Magnetic Skyrmions for Unconventional Computing and Revealing Latent Information

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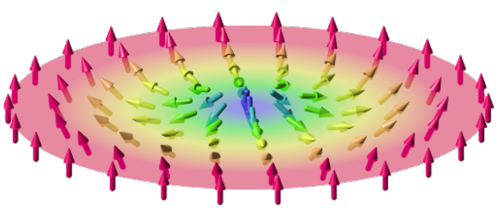
University of Duisburg-Essen

19.05.2021
SPICE-SPIN+X Seminars (online)



Acknowledgements:

Structure of the talk

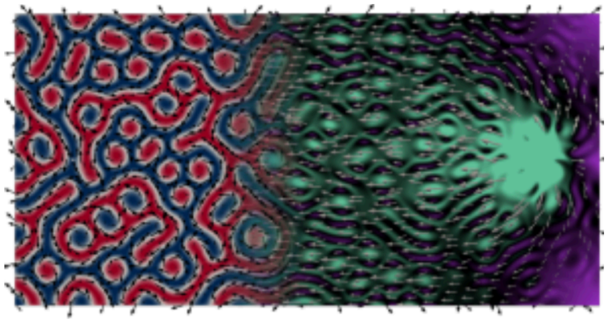
- Introduction to magnetic skyrmions
- Skyrmions for unconventional computing
  - Skyrmion reshuffler for stochastic computing

    Zázvorka, ..., KES, et al., Kläui, Nature Nanotechnology 2019

  - Skyrmions for reservoir computing

Thanks to

J. Zázvorka, F. Jakobs, D. Heinze, N. Keil, S. Kromina, S. Jaiswal, K. Litzius, G. Jakob, P. Virnau, D. Pinna, A. Donges, U. Nowak, M. Kläui



Thanks to

G. Bourianoff

M. Sitte, K. Litzius, D. Prychynenko, D. Pinna, B. Krüger, J. Sinova, M. Kläui

J. Love
Mumax^3 Team: in particular
Jeroen Mulkers, Jonathan Leliaert

Prychynenko, et al., KES, Phys. Rev. Appl. (2018), Bourianoff, et al., KES, AIP Advances, (2018),
Pinna, Bourianoff, KES, Phys. Rev. Appl. (2020)
Grollier, Querlioz, Camsari, KES, Fukami, Stiles, Nat. Electron. (2020)
Finocchio, Di Ventra, Camsari, KES, Amiri, Zeng JMMM (2021)
Vedmedenko, ..., KES, et. al., J. Phys. D: Appl. Phys. (2020)

- Data analysis, new tools for “microscopy”?

Horenko, et al., KES, arXiv1907.04601
Rodrigues, KES, et al., iScience 24, 3 (2021)

I. Horenko

D. Rodrigues

T. O’Kane

S. Gerber

What is a skyrmion?

TWIST
Topological Whirls In SpinTronics

WIKIPEDIA
The Free Encyclopedia

Wikipedia (English): “Skyrmion= homotopically non-trivial classical solution of a nonlinear sigma model with a non-trivial target manifold topology.”...

What is a skyrmion?

Skyrmion = object that is defined precisely mathematical

Occurs in different regions of physics

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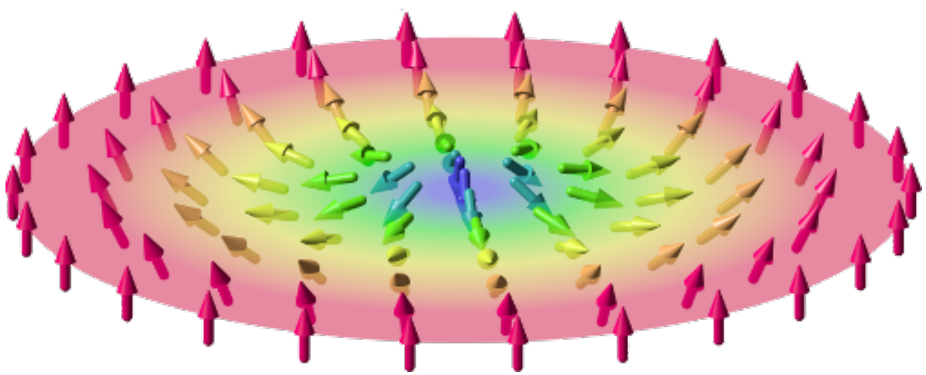

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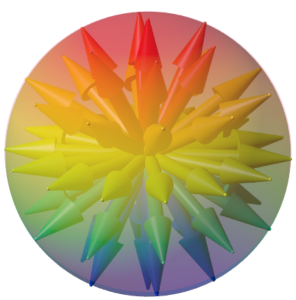
Occurs in different regions of physics

Originally (1959) introduced in particle physics by Tony Skyrme.

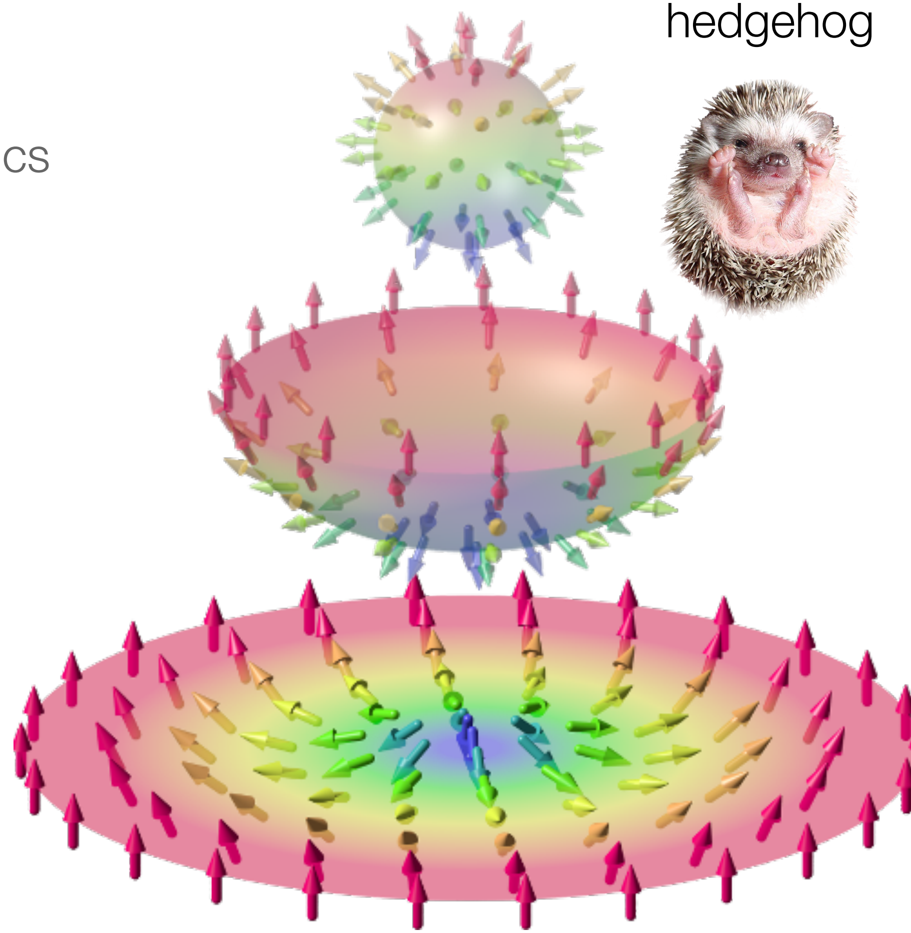
Here: magnetic skyrmions

Color code:



$\hat{M} = M/|M|$

magnetization direction



hedgehog

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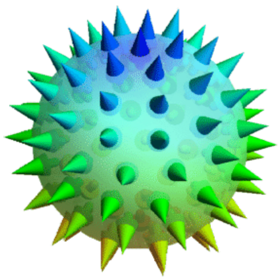

$$\hat{M} = M/|M|$$

magnetization
direction

thanks to Jan Masell (Müller)

http://www.thp.uni-koeln.de/~jmueller/download/movie_jan-mueller_projection.gif

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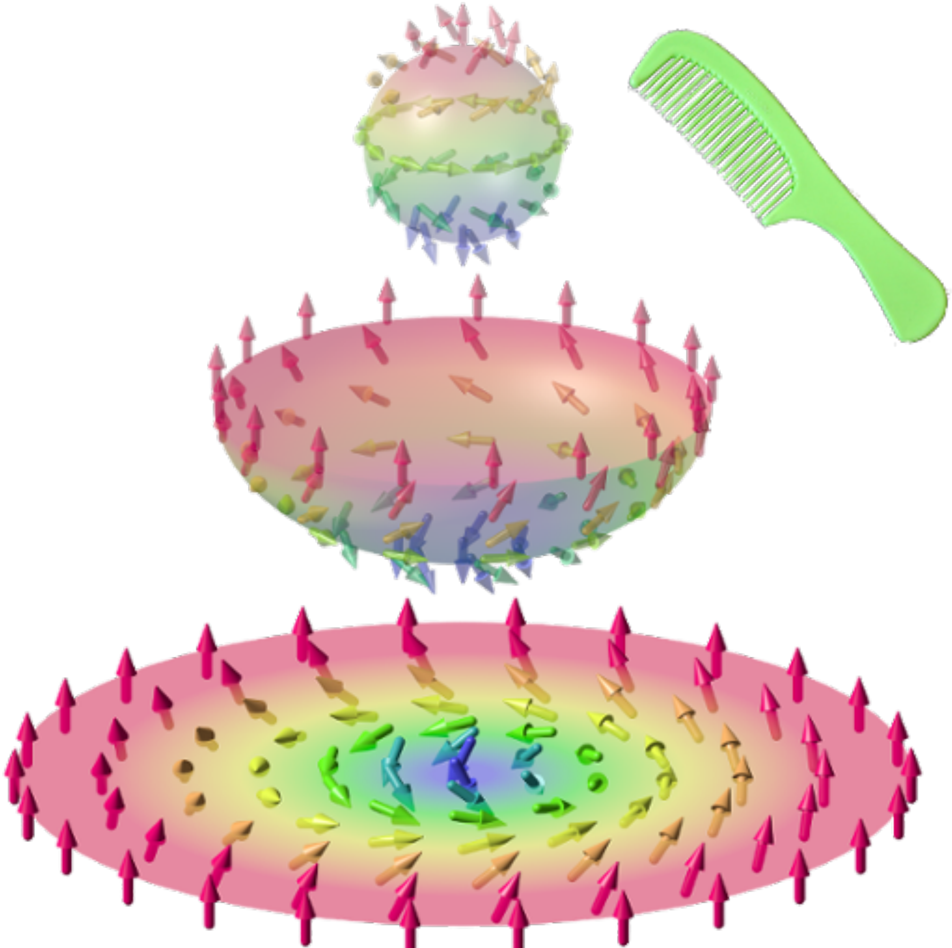

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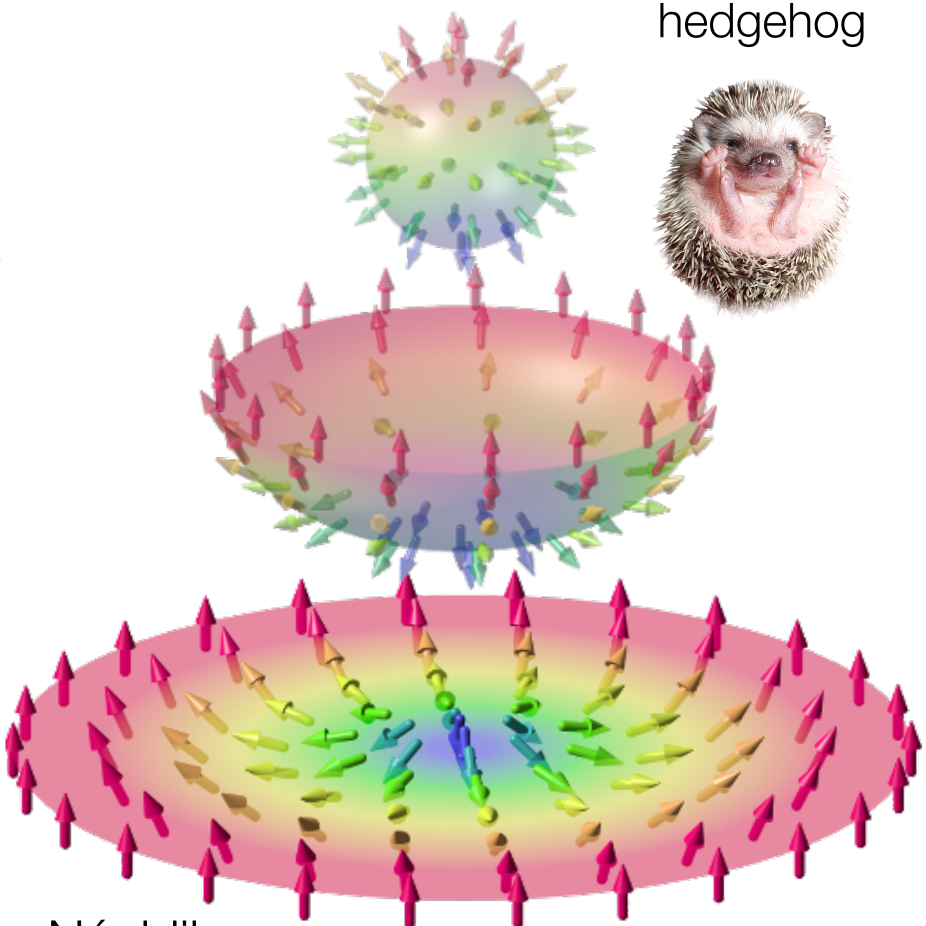
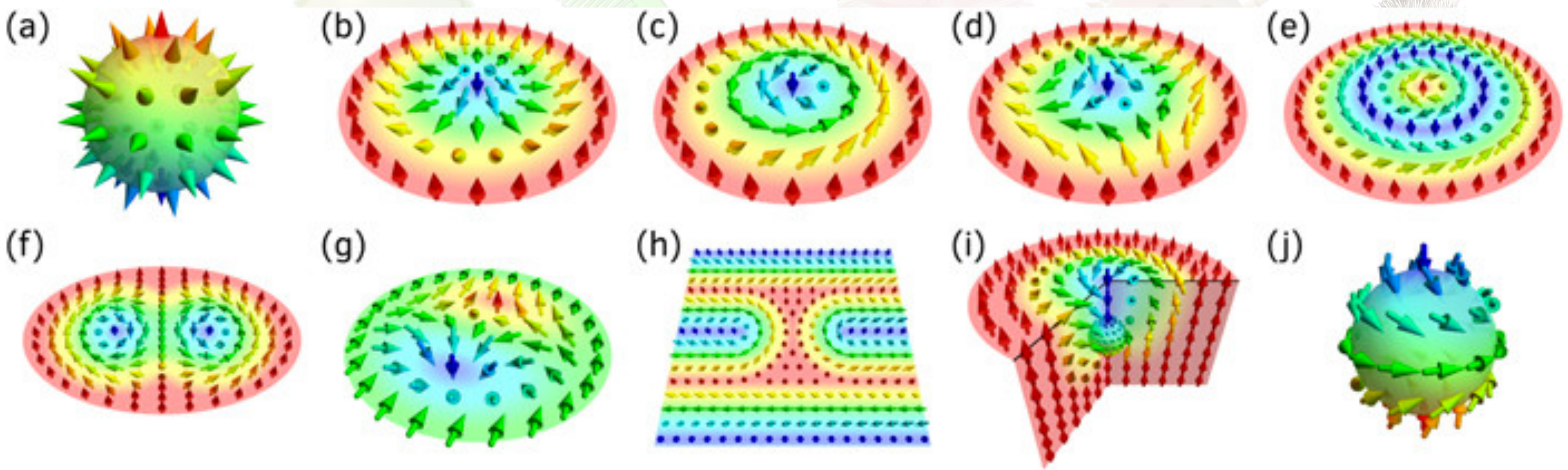


Bloch-like Néel-like

A zoo of magnetic textures

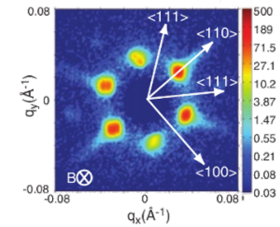
Skyrmion = object that is defined precisely mathematical



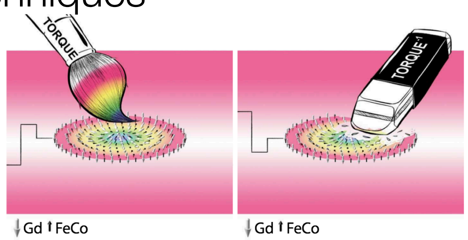
KES, et al., J. Appl. Phys. (2018)

Magnetic skyrmions

- theoretical predictions **Bogdanov and Yablonskii, Sov. Phys. JETP 1989**
- first experimental observation in 2009 in form of a skyrmion lattice in MnSi
- broken inversion symmetry
- occur in many different magnetic systems with competing (twisting) interactions
  - metals, semiconductors and insulators
  - bulk and thin films
  - low T up to above room temperature
  - size can be engineered
- detectable by various experimental techniques
- can be created, manipulated and destroyed by various means



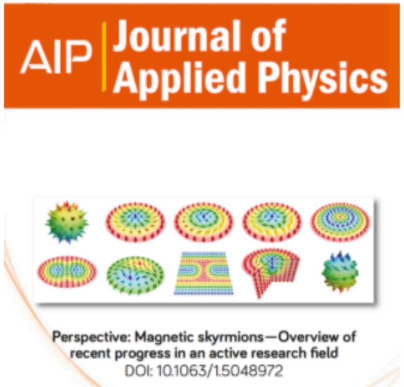
Mühlbauer et al., Science (2009)



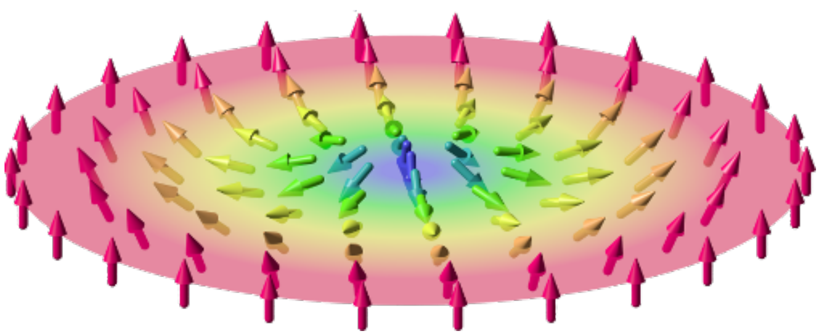
Thanks to Marco

Device relevant systems

KES et al., Nature Electronics (2018)



KES et al., J. of Appl. Phys. (2018)



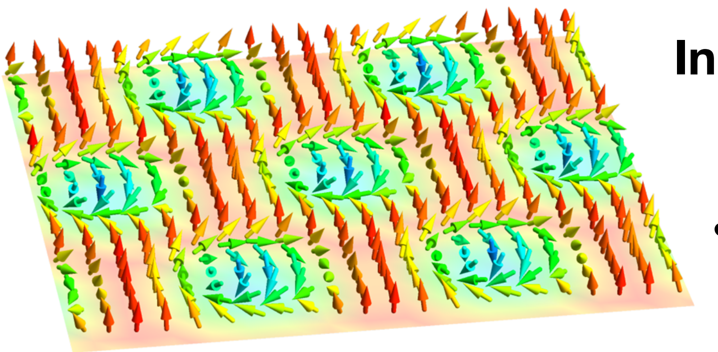
Magnetic skyrmions - why interesting?

