Ground state and excitations in BEC of magnons

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Group of NonLinear
Magnetic Dynamics

Westfälische
Wilhelms-Universität
Münster

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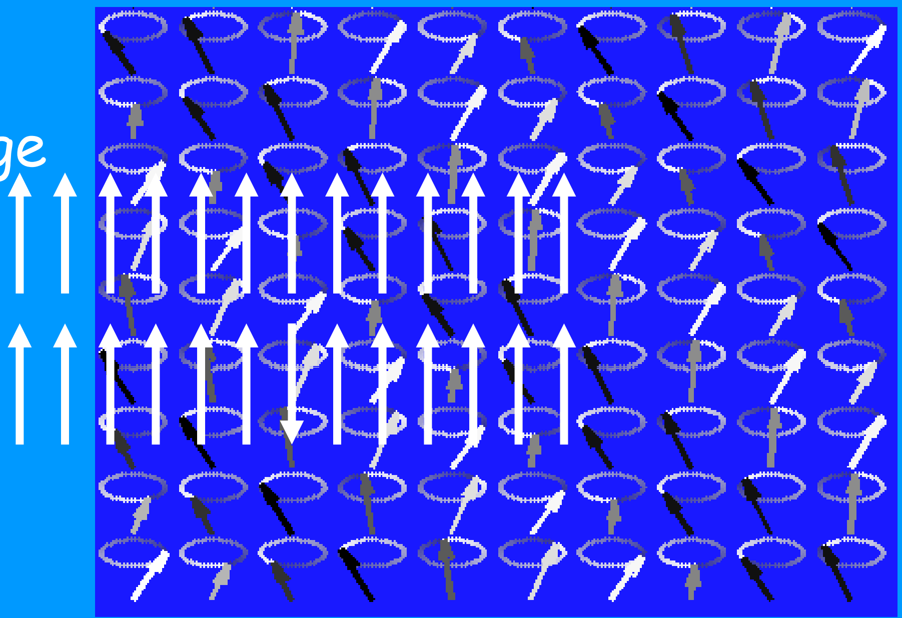
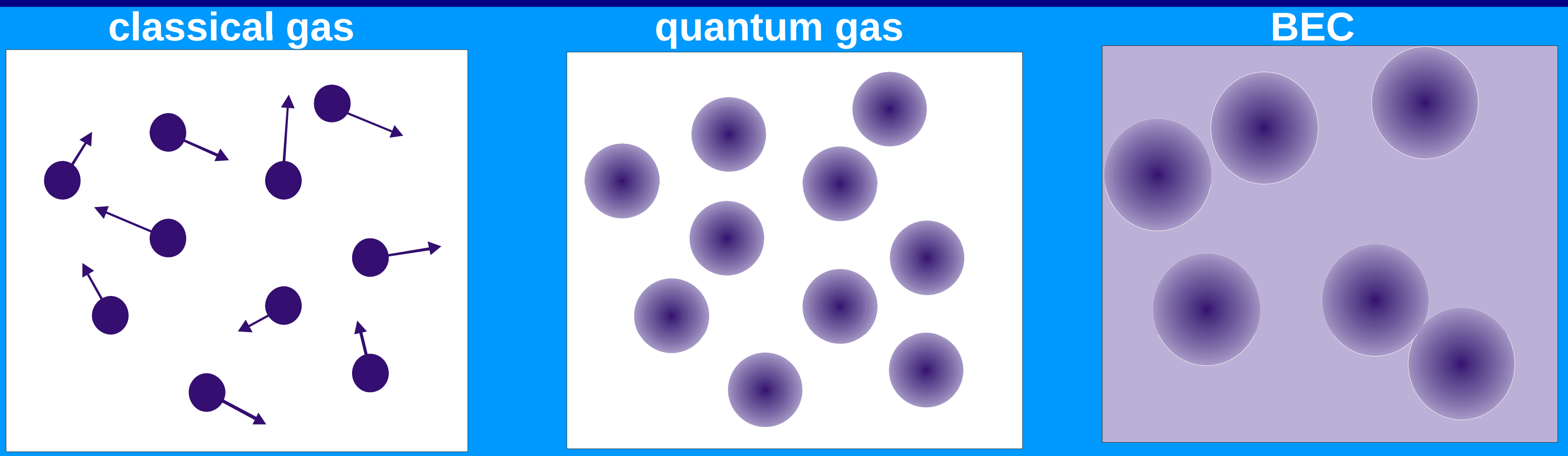
Spin waves ⇒ magnons



Courtesy: Prof. C. Patton

Magnons???
Ground state of a FM:
$S_z=Ns_z$
Excited states:
$S_z=Ns_z-1$, $S_z=Ns_z-2$, $S_z=Ns_z-3$, …
1 magnon, 2 magnons, 3 magnons,…
⇒magnons are Bose-particles
Carry transverse magnetization

Bose-Einstein-Condensation of atoms



Condition of BEC transition:

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

$$N_c^{2/3} = kT\frac{m}{3.31\hbar^2}$$

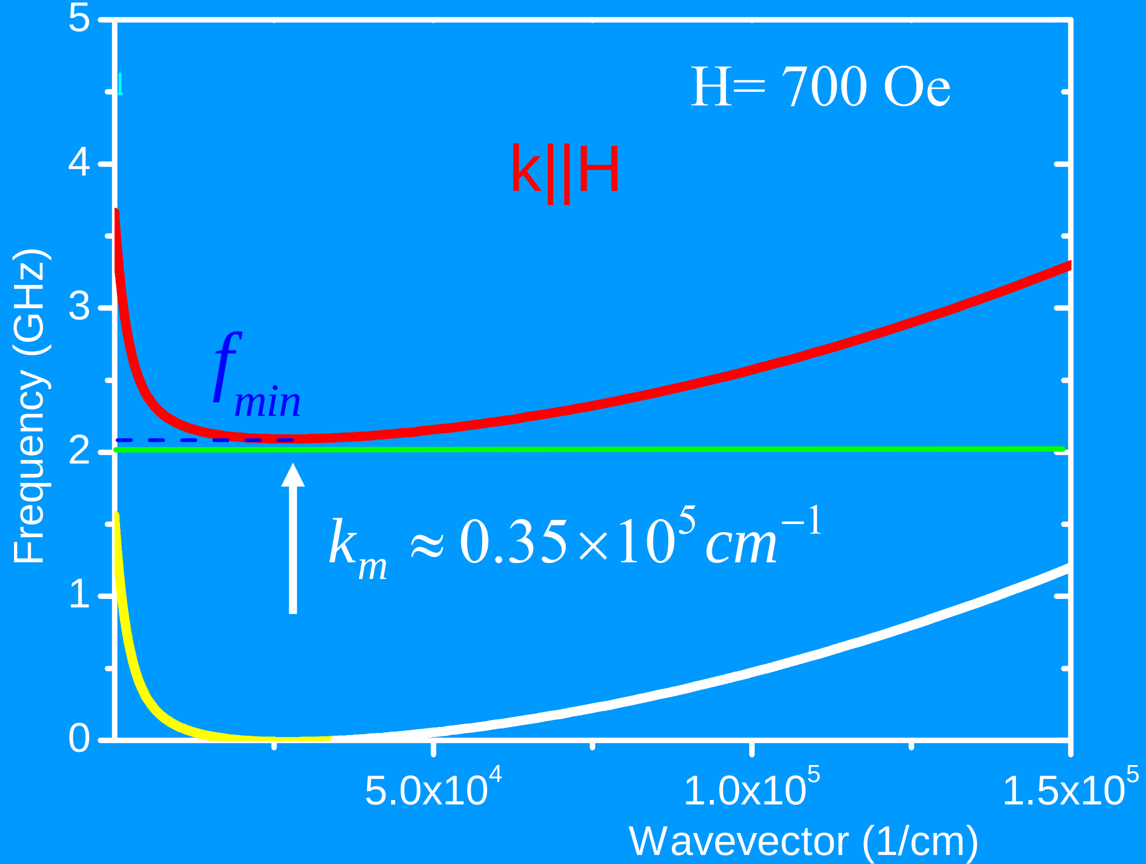
Thermodynamics of BEC:

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

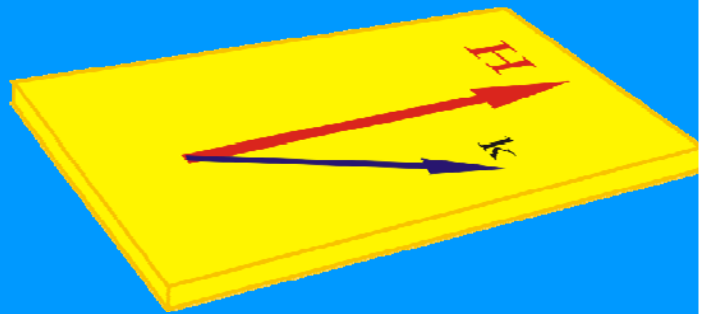
$$\mu(T_c, N_c) = E_{\min}$$

Magnons in ferromagnetic films

YIG (yttrium-iron-garnet)



Transparent ferromagnet
Films 5-10 μm thick
No domains

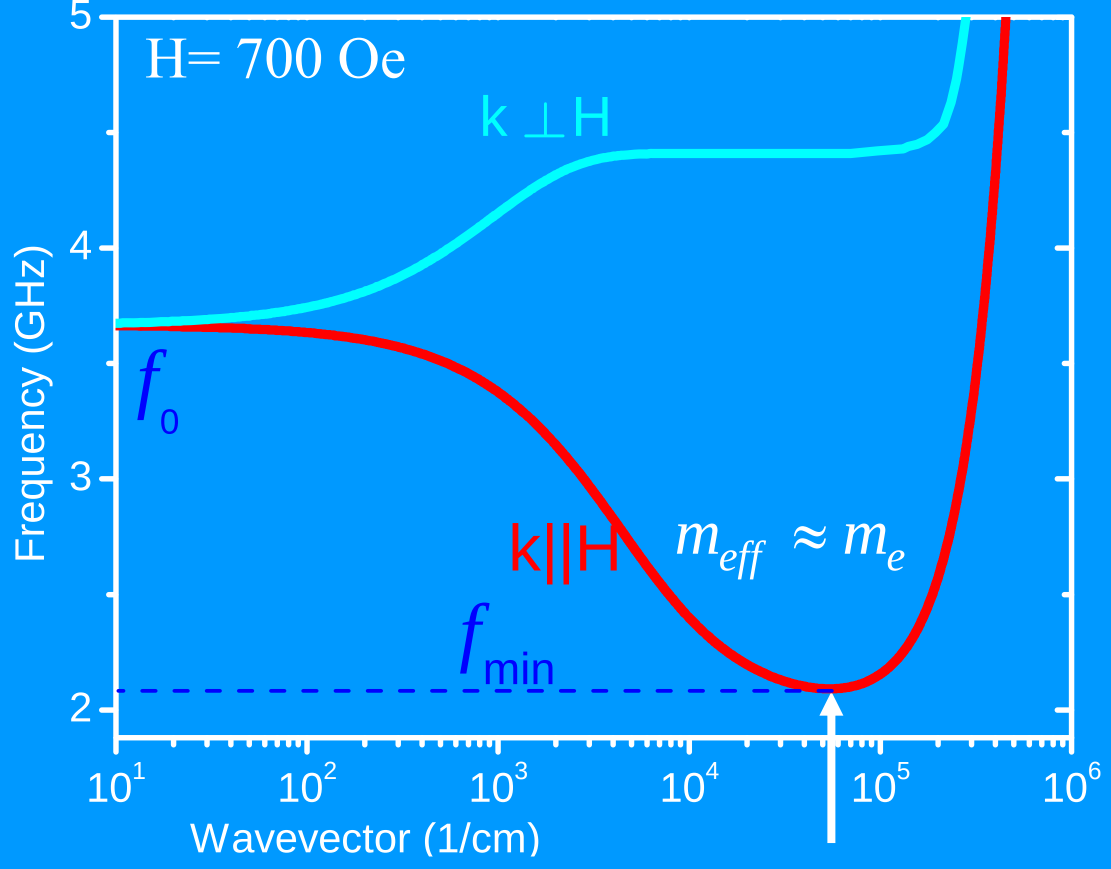


Three contributions to the magnon energy: Zeeman, exchange, and dipole-dipole

Scattering amplitude depends on wavevector

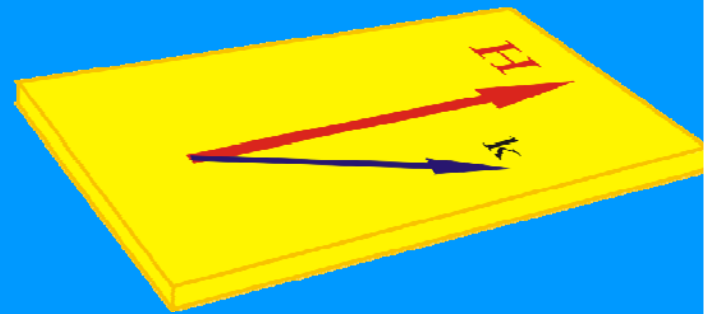
Magnons in ferromagnetic films

YIG (yttrium-iron-garnet)



$$k_m \approx 0.35 \times 10^5 \, cm^{-1}$$

Transparent ferromagnet
Films 5-10 μm thick
No domains



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

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

(Thermo)dynamic of magnons

In equilibrium:

$$\mu = 0 \ < E_{\min}$$

at any temperature

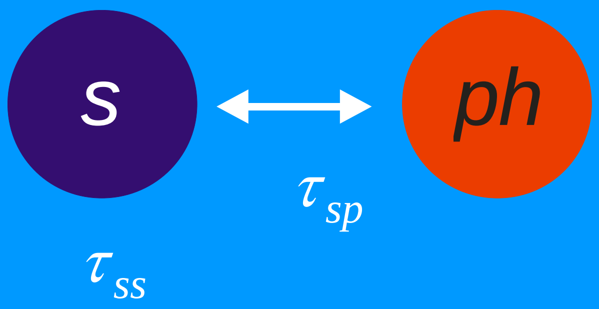
Magnons are quasi-particles with variable N (T).
In equilibrium with the lattice ($\boldsymbol{F}=\boldsymbol{F}_{\min}$).
Therefore:

$$\mu = \frac{\partial F}{\partial N} = 0$$

$E_{\min} > 0$.

No BEC possible.

