Stabilizing skyrmions in multiferroics materials

Bertrand Dupé

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www.tom.uliege.be

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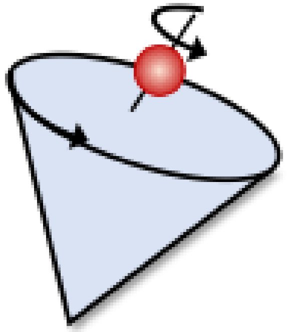
European School on Magnetism 2026

Spin-orbit driven magnetic phenomena

Ångström laboratory, Uppsala University, Sweden
August 17-28, 2026



Enjoy ten days of fascinating topics around magnetism at the oldest university of Scandinavia. Lectures and hands-on sessions will cover fundamental aspects, theoretical modelling as well as experimental characterization of a variety of topics:

- Nanomagnetism
- Ultrafast magnetization dynamics
- Spin-orbit torques
- Spin-dependent transport
- Spin and orbital Hall effect
- Skyrmions
- Permanent magnets
- 2D magnets
- AFM spintronics
- Altermagnetism...

Registration fee (including accommodation and lunch)

Onsite: 700 €, Online: 300 €

Information: WEBSITE

Organization:
ESM chair: Assoc. Prof. Biplab Sanyal
ESM co-chair: Dr. Heike Herper

UPPSALA UNIVERSITET

Ackowledgements

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Eric Bousquet
Philippe Ghosez
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Sebastian Meyer
Patrick Buhl

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Wulf Wulfhekel
Marie Hervé
Loic Mougel

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Ivan Lemesh

Stefan Blügel
Gustav Bihlmayer
Yuriy Mokrousov
Samir Lounis

Bin Xu

Laurent Bellaiche

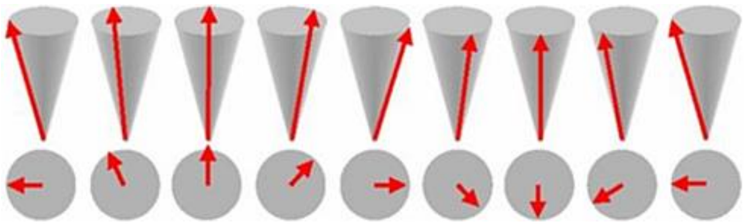
Topological orders in matter

Topological orders in Matter (TOM – tom.uliege.be)

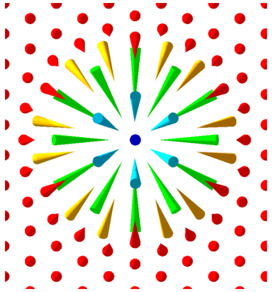
Magnonics and thermal driven long range excitations

Mexx Regout

In collaboration with
Matthieu Verstraete



Topological magnetic textures in real space (skyrmions, merons…)



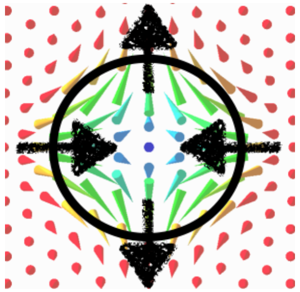
Sebastian Meyer
Olivier Gonnet

Topological orders in matter

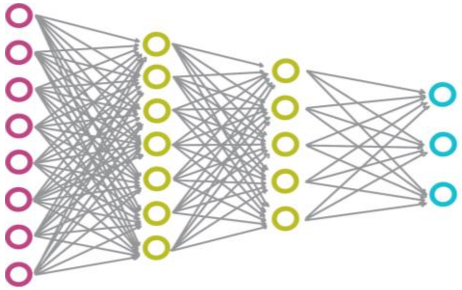
Github.com/bertdupe/Matjes

Topology and transport properties (Majorana states…)

In collaboration with
Marie Hervé
Tristan Cren
Wulf Wulfhekel



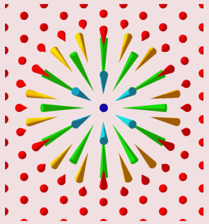
Artificial intelligence and topology



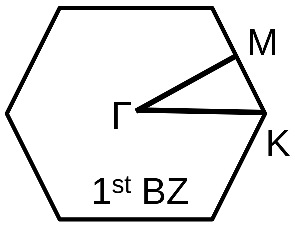
Xavier Bosch

Outline

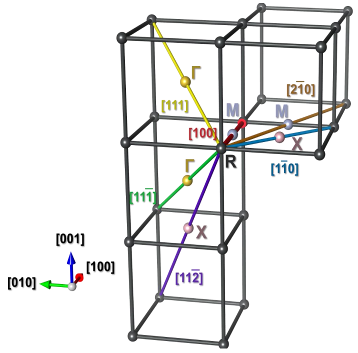
- Introduction on magnetic skyrmions
  - The discovery
  - The racetrack memory
  - Topology and stability



- The different magnetic interactions
  - Origin of the DM interaction
  - Obtaining magnetic interactions from density functional theory
  - Some examples of use



- Isolated skyrmions in Multiferroics
  - $BiFeO_3$ (BFO) as a good playground
  - Determining the magnetic interactions in BFO
  - Using strain to tune the interactions in BFO

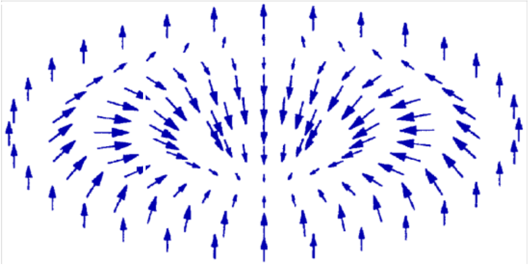


Skyrmions in bulk magnetic materials

Micromagnetic model prediction

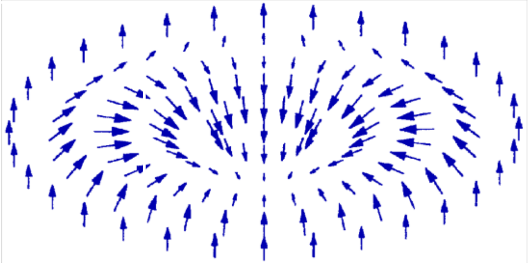
Existence of magnetic skyrmions

on a micrometer length scale



A. N. Bogdanov & D. A.Yablonskii, *Sov. Phys. JETP* **68**, 101 (1989)

Skyrmions in bulk magnetic materials



Micromagnetic model prediction

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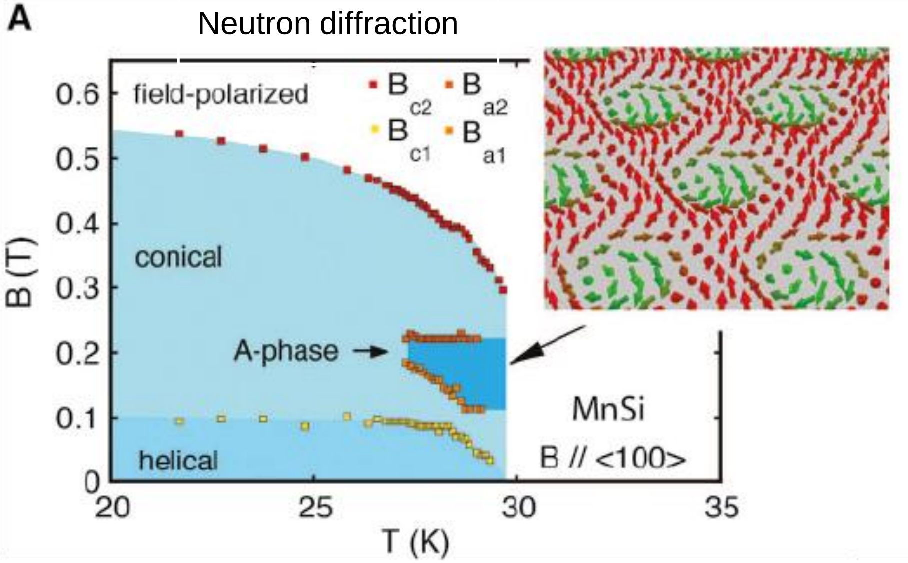
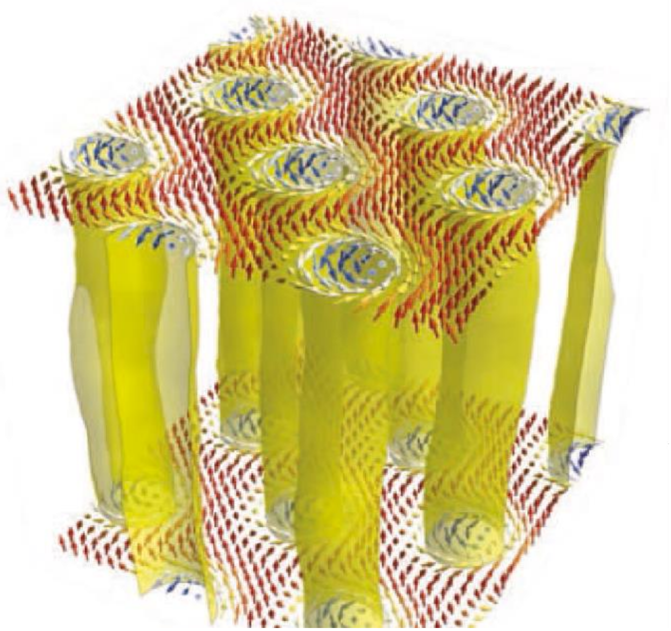
Experimental discovery





S. Mühlbauer *et al.*, Science **323**, 915 (2009)
A. Neubauer *et al.*, PRL **102**, 186602 (2009)
X. Z. Yu *et al.*, Nature **465**, 901 (2010)
M. Lee *et al.*, PRL **102**, 186601 (2009)

P. Milde *et al.*, *Science* **340**, 1076 (2013)

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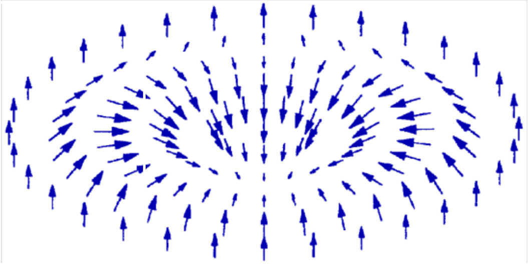

A. N. Bogdanov & D. A.Yablonskii, *Sov. Phys. JETP* **68**, 101 (1989)

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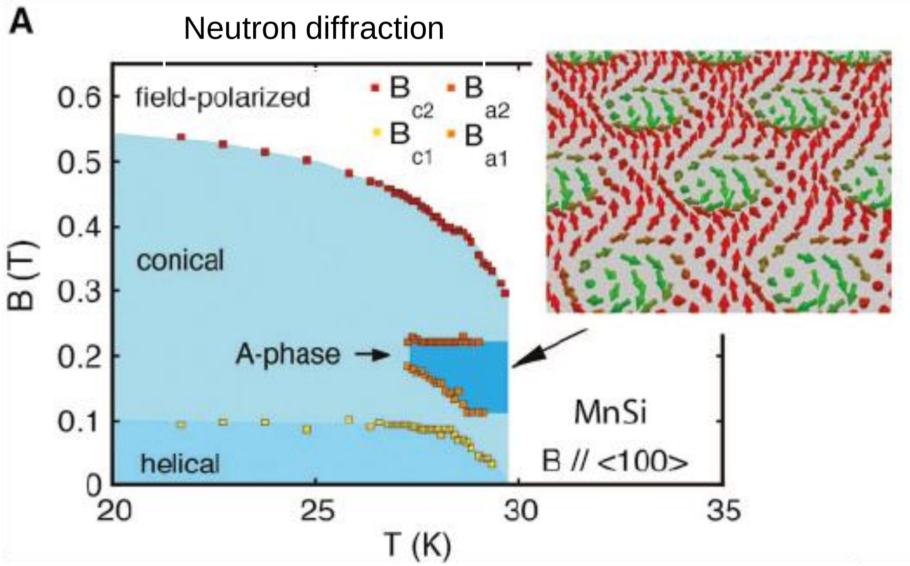
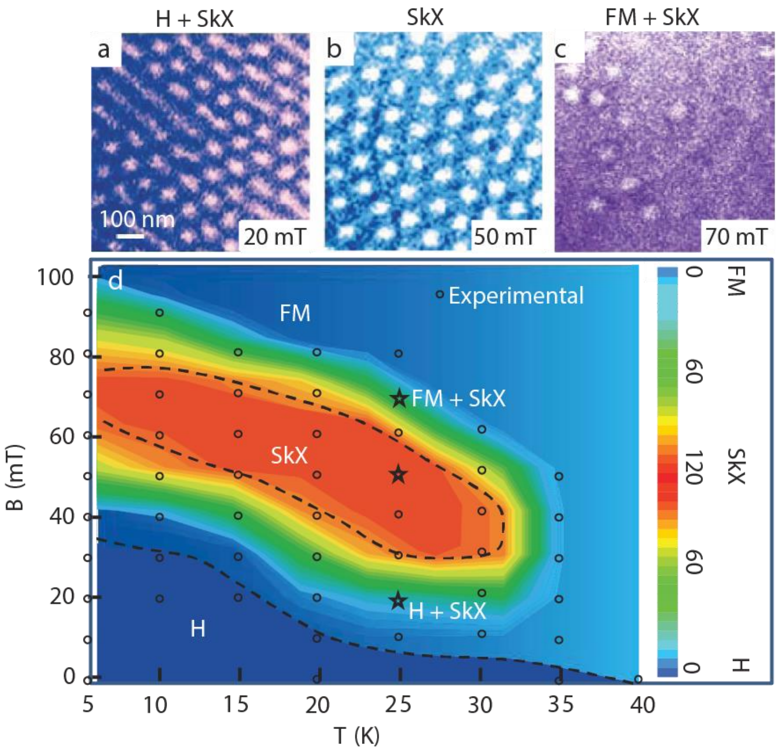


Lorentz TEM



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Topological orders in matter

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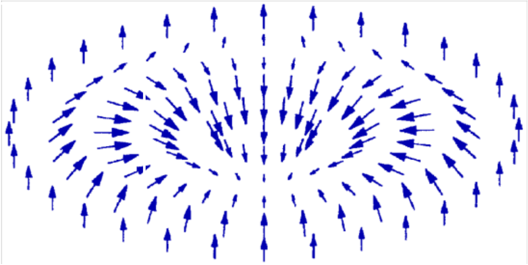

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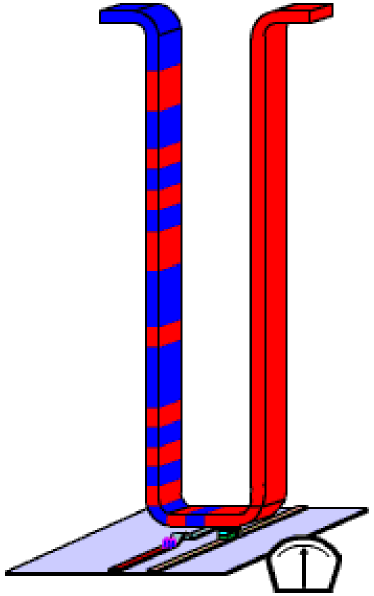

<u>race-track</u>

S. Parkin *et al.*, Science **320,** 190 (2008)

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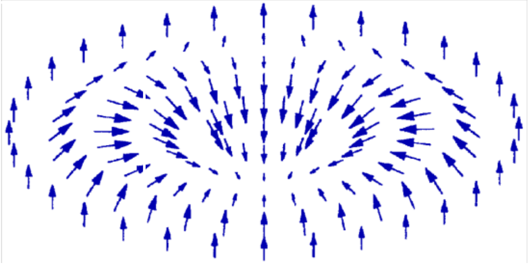
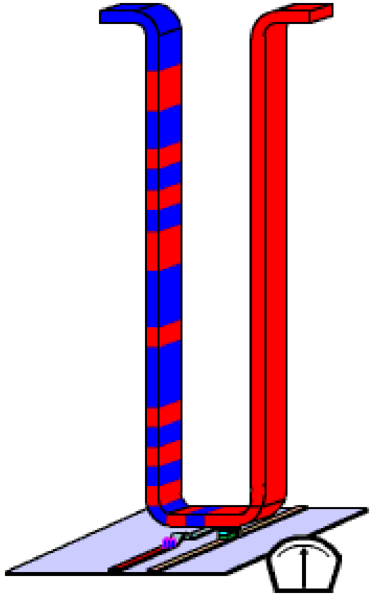
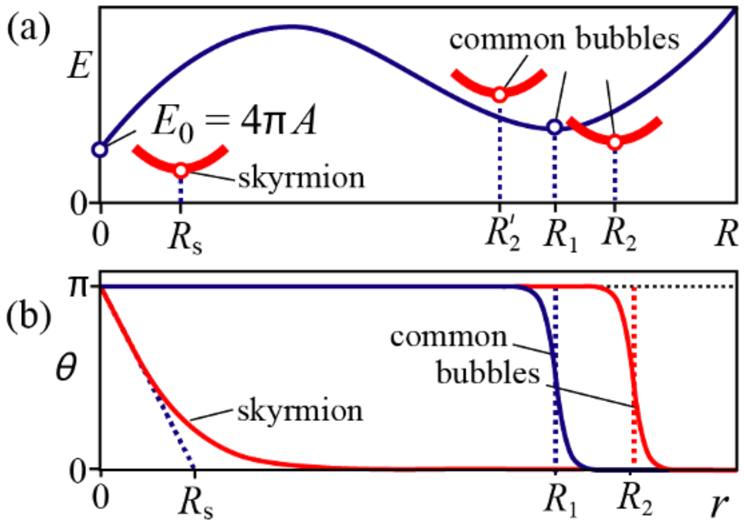


A. N. Bogdanov & D. A.Yablonskii, *Sov. Phys. JETP* **68**, 101 (1989)



Skyrmion race-track



S. Parkin *et al.*, Science **320,** 190 (2008)
A. Fert *et al.*, Nature Nanotech. **8**, 152 (2013)
W. Jiang *et al.*, Science **349**, 283 (2015)
K. Litzius *et al.*, Nature Phys. **13**, 170 (2016)

N. S. Kiselev *et al.*, J. Phys D **44**, 39201 (2011)

Skyrmions in bulk magnetic materials

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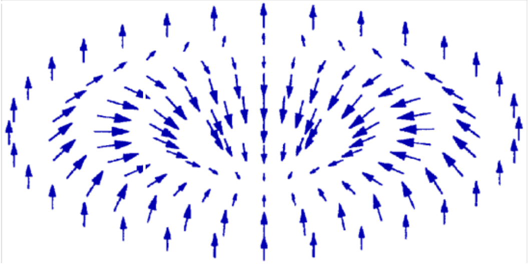

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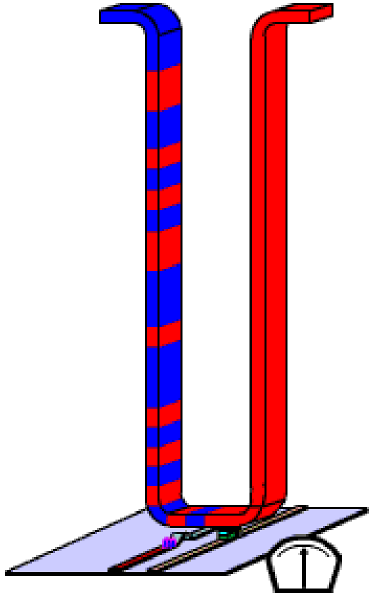
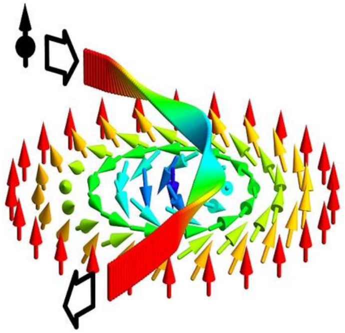


Skyrmion race-track

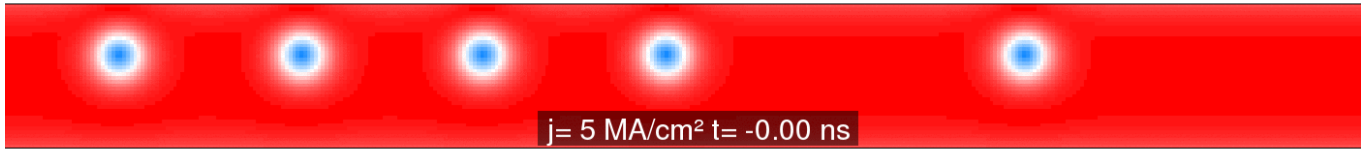


$$\mathbf{F}_{\sigma k} = e\mathbf{E} + \mathbf{F}_H + q_\sigma^e \cdot \mathbf{v}_k \times \mathbf{B}^e$$

$$\mathbf{B}^e = \frac{\hbar}{2}\mathbf{n}\left(\nabla_x \mathbf{n} \times \nabla_y \mathbf{n}\right)$$

$$\mathbf{E} = \hbar\mathbf{n}(\nabla_r \mathbf{n} \times \nabla_t \mathbf{n})$$

T. Schulz *et al.*, Nature Physics **8**, 301 (2012)



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K. Litzius *et al.*, Nature Phys. **13**, 170 (2016)

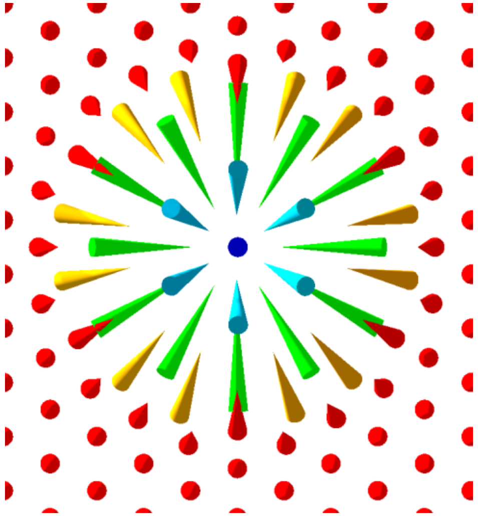
Skyrmions and topological charge

Skyrmion number (topological charge) of a vector field ***n***(*x,y):*

$$S = \frac{1}{4\pi}\int \mathbf{n}\cdot\left(\nabla_{\mathbf{x}}\mathbf{n}\times\nabla_{\mathbf{y}}\mathbf{n}\right)\mathrm{dA}$$

Ferromagnet (*S*=0): topologically trivial state

Skyrmion (*S*=+1)



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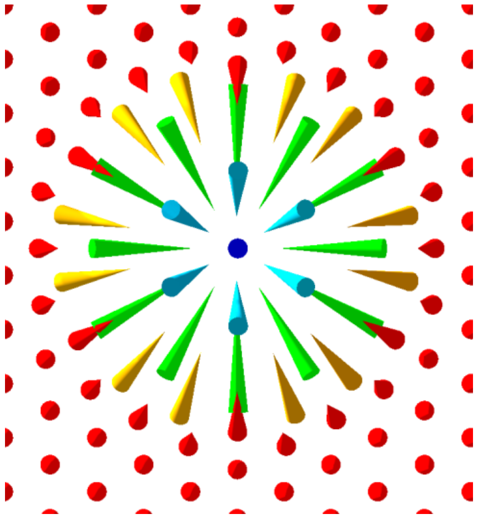
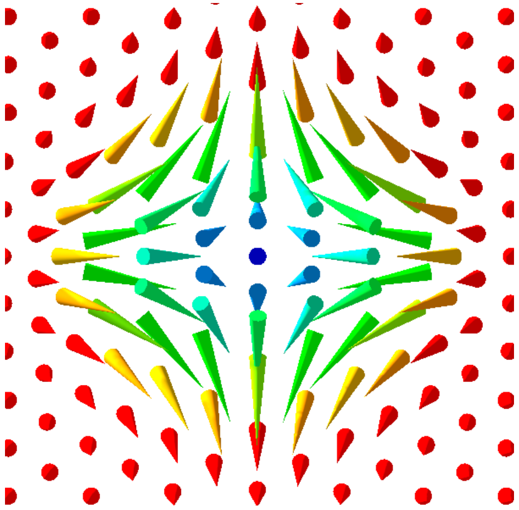
Ferromagnet (S=0): topologically trivial state

