Spin-dynamics in magnetic nanostructures

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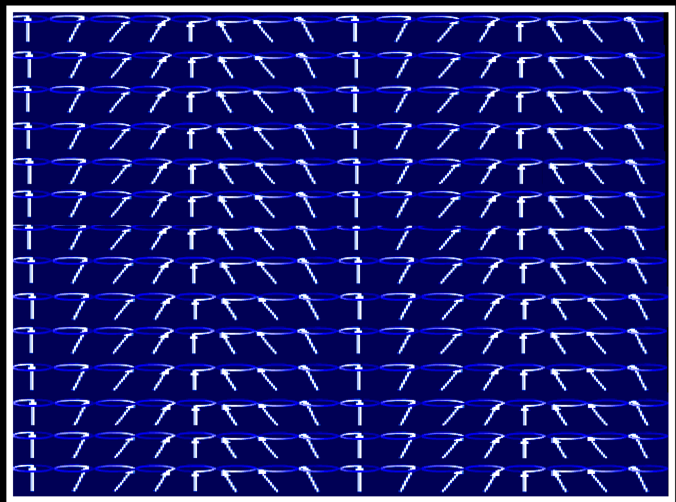
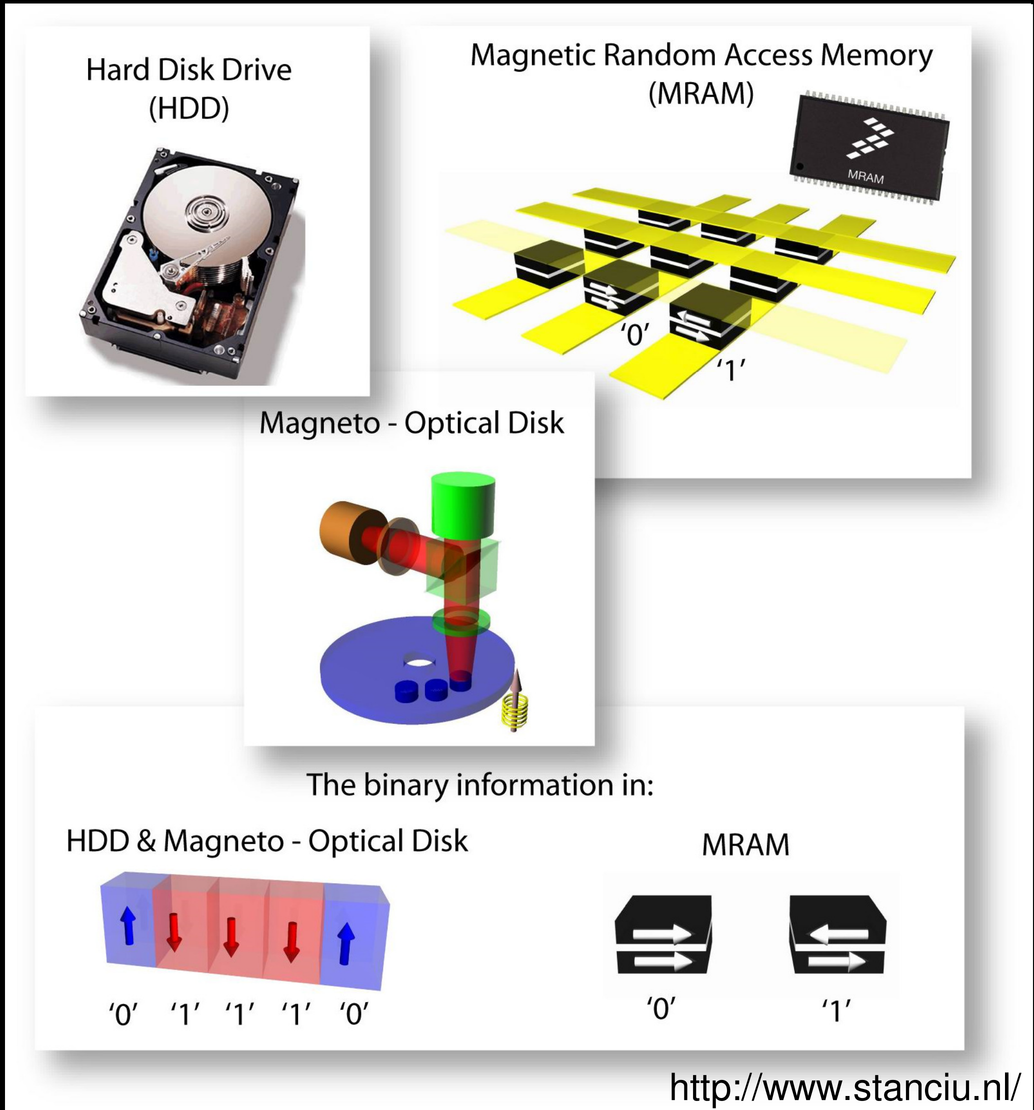


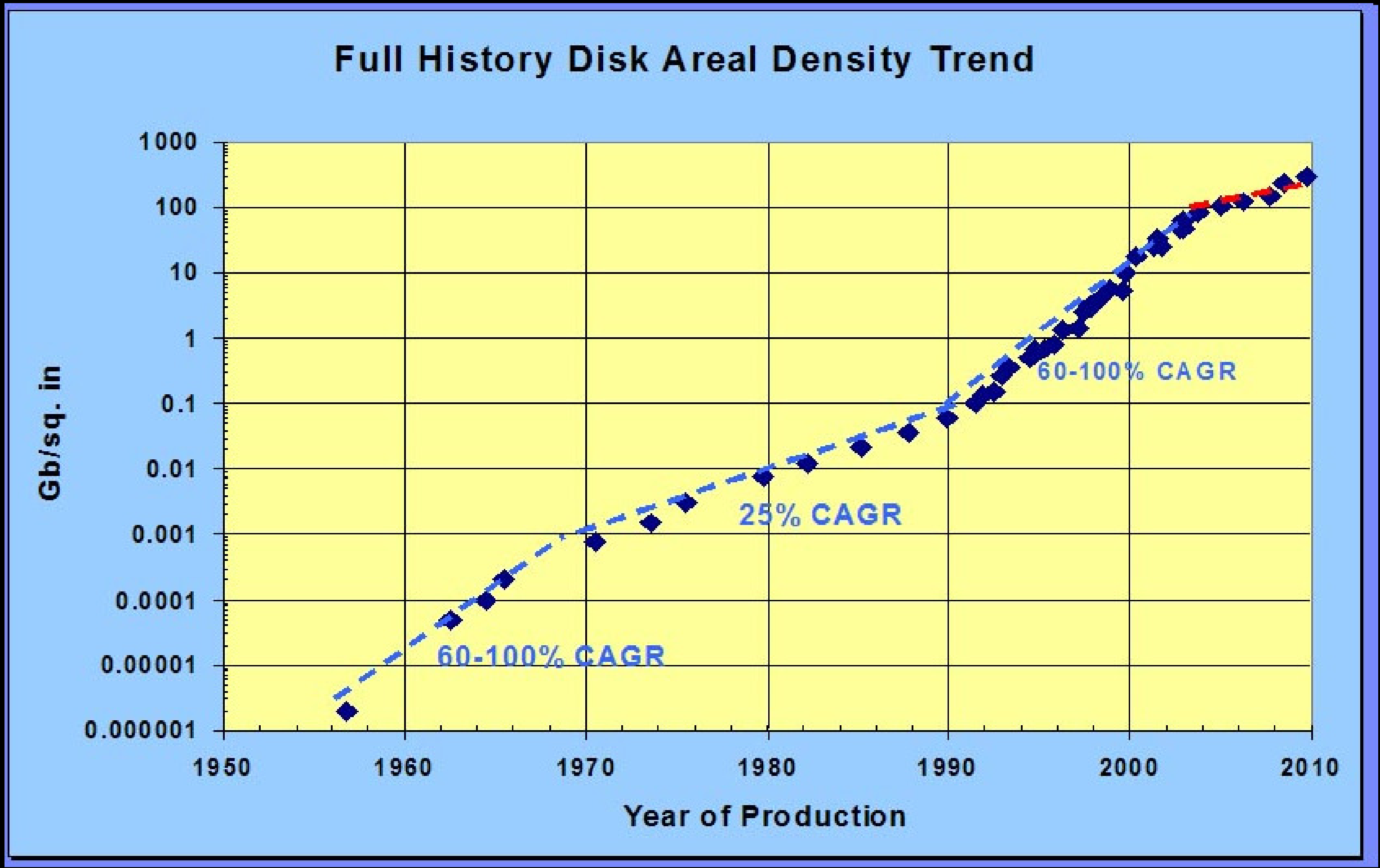
Experimental Department 1

MAX-PLANCK-GESELLSCHAFT

The importance of magnetic nanostructures

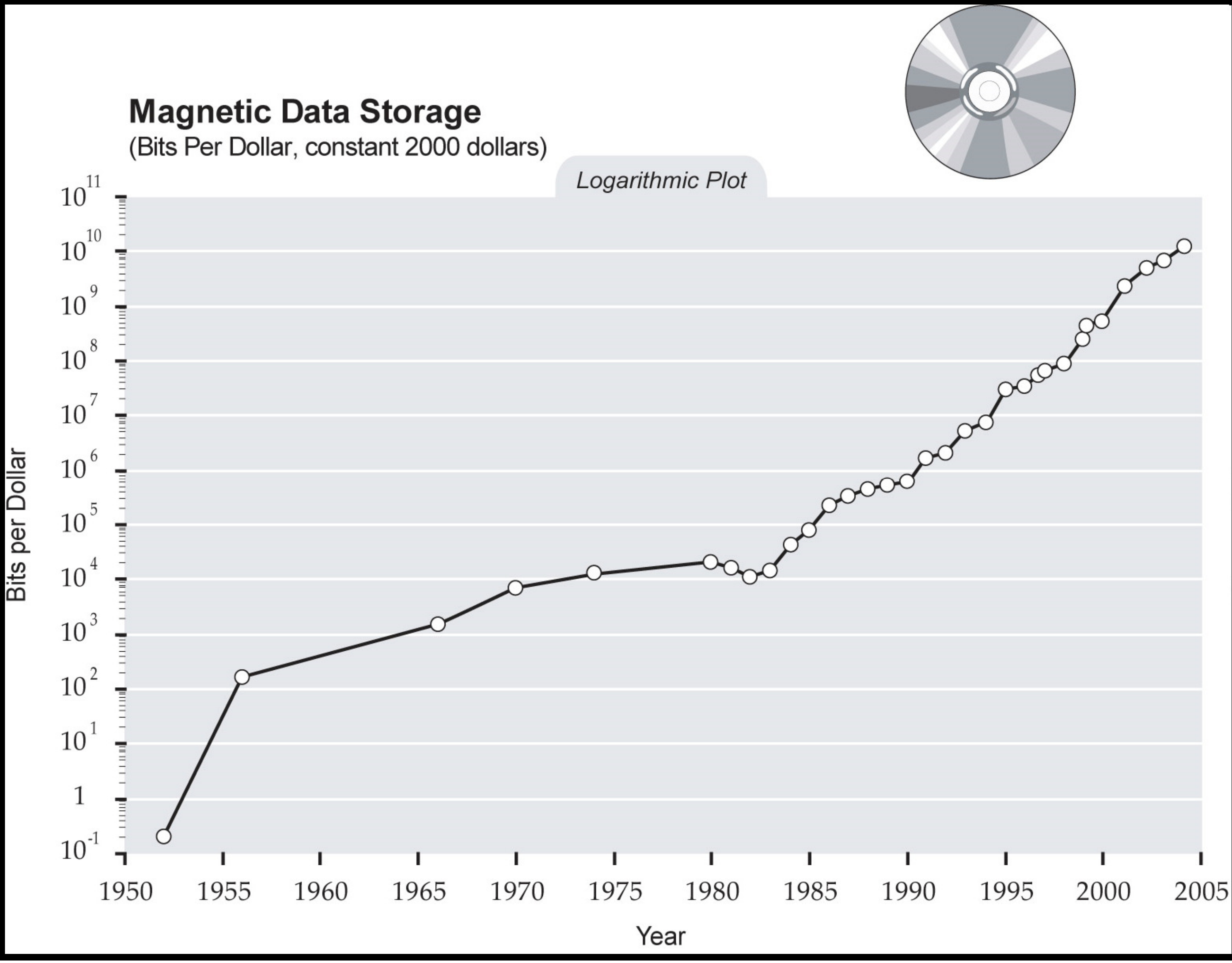


Timeline of magnetic storage media



Compound annual growth rate (*CAGR*)
is an average growth rate over a period of several years.

Timeline of magnetic storage media



Timeline of magnetic storage media

9.5mm height

Only $129

The importance of dynamic processes

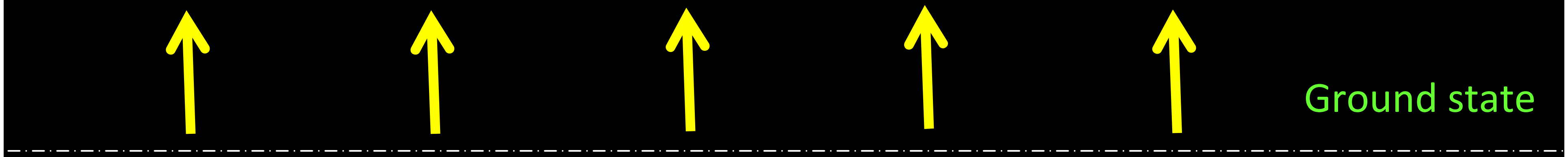
- ☞ The magnetic recording and magneto-electronic technologies push toward operation in GHz regime.

- ☞ Faster device performance needs reducing the device dimensions and understanding the processes in pico-second time scales.

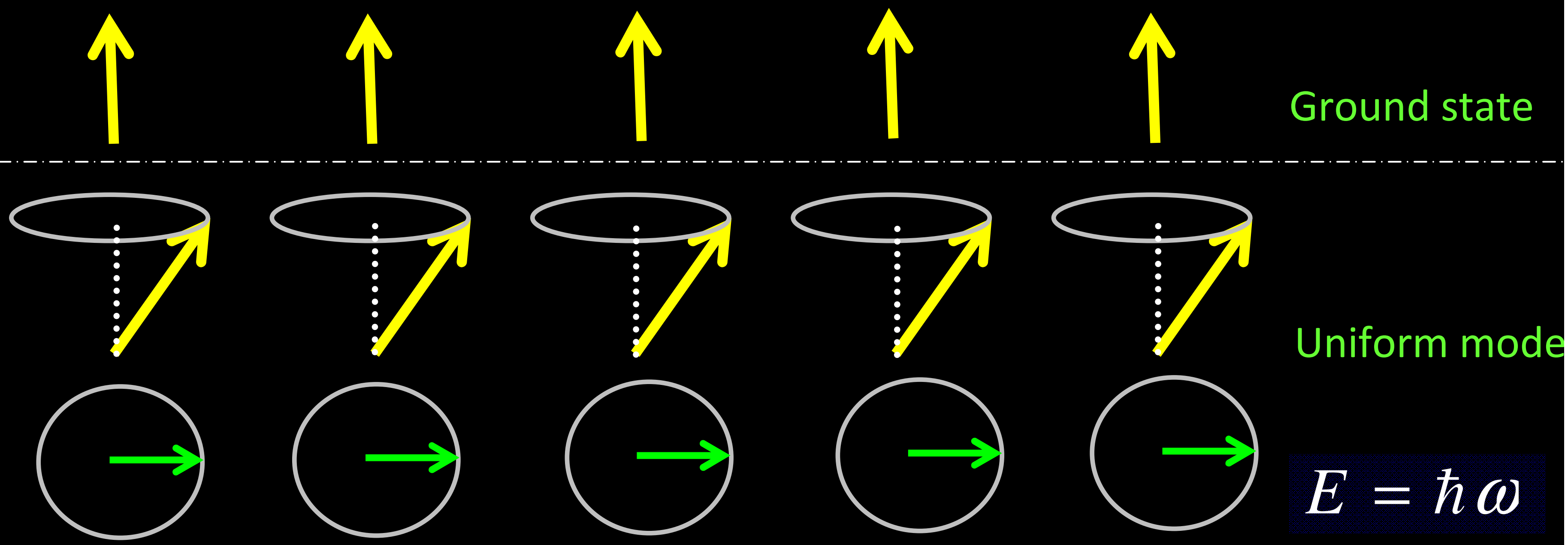
Outline

- The spin dynamics
  - Uniform precession
  - Spin-waves (magnons)
- The experimental techniques
  - Ferromagnetic resonance (FMR)
  - Brillouin light scattering (BLS)
  - Inelastic neutron scattering (INS)
  - Spin-polarized electron energy loss spectroscopy (SPEELS)