TWIST
Topological Whirls In SpinTronics

1) small and above room temperature

2) topology → stability

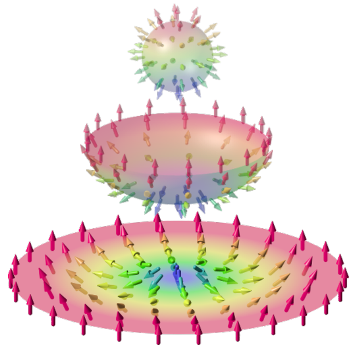
3) react to ultra-low electric currents



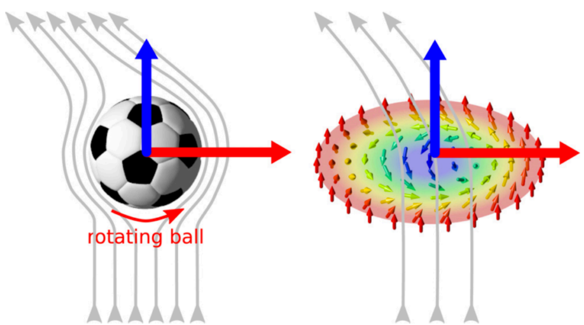
In skyrmion lattice:

$$j \sim 10^6 \, A/m^2$$

Jonietz, KES, et. al., Science, (2010)



skyrmion Hall effect



KES, M. Sitte, JAP (2014)

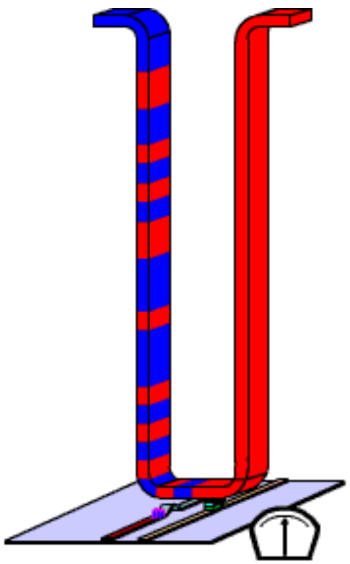
4) Interesting dynamics because of **Magnus force**

5) potential for spintronics applications

Device relevant systems

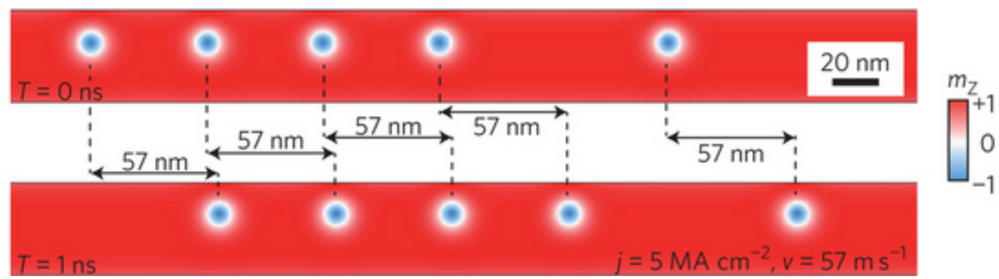
Skyrmion based devices ???

Probably most studied potential application: skyrmion racetrack memory



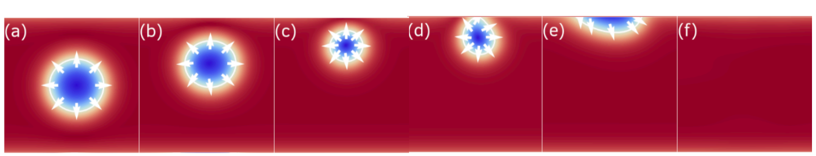
Parkin, IBM

Fert, Nature Nano., 2013



Advantages: skyrmions do not touch the edges

Detrimental: skyrmion Hall effect



KES, et al., JAP 124, (2018)

How to get rid of the skyrmion Hall effect?

TWIST
Topological Whirls In SpinTronics

Some suggestions:

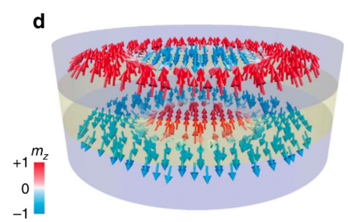
nature COMMUNICATIONS

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]



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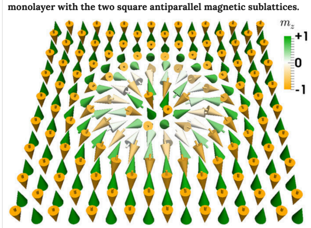
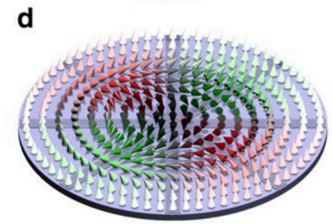
Antiferromagnetic Skyrmion: Stability, Creation and Manipulation

Xichao Zhang, Yan Zhou & Motohiko Ezawa

Figure 1: Illustration of an AFM skyrmion spin texture in a 2D AFM monolayer with the two square antiparallel magnetic sublattices.

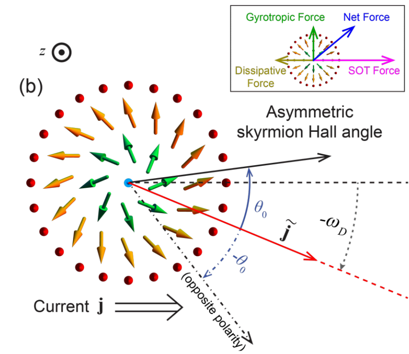


$Q = \pm 1$ $1+(-1)=0$

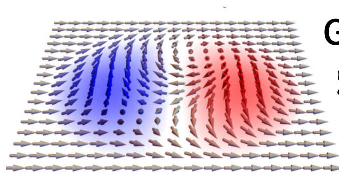


Hoffmann, et al., Nat. Comm. (2017)

Huang, et al., PRB (2017)



Kim, et al., KES, PRB (2018)



Göbel, et al., PRB (2019)

Zarzuela, ..., KES PRB (2020)

Zhang, et al., PRB (2020)

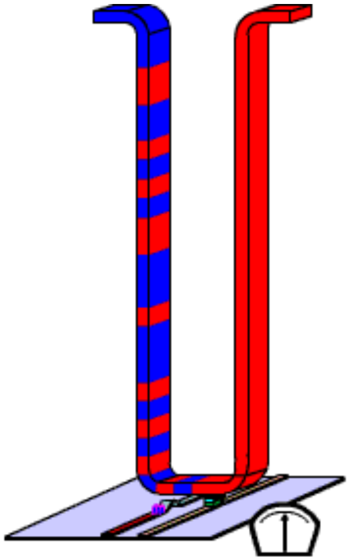
additional symmetry breaking

No net skyrmion Hall effect

SPICE

What is a device that optimally uses the properties of a skyrmion?

So far often: skyrmion instead of other magnetic texture like DW



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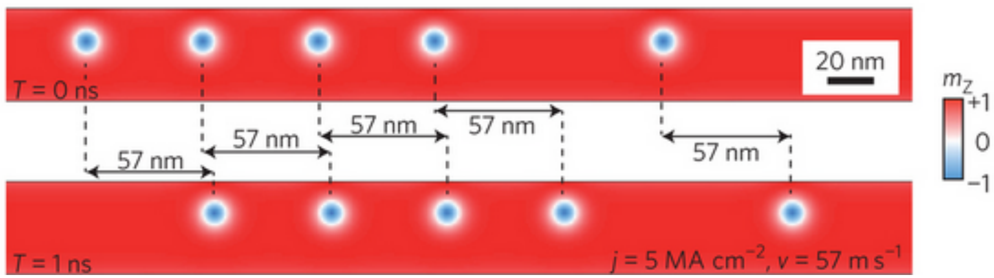
Fert, Nature Nano., 2013



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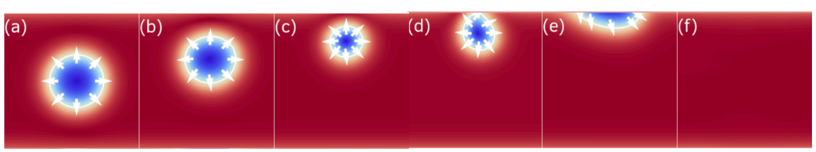

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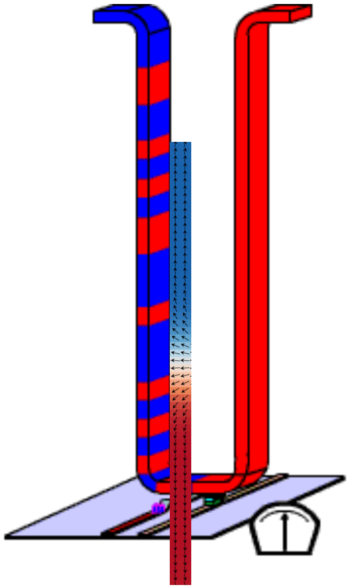
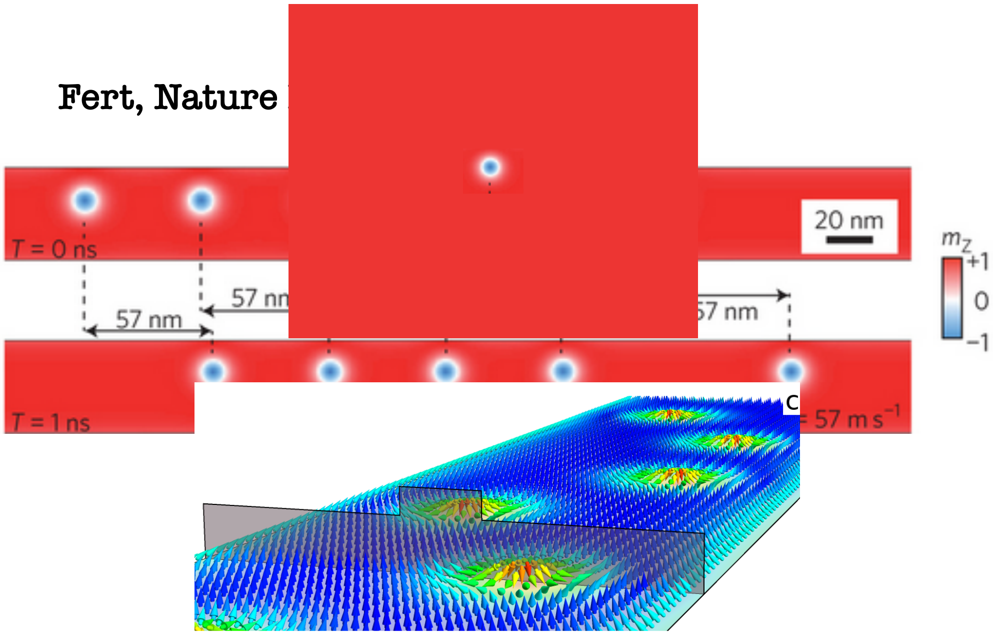




Müller, New. J. Phys, 2017

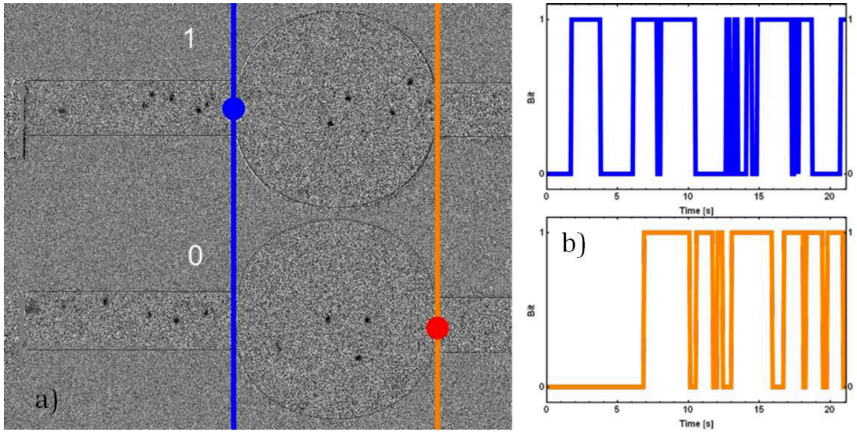
DW → 1d

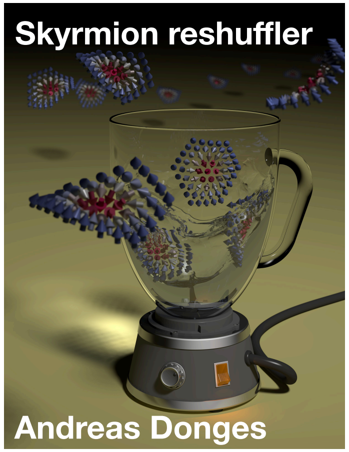
skyrmion → 2d

What is a device that optimally uses the properties of a skyrmion?

Zázvorka, ..., KES, et al., Kläui, Nature Nanotechnology 2019

Jakub Zázvorka





Skyrmions for Unconventional Computing?

Reservoir Computing

Stochastic Computing

DW → 1d

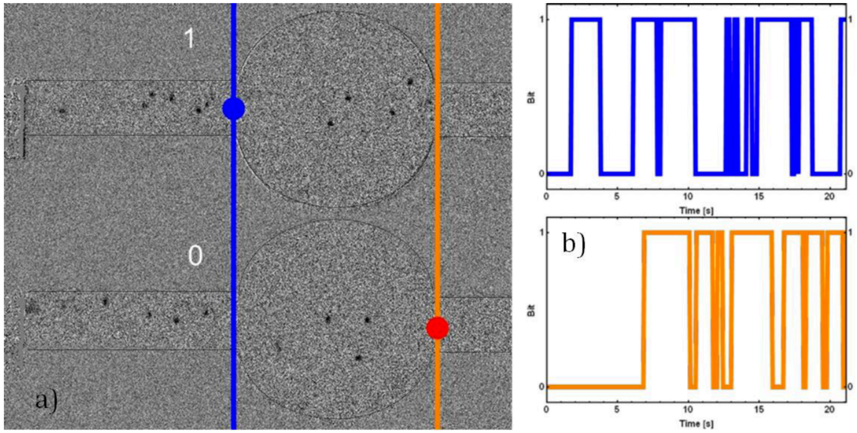
Pinna, et al., Phys. Rev. Appl. (2018)

Skyrmion based devices ???

What is a device that optimally uses the properties of a skyrmion?

Zázvorka, …, KES, et al., Kläui, Nature Nanotechnology 2019

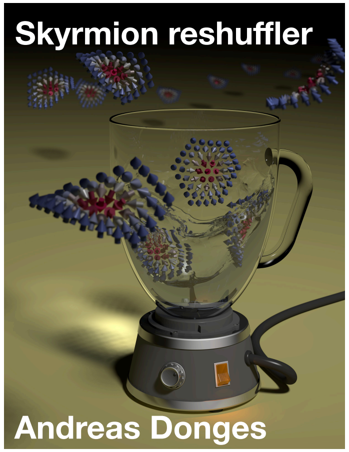
Jakub Zázvorka



DW → 1d

Skyrmions for Unconventional Computing?

