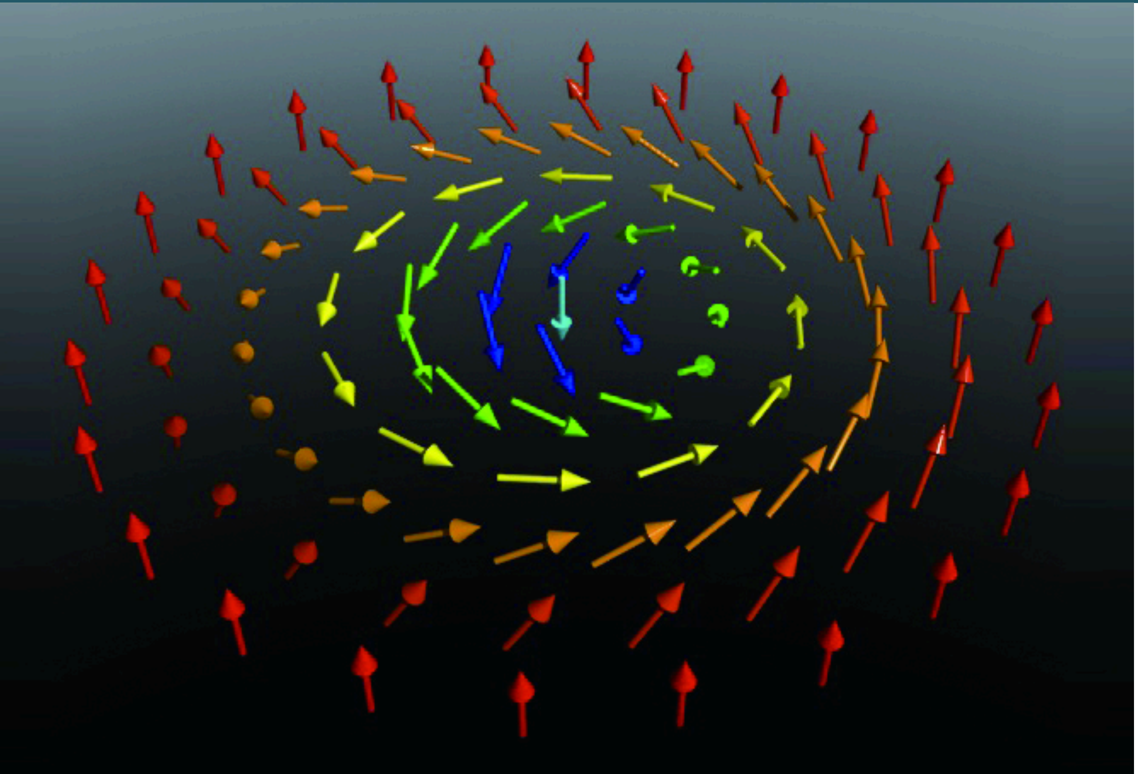
Topological protection of skyrmions in chiral magnetic materials



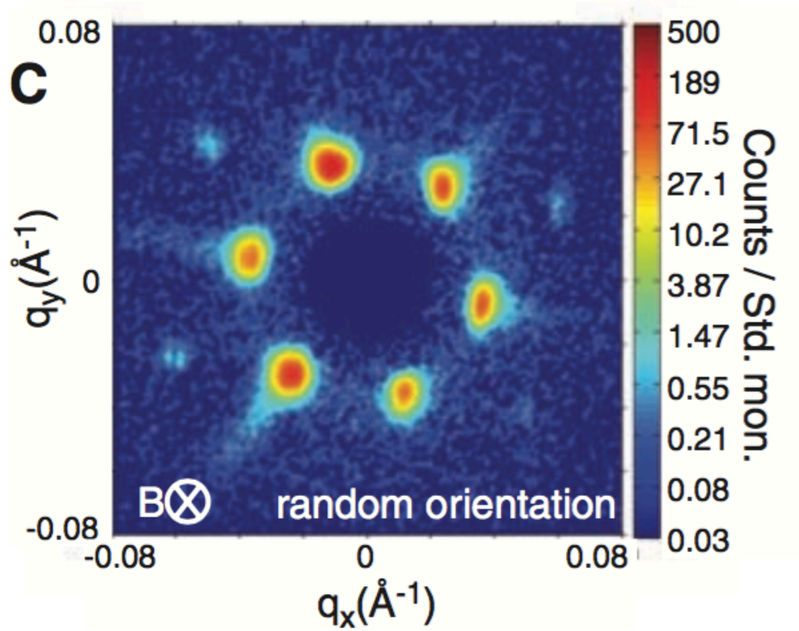
Joshua Bocarsly

MATRL 286G

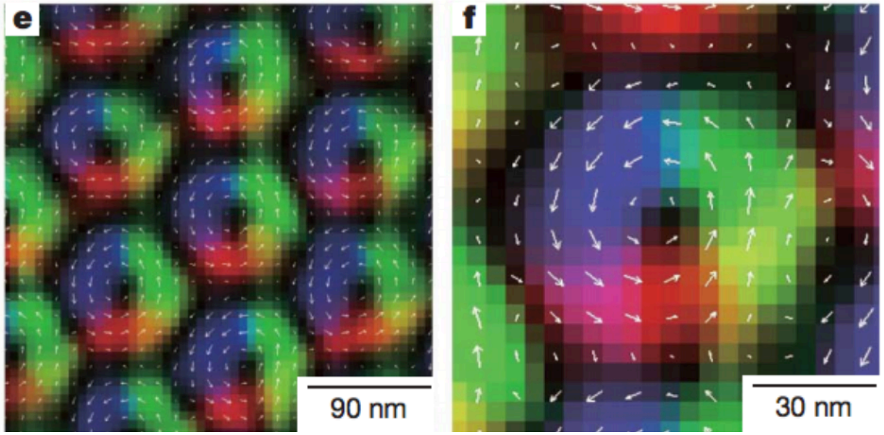
5 May 2016

Timeline

- **1962**: Tony Skyrme proposed a model of mesons and baryons as topologically protected solitons.
- **1964-1965:** Dzyaloshinksii explained helical spin arrangements in solids
- **1989:** Bogdanov and Yablonskii predicted that stable "skyrmions" could exist in helimagnetic materials
- **2009:** Skyrmions first observed in MnSi by SANS by Mühlbauer, Böni, and coworkers (*Science, 2009)*
- **2010:** Real-space observation of skyrmions in $Fe_{0.5}Co_{0.5}Si$ using by Yu, Tokura, and coworkers (*Nature*, 2010)



