Ultrafast magnetization reversal driven by optical phonons

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FELIX
Free Electron Lasers for
Infrared eXperiments

Radboud University

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IMM, Nijmegen D. Afanasiev, A.V. Kimel

UwB Bialystok K. Szerenos, A. Stupakiewicz

MPI Stuttgart K. Rabinovich, A.V. Boris

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MEGA GRANTS

NWO

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Britta Redlich
Lex van der Meer
Victor Claessen
René van Buuren
Wouter Stumpel
Bryan Willemsen

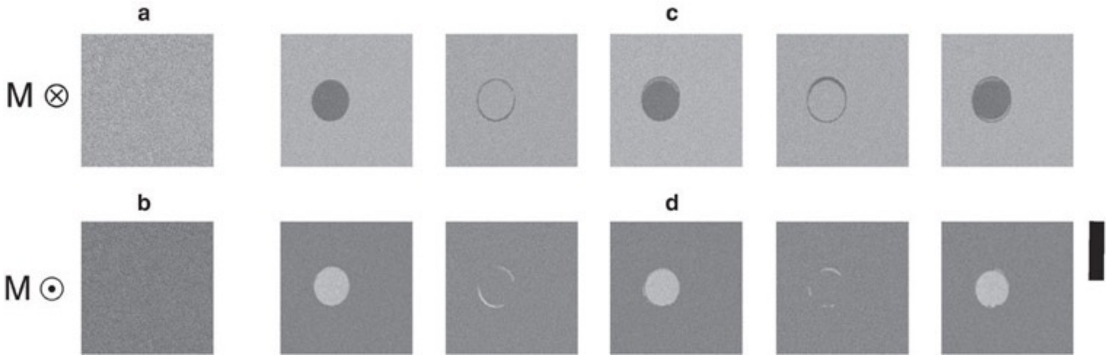
cost
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY

Spice

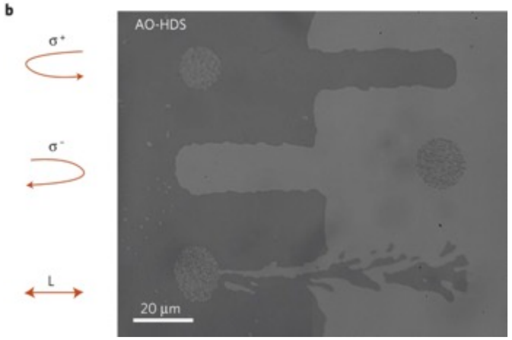
FEMTO
TERABYTE

Searching for a non-thermal switching mechanism

1. **Single-shot thermally-induced** switching; "just" fast heating in GdFeCo, Tb/Co, Mn_2Ru_xGa
    - I. Radu *et al*, Nature (2011)
    - T. Ostler *et al*, Nature Comms (2012)
    - J. H. Mentink *et al*, Phys. Rev. Lett (2012)
    - L. Aviles-Felix *et al*, Sci. Rep. (2020)
    - C. Banerjee et al, Nature Comms (2020)
    - C. S. Davies *et al*, Phys. Rev. Res. (2020)



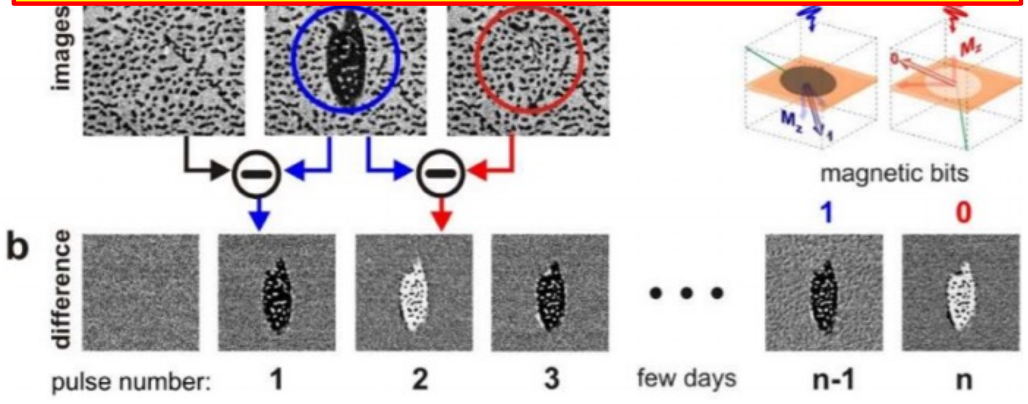
2. **Multi-shot helicity-dependent** switching; possible in Co/Pt, Co/Pd, HoFeCo, TbCo…



- C.-H. Lambert *et al*, Science (2014)
- S. Mangin *et al*, Nat. Materials (2014)
- R. Medapalli *et al*, Phys. Rev. B (2017)

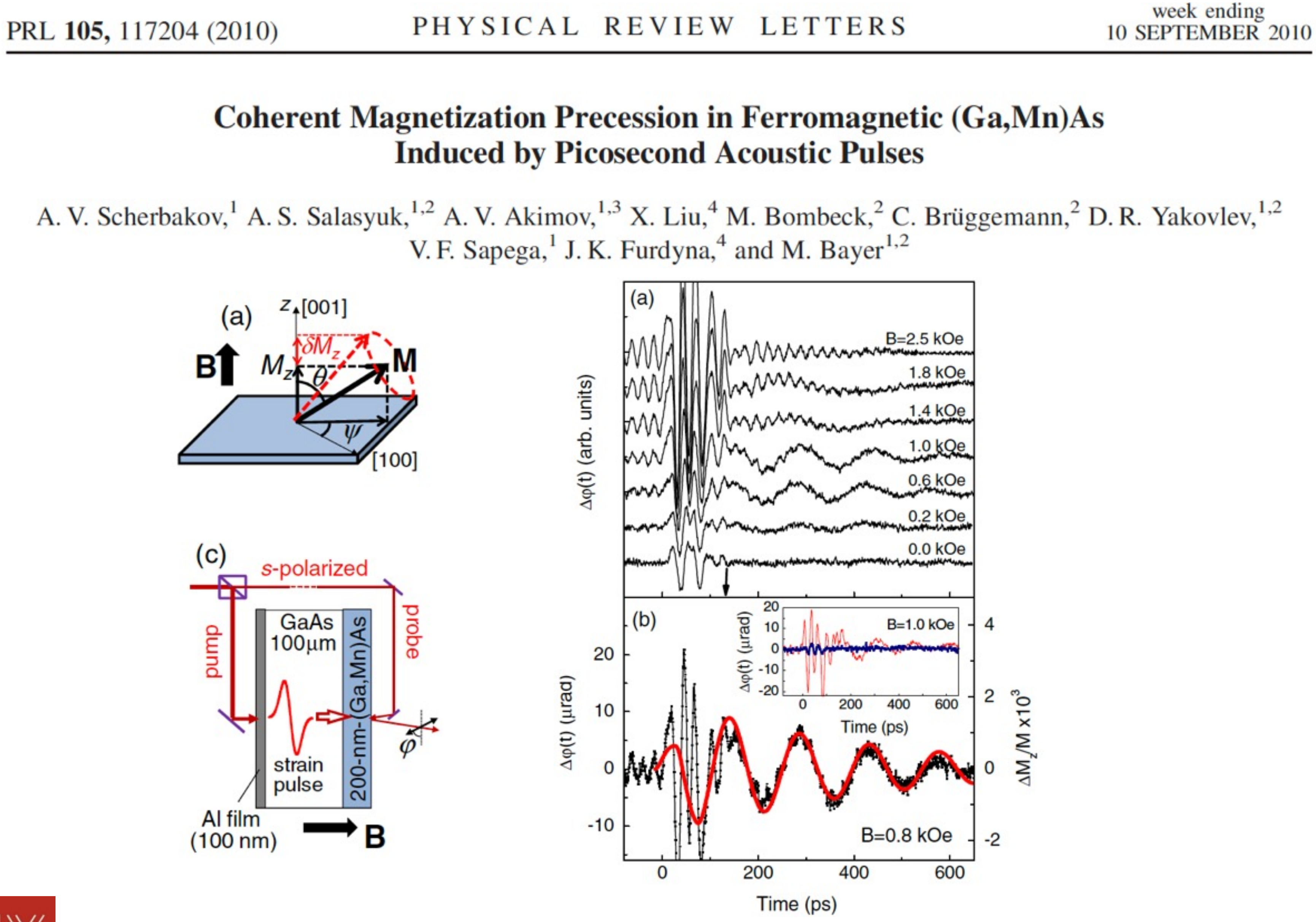
3. **Single-shot polarization-dependent** "cold"

Is there another non-thermal approach?



- A. Stupakiewicz *et al*, Nature (2017)

Crystallographic strains?

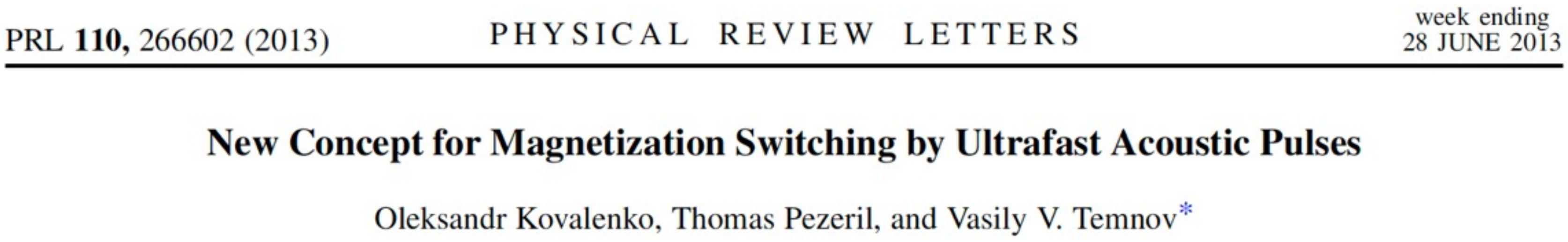


PRL **105,** 117204 (2010) PHYSICAL REVIEW LETTERS week ending 10 SEPTEMBER 2010

Coherent Magnetization Precession in Ferromagnetic (Ga,Mn)As Induced by Picosecond Acoustic Pulses

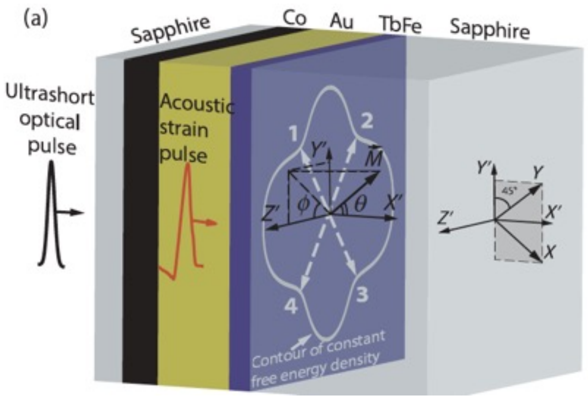
A. V. Scherbakov,[1] A. S. Salasyuk,[1,2] A. V. Akimov,[1,3] X. Liu,[4] M. Bombeck,[2] C. Brüggemann,[2] D. R. Yakovlev,[1,2]
V. F. Sapega,[1] J. K. Furdyna,[4] and M. Bayer[1,2]

