Spintronics and orbitronics for memory & unconventional computing

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- Introduction: devices & chiral interactions
- Topologically stabilized Skyrmions
- Fast dynamics: Spin and Orbital Torques
- Efficient dynamics: thermal diffusion
- Non-conventional logic with skyrmions

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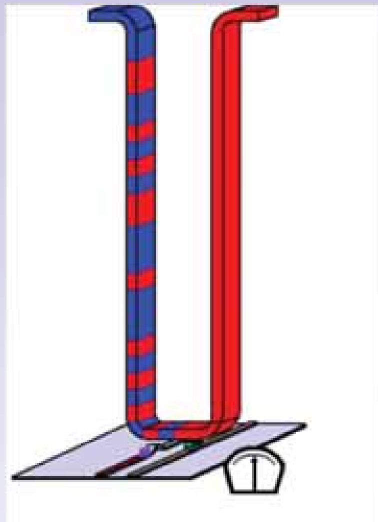
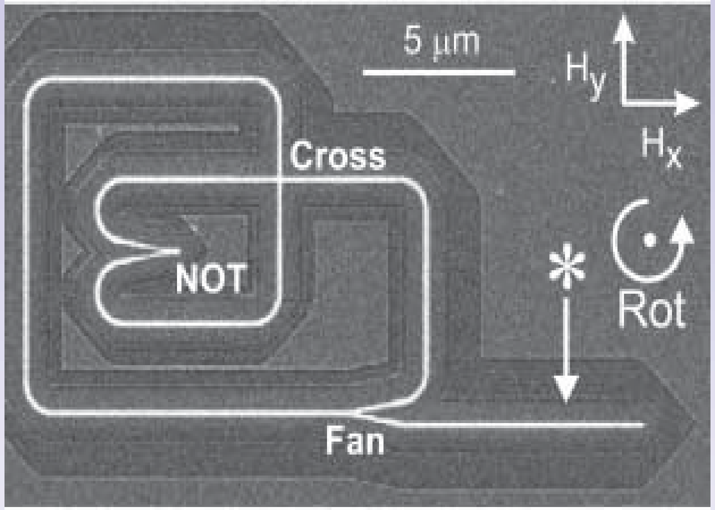
Devices based on Domain Walls and Skyrmions

Memory



Parkin et al, Science **320**, 190 ('08)
Fert et al., Nature Nano **8**, 152 ('13)

Magnetic Logic



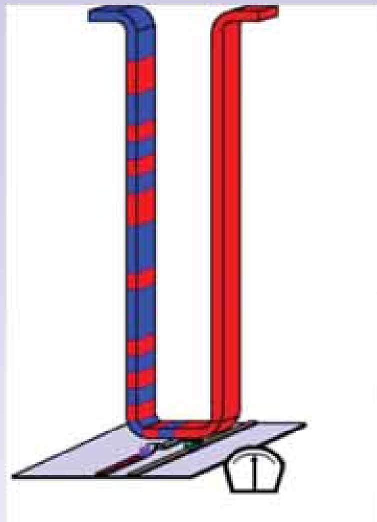
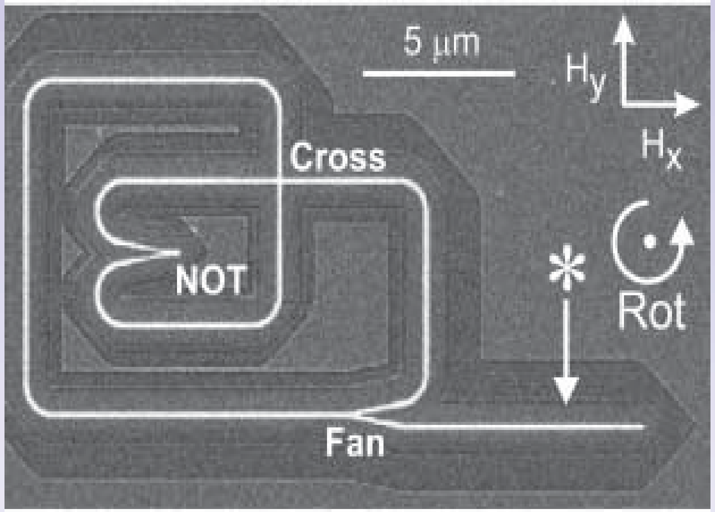
D. A. Allwood et al., Science **309,** 1688 (2005)
J. Grollier et al., Nature Electron. **3**, 360 (2020)

Position & angle sensors

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

- Key low power IT devices based on magnetic spin structures include:
- Memory: non – volatile, no mechanically moving parts, one memory fits all → low power and simplified device architecture
- Logic: non – volatile, non – contact, no constant power source necessary: → low power + thermally excited diffusive dynamics → ultra-low power logic
- Sensing - Angle and position sensors: non – volatile, no constant power source necessary → low power, low maintenance

Devices based on Domain Walls and Skyrmions

Memory	Magnetic Logic	Position & angle sensors
		
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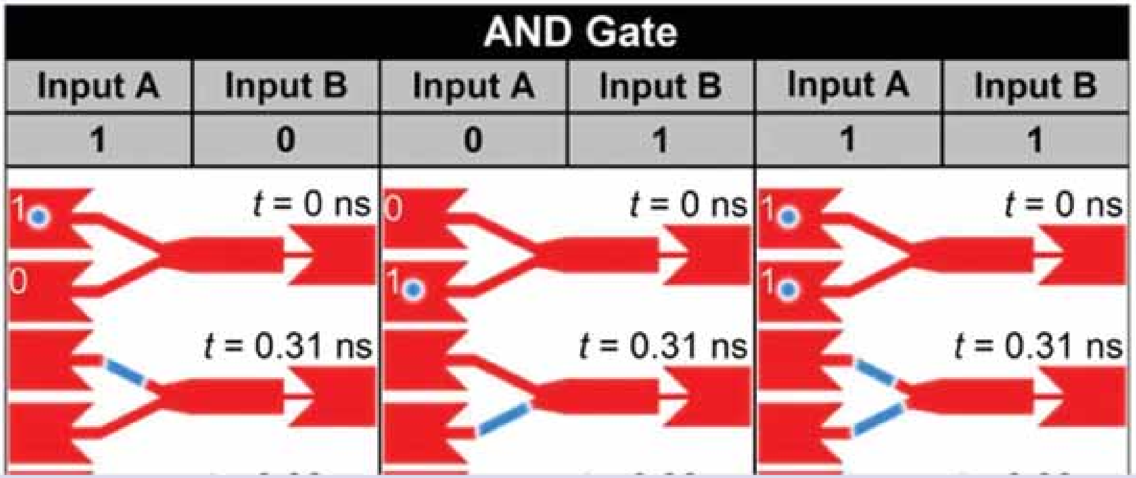
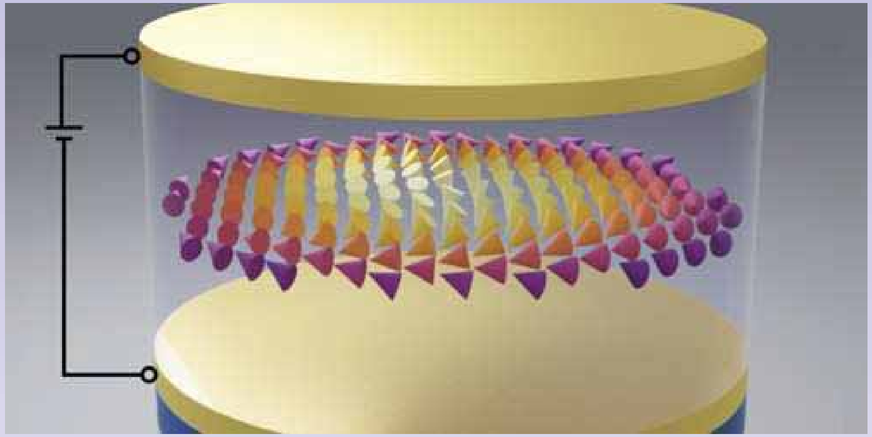
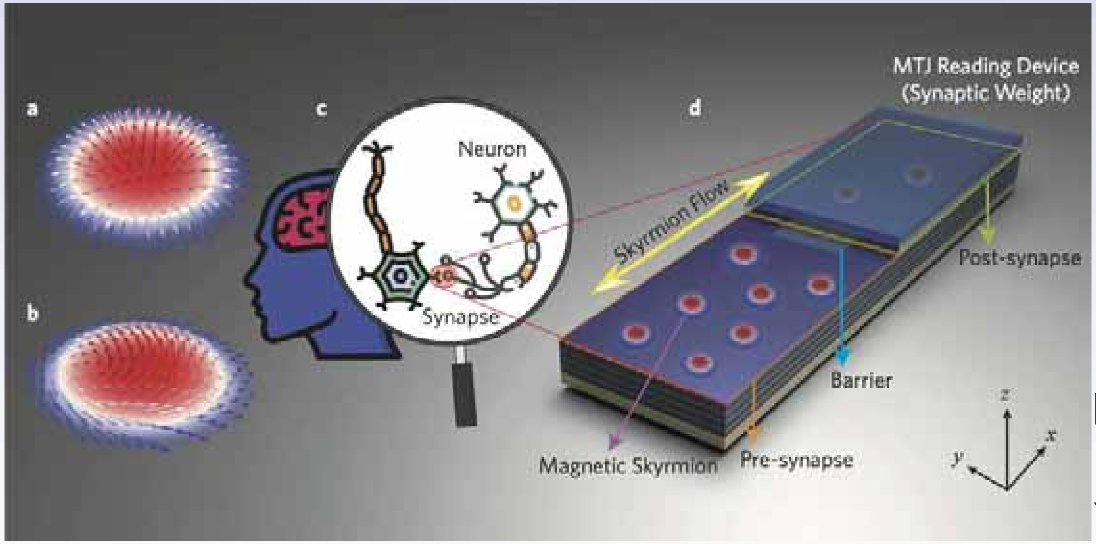
Introduction to logic devices based on spin structures

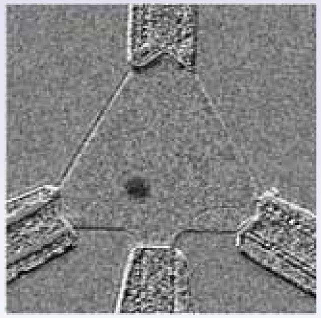


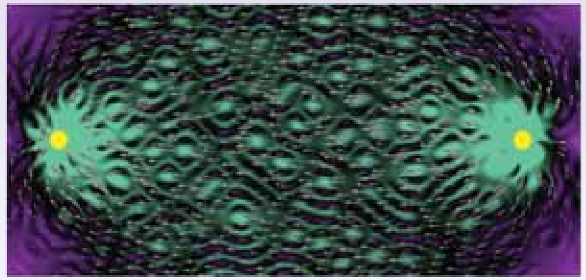


X. Zhang et al., Sci. Rep. **5**, 9400 (2015); Z. Yan et al., PRAppl. **15**, 064004 (2021)

C. Psaroudaki et al., Phys. Rev. Lett. **127**, 067201 (2021)



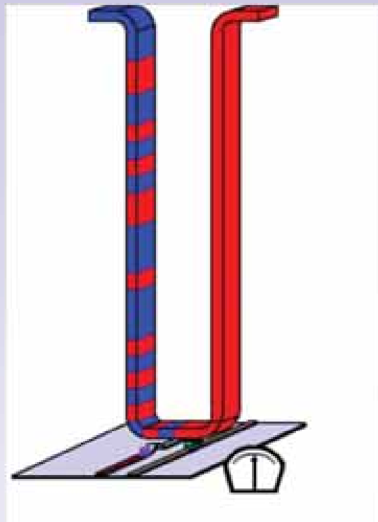
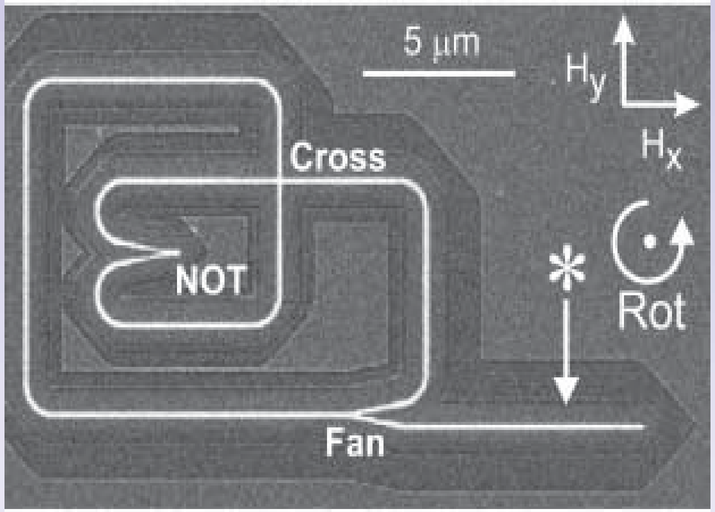




R. Chen et al., Phys. Rev. Appl. **14**, 014096 (2020);
K. Song et al., Nature Electron. **3**, 148 (2020);
Y. Huang et al., Nanotechnology **28**, 08LT02 (2017)

- Spin structures such as skyrmions have been suggested for logic schemes:
- -Conventional Boolean Logic
- -Non-conventional Logic (neuromorphic, stochastic, reservoir - later more!)
- -Quantum Computing

Devices based on Domain Walls and Skyrmions

Memory	Magnetic Logic	Position & angle sensors
		

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J. Grollier et al., Nature Electron. **3**, 360 (2020)

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

Challenges for Spintronics Devices:

Statics: Stability – Long term information retention
→ Topological Spin Structures to the rescue

Dynamics: Manipulation – Efficiency and Speed
→ Topological Spin Structures to the rescue

Devices based on Domain Walls and Skyrmions

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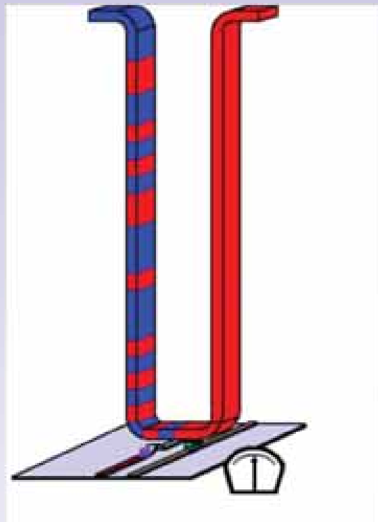

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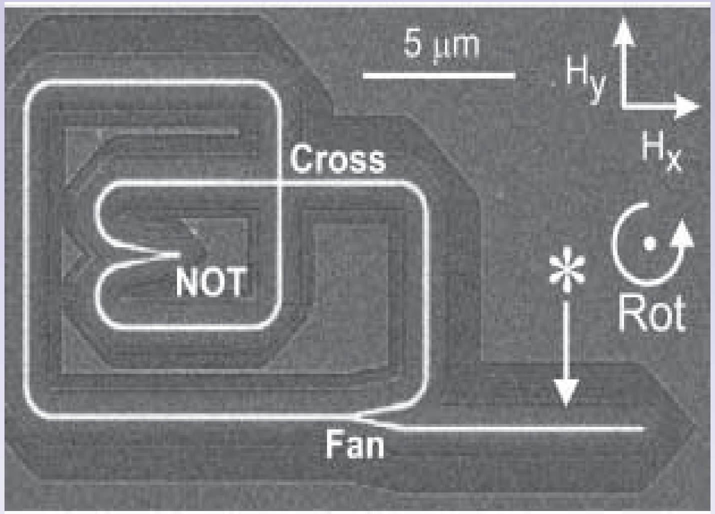

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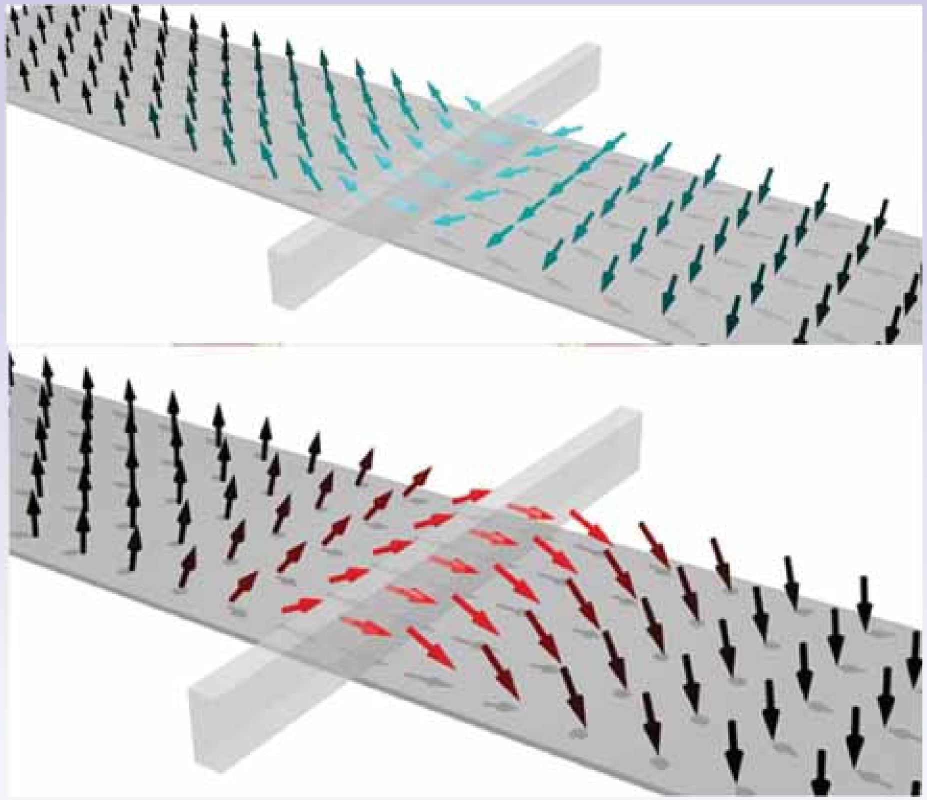
0. Magnetic coupling – Heisenberg exchange coupling

Conventional:

Spin-Spin Heisenberg exchange interaction

➡ Stabilization of states with **random topology and random chirality**

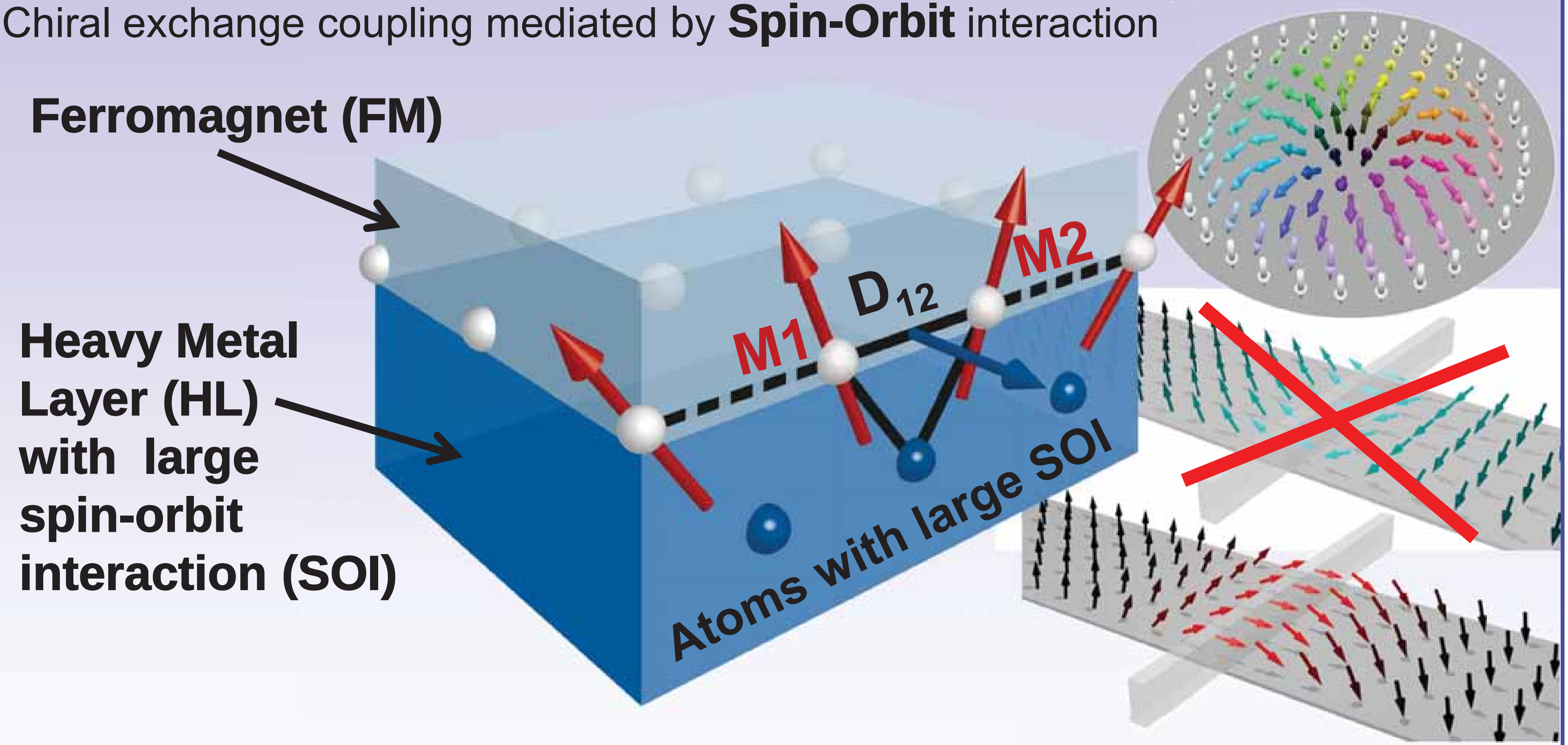


- Heisenberg exchange interaction sets the magnetic ordering.
- However many energetically degenerate spin structures can be stabilized → spin structures do not have a set chirality.

O. Boulle, MK et al., Mater. Sci. Eng. R. **72**, 159 (2011)

0. Chiral exchange coupling – Dzyaloshinskii-Moriya interaction

Chiral exchange coupling mediated by **Spin-Orbit** interaction

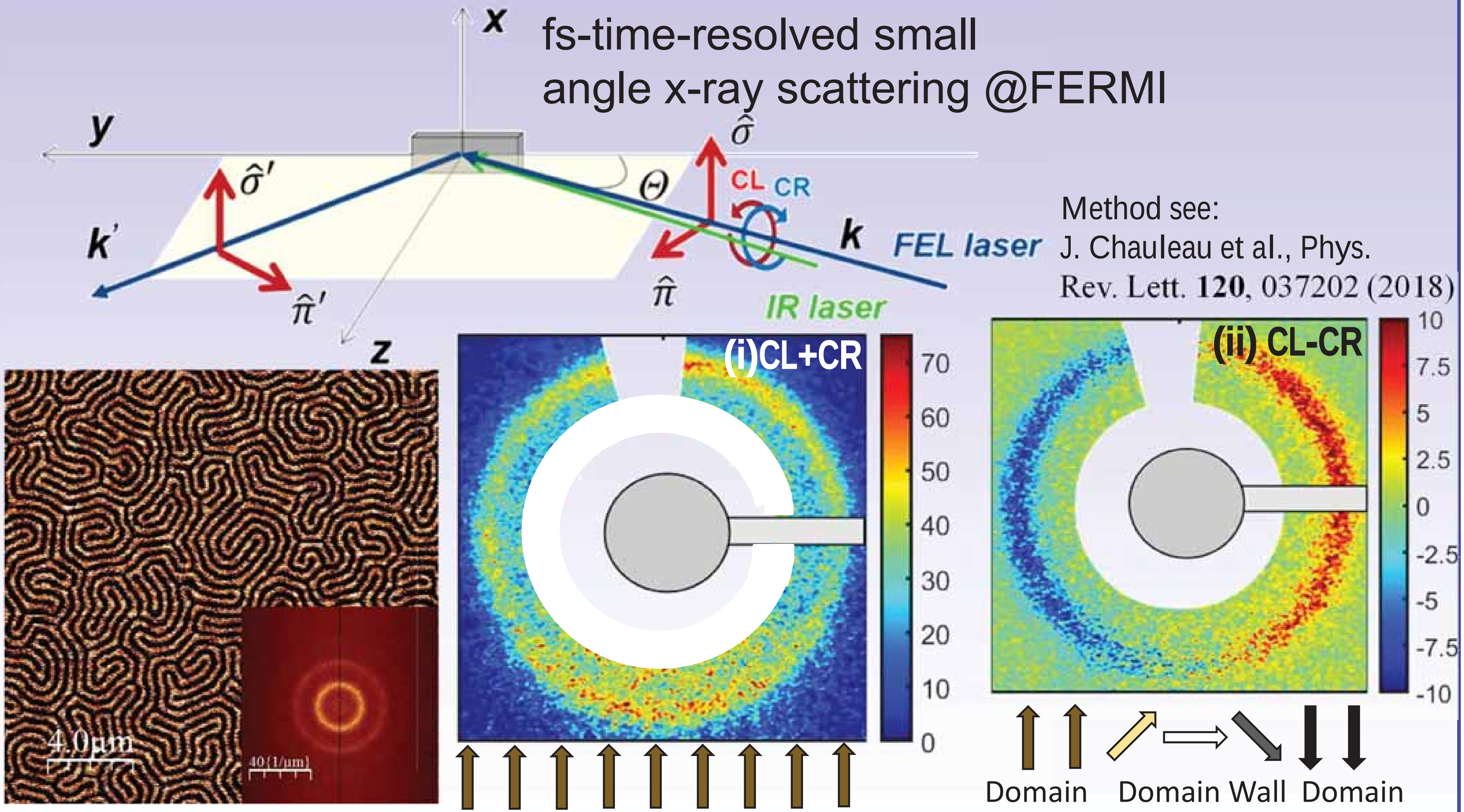


- Two spins in the ferromagnet are coupled via an atom with large SOI in a heavy metal layer → Dzyaloshinskii-Moriya interaction (DMI)
- Favours a spin canting with defined chirality → Chiral Domain Walls!

I. Dzyaloshinsky, J. Phys. Chem. Solids **4**, 241 (1958); T. Moriya, Phys. Rev. Lett. **4**, 228 (1960)

0. Chiral exchange coupling – ultra-fast spin-orbitronics

fs-time-resolved small
angle x-ray scattering @FERMI

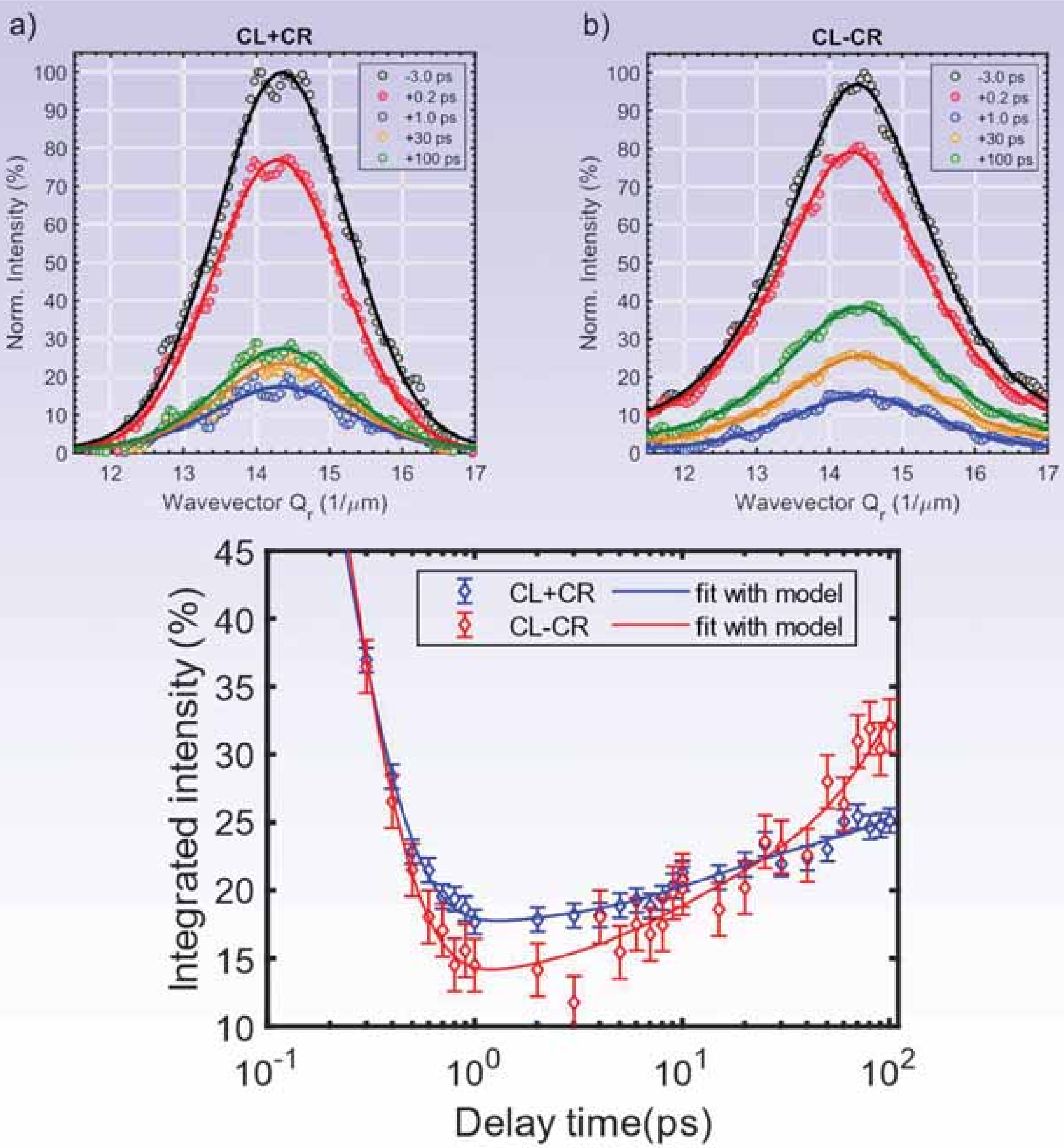


Method see:
J. Chauleau et al., Phys. Rev. Lett. **120**, 037202 (2018)

- Time evolution of (i) collinear order in domains and (ii) chiral order in DWs

N. Kerber, H. Zabel, Y. Mokrousov, C. Gutt, M. Kläui et al., Nature Commun. **11**, 6304 (2020)

0. Chiral exchange coupling – ultra-fast spin-orbitronics



- "Dechiralisation" of chiral domain walls: **same timescale** as "demagnetization" of the collinear domains.
- **Faster** recovery of **chiral** magnetic order than collinear magnetic order
- → Chiral magnetic order more robust
  → enhanced stability of chiral spin structures