Skyrmion (S=+1)

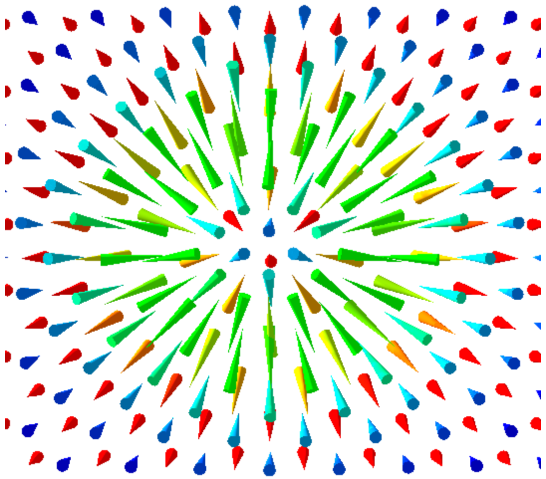


Antiskyrmion (S=−1)



L. Camosi *et al., Phys. Rev. B* **95**, 214422 (2017)
M. Hoffmann *et al., Nature Commun.* **8**, 308 (2017)
A. Nayak *et al., Nature* **548**, 561 (2017)

Skyrmion AFM (S=+1)



J. Barker *et al.,* Phys. Rev. Lett. **116**, 147203 (2016)
S. Meyer *et al.,* Phys. Rev. B **96**, 094408 (2017)
W. Legrand *et al.,* Nat. Materials (2019)
T. Dohi *et al.,* Nat. Commun (2019)
L. Desplat *et al.*, Phys. Rev. B **104**, L060409 (2021)

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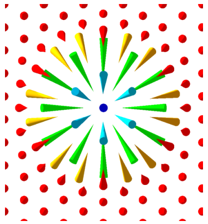
  - The racetrack memory
  - Topology and stability



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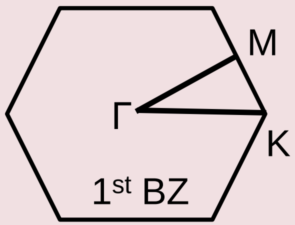

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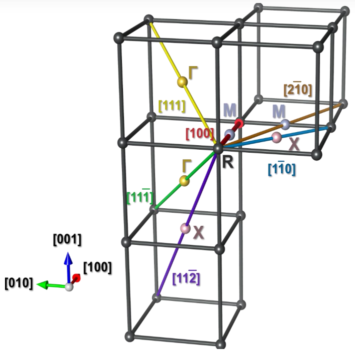
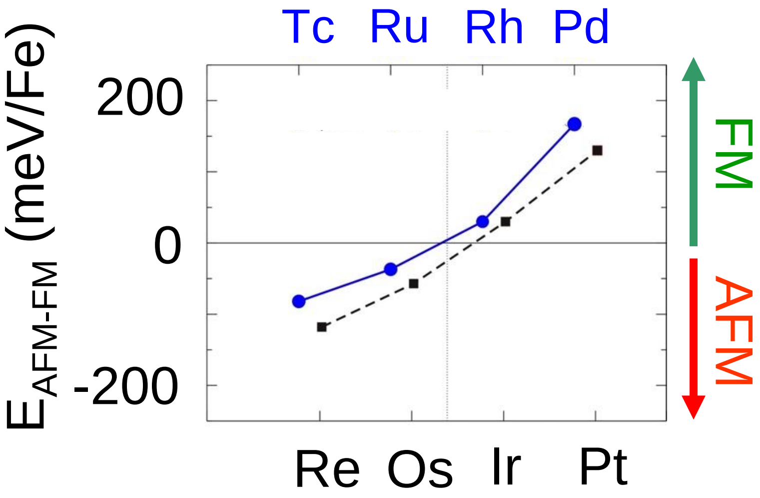
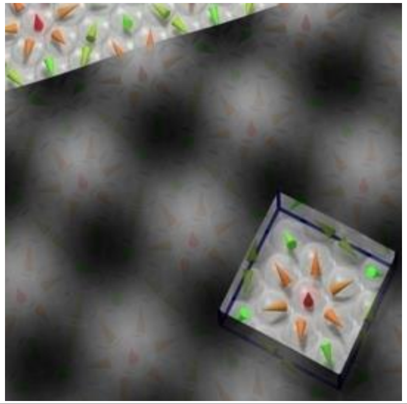


Tuning the magnetic exchange interaction in Fe monolayer



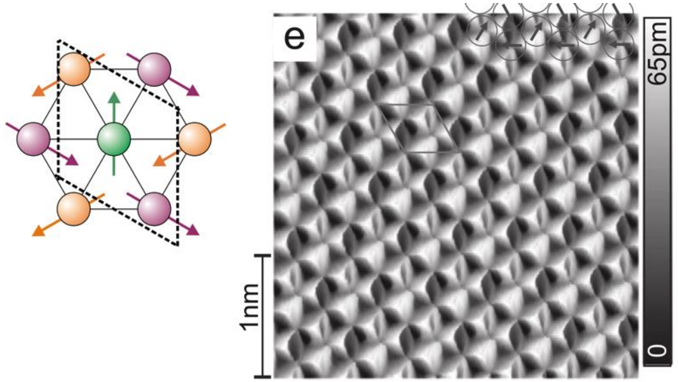
B. Hardrat *et al* PRB **79**, 094411 (2009)

Fe/Ir(111): nano-skyrmion lattice



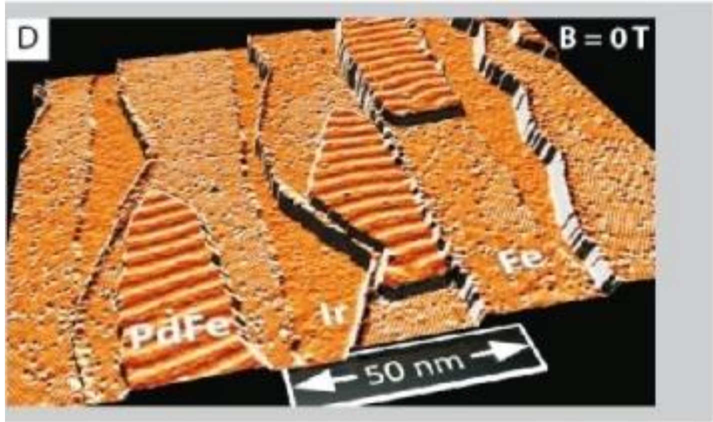
S. Heinze *et al* Nat. Phys. **7**, 713 (2011)

Fe/Re(0001) Néel state



S. Ouazi *et al* Sur. sci. **630**, 280 (2014)
S. Ouazi *et al* PRL **112**, 076102 (2014)

Pd/Fe/Ir(111) spin spiral ground state



N. Romming *et al* Science **341**, 636 (2013)
B. Dupé *et al* Nature Comm. **5**, 4030 (2014)

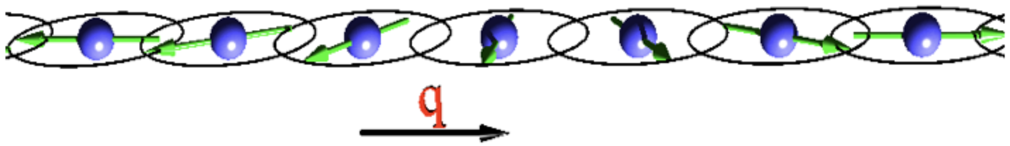
Topological orders in matter

Spin spiral energy calculation

Density-functional theory (DFT) using the FLEUR code:

- energy of non-collinear magnetic structures
- energies of spiral spin-density waves

Spin spirals



$$E(\mathbf{q}) = -N\sum_{\delta} J_{0,\delta}e^{-i\mathbf{R}_{\delta}\mathbf{q}}$$

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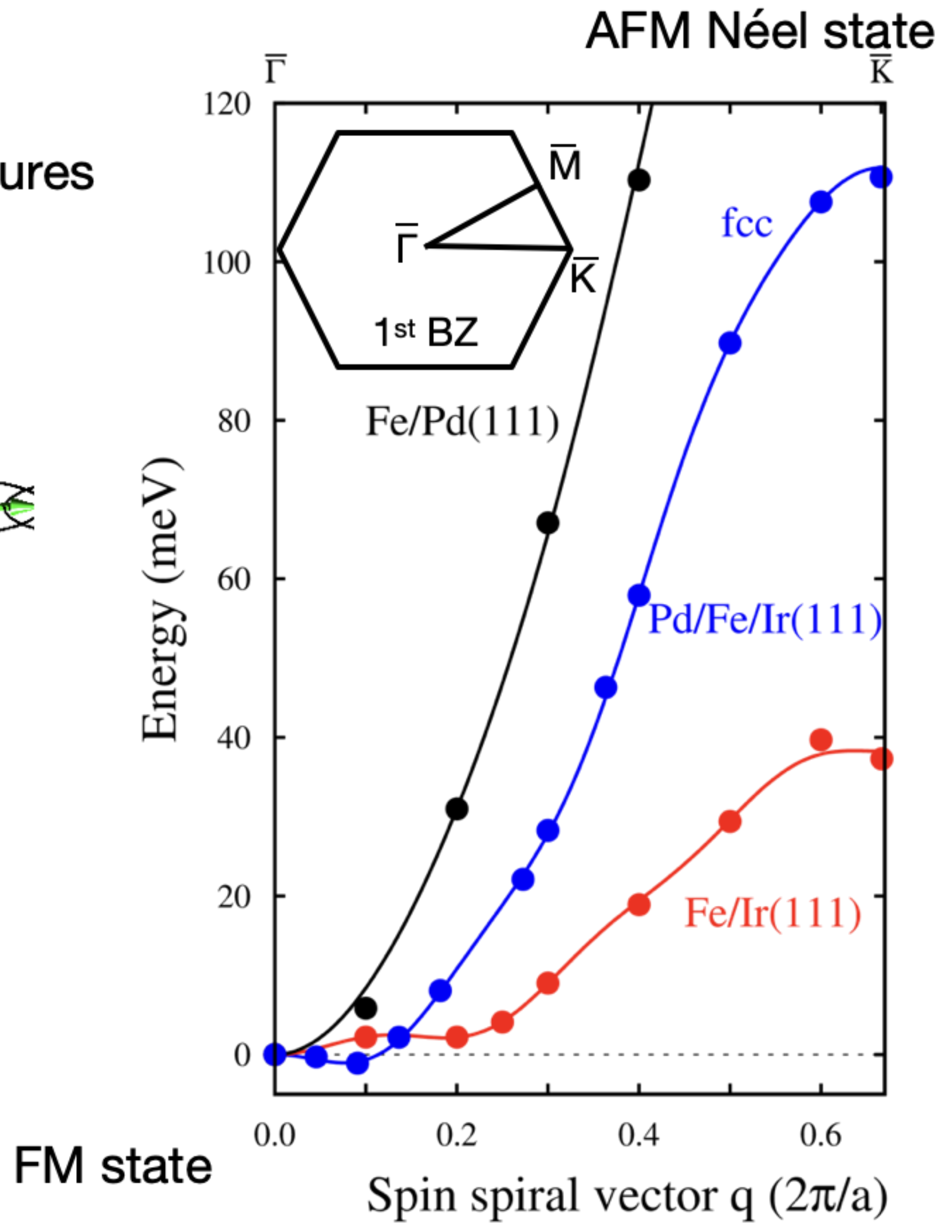
Fleur

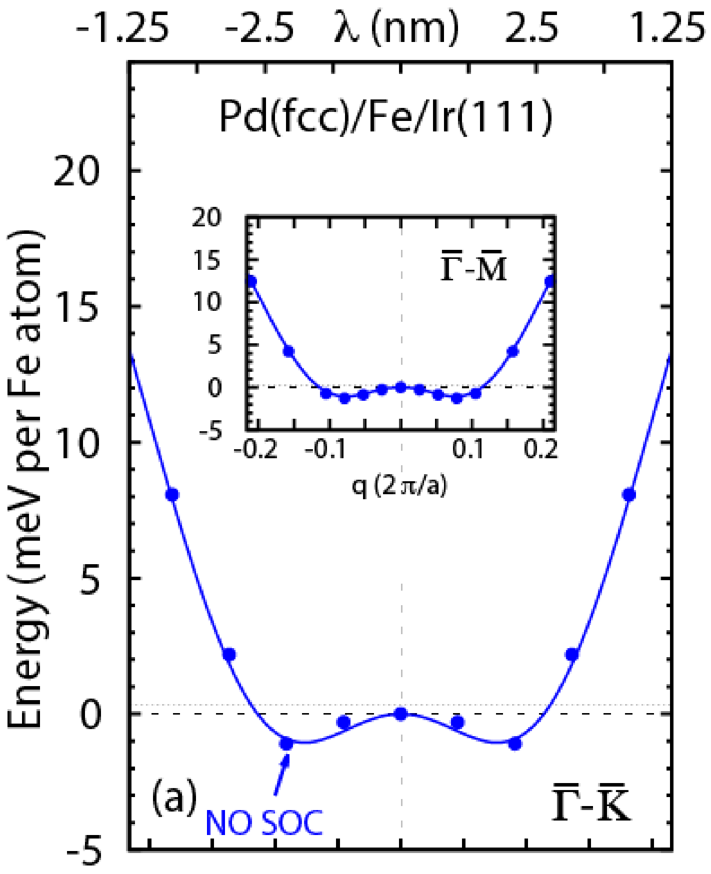
developed @ FZ Jülich

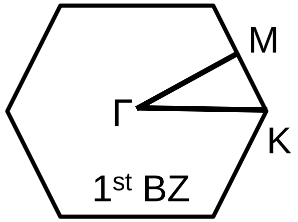


Heisenberg Hamiltonian parametrization Pd/Fe/Ir(111)

Spin Hamiltonian

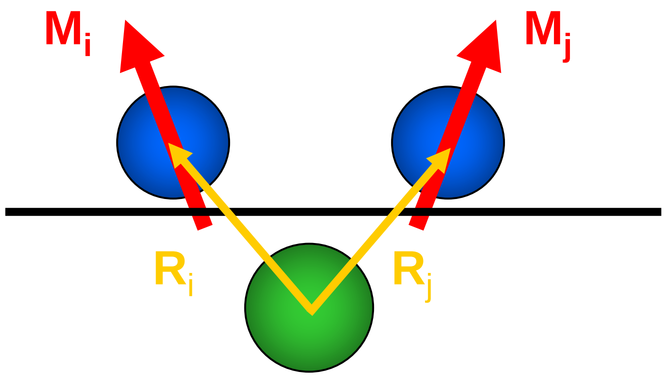
$$H = -\sum_{i,j} \mathbf{M}_i J_{ij} \mathbf{M}_j$$





Origin of the DM interaction at metal surface

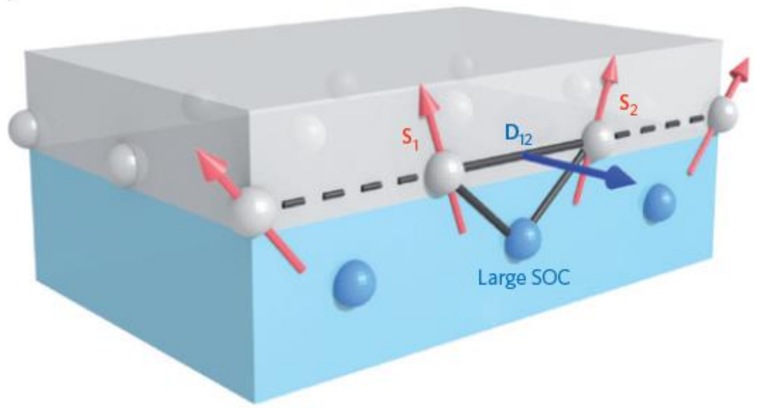
Interaction of two magnetic atoms via a surface atom with strong spin-orbit coupling



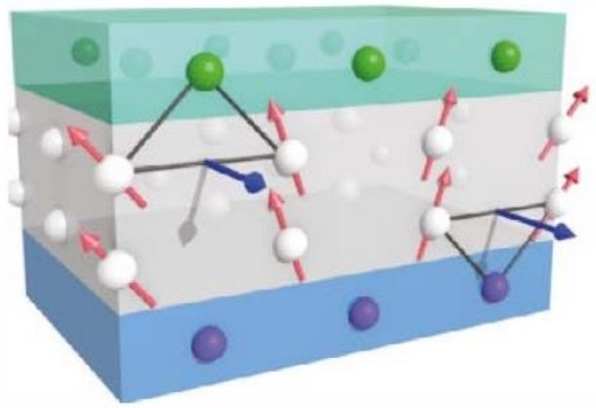
$$H_{DM} \propto -V(\xi)(\mathbf{R}_i \times \mathbf{R}_j)(\mathbf{M}_i \times \mathbf{M}_j)$$

$$H_{DM} \propto -\mathbf{D}_{ij}(\mathbf{M}_i \times \mathbf{M}_j)$$

Levy & Fert, Phys. Rev Lett. **44**, 1538 (1980)



J. Sampaio *et al.,* Nature Nanotech. **8**, 839 (2013)
O. Boulle *et al.,* Nature Nanotech. **5**, 449 (2016)



C. Moreau-Luchaire *et al.,* Nature Nanotech. **11**, 444 (2016)

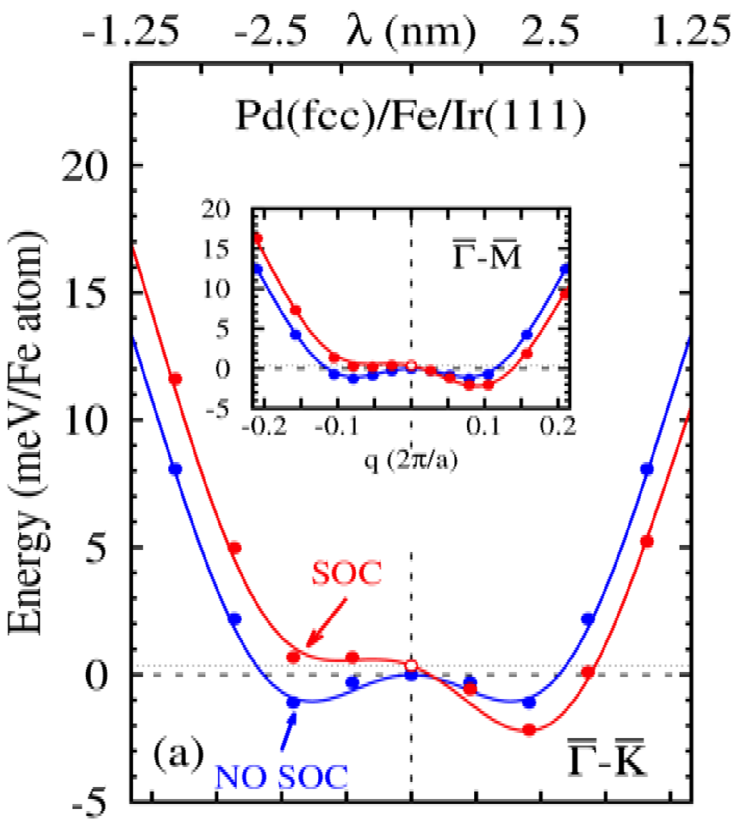
Heisenberg Hamiltonian parametrization: DMI

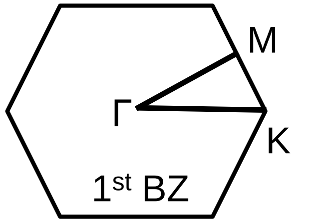
Spin Hamiltonian

$$H = -\sum_{i,j} \mathbf{M}_i J_{ij} \mathbf{M}_j$$

$$-\sum_{i} K M_z^2$$

$$-\sum_{i,j} \mathbf{D}_{ij} \cdot \left(\mathbf{M}_i \times \mathbf{M}_j\right)$$





Heisenberg Hamiltonian parametrization: DMI

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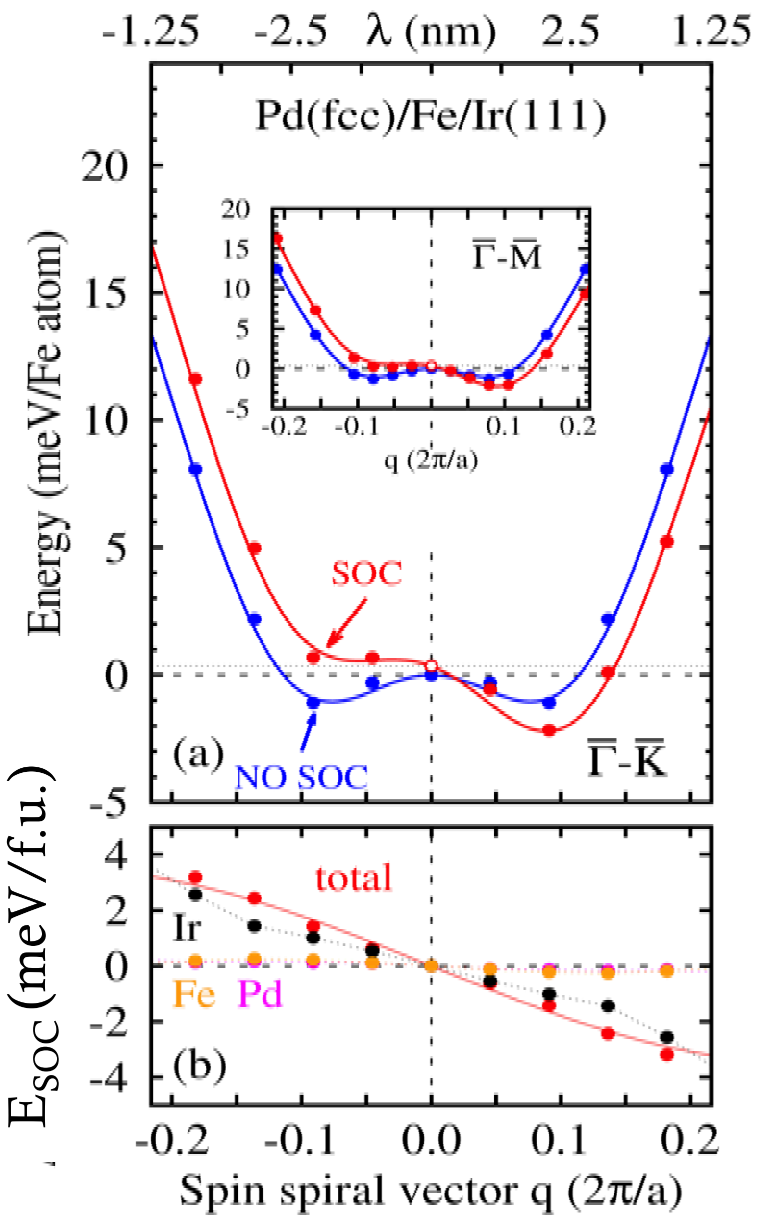
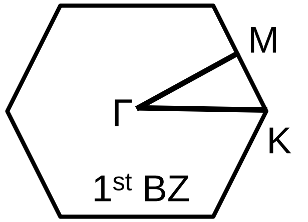




