Magnetic Solitons in Spin-Orbitronics: novel science and applications in memory & non-conventional 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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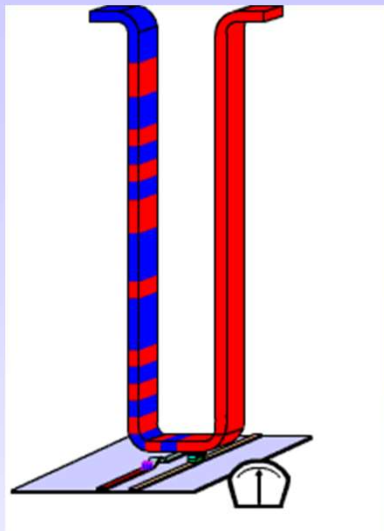
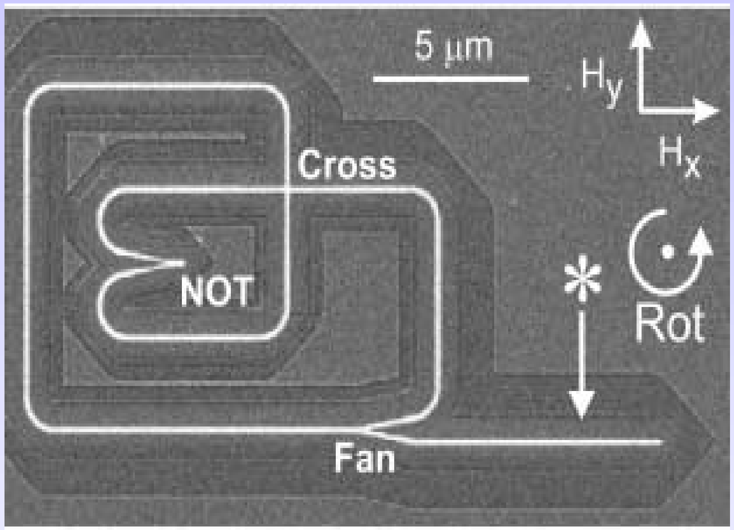
Devices based on Condensed Matter Solitons

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

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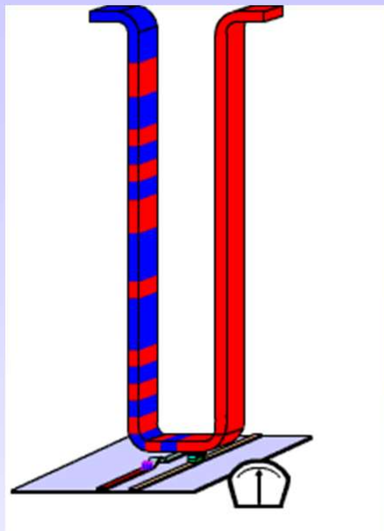

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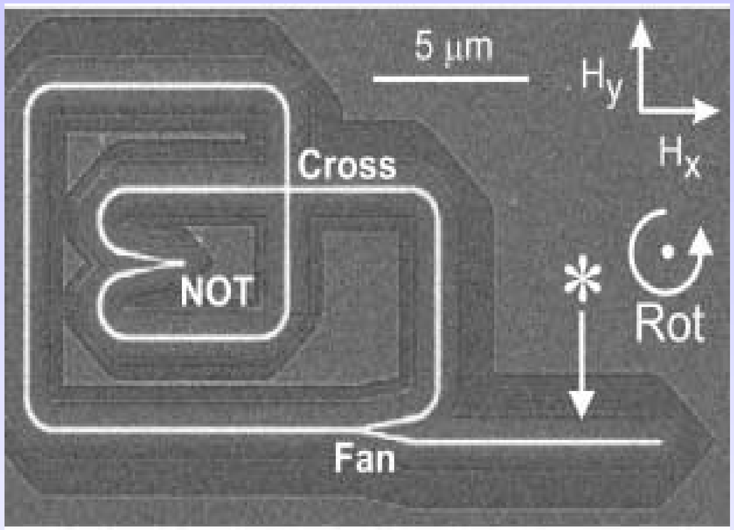

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Challenges for Spintronics Devices:

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 Condensed Matter Solitons

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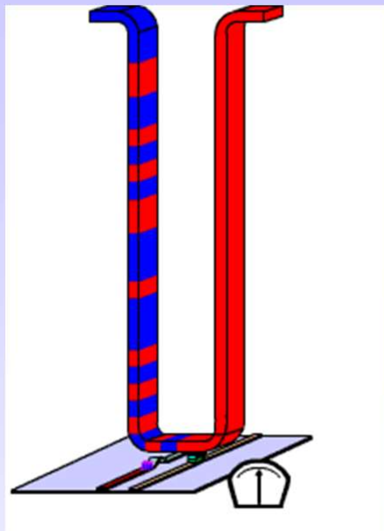

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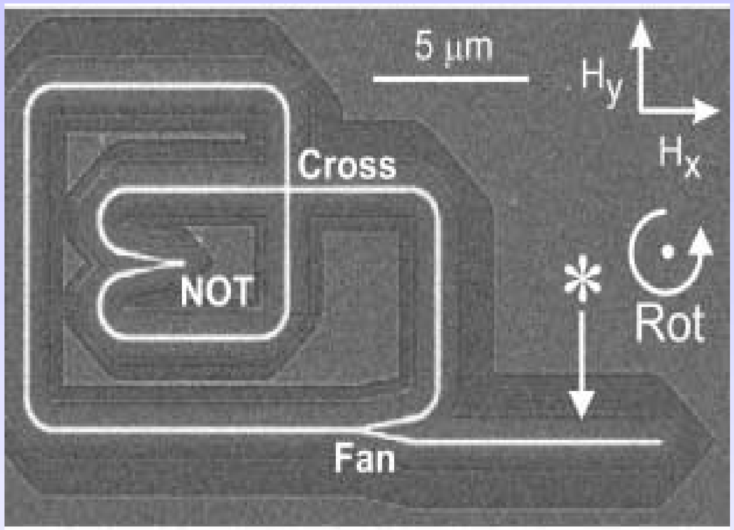

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Skyrmions in Spin-Orbitronics & Orbitronics: novel science and applications in memory & non-conventional computing

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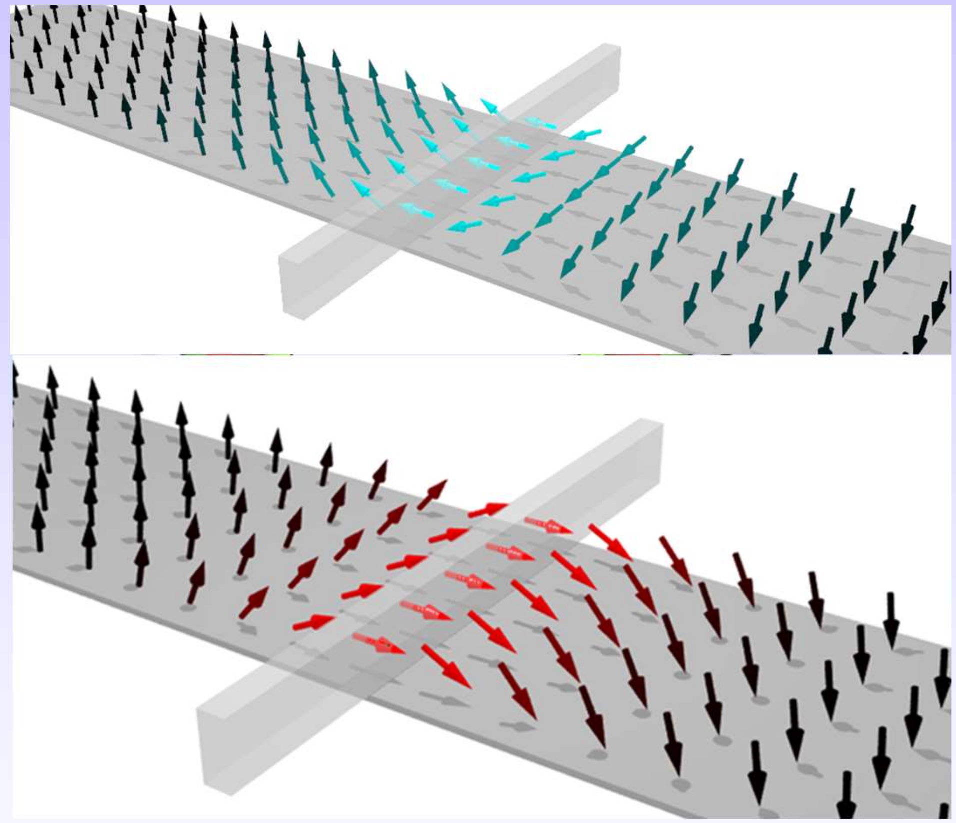
0. Magnetic coupling – Heisenberg exchange coupling

Conventional:

Spin-Spin Heisenberg exchange interaction

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

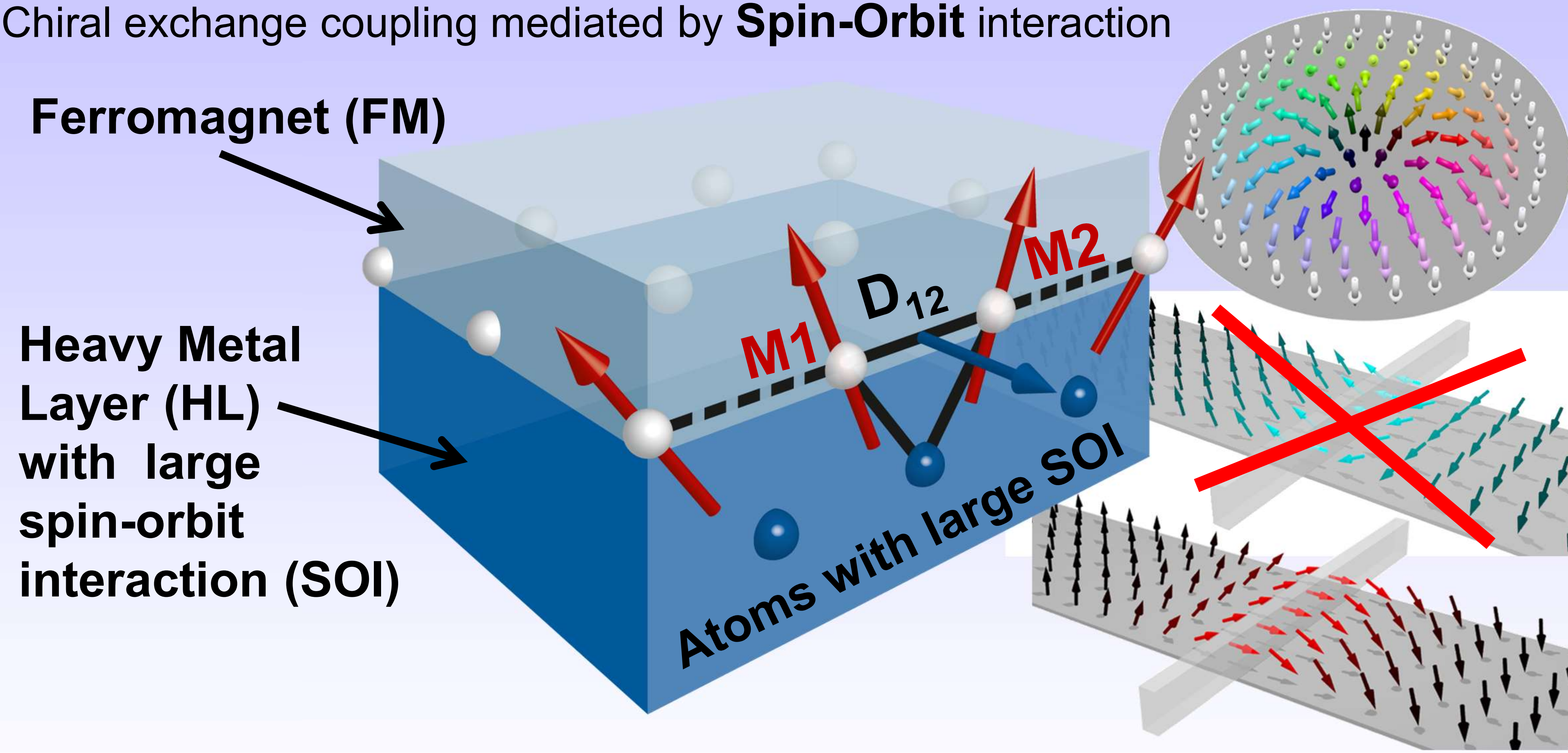


- Heisenberg exchange interaction sets the magnetic ordering.
- However many energetically degenerate spin structures can be stabilized → spin structures do not have a set chirality.

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

0. Chiral exchange coupling – Dzyaloshinskii-Moriya interaction

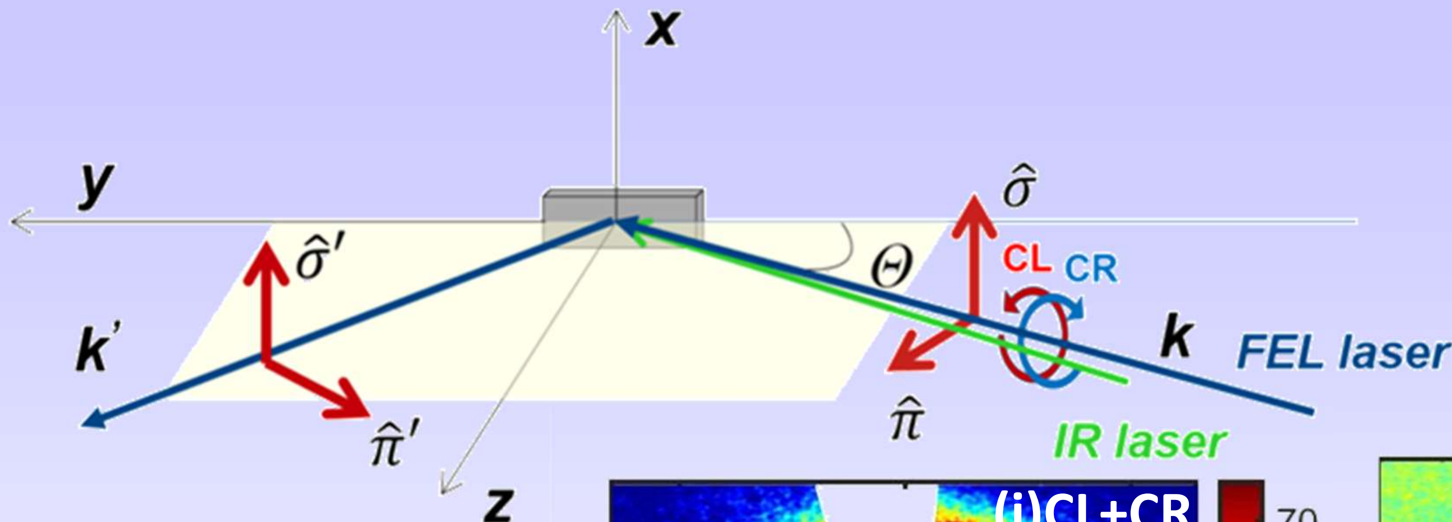
Chiral exchange coupling mediated by **Spin-Orbit** interaction



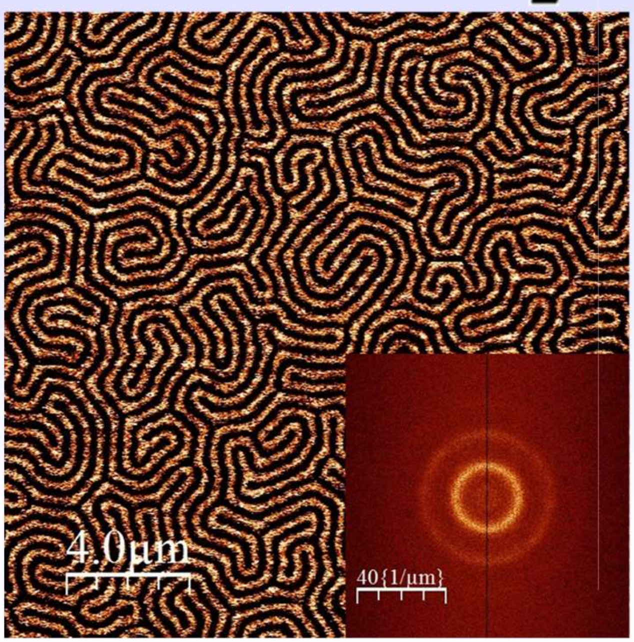
- Two spins in the ferromagnet are coupled via an atom with large SOI in a heavy metal layer → Dzyaloshinskii-Moriya interaction (DMI)
- Favours a spin canting with defined chirality → Chiral Domain Walls!

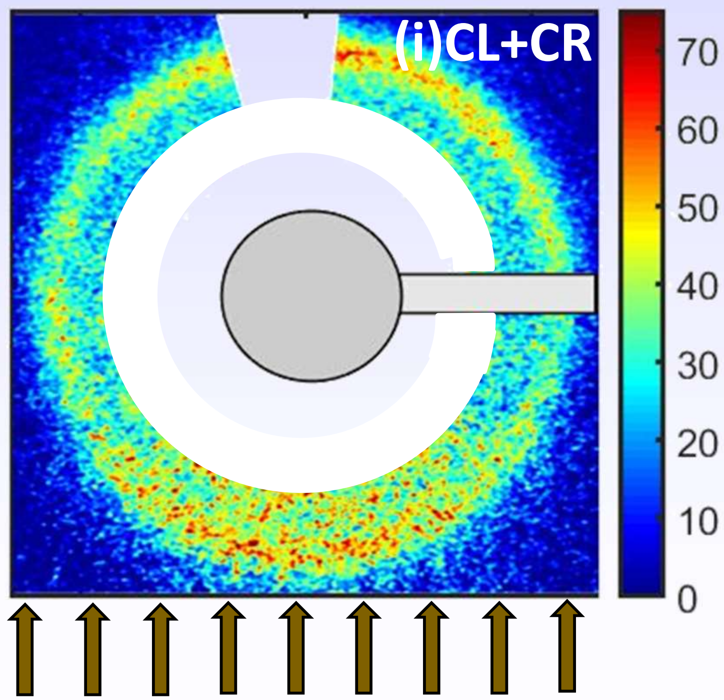
I. Dzyaloshinsky, J. Phys. Chem. Solids **4**, 241 (1958); T. Moriya, Phys. Rev. Lett. **4**, 228 (1960)

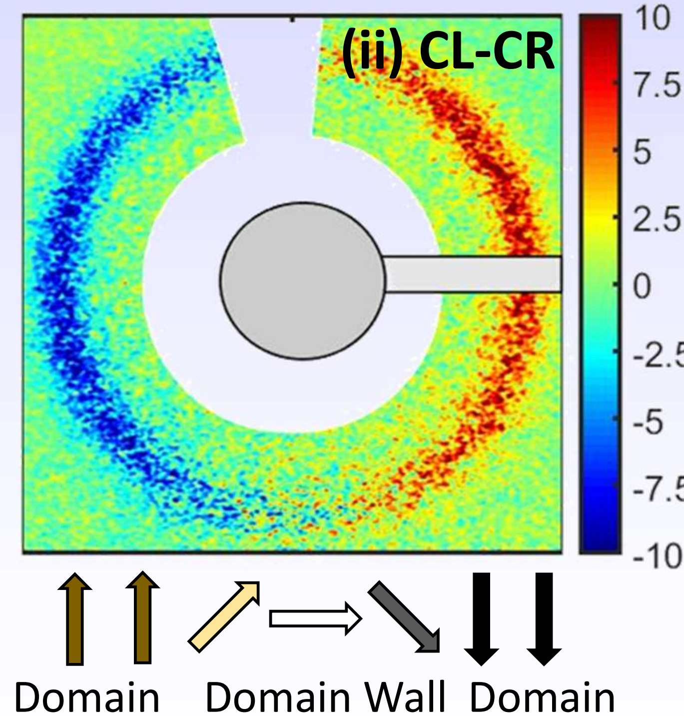
0. Chiral exchange coupling – ultra-fast spin-orbitronics



