Light-induced (de)magnetization processes and all-optical switching

THE EUROPEAN SCHOOL ON MAGNETISM

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FERROLAB

Experimental approaches

How one gets a time resolution

How one measures ultrafast magnetization dynamics

Laser-induced demagnetization

Experimental observation

Theories

Laser-induced changes of magnetic anisotropy

Through demagnetization

Through lattice heating

Through strain

Ultrafast opto-magnetic effects

Opto-magnetic effects and Impulsive stimulated Raman scattering

Control of magnetization via opto-magnetic effects

Laser-driven spin transport

Experimental approaches

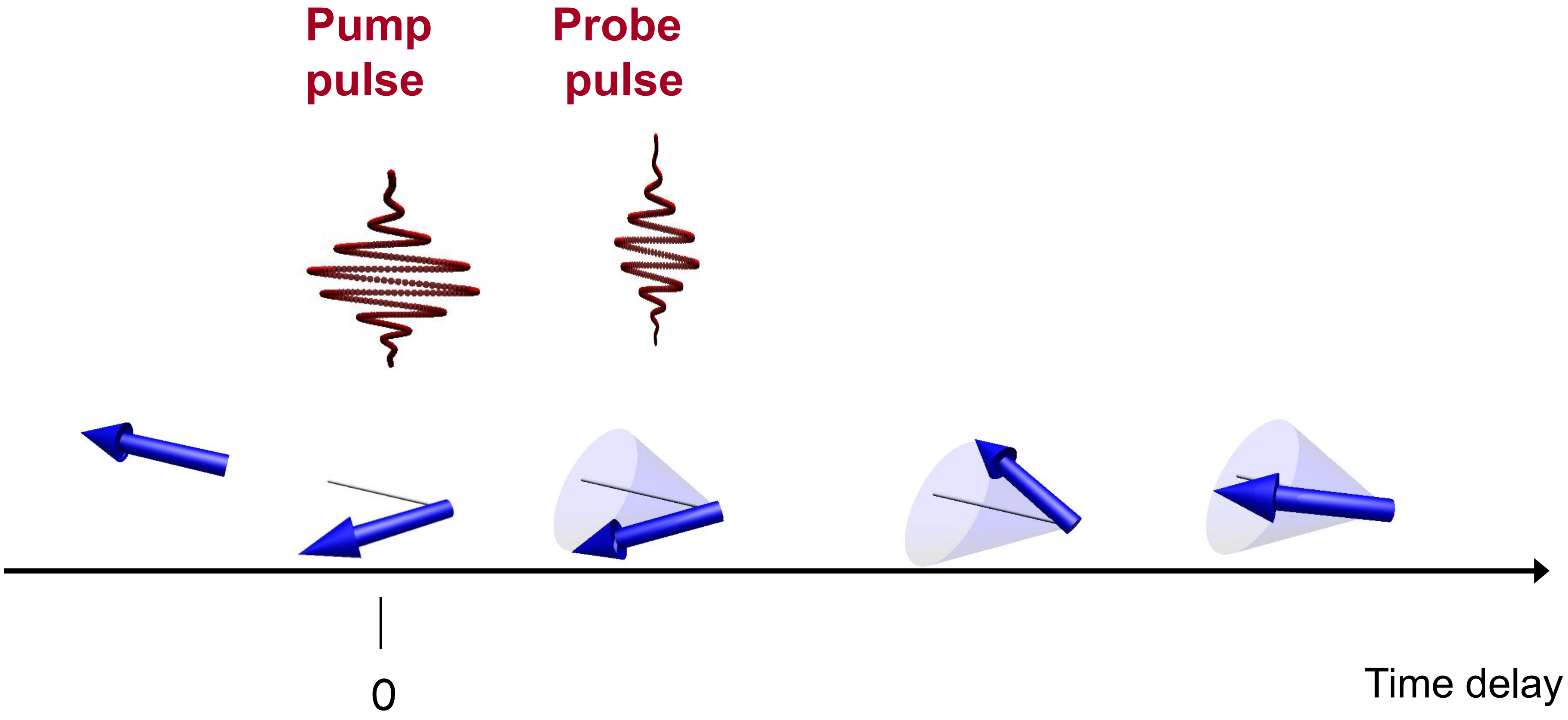
How does one get a time resolution?

How does one measure an ultrafast magnetization dynamics?

Experimental approaches

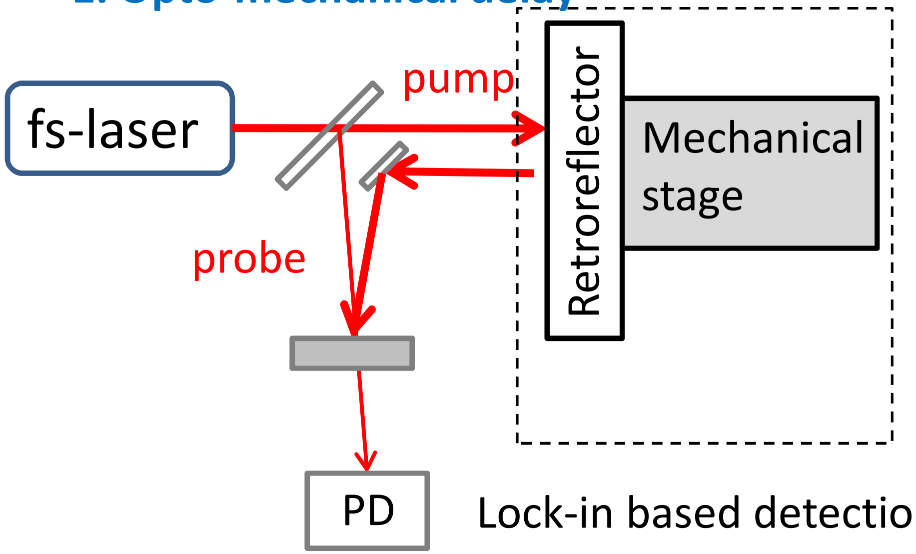
How to realize pump-probe delays?

What to measure?



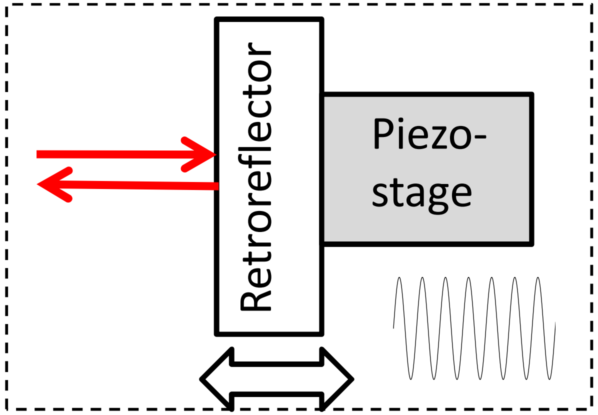
Pump-probe delays

1. Opto-mechanical delay



Lock-in based detection

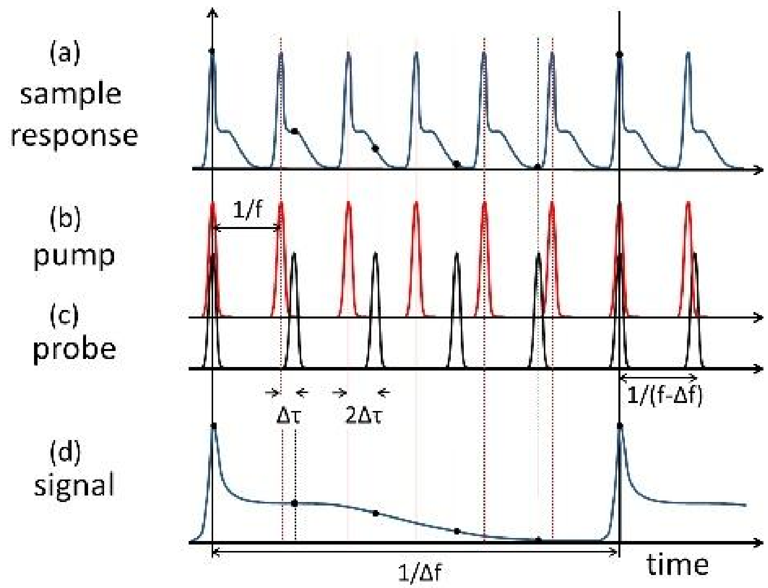
2. Opto-mechanical shaker



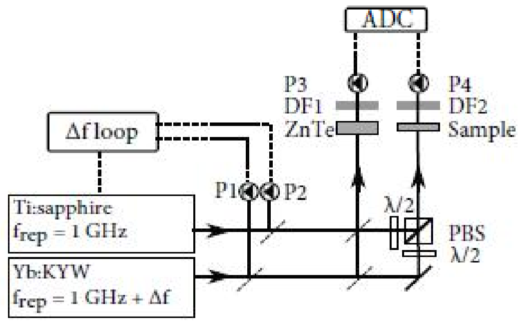
Ultrafast delays window
upto 150 ps

Fast oscilloscope

3. Asynchronous optical sampling systems (ASOPS)



[from Physicsworld.com]



[Krauß et al., Opt. Extpress 23, 18288 (2015)]

An example: f=1 GHz Δf=20 kHz

Ultrafast delays time window 0-1 ns
is starched to the time window of 50 µs

No need for a mechanical delay line!

Detecting ultrafast magnetization dynamics

Ferromagnets

Magneto-optical Kerr and Faraday effects

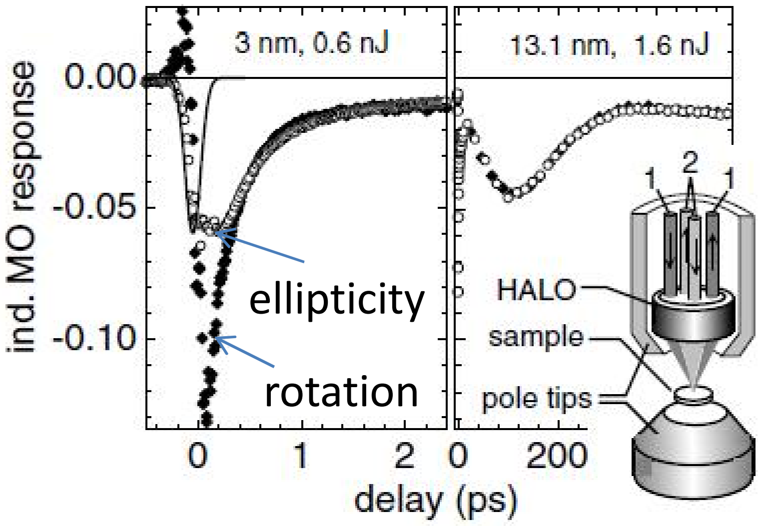
Quadratic MO effects

→ Tracing all components of magnetization

[See the lecture by Paolo VAVASSORI]

Are we sure we are detecting magnetization dynamics?

Time-resolved polar MOKE in Ni films:



[Koopmans et al., PRL 85, 844 (2000)]

MOKE rotation

$$\theta(t) \sim (\chi'_{xyz} + \delta\chi'_{xyz})(M_z + \delta M_z)$$

$$\delta\theta(t) \sim \chi'_{xyz}\,\delta M_z + \delta\chi'_{xyz}\,M_z$$

MOKE ellipticily

$$\delta\epsilon(t) \sim \chi''_{xyz}\,\delta M_z + \delta\chi''_{xyz}\,M_z$$

Magnetization dynamics ☺

Electronic, lattice dynamics ☹

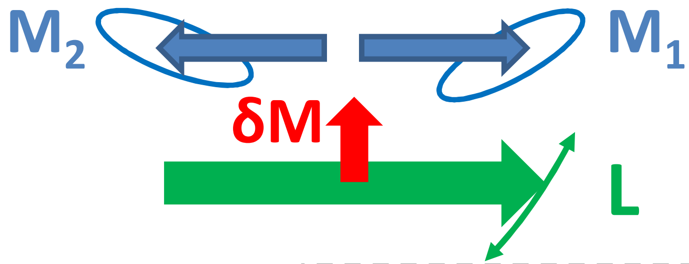
Measuring two MO effects is a good idea!

Detecting ultrafast magnetization dynamics

Antiferromagnets

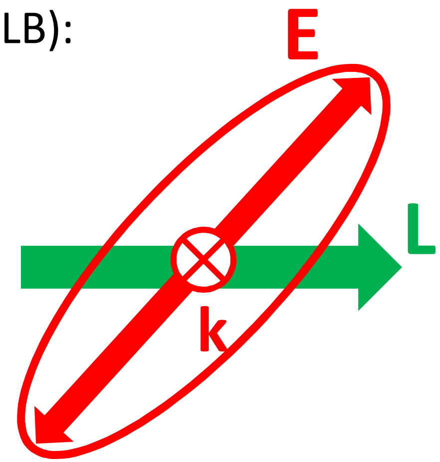
Static case: **M**=0; **L**

Dynamics case: **M≠0**; **L**



MO detection:

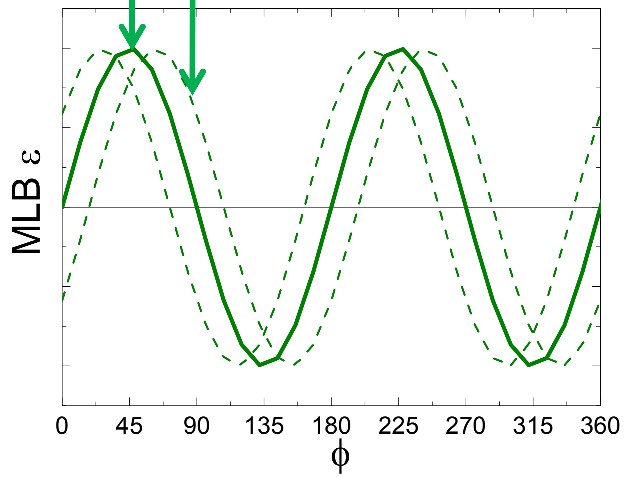
Magnetic linear birefringence (MLB):



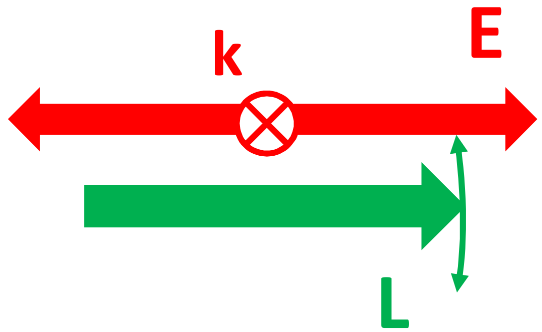
$$\epsilon(\varphi) \sim \sin 2\varphi$$

Static L
or changes of length of L

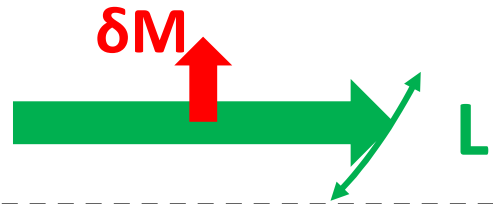
Oscillations of L



Time-resolved MLB:



Time-resolved FE (MOKE):

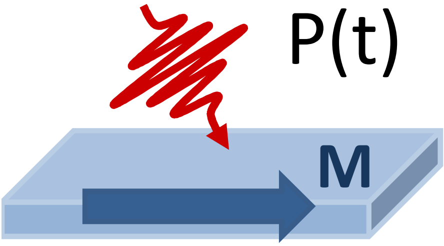


Laser-induced demagnetization

Experimental observation

Theories

Laser-induced electronic and lattice dynamics in metals

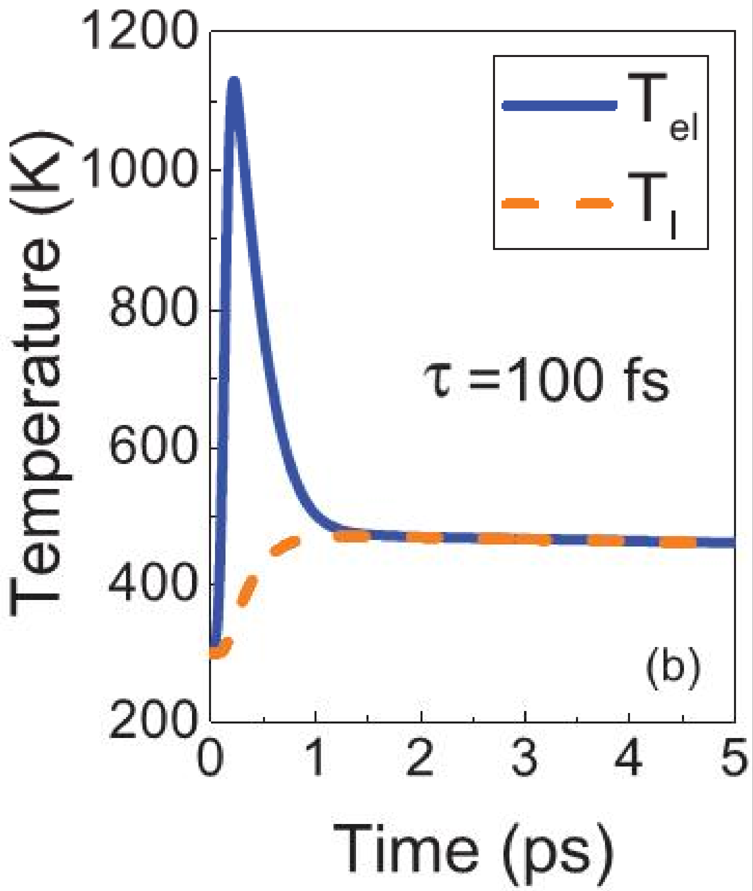


Nonmagnetic metal

$$C_{\text{el}}(T_{\text{el}})\frac{dT_{\text{el}}}{dt} = -G_{\text{el-ph}}(T_{\text{el}} - T_{\text{l}}) + P(t,r),$$

$$C_{\text{l}}(T_{\text{l}})\frac{dT_{\text{l}}}{dt} = -G_{\text{el-ph}}(T_{\text{l}} - T_{\text{el}}) - C_{\text{l}}\frac{T_{\text{l}} - T_0}{\tau_{\text{th}}},$$

[Kaganov et al.,
Sov. Phys.-JETP 31, 232 (1956)]

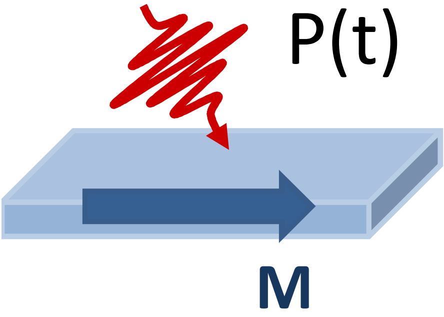


Electrons thermalization times:
350 fs (Ag), 500 fs (Au)

Electron-phonon relaxation times:
950 fs (Ag)

[Del Fatti et al., PRB 61, 16 956 (2000)]

Laser-induced spin dynamics in metals (transition-metal case)



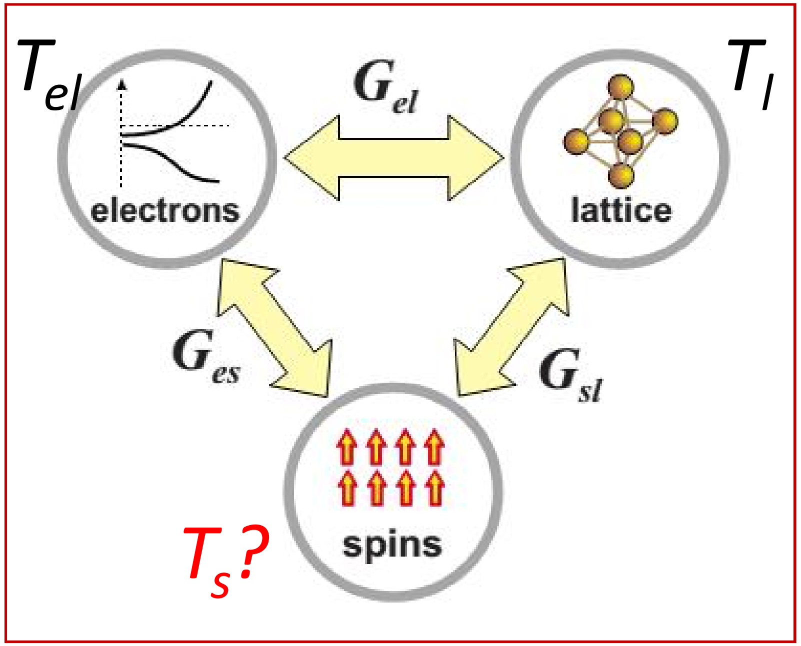
Magnetic metal (Fe, Ni....)

$$C_e d(T_e)/dt = -G_{el}(T_e - T_l) - G_{es}(T_e - T_s) + P(t),$$

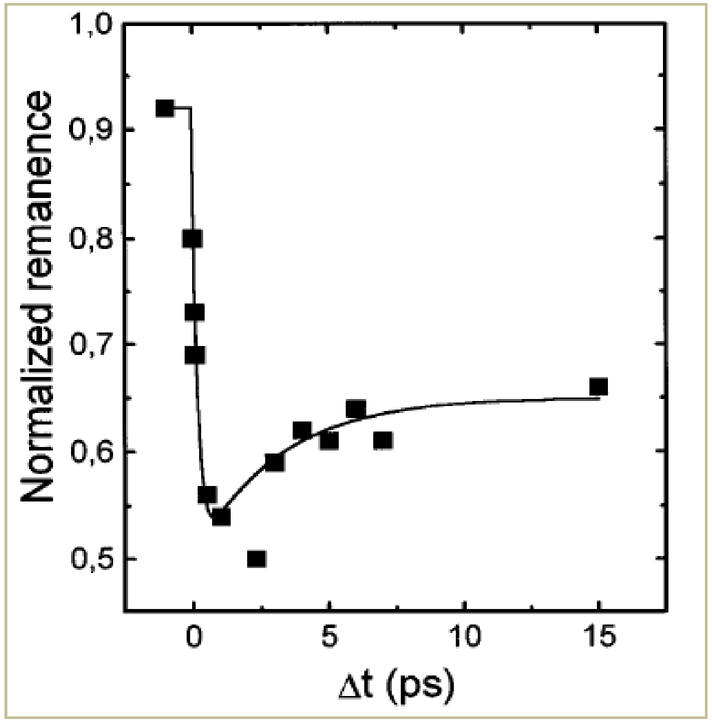
$$C_s d(T_s)/dt = -G_{es}(T_s - T_e) - G_{sl}(T_s - T_l),$$

$$C_l d(T_l)/dt = -G_{el}(T_l - T_e) - G_{sl}(T_l - T_s),$$

3-temperature model (3TM)

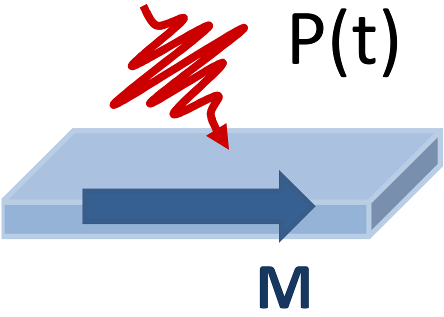


Thin Ni film



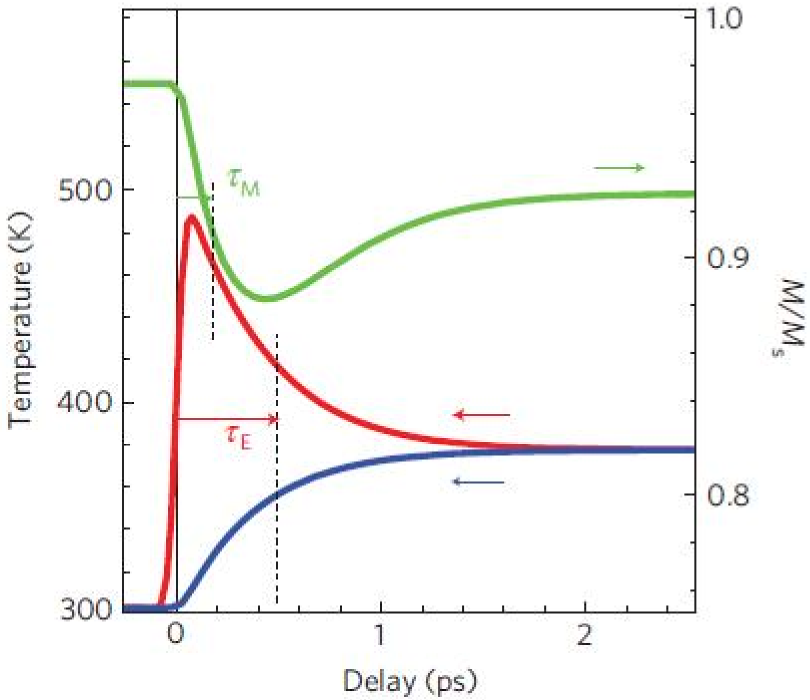
*[Beaurepaire et al., PRL **76**, 4250 (1996)]*

Laser-induced spin dynamics in metals (rare-earth case)

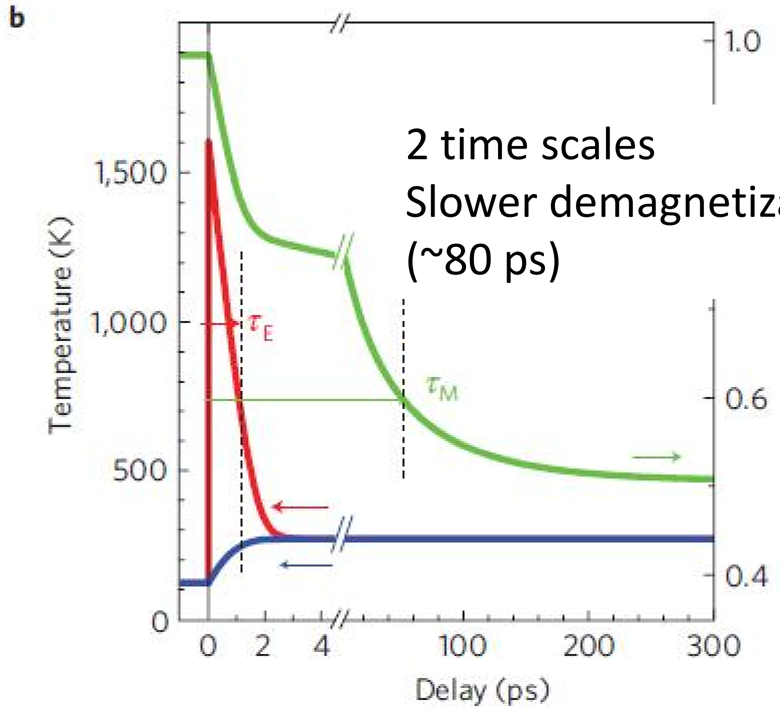


Magnetic metal
(Gd….)

Ni: type I dynamics



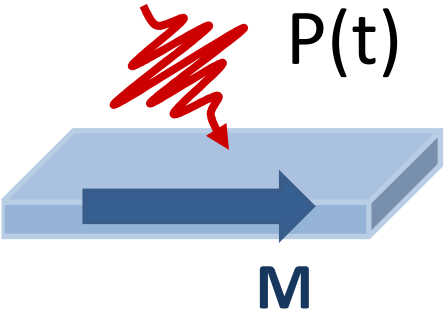
Gd: type II dynamics



2 time scales
Slower demagnetization
(~80 ps)

[Koopmans, et al., Nature Mater. 9, 259 (2009)
Vaterlaus et al., PRL 67, 3314 (1991)]

Ultrafast demagnetization: modified 3T model (M3TM)

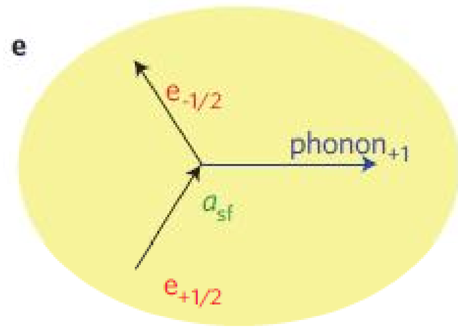


Electrons and lattice dynamics: 2T-model

$$C_{\text{el}}(T_{\text{el}})\frac{dT_{\text{el}}}{dt} = -G_{\text{el-ph}}(T_{\text{el}} - T_{\text{l}}) + P(t,r),$$

$$C_{\text{l}}(T_{\text{l}})\frac{dT_{\text{l}}}{dt} = -G_{\text{el-ph}}(T_{\text{l}} - T_{\text{el}}) - C_{\text{l}}\frac{T_{\text{l}} - T_0}{\tau_{\text{th}}},$$

Spin dynamics:
via el-ph spin flip scattering
with probability α_{sf}



α_{sf} is related to spin-mixing of electronic states at the Fermi energy due to SO interactions

Magnetization dynamics according to the M3T model

- ➢Electrons provide energy for the demagnetization
- ➢Lattice provides the sink for the angular momentum

$$\frac{dm}{dt} = Rm\frac{T_l}{T_C}\left(1 - \coth\left(\frac{mT_C}{T_{el}}\right)\right)$$

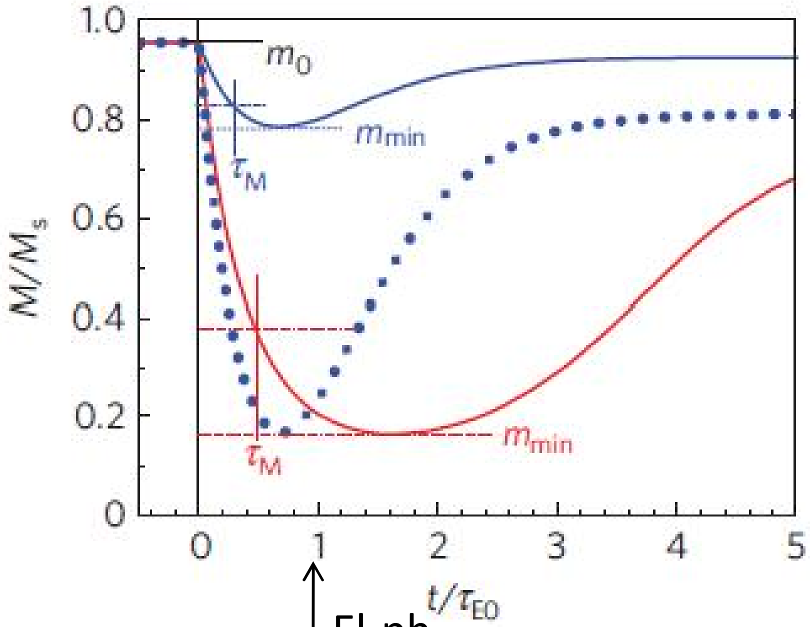
$$R \propto \frac{a_{sf}T_C^2}{\mu_{at}}$$

[Koopmans et al., Nature Mater. 9, 259 (2009]

Ultrafast demagnetization: modified 3T model (M3TM)

$$\frac{dm}{dt} = Rm\,\frac{T_l}{T_C}\left(1 - \coth\left(\frac{mT_c}{T_{el}}\right)\right) \qquad R \propto \frac{a_{sf}T_C^2}{\mu_{at}}$$

Large R (~5) **Type I dynamics**

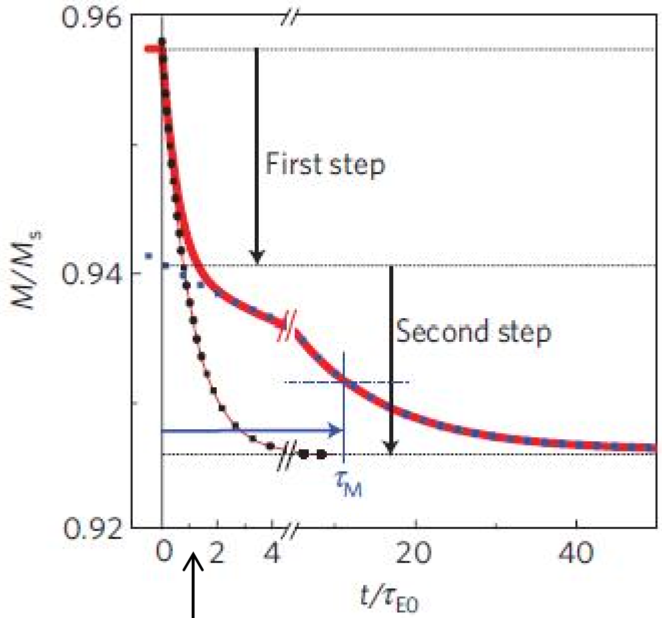


El-ph equilibration time

Slowing down as the pump fluence/ sample temperature increases

[Koopmans et al., Nature Mater. 9, 259 (2009)]

Small R (~0.5) **Type II dynamics**



Fast demagnetization before

Slow demagnetization after

El-ph equilibration time

Ultrafast demagnetization: modified 3T model (M3TM)

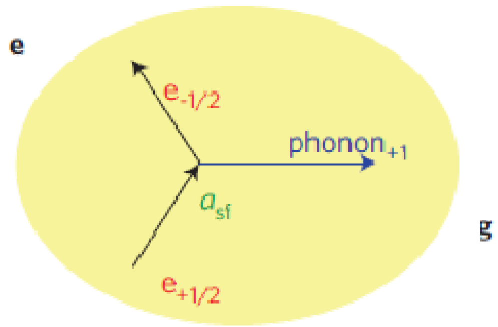
$$\frac{dm}{dt} = Rm\frac{T_l}{T_C}\left(1 - \coth\left(\frac{mT_c}{T_{el}}\right)\right)$$

$$R \propto \frac{a_{sf}T_C^2}{\mu_{at}}$$

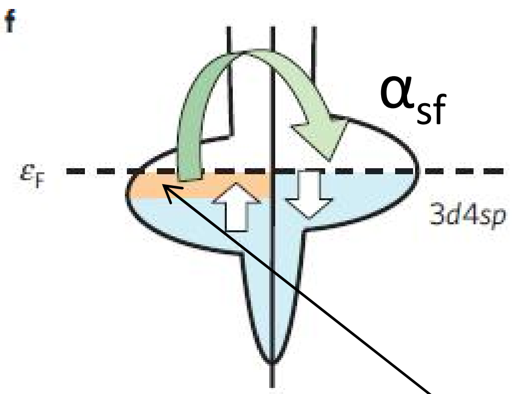
Type I dynamics

Type II dynamics

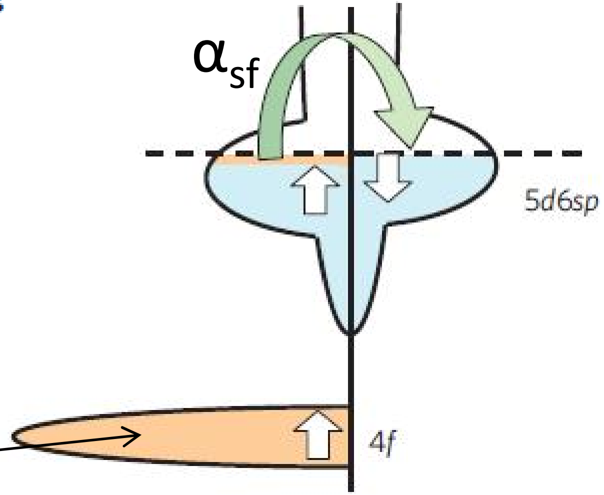
Difference in spin-flip scattering:



Transition metals



Rare-earth metals

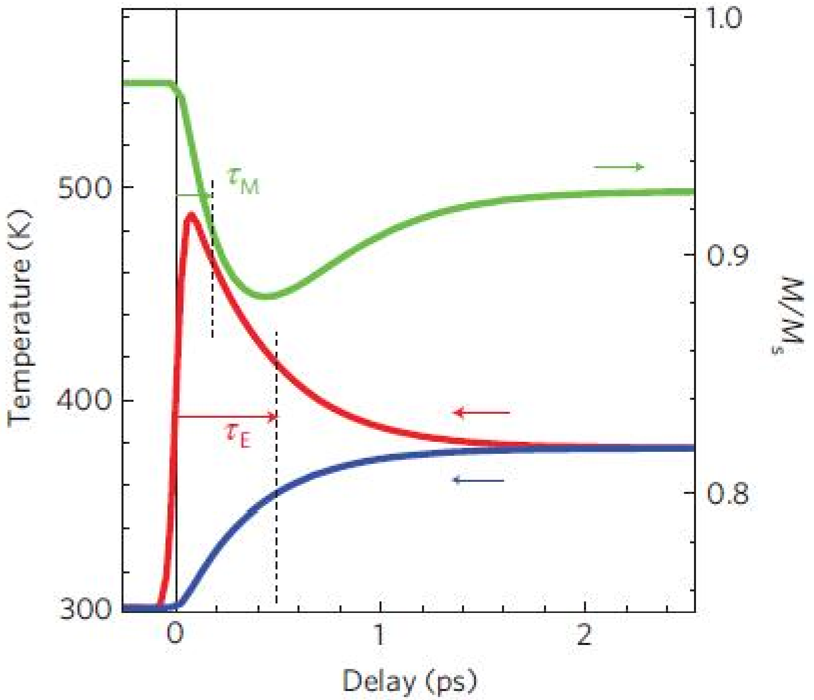


Electrons contributing to magnetism

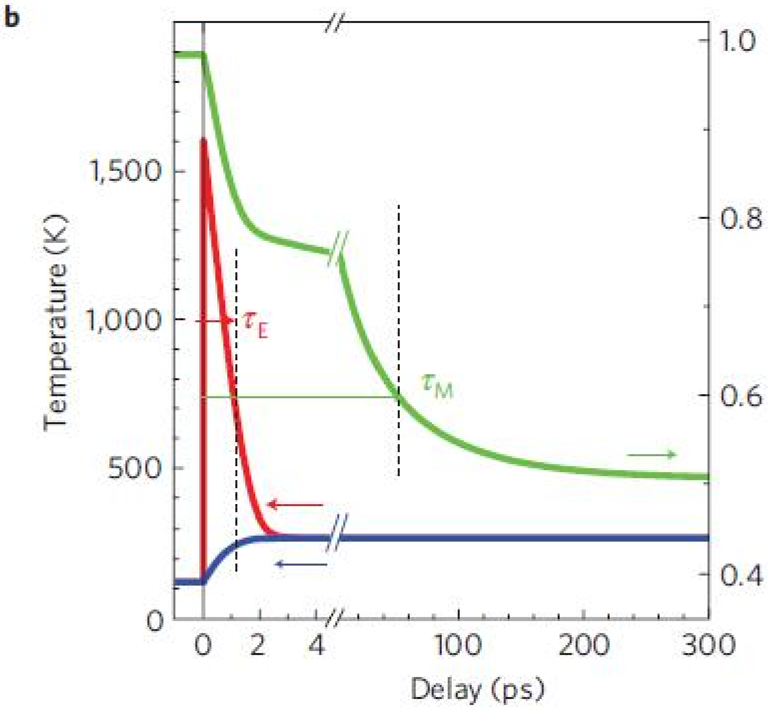
[Koopmans et al., Nature Mater. 9, 259 (2009)]

Ultrafast demagnetization: modified 3T model (M3TM)

Ni: type I dynamics



Gd: type II dynamics

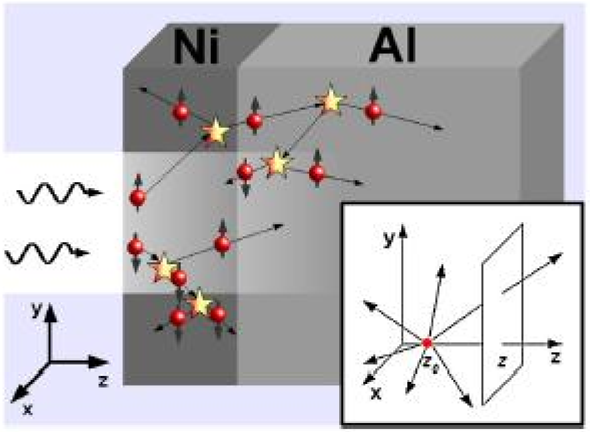


	a_{sf} (exp.)†	τ_M (theory)‡ (ps)	τ_M (exp.)‡ (ps)
Ni	0.185±0.015	0.21	0.16
Co	0.150±0.015	0.34	0.26
Gd	0.08±0.02	15	40

[Koopmans et al., Nature Mater. 9, 259 (2009)]

Ultrafast demagnetization: superdiffusive transport

Reason for demagnetization:
spin-dependent transport from the laser-heated area
in the superdiffusive regime:



- Electrons are excited from the d-band to sp-bands above the Fermi level: **high mobility electrons (~1nm/fs)**

- Spin-conserving scattering events

- Each scattering event is isotropic

- **Superdiffusive regime:** $\sigma^2 \propto t^{\gamma(t)}$ -variance of particle displacement distribution

γ>1 and decreases with time (γ=1 – diffusion; γ=2 - ballistics)

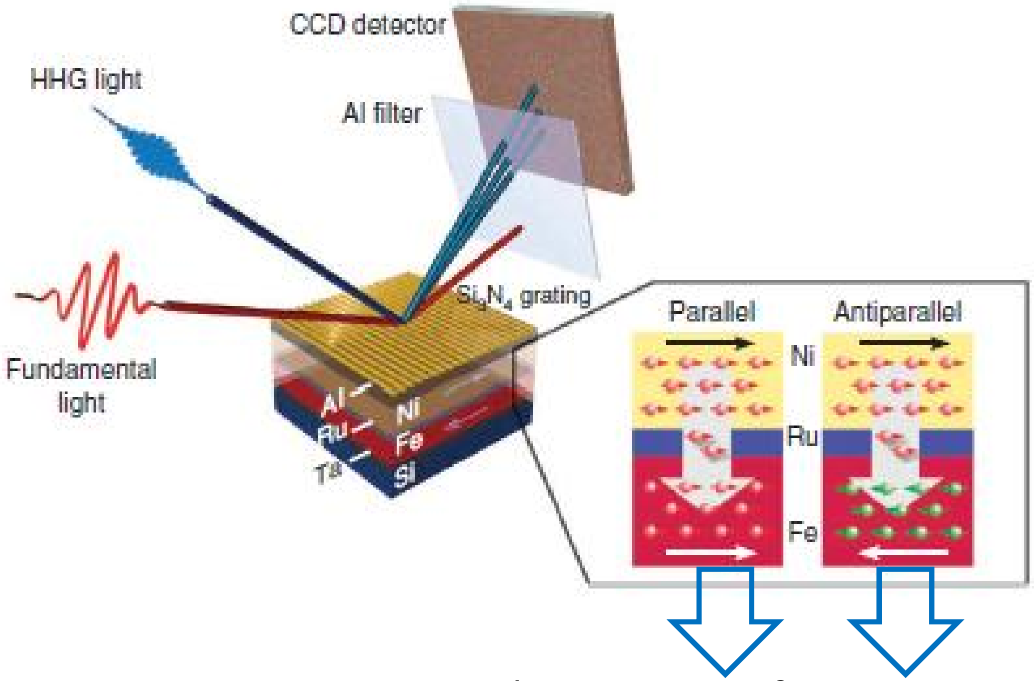
- Different life times for majority and minority electrons

Majority electrons transfer magnetization away from excited area

[Battiato et al., PRL ***105****, 027203 (2010)]*

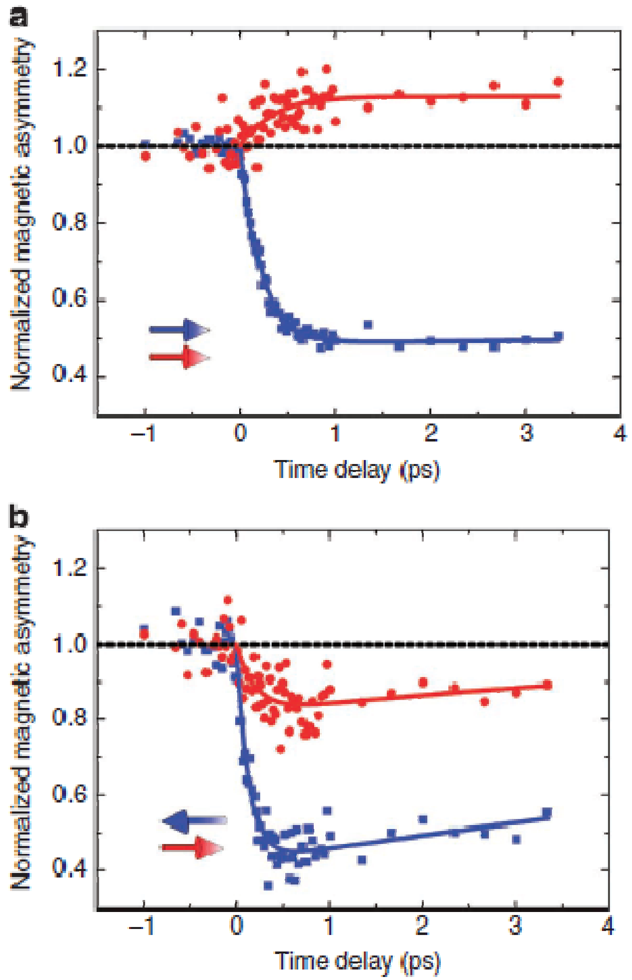
Ultrafast demagnetization: superdiffusive transport

Attempts to verify if this mechanism is present



Enhancement of Fe magnetization?

Decrease of Fe magnetization?



[Rudolf et al., Nature Comm. 3, 1037 (2012)]

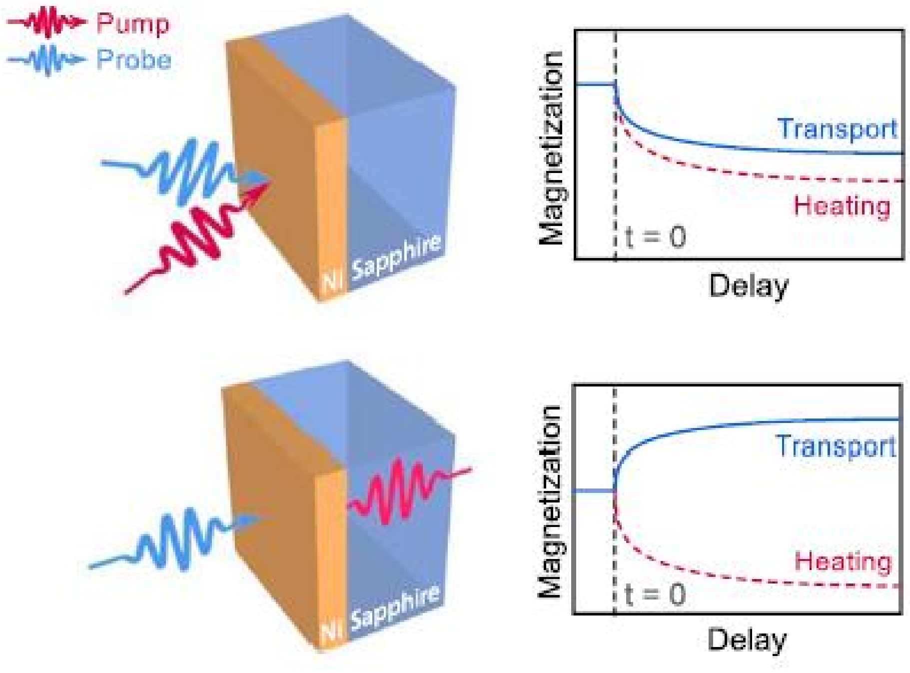
*See also Melnikov et al., PRL **107**, 076601 (2011)*

Agrees with the theory predictions

but…..

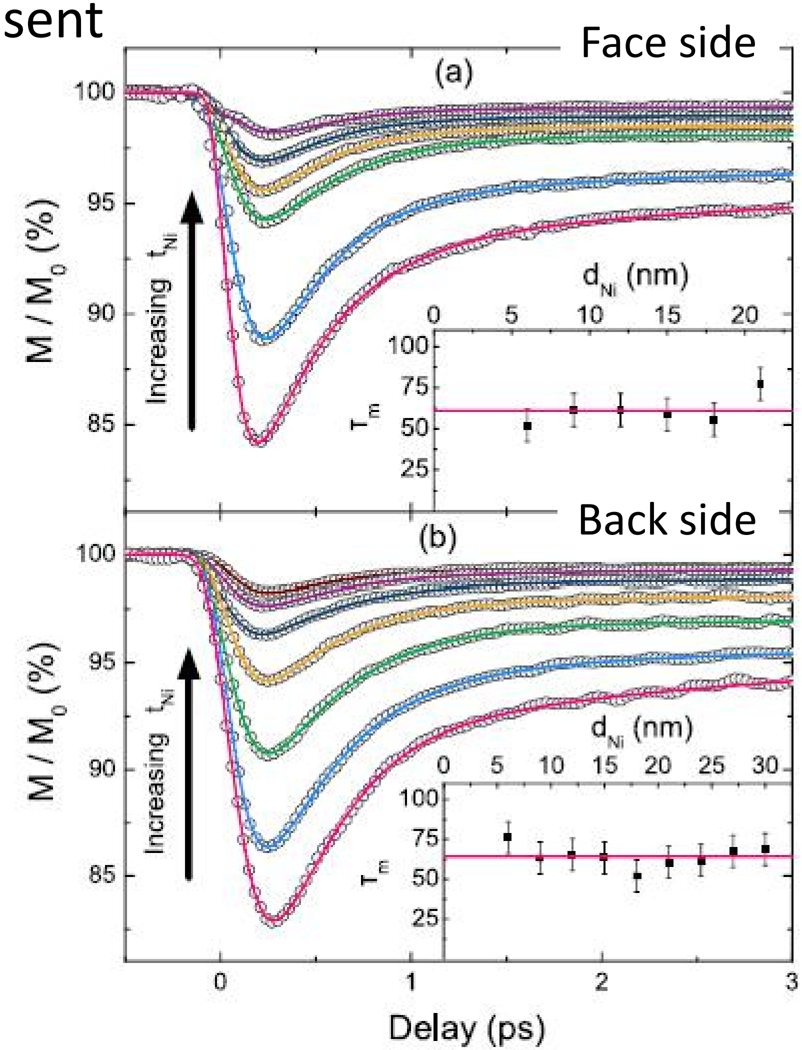
Ultrafast demagnetization: superdiffusive transport

Attempts to verify if this mechanism is present



Probing magnetization dynamics
from two sides of the laser-excited film

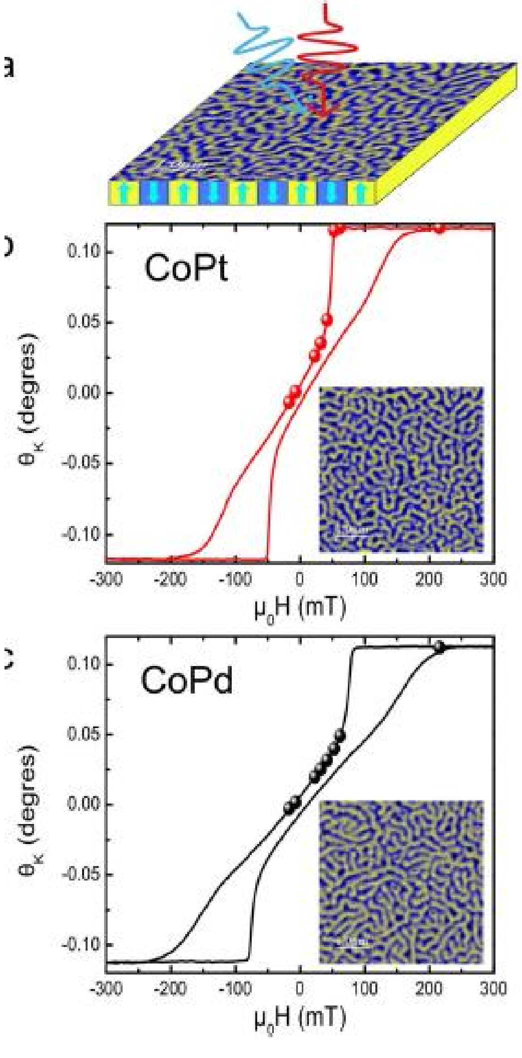
[Schellekens et al., APL 102, 252408 (2013)]



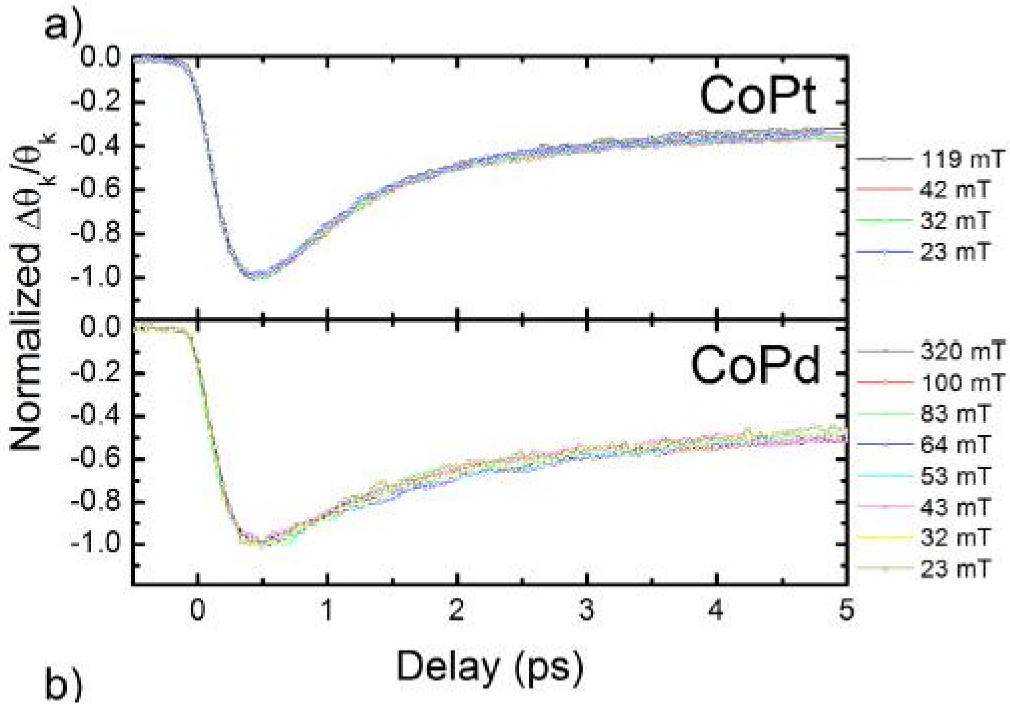
No signature from superdiffusive currents

Ultrafast demagnetization: superdiffusive transport

Attempts to verify if this mechanism is present



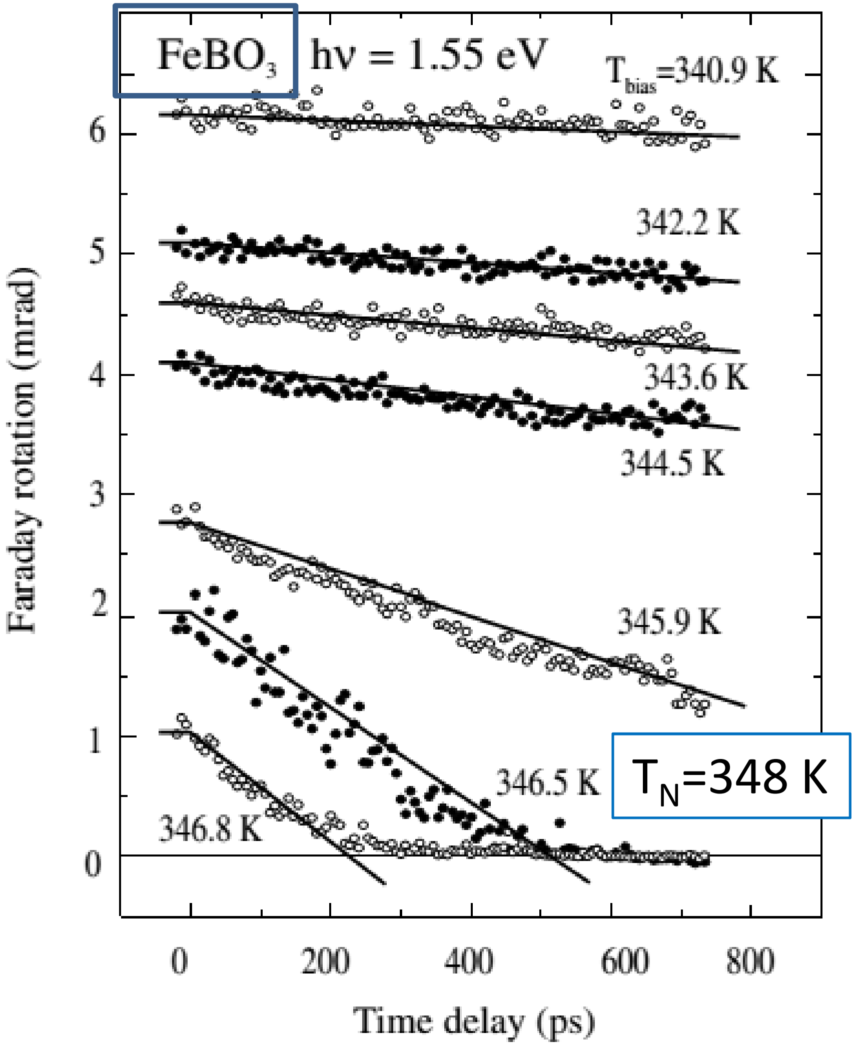
Spin transport between domains?



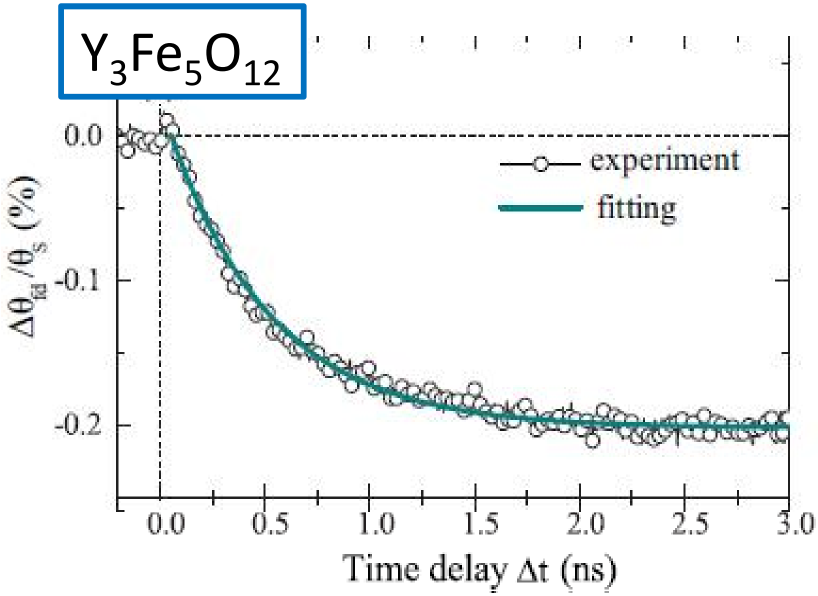
Multidomain state
does not affect the demagnetization

[Maison et al., Sci. Rep. 4, 4658 *(2014)]*

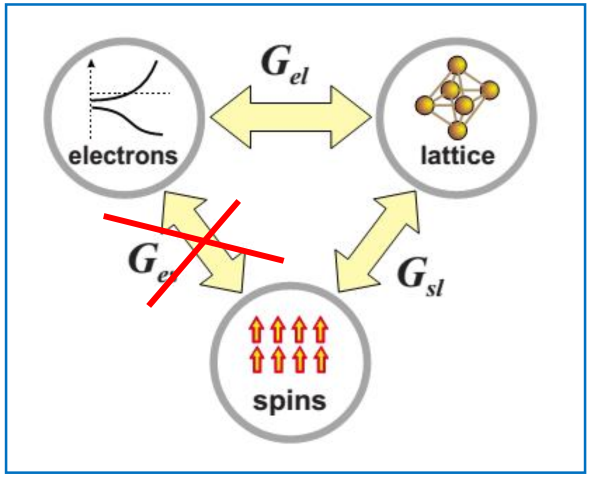
Ultrafast (?) demagnetization in dielectrics



[Kimel et al., PRL 89, 287401 (2002)]



[Shelukhin et al., PRB 97, 014422 (2018)*]*



Demagnetization in a dielectric
is mediated by the phonon-magnon interaction

See lecture by T. Kampfrath

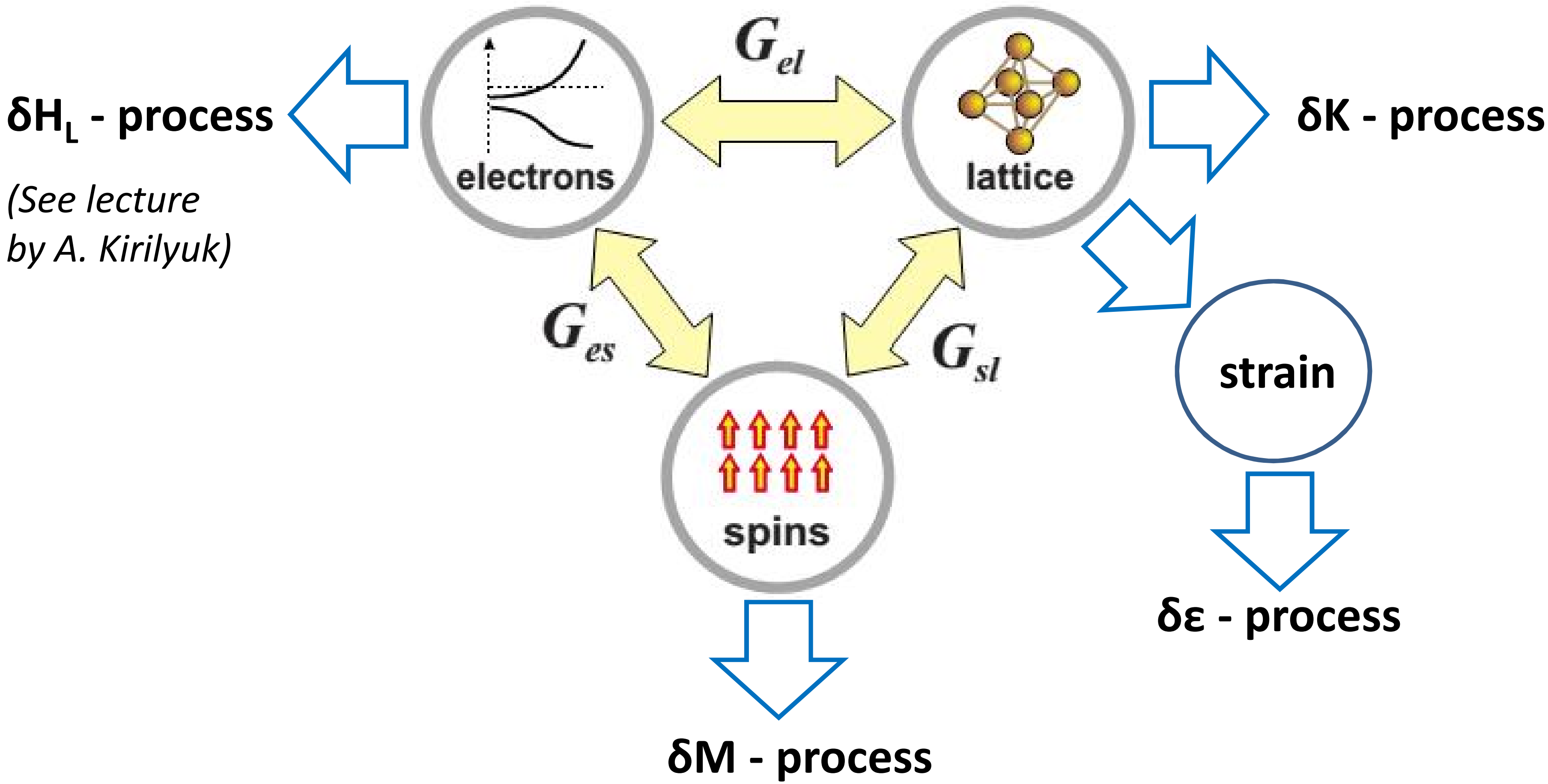
Laser-induced changes of magnetic anisotropy

Through demagnetization

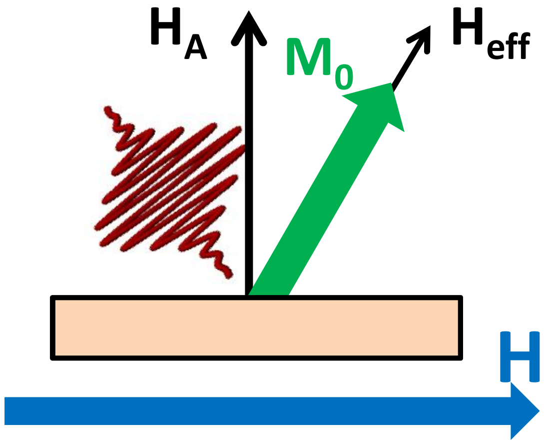
Through lattice heating

Through strain

Mechanisms of laser-induced changes of magnetic anisotropy



Probing laser-induced changes of magnetic anisotropy



Example: uniaxial easy axis-type anisotropy

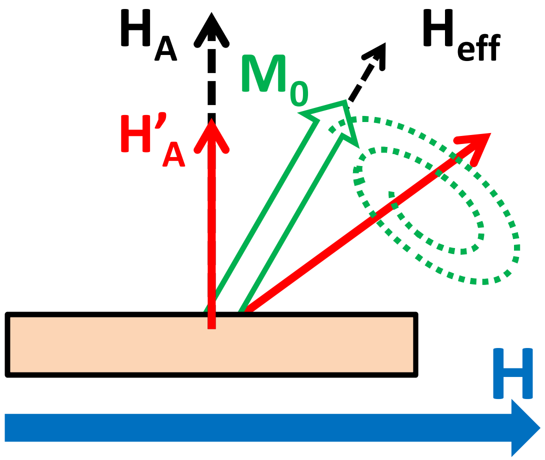
$$\mathbf{H}_a = -\frac{\partial F_a}{\partial \mathbf{M}} = -K_u m_z \mathbf{z}$$

$$\frac{d\mathbf{M}}{dt} = -\gamma[\mathbf{M} \times \mathbf{H}_{\mathrm{eff}}]$$

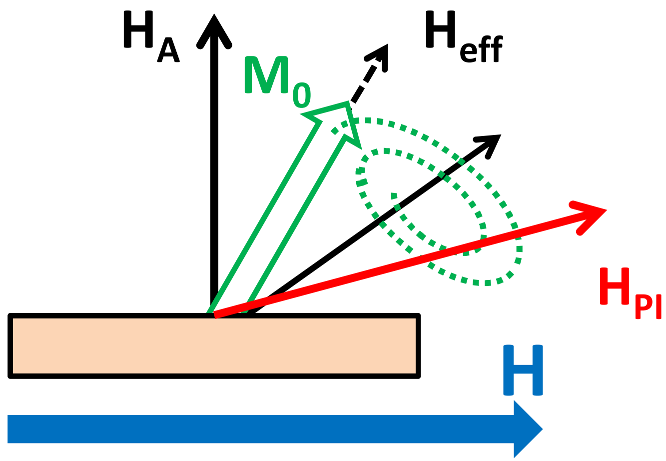
$$\mathbf{T}_0 = -\gamma[\mathbf{M}_0 \times \delta\mathbf{H}_{\mathrm{eff}}]$$

Anisotropy of the laser-pulse excited sample:

$$\mathbf{H}'_a = -K'_u m_z \mathbf{z}$$



$$\mathbf{H}'_a = -K_u m_z \mathbf{z} + \mathbf{H}_{PI}$$

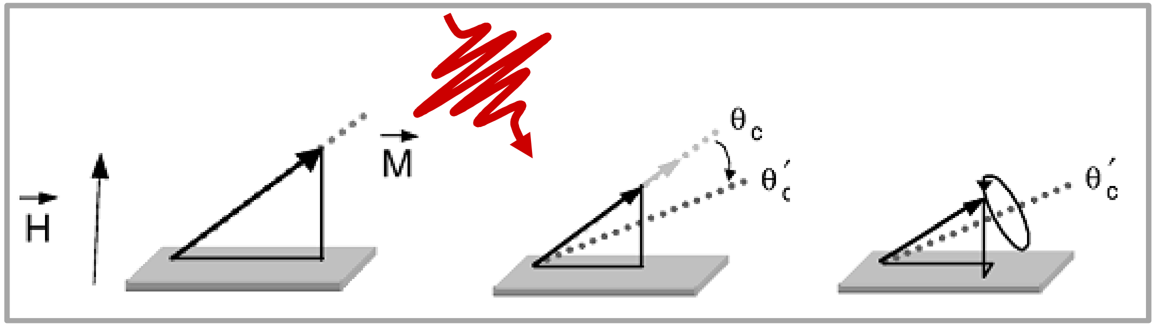


Magnetization precession serves as a probe of laser-induced anisotropy changes

Ultrafast demagnetization and shape anisotropy (δM-process)

Thin CoPt film

Shape anisotropy: $-2\pi M_{\perp}^{2}$



Ultrafast demagnetization

⇩

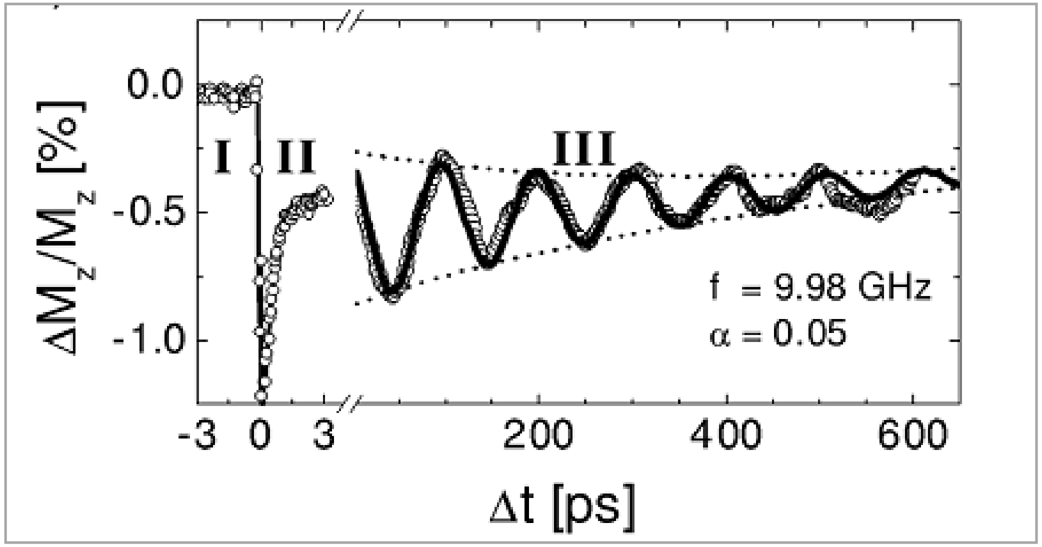
Change of effective anisotropy field

⇩

$$\frac{d\mathbf{M}}{dt} = -\gamma[\mathbf{M} \times \mathbf{H}_{\text{eff}}]$$

$$\mathbf{T}_0 = -\gamma[\mathbf{M_0} \times \delta\mathbf{H}_{\text{eff}}]$$

⇩



Laser-induced magnetization precession

[van Kampen et al., PRL 88, 227201 (2002)]

Laser-induced change of anisotropy constants (δK-process)