Magnetic excitations: Classical description

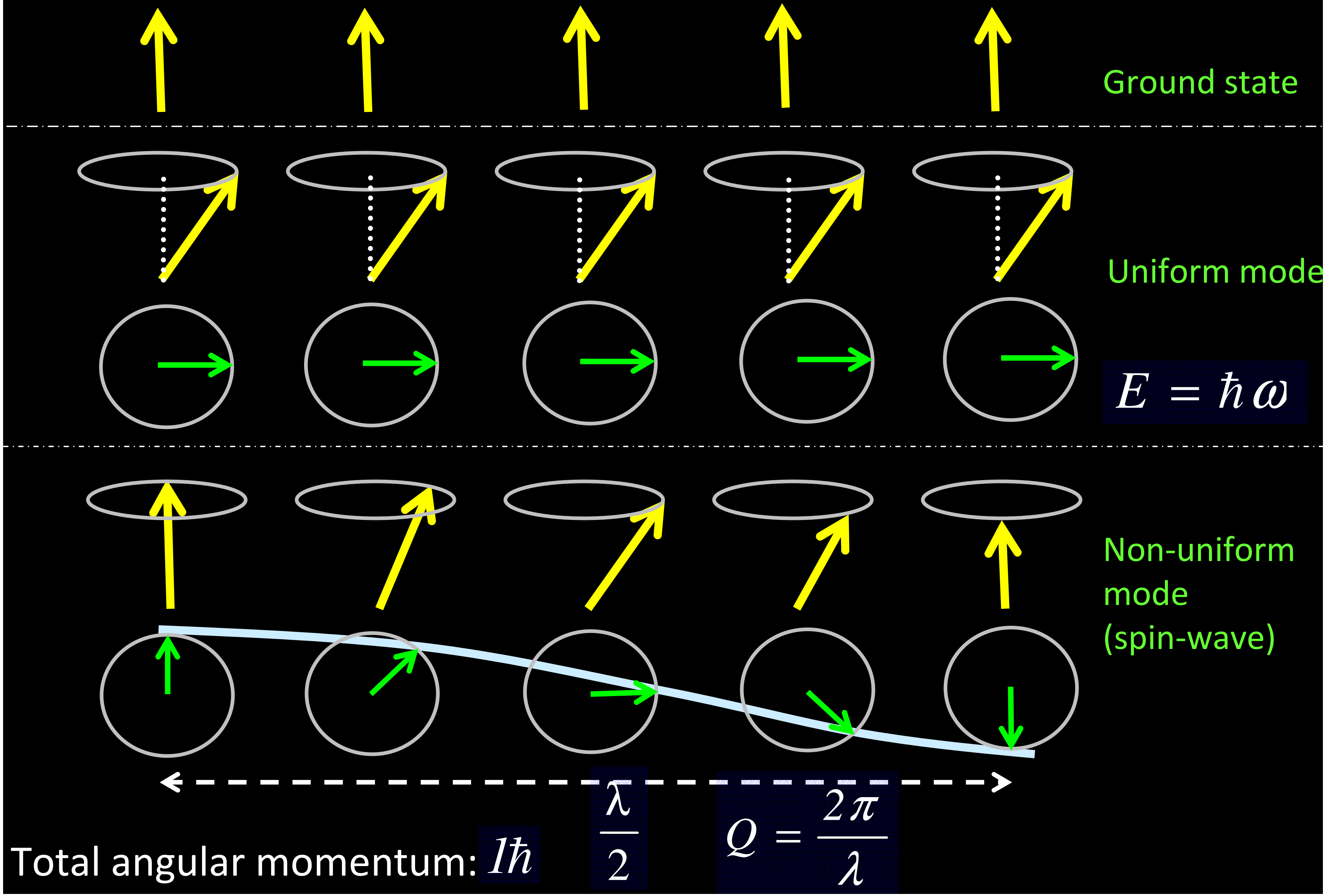


Magnetic excitations: Classical description

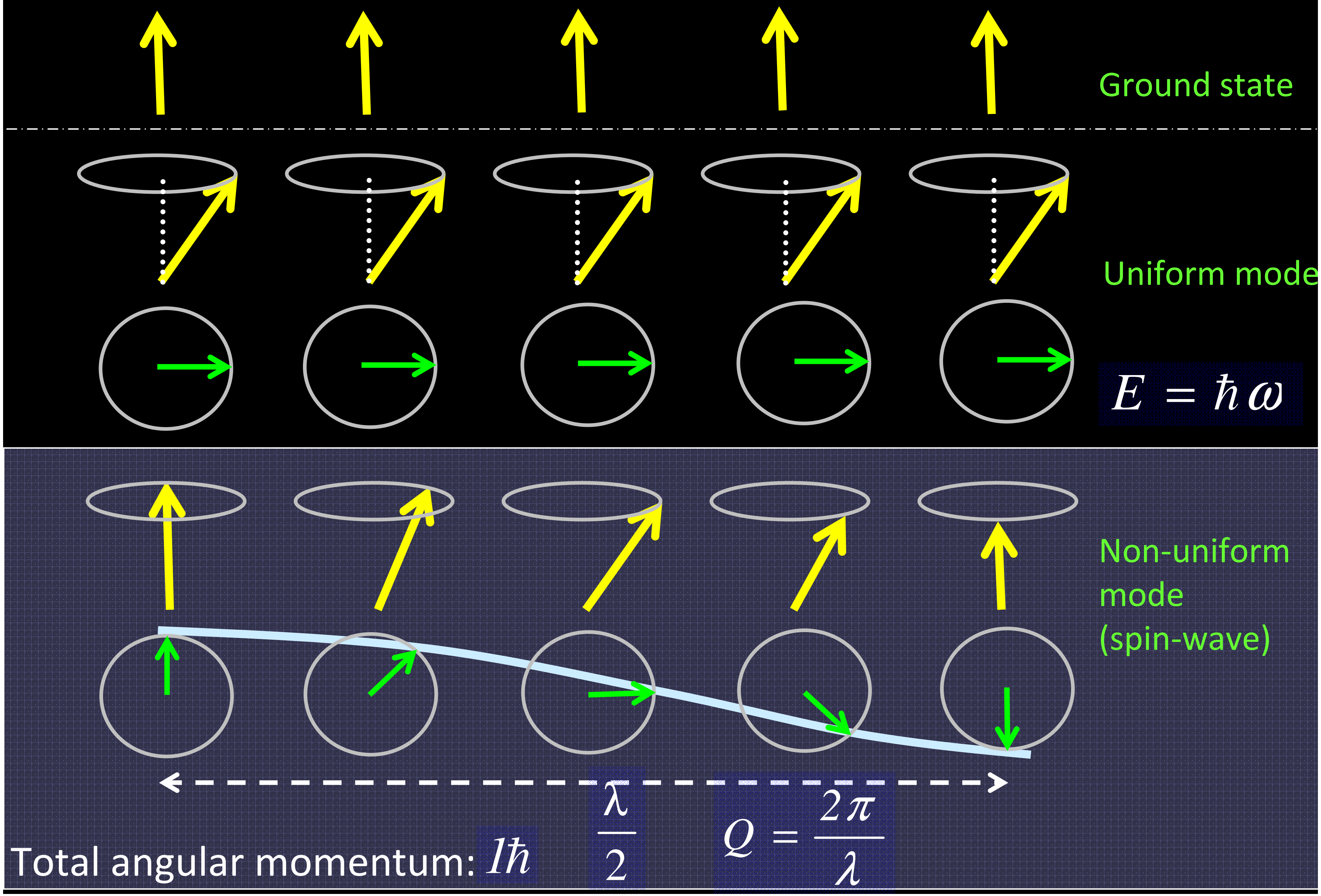


$$E = \hbar\omega$$

Magnetic excitations: Classical description

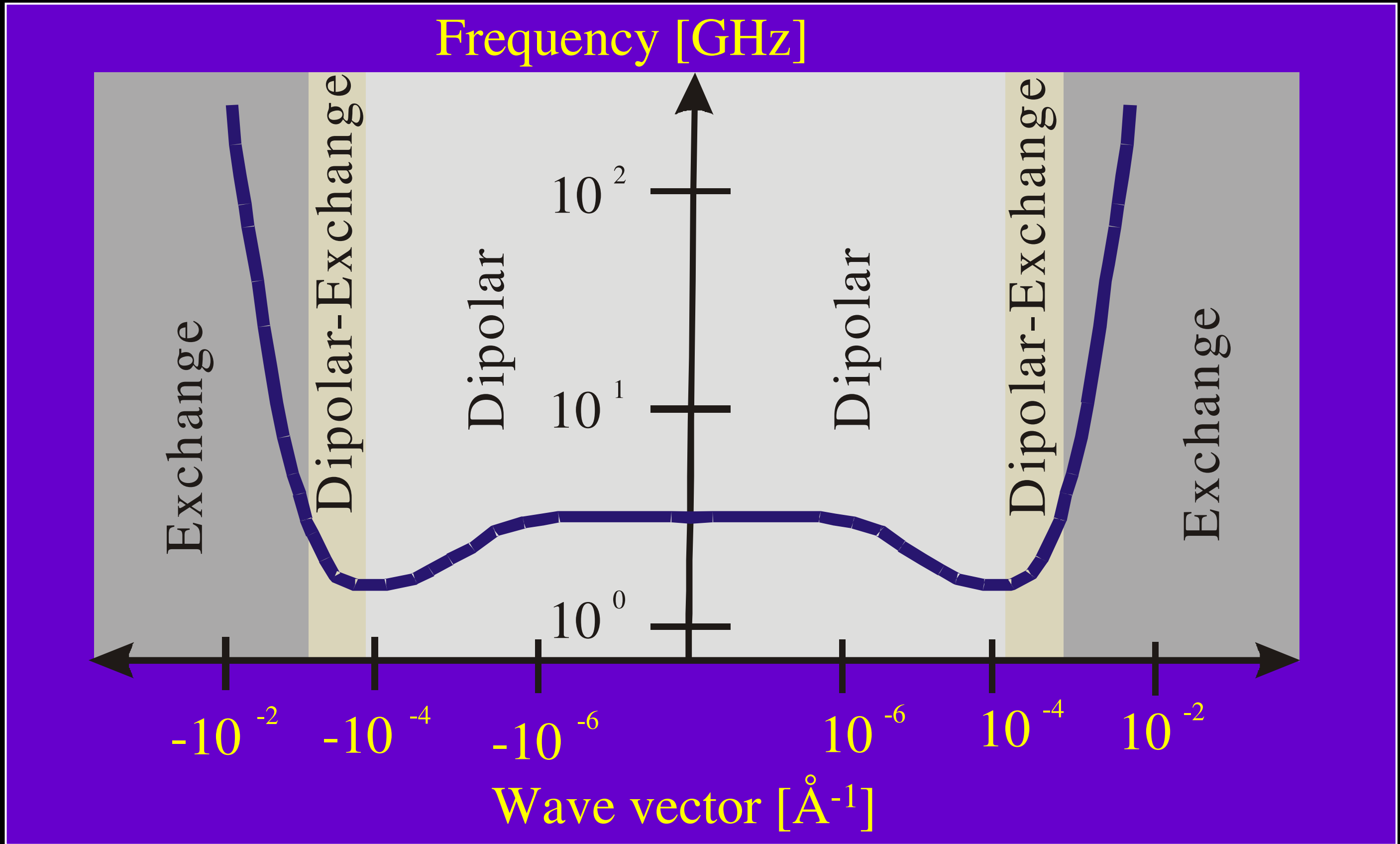


Magnetic excitations: Classical description



Different types of spin waves within the energy-momentum space

At the very low momentum values the dominating magnetic energy is the long-range dipolar interaction, hence the spin waves are called dipolar spin waves.



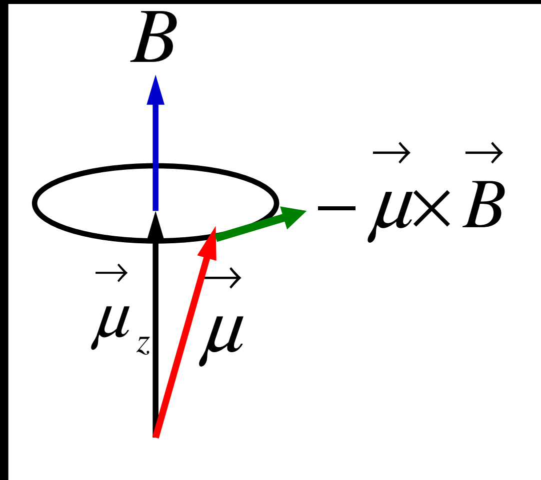
For the large momentum values the dominating magnetic energy is the exchange energy and thus it determines the energies of the spin waves.

Uniform precession

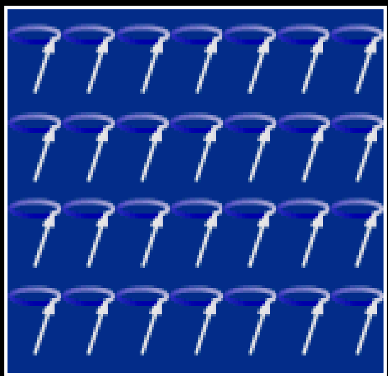
$$\vec{\mu} = -\gamma \cdot \vec{L}$$

$$\gamma = \frac{g \cdot \mu_B}{\hbar} \quad , \quad g = 2 \quad , \quad \mu_B = \frac{e}{2m}\hbar$$

$$\vec{\tau} = \dot{\vec{L}} \qquad \dot{\vec{\mu}} = -\gamma\left[\vec{\mu} \times \vec{B}\right]$$



- For NMR: nuclear spins, e.g. protons γ = 43 MHz/T
- For ESR, FMR, AFMR: electronic spins, γ = 28 GHz/T

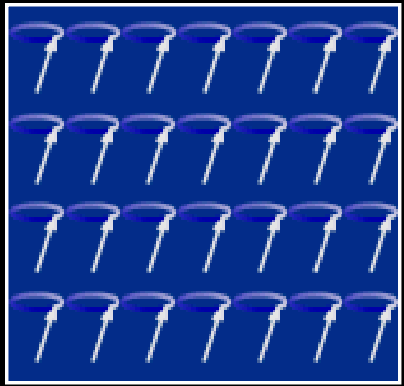


Equation of motion:

$$\frac{1}{\gamma}\frac{\mathrm{d}\vec{\mathrm{M}}}{\mathrm{dt}} = -\left[\vec{\mathrm{M}} \times \vec{\mathrm{B}}_{\mathrm{eff}}\right] + \vec{\mathrm{R}}$$

Precession torque   Damping torque

Ferromagnetic resonance (FMR)



Equation of motion:

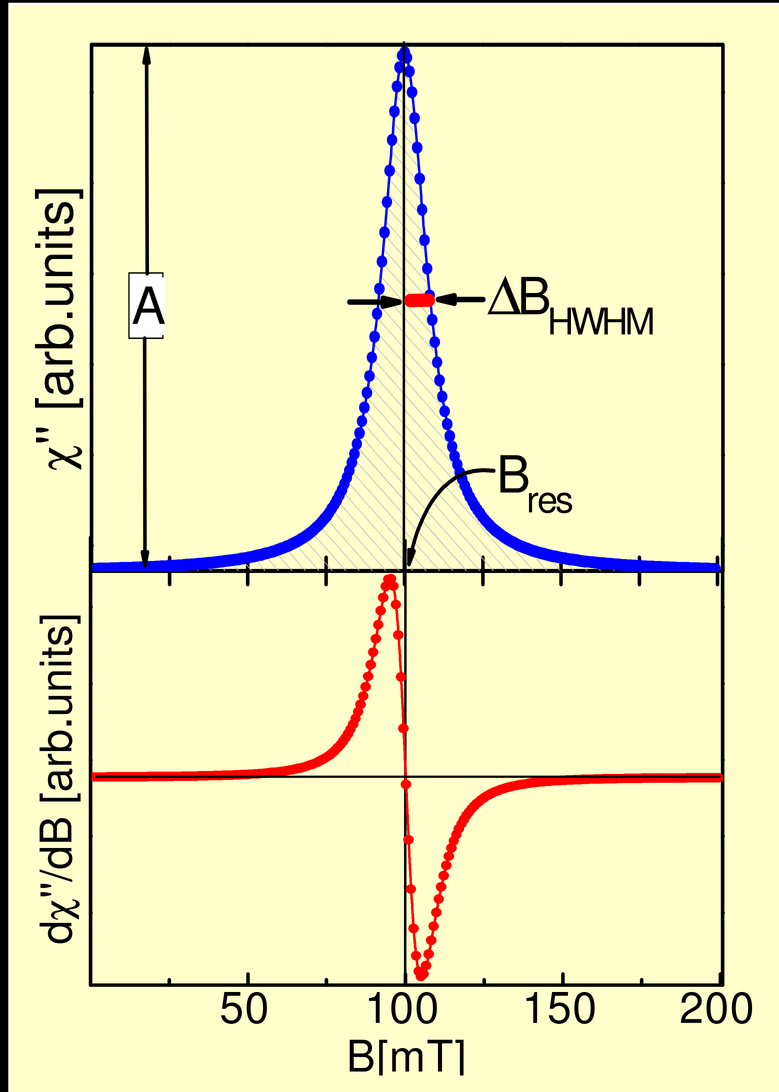
$$\frac{1}{\gamma}\frac{d\vec{M}}{dt} = -\left[\vec{M}\times\vec{B}_{eff}\right] + \vec{R}$$

