Eidgenössische Technische Hochschule Zürich
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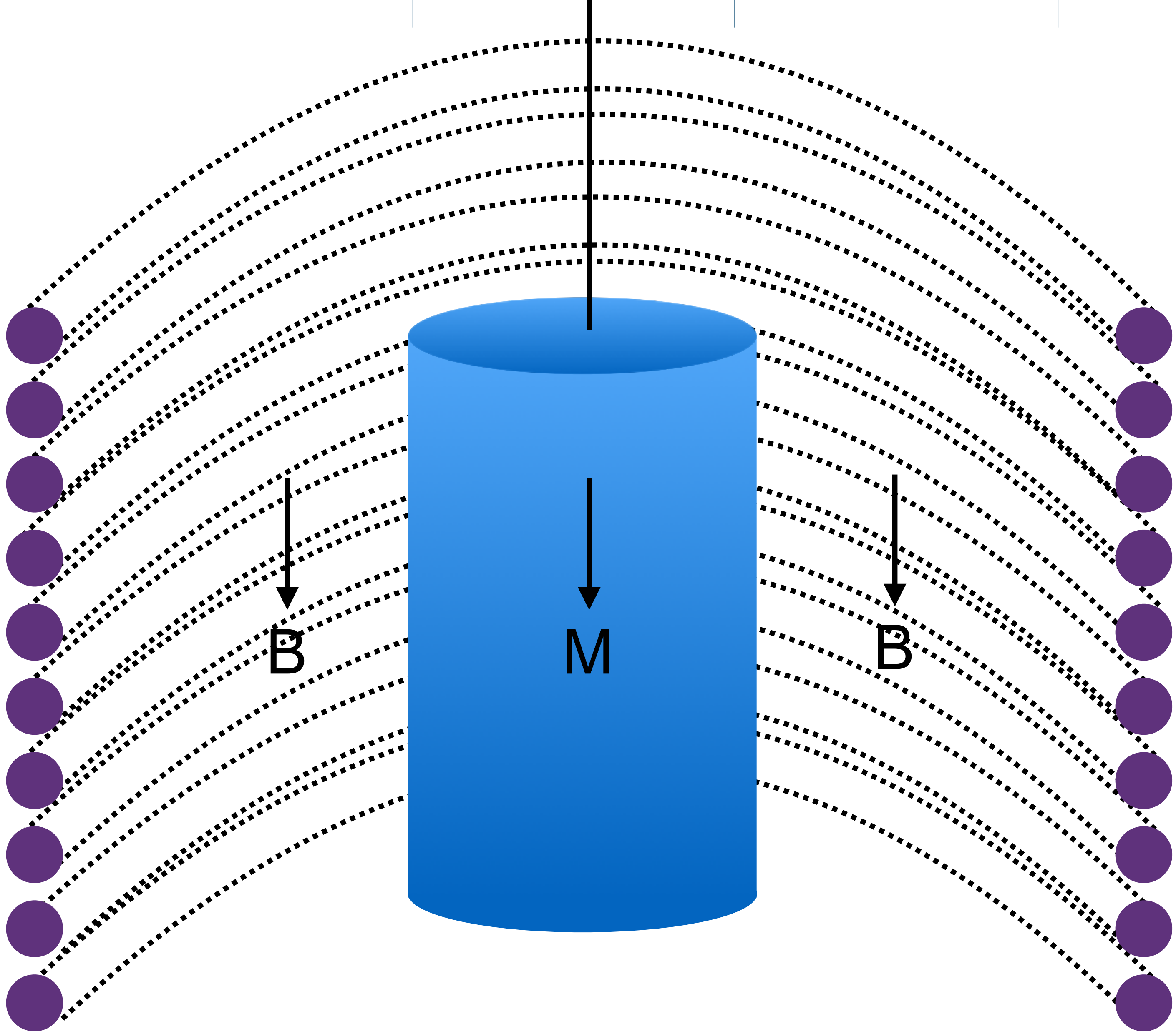
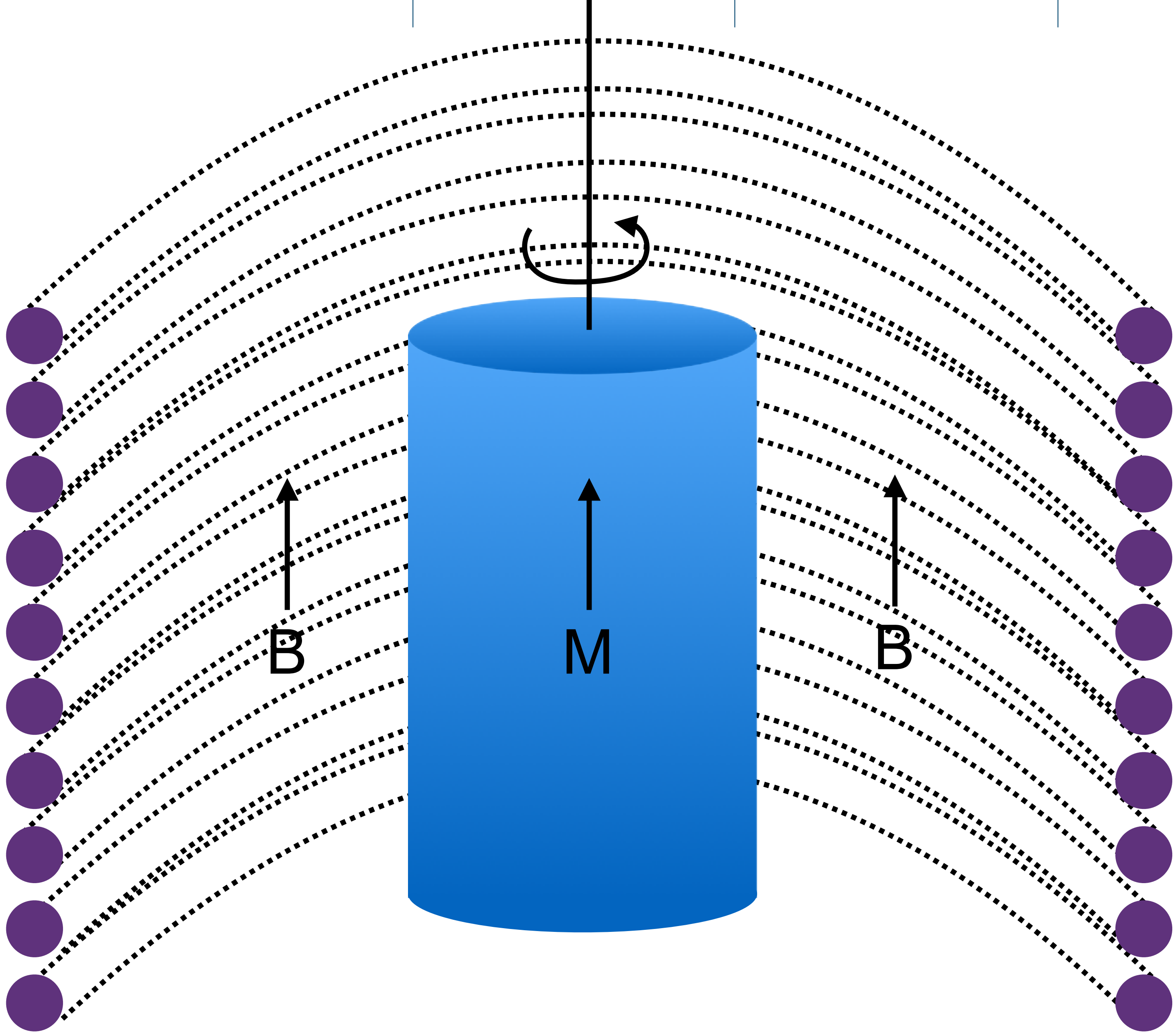
PAUL SCHERRER INSTITUT

The Ultrafast Einstein-de Haas effect

Steve Johnson

Dornes et al., *Nature* 565, 209 (2019)


B
M
B

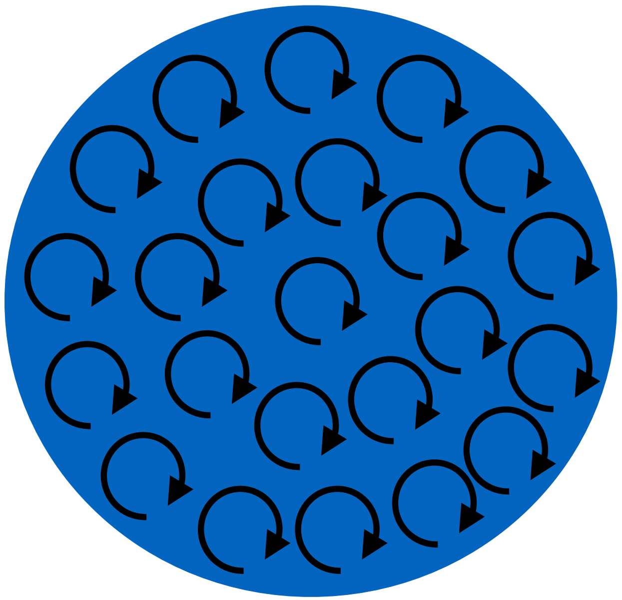

B
M
B

How does this happen dynamically?

