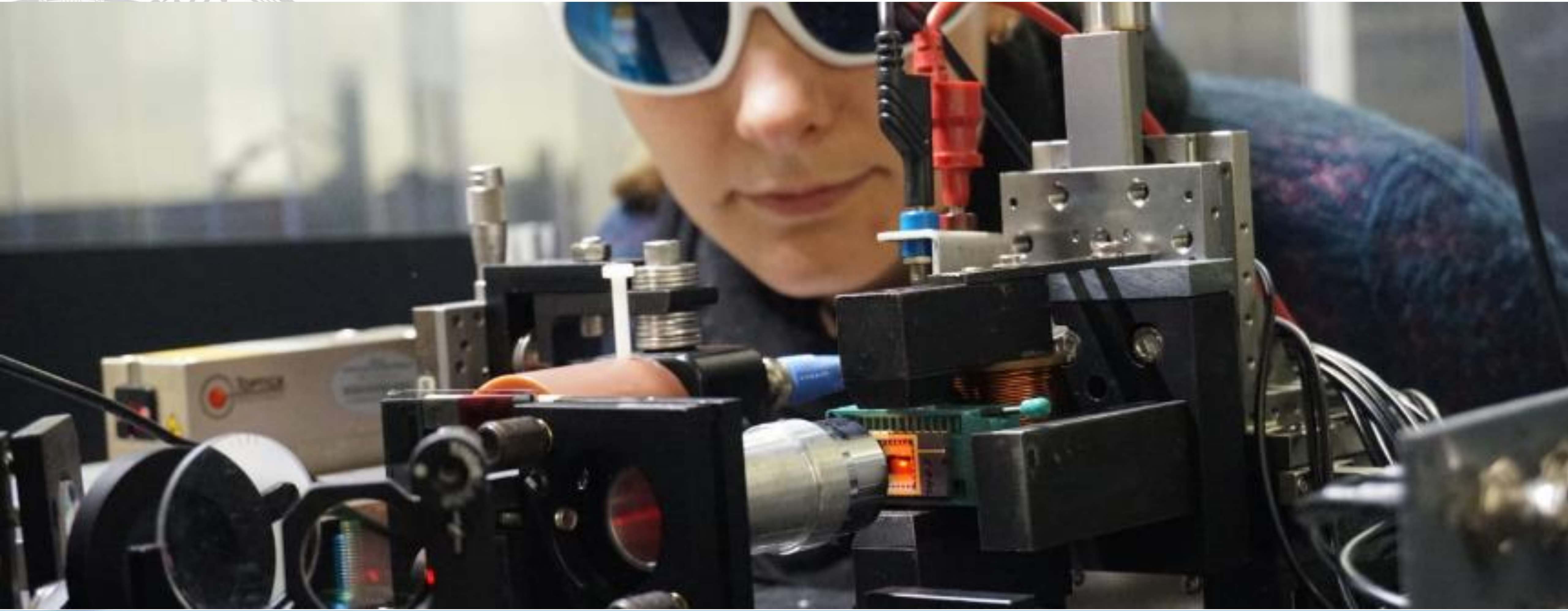
THz for spintronics and superresolution imaging

Markus Münzenberg



Collaborations

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Attosecond spin dynamics:

Florian Siegrist, Thomas Jauck, Martin Schultze, TU Graz/ MPQ Garching

Sangeeta Sharma, MBI Berlin, MPI Halle

THz emitter:

Tom Seifert, J. Nötzold, S. Mährlein, Lukas Braun, Tobias Kampfrath, *Fritz Haber Institute*

Marco Battiato, Pablo Maldonado, Peter Oppeneer, *Uppsala University*

F. Freimuth, Y. Mokrousov, S. Blügel, *FZ Jülich*

Mathias Kläui, *Mainz University*

SPINAGE

SpinAge: Nanoscillators and light for neuromorphic computing

INL INTERNATIONAL IBERIAN NANOTECHNOLOGY LABORATORY

Tim Böhnert, Ricardo Ferreira, INL
Farshad Moradi Aarhus University

Mona Rajbali, Akash Kumar, Johan Akermann, NanOsc and University of Gothenburg

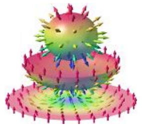
NanOsc

THz resonators

Sascha Schäfer, University of Regensburg

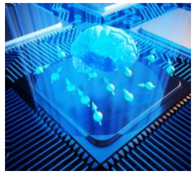
Deutsche Forschungsgemeinschaft DFG

SPP 1666
Topologische Isolatoren



Skyrmionics

HORIZON 2020



FET Open SpinAge

ZENTREN FÜR INNOVATIONSKOMPETENZ
UNTERNEHMEN REGION
Die BMBF-Innovationsinitiative Neue Länder

META ZIK PlasMark

Bundesministerium für Bildung und Forschung

DAAD

Deutsche Forschungsgemeinschaft DFG

SPP 1666
Topologische Isolatoren

Skyrmionics

HORIZON 2020
FET Open SpinAge

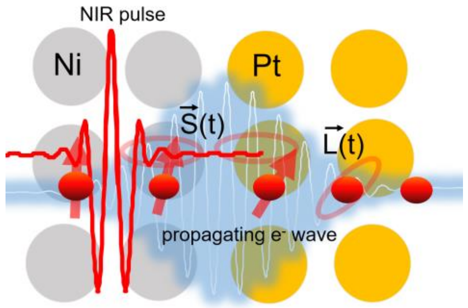
ZENTREN FÜR INNOVATIONSKOMPETENZ
UNTERNEHMEN REGION
Die BMBF-Innovationsinitiative Neue Länder
META ZIK PlasMark

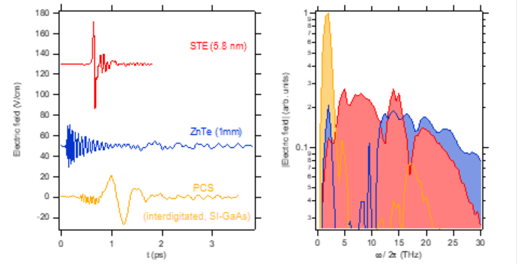
Bundesministerium für Bildung und Forschung

DAAD

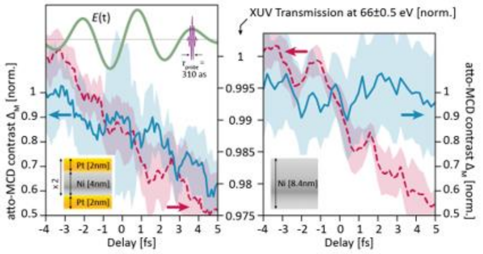
Outline

- Introduction
    - THz spintronic emitter – *applications*
    - Lightwave electronics – *coherent spintronics*
- Summary





T. Seifert, et al. Nature Photonics (2016)



F. Siegrist *et al.*, Light-wave dynamic control of magnetism, Nature **571**, 240–244 (2019)

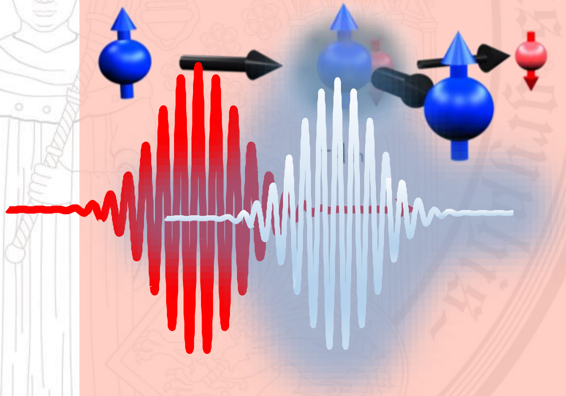
Let´s combine optics and spintronics:

Novel spintronic Photonic THz applications

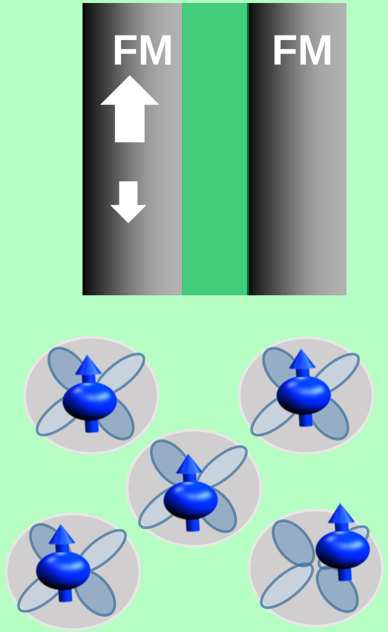
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Photonics

Attosecond
coherent
clocking

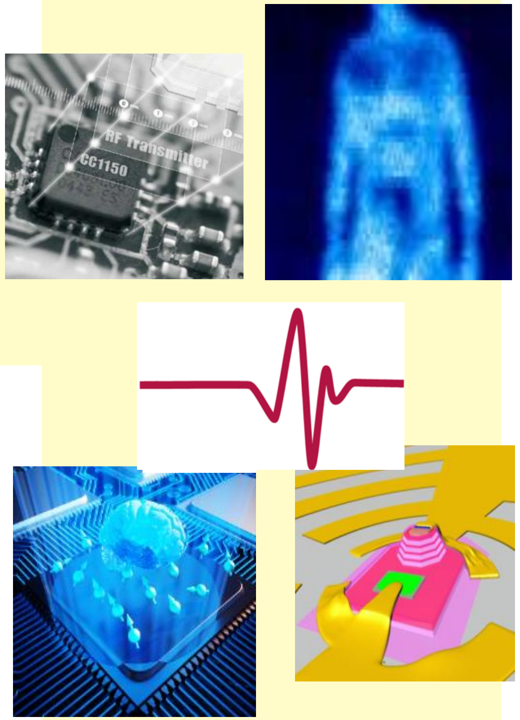


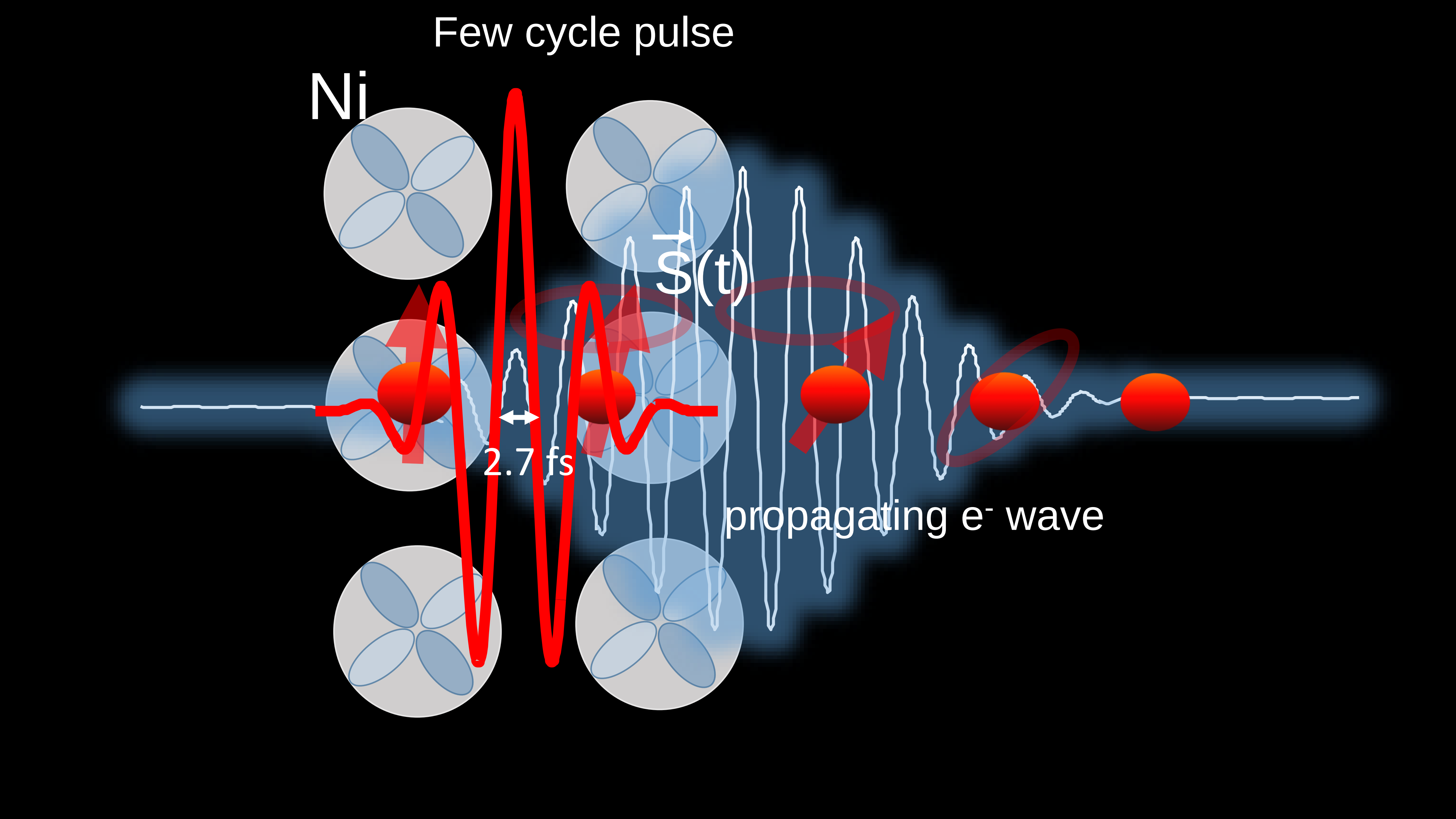
Spintronics

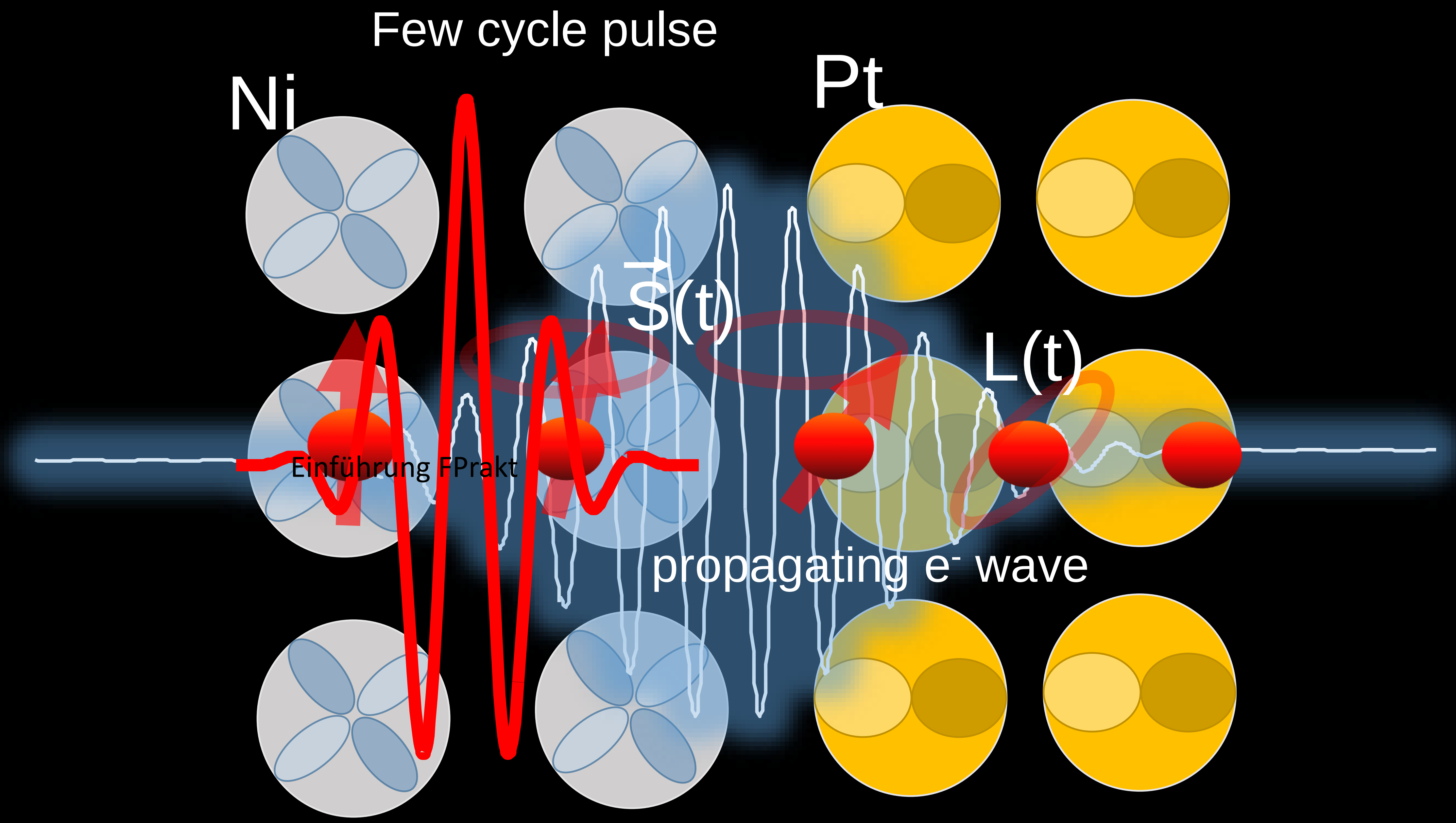


Electronics

THz applications




Few cycle pulse
Ni
S(t)
2.7 fs
propagating e- wave



Ultrafast Spintronics

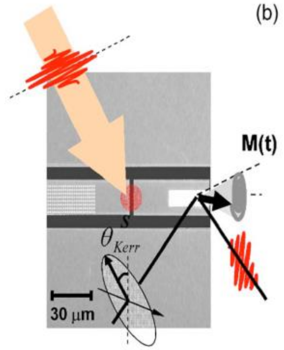
Ultrafast trigger

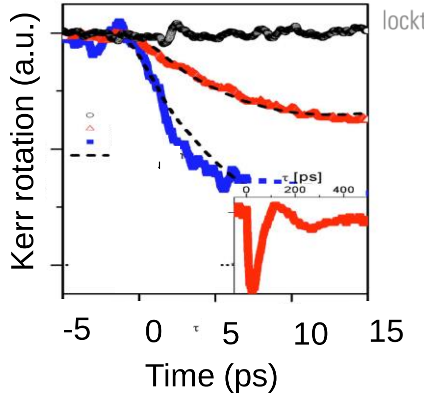
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Free THz B-field trigger

- Photoconductive switch, 1ps rise time, 0.2 Tesla

  Wang et al. JAP

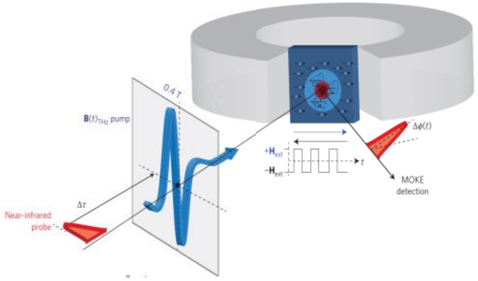


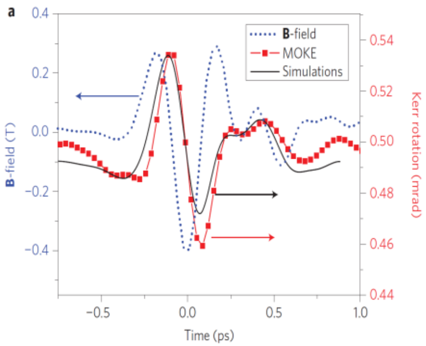


- Free THz pulse (organic crystals)

  ~1Tesla

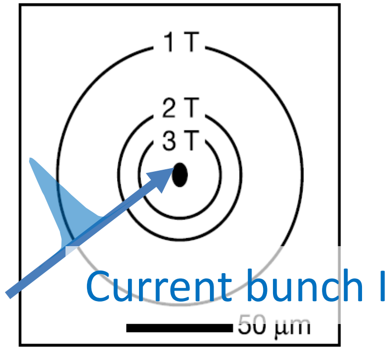
  C. Hauri et al. Nature Photon

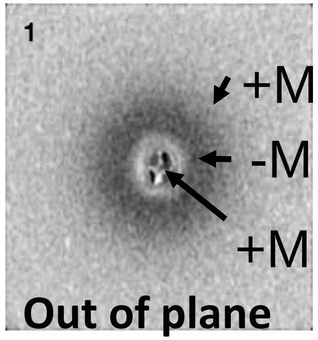




- Stanford accelerator

  Ch. Back et al. Science





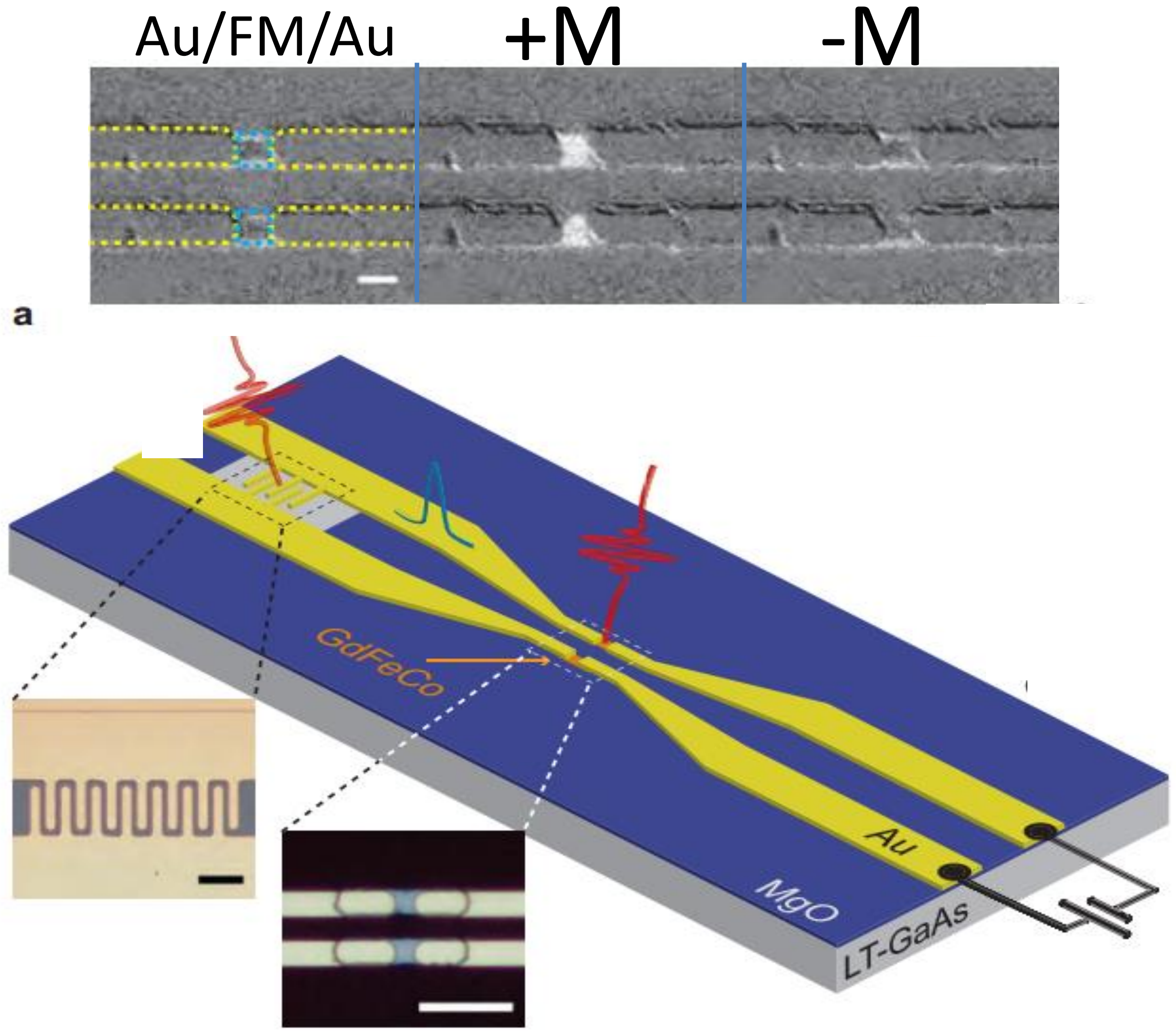
Ultrafast trigger

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Strip line THz B-field trigger

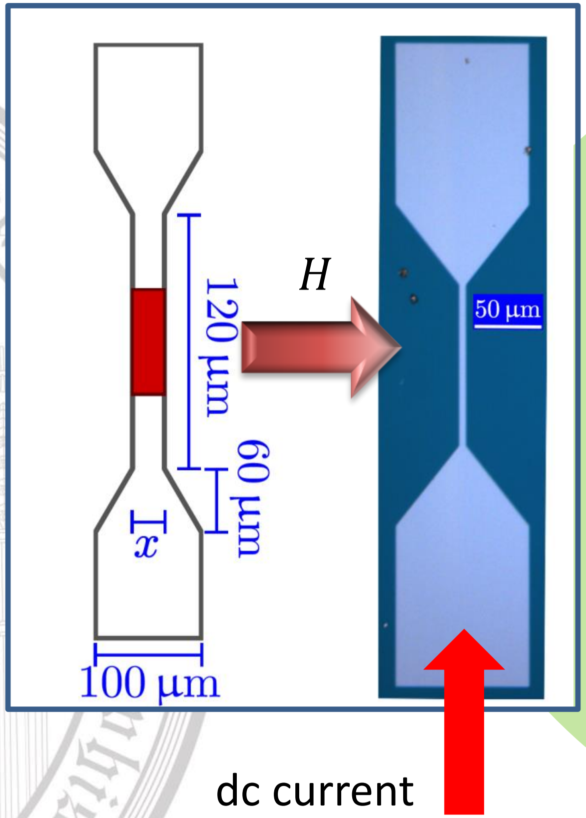
- Switching GdFeCo (FM)

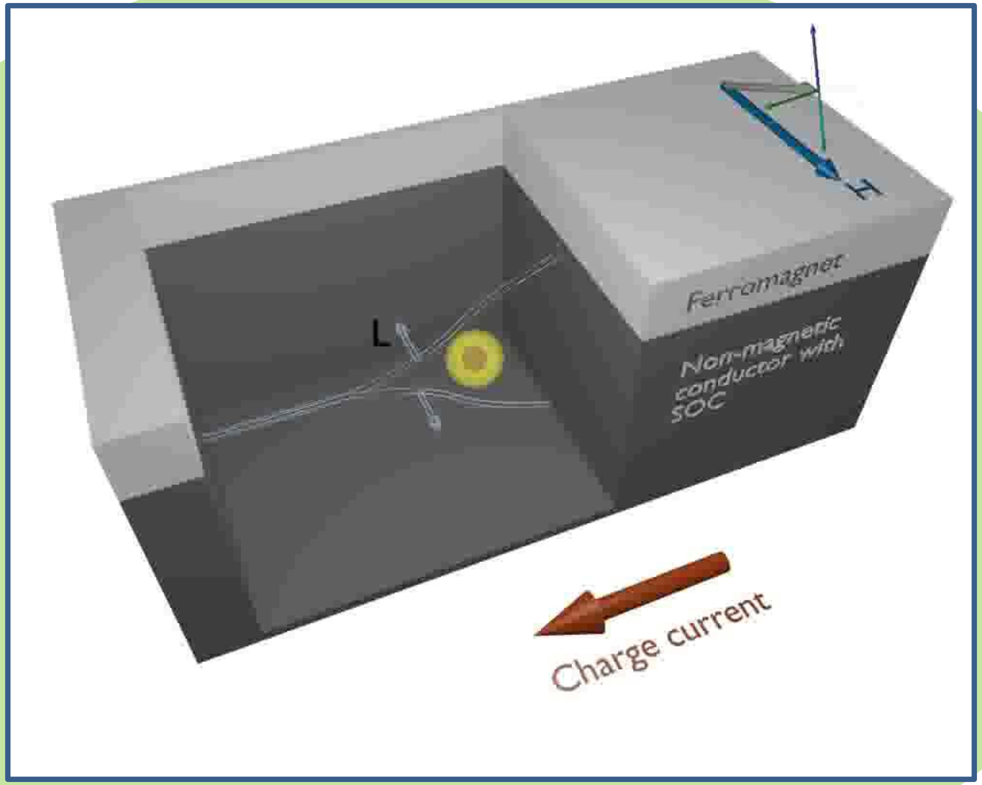
(Berkeley group)



Yang, et al. Science Advances, 03 Nov (2017)

Ultrafast trigger



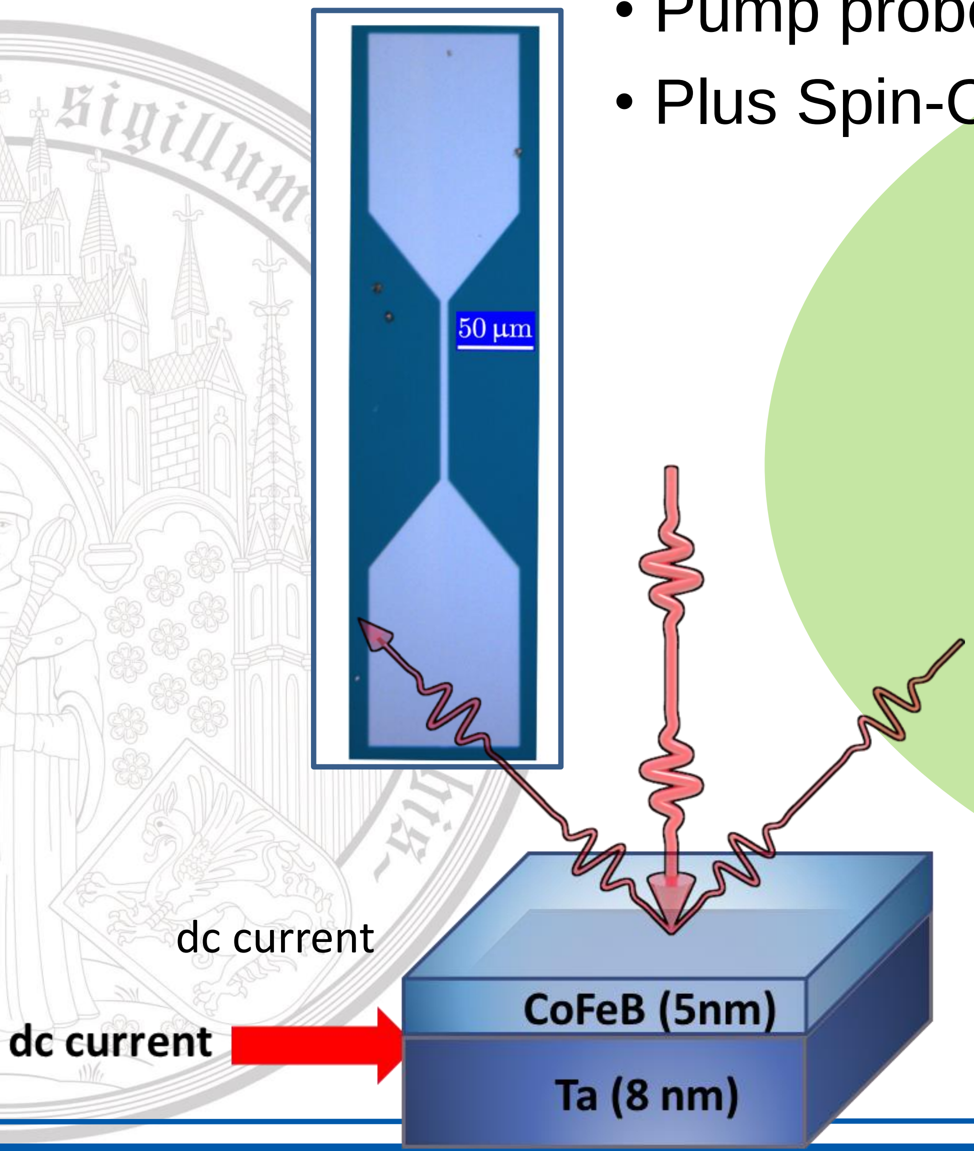


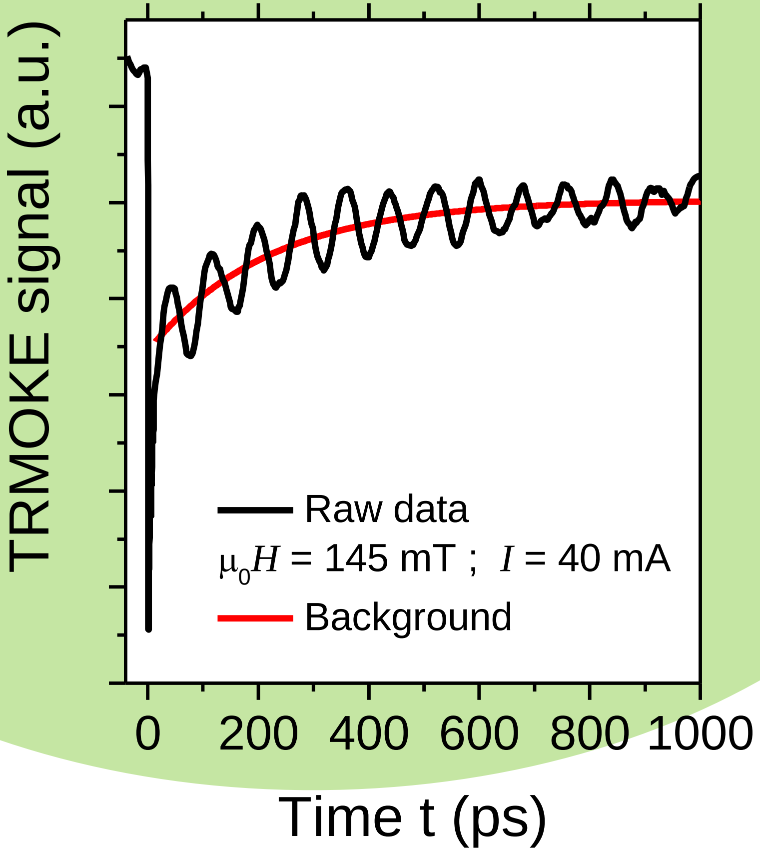
- Thin-film preparation Ta(8 nm)/CoFeB(5 nm)
- Lithography of the structures

Ultrafast trigger

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

- Pump probe spectroscopy Ta(8 nm)/CoFeB(5 nm)
- Plus Spin-Orbit Troque



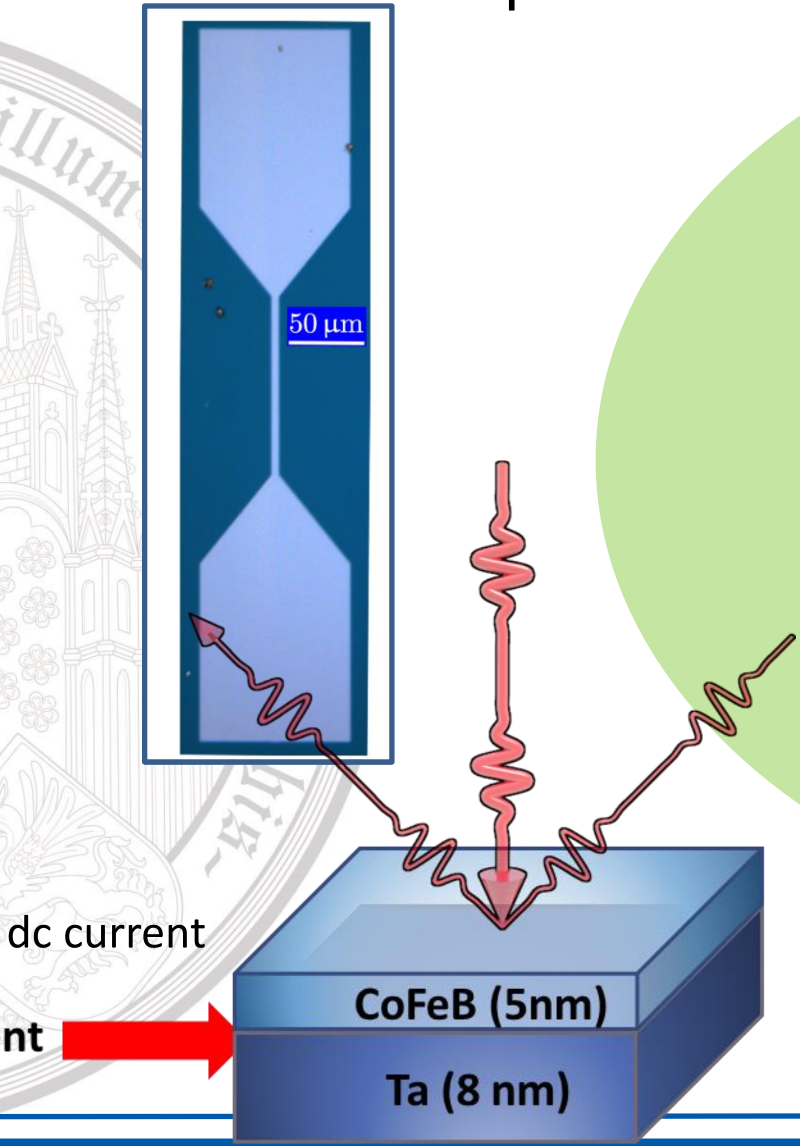


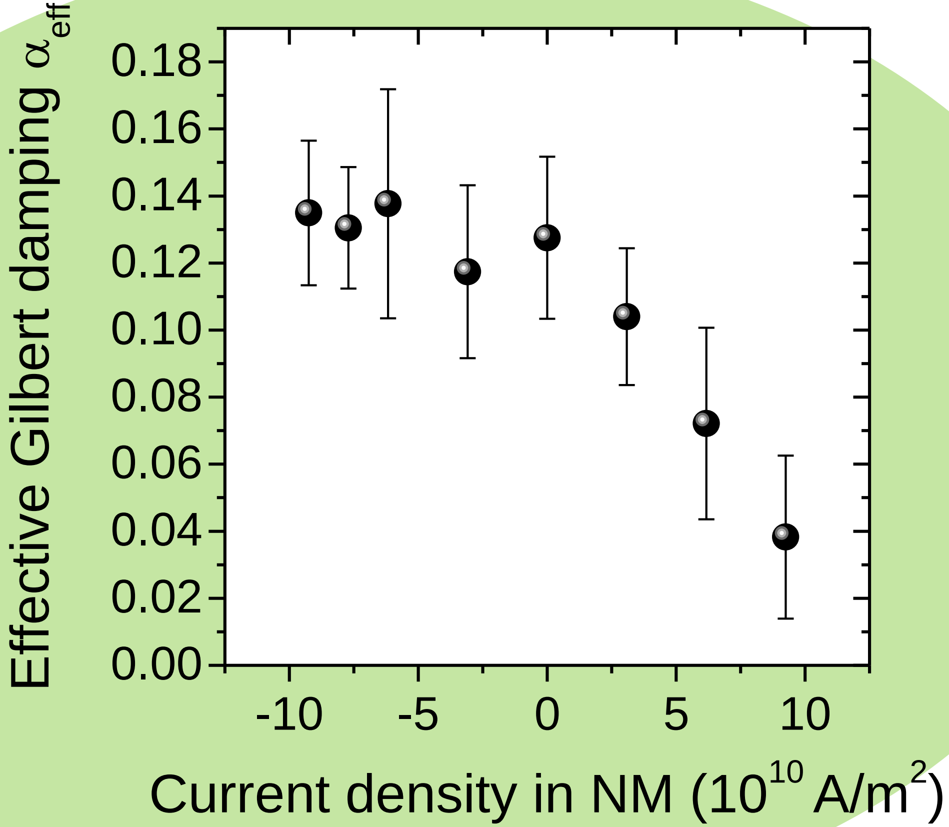
S. Wittrock et al., IEEE Transactions on Magnetics, 53 (2017).

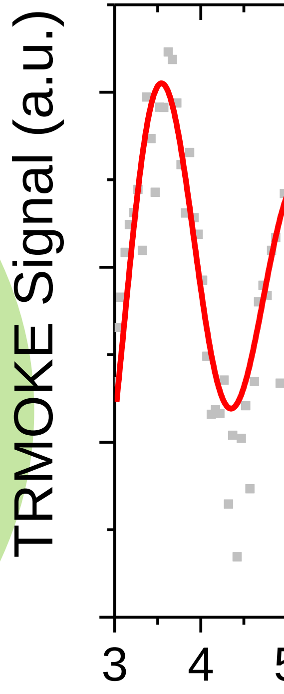
Ultrafast trigger

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

- Spin-Orbit Troque: Antidamping



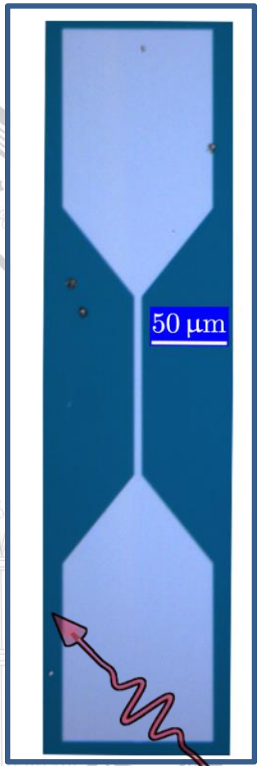


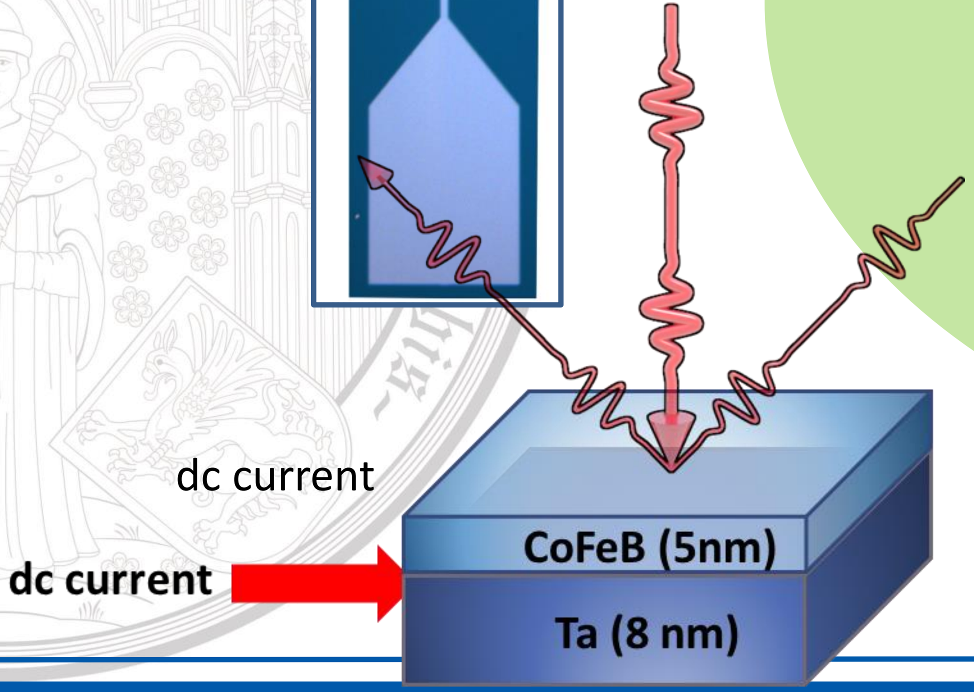


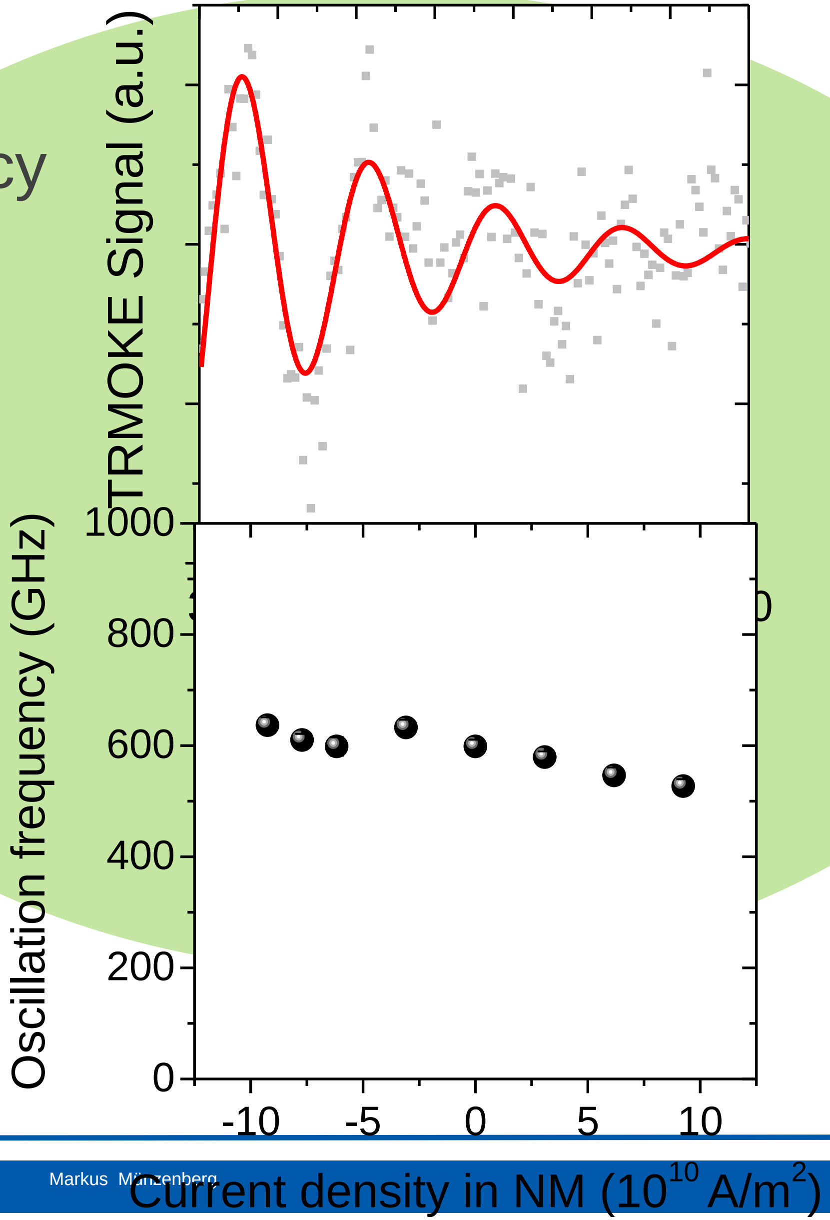
S. Wittrock et al., IEEE Transactions on Magnetics, 53 (2017).