$$\gamma = g\mu_B/\hbar$$

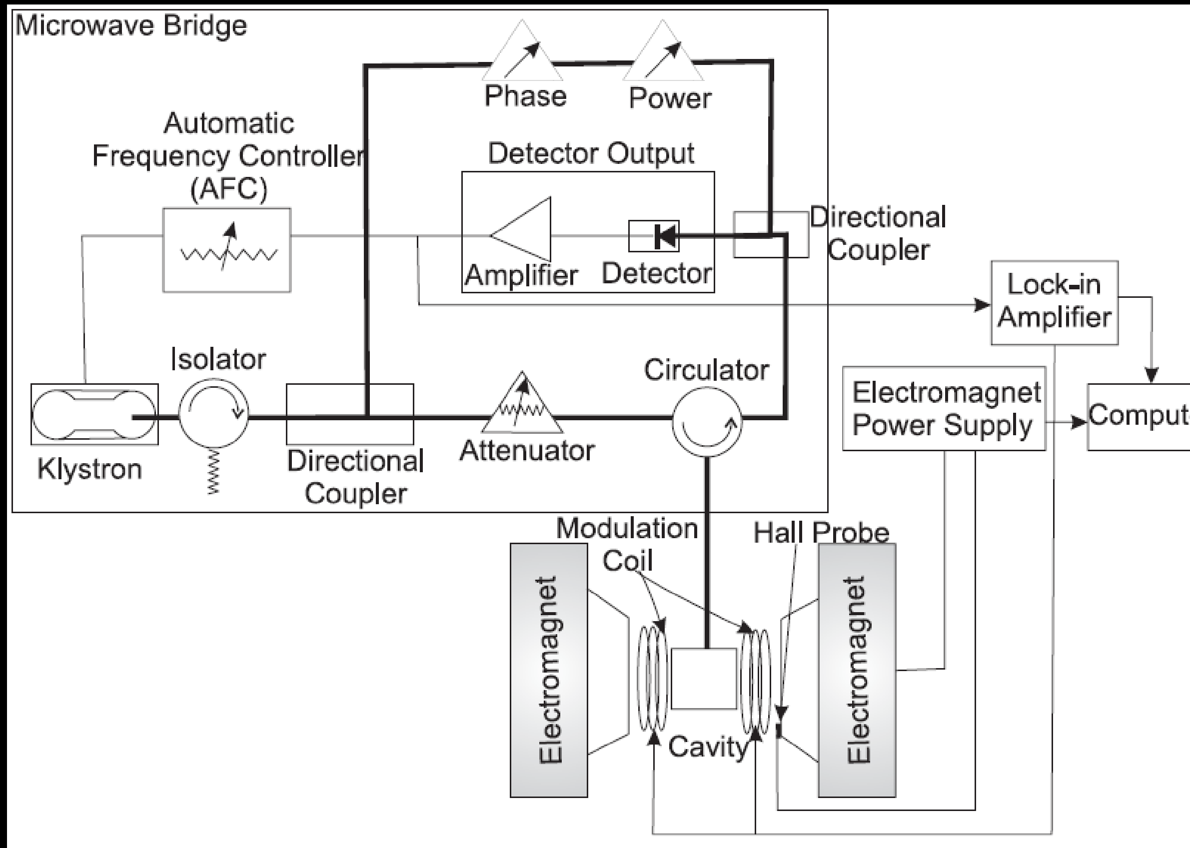
Precession torque

Damping torque

For ESR, FMR, AFMR: electronic spins, g = 28 GHz/T

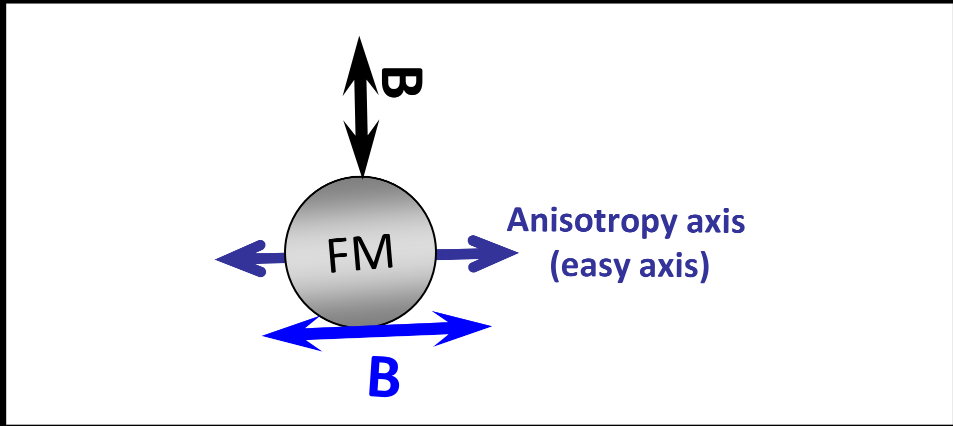


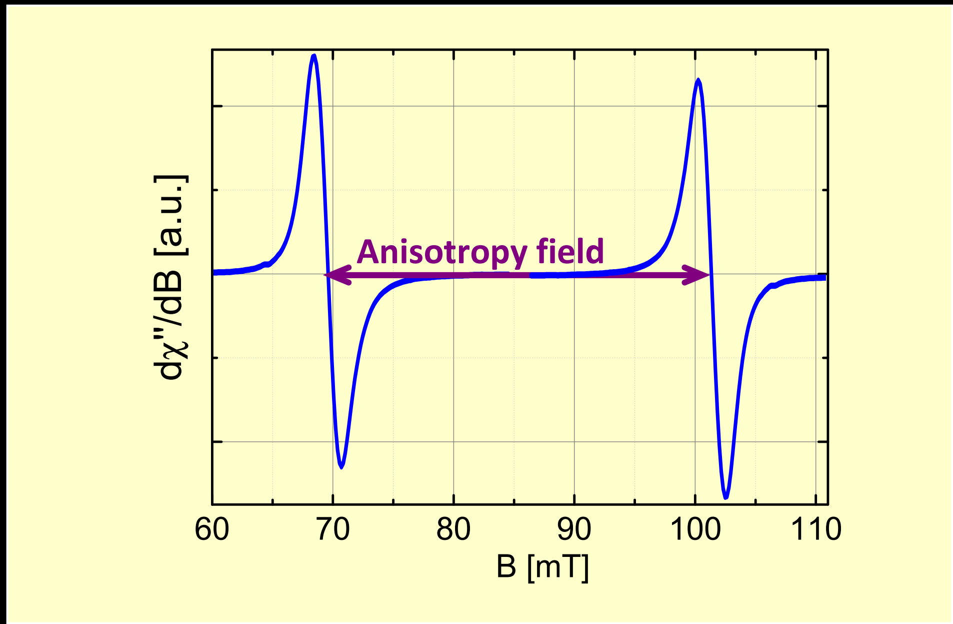
Block diagram of an FMR spectrometer



- Frequency is kept constant
- Usually sample is placed inside a microwave resonator
- External magnetic field is swept
- Principally other setups are possible
(frequency dependent measurements, zero external field)

Determination of magnetic anisotropy by FMR



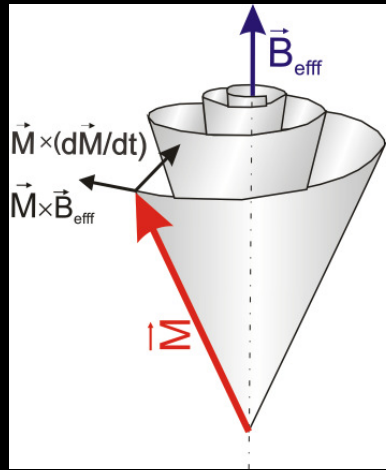


The use of ferromagnetic resonance to measure the magnetic anisotropy.

Spin damping mechanisms in uniform precession

Landau-Lifshitz equation of motion (1935)

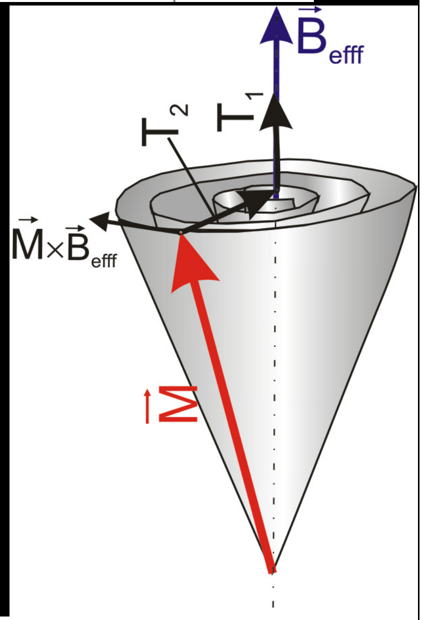
$$\frac{1}{\gamma}\frac{d\vec{M}}{dt} = -\left[\vec{M}\times\vec{B}\right] + \frac{\lambda}{\mu_0\gamma M^2}\left[\vec{M}\times\vec{M}\times\vec{B}\right]$$



Landau-Lifshitz-Gilbert equation of motion (1955)

$$\ldots + \frac{\alpha}{\gamma M}\left[\vec{M}\times\frac{d\vec{M}}{dt}\right]$$

$$\alpha = \frac{G}{\gamma M}$$



Bloch-Bloembergen damping (1946, 1950):

$$\ldots - \left[\frac{M_x}{\gamma T_2}\hat{e}_x + \frac{M_y}{\gamma T_2}\hat{e}_y + \frac{M_z - M_s}{\gamma T_1}\hat{e}_z\right]$$

Transversal Longitudinal

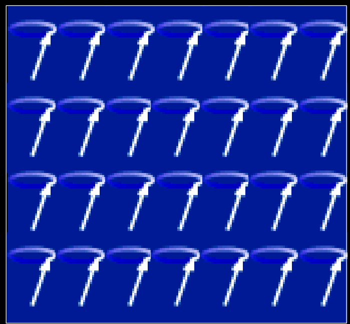
Spin damping mechanisms in uniform precession

Equation of motion:

$$\frac{1}{\gamma}\frac{\partial \vec{M}}{\partial t} = -\left[\vec{M} \times \vec{B}_{eff}\right] + \vec{R} + \frac{\alpha}{\gamma M}\left[\vec{M} \times \frac{\partial \vec{M}}{\partial t}\right]$$

$$\alpha = G/\gamma M$$

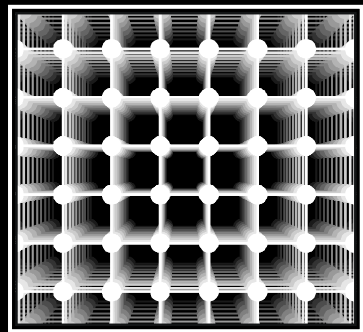
Uniform precession



Q=0

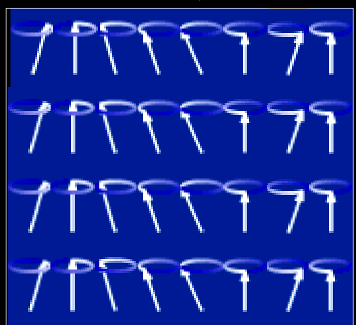
(2)

(1)



Dissipation to the lattice

(3)



Non-uniform precession

Q≠0

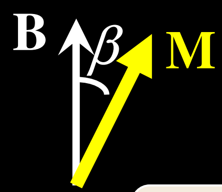
Non-Gilbert type relaxation mechanisms

$$\Delta B_{pp}^{total} \approx \Delta B_{pp}^{inhom}(0) + \frac{2}{\sqrt{3}}\frac{\alpha}{\gamma}\frac{\omega}{\cos\beta}$$

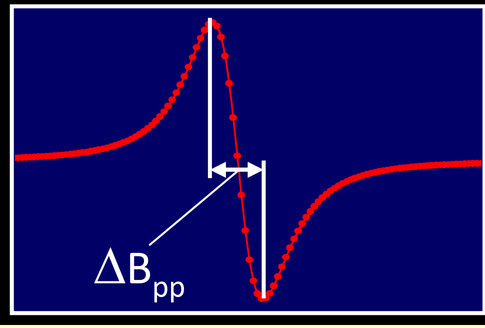
$$+\sum_{\langle x_i\rangle} \Gamma_{\langle x_i\rangle} \bullet \arcsin\left(\sqrt{\frac{\sqrt{\omega^2+\left(\frac{\omega_0}{2}\right)^2}-\frac{\omega_0}{2}}{\sqrt{\omega^2+\left(\frac{\omega_0}{2}\right)^2}+\frac{\omega_0}{2}}}\right)$$

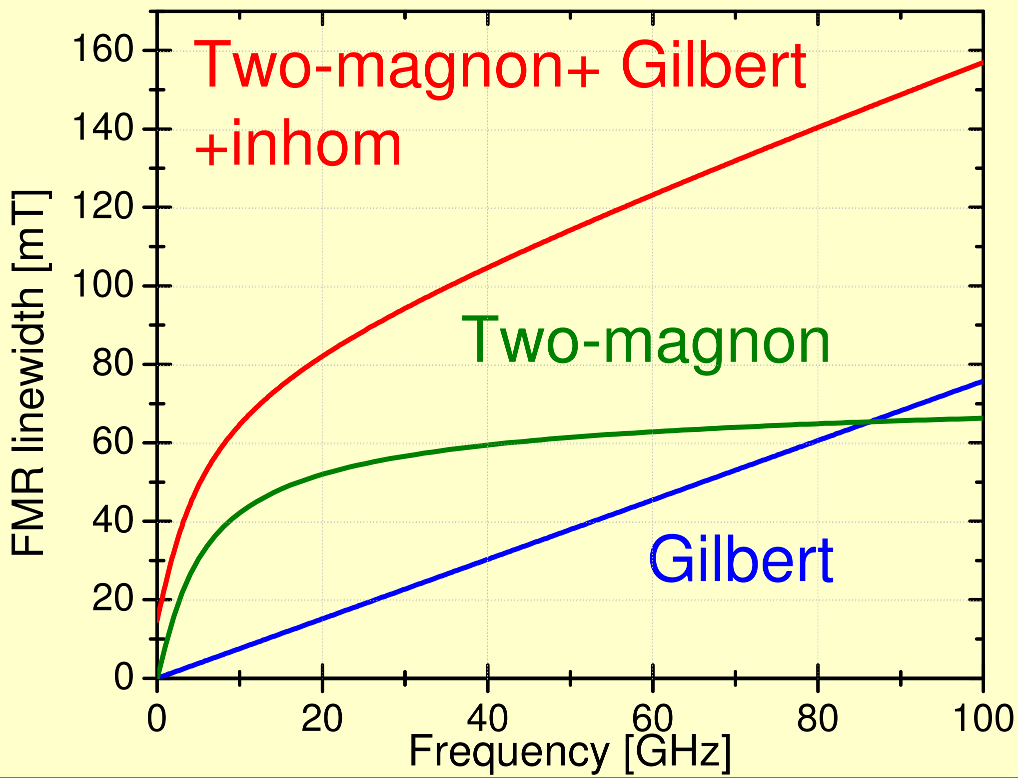
$$\times\cos^2\left[2\left(\phi_B-\phi_{\langle x_i\rangle}\right)\right]\bullet U\left(\theta_B-\theta_{\langle x_i\rangle}\right)$$

$$+\left(\frac{\partial B_{res}(\omega,\theta,\phi)}{\partial\phi_B}\right)\Delta\phi_B+\left(\frac{\partial B_{res}(\omega,\theta,\phi)}{\partial\theta_B}\right)\Delta\theta$$