fs-time-resolved small angle x-ray scattering @FERMI Free Electron Laser



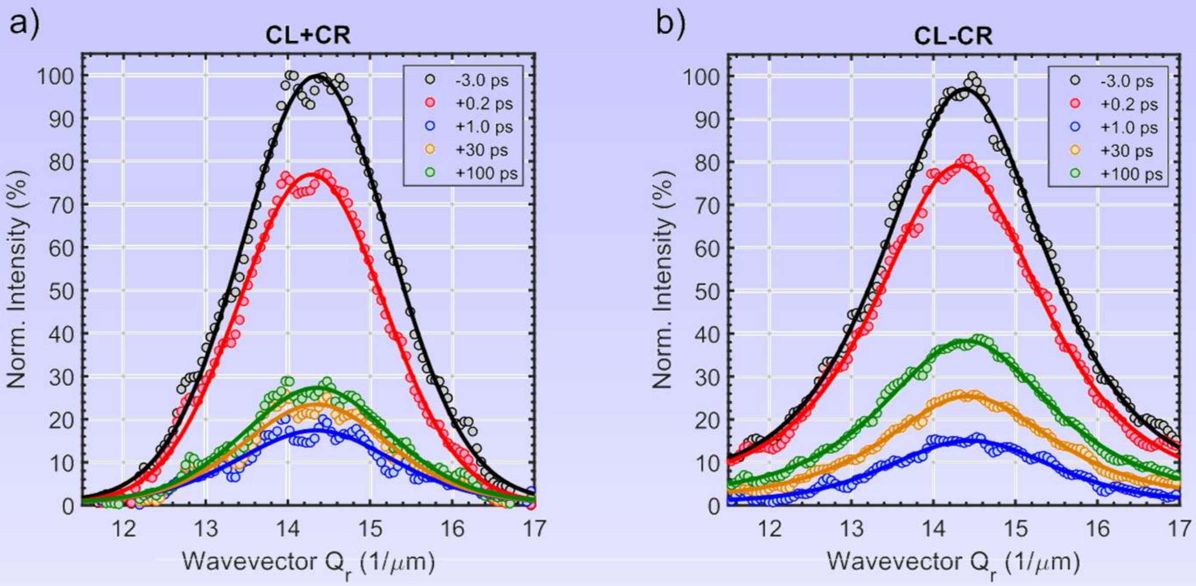


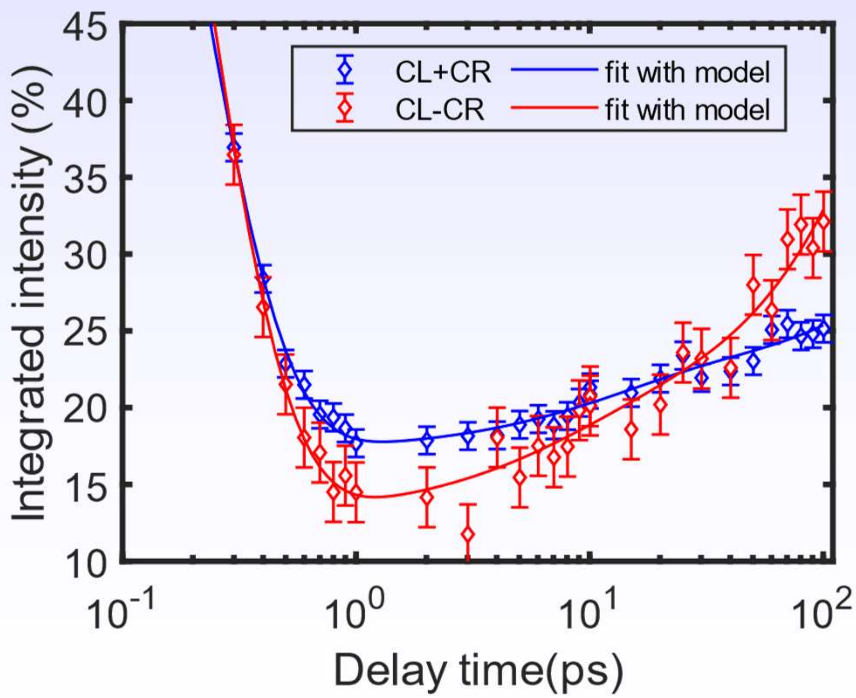


- Time evolution of (i) collinear order in domains and (ii) chiral order in DWs

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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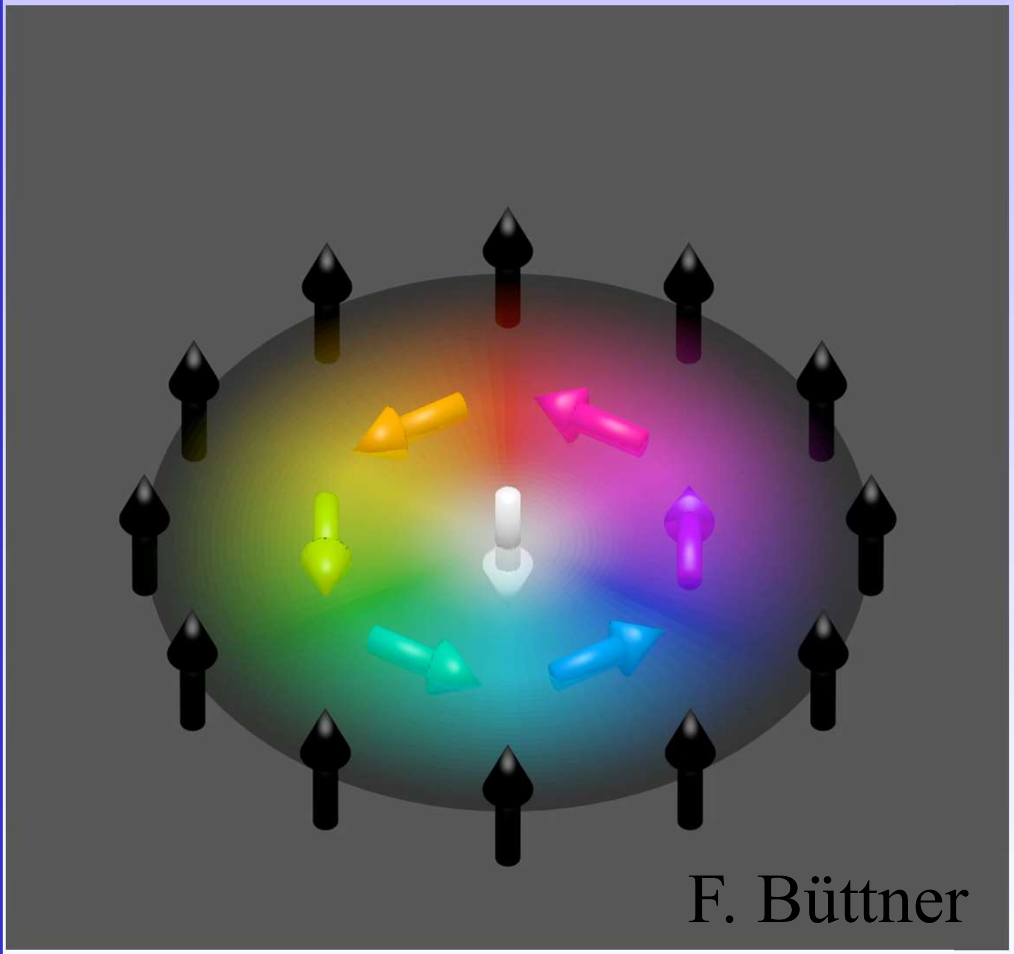
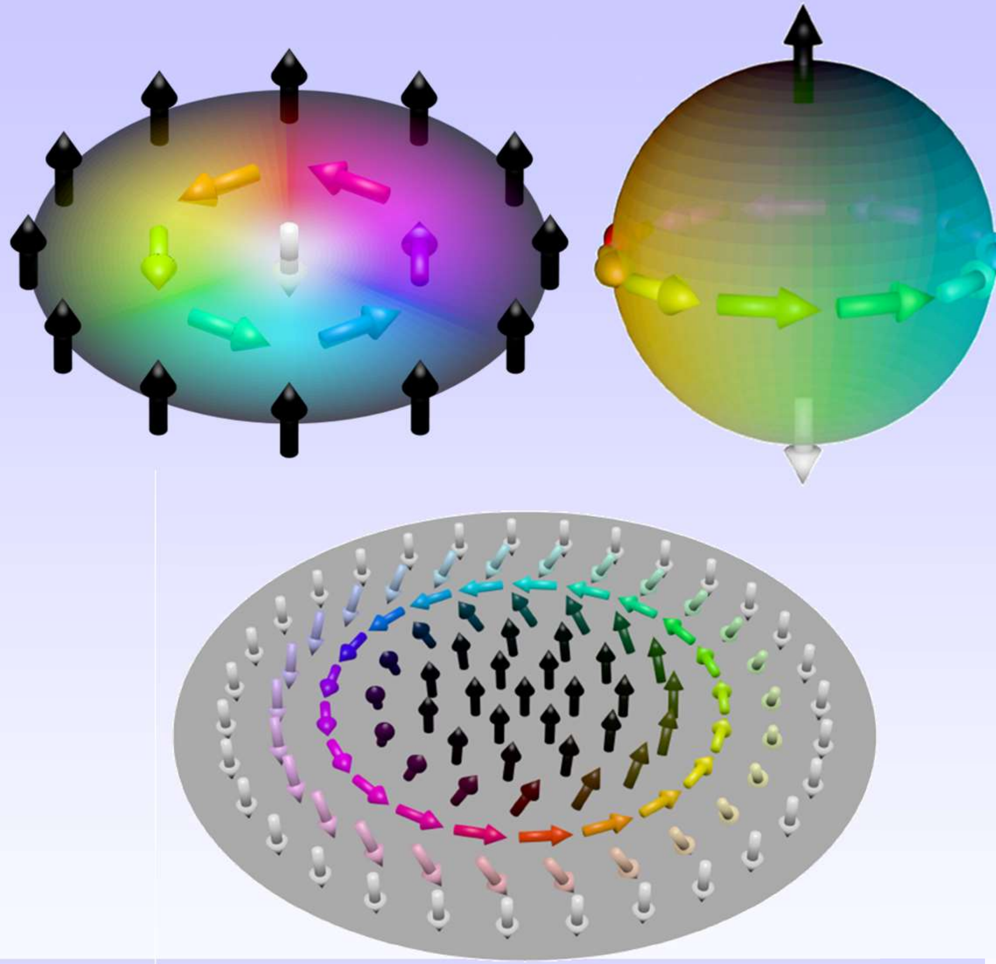
1. Topological Skyrmion Spin Structures in high-anisotropy materials

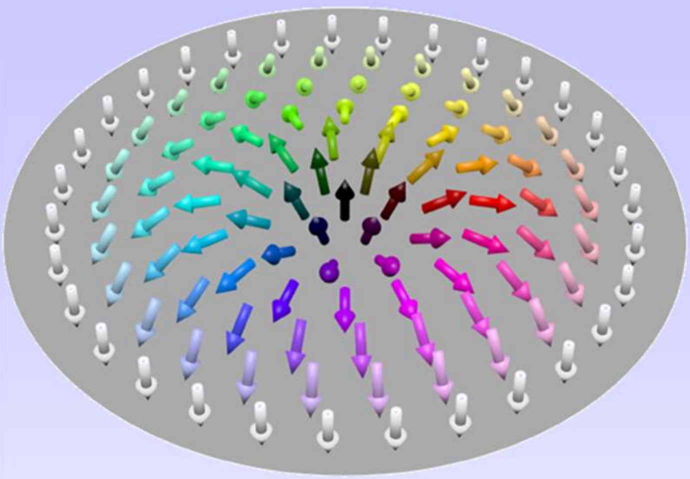




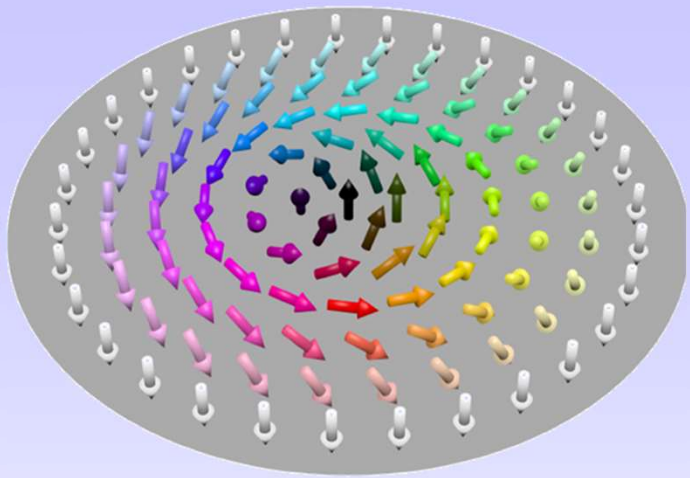
- Skyrmions are vector fields that can be continuously deformed into a sphere.
- For appropriately designed DMI, exchange, anisotropy, saturation magnetization, skyrmion spin structures can be stabilized as metastable states or ground states.

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)

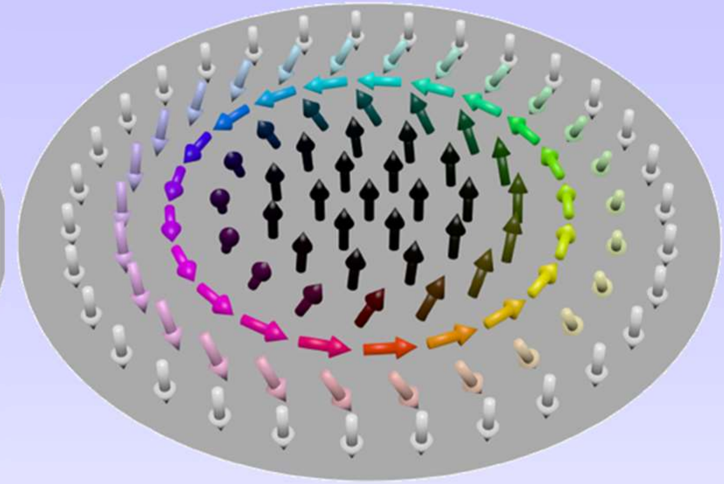
1. Spin Structures stabilized by the chiral DMI



Hedgehog skyrmion (N=1)



Chiral skyrmion (N=1)



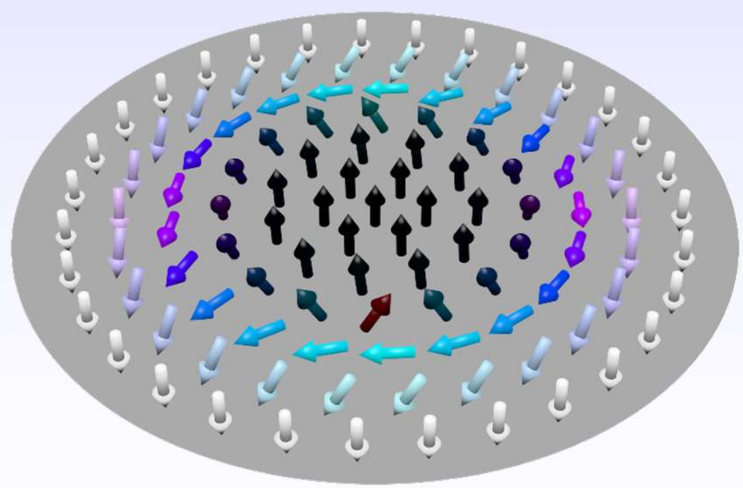
Bubble skyrmion (N=1)

- 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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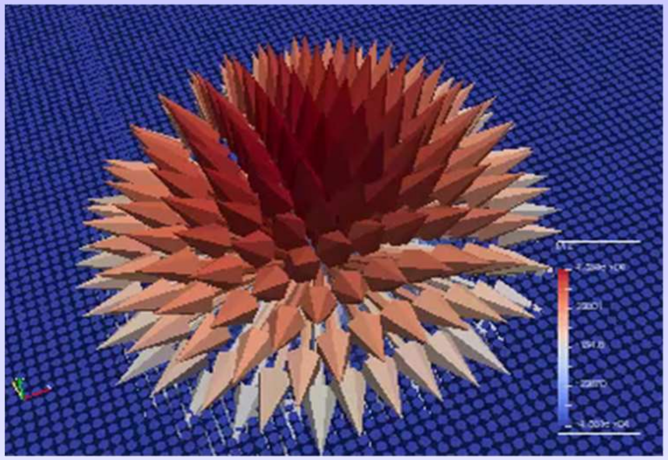
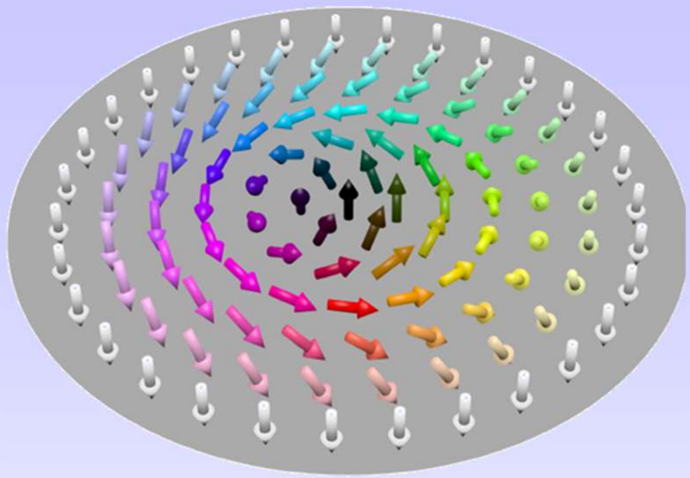
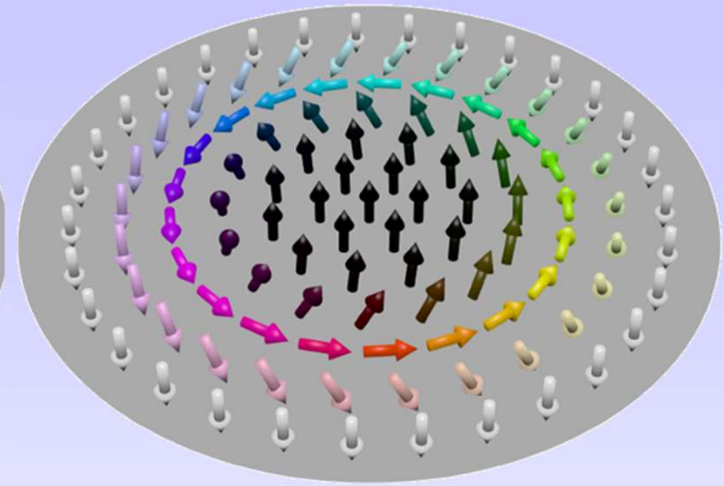


Hedgehog skyrmion (N=1)



Chiral skyrmion (N=1)



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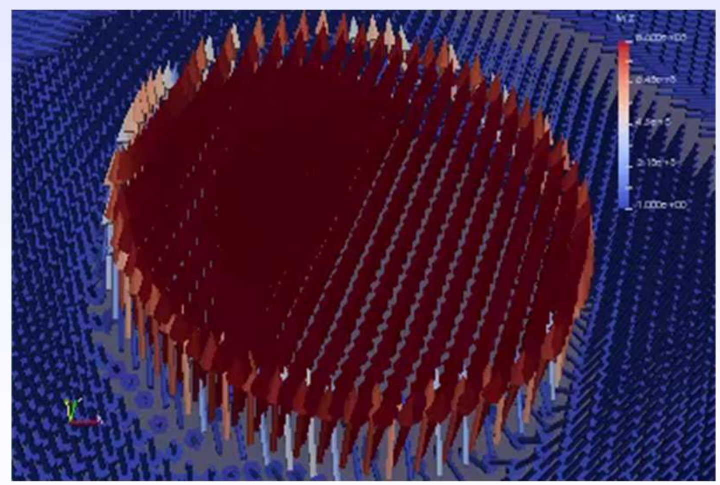
- Skyrmion with N=0 (topology of uni-form state) is less stable than N=1.



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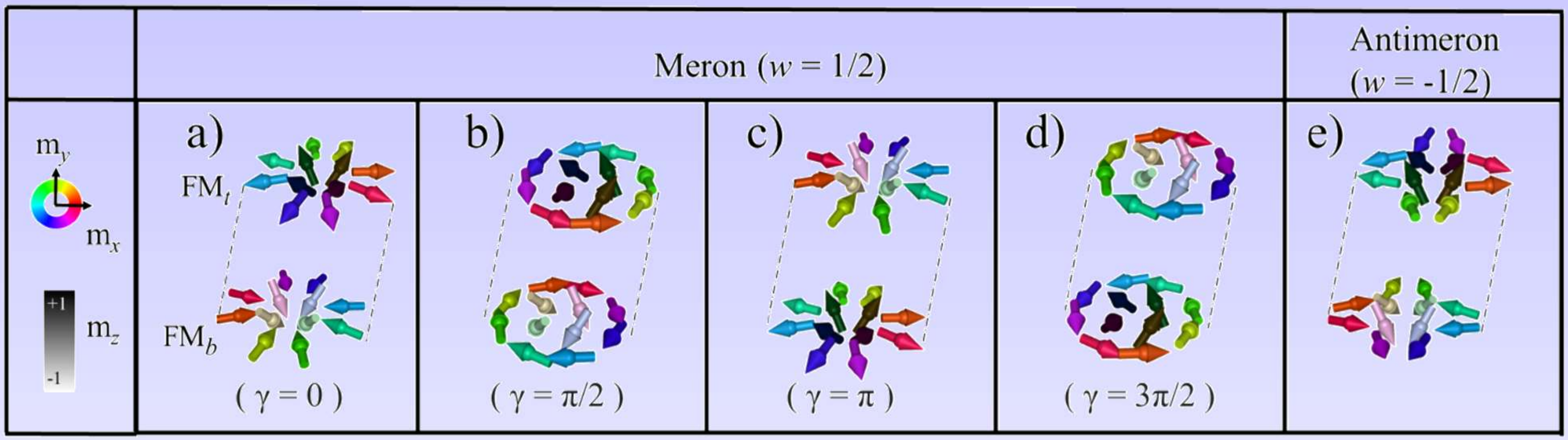
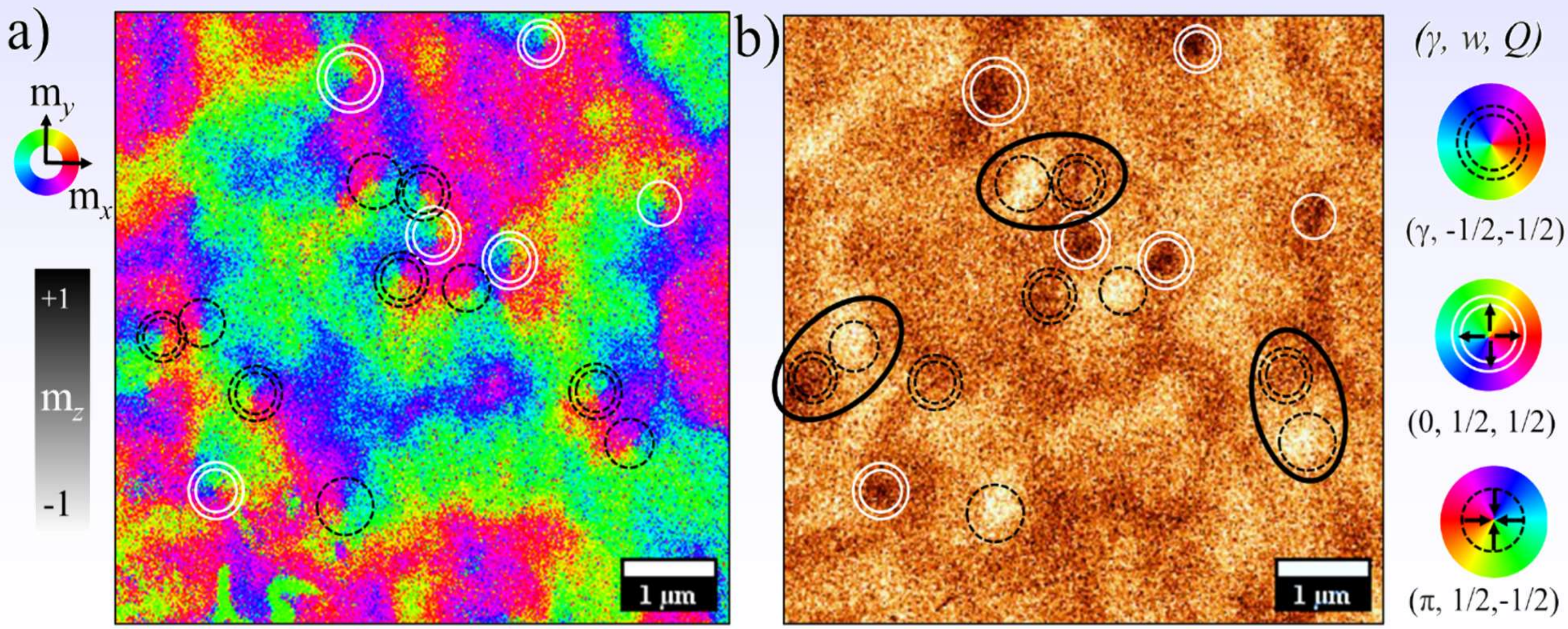
[1]N. Papanicolaou et al., Nuclear Physics B 360, 425–462 (1991)
F. Büttner, MK et al., Nature Phys. **11**, 225 (2015)

2. Bimerons in synthetic antiferromagnets

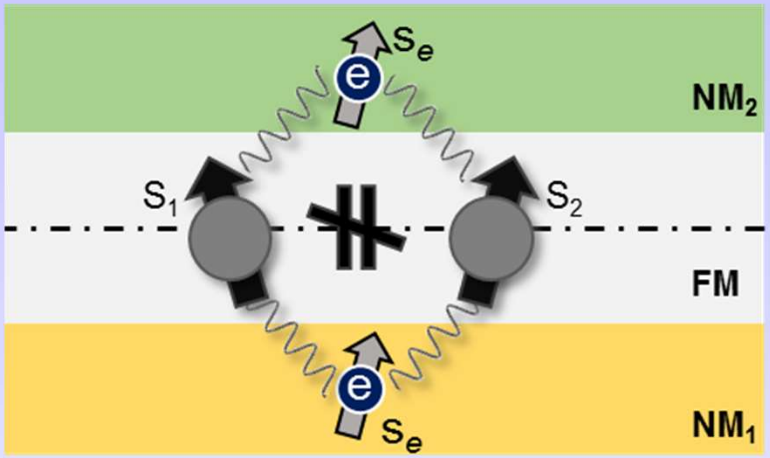
- In multi-layers: Different merons can be stabilized
- Obser-vation using combine: SEMPA + MFM[1]

