Ultrafast Spin-Orbitronics probed by x-rays

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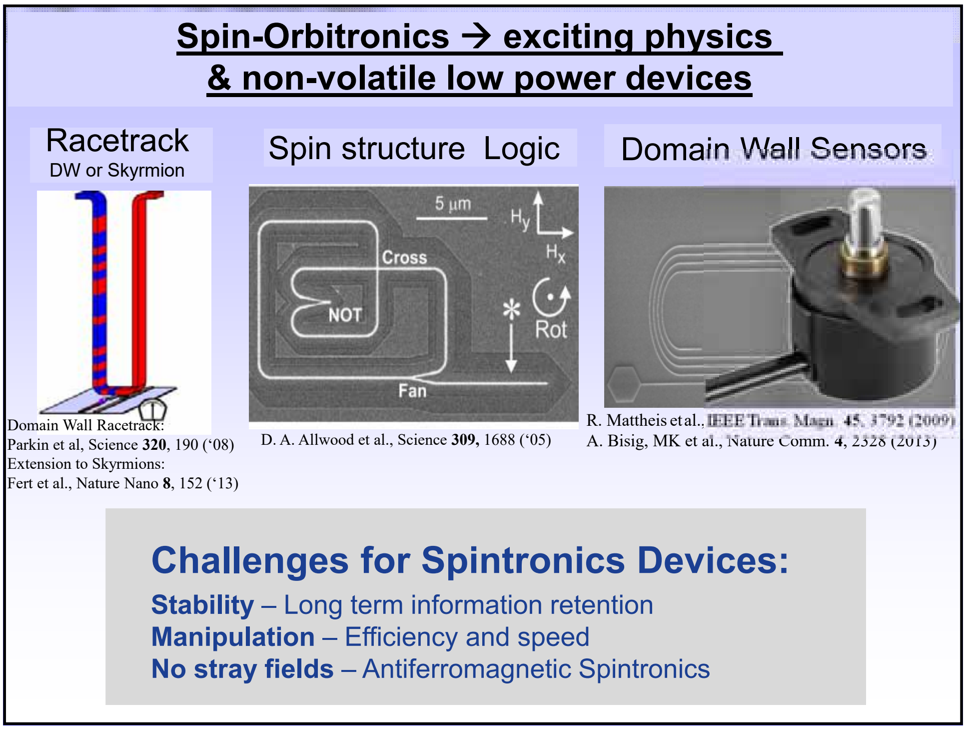
- Topologically stabilized Skyrmions (not sexy in 15 years?!?)
- Efficient switching and skyrmion motion by Spin Orbit Torques
- Skyrmion lattice dynamics in 2D
- Ultrafast spin switching by Spin Orbit
- Ultrafast switching in Antiferromagnets
- Further ideas for ultrafast x-ray probing

Ultrafast Spin-Orbitronics probed by x-rays

What‘s the problem?

My crystal ball is currently not working



Spin-Orbitronics → exciting physics & non-volatile low power devices

Racetrack
DW or Skyrmion

Domain Wall Racetrack:
Parkin et al, Science **320**, 190 (‘08)
Extension to Skyrmions:
Fert et al., Nature Nano **8**, 152 (‘13)

Spin structure Logic

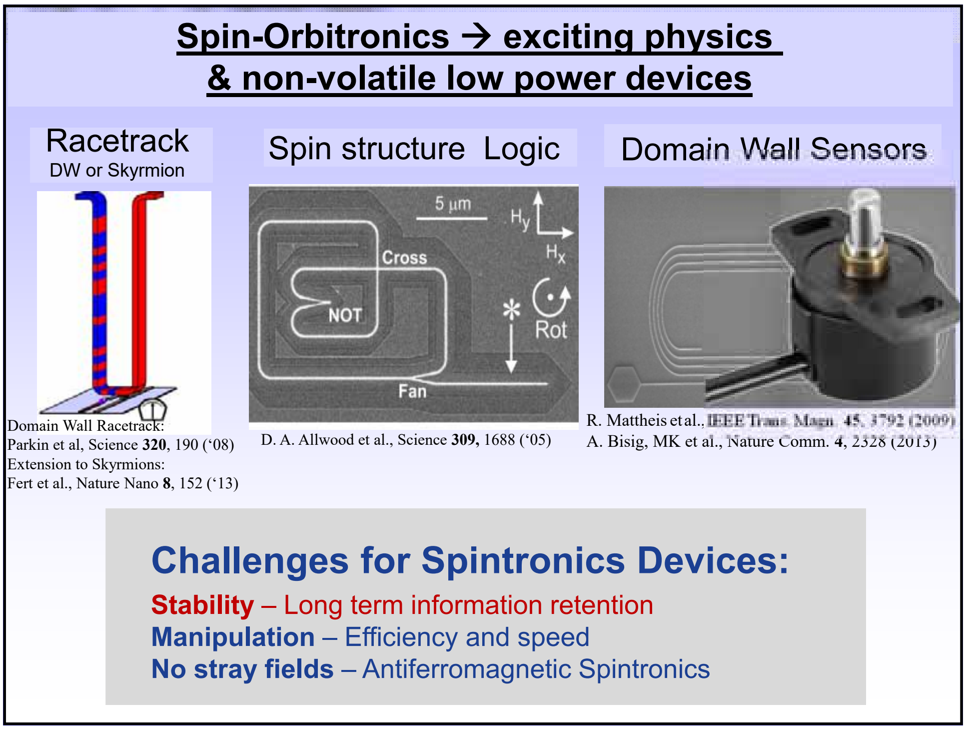
D. A. Allwood et al., Science **309,** 1688 (‘05)

Domain Wall Sensors

R. Mattheis et al., IEEE Trans. Magn. 45, 3792 (2009)
A. Bisig, MK et al., Nature Comm. **4**, 2328 (2013)

Challenges for Spintronics Devices:

Stability – Long term information retention
Manipulation – Efficiency and speed
No stray fields – Antiferromagnetic Spintronics



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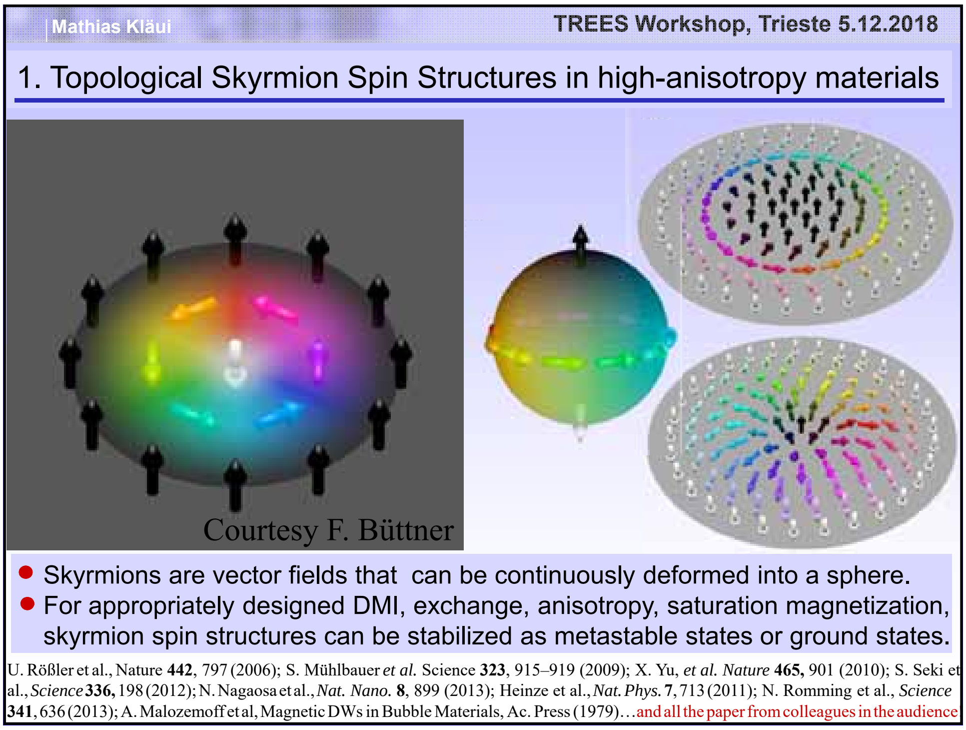

1. Topological Skyrmion Spin Structures in high-anisotropy materials

Courtesy F. Büttner

- Skyrmions are vector fields that can be continuously deformed into a sphere.
- For appropriately designed DMI, exchange, anisotropy, saturation magnetization, skyrmion spin structures can be stabilized as metastable states or ground states.

U. Rößler et al., Nature **442**, 797 (2006); S. Mühlbauer *et al.* Science **323**, 915–919 (2009); X. Yu, *et al. Nature* **465,** 901 (2010); S. Seki et al., *Science* **336,** 198 (2012); N. Nagaosa et al., *Nat. Nano.* **8**, 899 (2013); Heinze et al., *Nat. Phys.* **7**, 713 (2011); N. Romming et al., *Science* **341**, 636 (2013); A. Malozemoff et al, Magnetic DWs in Bubble Materials, Ac. Press (1979)…and all the paper from colleagues in the audience

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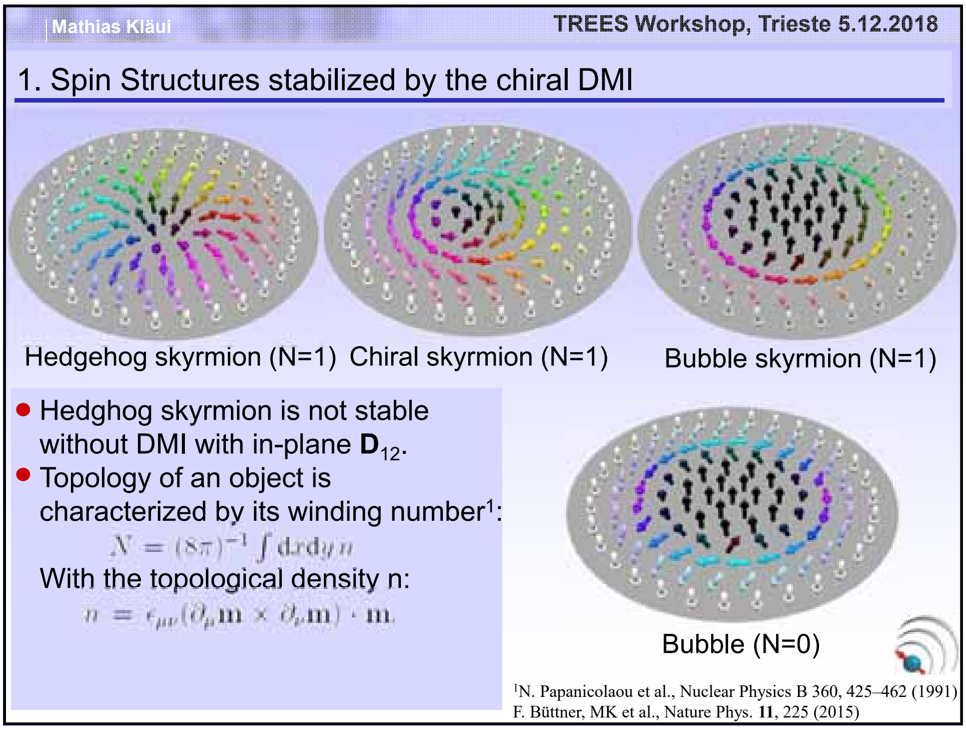


1. Spin Structures stabilized by the chiral DMI

Hedgehog skyrmion (N=1) Chiral skyrmion (N=1) Bubble skyrmion (N=1)

- Hedghog skyrmion is not stable without DMI with in-plane $\mathbf{D}_{12}$.
- Topology of an object is characterized by its winding number[1]:

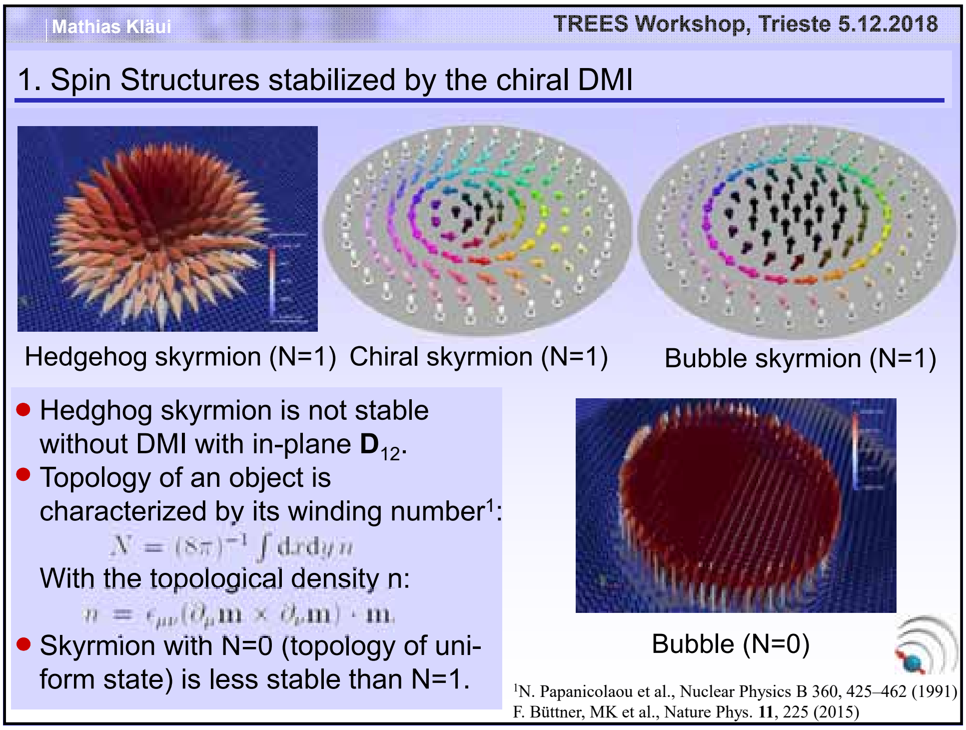
$$N = (8\pi)^{-1} \int \mathrm{d}x\mathrm{d}y\, n$$