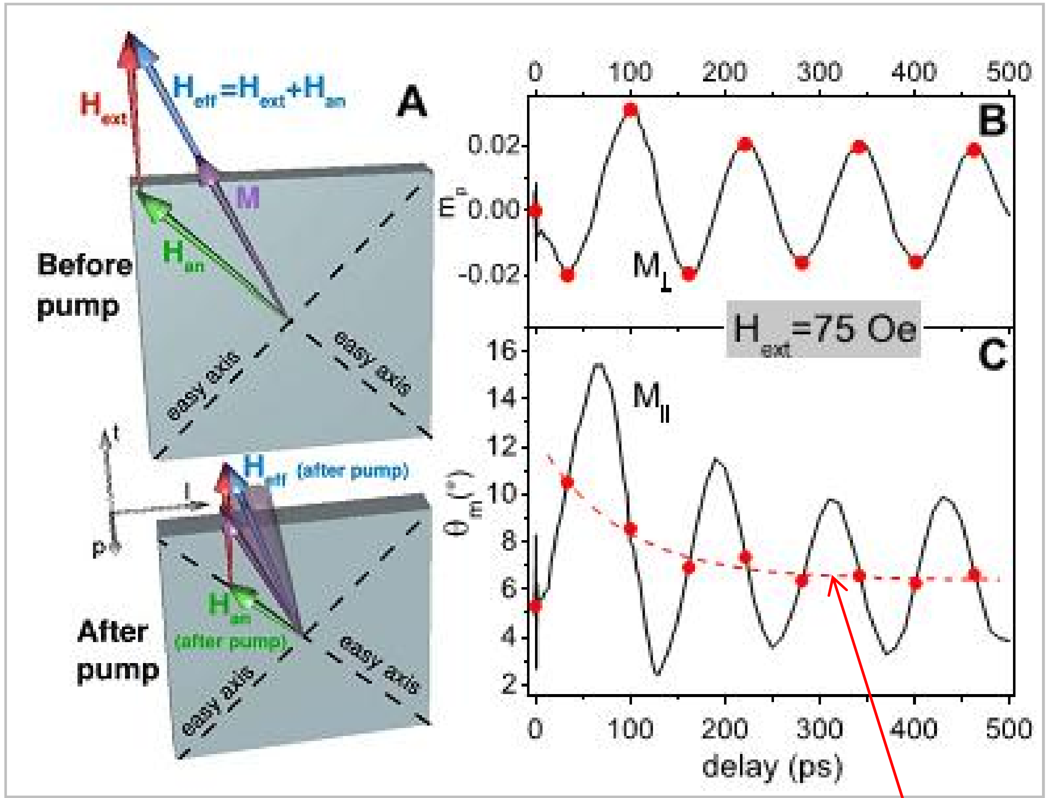
Epitaxial metallic film Fe/MgO

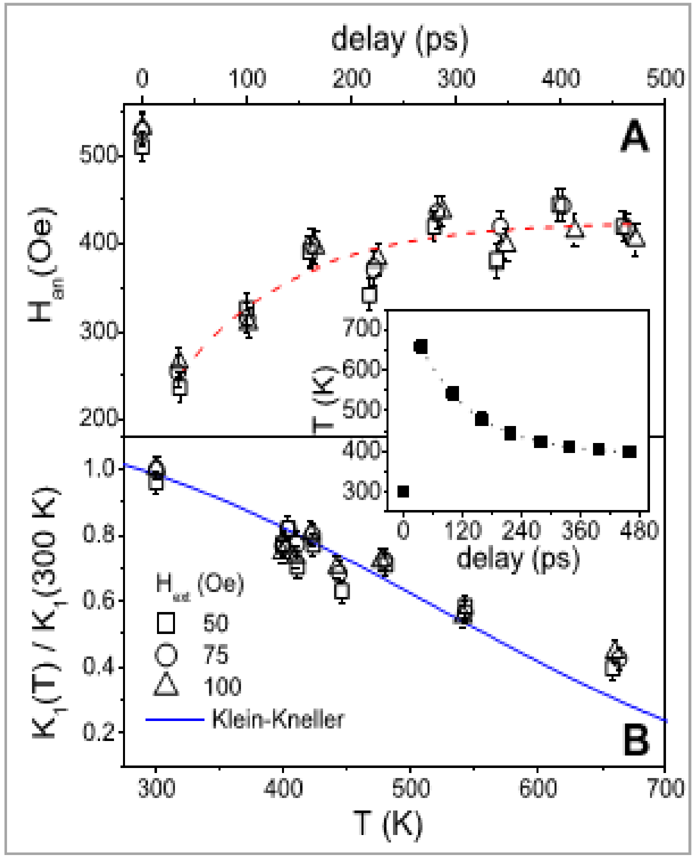
Cubic anisotropy:

$$E_a = K_1(T)\left(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_1^2\alpha_3^2\right)$$

$$\mathbf{T}_0 = -\gamma[\mathbf{M_0} \times \delta\mathbf{H}_{\mathrm{eff}}]$$

Dynamics of the anisotropy parameter K_1:



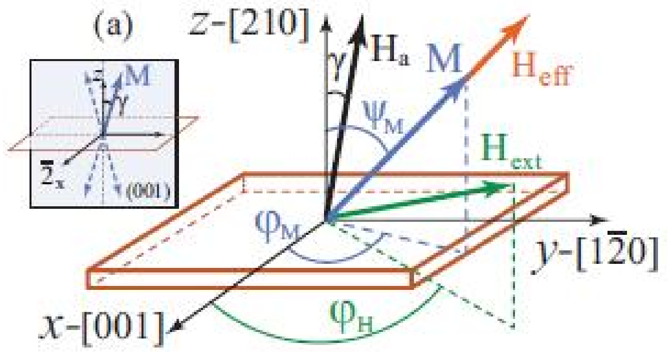


Deviation of $\mathbf{H}_{\mathrm{eff}}$

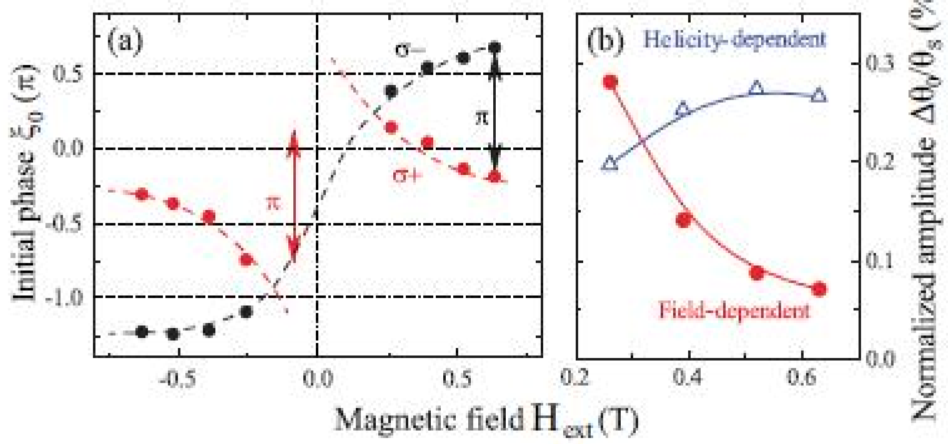
*[Carpene et al., PRB **81**, 060415(2010); Carpene et al., JAP **108**, 063919 (2010)]*

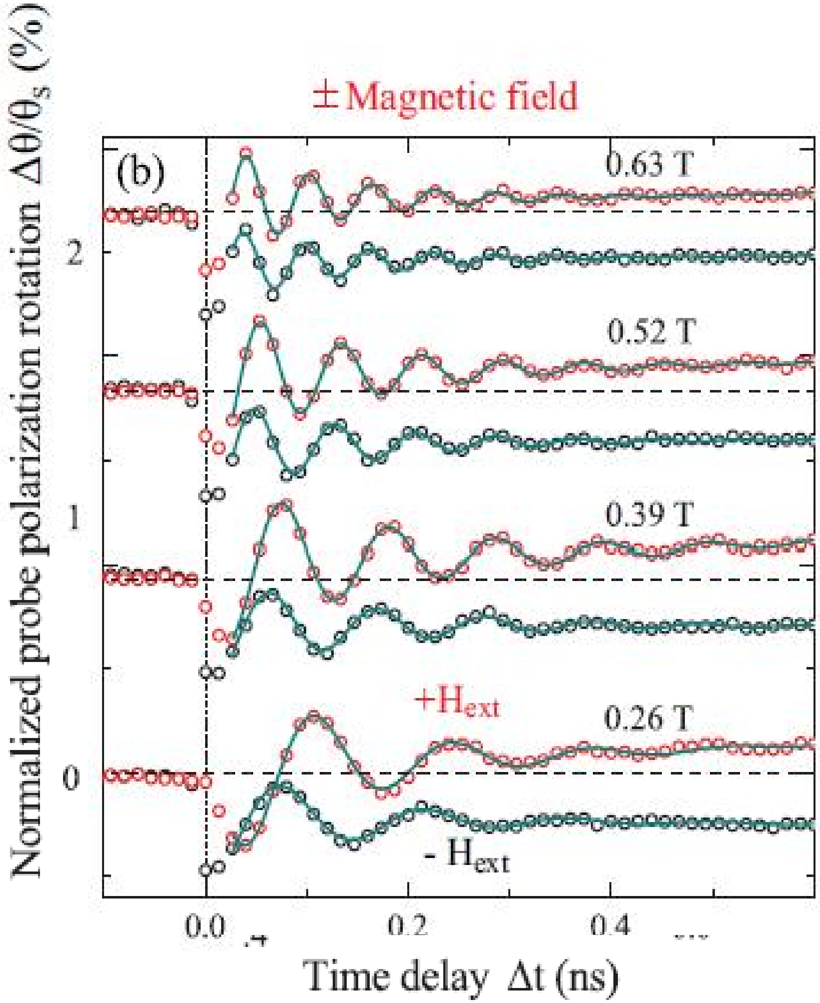
Laser-induced change of anisotropy constants (δK-process)

Epitaxial dielectric film $Y_3Fe_5O_{12}$/GGG



$$E_a = K_u m_z^2 + K_i m_y^2 + K_{yz} m_y m_z$$



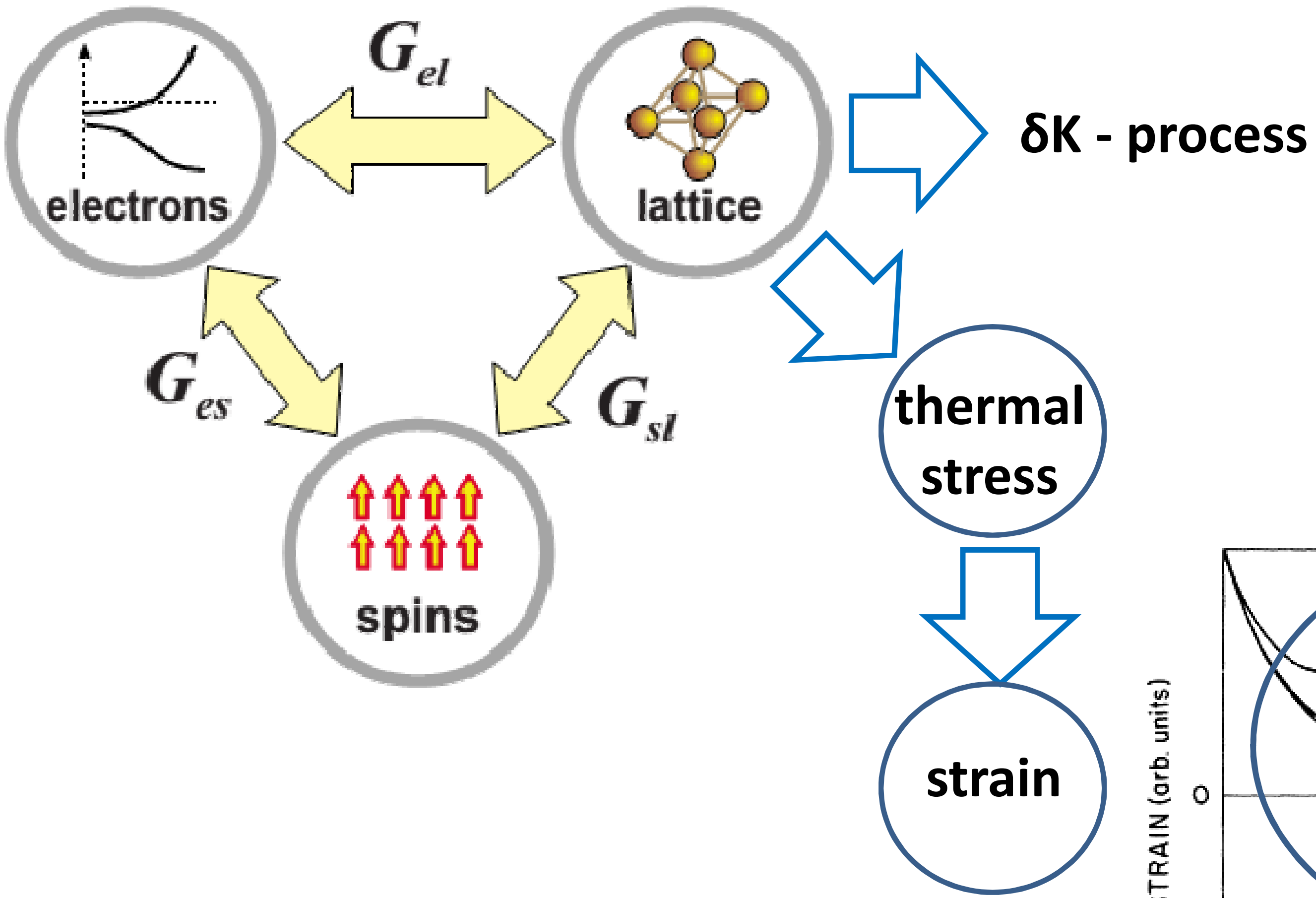


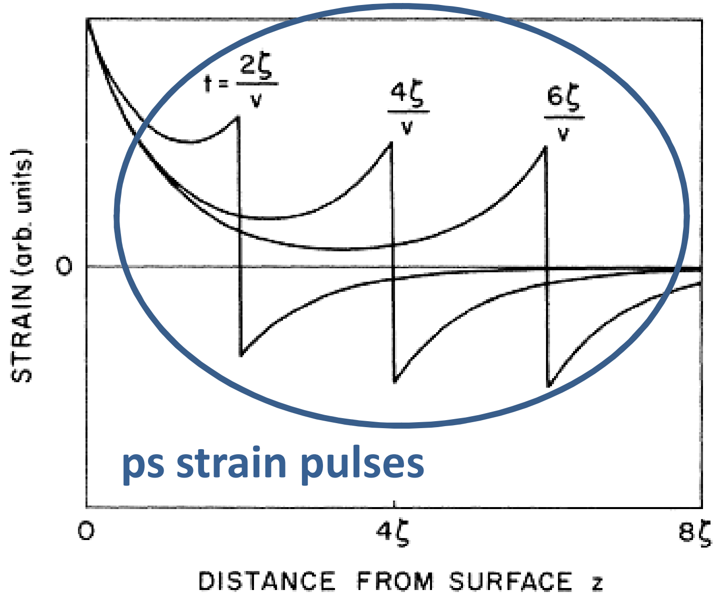
Contribution from laser-induced δK dominates at low fields

Laser-induced change of anisotropy *δK*~ 1%

[Shelukhin et al., PRB 97, 014422 (2018)*]*

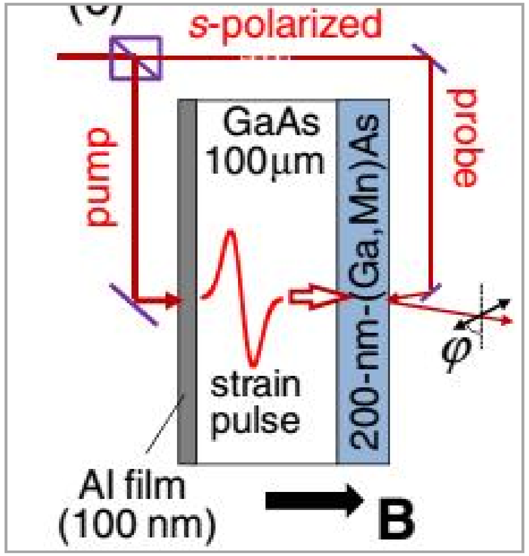
Laser-induced strain and inverse magnetostriction (δε-process)





*[Thomsen et al., PRB **34**, 4129 (1986)]*

Picosecond magnetoacoustics



Strain pulse injected to GaAs from the Al film

τ **~10 ps**

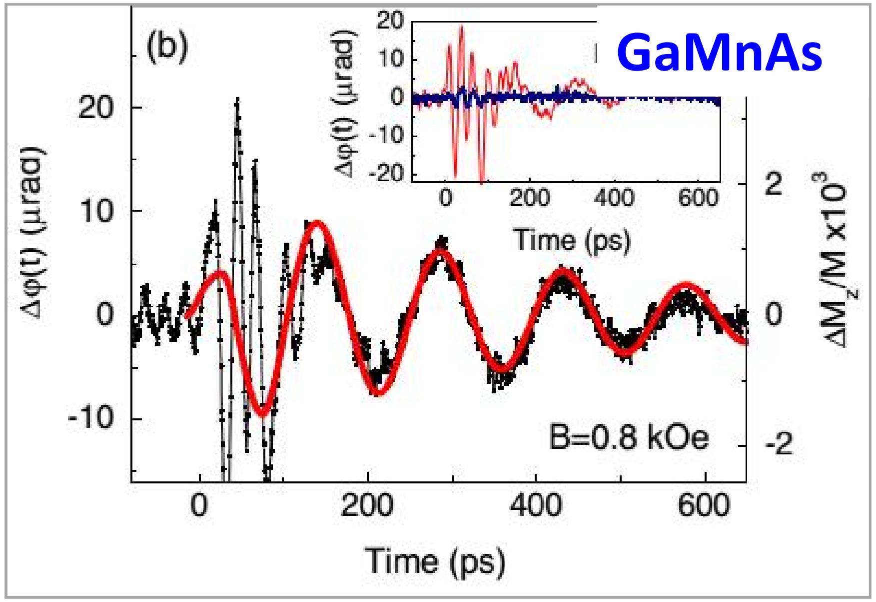
ε_{zz}**~10^{-3} – 10^{-4}**

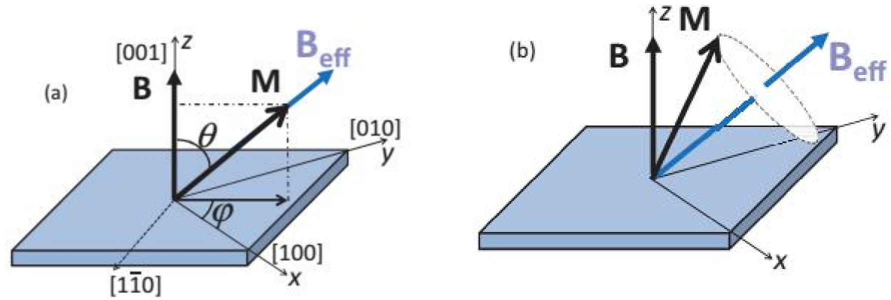
Magneto-elastic energy:

$$E_{me} = b\varepsilon_{ij} m_i m_j$$

Torque action on magnetization due to strain:

$$\mathbf{T}_0 = -\gamma\left[\mathbf{M}_0 \times b\varepsilon_{ij}\mathbf{m}_i\right]$$

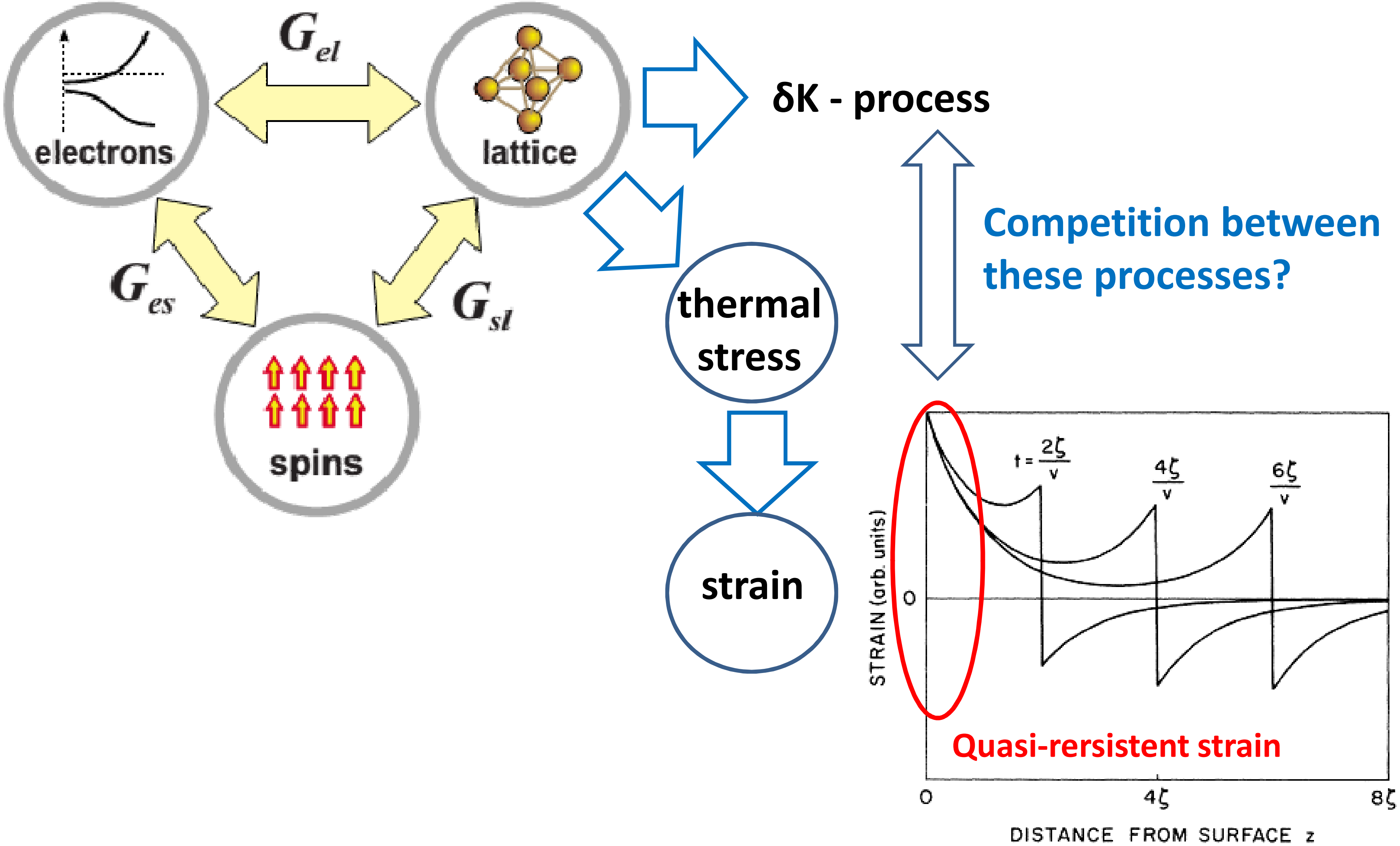




Propagating strain pulse modifies magnetocrystaline anisotropy and launches the precession

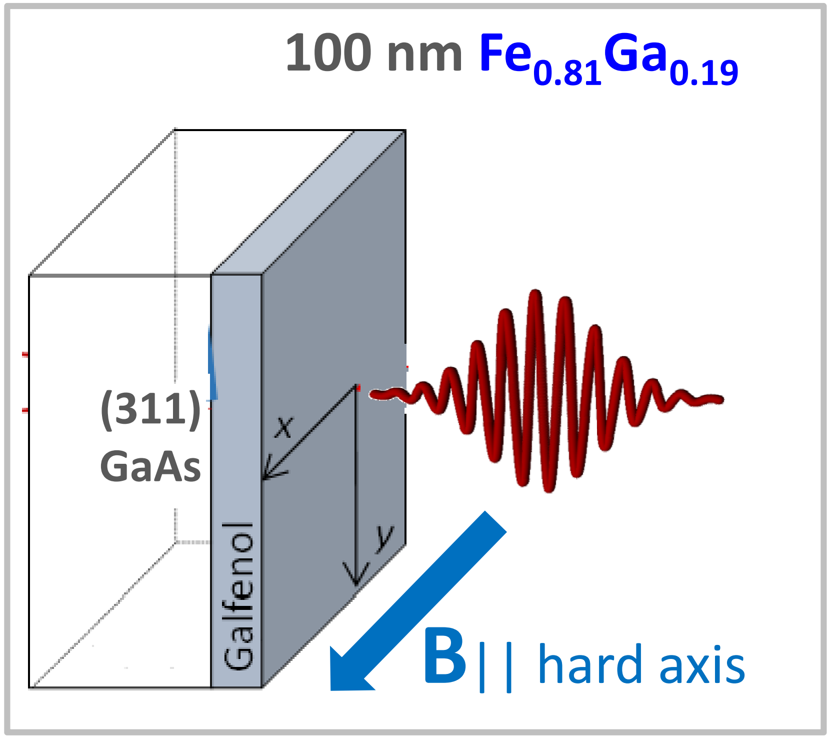
[Scherbakov et al., PRL ***105****,117204 (2010), Kim et al., PRL* ***109****, 166601 (2012)...]*

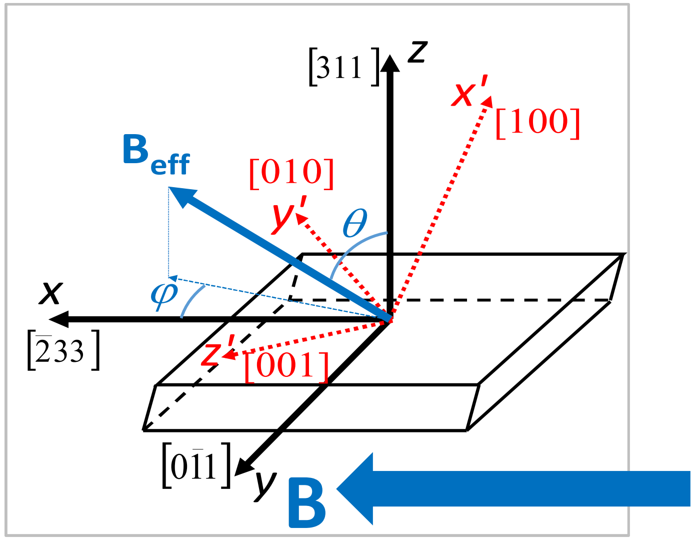
Laser-induced strain and inverse magnetostriction (δε-process)



*[Thomsen et al., PRB **34**, 4129 (1986)]*

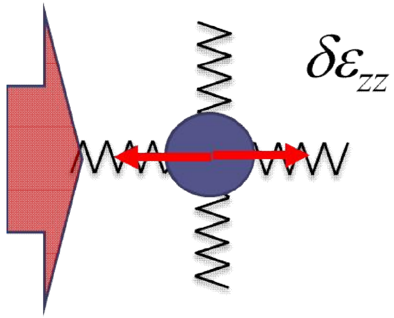
Low-symmetry magnetostrictive metallic film





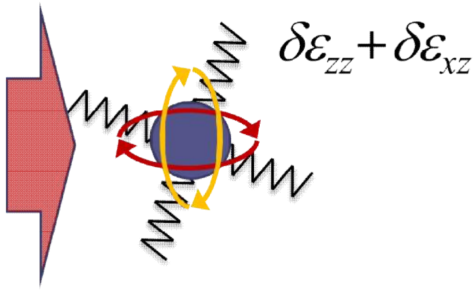
Why (311) substrate?

A film on a <001> substrate:



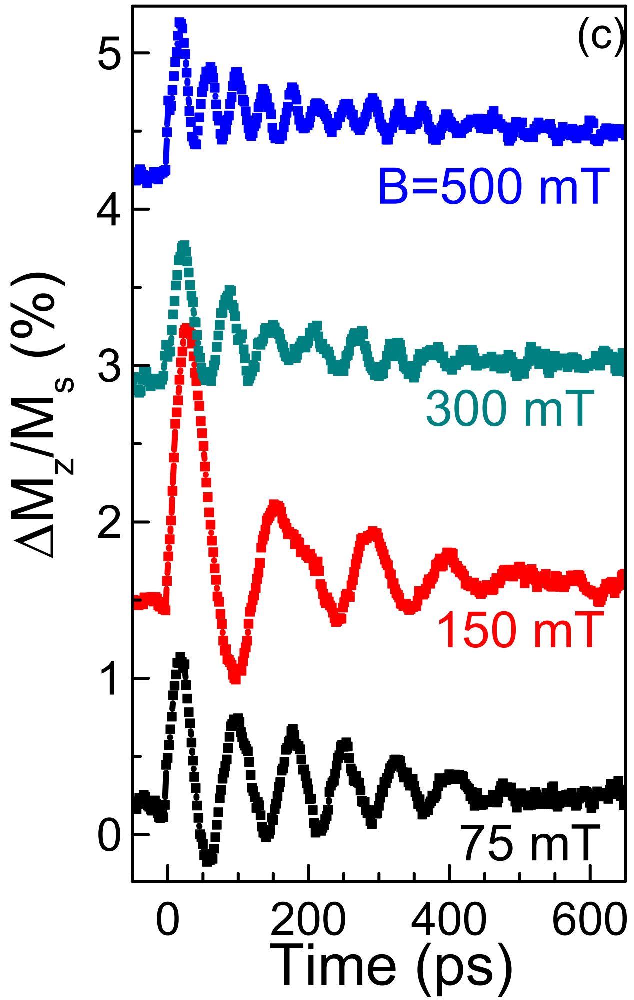
Only compressive/tensile strain

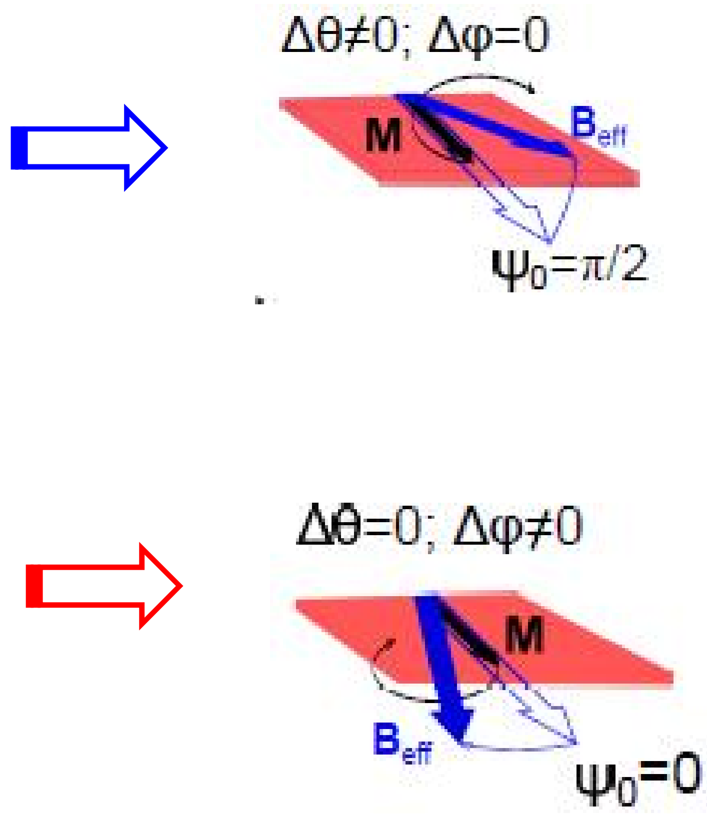
A film on a low-symmetry substrate:



Compressive/tensile & shear strain

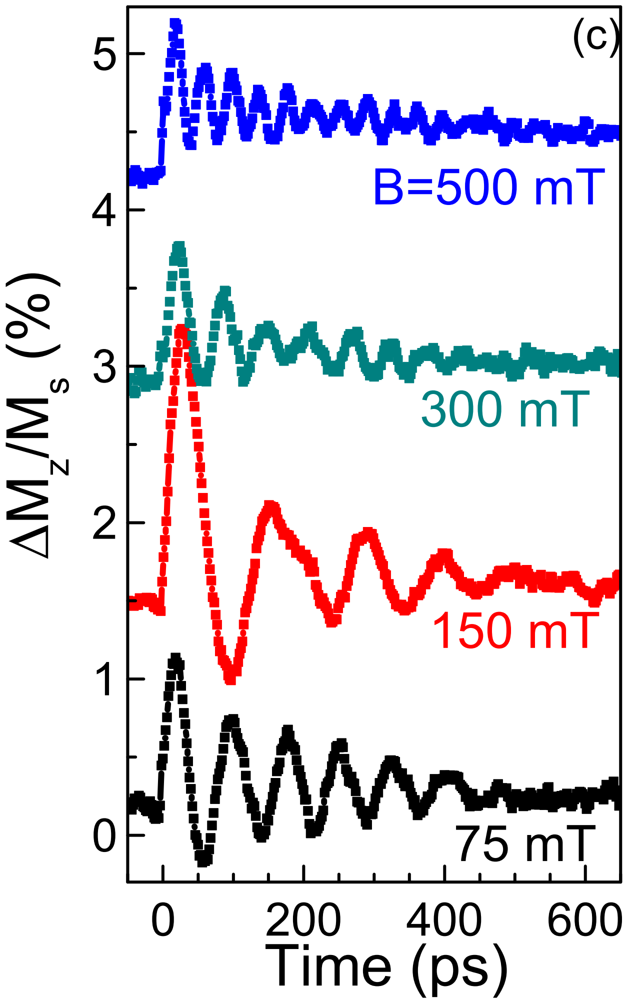
Direct optical excitation of precession: magnetic field dependence

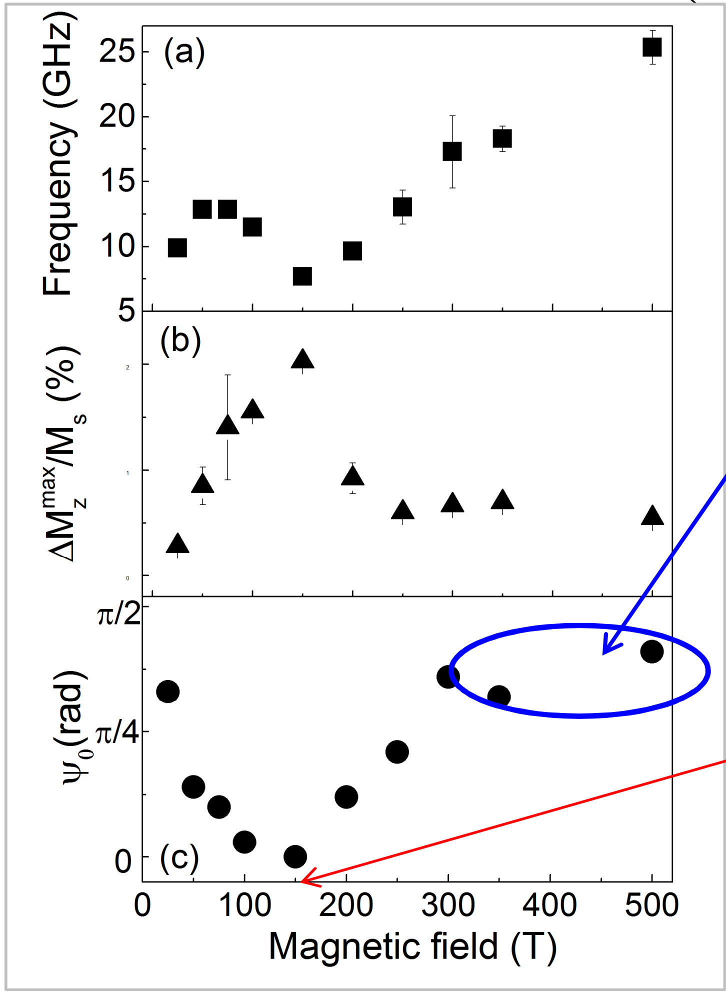


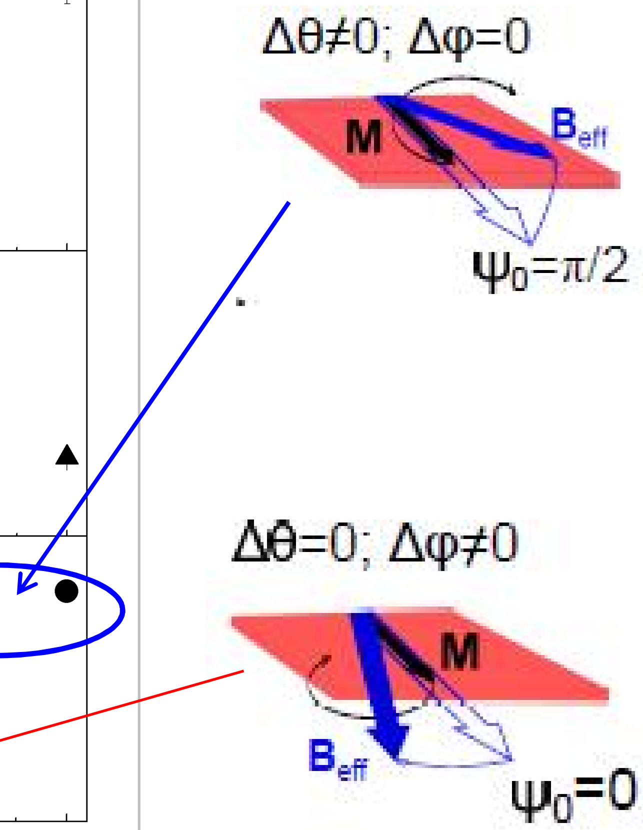


Direct optical excitation of precession: magnetic field dependence

$$\Delta M_z(t) = \Delta M_z^{max} \exp\left(-\frac{t}{\tau}\right)\sin(2\pi f t - \psi_0)$$

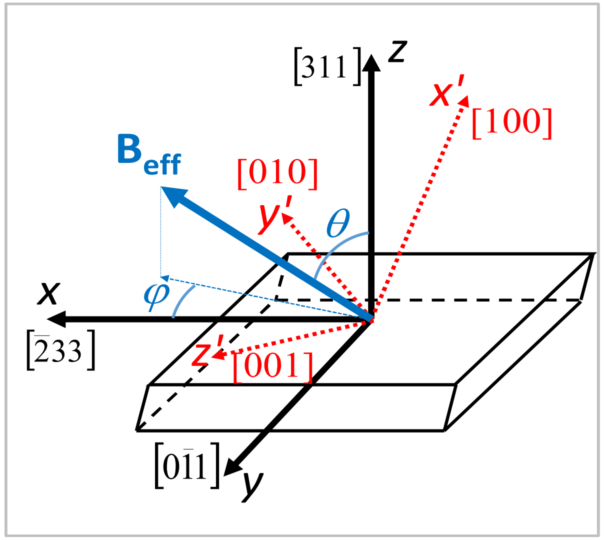






Two competing mechanisms of precession excitation!

