Geometry-governed effects in curvilinear magnetism

Novel physical effects caused by tailoring geometry

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RiTM

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WASEM Monastery, Ingelheim, Germany

Overview of curvilinear magnetism

- Curvilinear magnetism
  [Streubel, Fischer, Kronast, Kravchuk, Sheka, Gaididei, Schmidt, Makarov, J Phys D (2016)]
- Reviews on curvilinear magnetism
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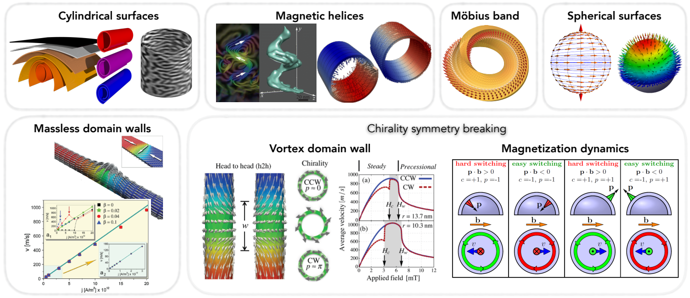
  [Sheka, Encyclopedia of Materials (2023)]
- [Makarov, Sheka, Curvilinear Micromagnetism: From Fundamentals to Applications, Springer (2022) https://doi.org/10.1007/978-3-031-09086-8]



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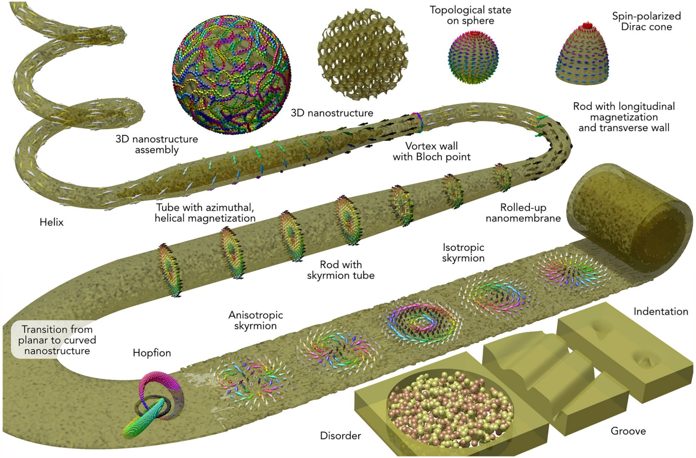

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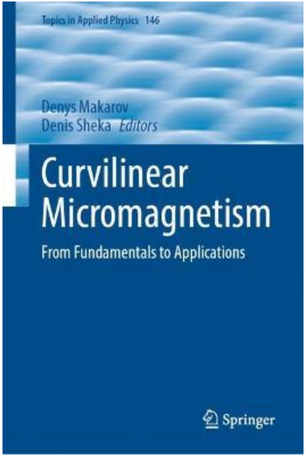
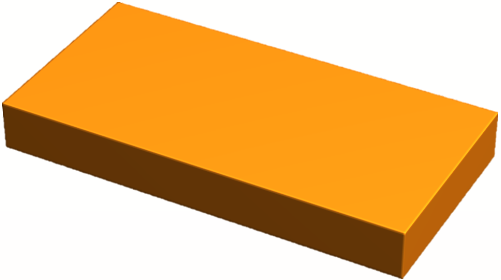


Curvature influence: sources of novel effects

- Flat magnet
  ⇒ spatial inversion symmetry
- Curved magnet
  ✓ Local geometrical properties
  ⇒ geometry-governed interactions
  ⟹ geometry-governed anisotropy
  ⟹ geometry-governed chiral interactions
  ⇒ Geometrical magnetochiral effects

  ✓ Global geometrical properties
  ⇒ Topology of curved magnets
  ⟹ Topological patterning

Flat film



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Curved film: geometry

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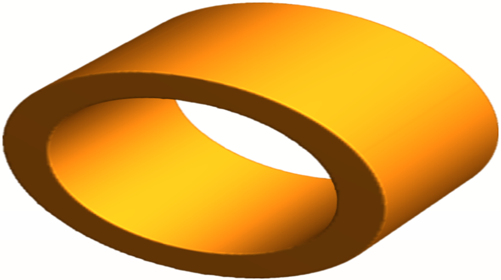
Curved film: topology



Typical magnetic interactions: minimal model

$$E = \int \mathrm{d}^3 x \Big[\underbrace{\mathscr{E}^{\mathrm{X}}}_{\text{exchange}} + \underbrace{\mathscr{E}^{\mathrm{A}}}_{\text{anisotropy}} \Big] + \underbrace{\mathscr{E}^{\mathrm{DMI}}}_{\text{Dzyaloshinskii–Moriya interaction}} + \underbrace{\mathscr{E}^{\mathrm{MS}}}_{\text{magnetostatics}} \Big]$$

- Ginzburg-Landau functional for the vector order-parameter

  ⇒ General approach for various condensed matter systems:
  - Magnets
  - Liquid crystals
  - Superconductors

- The curvature gets into the game due to the geometry-dependent anisotropy $\vec{e}_{\mathrm{an}} = \vec{e}_{\mathrm{an}}(x, y, z)$
- Strong anisotropy ⇒ Curvilinear reference frame

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Impact of curvature on nanomagnets

