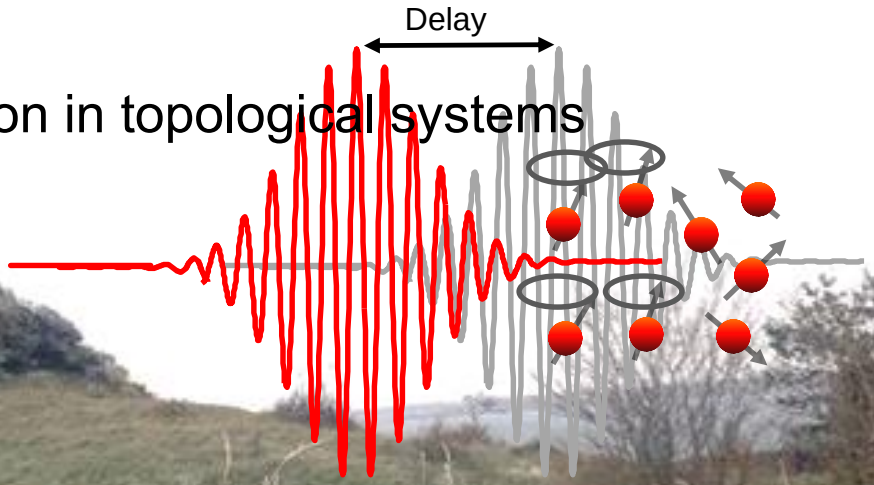
… study by the seaside
@spintronicsHGW

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

On the subtle interplay of light induced magnetization, driven currents and heat in ultrafast magnetism

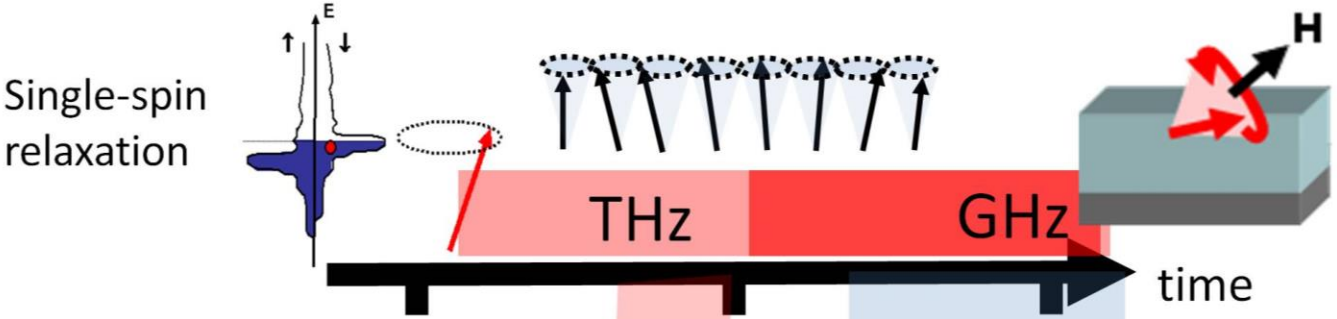
… ways towards optical spin manipulation in topological systems

Markus Münzenberg

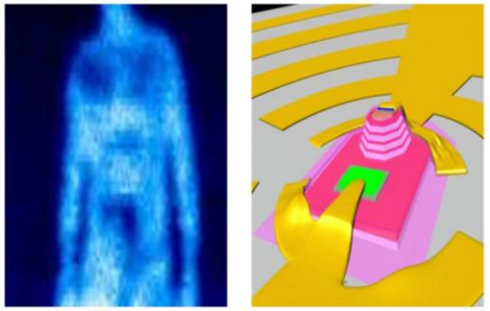


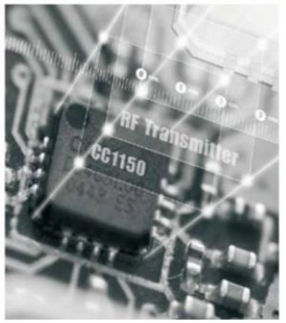
THz spintronics and ultrafast magnetism

Timescales of spin-dynamics and related applications



Applications: W-Lan, mobile phone,
inter-chip wireless, hard disc bit addressing





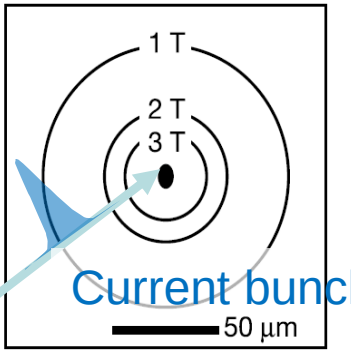
Perspective, J. Appl. Phys. 120, 140901 (2016)

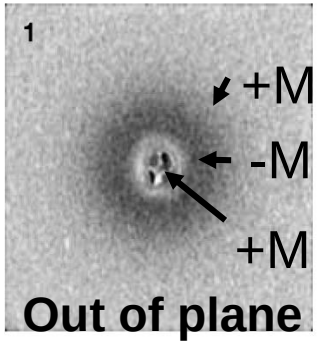
Ultrafast trigger

Free THz B-field trigger

- Stanford accelerator

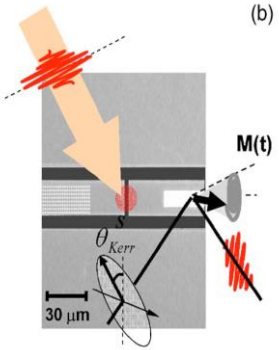
  Ch. Back et al., Science (1999)

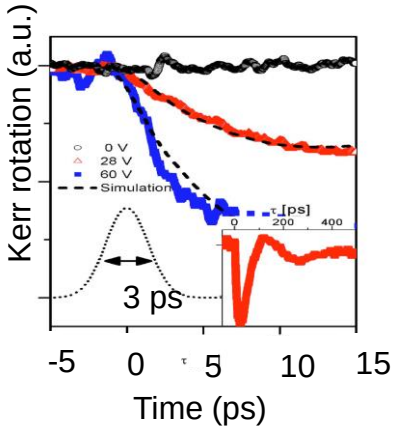




- Photoconductive switch, 1ps rise time, 0.2 Tesla

  Wang et al. JAP (2008)

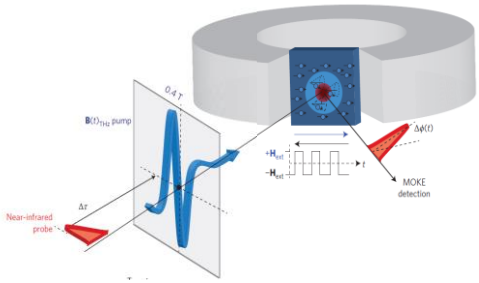


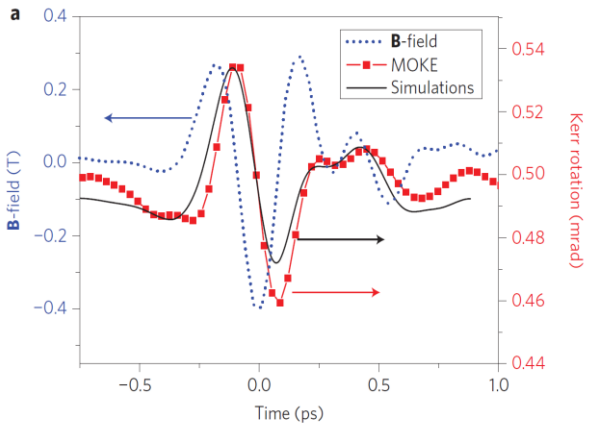


- Free THz pulse (organic crystals)

  0.5 ps rise time, ~1Tesla

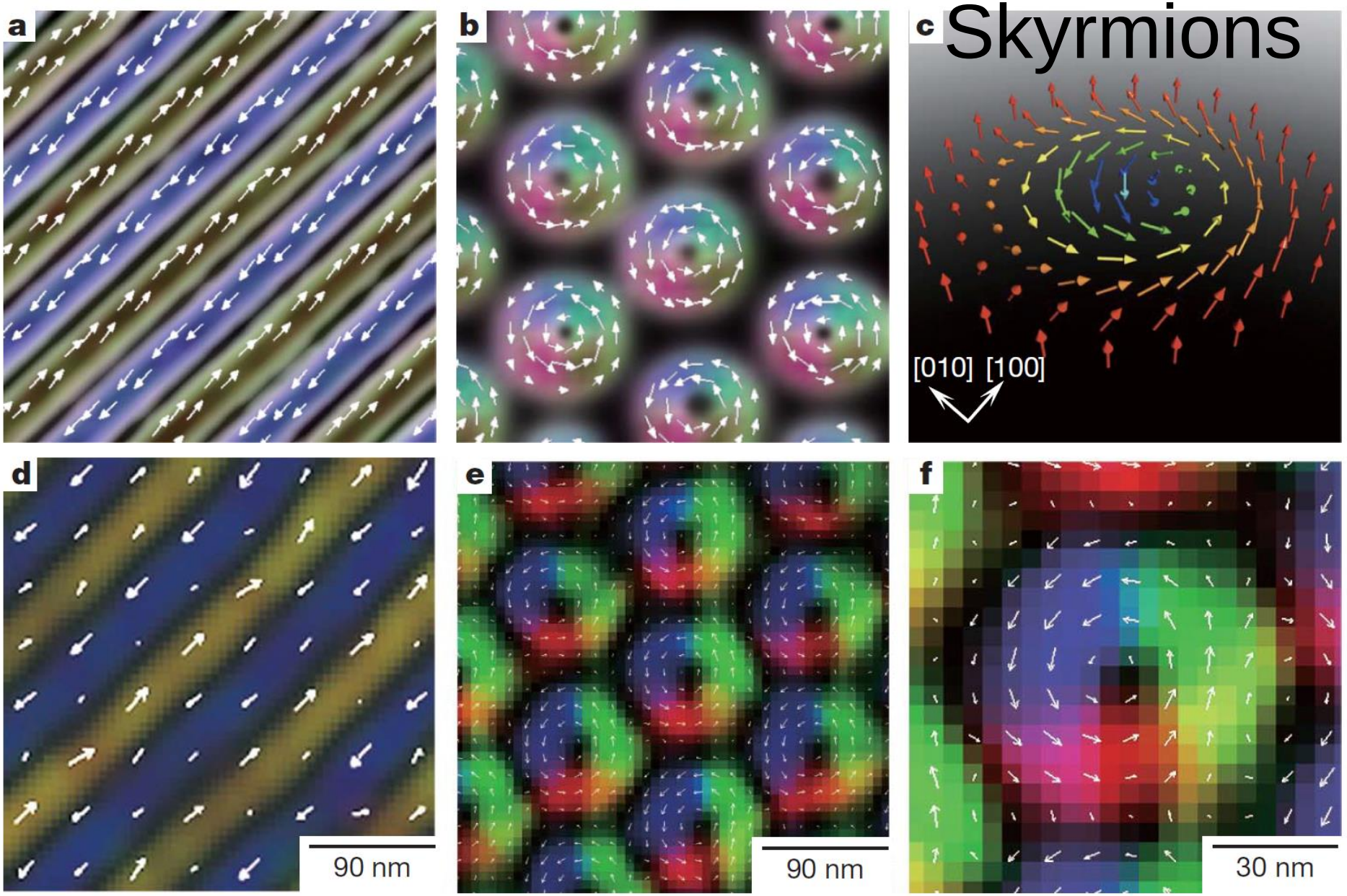
  C. Hauri et al. Nature Photon.(2013)





Perspective, J. Appl. Phys. 120, 140901 (2016)

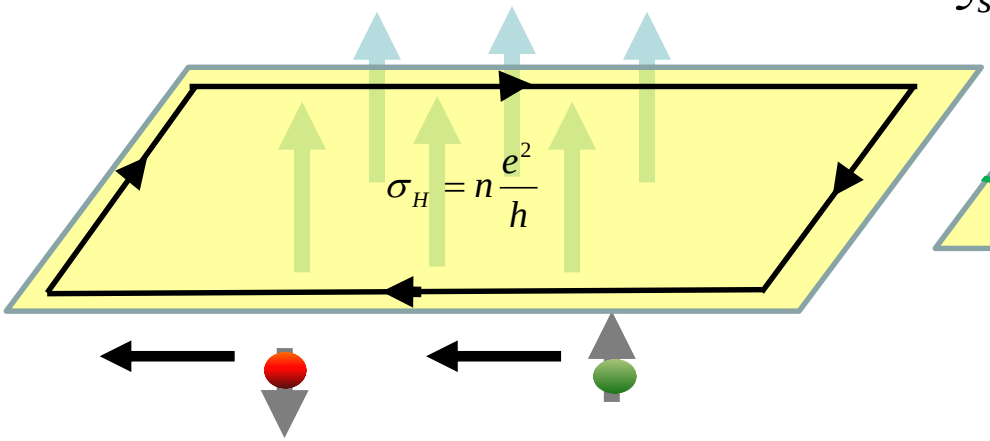
Topological matter

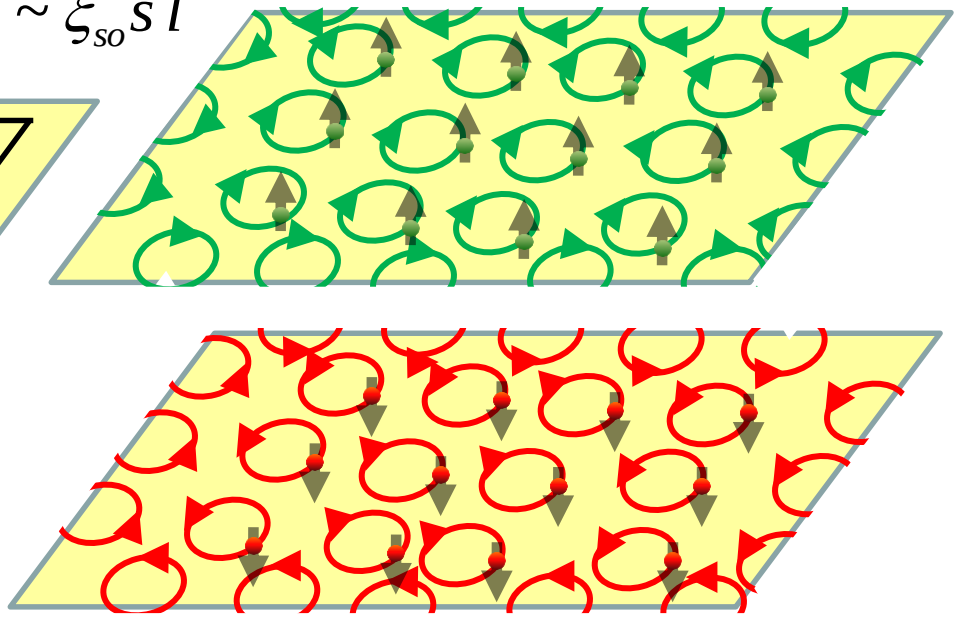


Topological Insulators

Internal spin-orbit field

$$E \sim \xi_{so} \vec{s}\,\vec{l}$$





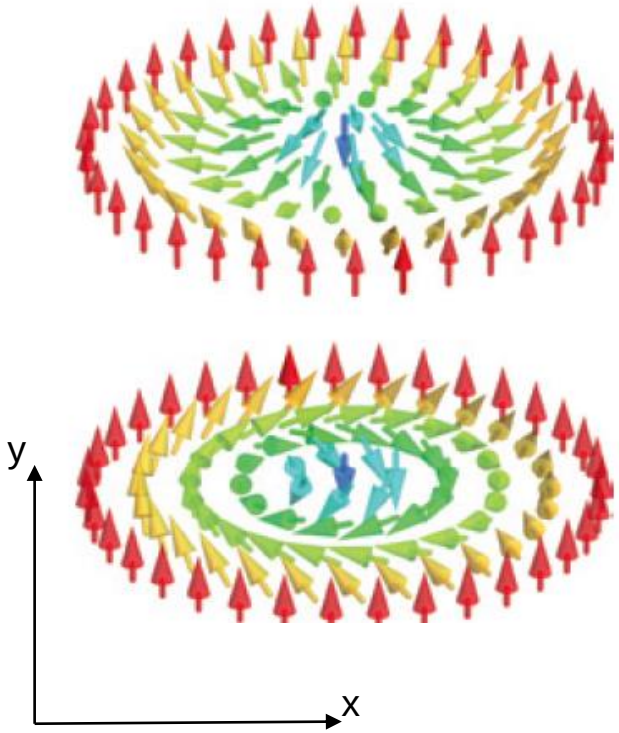
Cyclotron resonance, in 2D materials quantum Hall effect and edge states

Large spin-orbit coupling leads to cyclotron orbit

Topological matter

Skyrmions

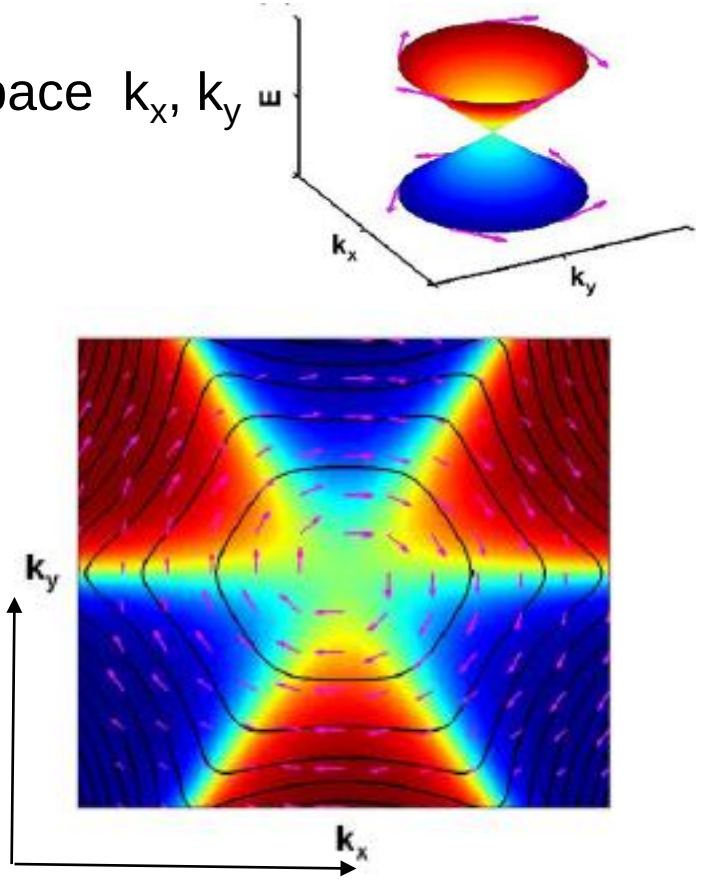
Real space x, y



From A. Fert, V. Cros, and J. Sampaio, Nat. Nano. 8, 152–156 (2013)

