Curvilinear magnetism: tutorial

Denys Makarov

HZDR:
Oleksandr Pylypovskyi, Oleksii Volkov, Pavlo Makushko, Attila Kakay, Jose Angel Fernandez Roldan, Sergio Oliveros, Ihor Veremchuk, Rui Xu

Uni Salerno:
Carmine Ortix

Uni Kyiv:
Denis D. Sheka

LBNL Berkeley:
Peter Fischer

Uni Frankfurt:
Michael Huth

Uni Valparaiso:
Pedro Landeros

Uni Uppsala:
F. Rybakov, O. Eriksson

Leibniz IFW Dresden:
Axel Lubk, Daniel Wolf, Volodymyr Kravchuk, Stanislav Avdoshenko, Rudolf Schäfer

Uni Basel:
Patrick Maletinsky

HZB BESSY II:
Florian Kronast, Florin Radu

CNR nM²-Lab:
Gaspare Varvaro

Uni Vienna:
Oleksandr Dobrovolskiy

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Bundesministerium für Wirtschaft und Energie
Partner von DRESDEN concept
HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Dresden, Germany

Dresden (~800 years old & ~500.000 inhabitants):

Capital of the Free State of Saxony

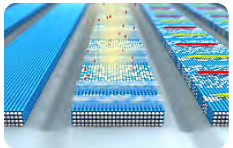
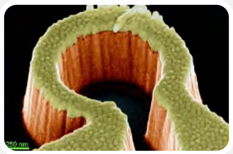
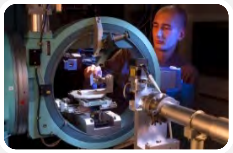
Scientific landscape:

Technical University of Dresden: about 40.000 students

Max Planck Institutes: 3 | Leibniz Institutes: 3
Fraunhofer Institutes: 8 | Helmholtz Center: 1

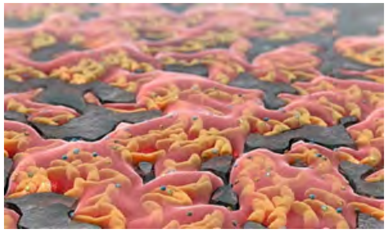
Helmholtz-Zentrum Dresden-Rossendorf (HZDR)

Research for the World of Tomorrow

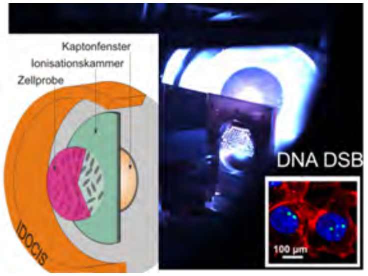
FZR	Established	1992 (1955)
	Member of Helmholtz Association	2011
	Base Budget	~ 120 Mio. €/a
	Employees	~ 1400
	10 Institutes 11 Junior Research Groups	
	Sites: Dresden, Leipzig, Freiberg, Grenoble (FR), Hamburg, Görlitz	

RESEARCH AREAS

ENERGY



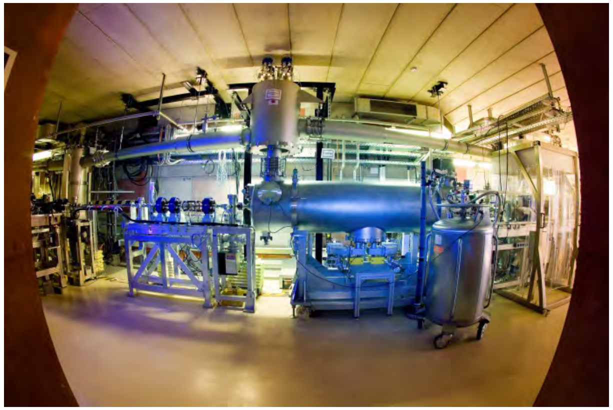
HEALTH (→ Oncology)



MATTER (→ Materials)

HZDR Facilities

- User Facilities



ELBE.

Center for High-Power Radiation Sources

IBC.

Ion Beam Center

Industry Services via

HZDR INNOVATION

HLD.

High-Magnetic Field Laboratory

PET Center

Team “Intelligent Materials and Systems”

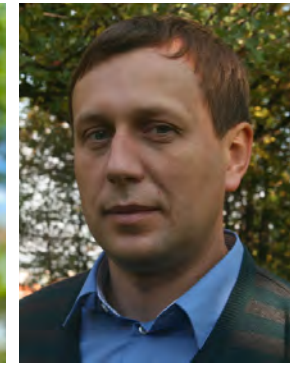

Yevhen Zabila
Postdoc


Rico Illing
Engineer


Olha Bezsmertna
PhD


Pavlo Makushko
PhD


Stefanie Schuba
PhD


Ihor Veremchuk
Group leader


Oleksandr Pylypovskyi
Postdoc

Physics | Material science | Electrical & Mechanical engineering | Chemistry | Microbiology


Shahrukh Shakeel
PhD


Rui Xu
Group leader


Oleksii Volkov
Group leader

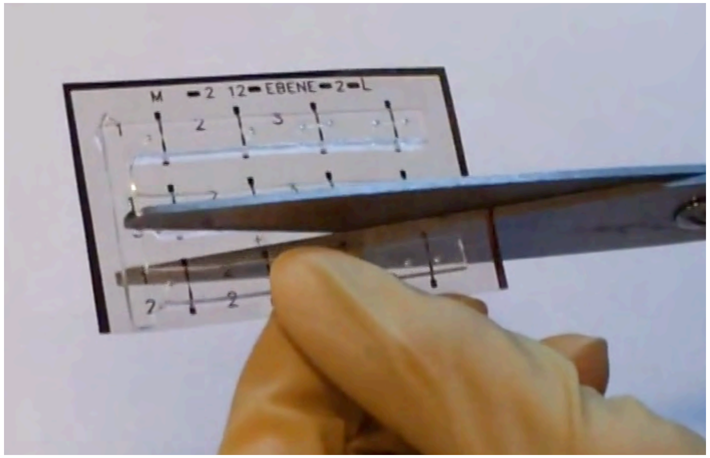

Conrad Schubert
Technician


Lin Guo
PhD

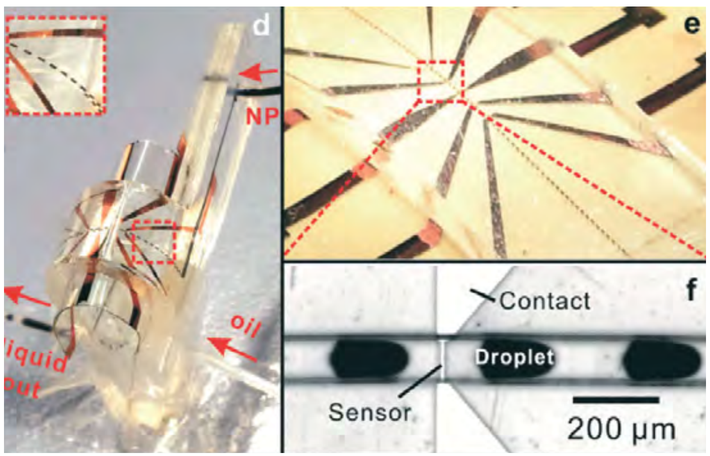

Sergio Oliveros
PhD


Tetiana Voitsekhivska
Business

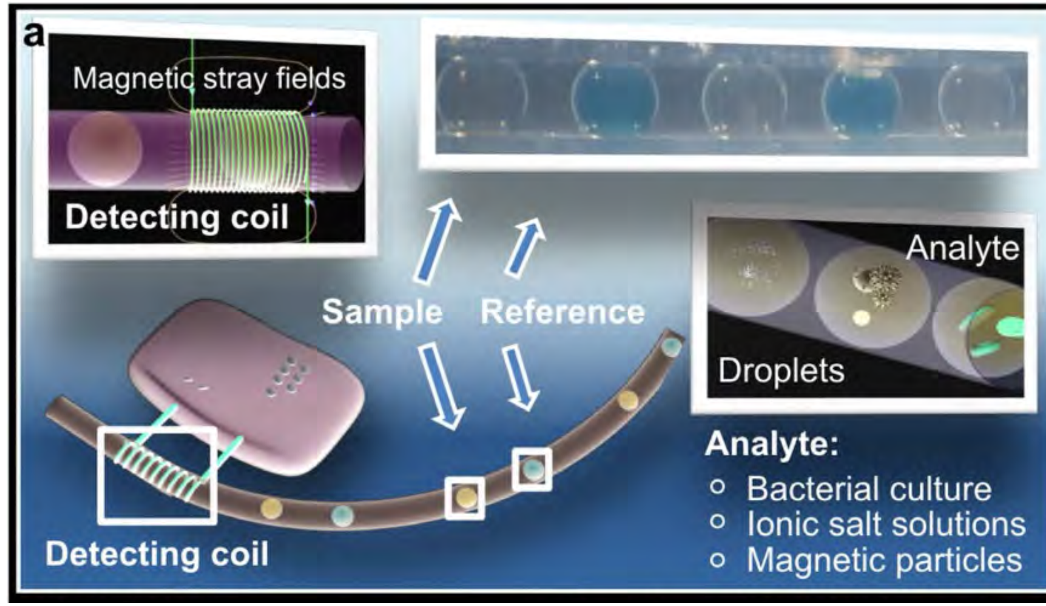
Functional fluidics



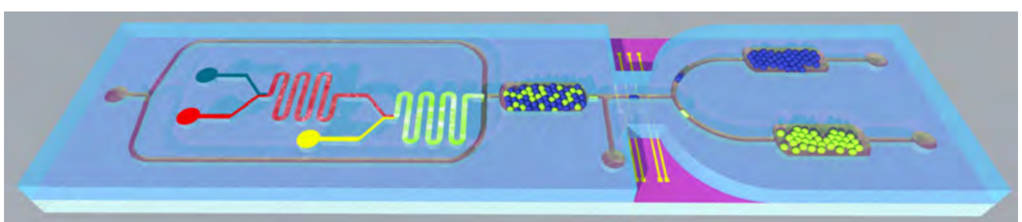
T. Voitsekhivska & R. Illing

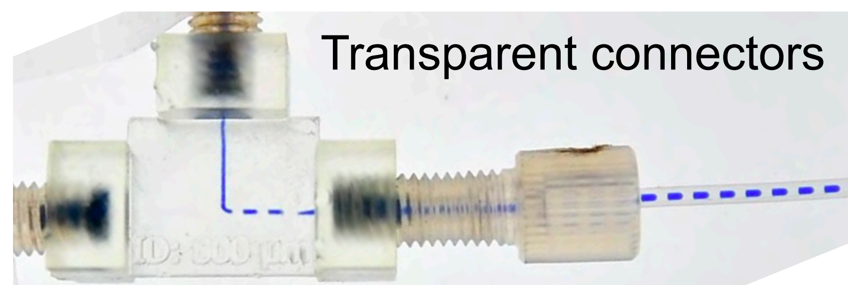


G. Lin, DM et al., *Lab Chip* **14**, 4050 (2014)



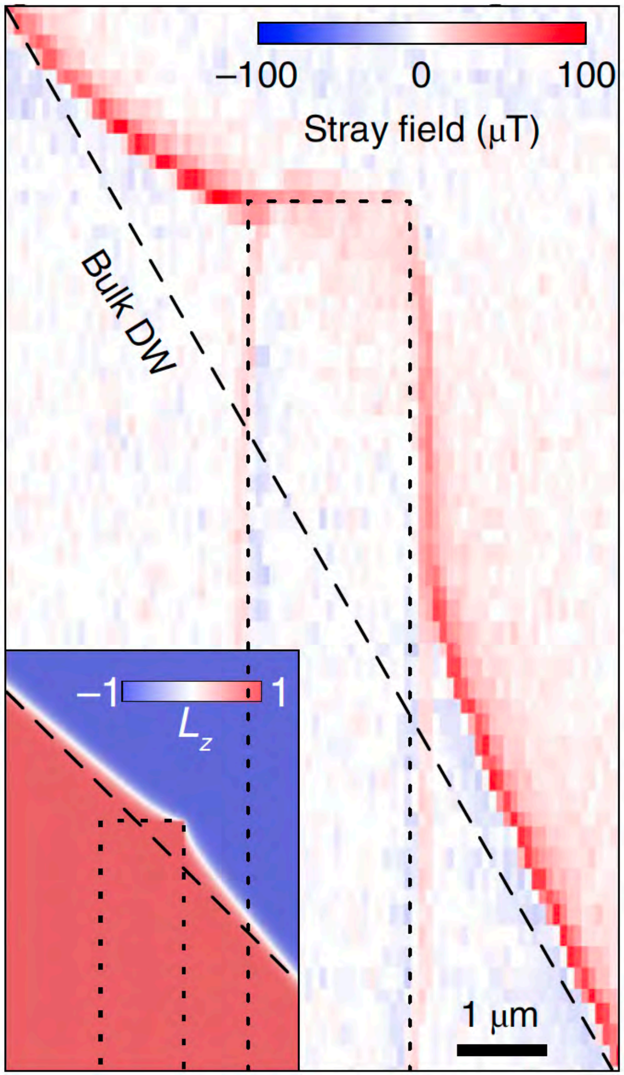
D. Karnaushenko, DM et al., *Sci. Rep.* **5**, 12878 (2015)



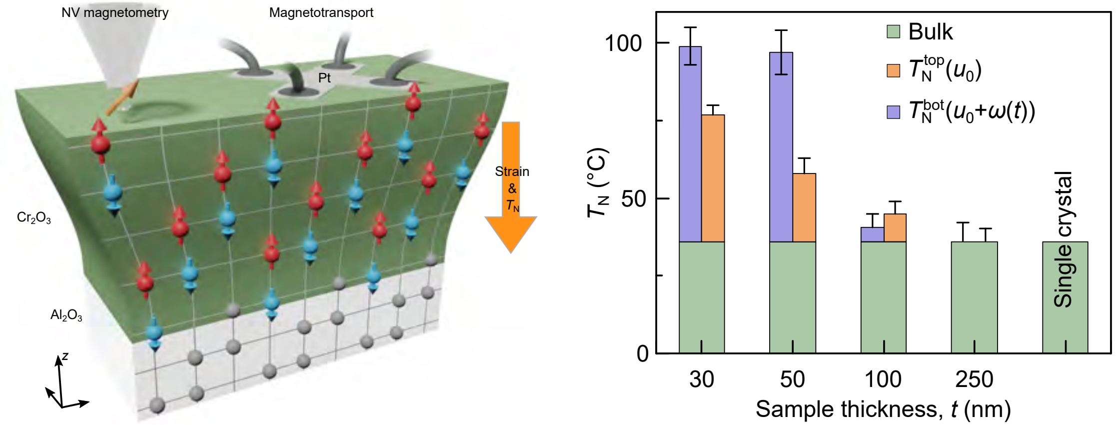


…*Lab Chip* **15**, 216 (2015); *Lab Chip* **17**, 1884 (2017); *Small* **12**, 5882 (2016); *ACS Sensors* **2**, 1839 (2017); *ACS Omega* **5**, 20609 (2020); *Adv. Mater. Technol.* **5**, 2000279 (2020), *Adv. Sens. Res.* 2300101 (2023)…