In quasi-equilibrium:



We can change N

Two important time scales: τ_{ss} τ_{sp}

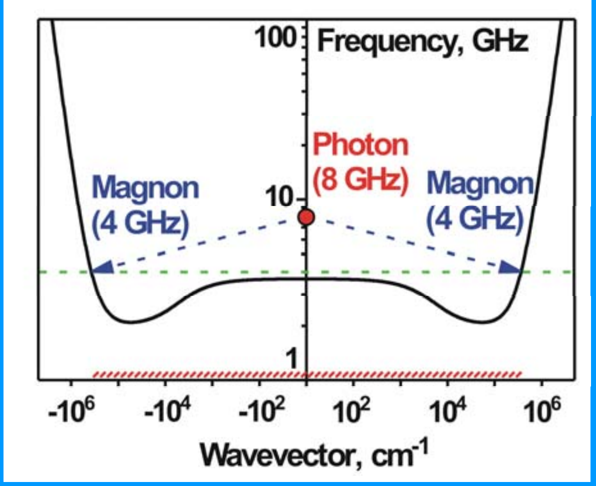
In YIG:

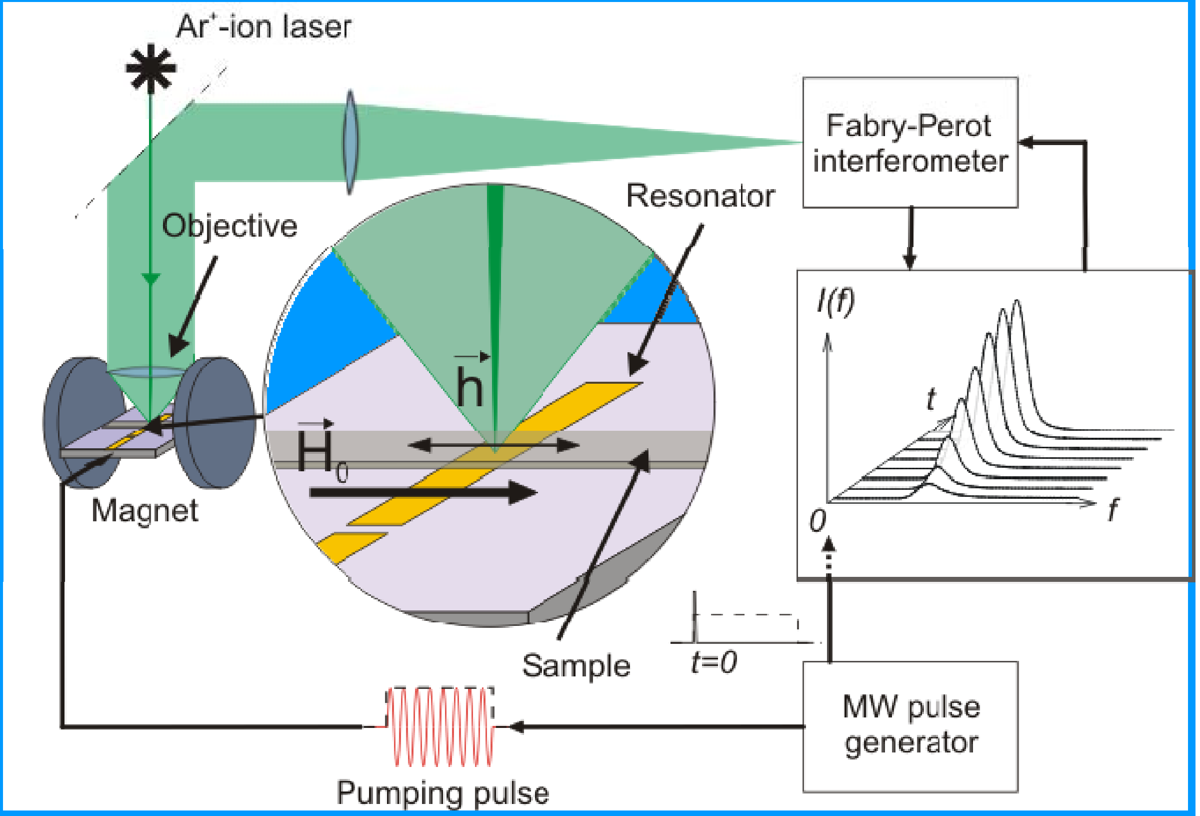
$$\tau_{ss} \approx 10 - 50 ns$$

$$\tau_{sp} \approx 0.2 - 0.5 \mu s$$

Experimental setup for BEC observation

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



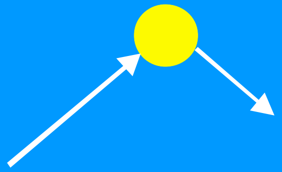


Two thresholds:

#1: pumping itself

#2: BEC

Mechanisms of magnon thermalization



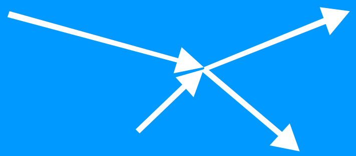
Two-magnon scattering

$$\omega_1 = \omega_2$$

$$k_1 \neq k_2$$

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

Elastic, *k*-thermalization



Four-magnon scattering:

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

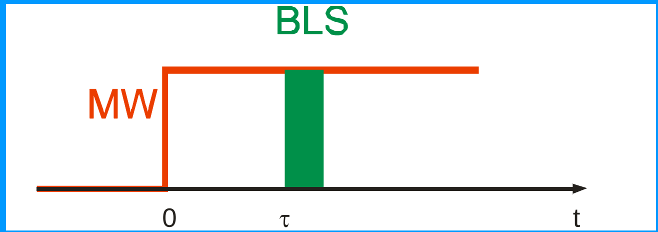
$$k_1 + k_2 = k_3 + k_4$$

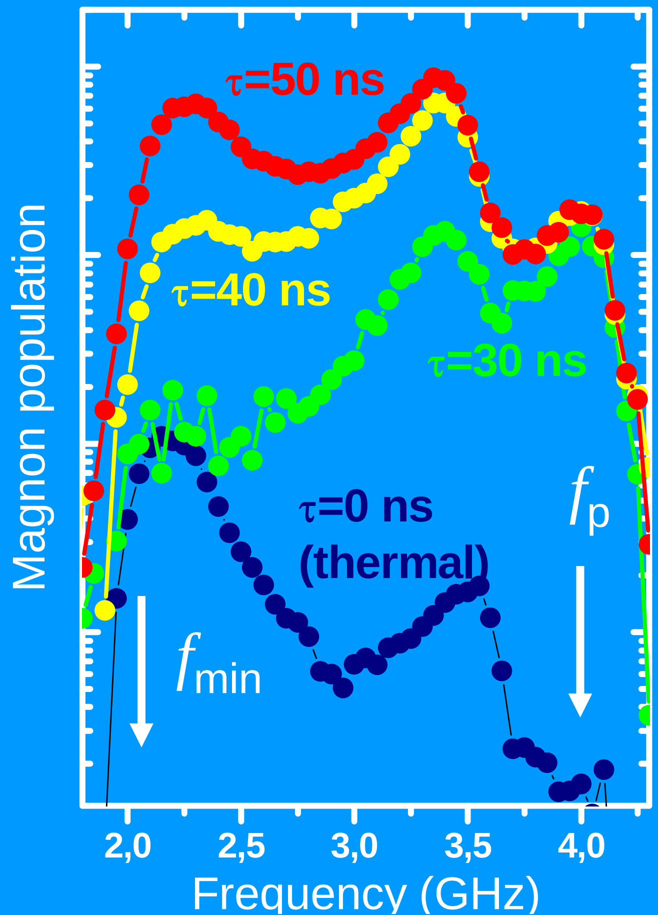
Nonlinear effect
(increase with increasing density)

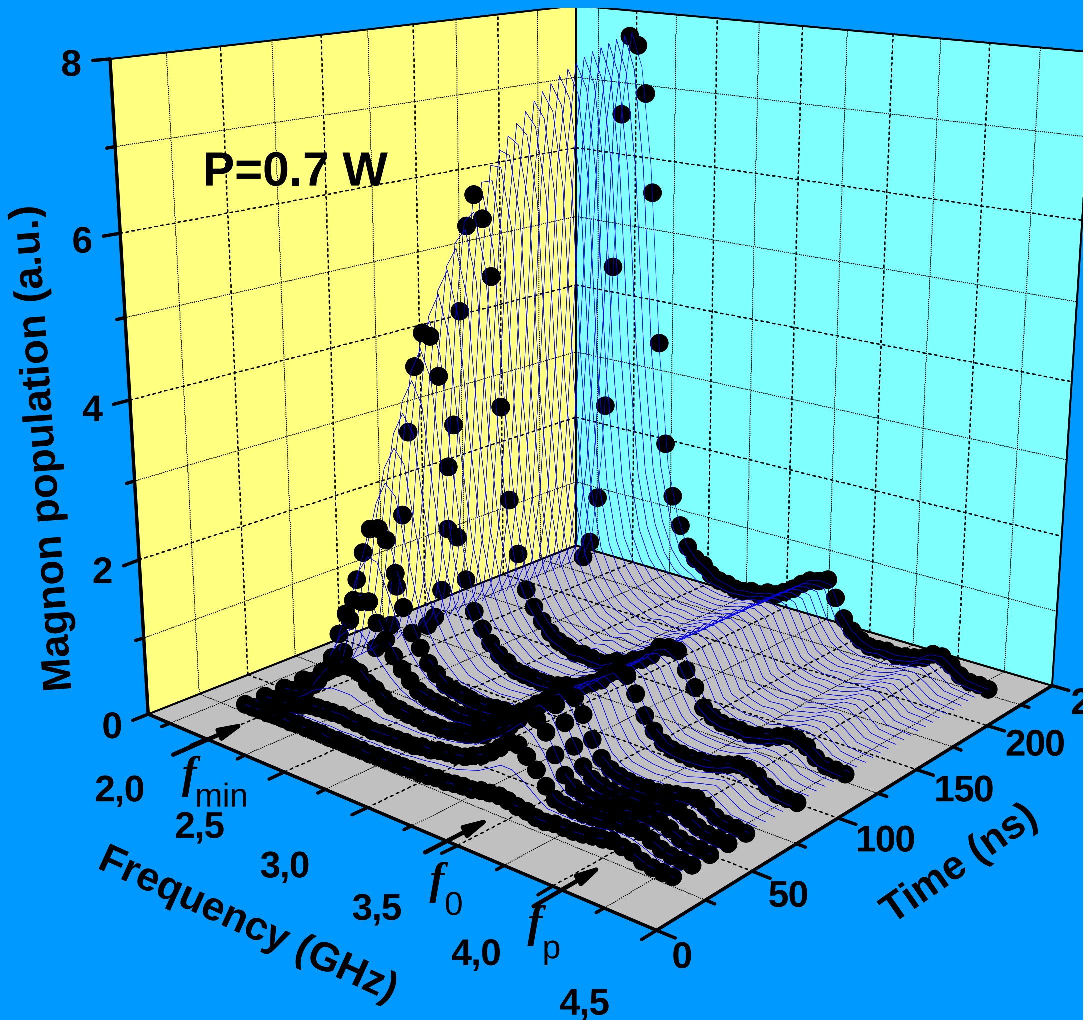
Inelastic, **ω**,*k*-thermalization

Magnon-magnon scattering keeps the number of particles constant

Magnon thermalization (step-like pumping)

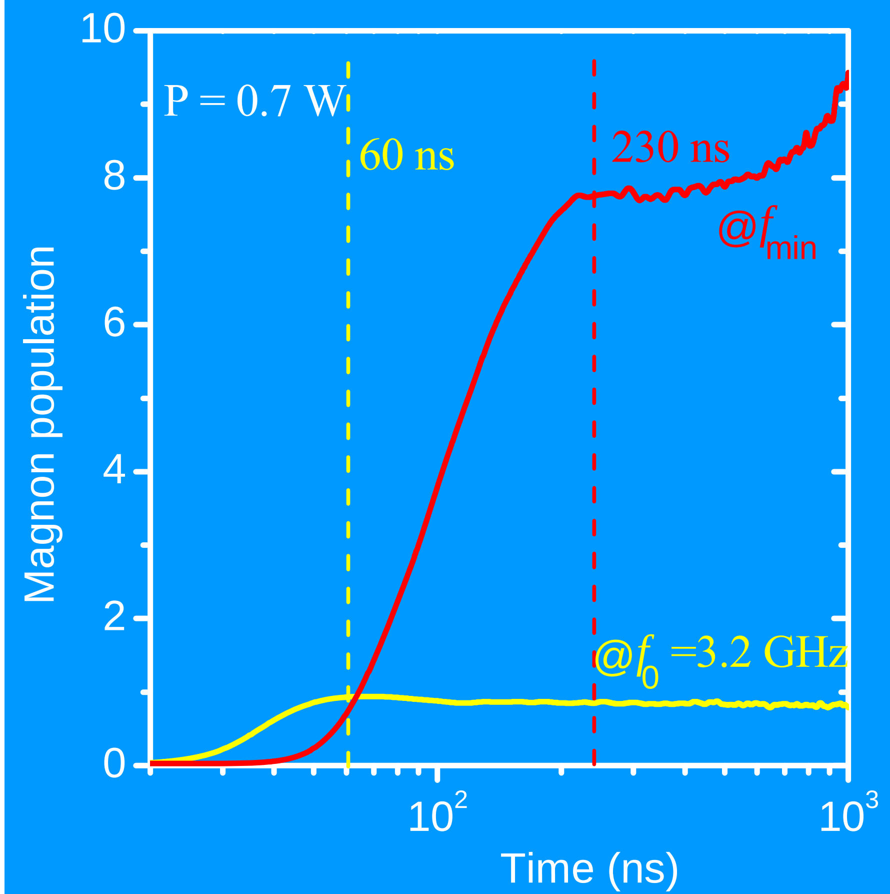


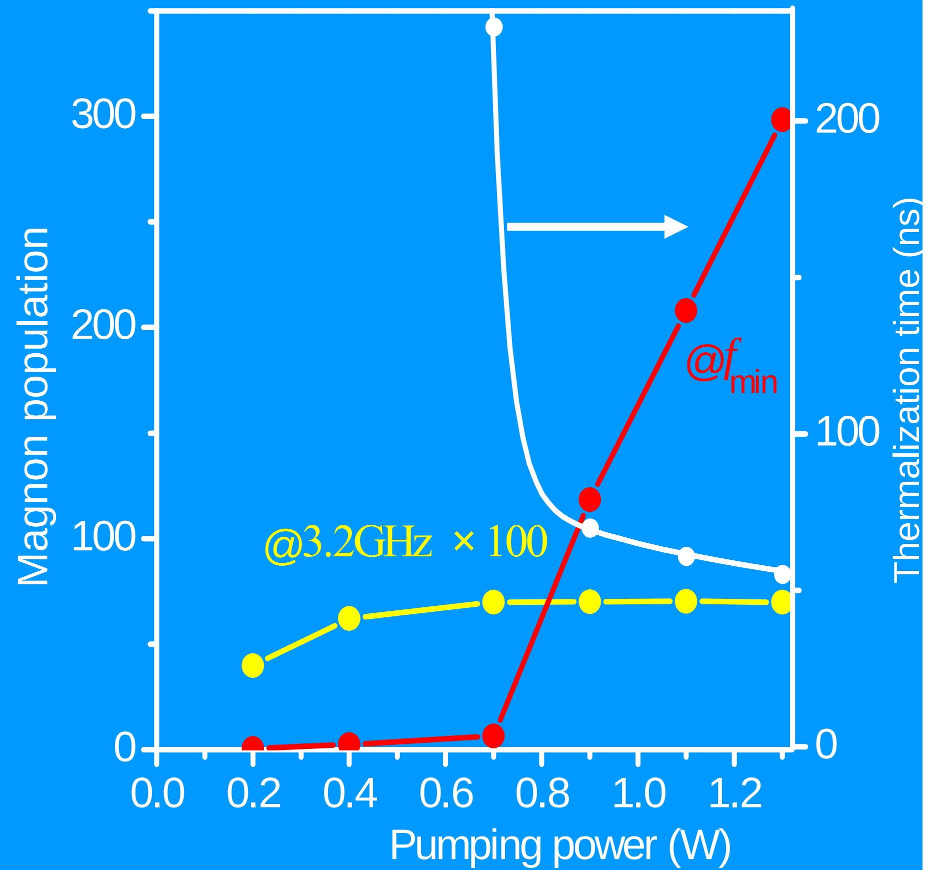




Thermalization happens „wave-like“

Thermalization time

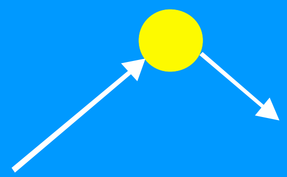




Thermalization time depends on the pumping power/magnon density
At high magnon densities is below 50 ns.