Topological insulators

Reciprocal space k_x, k_y

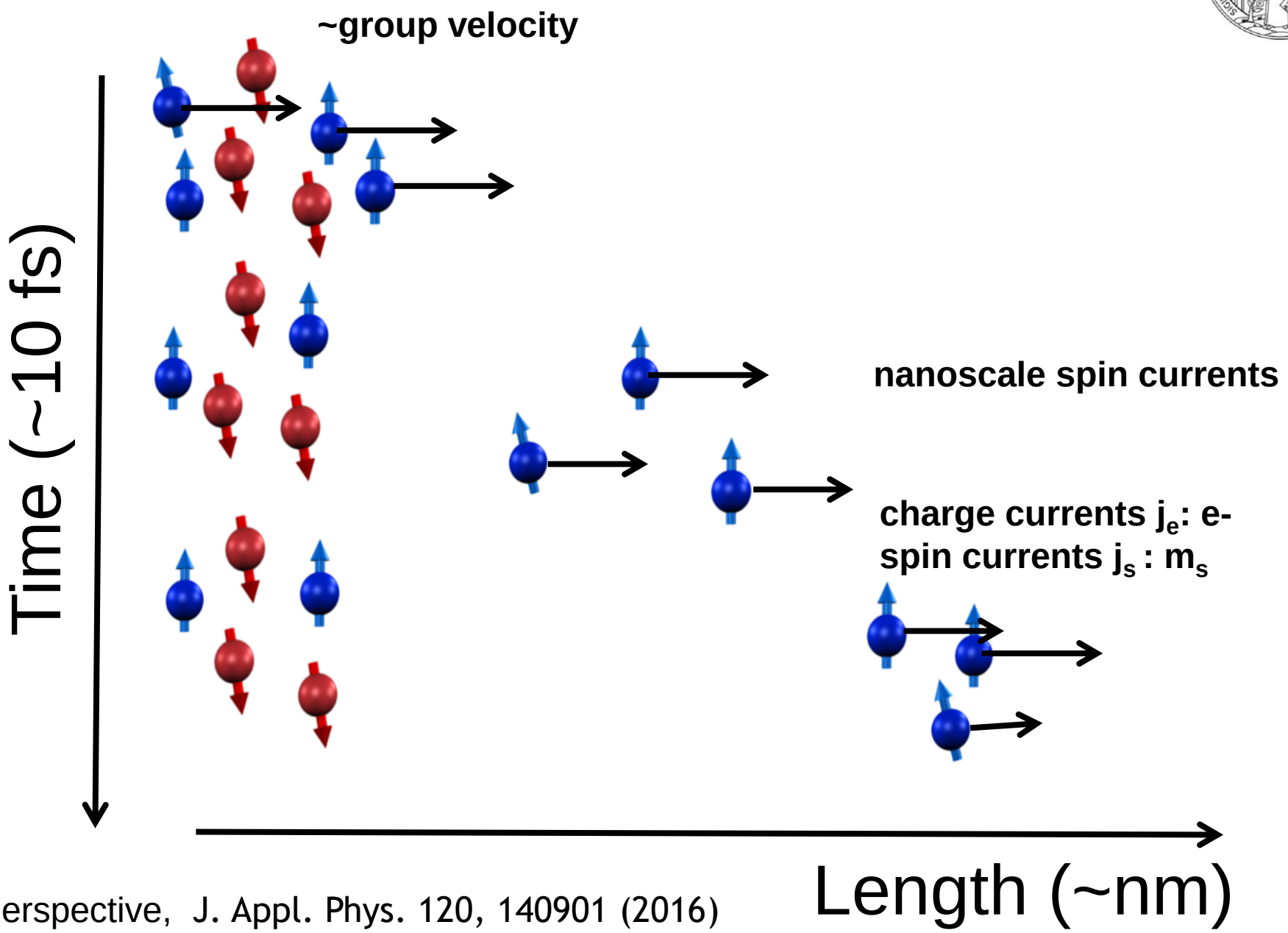


Nature Phys. 5 (2009) 438-42
Phys. Rev B 82 (2010) 045122

Outline

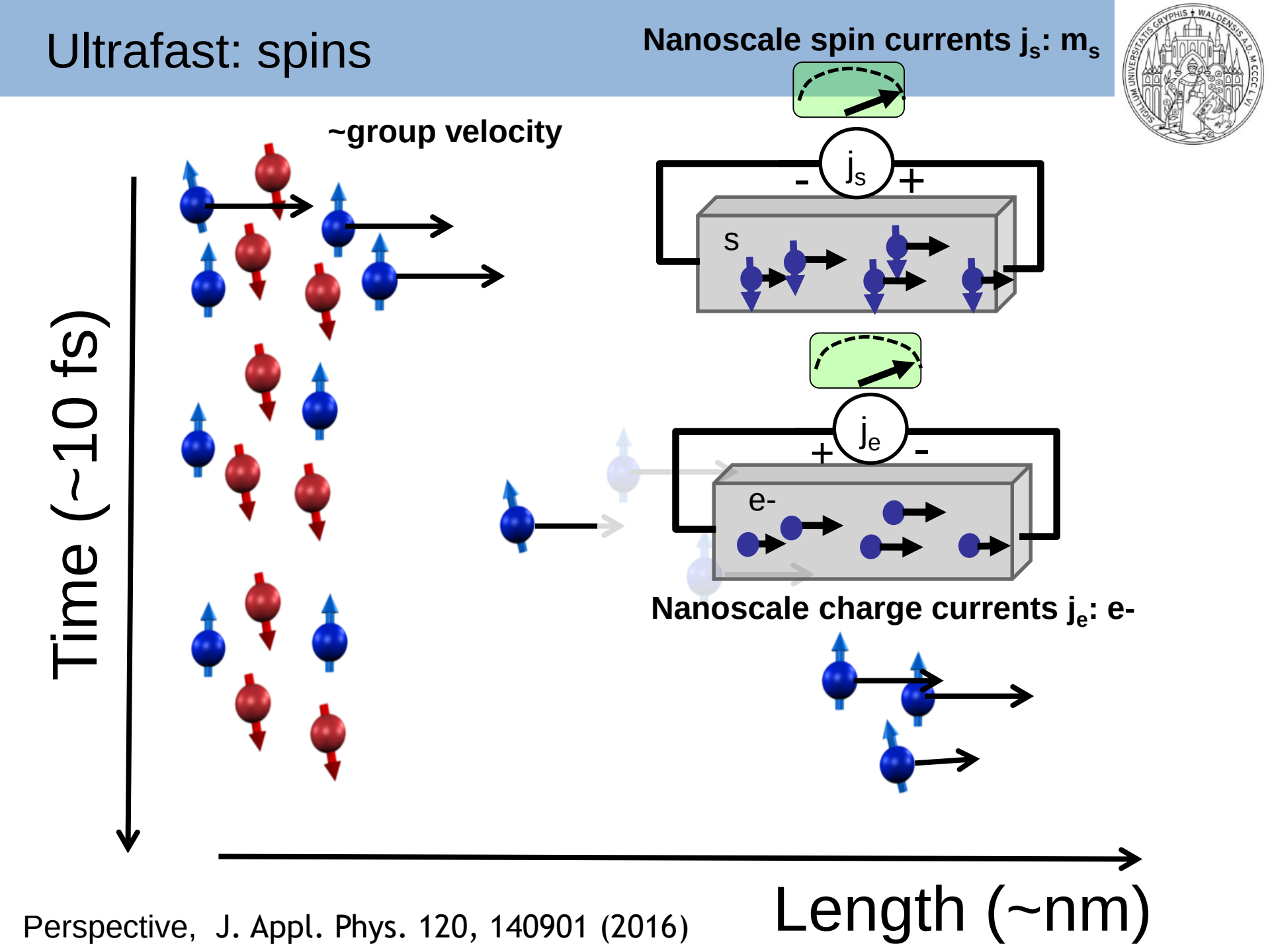
- The nature of femtosecond spin dynamics
- THz spintronic emitter
- Hard disc: state of the art
  - Thermal model of ultrafast demagnetization
  - FePt optical writing a storage media
- Summary

Ultrafast: spins



Perspective, J. Appl. Phys. 120, 140901 (2016)

Ultrafast: spins



Perspective, J. Appl. Phys. 120, 140901 (2016)

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Spintronic THz emitter

- *Fritz-Haber Institut,* Berlin, Germany

  THz: T. Kampfrath

Tobias Kampfrath

- Physics and Astronomy, Uppsala University, Sweden

  Theory Spin Currents: Battiato, Oppeneer

Tom Seifert

Peter Oppeneer

Published in Nature Nanotech. 8, 256 (2013),
Nature Photonics 10, 483–488 (2016).

Spintronic THz emitter

- *Johannes Gutenberg-Universität Mainz*

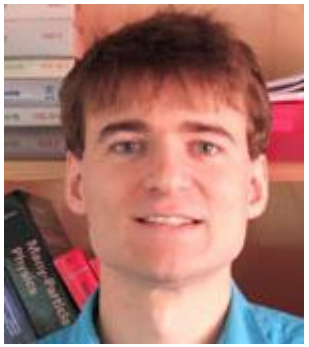
  Emitter: Kläui, Münzenberg

Mathias Kläui

- FZ Jülich

  Theory SHE: Mokrousov, Freimuth

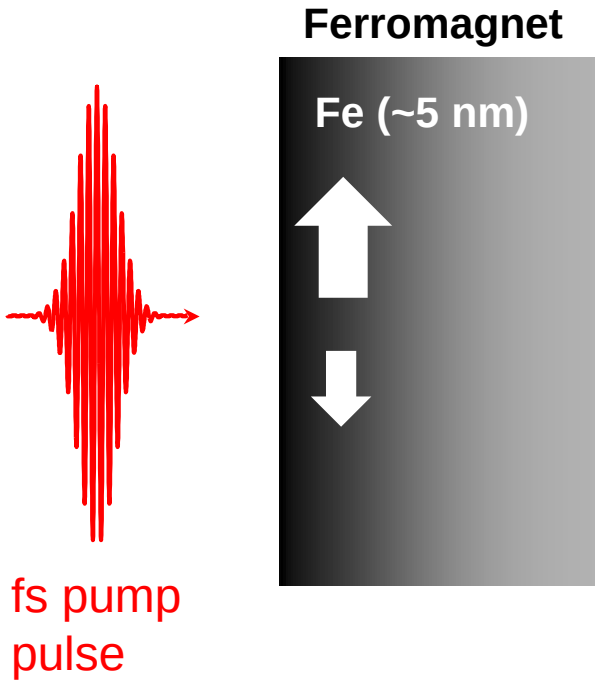
Yuri Mokrousov



Frank Freimuth

Published in Nature Nanotech. 8, 256 (2013),
Nature Photonics 10, 483–488 (2016).

Spintronic THz emitter



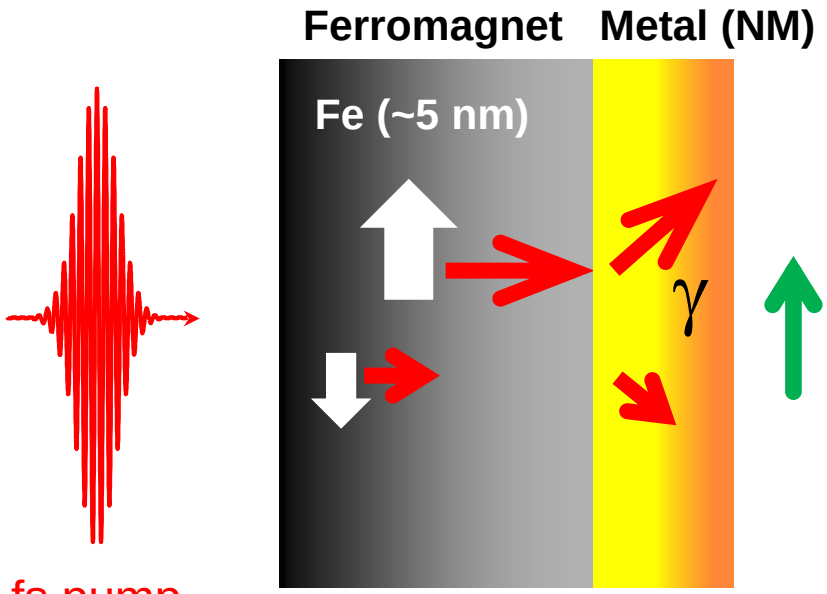
Pump pulse excites ↑ and ↓ electrons

↑: d → sp bands ⇒ become fast

Oppeneer *et al.,* PRL (2010)

Nature Nanotech. 8, 256 (2013).

Spintronic THz emitter

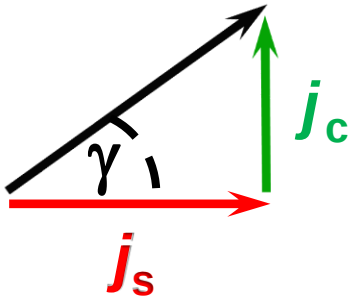


Inverse spin Hall effect (ISHE):

Spin-orbit coupling deflects electrons

$\Rightarrow$ transverse charge current

Spin hall angle $\gamma = \frac{\sigma_{SH}}{\sigma_{xx}}$



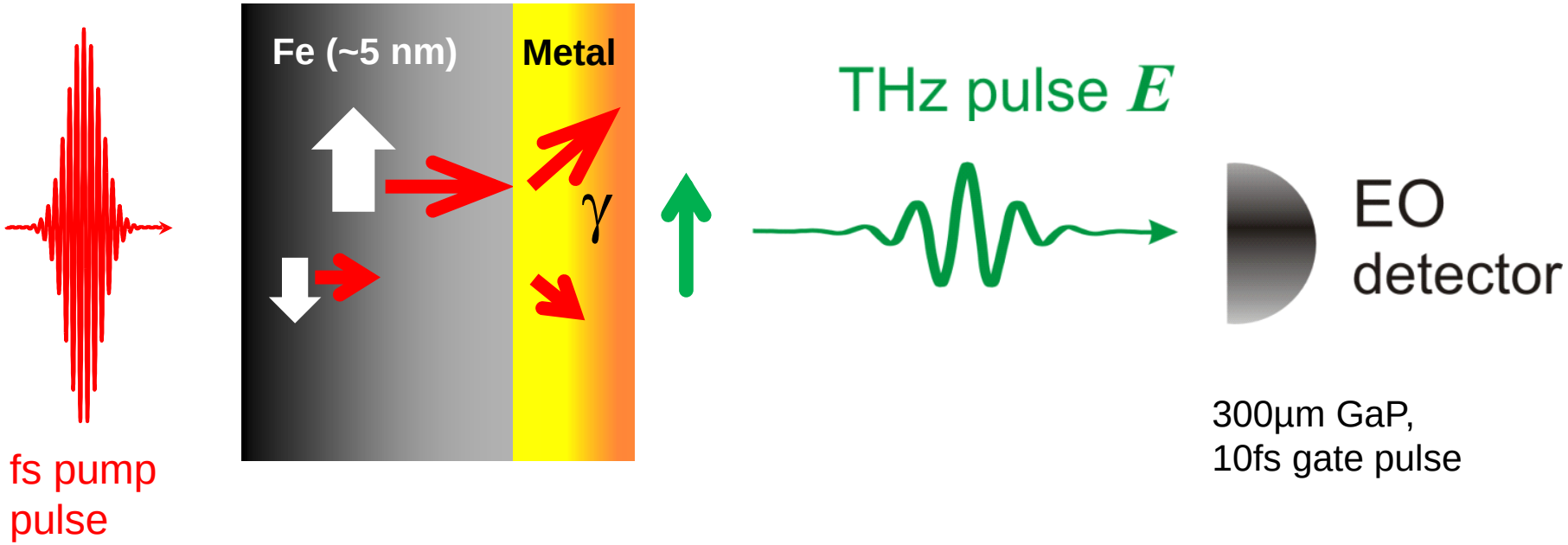
σ_{SH} - spin Hall conductivity

σ_{xx} - diagonal conductivity

Kampfrath, Battiato, Oppeneer, Wolf, Freimuth, Mokrousov, Münzenberg *et al.*, Nature Nanotech. 8, 256 (2013)

Nature Nanotech. 8, 256 (2013).

Spintronic THz emitter



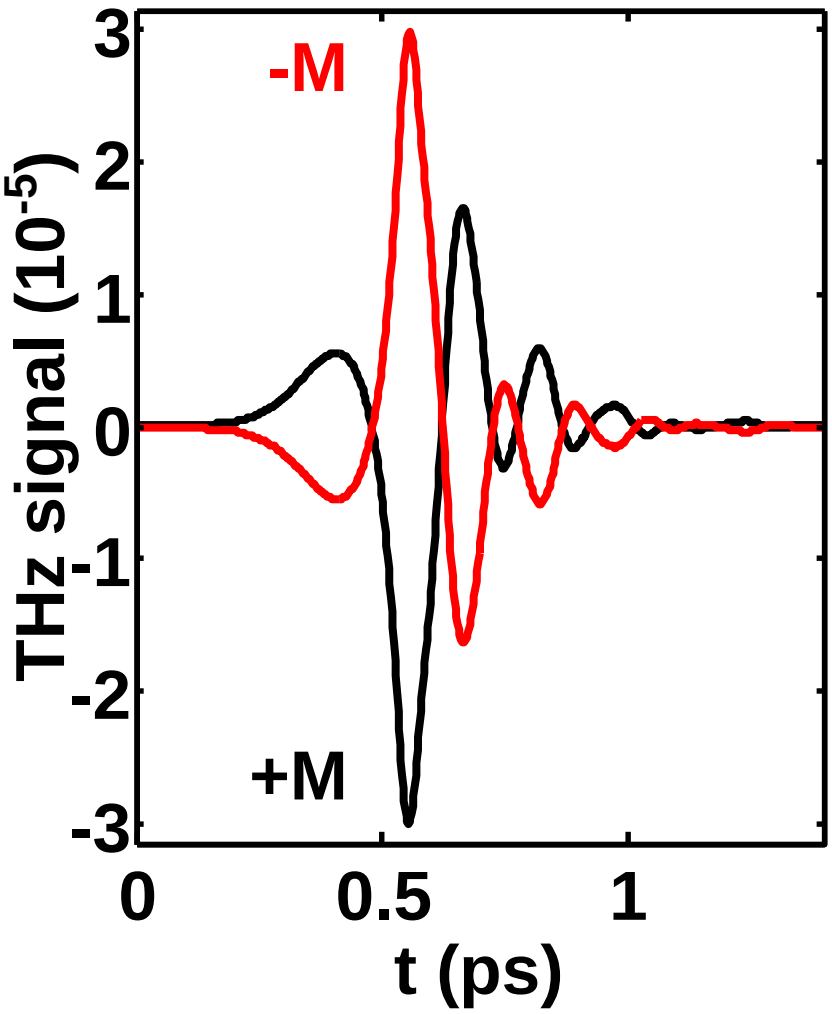
⇒ Measure THz emission from photoexcited FM/NM bilayers

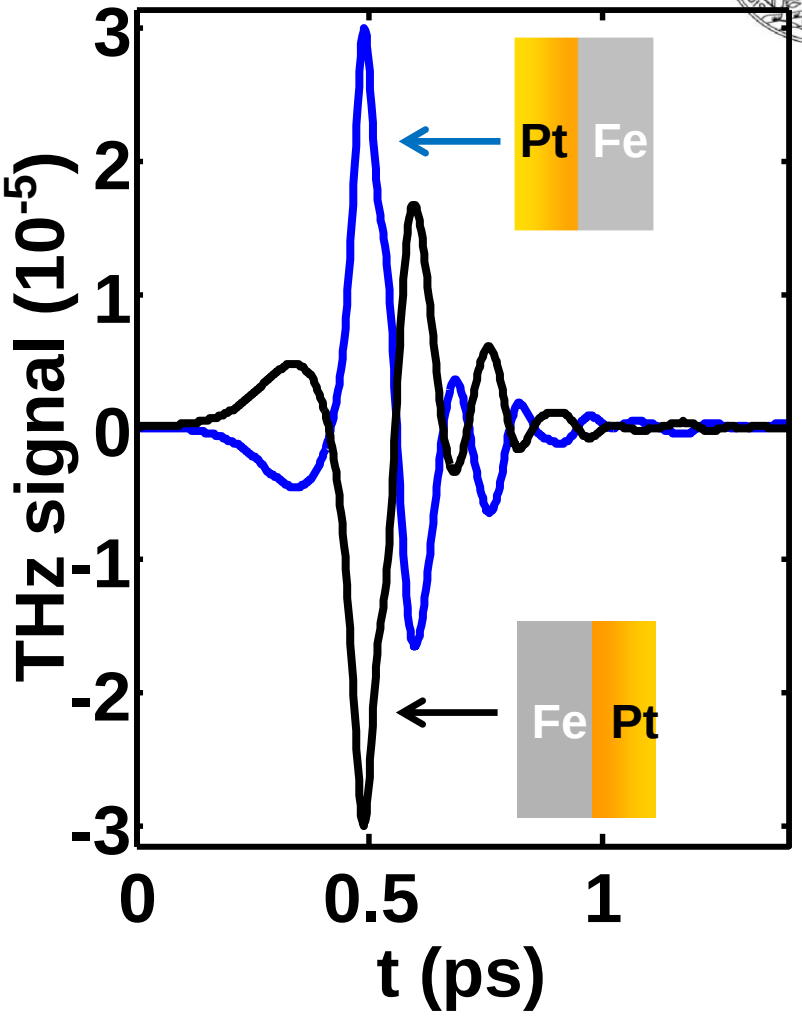
Note: just used a pulsed laser oscillator (10 fs, 80 MHz)

Kampfrath, Battiato, Oppeneer, Wolf, Freimuth, Mokrousov, Münzenberg *et al*.,

Nature Nanotech. 8, 256 (2013)

Spintronic THz emitter

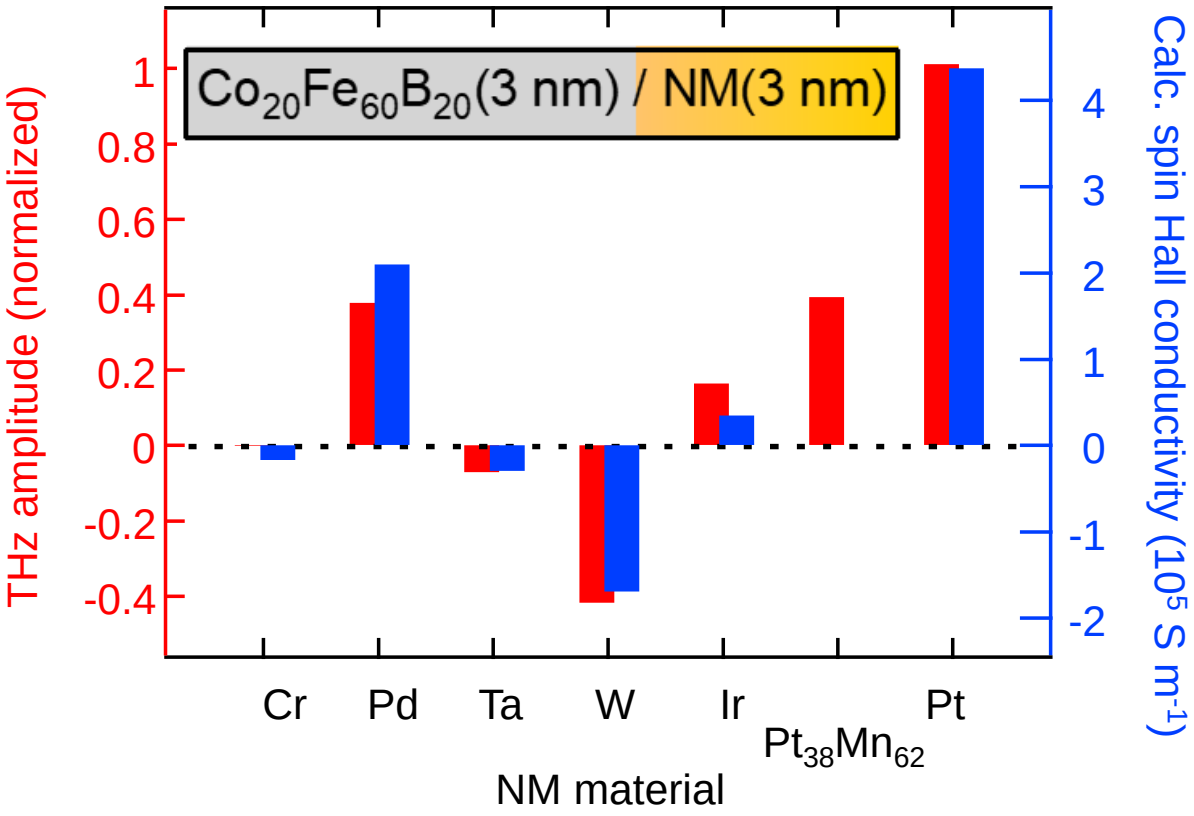


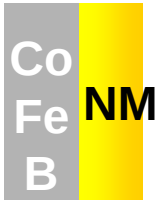


Transient changes polarity by reversing **M** or stacking order

Really SHE scenario? ⇨change NM layer

Spintronic THz emitter





Calculations:
Freimuth, Blügel, Mokrousov
e.g. PRL (2010)