N. Kerber, M. Kläui et al., Nature Comm. **11**, 6304 (2020); cf. C. Leveille et al., Nature Comm. **13**, 1412 (2022

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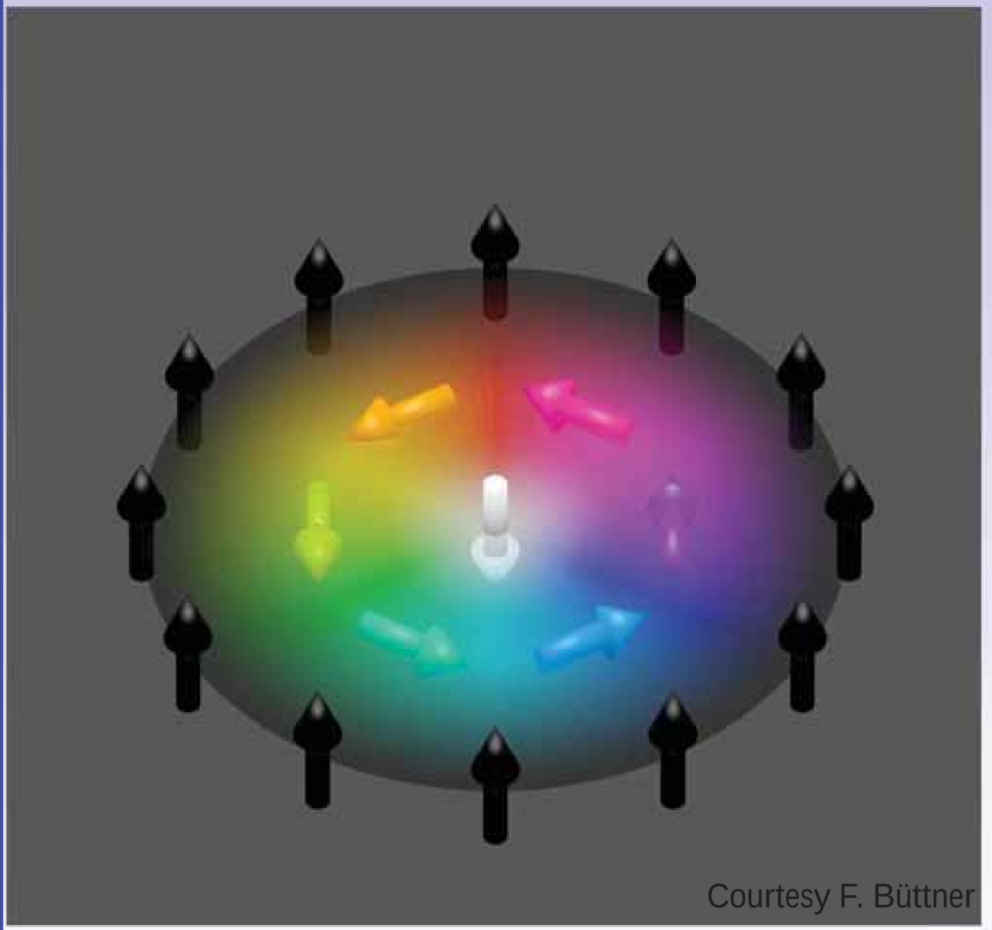
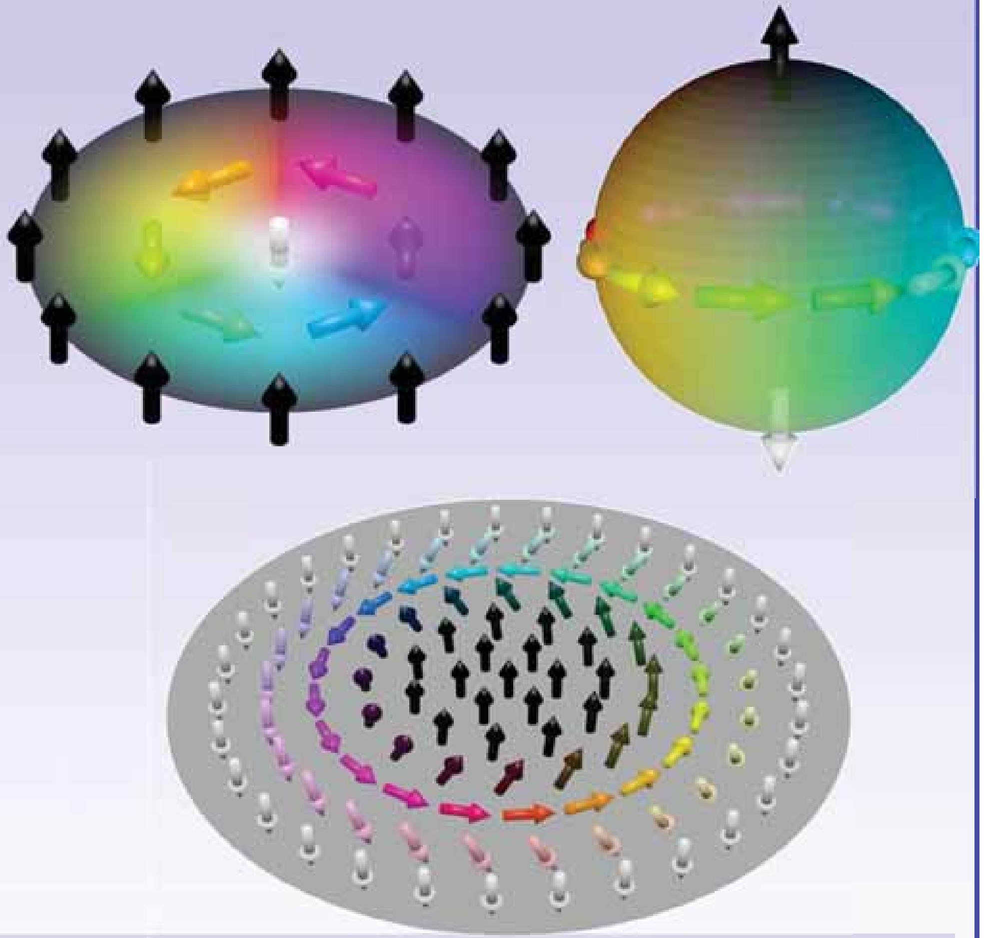
1. Topological Skyrmion Spin Structures in high-anisotropy materials

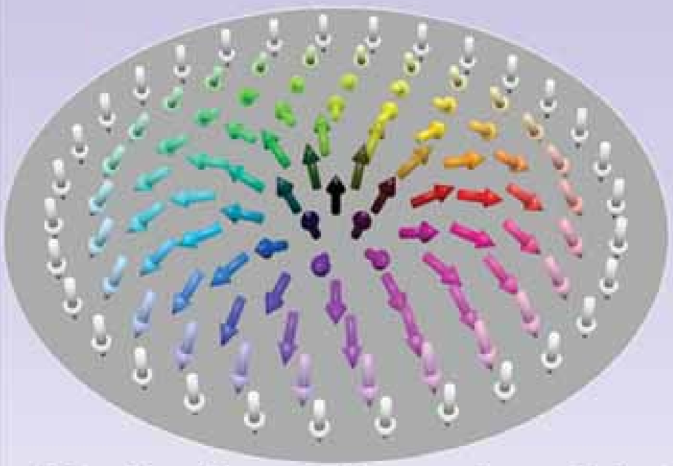


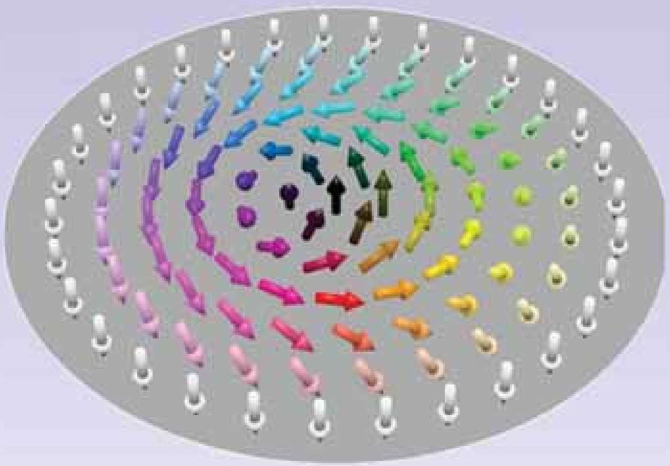


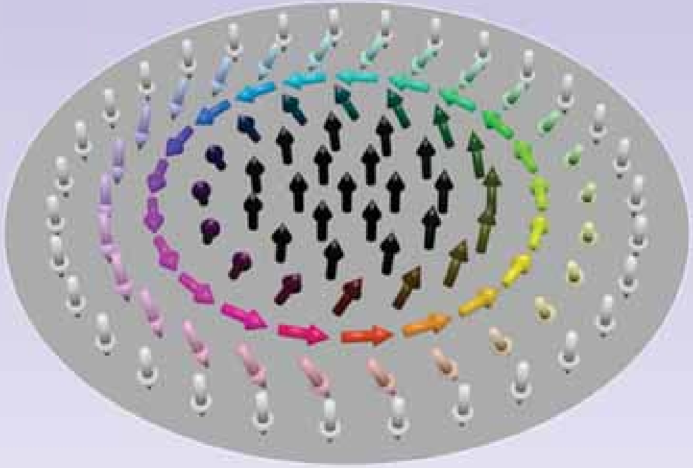
- Skyrmions are vector fields that can be continuously deformed into a sphere.
- For appropriately designed DMI, exchange, anisotropy, saturation magnetization, skyrmion spin structures can be stabilized as metastable states or ground states.

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); A. Nayak et al., Nature **561**, 548 (2017); 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)

1. Spin Structures stabilized by the chiral DMI


Hedgehog skyrmion (N=1)


Chiral skyrmion (N=1)

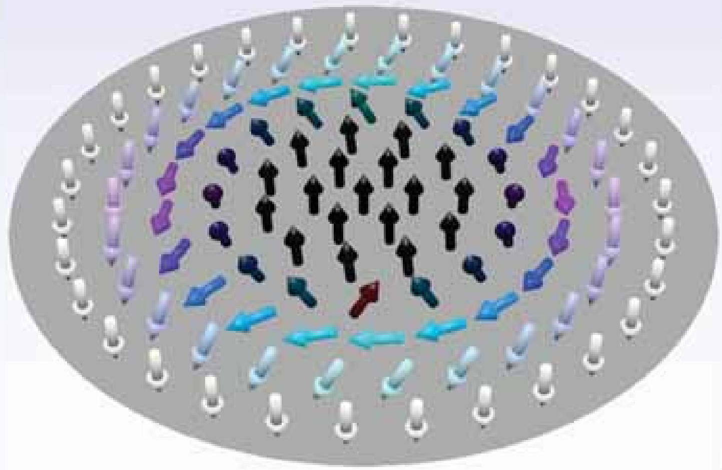

Bubble skyrmion (N=1)

- 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 Skyrmion (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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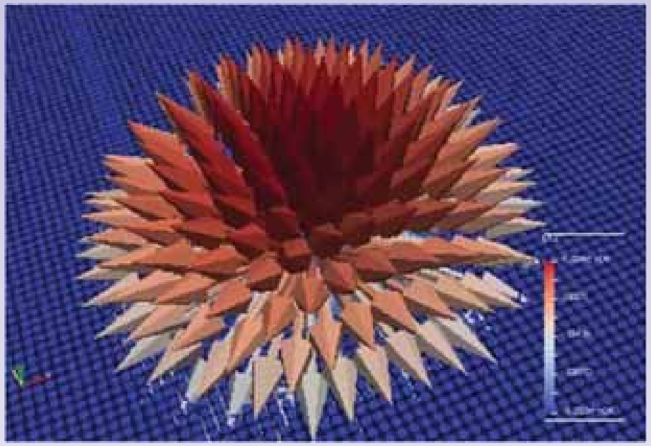
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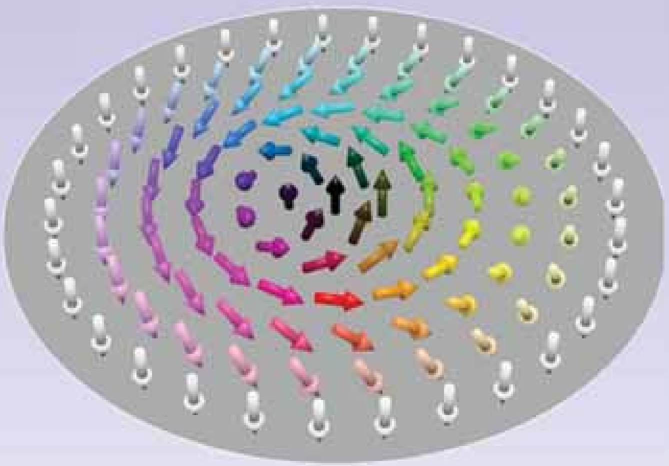
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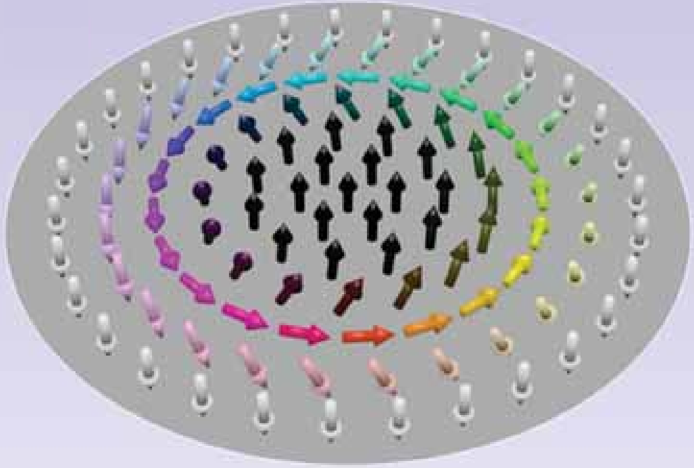
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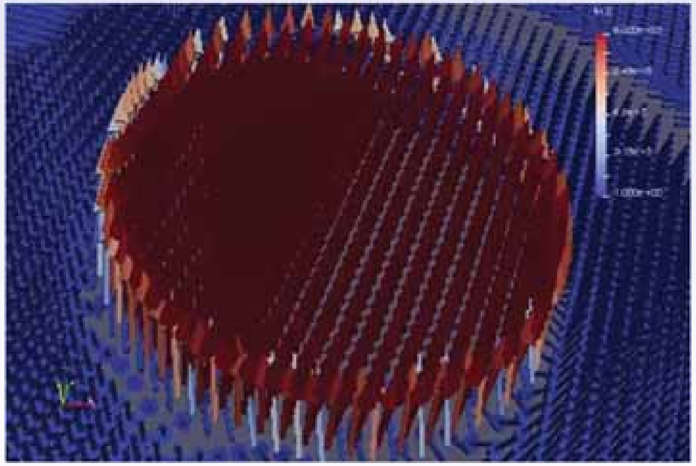
- Skyrmion with N=0 (topology of uni-form state) is less stable than N=1.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[1]N. Papanicolaou et al., Nuclear Physics B 360, 425–462 (1991)
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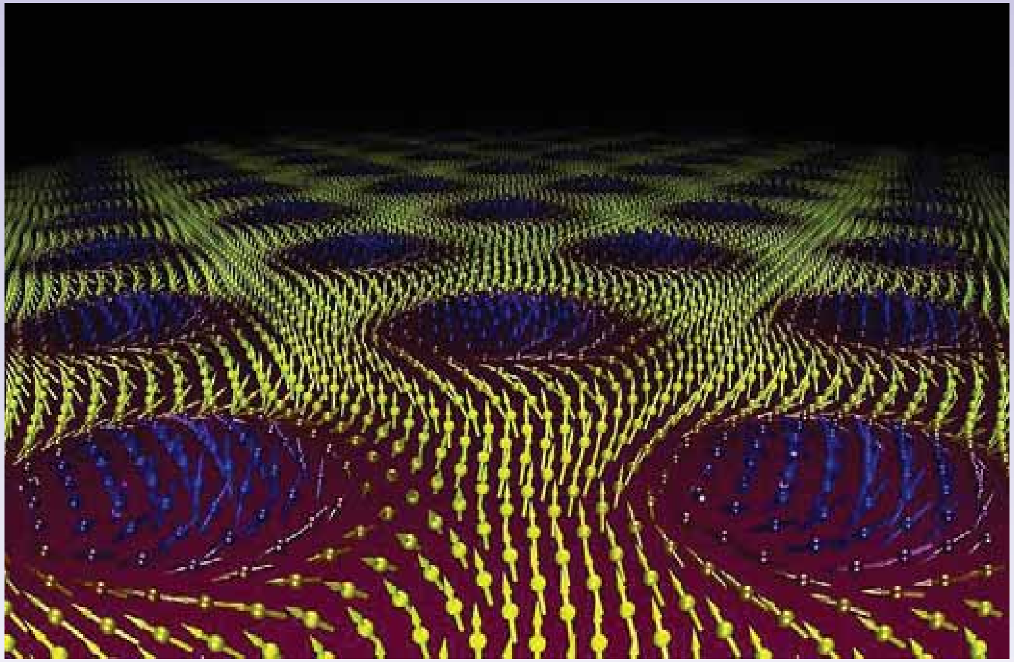
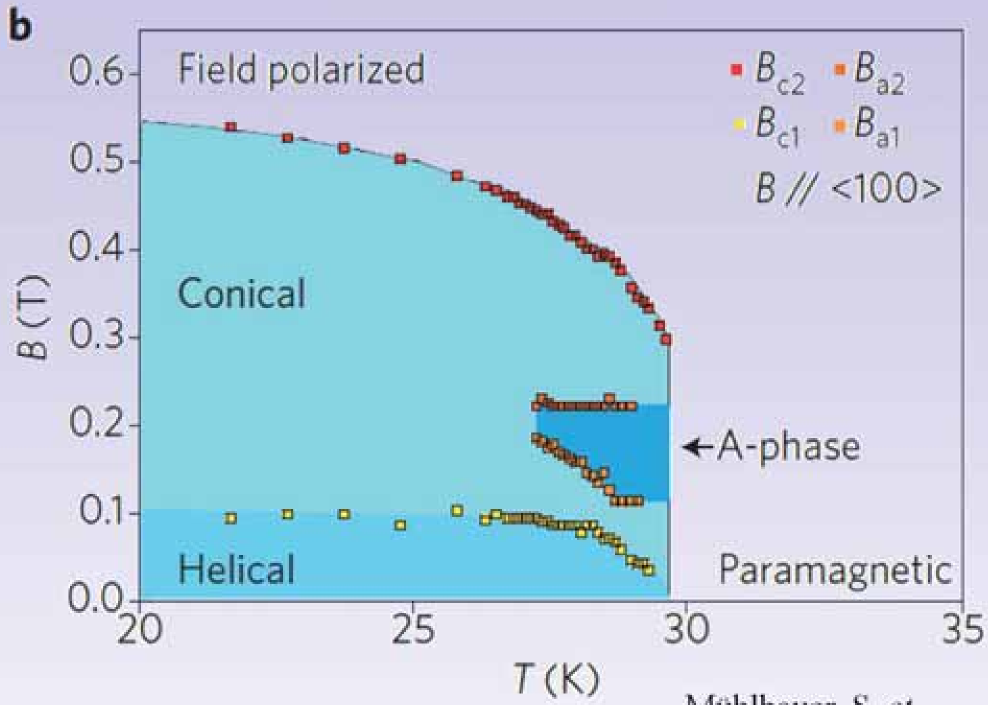
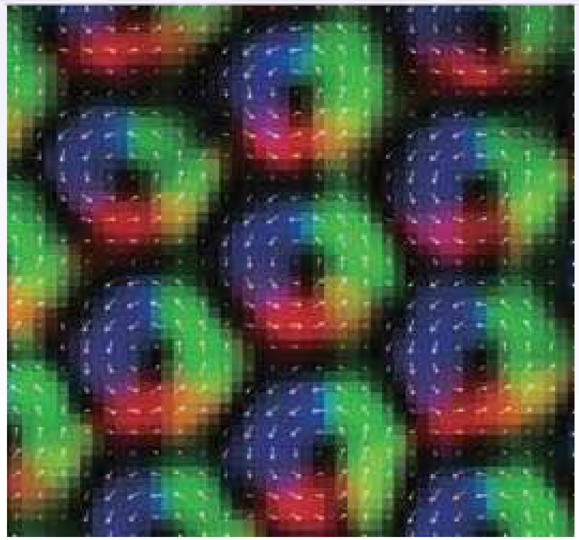
1. Experimental observation of Skyrmions in bulk systems





Mühlbauer, S. *et al.* Science **323**, 915–919 (2009).

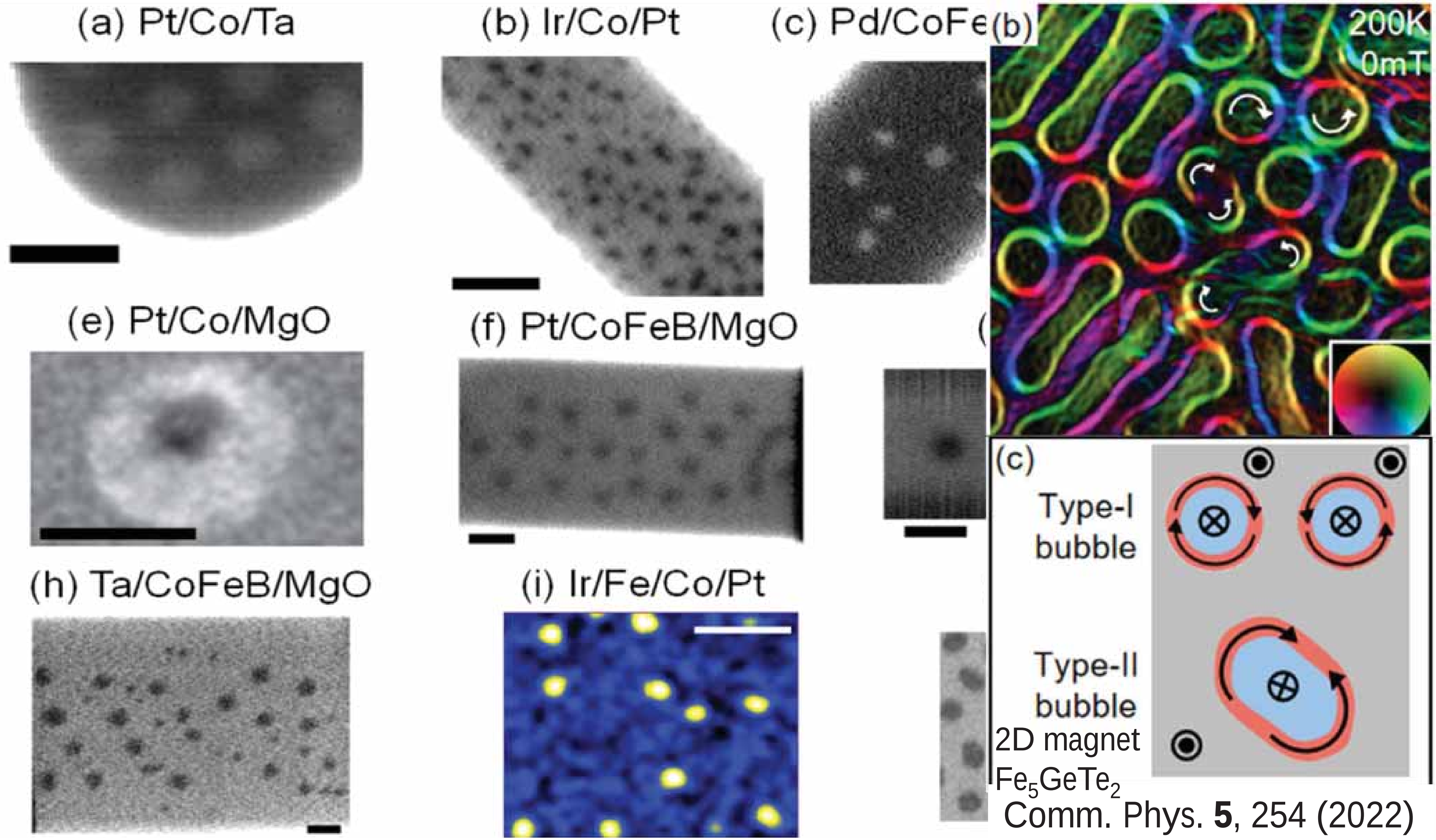


Yu, X. Z. *et al.* *Nature* **465**, 901 (2010).

- Skyrmions form in systems with inversion asymmetry a lattice (skyrmion-phase).
- So far observed at low temperatures in a small field and temperature range!
- Skyrmion – stability and size depends on DMI, M_s, anisotropy and exchange.

N. Papanicolaou et al., Nuclear Physics B 360, 425–462 (1991);

1. Experimental observation of skyrmions in multilayers

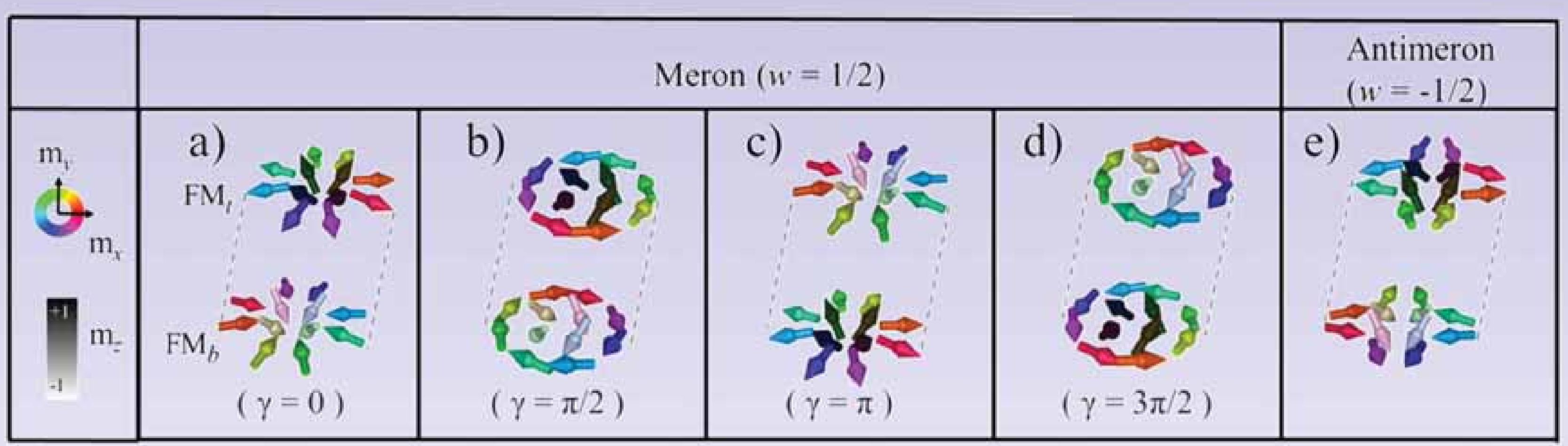


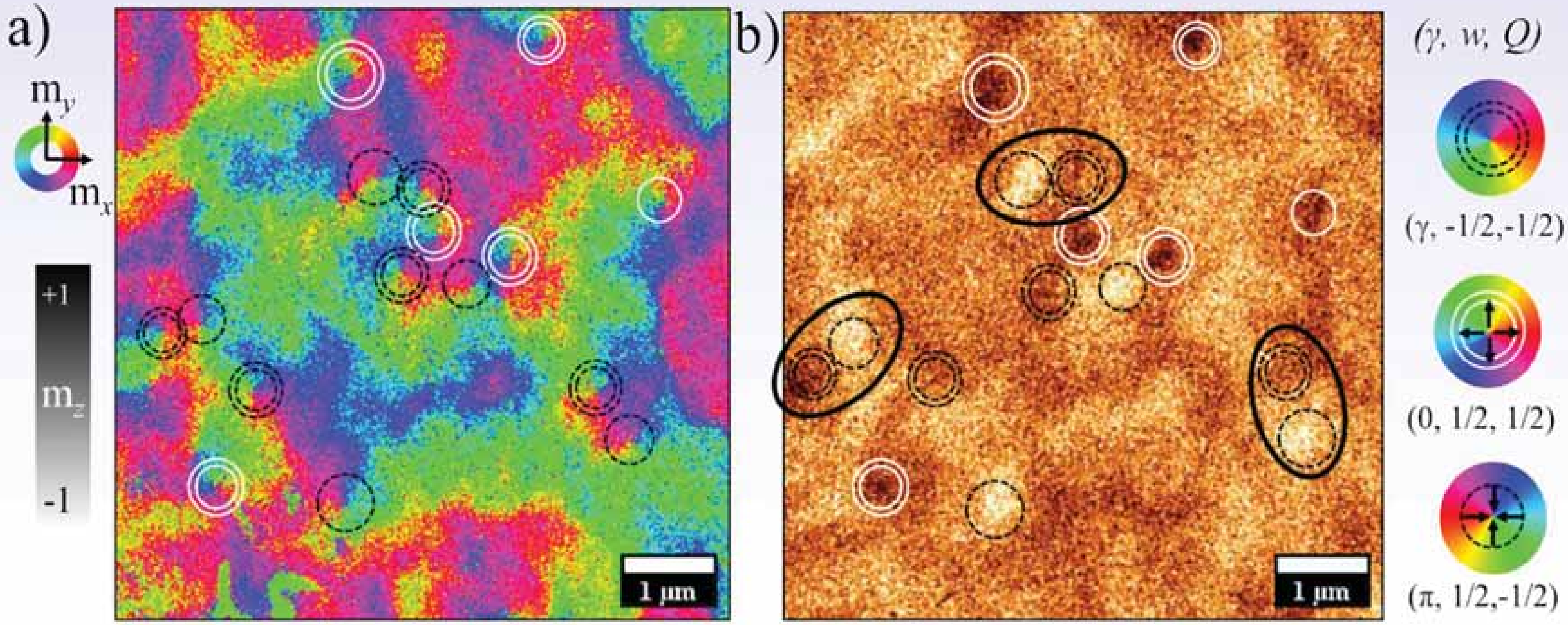
2D magnet Fe_5GeTe_2
Comm. Phys. **5**, 254 (2022)

K. Everschor-Sitte, JAP **124**, 240901 (2018); G. Finocchio et al., J.PhysD: Appl. Phys. **49**, 423001 (2016)
Nature Mater. **15**, 501 (2016); Science **349**, 283 (2015); Nat. Nano. **11**, 444; Nat. Nano. **11**, 449 (2016)

2. Bimerons in synthetic antiferromagnets

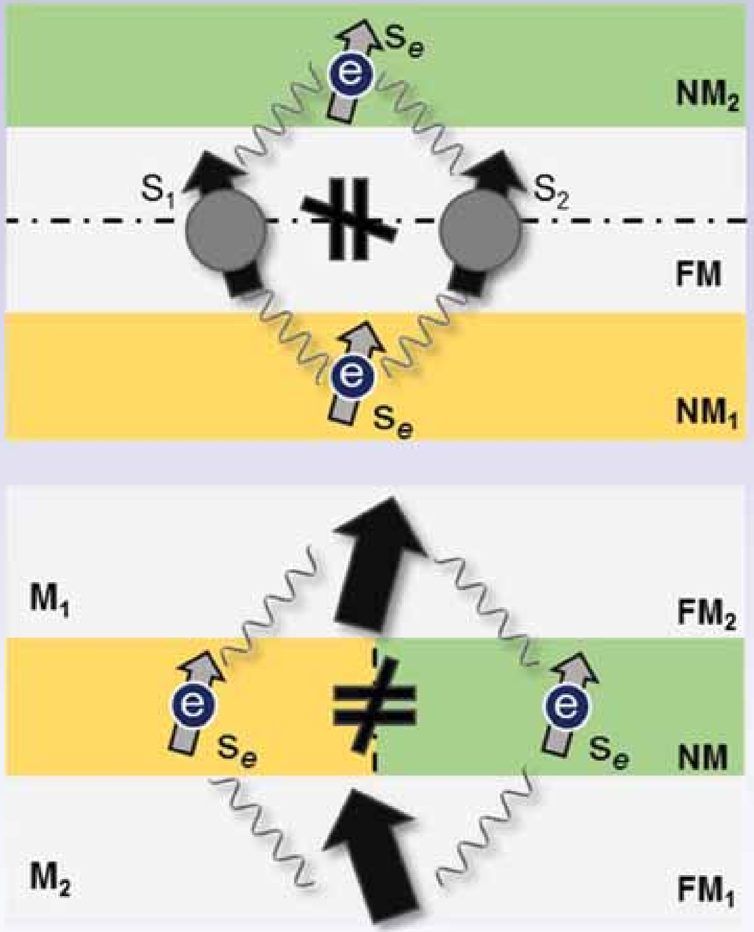
- In multi-layers: Different merons can be stabilized
- Obser-vation using combine: SEMPA + MFM[1]

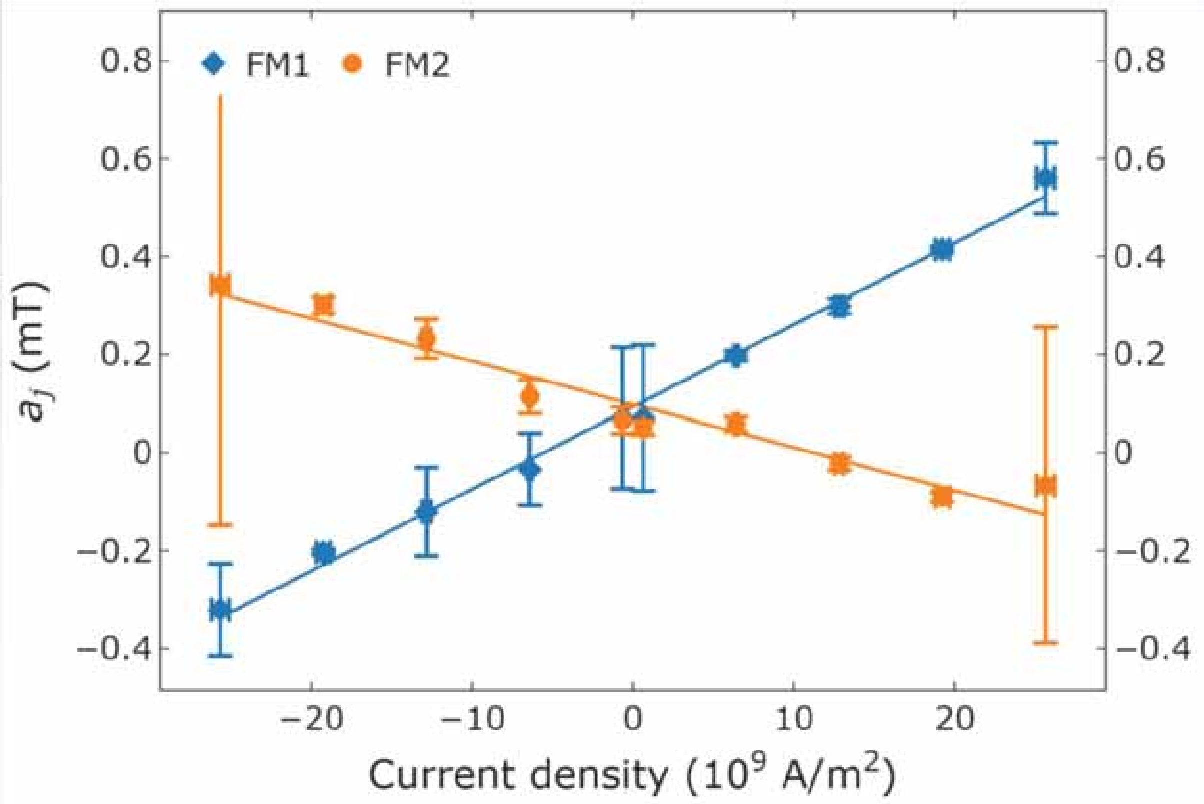




[1] M. Bhukta, MK et al., arxiv:2303:14853 (Nature Commun. in press 2024)

