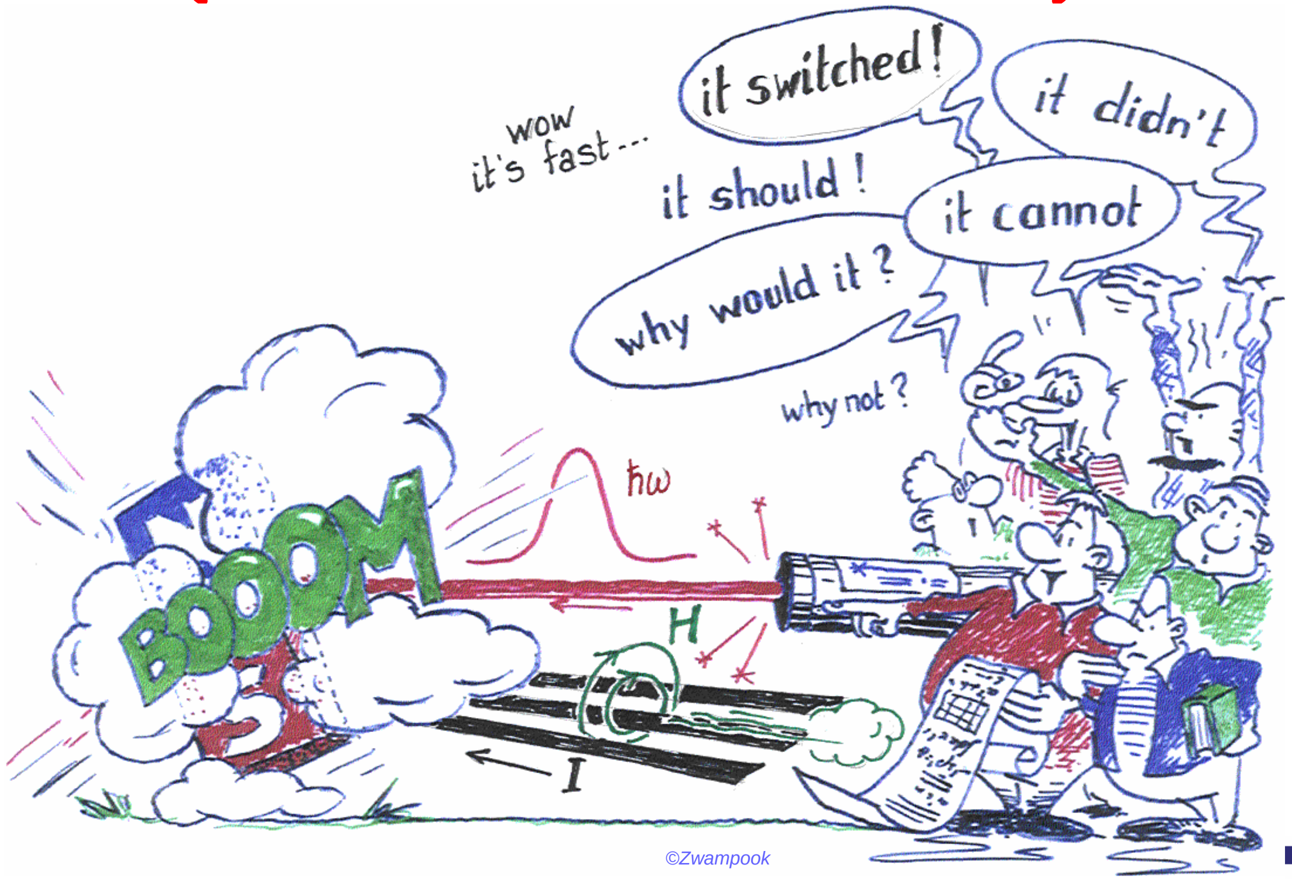
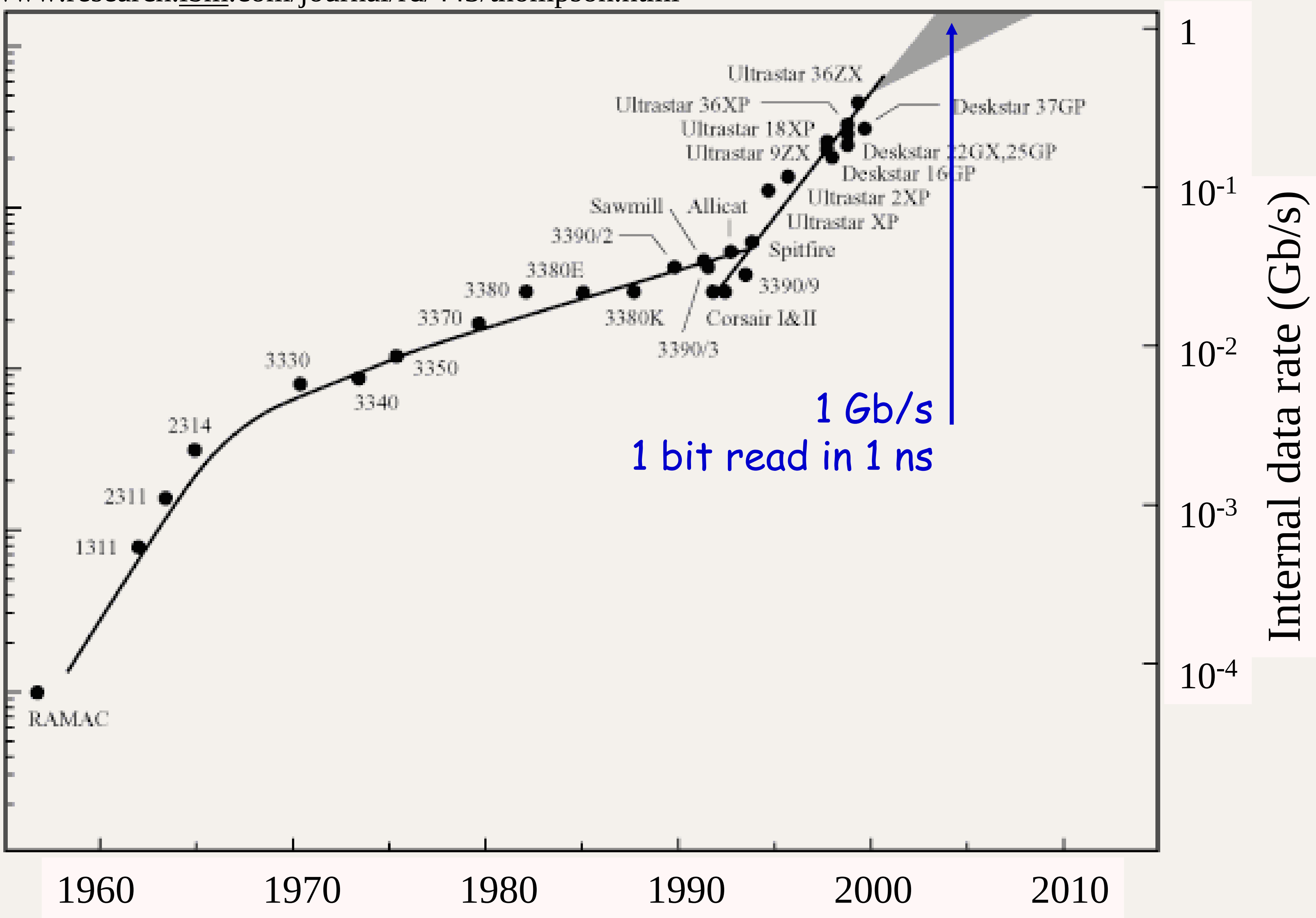
PRECESSIONAL MAGNETIZATION DYNAMICS
(in the f- and t-domain)



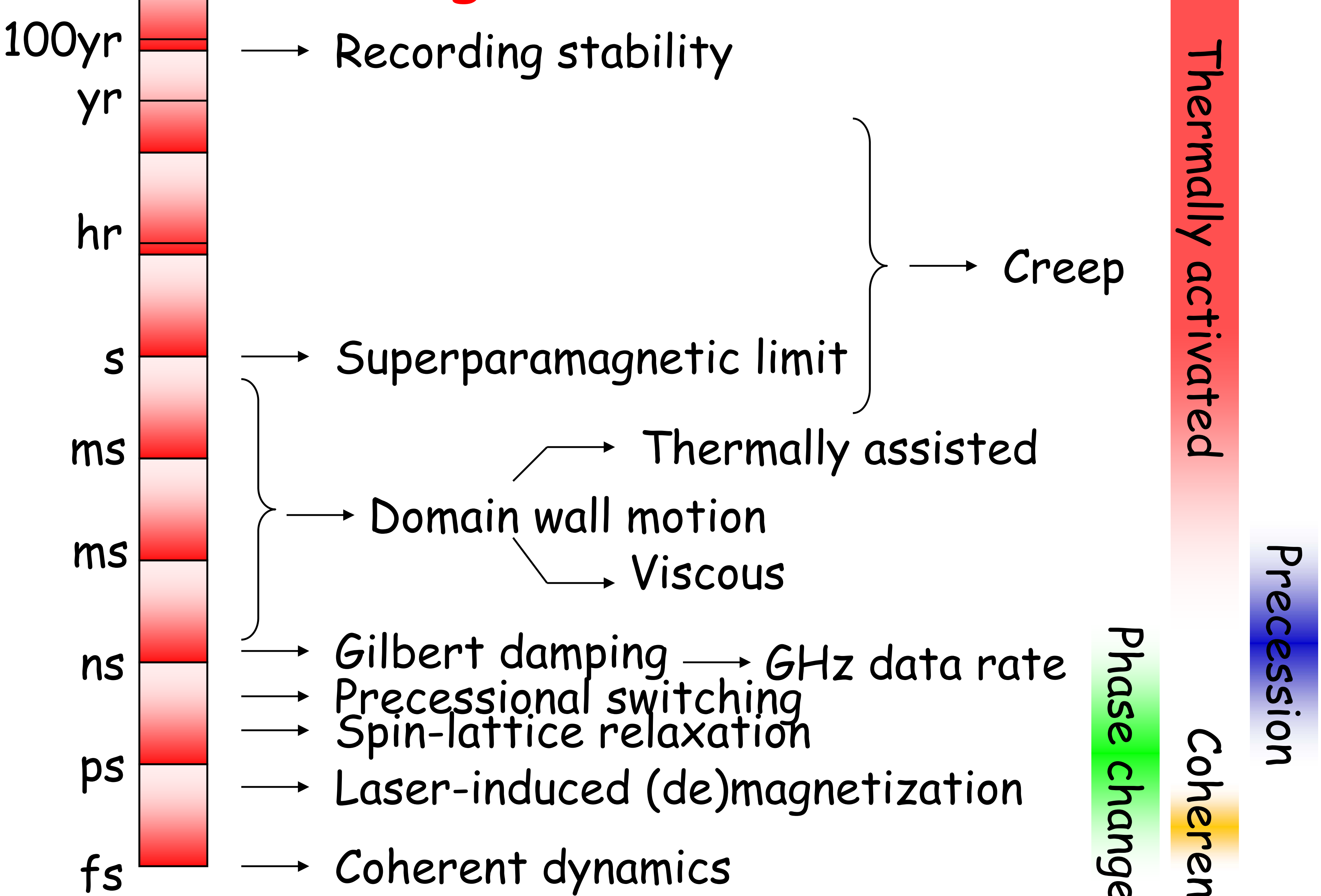
Bert Koopmans
Eindhoven University of Technology, The Netherlands

Hard disk: data rate road map

http://www.research.ibm.com/journal/rd/443/thompson.html



Magnetic time scales



This Lecture

Introduction

Local dynamics: "Macro-spin" behavior

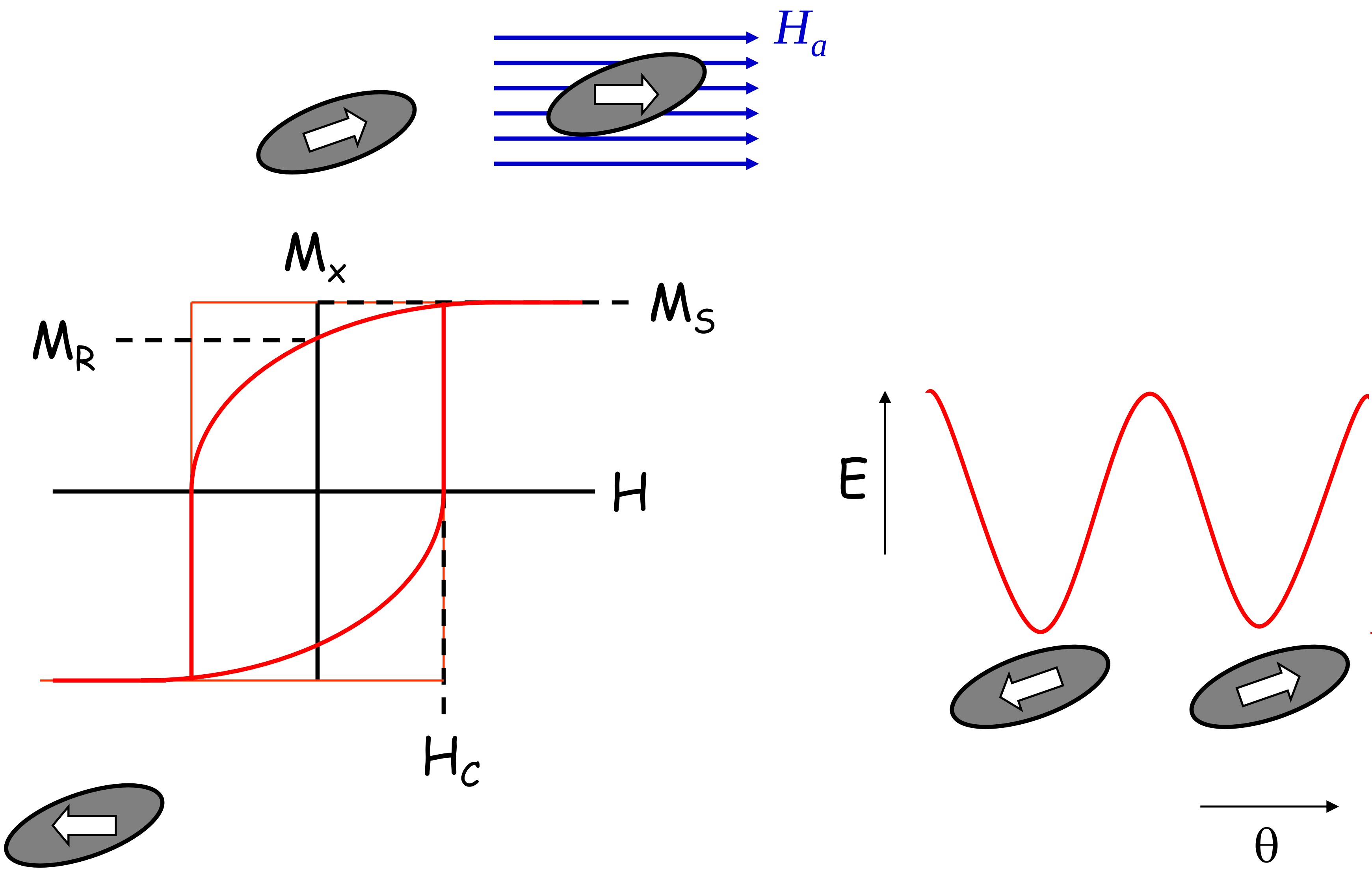
- From thermally-driven to precessional (LLG) dynamics
- Precessional modes in thin films (Kittel relation)
- Precessional switching

Measuring precessional dynamics

Nonlocal dynamics: Spin waves and confined structures

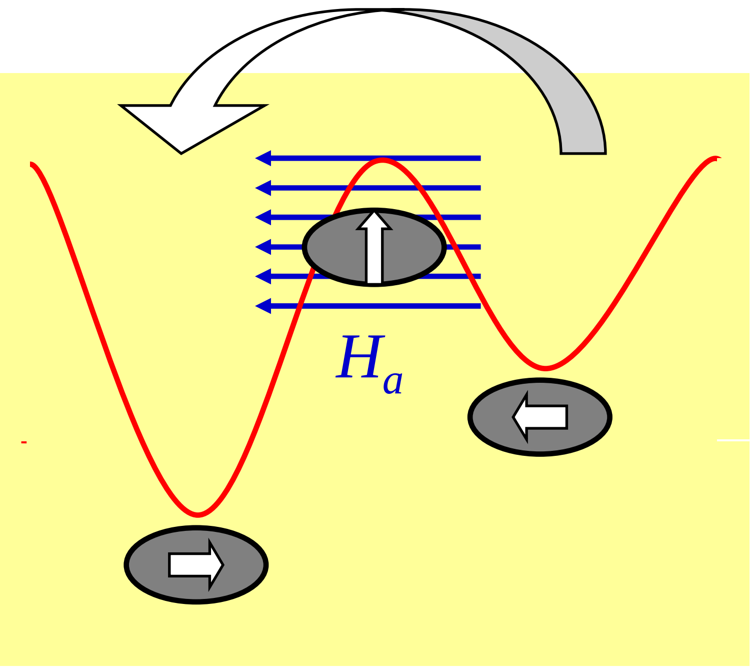
Summary

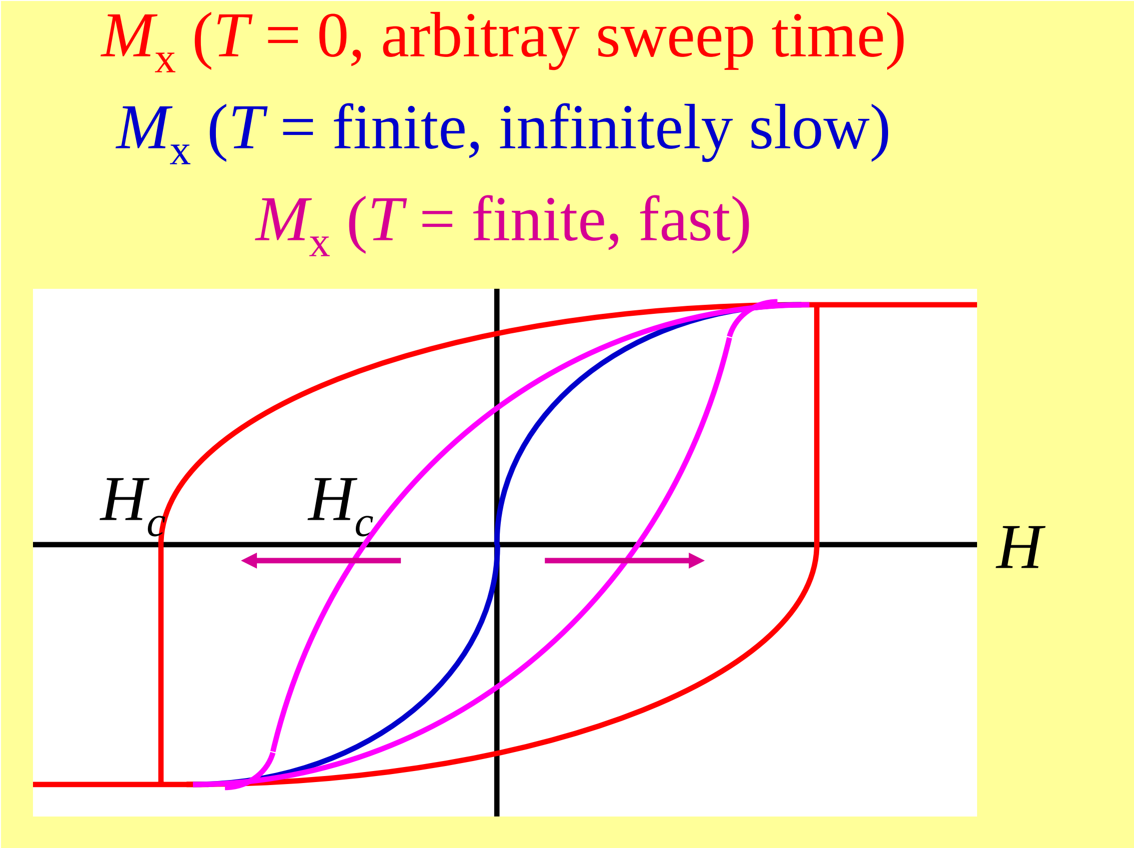
Statics (“macrospin”, small particle)



Dynamic Coercivity

Thermal activation



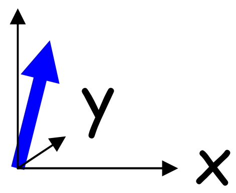


Observed for:

- Small particles
- Domain wall "unpinning"

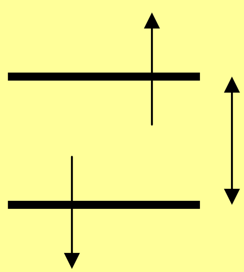
Spin precession

z (= quantization axis) $\Psi = (c_\uparrow, c_\downarrow)$ $|c_\uparrow|^2 + |c_\downarrow|^2 = 1$



e.g.: (1, 0) : along +z (1, exp(iϕ))/√2 : cos ϕ x + sin ϕ y
(1, 1)/√2 : x (cos(θ/2), sin(θ/2)) : cos θ z + sin θ x

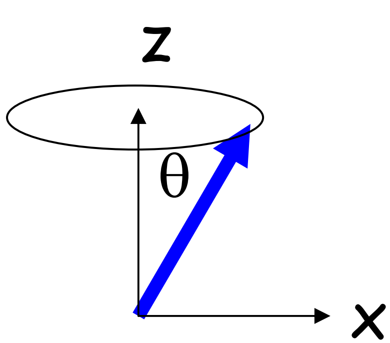
Switching on a field along z:



$\gamma\mu_0 H$

$$\Psi(t) = (e^{iE_\uparrow t/\hbar} \cos\tfrac{\theta}{2}, e^{iE_\downarrow t/\hbar} \sin\tfrac{\theta}{2})$$

$$= \ldots(\cos\tfrac{\theta}{2}, e^{i\Delta E t/\hbar} \sin\tfrac{\theta}{2})$$



precessing spin at frequency:

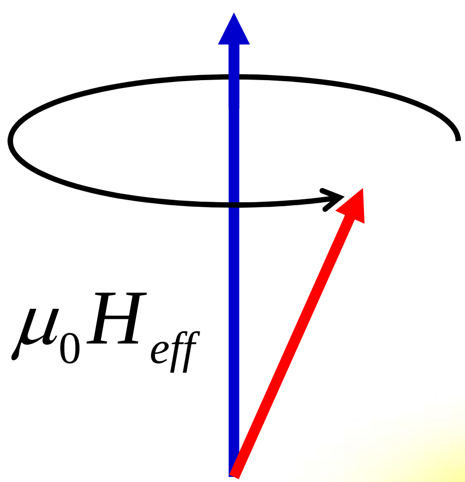
$$\omega_L = \frac{\gamma\mu_0 H}{\hbar}$$

