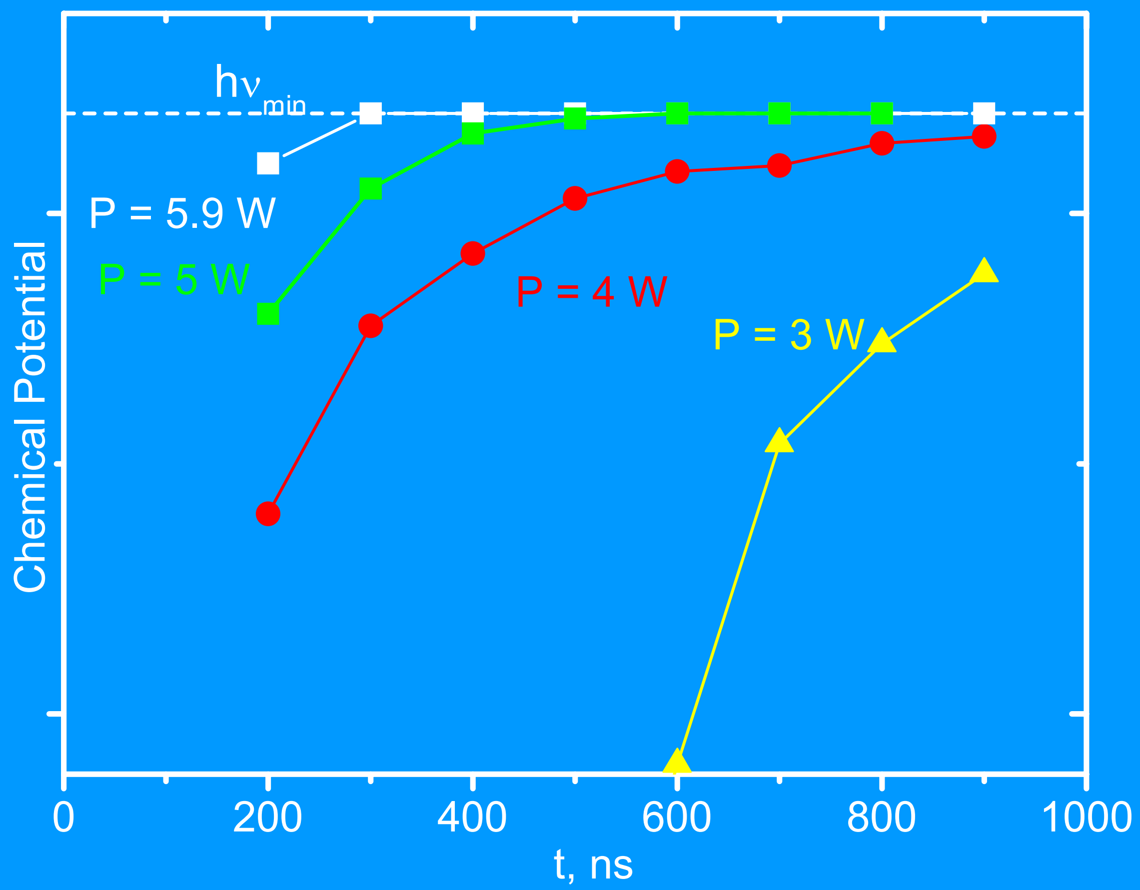
P = 5.9 W

Known DOS: $n(\omega)$ **fit with** μ





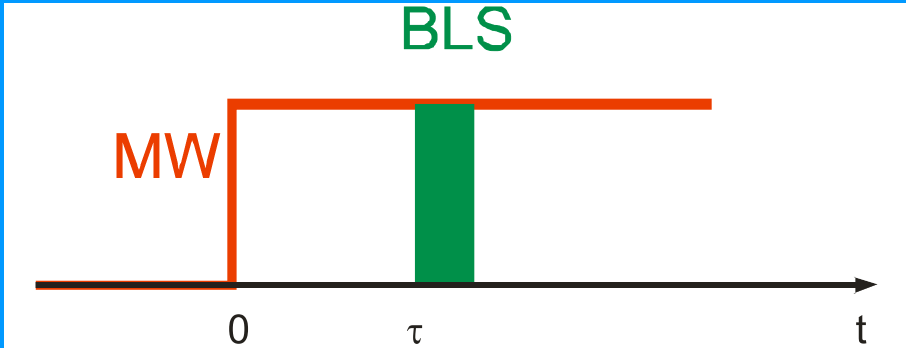
Time dependence of the chemical potential



Using pumping one can reach the critical density of magnons

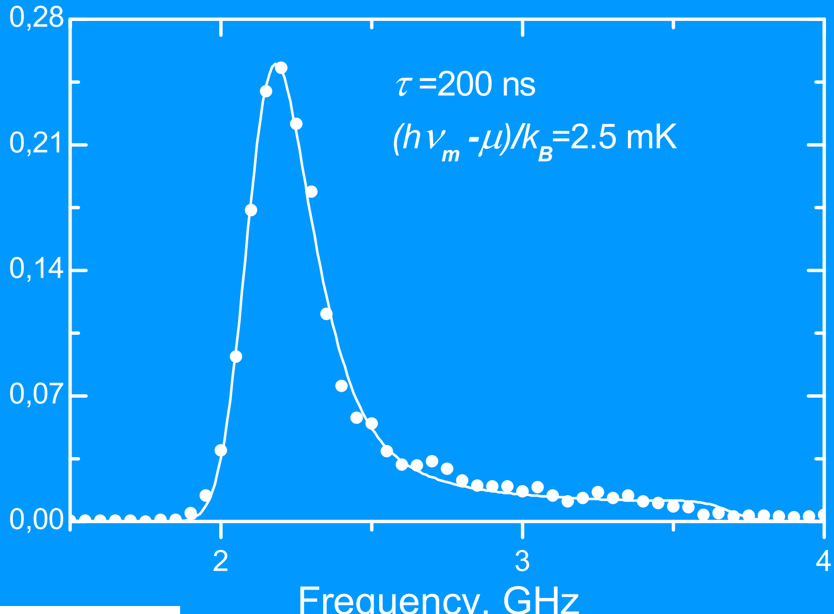
J. Appl. Phys.