SANS observation of skyrmions in MnSi

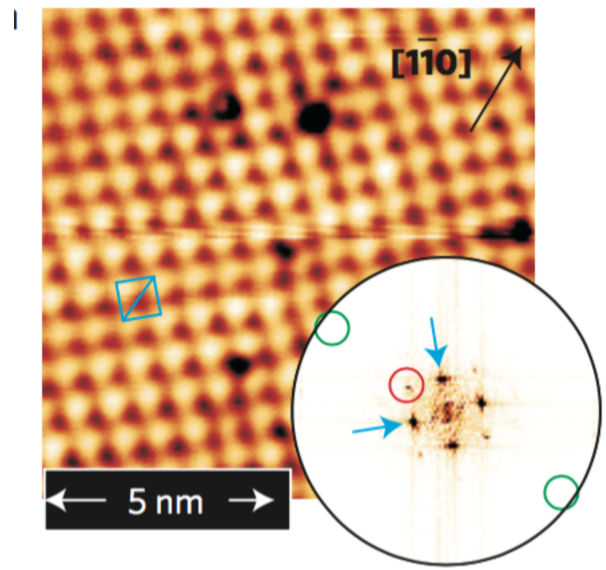


LTEM observation of skyrmions in $Fe_{0.5}Co_{0.5}Si$

Technological promise

Skyrmions have been observed in metals, semiconductors, and insulators across a wide temperature range (as high as 600 K for $Co_xZn_yMn_z$)

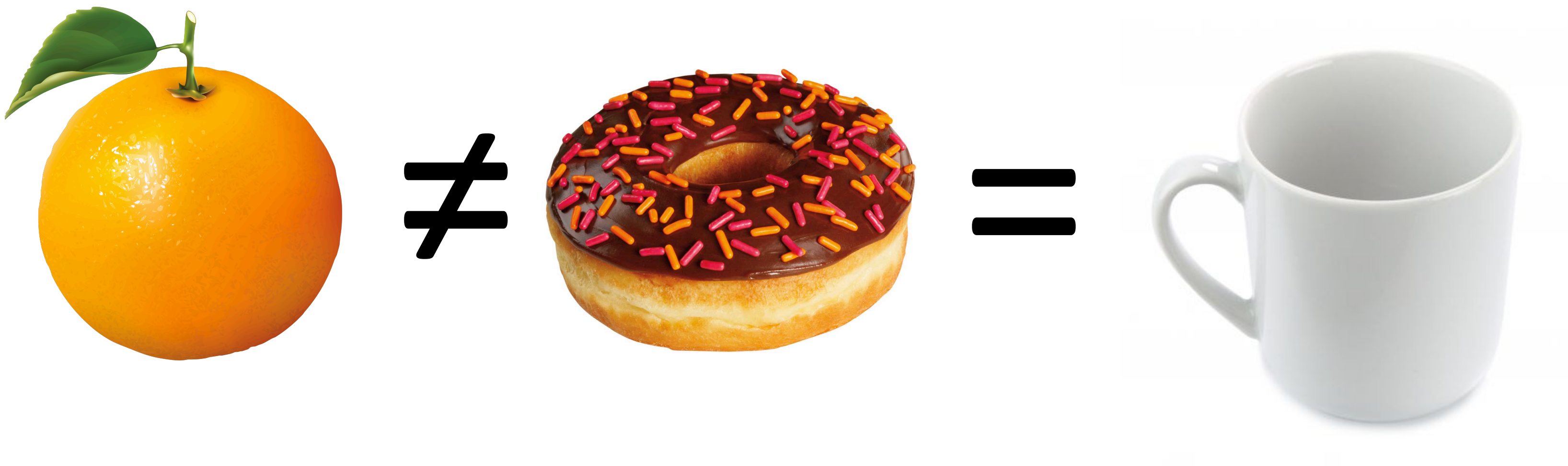
- Ultrahigh-density and low power magnetic storage (use skyrmions instead of magnetic domains as the bits)
- Novel applications based on skyrmion currents?
- Quantum computing?
- ???



"nanoskyrmions" as small as 1 nm in Fe on Ir (111)