Topological orders in matter

Bertrand Dupé

Heisenberg Hamiltonian parametrization

Spin Hamiltonian solved by Monte-Carlo & spin dynamics

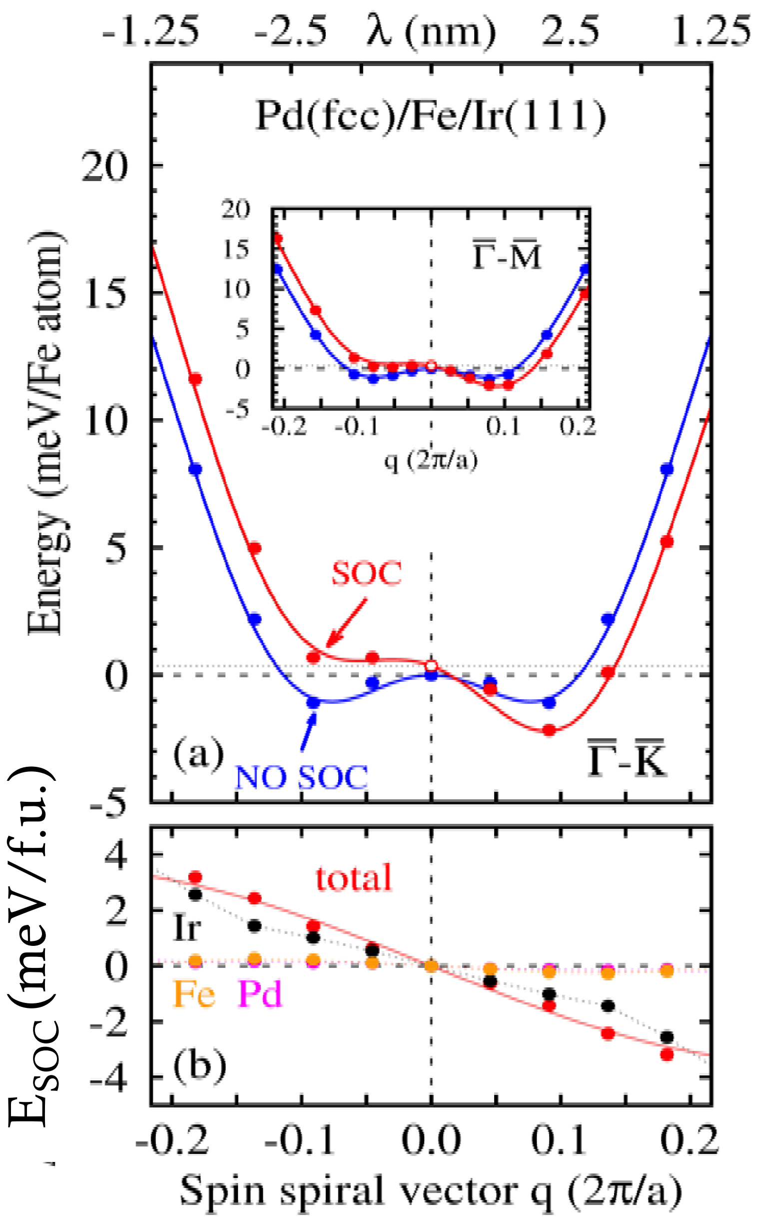
$$H = -\sum_{i,j} \mathbf{M}_i J_{ij} \mathbf{M}_j$$

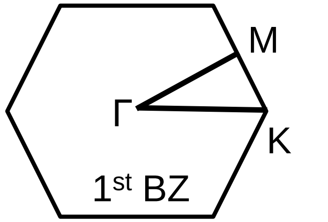
$$-\sum_{i} K M_z^2$$

$$-\sum_{i,j} \mathbf{D}_{ij} \cdot \left(\mathbf{M}_i \times \mathbf{M}_j\right)$$

$$-\sum_{i} \mathbf{M}_i \mathbf{B}$$

$$-\sum_{i,j} B_{ij}\left(\mathbf{M}_i \cdot \mathbf{M}_j\right)^2 + 4\text{spin}$$





Topological orders in matter

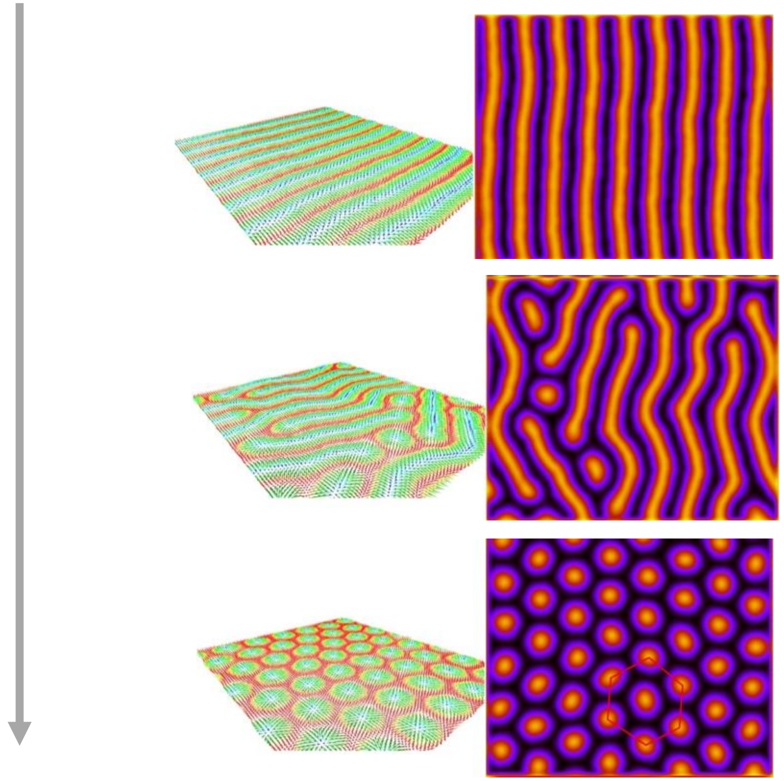
Bertrand Dupé

Phase diagram of of Pd/Fe(fcc)/Ir(111) at 0K

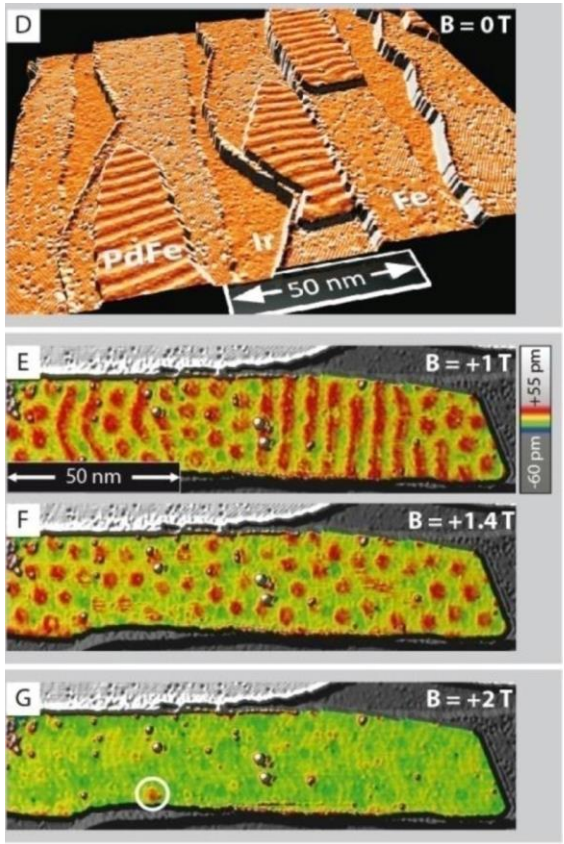
Spin spiral pitch from Monte Carlo: 5.4nm

Monte-Carlo Simulation

B



Experiments

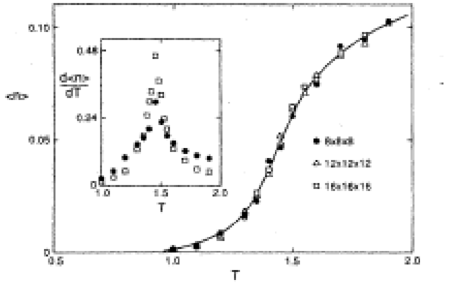


B. Dupé *et al* Nature Commun. **5**, 4030 (2014)
E. Simon *et al* Phys. Rev. B **90**, 094410 (2014)

N. Romming *et al* Science **341**, 636 (2013)
N. Romming *et al* Phys. Rev. Lett. **114**, 177203 (2015)

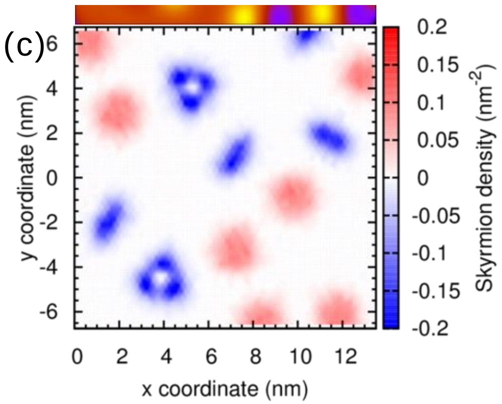
Phase diagram of of Pd/Fe(fcc)/Ir(111)

Creation of skyrmion/antiskyrmion density pairs



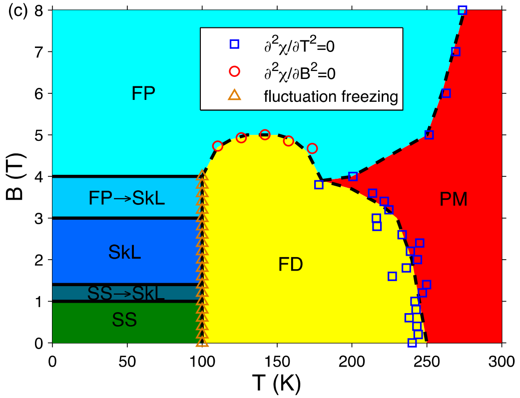
M. Lau *et al.*, Phys Rev B **39**, 7212 (1989)
Y. Nahas *et al.*, Phys. Rev. Lett. **119**, 117601 (2017)

Integrated skyrmion density is no order parameter



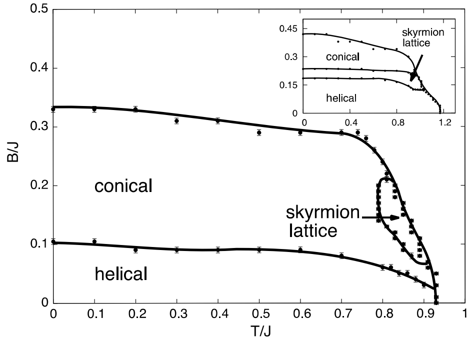
B. Dupé *et al.*, New J. Phys **18**, 055015 (2016)

Pd/Fe/Ir(111)



L. Rosza *et al.*, PRB **93**, 024417 (2016)

MnSi

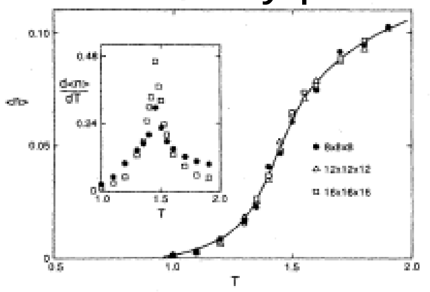


S. Bürhandt *et al.*, PRB **88**, 195137 (2013)

Topological orders in matter

Phase diagram of of Pd/Fe(fcc)/Ir(111)

Creation of skyrmion/antiskyrmion density pairs



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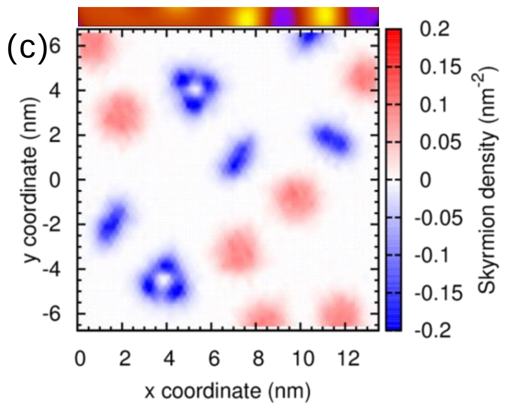
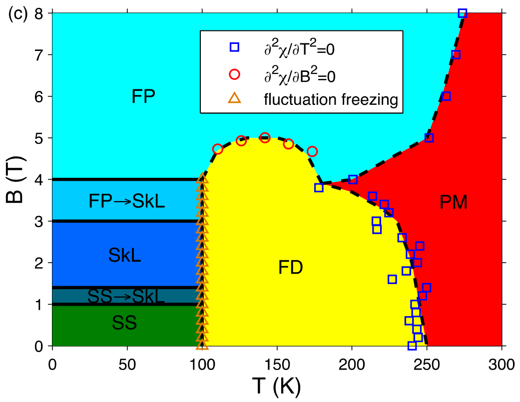
Y. Nahas *et al.*, Phys. Rev. Lett. **119**, 117601 (2017)

Integrated skyrmion density is no order parameter



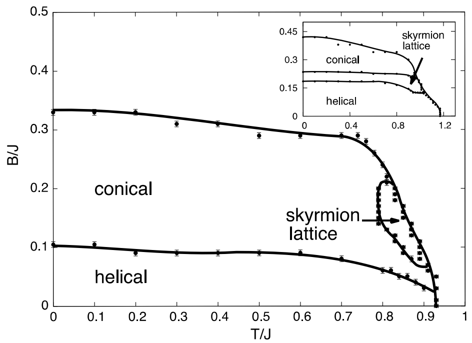
B. Dupé *et al.*, New J. Phys **18**, 055015 (2016)

Pd/Fe/Ir(111)



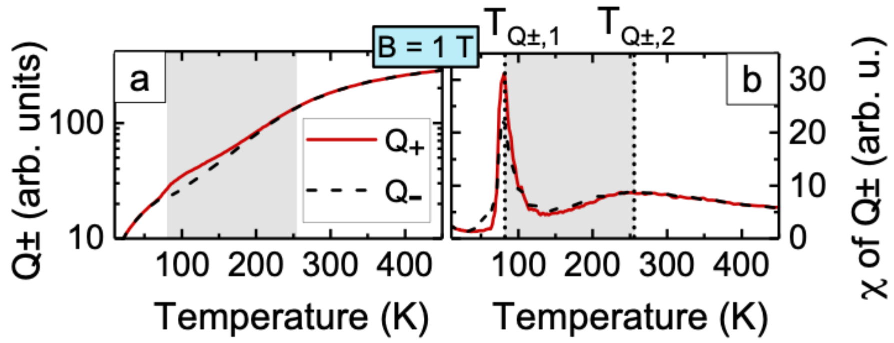
L. Rosza *et al.*, PRB **93**, 024417 (2016)

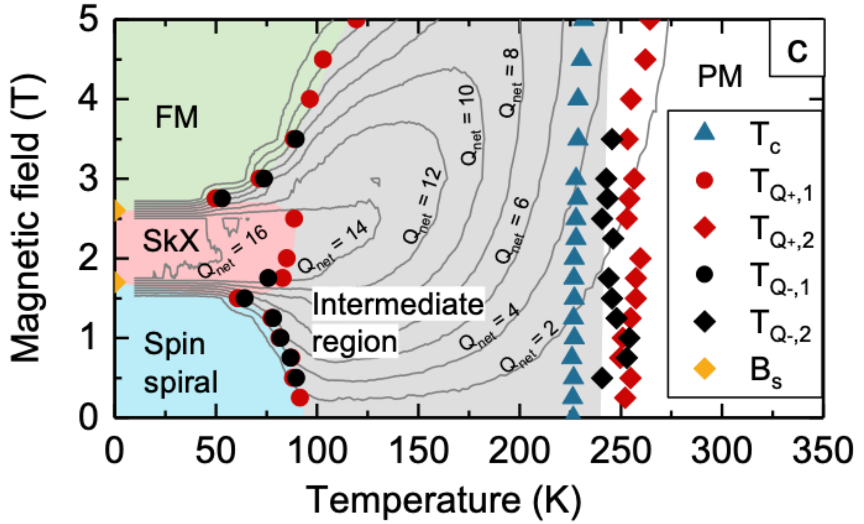
MnSi



S. Bürhandt *et al.*, PRB **88**, 195137 (2013)

Parallel tempering Monte Carlo

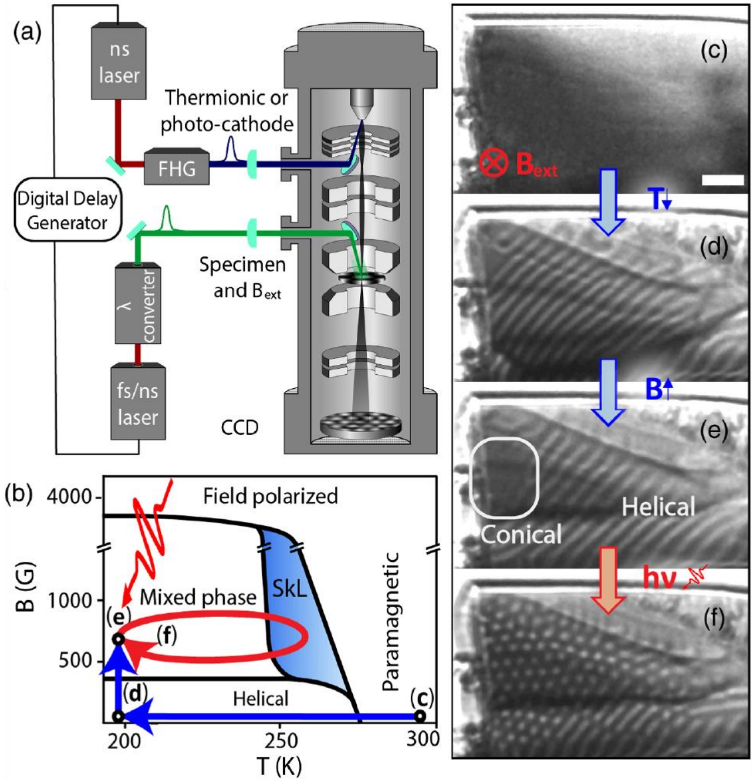




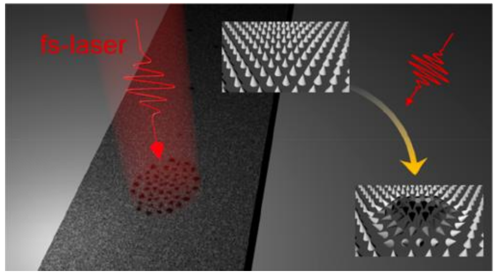
M. Böttcher *et al.*, New Journ. Phys. **20**, 103014 (2018)

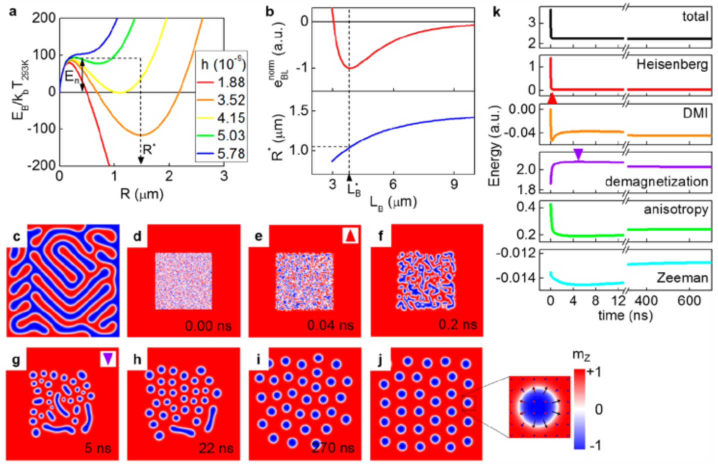
Temperature skyrmion-antiskyrmion generation

FeGe



TaOx/CoFeB/Ta



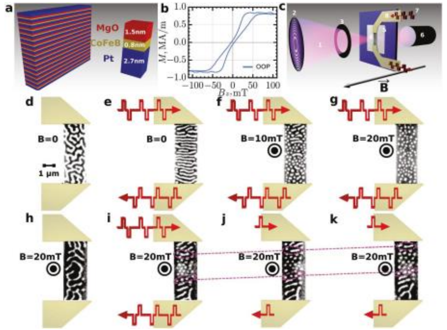


G. Berruto *et al. Phys. Rev.* Lett. **120**, 117201 (2018)

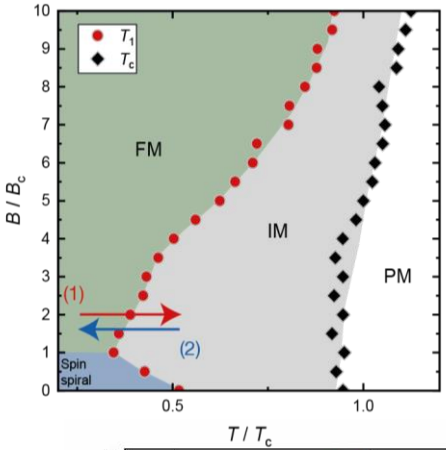
S.-G. Je *et al.* NanoLetters **18**, 7362 (2018)

Temperature skyrmion-antiskyrmion generation

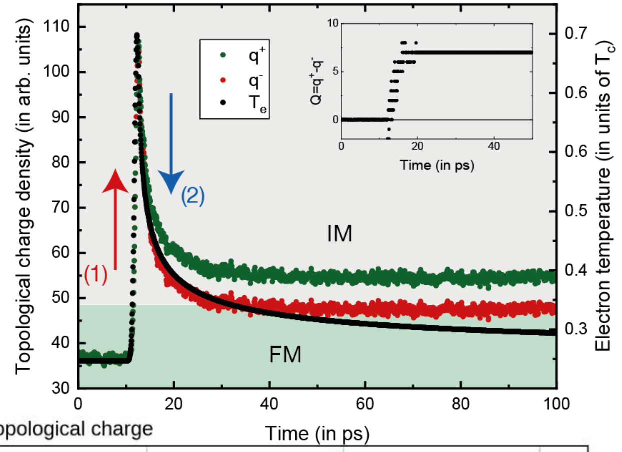
[MgO/Co/Pt]$_n$



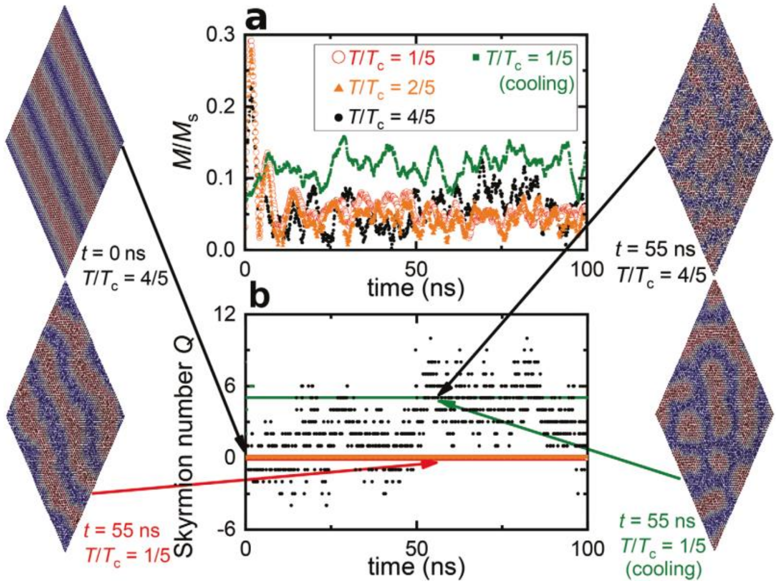
Phase diagram of [MgO/Co/Pt]$_n$

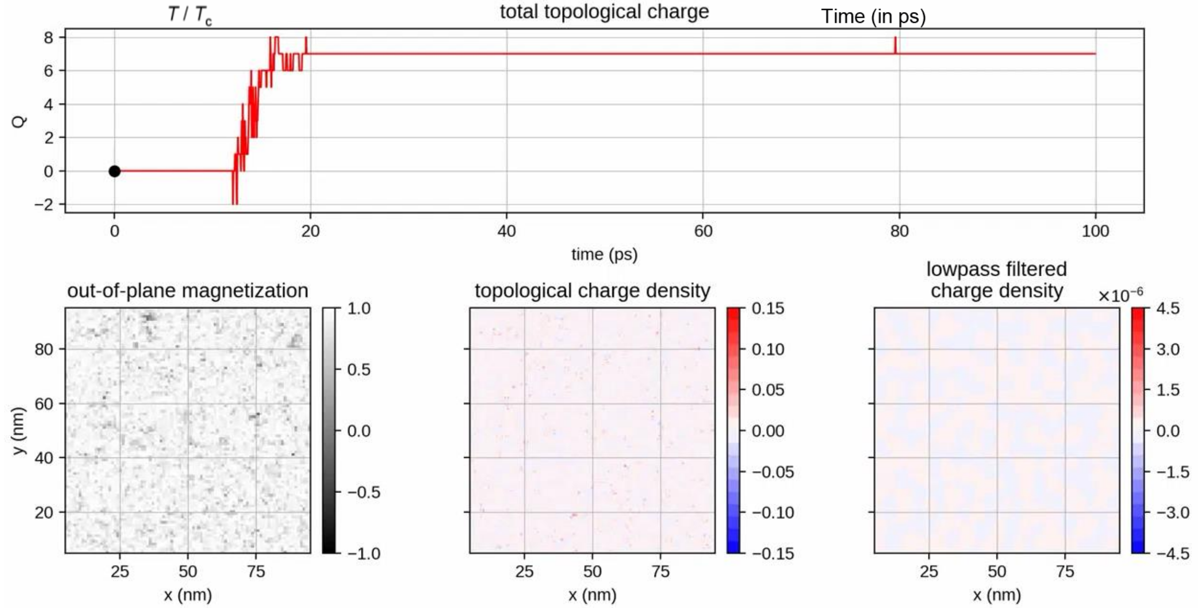


electron temperature



Magnetization dynamics simulations



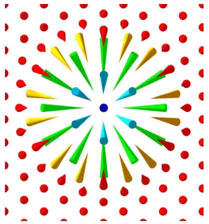


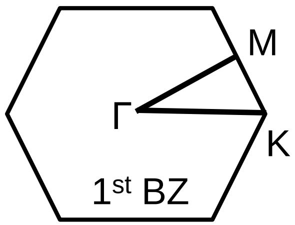
I. Lemesh, BD *et al.*, Advanced Materials **30**, 1805461 (2018)
F. Büttner *et al.*, Nature Mater. **20**, 30 (2021)