Assume provisionally:

(1) M changes "arbitrarily" fast, spatially uniform

(2) dM change in a volume dV → local torque



$$\sigma_M = \begin{pmatrix} 0 & \tau_3 & -\tau_2 \\ -\tau_3 & 0 & \tau_1 \\ \tau_2 & -\tau_1 & 0 \end{pmatrix}$$

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Assume provisionally:

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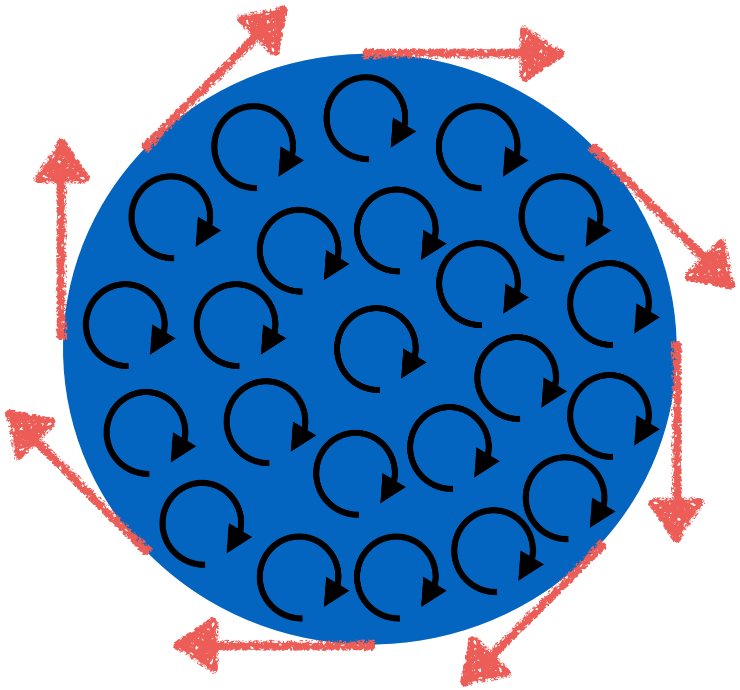
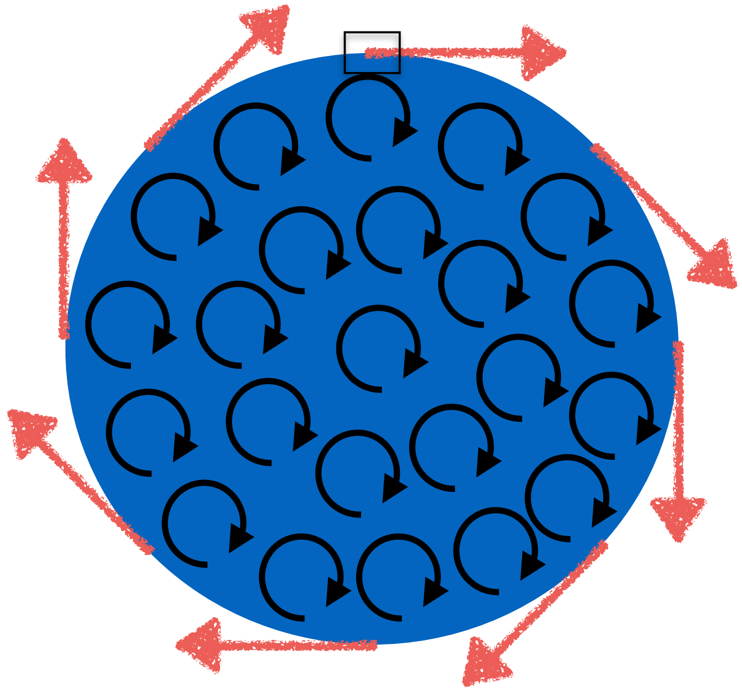
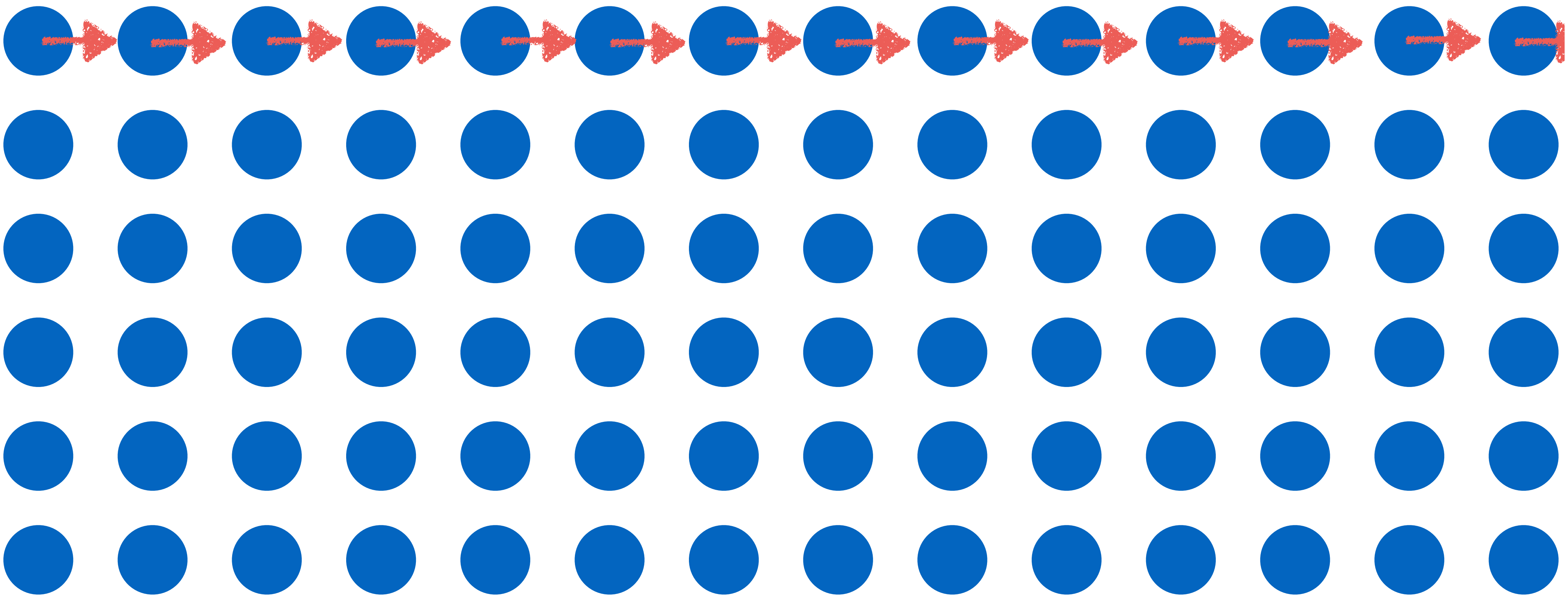


