School of Physics & Astronomy
FACULTY OF MATHS & PHYSICAL SCIENCES

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Skyrmions in chiral magnetic multilayers

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Acknowledgements

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Chiral Magnetic Skyrmions

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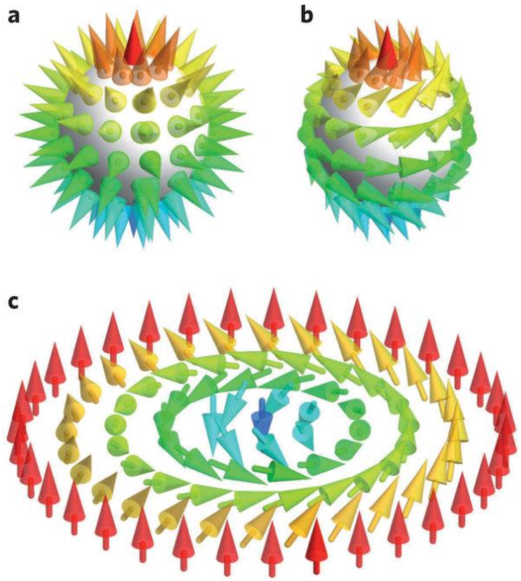
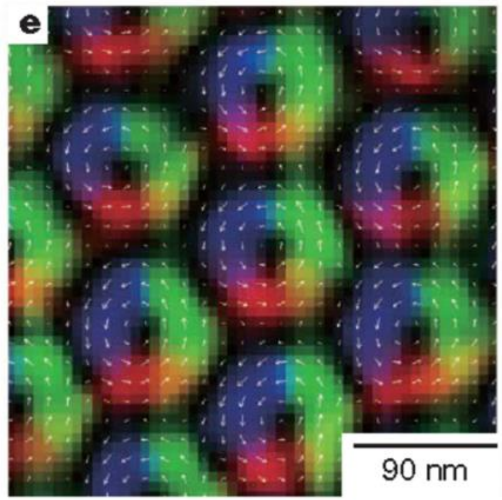
Topologically stable vector field object – integer winding numbers

"Combed hedgehog"

$$S = \frac{1}{4\pi} \int \hat{\mathbf{m}} \left(\frac{\partial \hat{\mathbf{m}}}{\partial x} \times \frac{\partial \hat{\mathbf{m}}}{\partial y} \right) dx dy$$

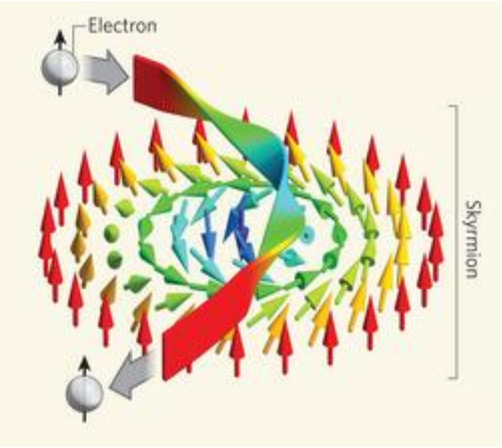


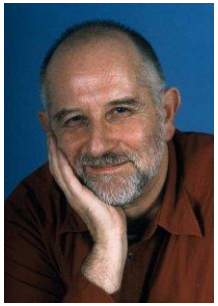
Skyrmion crystal



$Fe_{0.5}Co_{0.5}Si$ - Yu Nature (2010)

Tony Skyrme FRS





Sir Michael Berry FRS

Emergent electrodynamics arising from Berry phase

Each skyrmion = φ_0 of fictitious magnetic flux

Moving skyrmions => effective electric field

Topology

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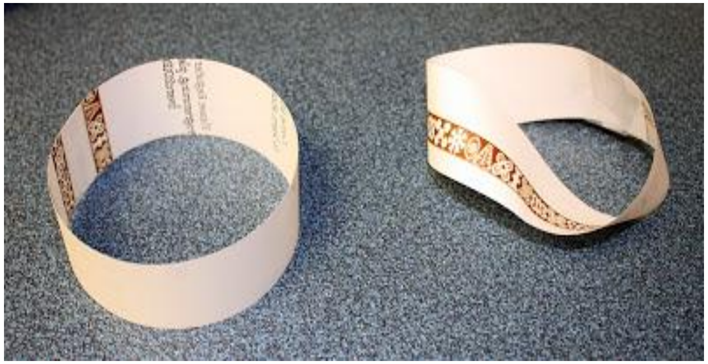
Topology is counting…

zero one two …

Möbius strip



zero one

Topology provides stability

"You cannot have half a hole in something"

Dzyaloshinskii-Moriya Interaction

requires structural inversion asymmetry + SOC

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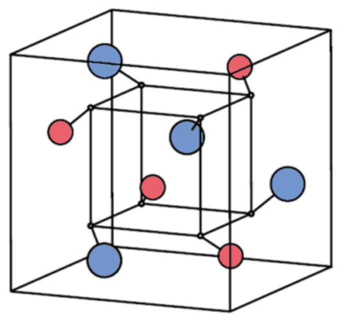
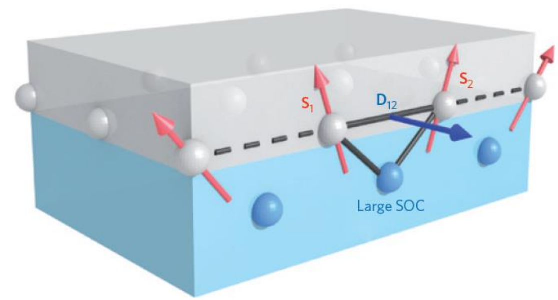
Chiral Interaction $E_{\mathrm{DM}} = \mathbf{D} \cdot \mathbf{S_1} \times \mathbf{S_2}$

bulk

crystal lacks inversion symmetry e.g. B20 unit cell

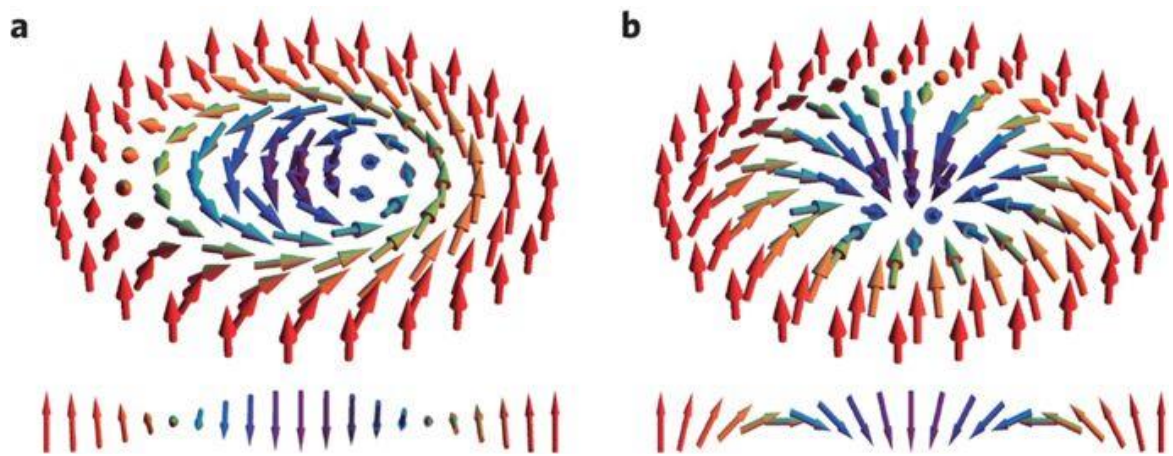


interface



asymmetric layers (with different SOC) around FM break inversion symmetry

Bloch skyrmion



Helicoid

Cycloid

Néel skyrmion

Fert et al. Nature Nano. **8**, 152 (2013)

Al-Sharif, J. of Phys: Cond. Matter, 13, 2807 (2001)

Room temperature magnetic skyrmions

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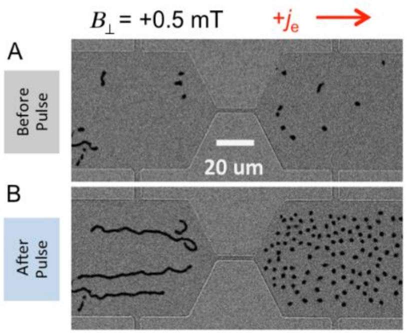
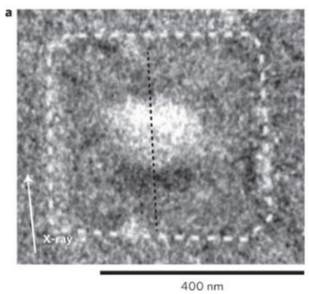
TRILAYER



D_S=700-2000 nm

Ta/CoFeB/TaO

Jiang et al. Science (2015)

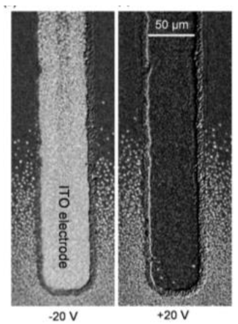


D_S=150 nm

Pt/Co/MgO

Boulle et al.

Nature Nanotech. (2016)

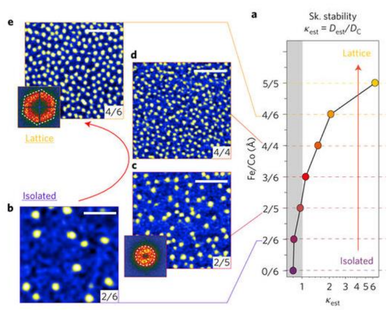


D_S>1000 nm

Pt/Co/AlO

Schott et al.

Nano Letters (2017)



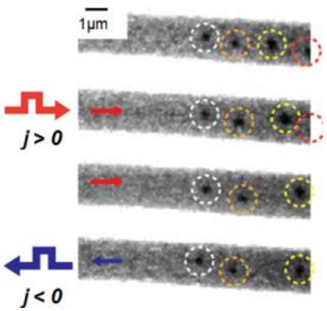
D_S=40-100 nm

Ir/Fe/Co/Pt

Soumyanarayanan et al.

Nature Materials (2017)

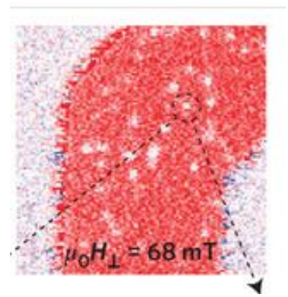
MULTILAYER



D_S=100-300 nm

[Pt/Co/Ta] ×15

Woo et al. Nature Materials (2016)

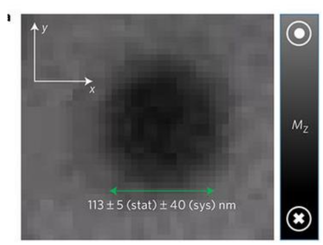


D_S=30-90 nm

[Pt/Co/Ir]×10

Moreau-Luchaire et al.

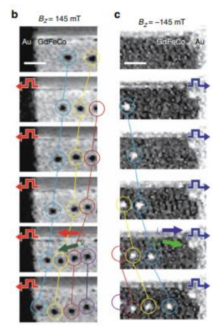
Nature Nanotech. (2016)



D_S=70 nm-150 nm

[Pt/CoFeB/MgO] ×15

Litzius et al. Nature Phys (2017)



D_S=180 nm

[Pt/GdFeCo/MgO] ×20

Woo et al. Nature Comm (2018)

LTEM under tilt: {Pt/Co/Ir}×2

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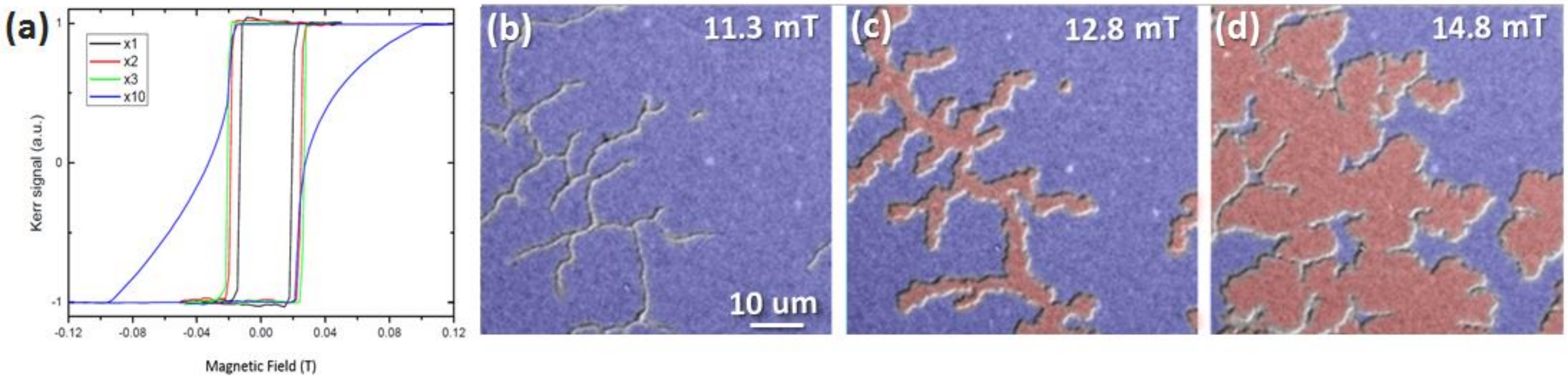
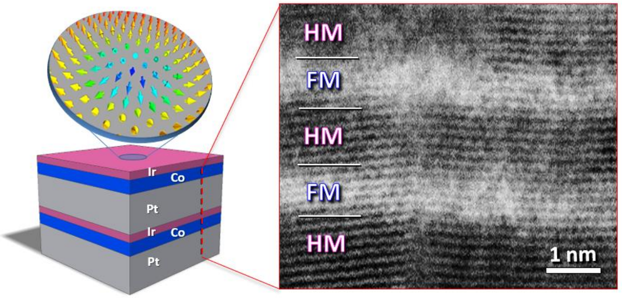
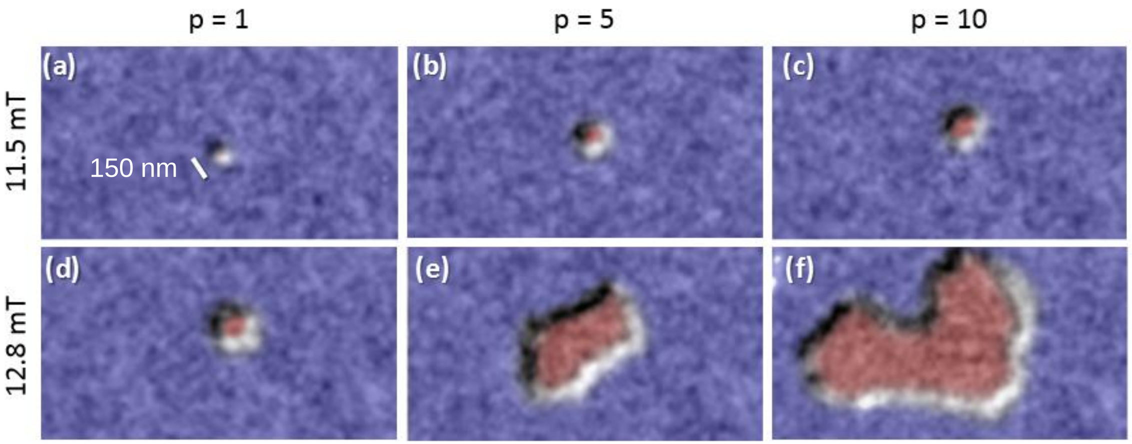
Chiral DWs and skyrmion bubbles