- Reservoir Computing
- Stochastic Computing

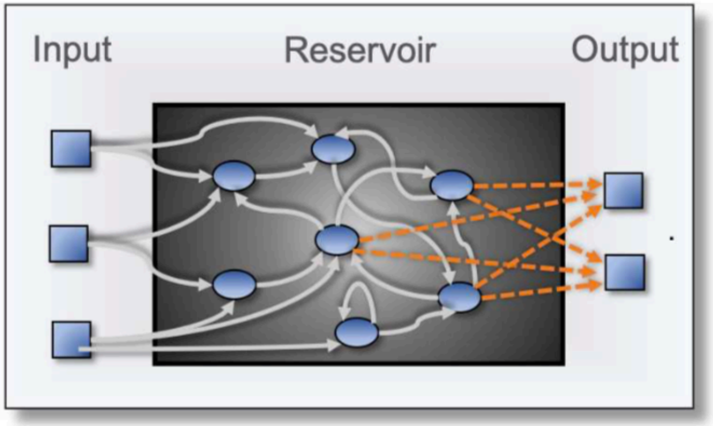


Pinna, et al., Phys. Rev. Appl. (2018)

Reservoir computing

Goal: map a complex problem to a linearly solvable one

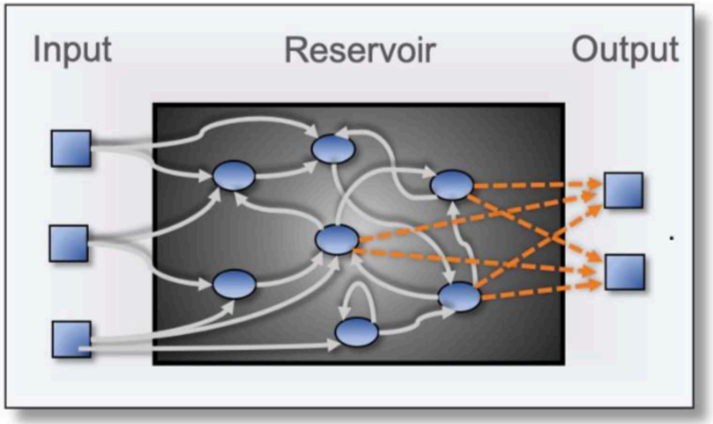
originally: artificial neural network with



recursive neural network

feed forward only

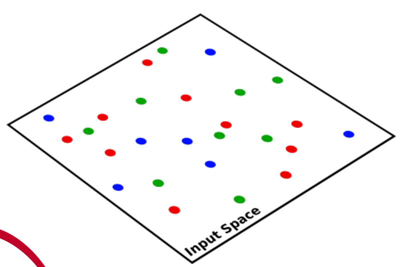
originally: artificial neural network with



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



Pinna, Bourianoff, KES, Phys. Rev. Appl. (2020)

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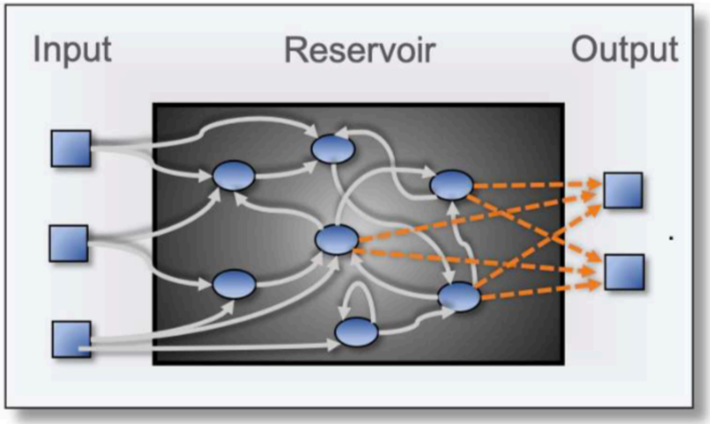

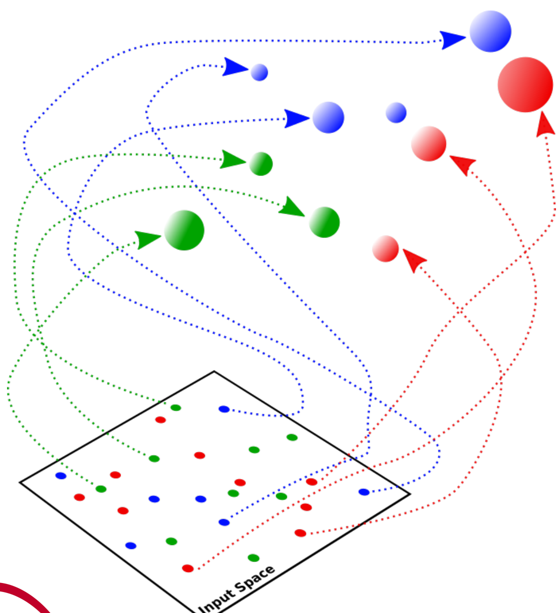

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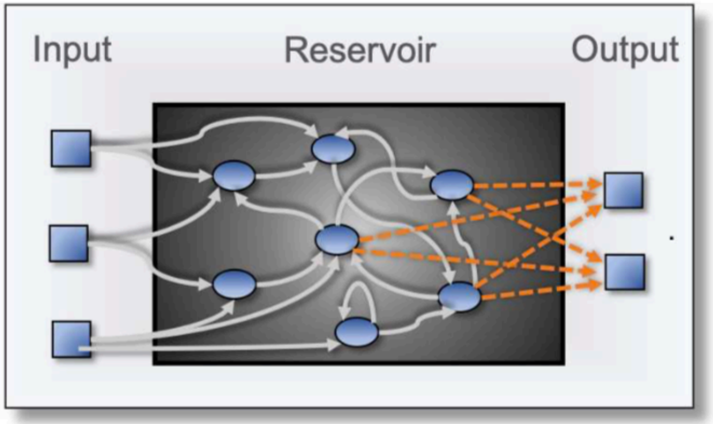

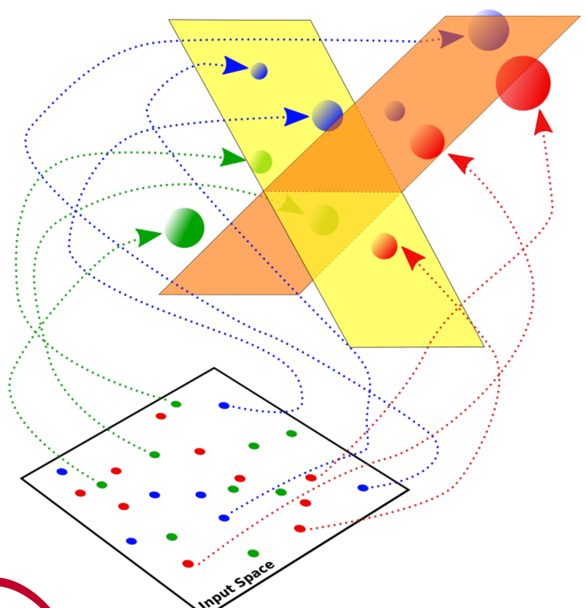

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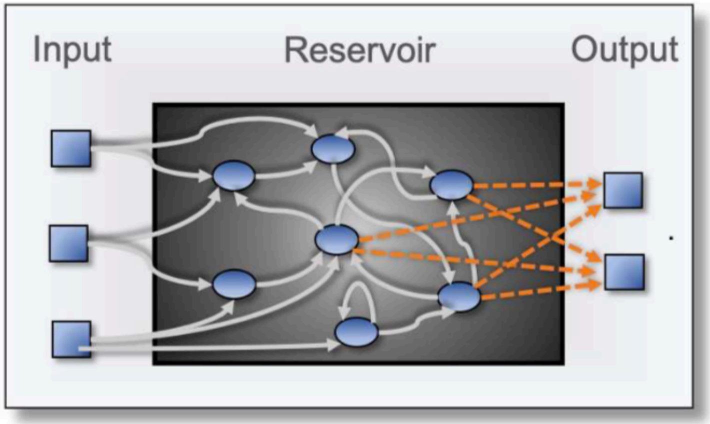

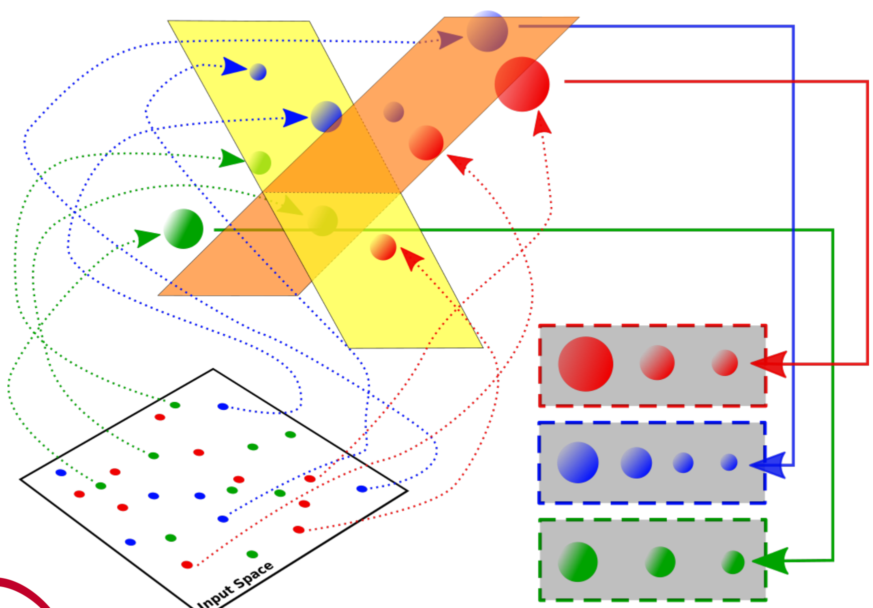

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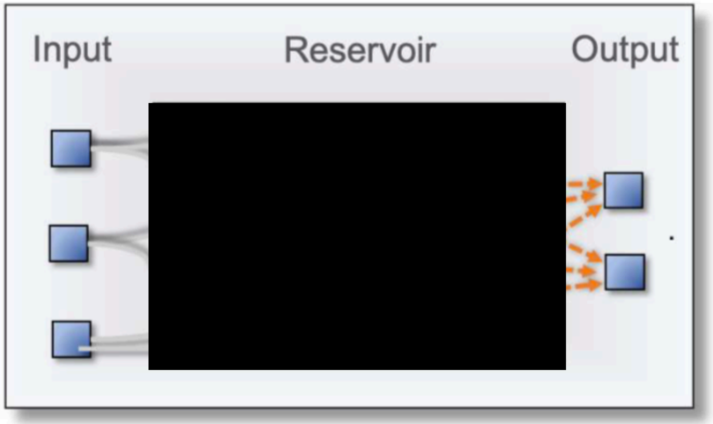

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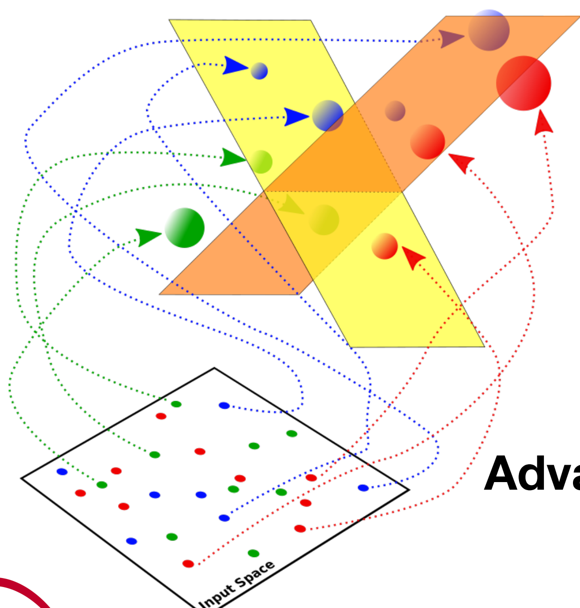


Useful for: Recognition and classification of spatial-temporal events like

- speech recognition
- sensor fusion type applications

Advantages:

- Multiple output arrays possible to search for different features simultaneously
- No detailed knowledge about reservoir required

Pinna, Bourianoff, KES, Phys. Rev. Appl. (2020)

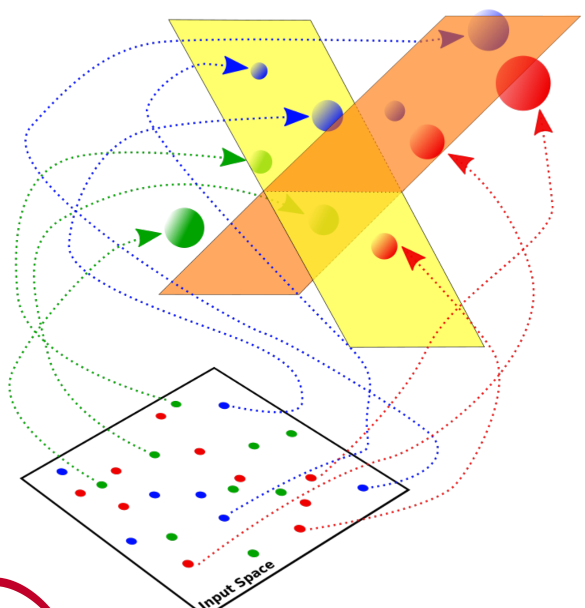
Reservoir computing

originally: artificial neural network with

Goal: map a complex problem to a linearly solvable one

Non-linear, complex system with short term memory

Mass, et al., Neural Comput. (2002)



Requirements for reservoir:

- Dimensionality of reservoir's state >> input array
- Response of reservoir nonlinear to input and previous state
- Short term memory (Echo state time > temporal input correlations)

Pinna, Bourianoff, KES, Phys. Rev. Appl. (2020)

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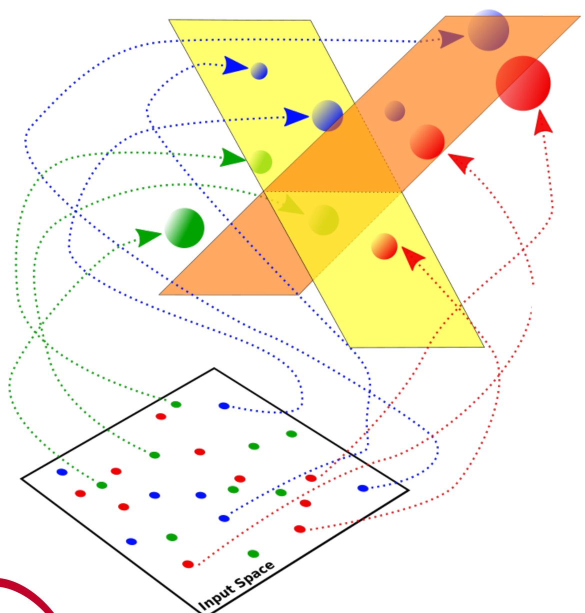
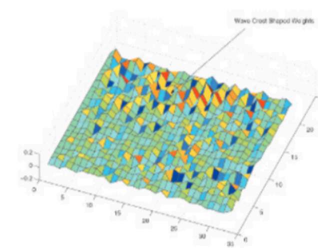
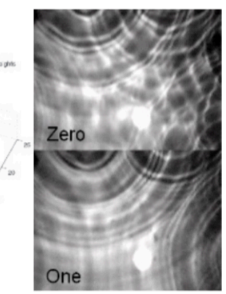
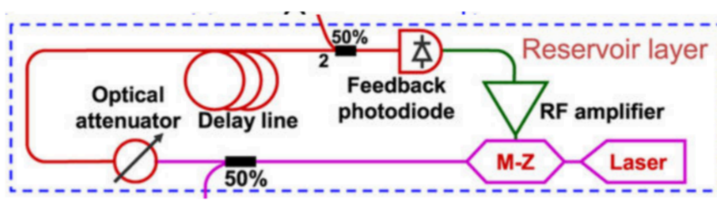


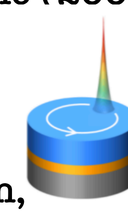




Fernando, et al., Adv. Artificial Life (2005)



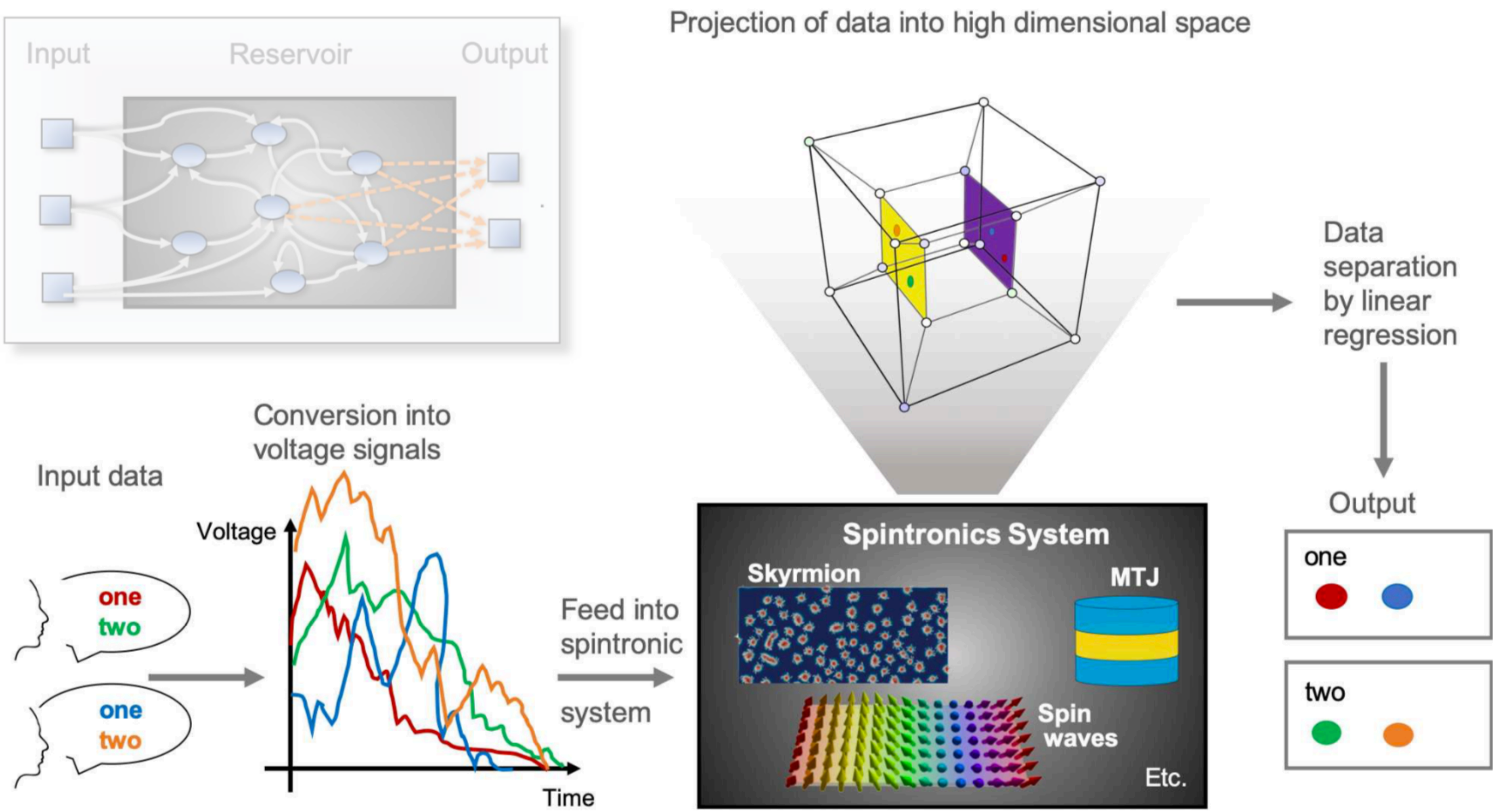
Duport, et al., Sci. Rep. (2016)