With the topological density n:

$$n = \epsilon_{\mu\nu}(\partial_\mu \mathbf{m} \times \partial_\nu \mathbf{m}) \cdot \mathbf{m}$$

Bubble (N=0)

[1] N. Papanicolaou et al., Nuclear Physics B 360, 425–462 (1991)
F. Büttner, MK et al., Nature Phys. **11**, 225 (2015)



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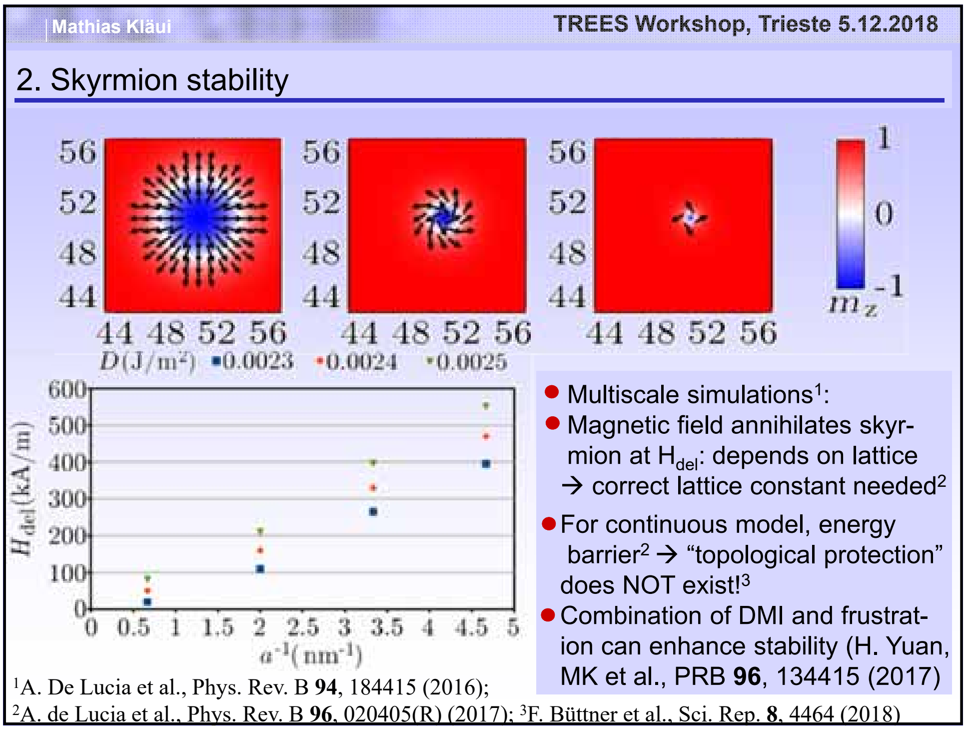
- Skyrmion with N=0 (topology of uniform state) is less stable than N=1.

Bubble (N=0)

[1] N. Papanicolaou et al., Nuclear Physics B 360, 425–462 (1991)
F. Büttner, MK et al., Nature Phys. **11**, 225 (2015)



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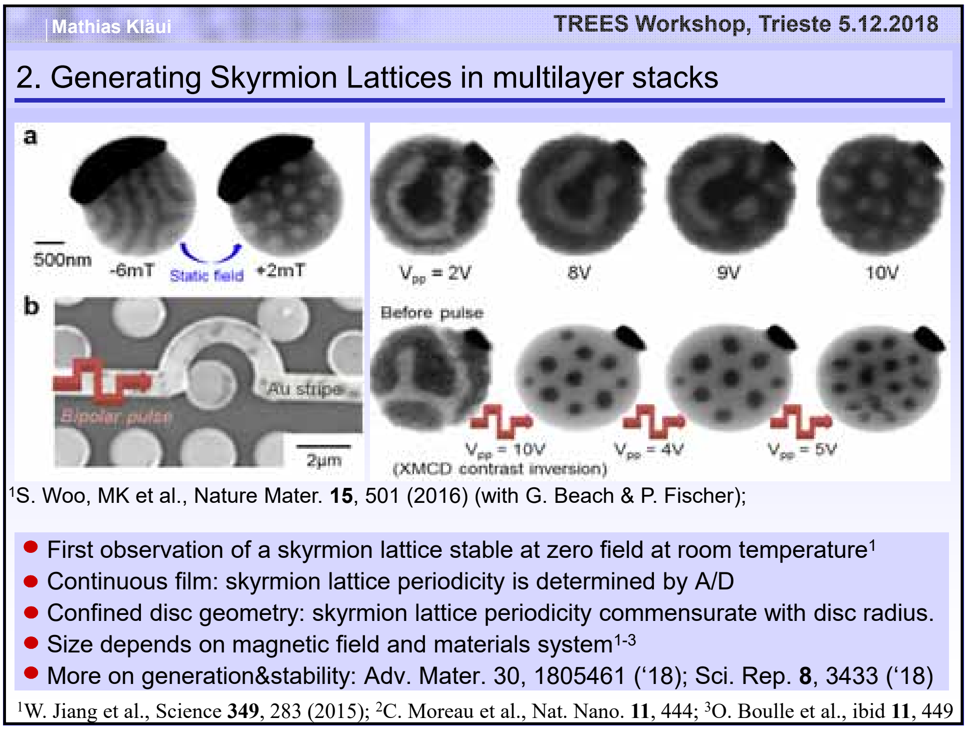
2. Skyrmion stability

- Multiscale simulations[1]:
- Magnetic field annihilates skyrmion at H_{del}: depends on lattice → correct lattice constant needed[2]
- For continuous model, energy barrier[2] → "topological protection" does NOT exist![3]
- Combination of DMI and frustration can enhance stability (H. Yuan, MK et al., PRB **96**, 134415 (2017)

[1] A. De Lucia et al., Phys. Rev. B **94**, 184415 (2016);
[2] A. de Lucia et al., Phys. Rev. B **96**, 020405(R) (2017); [3] F. Büttner et al., Sci. Rep. **8**, 4464 (2018)

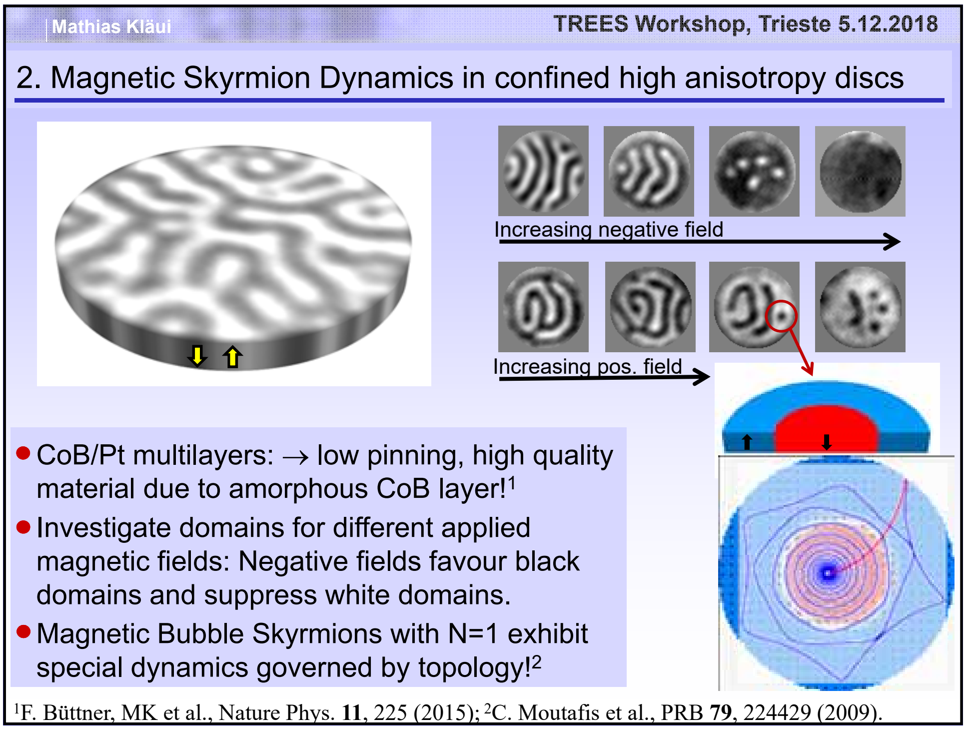


2. Generating Skyrmion Lattices in multilayer stacks

[1]S. Woo, MK et al., Nature Mater. **15**, 501 (2016) (with G. Beach & P. Fischer);

- First observation of a skyrmion lattice stable at zero field at room temperature[1]
- Continuous film: skyrmion lattice periodicity is determined by A/D
- Confined disc geometry: skyrmion lattice periodicity commensurate with disc radius.
- Size depends on magnetic field and materials system[1-3]
- More on generation&stability: Adv. Mater. 30, 1805461 ('18); Sci. Rep. **8**, 3433 ('18)

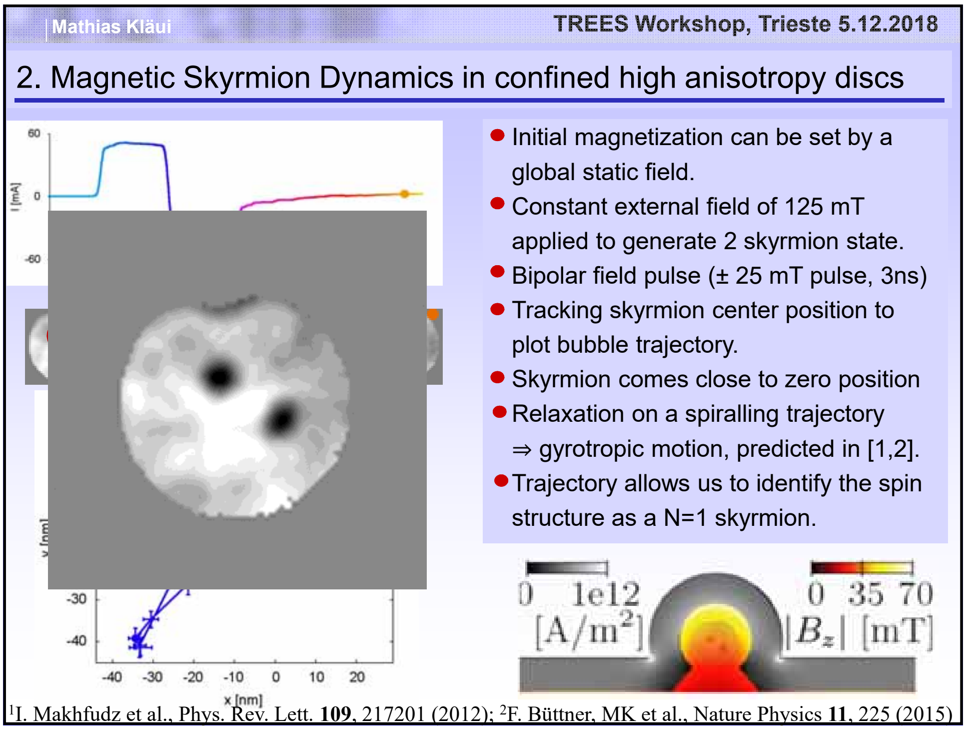
[1]W. Jiang et al., Science **349**, 283 (2015); [2]C. Moreau et al., Nat. Nano. **11**, 444; [3]O. Boulle et al., ibid **11**, 449



2. Magnetic Skyrmion Dynamics in confined high anisotropy discs

- CoB/Pt multilayers: → low pinning, high quality material due to amorphous CoB layer![1]
- Investigate domains for different applied magnetic fields: Negative fields favour black domains and suppress white domains.
- Magnetic Bubble Skyrmions with N=1 exhibit special dynamics governed by topology![2]

[1]F. Büttner, MK et al., Nature Phys. **11**, 225 (2015); [2]C. Moutafis et al., PRB **79**, 224429 (2009).



