Computer Simulation of Skyrmion Dynamics and Its Device Applications

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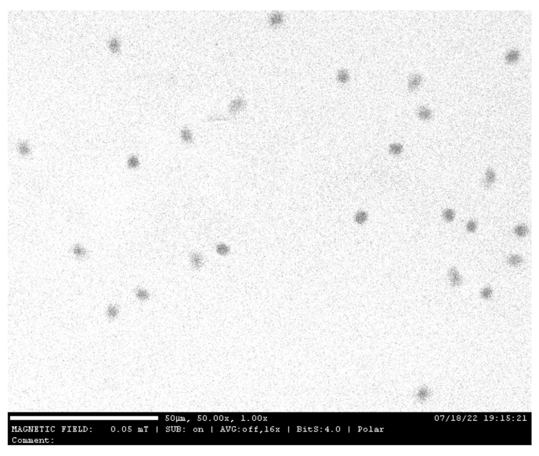
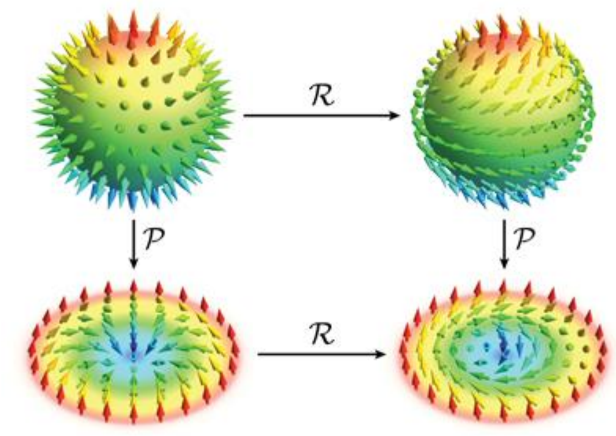
Introduction

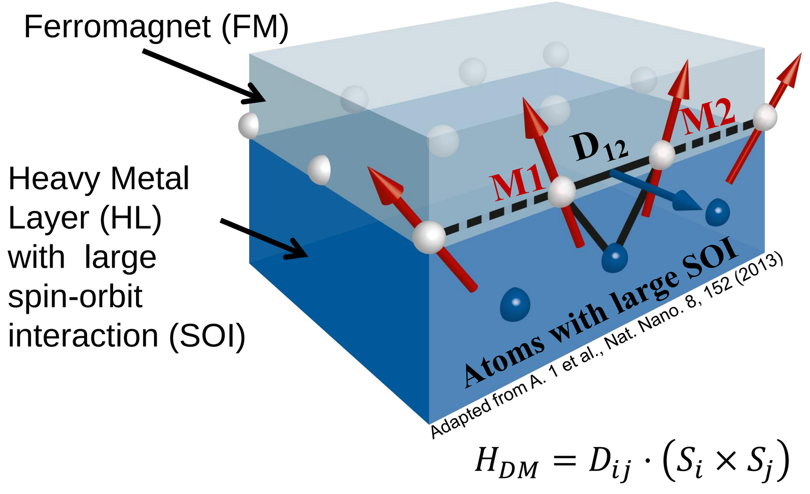
- Magnetic skyrmions are nanometer to micrometer scale magnetic textures with particle-like properties [1-5].
  - High stability due to spin structure topology being distinct from that of a uniformly magnetized state.
  - Can be imaged using magneto-optical Kerr-effect microscopy (MOKE).
  - Energy efficient current-induced motion makes them interesting for memory and logic devices [6-9].
  - Repelled by magnetic material boundaries, thus confineable [10, M1].
  - Exhibit thermally-activated dynamics at room-temperature [11].



