Coherent control of skyrmions

Prof. Fabrizio Carbone

Collaboration:

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- Damien McGrouther, R. Lamb, Glasgow UK
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- Achim Rosch, University of Koln

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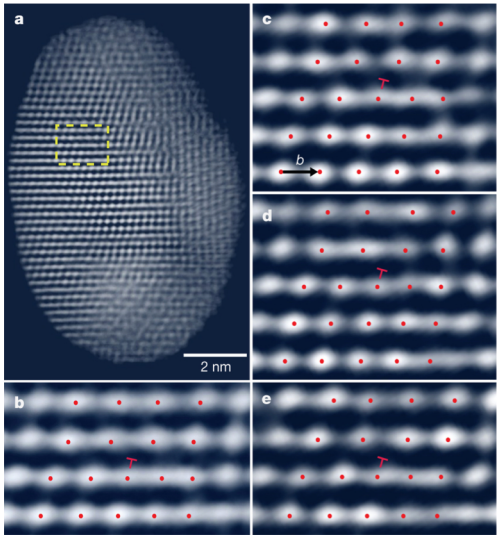
SWISS NATIONAL SCIENCE FOUNDATION

Introduction

- Dynamic imaging of magnetization in modern microscopy
- Magnetic skyrmions:
  - Properties
  - Control
- Coherent control of skyrmions

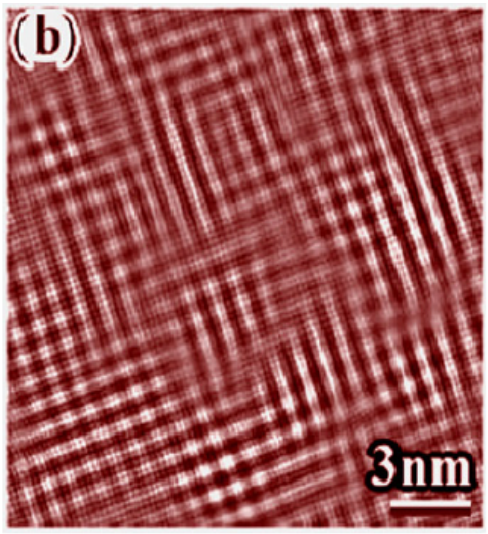
Modern Electron Microscopy

Observing atoms



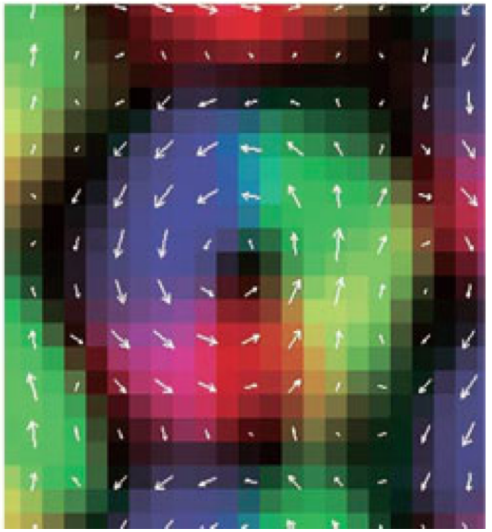
Nature 496 74 (2013)

Observing charges/orbitals



Tokunga et al., Nat. Mater. 5 (2006)

Observing spins



Seki et al, Science 336 (2012)

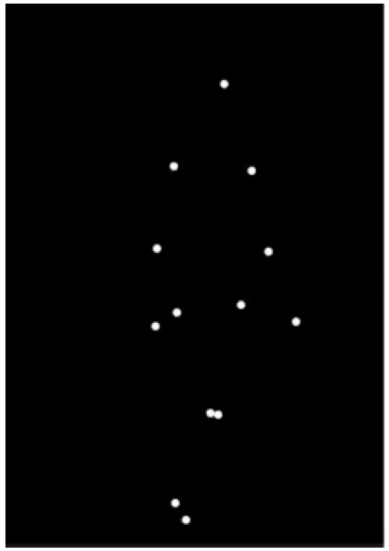
Textured ground states rule the physics of novel materials

Reciprocal-space probes average over the illuminated area

dynamical imaging

Why time-resolved experiments?

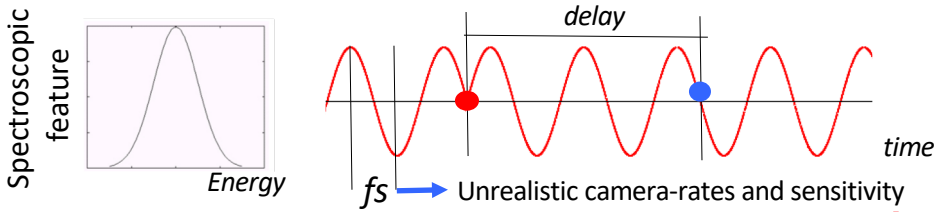
Given a distribution of
Ions
Spins or
Charges
Their dynamical evolution reveals
Their properties across phase-transitions



Blake R (1993) Cats perceive biological motion. Psychological Science 4, 54-57
http://www.psy.vanderbilt.edu/faculty/blake/BM/BioMot.html

The stroboscopic method

Stroboscopic pump-probe concept



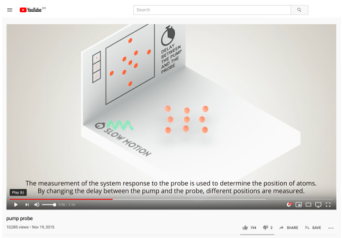
pump or clock

probe

Need for clocking (pump) and reversible processes

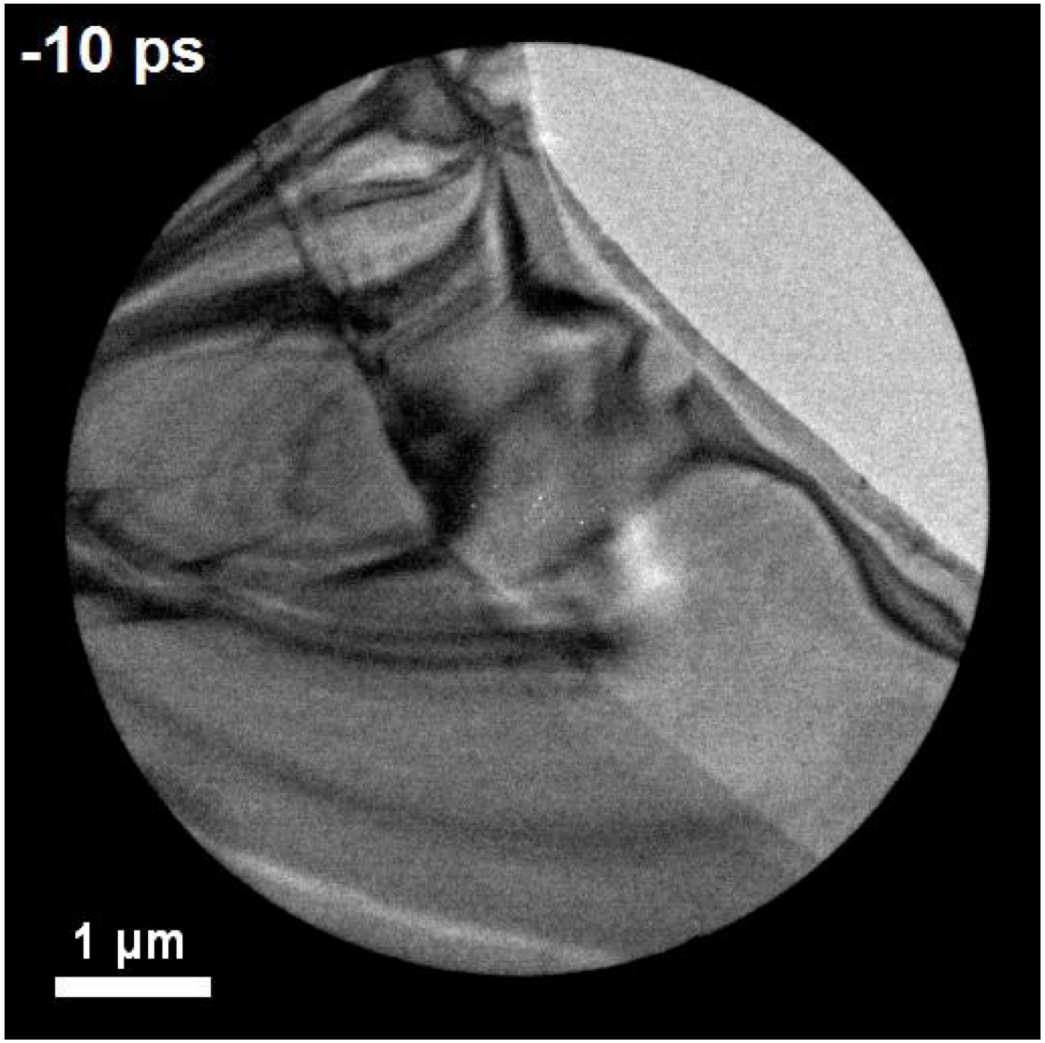
Pump is the hose ejecting a drop at periodic times (reversible-like process)

Probe is the light flash



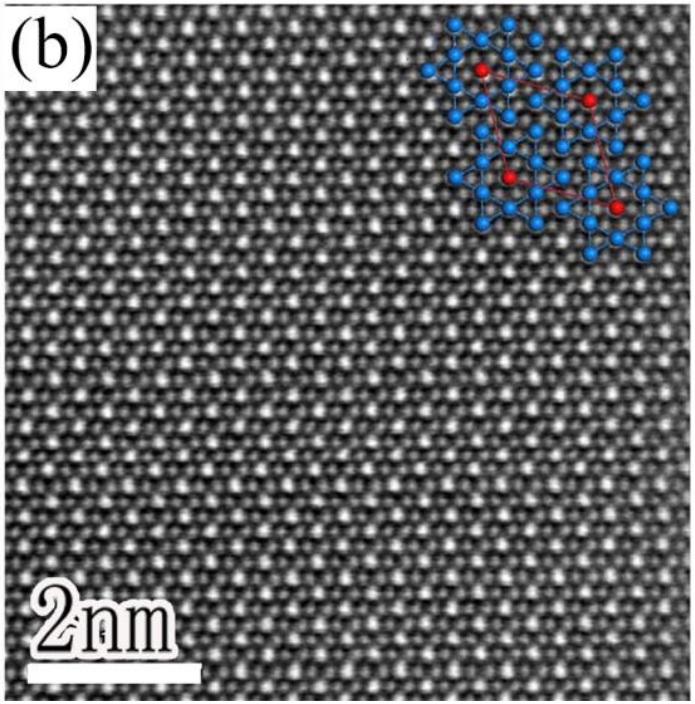
https://www.youtube.com/watch?v=YTj4Hi1HdJQ

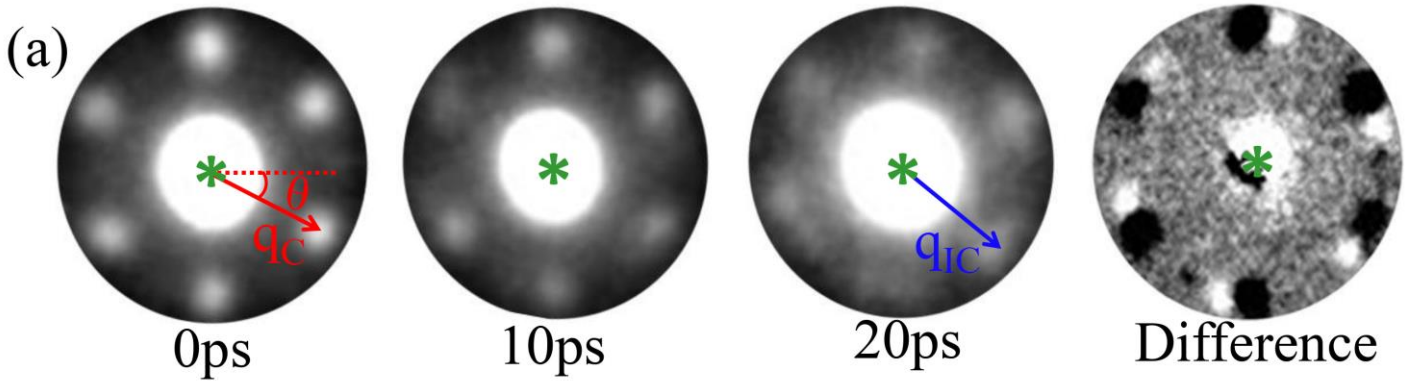
Lattice dynamics



Cremons et al, Nat. Comm. 7, 11230 (2016)

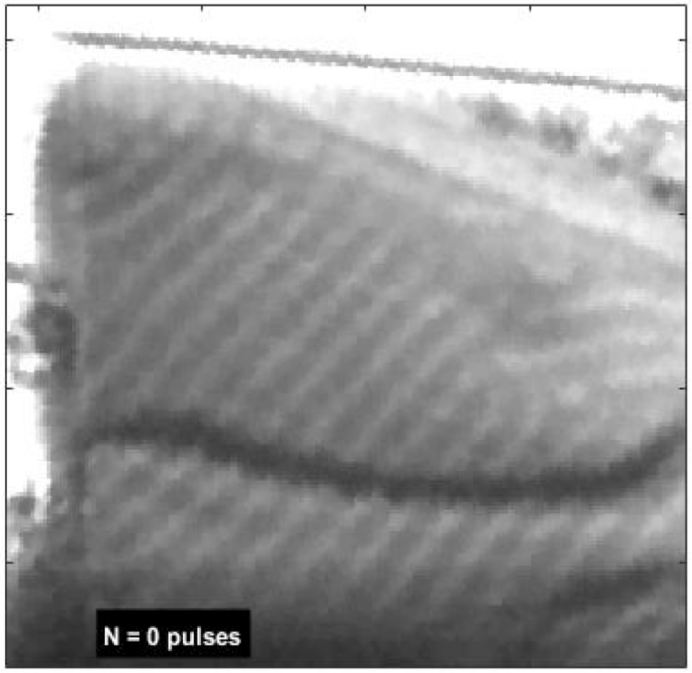
Charge dynamics





Sun et al., Phys. Rev. B 92 224303 (2015)

Spin dynamics



Berruto et al., Phys. Rev. Lett. 120 117201 (2018)

Magnetic skyrmions

Dzyaloshinskii-Moriya Interaction: favors canting of antiparallel spins. Promotes weak frerromagnetism in antiferro background

$$\mathcal{H}_{\mathrm{DMI}} = \sum_{i,j} \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j),$$

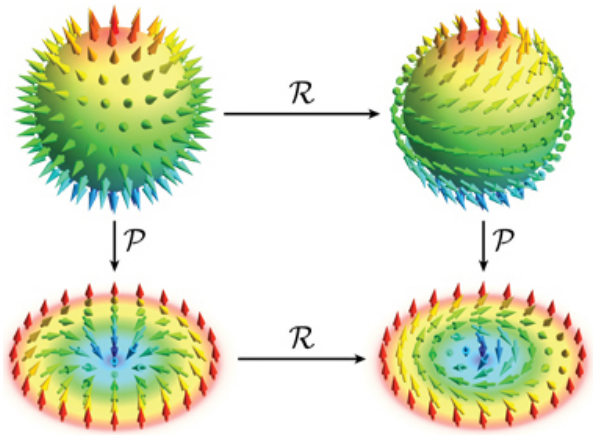
$$\mathcal{H}_{\mathrm{DMI}}^{\mathrm{Bloch}} = -D \sum_i \mathbf{S}_i \times \mathbf{S}_{i+\hat{x}} \cdot \hat{x} + \mathbf{S}_i \times \mathbf{S}_{i+\hat{y}} \cdot \hat{y},$$

$$\mathcal{H}_{\mathrm{DMI}}^{\mathrm{Néel}} = -D \sum_i \mathbf{S}_i \times \mathbf{S}_{i+\hat{x}} \cdot \hat{y} - \mathbf{S}_i \times \mathbf{S}_{i+\hat{y}} \cdot \hat{x},$$