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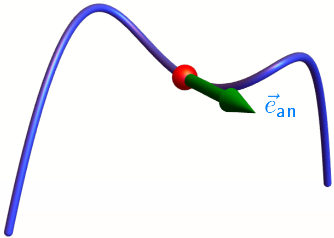

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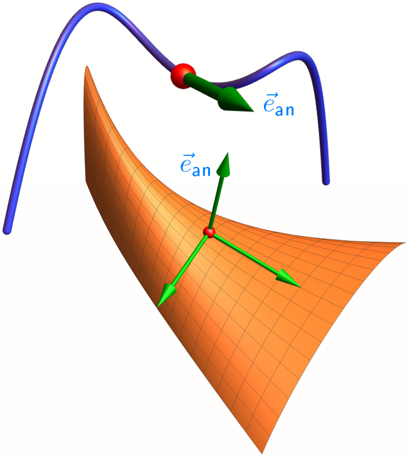


Minimal model of a curved magnet: **exchange driven effects**

Exchange energy:

$$\mathscr{E}^{\mathrm{x}} = \underbrace{A\left(\vec{\nabla} m_i\right)\left(\vec{\nabla} m_i\right)}_{\text{Cartesian frame}} = \underbrace{\mathscr{E}_0^{\mathrm{x}} + \mathscr{E}_{\mathrm{A}}^{\mathrm{x}} + \mathscr{E}_{\mathrm{D}}^{\mathrm{x}}}_{\text{Curvilinear frame}}$$

$\mathscr{E}_0^{\mathrm{x}} = A\left(\eth_\alpha m_\nu\right)\left(\eth_\alpha m_\nu\right)$ is a 'common' exchange $\qquad \nu,\mu = 1,2,3$

$\eth_\alpha m_\nu$ is covariant derivative $\qquad \alpha,\beta = 1,2$

Geometry-governed Anisotropy

$\mathscr{E}_{\mathrm{A}}^{\mathrm{x}} = K_{\mu\nu} m_\mu m_\nu$ $\qquad$ κ_1, κ_2 are principles curvatures

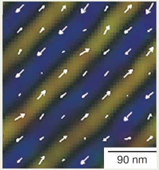
$K_{\mu\nu} = A\ \mathrm{diag}\left(\kappa_1^2, \kappa_2^2, \kappa_1^2 + \kappa_2^2\right)$ are coefficients of effective biaxial anisotropy

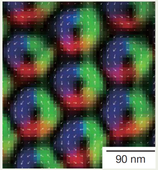
Geometry-governed Dzyaloshinskii–Moria Interaction (DMI)

$\mathscr{E}_{\mathrm{D}}^{\mathrm{x}} = A\kappa_1 L_{13}^{(1)} + A\kappa_2 L_{23}^{(2)}$

$L_{\mu\nu}^{(\alpha)} = m_\mu \eth_\alpha m_\nu - m_\nu \eth_\alpha m_\mu$ is a curvilinear-geometry analogue of Lifshitz invariants

Lifshitz invariants come from spin-orbit coupling, leading to helical structures and skyrmion crystals
[Bogdanov and Rößler, PhysRevLett (2001)]
[Yu, Onose, Kanazawa, Park, Han, Matsui, Nagaosa, Tokura, Nature (2010)]





[Gaididei, Kravchuk, Sheka, PhysRevLett (2014); Sheka, Kravchuk, Gaididei, JPhysA (2015)]

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Curvilinear geometry as a source of emergent Dzyaloshinskii–Moriya interaction

[Gaididei, Kravchuk, Sheka, PhysRevLett (2014); Sheka, Kravchuk, Gaididei, JPhysA (2015)]

Analogy with mechanics

Magnetic system in a curved frame

$$\mathscr{E} = \mathscr{E}_0 + \underbrace{K_{\alpha\beta} m_\alpha m_\beta}_{\text{Anisotropy}} + \underbrace{\mathcal{A}\kappa_\alpha \left(m_\alpha \eth_\alpha m_3 - m_3 \eth_\alpha m_\alpha\right)}_{\text{Dzyaloshinskii–Moriya interaction}}$$

Mechanical particle in a non inertial frame

$$E = E_0 + \underbrace{\frac{m}{2}\left[\vec{\Omega} \times \vec{r}\right]^2}_{\text{Centrifugal}} + \underbrace{m\dot{\vec{r}} \cdot \left[\vec{\Omega} \times \vec{r}\right]}_{\text{Coriolis}}$$

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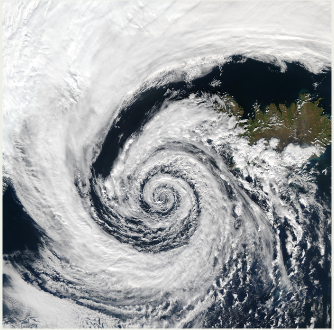
Centrifugal force in action

Coriolis force in action



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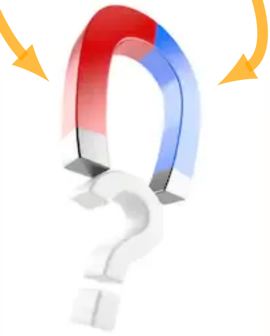

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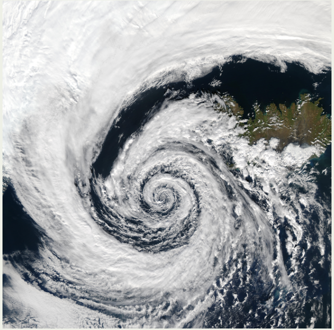
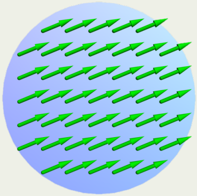