Magneto-optical Kerr-microscopy image of several skyrmions [M2]



Two configurations of skyrmions – Neél (left) and Bloch (right). [9]

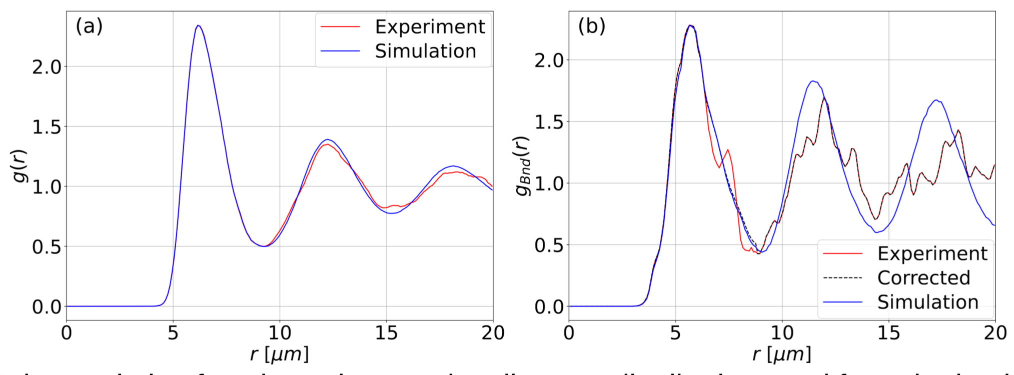


Material structure suitable for stabilizing skyrmions [1].

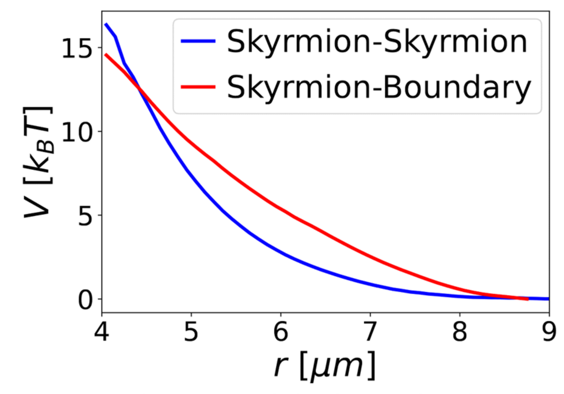
Predictive Modeling of Skyrmion Dynamics

Simulating Skyrmion Dynamics

- Conventional simulation methods like atomistic and micromagnetic simulations are usually computationally too expensive on experimental microscale systems.
- Use coarse grained Thiele model with equation of motion $-\gamma \boldsymbol{v} - G\boldsymbol{z} \times \boldsymbol{v} = \boldsymbol{F}_{SkSk} + \boldsymbol{F}_{SkBd} + \boldsymbol{F}_{thermal}$
- Determine Skyrmion-Skyrmion and Skyrmion-Boundary interactions using the Iterative Boltzmann Inversion (IBI) method established in computational soft-matter physics [M3].



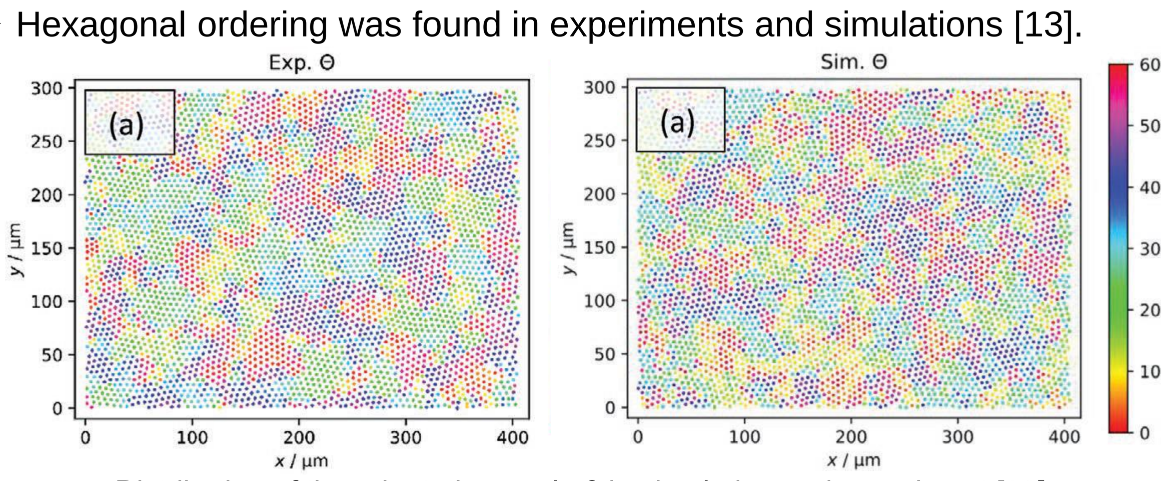
Pair correlation functions characterize distance distributions and form the basis of the IBI method [M3].