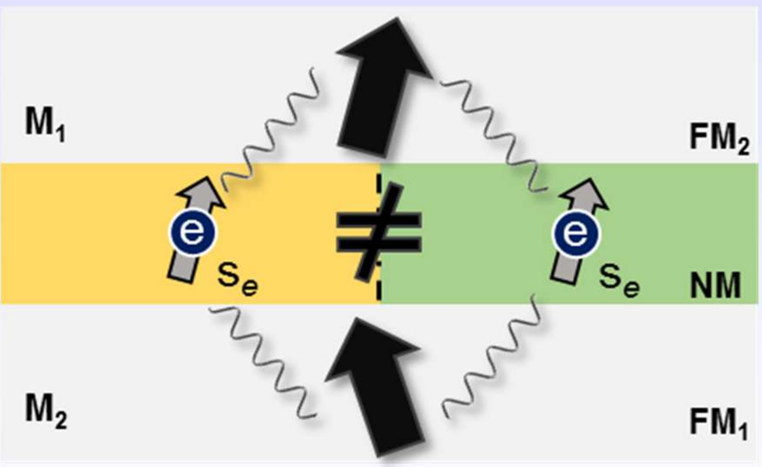


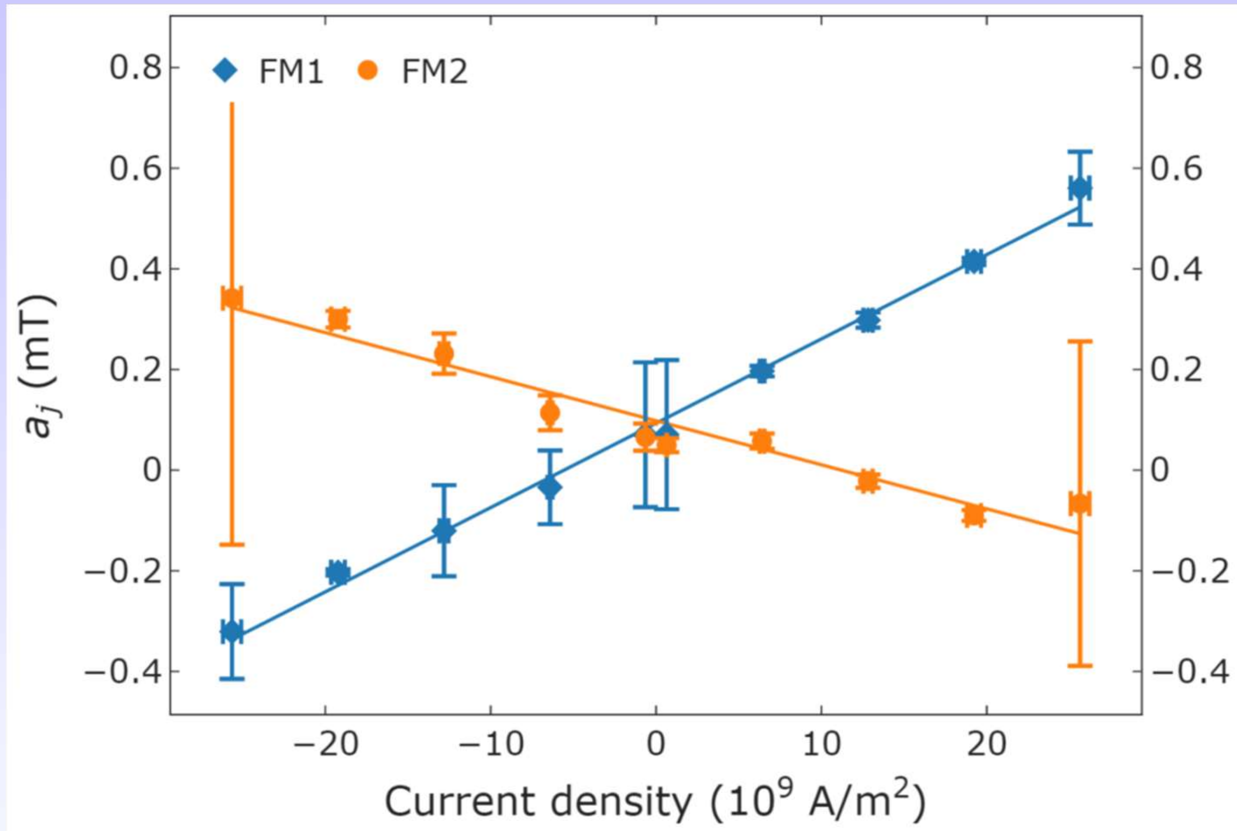


[1] M. Bhukta, MK et al., arxiv:2303:14853

2. Chiral **interlayer** exchange coupling



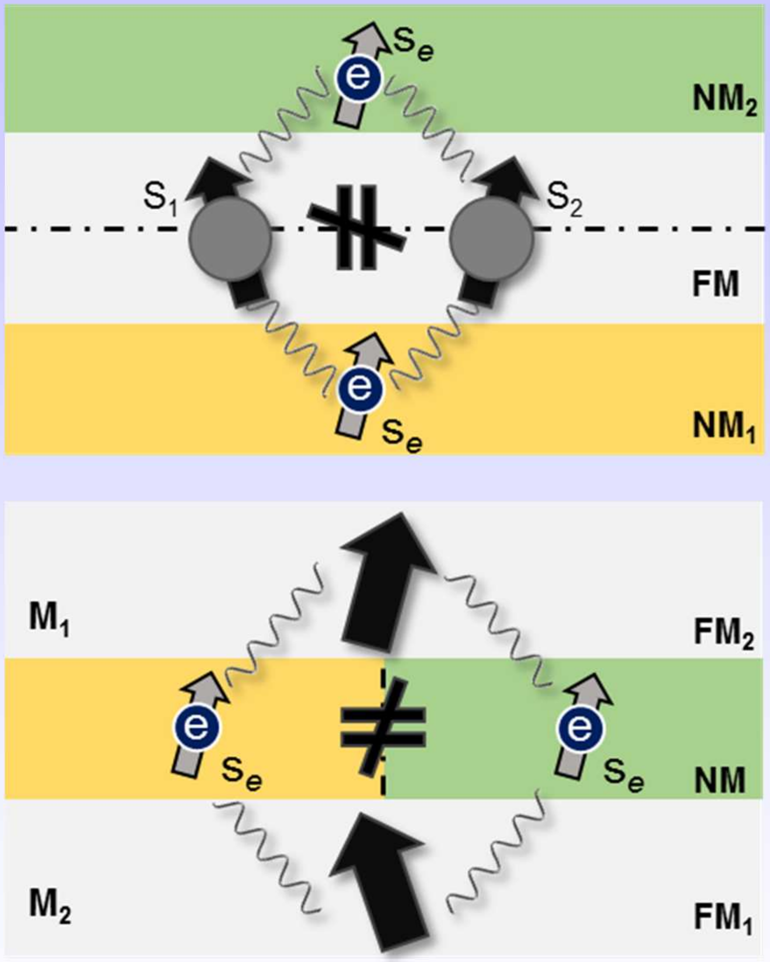


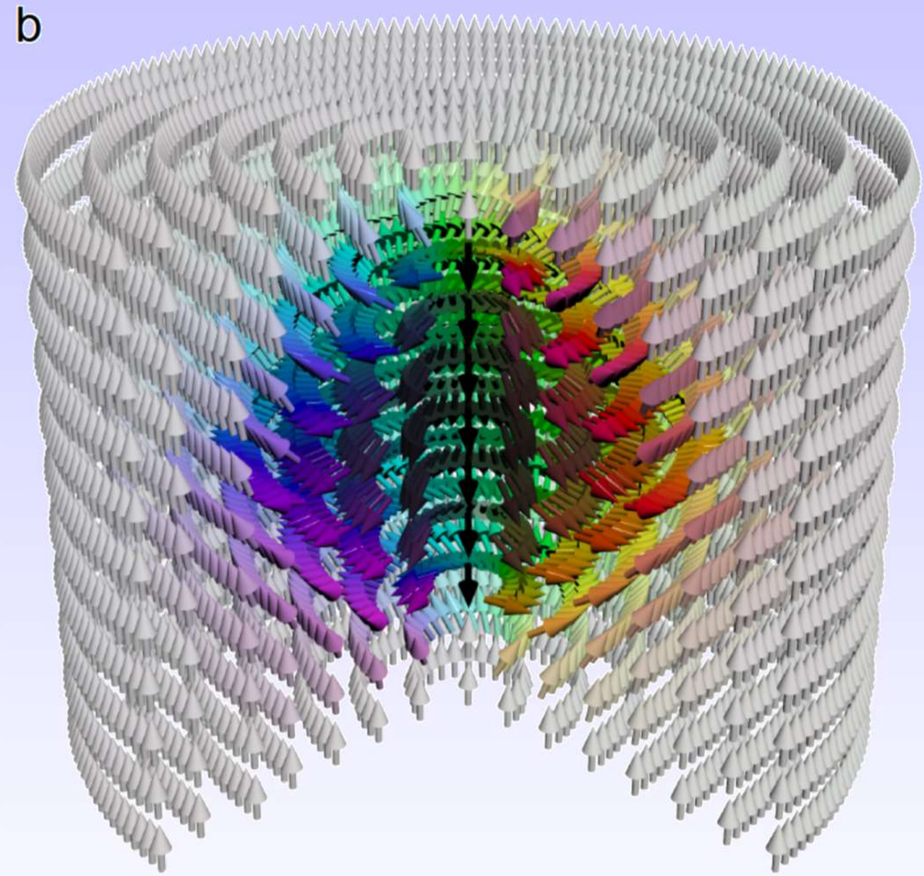


- Two spins in 2 magnetic layers are coupled by interlayer RKKY
- Chiral antisymmetric interlayer exchange coupling → RKKY-DMI[1]
- Strength of RKKY-DMI can be tuned by currents on-the-fly![2]

[1]D. Han, MK et al., Nat. Mat. **18**, 703 (2019); [2]F. Kammerbauer, MK et al., arxiv:2209.01450 (Nano Lett. 2023)

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



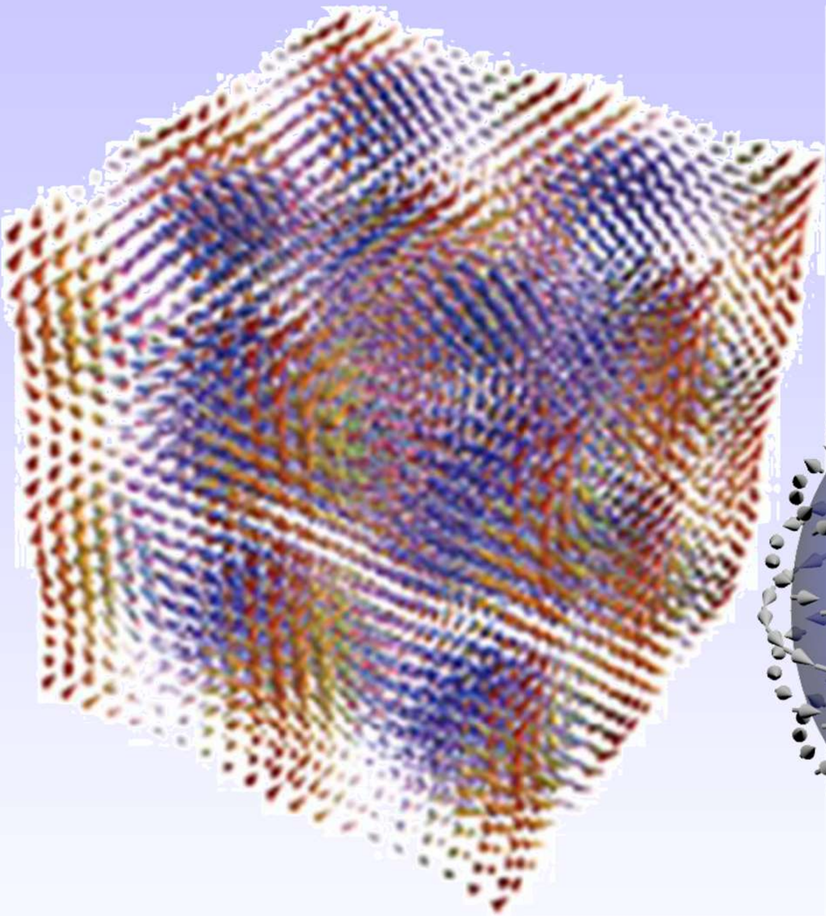


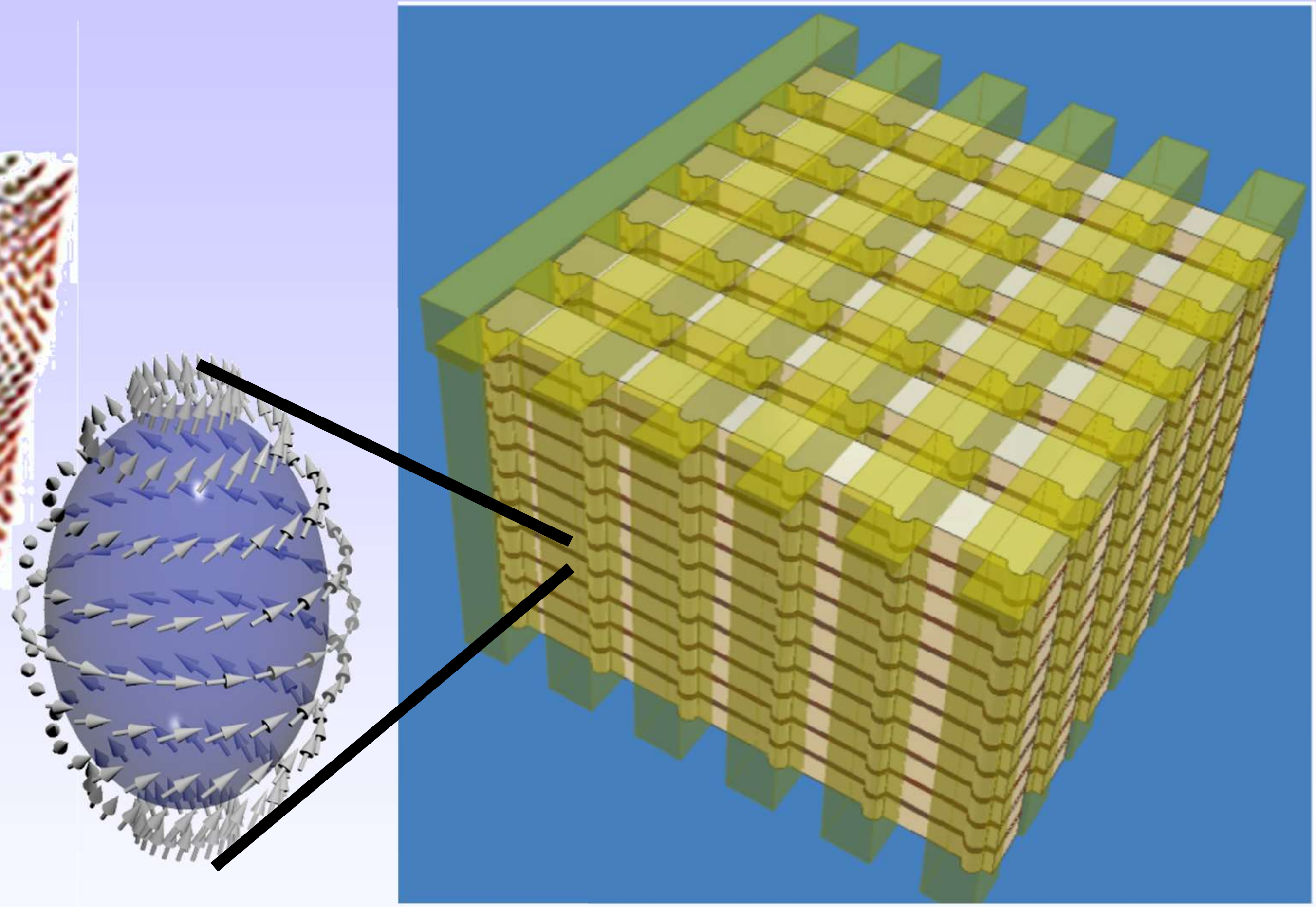
Courtesy N. Kiselev

- 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)

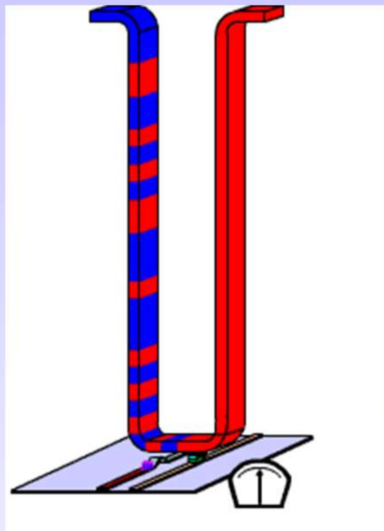
Courtesy R. Cowburn

- 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 Materials **18**, 703 (2019)

Devices based on Condensed Matter Solitons

Memory	Magnetic Logic	Position & angle sensors



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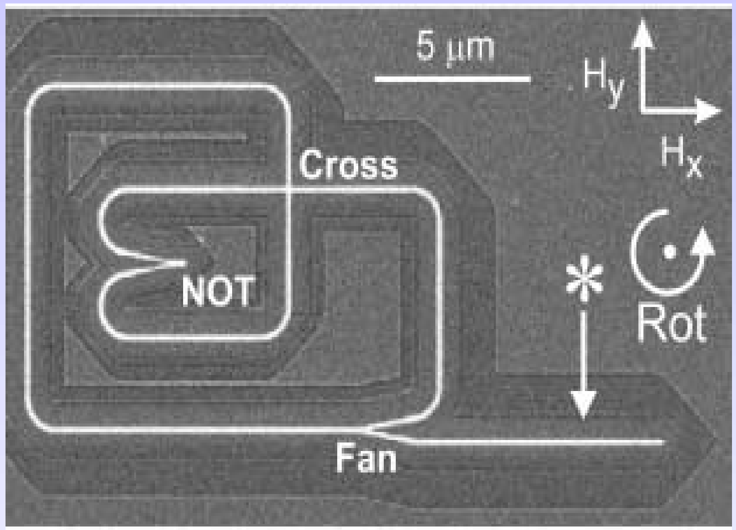
Fert et al., Nature Nano **8**, 152 (‘13)



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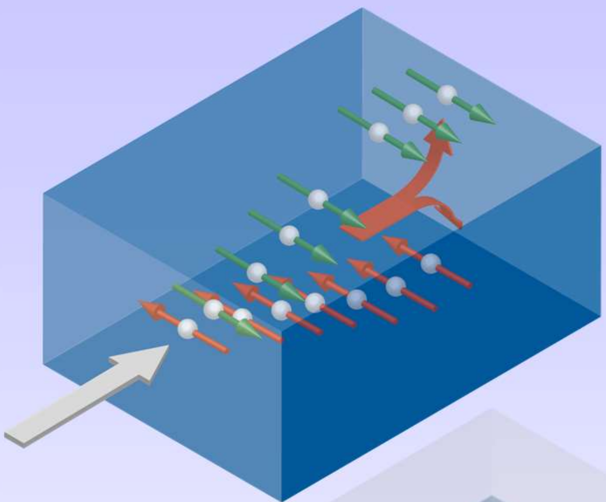
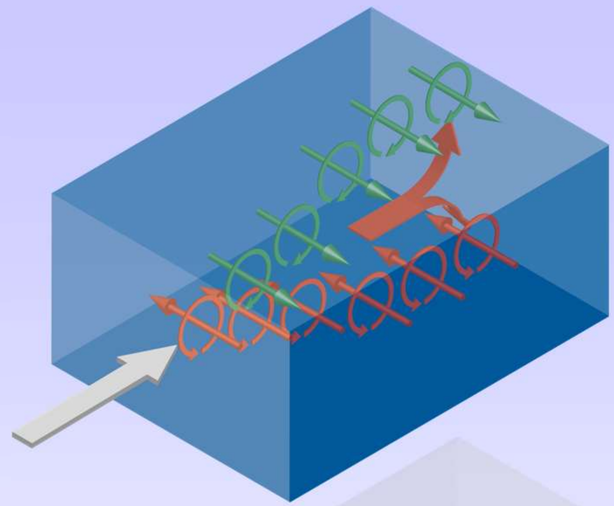
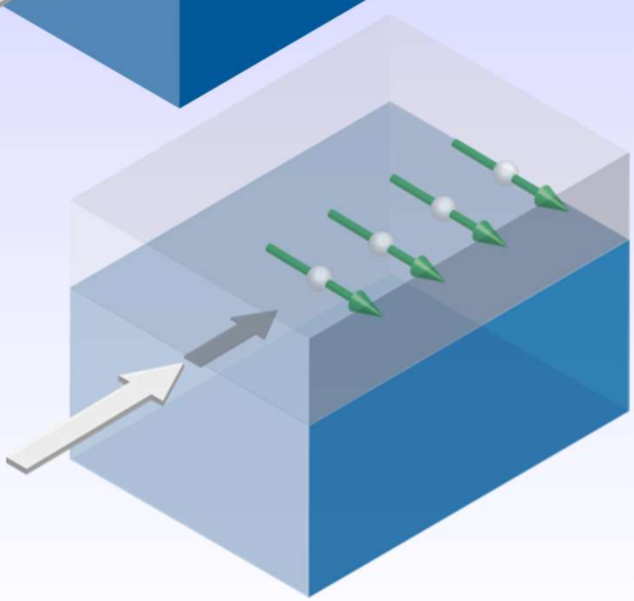
3. Spin-, Orbit- and Spin-Orbit Torques



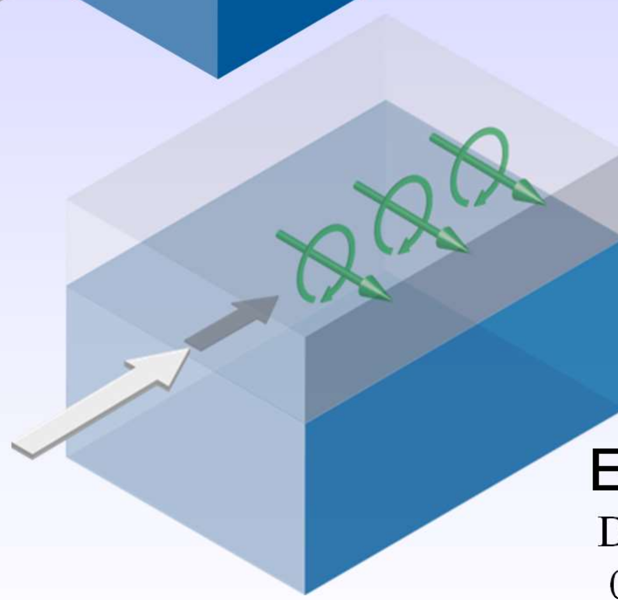
Spin Hall Effect
Rev. Mod. Phys. **87**, 1213 (2015)



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



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

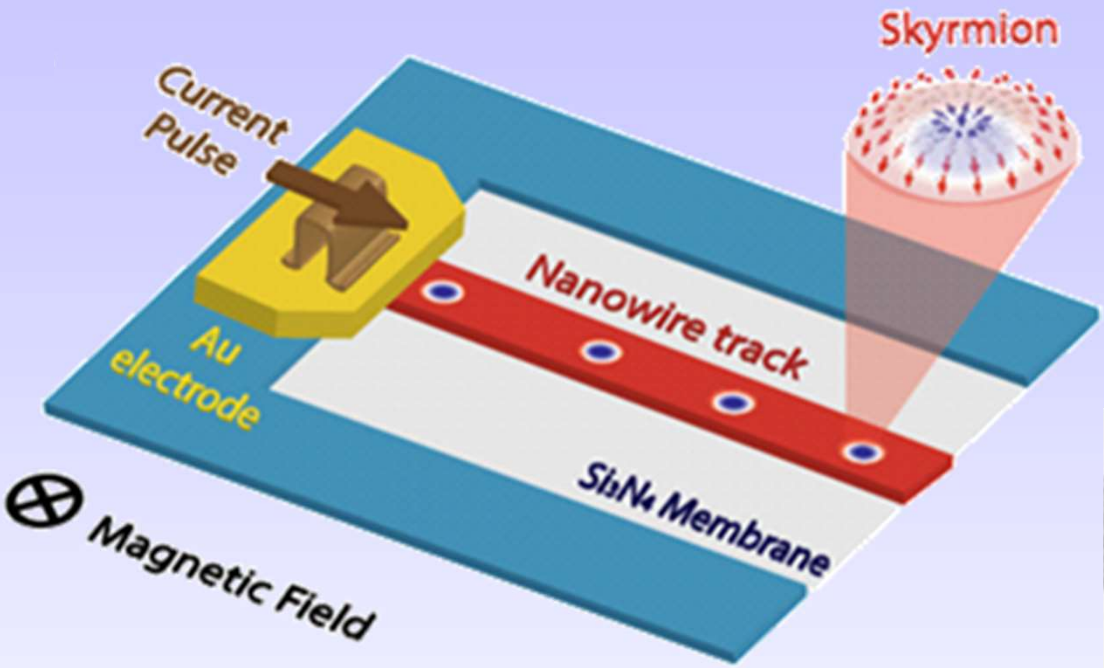


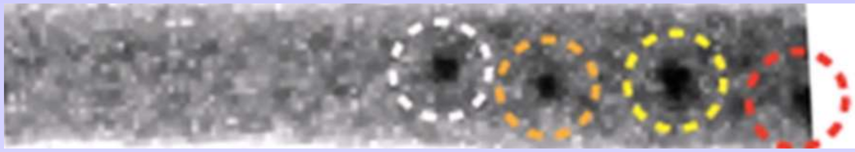
Orbital Rashba Edelstein Effect
D. Go et al., PRL **121**, 086602 (2018)

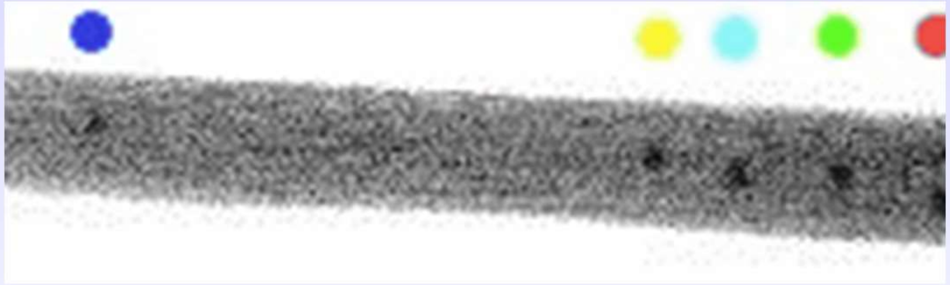
- Dynamics induced by spin-orbit torques due to SHE **(a)** and ISGE/REE **(b)**,
- Additionally orbital angular momentum: Orbital Hall Effect (OHE) **(c)** [1] & Orbital Rashba Edelstein Effect (OREE) **(d)** [2].