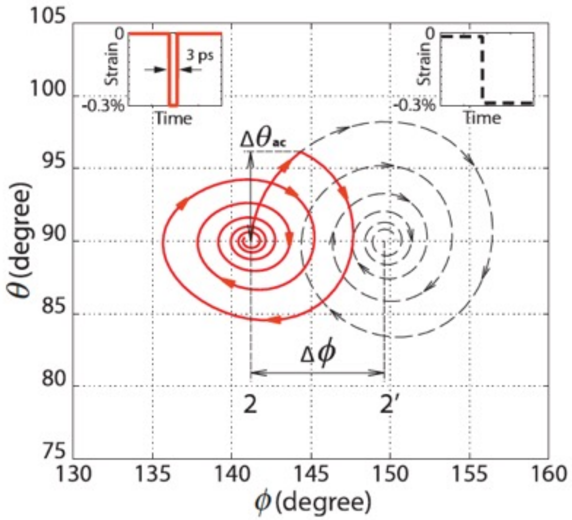
Strain-induced switching - proposal

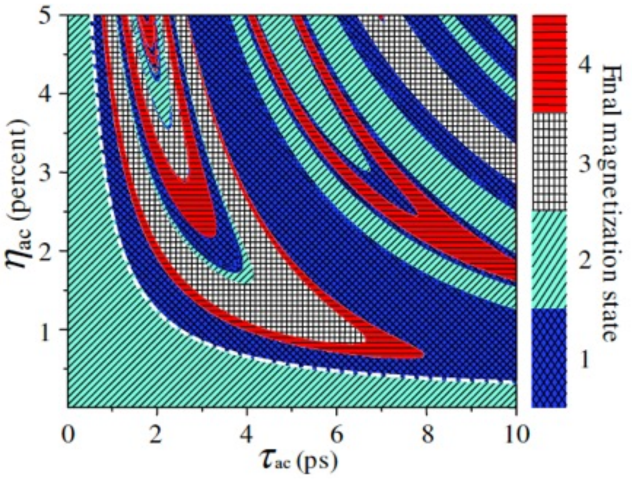

PRL **110,** 266602 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

New Concept for Magnetization Switching by Ultrafast Acoustic Pulses

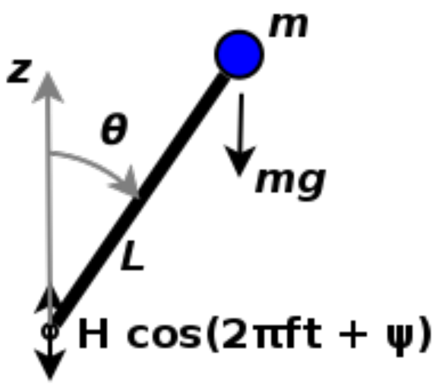
Oleksandr Kovalenko, Thomas Pezeril, and Vasily V. Temnov*



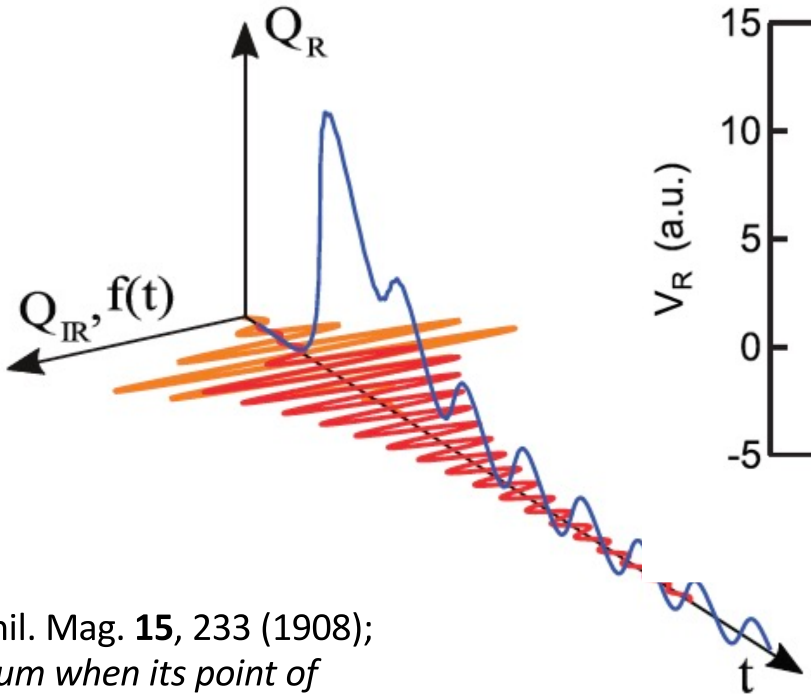


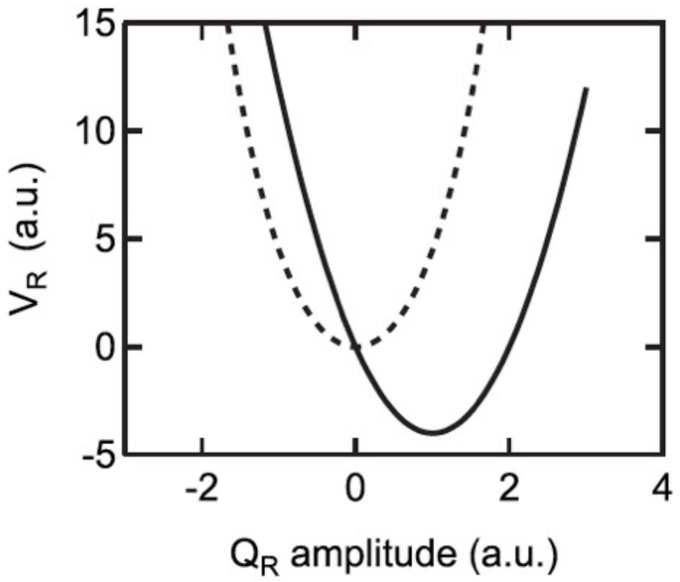


From coupled oscillators to 'nonlinear phononics'



KAPITZA'S INVERTED PENDULUM

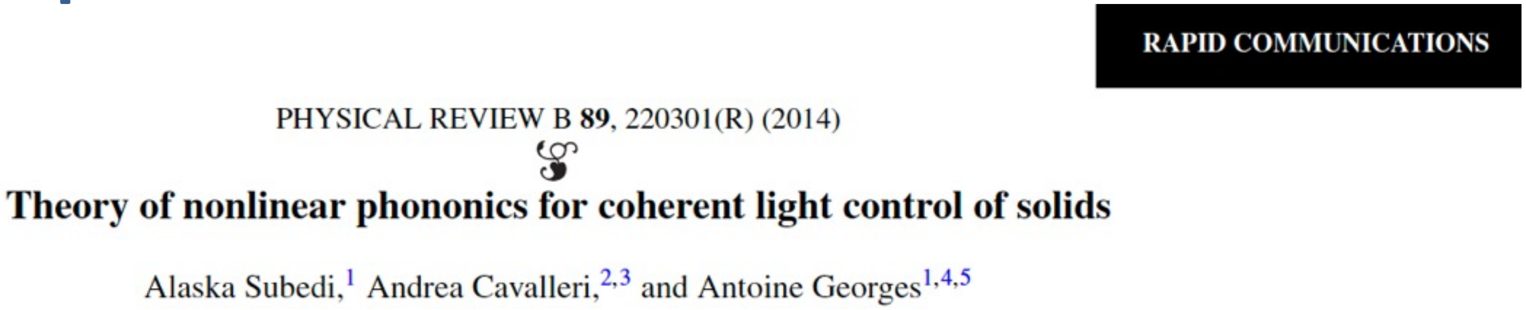




A. Stephenson, *On an induced stability,* Phil. Mag. **15**, 233 (1908);
P.L. Kapitza, *Dynamic stability of a pendulum when its point of suspension vibrates*, Sov. Phys. JETP **21**, 588 (1951).

Mankowsky et al, *Non-equilibrium control of complex solids by nonlinear phononics*, Rep. Prog. Phys. **79**, 064503 (2016)

Change of equilibrium

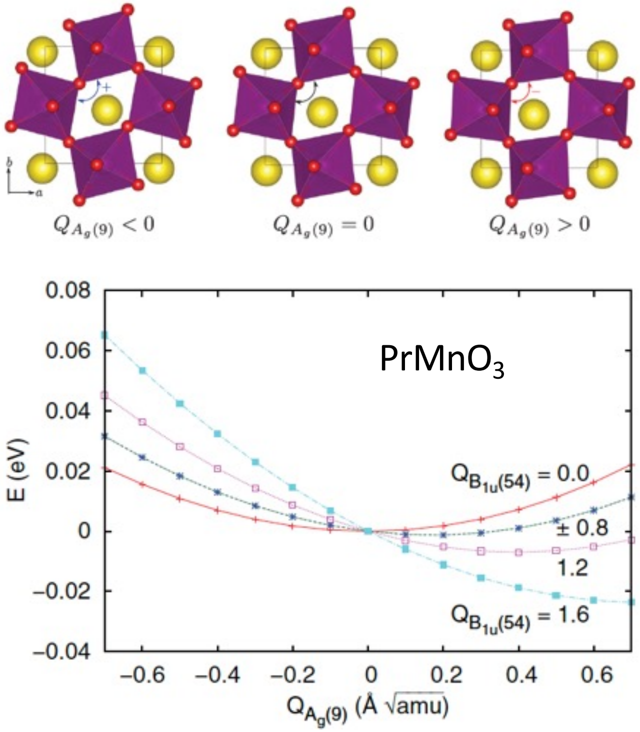


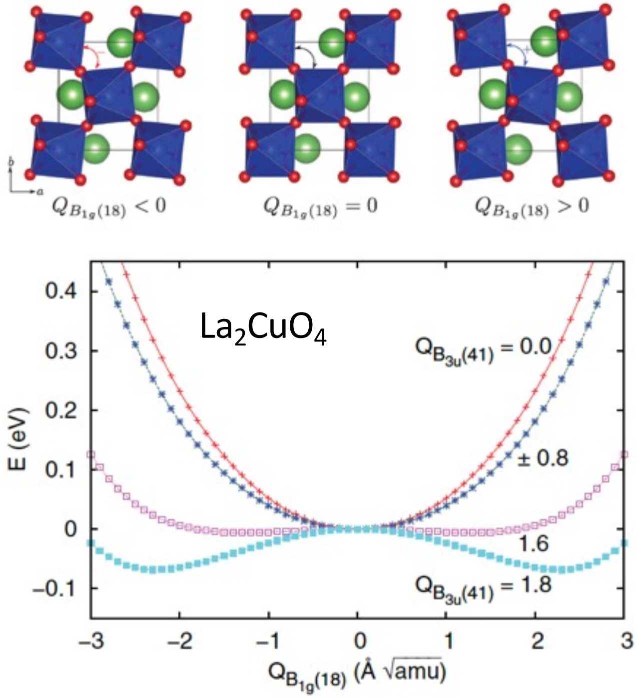
RAPID COMMUNICATIONS

PHYSICAL REVIEW B **89**, 220301(R) (2014)

Theory of nonlinear phononics for coherent light control of solids

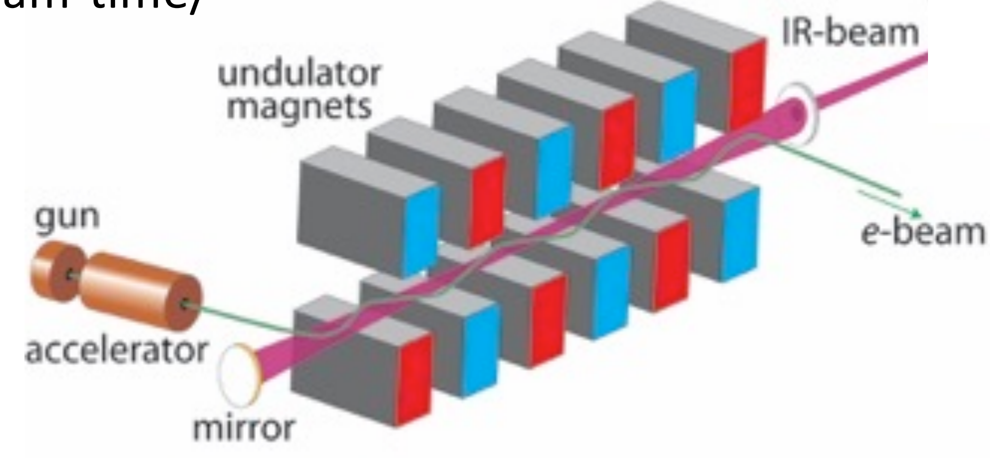
Alaska Subedi,[1] Andrea Cavalleri,[2,3] and Antoine Georges[1,4,5]