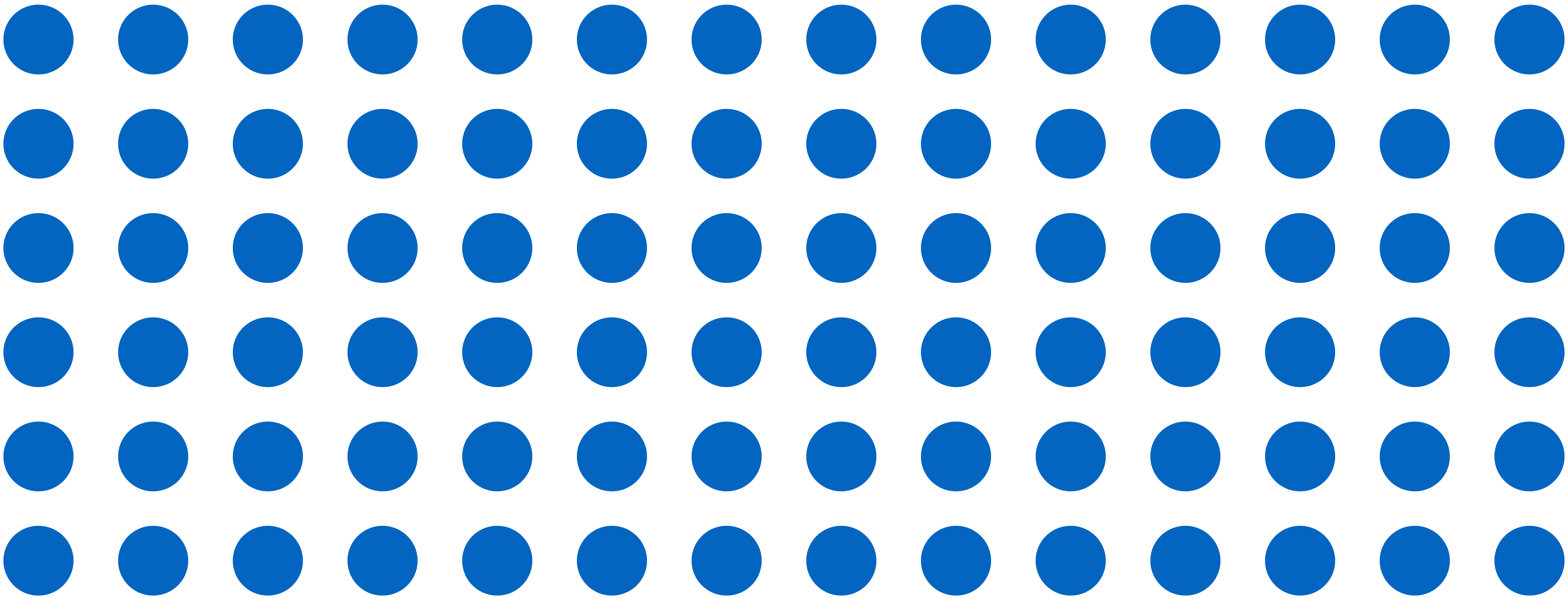
$$\vec{f} = \nabla \cdot \sigma_M$$

⇒ force density non-zero only at surfaces!!





Transverse displacement wave



Assume provisionally:

(1) M changes "arbitrarily" fast, spatially uniform

(2) dM change in a volume dV → local torque

APPLIED PHYSICS LETTERS **89**, 122502 (2006)

Einstein–de Haas effect in a NiFe film deposited on a microcantilever

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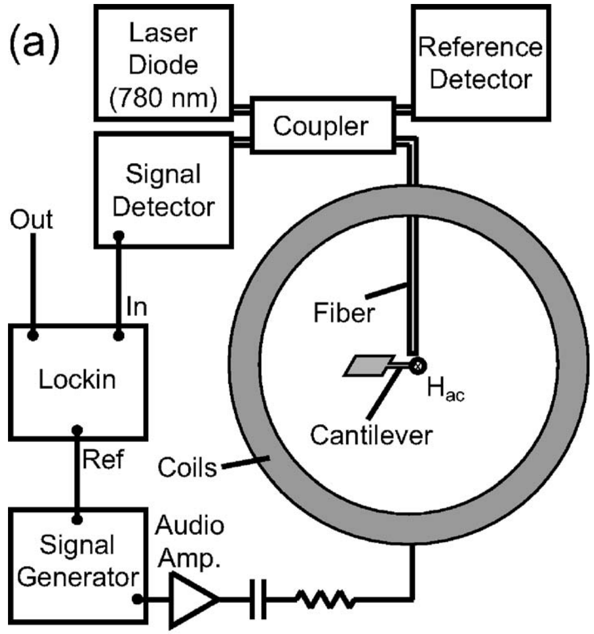
(Received 31 May 2006; accepted 27 July 2006; published online 18 September 2006)

A method is presented for determining the magnetomechanical ratio g' in a thin ferromagnetic film deposited on a microcantilever via measurement of the Einstein–de Haas effect. An alternating magnetic field applied in the plane of the cantilever and perpendicular to its length induces bending oscillations of the cantilever that are measured with a fiber optic interferometer. Measurement of g' provides complementary information about the g factor in ferromagnetic films that is not directly available from other characterization techniques. For a 50 nm $Ni_{80}Fe_{20}$ film deposited on a silicon nitride cantilever, g' is measured to be 1.83±0.10.
[DOI: 10.1063/1.2355445]



dM/dt limited by domain wall motion

~ 20 kHz

PHYSICAL REVIEW B **79**, 104410 (2009)

Dynamics of the Einstein–de Haas effect: Application to a magnetic cantilever

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(Received 17 November 2008; revised manuscript received 26 January 2009; published 11 March 2009)

The local time-dependent theory of Einstein–de Haas effect is developed. We begin with microscopic interactions and derive dynamical equations that couple elastic deformations with internal twists due to spins. The theory is applied to the description of the motion of a magnetic cantilever caused by the oscillation of the domain wall. Theoretical results are compared with a recent experiment on the Einstein–de Haas effect in a microcantilever.

DOI: 10.1103/PhysRevB.79.104410 PACS number(s): 75.80.+q, 72.55.+s, 07.55.Jg

…assumption (1) violated!

Ultrafast Demagnetization

Ultrafast Spin Dynamics in Ferromagnetic Nickel

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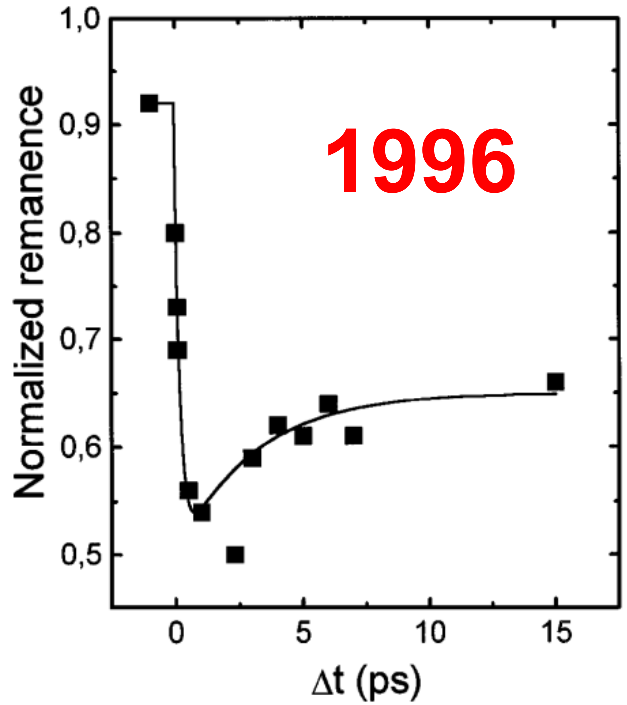
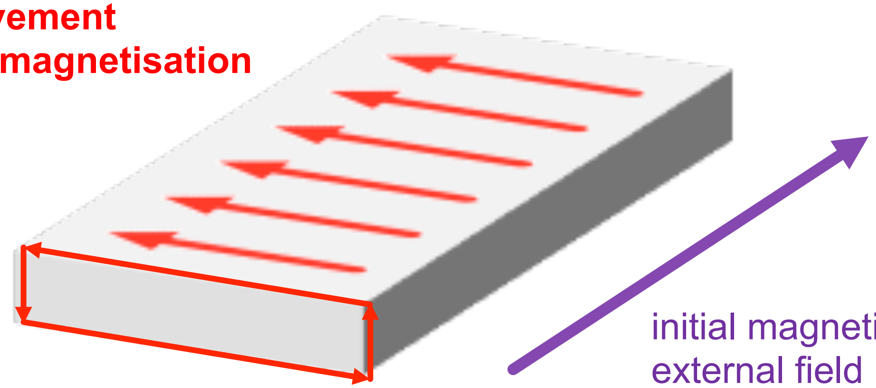
(Received 17 October 1995)