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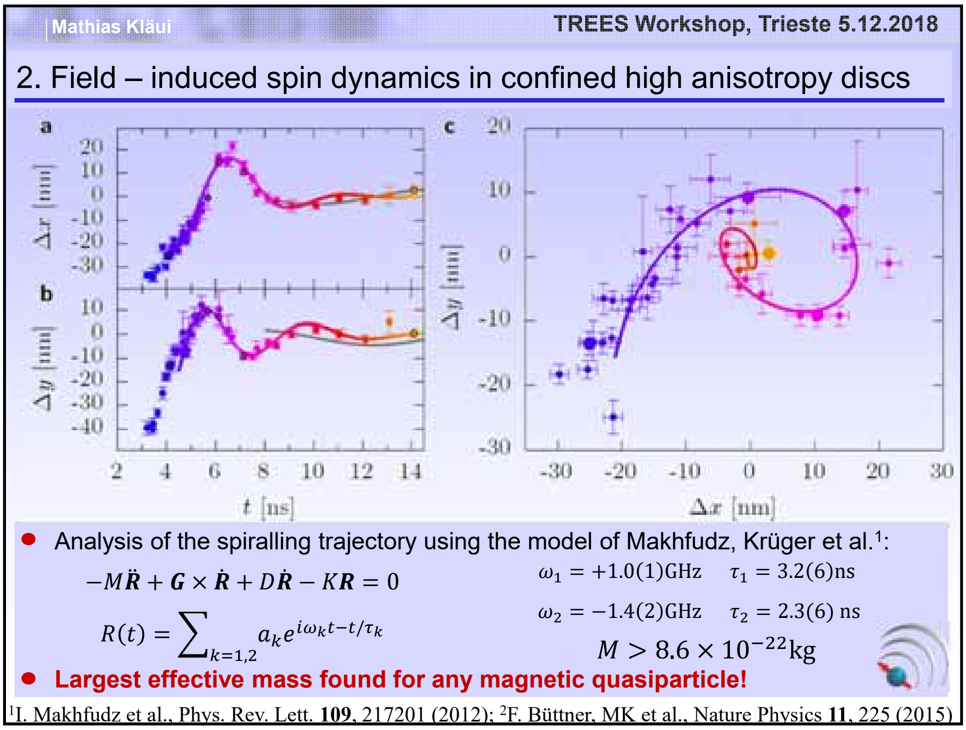
2. Magnetic Skyrmion Dynamics in confined high anisotropy discs

- Initial magnetization can be set by a global static field.
- Constant external field of 125 mT applied to generate 2 skyrmion state.
- Bipolar field pulse (± 25 mT pulse, 3ns)
- Tracking skyrmion center position to plot bubble trajectory.
- Skyrmion comes close to zero position
- Relaxation on a spiralling trajectory ⇒ gyrotropic motion, predicted in [1,2].
- Trajectory allows us to identify the spin structure as a N=1 skyrmion.

[1]I. Makhfudz et al., Phys. Rev. Lett. **109**, 217201 (2012); [2]F. Büttner, MK et al., Nature Physics **11**, 225 (2015)



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2. Field – induced spin dynamics in confined high anisotropy discs

- Analysis of the spiralling trajectory using the model of Makhfudz, Krüger et al.[1]:

$$-M\ddot{\boldsymbol{R}} + \boldsymbol{G}\times\dot{\boldsymbol{R}} + D\dot{\boldsymbol{R}} - K\boldsymbol{R} = 0$$

$$R(t) = \sum_{k=1,2} a_k e^{i\omega_k t - t/\tau_k}$$

$$\omega_1 = +1.0(1)\text{GHz} \quad \tau_1 = 3.2(6)\text{ns}$$

$$\omega_2 = -1.4(2)\text{GHz} \quad \tau_2 = 2.3(6)\text{ ns}$$

$$M > 8.6\times10^{-22}\text{kg}$$

- **Largest effective mass found for any magnetic quasiparticle!**

[1]I. Makhfudz et al., Phys. Rev. Lett. **109**, 217201 (2012); [2]F. Büttner, MK et al., Nature Physics **11**, 225 (2015)

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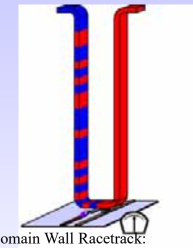

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Extension to Skyrmions:
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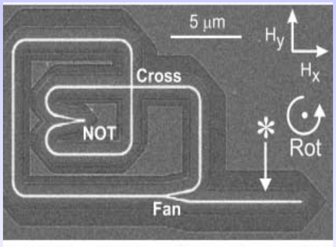
Spin structure Logic



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No stray fields – Antiferromagnetic Spintronics

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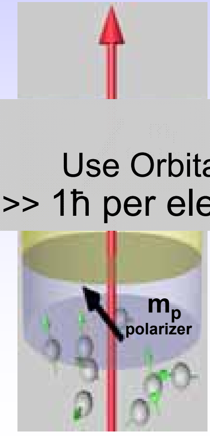
3. Challenge Efficient Manipulation - Spin Transfer Torques (STT)

Conventional STT: Transfer electron **Spin** (↕) to switch magnetization
Efficiency: 1ħ per electron for
➡ **spin transfer torque**

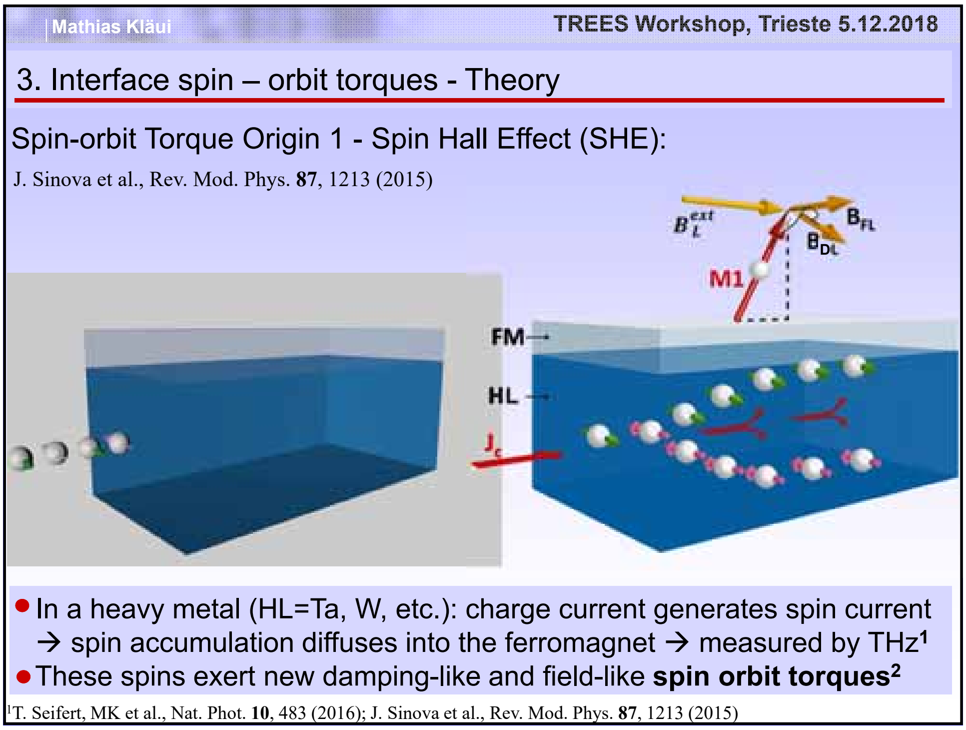
Domain Wall motion: In the adiabatic limit, each electron also transfers 1ħ of spin angular momentum due to the **spin transfer torque**

Higher efficiency:
Use Orbital Angular Momentum from lattice
→ >> 1ħ per electron transferred by spin orbit torques



Side view of a wire with a Bloch wall

O. Boulle, MK et al., Mat. Sci. Eng. R. **72**, 159 (‘11); A. Bisig, K.-J. Lee, MK et al., PRL **117**, 277203 (2016)



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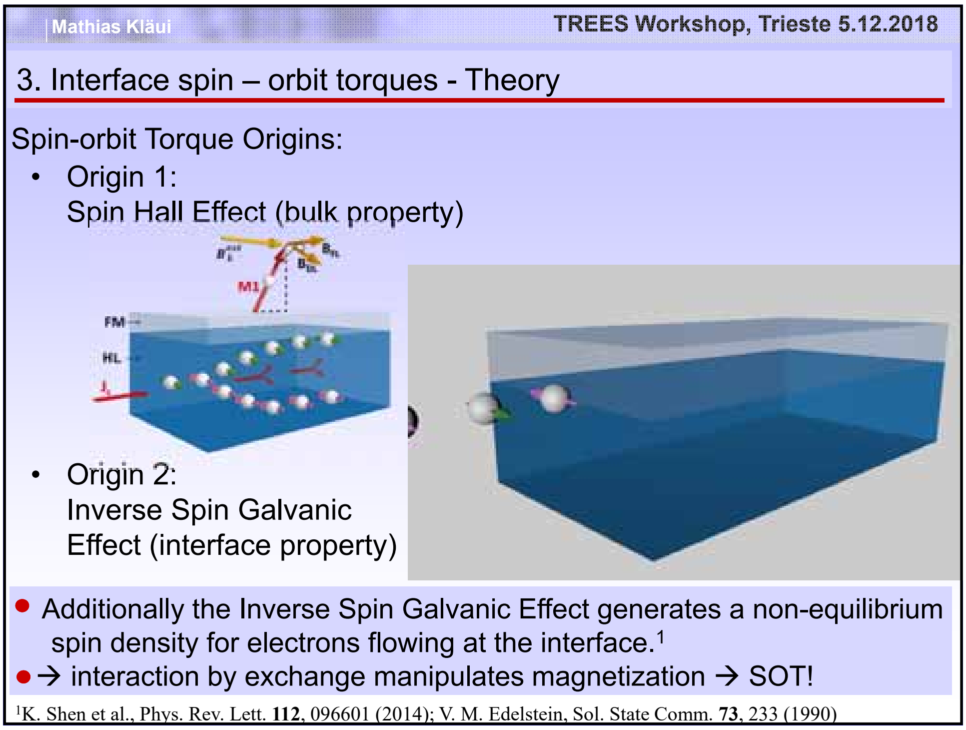
3. Interface spin – orbit torques - Theory

Spin-orbit Torque Origin 1 - Spin Hall Effect (SHE):

J. Sinova et al., Rev. Mod. Phys. **87**, 1213 (2015)

- In a heavy metal (HL=Ta, W, etc.): charge current generates spin current → spin accumulation diffuses into the ferromagnet → measured by THz[1]
- These spins exert new damping-like and field-like **spin orbit torques**[2]

[1] T. Seifert, MK et al., Nat. Phot. **10**, 483 (2016); J. Sinova et al., Rev. Mod. Phys. **87**, 1213 (2015)



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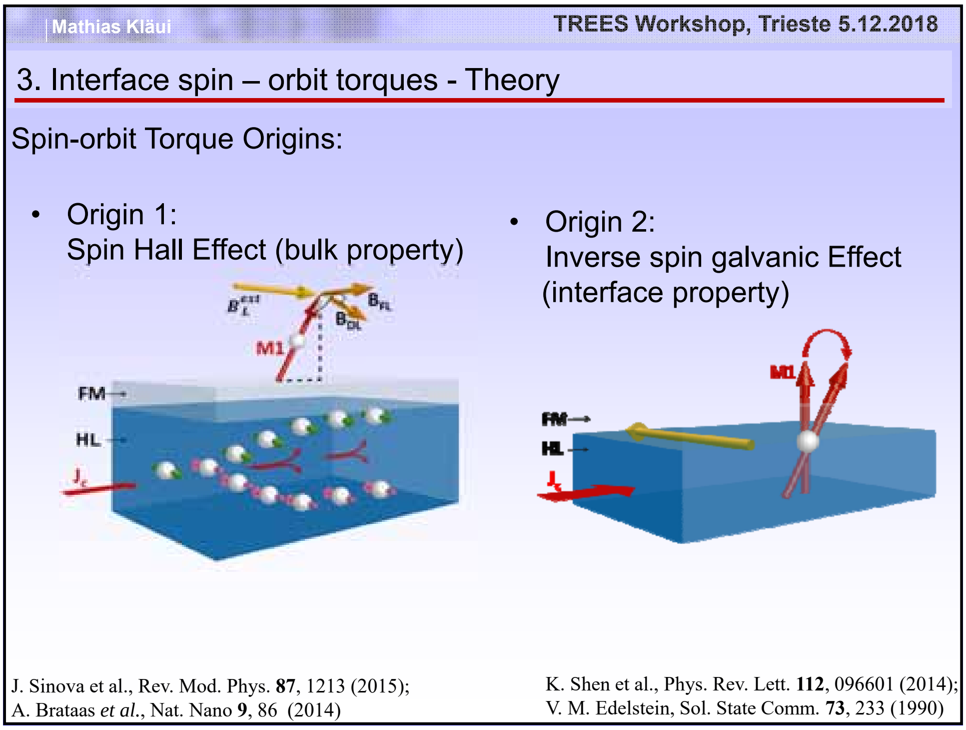
3. Interface spin – orbit torques - Theory

Spin-orbit Torque Origins:

- Origin 1:
  Spin Hall Effect (bulk property)
- Origin 2:
  Inverse Spin Galvanic Effect (interface property)

- Additionally the Inverse Spin Galvanic Effect generates a non-equilibrium spin density for electrons flowing at the interface.[1]
- → interaction by exchange manipulates magnetization → SOT!