$$\omega_0 = \gamma\mu_0 M_{eff}$$

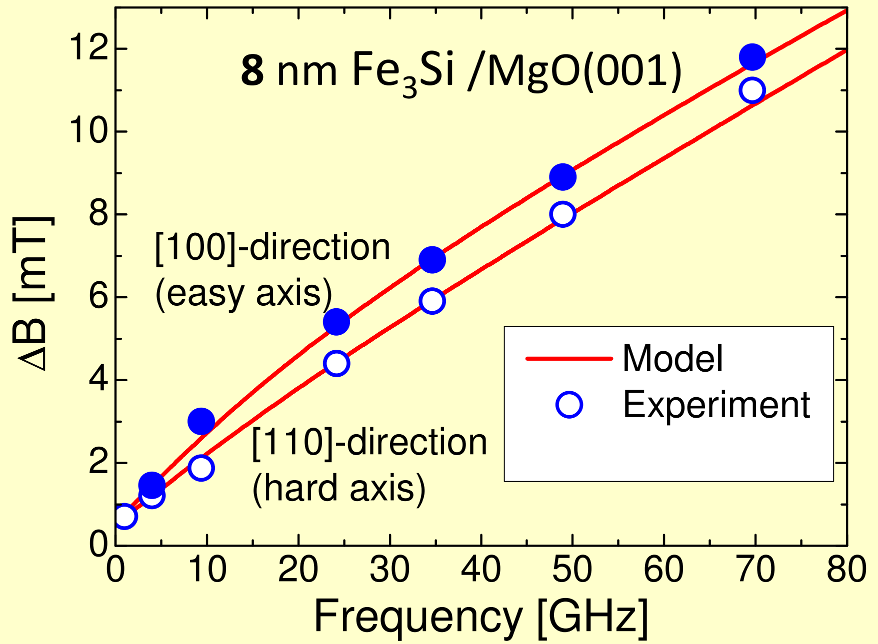


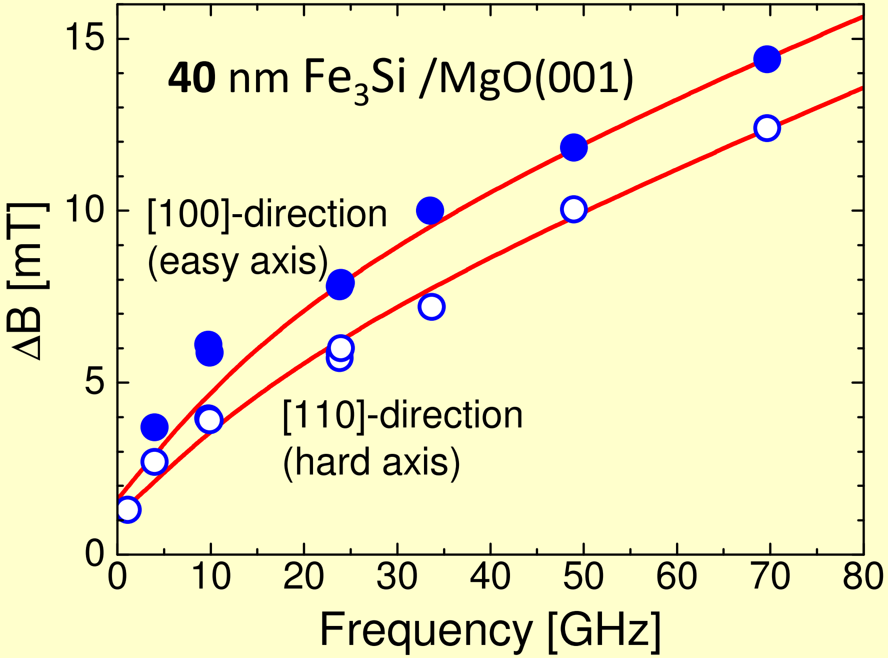


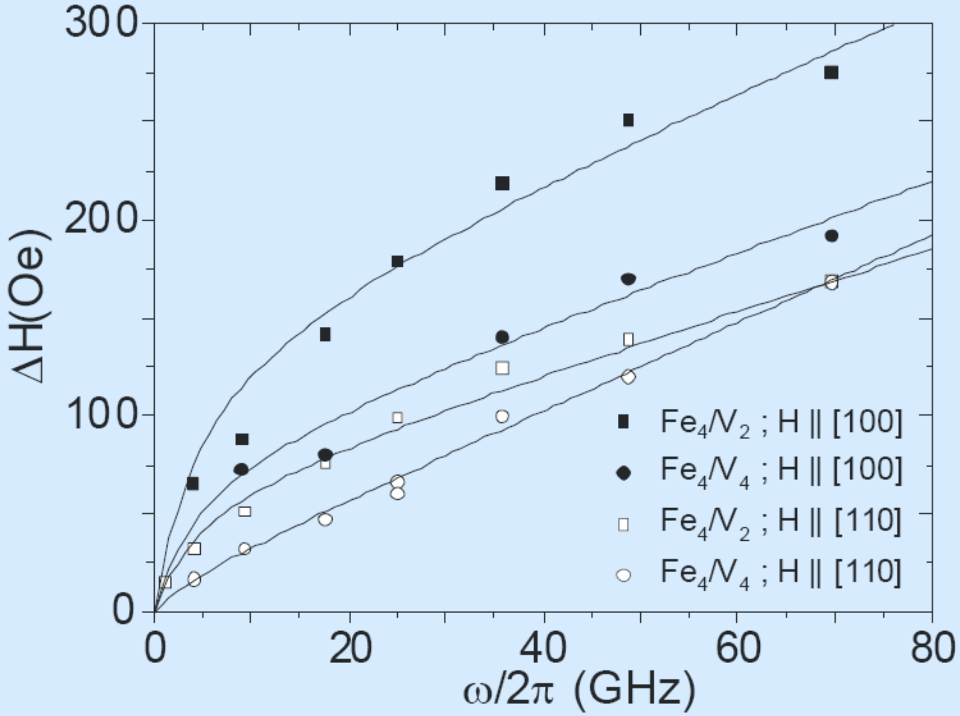
Arias and Mills, Phys. Rev. B **60**, 7395 (1999).
J. Appl. Phys. **87**, 5455 (2000).

Zakeri et al., Phys. Rev. B **76**, 104416 (2007).

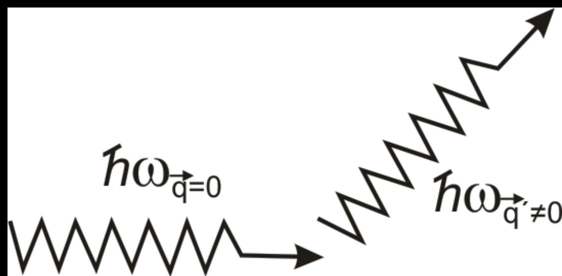
Non-Gilbert type relaxation mechanisms







J. Lindner et al. Phys. Rev. B **68**, 060102(R) (2003)



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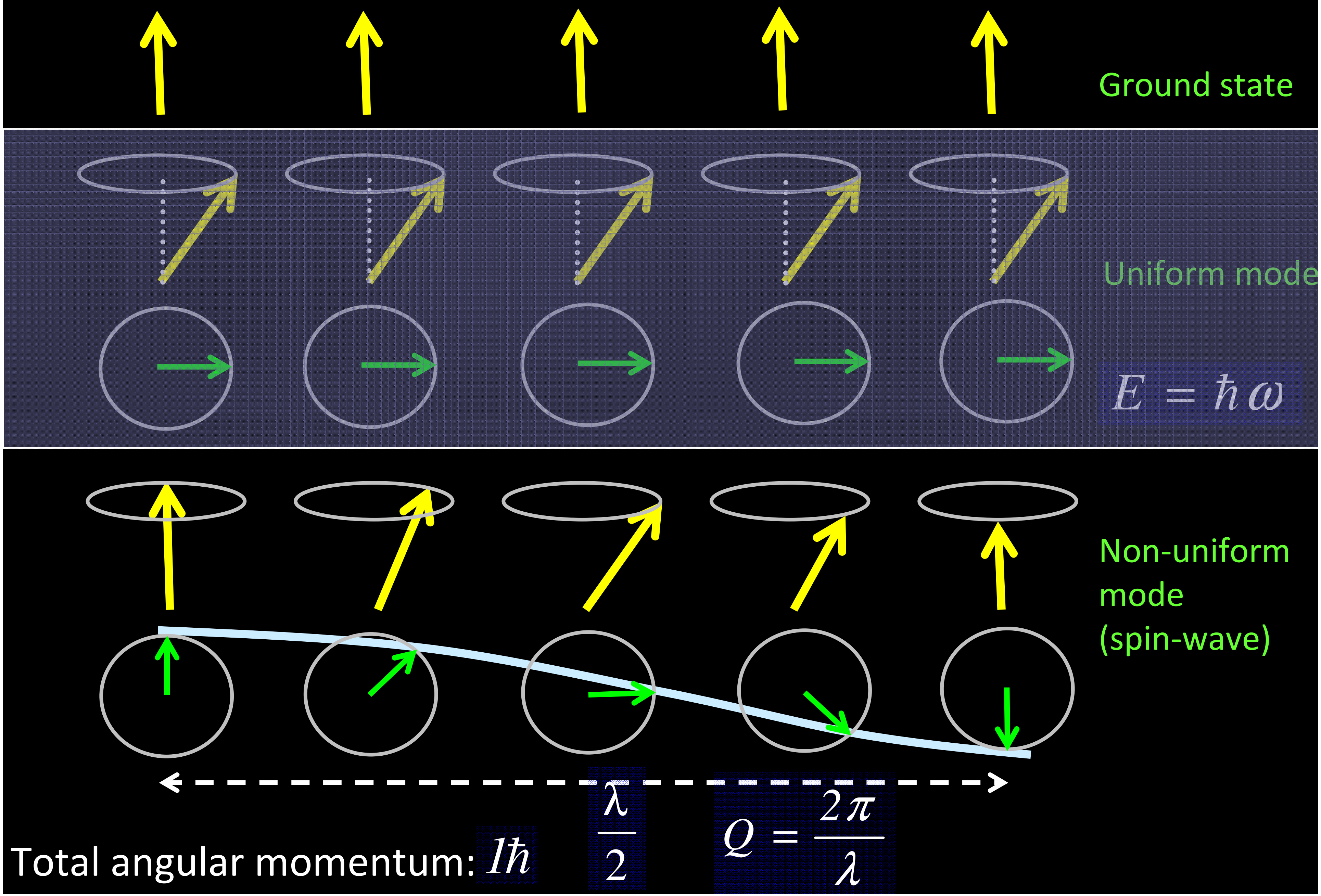
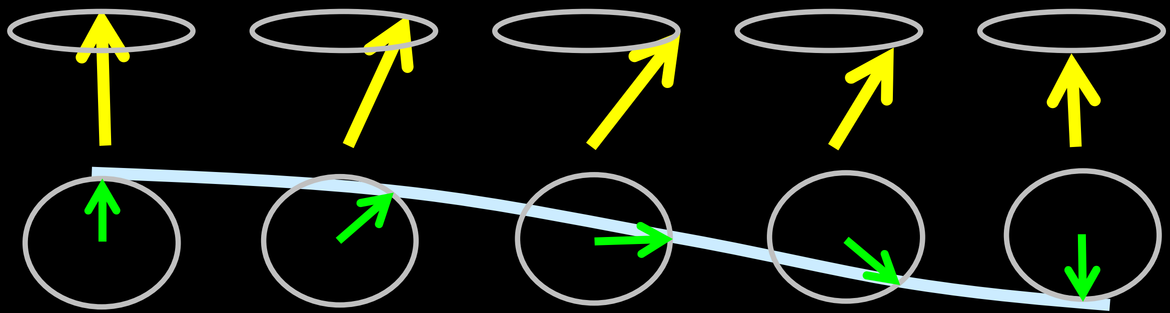


Spin-wave excitations: Classical magnons



$$Q = \frac{2\pi}{\lambda}$$

$$\vec{\mu}_i = g\mu_B \vec{S}_i$$

Heisenberg Hamiltonian

$$H_s = -\sum_{i \neq j} J_{ij} \vec{S} \cdot \vec{S}$$

$$E = \sum_i \vec{\mu}_i . \vec{B}_{ij}$$

$$\vec{B}_{ij} = \sum_j \frac{2J}{g\mu_B} \vec{S}_j$$

J exchange coupling constant
S magnitude of the spin

Dispersion relation:

nearest neighbor interaction (NNH)

$$E = \hbar\omega = 4JS(1 - \cos Qa)$$
$$\approx 2JSa^2Q^2 + \ldots = DQ^2 + \ldots$$

Spin-waves

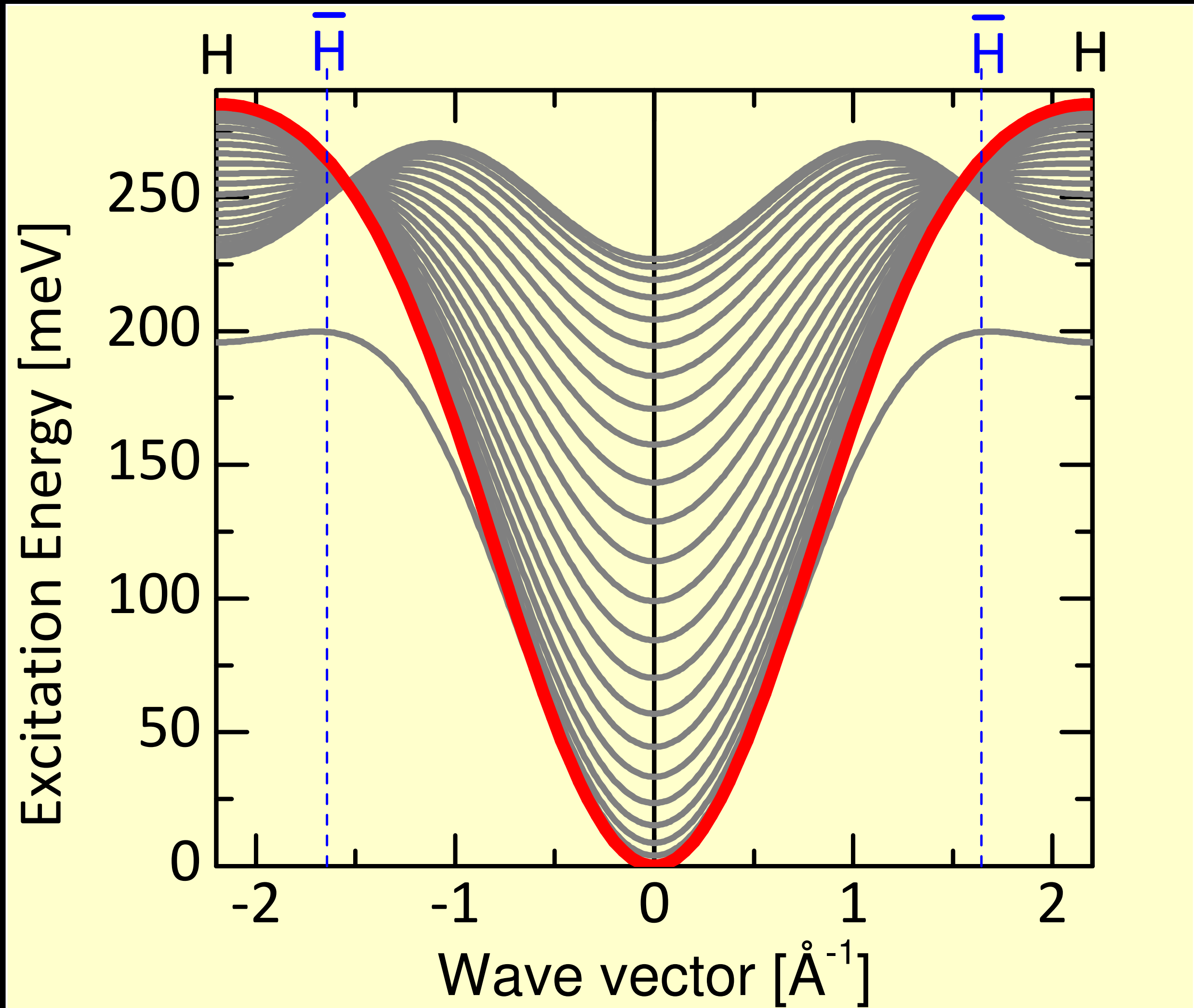
Many particles collective excitations

Magnon carries

Energy: $\hbar\omega$, Momentum: Q, Spin: $1\hbar$

Spin waves dispersion in the Heisenberg model

Dispersion for a 24 ML Fe bcc film with the (110) surface in the NNNH model

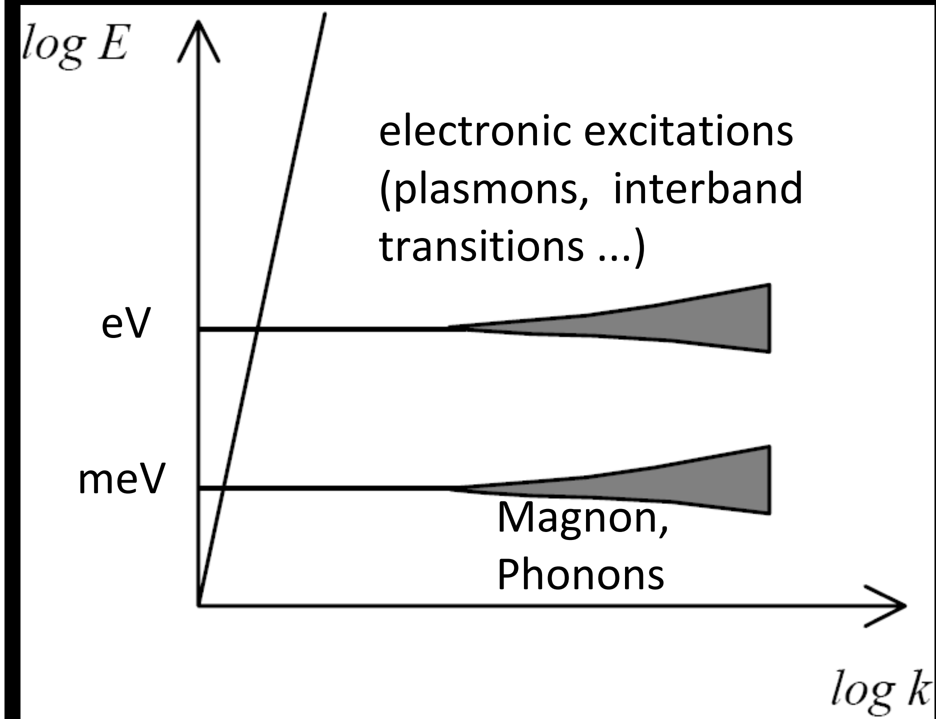


For N atomic layers
$\Rightarrow$ N modes

How one can measure the dispersion of magnons experimentally?