Multilayer stack



Bursting skyrmion bubbles, p = number of field pulses



p = number of field pulses

Pulecio et al., arXiv:1611.06869 [cond-mat.mtrl-sci]

Magnetic imaging using STXM

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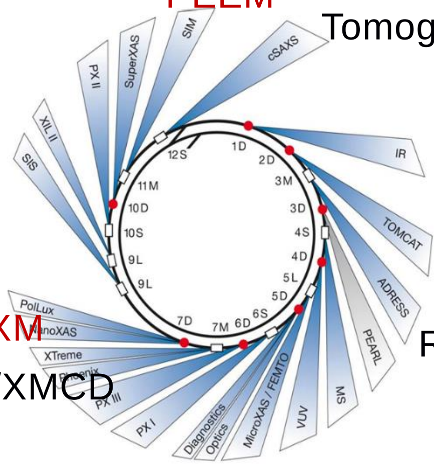
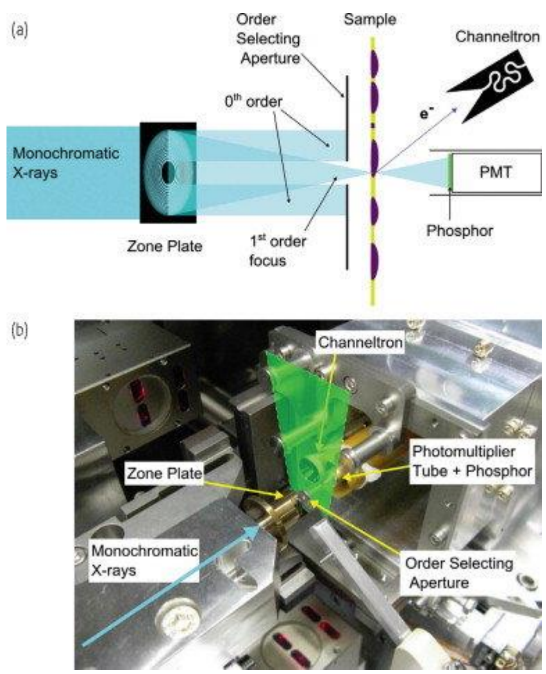
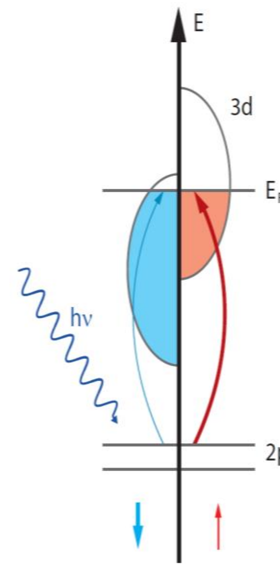
PolLux at Swiss Light Source, PSI

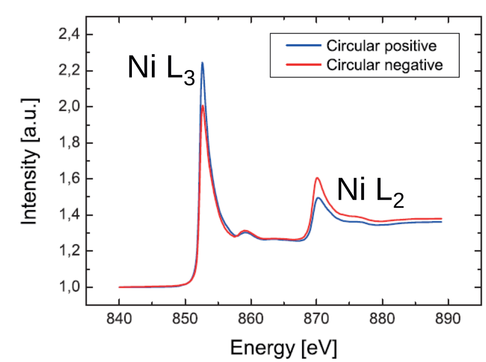


Zone plate optics



Watts and Ade, Materials Today (2012)





XMCD contrast

X-ray magnetic circular dichroism (XMCD)

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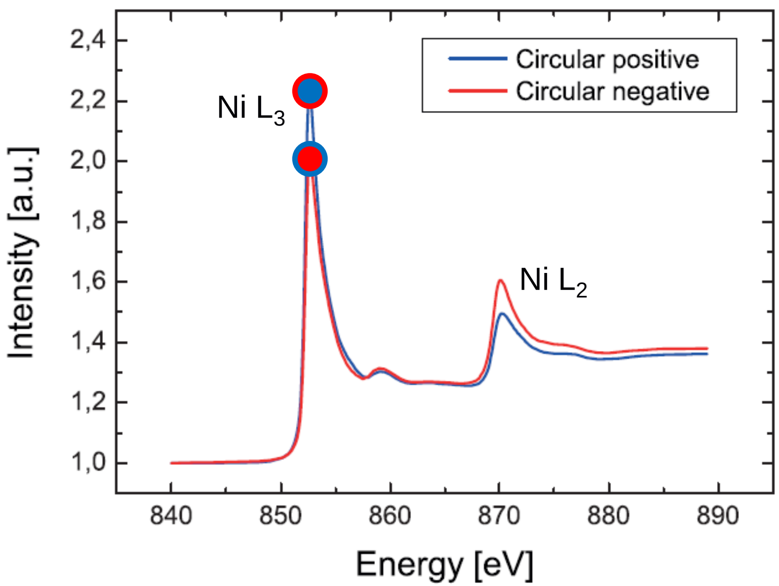
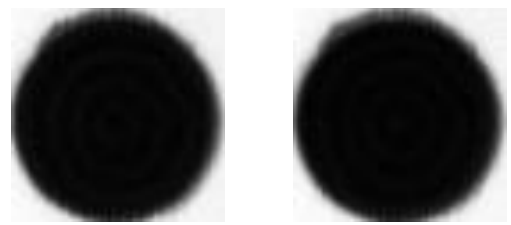
- Magnetic images can be acquired by employing the x-ray magnetic circular dichorism effect
- Different absorption of circularly-polarized x-rays depending on the local magnetization of the sample





$$I_{XMCD} = \frac{I_+ - I_-}{I_+ + I_-}$$

Slide courtesy of Simone Finizio, PSI

Magnetic imaging of nanodiscs by STXM

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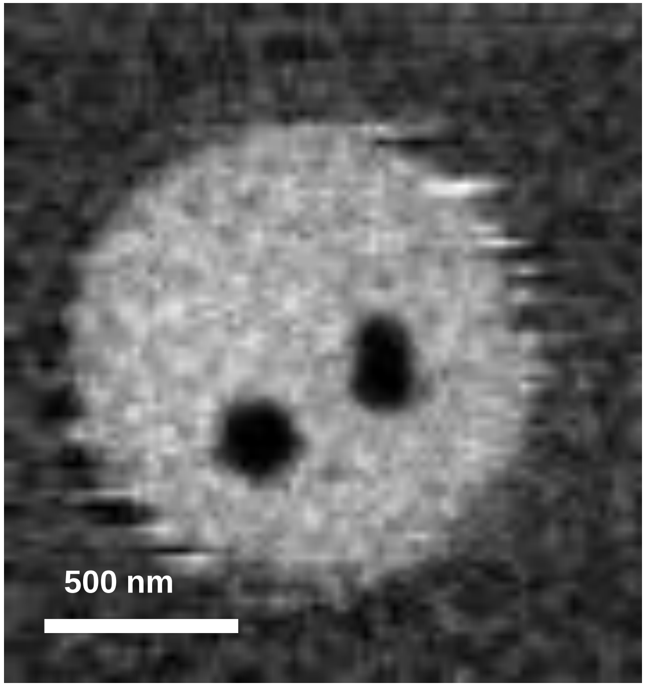
Ta(4.6 nm)/Pt(7.5 nm)/[Co(0.7 nm)/Ir(0.5 nm)/Pt(2.3 nm)]$_{\times 10}$/Ir(1.3 nm)

STXM AT PolLux/PSI

- Co L_3 edge (779.5 eV)
- Room temperature
- Field applied out-of-plane
- X-ray absorption proportional to out-of-plane magnetization M_z
- Dark and bright contrast represents oppositely out-of-plane magnetized regions
- Spatial resolution ~25 nm
- Temporal resolution ~200 ps
- Skyrmion bubbles are observed



Skyrmions for future computing

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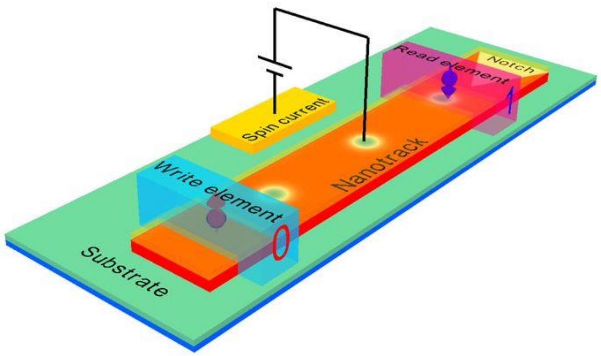
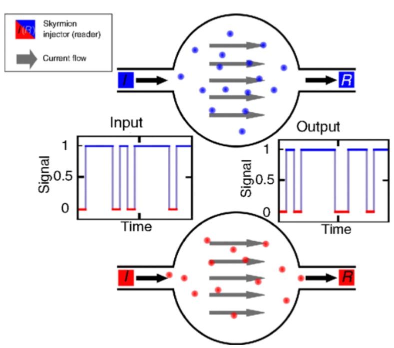
Digital racetrack memory



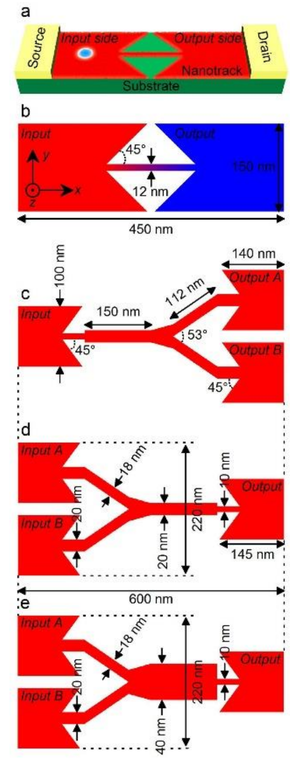
X. Zhang et al., *Sci. Rep.* **5**, 7643 (2015)

Neuromorphic computing



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

Boolean logic



Fanout

OR

AND

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

Basic skyrmion operations

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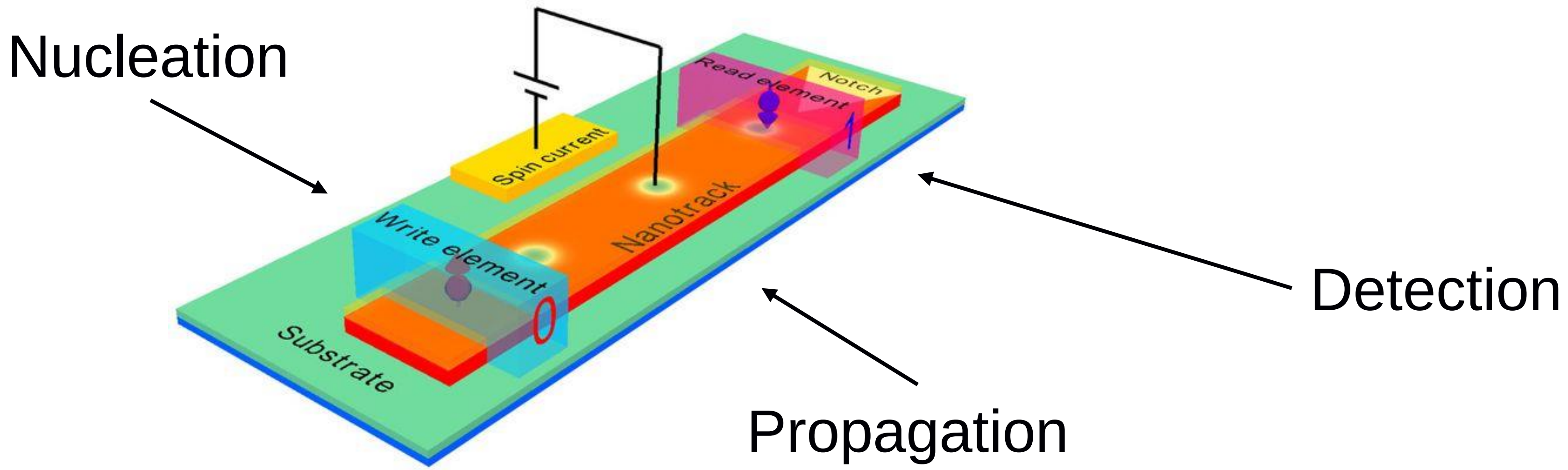

All need to be accomplished by electrical means for spintronics

X. Zhang et al., *Sci. Rep.* **5**, 7643 (2015)

Basic skyrmion operations

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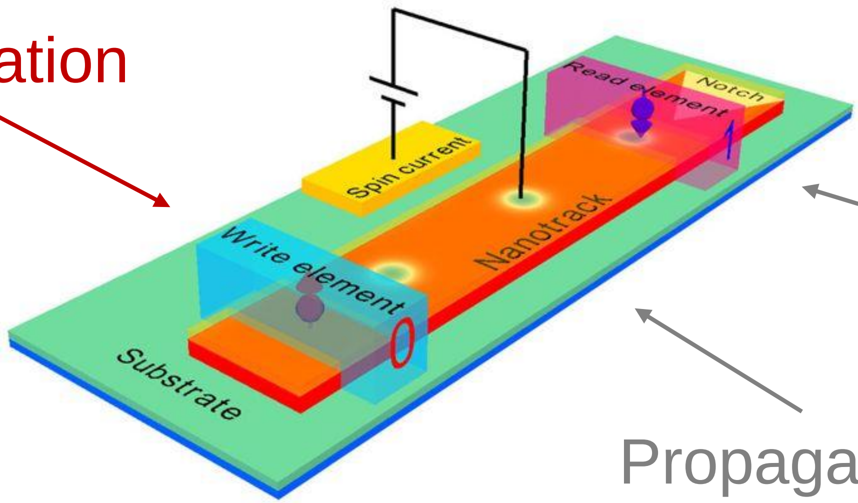
Nucleation