Phys. Rev.Lett. ´07.

Mechanisms of magnon thermalization



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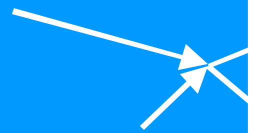
Elastic, *k*-thermalization



nsity)

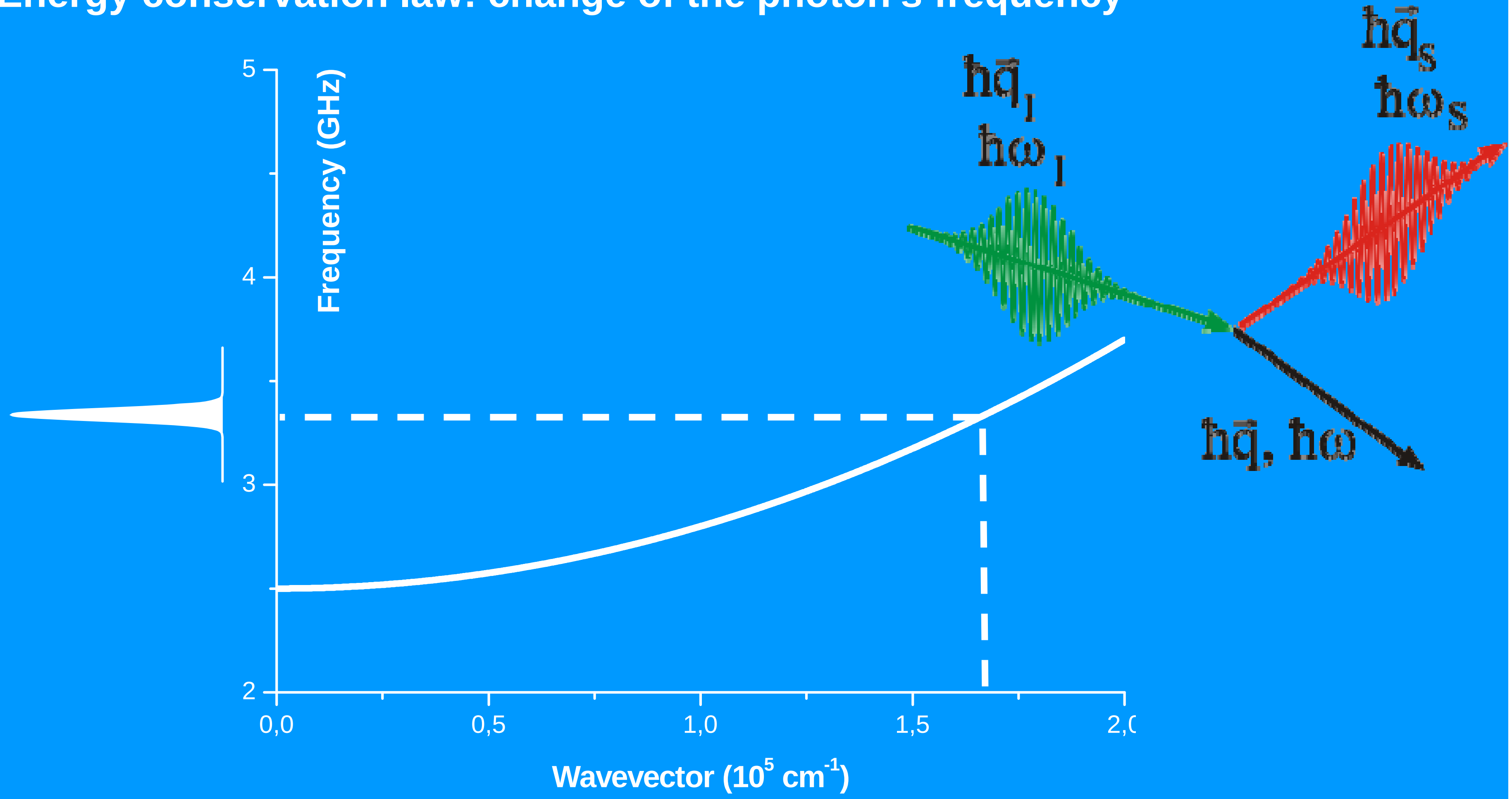
Under external influence magnon gas in YIG first thermalizes itself to a quasi-equilibrium
(and then relax as a whole,
if pumping is switched off)

Magnon-magnon scattering keeps the number of particles constant

Thermalization happens fast if the number of magnons is high enough

Brillouin Light Scattering

Momentum conservation law: the geometry defines the spin-wave wavevector
Energy conservation law: change of the photon's frequency



Brillouin Light Scattering

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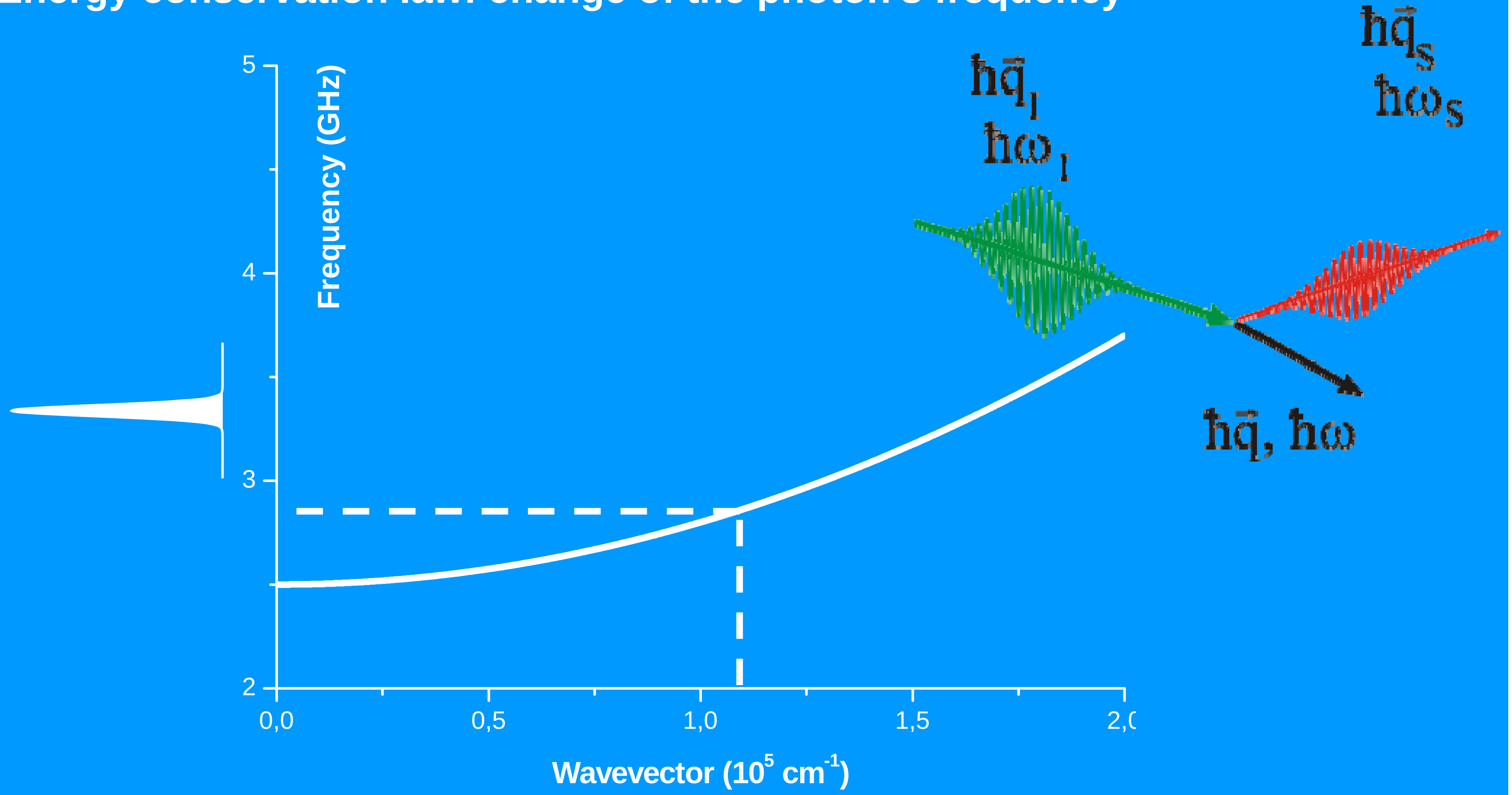
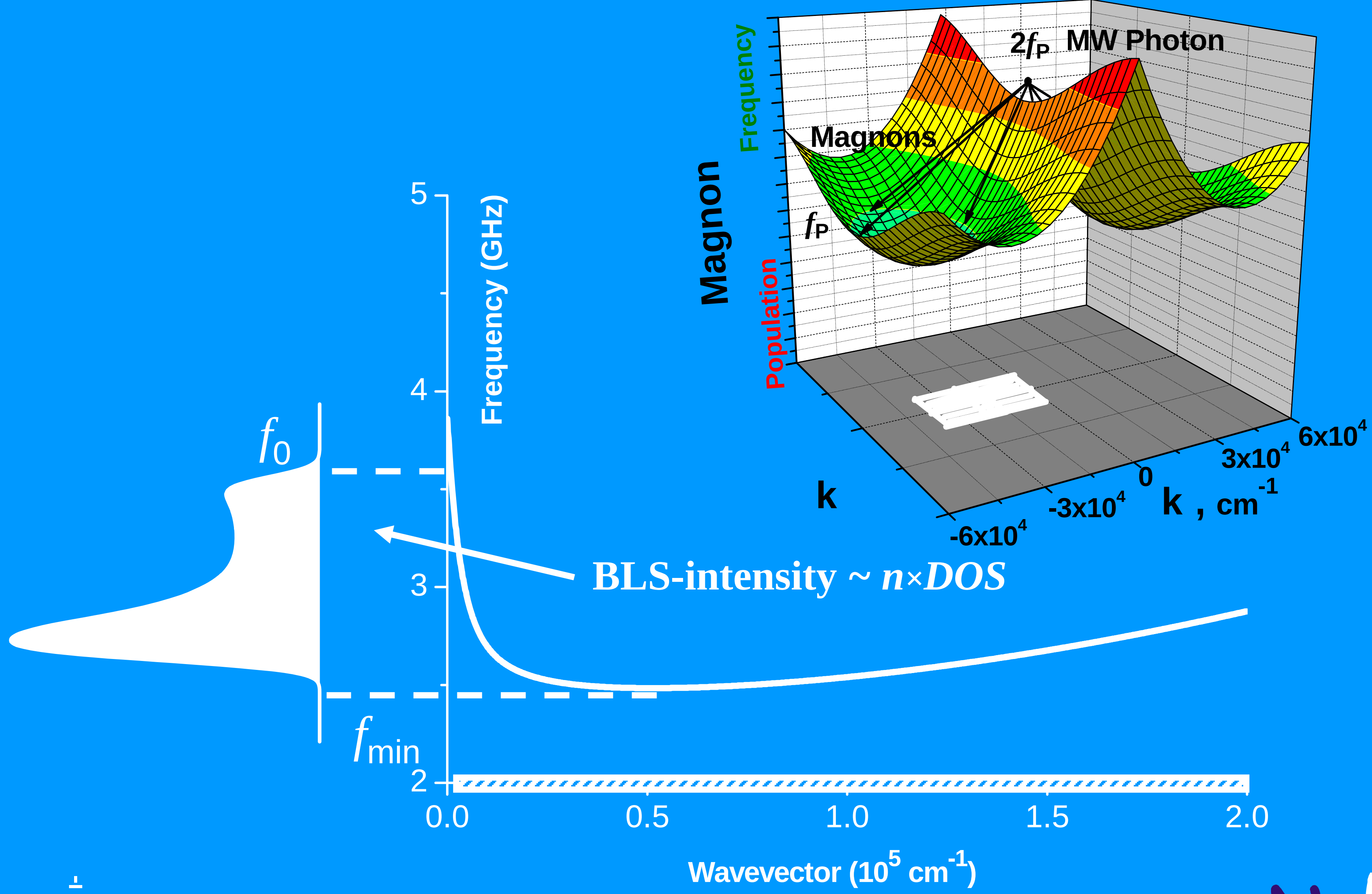
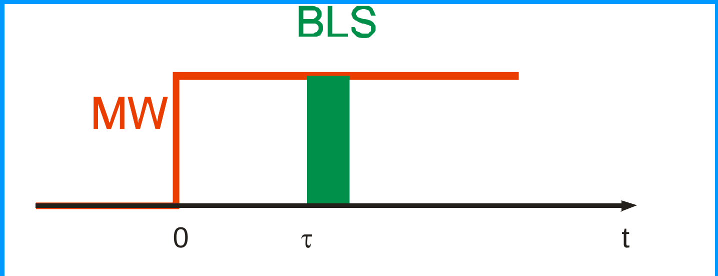


BLS spectroscopy



Pumped magnons (step-like pumping)