$\gamma \sim 10^{-4}$ eV/T
$\hbar \sim 1$ eV fs
so, GHz

Landau-Lifshitz-Gilbert Eq.

$$\frac{d\vec{M}}{dt} = \gamma\mu_0\left(\vec{M}\times\vec{H}_{eff}\right) + \frac{\alpha}{M_s}\left(\vec{M}\times\frac{d\vec{M}}{dt}\right)$$

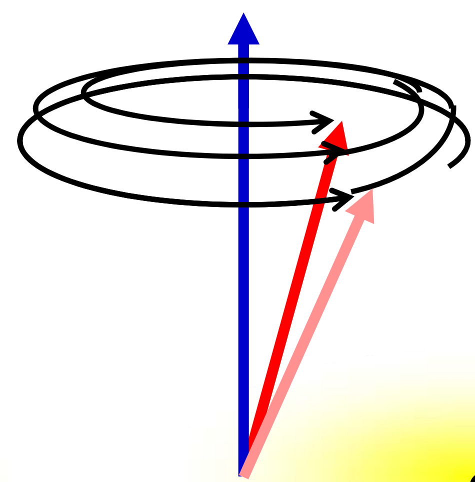
Spin Precession



$$f_L = \frac{\gamma}{2\pi}\mu_0 H_{eff}$$

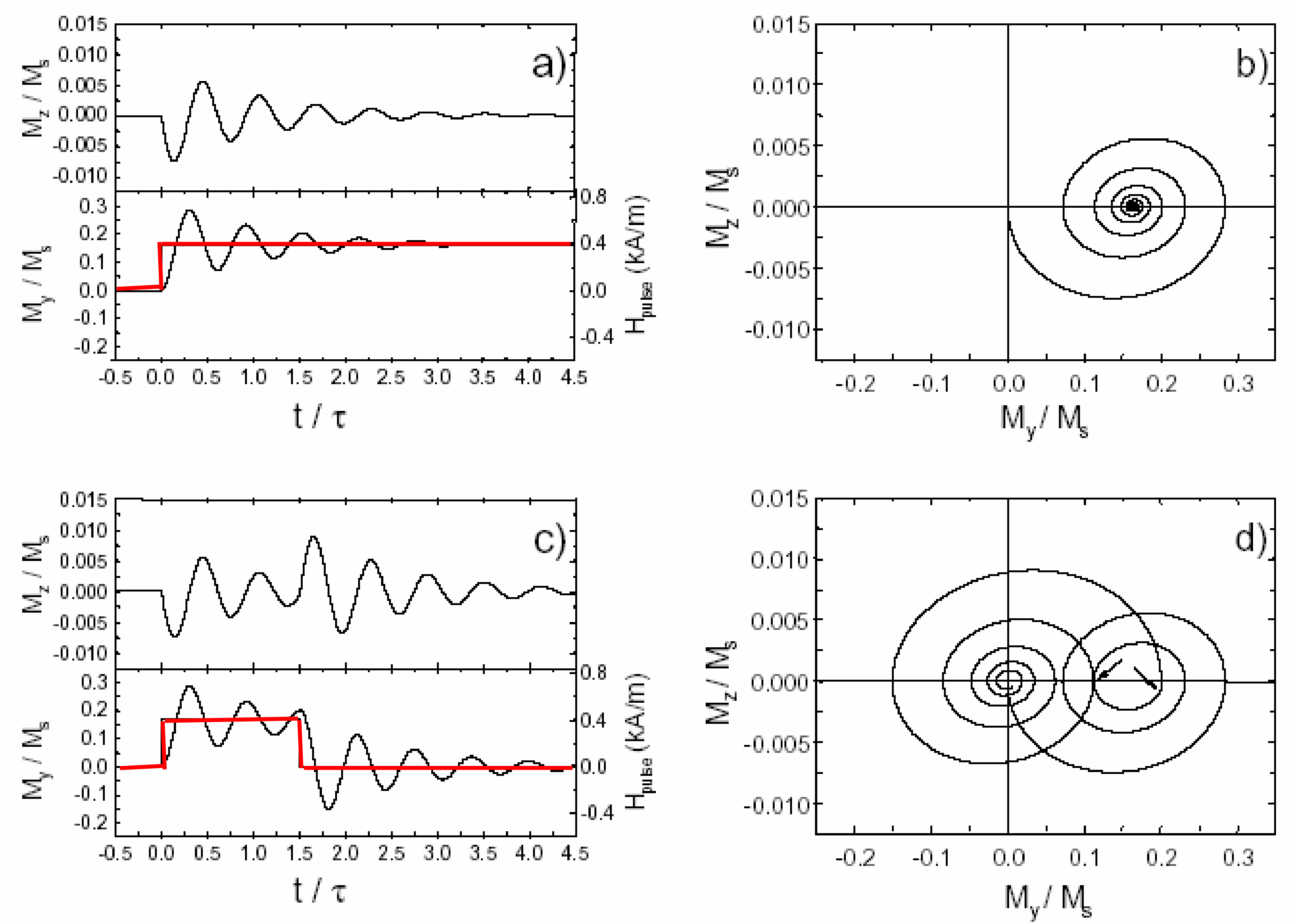
→ 30 GHz / T

Damping

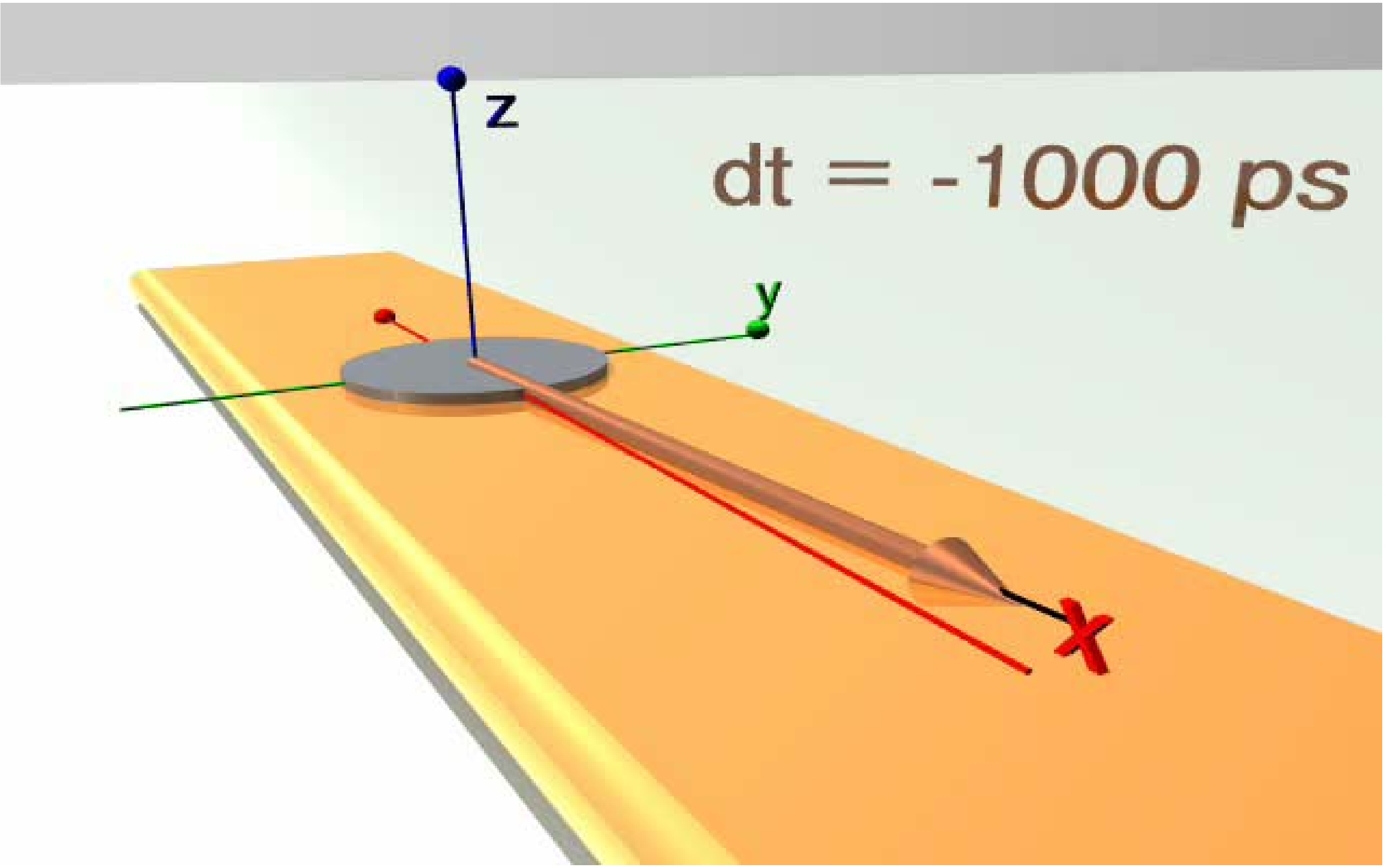


$\alpha \sim 0.01$

Examples of Precessional Dynamics



A real experiment



Rietjens, Jozsa (TU/e)

The effective field =

Applied field +

Shape anisotropy:

$$\vec{H}_{eff} = -\overline{\overline{N}} \cdot \vec{M}$$ Thin film: $$= -N_{zz} M_z \hat{z} = -\mu_0^{-1} M_z \hat{z}$$

Crystalline anisotropy:

$$\vec{H}_{eff} = -\frac{1}{|M|} \vec{\nabla} E_{anis}\left(\vec{M}\right)$$

Many shapes!
(neglect it here)

Exchange:

Exchange stiffness

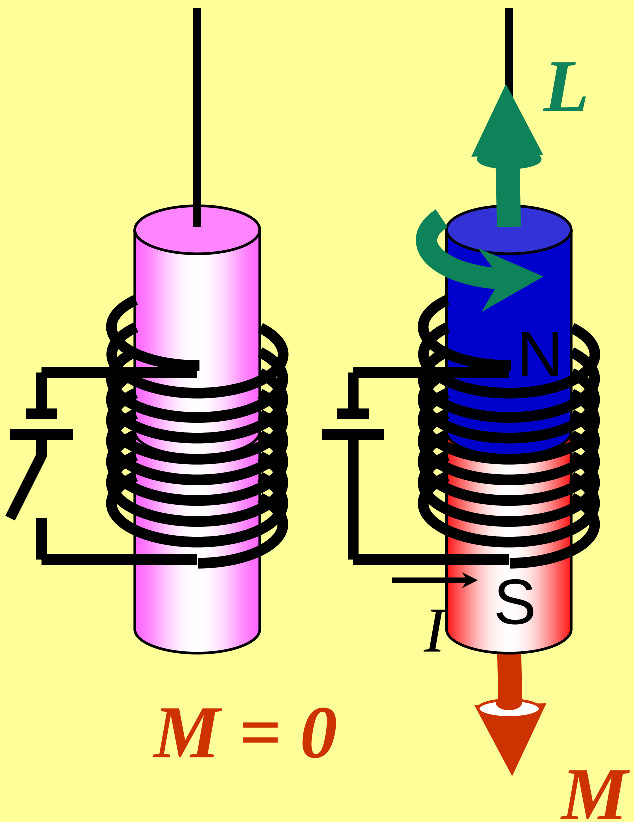
$$\vec{H}_{eff} = \frac{D}{M} \nabla^2 \vec{M}$$

Macro spin: $= 0$

Damping of precessional modes

Highly interesting and non-trivial...

... but let's discuss it a next time...

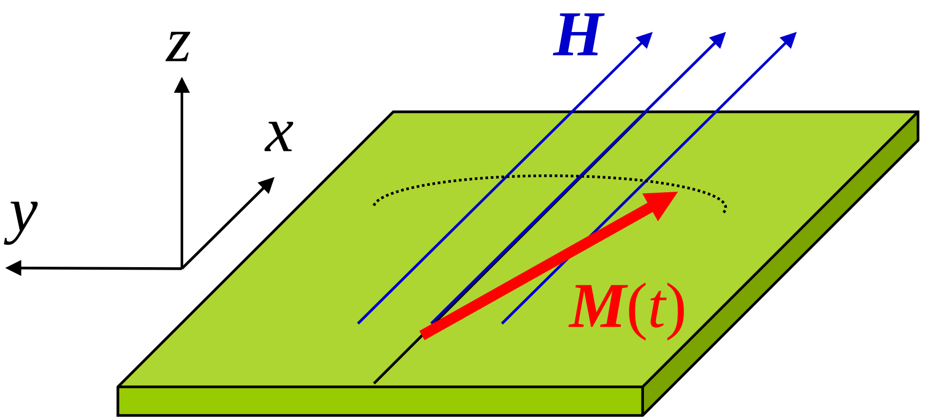


De Haas &Einstein
(1918)

But just let's discuss spin-lattice relaxation in a "macroscopic" limit...

$$L = -M$$

Kittel equation – Thin films



thin film system

$\boldsymbol{H}_{\text{eff}}(t) = H\,\hat{\boldsymbol{x}} - M_z(t)\,\hat{z}$

<u>assumption</u>: small amplitude

no damping

<u>solution:</u>

$M_y = \cos(\Omega t)$

$M_z = \varepsilon \sin(\Omega t)$

Just plug trial solution into LLG

$$\varepsilon^2 = H \,/\, (H + M_s) < 1$$

$$\Omega = \gamma \sqrt{H\,(H + M_s)}$$

…rather than γH

derivation

$$\vec{M} = M_s\hat{x} + M_y\hat{y} + M_z\hat{z}$$

$$\vec{H}_{eff} = H\hat{x} - \mu_0^{-1}M_z\hat{z}$$

$$\frac{d\vec{M}}{dt} = -\gamma\mu_0\vec{M}\times\vec{H}_{eff}$$

$$dM_y / dt = -\gamma\mu_0\left(H + \mu_0^{-1}M_s\right)M_z$$

$$dM_z / dt = -\gamma\mu_0\left(-H\right)M_y$$

$$M_y = e^{i(\omega t - kz)}\delta M$$

$$M_z = \varepsilon i e^{i(\omega t - kz)}\delta M$$

$$i\omega = -\gamma\mu_0 \cdot i\varepsilon\left(H + \mu_0^{-1}M_s\right) \qquad (a)$$

$$-\varepsilon\omega = -\gamma\mu_0 \cdot -H \qquad (b)$$

$$i\omega = \left(-\gamma\mu_0\right)^2\frac{iH}{\omega}\left(H + \mu_0^{-1}M_s\right)$$

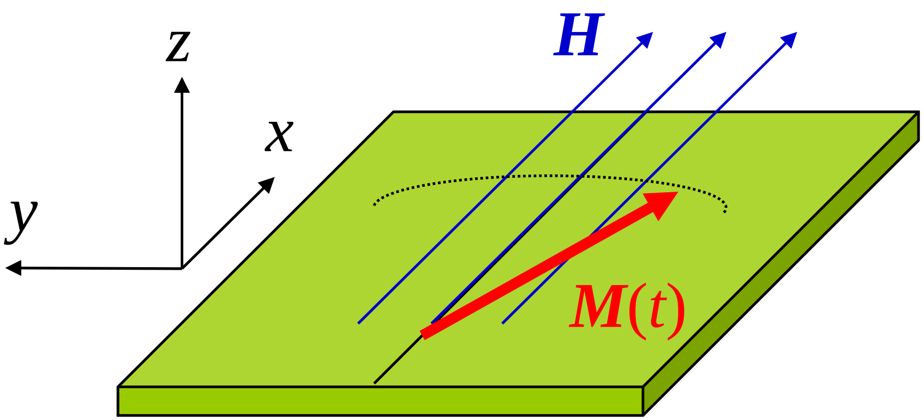
$$i\frac{H}{\varepsilon}\left(-\gamma\mu_0\right) = -\gamma\mu_0 \cdot i\varepsilon\left(H + \mu_0^{-1}M_s\right)$$

$$\Rightarrow$$

$$\omega = \gamma\mu_0\sqrt{H\left(H + \mu_0^{-1}M_s\right)}$$

$$\varepsilon^2 = \frac{H}{H + \mu_0^{-1}M_s}$$

(Reversal by) Damping



with damping

solution:

$M_y = \cos(\omega t)\exp(-t/\tau)$

$M_z = \varepsilon\sin(\omega t+\phi)\exp(-t/\tau)$

$$\tau = \frac{2\left(1+\alpha^2\right)}{\alpha\gamma\mu_0\left(2H+\mu_0^{-1}M_s\right)}$$

derive it yourself!

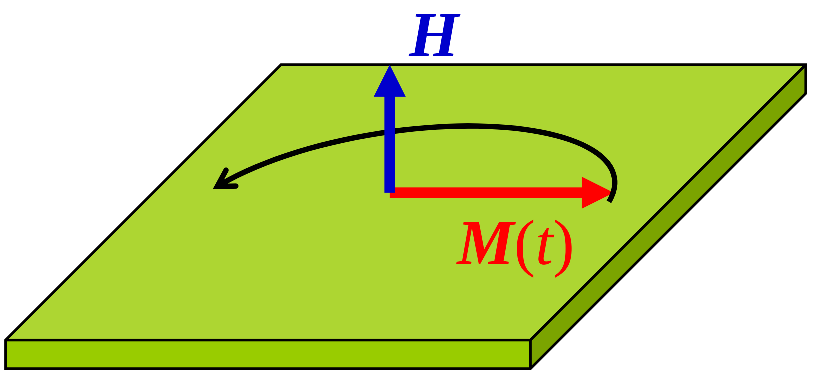
$\mu_0 H >> M_s$: $\omega\tau = \alpha^{-1}$ $\approx 1/2\pi\alpha$ periods

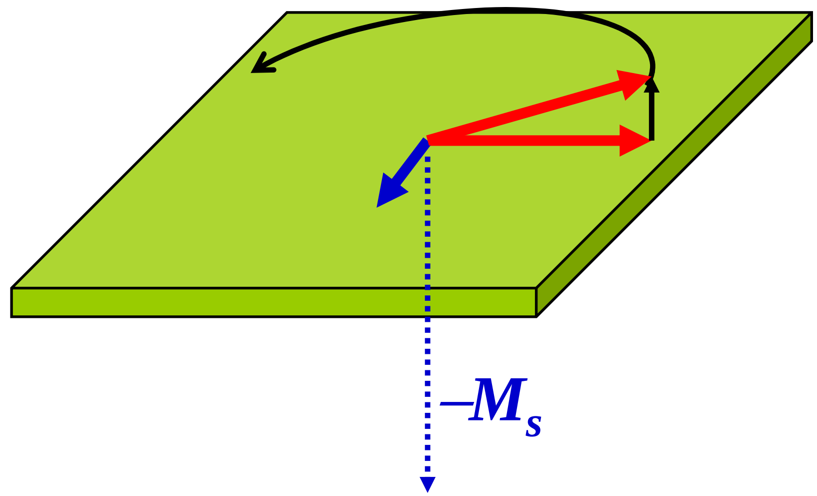
$\mu_0 H << M_s$: $\tau = 2/\alpha\gamma M_s$ ≈ 10 ps$/\alpha$

} indep. of ***H***

Switching: $\tau_s >> 1$ ns for $\alpha = 0.01$

Precessional switching





$$\tau_s = \frac{\pi}{\omega_L} = \frac{\pi}{\gamma\mu_0 H}$$

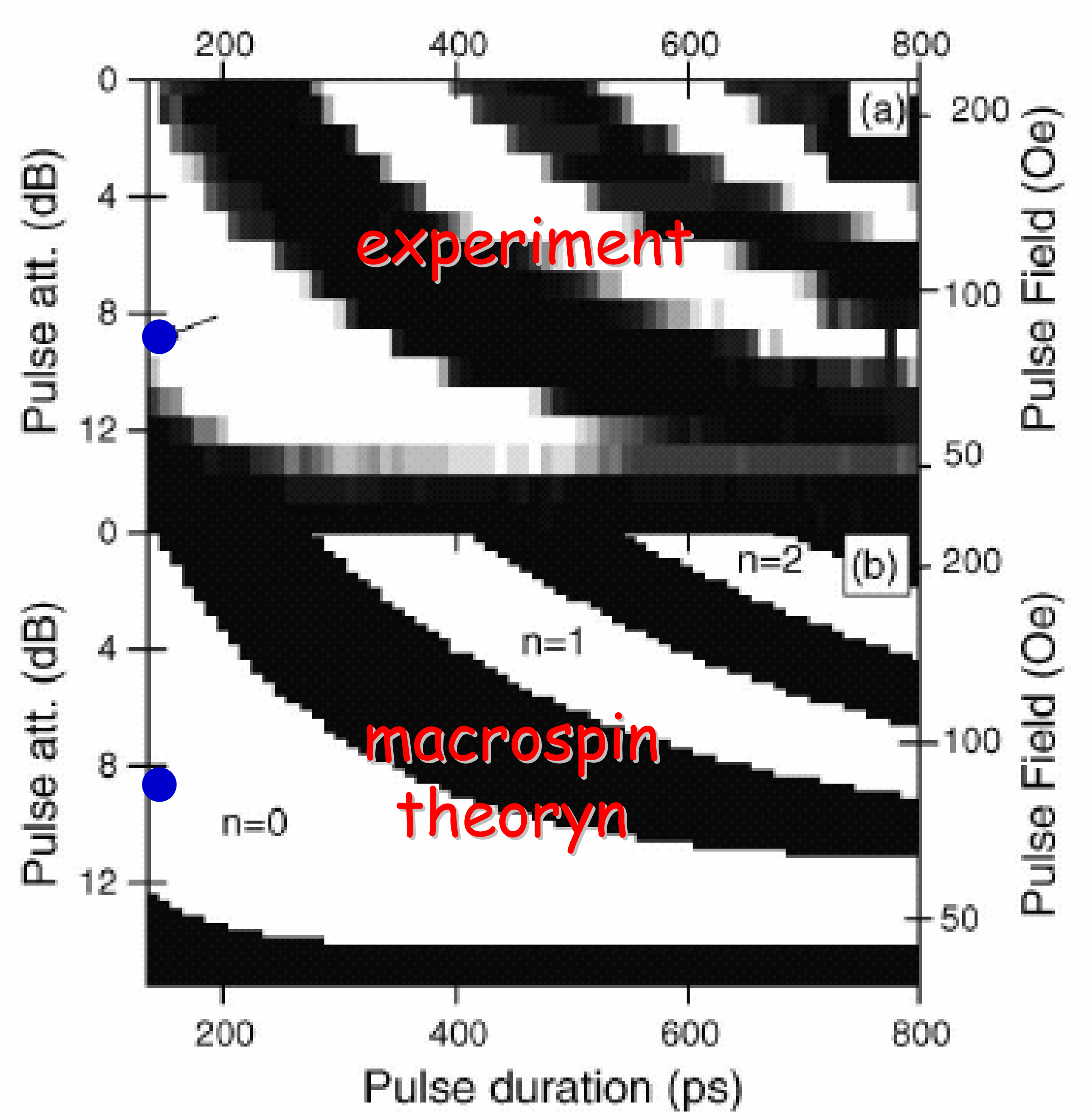
$$\tau_s \approx \frac{\pi}{\gamma\mu_0 \sqrt{(H(H+M_s))}}$$