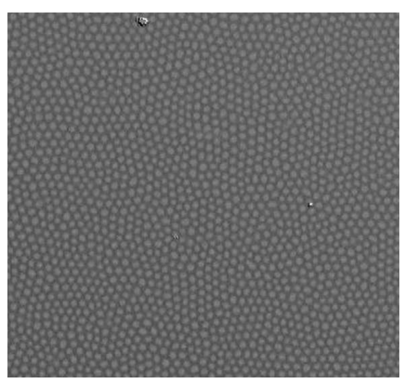
Interaction potentials determined using the IBI method [M3].

Application to hexatic phases in skyrmion lattices:

- Skyrmion systems in thin films are in excellent approximation two-dimensional.
- Two dimensional systems may have an additional phase in between liquid and solid, called hexatic phase, characterizable by the local orientation angle θ [12].
- Hexagonal ordering was found in experiments and simulations [13].



Distribution of the orientation angle θ in simulation and experiment [13].



MOKE picture of skyrmion lattice with μm skyrmions [13].

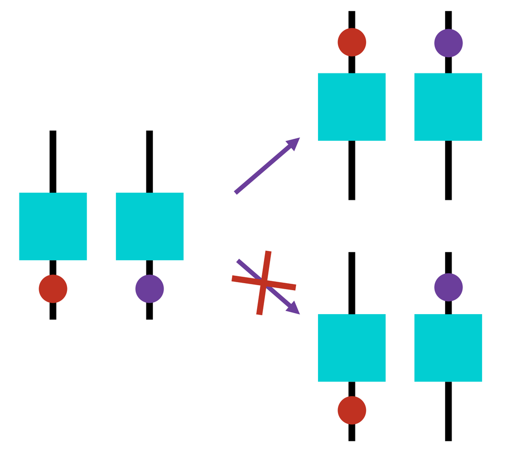
Brownian Token-based Computing using Skyrmions

Exploiting Thermal Fluctuations for Computing

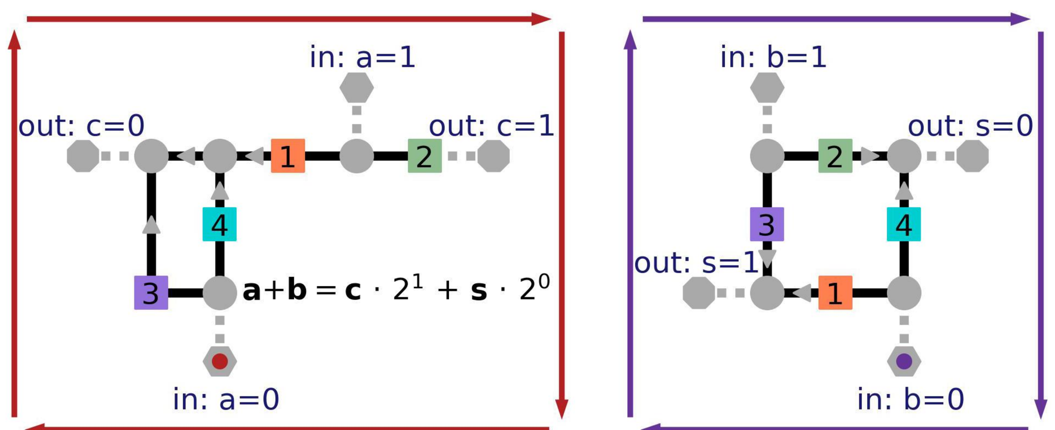
- In Brownian computing, thermal energy from the surrounding is exploited for energy-efficient computation.
- A Brownian token-based computer performs computations as the signal carriers (tokens) find a path trough the circuit network.
- The price to pay for low-energy computation is a non-deterministic computation duration. This can be mitigated using acceleration methods such as induced [M4,M5] or enhanced [M2,M5] diffusion.