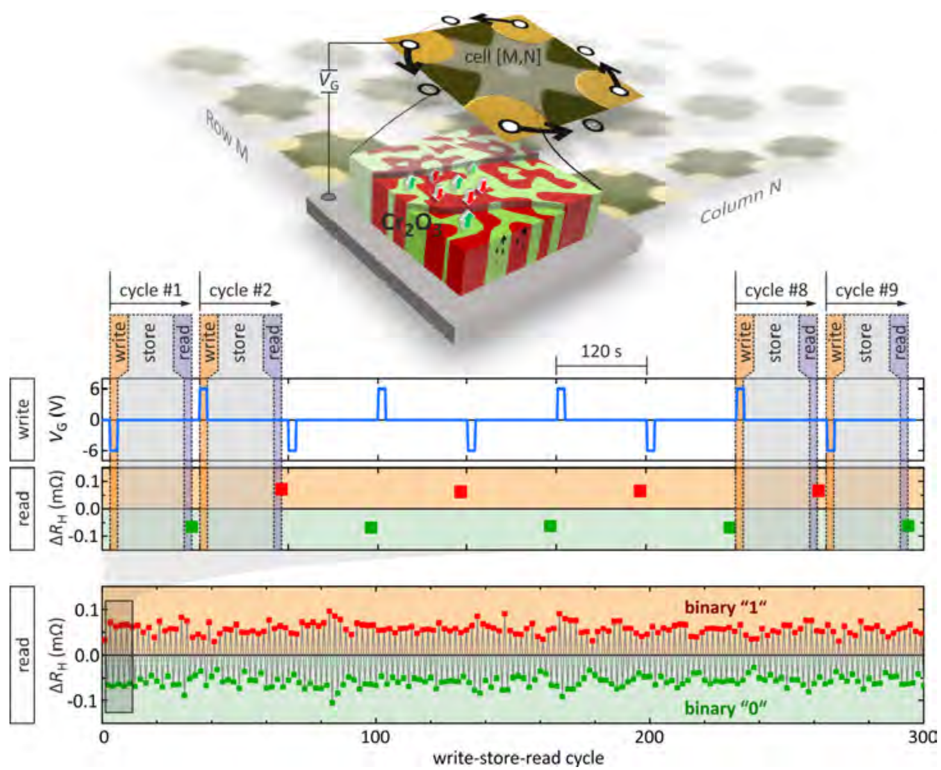
Activities on (magnetoelectric) antiferromagnets



N. Hedrich, DM et al., *Nature Physics* (2021)

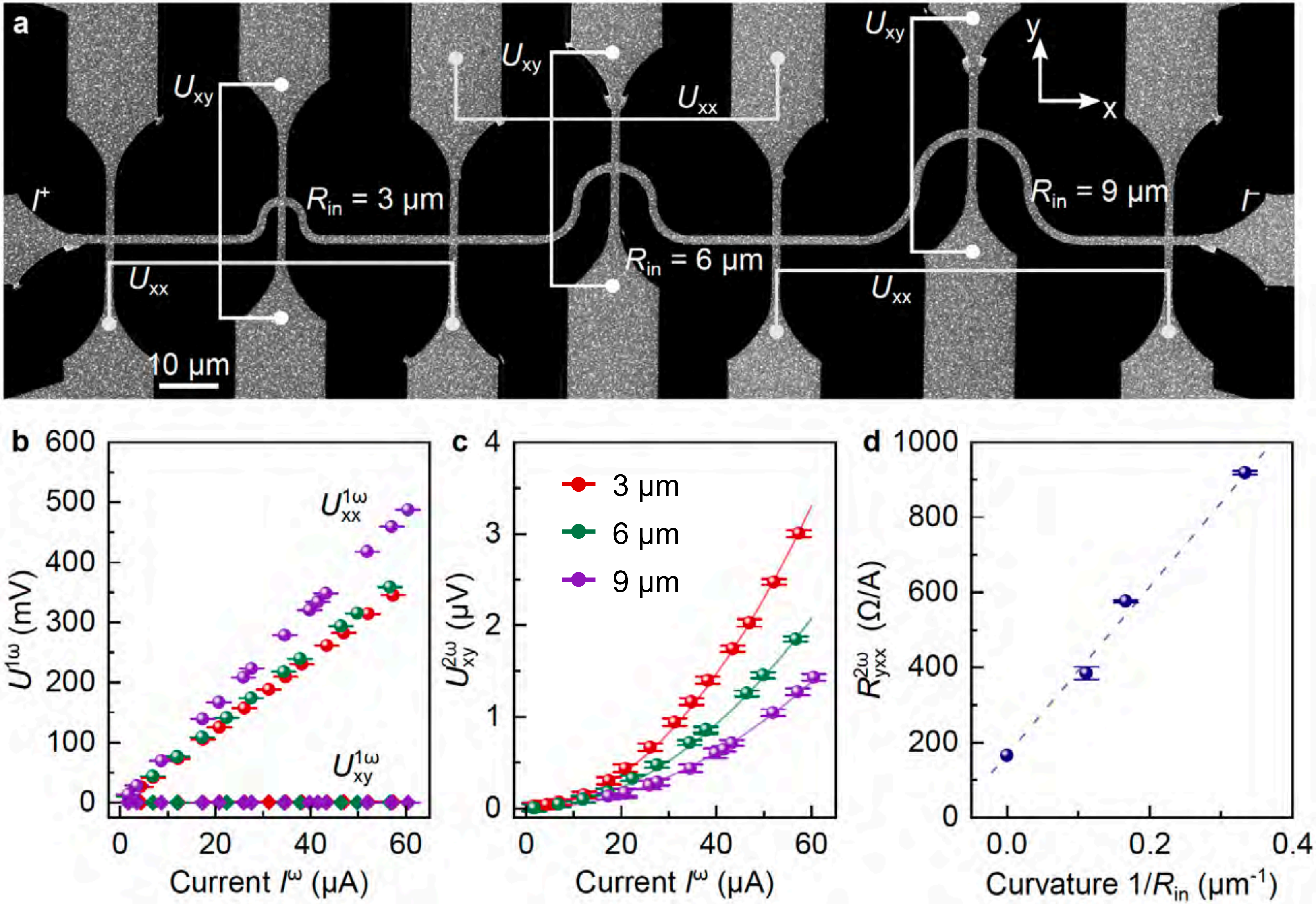


P. Makushko, DM et al., *Nature Commun.* (2022)



T. Kosub, DM et al., *Nature Commun.* (2017)

Nonlinear Hall effect in elementary Bi thin films



P. Makushko, DM et al., *Nature Electronics* **7**, 207 (2024)

nature electronics

REVIEW ARTICLE

https://doi.org/10.1038/s41928-022-00820-z

Check for updates

Electronic materials with nanoscale curved geometries

Paola Gentile[1,2], Mario Cuoco[1,2], Oleksii M. Volkov[3], Zu-Jian Ying[4], Ivan J. Vera-Marun[5,6], Denys Makarov[3] and Carmine Ortix[2,7] ✉

- ➡ Superconductors
- ➡ Semiconductors
- ➡ Topological insulators
- ➡ 2D materials
- ➡ Magnetic materials

✓ Quantum effects

Curvature can impact intrinsic electronic properties due to confinement and electromechanical coupling when the curvature radius approaches the de Broglie wavelength of electrons near the Fermi level

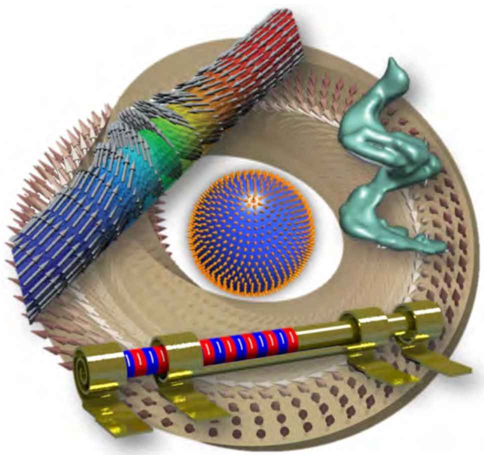
✓ Classical effects

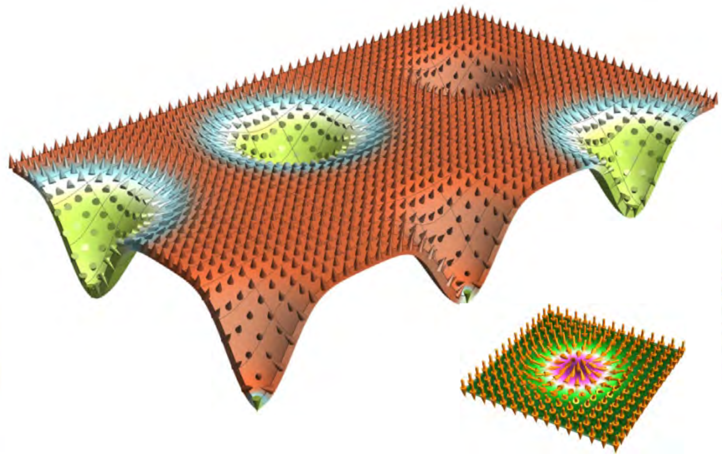
In electronic systems with Fermi wavelengths much smaller than the curvature radii, geometry-induced effects are purely classical and are a direct consequence of the geometric shape

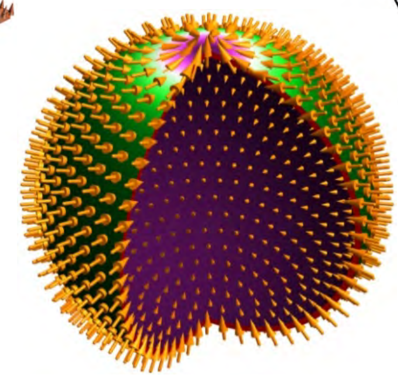
Review: Gentile, DM et al., *Nature Electronics* **5**, 551 (2022)

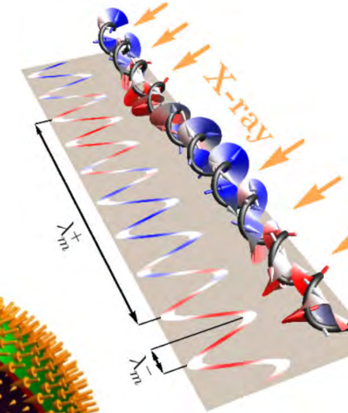
Activities on curvilinear magnetism

I. Curvilinear magnetism (3-dimensional geometries)





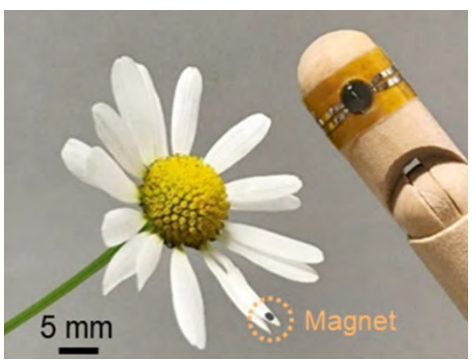


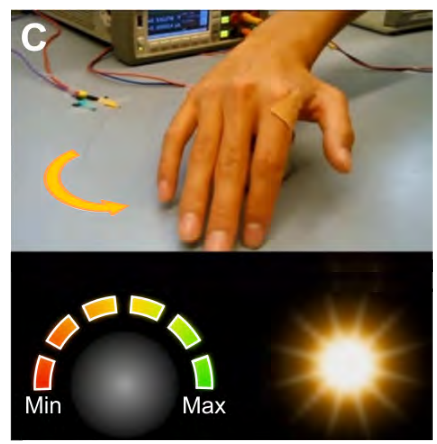


Nature Physics & *Nature Electronics* & *Nature Communications* & *Phys. Rev. Lett.* & *Nano Letters* & *Advanced Materials*

<u>Review:</u> DM et al., *Advanced Materials* **34**, 2101758 (2022)

II. Flexible sensors & Flexible actuators



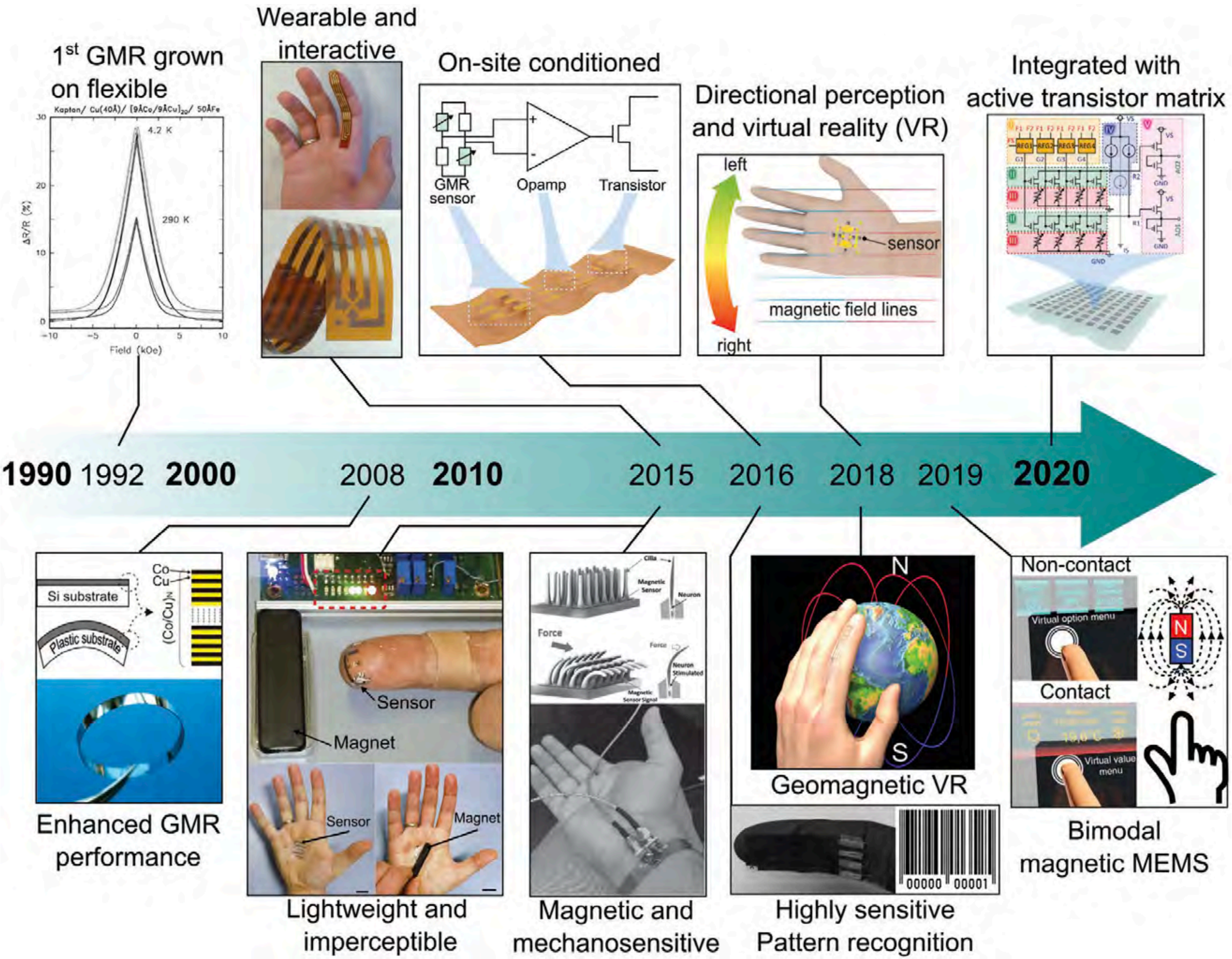


Science Advances & *Nature Electronics* & *Nano Letters* & *Advanced Materials* & *npj Flexible Electronics* & *Nature Commun.*

<u>Review:</u> Santiago Canon and DM, *Adv. Funct. Mater.* **31**, 2007788 (2021)

DRESDEN concept

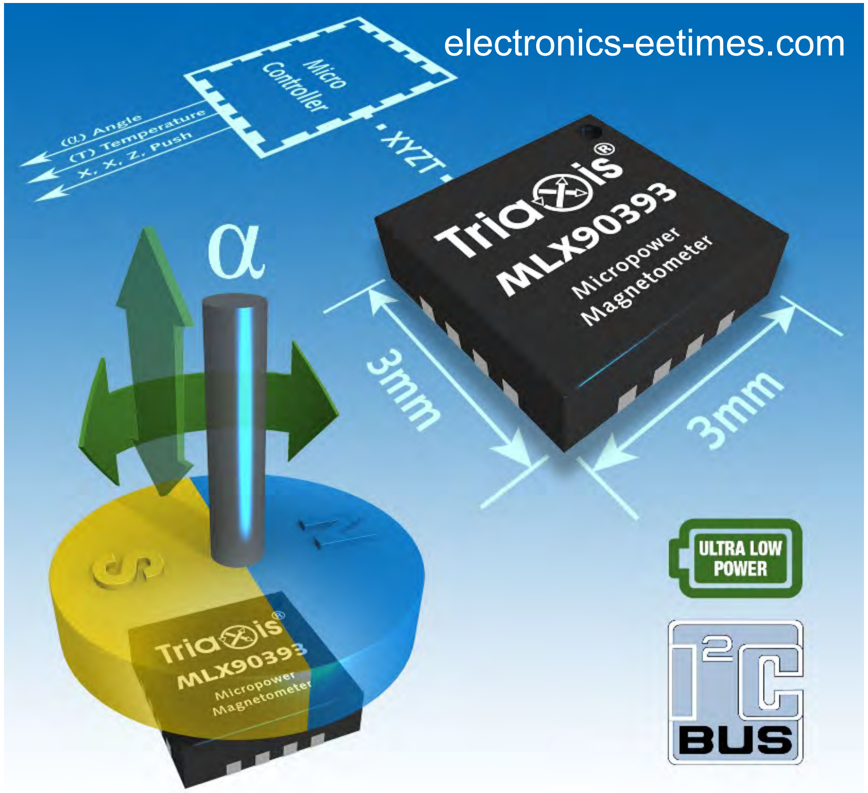
HZDR



Review: Santiago Canon and DM, *Adv. Funct. Mater.* **31**, 2007788 (2021)