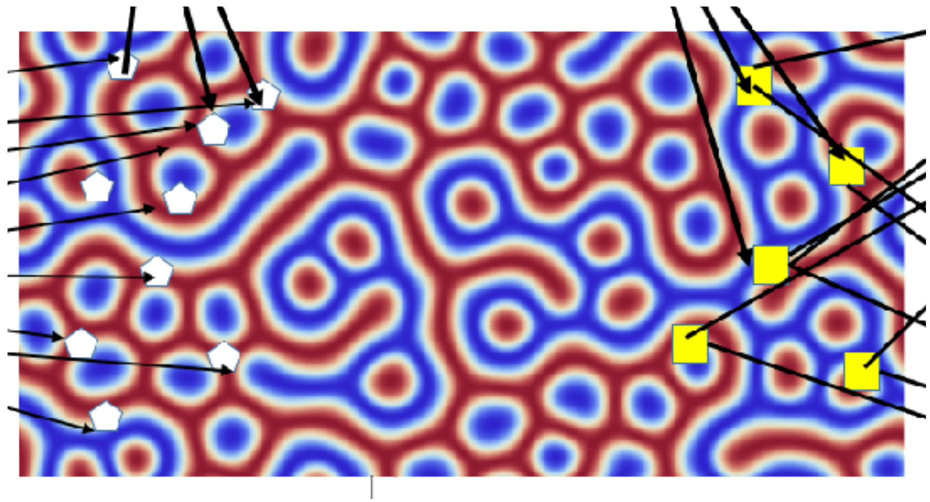
Torrejon, et al., Nature (2017)

Pinna, Bourianoff, KES, Phys. Rev. Appl. (2020)

Reservoir computing with matter



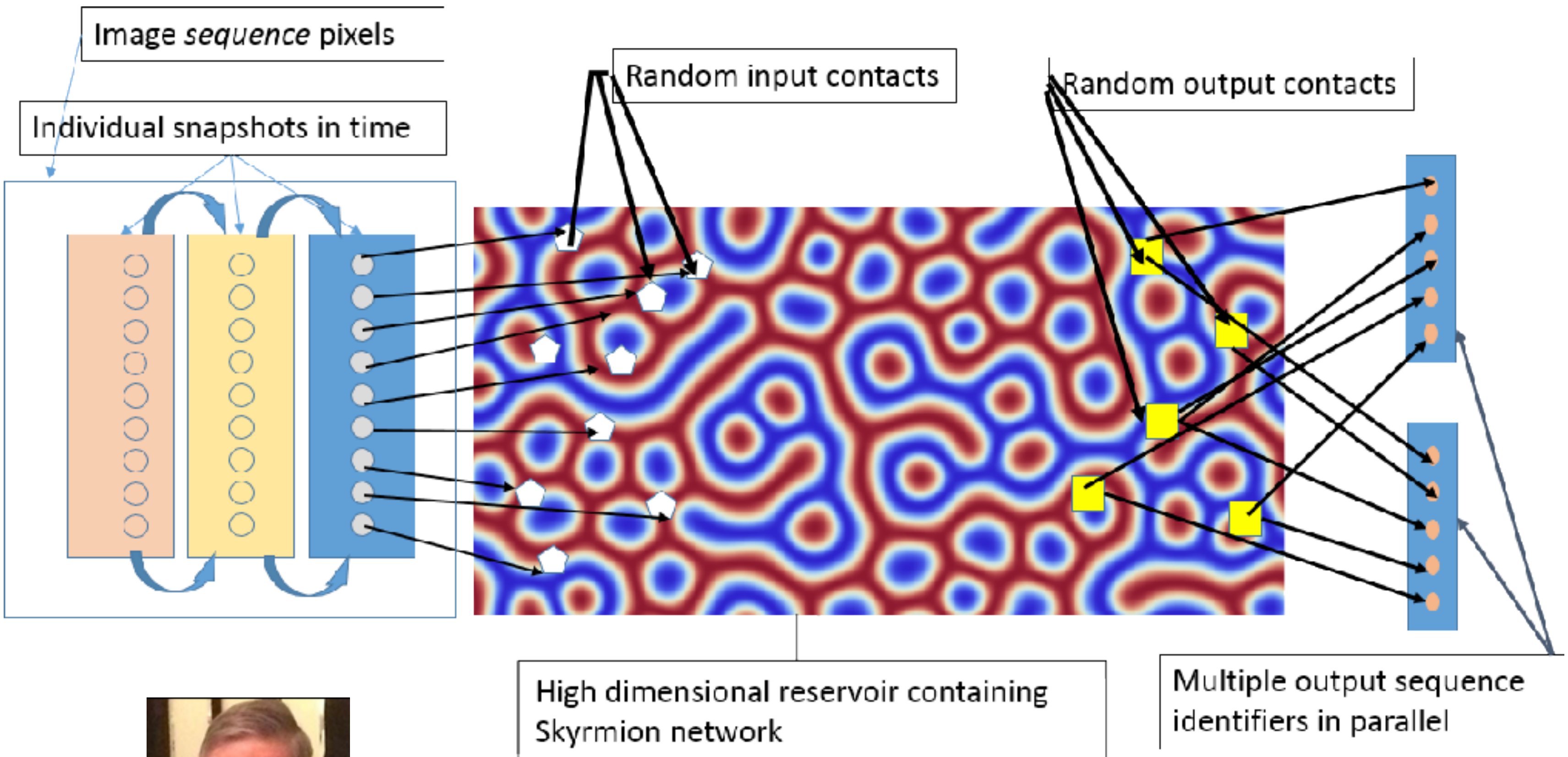
Finocchio, Di Ventra, Camsari, KES, Amiri, Zeng et al. JMMM (2021)



“skyrmion fabrics” as reservoir

George Bourianoff

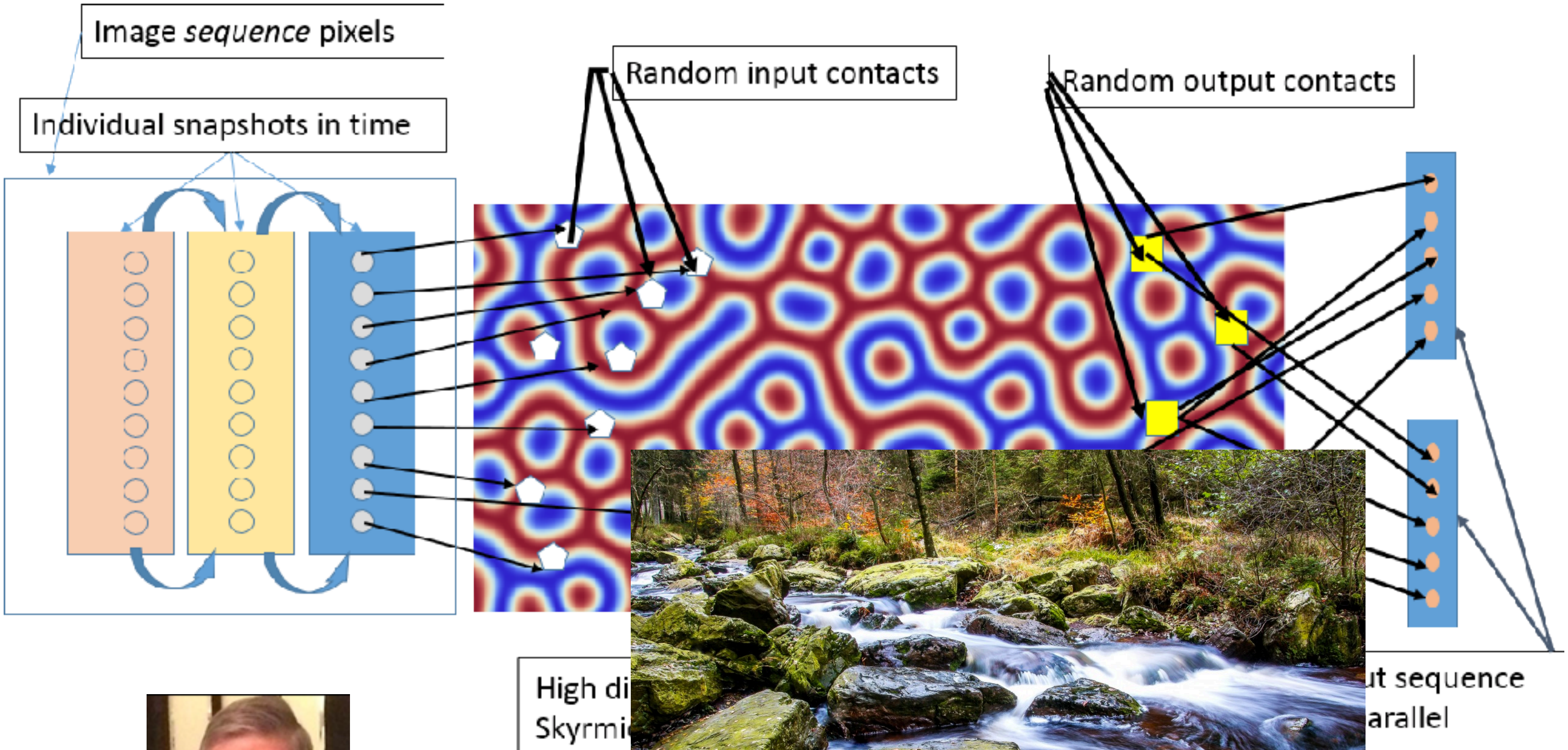
Using skyrmions for reservoir computing



George Bourianoff

Using skyrmions for reservoir computing

TWIST
Topological Whirls In SpinTronics



George Bourianoff

intel

First steps towards: skyrmions for reservoir computing

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Topological Whirls In SpinTronics

A magnetic skyrmion as a non-linear resistive element
a potential building block for reservoir computing


Diana Prychynenko


Matthias Sitte

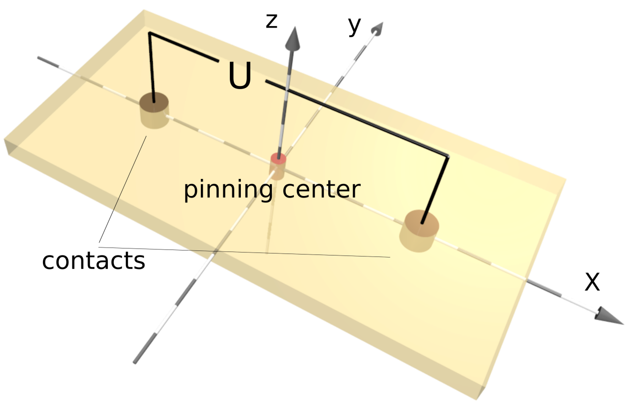

Kai Litzius


Benjamin Krüger


George Bourianoff


Mathias Kläui


Jairo Sinova

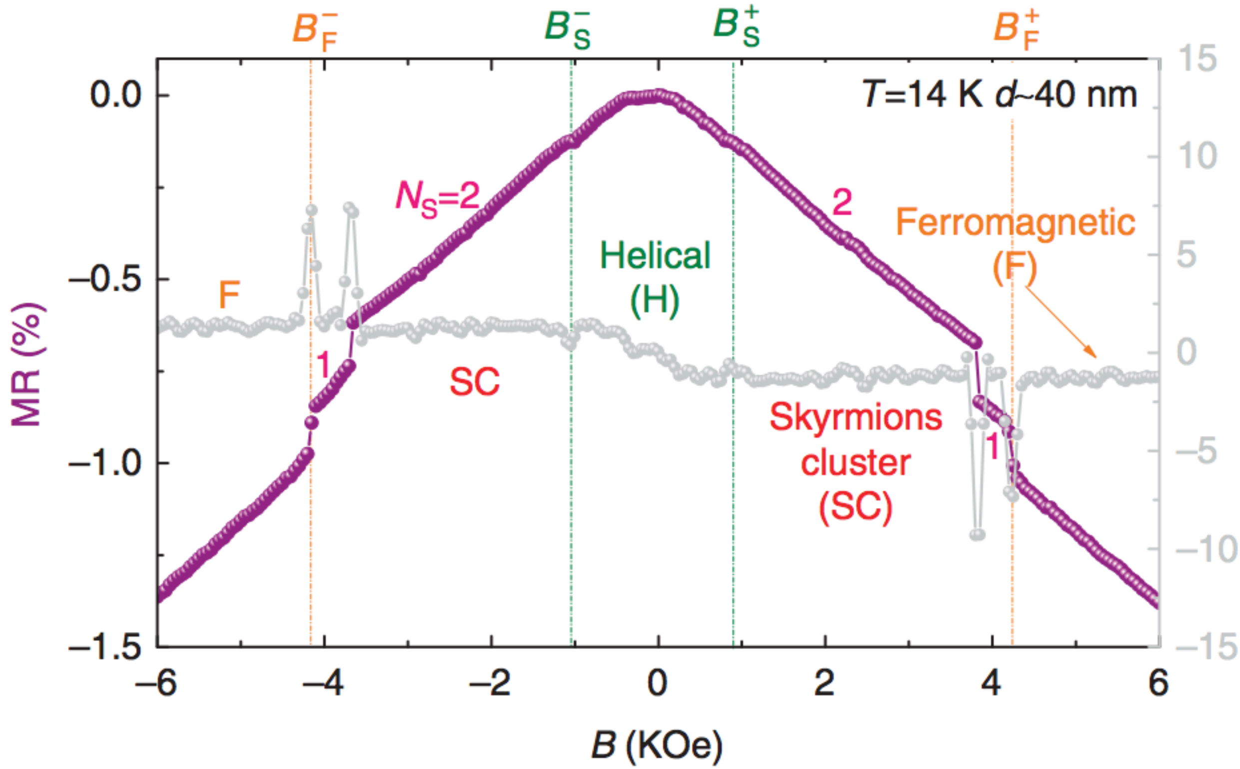


Magnetisation dependent magneto-resistive effects

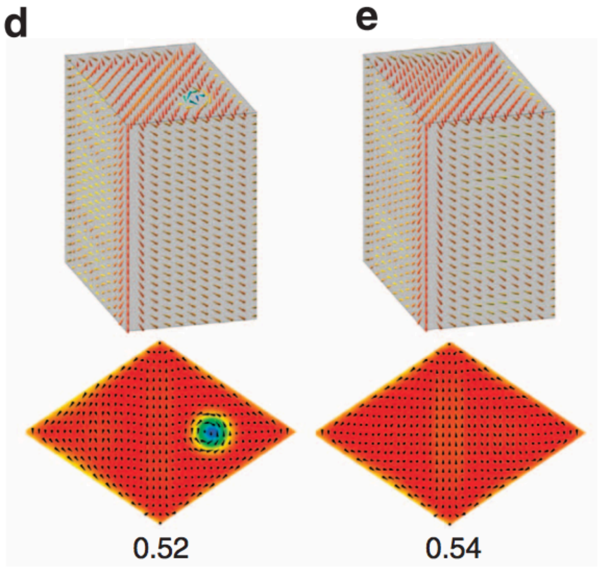
- Anisotropic Magnetoresistance (AMR)
- Non-collinear Magnetoresistance (NCMR)
- …

Prychynenko, et al., KES, Phys. Rev. Appl. (2018)