2. Chiral **interlayer** exchange coupling

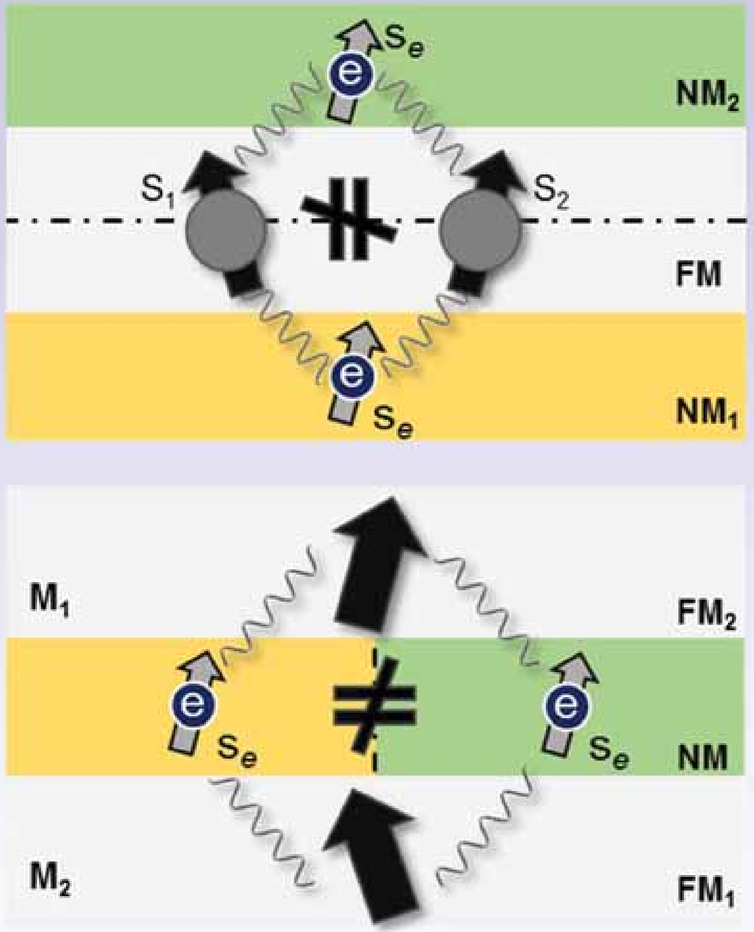


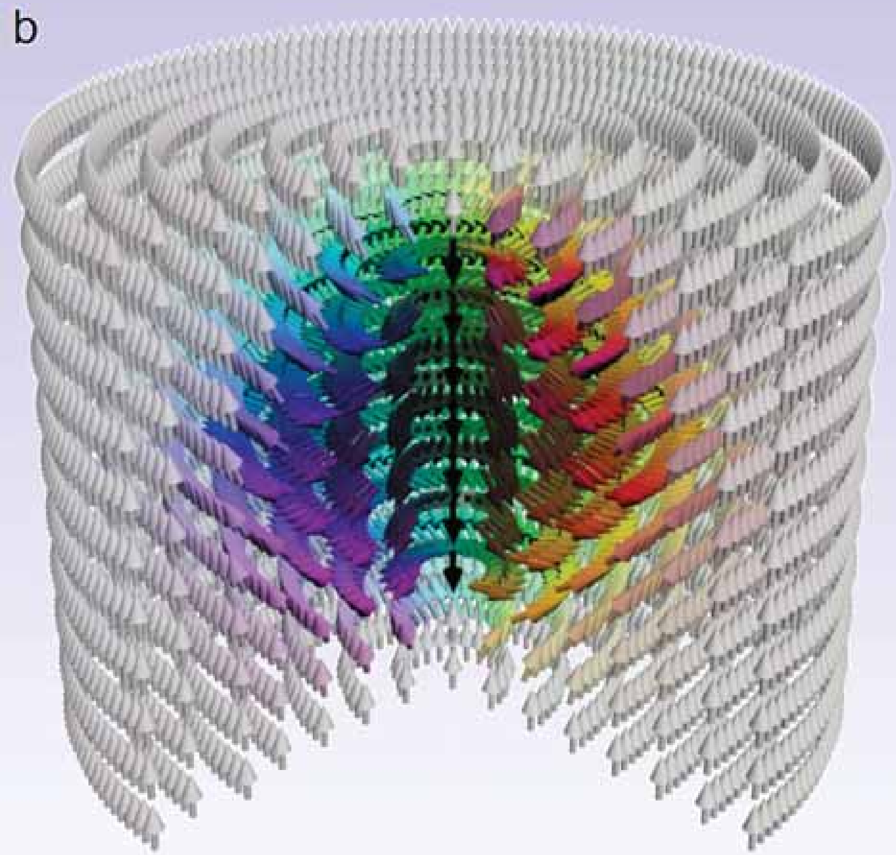


- Two spins in 2 magnetic layers are coupled by interlayer RKKY
- Chiral antisymmetric interlayer exchange coupling → RKKY-DMI[1]
- Strength of RKKY-DMI can be tuned by currents on-the-fly![2]

[1]D. Han, MK et al., Nat. Mat. **18**, 703 (2019); [2]F. Kammerbauer, MK et al., Nano Lett. **23**, 7070 (2023)

2. Chiral **interlayer** exchange coupling – 3D skyrmion structures



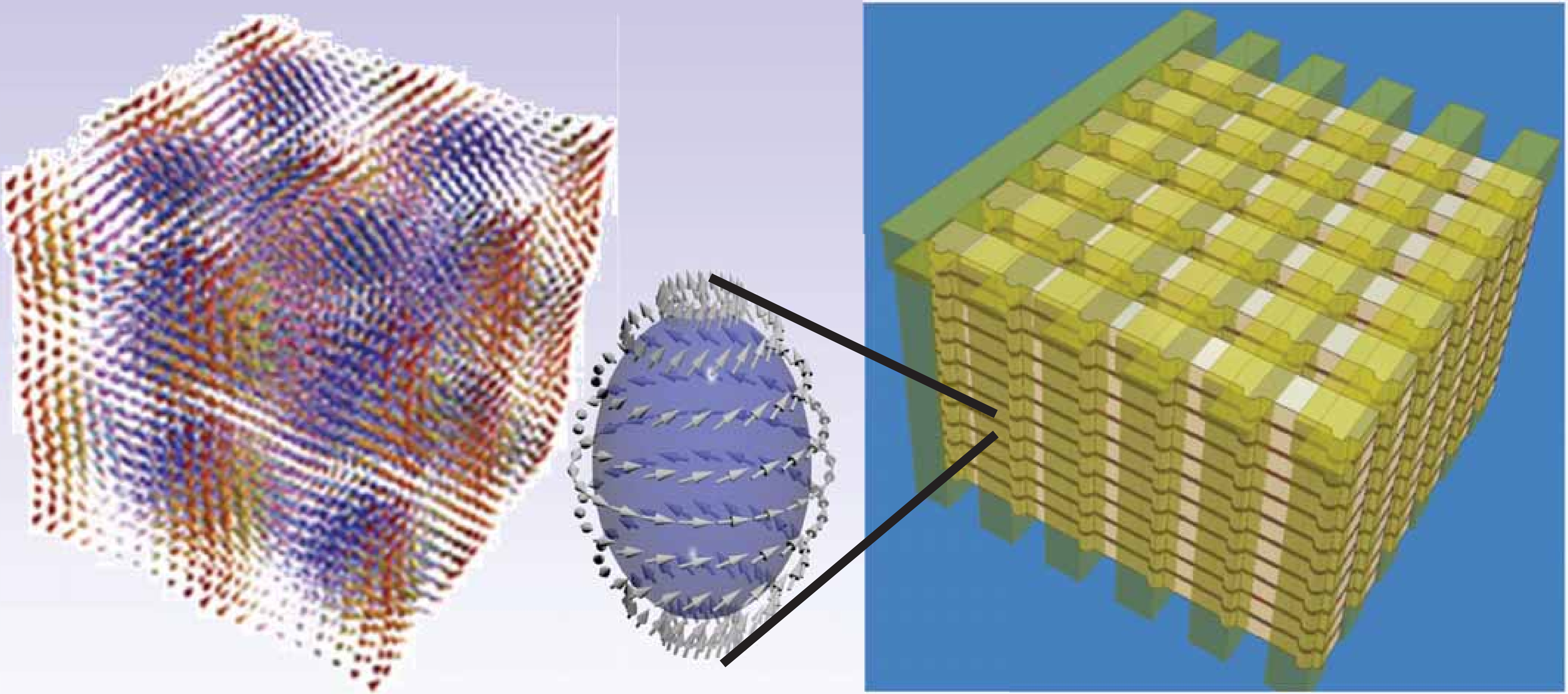


Courtesy N. Kiselev

- Two spins in 2 magnetic layers are coupled by interlayer RKKY
- Recently we found a chiral antisymmetric interlayer exchange coupling: → RKKY-DMI[1] stabilizes three-dimensional spin structures!

[1]D. Han, MK et al., Nat. Mat. **18**, 703 (2019); see also A. Fernandez-Pacheco et al., Nat. Mat. **18**, 679 (2019)

2. 3D skyrmion structures – interconnectivity in 3D space



[1]T. Tanigaki et al., Nano Lett. 15, 5438 (2015)

Courtesy R. Cowburn

- Claimed observation of a 3D lattice of 3D skyrmions[1]
- Possible 3D interconnects→move 3D particles in all directions in space
  → realize (potentially) the huge interconnectivity of neurons in 3D![2]

[2]D. Han, MK et al., Nature Mater. **18**, 703 (2019); Computing: X. Zhang, MK et al., Sci. Adv. **9**, ade7439 (2023

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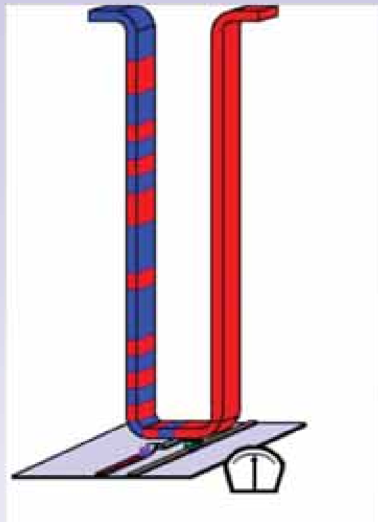

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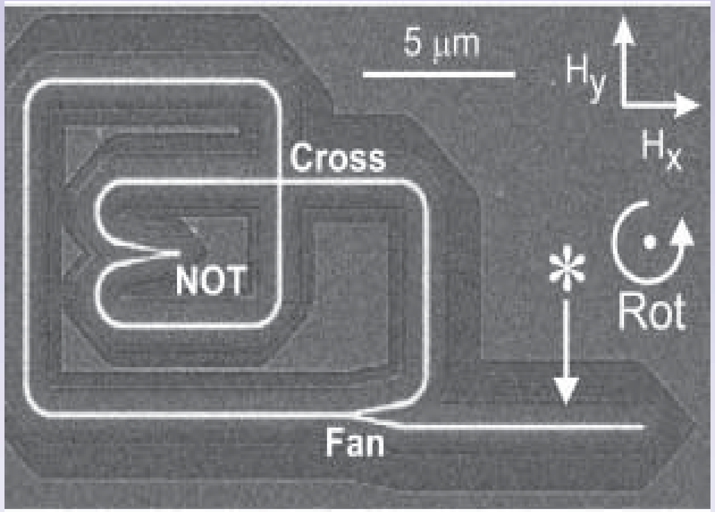
Magnetic Logic



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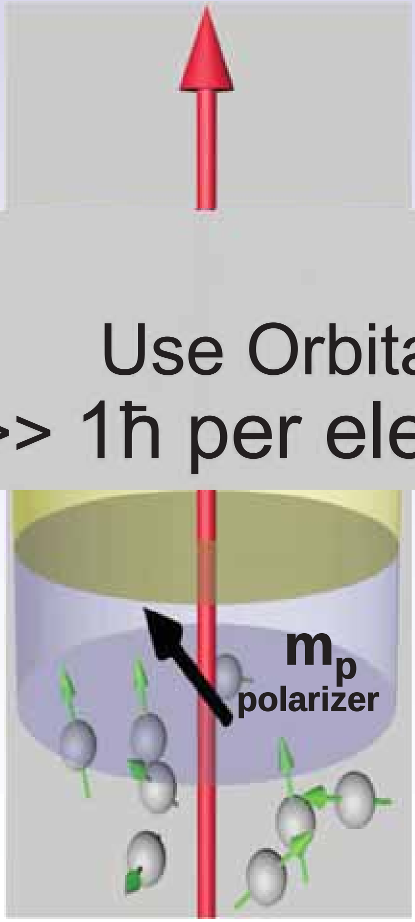
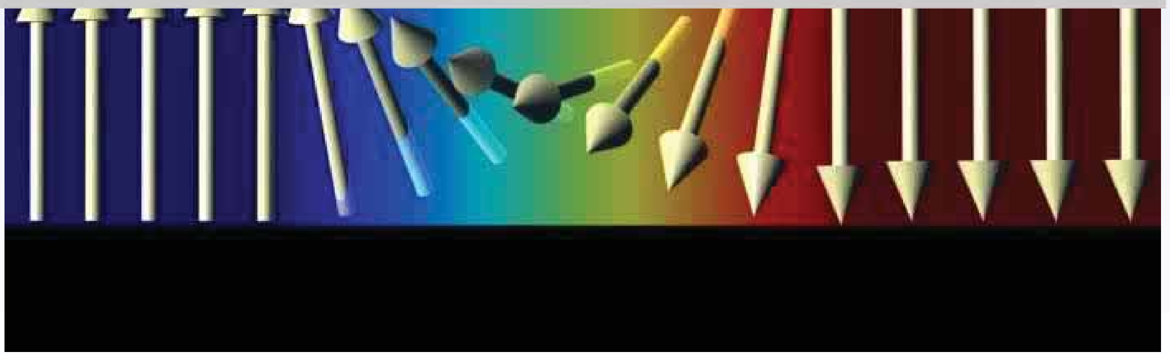
3. Challenge Efficient Manipulation - Spin Transfer Torques (STT)

Conventional STT: Transfer electron **Spin** ($\frac{\hbar}{2}$) 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



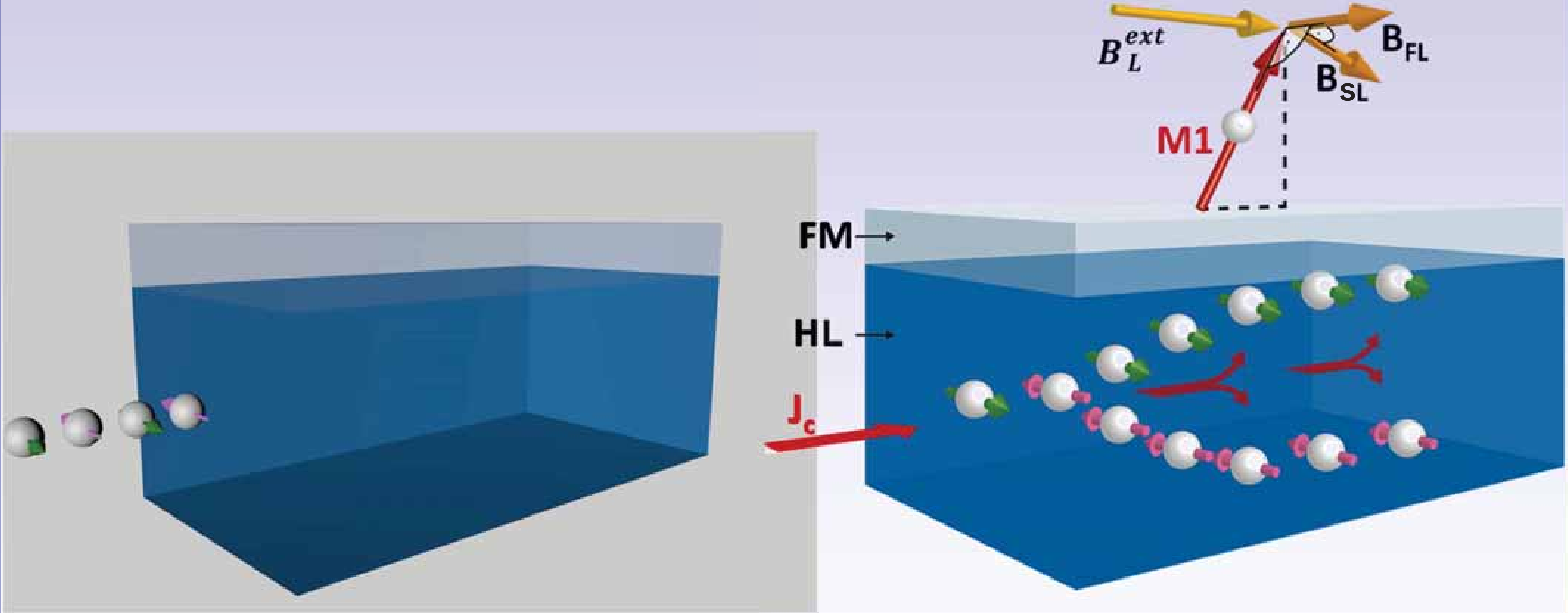
Side view of a wire with a Bloch wall

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

3. Spin – orbit torques in multilayers - Theory

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

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



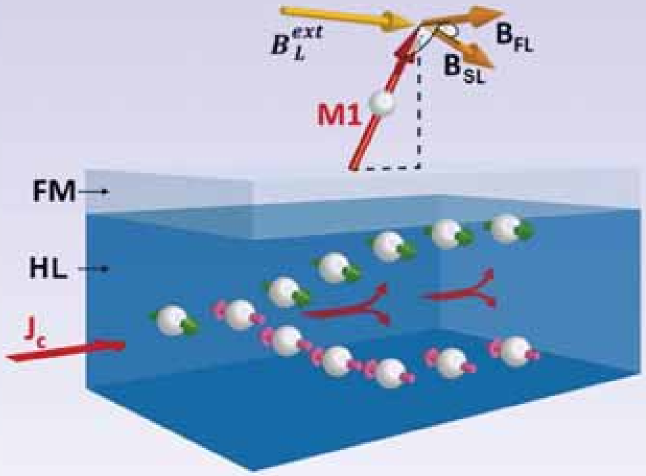
- In a heavy metal (HL=Ta, W, etc.): charge current generates spin current → spin accumulation diffuses into the ferromagnet → measured by THz[1]
- These spins exert new damping-like and field-like **spin orbit torques**[2]

[1]T. Seifert et al., Nat. Phot. **10**, 483 (2016); [2]A. Brataas et al., Nat. Nano **9**, 86 (‘14); A. Manchon et al., RMP 91, 035004 (‘19)

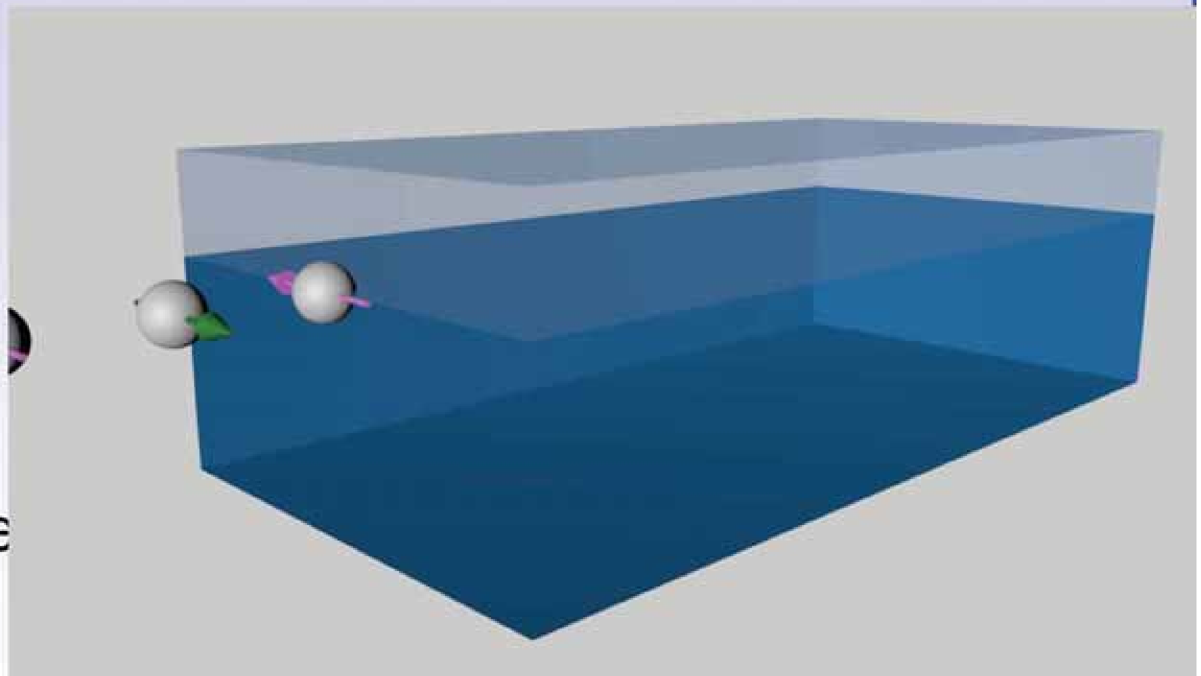
3. Spin – orbit torques in multilayers - Theory

Spin-orbit Torque Origins:

- Origin 1:
  Spin Hall Effect (bulk property)



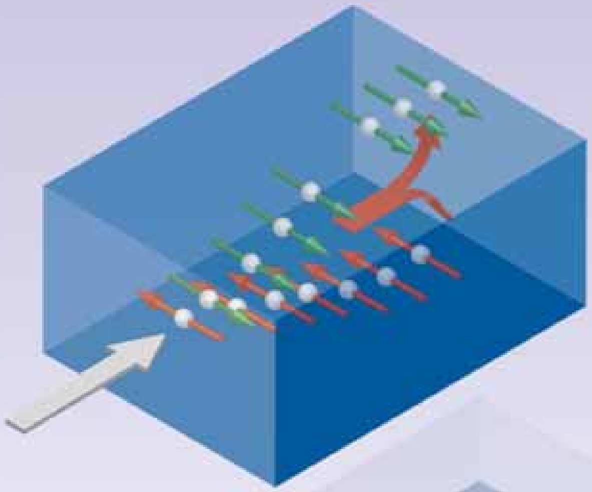
- Origin 2:
  Inverse Spin Galvanic Effe
  (interface property)



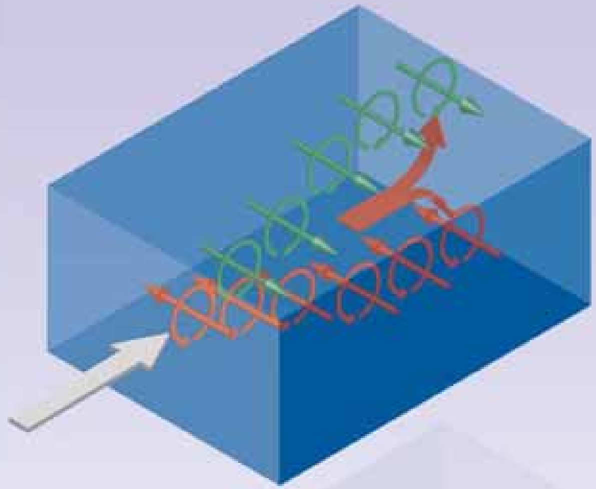
- Additionally the Inverse Spin Galvanic Effect generates a non-equilibrium spin density for electrons flowing at the interface.[1]
- → interaction by exchange manipulates magnetization → SOT!

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

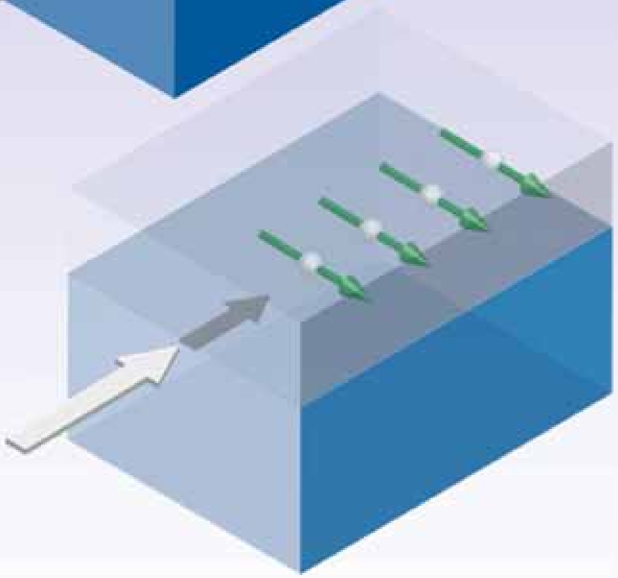
3. Spin-, Orbit- and Spin-Orbit Torques



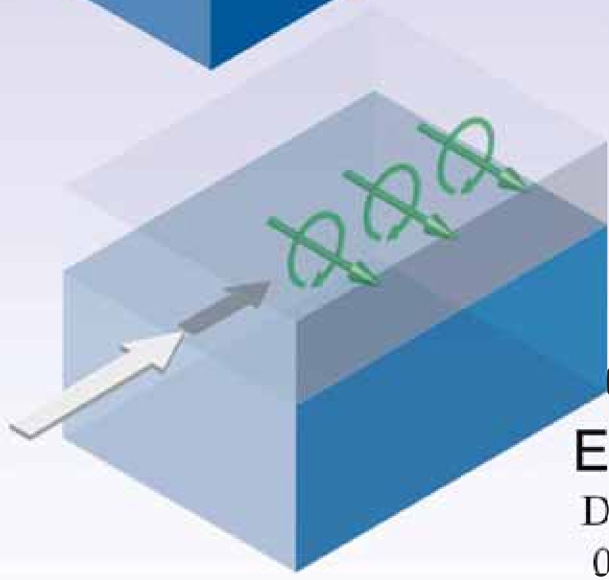
Spin Hall Effect
Rev. Mod. Phys. **87**, 1213 (2015)



Orbital Hall Effect
H. Kontani et al., PRL **102**, 016601 (2009)



Inverse Spin Galvanic Effect / Rashba Edelstein Effect
PRL **112**, 096601 (2014)

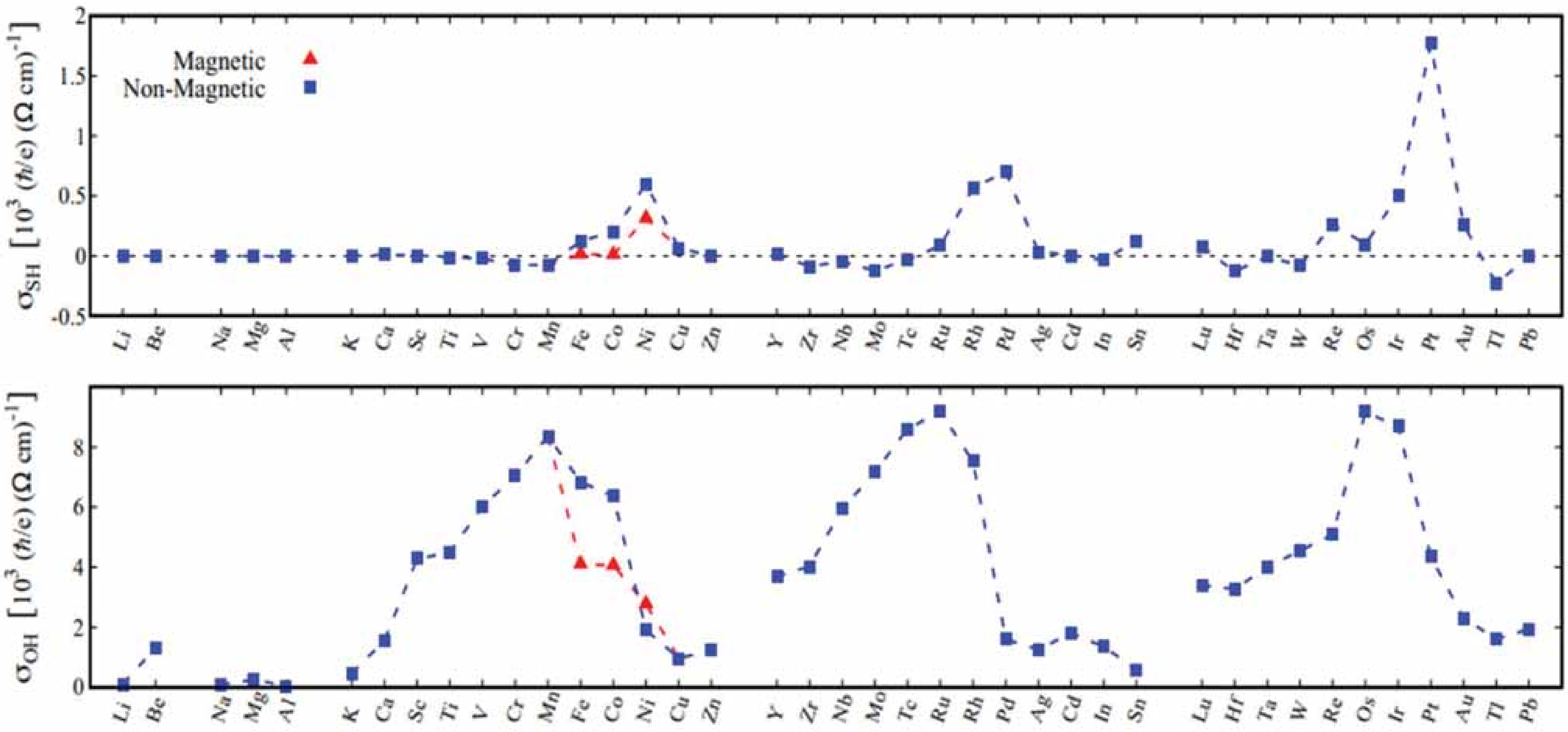


Orbital Rashba Edelstein Effect
D. Go et al., PRL **121**, 086602 (2018)

- Dynamics induced by spin-orbit torques due to SHE **(a)** and ISGE/REE **(b)**,
- Additionally orbital angular momentum: Orbital Hall Effect (OHE) **(c)** [1] & Orbital Rashba Edelstein Effect (OREE) **(d)** [2].

[1] S. Ding, MK et al., Phys. Rev. Lett. **125**, 177201 (2020): [2] S. Ding, MK et al., Phys. Rev. Lett. **128**, 067201 (2022)

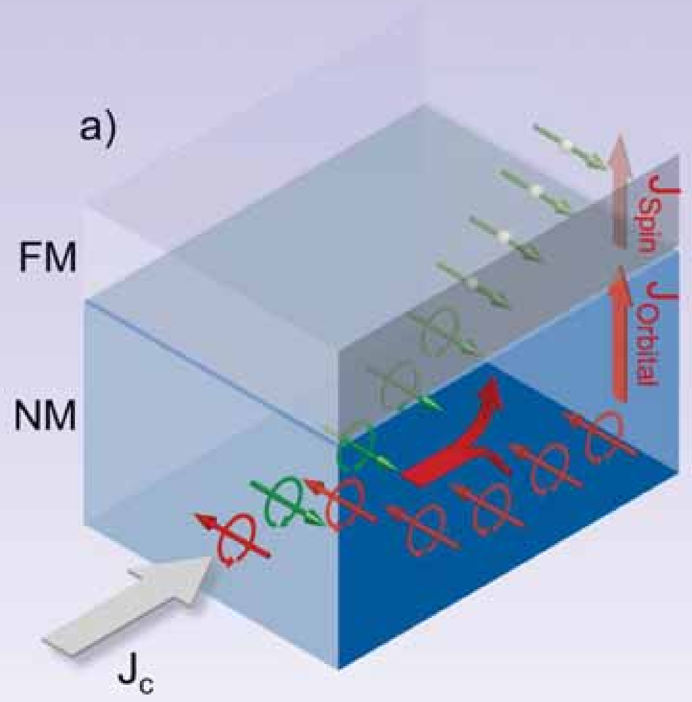
3. Spin-, Orbit- and Spin-Orbit Torques



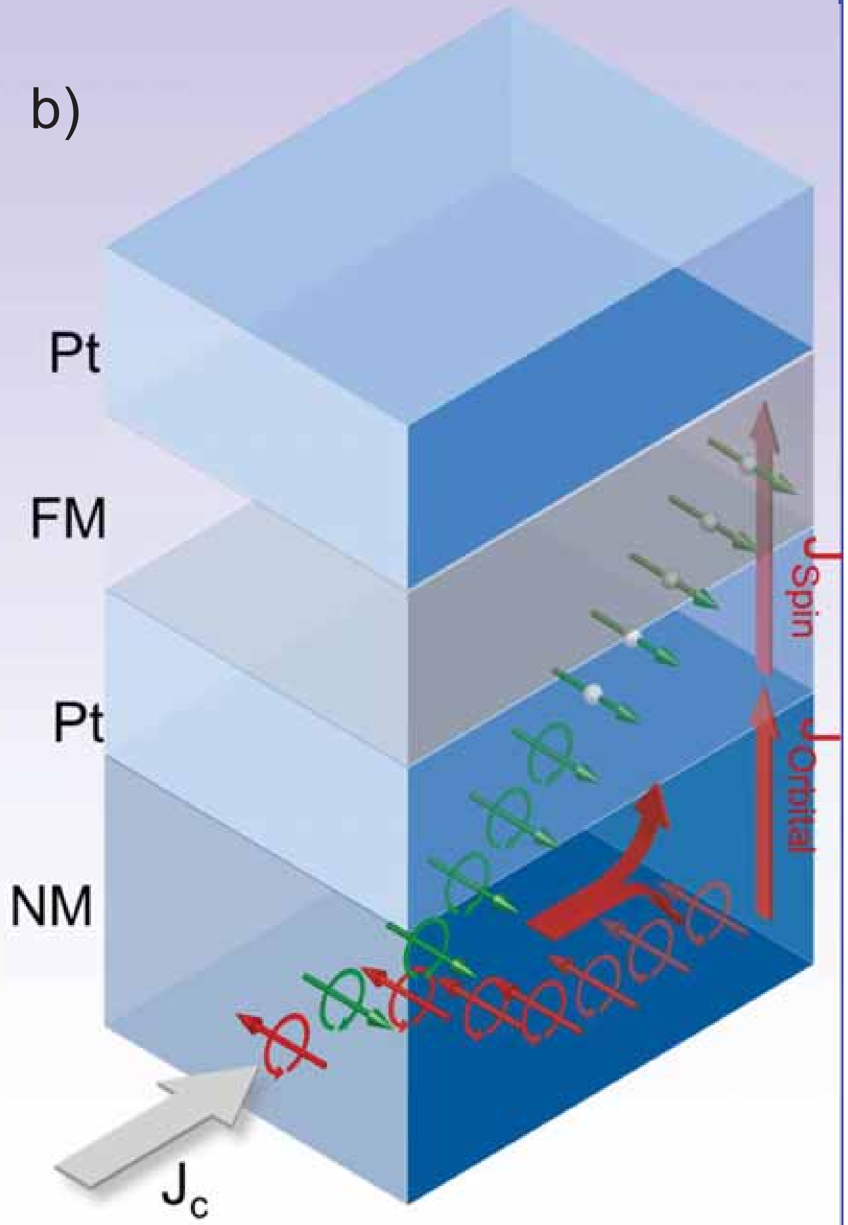
- Prediction of orbital currents orders of magnitude larger than spin currents[1]
  → potentially orders of magnitude larger torques (also for CuOx)!
- Also possibly larger Orbital Rashba Edelstein Effects[2]

[1]D. Jo et al. PRB **98**, 214405 (2018); T. Tanaka et al. PRB **77**, 165117 (2008); L. Salemi et al., Phys. Rev. B **106**, 024410 (2022); [2]J. Kim et al. Phys. Rev. B **103**, L020407 (2021); S. Park et al. Phys. Rev. Lett. **107**, 156803 (2011).