Light scattering

Light dispersion: $E = h\upsilon = \hbar\omega = hck$



Dispersion of magnons $E=Dq^2$

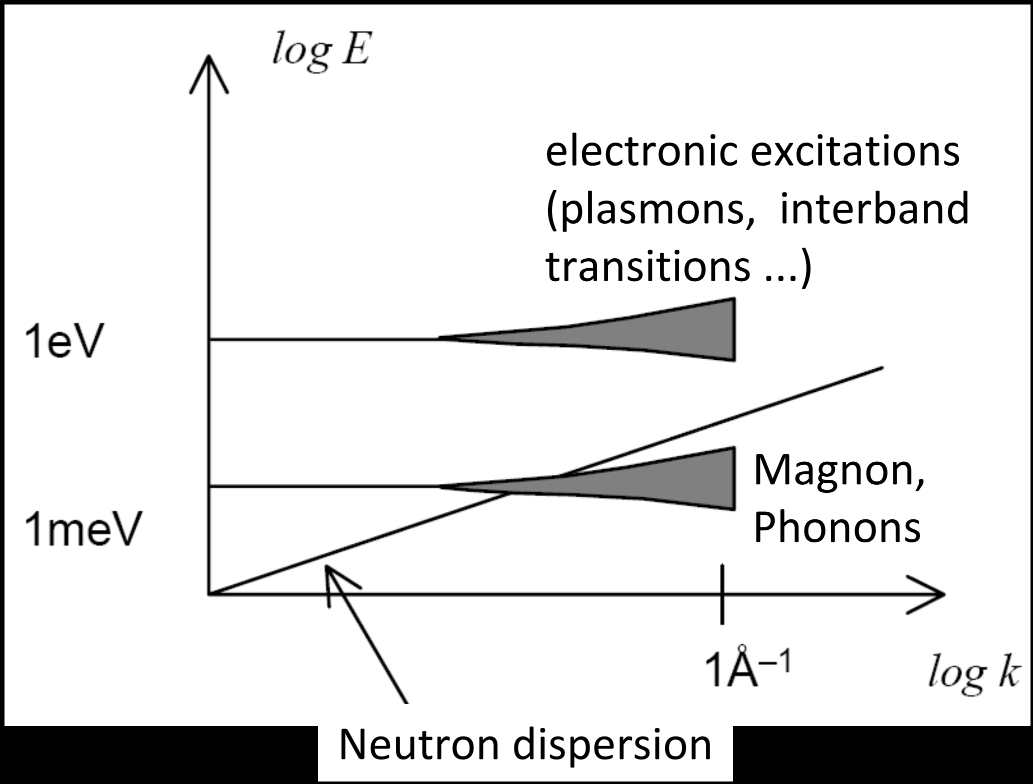
Light always measures effectively q~0

Particles scattering

particles:
- neutron
- He atom
- Muon
- Electron

particles de Broglie wave length:

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2m_n E}} = \frac{2\pi}{k} \Rightarrow E = \frac{\hbar^2 k^2}{2m_n}$$

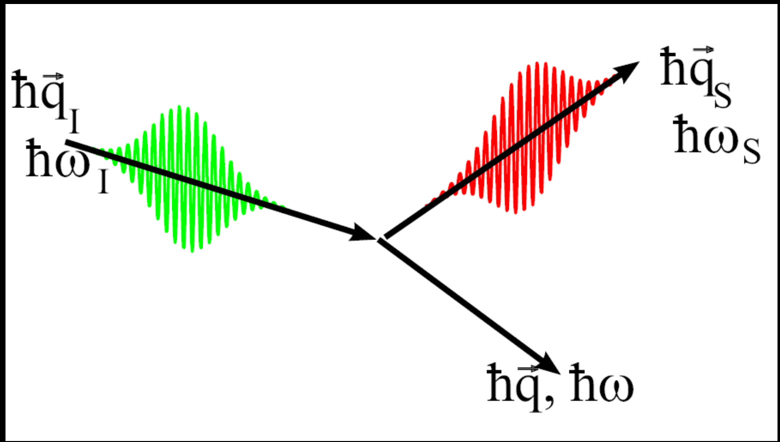


Neutron dispersion relation well matched to dispersion relation of collective excitations in solid can measure phonons, magnons throughout Brillouin zone.

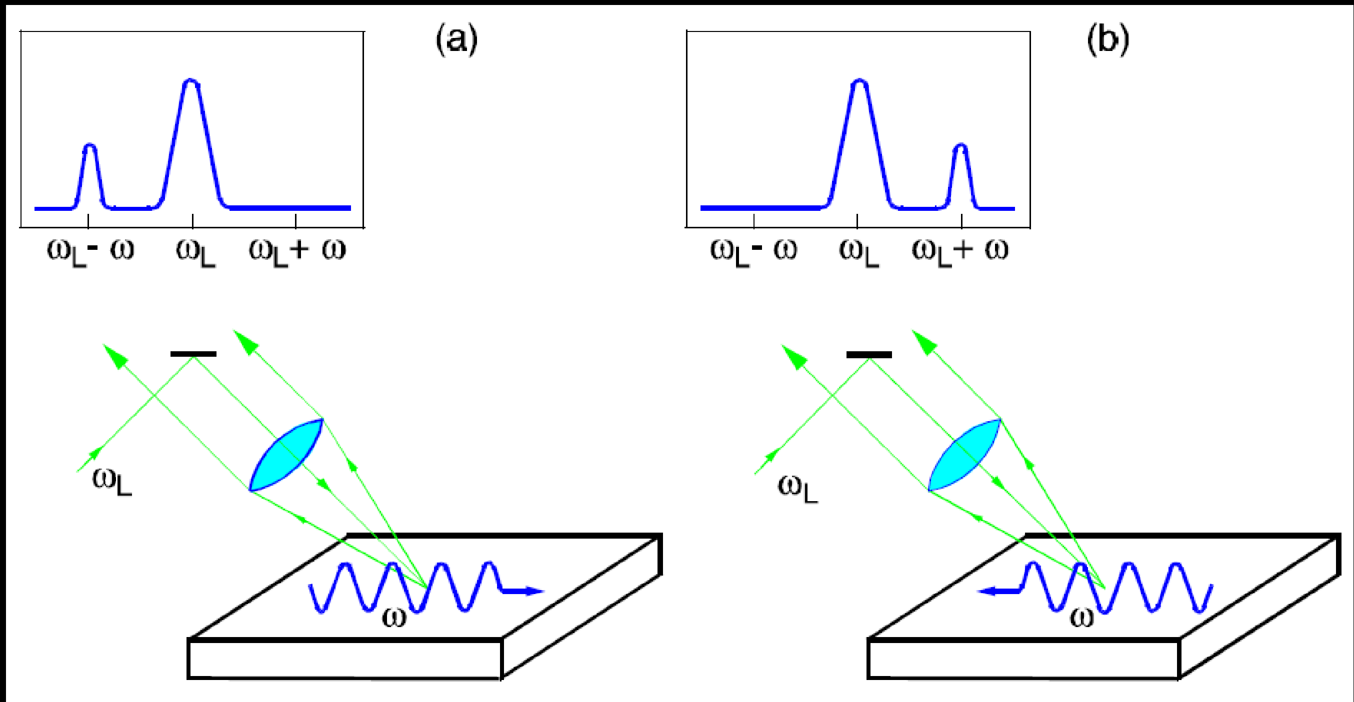
Established methods:

1. Ferromagnetic resonance (FMR)
2. Brillouin light scattering (BLS)
3. Inelastic magnetic neutron scattering (INS)
4. Spin-polarized electron energy-loss spectroscopy (SPEELS)

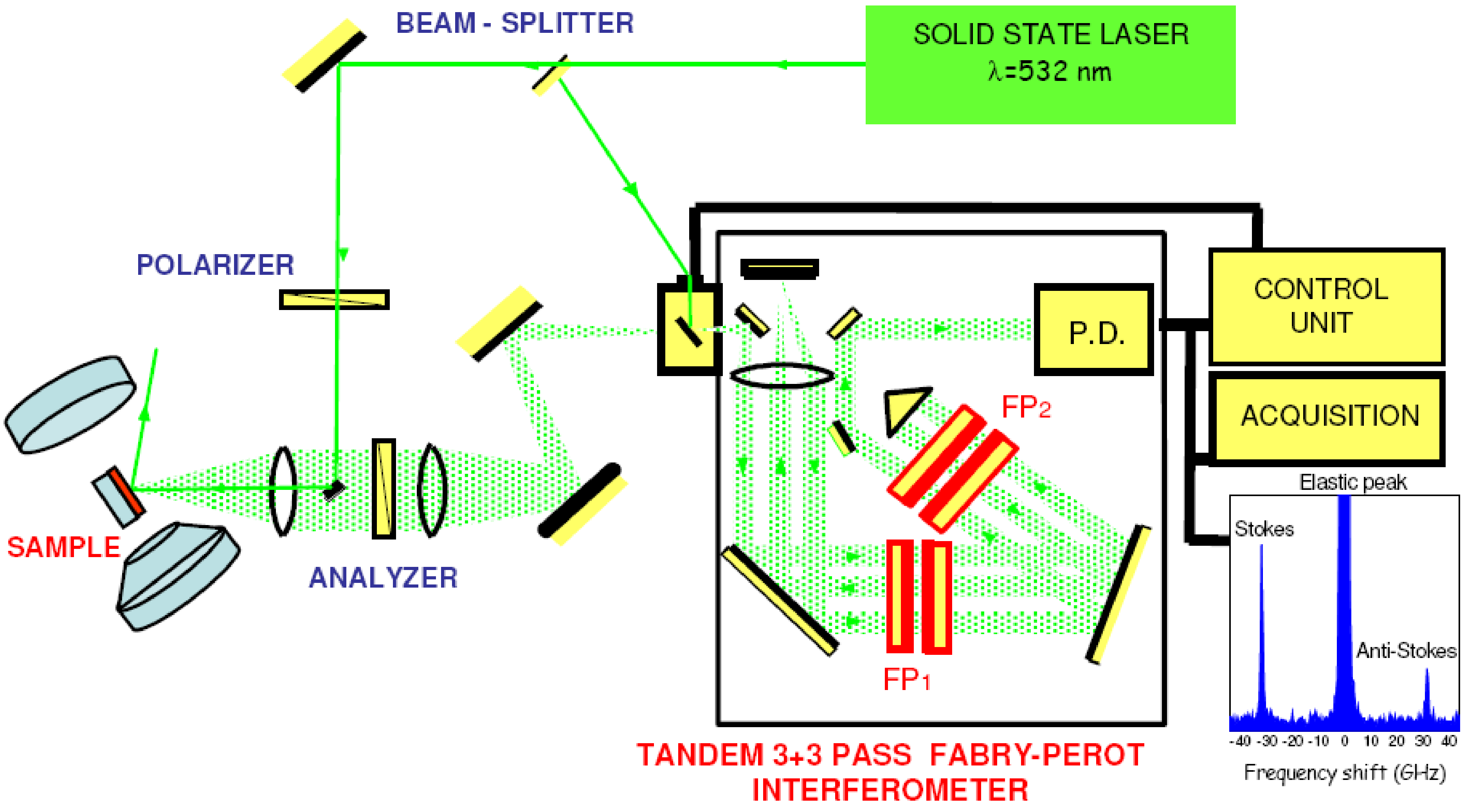
Brillouin light scattering (BLS)



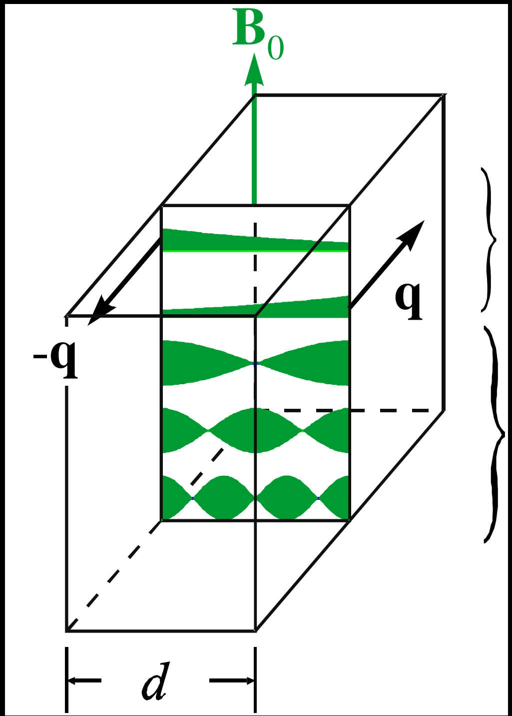
Brillouin scattering is similar to Raman Scattering, both phenomena represent inelastic scattering processes of light with quasiparticles.

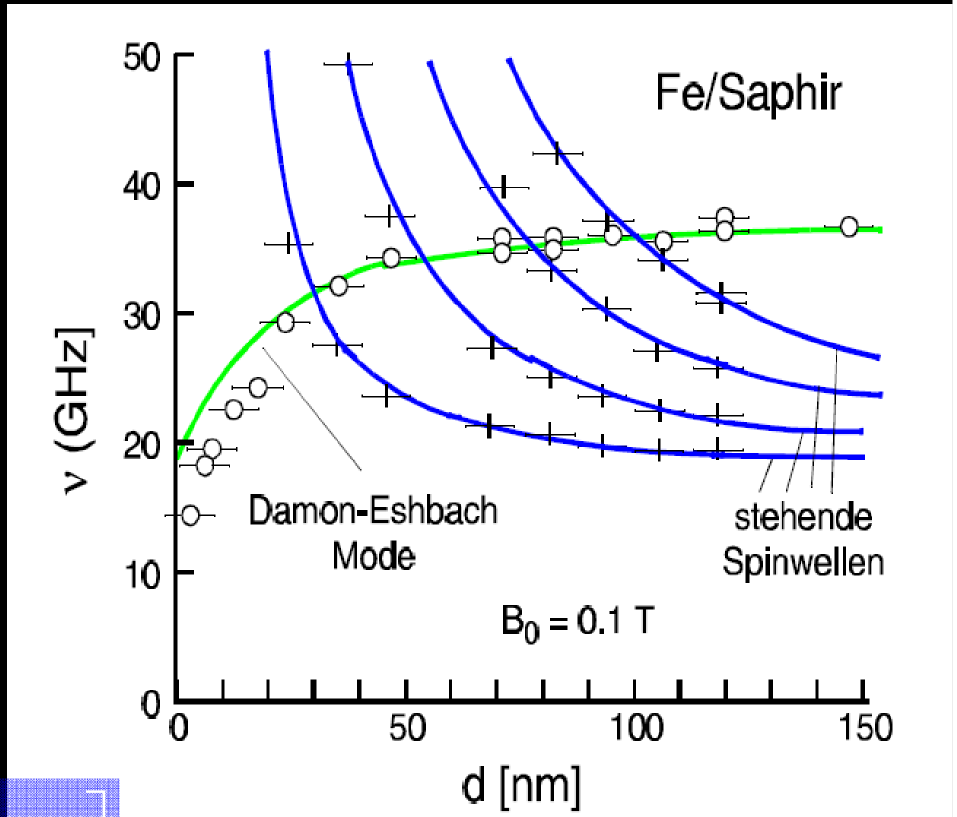


Brillouin light scattering (BLS)



Confinements in thin films





DDE: Dipolar Damon-Eshbach mode

$$\left(\frac{\omega}{\gamma}\right)^2 = \left[B(B+\mu_0 M_s)+\left(\frac{\mu_0 M_s}{2}\right)^2\left(1-e^{-2Qd}\right)\right]$$