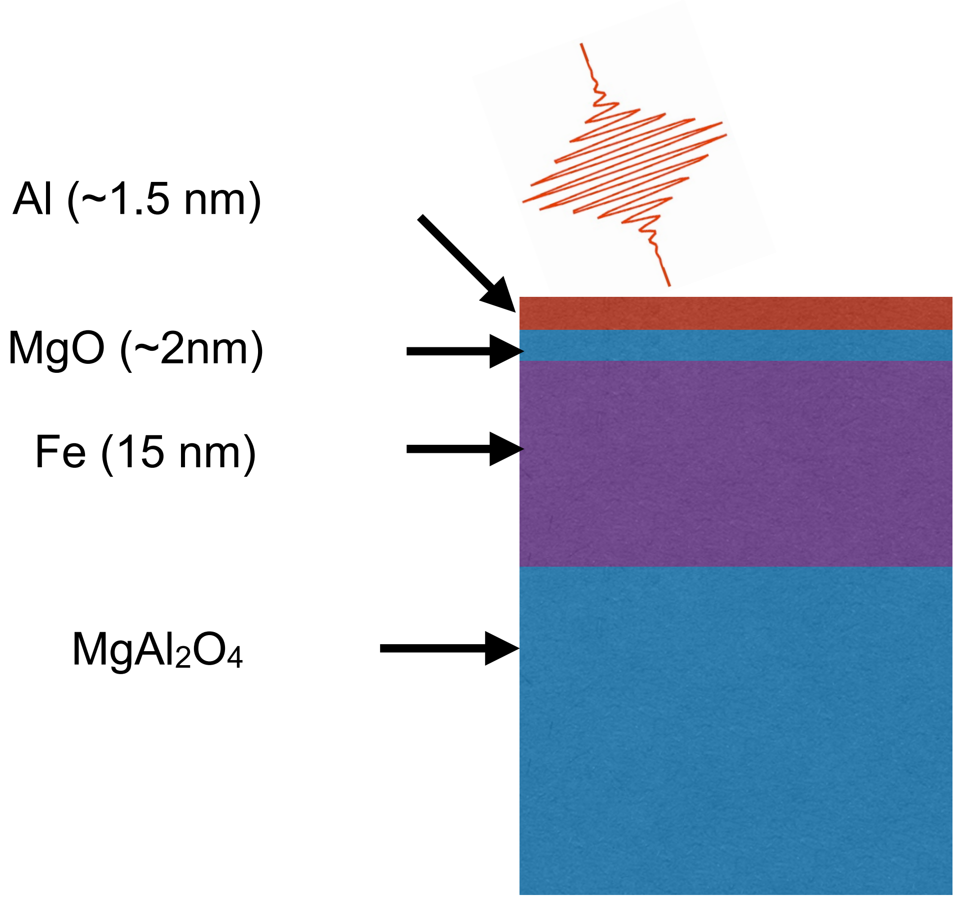
- Intense fs laser excitation of Ni → fast drop in magnetization
- Subsequently seen in Fe, Co, alloys
- Significant drop in M over ~ 10-30 fs
- Where does the angular momentum go?
  - ~~Orbitals?~~ e.g. Stamm et al. Nature Mater. 6, 740 (2007); Hennecke et al. PRL 122, 157202 (2019)
  - ~~EM field?~~ Koopmans et al. J. Phys. Cond. Mat. 15, S723 (2003)
  - Elsewhere in space, but still in spins? "Superdiffusion" Battiato et al. PRL 105, 027203 (2010)
  - Lattice / phonons?

Coupling of magnetism to lattice: ultrafast Einstein-de Haas effect



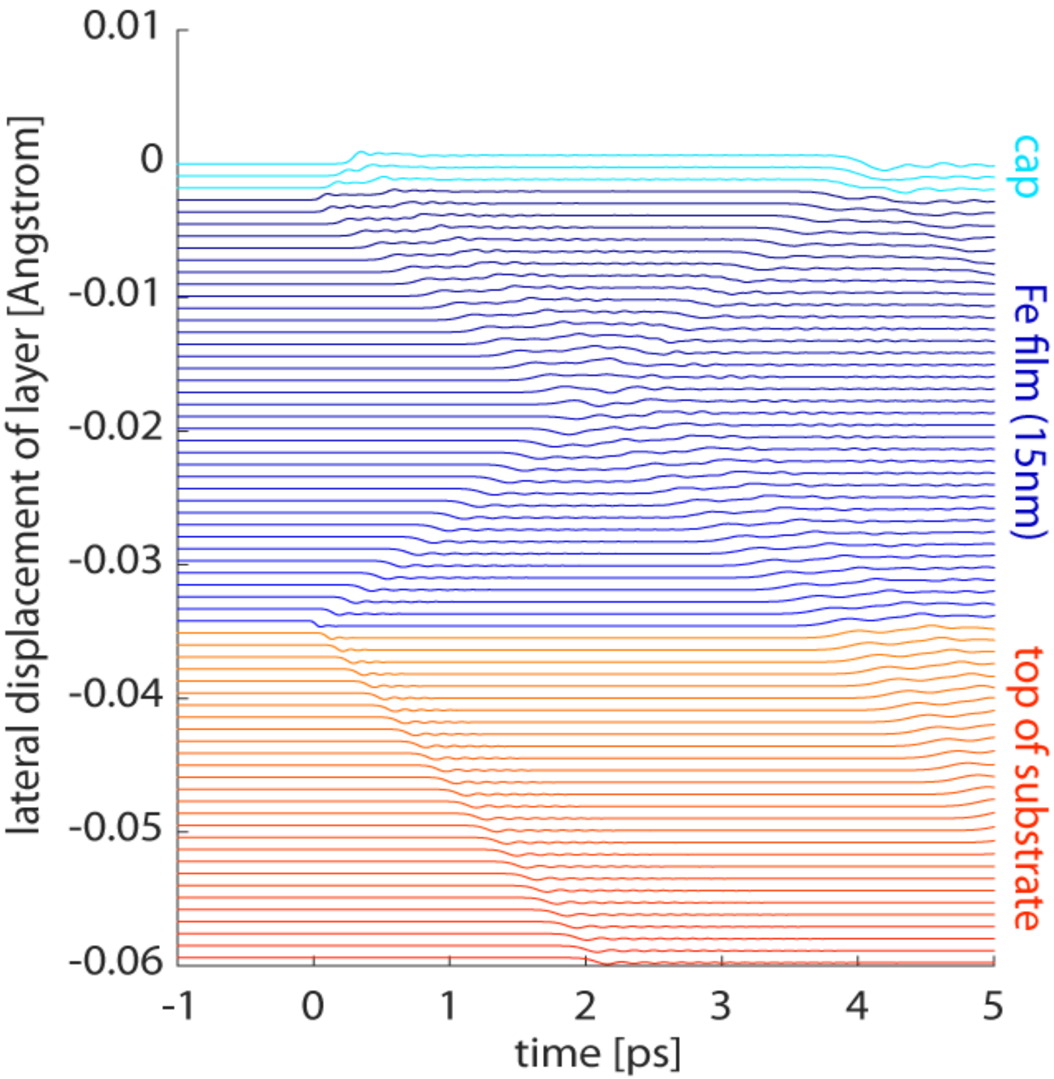
- Fast demagnetization → in-plane force on all surfaces with a normal not parallel to ΔM ($f \propto n \times dM/dt$)
- Leads to a transverse strain wave from surface
- Sign of force/displacement depends on sign of M

Thin film sample



Simulated transverse strain dynamics

Simulated atomic displacements (atomistic model, Born-von Karman)



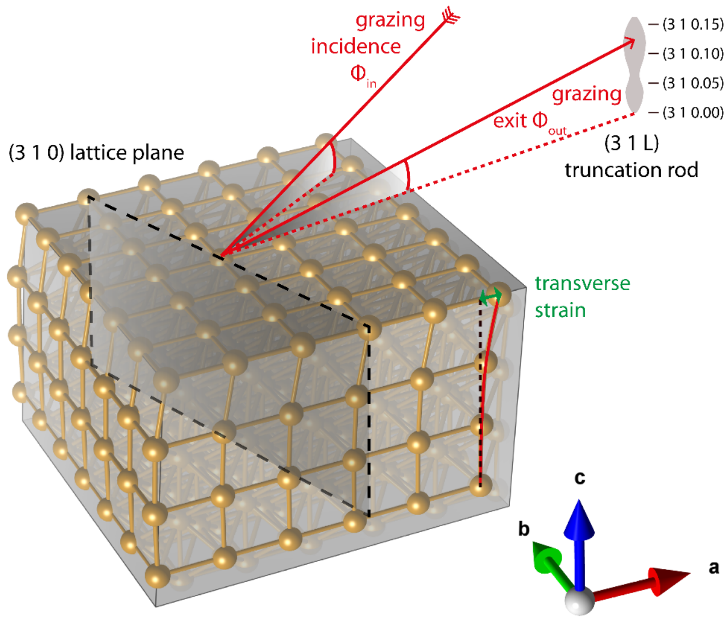
peak strain ~ 1.2 x 10^{-4}

(assumes all lost angular momentum goes to lattice)