Detection

Propagation

X. Zhang et al., *Sci. Rep.* **5**, 7643 (2015)

Disordered Simulation

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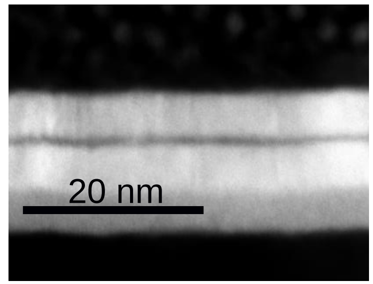
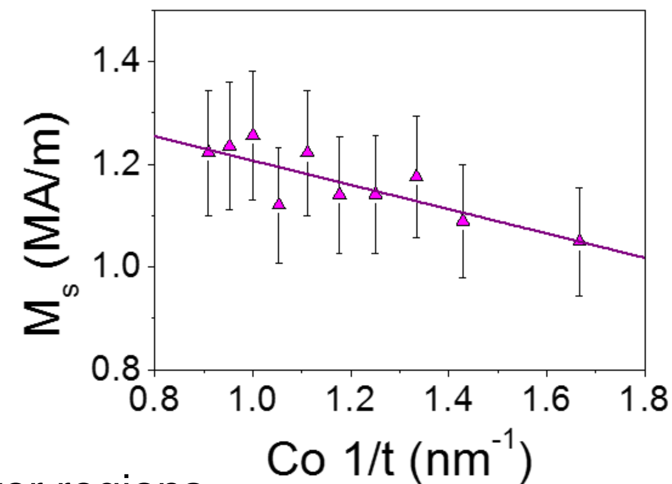
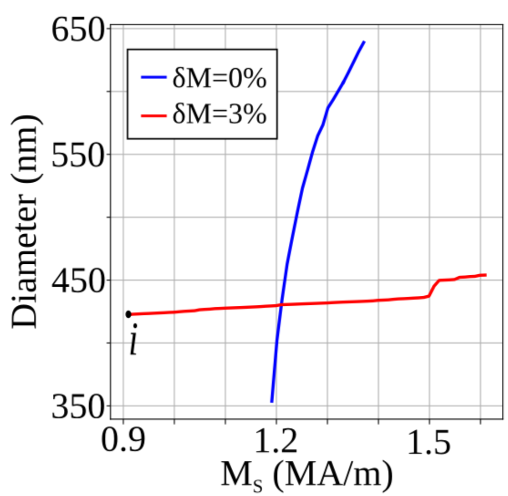
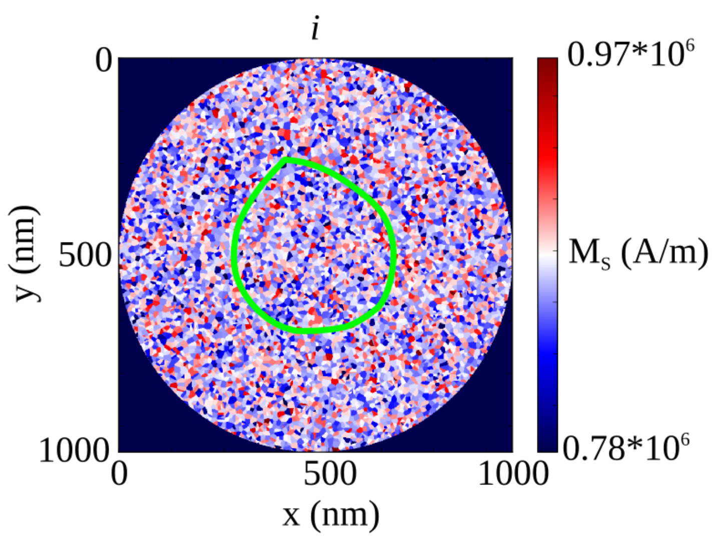
DISORDER

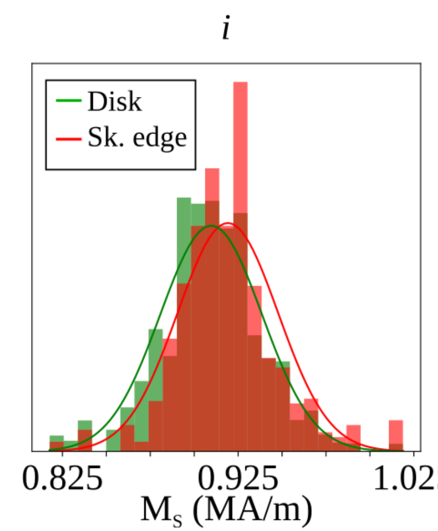
- Modulate thickness
- 10 nm grain size
- Average M_S with standard deviation of $\delta M/M$, 3%
- Stabilizes skyrmion bubble
- Domain boundary found in regions of high M_S i.e. thicker regions











Electrical nucleation in Pt/CoB/Ir

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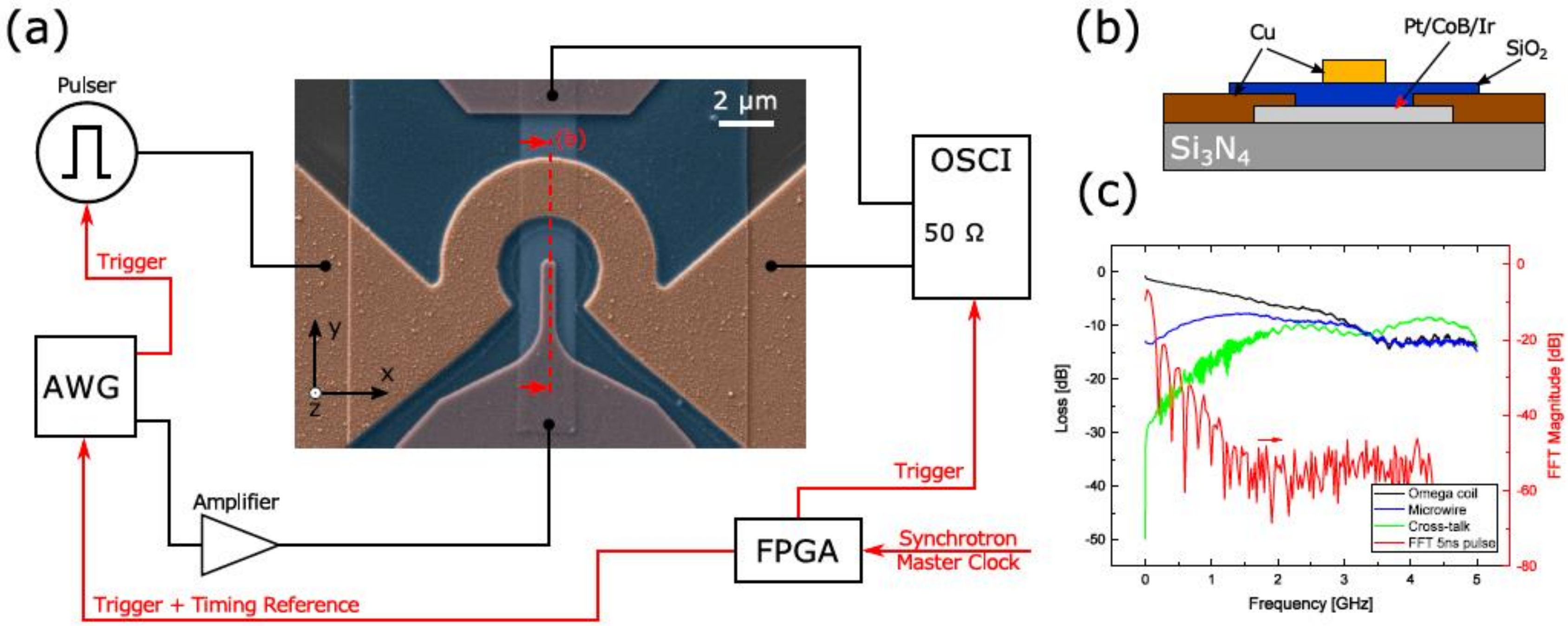
- Fabrication of point-contact geometries to facilitate the injection of magnetic skyrmions
- Design combined with Omega coils for investigation of gyration dynamics and for providing transient fields during nucleation/motion (5 step lithography process)



Finizio et al., Nano Letters **19**, 7246 (2019)

Skyrmion nucleation in Pt/CoB/Ir

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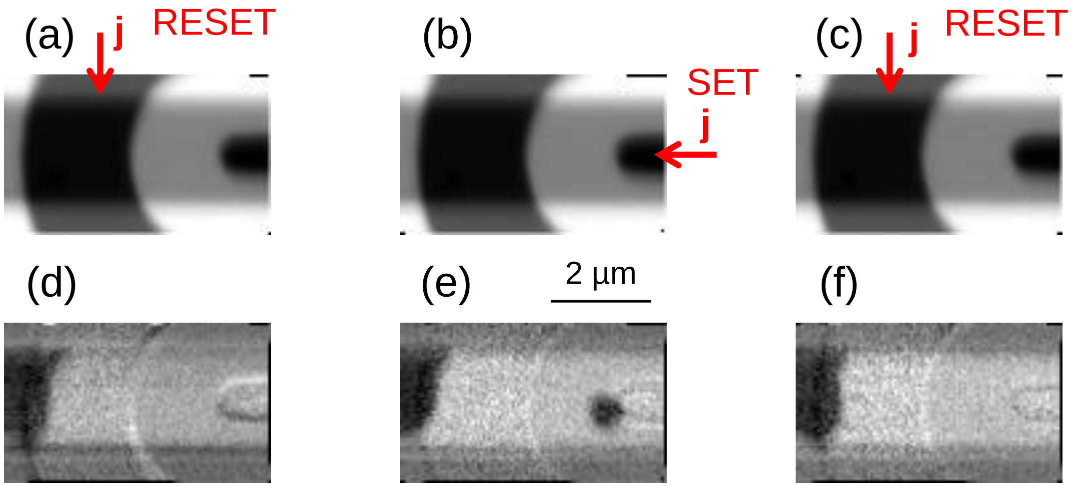
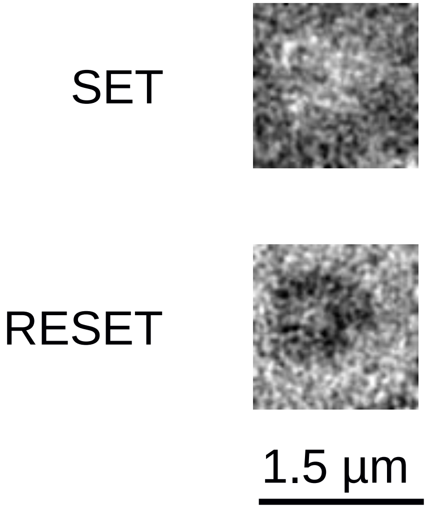
- Nucleation of magnetic skyrmions from the point contact (current densities ~1-1.5×10^{12} A/m^2) - SET
- Annihilation of the skyrmion by pulsed magnetic field (generated by the omega coil) - RESET
- XMCD-STXM imaging at a time resolution of 2 ns
- All measurements were done at the remnant state (0 mT), normalised to average contrast throughout movie



32 ns loop



Finizio et al., Nano Letters **19**, 7246 (2019)

Skyrmion nucleation in Pt/CoB/Ir

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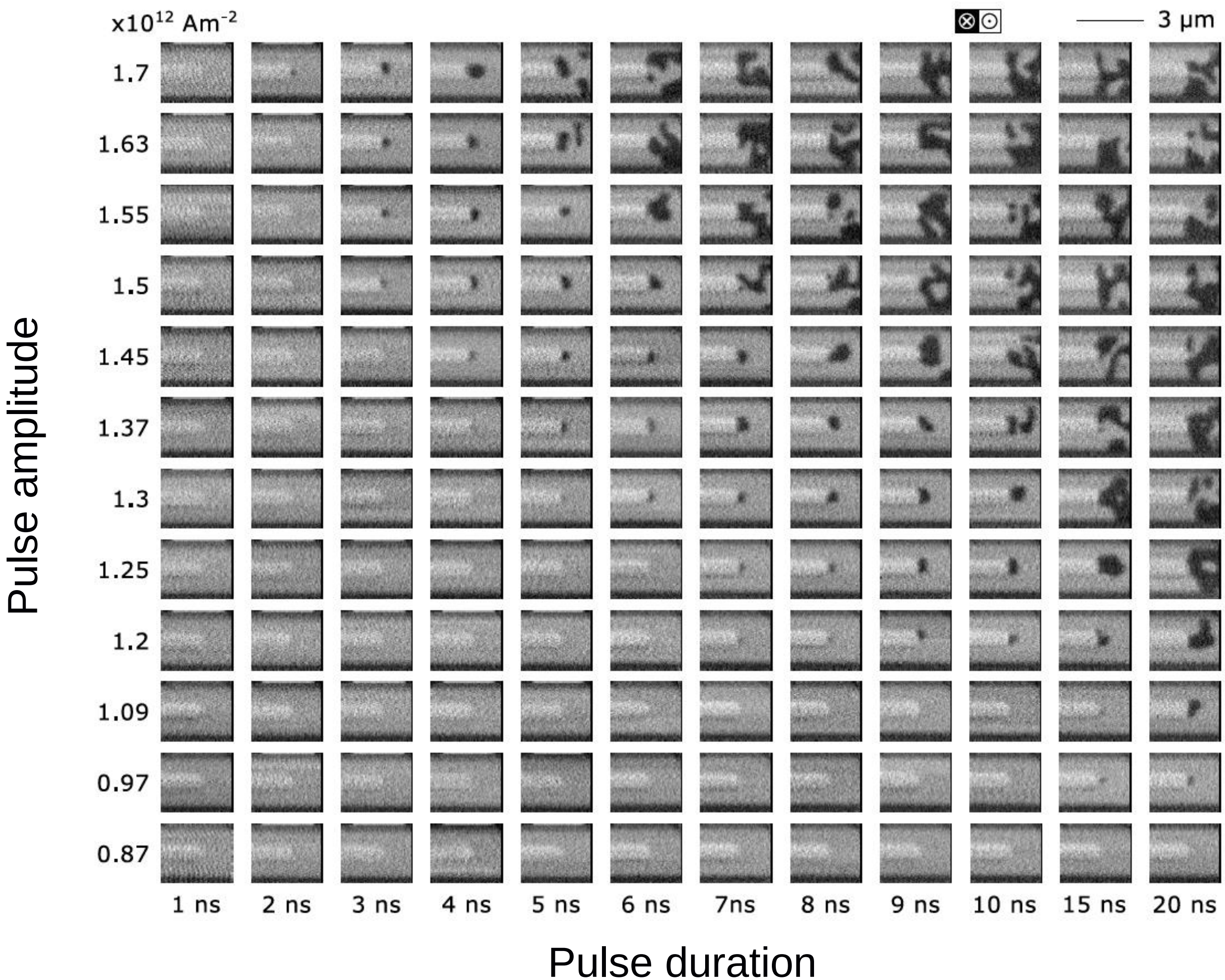