Evolution of magnetic field sensors: rigid...flexible

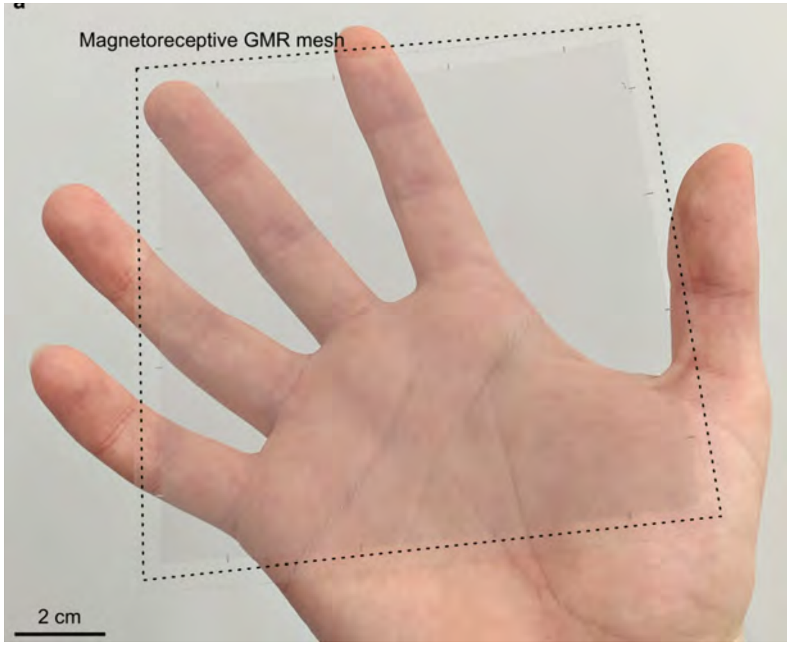
Heavy & Thick & Rigid



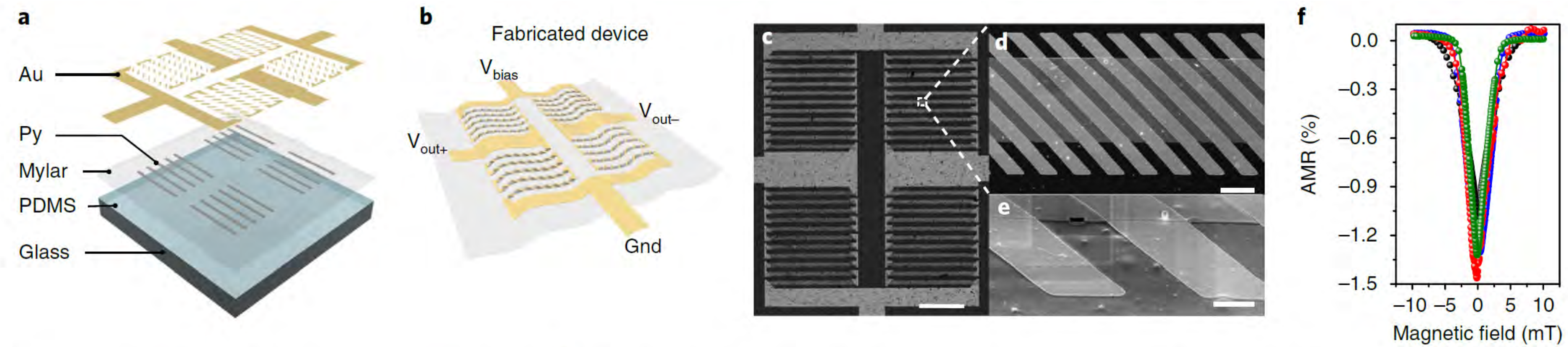
Magnetic field sensors are applied for monitoring any kind of motion:

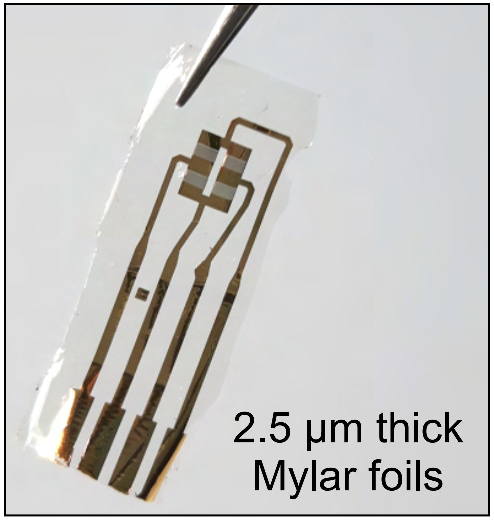
- ➡ Displacement
- ➡ Rotation
- ➡ Proximity sensing
- ➡ Vibration

Lightweight & Flexible & Stretchable



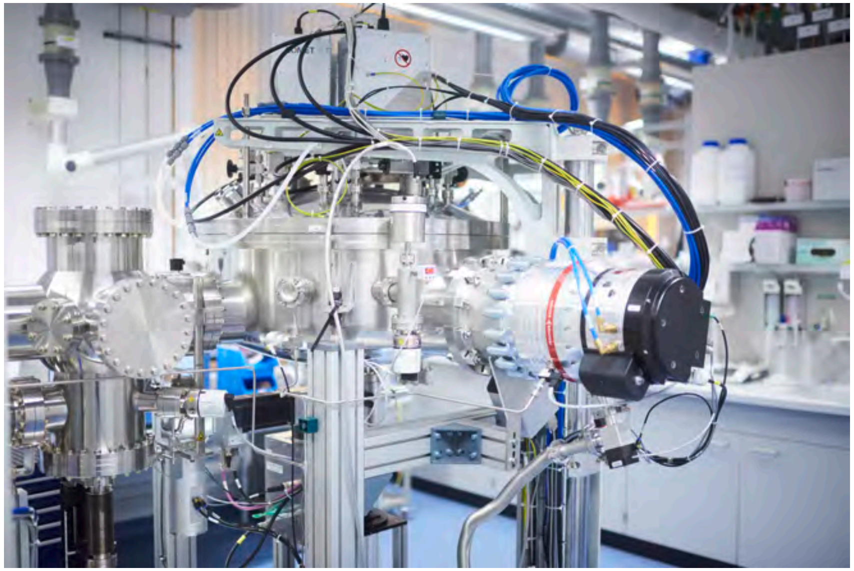
Characterization of skin conformal sensors

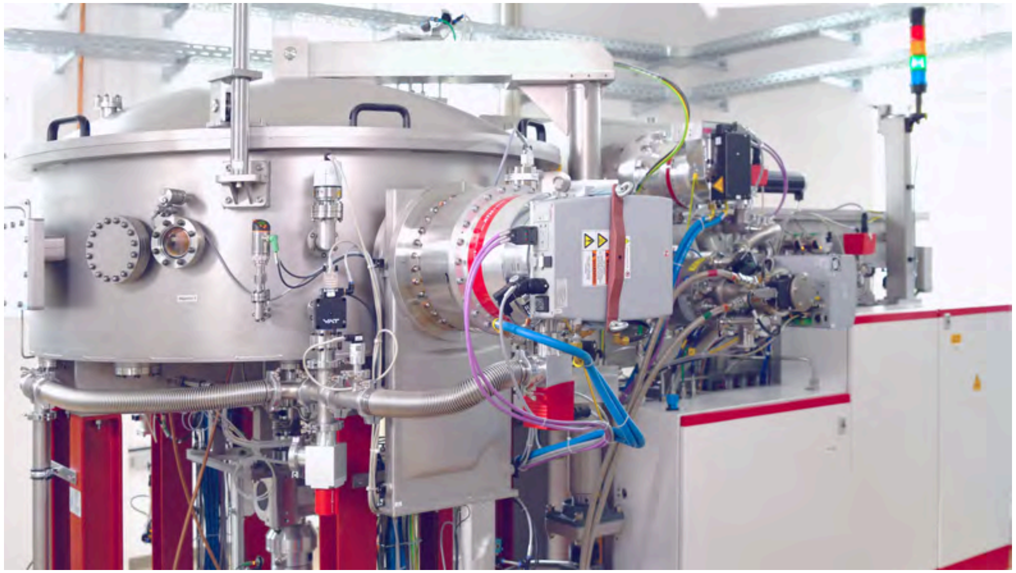




G. S. Canon Bermudez et al., *Nature Electronics* **1**, 589 (2018)

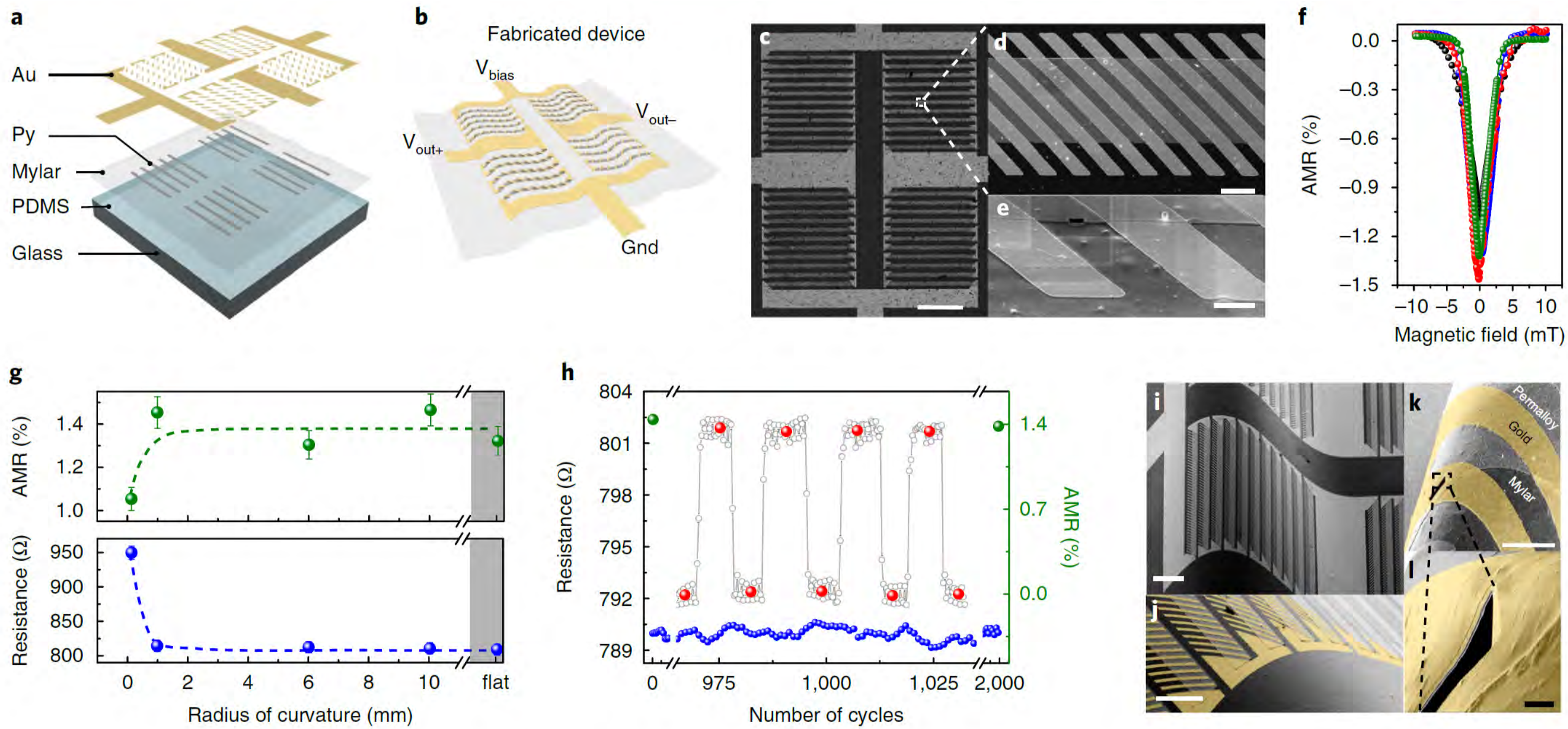
Large area deposition facilities





Deposition facilities	4 inch substrates:	Magnetrons: Co / Pt / Cr / Au / Cr_2O_3 / Bi
	6 inch substrates:	Magnetrons: Ta / Co / Cu
	12 inch substrates:	Magnetrons: Co / Py / Cu

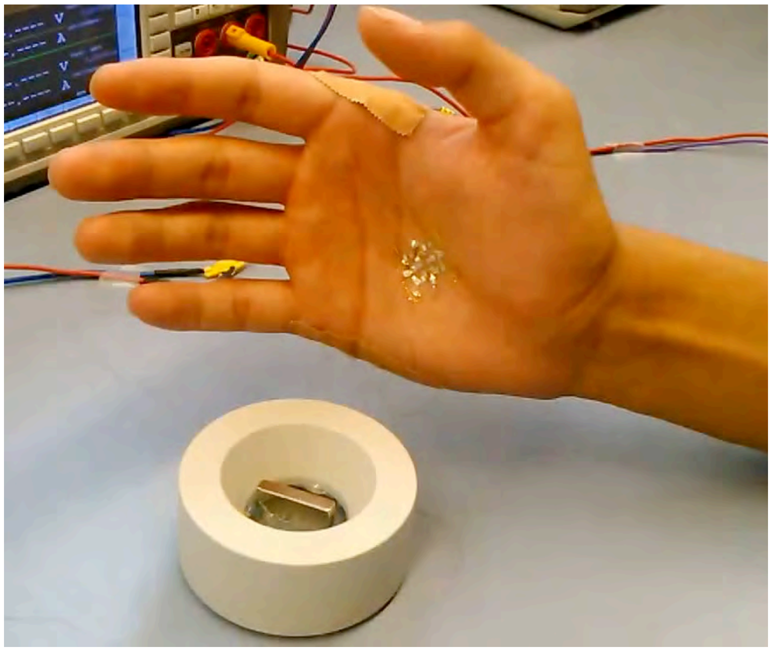
Characterization of skin conformal sensors



G. S. Canon Bermudez et al., *Nature Electronics* **1**, 589 (2018)

On-skin magnetoelectronics for touchless interaction

Augmented reality applications



Magnetic field of a permanent magnet (4 mT)

G. S. Canon Bermudez, DM et al.,
Science Advances **4**, eaao2623 (2018)

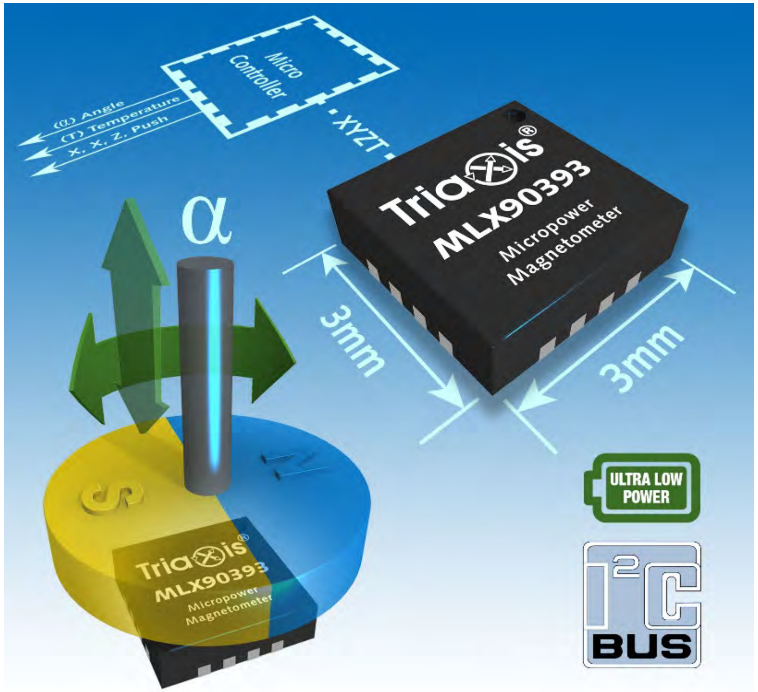
Virtual reality applications

Geomagnetic field (40 μT)