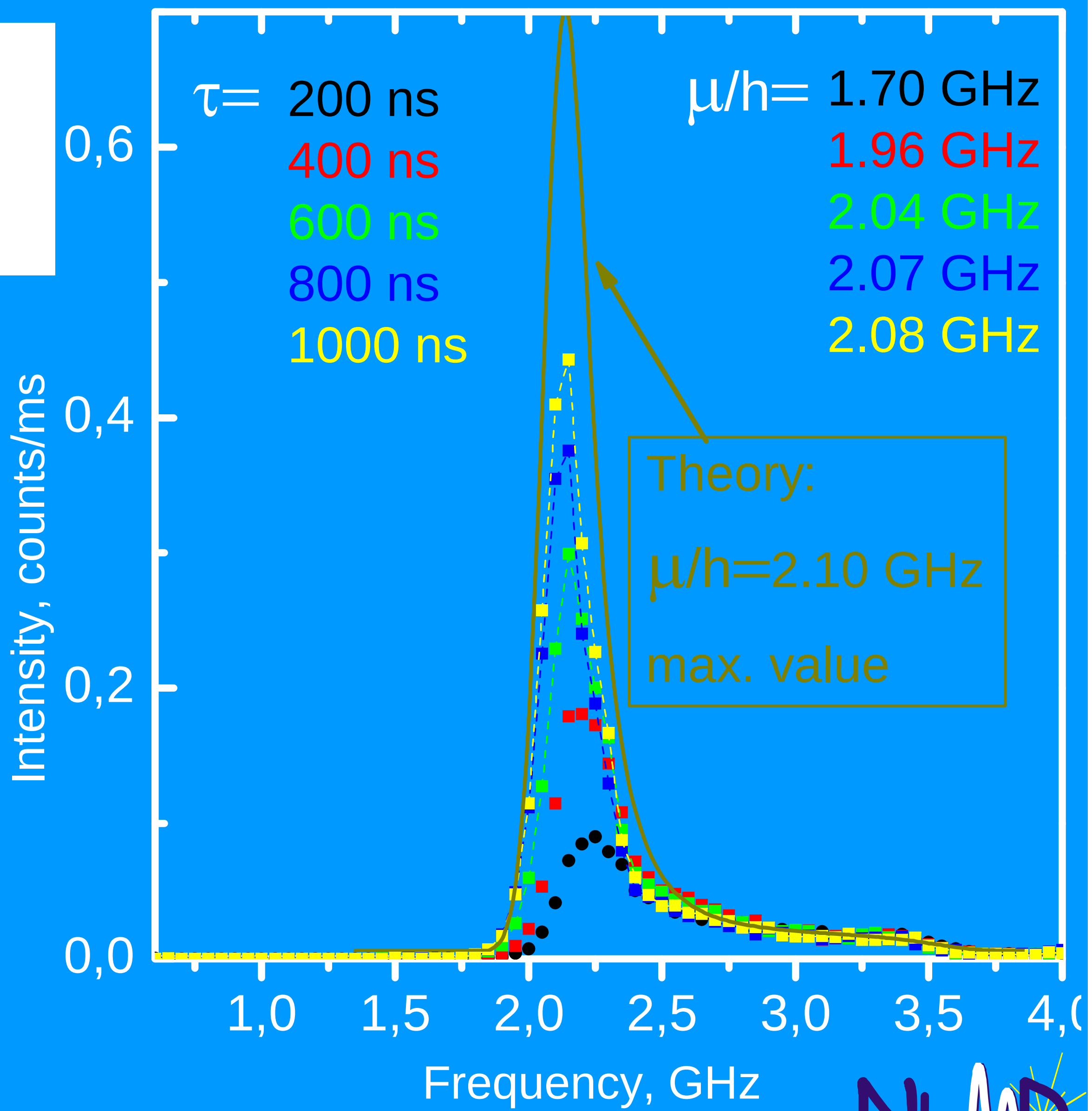


P = 4 W

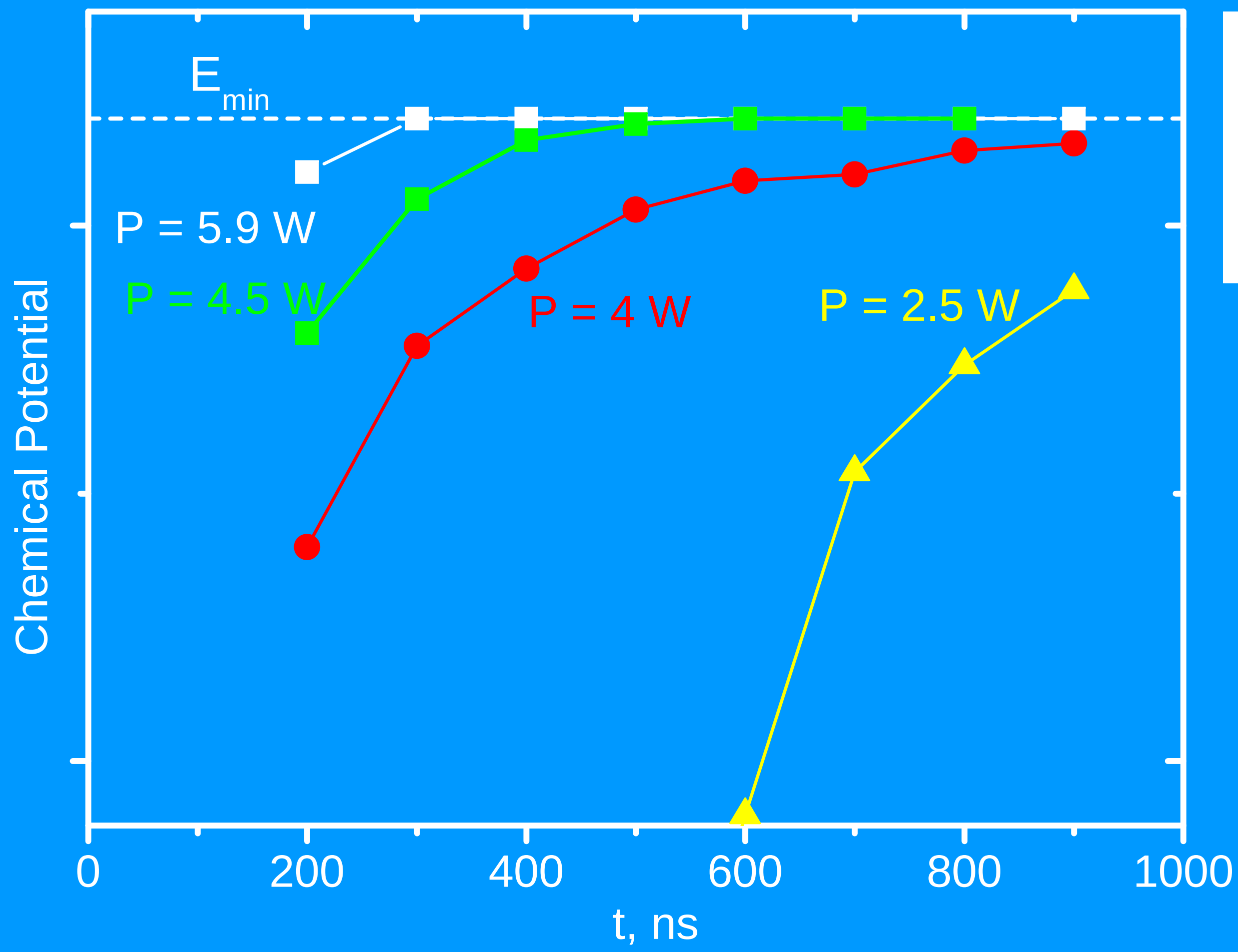
Time development of magnon distribution

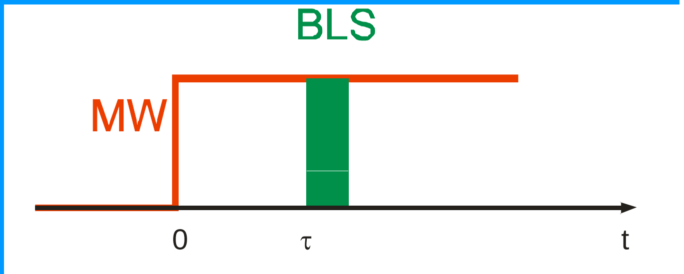
Known DOS: $n(\omega)$ **fit with** μ

Bose-statistics with non-zero $\mu < \mu_{max}$



Time dependence of the chemical potential

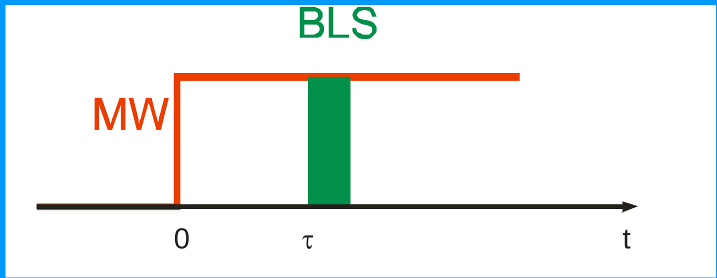




Stationary state due to spin-lattice relaxation

For high pumping power one can reach the critical density of magnons

Pumped magnons (step-like pumping)



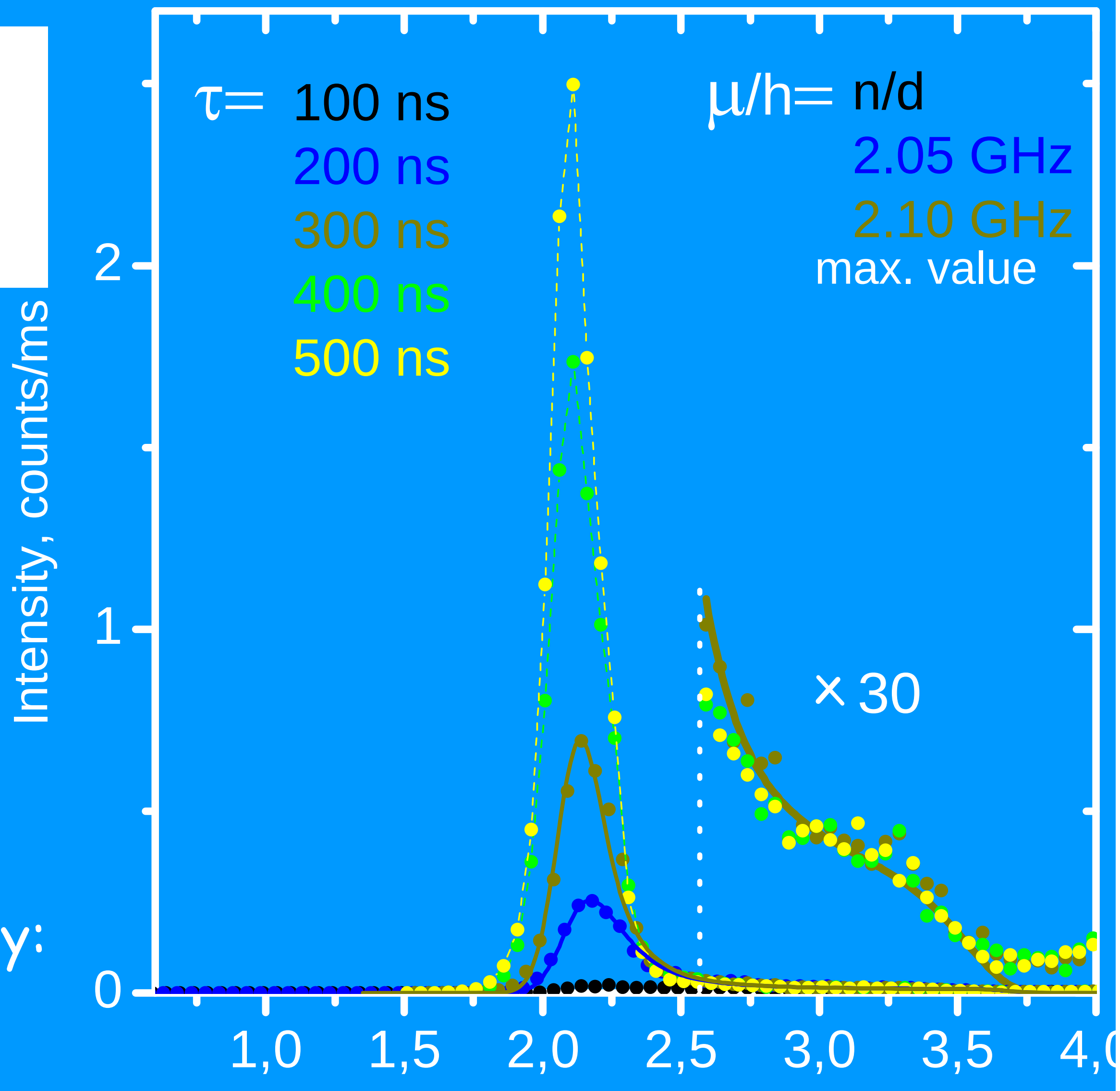
P = 5.9 W

Time development of magnon distribution

Known DOS: $n(\omega)$ **fit with** μ

Bose-statistics.
At 300 ns critical density:

$$\mu \approx \mu_{\max}$$



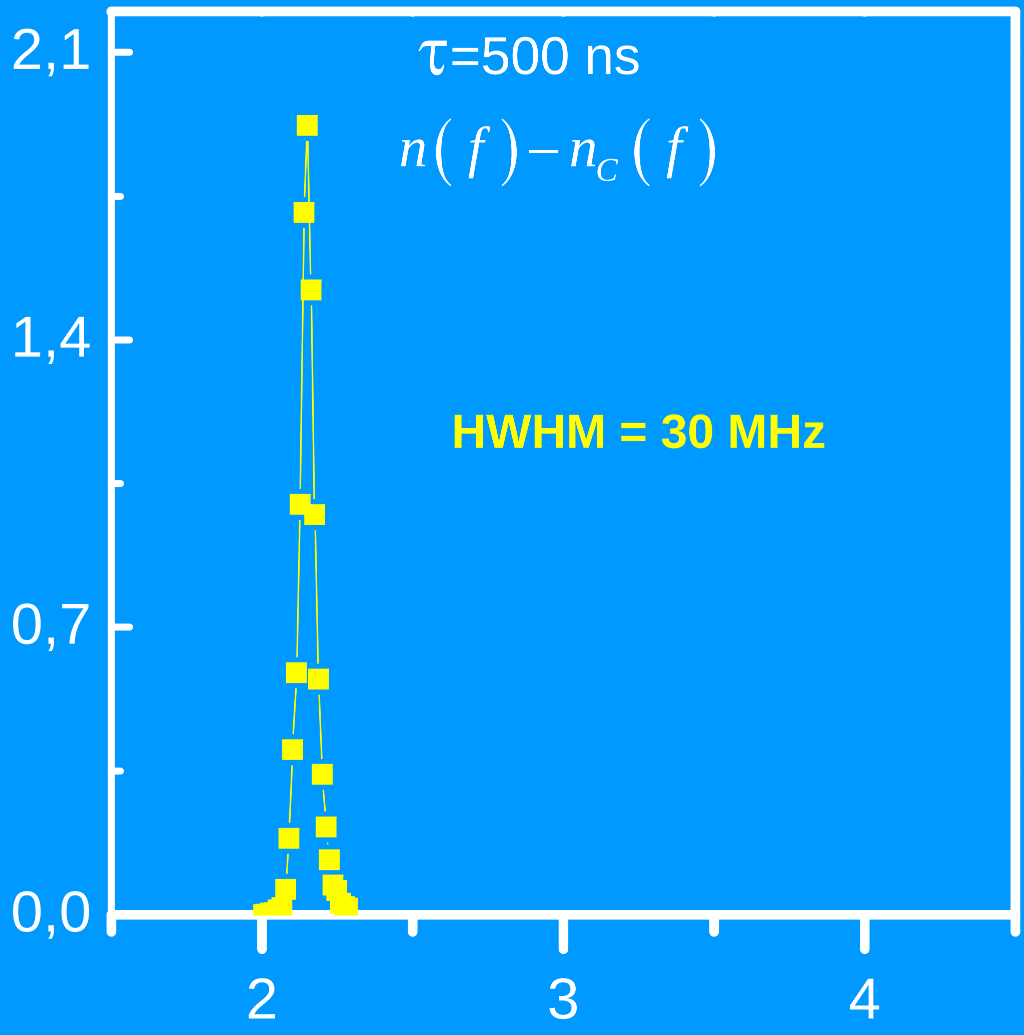
Experiments with ultimate resolution

The addition to the critical density is of δ – type (width is <1.5 mK, i.e. <10^{-5}kT).

A condensate is created!