Topological charge of a skyrmion:

$$Q = \frac{1}{4\pi} \int dx dy \; \mathbf{m} \cdot \left(\frac{\partial \mathbf{m}}{\partial x} \times \frac{\partial \mathbf{m}}{\partial y} \right),$$

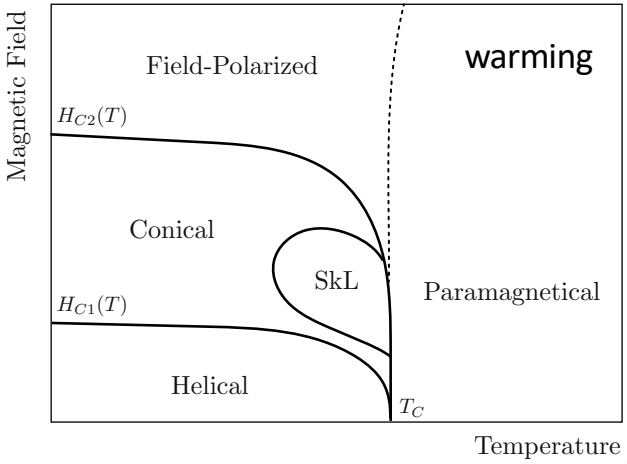
$$\mathbf{m}(x, y) = \mathbf{M}(x, y) / |\mathbf{M}|$$



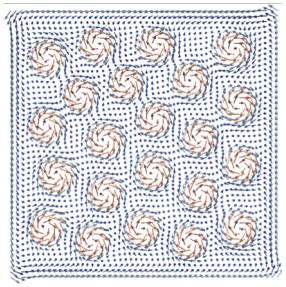
Néel skyrmion Bloch skyrmion

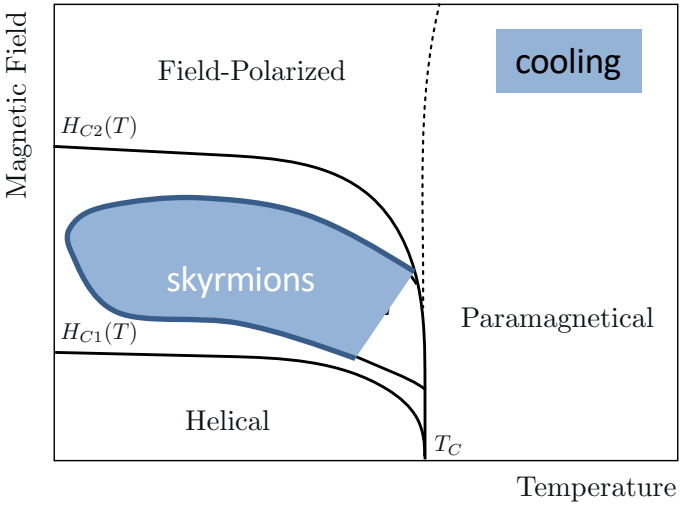
Roszler, Bodganov, Pfleiderer **Nature** 442 797 (2006)

Magnetic phase diagram

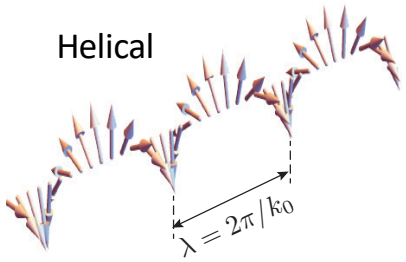


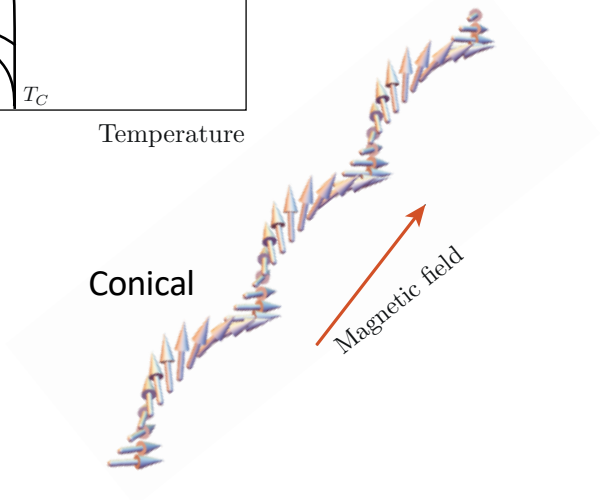
Skyrmion lattice





Histeretic phase diagram



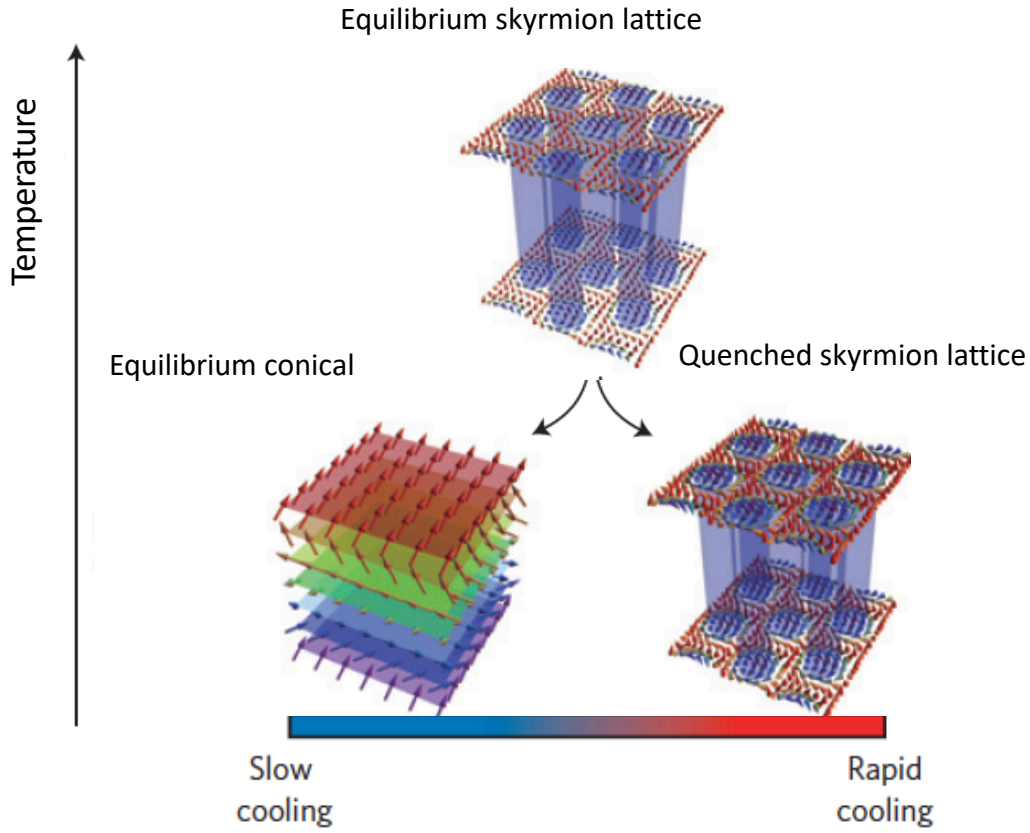


A. Krutchkov PhD thesis, EPFL 2017

Topological protection vs thermodynamical fluctuations

Topological magnetization patterns determined by dynamical interplay between

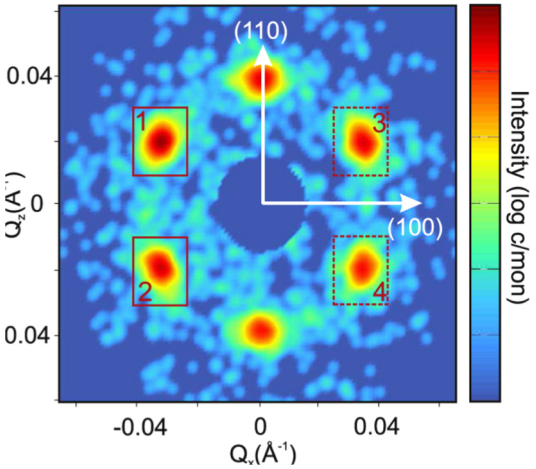
- Topological protection
- Thermodynamical fluctuations



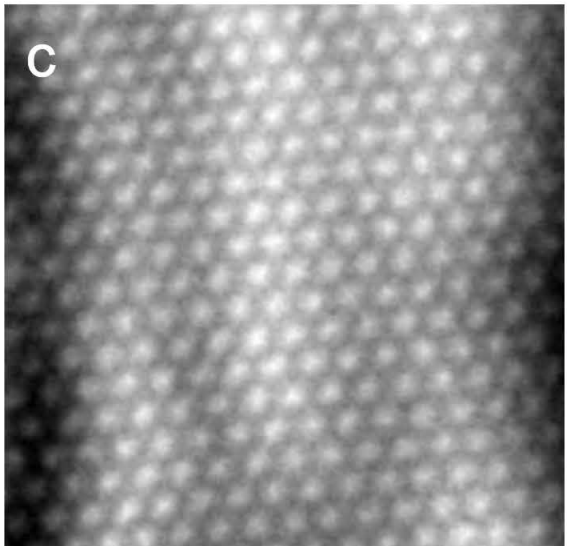
Nat. Phys. 12, 62 (2015)

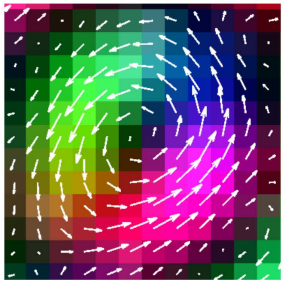
How to look at skyrmions

Reciprocal space: neutron scattering

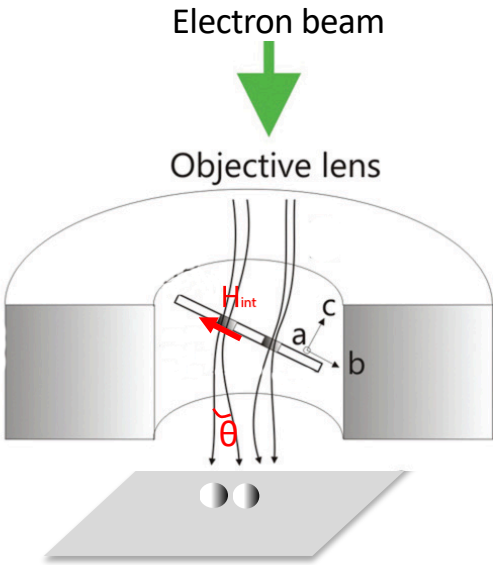


Real space: Lorentz TEM



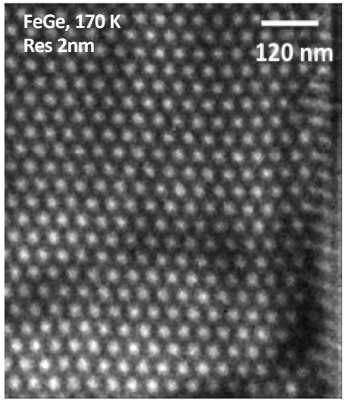


Fs Lorentz microscopy

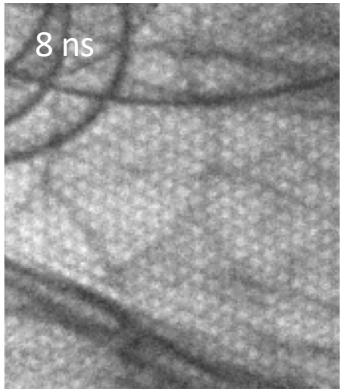


- θ ≈ µrad
- defocus = nm – cm
- parallel illumination:
  beam diameter >sample
- pulsed beam: very few e^-