Ultrafast trigger

- SSPW in Ta/CoFeB 5nm
- 0.6 THz frequency

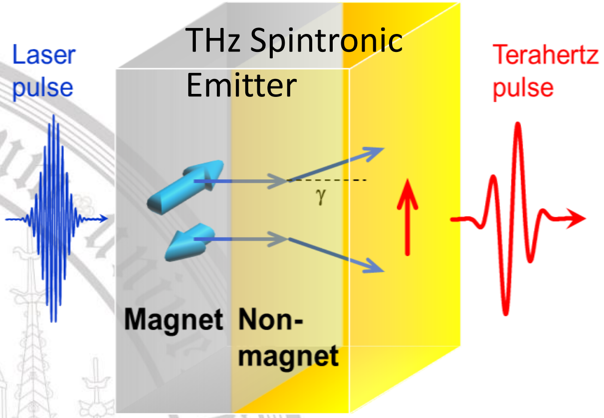


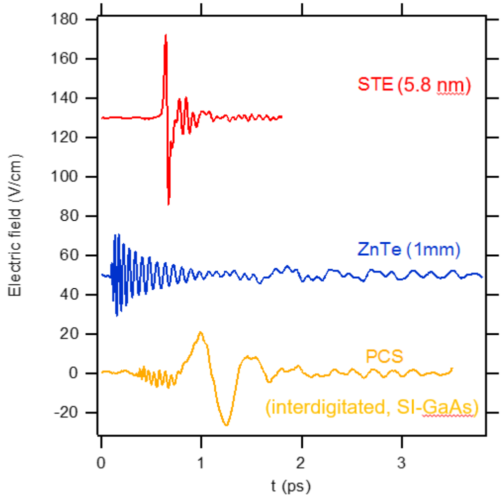


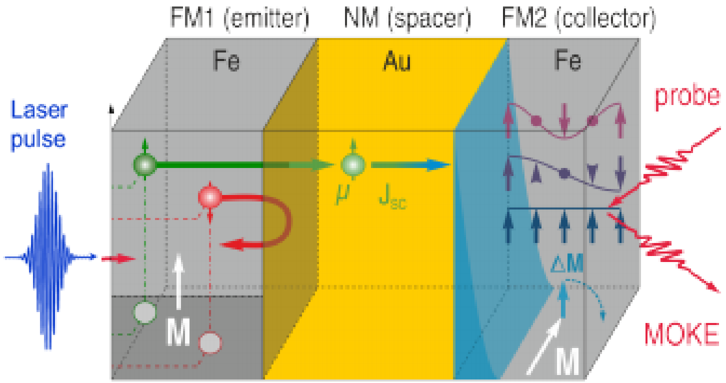


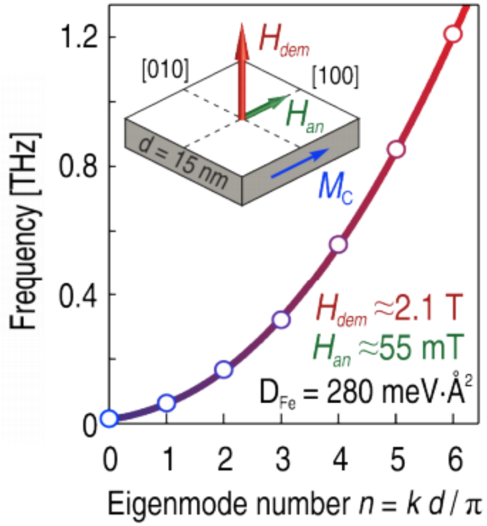
Ultrafast trigger

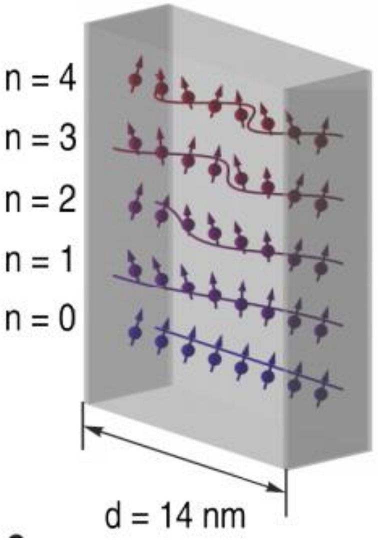
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456





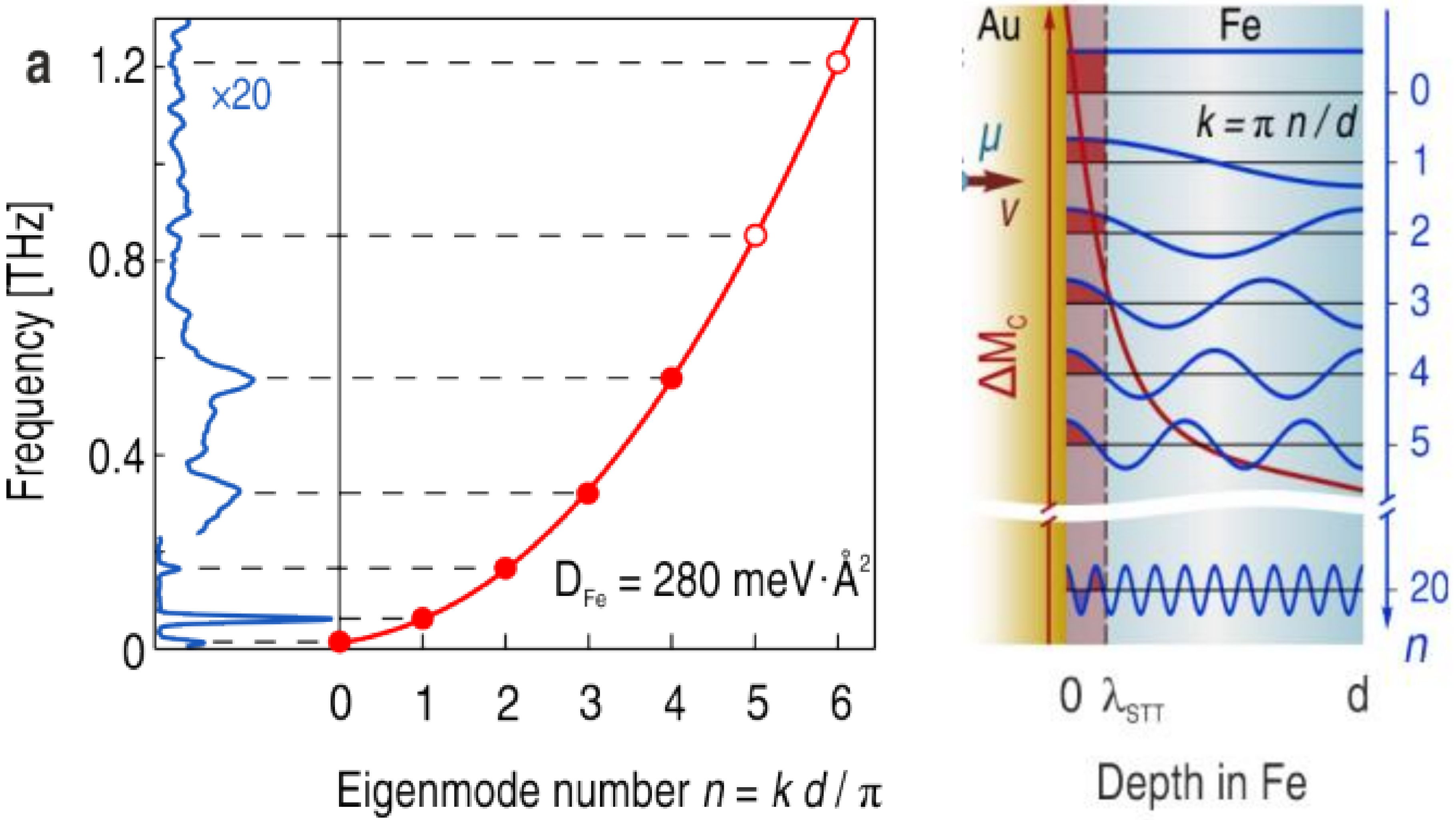






Ilya Razdolski,Alexey Melnikov et al. Nature Commu. 8 (2017)

Ultrafast trigger



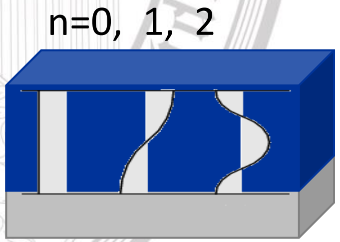
Ilya Razdolski,Alexey Melnikov et al. Nature Commu. 8 (2017)

Zeitaufgelöste Spektroskopie

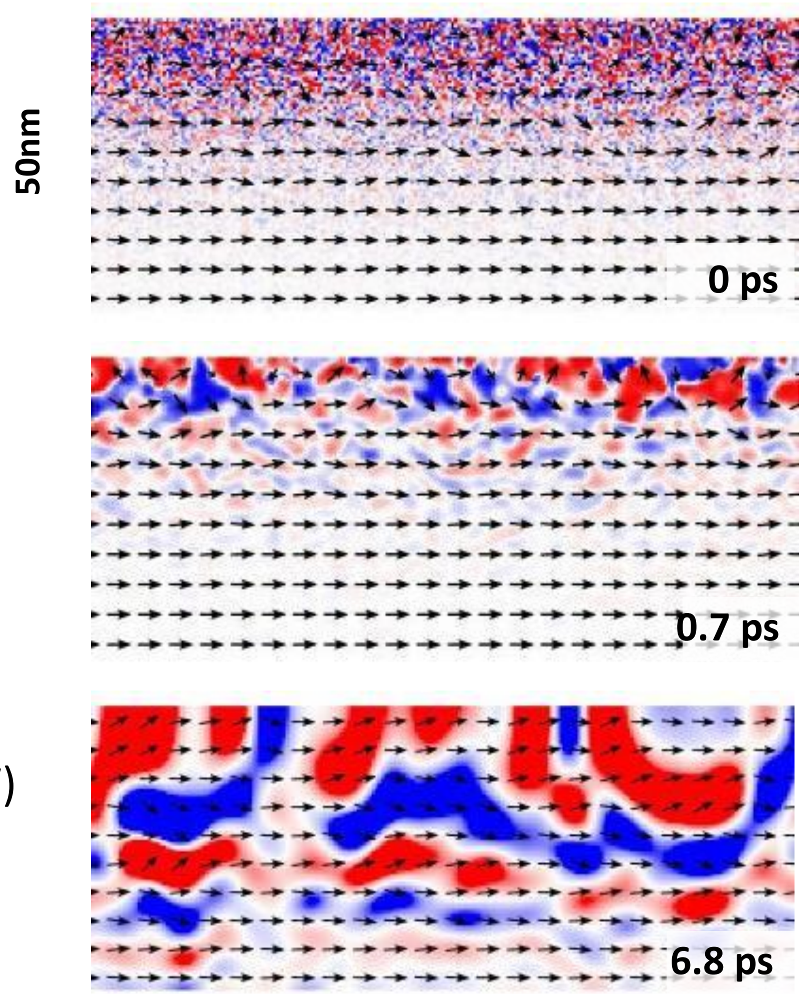
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Simulation der Spinwellen in einer 50 nm dicken Schicht

- Innerhalb der optische Eindringtiefe von 25nm wird die Probe entmagnetisiert



- Stehende Spinwellen: Perpendicular standing spin-wave mode (PSSW)



M. Djordjevic, *Phys. Rev. B* ***75***, 012404 (2007)
G. Eilers,*Phys. Rev. B* ***74***, 054411 (2006)

Photo excitation of spin waves: theory

- Simulation of the laser pulse excitation – spin-wave on the picosecond and nanometer time scale

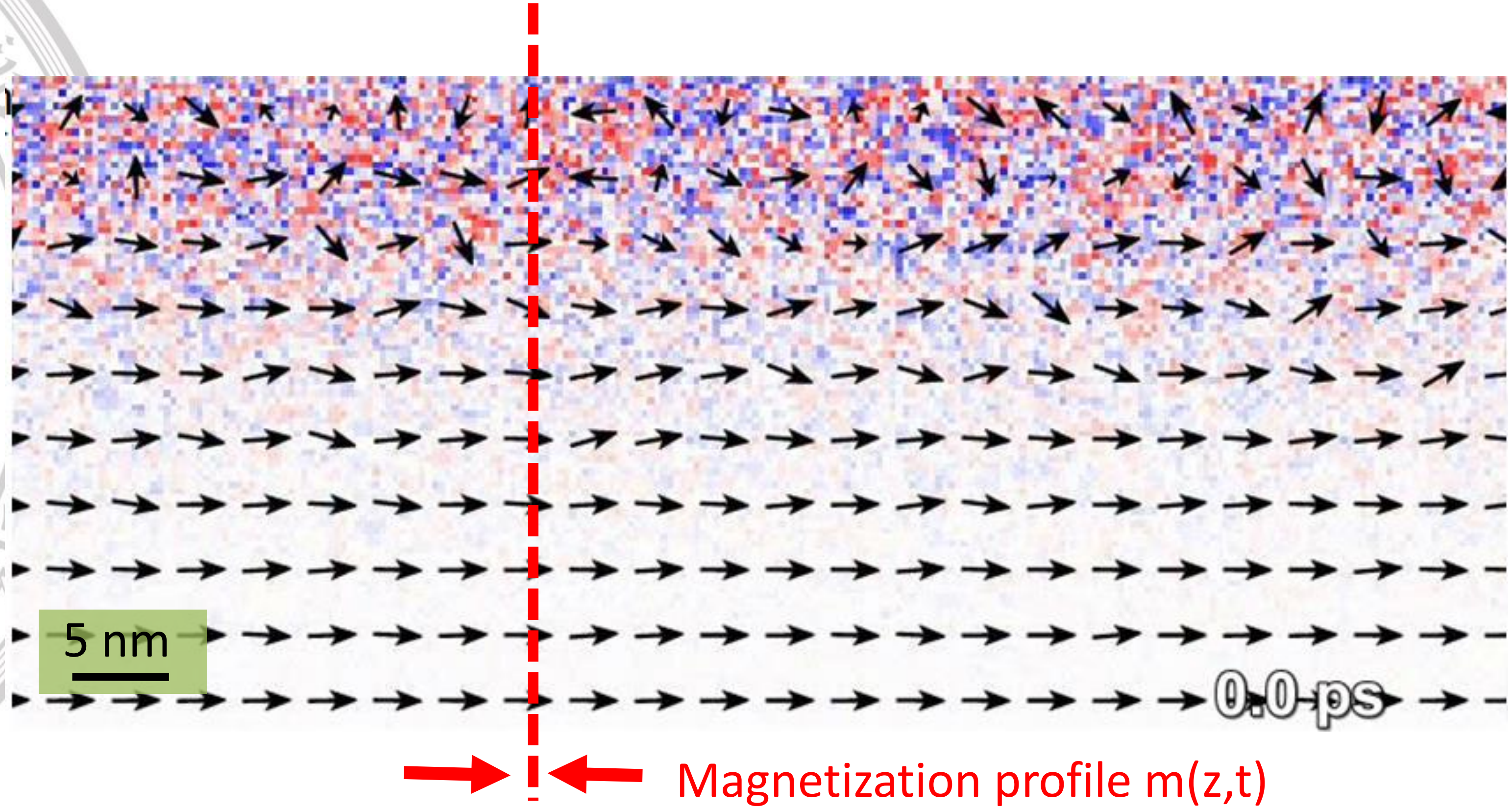
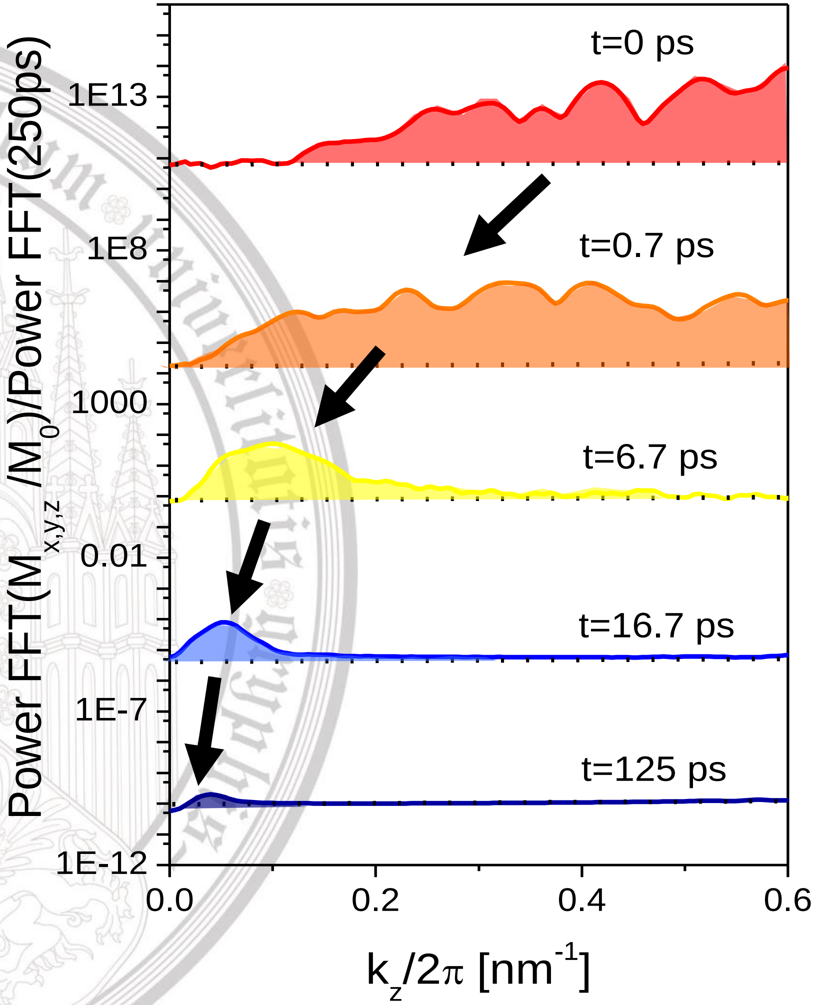
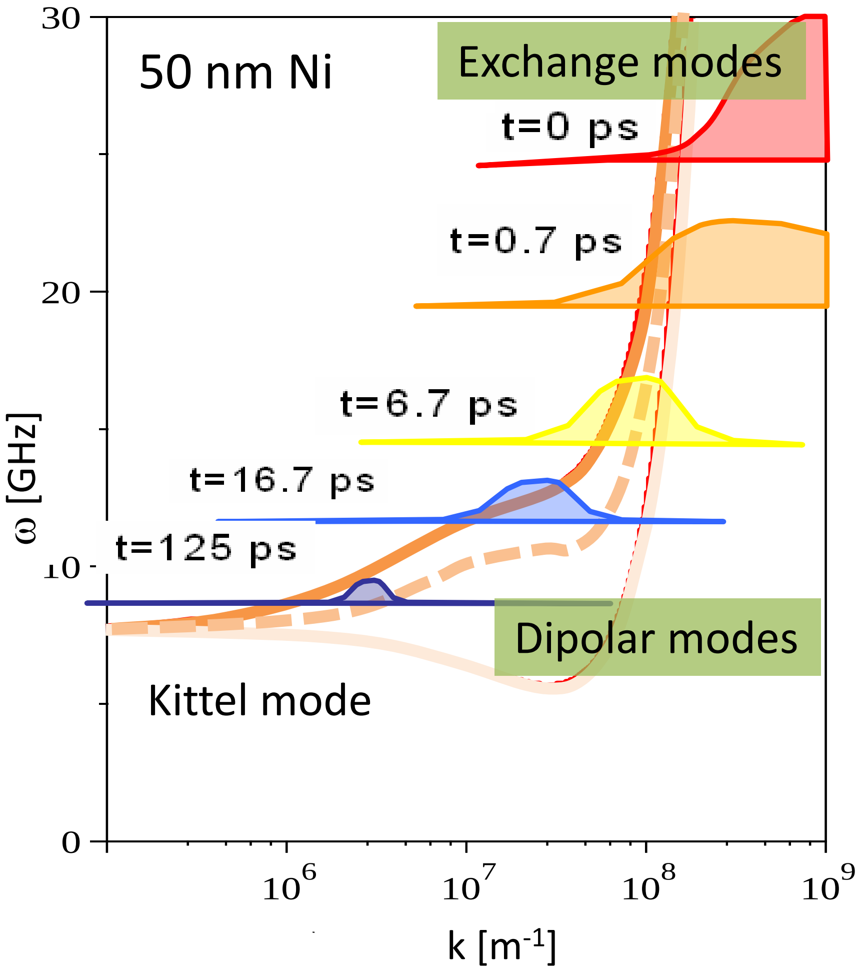


Photo excitation of spin waves: theory

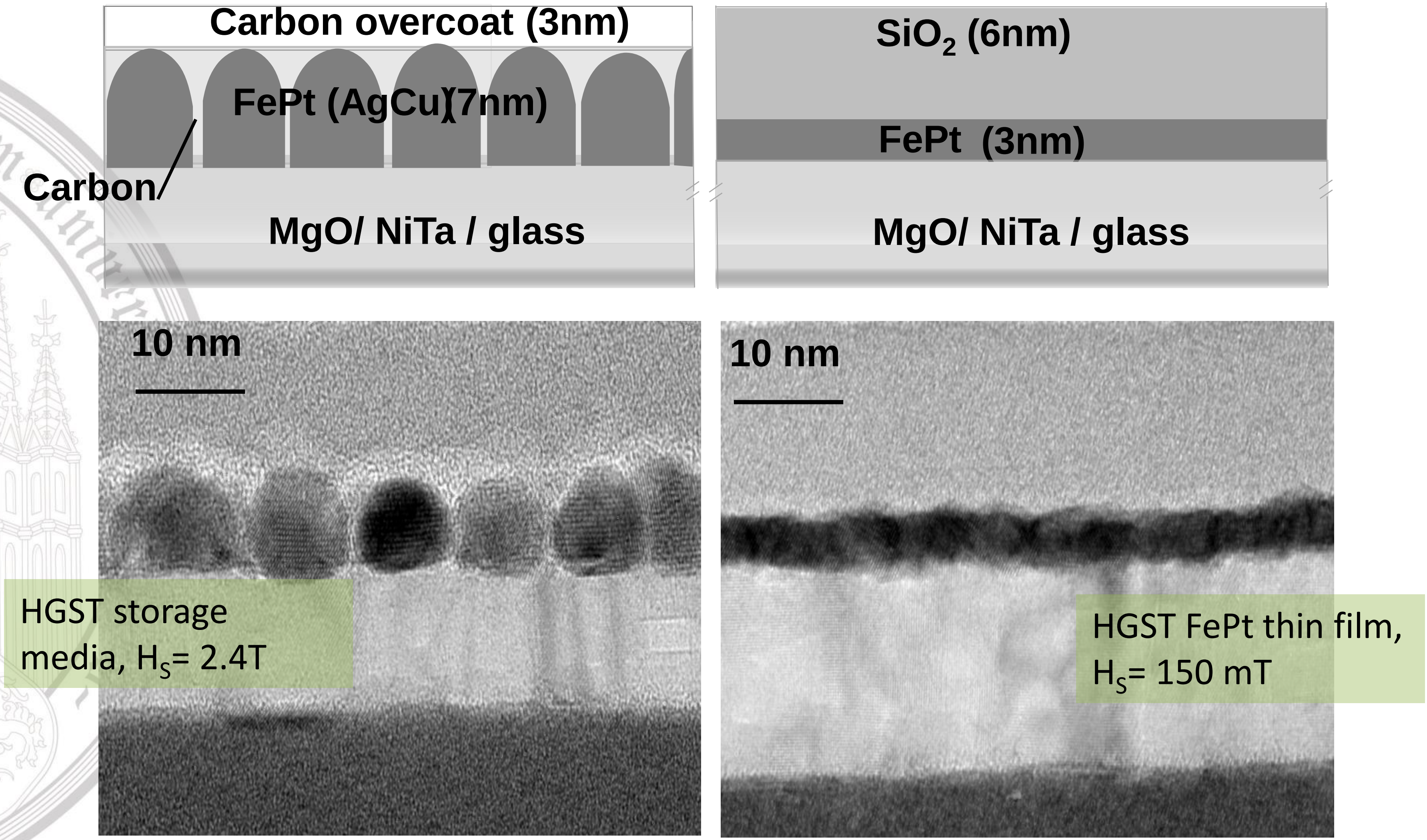




- *also*: microscopic model for ultrafast demagnetization

FePt optical writing a storage media

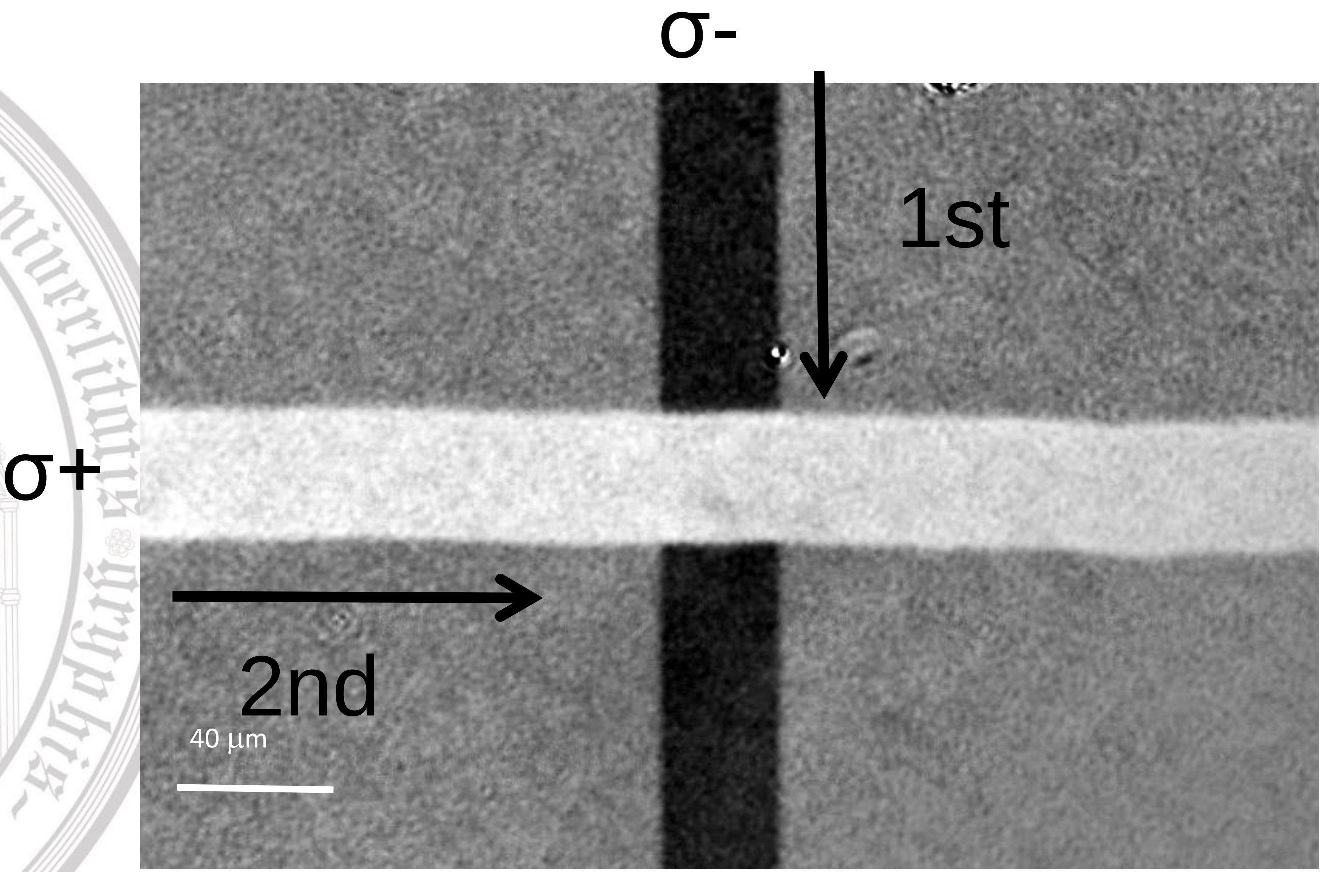
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456



Mendil et al. Sci. Rep. **4**,3980 (2014)

FePt optical writing a storage media

Writing using the helicity of light:

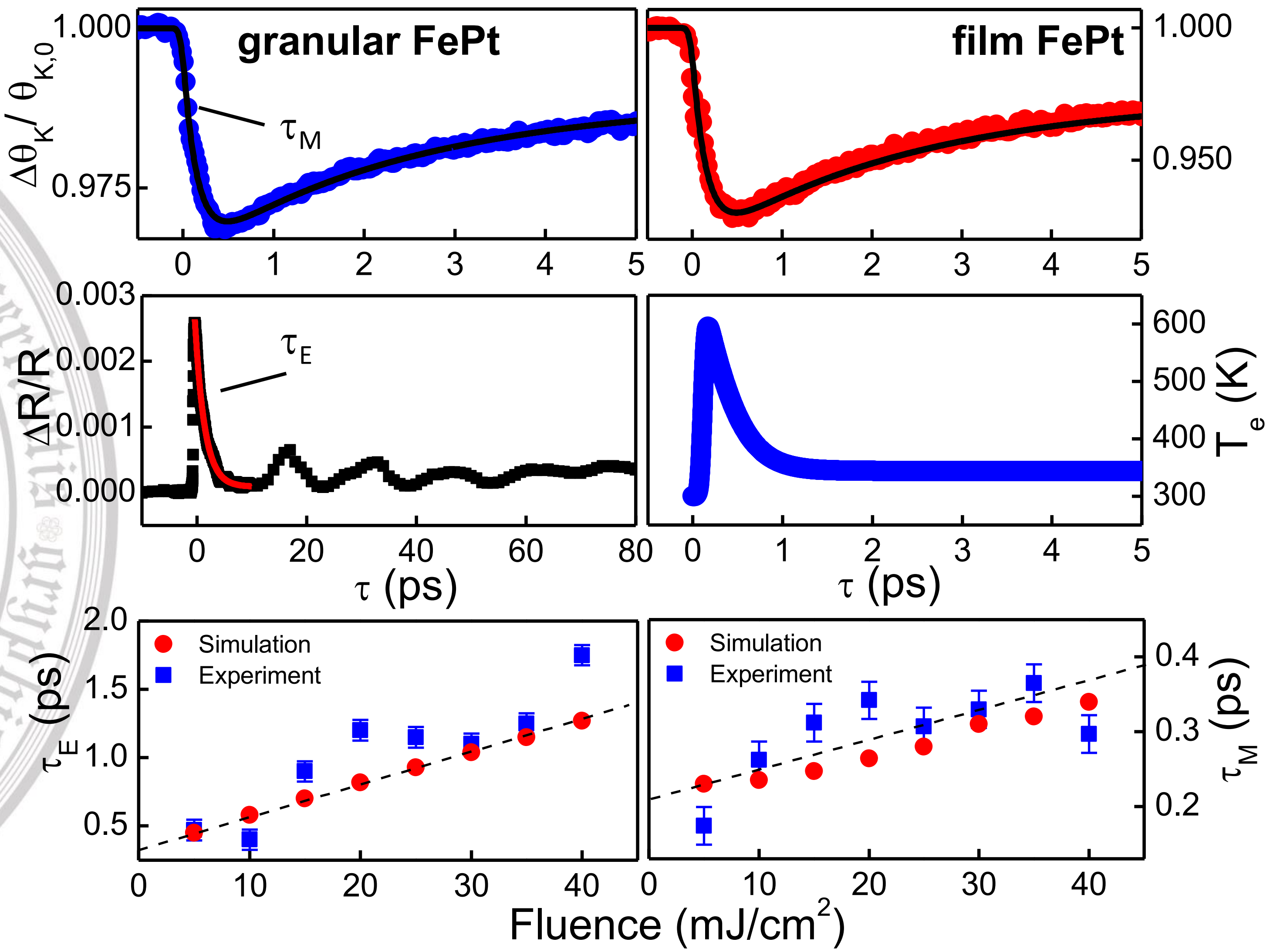


10 mW
Beamwaist 15 μm

FePt (AgCu) granular recording media

FePt optical writing a storage media

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

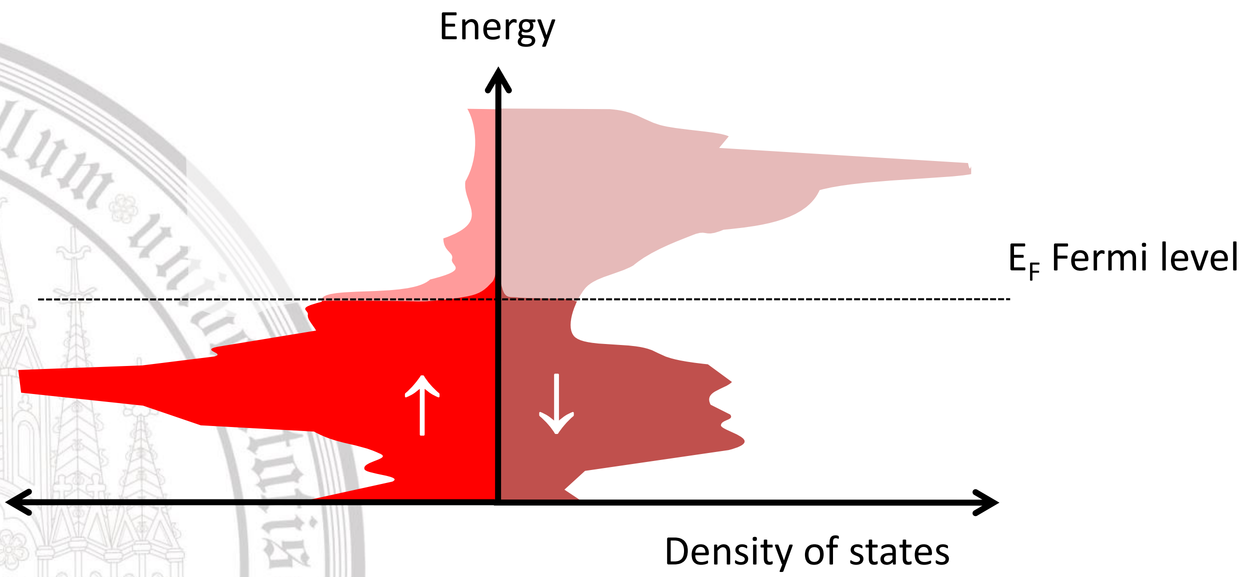


Mendil et al. Sci. Rep. **4**,3980 (2014)

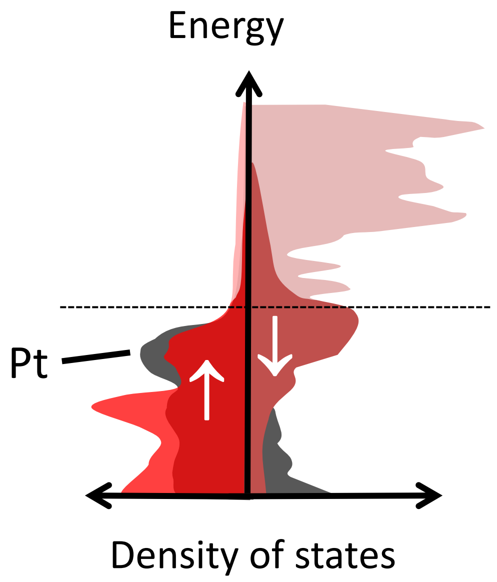
FePt optical writing a storage media

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Fe (bcc)

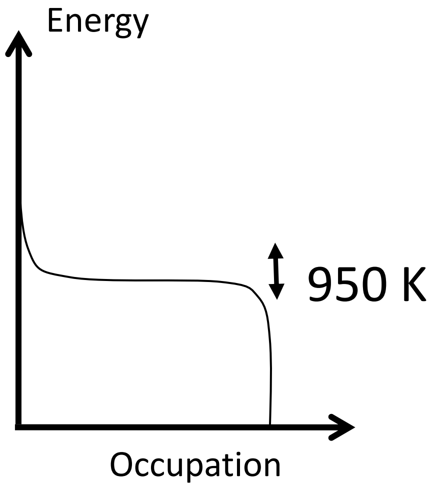


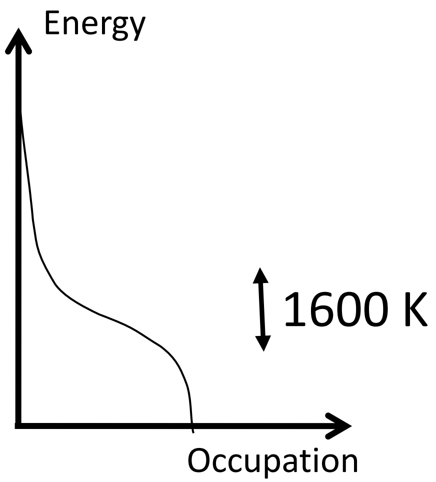
FePt $L1_0$ “noble metal“



Large electron
specific heat

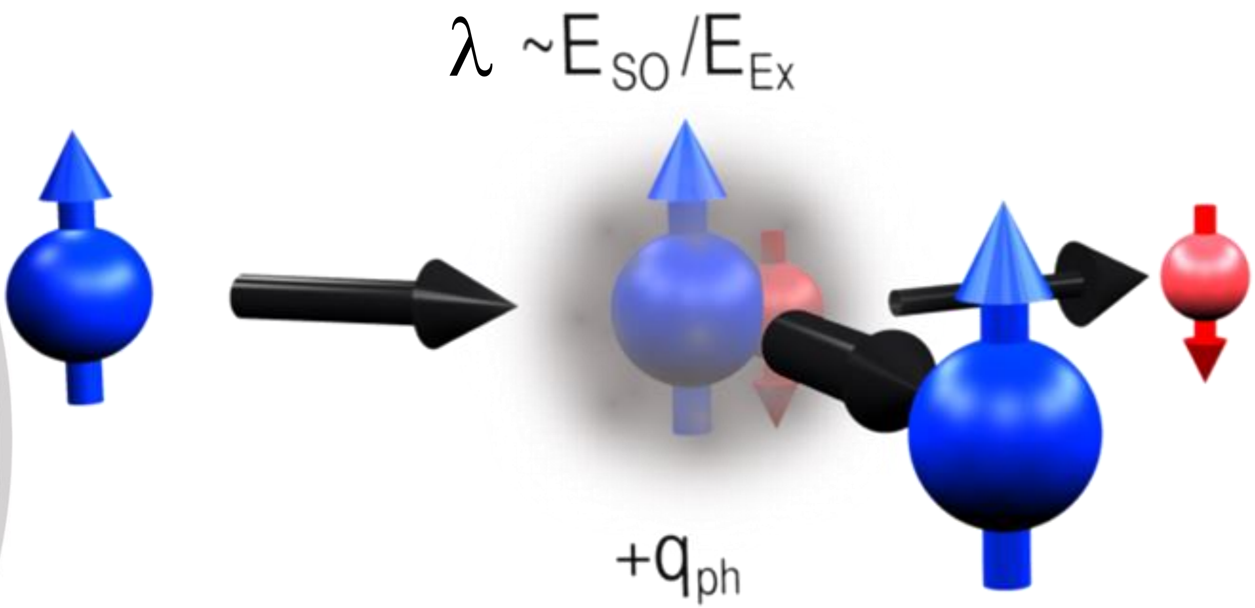
$$c_e = \gamma_e T$$





FePt optical writing a storage media

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456



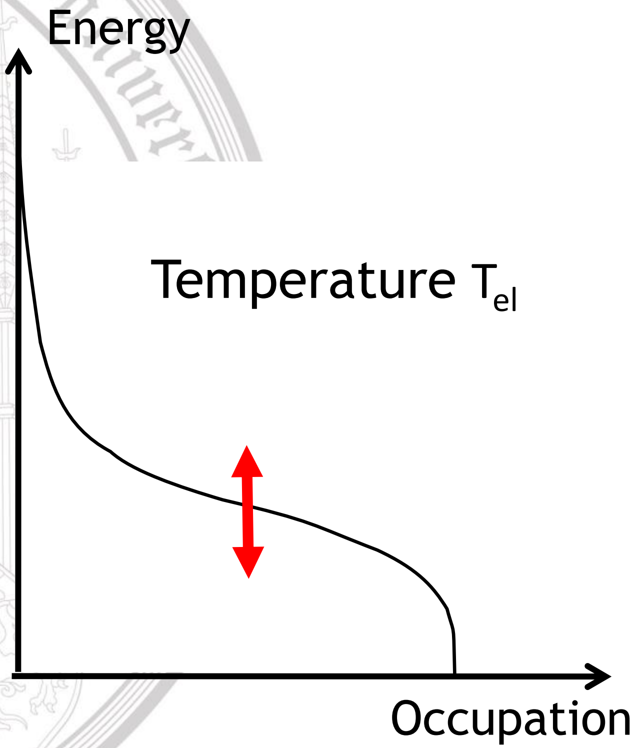
Spin scattering

Spin-orbit coupling:
•Mixes spin-up and spin-down states

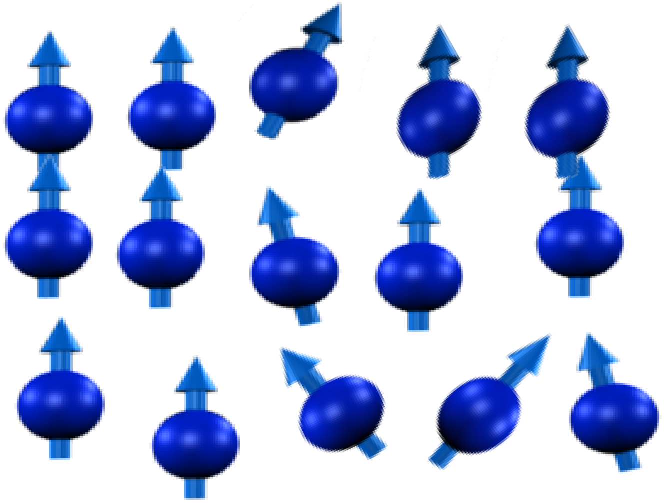
U. Atxitia, *Phys. Rev. B* 81, 174401 (2010).
M. Münzenberg, *New's View's* (2010)

FePt optical writing a storage media

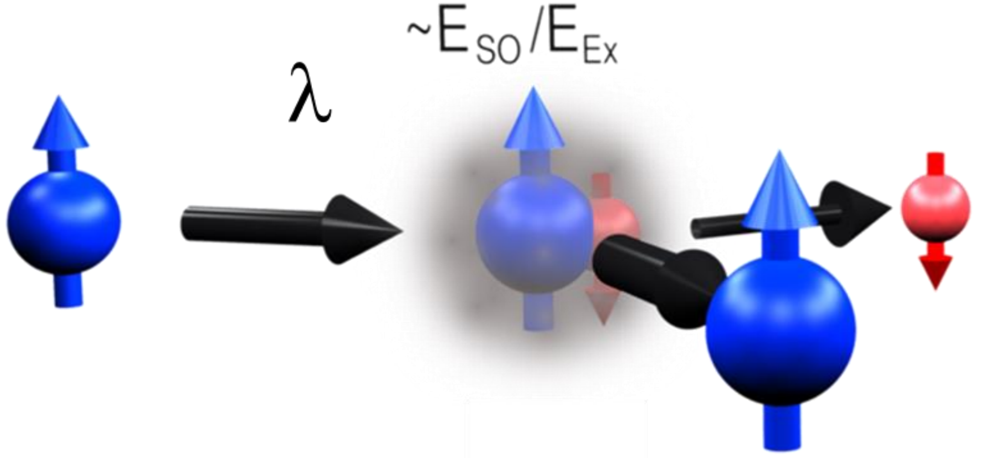
- Coupling of electrons and spins

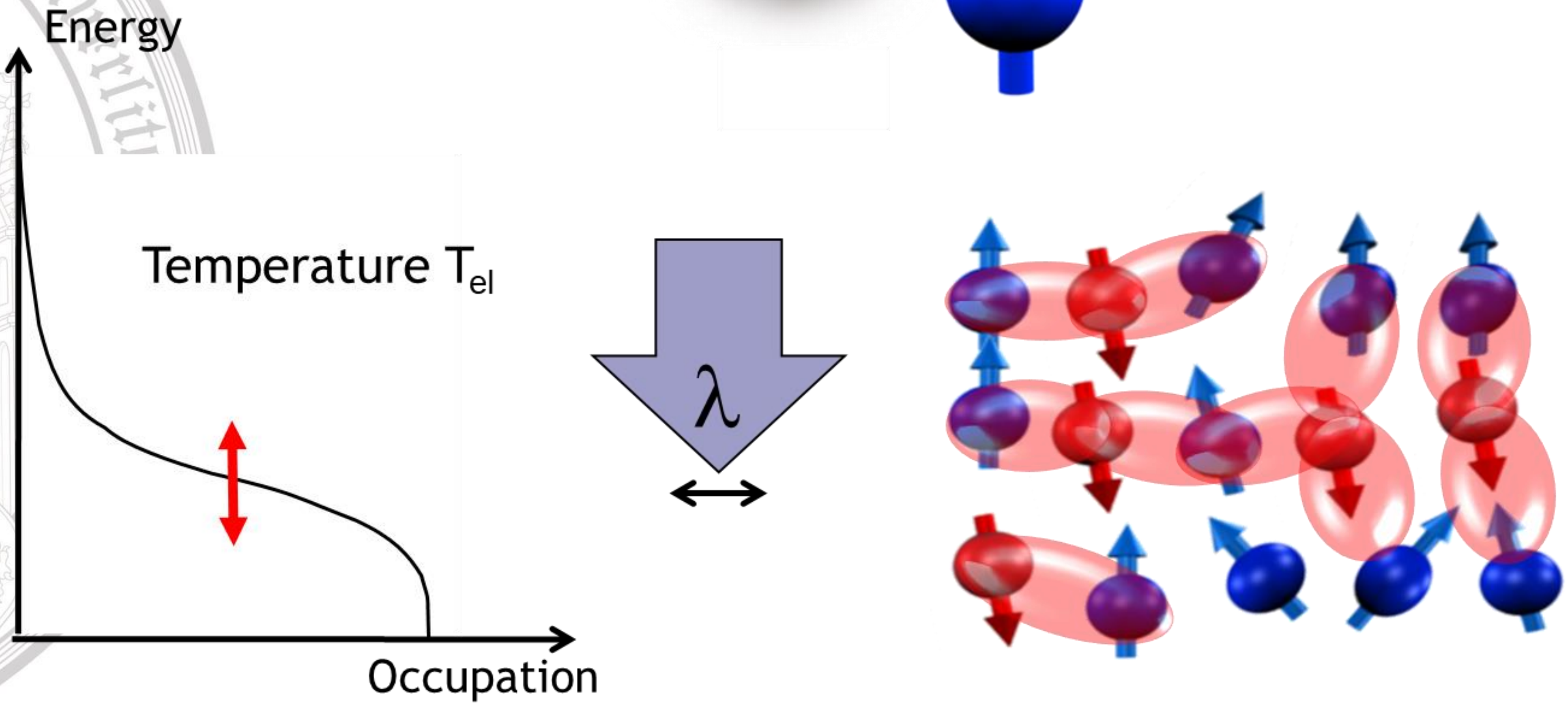


↔



FePt optical writing a storage media





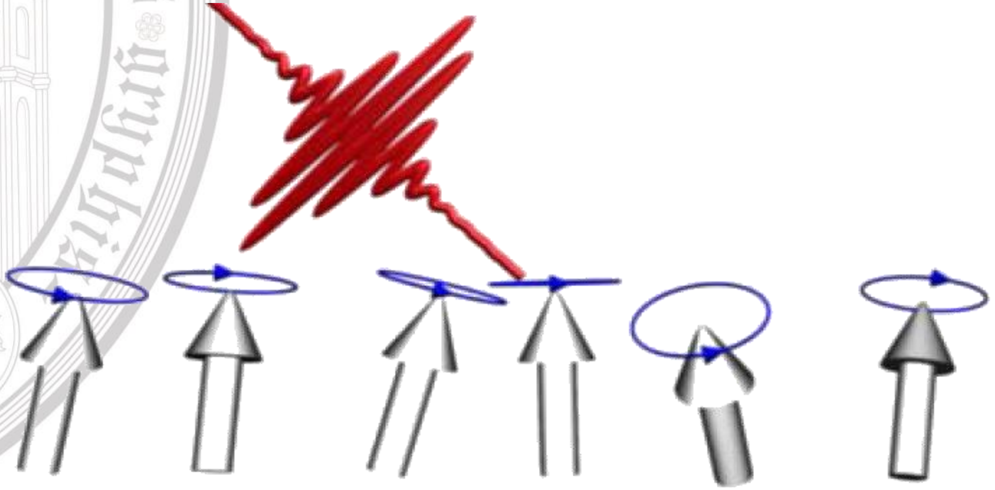
Thermal model of ultrafast demagnetization

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Magnetization dynamics with magnetic fluctuations

$$\frac{dm_i}{dt} = \gamma\, m_i \times H_{eff}(T_{el}, \lambda) + \frac{\gamma\alpha}{m^2} m_i \times m_i \times H_{eff}$$

Include stochastic fluctuations of the spin system by a Fokker-Planck equation



D.A. Garanin, Phys. Rev. B 55, 1997, R. Chantrell, U. Novak, O. Fesenko 2007

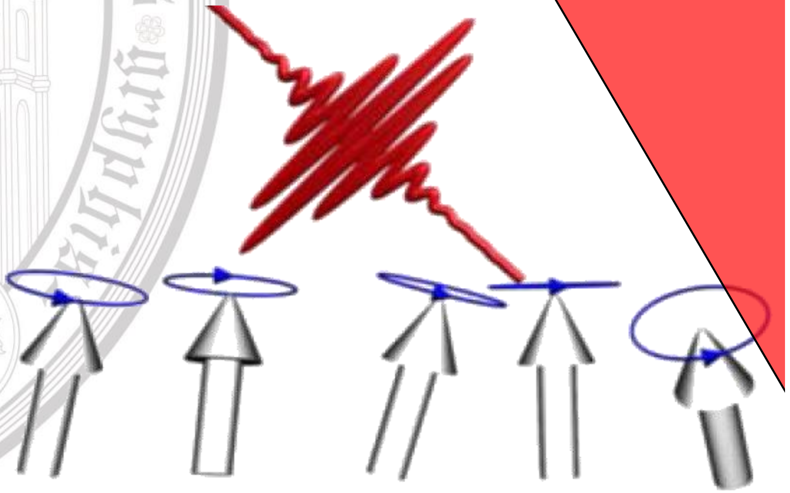
Thermal model of ultrafast demagnetization

Magnetization dynamics: Landau-Lifshitz-Bloch equation

m, α and H_{eff}, are coupled to electron temperature T_{el}

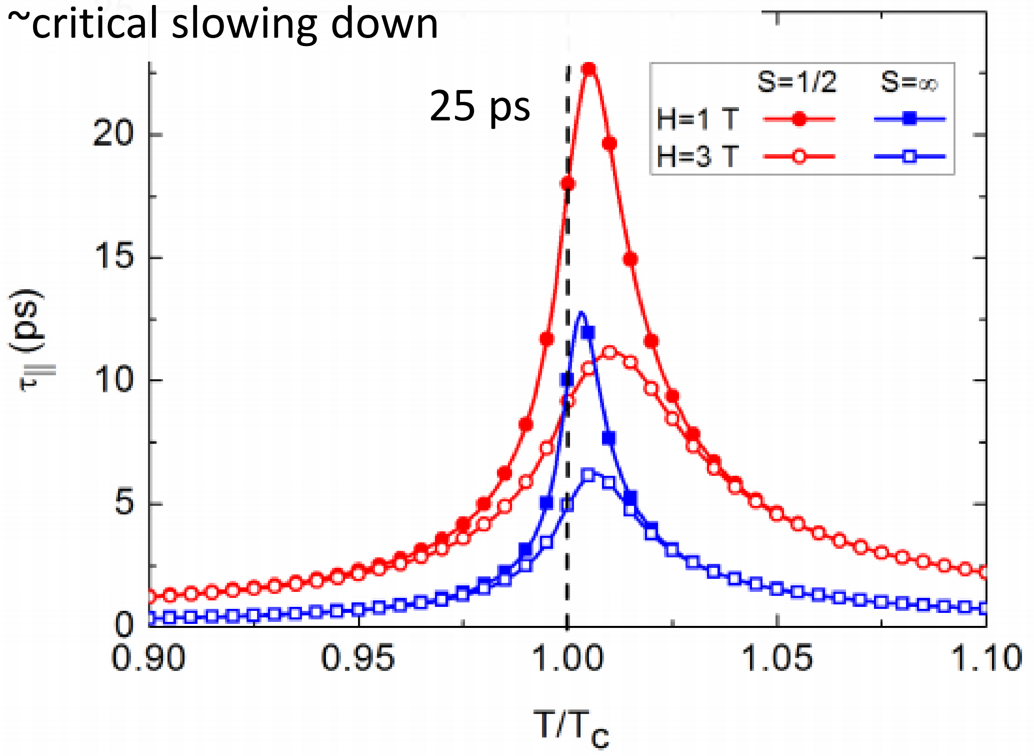
$$\frac{dm}{dt} = \gamma\, m \times H_{eff}(T_{el}) + \frac{\gamma \alpha_{||}(T_{el})}{m^2}\left(m \cdot \right.$$

$$H_{therm} = \frac{1}{\tilde{\chi}_{||}}\left(1 - \frac{m^2}{m_e(T_{el})^2}\right) m \qquad T \leq T_c$$



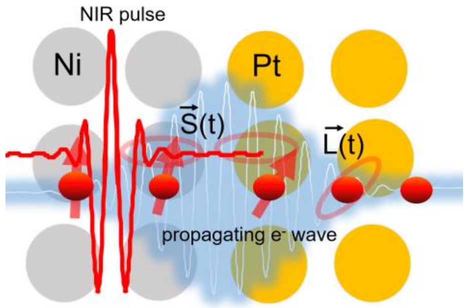
Signature of the phase transition:

~critical slowing down



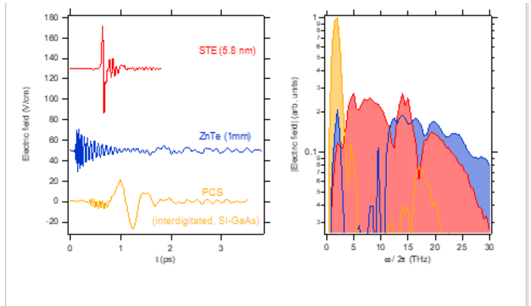
D.A. Garanin, Phys. Rev. B 55, 1997, R. Chantrell, U. Novak, O. Fesenko 2007

Outline



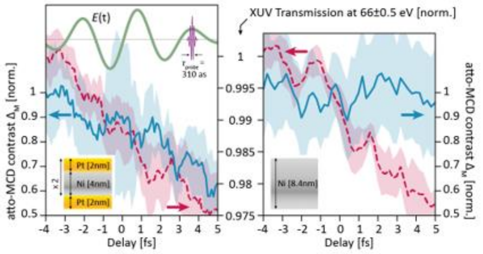
- Introduction

  - THz spintronic emitter – *applications*



T. Seifert, et al. Nature Photonics (2016)

  - Lightwave electronics – *coherent spintronics*

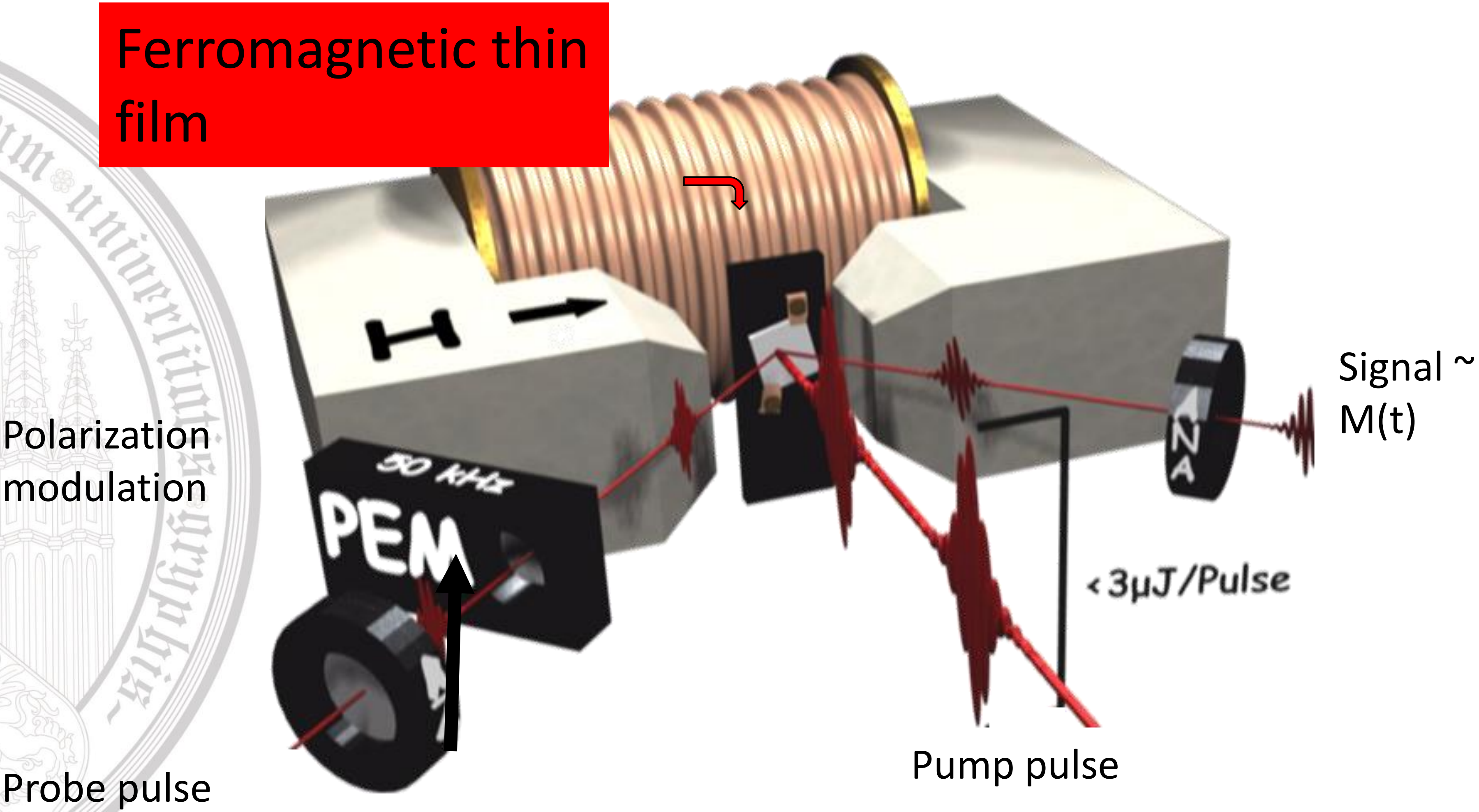


F. Siegrist *et al.*, Light-wave dynamic control of magnetism, Nature **571**, 240–244 (2019)

- Summary

Femtosecond pump-probe

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

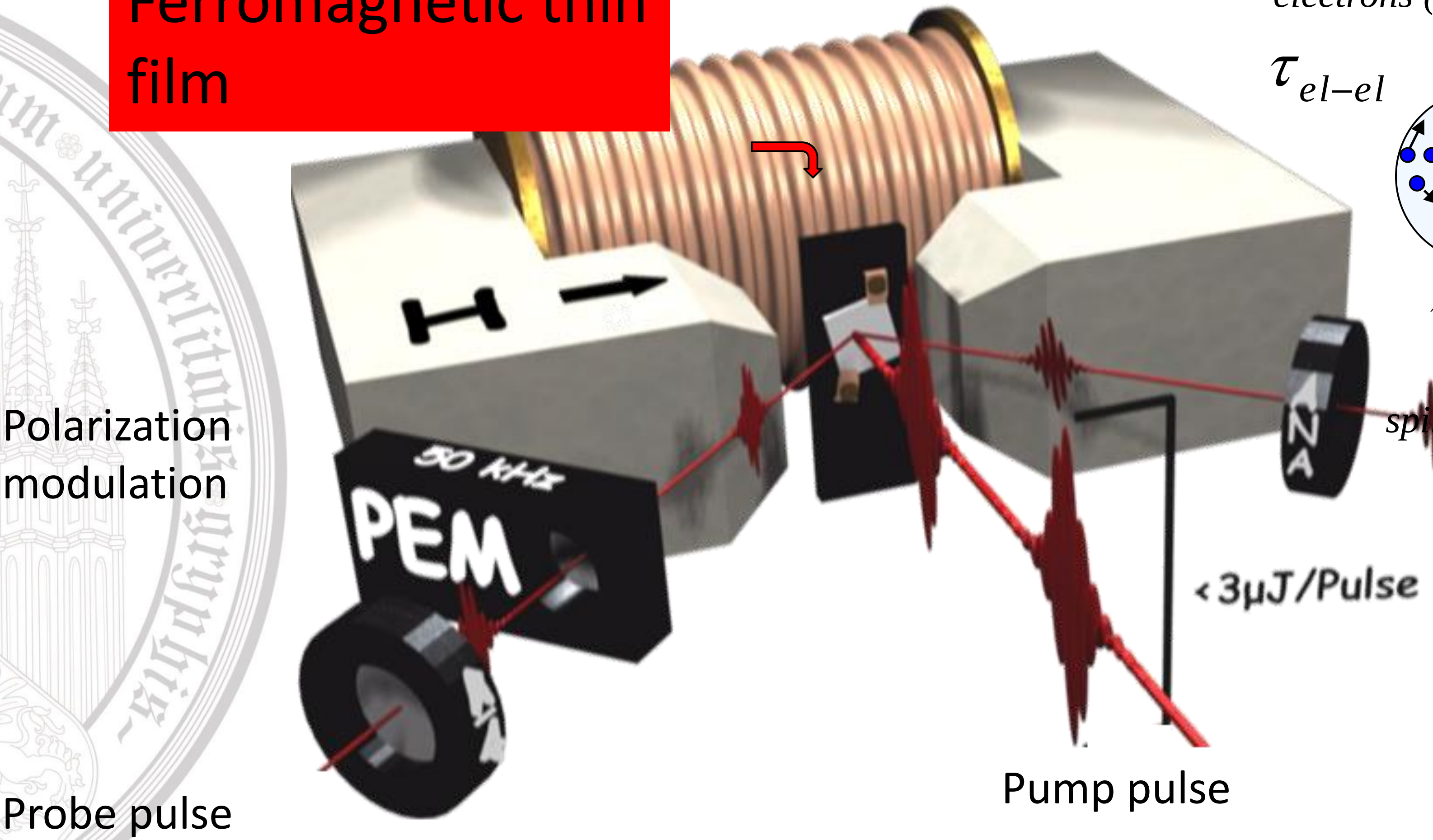


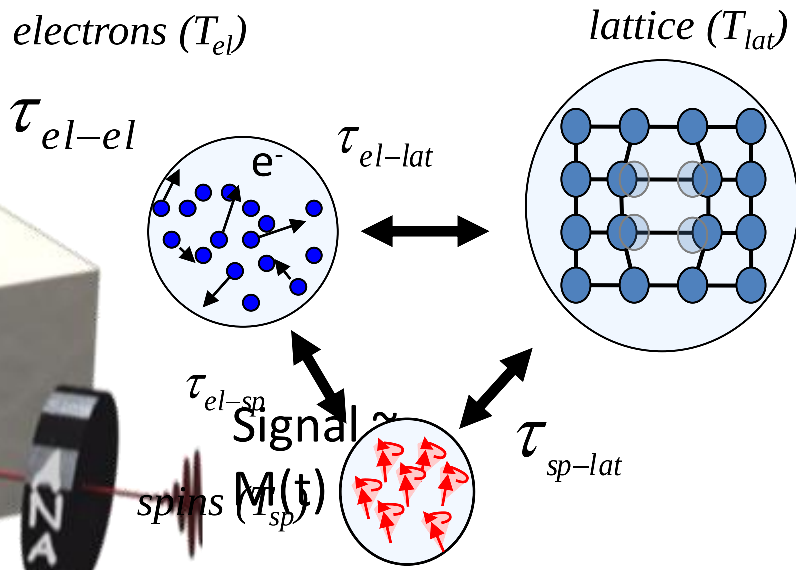
- Access to ultrafast the relaxation (40 fs, λ=800nm)