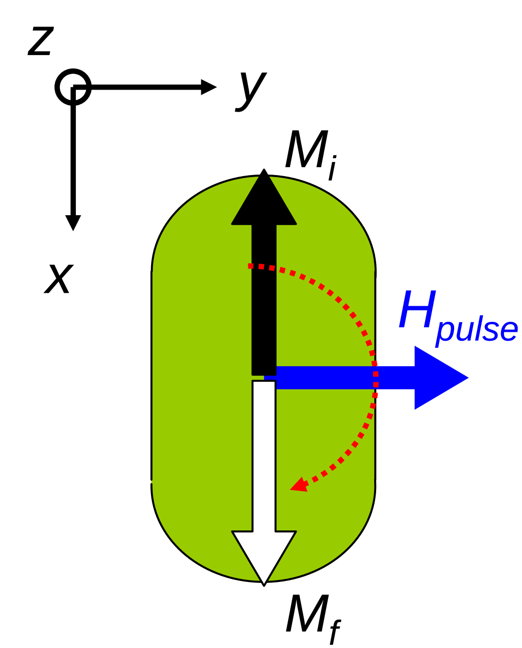
$$\left.\begin{array}{l} M_s = 1\ \mathrm{T} \\ \gamma\mu_0 \mathrm{H} = 0.01\ \mathrm{T} \end{array}\right\}$$

~ 1.5 ns

~ 150 ps

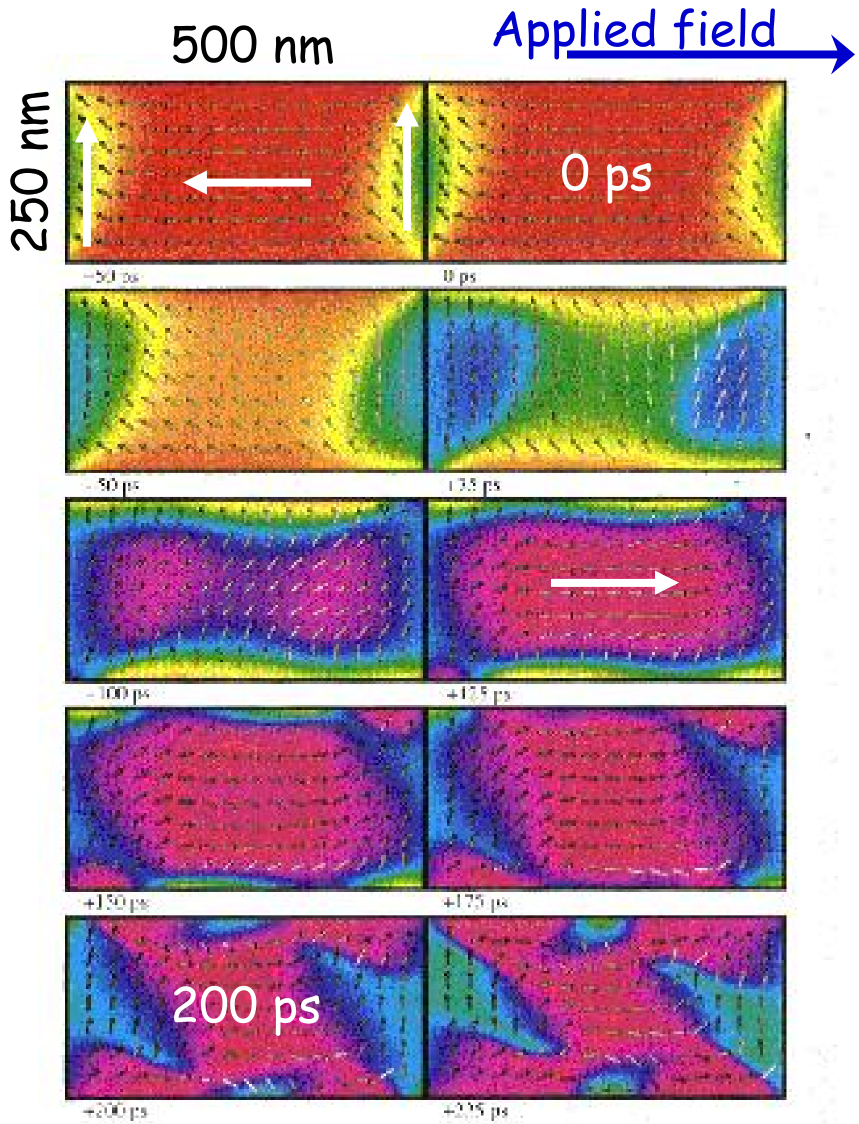
Switching/NoSwitching diagrams





2 x 4 μm Permalloy
Schumacher *et al.*,
PRL **90**, 017201 (2003)

Switching a real device



5 nm Permalloy element (J. Miltat)

Homogeneous excitation, still strongly non-homogeneous response !!!

Due to:

- Non-homogeneous groundstate
- Excitation of spin waves

Thereby a slow relaxation…

Where are we...

Introduction

Local dynamics: “Macro

Measuring precessional dynamics

- Frequency domain
- Time domain
- All-optical techniques

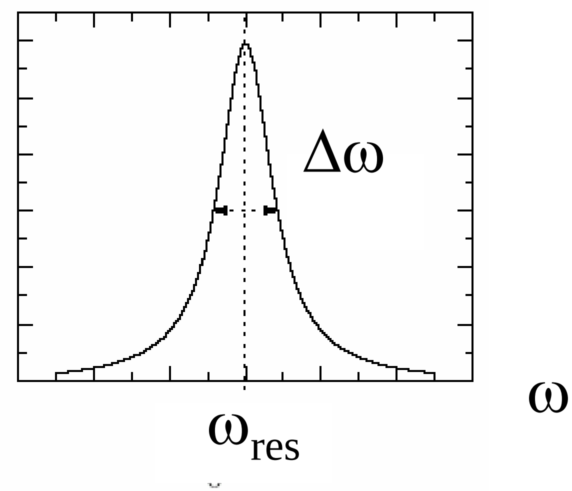
Nonlocal dynamics: Spin waves and confined structures

Outlook & Summary

Probing spin dynamics

Frequency domain techniques

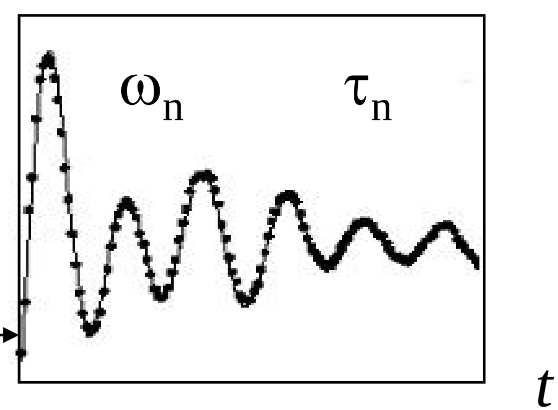
- Ferromagnetic Resonance
- Brillouin Light Scattering



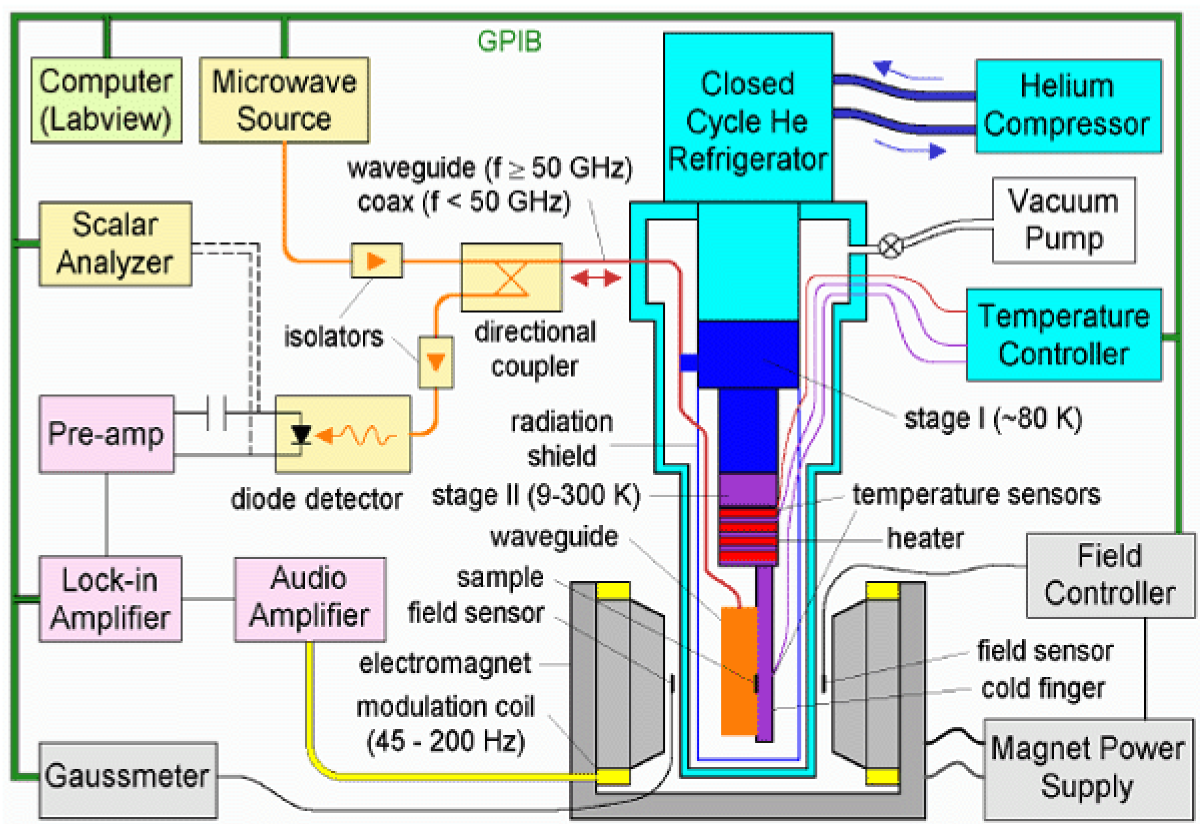
Time-domain techniques

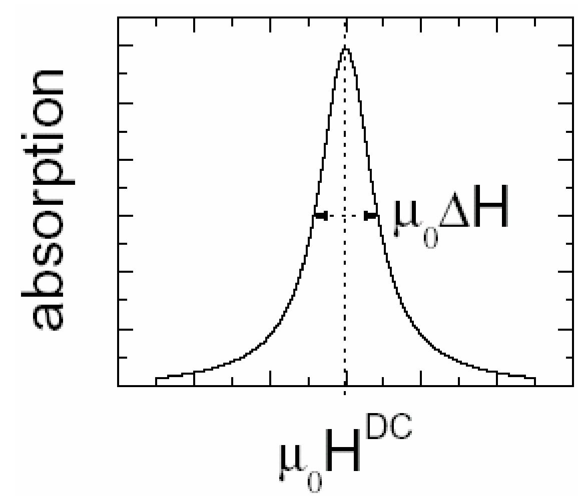
- Using fast electronics (> 100 ps)
  - Real-time scheme
- Using short laser pulses (down to fs)
  - Stroboscopic techniques
  - Scanning approaches

- Specific case: Pulsed excitation



Ferromagnetic Resonance



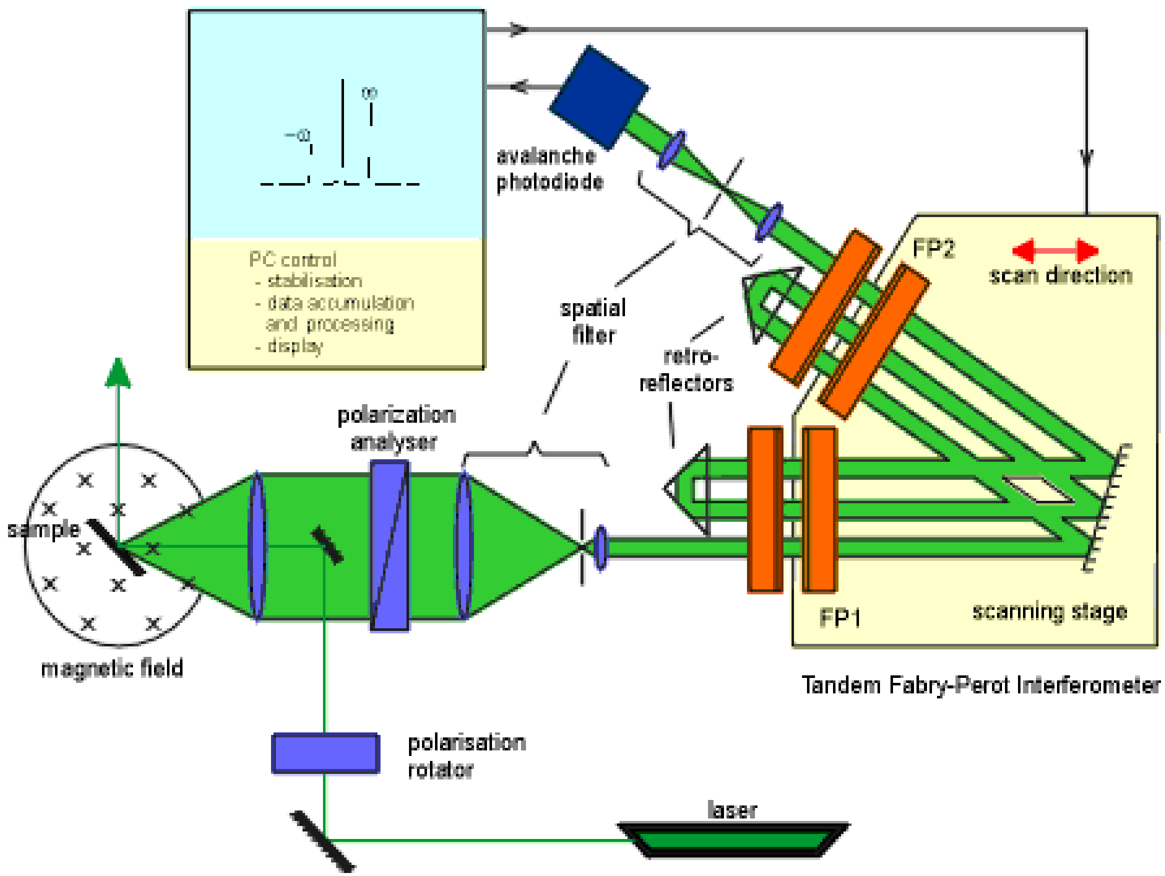


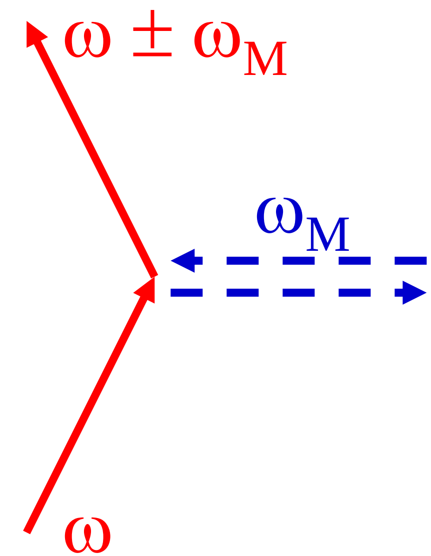
Damping as well:

$$\Delta\omega = \frac{d\omega_{res}}{dH}\Delta H$$

$$\alpha = \frac{\Delta\omega}{\omega_{res}}$$

Brillouin Light Scattering





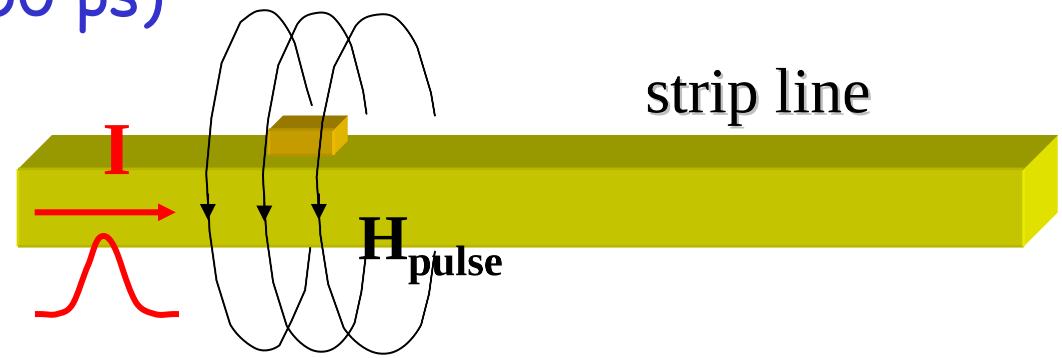
$h\omega$ ~ 1 eV

$h\omega_M$ ~ 10^{-4}…10^{-6} eV

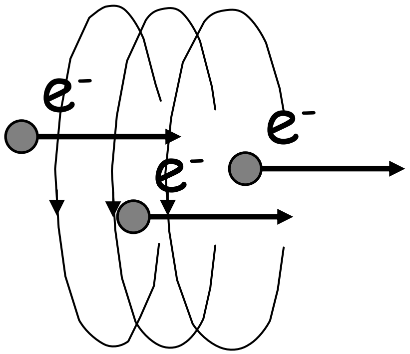
Hillebrands, U. Kaiserslautern, website

Time-Domain Techniques: Excitation

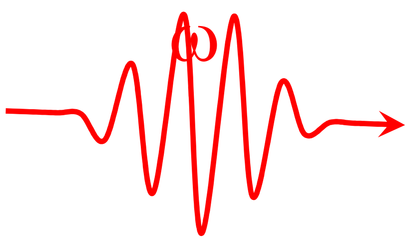
Magnetic field pulses (50 ps)



Electron bunches (~ ps)



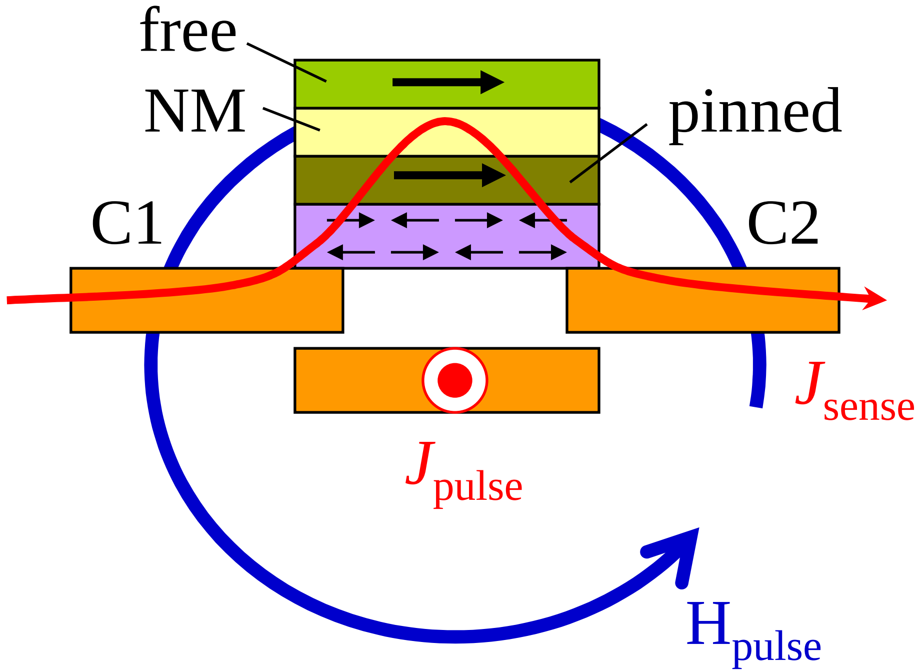
Laser pulses (30 fs)

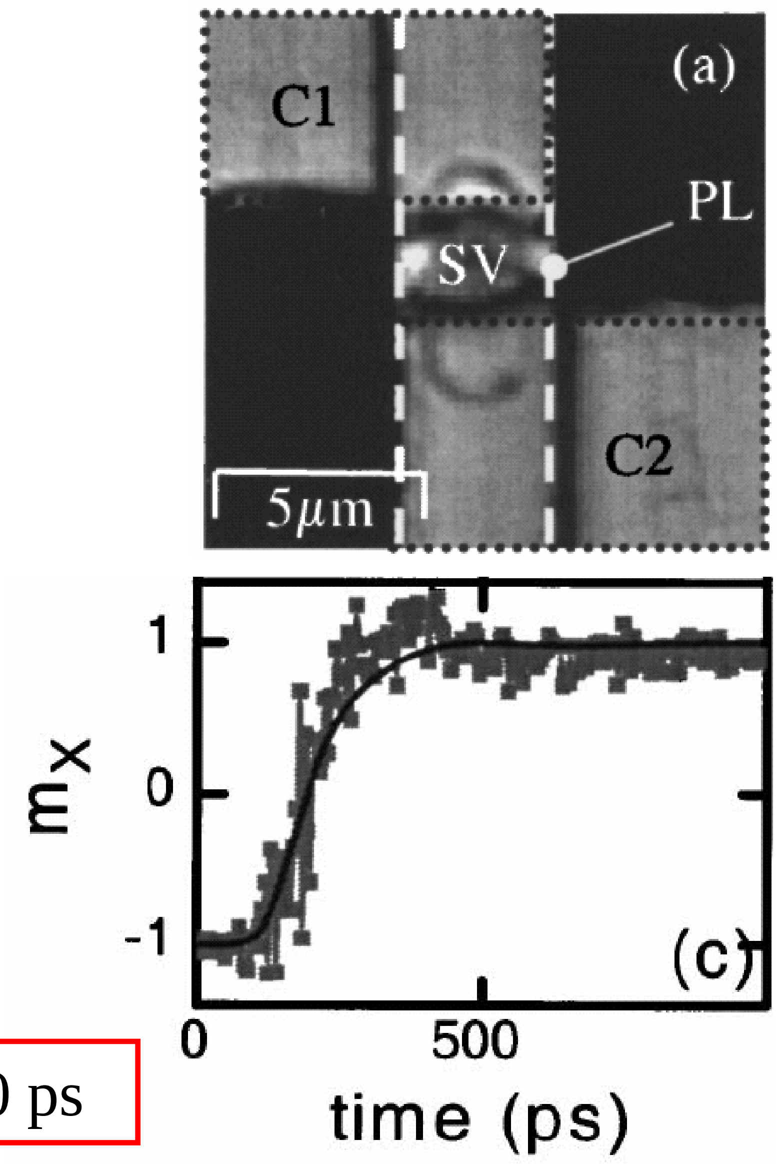


Or combinations thereof?