Skyrmion nucleation in Pt/CoB/Ir

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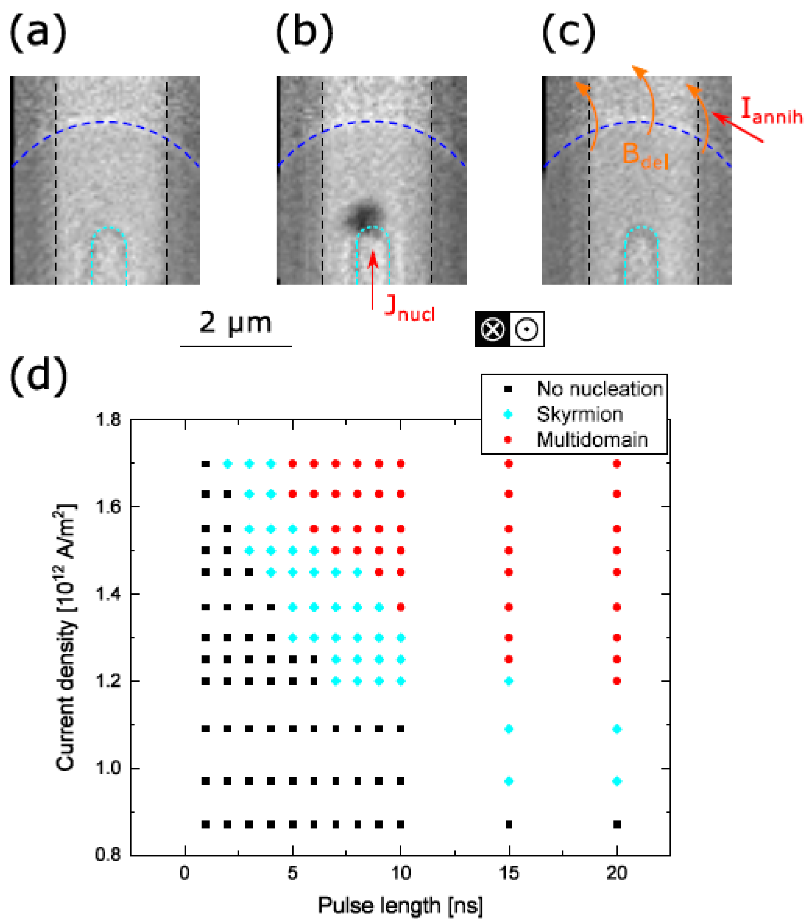
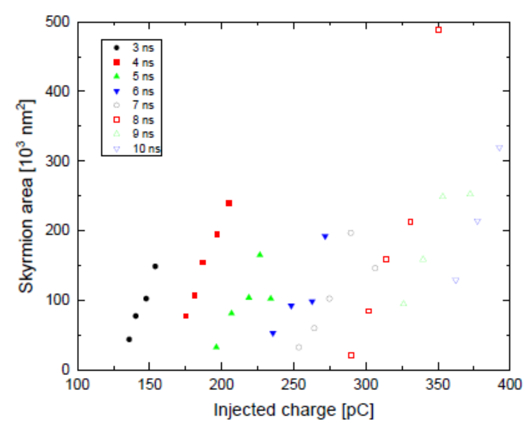


Phase diagram at zero field

Broad range of values where single skyrmion is reliably nucleated by a single current pulse

Skyrmion size determined by the charge contained in the pulse



Skyrmion nucleation dynamics

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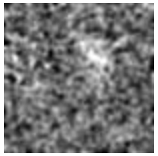
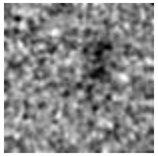
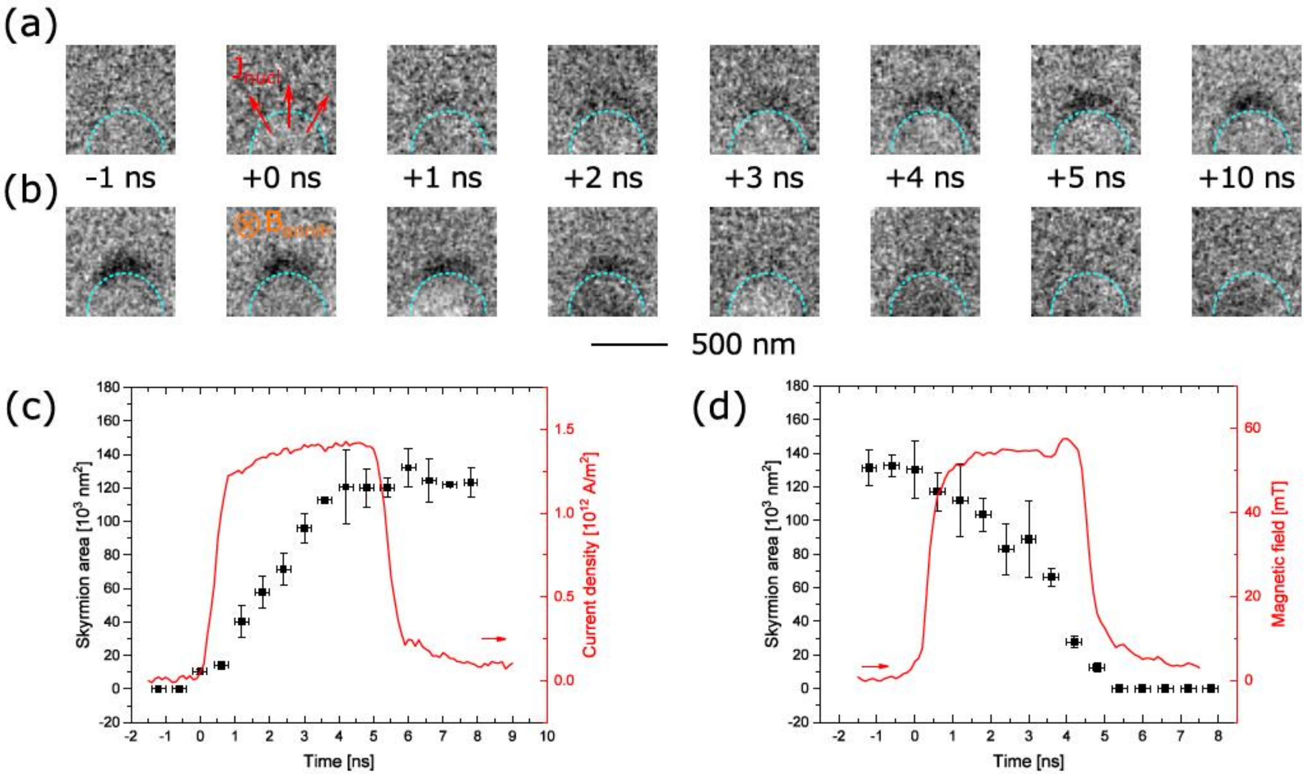
SET
30 ns loop



RESET
20 ns loop



2 μm



Improved temporal resolution to 200 ps

No incubation time for skyrmion nucleation or deletion

Finizio et al., Nano Letters **19**, 7246 (2019)

Basic skyrmion operations

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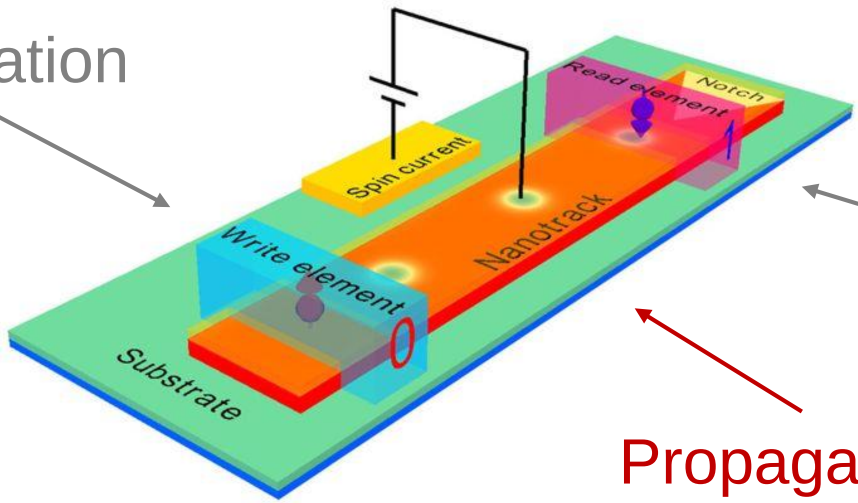
Nucleation



Detection

Propagation

X. Zhang et al., *Sci. Rep.* **5**, 7643 (2015)

Skyrmion Motion

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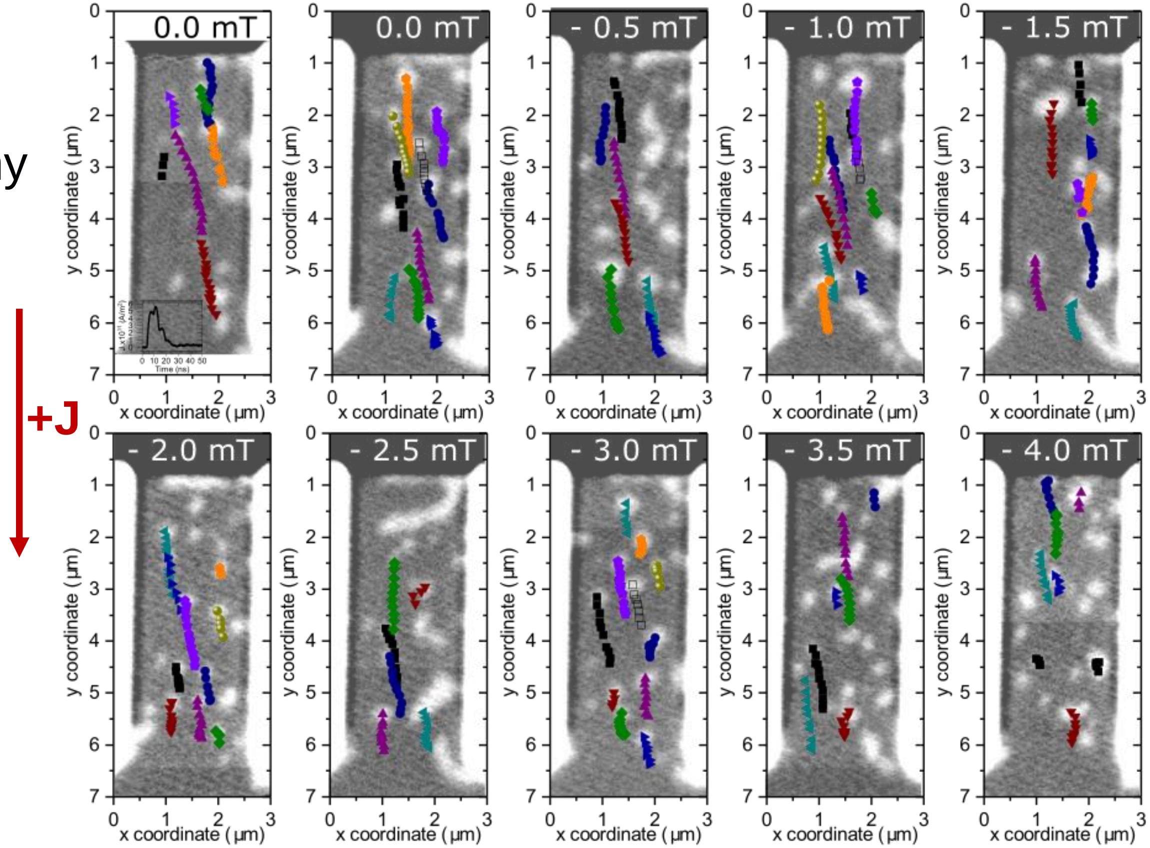
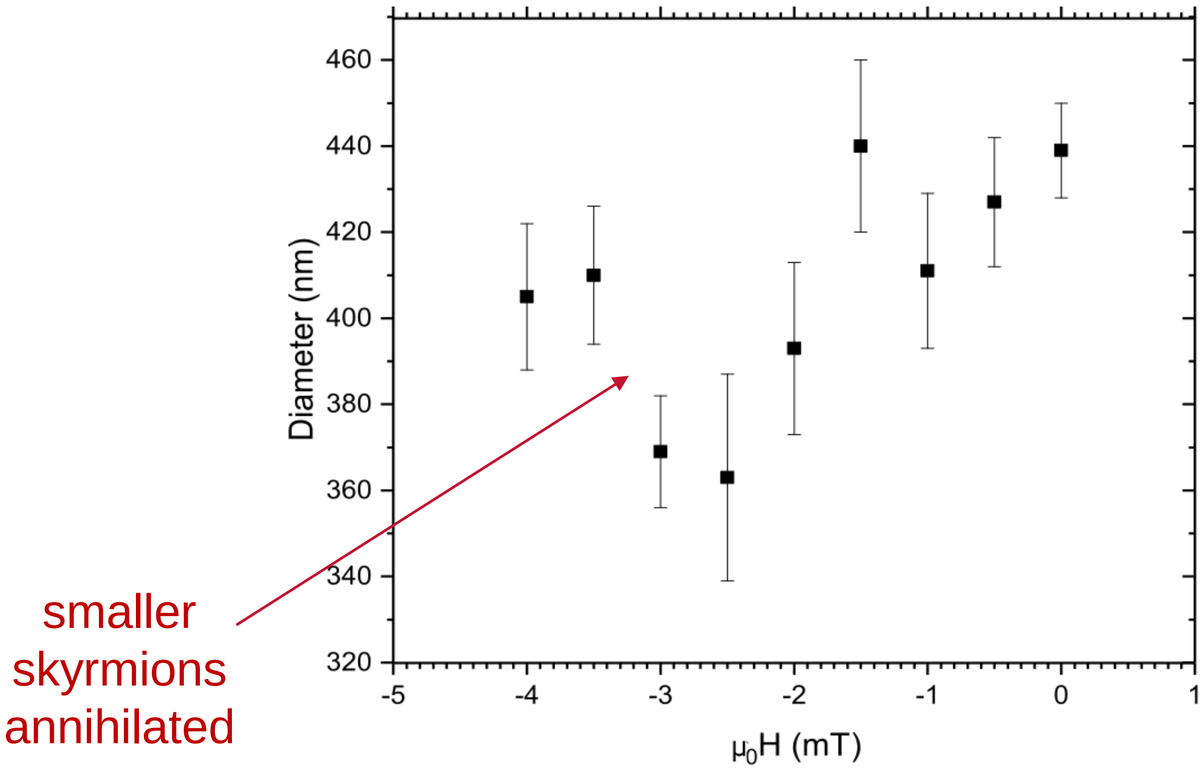
- [$Co_{68}B_{32}$ (0.8 nm)/Ir (0.4 nm)/Pt (0.6 nm)]x5
- Lift off electron beam lithography
- 200 nm Silicon nitride membranes
- 3 µm wide wire
- Skyrmions nucleated with 9 ns current pulse in the mid peak 10^{12} A/m^2 range
- 9 ns pulse, peak J 5.6 x 10^{11} A/m^2
- Two pulses between images
- Centre of skyrmion tracked with linear assignment problem algorithm, ImageJ Trackmate



TrackMate: Tinevez, JY.; Perry, N. & Schindelin, J. et al. (2016), *Methods* **115**: 80-90, PMID 27713081

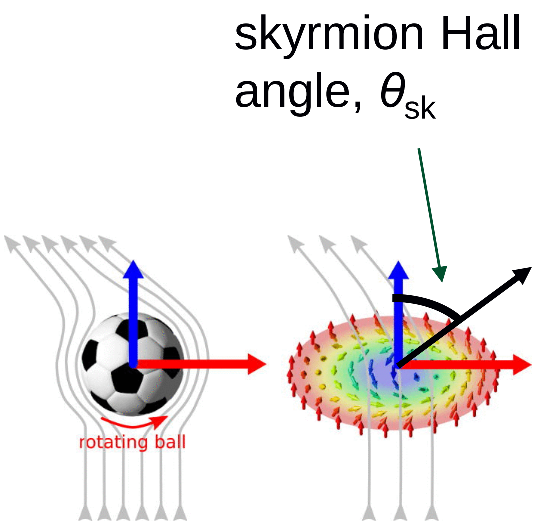
Skyrmion Motion

- Average diameter at each field calculated by counting pixels of each skyrmion and converting area into a diameter assuming a cylindrical skyrmion
- Average diameter decreases with increasing field
- Access to a larger skyrmion size range