G. S. Canon Bermudez, DM et al.,
Nature Electronics **1**, 589 (2018)

Evolution of magnetic field sensors: rigid...flexible...printable

Heavy & Thick & Rigid



electronics-eetimes.com

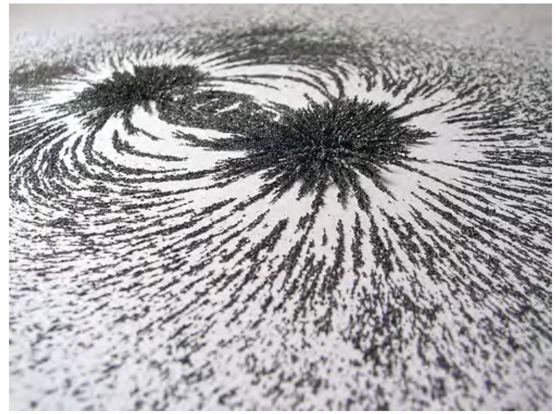
Magnetic field sensors are applied for monitoring any kind of motion:

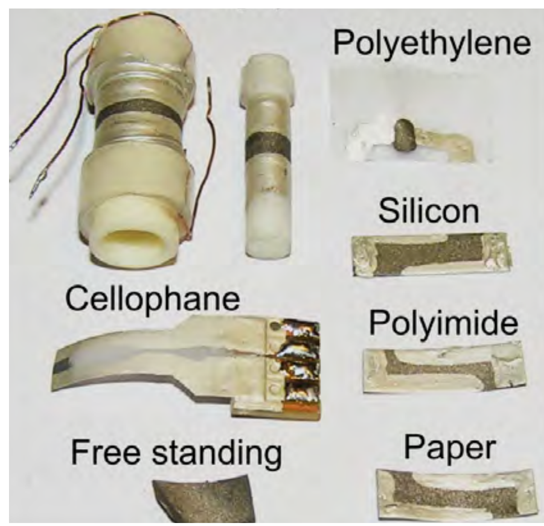
➡ Displacement ➡ Rotation

➡ Proximity sensing ➡ Vibration

Printable & Healable & Biodegradable

Magnetic powder & Binder = Paste





D. Karnaushenko, DM et al., *Advanced Mater.* **24**, 4518 (2012)

Patent: DE 10 2011 077 907.8

Patent: US 13/528,076

Adv. Mater. **24**, 4518 (2012)

Adv. Mater. **27**, 880 (2015)

Appl. Phys. A **127**, 280 (2021)

Adv. Mater. **33**, 2005521 (2021)

Advanced Materials Technol. **7**, 2200227 (2022)

Nature Comm. **13**, 6587 (2022)

PR Applied **20**, 060501(2023)

DRESDEN concept

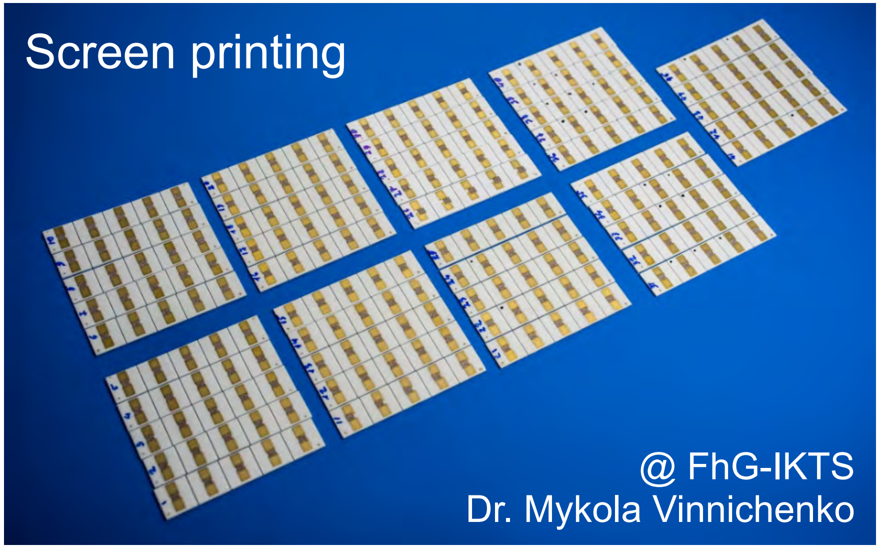
HZDR

New technology: printed magnetoelectronics

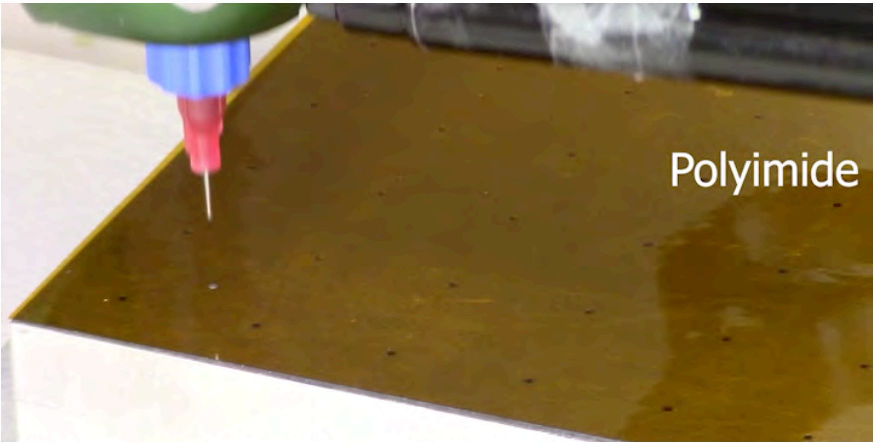
Not just an improvement but a shift in technology

Patent application: DE 10 2019 211 970.0

- REED contacts: 100s Mio sensors per year
- New application fields including printable and wearables
- No mechanical parts
- Isotropic magnetic field sensing performance



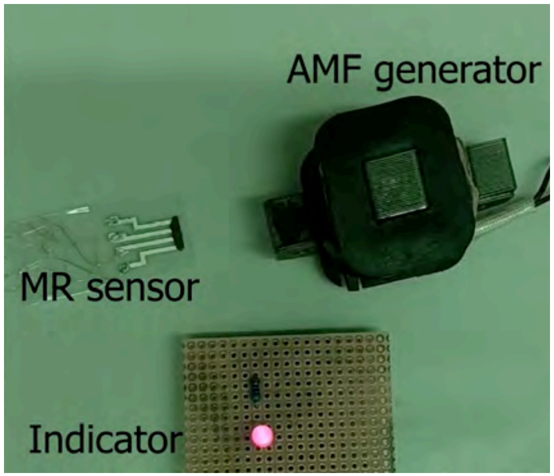
Dispenser printing

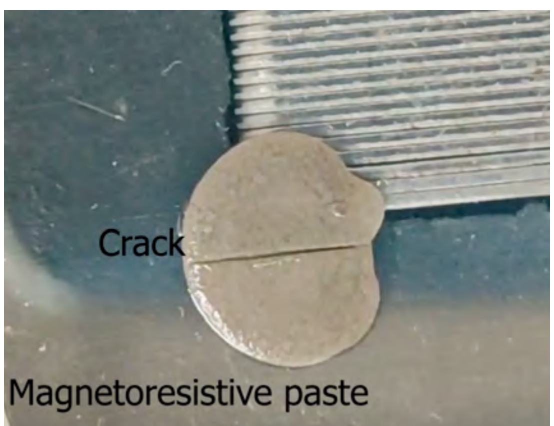


Oliveros et al., *Adv. Mater. Technol.* **7**, 2200227 (2022)

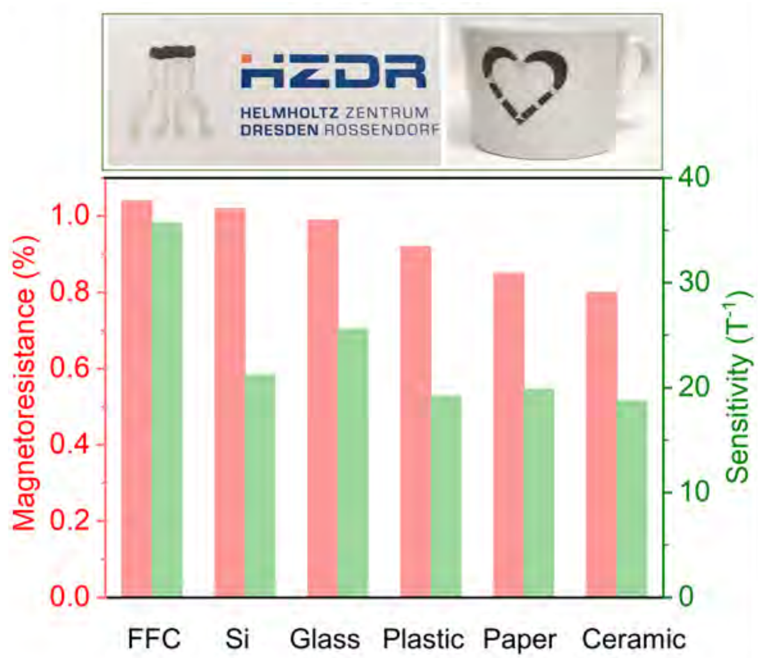
Self-healable printed magnetic field sensors

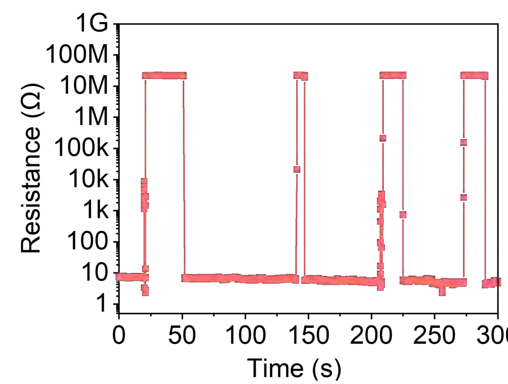
Permalloy particles (5 μm) | PDMS: polydimethylsiloxane | PBS: polyborosiloxane





Versatility of the technology





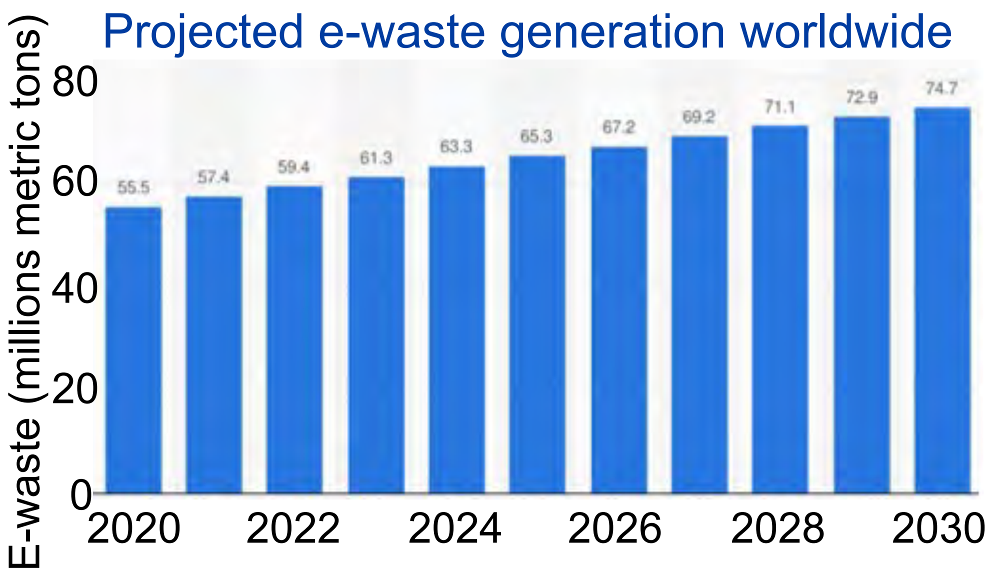
R. Xu et al., *Nature Communications* **13**, 6587 (2022)

Responsibility: dealing with electronic waste

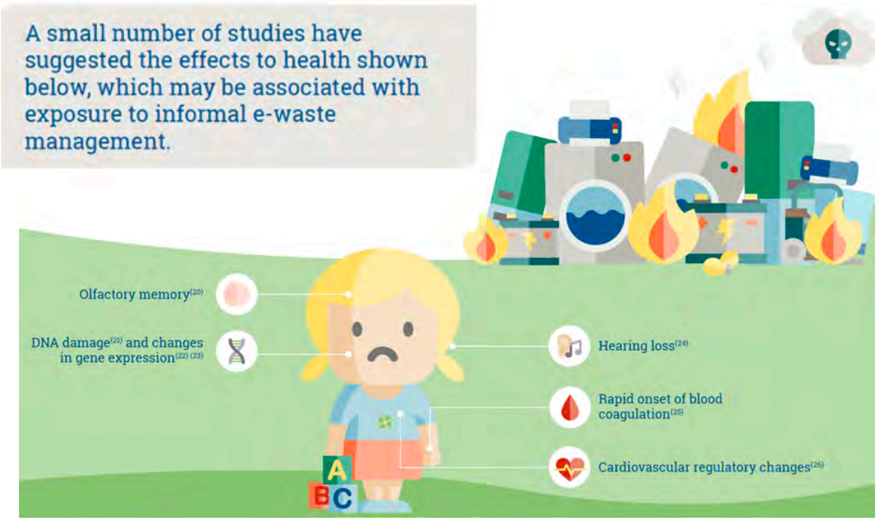
www.umweltbundesamt.de

www.africatimes.com

Global electronic waste monitor



Global electronic waste monitor 2020



DRESDEN concept HZDR

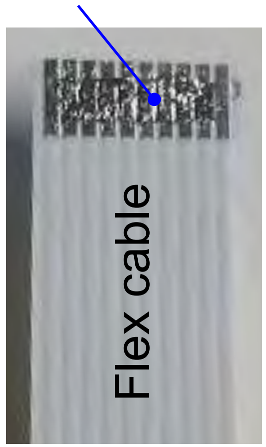
Eco-sustainable printed magnetic field sensors

Biodegradable & Biocompatible magnetoelectronics

Starch

www.owlting.com

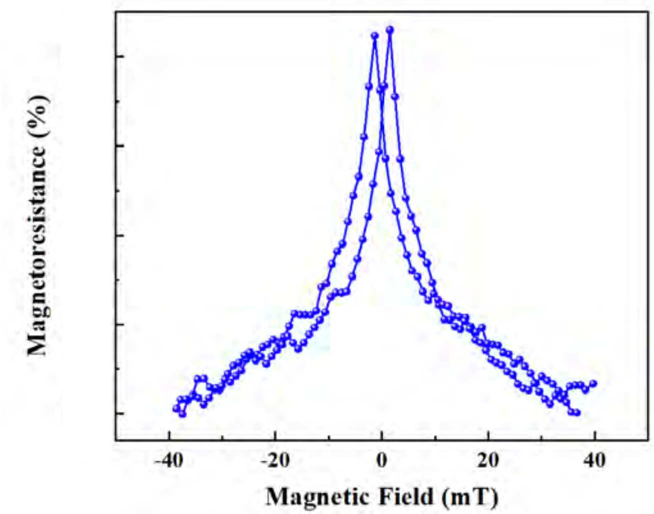
Printed sensor

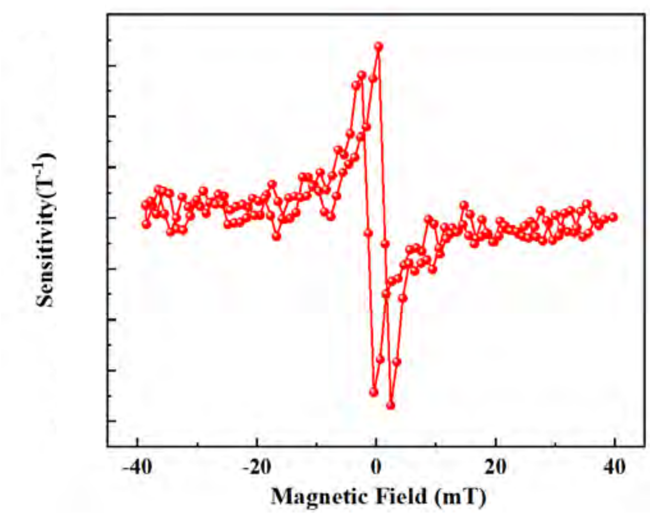


Iron particles

blog.coolhealth.com

www.storm.mg





Flexible Magnetoelektronik

Neuartige Sensoren mit unkonventionellen mechanischen Eigenschaften

Das Team „flexible Magnetoelektronik" der HZDR Innovation beschäftigt sich mit der Entwicklung eines flexiblen und druckbaren Magnetfeldsensors (Hall-Effekt und magnetoresistive Effekte). Wir bieten neuartige Hochleistungs-Magnetfeldsensoren auf ultradünnen flexiblen Substraten, die eine hohe mechanische Anpassungsfähigkeit besitzen. Flexible und gedruckte Sensoren können aufgrund ihrer extrem dünnen und unkonventionellen mechanischen Eigenschaften nicht nur auf verschiedene flache, sondern auch gekrümmte Objekte angewendet werden.