3. Orbital Currents and Orbital Torques

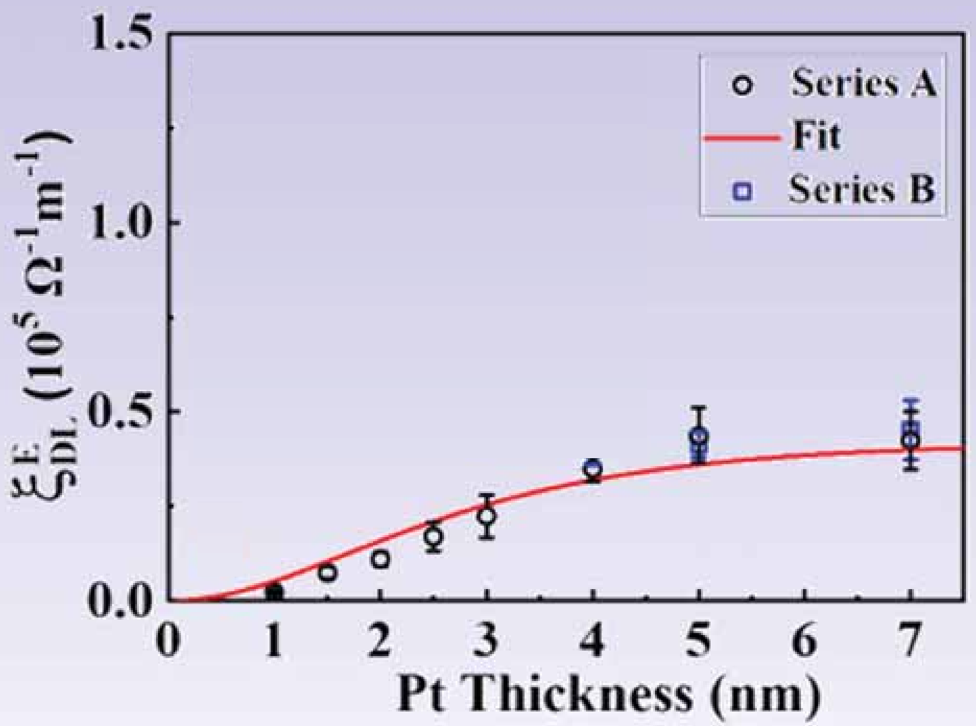


- Interaction of orbital currents with magn.:
  (i) Generation of spin and orbital currents in a non-magnetic layer
  (ii) Conversion of an orbital current into a spin current in the ferromagnet (a)
  (iii) Conversion of an orbital current into a spin current in a heavy metal (b)



H. An et al., Nat. Com. **7**, 13069 (‘16); S. Ding, MK et al., PRL **125**, 177201 (‘20); G. Sala et al., PRR **4**, 033037 (‘22)

3. Orbital Currents and Orbital Torques



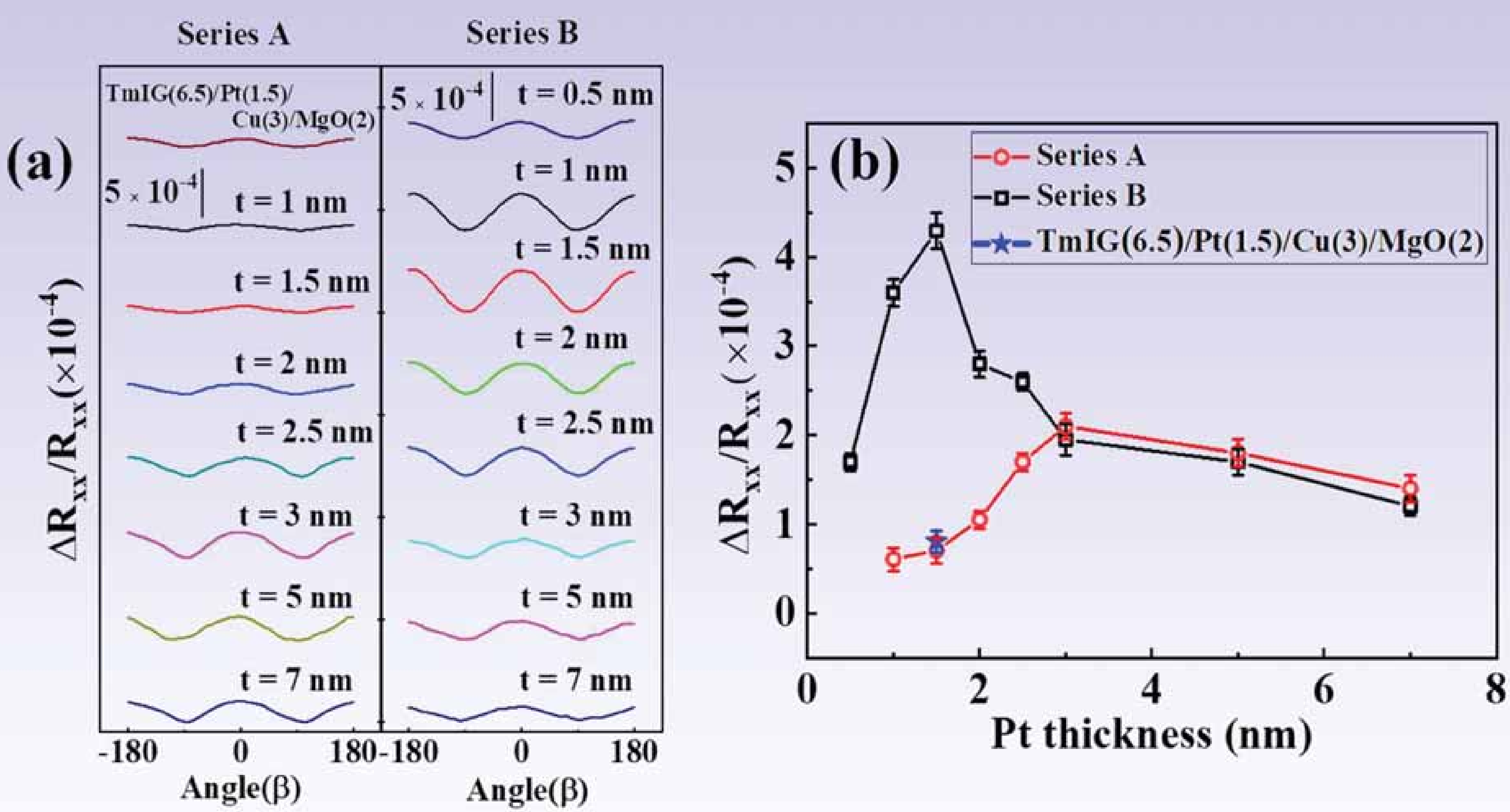
Series A: TmIG（6.5）/ Pt（t_{Pt}）
Series B: TmIG（6.5）/ Pt（t_{Pt}）/ CuO_x

- $\xi^E_{DL} = \xi^E_{DL-SHE} + \xi^E_{DL-OREE}$

- Conventional TmIG/Pt: SOTs due to SHE
- In TmIG/Pt/CuOx: 1. Orbital Rashba Edelstein Effect generates orbital current at CuOx interface; 2. Conversion of orbital current to spin current by spin-orbit coupling in Pt; 3. Spin current generates SOT on magnetization.
- Torques are 16x larger with CuOx than without → massive improvement!

S. Ding, MK et al., Phys. Rev. Lett. **125**, 177201 (2020); S. Ding, MK et al., Phys. Rev. Lett. **128**, 067201 (2022

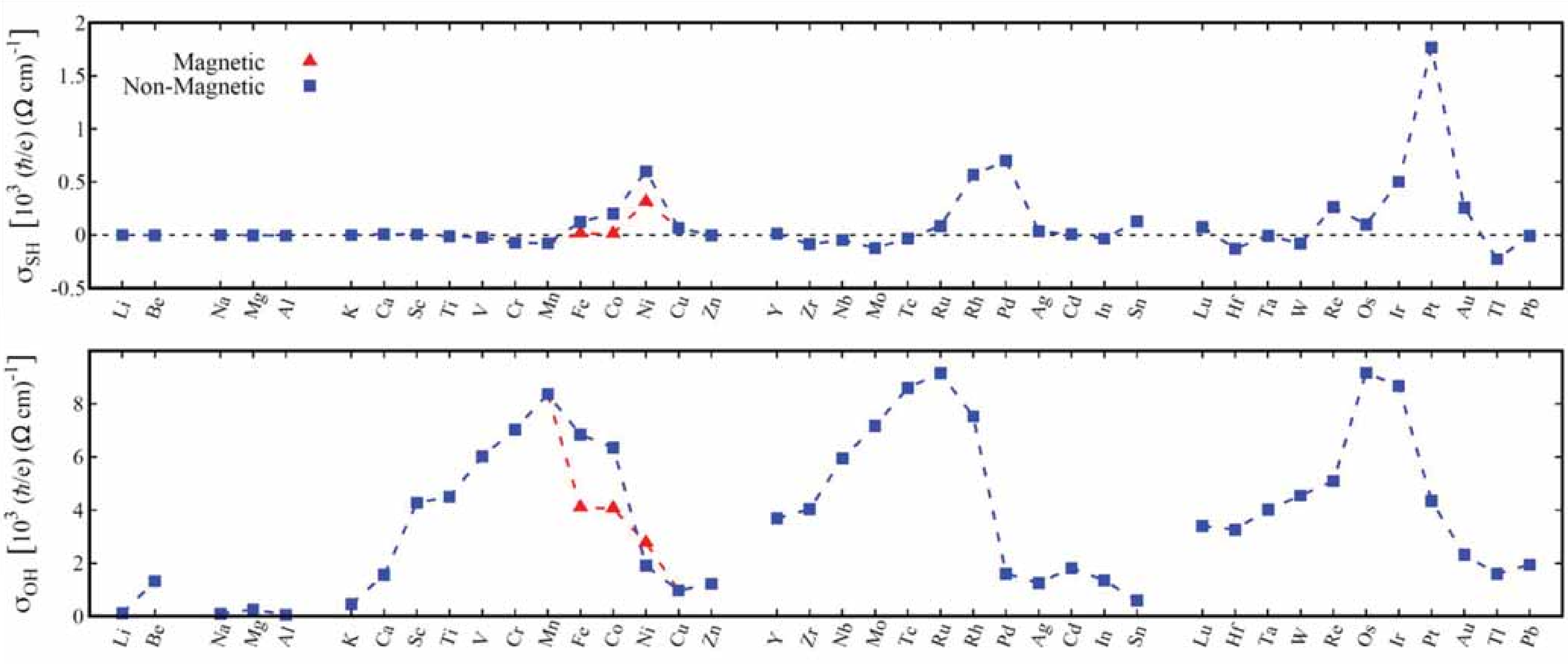
3. Magnetoresistance effects in TmIG-CuOx



- Spin Hall Magnetoresistance – type measurements show similar thickness dependence as the torques in series B: increase & decrease with Pt thickness indicating orbital current contribution to magnetoresistance signal.[1]

[1]S. Ding, D. Go, Y. Mokrousov, MK et al., Phys. Rev. Lett. **125**, 177201 (2020)

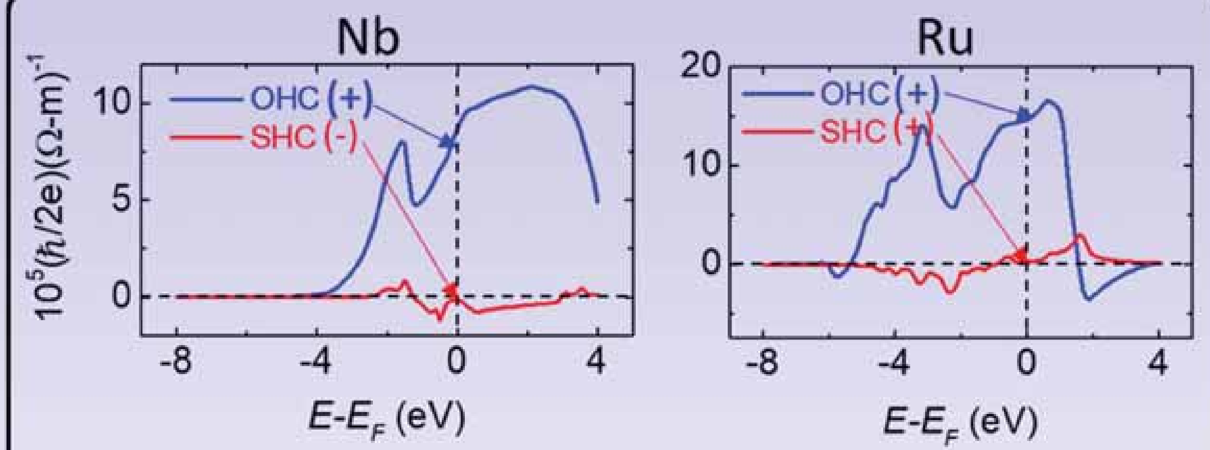
3. Orbital currents and orbital torques from Nb and Ru



- In particular for Nb and Ru large orbital hall and negligible spin Hall conductivity have been calculated.[1-4]

[1]H. Kontani et al., PRL **102**, 016601 (2009); [2]L. Salemi et al., PRB **106**, 024410 (2022); [3]L. Salemi et al., Phys. Rev. Mater. **6**, 095001 (2022); [4]A. Bose, D. Go, Y. Mokrousov, MK et al., Phys. Rev. B **107**, 134423 (2023)

3. Orbital currents and orbital torques from Nb and Ru



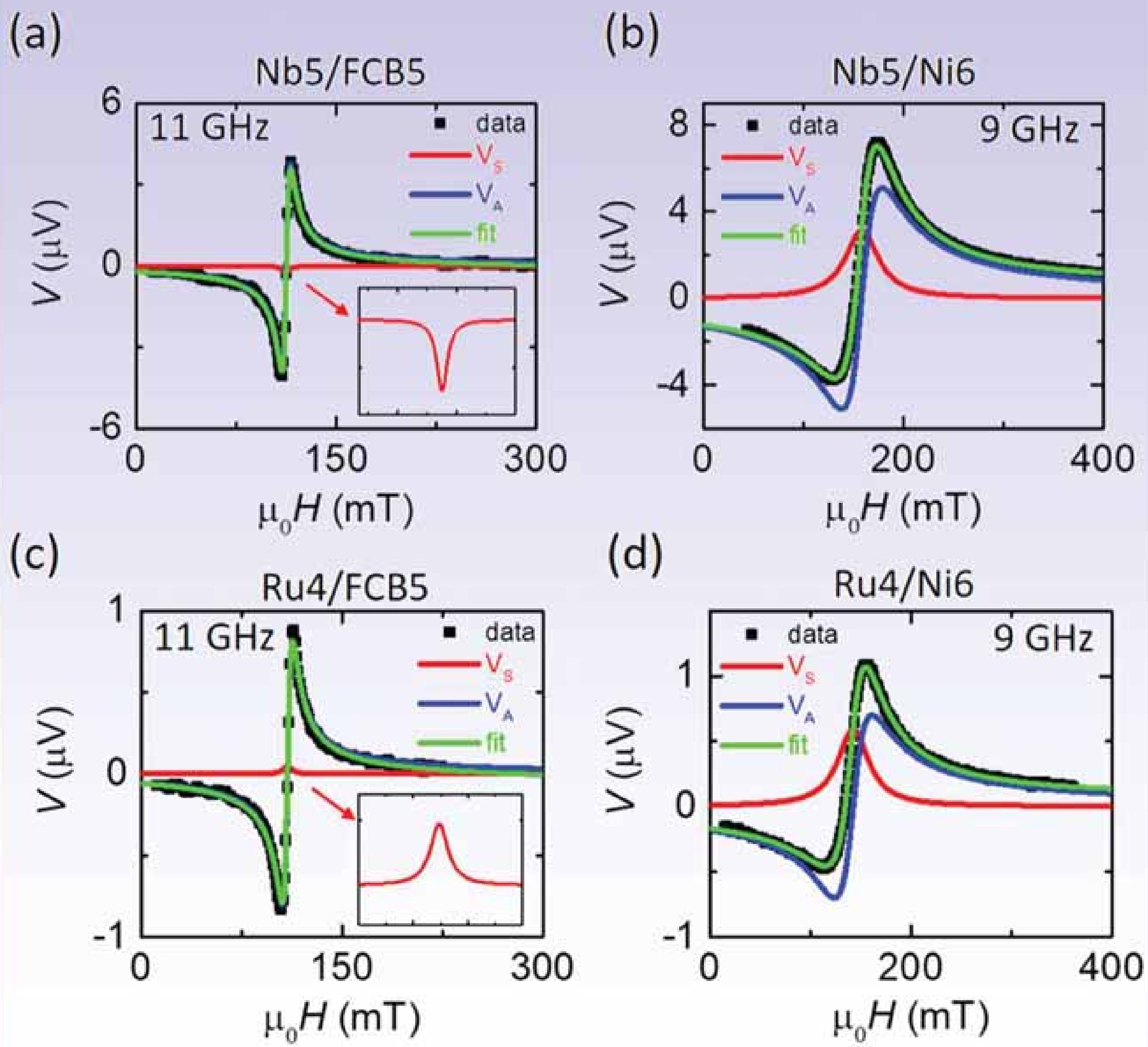
Theory: (1) Negligible SHE and (2) large OHE

NM	SHC	OHC
Ru	+ve	+ve
Nb	-ve	+ve

- Predicted strong +ve orbital Hall effect in Nb and Ru but small +ve spin Hall effect in Ru and small –ve in Nb.

[1]A. Bose, D. Go, Y. Mokrousov, MK et al., Phys. Rev. B **107**, 134423 (2023)

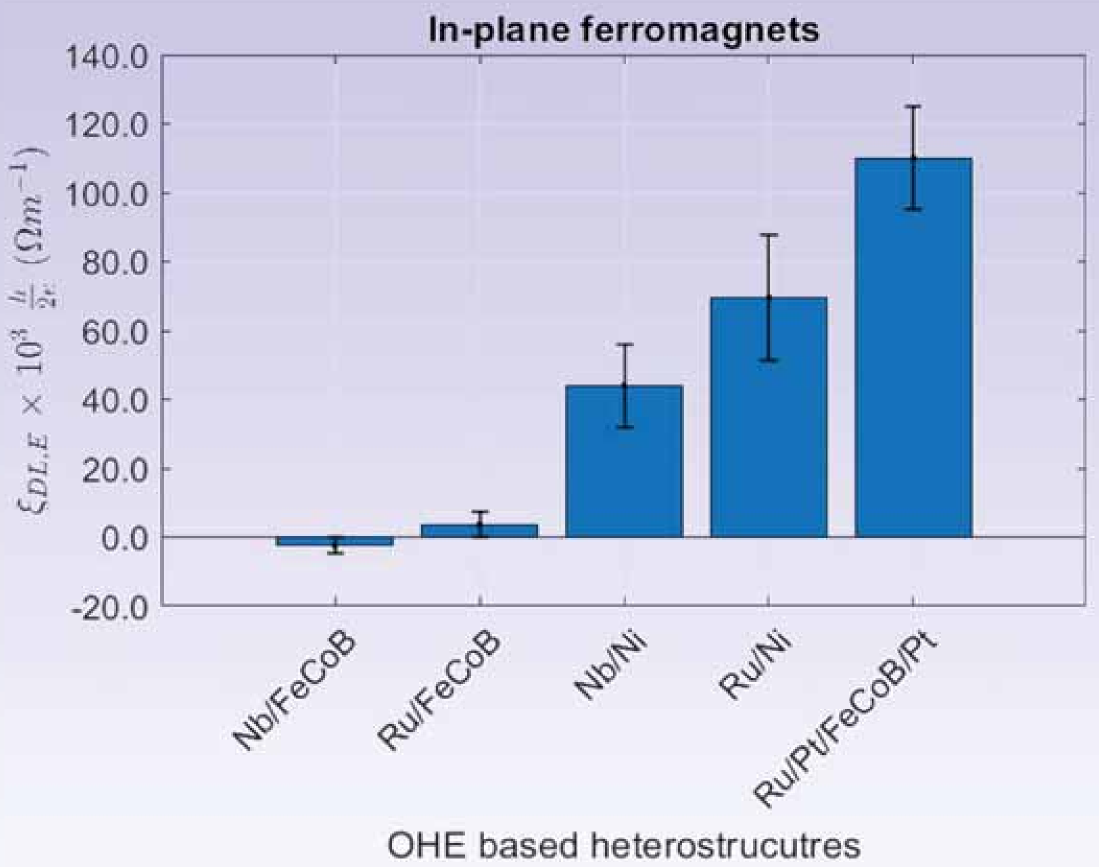
3. Orbital currents and orbital torques from Nb and Ru

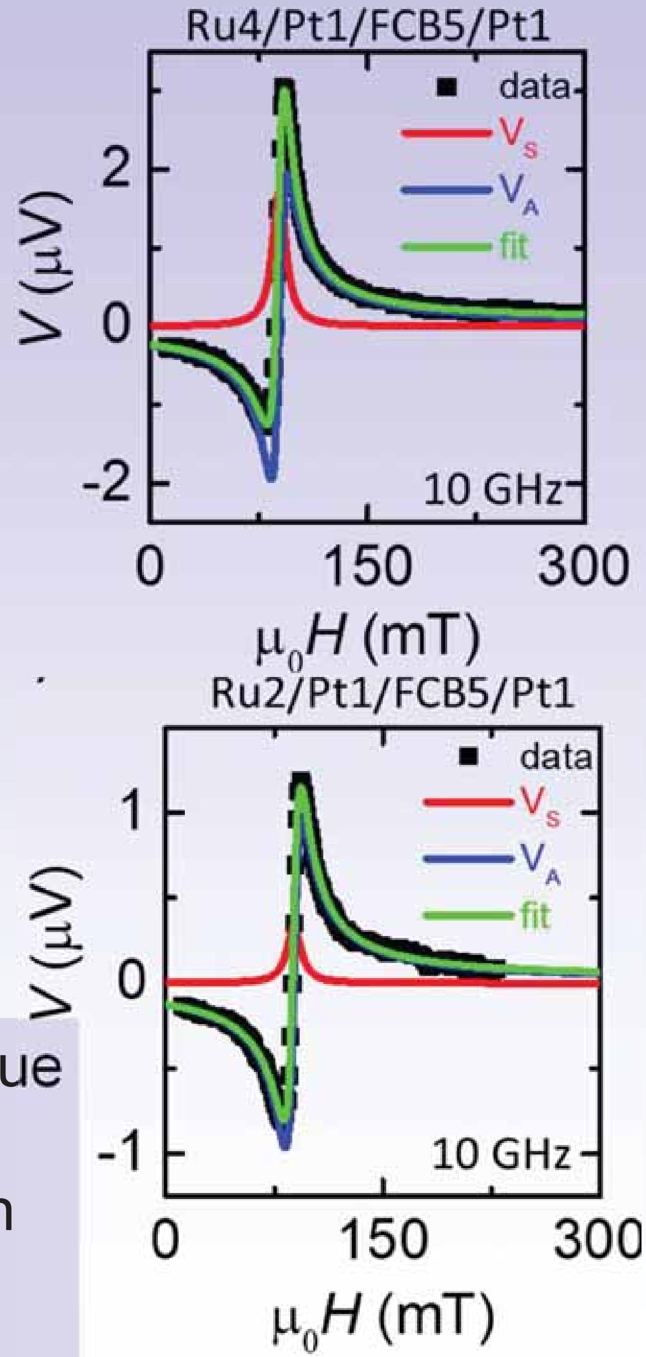


- Predicted strong +ve orbital Hall effect in Nb and Ru but small +ve spin Hall effect in Ru and small –ve in Nb.
- Nb/Ni and Ru/Ni show strong orbital torques Nb/CoFeB and Ru/CoFeB show small SOTs (different signs) (measured by ST-FMR)

[1] A. Bose, D. Go, MK et al., Phys. Rev. B **107**, 134423 (2023); see also S. Krishnia et al., Nano Lett. **23**, 6785

3. Orbital orbital torques from Nb and Ru



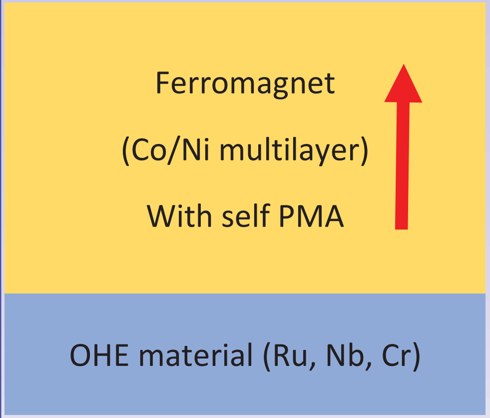


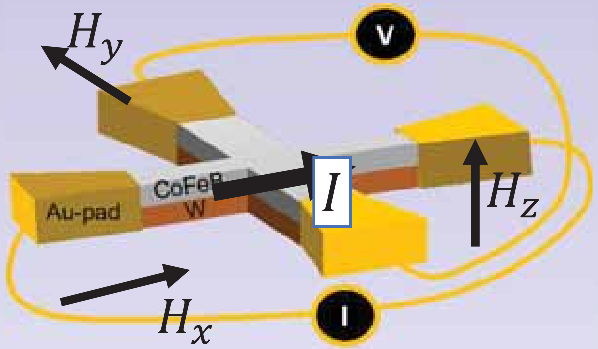
- Ru/CoFeB does not generate sizeable orbital torque
- Ru/Pt/CoFeB does generate a large torque → Orbital Hall current is converted by Pt layer to spin current that acts on CoFeB
- Maximum torque by converting Orbit to Spin!

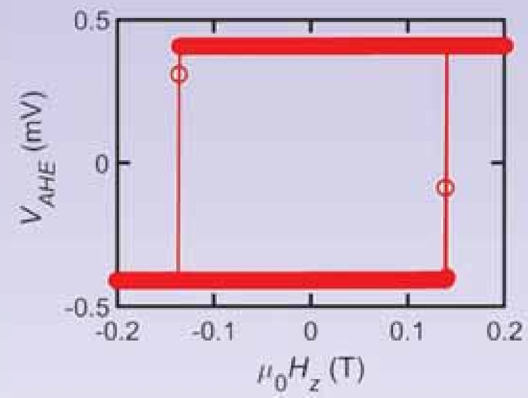
[1]A. Bose, D. Go, MK et al., Phys. Rev. B **107**, 134423 (2023); see also S. Krishnia et al., Nano Lett. **23**, 6785

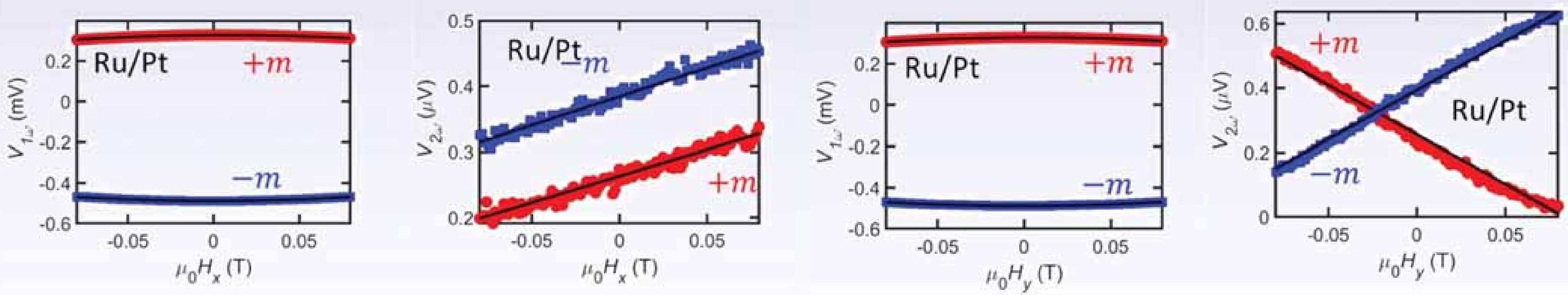
3. Orbital torque switching of perpendicularly magnetized stack

PMA magnet









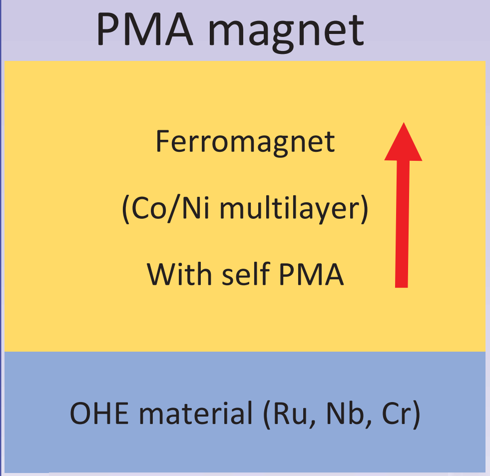
$\Gamma_{DL} \rightarrow m \times (\sigma \times m)$

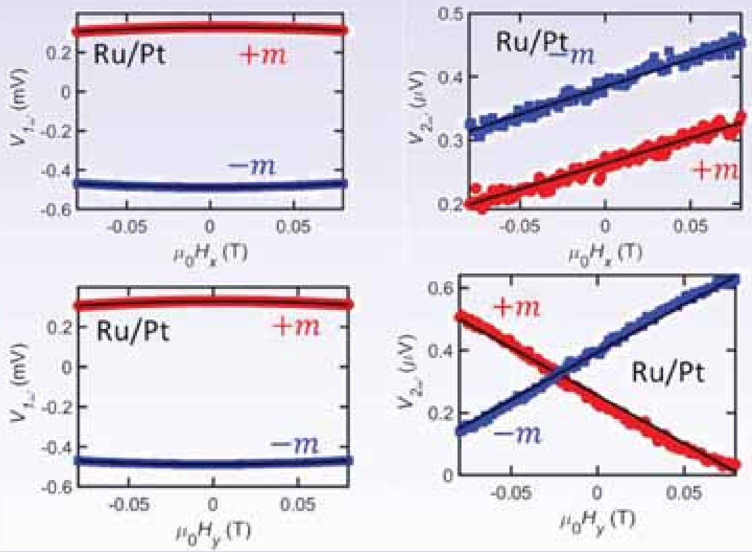
$\Gamma_{FL} \rightarrow (m \times \sigma)$

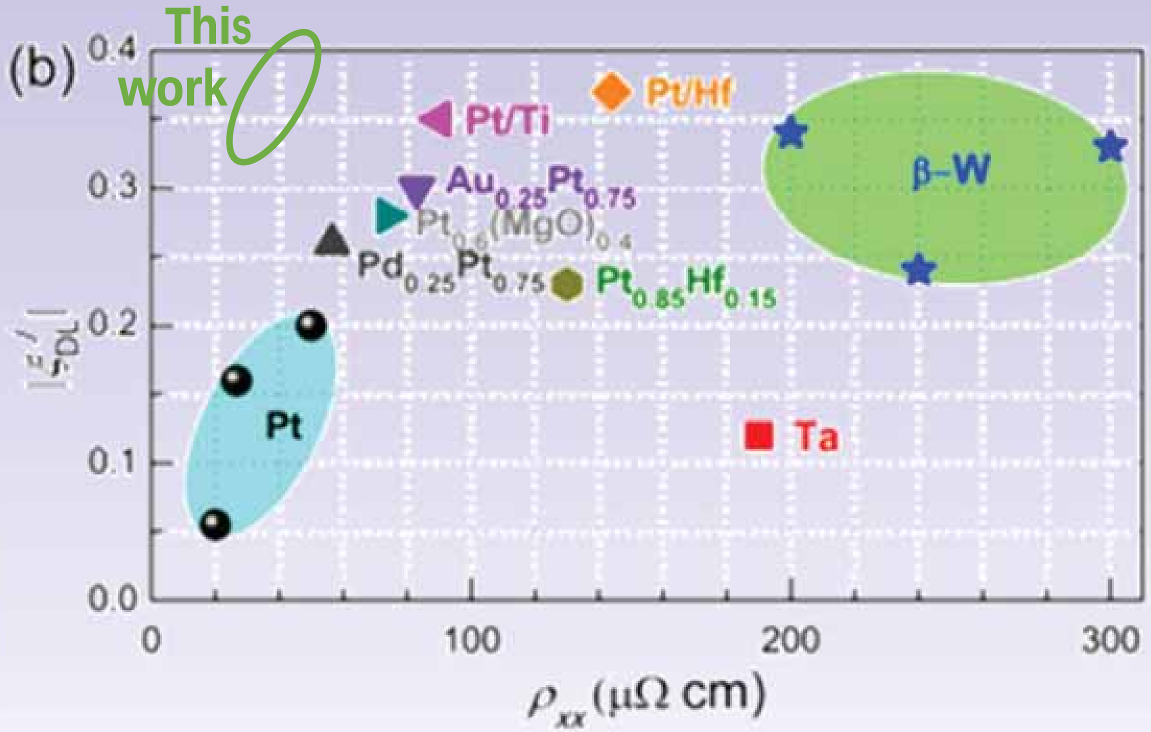
[1]R. Gupta et al., in preparation (2023)