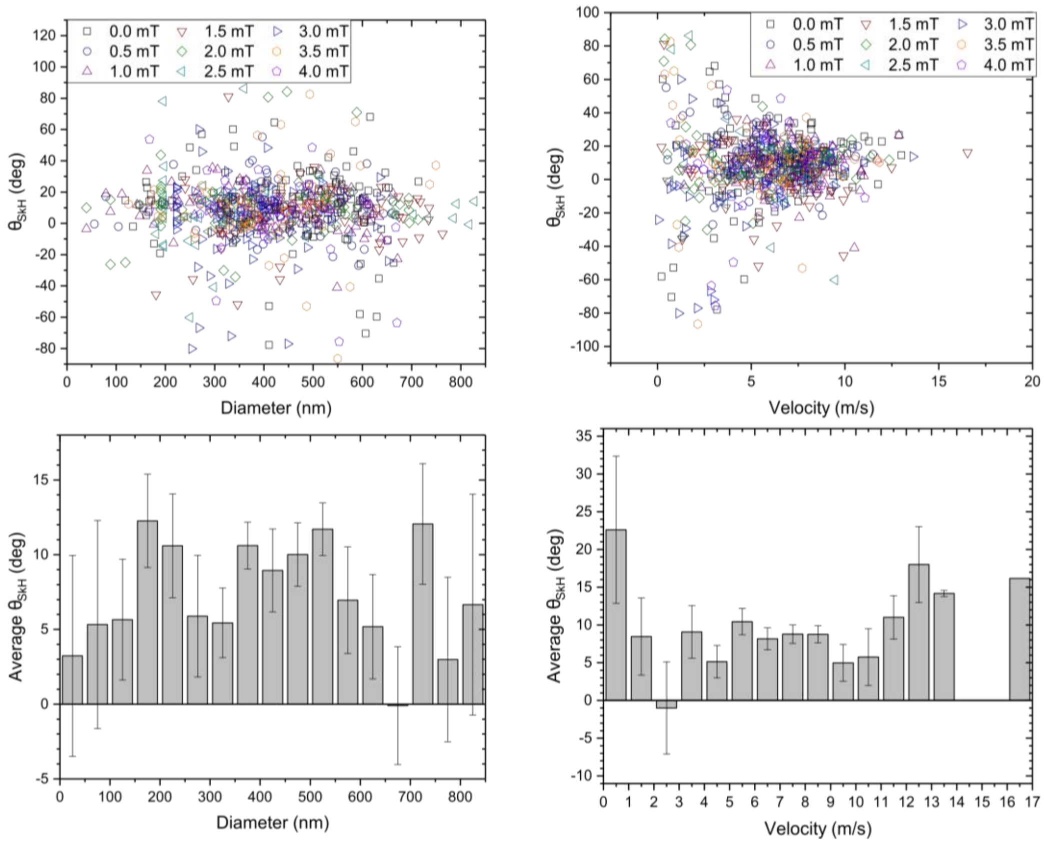
Skyrmion Motion

- Each individual motion event
- Skyrmion Hall angle scatter decreases with increasing velocity
- Skyrmion Hall angle scattered around 9 ± 2 °



'skyrmion soccer'

Everschor-Sitte, JAP **115**, 172602 (2014) (2013)



Zeissler et al., Nature Commun. **11**, 428 (2020)

Skyrmion Motion

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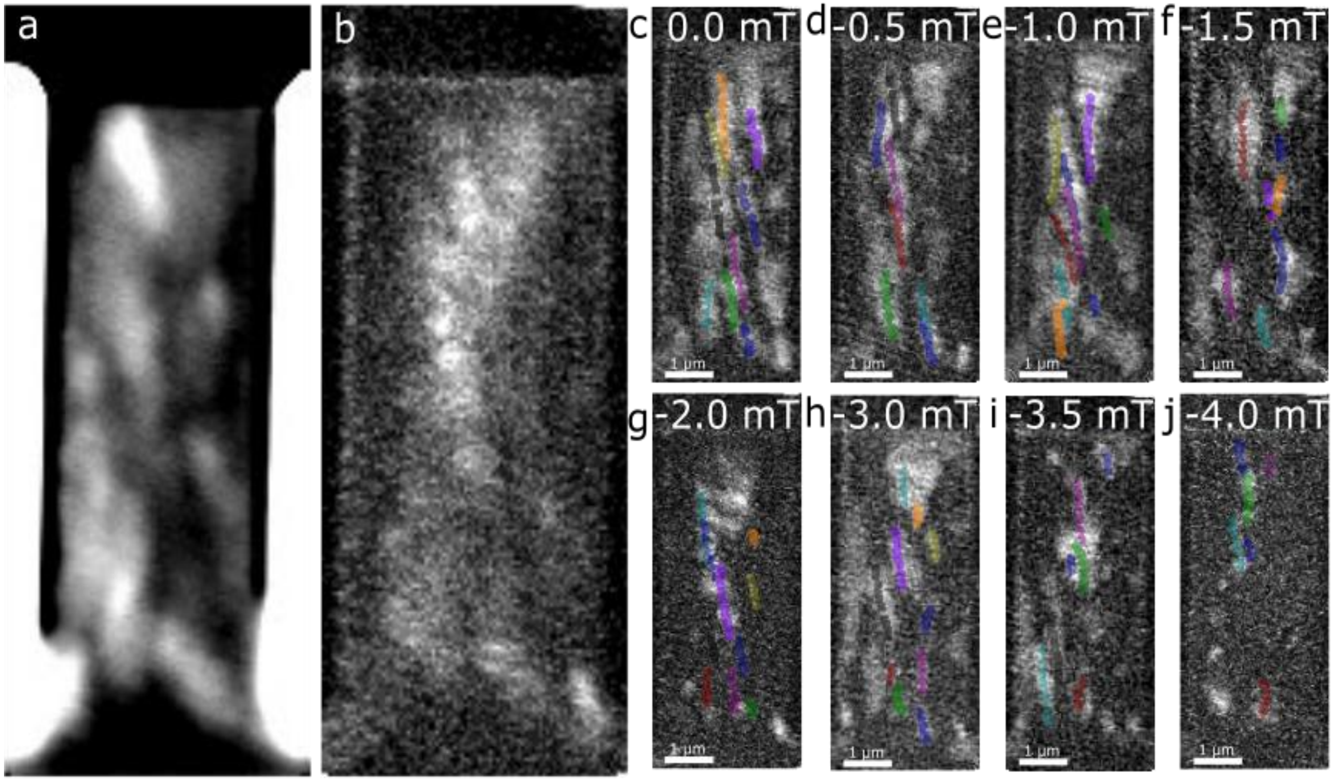
- Average of all images (**a**) skyrmion positions (**b**) skyrmion motion.
- Shows skyrmion prefer certain sites and to move along certain tracks – local environment dominates skyrmion motion



Other skyrmions matter

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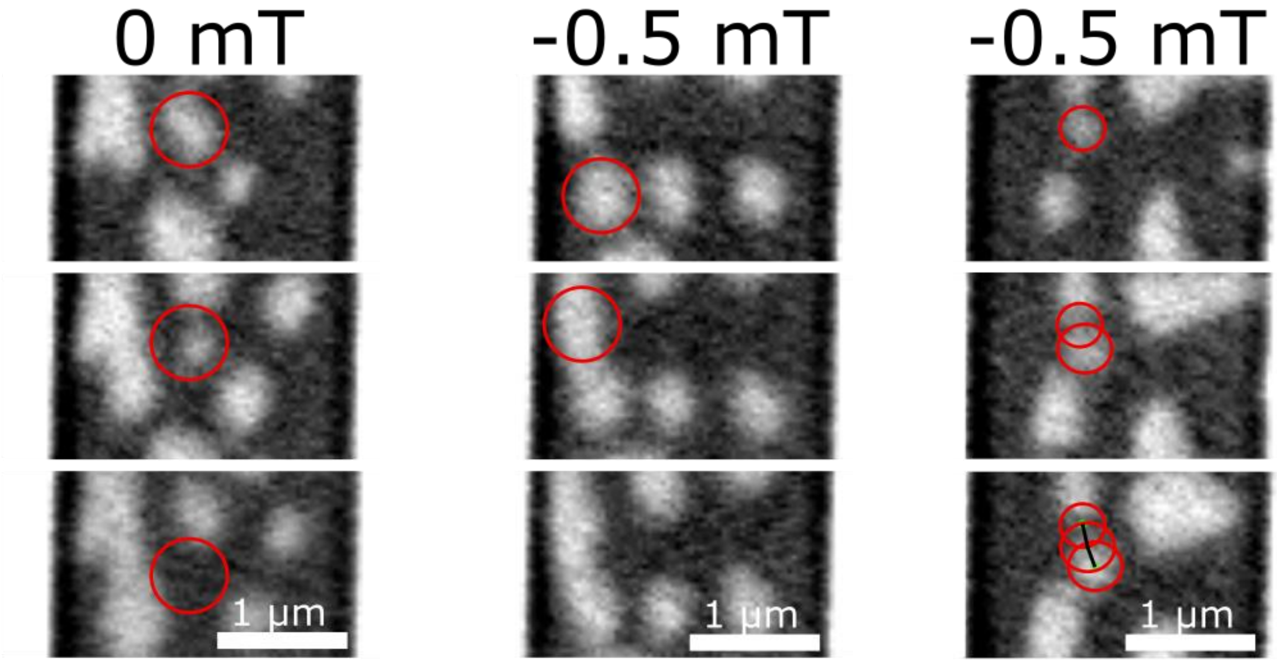
- Skyrmion anihilation due to pinning
- Skyrmion fusion
- Skyrmion-skyrmion deflection – leads to a change in skyrmion Hall angle



Basic skyrmion operations

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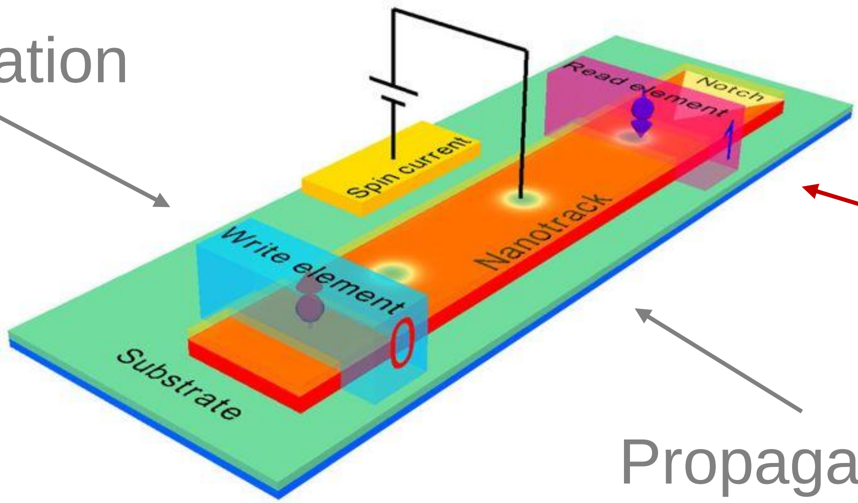
Nucleation



Detection

Propagation

X. Zhang et al., *Sci. Rep.* **5**, 7643 (2015)

Topological Hall effect in B20 materials

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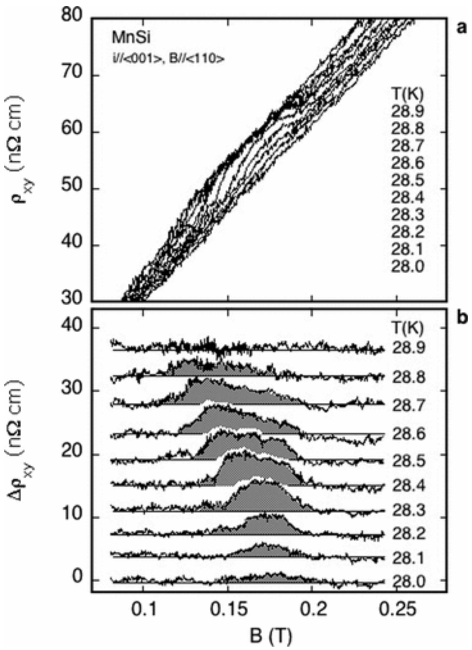
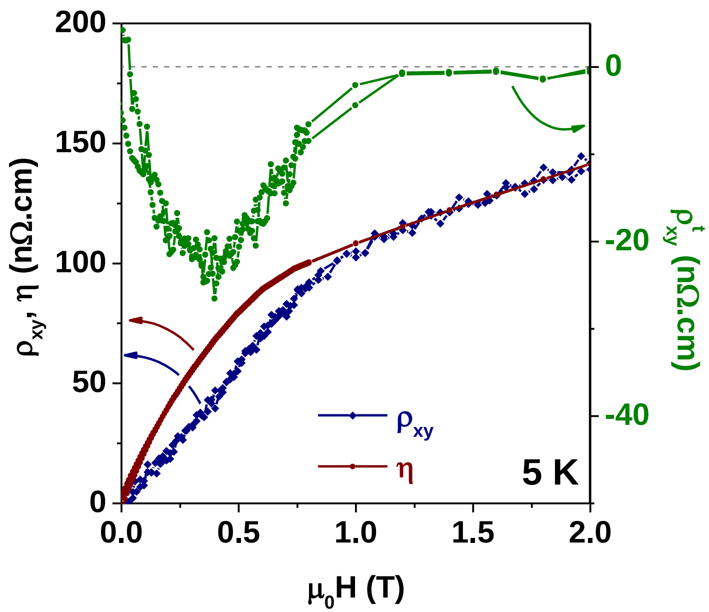
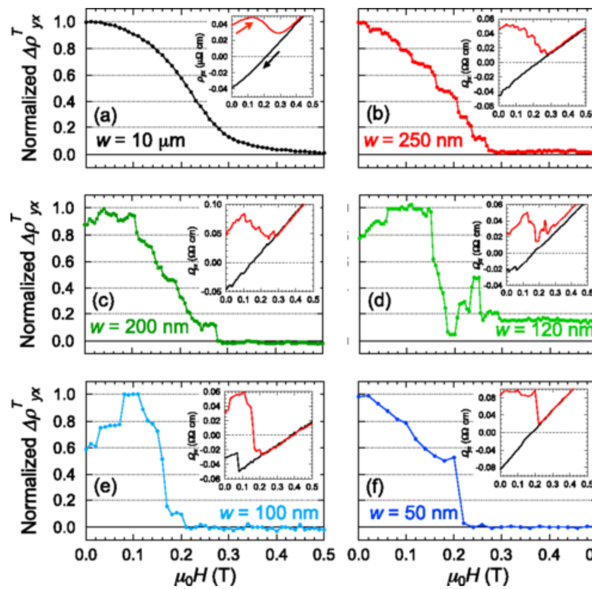
MnSi crystal