M. Djordjevic, PRB **75**, 012404 (2007)

Femtosecond pump-probe

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

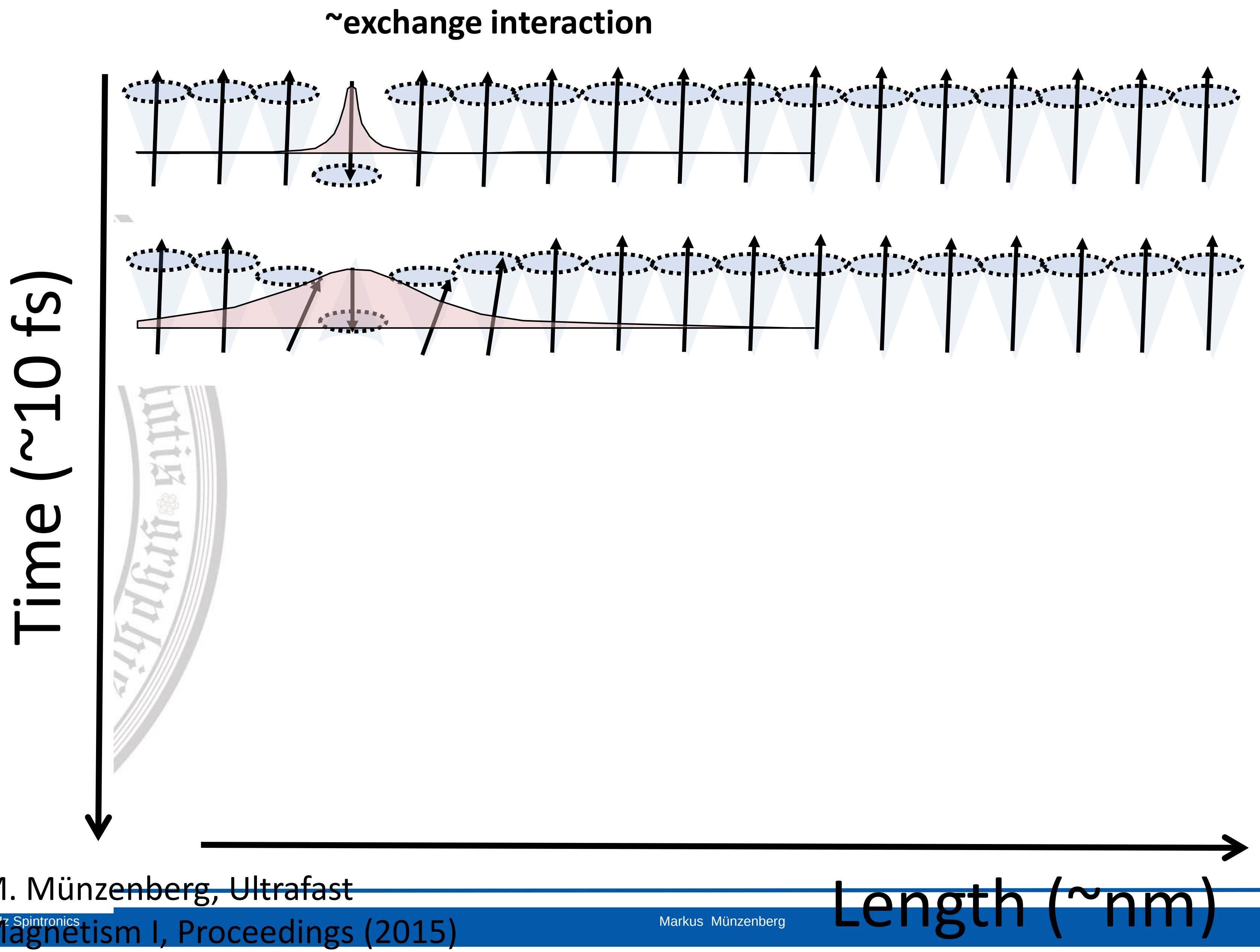




- Access to ultrafast the relaxation (40 fs, λ=800nm)

M. Djordjevic, PRB **75**, 012404 (2007)

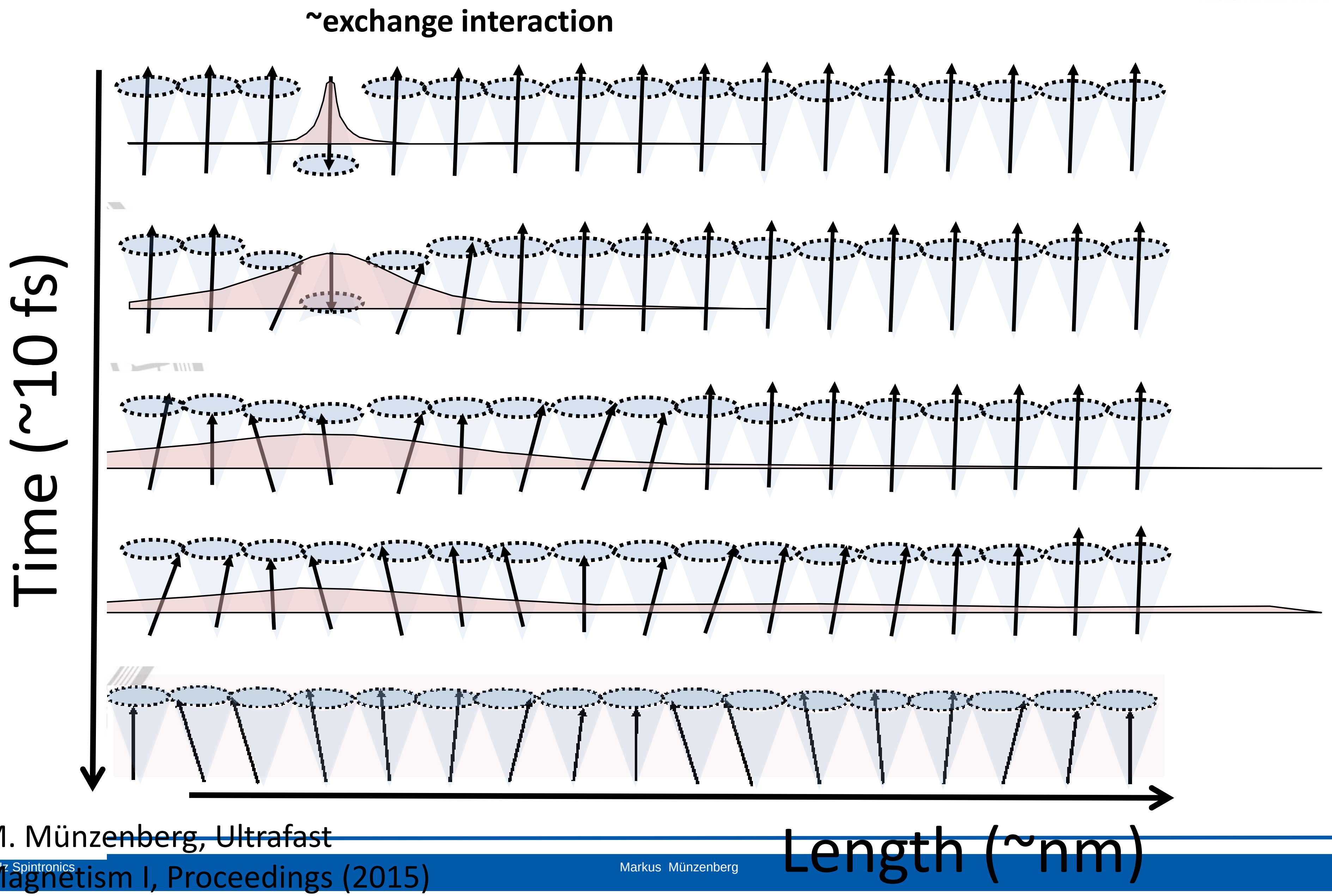
Ultrafast: spins



M. Münzenberg, Ultrafast Magnetism I, Proceedings (2015)

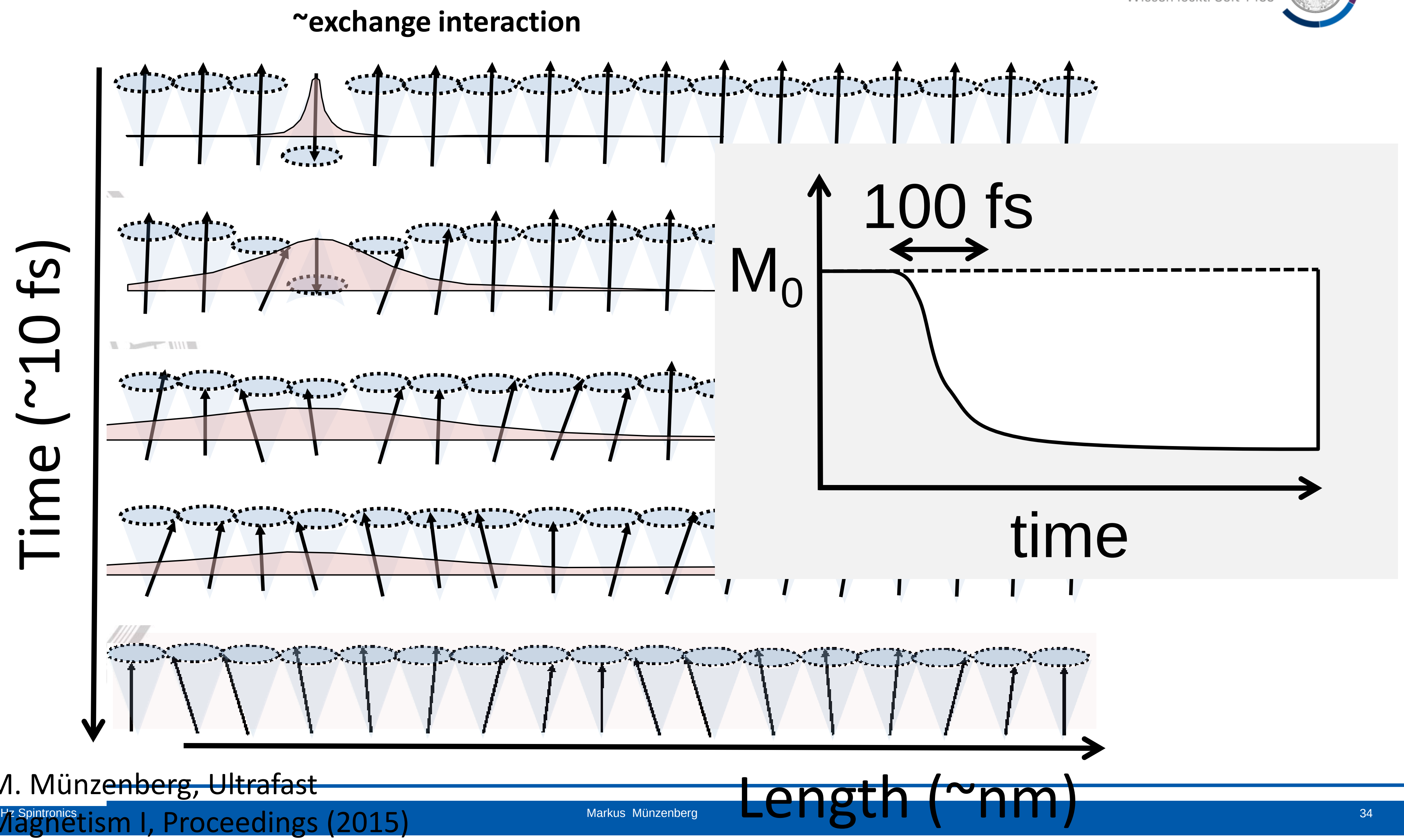
Ultrafast: spins

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456



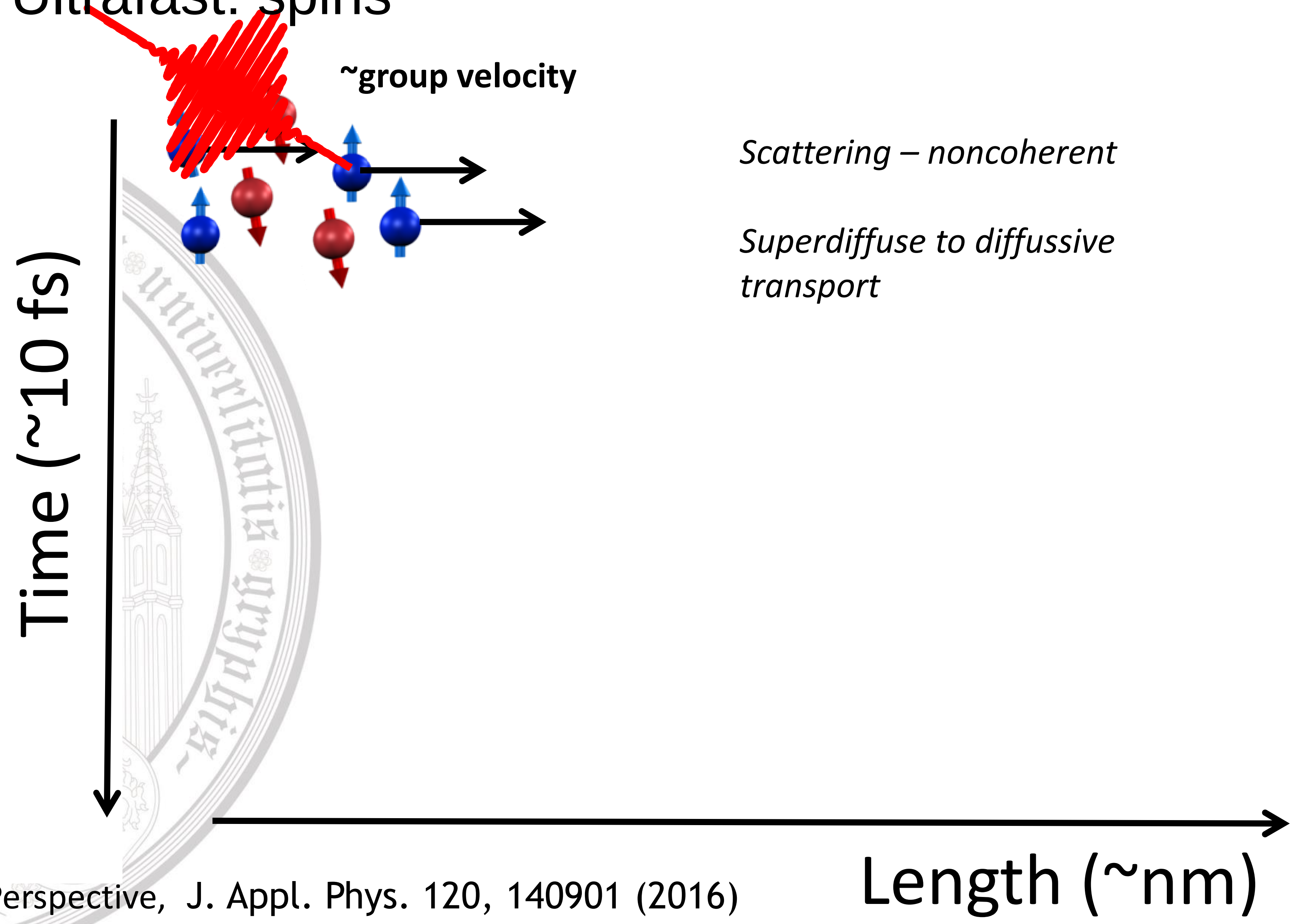
M. Münzenberg, Ultrafast Magnetism I, Proceedings (2015)

Ultrafast: spins



M. Münzenberg, Ultrafast Magnetism I, Proceedings (2015)

Ultrafast: spins

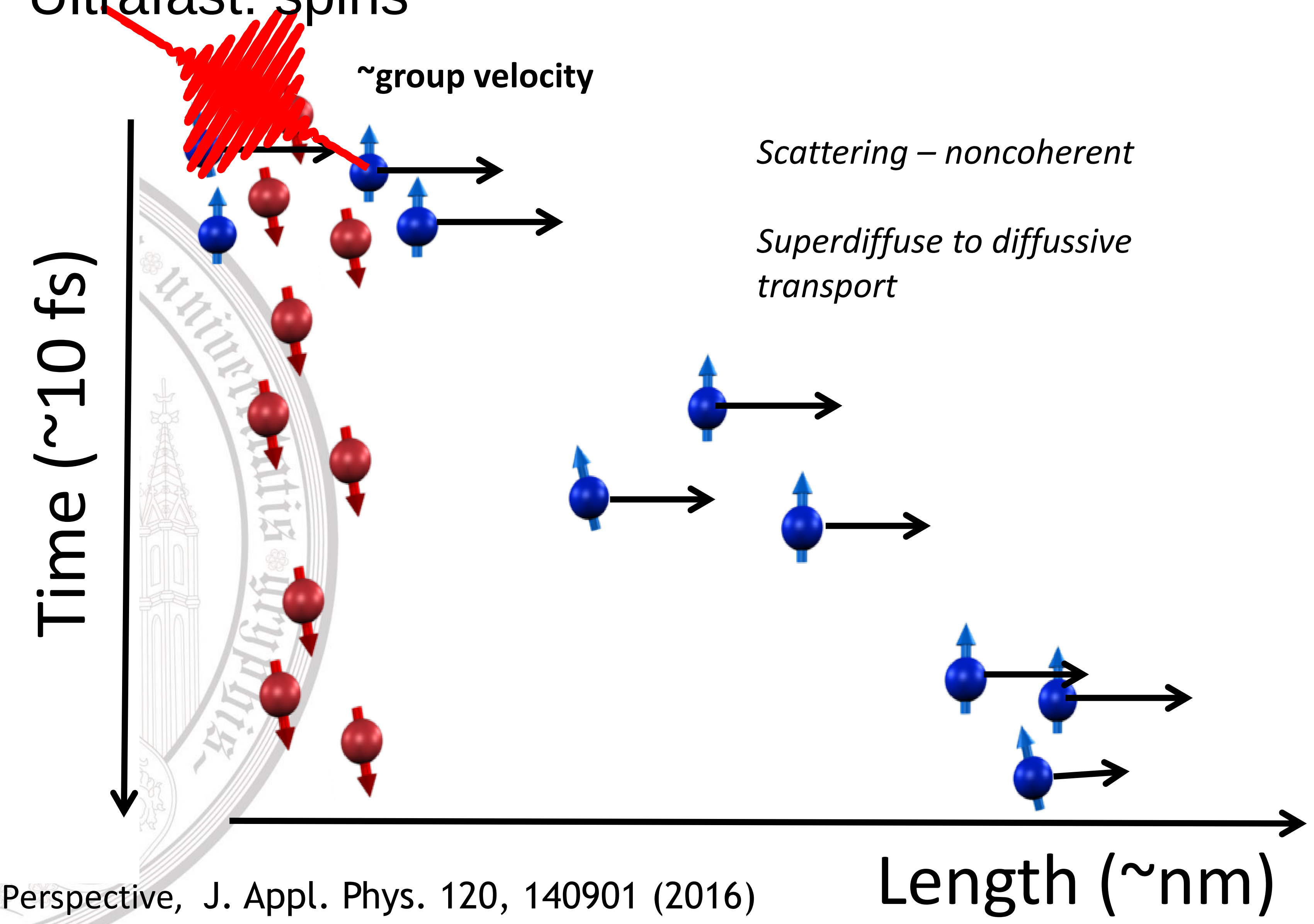


Scattering – noncoherent

Superdiffuse to diffussive transport

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

Ultrafast: spins

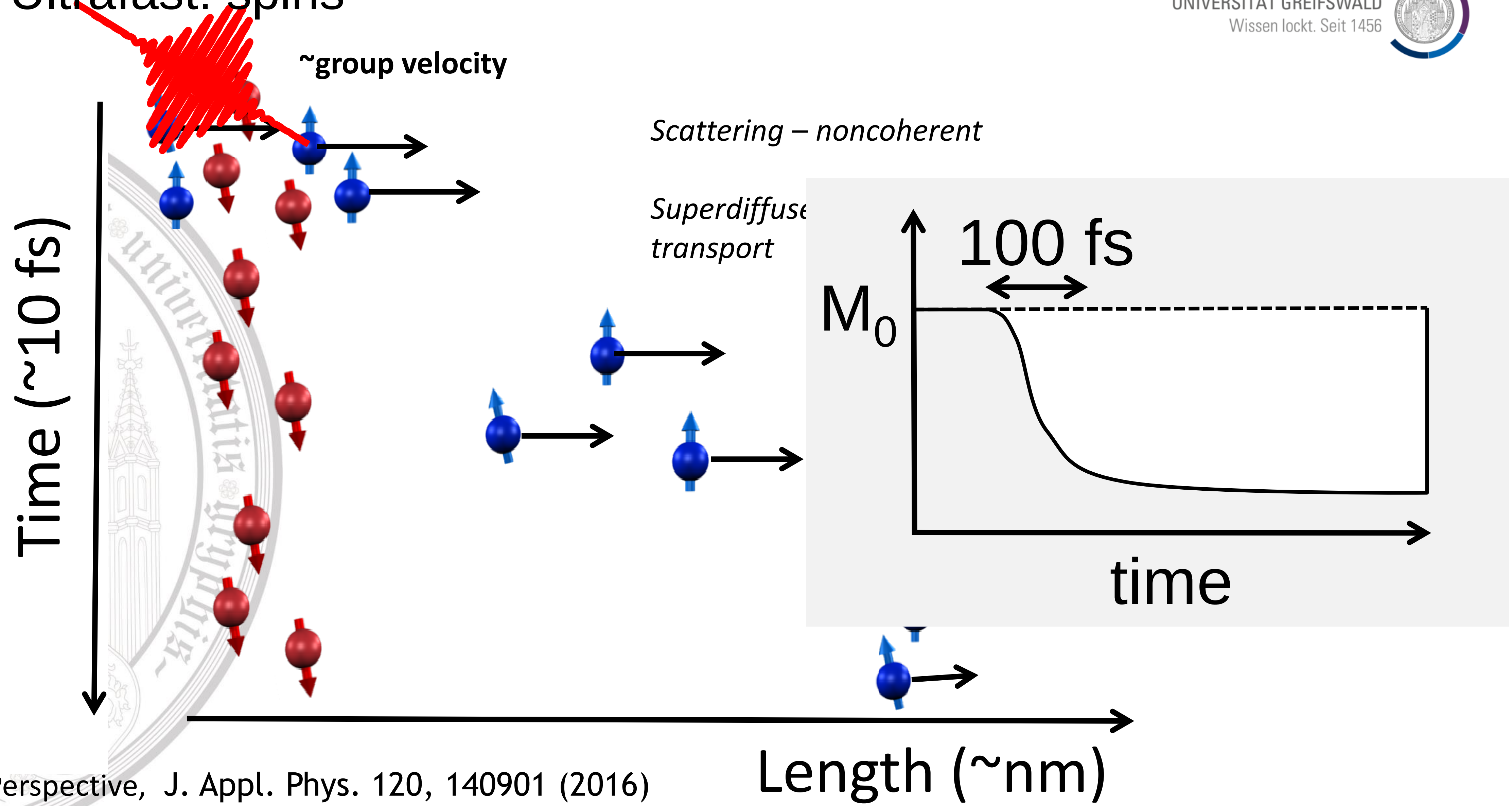


Scattering – noncoherent

Superdiffuse to diffussive transport

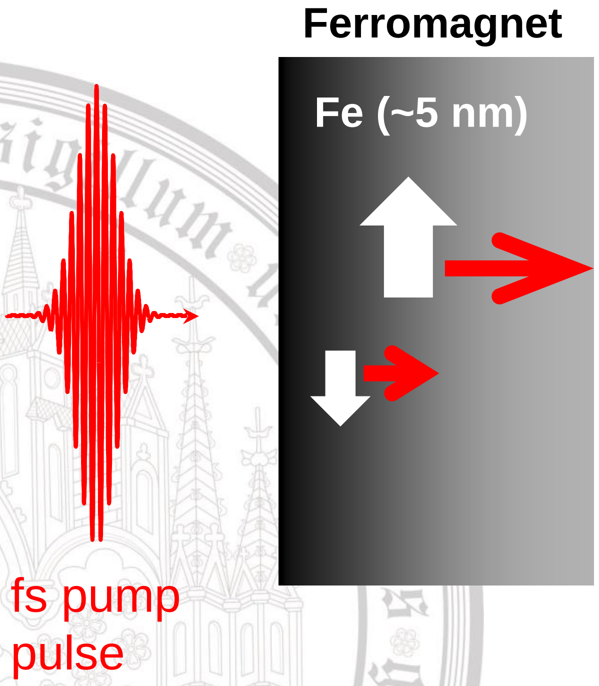
Perspective, J. Appl. Phys. 120, 140901 (2016)

Ultrafast: spins



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

Spintronic THz emitter



Pump pulse excites ↑ and ↓ electrons

↑: d → sp bands ⇒ become fast

↓: d → d bands ⇒ stay slow

Battiato *et al.,* PRL (2010)

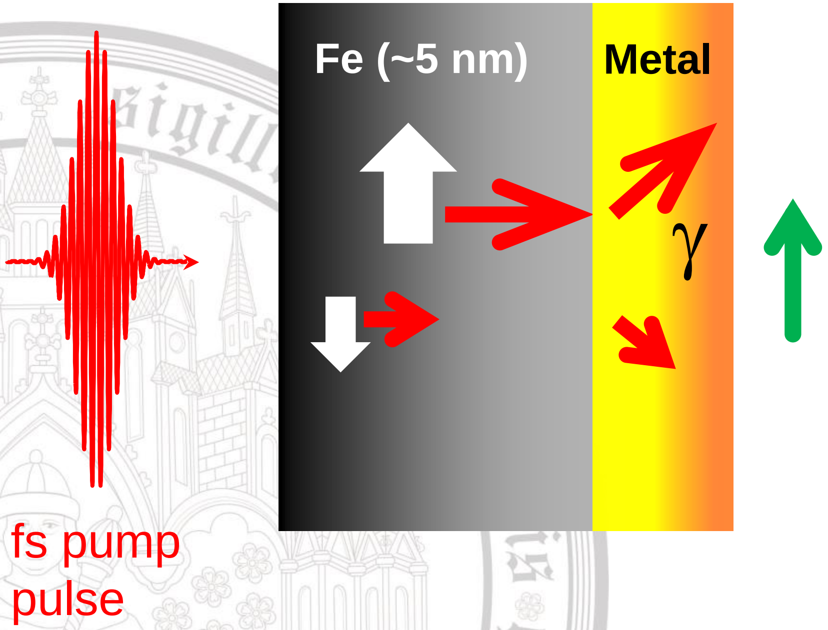
⇒ Pump launches spin-polarized current

Melnikov *et al.,* PRL (2011)
Rudolf *et al.*, NatComm (2012)
Turgut *et al.*, PRL (2013)

How to detect the spin current?
Idea: convert spin current into charge current

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

Spintronic THz emitter

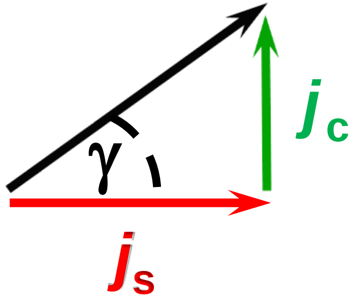


Inverse spin Hall effect (ISHE):

Spin-orbit coupling deflects electrons

$\Rightarrow$ transverse charge current

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

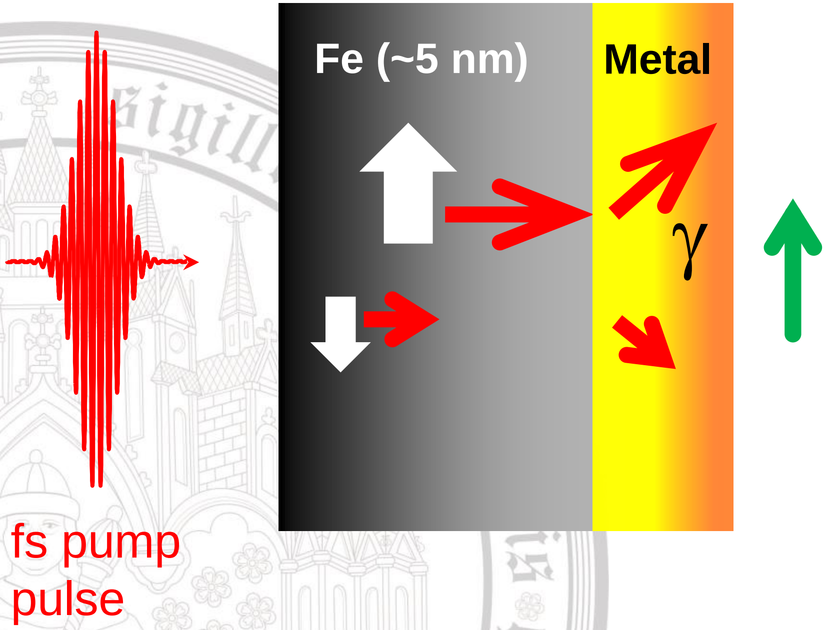


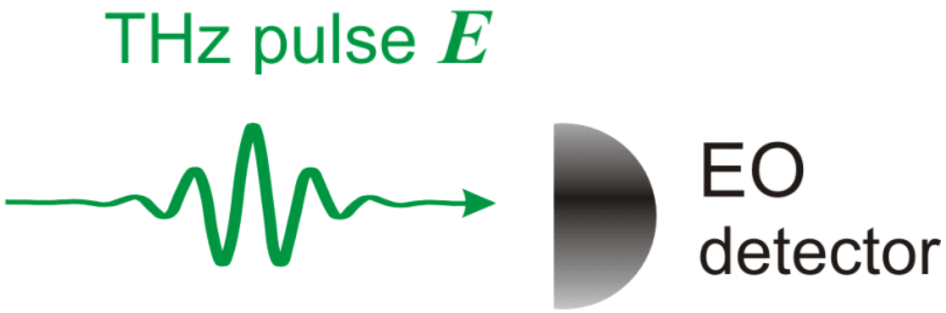
σ_{SH} - spin Hall conductivity

σ_{xx} - diagonal conductivity

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

Spintronic THz emitter





300µm GaP,
10fs gate pulse

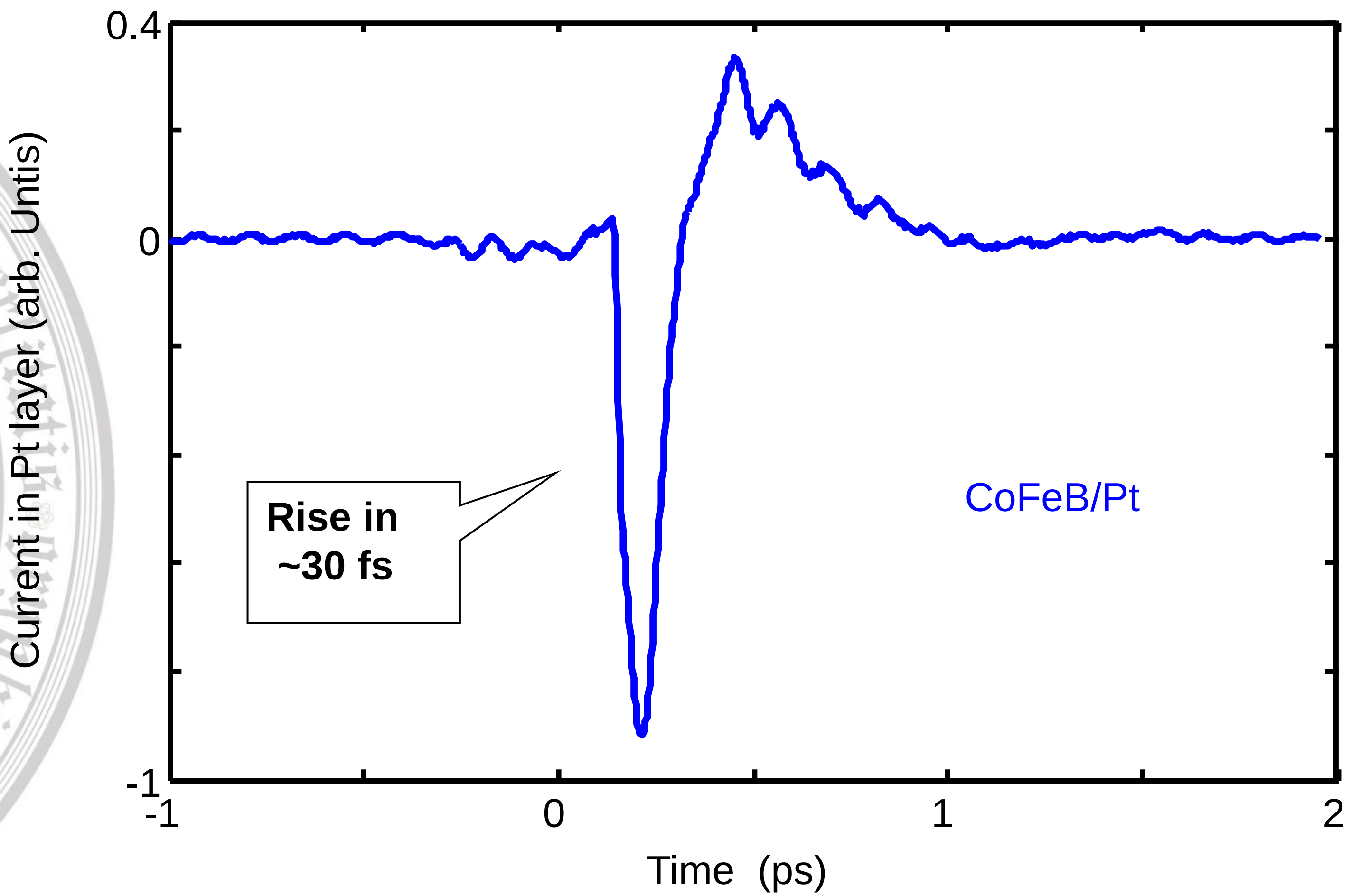
⇒ Measure THz emission from photoexcited FM/NM bilayers

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

Spintronic THz emitter

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

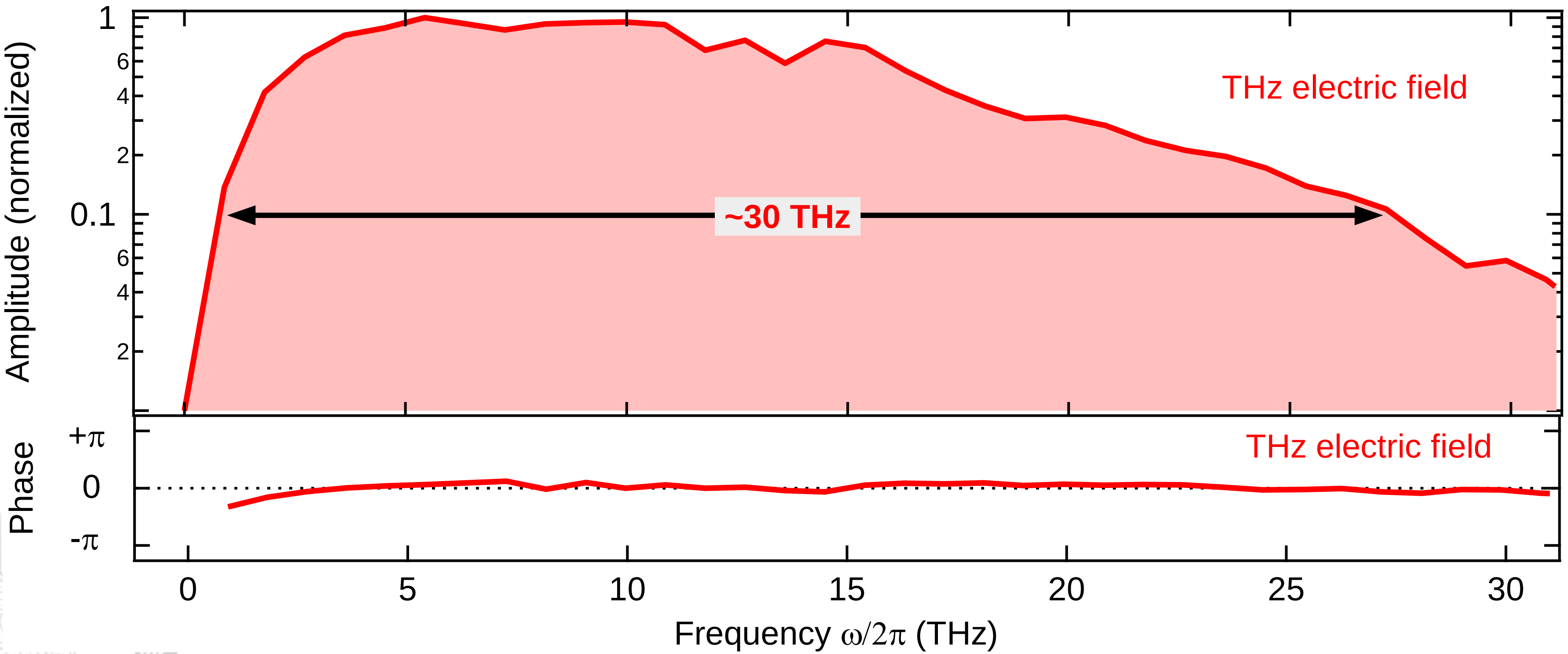
THz Pt sheet current



Reveals spin transport dynamics with 10 fs resolution

Spintronic THz emitter

Fourier transform of time-domain data yields spectrum



Gap-free emission from 1-30 THz

T. Seifert, et al. Nature Photonics 10, 483–488 (2016)

Spintronic THz emitter

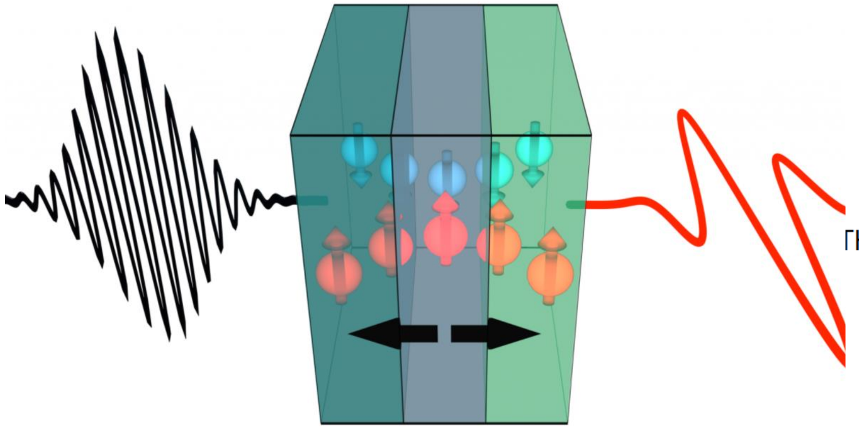
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

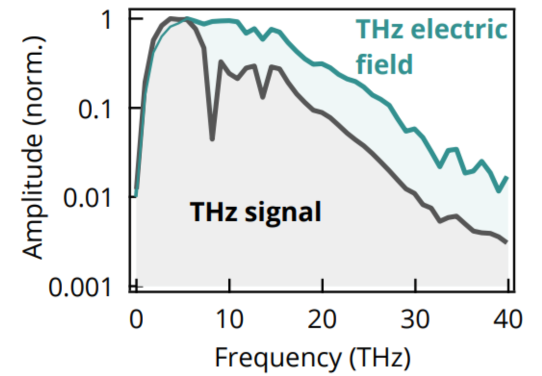
TeraSpinTec

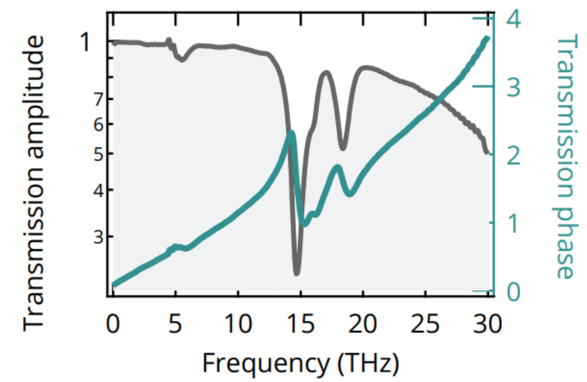
Home Products Insights Contact

Your Key to Ultrabroadband Terahertz Spectroscopy

Spin it right.





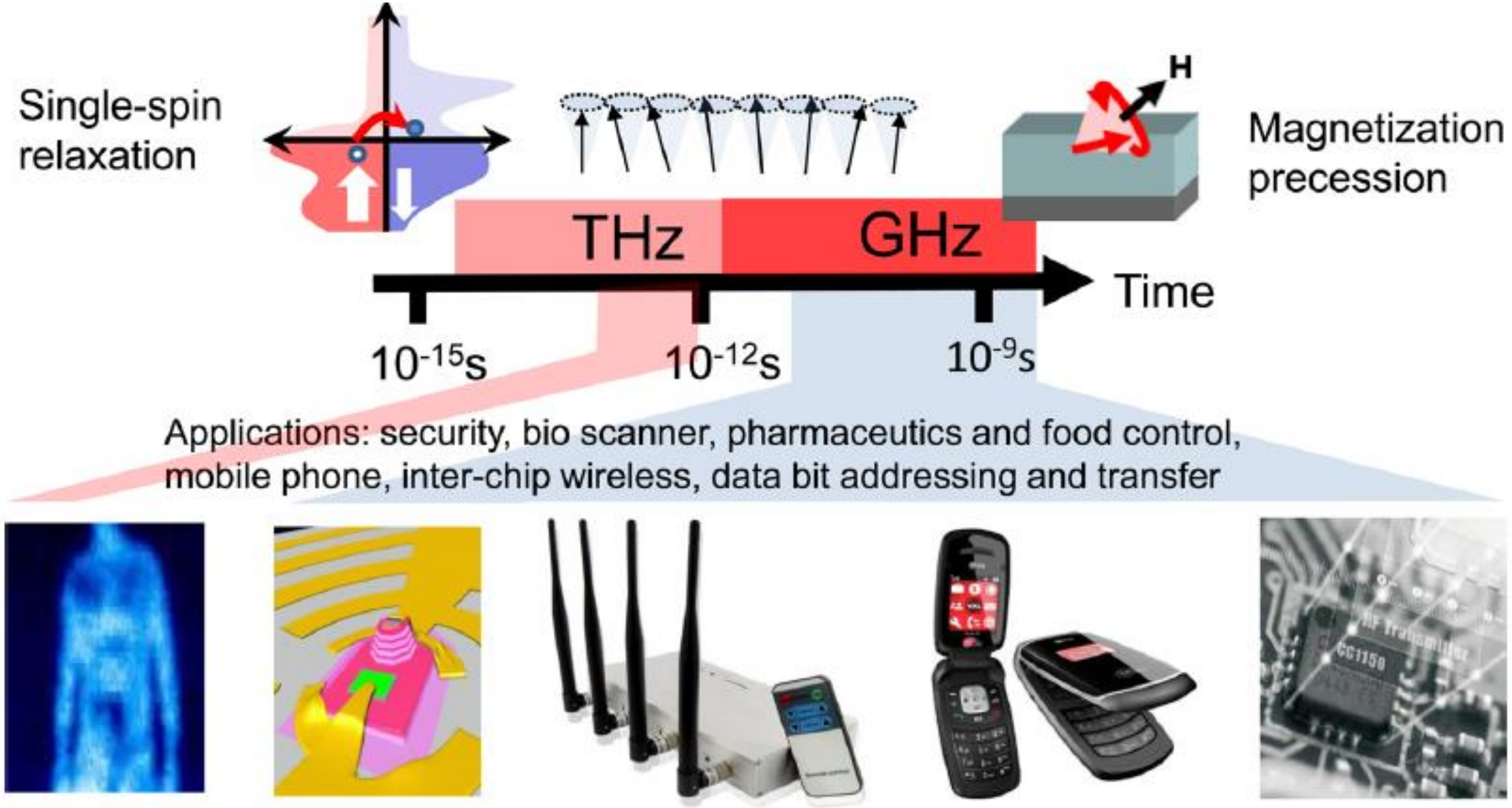


Let our innovative spintronic terahertz emitter

T-Spin

Robust, low cost, scalable, easy to handle and flexible

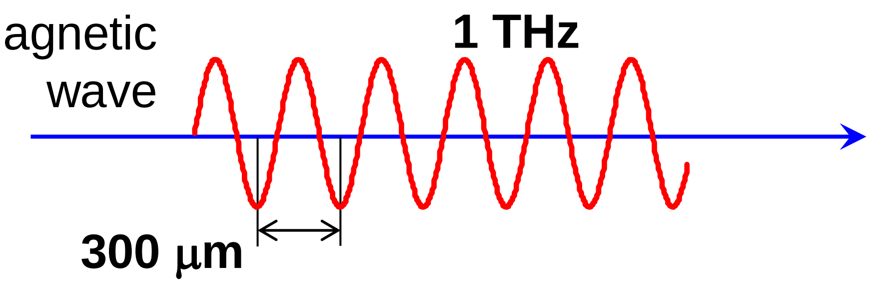
Novel spintronic THz applications



Communicationand data frequencies:
3G and LTE: 0.7 to 2.6 GHz 5G: 24.25 – 27.5 GHz
6G reaches THz frequency: > 95 GHz to 3 THz range

Novel spintronic THz applications

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

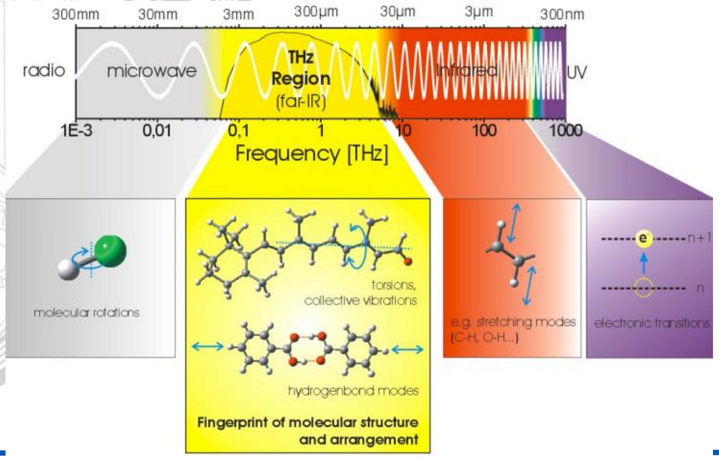


1 THz
$= 10^{12}$ Hz
$= (1\text{ps})^{-1}$

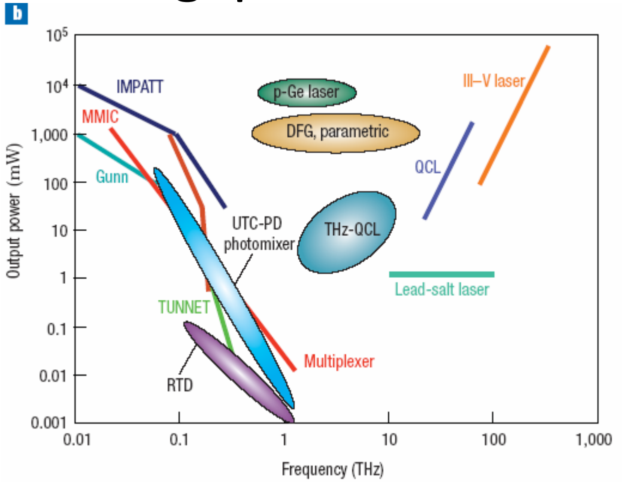
RF cm-waves | **THz window 0.3 … 30 THz** | IR VIS UV

Electronics | **Photonics (lasers)**

Biophysical and medical sensing



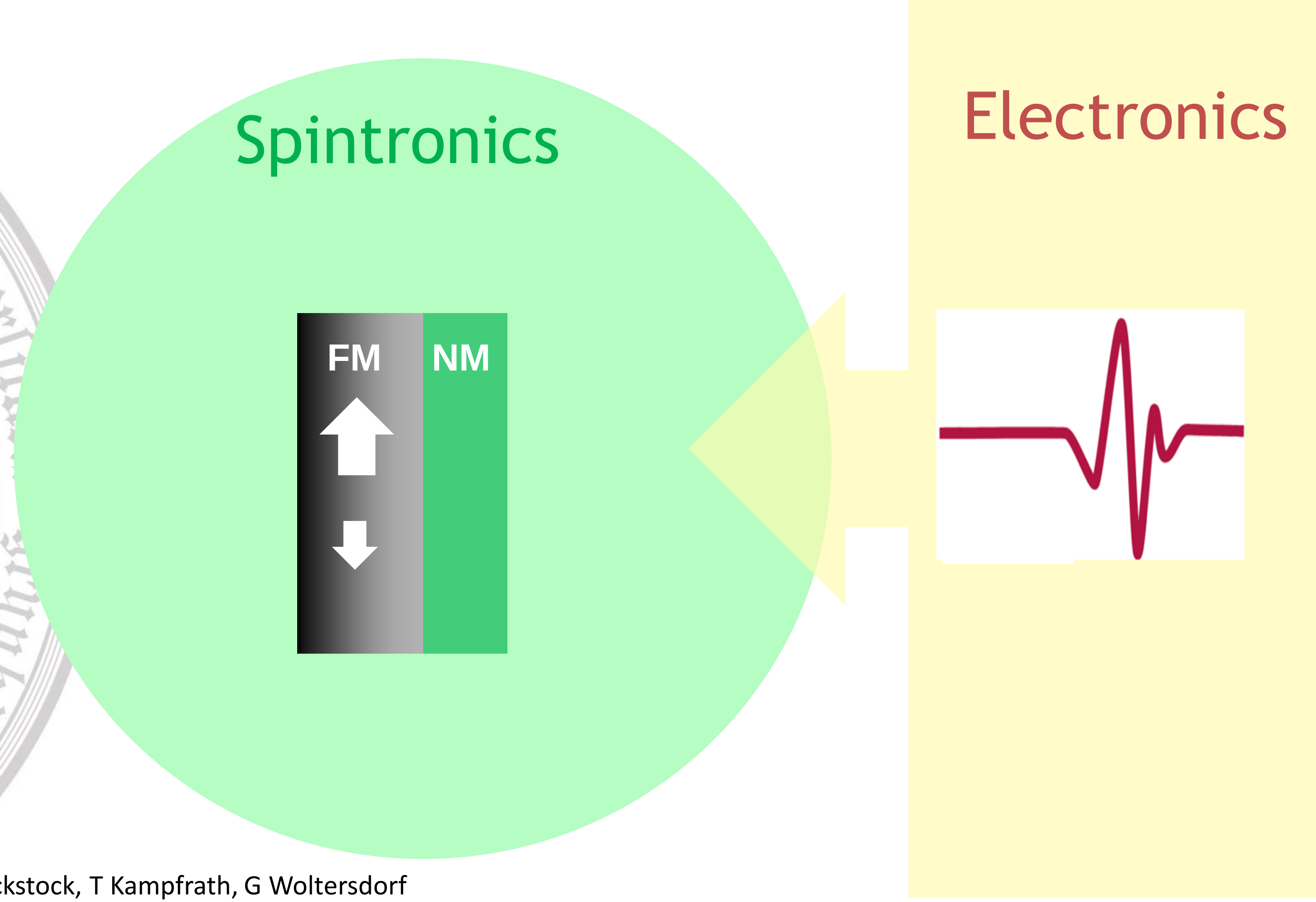
Novel THz sources bridge the THz gap



ZENTREN FÜR INNOVATIONSKOMPETENZ
UNTERNEHMEN REGION
Die BMBF-Innovationsinitiative Neue Länder
Bundesministerium für Bildung und Forschung