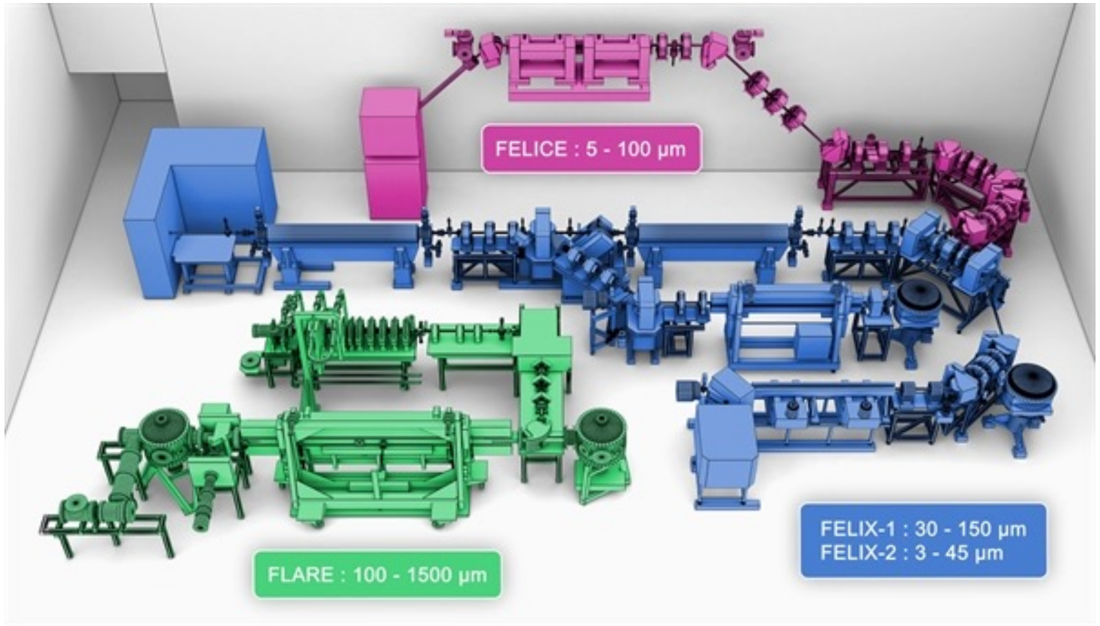




Infrared / THz lasers at FELIX Laboratory

https://www.ru.nl/felix/facility/apply-beam-time/

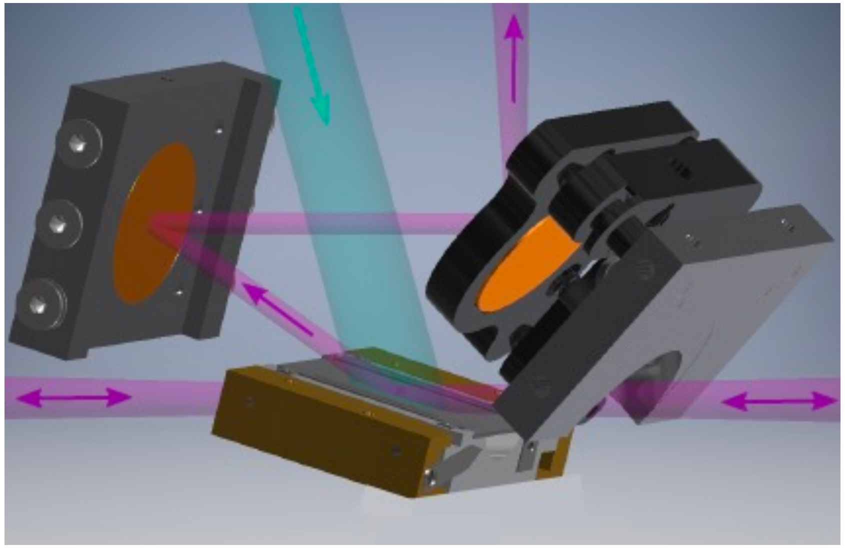


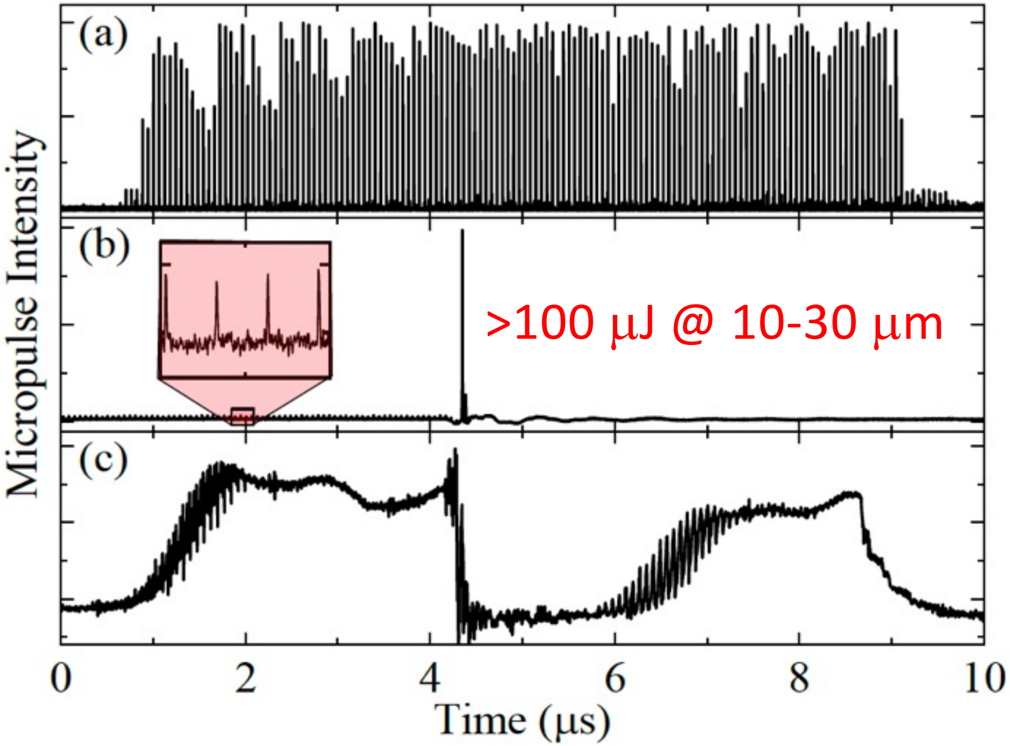


- λ tunable between 2.7µm and 1.5mm
  or between 0.2 – 90 THz
- 10s µJ’s per (sub)ps pulse
- 0.4 – 2% bandwidth, Fourier-transform limited

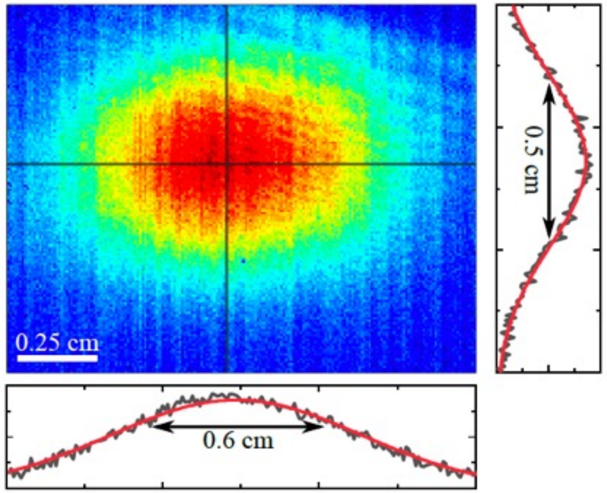
D. Oepts, A. F. G. van der Meer, and P. van Amersfoort, “The free-electron-laser user facility FELIX,” Infrared Phys. Technol. **36**, 297 (1995)

Strong single picosecond pulses from cavity-dump





>100 μJ @ 10-30 μm

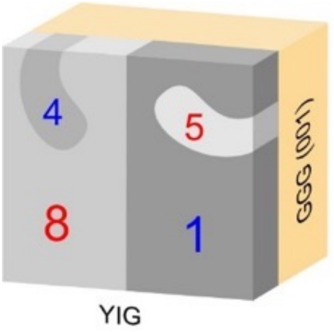


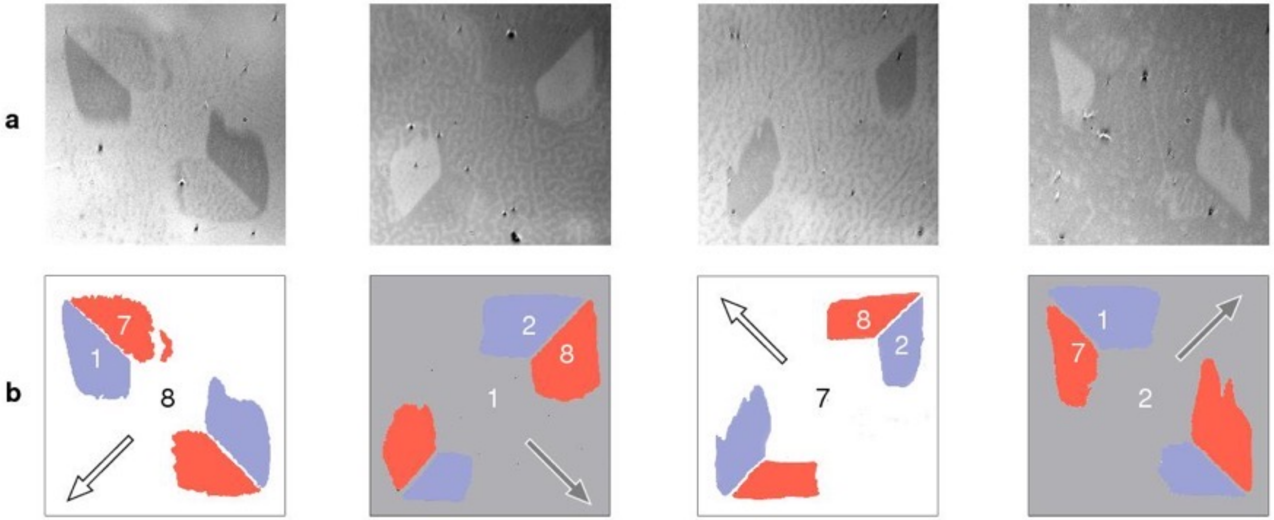
to compare: Pulse-slicing of FELIX output typically delivers pulse energies of 10-12 μJ maximum

T. Janssen et al, Rev. Sci. Instr., in press (2022)

FELIX-induced switching

- Polarizing microscope





- Single micropulse
  (λ = 14 µm, τ ≈ 1 ps)

1 pulse, 10 pulses, 100's of pulses…

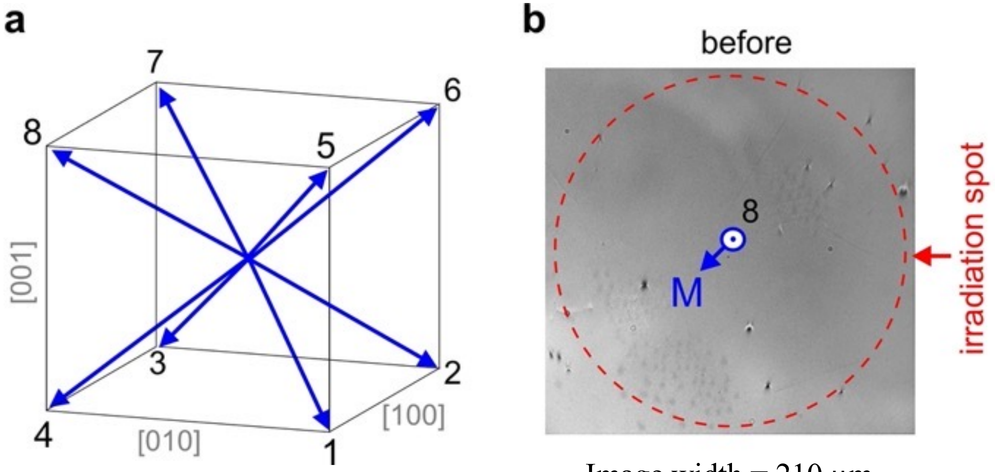
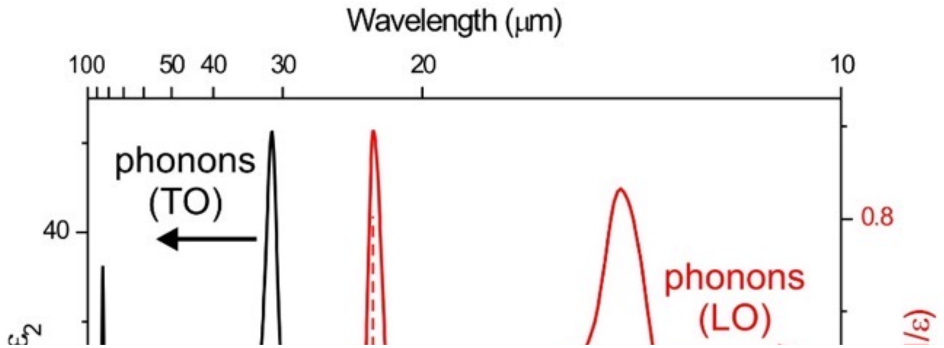