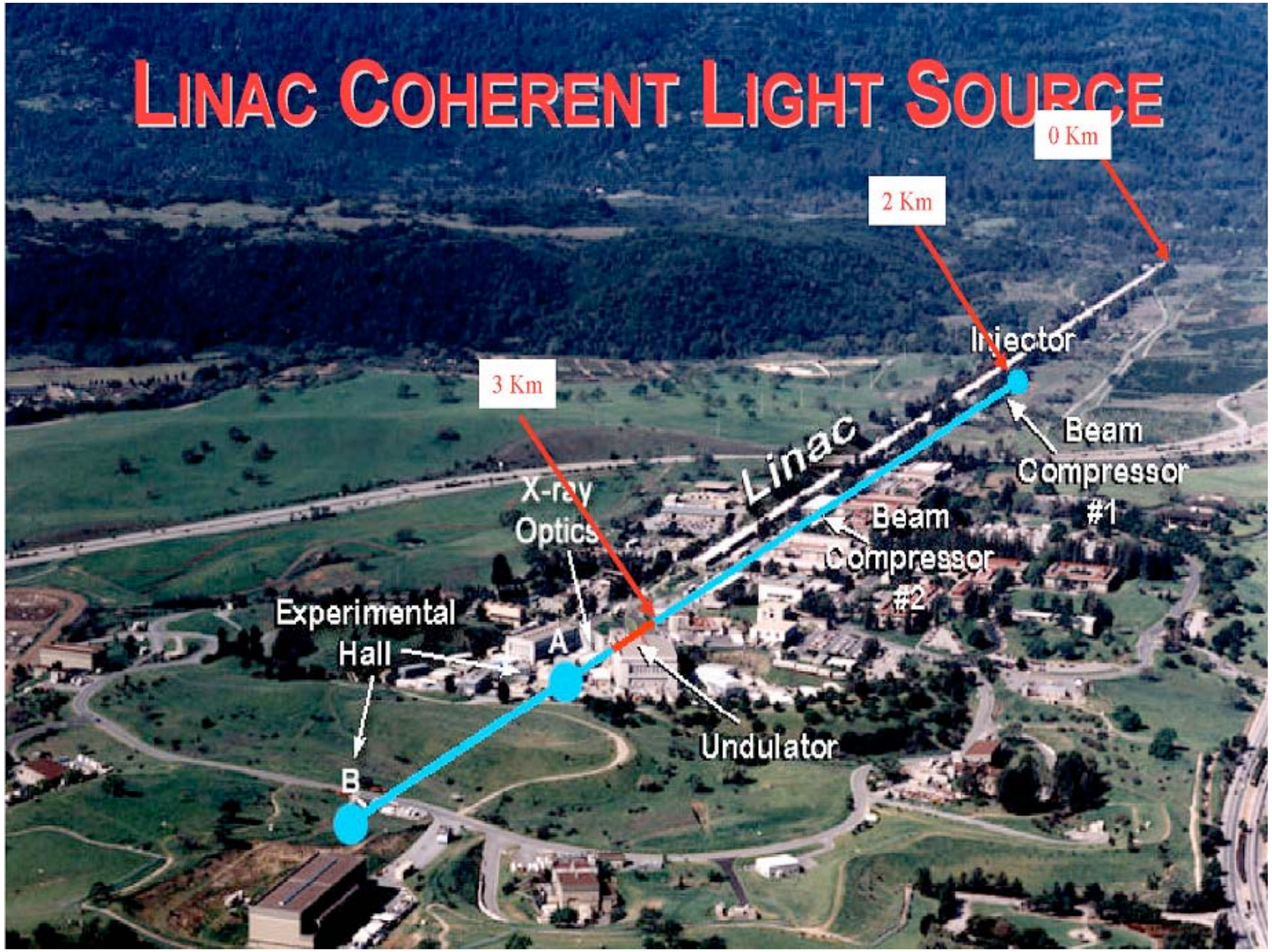
… a tiny change!!

compare to longitudinal strain from heating, up to ~ 1 x 10^{-2}

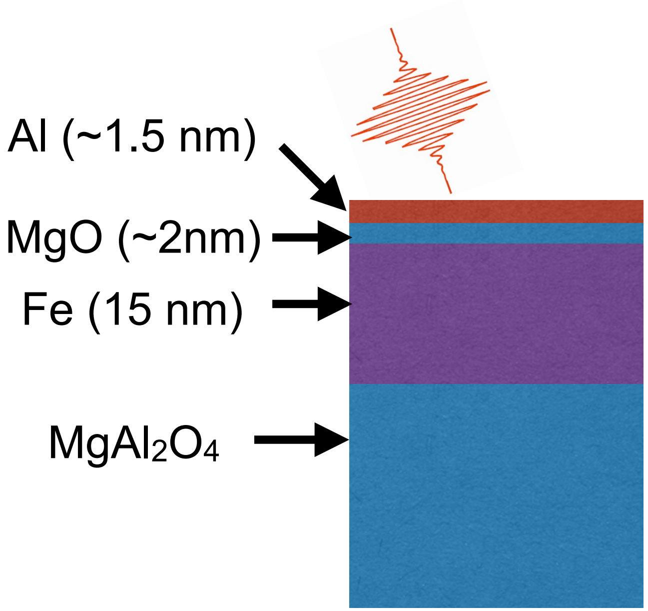
Coupling of magnetism to lattice: ultrafast Einstein-de Haas effect

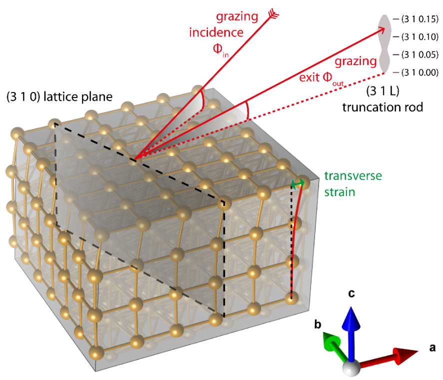


- Can see transverse strain by x-ray diffraction
- Look at a crystal truncation rod (CTR) of an in-plane reflection
- Position along CTR selects momentum
- *Coherent* strain gives *oscillating* intensity contribution, sign depends on sign of M