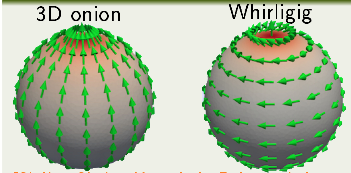
Topological patterning

Formation of topologically protected textures in curved geometries

Flat Film



Spherical shell



[Sloika, Sheka, Kravchuk, Pylypovskyi, Gaididei, JMMM (2017)]

Nanotube

Toroidal shell

Hyperboloid shell

Möbius ring

Topological patterning

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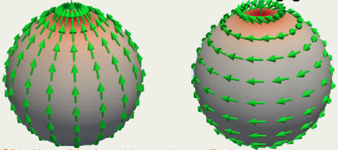
Hairy Ball Theorem

You cannot comb a hairy ball flat without creating a cowlick [Poincaré (1885)]

Spherical shell

3D onion Whirligig



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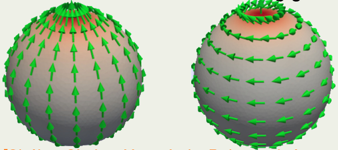
3D onion — Whirligig



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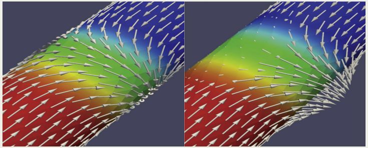
Nanotube

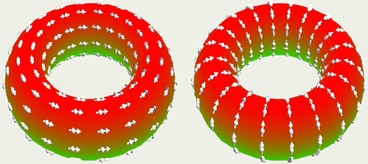
Vortex wall — Transversal wall



[López-López, Cortés-Ortuño, Landeros, JMMM (2012)]

Toroidal shell

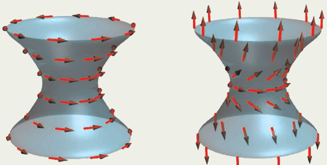
Toroidal vortex — Poloidal vortex



[Teixeira, Castillo-Sepúlveda, Vojkovic, Fonseca, Altbir, Núñez, Carvalho-Santos, JMMM (2019)]

Hyperboloid shell

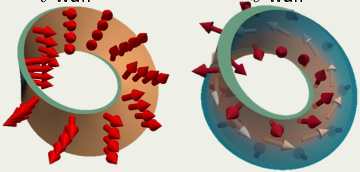
Vortex — Skyrmion



[Carvalho-Santos, Elias, Altbir, Fonseca, JMMM (2015)]

Möbius ring

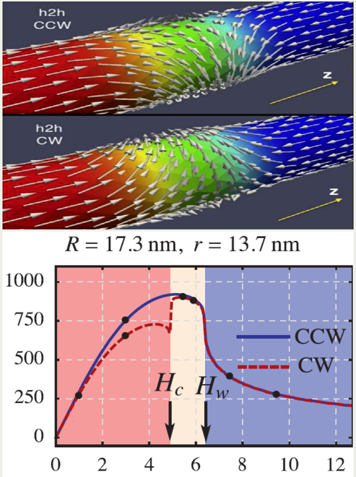
t-wall — ℓ-wall



[Pylypovskyi, Kravchuk, Sheka, Makarov, Schmidt, Gaididei, PRL (2015)]

Geometrical magnetochiral effects: **pattern-induced chirality breaking**

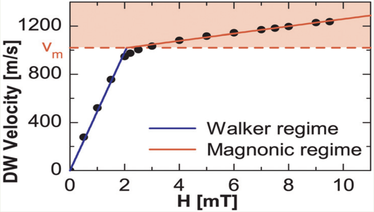
Chiral symmetry breaking in moving vortex domain wall



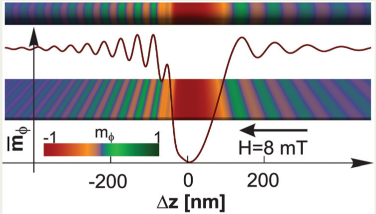
[Landeros, Núñez, JAP (2010)]

Ultrafast domain walls in nanotubes

Supression of Walker breakdown



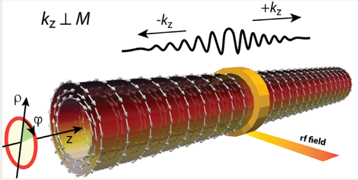
Spin-Cherenkov effect



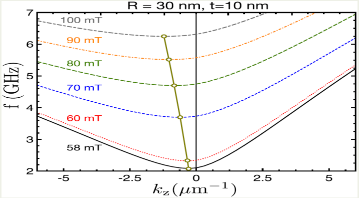
[Yan, Andreas, Kákay, García-Sánchez, Hertel, APL (2011)]

Chiral spin-wave dynamics

Spin waves on a vortex state background



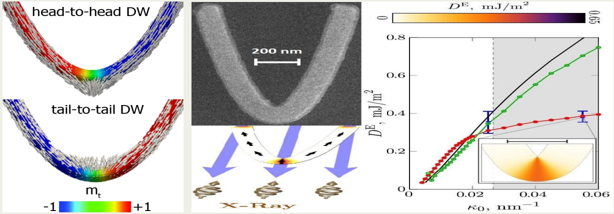
Asymmetric dispersion law
$\omega(k_z) \neq \omega(-k_z)$