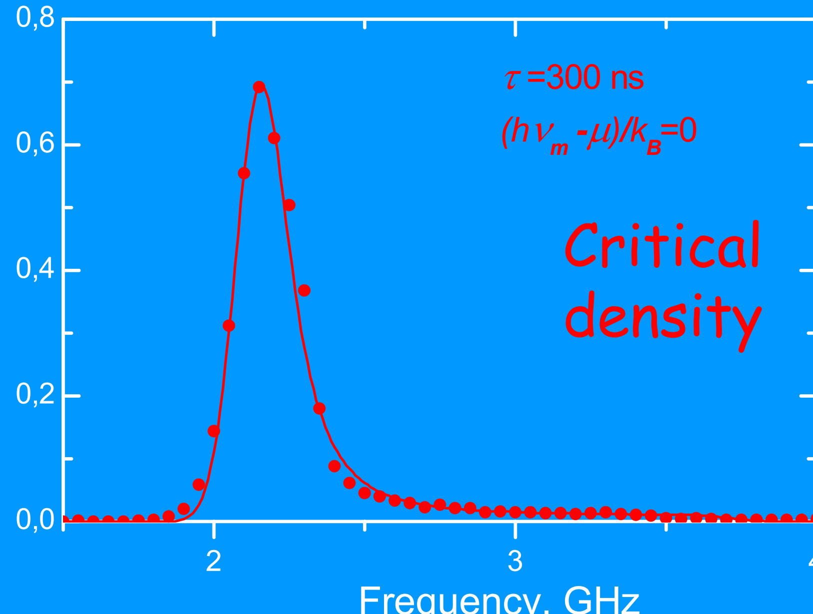
Pumped magnons



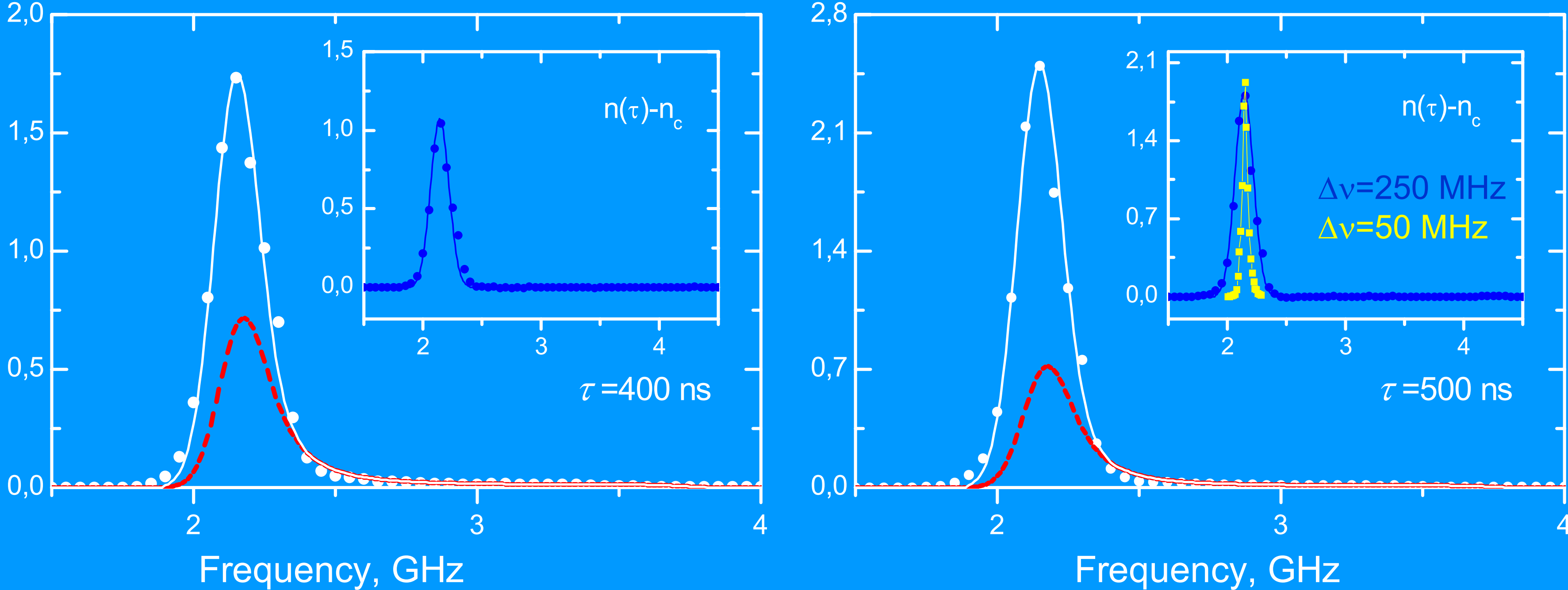
Time development of magnon distribution is measured.

Known DOS: $n(\omega)$ **fit with** μ, T





Magnon distribution above the critical density



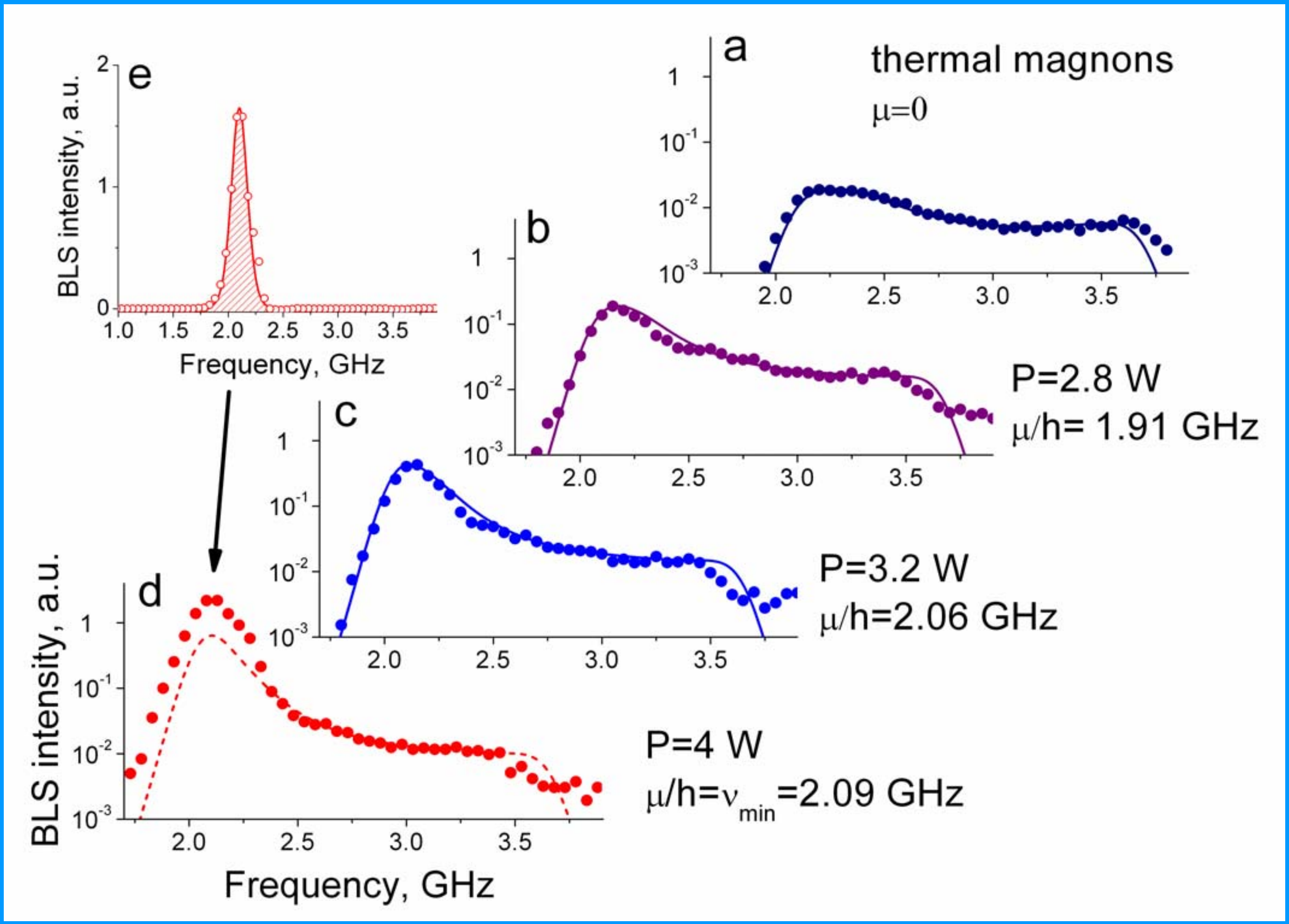
The addition to the critical density is of δ – type (width is 2mK, i.e. 10^{-5}kT).

A condensate is created

Nature '06

BEC in a stationary case

Stationary state due to spin-lattice relaxation



Magnon distributio
at τ=800 n

Variable power

New J. Phys. ´07.

Two decisive questions

Do we reach quasi-equilibrium in the above experiments?

Is the obtained state COHERENT?