Laser-induced change of anisotropy in a metallic film: model



$$\frac{d\mathbf{m}}{dt} = -\gamma \cdot \mathbf{m} \times \mathbf{H}_{\mathrm{eff}}(\mathbf{m}, t)$$

$$\mathbf{H}_{\mathrm{eff}}(\mathbf{m}, t) = -\frac{\partial F_M(\mathbf{m}, t)}{\partial \mathbf{m}}$$

temperature-dependent terms

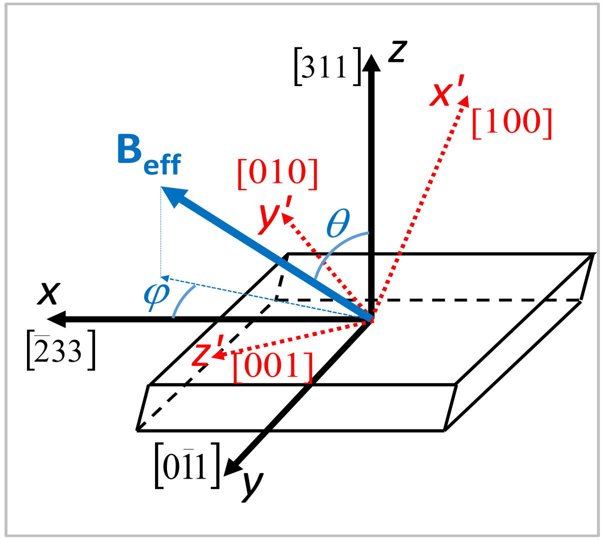
~~Shape anisotropy~~ — cubic anisotropy — uniaxial

$$F_M(\mathbf{m}) = -(\mathbf{m}\cdot\mathbf{H}) + \mathbf{H}_d m_z^2 + K_1(m_{x'}^2 m_{y'}^2 + m_{z'}^2 m_{y'}^2 + m_{x'}^2 m_{z'}^2) - K_u(\mathbf{m}\cdot\mathbf{u})^2 +$$

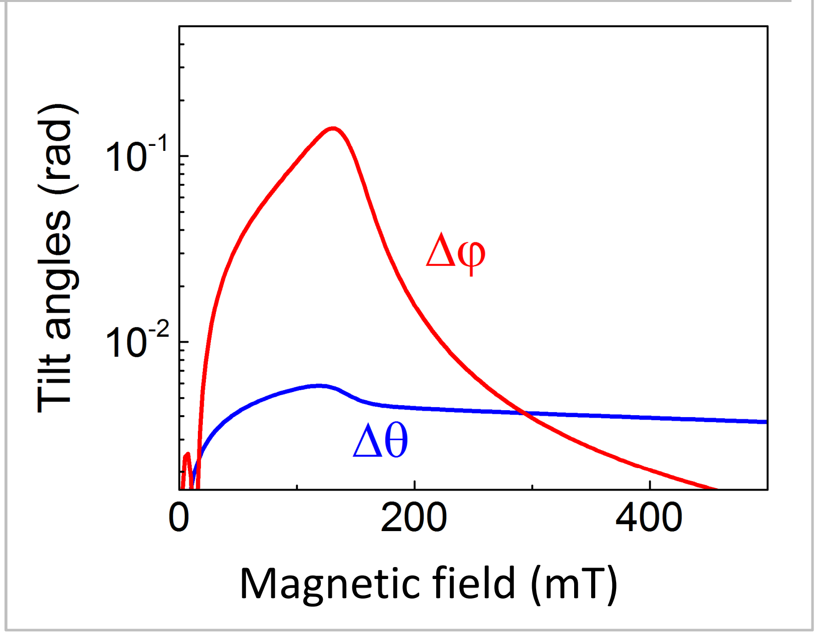
$$+ b_1\left(\varepsilon_{x'x'} m_{x'}^2 + \varepsilon_{y'y'} m_{y'}^2 + \varepsilon_{z'z'} m_{z'}^2\right) + b_2(\varepsilon_{x'y'} m_{x'} m_{y'} + \varepsilon_{x'z'} m_{x'} m_{z'} + \varepsilon_{y'z'} m_{y'} m_{z'})$$

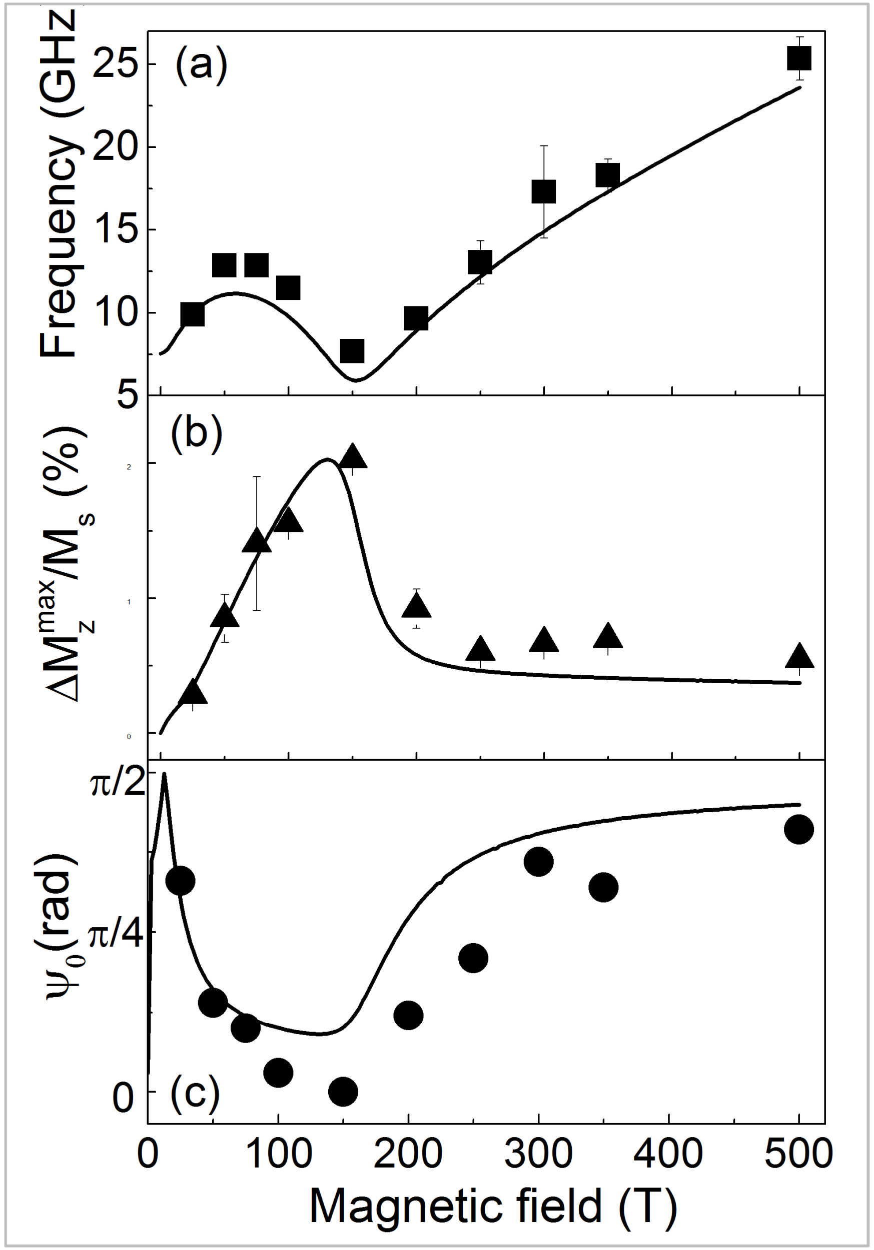
strain-dependent terms

Laser-induced change of anisotropy in a metallic film



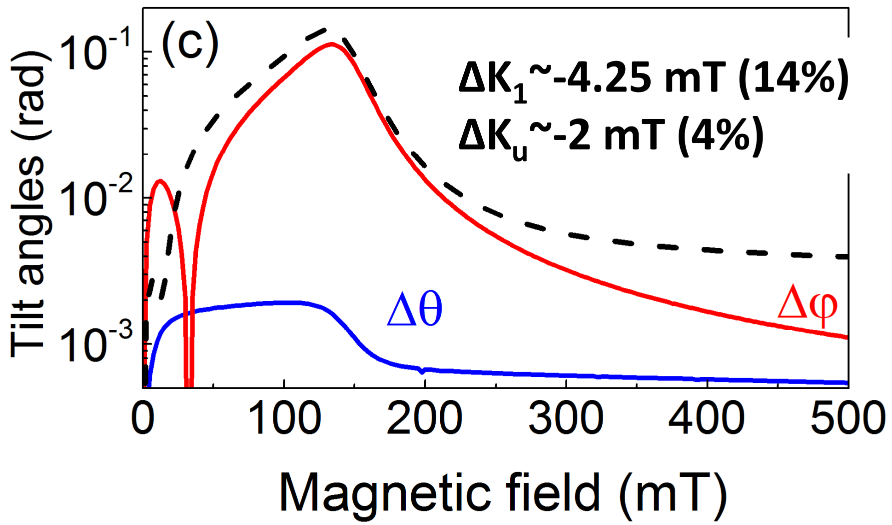
Laser-induced tilt of the effective field



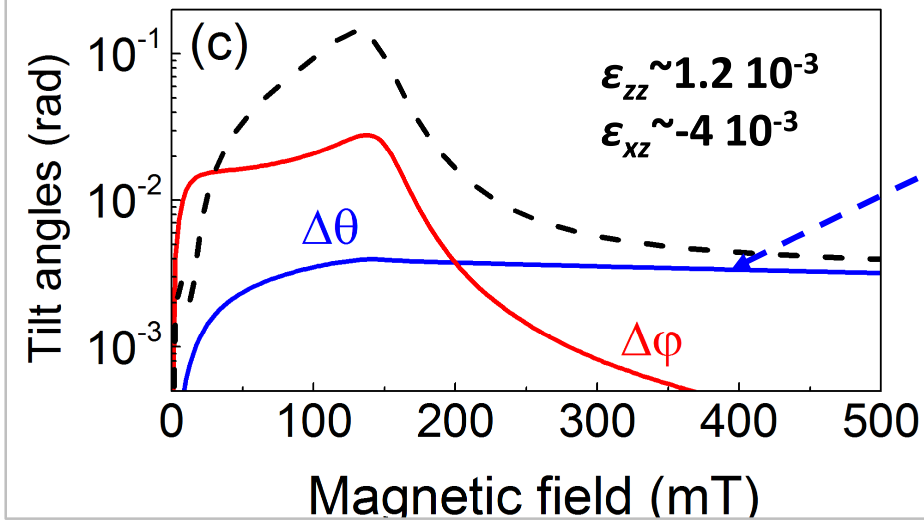


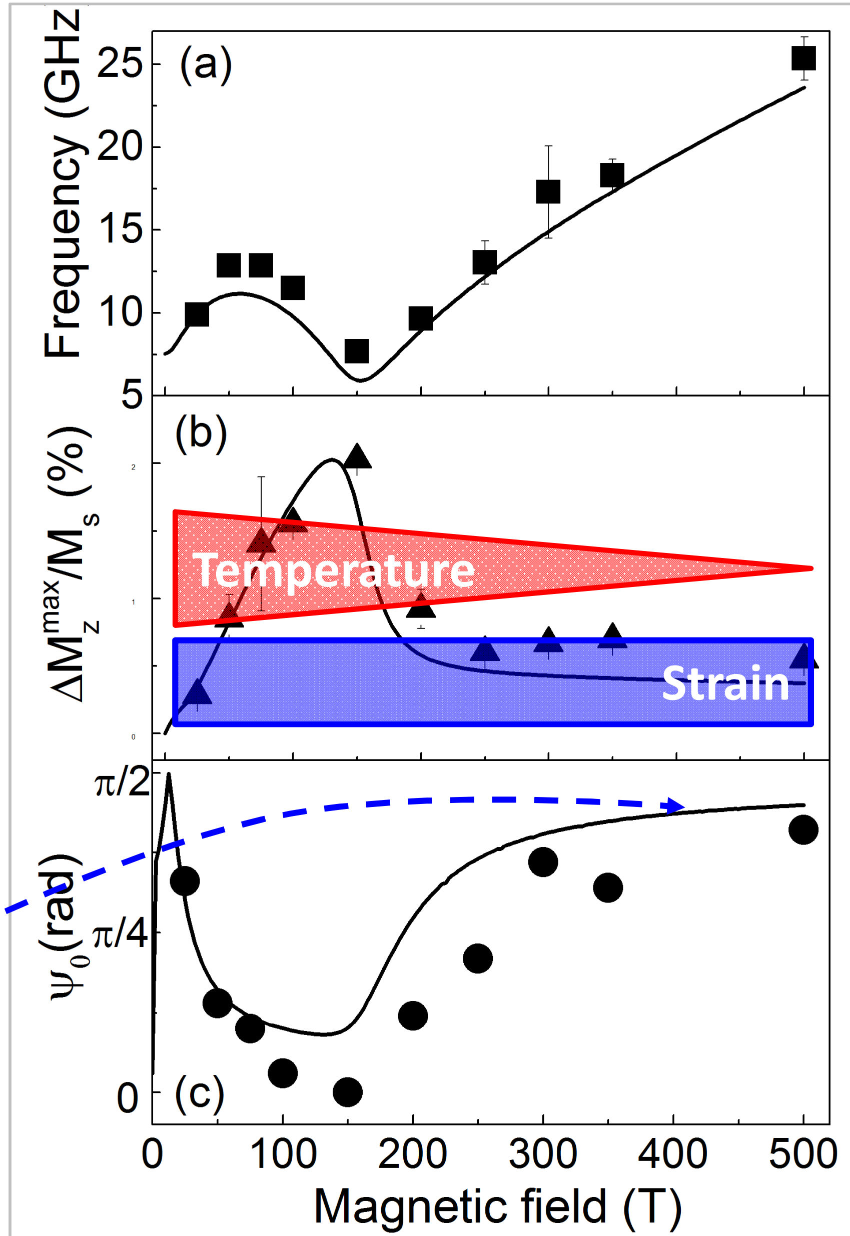
Laser-induced change of anisotropy in a metallic film

Contribution from the lattice temperature

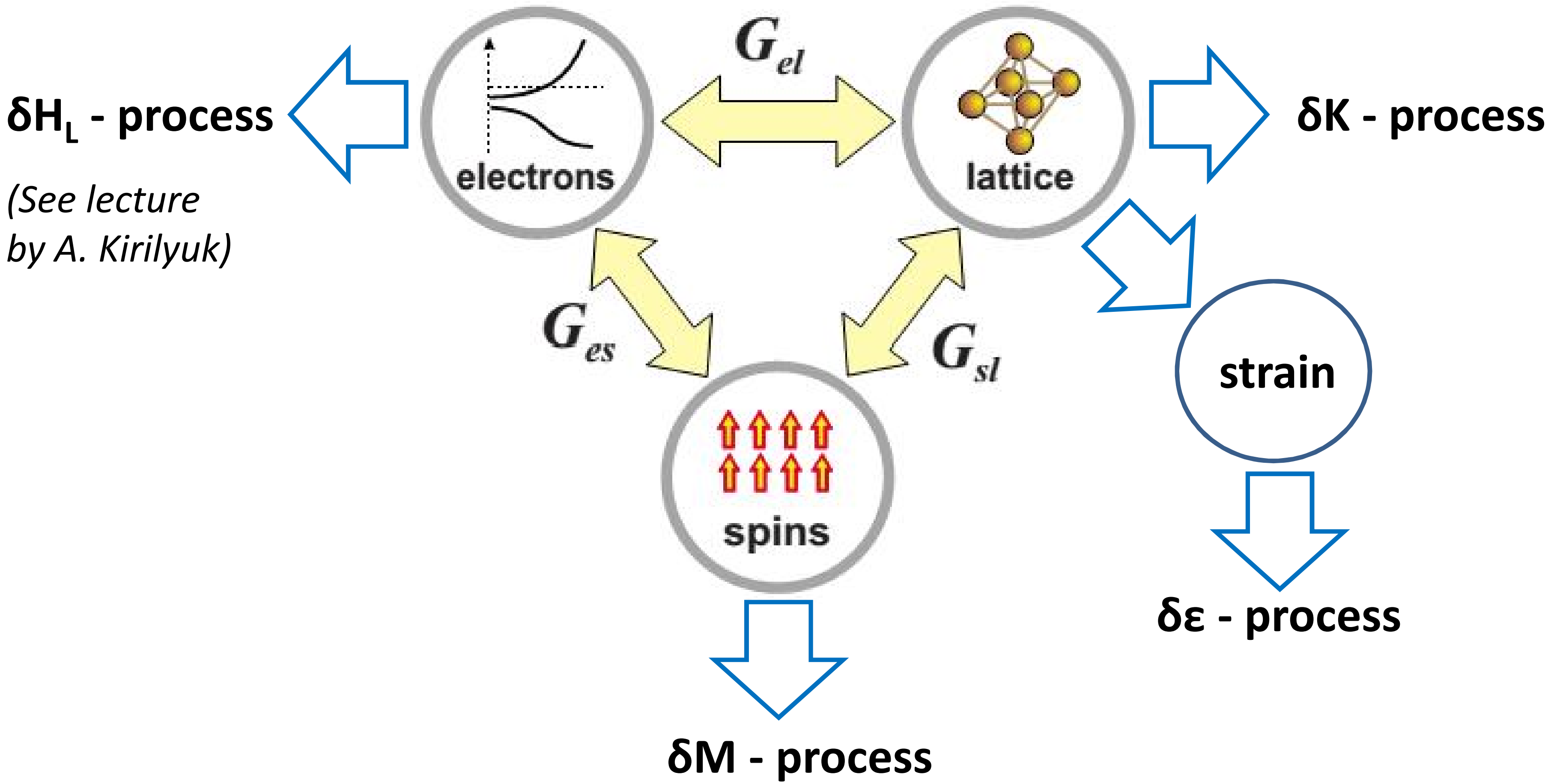


Contribution from the strain





Mechanisms of laser-induced changes of magnetic anisotropy



Light-induced (de)magnetization processes and all-optical switching

THE EUROPEAN SCHOOL ON MAGNETISM

Alexandra Kalashnikova

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Ioffe Institute

FERROLAB

Experimental approaches

How one gets a time resolution

How one measures ultrafast magnetization dynamics

Laser-induced demagnetization

Experimental observation

Theories

Laser-induced changes of magnetic anisotropy

Through demagnetization

Through lattice heating

Through strain

Ultrafast opto-magnetic effects

Opto-magnetic effects and Impulsive stimulated Raman scattering

Control of magnetization via opto-magnetic effects

Laser-driven spin transport

Light-induced (de)magnetization processes and all-optical switching

Ultrafast opto-magnetic effects

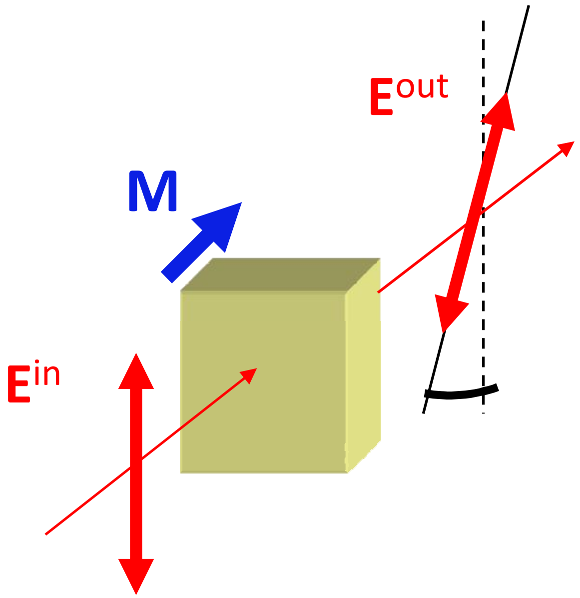
Opto-magnetic effects and Impulsive stimulated Raman scattering

Control of magnetization via opto-magnetic effects

Interaction of light with a magnetic medium

$$\Phi_{\text{int}} = \varepsilon_{ij} E_i E_j^* + \alpha_{ijk} E_i E_j^* M_k + \beta_{ijkl} E_i E_j^* M_k M_l + \ldots$$

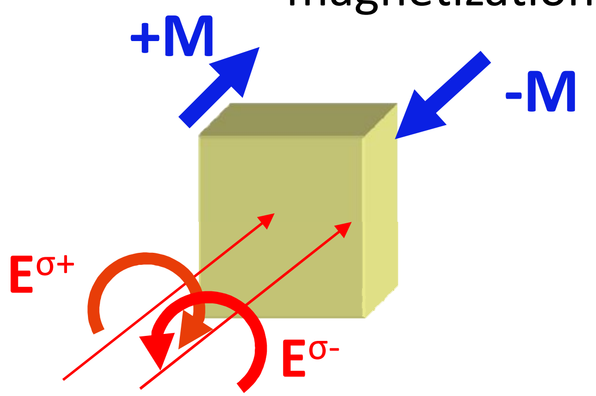
Faraday effect



[M. Faraday, 1845]

$$\Delta n_{\sigma^+ - \sigma^-} \sim \alpha_{xyz} M_z$$

Inverse Faraday effect



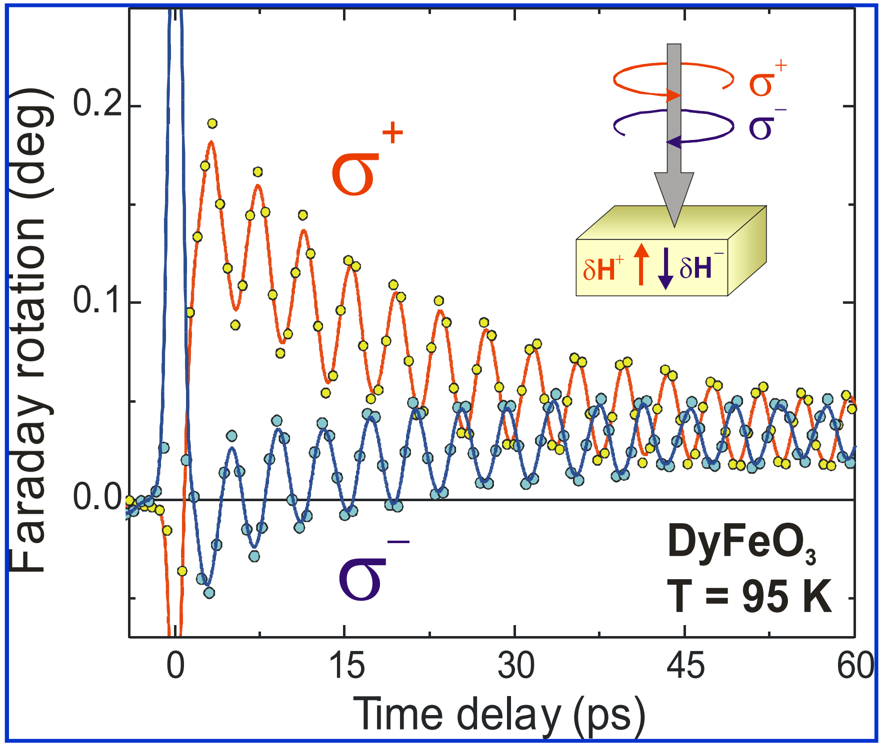
*[Pitaevskii, Sov. Phys. JETP **12**, 1008 (1961)*
*van der Ziel PRL. **15**, 190 (1965)]*

$$\mathbf{M} \sim \alpha_{xyz} \mathbf{E} \times \mathbf{E}^*$$

What about short laser pulses and magnetic medium?

Ultrafast inverse Faraday effect

$DyFeO_3$



[A. V. Kimel et al., Nature (2005)]

Laser-induced
femtosecond pulse
of an effective magnetic field

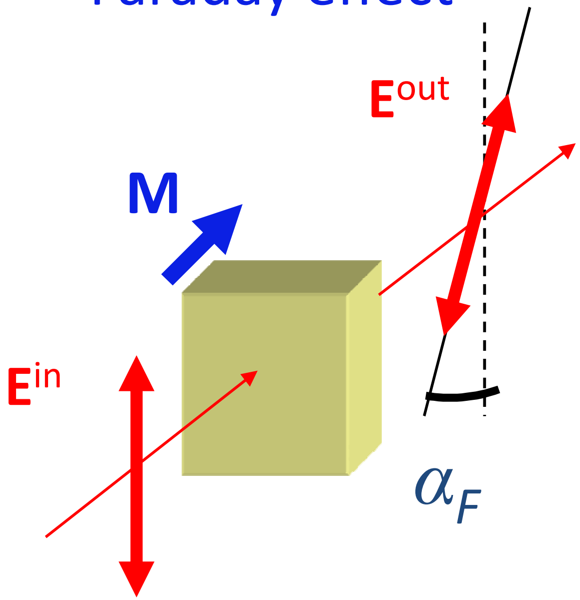
$$\mathbf{H}_{eff} \sim \alpha_{xyz} \mathbf{E} \times \mathbf{E}^*$$

Ultrafast
inverse Faraday effect

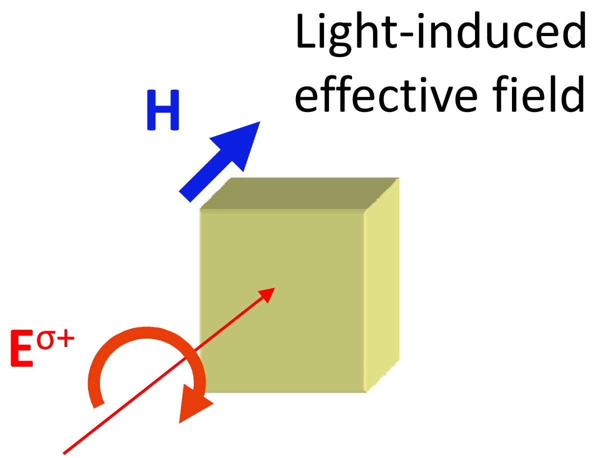
Controlling the phase of the coherent spin precession by circularly-polarized light

Ultrafast opto-magnetic effects

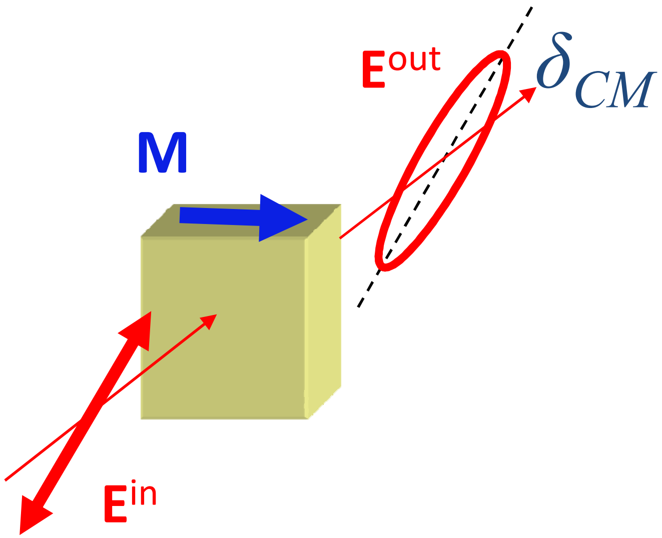
Faraday effect



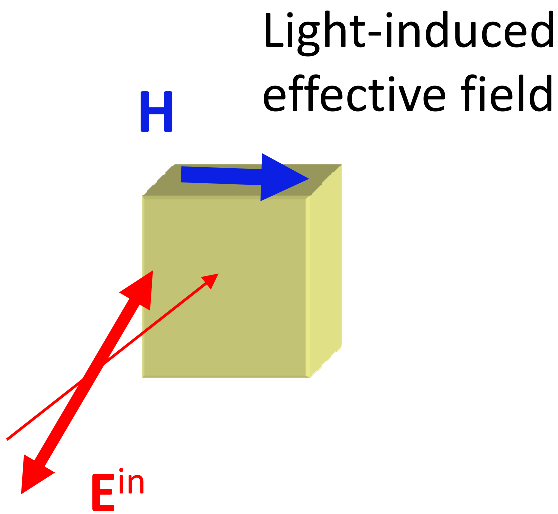
Inverse Faraday effect



Voigt (Cotton-Mouton) effect

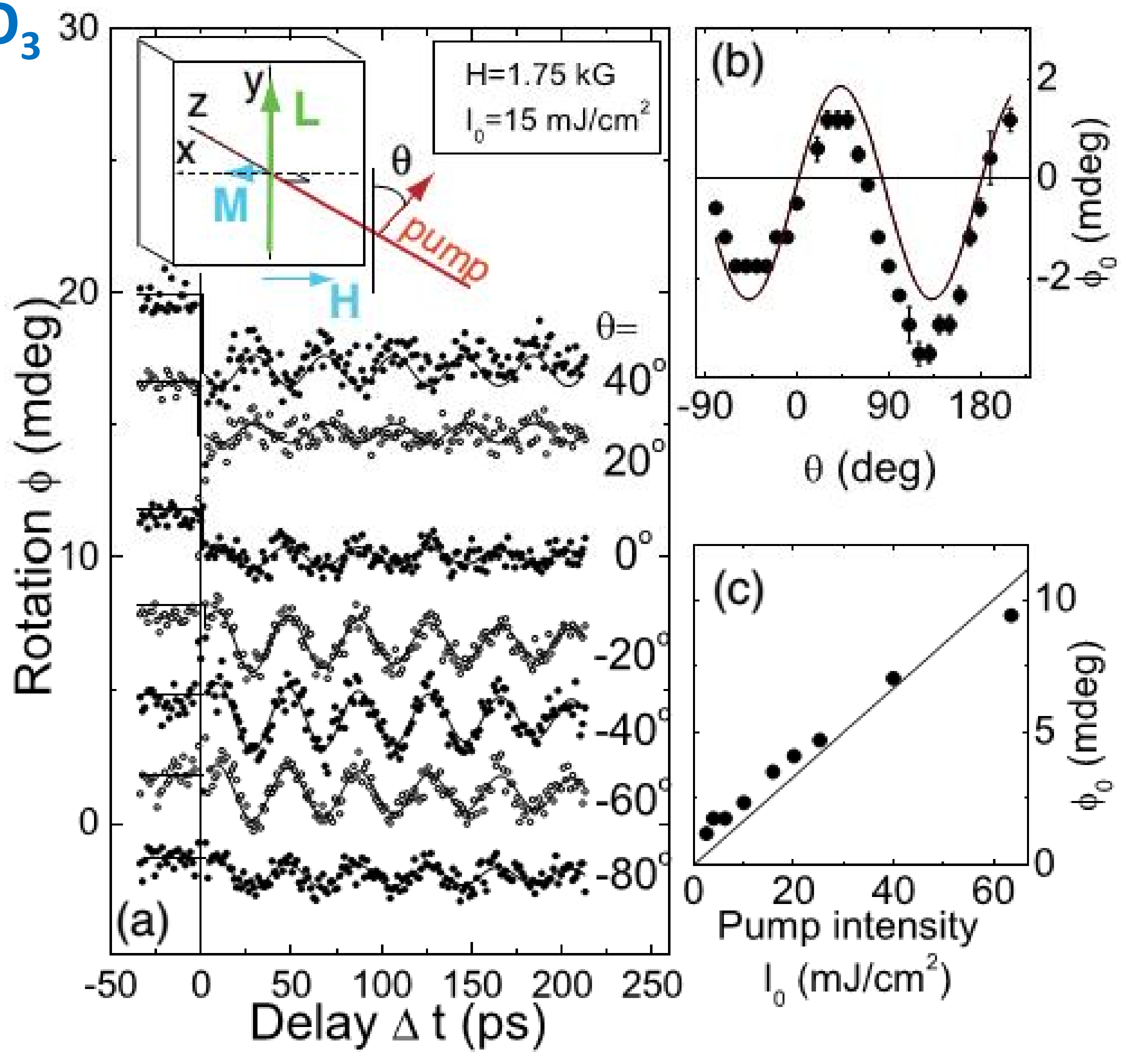


Inverse Cotton-Mouton effect



Ultrafast inverse Cotton-Mouton effect

$FeBO_3$



Ultrafast inverse Cotton-Mouton effect

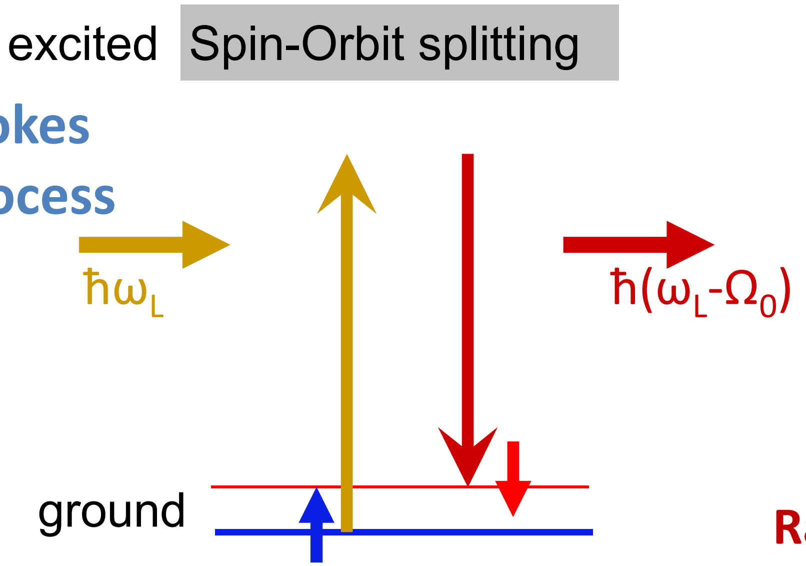
$$H_y^{\text{eff}} \sim \beta_{xyxy_E} E_x E_y^* M_x$$

