Exchange-driven chiral effects in curvilinear magnetism:

theoretical abstraction or experimental observable

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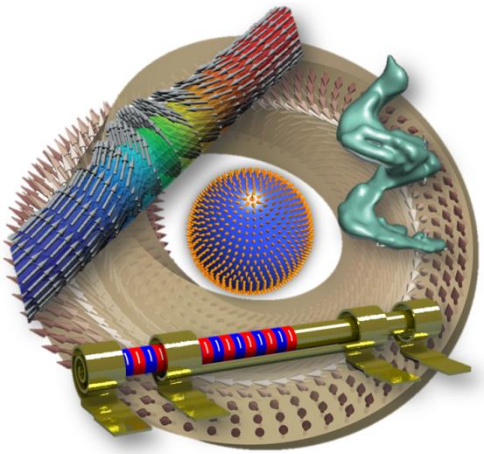
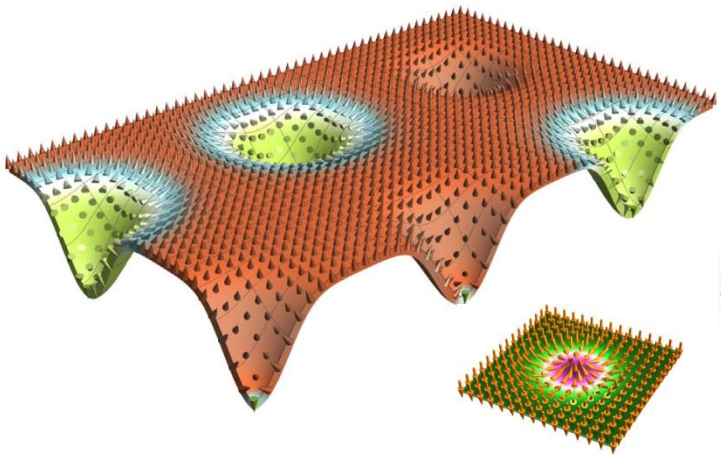
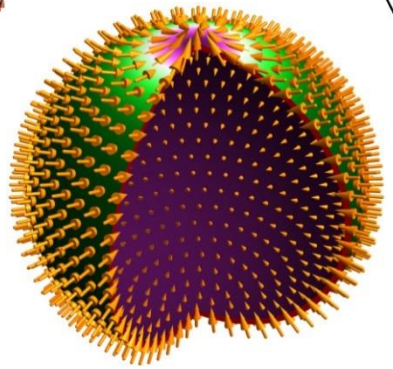
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

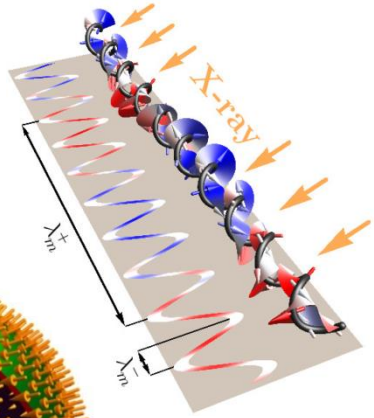
Overview of activities

I. Curvilinear magnetism (3-dimentional geometries)



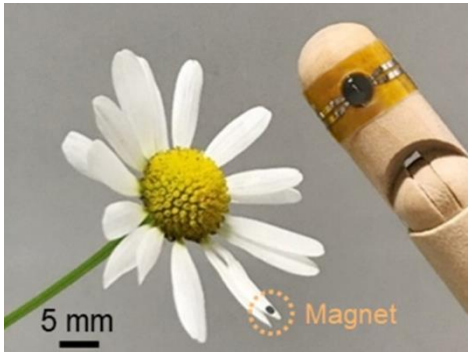


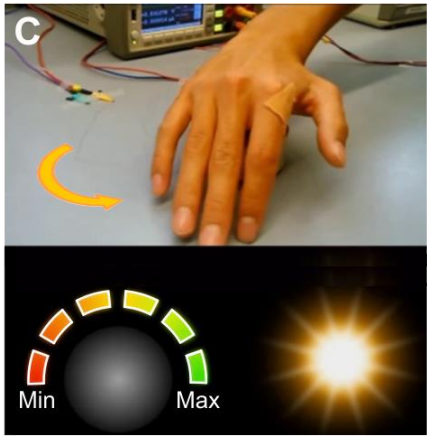




Nature Commun. & Phys. Rev. Lett. & Nano Lett. & Adv. Mater. & Phys. Rev. B & Appl. Phys. Lett. & Soft Matter & Small

II. Compliant sensors & actuators





Science Advances & Nature Electronics & Nano Letters & Advanced Materials & npj Flexible Electronics & Nature Commun.

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On-skin electronics for artificial magnetoception

Interactive, on-skin devices for detecting magnetic fields

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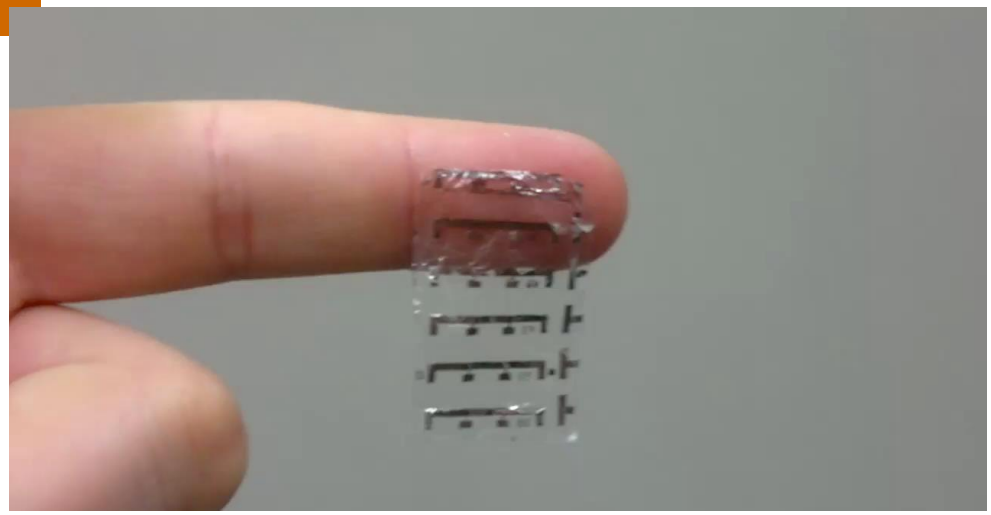
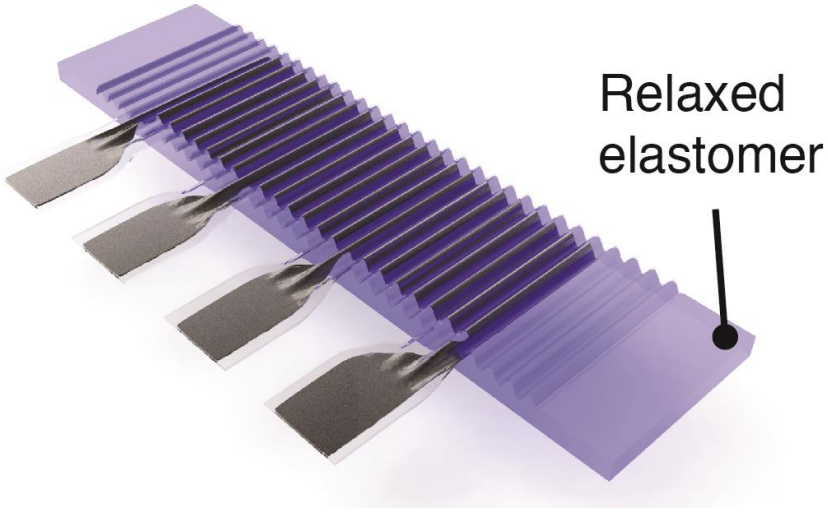
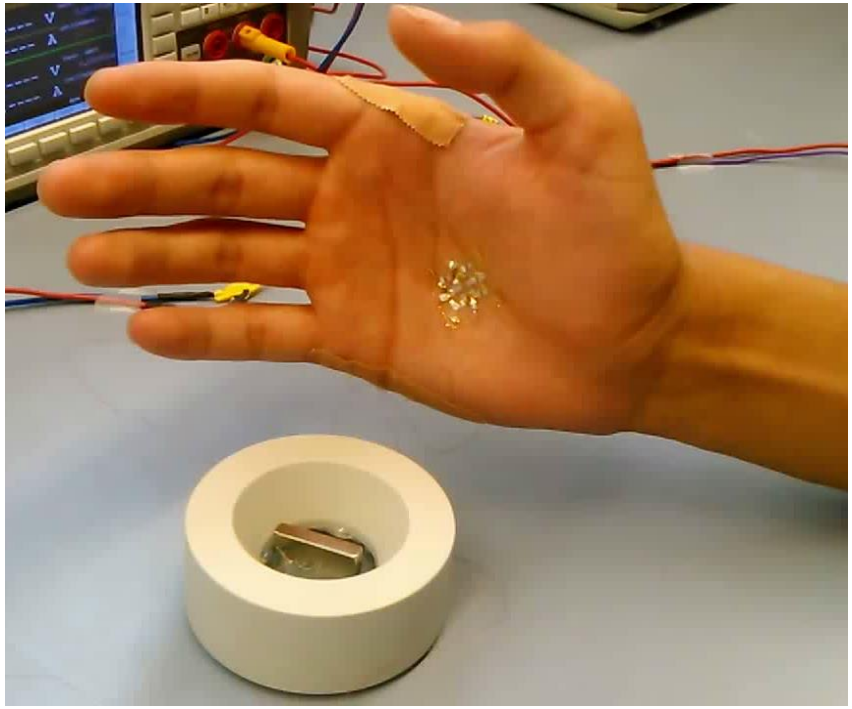


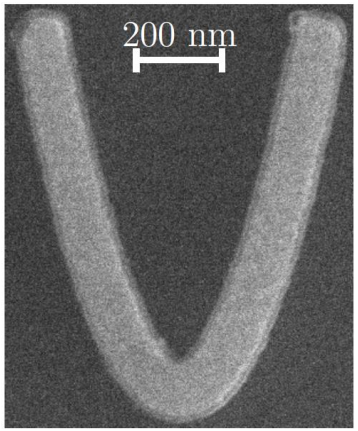


Nature Communications **6**, 6080 (2015)

Nature Electronics **1**, 589 (2018)



Science Advances **4**, eaao2623 (2018)