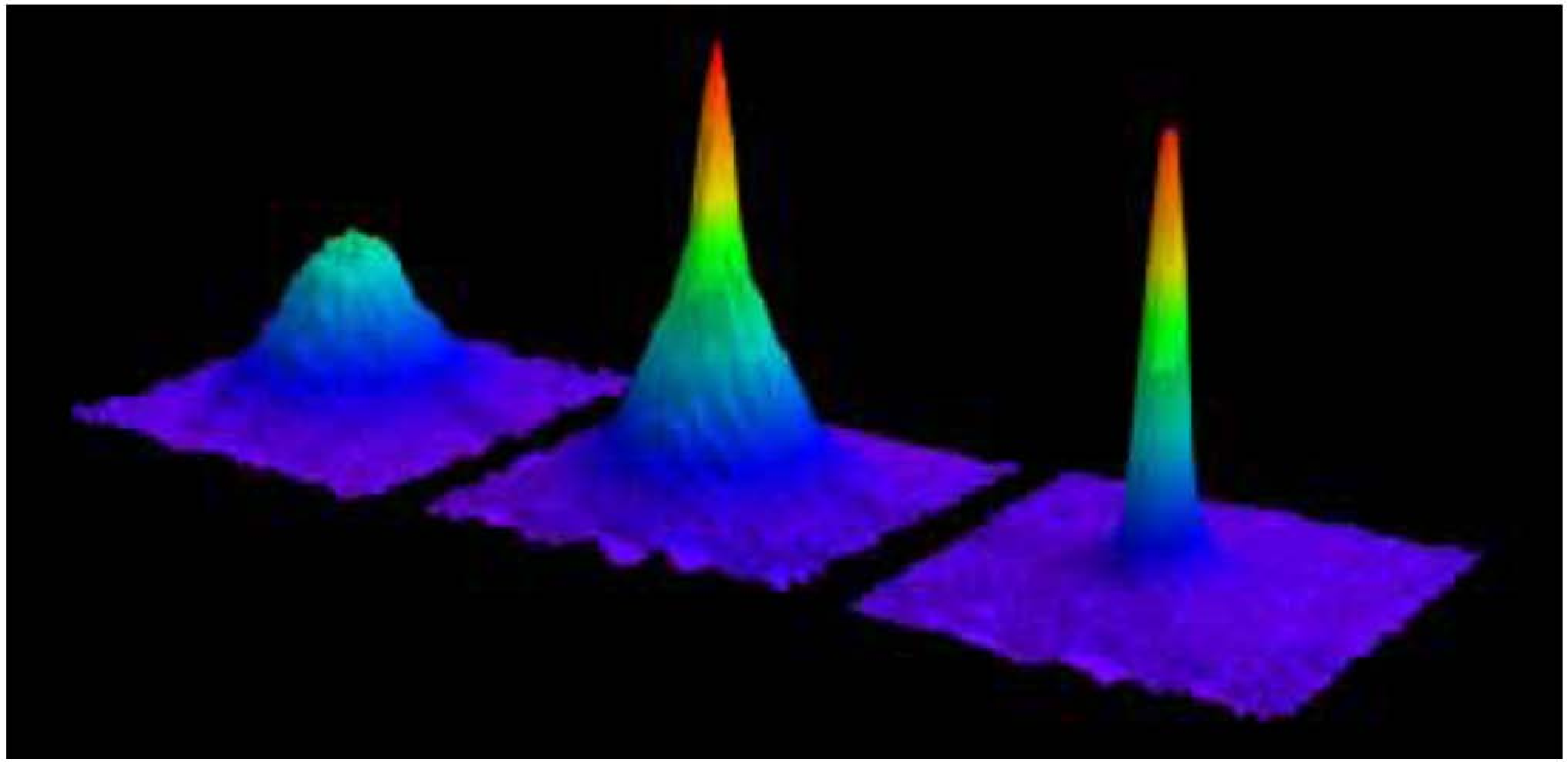
Two decisive questions

Do we reach quasi-equilibrium in the above experiments?

Is the obtained state COHERENT?

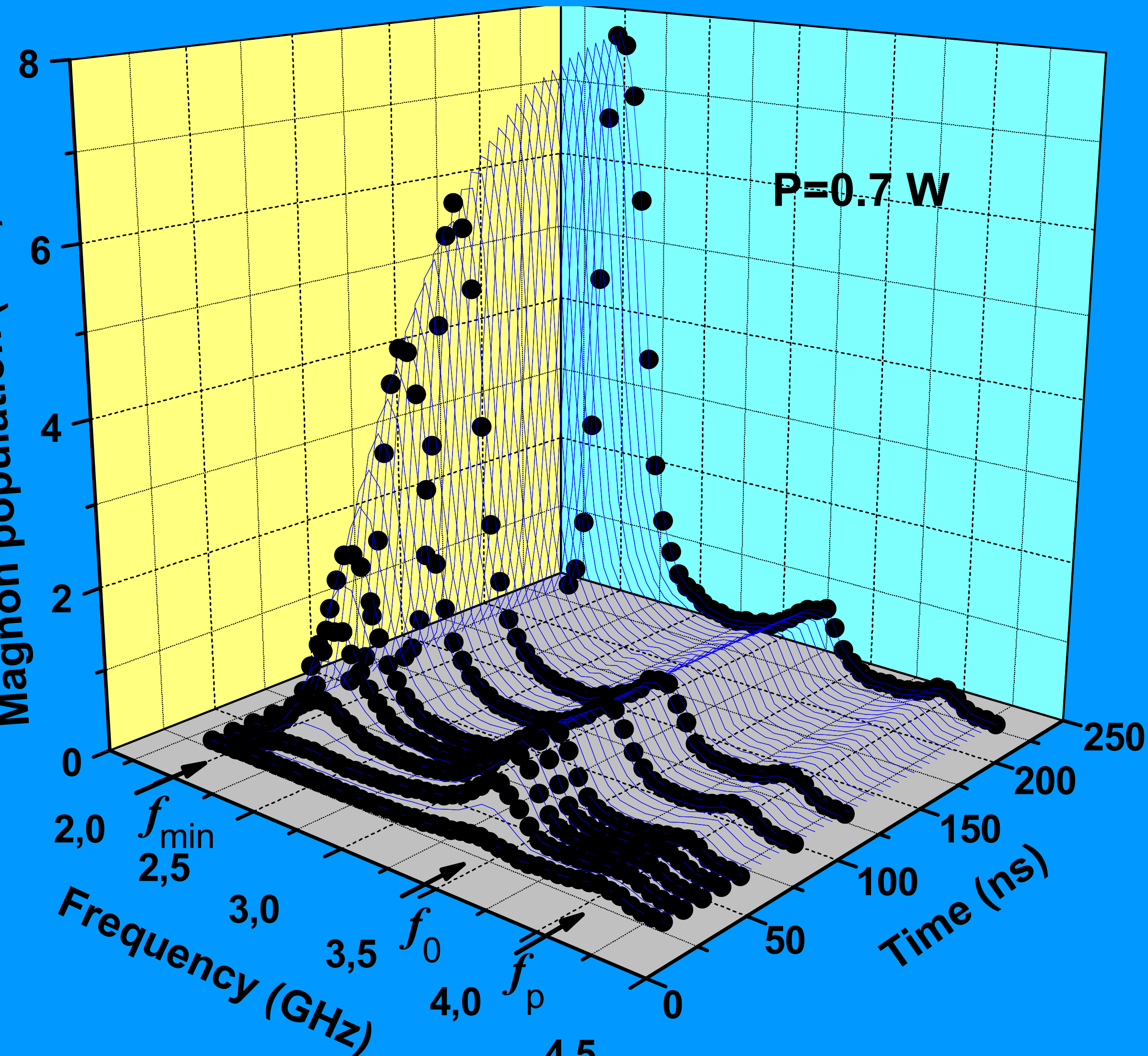
YES!!!

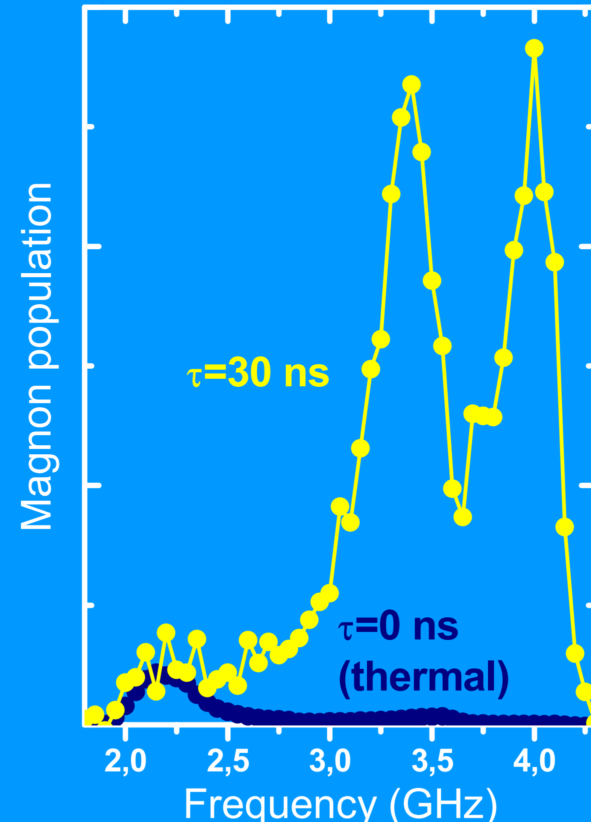
Thermalization: BEC of atoms



Livetime ≈ 30 s, thermalization time ≈ 2 s

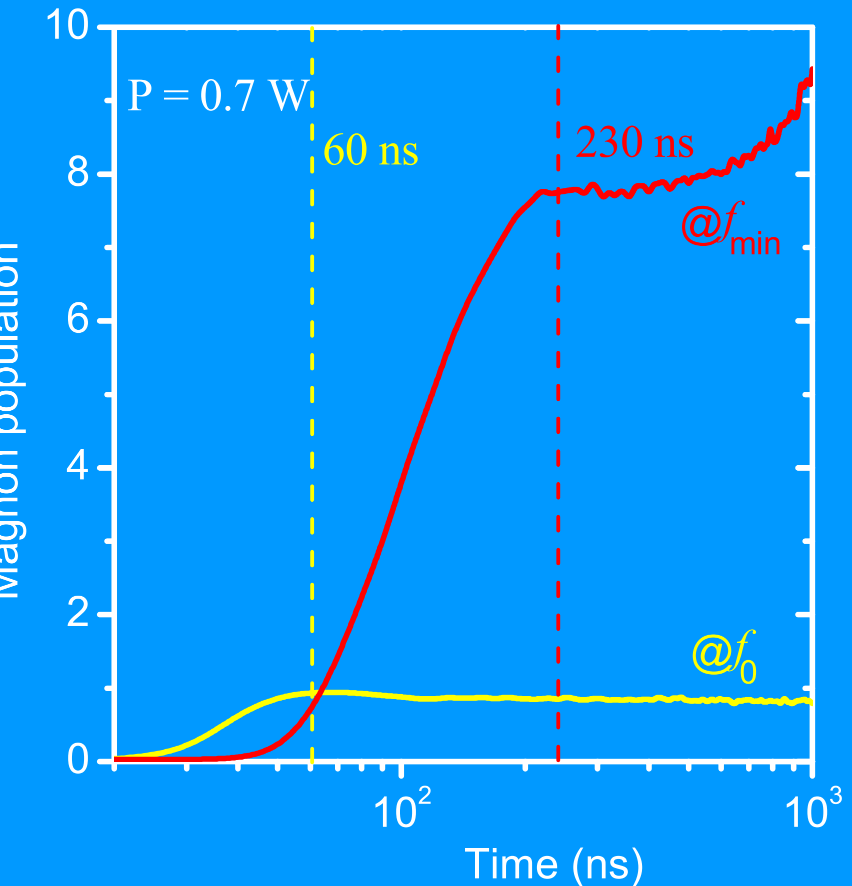
Magnon thermalization (step-like pumping)