[Otálora, Yan, Schultheiss, Hertel, Kákay, PRL (2016); PRB (2017)]

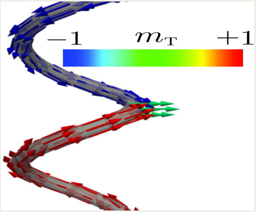
Geometrical magnetochiral effects: geometry-induced chirality breaking

Flat curved stripes: domain wall pinning



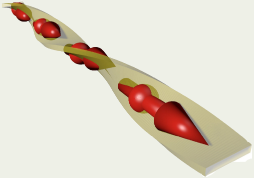
[Yershov, Kravchuk, Sheka, Gaididei, PRB (2015)]
[Volkov, Kákay, Kronast, Mönch, Mawass, Fassbender, Makarov, PRL (2019)]

Helix wire



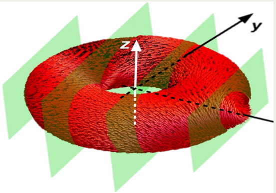
[Yershov, Kravchuk, Sheka, Gaididei, PRB (2016)]

Helicoid ribbon



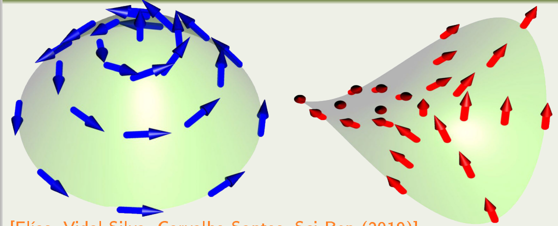
[Gaididei, Goussev, Kravchuk, Pylypovskyi, Robbins, Sheka, Slastikov, Vasylkevych, JPA (2017)]

Toroidal shell



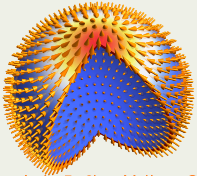
[Vojkovic, Carvalho-Santos, Fonseca, Nunez, JAP (2017)]

Parabolic and Hyperbolic shells



[Elías, Vidal-Silva, Carvalho-Santos, Sci Rep (2019)]

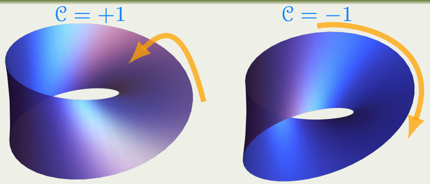
Skyrmion on a spherical shell



[Kravchuk, Rößler, Volkov, Sheka, van den Brink, Makarov, Fuchs, Fangohr, Gaididei, PRB (2016)]

Coupling between geometrical chirality $\mathcal{C}$ and the magnetochirality $\mathfrak{C}$

Möbius geometrical chirality

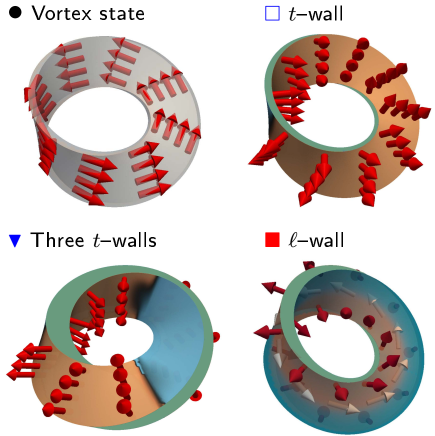


Topologically protected domain wall

Chiral symmetry breaking

t–wall energy gain $\Delta E \propto \mathcal{C}\ \mathfrak{C}$

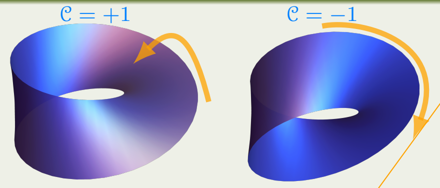
$m_{\text{thickness}} = \mathfrak{C} = \pm 1$ (inward or outward)

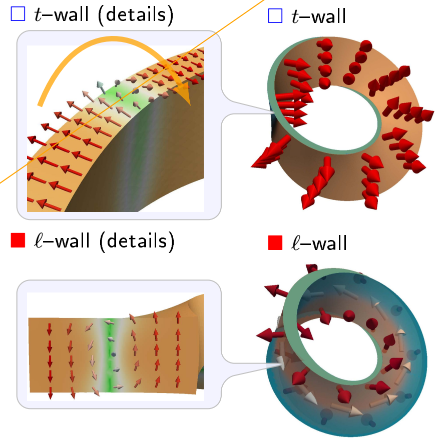


[Pylypovskyi, Kravchuk, Sheka, Makarov, Schmidt, Gaididei, PhysRevLett (2015)]

Coupling between geometrical chirality $\mathcal{C}$ and the magnetochirality $\mathfrak{C}$

Möbius geometrical chirality





Topologically protected domain wall

Chiral symmetry breaking

t–wall energy gain $\Delta E \propto \mathcal{C}\,\mathfrak{C}$

$m_{\text{thickness}} = \mathfrak{C} = \pm 1$ (inward or outward)

[Pylypovskyi, Kravchuk, Sheka, Makarov, Schmidt, Gaididei, PhysRevLett (2015)]

Coupling between geometrical chirality $\mathcal{C}$ and the magnetochirality $\mathfrak{C}$

Co Möbius (FEBID)

[Skoric, Sanz-Hernández, Meng, Donnelly, Merino, Aceituno, Fernández-Pacheco, Nano Lett (2020)]