[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. Skyrmion Racetrack



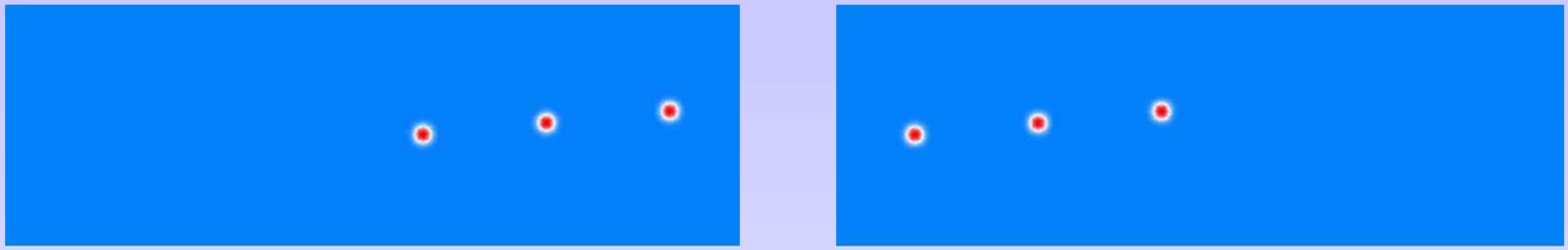


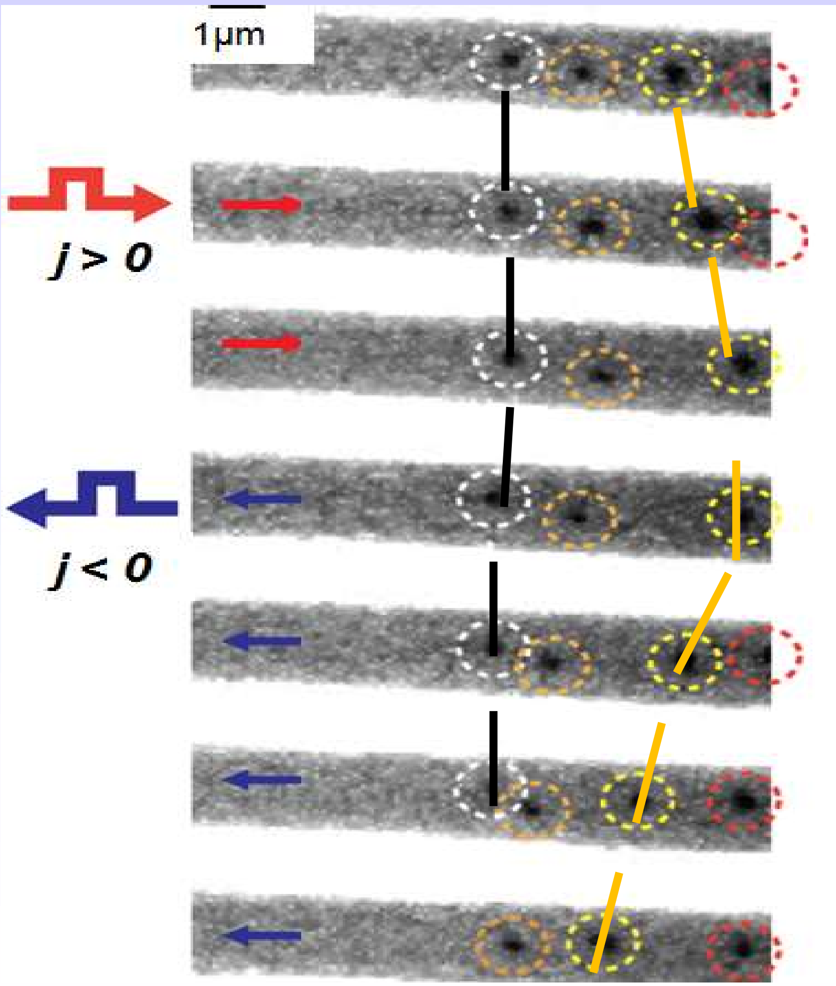


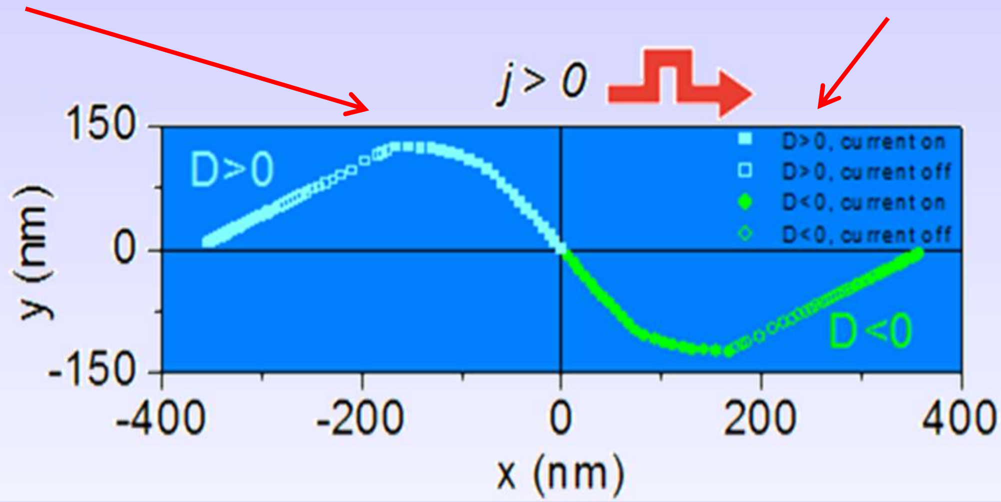
- Skyrmion racetrack[1]: advantages compared to a DW-based racetrack: total magnetization does not change with skyrmion motion
  → less susceptible to stray fields.
- Topological protection of skyrmions → more reliable motion?
- Nanowire is patterned out of Pt/Co/Ta (µm width)[2]
- Single skyrmions can be moved by spin orbit torques on the nano-track[3]

[1]A. Fert et al., Nat. Nano **8**, 152 (2013); [2]S. Woo, MK et al., Nat. Mat. **15**, 401 (2016); [3]J. Iwasaki et al., Nat. Nano. **8**, 742 (2013

3. Skyrmion Racetrack



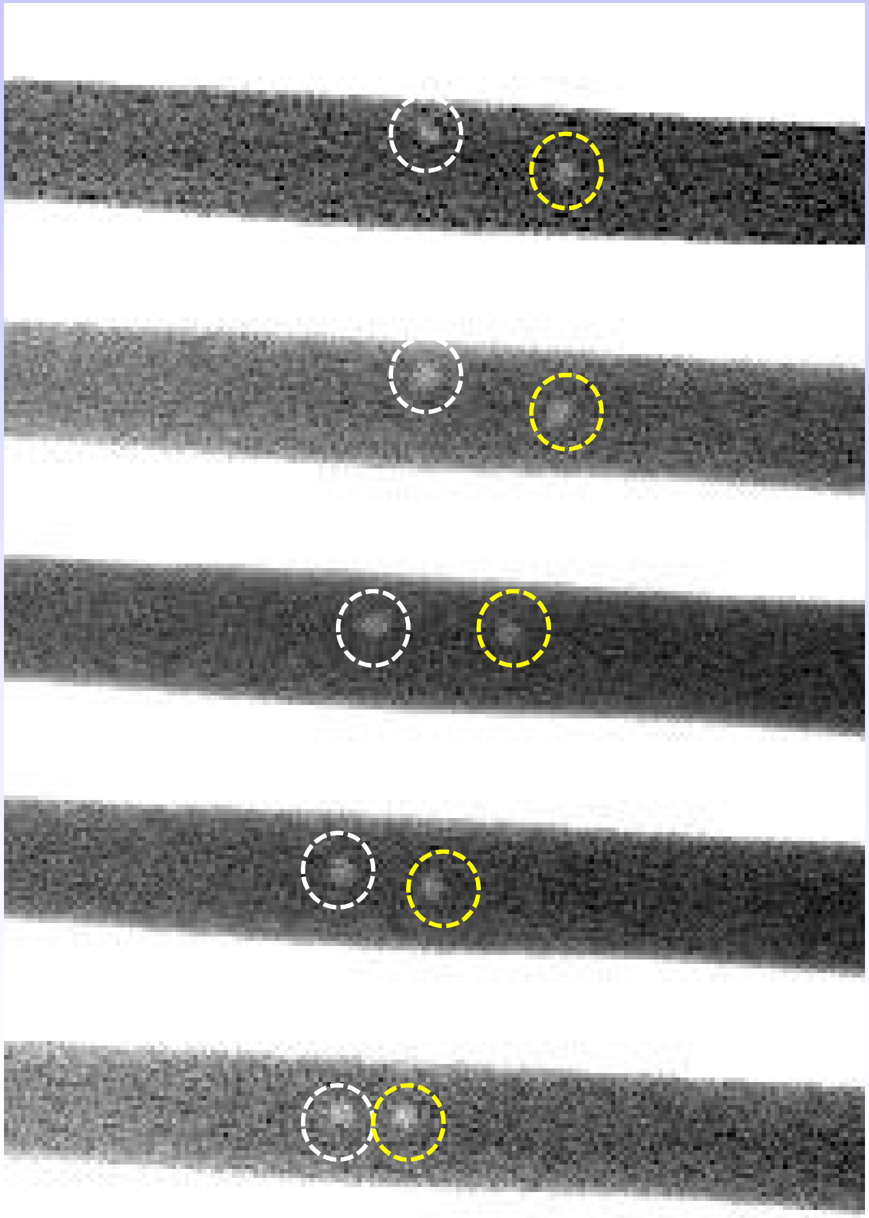


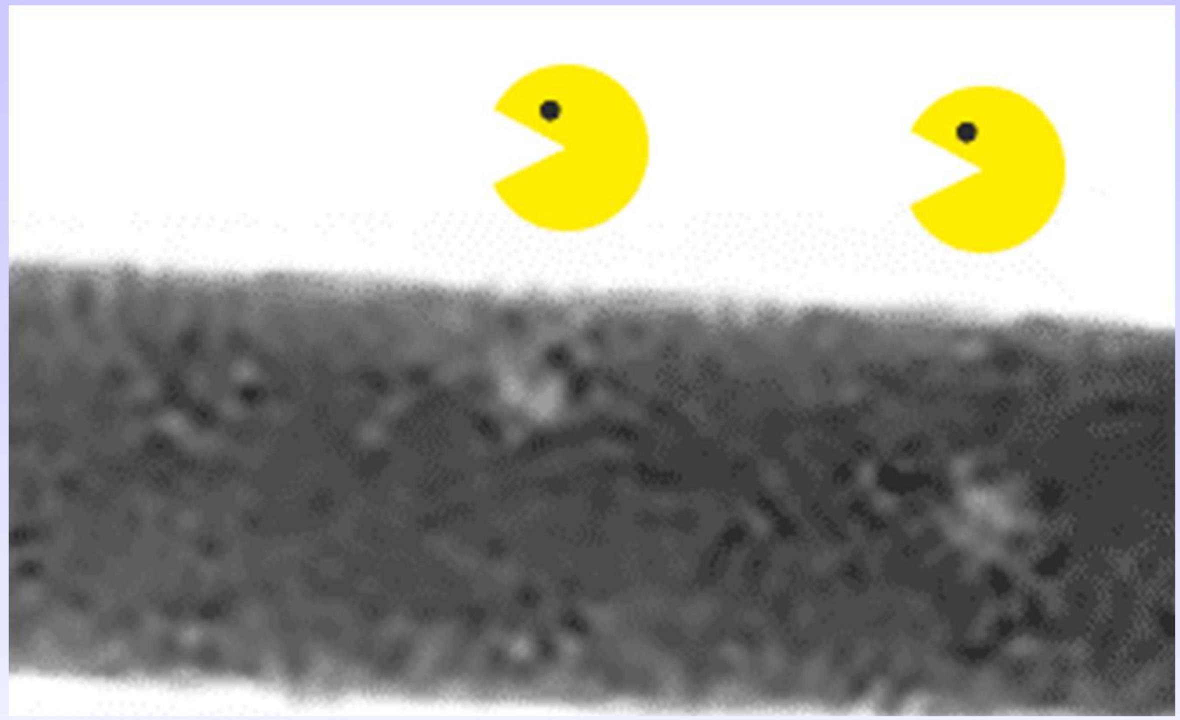


- Simulations show that skyrmions move synchronously on a complex trajectory.
- DMI and current set the motion direction.
- In the experiment skyrmions move at different velocities and can be pinned.

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

3. Skyrmion Racetrack - Stability

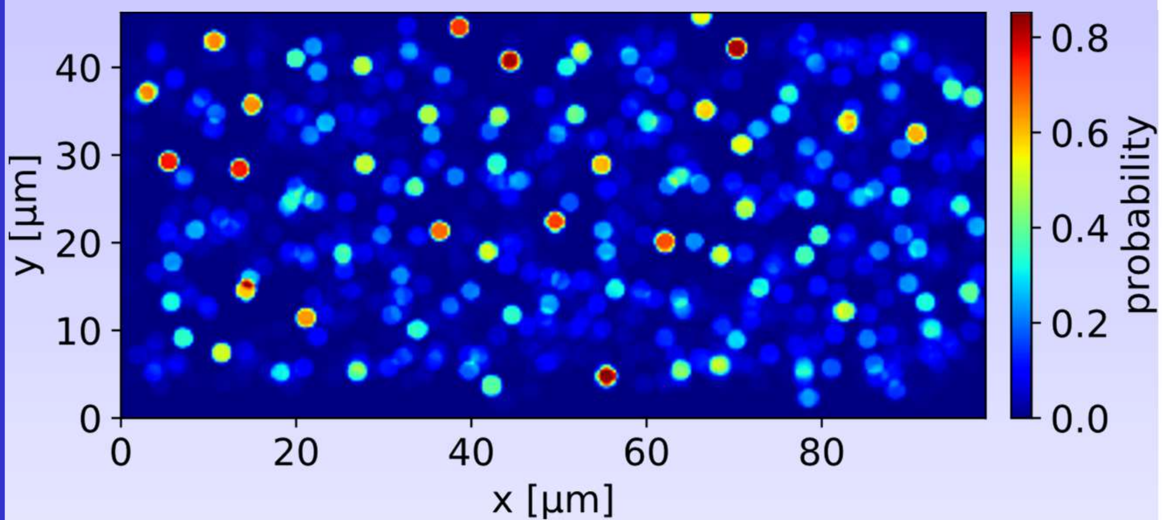


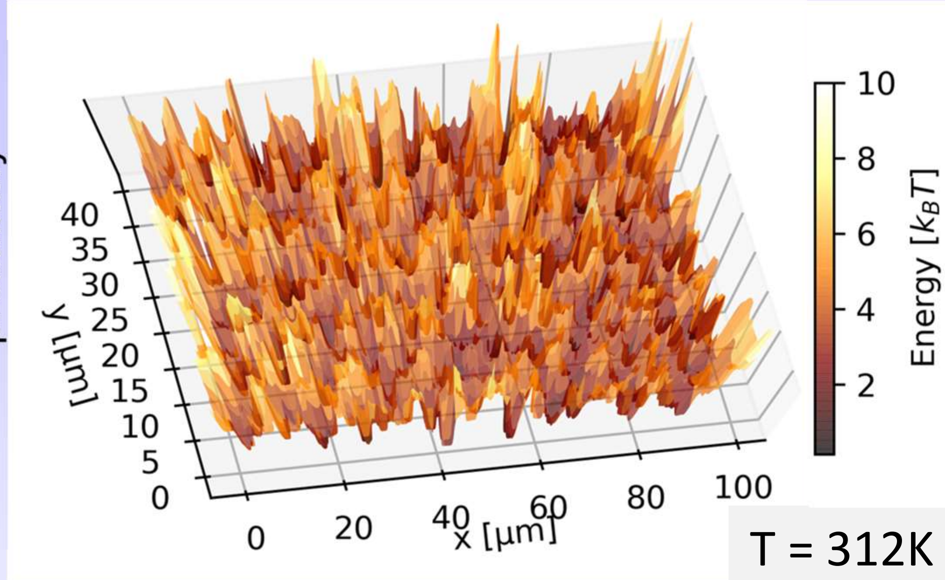


- Simulations show that skyrmions move synchronously on a complex trajectory.
- DMI and current set the motion direction.
- In the experiment skyrmions move at different velocities and can be pinned.
- Only pinned skyrmions can be annihilated!

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

3. Origin of pinning





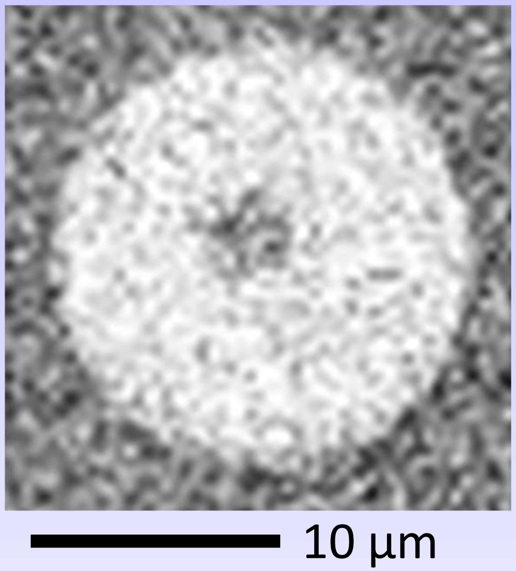
- Measure pinning and depinning of skyrmions
- Determine probability of finding skyrmions at a certain position

→ 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)

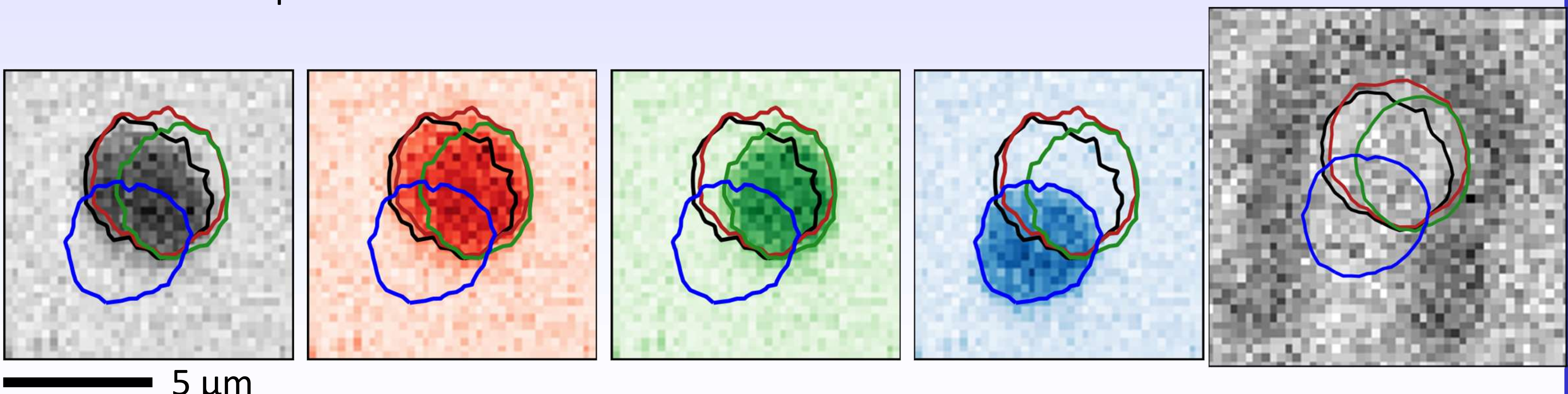
3. Origin of pinning



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

→ obtain statistics to investigate pinning effects

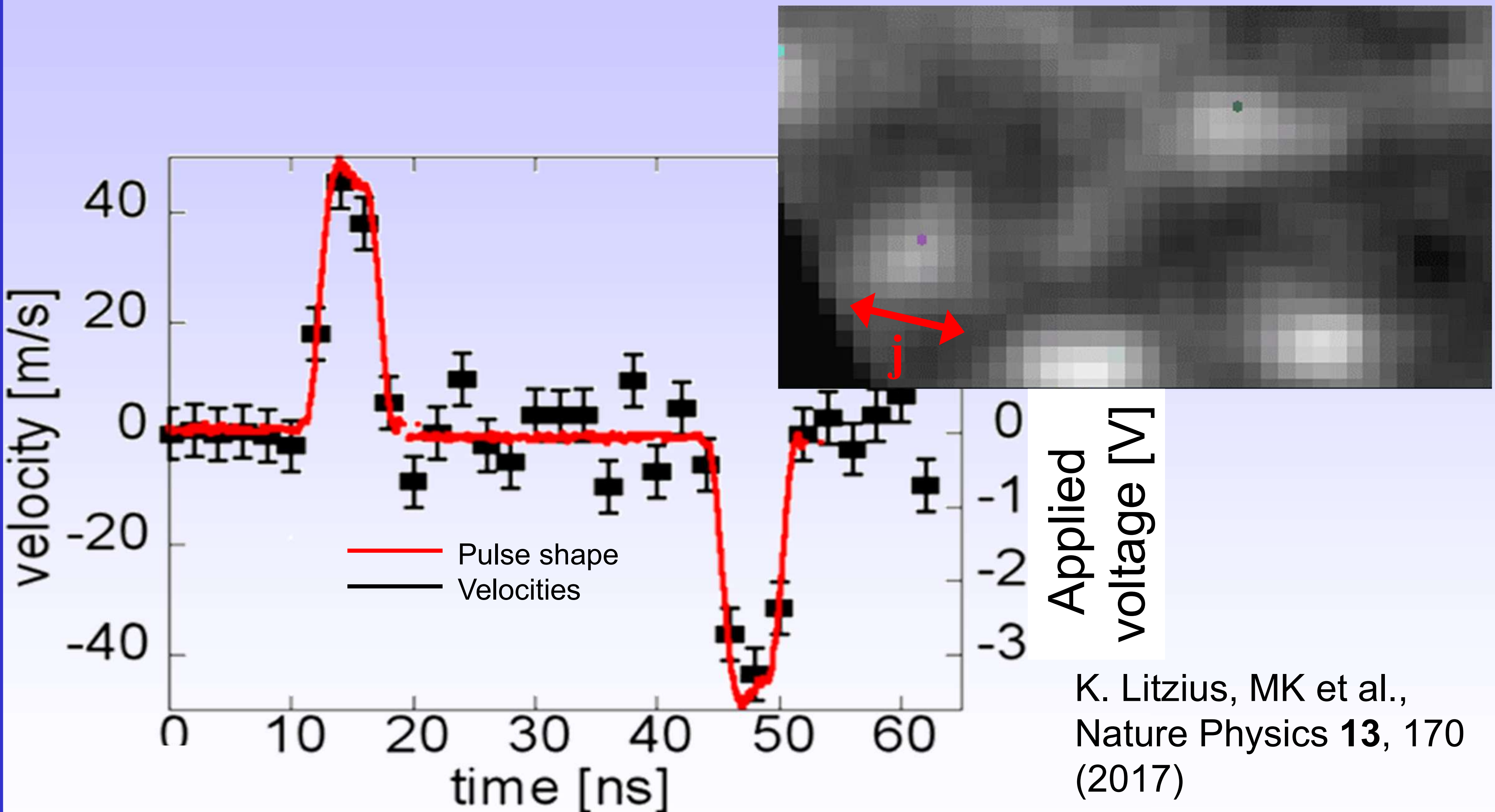
→Skyrmions are found in characteristic configurations of the domain wall.