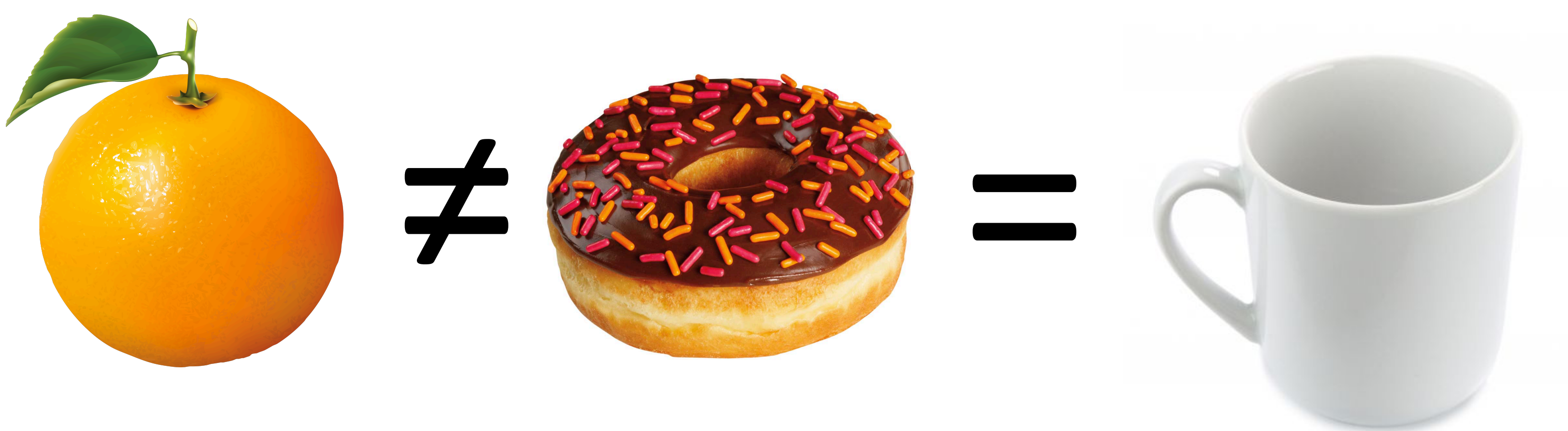
Heinze, S., von Bergmann, K., Menzel, M., Brede, J., Kubetzka, A., Wiesendanger, R., … Blügel, S. (2011). Spontaneous atomic-scale magnetic skyrmion lattice in two dimensions. Nature Physics, 7(9), 713–718.

What is topological protection?



What is topological protection?

- Two fields are topologically identical if you can transform one to the other by bending and stretching, but not tearing or gluing
- An object is **topologically protected** if it is topologically inequivalent to the uniform field.

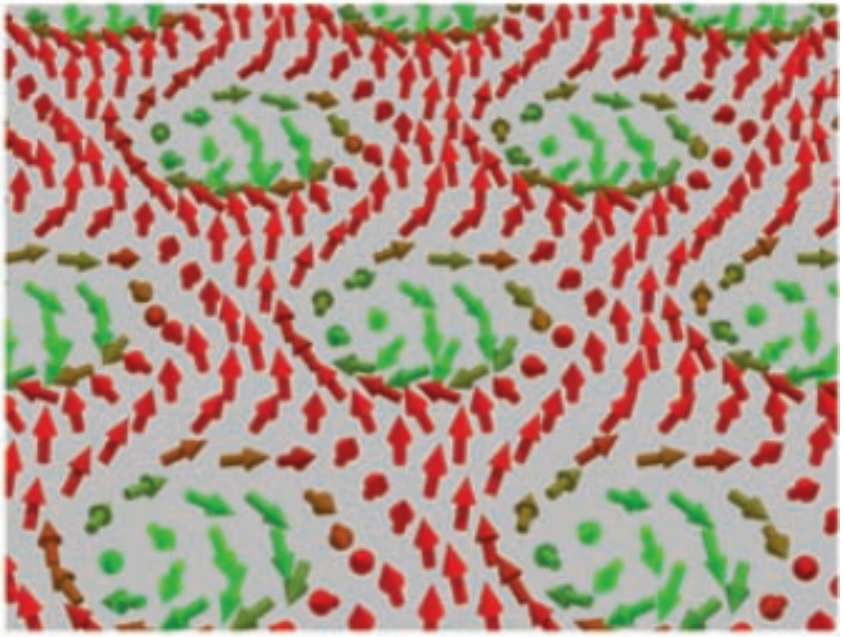


What does topology have to do with solids?

If you can approximate some feature of a solid as a continuous surface, then you can use the tools of topology to analyze it.

Examples of surfaces:

- magnetization
- electric field in ferroelectric
- electrons in k-space



magnetization field in MnSi

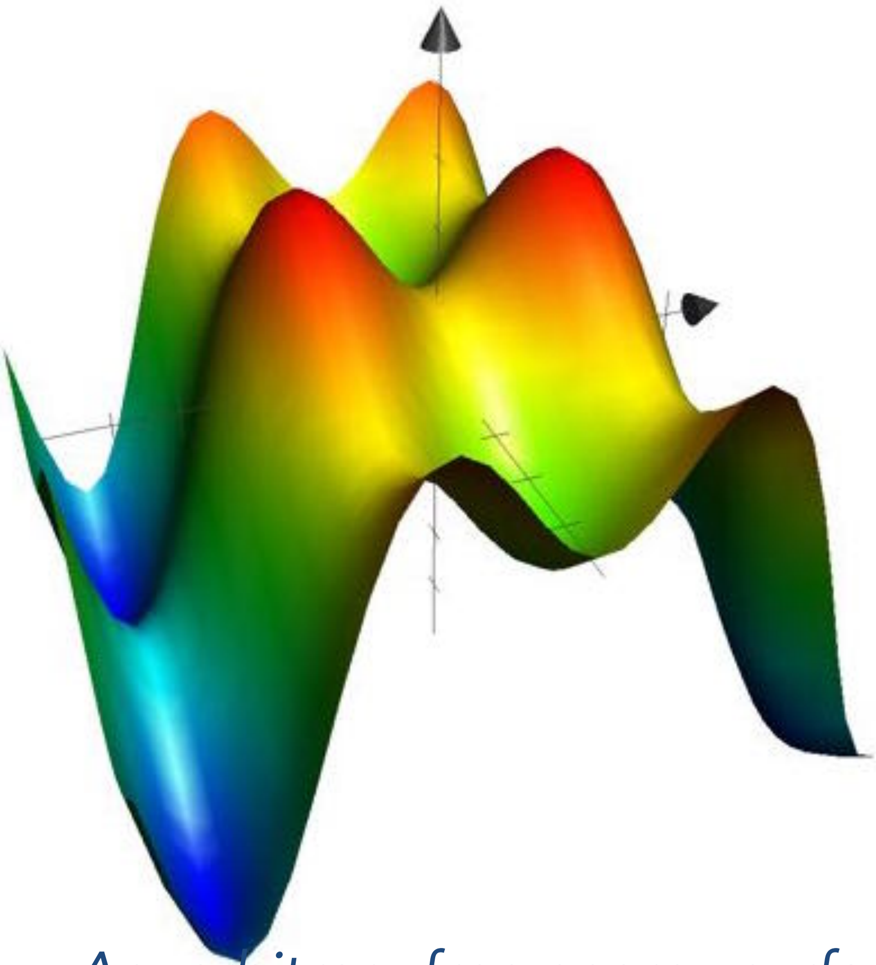
S. Mühlbauer, B. Binz, F. Jonietz, C. Pfleiderer, a Rosch, a Neubauer, et al., Skyrmion lattice in a chiral magnet., Science. 323 (2009) 915–919. doi:10.1126/science.1166767.