- Design of complex multilayer stack that allows for switching experiments.
- Strong damping-like torque and sizeable field-like torques found.[1]

3. Orbital torque switching of perpendicularly magnetized stack





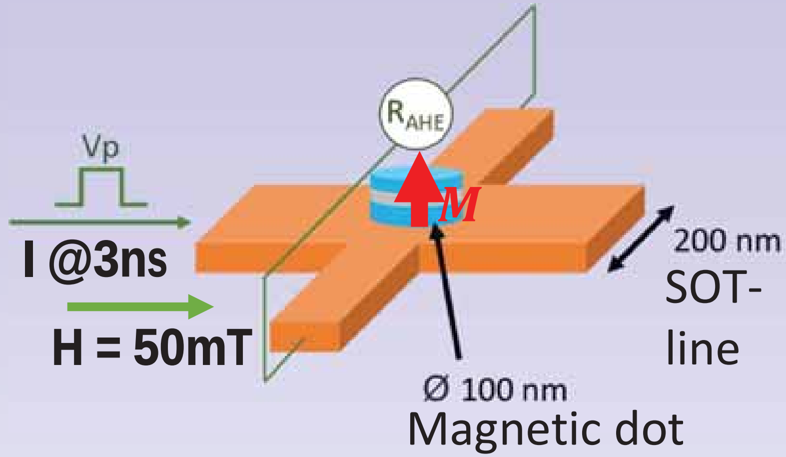


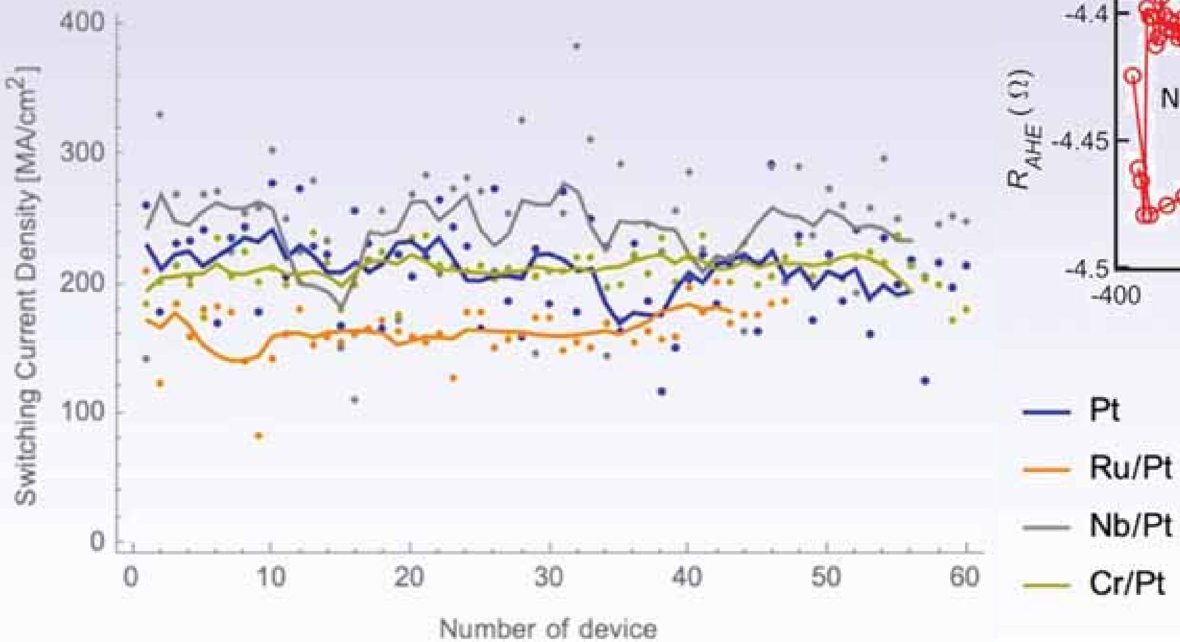
L. Zhu et al., Phys. Rev. Appl **12**, 051002 (2019)

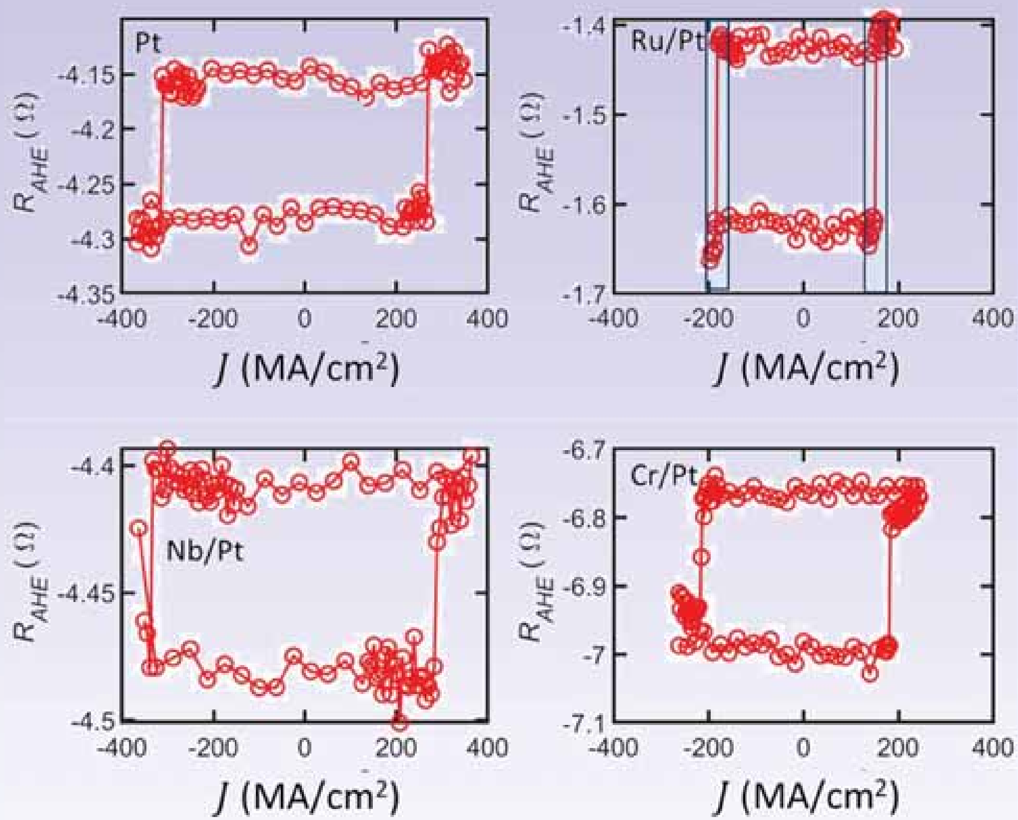
[1]A. Bose, D. Go, MK et al., Phys. Rev. B **107**, 134423 (2023)
[2]R. Gupta et al., in preparation (2023)

- Analysis of 2nd harmonic measurements to account for planar Hall effect
- Damping – like torque efficiency is in a par with the best SOT materials[1]
- Resistivity is significantly lower → low power switching[2]

3. Orbital torque switching of perpendicularly magnetized stack



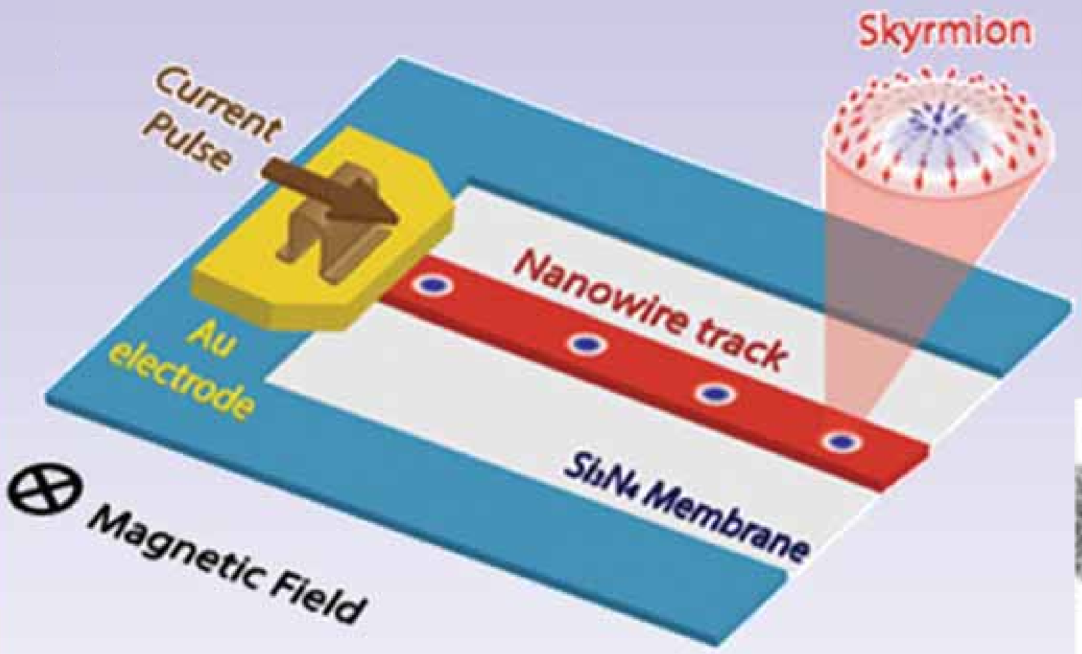


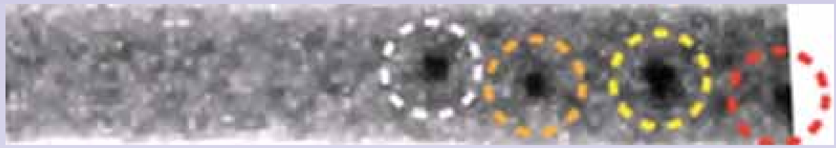


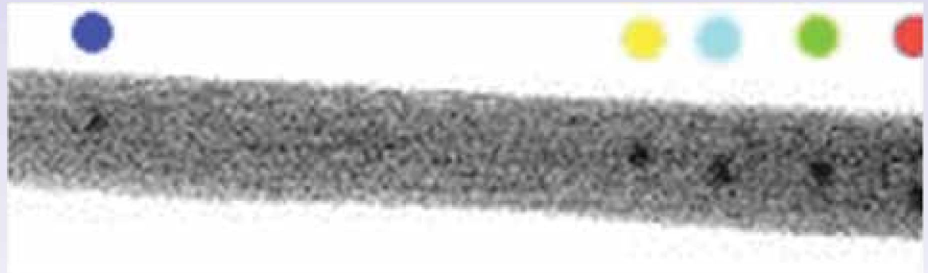
[1]A. Bose, D. Go, MK et al., Phys. Rev. B **107**, 134423 (2023)
[2]R. Gupta et al., in preparation (2023)

- Massive systematic study of switching current densities in >250 devices.
- Lowest critical current density in Ru/Pt based stack 30% lower than Pt!

3. Skyrmion Racetrack



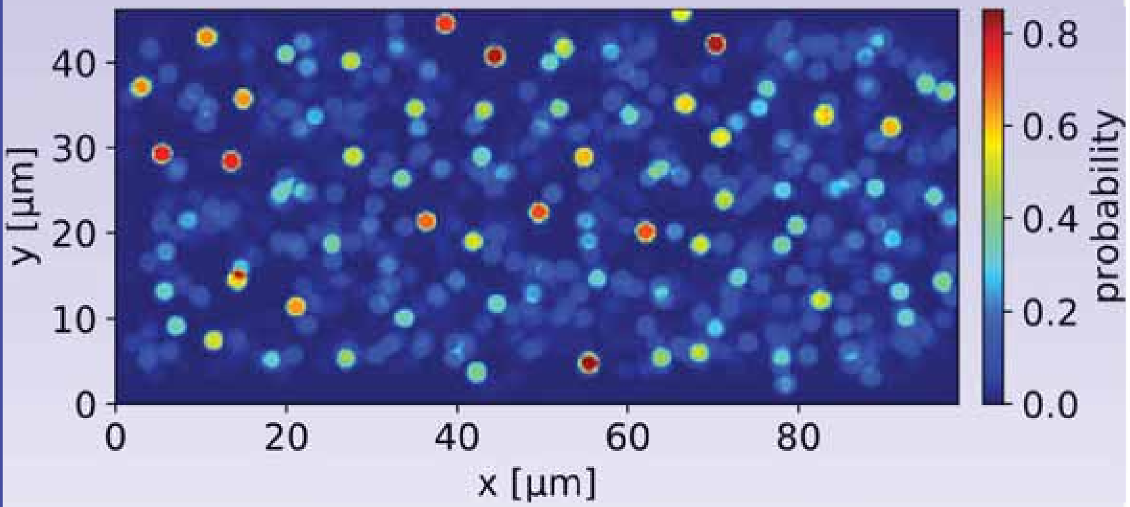


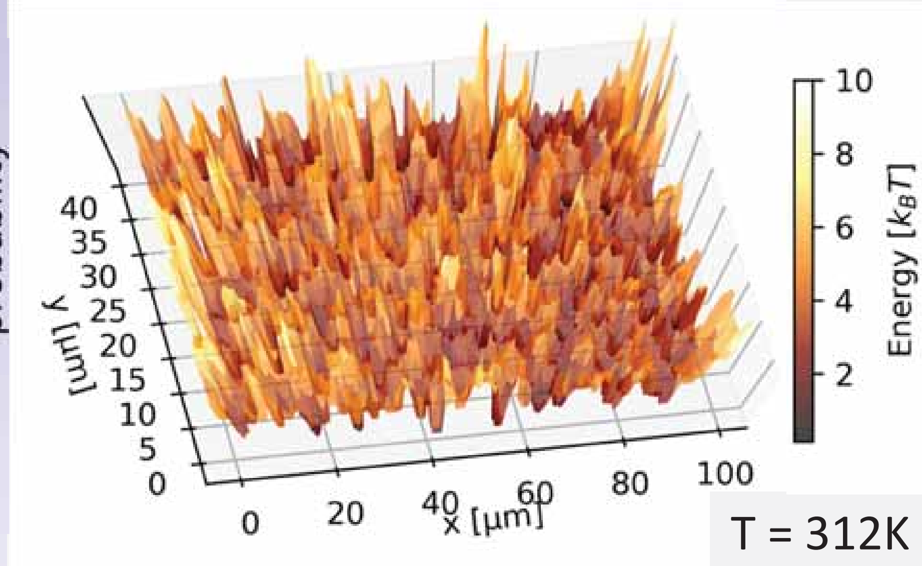


- Skyrmion racetrack[1]: advantages compared to a DW-based racetrack: total magnetization does not change with skyrmion motion
  → less susceptible to stray fields.
- Topological protection of skyrmions → more reliable motion?
- Nanowire is patterned out of Pt/Co/Ta (µm width)[2]
- Single skyrmions can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

[1] A. Fert et al., Nature Nano **8**, 152 (2013); [2] S. Woo, MK et al., Nature Mater. **15**, 401 (2016)

3. Origin of pinning





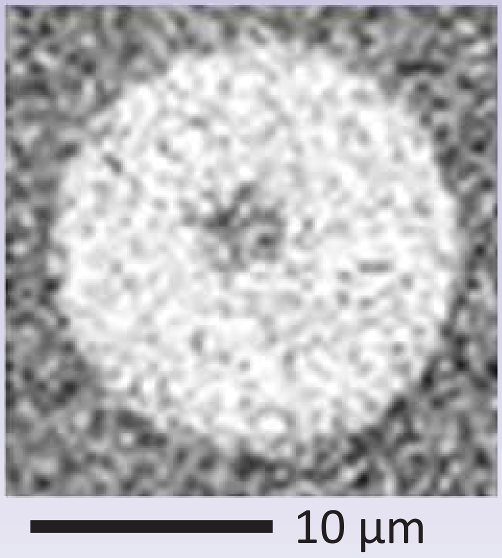
- Measure pinning and depinning of skyrmions
- Determine probability of finding skyrmions at a certain position

→ Variations due to non-flat energy landscape (pinning sites present)

- Use probability density to calculate energy landscape
- Pinning and thermal energy on same scale
- Look at specific pinning site to understand origin:
  → grain boundaries

[1]R. Gruber, MK et al., Nature Commun. **13**, 3144 (2022)

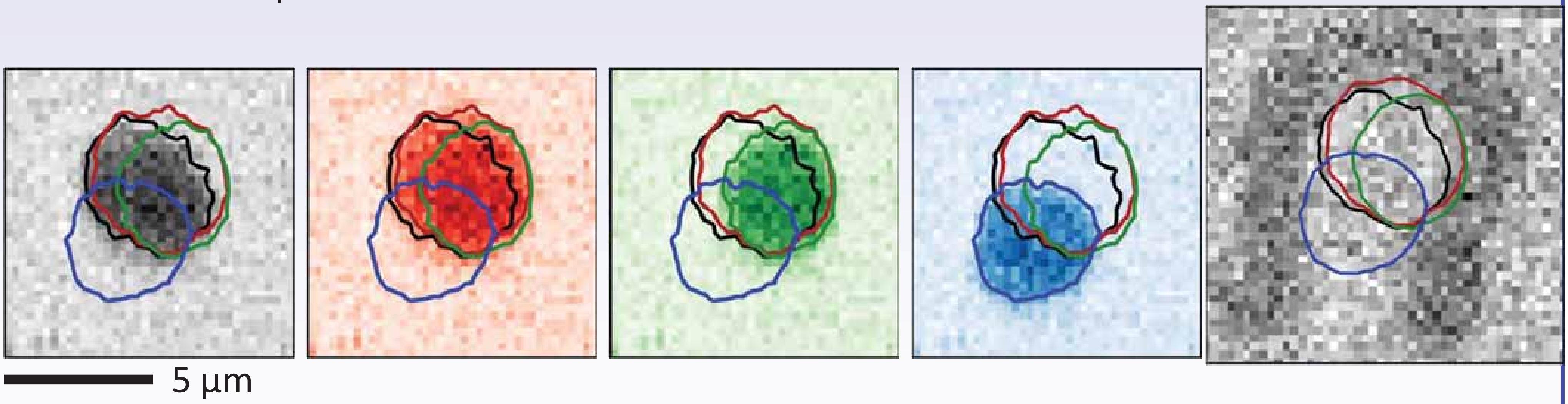
3. Origin of pinning



- Single skyrmion moving in confined geometry
- Skyrmion moves between distinct positions

→ obtain statistics to investigate pinning effects

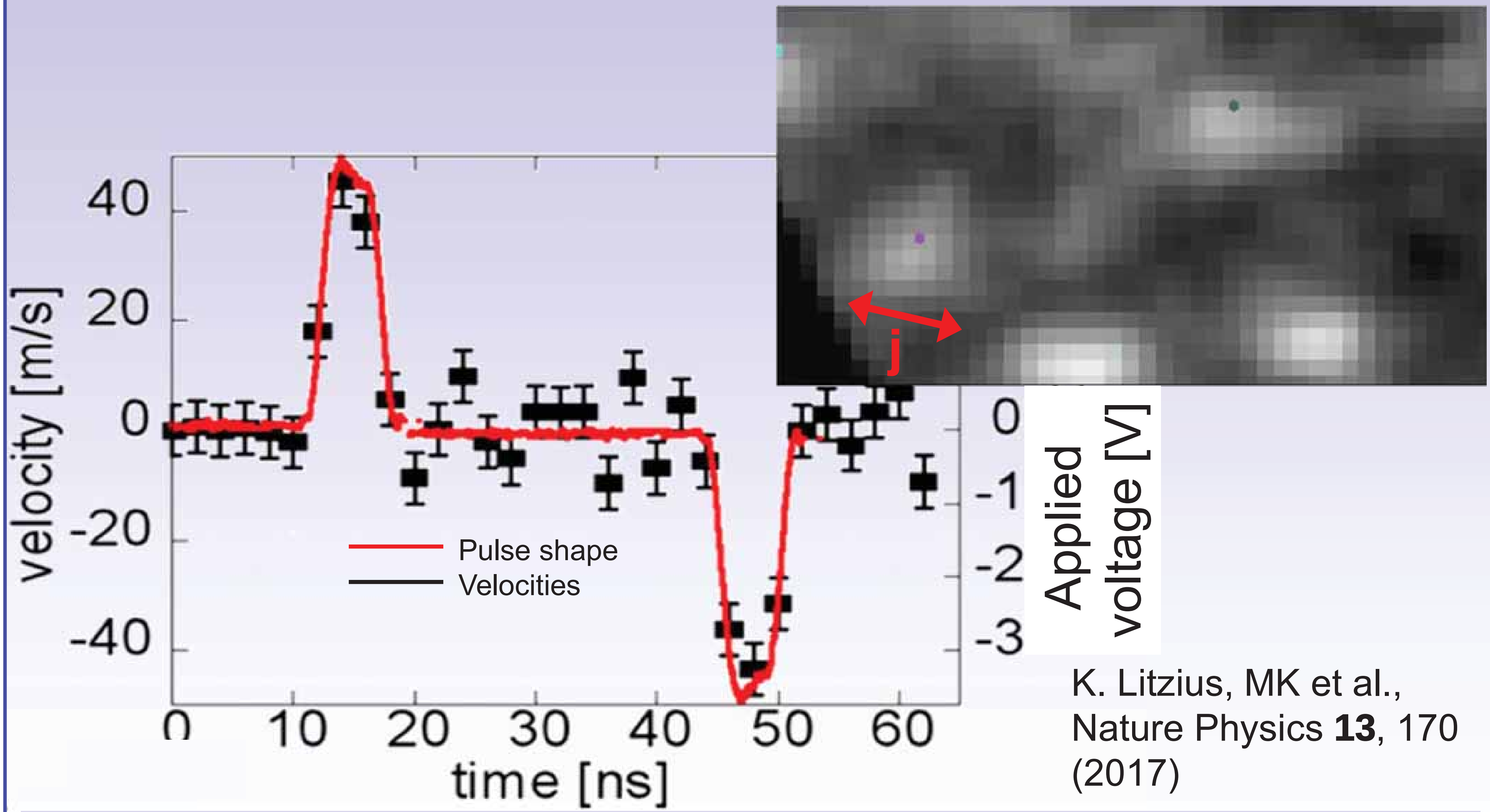
→Skyrmions are found in characteristic configurations of the domain wall.



- Pinning of the skyrmion boundary domain wall: confirmed by stripe domain pinning

[1]R. Gruber, MK et al., Nature Commun. **13**, 3144 (2022)

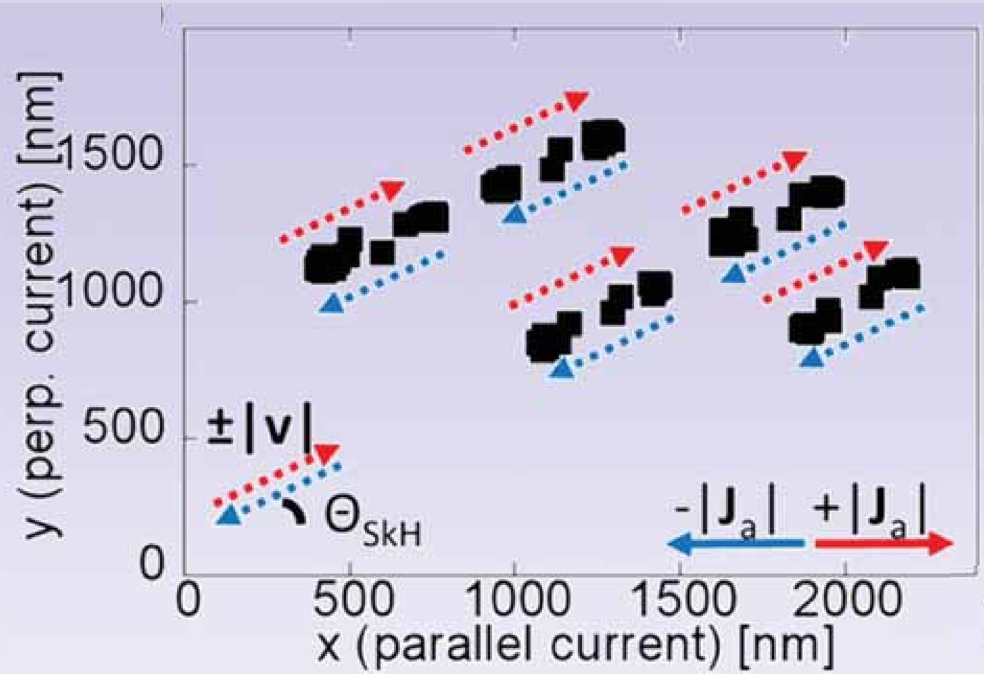
3. Real time magnetic imaging of spin-orbit torque induced dynamics

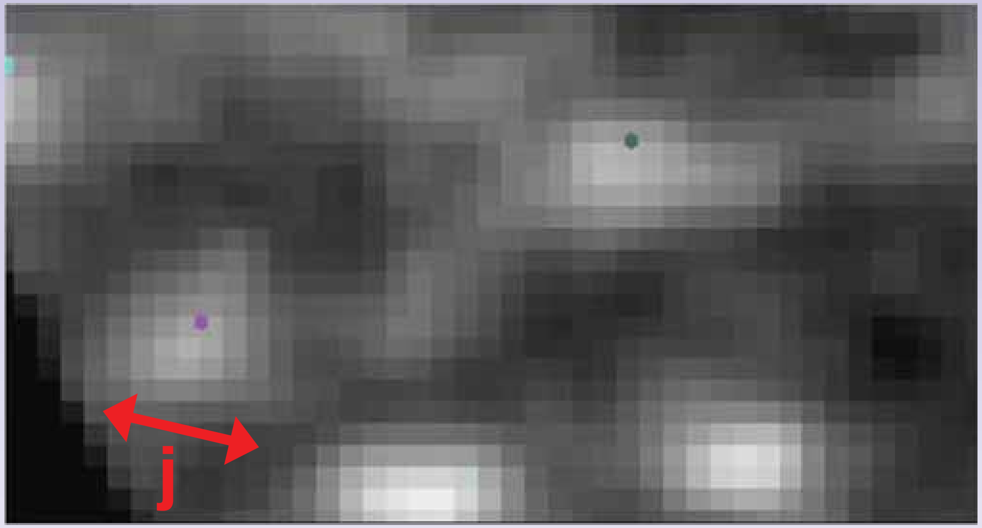


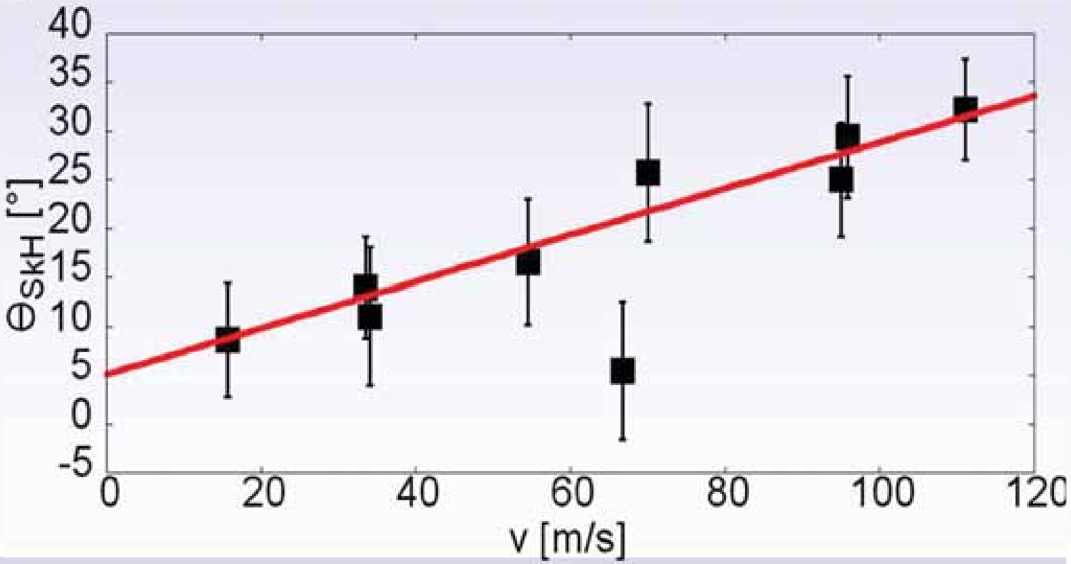
K. Litzius, MK et al., Nature Physics **13**, 170 (2017)

- 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.