CW

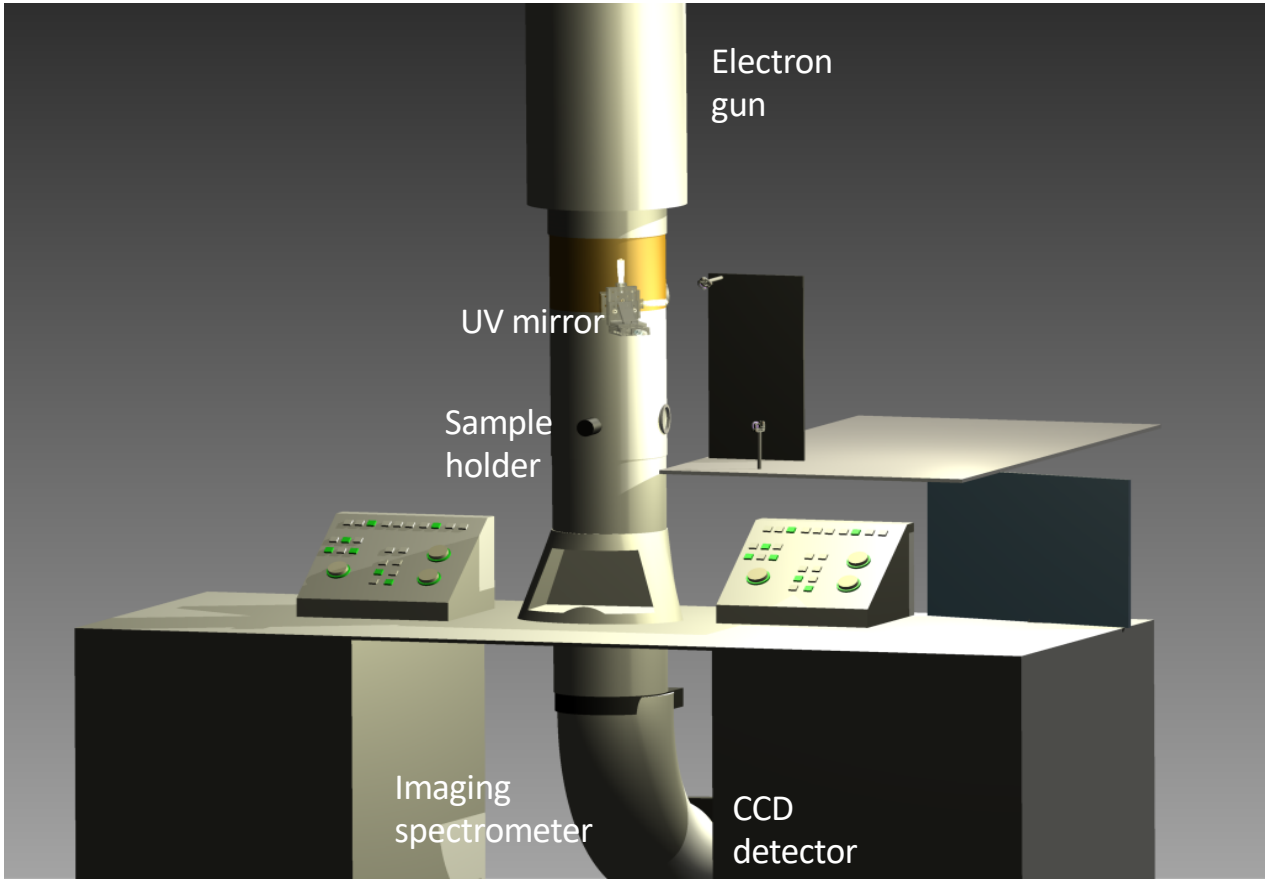


ns

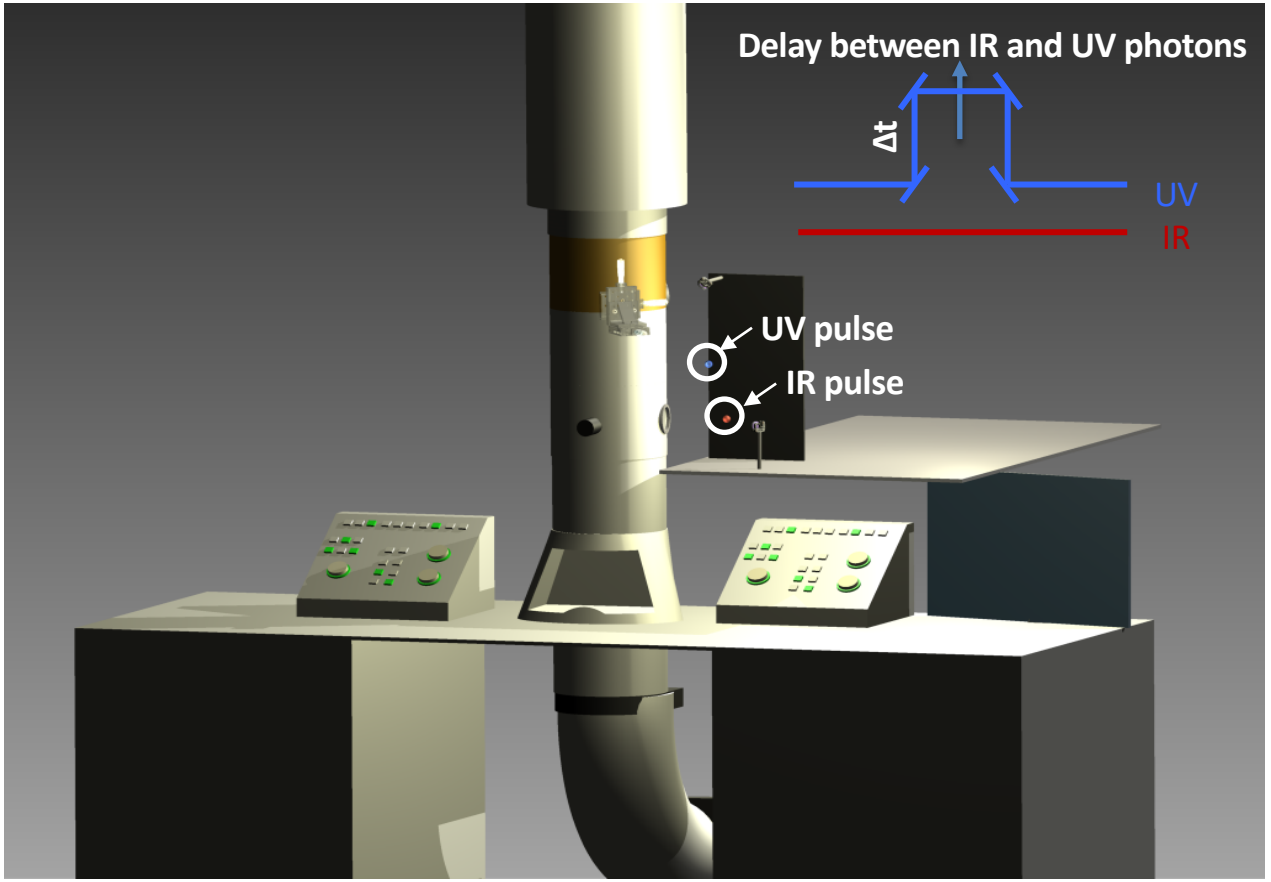


- Static images
- Camera-rate resolved movies
- Ns to fs-resolved stroboscopic movies