- Photo switches, Breaking Schottky barrier, ...

Real time: MR detection

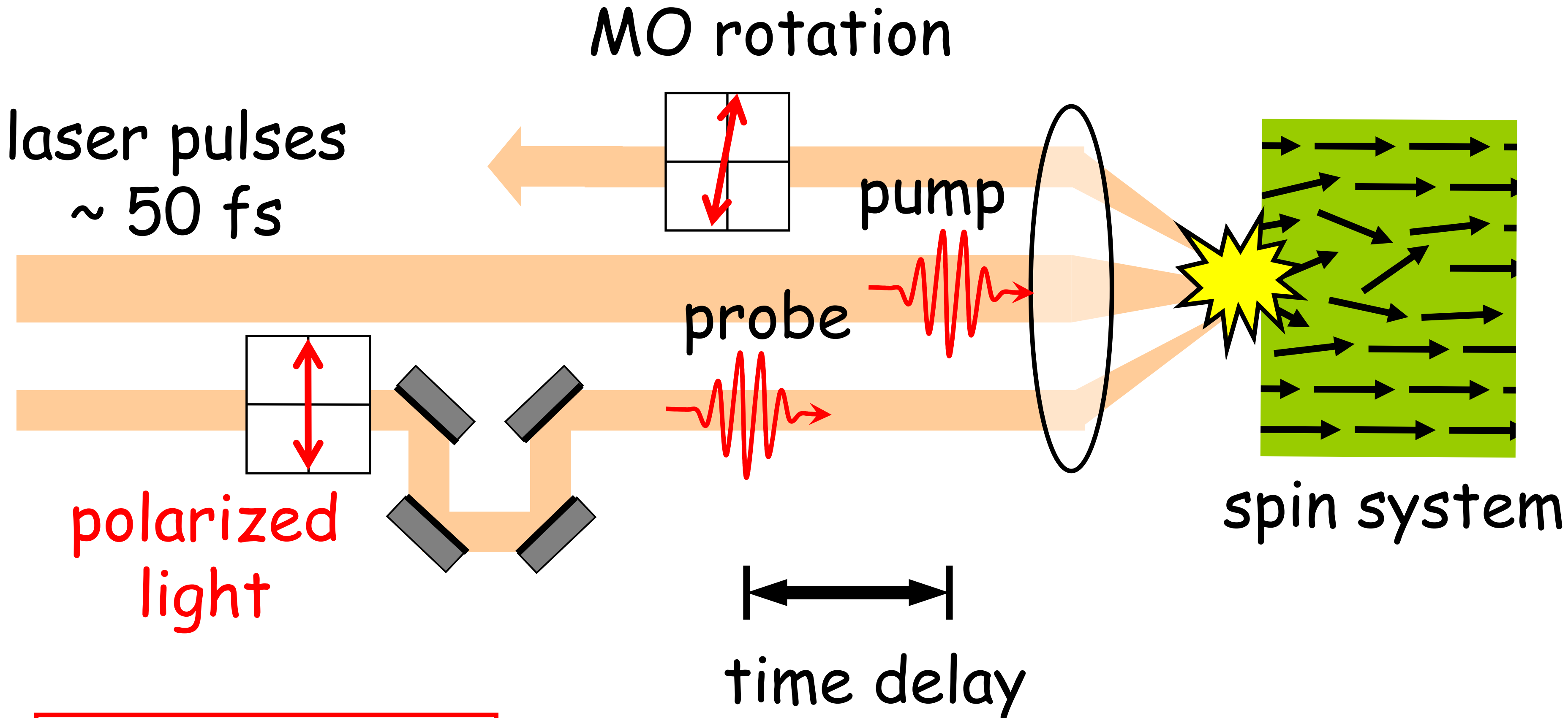




5 x 2.3 μm Py/CoFe
Schumacher *et al.*,
PRL **90**, 017204 (2003)

resolution ~ 100 ps

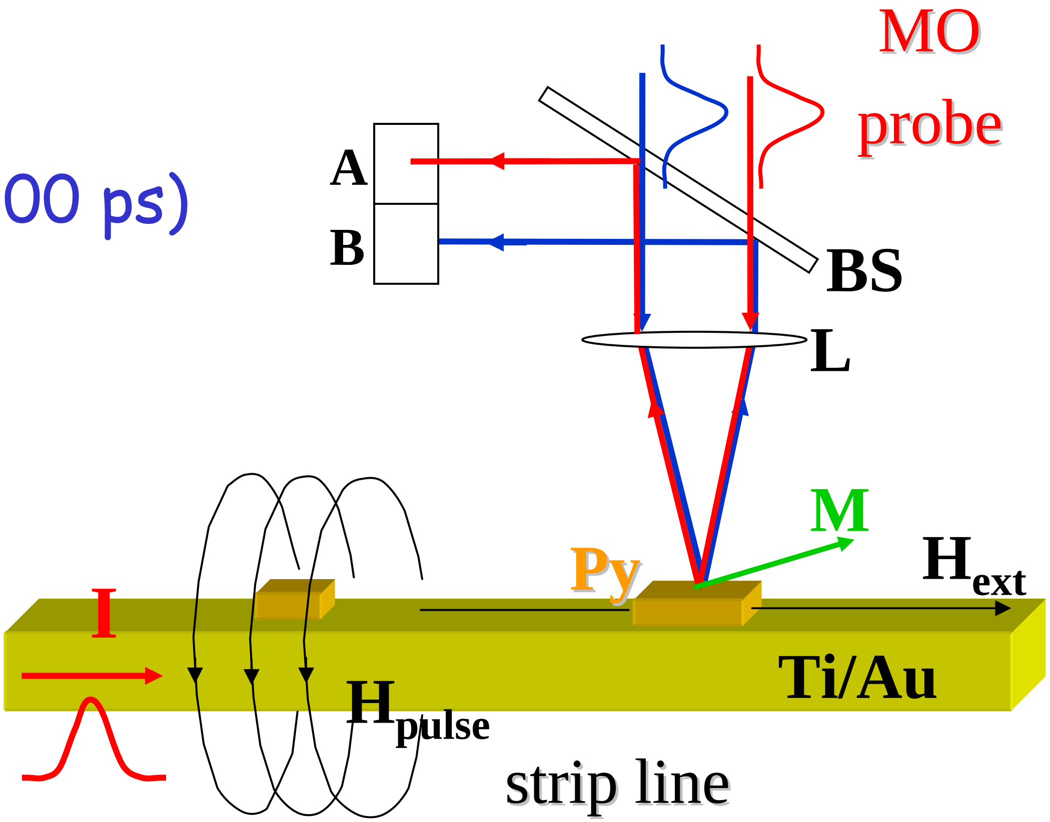
Stroboscopic: Pump-probe Optics



jitter < fs
pulses < 30 fs

Strob.: Pump-probe "Hybrid"

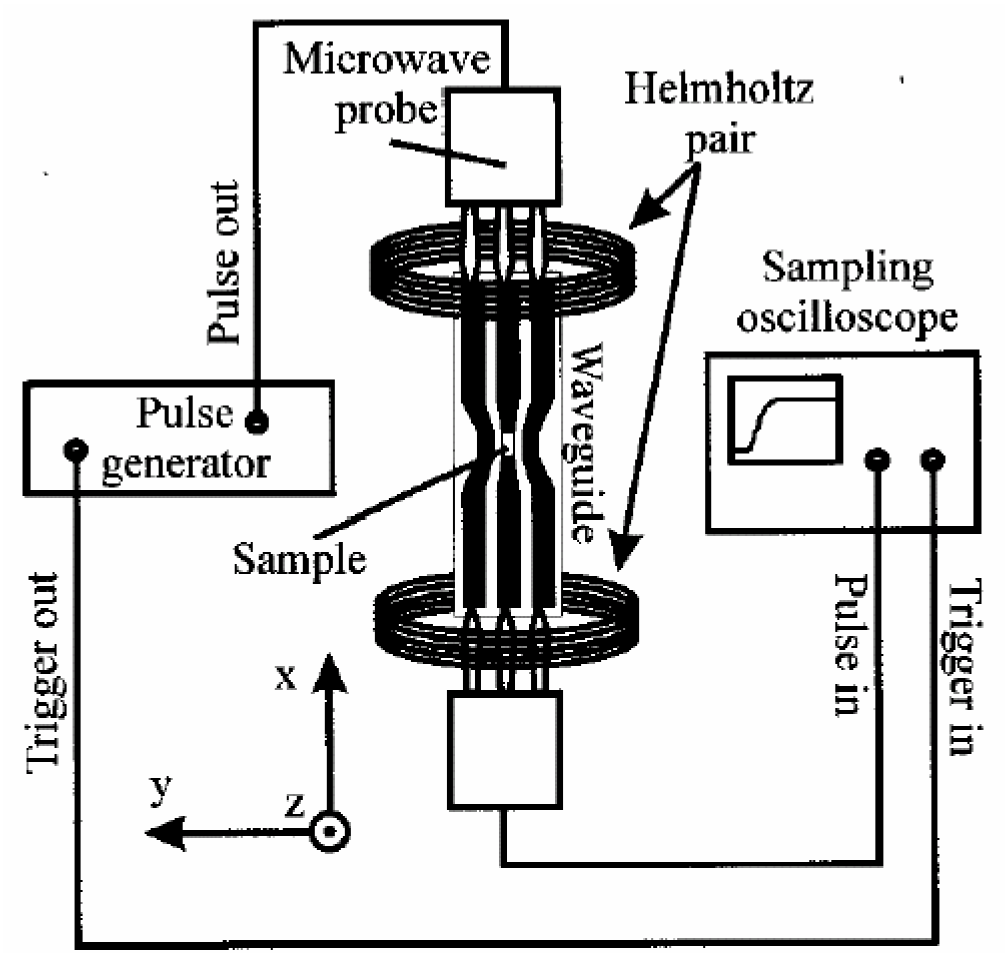
Electrically generated magnetic field pulses (100 ps)

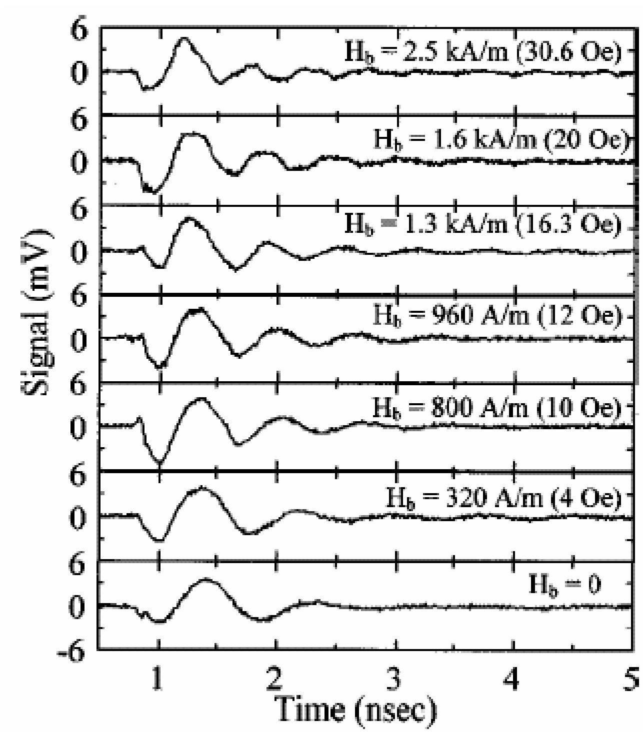


Capabilities

- Vectorial resolution (4-quadrant detector)
- Time resolution 100 ps ("no limit" for fully optical)
- Spatial resolution (~ 400 nm, diffraction limit)

PIMM ("real time FMR")





Silva *et al.*, JAP **85**, 7849 (1999)

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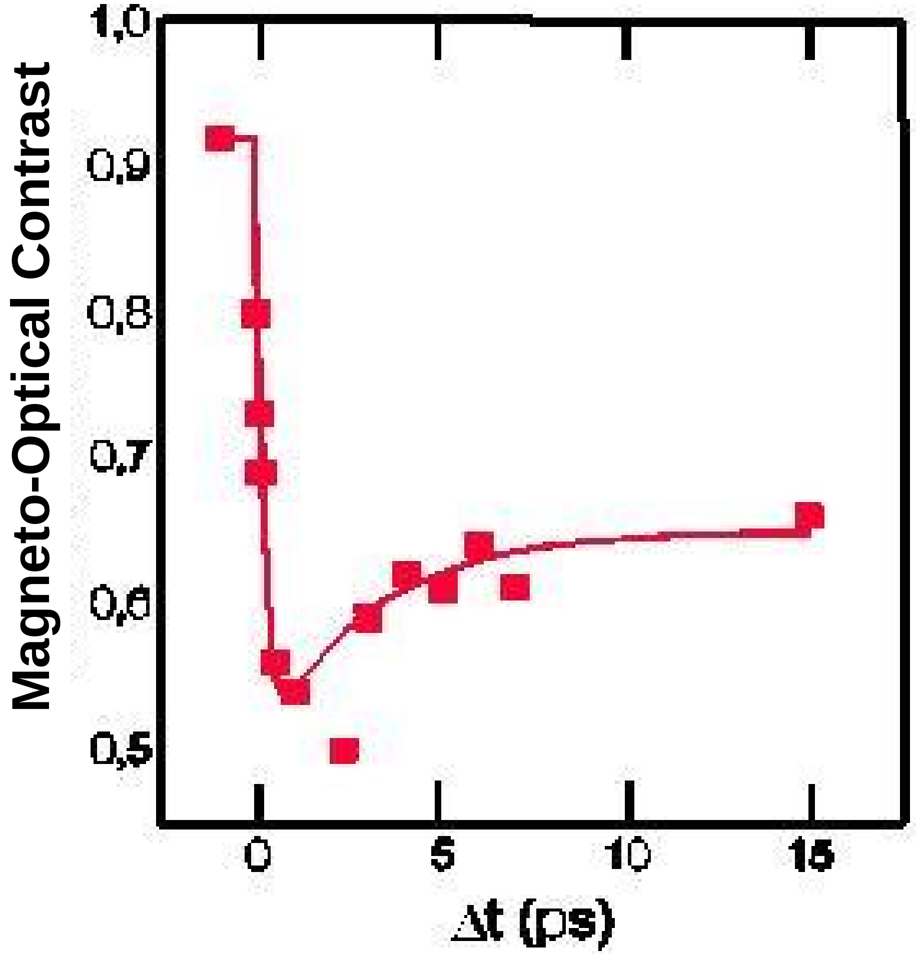
- All-optical techniques

Nonlocal dynamics: Spin waves and confined structures

Outlook & Summary

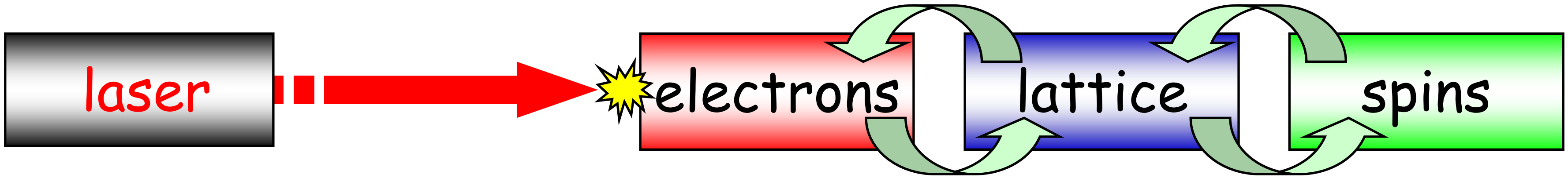
A surprising experiment

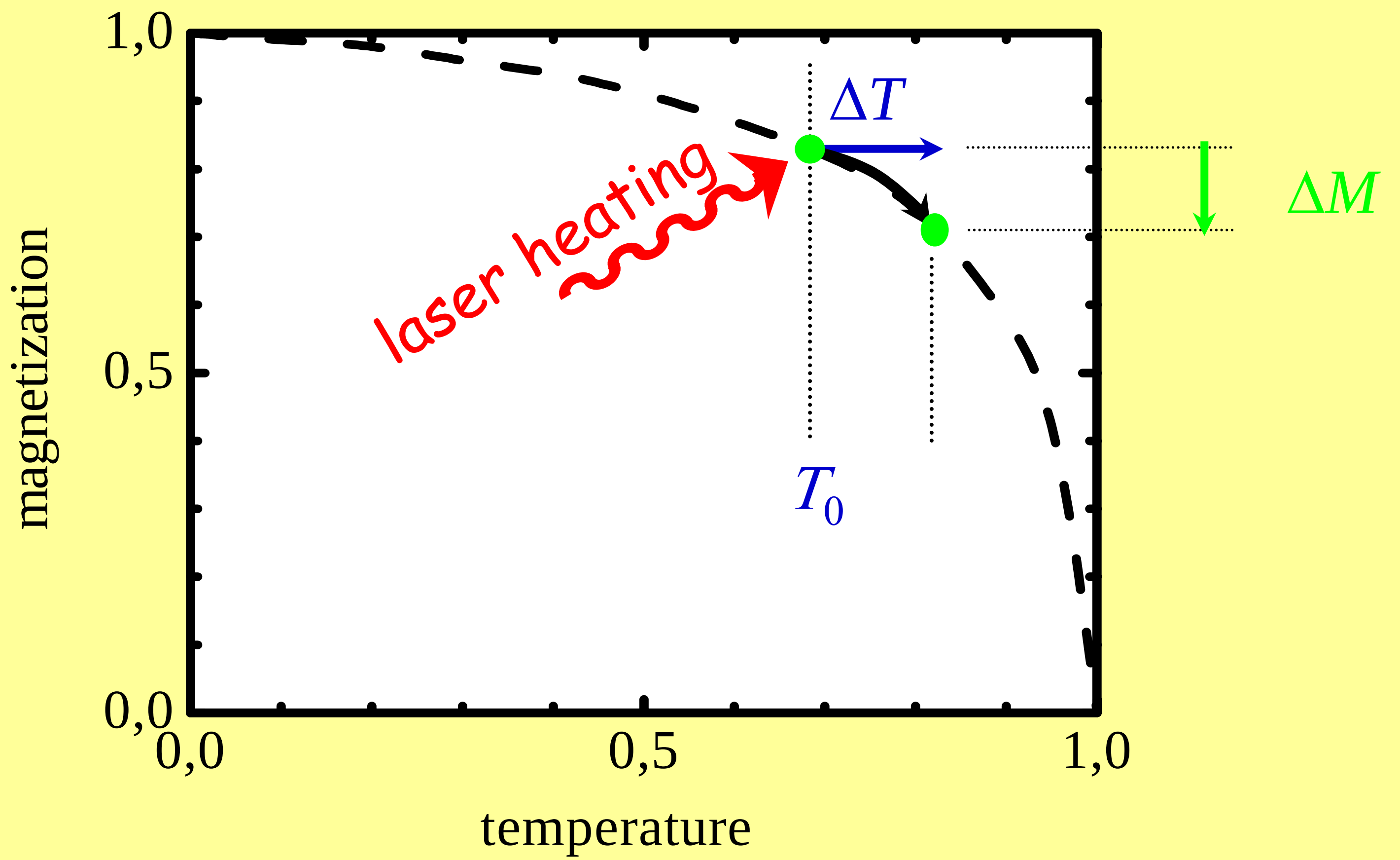
Heating ferromagnetic Nickel with a 50 fs laser pulse



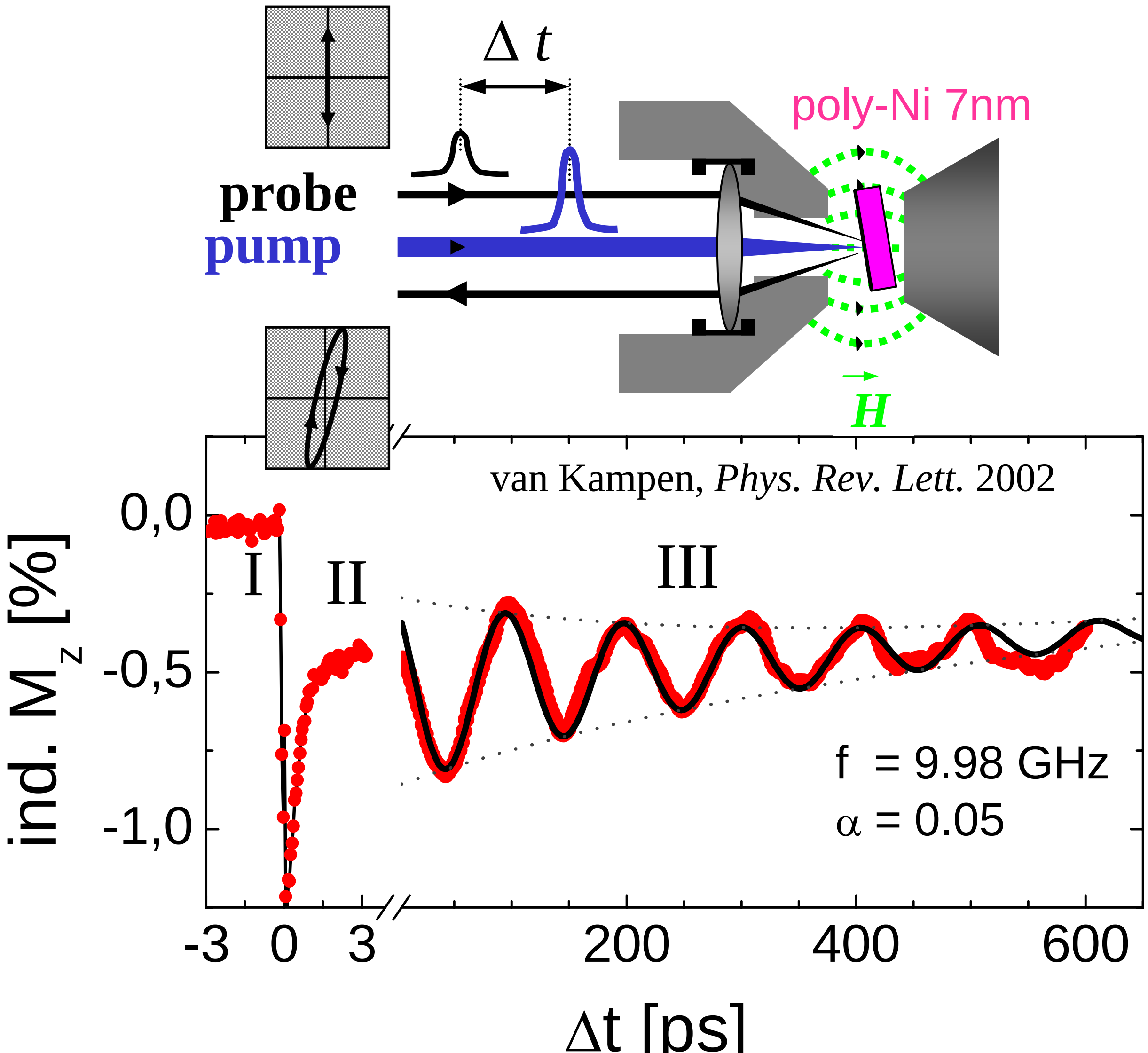
Beaurepaire *et al.*,
PRL **76**, 4250 (1996)

