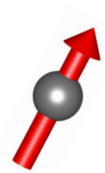
Exotic spin states

spin glass and spin liquid,
quantum fluctuations

muon spin relaxation (μSR)

skyrmions

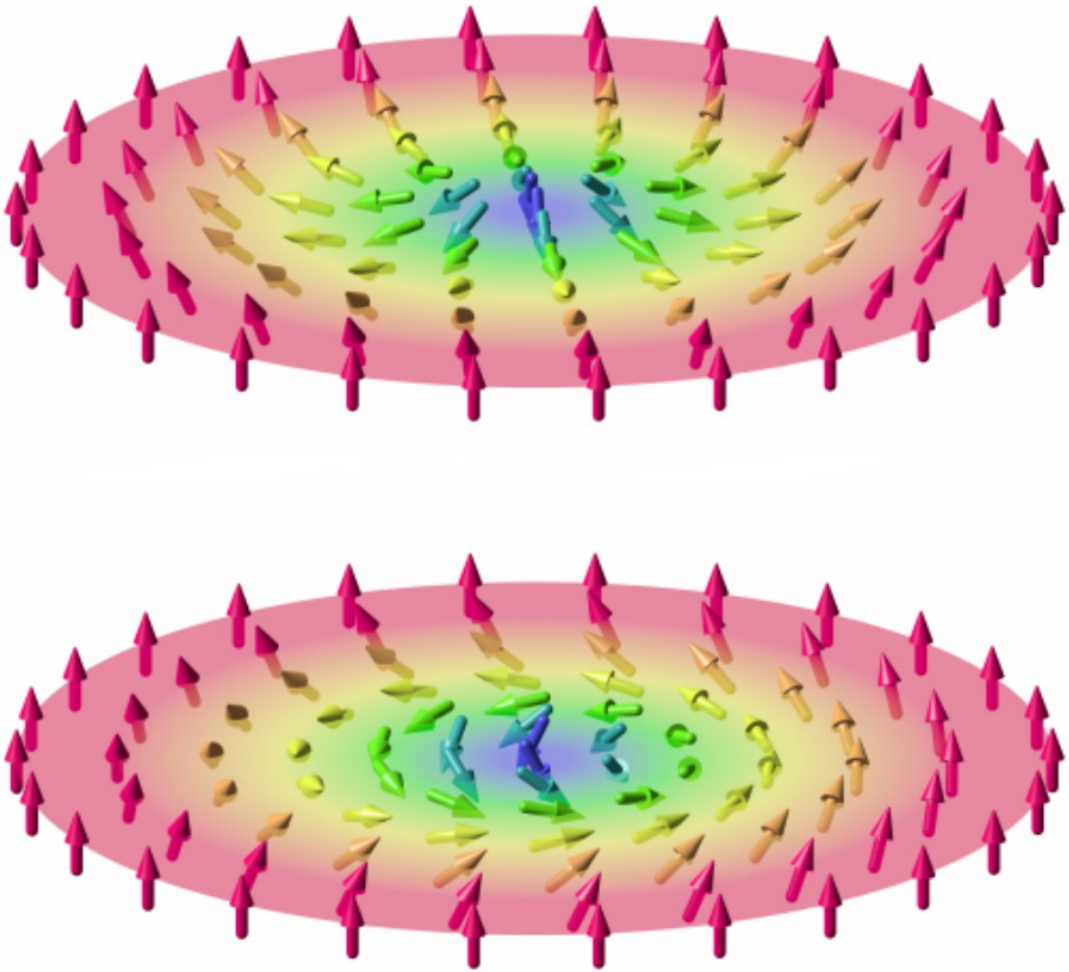


by Alexander Tsirlin, Leipzig University

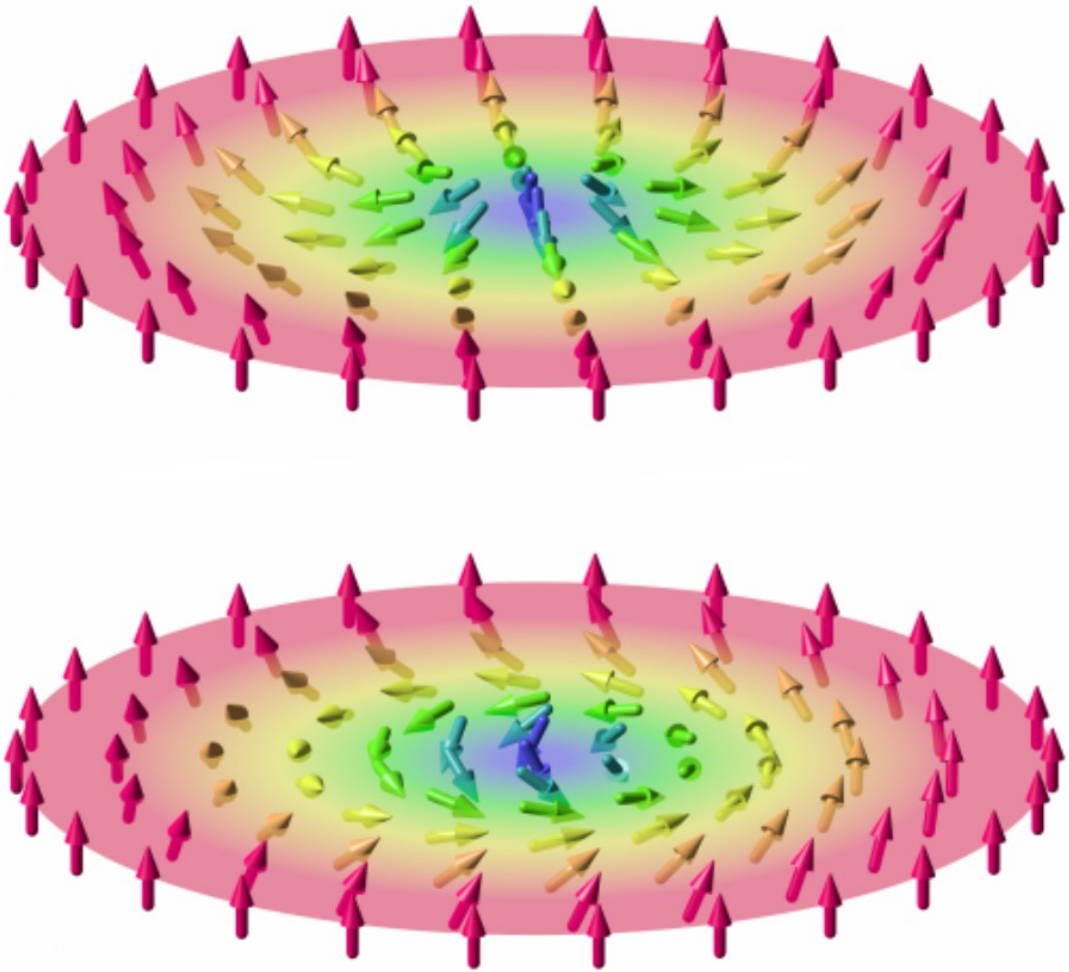
Lecture 11: January 27, 2025

Material / Technology

skyrmions

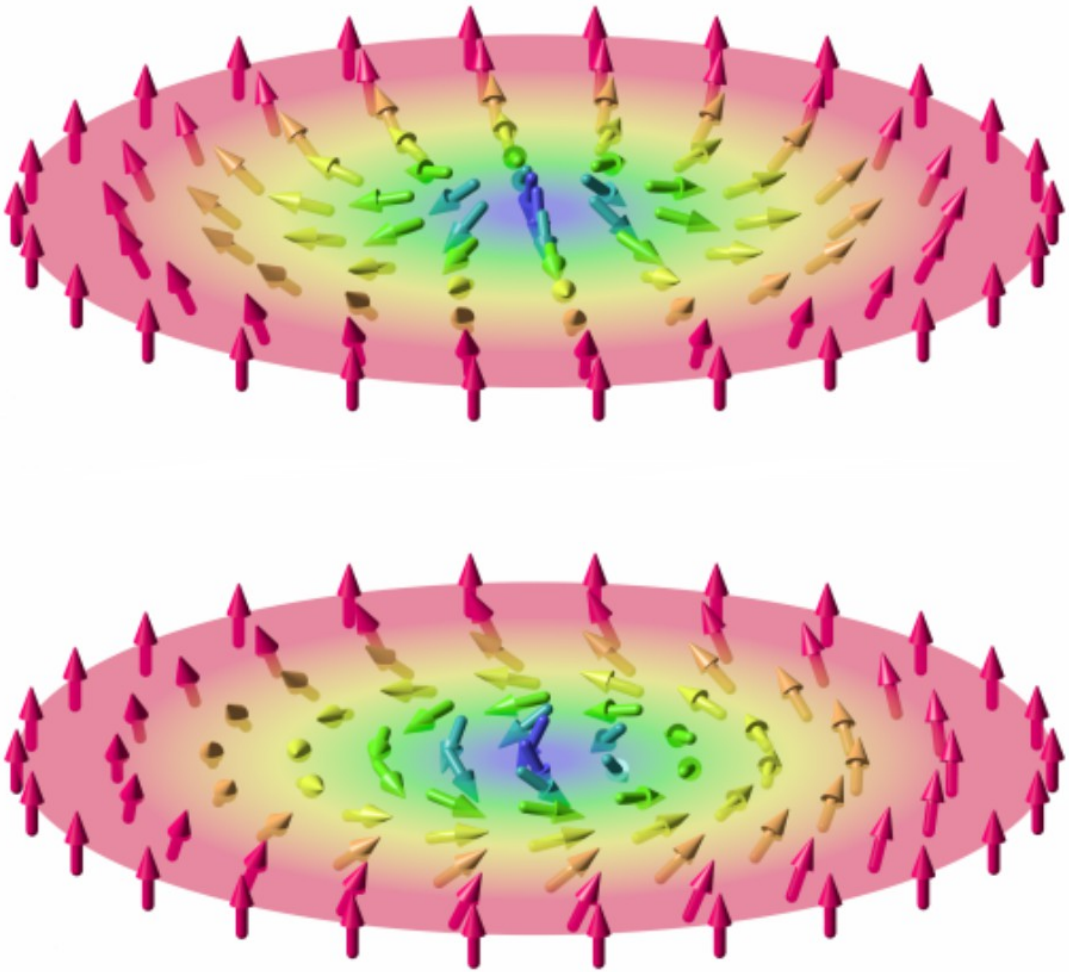


1961: Tony Skyrme model of nucleon, pion field



1961: Tony Skyrme model of nucleon, pion field

1989: Alexey Bogdanov skyrmions as topological defects in ferromagnets



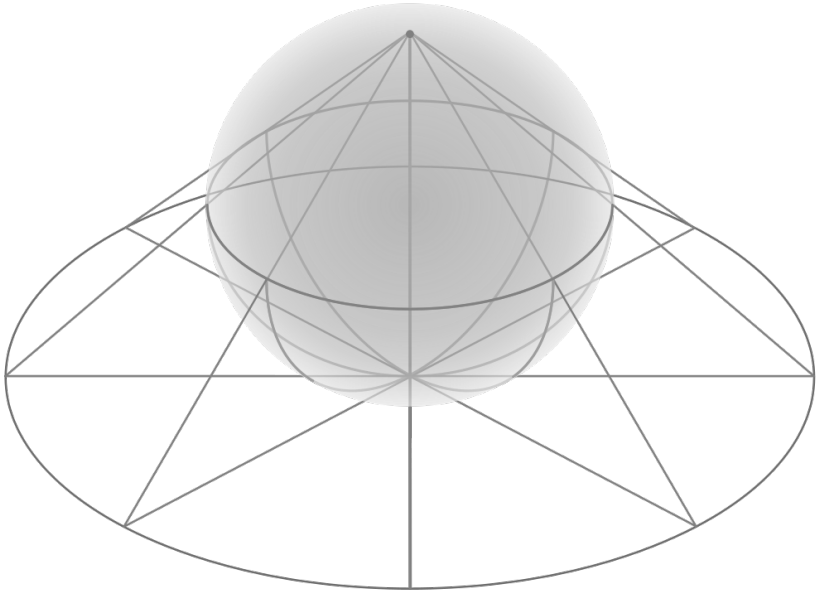
1961: Tony Skyrme model of nucleon, pion field