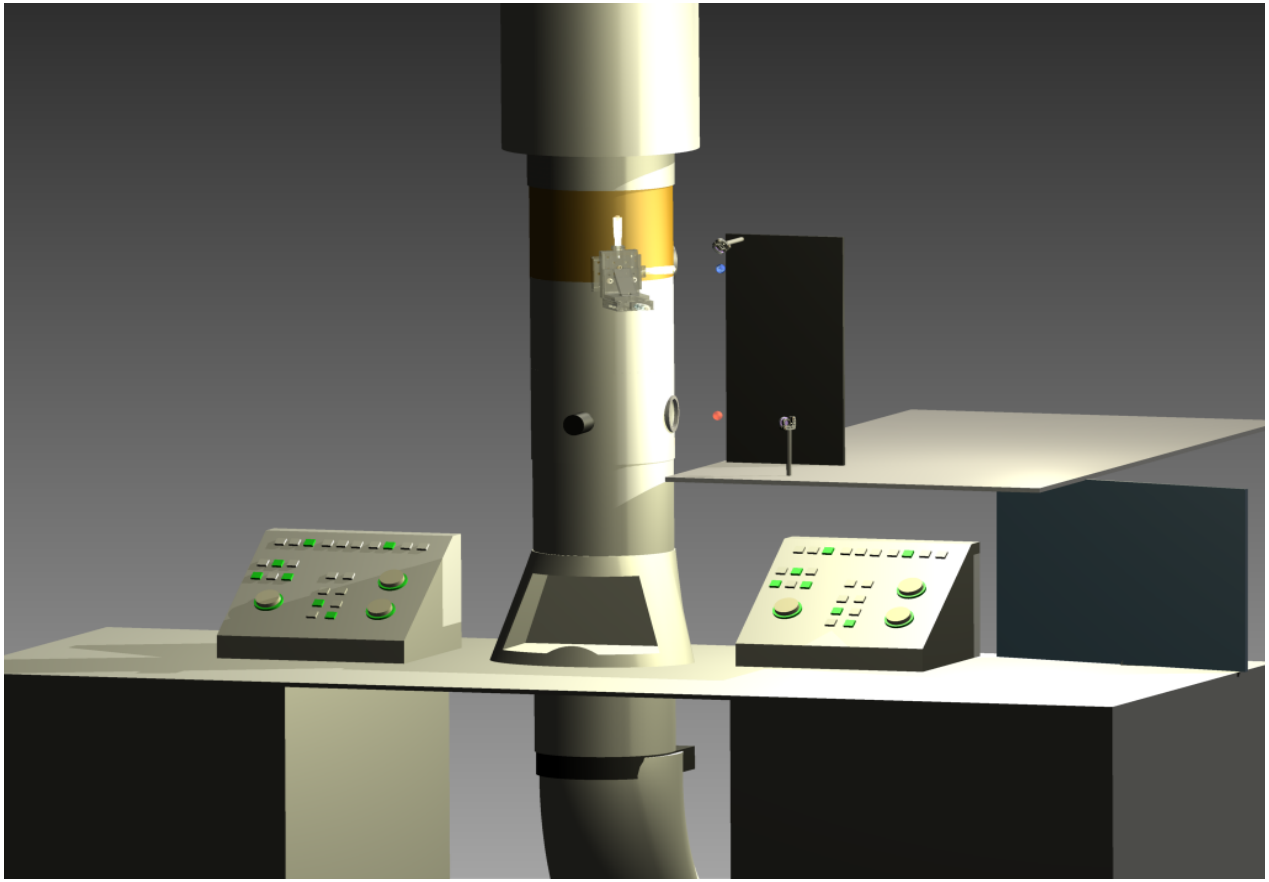
The Ultrafast TEM



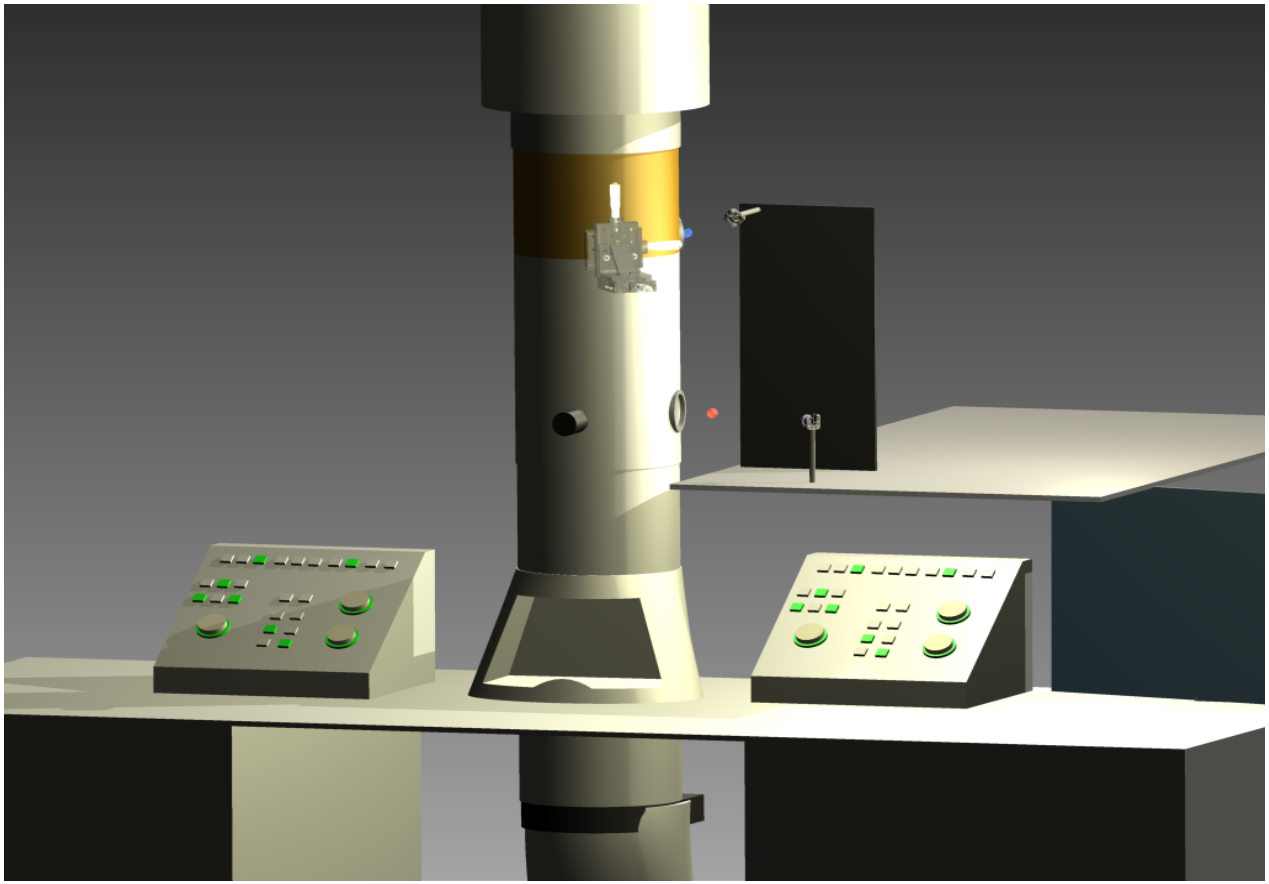
The Ultrafast TEM



The Ultrafast TEM



The Ultrafast TEM



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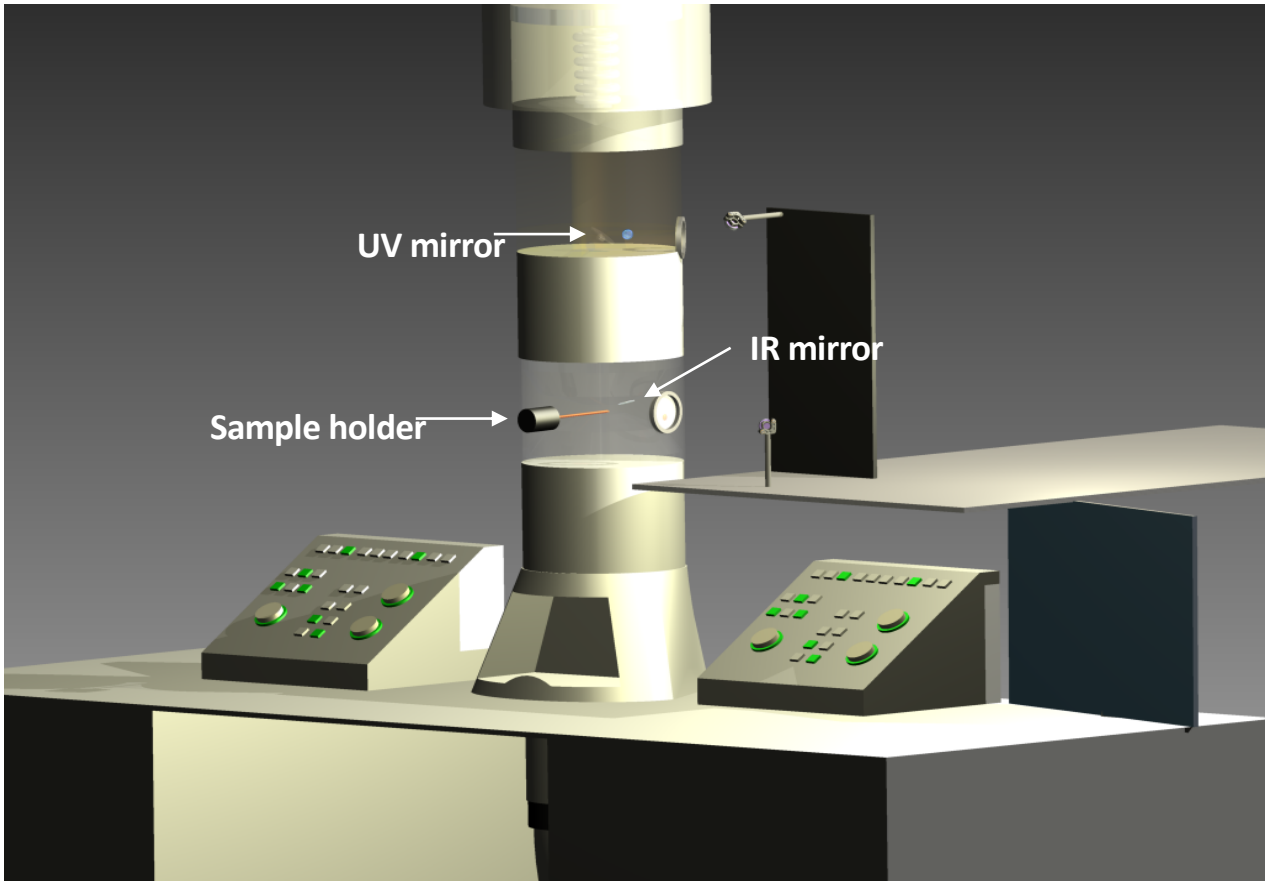
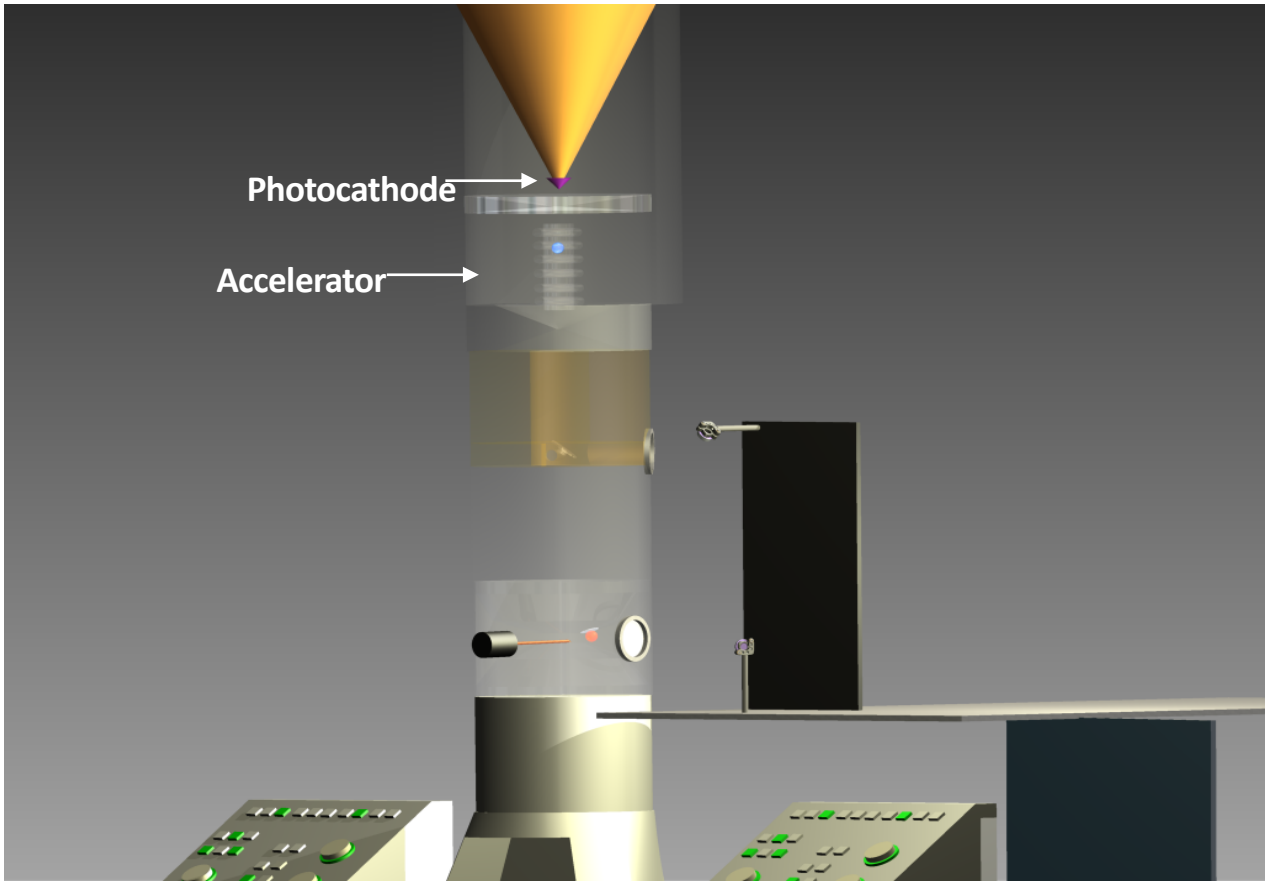
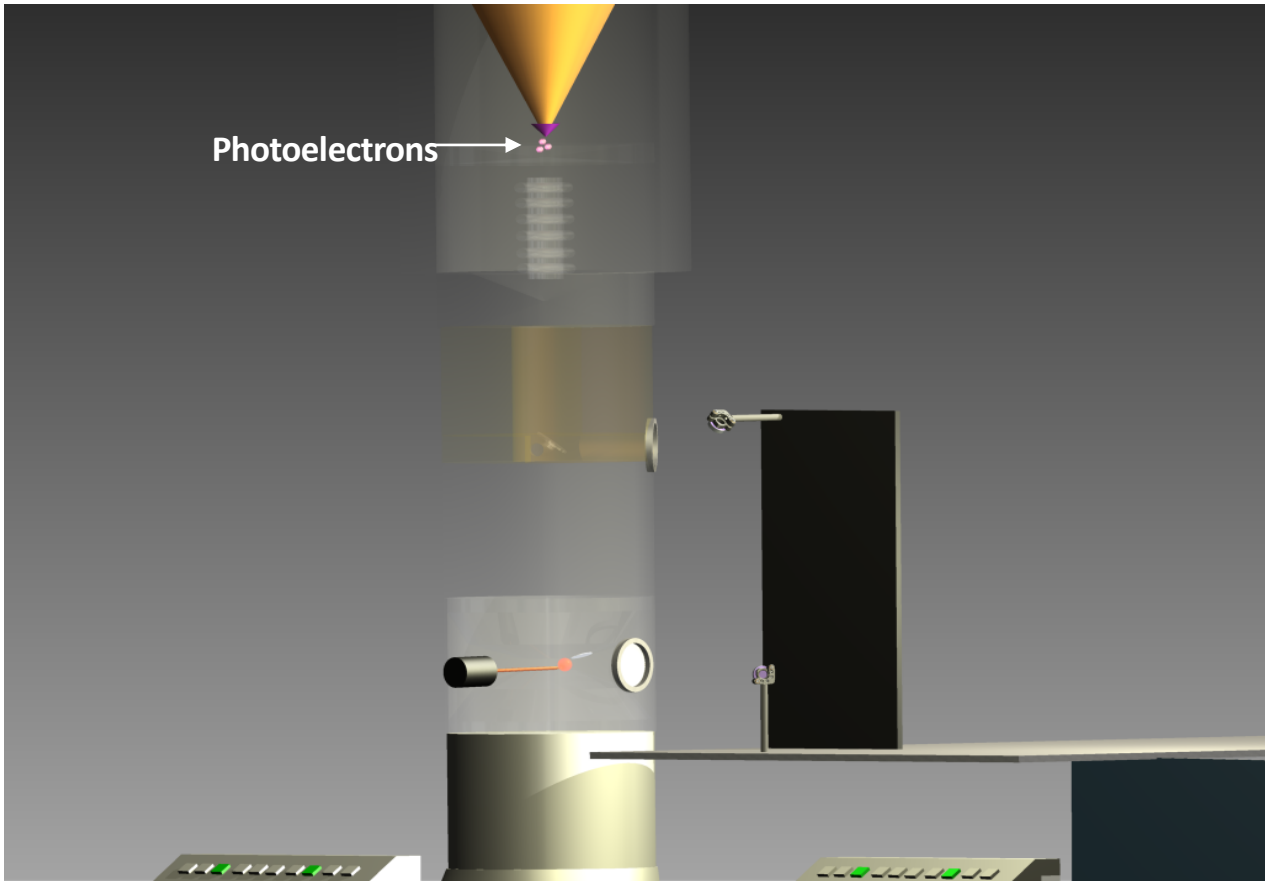


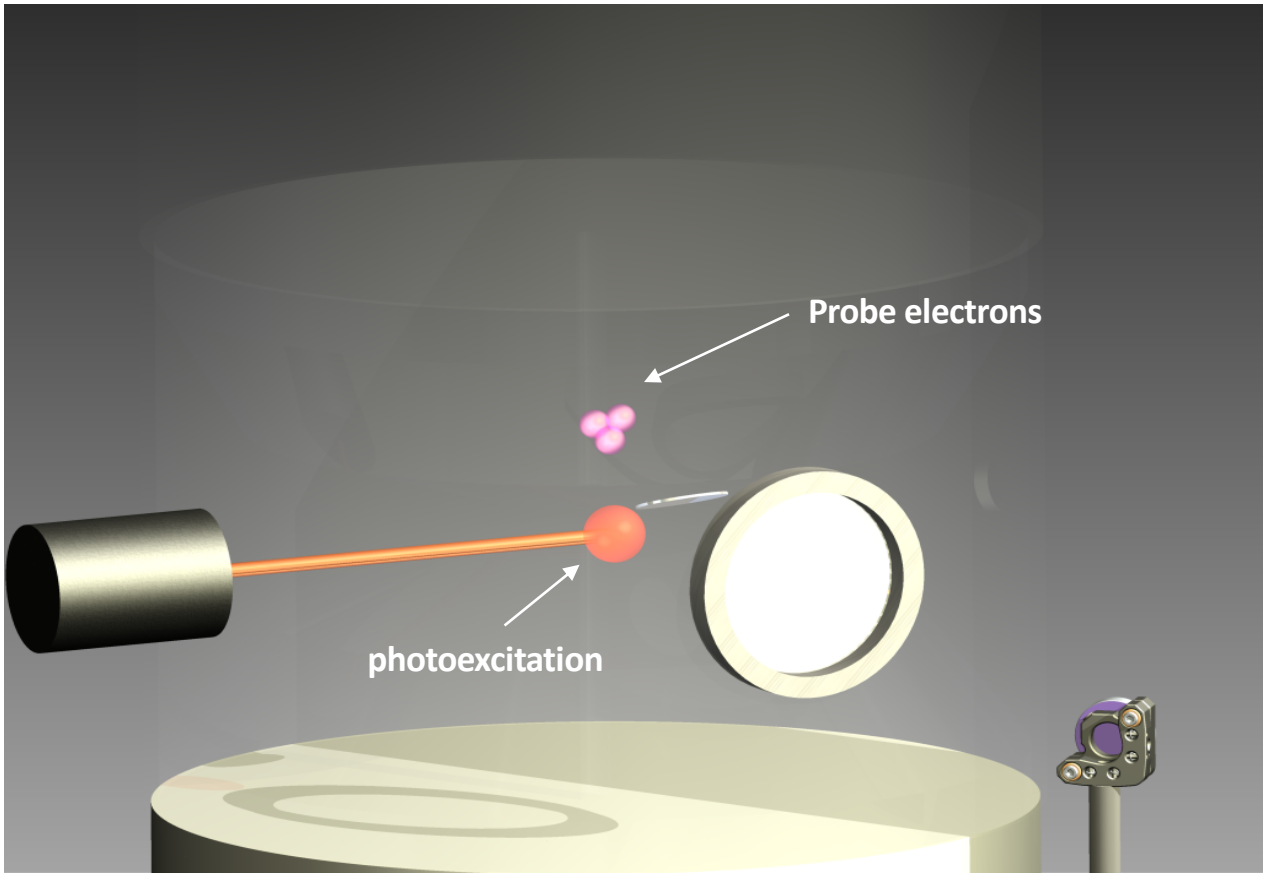
The Ultrafast TEM



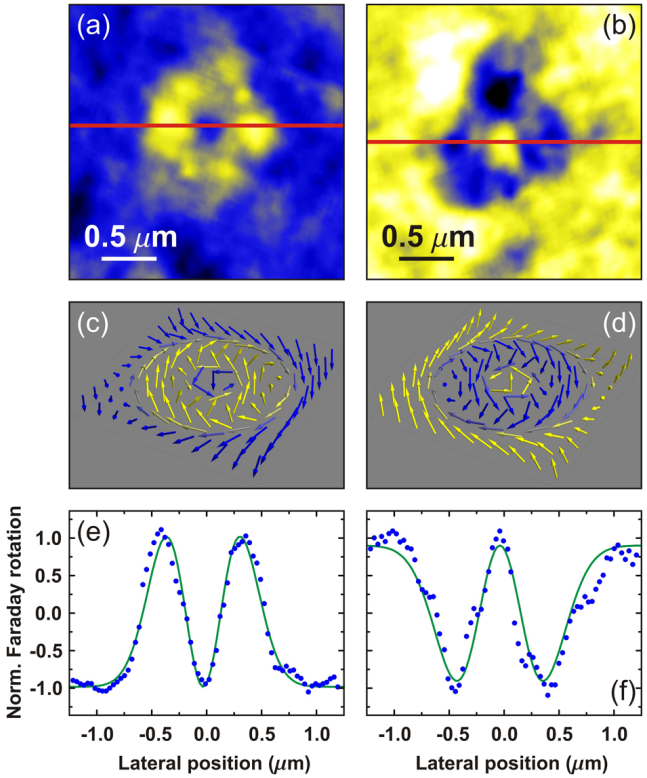
The Ultrafast TEM



The Ultrafast TEM



Light-control of magnetic bubbles in Co films



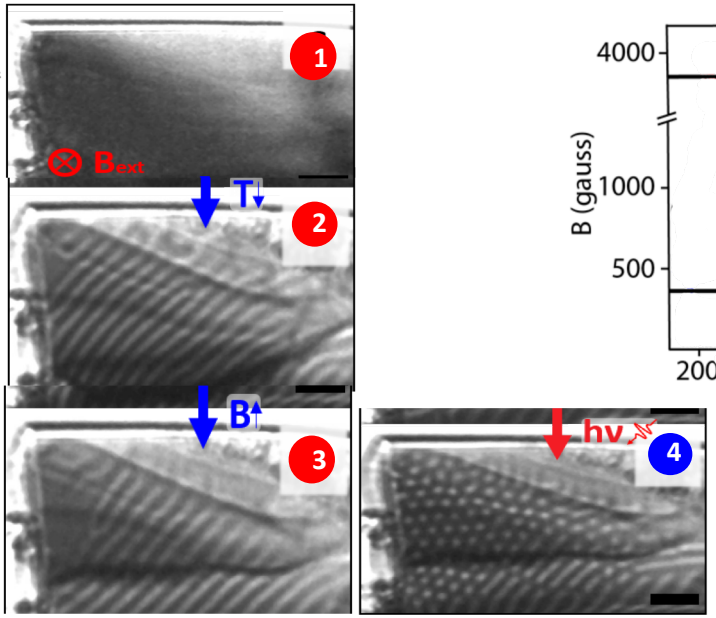
Stabilization mechanism for bubbles:
- anysotropic exchange + dipole/dipole interaction
- Chiral bubble size proportional to beam diameter

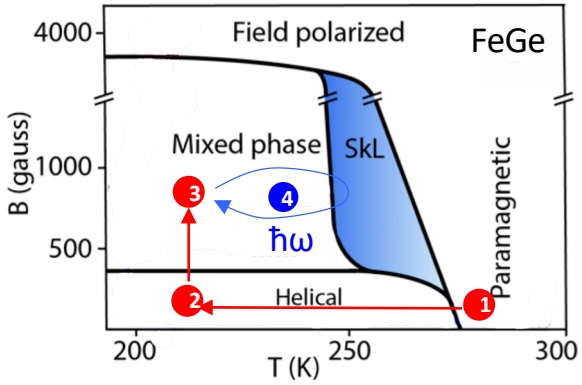
The laser beam demagnetize the core of the bubble and a whirling spin distribution forms around it

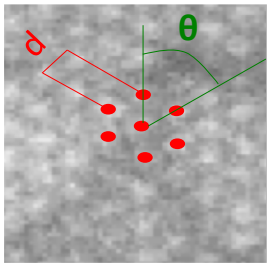
Finazzi et al., **Phys. Rev. Lett.** 110, 177205 (2013)

Dynamics of skyrmions in a metallic background

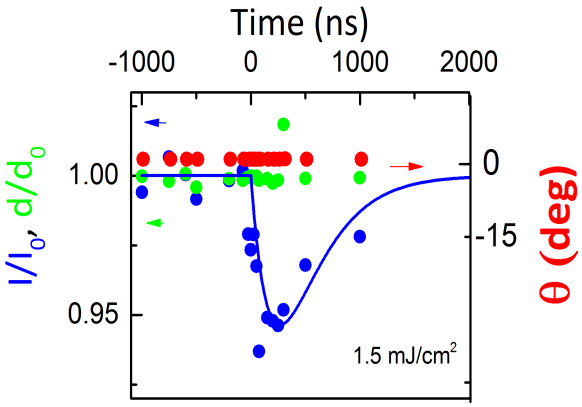
Controlling skyrmions: light-induced writing/erasing in a metal