Thermodynamic stability vs Topological protection

Topological protection means there is an energy barrier to decomposition of a state

- The state may be metastable or stable

Topology allows you to make some predictions about stability without full knowledge of the free energy surface



An arbitrary free energy surface with local and global minima

Magnetic skyrmions

This term refers to a variety of topologically protected spin textures

hedgehog skyrmion

vortex skyrmion

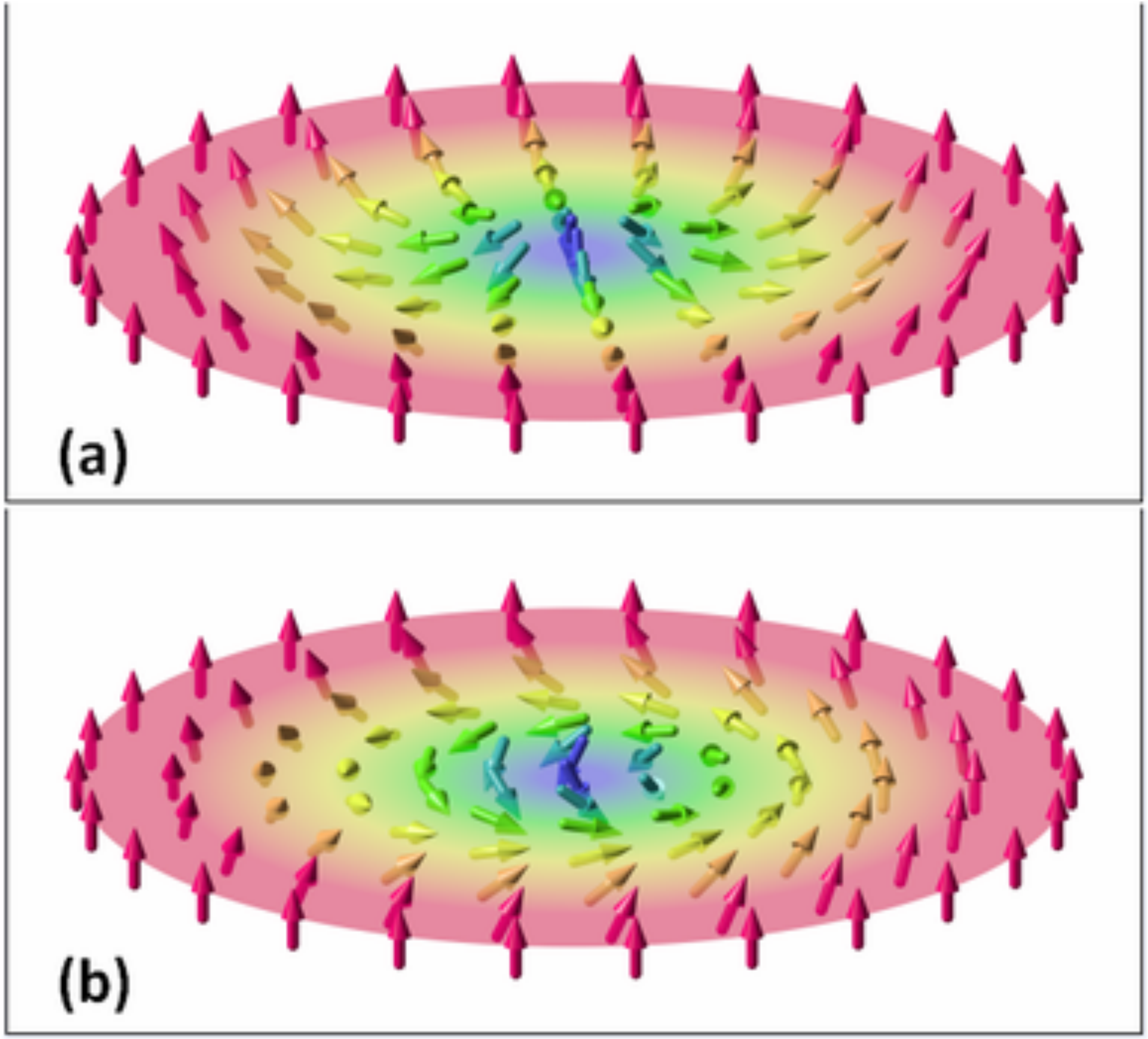
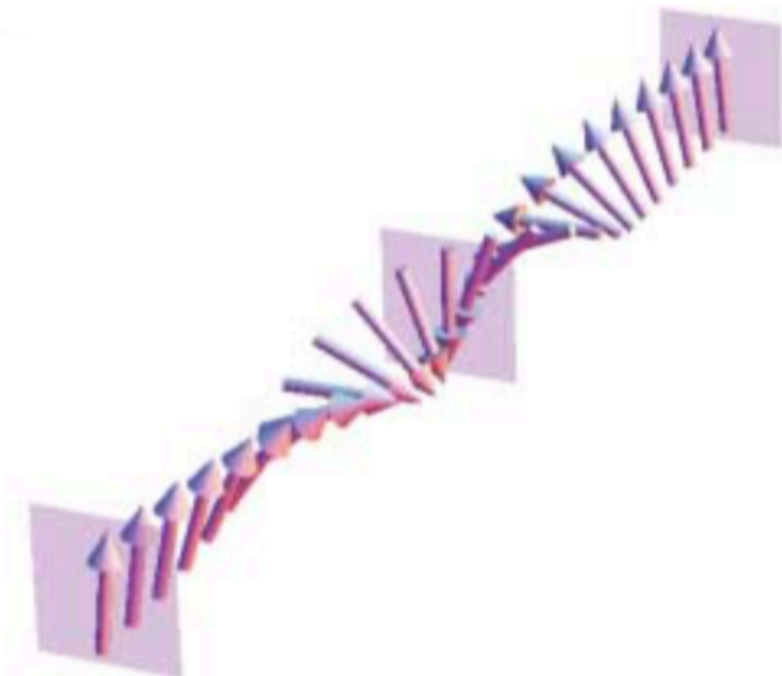