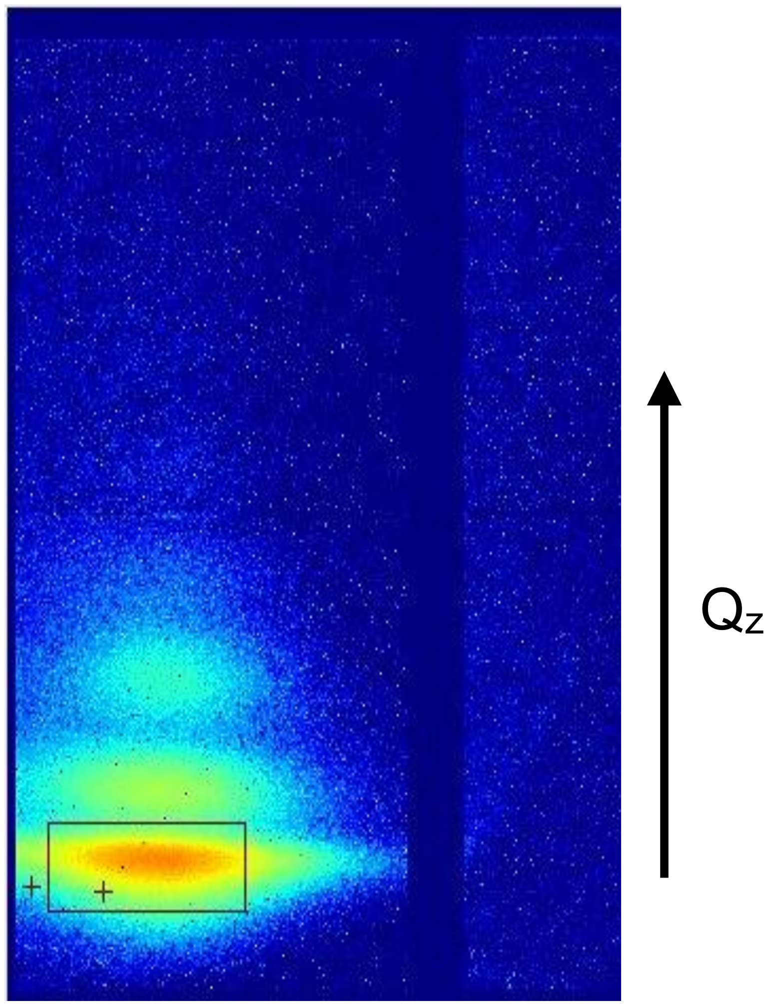

LINAC COHERENT LIGHT SOURCE
0 Km
2 Km
3 Km
Injector
Beam
Compressor
#1
Linac
Beam
Compressor
#2
X-ray
Optics
Experimental
Hall
A
Undulator
B

Measurement of truncation rod

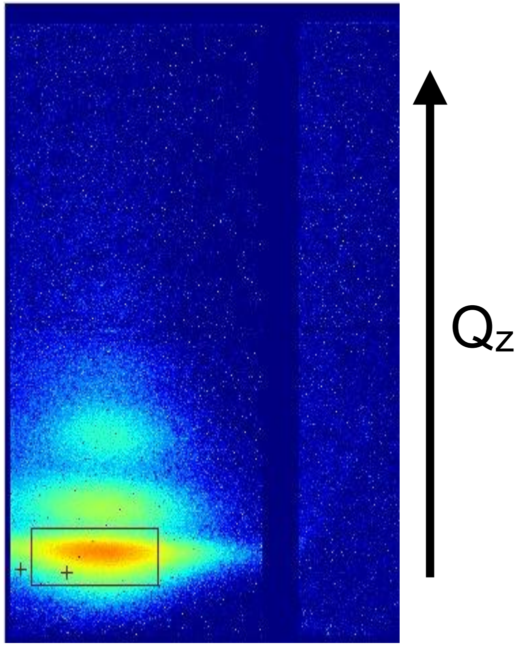




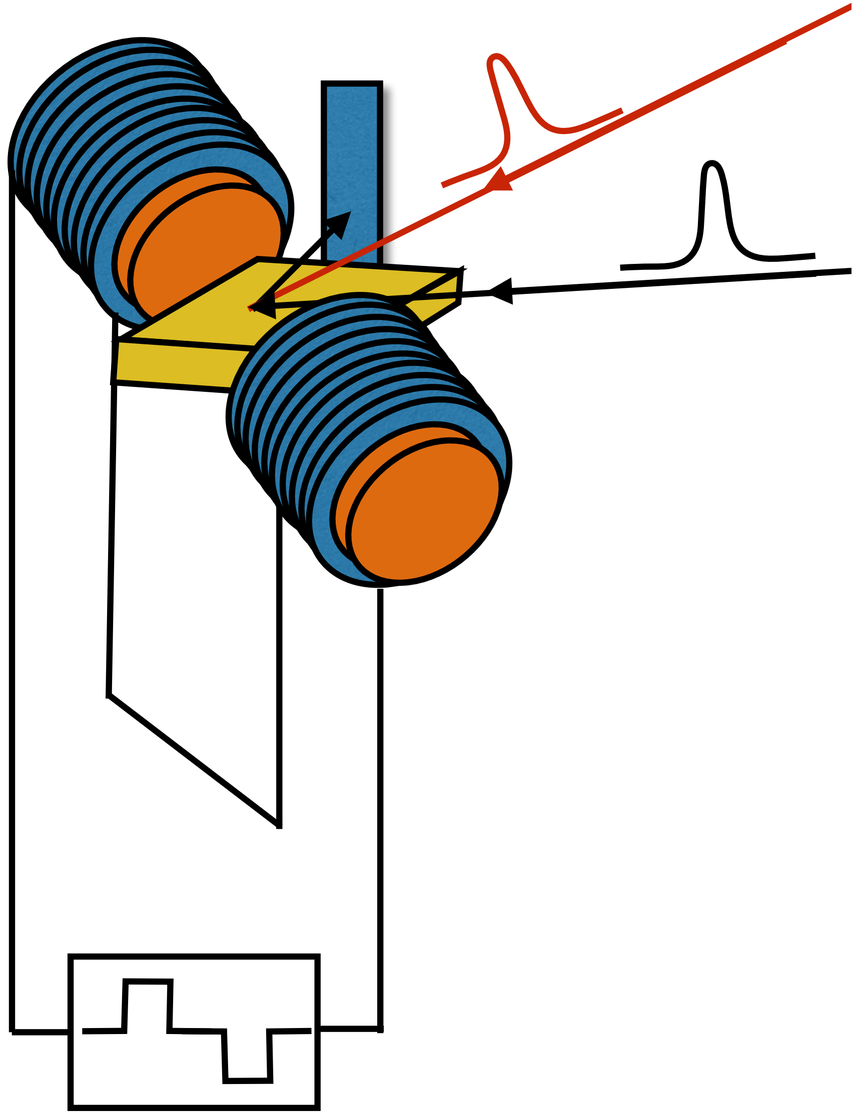
Dornes et al., *Nature* 565, 209 (2019)