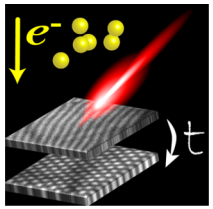




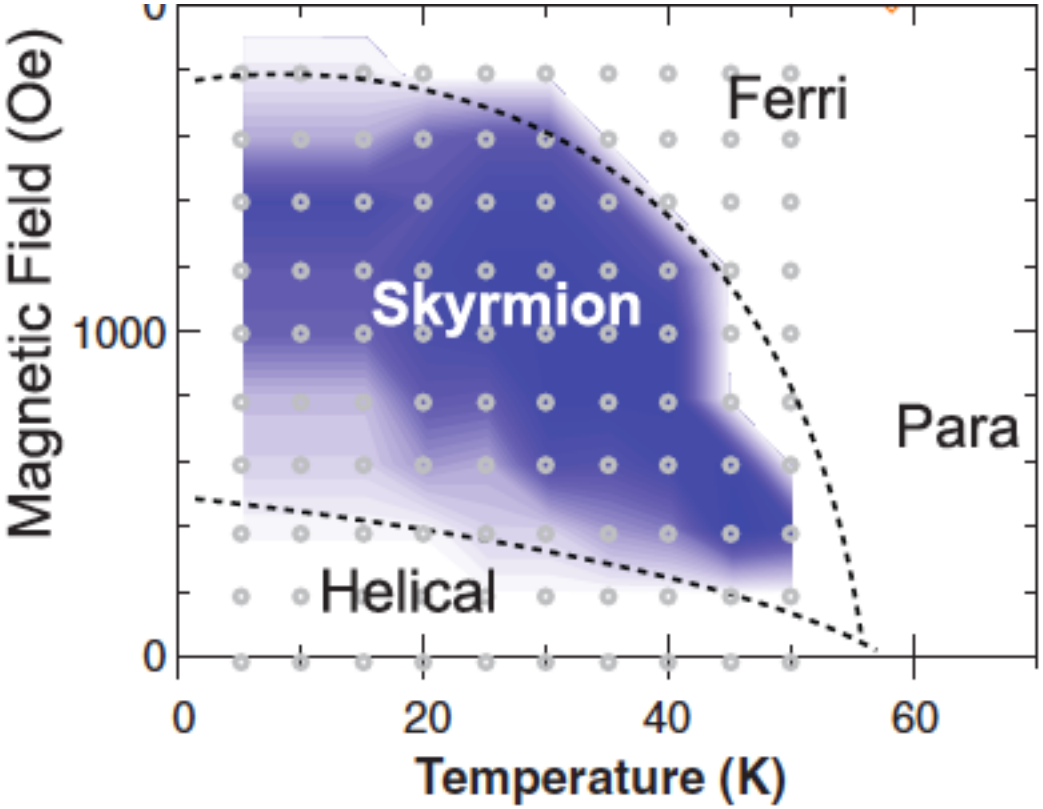
- T = 170 K, 25 ns and 2 nm resolution
- Light injects topological charge
- Skyrmion lattice melts without disordering
- Energy consumption fJ/skyrmion

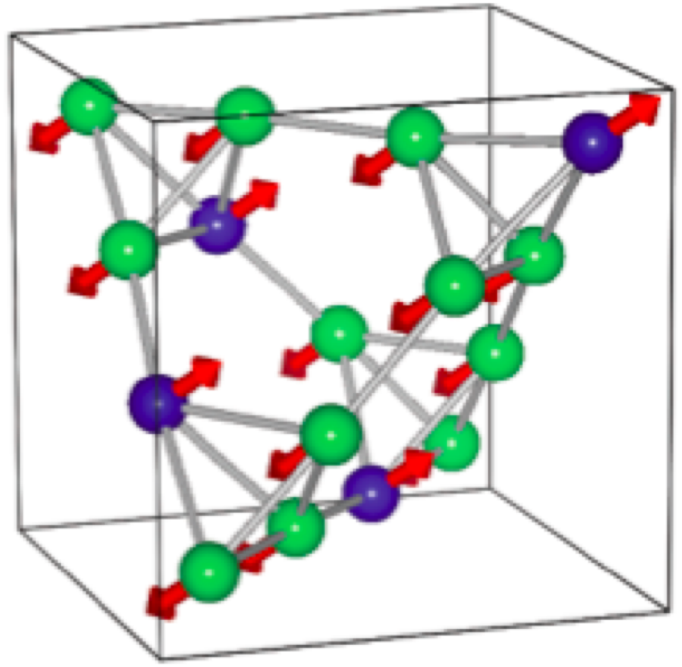


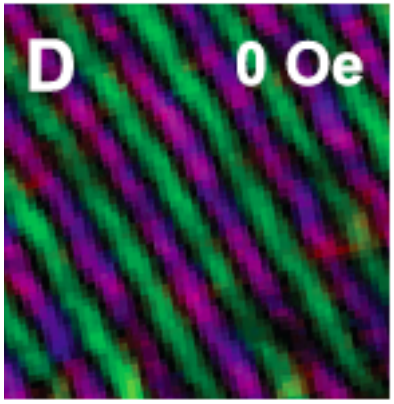
Berruto et al., Phys. Rev. Lett. 120 117201 (2018). Editor's suggestion

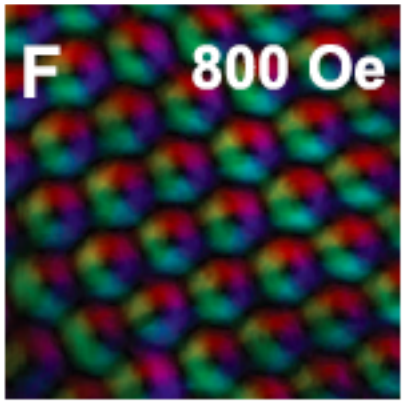


Skyrmions in Cu_2OSeO_3



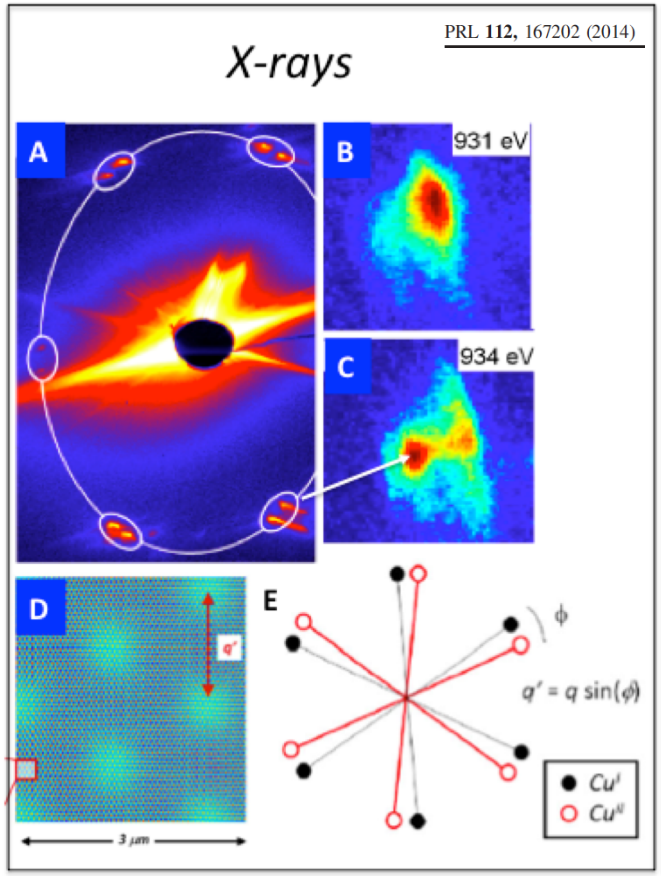


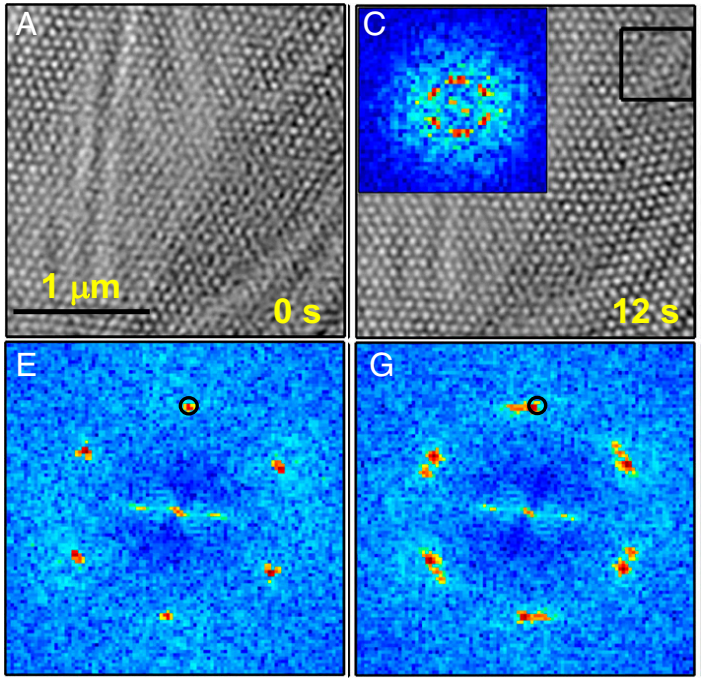




Observation of Skyrmions in a Multiferroic Material
S. Seki *et al.*
Science **336**, 198 (2012);

Skyrmions lattice ordering properties (camera-rate)



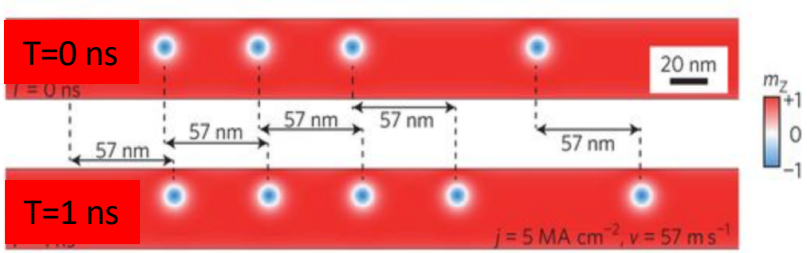


No overlapped skyrmion lattices, time-space fluctuating domains with different orientations (switching)

Rajeswary et al. PNAS 112 14212 (2015)

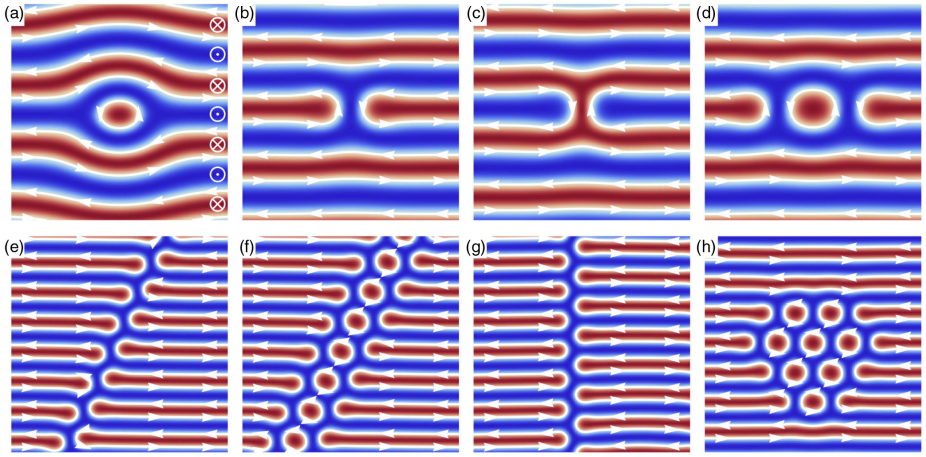
Skyrmions flowing in different background

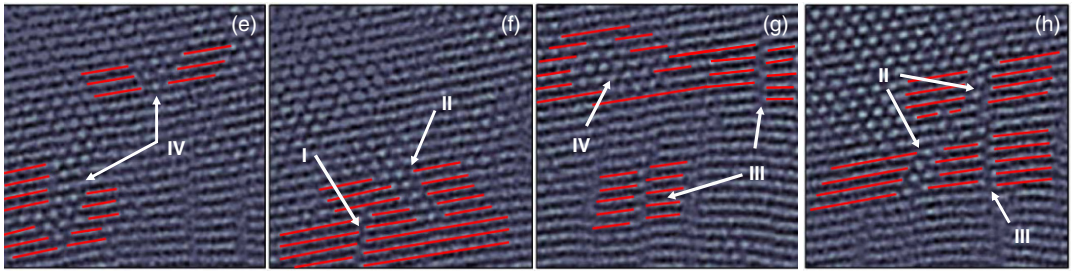
Skyrmions motion in a ferromagnetic background (MnSi)

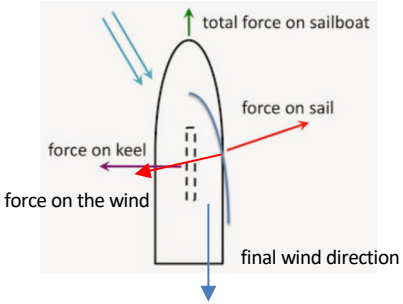


Fert et al., **Nature Nanotechnology** 8, 152–156 (2013)

Skyrmions/antiskyrmions and skyrmions clusters in the helical background Cu_2OSeO_3







In ferromagnets:

$V_{skyrmions} = V_{current}$

In helimagnet:

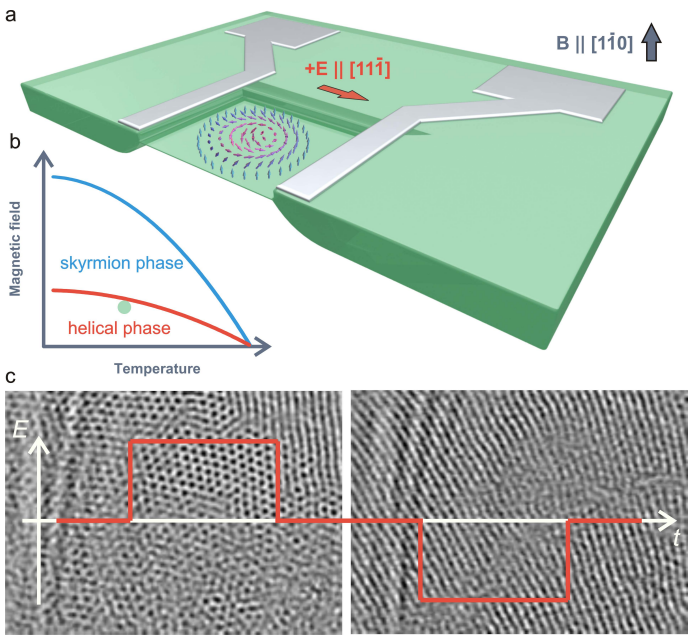
$V_{skyrmions} = V_{current}/a$

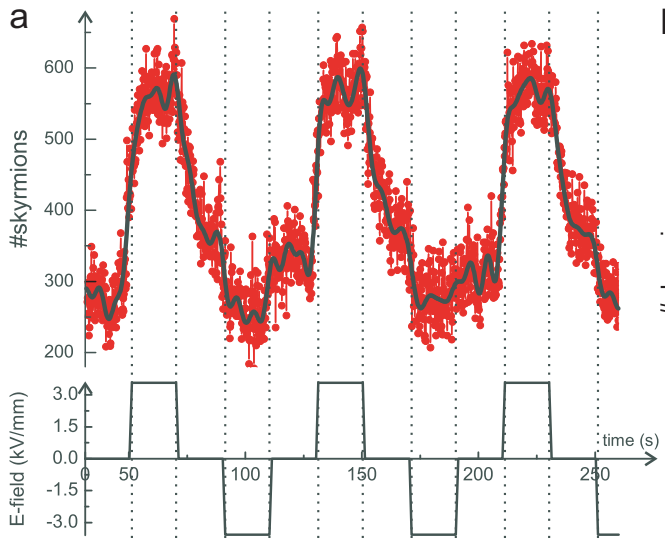
a = Gilbert damping<1

Helical background = keel

Muller et al., **Phys. Rev. Lett.** 119, 137201 (2017)