3. Real time magnetic imaging of spin-orbit torque induced dynamics



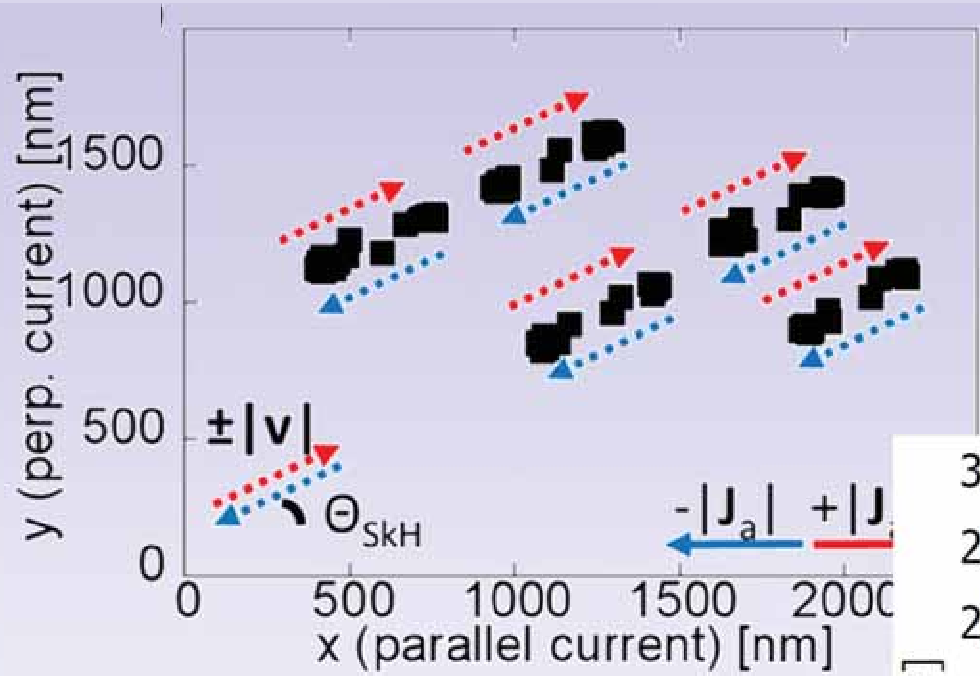


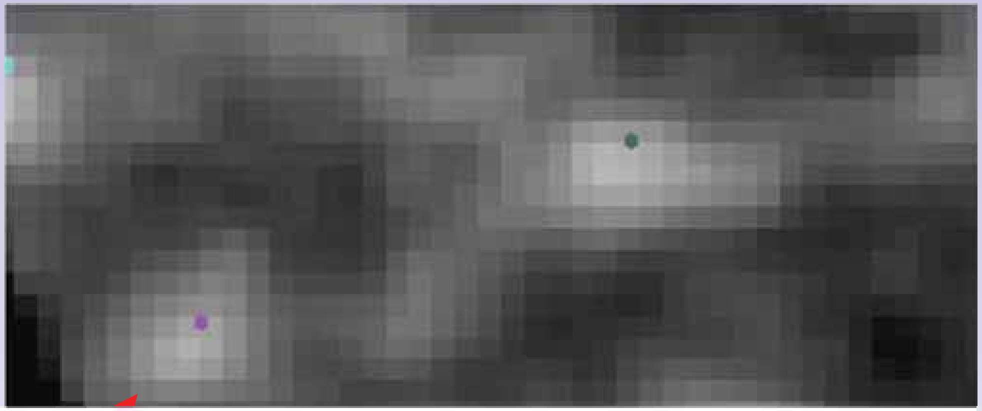


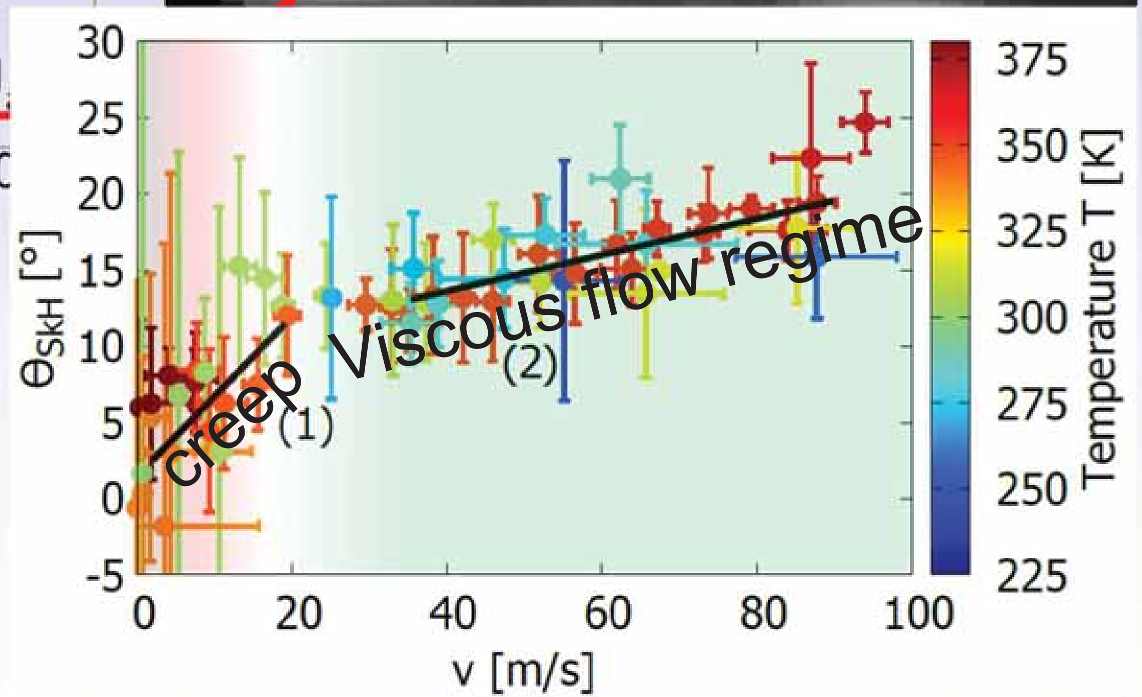
K. Litzius, MK et al.,
Nature Physics **13**, 170 (2017)
W. Jiang et al.,
Nature Physics **13**, 162 (2017)

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

3. Skyrmion Hall Angle





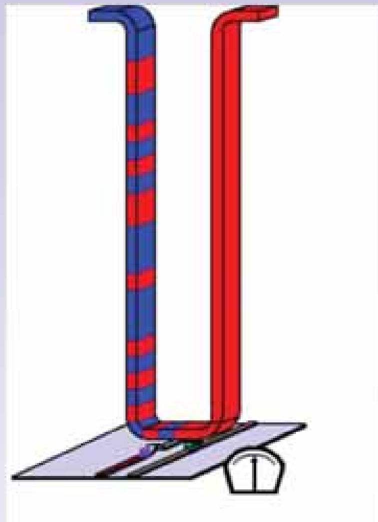
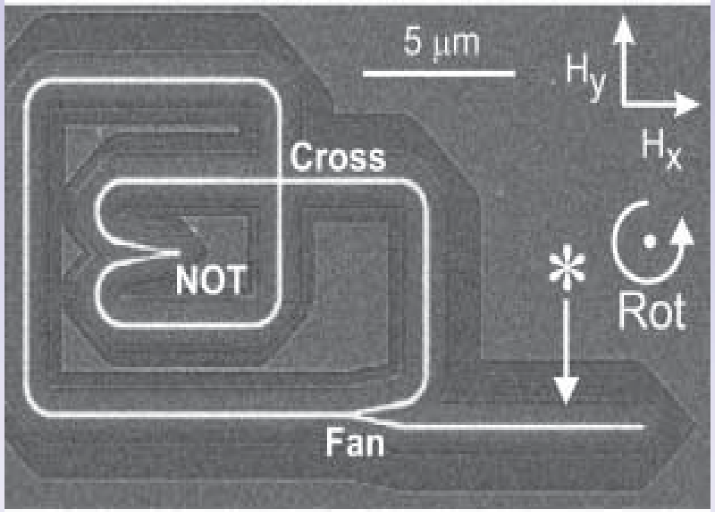


K. Litzius et al., Nat. Electron. **3**, 30 (2020)

K. Litzius et al., Nat. Phys. **13**, 170 (2017)
W. Jiang et al., Nat. Phys. **13**, 162 (2017)
K. Zeissler et al., Nat. Com. **11**, 428 (2020)
R. Juge et al., PR Appl. **12**, 044007 (2019)
C. Reichhardt et al., Nat. Com. **11**, 738 (2020)

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

Devices based on Domain Walls and Skyrmions

Memory	Magnetic Logic	Position & angle sensors
		
Parkin et al, Science **320**, 190 (‘08) Fert et al., Nature Nano **8**, 152 (‘13)	D. A. Allwood et al., Science **309,** 1688 (2005) J. Grollier et al., Nature Electron. **3**, 360 (2020)	R. Mattheis et al., IEEE Trans. Magn. **45**, 3792 (2009) A. Bisig et al., Nature Comm. **4**, 2328 (2013)

Challenges for Spintronics Devices:

Statics: Stability – Long term information retention
→ Topological Spin Structures to the rescue

Dynamics: Manipulation – Efficiency and Speed
→ Topological Spin Structures to the rescue

Spintronics and orbitronics for memory & unconventional computing

M. Kläui

Institut für Physik & Materials Science in Mainz

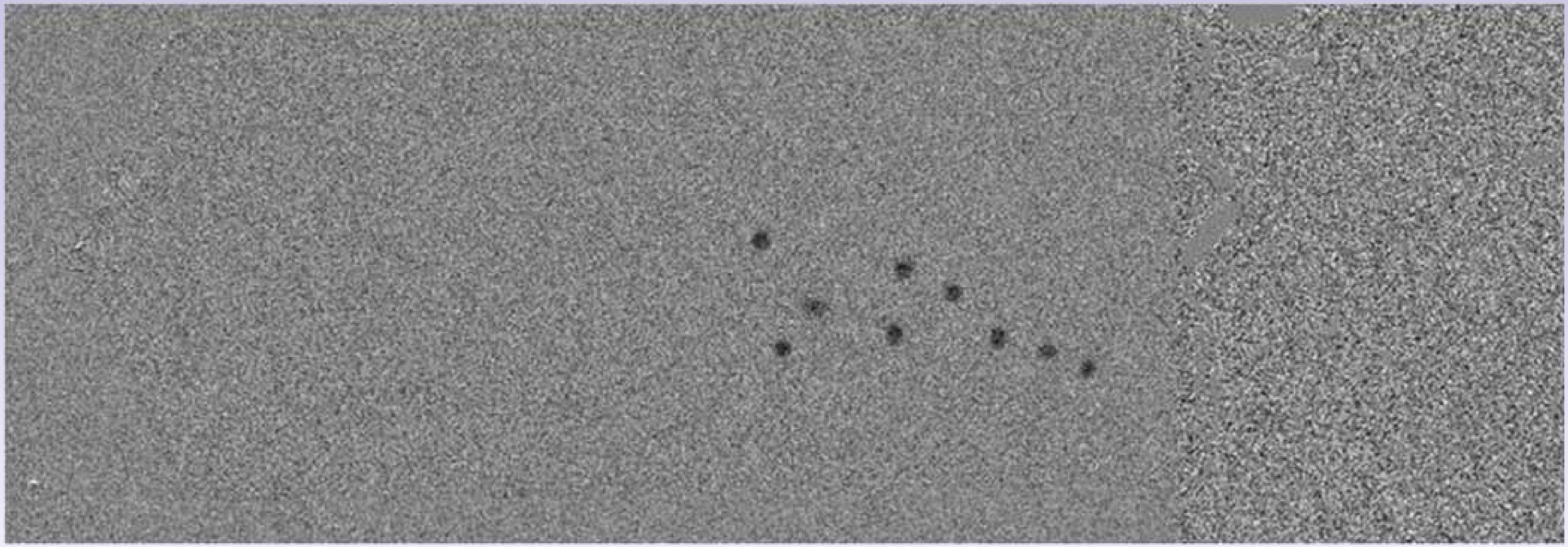
Johannes Gutenberg-Universität Mainz

Centre for Quantum Spintronics, NTNU Trondheim

www.klaeui-lab.de

- Introduction: devices & chiral interactions
- Topologically stabilized Skyrmions
- Fast dynamics: Spin and Orbital Torques
- **Efficient dynamics: thermal diffusion**
- Non-conventional logic with skyrmions

4. Skyrmion Writing and Skyrmion Motion in low pinning materials

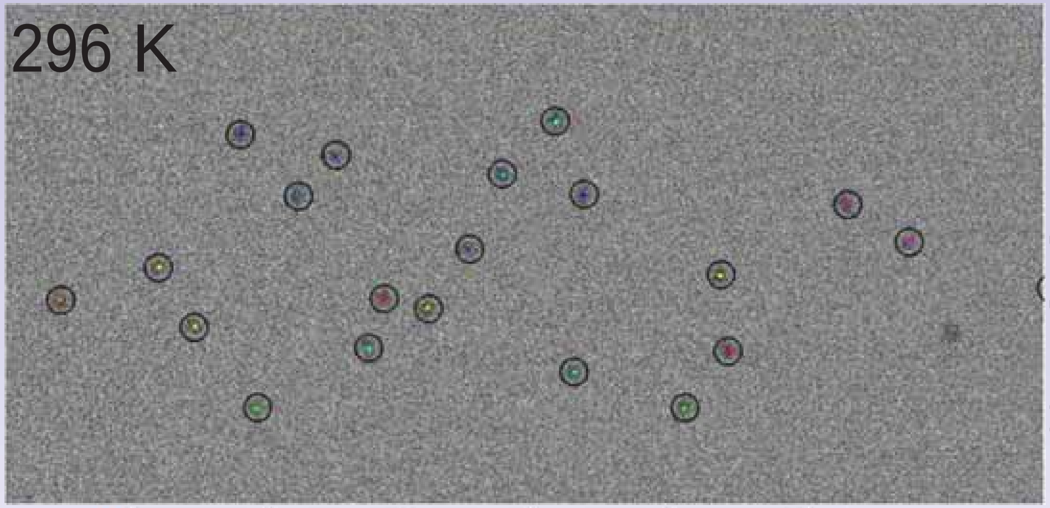


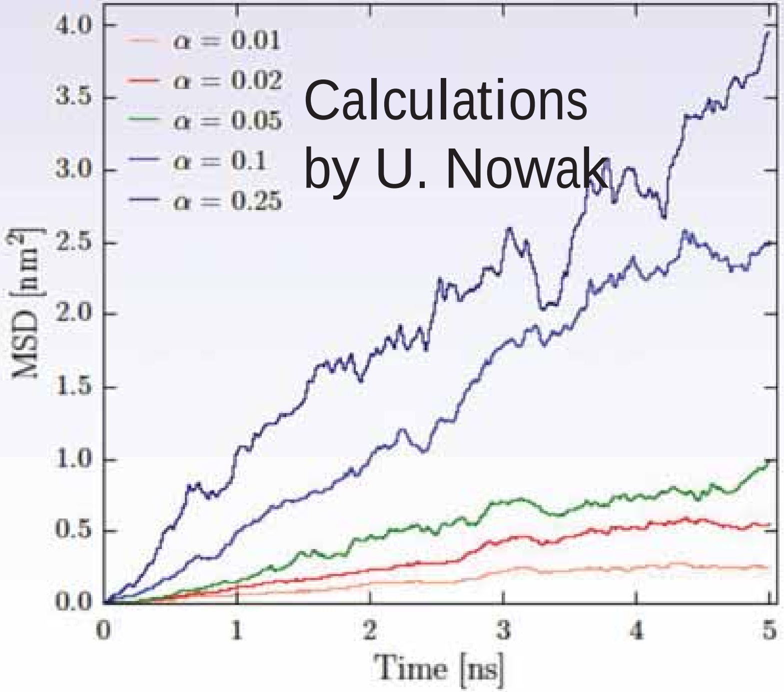
- Ultra-low pinning stack: Ta(5)/CoFeB(1)/Ta(0.08)/MgO(2)/Ta(5)[1]
- Using spin-orbit torques, skyrmions can be produced by pulses „on-demand“[2]
- Synchronous displacement along current flow → chiral skyrmions

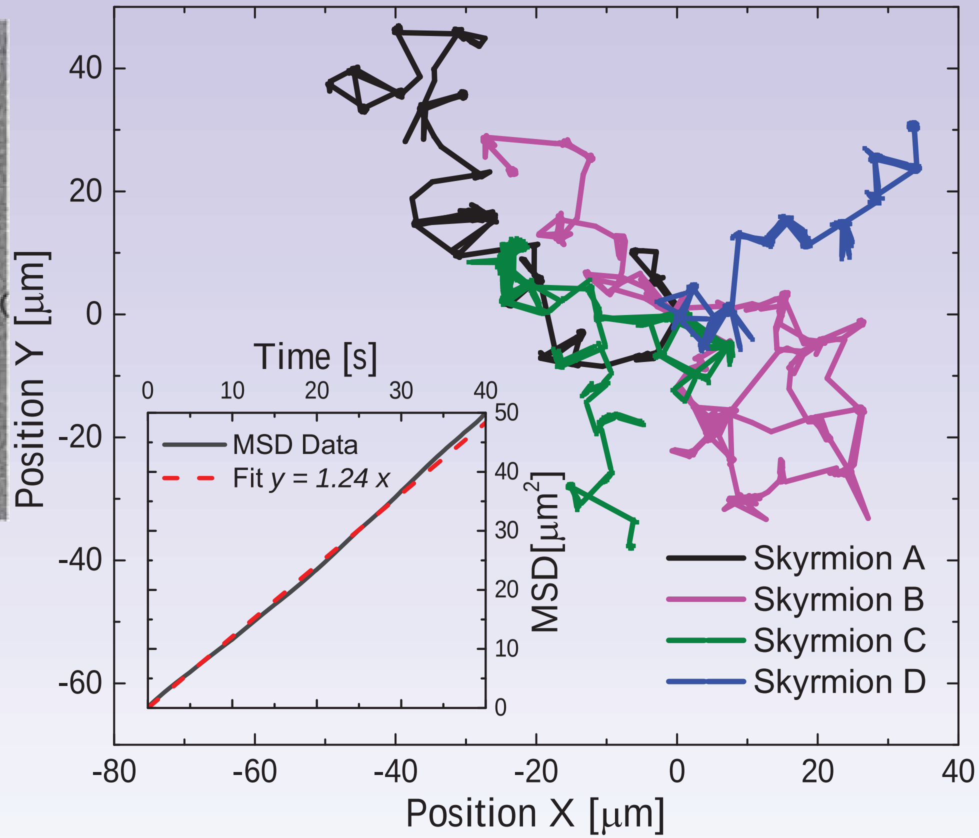
In addition to deterministic „writing“ and „shifting“, we see thermally induced dynamics leading to random motion → diffusion? Predicted to be suppressed[3]

[1]G. Yu et al., Nano Lett **16**, 1981 (2016); J. Zazvorka, K. Everschor-Sitte, U. Nowak et al., Nature Nano. **14**, 658 (2019)
[2]K. Everschor-Sitte et al., NJP **19**, 92001 (2017); M. Stier et al., PRL **118**, 267203 (2017); Z. Wang et al., Nat. El. **3**, 672 (2020)
[3]C. Schütte et al., Phys. Rev. B **90**, 174434 (2014)

4. Skyrmion Diffusion





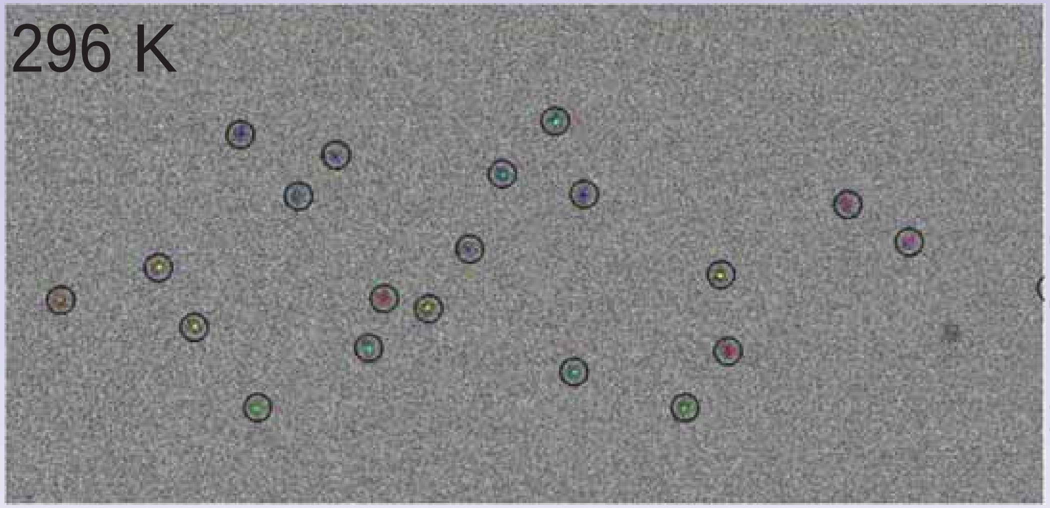


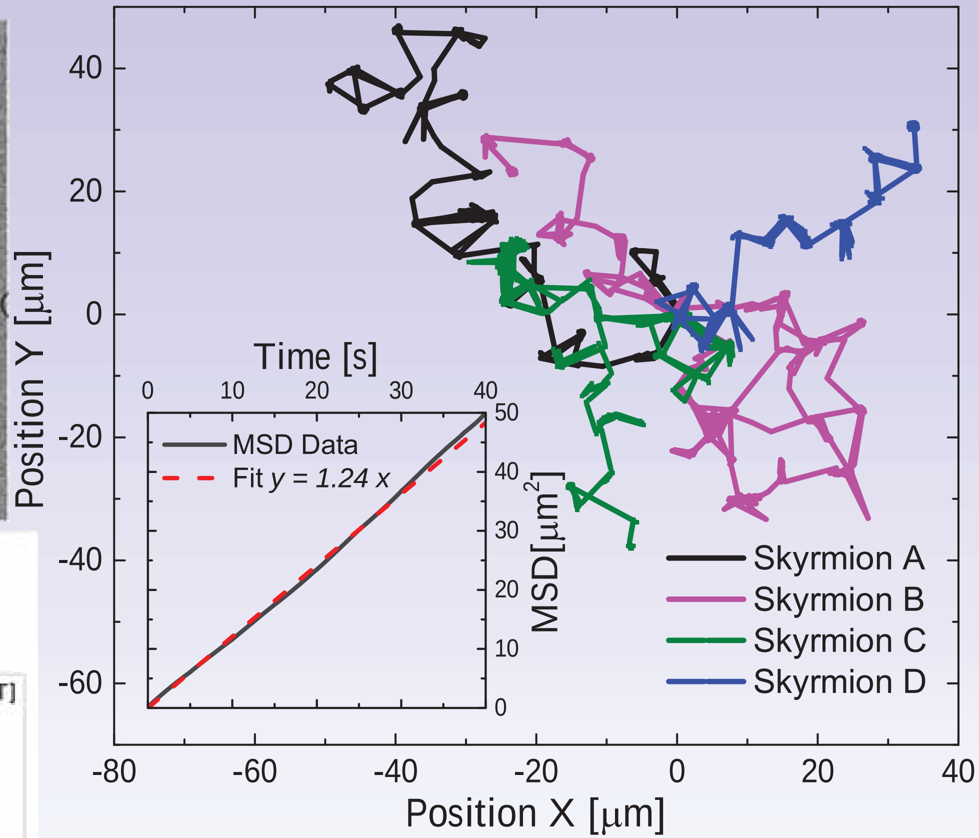
- Random motion exhibits linear scaling for mean square displacement → diffusion!
- Theoretical numerical spin simulations reproduce diffusion
- Use in unconventional computing?[1,2]

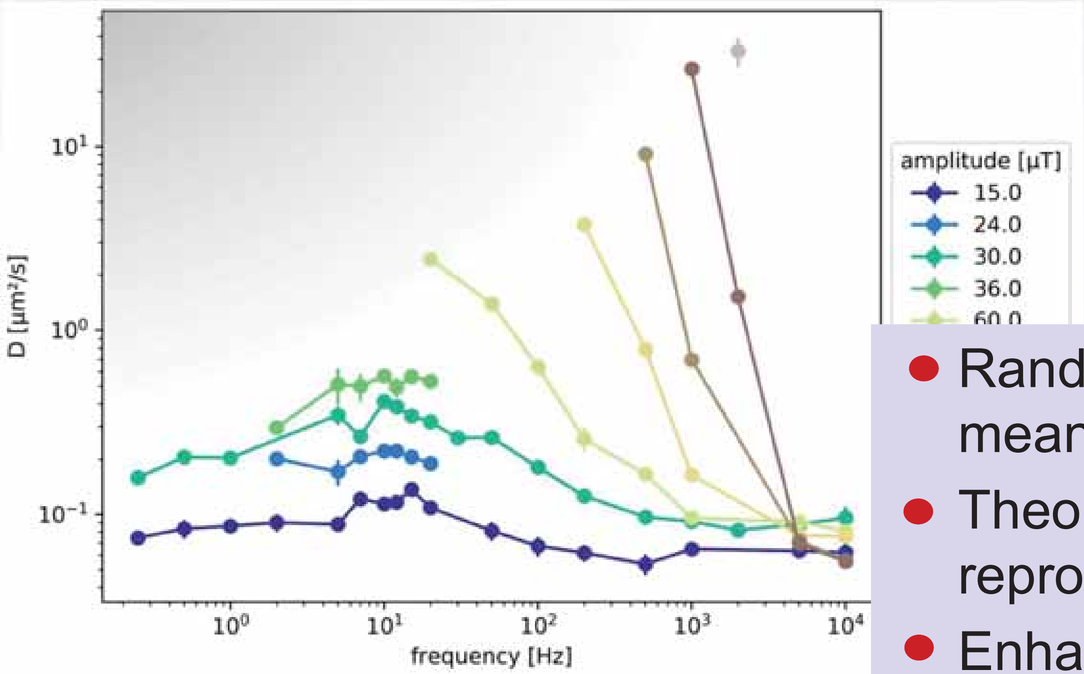
[1]J. Zazvorka, MK et al., Nature Nano. **14**, 658 (2019)
cf. L. Zhao et al., PRL **125**, 027206 (2020)

[2]D. Pinna et al., PRAppl. **9**, 064018 ('18); PRAppl. **9**, 014034 ('18)

4. Skyrmion Diffusion







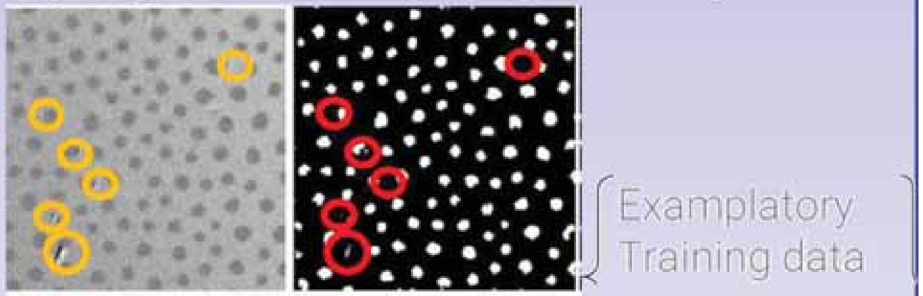
- Random motion exhibits linear scaling for mean square displacement → diffusion!
- Theoretical numerical spin simulations reproduce diffusion
- Enhanced diffusion by AC excitations[2]

[1]J. Zazvorka, MK et al., Nature Nano. **14**, 658 (2019)
Tracking using U-NET: I. Labrie, MK et al., PRAppl. **21**, 014014 (2024) [2]R. Gruber, MK et al., Adv. Mat. **35**, 2208922 (2023)

4. Skyrmion Detection

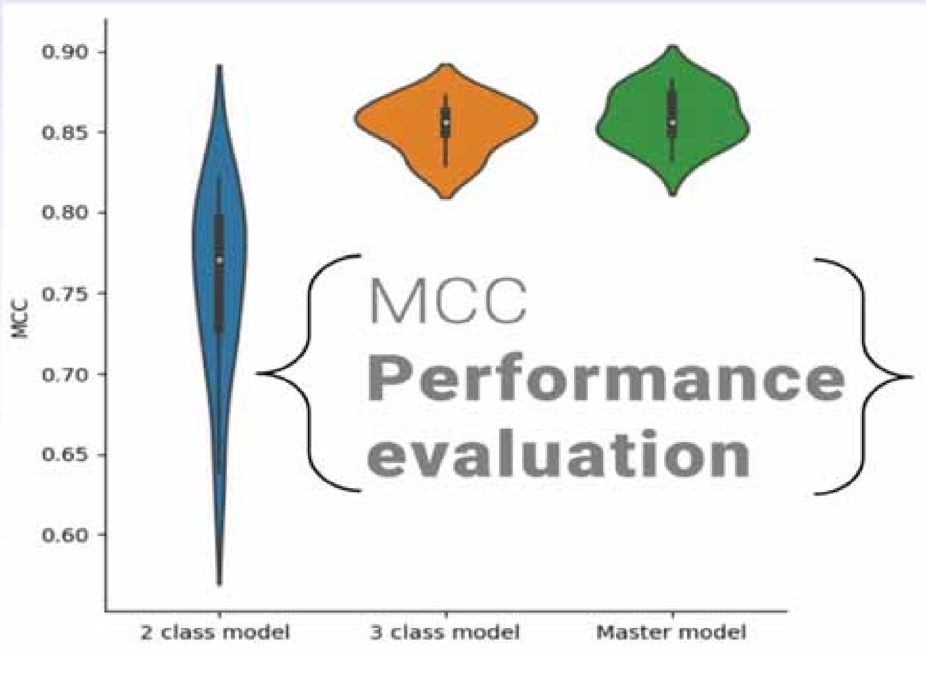
First approach: 2-class prediction task (skyrmion, background)

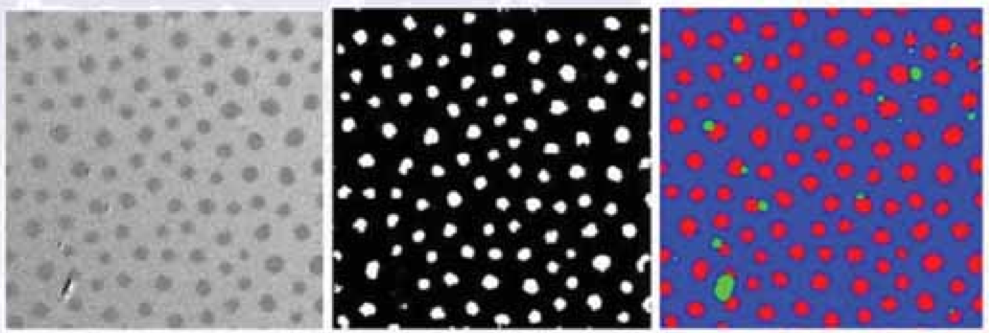
- One-hot encoding
- dark skyrmions, bright background
- Training set: 1900 images,



Second approach: 3-class prediction (skyrmion, defect, background)

- Small dataset focusing on defects (100 images)

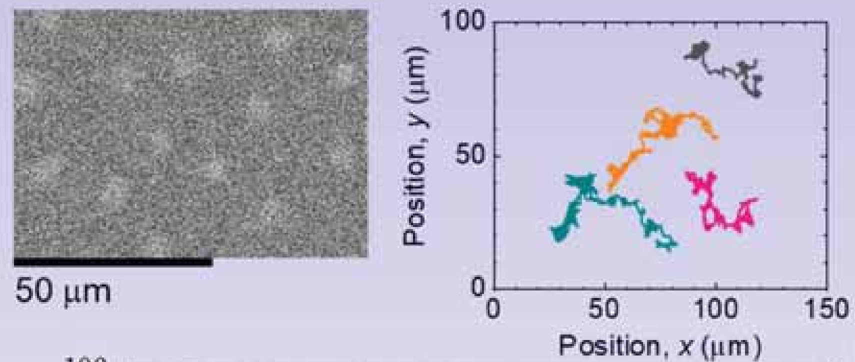


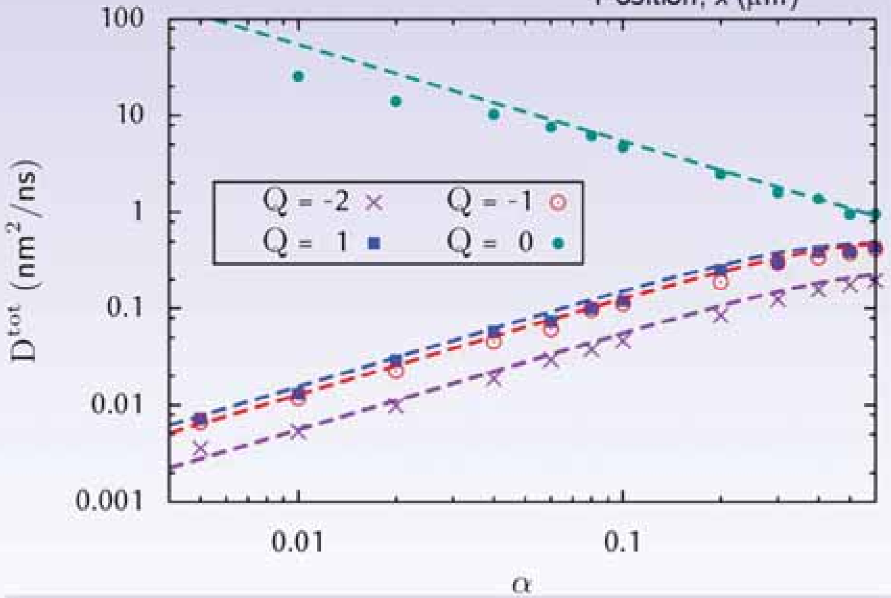


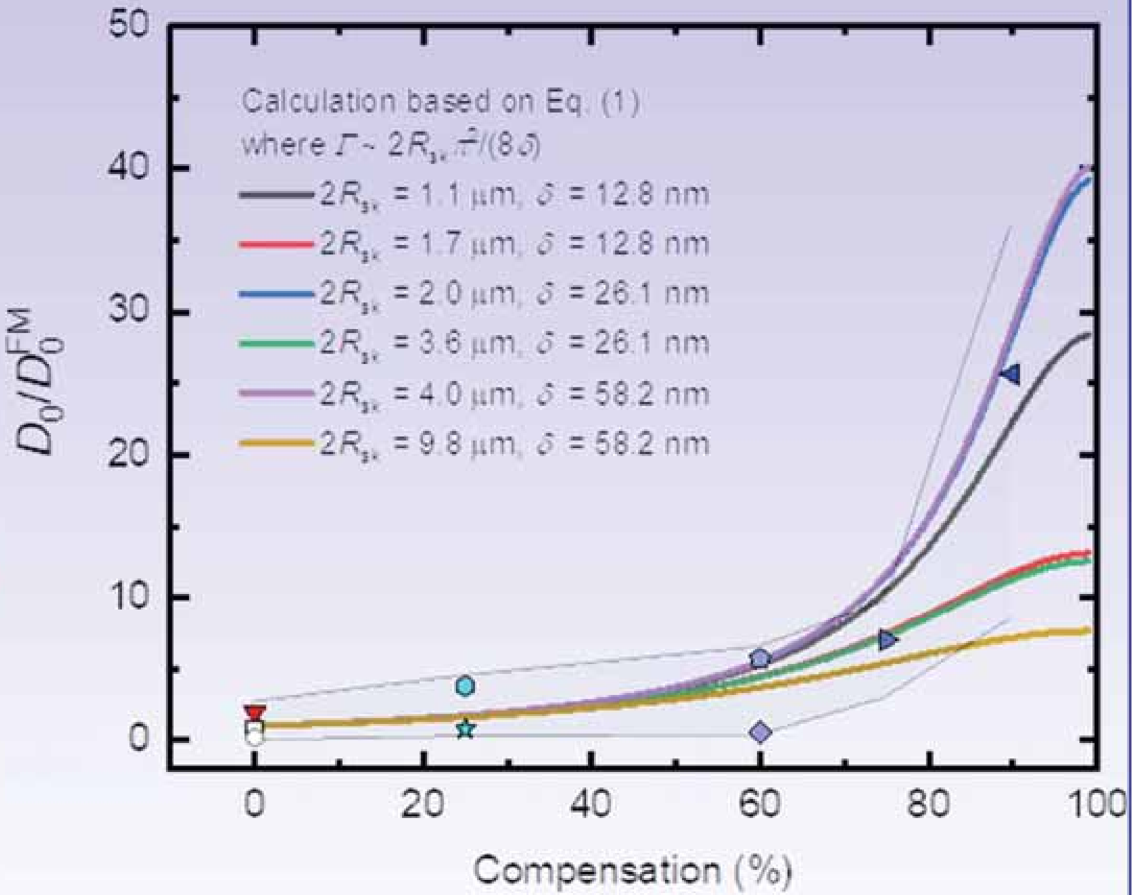
- Convolutional neural network for optical pattern recognition to detect skyrmions
- 2-class model labels defect as skyrmion
- 3-class prediction works well (MCC=0.9)
- Hands-on training at Intermag24 (event)!