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

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

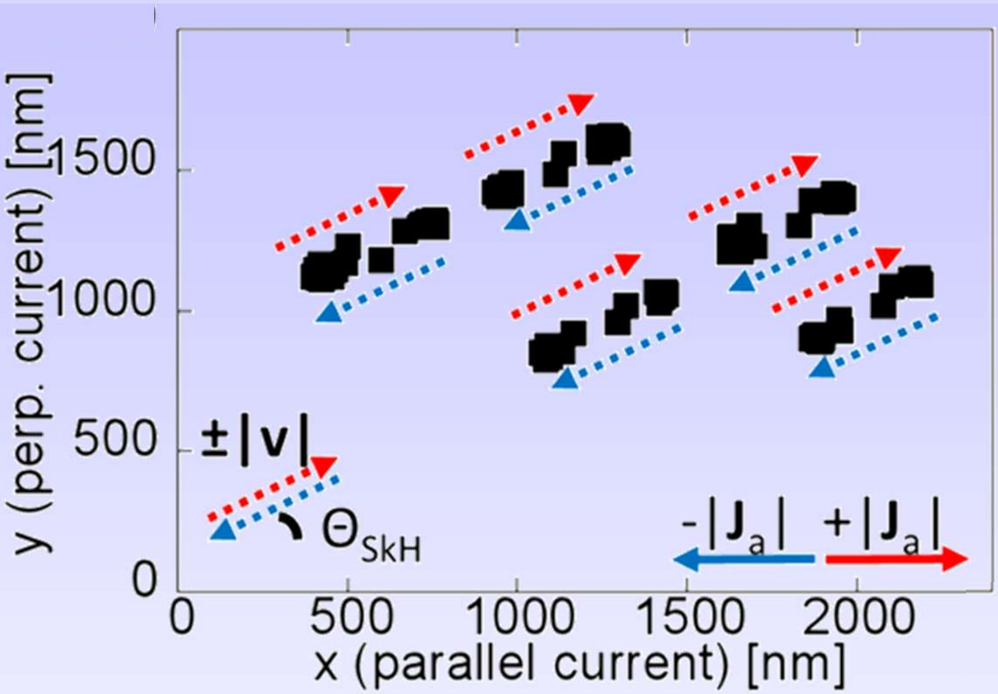
3. Real time magnetic imaging of spin-orbit torque induced dynamics

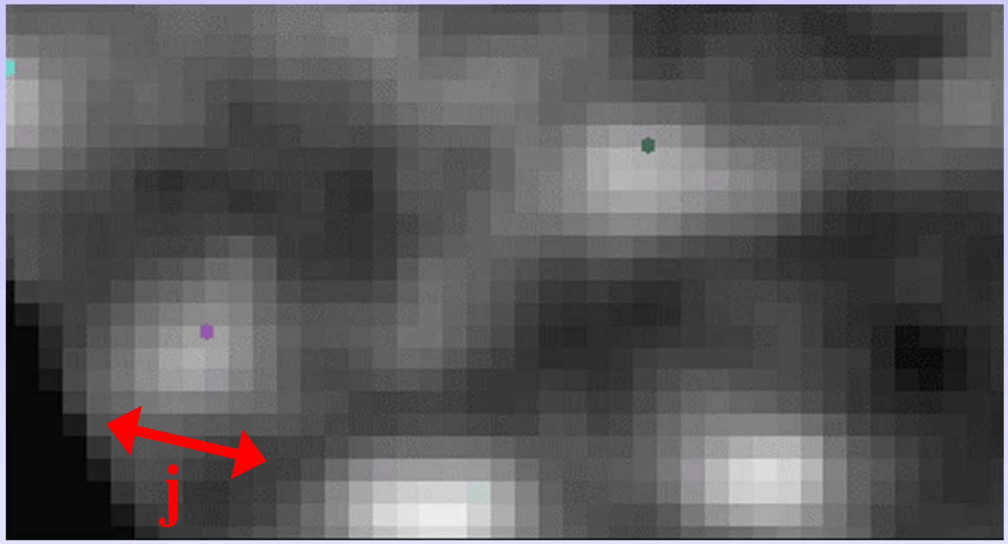


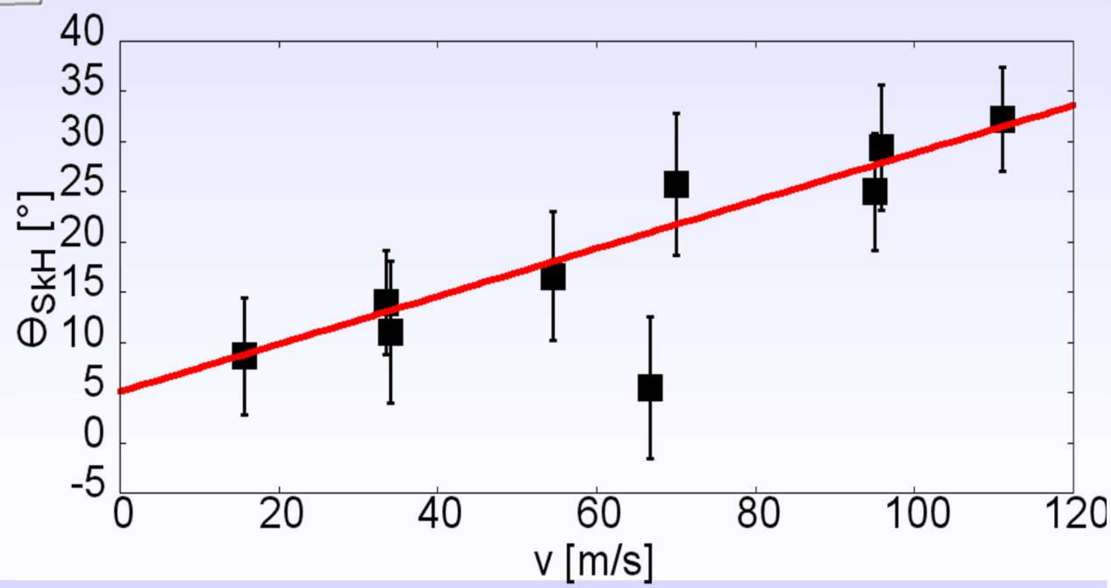
K. Litzius, MK et al., Nature Physics **13**, 170 (2017)

- 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



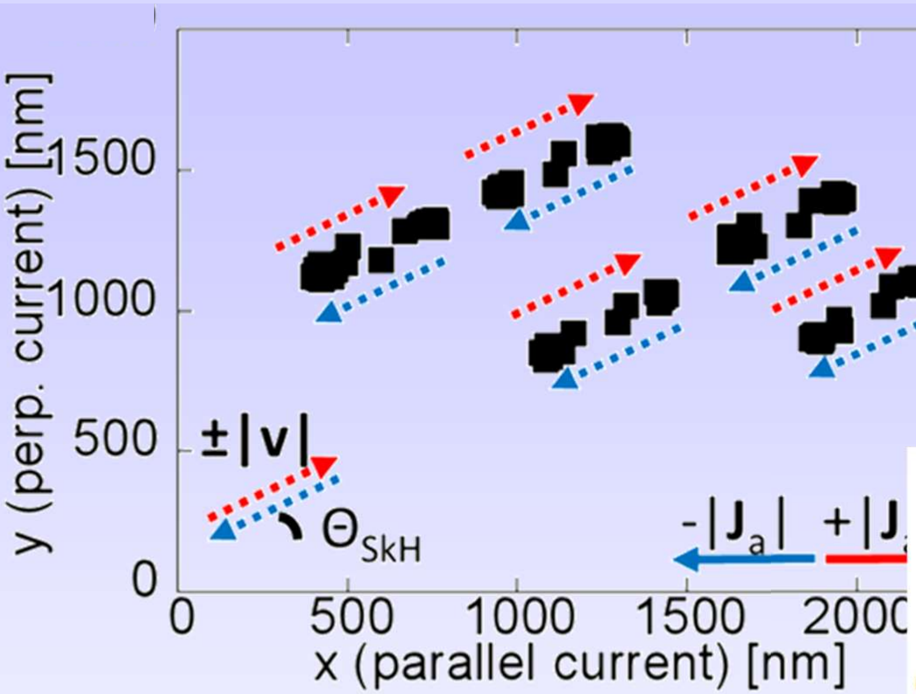


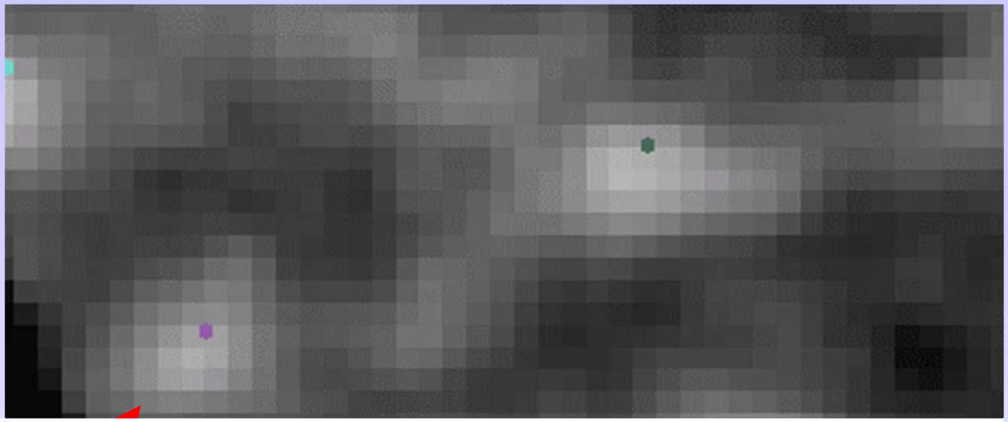


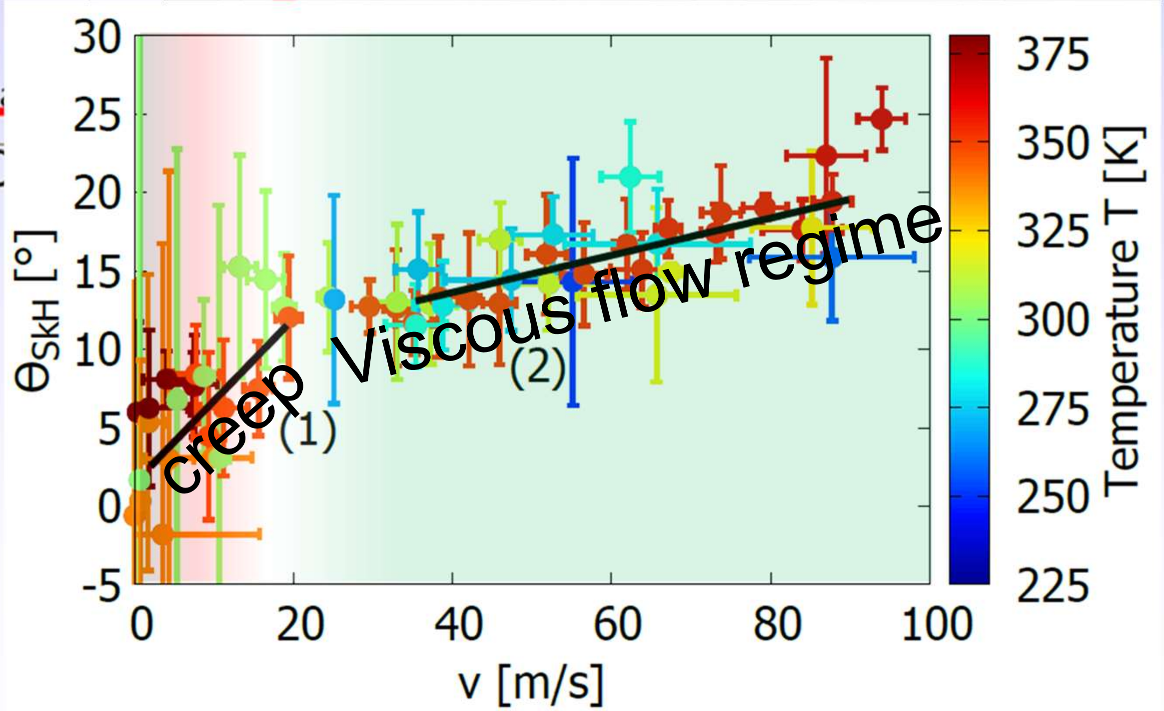
K. Litzius, MK et al.,
Nature Physics **13**, 170 (2017)
W. Jiang et al.,
Nature Physics **13**, 162 (2017)

- 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







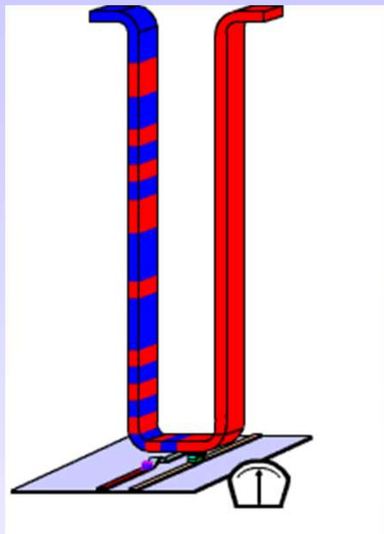
K. Litzius et al., Nat. Electron. **3**, 30 (2020)

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!

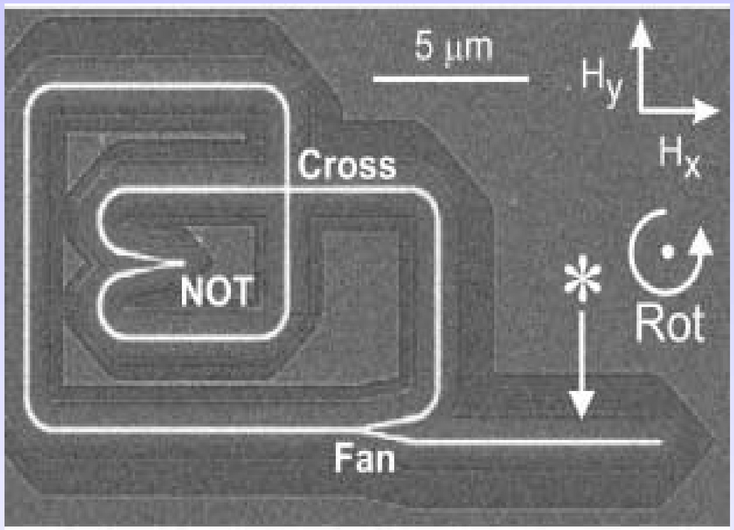
Devices based on Domain Walls and Skyrmions

Memory



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)

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

Skyrmions in Spin-Orbitronics & Orbitronics: novel science and applications in memory & non-conventional 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

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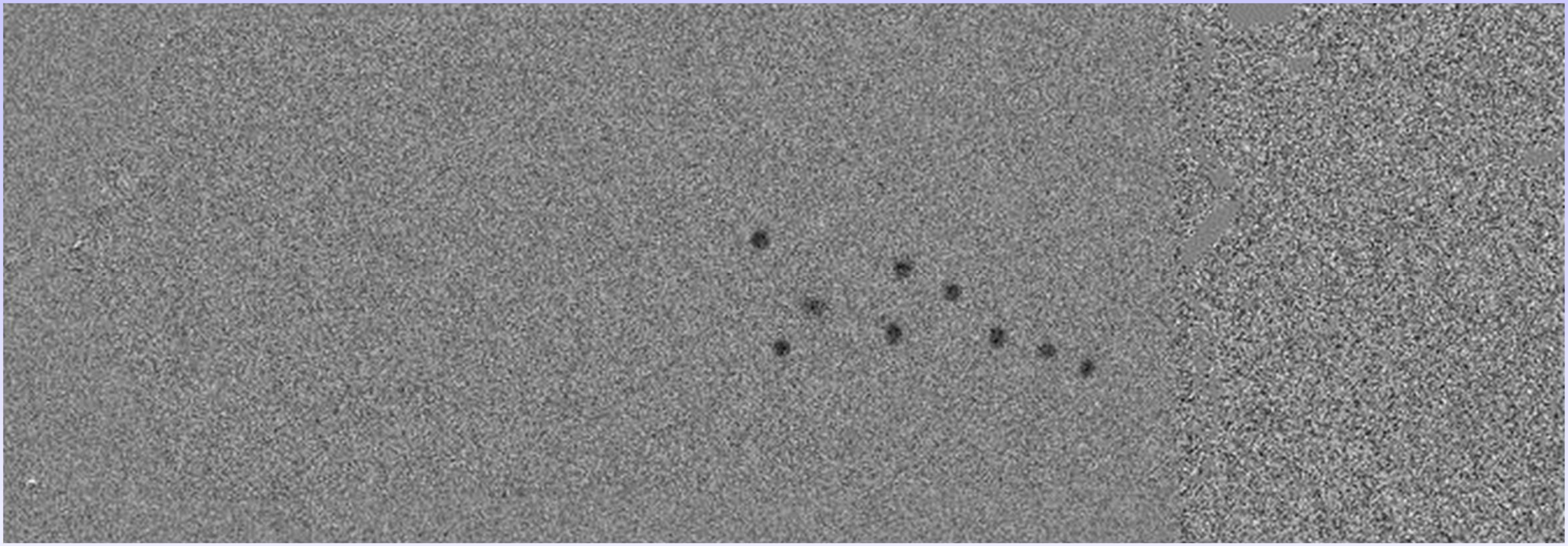
4. Skyrmion Writing and Skyrmion Motion in low pinning materials

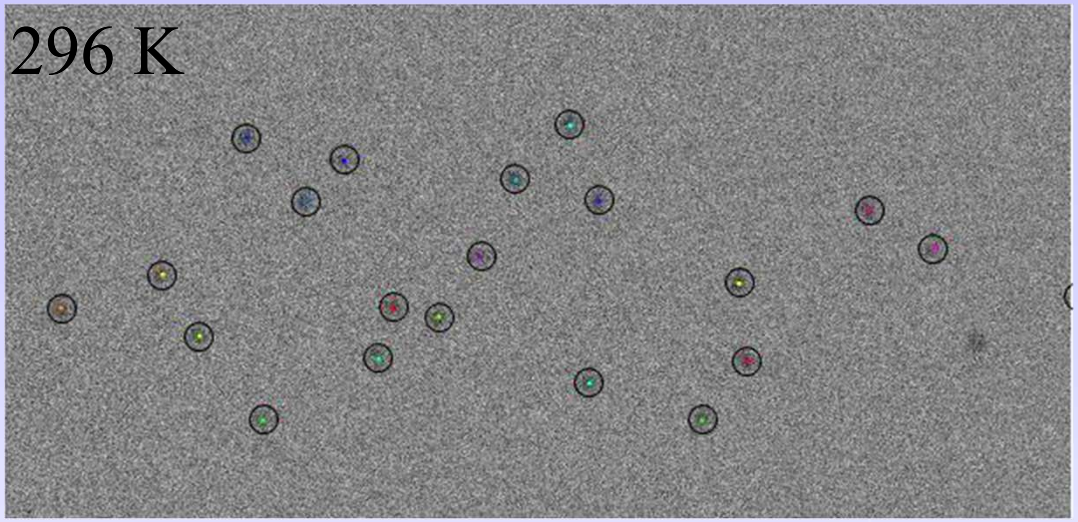


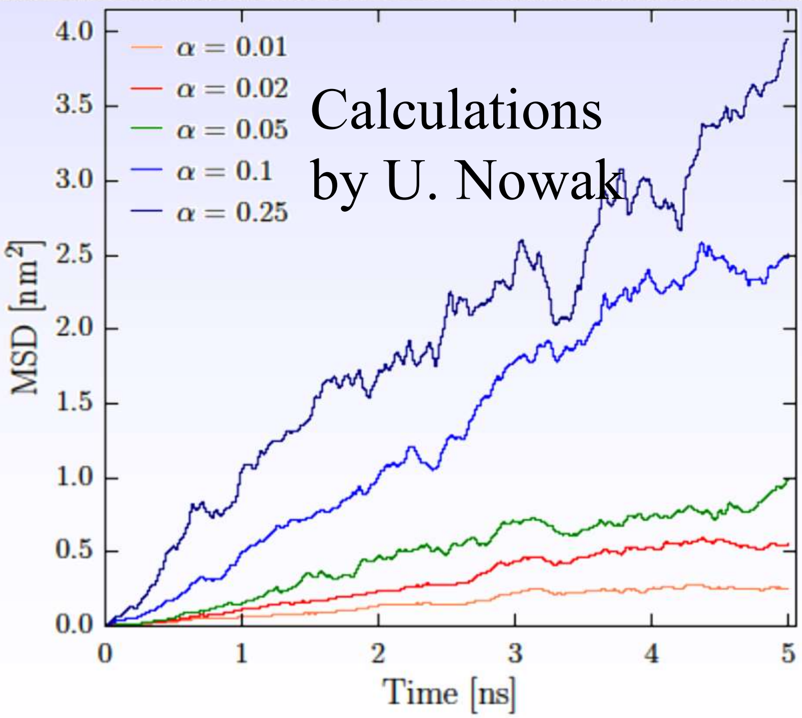
- Ultra-low pinning stack: Ta(5)/CoFeB(1)/Ta(0.08)/MgO(2)/Ta(5)[1]
- Using spin-orbit torques, skyrmions can be produced by pulses „on-demand“[2]
- Synchronous displacement along current flow → chiral skyrmions