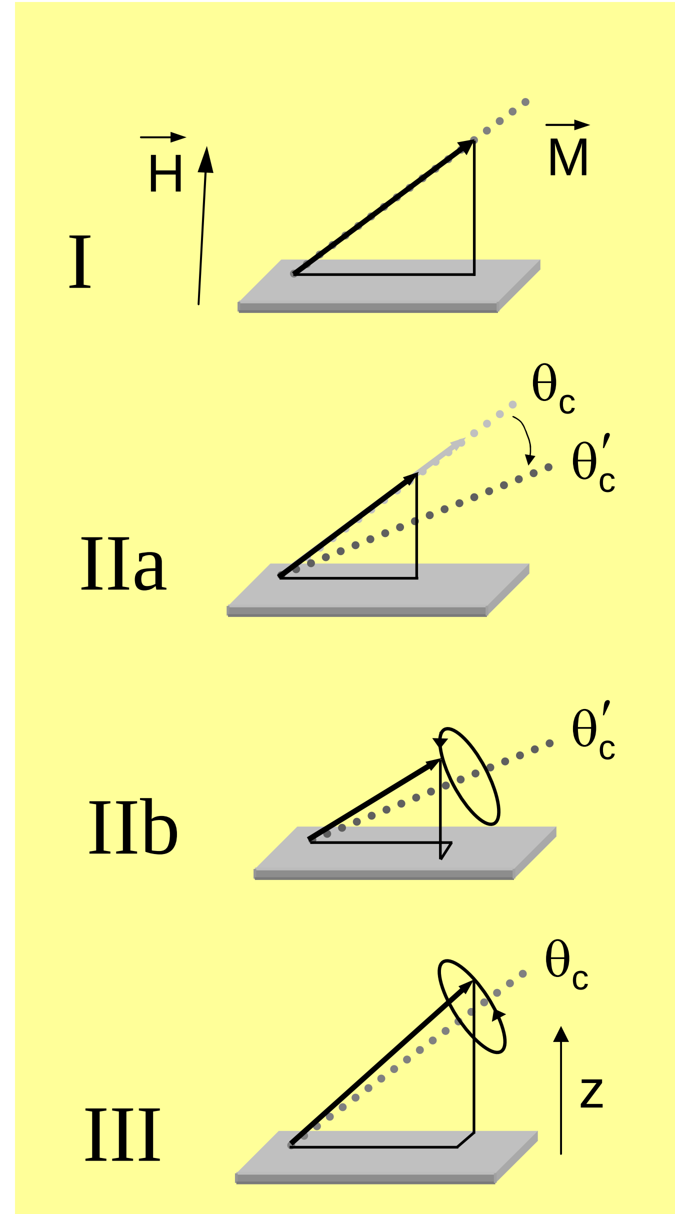
Laser-induced Demagnetization



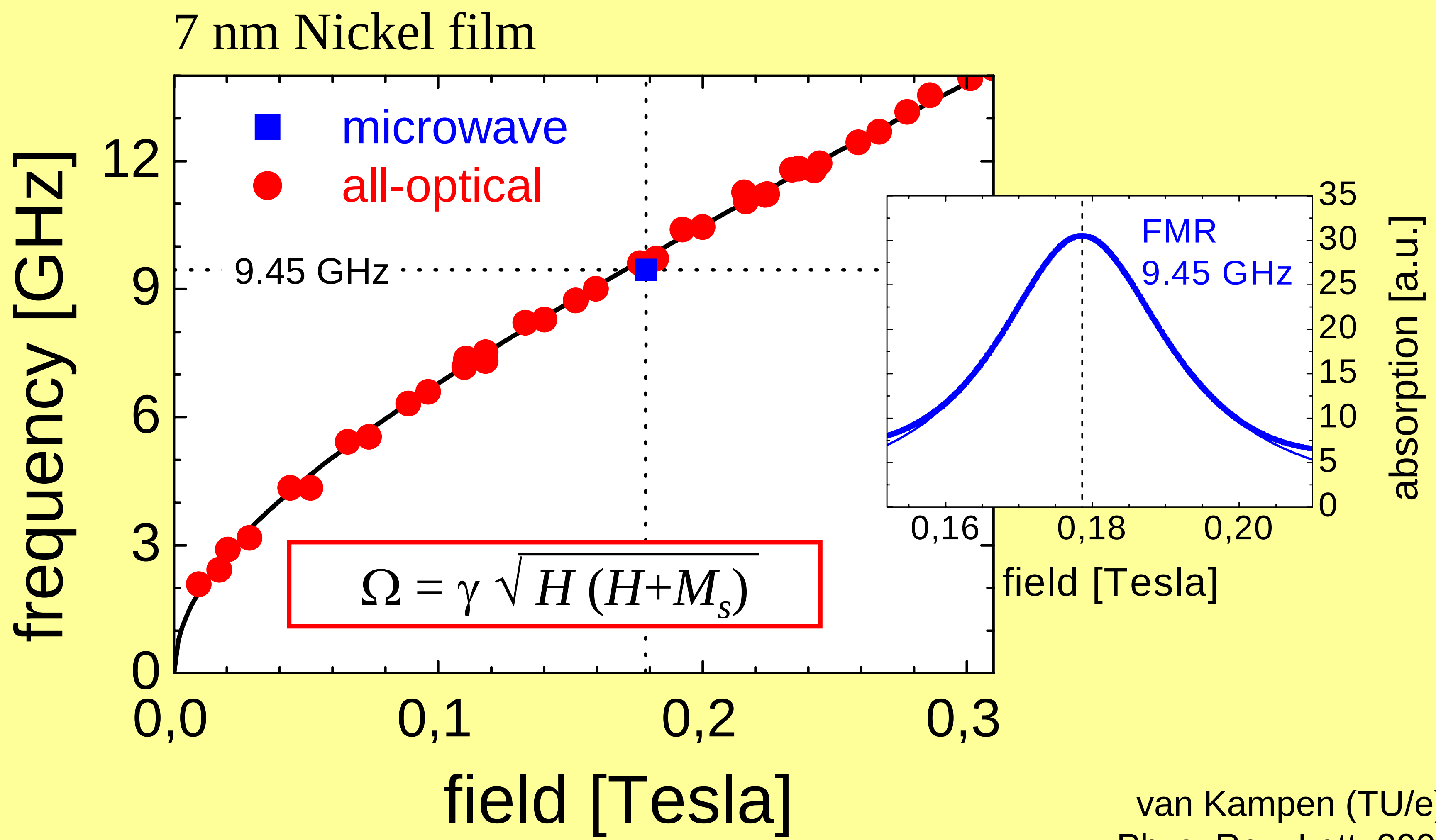


All-Optical Probing of Spin Precession





Frequency vs. Time-Domain



van Kampen (TU/e),
Phys. Rev. Lett. 2002

Where are we…

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Local dynamics: "Macro-spin" behavior

Measuring precessional dynamics

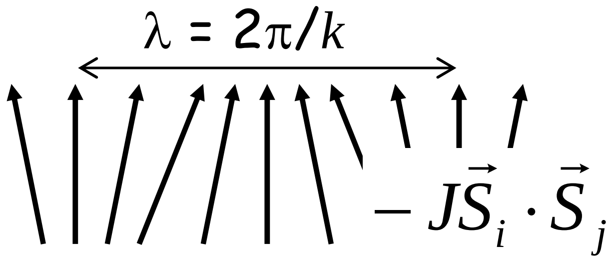
Nonlocal dynamics: Spin waves and confined structures

- Exchange-driven: Perpendicular spin waves in thin films
- Dipole-driven: Lateral spin waves
- Laterally confined structures

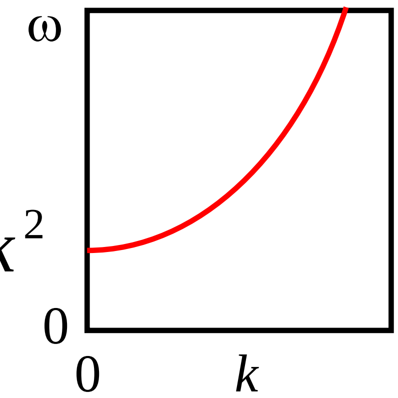
Outlook & Summary

Sources of Non-homogeneous Response

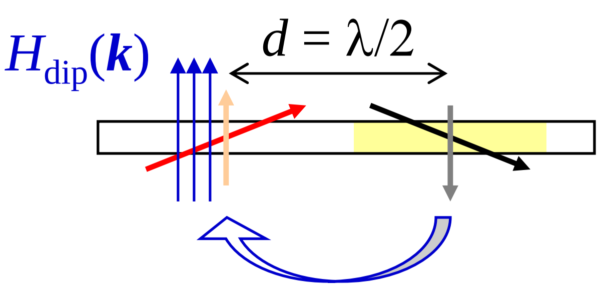
Exchange field + finite *k*



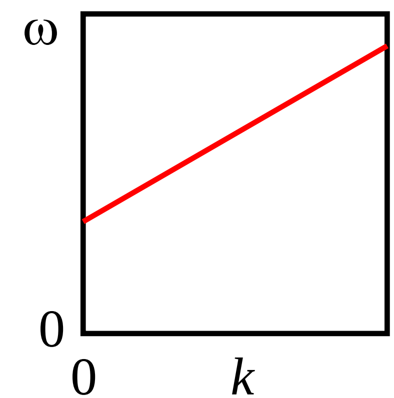
$$\vec{H}_{eff} = \frac{D}{M}\nabla^2\vec{M} \propto Dk^2$$



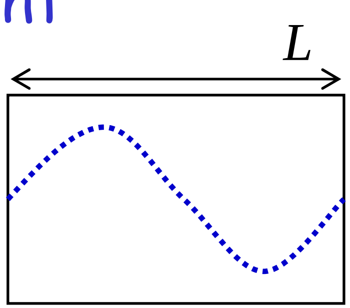
Dipole field + finite *k*



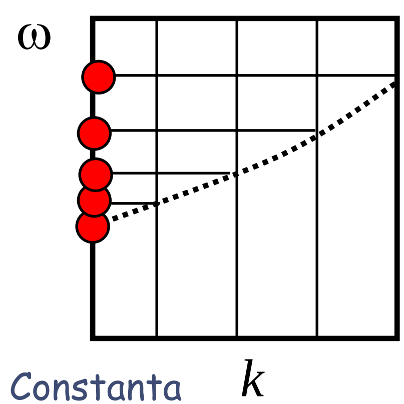
$$\vec{H}_{eff} \propto \frac{1}{d} \propto k$$



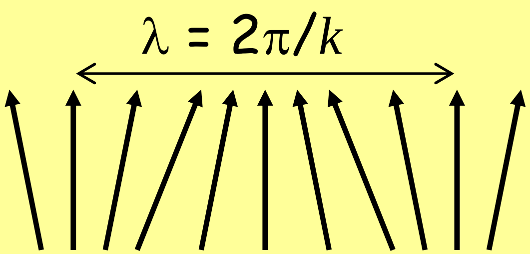
nfinement



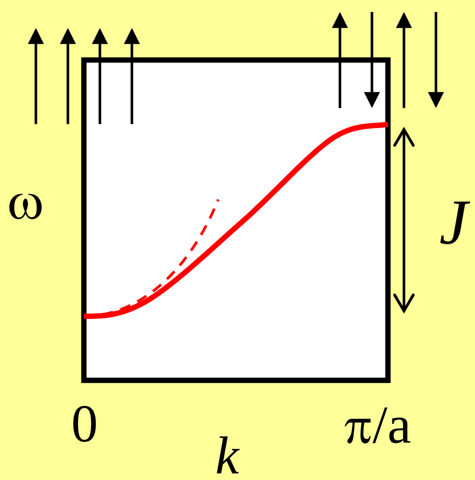
$$k = n\frac{\pi}{L}$$



Spin Waves - Exchange driven



$$-J\vec{S}_i \cdot \vec{S}_j$$



$$D = 2JSa^2$$

$$\approx 1\,\mathrm{eVA}^2$$

Using:

$$\vec{M} = \vec{M}_0 + \delta\vec{M} \cdot e^{i(\vec{k}\cdot\vec{r}-\omega t)}$$

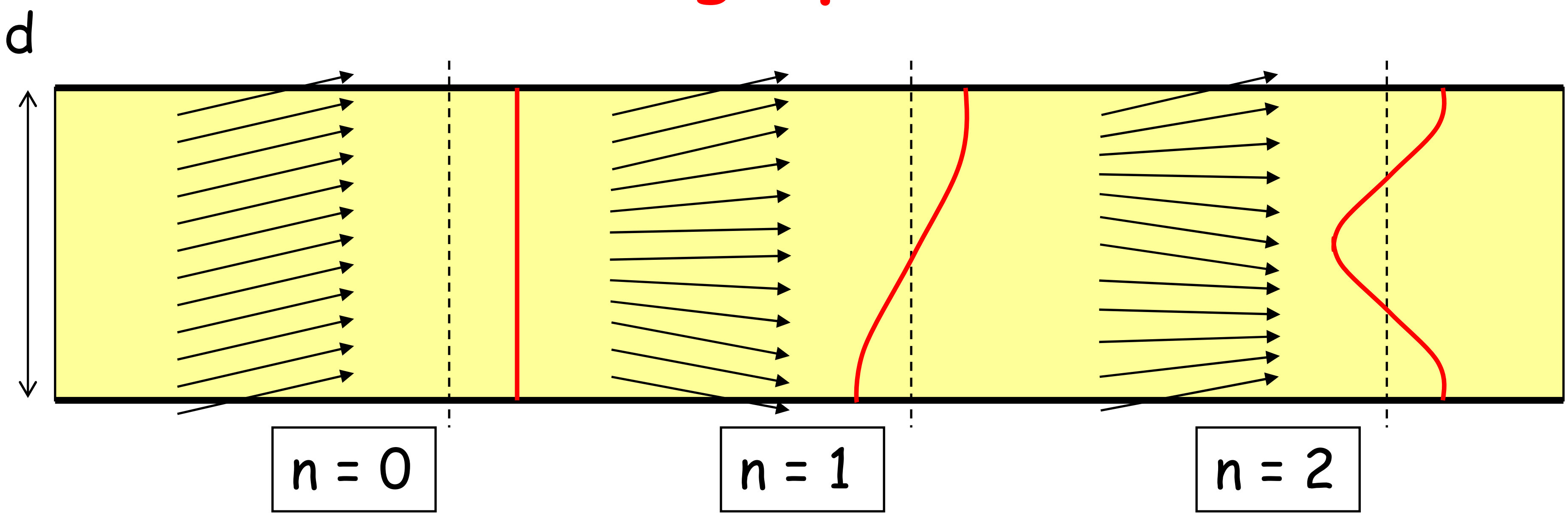
$$\vec{H}_{eff} = \vec{H}_{appl} + \frac{D}{M}\nabla^2\vec{M} = \vec{H}_{appl} + Dk^2\frac{\delta\vec{M}}{M}$$

we find:

$$\omega = \gamma\mu_0\sqrt{\left(H + Dk^2\right)\left(H + Dk^2 + \mu_0^{-1}M_s\right)}$$

i.e., mode <u>stiffening</u>, <u>independent</u> of <u>direction</u> of wave vector

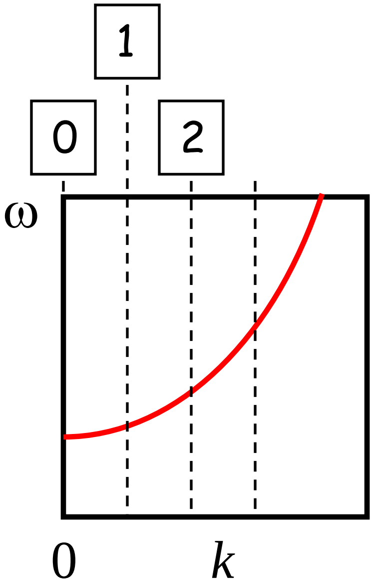
Standing Spin Waves



Free surface:

$$\left.\frac{d\delta\vec{M}}{dz}\right|_{\text{int}} = 0$$

$$\omega = \omega_0 + D\left(\frac{n\pi}{d}\right)^2$$

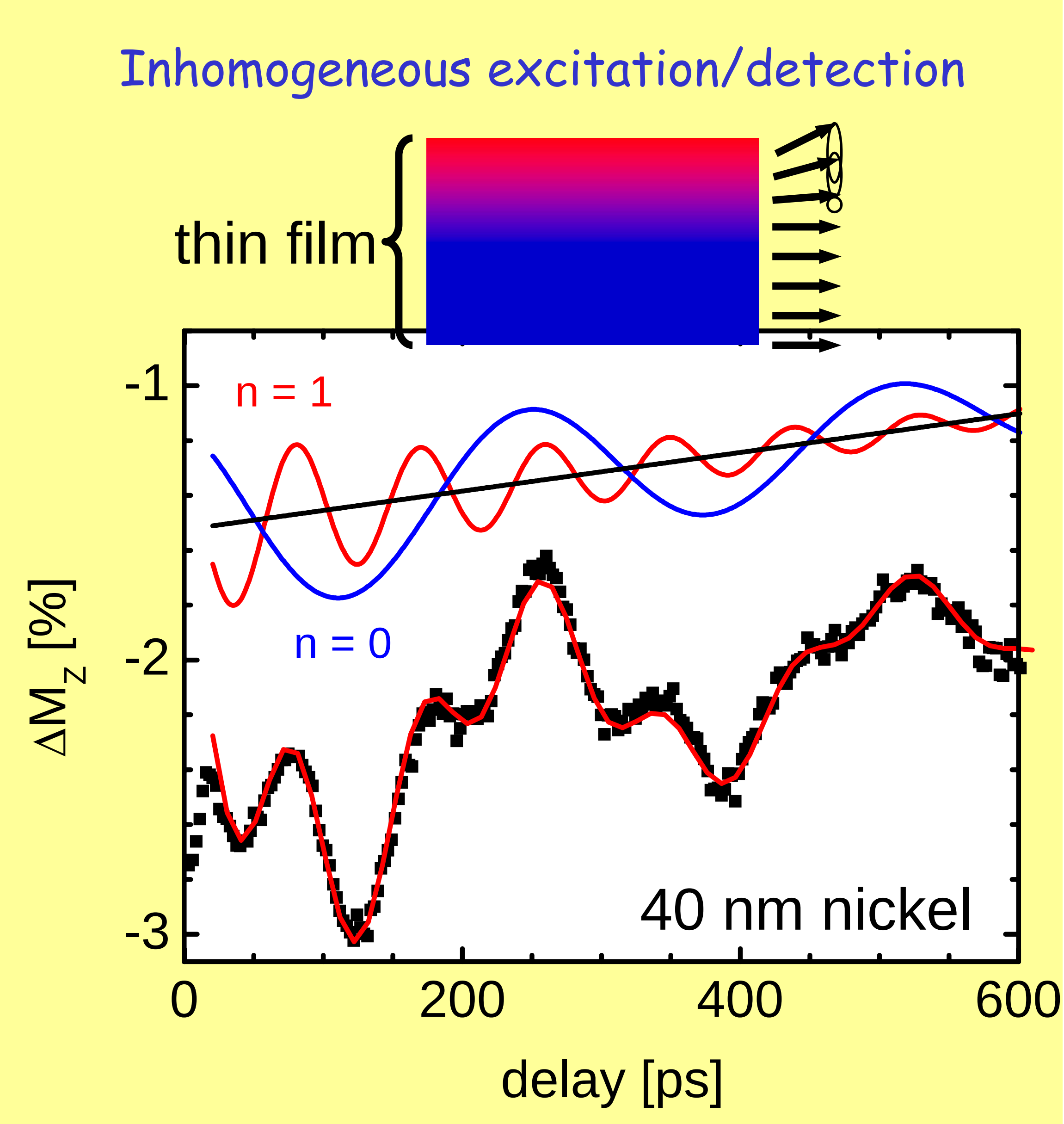


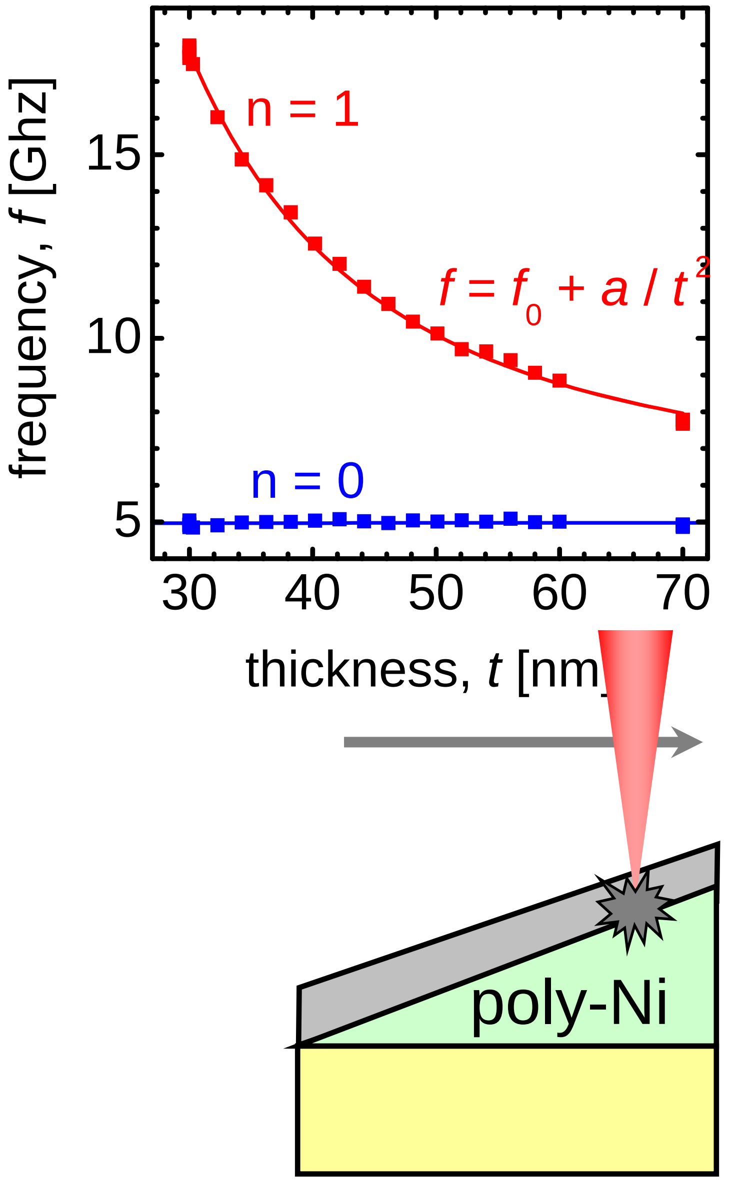
General:

$$\left.\frac{d\delta\vec{M}}{dz}\right|_{\text{int}} + \frac{K_s}{D}\left.\delta\vec{M}\right|_{\text{int}} = 0$$

$$\omega = \omega_0 + D\left(\frac{(n+\phi)\pi}{d}\right)^2$$

All-Optically Probing Standing Spin-Waves





Optically Probing Spin Waves: Analysis

Observed:

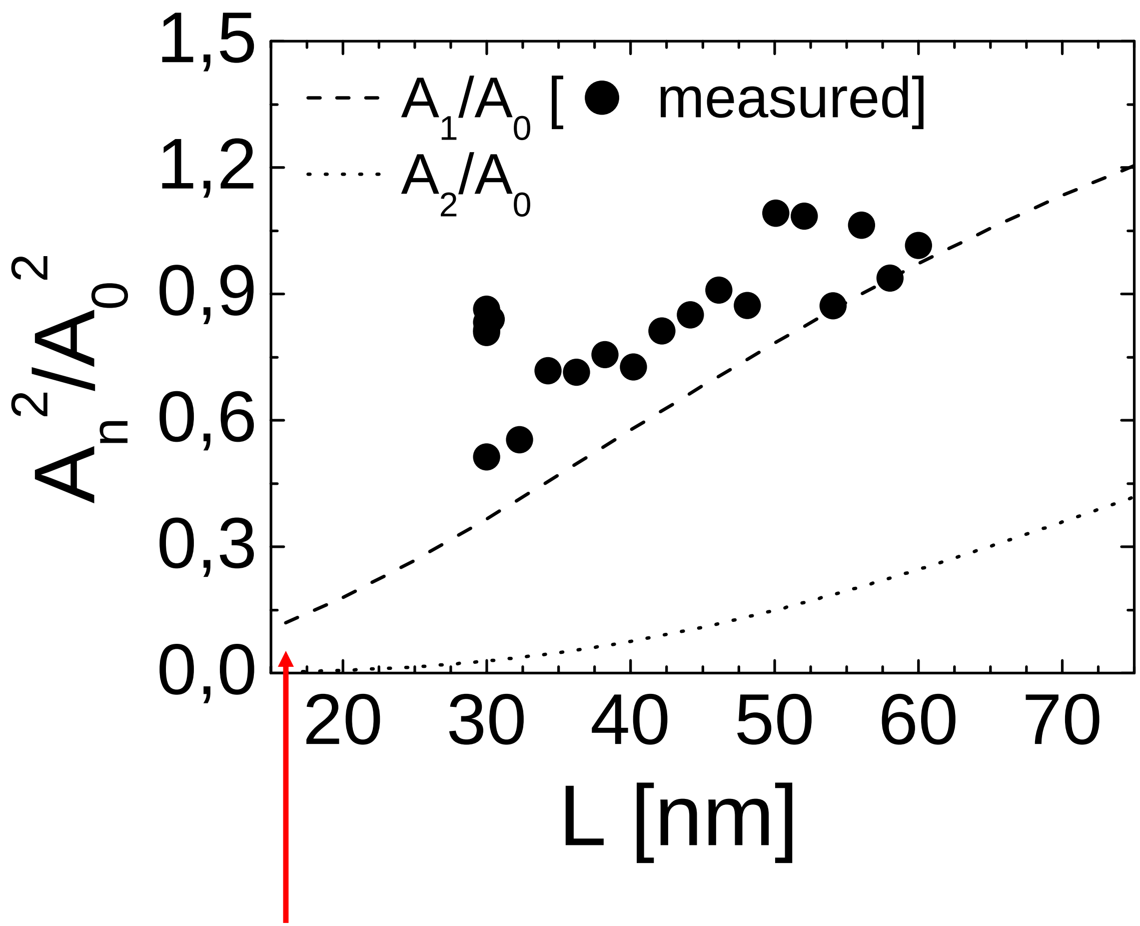
$$\omega = \omega_0 + Dk^2$$

Conclusions:

Boundary conditions: Free surface

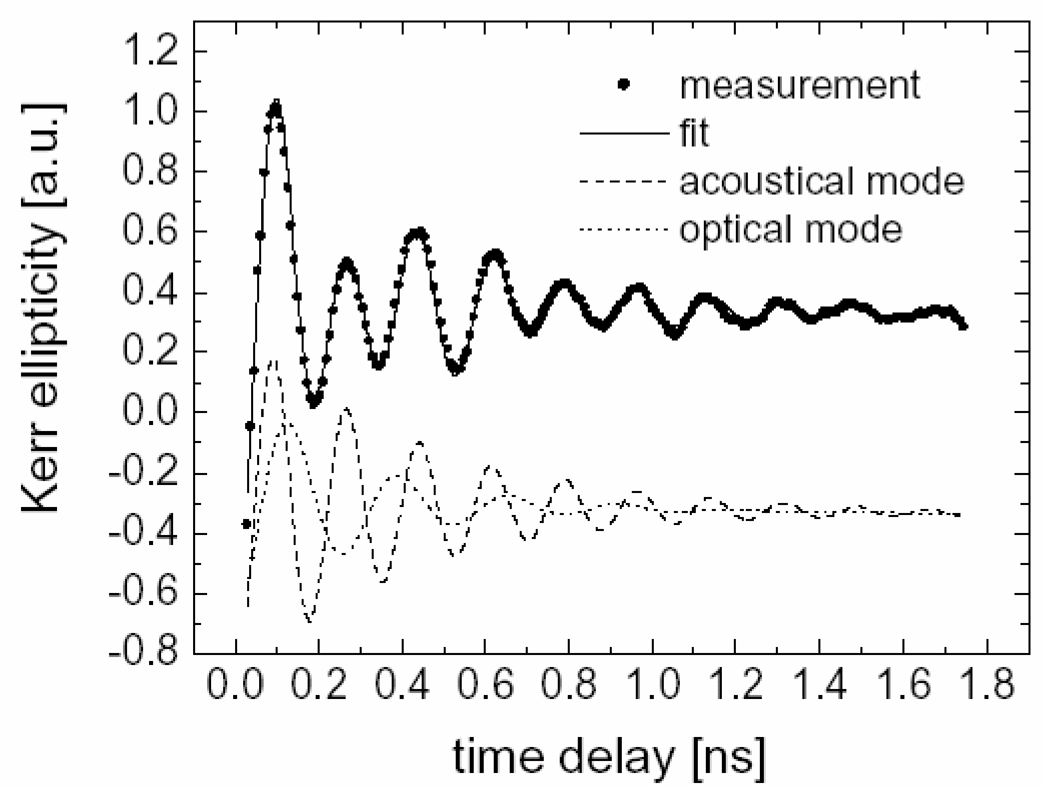
D = 0.44 eVA^2 (as wexpected)

And the amplitudes… (why no n = 2?)

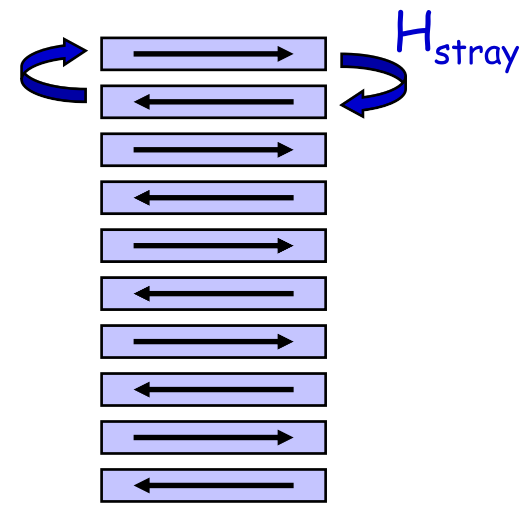


Laser extinction depth ~ 15 nm

Artificial Spin-Chains: Basic Results

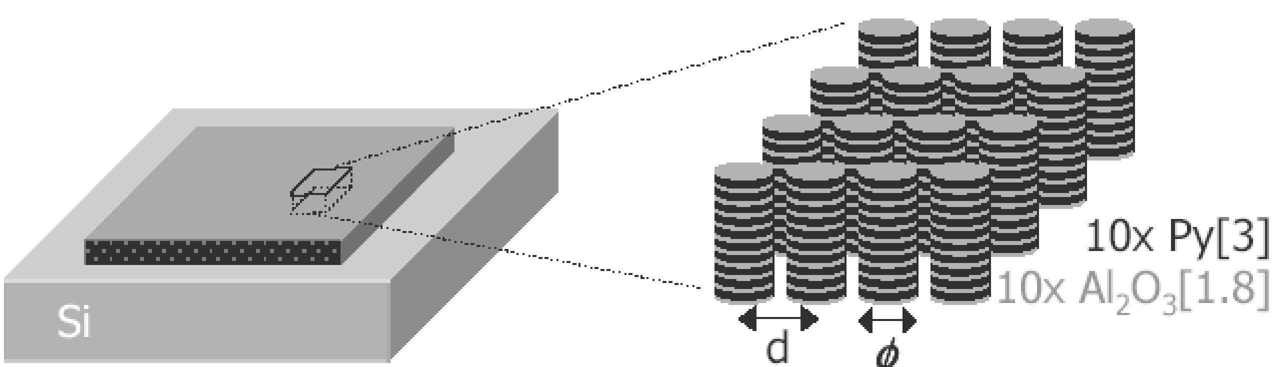


300 nm pillars

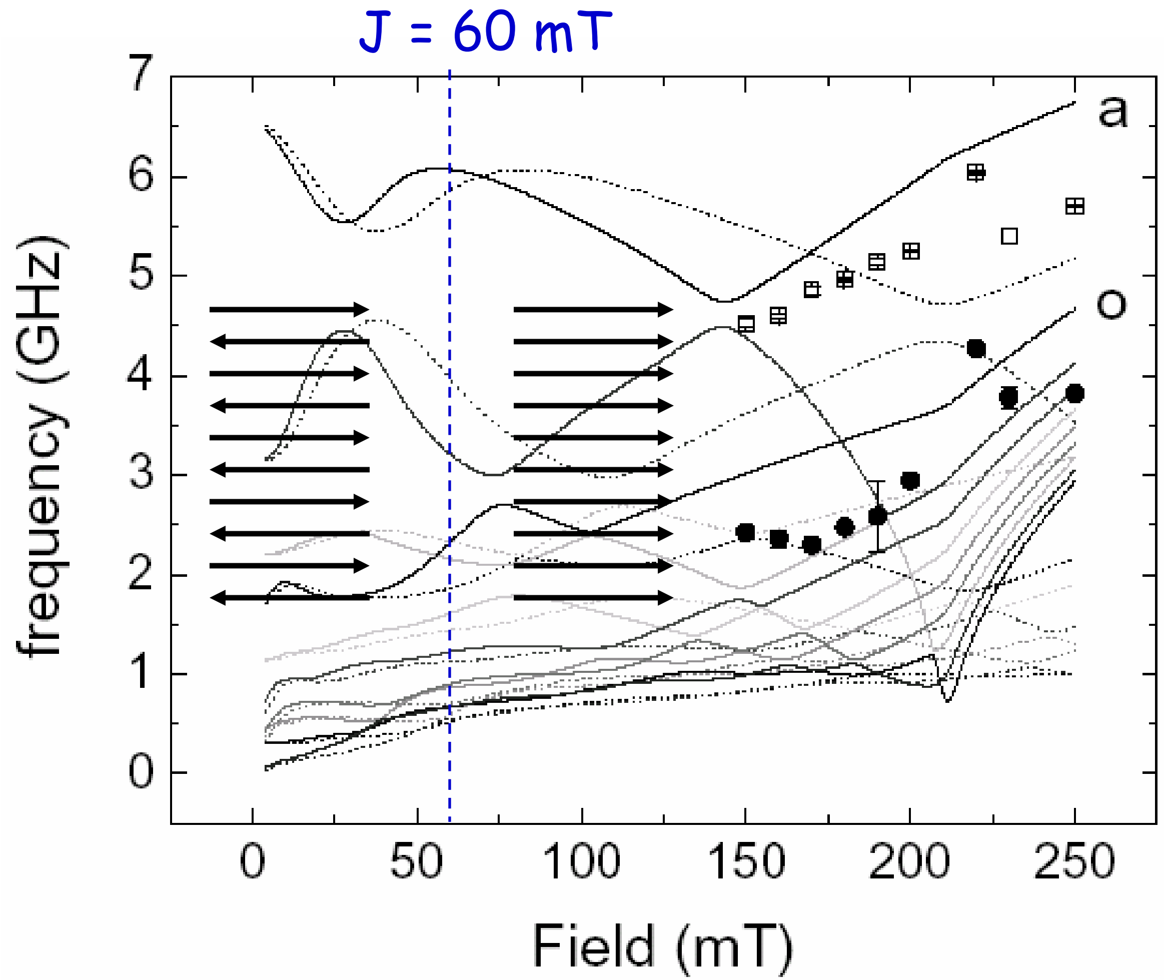


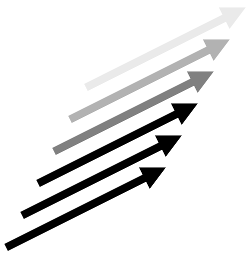
1d-Heisenberg system

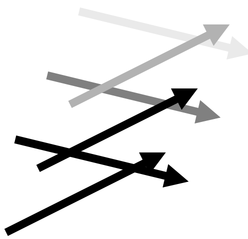
$$H = -J\vec{S}_i \cdot \vec{S}_{i+1}$$



Artificial Spin Chains: Analysis





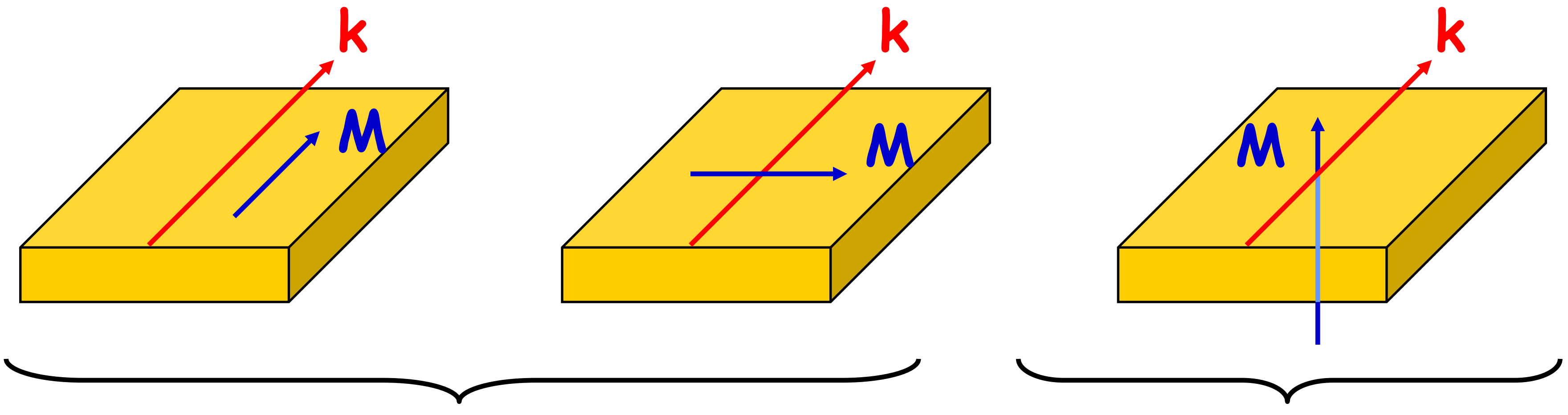


Surprising! Mode with more nodes has lower frequency...
Negative dispersion...

Yes! System likes to be in anti-phase...

Spin waves - Dipole driven

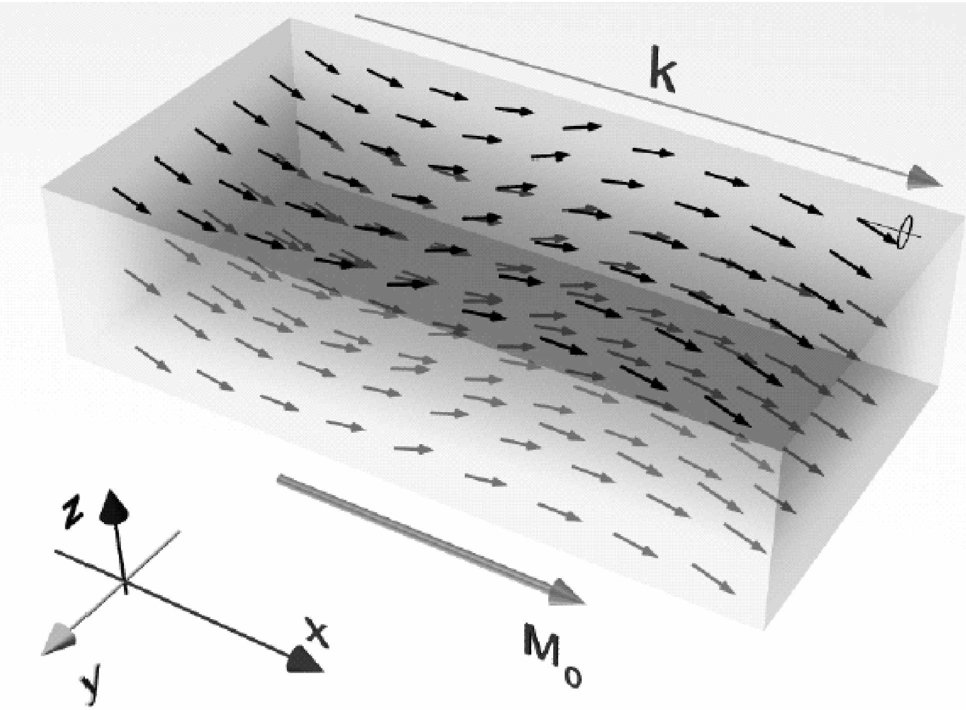
Three sorts

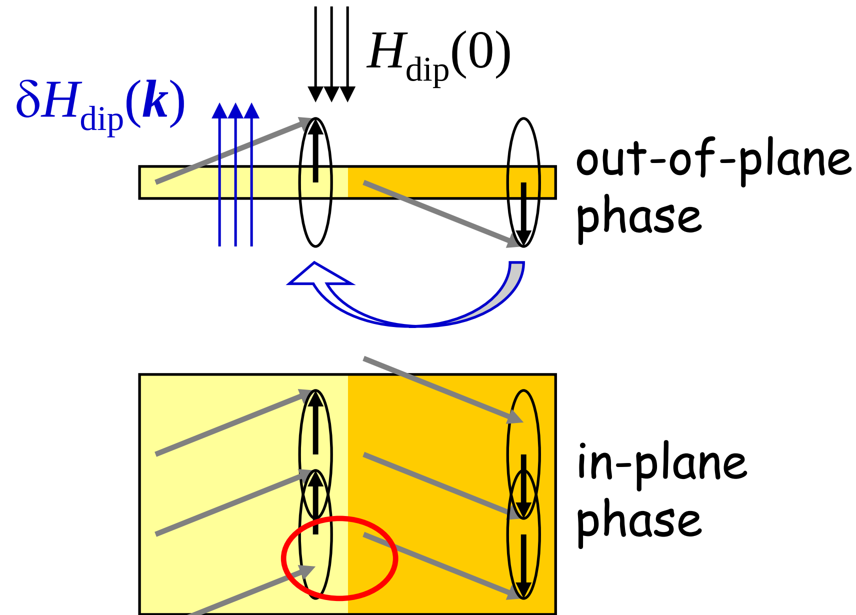


$$\omega = \gamma\mu_0\sqrt{H\left(H + \mu_0^{-1}M_s\right)}$$

$$\omega = \gamma\mu_0 H$$

Magnetostatic Backward Volume Mode



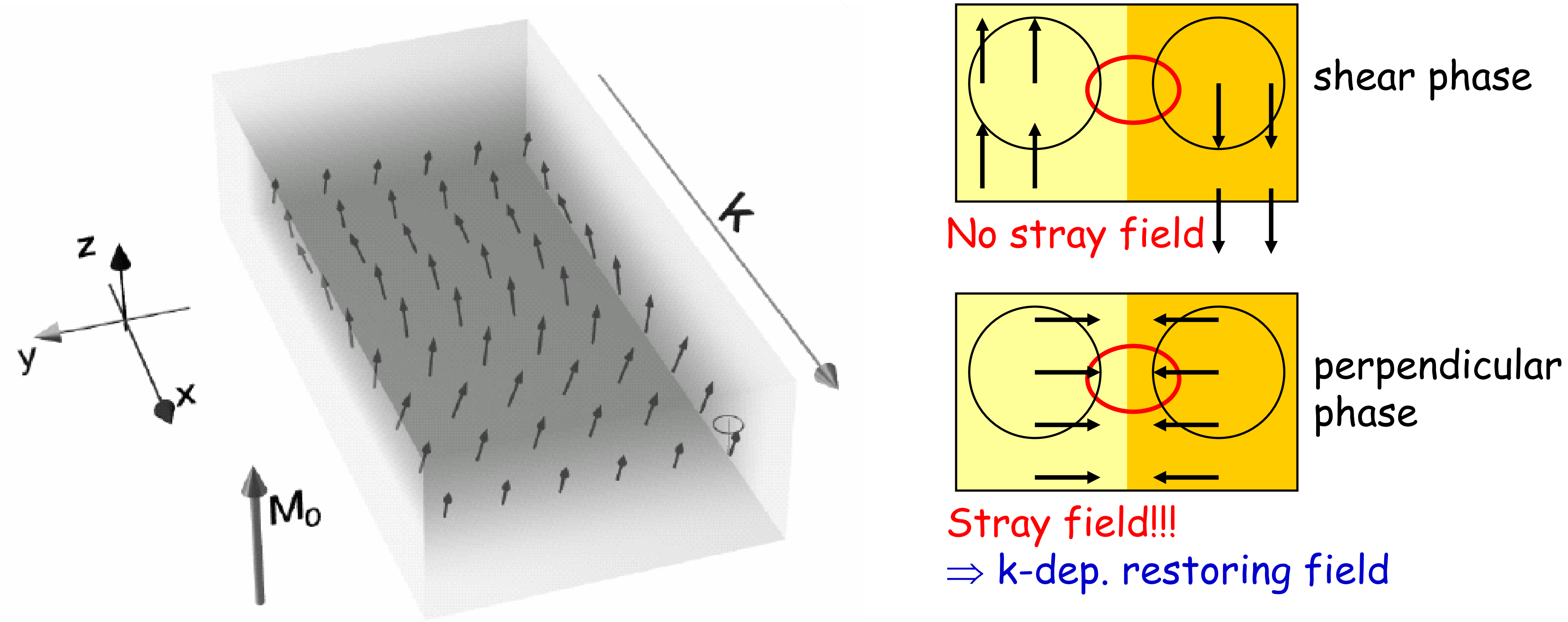


- Just replace: $\mu_0^{-1} M_s \rightarrow \mu_0^{-1} M_s - kd \cdot A_{MBVM}$

then: $\omega = \gamma \mu_0 \sqrt{H\left(H + \mu_0^{-1} M_s - kd \cdot A_{MBVM}\right)}$