META ZIK PlasMark

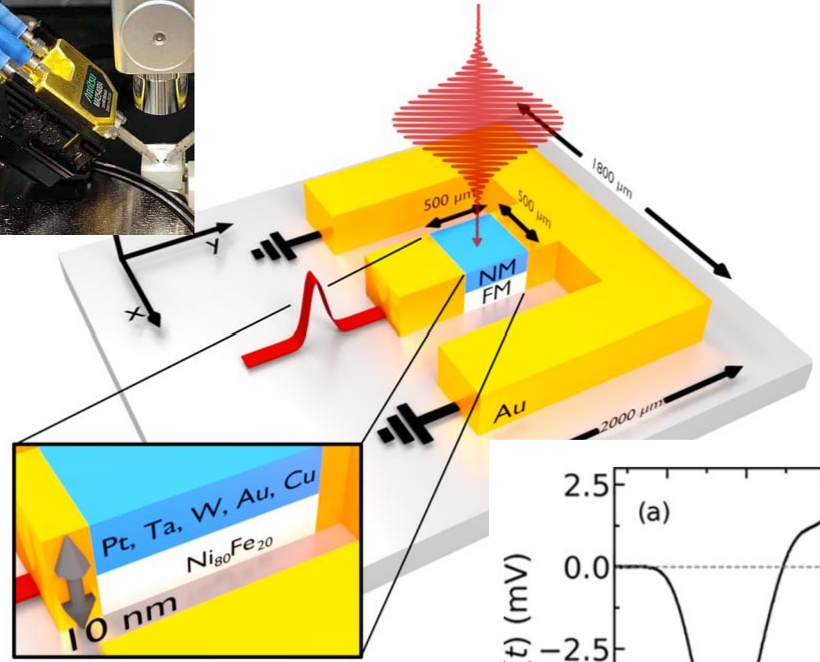
Spintronic THz emitter

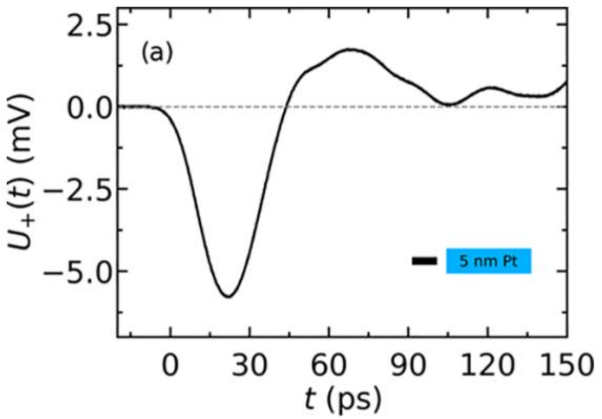


W Hoppe, J Weber, S Tirpanci, O Gueckstock, T Kampfrath, G Woltersdorf
ACS Applied Nano Materials 4 (7), 7454-7460

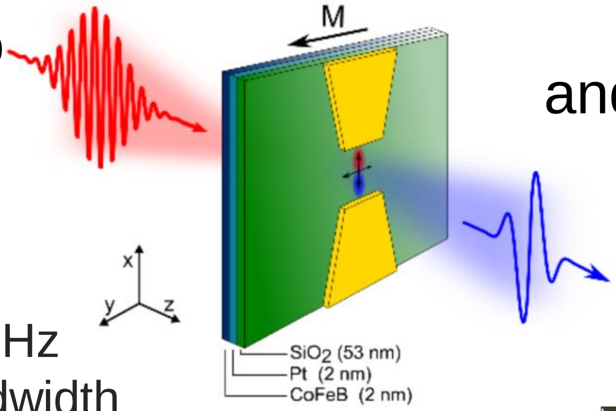
Spintronic THz emitter

Real time current pulses fo electronics: strip line

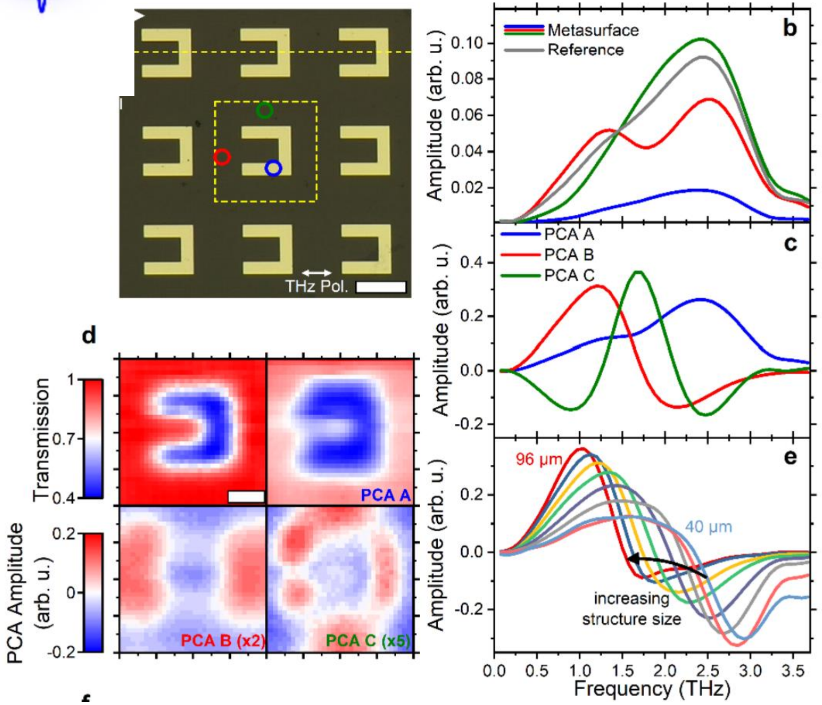




50 GHz Bandwidth



and ring resonator metasurfaces



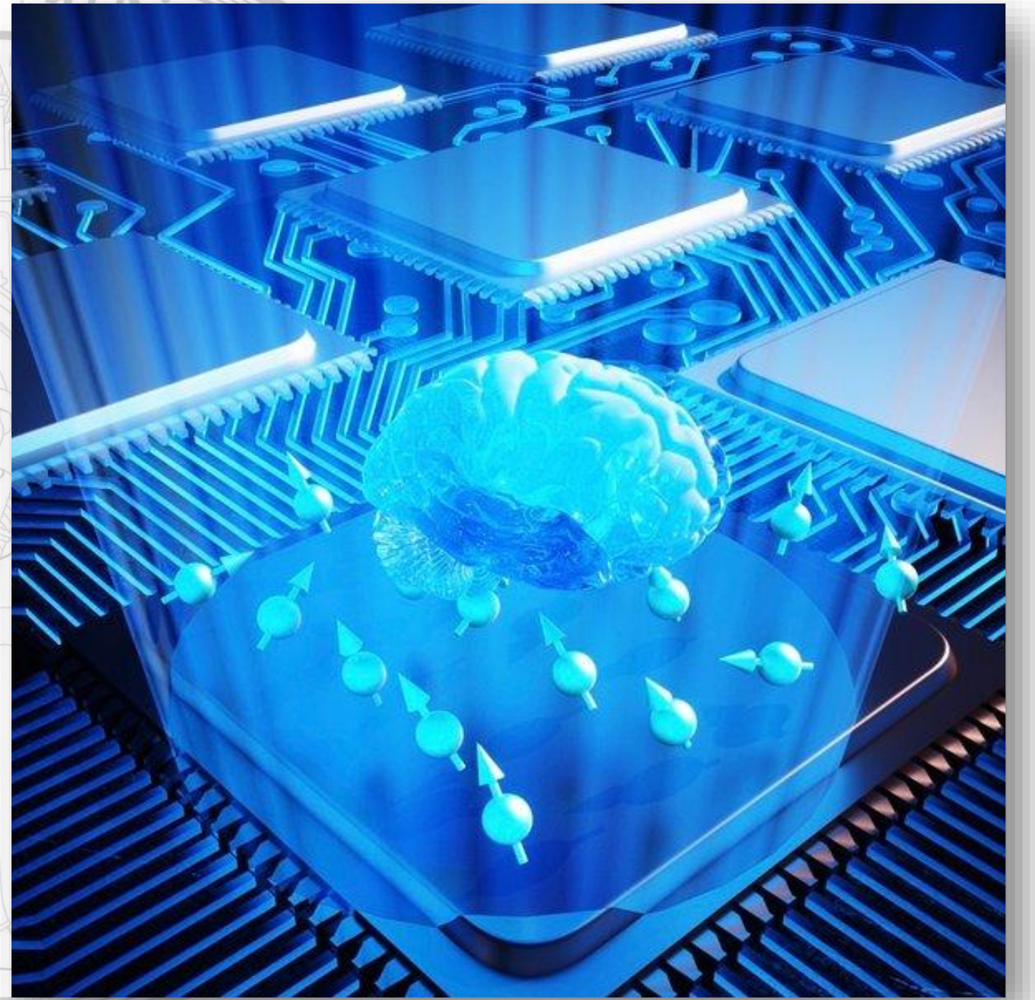
W Hoppe, J Weber, S Tirpanci, O Gueckstock, T Kampfrath, G Woltersdorf
ACS Applied Nano Materials 4 (7), 7454-7460

C. Rathje, R. von Seggern, L. A. Gräper, J. Kredl, J. Walowski, M. Münzenberg, Sascha Schäfer,
arXiv:2209.02542

Spintronic THz emitter

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Fundamental properties of the charge-to-spin conversion

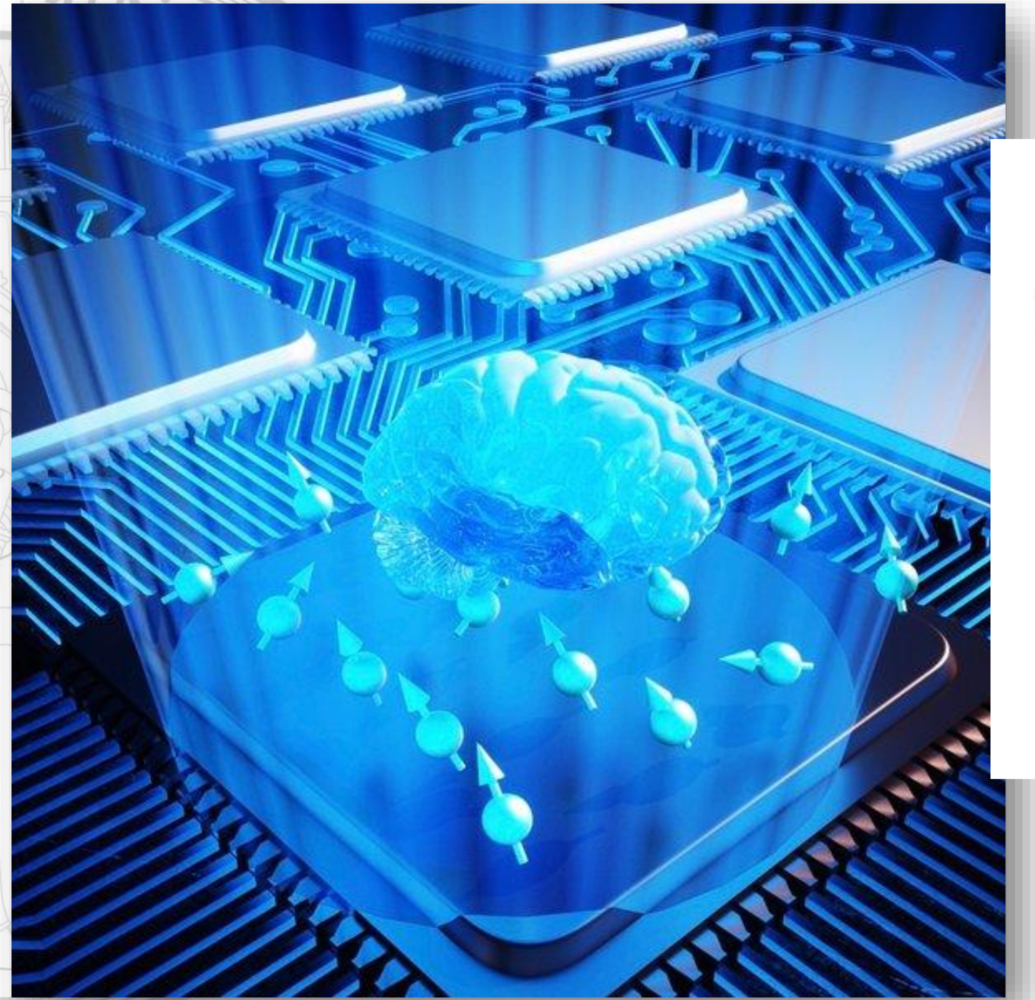


Test for spintronic device optimization

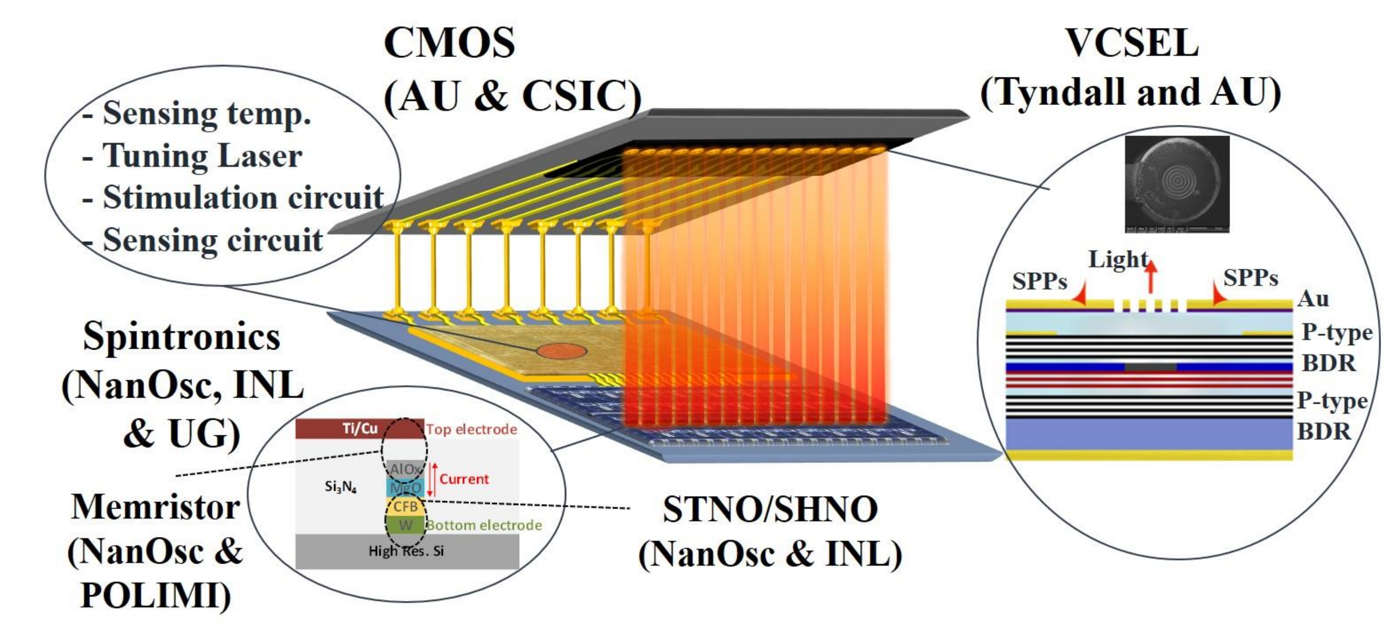
Spintronic THz emitter

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Fundamental properties of the charge-to-spin conversion

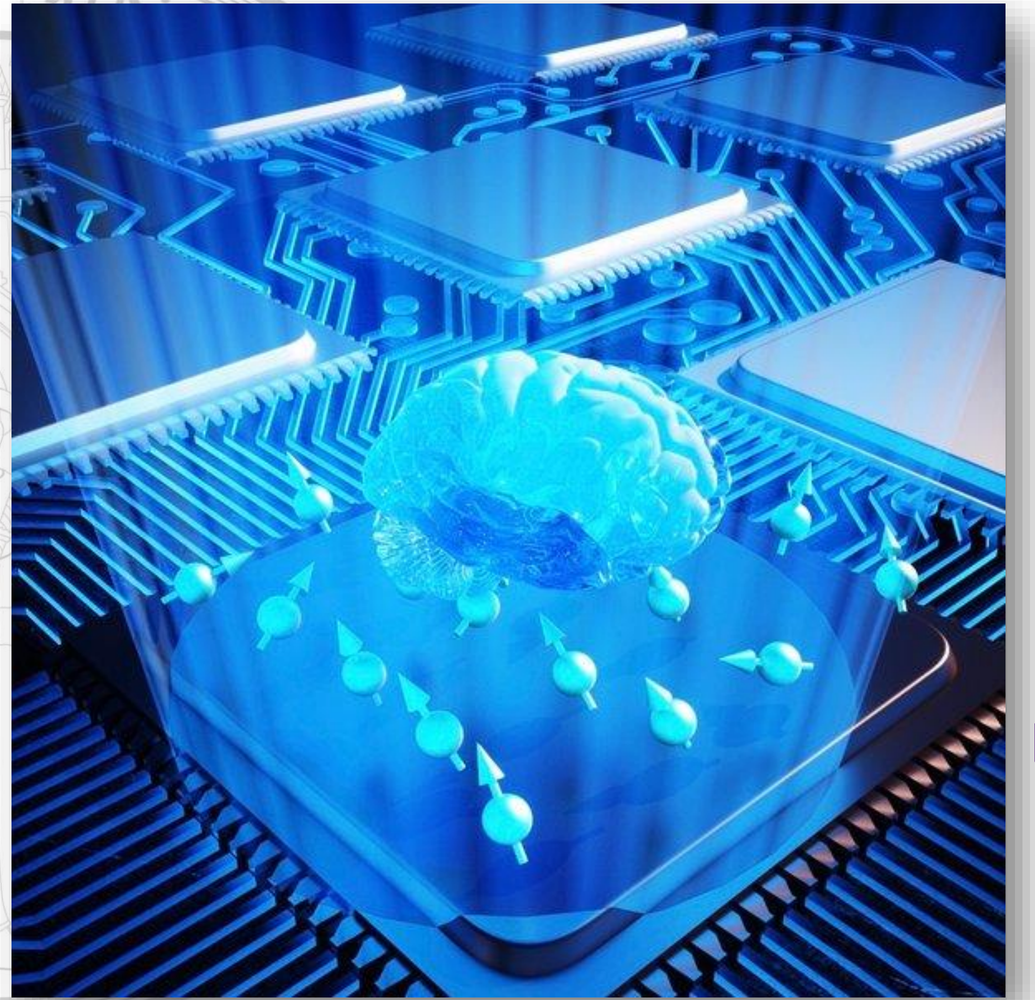


Test for spintronic device optimization

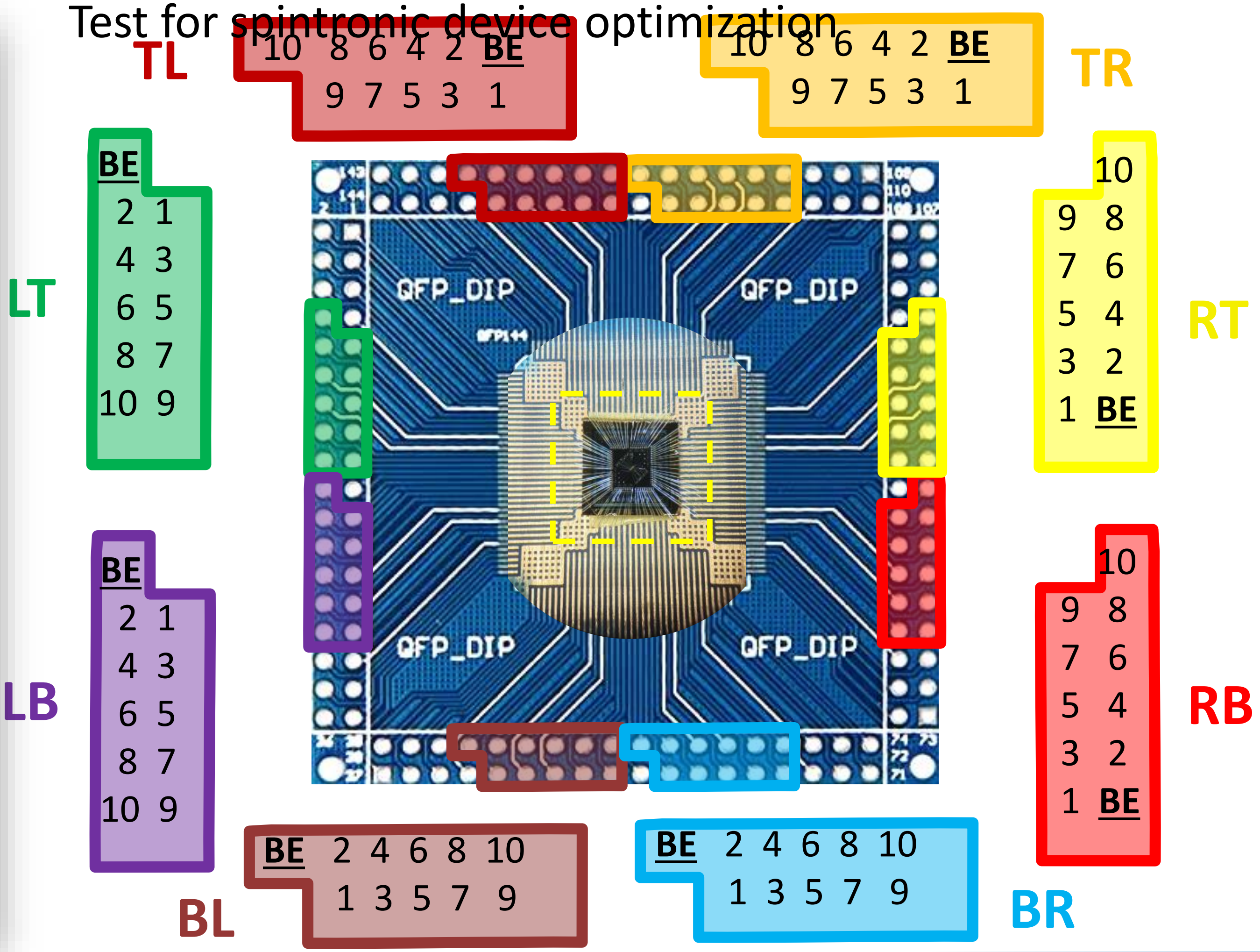


Spintronic THz emitter

Fundamental properties of the charge-to-spin conversion

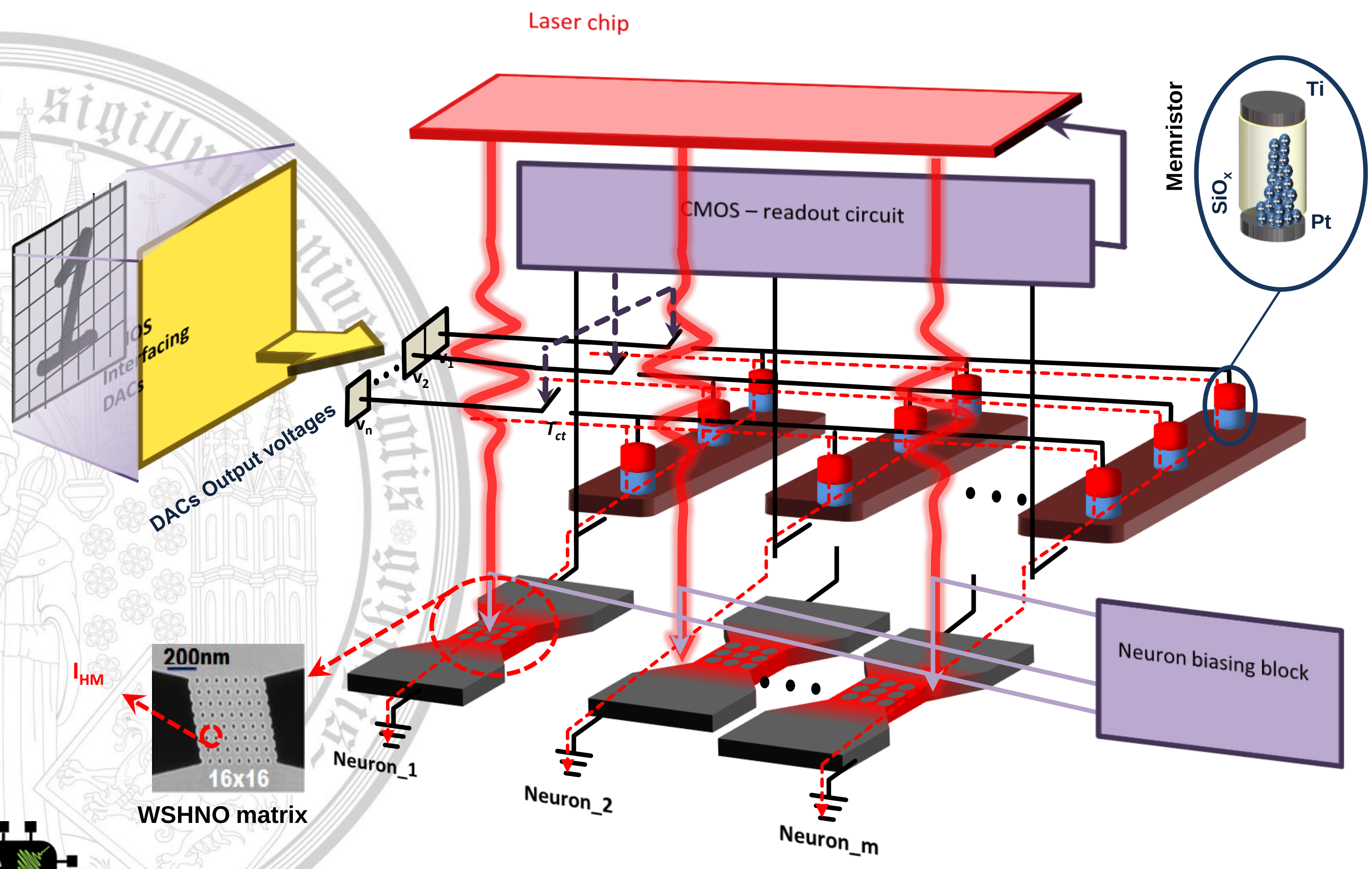


Test for spintronic device optimization



Nanooscillators for neuromorphic computing

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456



NanOsc samples

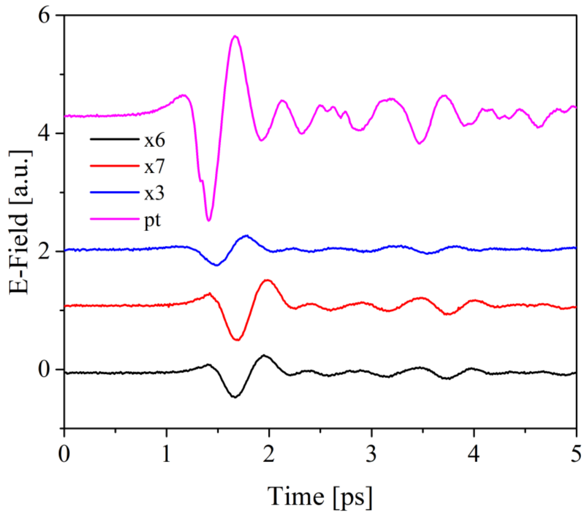
Direct study of the THz emission

X3:W-Ta(5nm)/NiFe (3nm)/Pt(2nm)

X6:W (5nm)/NiFe (3nm)

X7:W (5nm)/NiFe (3nm)/Pt(2nm)

Pt: Ta/ CoFeB/ W reference

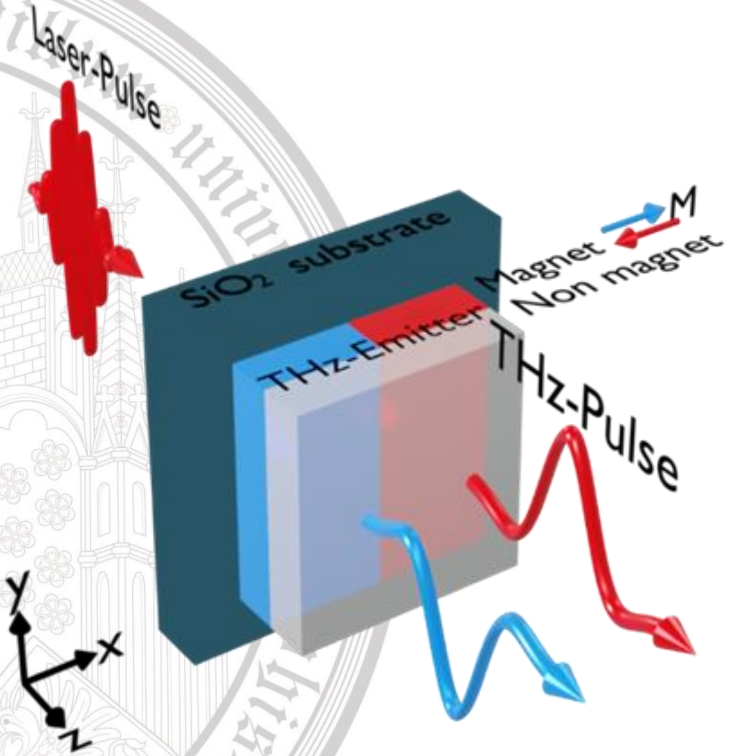


HORIZON 2020

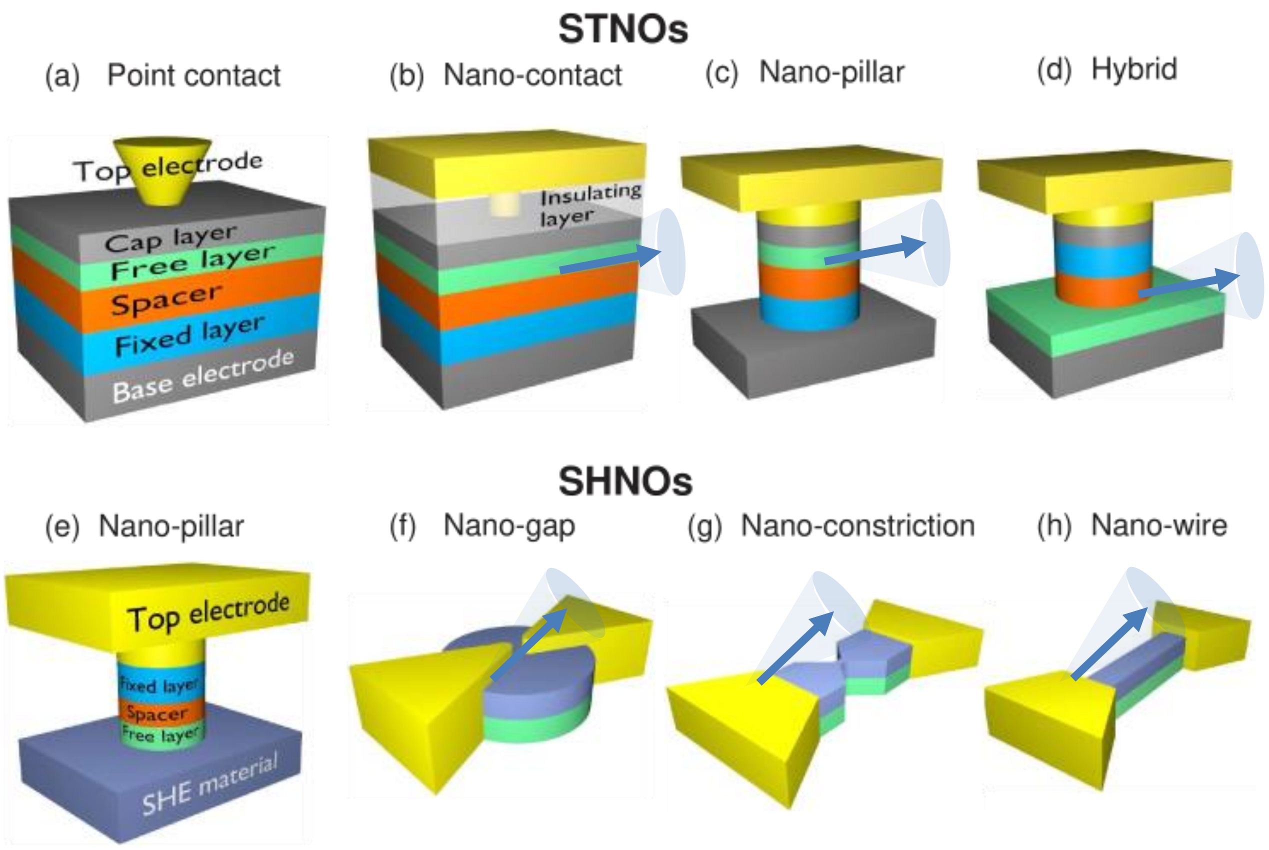
FET Open SpinAge

Spintronic THz emitter

Fundamental properties of the charge-to-spin conversion



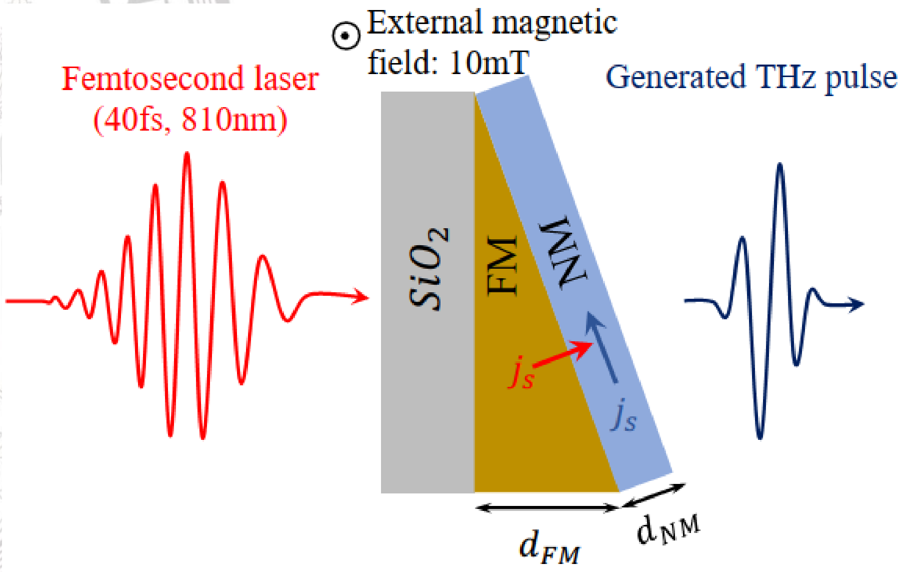
Test for spintronic device optimization



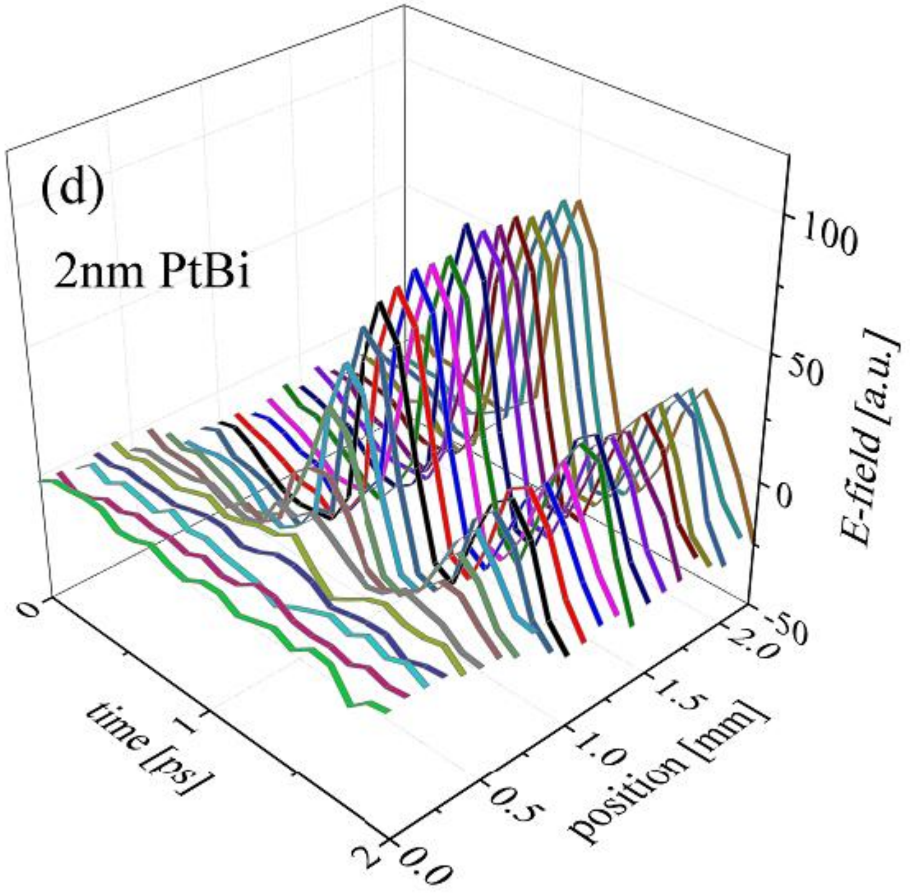
Spintronic THz emitter

Spintronic THz Emitters with diverse nonmagnetic Layers, Bi Alloys, and layer thickness gradient

FM: CoFeB
NM: Pt, W, Ru, Au, PtBi, AgBi



New Bi alloys

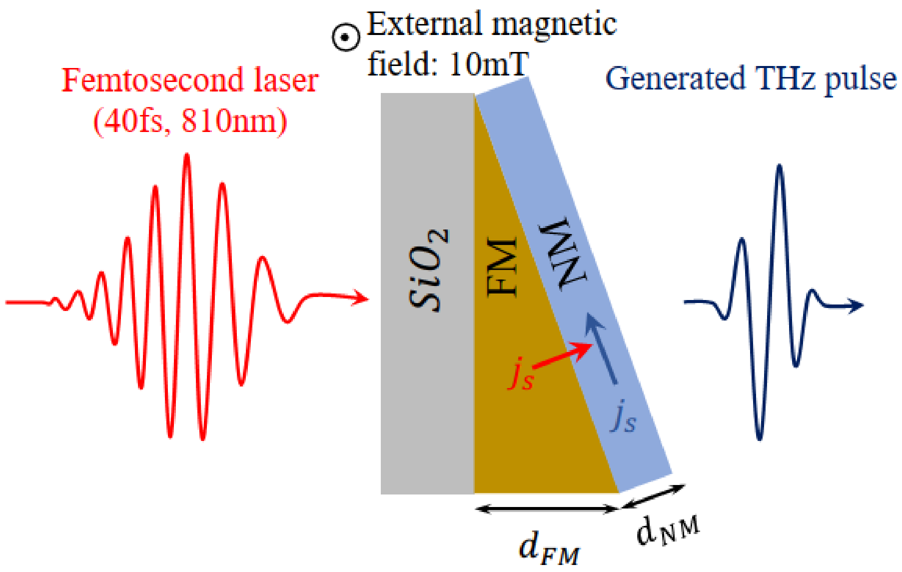


Tristan Joachim Winkel, Tahereh Sadat Parvini, Finn-Frederik Stiewe, Jakob Walowski, Farshad Moradi, Markus Münzenberg, arXiv:2307.02232

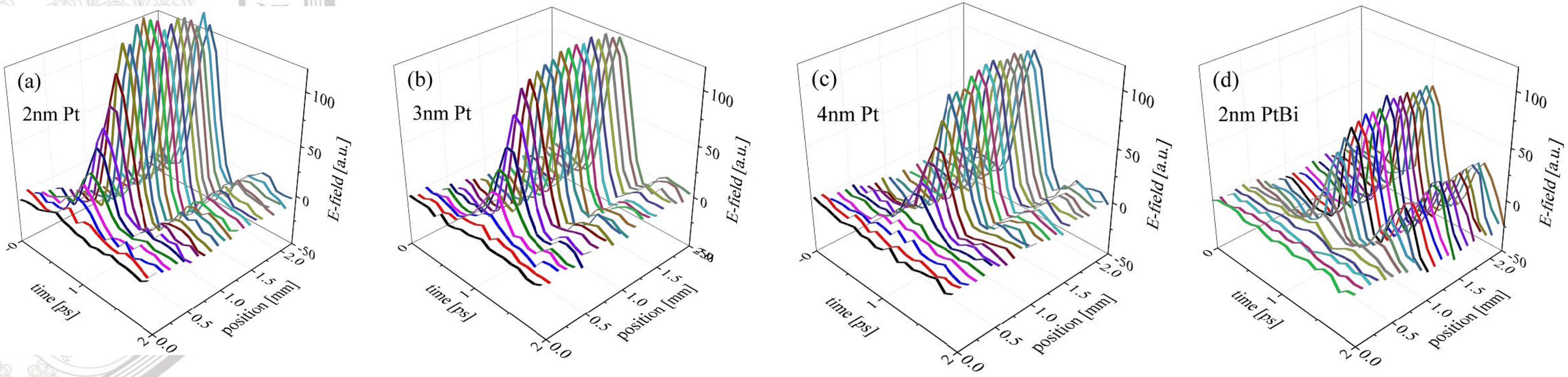
Spintronic THz emitter

Spintronic THz Emitters with diverse nonmagnetic Layers, Bi Alloys, and layer thickness gradient

FM: CoFeB
NM: Pt, W, Ru, Au, PtBi, AgBi



New Bi alloys



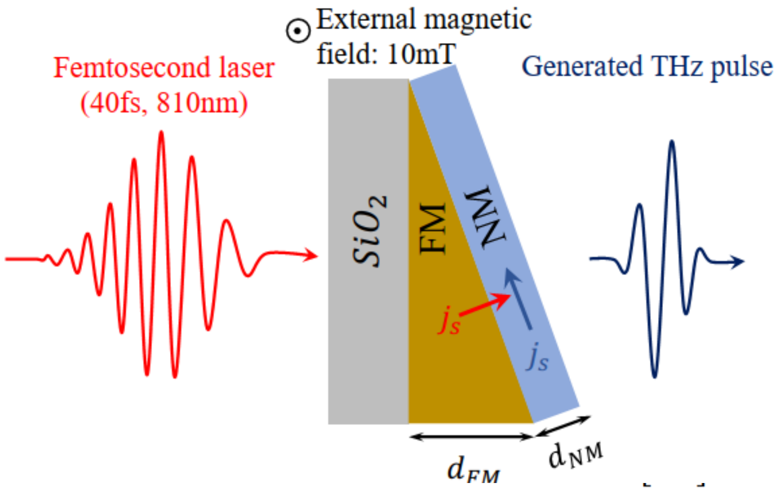
Tristan Joachim Winkel, Tahereh Sadat Parvini, Finn-Frederik Stiewe, Jakob Walowski, Farshad Moradi, Markus Münzenberg, arXiv:2307.02232

Spintronic THz emitter

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Spintronic THz Emitters with Nonmagnetic Layers (NM):

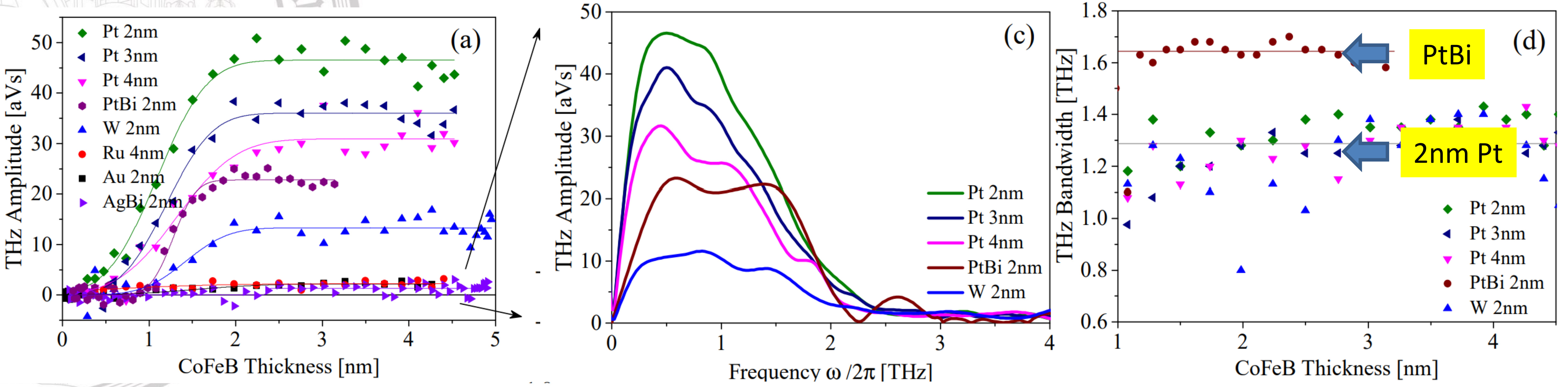
- Bi alloys



PtBi:

- 400GHz wider bandwidth than other emitters
- Higher frequency peak (300GHz)

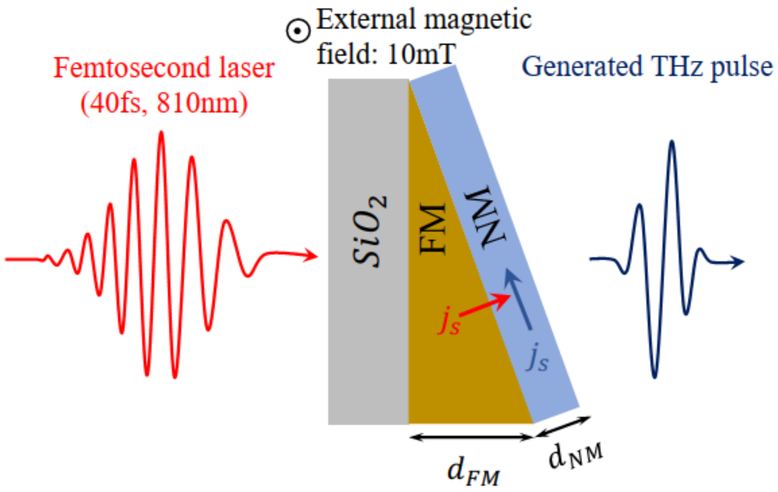
FM: CoFeB
NM: Pt, W, Ru, Au, PtBi, AgBi



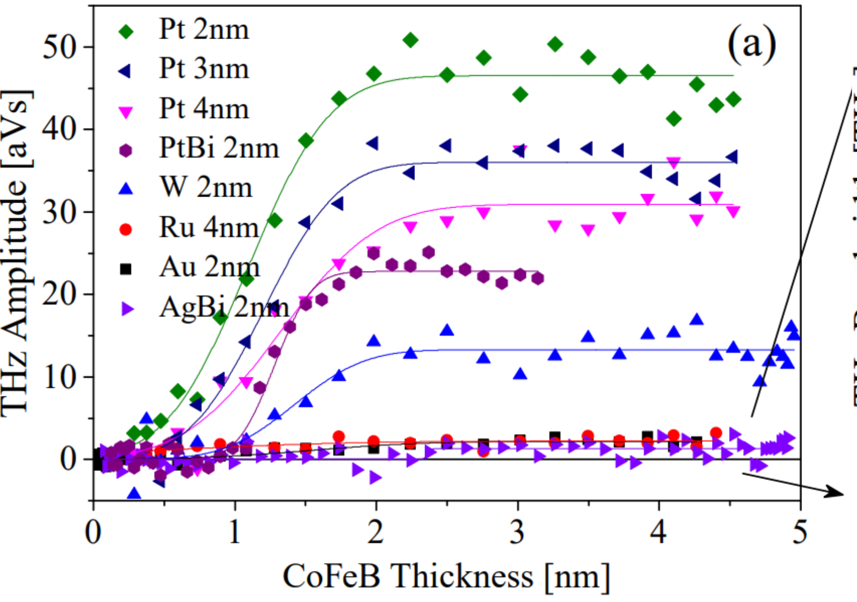
Spintronic THz emitter

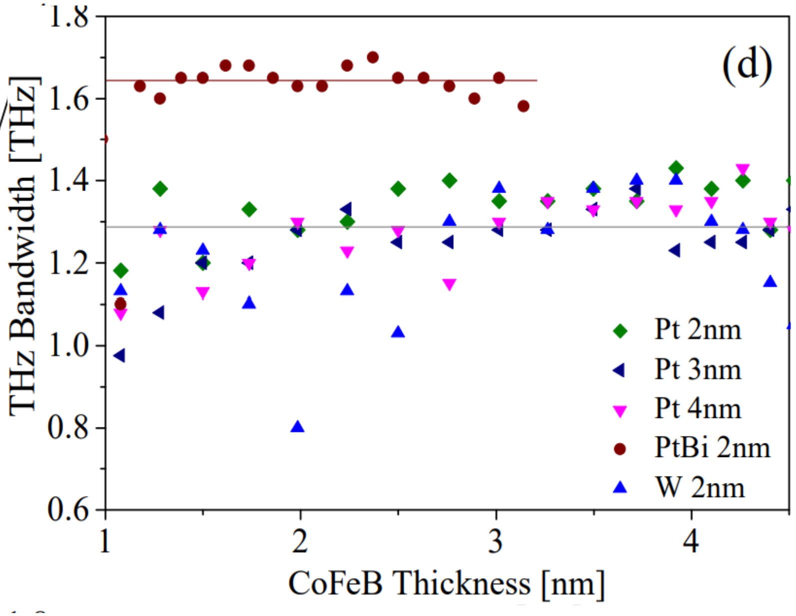
Spintronic THz Emitters with Nonmagnetic Layers (NM):
- Bi alloys

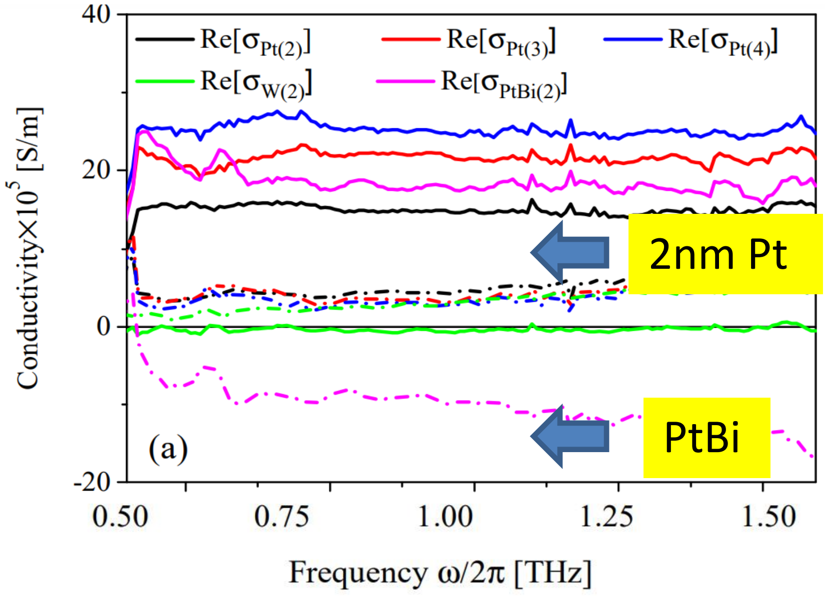
FM: CoFeB
NM: Pt, W, Ru, Au, PtBi, AgBi



PtBi:
- 400GHz wider bandwidth than other emitters
- Higher frequency peak (300GHz)
- Negative imaginary condutance







Nanooscillators for neuromorphic computing

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Absorbed fraction laser

Pump fluence

spin-current density

spin

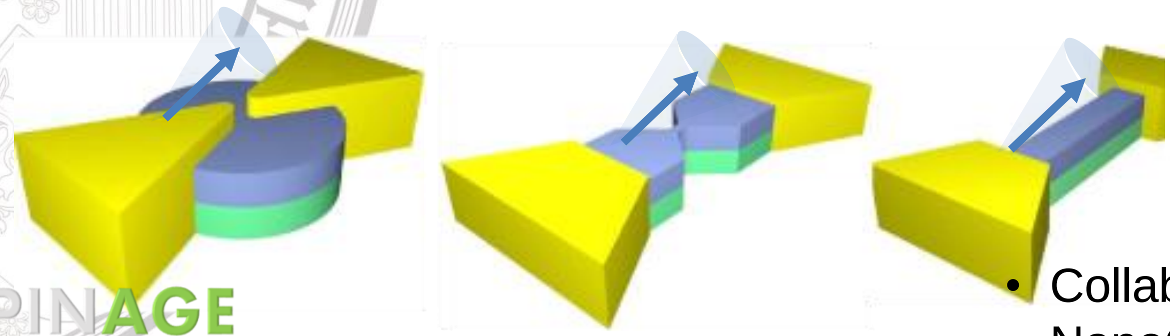
$$E_{THz} = \frac{AF}{d_{NM} + d_{FM}} j_S^0 t_{FM/NM} \lambda_{NM} tanh\left(\frac{d_{NM}}{\lambda_{NM}}\right) . \theta_S$$

interfacial sp
transmission

Optimizing spin Hall effects: Spin Hall Nanooscillators (SHNOs)

SHNOs

(f) Nano-gap (g) Nano-constriction (h) Nano-wi



NanOsc samples

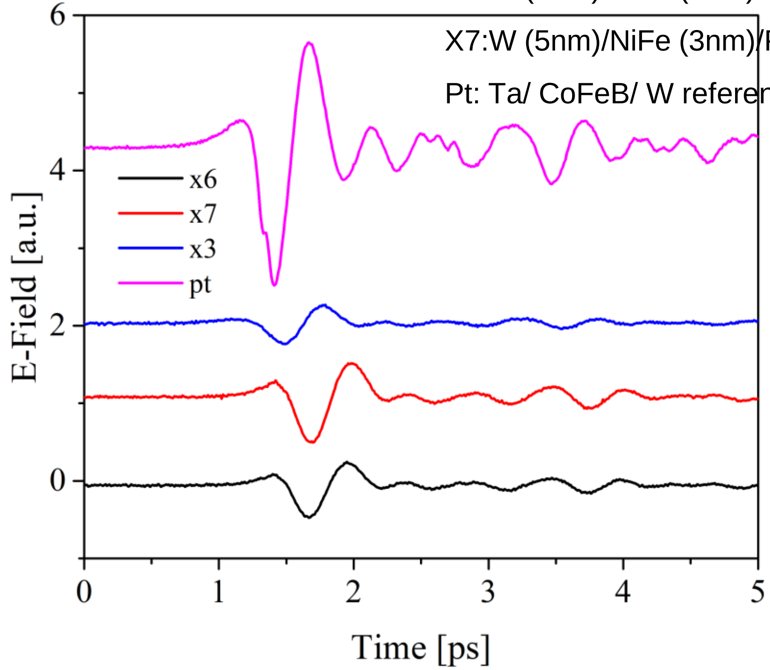
Direct study of the THz emission

X3:W-Ta(5nm)/NiFe (3nm)/Pt(2nm)