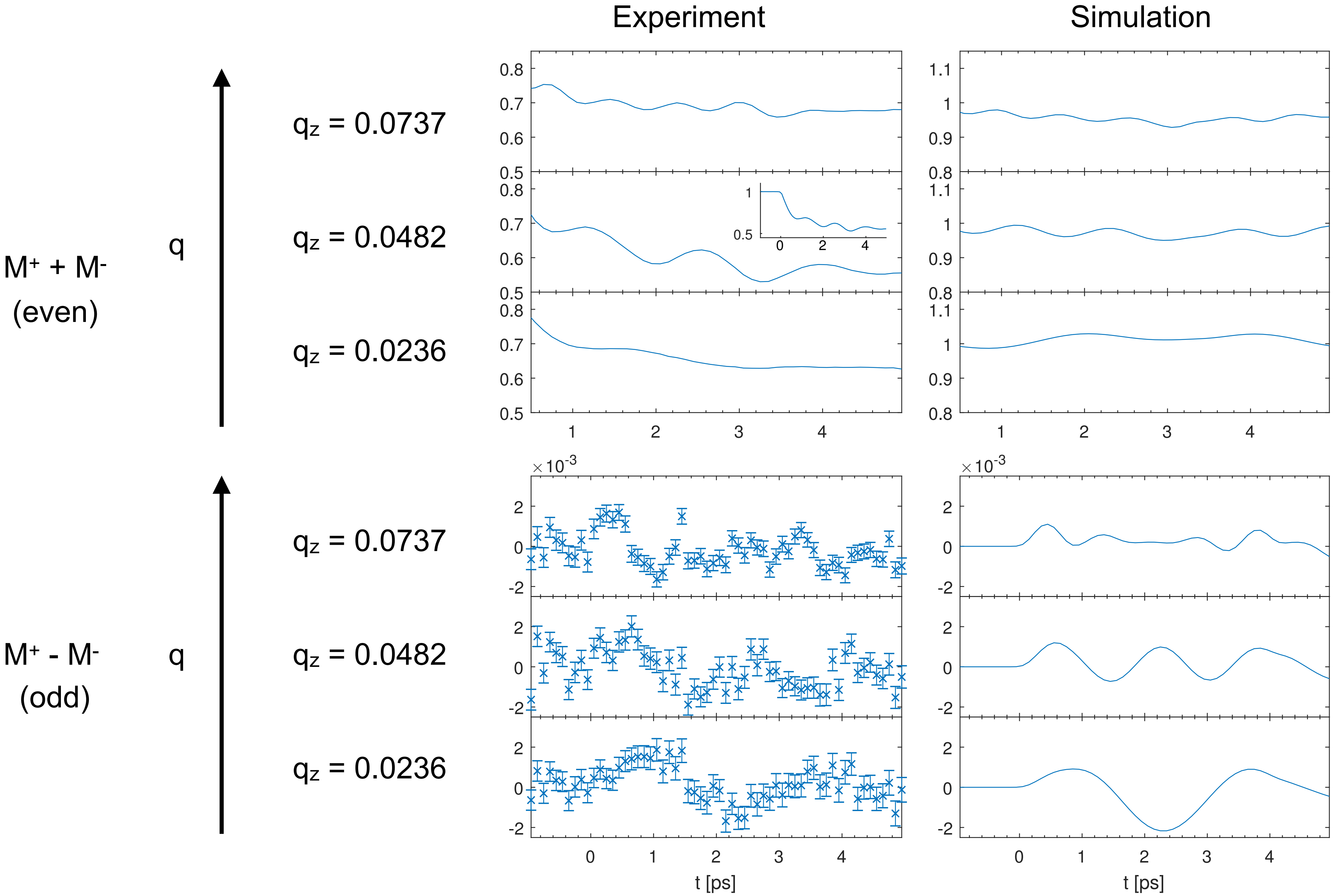
(220) truncation rod



- Pump-probe for time resolution
- Pulser + electromagnet sets +/- M
- Sort data by polarity
- $M^+ + M^-$: "even" effects (heat, magnetostriction)
- $M^+ - M^-$: "odd" effects (EdH transverse strain)

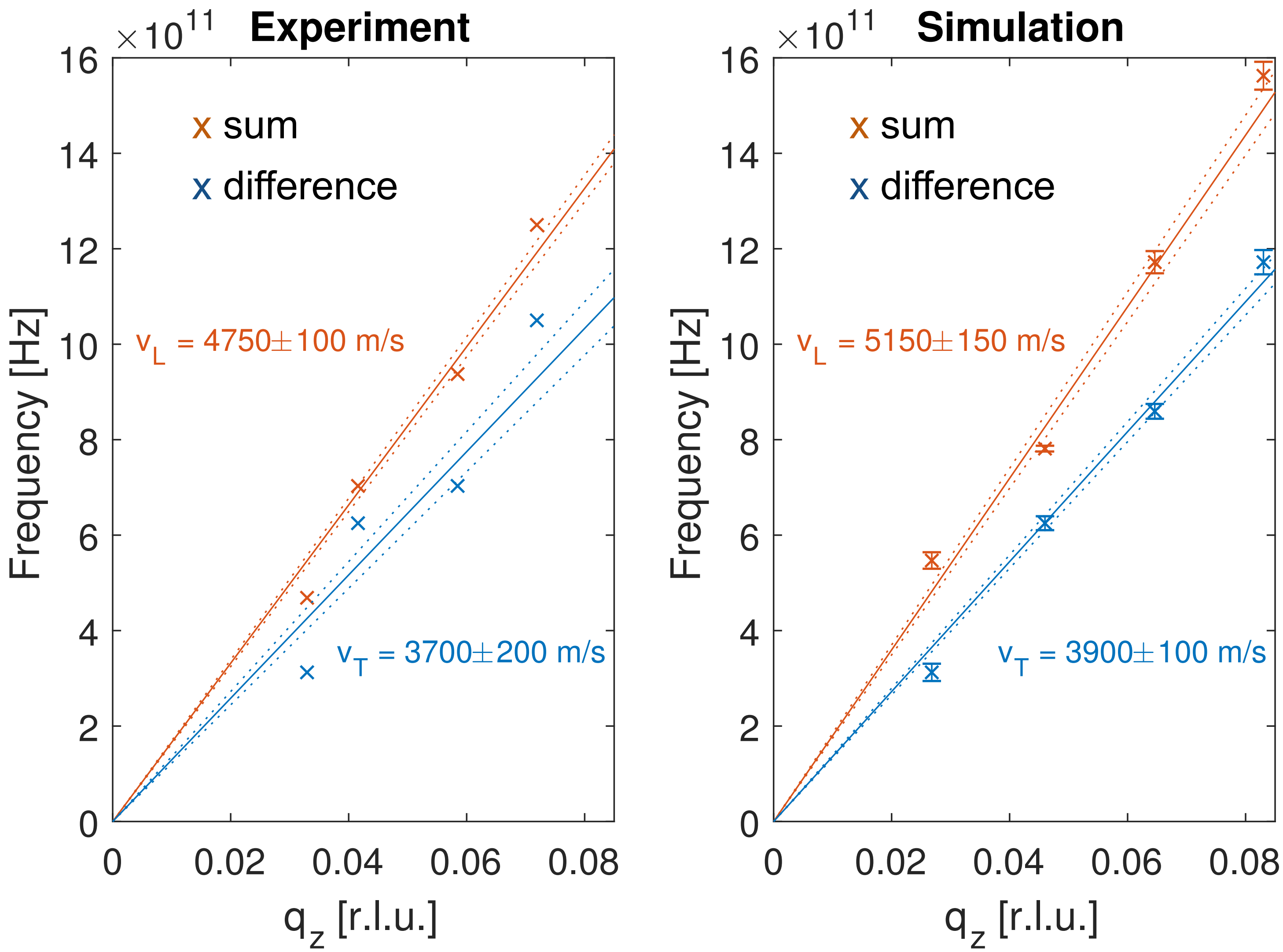


Dornes et al., *Nature* 565, 209 (2019)



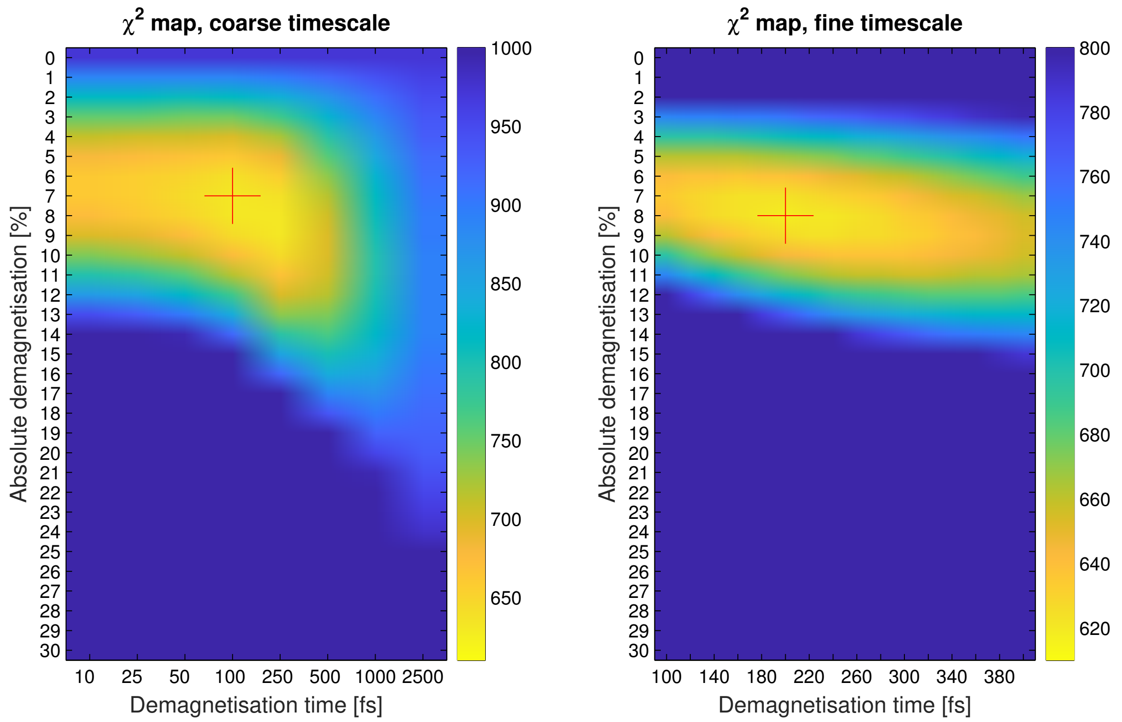
Dornes et al., *Nature* 565, 209 (2019)