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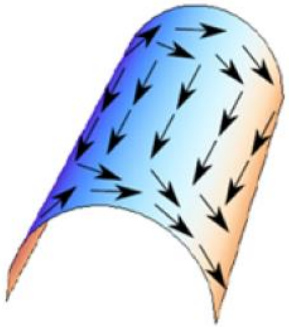
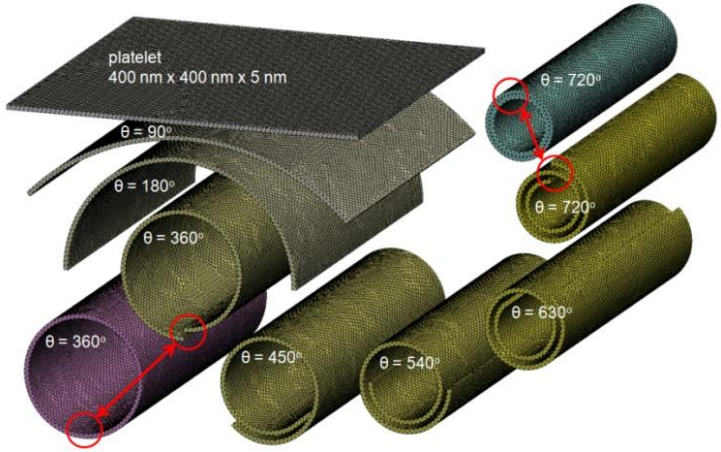
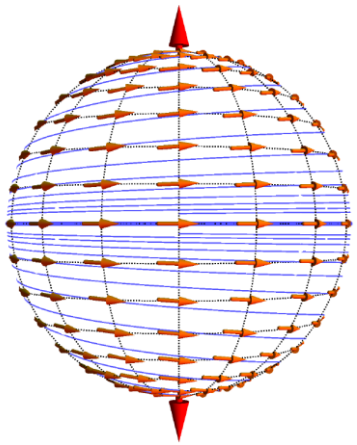
Impact of curvature on a magnetic system

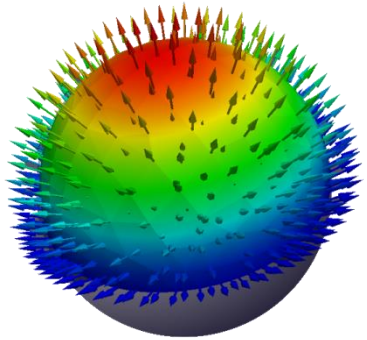


Cylindrical surfaces



Streubel, DM et al., *Nano Lett.* (2012) & (2014) & *Adv. Mat.* (2014)

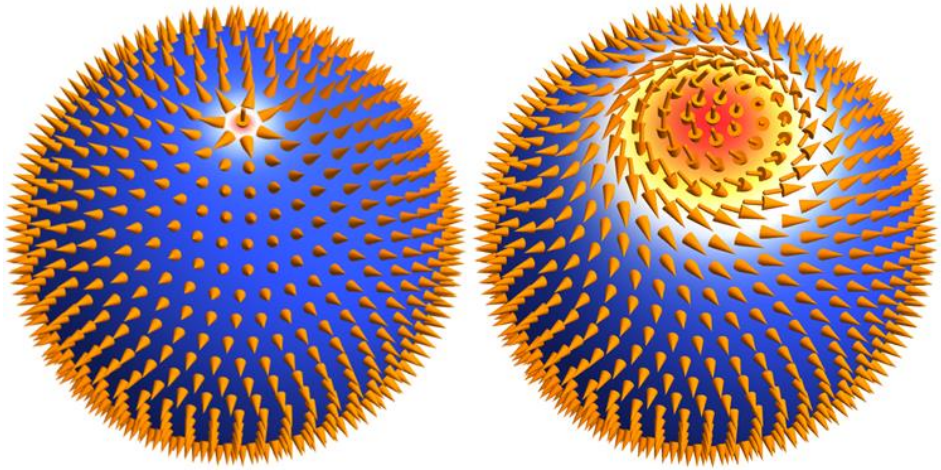




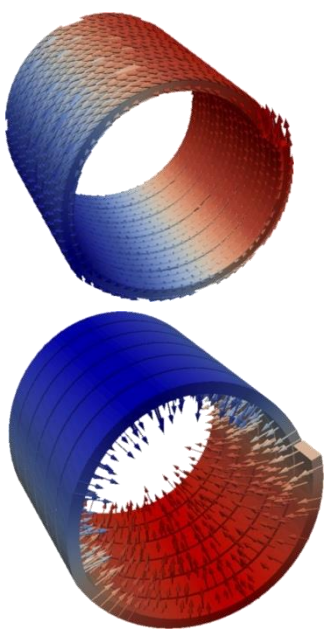
Spherical surfaces

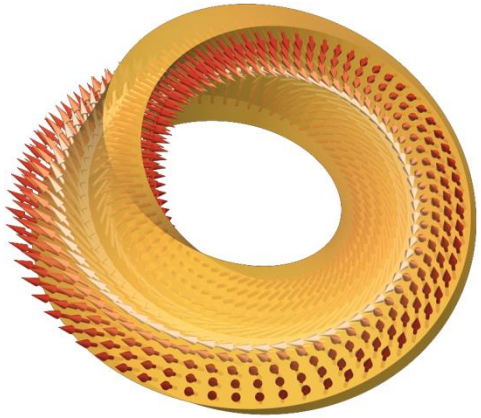
Albrecht et al., *Nat. Mater.* **4**, 203 (2005)
Ulbrich, DM et al., *PRL* (2006); DM et al., *APL* (2007)
Kravchuk, DM et al., *PRB* **85**, 144433 (2012)

Curvature induced skyrmions on a sphere



Kravchuk, DM et al., *PRB* (2016); *PRL* (2018)

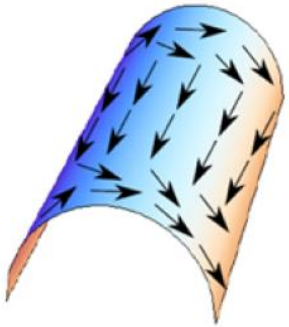




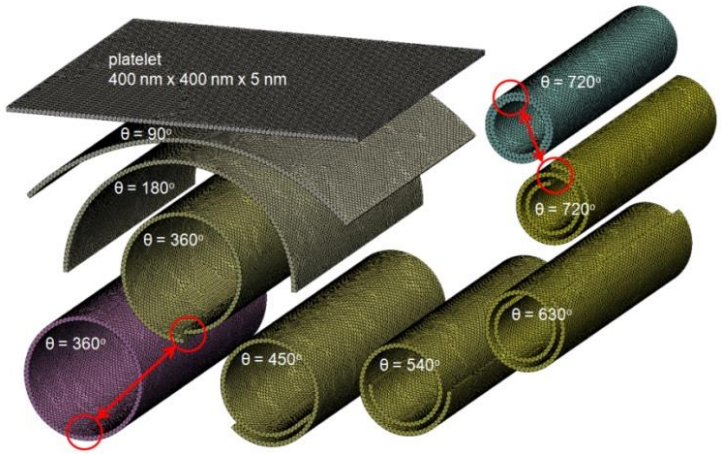
Pylypovskyi, DM et al., *PRL* (‘15)

Smith, DM et al.,
PRL **107**, 097204 (2011)

Impact of curvature on a magnetic system

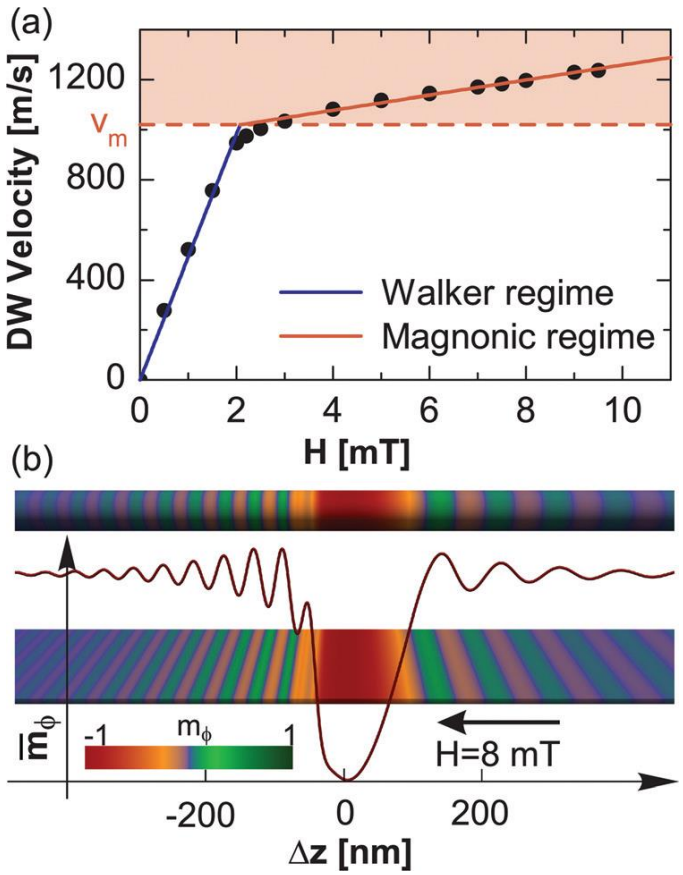


Cylindrical surfaces



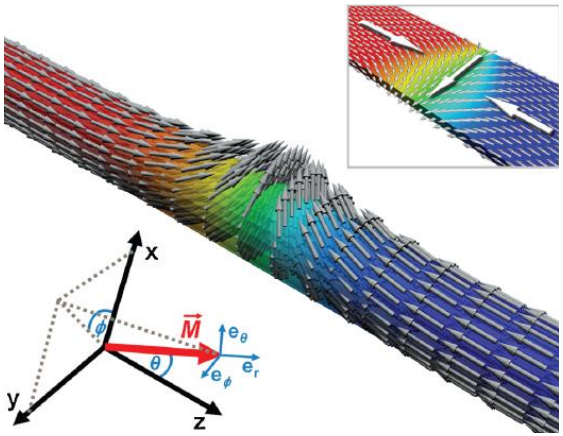
Streubel, DM et al., *Nano Lett.* (2012) & (2014) & *Adv. Mat.* (2014)