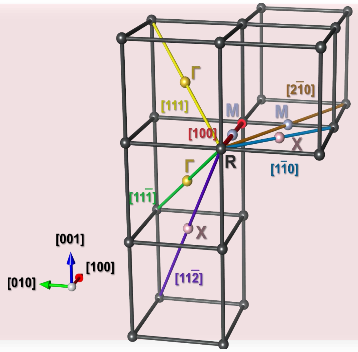
Topological orders in matter

Outline

- Introduction on magnetic skyrmions
  - The discovery
  - The racetrack memory
  - Topology and stability
- The different magnetic interactions
  - Origin of the DM interaction
  - Obtaining magnetic interactions from density functional theory
  - Some examples of use
- Isolated skyrmions in Multiferroics
  - $BiFeO_3$ (BFO) as a good playground
  - Determining the magnetic interactions in BFO
  - Using strain to tune the interactions in BFO

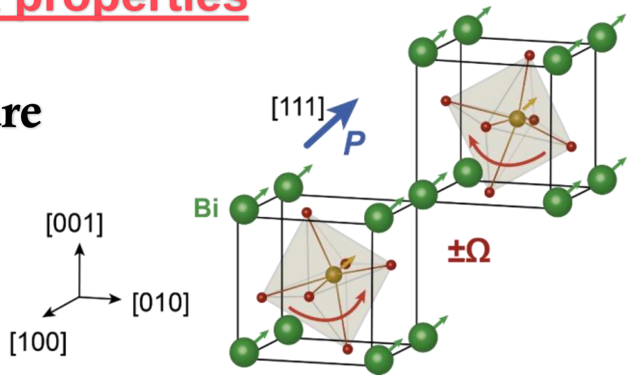






Order parameters of $BiFeO_3$

Bulk properties



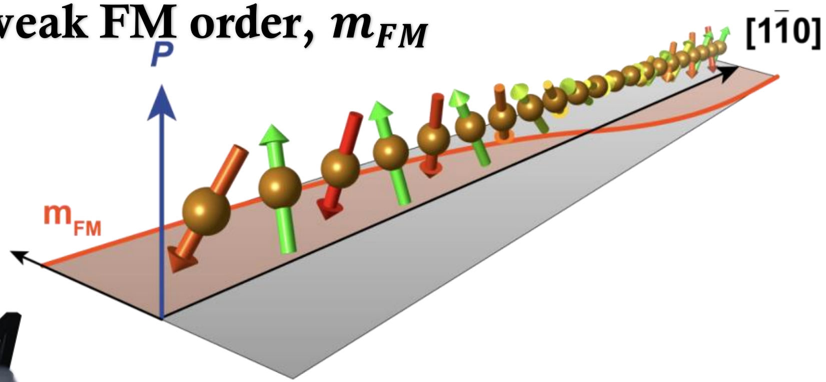
1. **Perovskite structure**
   Bi Cations
   Fe Cations
   O Anions

2. **Fe-Bi displacement**
   Polarization along [111] direction

$$P \approx \frac{90\mu C}{cm^2}, T_C = 1123\ \mathrm{K}$$

} *R3c*

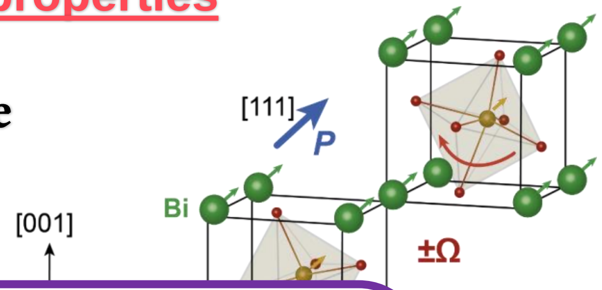
3. **Oxygen tilt in antiphase $\pm\Omega$**
4. **Local antiferromagnetic order with long-ranged spin cycloid, $\lambda \approx 62$ nm + weak FM order, m_{FM}**



Topological orders in matter

Order parameters of $BiFeO_3$

Bulk properties



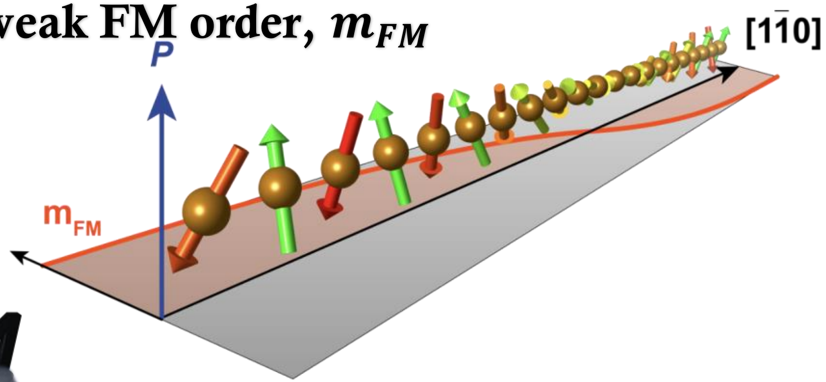
1. Perovskite structure
   Bi Cations
   Fe Cations
   O A…

Objective:

Investigation of different spin cycloids

2. Fe-…
   Pol…
   …βc

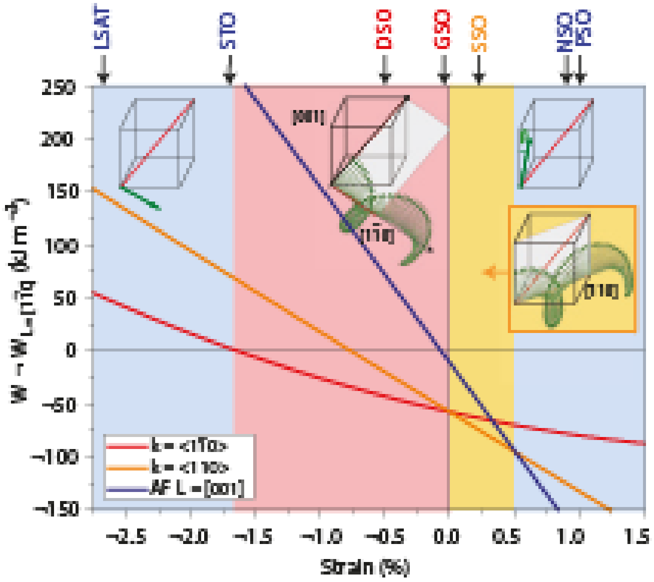
3. Oxygen tilt in antiphase $\pm\Omega$
4. Local antiferromagnetic order with long-ranged spin cycloid, $\lambda \approx 62$ nm + weak FM order, m_{FM}



Topological orders in matter

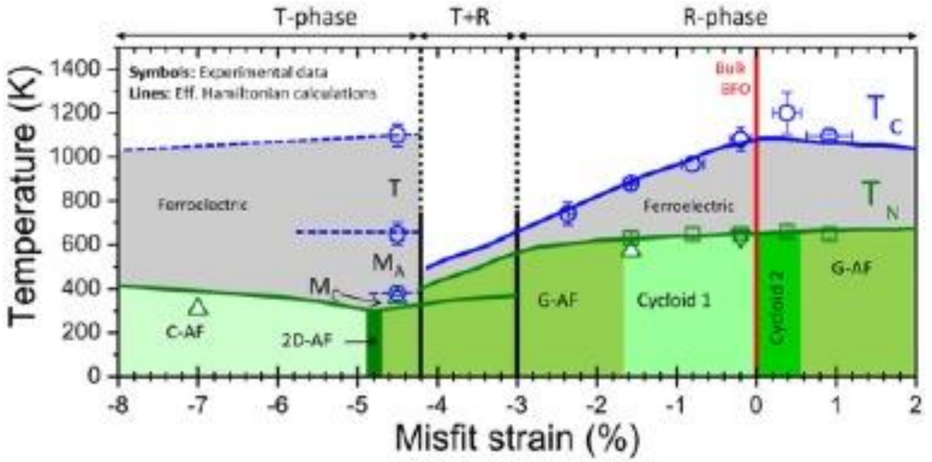
Magnetic properties and orders in BFO

Spin spirals from experiments



D. Sando, *et al*., Nature Mater. **12**, 641-646 (2013)

Computed phase diagram from effective Hamiltonian



D.Sando. *et al*., J. Phys.: Condens. Matter **26**, 473201 (2014)

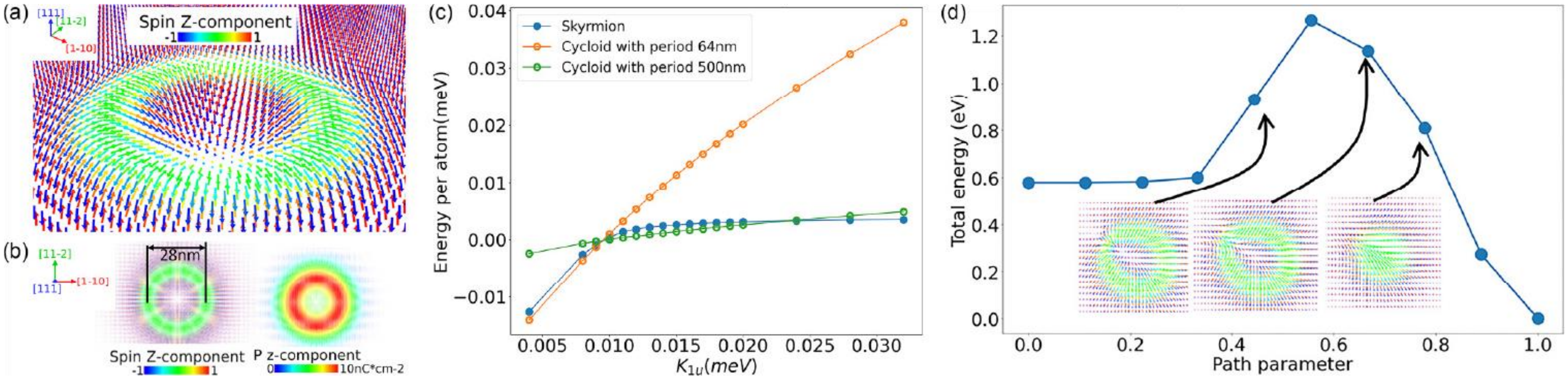
Experimental based Hamilmtonian

Heisenberg Hamiltonian obtained from Neutron diffraction
Easy axis anisotropy

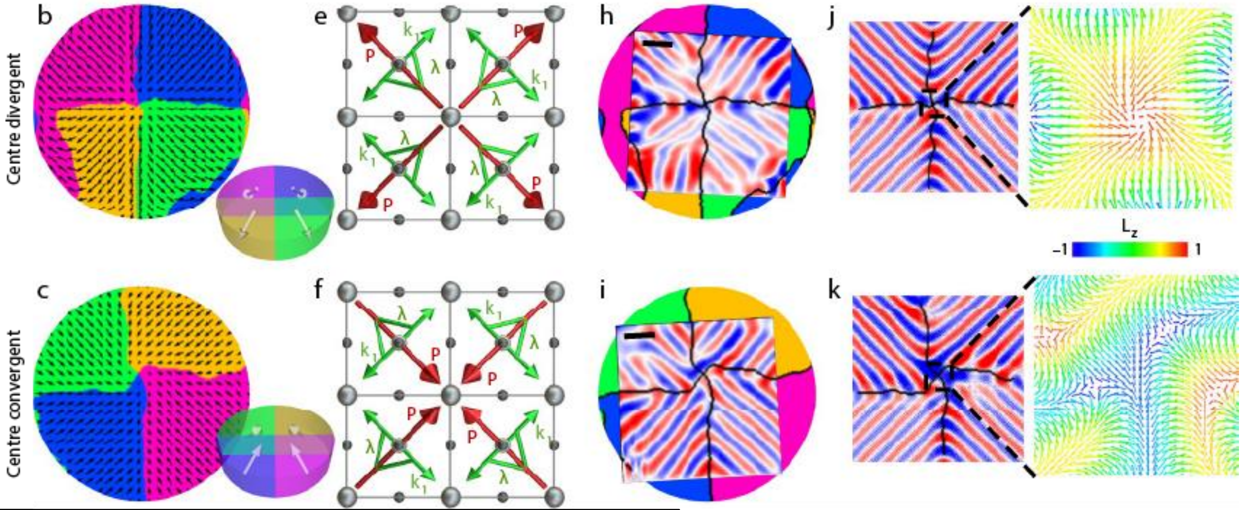
C. Weingart, *et al*., Phys. Rev. B **86,** 094413 (2012)
R. Fishman, Phys. Rev. B **87,** 134416 (2013)

Topological textures in BFO

Stable Skyrmion in BFO with imposed out-ou-plane anisotropy



Experimental observation of a skyrmion embedded in a spin spiral ground state

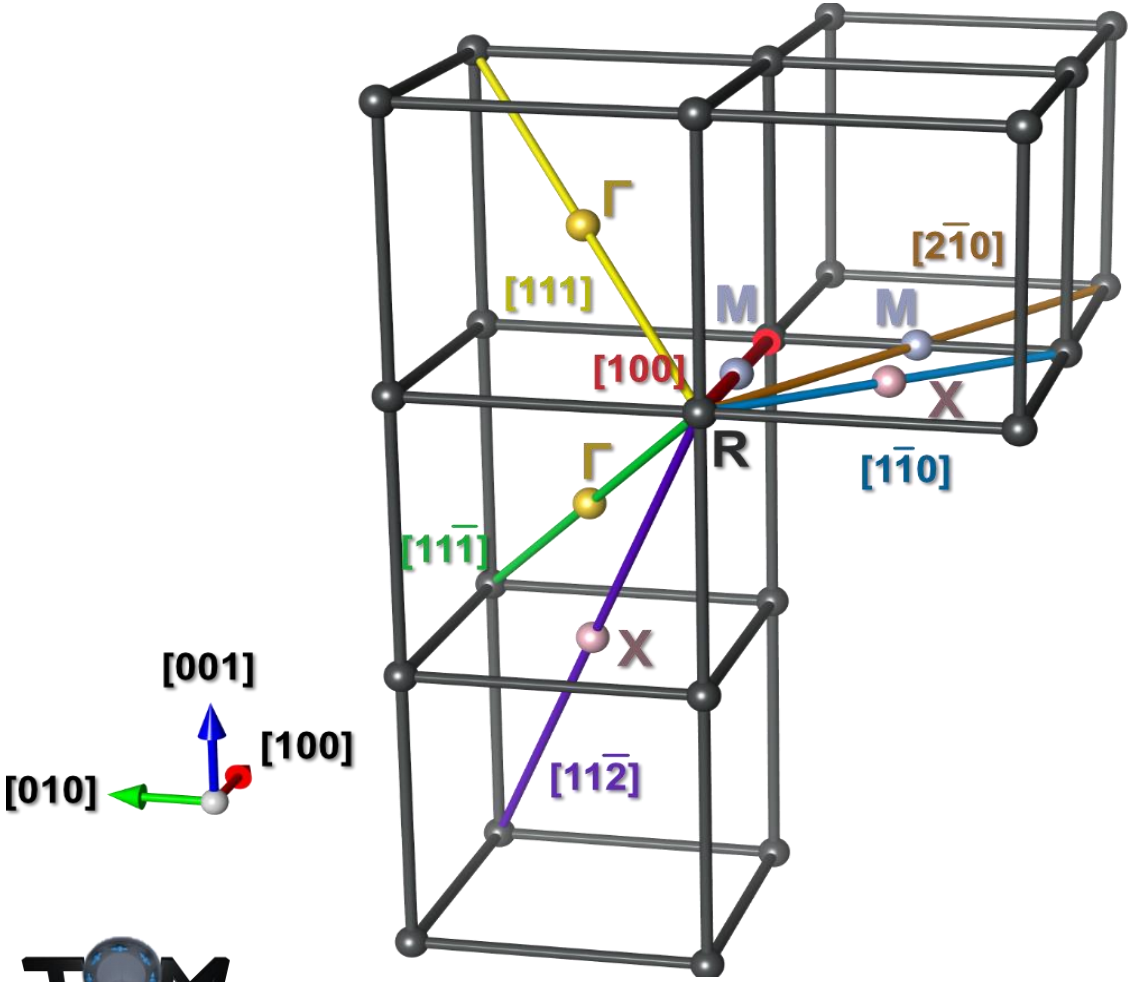


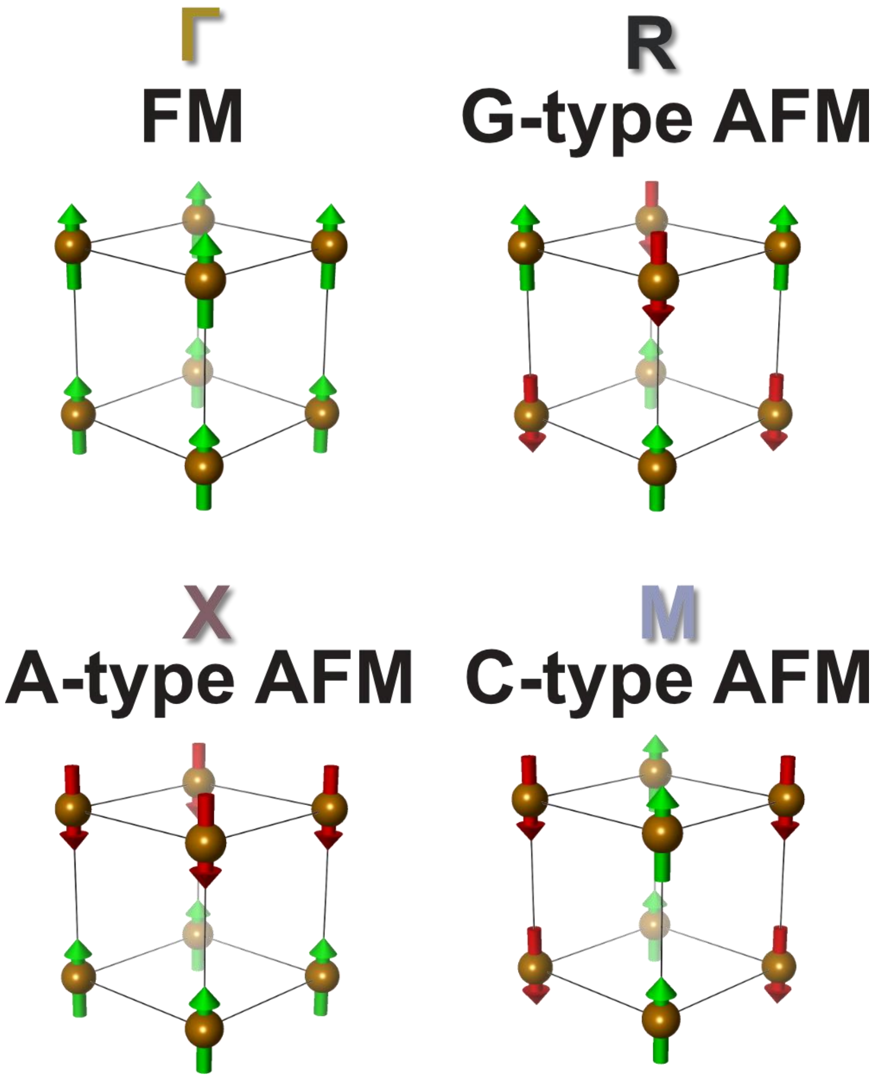
Z. Li, *et al.*, Phys. Rev. Research **5**, 043109 (2023)
A. Chaudron *et al.*, Nat. Matter **23**, 905-911 (2024)