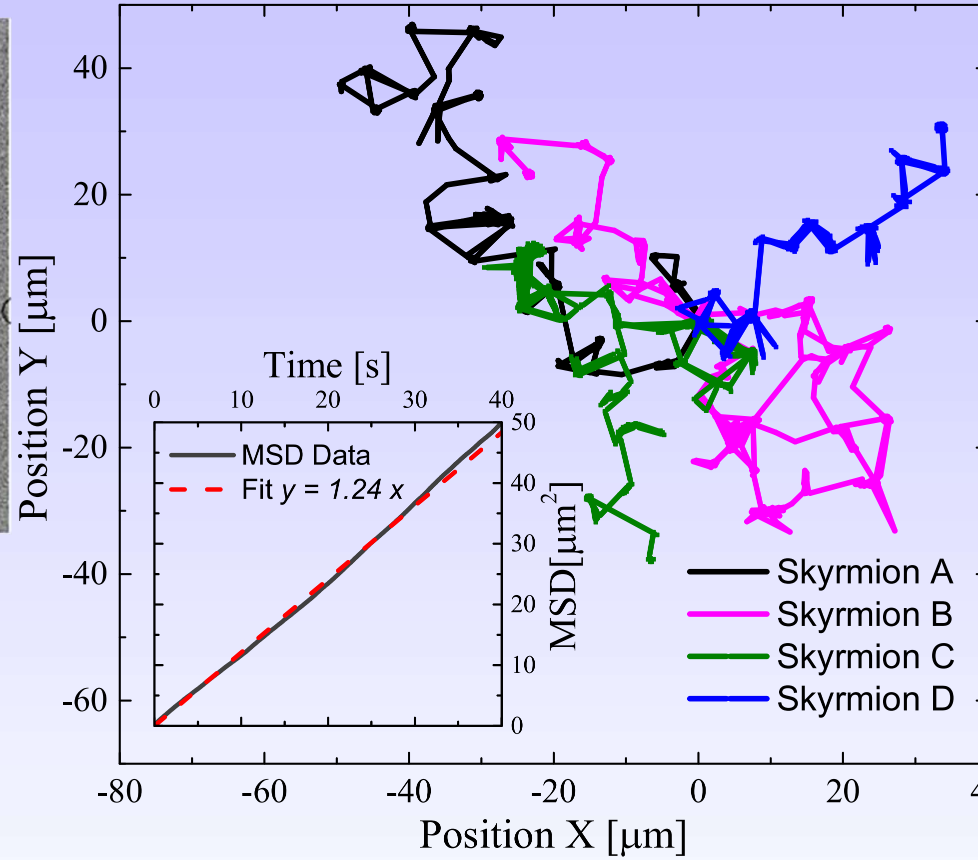
In addition to deterministic „writing“ and „shifting“, we see thermally induced dynamics leading to random motion → diffusion? Predicted to be suppressed[3]

[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





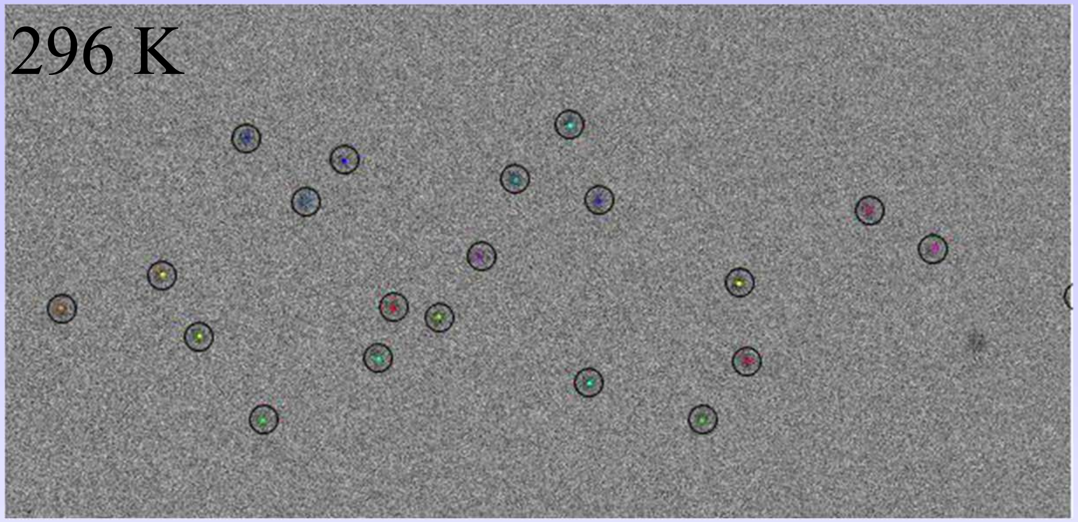


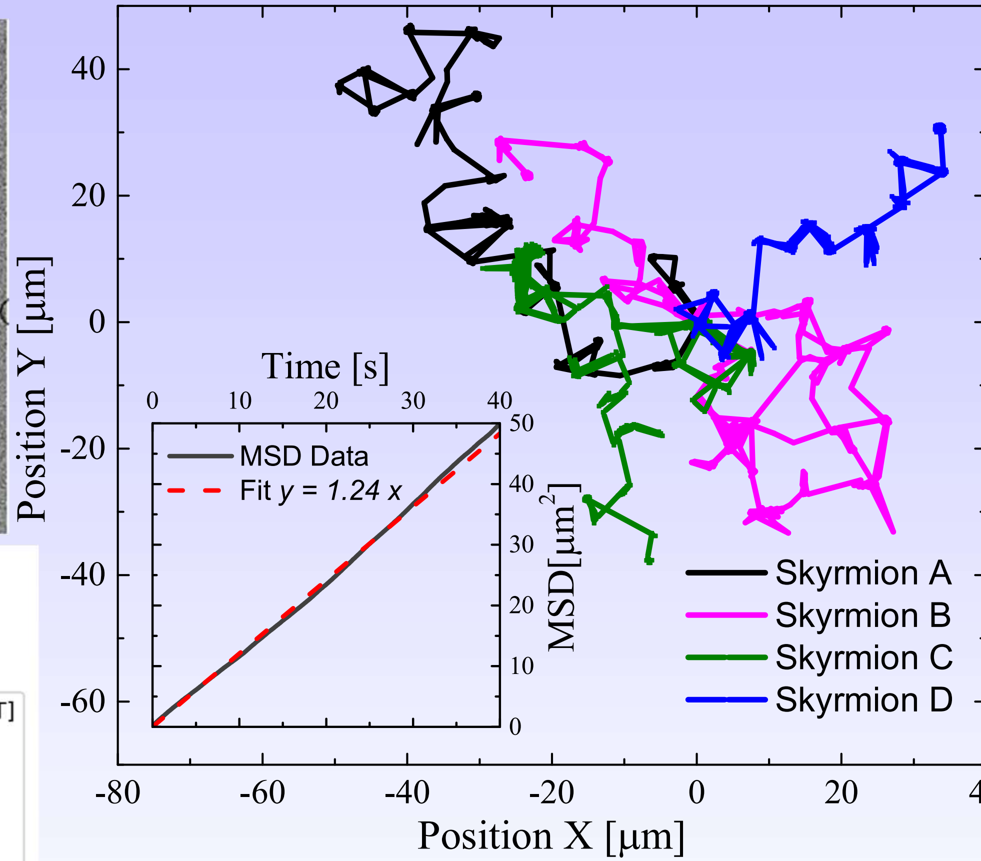
- Random motion exhibits linear scaling for mean square displacement → diffusion!
- Theoretical numerical spin simulations reproduce diffusion
- Use in unconventional computing?[1,2]

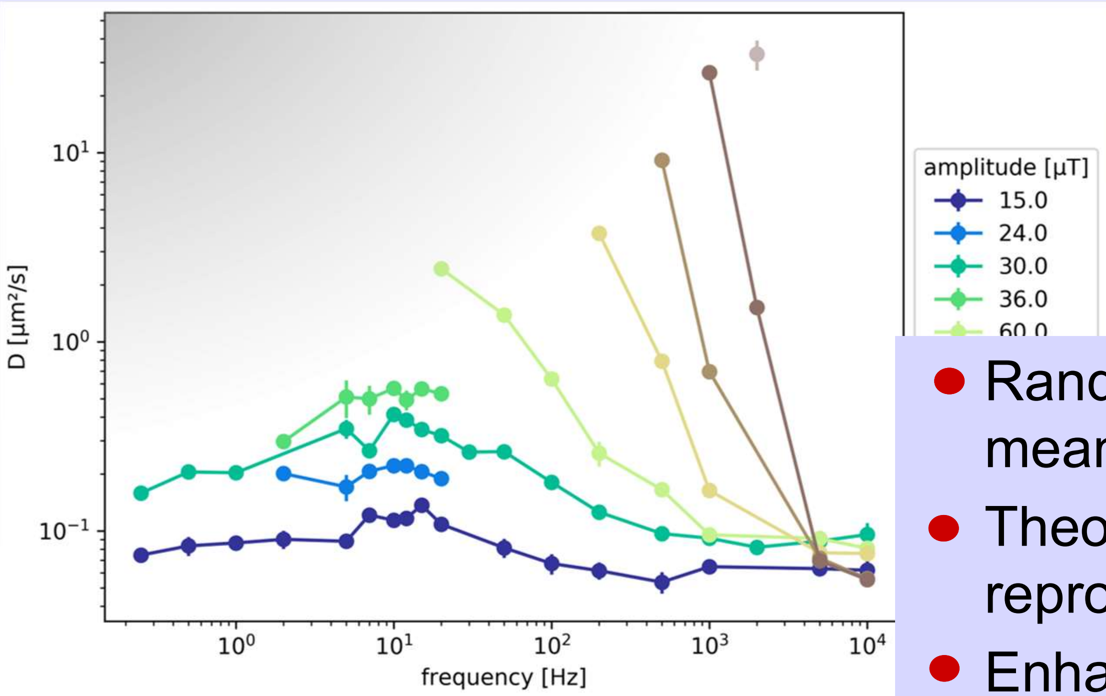
[1] J. Zazvorka, MK et al., Nature Nano. **14**, 658 (2019) cf. L. Zhao et al., PRL **125**, 027206 (2020)

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

4. Skyrmion Diffusion





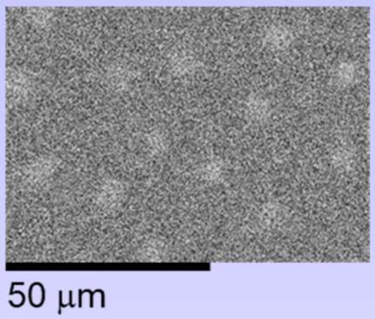


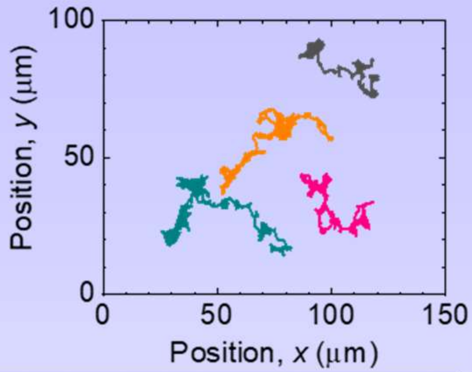
- Random motion exhibits linear scaling for mean square displacement → diffusion!
- Theoretical numerical spin simulations reproduce diffusion
- Enhanced diffusion by AC excitations[2]

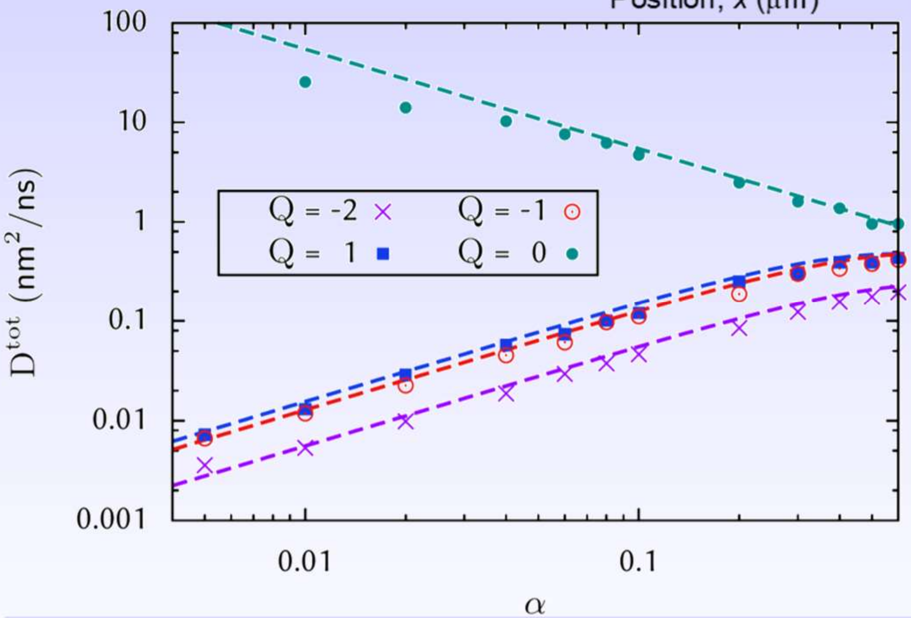
[1]J. Zazvorka, MK et al., Nature Nano. **14**, 658 (2019)
cf. L. Zhao et al., PRL **125**, 027206 (2020)

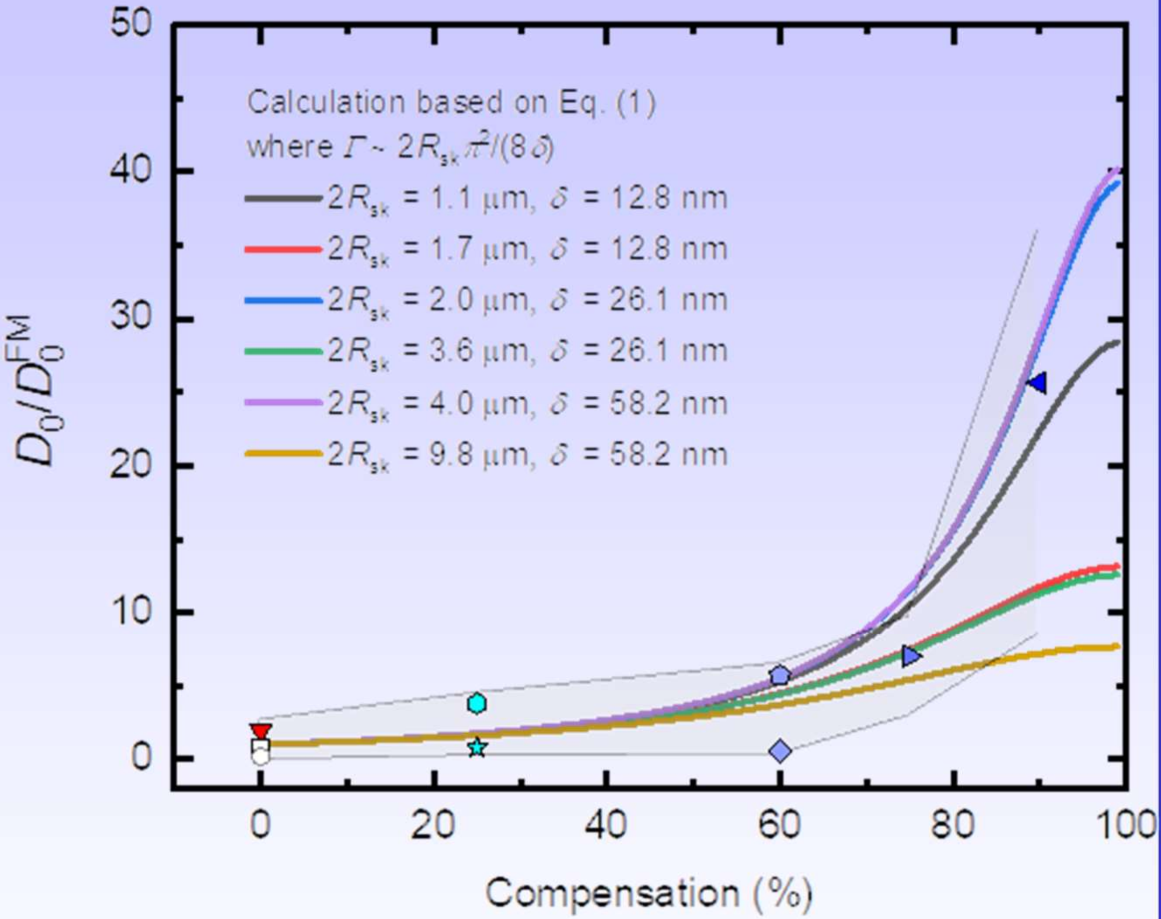
[2]R. Gruber, MK et al., Adv. Mater. 2208922 (2023)

4. Ultimately fast Skyrmion Diffusion in (synthetic) antiferromagnets









- Synthetic antiferromagnets: topological charge tuned by compensation ratio!
- Developed synthetic antiferromagnets SAFs with tailored compensation ratio[1]
- Thermal dynamics: predicted to be suppressed by finite topological charge[2]
- Diffusion enhanced >20 times for maximally compensated (fully AFM) SAFs[3]

[1]D. Han et al., Nat. Mat. **18,** 905 (2019); [2]M. Weissenhofer et al., NJP **22**, 103059 (2020); [3]T. Dohi et al., arxiv:2206.00791

Skyrmions in Spin-Orbitronics & Orbitronics: novel science and applications in memory & non-conventional computing

M. Kläui
Institut für Physik & Materials Science in Mainz
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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**

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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

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

5. Stochastic Computing

- Stochastic computing – information representation

X

Coin

P{X=1} = 0.50 “Heads”

Bitstream X: 0 1 0 0 1 1 1 1 0 1 0 1 1 0 0…
50% = 1 “Heads” and 50% = 0 “Tails”

Y

Cards

P{Y=1} = 0.25 “Ace”

Bitstream Y: 0 0 0 0 1 0 0 0 0 0 1 1 0 0 0…
25% = 1 “Ace” and 75% = 0 “other card”

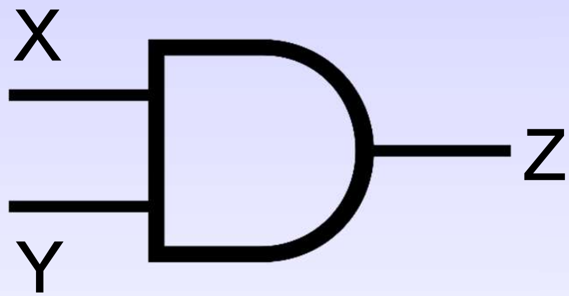
Bernoulli experiments

5. Stochastic Computing

- Stochastic computing – implementing operations

Bitstream X: 010011110101100…
50% = 1 - "Heads" and 50% = 0 - "Tails"

Bitstream Y: 000010000011001…
25% = 1 - "Ace" and 75% = 0 - "other card"



AND - Gate

Bitstream X:	0 1 0 0 1 1 1 1 0 1 0 1 1 0 0…
Bitstream Y:	0 0 0 0 1 0 0 0 0 0 1 1 0 0 1…
Bitstream Z:	0 0 0 0 1 0 0 0 0 0 0 1 0 0 0…

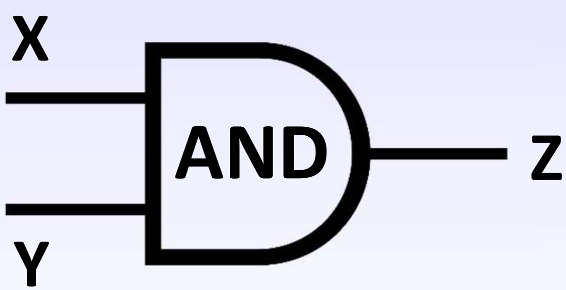
5. Stochastic Computing

- Stochastic computing – implementing multiplication

Bitstream X: 0 1 0 0 1 1 1 1 0 1 0 1 1 0 0… ≈ a = 0.50

Bitstream Y: 0 0 0 0 1 0 0 0 0 0 1 1 0 0 1… ≈ b = 0.25

Bitstream Z: 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0… ≈ c = result



If X and Y are independent, then (a) * (b) = P{X=1 and Y=1} = c

P{Z=1} = (0.5) (0.25) = 0.125 = c

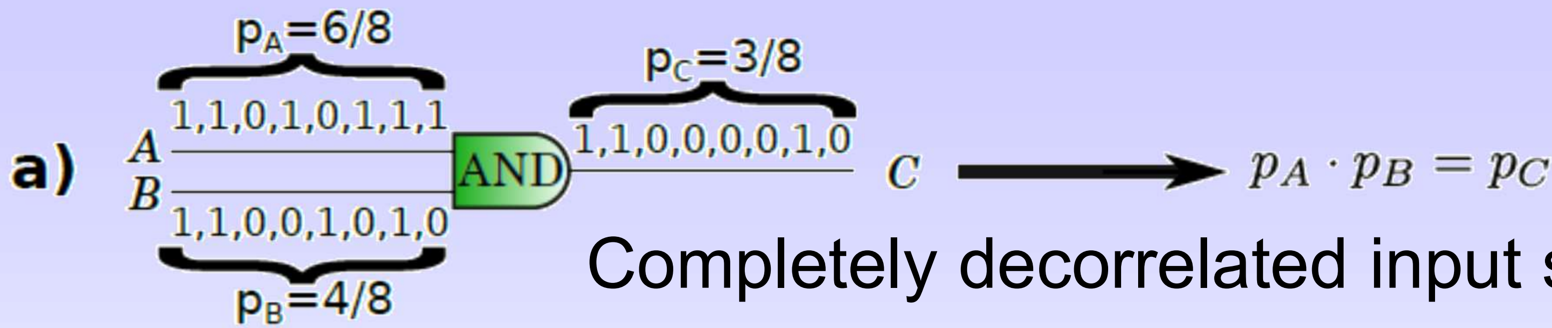
P{Z=1} = P{X=1 and Y=1}

Chance for "Heads" <u>and</u> "Ace": 12.5% ☑

Result c is only correct if Bitstreams X and Y are uncorrelated

5. Skyrmion Diffusion for probabilistic computing

- Examples of stochastic computing :



Completely decorrelated input streams ☑

To obtain decorrelated input streams → reshuffler needed

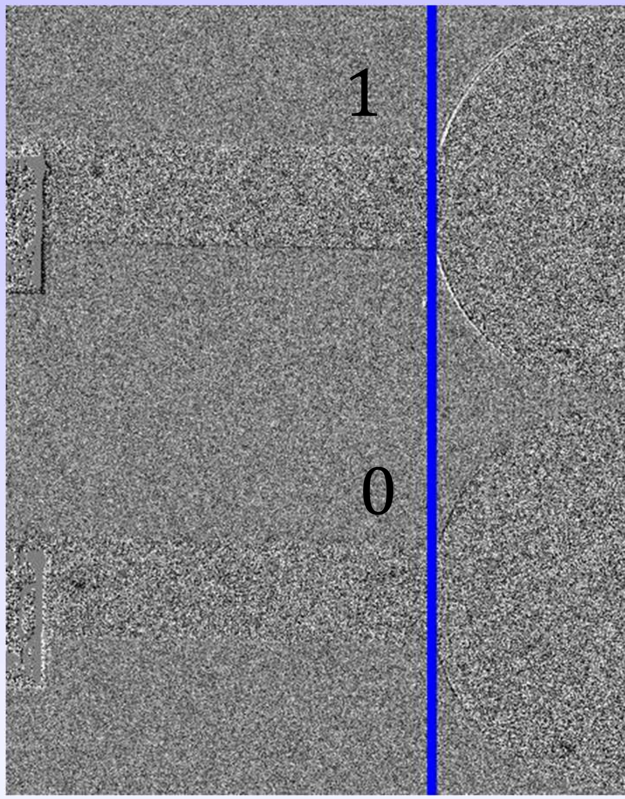
J. Zazvorka, MK et al., Nature Nano. **14**, 658 (2019)