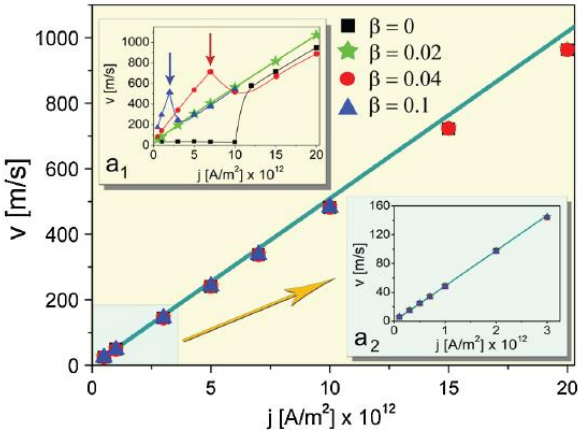
Cherenkov-like spin wave emission



Yan et al., *Appl. Phys. Lett.* (2011)

Massless magnetic domain walls in nanotubes

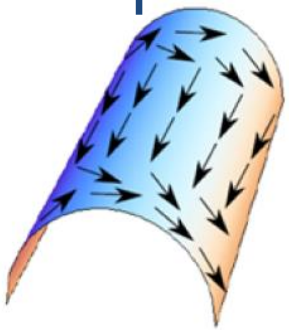




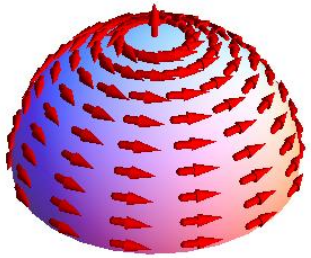
Yan et al., *Phys. Rev. Lett.* (2010)

Group of Dr. Attila Kákay (HZDR)

Impact of curvature on a magnetic system



Cylindrical surfaces



Spherical surfaces

Typical magnetic interactions in the system:

$$E = L \int_S \left[A \sum_{i=x,y,z} (\nabla m_i)^2 + K(\boldsymbol{m} \cdot \boldsymbol{n})^2 \right] \mathrm{d}\mathcal{S}$$

Exchange energy Anisotropy energy

In a curvilinear basis, energy of the magnetic material can be rewritten:

$$\mathscr{E}_{ex} = \left[\boldsymbol{\nabla}\theta - \boldsymbol{\Gamma}(\varphi)\right]^2 + \left[\sin\theta\left(\boldsymbol{\nabla}\varphi - \boldsymbol{\Omega}\right) - \cos\theta\frac{\partial\boldsymbol{\Gamma}(\varphi)}{\partial\varphi}\right]^2$$

$$\mathscr{E}_{ex} = \mathscr{E}^0_{ex} + \mathscr{E}^A_{ex} + \mathscr{E}^D_{ex} \qquad \mathscr{E}^0_{ex} = (\boldsymbol{\nabla}\theta)^2 + \sin^2\theta(\boldsymbol{\nabla}\varphi)^2$$

Effective anisotropy interaction: $\mathscr{E}^A_{ex} = \boldsymbol{\Gamma}^2 + \sin^2\theta\boldsymbol{\Omega}^2 + \cos^2\theta(\partial_\varphi\boldsymbol{\Gamma})^2$

Effective Dzyaloshinskii interaction: $\mathscr{E}^D_{ex} = D_{\alpha\beta\gamma} m_\beta \nabla_\gamma m_\alpha, \quad D_{\alpha\beta\gamma} = -D_{\beta\alpha\gamma}$

$$\mathscr{E}^D_{ex} = -2\left[(\boldsymbol{\nabla}\theta\cdot\boldsymbol{\Gamma}) + \sin\theta\boldsymbol{\nabla}\varphi\cdot(\boldsymbol{\Omega} + \cos\theta\partial_\varphi\boldsymbol{\Gamma})\right]$$

Gaididei et al., *PRL* (2014); Pylypovskyi, DM et al., *PRL* (2015); Kravchuk, DM et al., *PRL* (2018)…

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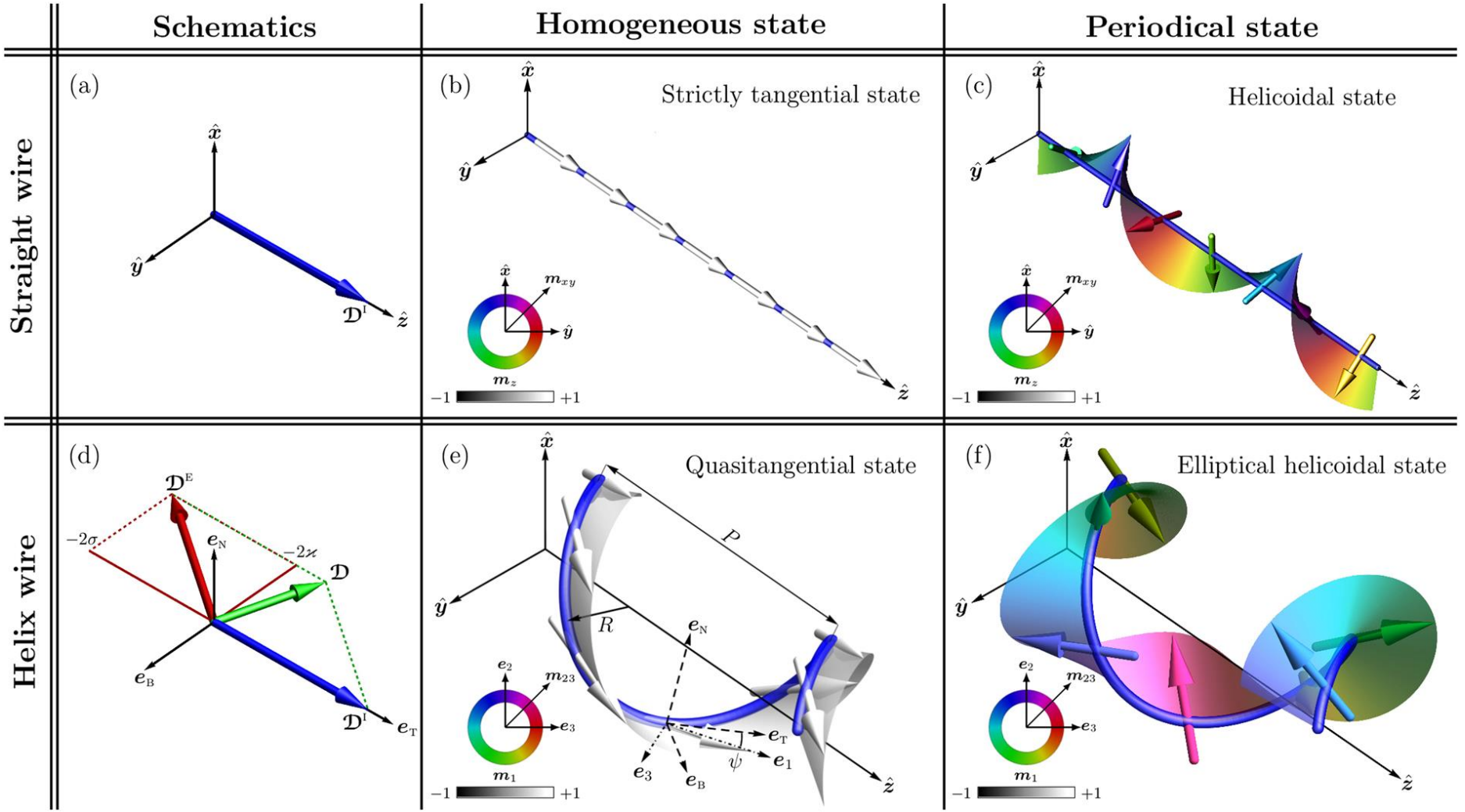
Mesoscale Dzyaloshinskii-Moriya interaction



Pylypovskyi, DM et al., *Sci. Rep.* (2016); Volkov, DM et al., *Sci. Rep.* (2018)

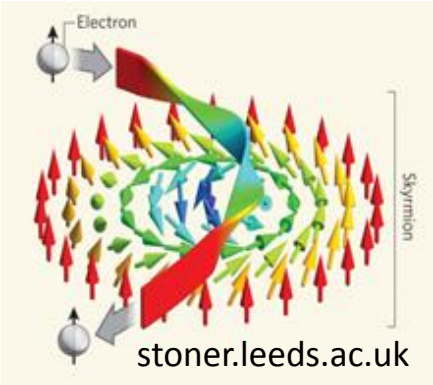
Chiral effects in magnetism

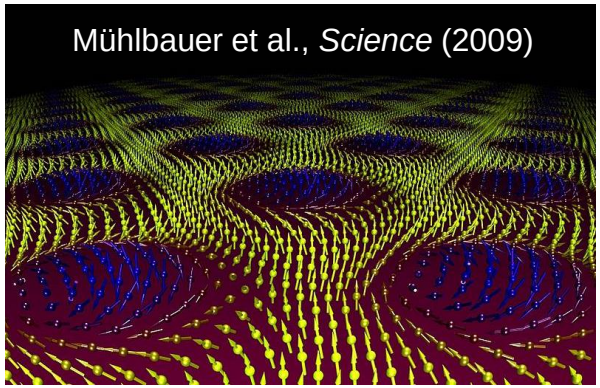
Single crystals with asymmetric exchange interaction (B20 phase)

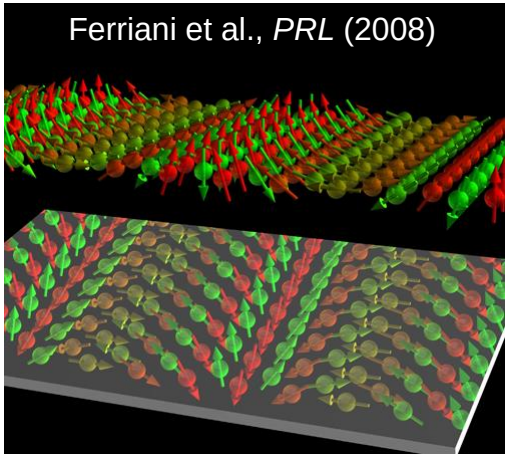
- Spin helices
- Spin spirals
- Skyrmions