FeGe thin film



FeGe nanoscale Hall bar



Neubauer et al., PRL (2013) **Porter et al. PRB (2014)** **Kanazawa et al. PRB (2015)**

Widely accepted as a signature for the presence of Bloch skyrmions in B20s

$\rho_{xy}(H) = \rho_{xy}{}^{o}(H) + \rho_{xy}{}^{a}(H) + \rho_{xy}{}^{t}(H)$ $\rho_{xy}{}^{t} = PR_0B_{eff}$

Anomalous and topological Hall effect measurements in thin films

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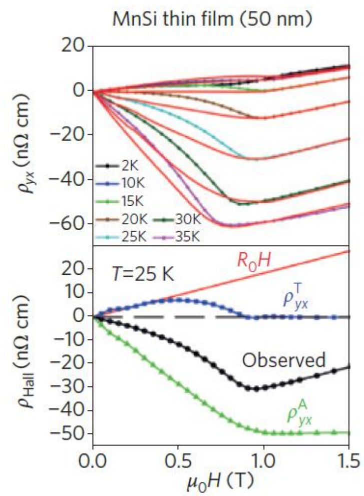
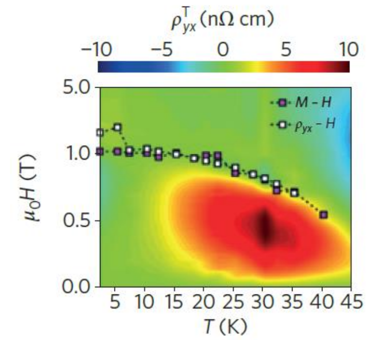
BULK DMI SYSTEMS

- B20 e.g. MnSi

  $\rho^{T}_{xy} \sim 4$ - 10 nΩ cm





YuFan Li et al., PRL 110, 117202 (2013)

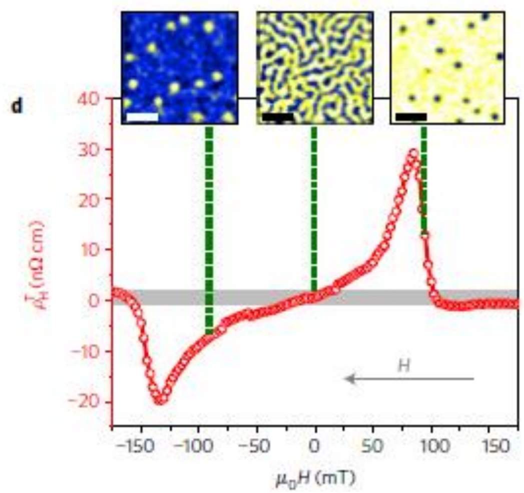
INTERFACIAL DMI SYSTEMS

- Ir/Fe/Co/Pt

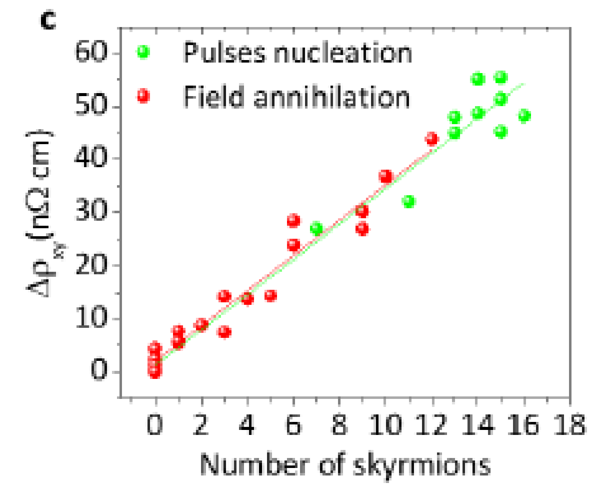
  ρ^{T}_{xy} = 30 nΩ cm

- $[Pt/Co/Ir]_{x20}$

  ρ_{xy} = 3.5±0.5 nΩ cm



A. Soumyanarayanan
Nature Materials 16 898 (2017)



D. Maccariello et al. Nature Nanotech. (2018)

In situ electrical measurement set-up

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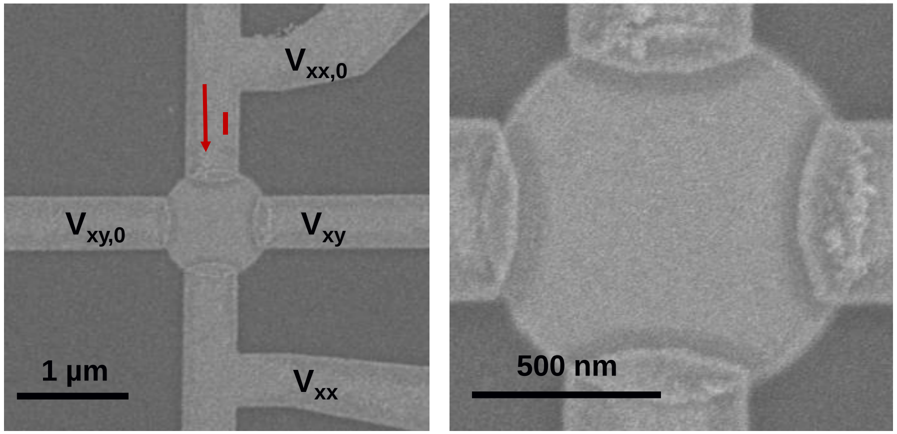
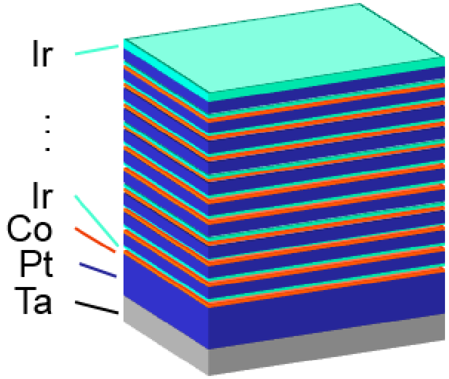
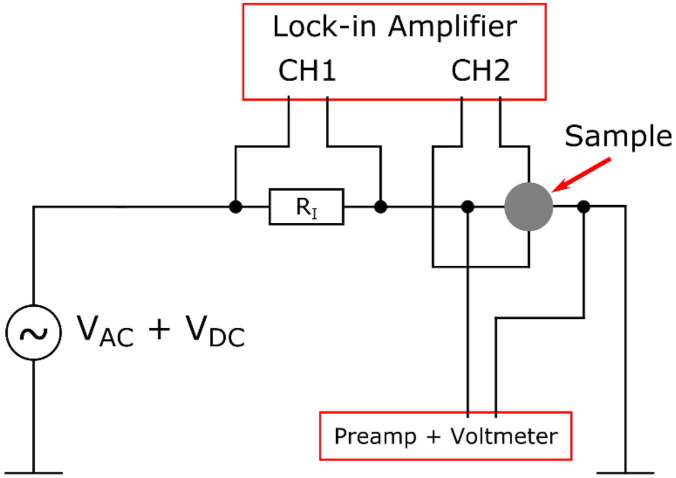
- Ta(3.5 nm)/Pt(3.8 nm)/[Co(0.5 nm)/Ir(0.5 nm)/Pt(1.0 nm)]$_{x10}$ Pt(3.2 nm)
- DC sputtered on 200 nm silicon nitride membrane
- Top down e-beam lithography
- 1000 nm diameter
- Quasi 4 point measurements
- 10 kΩ series resistor
- 17 Hz AC voltage
- DC offset voltage







Finizio et al., Microsc. Microanal. **24 (Suppl 2)** 76, 2018.

Field-driven reversal & skyrmion nucleation

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- Out-of-plane field applied
- XMCD contrast

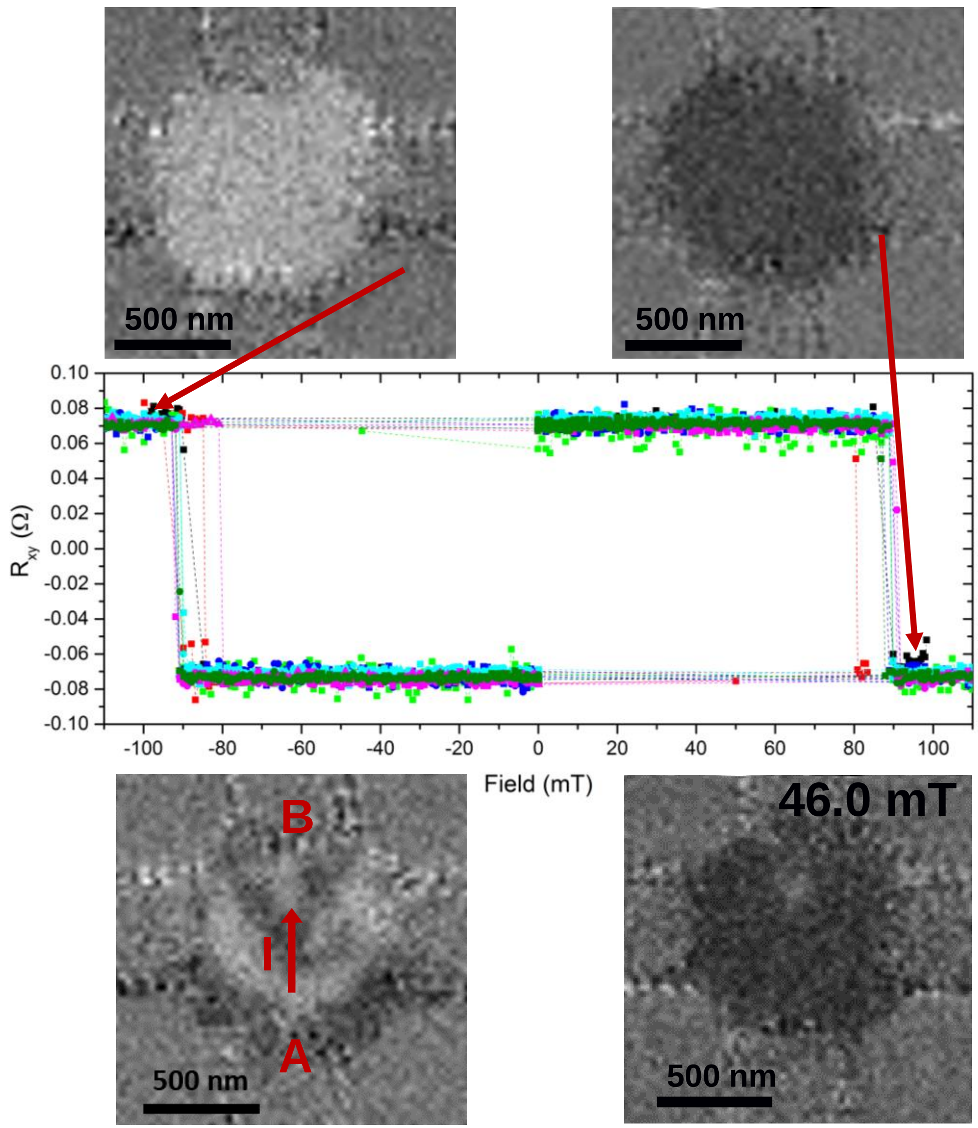
  BLACK = +90 mT

  WHITE = -90 mT
- Clear Hall signal

Skyrmion nucleation protocol

- +100 mT saturation
- Return to 0 mT
- 5× 5 ns 0.5 V pulses separated by 200 ns

  $J \sim 7\times10^{11}$ A/m^2
- Apply positive field to collapse domains
- Last object left before saturation is a skyrmion



Skyrmion: shrinking and annihilation

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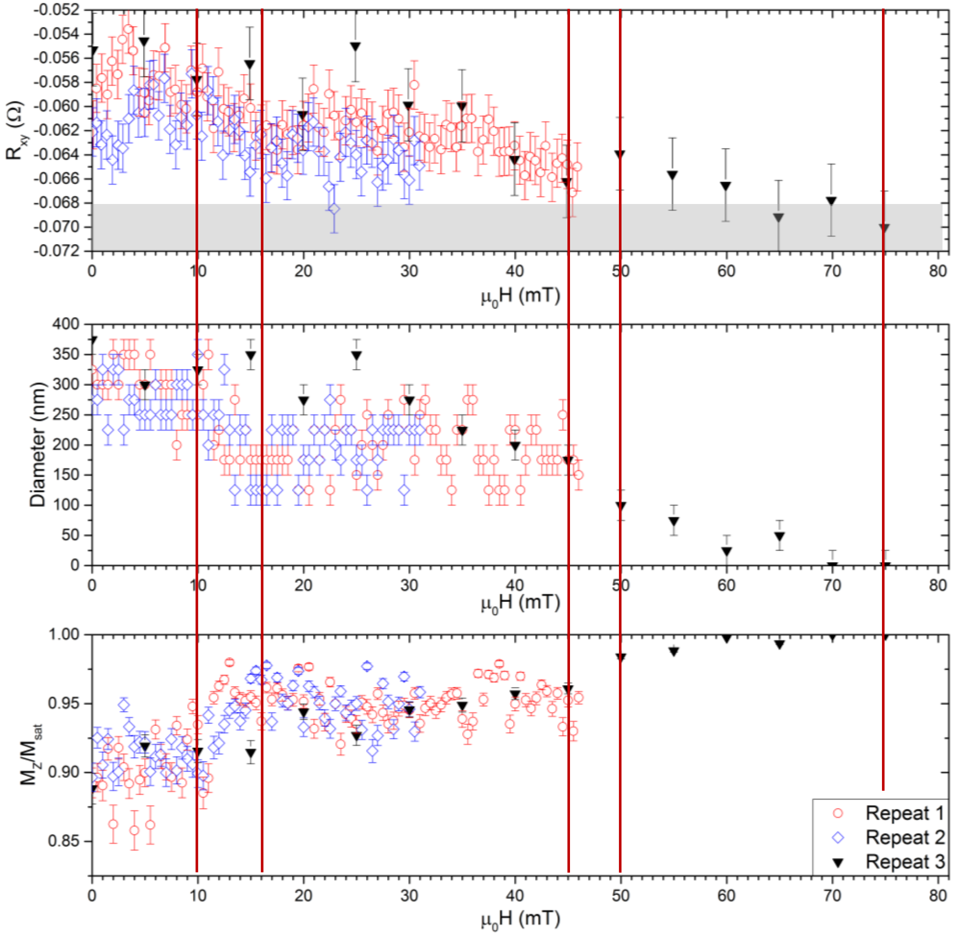
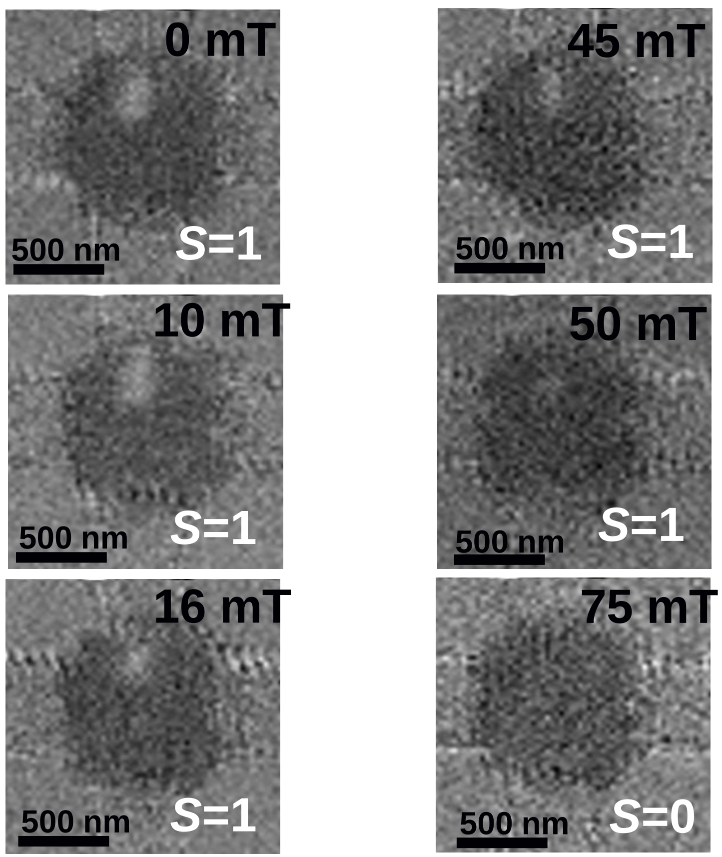
- Return to 0 mT - 300 nm Skyrmions
- Increase field – shrinks skyrmion ; Resistance follows diameter
- 24 % change in the Hall resistance when skyrmion is present