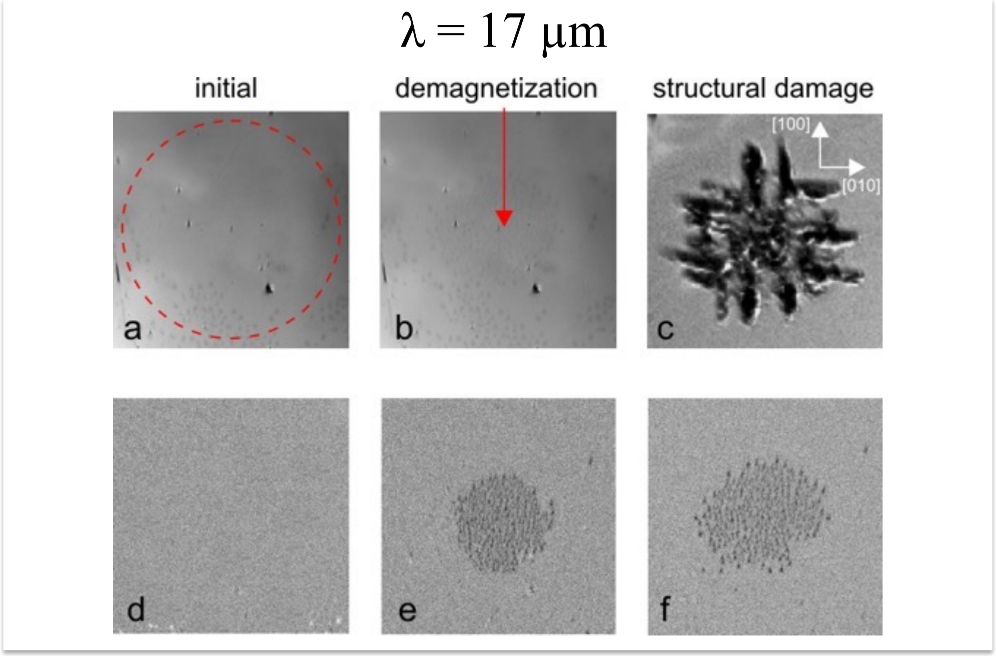
Image width = 210 µm

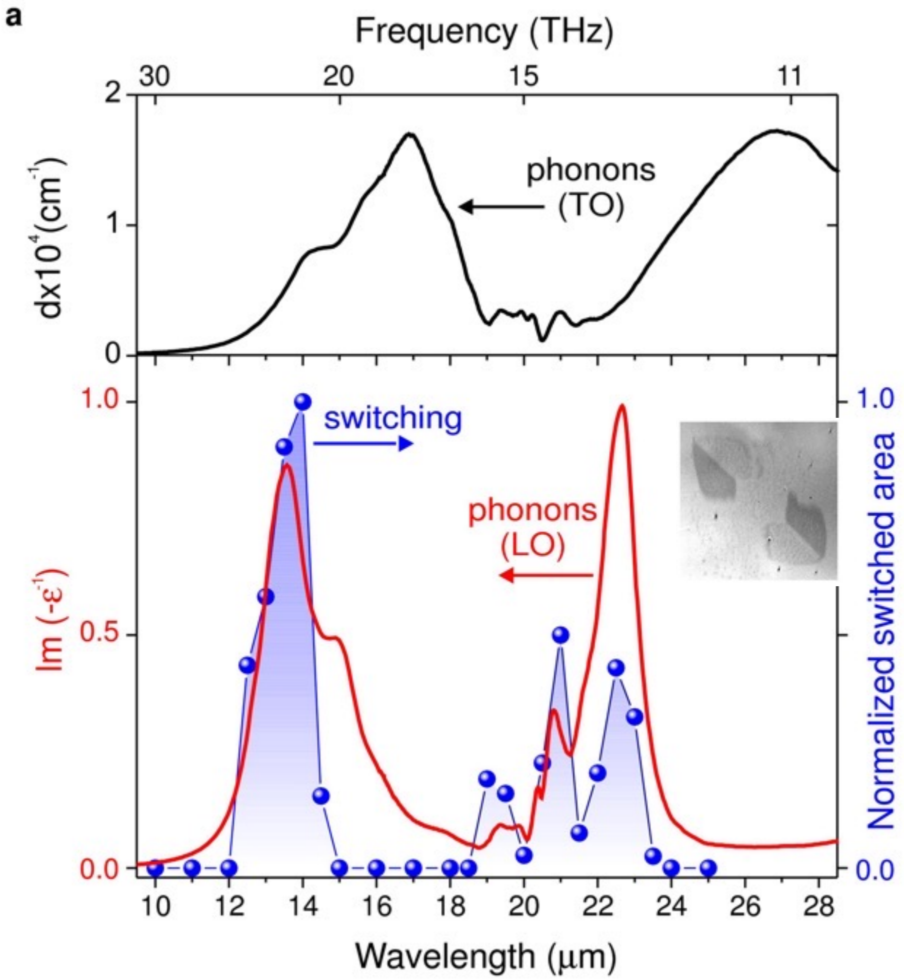
A. Stupakiewicz et al, Nature Physics **17**, 489 (2021)

Spectral dependence of switching

Using ellipsometry, we measure the phonon spectra



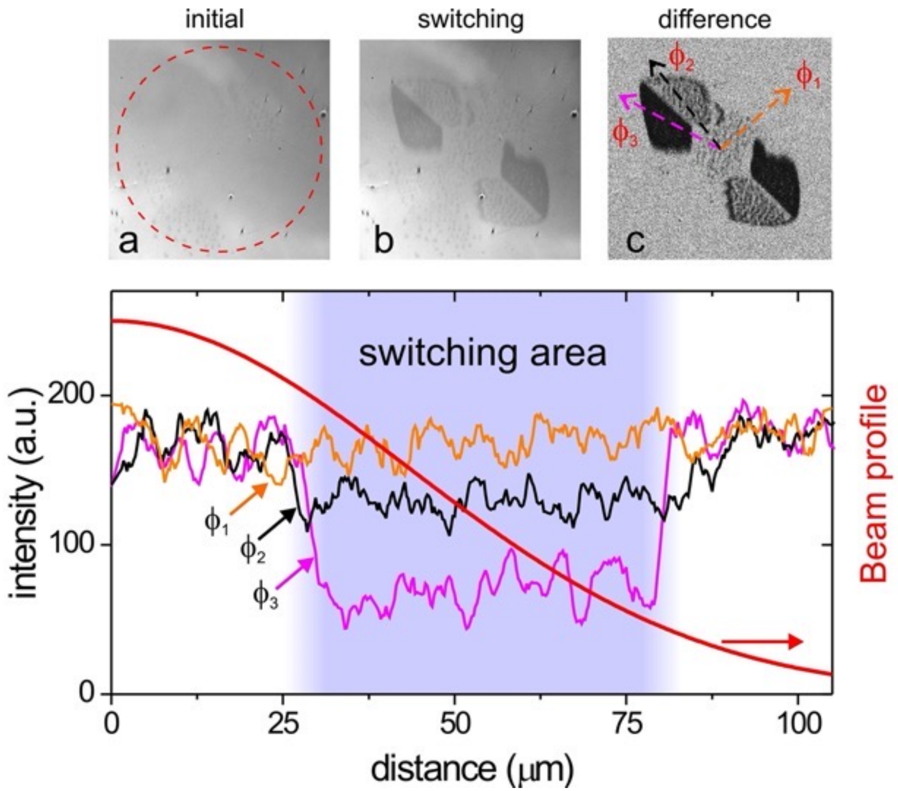

λ = 17 µm

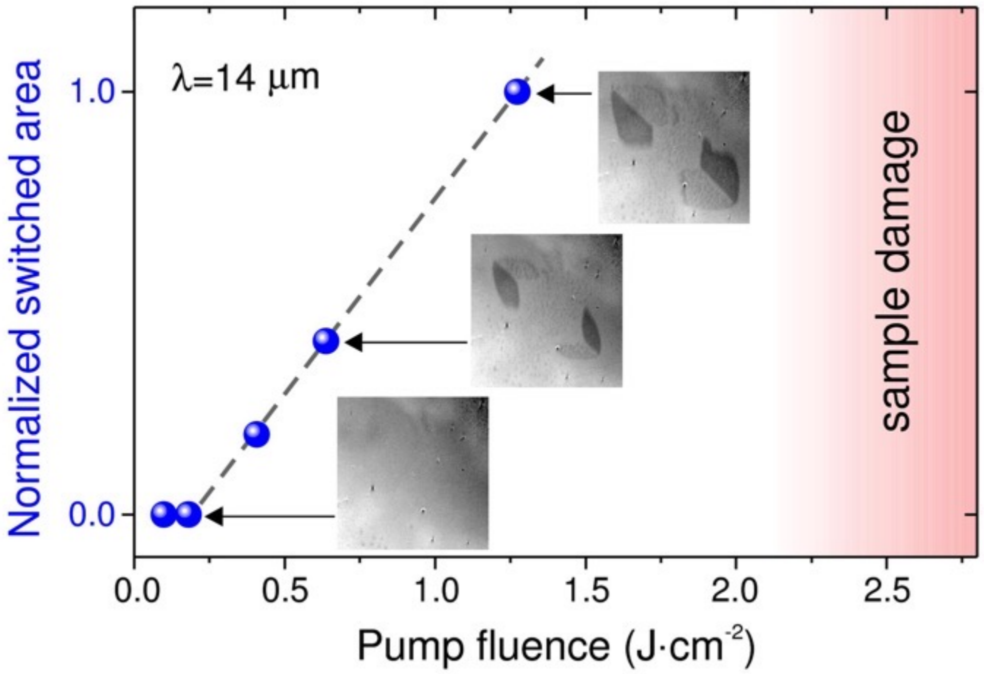


Good correlation between the spectral dependence of **longitudinal** phonons and the switching

Induced spatial pattern

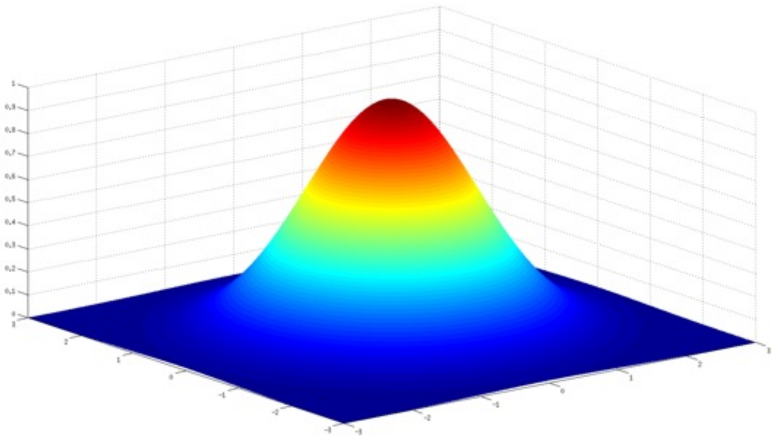
Gaussian pulse, but the switching is off-center

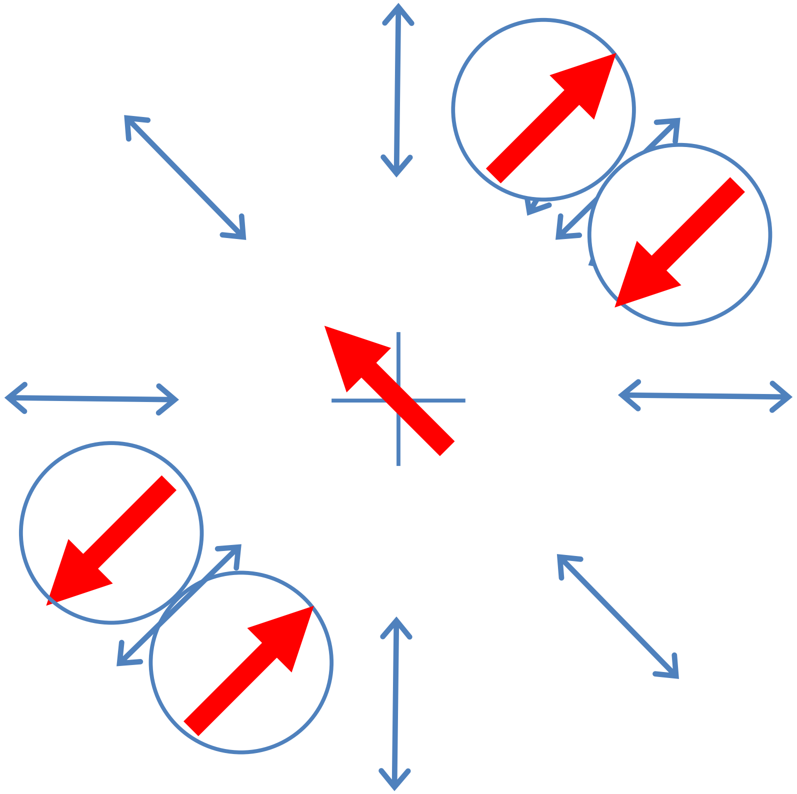




As we increase fluence, the pattern grows in size

Shape of the domains?