+

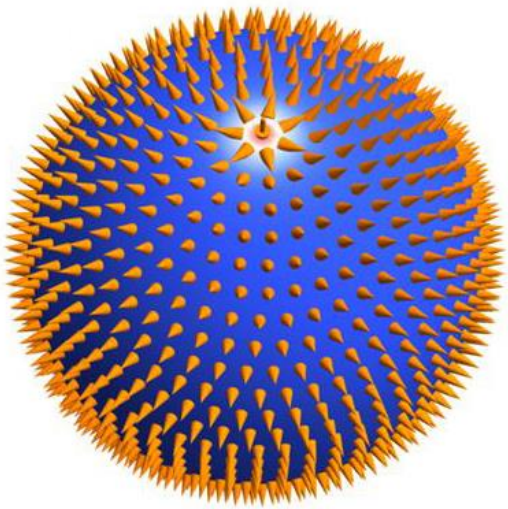
applications in spintronics



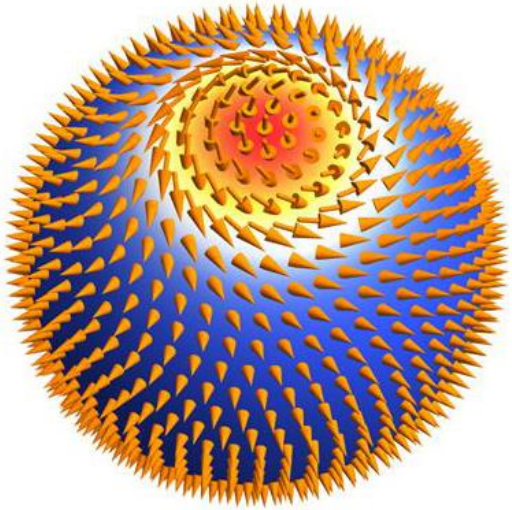




Curvature stabilized magnetic skyrmions



curvature effect only



curvature + DMI effects

Skyrmions on a spherical shell are topologically trivial

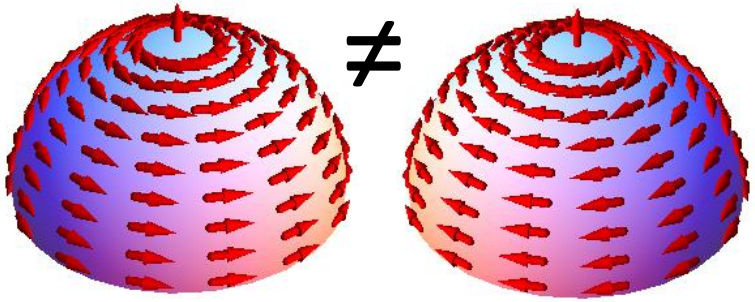
Kravchuk, DM et al., *PRB* (2016)

Curvature induced DMI

Exchange energy of curvilinear magnet contains DMI term:

$$\mathscr{E}_{ex}^{D} = -2\left[(\boldsymbol{\nabla}\theta \cdot \boldsymbol{\Gamma}) + \sin\theta \boldsymbol{\nabla}\varphi \cdot (\boldsymbol{\Omega} + \cos\theta \partial_{\varphi}\boldsymbol{\Gamma})\right]$$

Gaididei et al., *PRL* (2014)



DRESDEN concept

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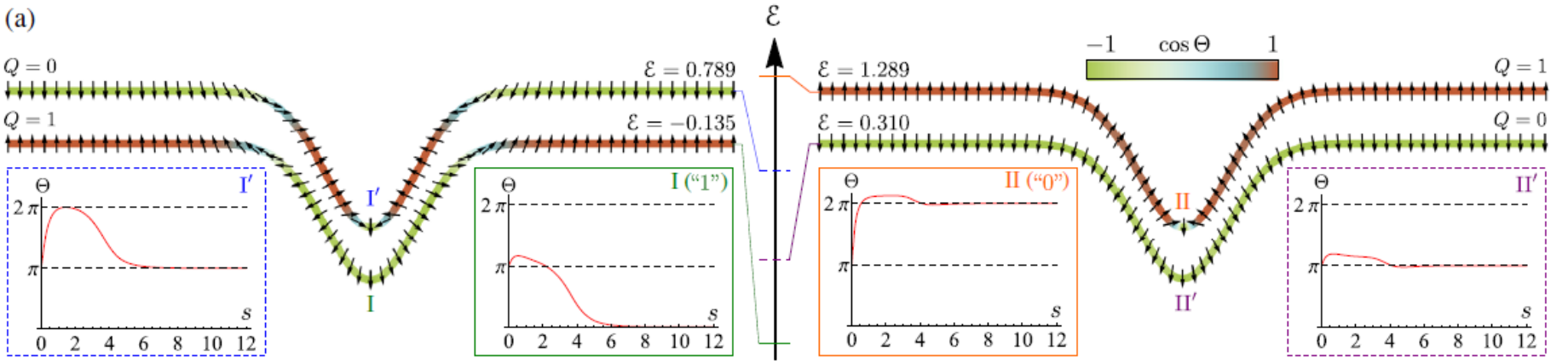
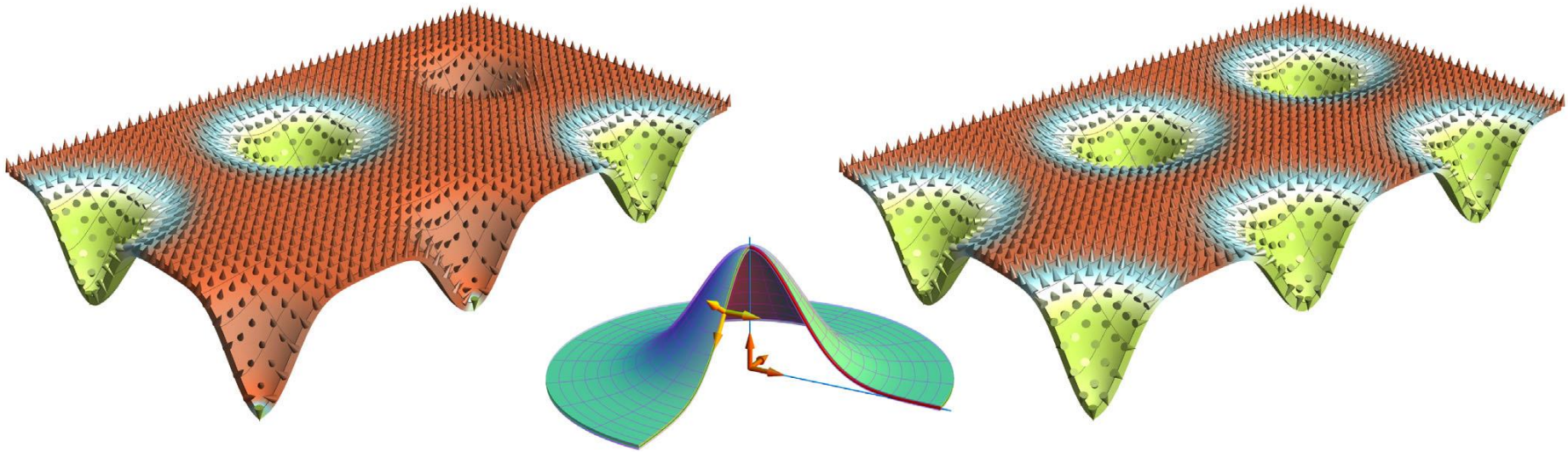
Multiplet of Skyrmion States on a Curvilinear Defect





Kravchuk, DM et al., *Phys. Rev. Lett.* (2018)

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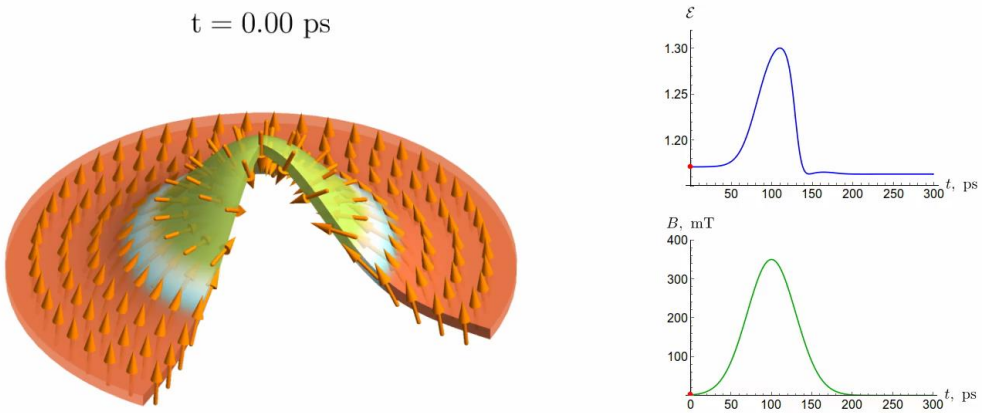
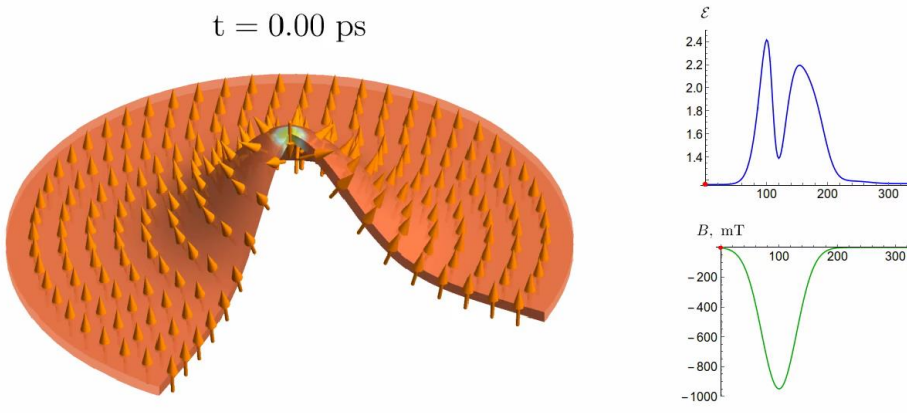
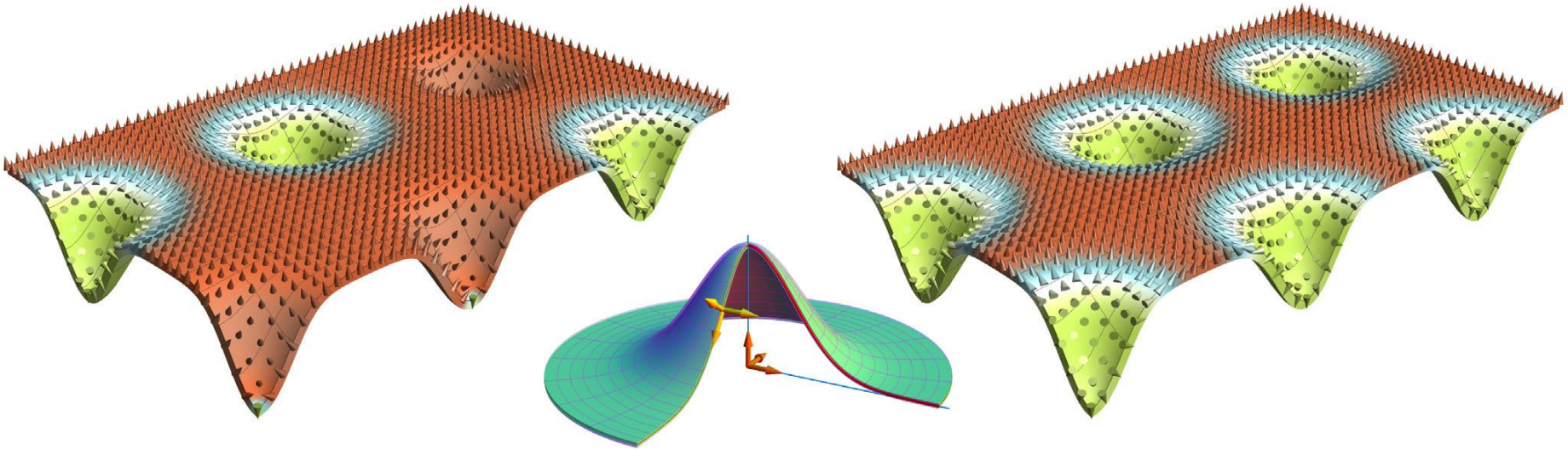
Multiplet of Skyrmion States on a Curvilinear Defect