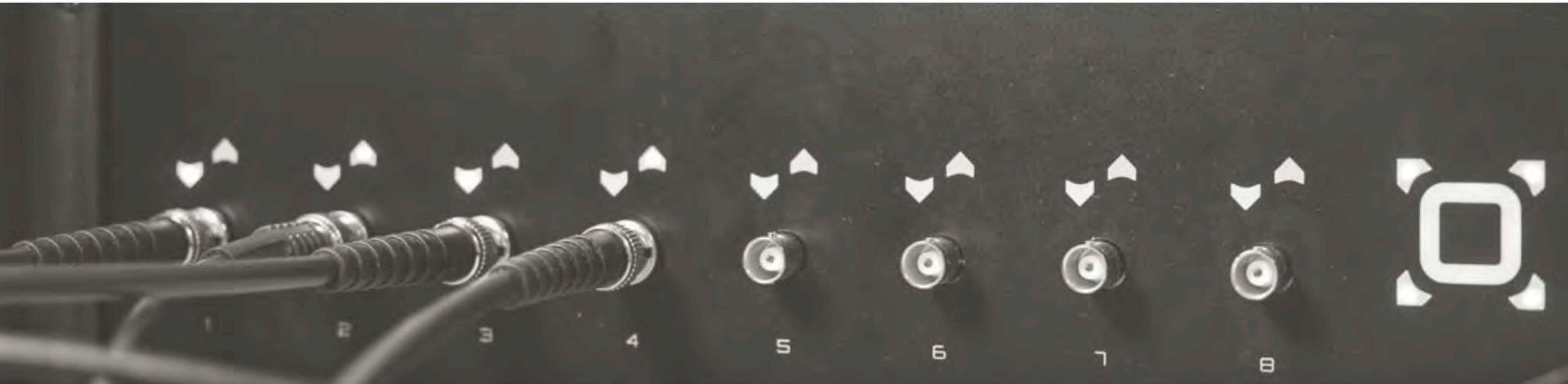
↗ Helmholtz Innovation Lab FlexiSens

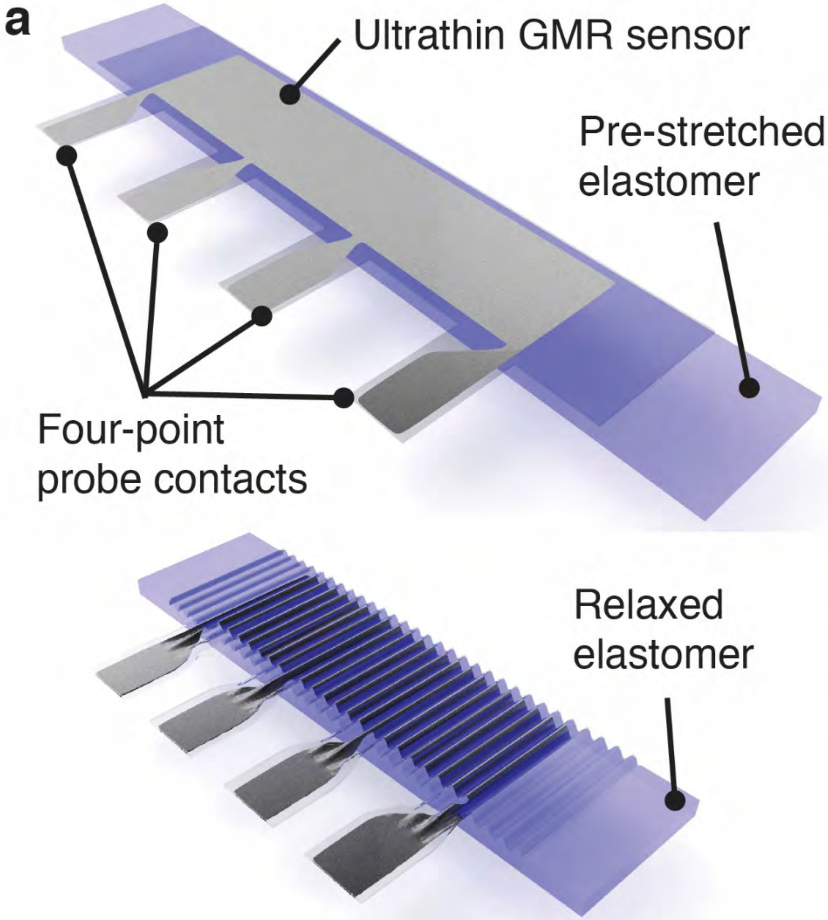
↗ Forschungsseite SmartSensorics

Tensormeter

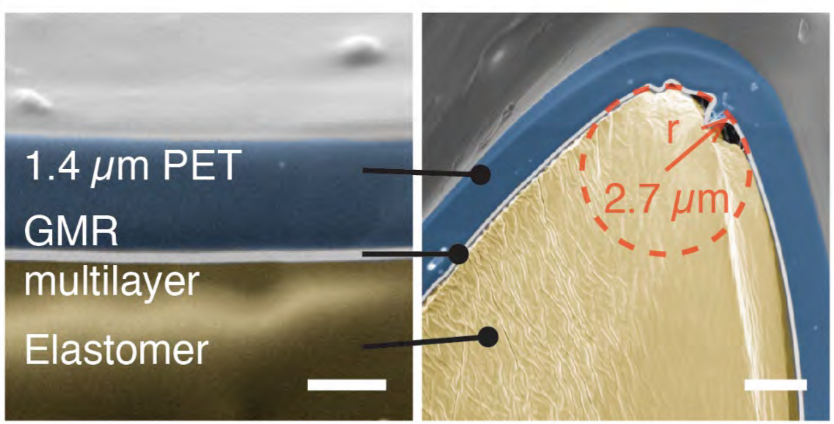
Eine neue Dimension der Widerstandsmessung

Mit dem Tensormeter können alle Komponenten des elektrischen Widerstands von dünnen Schichten wie zum Beispiel von Siliziumwafern schnell, einfach und präzise mit einer Messung erfasst werden. Das Tensormeter bestimmt den kompletten Widerstandstensor einer oder mehrerer Dünnschichtproben wofür sonst eine Vielzahl von Messgeräten und aufwendigen Messaufbauten nötig ist. Zudem misst das Tensormeter exakt in hoher Auflösung und bei geringstem Rauschen ohne Probenstrukturierung (z.B. Lithografie).

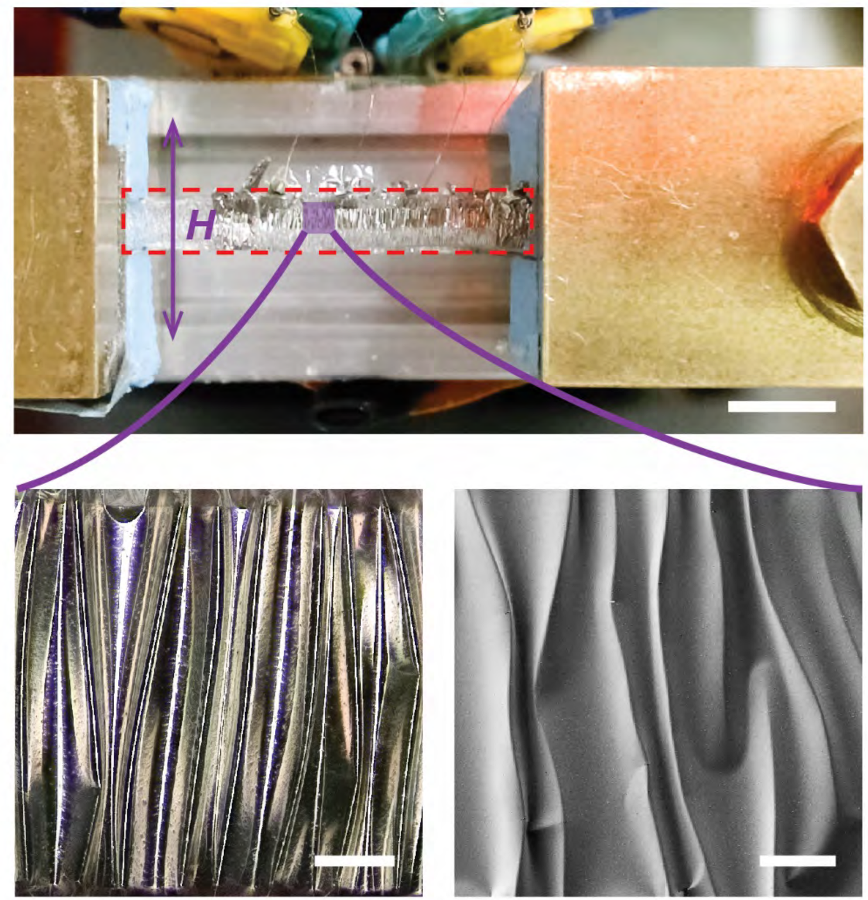




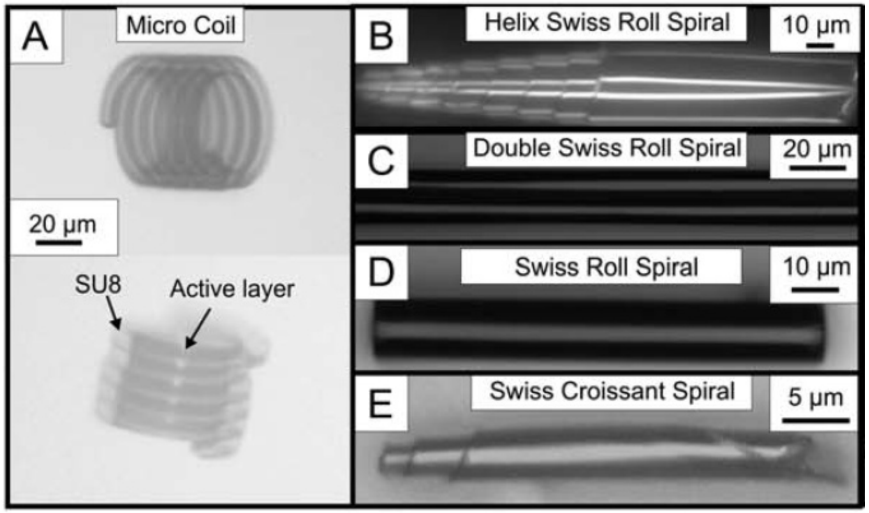
Melzer, DM et al., *Nature Commun.* **6**, 6080 (2015)



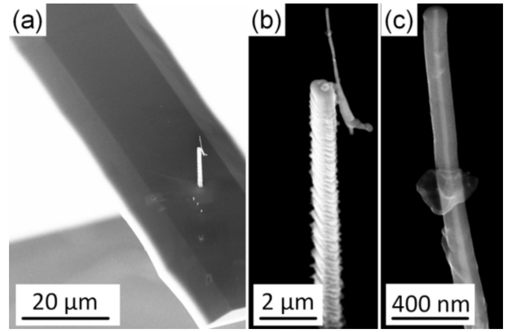
Minjeong Ha, DM et al., *Adv. Mater.* **33**, 2005521 (2021)



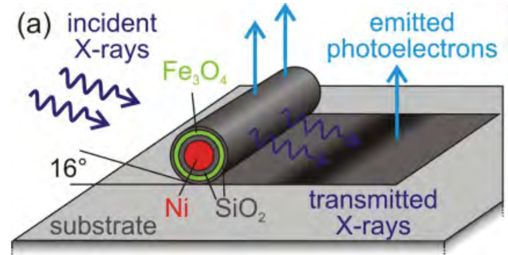
Experimental realizations



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



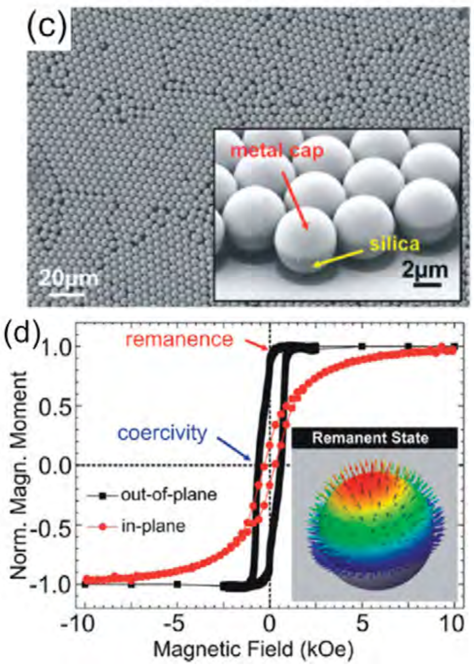
Mühl et al., *APL* (2012)



Kimling et al., *PRB* (2011)

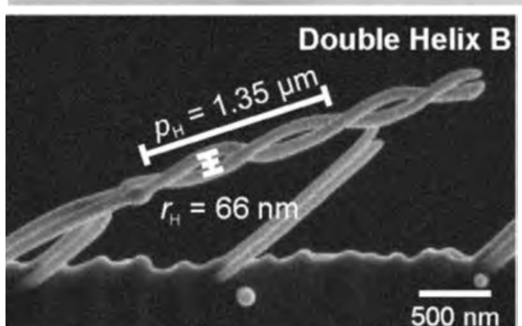
Magnetic soft x-ray tomography

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

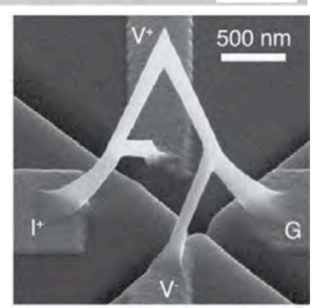


Baraban, DM et al., *ACS Nano* (2012)

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



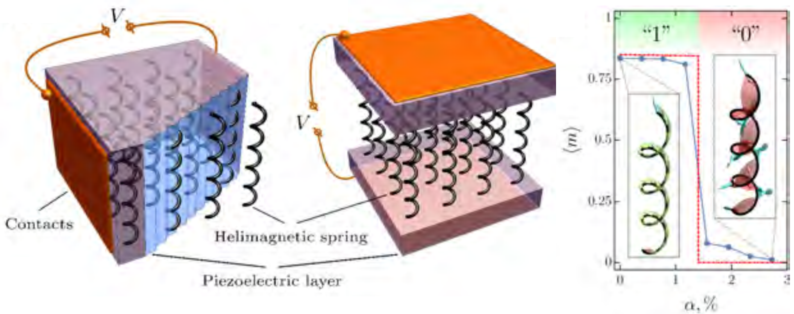
Donnelly et al., *Nature Nano* (2022)



Meng et al., *ACS Nano* (2021)

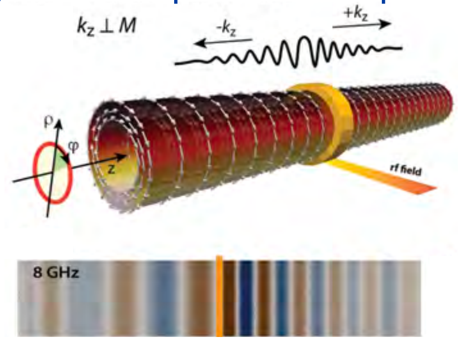
Application-oriented explorations

Artificial magnetoelectric structure



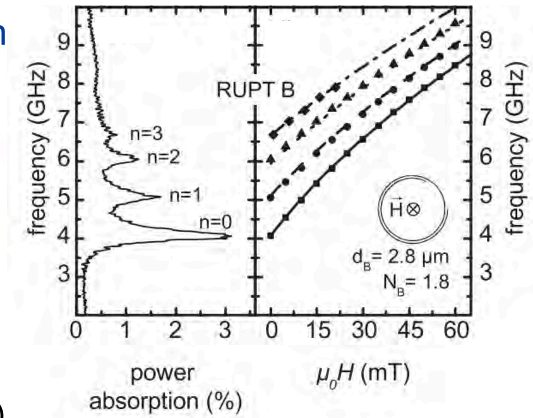
Volkov, DM et al., *J. Phys. D* **52**, 345001 (2019)