X6:W (5nm)/NiFe (3nm)

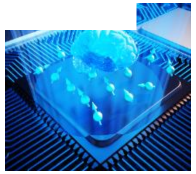
X7:W (5nm)/NiFe (3nm)/Pt(2nm)

Pt: Ta/ CoFeB/ W reference



- Collaboration with Johan Akermann NanoOsc

HORIZON 2020

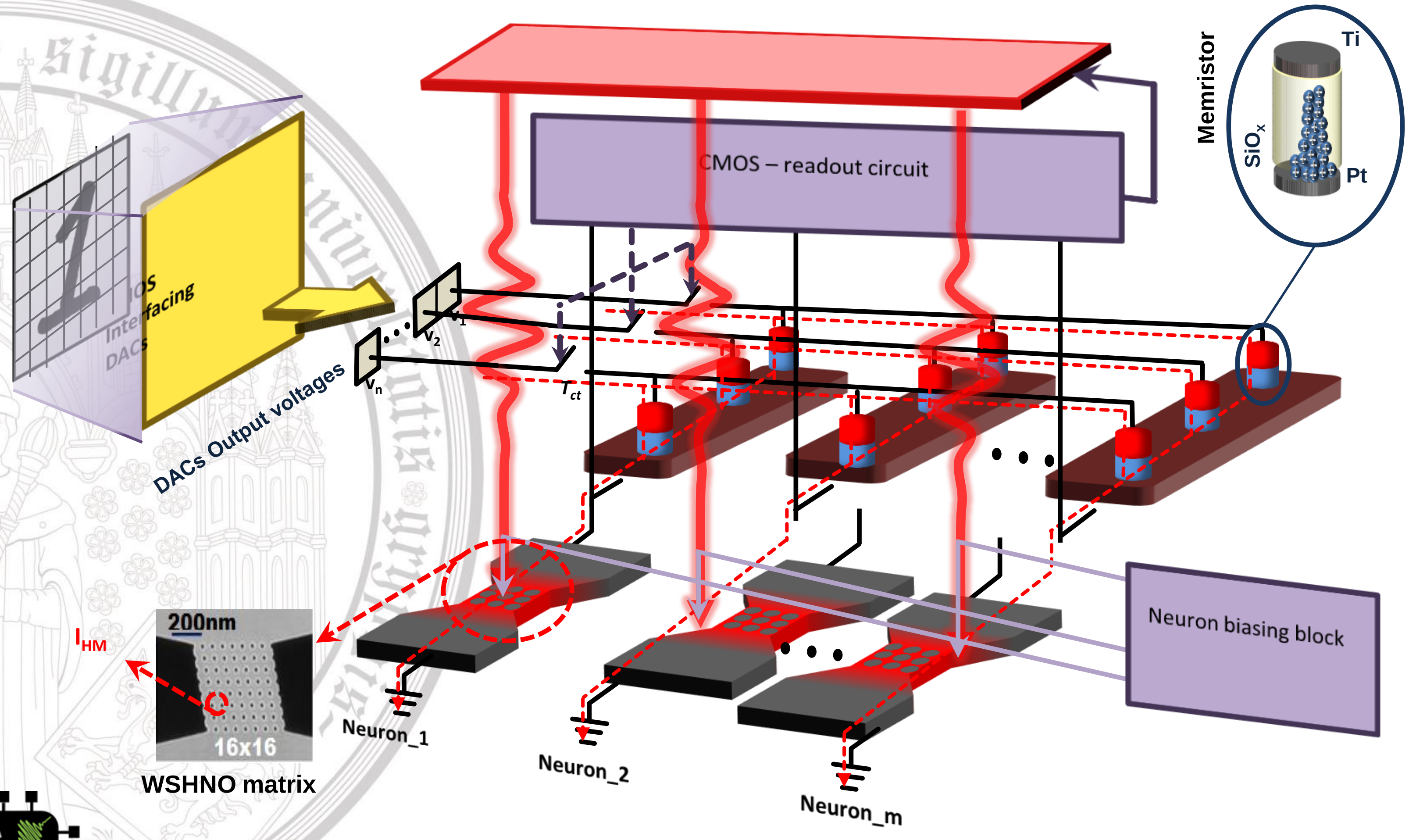


FET Open SpinAge

SPINAGE

Nanooscillators for neuromorphic computing

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456



NanOsc samples

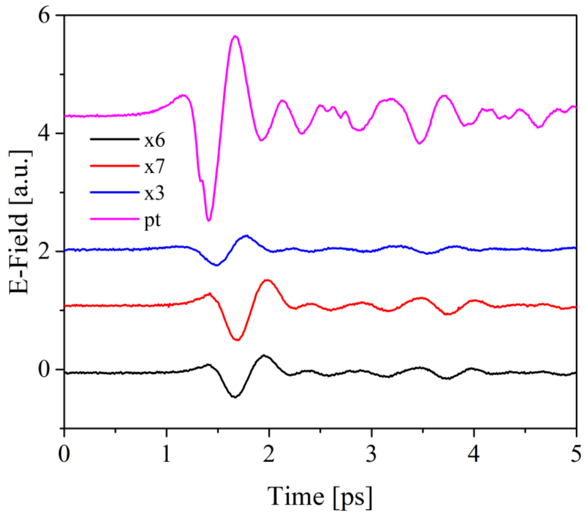
Direct study of the THz emission

X3:W-Ta(5nm)/NiFe (3nm)/Pt(2nm)

X6:W (5nm)/NiFe (3nm)

X7:W (5nm)/NiFe (3nm)/Pt(2nm)

Pt: Ta/ CoFeB/ W reference



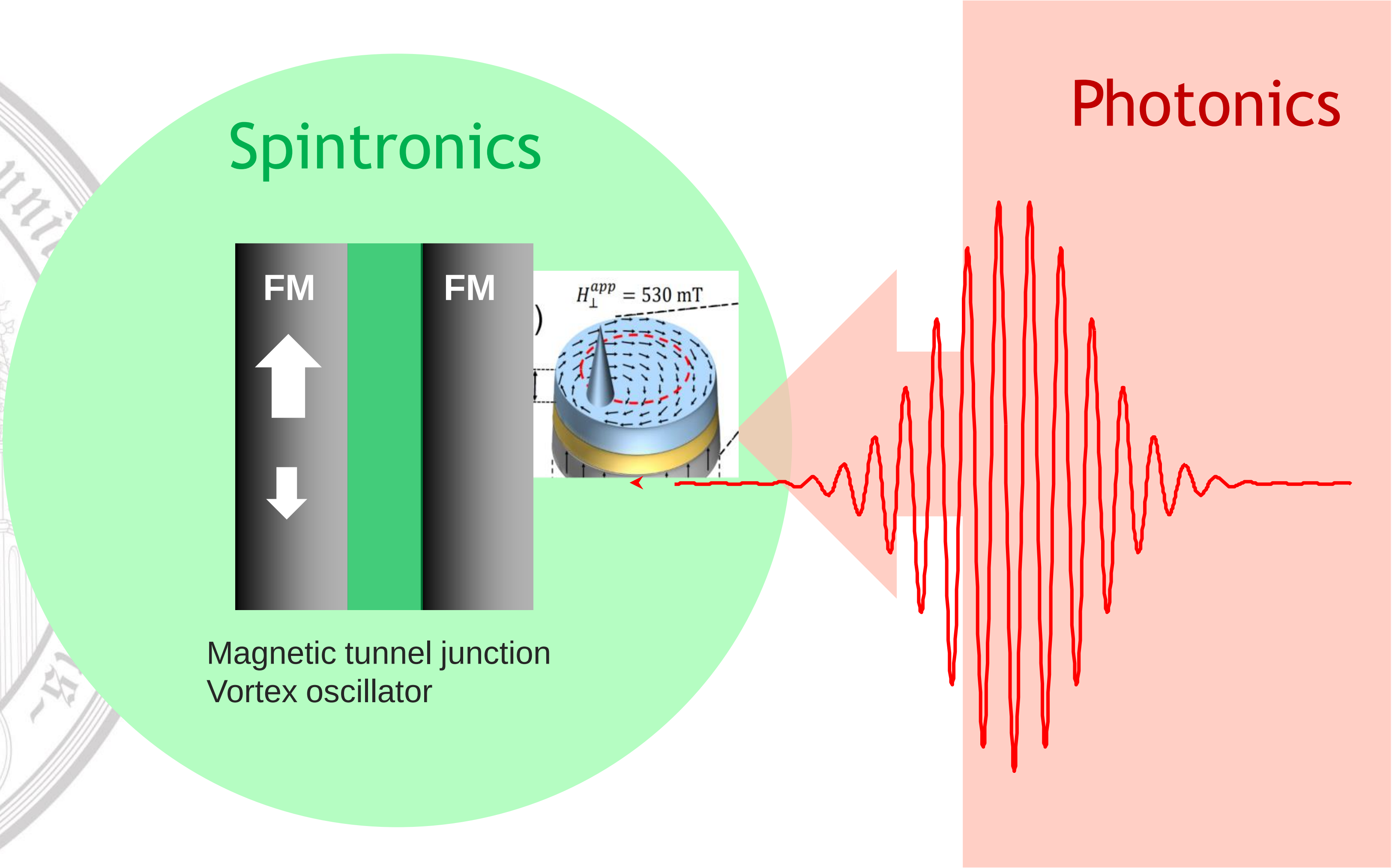
HORIZON 2020

FET Open SpinAge

SPINAGE

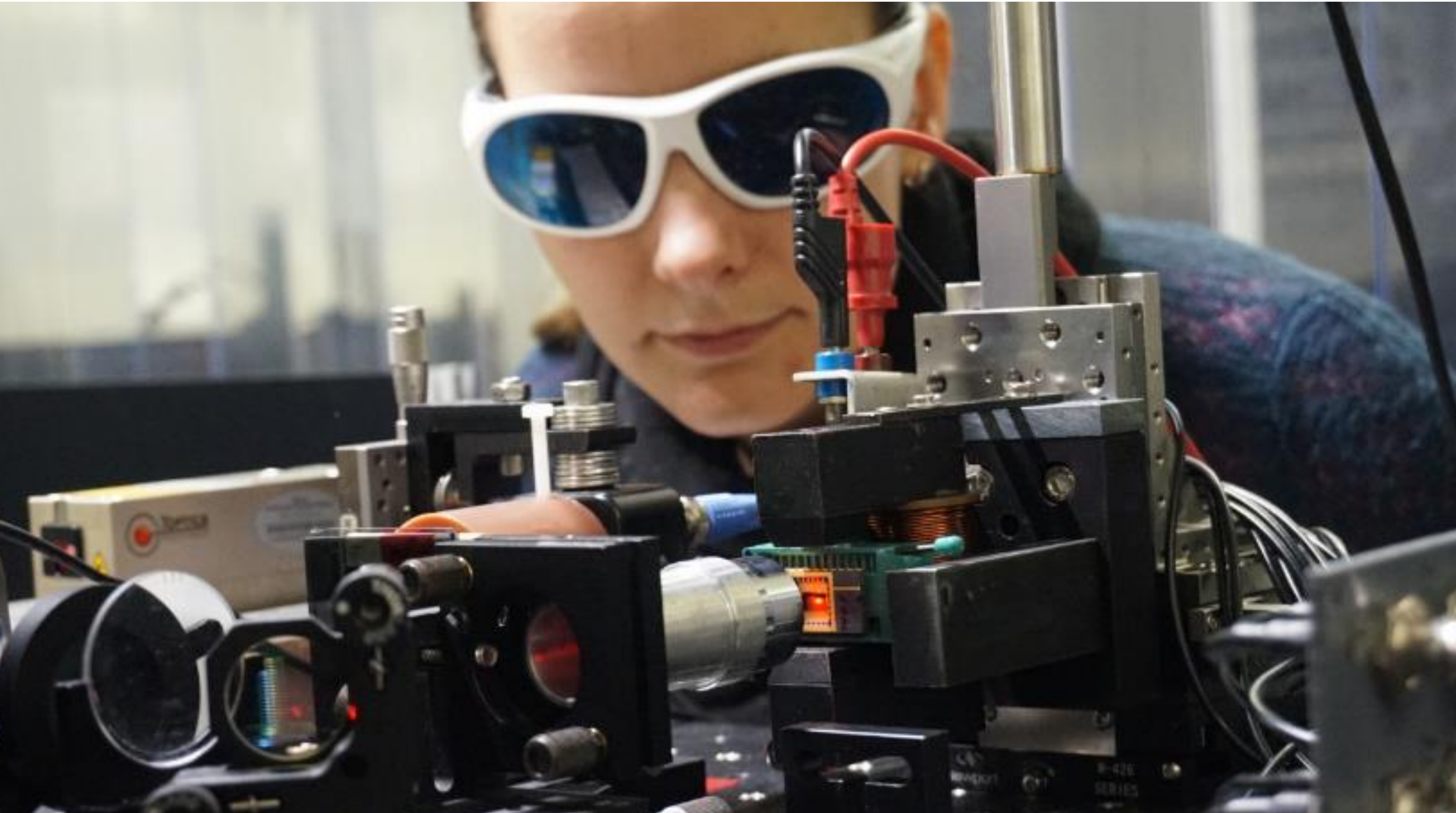
Nanooscillators for neuromorphic computing

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

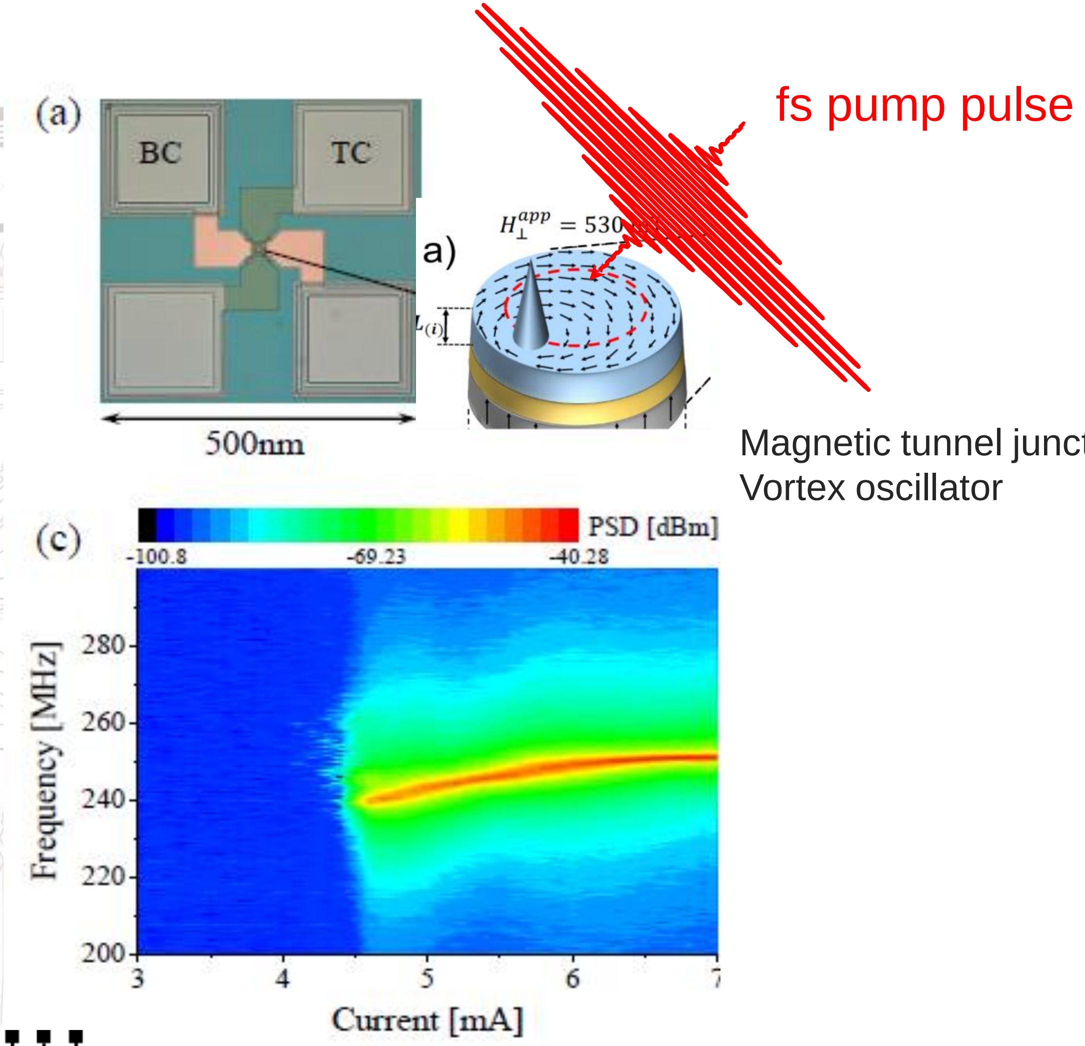


Magnetic tunnel junction
Vortex oscillator

FET Open SpinAge



Nanooscillators for neuromorphic computing



Magnetic tunnel junction
Vortex oscillator

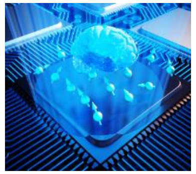
Optical control plus: Spin Torque Nanooscillators (SHNOs) based on vortex oscillators

SPINAGE

INL INTERNATIONAL IBERIAN NANOTECHNOLOGY LABORATORY

- Collaboration with Tim Böhnert, Ricardo Ferreira, INL

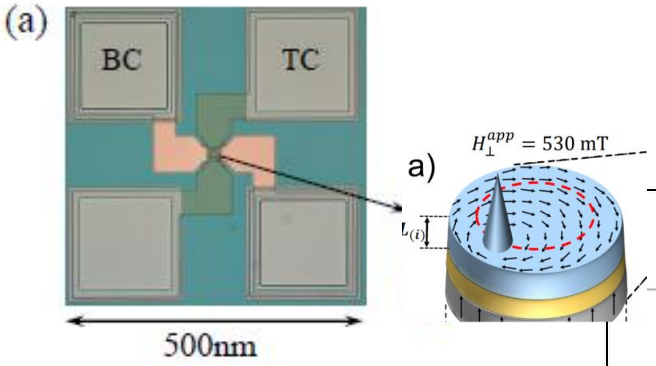
HORIZON 2020



FET Open SpinAge

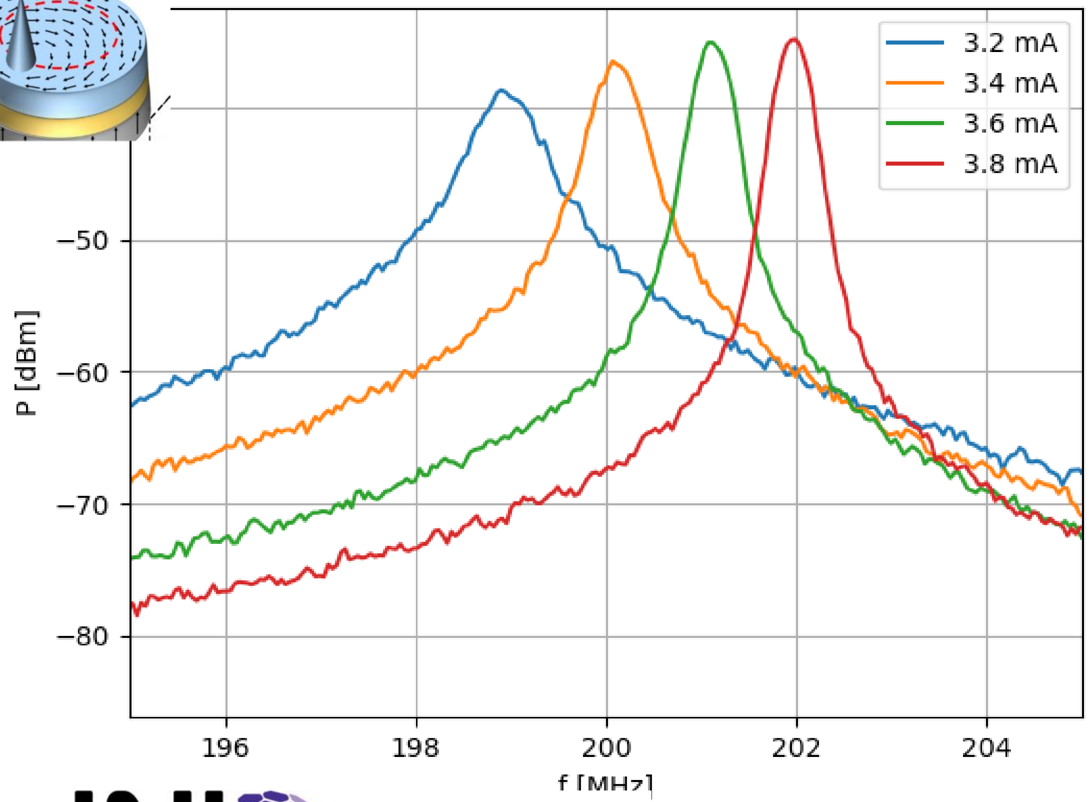
Nanooscillators for neuromorphic computing

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

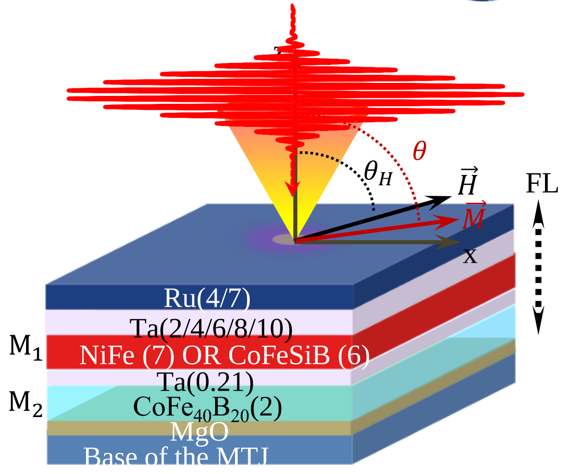


Magnetic tunnel junction
Vortex oscillator

Optical control plus: Spin Torque Nanooscillators (SHNOs) based on vortex oscillators



Oscillator frequency shift

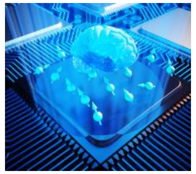


Magnetic tunnel junction

SPINAGE

INTERNATIONAL IBERIAN NANOTECHNOLOGY LABORATORY

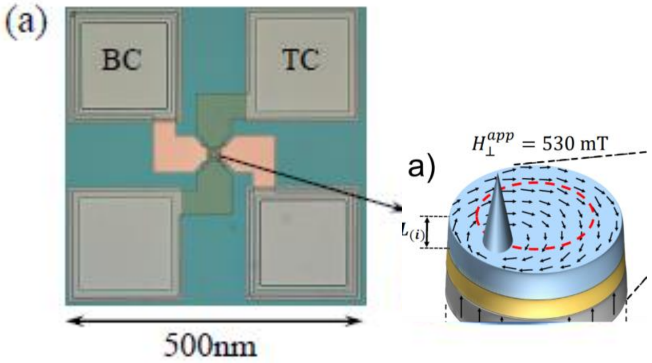
HORIZON 2020



FET Open SpinAge

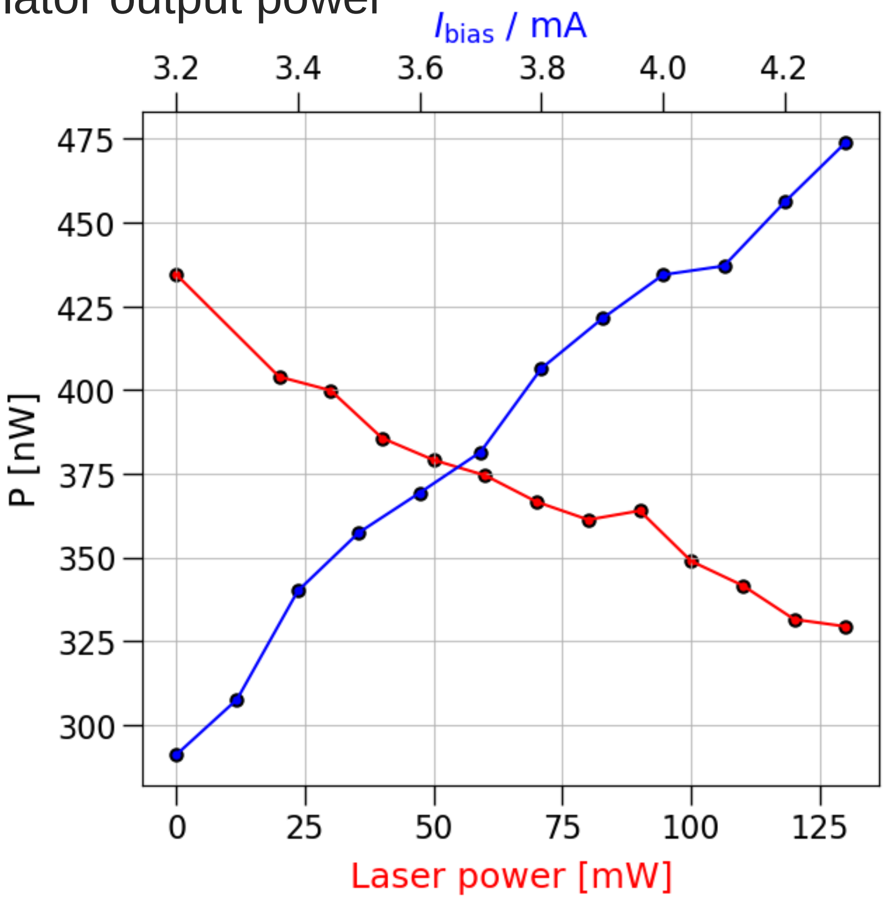
Nanooscillators for neuromorphic computing

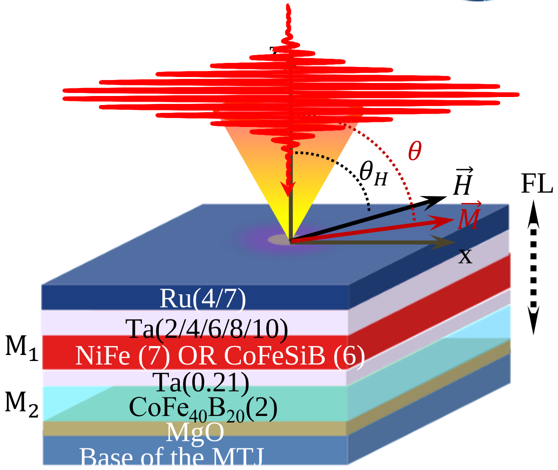
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456



Magnetic tunnel junction
Vortex oscillator

Oscillator output power



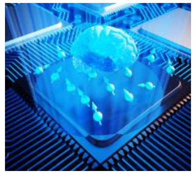


Magnetic tunnel junction

SPINAGE

INTERNATIONAL IBERIAN NANOTECHNOLOGY LABORATORY

HORIZON 2020

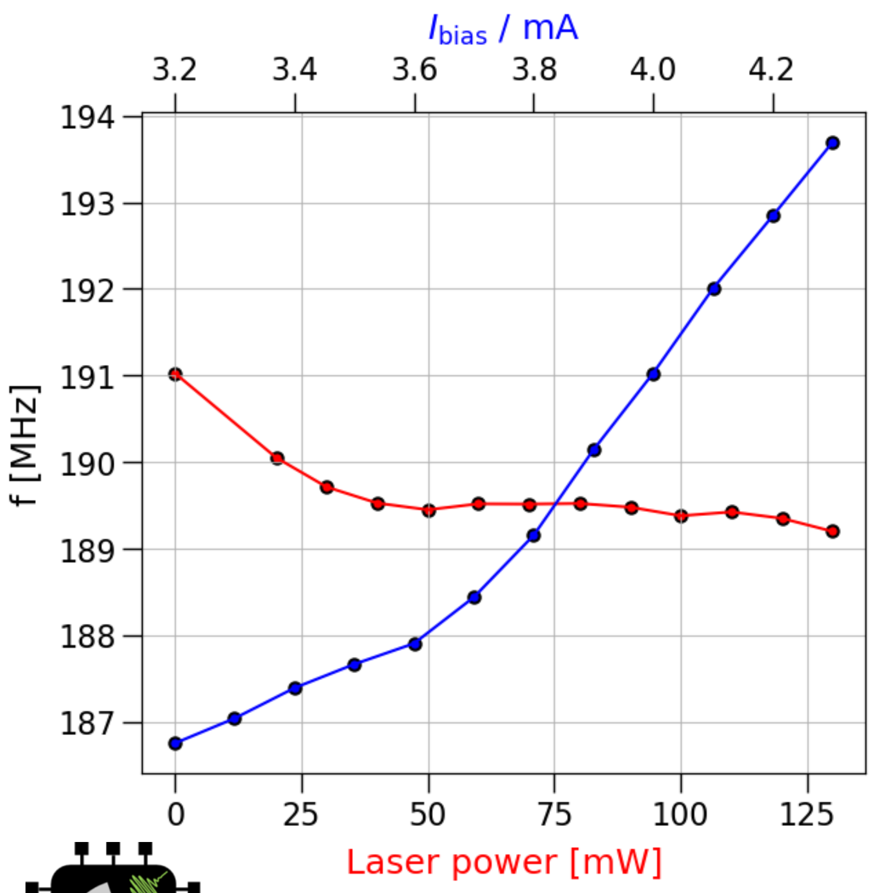


FET Open SpinAge

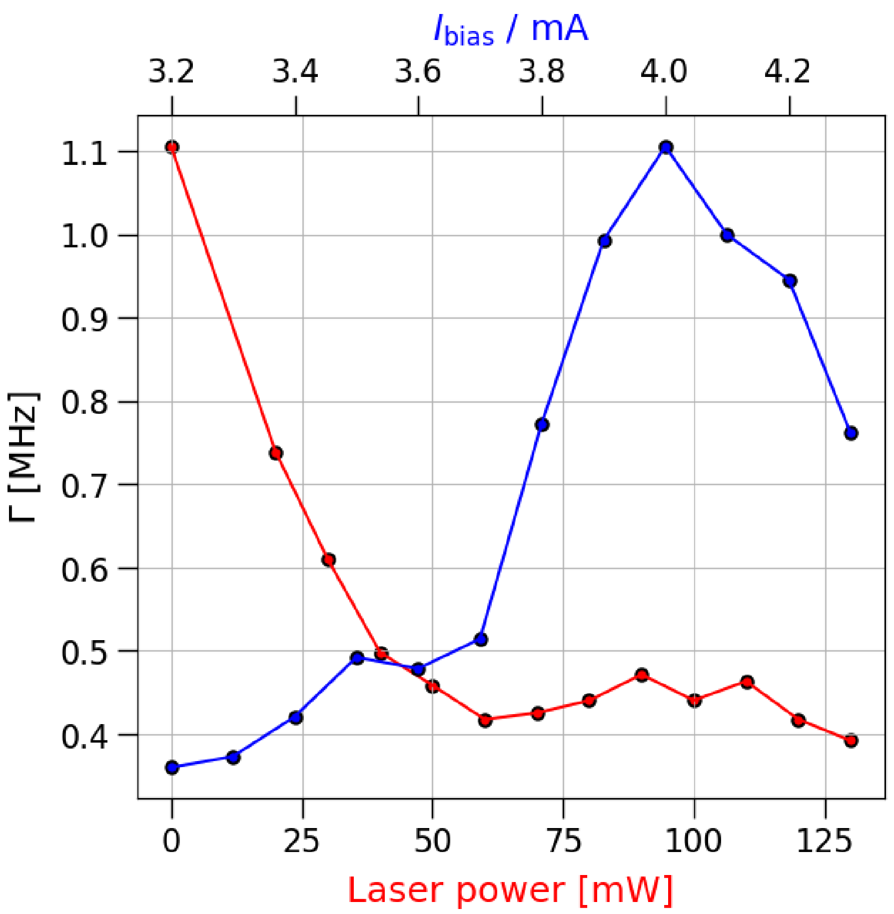
Nanooscillators for neuromorphic computing

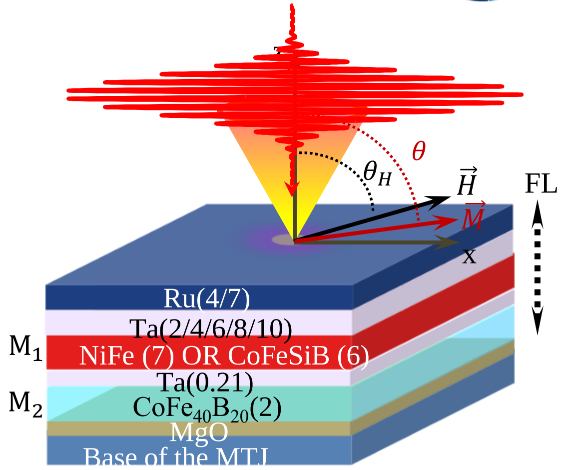
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Oscillator frequency shift



Line width





Magnetic tunnel junction

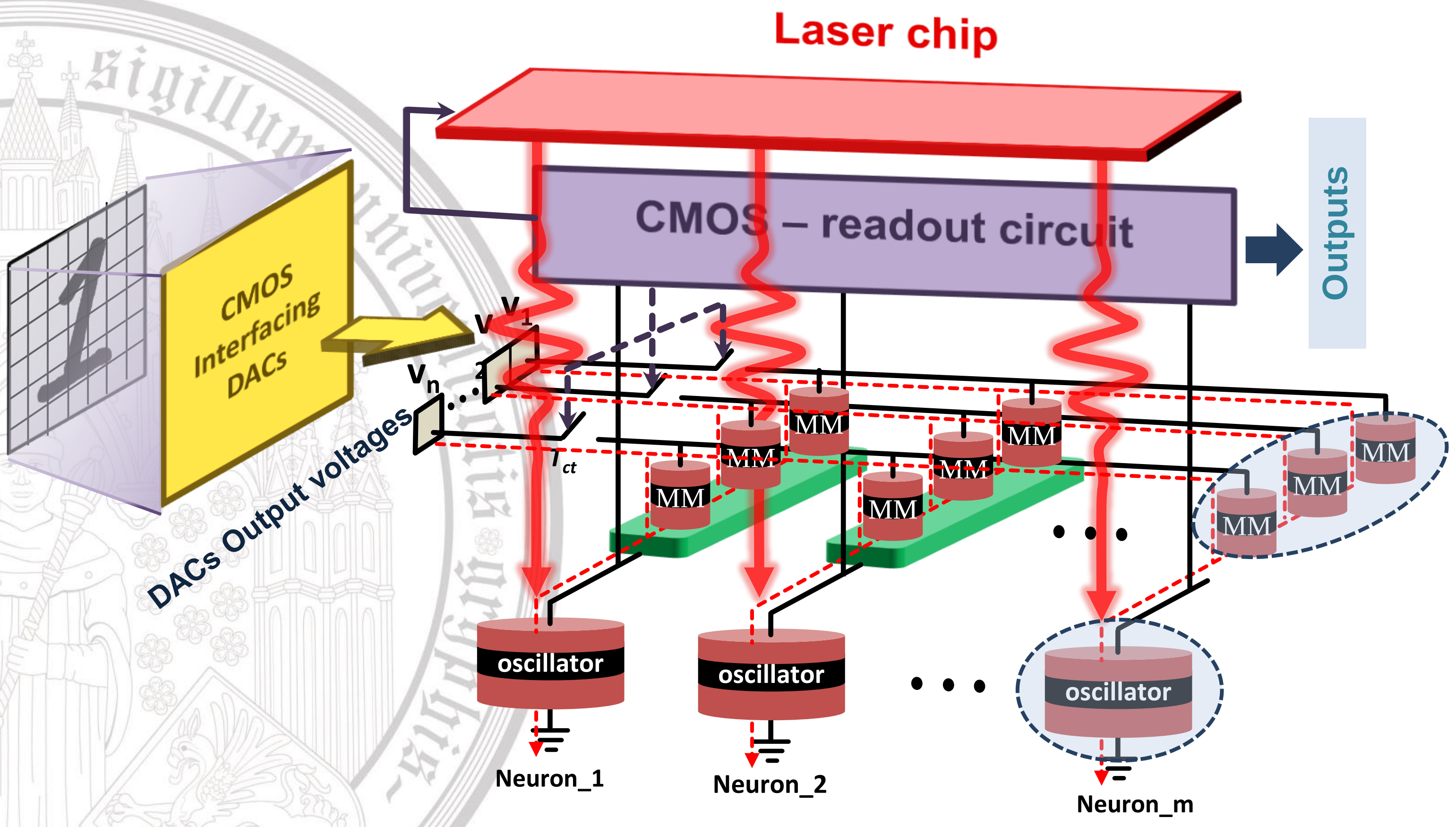
SPINAGE

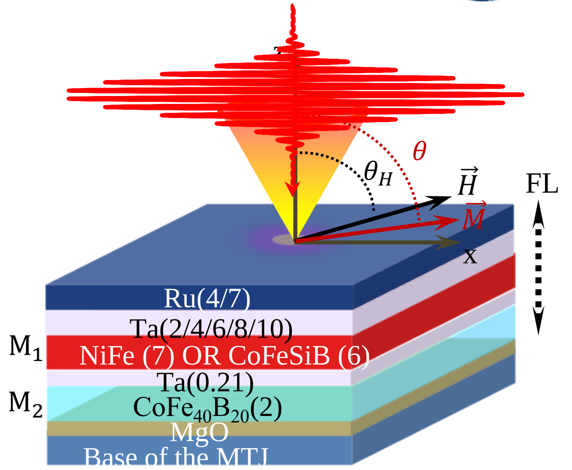
HORIZON 2020

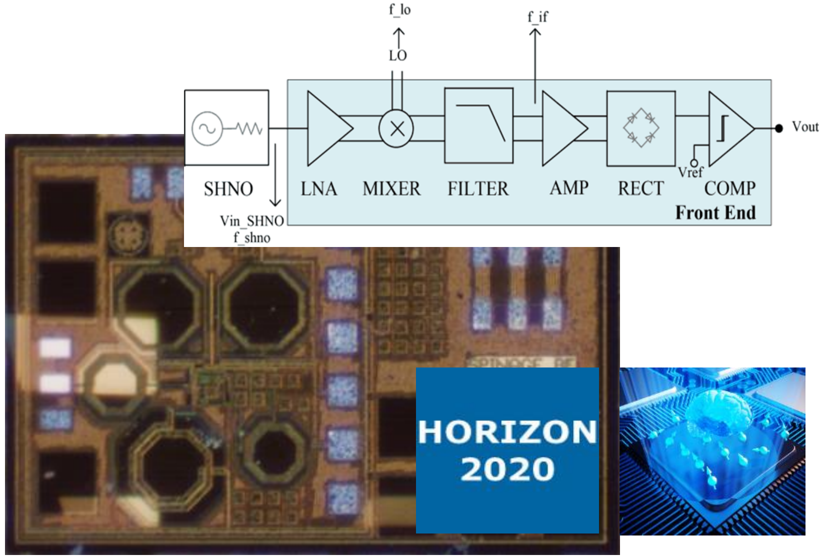
FET Open SpinAge

Nanooscillators for neuromorphic computing

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456





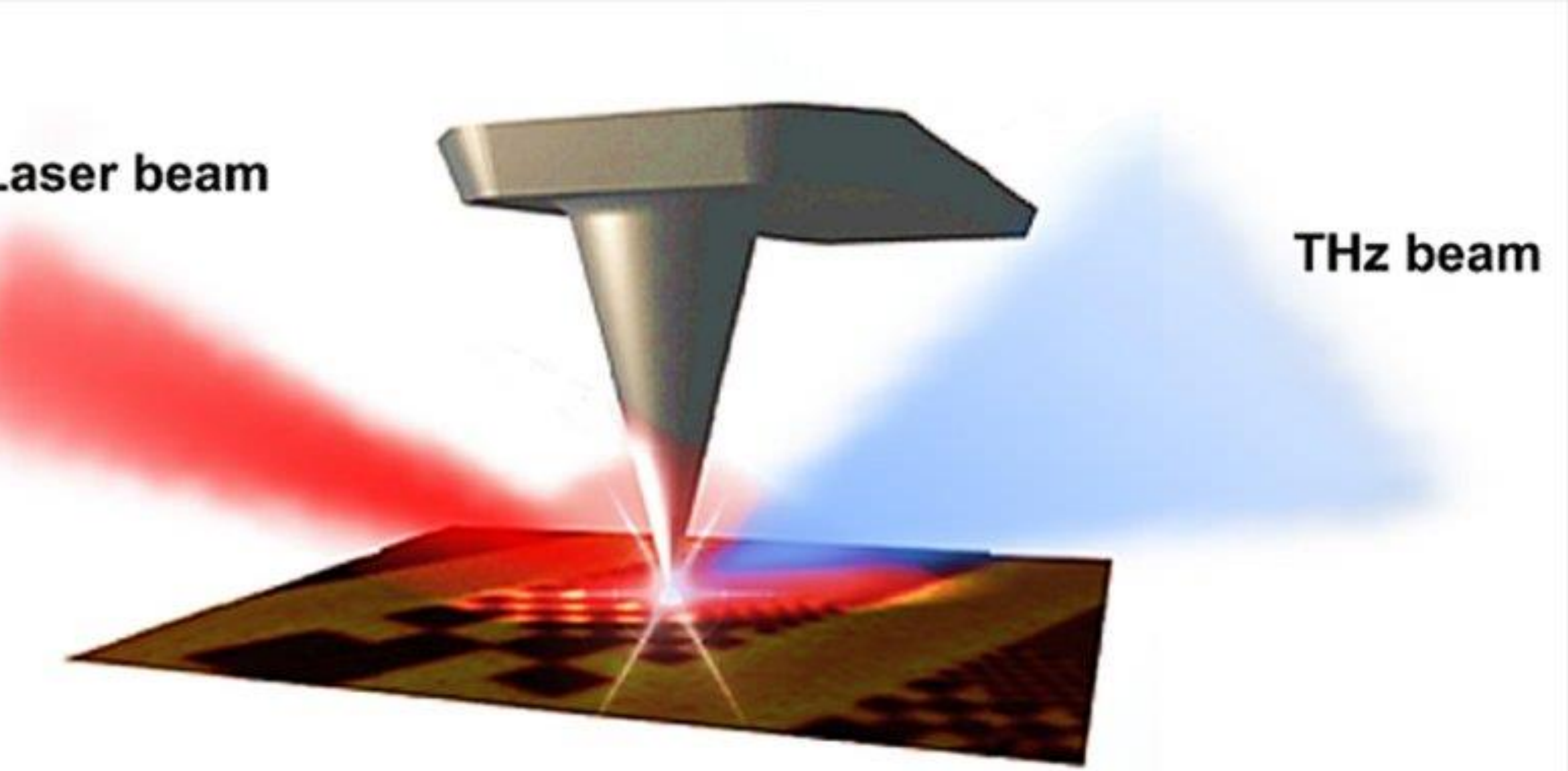


FET Open SpinAge

SPINAGE

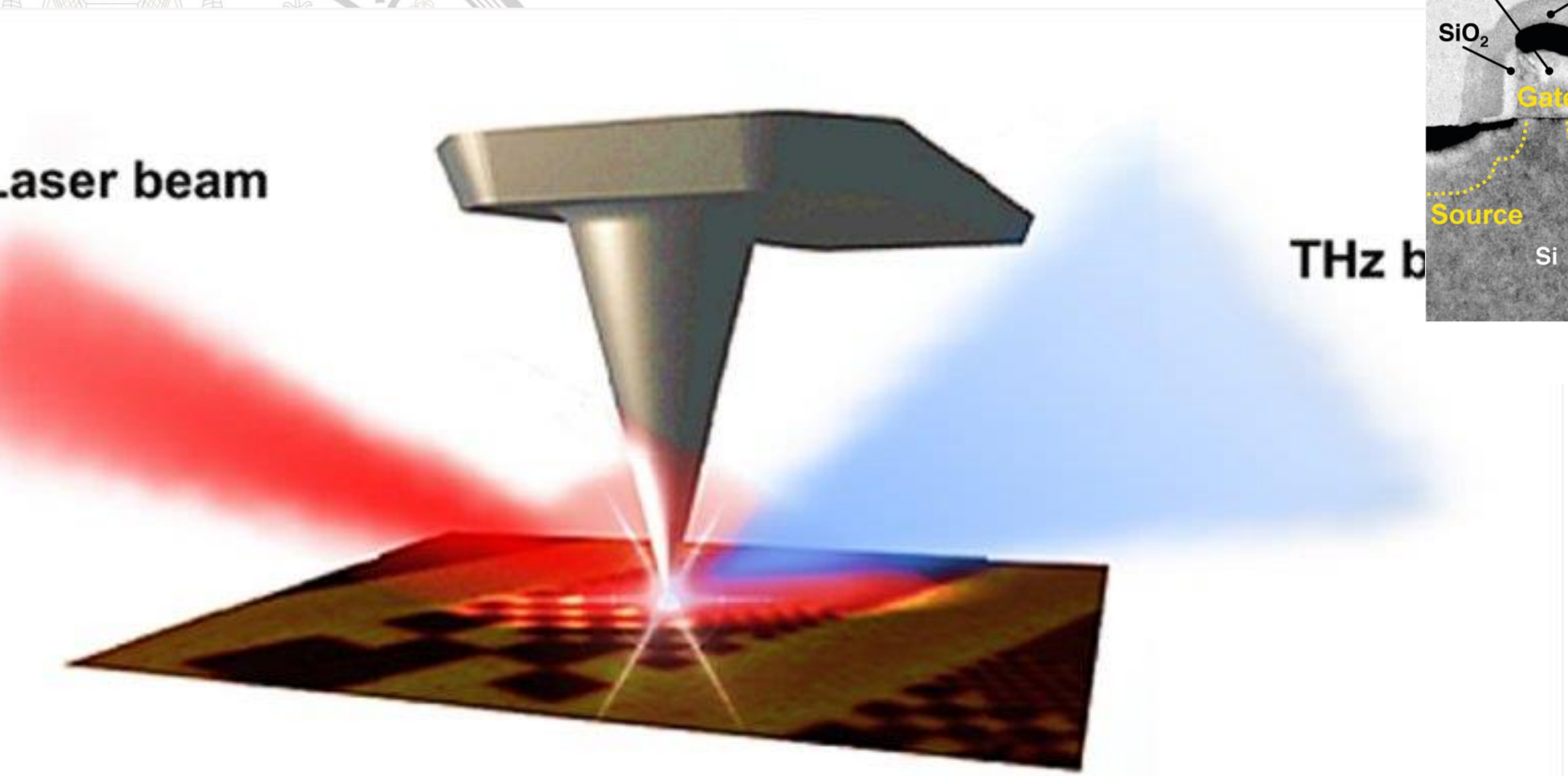
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

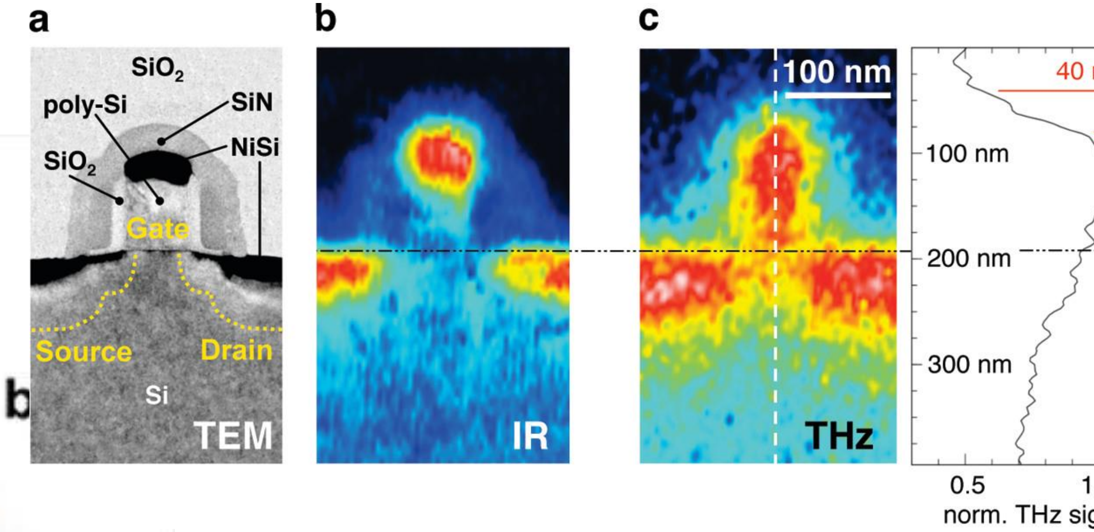
Imaging on THz and nm scale of spin dynamics?



Terahertz Field Confinement in Nonlinear Metamaterials and Near-Field Imaging
by George R. Keiser and Pernille Klarskov

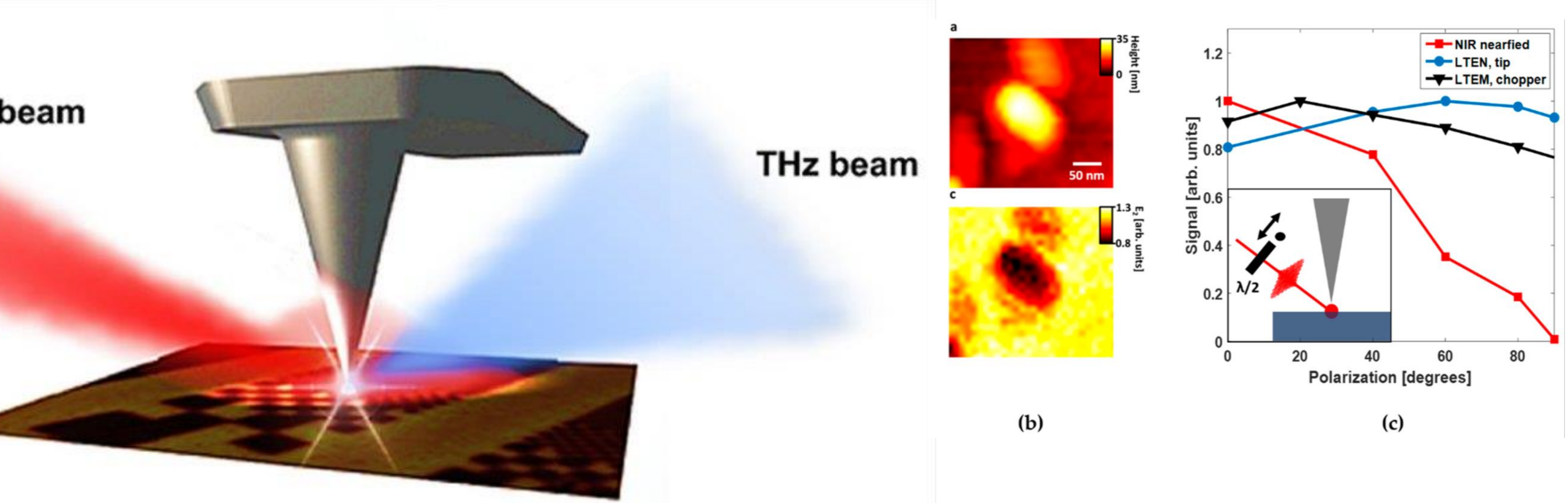
Imaging on THz and nm scale of spin dynamics?





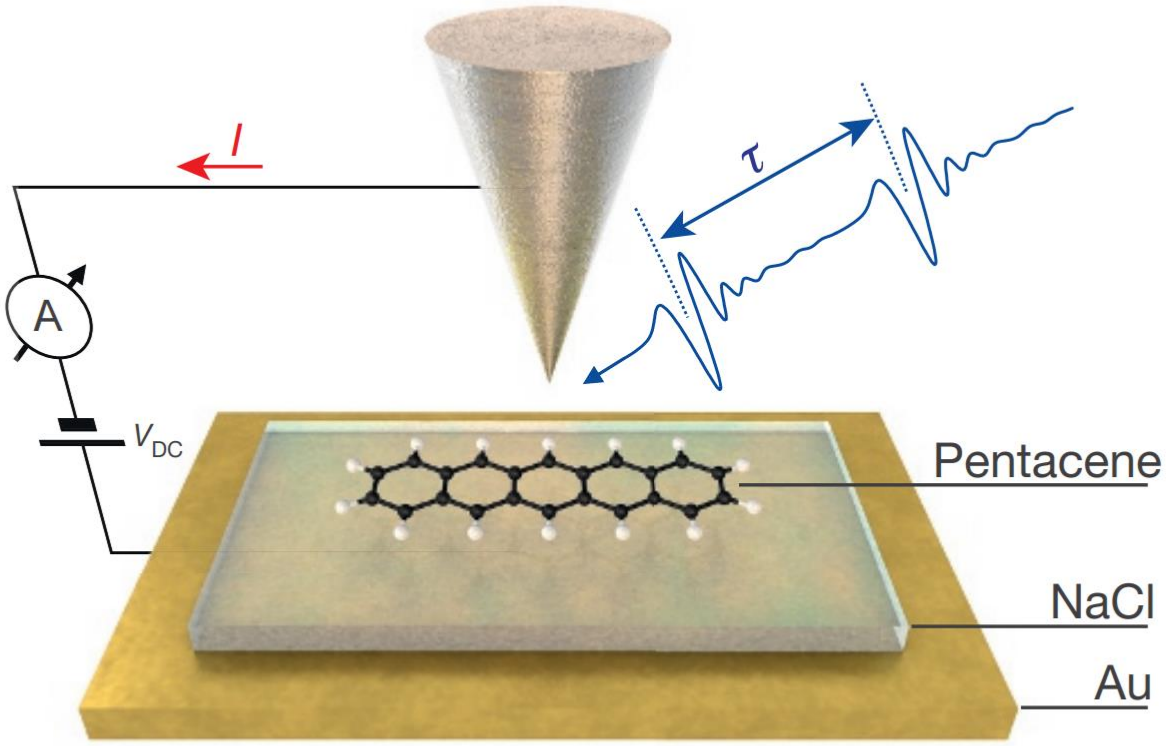
Terahertz Field Confinement in Nonlinear Metamaterials and Near-Field Imaging
by George R. Keiser and Pernille Klarskov

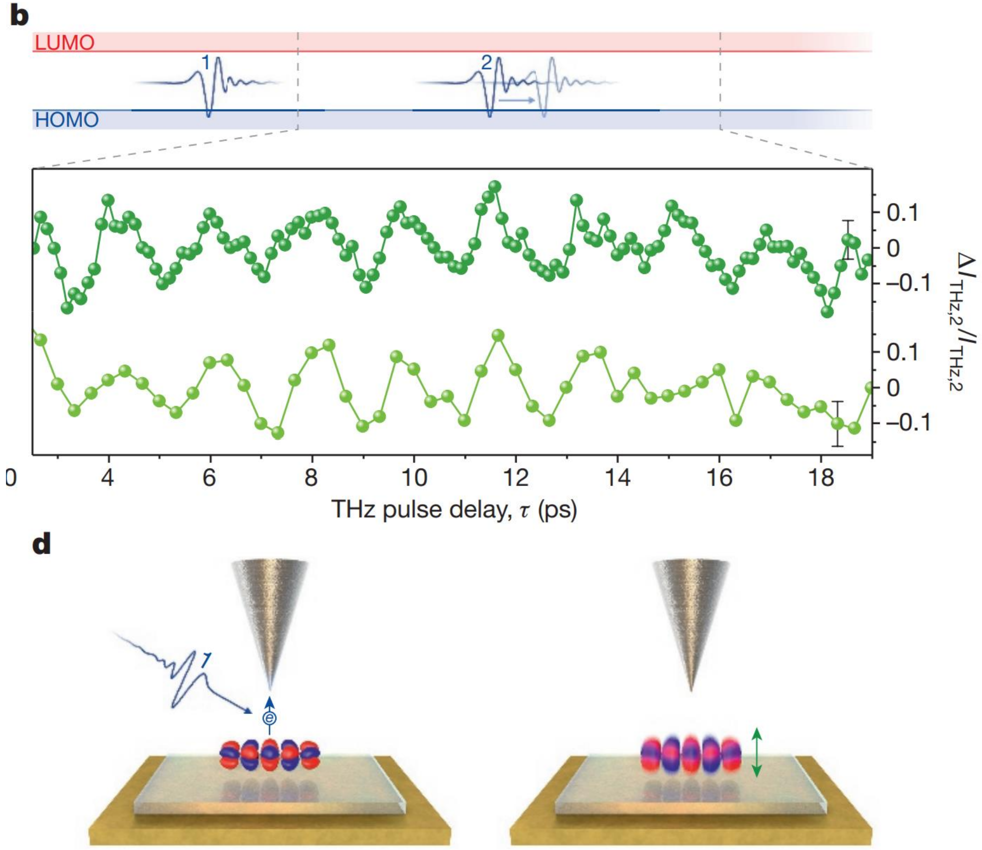
Imaging on THz and nm scale of spin dynamics?