Kravchuk, DM et al., *Phys. Rev. Lett.* (2018)

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Is it real?

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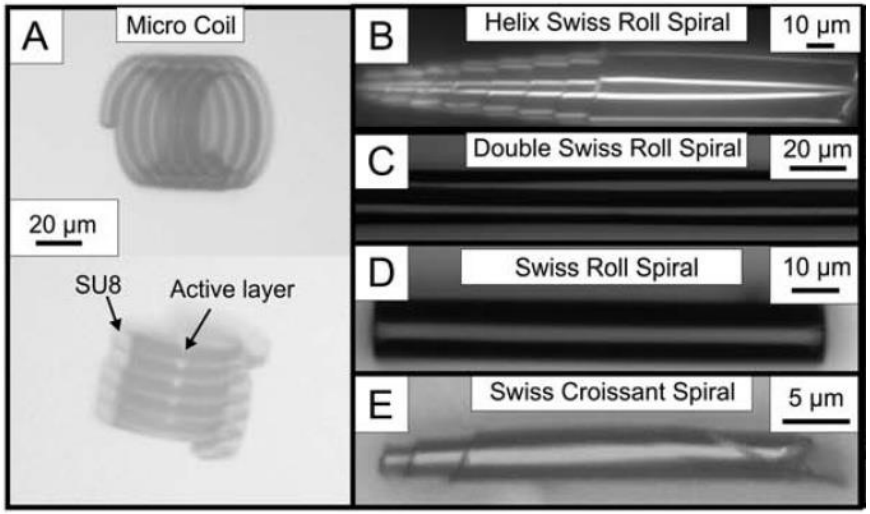
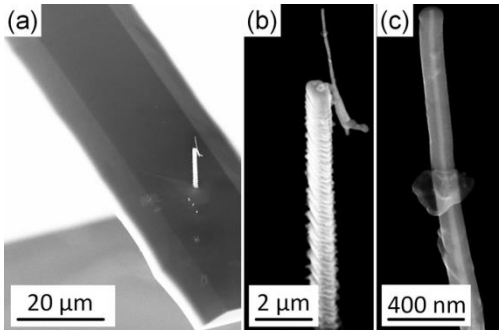
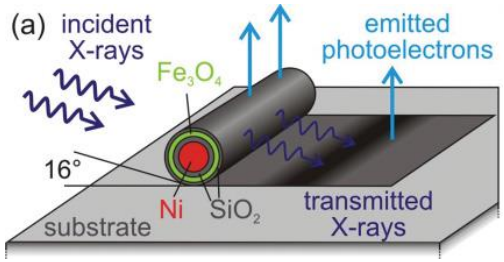
Experimental realizations



Smith, DM et al., *Phys. Rev. Lett.* (2011) & *Soft Mat.* (2011)



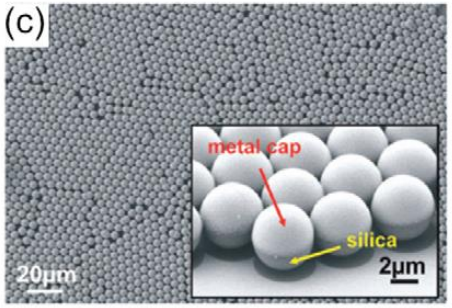
Mühl et al., *APL* (2012)

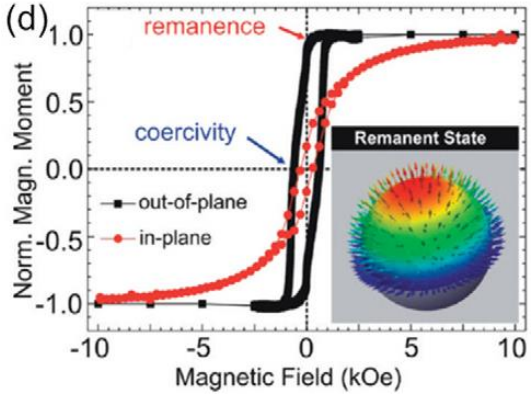


Kimling et al., *PRB* (2011)

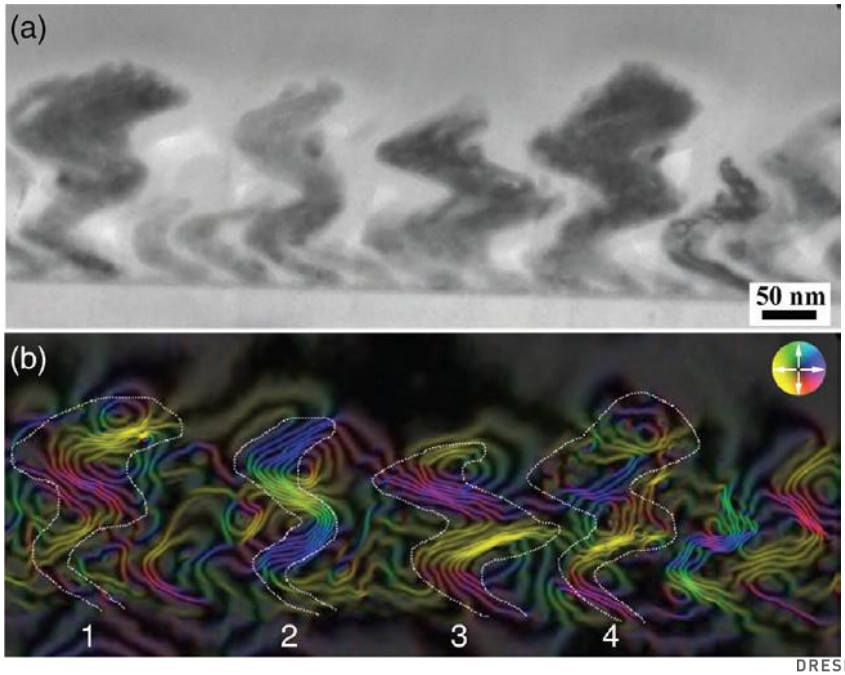
Magnetic soft x-ray tomography

Streubel, DM et al., *Nature Commun.* (2015)





Baraban, DM et al., *ACS Nano* (2012)



Phatak et al., *Nano Lett.* (2014)

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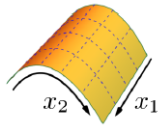
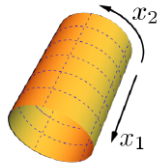
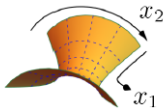
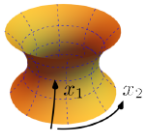
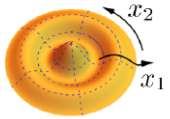
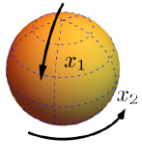
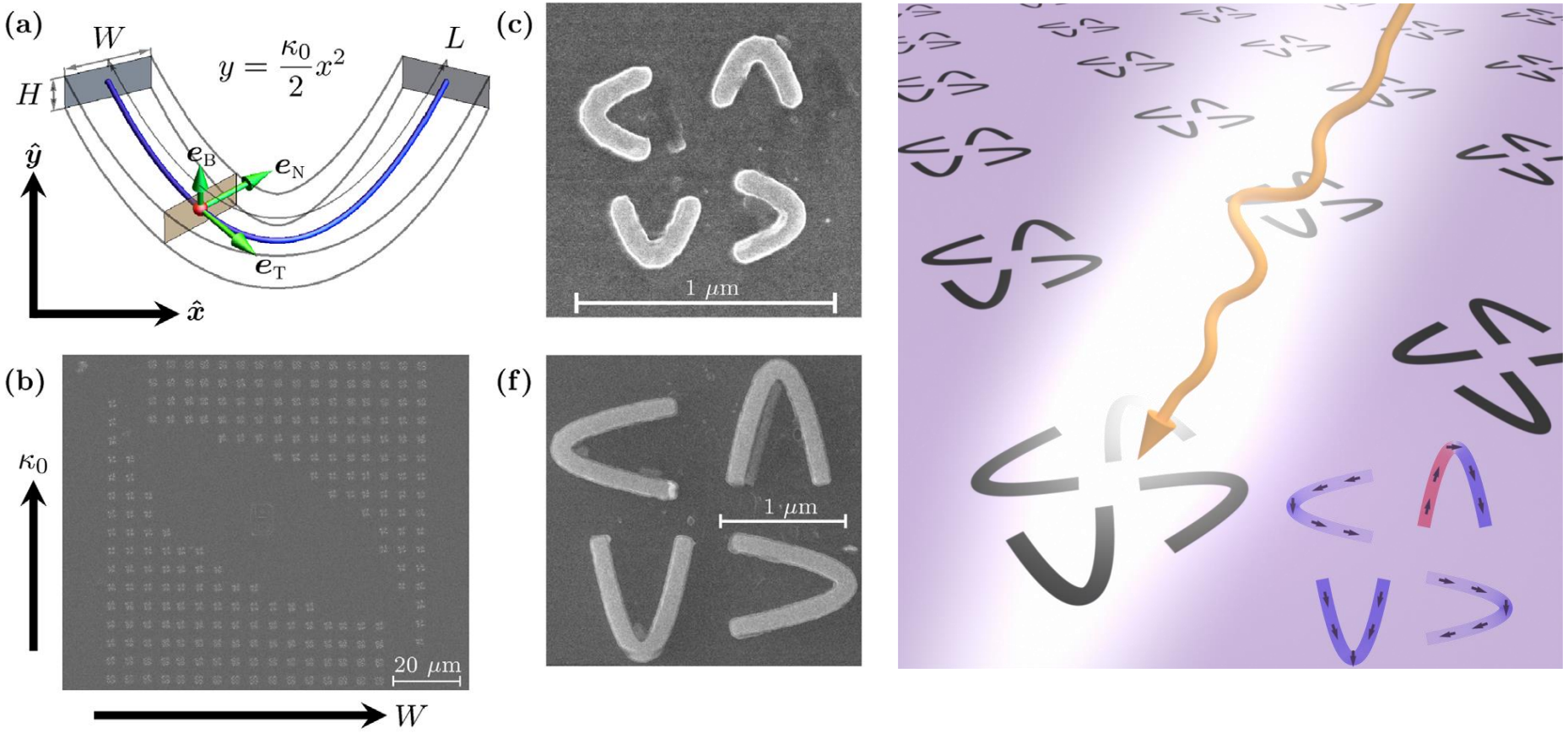
Complication due to curvature effects in magnetostatics