Skyrmions and Magnetoresistance



Du, et al., Nat. Commun. 2015

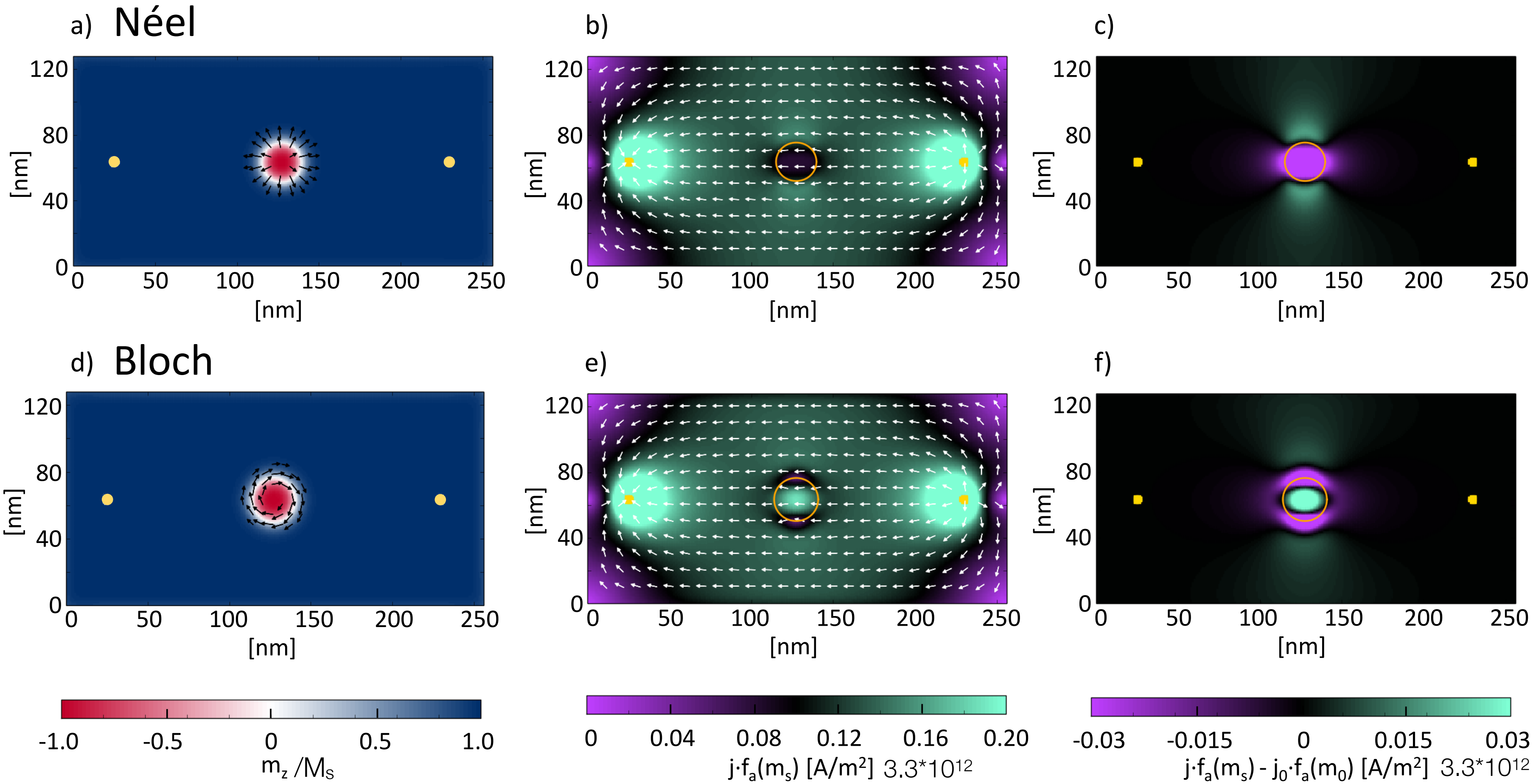


"scales with volume of twisted spins"

$$\boldsymbol{j}[U,\boldsymbol{m}] = -\boldsymbol{\sigma}[\boldsymbol{m}] \cdot \boldsymbol{E}[U]$$

Single skyrmion

A magnetic skyrmion as a non-linear resistive element
a potential building block for reservoir computing

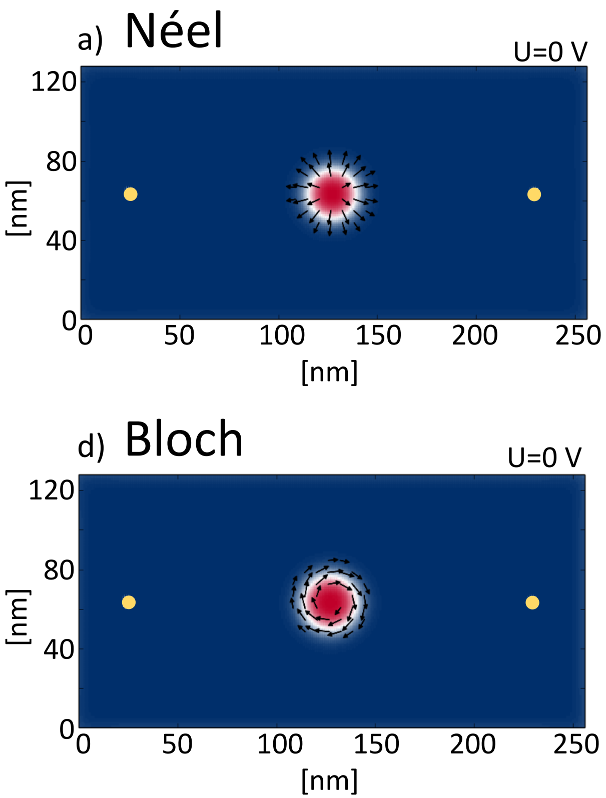


current flow based on AMR

Prychynenko, et al., KES, Phys. Rev. Appl. (2018)

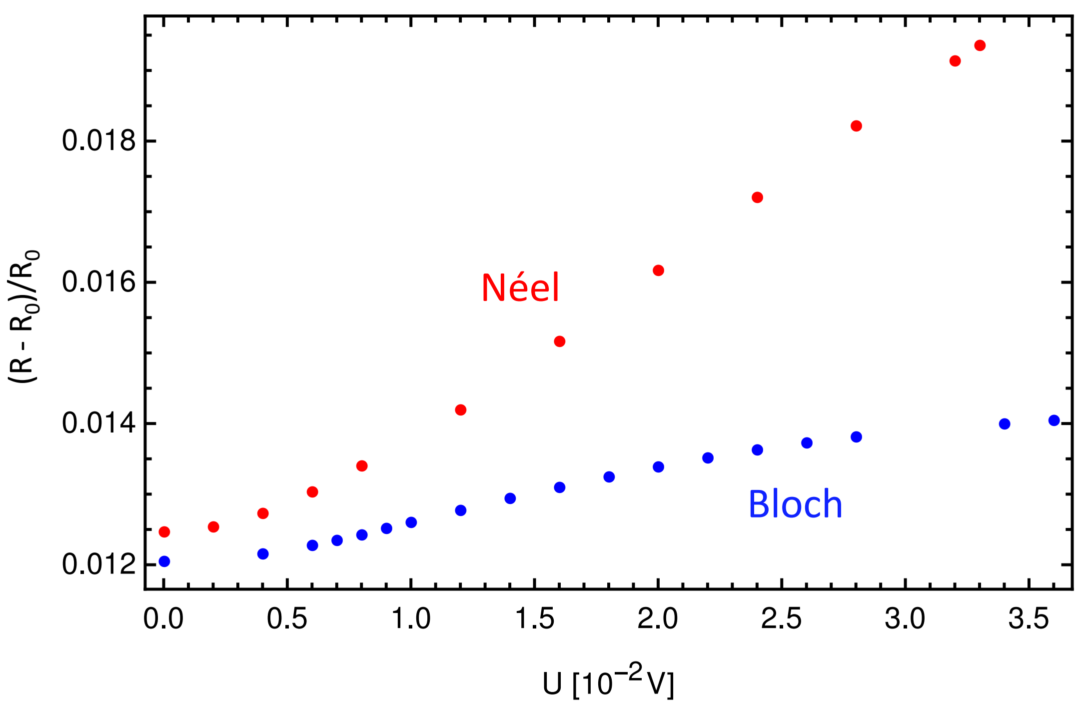
"small" voltages deform a pinned skyrmion

Skyrmions behave as non-linear resistive elements



"consider as a device"

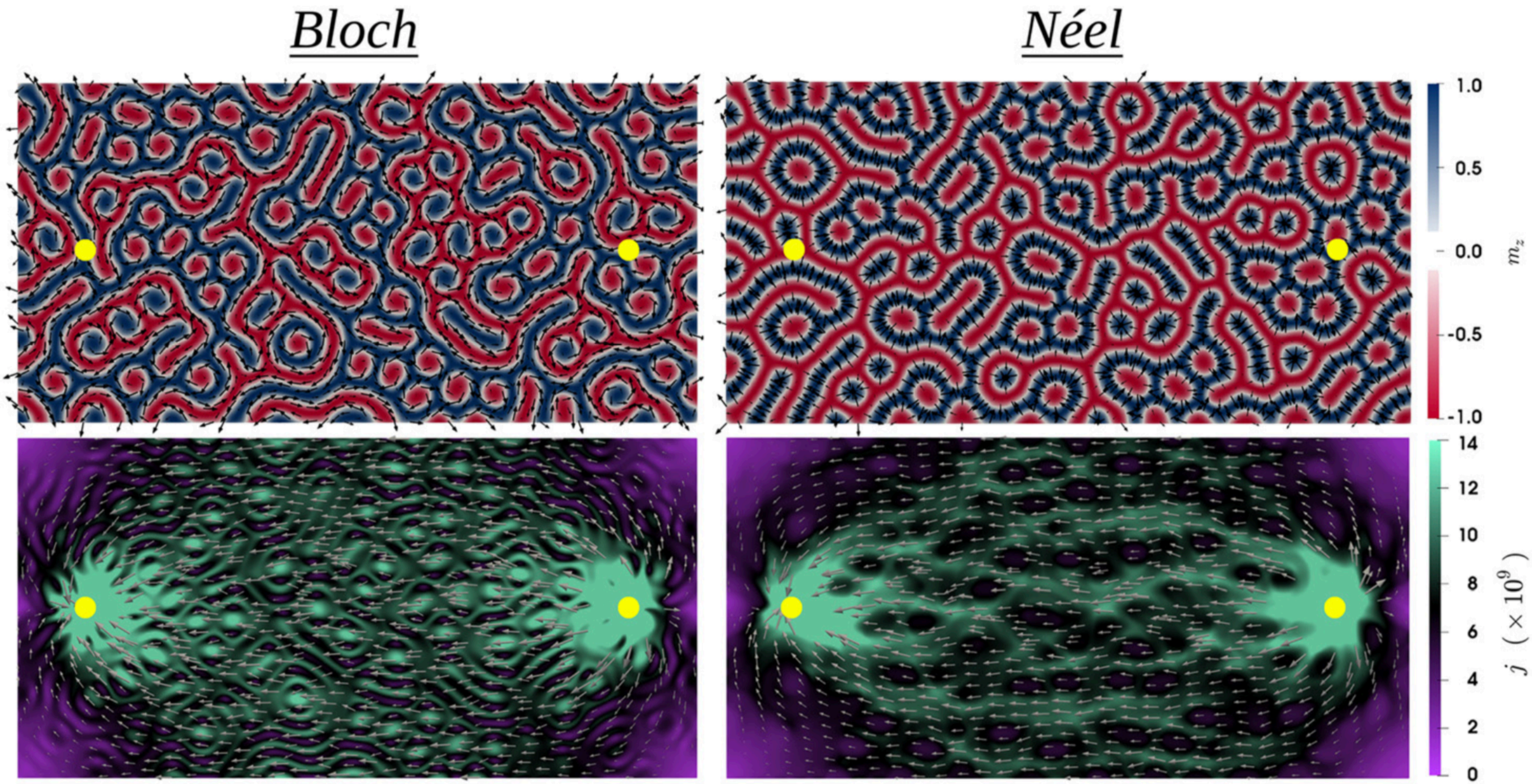
Non-linear IV characteristic



Prychynenko, et al., KES, Phys. Rev. Appl. (2018)

First steps towards: skyrmions for reservoir computing

TWIST
Topological Whirls In SpinTronics



current flow based on AMR

Bourianoff, Pinna, Sitte, KES, AIP Advances, (2018)

Skyrmion Reservoir

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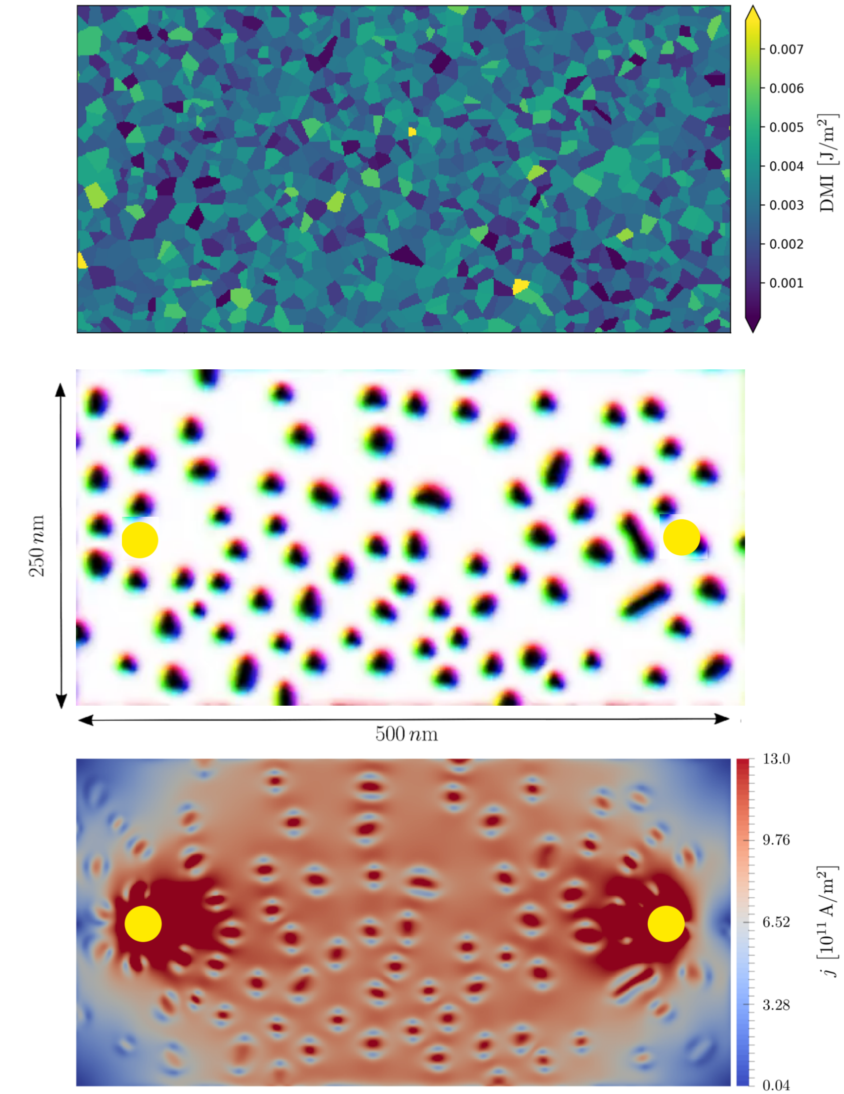
Topological Whirls In SpinTronics

Simulations: model pinning through grains

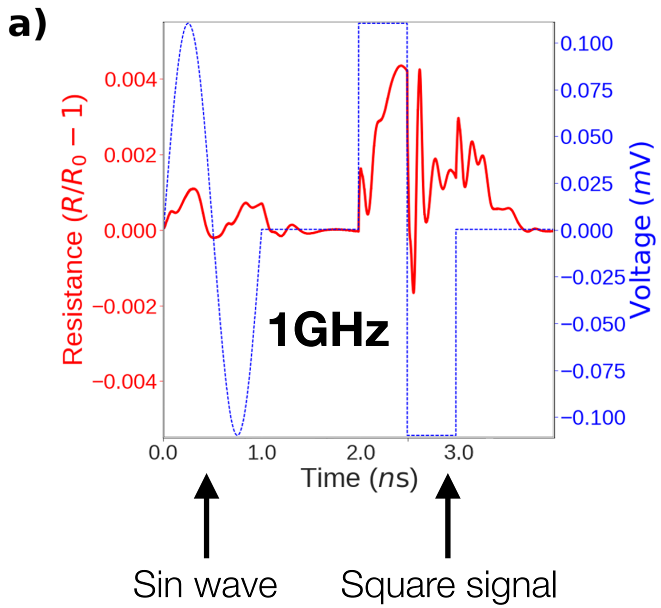
Skyrmions must not displace significantly
for the reservoir to work properly

Texture topology has been shown
to **not** change significantly due to
thermal and current-driven excitations

Non-linear, complex system
with short term memory



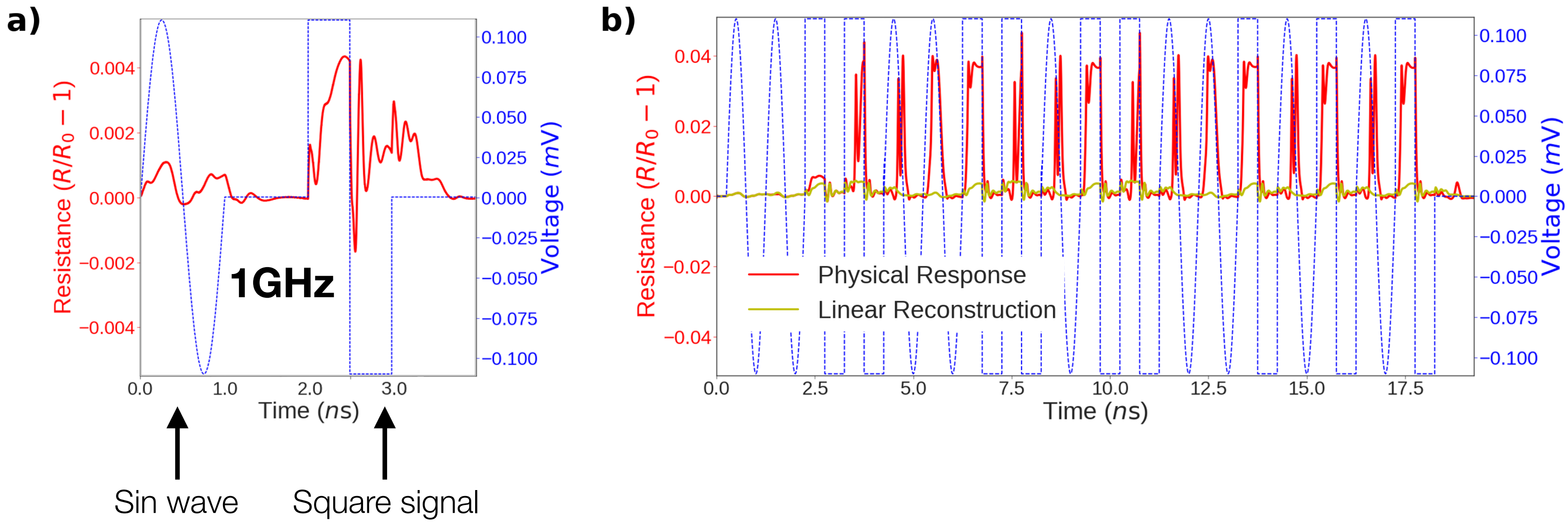
Pinna, Bourianoff, KES, Phys. Rev. Appl. (2020)