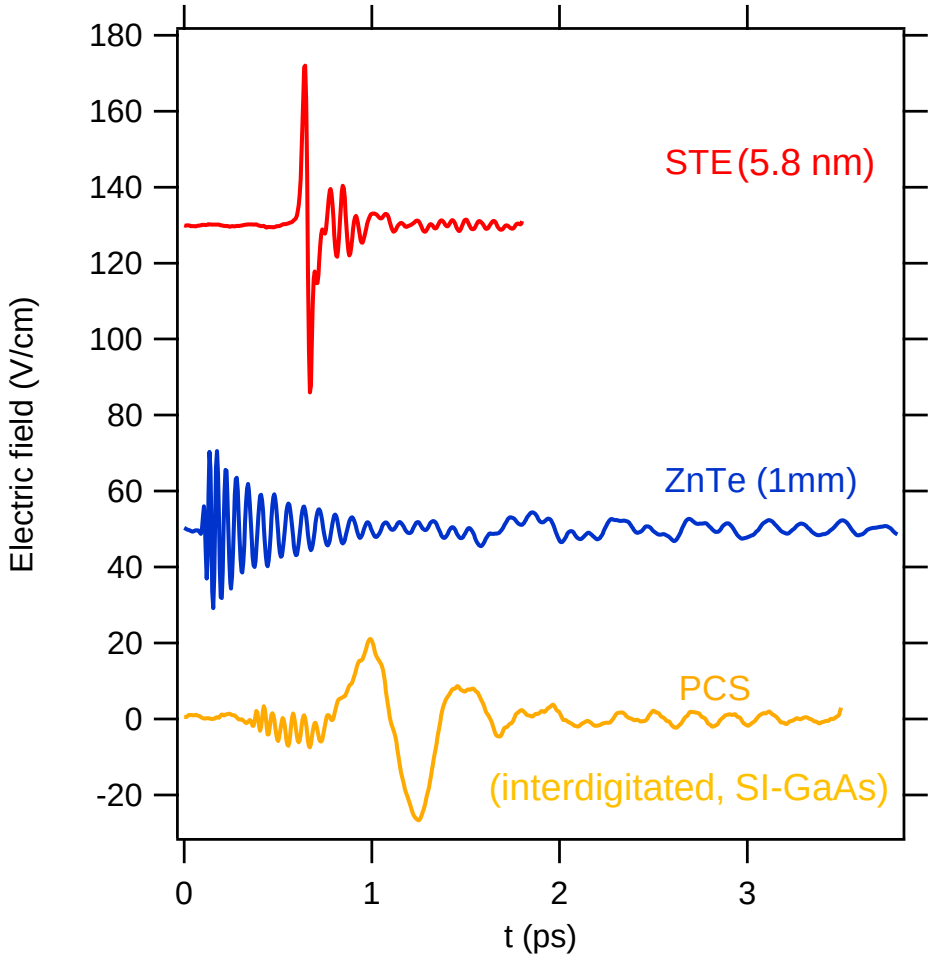
Good relative agreement

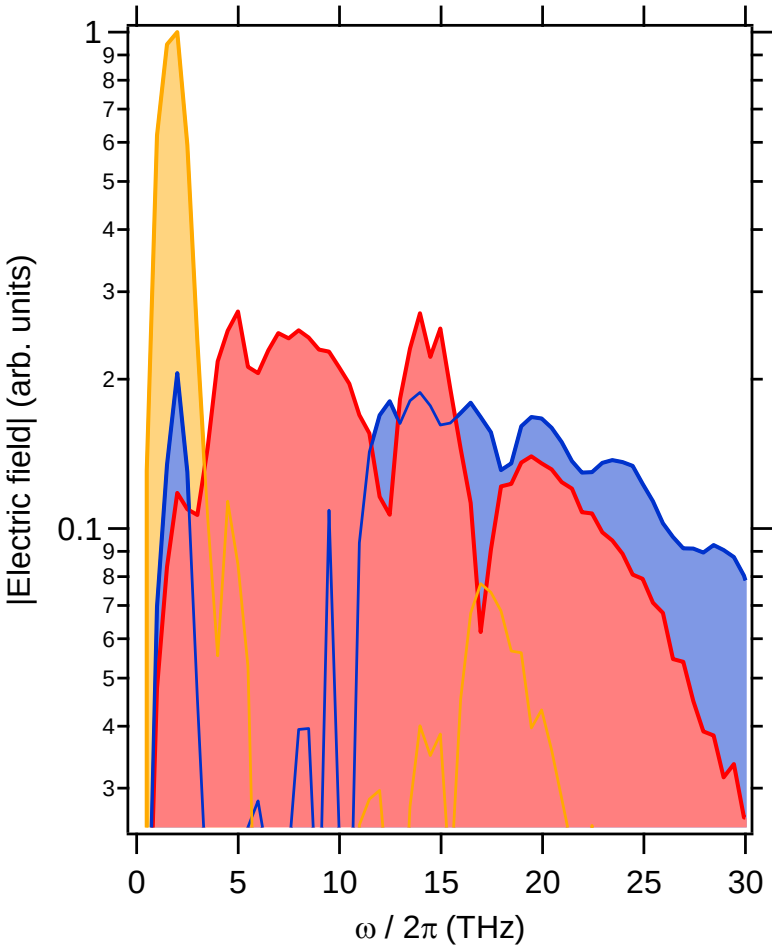
⇒ Simple method to get relative estimates of spin-Hall conductivity

Is CoFeB/Pt useful as a THz emitter?

Spintronic THz emitter

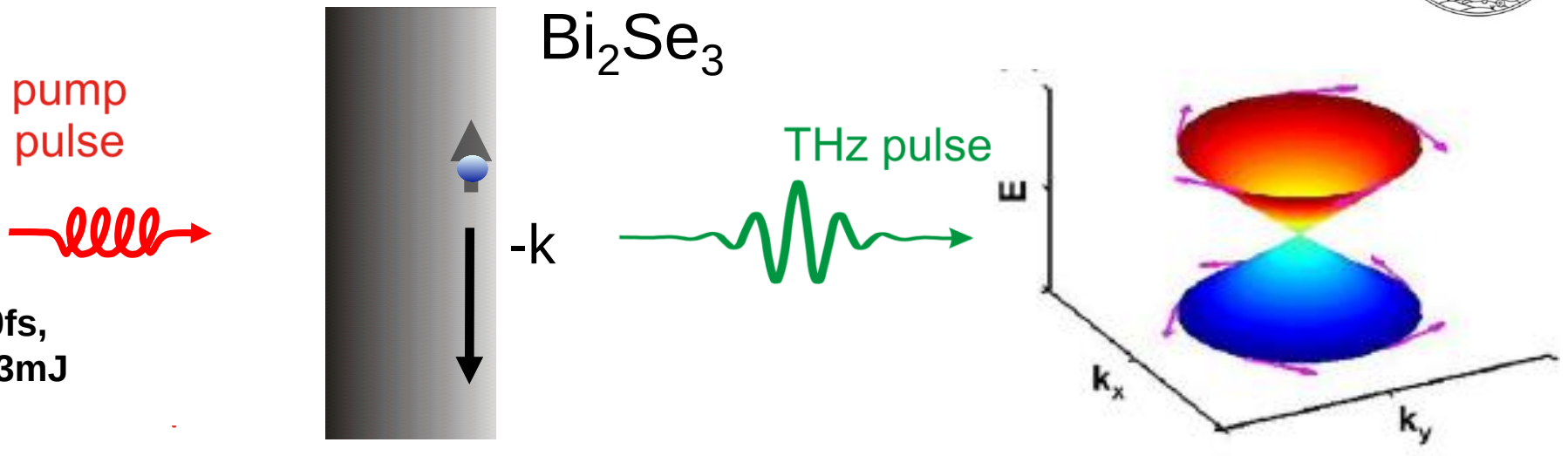
Comparison to standard emitters: Spintronic Emitter (STE), Photoconductive Switch (PCS)



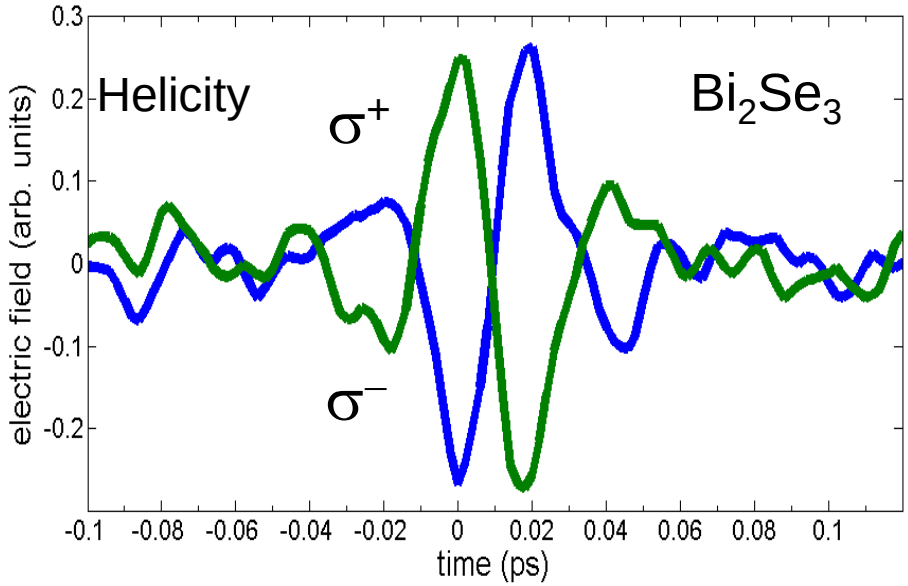


Spintronic metalic emitter outperforms standard emitters over large frequency intervals

Topological matter



- Spin-momentum locking

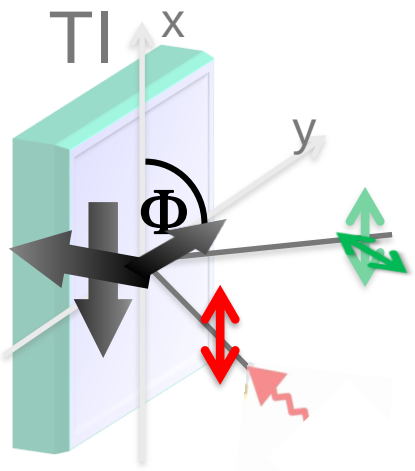


- THz emission is polarization dependent
- Circular photogalvanic effects?

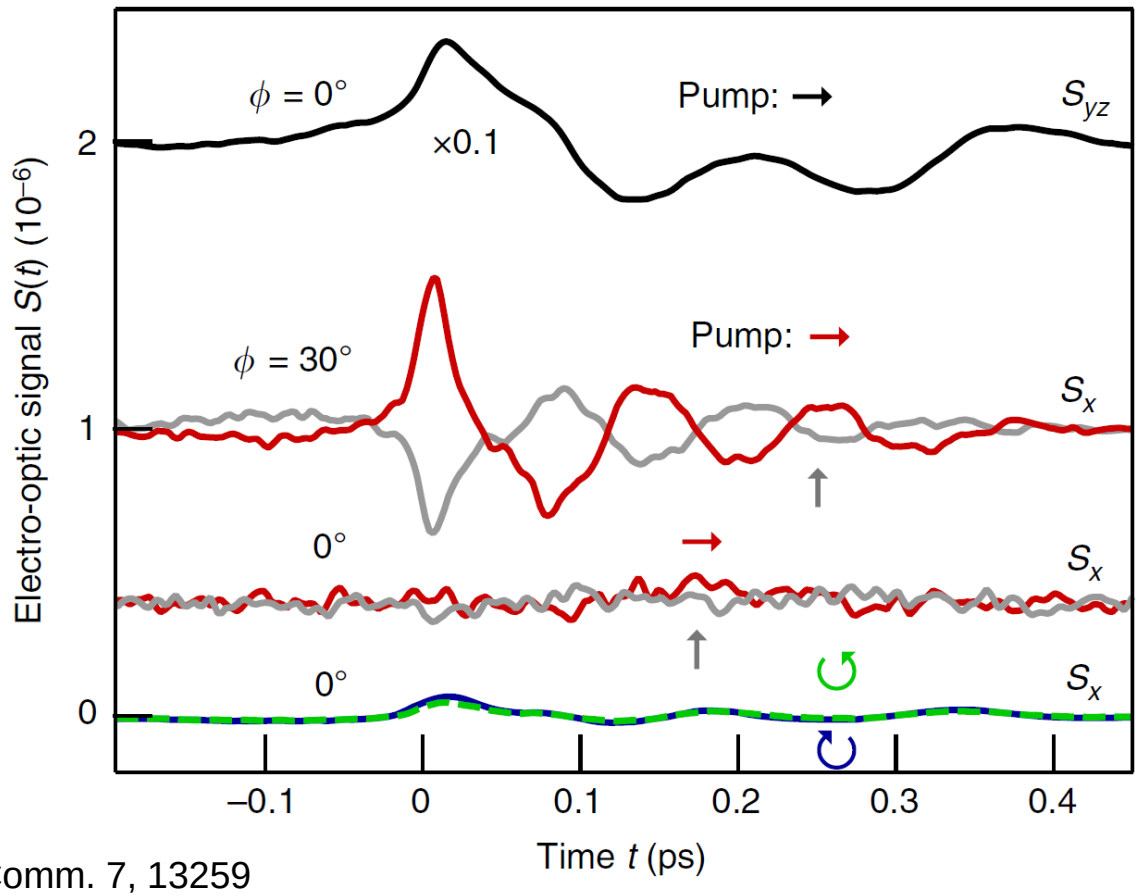
J. W. McIver, et al. Nature Nano.(2011).
Ganichev et al. Nature (2002).
T. Seifert and et al. (2016).

Topological matter

- THz emission



Dependence of pump polarization and sample orientation:
J_S: strongly dependent on both
J_P: independent



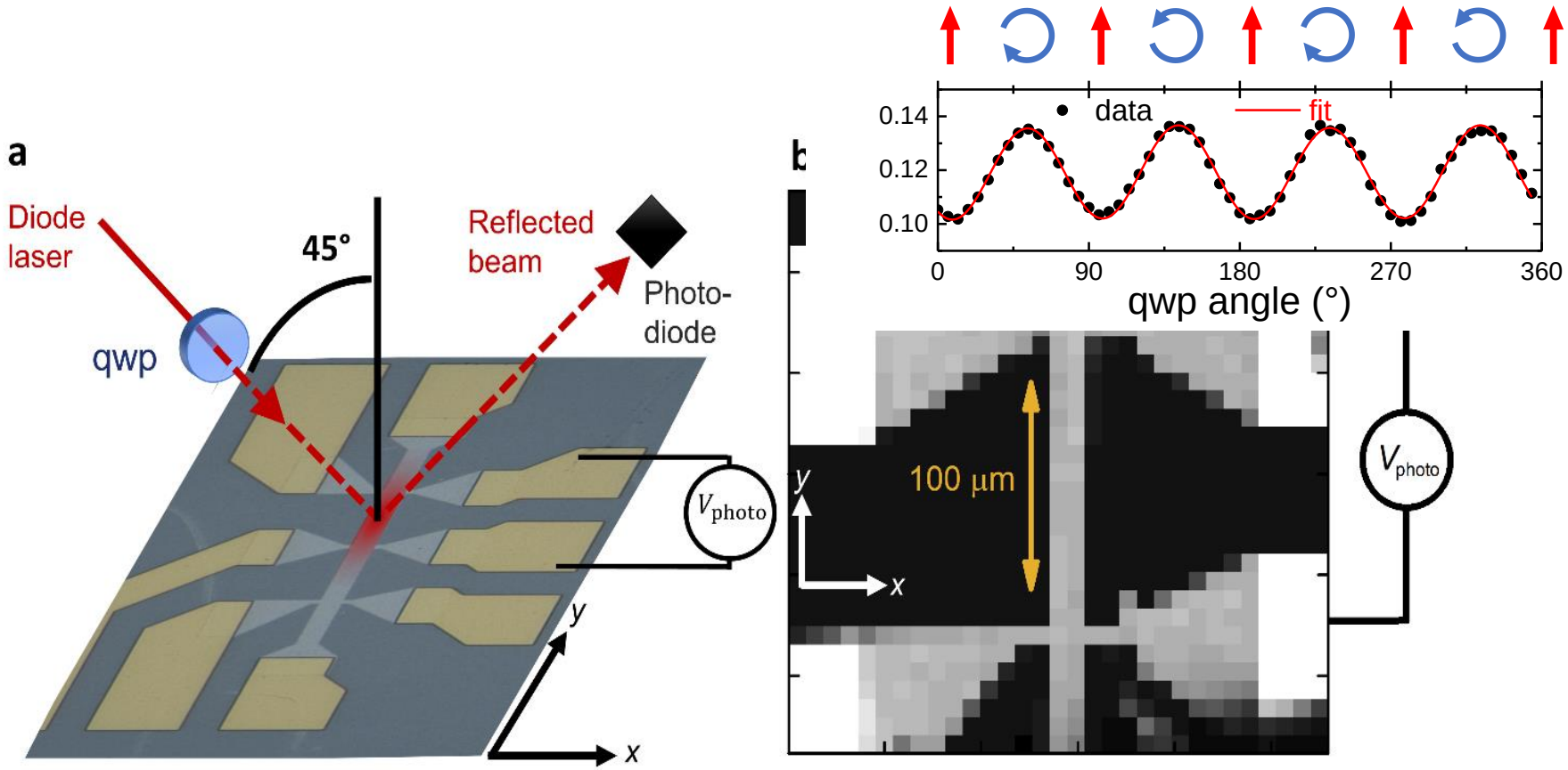
What is the source?