[A. M. Kalashnikova et al., PRL (2007), PRB (2008)]

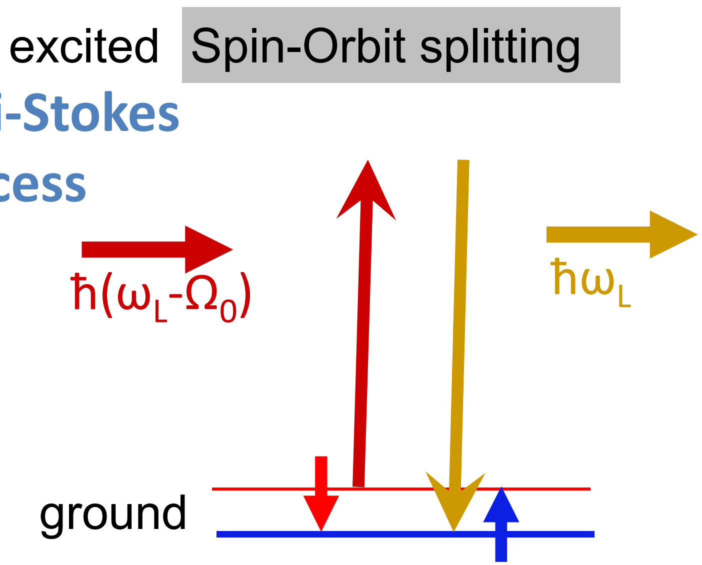
Controlling the phase of the coherent spin precession by linearly-polarized light

Spontaneous Raman scattering on magnons

Stokes process



Anti-Stokes process



Excitation/annihilation of a magnon

Induced electric dipole:

$$\vec{p} = \alpha_0 \vec{E}_L \cos(\omega_L t) +$$

$$\frac{1}{2}\frac{\partial \alpha}{\partial Q}\Big|_{Q_0} \vec{E}_L Q_0 [\cos((\omega_L + \Omega_0)t) +$$

Anti-Stokes process

Raman tensor

$$+ \cos((\omega_L - \Omega_0)t)]$$

Stokes process

α - polarizability

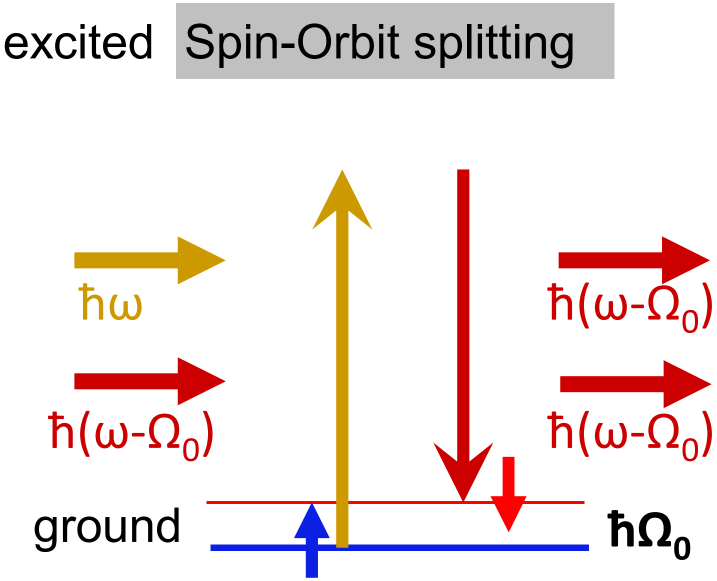
Normal coordinate:

$$Q = (2\gamma M_0)^{-1/2}(M_x + iM_y)$$

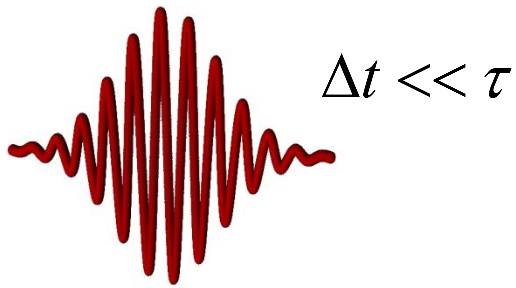
(an example for a 1-sublattice ferromagnet)

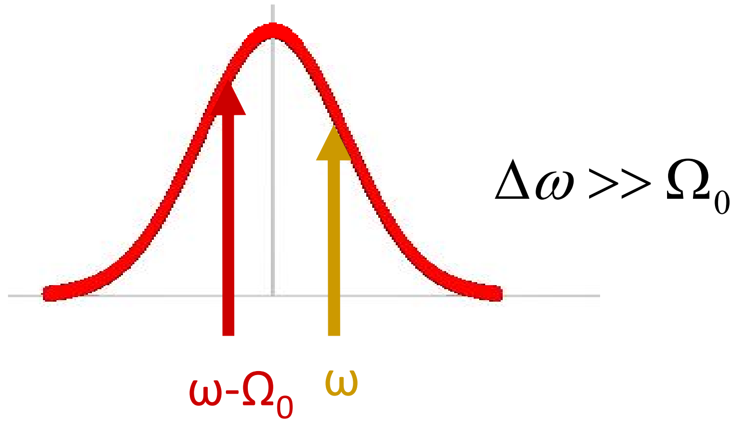
Stimulated Raman scattering with femtosecond pulses

Stimulated Raman scattering on magnons



When the laser pulse is shorter than spin precession period



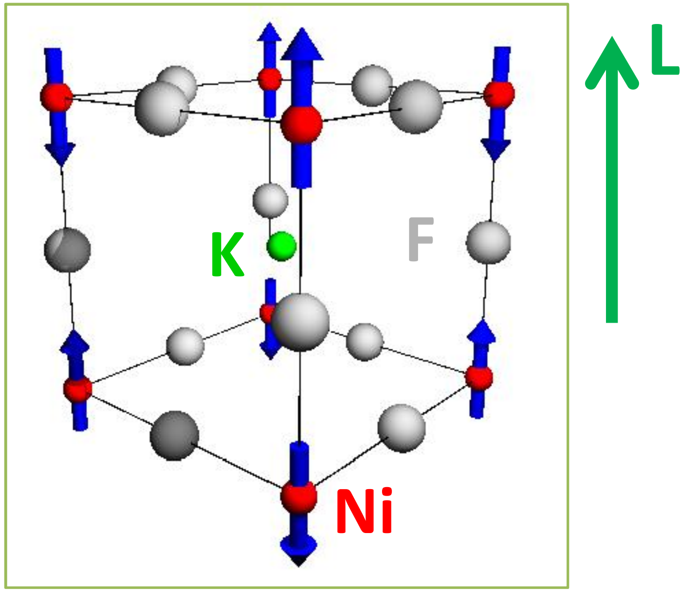


Impulsive stimulated Raman scattering (ISRS) on magnons

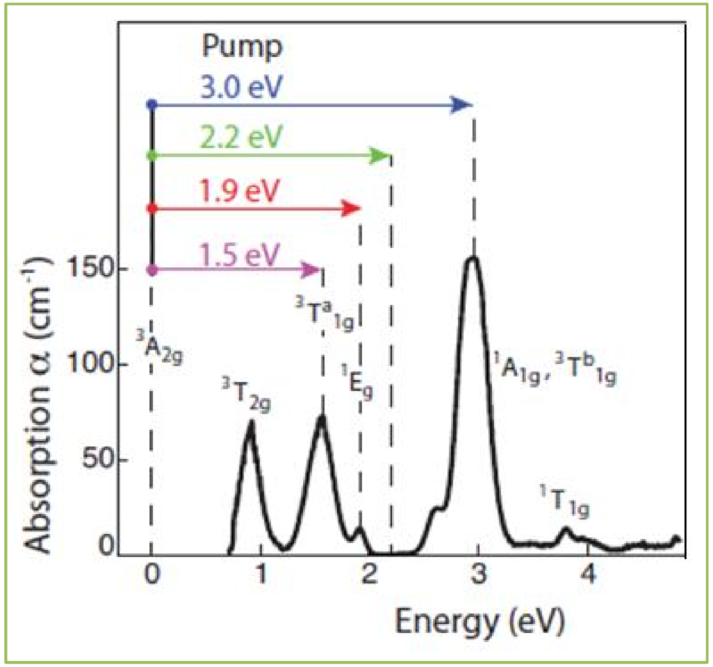
[A. M. Kalashnikova et al., PRL (2007), PRB (2008); V. N. Gridnev, PRB (2008)]

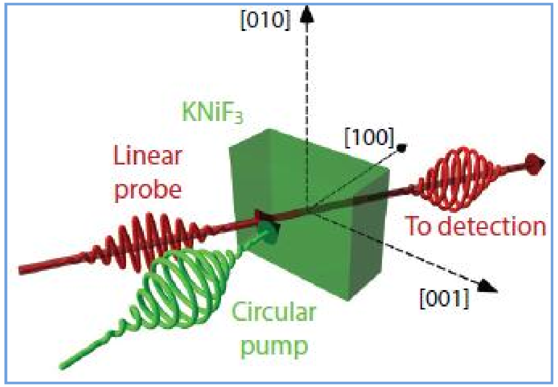
A role of absorption in the magnon excitation?

$KNiF_3$



T_N=246 K H_{ex}/H_A=10^5

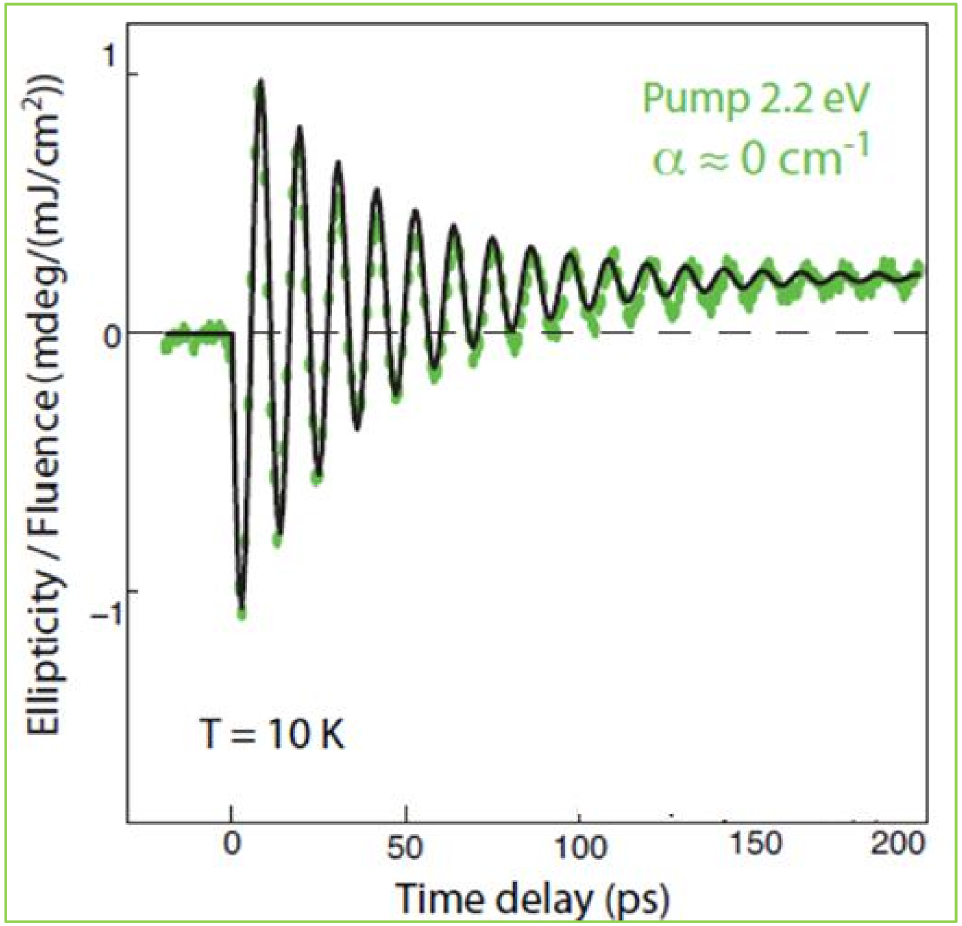


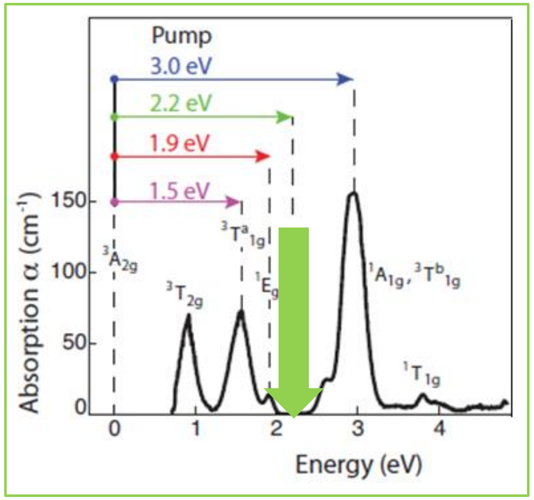


Approach: tuning the pump wavelength between transparency windows and absorption bands

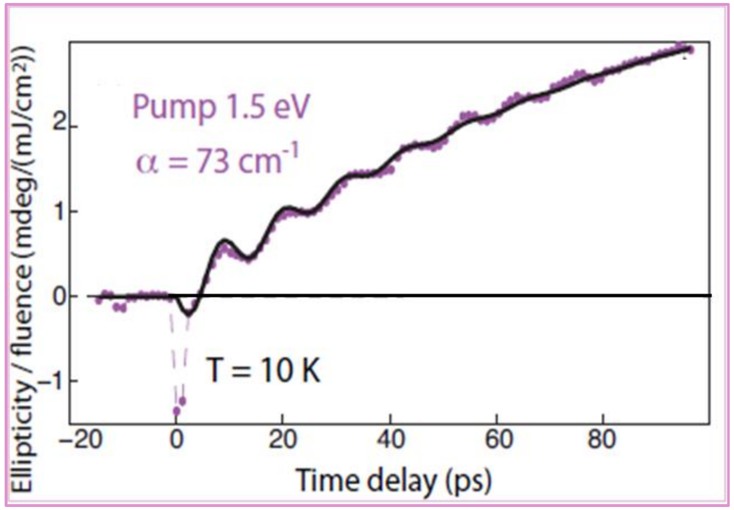
*[D. Bossini et al., PRB **89**, 060405(R) (2014)]*

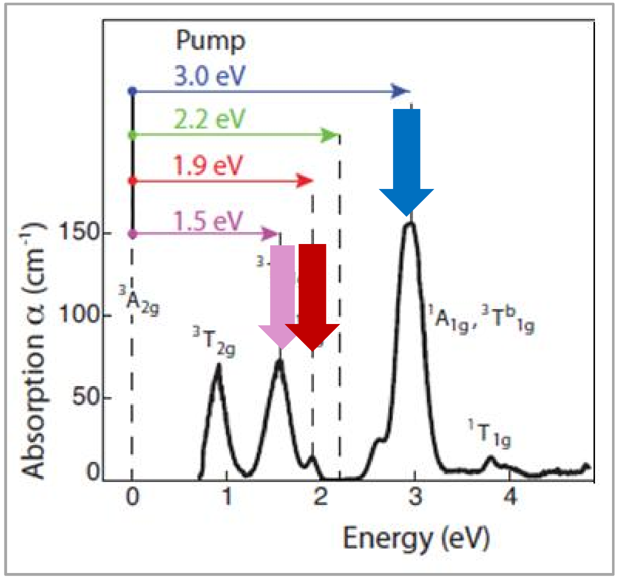
Excitation of magnons without absorption



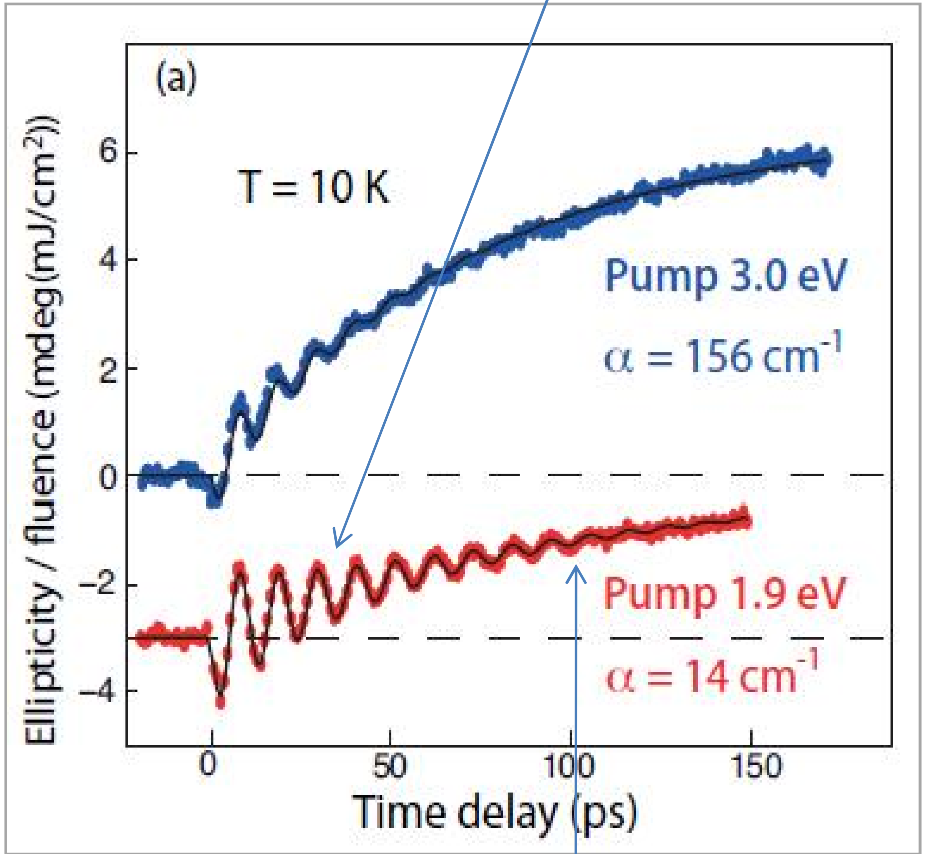


How does absorption affects the process of excitation?



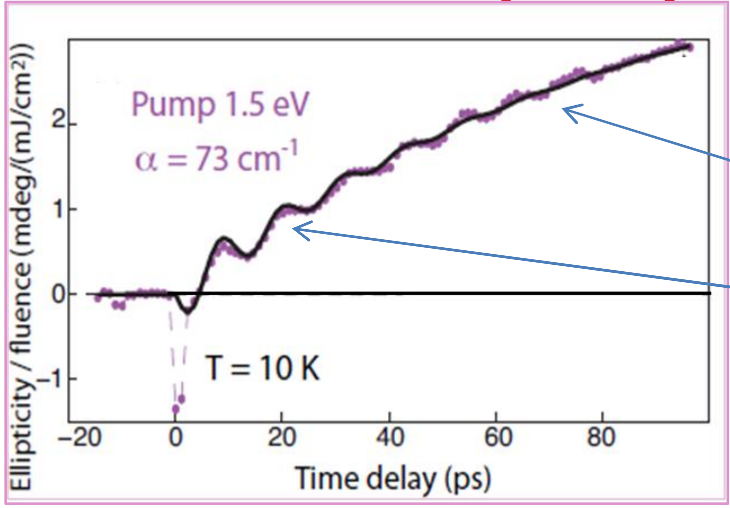


Coherent magnons excited via ISRS



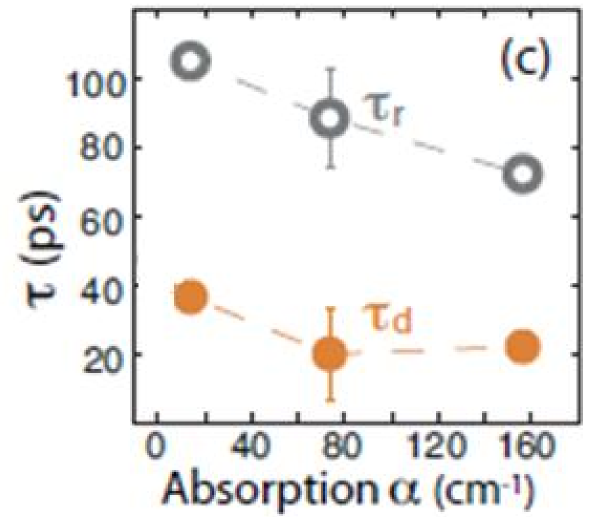
decrease of |L| due to laser-induced heating

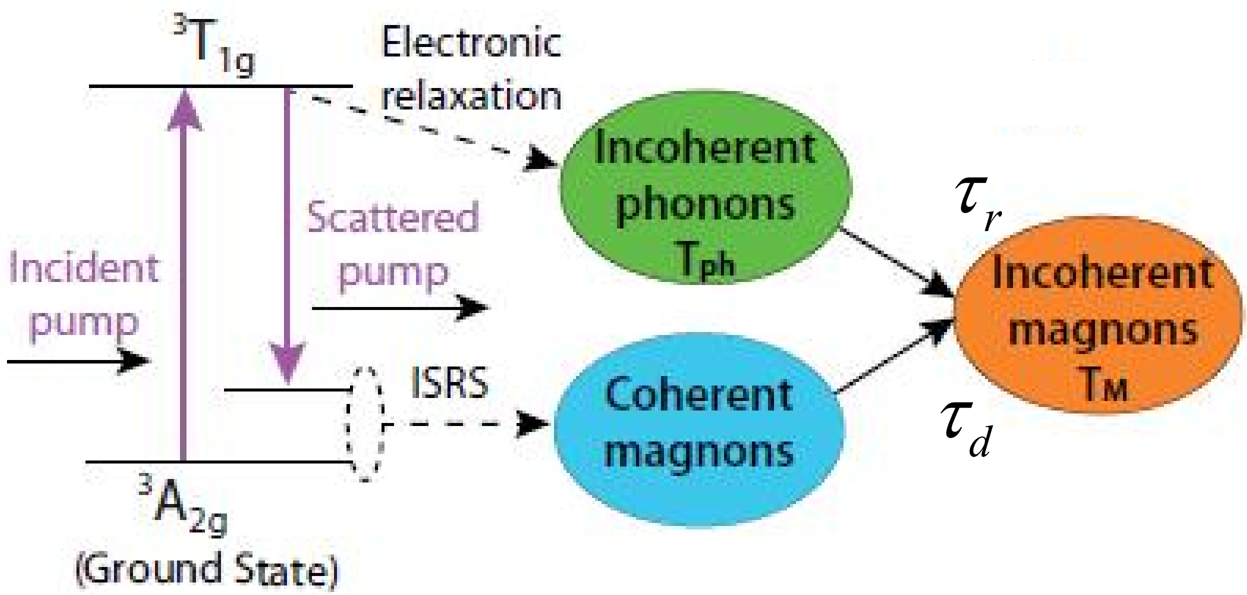
Mechanism of excitation of coherent and incoherent spin dynamics



$B(1-e^{-t/\tau_r})$

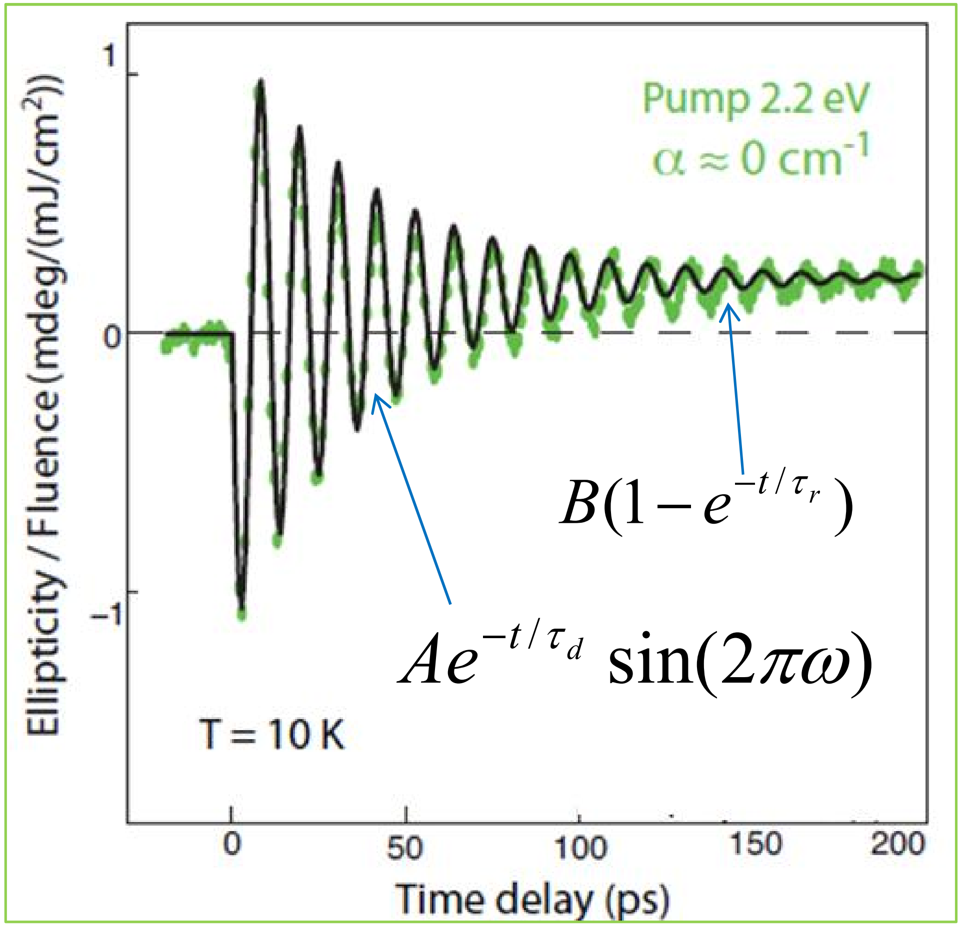
$Ae^{-t/\tau_d}\sin(2\pi\omega)$

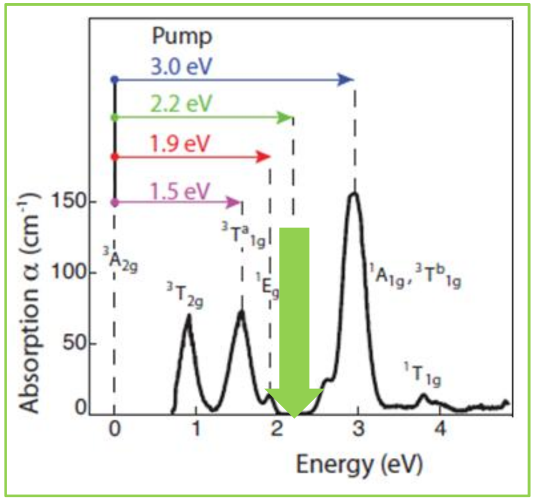


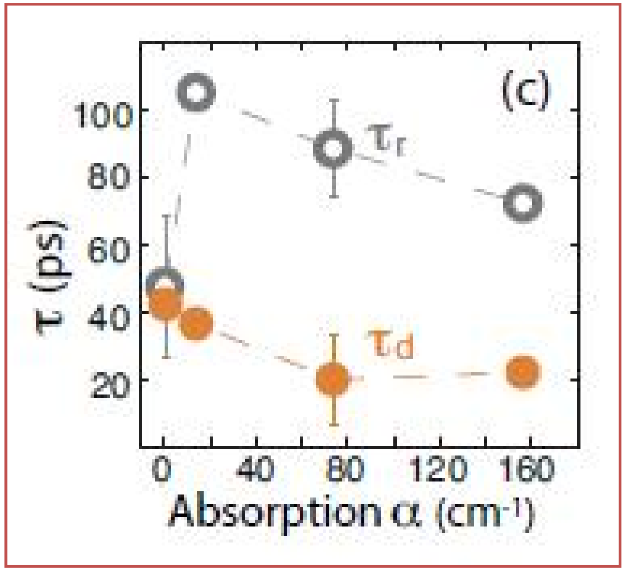


Absorption results in excitation of incoherent magnons (demagnetization) mediated by lattice heating

Excitation of spin system: regime of zero-absorption



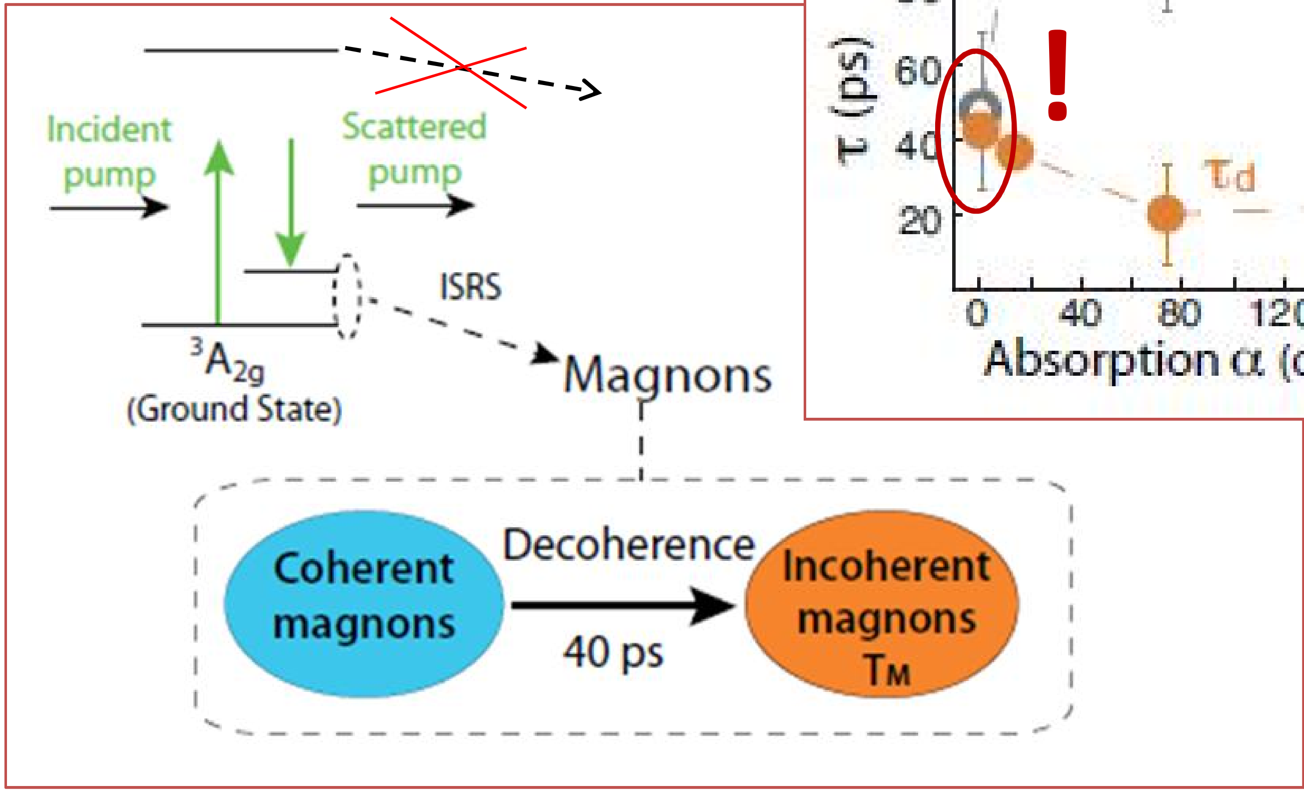


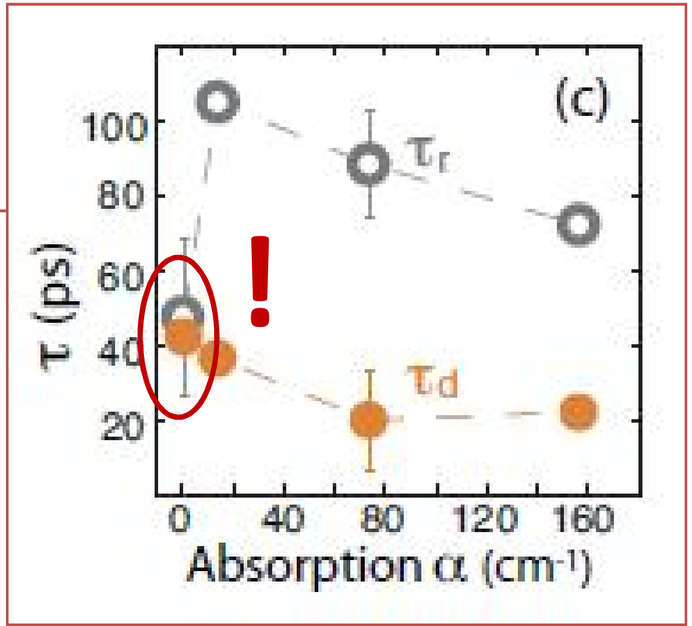


Coherent magnons excited via ISRS
and decrease of |**L**| due to …. ?