Non-linear, complex system with short term memory

Pinna, Bourianoff, KES, Phys. Rev. Appl. (2020)

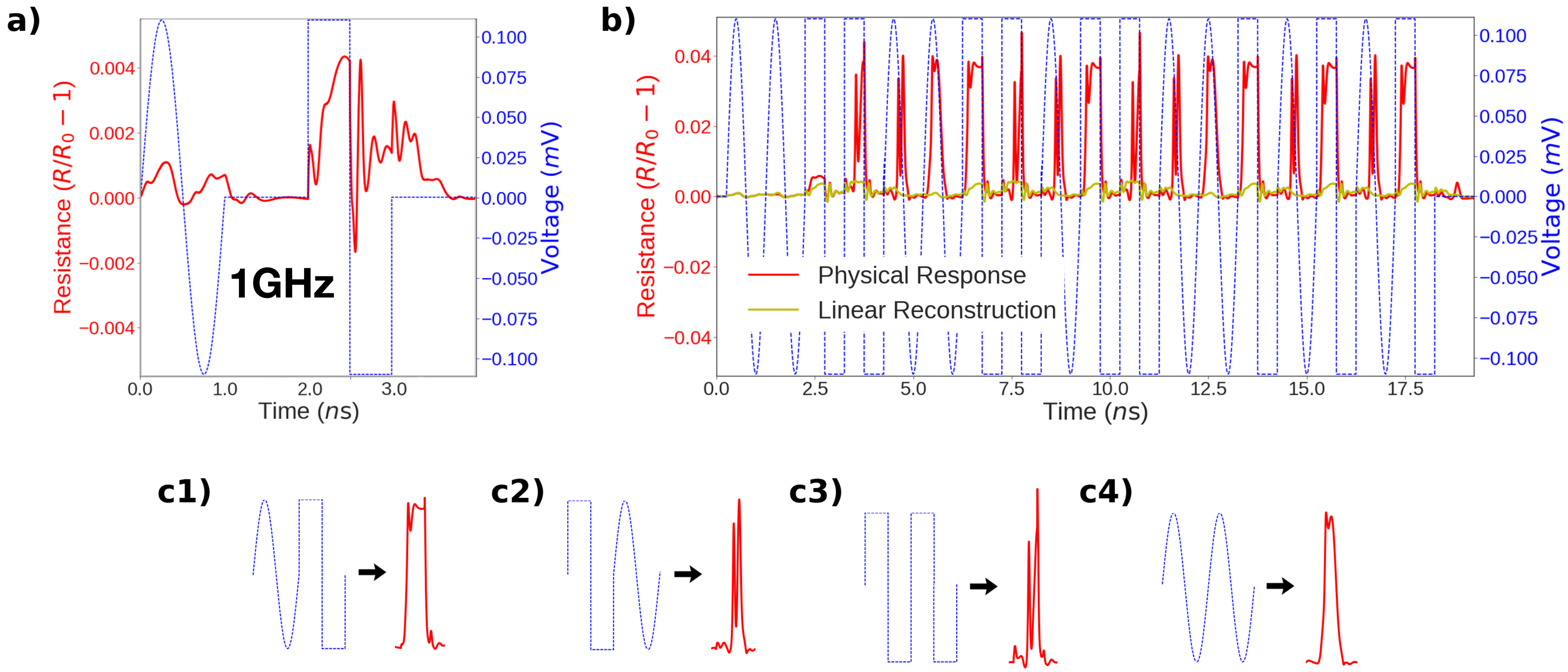
Skyrmion Reservoir



Non-linear, complex system with short term memory

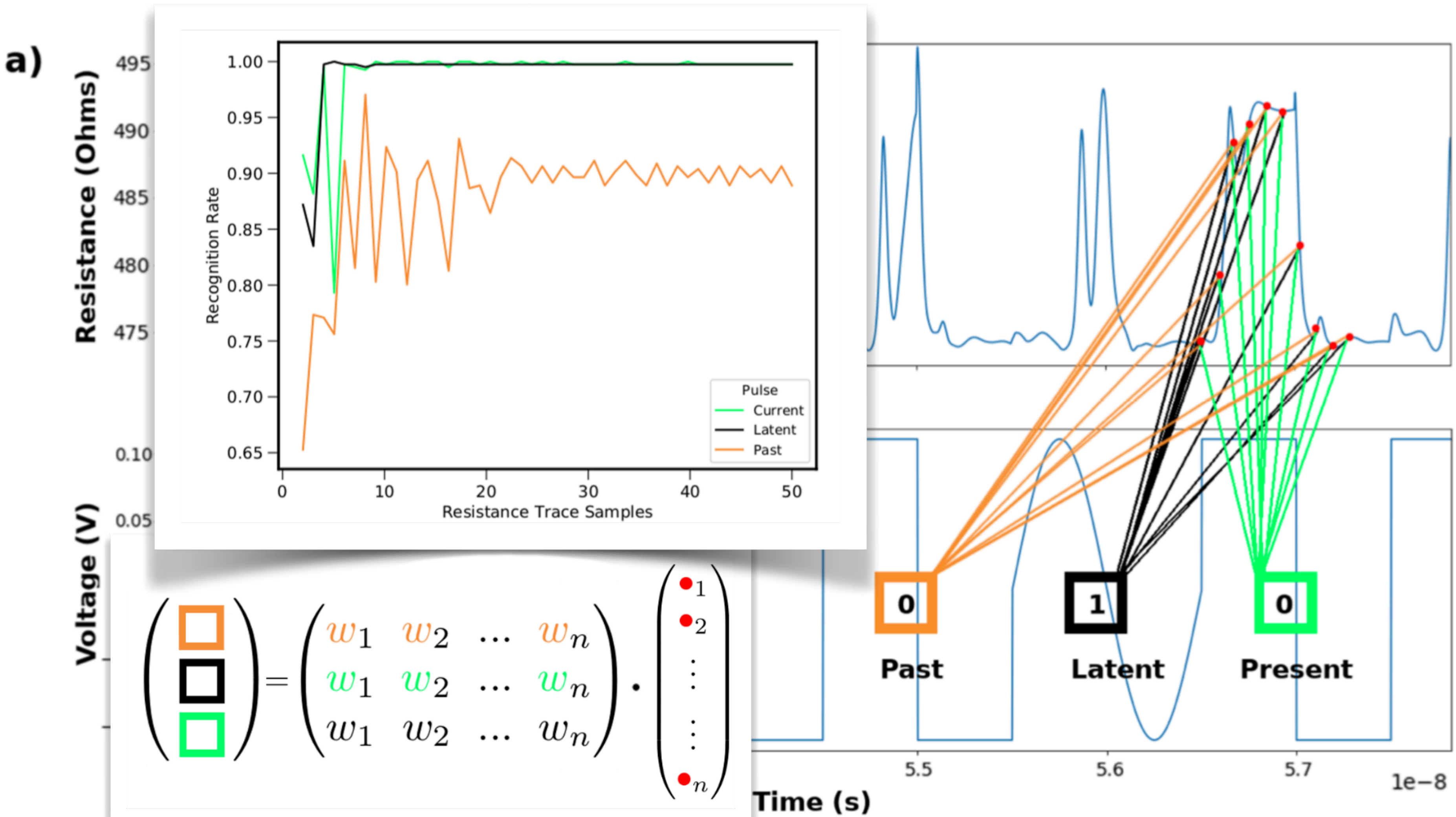
Pinna, Bourianoff, KES, Phys. Rev. Appl. (2020)

Skyrmion Reservoir



-> simple pattern recognition

Pinna, Bourianoff, KES, Phys. Rev. Appl. (2020)

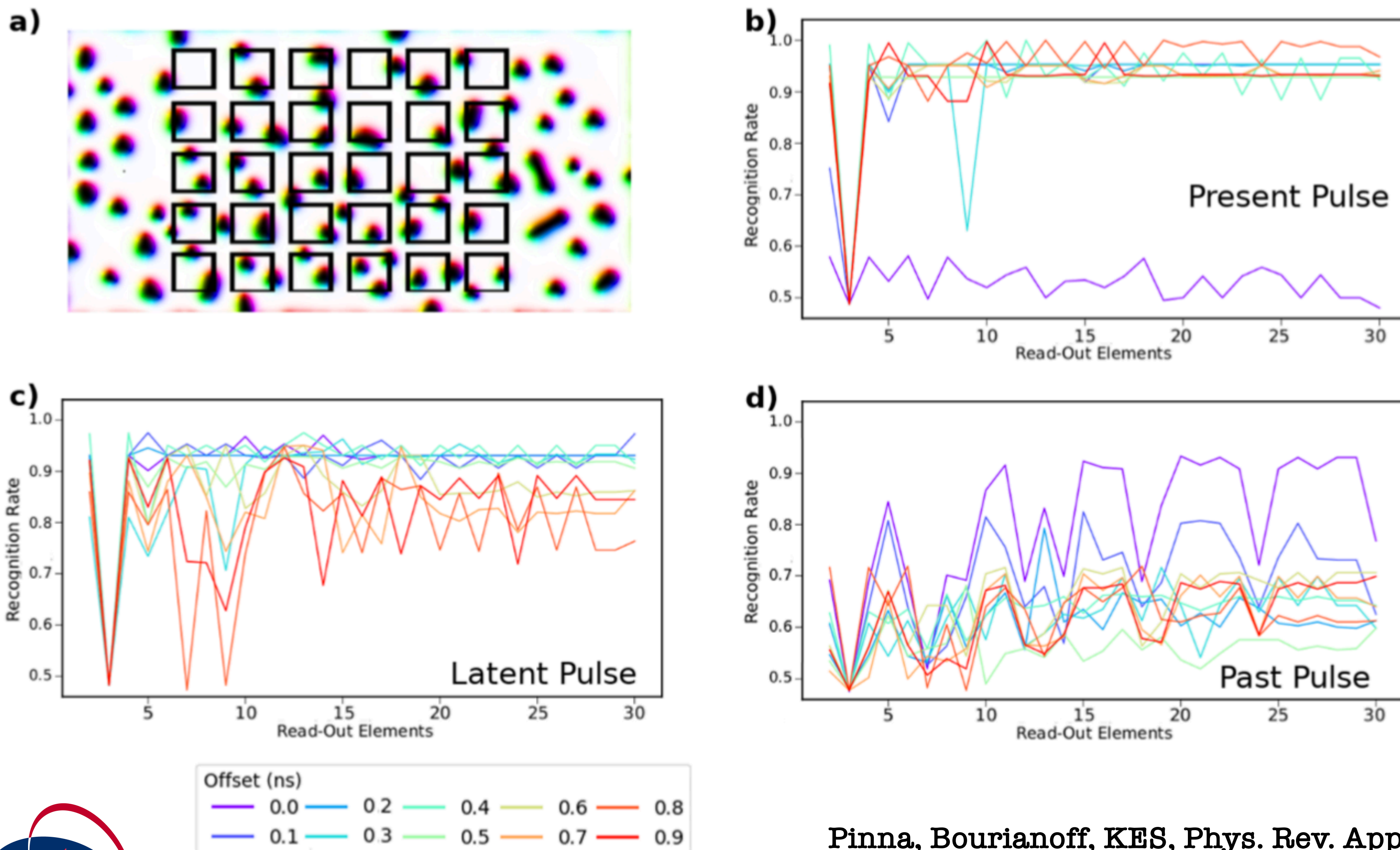


$$\begin{pmatrix} \square \\ \blacksquare \\ \square \end{pmatrix} = \begin{pmatrix} w_1 & w_2 & \cdots & w_n \\ w_1 & w_2 & \cdots & w_n \\ w_1 & w_2 & \cdots & w_n \end{pmatrix} \cdot \begin{pmatrix} \bullet_1 \\ \bullet_2 \\ \vdots \\ \vdots \\ \bullet_n \end{pmatrix}$$

Pinna, Bourianoff, KES, Phys. Rev. Appl. (2020)

Patter recognition - in space

Exploiting the complex magnetic structure, no time tracing needed!



Pinna, Bourianoff, KES, Phys. Rev. Appl. (2020)

Summary: RC with Skyrmion Fabrics

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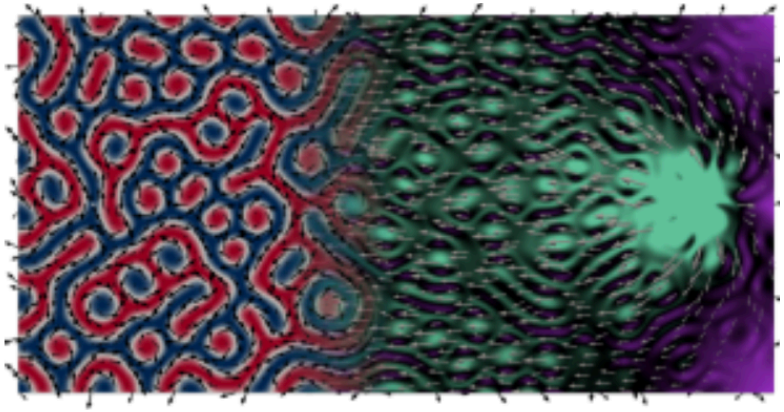
Topological Whirls In SpinTronics



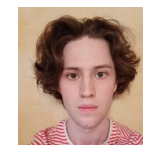
Non-linear, complex system with short term memory

Simple pattern recognition by a single measurement

Potential advantages of Skyrmion Reservoir:

- small (~nm)
- low energy consumption (~μW)
- complexity / many degrees of freedom

J. Love
Mumax³ Team: in particular
Jeroen Mulkers, Jonathan Leliaert



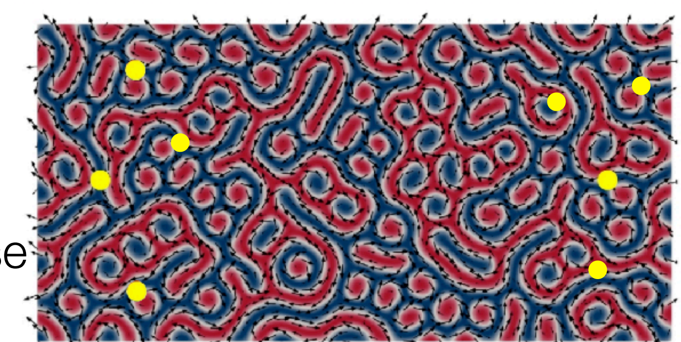
Jake Love

Outlook:

“Finding optimal settings for magnetic texture”

Resistances across multiple input and output contacts

→ capture more information about the fabric’s response



Prychynenko, et al., KES, Phys. Rev. Appl. (2018)

Bourianoff, et al., KES, AIP Advances, (2018)

Pinna, Bourianoff, KES, Phys. Rev. Appl. (2020)

TWIST
Topological Whirls In SpinTronics

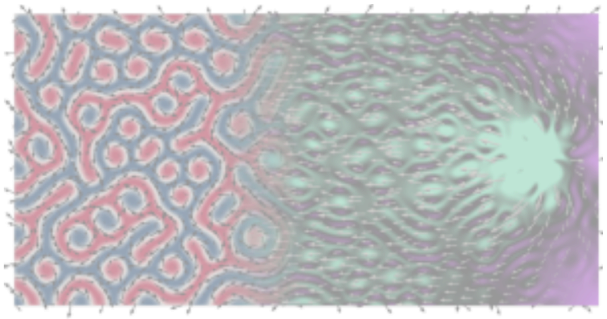
- Introduction to magnetic skyrmions
- Skyrmions for unconventional computing
  - Skyrmion reshuffler for stochastic computing

    Zázvorka, ..., KES, et al., Kläui, Nature Nanotechnology 2019

  - Skyrmions for reservoir computing

Thanks to

J. Zázvorka, F. Jakobs, D. Heinze, N. Keil, S. Kromina, S. Jaiswal, K. Litzius, G. Jakob, P. Virnau, D. Pinna, A. Donges, U. Nowak, M. Kläui



Thanks to

G. Bourianoff

M. Sitte, K. Litzius, D. Prychynenko, D. Pinna, B. Krüger, J. Sinova, M. Kläui

J. Love
Mumax^3 Team: in particular Jeroen Mulkers, Jonathan Leliaert

Prychynenko, et al., KES, Phys. Rev. Appl. (2018), Bourianoff, et al., KES, AIP Advances, (2018), Pinna, Bourianoff, KES, Phys. Rev. Appl. (2020)
Grollier, Querlioz, Camsari, KES, Fukami, Stiles, Nat. Electron. (2020)
Finocchio, Di Ventra, Camsari, KES, Amiri, Zeng JMMM (2021)
Vedmedenko, ..., KES, et. al., J. Phys. D: Appl. Phys. (2020)

- Data analysis, new tools for “microscopy”?

  Horenko, et al., KES, arXiv1907.04601
  Rodrigues, KES, et al., iScience 24, 3 (2021)

I. Horenko

D. Rodrigues

T. O’Kane

S. Gerber

SPICE

Outlook & personal view

- Economically: Moore's law has already come to an end -> new approaches are needed!

- This talk: Skyrmions for unconventional computing.
- More general: **computing with matter**,
  improving hardware for computing -> spintronics-based (?)

- Some novel concepts require going back from digital to **analog** type of information storing.

Still tremendous progress in computer science: -> **machine learning**

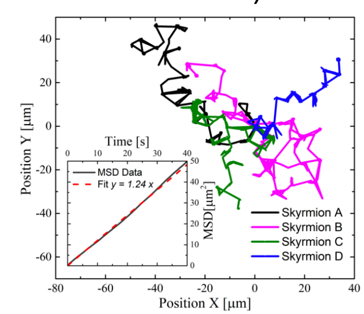
Basic ideas more than 50 years old, progress enormously relying on graphic cards.