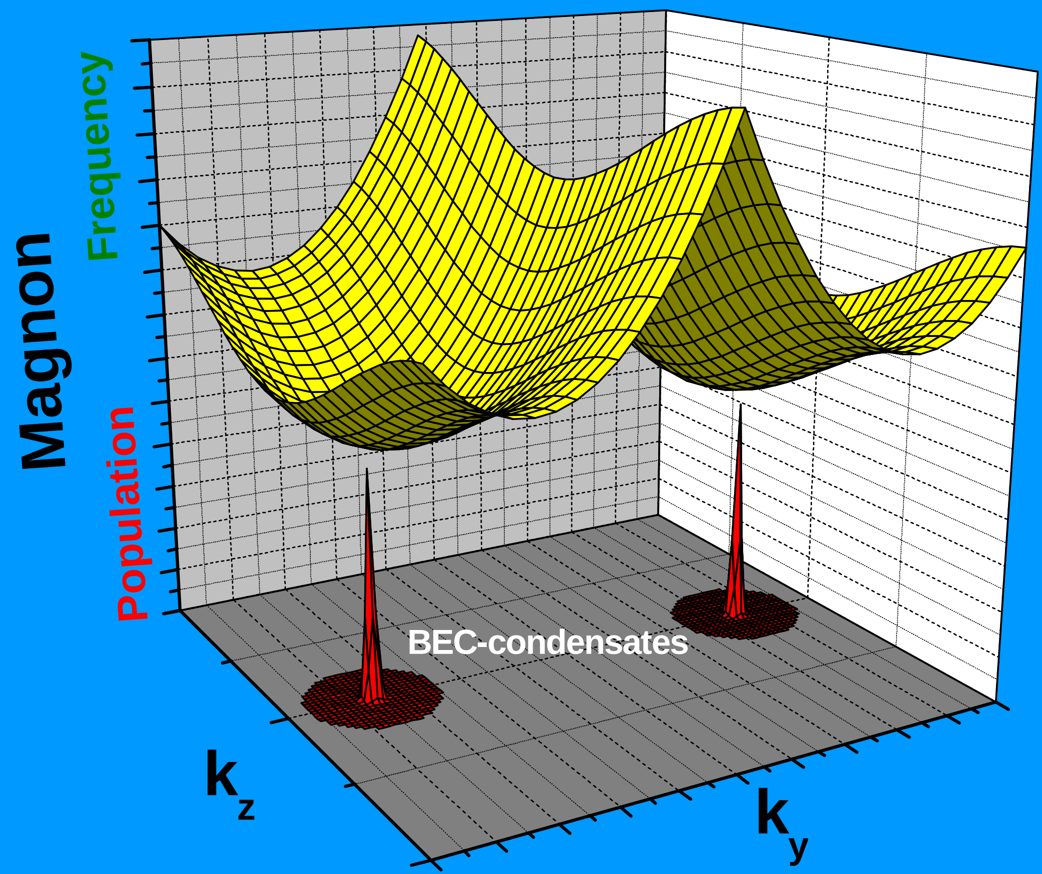
Condensate: a lot of spins precess in phase.

Nature ***443*** *430 '06*



The condensate is doubly degenerate

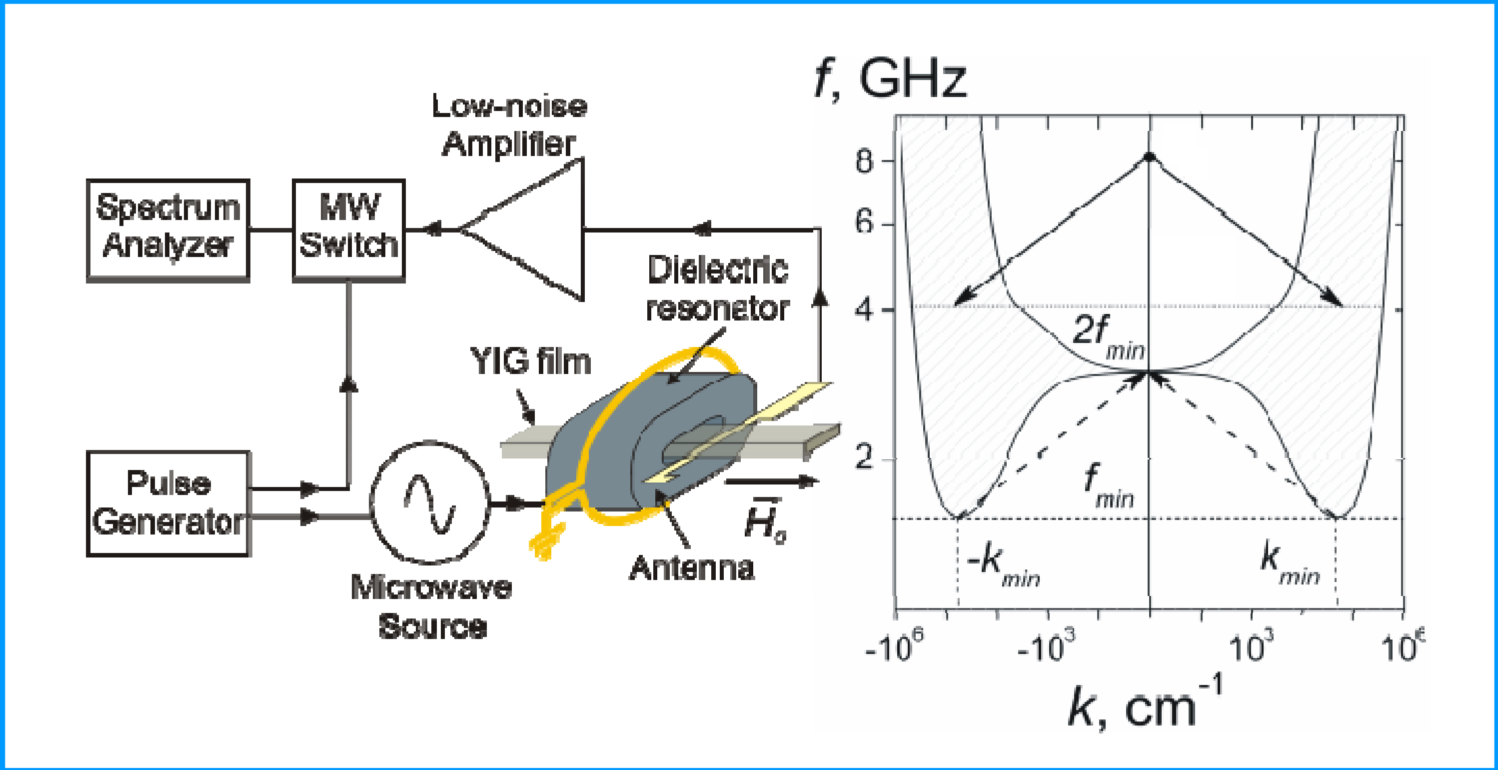
$$\psi(y,z,t)=\left(\psi_+(y,z,t)e^{ik_0z}+\psi_-(y,z,t)e^{-ik_0z}\right)e^{-\frac{i\mu_c t}{\hbar}}$$



Detection of the coherent magnetic precession

Condensate: a lot of spins precess in phase.

The precessing spins should radiate at f_{min}



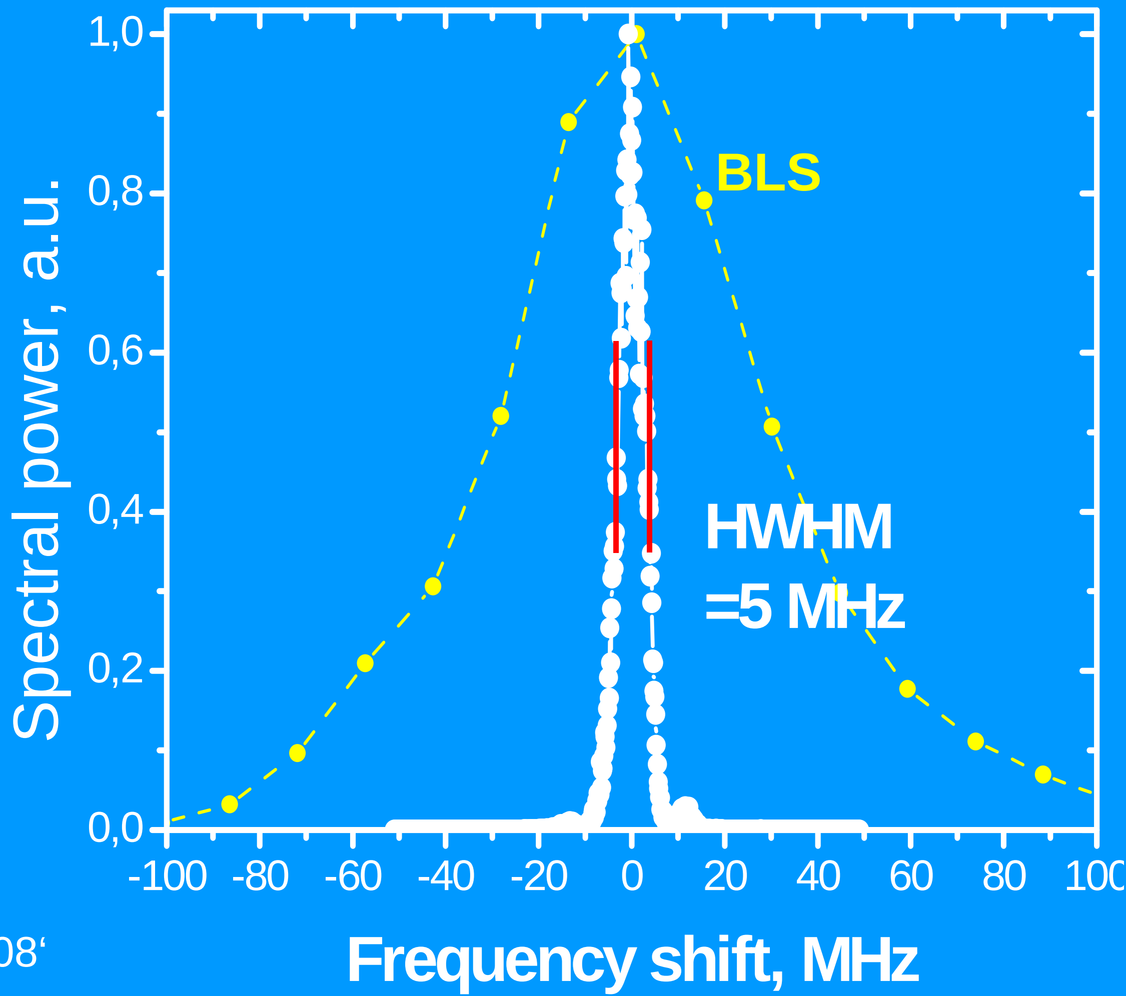
Pump magnons.

Analyze the ringing of the sample using MW spectrum-analyzer.

Spectrum of magnetic precession

The measured width corresponds to 0.3 mK, i.e. $2{\cdot}10^{-6}kT$

Very high temporal coherence of the condensate



Appl. Phys. Rev. Lett. **92** 162510 08‘

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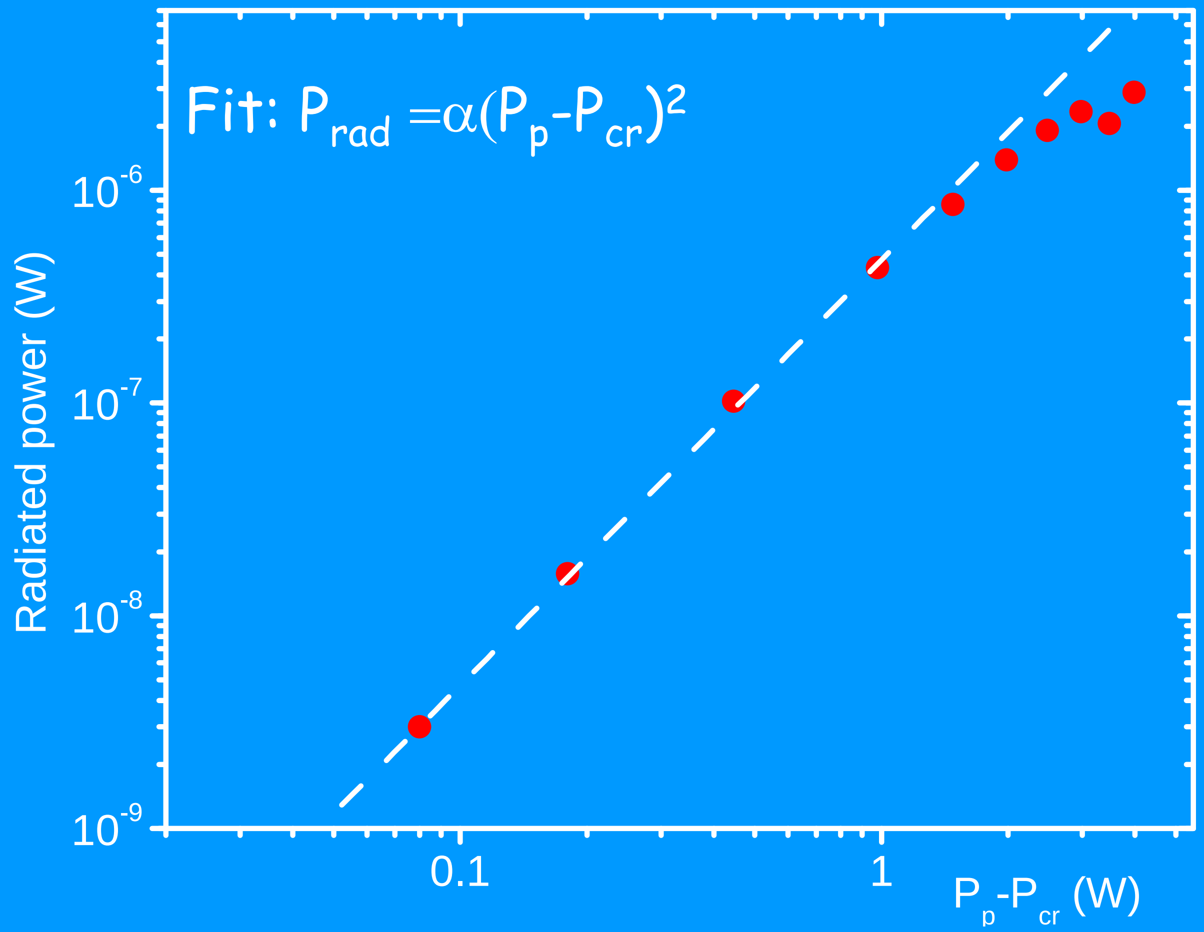
Critical index