[1] K. Shen et al., Phys. Rev. Lett. **112**, 096601 (2014); V. M. Edelstein, Sol. State Comm. **73**, 233 (1990)



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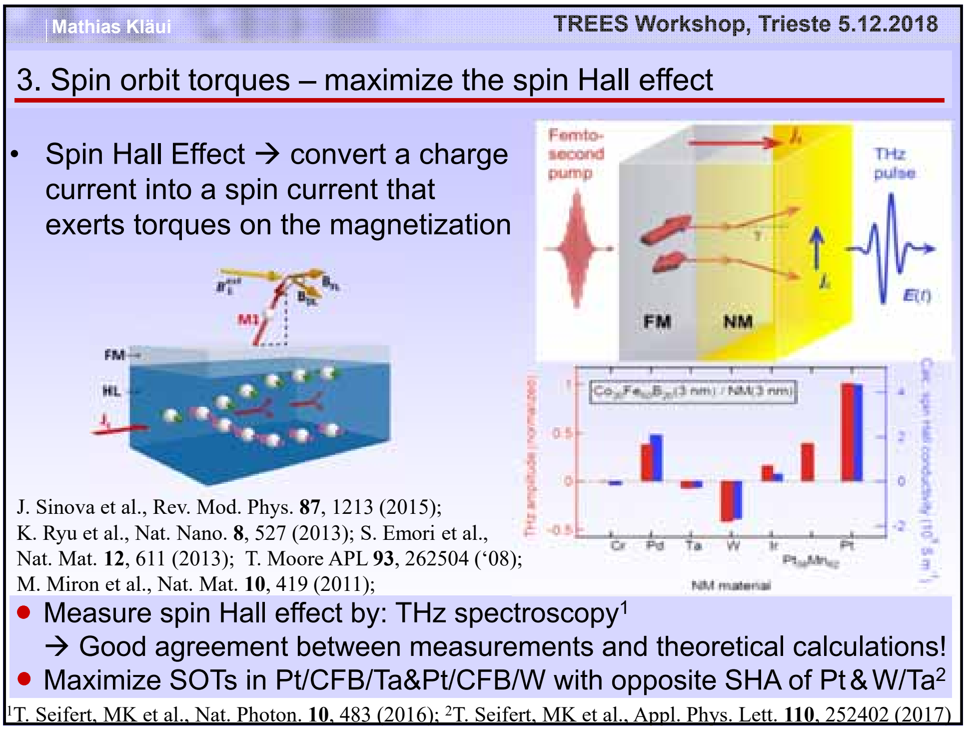
J. Sinova et al., Rev. Mod. Phys. **87**, 1213 (2015);
A. Brataas *et al.*, Nat. Nano **9**, 86 (2014)

K. Shen et al., Phys. Rev. Lett. **112**, 096601 (2014);
V. M. Edelstein, Sol. State Comm. **73**, 233 (1990)



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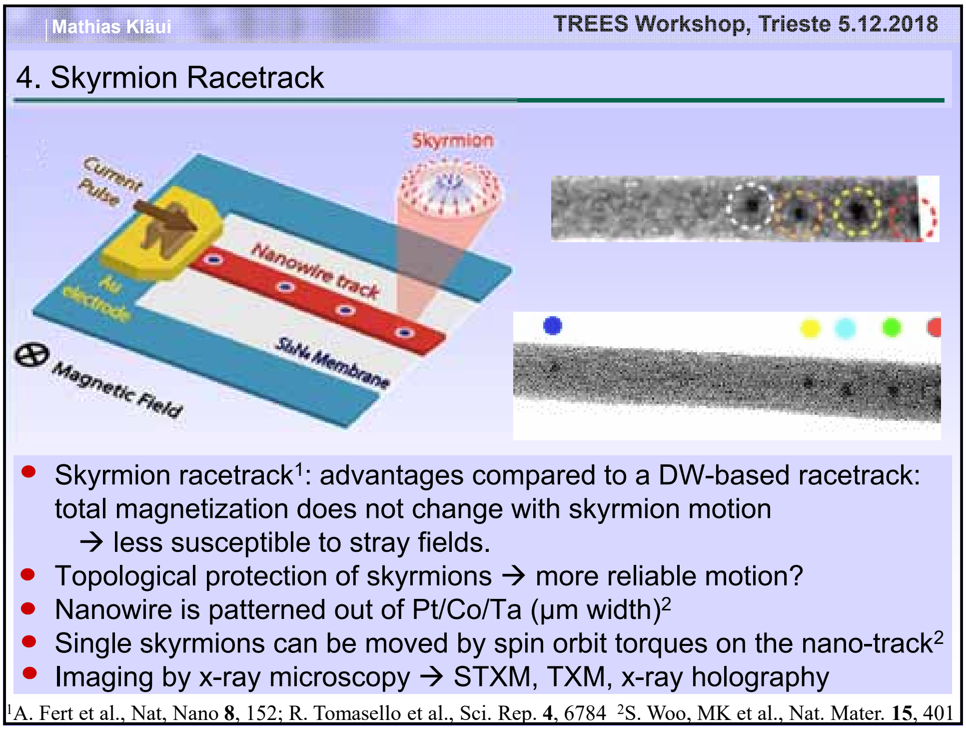
3. Spin orbit torques – maximize the spin Hall effect

- Spin Hall Effect → convert a charge current into a spin current that exerts torques on the magnetization

J. Sinova et al., Rev. Mod. Phys. **87**, 1213 (2015);
K. Ryu et al., Nat. Nano. **8**, 527 (2013); S. Emori et al., Nat. Mat. **12**, 611 (2013); T. Moore APL **93**, 262504 (‘08);
M. Miron et al., Nat. Mat. **10**, 419 (2011);

- Measure spin Hall effect by: THz spectroscopy[1]
  → Good agreement between measurements and theoretical calculations!
- Maximize SOTs in Pt/CFB/Ta&Pt/CFB/W with opposite SHA of Pt & W/Ta[2]

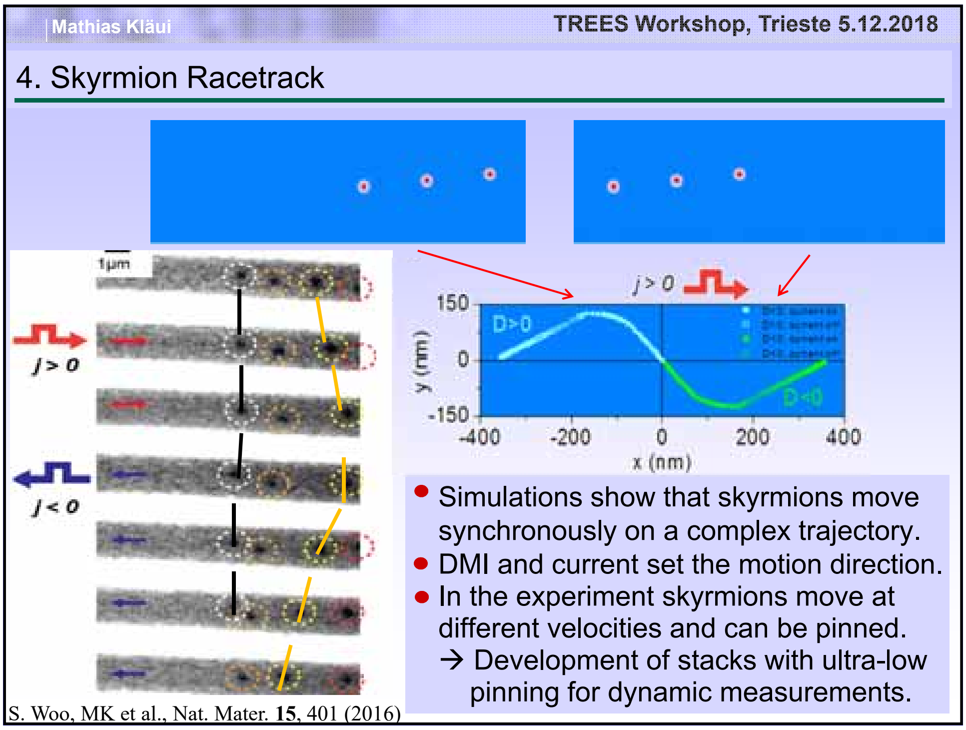
[1]T. Seifert, MK et al., Nat. Photon. **10**, 483 (2016); [2]T. Seifert, MK et al., Appl. Phys. Lett. **110**, 252402 (2017)



4. Skyrmion Racetrack

- Skyrmion racetrack[1]: advantages compared to a DW-based racetrack: total magnetization does not change with skyrmion motion
  → less susceptible to stray fields.
- Topological protection of skyrmions → more reliable motion?
- Nanowire is patterned out of Pt/Co/Ta (µm width)[2]
- Single skyrmions can be moved by spin orbit torques on the nano-track[2]
- Imaging by x-ray microscopy → STXM, TXM, x-ray holography

[1] A. Fert et al., Nat, Nano **8**, 152; R. Tomasello et al., Sci. Rep. **4**, 6784 [2] S. Woo, MK et al., Nat. Mater. **15**, 401

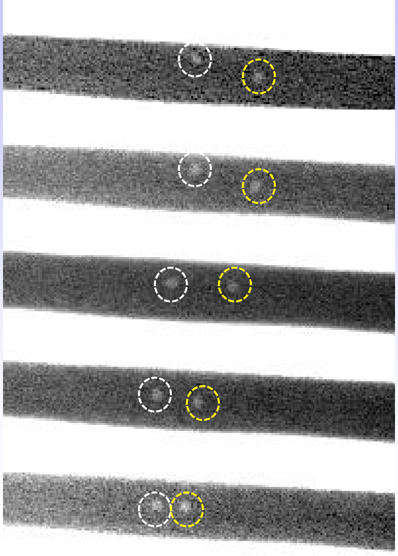


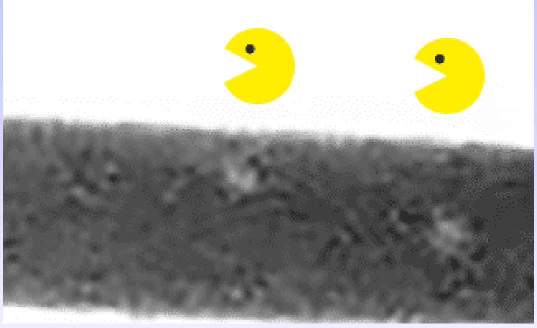
4. Skyrmion Racetrack

- Simulations show that skyrmions move synchronously on a complex trajectory.
- DMI and current set the motion direction.
- In the experiment skyrmions move at different velocities and can be pinned.
  → Development of stacks with ultra-low pinning for dynamic measurements.

S. Woo, MK et al., Nat. Mater. **15**, 401 (2016)

4. Skyrmion Racetrack - Stability





- Simulations show that skyrmions move synchronously on a complex trajectory.
- DMI and current set the motion direction.
- In the experiment skyrmions move at different velocities and can be pinned.
- Only pinned skyrmions can be annihilated!

S. Woo, MK et al., Nat. Mater. **15**, 401 (2016)

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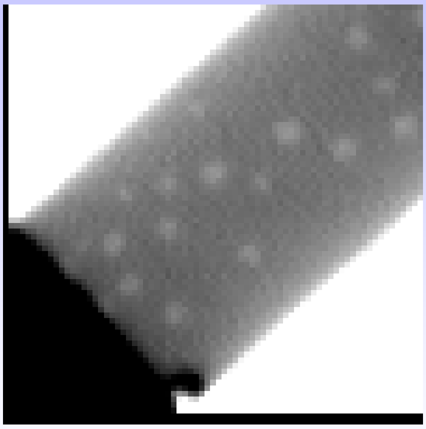
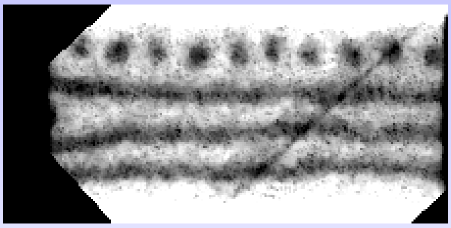
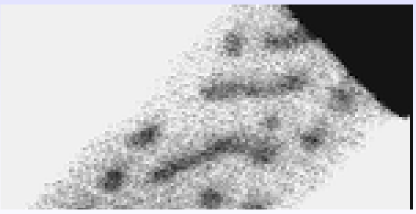
4. Skyrmion Racetrack

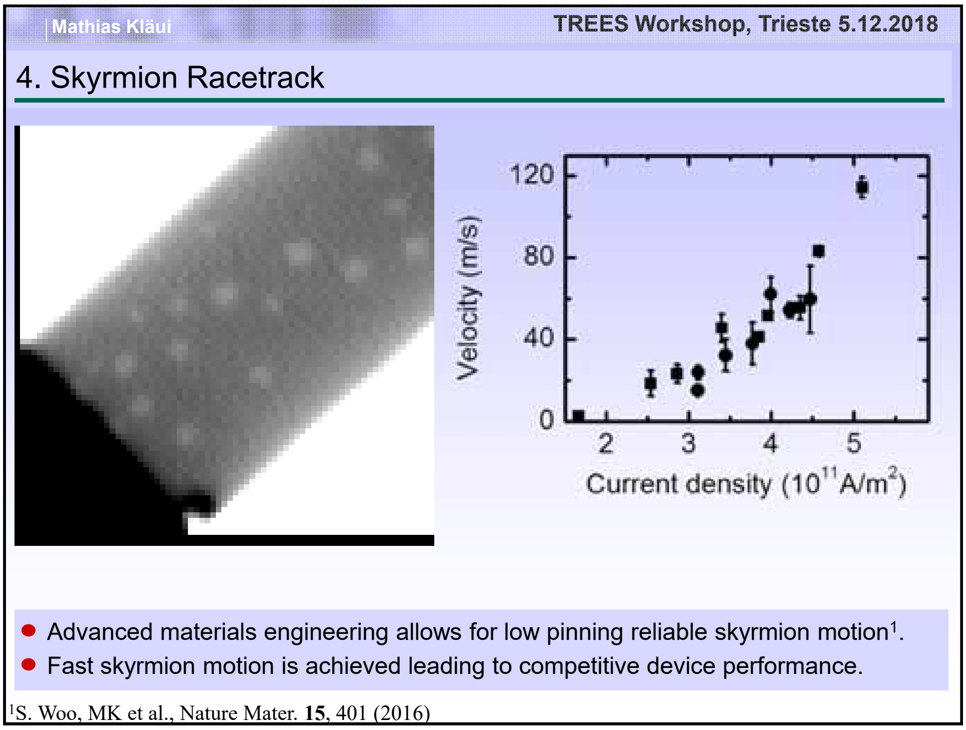






- Advanced materials engineering allows for low pinning reliable skyrmion motion[1].