Asymmetric spin-wave dispersion



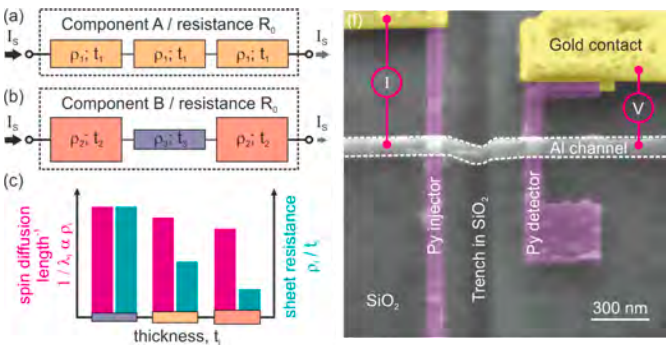
Otalora et al., *PRL* **117**, 227203 (2016)

Spin-wave interference in scrolls

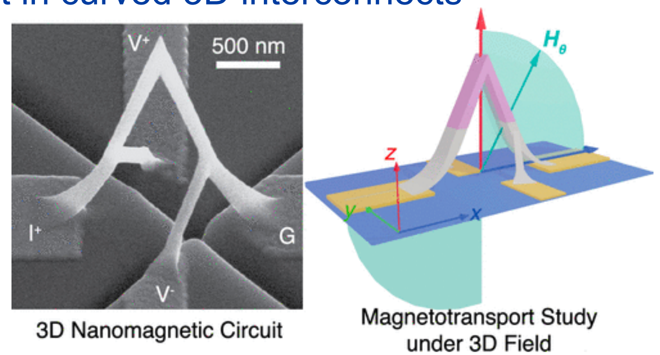


Balhorn et al., *PRL* **104**, 037205 (2010)

Pure spin and electron transport in curved 3D interconnects

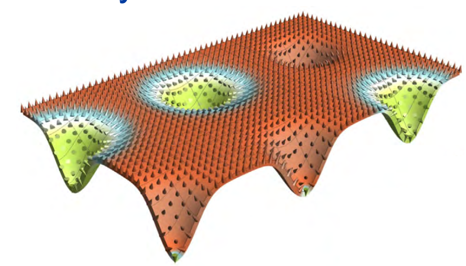


Das, DM et al., *Nano Lett.* **19**, 6839 (2019)



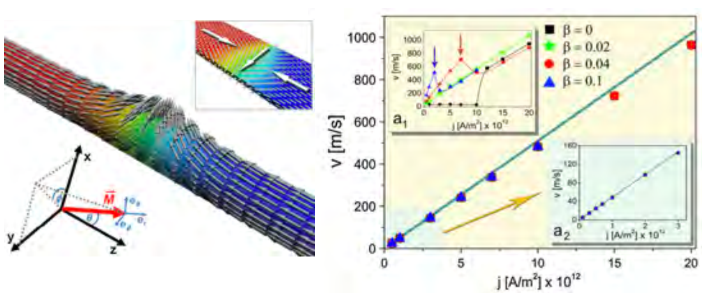
Meng et al., *ACS Nano* **15**, 6765 (2021)

Memory on localised solitons

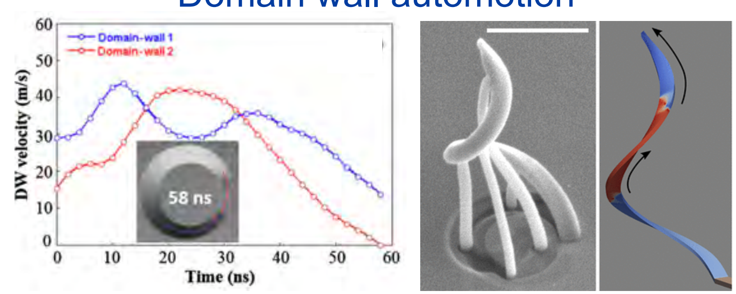


Kravchuk, DM et al., *PRL* **120**, 067201 (2018)

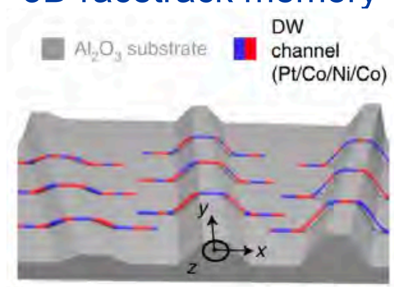
Massless domain wall motion in nanotubes



Domain wall automotion



3D racetrack memory



Yan et al, *PRL* **104**, 057201 ('10); Mawaas et al, *PRAppl.* **7**, 044009 ('17); Skoric et al, *ACS Nano* **16**, 8860 ('22); Gu et al, *Nat. Nano* **17**, 1065 ('22)

Magnetization dynamics and Strain effects

Journal of Applied Physics PERSPECTIVE scitation.org/journal/jap

Prospects toward flexible magnonic systems

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Published Online: 18 October 2021

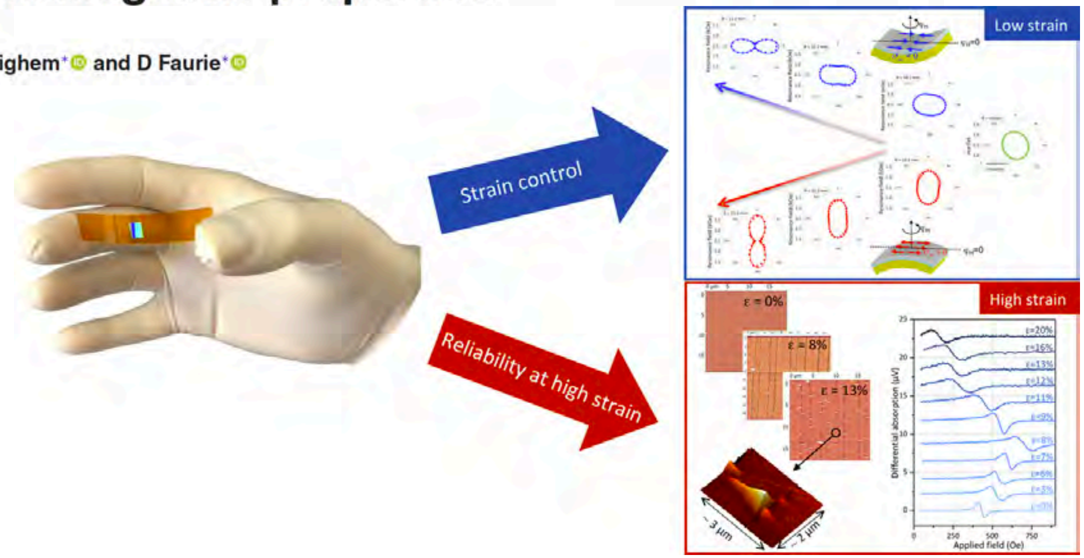
D. Faurie,[1,a] A. O. Adeyeye,[2,3] and F. Zighem[1,b]

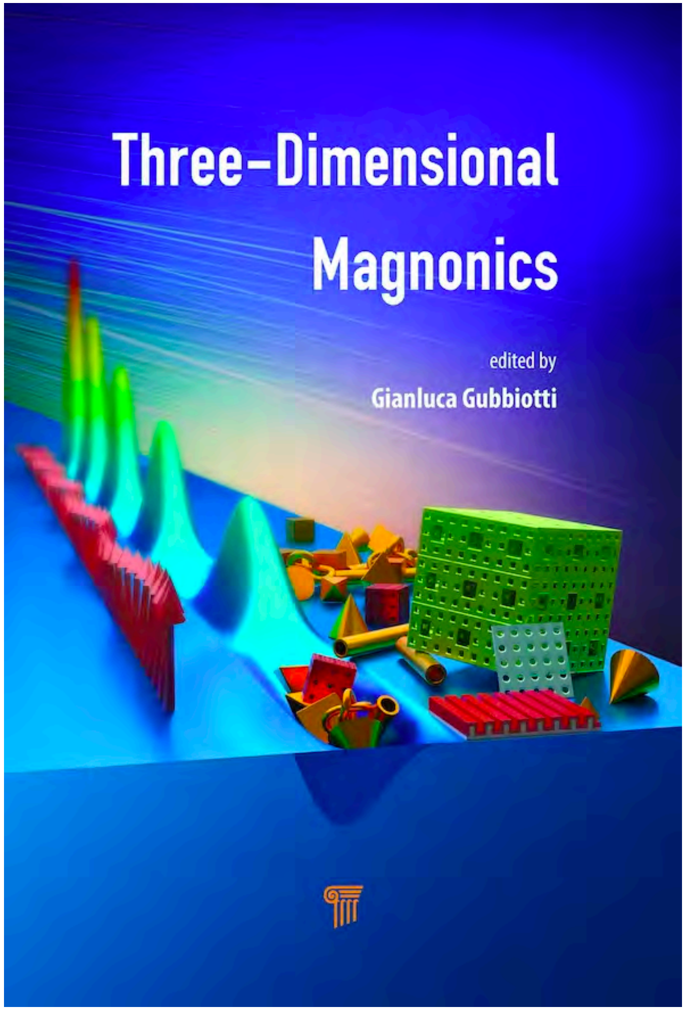
IOP Publishing Journal of Physics: Condensed Matter
J. Phys.: Condens. Matter 33 (2021) 233002 (17pp) https://doi.org/10.1088/1361-648X/abe96c

Topical Review

A review on nanostructured thin films on flexible substrates: links between strains and magnetic properties

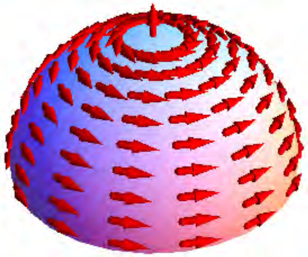
F Zighem* and D Faurie*





Impact of curvature on a magnetic system

Cylindrical surfaces



Spherical surfaces

Magnetic interactions in the anisotropic Heisenberg ferromagnet:

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

Exchange energy Anisotropy energy

In a curvilinear basis, micromagnetic energy can be rewritten:

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

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

Induced anisotropy responses: $\mathscr{E}_{ex}^A = \boldsymbol{\Gamma}^2 + \sin^2\theta\boldsymbol{\Omega}^2 + \cos^2\theta(\partial_\varphi\boldsymbol{\Gamma})^2$ Quadratic in curvature

Induced chiral responses: $\mathscr{E}_{ex}^D = D_{\alpha\beta\gamma} m_\beta \nabla_\gamma m_\alpha, \quad D_{\alpha\beta\gamma} = -D_{\beta\alpha\gamma}$

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

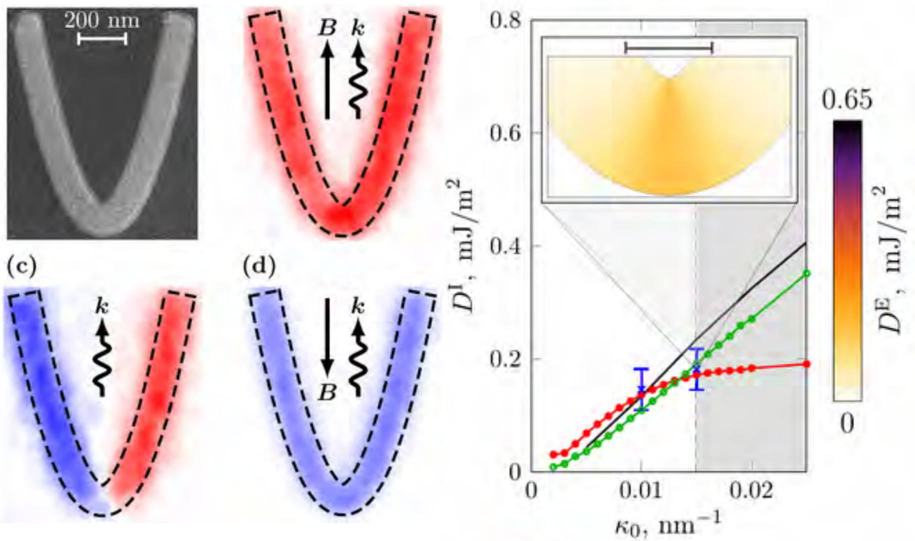
Linear in curvature

Gaididei et al., *PRL* ('14); Pylypovskyi, DM et al., *PRL* ('15); Kravchuk, DM et al., *PRL* ('18); Volkov, DM et al., *PRL* ('19)…

Review 2D shells: DM et al., *Adv. Mat.* **34**, 2101758 (2022) | Review 1D wires: Sheka, DM et al., *Small* **18**, 2105219 (2022)

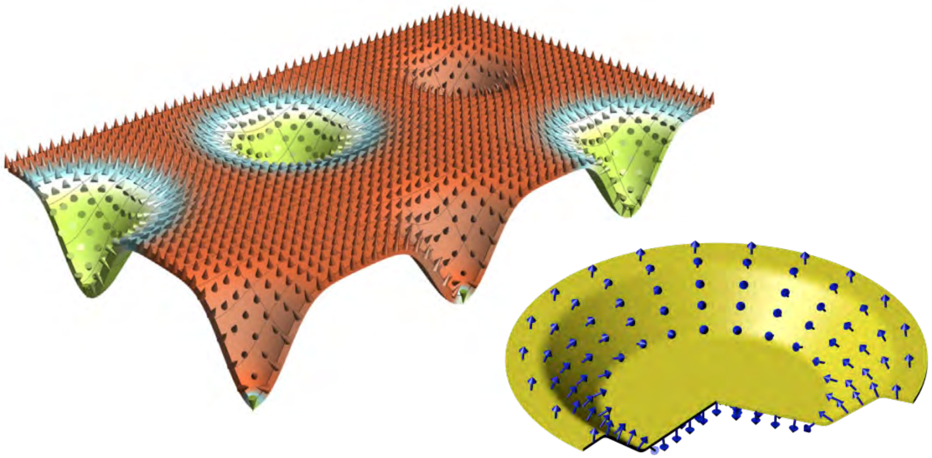
Curvilinear ferromagnetism: local interactions

Experimental confirmation of curvature effect



Volkov, DM et al., *Phys. Rev. Lett.* **123**, 077201 (2019)

Magnetic skyrmion states on a curvilinear defect



Kravchuk, DM et al., *PRL* **120**, 067201 (2018)

Pylypovskyi, DM et al., *PR Appl.* **10**, 064057 (2018)

$$E = E_0 + Ah \int \mathrm{d}S \left(w_{\mathrm{A}}^{\mathrm{x}} + w_{\mathrm{D1}}^{\mathrm{x}} + w_{\mathrm{D2}}^{\mathrm{x}} \right)$$

$$+ \; M_s^2 \int \mathbf{dr} \left(w_{g-\sigma} + w_{g-g} + w_{g-\rho} + w_{\sigma-\rho} \right)$$

D. Sheka, O. Pylypovskyi et al., *Communications Physics* **3**, 128 (2020)

…nonlocal interactions

Nonlocal chiral symmetry break

Terms supporting chiral symmetry breaking:

$$w_{g-\rho} = \rho(\mathbf{r}) \int \frac{g(\mathbf{r}')\mathrm{d}\mathbf{r}'}{|\mathbf{r}-\mathbf{r}'|}$$

$$w_{\sigma-\rho} = \rho(\mathbf{r}) \int \frac{\sigma(\mathbf{r}')\mathrm{d}S'}{|\mathbf{r}-\mathbf{r}'|}$$