Terahertz Field Confinement in Nonlinear Metamaterials and Near-Field Imaging by George R. Keiser and Pernille Klarskov

Imaging on THz and nm scale of spin dynamics?

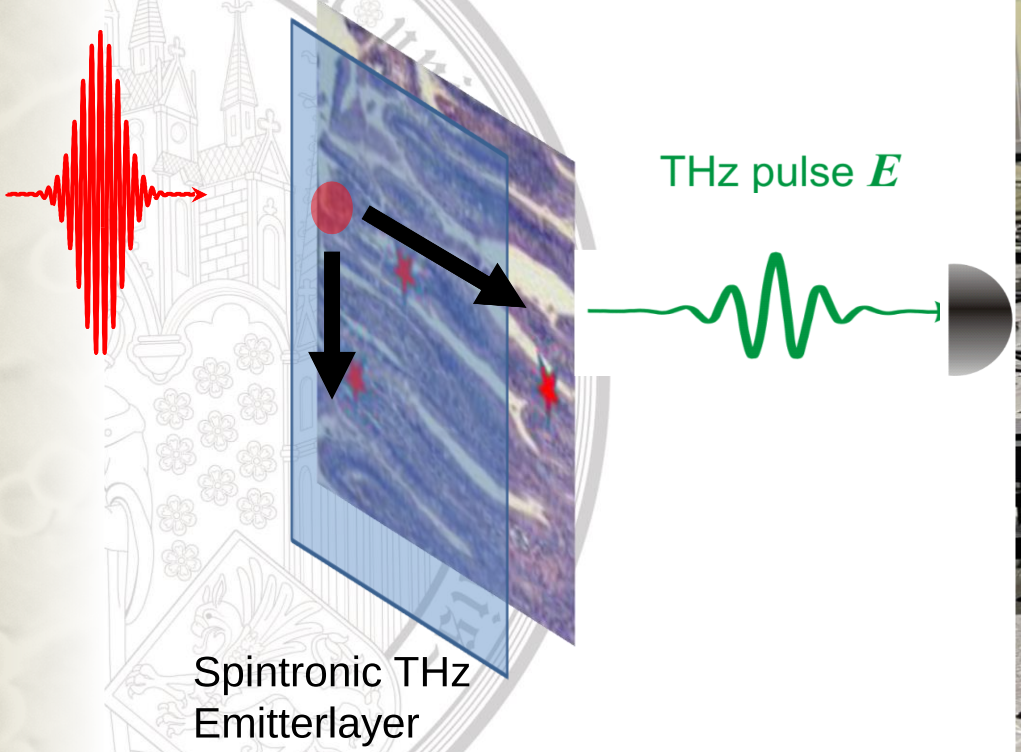


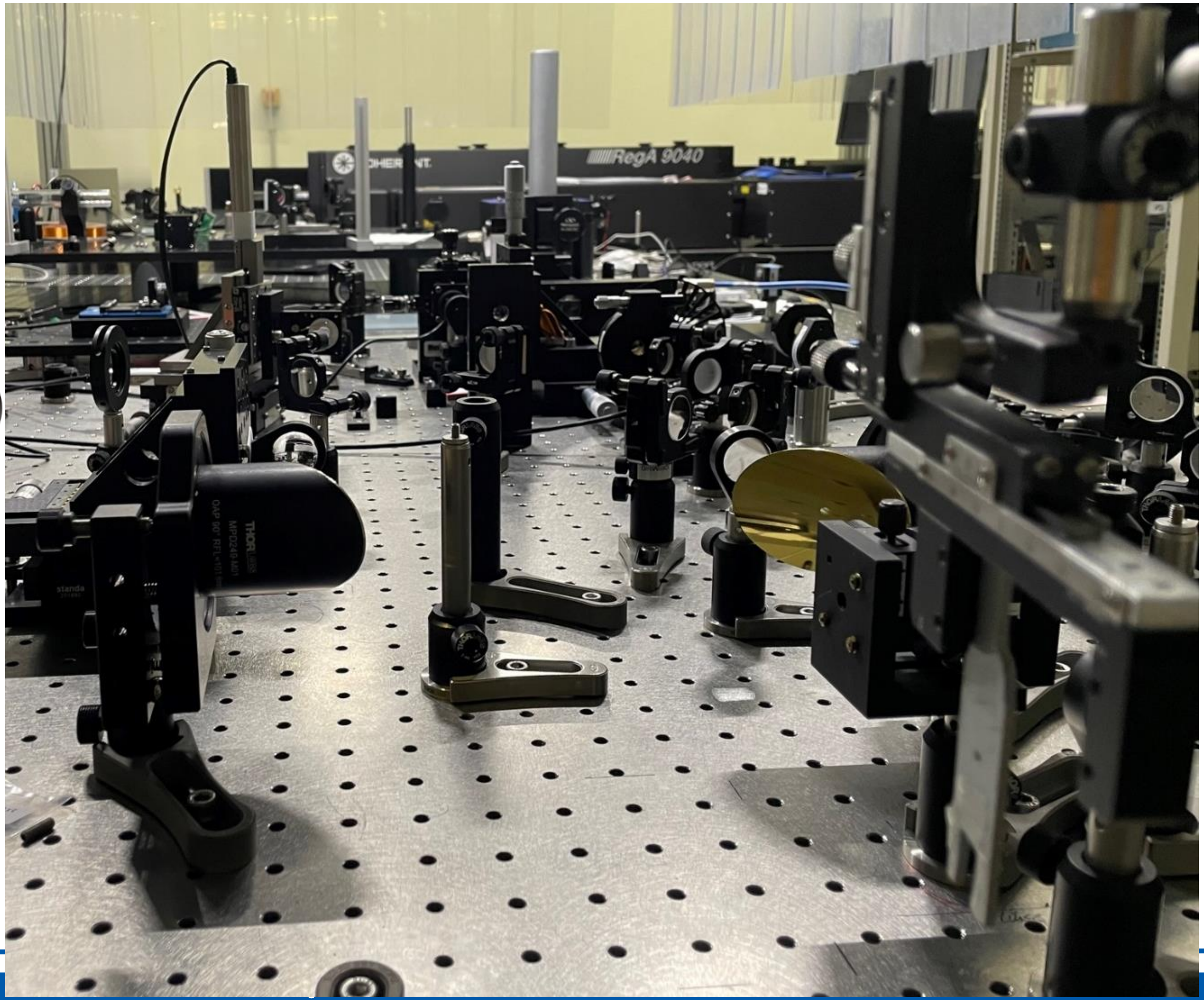


Tyler L. Cocker, Dominik Peller, Ping Yu, Jascha Repp & Rupert Huber
Nature volume 539, pages263–267 (2016)

Development of a superresolution THz spectro-microscopy

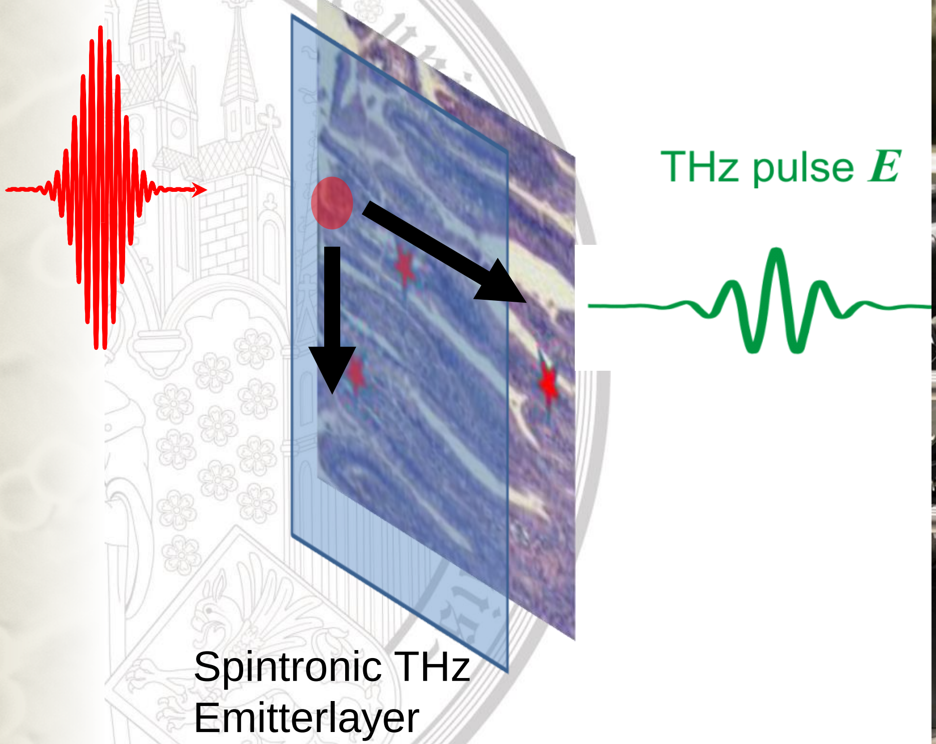
The spintronic THz emitters: Towards high spatial resolution

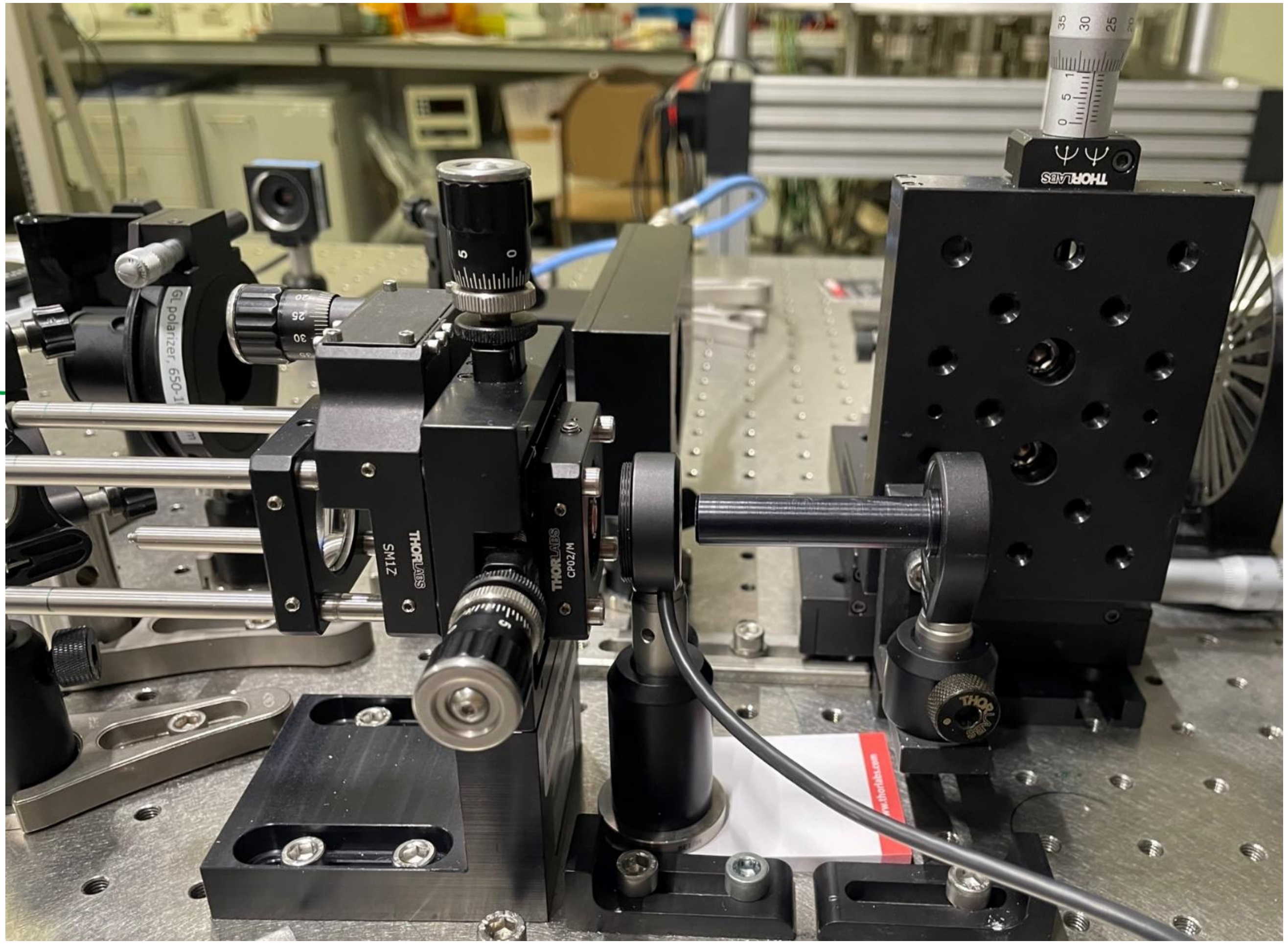




Development of a superresolution THz spectro-microscopy

The spintronic THz emitters: Towards high spatial resolution

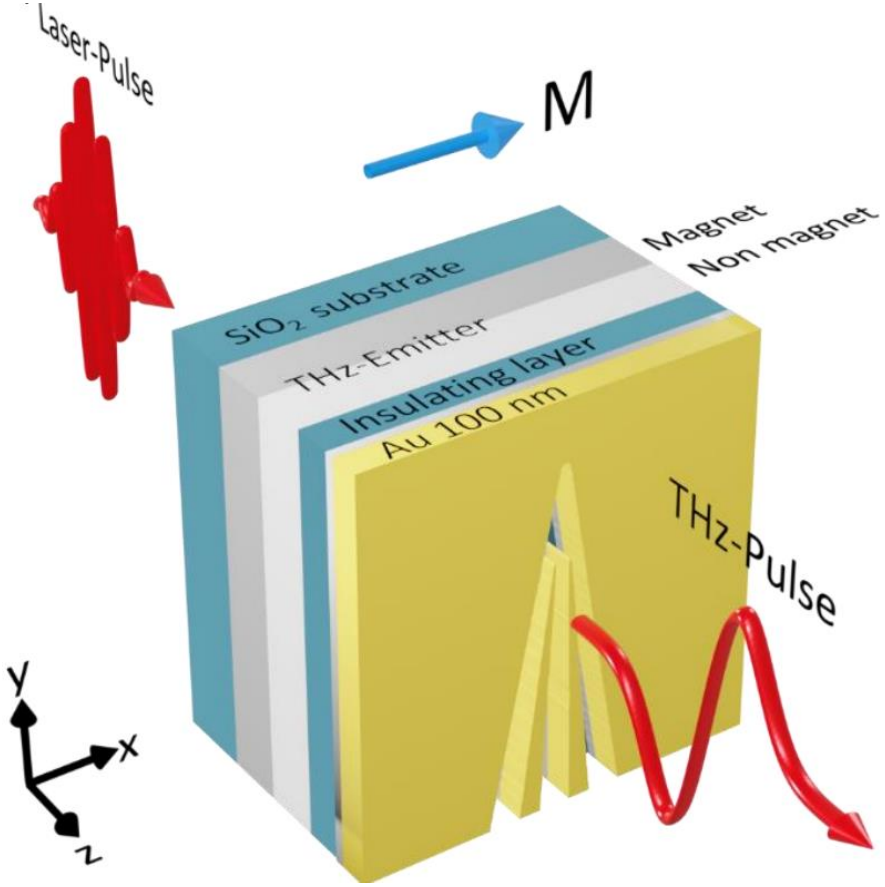




Spintronic THz superresolution spectroscopy

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

The spintronic THz emitters: Towards high spatial resolution



Imaging a Au test aperture

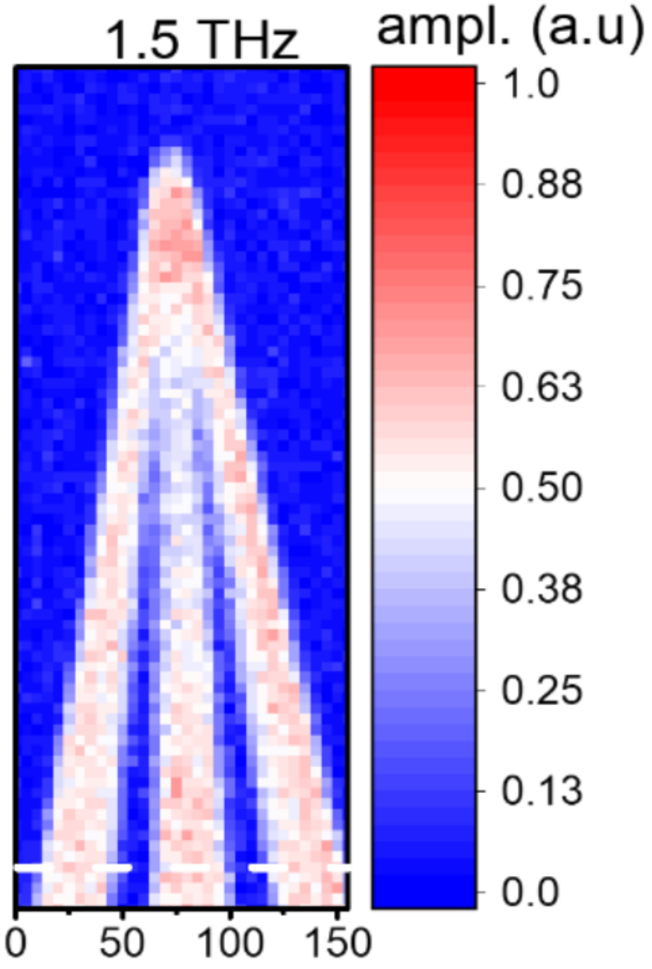
F.-F. Stiewe et al. Appl. Phys. Lett. 120, 032406 (2022).

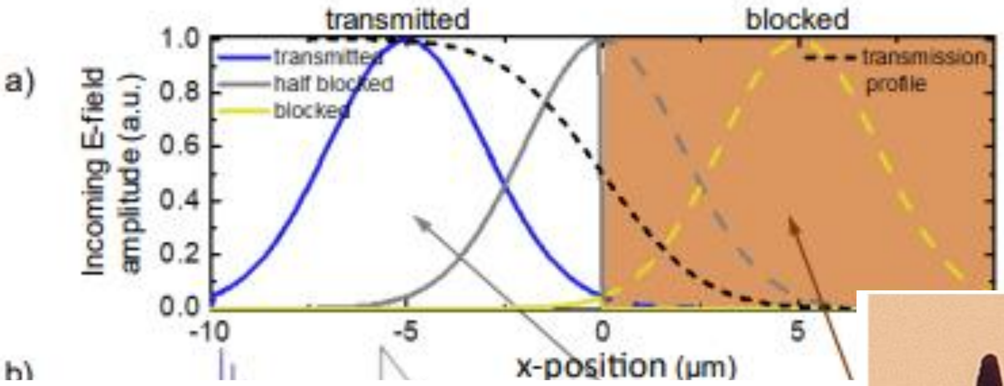
PlasMark
innoFSPEC | HIKE | plasmatis

Spintronic THz superresolution spectroscopy

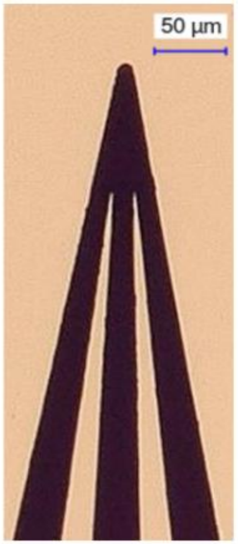
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

The spintronic THz emitters: Towards high spatial resolution





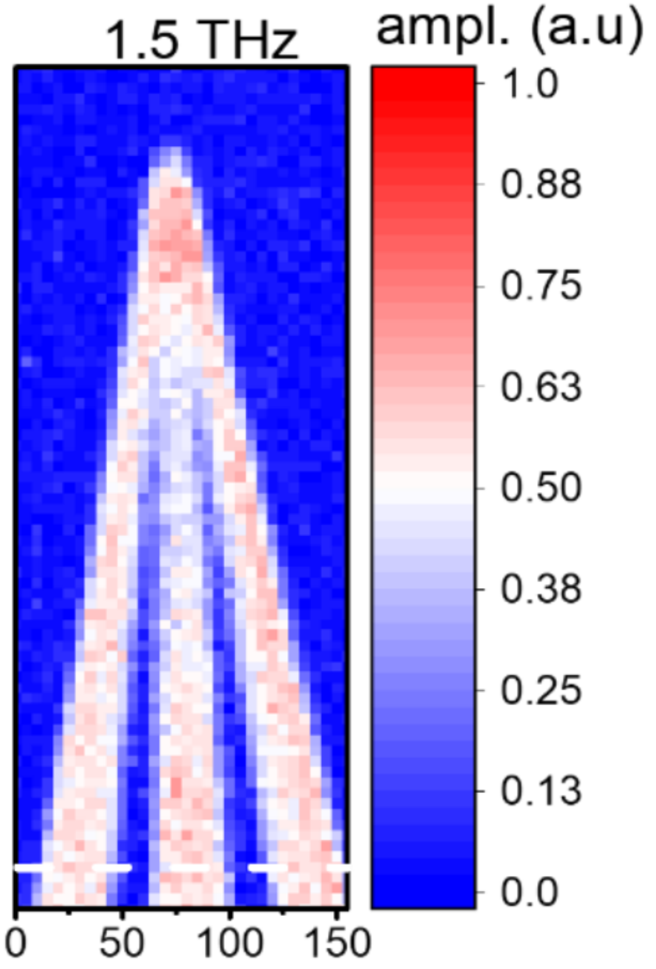
Calculation of the THz propagation

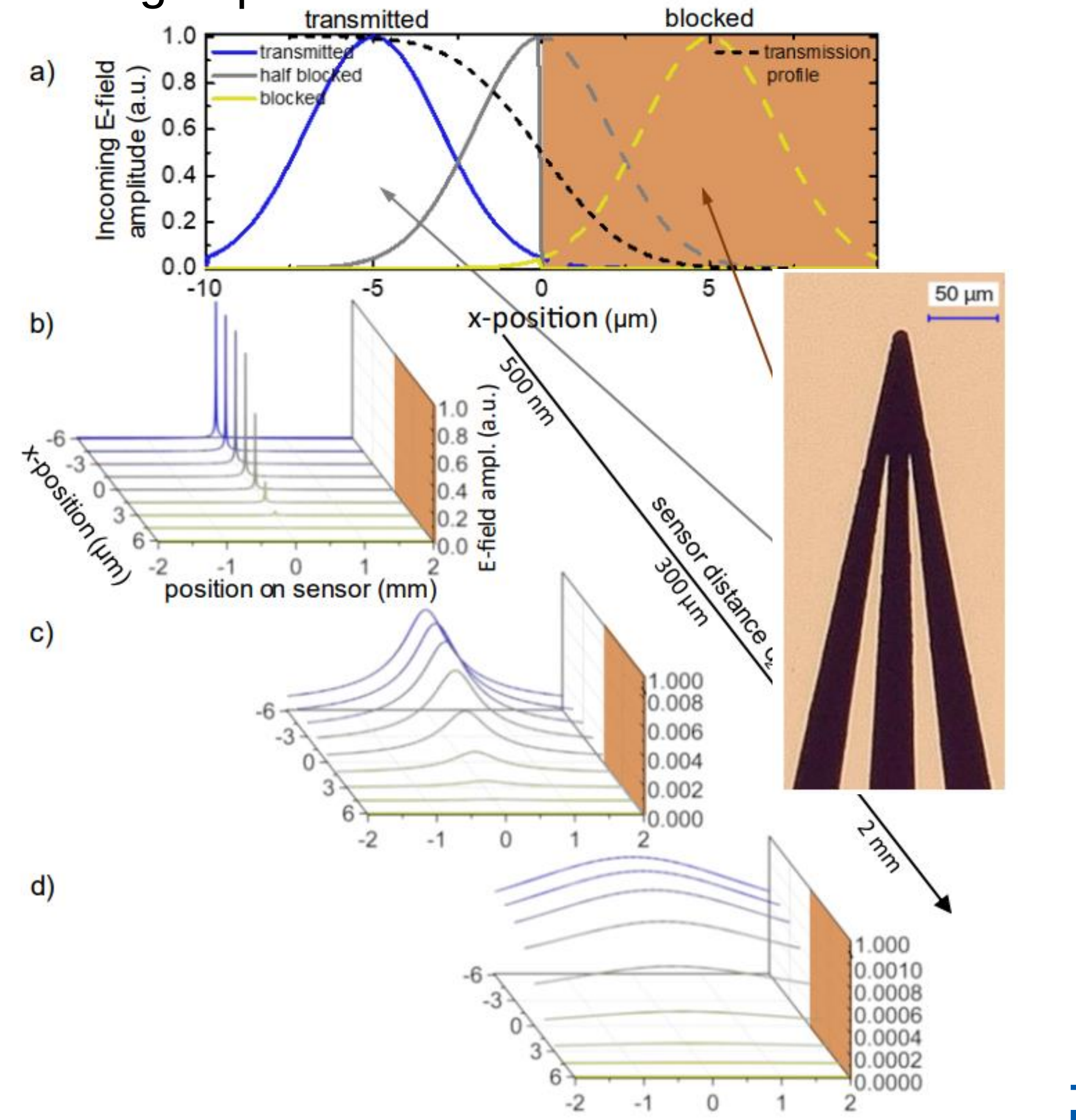


Au aperture

Spintronic THz superresolution spectroscopy

The spintronic THz emitters: Towards high spatial resolution





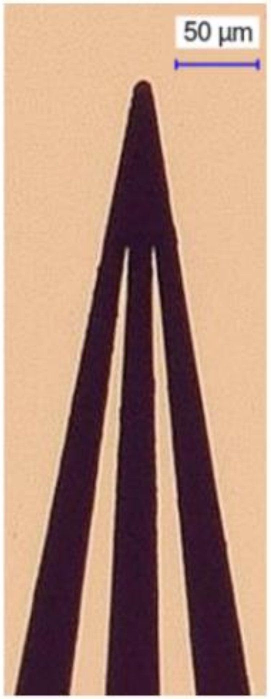
Spintronic THz superresolution spectroscopy

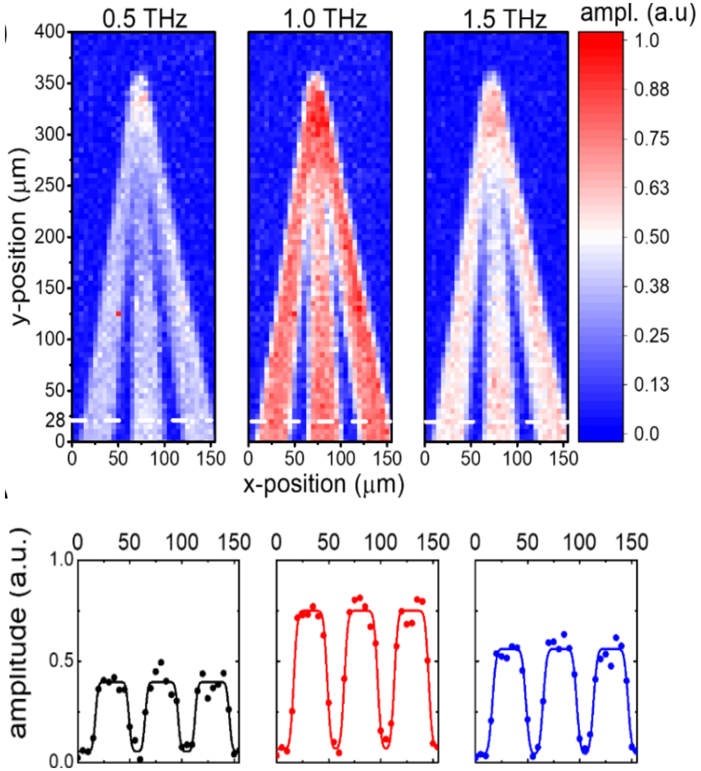
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

The spintronic THz emitters: Increase of the resolution by x100!

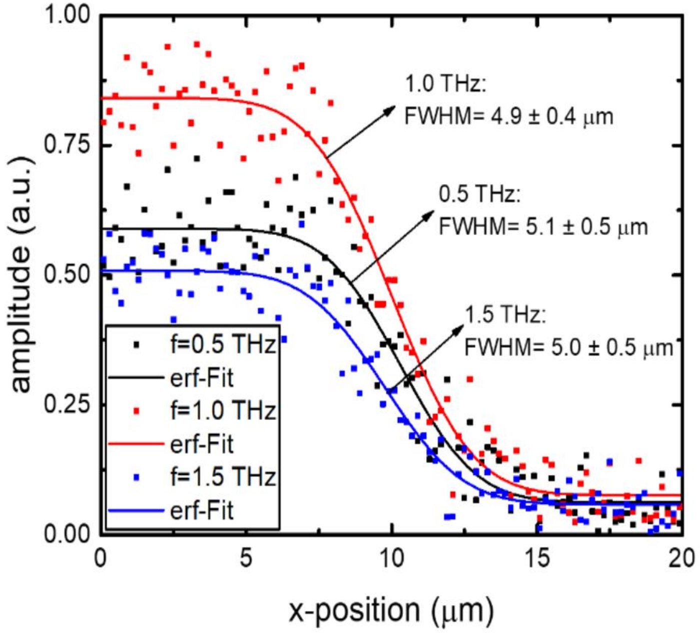
3-5 μm / 300 μm

THz imaging





Resolution: Knife edge method



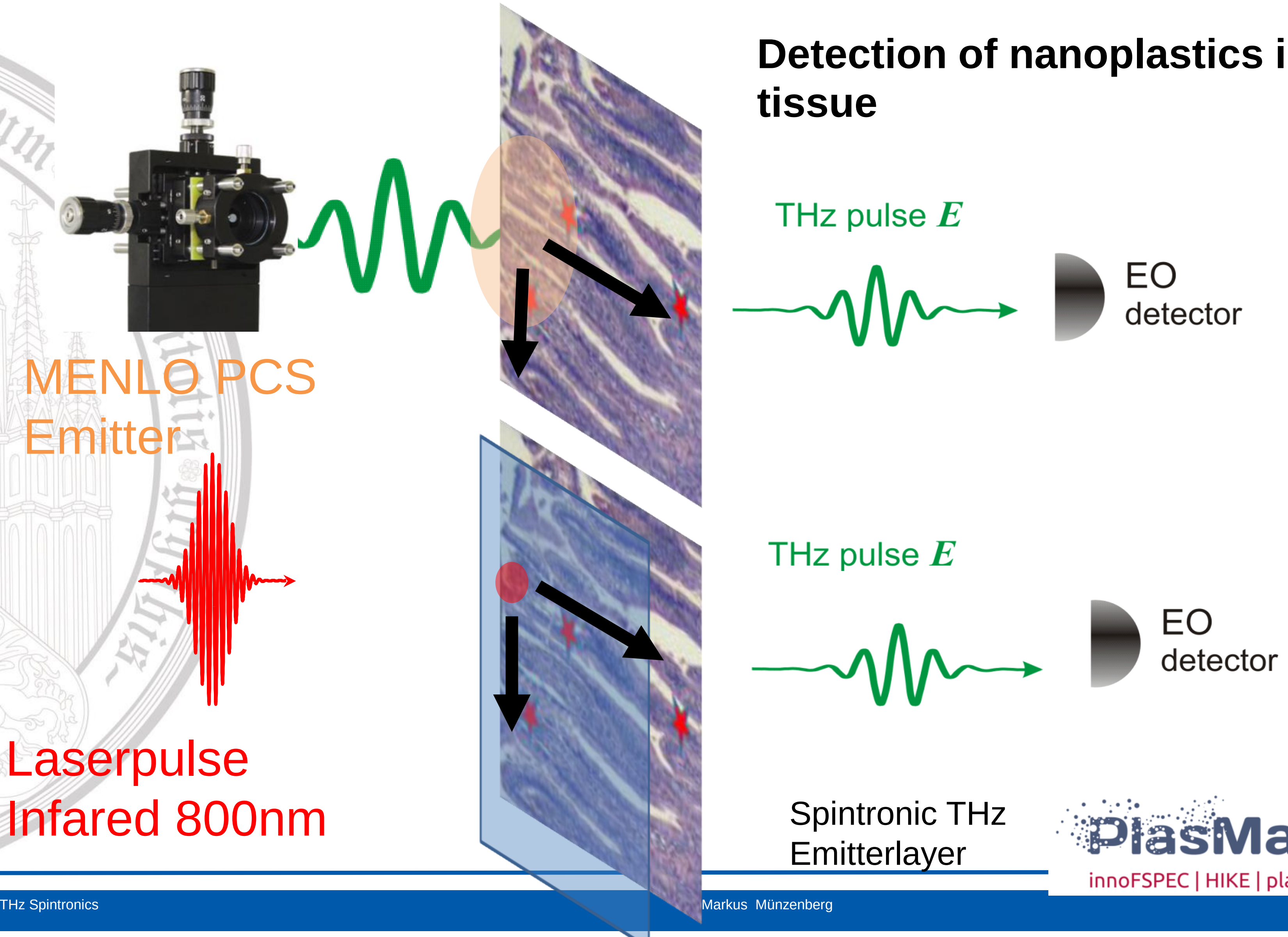
F.-F. Stiewe et al. Appl. Phys. Lett. 120, 032406 (2022).

PlasMark
innoFSPEC | HIKE | plasmatis

Spintronic THz superresolution spectroscopy

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Detection of nanoplastics in live tissue

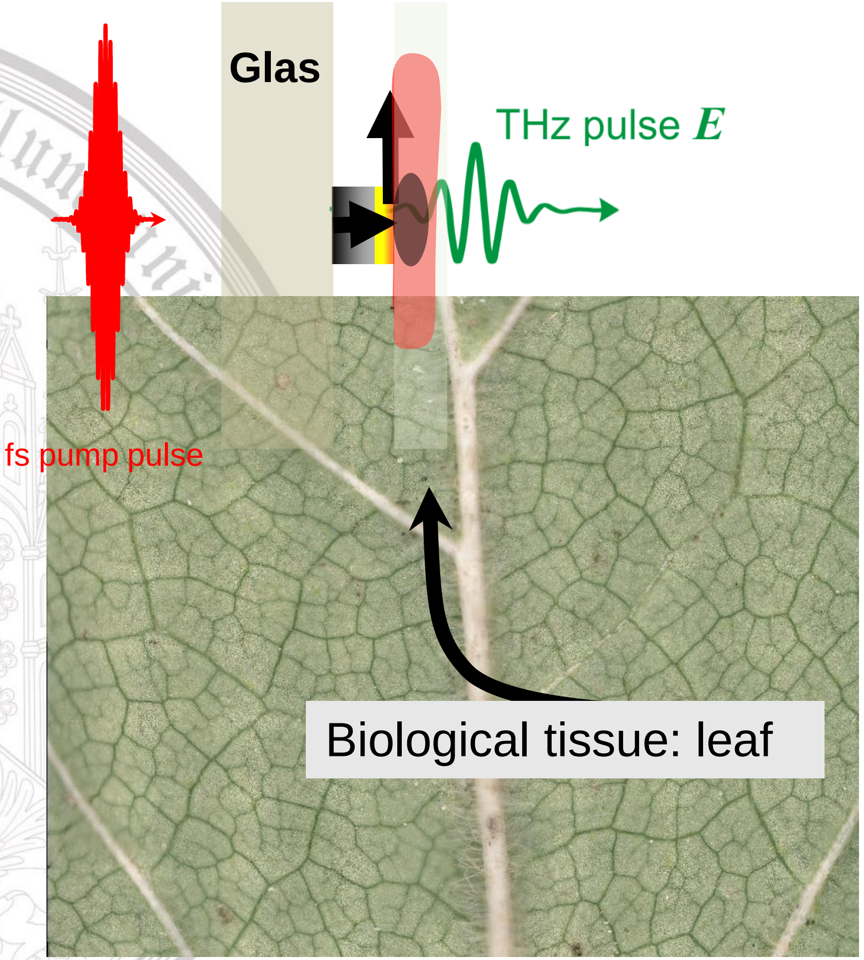


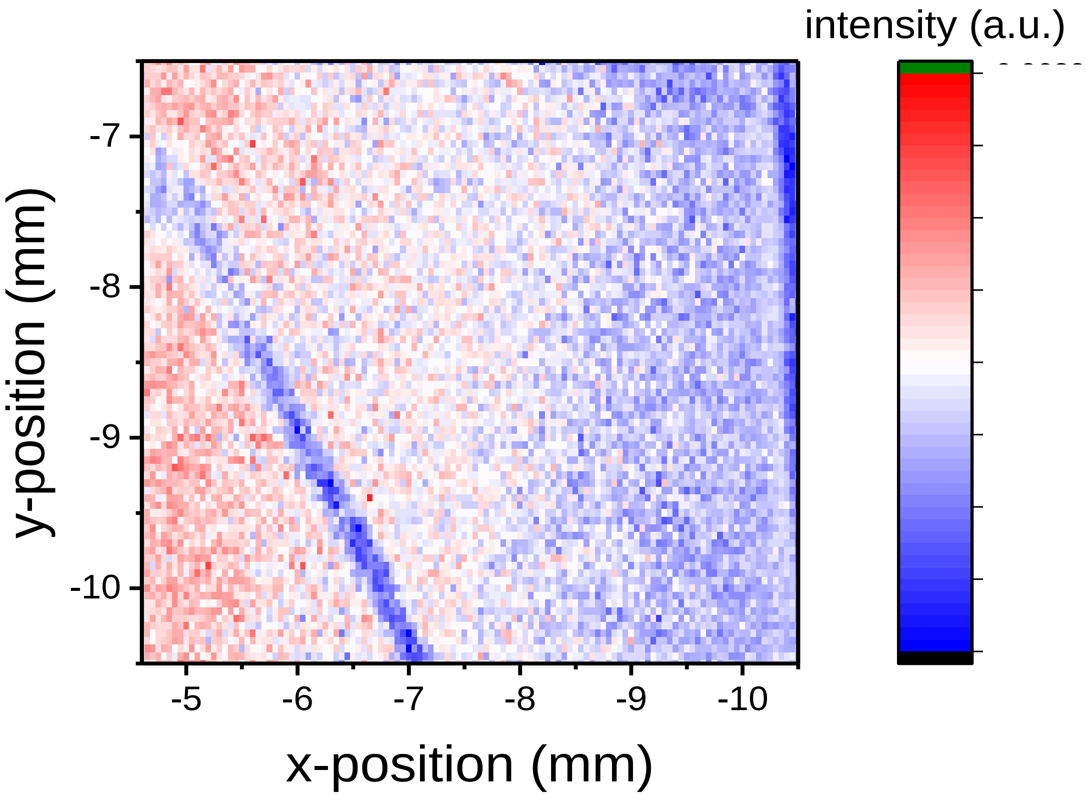
PlasMark
innoFSPEC | HIKE | plasmatis

Spintronic THz superresolution spectroscopy

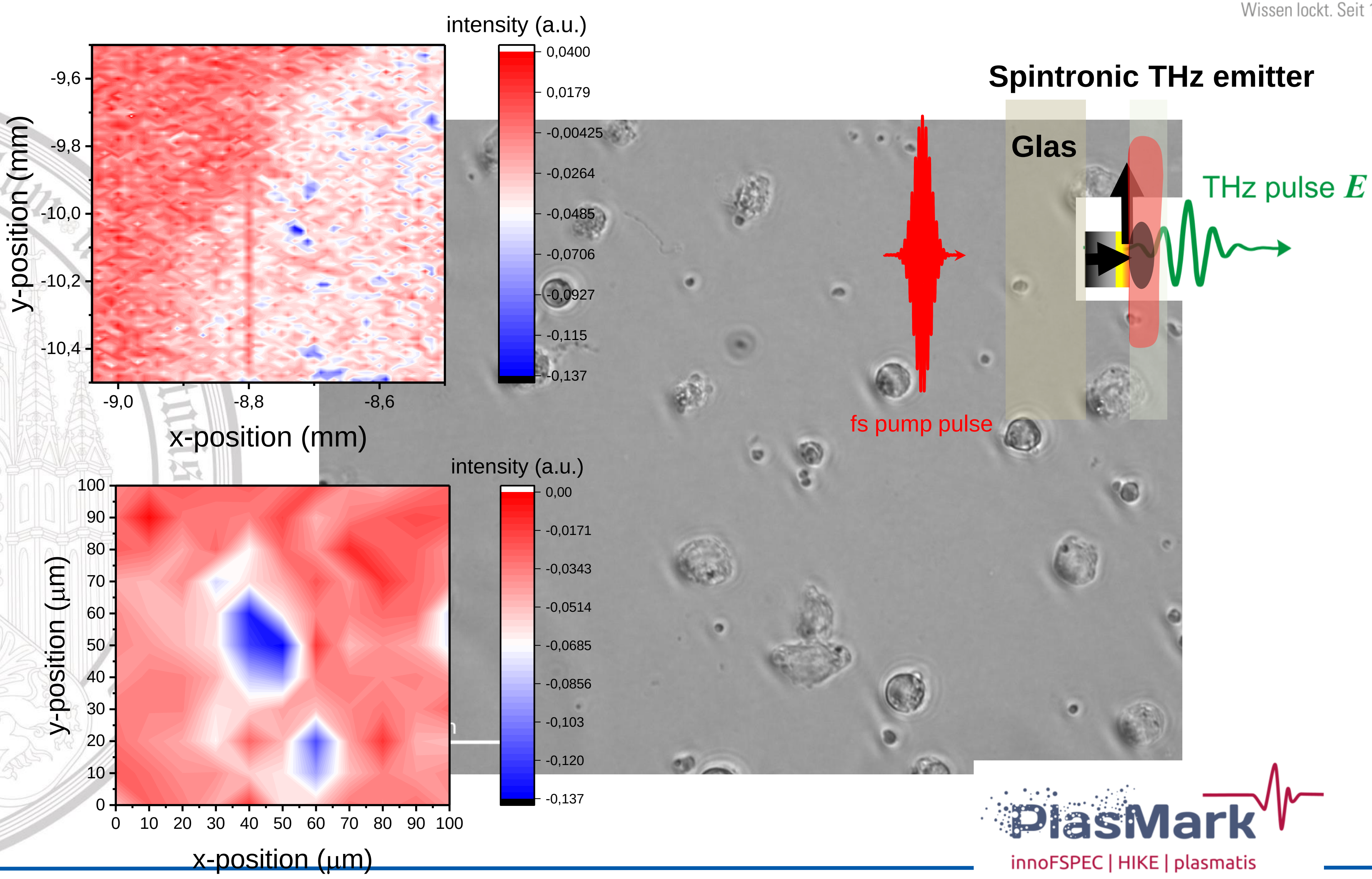
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Spintronic THz emitter





Spintronic THz superresolution spectroscopy

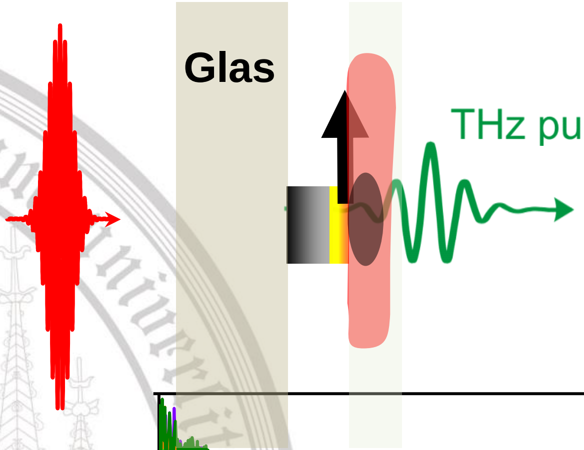


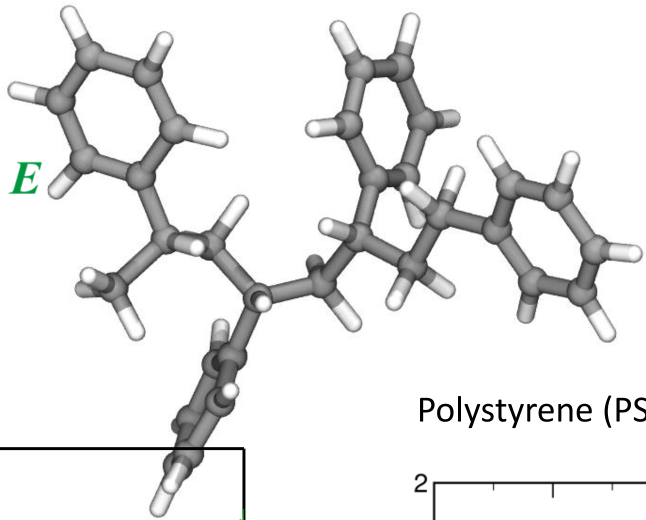
Cell growth on THz emitter Doreen Biedenweg, Stefanie Spiegler (Otto group)

Spintronic THz superresolution spectroscopy

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

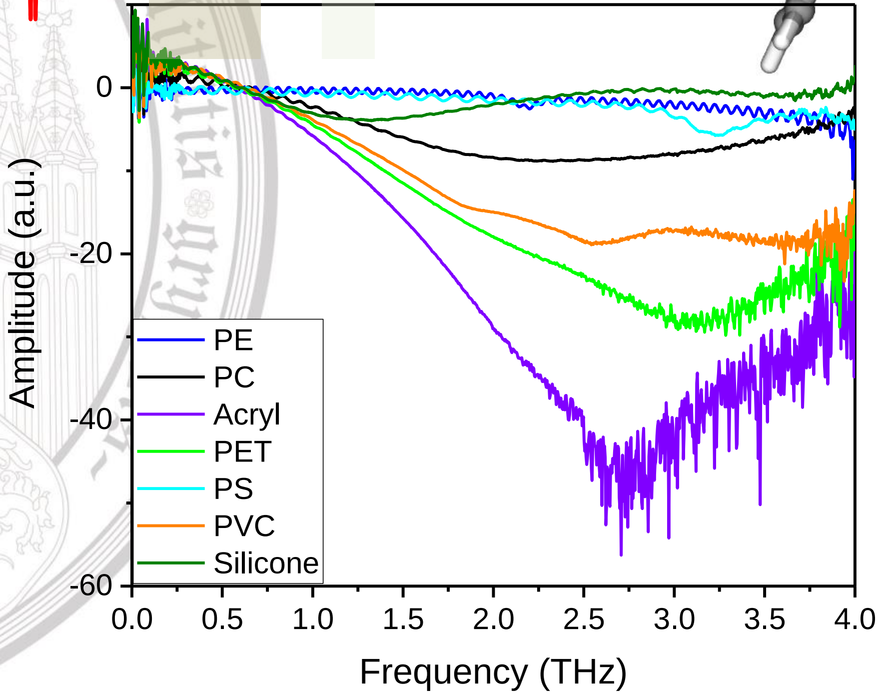
Spintronic THz emitter



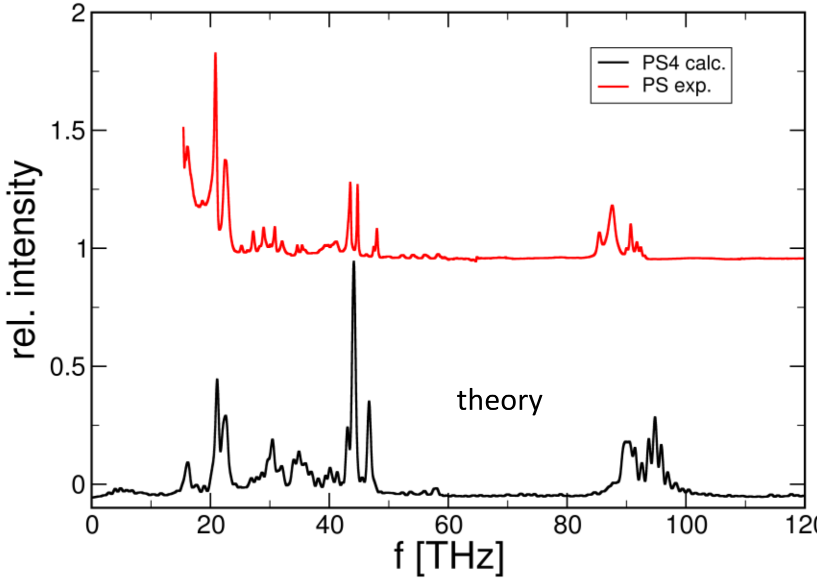


PlasMark
innoFSPEC | HIKE | plasmatis

THz data base for plastics



Polystyrene (PS)

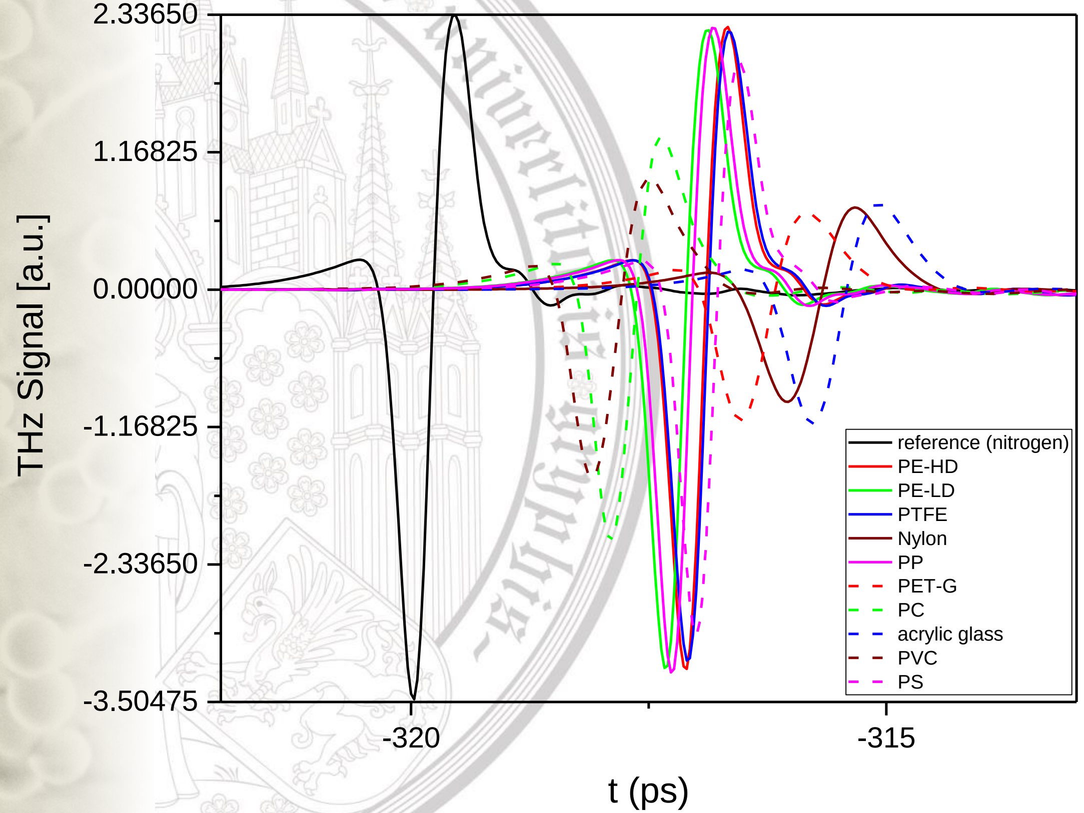


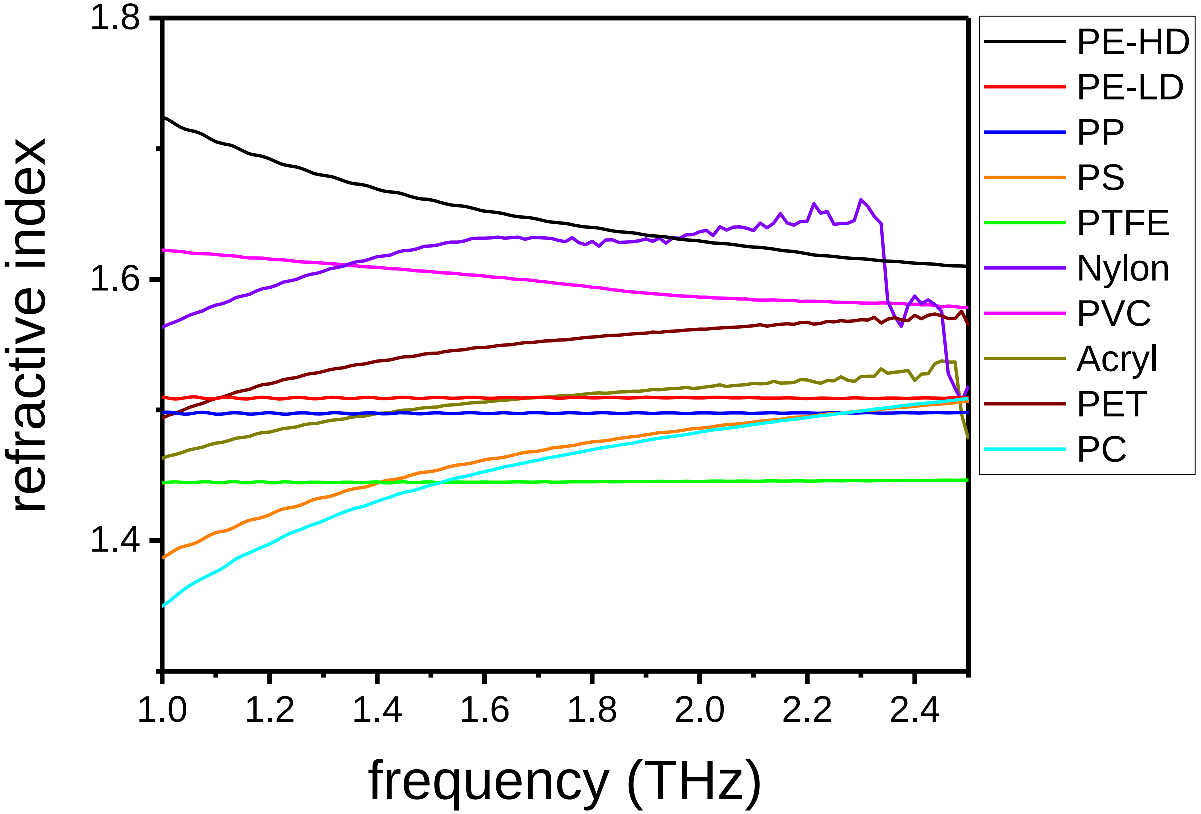
Modelling Norman Geist (Delcea group)