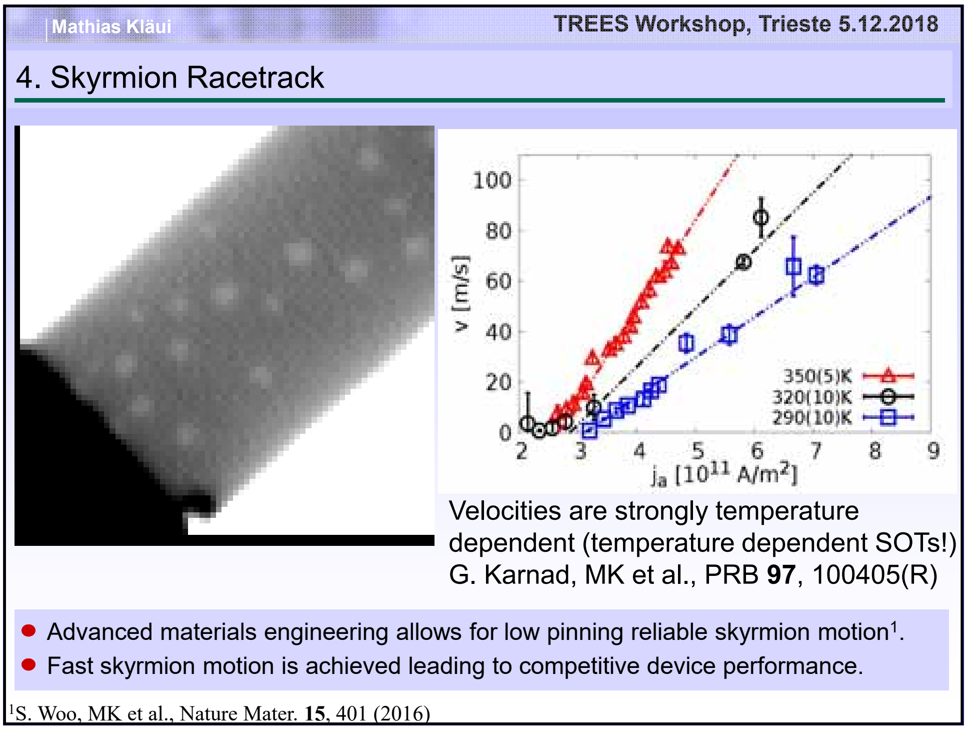
[1] S. Woo, MK et al., Nature Mater. **15**, 401 (2016)



4. Skyrmion Racetrack

- Advanced materials engineering allows for low pinning reliable skyrmion motion[1].
- Fast skyrmion motion is achieved leading to competitive device performance.

[1] S. Woo, MK et al., Nature Mater. **15**, 401 (2016)



4. Skyrmion Racetrack

Velocities are strongly temperature dependent (temperature dependent SOTs!)
G. Karnad, MK et al., PRB **97**, 100405(R)

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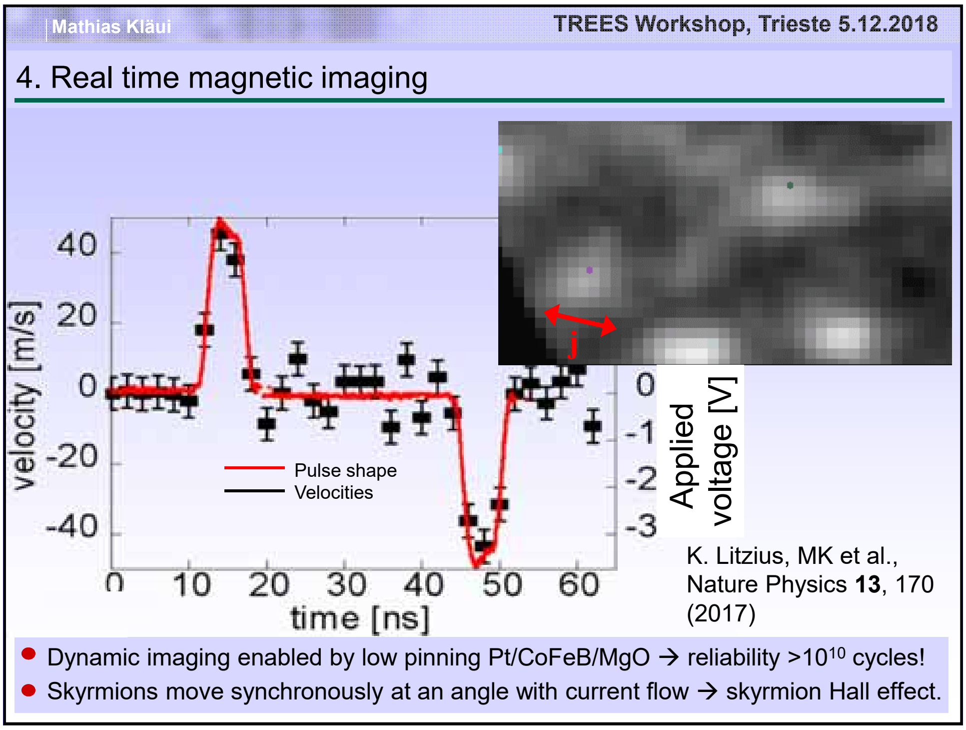
[1] S. Woo, MK et al., Nature Mater. **15**, 401 (2016)



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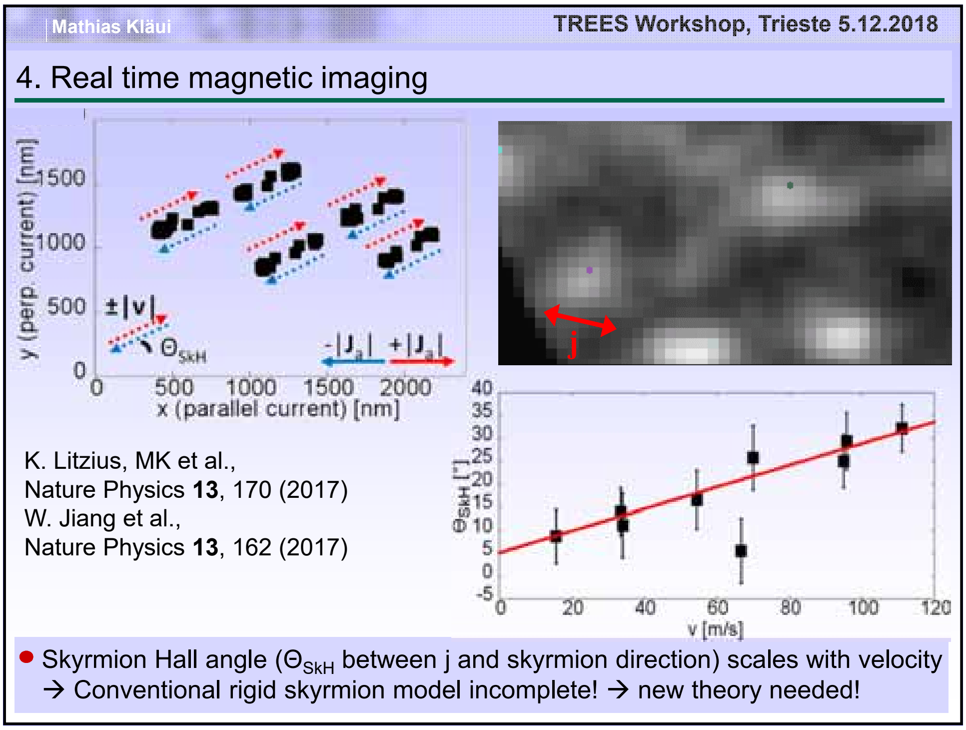
4. Real time magnetic imaging

K. Litzius, MK et al., Nature Physics **13**, 170 (2017)

- Dynamic imaging enabled by low pinning Pt/CoFeB/MgO → reliability $>10^{10}$ cycles!
- Skyrmions move synchronously at an angle with current flow → skyrmion Hall effect.



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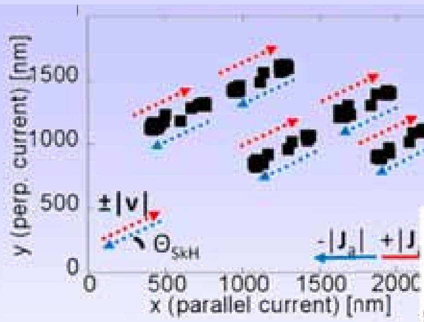
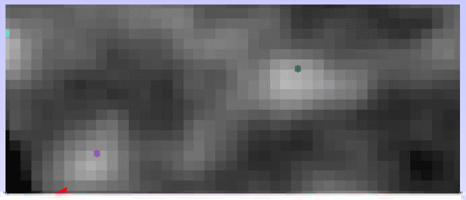
4. Real time magnetic imaging

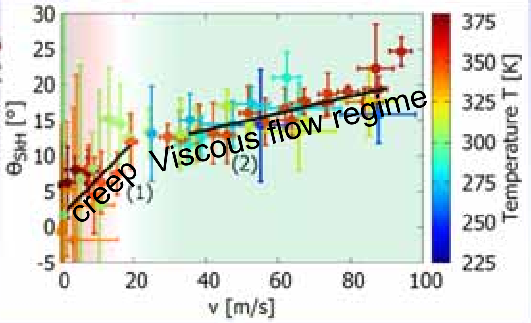
K. Litzius, MK et al.,
Nature Physics **13**, 170 (2017)
W. Jiang et al.,
Nature Physics **13**, 162 (2017)

- Skyrmion Hall angle (Θ_{SkH} between j and skyrmion direction) scales with velocity → Conventional rigid skyrmion model incomplete! → new theory needed!

4. Real time imaging of skyrmion dynamics







K. Litzius, MK et al.,
Nature Physics **13**, 170 (2017)
W. Jiang et al.,
Nature Physics **13**, 162 (2017)
K. Litzius, MK et al. (2018)

- Skyrmion Hall angle (Θ_{SkH} between j and skyrmion direction) scales with velocity → Two different slopes in creep and viscous flow regime → different origins!