Topologically protected domain wall

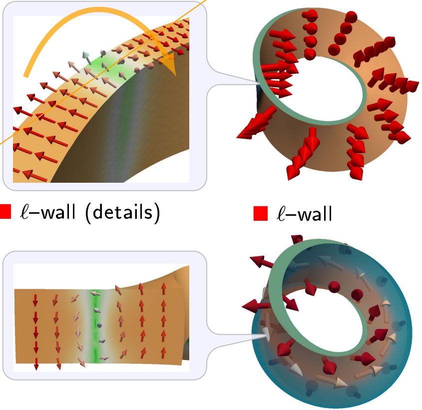
Chiral symmetry breaking

t–wall energy gain $\Delta E \propto \mathcal{C}\,\mathfrak{C}$

$m_{\text{thickness}} = \mathfrak{C} = \pm 1$ (inward or outward)

□ t–wall (details) □ t–wall

■ ℓ–wall (details) ■ ℓ–wall



[Pylypovskyi, Kravchuk, Sheka, Makarov, Schmidt, Gaididei, PhysRevLett (2015)]

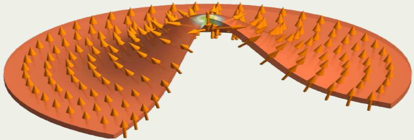
Geometrical magnetochiral effects: exchange-driven DMI

Geometry-governed DMI: $\mathscr{E}_{\mathrm{D}}^{\mathrm{x}} = A\kappa_1 L_{13}^{(1)} + A\kappa_2 L_{23}^{(2)}$

Small radius skyrmions: theory

Radius R is determines by $\mathscr{H}$

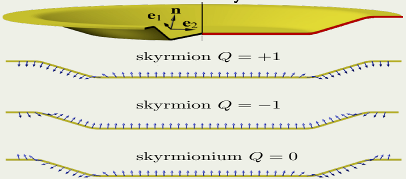
$\mathscr{H} = \kappa_1 + \kappa_2$ is a mean curvature



[Kravchuk, Sheka, Kákay, Volkov, Rößler, van den Brink, Makarov, Gaididei, PRL (2018)]

Tunable radius skyrmion: theory

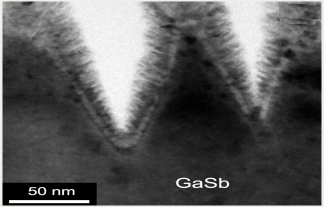
Radius R is determines by $\nabla\mathscr{H}$

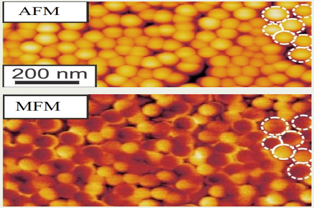


[Pylypovskyi, Makarov, Kravchuk, Gaididei, Saxena, Sheka, PRApplied (2018)]

Geometrically stabilized magnetic states: experiment

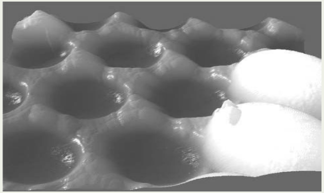
CoCrPt:SiO_2 deposited on nanocones

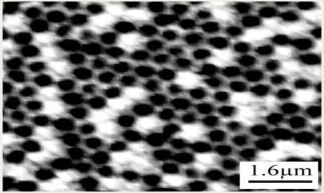




[Ball, Lenz, Fritzsche, Varvaro, Günther, Krone, Makarov, Mücklich, Facsko, Fassbender, Albrecht, Nanotechnology (2014)]

Spherical nanoindentations





[Makarov, Baraban, Guhr, Boneberg, Schift, Gobrecht, Schatz, Leiderer, Albrecht, APL (2007)]

Geometrical magnetochiral effects: **mesoscale DMI**

Vector of Mesoscale DMI: geometrical tailoring of the magnetochirality

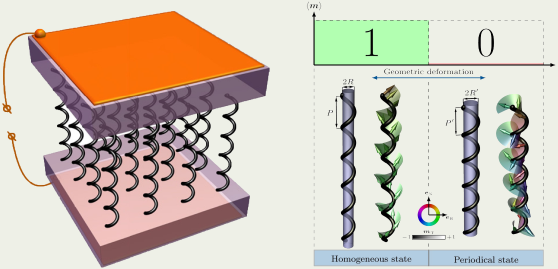
$$\vec{D} = \underbrace{\vec{D}^i}_{\text{intrinsic}} + \underbrace{\vec{D}^e}_{\text{extrinsic}}$$

Two types of DMI are characterized by:

- different scales
- different directions
- different symmetries

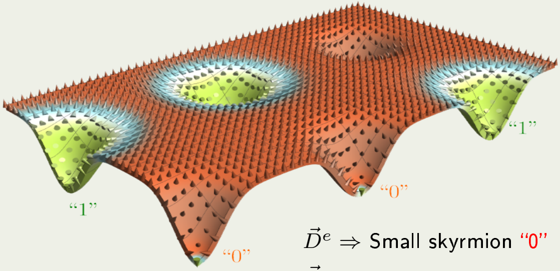
[Volkov, Sheka, Gaididei, Kravchuk, Rößler, Fassbender, Makarov, Sci. Rep. (2018)]

Concept of artificial magnetoelectric materials



[Volkov, Rößler, Fassbender, Makarov, JPD (2019)]