Input: a	Input: b	Output: Carry (2^1)	Output: Sum (2^0)
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	0

Input-output table of a half-adder composite module adding two bits.



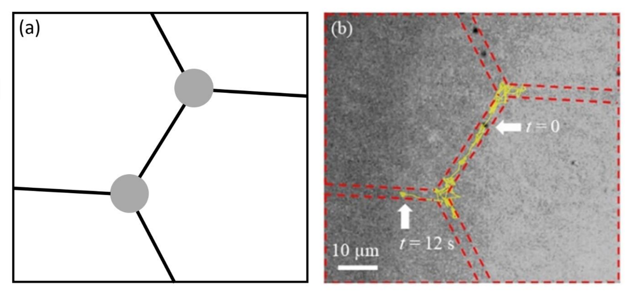
Tokens can only pass a Cjoin module in pairs.

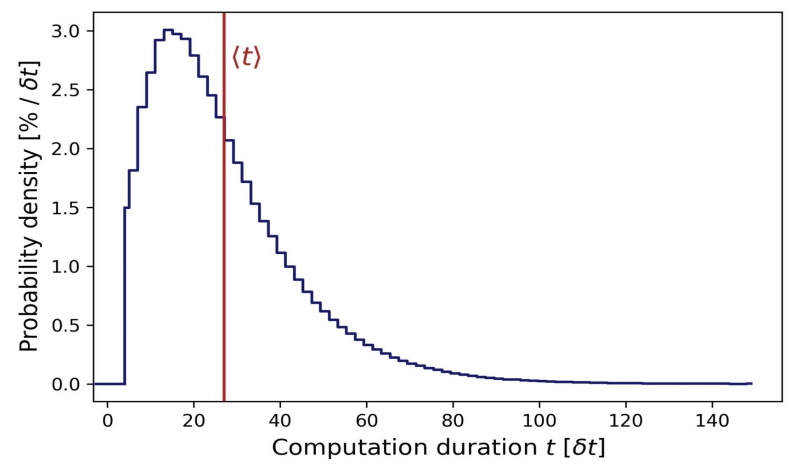


Crossing-free skyrmion-suitable half-adder circuit [M4].

Circuit (Method)	Condition	L = 10 μm	L = 5 μm
Crossing (thermal)	T = 307.6 K	16 min	4 min
Cross.-free (thermal)	T = 307.6 K	4 min	1 min
Cross.-free (induced)	$\langle v \rangle \approx 22$ m/s	38.9 μs	19.4 μs

Schematic (a) and experimental implementation (b) of a basic skyrmion pathway [14].



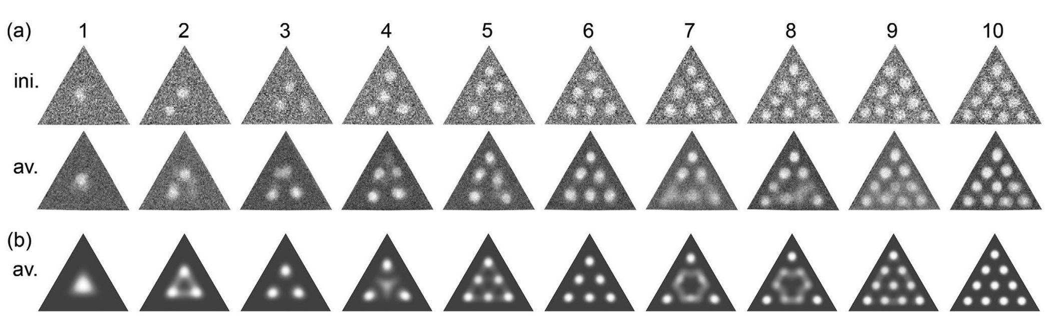


Distribution function of the non-deterministic computation time for the half-adder [M4].