TOM
Topological orders in matter

Brillouin zone and high symmetry points of BFO

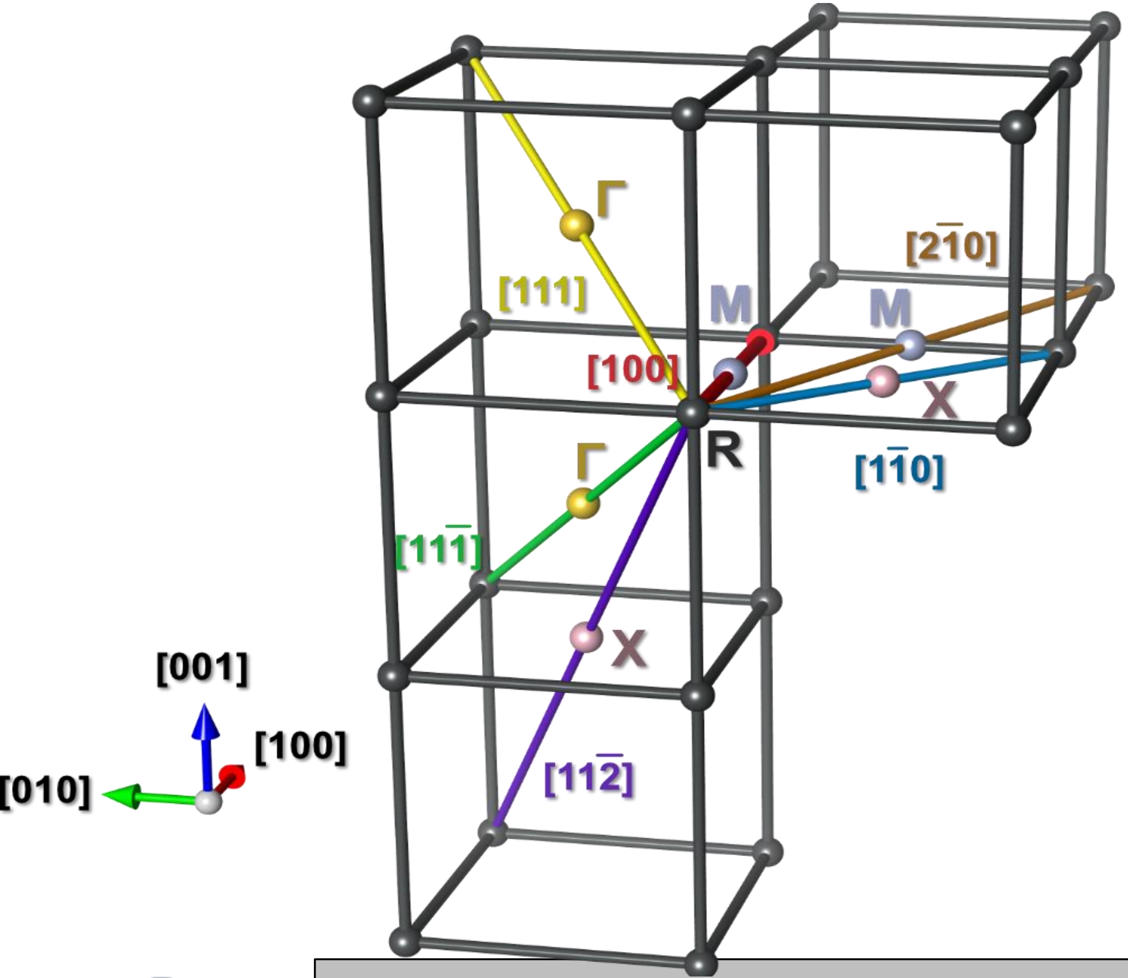
Detailed path of the q-vector

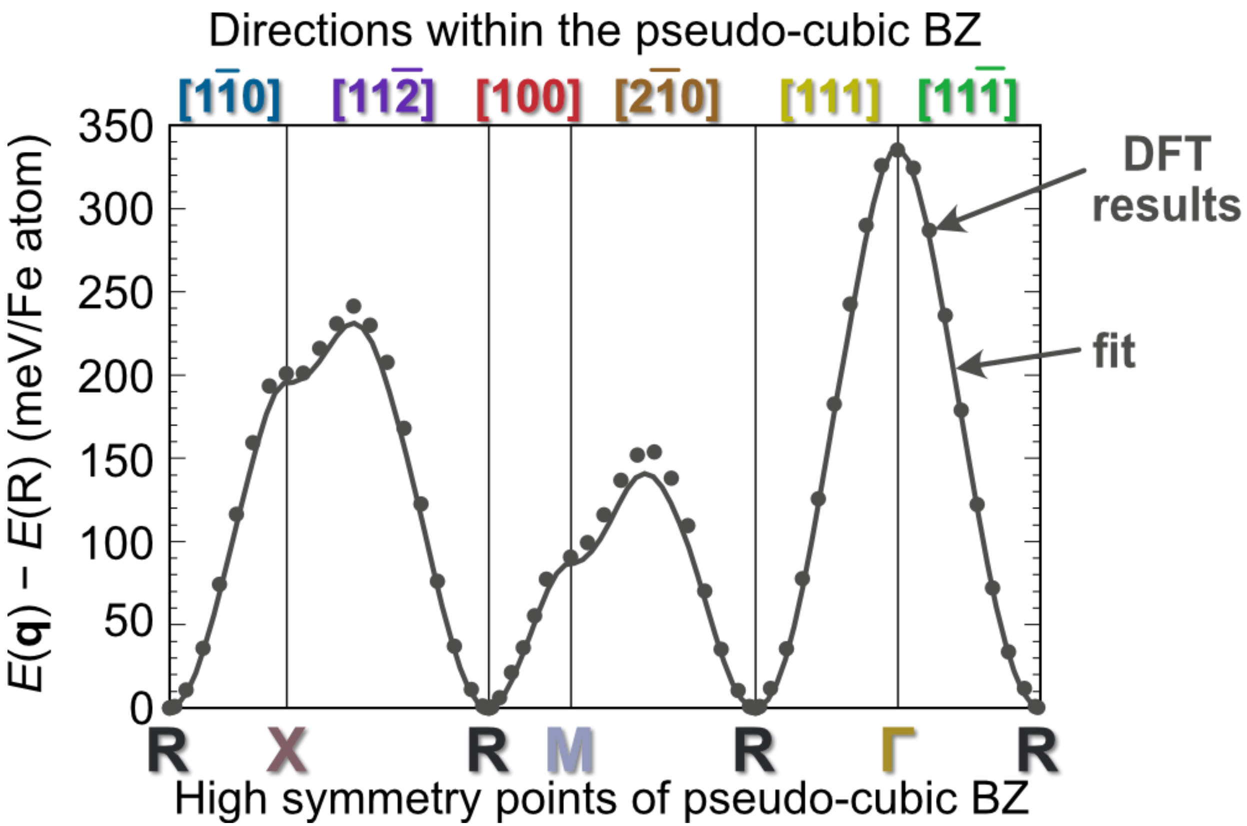




Spin spiral energy calculation in BFO

Detailed path of the q-vector





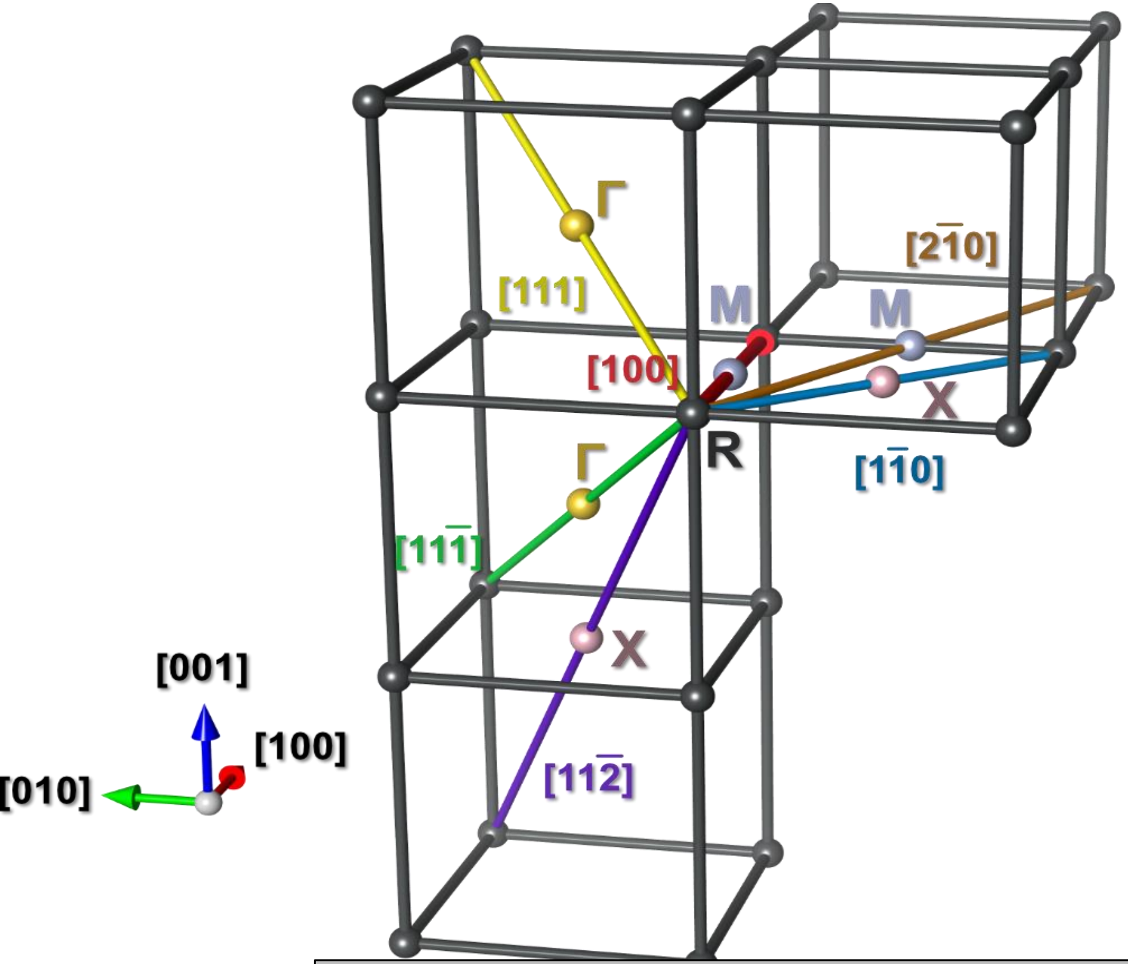
B. Xu, *et al.*, Phys. Rev. B **103**, 214423 (2023)
S. Meyer, *et al.*, Phys. Rev. B **108**, 024403 (2023)

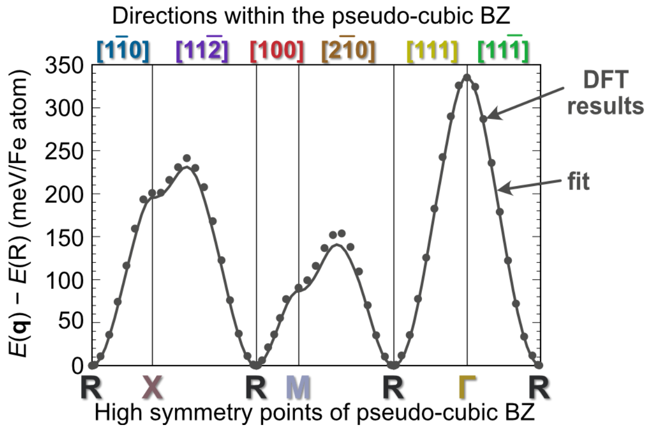
Conclusions
Dominant NN exchange J_1
Exchange fully isotropic in 3D BZ

Topological orders in matter

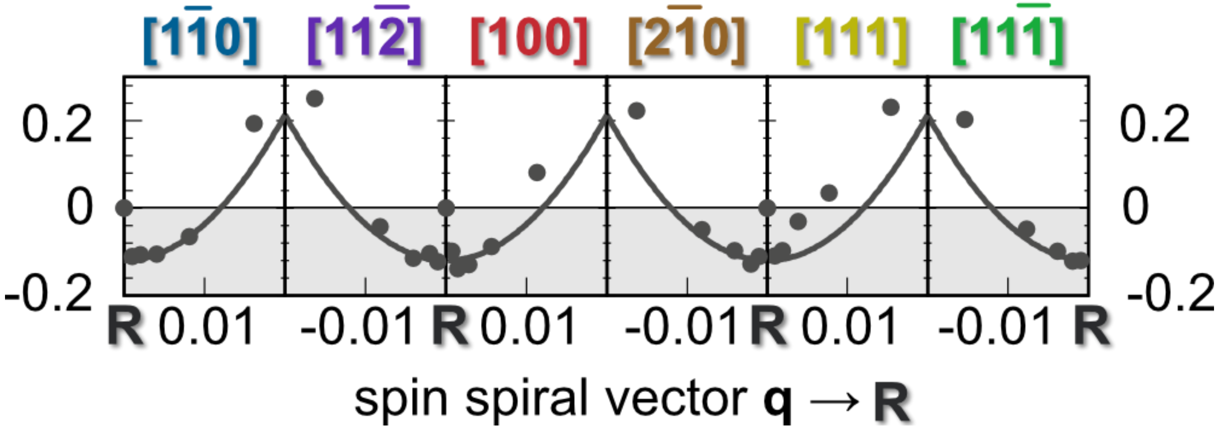
Spin spiral energy calculation in BFO

Detailed path of the q-vector





Zoom around ground state



B. Xu, *et al.*, Phys. Rev. B **103**, 214423 (2023)
S. Meyer, *et al.*, Phys. Rev. B **108**, 024403 (2023)

Conclusions
Dominant NN exchange J_1
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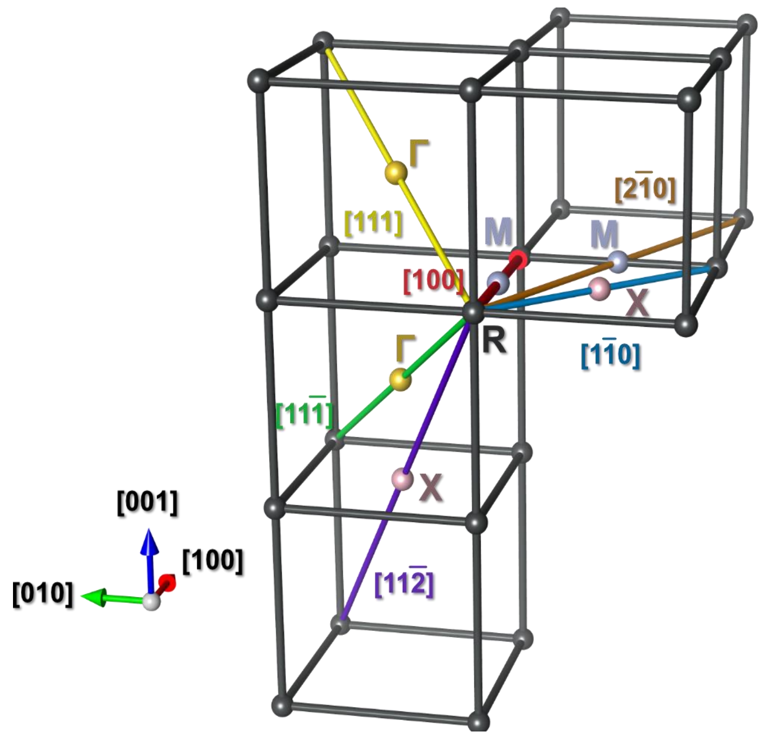
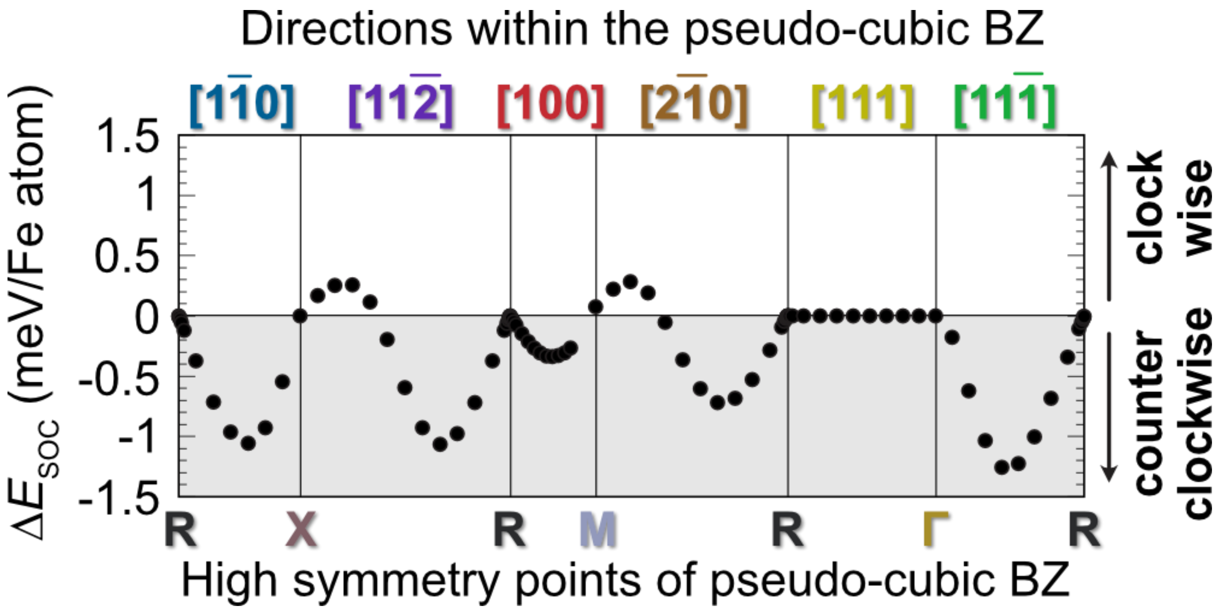
DM interaction energy calculation in BFO

Detailed path of the q-vector





B. Xu, *et al*., Phys. Rev. B **103**, 214423 (2023)
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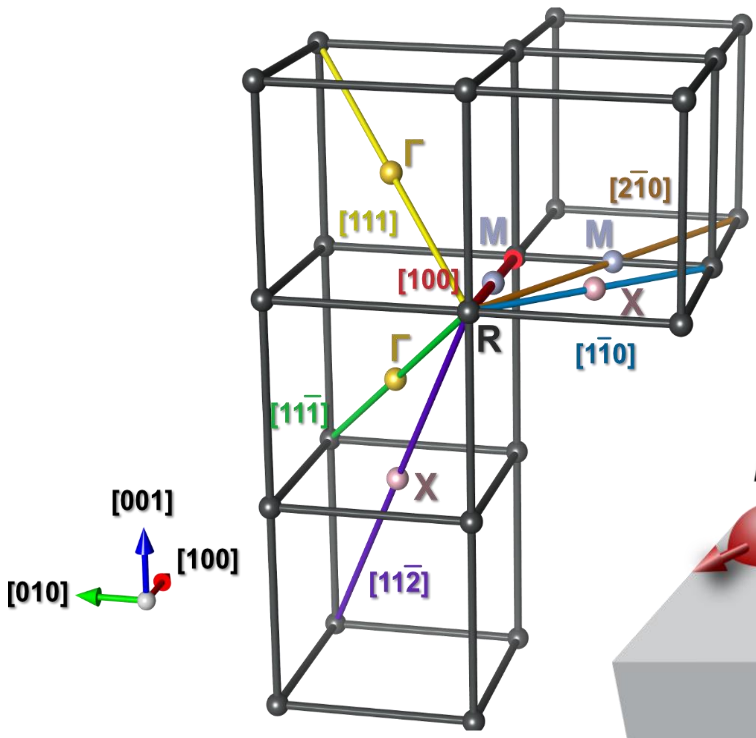
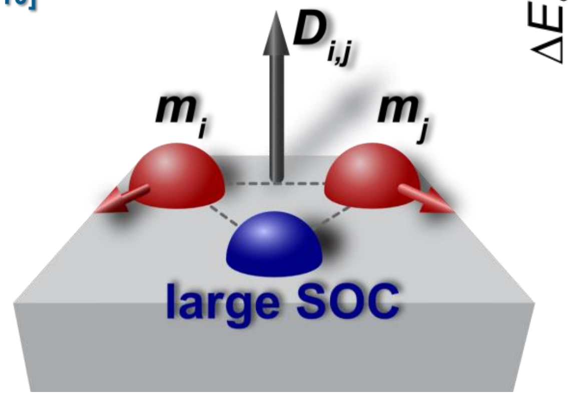
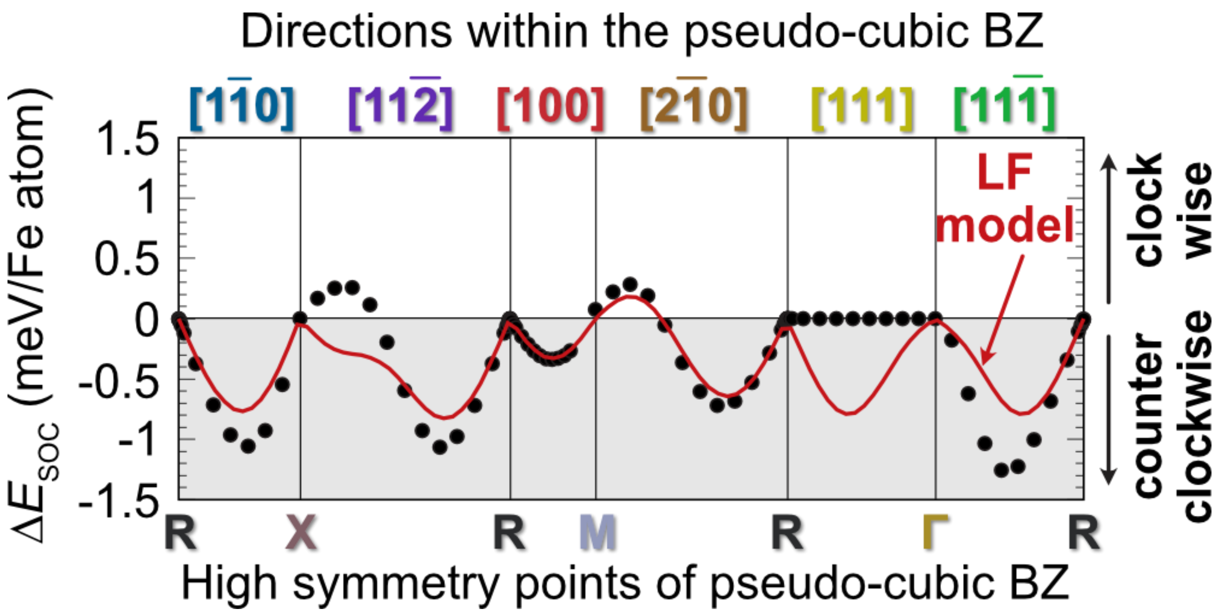
DM interaction energy calculation in BFO

Detailed path of the q-vector







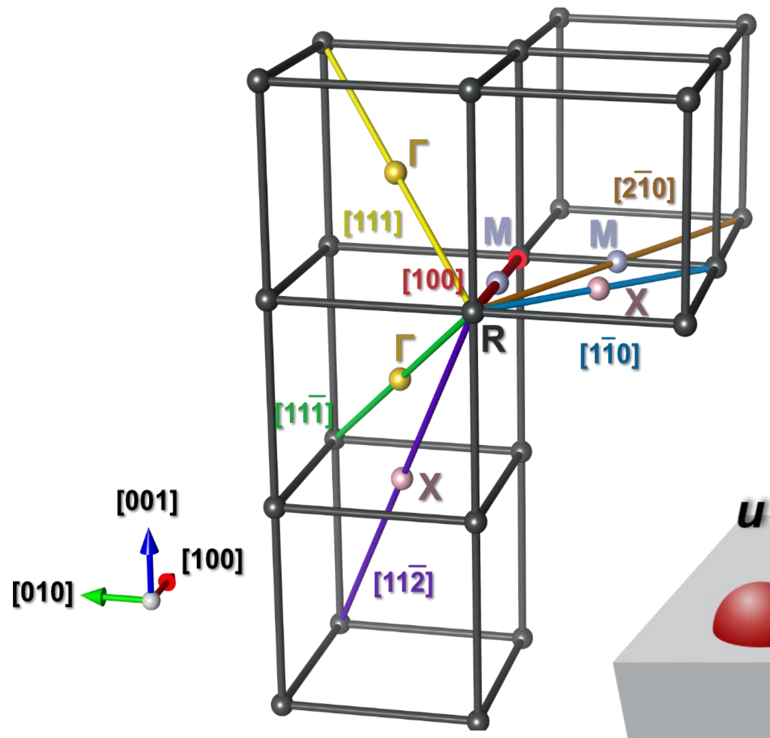
D_{ij} **from Fe-O-Fe bonds**

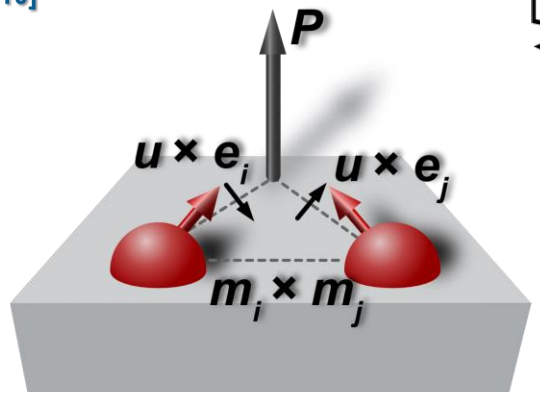
$$\mathcal{H}_{DMI}^{LF} = -\sum_{i,j} \boldsymbol{D}_{ij} \left(\boldsymbol{m}_i \times \boldsymbol{m}_j\right)$$