1989: Alexey Bogdanov skyrmions as topological defects in ferromagnets

2009: experimental observation in MnSi

from 2010: mainstream in solid-state research

Skyrmion as hedgehog



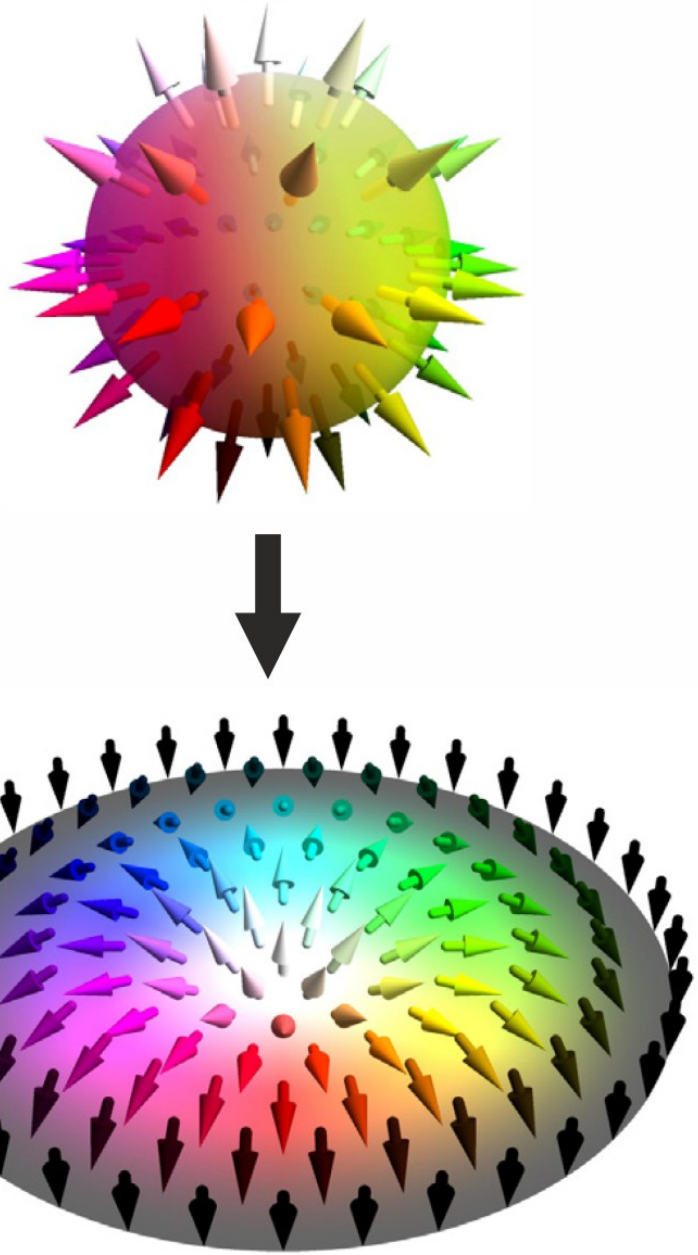
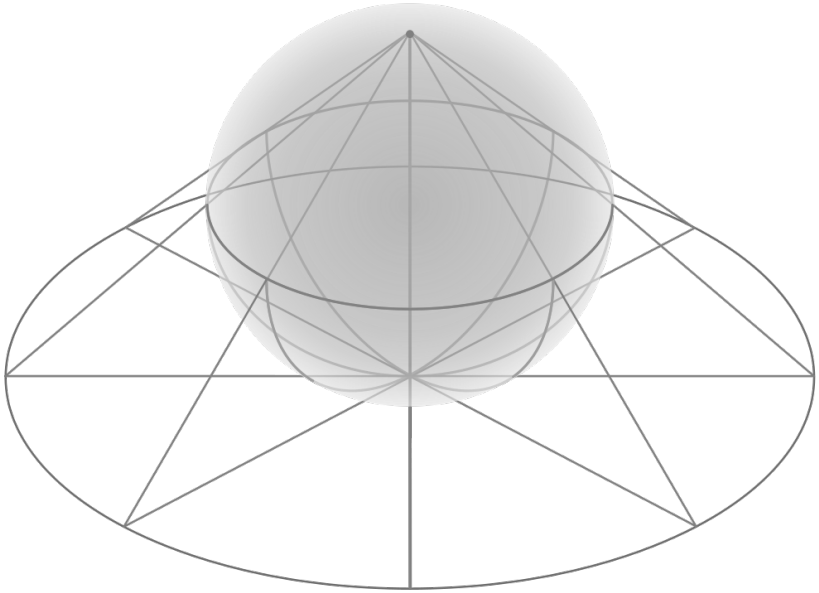
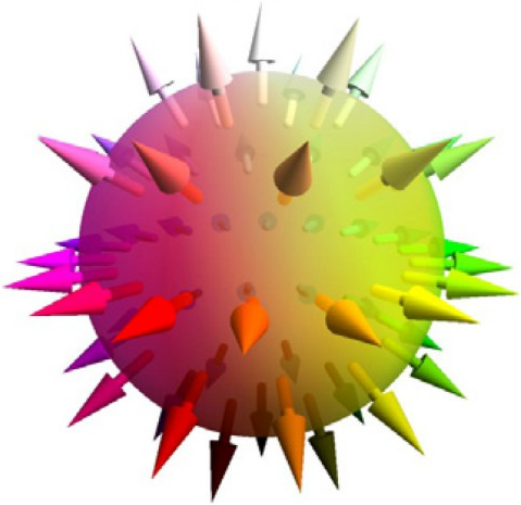


Image credits: Mark.Howison and V-wolf (CC-BY-SA); Physics Reports 895, 1 (2021)

Skyrmion as hedgehog





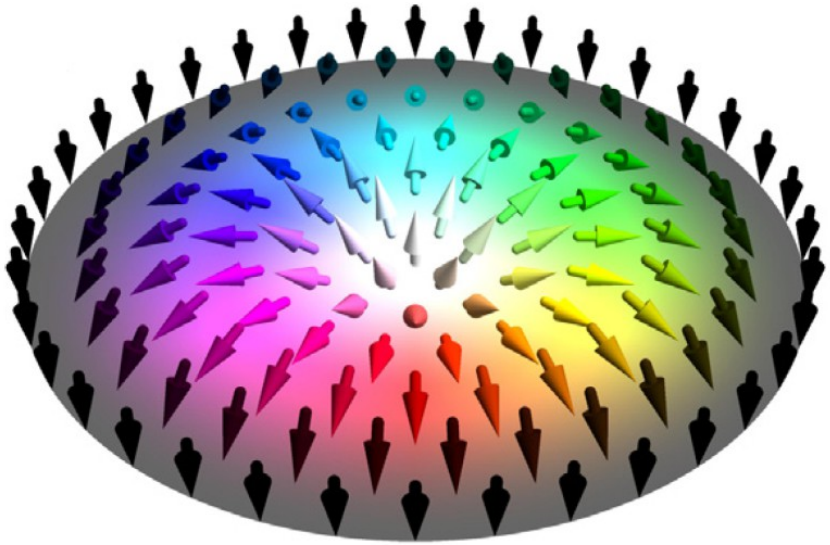
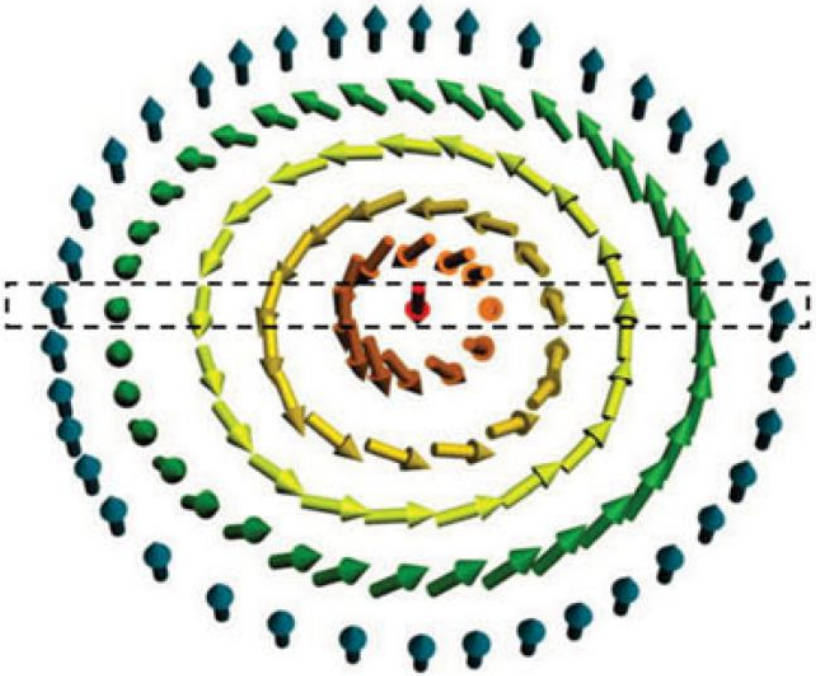
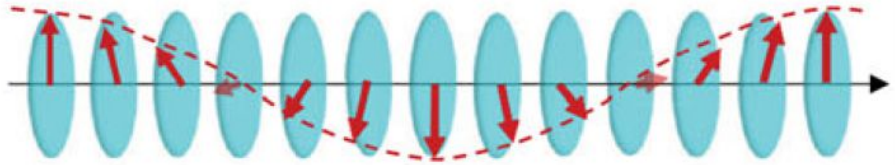


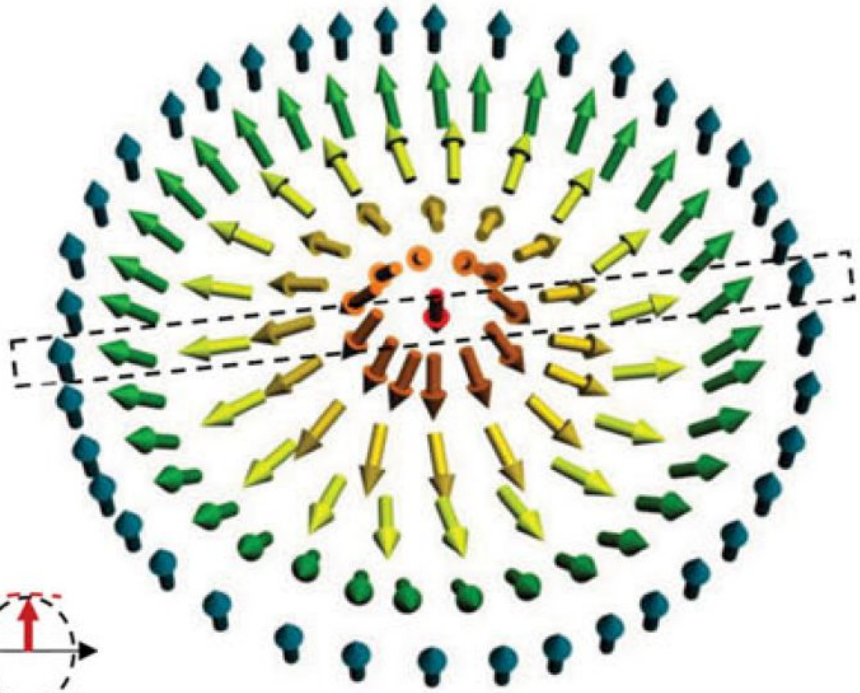
Image credits: Mark.Howison and V-wolf (CC-BY-SA); Physics Reports 895, 1 (2021)

Bloch vs. Néel





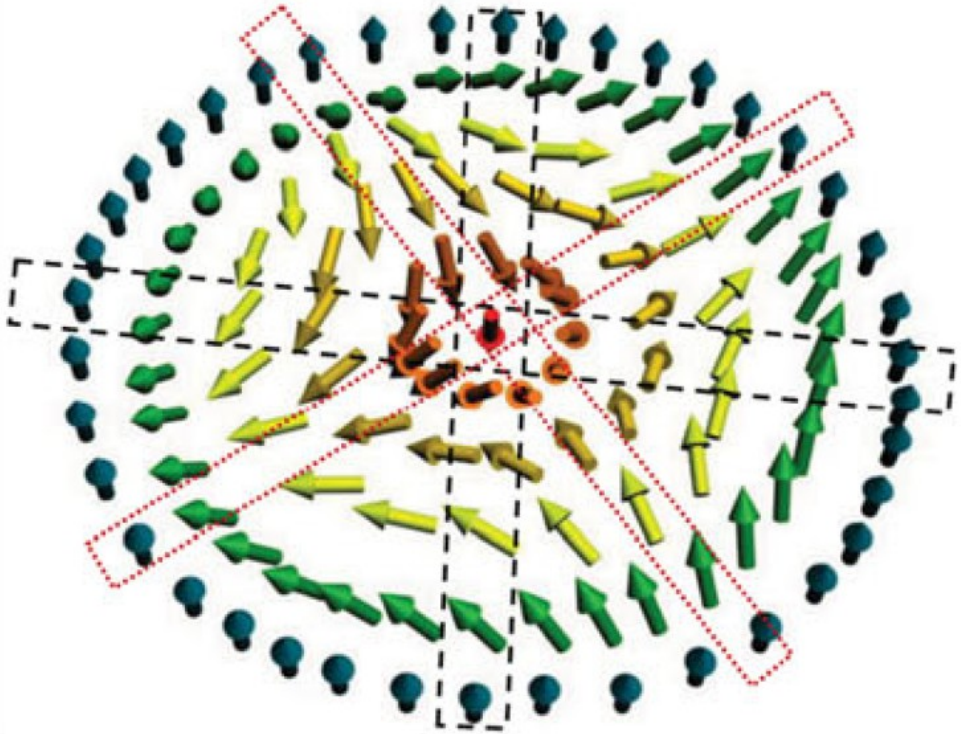
Bloch skyrmion

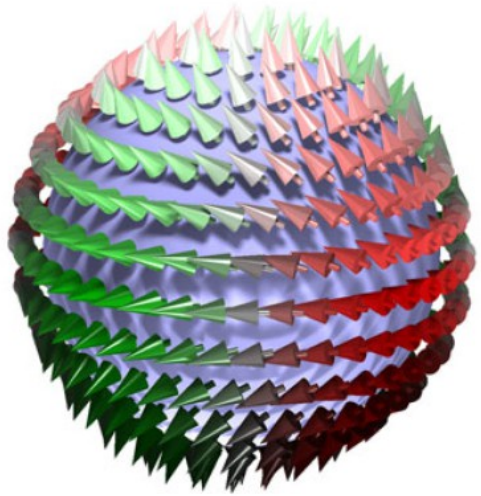


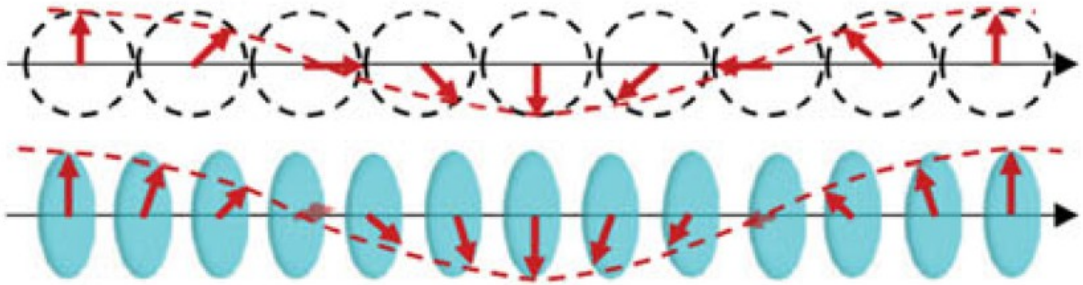
Néel skyrmion

Contemp. Phys. 60, 246 (2019)