Reconfigurable skyrmion lattices

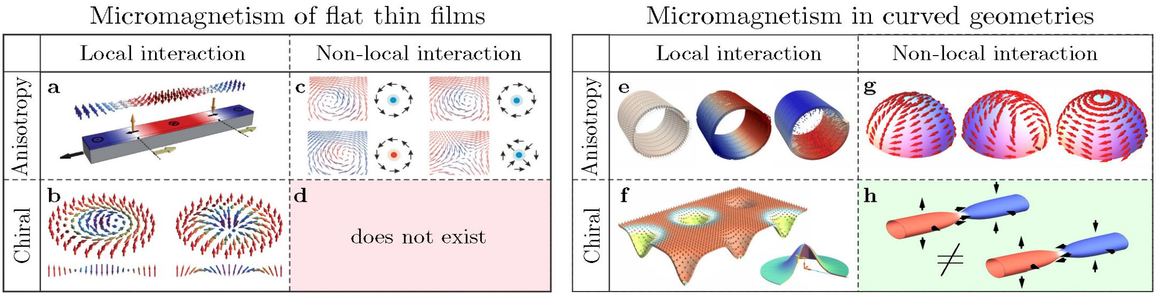


$\vec{D}^e \Rightarrow$ Small skyrmion "0"

$\vec{D} \Rightarrow$ Large skyrmion "1"

[Kravchuk, Sheka, Kákay, Volkov, Rößler, van den Brink, Makarov, Gaididei, PRL (2018)]

Geometrical magnetochiral effects: **Nonlocal** chiral symmetry breaking

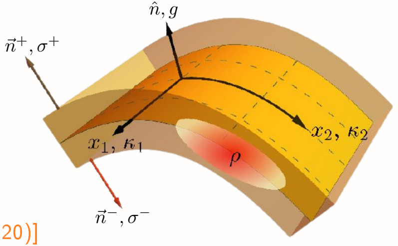


$-\nabla \cdot \vec{m} = \rho(\vec{r}) + g(\vec{r})$

$\rho(\vec{r}) = -\eth_\alpha m_\alpha$: tangential charge

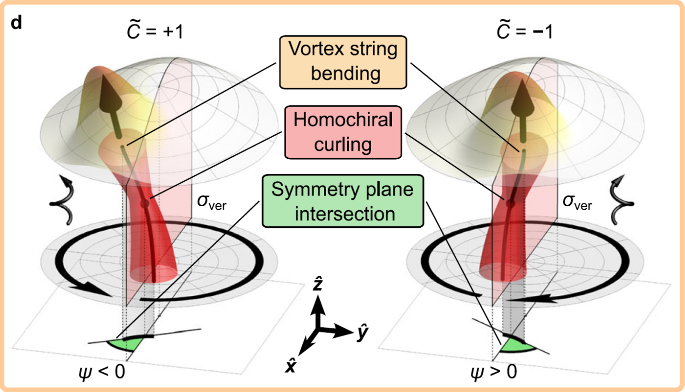
$g(\vec{r}) = (\kappa_1 + \kappa_2)\, \vec{m} \cdot \hat{n}$: geometrical charge

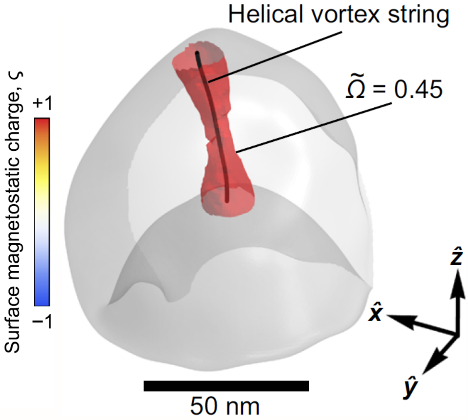
$\sigma^{\pm}(\vec{r}) = \vec{m} \cdot \vec{n}^{\pm}$: surface charge



[Sheka, Pylypovskyi, Landeros, Gaididei, Kákay, Makarov, Comms. Phys (2020)]

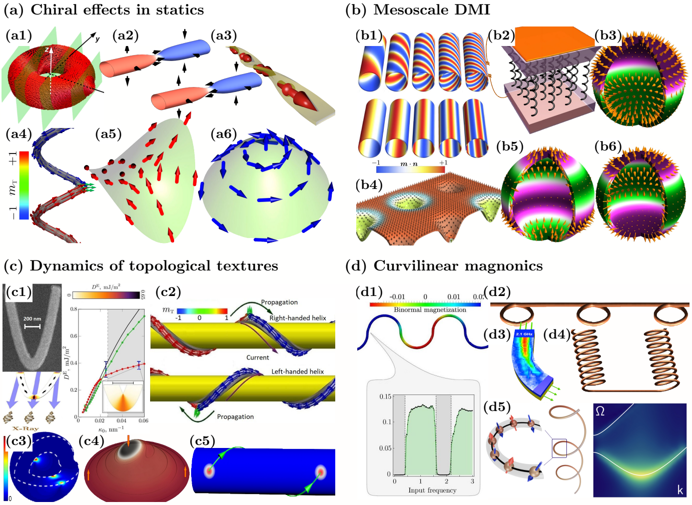
experimental validation





[Volkov, Wolf, Pylypovskyi, Kákay, Sheka, Büchner, Fassbender, Lubk, Makarov, Nature Comms. (2023)]

Current and future challenges



Fundamental researches:

- Curvilinear antiferromagnetism
- Tayloring cross section in curvilinear magnetism

Prospect for applications:

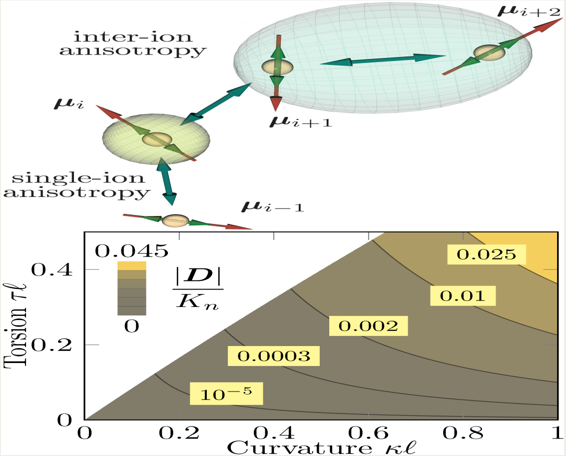
- Shapeable magnetoelectronics
- Curvilinear spintronics
- Curvilinear magnonics
- Curvilinear skyrmionics
- Magnetic soft robotics

[Sheka, ‘A perspective on curvilinear magnetism’, APL (2021)]

Curvilinear antiferromagnetism: curvature effects

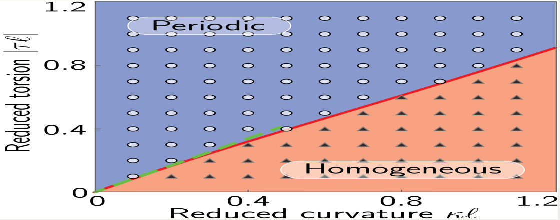
Theory

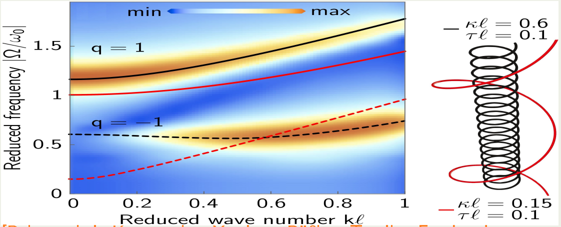
Anisotropy and homogeneous DMI



[Pylypovskyi, Borysenko, Fassbender, Sheka, Makarov, APL (2021)]

Helix as a case study

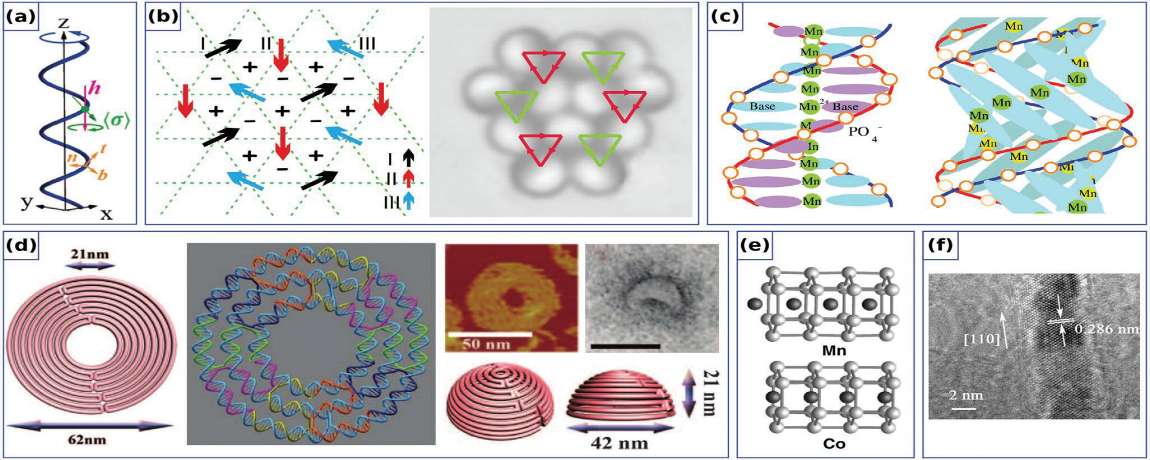




[Pylypovskyi, Kononenko, Yershov, Rößler, Tomilo, Fassbender, van den Brink, Makarov, Sheka, Nano Lett (2020)]

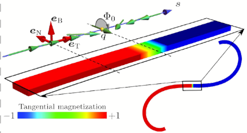
Curvilinear antiferromagnetism: curvature effects

Perspectives of curvilinear antiferromagnetism

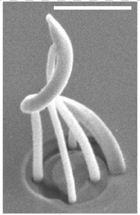


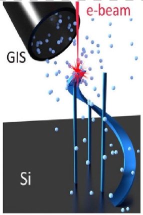
[Makarov, Volkov, Kákay, Pylypovskyi, Budinská, Dobrovolskiy (review), Adv. Mat. (2021)]

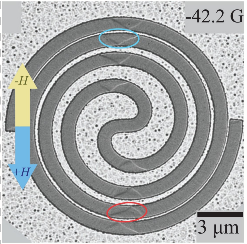
Geometry-induced automotion



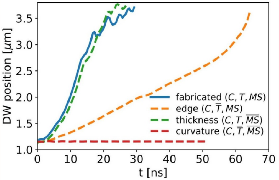
[Yershov, Kravchuk, Sheka, Pylypovskyi, Makarov, Gaididei, PRB (2018)]