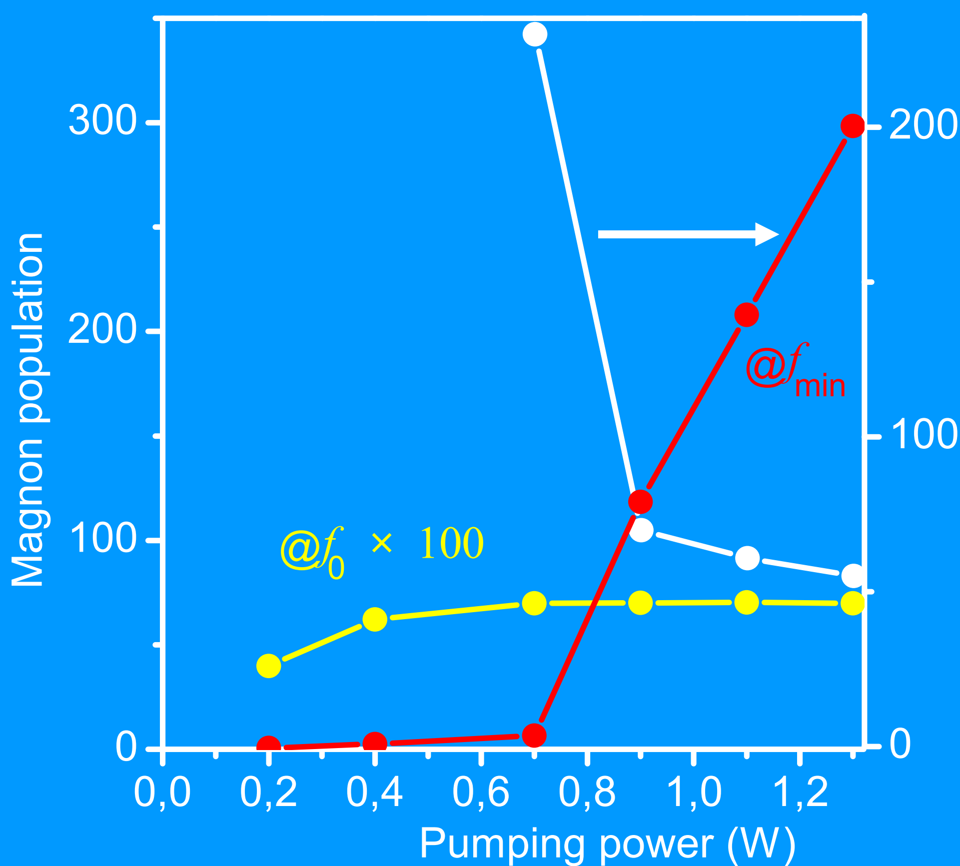




Thermalization happens „wave-like"

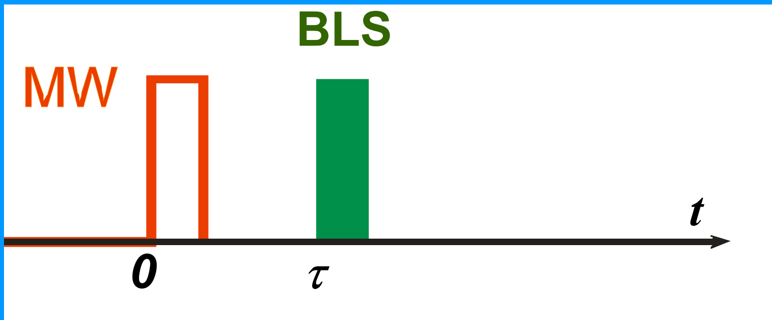
Thermalization time



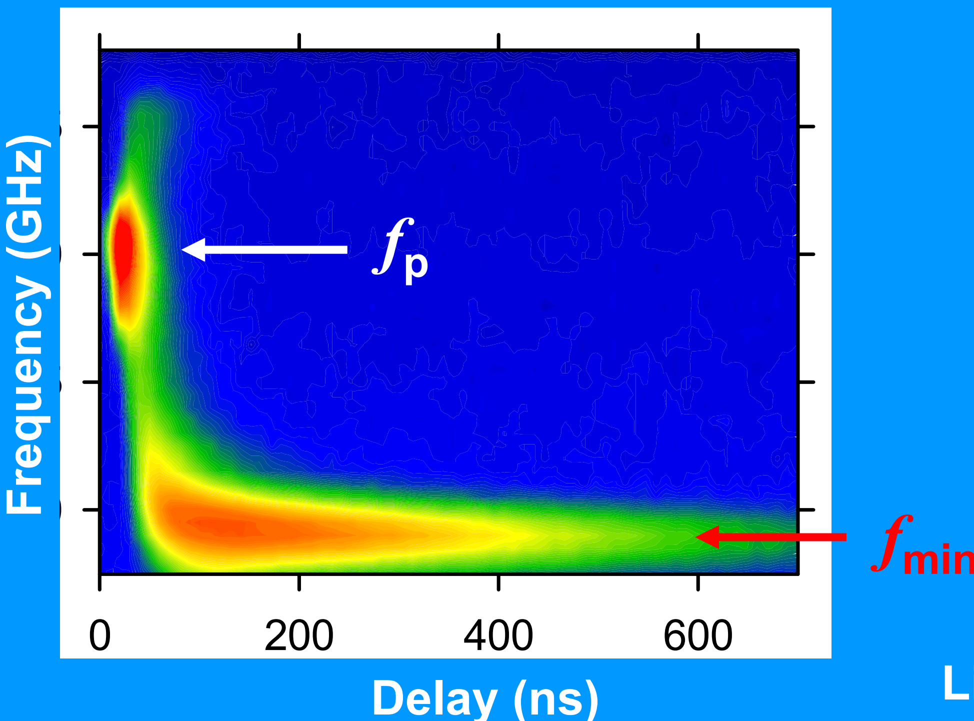


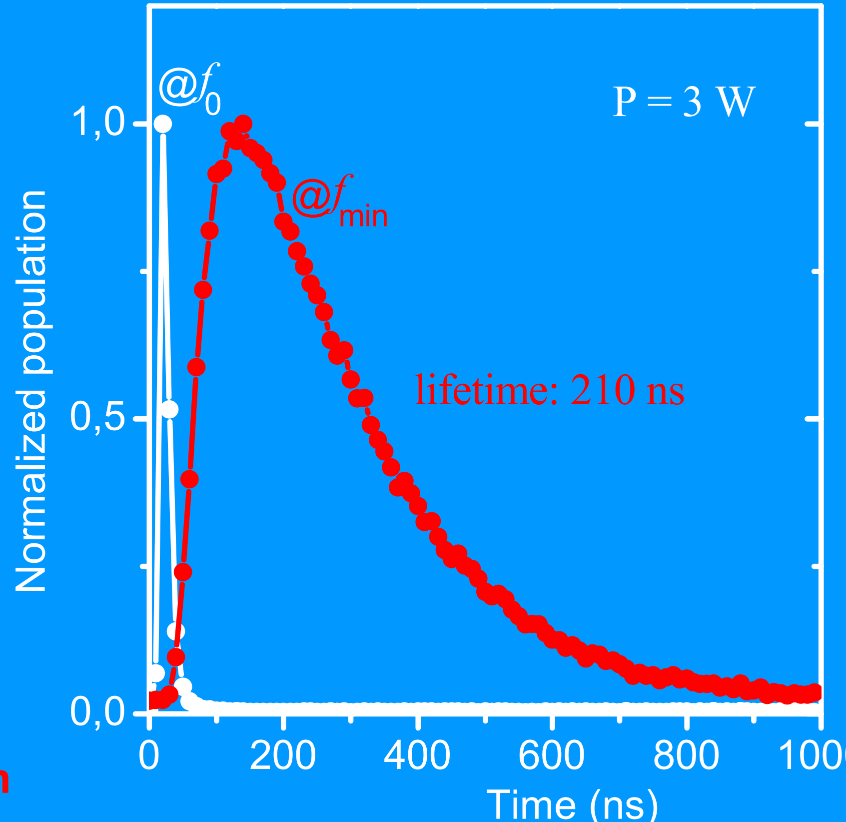
Thermalization time strongly depends on the pumping power (i.e., magnon density)
At the densities of BEC it is below 50 ns