Sweeping pumping power just above the BEC threshold



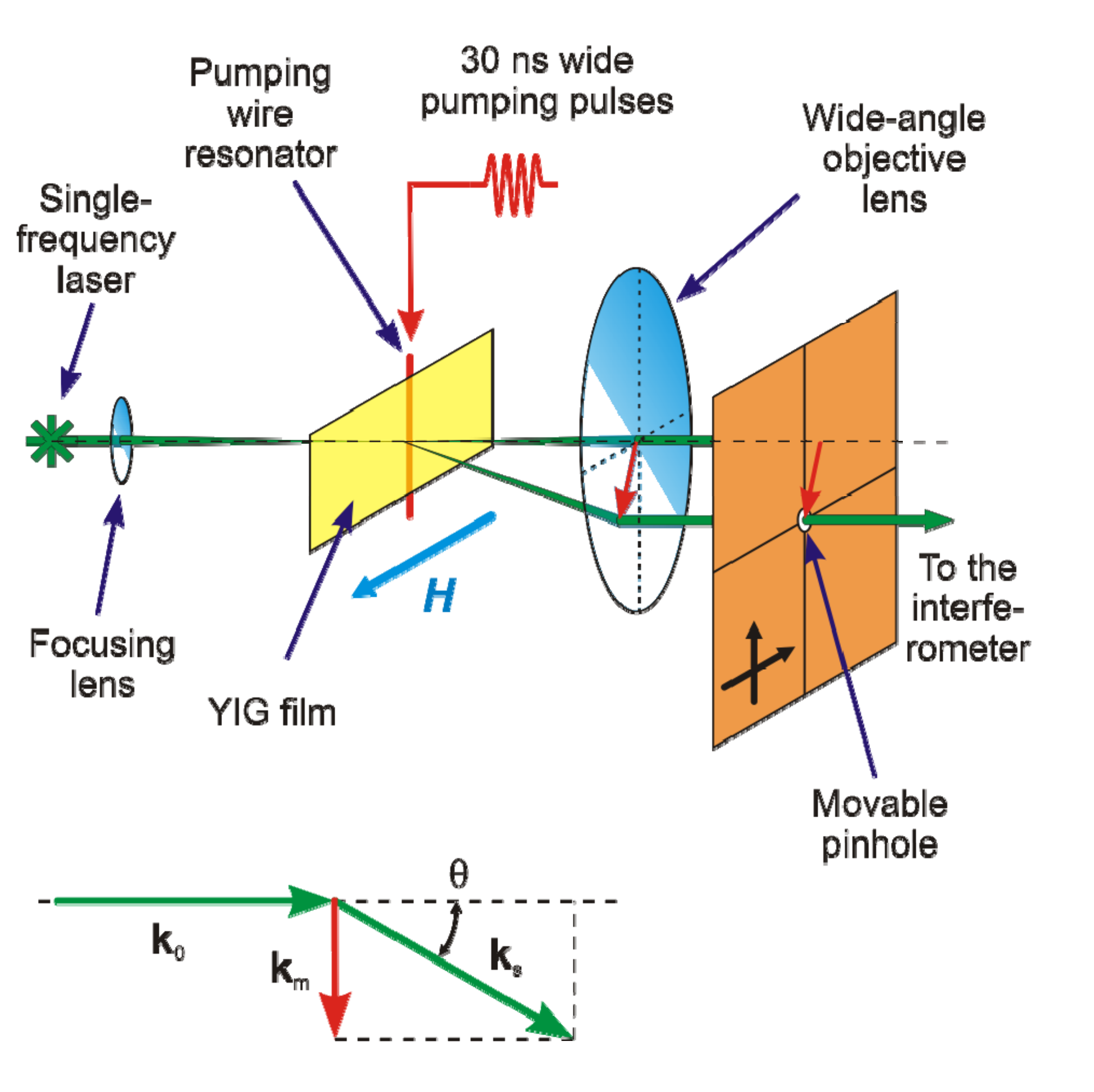
Kalafati & Safonov predicted (1993)

$P_{rad} \propto (P_p - P_{cr})^2$

for BEC of magnons due to double degeneracy of the spectrum and phase-locking between to components of the condensate

NLD

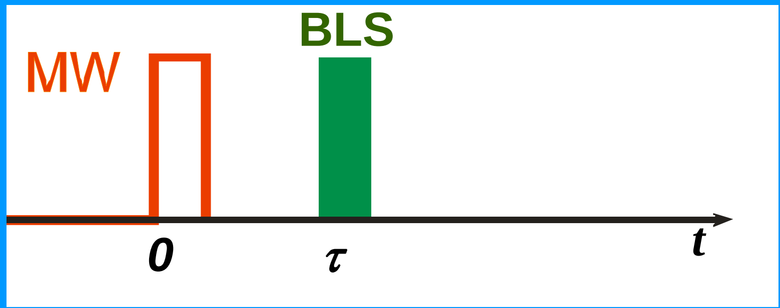
Study with k-resolution

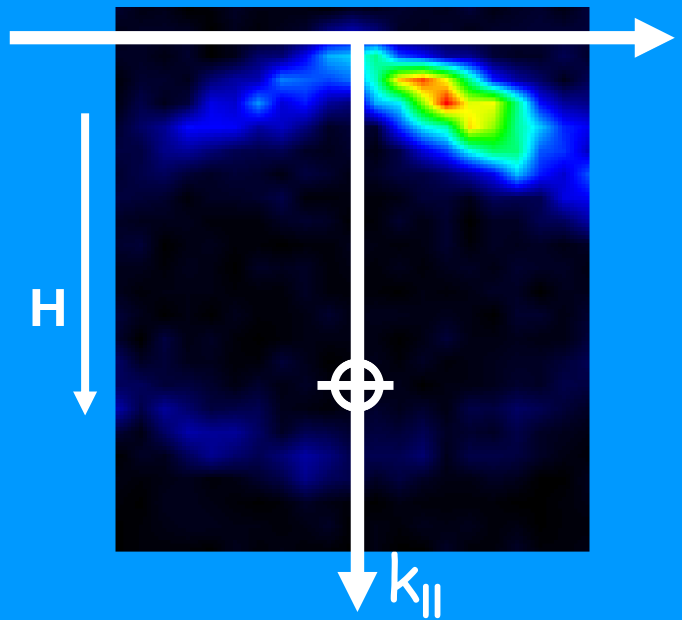


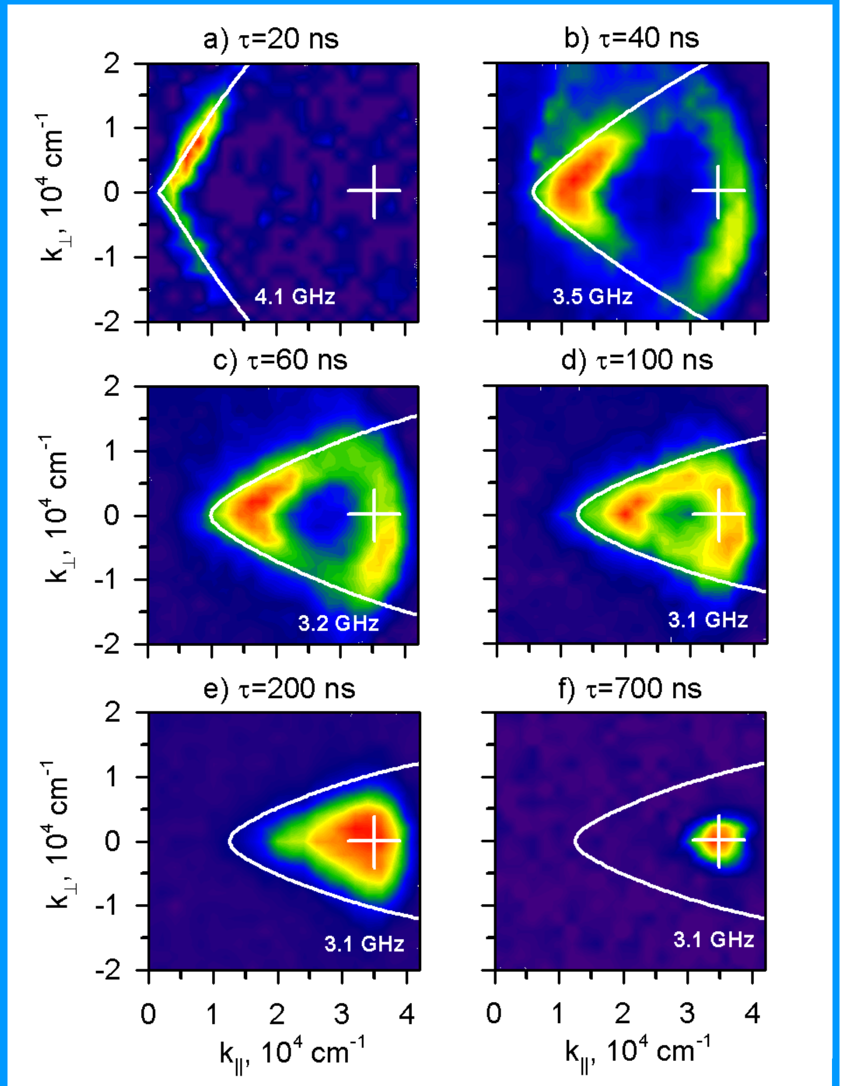
Instead integrating the signal over ($k_{||}$, $k_{\perp}$) k-resolved measurements are performed.

Goal: investigation of magnon kinetics during the formation of the condensate and spatial coherence properties of the condensate.

Magnon kinetics in the phase space



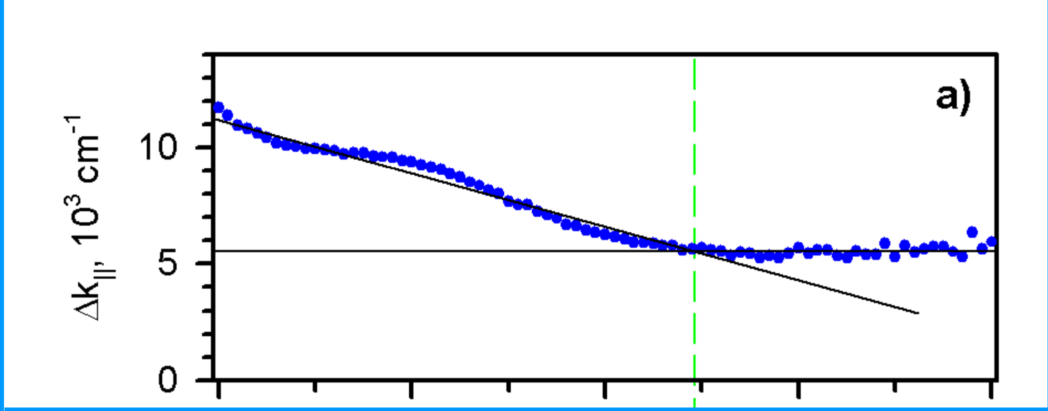




Magnons are gathered at the point in the phase space corresponding to the minimum frequency.

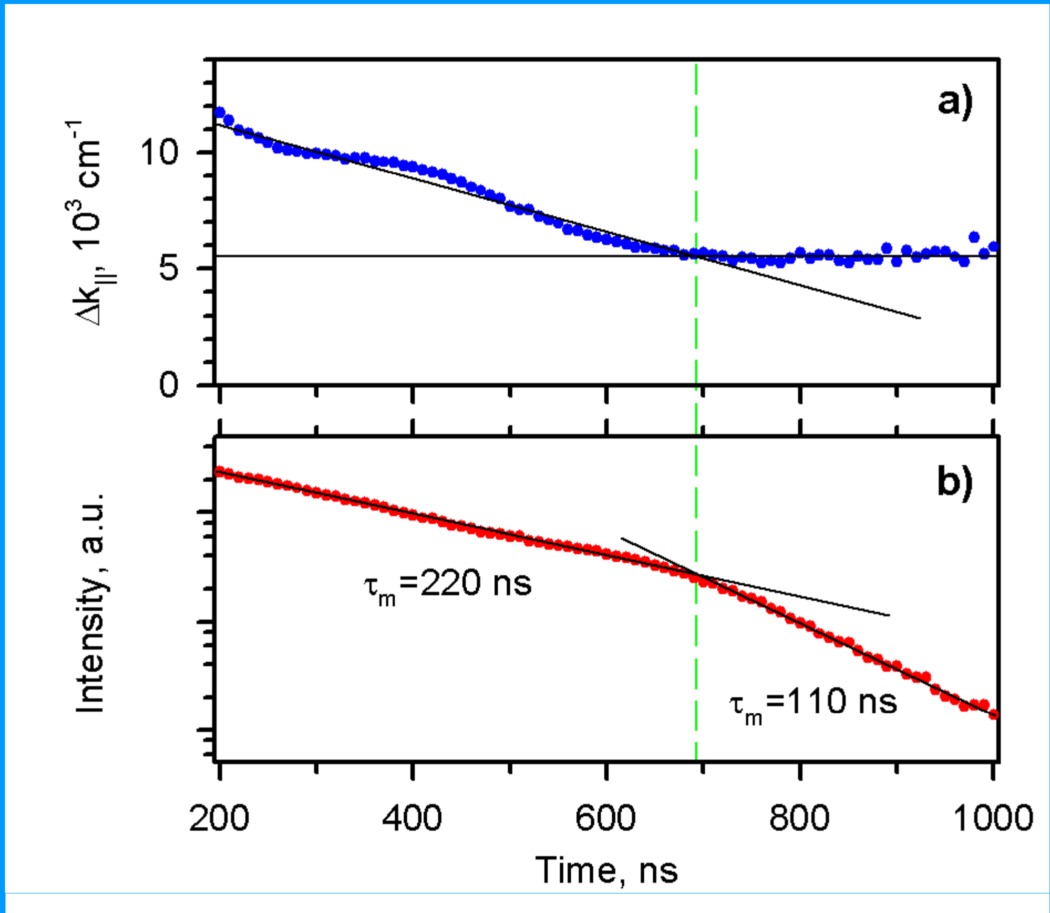
Phys. Rev. Lett. **101** 257201 ´08.

Spatial coherence of the condensate



The width of the magnon cloud in the k-space first decreases and then saturates.
The corresponding coherence length $\xi = \pi/\Delta k$ can be determined:

Spatial coherence of the condensate



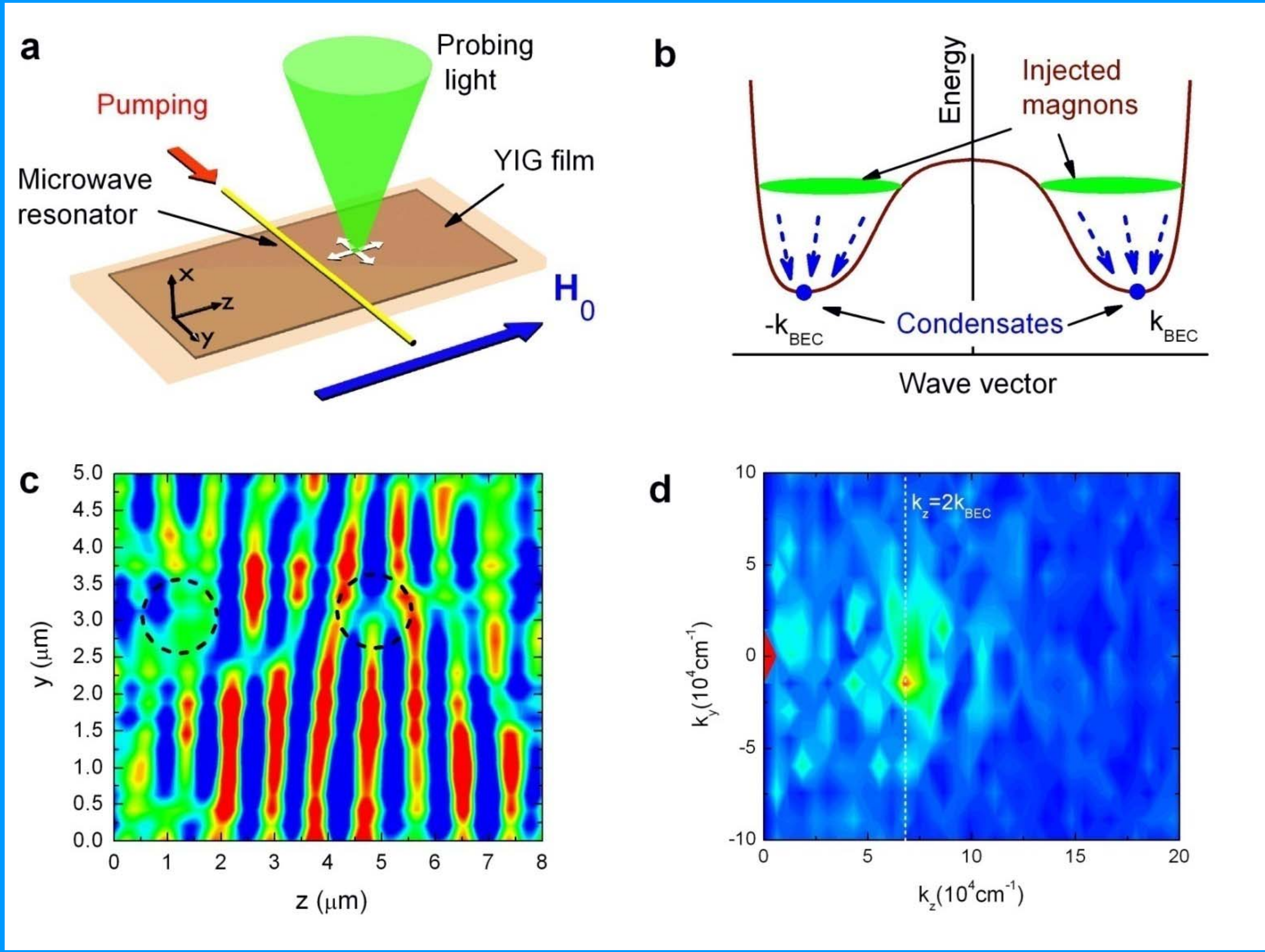
The width of the magnon cloud in the k-space first decreases and then saturates.
The corresponding coherence length $\xi = \pi/\Delta k$ can be determined:

$$\xi_{||} = 6\ \mu m \qquad \xi_{\perp} > 10\ \mu m$$

The coherence length is anisotropic, reflecting the anisotropy of the magnon spectrum.