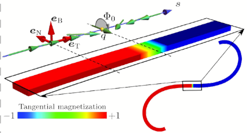
[Brajuskovic, Phatak, APL (2021)]



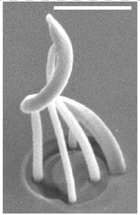
[Skoric, Donnelly, Hierro-Rodriguez, Cascales Sandoval, Ruiz-Gómez, Foerster, Niño Orti, Belkhou, Abert, Suess, Fernández-Pacheco, ACS Nano (2022)]

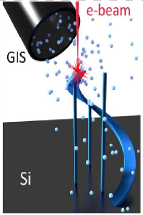
Curvilinear magnetism of nanowires with varying cross section

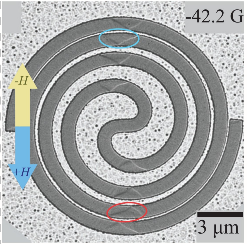
Geometry-induced automotion



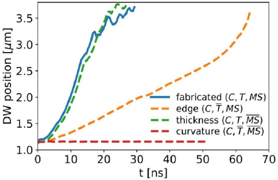
[Yershov, Kravchuk, Sheka, Pylypovskyi, Makarov, Gaididei, PRB (2018)]





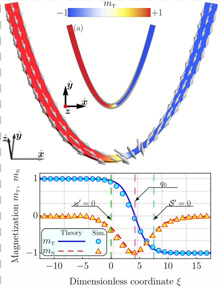


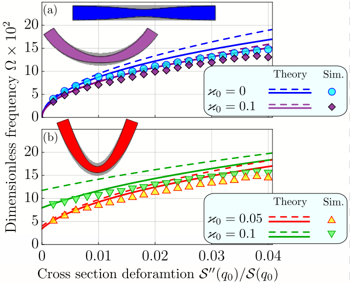
[Brajuskovic, Phatak, APL (2021)]

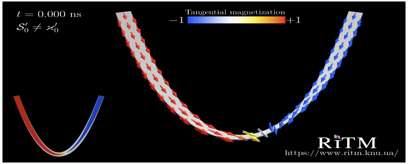


[Skoric, Donnelly, Hierro-Rodriguez, Cascales Sandoval, Ruiz-Gómez, Foerster, Niño Orti, Belkhou, Abert, Suess, Fernández-Pacheco, ACS Nano (2022)]

Control of magnetic response by tailoring the cross section



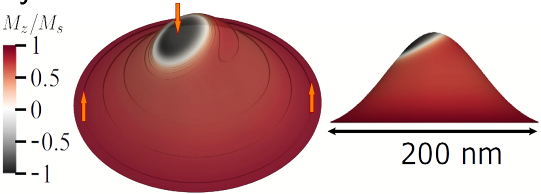




[Yershov, Sheka, PRB (2023)]

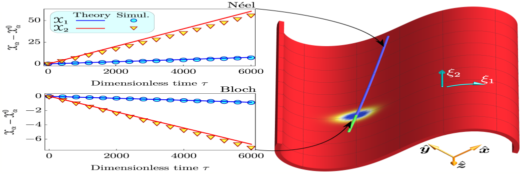
Curvature-induced automotion

Gyromotion



[Korniienko, Kákay, Sheka, Kravchuk, PRB (2020)]

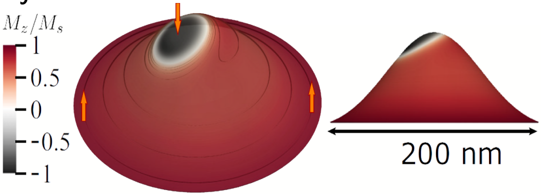
Drift



[Yershov, Kákay, Kravchuk, PRB (2022)]

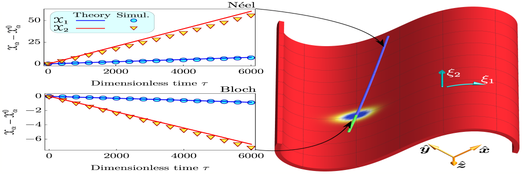
Curvature-induced automotion

Gyromotion



[Korniienko, Kákay, Sheka, Kravchuk, PRB (2020)]

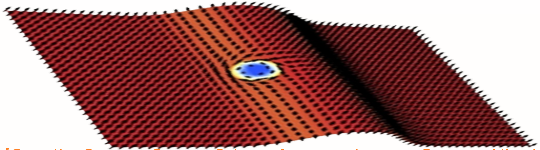
Drift



[Yershov, Kákay, Kravchuk, PRB (2022)]

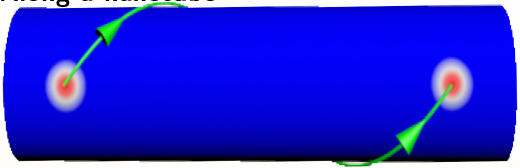
Current-induced propagation

Along a curved racetrack



[Carvalho-Santos, Castro, Salazar-Aravena, Laroze, Corona, Allende, Altbir, APL (2021)]

Along a nanotube



[Wang, Wang, Wang, Yang, Cao, Yan, APL (2019)]

Acknowledgements

Our team (RiTM):: http://ritm.knu.ua

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DFG Deutsche Forschungsgemeinschaft
DAAD Deutscher Akademischer Austausch Dienst German Academic Exchange Service
erc European Research Council

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DAAD Deutscher Akademischer Austausch Dienst
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erc European Research Council