Single skyrmion Hall signal

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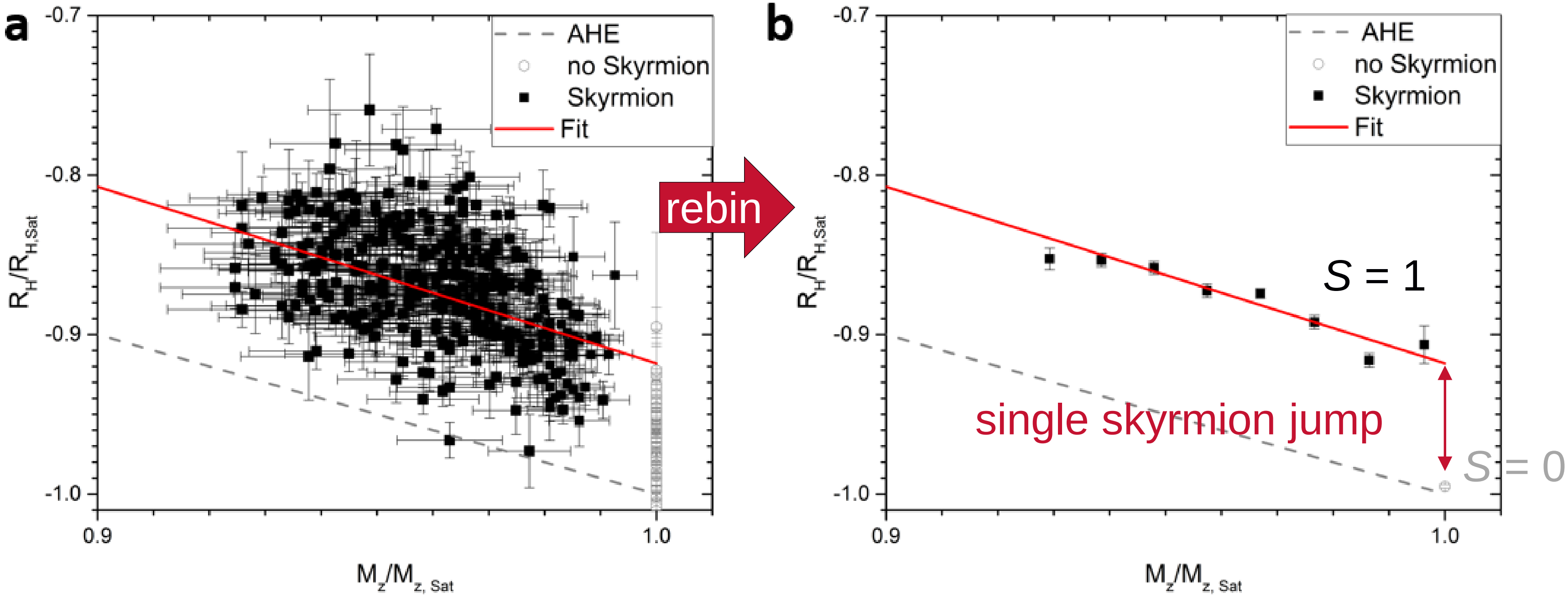

Fitted slope = 1.1 ± 0.1 AHE ✓

Fitted jump = 8.2±0.5 % of $R_{H,Sat}$ ~ 11±1 nΩ cm

Multiple skyrmion states

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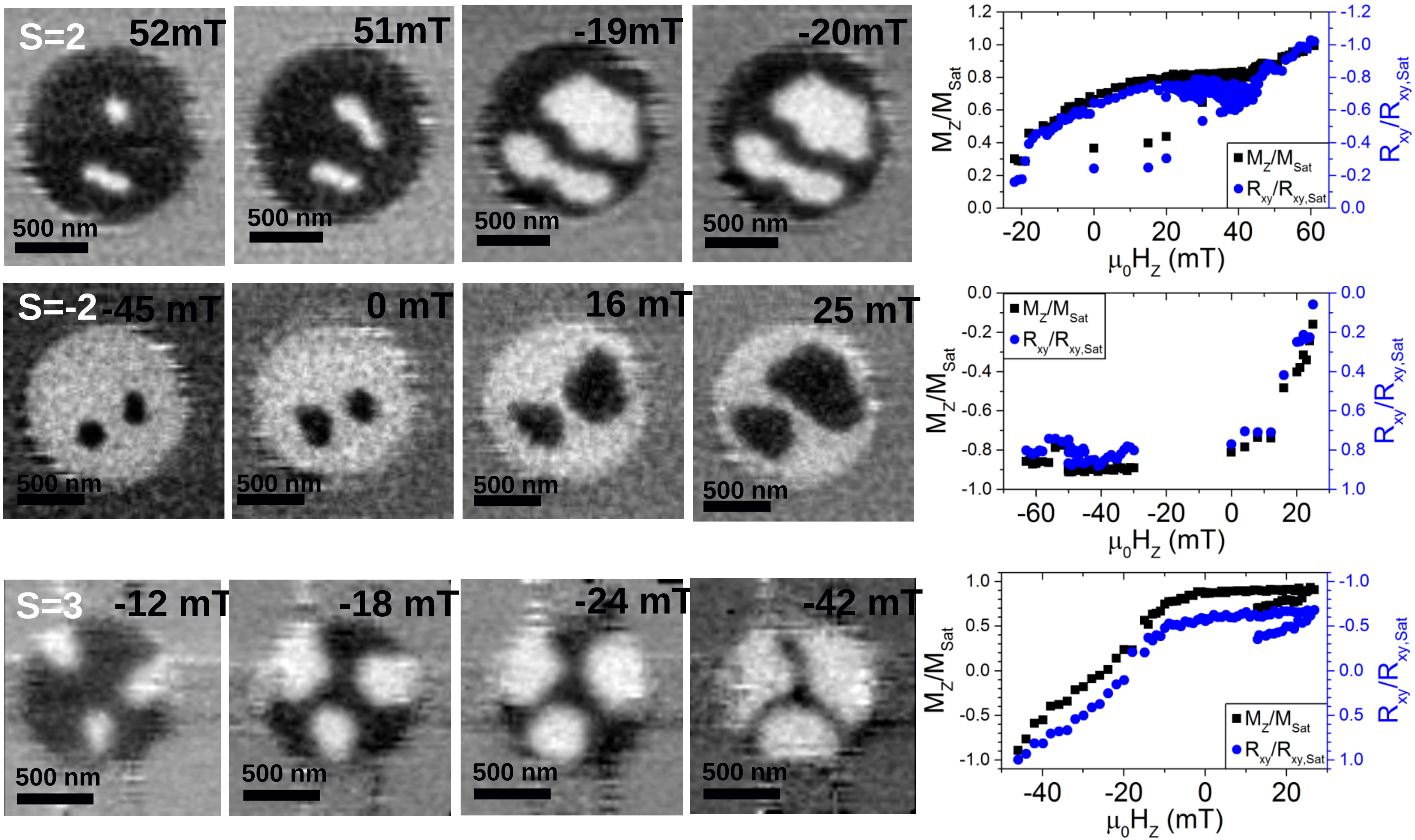

Hall resistance contributions

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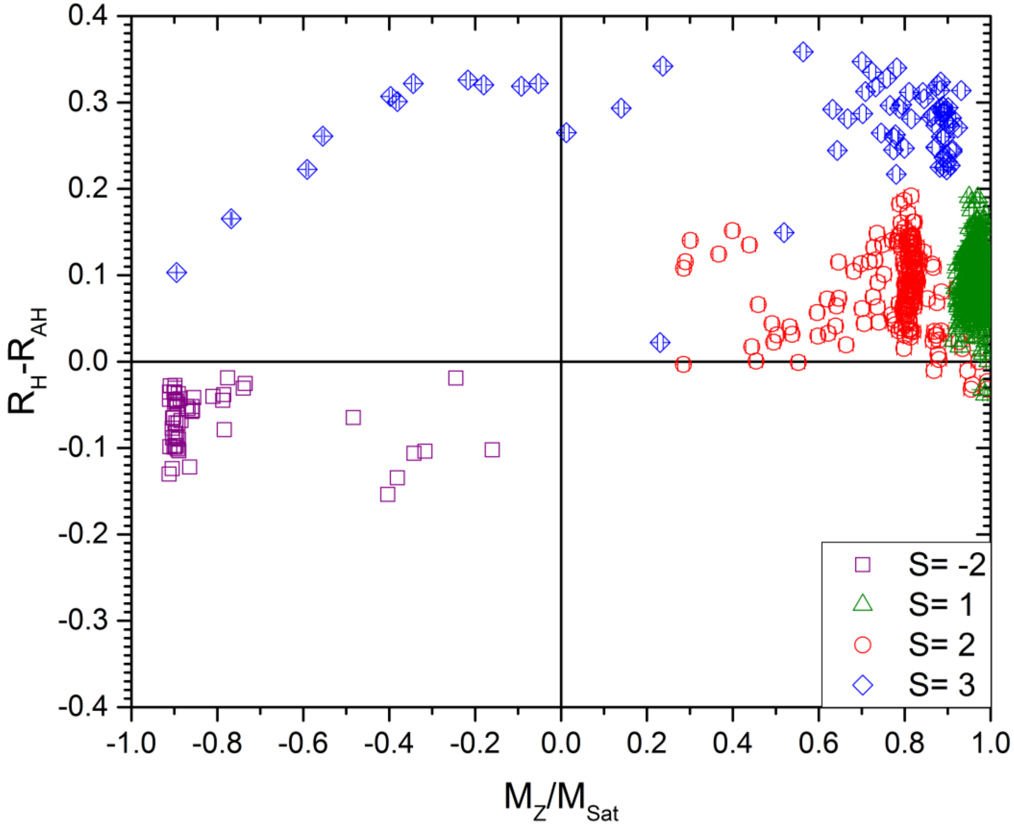
- Normalise Hall resistance and magnetisation to saturated values
- $R_{xy}= R_0B + \mu_0R_SM + R_{Int}$
- Measured R_0=-(1.9±0.2)×10^{-11} Ωm/T
- $R_H = R_{xy}- R_0B = \mu_0R_SM + R_{int}$

- Plot R_H vs M_z
- Intercept at R_{int}

- Plot $R_H – R_{AH}$ vs M_z to see R_{int}
- This is the signal that remains once ordinary and anomalous effects are accounted for.



Topological Hall resistivity?

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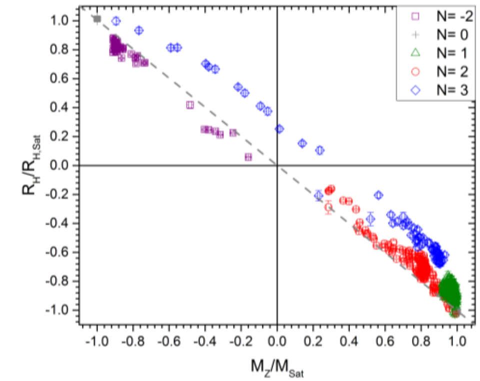
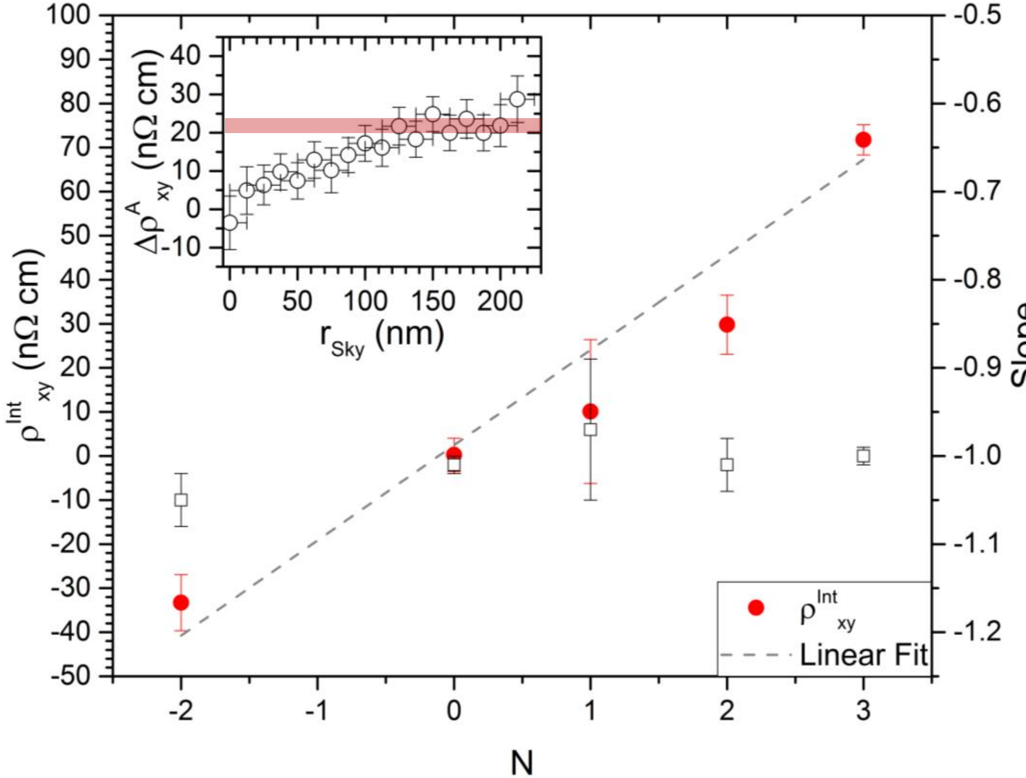


- Linear fit of normalised R_H vs M_z for different N
- Anomalous Hall contribution: Slope of -1 independent of N
- Intercept ρ^{Int}_{xy} proportional to N
- ρ^{Int}_{xy} = 22±2 nΩ cm per N
- Comparable to anomalous Hall signal for r_{sky} > 125 nm

TOPOLOGICAL HALL RESISTIVITY expected from Berry phase theory

- $\rho^{T}_{xy} = (P\ R_0\ \phi_0/A)\ S \approx 0.003$ nΩ cm

Signal of similar magnitude observed by Raju et al. arXiv:1708.04084



Zeissler et al., Nature Nanotech. **13**, 1161 (2018).