- Use Φ dependence to reduce data (crystal symmetry)

L. Braun, G. Mussler, et al., Nature Comm. 7, 13259 (2016).

Topological matter

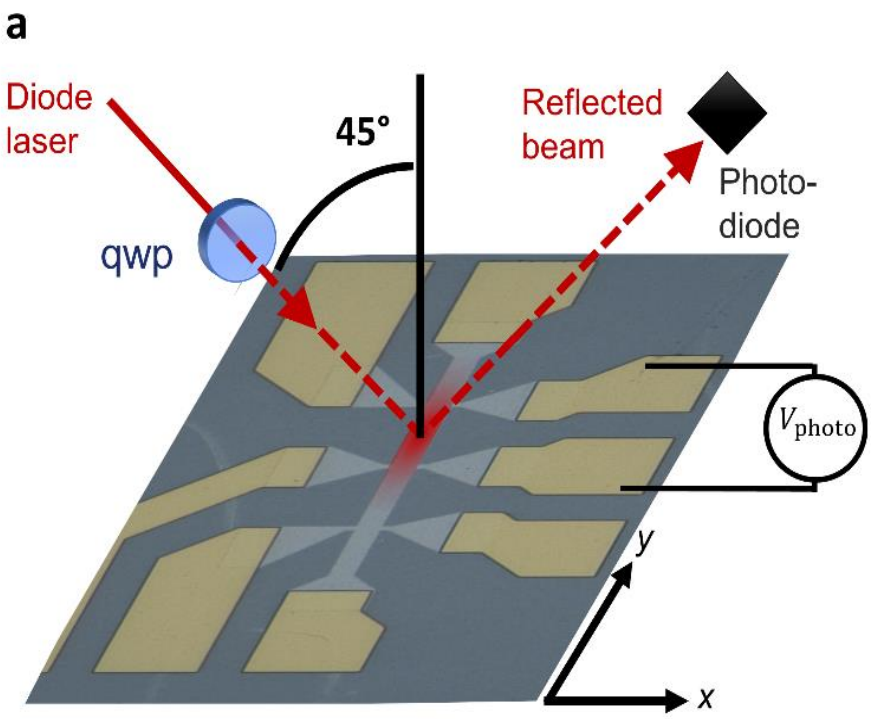
- Circular photogalvanic effect C, thermovoltage D

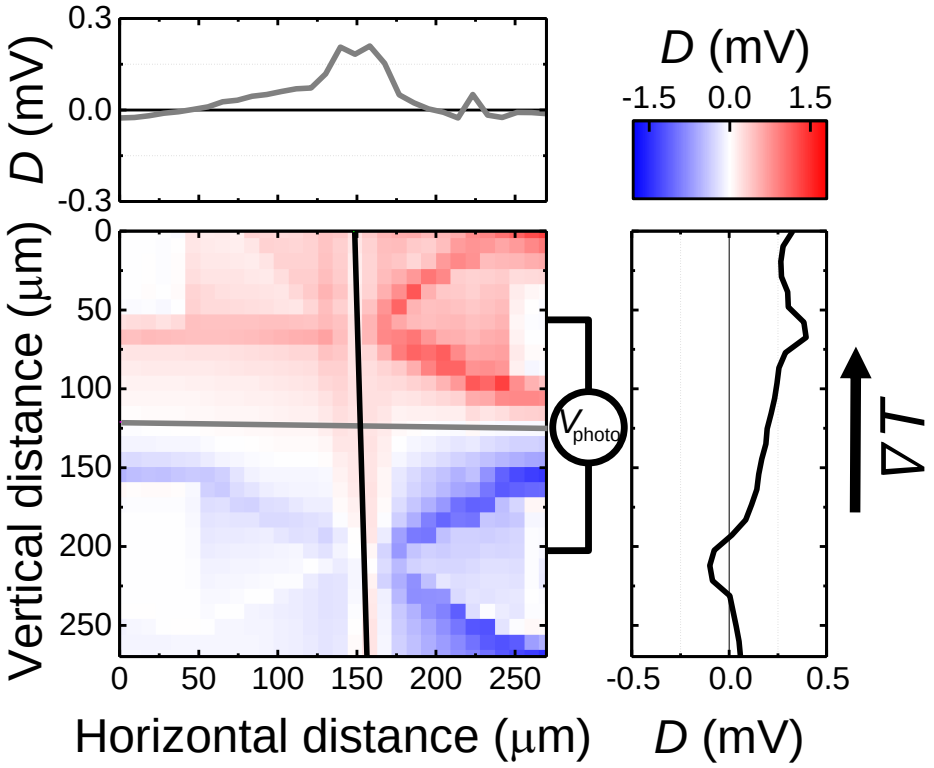


- 3D topological insulator intrinsic doping, 16 nm $(Bi_{0.57}Sb_{0.43})_2Te_3$)

Topological matter

- Circular photogalvanic effect C, thermovoltage D





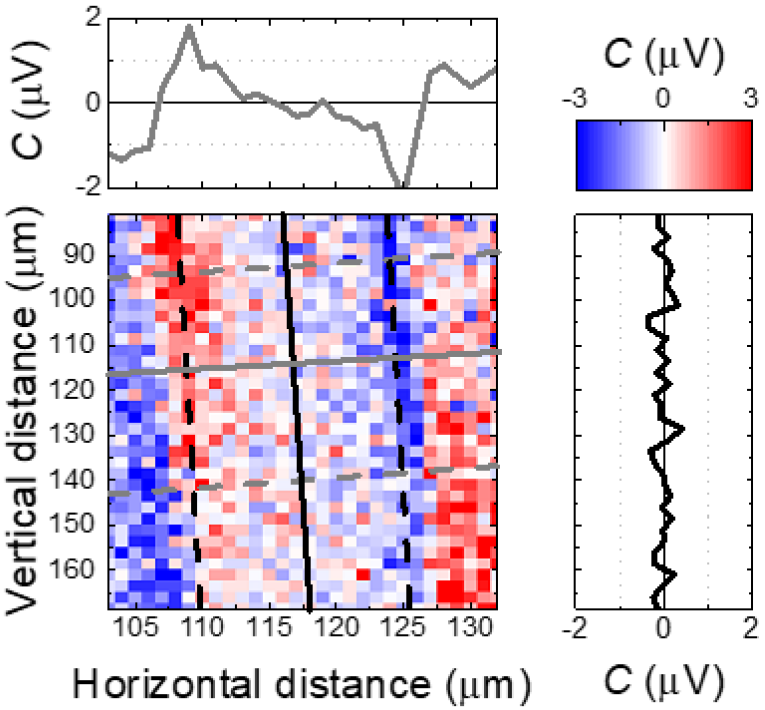
- 3D topological insulator intrinsic doping, 16 nm $(Bi_{0.57}Sb_{0.43})_2Te_3$)

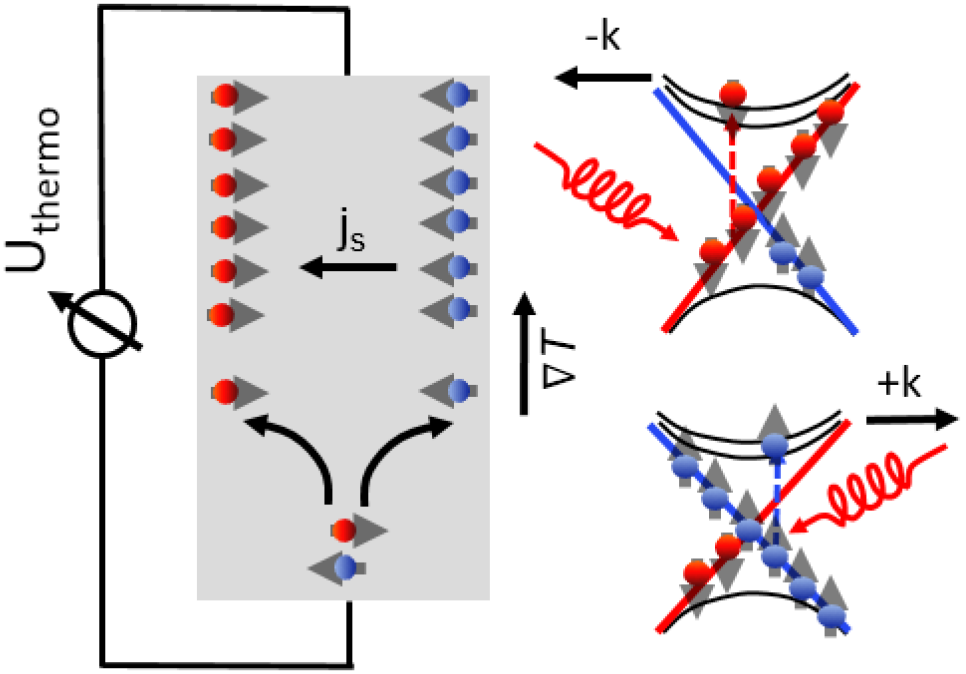
SPP 1666

Topological matter

- Circular photogalvanic effect C, thermovoltage D

Detail: Hall bar





- Spin accumulation by Spin-Nernst effect

See also S. Meyer et al. Nature Materials (2017).

SPP 1666

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FePt optical writing a storage media

- *CSIC, Madrid*

  Thermal macrospin modelling

  Pablo Nieves, Oksana Chubykalo-Fesenko

Oksana Chubykalo-Fesenko

- Western Digital Corporation, San Jose

  FePt storage media

  Simone Pisana, Tiffany Santos

Tiffany Santos

FePt optical writing a storage media

- Kiel University

  MO-Imaging

  Cai Müller, Jeffrey McCord,

Jeffrey McCord

- Uppsala University

  Inverse Faraday

  Marco Berritta, Ritwik Mondal, Peter Oppeneer

Peter Oppeneer

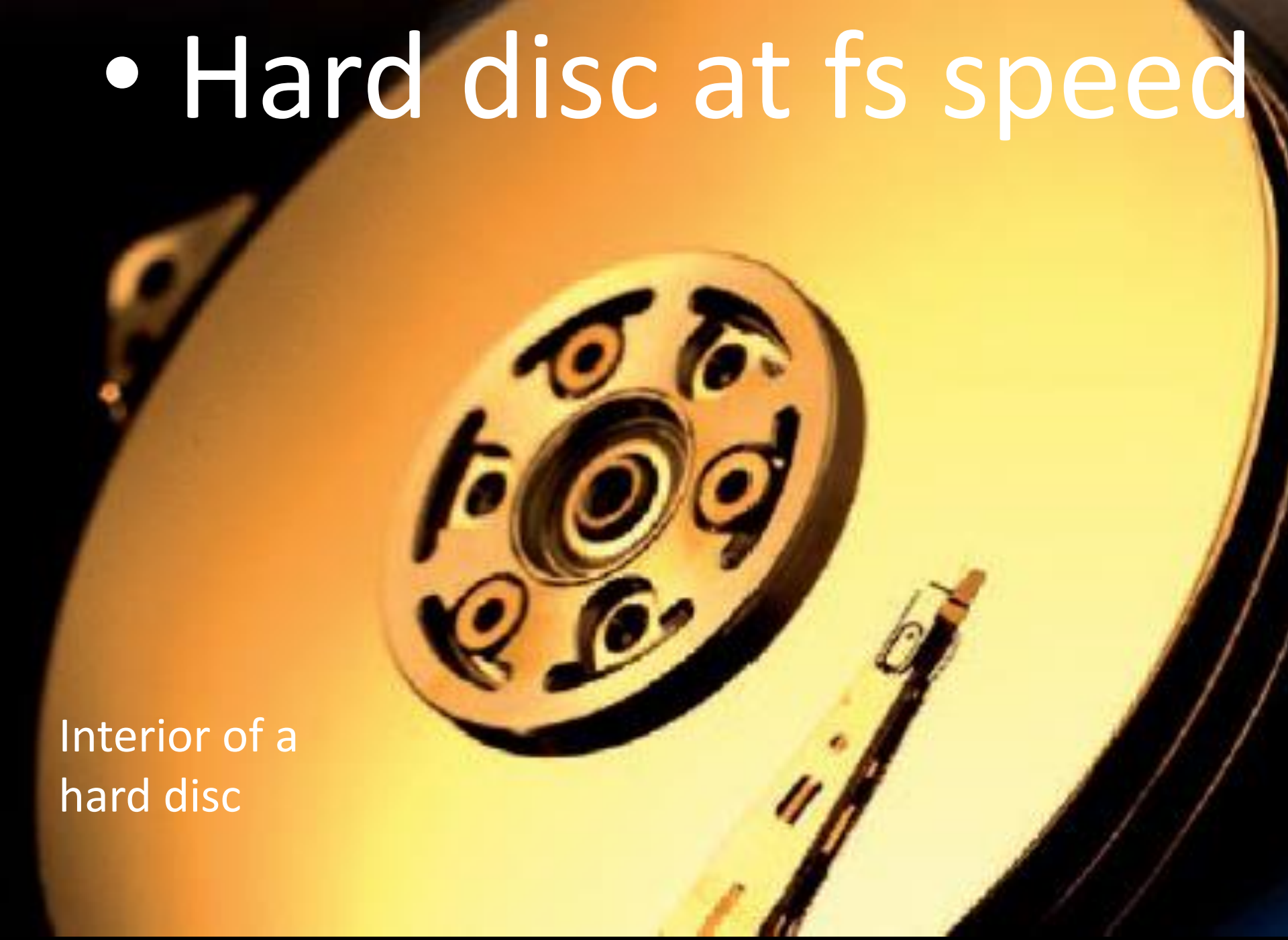
- Konstanz University

  Thermal spin modelling

  Denise Hinzke, Ulrich Nowak

Uli Nowak

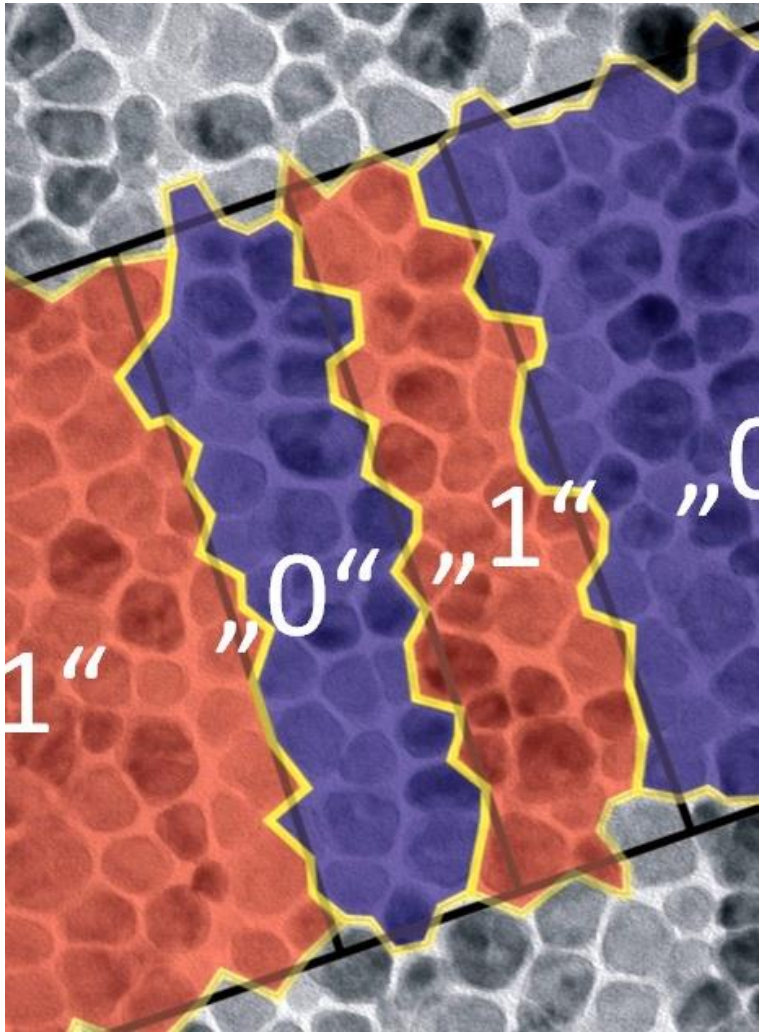
- Hard disc at fs speed

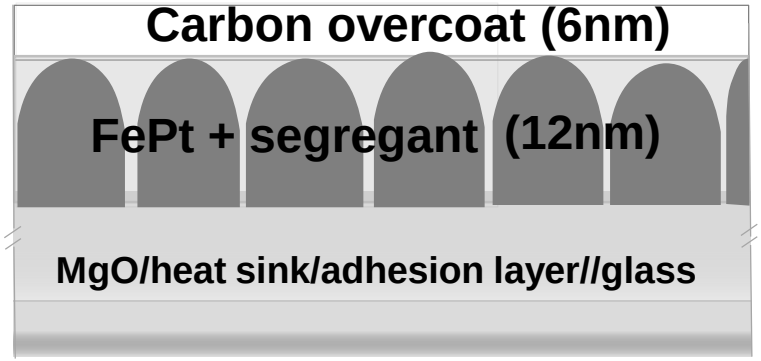


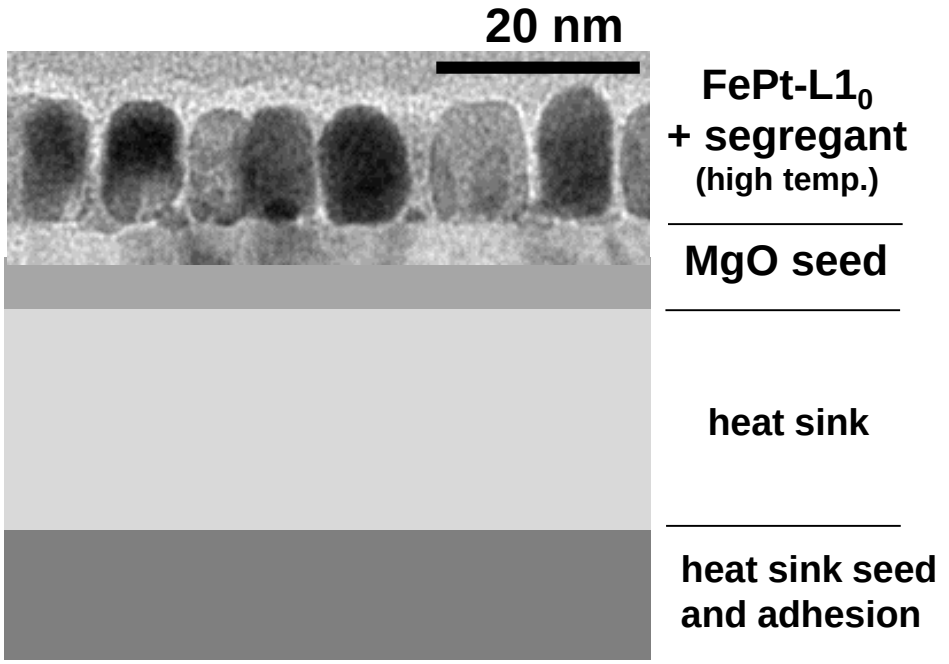
Interior of a hard disc

Hard disc at ultrafast speed

Western Digital Corporation HAMR media, H_C= 4T at room temperature

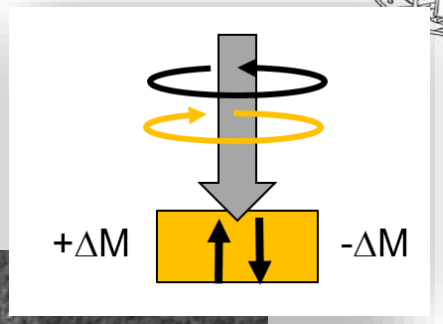




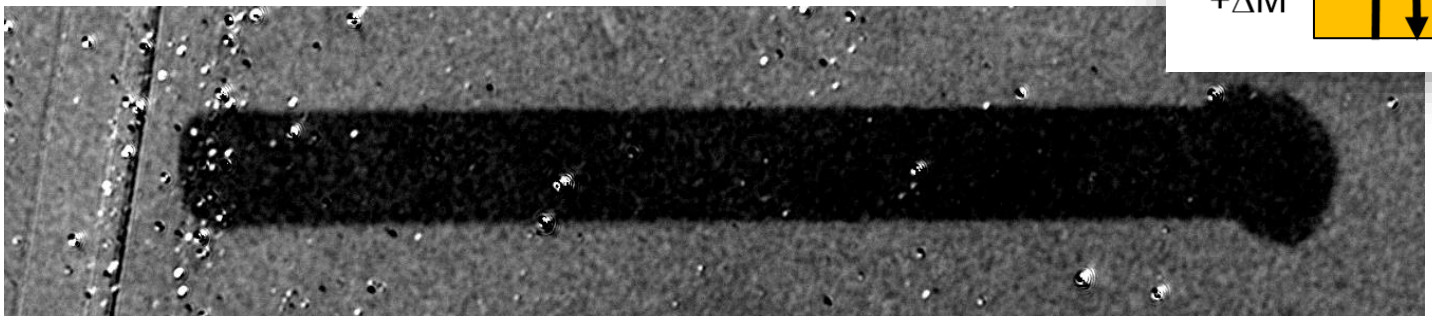


FePt optical writing a storage media

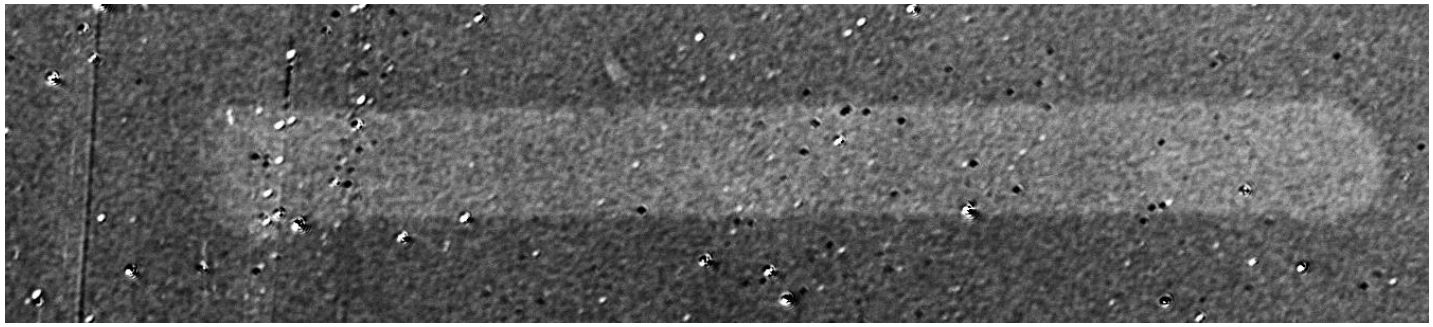
Writing using the helicity of light:



σ-



σ+



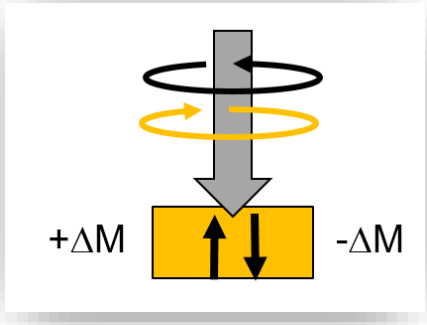
12.7 mJ/cm^2 (10 mW)

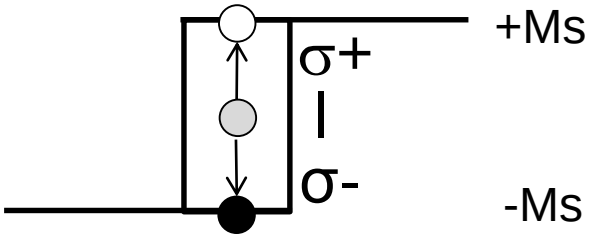
Magneto-optical contrast (Kerr microscopy)
FePt (AgCu) granular recording media