Pumped magnons (pulse-like pumping)



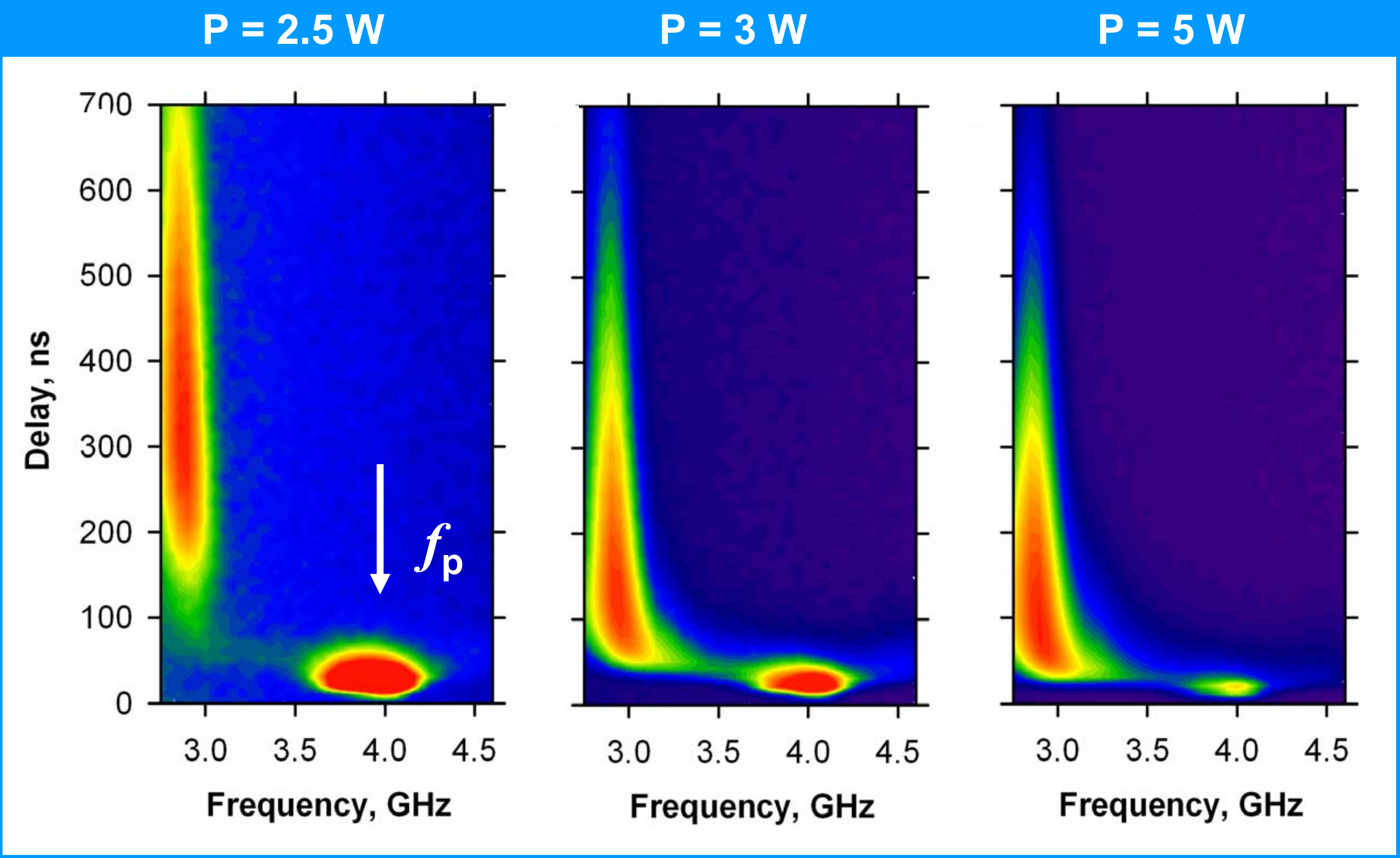
Magnons are pumped just for 30 ns.
Higher peak powers as before.





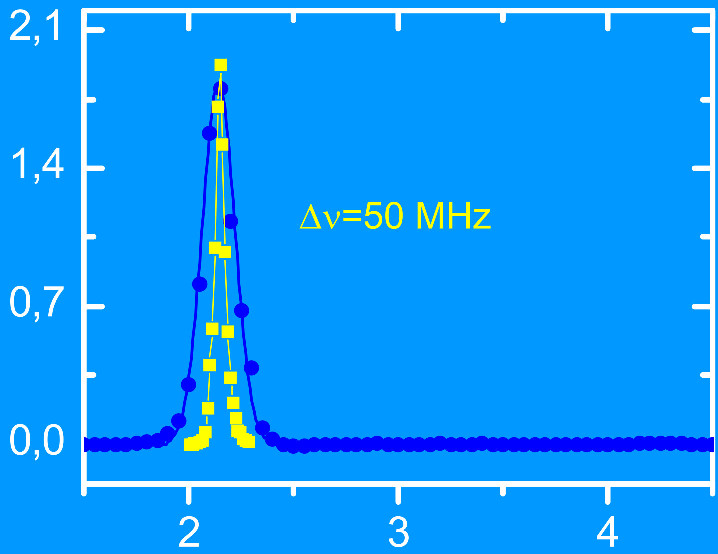
Lifetime is determined by interaction with the lattice: τ_{sp}

Thermalization at different densities



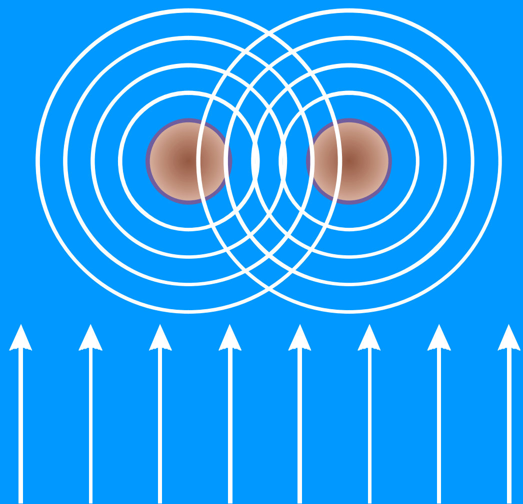
"Lifetime" depends on the magnon density

Coherency question



The peak width is 50 MHz,
i.e. $10^{-5}kT$.
A single quantum state?
50 MHz $\Leftrightarrow$ 20 ns (« lifetime)

How can we prove the coherency?



BLS-intensity $\sim n \times$ *DOS*

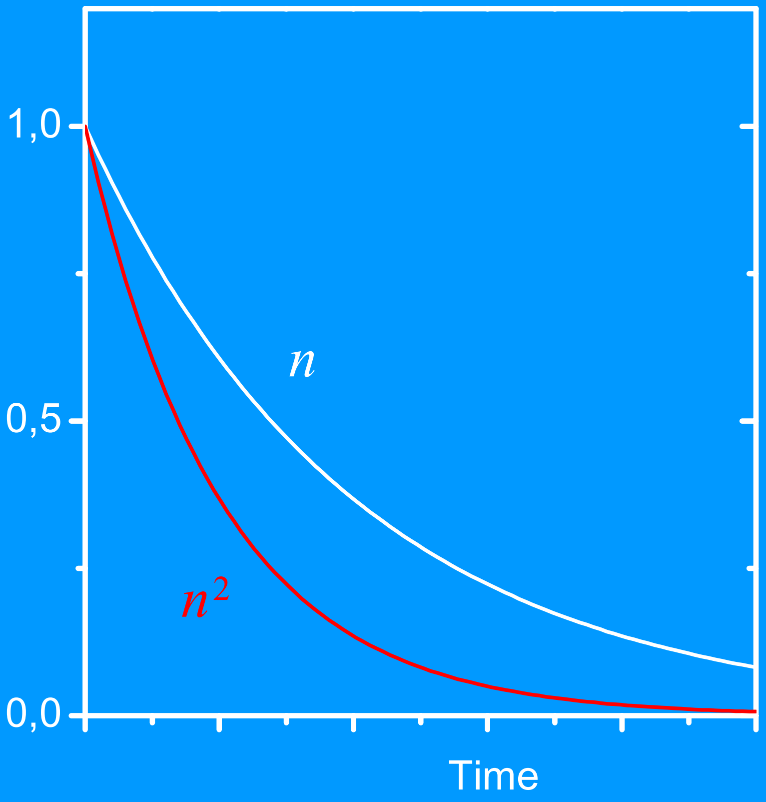
$I = \langle (E_1+E_2)^2 \rangle = \langle (E_1)^2 \rangle + \langle (E_2)^2 \rangle + 2\langle E_1 E_2 \rangle$

Incoherent scatterers: $\langle E_1 E_2 \rangle = 0 \Rightarrow I = 2I_1$

Coherent scatterers: $\langle E_1 E_2 \rangle \neq 0 \Rightarrow I = 4I_1$

In general: for coherent scatterers the scattering intensity is $\propto n^2$!