Spatial distribution of strain

Assume the induced in-plane shift of potential ***u*** has a 2D Gaussian profile

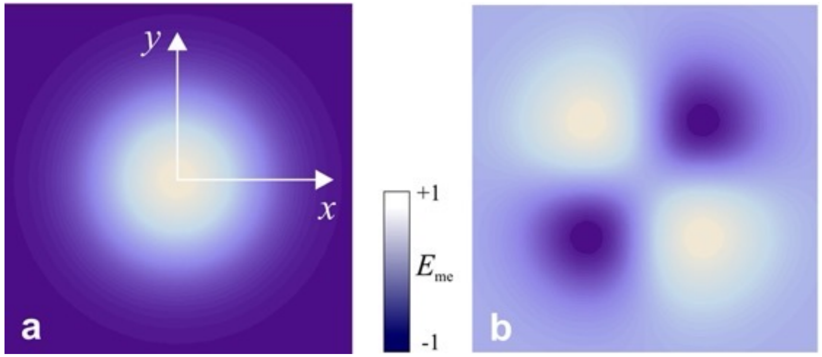
$$u = \frac{Aqa^2}{3}\frac{1+\sigma}{1-\sigma}\left[\frac{1}{r}\left(1-e^{-\frac{r^2}{2a^2}}\right)+(1-2\sigma)\frac{r}{R^2}e^{-\frac{R^2}{2a^2}}\right]$$

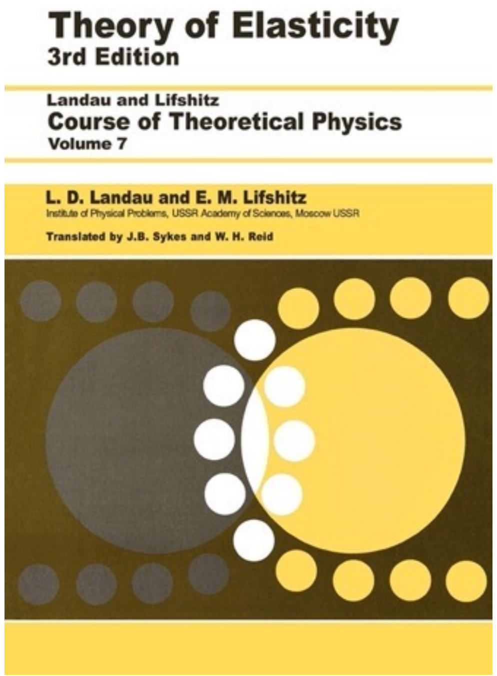
L.D. Landau and E.M. Lifshitz, *Course of Theoretical Physics, vol. 7: Theory of Elasticity (3rd ed.)* (Elsevier, Amsterdam, 1986).

Induced strain →

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial \boldsymbol{u}_i}{\partial x_j}+\frac{\partial \boldsymbol{u}_j}{\partial x_i}\right)$$

$$E_{me} = b_1\left(\varepsilon_{xx}m_x^2+\varepsilon_{yy}m_y^2\right)+2b_2\varepsilon_{xy}m_xm_y$$




Theory of Elasticity
3rd Edition

Landau and Lifshitz
Course of Theoretical Physics
Volume 7

L. D. Landau and E. M. Lifshitz
Institute of Physical Problems, USSR Academy of Sciences, Moscow USSR

Translated by J.B. Sykes and W. H. Reid

Micromagnetic simulations

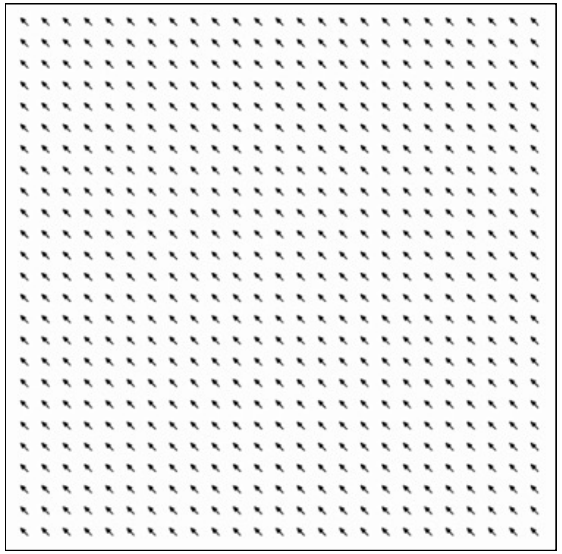
OOMMF with magnetoelastic extension

$$h_{\mathrm{me}}(r,t) = h_{\mathrm{me},0} \cdot h_{\mathrm{me}}(\mathrm{r}) \cdot h_{\mathrm{me}}(\mathrm{t})$$

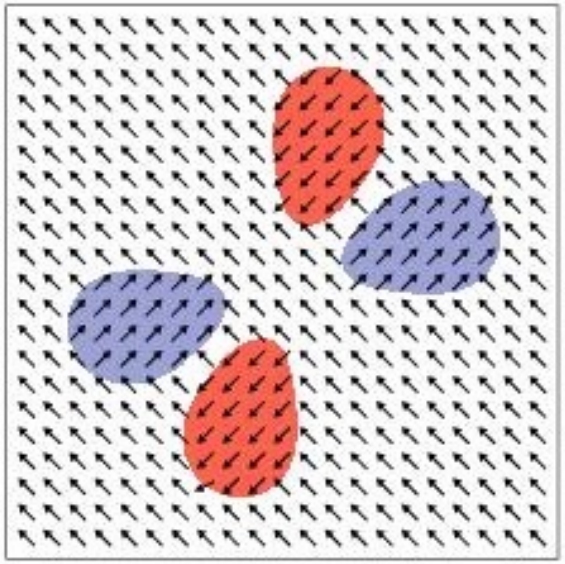
$$h_{me}(r) = -\frac{\delta U_{me}}{\delta \vec{M}}$$

$$h_{me}(t) = exp\left(-\frac{[t-t_0]^2}{[t^2/(4ln2)]}\right),$$

Initial magnetization



Magnetization

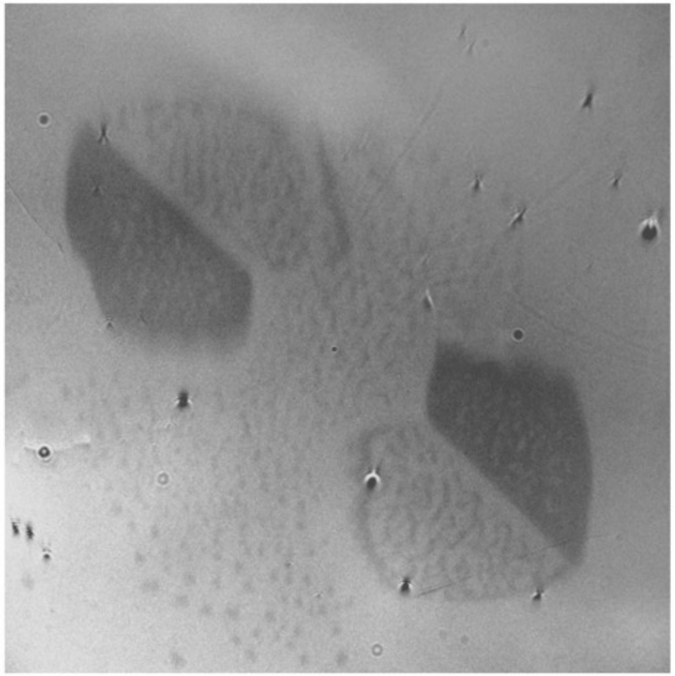


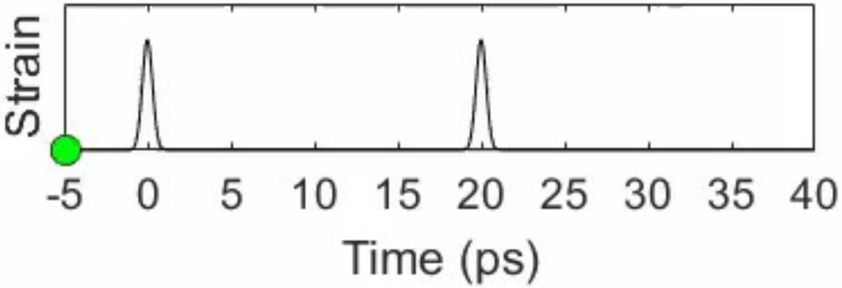
M. Donahue and D. G. Porter, OOMMF User's Guide (1999).

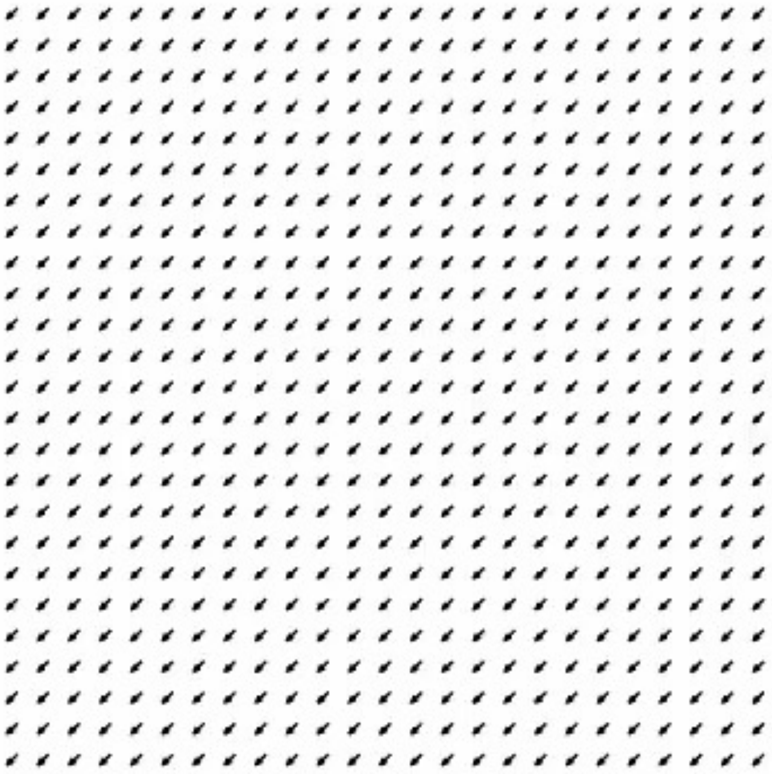
A. V. Sadovnikov et al, *Appl. Phys. Lett.* **106**, 192406 (2015).