Extra channel for demagnetization in a transparent dielectric

Selective optical excitation of spins





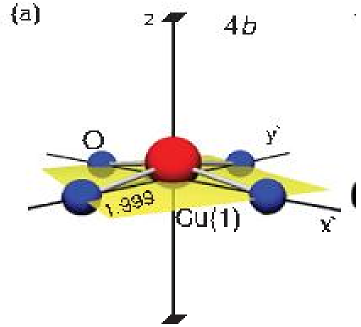
Criterion: $\tau_r = \tau_d$

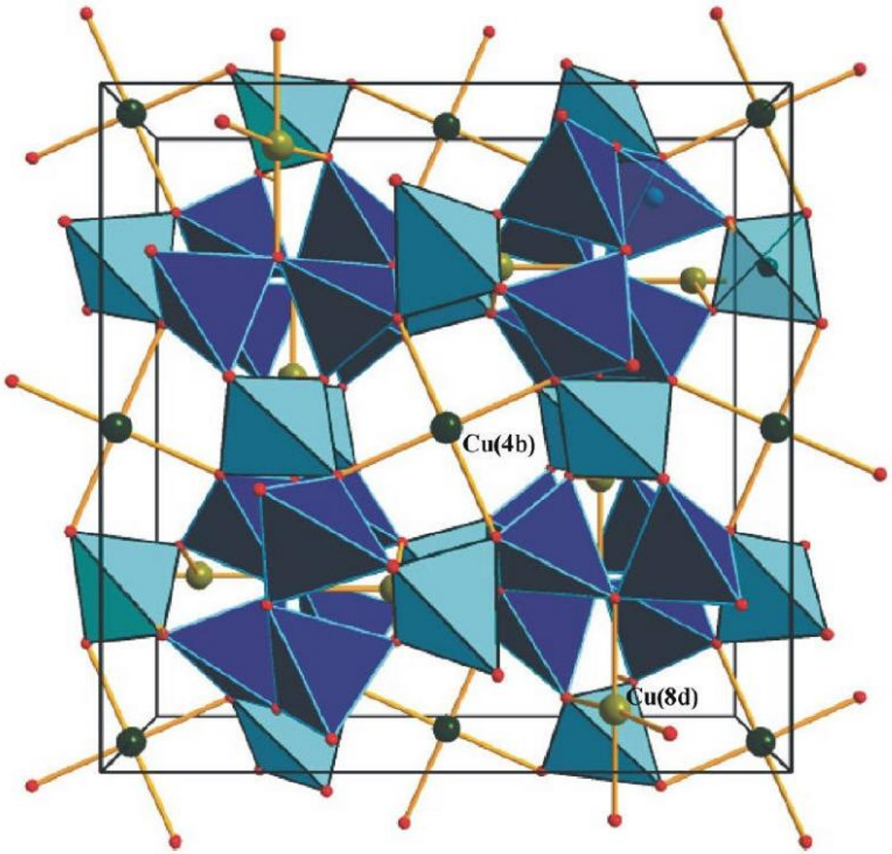
A brief detour: Raman scattering and ISRS (on phonons) and the link between them

Coherent optical phonons via ISRS:
Merlin, Solid State Commun. ***102****, 207 (1997)*
Dhar, et al., Chem. Rev. ***94****, 157 (1994)*
Yan and Nelson, J. Chem. Phys. ***87****, 6257 (1987)*

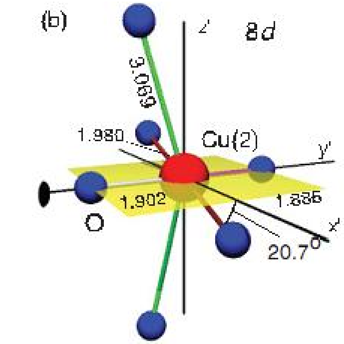
Crystal structure of CuB_2O_4

4b





8d

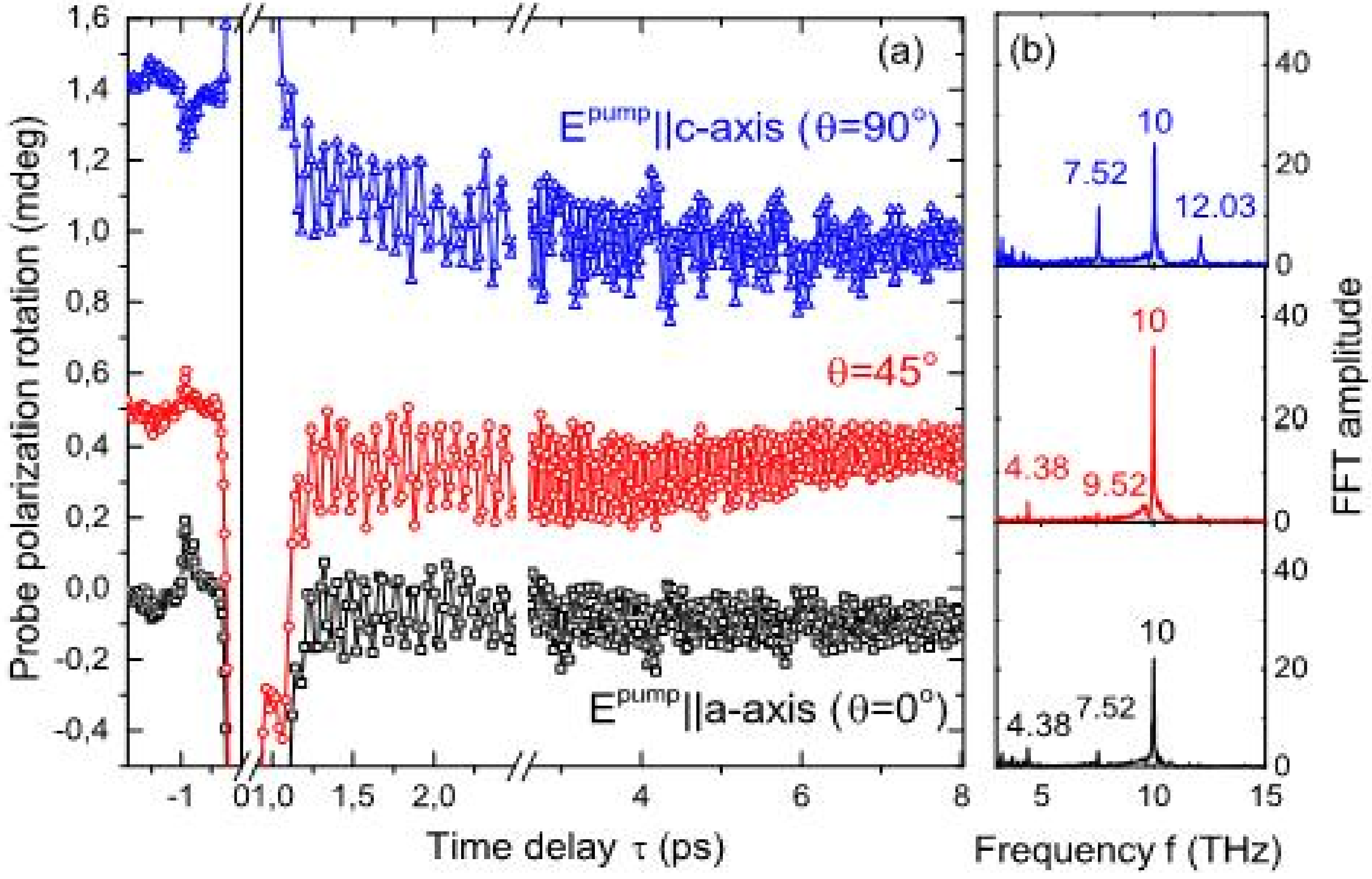


123 optical phonon above above 4 THz

P.G.-*42m*; S.G. *I-42d*; *Z*=12; Cu^{2+} ions in 4*b* and 8*d* positions.

[Garcia et al Acta Cryst (1971)]

Excitation of coherent phonons in CuB_2O_4 via impulsive stimulated Raman scattering



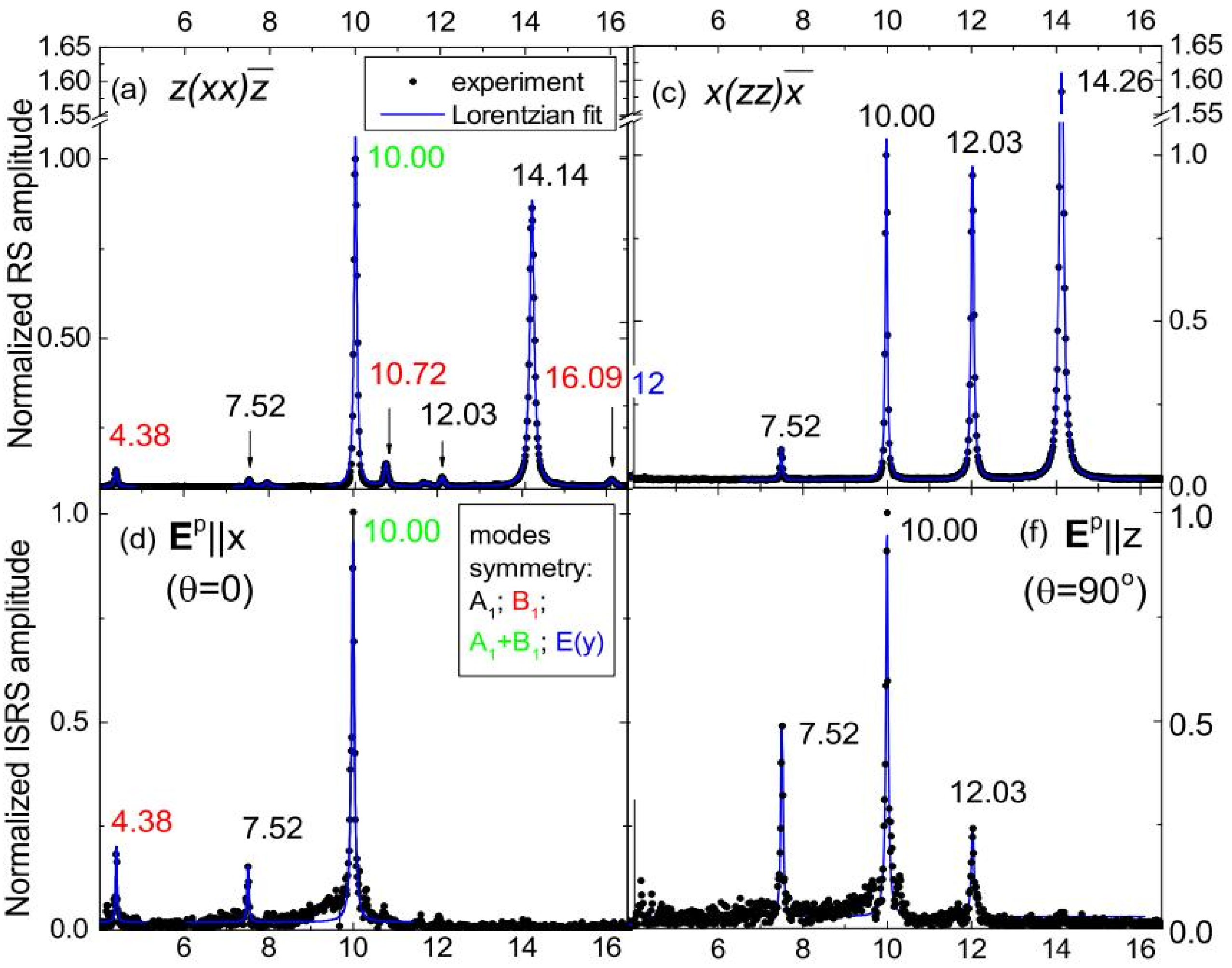
FFT reveals several phonon modes

[Imasaka et al., PRB ***98****,* 054303 (2018)]

Spontaneous and impulsive stimulated Raman scattering

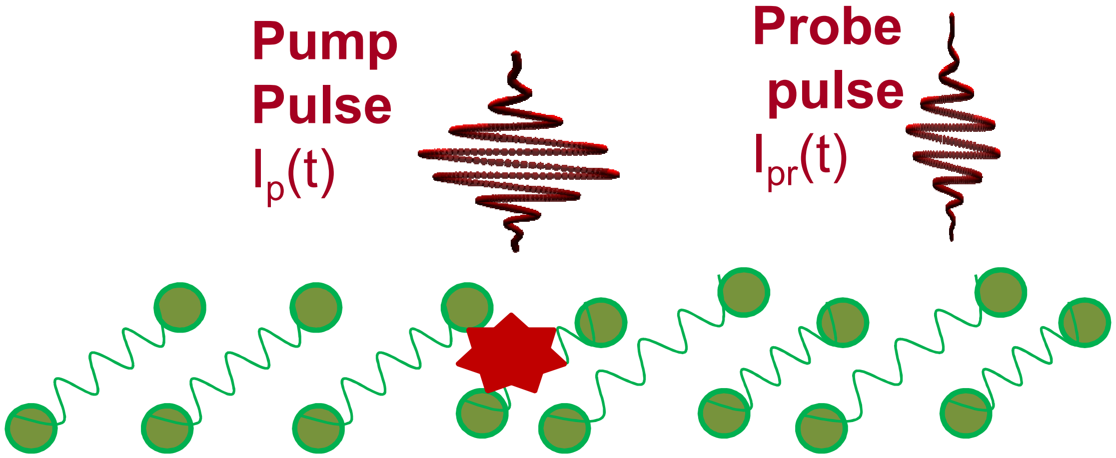
Spontaneous Raman scattering spectra

FFT spectra of the pump-probe data



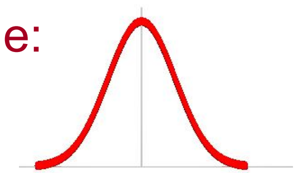
Why are the amplitudes so different?

Excitation and detection of coherent phonons in the ISRS experiment



Pulse profile:

$\tau \rightarrow \sigma$



Q(t) is the phonon normal coordinate

1. Excitation via ISRS:

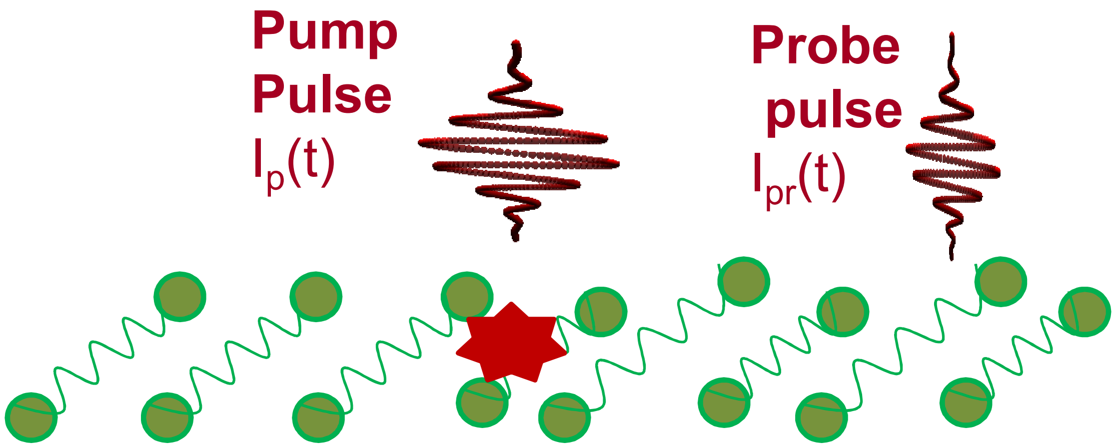
Dependence on the polarization and intensity

$$\frac{d^2Q}{dt^2} + \Omega_0^2 Q = \frac{1}{4nc} \mathcal{R}_{ij}^{\Omega_0}(\omega_{\mathrm{P}}) I_{\mathrm{P}}^0 \mathrm{Re}[e_i e_j^*] \alpha(\tau_{\mathrm{P}}, \Omega_0),$$

Pump-pulse duration factor

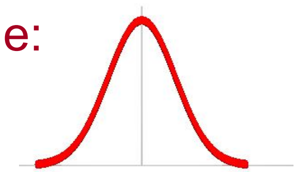
$$\alpha_k(\tau_{\mathrm{P}}, \Omega_0) = \frac{\sqrt{\ln 2}}{\sqrt{\pi}\sigma_{\mathrm{P}}} e^{-\ln 2(\Omega_0^2/\sigma_{\mathrm{P}}^2)}.$$

Excitation and detection of coherent phonons in the ISRS experiment



Pulse profile:

$\tau \rightarrow \sigma$



Q(t) is the phonon normal coordinate

2. Detection via ISRS:

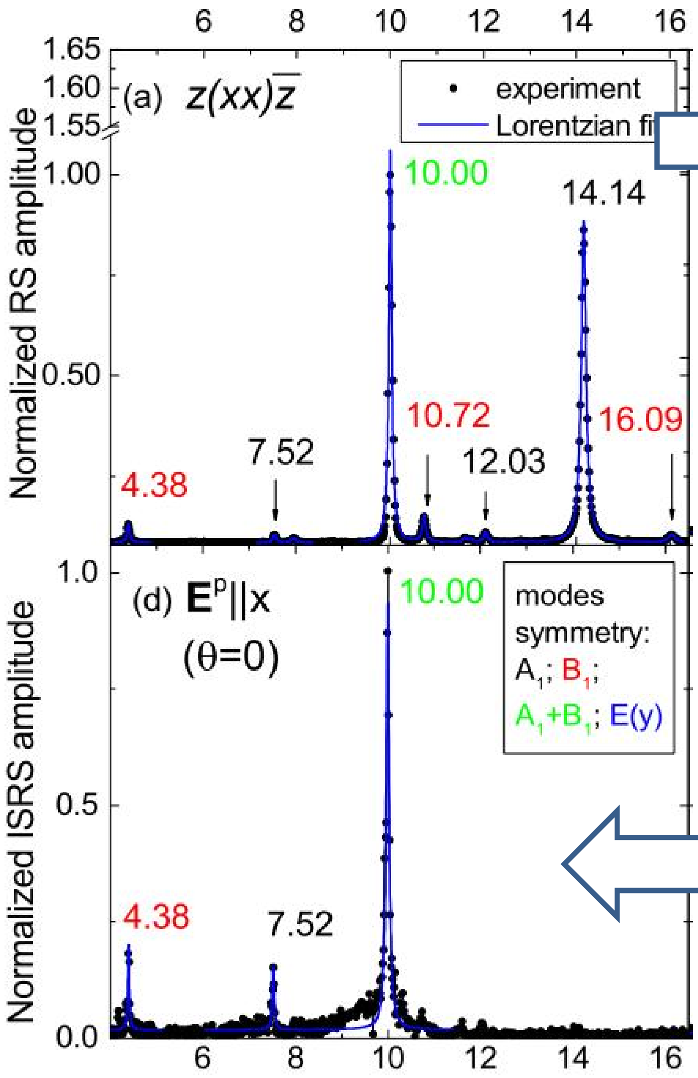
Dependence on the polarization

$$\Delta\eta(t) = \frac{\pi d_0}{\lambda_{\mathrm{pr}}} \frac{\mathcal{R}_{ij}^{\Omega_0}(\omega_{\mathrm{pr}})}{\sqrt{\varepsilon_{ij}}} Q(t) * \frac{I_{\mathrm{pr}}(t)}{I_{\mathrm{pr}}^0},$$

Change of ellipticity. Excited phonons modulate index of refraction

Effect is integrated over the probe-pulse duration

Link between spontaneous Raman intensity spectra and ISRS-driven phonon amplitudes



Extract Raman tensor components
(necessary to account for **phonons population factor**)

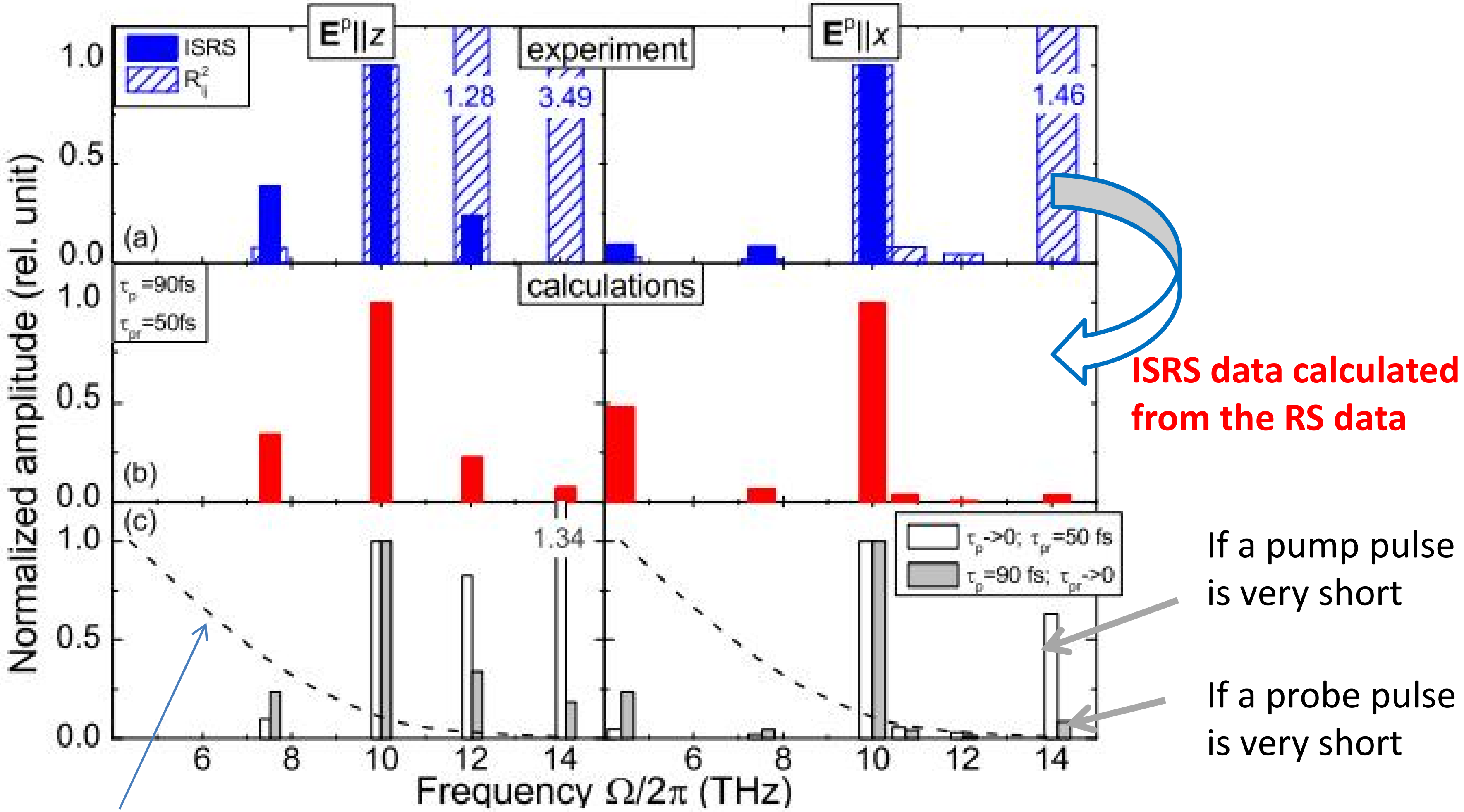
$$C_k \sim (N(\Omega_k)+1)\left[\mathcal{R}_{ij}^{\Omega_k}(\omega)\right]^2$$

Calculate coherent phonon amplitude excited by a pulse of particular duration

Calculate modulation of the probe-pulse polarization of a particular duration (convolution with the probe profile)

Experiment and calculations

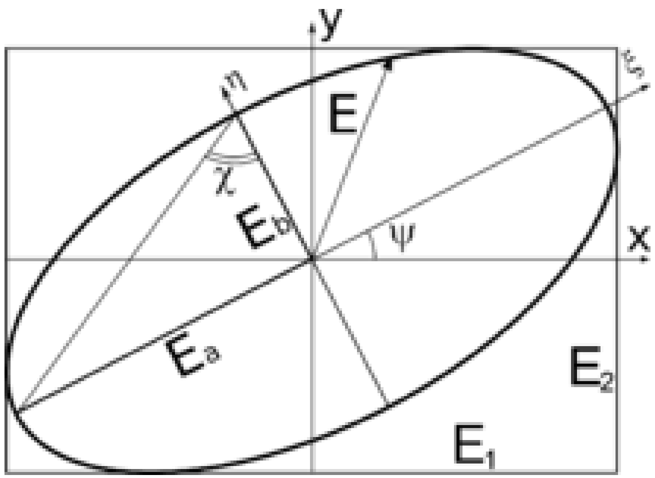
Comparison of ISRS ( ) and SR, R^2_{ij} ( ) experimental results



Pump-pulse duration factor: $$\alpha_k(\tau_p, \Omega_0) = \frac{\sqrt{\ln 2}}{\sqrt{\pi}\sigma_p} e^{-\ln 2(\Omega_0^2/\sigma_p^2)}.$$

Back to ISRS and magnons

Encoding light polarization state in an antiferromagnet

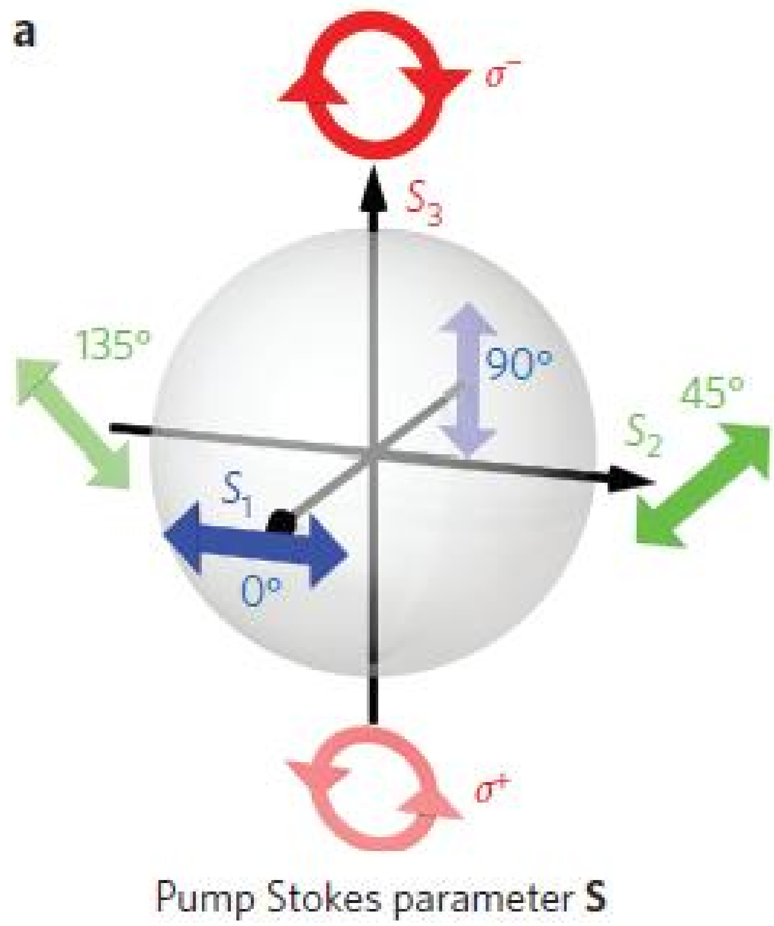


Stokes parameters

$$\begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} I = (E_a^2 + E_b^2) \\ I \cos 2\psi \cos 2\chi \\ I \sin 2\psi \cos 2\chi \\ I \sin 2\chi \end{bmatrix}$$

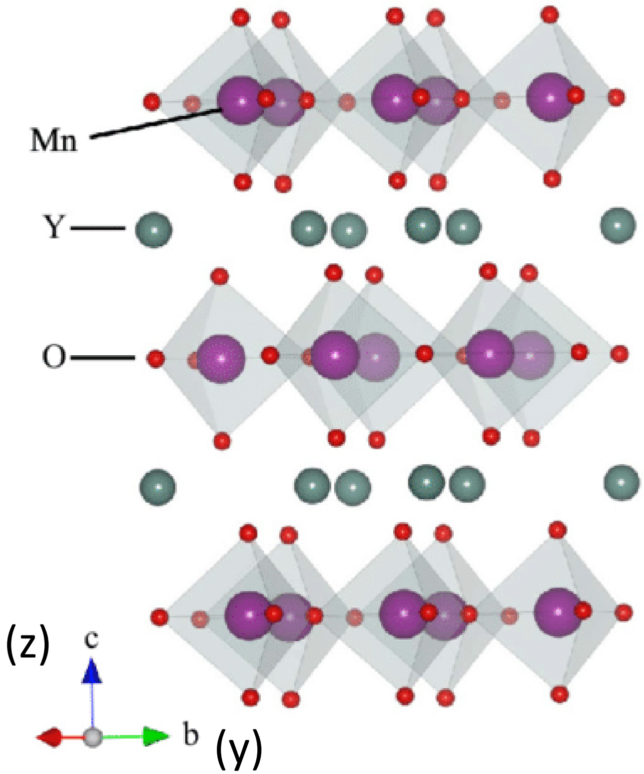
3 Stokes parameters requires three magnon modes