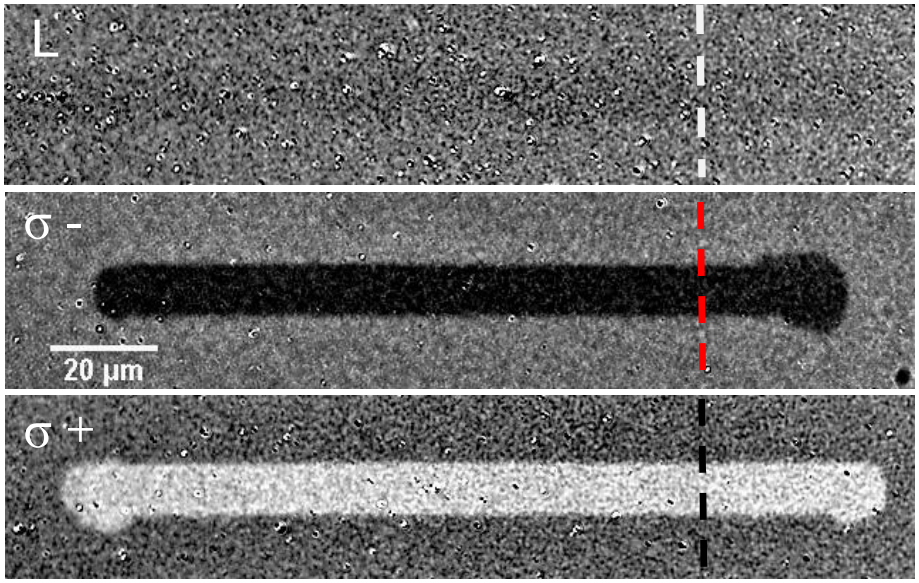
R. John, P. M. Oppeneer, U. Nowak, and M. Münzenberg, Sci. Rep. 7, 4114 (2017)

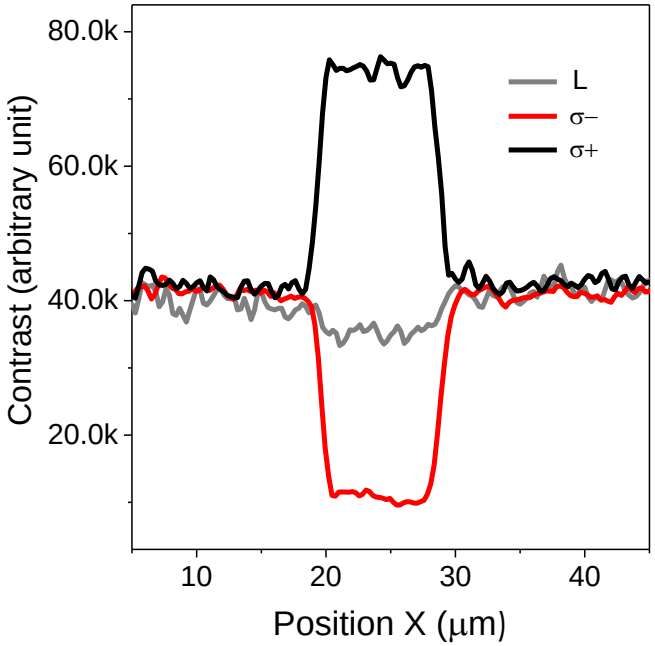
FePt optical writing a storage media

Starting with remnant magnetization 0% Ms after growth:





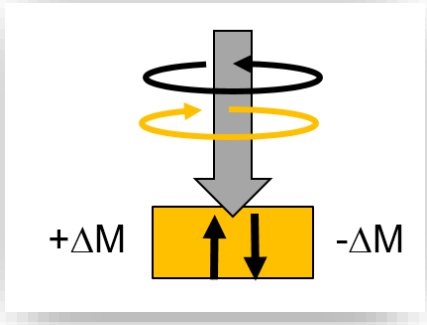


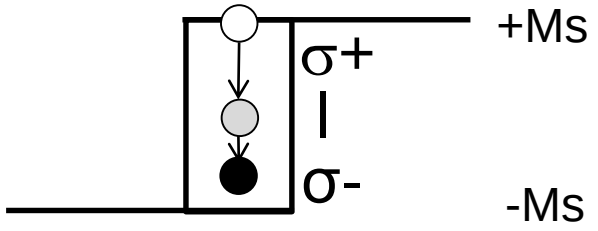


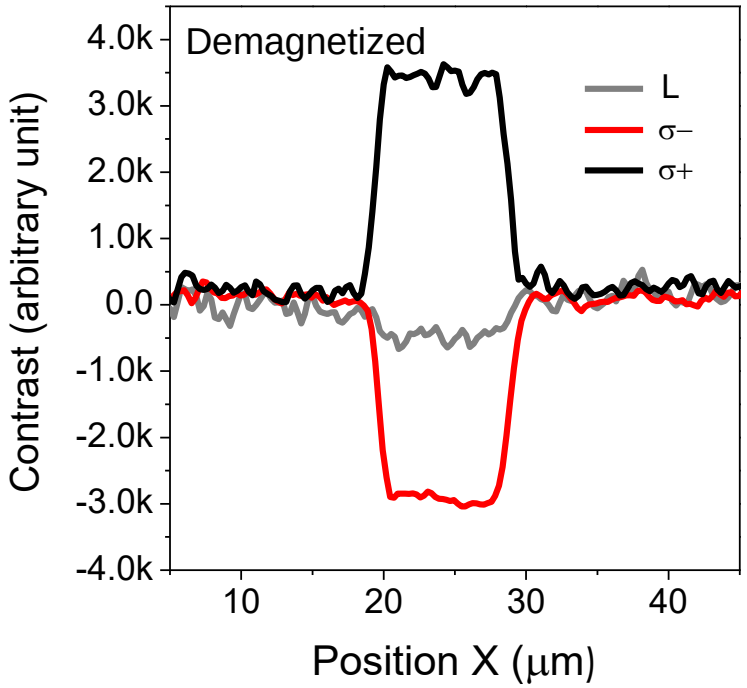
7.5 mW (6.6 mJ/cm^2 per pulse)

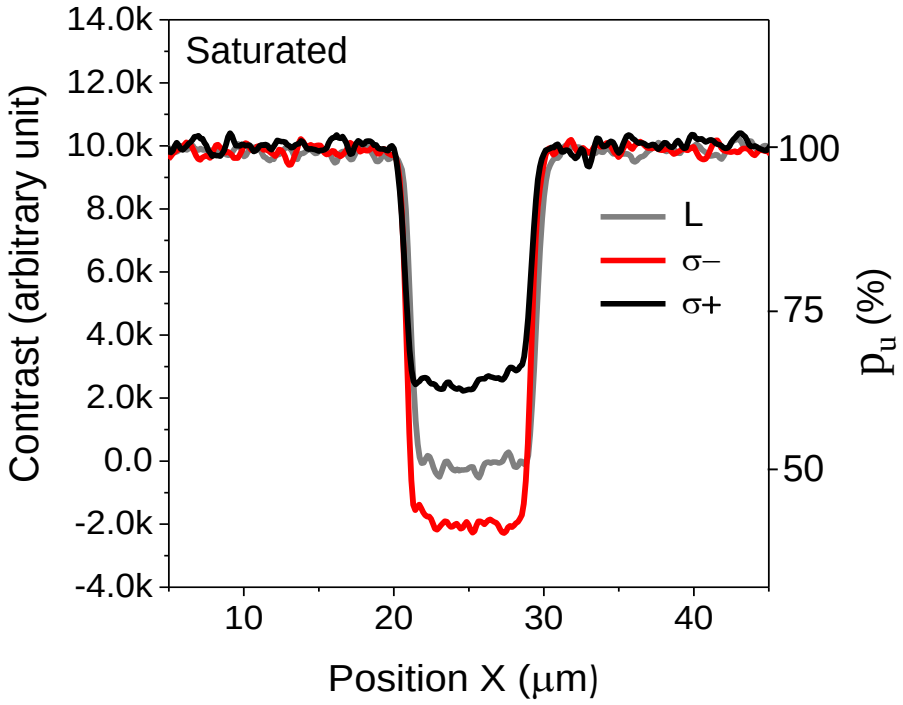
FePt optical writing a storage media

Starting with magnetization 100% Ms, saturated case:









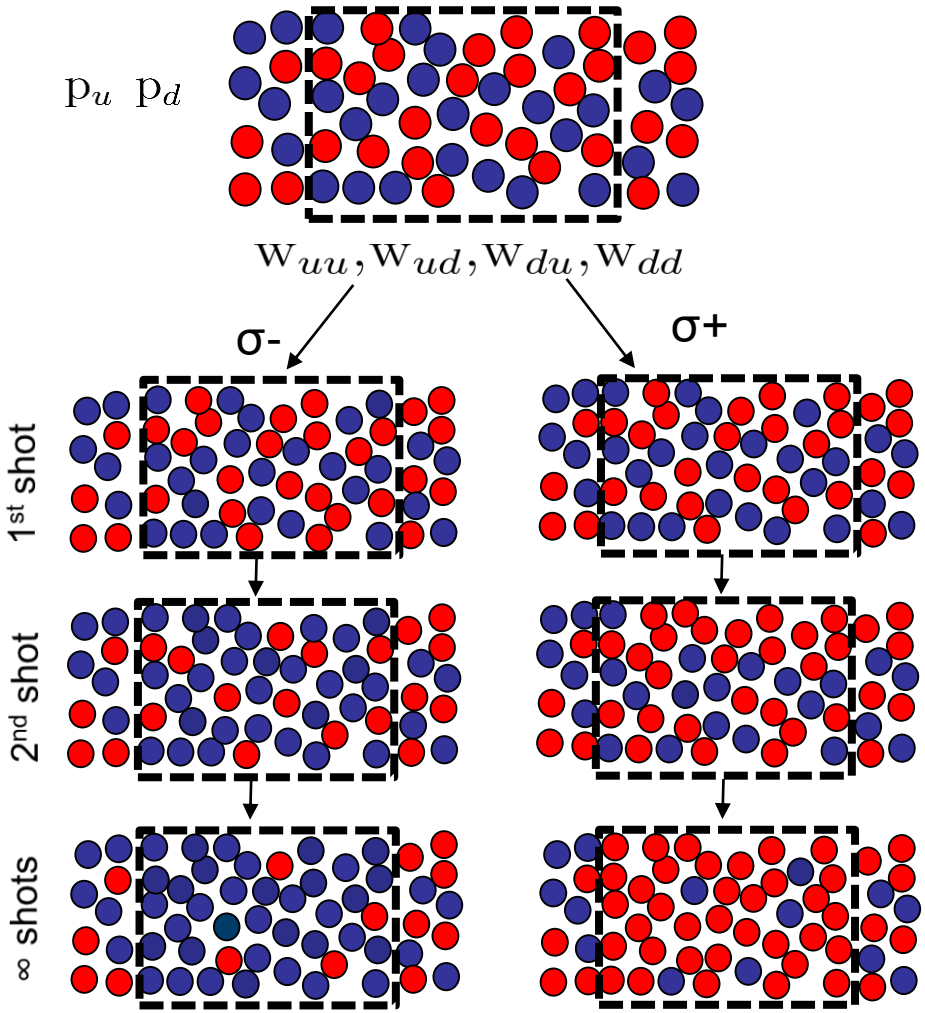
No full writing! What is the mechanism?

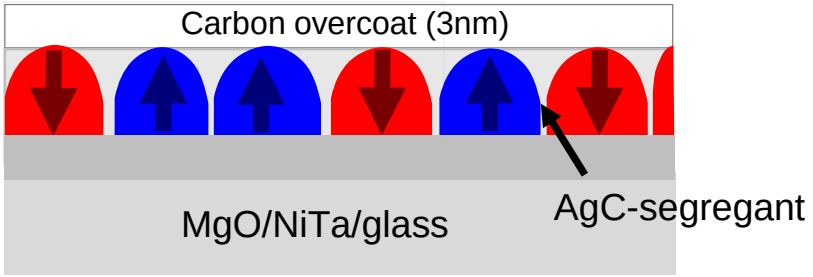
15 mW (13.2 mJ/cm^2 per pulse)

FePt optical writing a storage media

- **Model to describe the data:**

Transition rates $w_{uu}, w_{ud}, w_{du}, w_{dd}$





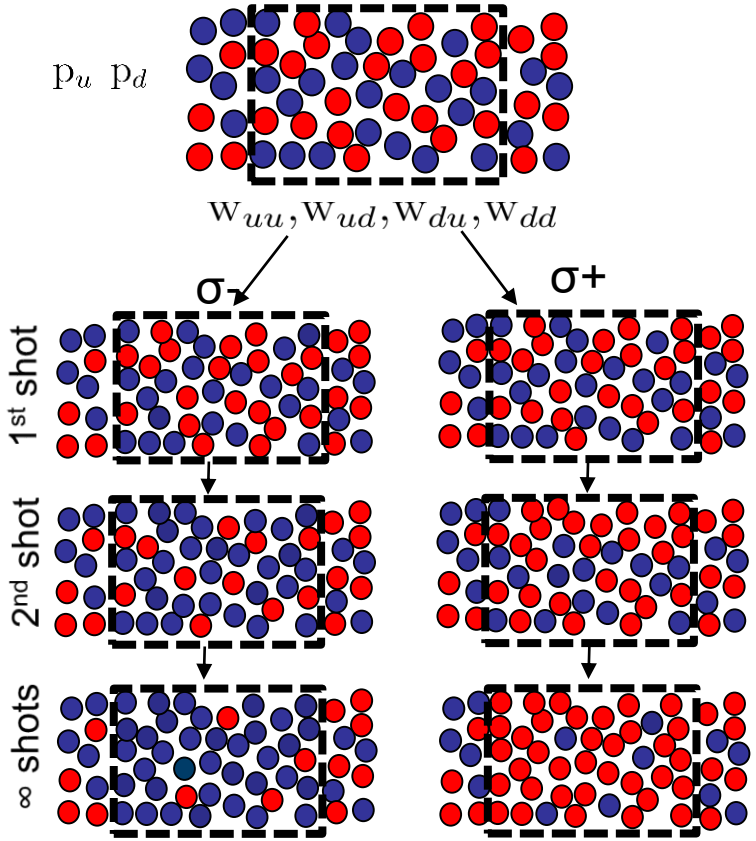
Laser writing region

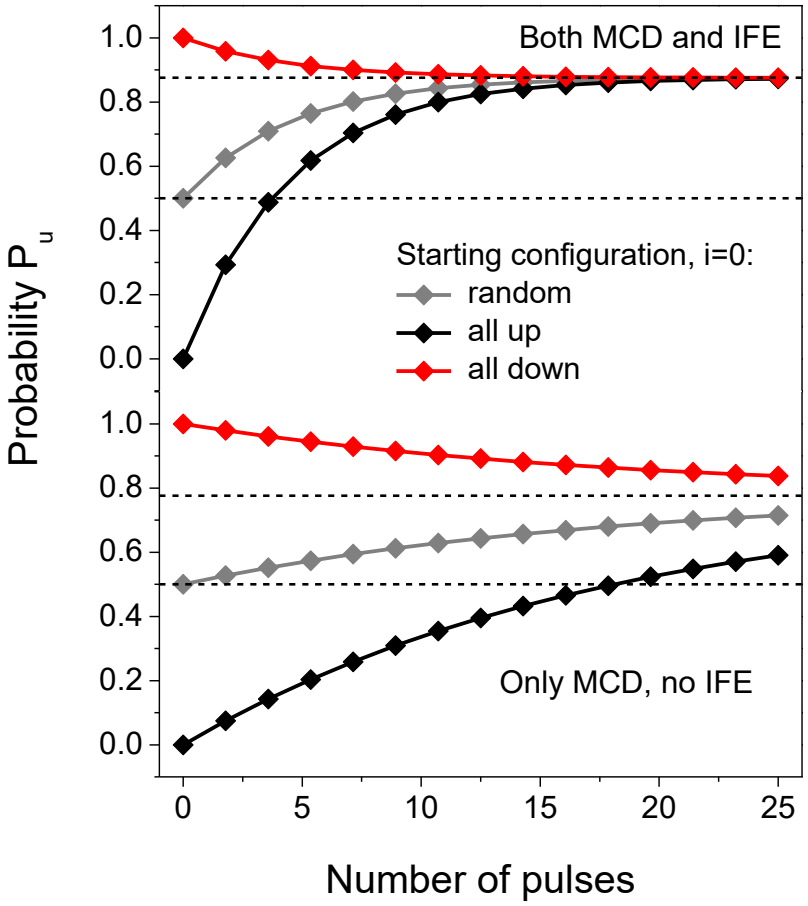
FePt optical writing a storage media

- **Model to describe the data:**

Transition rates $w_{uu}, w_{ud}, w_{du}, w_{dd}$

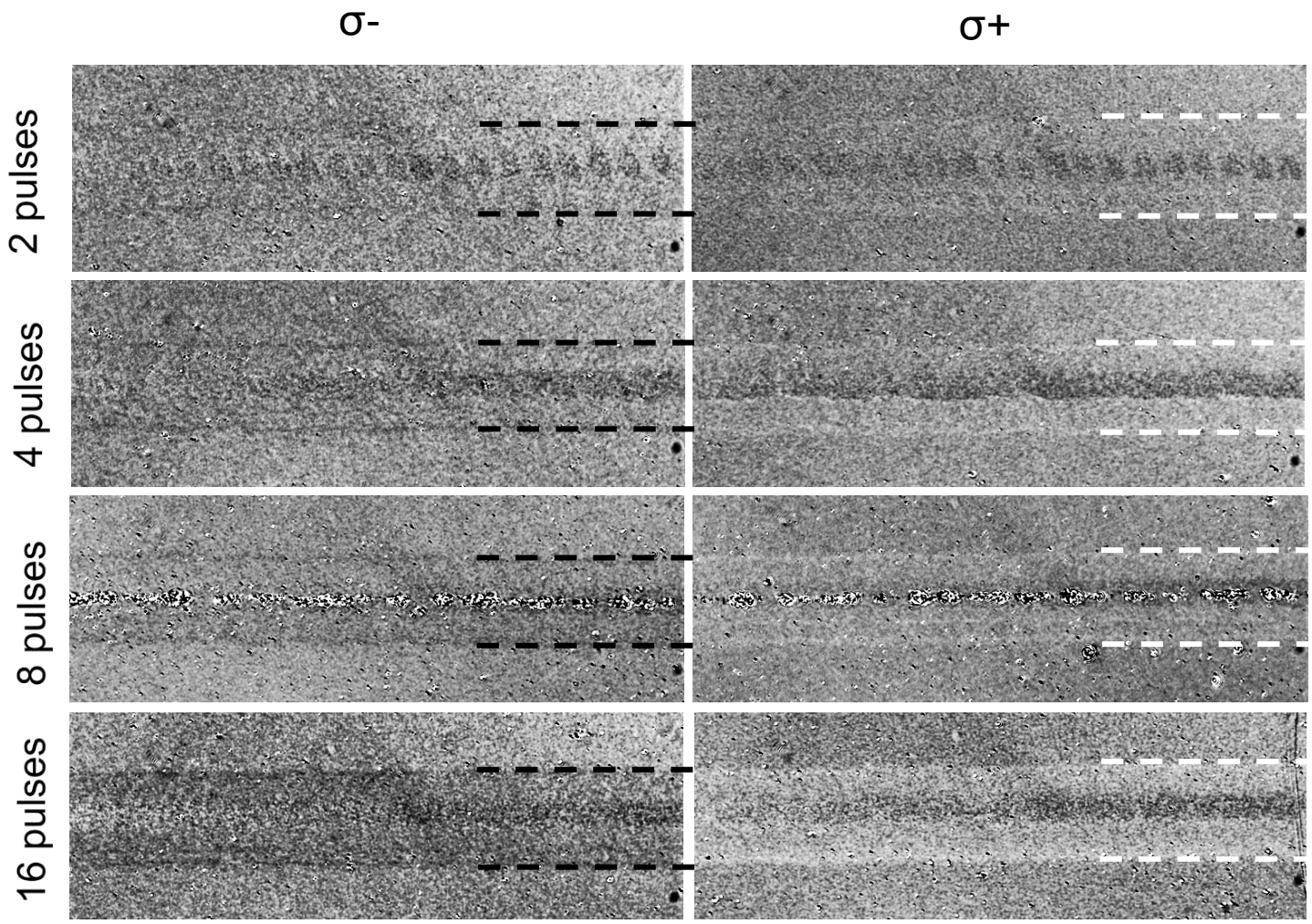
$$p_u(n \to \infty) = \frac{w_{du}}{w_{ud} + w_{du}}$$