Electric field control of skyrmions

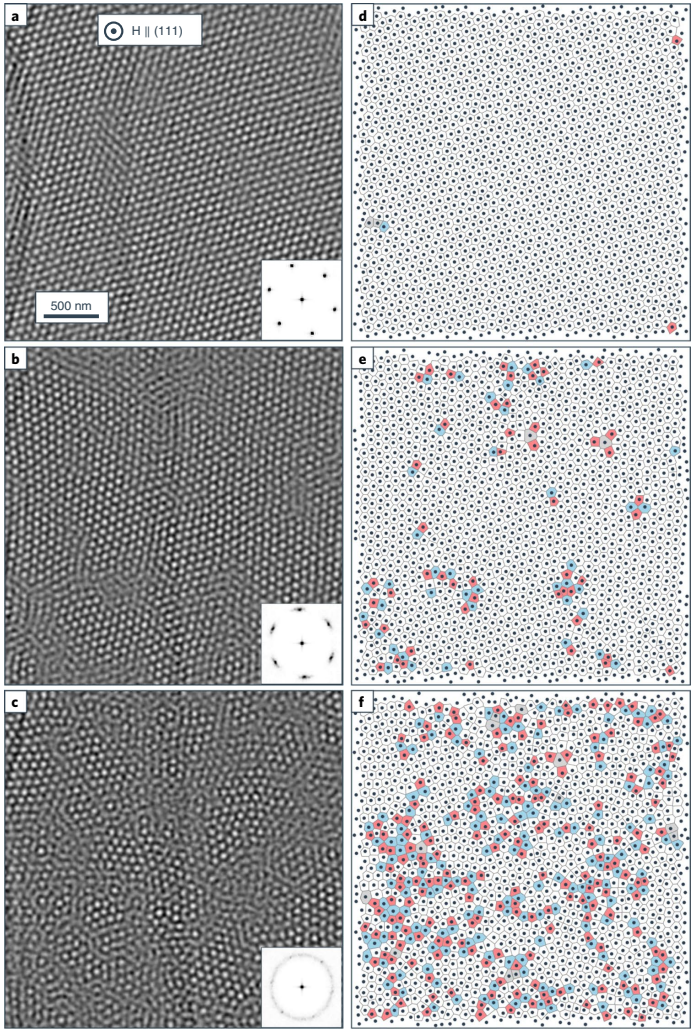


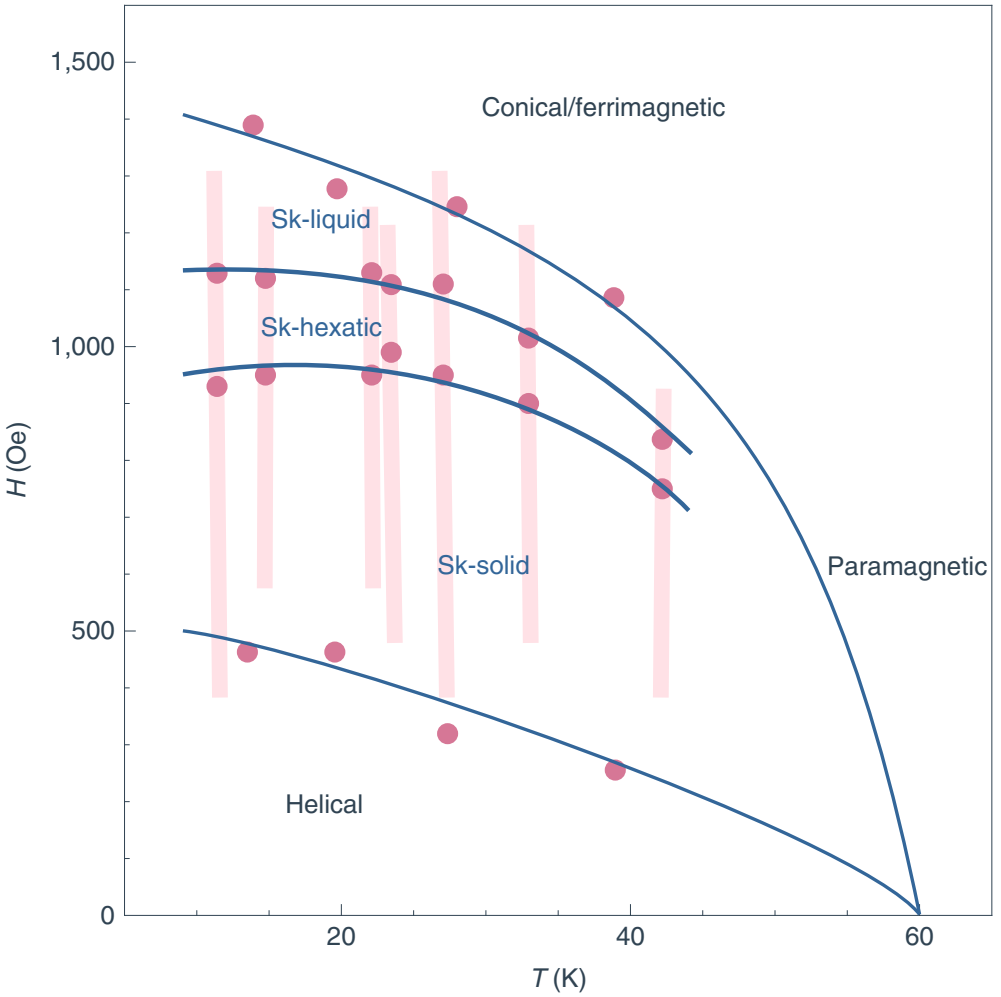


Currently limited to ms E-field pulse. Energy consumption: fJ/skyrmion

Huang et al., **Nanoletters** under review: arXiv:1710.09200

Discovery of the hexatic phase of the SkL





Huang et al, Nat. Nano 15 761 (2020)
News & Views Klaui Nat. Nano

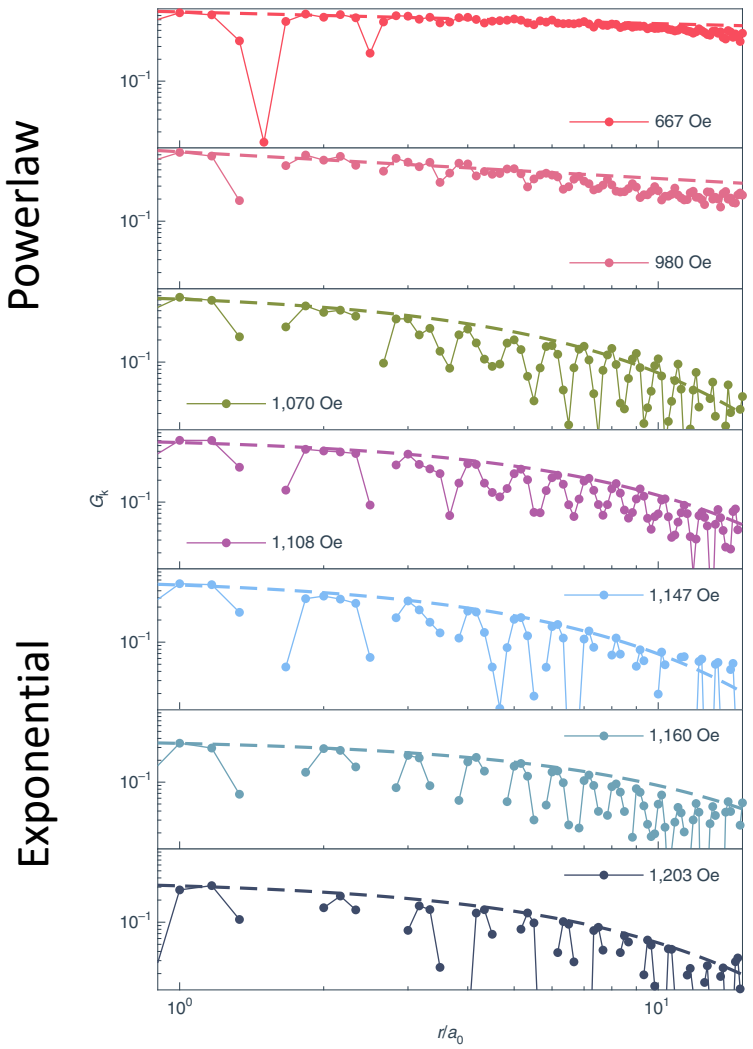
Skyrmion lattice melting

Translational order parameter

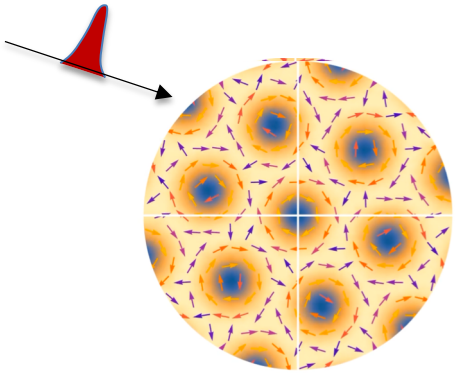
$$\Psi_{q_l}(\mathbf{r}) = \mathrm{e}^{-i\mathbf{q}_l\mathbf{r}}$$

Translational correlation function

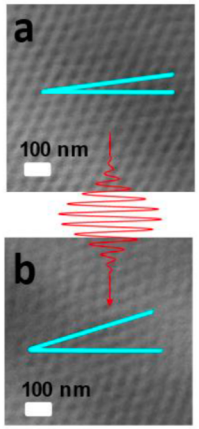
$$G_k(r) = \frac{1}{6}\sum_{l=1}^{6}\frac{1}{N_r}\sum_{\langle i,j\rangle}^{N_r}\Psi_{q_l}(\mathbf{r}_i)\Psi^*_{q_l}(\mathbf{r}_j)$$

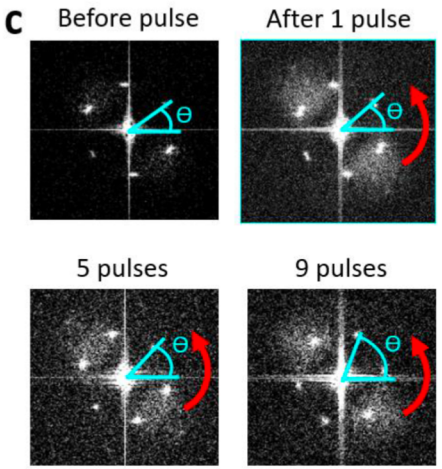


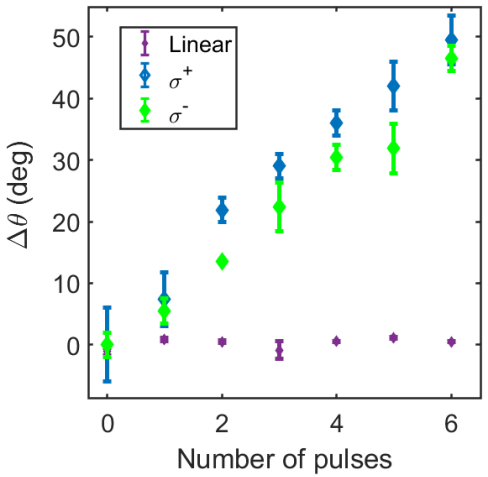
Coherent control of skyrmions



1 fs circularly polarized IR (>1μm) laser pulse induces a rotation

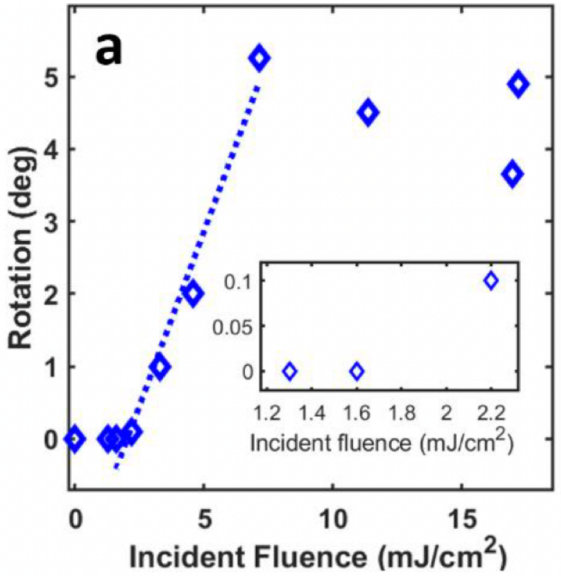






How fast does it rotate? What causes it?

- First hint: rotation has a threshold 2mJ/cm^2

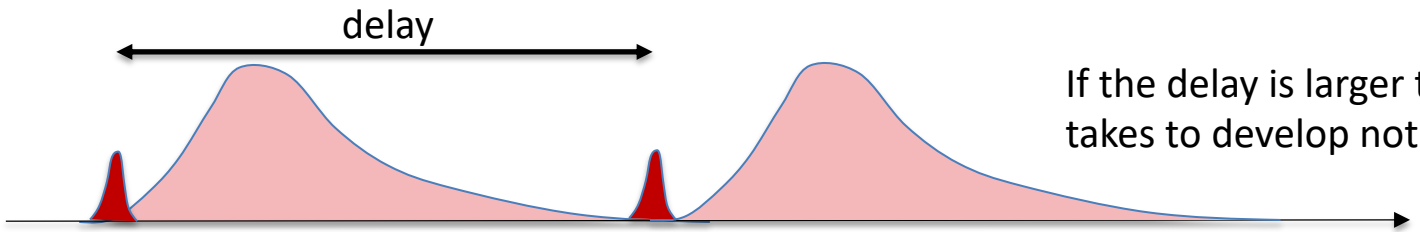


Coherent control of skyrmions

- Is it a thermal effect? Above a certain temperature jump the lattice rotates?
  - Happens on a slow time-scale (ns to μs) ?
  - Should not depend on polarization (CuOSeO is optically isotropic)
  - Threshold fluence should be higher for wavelengths corresponding to lower absorption coefficient

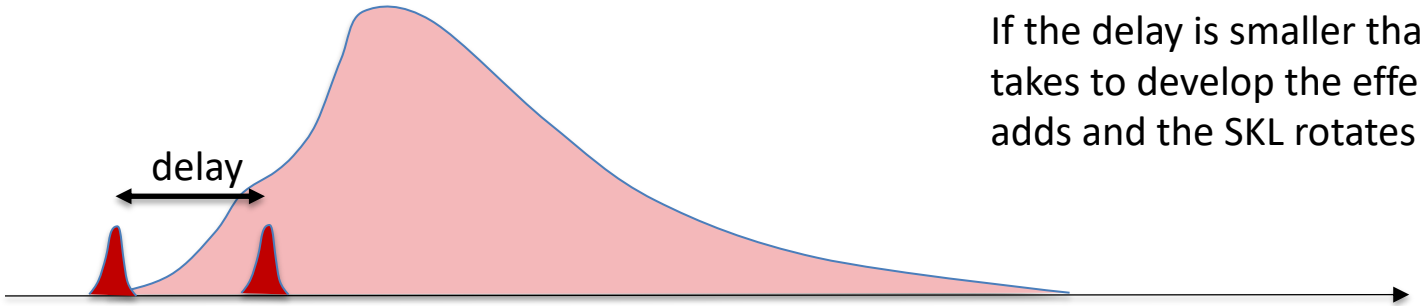
Rotation is an **IRREVERSIBLE** effect, no stroboscopic method possible