SSW: Standing spin-waves

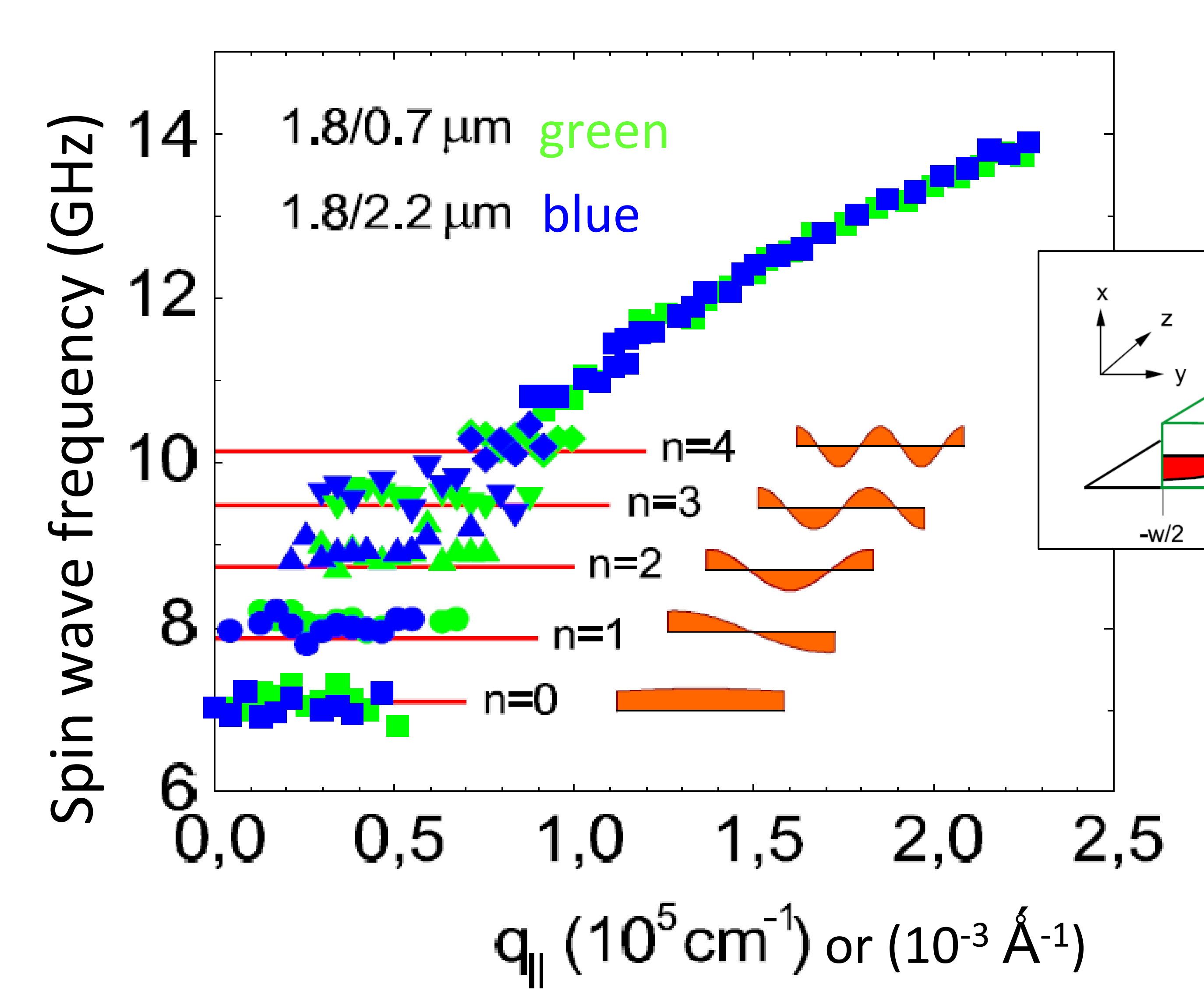
A : Exchange stiffness constant

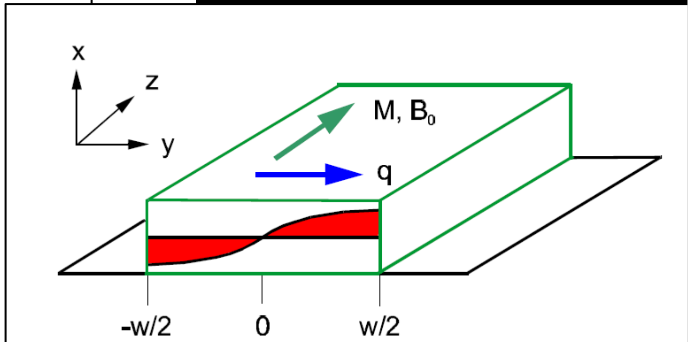
M_s: Magnetization

$$\left(\frac{\omega}{\gamma}\right) = \frac{2A}{M_s}\cdot Q^2 = \frac{2A}{M_s}\cdot\left(\frac{n\pi}{d}\right)^2$$

P. Grünberg, C. M. Mayr, W. Vach, M. Grimsditch, J. Magn. Mater. 28, 319 (1982).

Lateral confinements in stripes





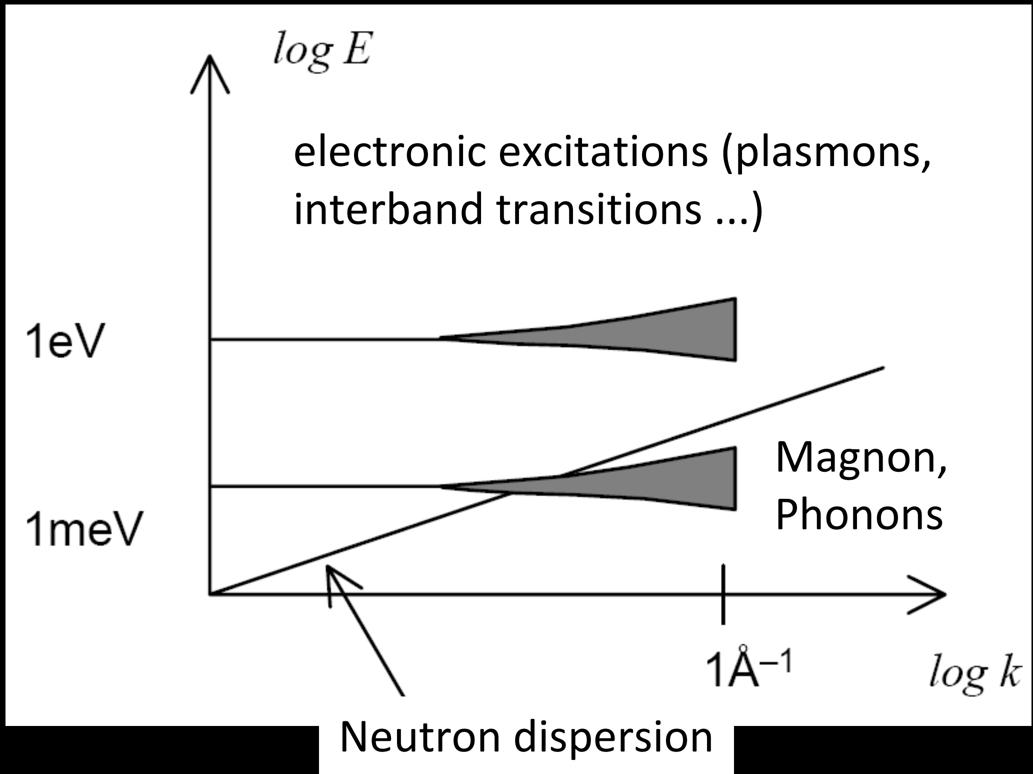
*S.O. Demokritov et al. Physics Reports **348** 441 (2001)*

Particles scattering

particles:
- neutron
- He atom
- Muon
- Electron

particles de Broglie wave length:

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2m_n E}} = \frac{2\pi}{k} \Rightarrow E = \frac{\hbar^2 k^2}{2m_n}$$



Neutron dispersion relation well matched to dispersion relation of collective excitations in solid can measure phonons, magnons throughout Brillouin zone.

Neutron scattering

A neutron is a particle with the charge 0 and spin ½
Charge 0   no long range coulomb interaction with nuclei/electrons in solid.

Interaction with matter through
– strong force interaction with nuclei interaction strong, but very short range (10^{-15}m)
– magnetic dipole–dipole interaction with electron magnetic moment (spin and orbital)

recall that nuclear magnetic moment is very small:

$$\mu_N = \frac{e\hbar}{2m_n}$$

Both interactions are effectively much weaker than Coulomb interaction neutrons penetrate deeply into materials, whereas charged muons, electrons are stopped close to the surface.

Neutron scattering

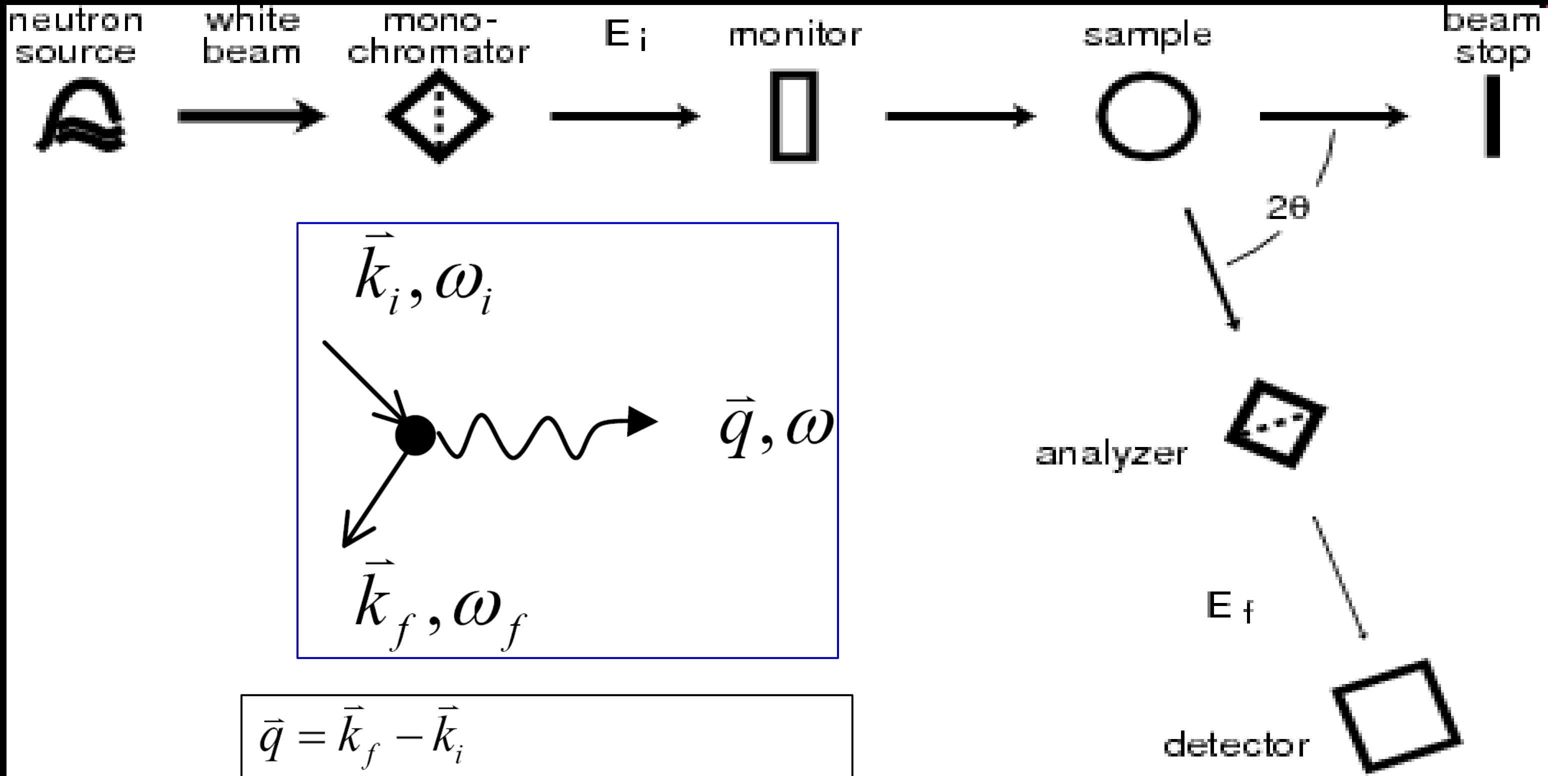
Production of thermal neutrons:
Research reactor

$$^{235}U + n \quad A + B + 2.3n$$

(A, B: fission fragments) chain reaction, keeps going by itself until "fuel" (uranium enriched by ^{235}U) is exhausted source of both ***energy*** (nuclear power reactors) and ***neutrons*** (research reactors)

research reactors optimized for neutron flux low power fission reaction most favorable for thermal neutrons fast neutrons slowed down by "moderator" (H_2O, D_2O)

Basic idea of the neutron scattering experiment



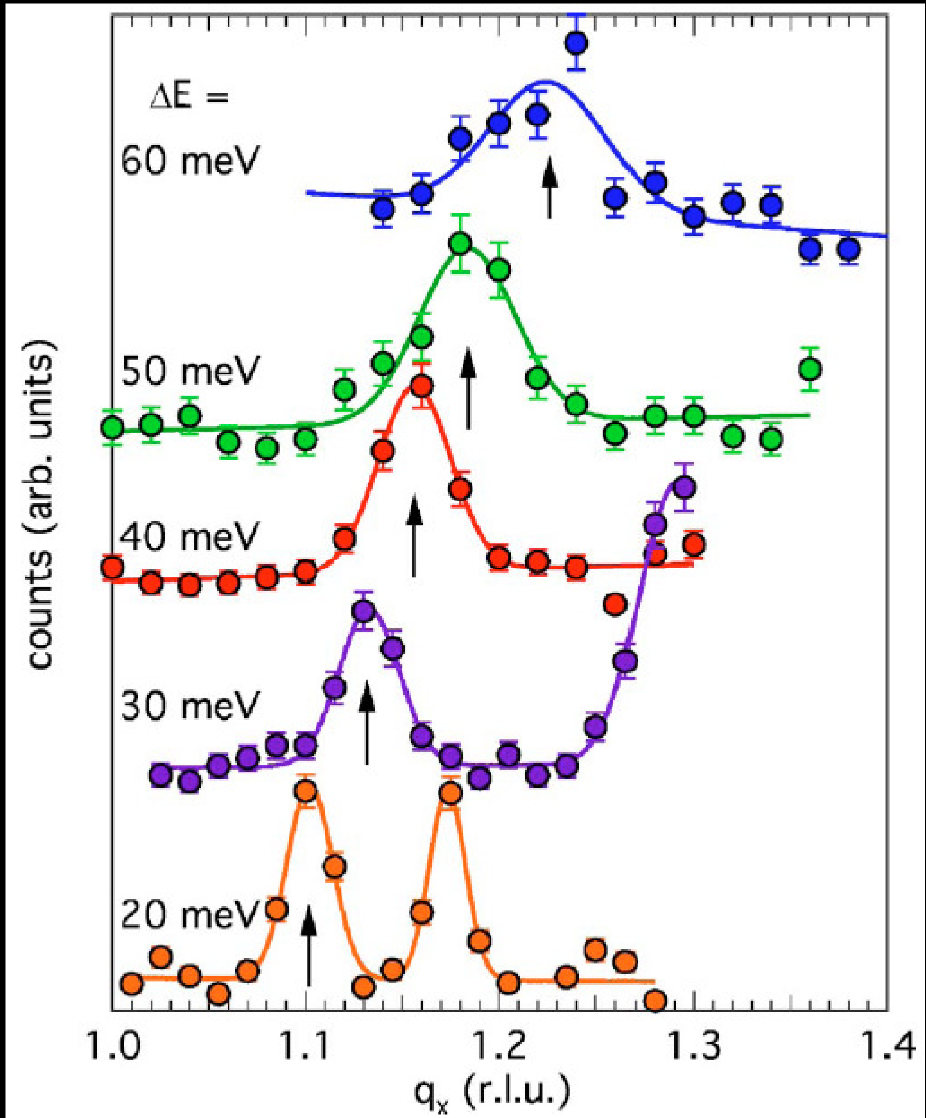
$$\vec{q} = \vec{k}_f - \vec{k}_i$$

$$\omega = \omega_f - \omega_i = \frac{\hbar}{2m_n}\left(k_f^{\,2} - k_i^{\,2}\right)$$

$\omega = 0$ elastic scattering

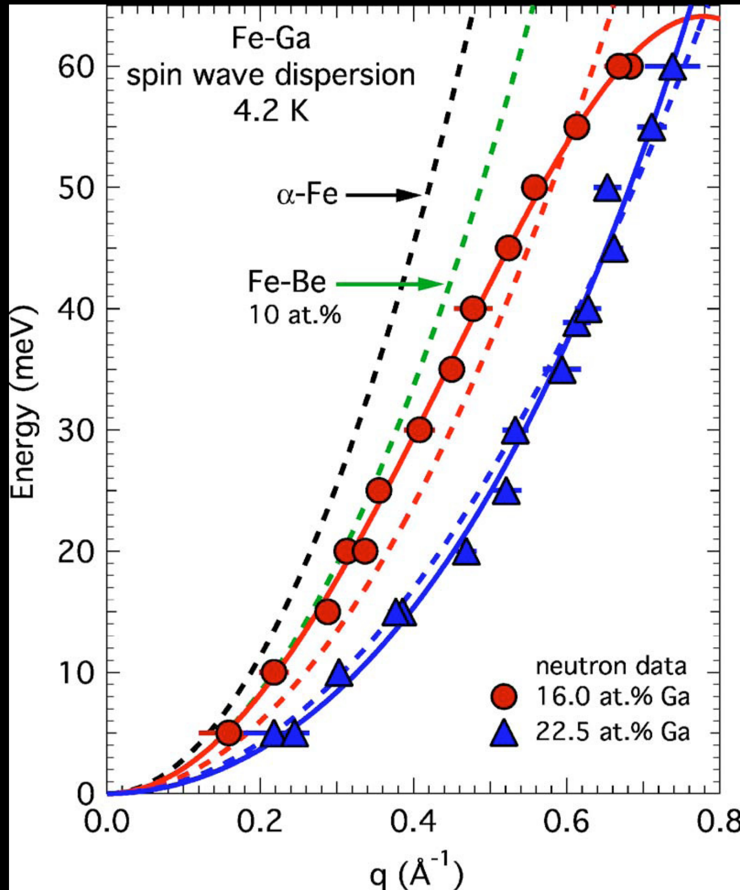
$\omega \neq 0$ inelastic scattering

Magnon dispersion relation measured by INS



(Reciprocal lattice units)

Neutron scattering data for constant energy scans on **$Fe_{84}Ga_{16}$**. The second peaks in the 20 and 30 meV scans are scattered from the phonons.