D. Sheka, O. Pylypovskyi et al., *Communications Physics* **3**, 128 (2020)

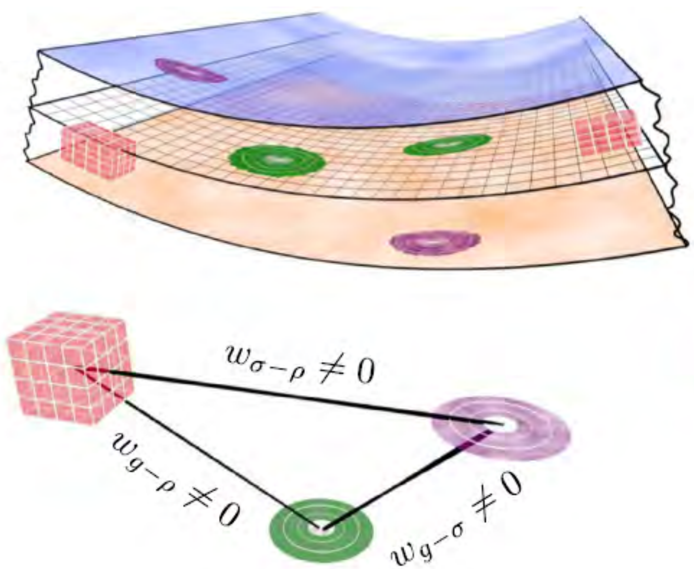
$$-\nabla \cdot \mathbf{m} = \rho + g,$$

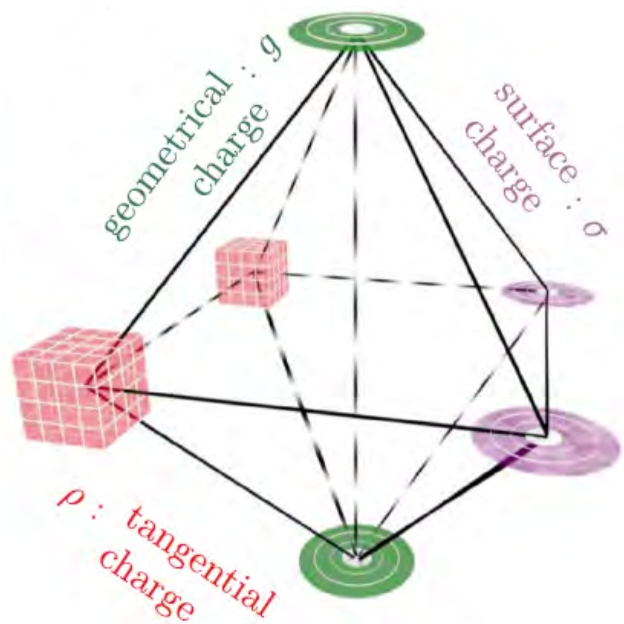
$$\rho(\mathbf{r}) = -\eth_i m_i \equiv -\eth_\alpha m_\alpha, \qquad g(\mathbf{r}) = \mathcal{H}(\mathbf{r}) m_n(\mathbf{r})$$

$\eth_i$: tangential derivative $\qquad$ $\mathcal{H}$: mean curvature

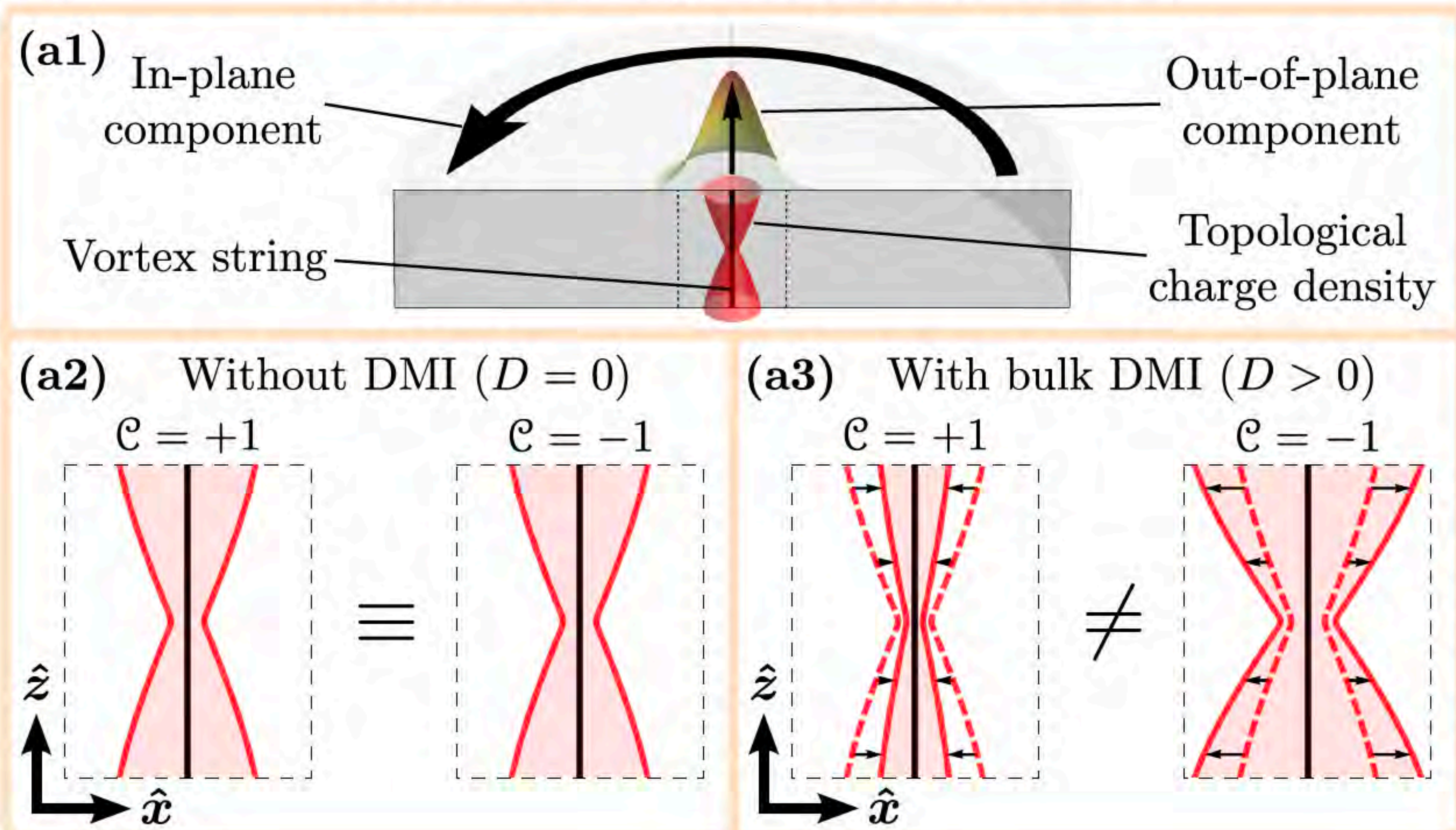
$$E_\mathrm{d} = M_\mathrm{s}^2 \int \mathrm{d}S w_{\sigma-\sigma} + M_\mathrm{s}^2 \int \mathrm{d}\mathbf{r} w_{\rho-\rho}$$

$$+M_\mathrm{s}^2 \int \mathrm{d}\mathbf{r} \left(w_{g-\sigma} + w_{g-g} + w_{g-\rho} + w_{\sigma-\rho} \right)$$