Two pump pulses, CW imaging with LTEM



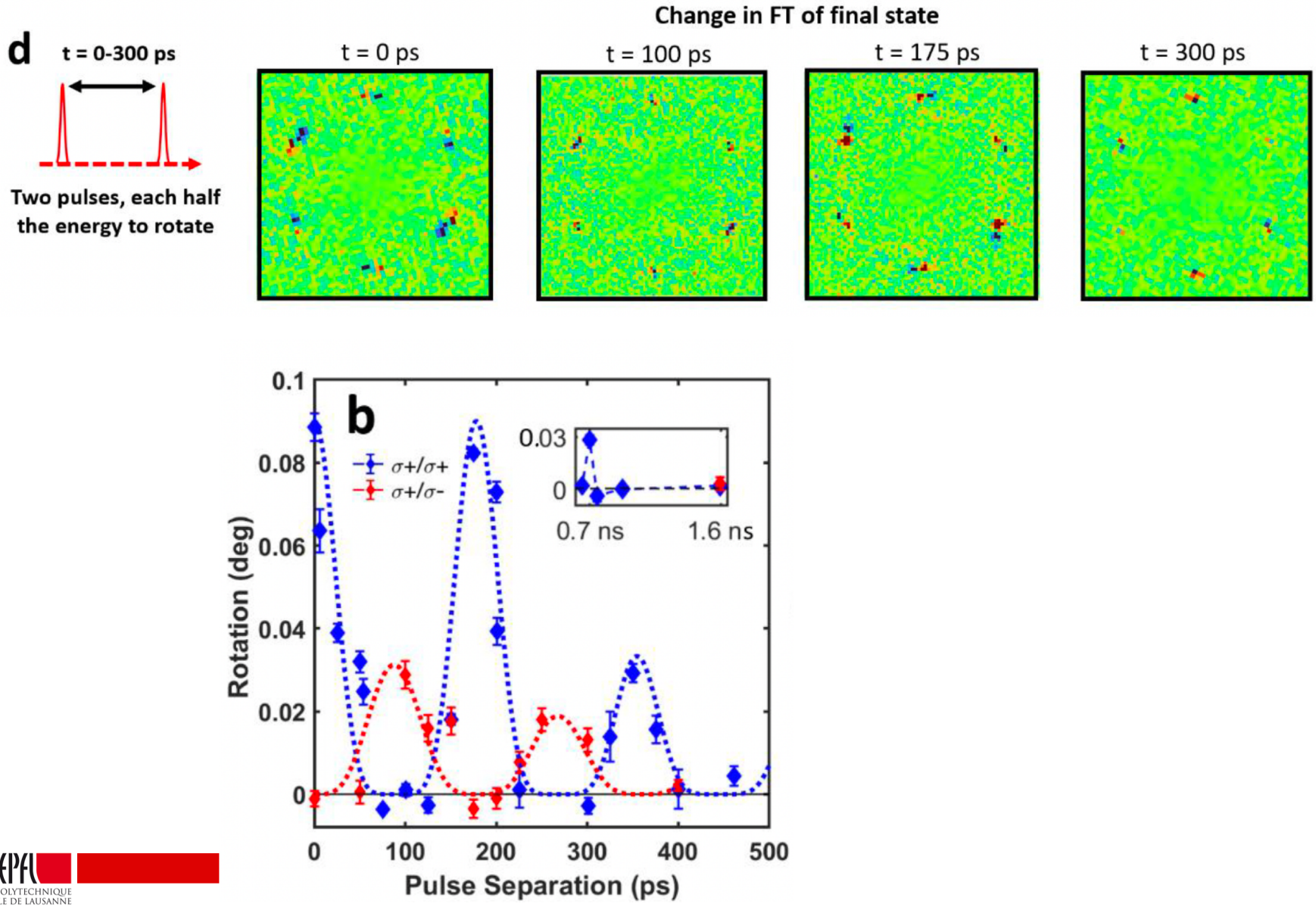
If the delay is larger than the time heat takes to develop nothing happens

Each pulse is **half** what is needed to induce rotation



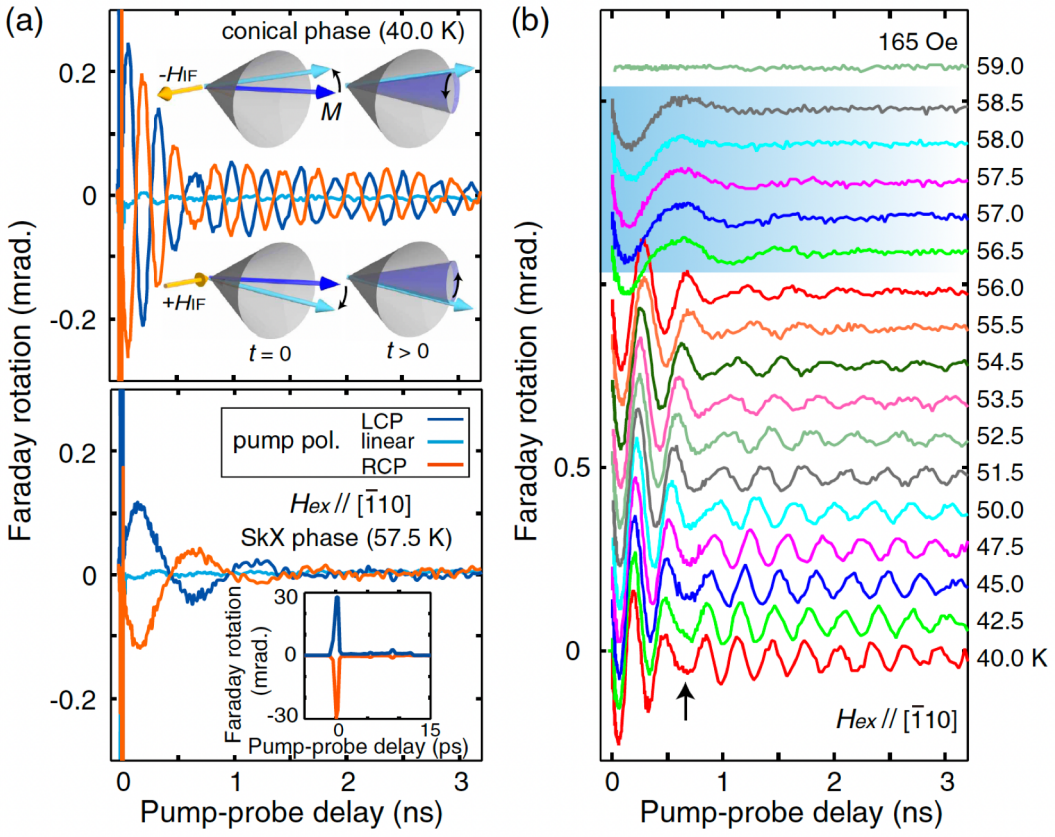
If the delay is smaller than the time heat takes to develop the effect of the two pulses adds and the SKL rotates

Coherent control of skyrmions



Inverse-Farady induced coherent magnons

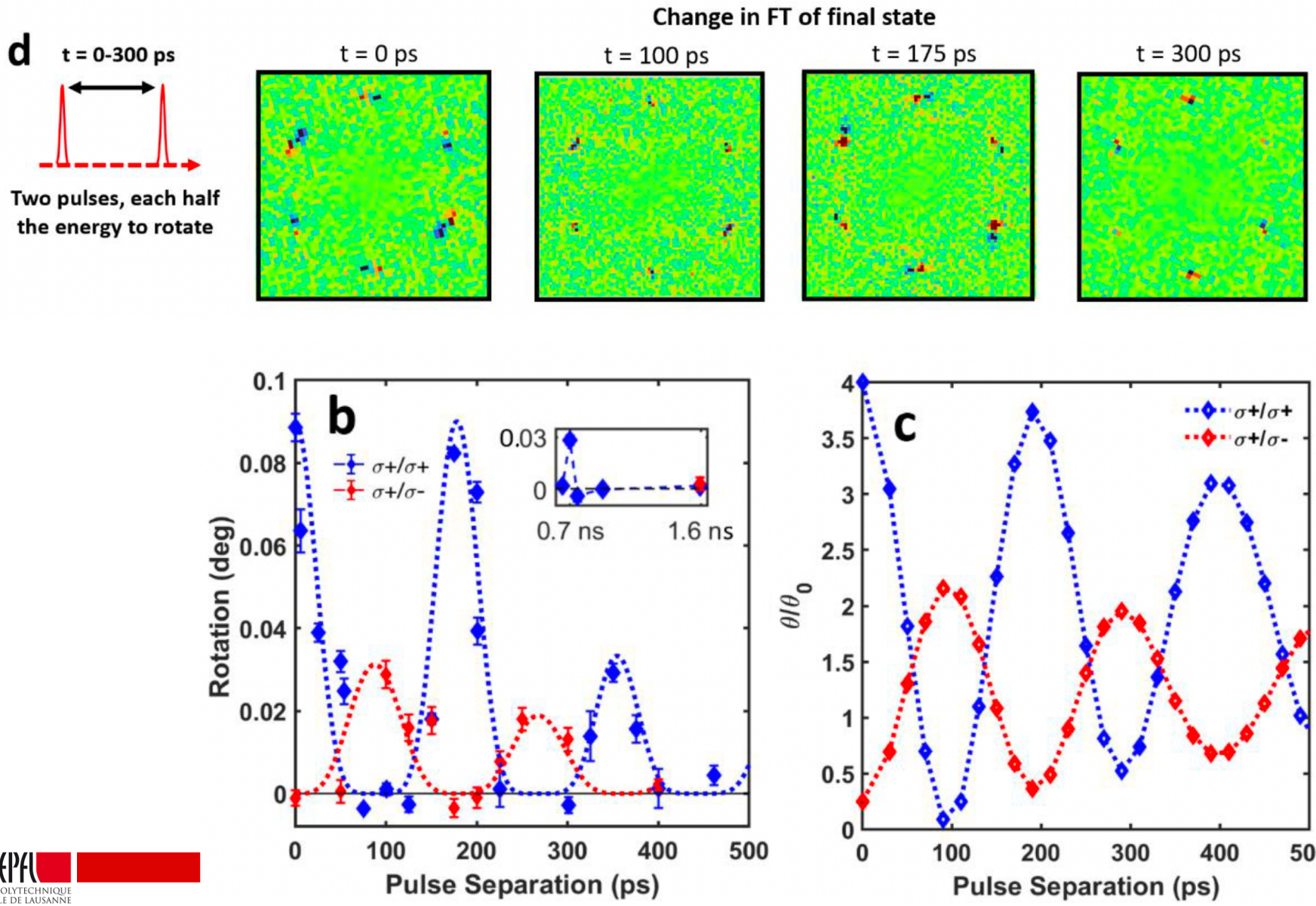
IR pump, induces coherent oscillations of the magnetization via inverse Faraday effect. Oscillations are vibration modes of the SKL



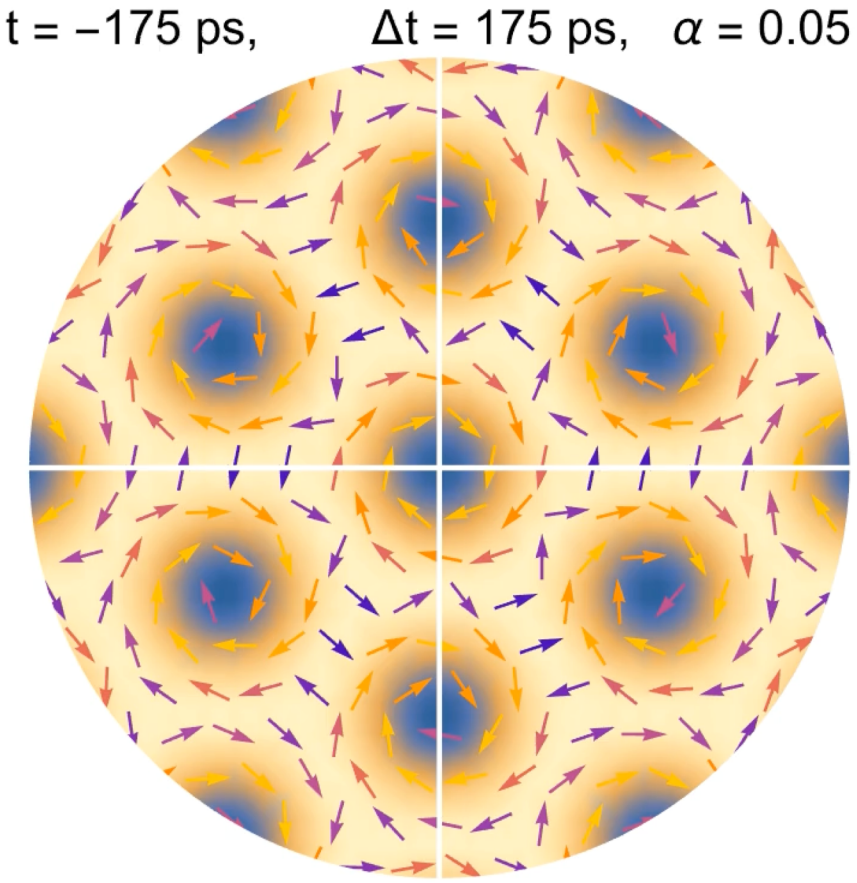
Ultrafast MOKE on CuOSeO

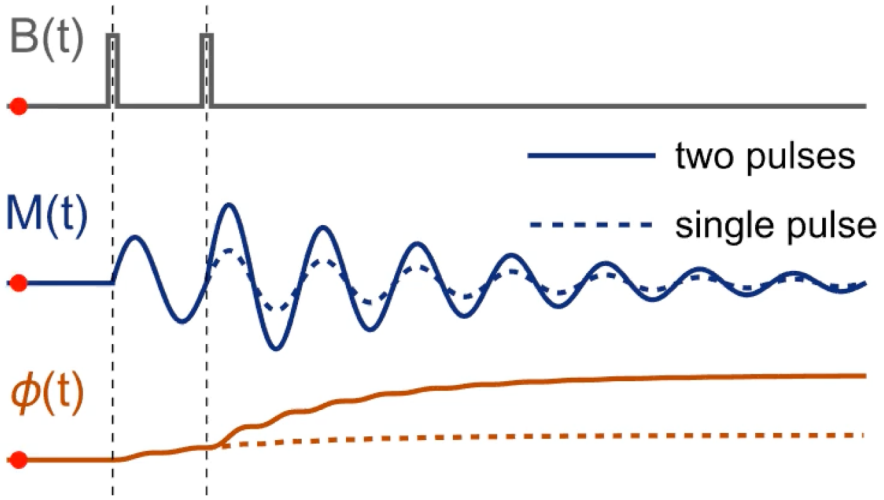
Ogawa, Seki, Tokura,
Sci. Rep. (2015)

Coherent control of skyrmions



Coherent control of skyrmions

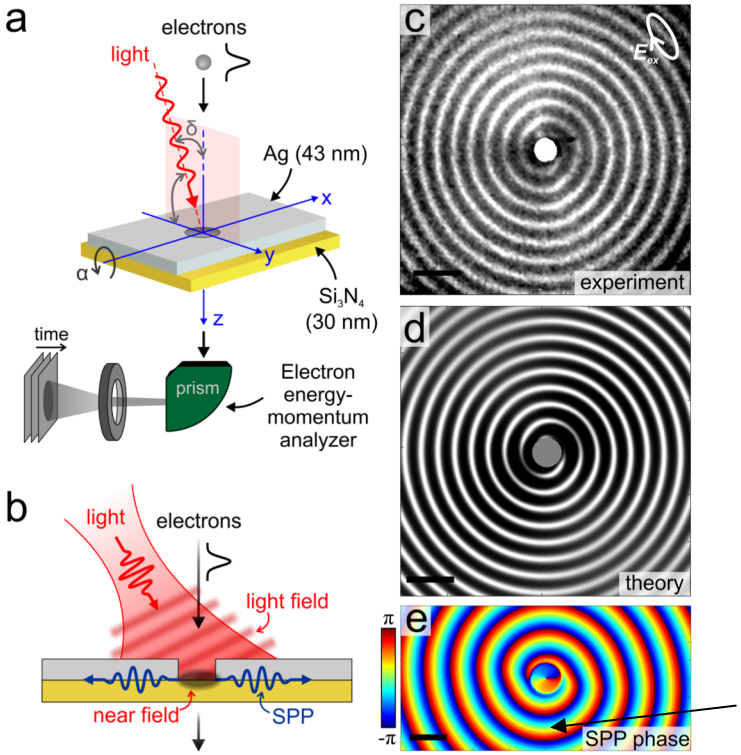




Take home messages

- Magnetic background influences skyrmions motion
- Laser light can write/erase skyrmions via super-cooling effects
- Electric fields can move/create skyrmions efficiently
- Inverse Faraday effect provides the possibility to coherently control the skyrmions