Illustration by Karin Everschor-Sitte and Matthias Sitte

1-D skyrmions

In 1-D, skyrmions are made of pairs of domain walls of the same chirality.



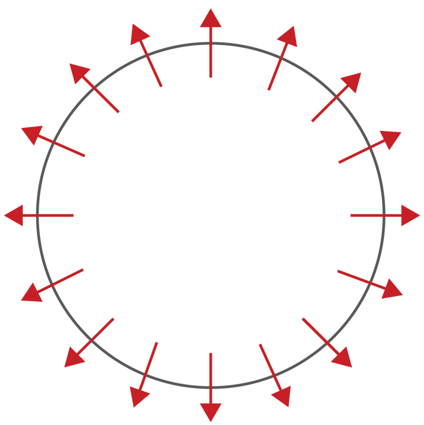
This structures is topologically protected as long as the ends are fixed (*i.e.* the skyrmion embedded in a

H.-B. Braun, Topological effects in nanomagnetism: from superparamagnetism to chiral quantum solitons, Adv. Phys. 61 (2012) 1–116. doi:10.1080/00018732.2012.663070.

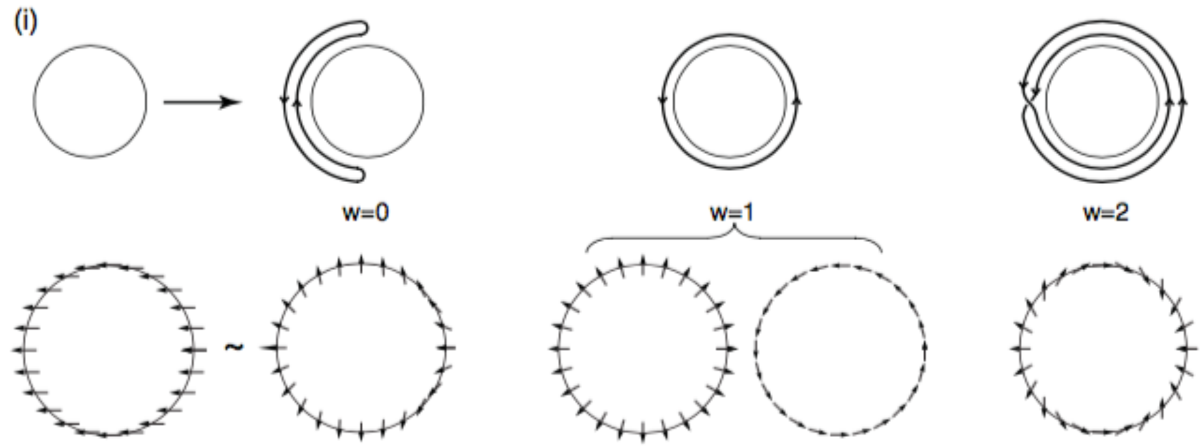
Topological charge

Skyrmions behaves as quasi-particles, characterized by a "**topological charge**" $w = \pm 1$

Formally, this is the "winding number", the number of times a mapping from the surface to configuration space winds around the unit sphere.



The configuration of space of possible spin direction



Real-space spin structures with different winding numbers

H.-B. Braun, Topological effects in nanomagnetism: from superparamagnetism to chiral quantum solitons, Adv. Phys. 61 (2012) 1–116. doi:10.1080/00018732.2012.663070.

Thermodynamic analysis of skyrmions

The energy of a cubic, noncentrosymmetric, isotropic magnet near its Curie temperature can be described as

$$w(\boldsymbol{M}) = A(\boldsymbol{\nabla}\boldsymbol{M})^2 - D\boldsymbol{M}\cdot(\boldsymbol{\nabla}\times\boldsymbol{M}) - \boldsymbol{M}\cdot\boldsymbol{H}$$