Poincare sphere

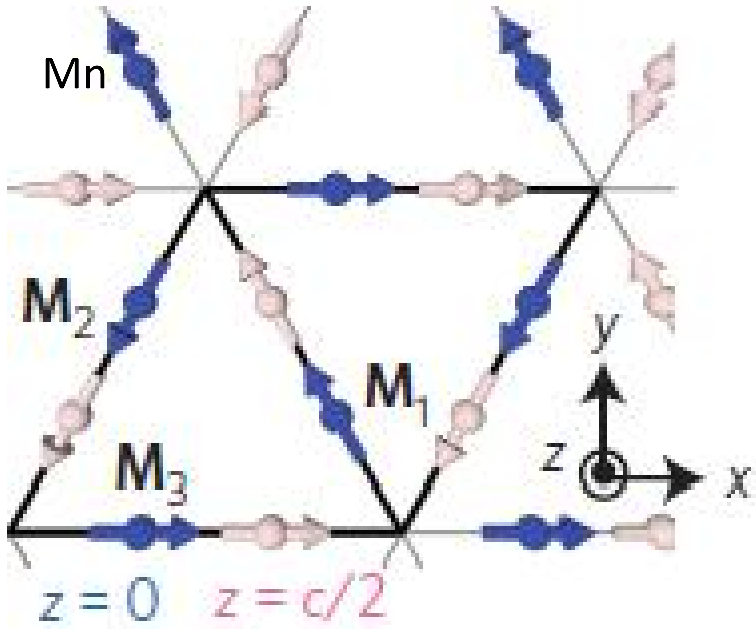


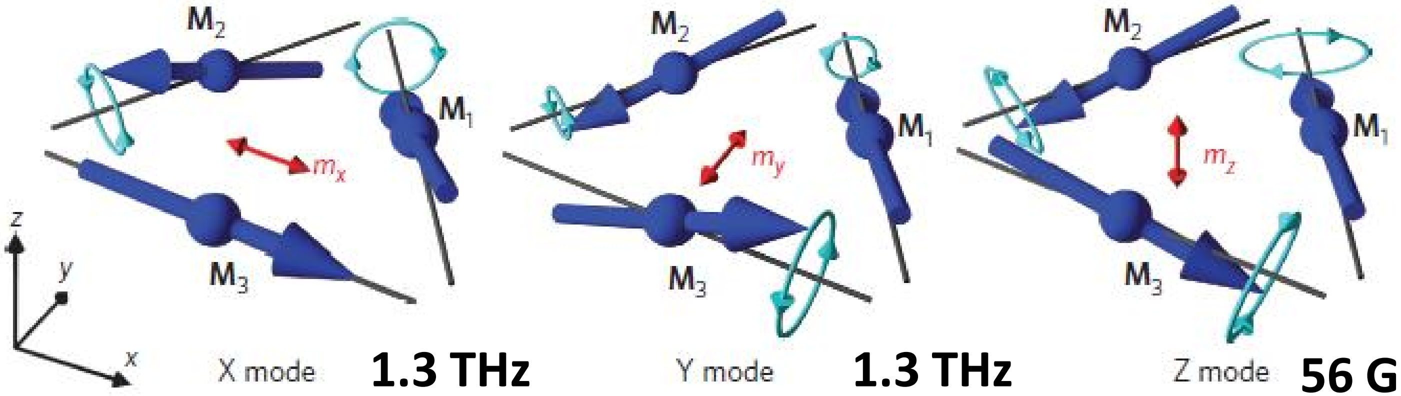
$YMnO_3$: 3-sublattice antiferromagnet

Crystal structure



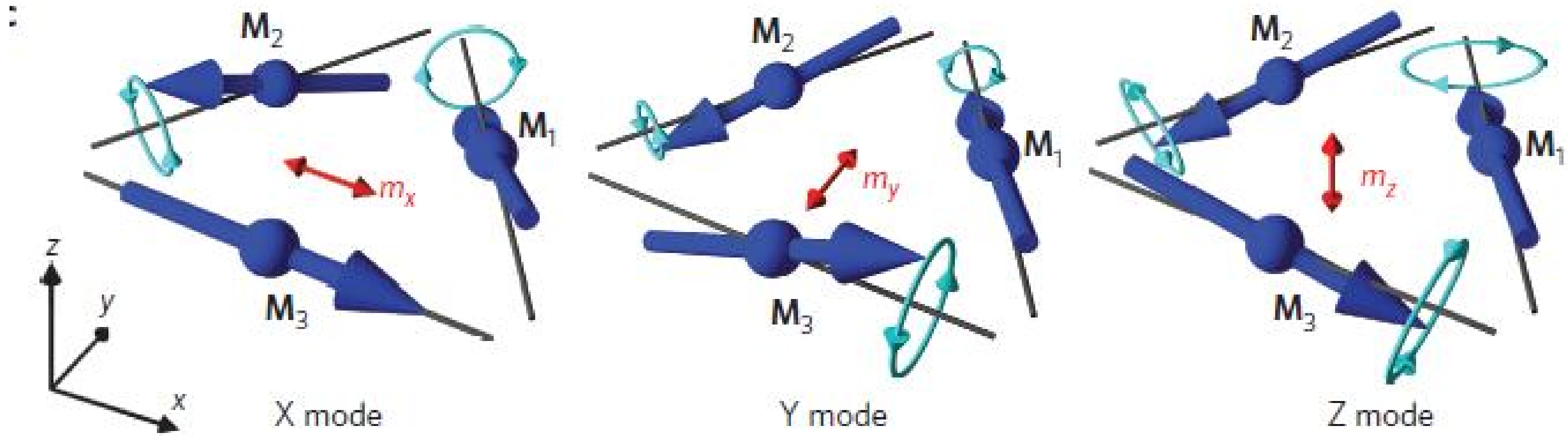
Magnetic structure

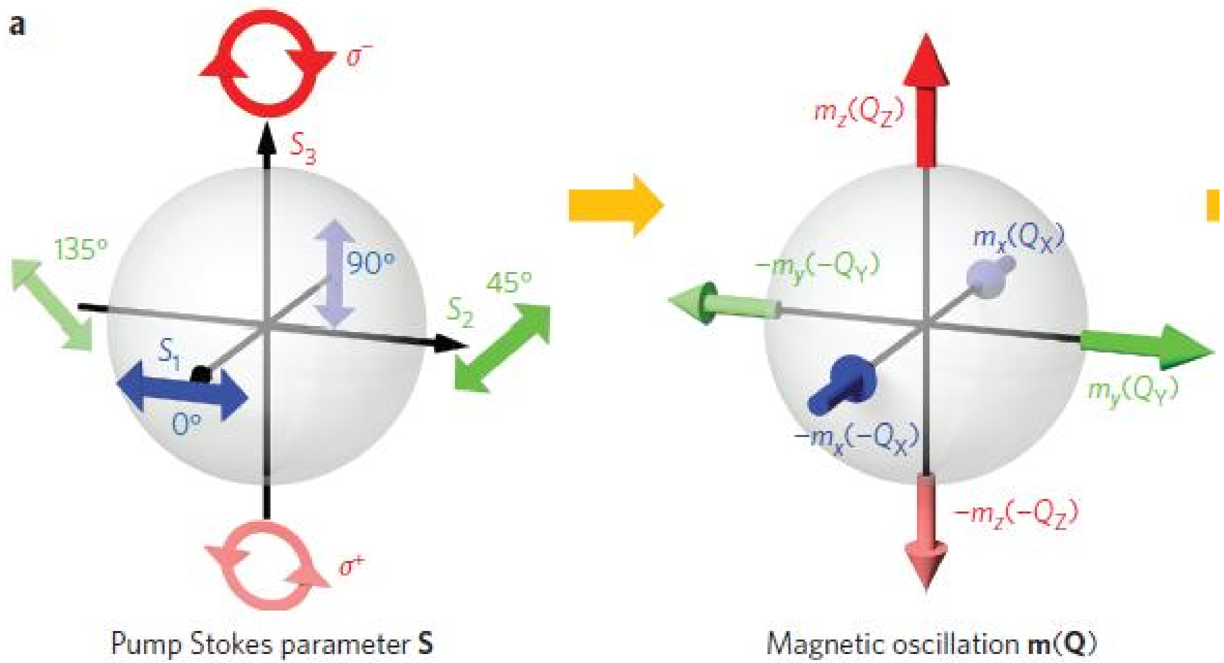




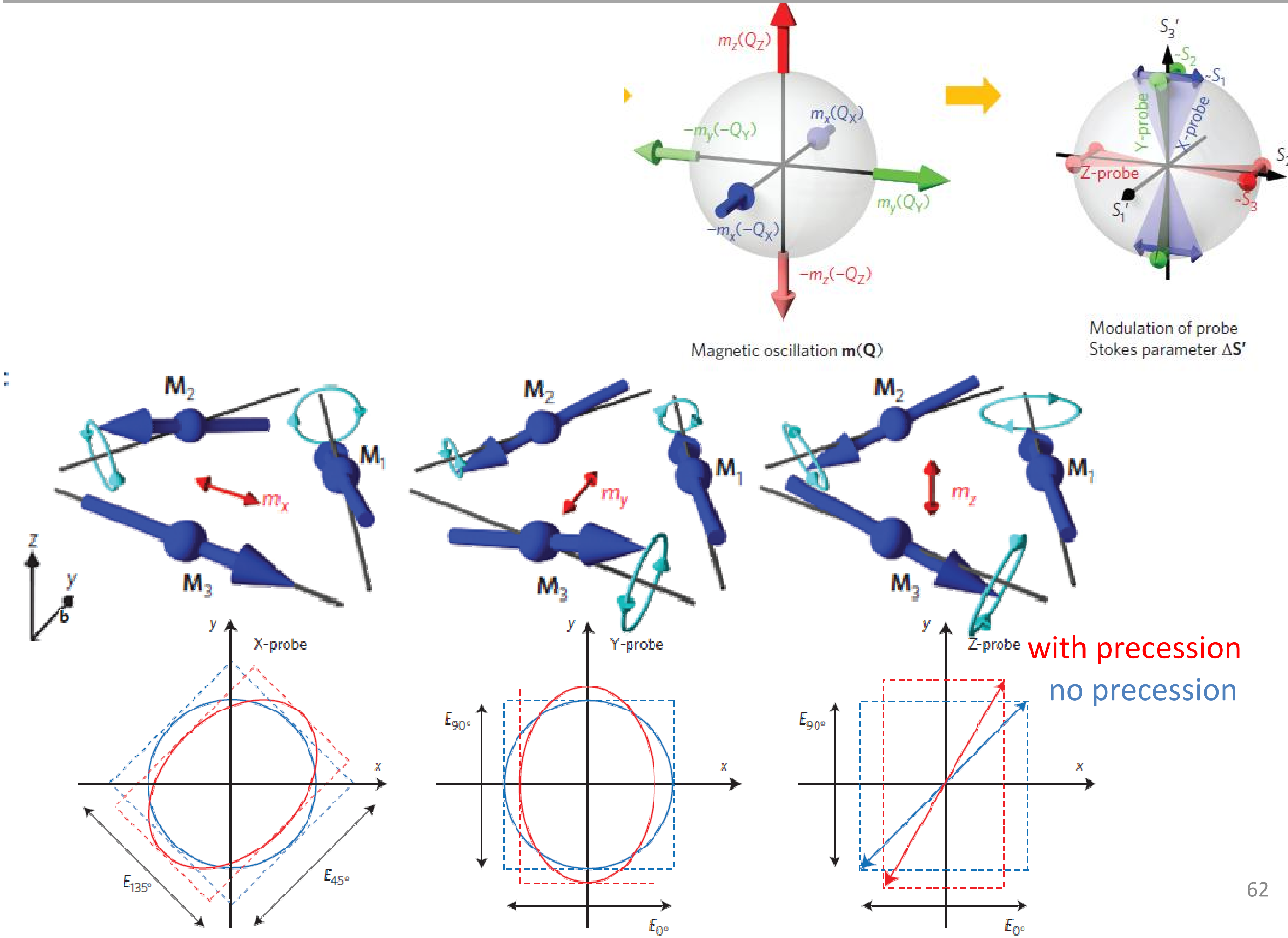
1.3 THz **1.3 THz** **56 GHz**

“Writing” light polarization into a magnon mode

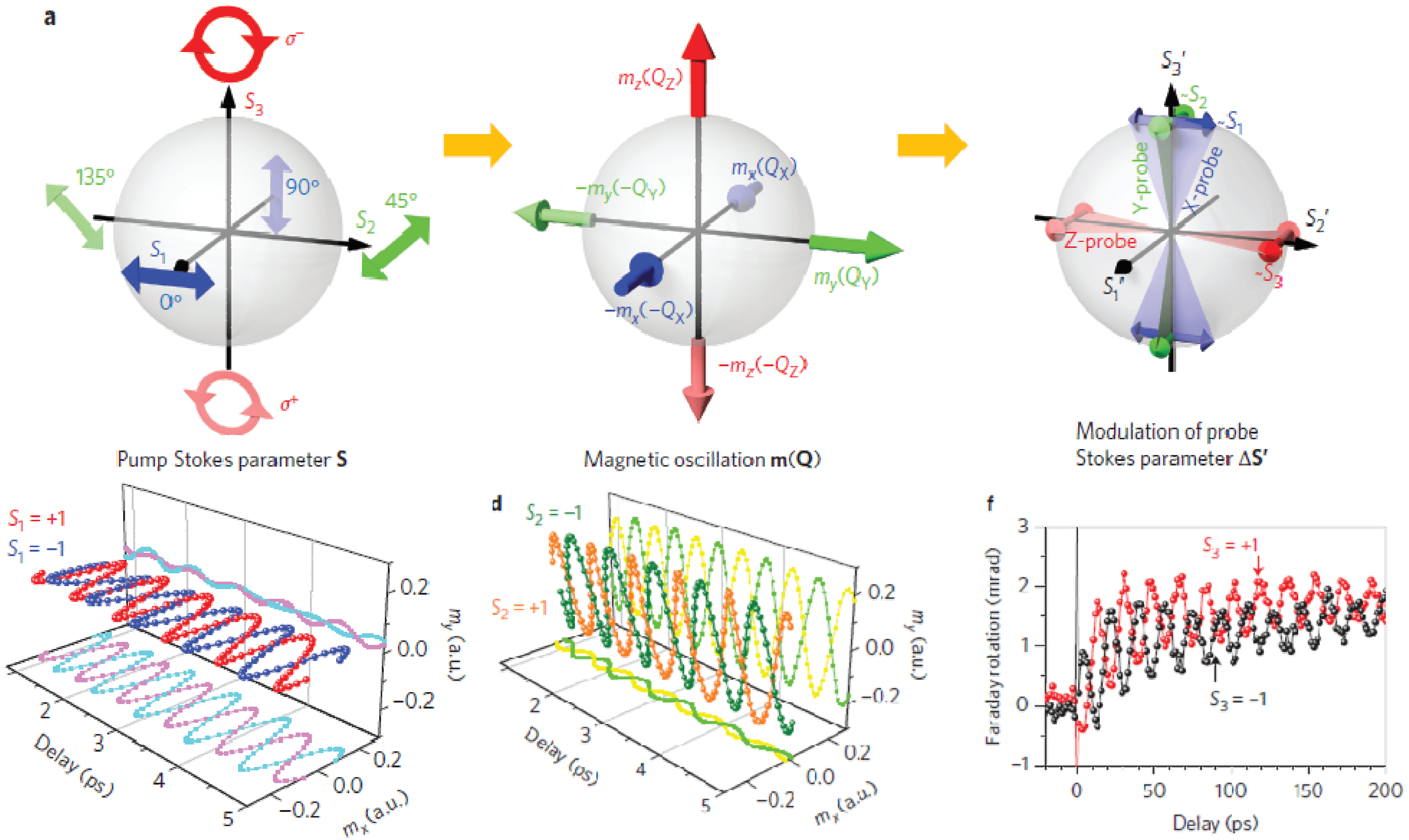




“Reading” magnon mode via light polarization



Experimental verification



X-probe

Y-probe

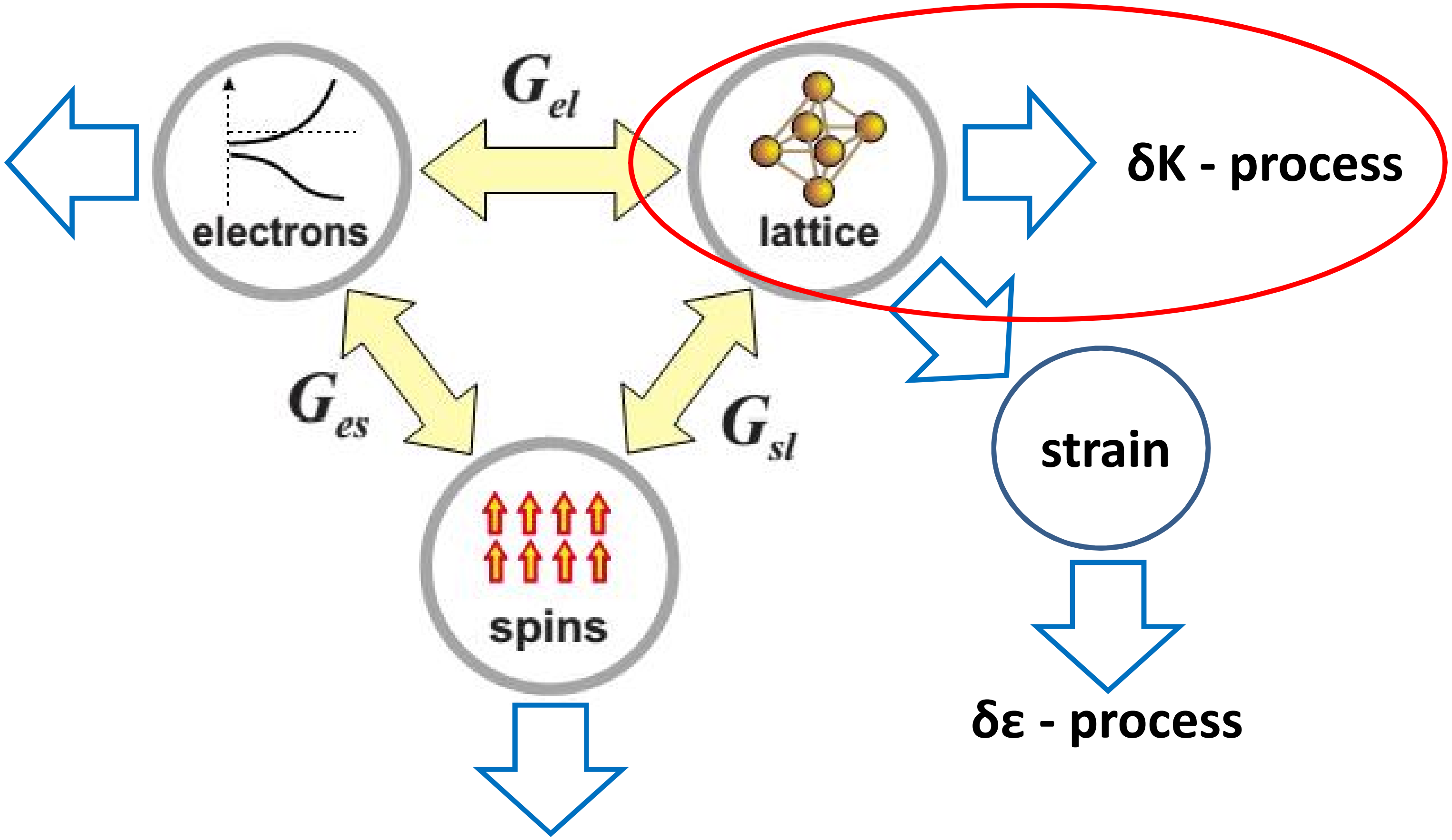
Z-probe

[Satoh et al., Nature Photonics, 9, 25 (2014)]

We've already discussed:
laser-induced changes of anisotropy

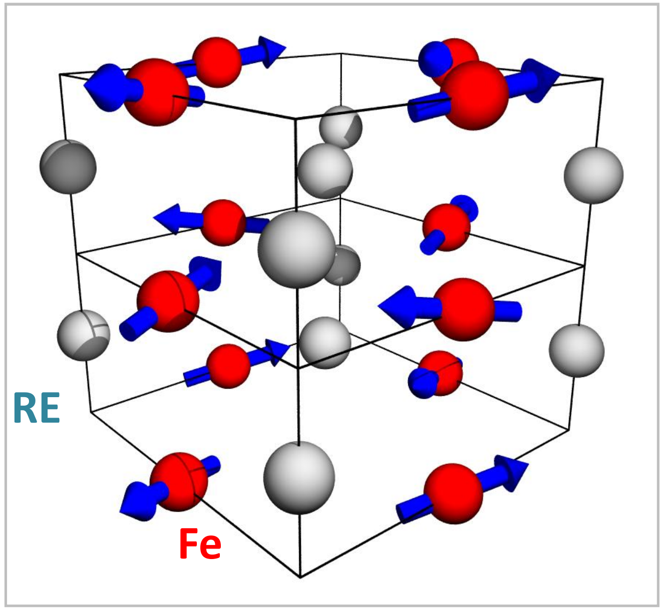
δH_L - process

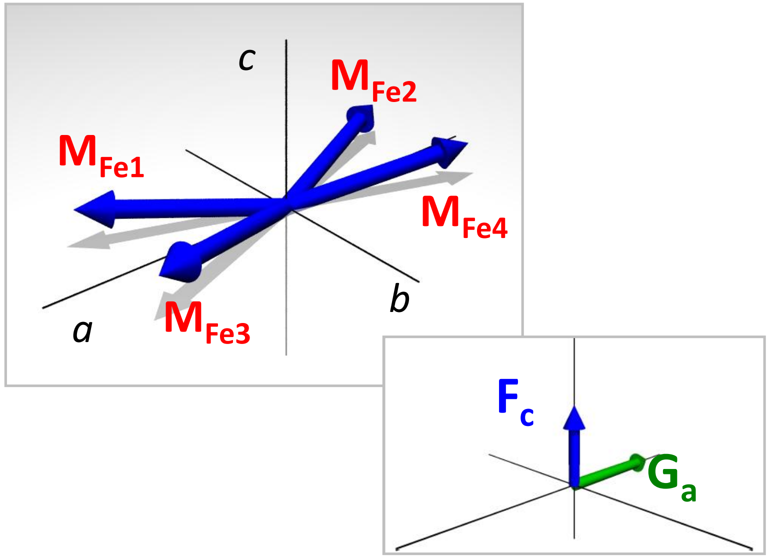
(See lecture
by A. Kirilyuk)



δM - process

Spin reorientation phase transition in *RE*FeO_3

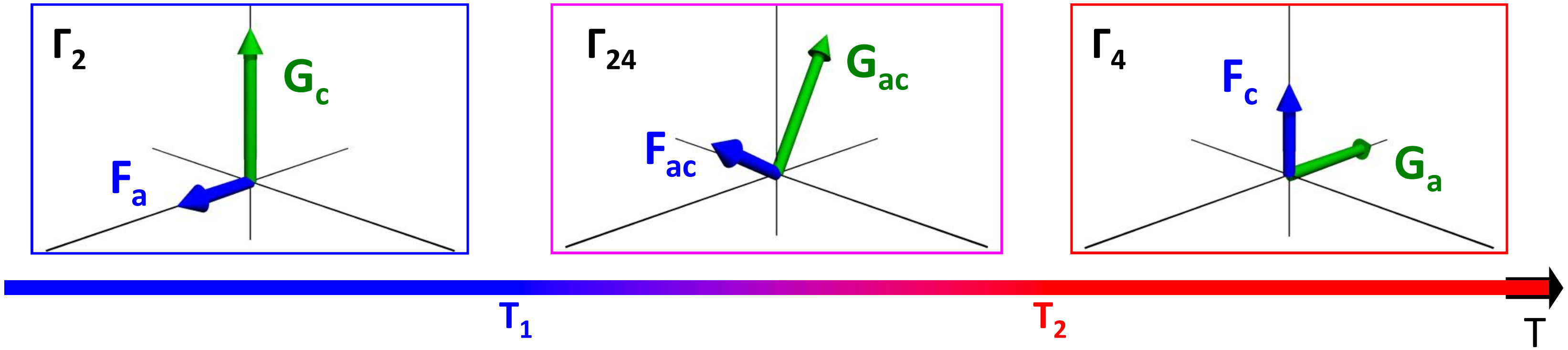




Spin reorientation (SRT) phase transition

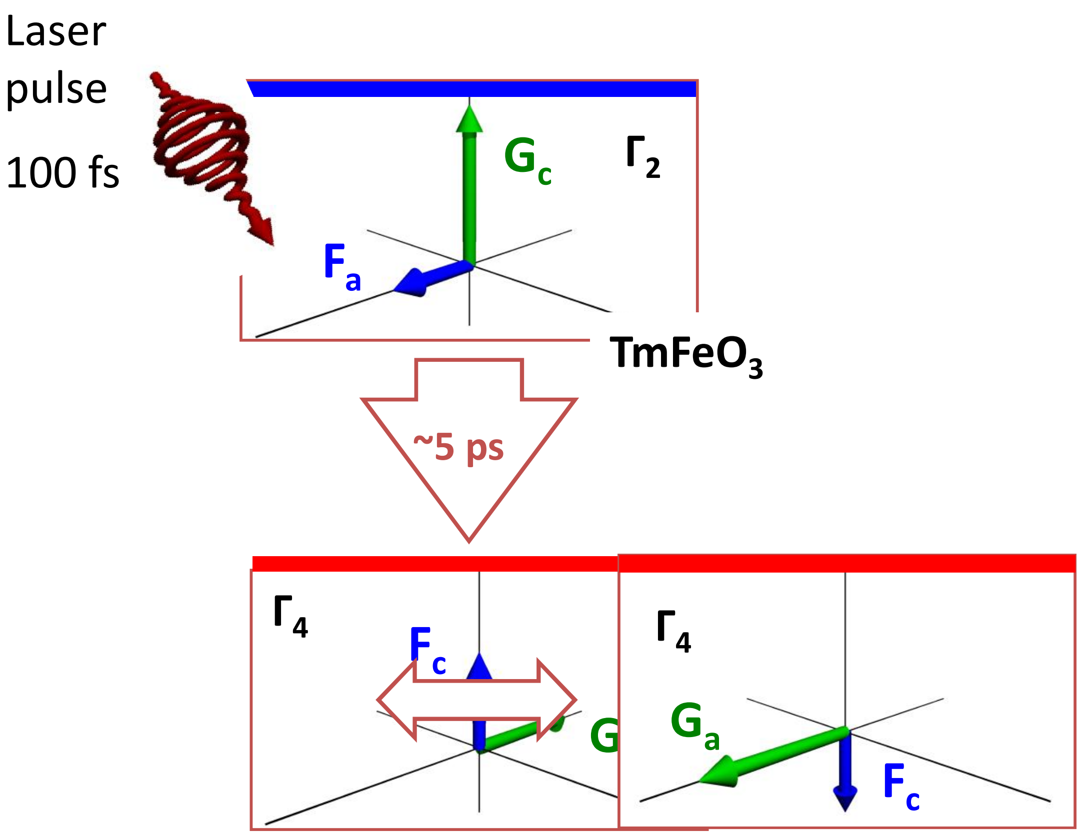
Changes sign with temperature

$$F(T) = K_0 + K_2(T) f_c^2 + K_4(T) f_c^4$$

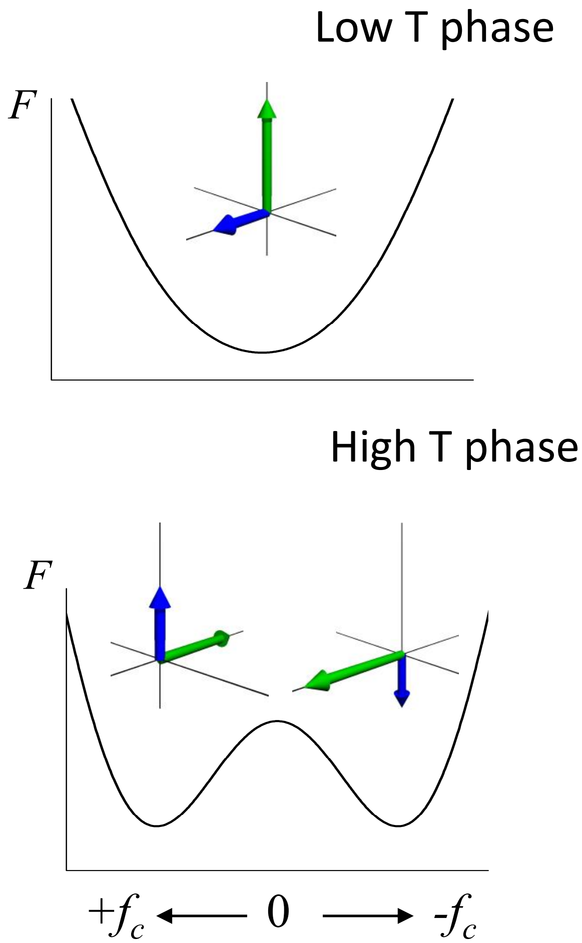


[*Belov et al., Sov. Phys. Usp.* **19** 574 (1976)]

Laser-induced spin-reorientation phase transition



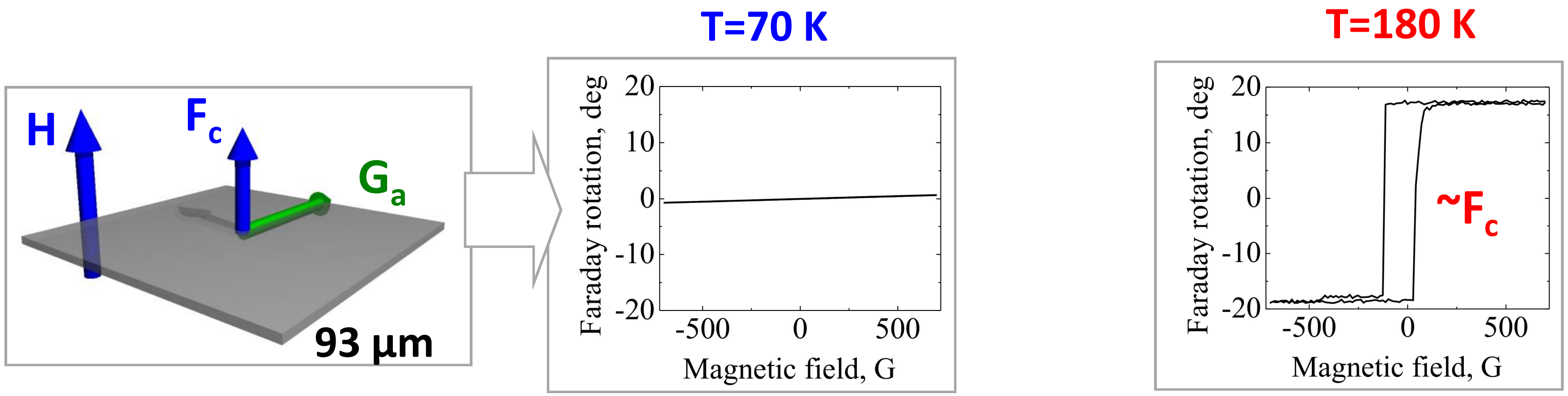
[Kimel et al., Nature ***429****, 850 (2004)]*



How to lift the degeneracy?

Controlling the phase transition by a single laser pulse alone?

Sample: rare-earth orthoferrite $(Sm_{0.5}Pr_{0.5})FeO_3$

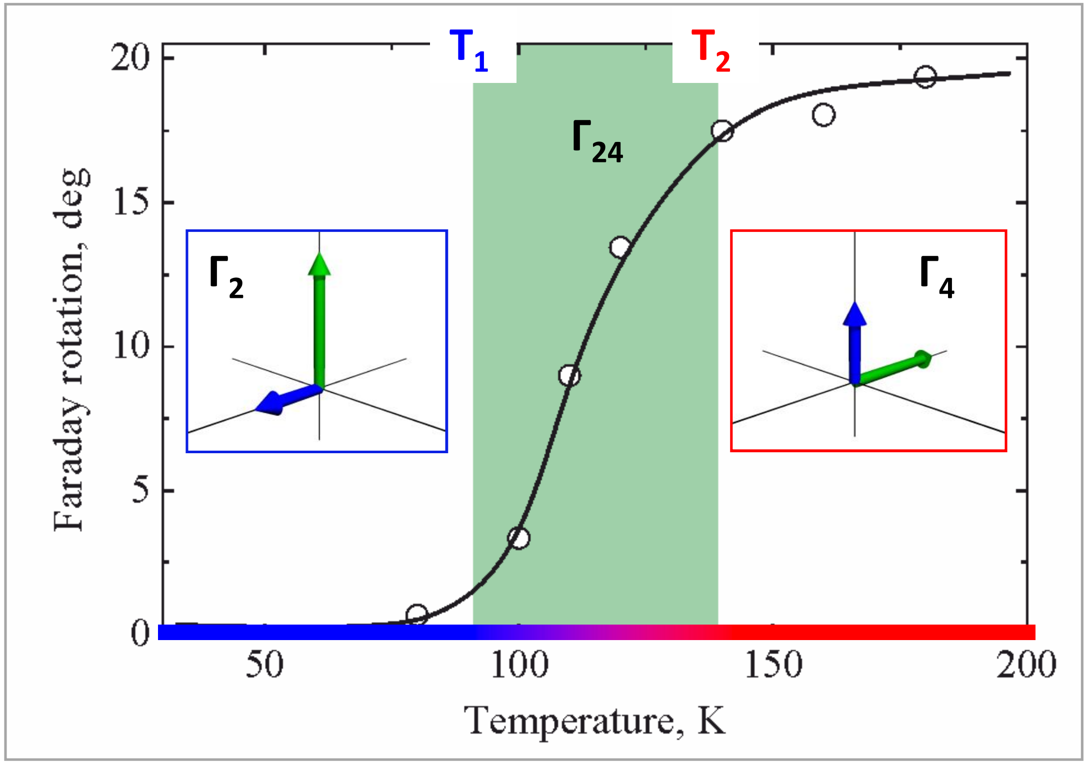


➢**Spin reorientation phase transition at**

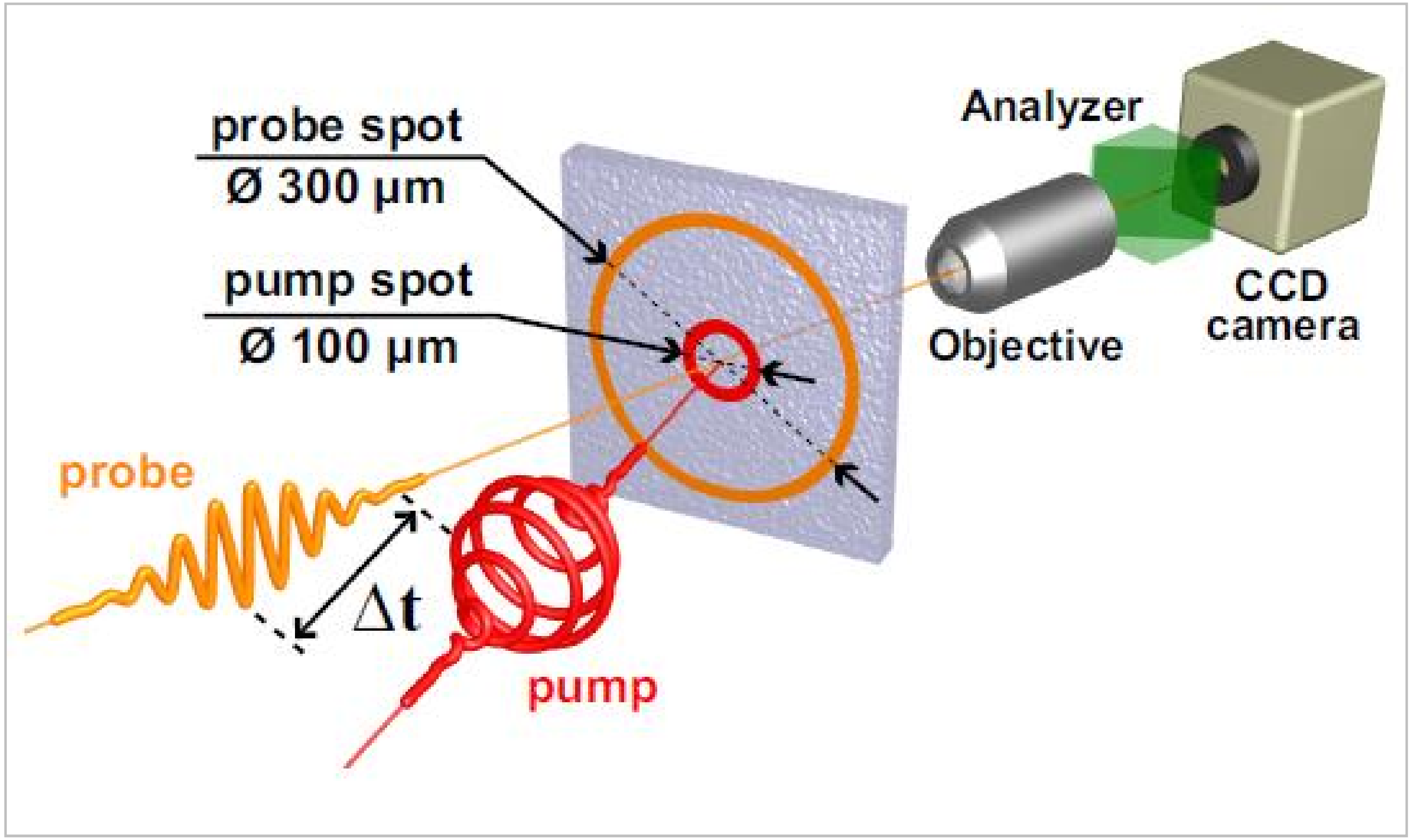
98-130 K

➢**Large Faraday rotation**

~20^o / 90 µM

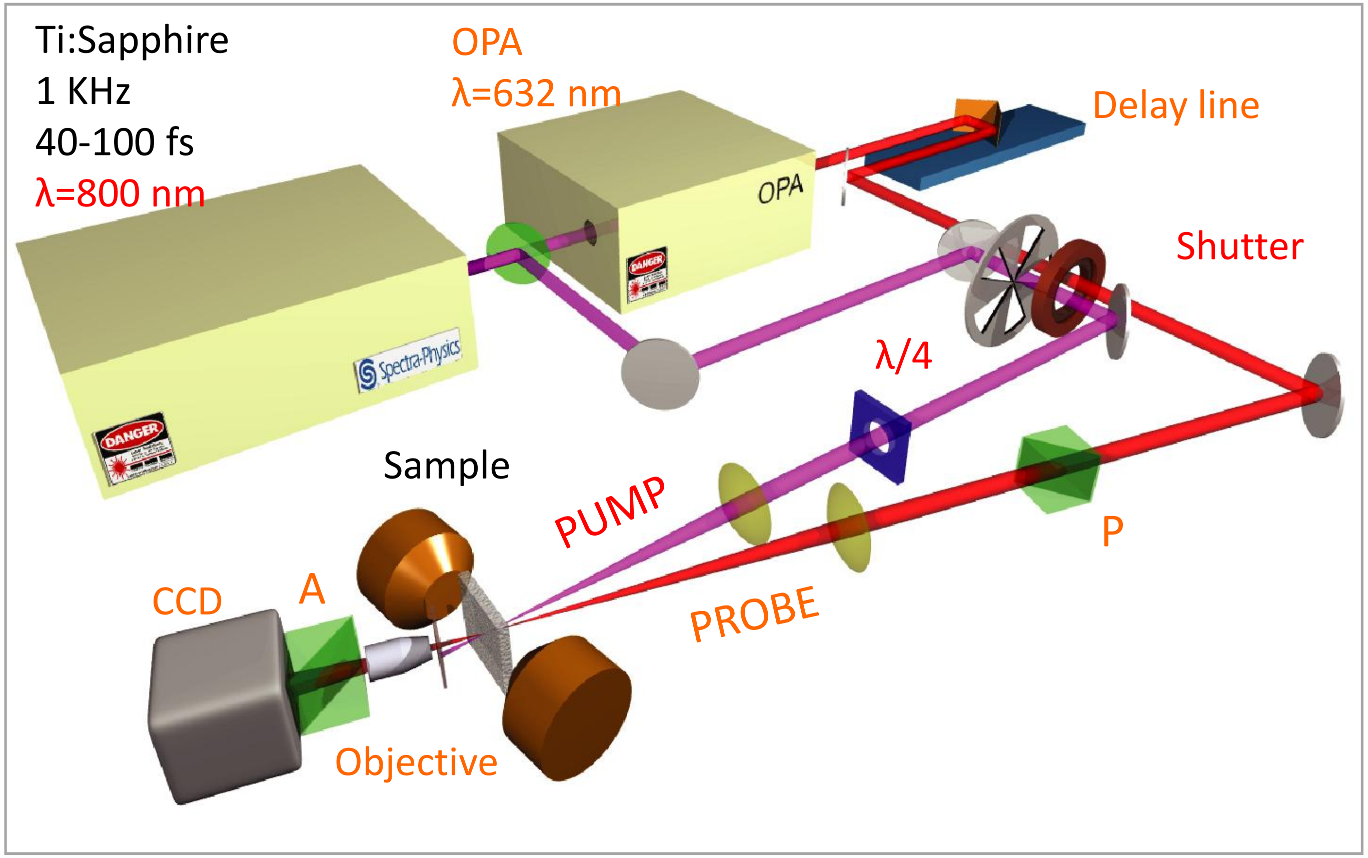


Single-shot femtosecond time-resolved magneto-optical imaging

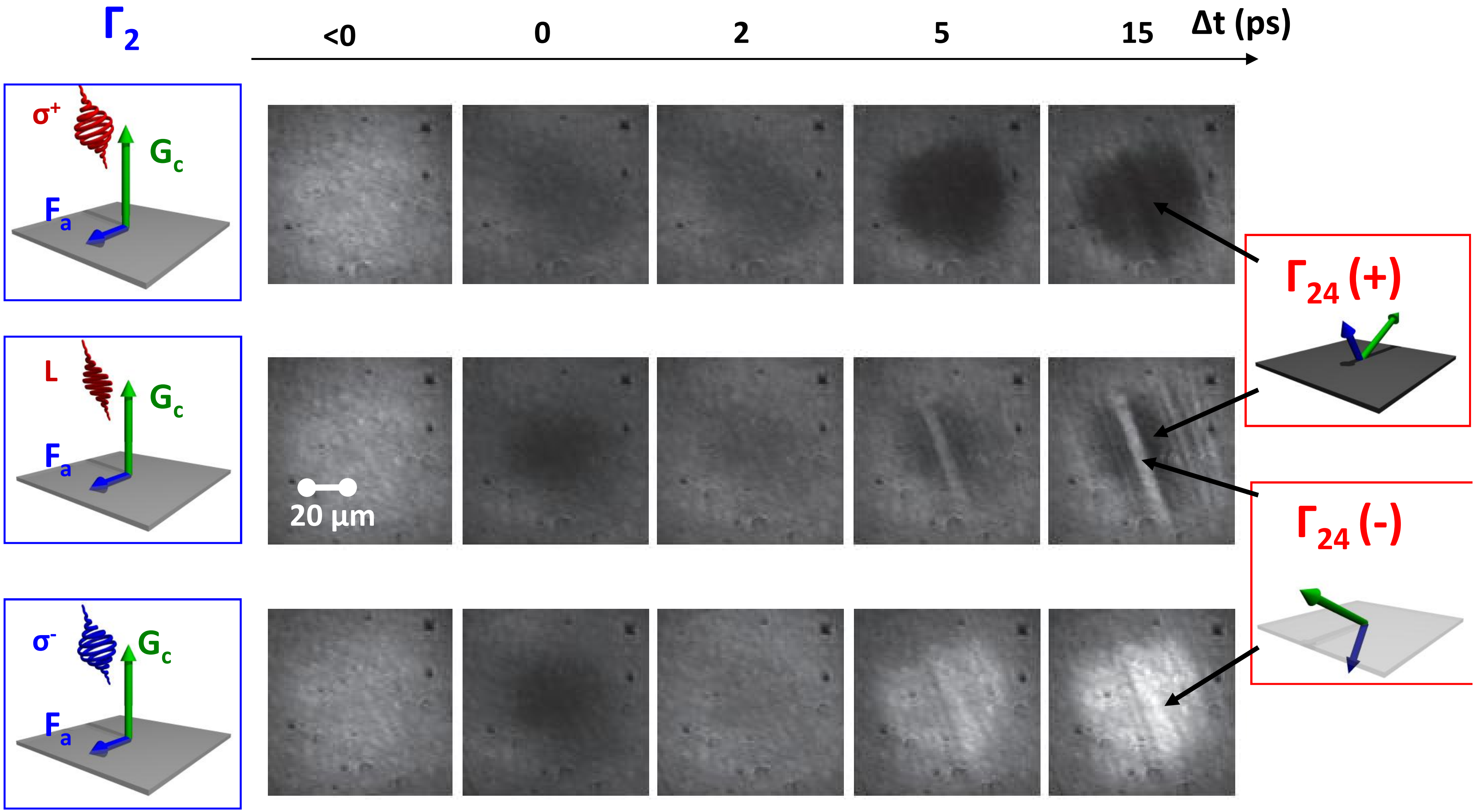


Magneto-optical images with subpicosecond resolution

Single-shot femtosecond time-resolved magneto-optical imaging



Laser-induced magnetization dynamics in (Sm,Pr)FeO_3



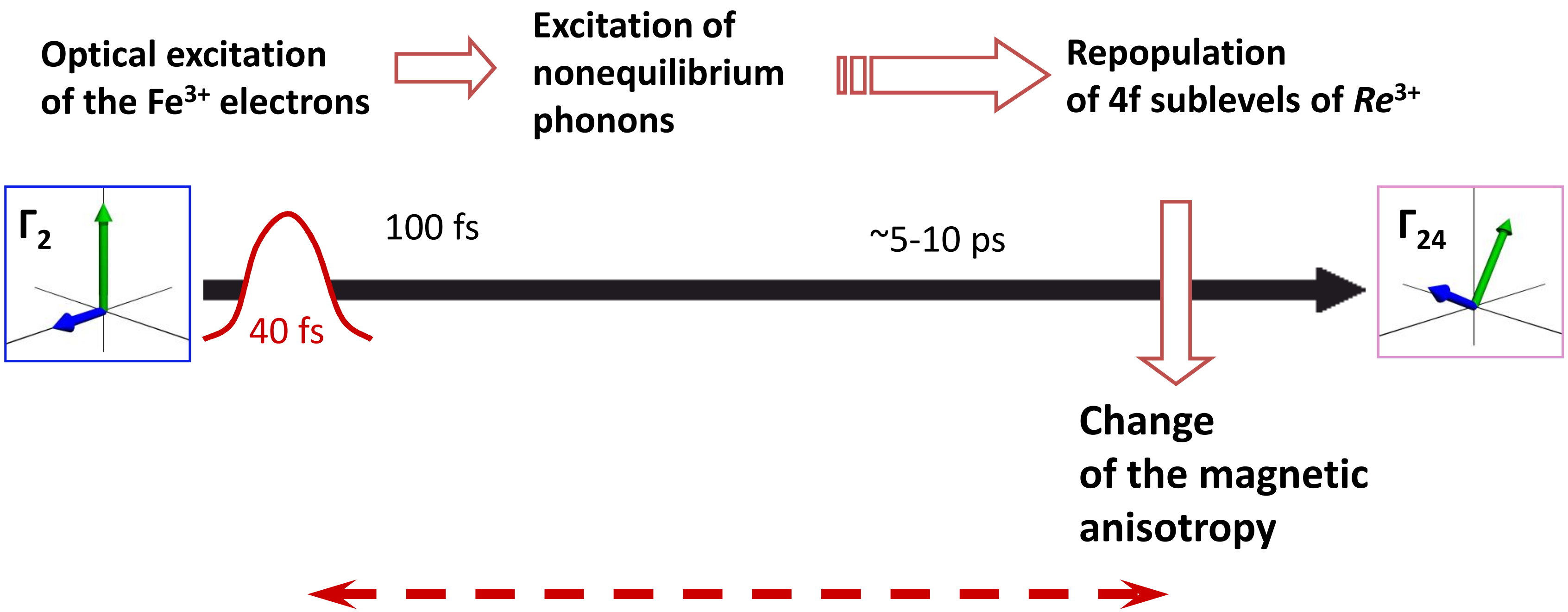
*[de Jong et al., PRL **108** 157601 (2012)]*