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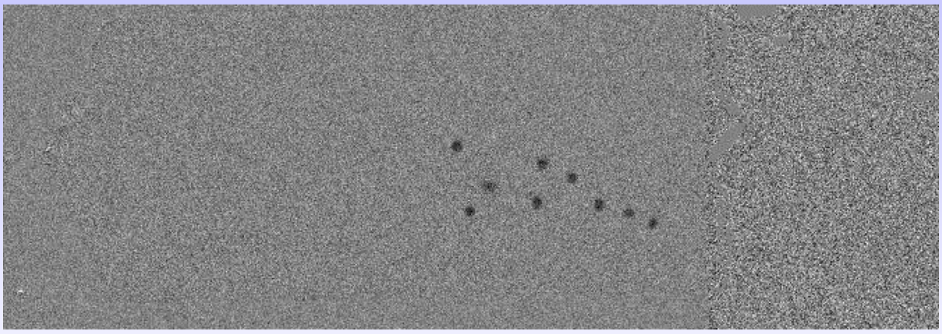
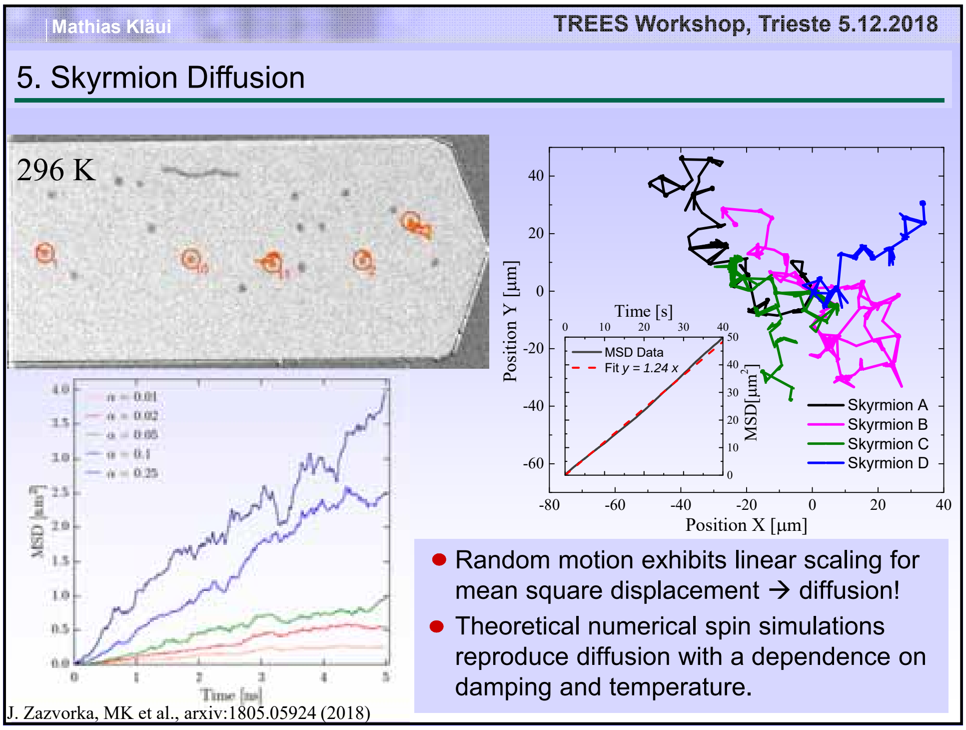
5. Skyrmion Writing and Skyrmion Diffusion



- Using spin-orbit torques, skyrmions can be produced by pulses „on-demand“[1]
- Synchronous displacement along current flow → N=1 skyrmions
- In addition to deterministic „writing“ and „shifting“, we see in ultra-low pinning materials stacks also thermally induced dynamics leading to random motion → diffusion? Predicted to be suppressed: Ref. 2

[1] K. Everschor-Sitte et al., NJP **19**, 092001 (2017); M. Stier et al, Phys. Rev. Lett. **118**, 267203 (2017); F. Büttner et al., Nature. Nan. **12**, 1040 (2017); G. Finocchio, MK et al., J. Phys. D: Appl. Phys. **49**, 423001 (2016).

[2] C. Schütte et al., Phys. Rev. B **90**, 174434 (2014).



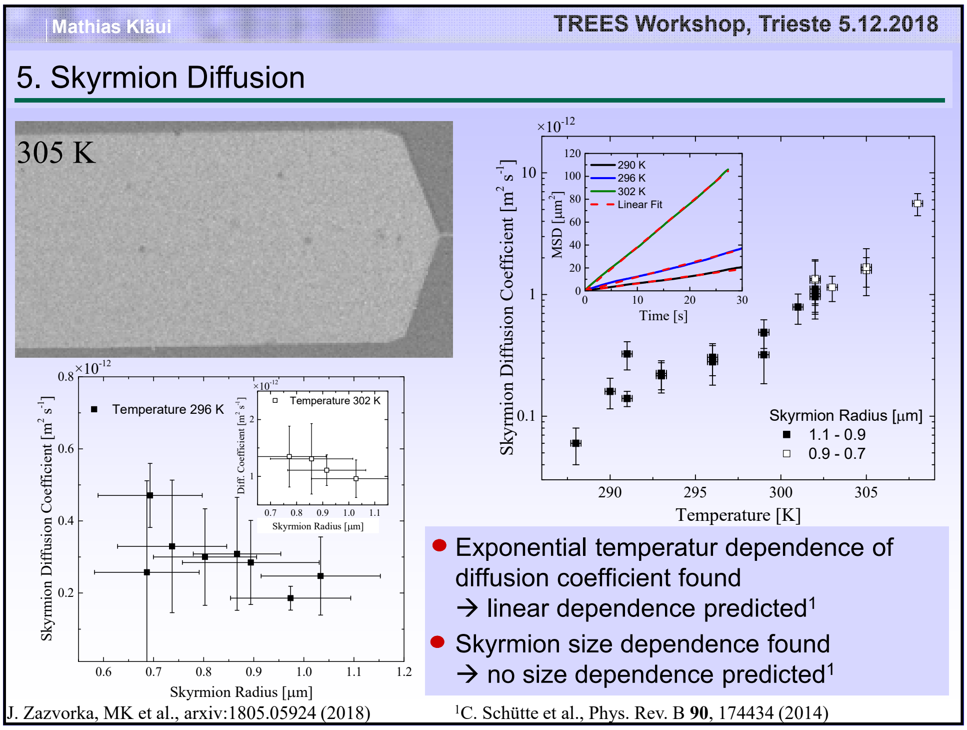
Mathias Kläui

TREES Workshop, Trieste 5.12.2018

5. Skyrmion Diffusion

- Random motion exhibits linear scaling for mean square displacement → diffusion!
- Theoretical numerical spin simulations reproduce diffusion with a dependence on damping and temperature.

J. Zazvorka, MK et al., arxiv:1805.05924 (2018)



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5. Skyrmion Diffusion

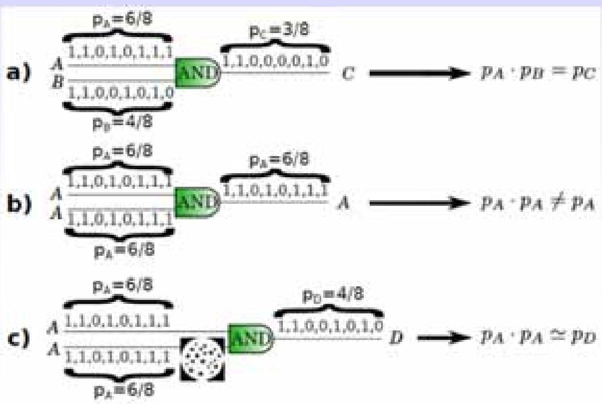
- Exponential temperatur dependence of diffusion coefficient found → linear dependence predicted[1]
- Skyrmion size dependence found → no size dependence predicted[1]

J. Zazvorka, MK et al., arxiv:1805.05924 (2018)

[1]C. Schütte et al., Phys. Rev. B **90**, 174434 (2014)

5. Skyrmion Diffusion for probabilistic computing

- Application of skyrmion diffusion: stochastic computing
  - Operating with probability (*p-value*) of seeing a “1” or “0”
    → p-value is statistical ratio of “1” to “0”:
    p=0.5 → 50% of the time “1” and 50% “0” in telegraph noise
  - Multiplication achieved by AND gate
  - Need to reshuffle signals to be uncorrelated
  - Reshuffler: copying an input stream into uncorrelated new one while preserving the original *p-value*



J. Zazvorka, MK et al., arxiv:1805.05924 (2018)

D. Pinna et al., Phys. Rev. Appl. **9**, 064018 (2018)

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5. Skyrmion Diffusion for probabilistic computing

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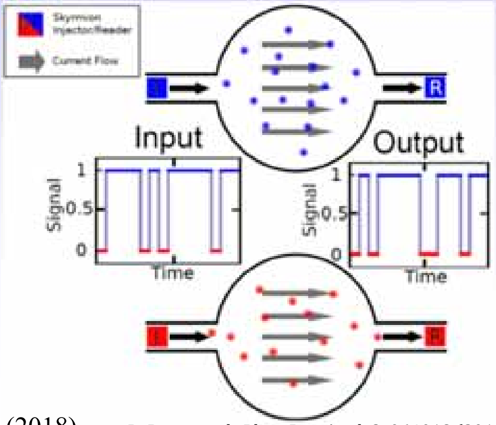
- Proposing a device utilizing skyrmion diffusion
  - Two reshuffling chambers corresponding to bit 1 and bit 0
  - Driving skyrmions with a constant DC current



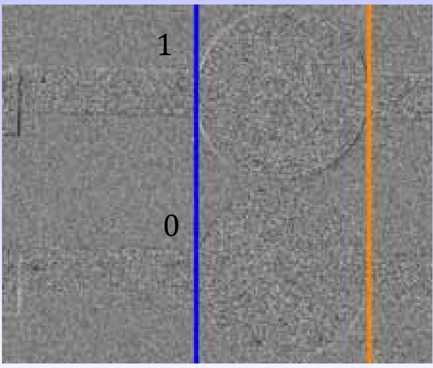
J. Zazvorka, MK et al., arxiv:1805.05924 (2018)

D. Pinna et al., Phys. Rev. Appl. **9**, 064018 (2018)

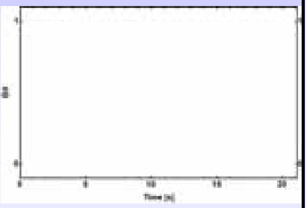
5. Skyrmion Diffusion for probabilistic computing

Realization:

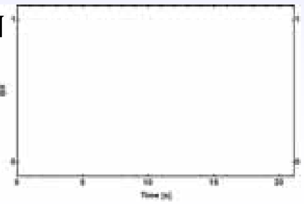
- -Skyrmion nucleation with pulses or DC.
- -Readout with imaging.
- -Skyrmions enter the chamber (blue line→input)
- -Exiting chamber (orange) triggers corresponding bit ➔output signal



OUT



IN



$$\rho = \frac{cov(in, out)}{\sigma_{in} \cdot \sigma_{out}}$$

J. Zazvorka, MK et al., arxiv:1805.05924 (2018)

Analysis of videos yields

Current density [A·m^{-2}]	3×10^8
p-value change	0.01 ± 0.08
Correlation ρ	0.11 ± 0.14

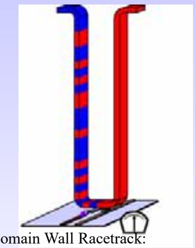
Perfect p-value retention and good decorrelation!

D. Pinna et al., Phys. Rev. Appl. **9**, 064018 (2018)

Spin-Orbitronics → exciting physics & non-volatile low power devices

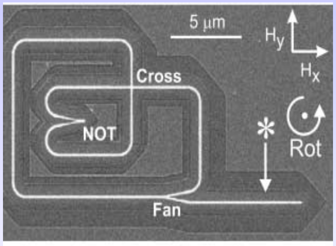
Racetrack

DW or Skyrmion



Domain Wall Racetrack:
Parkin et al, Science **320**, 190 ('08)
Extension to Skyrmions:
Fert et al., Nature Nano **8**, 152 ('13)

Spin structure Logic



D. A. Allwood et al., Science **309,** 1688 ('05)

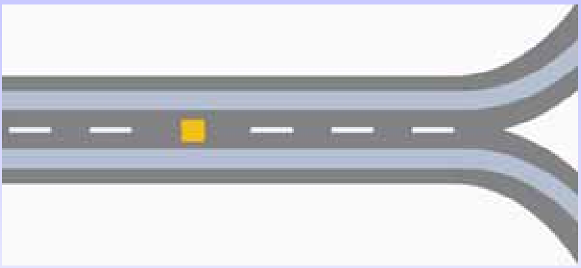
Domain Wall Sensors

R. Mattheis et al., IEEE Trans. Magn. **45**, 3792 (2009)
A. Bisig, MK et al., Nature Comm. **4**, 2328 (2013)

Challenges for Spintronics Devices:

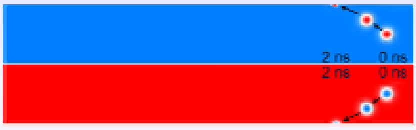
Stability – Long term information retention
Manipulation – Efficiency and speed
No stray fields – Antiferromagnetic Spintronics

6. New devices based on multi-lane racetrack

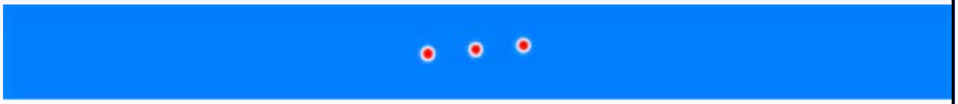


New multilane highway[1] matrix for reconfigurable and synaptic logic!

K. Litzius, MK et al., Nature Physics **13**, 170 (2017)



Skyrmion Hall Effect makes change of lanes difficult
→ how to overcome this problem?



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[1] J. Müller, New J. Phys. **19**, 025002 (2017).