FePt optical writing a storage media

- FePt (AgCu) granular recording media: single/ multiple pulse writing



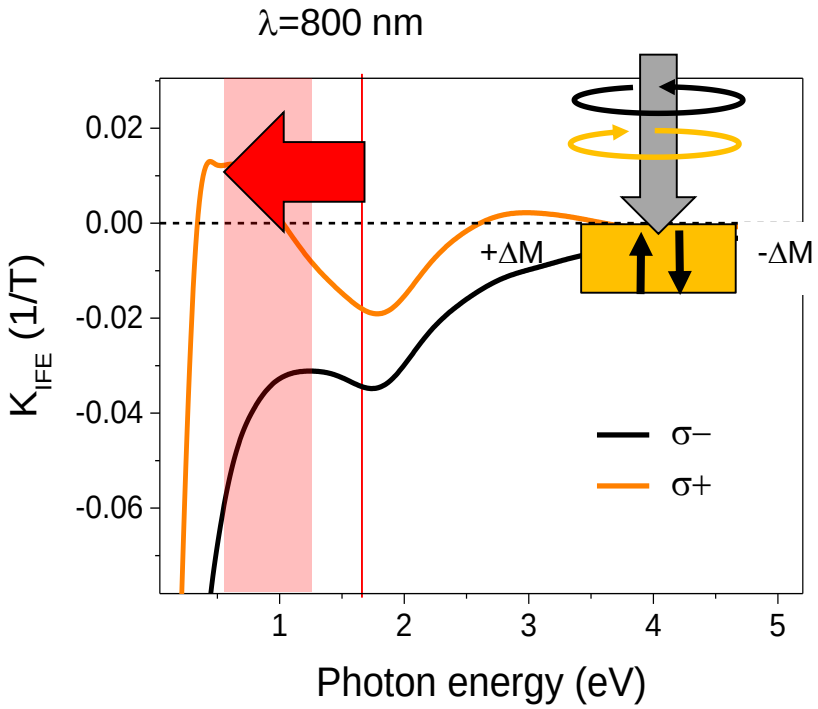
5 mW (30 mJ/cm^2 per pulse)

FePt optical writing a storage media

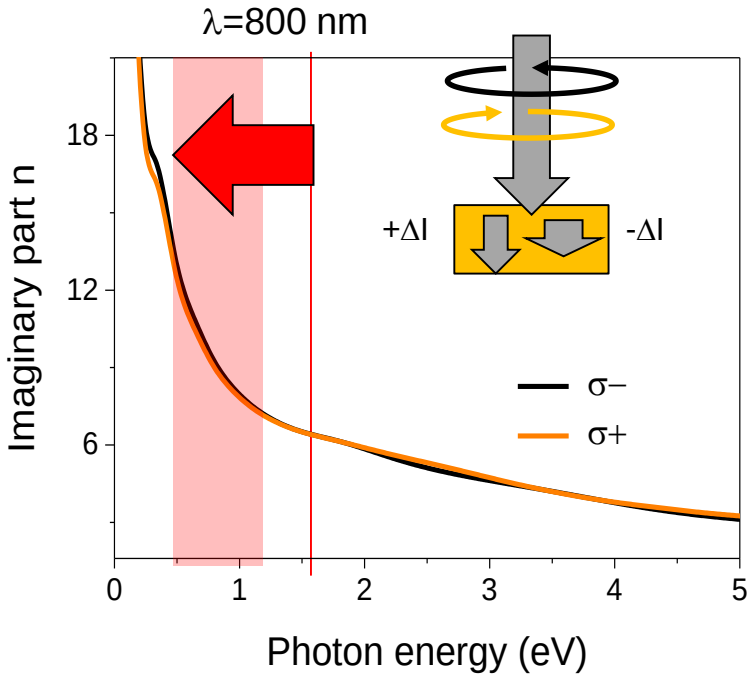
- **What about the wave lenght dependence?**

Inverse Faraday effect (IFE)

1200 nm to 1350 nm, 1.03 to 0.92 eV

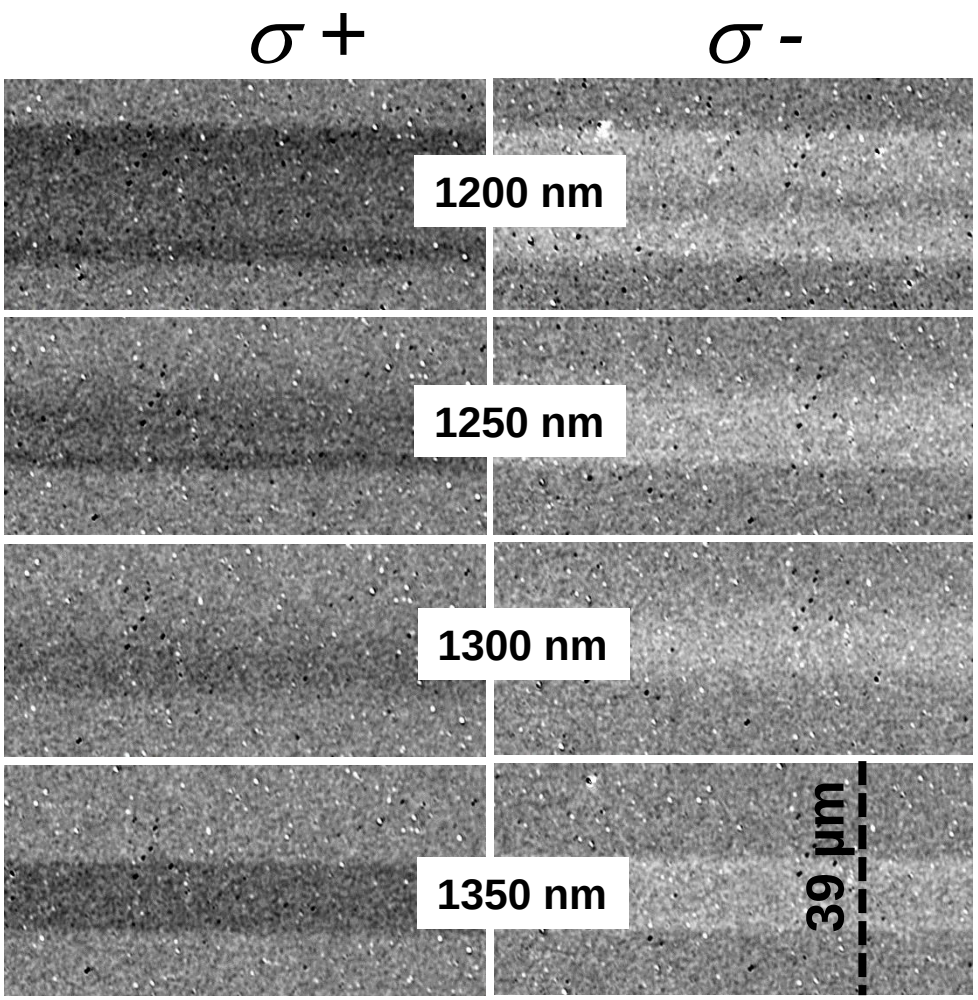


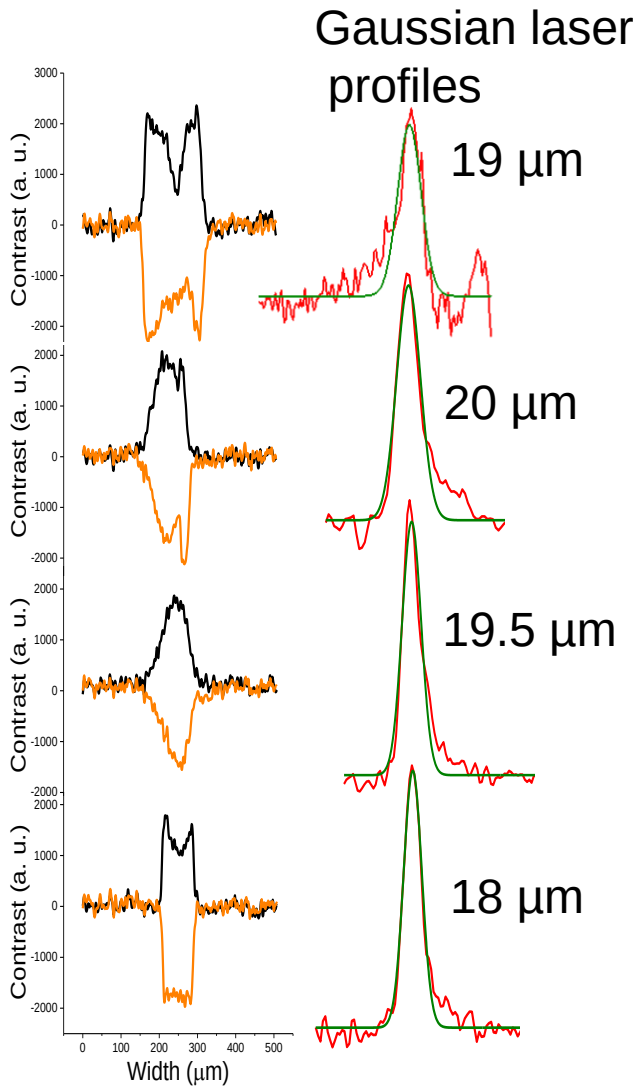
Magnetic circular dichroism (MCD)



FePt optical writing a storage media

- **What about the wave lenght dependence?**





Writing efficiency can be increased by a factor of two to three.

Glassy vortex networks

- What about topological objects?

Glassy vortex networks

- *Göttingen University*

  UTEM developement

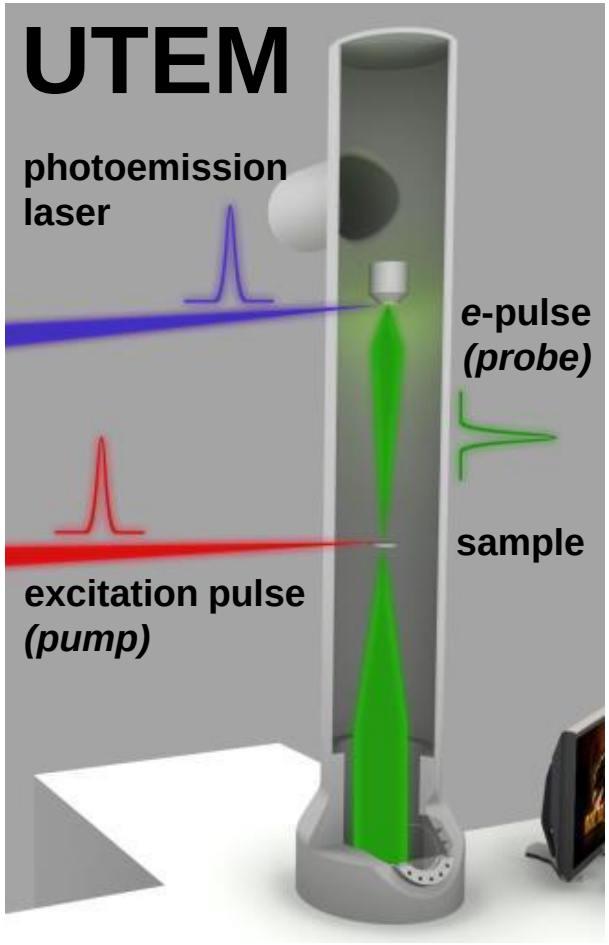
  Tim Eggebrecht, Marcel Möller, Nara Rubiano da Silva, Claus Ropers, Sascha Schäfer

Claus Ropers

Sascha Schäfer

T. Eggebrecht, et al., Phys. Rev. Lett. 118, 097203 (2017).

Glassy vortex networks



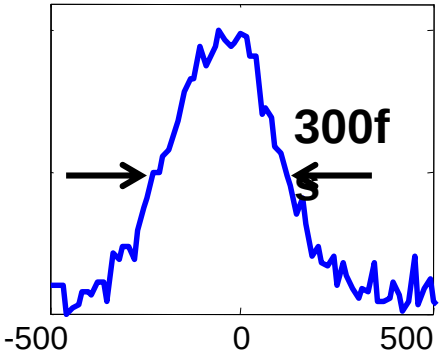
Imaging / Diffraction / Spectroscopy

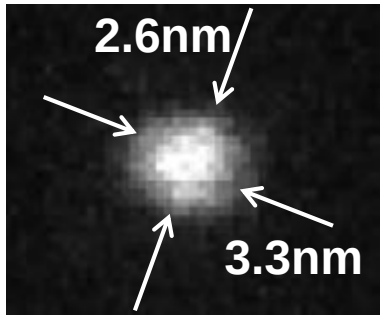
Ultrafast Transmission Electron Microscopy

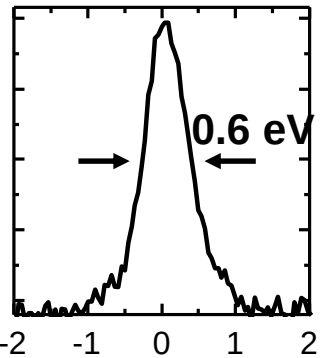
Principle

- photoemission from needle shaped emitter
- Laser-pump/electron-probe experiments

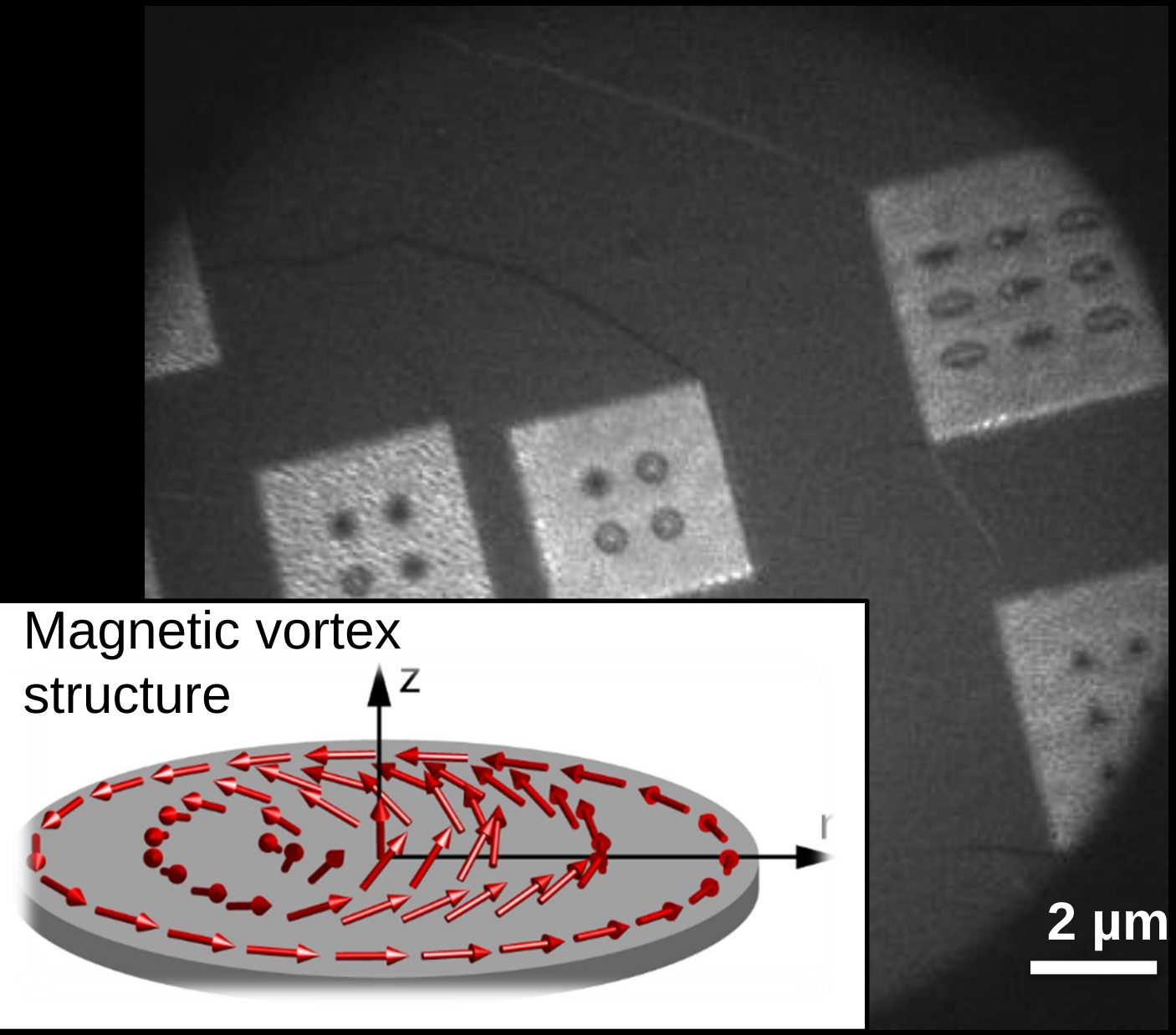
Temporal/spatial/spectral electron pulse properties







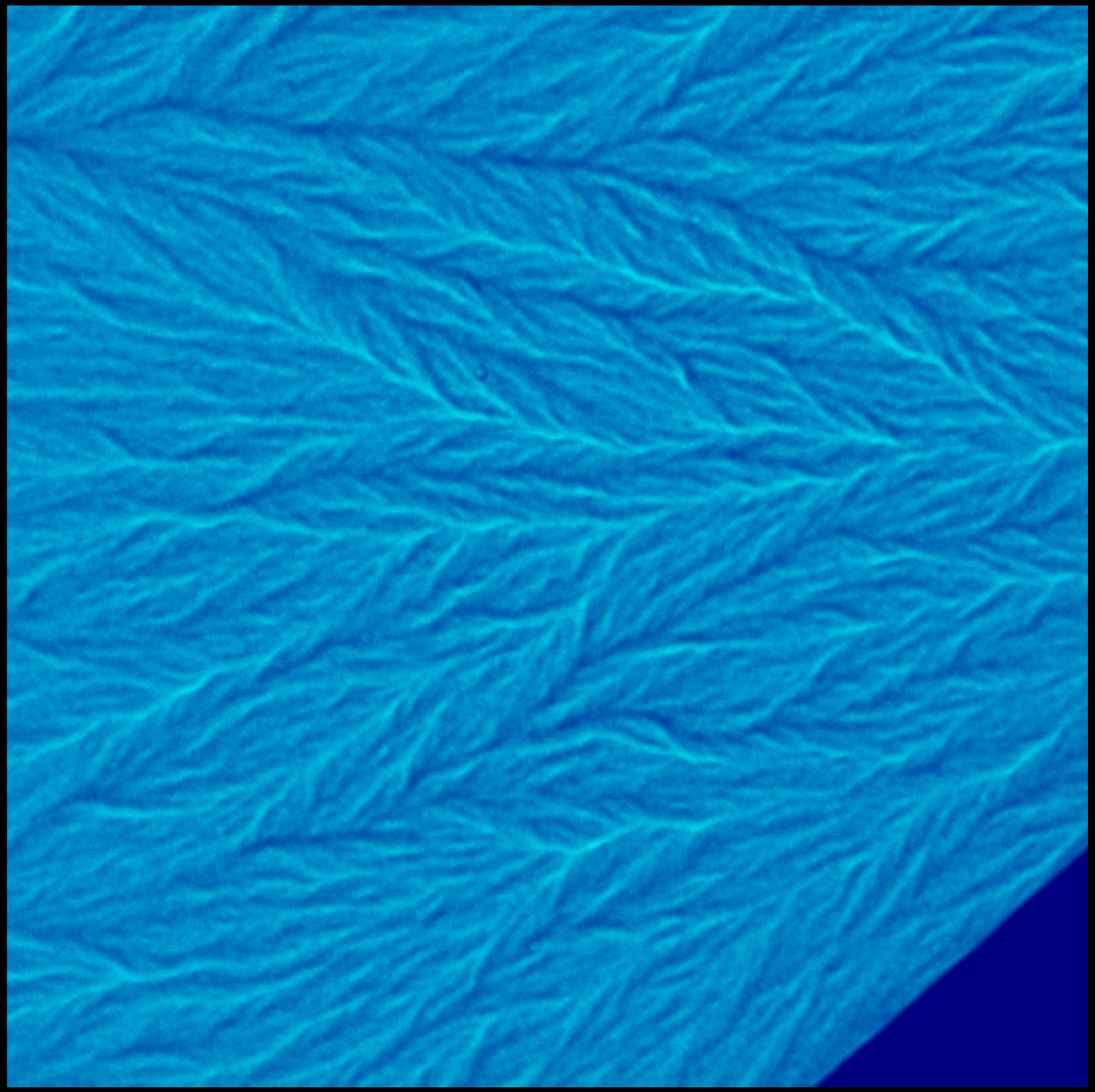
Lorentz imaging with ultrashort electron pulses



- permalloy thin film on silicon-nitride membrane
- FIB patterned magentic nano islands

Δf < 0
Out-of-focus
(add. magnetic contrast)

Imaging conditions
- 1.5 e^-/pulse
- 250 kHz rep. rate, 60 s exposure
- Total electron number: 2×10^7 e^-