Antiskyrmion

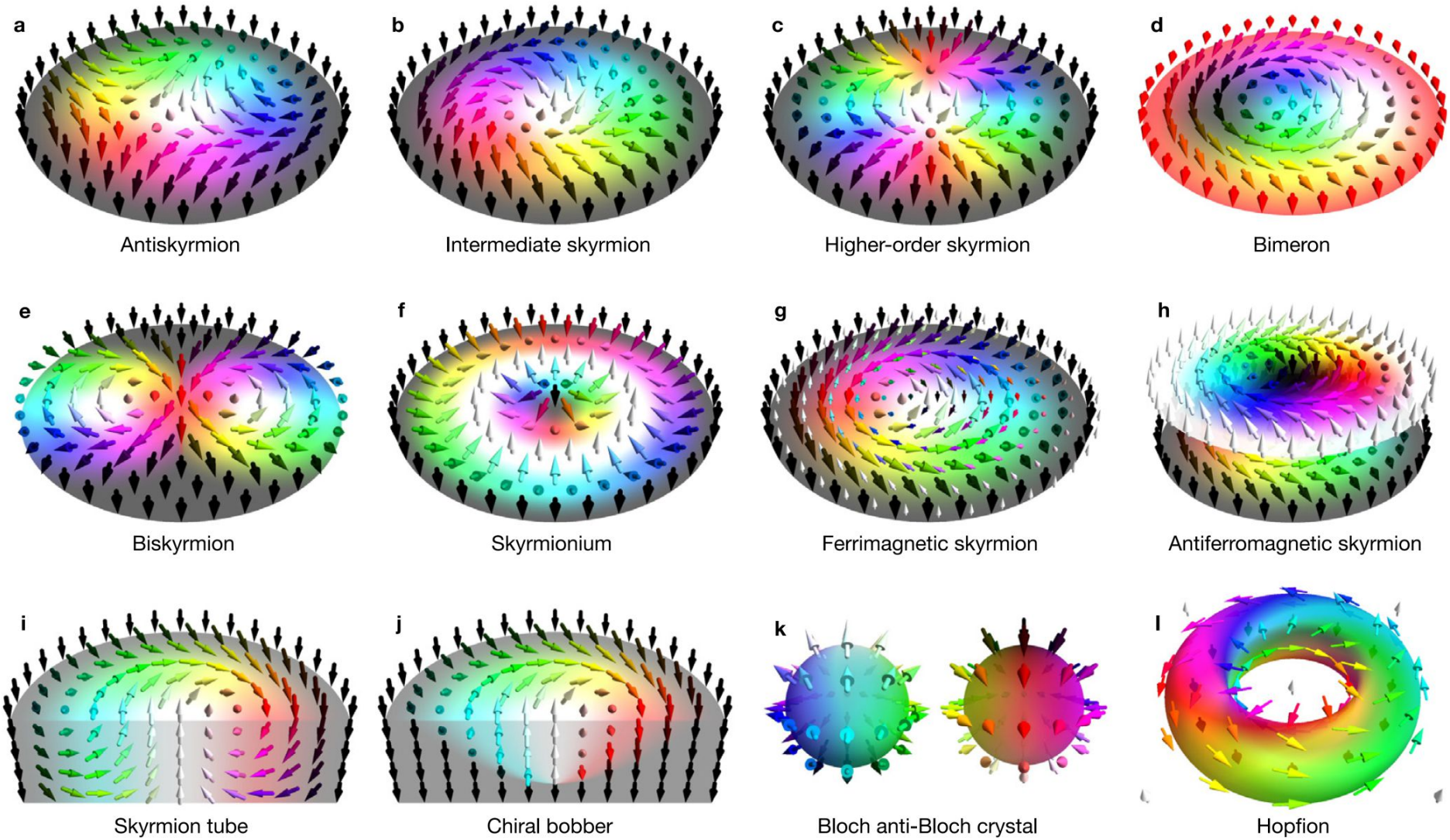






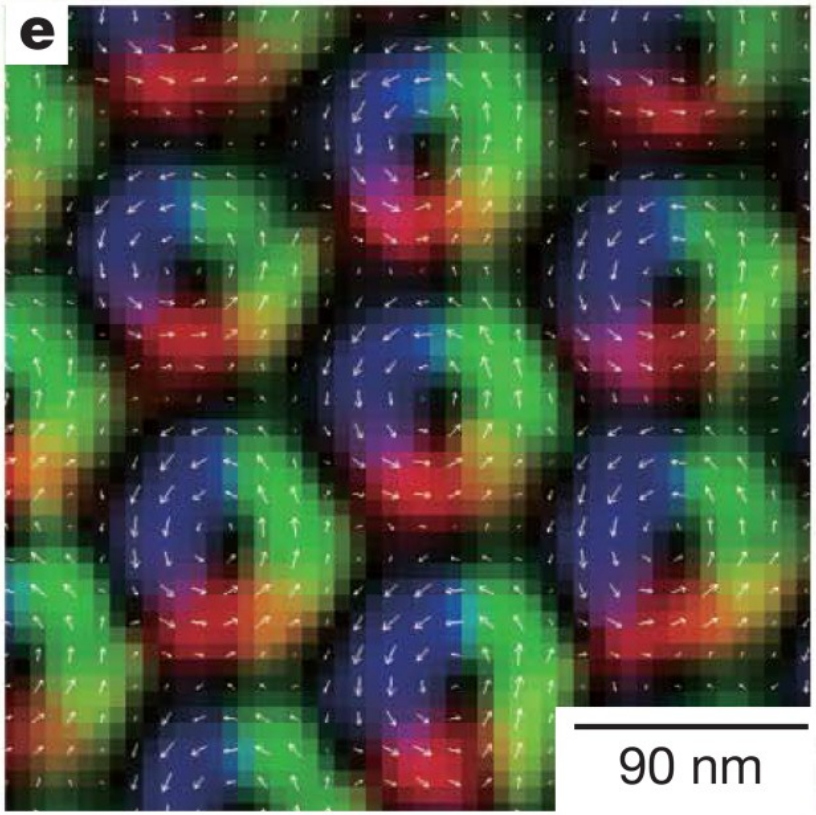
Contemp. Phys. 60, 246 (2019); Nature Comm. 8, 308 (2017)

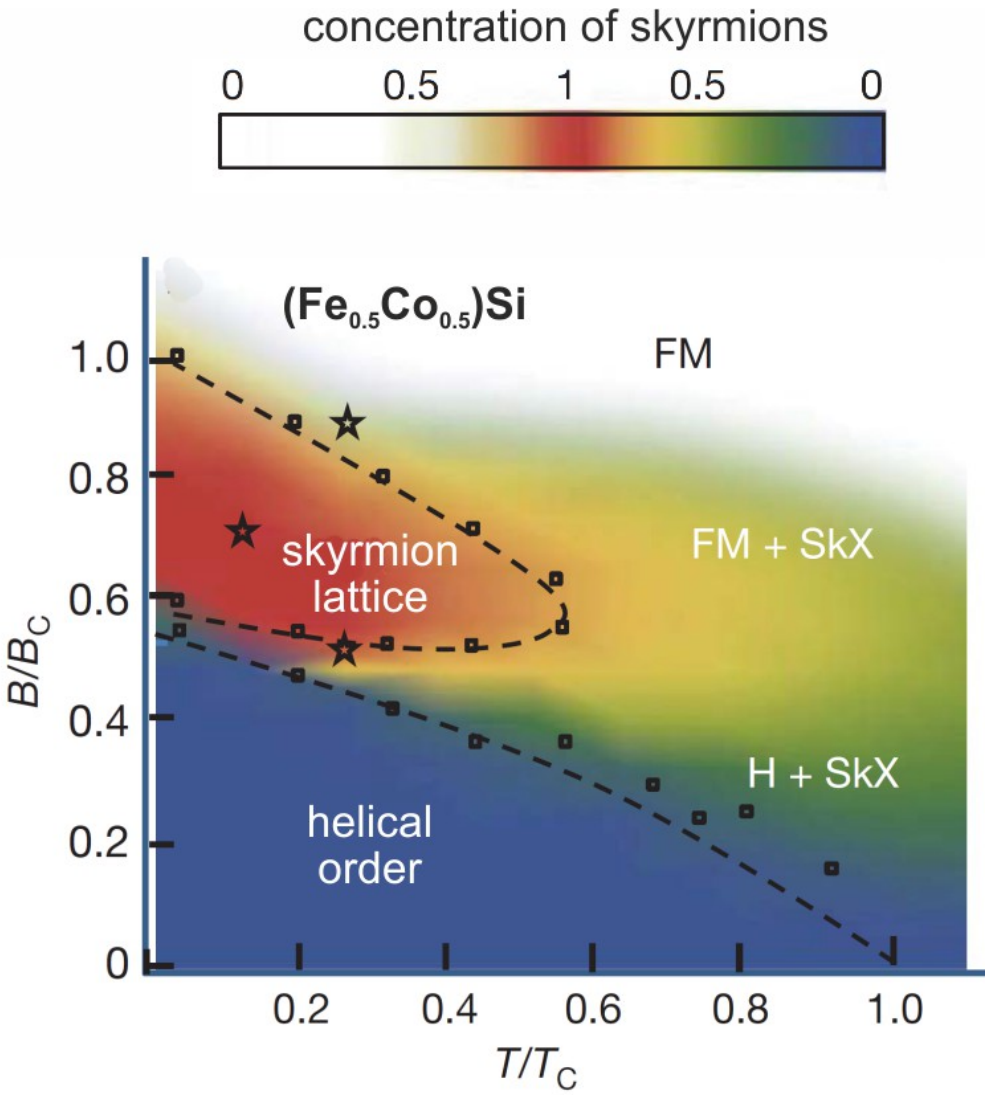
Variety of spin textures



Physics Reports 895, 1 (2021)

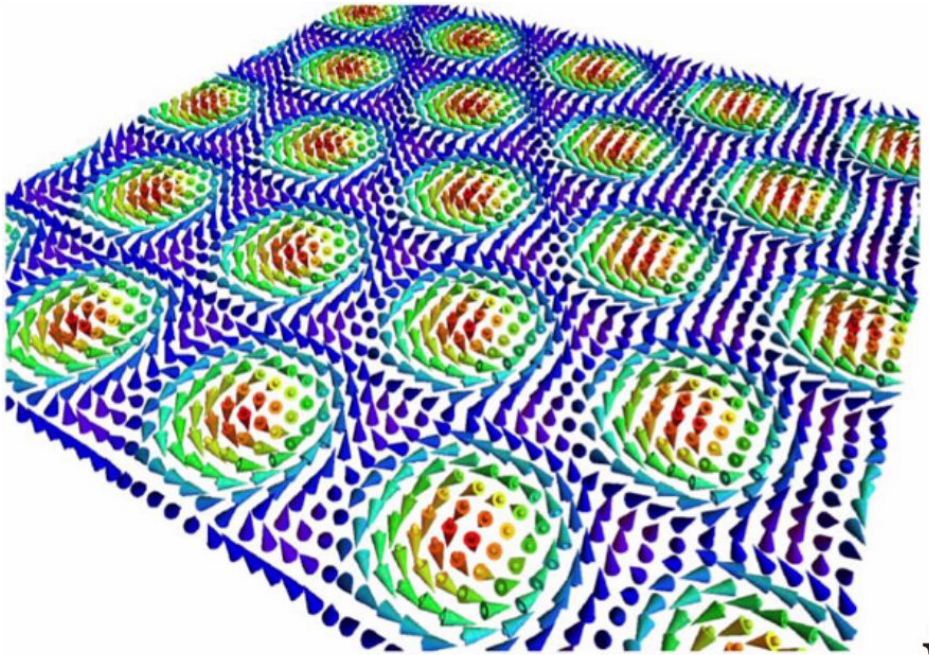
Visualization of skyrmions: Lorentz TEM



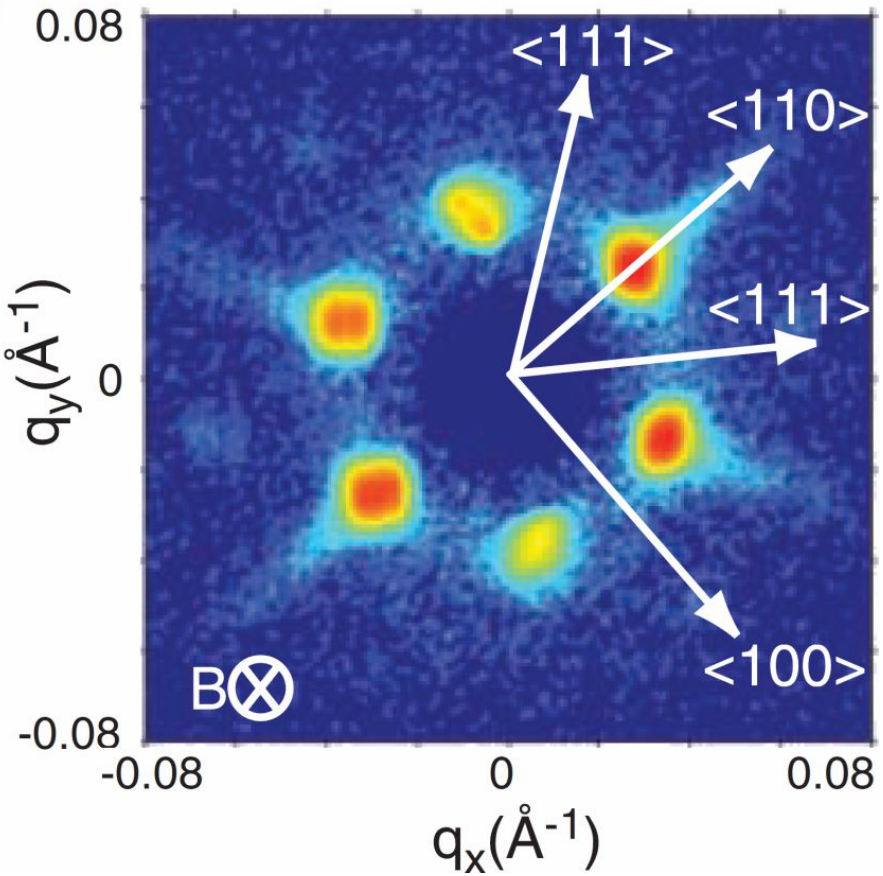


Nature 465, 901 (2010)