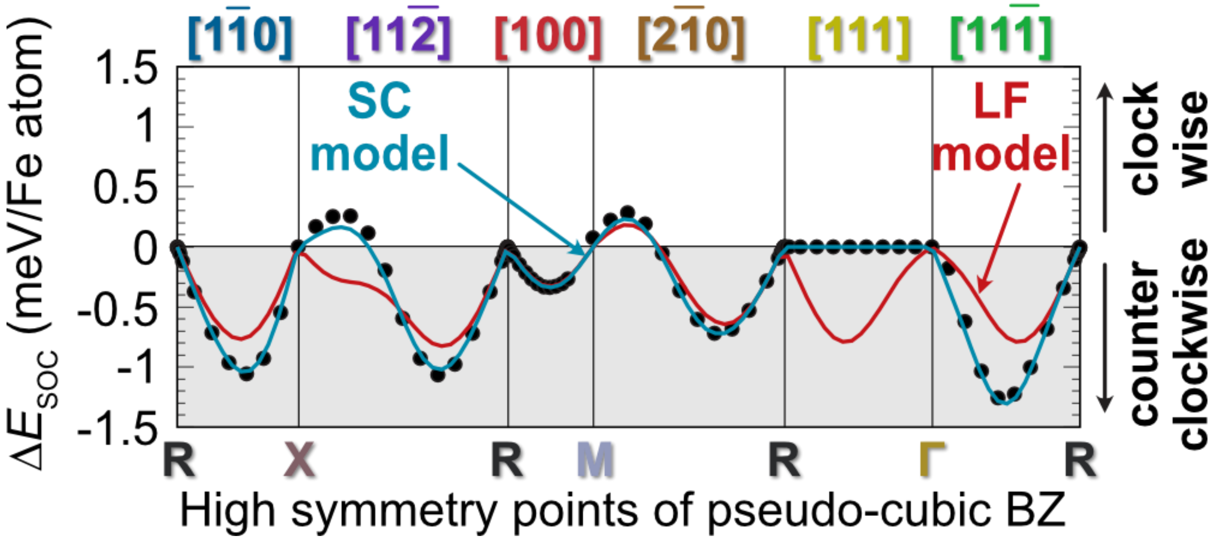
B. Xu, *et al.*, Phys. Rev. B **103**, 214423 (2023)
S. Meyer, *et al.*, Phys. Rev. B **108**, 024403 (2023)

DM interaction energy calculation in BFO

Detailed path of the q-vector





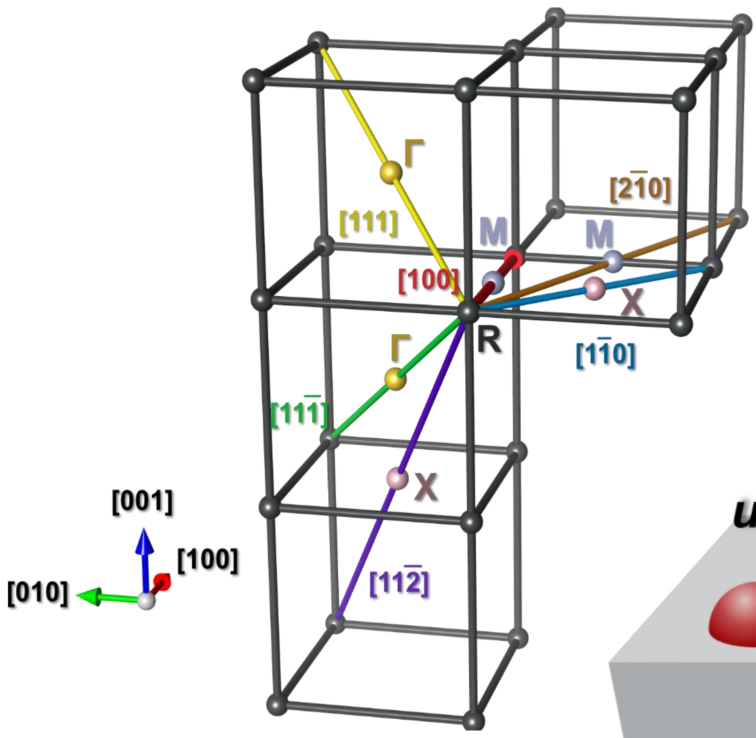


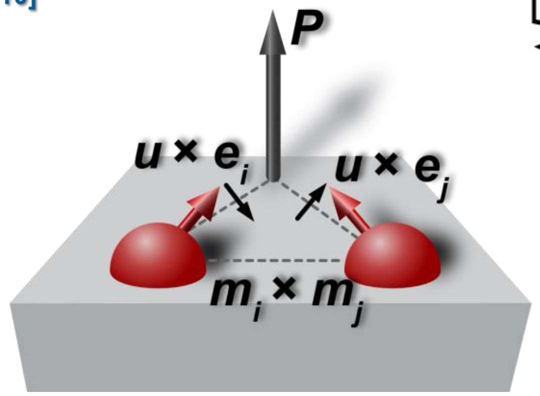
$$\mathcal{H}_{DMI}^{SC} = -\sum_{i,j} C_{ij}(\boldsymbol{u}_i \times \boldsymbol{e}_{ij})\,(\boldsymbol{m}_i \times \boldsymbol{m}_j)$$

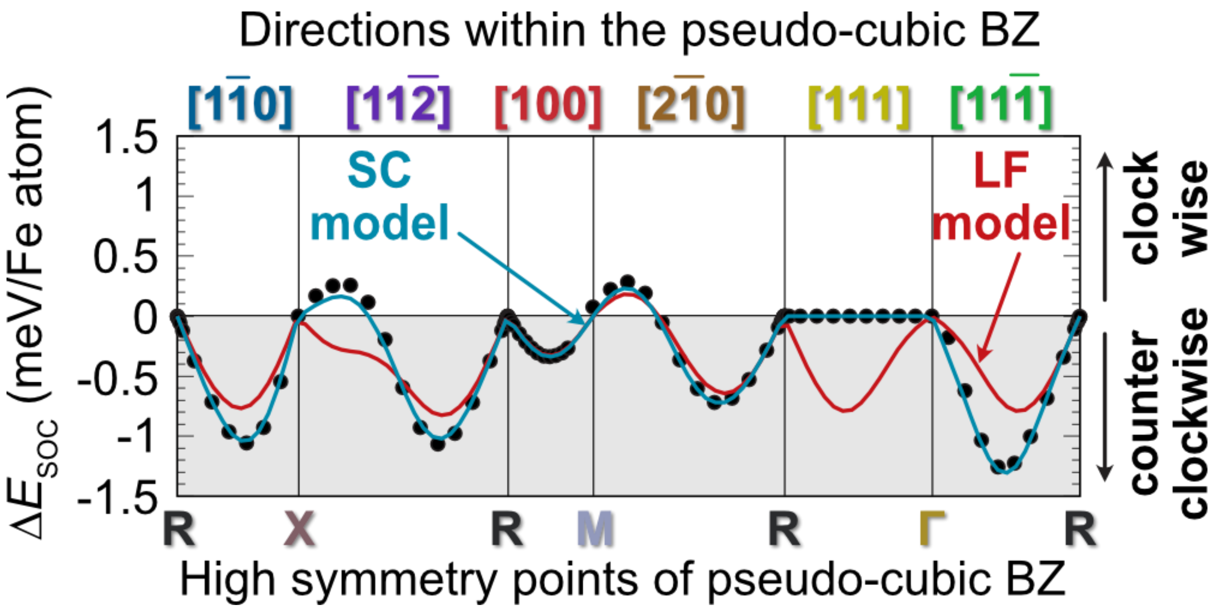
B. Xu, *et al.*, Phys. Rev. B **103**, 214423 (2023)
S. Meyer, *et al.*, Phys. Rev. B **108**, 024403 (2023)

DM interaction energy calculation in BFO

Detailed path of the q-vector







$$\mathcal{H}_{DMI}^{SC} = -\sum_{i,j} C_{ij}(\boldsymbol{u}_i \times \boldsymbol{e}_{ij})\,(\boldsymbol{m}_i \times \boldsymbol{m}_j)$$

Conclusions

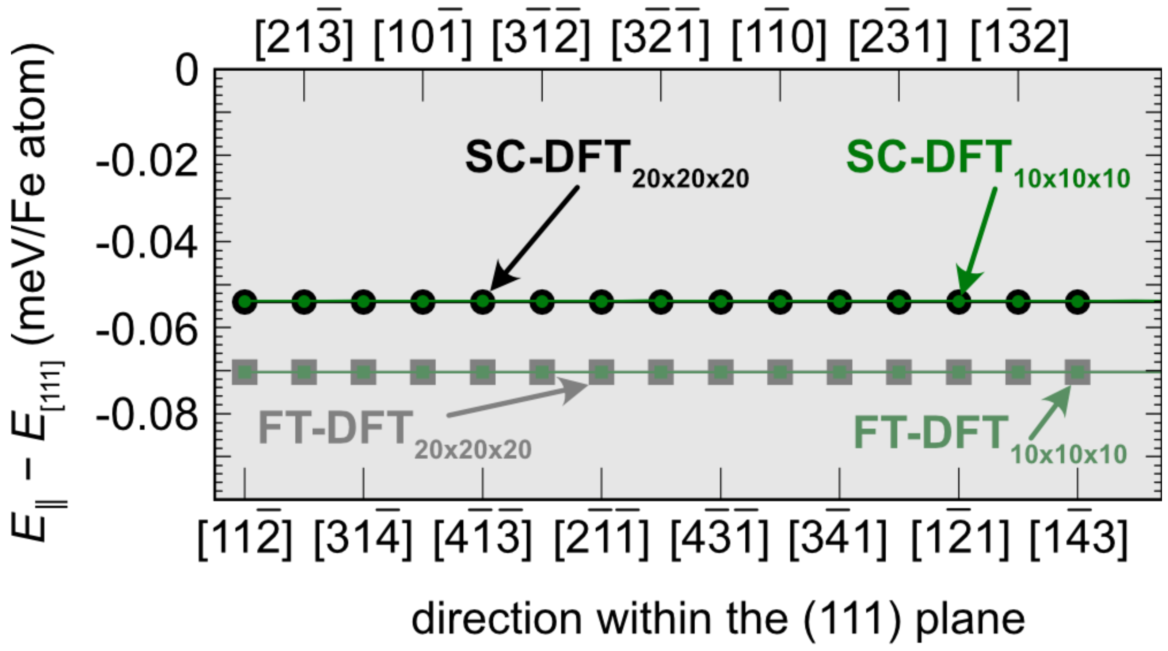
No SOC contribution in [111] direction

Disagreement with LF model

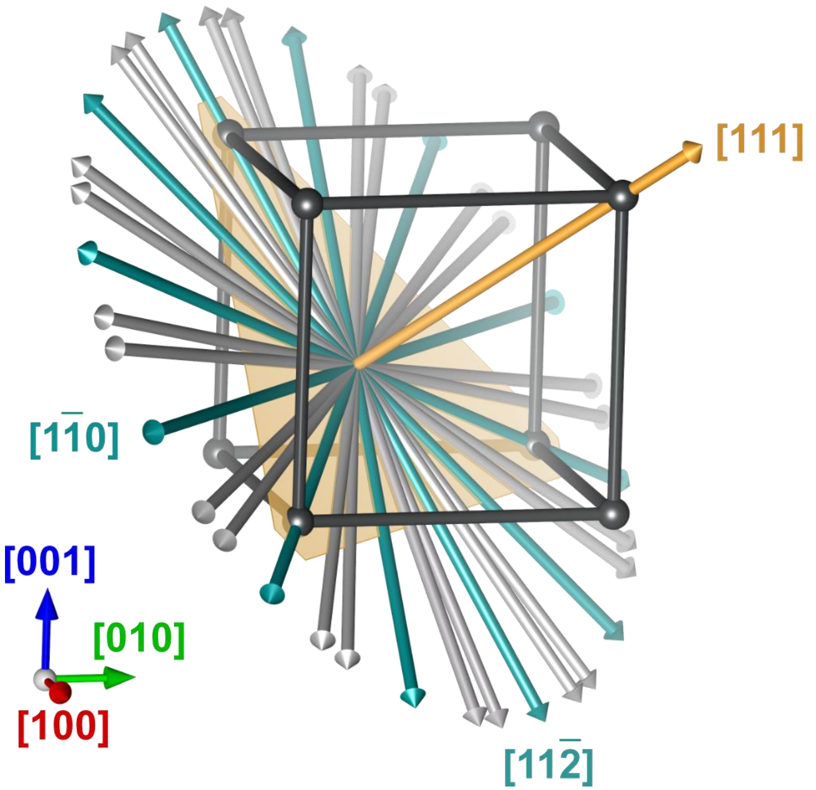
Spin-current model in agreement with data

B. Xu, *et al.*, Phys. Rev. B **103**, 214423 (2023)
S. Meyer, *et al.*, Phys. Rev. B **108**, 024403 (2023)

Magnetocrystalline anisotropy in BFO

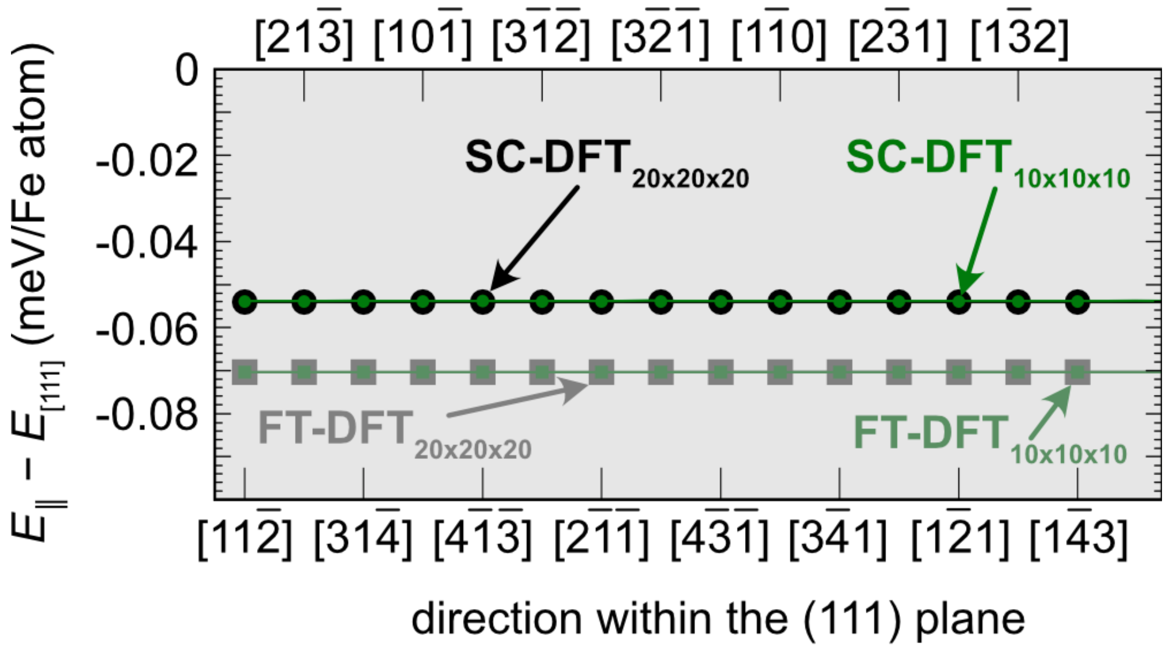


Calculations of preferred magnetization direction

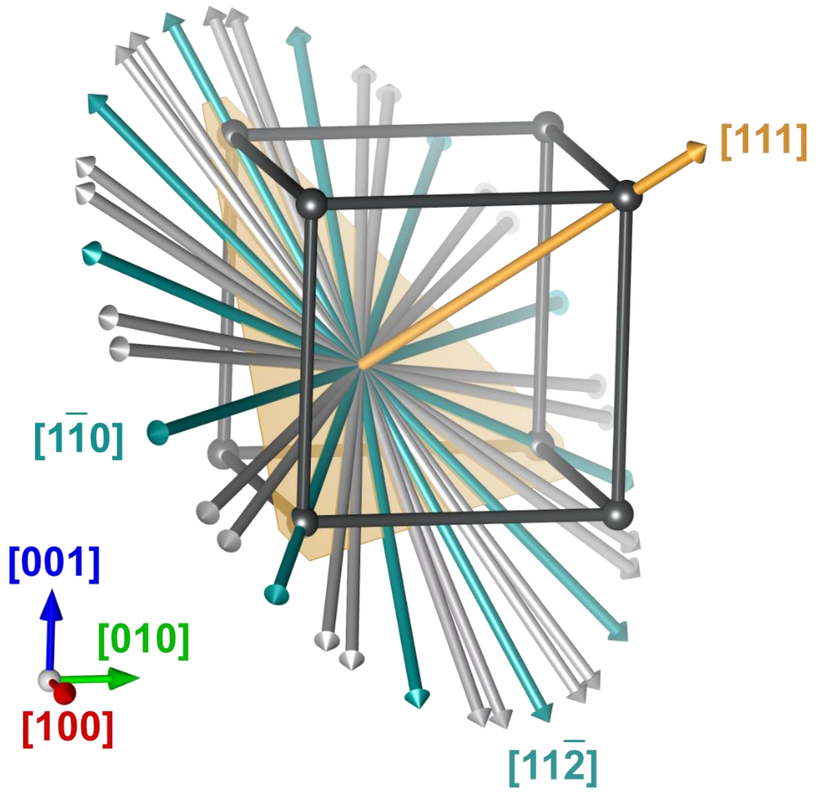


B. Xu, *et al*., Phys. Rev. B **103**, 214423 (2023)
S. Meyer, *et al*., Phys. Rev. B **108**, 024403 (2023)

Magnetocrystalline anisotropy in BFO



Calculations of preferred magnetization direction

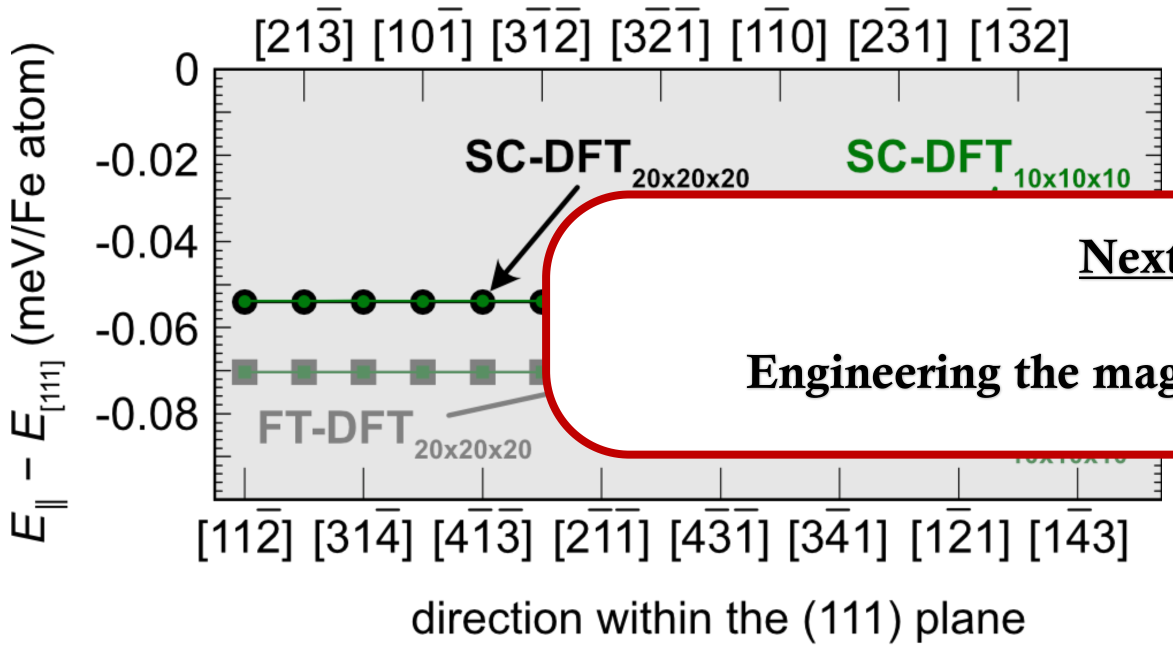


Conclusions

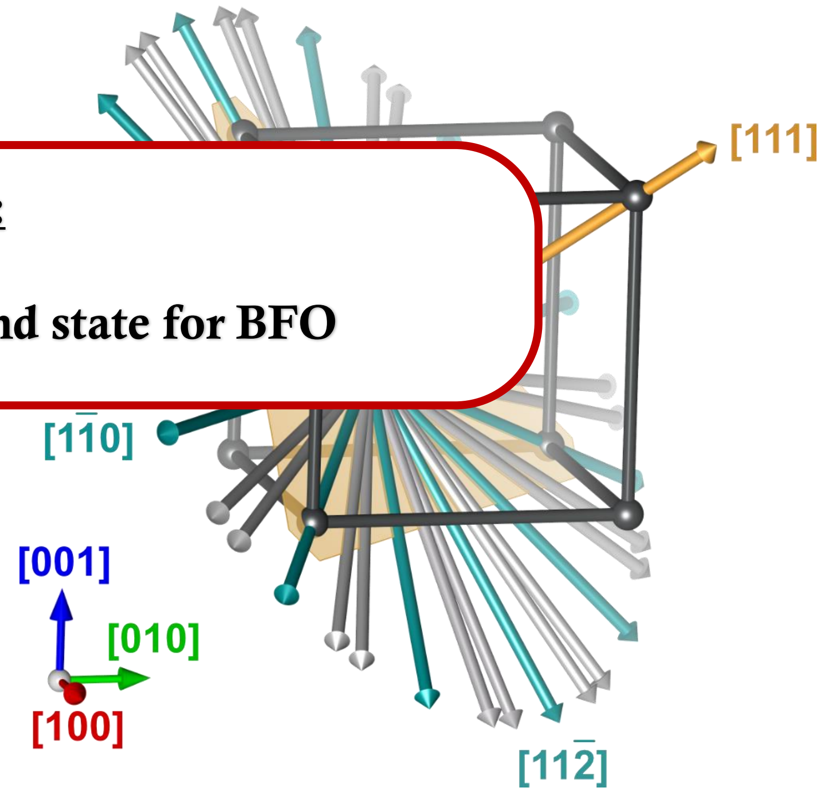
- Extremely small anisotropy
- Hard [111] axis
- Completely easy (111) plane of magnetization

B. Xu, *et al.*, Phys. Rev. B **103**, 214423 (2023)
S. Meyer, *et al.*, Phys. Rev. B **108**, 024403 (2023)

Magnetocrystalline anisotropy in BFO



Calculations of preferred magnetization direction



Next Objective:

Engineering the magnetic ground state for BFO

Conclusions

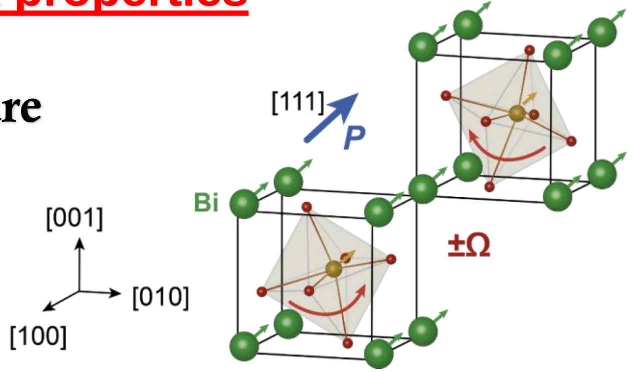
- Extremely small anisotropy
- Hard [111] axis
- Completely easy (111) plane of magnetization