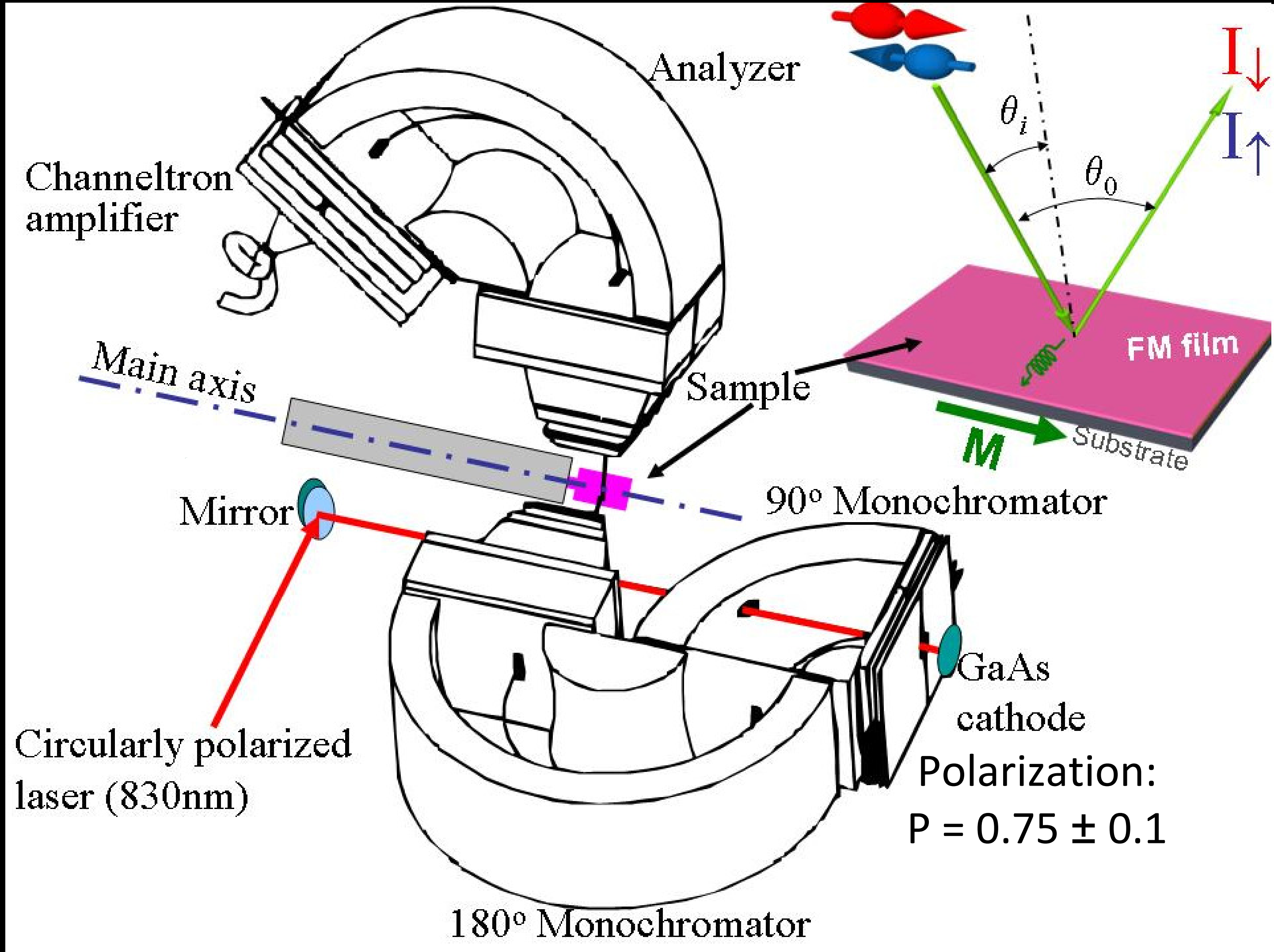
Zarestky et al., PRB **75**, 052406 (2007)

Advantages and disadvantages

- Neutrons penetrate deeply into materials, whereas charged muons, electrons are stopped close to the surface.
- The Interaction of neutrons with the matter is weak Cannot be applied to nanostructures.

We may use the electrons instead of neutrons !!!
Inelastic electron scattering

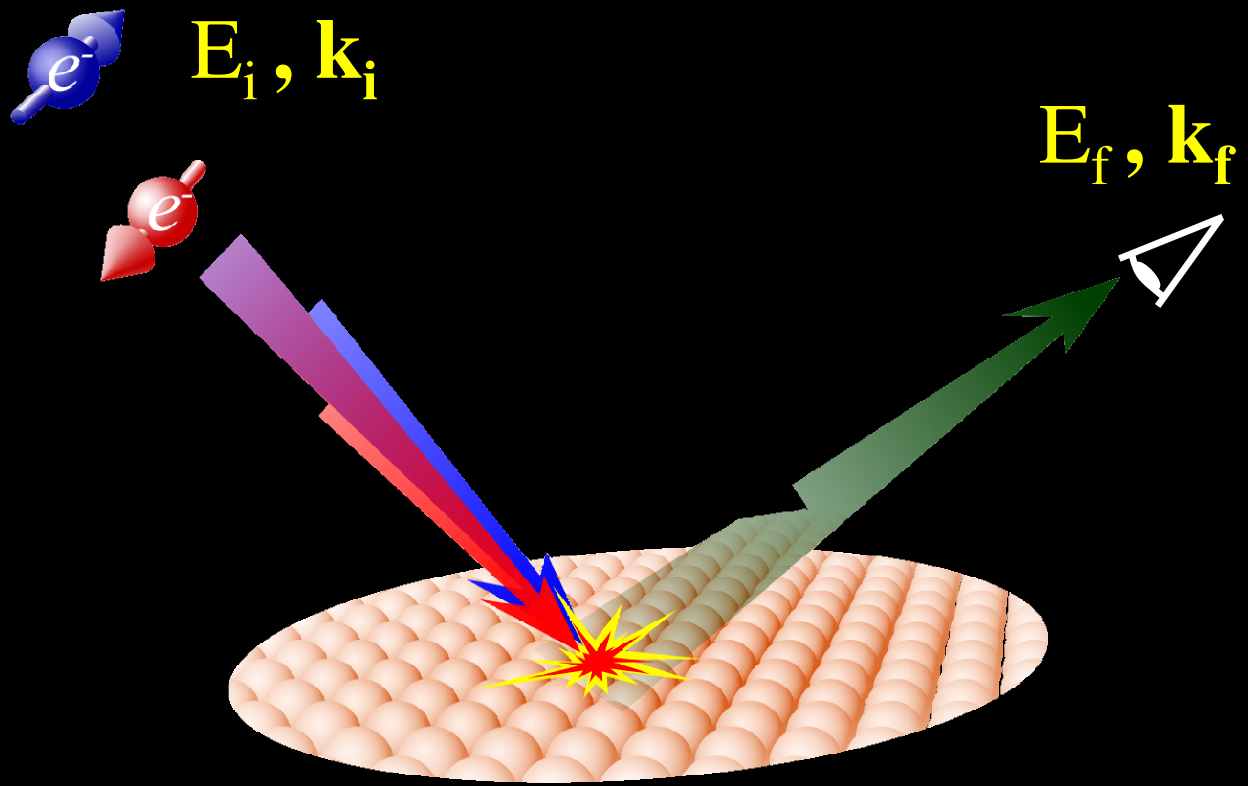
Basic idea of spin-polarized electron energy loss spectroscopy



Polarization:
P = 0.75 ± 0.1

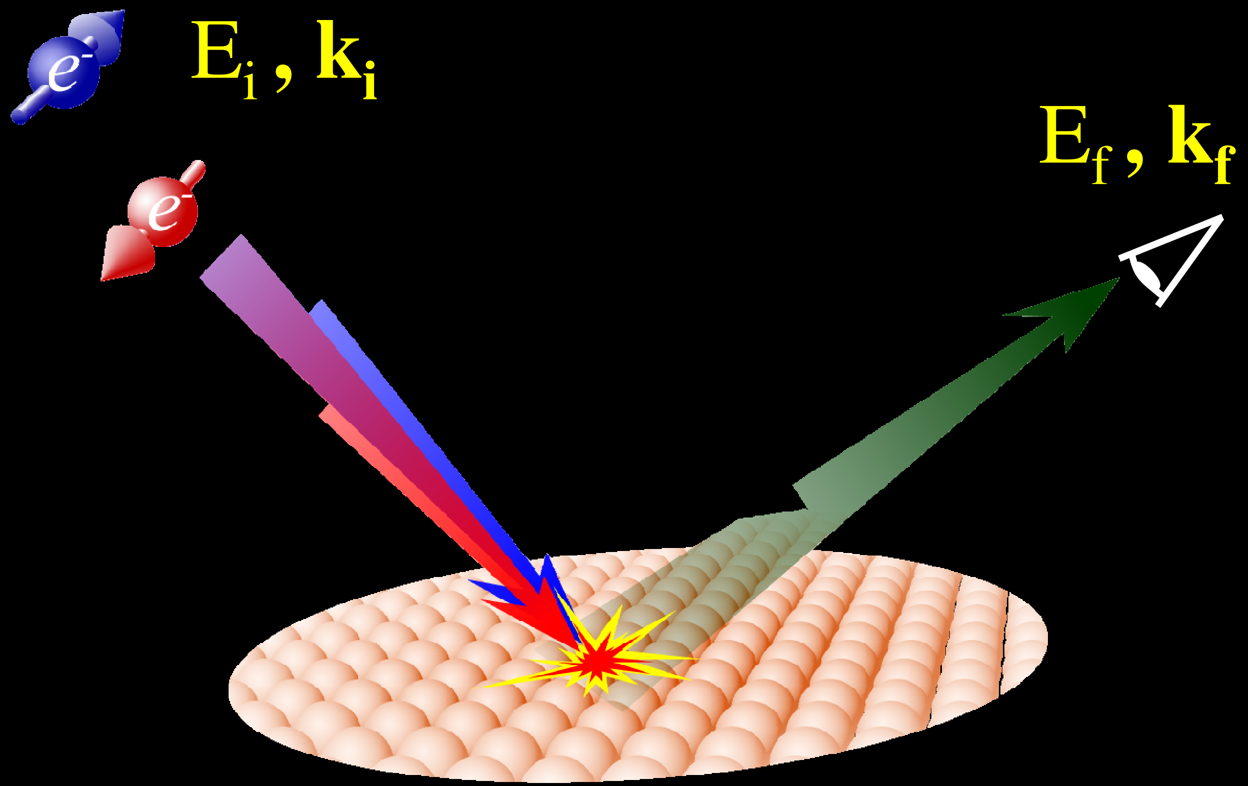
H. Ibach, et al., Rev. Sci. Instrum., 74 (2003) 4089.

Spin-polarized electron energy loss spectroscopy (SPEELS)



- M. Phihal, D.L. Mills and J.Kirschner, Phys. Rev. Lett. **82**, 2579 (1999).
- R. Vollmer, *et al.,* Phys. Rev. Lett. **91**, 147201 (2003).
- H. Ibach*, et al.,* Rev. Sci. Instrum., **74**, 4089 (2003) .

Spin-polarized electron energy loss spectroscopy (SPEELS)



Conservation of momentum:

$$-Q^{\parallel} = \Delta k^{\parallel} = k_f^{\parallel} - k_i^{\parallel}$$

Conservation of energy:

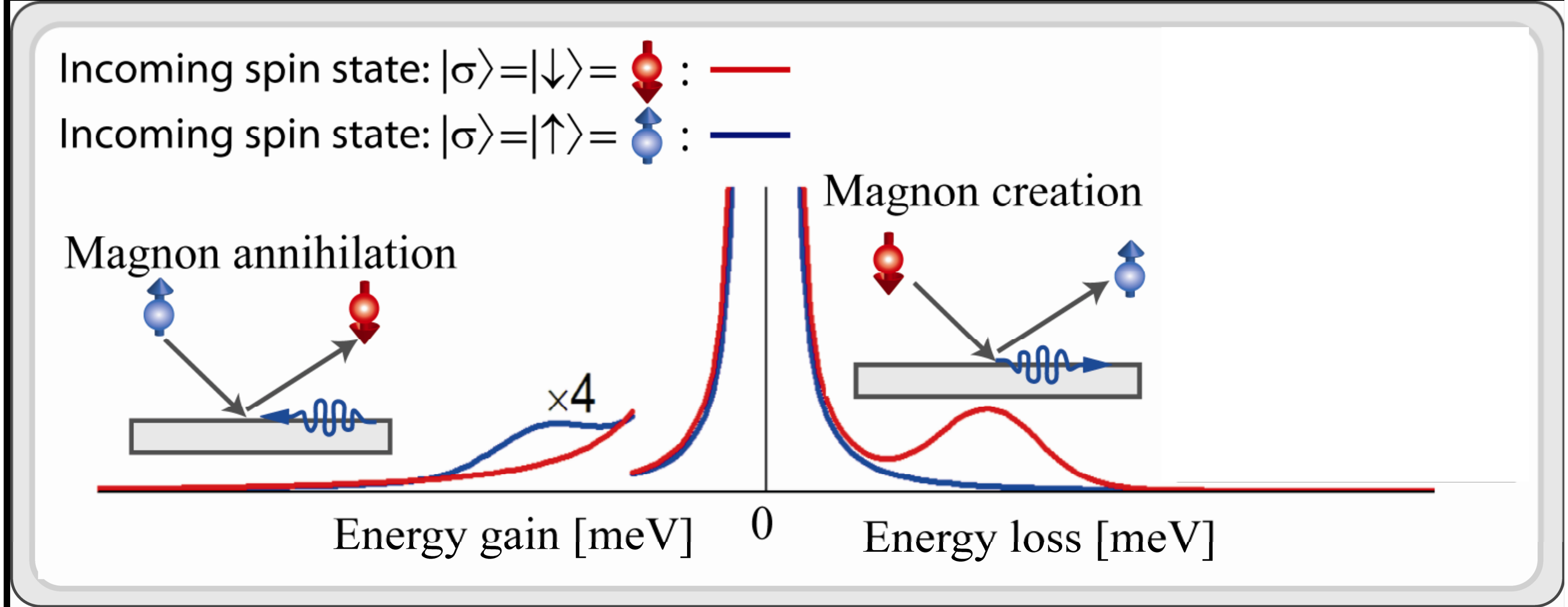
$$\hbar\omega = E_i - E_f$$

Conservation of total angular momentum:

$$\sigma = \sigma_f^{Total} - \sigma_i^{Total}$$

- M. Phihal, D.L. Mills and J.Kirschner, Phys. Rev. Lett. **82**, 2579 (1999).
- R. Vollmer, *et al.,* Phys. Rev. Lett. **91**, 147201 (2003).
- H. Ibach*, et al.,* Rev. Sci. Instrum., **74**, 4089 (2003) .

Magnon excitation mechanism in SPEELS

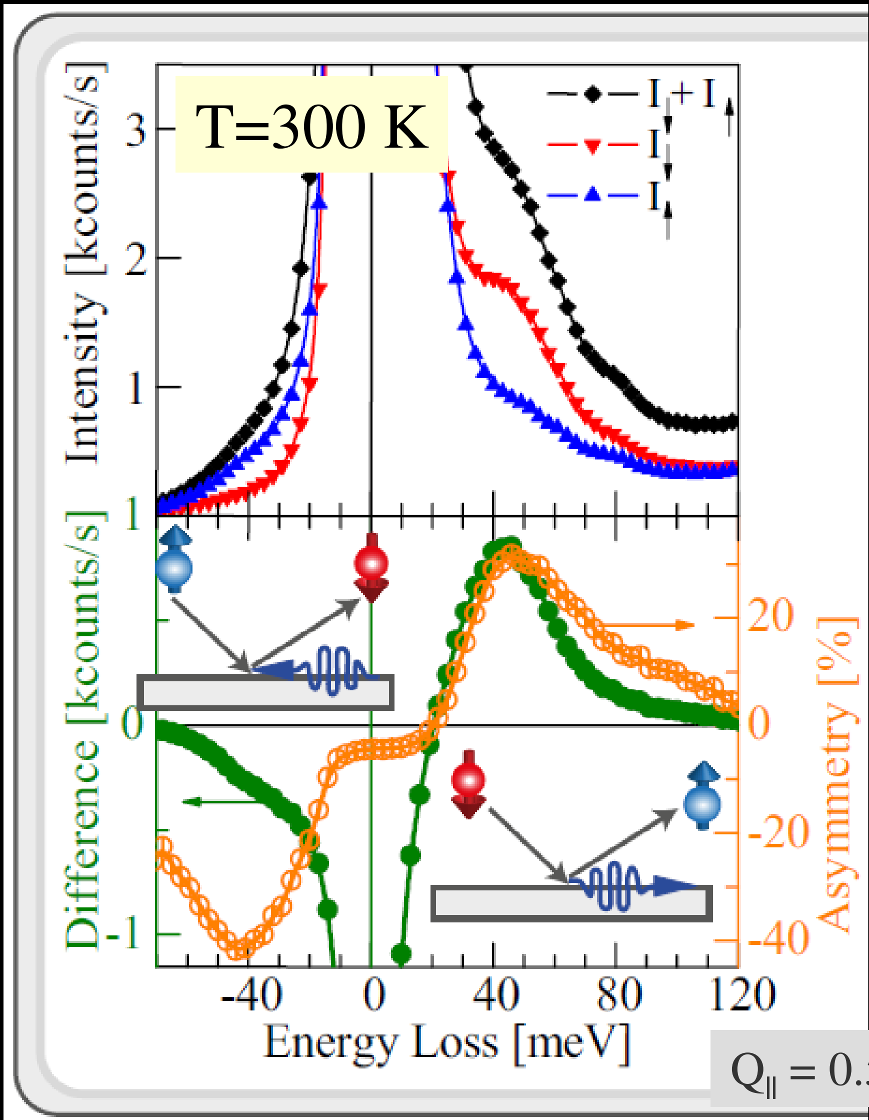


- The magnon annihilation process is allowed for incident electrons of majority character.
- The magnon creation process is allowed for incident electrons of minority character.