Visualization of skyrmions: SANS



SANS = small-angle neutron scattering



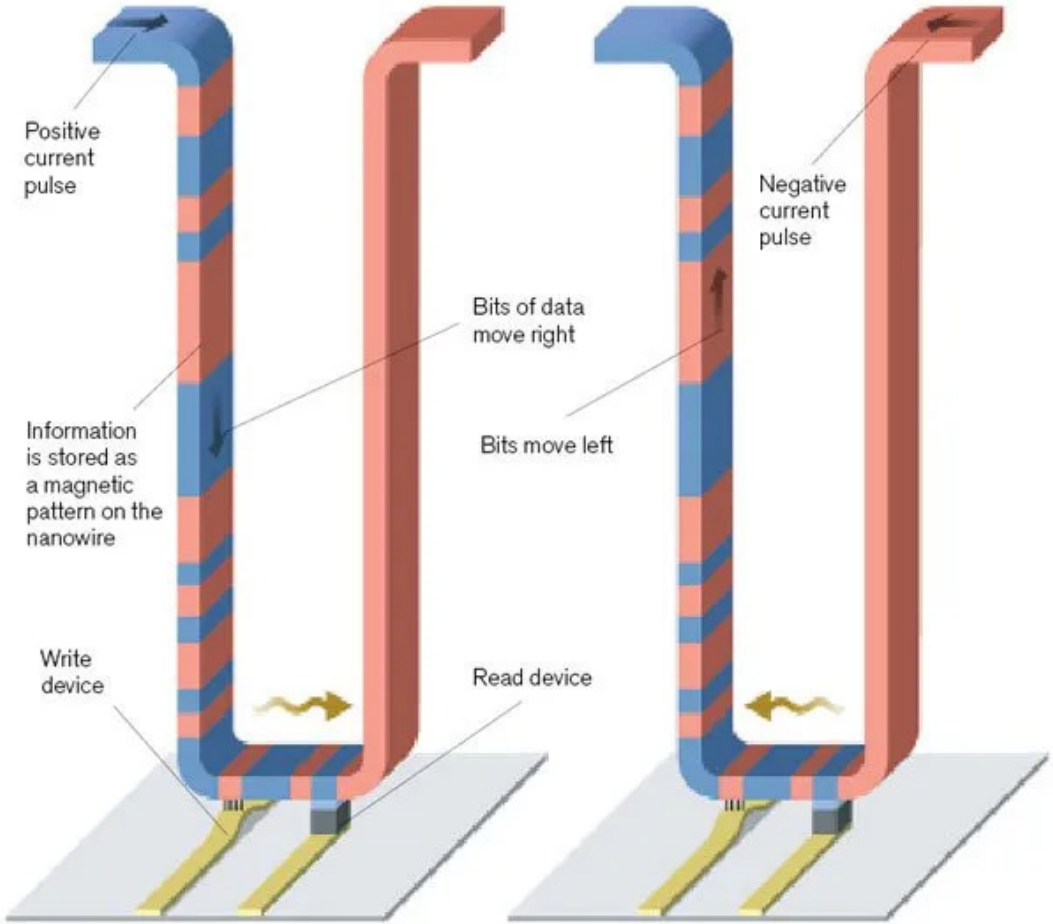
Periodicity: 10 – 100 nm

(cf. vortex lattice in superconductors)

Science 323, 915 (2009) and Yoichi Nii (phys.org)

Racetrack memory

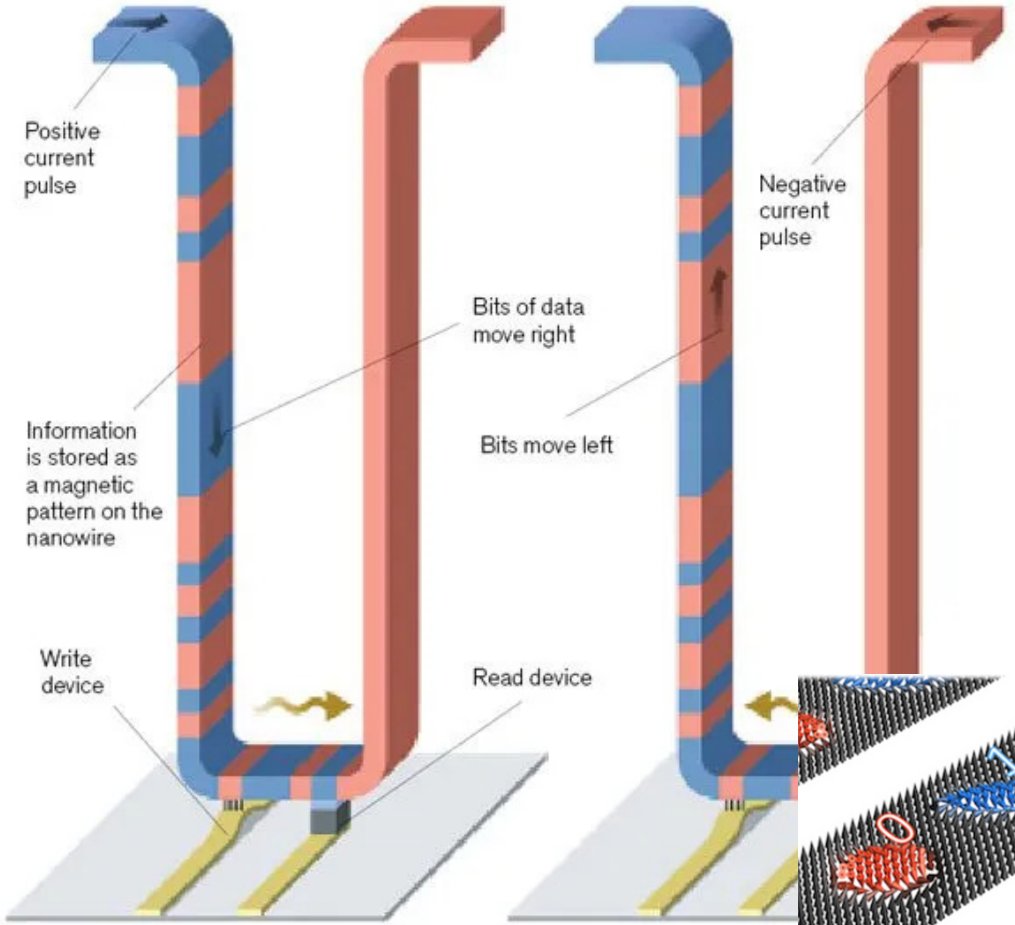
Image credit: MIT Technology Review



High memory density and no moving parts

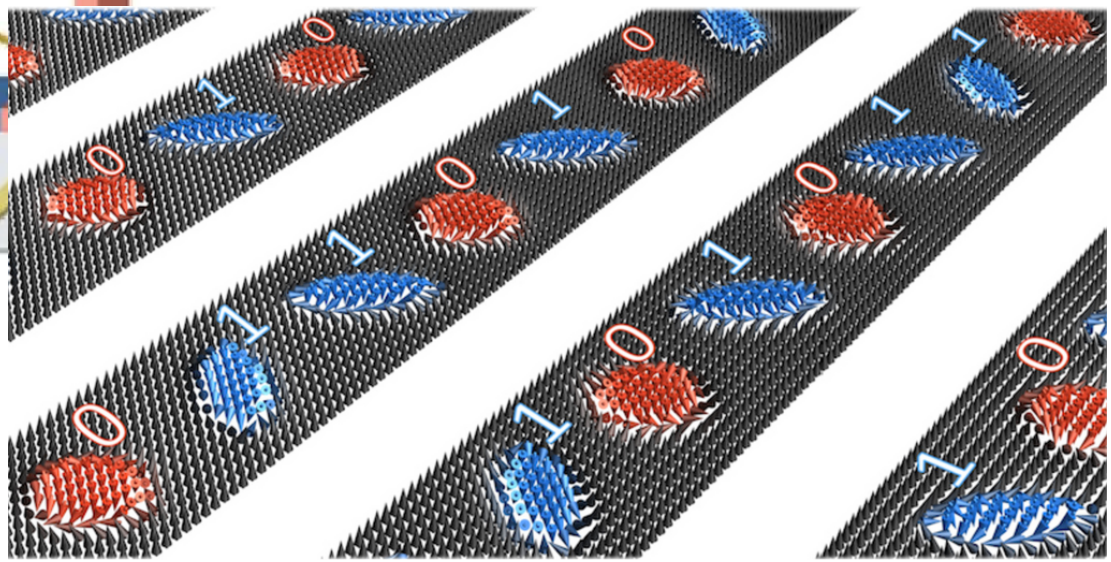
Racetrack memory

Image credit: MIT Technology Review and Physics Reports 895, 1 (2021)