Development of a superresolution THz spectro-microscopy

The spintronic THz emitters: Towards high frequency resolution

Thickness dependence – Refractive index

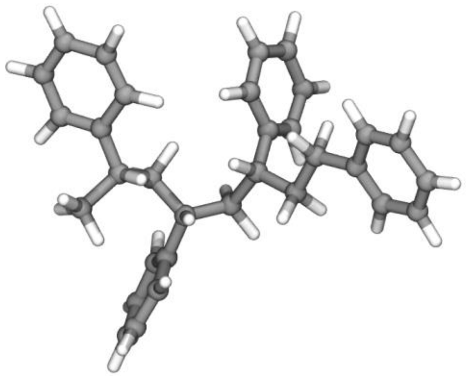




„Identification and characterization of various plastics using THz-spectroscopy", T. Kleinke, F.-F. Stiewe, T. Winkel, N. Geist, U. Martens, M. Delcea, Mihaela, J. Walowski, M. Münzenberg, **Soft Matter** (2022). Submitted manuscript ID SM-ART-11-2022-001526

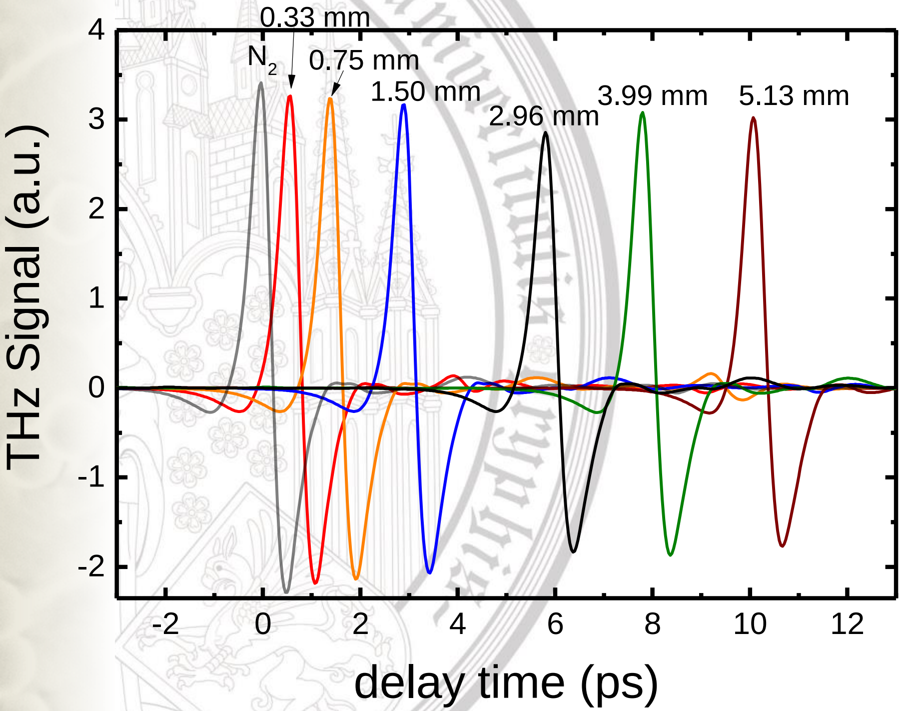
Development of a superresolution THz spectro-microscopy

The spintronic THz emitters: Towards high frequency resolution

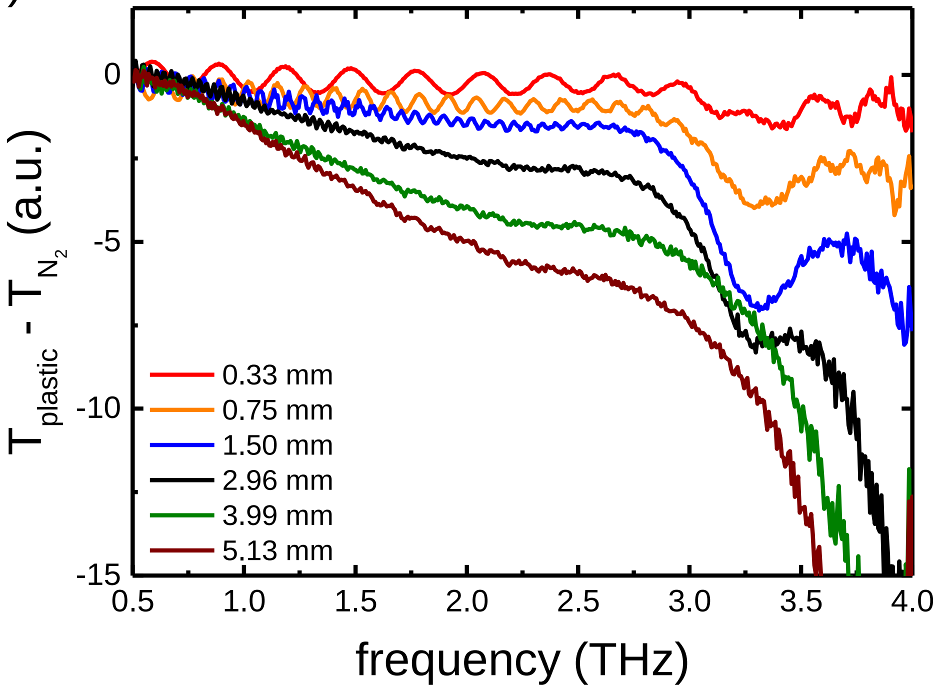


Thickness dependence – Polystyrene (PS)

a)



b)



„Identification and characterization of various plastics using THz-spectroscopy“, T. Kleinke, F.-F. Stiewe, T. Winkel, N. Geist, U. Martens, M. Delcea, Mihaela, J. Walowski, M. Münzenberg, **Soft Matter** (2022). Submitted manuscript ID SM-ART-11-2022-001526

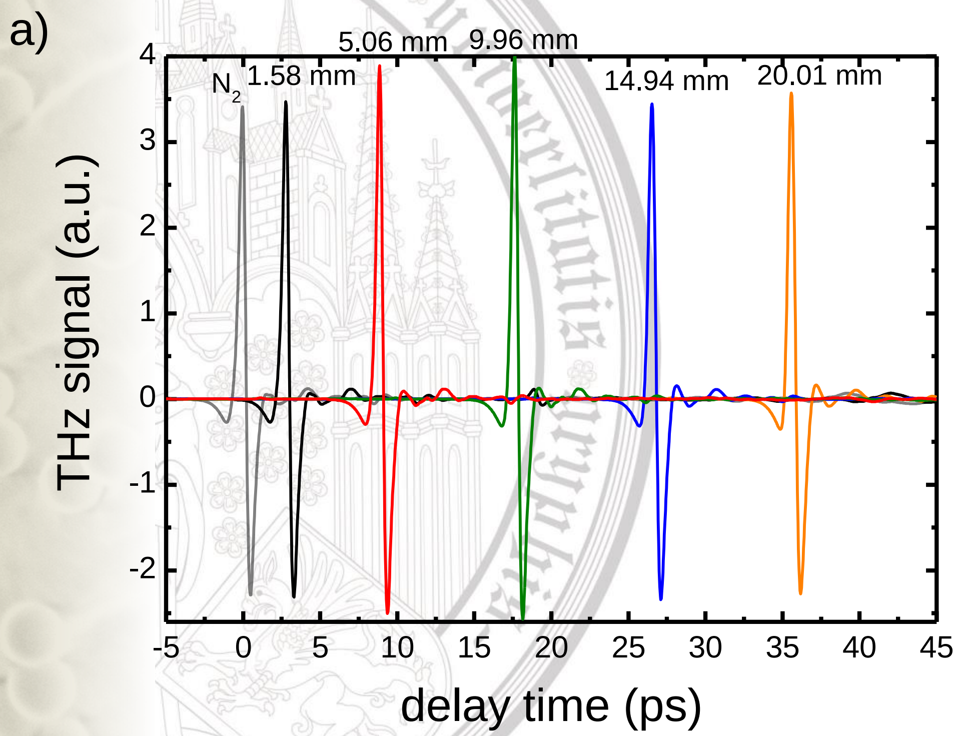
Development of a superresolution THz spectro-microscopy

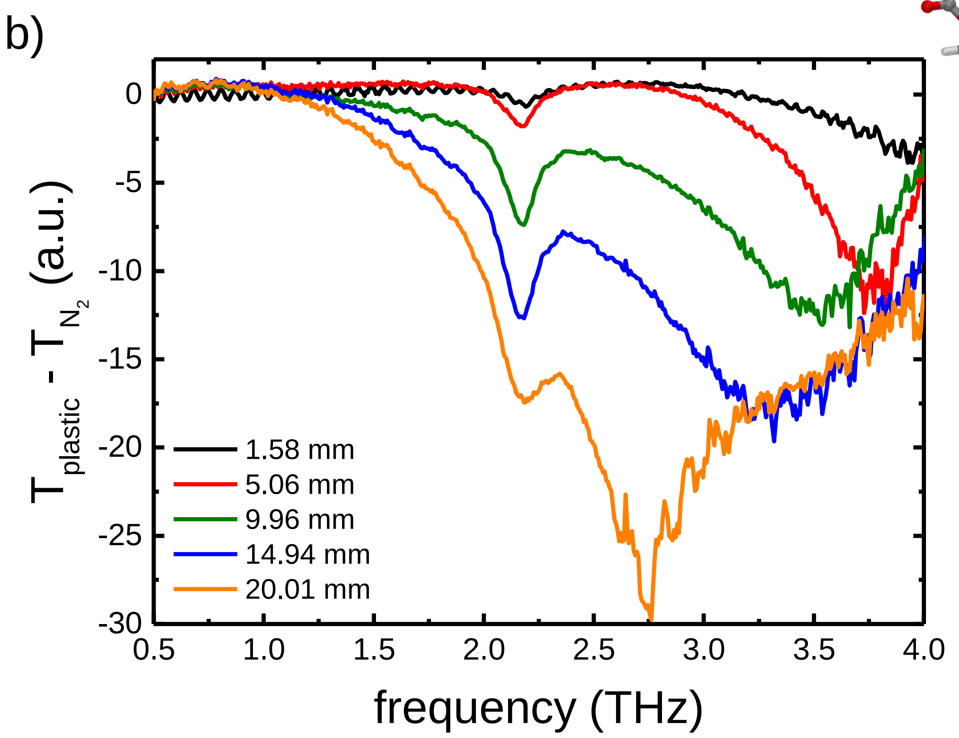
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

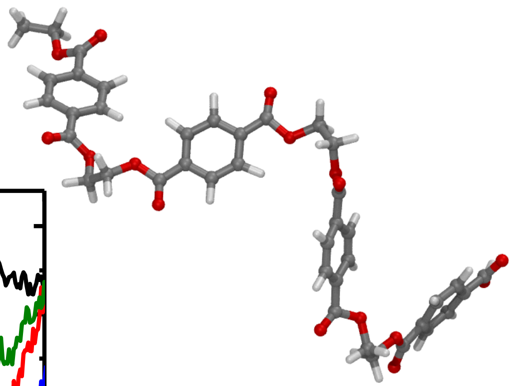
PlasMark
innoFSPEC | HIKE | plasmatis

The spintronic THz emitters: Towards high frequency resolution

Thickness dependence – Polyethylene (PET)







„Identification and characterization of various plastics using THz-spectroscopy“, T. Kleinke, F.-F. Stiewe, T. Winkel, N. Geist, U. Martens, M. Delcea, Mihaela, J. Walowski, M. Münzenberg, **Soft Matter** (2022). Submitted manuscript ID SM-ART-11-2022-001526

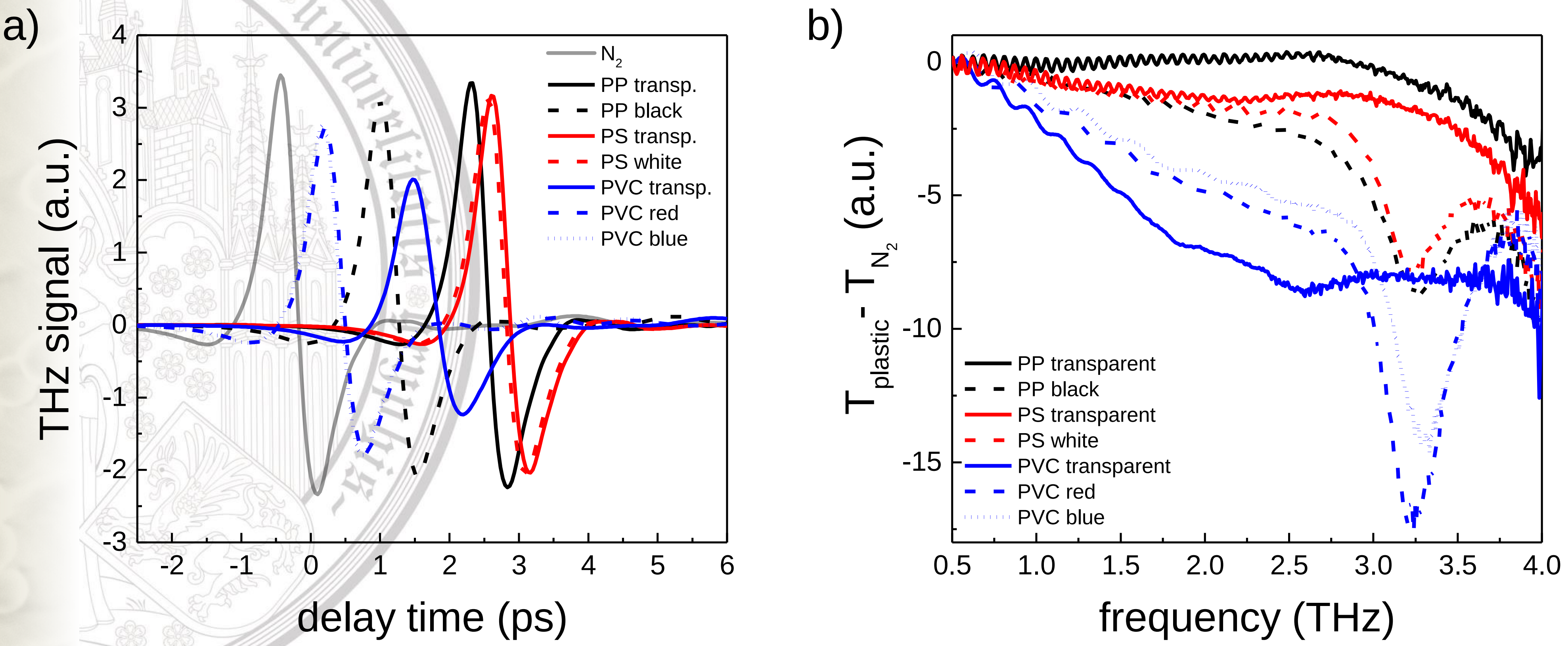
Development of a superresolution THz spectro-microscopy

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

PlasMark
innoFSPEC | HIKE | plasmatis

The spintronic THz emitters: Towards high frequency resolution

Absorption characteristics for color additives

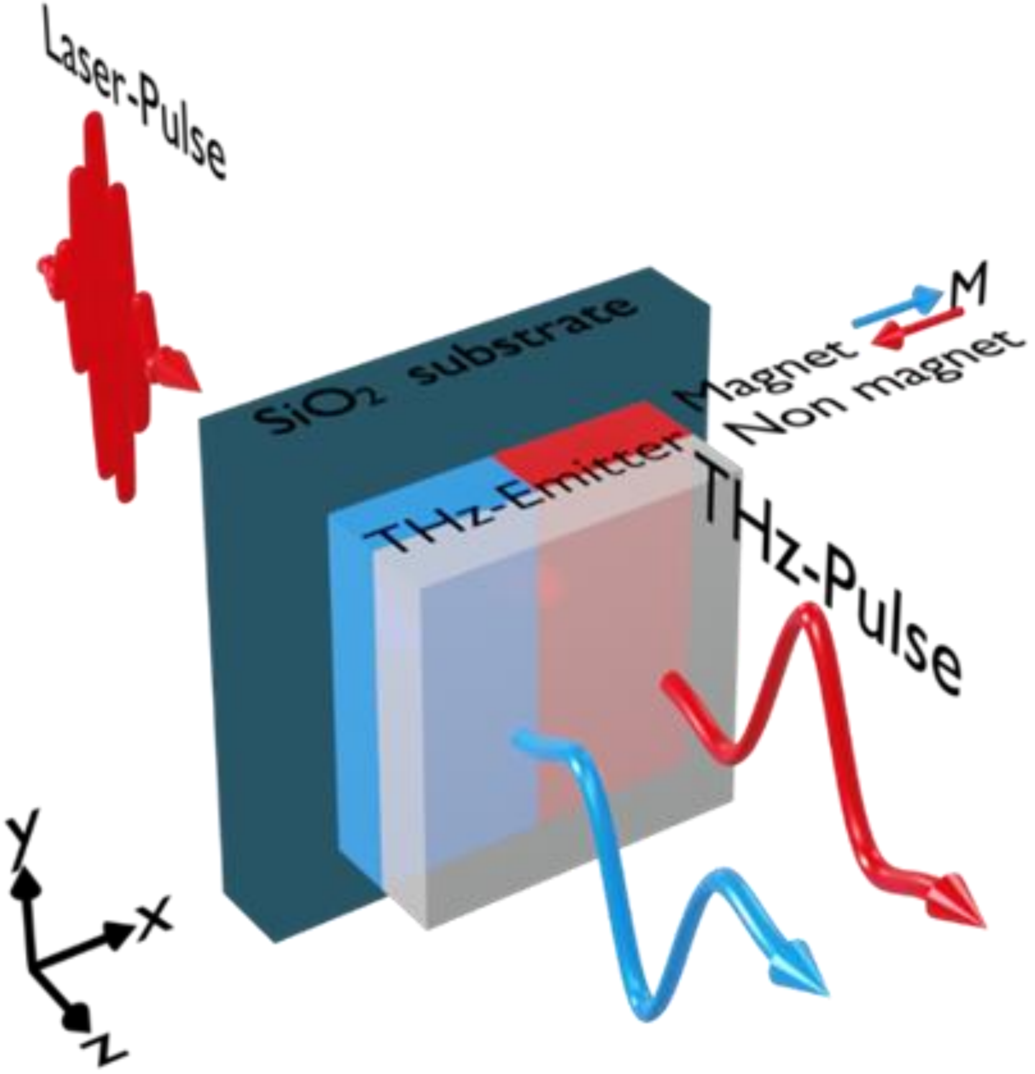


„Identification and characterization of various plastics using THz-spectroscopy“, T. Kleinke, F.-F. Stiewe, T. Winkel, N. Geist, U. Martens, M. Delcea, Mihaela, J. Walowski, M. Münzenberg, **Soft Matter** (2022). Submitted manuscript ID SM-ART-11-2022-001526

Spintronic THz superresolution spectroscopy

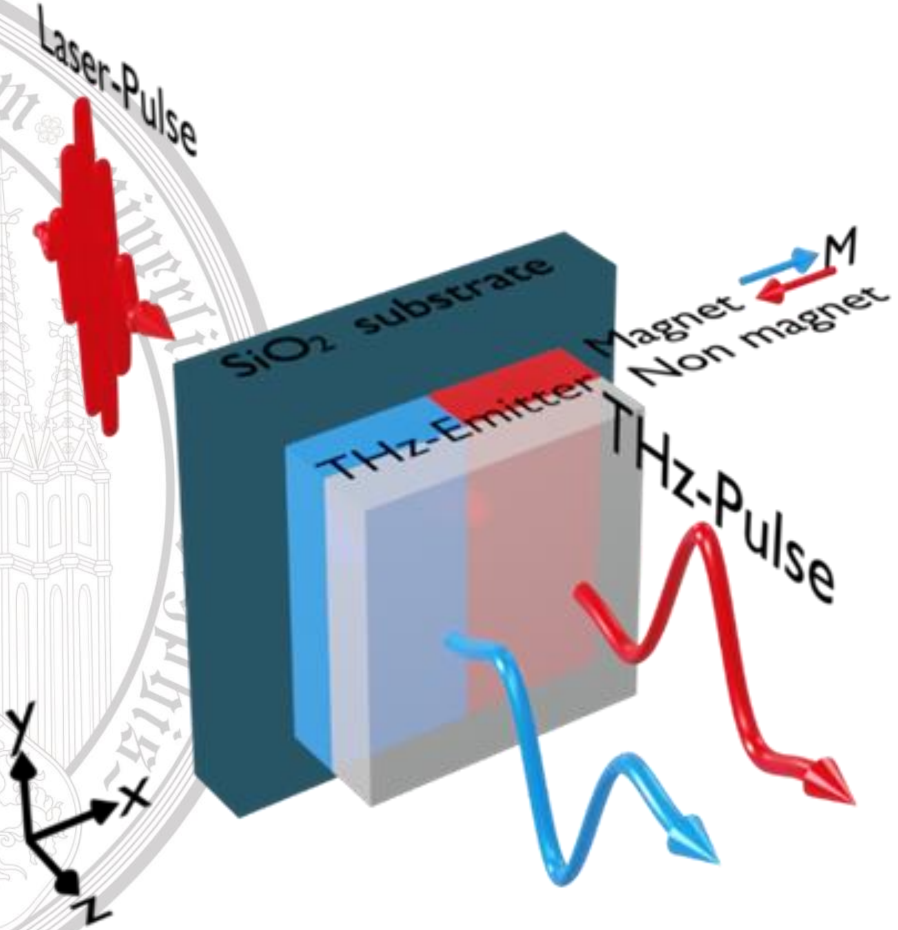
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

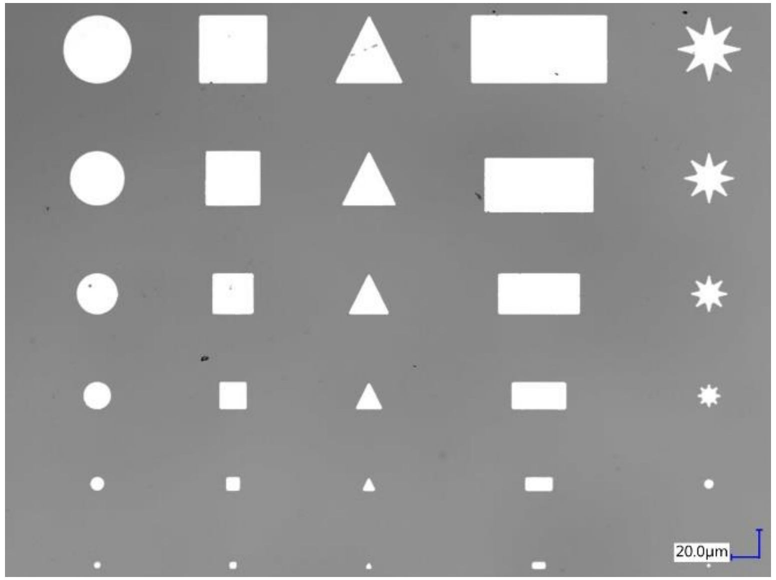
Magnetic THz imaging

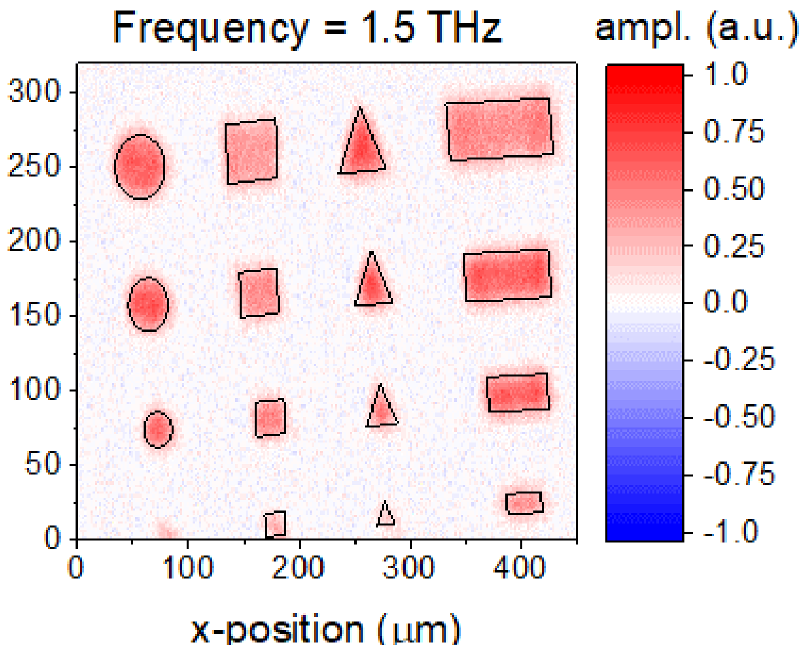


Spintronic THz superresolution spectroscopy

Magnetic THz imaging



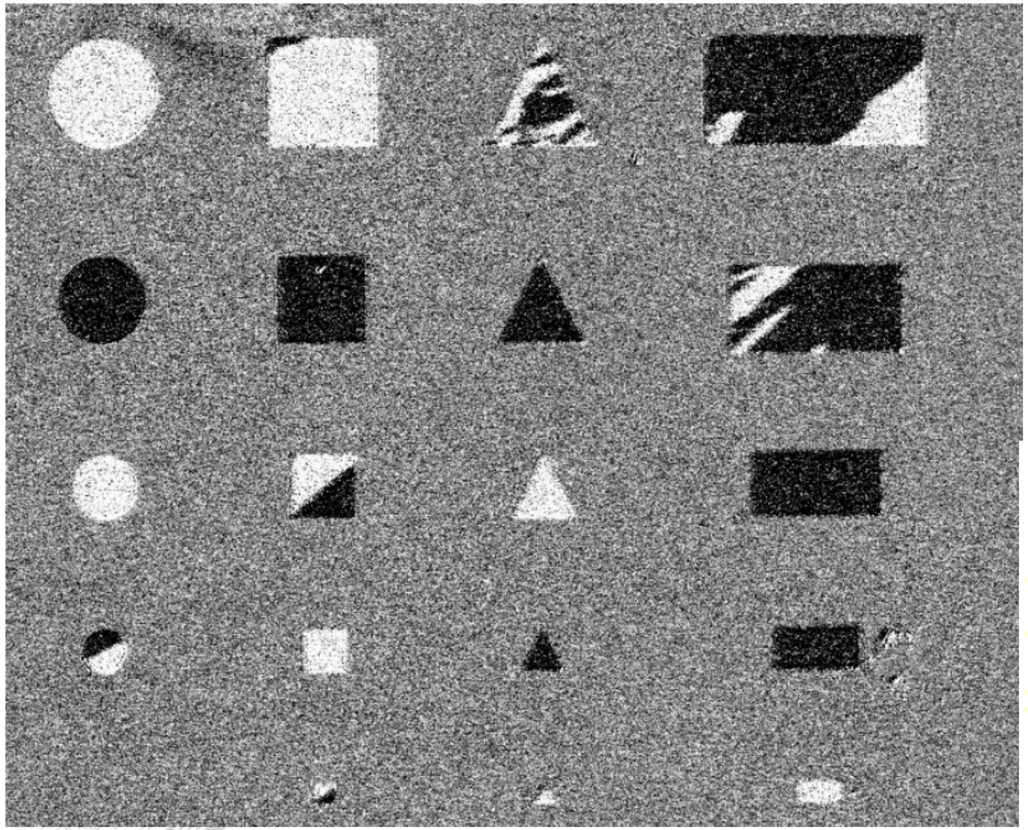




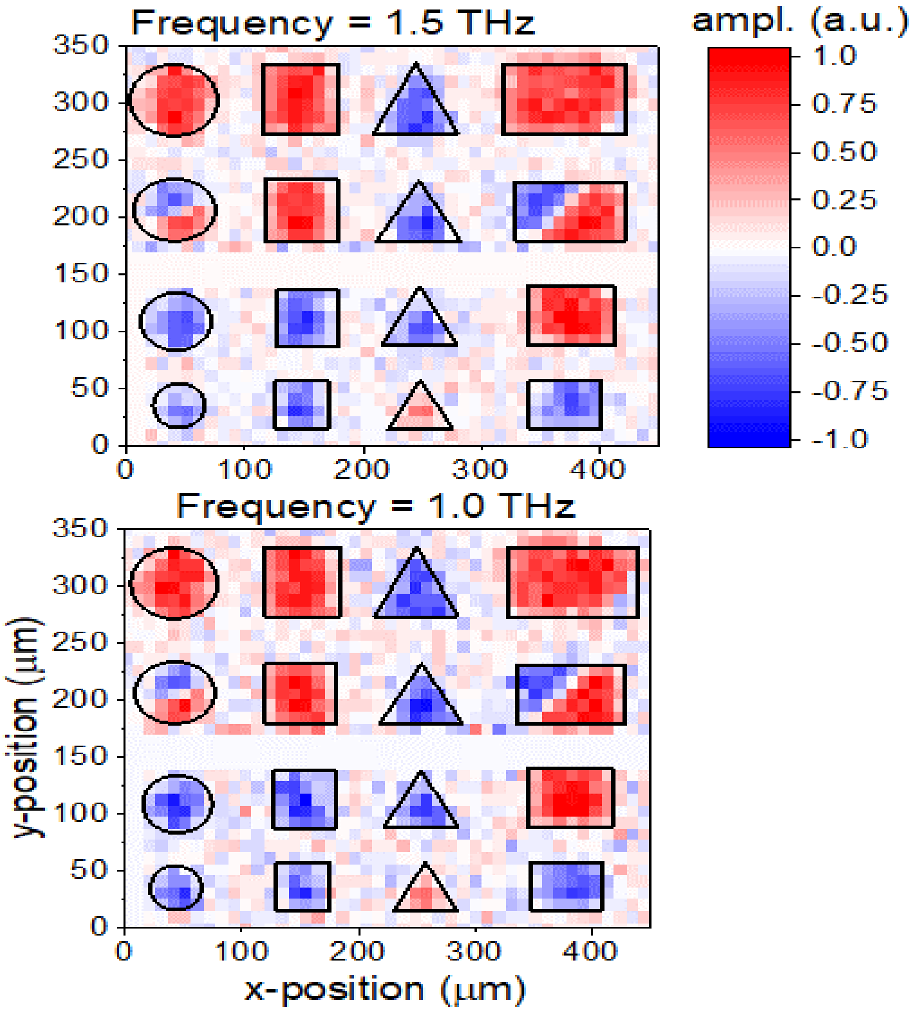
Spintronic THz superresolution spectroscopy

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

MOKE



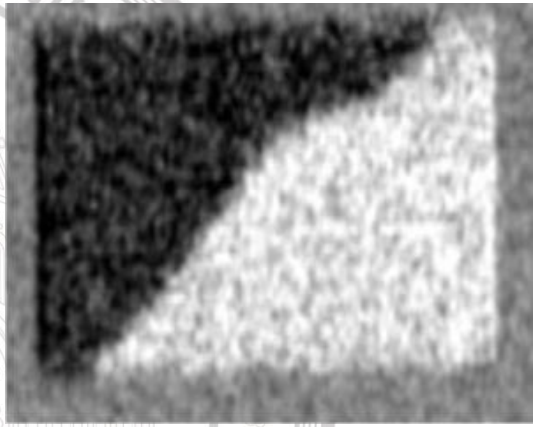
THz

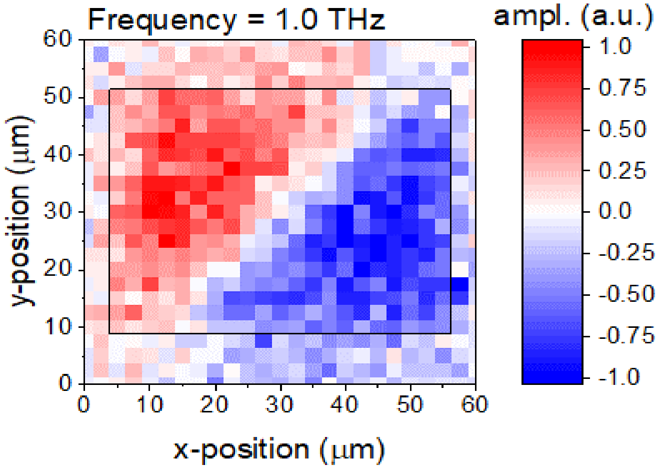


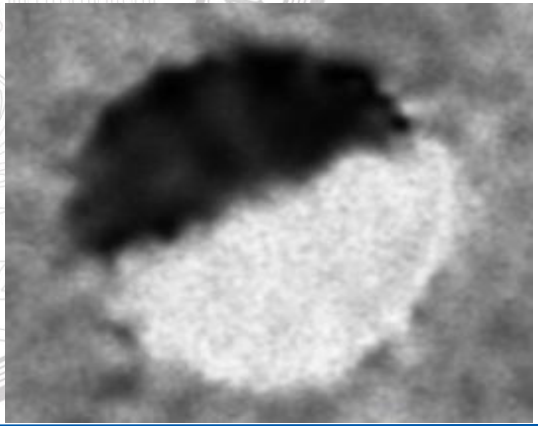
Spintronic THz superresolution spectroscopy

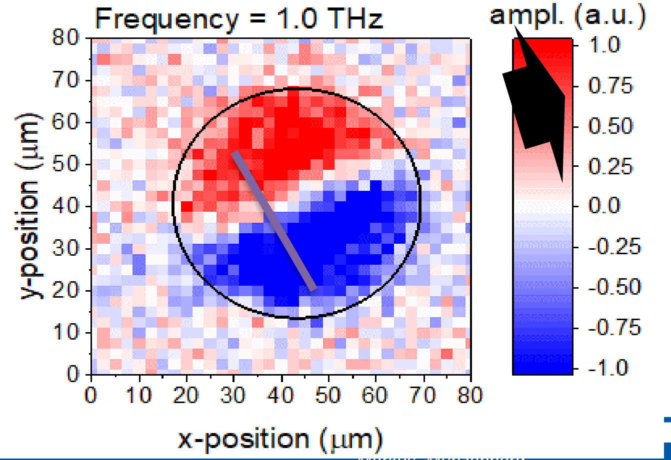
- Magnetic spectral imaging in the frequency domain
- Local spin current effects
- Mapping local THz dynamics in antiferromagnets

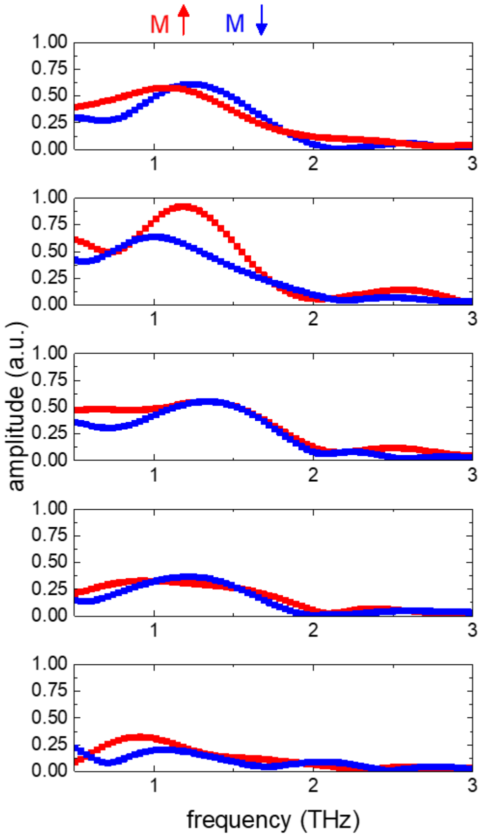
- Magnetic spectral imaging of a domain wall









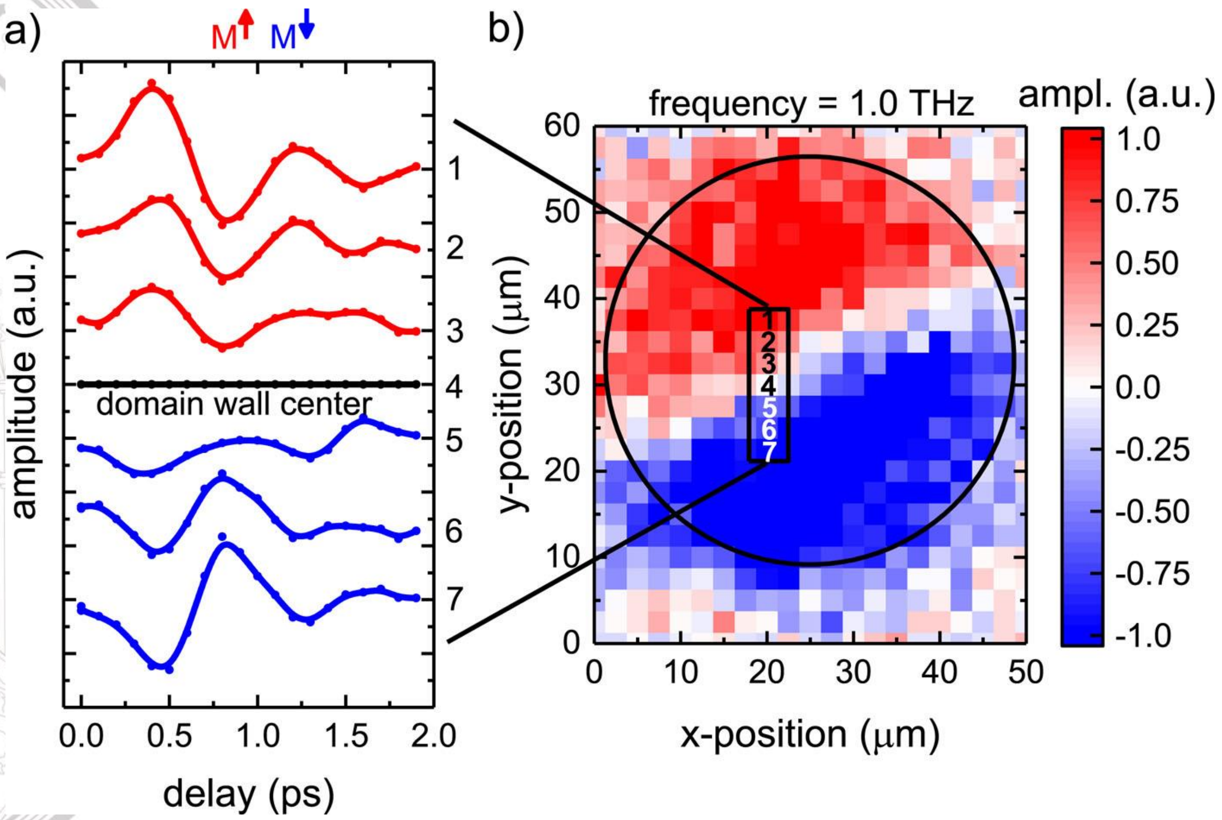


Spintronic THz superresolution spectroscopy

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

- Magnetic spectral imaging in the frequency domain
- Local spin current effects
- Mapping local THz dynamics in antiferromagnets

Local THz emission



- Magnetic spectral imaging of a domain wall
- Full spectral information at each point: THz dynamics

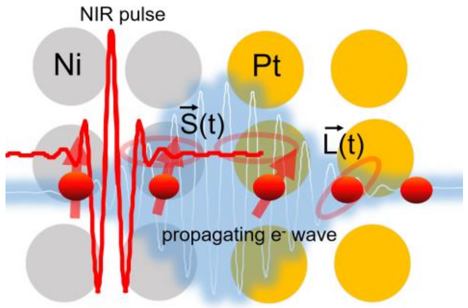
THz emission at 1THz

F.-F. Stiewe, T. Winkel, T. Kleinke, T. Tubandt, H. Heyen, L. Vollroth, U. Martens, C. Müller, J. McCord, J. Walowski, M. Münzenberg, AIP Advances 12, 095010 (2022).

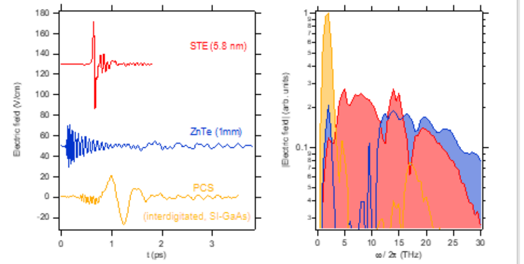
PlasMark
innoFSPEC | HIKE | plasmatis

Outline

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456



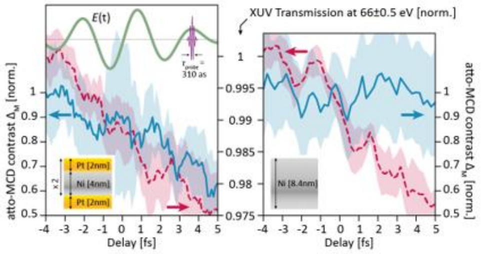
- Introduction



T. Seifert, et al. Nature Photonics (2016)

- THz spintronic emitter – *applications*

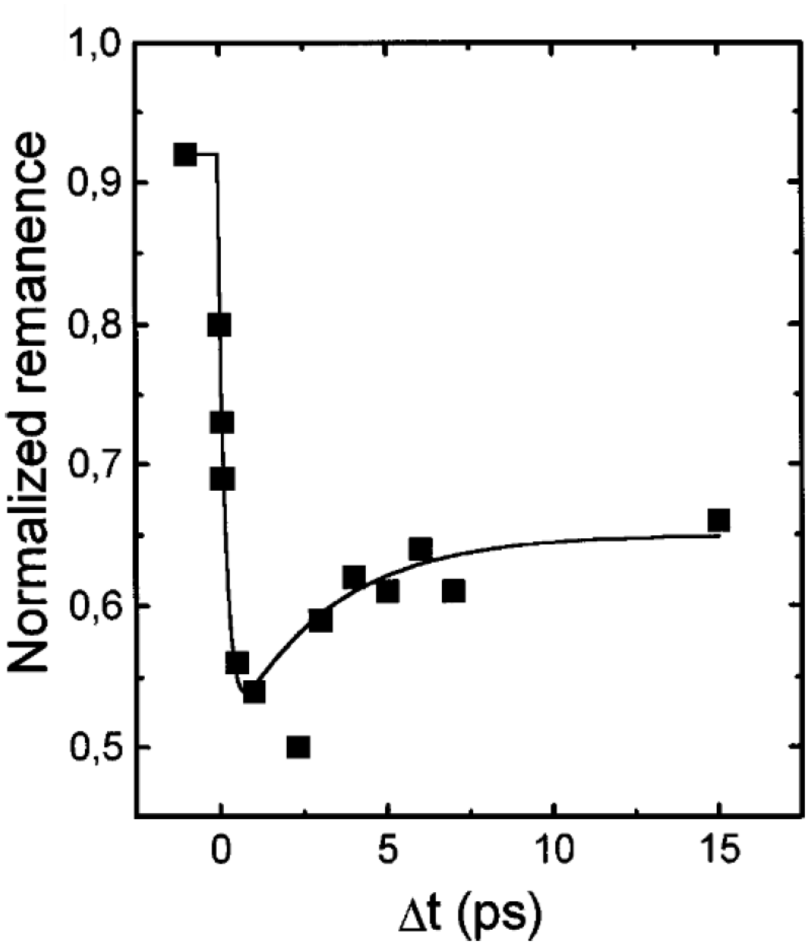
- Lightwave electronics – *coherent spintronics*



F. Siegrist *et al.*, Light-wave dynamic control of magnetism, Nature **571**, 240–244 (2019)

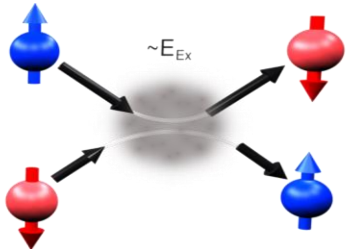
- Summary

Lightwave Spintronics – Attosecond dynamics

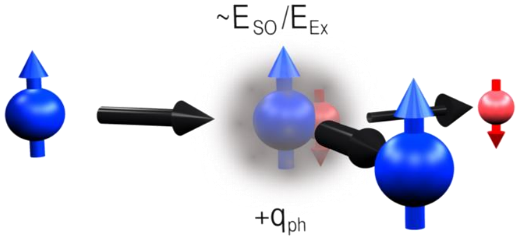


Laser-induced **demagnetization**

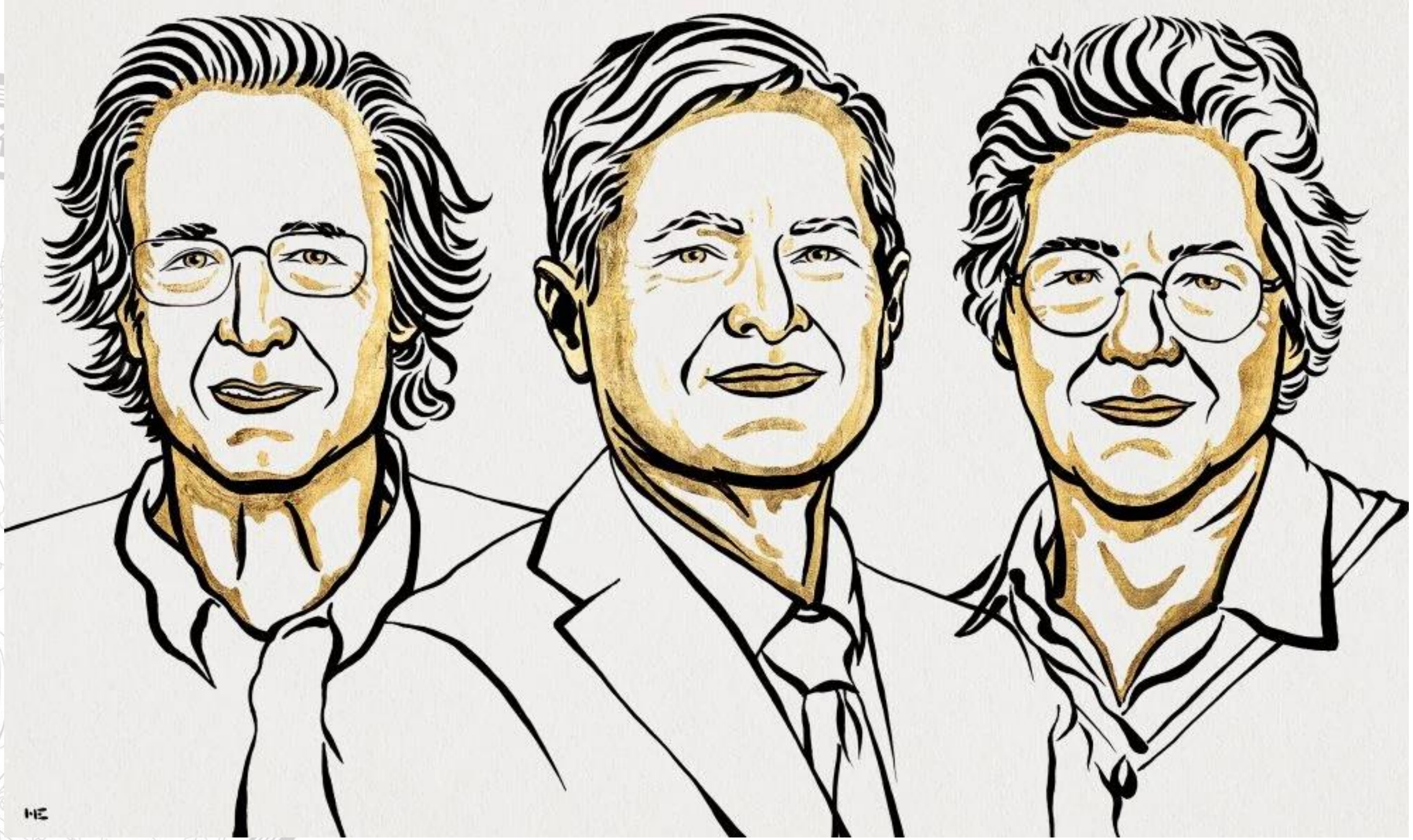
Beaurepaire et al. PRL 76, 4250 (1996)



Metal	Exchange	Spin-orbit
Fe	52 fs	50 fs
Co	80 fs	52 fs
Ni	380 fs	48 fs



Nobel Prize in Physics 2023 to Pierre Agostini, Ferenc Krausz and Anne L'Huillier



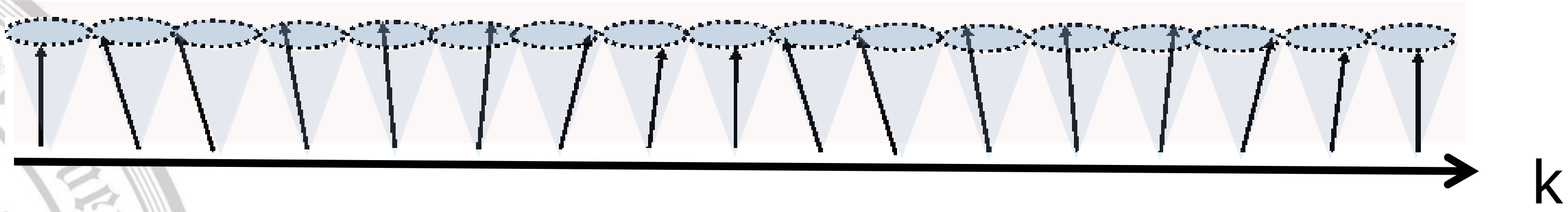
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

["for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter"]

Lightwave Spintronics – Attosecond dynamics

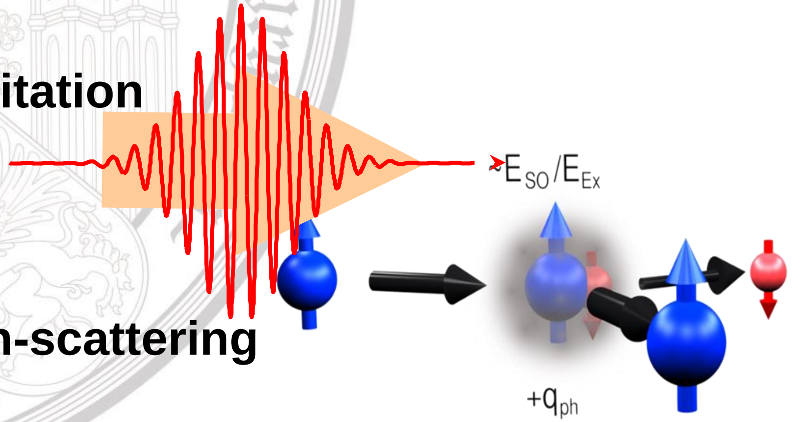
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

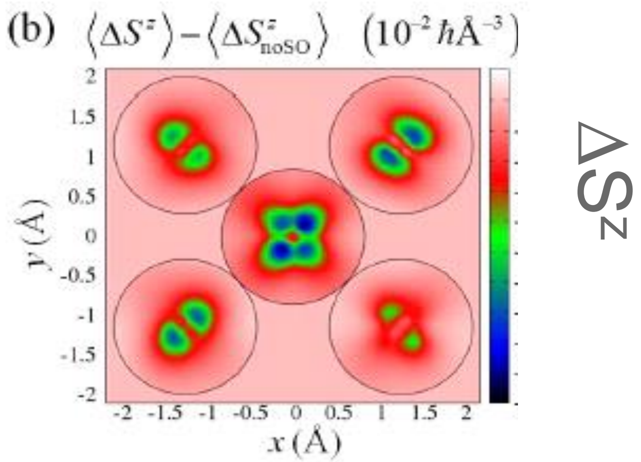
How to access fundamental interactions?



Spin **S**, exchange J

Go to attoseconds!