Y. Yahagi et al, *Phys. Rev. B* **90**, 140405(R) (2014).

Multiple-pulse excitation



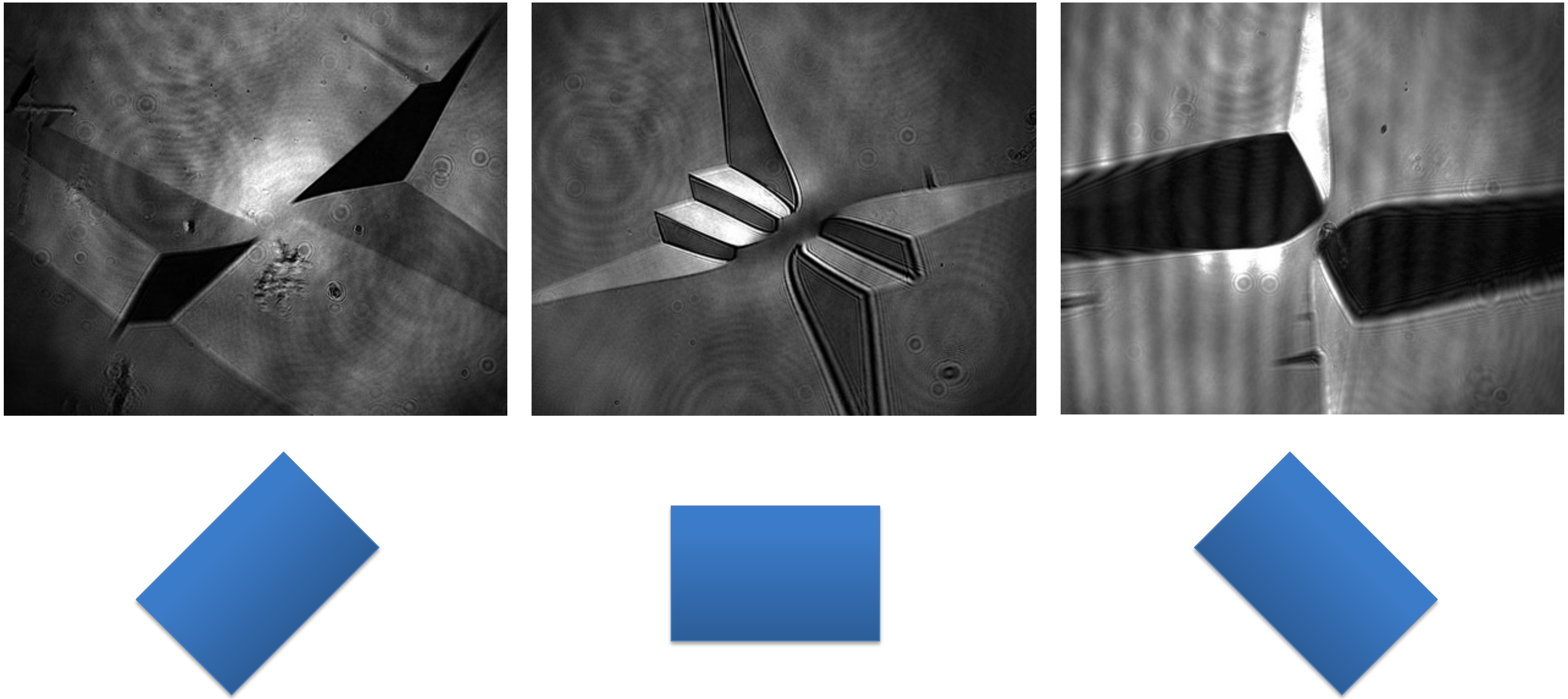




We saw the switching pattern after multiple pulses… How come?

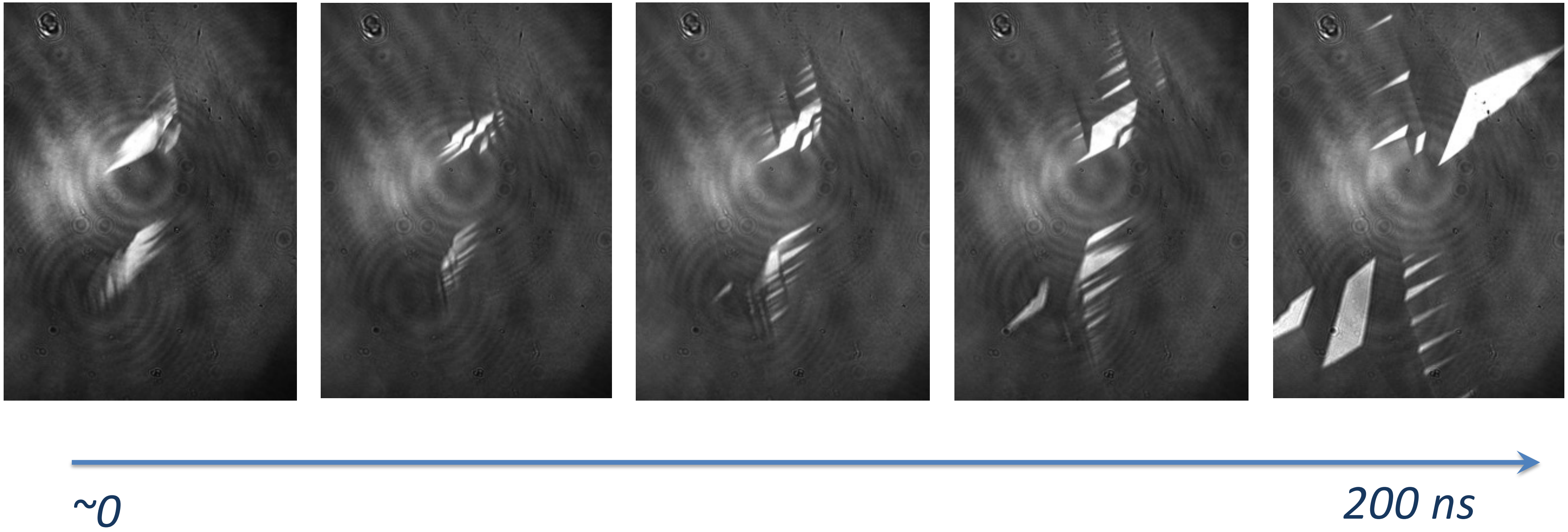
Different magnetization & anisotropy – same pattern

$(LuYBi)_3(FeGa)_5O_{12}$ magnetic garnet, (001) substrate, 6 μm thick, ‘horizontal’ field



qualitatively the same picture of ‘quadrupole’-like domains pattern, with some variations

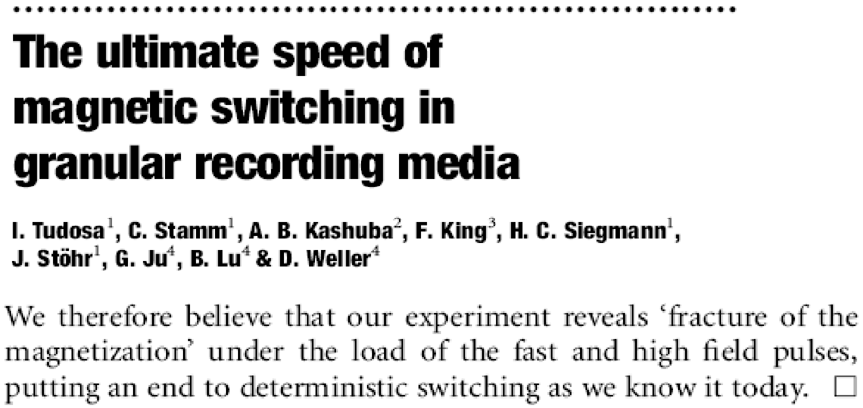
dynamics



propagation with a speed of >1000 m/s

Where does this pattern come from???

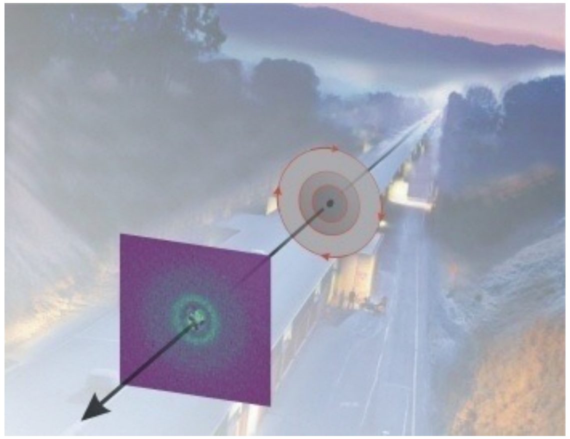
Spin-wave instabilities?

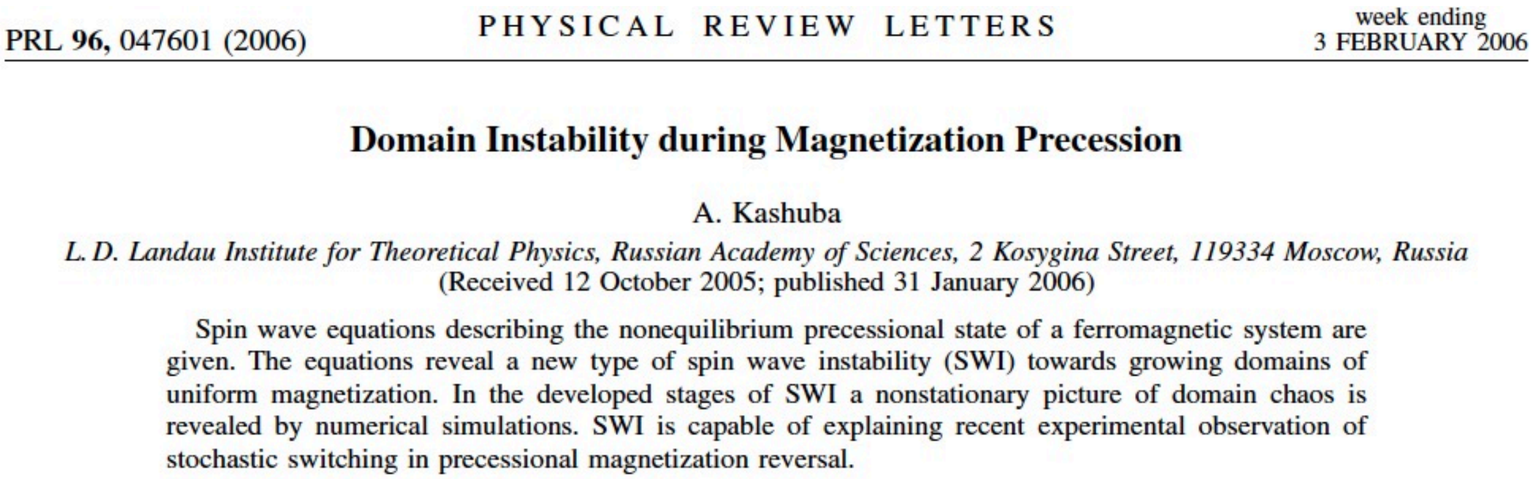


The ultimate speed of magnetic switching in granular recording media

I. Tudosa[1], C. Stamm[1], A. B. Kashuba[2], F. King[3], H. C. Siegmann[1],
J. Stöhr[1], G. Ju[4], B. Lu[4] & D. Weller[4]

We therefore believe that our experiment reveals 'fracture of the magnetization' under the load of the fast and high field pulses, putting an end to deterministic switching as we know it today. ☐





PRL **96,** 047601 (2006) PHYSICAL REVIEW LETTERS week ending 3 FEBRUARY 2006

Domain Instability during Magnetization Precession

A. Kashuba

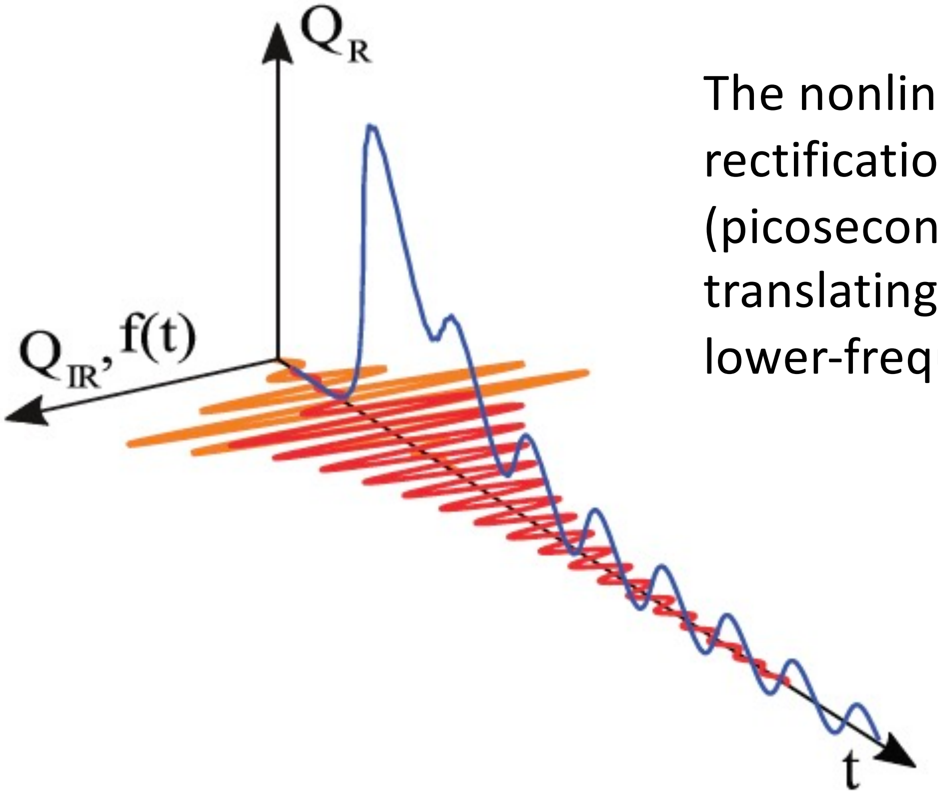
L. D. Landau Institute for Theoretical Physics, Russian Academy of Sciences, 2 Kosygina Street, 119334 Moscow, Russia