B. Xu, *et al.*, Phys. Rev. B **103**, 214423 (2023)
S. Meyer, *et al.*, Phys. Rev. B **108**, 024403 (2023)

Order parameters of $BiFeO_3$

Bulk properties

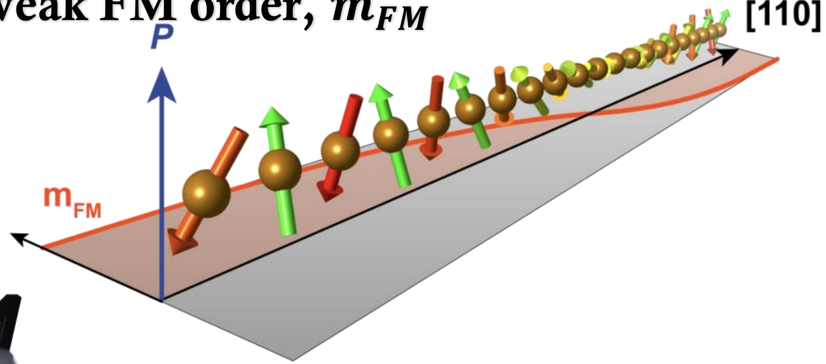
1. Perovskite structure
   Bi Cations
   Fe Cations
   O Anions



2. Fe-Bi displacement
   Polarization along [111] direction
   $P \approx \frac{90\mu C}{cm^2}, T_C = 1123$ K

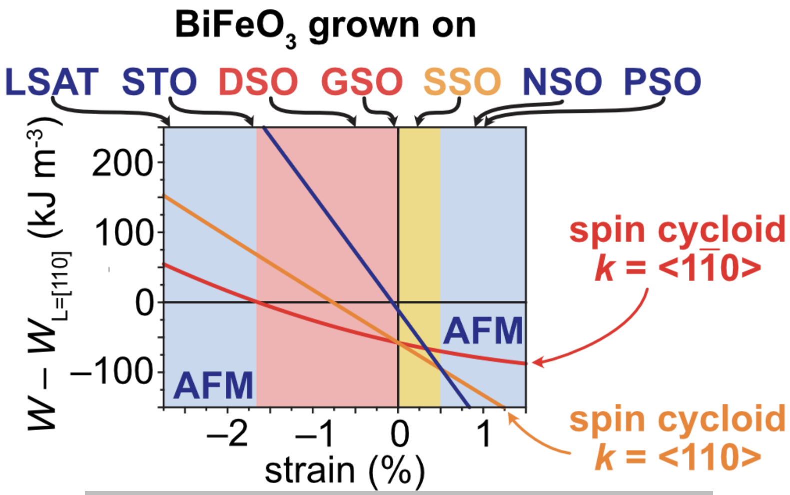
   } $R3c$

3. Oxygen tilt in antiphase $\pm\Omega$
4. Local antiferromagnetic order with long-ranged spin cycloid, $\lambda \approx 62$ nm + weak FM order, m_{FM}



Strain properties

1. Precise modification of material's lattice parameters
2. Modification of multiferroic properties:



D. Sando, *et al*., Nature Mater. **12**, 641 (2013)

3. Collinear AFM state for strain $\varepsilon < -0.5\%$ and $\varepsilon > +0.5\%$
4. Large sensitivity of magnetic ground states
   Different results for equivalent substrates

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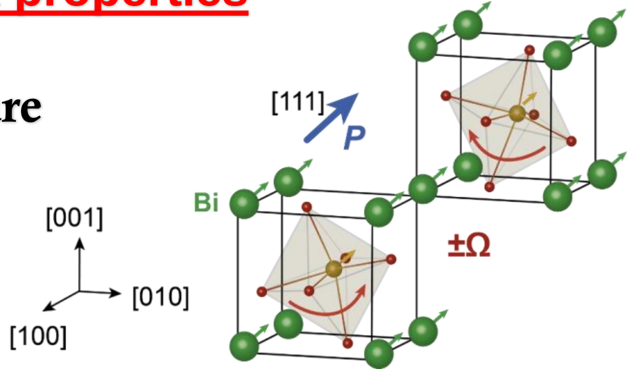

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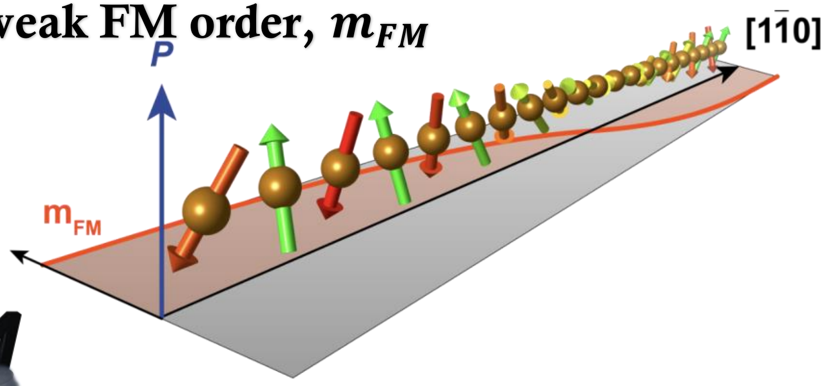


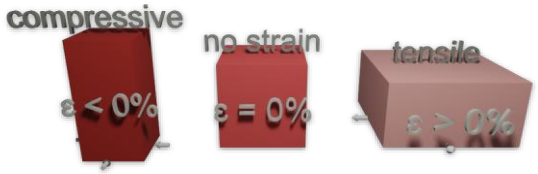
Strain properties

1. Precise modification of material's lattice parameters
2. Modification of multiferroic properties:

$BiFeO_3$ grown on

Objective:

Investigation of magnetic energies with epitaxial strain



3. Collinear AFM state for strain $\varepsilon < -0.5\%$ and $\varepsilon > +0.5\%$
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   Different results for equivalent substrates

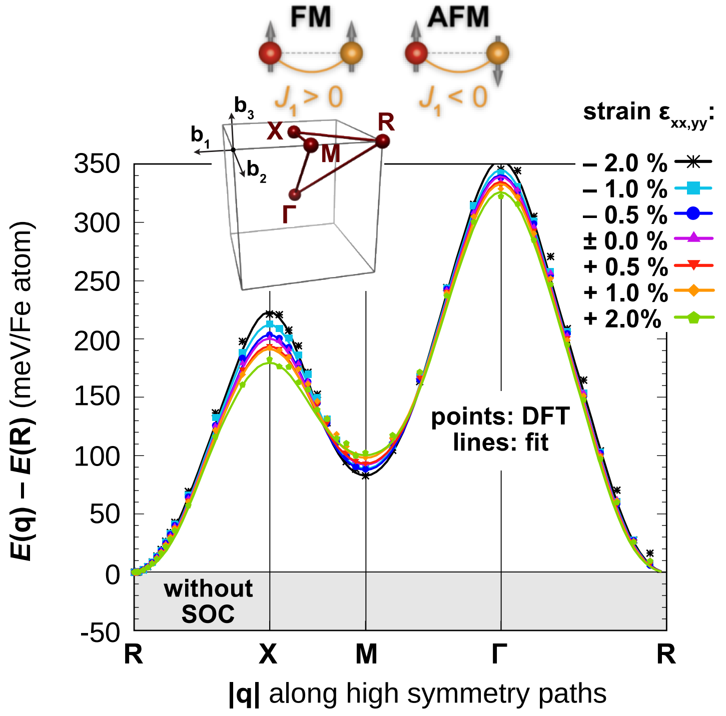
Topological orders in matter

Evolution of magnetic interactions with strain

S. Meyer, *et al.*, Phys. Rev. B **109**, 184431 (2024)

Exchange interaction

$$\mathcal{H}_{ex} = -\sum_{i,j} J_{ij}\,(\boldsymbol{m}_i \cdot \boldsymbol{m}_j)$$



Linearly decreasing strength

Topological orders in matter

Bertrand Dupé

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S. Meyer, *et al.*, Phys. Rev. B **109**, 184431 (2024)

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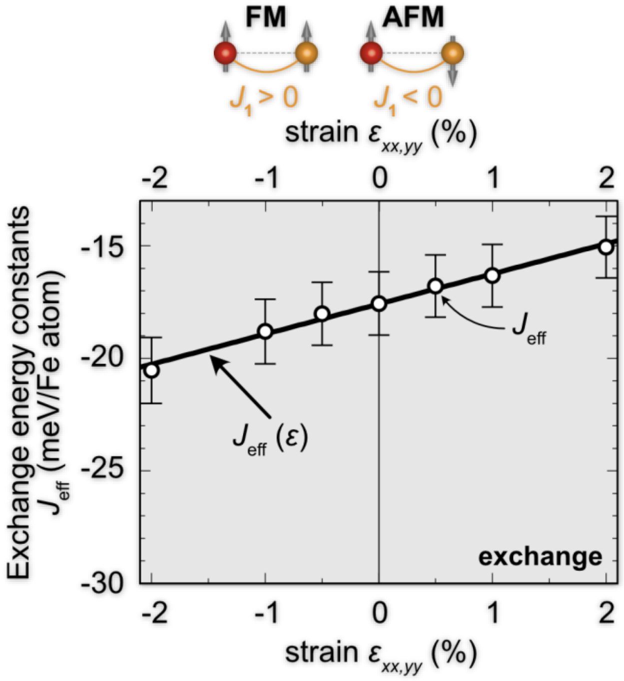

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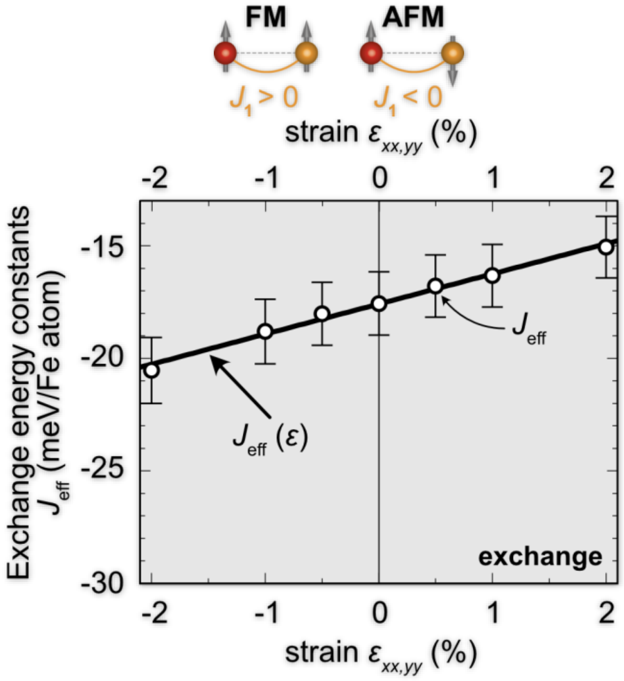
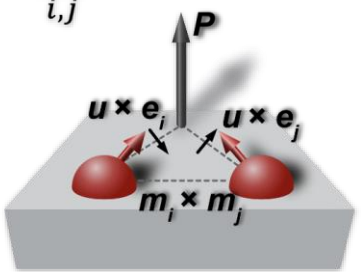
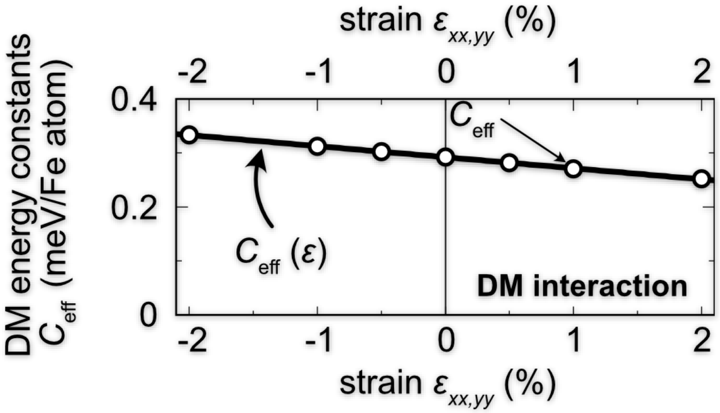


Linearly decreasing strength

Dzyaloshinskii-Moriya interaction

$$\mathcal{H}_{DMI}^{SC} = -\sum_{i,j} C_{ij}(\boldsymbol{u}\times\boldsymbol{e}_{ij})\,(\boldsymbol{m}_i\times \boldsymbol{m}_j)$$





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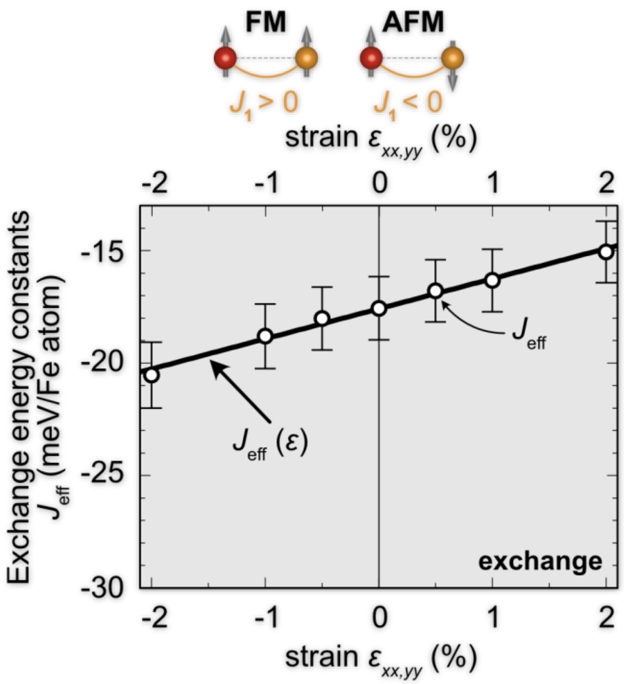

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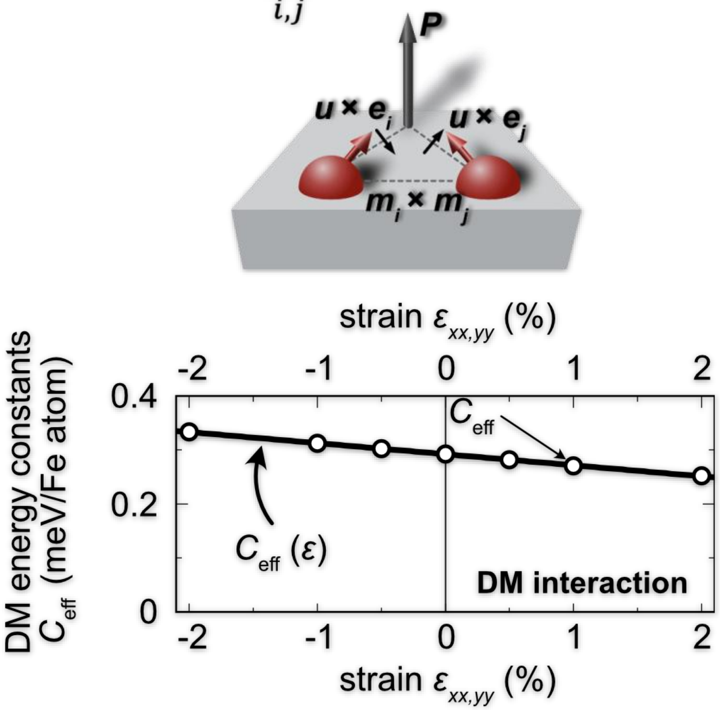
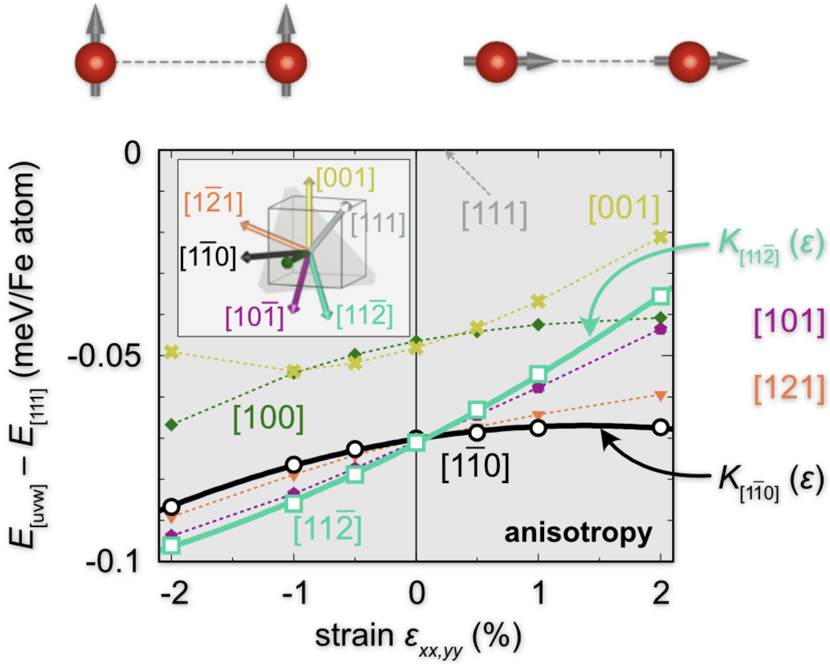


Linearly decreasing strength

Magnetocrystalline anisotropy

$$\mathcal{H}_{ani} = -\sum_{i} K\boldsymbol{m}_{[111]}^2$$



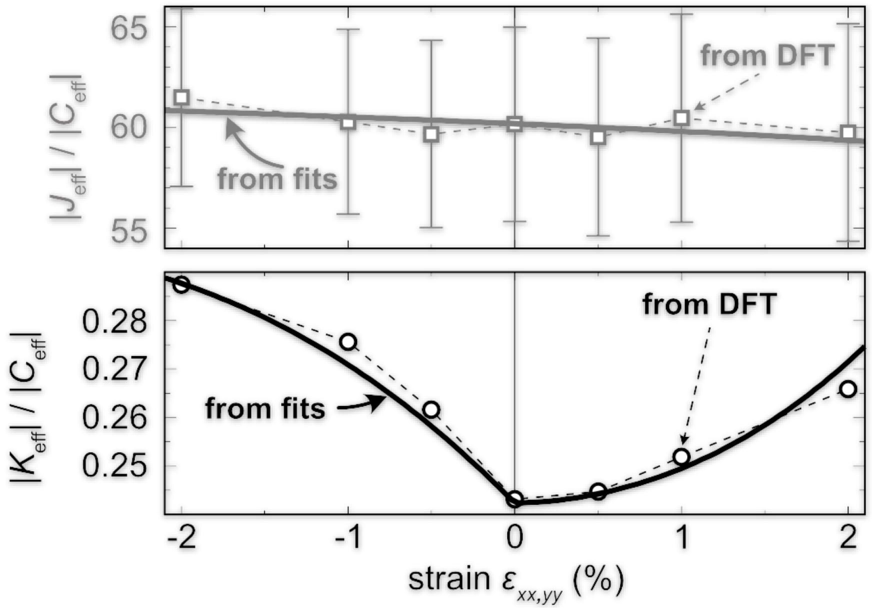
$[11\bar{2}]$ **easy axis for** $\boldsymbol{\varepsilon} < 0$

$[1\bar{1}0]$ **easy axis for** $\boldsymbol{\varepsilon} > 0$

TOM
Topological orders in matter

Evolution of the ratio between Exchange, anisotropy and DM

Ratios of magnetic interactions



S. Meyer, *et al*., Phys. Rev. B **109**, 184431 (2024)

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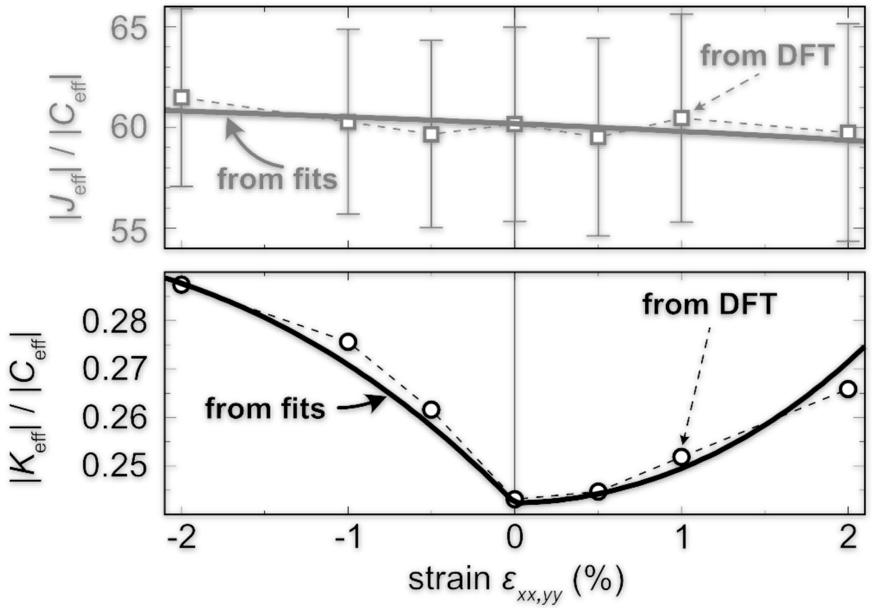


Conclusions

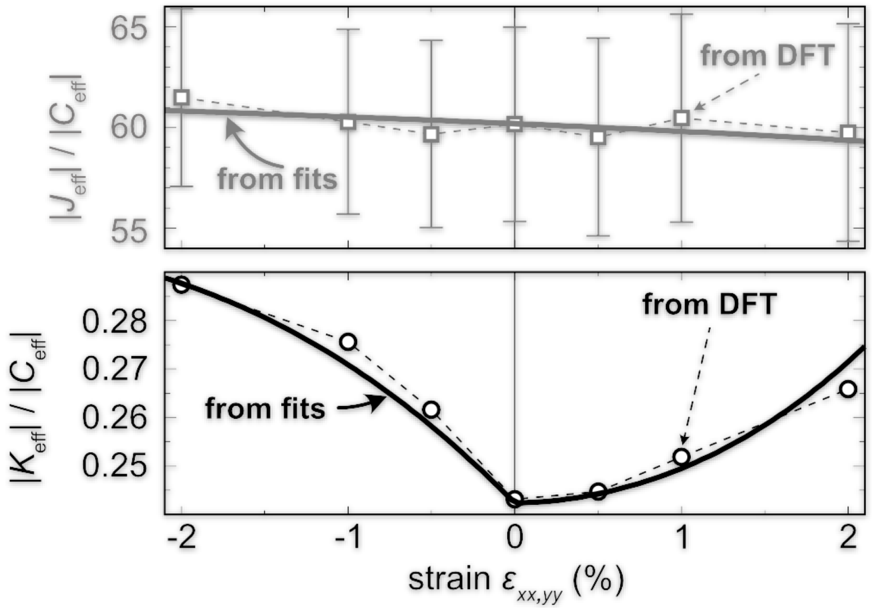
- $\varepsilon < 0$: Preffered collinear order from exchange and anisotropy
- $\varepsilon > 0$: Weaker collinear order from exchange vs. DMI, but Stronger due to MAE

Topological orders in matter

S. Meyer, *et al.*, Phys. Rev. B **109**, 184431 (2024)

Domain wall energy

Ratios of magnetic interactions



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S. Meyer, *et al.*, Phys. Rev. B **109**, 184431 (2024)

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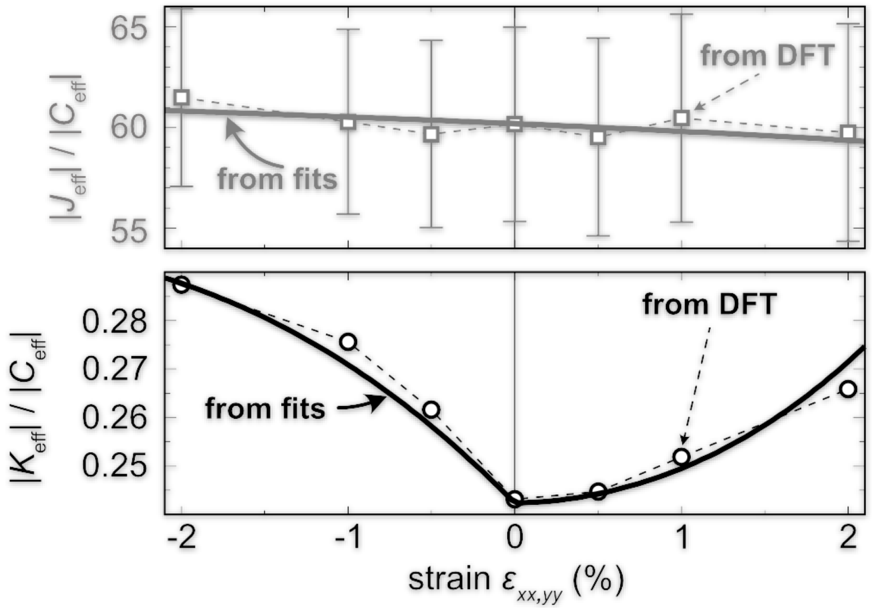