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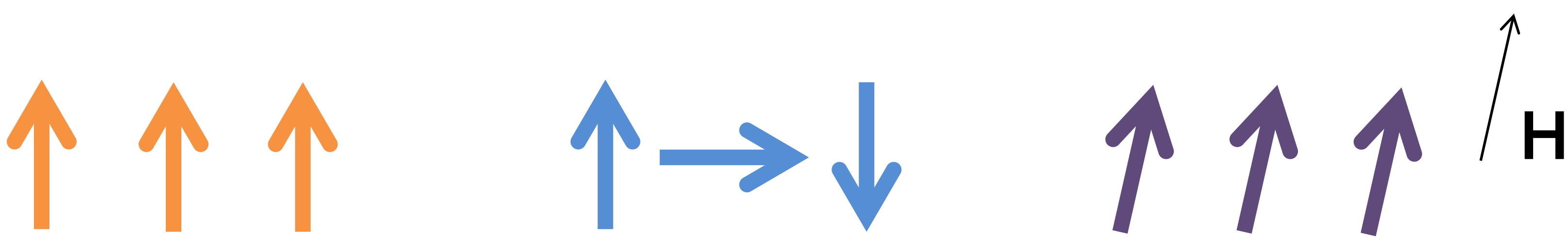
Exchange energy

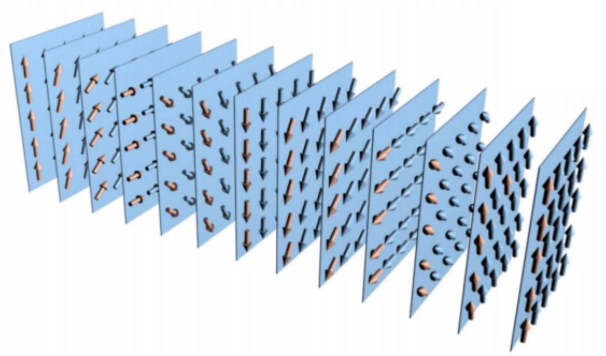
Dzyaloshinskii–Moriya interaction

Zeeman energy

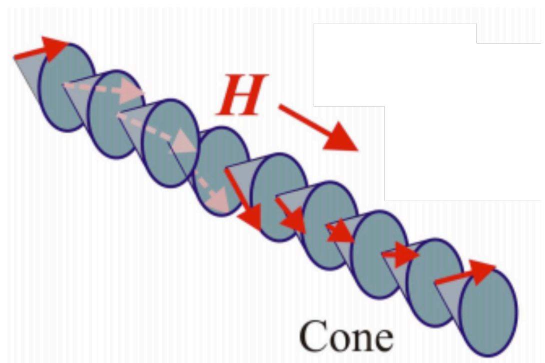


Thermodynamic analysis of skyrmions

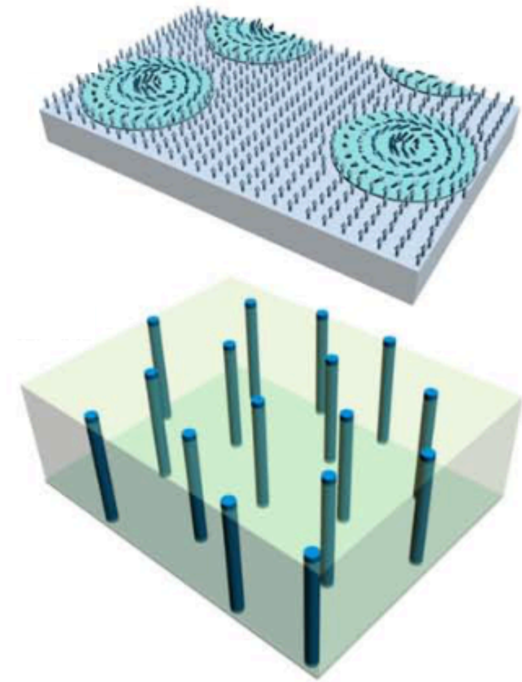
Energy-minimizing arrangements:



helicoid



conical



skyrmions

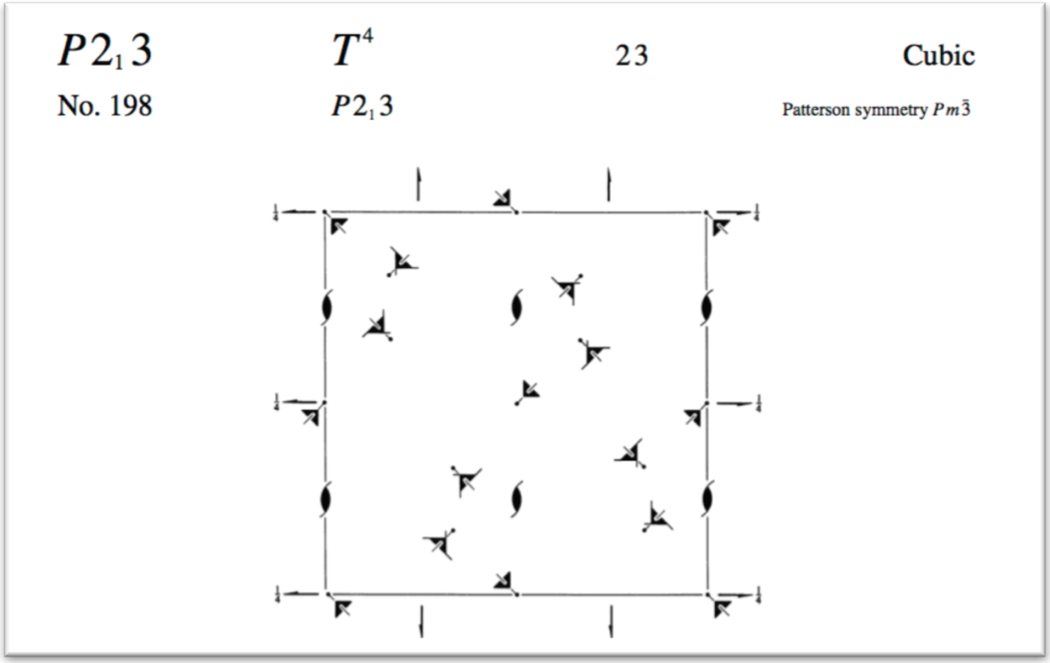
Rößler, U. K., Leonov, A. A., & Bogdanov, A. N. (2011). Chiral Skyrmionic matter in non-centrosymmetric magnets. Journal of Physics: Conference Series, 303(1), 012105.