(Received 12 October 2005; published 31 January 2006)

Spin wave equations describing the nonequilibrium precessional state of a ferromagnetic system are given. The equations reveal a new type of spin wave instability (SWI) towards growing domains of uniform magnetization. In the developed stages of SWI a nonstationary picture of domain chaos is revealed by numerical simulations. SWI is capable of explaining recent experimental observation of stochastic switching in precessional magnetization reversal.

homogeneous precession of large amplitude decays into a large number of spin waves with various wave vectors

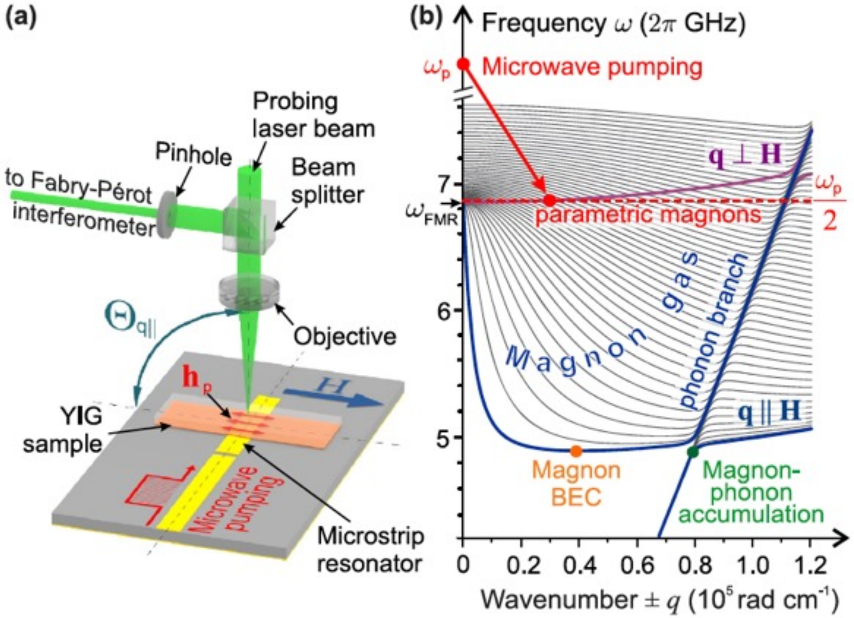
Strong population of acoustic phonons



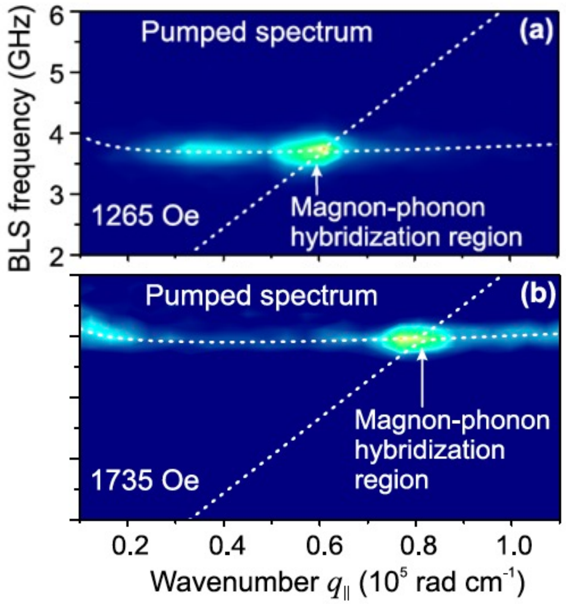
The nonlinear phononic interaction leads to a rectification of QR mode, for its life-time (picoseconds). This is equivalent to shock waves, translating into a considerable population of lower-frequency (acoustic) phonons

Result: lots of magnons and phonons in the system

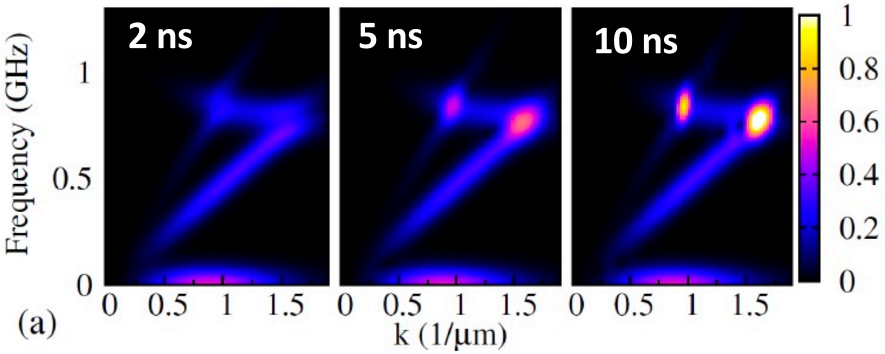
‘Condensation’ of magnon-polarons?



Bozhko et al, *Bottleneck Accumulation of Hybrid Magnetoelastic Bosons*,
Phys. Rev. Lett. **118**, 237201 (2017)



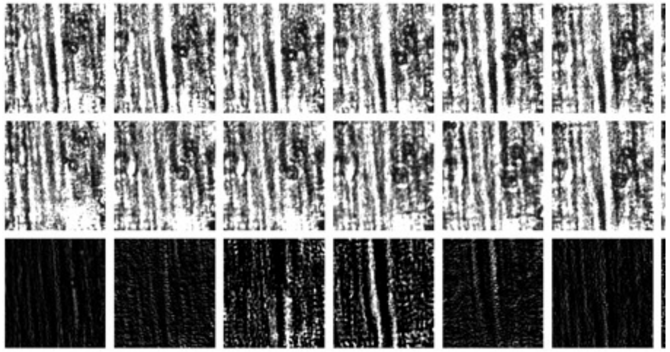
from classical point of view:

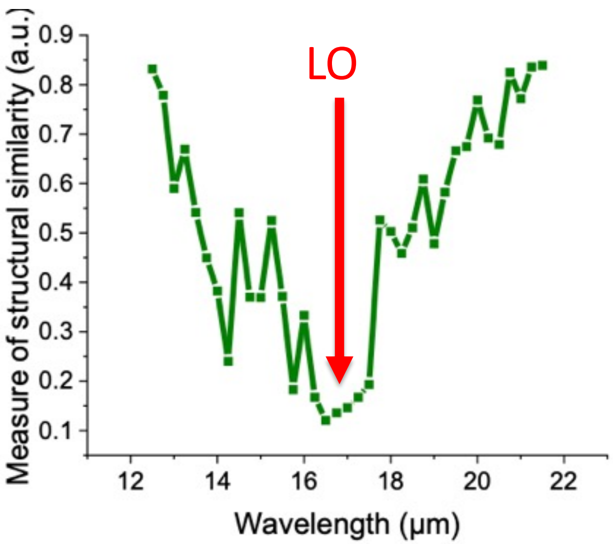


Shen and Bauer, *Theory of spin and lattice wave dynamics excited by focused laser pulses*,
Phys. Rev. Lett. **115** 197201 (2015)
J. Phys. D: Appl. Phys. **51**, 224008 (2018)

The mechanism is very universal

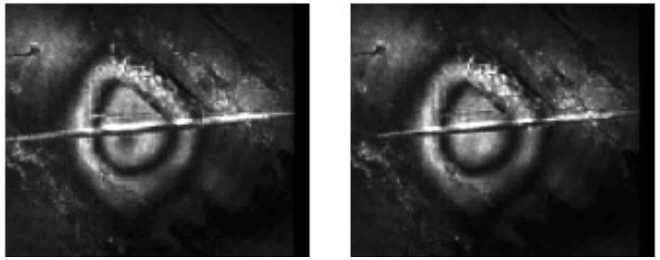
Antiferromagnet: NiO (111) and (001)

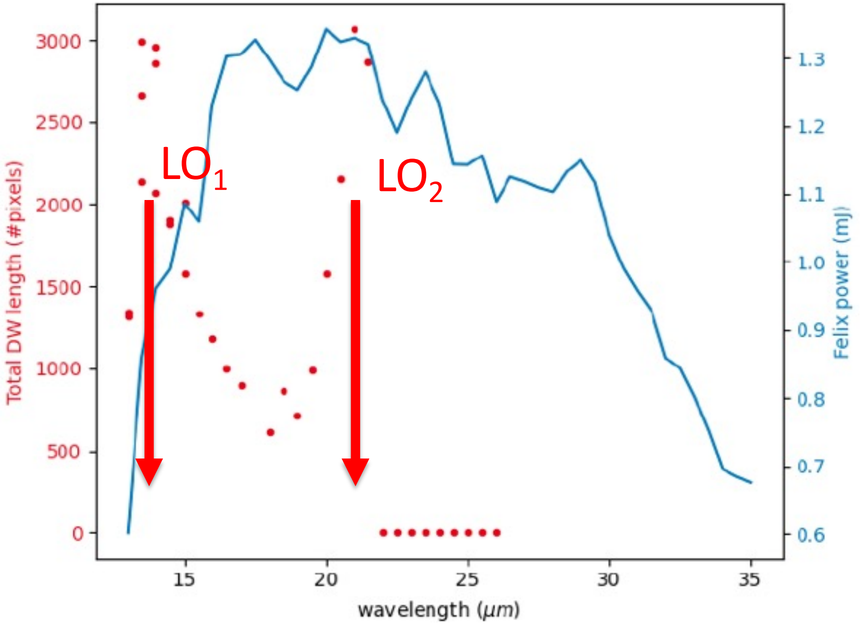




P. Stremoukhov et al, New J. Physics **24**, 023009 (2022).

Ferroelectric: $BaTiO_3$





M. Kwaaitaal et al, to be published

Mechanism?

- it looks **very universal**: everything (well, almost) switches
- however, **LO phonon is not IR active**
- so how come it works better than the TO one??

Transverse and longitudinal optical phonons

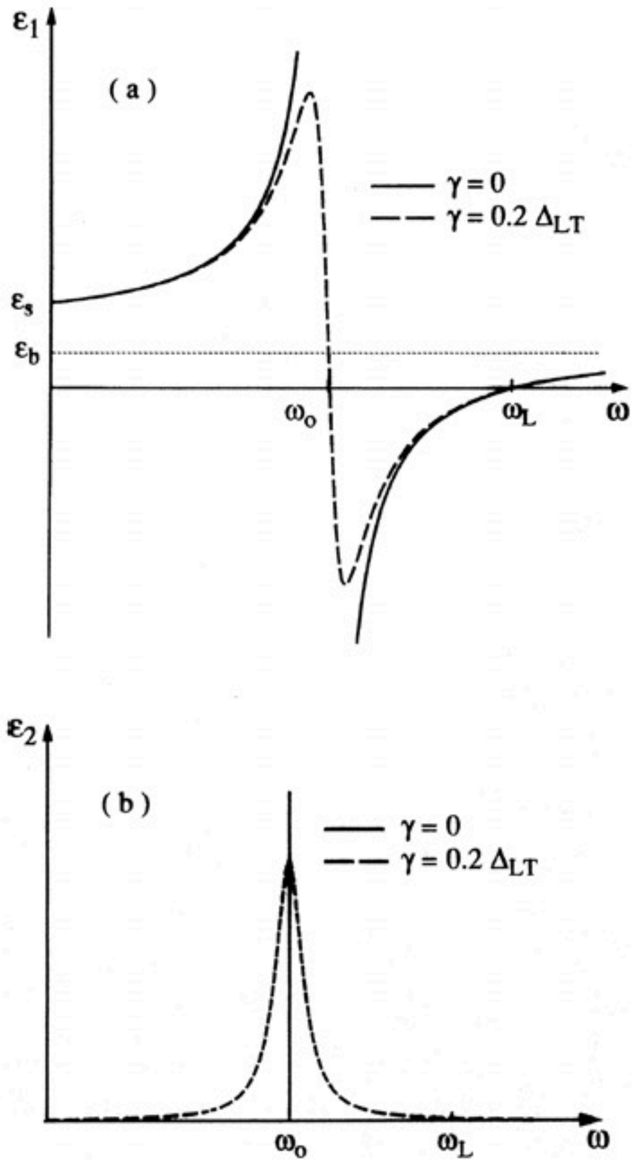


Fig. 4.3. The real (a) and imaginary (b) parts of the dielectric function for zero and finite damping