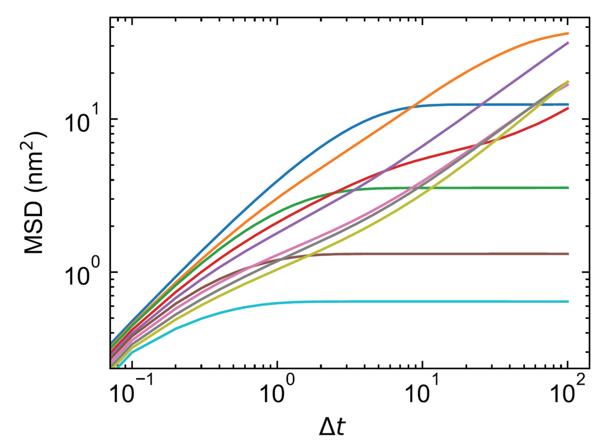
Brownian Reservoir Computing using Confined Skyrmions

Dynamics of Confined Skyrmions

- Reservoir computing requires complex non-linear dynamics of the reservoir system.
- Study skyrmions in confinement as potential reservoir [M1].
- Analyze the mean squared displacement $MSD(\Delta t) = \left\langle \left(\vec{r}(t+\Delta t) - \vec{r}(t) \right)^2 \right\rangle_t$ of the skyrmions.
- MSD behavior indicates simple or complex dynamics as (non-)existence of an early plateau [M1].

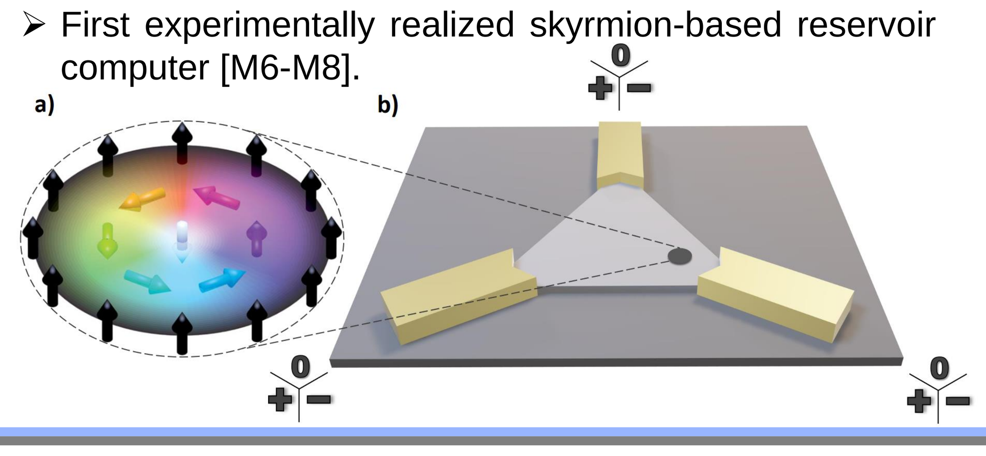


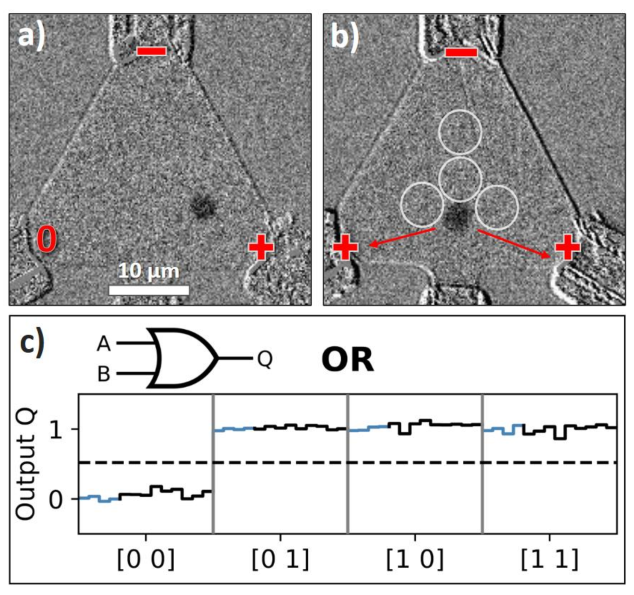
(a) Experimental images of different numbers of skyrmions in a 26.8 μm triangle, the top row shows the initial state, the center row shows an average image over 10 minutes. (b) Corresponding simulation results [M1].