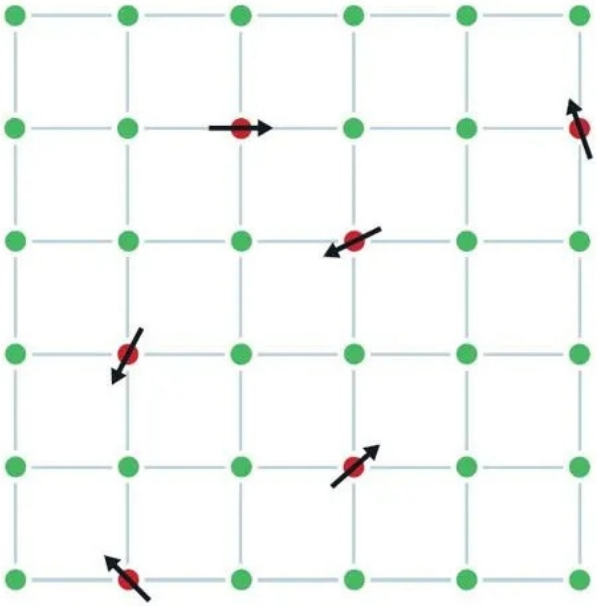


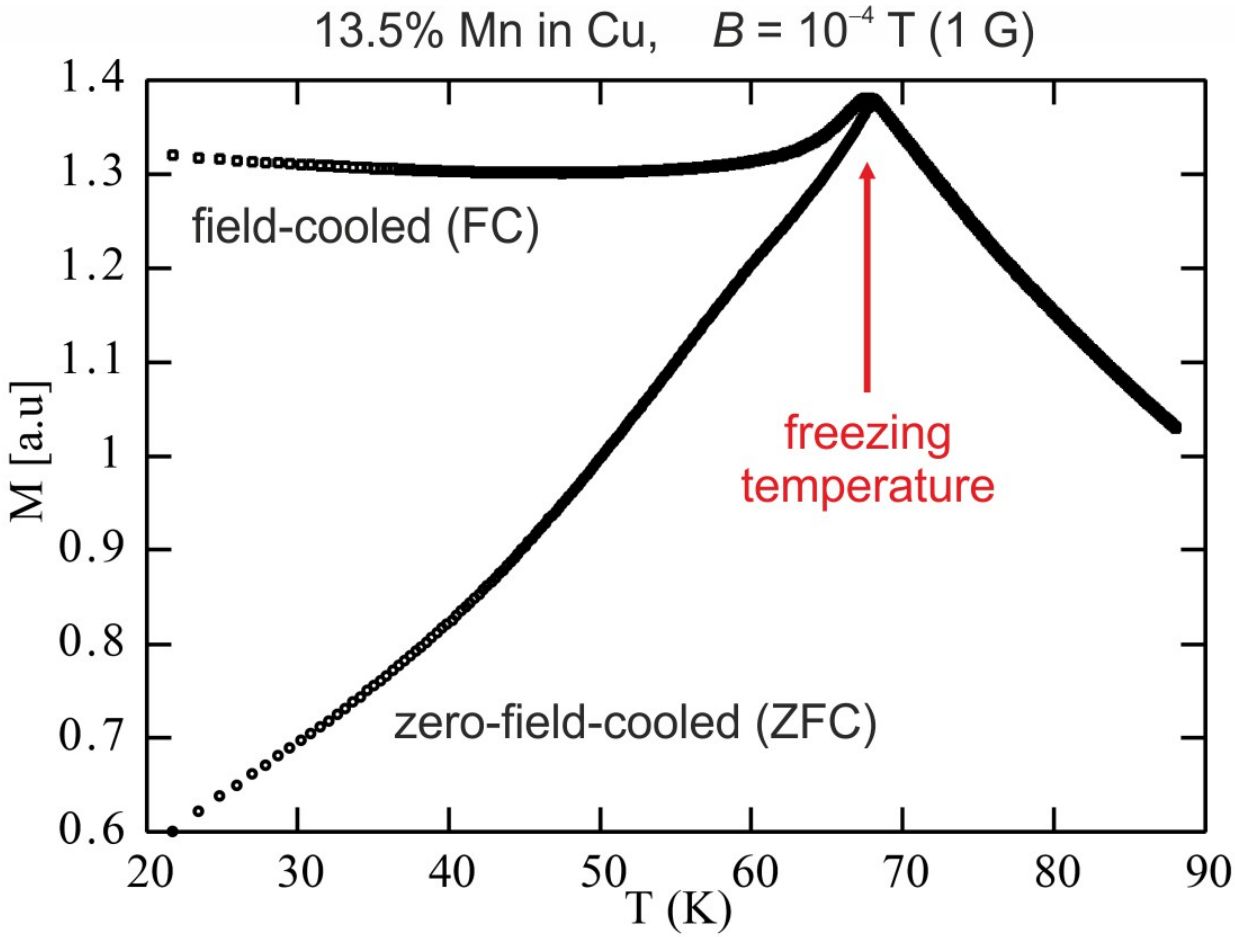
High memory density and no moving parts

Antiskyrmions and skyrmions as '0' and '1' bits

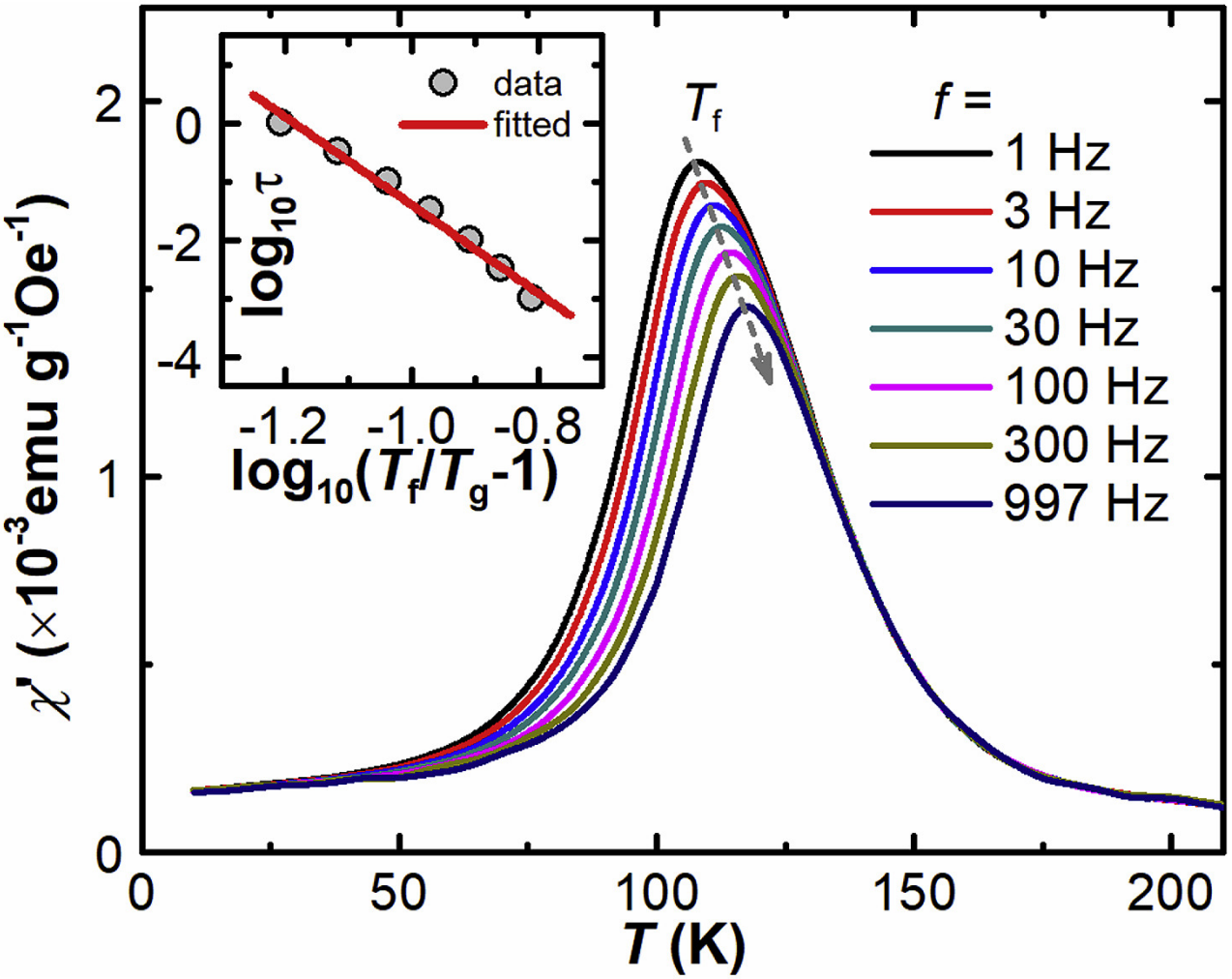


Spin glass





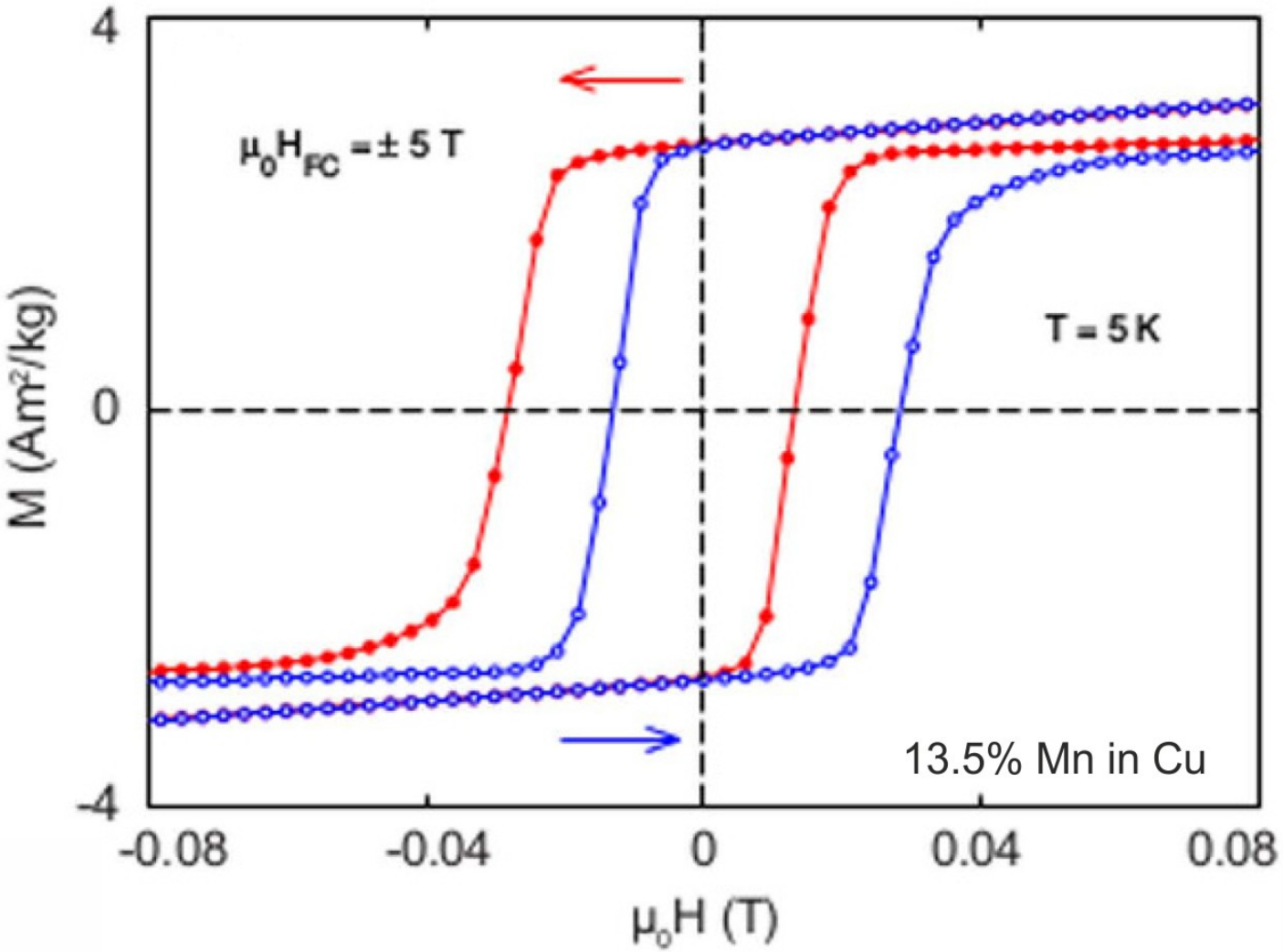
Royal Swedish Academy of Sciences and Eur. Phys. J. B 10, 15 (1999)



Magnetic response depends on: i) cooling history
ii) frequency of the applied field

J. Alloys Comp. 816, 152678 (2020)

Hysteresis and order?



Sci. Reports 6, 19964 (2016)

Travel in a rugged landscape

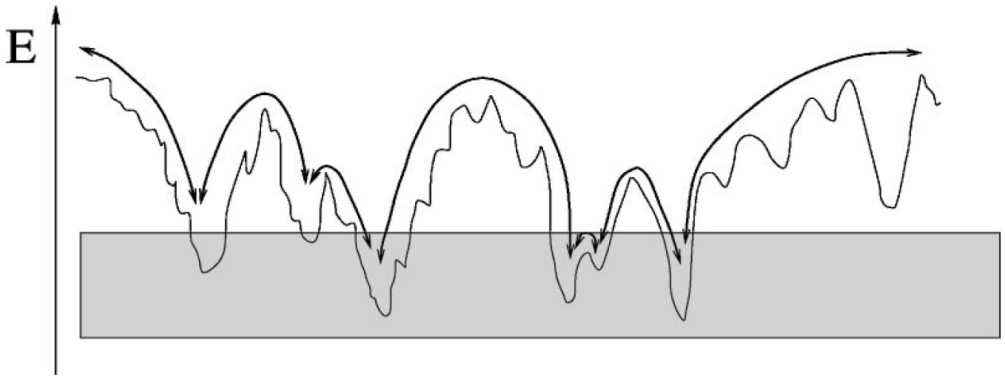
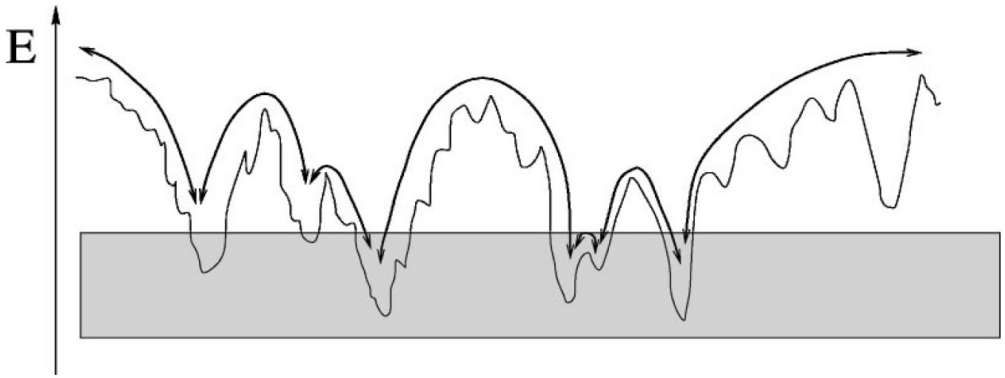


Image credits: Phys. Rev. B 64, 104417 (2001)

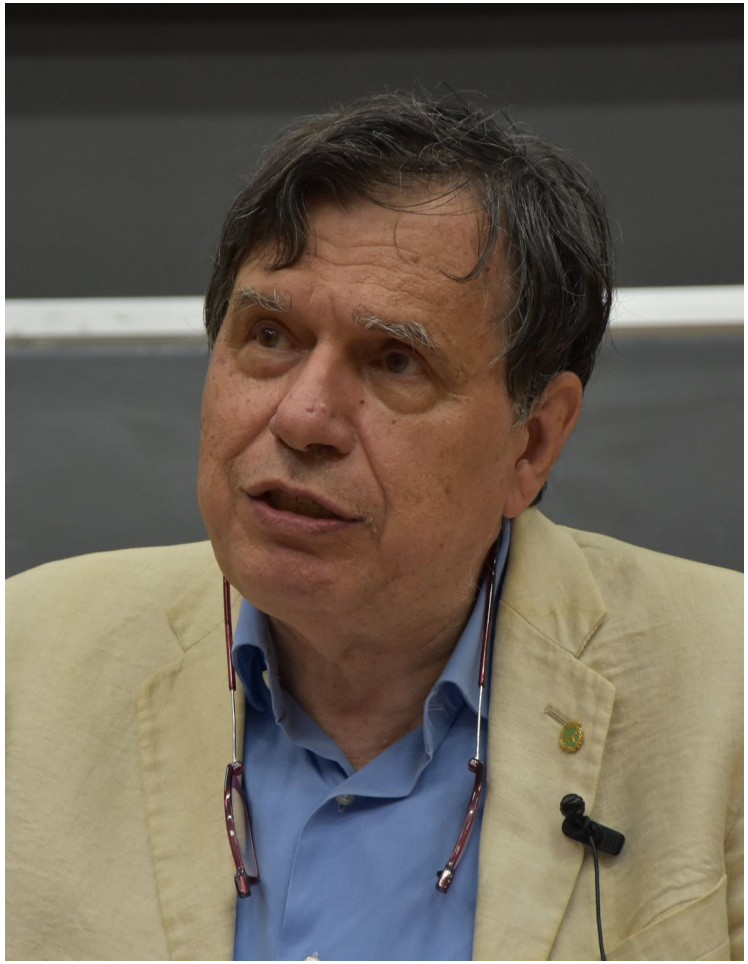
Travel in a rugged landscape



2021 Nobel prize in physics

"discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales"

spin glasses, protein folding, collective motion of animals (swarms and flocks)

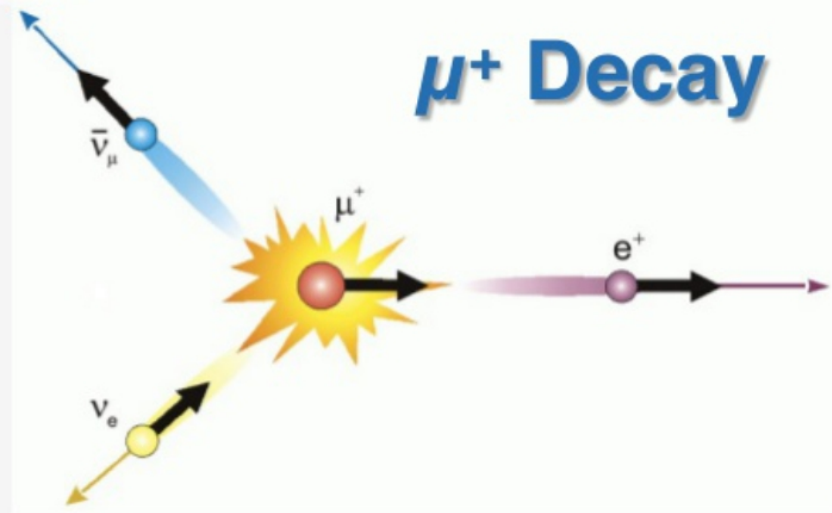


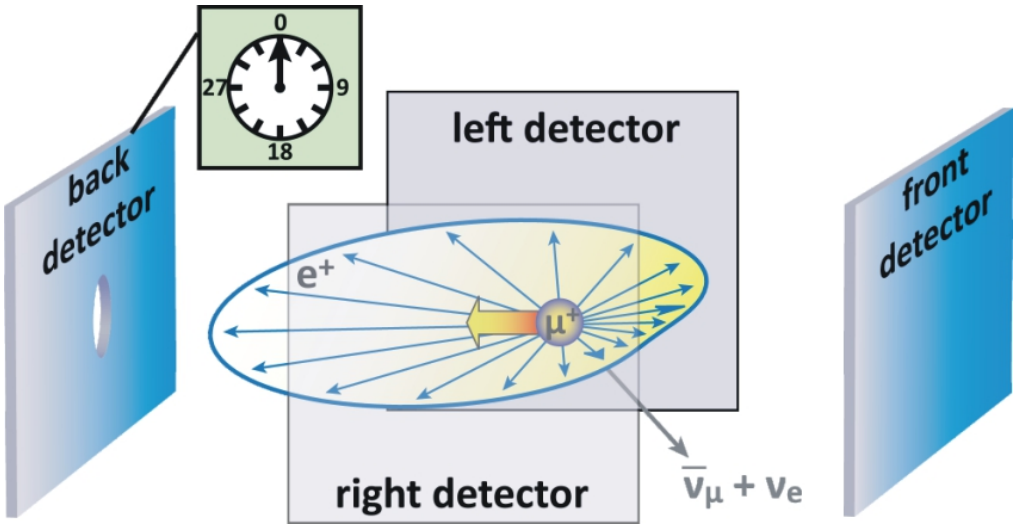
Giorgio Parisi
born 1948

Image credits: Phys. Rev. B 64, 104417 (2001) and Sapienza Universitá di Roma (CC-BY-NC)