- Limit of $kd >> 1$: $\omega = \gamma \mu_0 H$

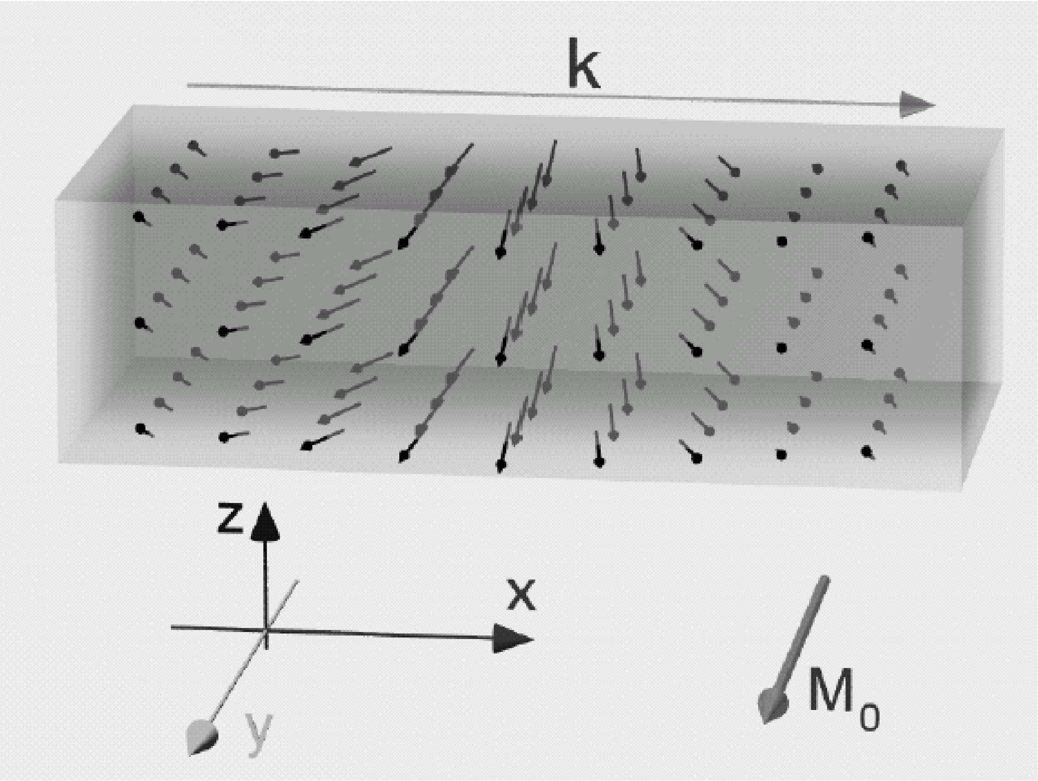
Magnetostatic Forward Volume Mode

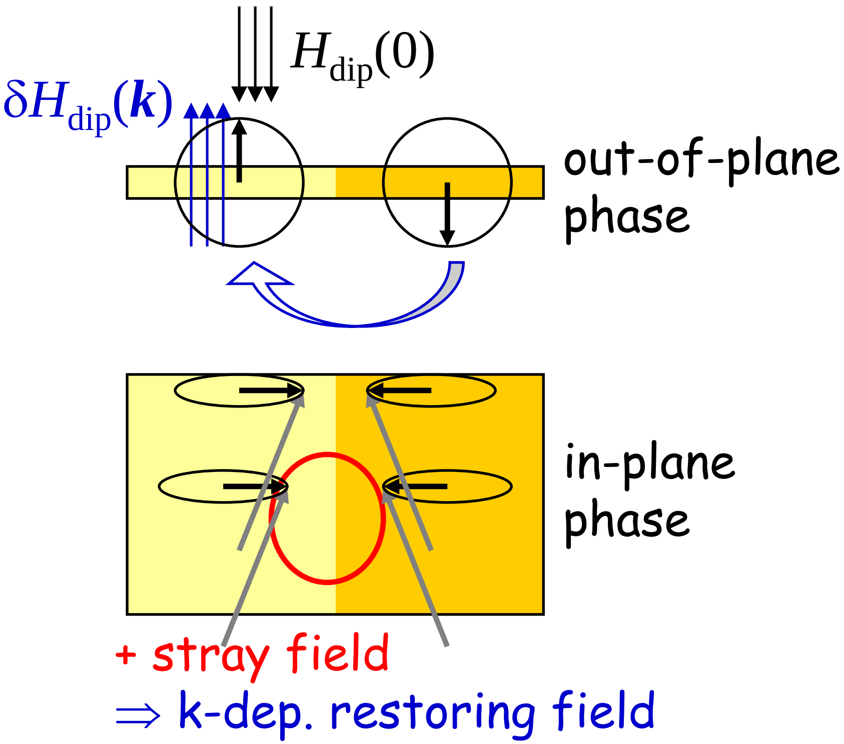


- Now we get a stiffening, rather than a softening!

- Limit of $kd >> 1$: $$\omega = \gamma\mu_0\sqrt{H\left(H + \mu_0^{-1}M_s\right)}$$

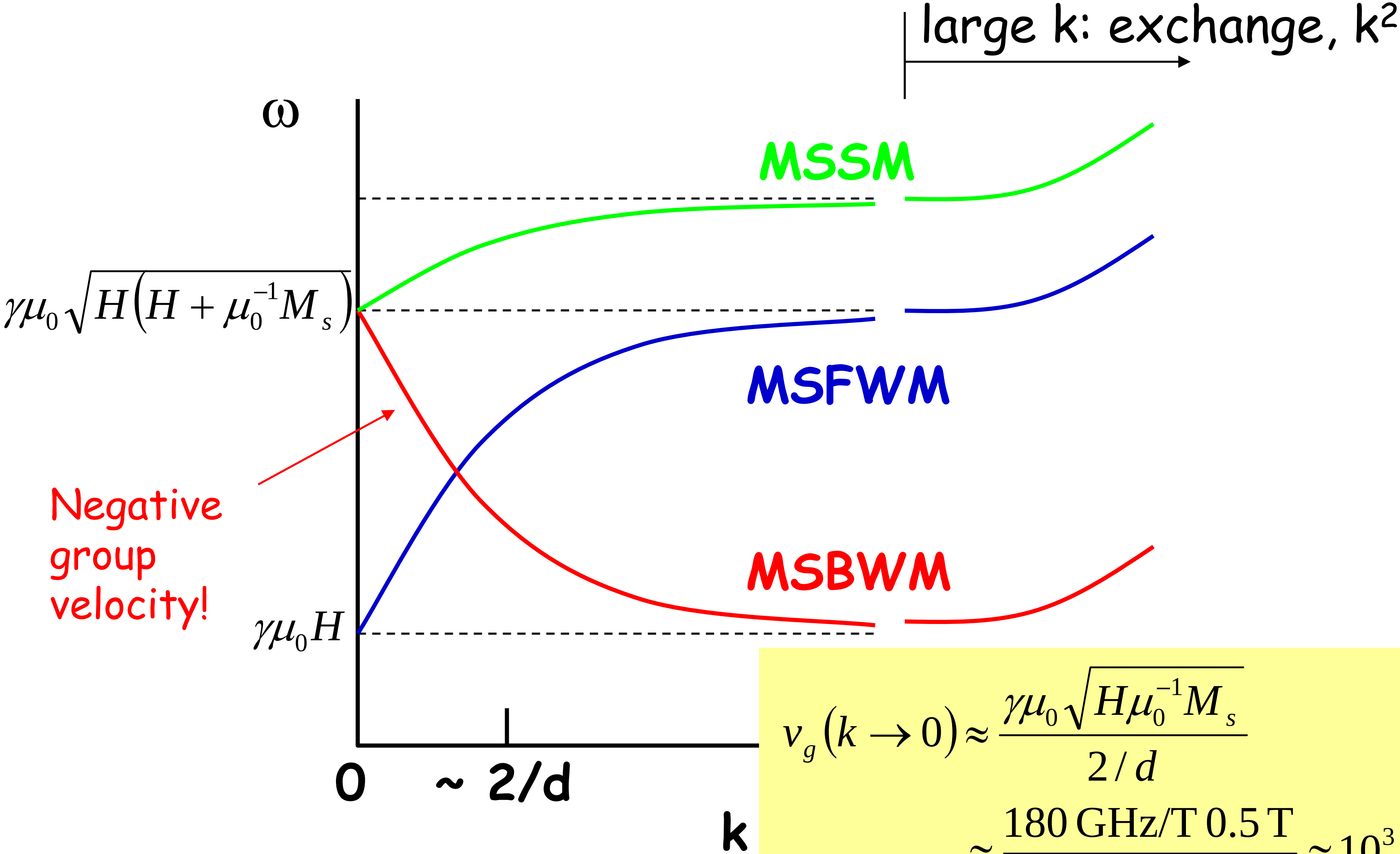
Magnetostatic surface mode (Damon-Eshbach)





- Now it gets complicated:
  - Softening during out-of-plane phase
  - Hardening during in-plane phase
- The latter is known to win...

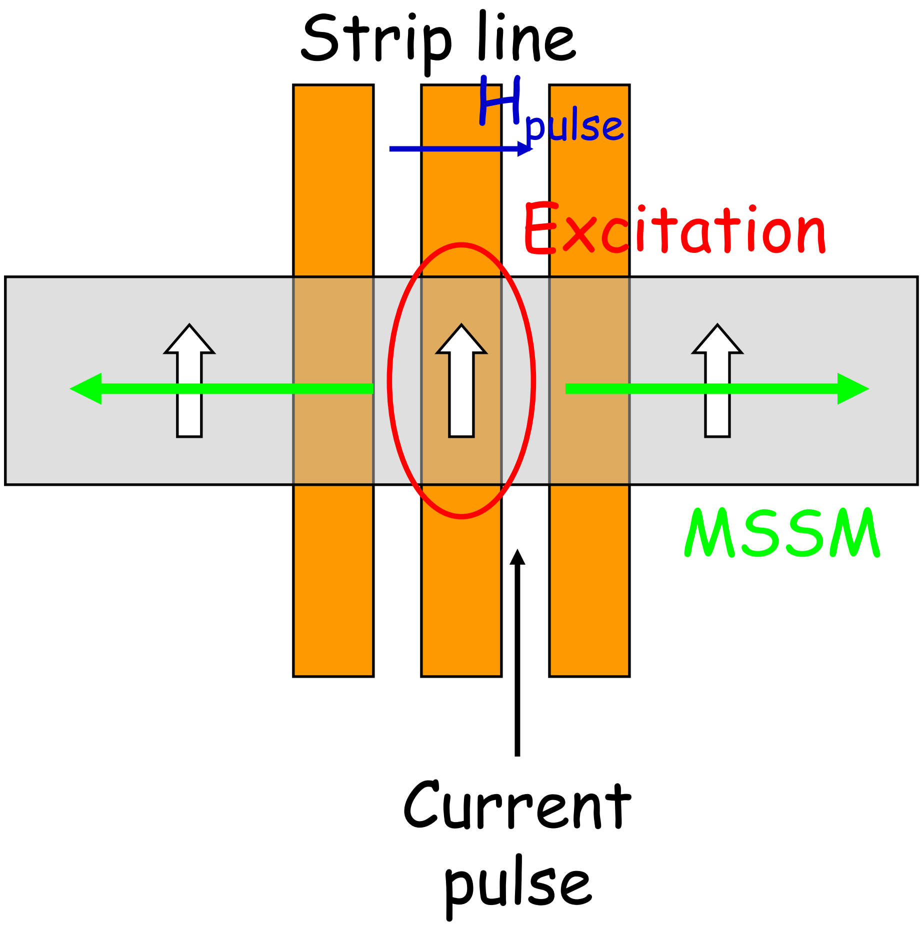
Dipolar modes - Summary

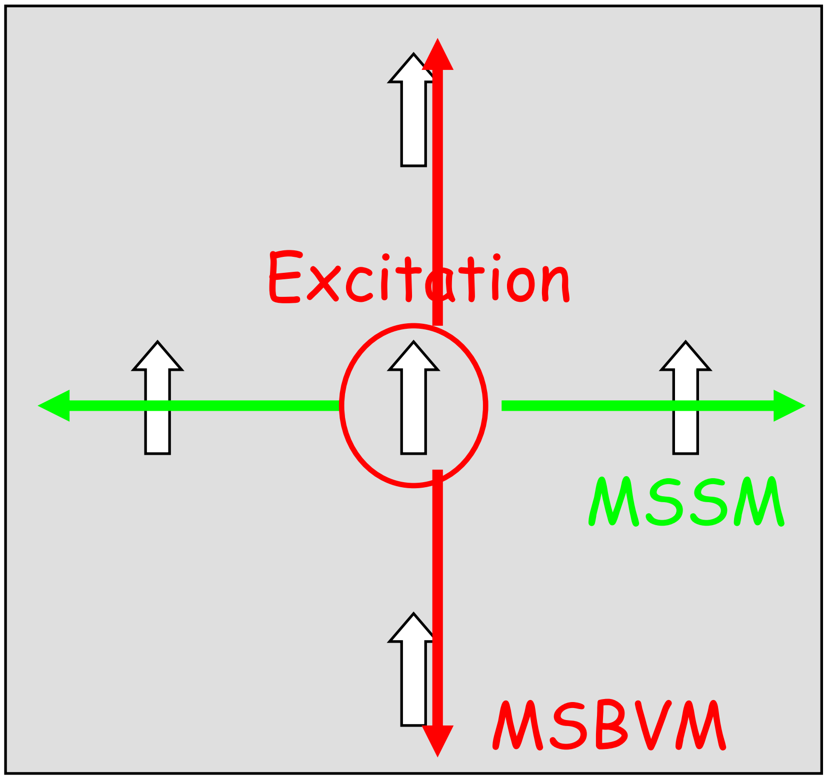


$$v_g(k\to 0)\approx\frac{\gamma\mu_0\sqrt{H\mu_0^{-1}M_s}}{2/d}$$

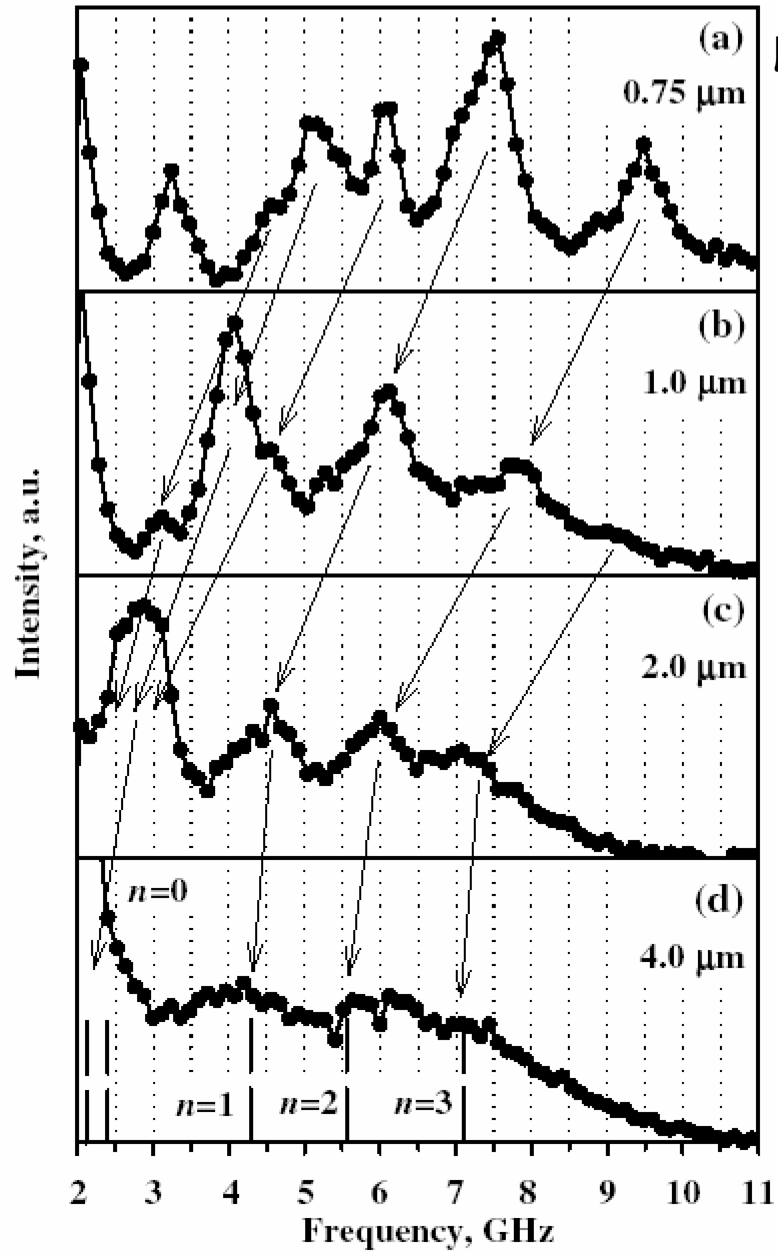
$$\approx\frac{180\,\mathrm{GHz/T}\;0.5\,\mathrm{T}}{1/10\,\mathrm{nm}}\approx 10^3\ \mathrm{m/s}$$