<u>potential problems:</u>

- large data are needed
- curse of dimension
- overfitting
- not all information accessible (latent effects)

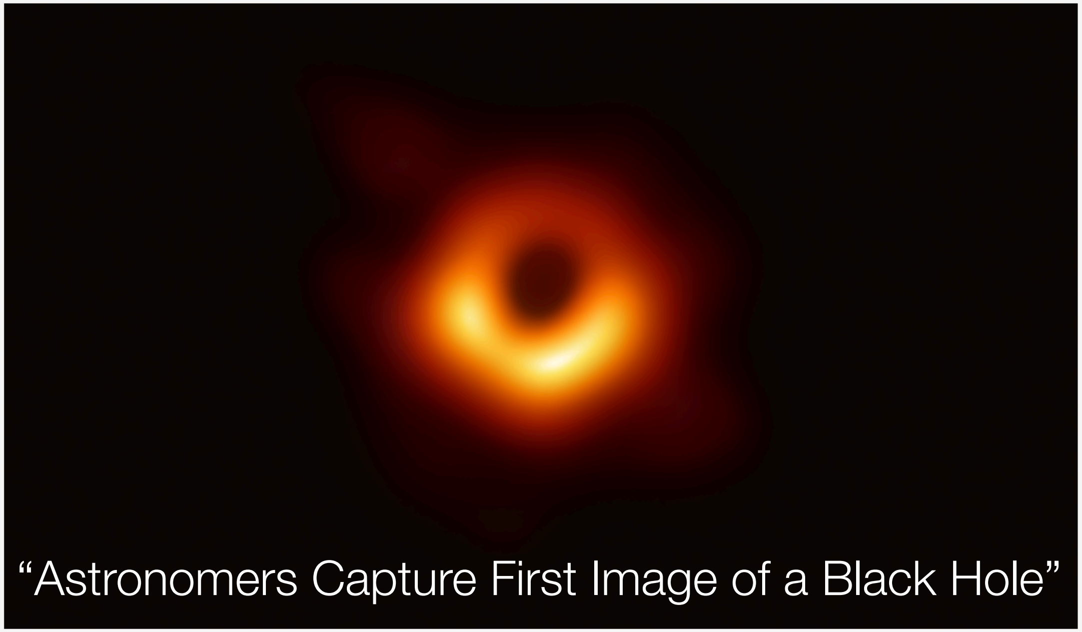
<u>frequent assumptions:</u>

- i.i.d. (identically, independent distributed)
- Gaussianity



Outlook & personal view

TWIST
Topological Whirls In SpinTronics



https://www.almaobservatory.org/en/press-release/astronomers-capture-first-image-of-a-black-hole/

progress in
telescopes
and
data analysis
(Gaussian Mixture Models)

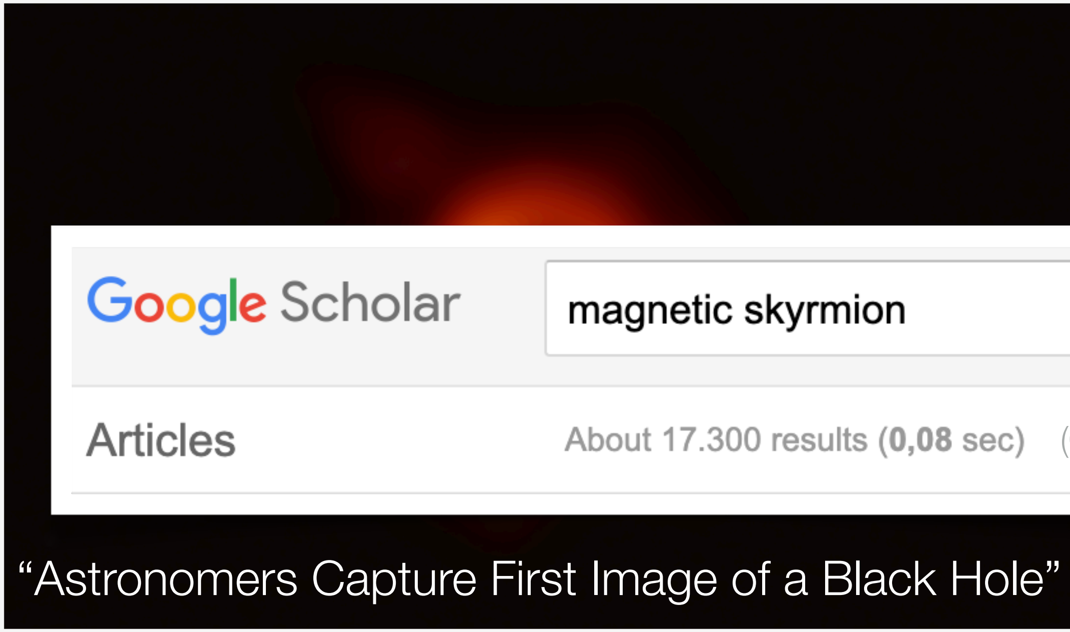
GMMs exhibit **polynomial** scaling of their computational cost **in every iteration** with the **data dimension**

The telescopes contributing to this result were ALMA, APEX, the IRAM 30-meter telescope, the James Clerk Maxwell Telescope, the Large Millimeter Telescope Alfonso Serrano, the Submillimeter Array, the Submillimeter Telescope, and the South Pole Telescope [7]. Petabytes of raw data from the telescopes were combined by highly specialised supercomputers hosted by the Max Planck Institute for Radio Astronomy and MIT Haystack Observatory.

using a methodology based on a **Gaussian Mixture Model** analysis of the overlapping pixel patches from Fourier-transformed radiointerferometric data. Here, it was assumed that every image patch time series can be described by a discrete latent independent and identically distributed (i.i.d.) process with Gaussian outputs.

Horenko, et al., KES, arXiv1907.04601

belong to the most popular latent inference methods



Google Scholar | magnetic skyrmion
Articles — About 17.300 results (**0,08** sec) (02/2021)

progress in
telescopes
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aussian Mixture Models)

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https://www.almaobservatory.org/en/press-release/astronomers-capture-first-image-of-a-black-hole/

The telescopes contributing to this result were ALMA
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raw data from the telescopes were combined by high
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Google Scholar | Gaussian Mixture Model
Articles — About 1.880.000 results (**0,06** sec) (02/2021)

using a methodology based on a **Gaussia**
Fourier-transformed radiointerferometric data. Here, it was assumed that every image patch time series can be described by a discrete latent independent and identically distributed (i.i.d.) process with Gaussian outputs.

Horenko, et al., KES, arXiv1907.04601

belong to the most popular latent inference methods

Data analysis: New tools for “microscopy”?

Topological Whirls In SpinTronics

Illia Horenko
(Head of the Computational Time Series Group, USI Lugano)

Davi Rodrigues
(TWIST group)

Terence O’Kane
(Head of Climate Forecast, CSIRO Australia)

two low cost tools for extraction of latent patterns

latent entropy:
encodes **stochasticity** (predictability) of the system

the higher the latent entropy
the higher the stochasticity

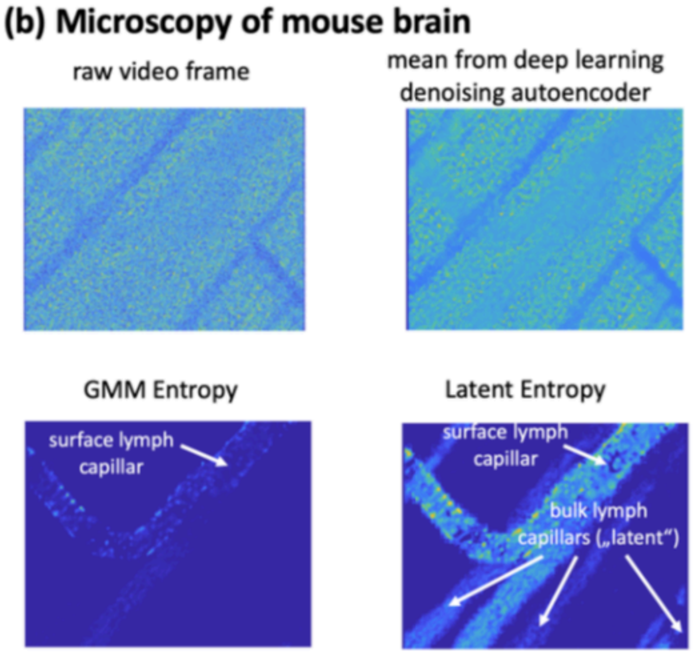
latent dimension:
encodes **memory** of the system

the higher the latent dimension
the higher the memory

(no i.i.d. assumption or Gaussianity)

low cost = computational iteration costs and memory requirements are **independent** of the data statistics size & the observed data dimension **Horenko, et al., KES, arXiv1907.04601**

Data analysis: New tools for “microscopy”?



flow of transparent fluid
through the capillaries
of the glymphatic system

recently discovered anatomic organ,
responsible for waste clearance

Ising model

Micromagnetic model

Magnetic imaging data

Rodrigues, KES, Gerber, Horenko, iScience (2021)

Horenko, et al., KES, arXiv1907.04601

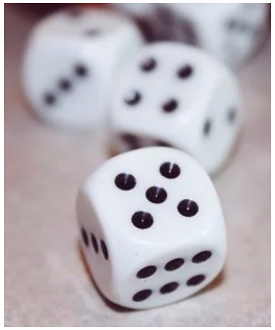
Average latent entropy S and dimension K

Horenko, et al., KES, arXiv1907.04601

Average latent entropy S and dimension K

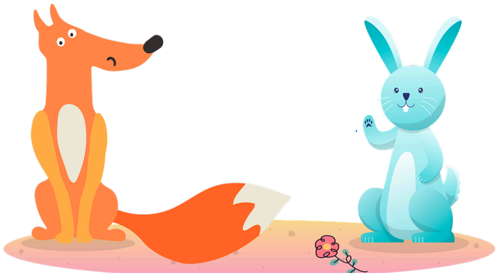
K=1 (Bernoulli):

Y $\quad \mathbb{P}[Y|X]=\mathbb{P}[Y] \quad$ X



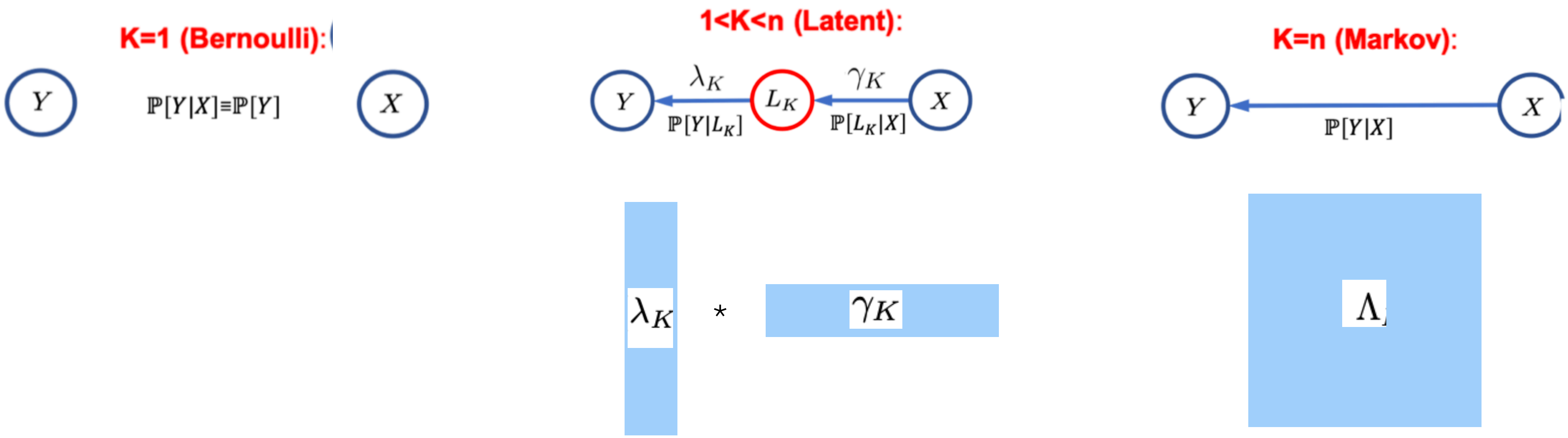
K=n (Markov):

$$Y \xleftarrow[\mathbb{P}[Y|X]]{} X$$



Horenko, et al., KES, arXiv1907.04601

Average latent entropy S and dimension K



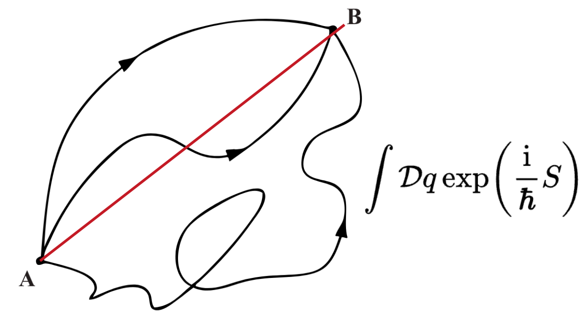
Horenko, et al., KES, arXiv1907.04601

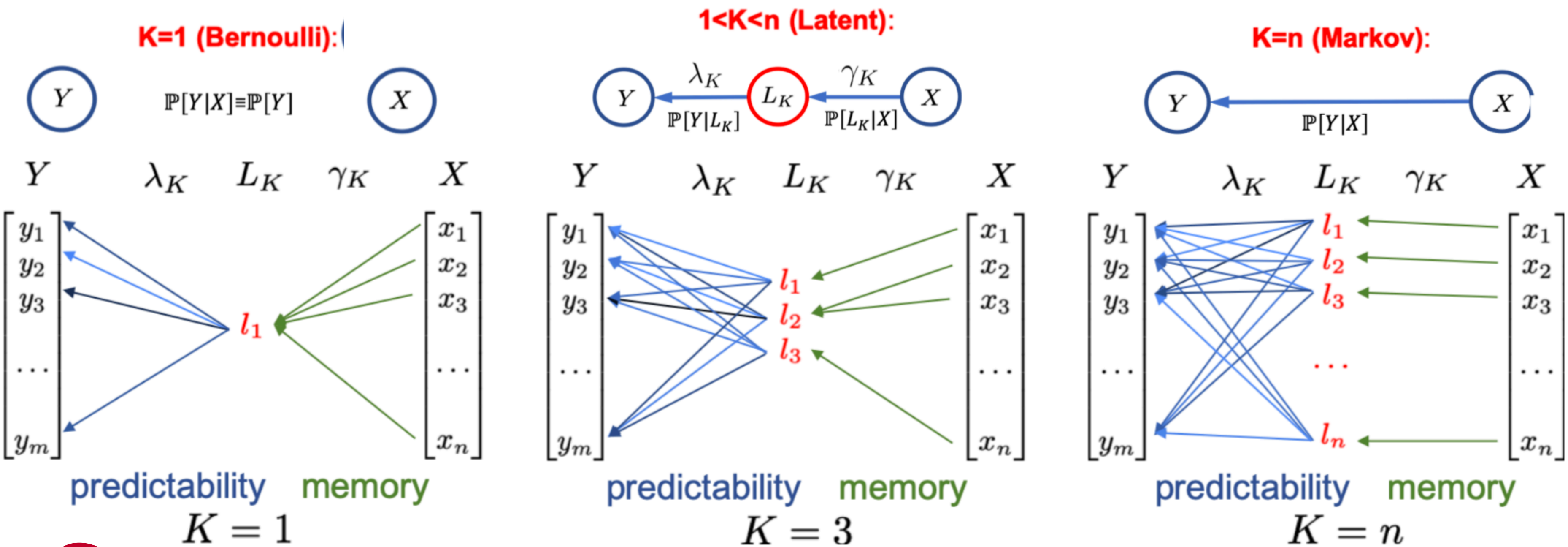
Algorithm for expected latent entropy $\bar{S}$ and dimension $\bar{K}$

Step 1: For discrete data sets $\{X(1), X(2), \ldots, X(N)\}$ and $\{Y(1), Y(2), \ldots, Y(N)\}$, compute relation matrix $\Lambda_K = \lambda_K \gamma_K$ and S_K (with the DBMR algorithm from [5]) $\forall K \in \{1, \ldots, n\}$;

Step 2: Compute posterior probabilities $\{p_1, p_2, \ldots, p_n\}$ as Akaike weights based on $\{S_1, \cdots, S_n\}$;

Step 3: Compute expected latent entropy and dimension as $\bar{S} = \sum_{K=1}^{n} p_K S_K$ and $\bar{K} = \sum_{K=1}^{n} p_K K$.