Experiment

muon spin relaxation (μSR)

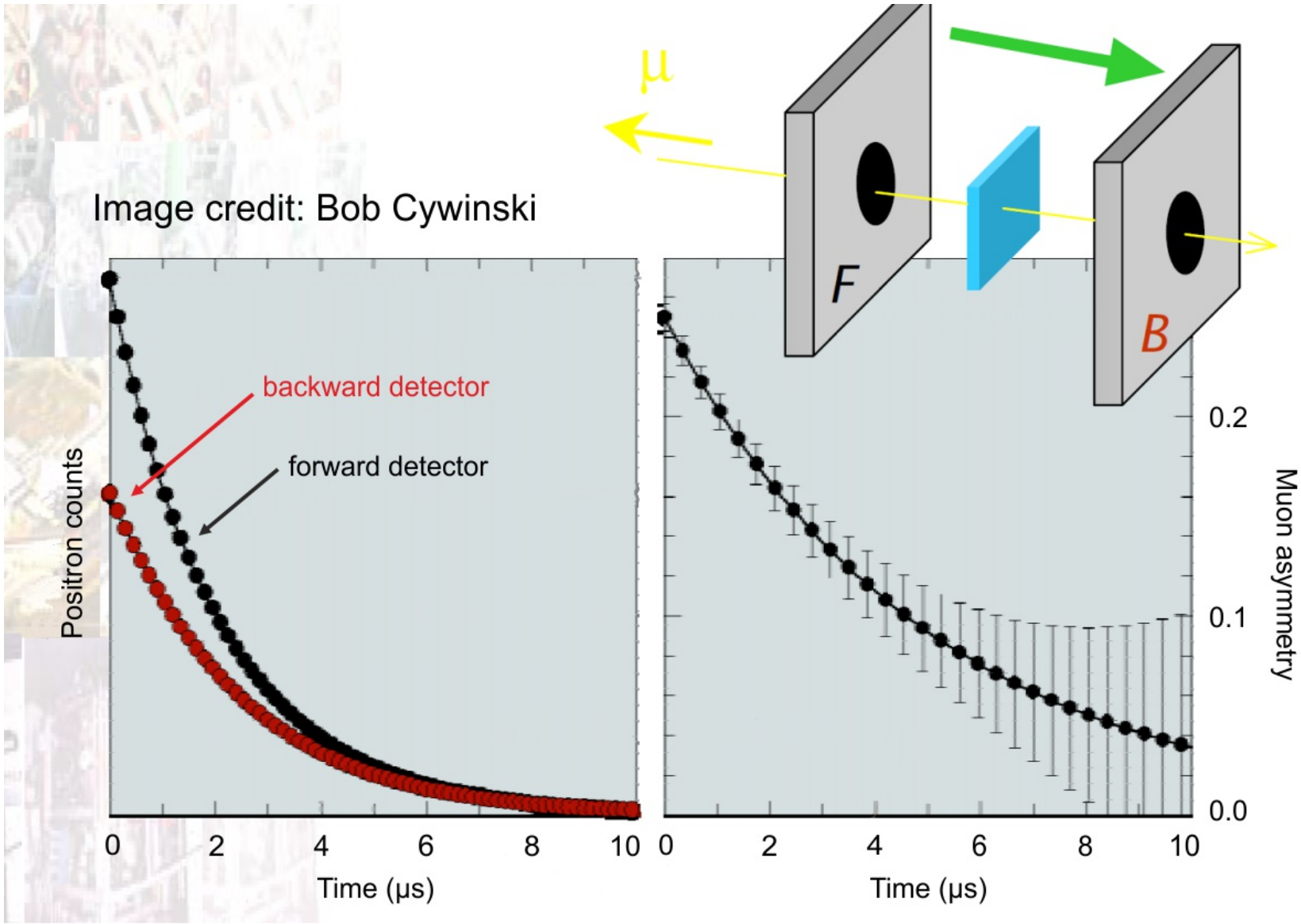




- What happens: positron follows the direction of muon spin
- Measure: asymmetry of the positron emission
- Extract: local magnetization

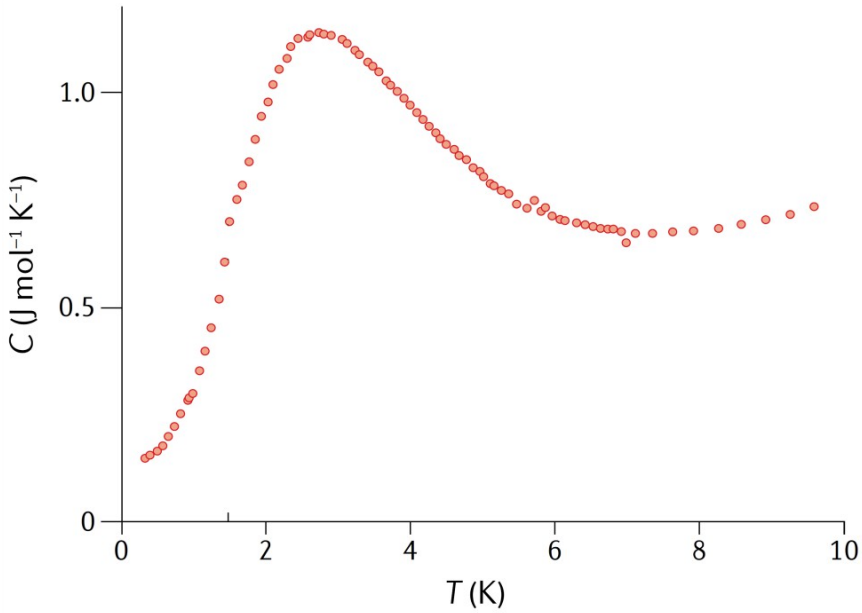
Image credit: J.H. Brewer, slides at Int. Conference on Hyperfine interactions (2014)

Muon depolarization



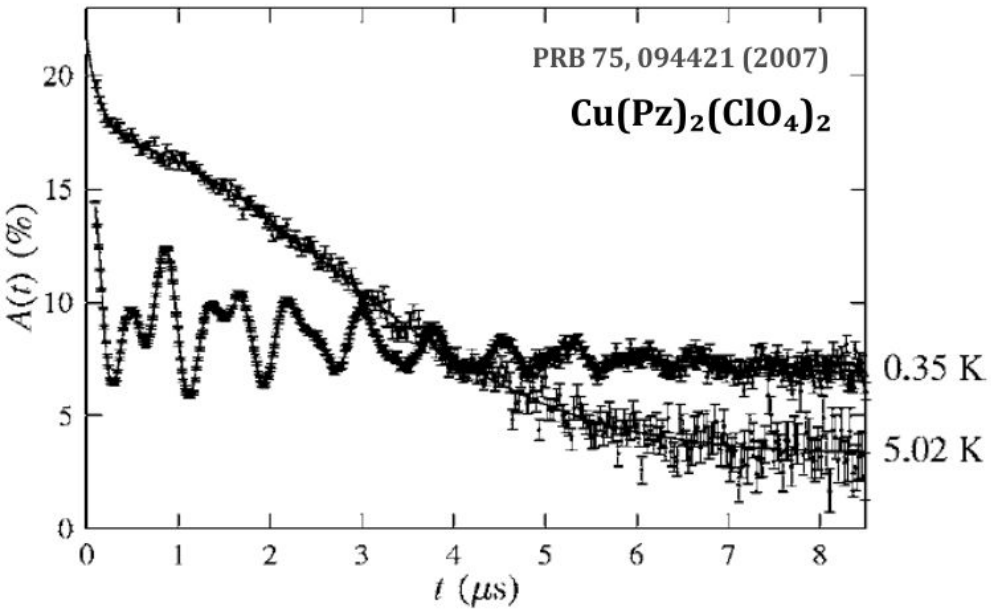
Further reading: A. Hillier *et al. Nature Rev. Methods Primer* **2**, 4 (2022)

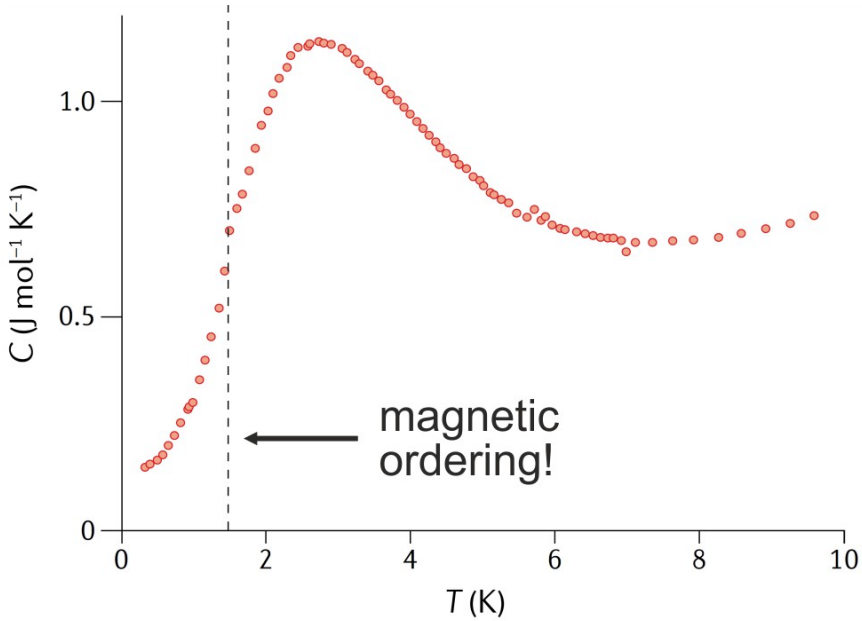
Probe of local fields

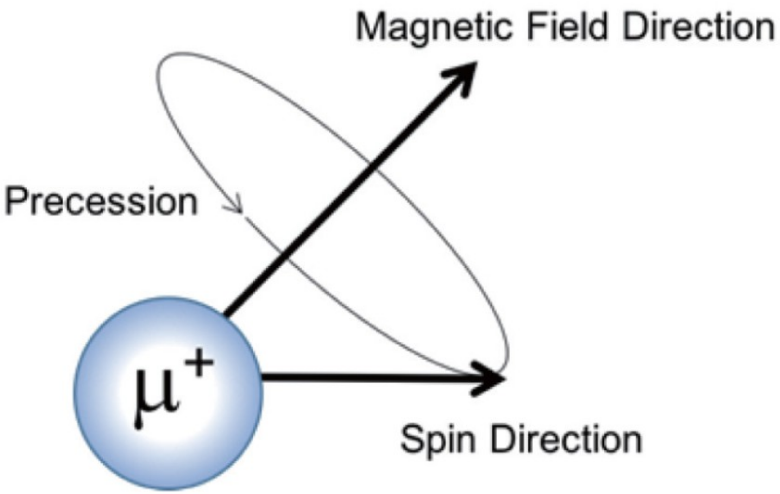


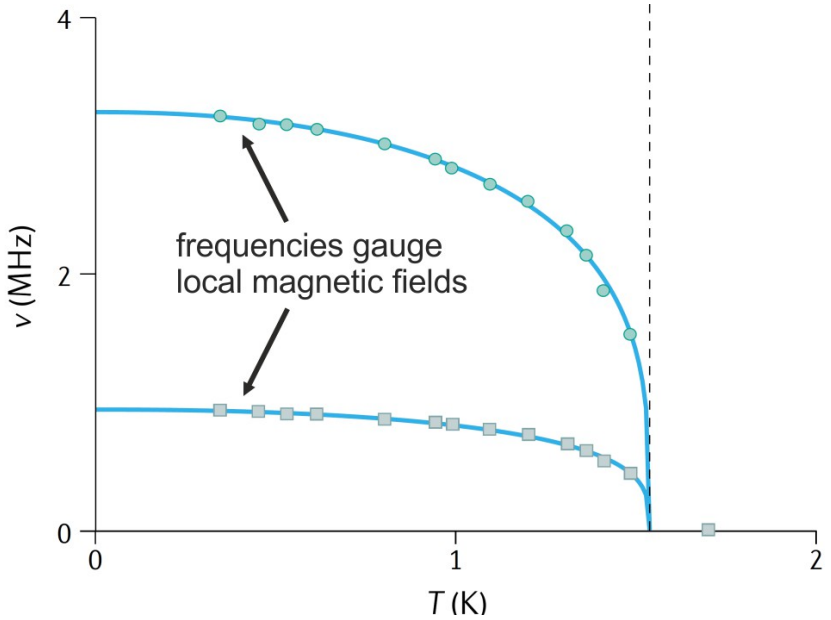
Nature Rev. Methods Primer 2, 4 (2022); J. Comput. Chem. Japan 16, A12 (2017)