Brownian Reservoir Computing

- Overlay complex thermal dynamics in confinement with current-driven motion: Brownian Reservoir Computing.
- First experimentally realized skyrmion-based reservoir computer [M6-M8].

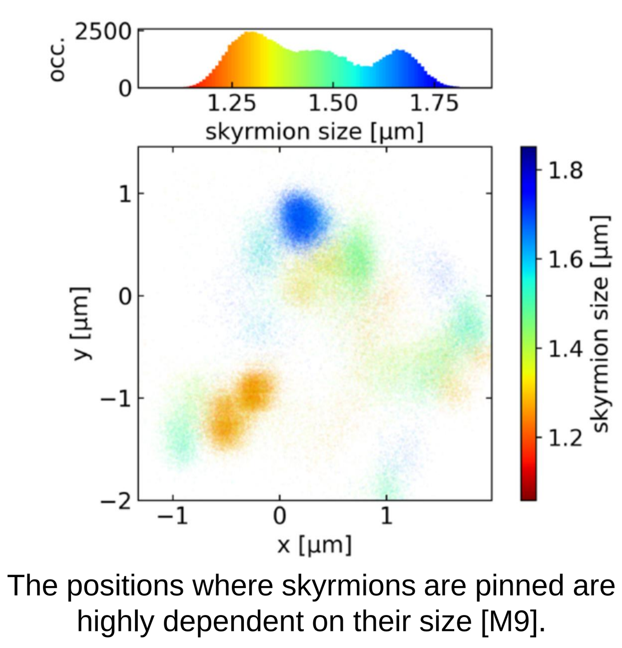




Understanding Skyrmion Pinning for Tunable Diffusion

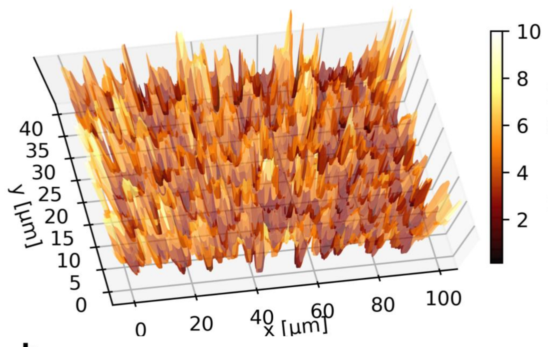
Size-Dependence of the Skyrmion Pinning-Effect

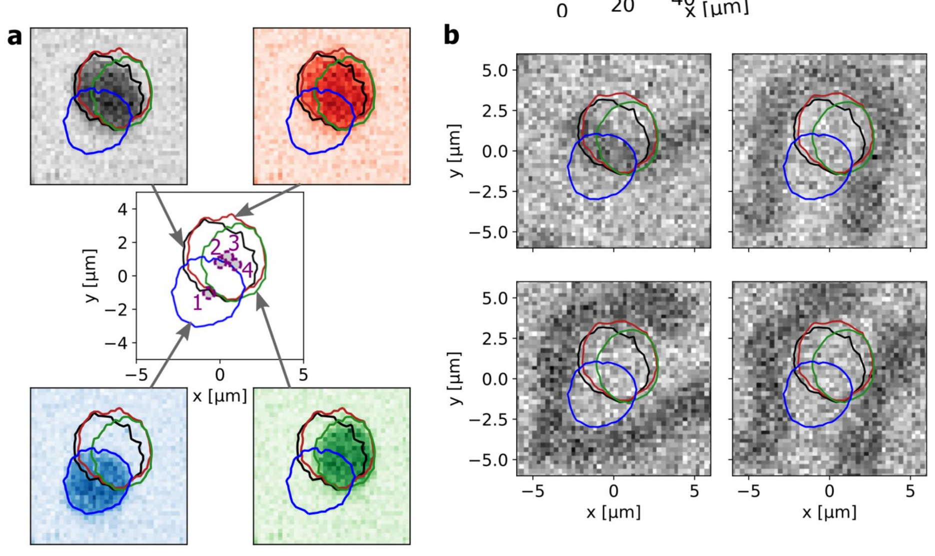
- In real materials, skyrmions tend to dwell at certain spots.
- These "pinning sites" impact thermal diffusion and are thus of high significance for Brownian computing.
- By changing the out-of-plane magnetic field, the skyrmion size can be varied, revealing size-dependent pinning.
- Manipulate pinning to increase diffusion [M2].