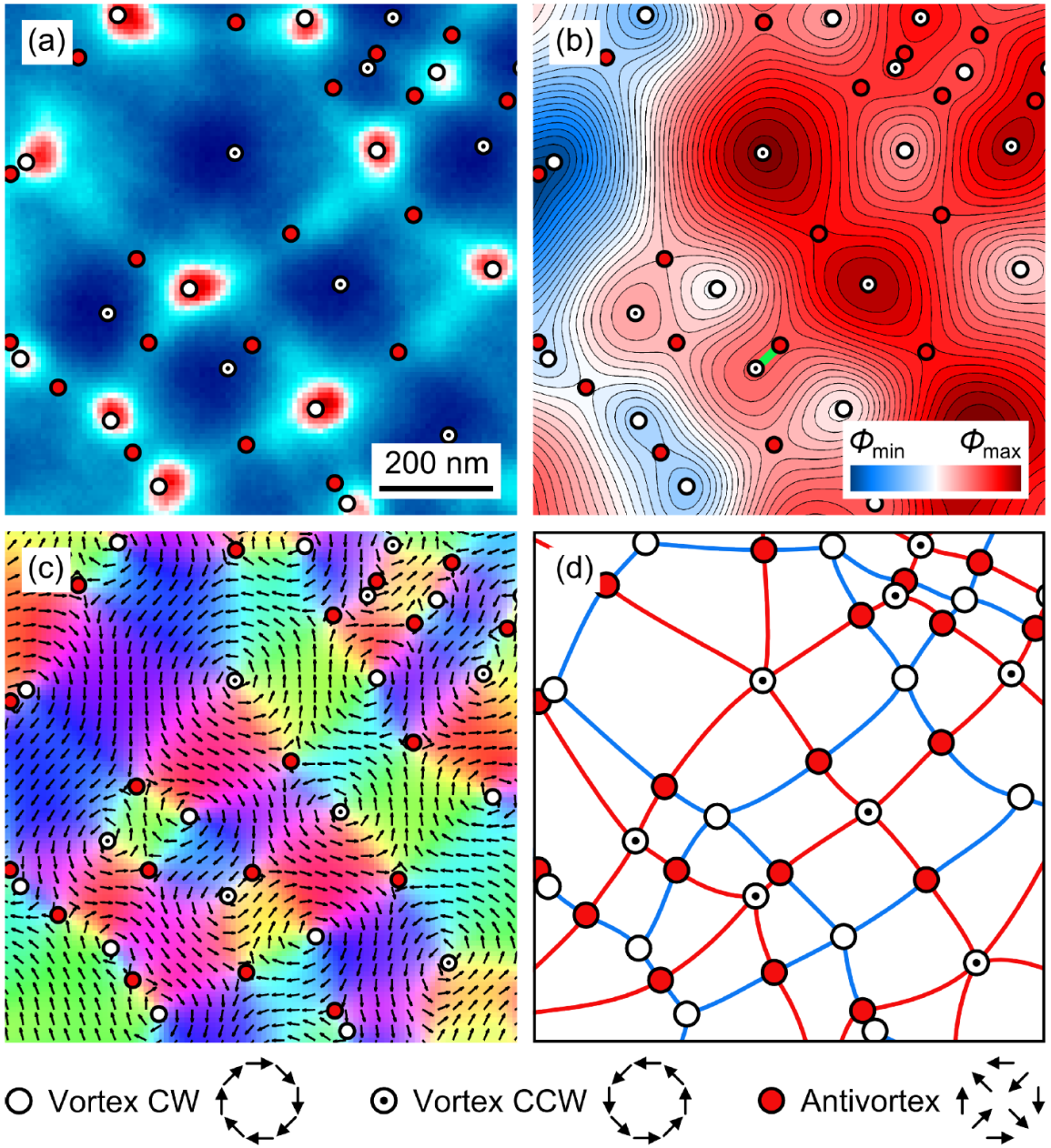
Writing of vortex networks

Electron intensity

Phase

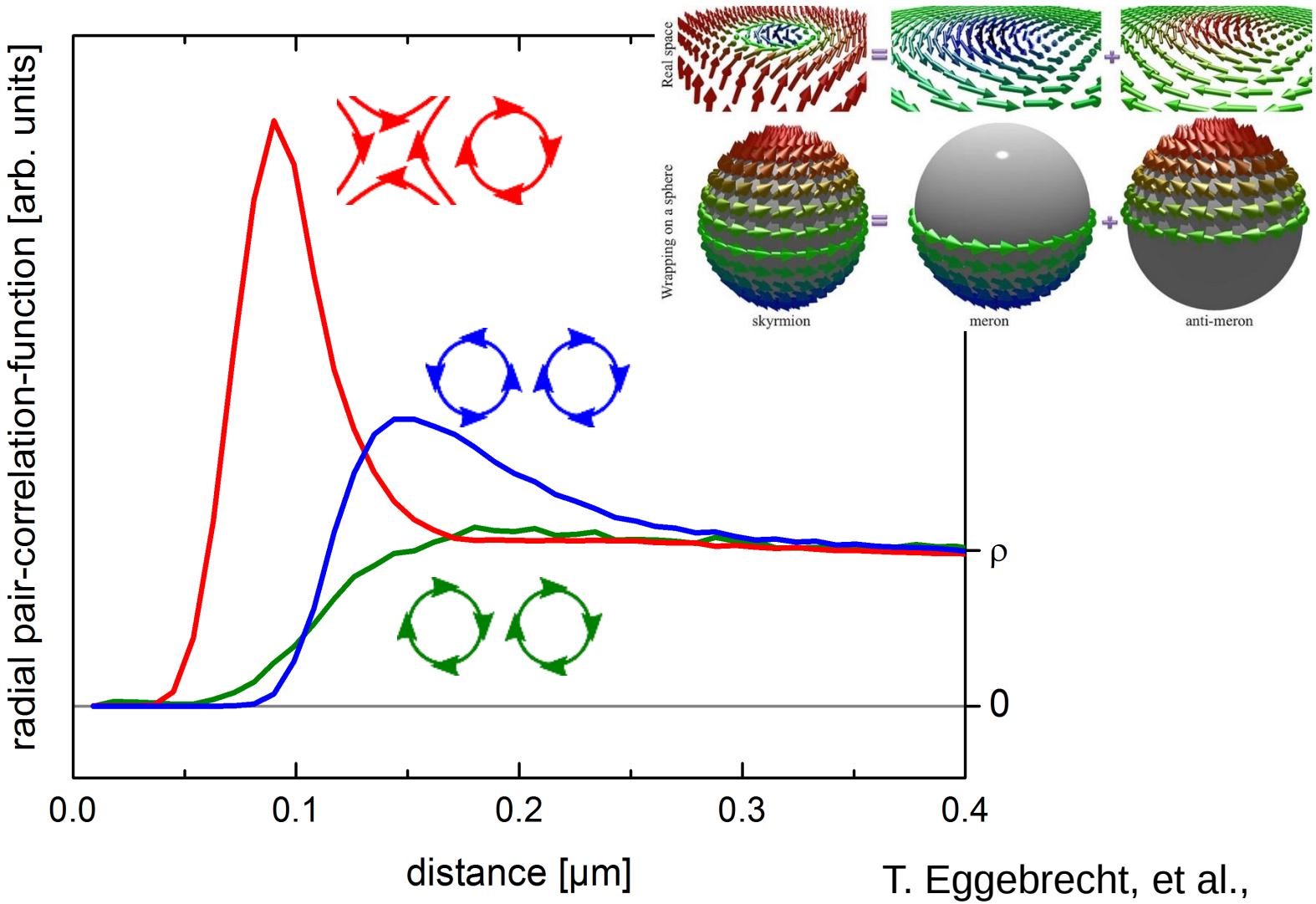
Magneti -zation

Network



Writing of vortex networks

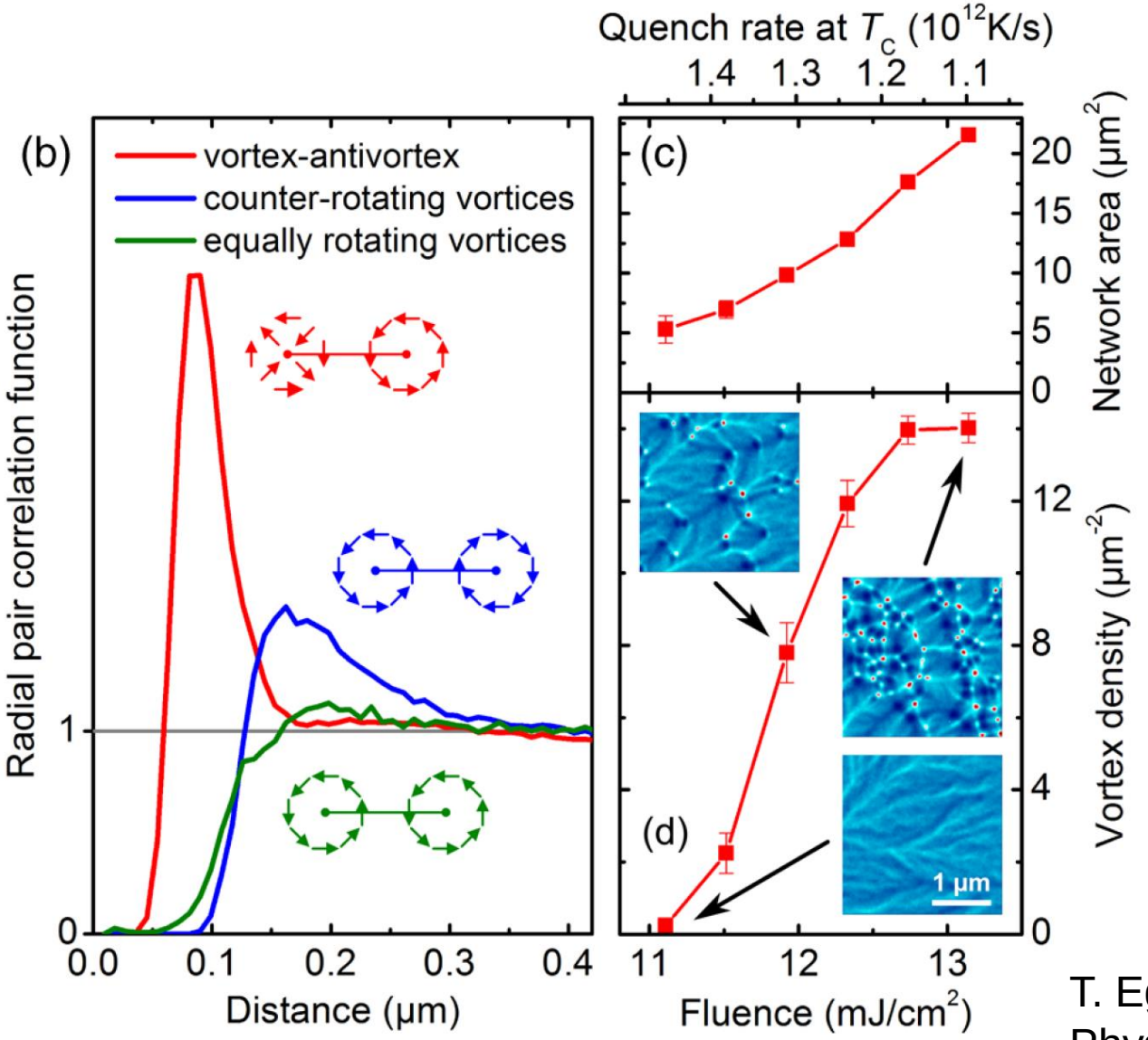
Well defined network that depends on the quench rate



T. Eggebrecht, et al.,
Phys. Rev. Lett., 2017.

Writing of vortex networks

Well defined network that depends on the quench rate



T. Eggebrecht, et al., Phys. Rev. Lett., 2017.

Skyrmion-Bubbles

- Kiel University

  MO-Imaging

  Enno Lage, Jeffrey McCord,

Jeffrey McCord

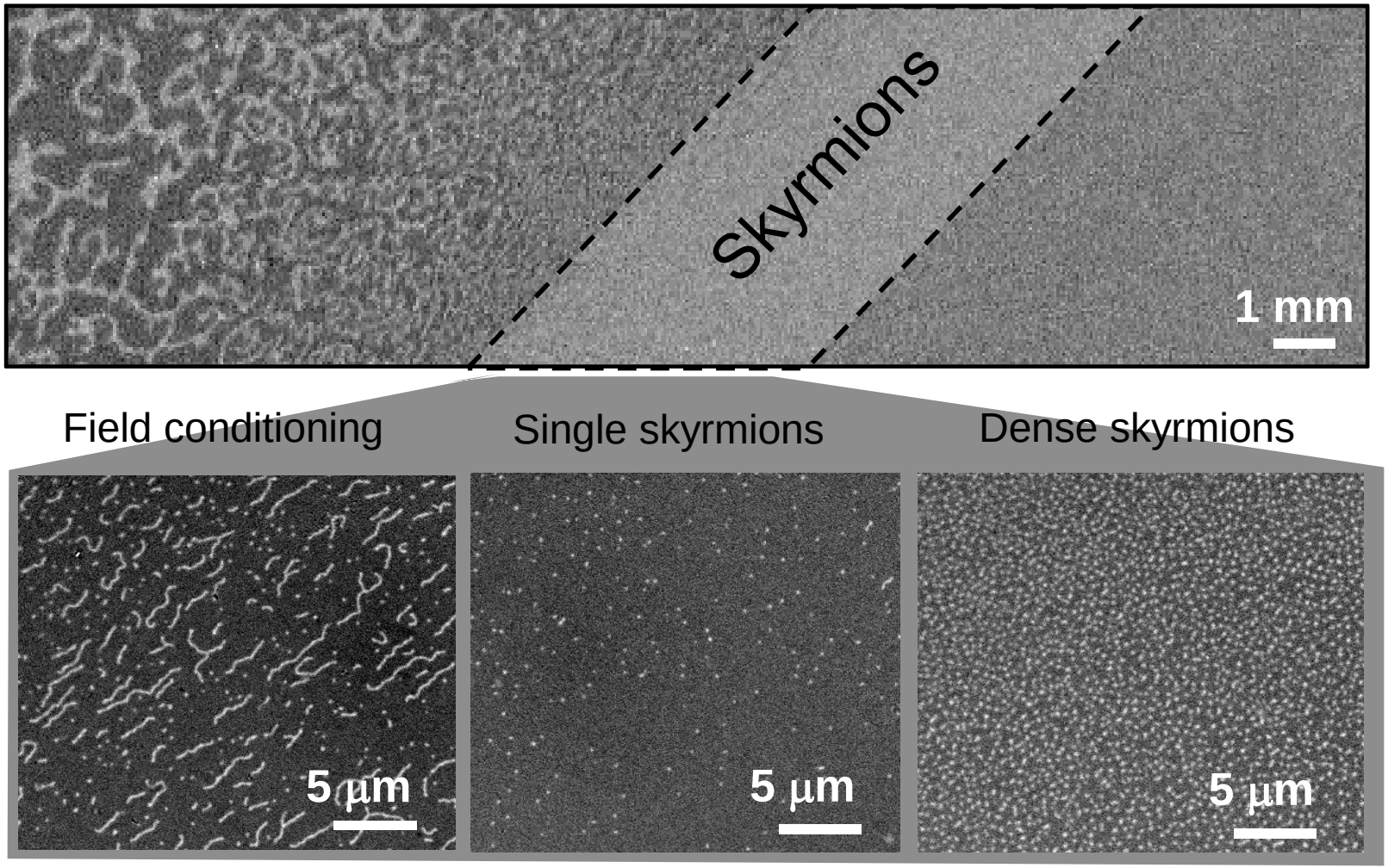
- Konstanz University

  Ulrich Nowak

Uli Nowak

Writing of vortex networks

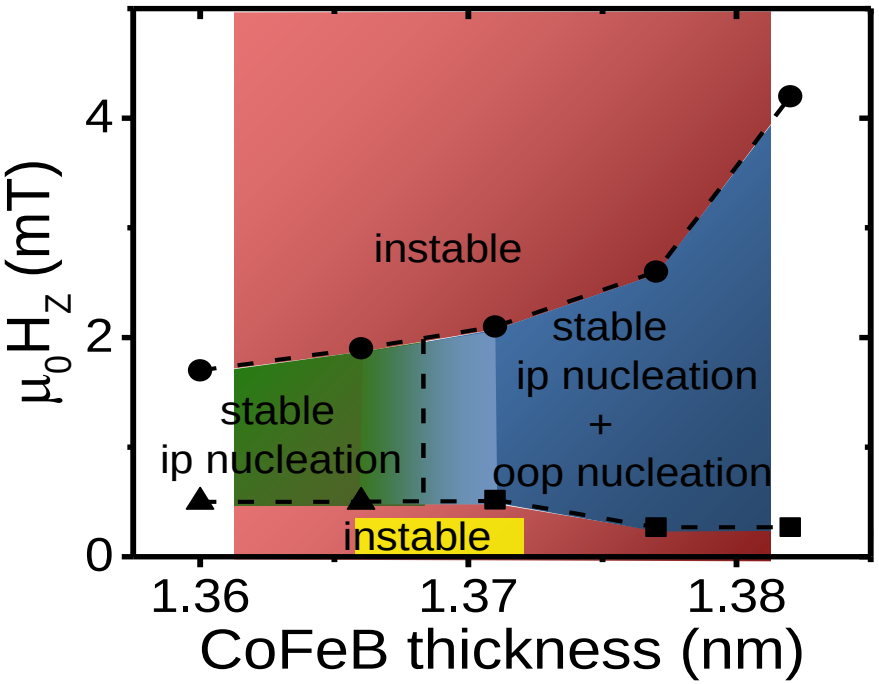
Ta/CoFeB/MgO layer wedge system



- Skyrmions with diameters below 200 nm, DMI

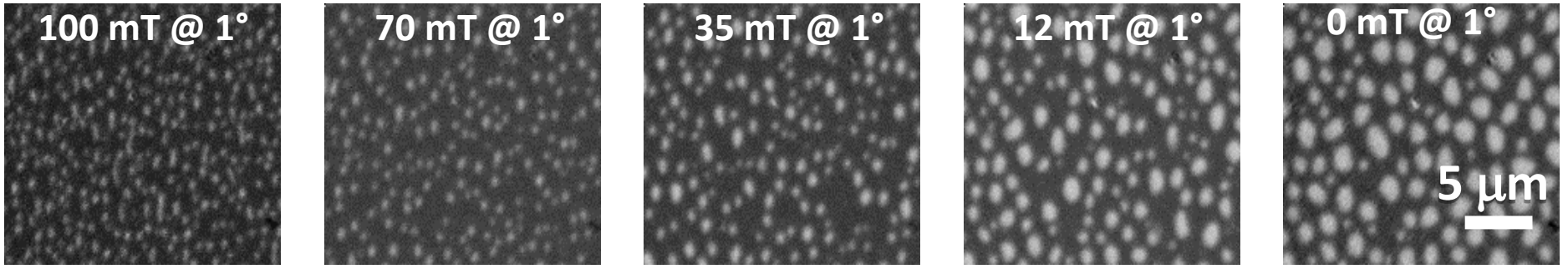
Writing of vortex networks

- Tilted magnetic field



- In plane static magnetic field with 1° tilt
- Bubbles grow with decreasing field
- Zero field stable bubble phase

  d_{CoFeB} = 1.367 nm to 1.375 nm

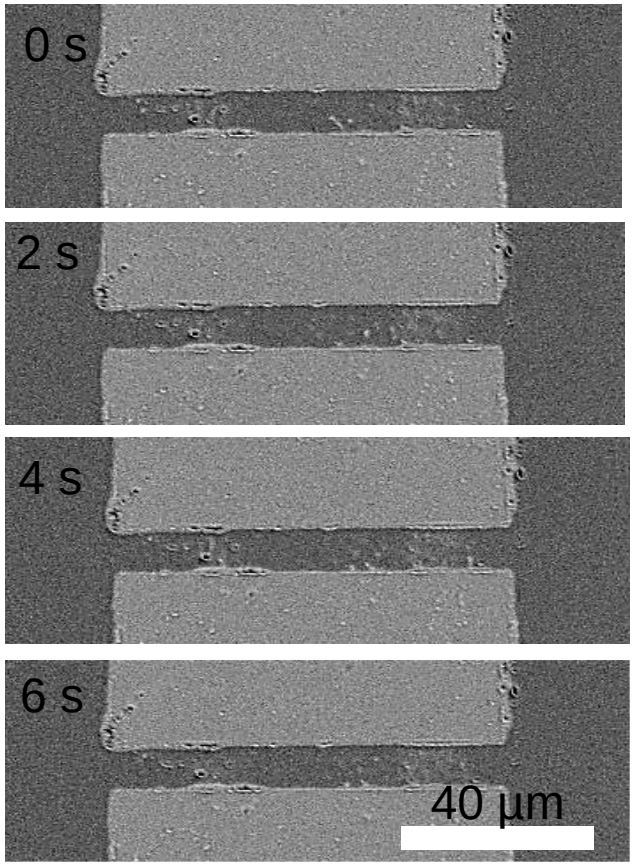


Increasing H_{tilted}

Writing of vortex networks

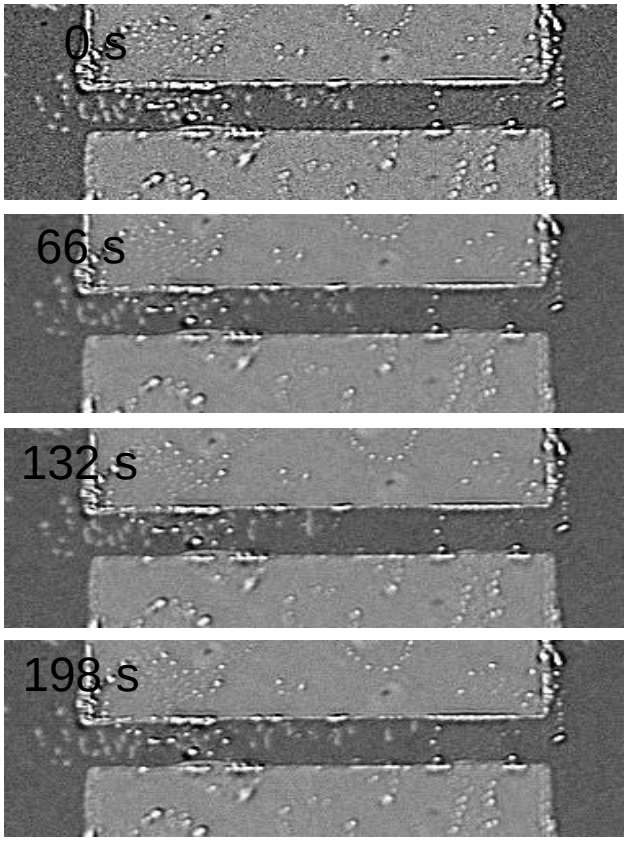
- Current driven motion: 10 µm constriction