Probe of local fields

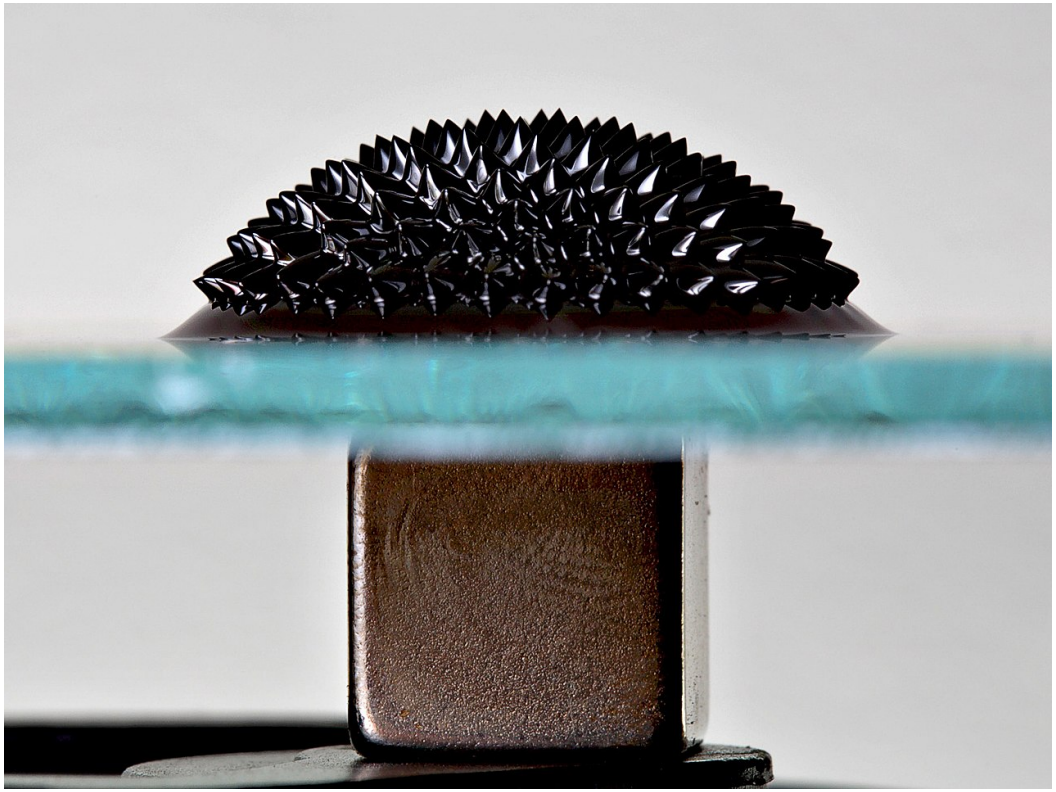








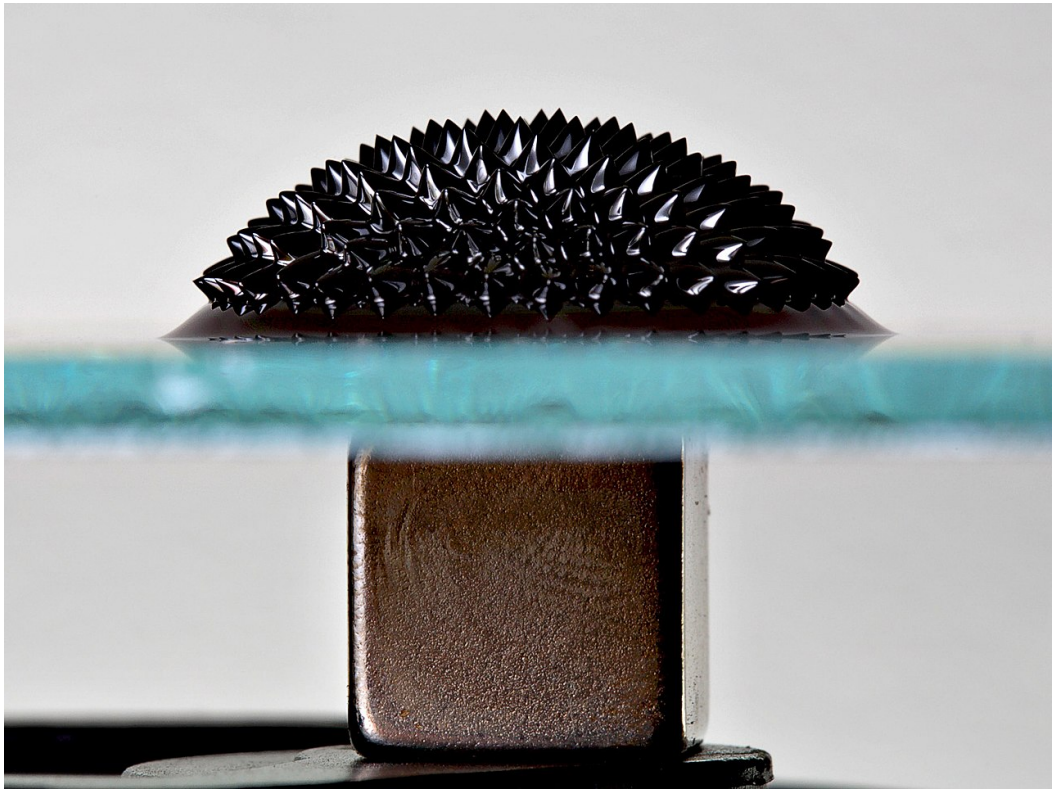
Nature Rev. Methods Primer 2, 4 (2022); J. Comput. Chem. Japan 16, A12 (2017)



Spin liquid

not a ferrofluid

Image credit: Gregory F. Maxwell (CC-BY-SA), ISIS



Spin liquid

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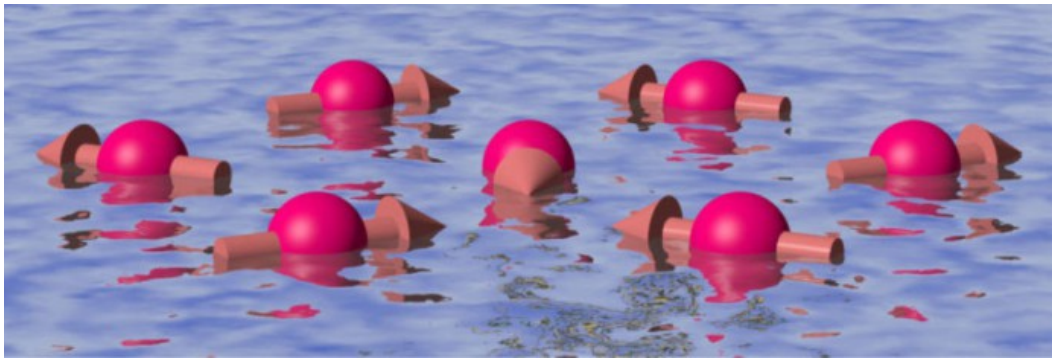
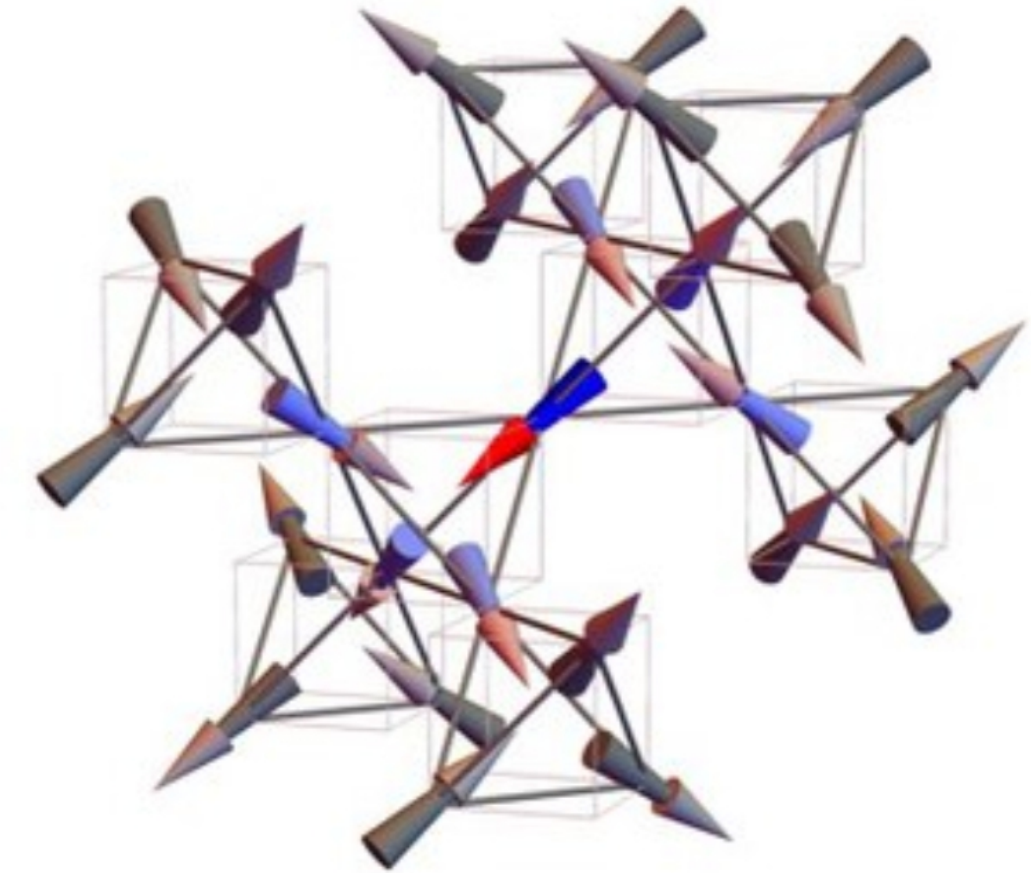


but a state with
persistent spin dynamics

Image credit: Gregory F. Maxwell (CC-BY-SA), ISIS

Spin ice (classical spin liquid)



All the 2-in-2-out configurations have the same energy (degenerate classical states)

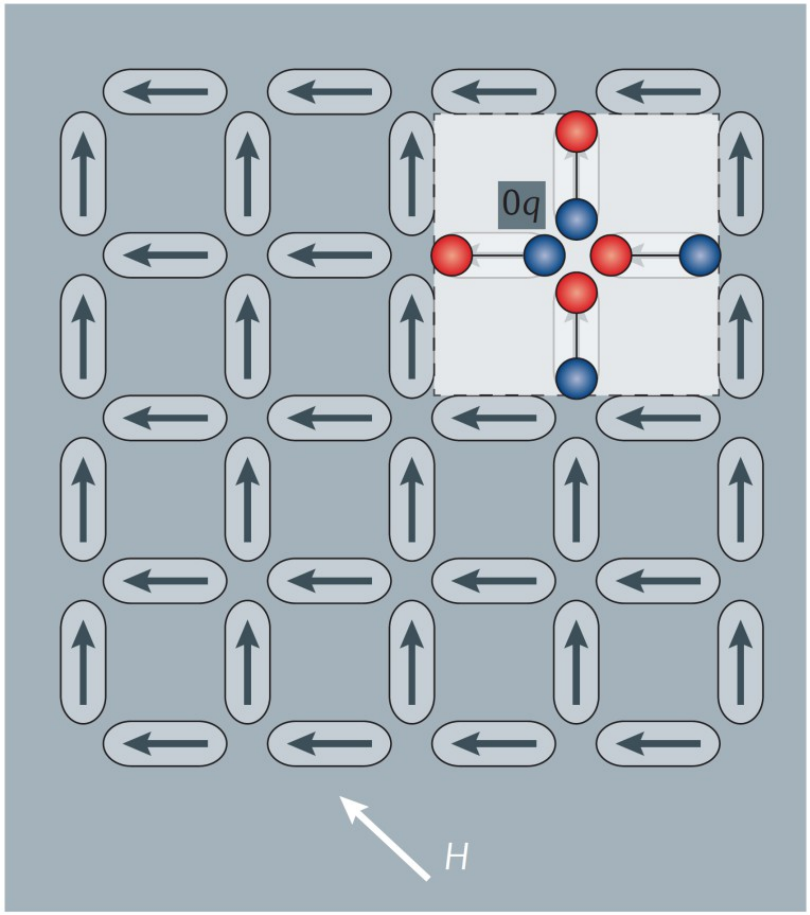
Higher T's: system evolves due to thermal fluctuations

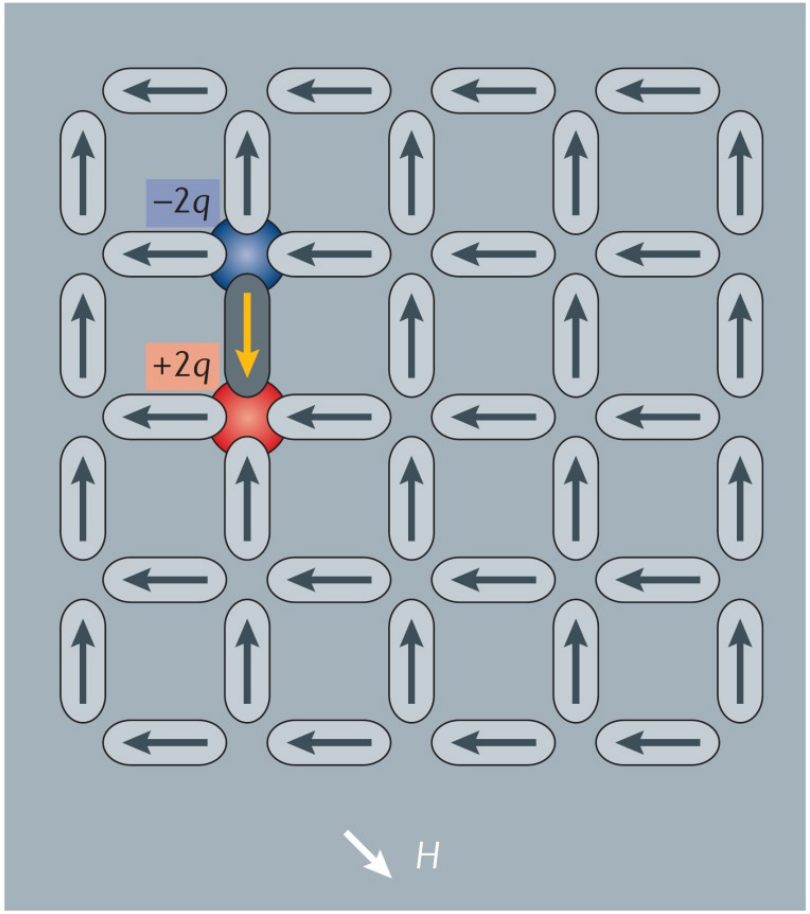
Lower T's: freezing

Image credit: B. Tomasello (TU Dresden)