[1] I. Labrie, MK et al., Phys. Rev. Appl. **21**, 014014 (2024)

4. Ultimately fast Skyrmion Diffusion in (synthetic) antiferromagnets







- Synthetic antiferromagnets: topological charge tuned by compensation ratio!
- Developed synthetic antiferromagnets SAFs with tailored compensation ratio
- Thermal dynamics: predicted to be suppressed by finite topological charge[1]
- Diffusion enhanced >20 times for maximally compensated (fully AFM) SAFs[2]

[1] M. Weissenhofer et al., NJP **22**, 103059 (2020); [2] T. Dohi, MK et al., Nature Comm. **14**, 5424 (2023)

Spintronics and orbitronics for memory & unconventional computing

M. Kläui

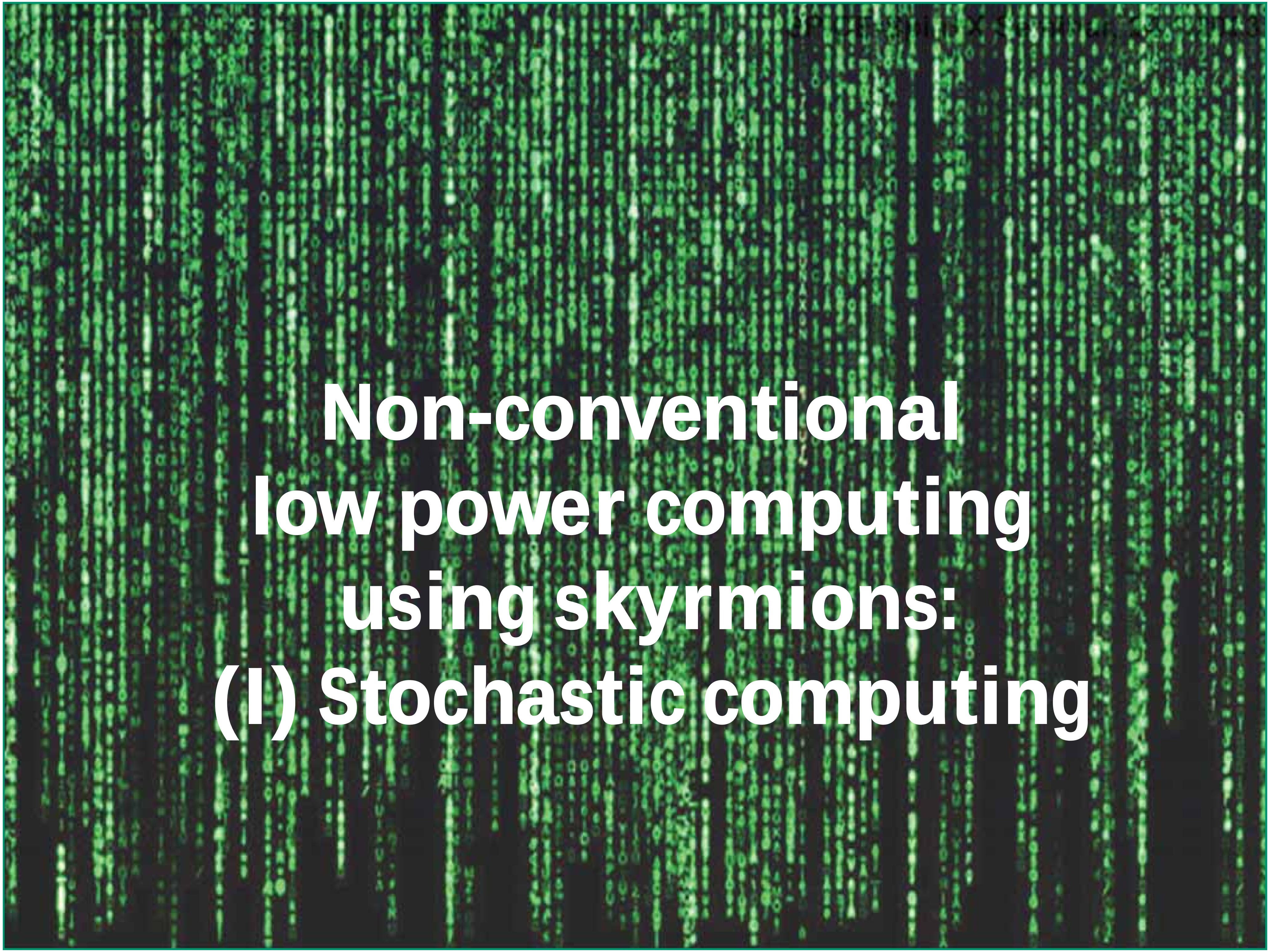
Institut für Physik & Materials Science in Mainz

Johannes Gutenberg-Universität Mainz

Centre for Quantum Spintronics, NTNU Trondheim

www.klaeui-lab.de

- Introduction: devices & chiral interactions
- Topologically stabilized Skyrmions
- Fast dynamics: Spin and Orbital Torques
- Efficient dynamics: thermal diffusion
- **Non-conventional logic** with skyrmions


Non-conventional
low power computing
using skyrmions:
(I) Stochastic computing

5. Stochastic Computing

- Stochastic computing

- Non-arithmetic way of calculation using random bit streams

- Only approximation of result - “progressive precision”

- Simple way of multiplying numbers using only AND-gates (and some other functions such as scaled addition, etc.)

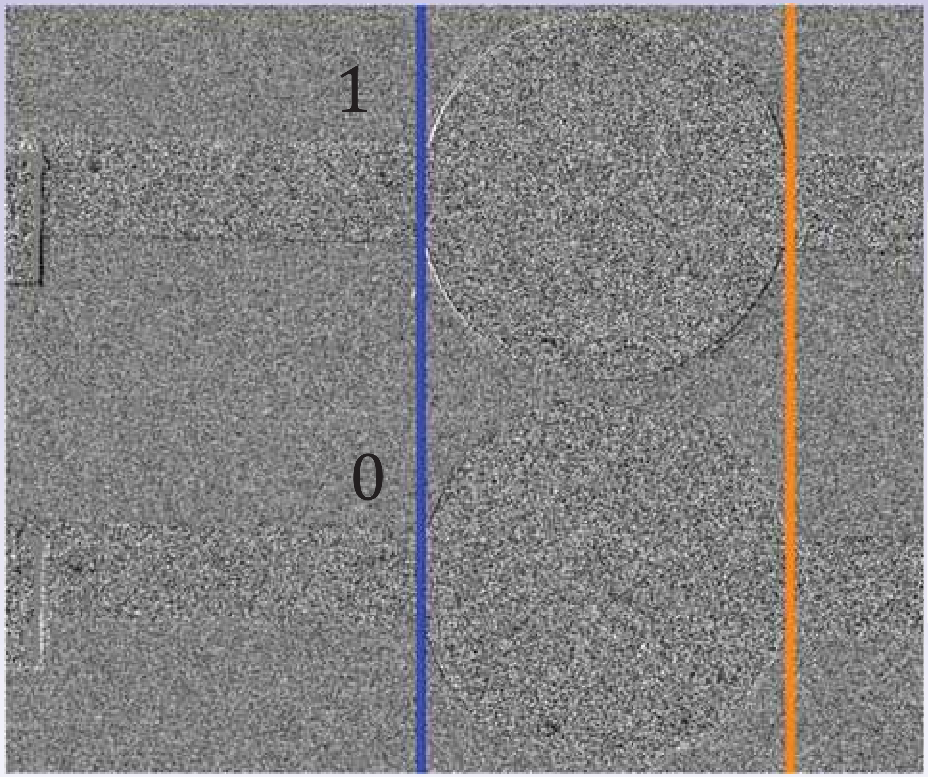
- Problem in stochastic computing is the creation of unbiased, uncorrelated bit streams
  → reshuffler to decorrelate streams needed

D. Pinna et al, Phys. Rev. Applied **9**, 064018

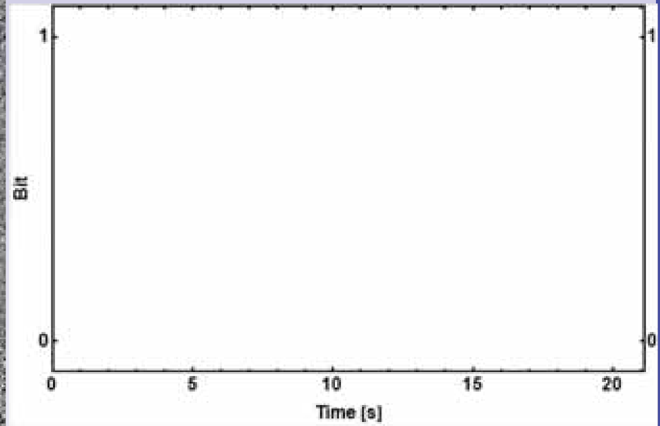
5. Skyrmion Reshuffler to create uncorrelated bitstreams

Realization:

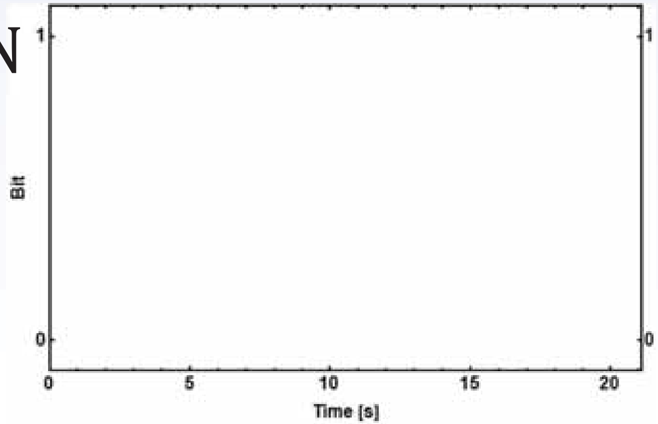
-Skyrmion nucleation with pulses or DC.
-Readout with imaging.
-Skyrmions enter the chamber (blue line→input)
-Exiting chamber (orange) triggers corresponding bit
➔output signal



OUT



IN



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

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!

J. Zazvorka, MK et al., Nature Nano. **14**, 658 (2019)

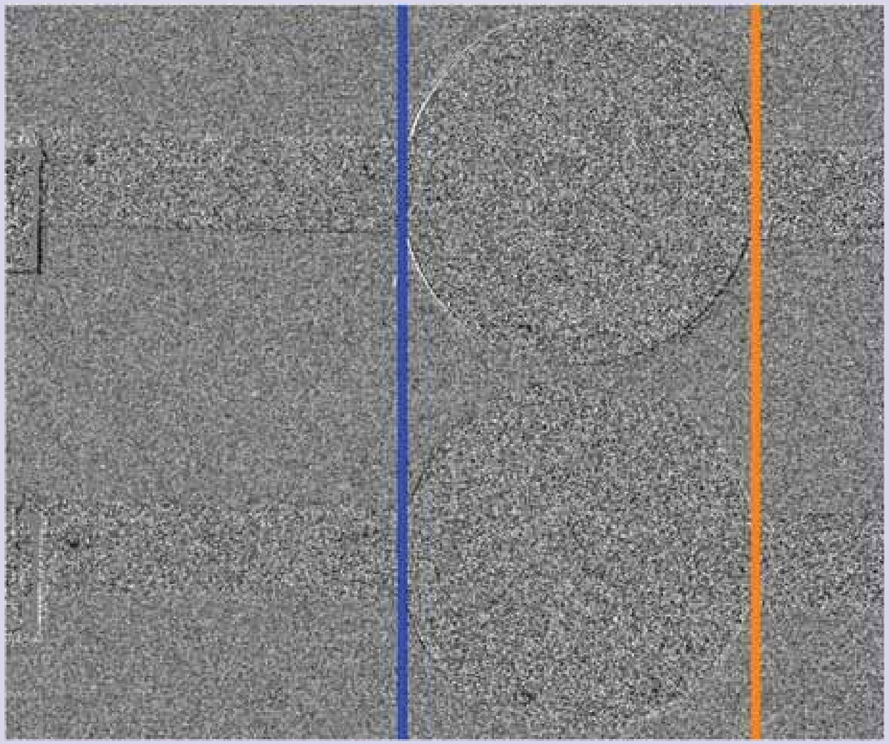
D. Pinna et al., Phys. Rev. Appl. **9**, 064018 (2018)

5. Logic using skyrmions

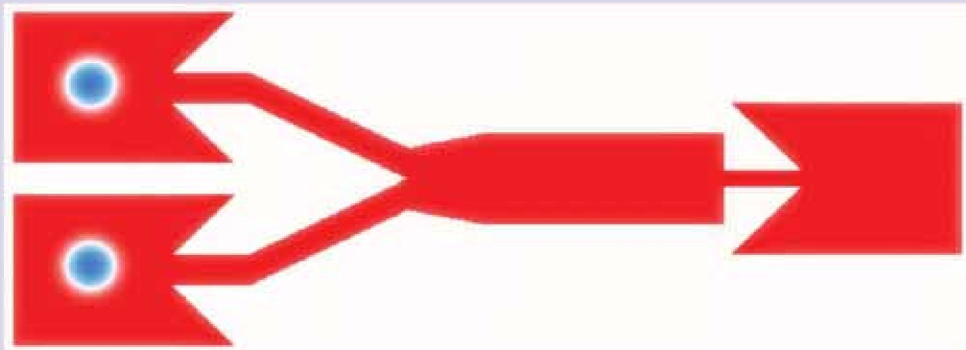
- Stochastic Logic can be realized with Skyrmions

- Combining:

1. Skyrmion Reshuffler
J. Zazvorka, MK et al., Nature Nano. **14**, 658 (‘19)



2. AND Gate
X. Zhang et al., Sci. Rep. **5**, 9400 (2015)



→Multiplication using probabilistic computing approach

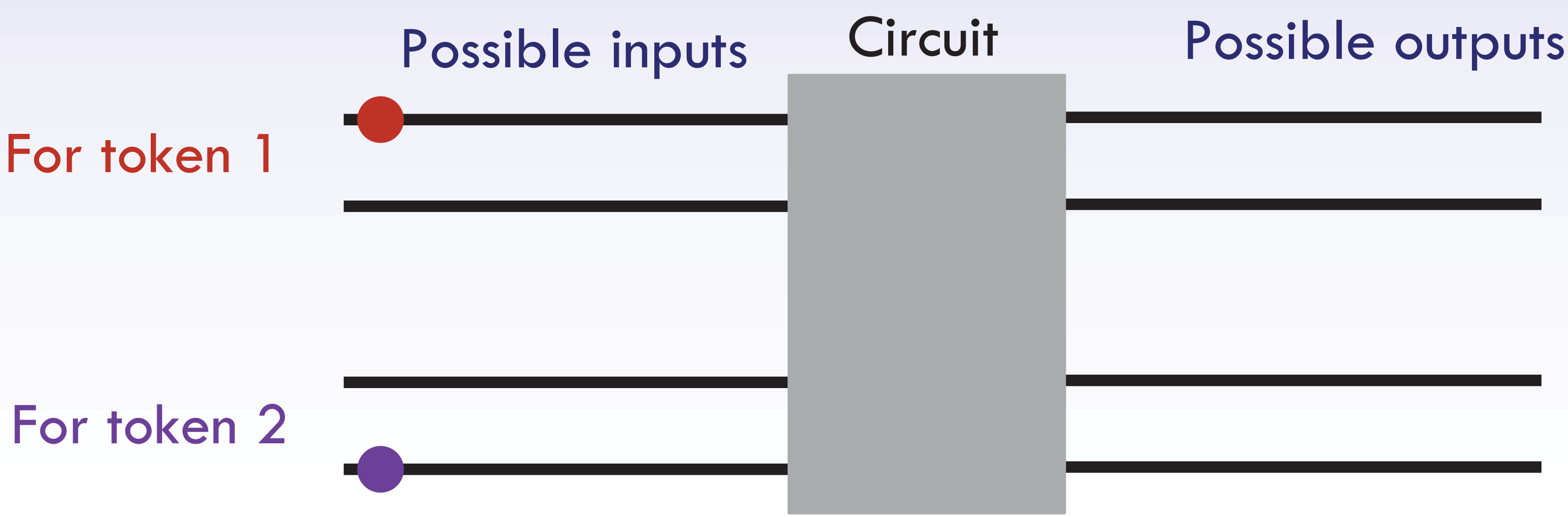
Non-conventional low power computing using skyrmions: (II) Token-based Brownian Computing

6. Token-based Brownian Computing - Basics

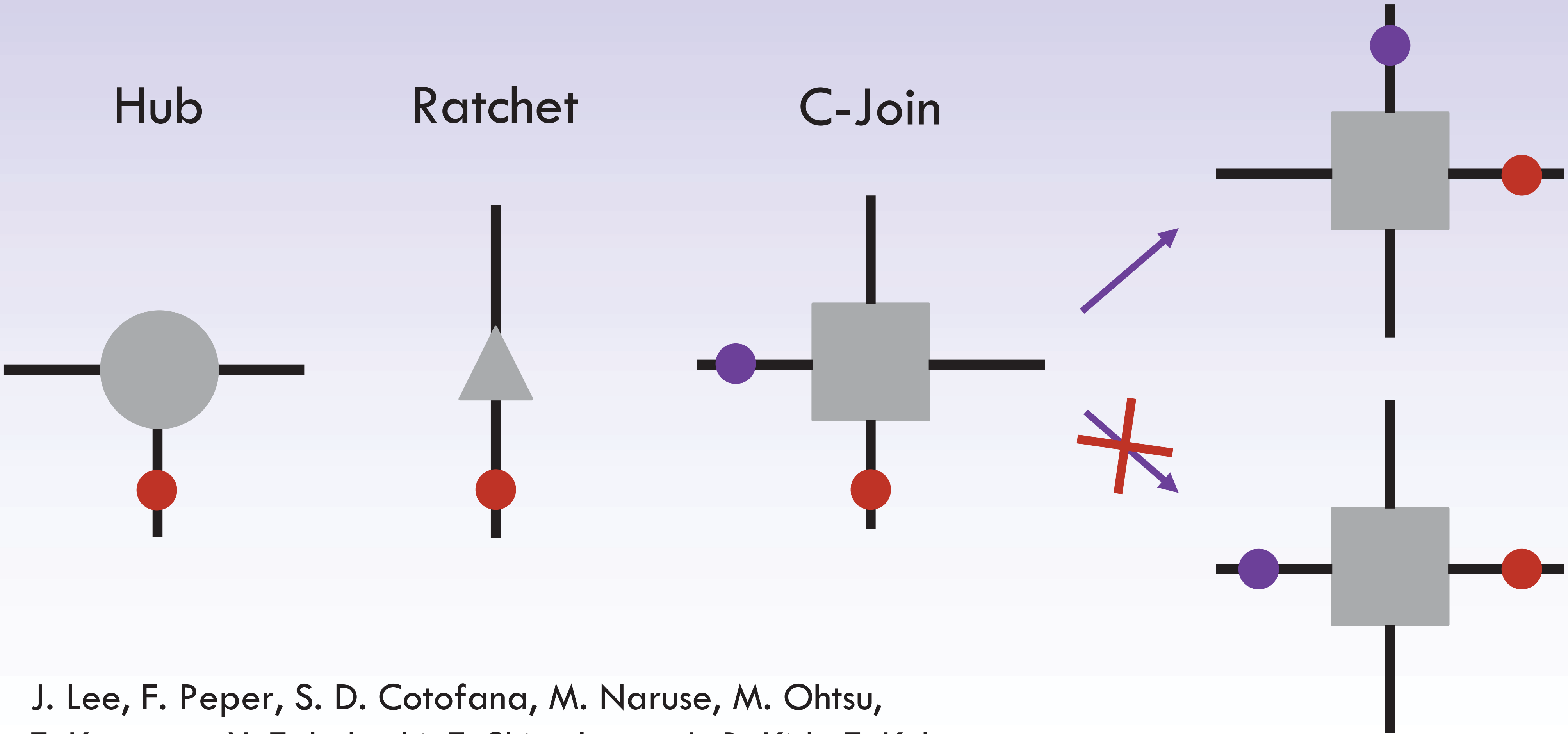
TOKEN-BASED COMPUTING FUNDAMENTALS

Token: Discrete signal carrier

Circuit: Network with special transition rules



6. Token-based Brownian Computing – Circuit Components



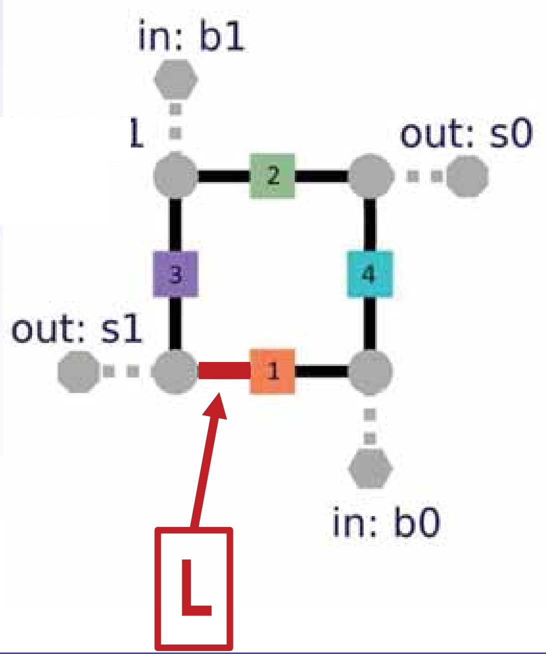
J. Lee, F. Peper, S. D. Cotofana, M. Naruse, M. Ohtsu,
T. Kawazoe,Y. Takahashi, T. Shimokawa, L. B. Kish, T. Kubota,
“Brownian circuits: Designs”, Int. J. Unconv. Comput. 12, 341-362 (2016)

6. Token-based Brownian Computing

COMPARISON IN REAL TIME

Layout	Condition	L = 10 µm	L = 5 µm
Crossing (thermal)	T = 307.6 K	16 min	4 min

Using synthetic antiferromagnet: sub-µs operation![2]

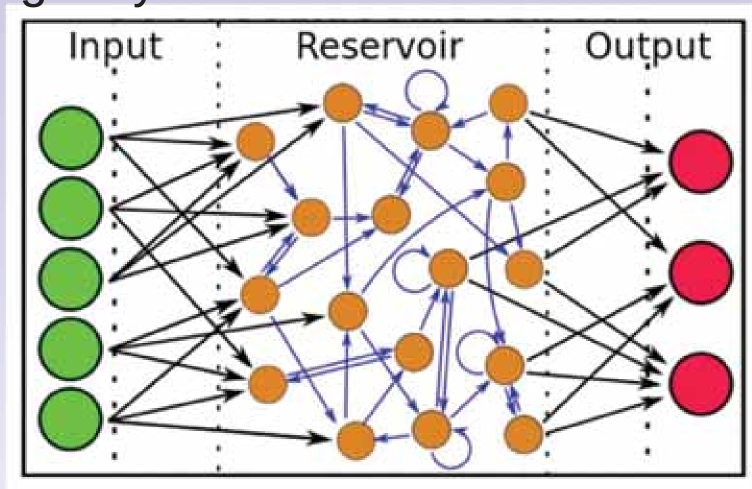


[1]M. A. Brems, P. Virnau, M. Kläui,
"Circuits and excitations to enable Brownian token-based computing with skyrmions", Appl. Phys. Lett. **119**, 132405 (2021)
M. A. Brems, P. Virnau, M. Kläui,
"Information processing apparatus",
European patent disclosure, EP21164676.5 (2021)
[2]T. Dohi, MK et al., Nature Comm. **14**, 5424 (2023)

Non-conventional low power computing using skyrmions: (III) Reservoir Computing

6. Reservoir Computing with Skyrmions

originally: artificial neural network with



recursive neural network

feed forward only

Goal: map a complex problem to a linearly solvable one

- **Network does not need tuning**: internal connections are fixed
- Only output connections are trained

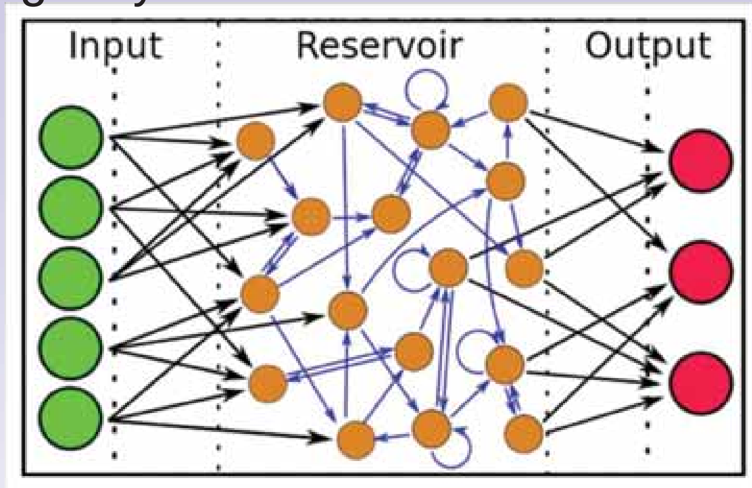
RC bypasses training constraints

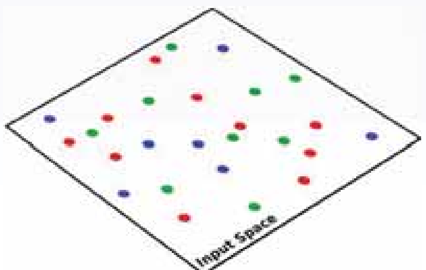
Courtesy Karin Everschor-Sitte

D. Pinna, et al., Phys. Rev. Appl. **14**, 054020 (2020)

6. Reservoir Computing with Skyrmions

originally: artificial neural network with





Goal: map a complex problem to a linearly solvable one

Functionality:

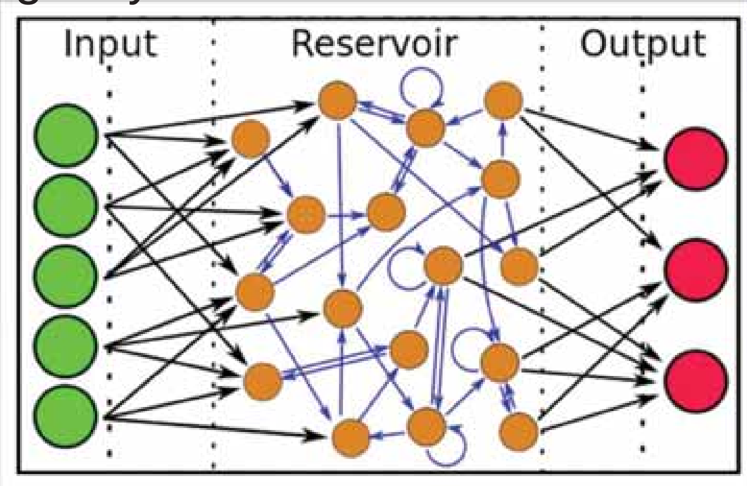
Reservoir projects different spatial-temporal events into a sparsely populated high dimensional space where they become easier to recognise and categorise

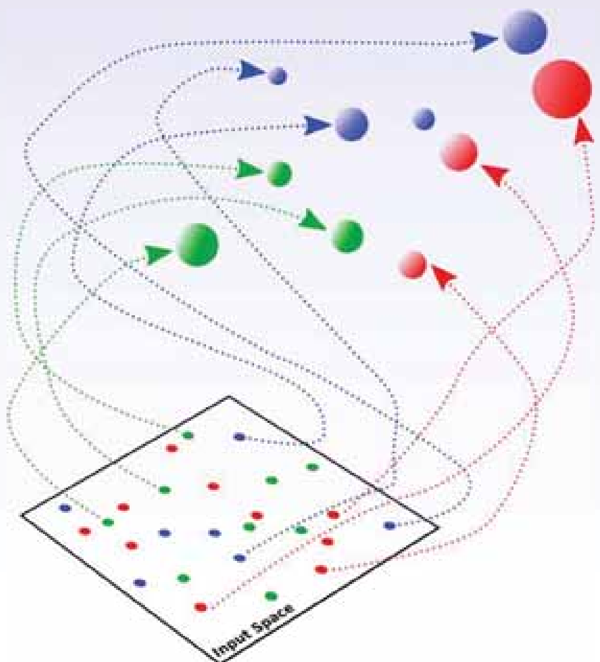
Courtesy Karin Everschor-Sitte

D. Pinna, et al., Phys. Rev. Appl. **14**, 054020 (2020)

6. Reservoir Computing with Skyrmions

originally: artificial neural network with





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D. Pinna, et al., Phys. Rev. Appl. **14**, 054020 (2020)

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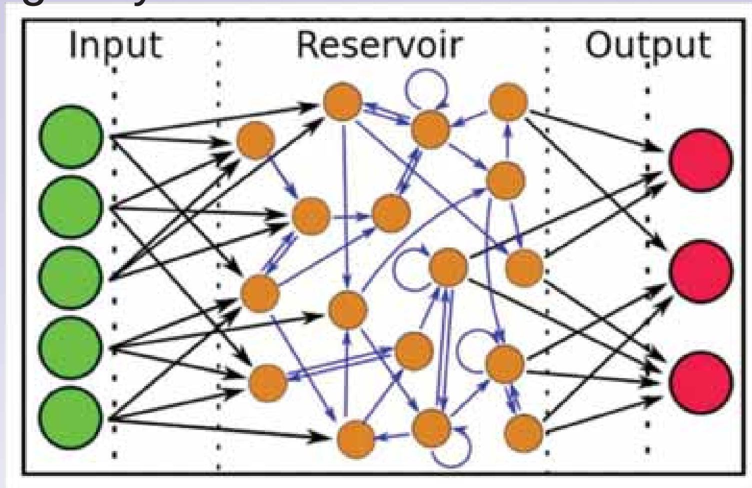
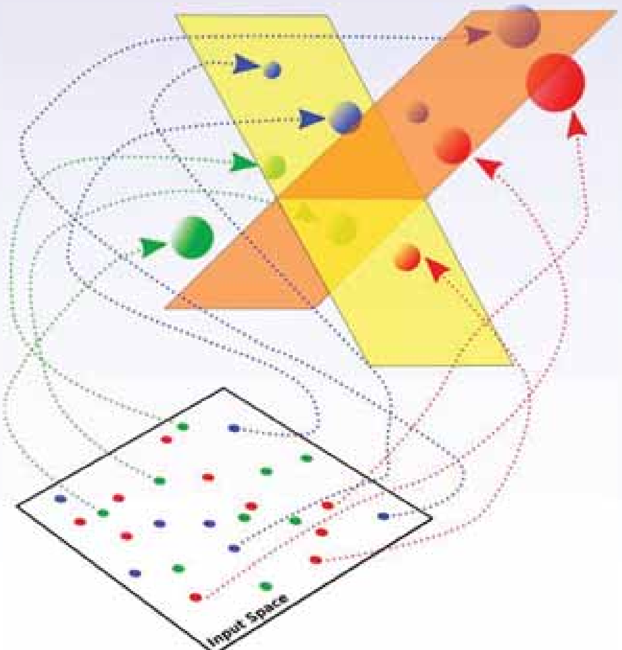
originally: artificial neural network with





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D. Pinna, et al., Phys. Rev. Appl. **14**, 054020 (2020)

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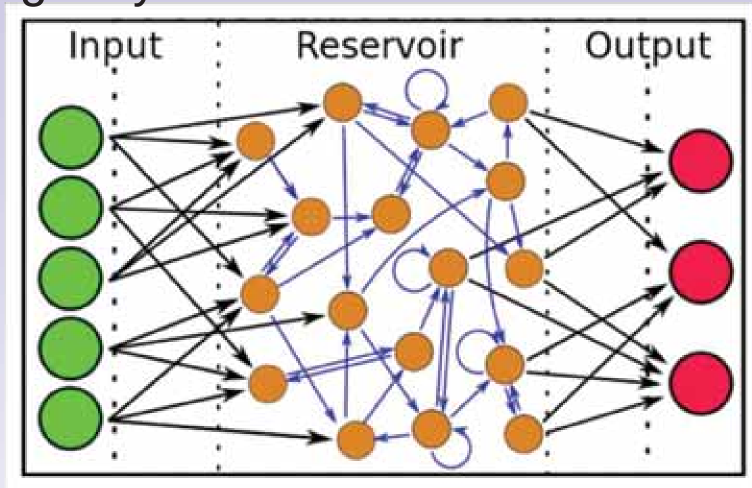