Scattering from the bottom of the spectrum



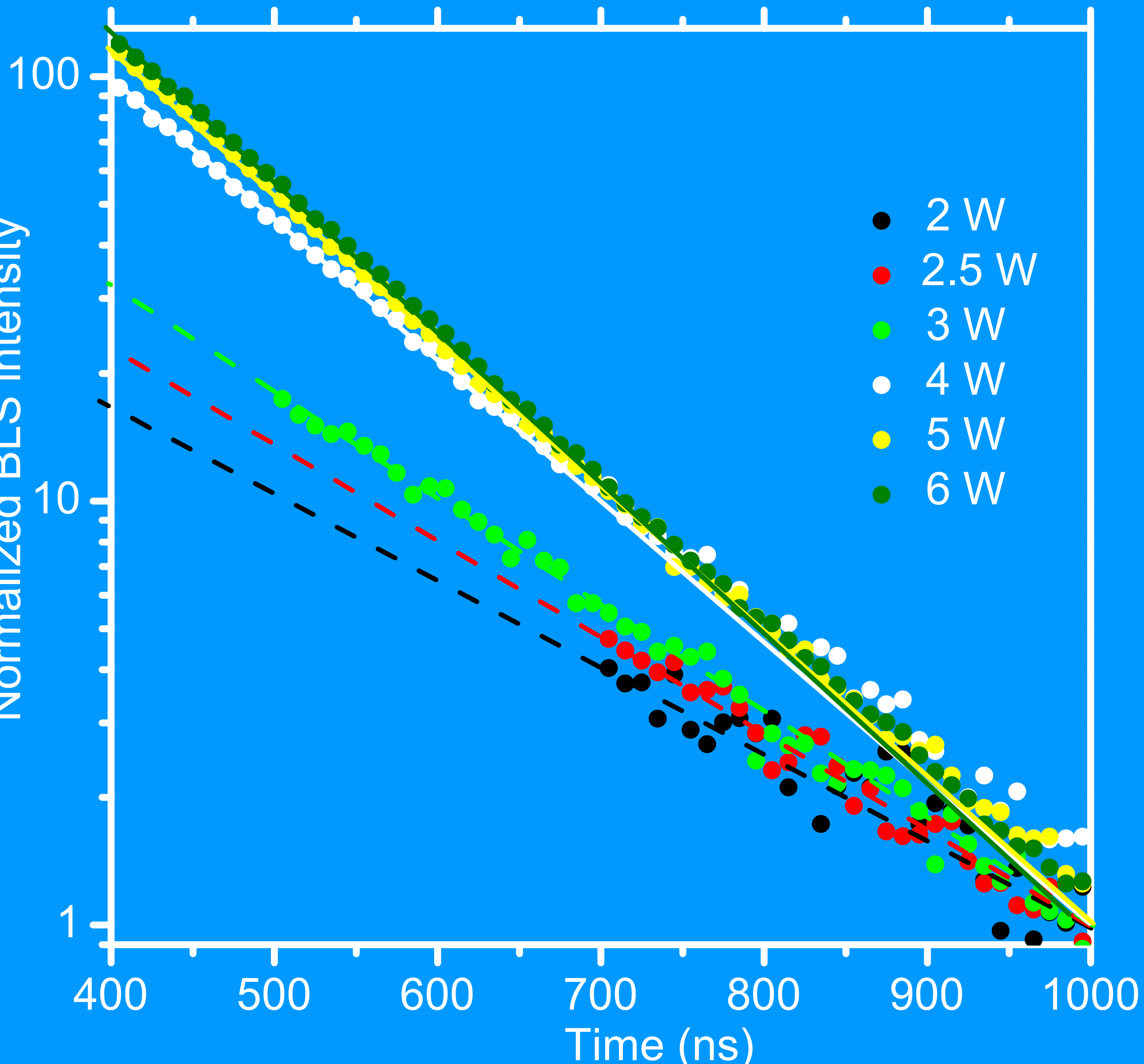
Number of magnons decays

The decay rate is determined by the livetime: $\alpha = 1/\tau_{sp}$

BLS-intensity from incoherent magnons $\propto n \propto \exp(-\alpha t)$

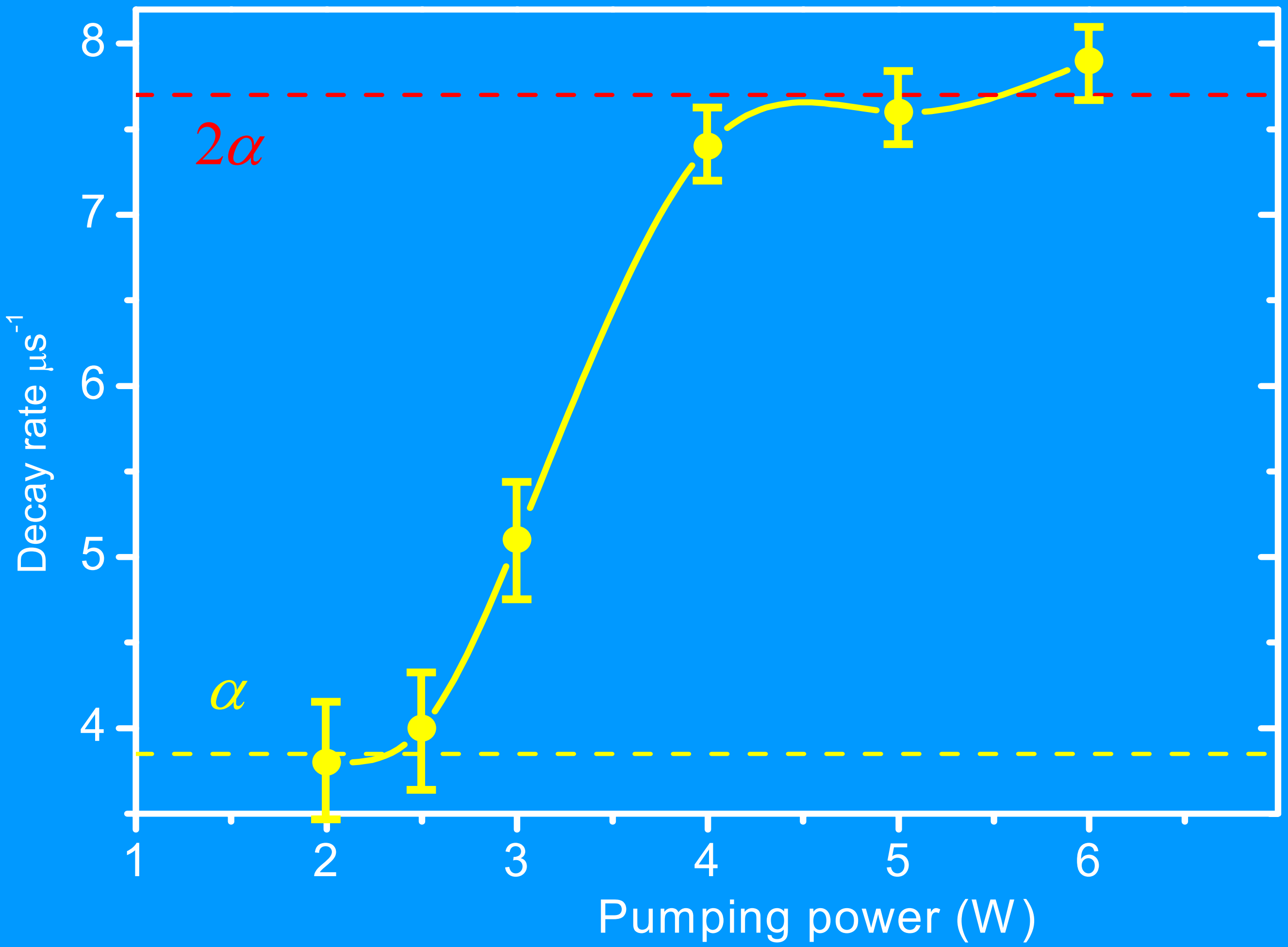
BLS-intensity from coherent magnons $\propto n^2 \propto \exp(-2\alpha t)$