Materials candidates for skyrmions

While skyrmions are topologically protected, they are usually not **stable**. Skyrmion hosts should have:

- noncentrosymmetric (and especially **chiral**) space groups
- exchange energy on the same order as spin-orbit coupling (light elements)
- T_C in desired temperature range

An example of spacegroup hosting skyrmions:

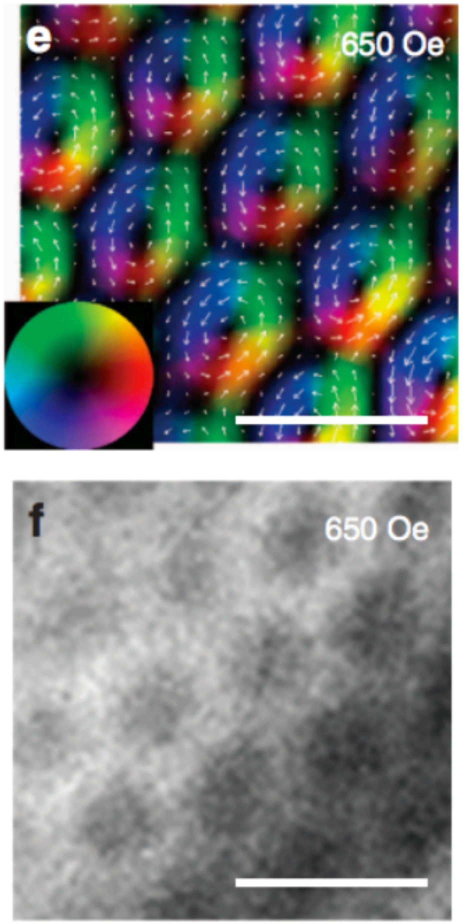


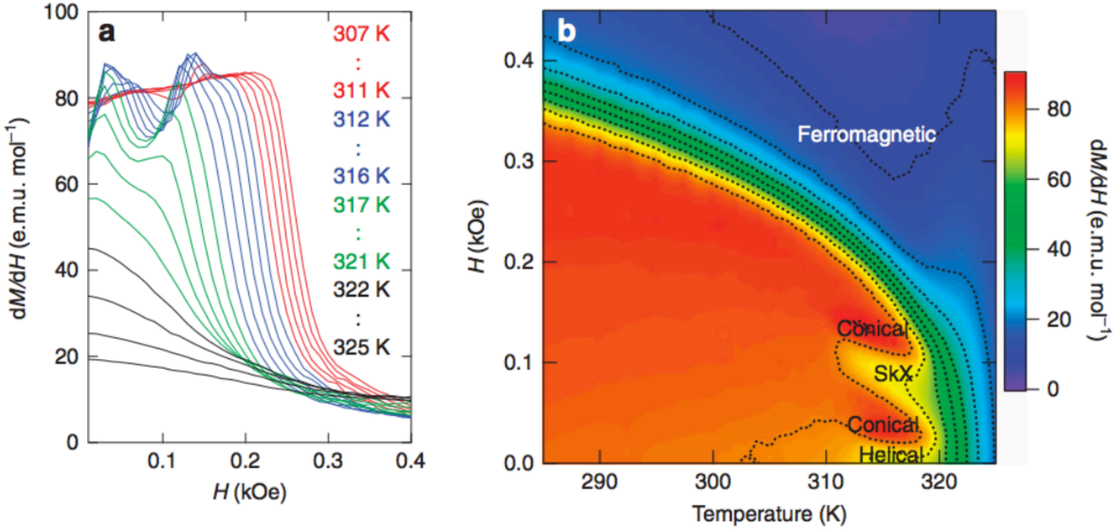
it.iucr.org/Ab/ch7o1v0001/sgtable7o1o198.pdf

Experimental observation of skyrmions

$Co_8Zn_8Mn_4$ ($P4_132$)

At the correct *H*, *T*, a close-packed lattice of skyrmions can be observed by LTEM