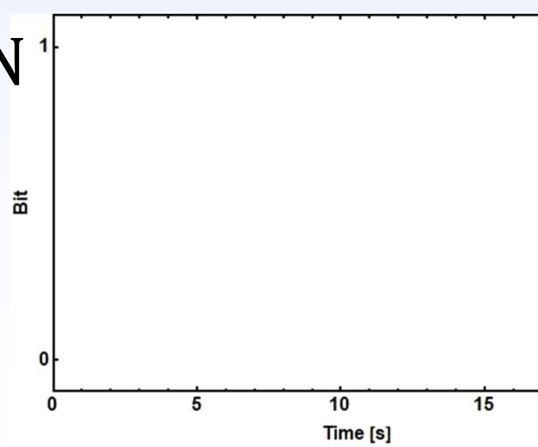
D. Pinna et al, Phys. Rev. Applied **9**, 064018

5. Skyrmion Reshuffler to create uncorrelated bitstreams

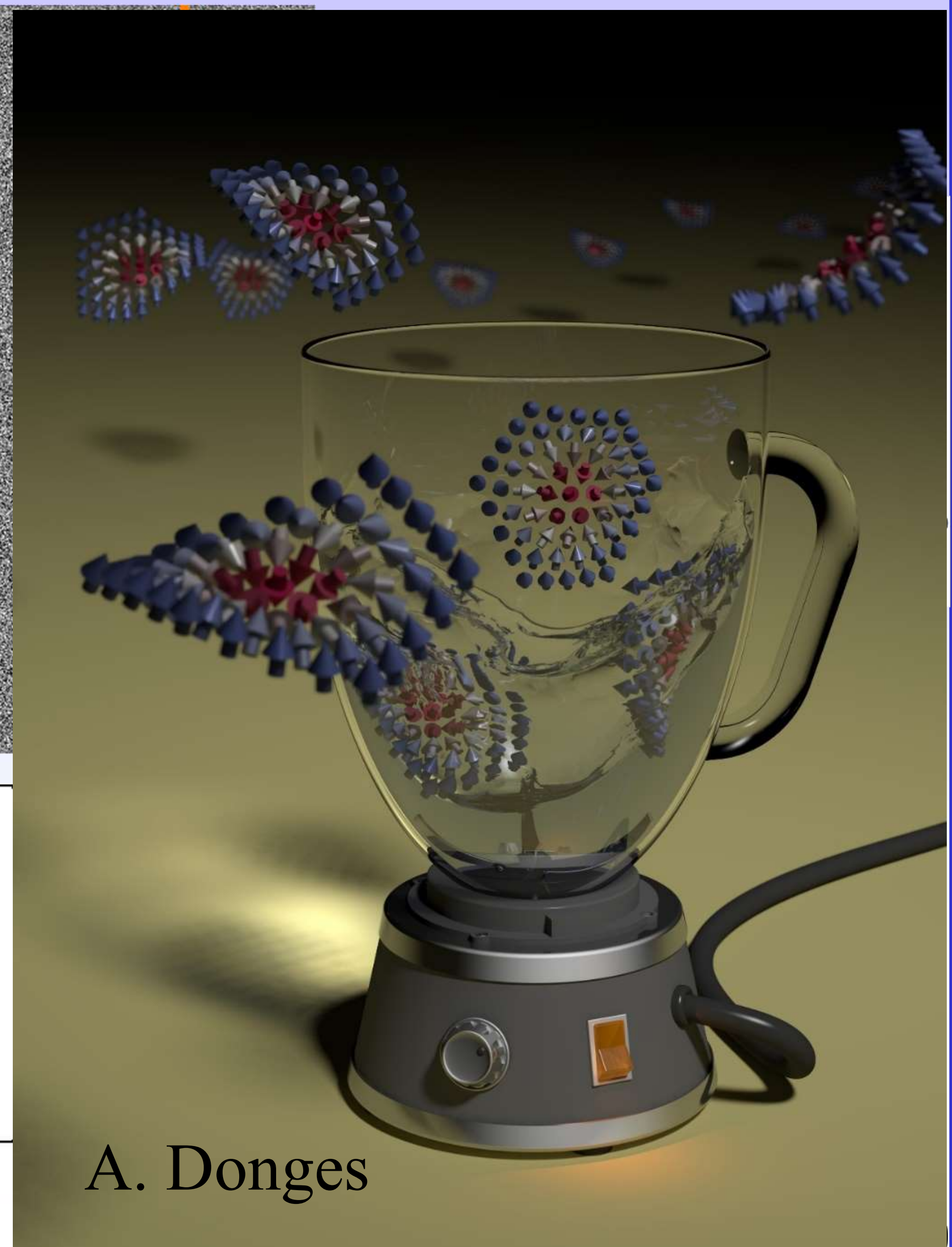
Realization:

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





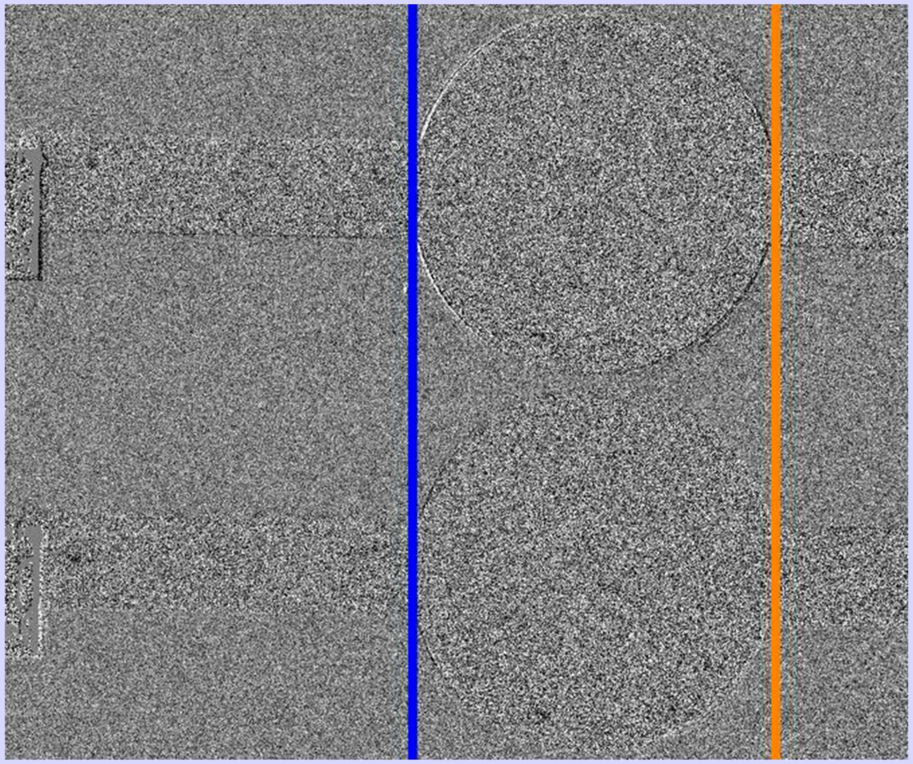
$$\rho = \frac{cov(in, out)}{\sigma_{in} \cdot \sigma_{out}}$$



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

5. Logic using skyrmions

- Stochastic Logic can be realized with Skyrmions

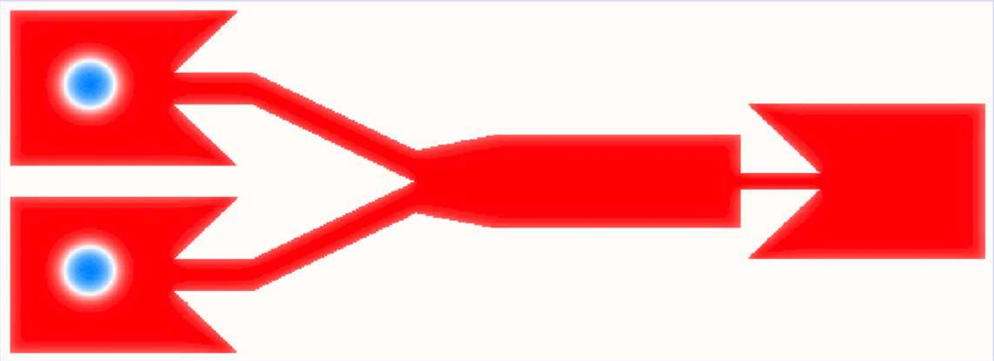


- Combining:

  1. Skyrmion Reshuffler

  2. AND Gate

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



→Multiplication using probabilistic computing approach

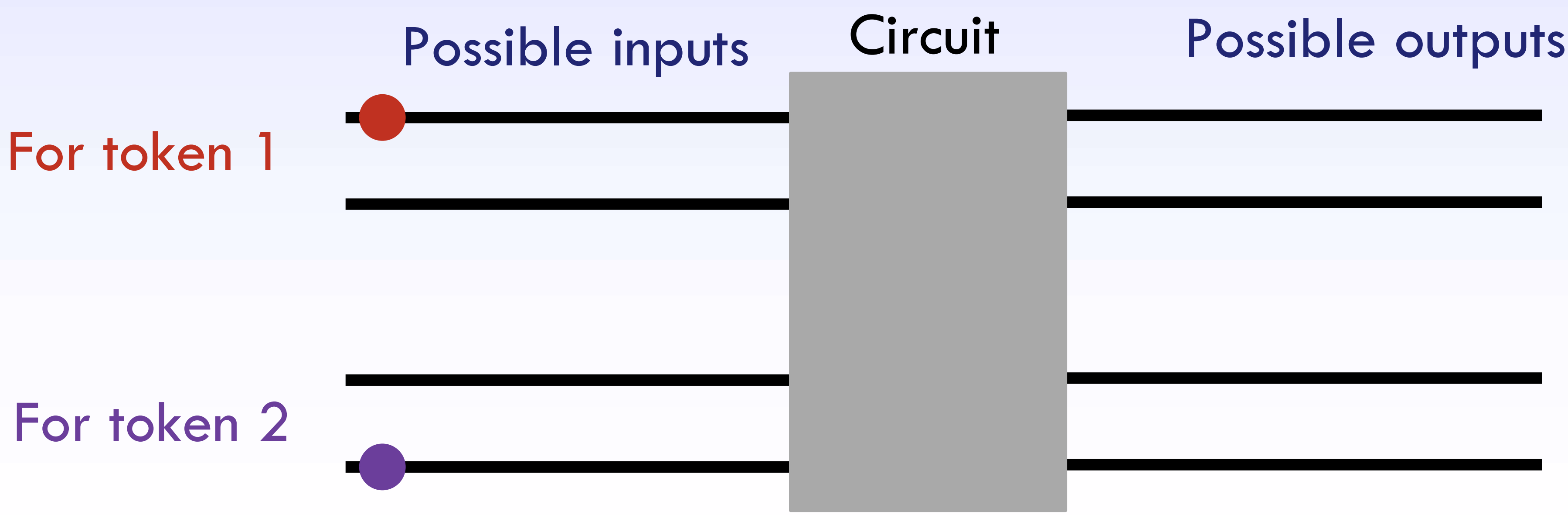
Non-conventional low power computing using skyrmions: (II) Token-based Brownian Computing

6. Token-based Brownian Computing - Basics

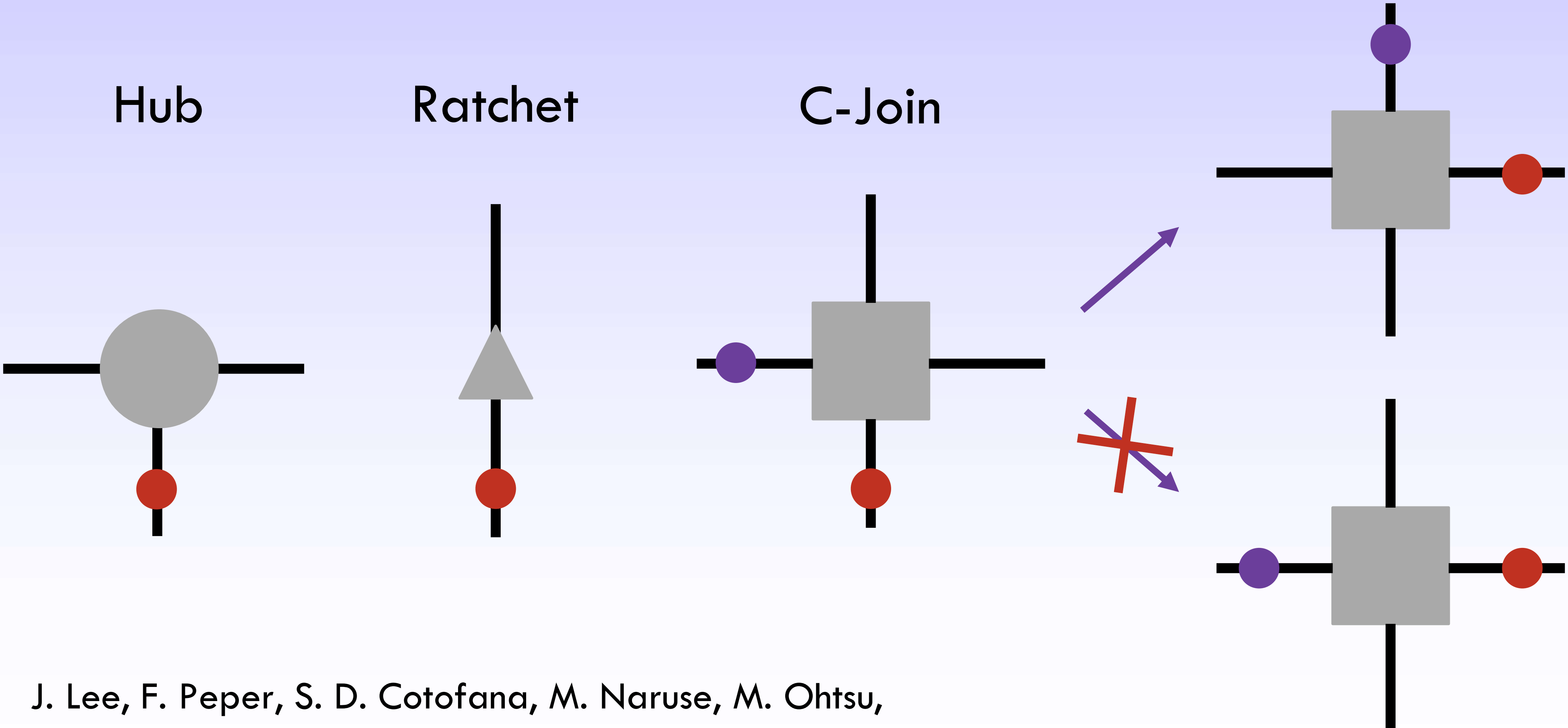
TOKEN-BASED COMPUTING FUNDAMENTALS

Token: Discrete signal carrier

Circuit: Network with special transition rules



6. Token-based Brownian Computing – Circuit Components



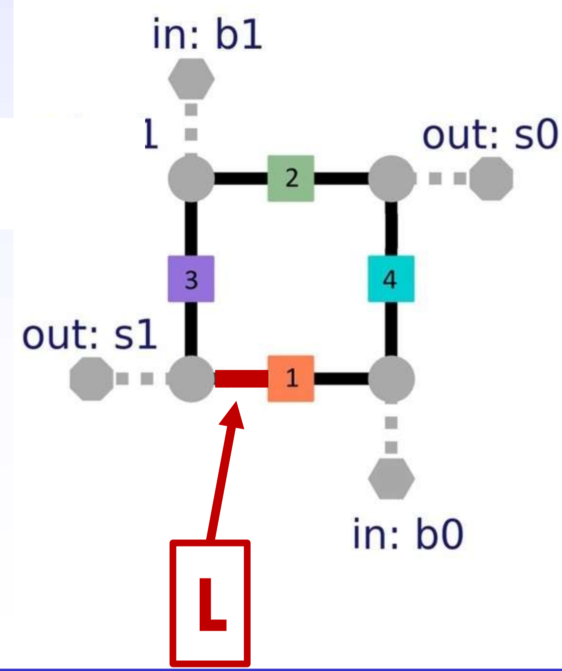
J. Lee, F. Peper, S. D. Cotofana, M. Naruse, M. Ohtsu,
T. Kawazoe,Y. Takahashi, T. Shimokawa, L. B. Kish, T. Kubota,
"**Brownian circuits: Designs**", Int. J. Unconv. Comput. 12, 341-362 (2016)

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]

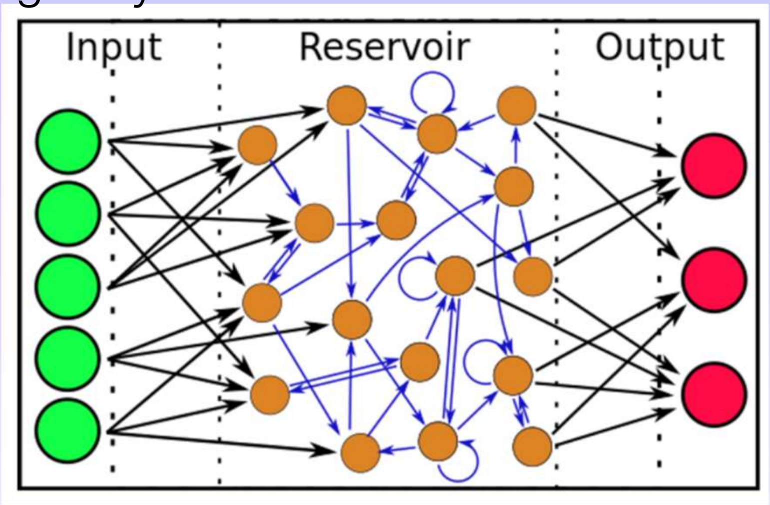


[1]M. A. Brems, P. Virnau, M. Kläui, "**Circuits and excitations to enable Brownian token-based computing with skyrmions**", Appl. Phys. Lett. **119**, 132405 (2021)
M. A. Brems, P. Virnau, M. Kläui, "**Information processing apparatus**", *European patent disclosure,* EP21164676.5 (2021)
[2]T. Dohi, MK et al., arxiv:2206.00791 (under review 2022)

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

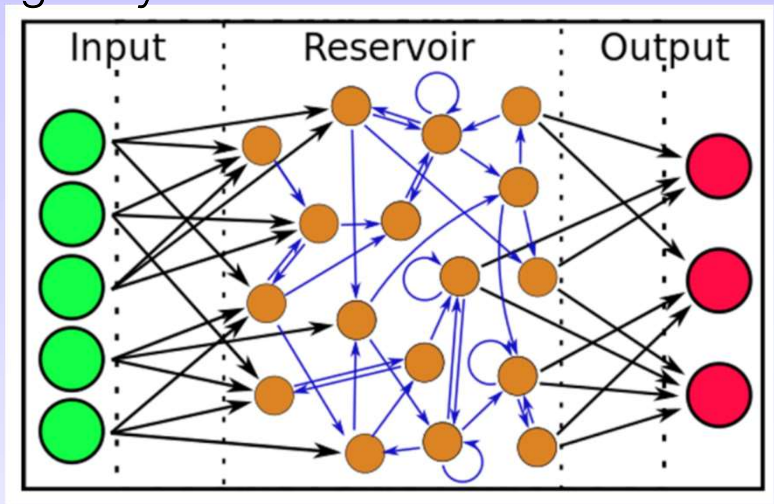
Goal: map a complex problem to a linearly solvable one

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

RC bypasses training constraints

6. Reservoir Computing with Skyrmions

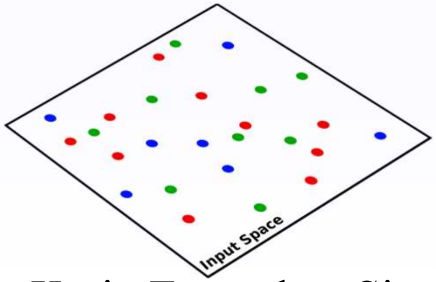
originally: artificial neural network with



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

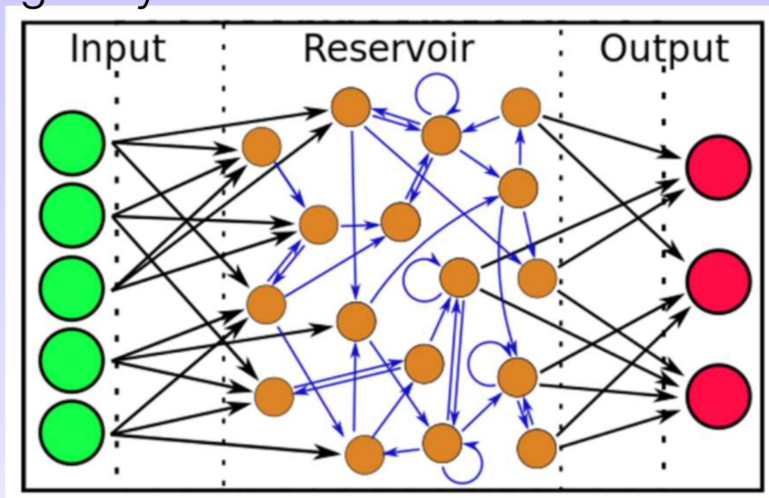


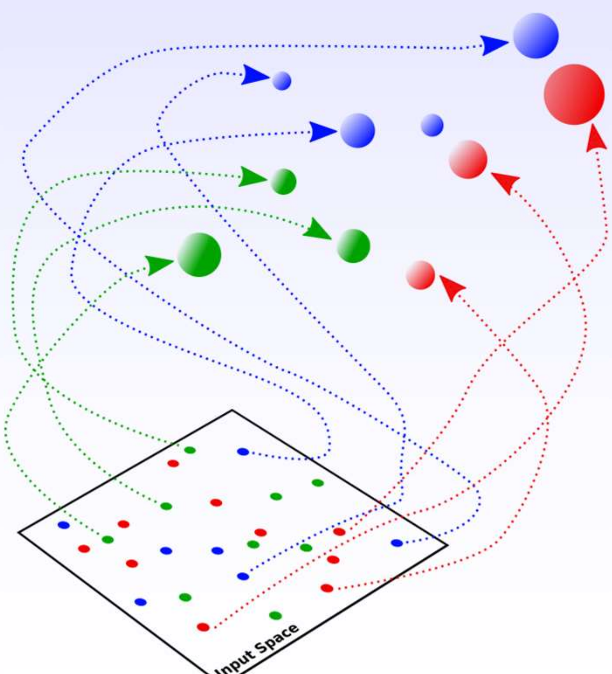
Courtesy Karin Everschor-Sitte

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

6. Reservoir Computing with Skyrmions

originally: artificial neural network with





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)

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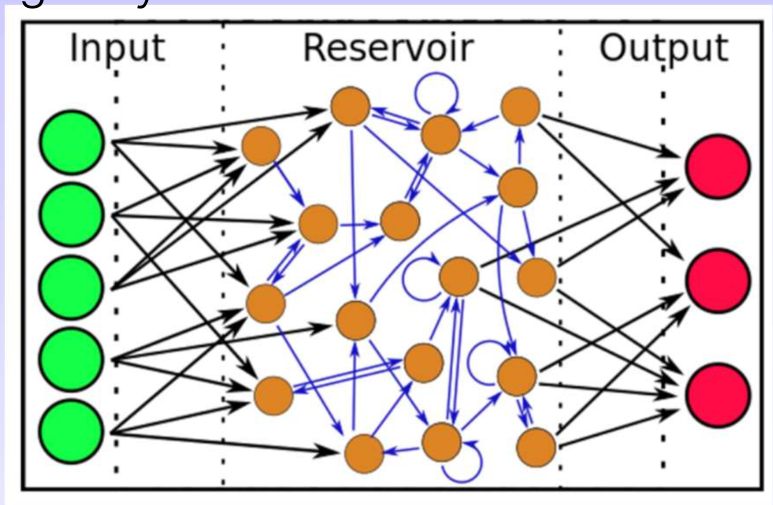