Dispersion



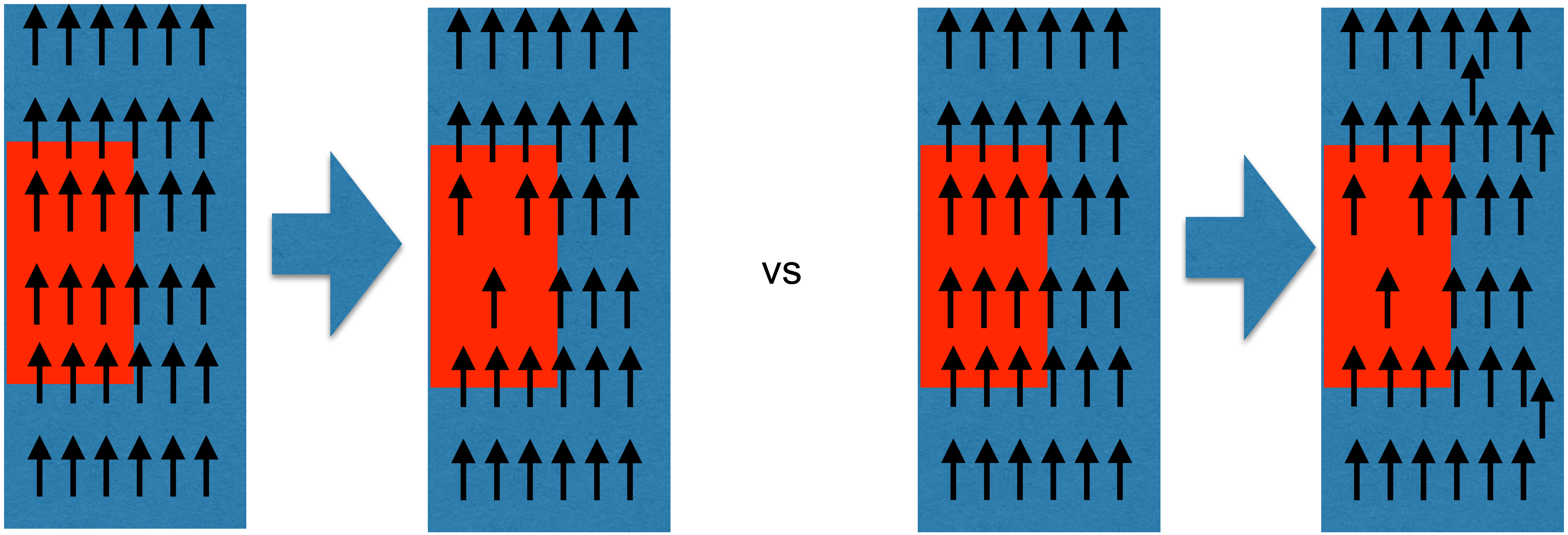
- Consistency check: “odd” M oscillations vs. q agree with transverse sound velocity (3875 ± 20 m/s)

Quantitative analysis



- Best fit of simulation to data consistent with 200 fs time scale of torque, 80% of lost angular momentum
- Large uncertainties, could easily be any time scale below 300 fs and as much as 100%
- Limited mostly by S/N at high wavevectors

Mechanisms: Local vs. superdiffusion



- Is angular momentum transferred to lattice on fast time scales? YES!
- Appears as a coherent strain wave in < 0.3 ps
- Outstanding question: how does it get there?
  - Via incoherent phonons?
  - More direct path?
  - Needs better time & q resolution

Theory…

- Some theories predict a fast (~ 10 fs) transfer via spin-orbit coupling / non-perpturbative coupling to phonons

PRL **115,** 217204 (2015) PHYSICAL REVIEW LETTERS week ending 20 NOVEMBER 2015

Many-Body Theory of Ultrafast Demagnetization and Angular Momentum Transfer in Ferromagnetic Transition Metals

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(Received 12 June 2015; published 20 November 2015)

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Editors' Suggestion

Quantum many-body dynamics of the Einstein–de Haas effect

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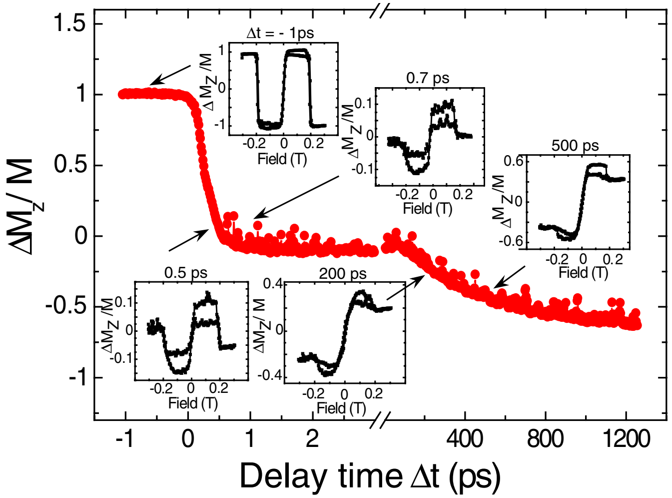
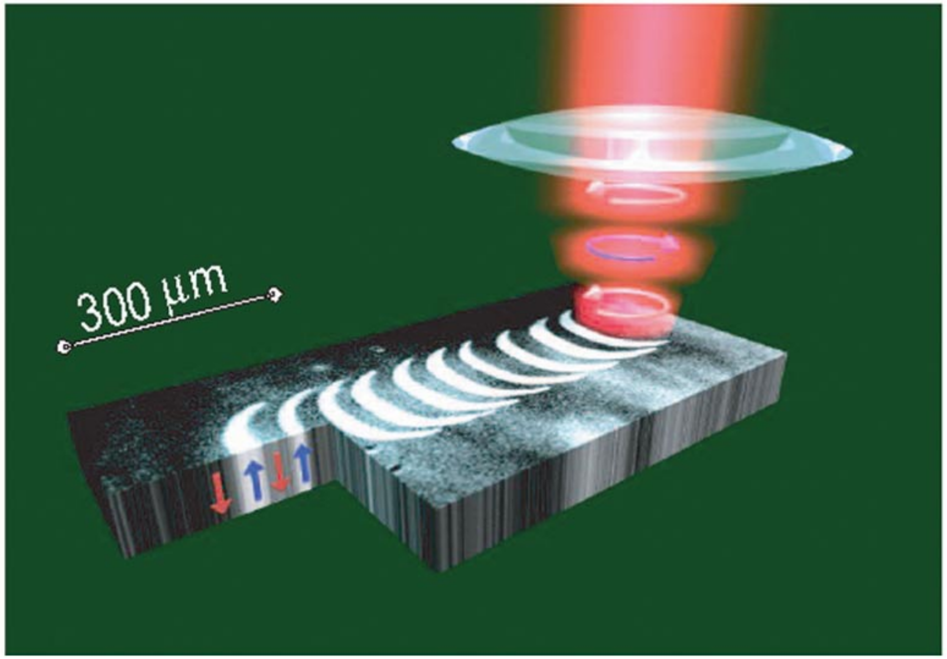
Outlook





[Stanciu et al. PRL 99, 047601 (2007)

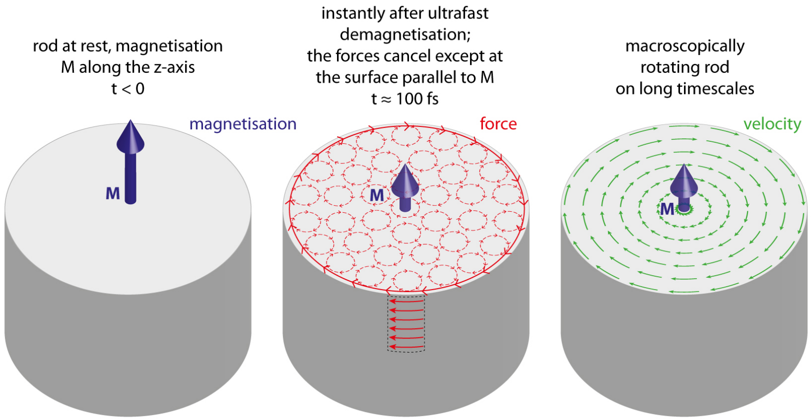
& PRL 99, 217204 (2007)]

GdFeCo alloys

- All optical switching of magnetism in ferrimagnets
- Demagnetization is an intermediate: role/constraints from Einstein-de Haas coupling?

Conclusions

- Experimental evidence for a coupling of dM/dt to antisymmetric stress in response to strong electronic excitation
  - Not magnetostriction (odd in M, depends on dM/dt not M)
- Makes transverse strain wave propagating from interfaces
- May play a role in ultrafast switching of ferrimagnets



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