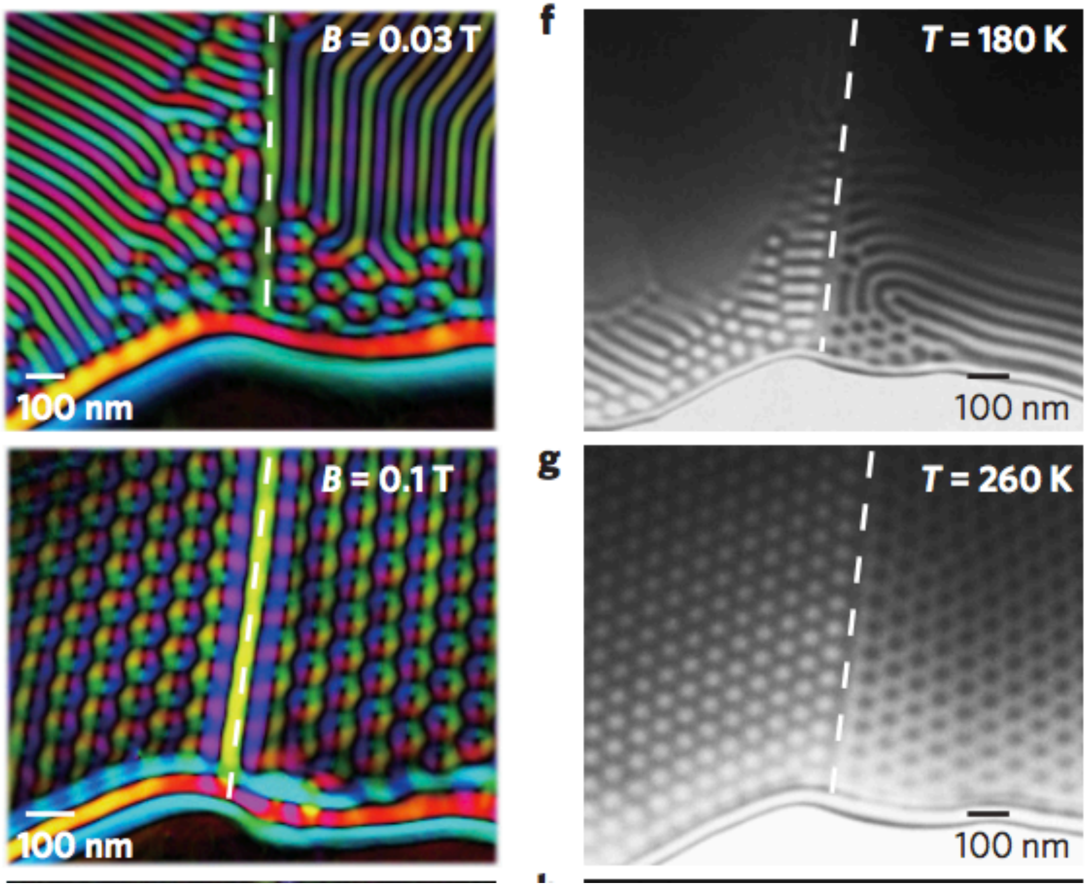




Tokunaga, Y., Yu, X. Z., White, J. S., Rønnow, H. M., Morikawa, D., Taguchi, Y., & Tokura, Y. (2015). A new class of chiral materials hosting magnetic skyrmions beyond room temperature. Nature Communications, 6(May), 7638.

Experimental observations of skyrmions

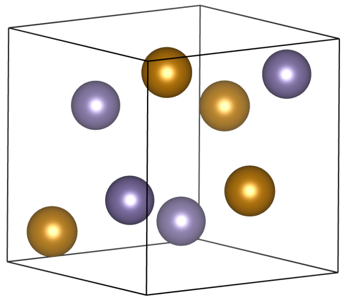
FeGe ($P2_13$)



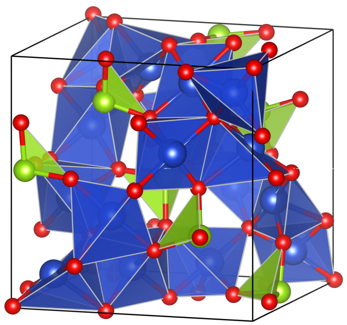
Yu, X. Z., Kanazawa, N., Onose, Y., Kimoto, K., Zhang, W. Z., Ishiwata, S., … Tokura, Y. (2011). Near room-temperature formation of a skyrmion crystal in thin-films of the helimagnet FeGe. Nature Materials, 10(2), 106–109.

Known magnetic skyrmion hosts

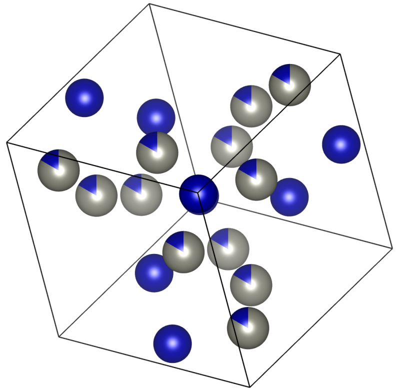
Chiral solids



B20 alloys – MnSi, FeGe, *etc.*
P$2_1$3
metals or semiconductors



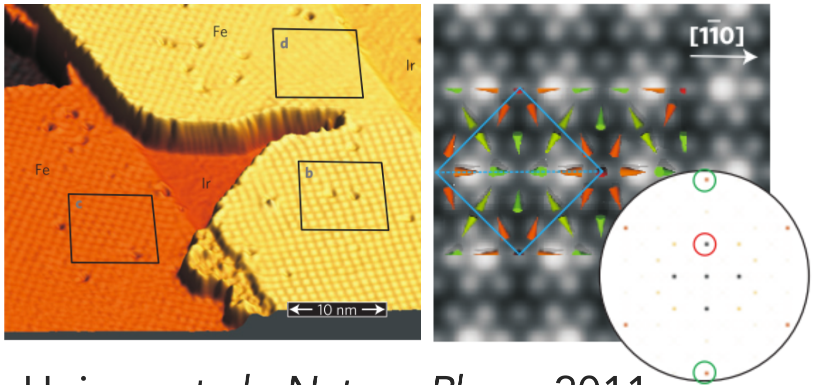
Cu_2OSeO_3
P$2_1$3
insulator



β-Mn alloys $Co_xZn_yMn_z$
P$4_1$32

Asymmetric heterostructures

- Monotomic layer of Fe on Ir(111)
- Ir|Co|Pt films



Heinze *et al.*, *Nature Phys.*, 2011

References for more information

U.K. Rößler, A.A. Leonov, A.N. Bogdanov, Chiral Skyrmionic matter in non-centrosymmetric magnets, J. Phys. Conf. Ser. 303 (2011) 012105. doi:10.1088/1742-6596/303/1/012105.

N. Nagaosa, Y. Tokura, Topological properties and dynamics of magnetic skyrmions, Nat. Nanotechnol. 8 (2013) 899–911. doi:10.1038/nnano.2013.243.

H.-B. Braun, Topological effects in nanomagnetism: from superparamagnetism to chiral quantum solitons, Adv. Phys. 61 (2012) 1–116. doi:10.1080/00018732.2012.663070.