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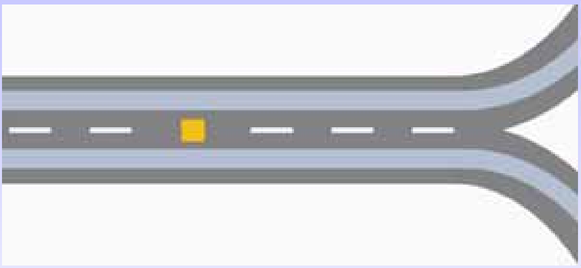
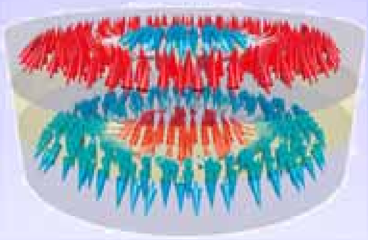
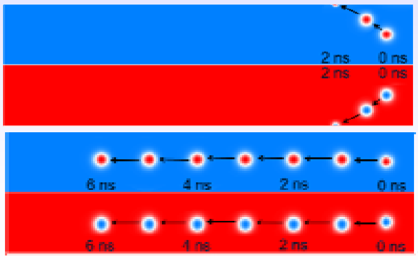
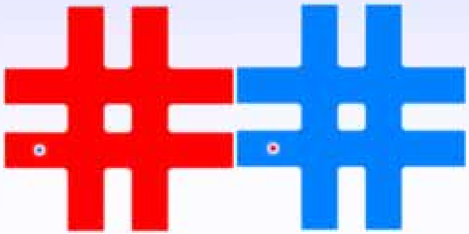
6. Skyrmions in synthetic Antiferromagnets





X. Zhang et al., Nat. Comms.**7**, 10293 ('15)





G. Finocchio, MK et al., J. Phys. D: Appl. Phys. **49**, 423001 ('16)

- Skyrmion Hall Angle reduced in antiferromangets and ferrimagnets[1,2]

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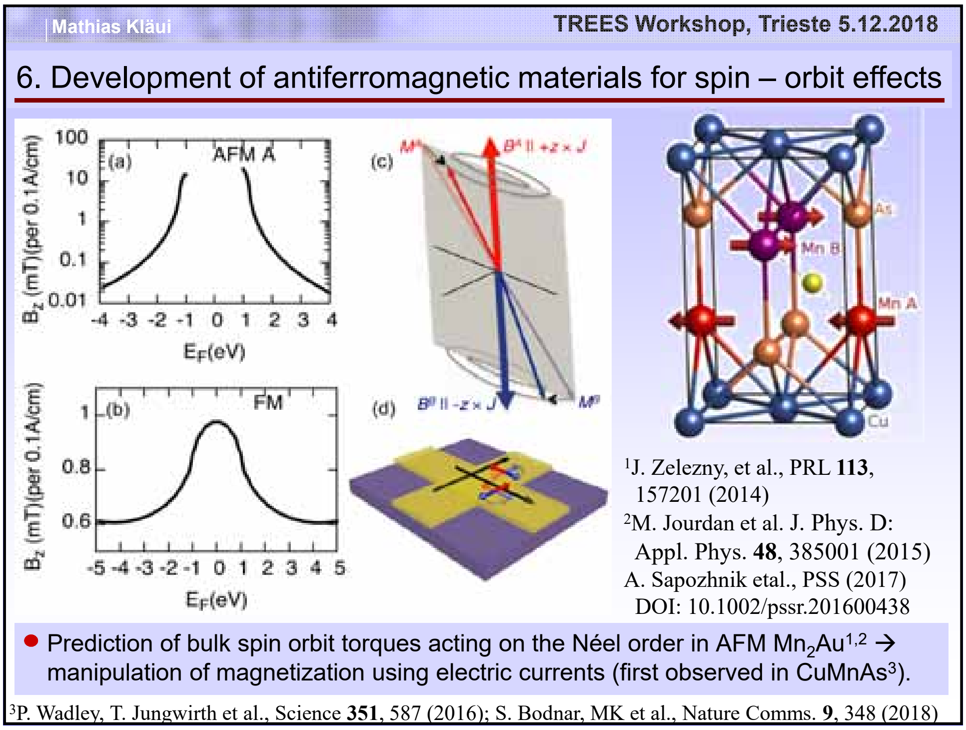
[1] J. Barker and O. Tretiakov, Phys. Rev. Lett. **116**, 147203 (2016); [2] S. Woo et al., Nat. Comm. **9**, 959 (2018).



6. Development of antiferromagnetic materials for spin – orbit effects

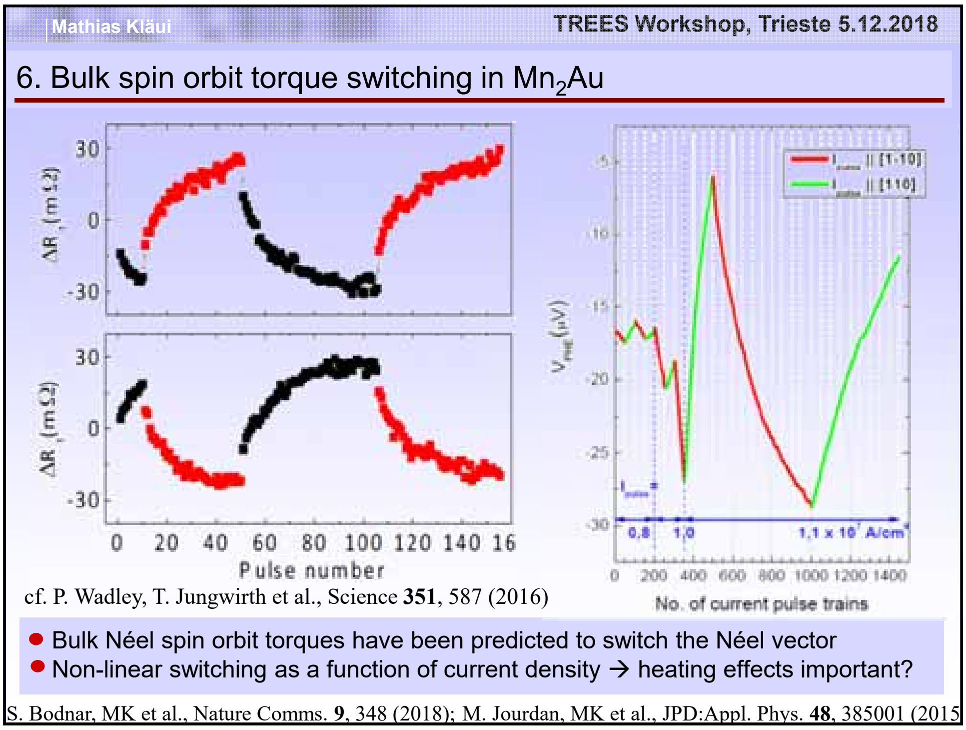
[1]J. Zelezny, et al., PRL **113**, 157201 (2014)

[2]M. Jourdan et al. J. Phys. D: Appl. Phys. **48**, 385001 (2015)

A. Sapozhnik etal., PSS (2017) DOI: 10.1002/pssr.201600438

- Prediction of bulk spin orbit torques acting on the Néel order in AFM Mn_2Au[1,2] → manipulation of magnetization using electric currents (first observed in CuMnAs[3]).

[3]P. Wadley, T. Jungwirth et al., Science **351**, 587 (2016); S. Bodnar, MK et al., Nature Comms. **9**, 348 (2018)

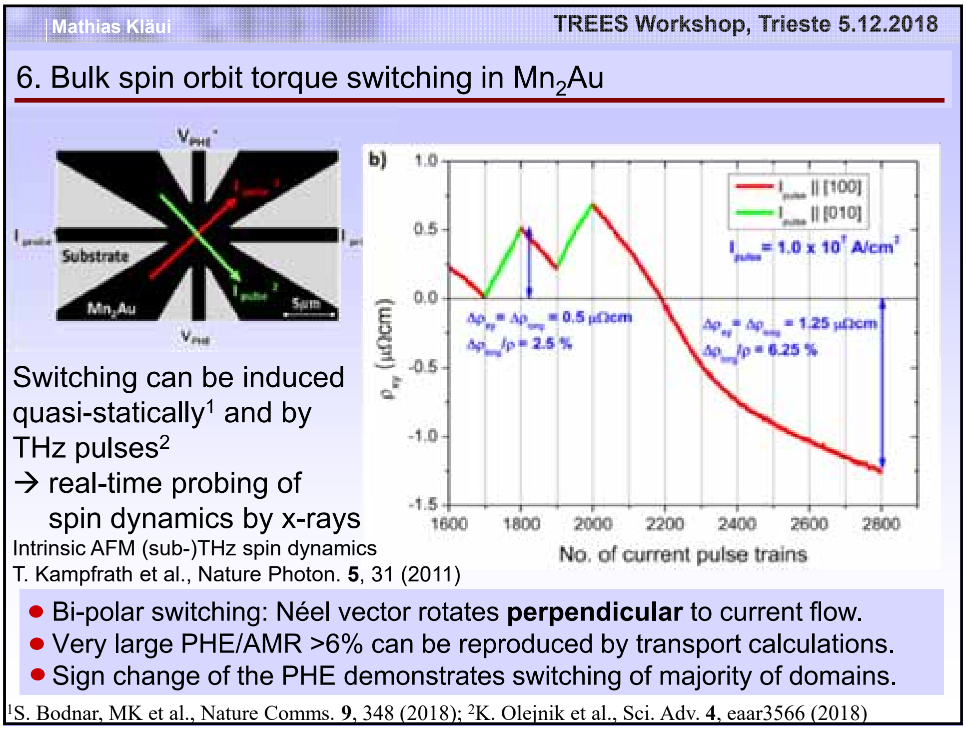


6. Bulk spin orbit torque switching in Mn_2Au

cf. P. Wadley, T. Jungwirth et al., Science **351**, 587 (2016)

- Bulk Néel spin orbit torques have been predicted to switch the Néel vector
- Non-linear switching as a function of current density → heating effects important?

S. Bodnar, MK et al., Nature Comms. **9**, 348 (2018); M. Jourdan, MK et al., JPD:Appl. Phys. **48**, 385001 (2015



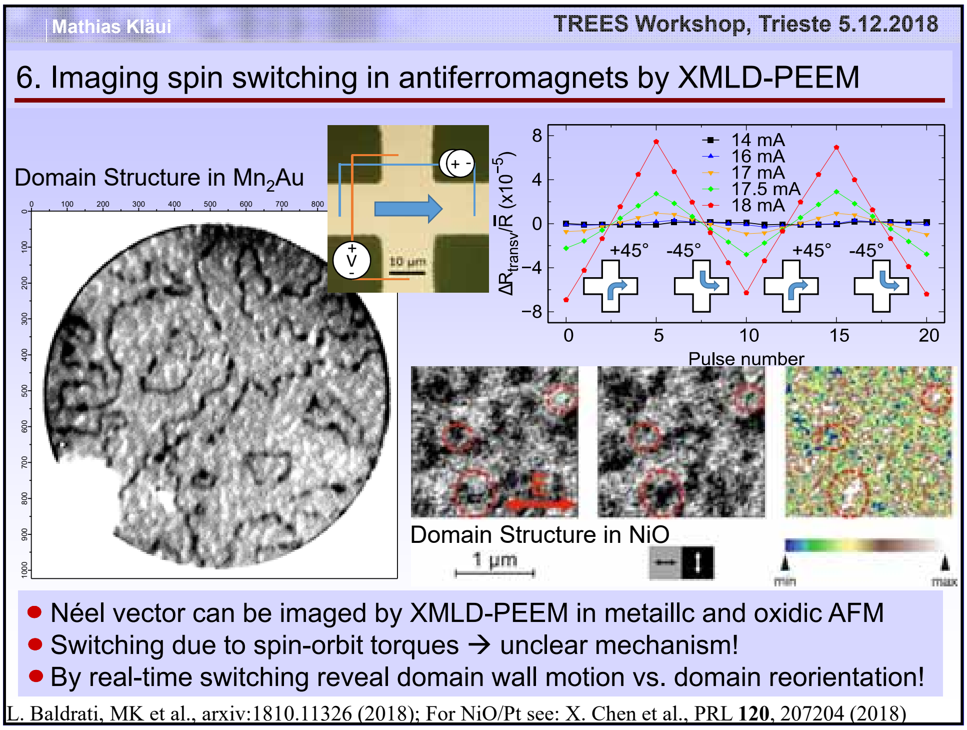
6. Bulk spin orbit torque switching in Mn_2Au

Switching can be induced quasi-statically[1] and by THz pulses[2]
→ real-time probing of spin dynamics by x-rays

Intrinsic AFM (sub-)THz spin dynamics
T. Kampfrath et al., Nature Photon. **5**, 31 (2011)

- Bi-polar switching: Néel vector rotates **perpendicular** to current flow.
- Very large PHE/AMR >6% can be reproduced by transport calculations.
- Sign change of the PHE demonstrates switching of majority of domains.