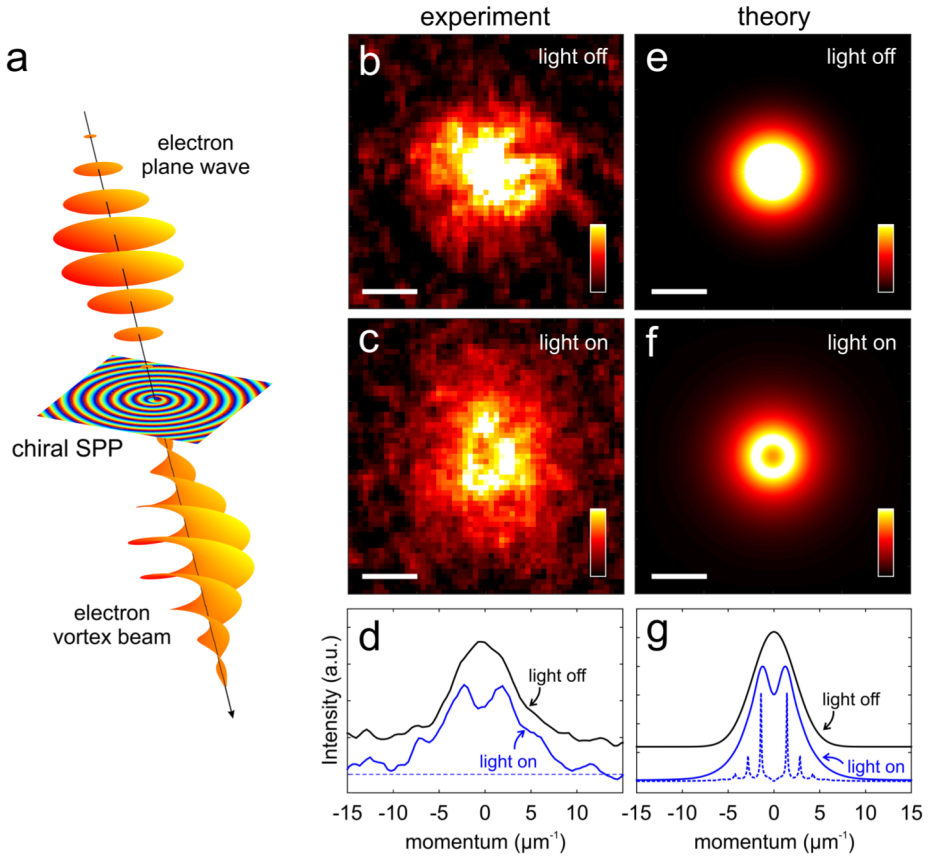
Imparting topological charge to electrons



- Chiral SPP launched by elliptically polarized light
- Simulated Chiral SPP
- A chiral plasmonic field can impart a phase singularity onto the transverse component of an e^- wavefunction

Vanacore et al., arXiv:1806.00366

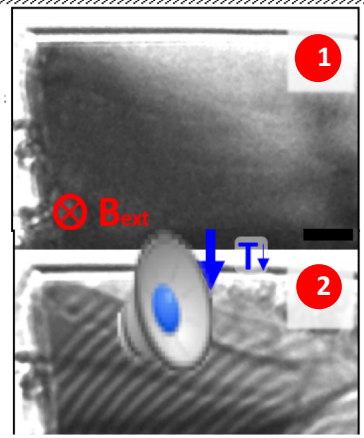
Electron vortex beam, m = 1

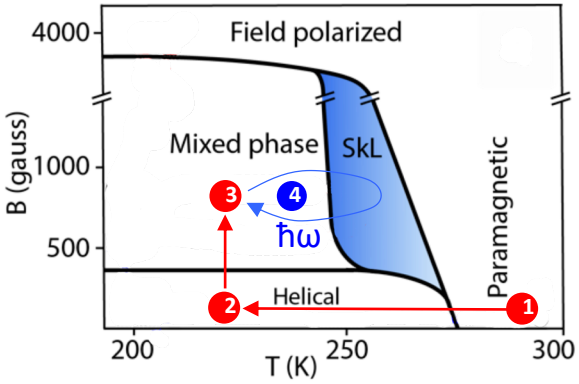


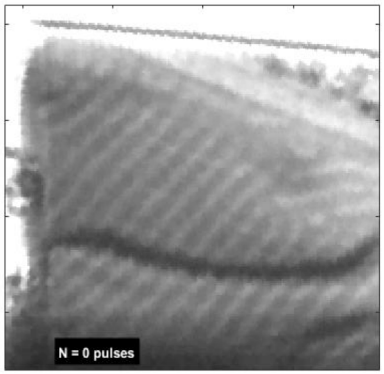
Electron wavefunction microscopy in momentum space

Vanacore et al., arXiv:1806.00366

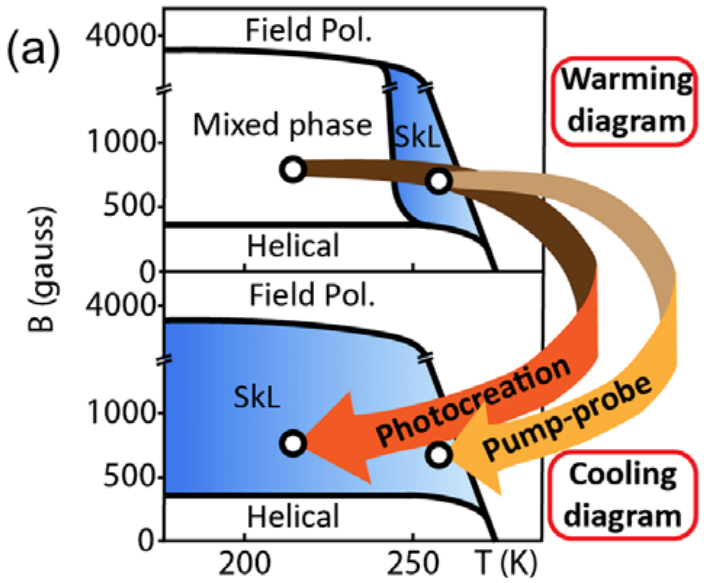
Light-control of skyrmions in FeGe (metallic)





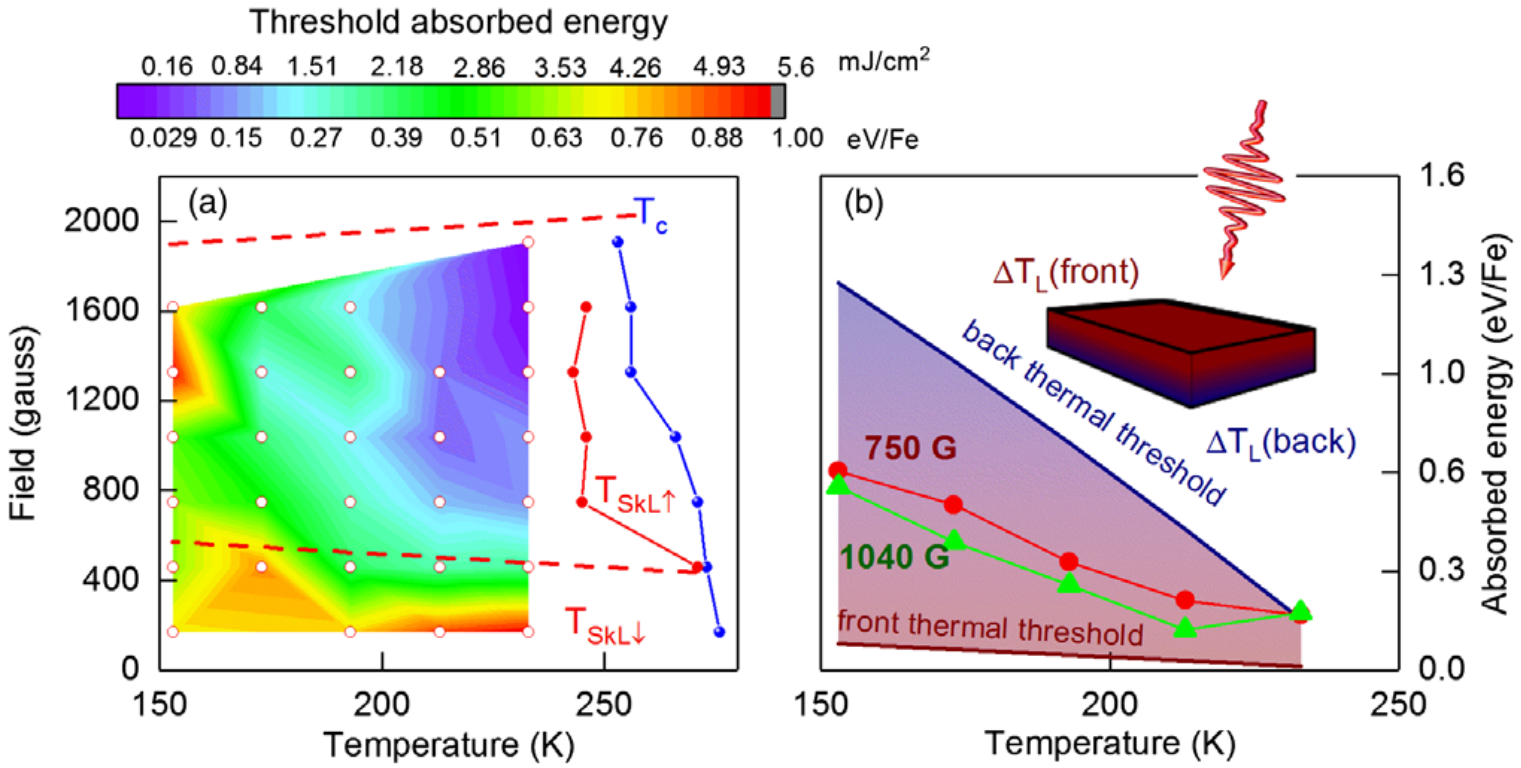


- Supercooling stabilizes skyrmions
- Light injects topological charge
- Energy consumption fJ/bit
- Histeretic PD shape depends on cooling rate



Berruto et al., **Phys. Rev. Lett.** 120, 117201 (2018)

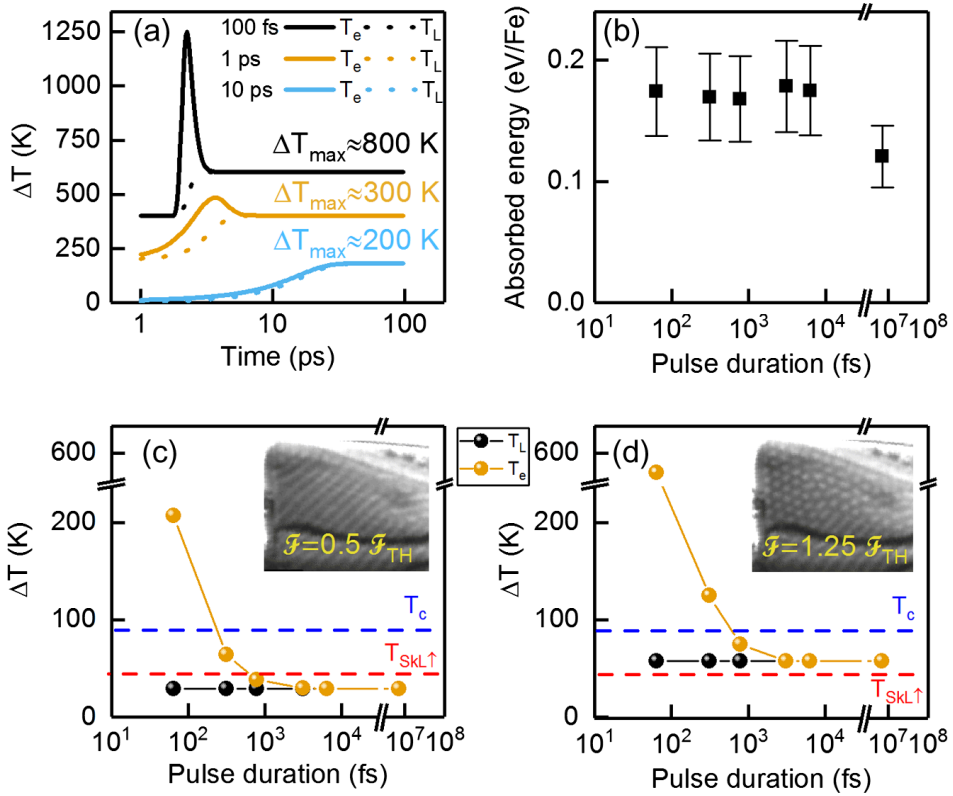
Skyrmion writing mechanism



Transient lattice temperature must exceed $T_{Sk\uparrow}$

Berruto et al., **Phys. Rev. Lett.** 120, 117201 (2018)

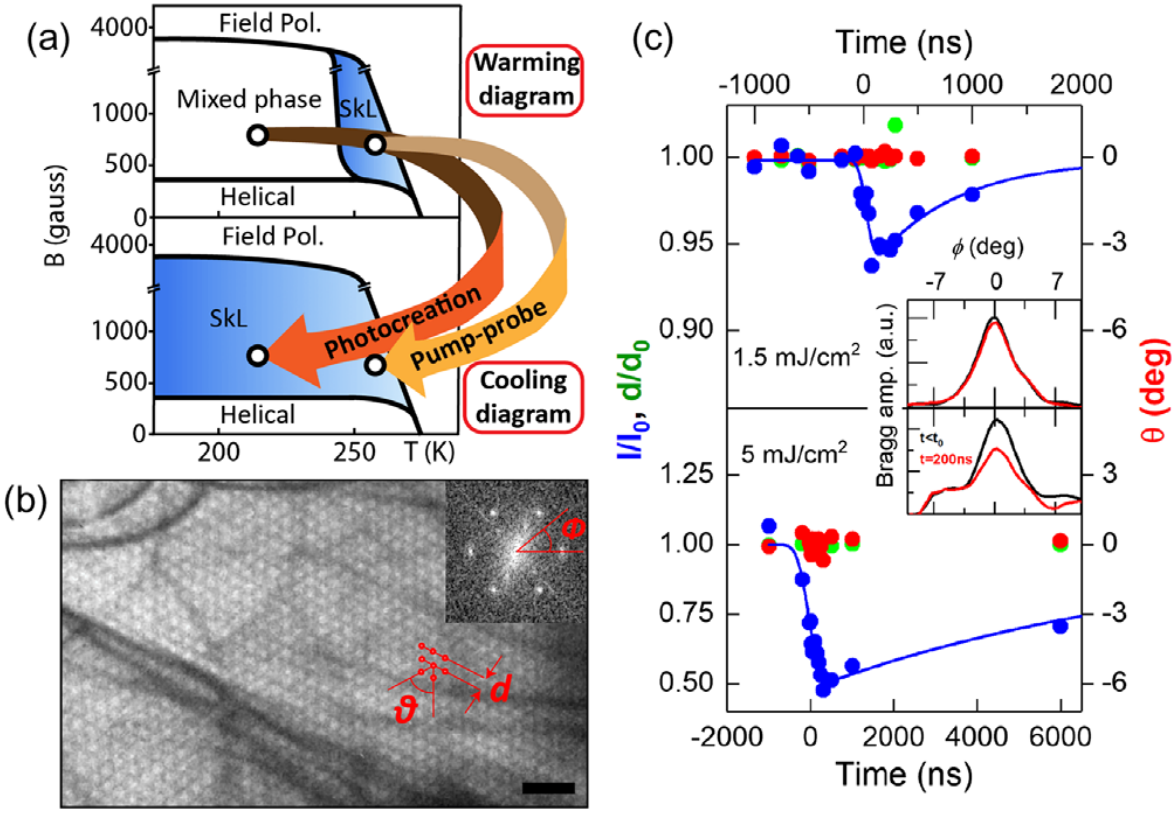
Skyrmion writing mechanism



- No effect of the electronic temperature (slow response of the magnetic system)

Berruto et al., **Phys. Rev. Lett.** 120, 117201 (2018)

Skyrmions erasing mechanism (ns pump-probe)



- Skyrmion lattice quenched without distorting it
- Melting the SkL with B does go through positional and orientational disorder (paper in prep.)

Berruto et al., **Phys. Rev. Lett.** 120, 117201 (2018)