Surface		Local characteristics of a surface			Anisotropy		Texture symmetry	Exchange			Magnetostatics	
		κ_1	κ_2	Surface element	Type	e_a		$w_{\mathrm{ex}}^{\mathrm{D}\,1}$	$w_{\mathrm{ex}}^{\mathrm{D}\,2}$	w_{ex}^{a}	$w_{\mathrm{ms}}^{\mathrm{c}}$	w_{ms}^{a}
Developable, $\mathcal{K}=0$	Generalized cylinders (elliptical cylinders, ripples etc.)	0	$\kappa_2(x_2)$		EA	n, e_2	$m(x_2)$	–	✓	✓	✓	✓
					HA	n	$m=e_1$	–	–	✓	–	–
					EA	e_1						
					EA or HA	e_a	$m(x_1,x_2)$	–	✓	✓	✓	✓
	Circular cylinder	0	const		EA	n	$m=\hat{n}$	–	–	✓	–	✓
					HA	n	$m=e_1$	–	–	✓	–	–
					EA	e_1						
					EA	e_2	$m=e_2$	–	–	✓	–	–
Minimal, $\mathcal{H}=0$	Minimal surface	$\kappa_1(x_1,x_2)$	$-\kappa_1(x_1,x_2)$		EA or HA	e_a	$m(x_1,x_2)$	✓	✓	✓	–	–
	Catenoid	$\kappa_1(x_1)$	$-\kappa_1(x_1)$		EA	n, e_1	$m(x_1)$	✓	✓	✓	–	–
General case, $\mathcal{K}\neq 0, \mathcal{H}\neq 0$	A curvilinear shell	$\kappa_1(x_1,x_2)$	$\kappa_2(x_1,x_2)$		EA or HA	e_a	$m(x_1,x_2)$	✓	✓	✓	✓	✓
	Sphere	const	const		EA	n	$m=\hat{n}$	–	–	✓	–	✓
					EA or HA	e_a	$m(x_1,x_2)$	✓	✓	✓	✓	✓

Sheka, Pylypovskyi, Landeros, Kravchuk, Gaididei, Kakay, DM, *in preparation*

Dr. Denys Makarov I E-Mail: d.makarov@hzdr.de I Intelligent Materials and Devices

Parabola: flat yet curved geometry with simple textures



Volkov, DM et al., *PSS – Rapid Research Letters* 1800309 (2018)

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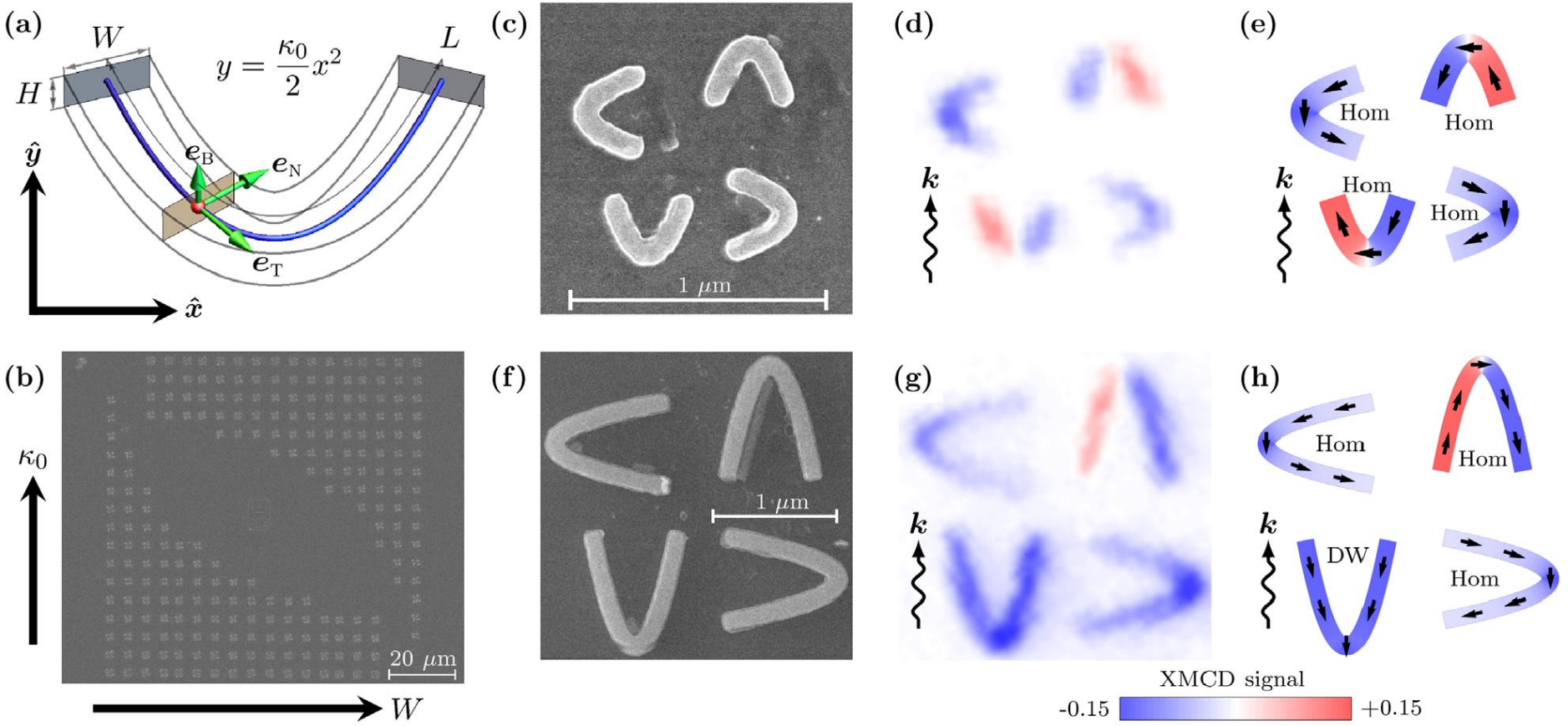
Parabola: flat yet curved geometry with simple textures



Volkov, DM et al., *PSS – Rapid Research Letters* 1800309 (2018)

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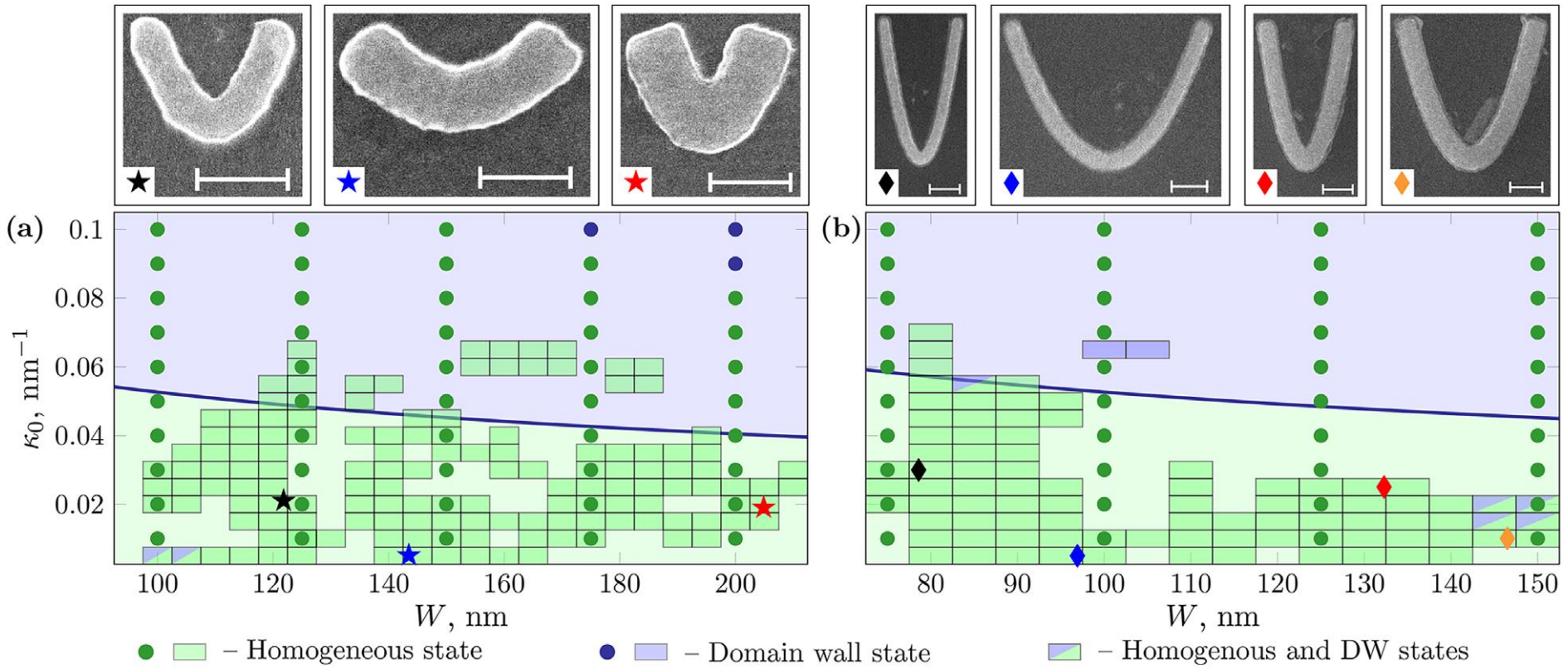
Parabola: flat yet curved geometry with simple textures