[1] S. Bodnar, MK et al., Nature Comms. **9**, 348 (2018); [2] K. Olejnik et al., Sci. Adv. **4**, eaar3566 (2018)



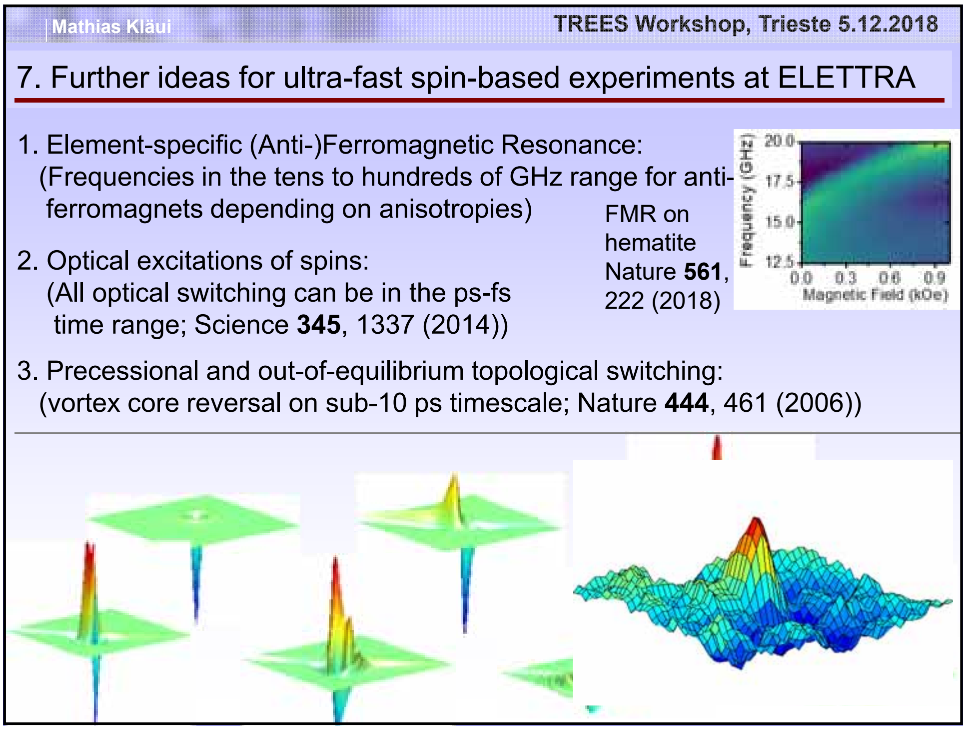
6. Imaging spin switching in antiferromagnets by XMLD-PEEM

Domain Structure in Mn_2Au

Domain Structure in NiO

- Néel vector can be imaged by XMLD-PEEM in metaillc and oxidic AFM
- Switching due to spin-orbit torques → unclear mechanism!
- By real-time switching reveal domain wall motion vs. domain reorientation!

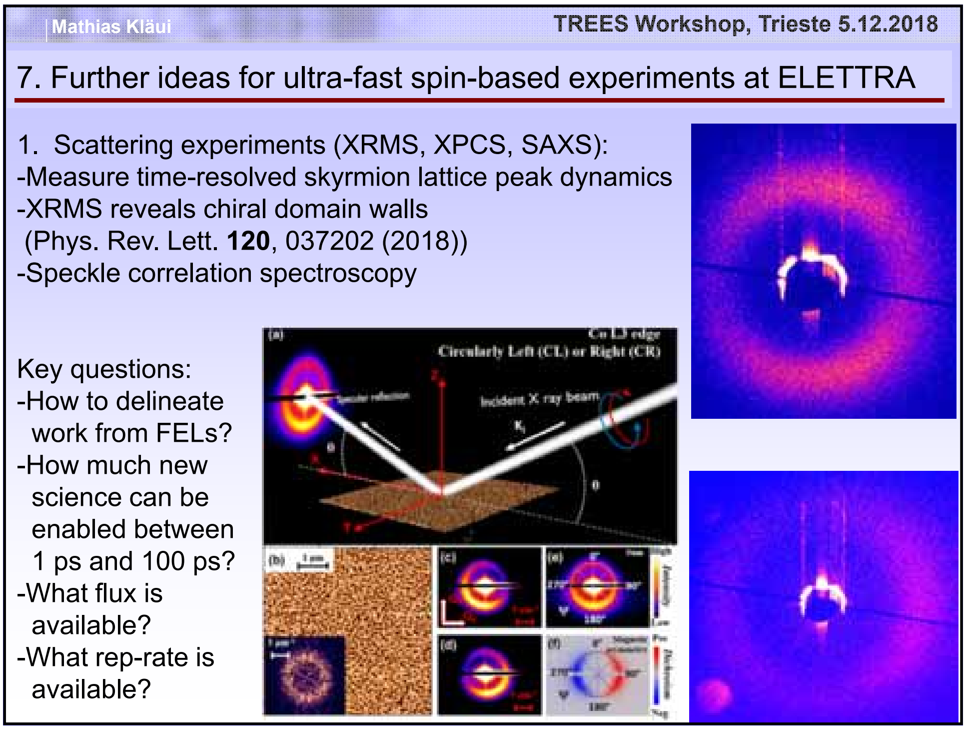
L. Baldrati, MK et al., arxiv:1810.11326 (2018); For NiO/Pt see: X. Chen et al., PRL **120**, 207204 (2018)



7. Further ideas for ultra-fast spin-based experiments at ELETTRA

1. Element-specific (Anti-)Ferromagnetic Resonance: (Frequencies in the tens to hundreds of GHz range for anti-ferromagnets depending on anisotropies)
2. Optical excitations of spins: (All optical switching can be in the ps-fs time range; Science **345**, 1337 (2014))
3. Precessional and out-of-equilibrium topological switching: (vortex core reversal on sub-10 ps timescale; Nature **444**, 461 (2006))

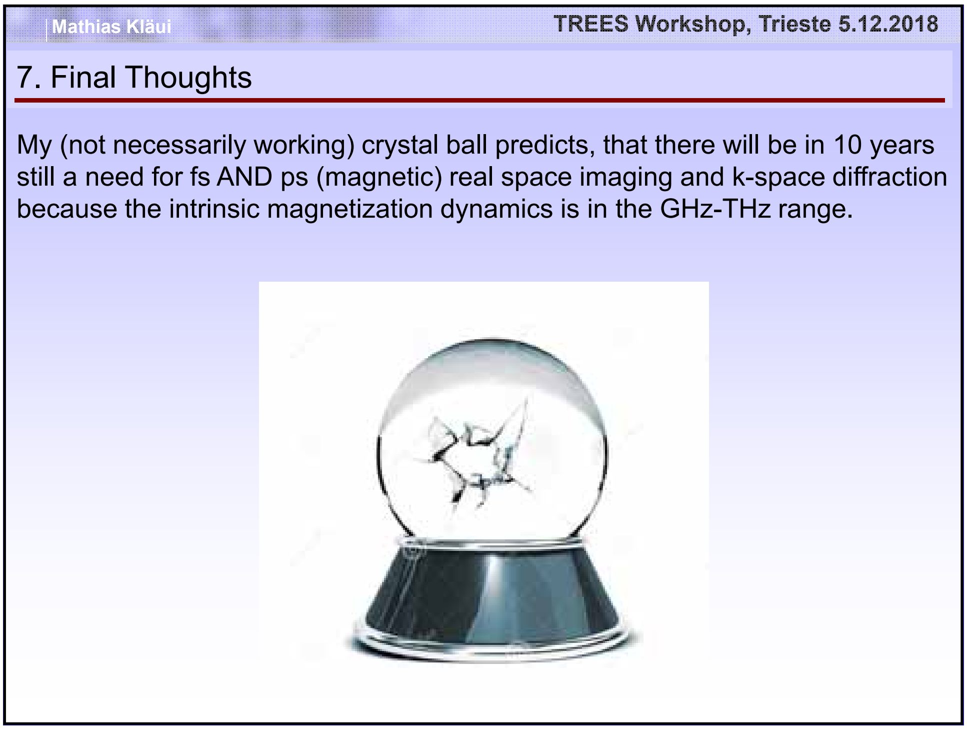
FMR on hematite Nature **561**, 222 (2018)



7. Further ideas for ultra-fast spin-based experiments at ELETTRA

1. Scattering experiments (XRMS, XPCS, SAXS):
-Measure time-resolved skyrmion lattice peak dynamics
-XRMS reveals chiral domain walls
(Phys. Rev. Lett. **120**, 037202 (2018))
-Speckle correlation spectroscopy

Key questions:
-How to delineate work from FELs?
-How much new science can be enabled between 1 ps and 100 ps?
-What flux is available?
-What rep-rate is available?



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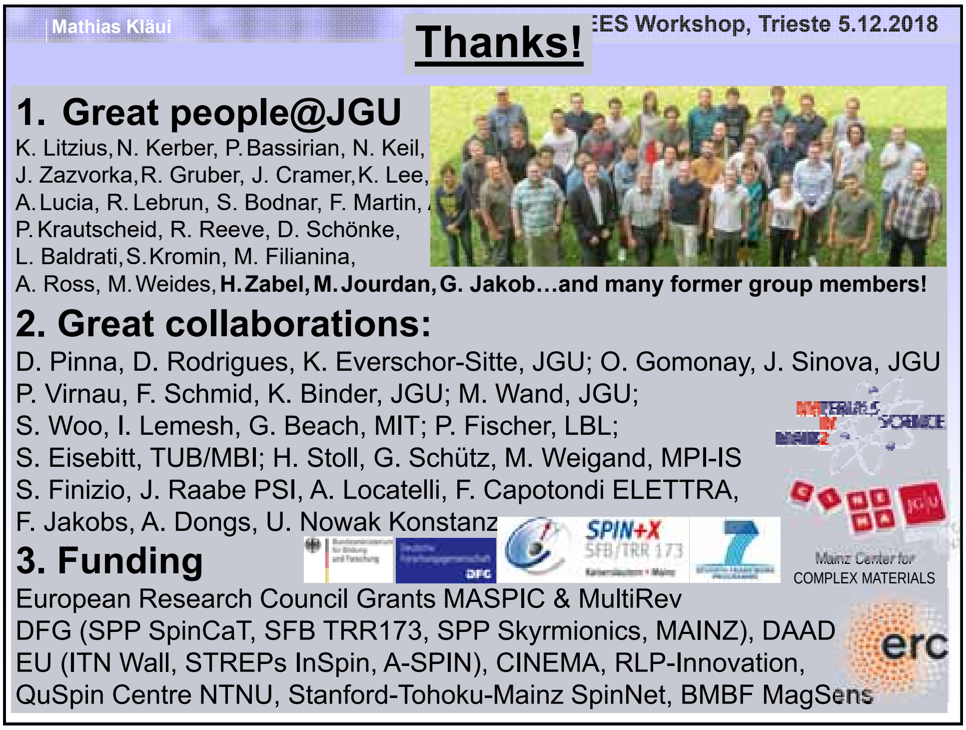
7. Final Thoughts

My (not necessarily working) crystal ball predicts, that there will be in 10 years still a need for fs AND ps (magnetic) real space imaging and k-space diffraction because the intrinsic magnetization dynamics is in the GHz-THz range.



Mathias Kläui EES Workshop, Trieste 5.12.2018

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1. Great people@JGU

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S. Woo, I. Lemesh, G. Beach, MIT; P. Fischer, LBL;
S. Eisebitt, TUB/MBI; H. Stoll, G. Schütz, M. Weigand, MPI-IS
S. Finizio, J. Raabe PSI, A. Locatelli, F. Capotondi ELETTRA,
F. Jakobs, A. Dongs, U. Nowak Konstanz

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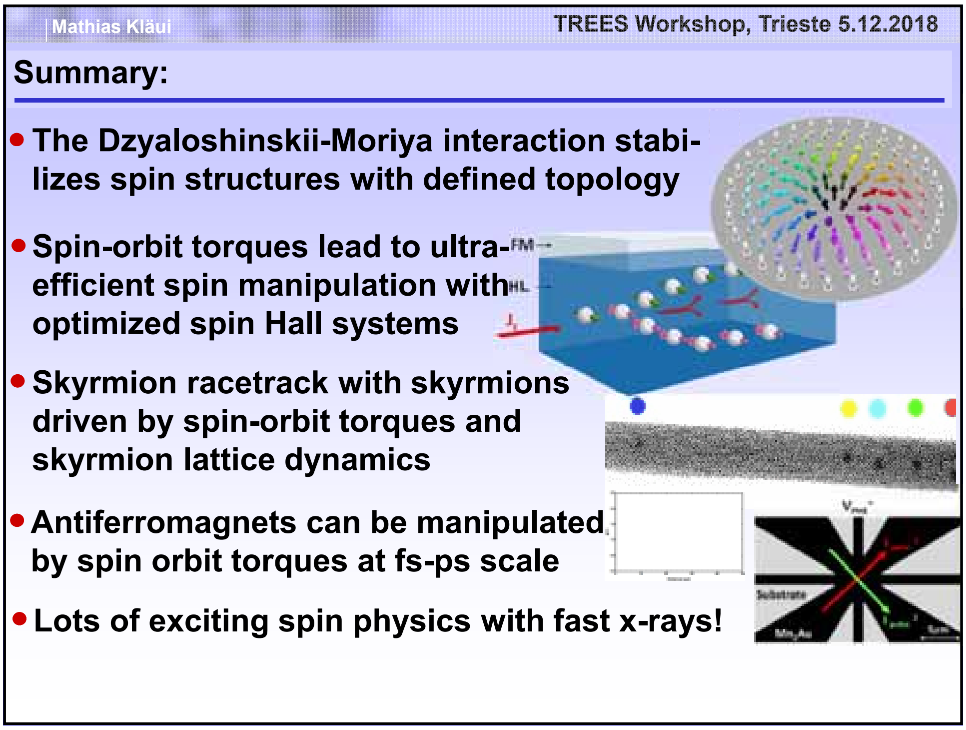
QuSpin Centre NTNU, Stanford-Tohoku-Mainz SpinNet, BMBF MagSens



Summary:

- The Dzyaloshinskii-Moriya interaction stabilizes spin structures with defined topology
- Spin-orbit torques lead to ultra-efficient spin manipulation with optimized spin Hall systems
- Skyrmion racetrack with skyrmions driven by spin-orbit torques and skyrmion lattice dynamics
- Antiferromagnets can be manipulated by spin orbit torques at fs-ps scale
- Lots of exciting spin physics with fast x-rays!