Phase-locking between the k and -k components

CW measurements

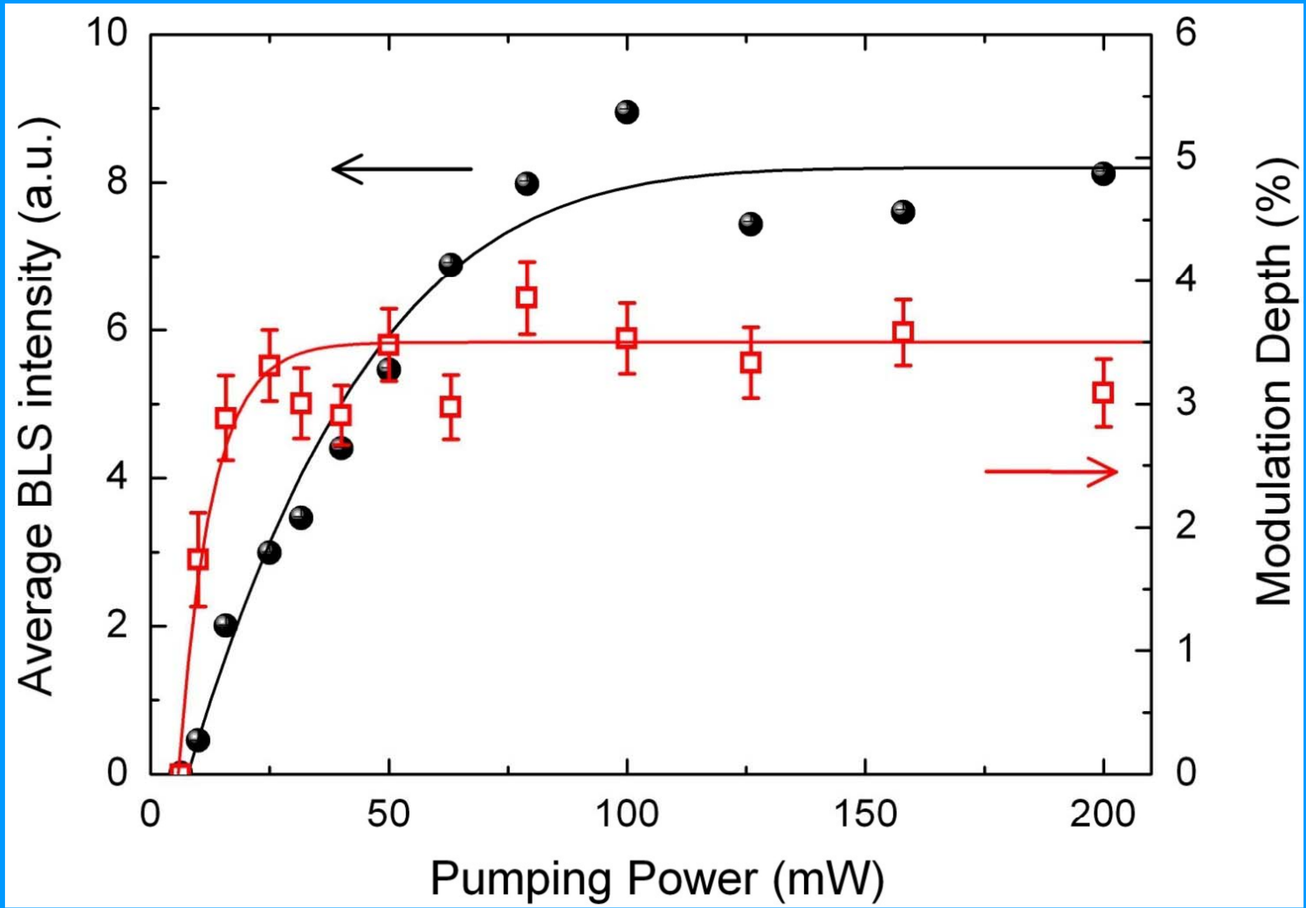


Two components of the condensate are phase locked
The pase-locking is probably due to the defect-mediated coupling

In addition to regular periodic structure stationary vortices are observed

Correlation of the k and -k components

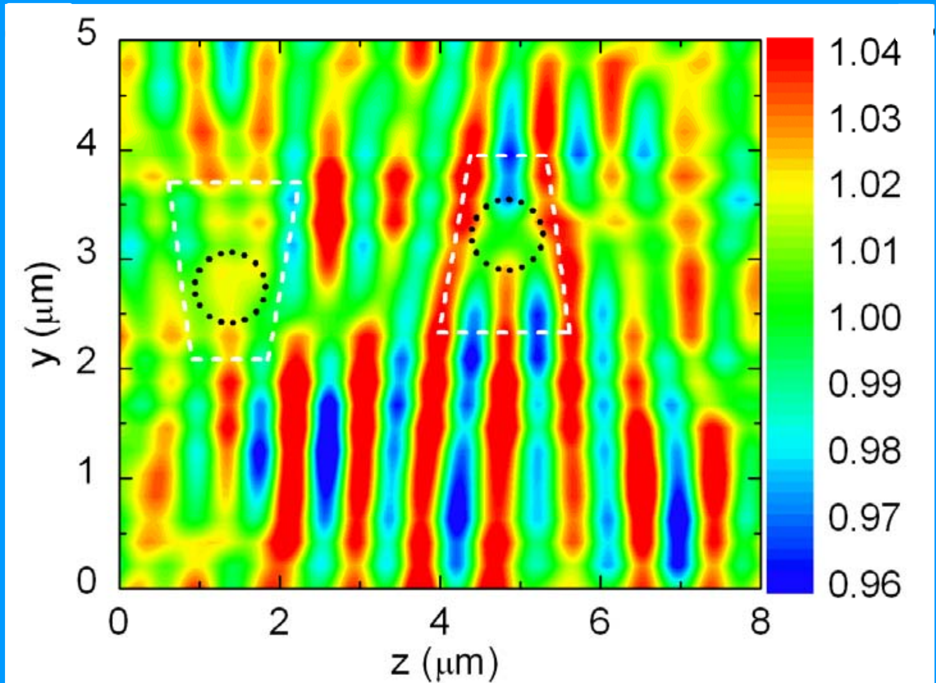
CW measurements

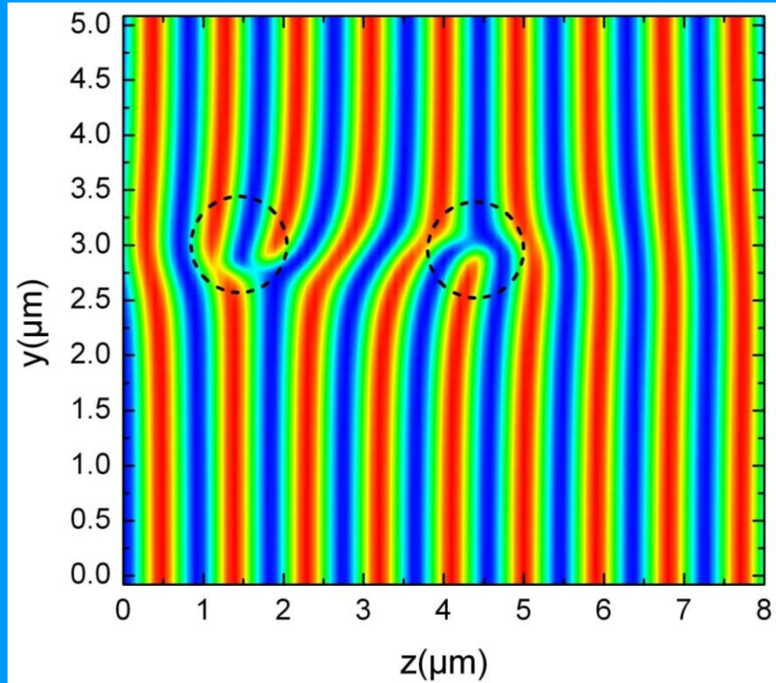


The amplitude of the modulation grows faster than the total density.

The pase-locking is due a nonlinear interaction between the components of the condensate

Vortices in the condensate





$$\psi(y,z,t)=\left(\psi_+(y,z,t)e^{ik_0 z}+\psi_-(y,z,t)e^{-ik_0 z}\right)e^{-\frac{i\mu_c t}{\hbar}}$$

$$i\hbar\partial_t\psi_\pm=\left[-\frac{\hbar^2\partial_{zz}}{2m_\parallel}-\frac{\hbar^2\partial_{yy}}{2m_\perp}-\mu_C+U_s\left|\psi_\pm\right|^2+iP(\psi_\pm)\right]\psi_\pm+J\psi_\mp^*$$

$$P(\psi_\pm)=\gamma_{eff}-i\hbar\eta\partial_t-\Gamma_s\left|\psi_\pm\right|^2 \qquad \Gamma_s(\vec{r})$$

Scientific Reports, in press

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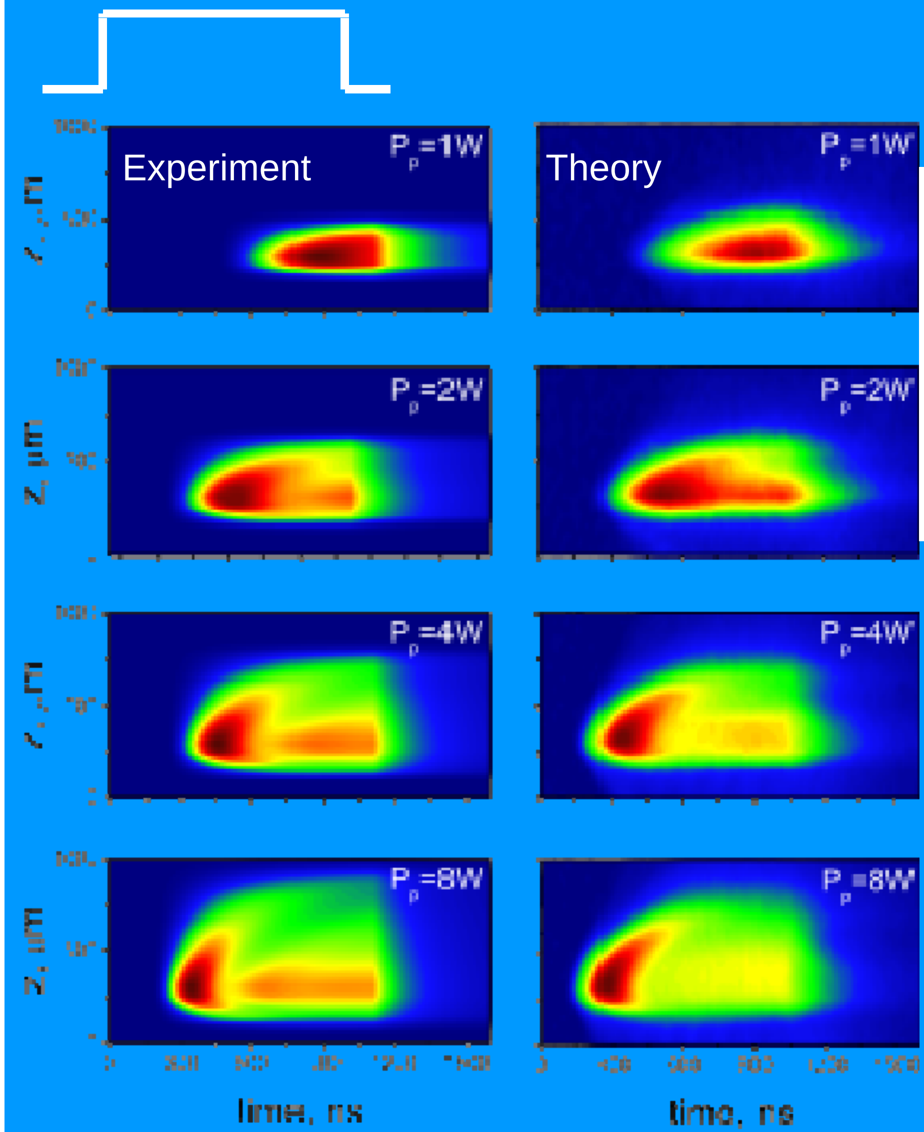
Spatio-temporal evolution of the condensate



$$\Psi(z,t) = \Psi_+(z,t)e^{ik_0 z} + \Psi_-(z,t)e^{-ik_0 z}$$

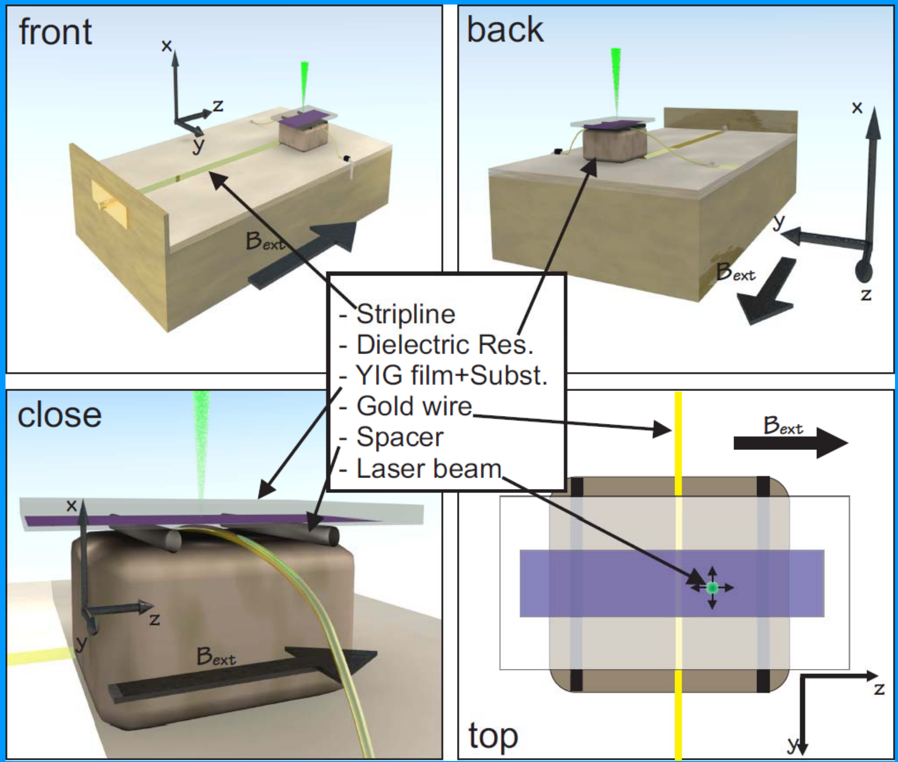
$$i(\Psi_+)_t + \mu_0\Psi_+ + \frac{1}{2}(\Psi_+)_{zz} + i\eta\Psi_+ + \left(|\Psi_+|^2 + \sigma_1|\Psi_-|^2\right)\Psi_+ + i\tau\left(|\Psi_+|^2 + \sigma_2|\Psi_-|^2\right)\Psi_+ = -f\ \delta(z)$$