Synthetic Antiferromagnets

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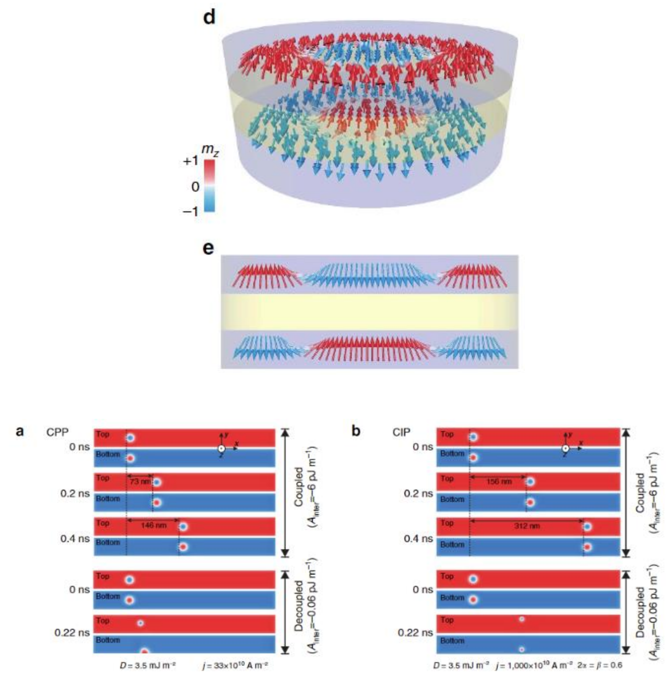
ARTICLE
Received 21 Apr 2015 | Accepted 26 Nov 2015 | Published 19 Jan 2016 DOI: 10.1038/ncomms10293 OPEN

Magnetic bilayer-skyrmions without skyrmion Hall effect

Xichao Zhang[1,2], Yan Zhou[1,2] & Motohiko Ezawa[3]

Magnetic skyrmions might be used as information carriers in future advanced memories, logic gates and computing devices. However, there exists an obstacle known as the skyrmion Hall effect (SkHE), that is, the skyrmion trajectories bend away from the driving current direction due to the Magnus force. Consequently, the skyrmions in constricted geometries may be destroyed by touching the sample edges. Here we theoretically propose that the SkHE can be suppressed in the antiferromagnetically exchange-coupled bilayer system, since the Magnus forces in the top and bottom layers are exactly cancelled. We show that such a pair of SkHE-free magnetic skyrmions can be nucleated and be driven by the current-induced torque. Our proposal provides a promising means to move magnetic skyrmions in a perfectly straight trajectory in ultra-dense devices with ultra-fast processing speed.

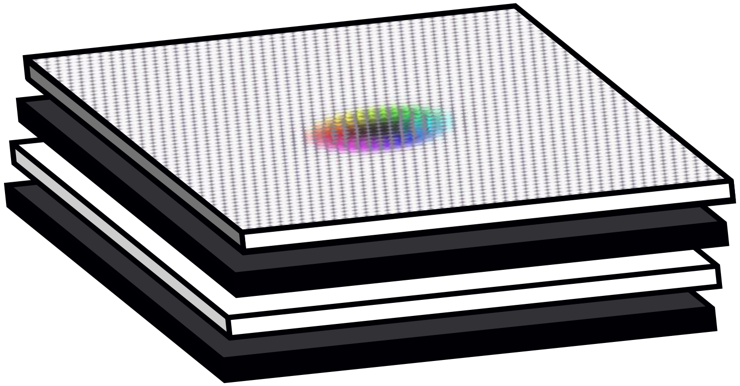


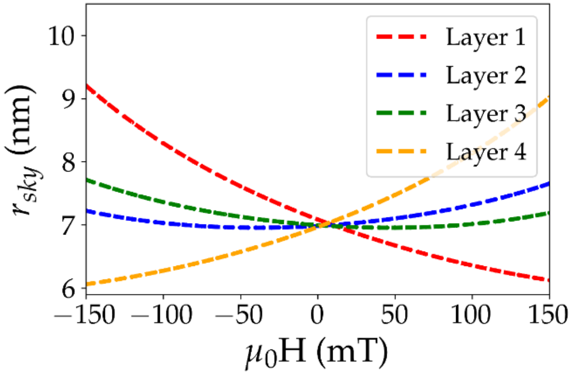
- Antiferromagnetically coupled layers
- No skyrmion Hall effect – no net topological charge

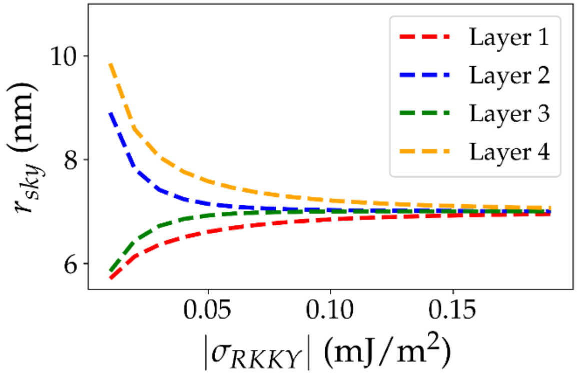
X. Zhang et al., Nat. Comm. **7**, 10293 (2016)

SAF skyrmion breathing modes: our model

MuMax[3]

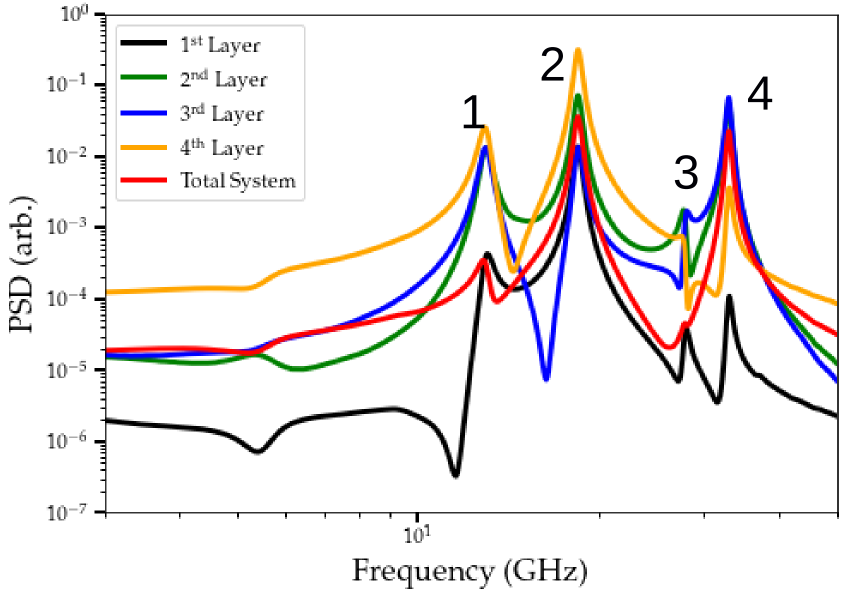


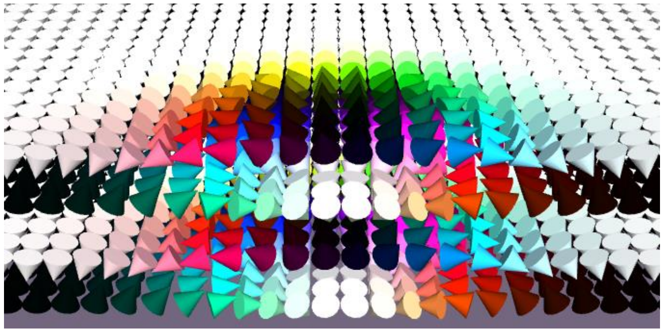




- 100 nm square
- Periodic boundary conditions
- M_s = 1×10^6 A/m, A = 15×10^{-12} J/m, K = 1×10^6 J/m^3, D = 2.5×10^{-3} J/m^2

SAF skyrmion breathing modes



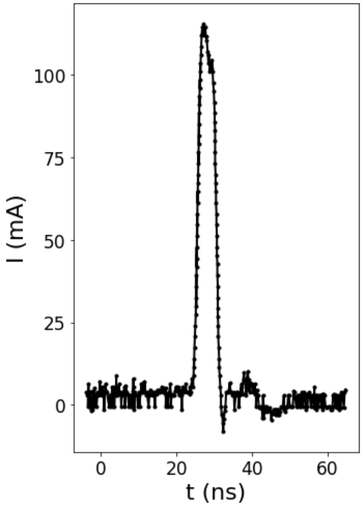


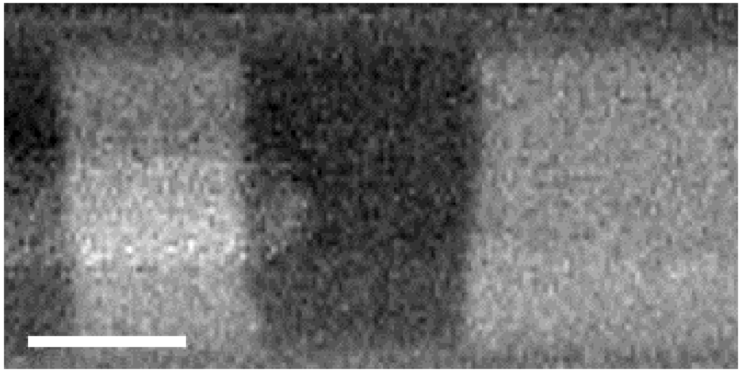
4 layers => 4 modes

C. E. A. Barker et al., arXiv:2112.05481

Domain wall motion – current pulse response

Nominally 5 ns pulses





1 µm

Sequences of 10 positive, then 10 negative pulses

$3.6 – 5.0 \times 10^{11}$ A/m^2

XMCD images

Domain wall motion – current pulse response

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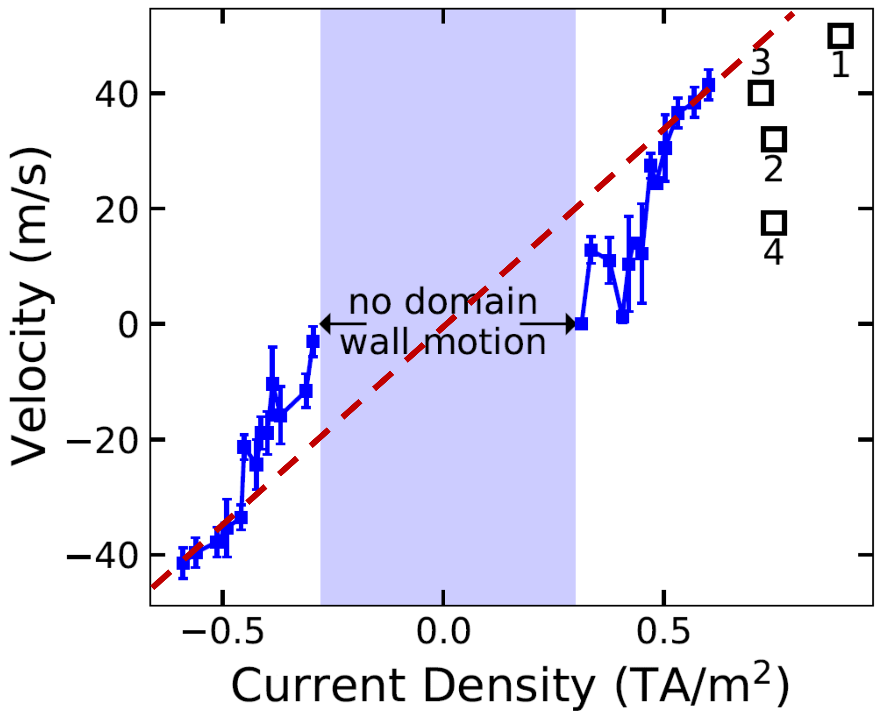

[1] S. Finizio *et al.*, Nano Lett. 19, 375–380 (2018). [2,4] 19S. Finizio, S. *et al.*, Appl. Phys. Lett. 117, 212404 (2020). [3] 20S. Finizio, S. *et al.*, Appl. Phys. Lett. 116, 182404 (2020).

C. E. A. Barker et al., arXiv: 2205.03126

Electrical SAF skyrmion injection

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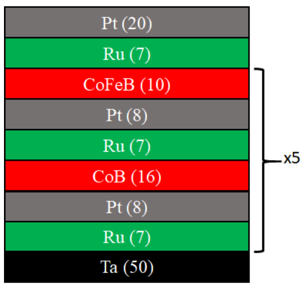
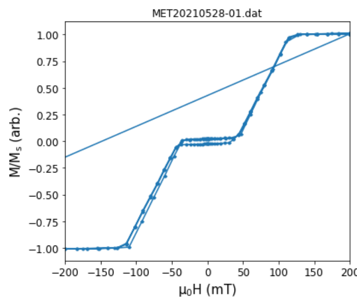
10 ns pulses



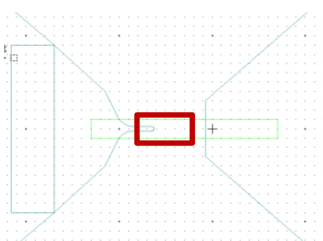


0.8×10^12 A/m^2

0.9×10^12 A/m^2

1.1×10^12 A/m^2

Co edge +50 Oe



As-grown domain pattern

Co edge

Fe edge

Wire 2 μm wide

Injector 250 nm radius of curvature

Conclusions

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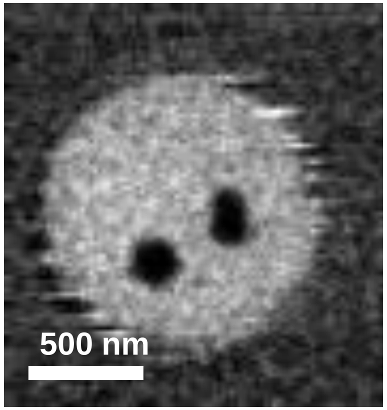
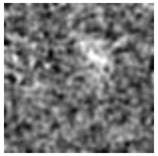
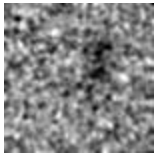
- Deterministic nucleation of single skyrmions observed at 200 ps resolution
  Finizio et al., Nano Letters **19**, 7246 (2019)



- Observed propagation quasistatically through complex energy landscape
  Zeissler et al., Nature Commun. **11**, 428 (2020)





- Hall signal for detection has two parts
  - size-dependent part ⟶ AHE ✓
  - size-independent part, 22±2 nΩcm per skyrmion
    ↘ revised Berry-phase THE or new mechanism?

  Zeissler et al., Nature Nanotech. **13**, 1161 (2018)