500 nm long parabolas

2 μm long parabolas



Volkov, DM et al., *PSS – Rapid Research Letters* 1800309 (2018)

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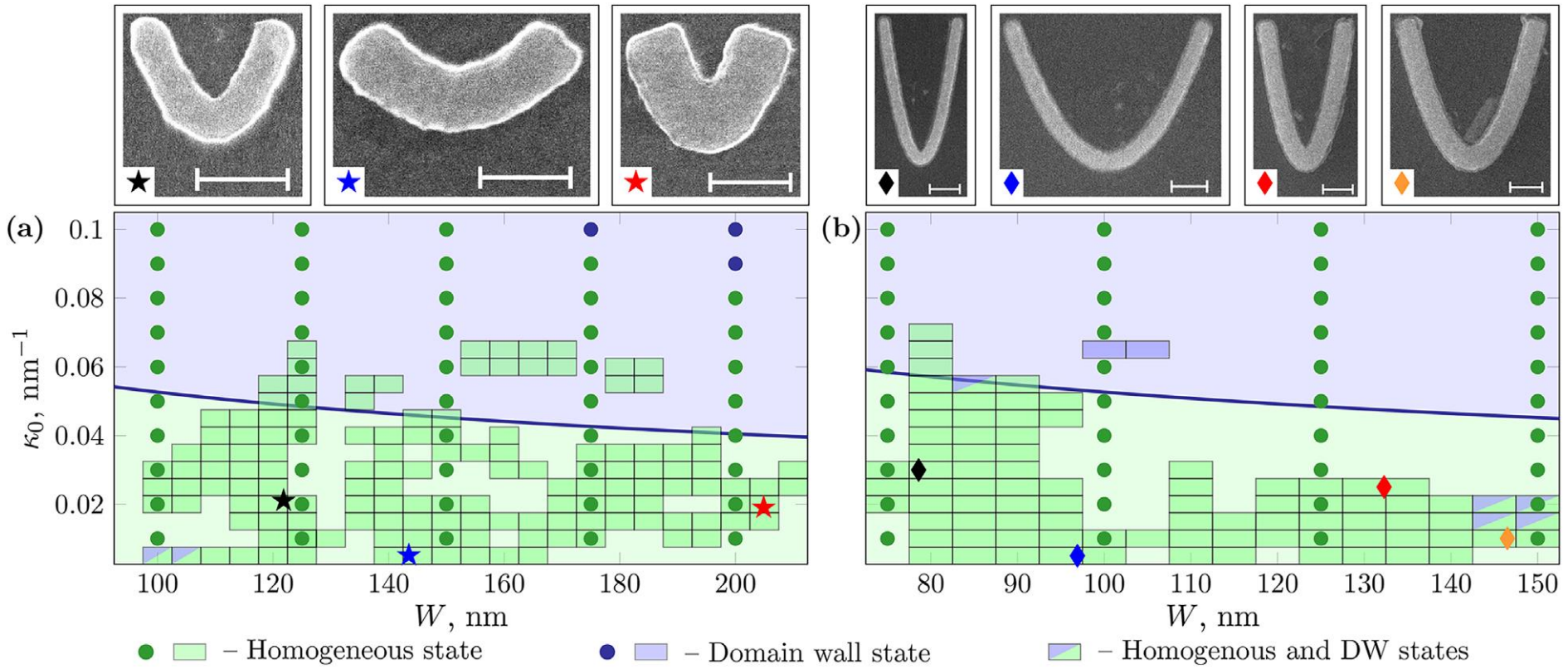

In line with everything what Kostya published years ago: Yershov et al., *PRB* **92**, 104412 (2015)

Volkov, DM et al., *PSS – Rapid Research Letters* 1800309 (2018)

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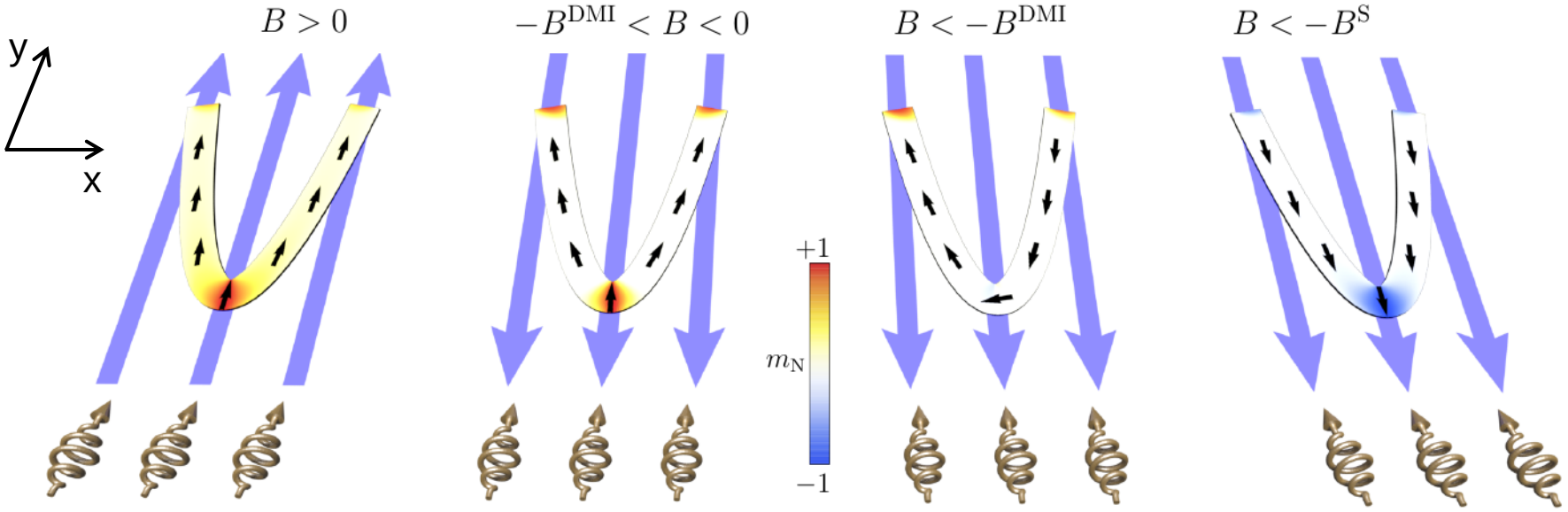
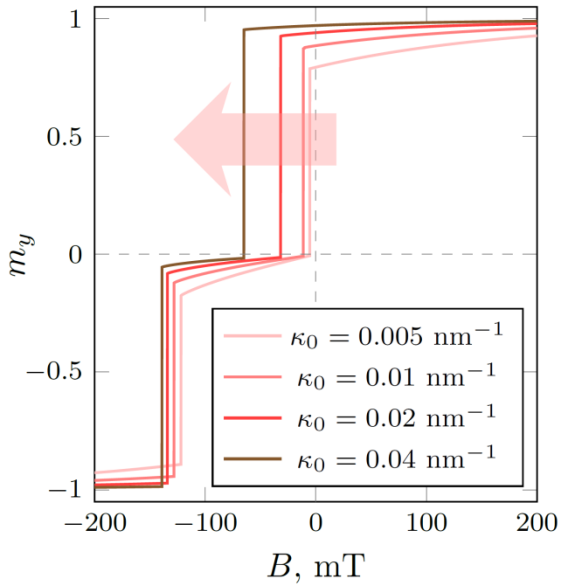
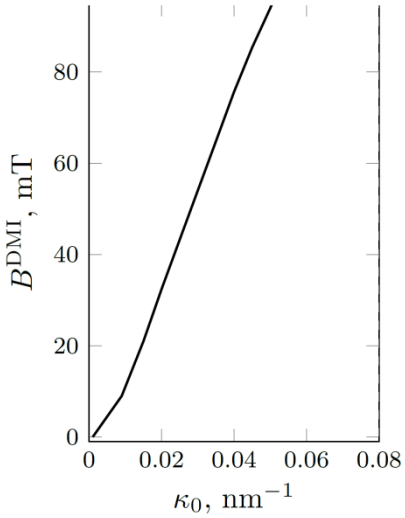
Parabola in a magnetic field