Monopole excitations

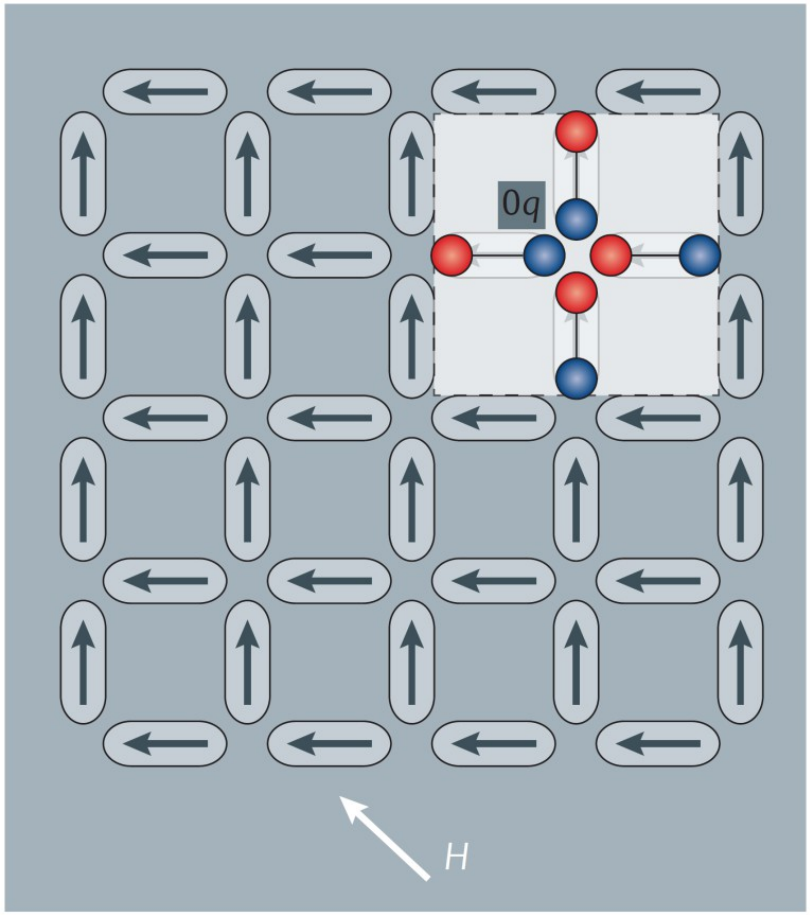
Nature Rev. Phys. 2, 13 (2020)

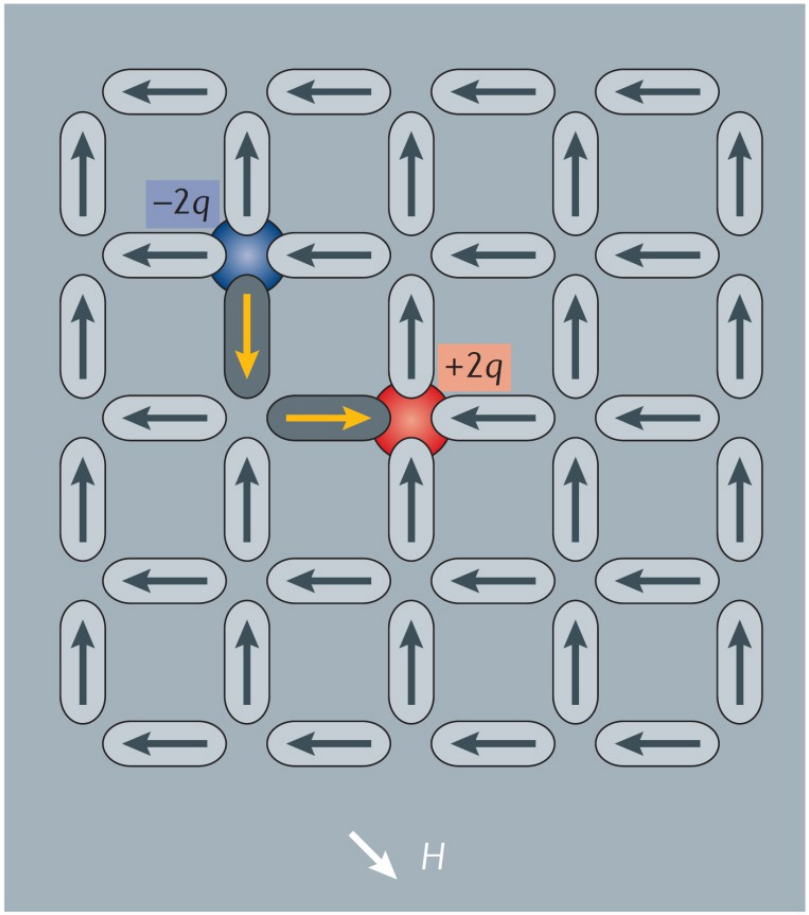




Monopole excitations

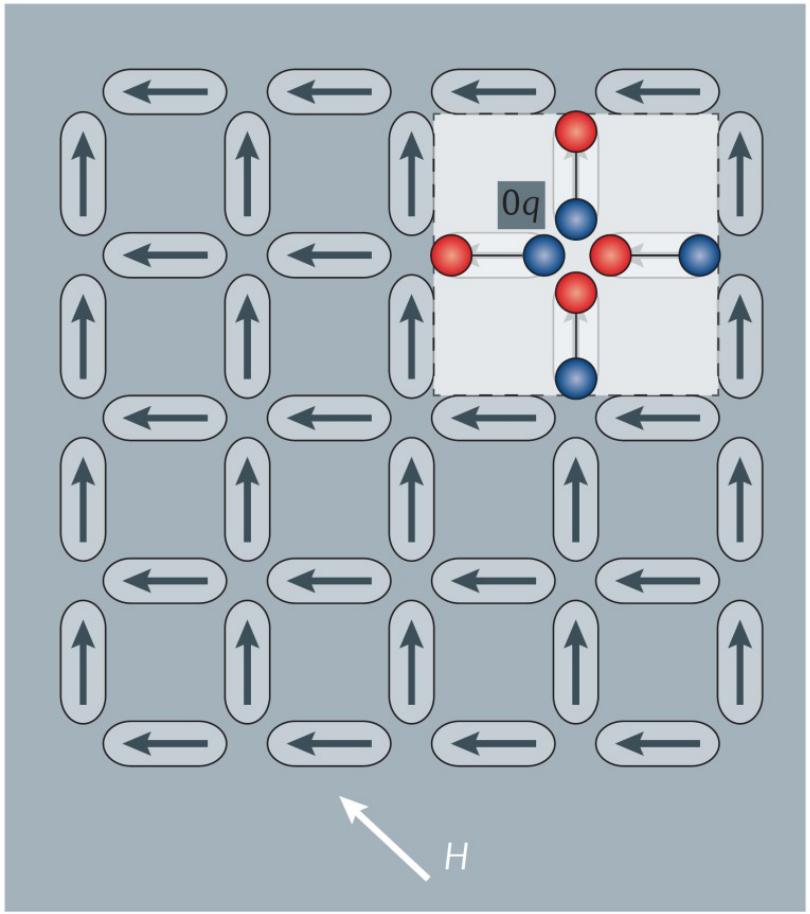
Nature Rev. Phys. 2, 13 (2020)

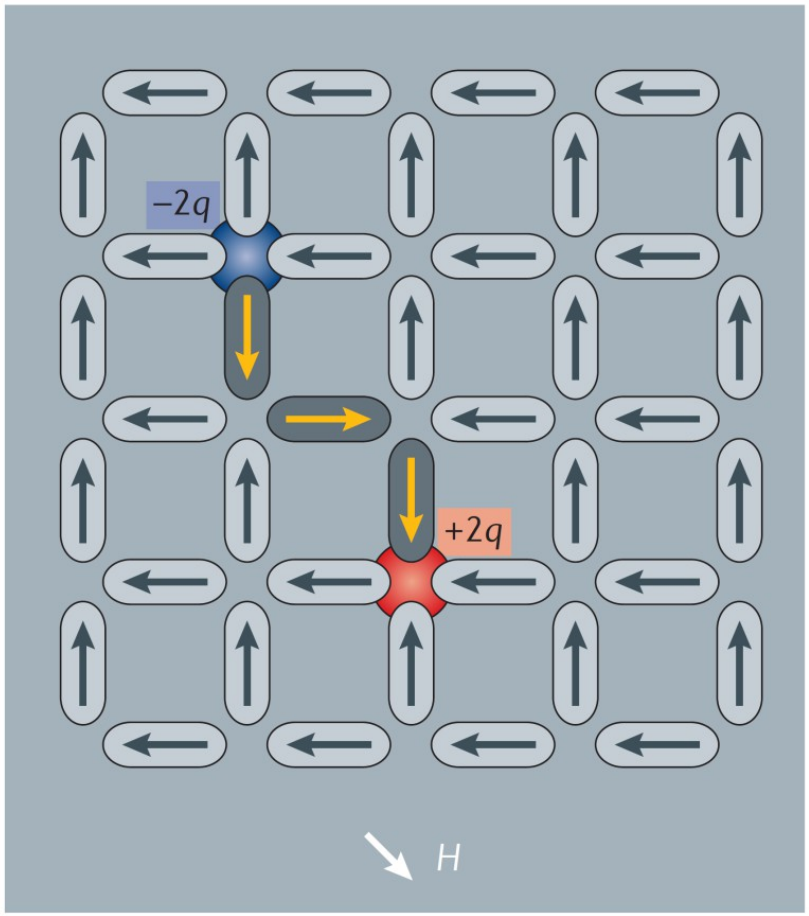




Monopole excitations

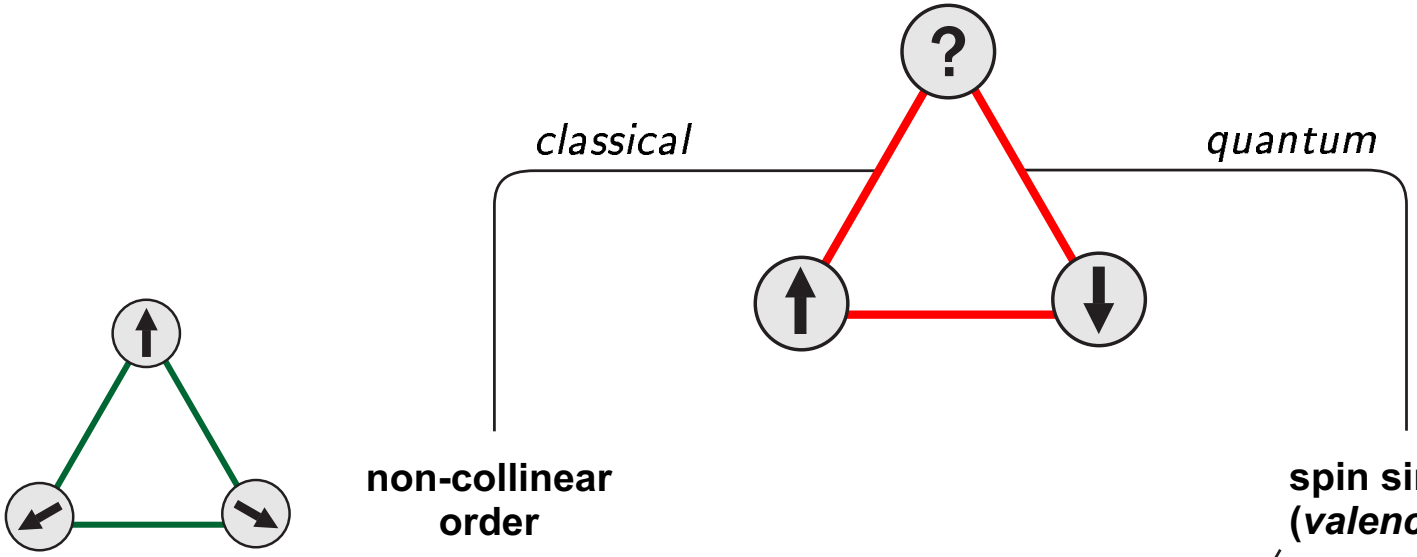
Nature Rev. Phys. 2, 13 (2020)

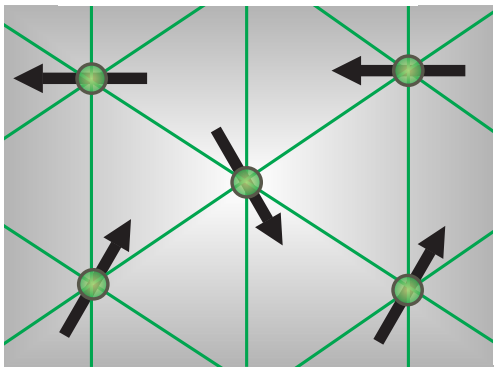


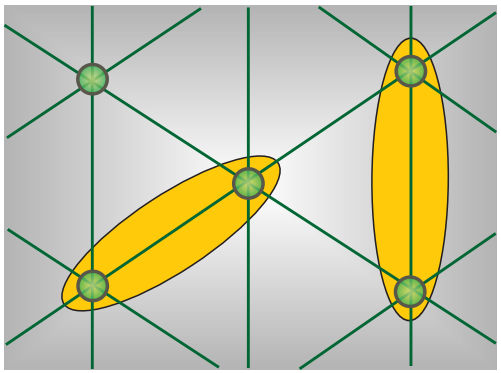


Magnetic excitation of spin ice breaks down into two **monopoles**

Spin liquid: also quantum







still ordered...

"valence bonds" form a spin liquid

proposed: 1973 (P.W. Anderson)

realized: 20??