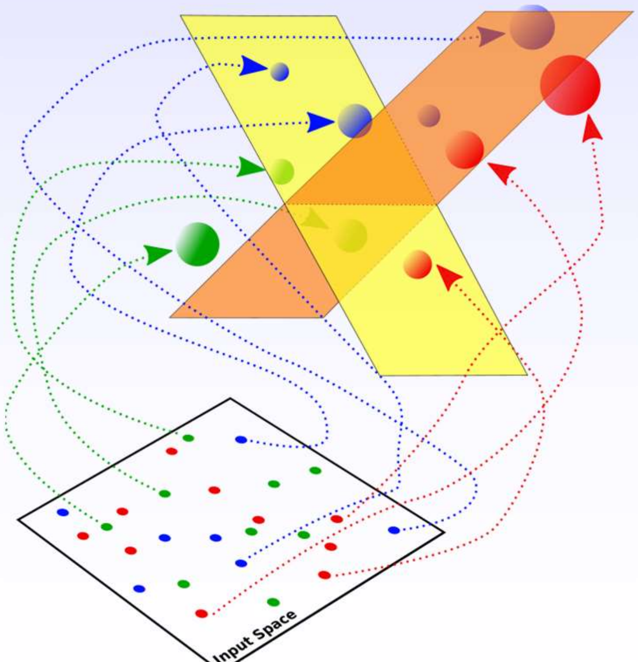

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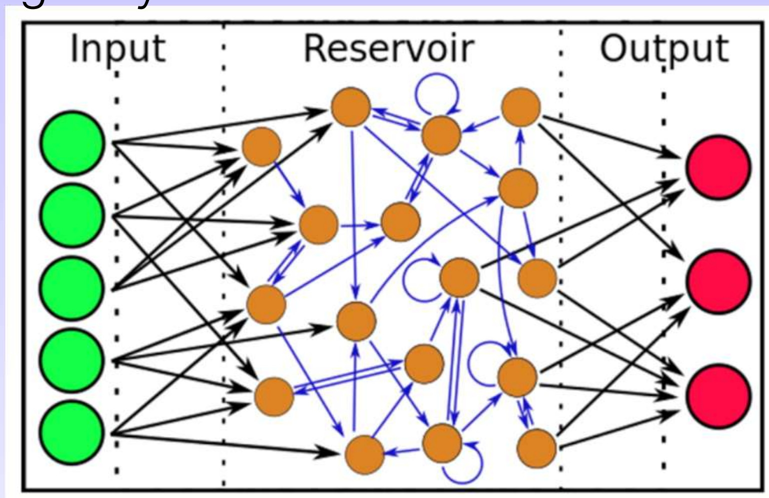

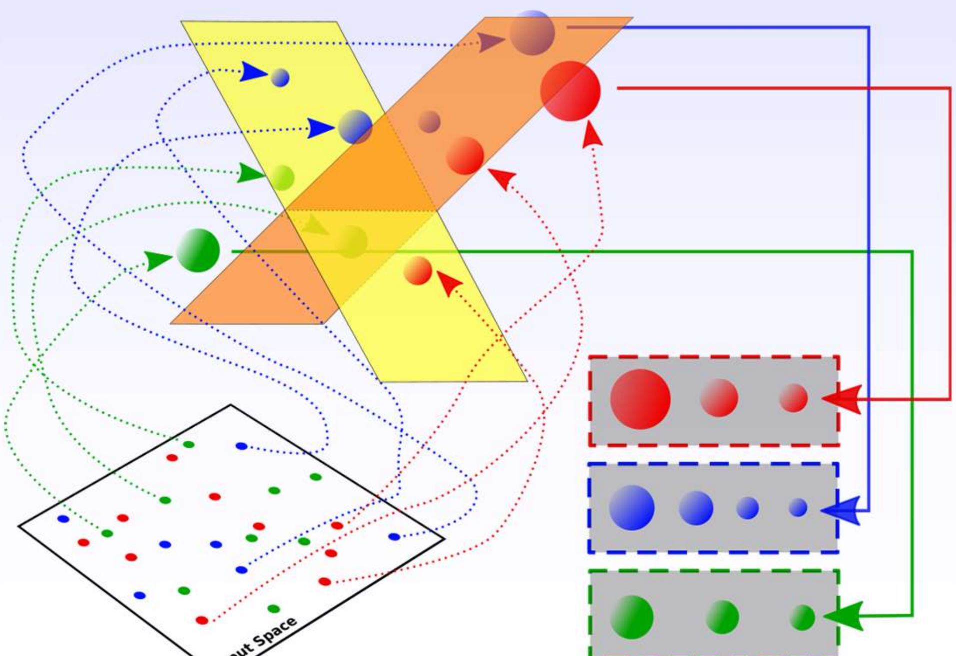

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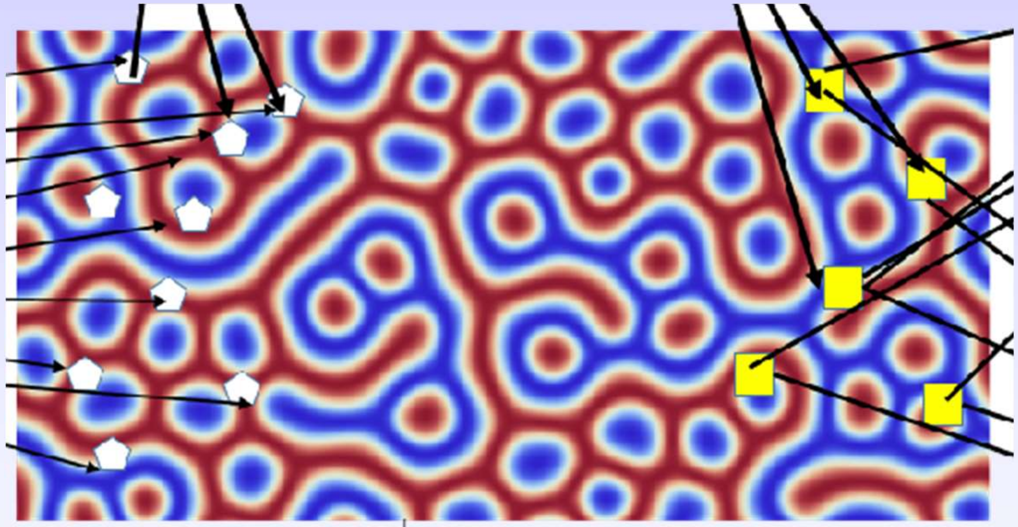

"skyrmion fabrics" as reservoir

George Bourianoff

K. Everschor- Sitte (DUE)

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

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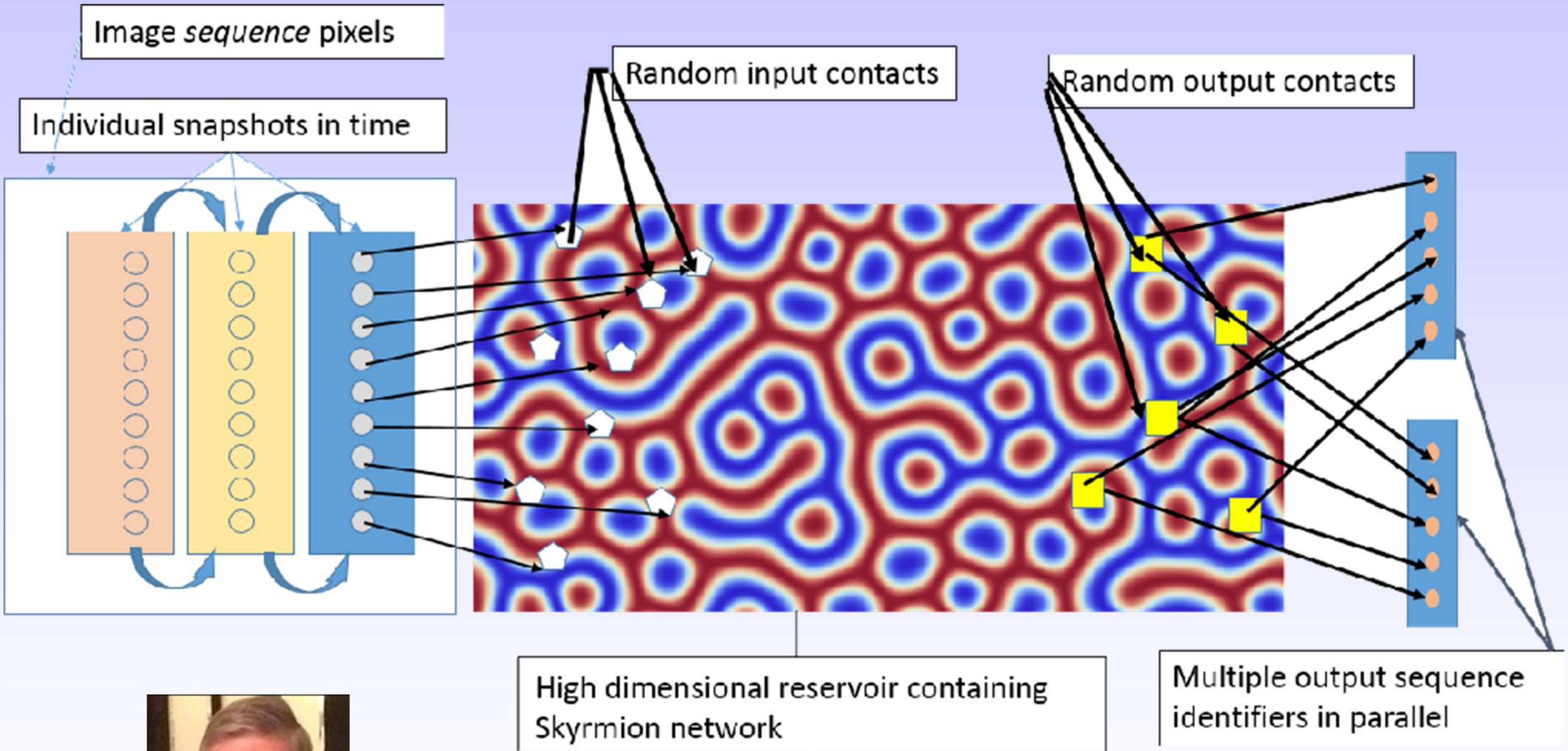


George Bourianoff

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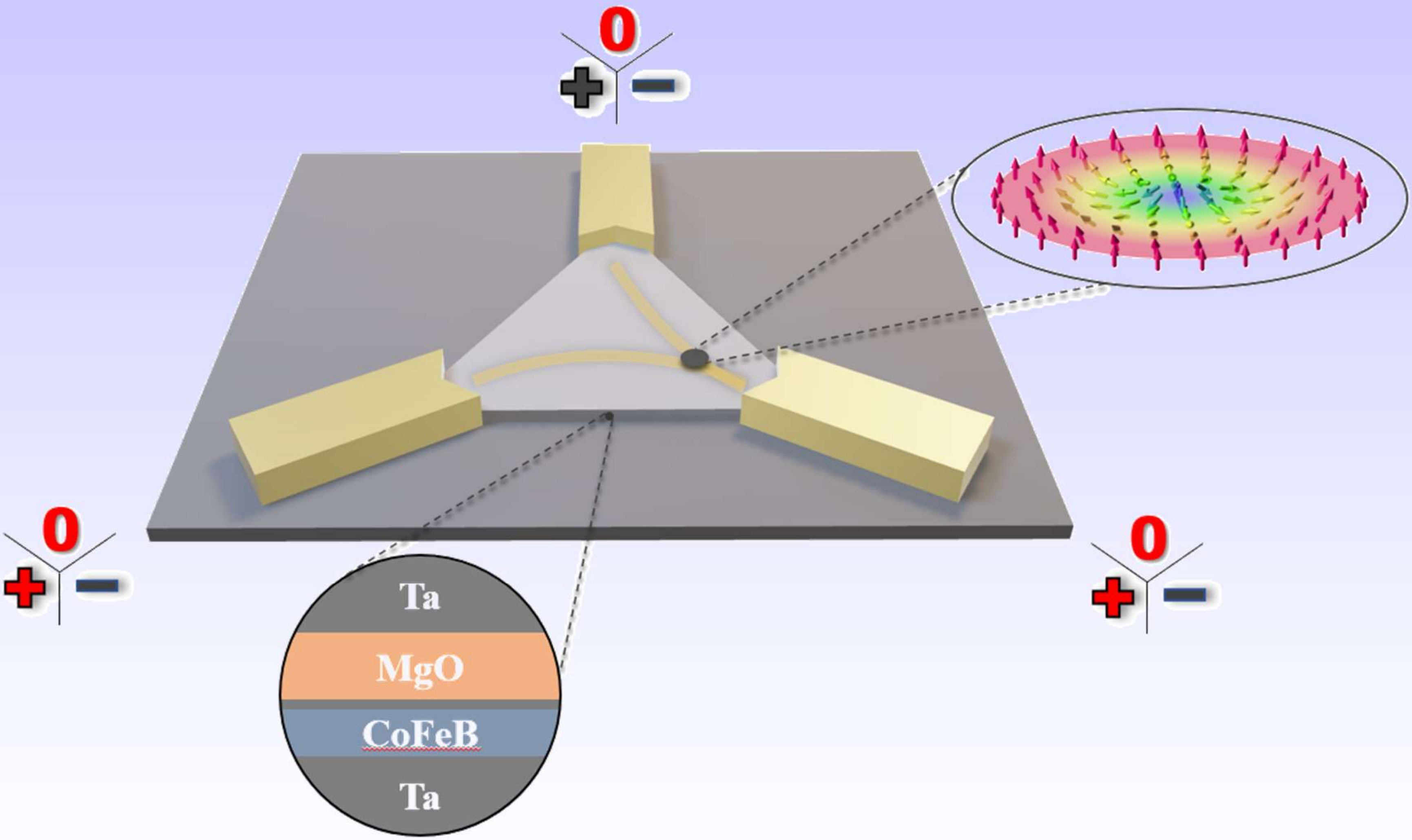
7. Realization of spatial multiplexing reservoir computing



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.

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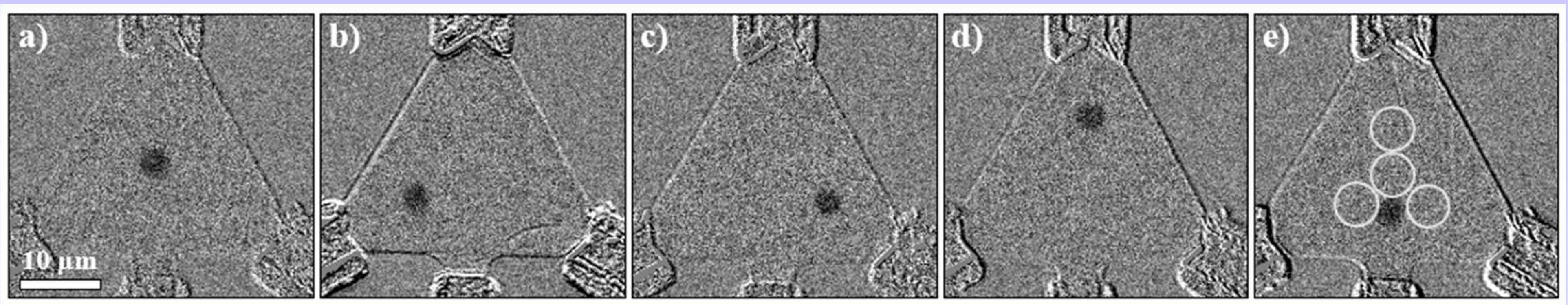

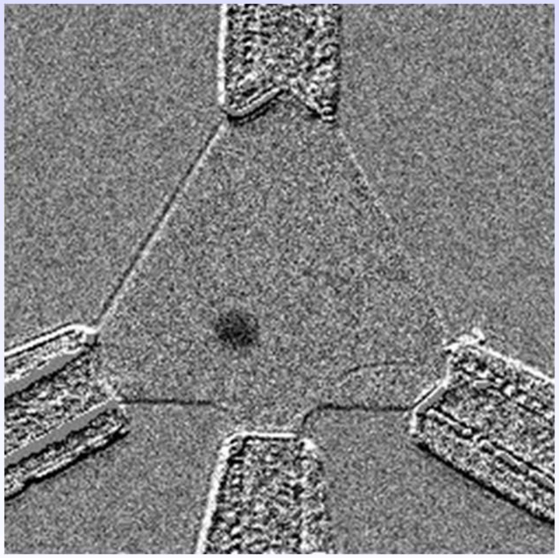

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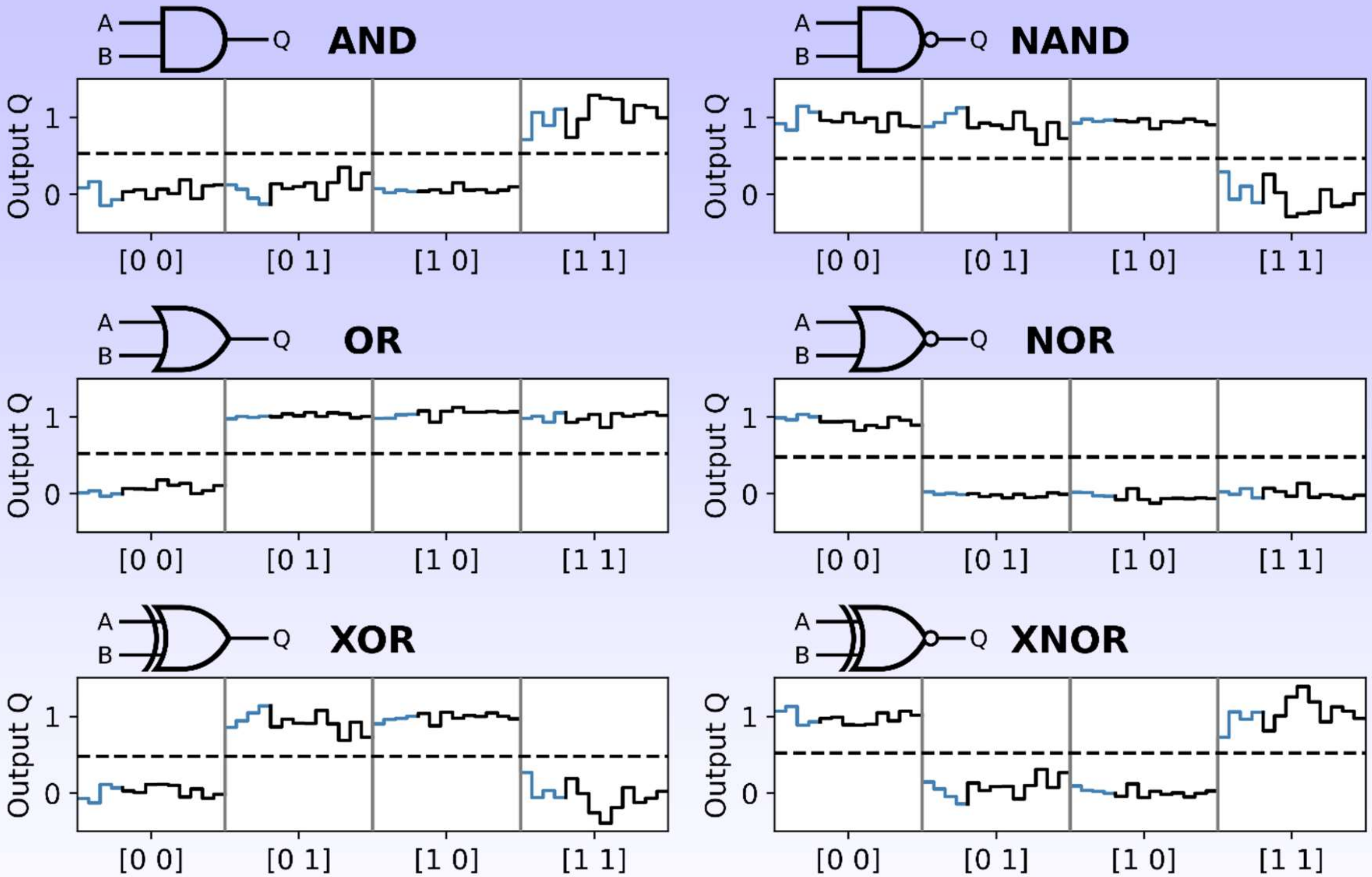

K. Raab, MK et al., Nature Comm. **13**, 6982 (2022)

← 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.

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SEVENTH FRAMEWORK PROGRAMME
MATERIALS IN MAINZ SCIENCE

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Stanford-Tohoku-Mainz SpinNet, Samsung, TopDyn Centre

QuSpin
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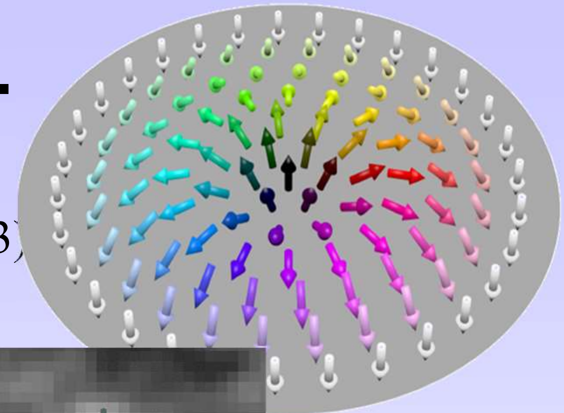
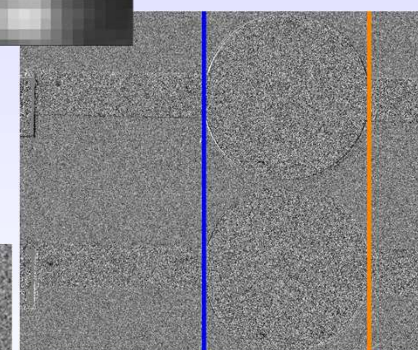
Summary:

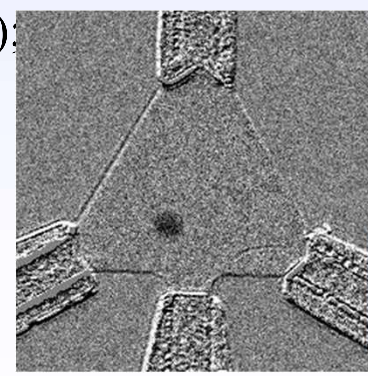


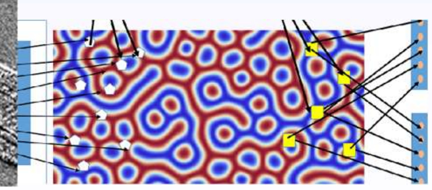
- **DMI stabilizes chiral spin structures with defined topology: pinning at domain walls**
  Nature Materials **15**, 501 (2016); Nature Materials **18**, 703 (2019); Nano Lett ('23);
  Nature Commun. **11**, 6304 (2020); Nature Commun. **13**, 3144 (2022);

- **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)



- **Thermally induced diffusion (in sAFMs!) used for probabilitistic logic** Comm. Phys. **6**, 30 (2023); Adv. Mater. **35**, 2208922 (2023), arxiv:2206.00791; Nature Nano. **14**, 658 (2019);





- **Low power Token-based Brownian Computing and Reservoir Computing**
  Nature Nano. **15**, 726 (2020); PRAppl. **9**, 14034 (2018);
  APL **119**, 132405 (2021); Nature Comm. **13**, 6982 (2022)

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