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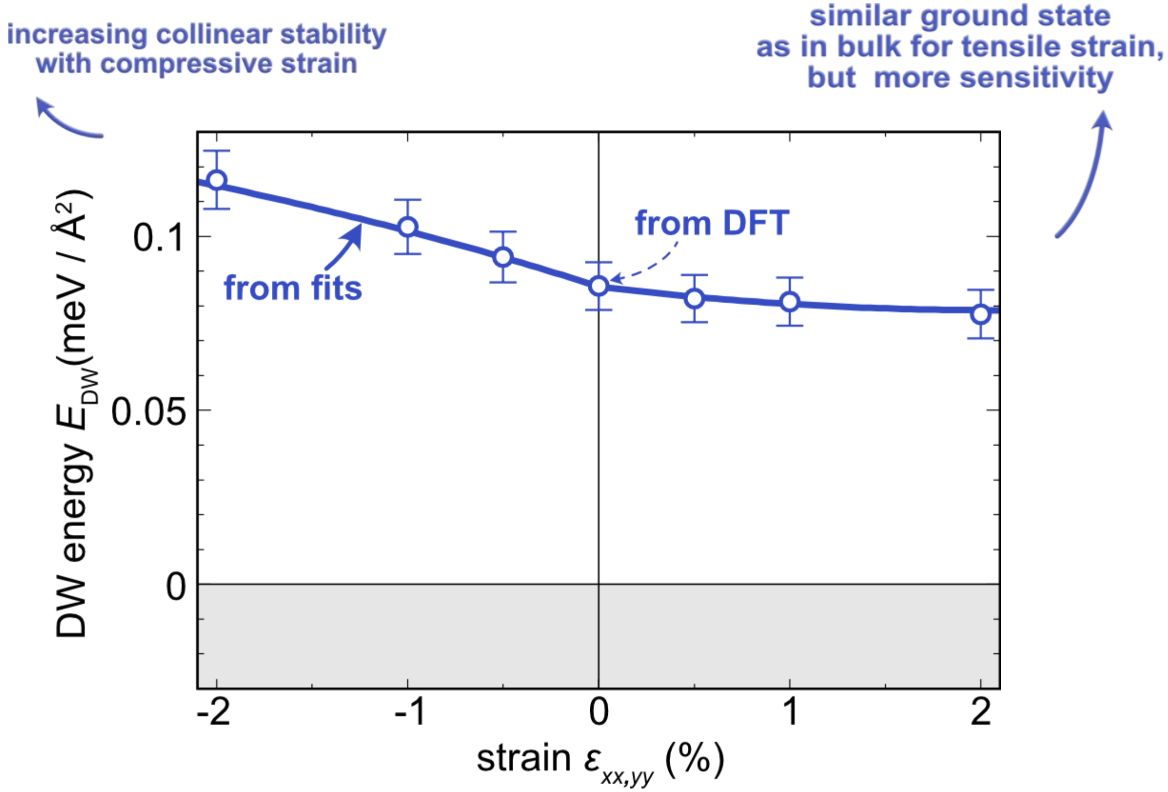

S. Meyer, *et al.*, Phys. Rev. B **109**, 184431 (2024)

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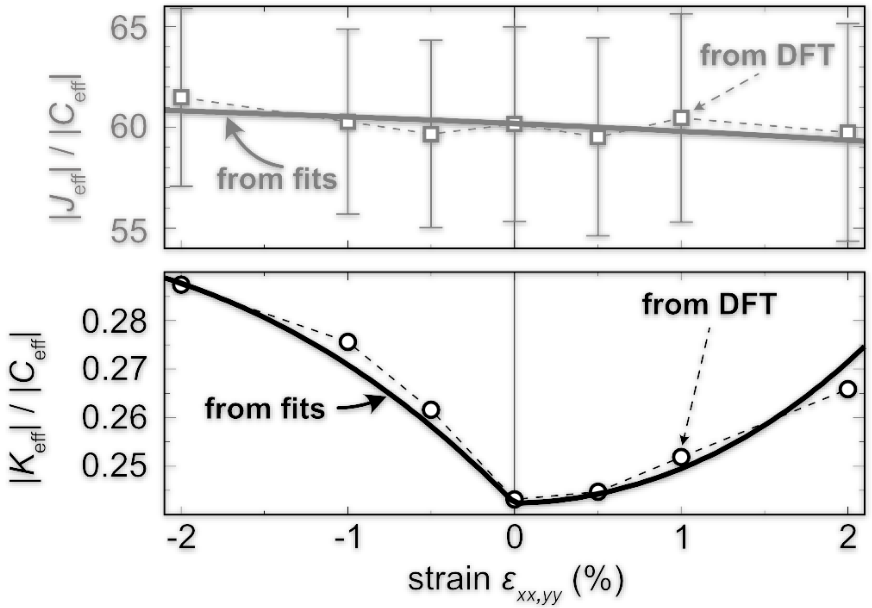

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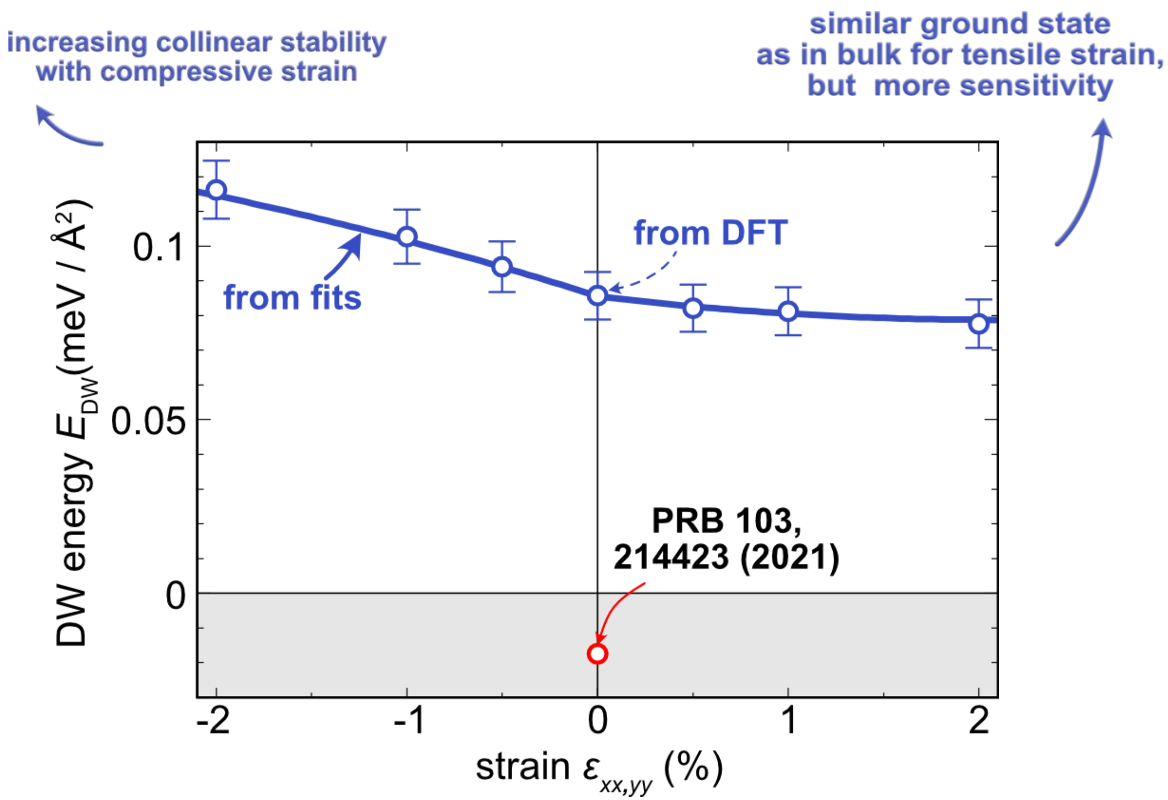

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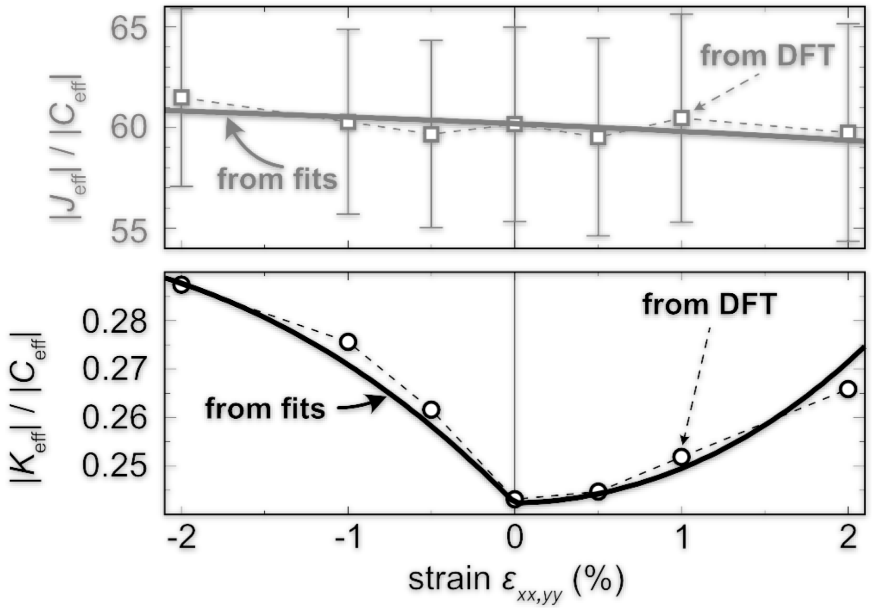

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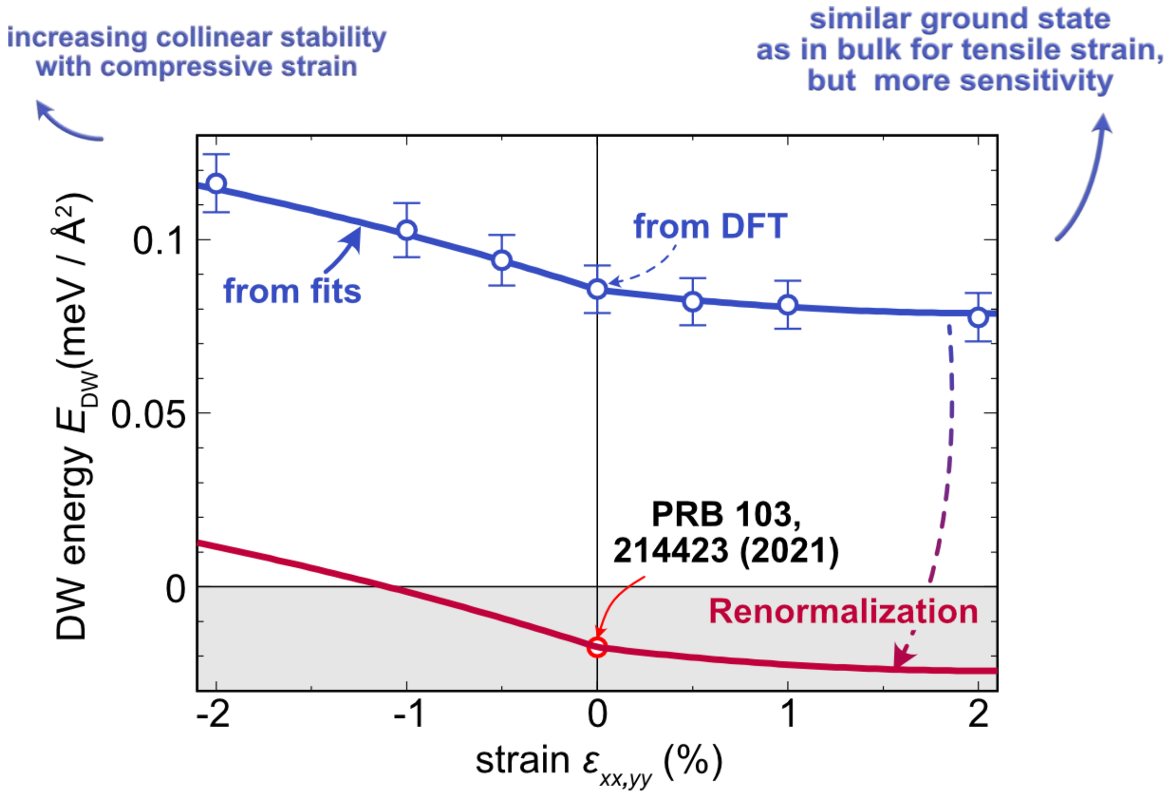

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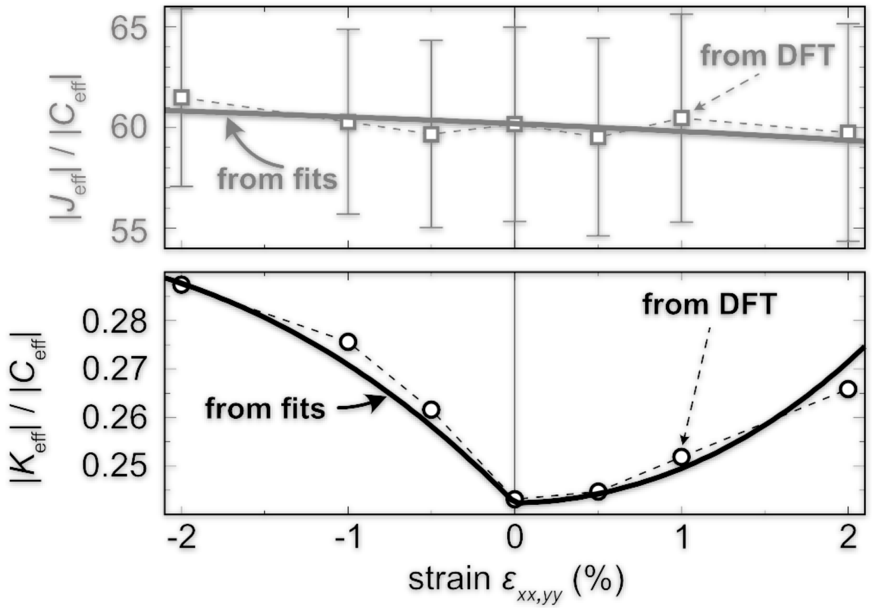

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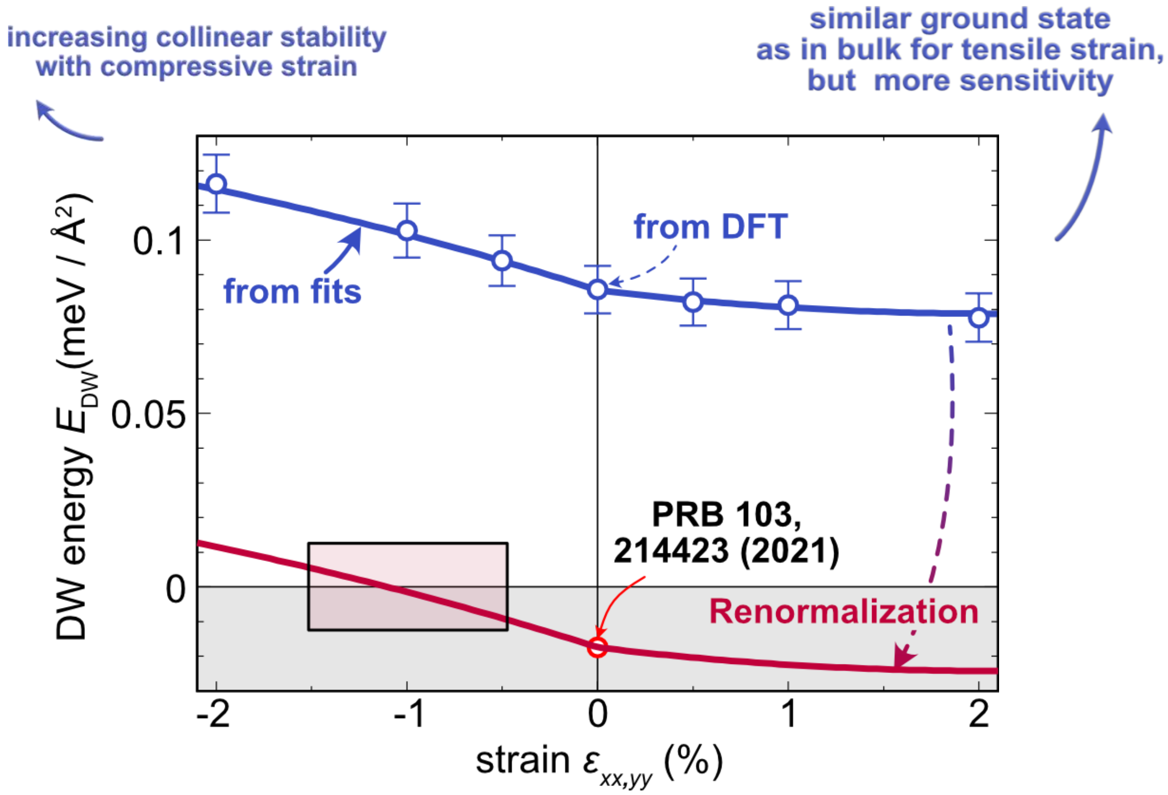

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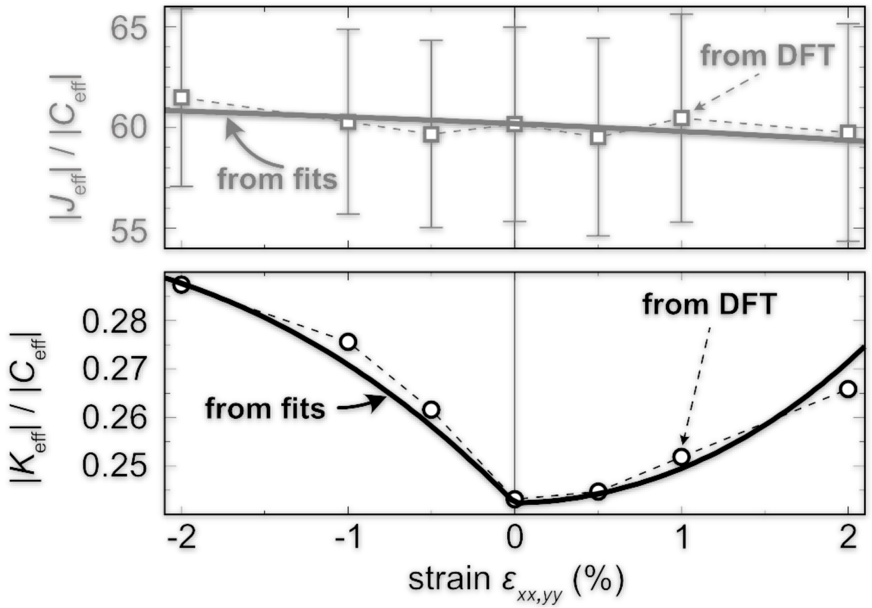

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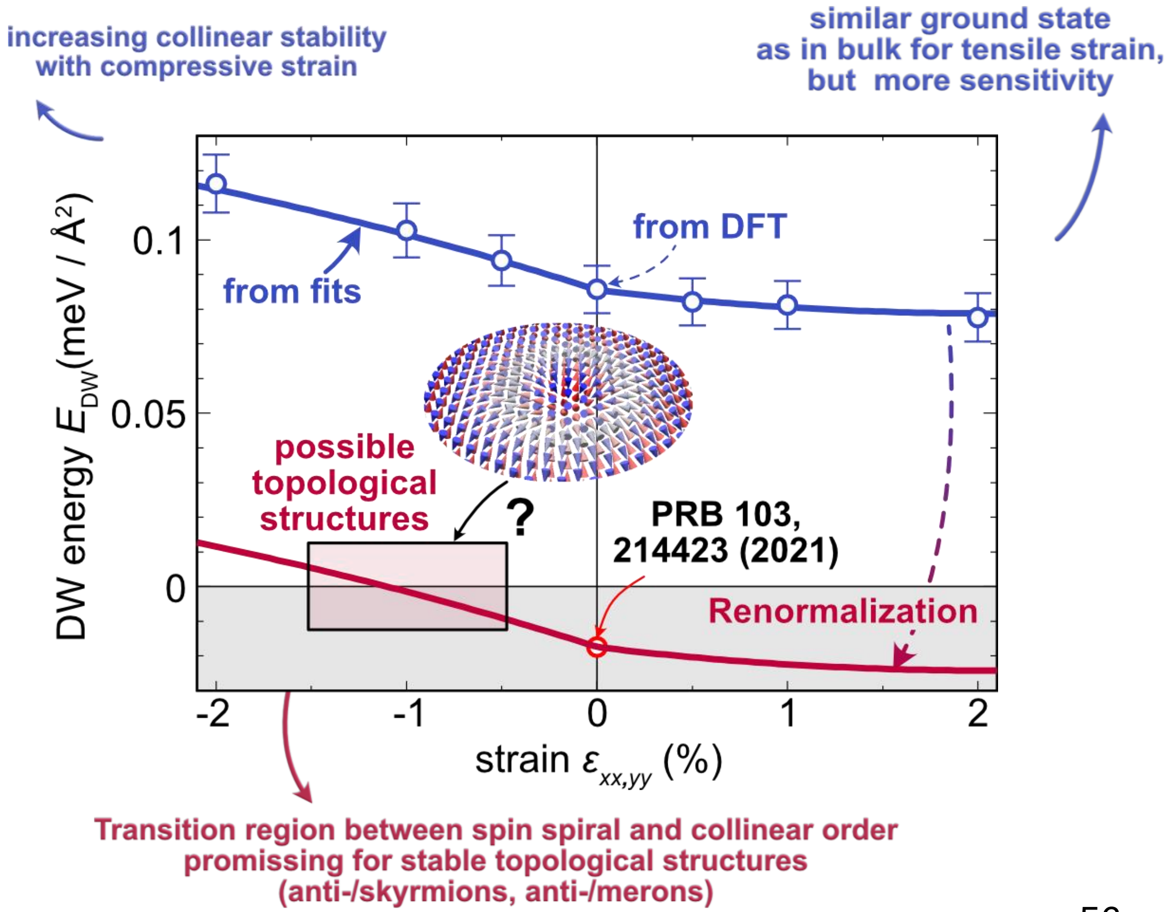

S. Meyer, *et al.*, Phys. Rev. B **109**, 184431 (2024)

Topological orders in matter

Conclusion

- Topology is a very rich playground to do physics
- Multiferroics offer an excellent platform to stabilize ferroelectric and magnetic skyrmions
- Skyrmions can be functionalize for
  - neuromorphic computing,

    D. Pinna *et al.,* J. Phys. Rev. Applied **9**, 064018 (2018)
    D. Prychynenko *et al.,* Phys. Rev. Applied **9**, 014034 (2018)
    G. Bourianoff *et al.,* AIP Advances **8**, 055602 (2018)
    J. Zázvorka *et al.,* Nature Nanotech. (2019)

  - Particle physics

    U. Ritzmann *et al.,* Phys. Rev. B **102**, 174409 (2020)
    U. Ritzmann *et al.,* Nature Electronics **1**, 451-457 (2018)

  - Quantum computing

    L. Mougel, *et al.* Appl. Phys. Lett. **121**, 231605 (2021)
    M. Garnier, *et al.* Commun. Phys. **2**, 126 (2019)
    G. Yang, *et al.* Phys. Rev. B **93**, 224505 (2016)

- Check our code github.com/bertdupe/Matjes

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