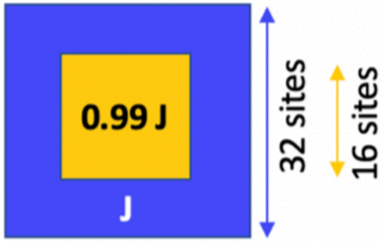


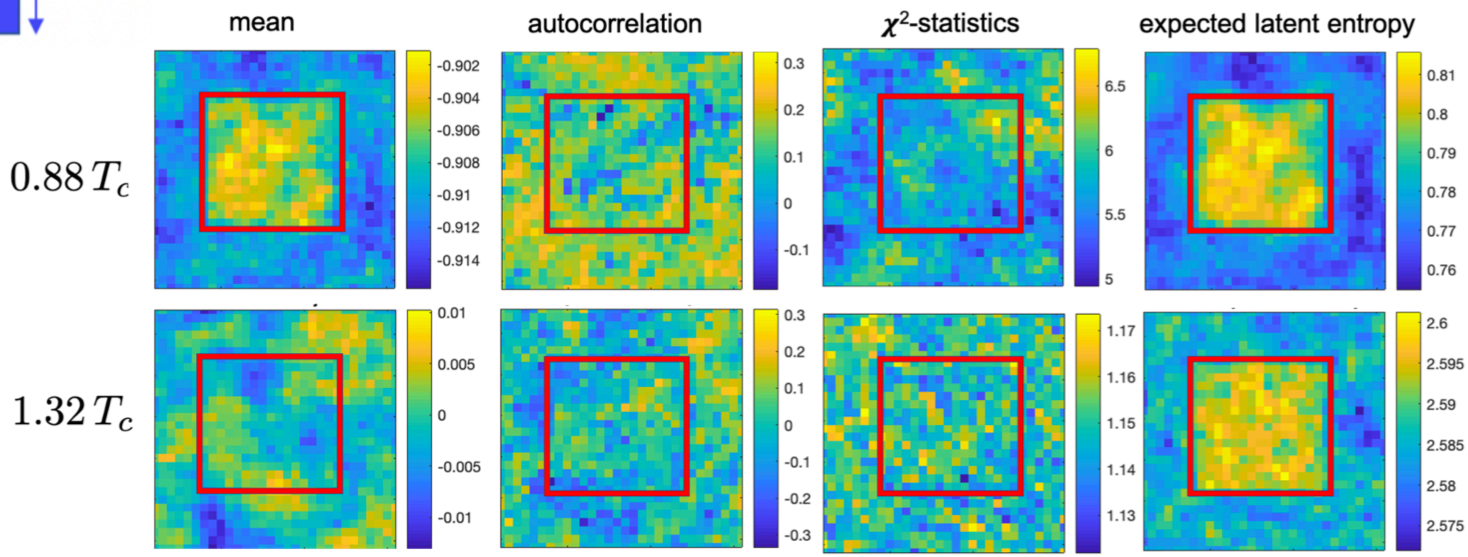


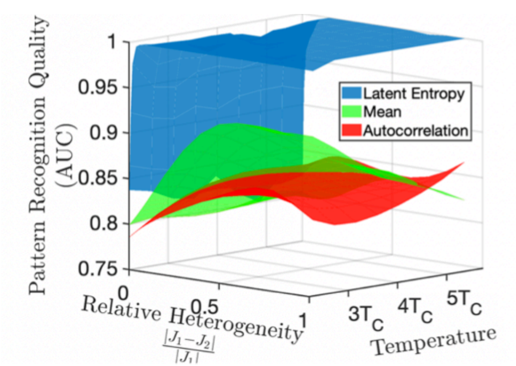
DBMR = Direct Bayesian Model Reduction

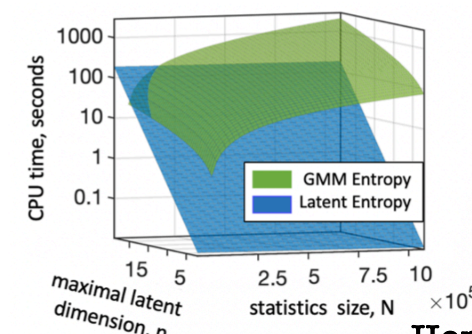
Horenko, et al., KES, arXiv1907.04601

Ising model



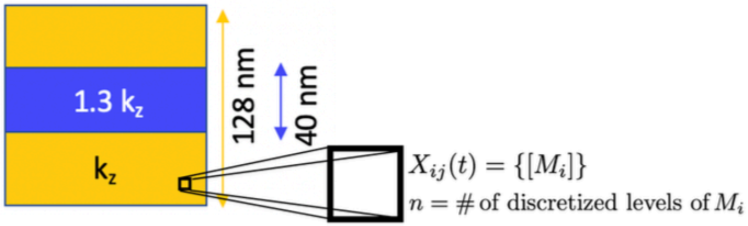






Horenko, et al., KES, arXiv1907.04601

a) Micromagnetic Model Data Representation and Analysis



$$\dot{\boldsymbol{m}} = -\frac{\gamma}{1+\alpha^2}\left(\boldsymbol{m}\times\boldsymbol{H} + \alpha\boldsymbol{m}\times(\boldsymbol{m}\times\boldsymbol{H})\right), \quad \boldsymbol{H} = \boldsymbol{H}_{\text{eff}} + \boldsymbol{H}_{\text{therm}}(T)$$

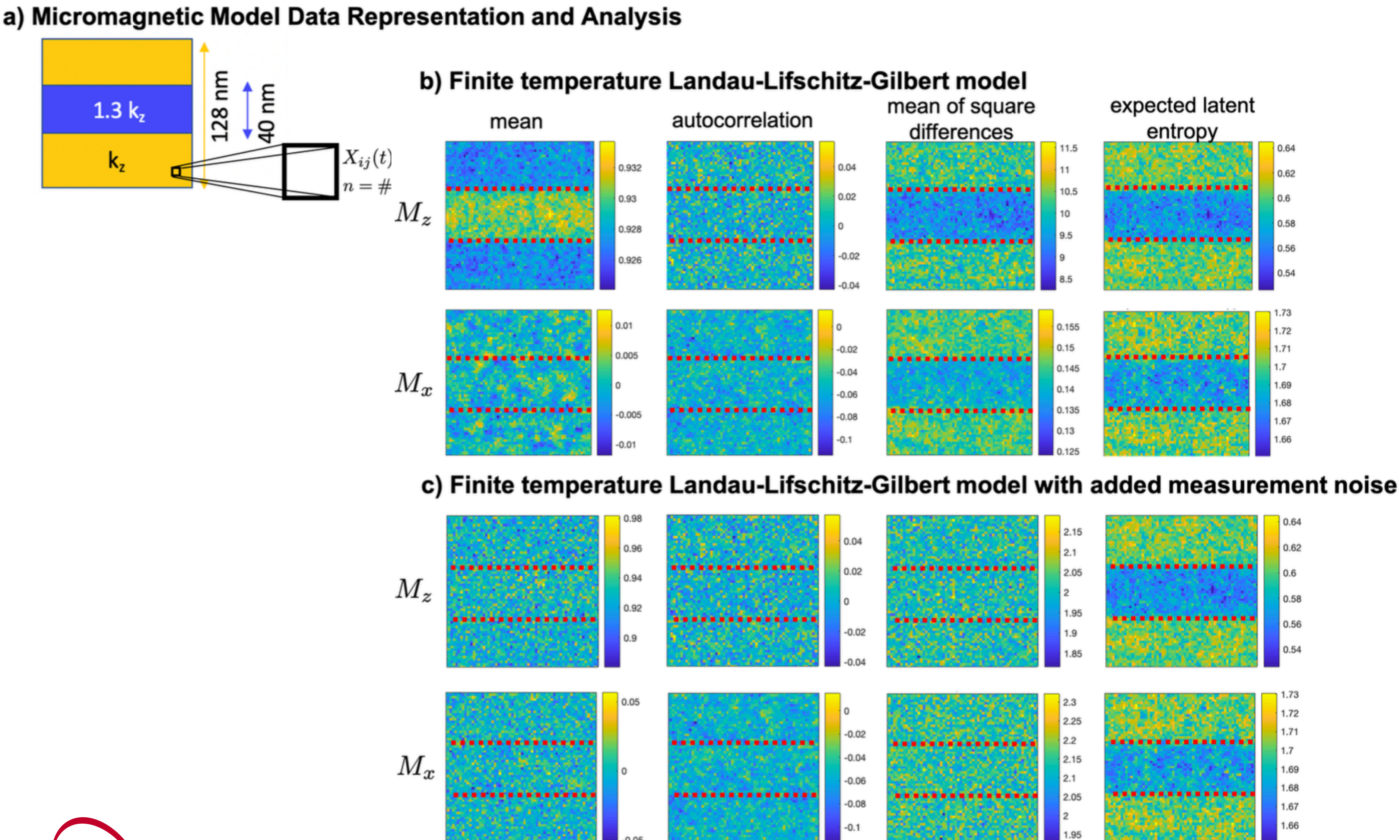
$$\langle \boldsymbol{H}_{\text{therm}} \rangle = 0$$

$$\langle \boldsymbol{H}_{\text{therm}\,i}(t)\boldsymbol{H}_{\text{therm}\,j}(t')\rangle = \frac{2k_B T\alpha}{M_S\gamma V}\delta(t-t')\delta_{ij}$$

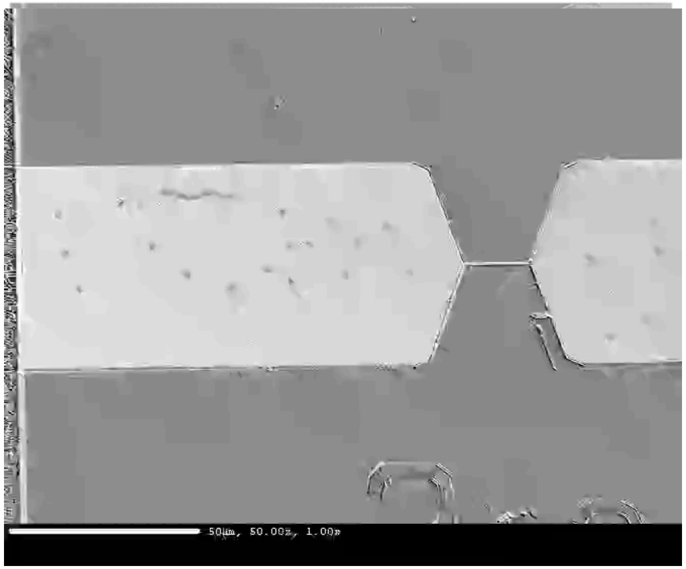
Horenko, et al., KES, arXiv1907.04601

TWIST

Topological Whirls In SpinTronics



(a) Magnetization measurements (MOKE)

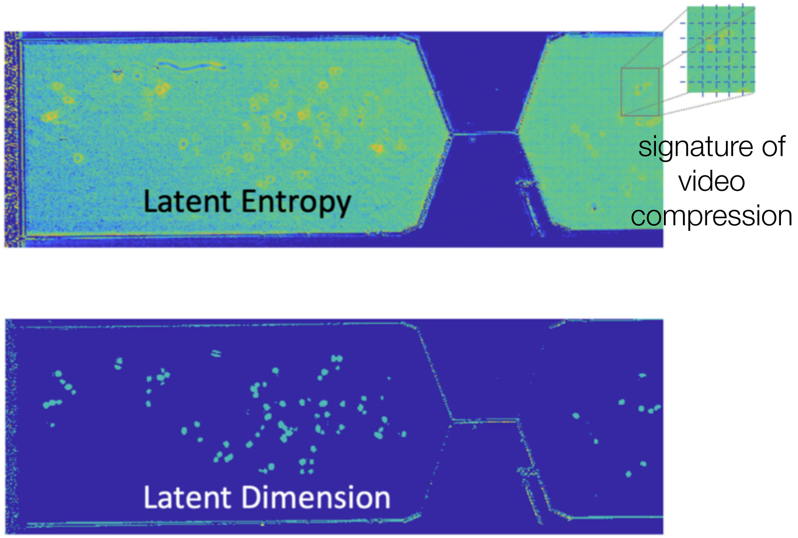


$Ta/Co_{20}Fe_{60}B_{20}/Ta/MgO/Ta$

Raw data from Zázvorka, ..., KES, et al., Kläui, Nature Nanotechnology 2019

Horenko, et al., KES, arXiv1907.04601

(a) Magnetization measurements



Raw data from Zázvorka, ..., KES, et al., Kläui, Nature Nanotechnology 2019

Horenko, et al., KES, arXiv1907.04601

Data analysis: New tools for “microscopy”?

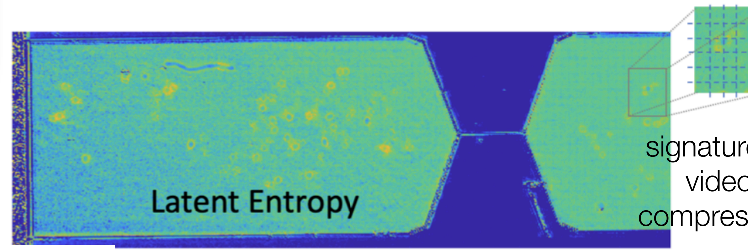
(a) Magnetization measurements

Two low cost tools for extraction of latent patterns

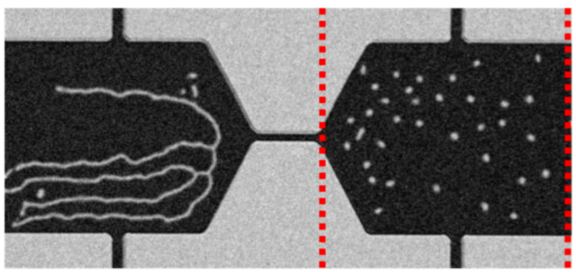
latent entropy: (predictability of the system)

latent dimension: (memory of the system)

(no i.i.d. assumption or Gaussianity)

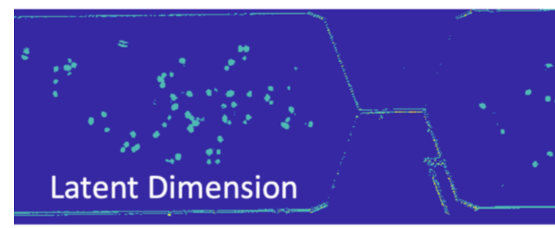


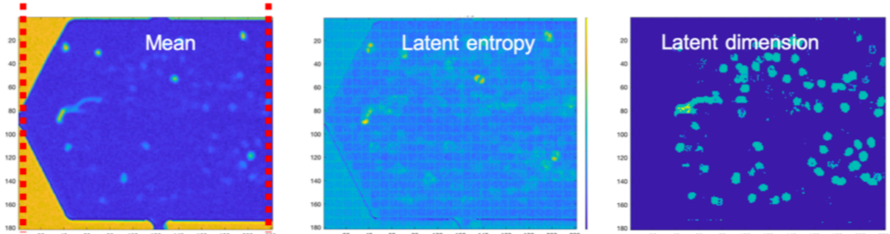
Ta(5 nm)/$Co_{20}Fe_{60}B_{20}$(CoFeB)(1.1 nm)/TaO_x(3 nm)



Raw data from

Jiang, et al., Science 2015





from Zázvorka, ..., KES, et al., Kläui,

Nature Nanotechnology 2019

Horenko, et al., KES, arXiv1907.04601

Data analysis: New tools for “microscopy”?

TWIST
Topological Whirls In SpinTronics

Two low cost tools for extraction of latent patterns

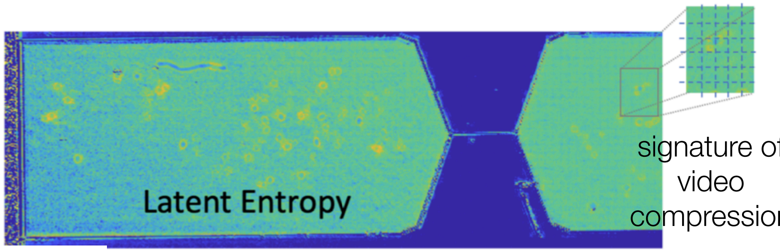
latent entropy: (predictability of the system)

latent dimension: (memory of the system)

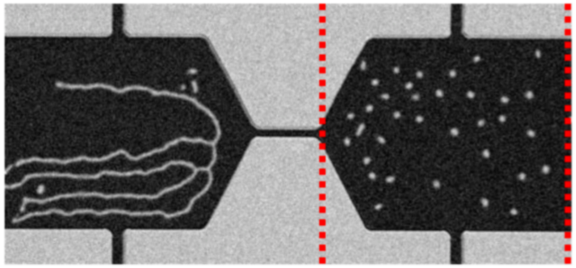
(no i.i.d. assumption or Gaussianity)

Outlook:
Strategic Categorization of magnetization data

S. Jenkins

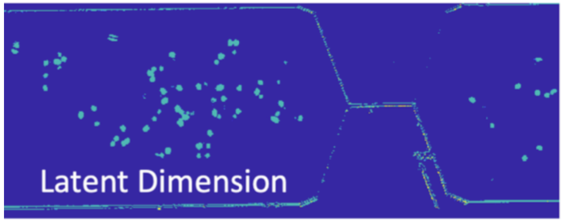


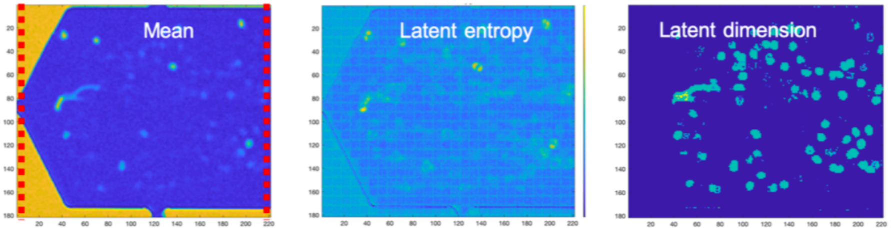
Ta(5 nm)/$Co_{20}Fe_{60}B_{20}$(CoFeB)(1.1 nm)/TaO_x(3 nm)



Raw data from

Jiang, et al., Science 2015





from Zázvorka, ..., KES, et al., Kläui, Nature Nanotechnology 2019

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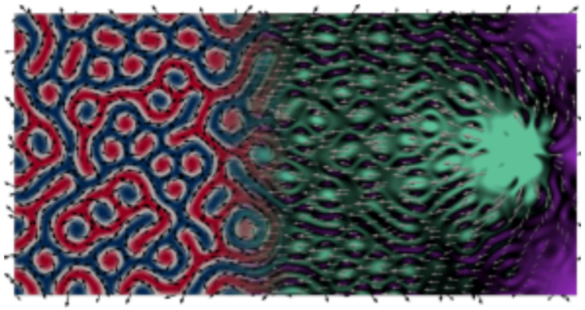
THANK YOU FOR YOUR ATTENTION

TWIST
Topological Whirls In SpinTronics

- Skyrmion reshuffler for stochastic computing — Zázvorka, ..., KES, et al., Kläui, Nat. Nano. (2019)
- Skyrmions for reservoir computing



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George Bourianoff

- Data analysis: New tools for "microscopy"?

Illia Horenko
(Head of the Computational Time Series Group, USI Lugano)

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