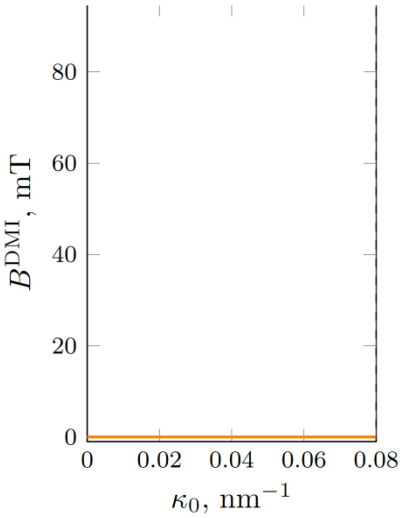




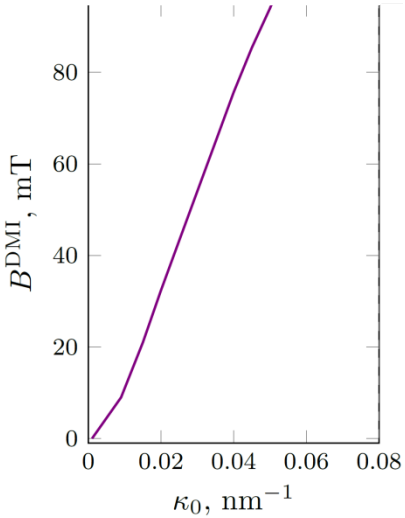
w/ anisotropy and w/ DMI



w/ anisotropy & w/o DMI

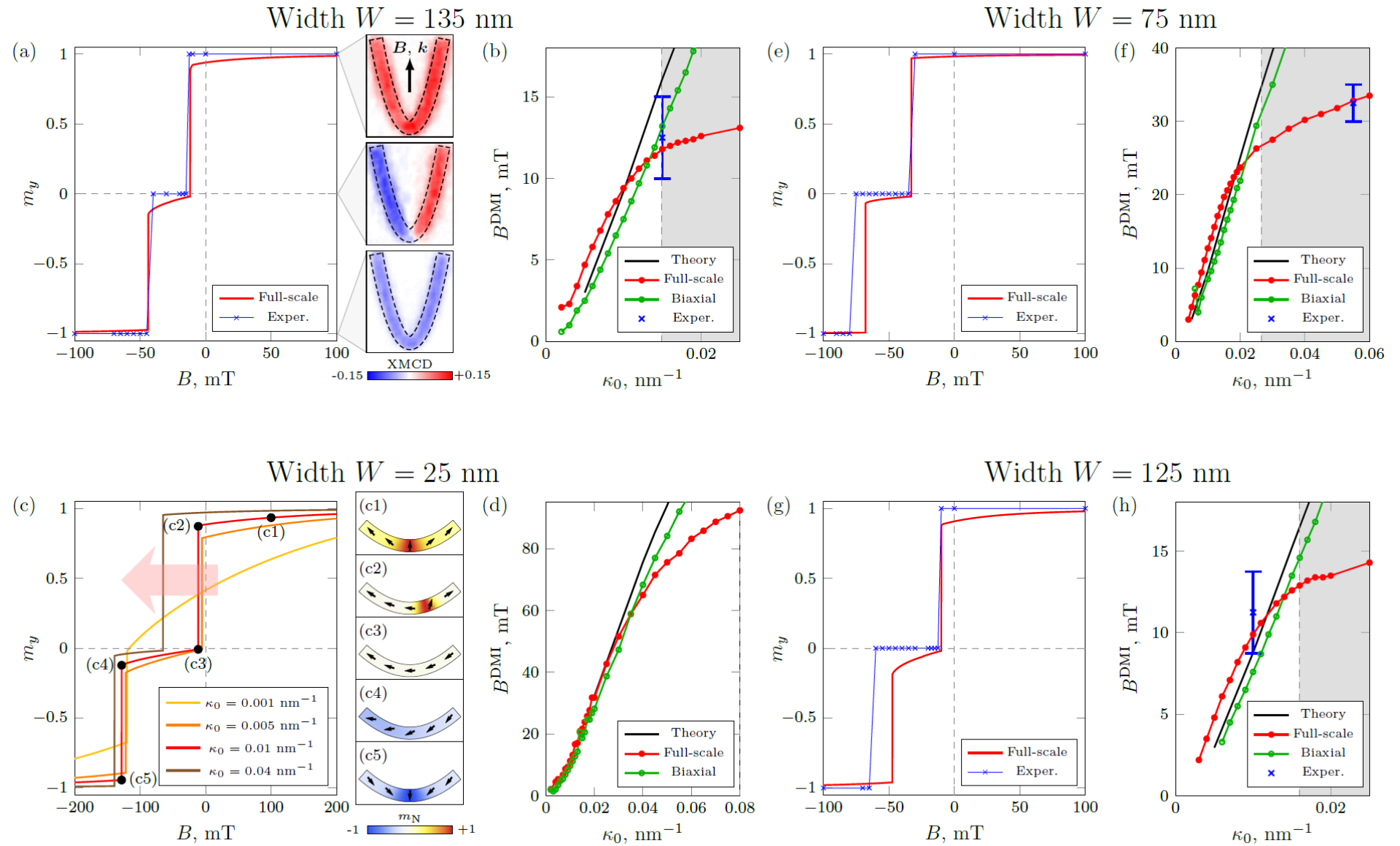


w/o anisotropy & w/ DMI



Volkov, Kakay, Kronast, Mönch, Mawass, Fassbender, DM, *in preparation*

Measurement of depinning field in 2-µm-long parabolas



Volkov, Kakay, Kronast, Mönch, Mawass, Fassbender, DM, *in preparation*

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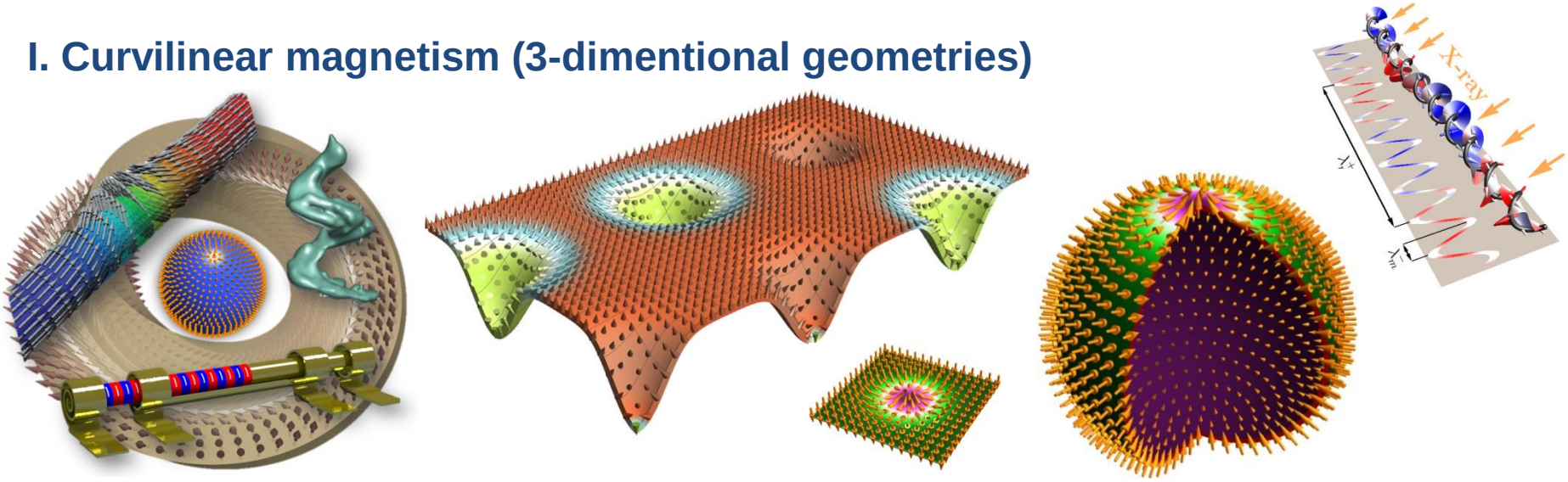
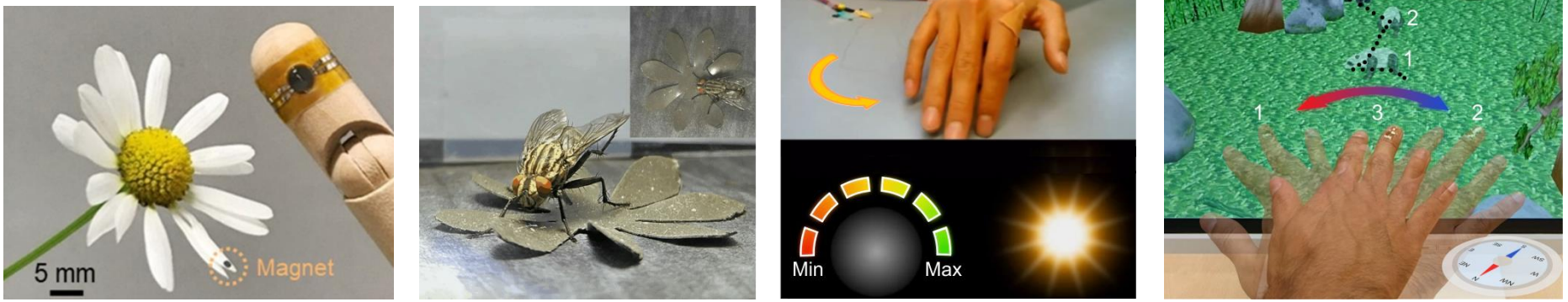
- Streubel, DM et al., Magnetism in curved geometries, *J. Phys. D: Appl. Phys.* **49**, 363001 (2016)

I. Curvilinear magnetism (3-dimentional geometries)



Nature Commun. & Phys. Rev. Lett. & Nano Lett. & Adv. Mater. & Phys. Rev. B & Appl. Phys. Lett. & Soft Matter & Small

II. Compliant sensors & actuators



Science Advances & Nature Electronics & Nano Letters & Advanced Materials & npj Flexible Electronics & Nature Commun.

- DM et al., Shapeable magnetoelectronics, *Appl. Phys. Rev.* **3**, 011101 (2016)

Focused Session of the Magnetism Division

"Curvilinear magnetism: fundamentals and applications"

--Denys Makarov--

Annual Spring Meeting of the German Physical Society

2019, Regensburg, Germany

Alexander-von-Humboldt funded workshop

"Curvilinear micromagnetism"

--Denys Sheka and Denys Makarov--

2019, Kyiv, Ukraine

WE-Heraeus-Seminar

"Curvilinear condensed matter: fundamentals and applications"

--Denys Sheka and Denys Makarov--

2020, Bad Honnef, Germany

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Magnetism

Prof. Denys Sheka | Prof. Martino Poggio
KNU, Kyiv, UA | Uni Basel, Basel, CH

Magnetism in curved geometries,
J. Phys. D: Appl. Phys. 49, 363001 (2016)

Liquid crystals

Prof. Gaetano Napoli (Uni Salerno, Salerno, IT)

Curvature Effects on Nematic Shells,
PRL 108, 207803 (2012)

Curvature-Induced Ordering in Cylindrical Nematic Shells,
Int. J. NonLinear Mech. 49, 66 (2013)

Interdivisional SKM Symposium

"Geometry, topology, and condensed matter"

--Carmine Ortix and Denys Makarov--

Annual Spring Meeting of the German Physical Society
2019, Regensburg, Germany

2D materials & Semiconductors

Dr. Ivan Vera Marun
University of Manchester, Manchester, UK

Quantum mechanics of a spin-orbit coupled electron constrained to a space curve,
Physical Review B 91, 245412 (2015)

Theoretical prediction of a giant anisotropic magnetoresistance in carbon nanoscrolls,
Nano Letters 17, 3076 (2017)

Superconductivity

Dr. Jose Lorenzana
University of Rome La Sapienza, Rome, IT

Phase nucleation in curved space,
Nature Commun. 6, 6856 (2015)

Thank you for your attention

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