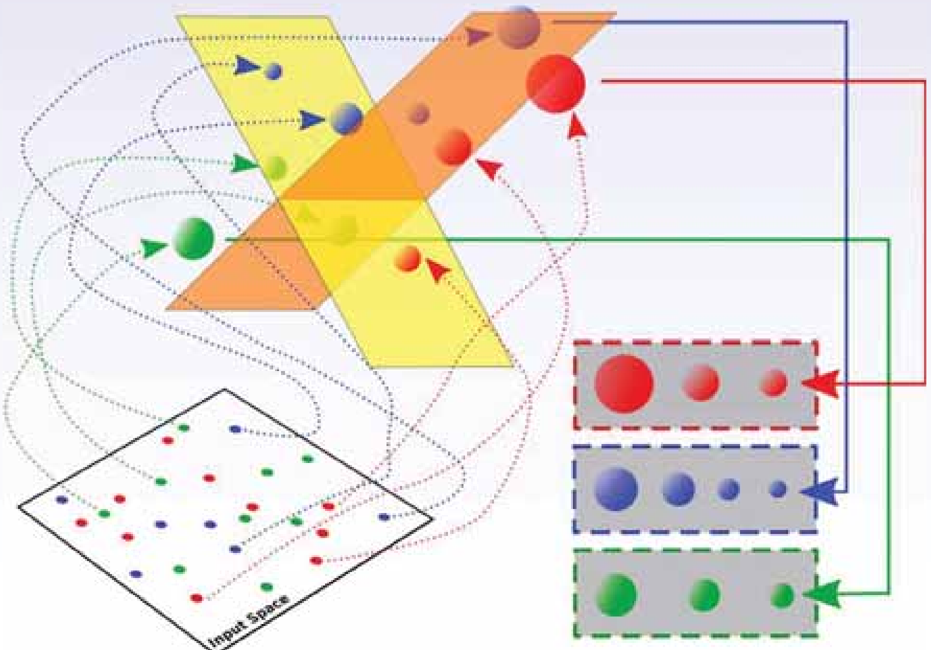

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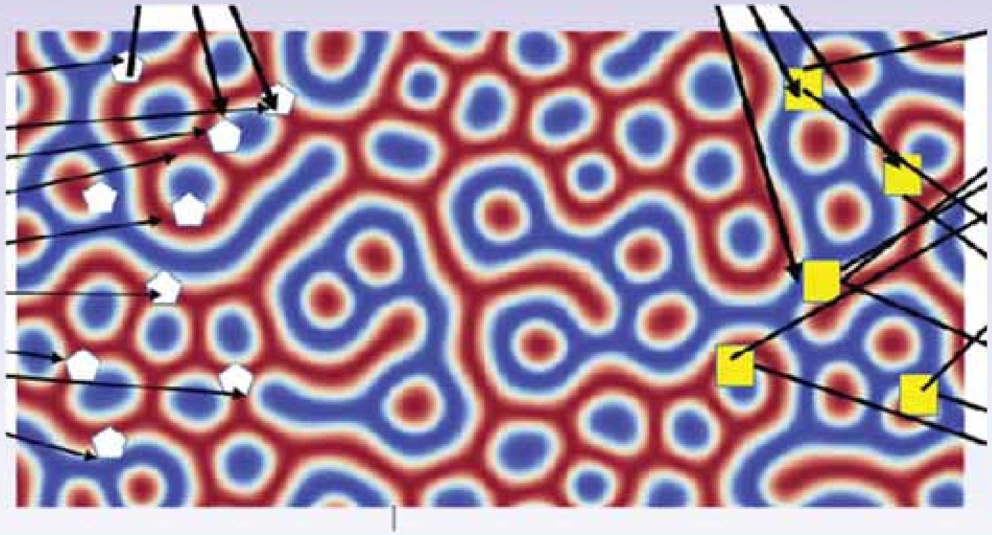
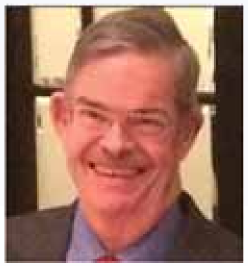
Courtesy Karin Everschor-Sitte

D. Pinna, et al., Phys. Rev. Appl. **14**, 054020 (2020)

6. Reservoir Computing using Skyrmions



“skyrmion fabrics” as reservoir

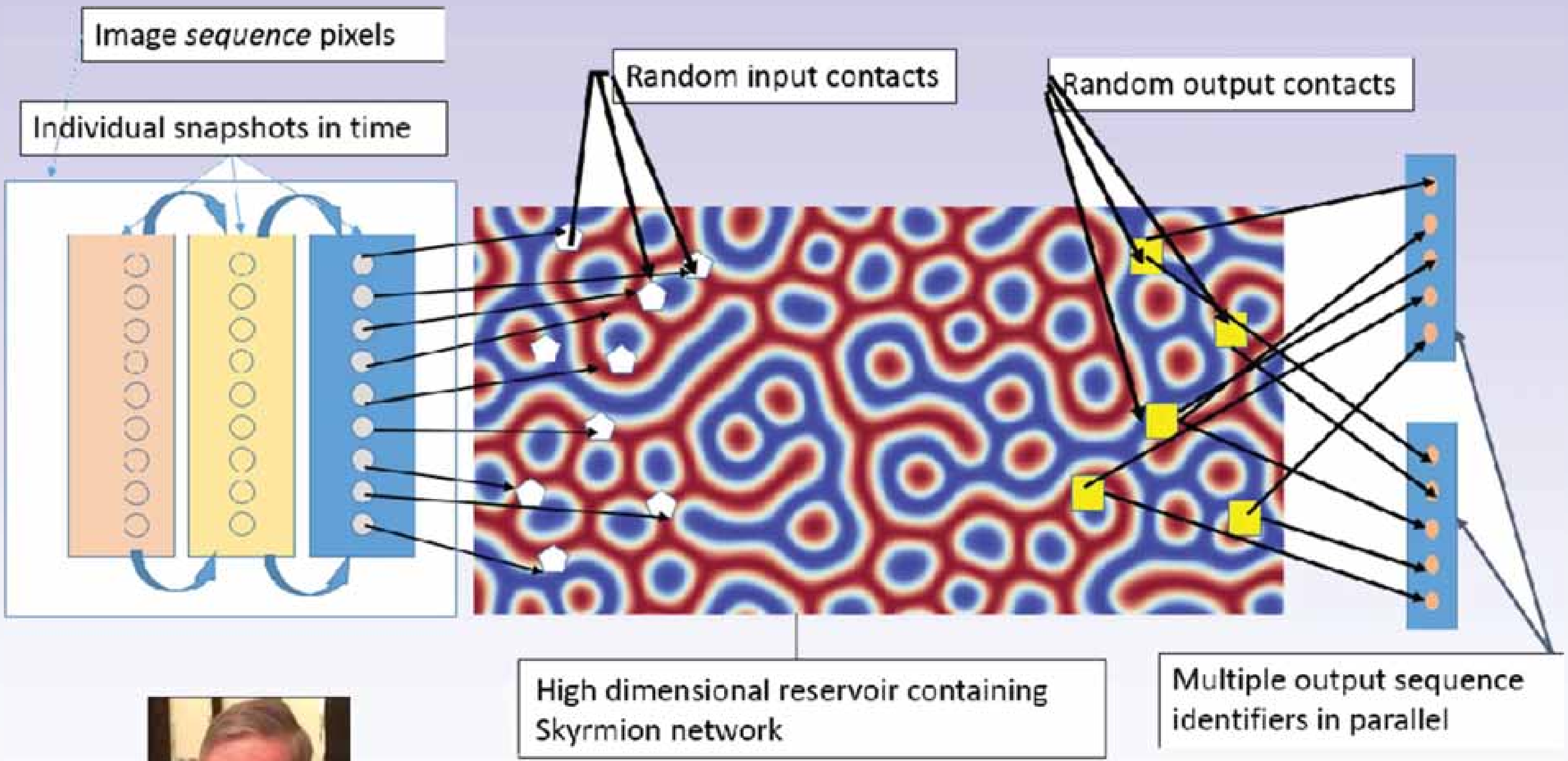


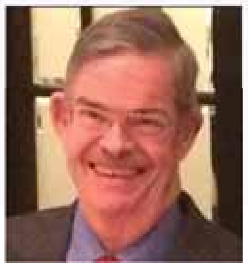
George Bourianoff

courtesy K. Everschor-Sitte

D. Prychynenko, MK et al., Phys. Rev. Appl. **9**, 14034 (2018)

6. Reservoir Computing using Skyrmions



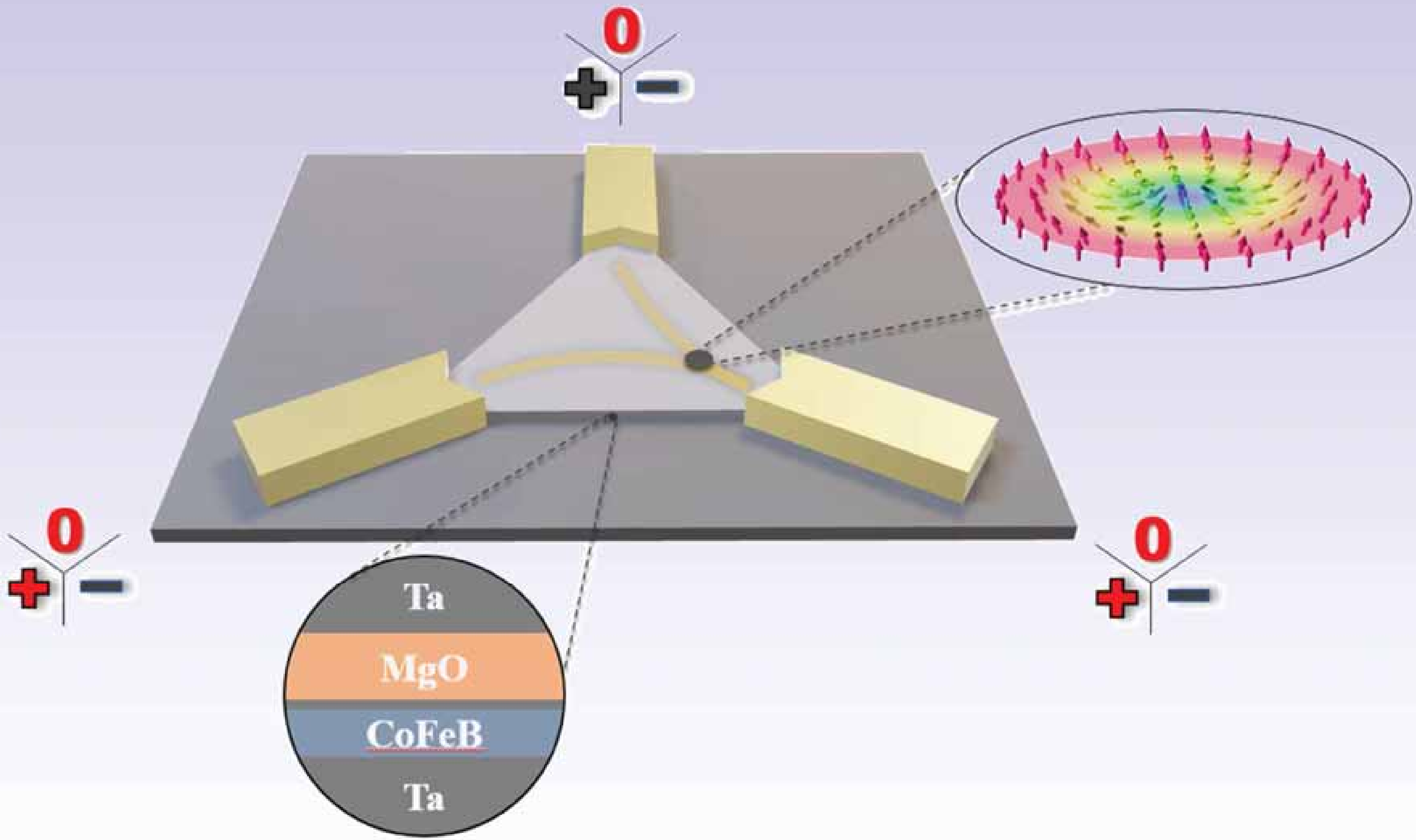


George Bourianoff

courtesy K. Everschor-Sitte

D. Prychynenko, MK et al., Phys. Rev. Appl. **9**, 14034 (2018)

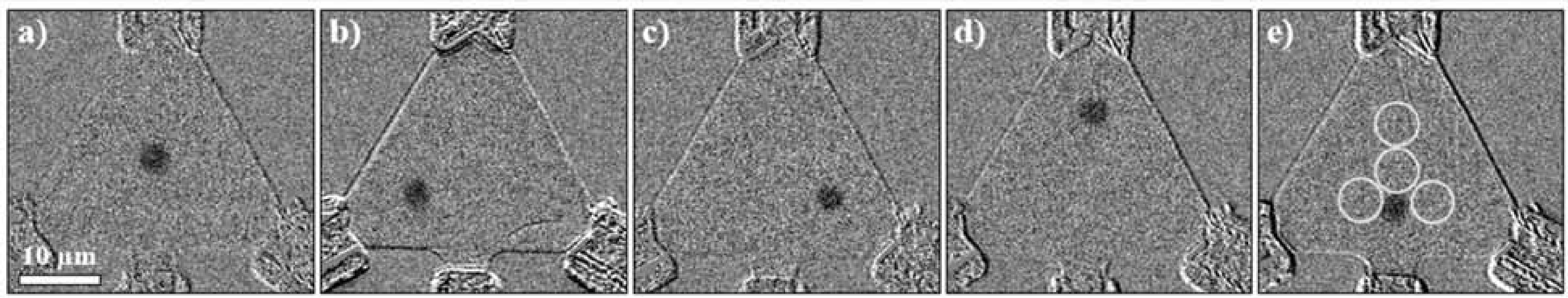
7. Realization of spatial multiplexing reservoir computing

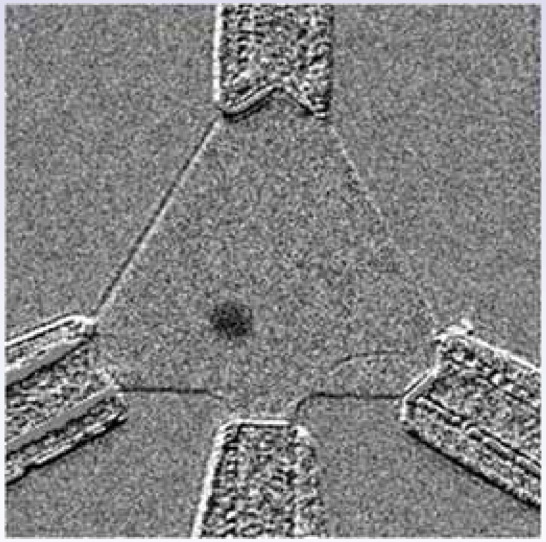


K. Raab, MK et al., Nature Comm. **13**, 6982 (2022)

- Analysis of dynamics of skyrmions in a confined geometry with additional **input currents** → aim to learn input current combinations from skyrmion positions.

7. Realization of spatial multiplexing reservoir computing

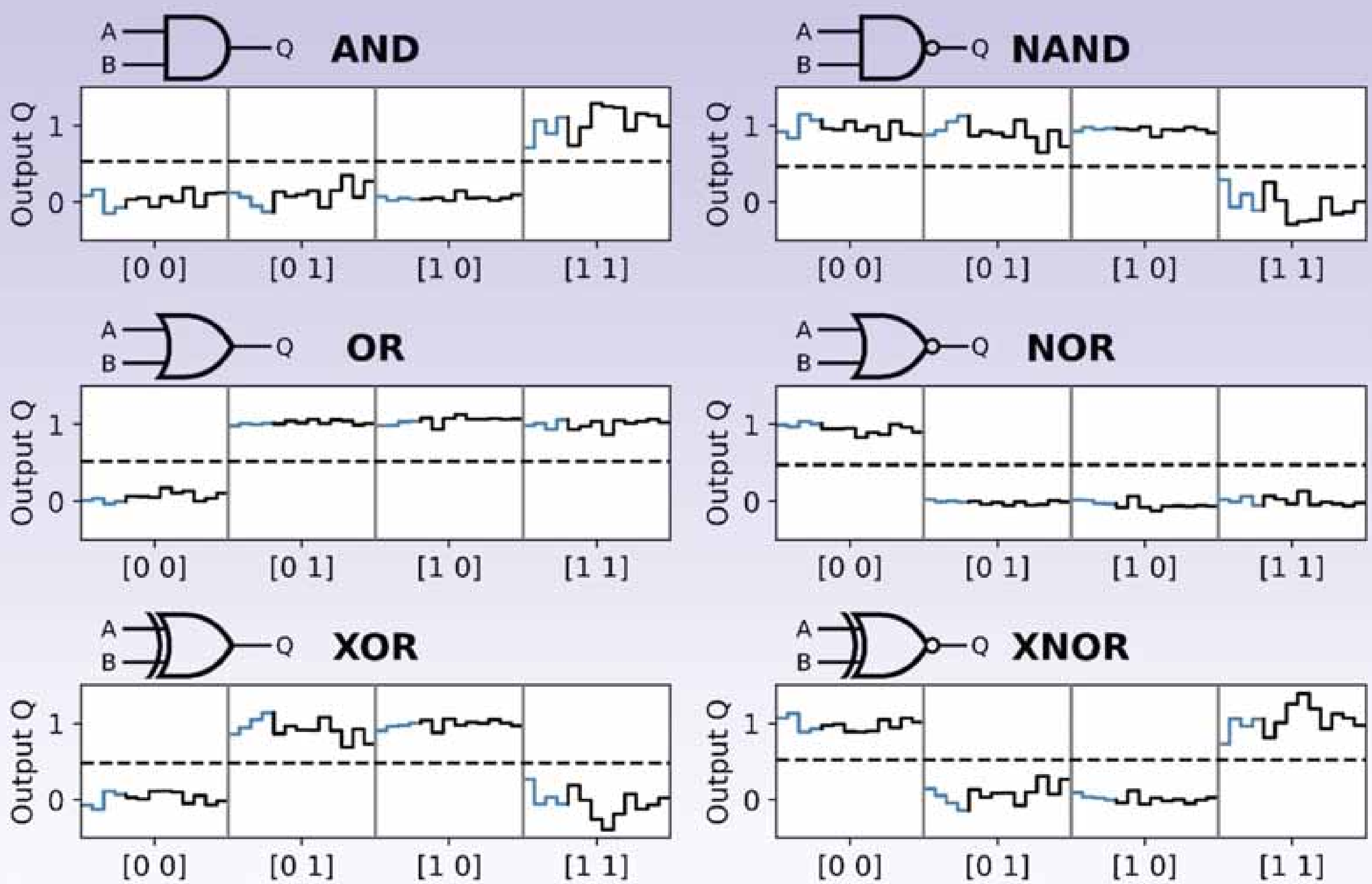




K. Raab, MK et al., Nature Comm. **13**, 6982 (2022)

- Analysis of dynamics of skyrmions in a confined geometry with additional **input currents** → aim to learn input current combinations from skyrmion positions.

7. Realization of spatial multiplexing reservoir computing



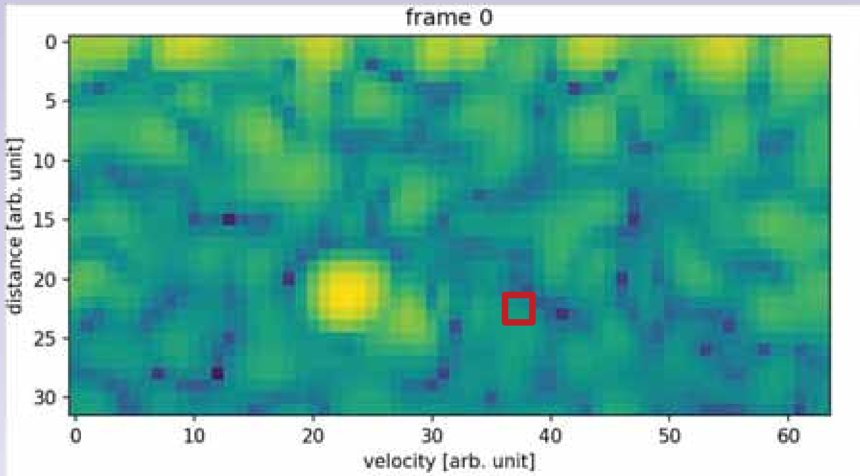
K. Raab, MK et al., Nature Comm. **13**, 6982 (2022)

← Non-separable functions (outperforming simple perceptron)

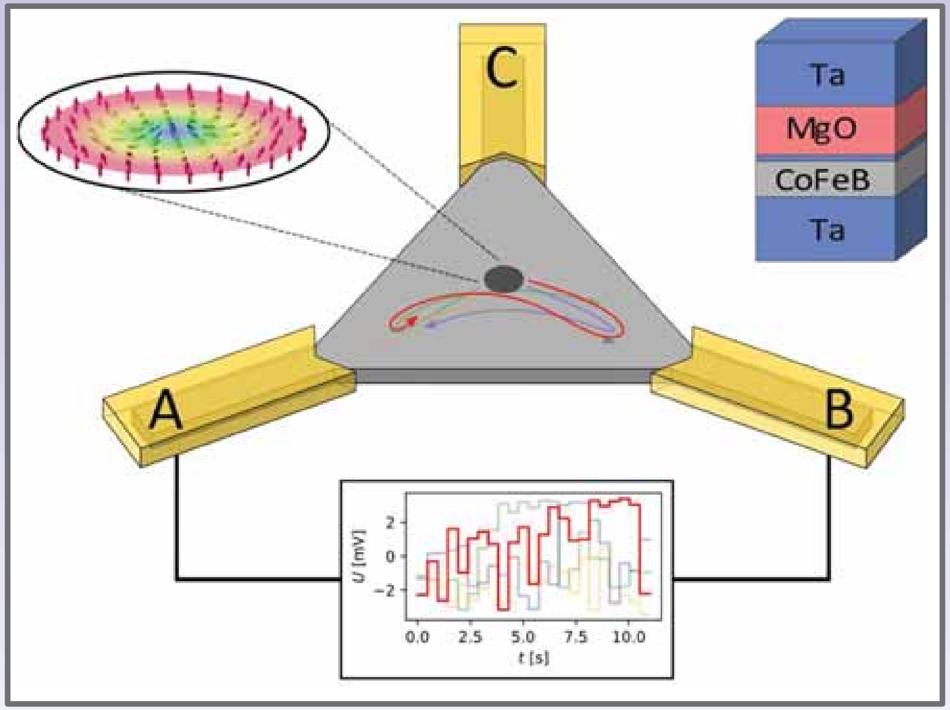
Analysis of Output $Q = W_{left}P_{left} + W_{right}P_{righ} + W_{top}P_{top} + W_{middle}P_{middle} + W_{intercept}$

- Outputs of the linear read-out optimized for different Boolean operations.
- For each input combination [A B] the output Q of the linear read-out is shown for sets of local skyrmion occurrence probabilities. Light blue: training sets; Black: sets used for testing
- Dashed horizontal line indicates a possible threshold for perceptron read-out.

7. Realization of time-multiplexed reservoir computing



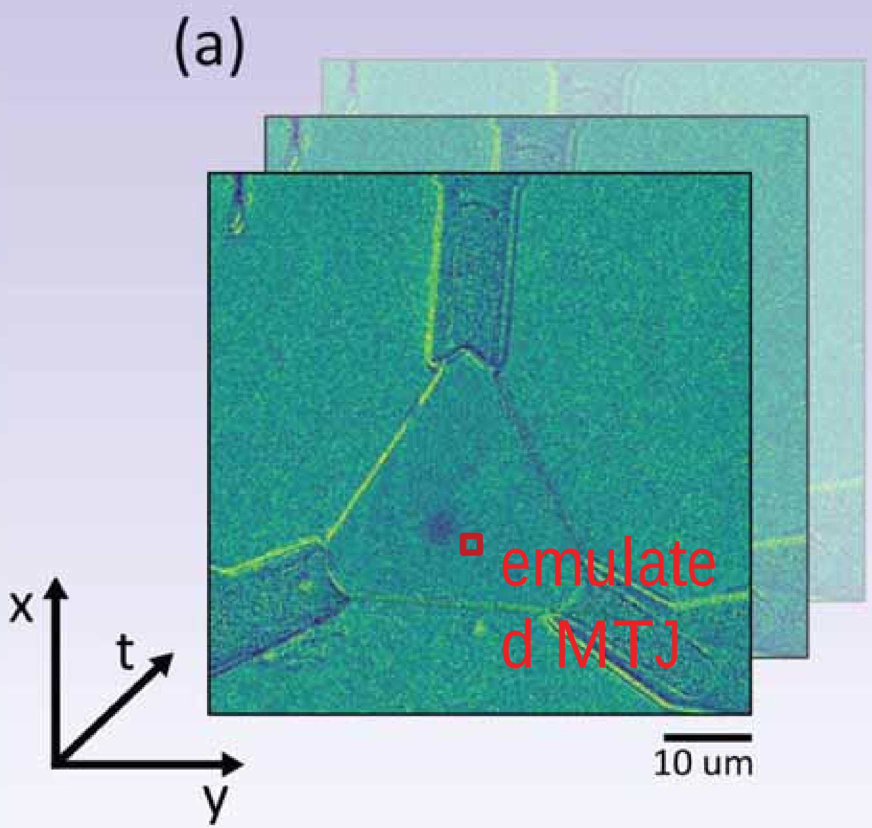
Gesture	Name
	push
	swipe left
	swipe right
X	no gesture



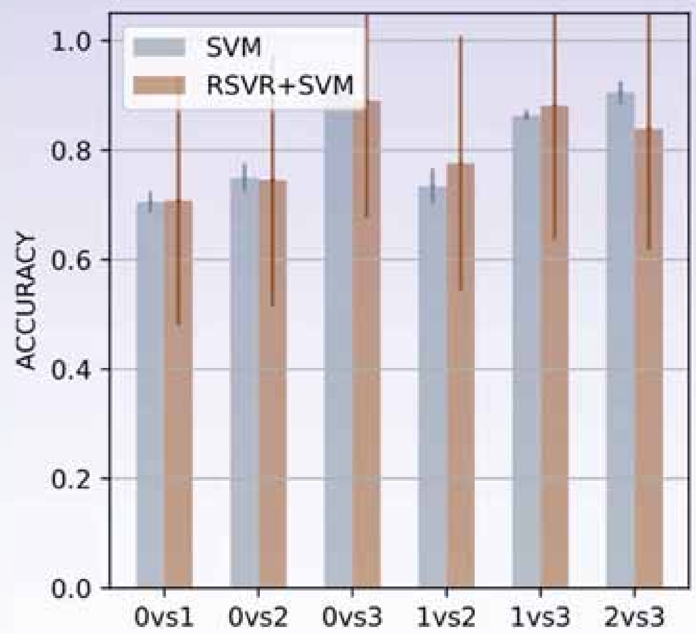
G. Beneke, MK et al., (submitted)

- Distinguish different hand gestures using reservoir computing
- Conversion of radar data to time dependent voltage and feeding into reservoir
- Observation of time dependent skyrmion position

7. Realization of time-multiplexed reservoir computing



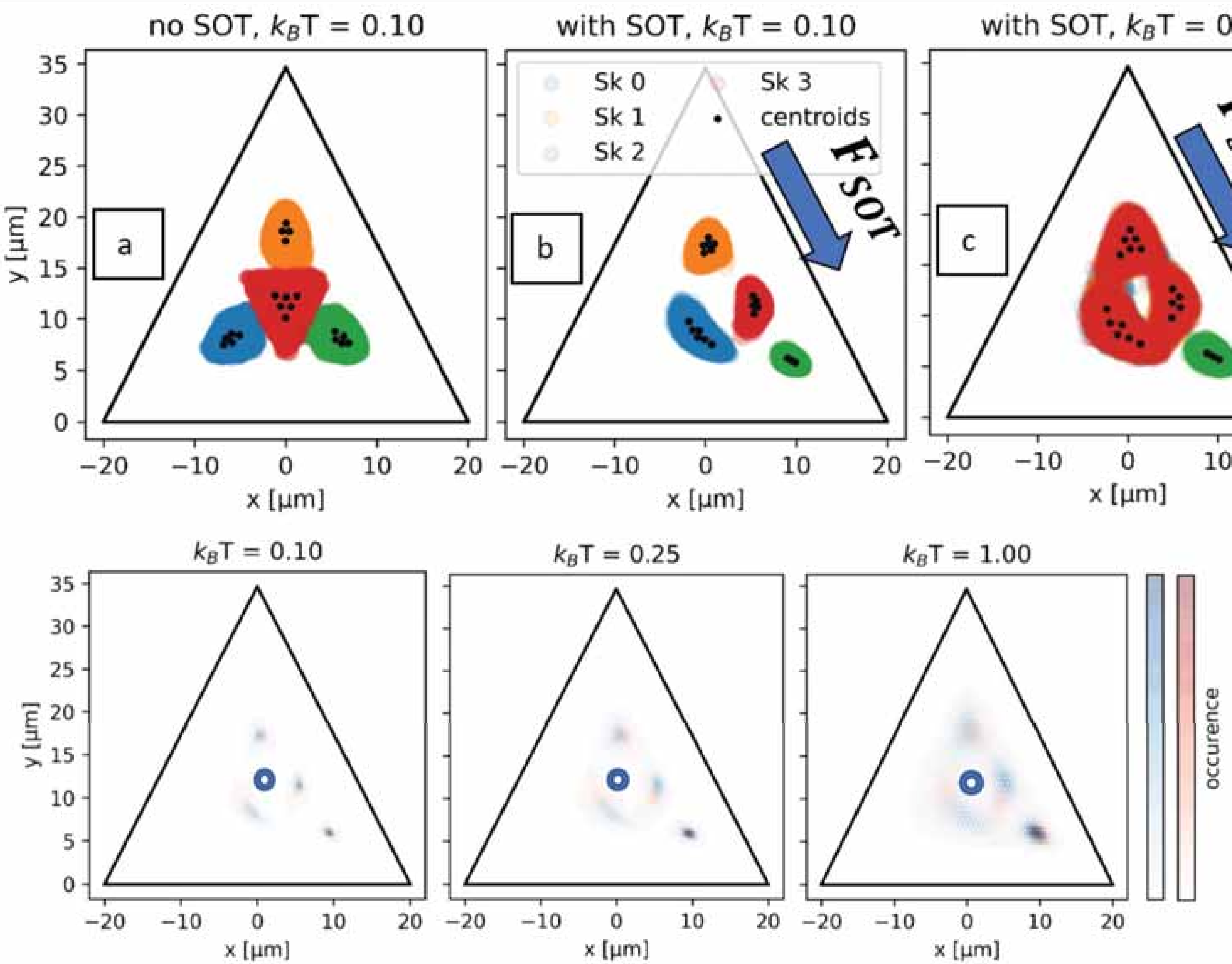
Gesture	Number	Name
	0	push
	1	swipe left
	2	swipe right
X	3	no gesture



G. Beneke, MK et al., (submitted)

- Conversion of MOKE video to magnetic tunnel junction (MTJ) signal
- Learn linear support vector machine on MTJ signal
- Reservoir (RSVR) delivers competitive results compared to state-of-the-art support vector machine (SVM)

8. Coarse graining



T. Winkler, MK et al., Appl. Phys. Lett. **124**, 022403 (2024)

- Study different positions of 4 skyrmions in a triangle with current injection.
- Use different analysis methods including PCA and generalized Peron cluster cluster analysis (GPCCA), which uses Schur decomposition techniques to coarse-grain the system.

Thanks!

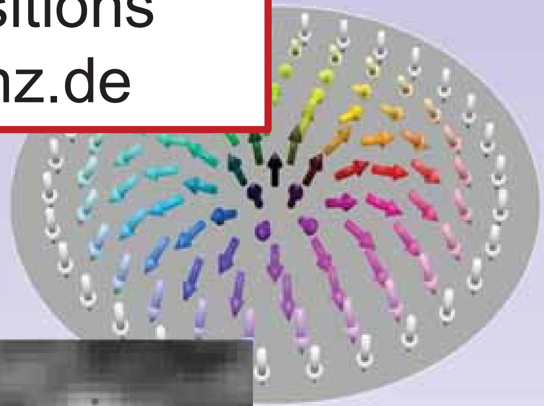
1. Great people@JGU

M. Bhukta, F. Kammerbauer, N. Kerber
K. Raab, A. Lucia, M. Syskaki, S. Krishnia
R. Gruber, M. Brems, S. Ding, A. Bose,
J. Rothörl, T. Winkler, R. Gupta, O. Ledsm
T. Sparmann, G. Beneke, T. Saunderson,
K. Leutner, **P. Virnau**, **R. Frömter, M. Jourdan, G. Jakob & many former group members!**

European Research Council Grant 3D MAGiC, ADI, Infineon,
Stanford-Tohoku-Mainz SpinNet, TopDyn Centre, MagSens

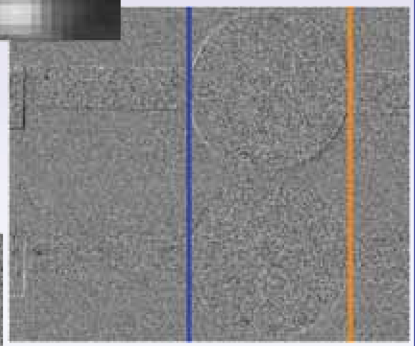
Summary:

Interested in the slides? Interested in joining us?
We have open PhD and Postdoc positions
Send me an email: klaeui@uni-mainz.de



- **DMI stabi... fined topology: pinning at domain walls**
  Nature Mater. **15**, 501 (2016); Nature Mater. **18**, 703 (2019); Nano Lett. **23**, 7070 (2023); Nature Com. **11**, 6304 (2020); Nature Com. **13**, 3144 (2022);

- **Skyrmion motion due to spin-orbit & orbital torques → Skyrmion Hall Angle**
  Nature Physics **13**, 170 (2017); Nature Electron. **3**, 30 (2020); Phys. Rev. Lett. **125**, 177201 ('20); Phys. Rev. Lett. **128**, 067201 ('22)



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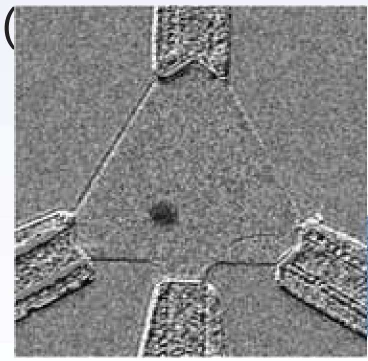

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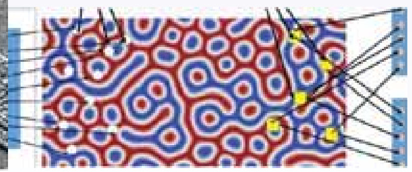

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