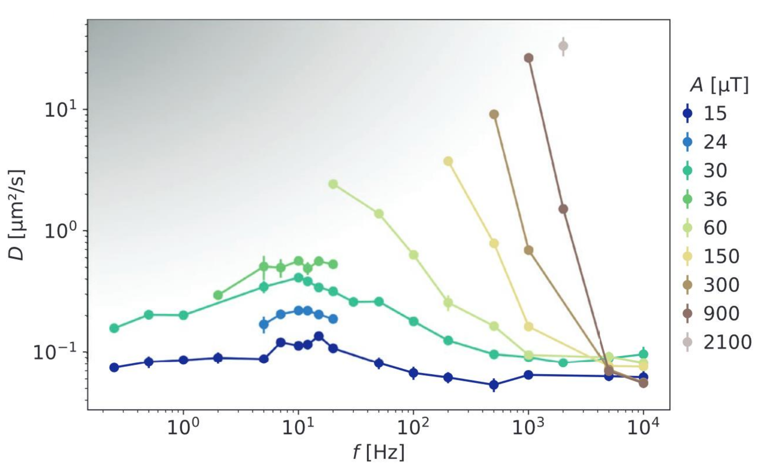
The positions where skyrmions are pinned are highly dependent on their size [M9].

Roughness of the effective energy landscape due to pinning effects [M9].





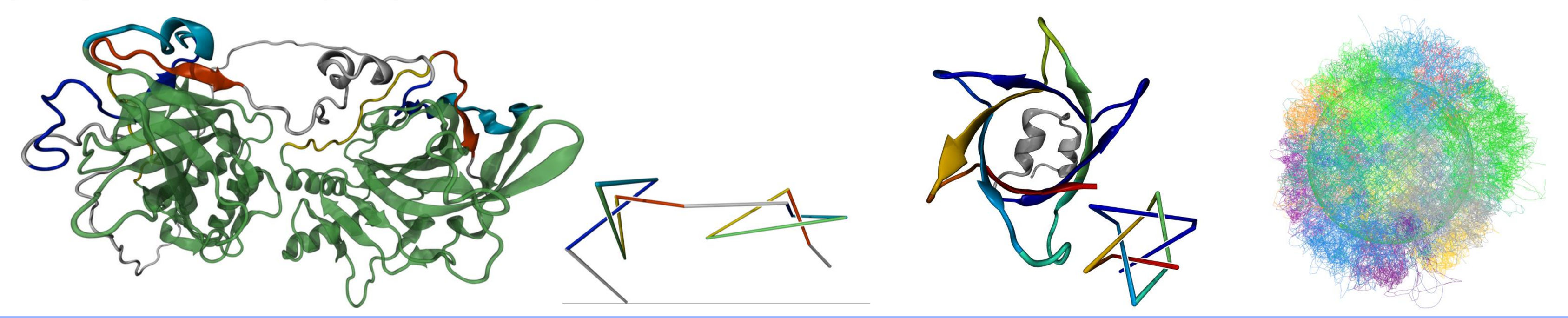
Domain walls (boundaries) of pinned skyrmions (a) and pinned stripe domains (b) indicating that the skyrmion is actually pinned at its domain wall and not its core [M9].



By exploiting the size dependence of the pinning-effect using an oscillating out-of-plane magnetic field, effective pinning can be drastically reduced. As a consequence, the diffusion speed can be enhanced/tuned [M2], which is particularly valuable for Brownian computing.

Topology in Biomolecules

The importance of topology extends beyond magnetism to systems like biomolecules including proteins [M10] and chromatin [M11] as a test for predicted structures from simulations and artificial intelligence.



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