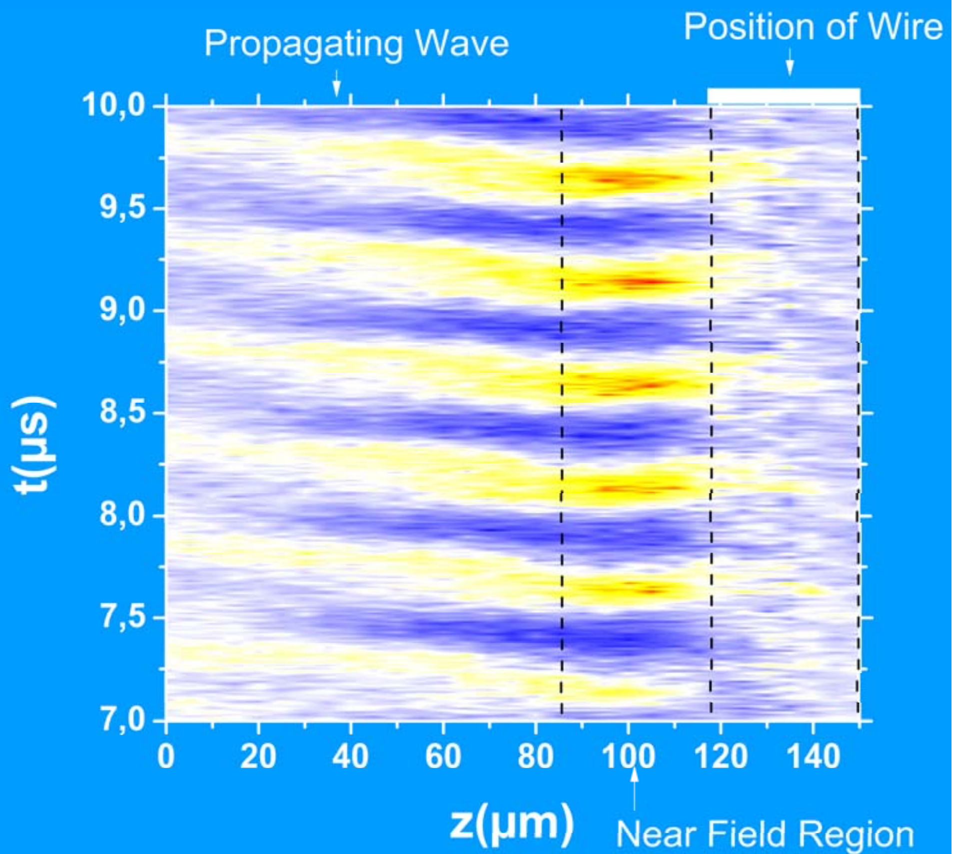
$$i(\Psi_-)_t + \mu_0\Psi_- + \frac{1}{2}(\Psi_-)_{zz} + i\eta\Psi_- + \left(|\Psi_-|^2 + \sigma_1|\Psi_+|^2\right)\Psi_- + i\tau\left(|\Psi_-|^2 + \sigma_2|\Psi_+|^2\right)\Psi_- = -f\ \delta(z)$$

The nonlinearly coupled equations, written for amplitudes of the right- ($\vec{k}_0$) and left-traveling ($-\vec{k}_0$) waves, combininig basic features of the Gross-Pitaevskii and complex Ginzburg-Landau models.

B.Malomed et al., *Phys. Rev. B* **81** 024418 ´10

Sound in the condensate

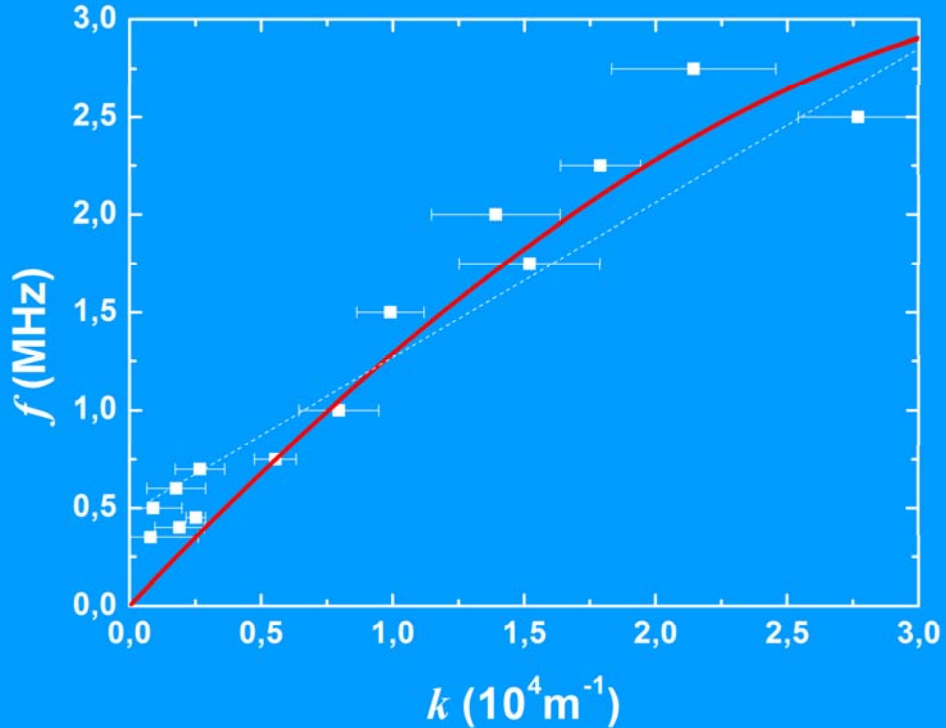


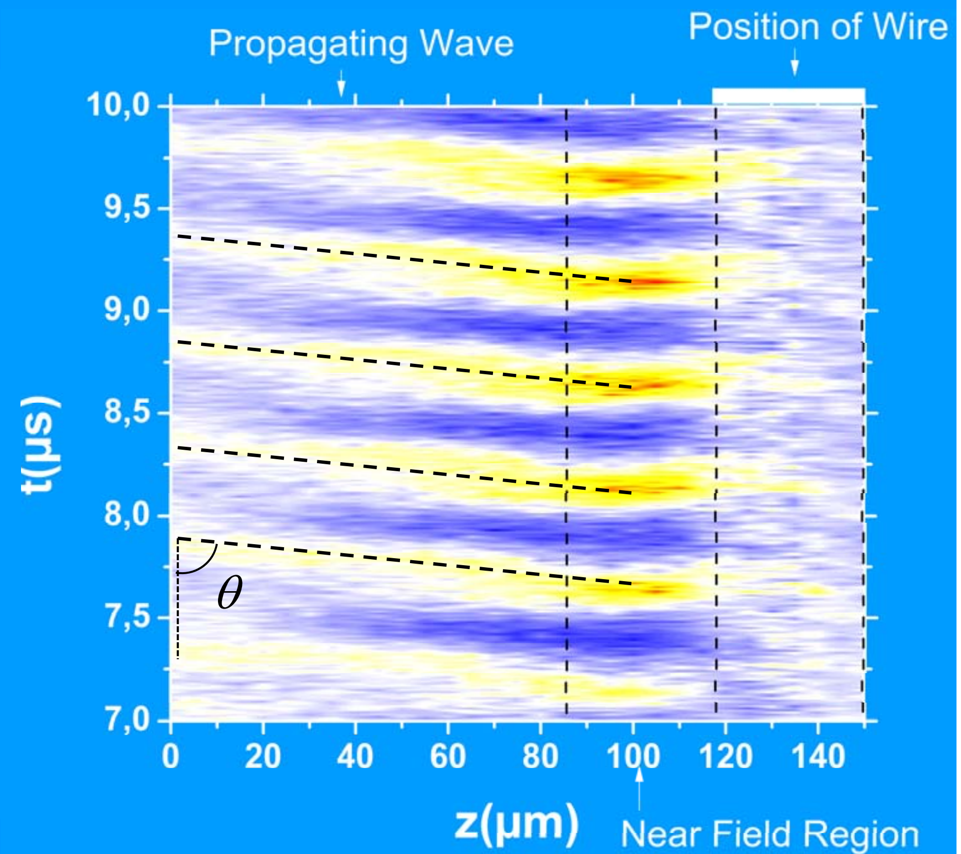


Condensate is created by the microwave pumping via dielectric resonator
It is disturbed by radio-field using a narrow wire

The wire excites waves propagating in the condensate

Sound in the condensate



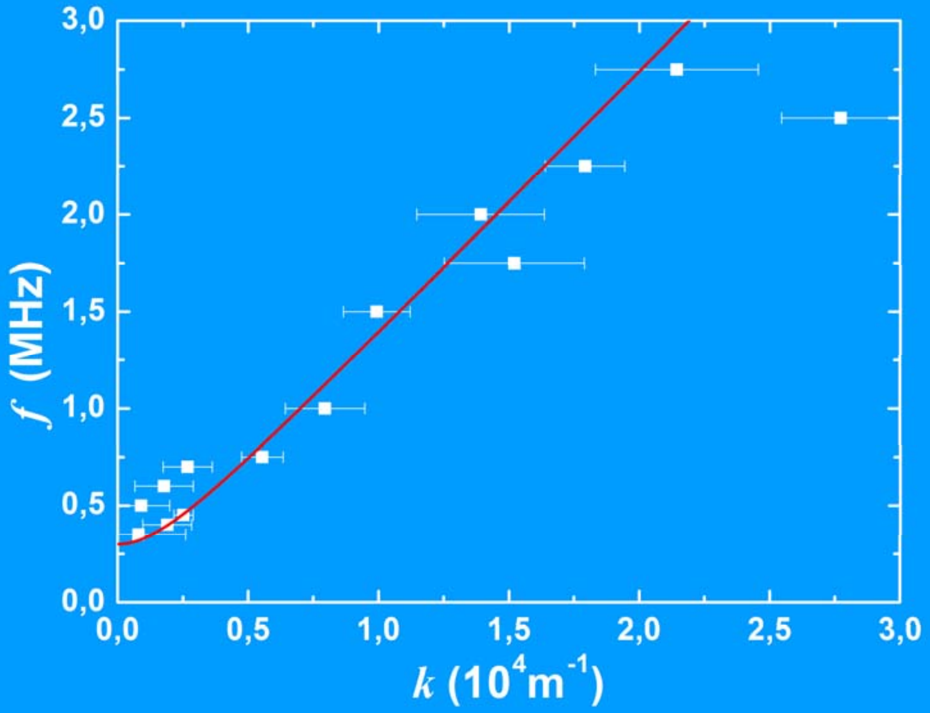


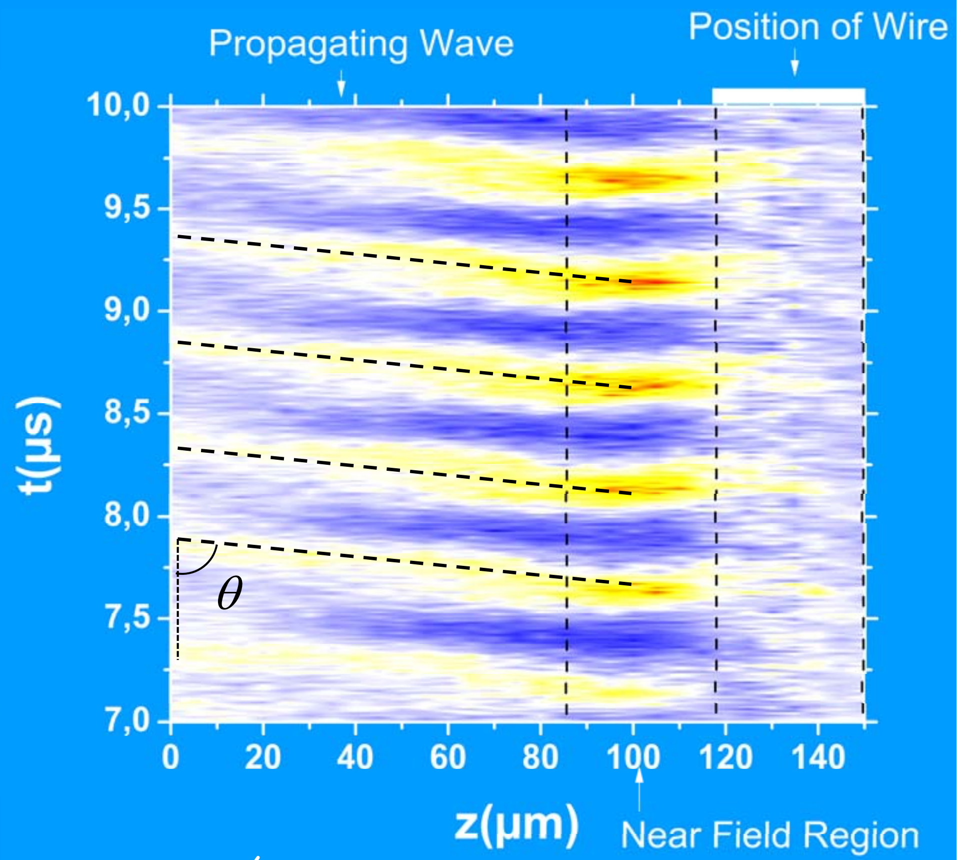
$$v_{ph} = \omega / k = \tan \theta$$

Theory based on the GPE and the known spectrum of magnons.

The wire excites waves propagating in the condensate

Sound in the condensate





$$v_{ph} = \omega / k = \tan\theta$$

Theory based on the GPE and the known spectrum of magnons.

The wire excites waves propagating in the condensate

Summary

- Doubly degenerated Bose-Einstein condensate of magnons is created at room temperature
- Coherence properties of the condensate as well its spatio-temporal dynamics are studied

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