& Kh. Zakeri and J. Kirschner, Magnonics, Eds. Sergej O. Demokritov and Andrei N. Slavin, Topics in Applied Physics, Vol. **125**, pp. 83–99 (2013), Springer Berlin Heidelberg

Magnon creation and annihilation

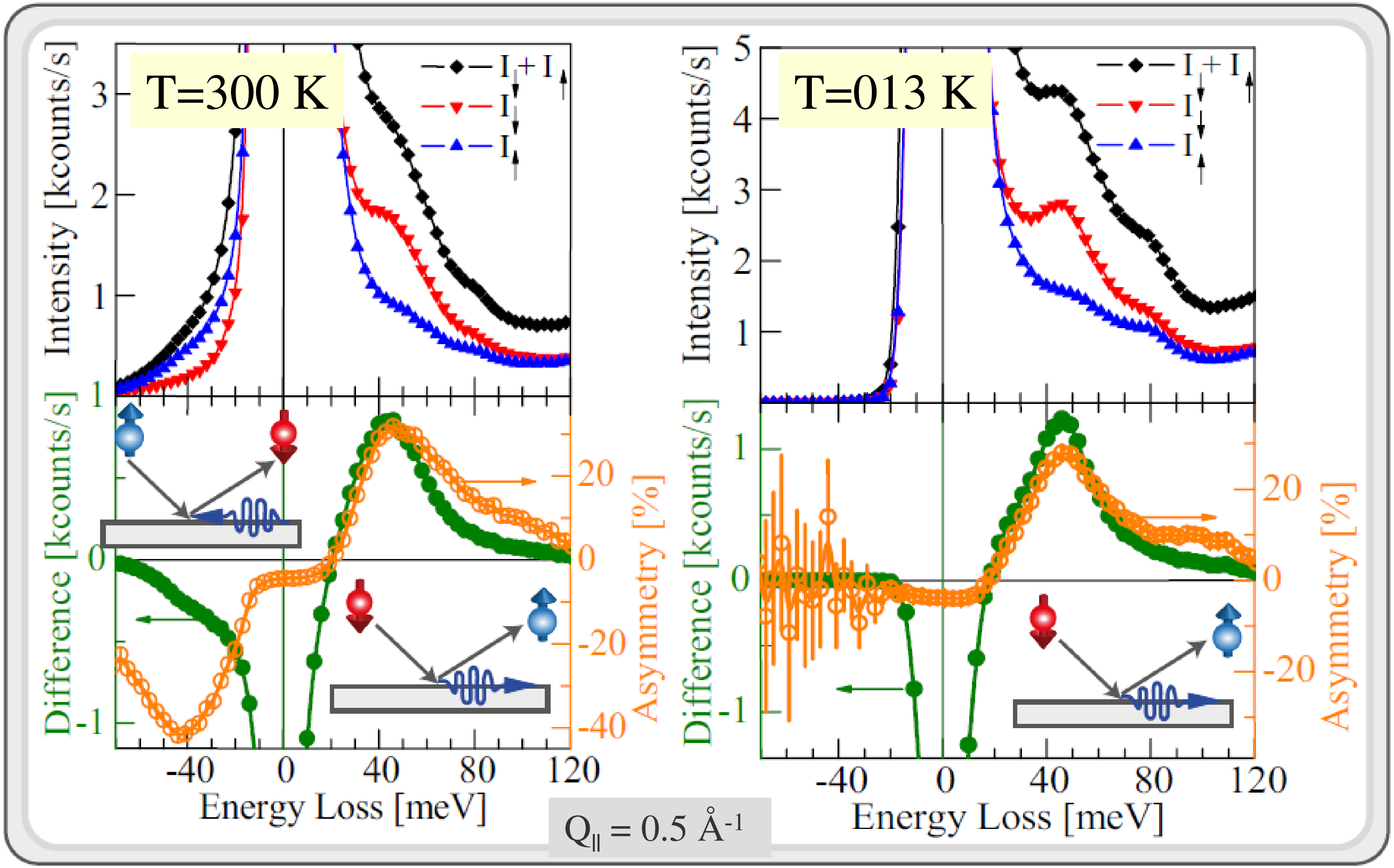
2 ML Fe/W(110)



$Q_{||} = 0.5$ Å^{-1}

Magnon creation and annihilation

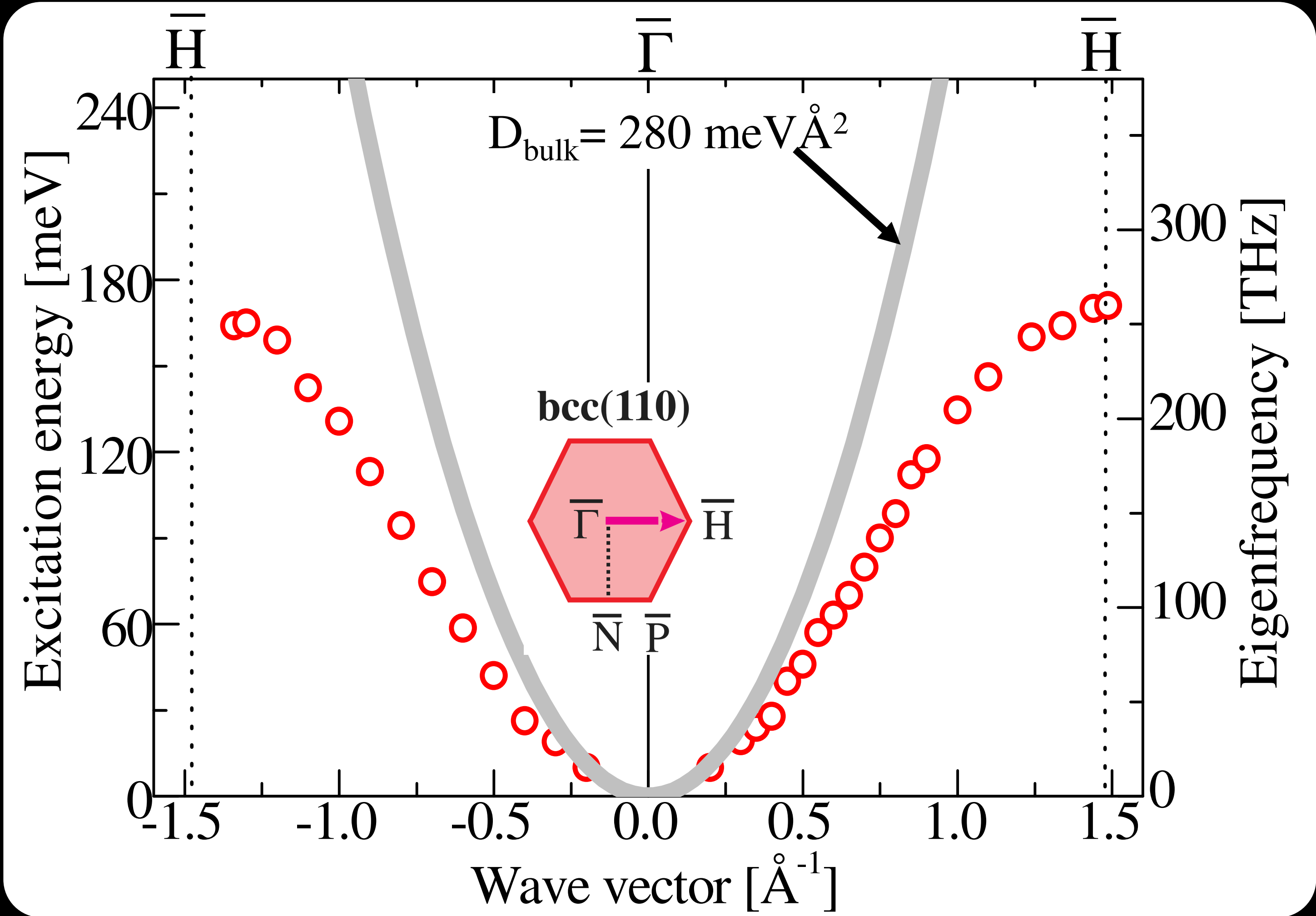
2 ML Fe/W(110)



$Q_{||} = 0.5$ Å^{-1}

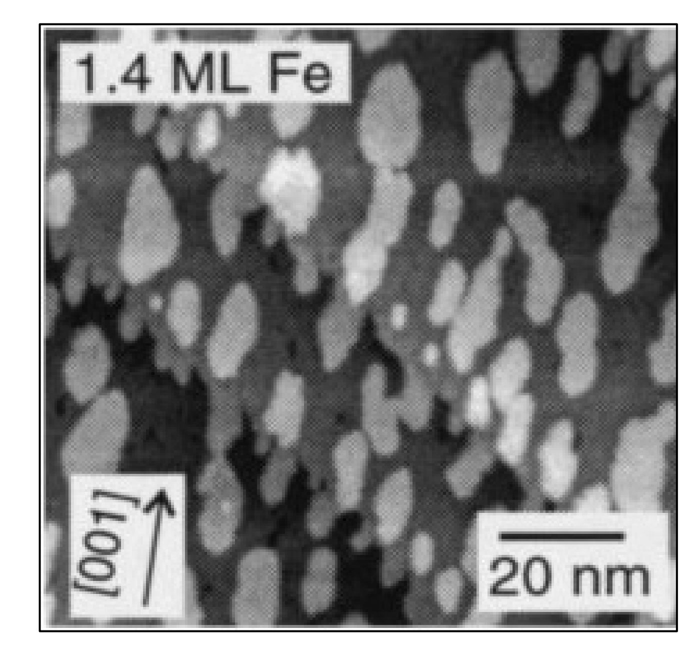
Magnon dispersion relation

Example: Two atomic layers of Fe on W(110)

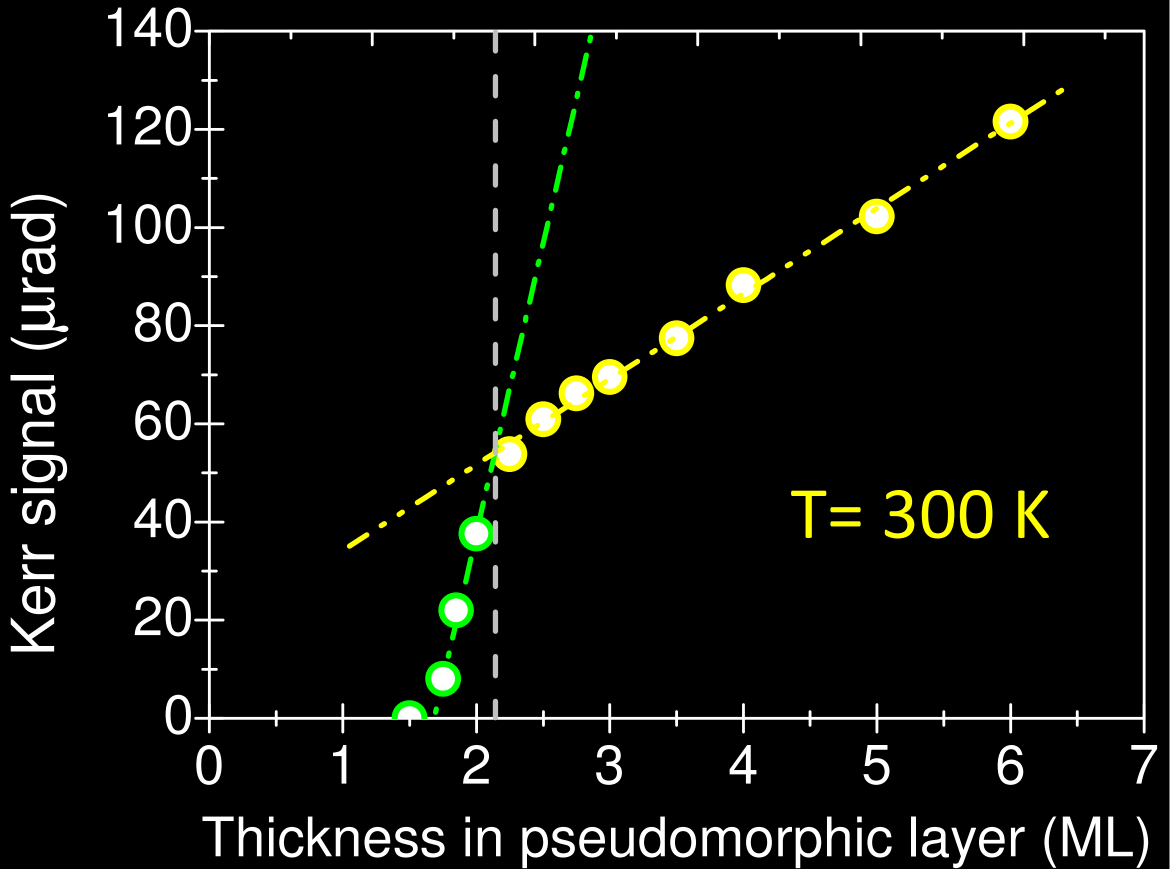


& W.X. Tang, *et al.*, Phys. Rev. Lett. **99**, 087202 (2007).

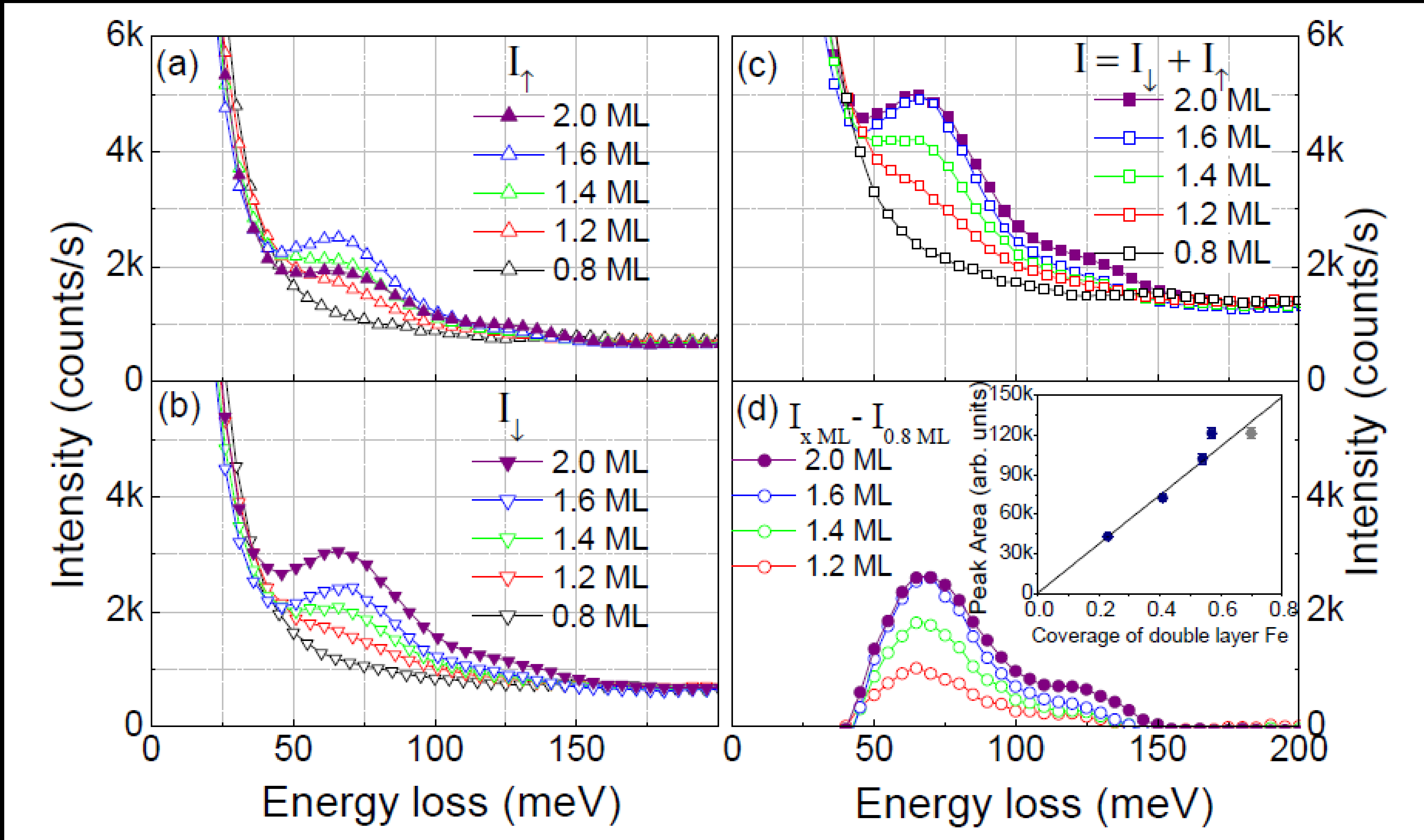
Fe nanoislands on W(110)



STM images of 1.4 ML Fe
on W(110) grown at 300 K.
Sander, *et al.*, PRL **77**, 2566(1996)



Fe nanoislands on W(110)



Summary

- Ferromagnetic resonance (FMR)   wave-vectors close to 0

- Brillouin light scattering (BLS)   small wave-vectors (10^{-2} Å^{-1})

- Inelastic magnetic neutron scattering (INS)   Bulk samples

- Spin-polarized electron energy-loss spectroscopy (SPEELS)

Momentum and spin resolution, very high sensitivity.