T=90 K

Ultrafast laser-induced SR transition

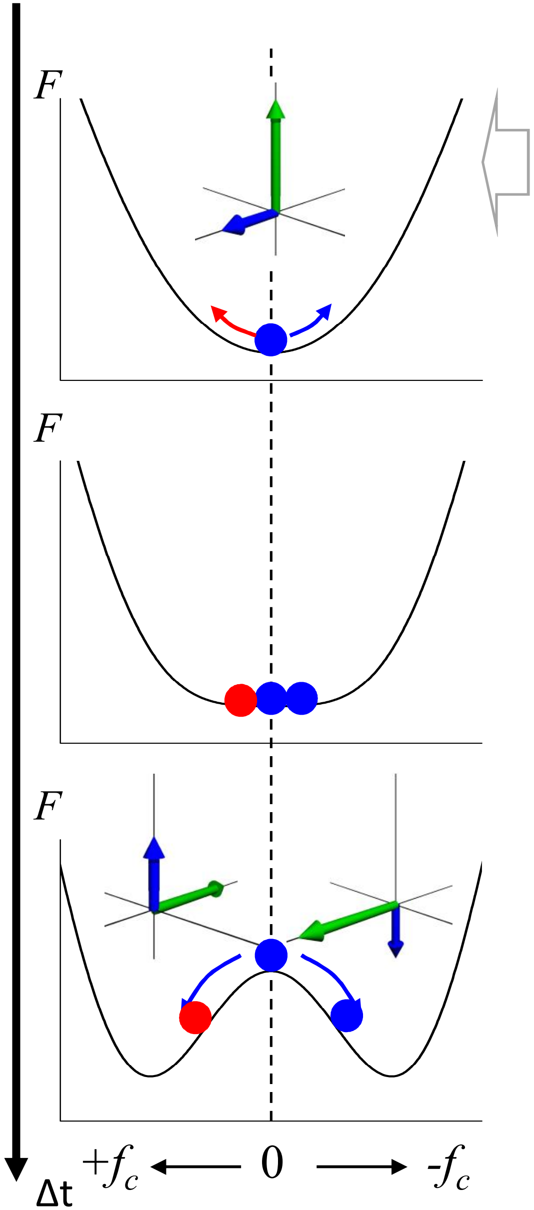
controlled by a laser pulse polarization alone!

Mechanism of the laser-induced SR transition



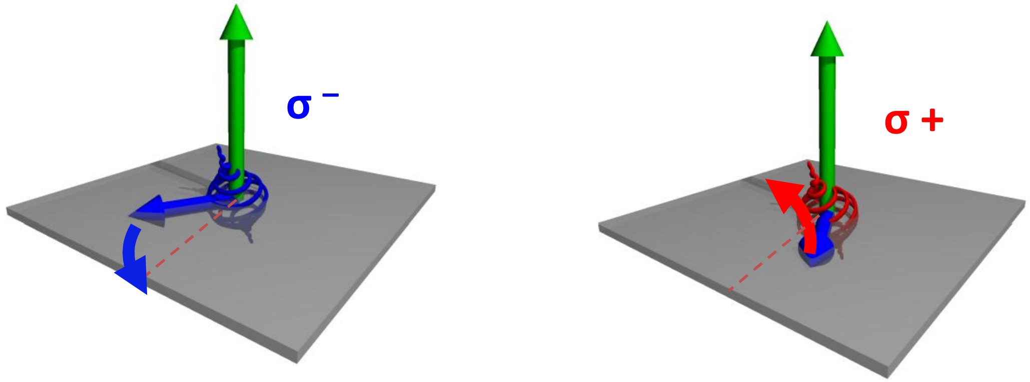
How and where the information
about the laser pulse polarization is stored?

Coherent control of the laser-induced SR transition



Ultrafast inverse Faraday effect

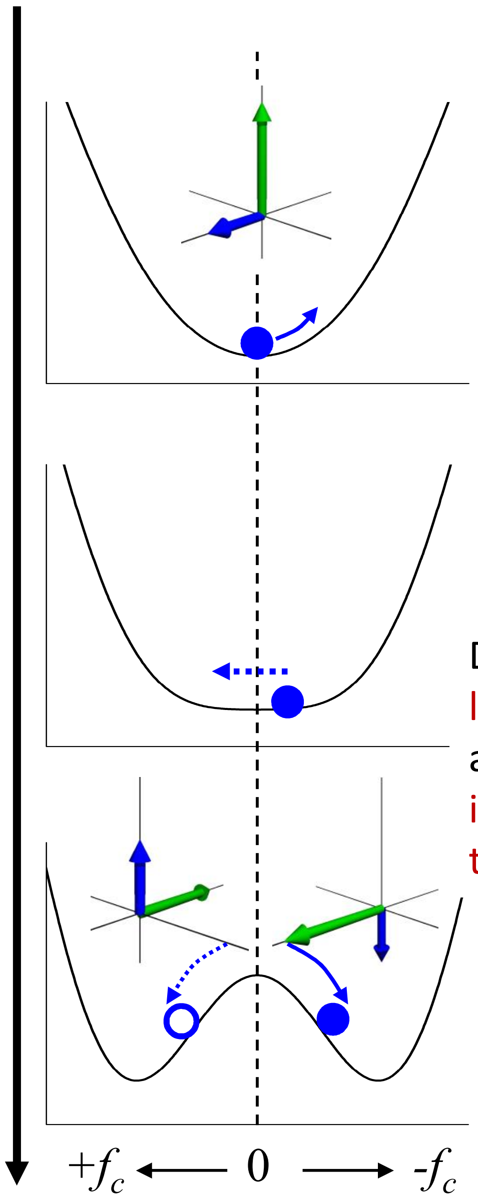
Impulsive excitation of the <u>low amplitude</u> magnetization precession (<10°)



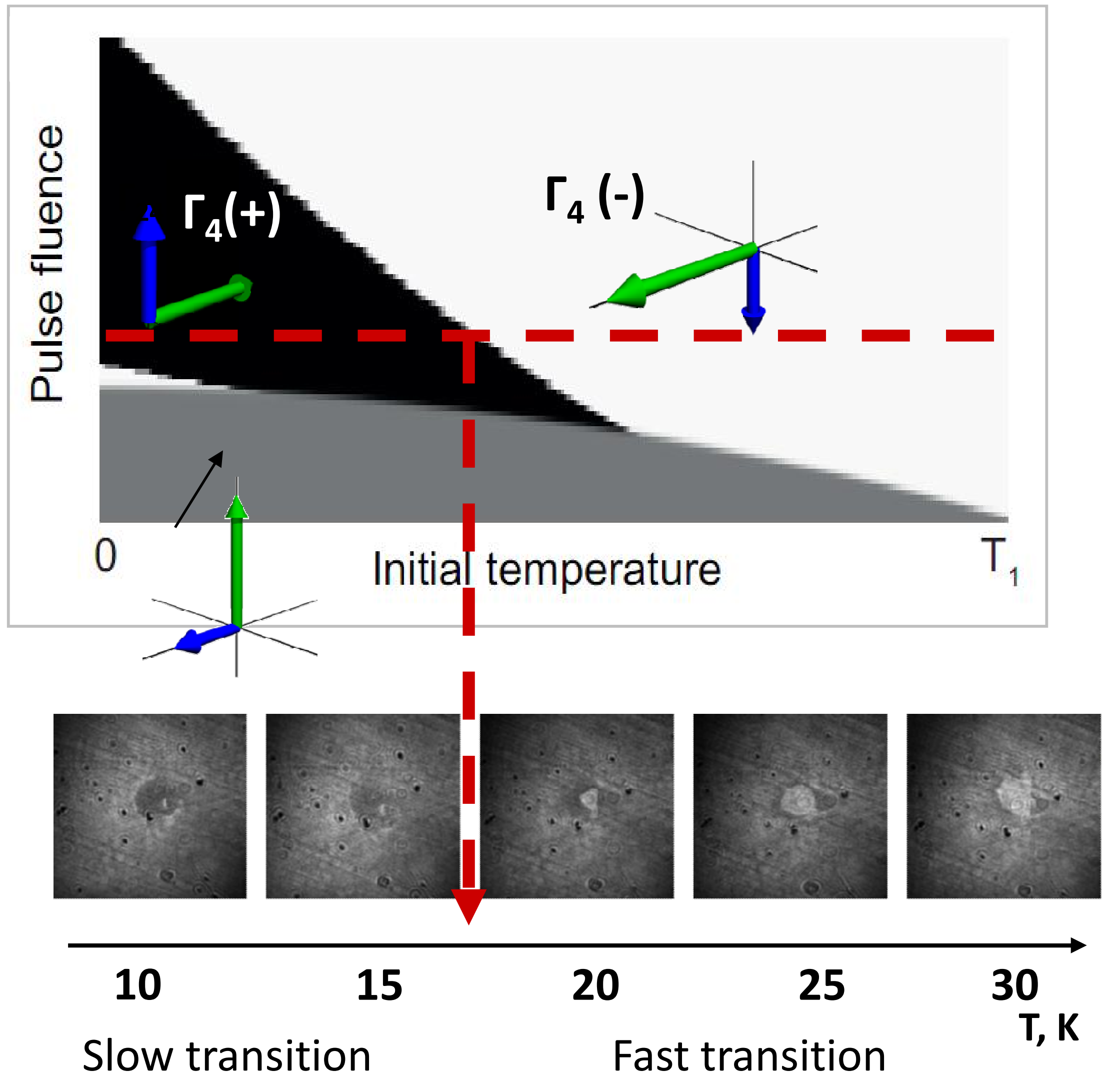
Phase of the precession is helicity-dependent

Degeneracy between two states is lifted dynamically

Control of the SR transition: temperature and fluence



Depends on
laser fluence
and
initial sample
temperature

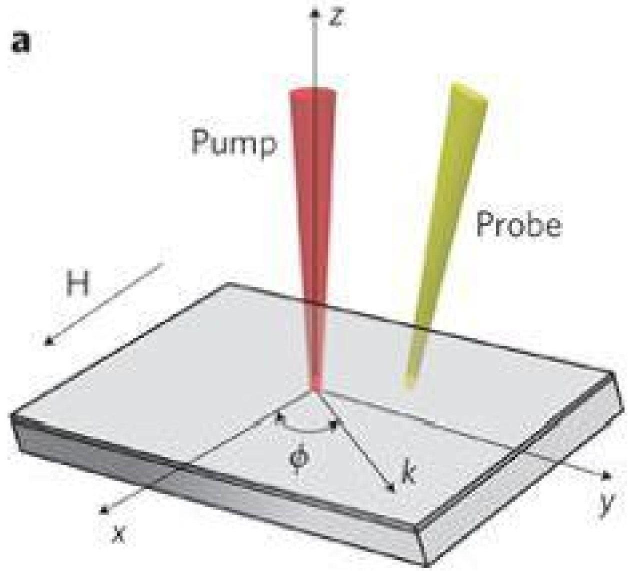


*[Jong et al., PRL **108** 157601 (2012);*
Afanasiev et al., PRL PhD thesis]

Laser-driven spin transport

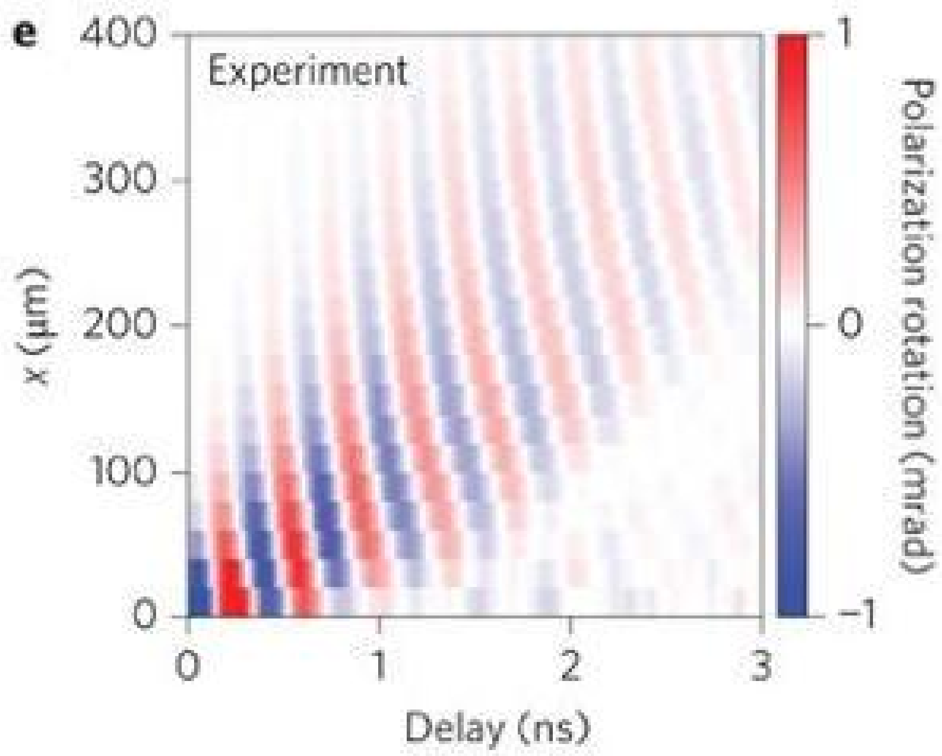
Optically-driven magneto-static waves

Pump-probe scans in time and space:



Pump and probe spot sizes ~1 µm

BVMSSW driven by ultrafast inverse Faraday effect

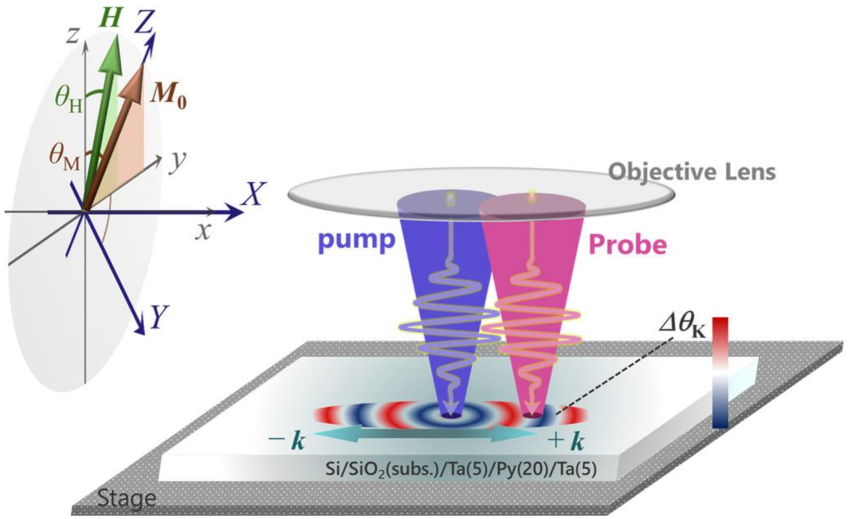


MS waves driven by ultrafast opto-magnetic effects

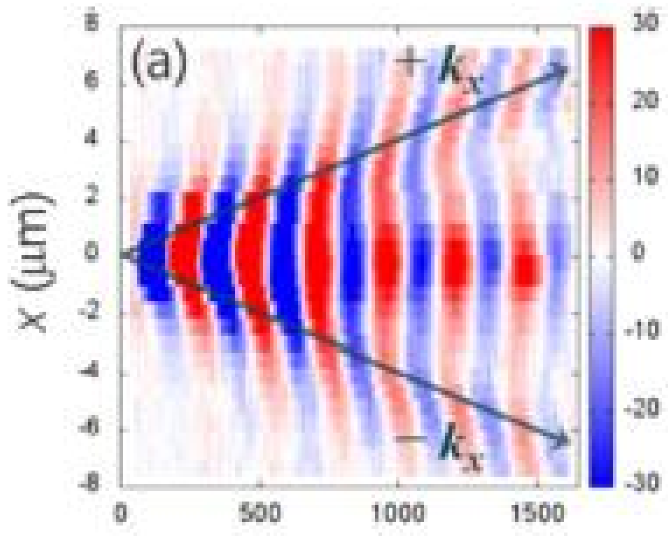
Only in substituted YIG films so far

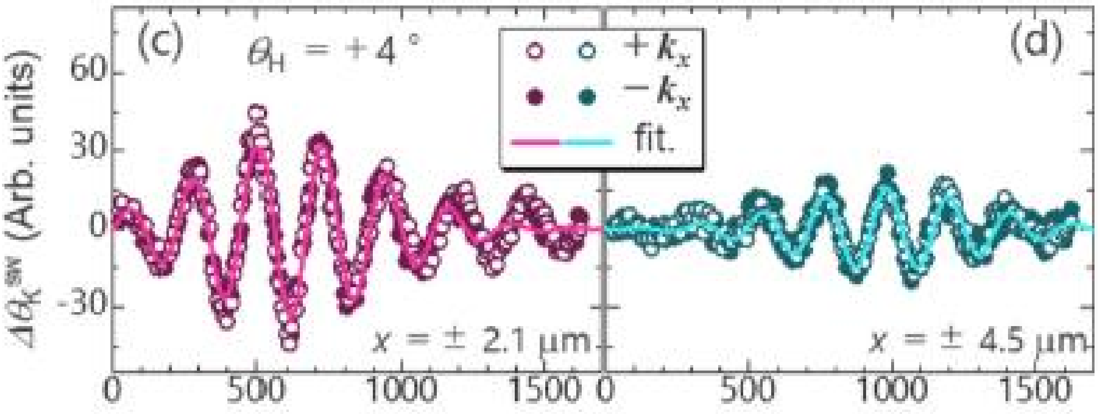
[Satoh et al. Nature Photon. ***6****, 662 (2012)*
.....
Jackl et al., PRX ***2****, 021009 (2017)]*

Optically-driven magneto-static waves



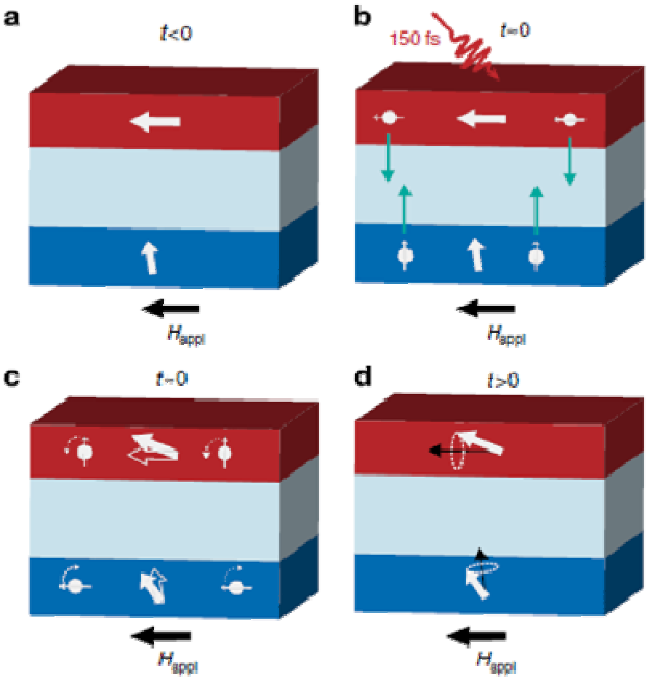
MSSW (and BVMSSW) driven by ultrafast change of shape anisotropy (δM-process)



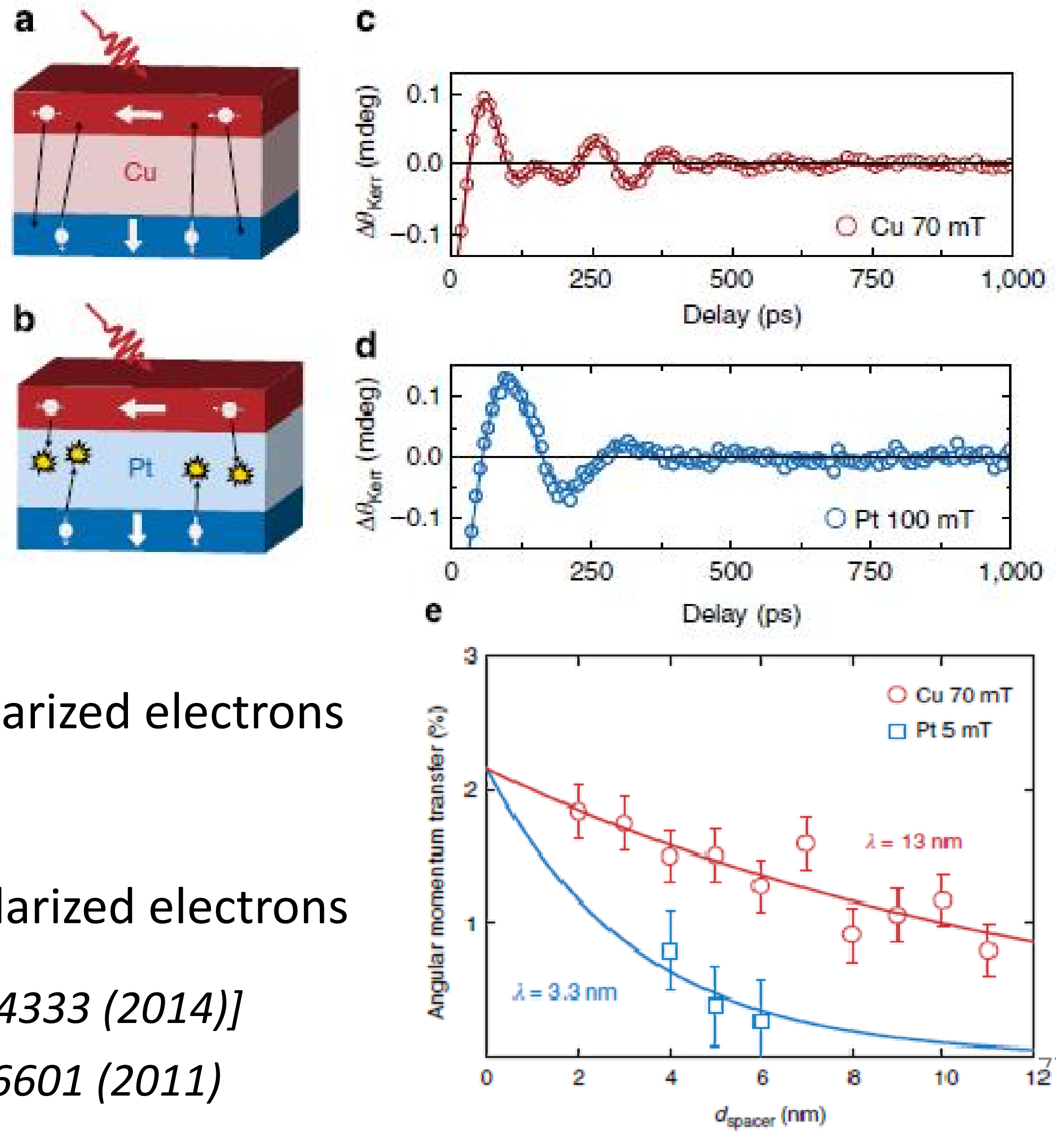


[Au et al., PRL ***110****, 097201 (2013)*
Kamikaki et al., ***96****, 014438 (2017)*
….]

Optically-driven spin polarized currents and precession



Spin-transfer torques due to hot spin polarized electrons



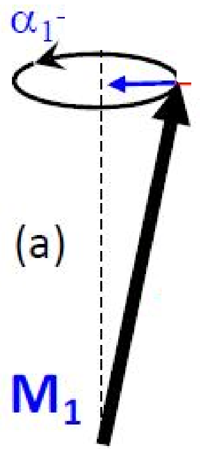
Cu: long propagation for spin-polarized electrons

Pt: short propagation for spin-polarized electrons

[Schellekens et al., Nature Comm. ***5****, 4333 (2014)]*

See also Melnikov et al., PRL ***107****, 076601 (2011)*

Spin pumping and dissipative coupling of precessions

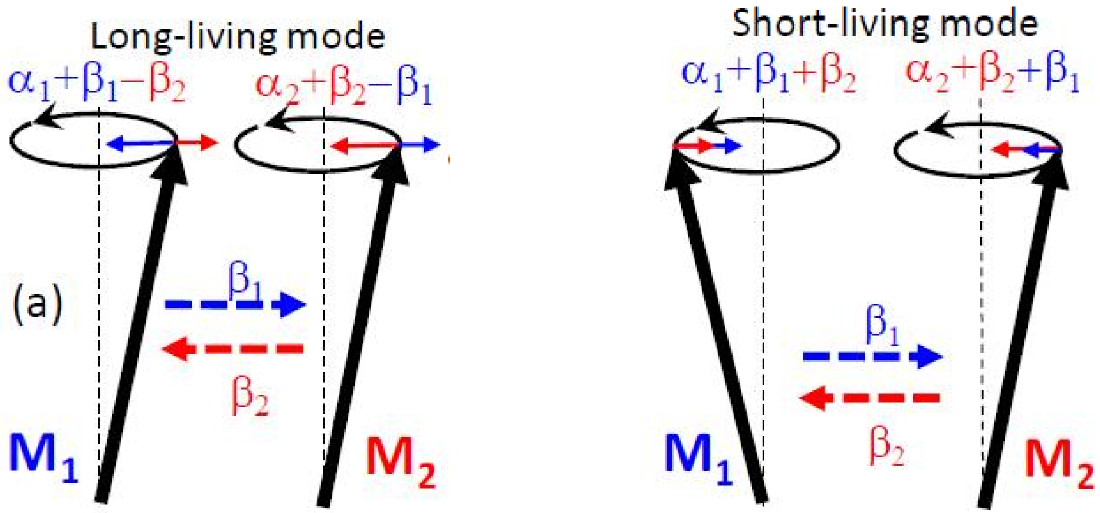


$m_\perp \sim A_a \sin(2\pi f_a t - \phi_a) \exp(-\zeta_a t)$

α_i - intrinsic (Gilbert) damping

β_i - damping due to spin pumping

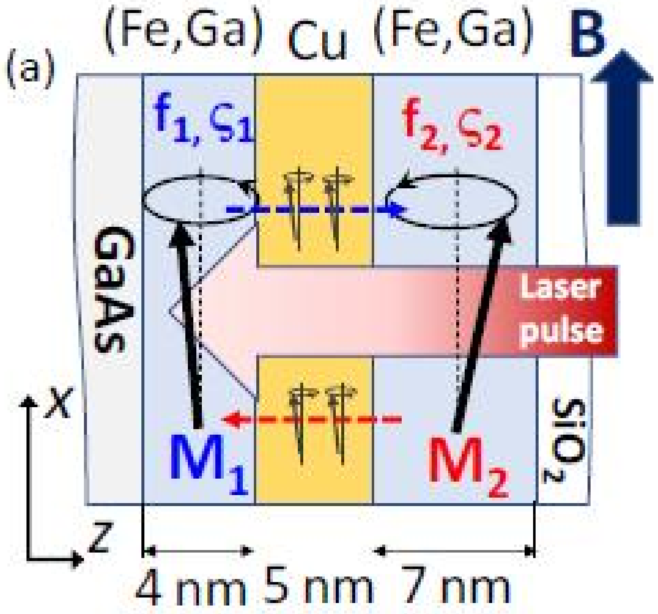
Two magnetic layers coupled via spin current



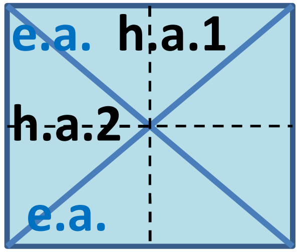
Dissipative coupling:
two modes of the same frequency but of different dumpings

$$\zeta_{a,b} \sim \frac{\alpha_1+\beta_1+\alpha_2+\beta_2 \mp \sqrt{4\beta_1\beta_2+(\alpha_1+\beta_1-\alpha_2-\beta_2)^2}}{2}$$

Laser-driven spin pumping and dissipative coupling



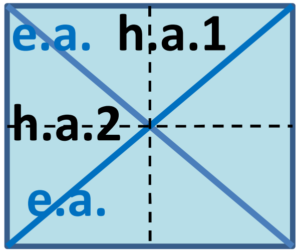
Top view:



(Fe,Ga)/GaAs

Cubic anisotropy

+ Uniaxial anisotropy

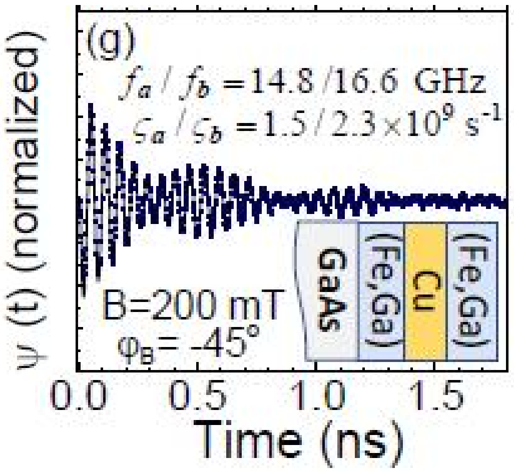


(Fe,Ga)/Cu/GaAs

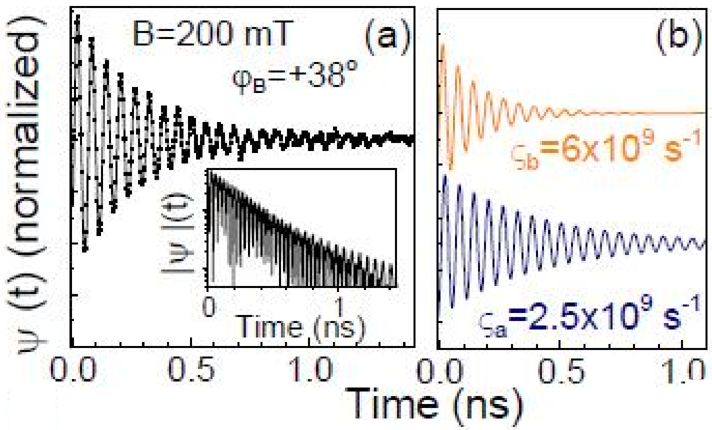
Cubic anisotropy

Excitation via δK-process

No resonance $f_1 \neq f_2$ -> No coupling



Resonance $f_1 = f_2$ -> dissipative coupling & both modes are excited and observed



[Danilov et al., Phys. Rev. B ***98****, 060406 (2018)]*

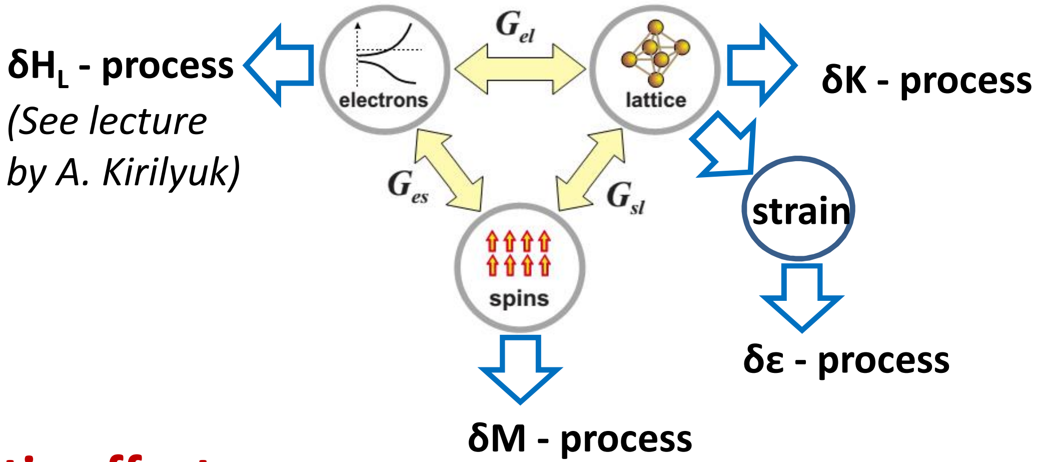
Light-induced (de)magnetization processes and all-optical switching

Laser-induced demagnetization

Is ultrafast in metals but slow in dielectrics

Different theories of ultrafast demagnetization in metals

Laser-induced changes of magnetic anisotropy



Ultrafast opto-magnetic effects

No heating is involved

Control of spins by polarized laser pulses

Laser-driven spin transport