Damping by Emission of Spin Waves



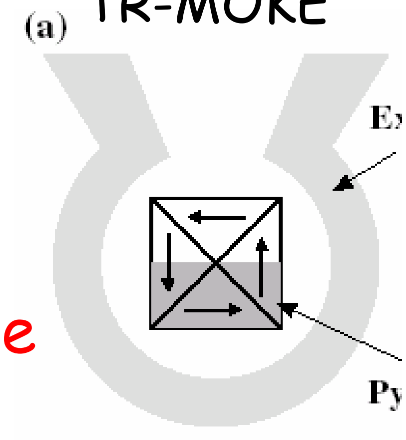


Observation of localized modes



μ-BLS

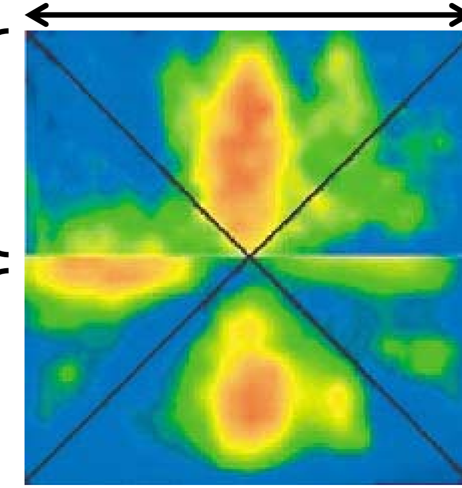
TR-MOKE



Vortex state

4 μm

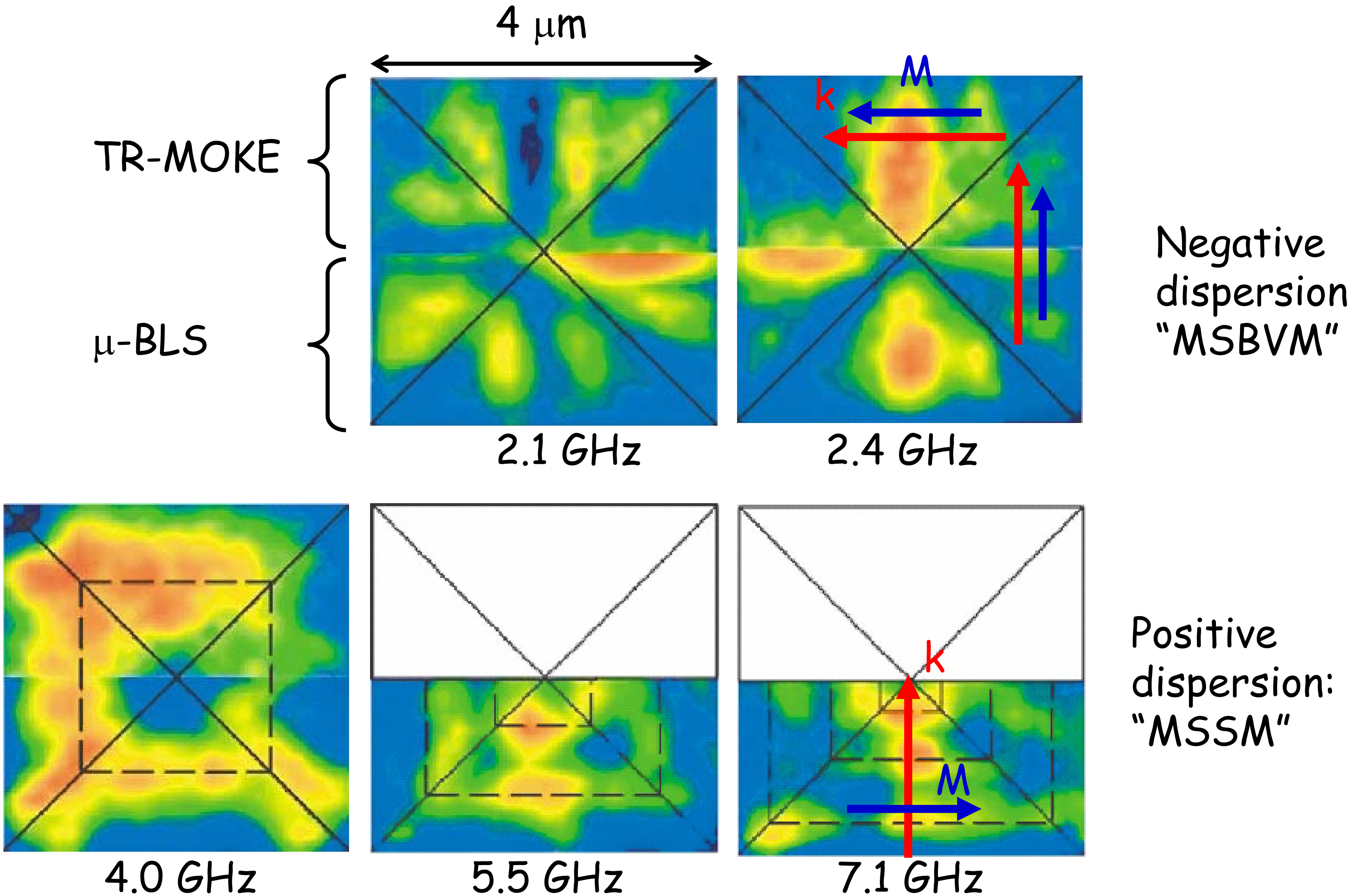
TR-MOKE



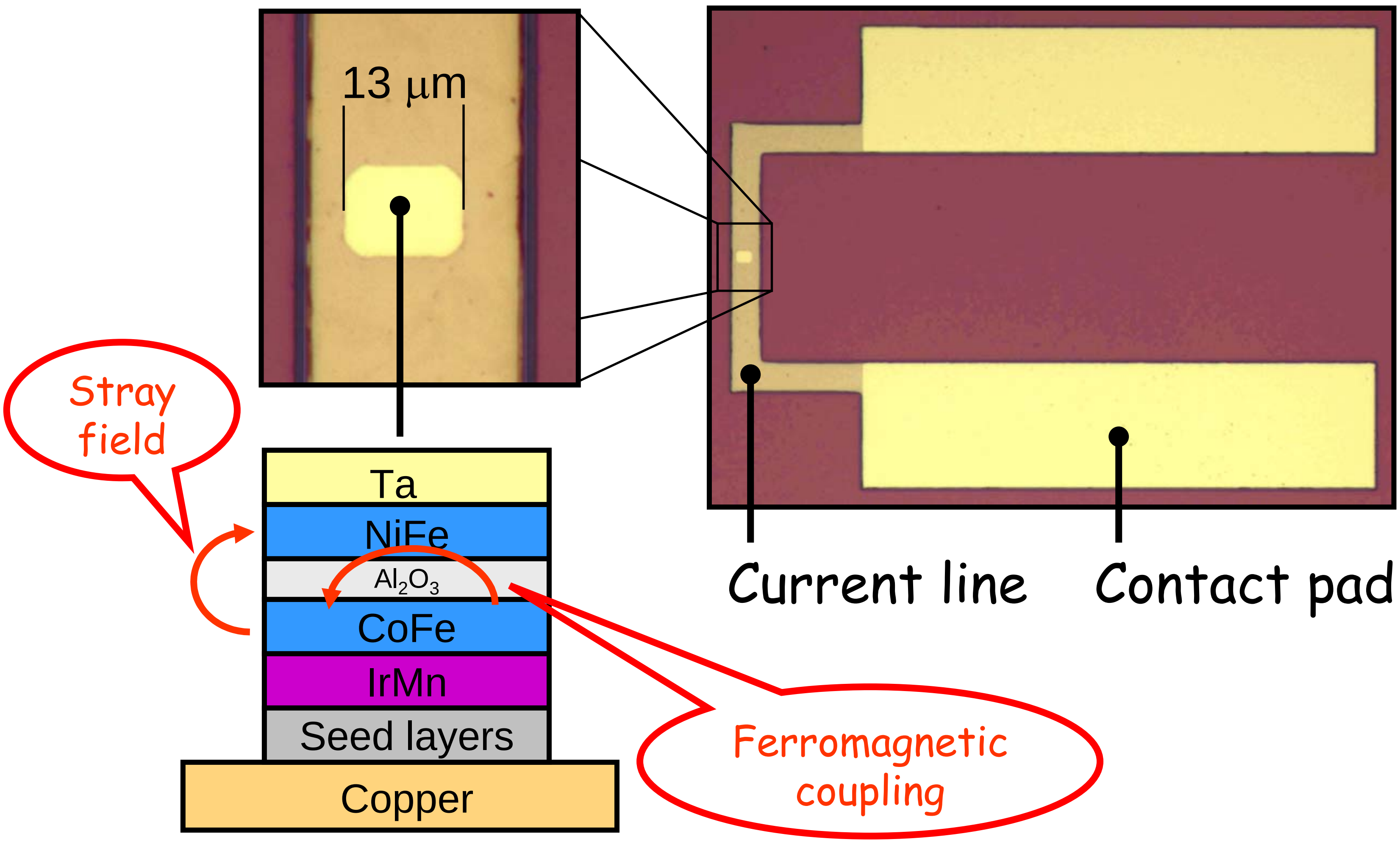
μ-BLS

Perzlmaier, PRL **94**, 057202 (2005)

Link with lateral spin waves



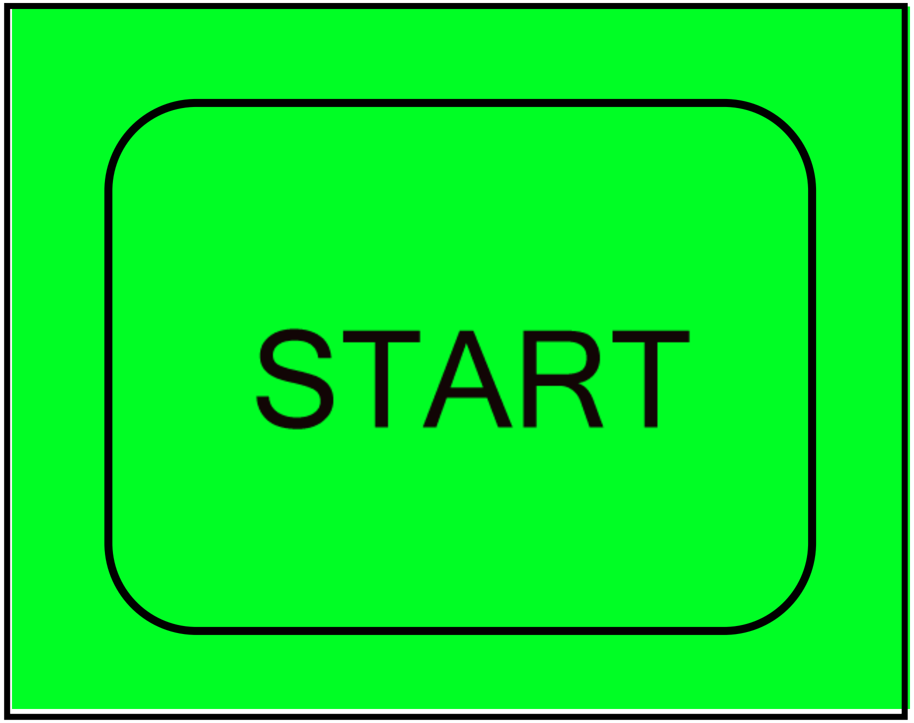
Dynamics of Real Devices

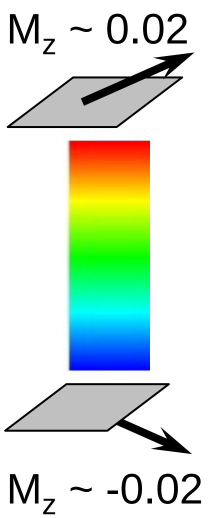


Rietjens (TU/e) – Boeve (Philips Research) et al., APL submitted

Dephasing after homogeneous excitation

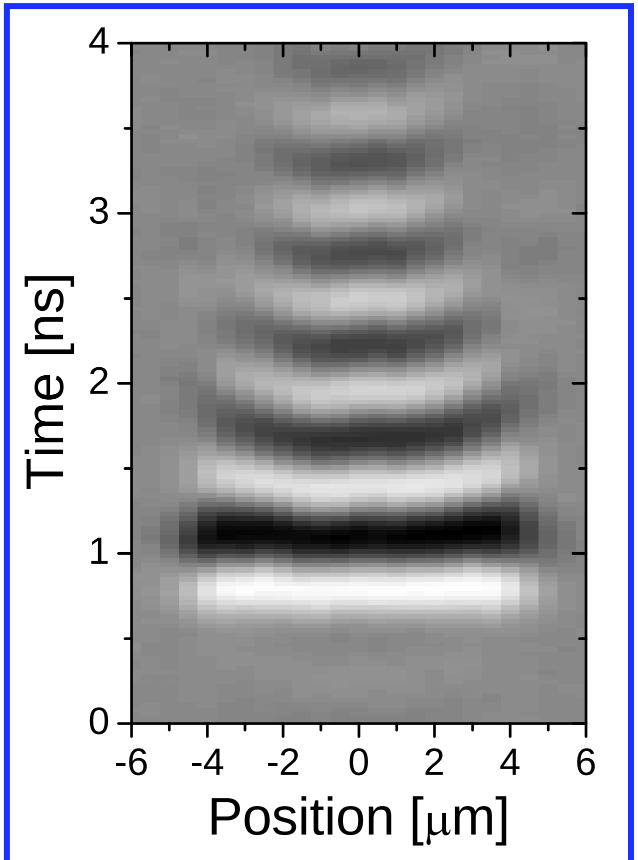
Raster scans at fixed time delay (50 ps steps)



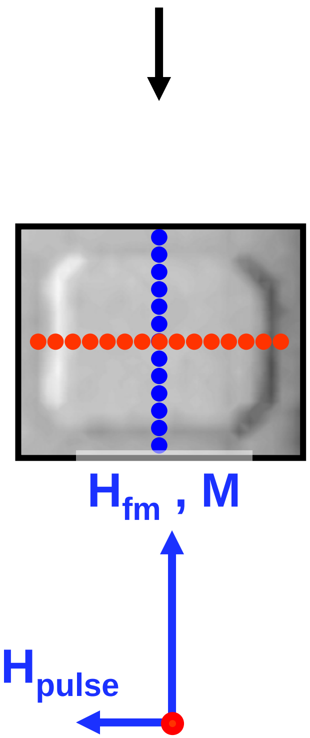


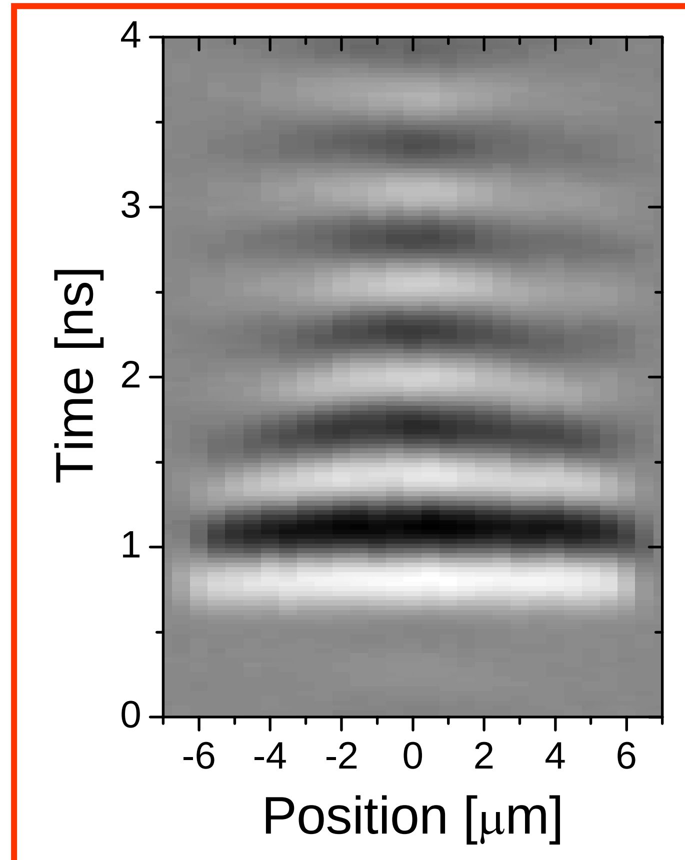
Different frequency and damping at edges

Results: Time domain



Positions of time scans





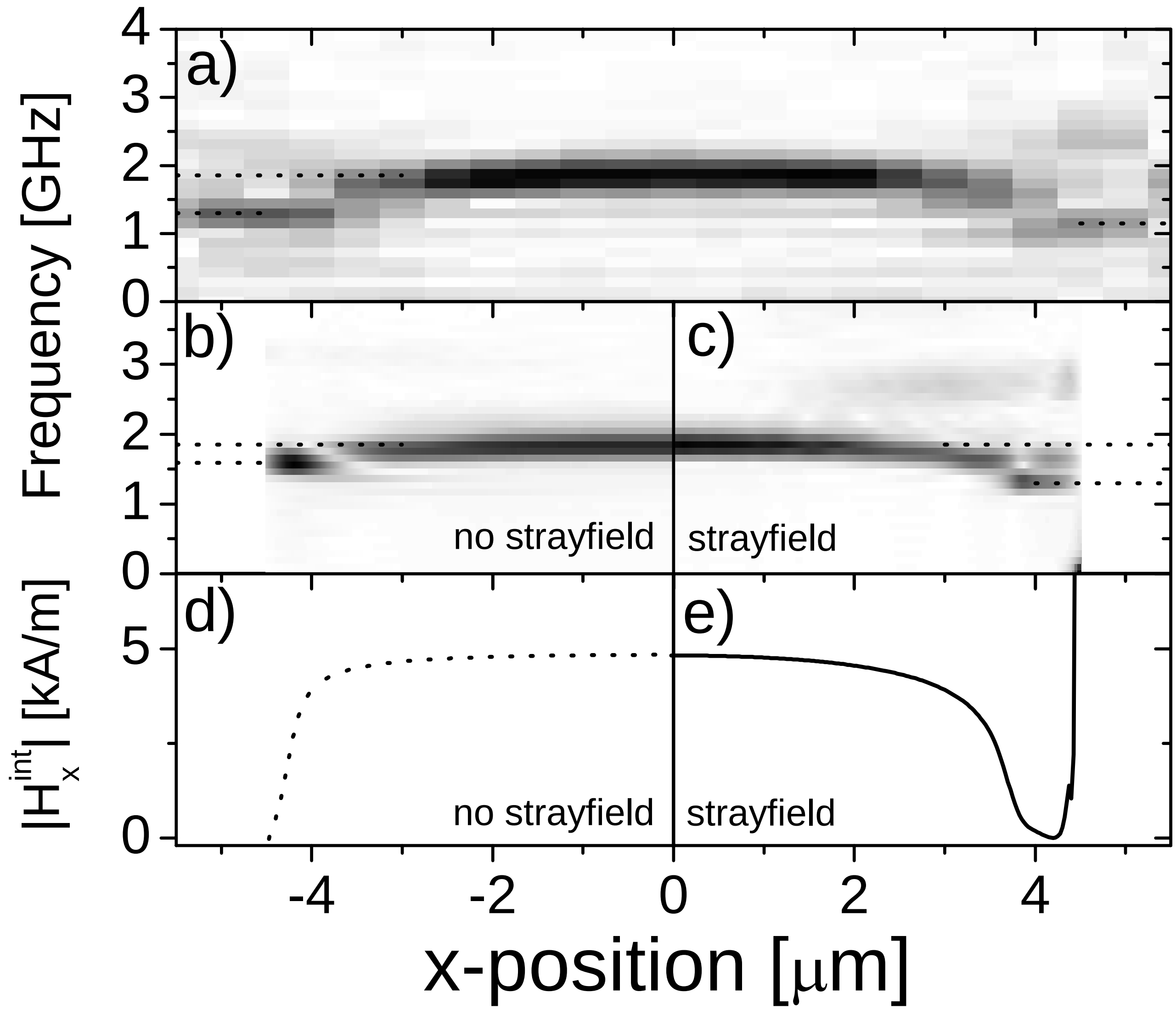
Lower frequency, higher damping

EDGES

Same frequency, higher damping

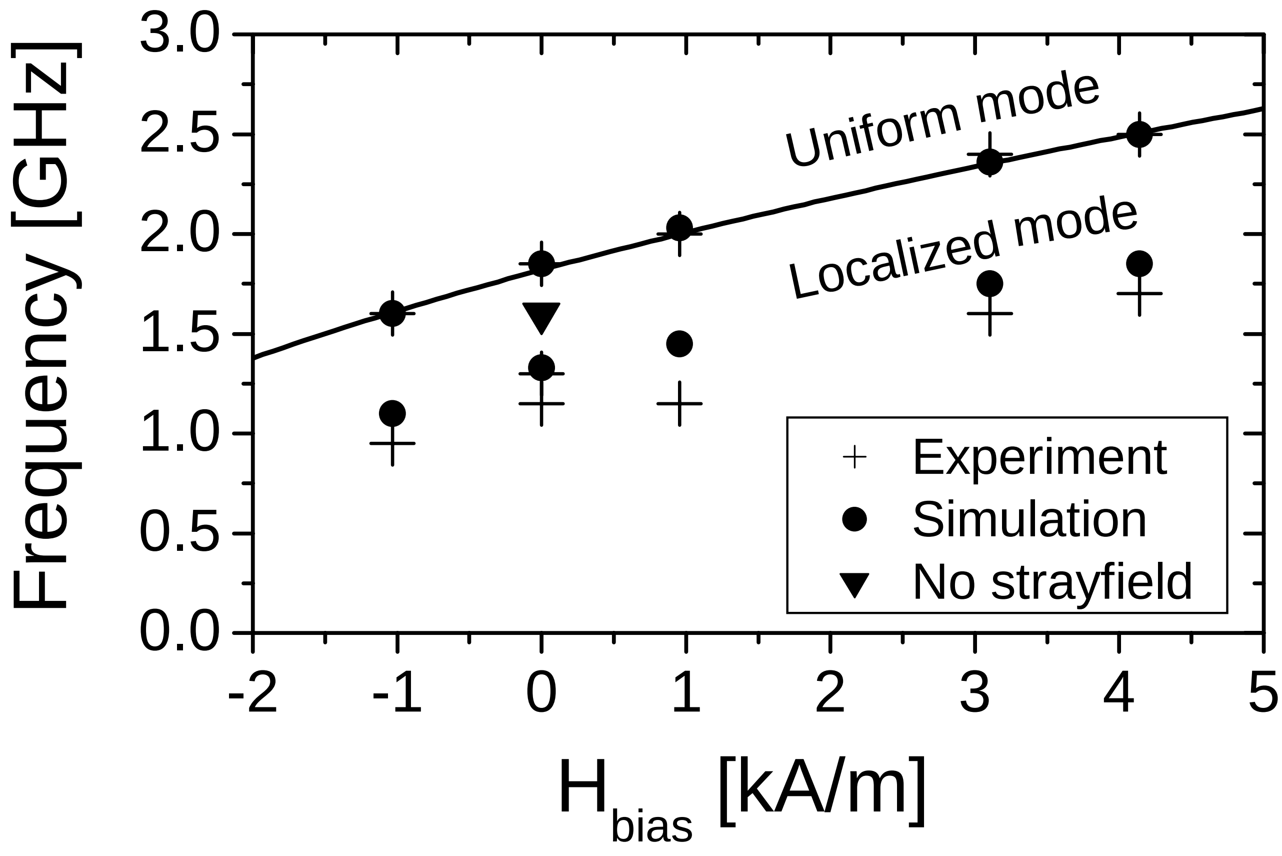
Results: Frequency domain

Comparing simulations with experiment



Final analysis

Bias field dependence of uniform and localized mode



Summary

Local dynamics: "Macro-spin"

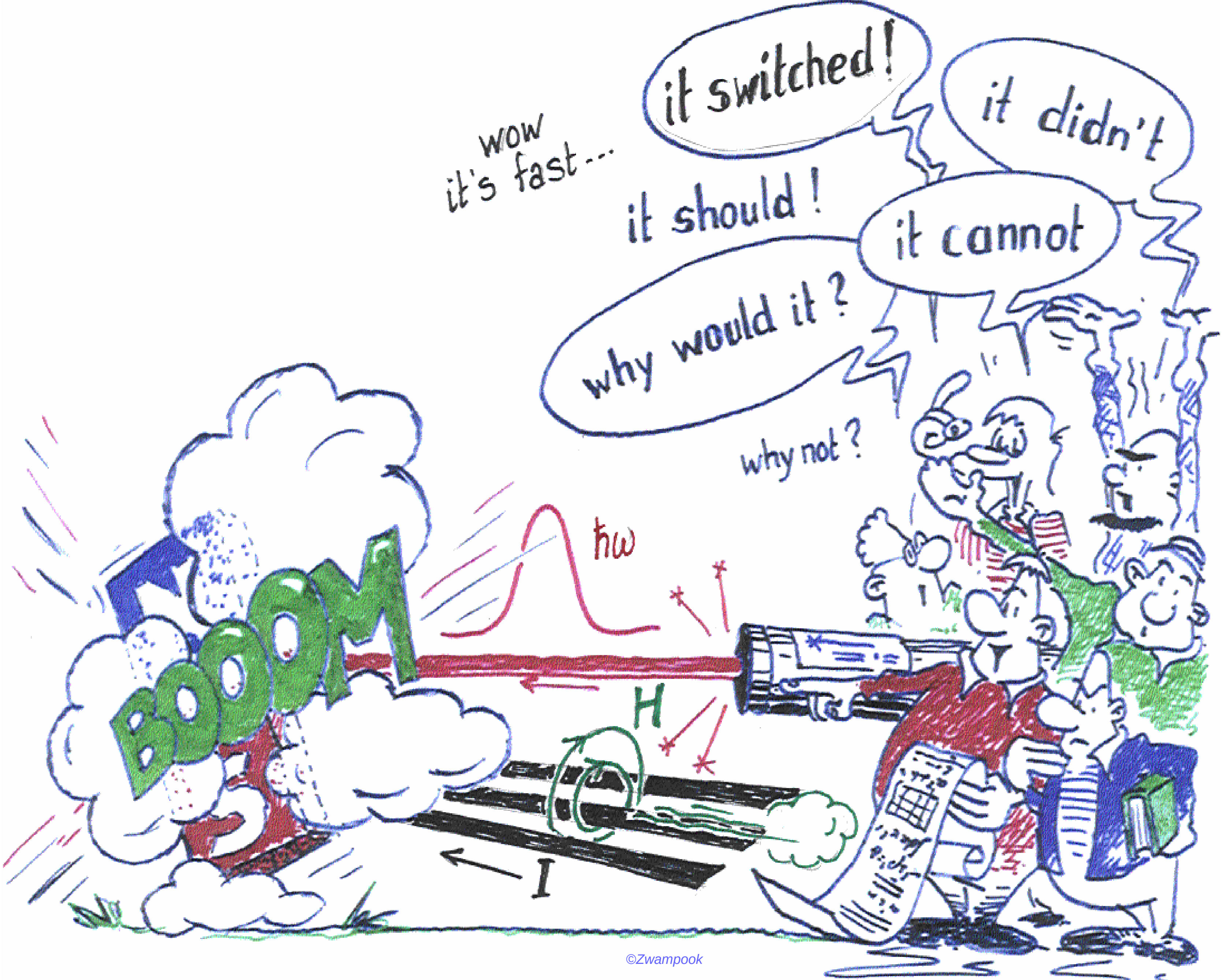
- LLG equation
- Kittel relation for thin films
- Precessional Switching

Measuring precessional dynamics

- In the f- and t-domain (including "all-optical")

Nonlocal dynamics: Spin waves and confined structure

- Exchange modes
- Dipolar modes (positive and negative dispersions!)
- Manifestation in confined structures
- Complicated dynamics in "real" devices


wow
it's fast...
it switched!
it didn't
it should!
it cannot
why would it?
why not?
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H
I
BOOOM
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