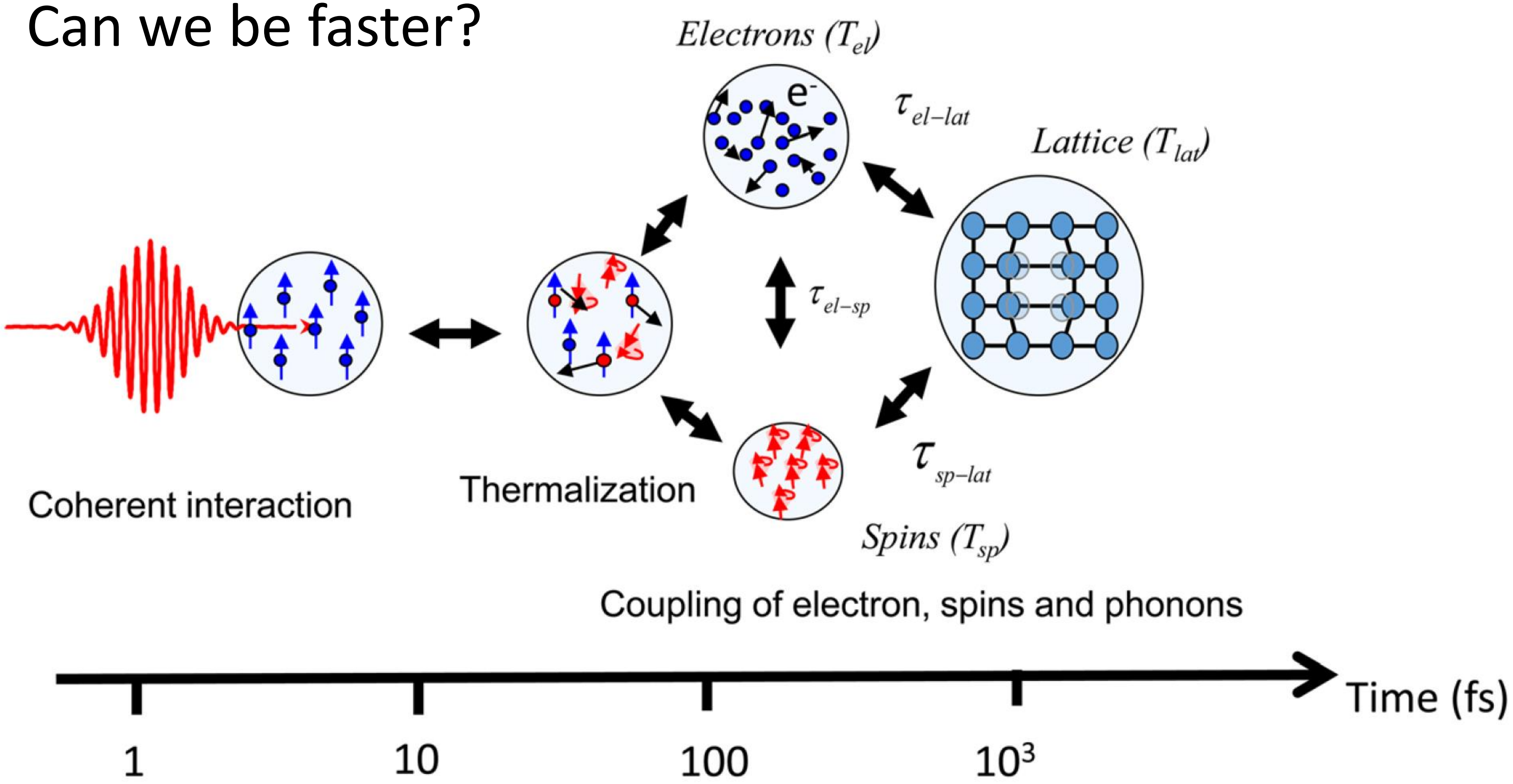


Time dependent density functional theory (TDDFT)

Lightwave Spintronics – Attosecond dynamics

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

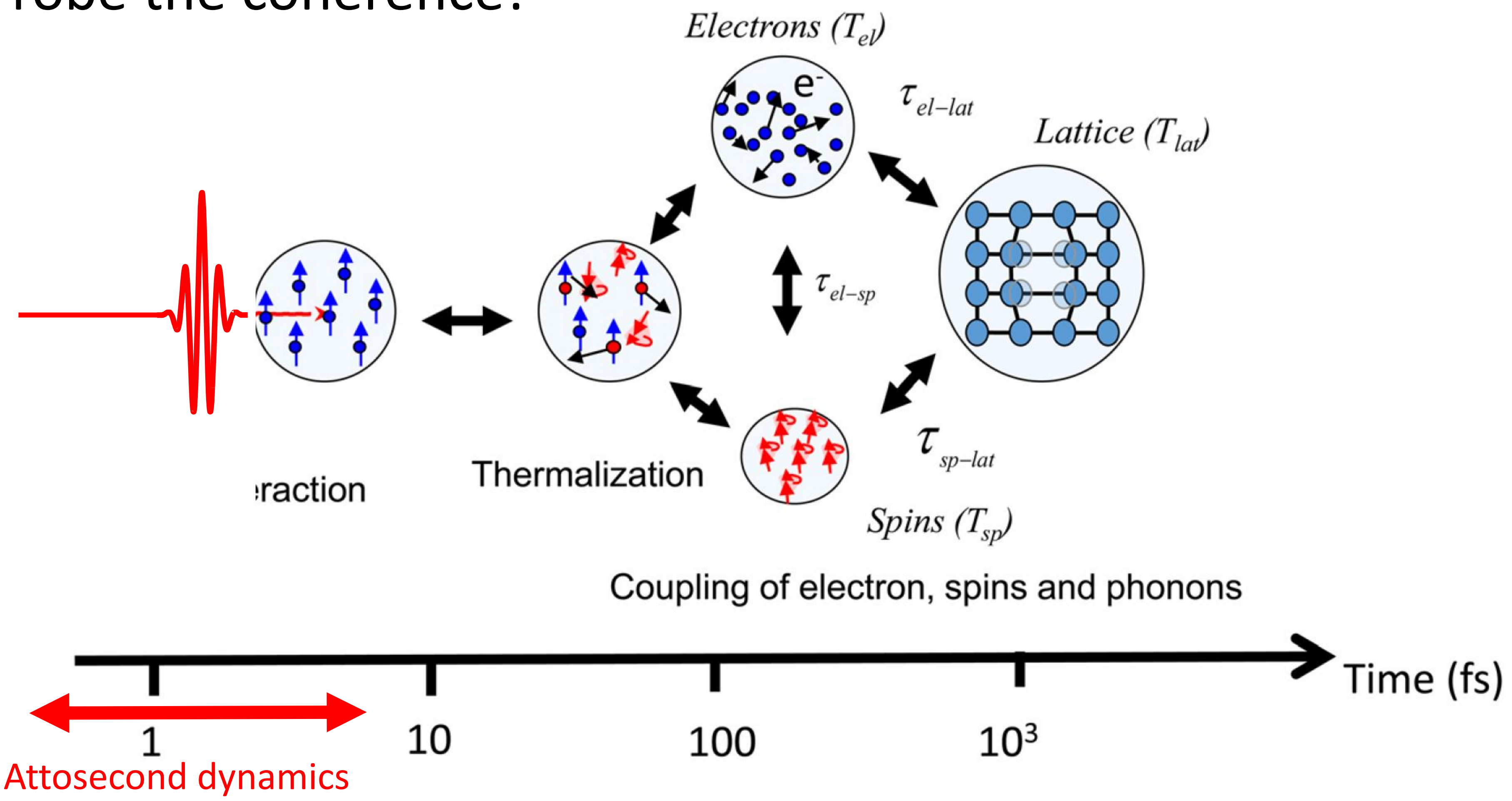
Can we be faster?



Lightwave Spintronics – Attosecond dynamics

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

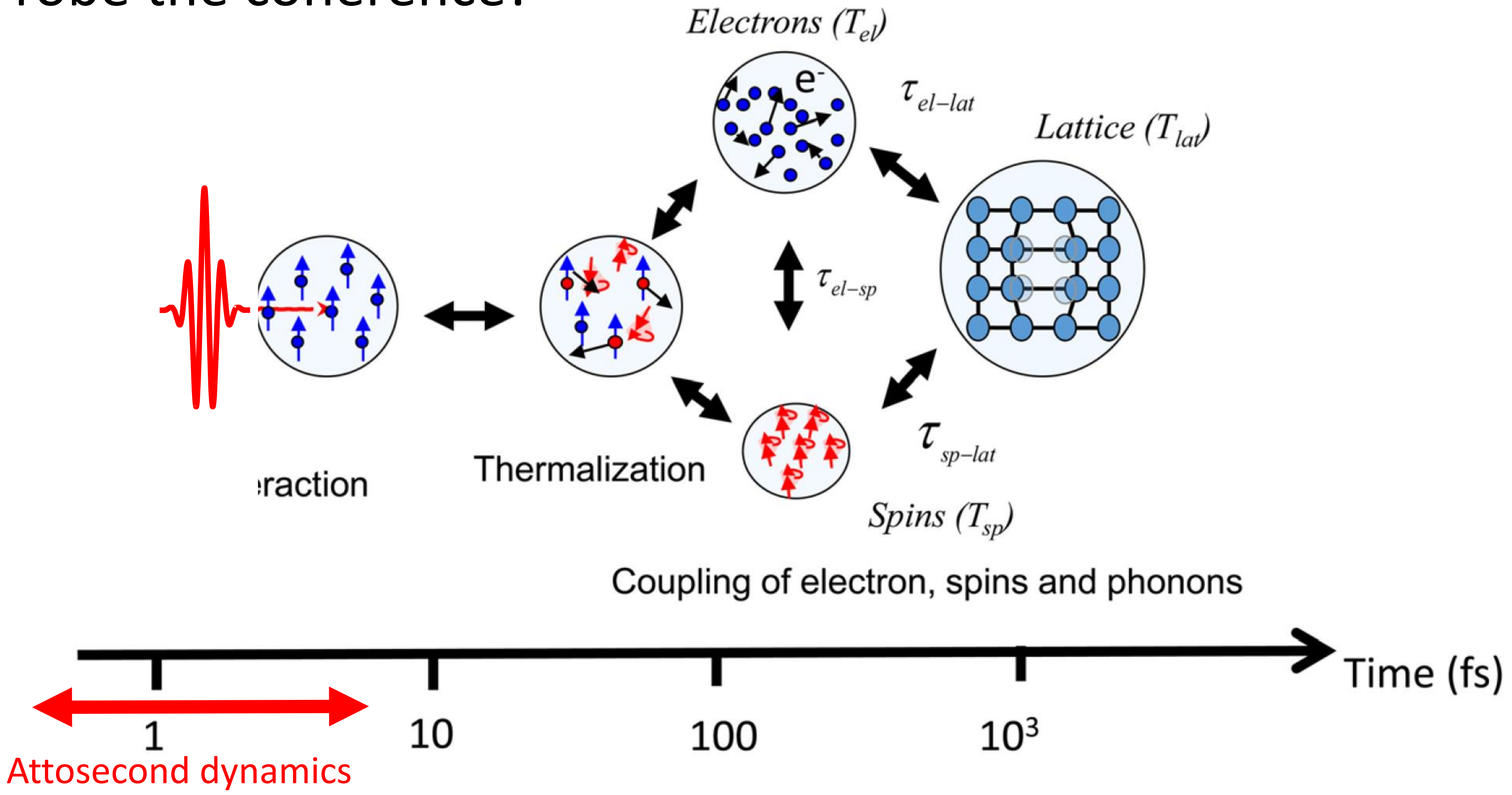
Probe the coherence!

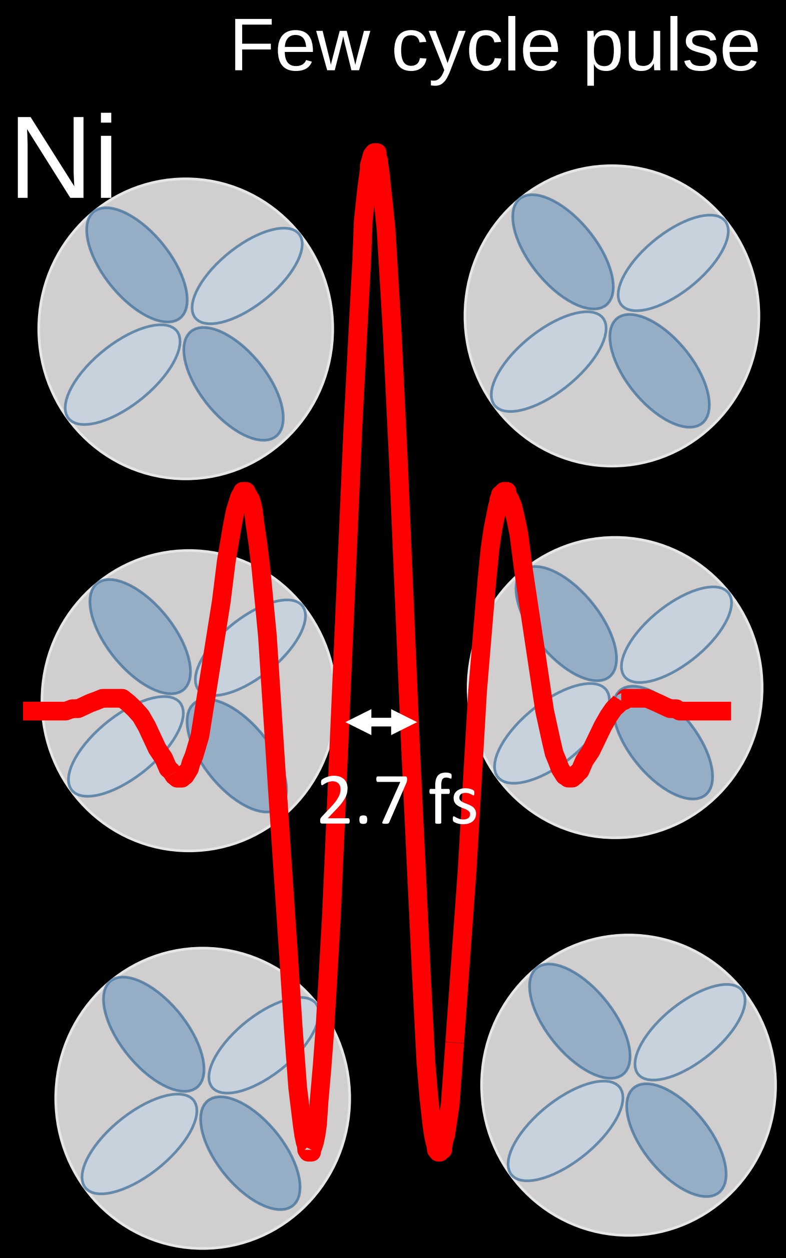


Lightwave Spintronics – Attosecond dynamics

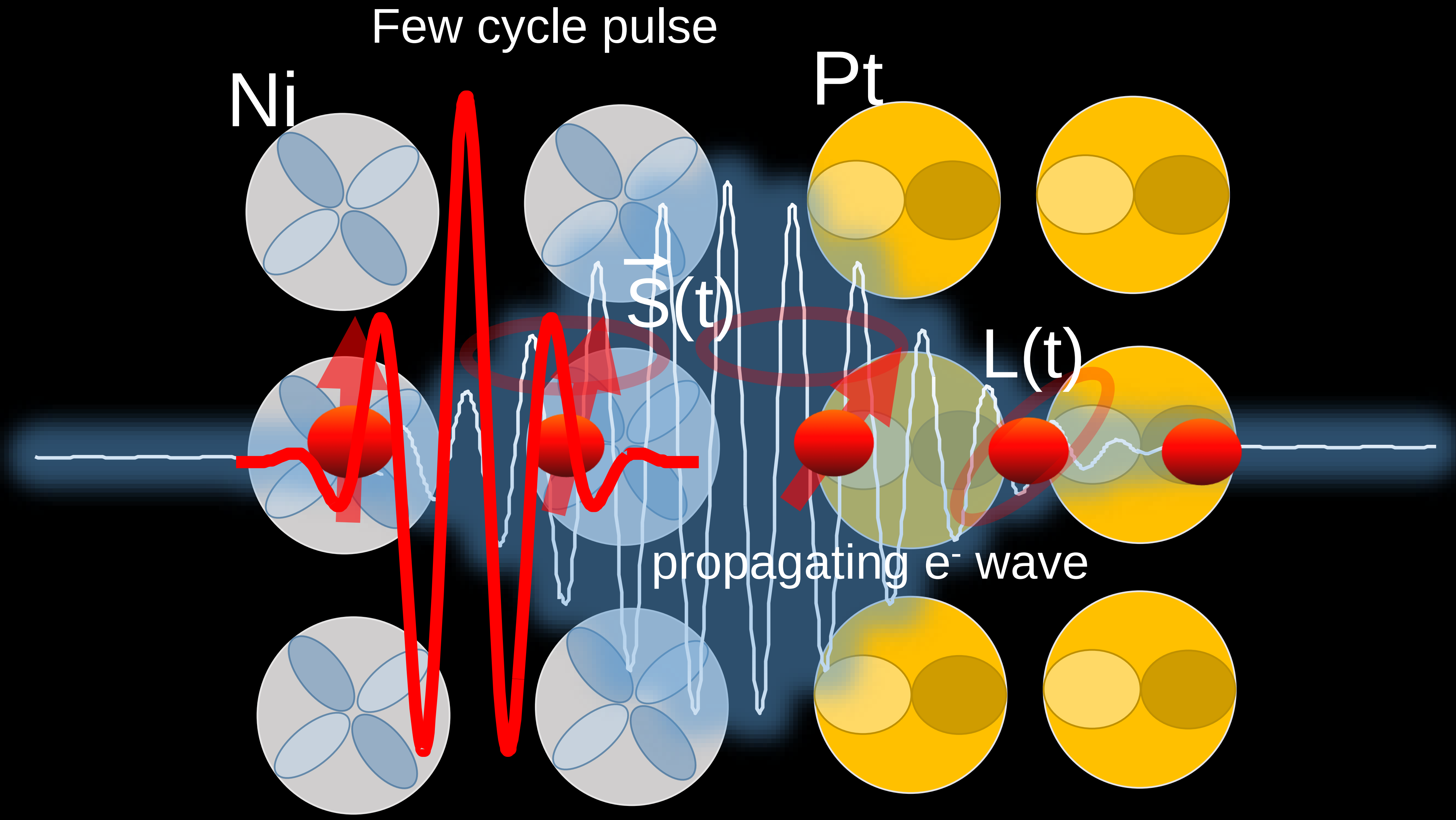
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Probe the coherence!



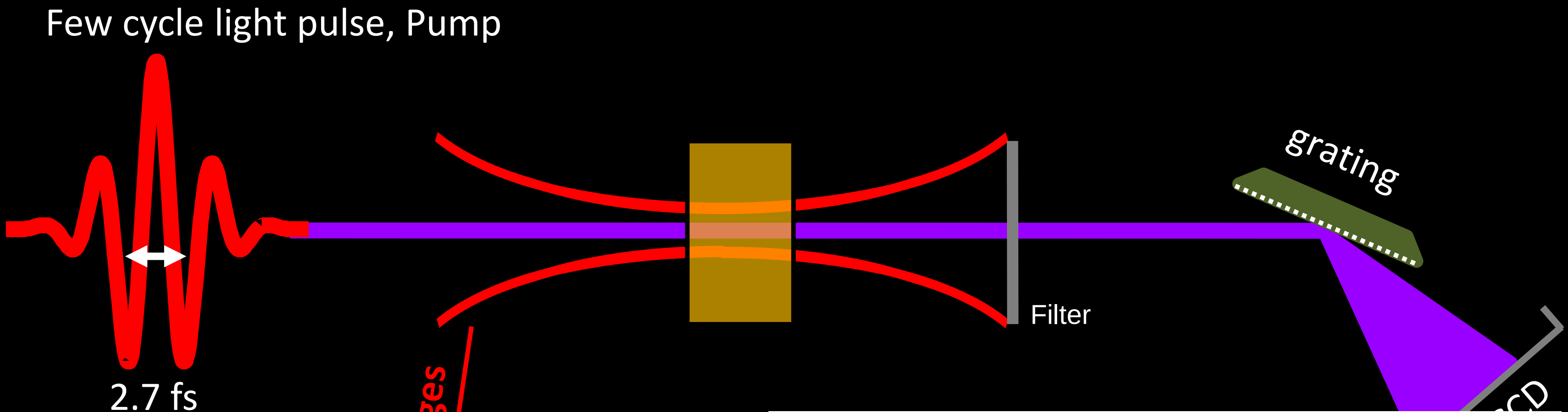


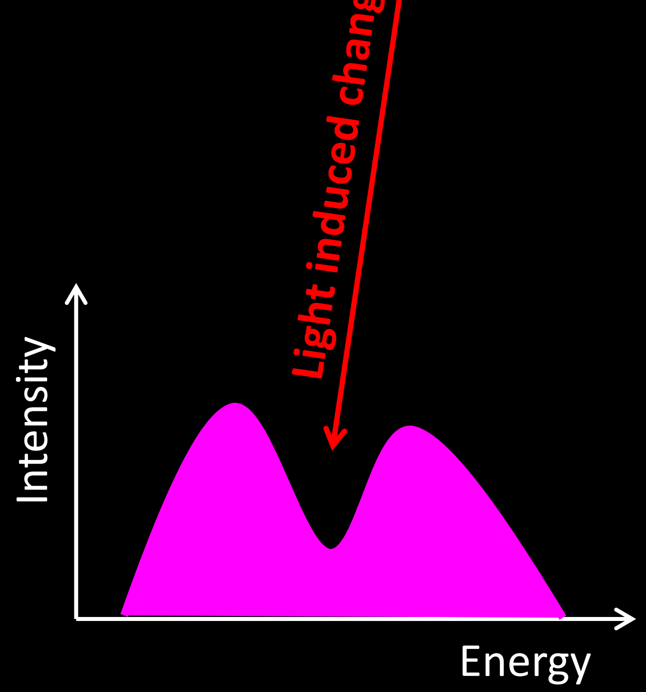
Few cycle pulse
Ni
2.7 fs

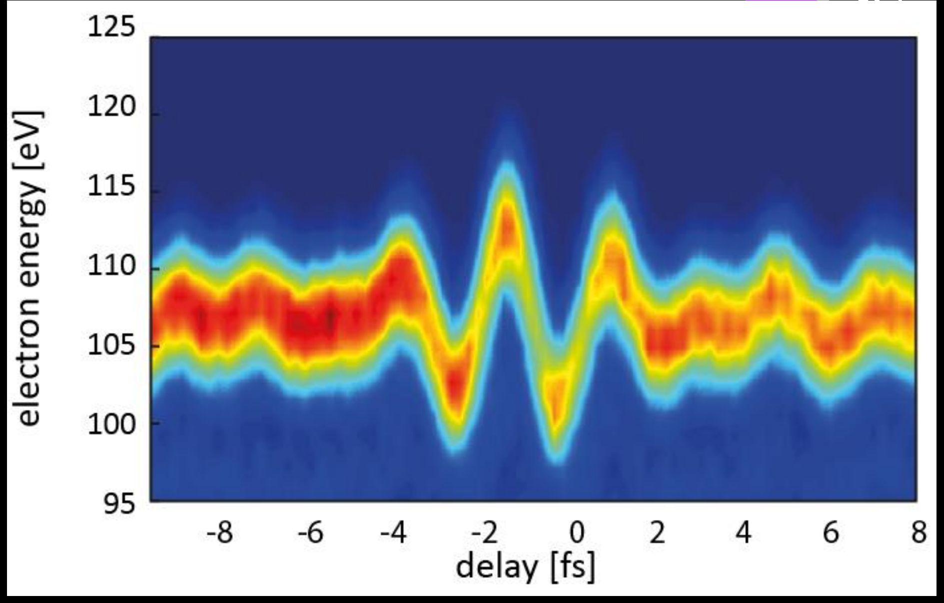


Attosecond Coherent Spintronics

Lightwave Spintronics – Attosecond dynamics



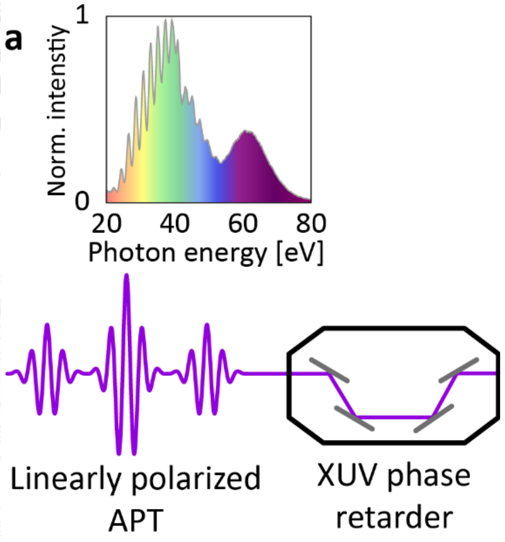


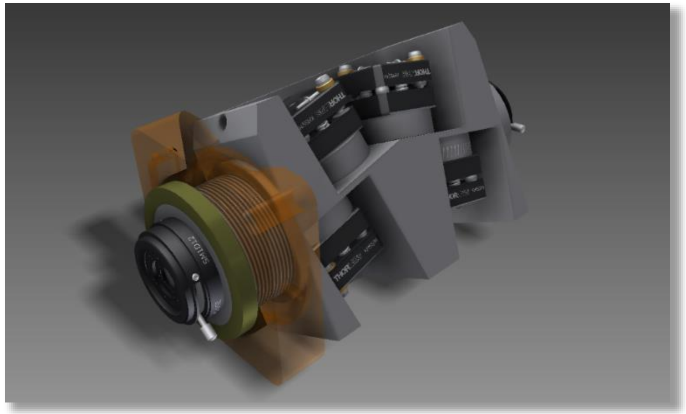


Time resolved coherent excitations
Attosecond resolution

Lightwave Spintronics – Attosecond dynamics

For ferromagnets we need attosecond x-ray dichroism:



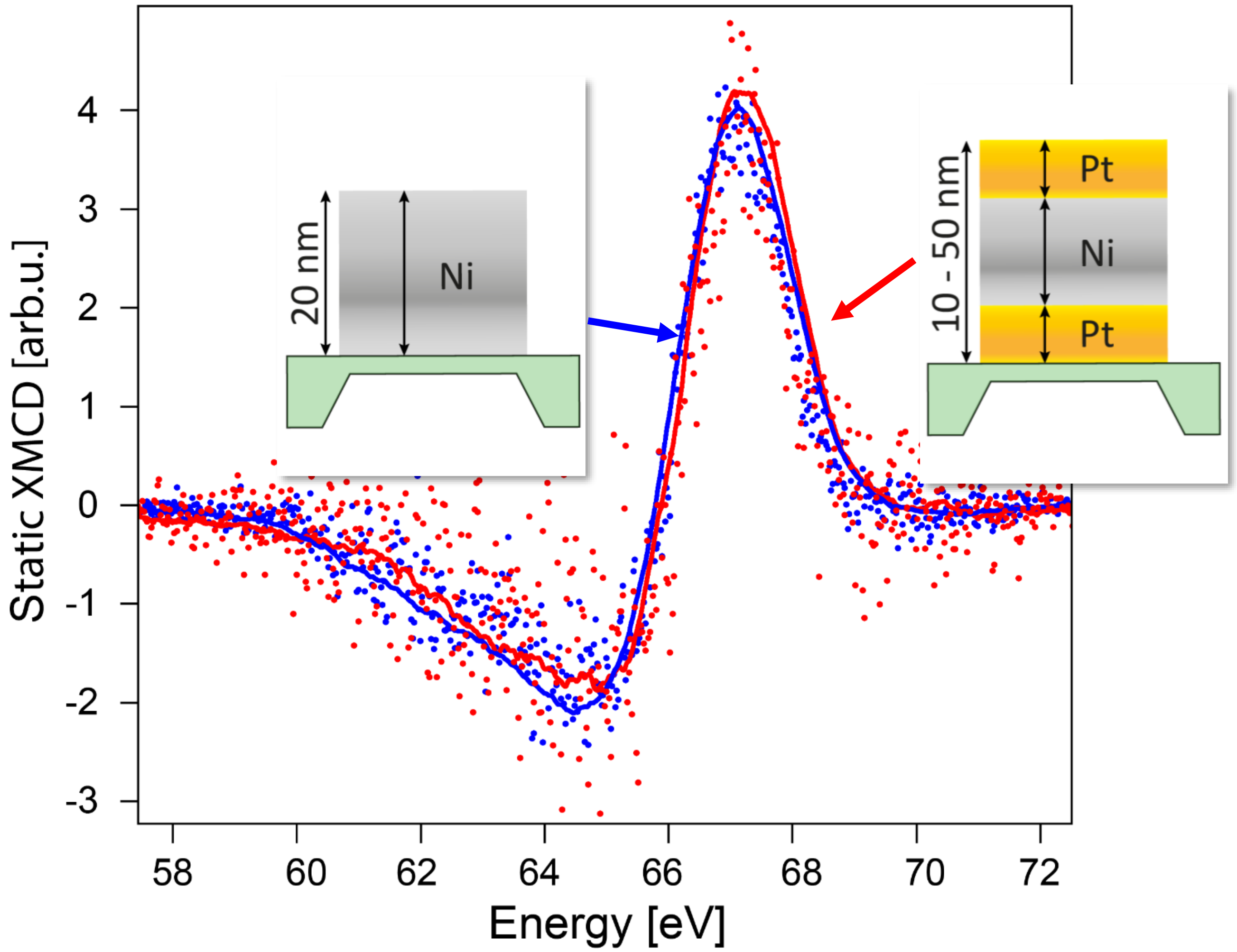


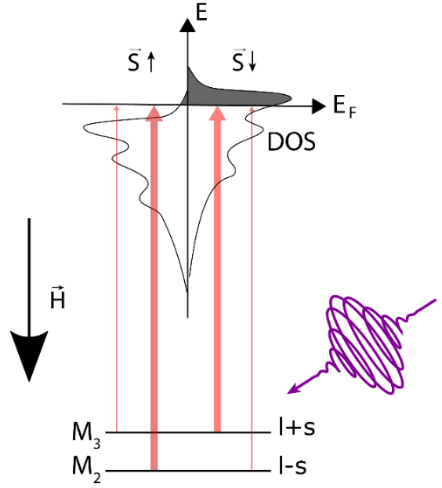
Mirror based Quarter Wave Plate (QWP)

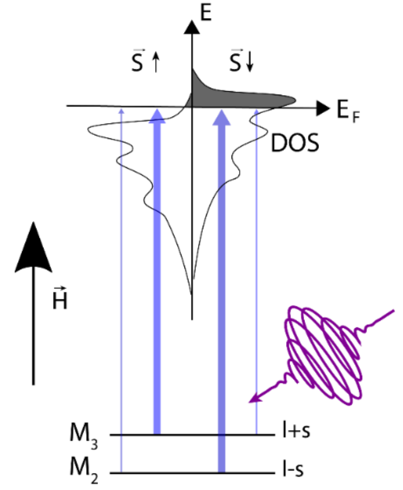
Attoseconds:
Martin Schultze, TU Graz

Lightwave Spintronics – Attosecond dynamics

X-Ray **M**agnetic **C**ircular **D**ichroism

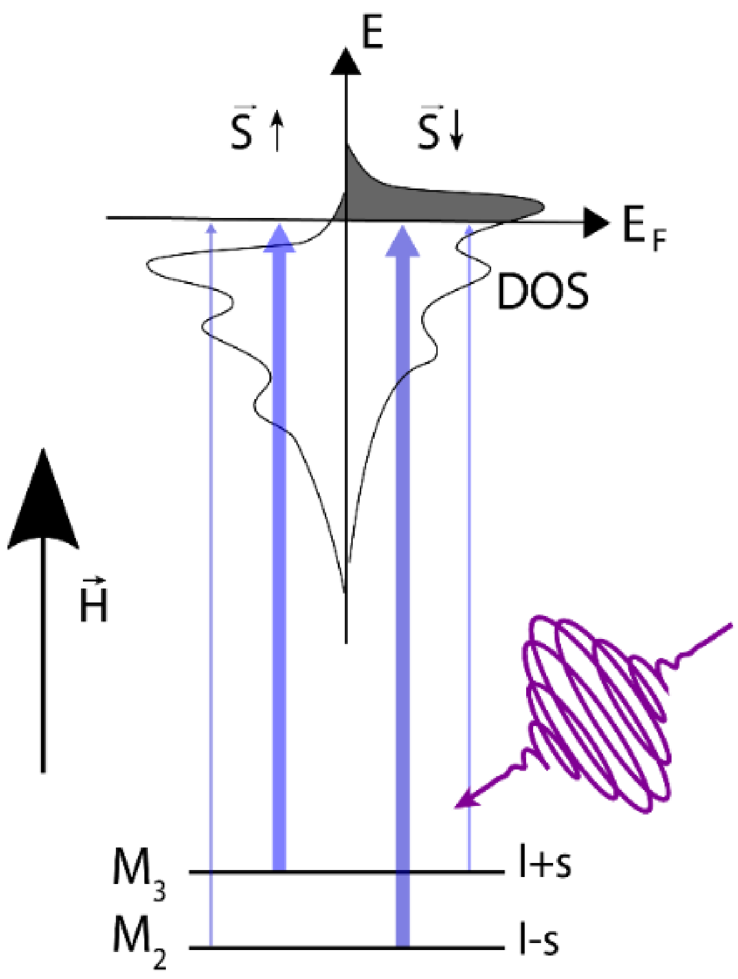




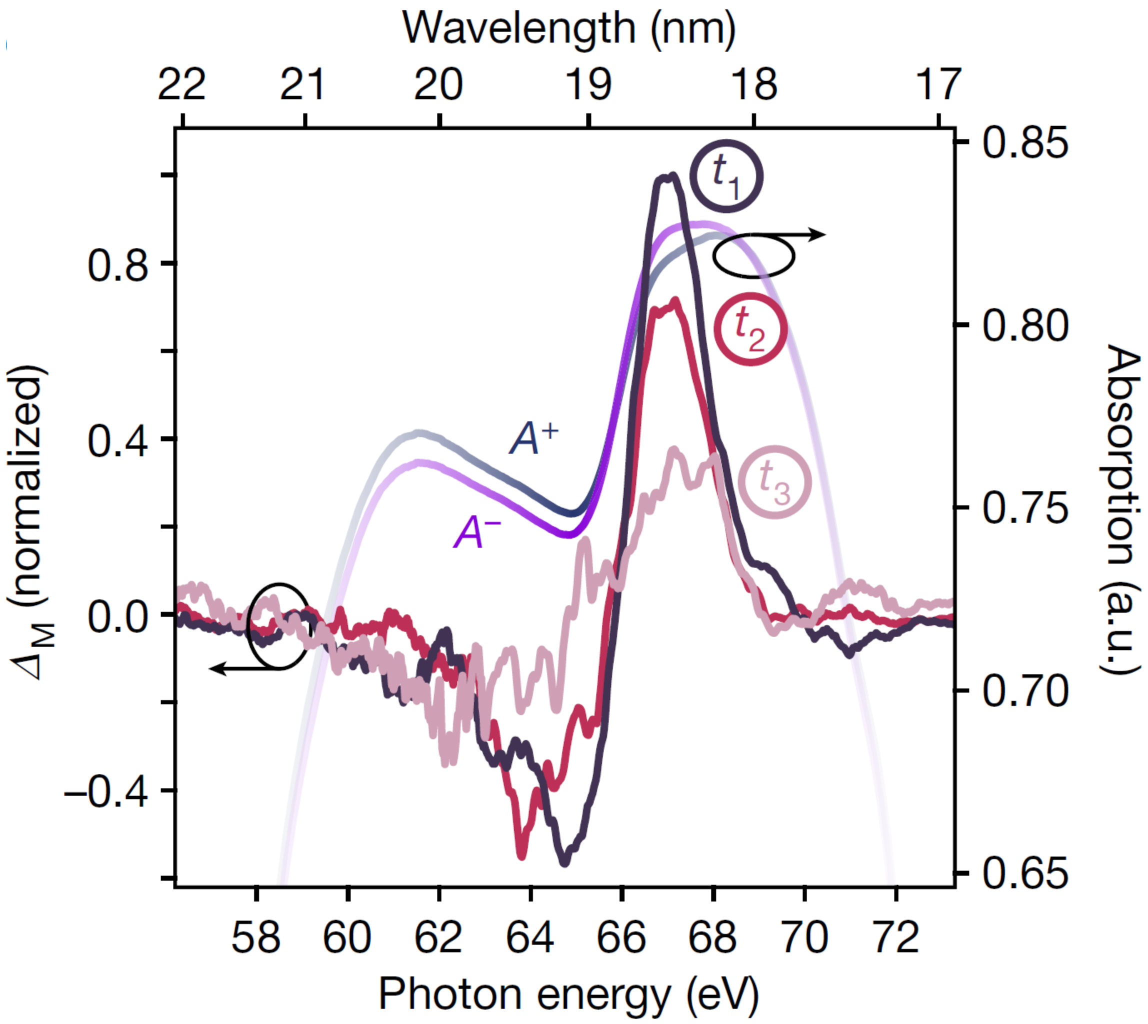


Lightwave Spintronics – Attosecond dynamics

Ni $M_{2,3}$ edge



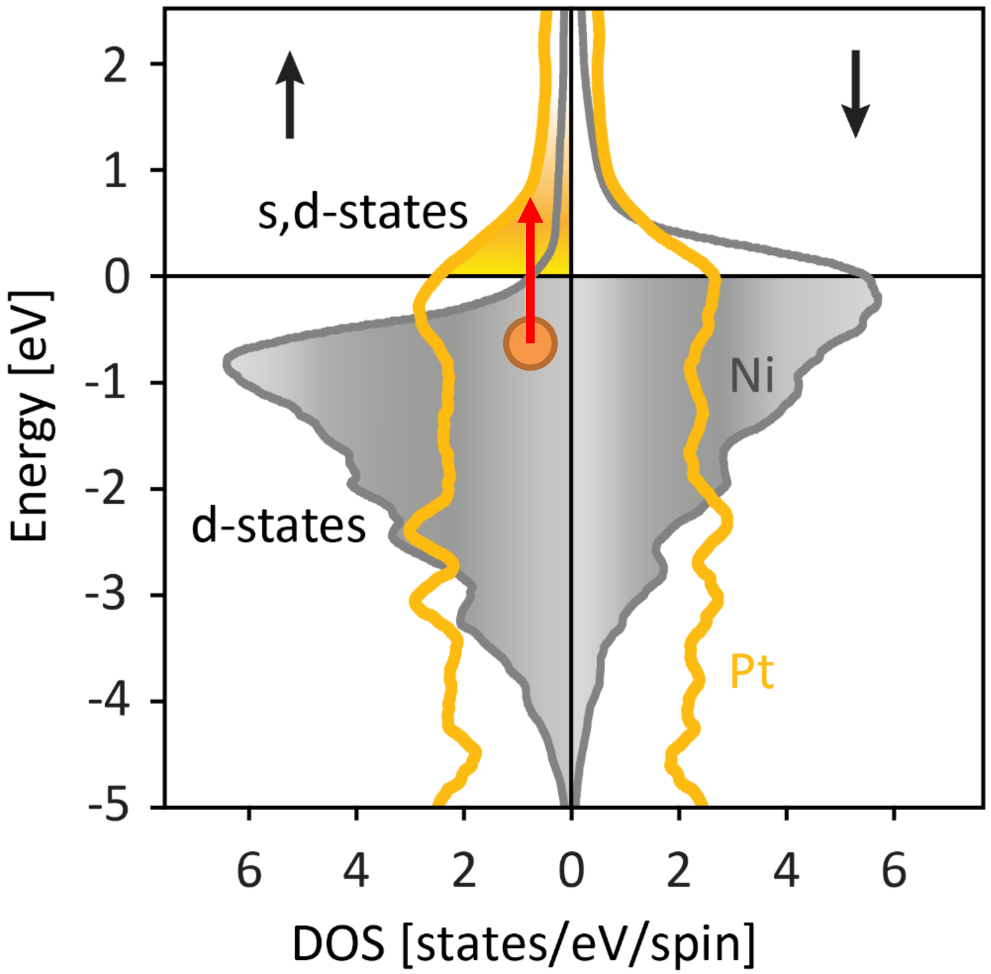
XMCD for different delay t_1, t_2, t_3

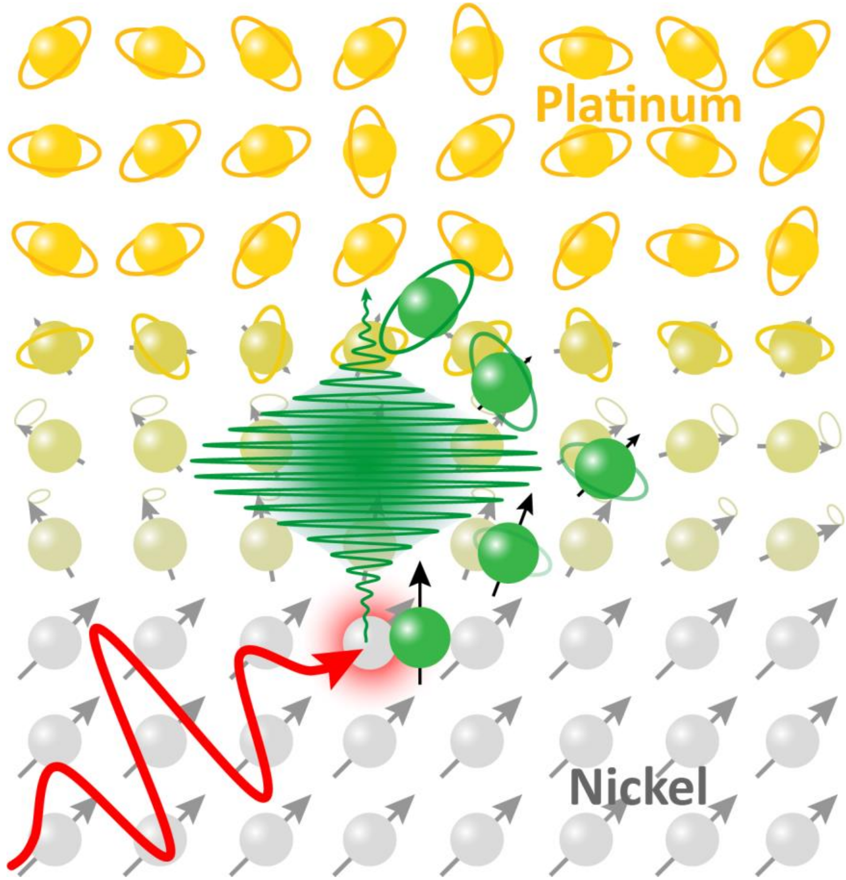


Lightwave Spintronics – Attosecond dynamics

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Optically Induced Spin Transfer (OISTR): coherent spin motion





F. Siegrist *et al.*, Light-wave dynamic control of magnetism, Nature **571**, 240–244 (2019)

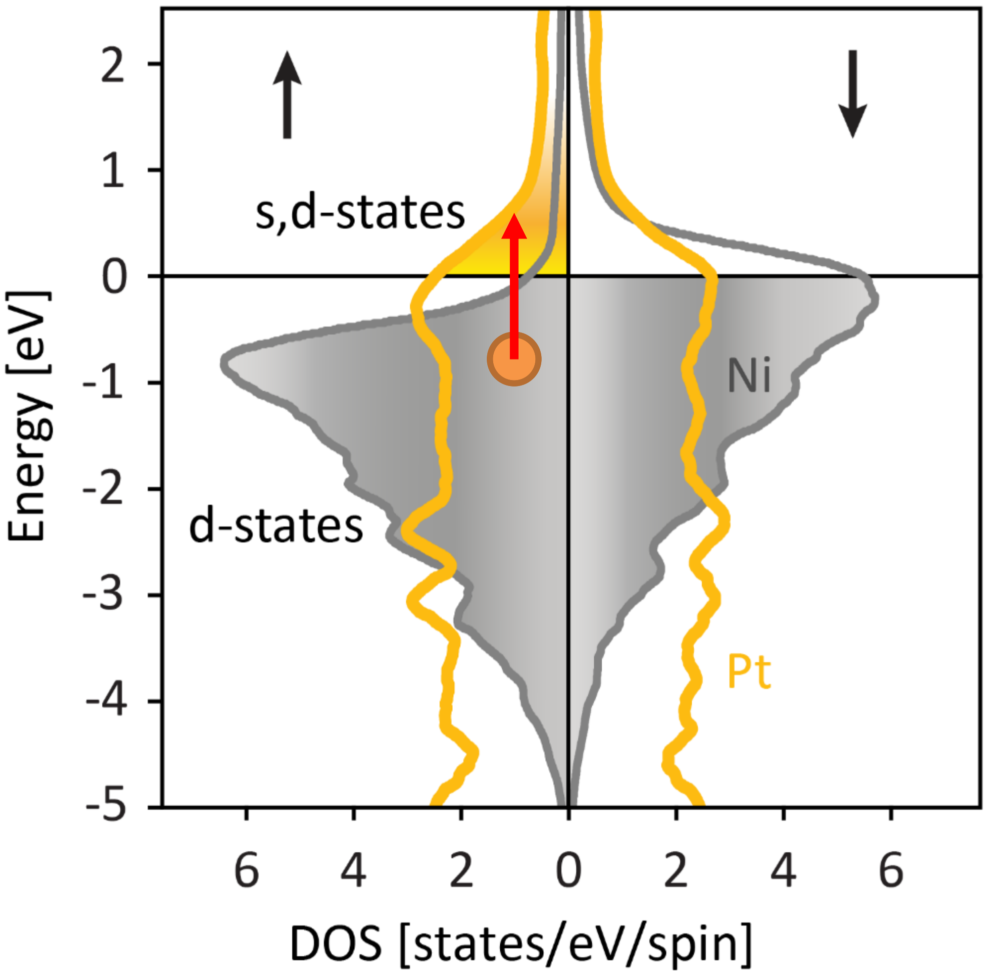
Lightwave Spintronics – Attosecond dynamics

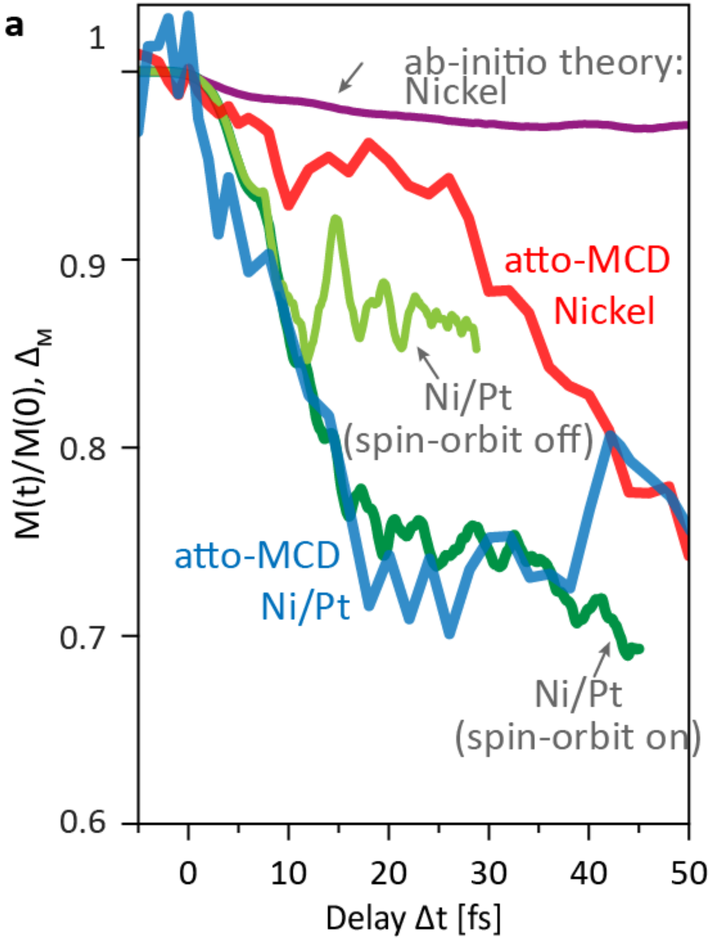
UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Optically Induced Spin Transfer (OISTR):
coherent spin motion

Fluence NIR = 2×10^{12} W cm^{-2}

Ab-initio theory by trDFT:
Sangeeta Sharma MBI Berlin



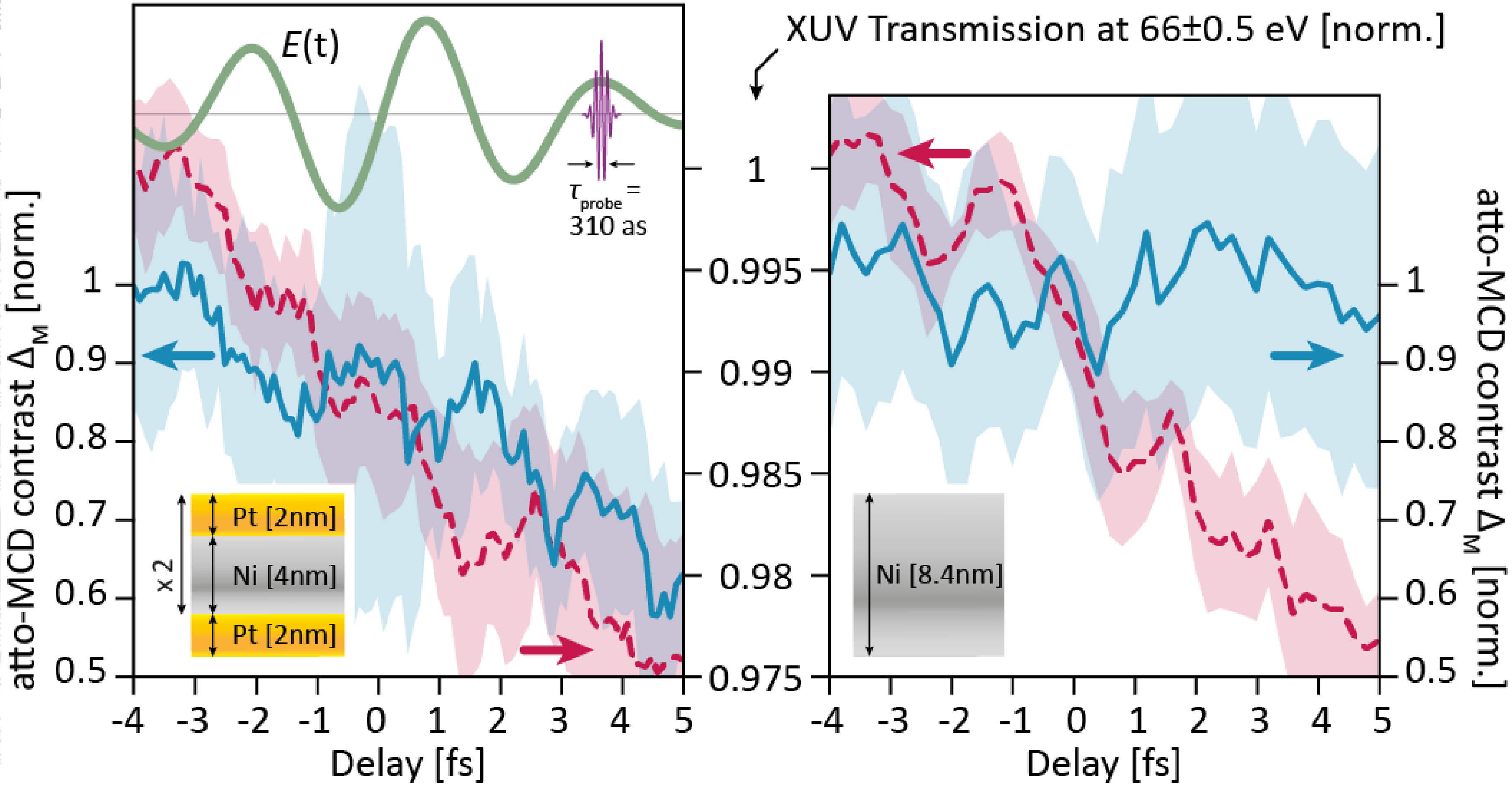


F. Siegrist *et al.*, Light-wave dynamic control of magnetism, Nature **571**, 240–244 (2019)

Lightwave Spintronics – Attosecond dynamics

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

Few fs step like decay with Pt interface (resolution 310 as)

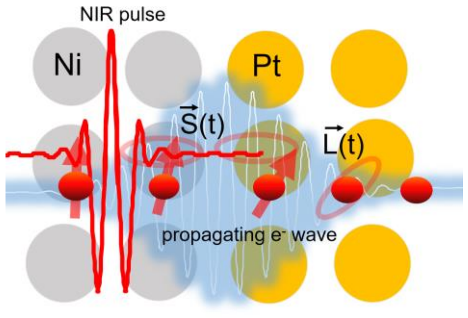


Fluence NIR = 4×10^{12} W cm^{-2}

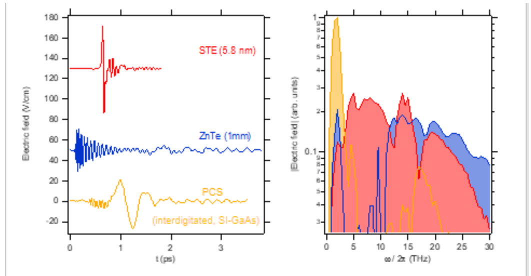
F. Siegrist *et al.*, Light-wave dynamic control of magnetism, Nature **571**, 240–244 (2019)

Outline

- Introduction

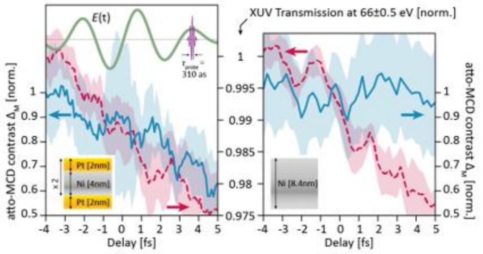


  - THz spintronic emitter – *applications*



T. Seifert, et al. Nature Photonics (2016)

  - Lightwave electronics – *coherent spintronics*



F. Siegrist *et al.*, Light-wave dynamic control of magnetism, Nature **571**, 240–244 (2019)

- Summary

Thanks