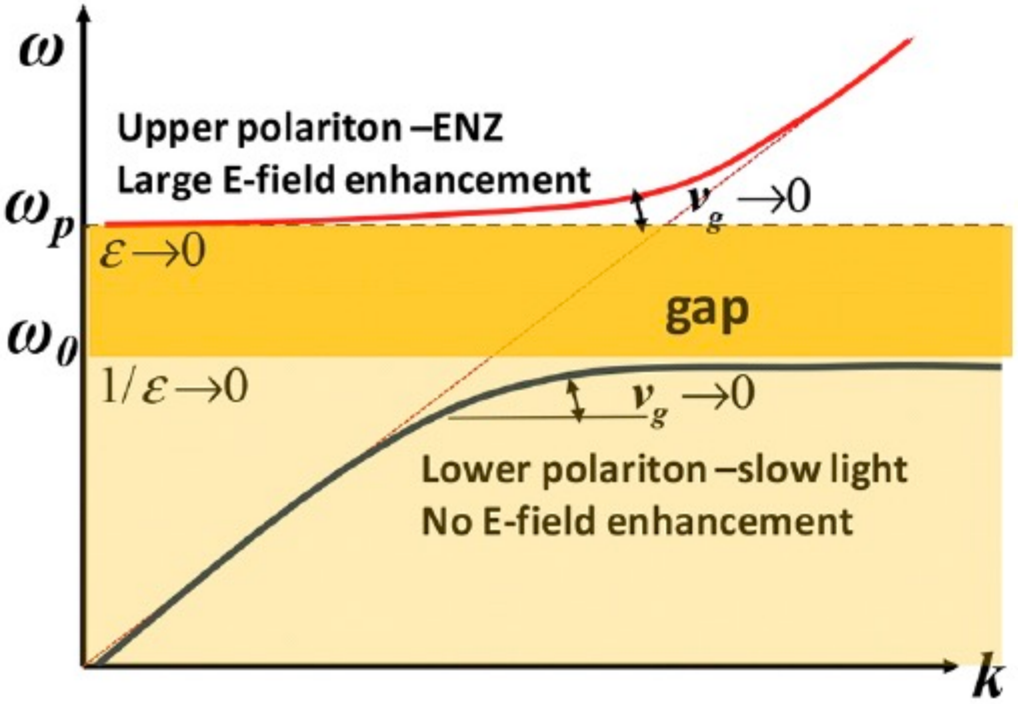
Lyddane-Sachs-Teller relation

$$\frac{\varepsilon(0)}{\varepsilon(\infty)} = \frac{\omega_{\mathrm{LO}}^2}{\omega_{\mathrm{TO}}^2}.$$

microscopically, it is the same phonon

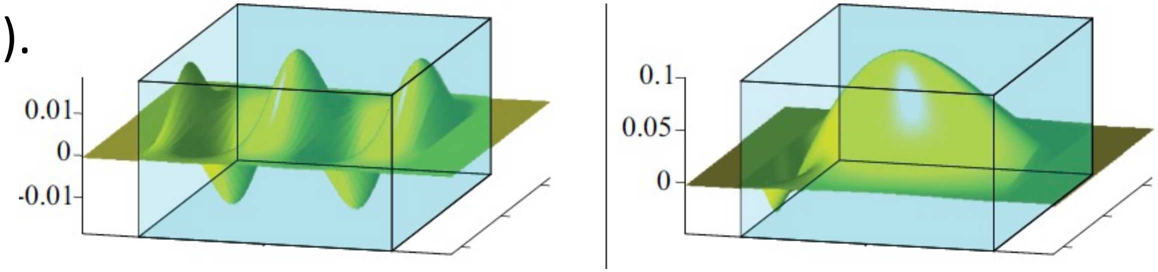
but not macroscopically!

Enhancement of light-matter interaction at LO frequency



- infinite wavelength (‘static’ optics) => no zero’s
- enhancement of optical field
- zero group velocity => long interaction time
- strong nonlinearity of pulse propagation

Kinsey & Khurgin,
Opt. Mater. Express **9**, 2793 (2019).



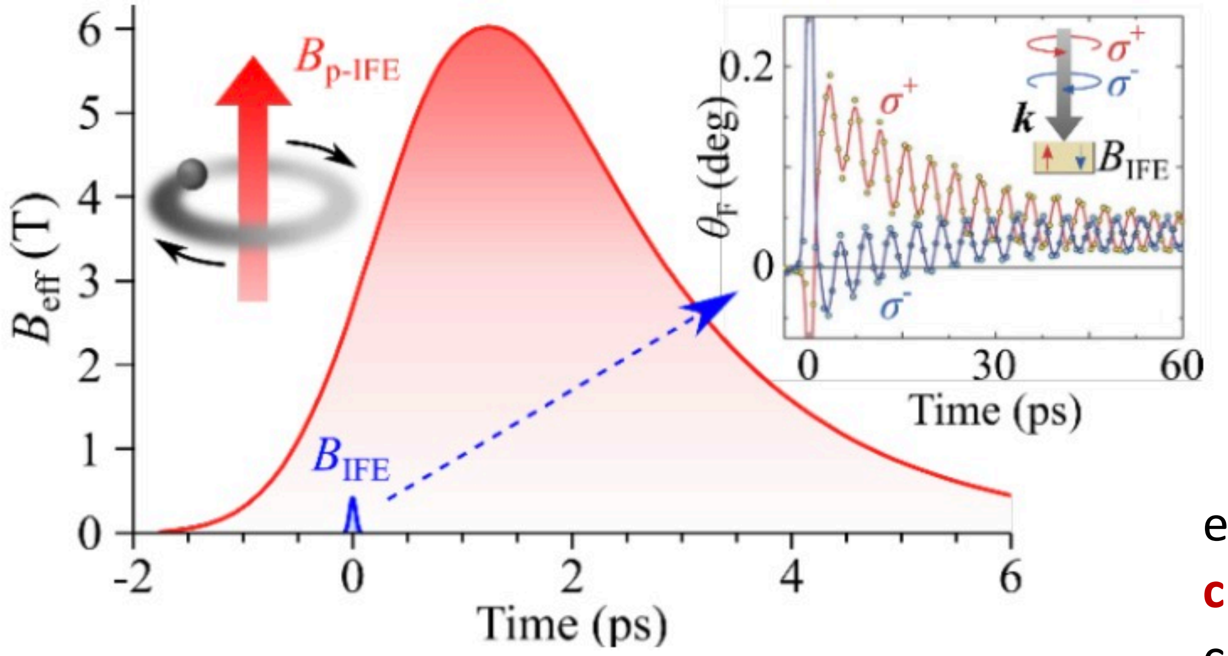
Ciattoni et al, Laser Phot. Reviews **10**, 517 (2016).

Displacive vs impulsive stimuli

- **displacive**: stimulus changes the equilibrium, magnetization follows
  - for example, photo-induced anisotropy
  - limited by the life-time of the excited states

- **impulsive**: stimulus changes the magnetization directly
  - for example, inverse Faraday effect
  - limited by the pulse width & coherence of excited states

Phono-magnetic effect?



D. M. Juraschek, P. Narang & N. A. Spaldin, "Phono-magnetic analogs to opto-magnetic effects."
Phys. Rev. Res. **2**, 043035 (2020).

exciting phonons with **circularly polarized light** creates a superposition of two orthogonal modes and thus effectively circular motion of atoms

GdFeCo films

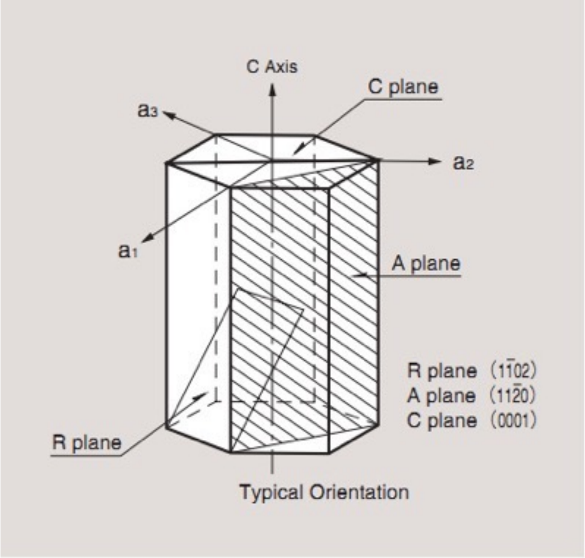
Samples:

Si_3N_4 (60nm)

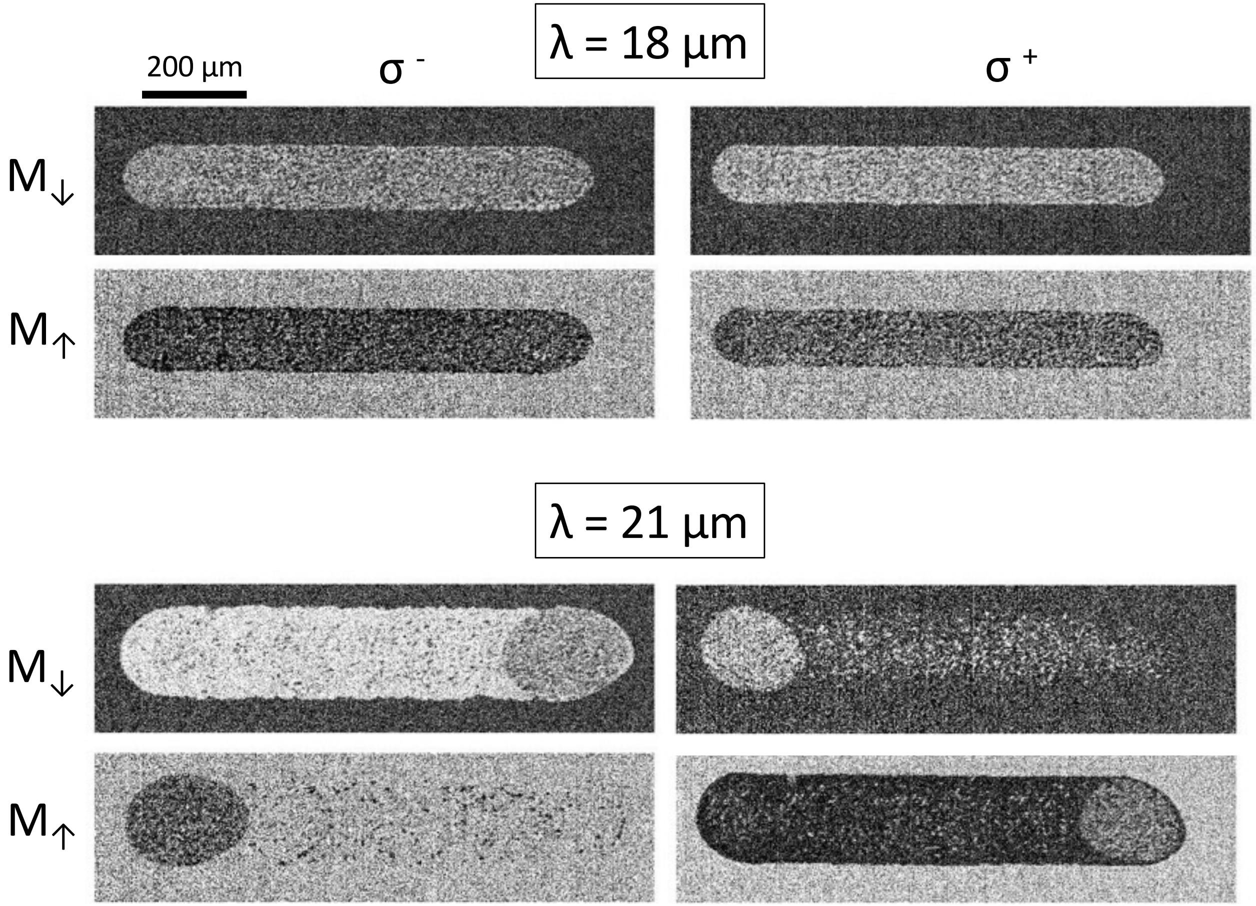
$Gd_{24}(FeCo)_{76}$ (20nm)

Si_3N_4 (5nm)

Sapphire (c-cut)



Unit Cell of Sapphire



Sweep speed = 50 μm/s

Summary

- **Strong excitation of optical phonons leads to high-amplitude strains and transient magnetic anisotropy**
- **Peculiar shape of switching pattern provides a fingerprint confirming the mechanism**
- **Large amplitudes of magnetic precession during switching lead to instabilities and pattern formation**
- **Circular-polarized TO phonons give rise to an impulsive phono-magnetic effect**