Scattering from the bottom of the spectrum



The decay rate increases with pumping power (total magnon density

Doubling of the decay rate



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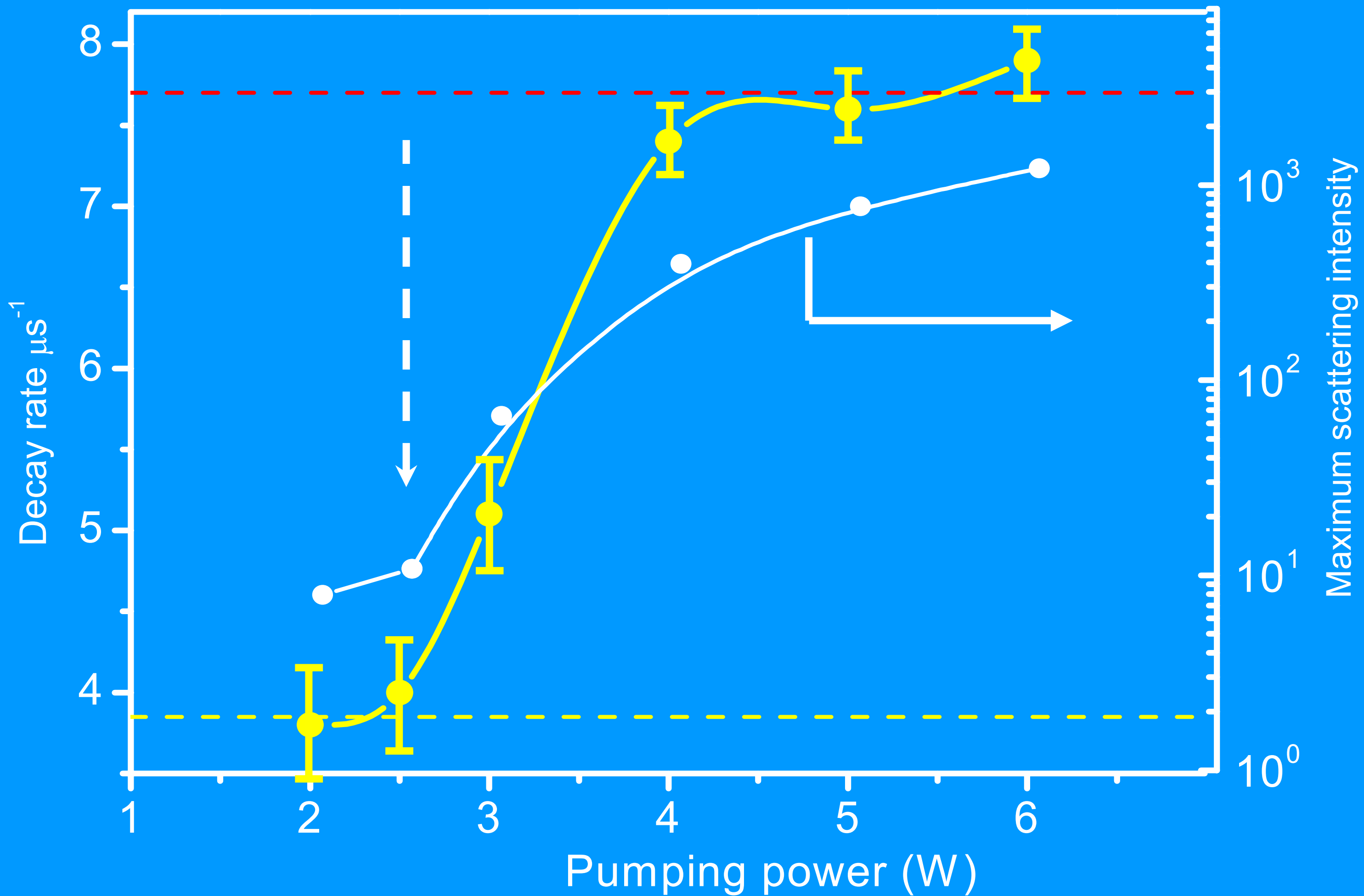
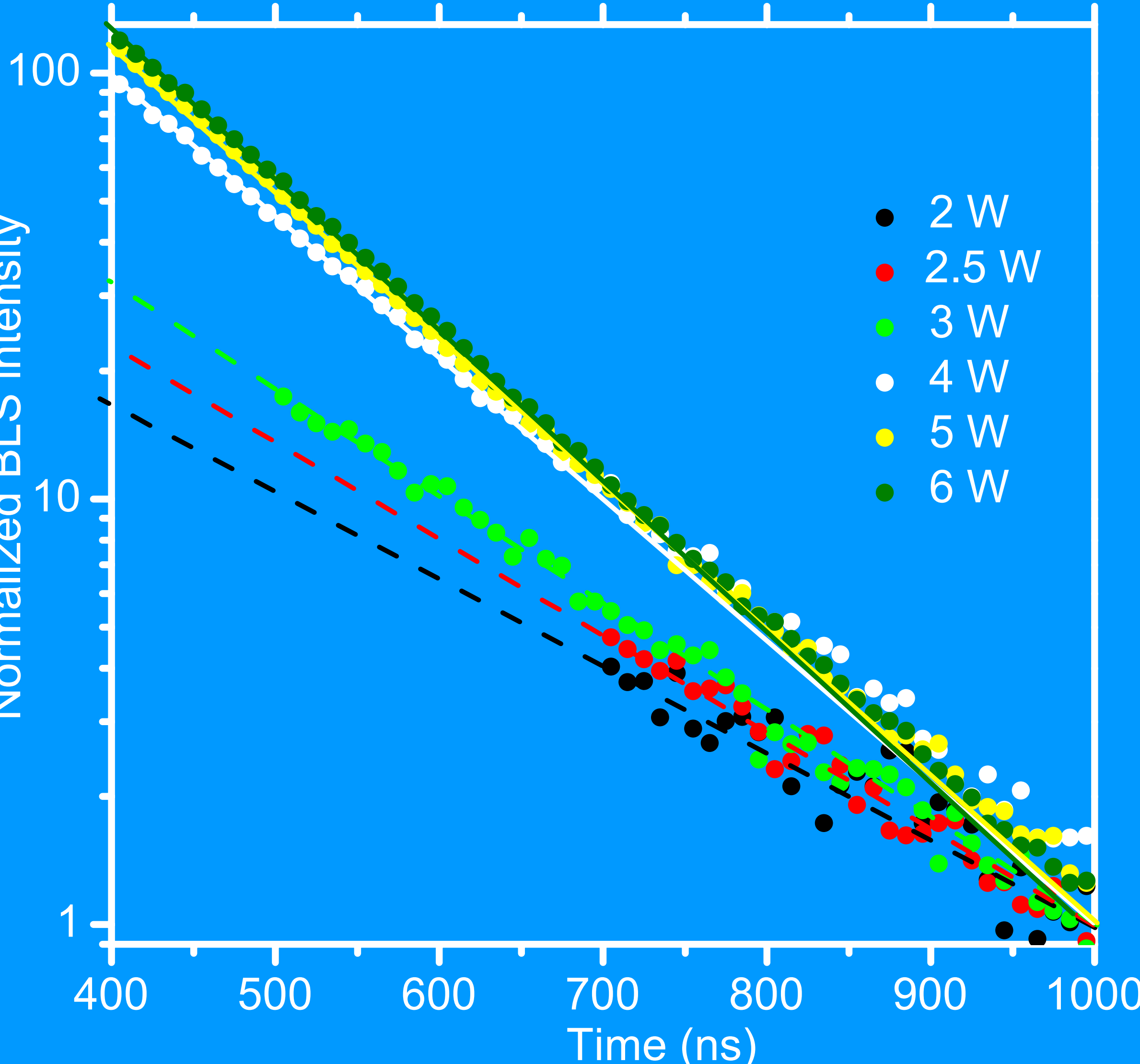