Forward



38V at 545Ohm => I = 2 e12 A/m^2 (2e8 A/cm^2)
B = 0,56 mT

Backwards



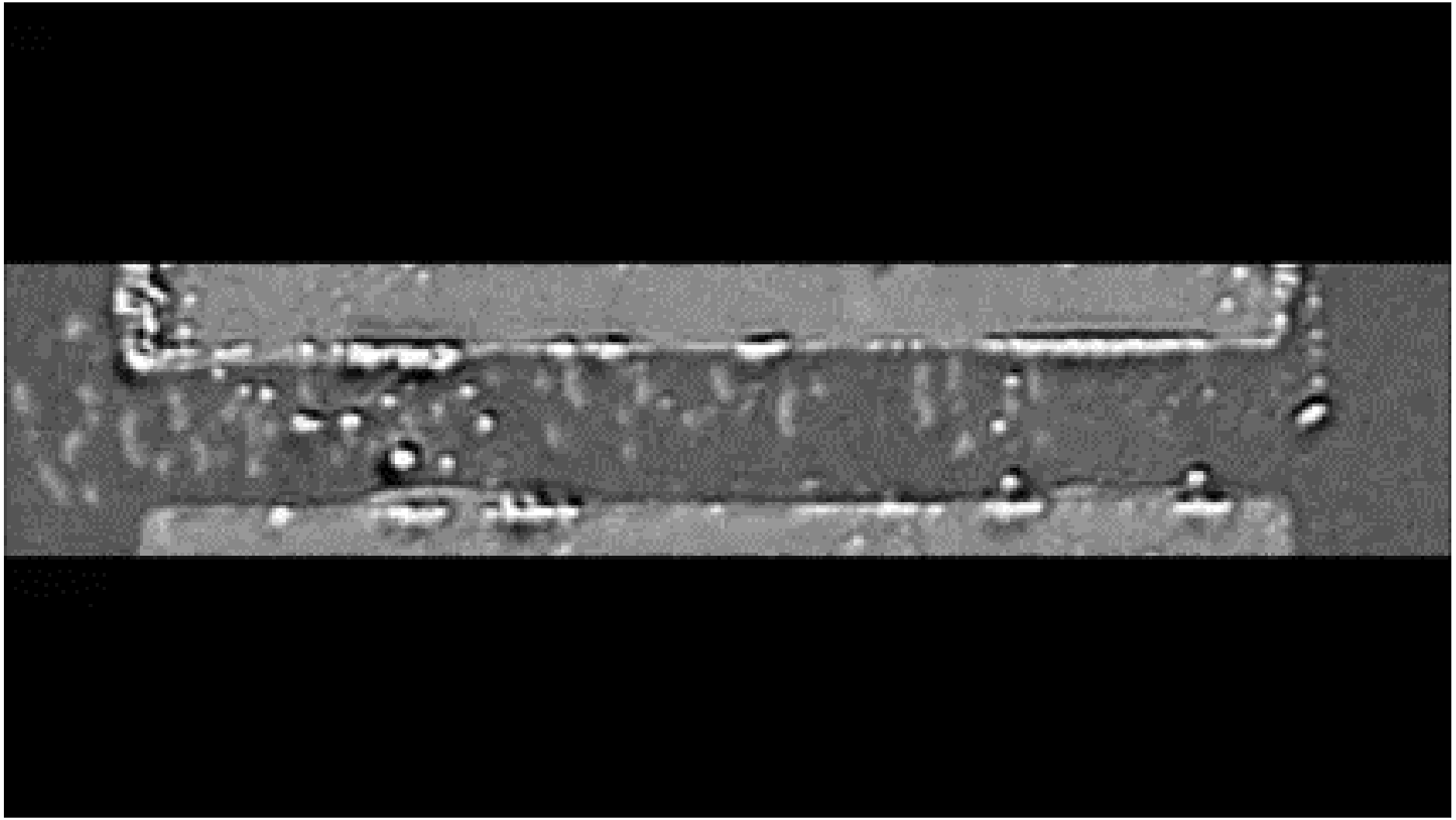
38V at 545Ohm => I = 2 e12 A/m^2 (2e8 A/cm^2)
B = 0,69 mT

- Forward and backward motion
- Currents needed $j=2\ 10^8$ A/cm^2
- Already in regime of current induced bubble generation by heat pulses

Show vid_probe2_8.avi

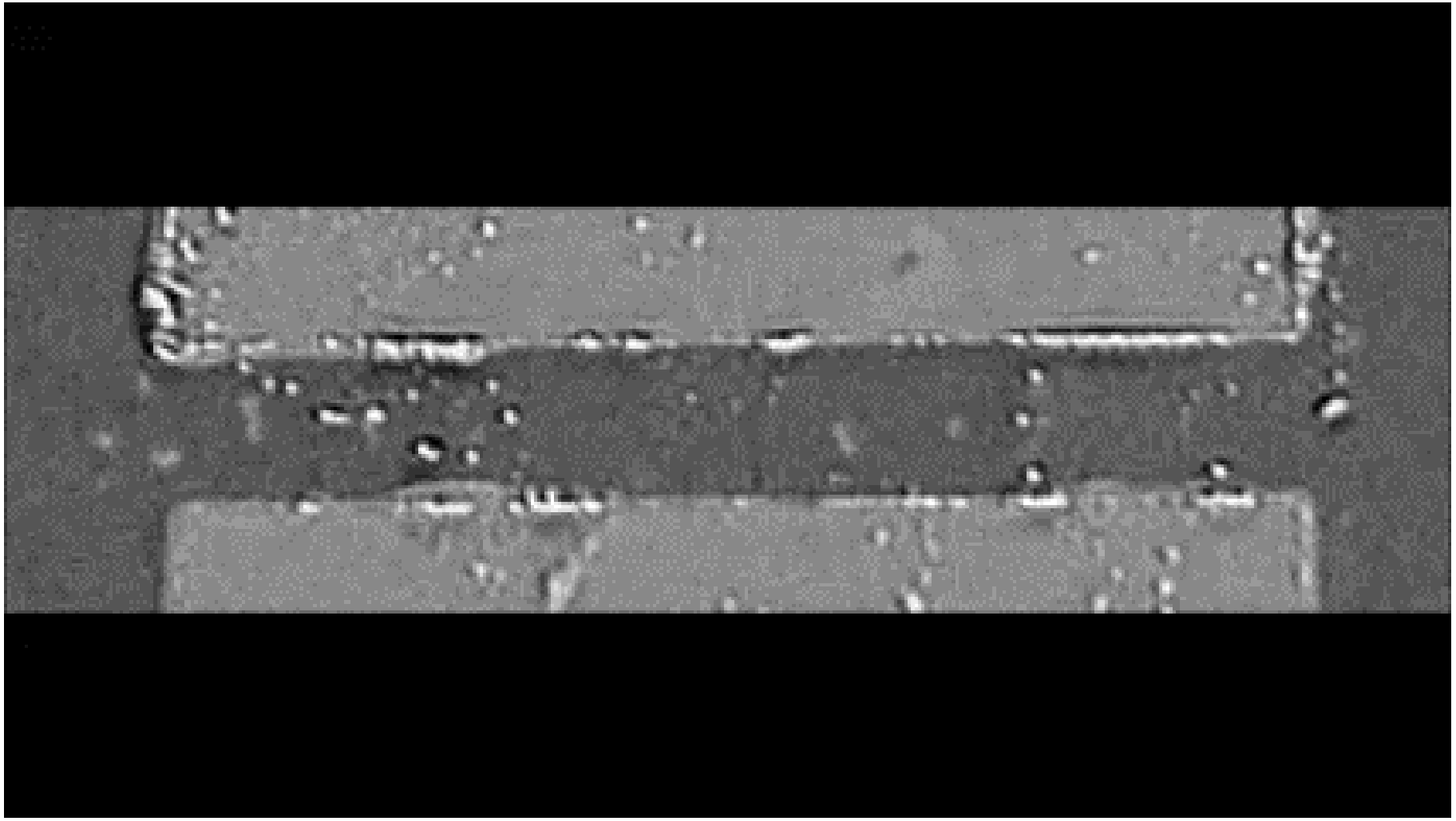
Writing of vortex networks

- Current driven motion: 10 µm constriction



Writing of vortex networks

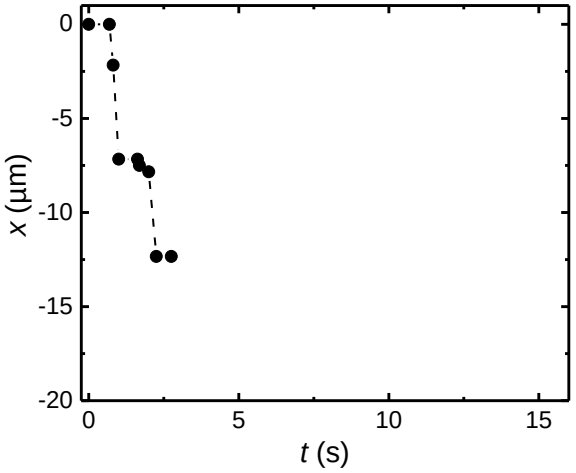
- Current driven motion: 10 µm constriction

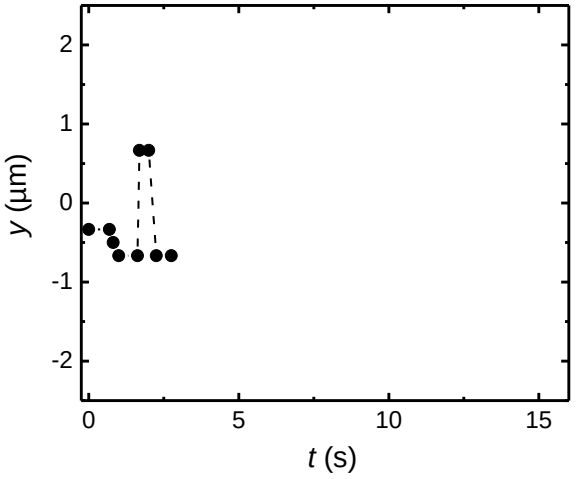


Writing of vortex networks

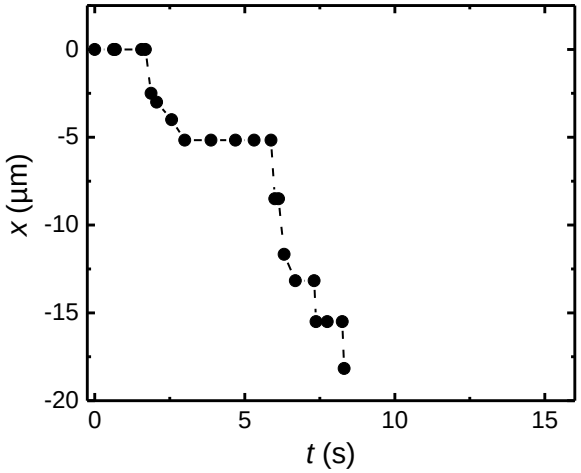
- Motion tracking – testing the local potential

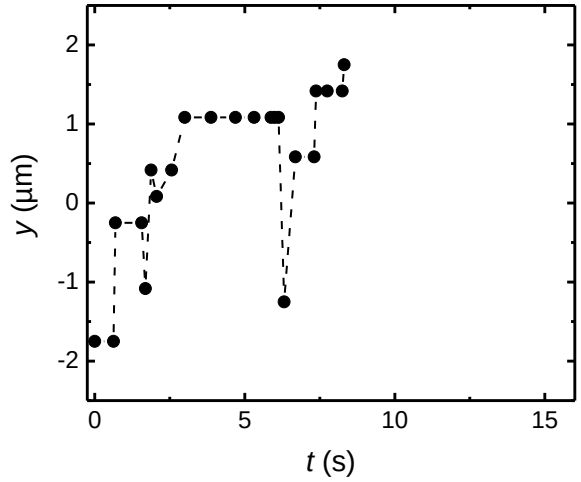
Skyrmion 1



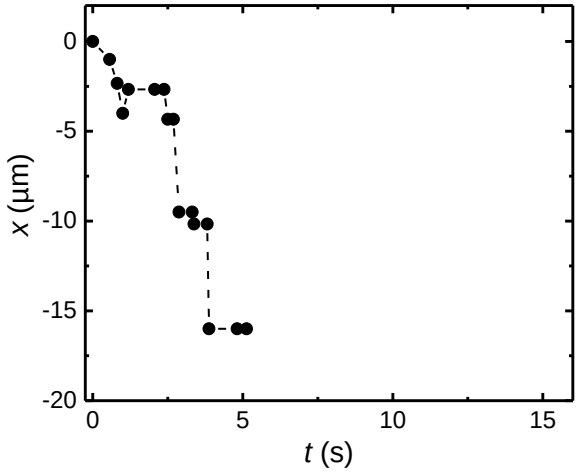


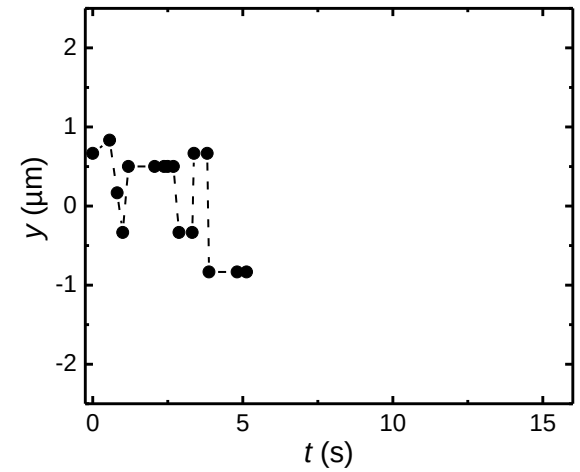
Skyrmion 2





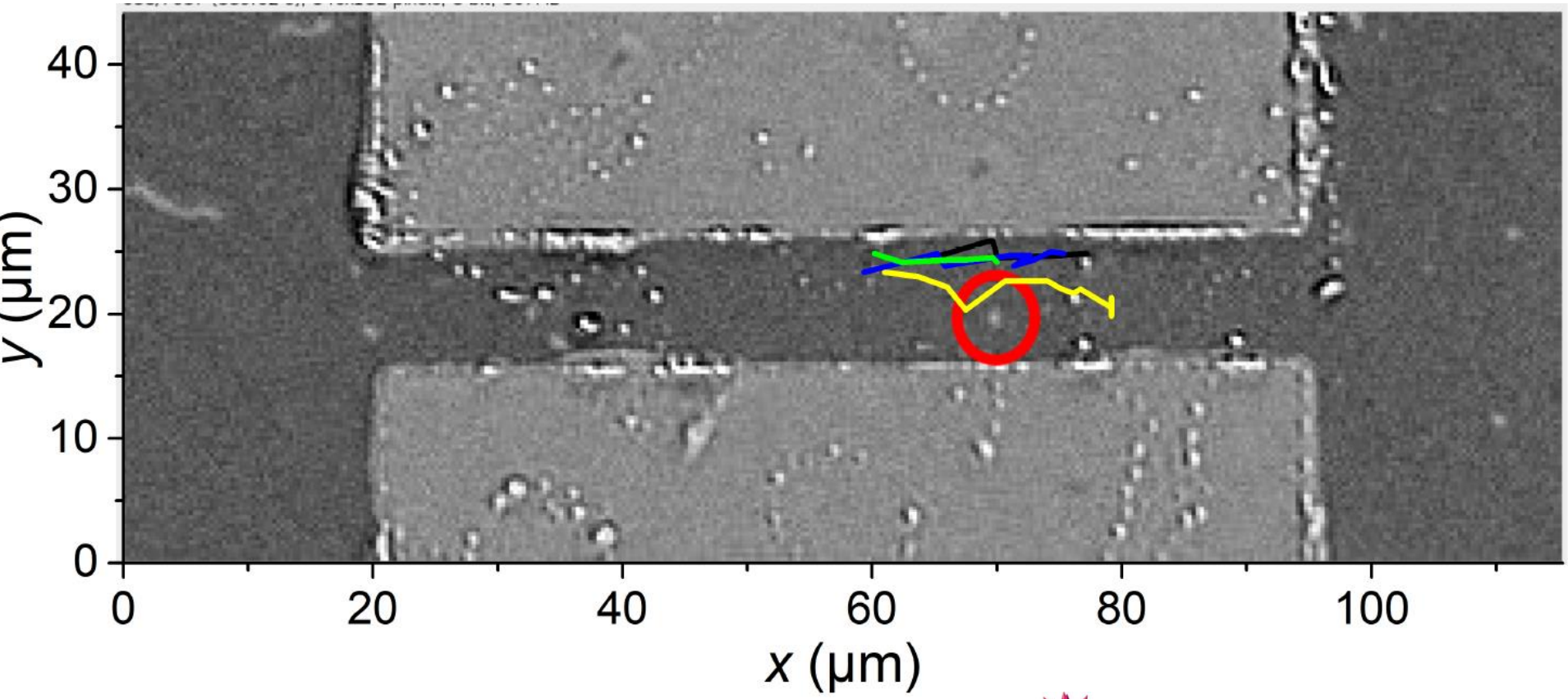
Skyrmion 3

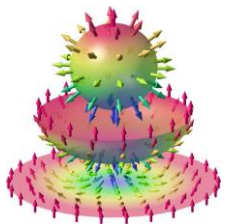




Writing of vortex networks

- Motion tracking





SPP Skyrmionics

Outline

- The nature of femtosecond spin dynamics
- THz spintronic emitter
- Hard disc: state of the art
  - Thermal model of ultrafast demagnetization
  - FePt optical writing a storage media
  - Writing of topological objects
- Summary

Contributions

@spintronicsHGW

Deutsche Forschungsgemeinschaft DFG

Magnonics: Materials and Devices

Priority program SpinCaT

SPP 1666

Priority program Topologische Isolatoren

Priority program Skyrmionics

Collaborations

@spintronicsHGW

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Günter Reiss, Thorsten Hübner Timo Kuschel
Bielefeld University

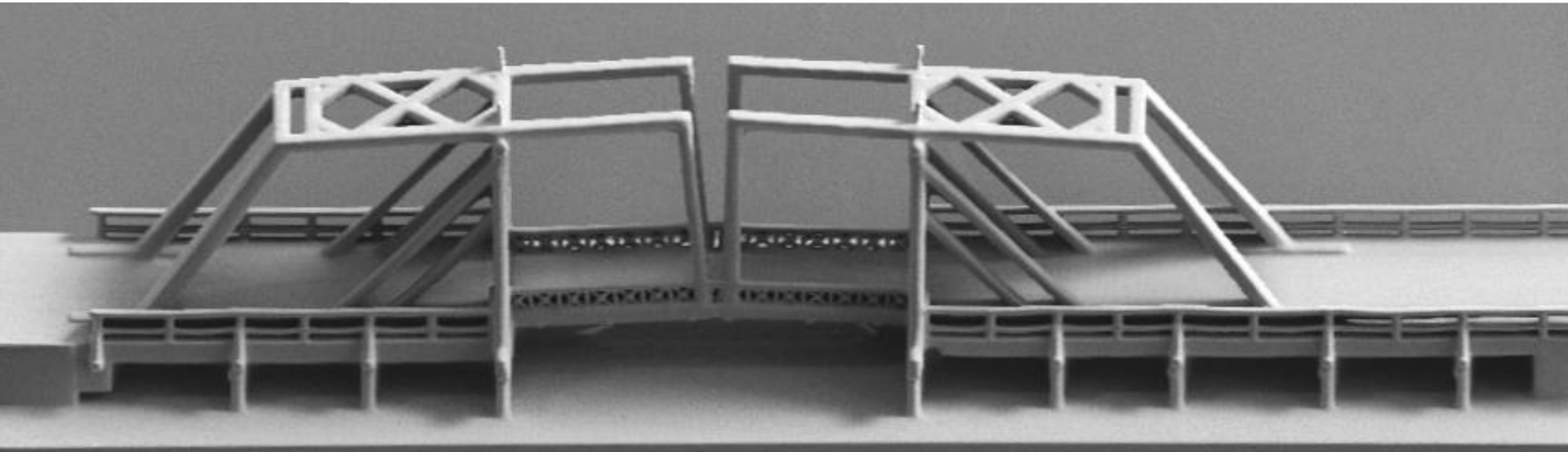
Deutsche Forschungsgemeinschaft DFG

SPP 1666

SPP Skyrmionics

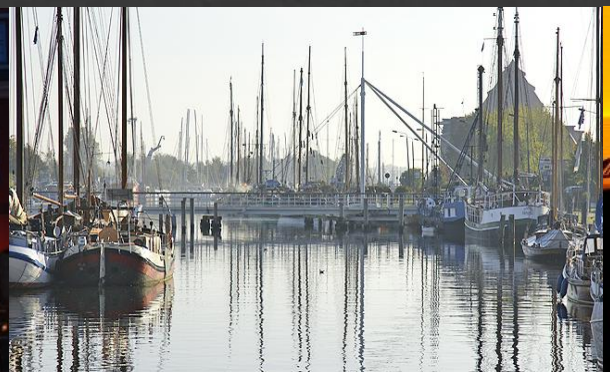
NDR.de
Das Beste am Norden

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456



See NDR feature on our new labs: Nordmagazin or http://www.physik.uni-greifswald.de/aktuelles.html @spintronicsHGW


Greifswald




Physics