Experimental confirmation of the time coherency of the condensa

Nature, submitted

Scattering from the bottom of the spectrum



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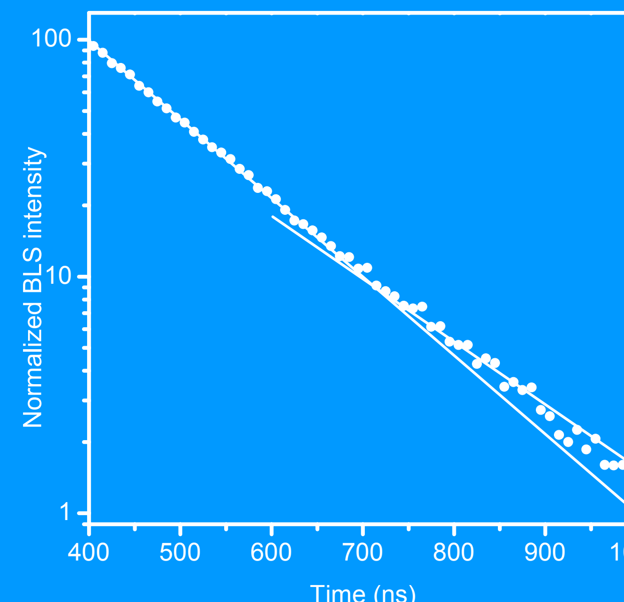
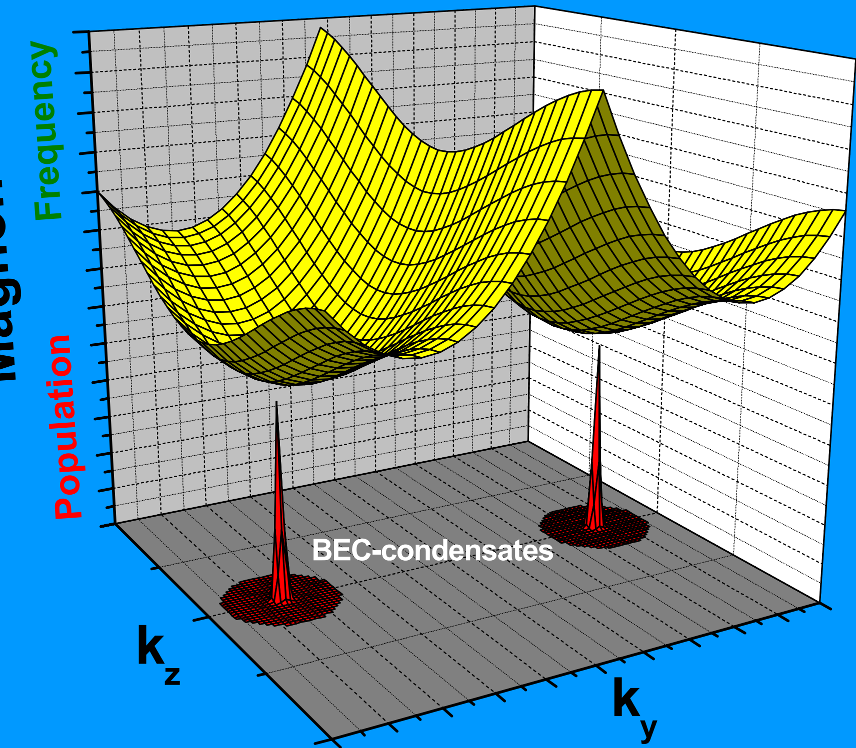
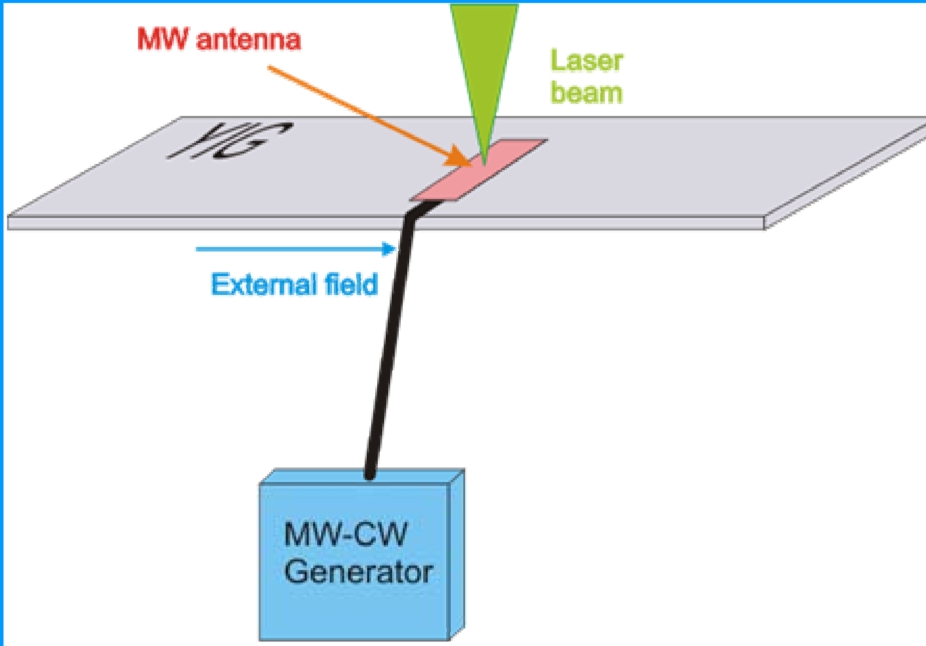


Spatial coherence



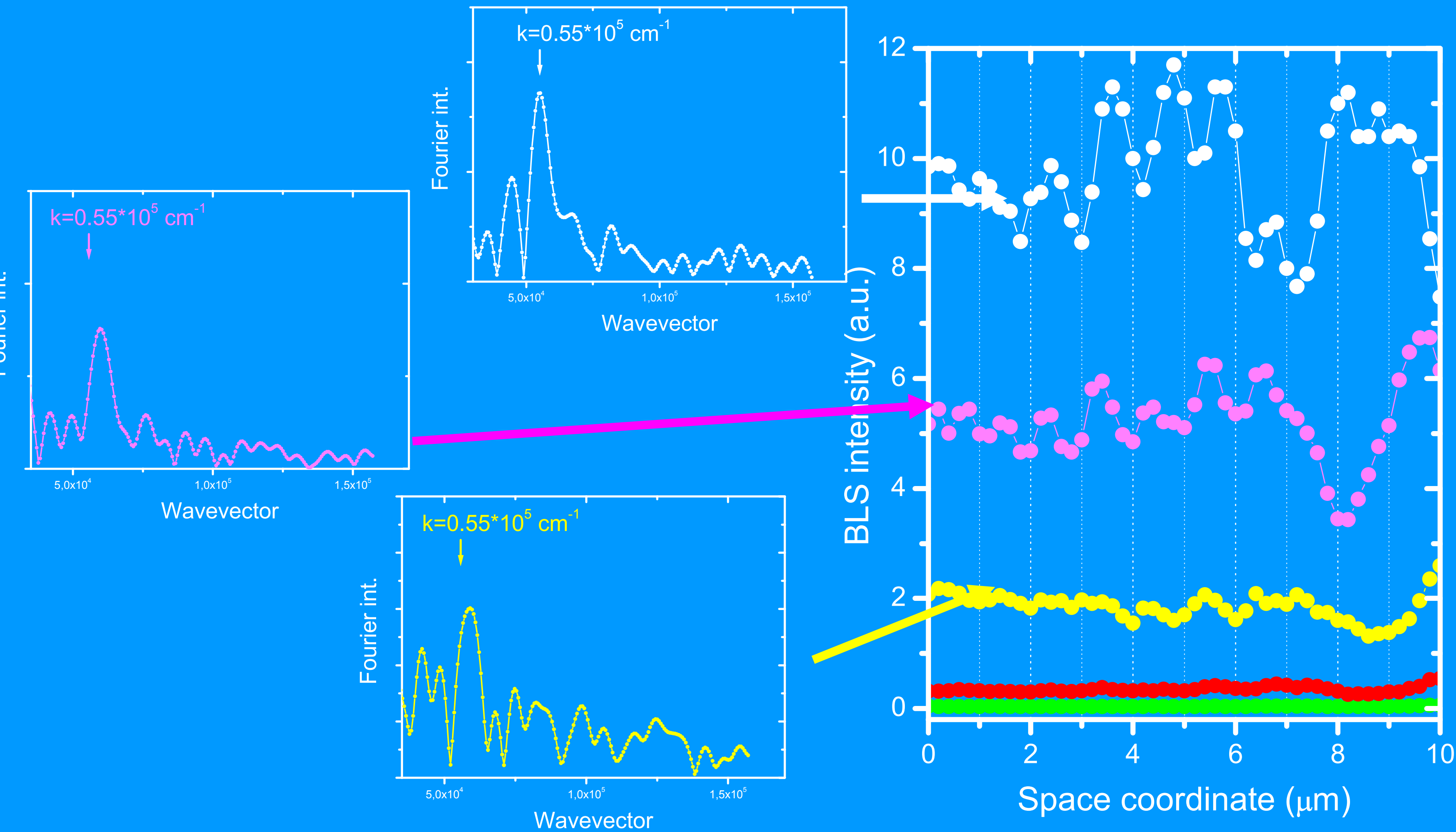
Two condensation points in the k-space

Check the spatial coherence – space resolved measurements



Magnon mapping
Resolution 250 nm

Space coherence of the condensate



The created condensate is COHERENT in space

Summary

- Gas of magnons with chemical potential $\mu \neq 0$ undergoing BEC transition with $k_{cond} \neq 0$ can be created at room temperature
- Temporal coherency of the observed state is experimentally confirmed
- Standing wave of condensate density is detected at high magnon densities (spatial coherency)

Presented at the PITP/SpinAps Asilomar Conference in June 2007

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Make research in Germany

Opennings in Münster, Germany:
Ph.D student, PostDoc

A young, growing group. Different projects on magnetic dynamics
Experience in magnetism and (pulsed laser) optics is wellcome.

http://www.uni-muenster.de/Physik/AP/Demokritov/