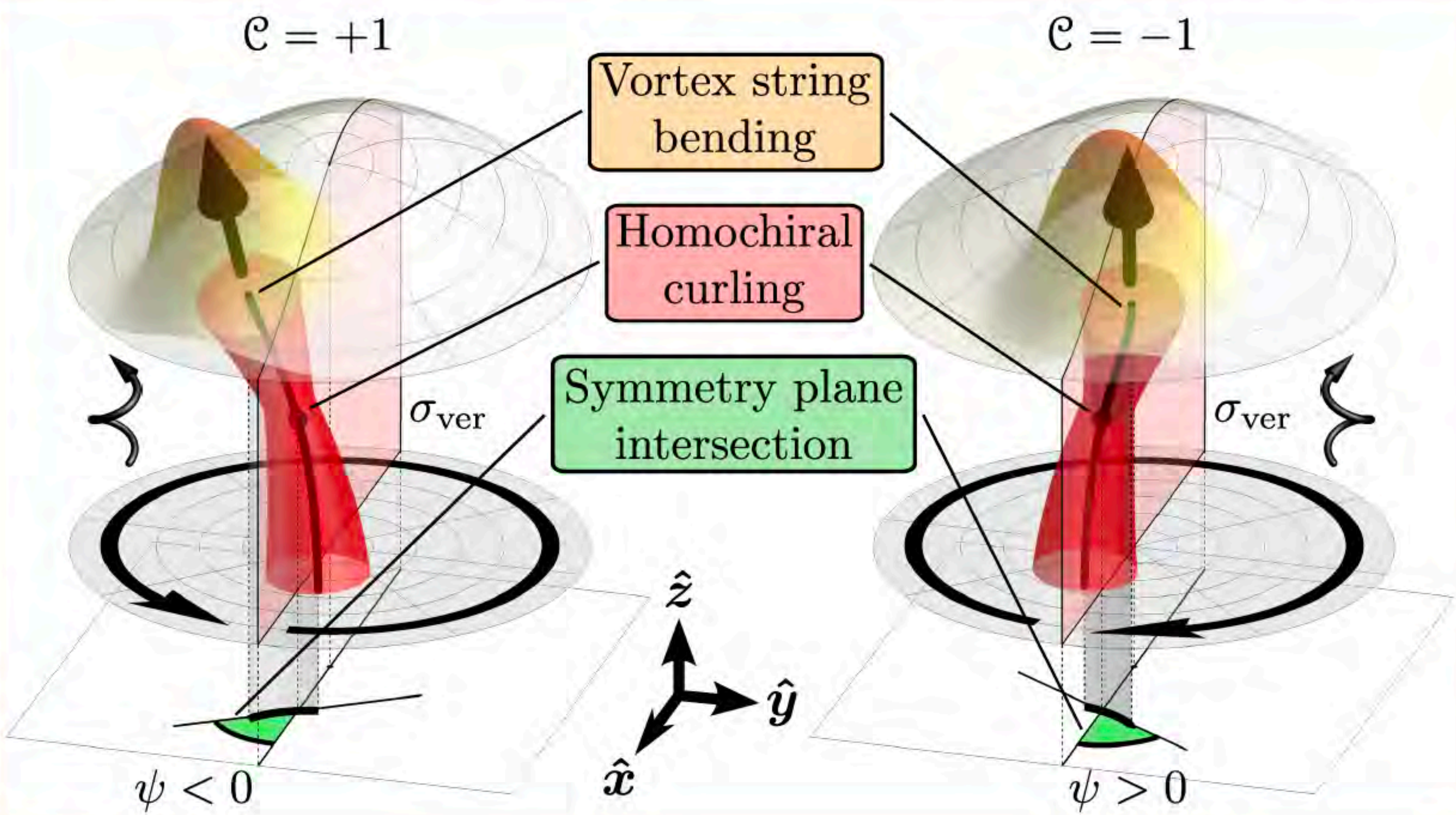


Vortex in a symmetric nanodisk



A. Butenko et al., *Physical Review B* **80**, 134410 (2009)

Coupling of two magnetochiralities within one object

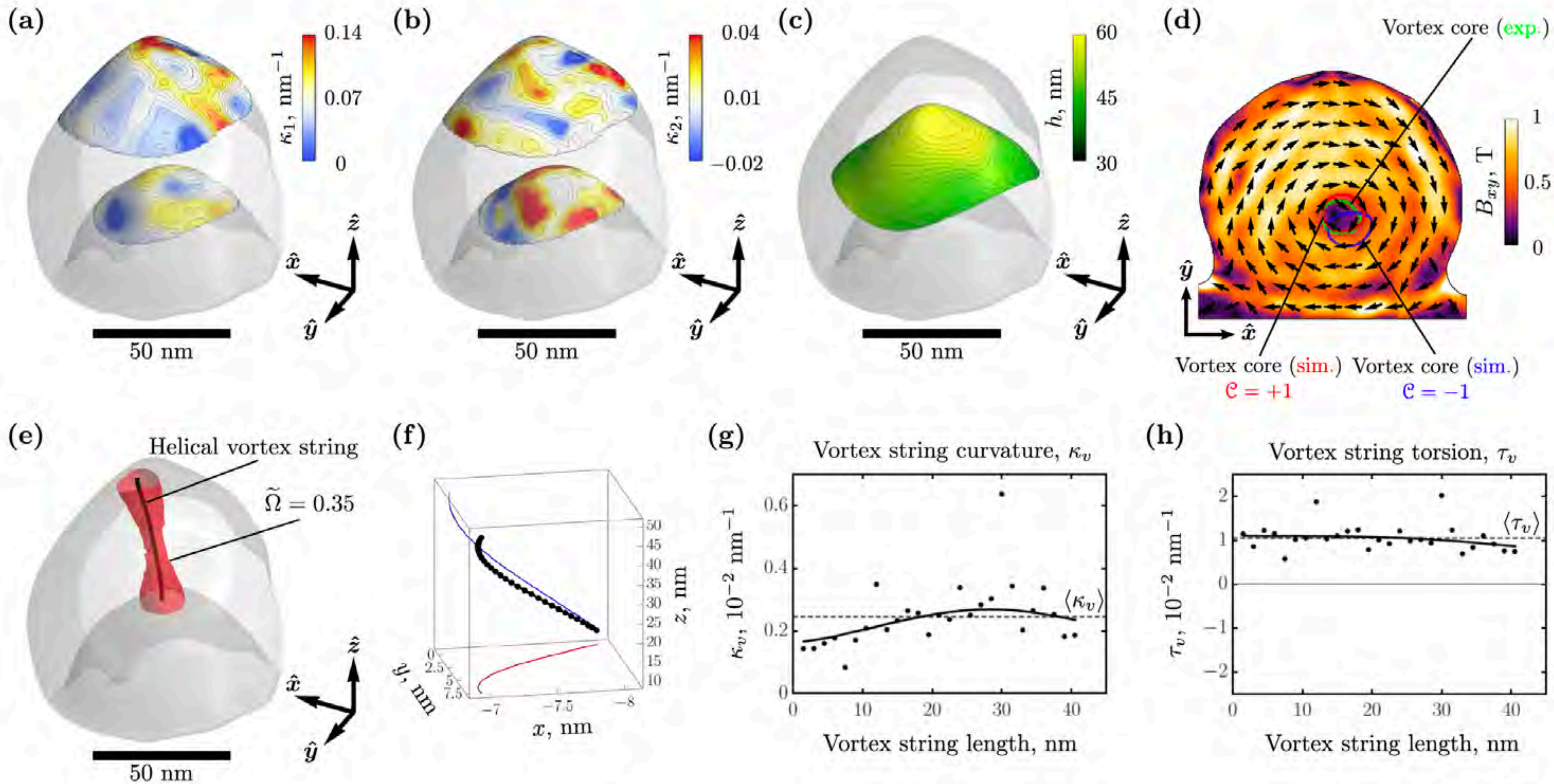


O. Volkov, DM et al., *Nature Communications* **14**, 1491 (2023)

Vortex in 80-nm-thick Permalloy nanocap

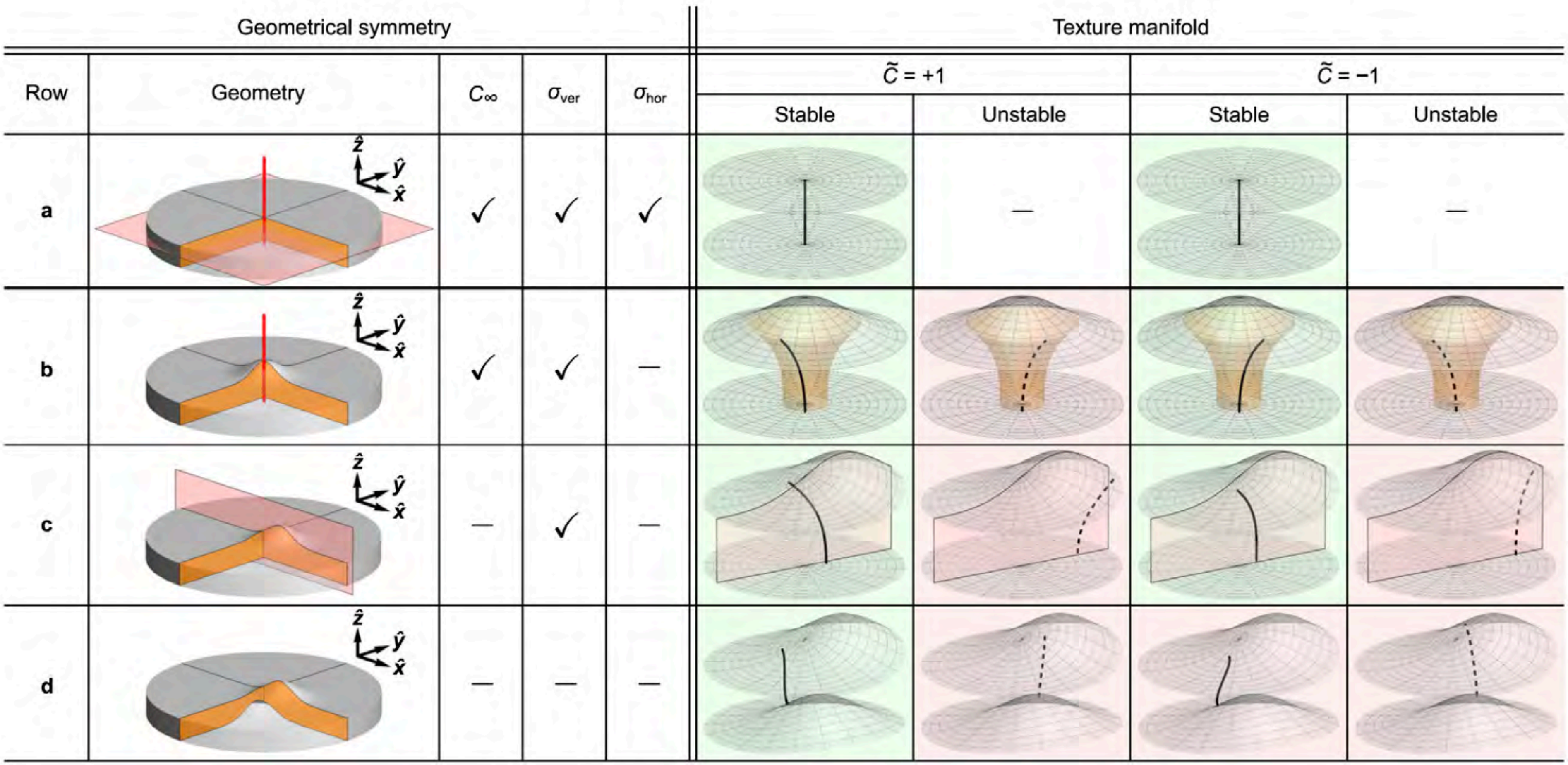
Nonlocal chiral symmetry break:

Coupling of chiralities in magnetic objects possessing multiple magnetochiral parameters



O. Volkov, DM et al., *Nature Communications* **14**, 1491 (2023)

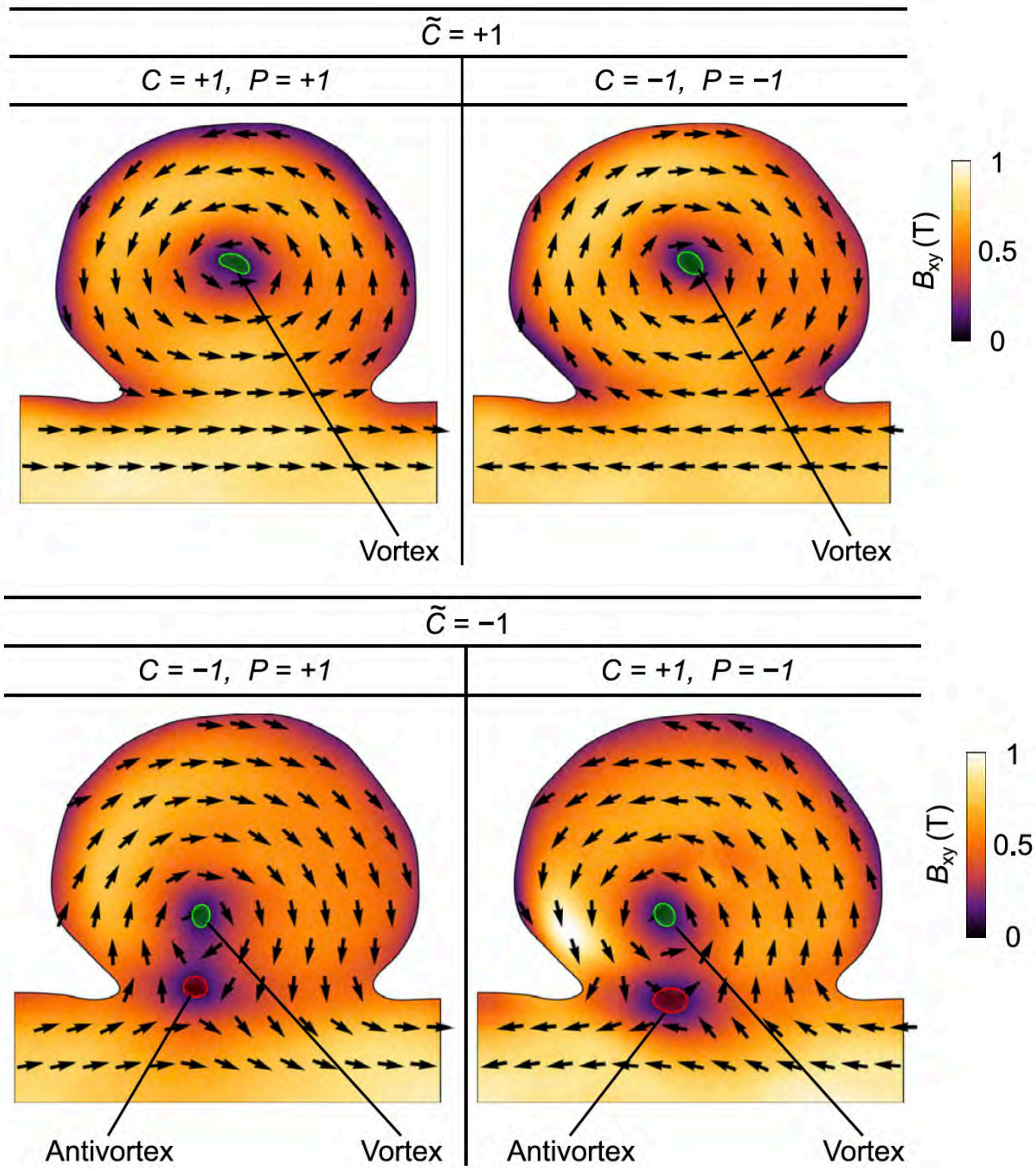
Evolution of the shape of the vortex string



Row	Geometry	C_∞	σ_{ver}	σ_{hor}	Texture manifold: $\tilde{C} = +1$ Stable	$\tilde{C} = +1$ Unstable	$\tilde{C} = -1$ Stable	$\tilde{C} = -1$ Unstable
a		✓	✓	✓		—		—
b		✓	✓	—				
c		—	✓	—				
d		—	—	—				

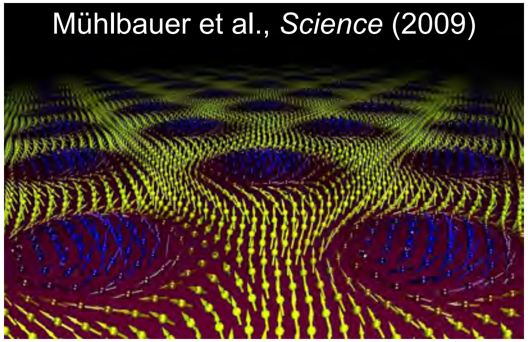
O. Volkov, DM et al., *Nature Communications* **14**, 1491 (2023)

Equilibrium magnetic vortex states in permalloy caps



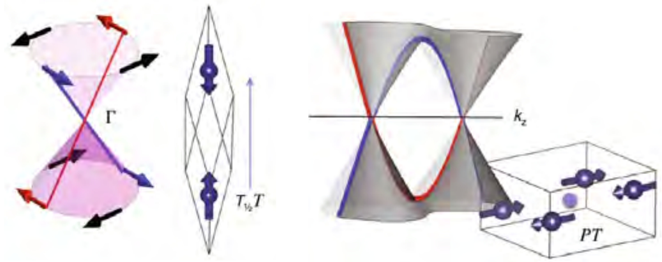
Curvilinear and Topology

Effects of topology



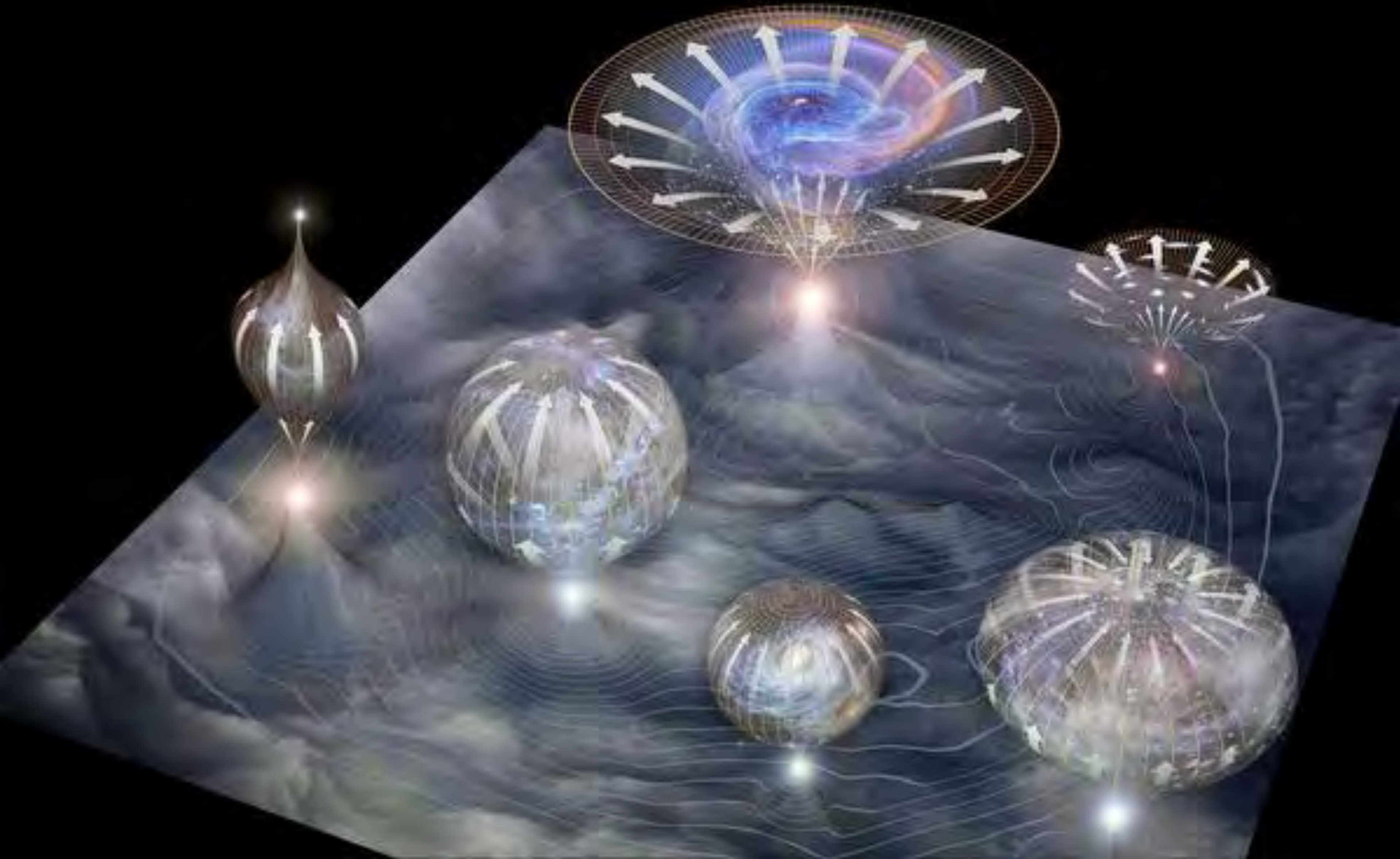
- **Texture**
  - Domain walls, skyrmions, vortices
  - Dislocations and disklinations (antiferromagnetic textures)

- **Band structure**
  - Topological insulators, Weyls…
  - 2D materials and heterostructures



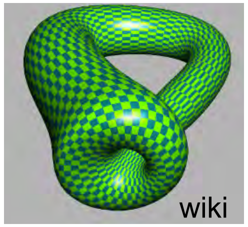
Smeikal et al., *Nat. Phys.* (2018)

Topology of the curved space-time universe

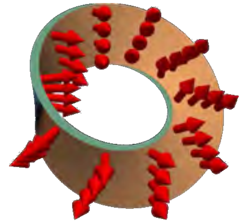


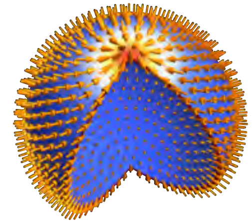
https://tallbloke.wordpress.com/2014/03/21/p-a-semi-topology-of-the-curved-space-time-universe/

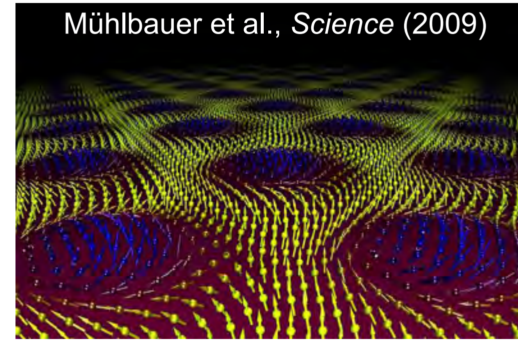
Effects of topology


wiki


pngkit.com


Pylypovskyi et al., *PRL* (2015)


Kravchuk et al., *PRB* (2016)


Mühlbauer et al., *Science* (2009)

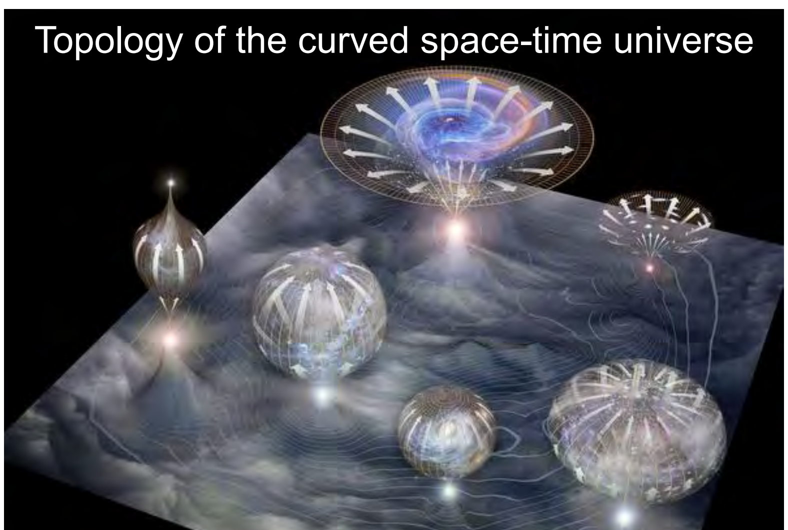
Curvilinear magnetism

- **Geometry**
  - Symmetric boundary conditions (tubes and spheres)
  - Antisymmetric boundary conditions (Möbius rings and Klein bottles)
  - Shells with perforations…

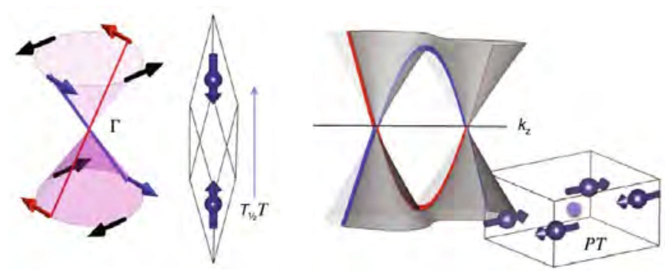
- **Texture**
  - Domain walls, skyrmions, vortices
  - Dislocations and disklinations (antiferromagnetic textures)

Flexomagnetism, Magnetostriction…

- **Band structure**
  - Topological insulators, Weyls…
  - 2D materials and heterostructures


Topology of the curved space-time universe

https://tallbloke.wordpress.com/2014/03/21/p-a-semi-topology-of-the-curved-space-time-universe/



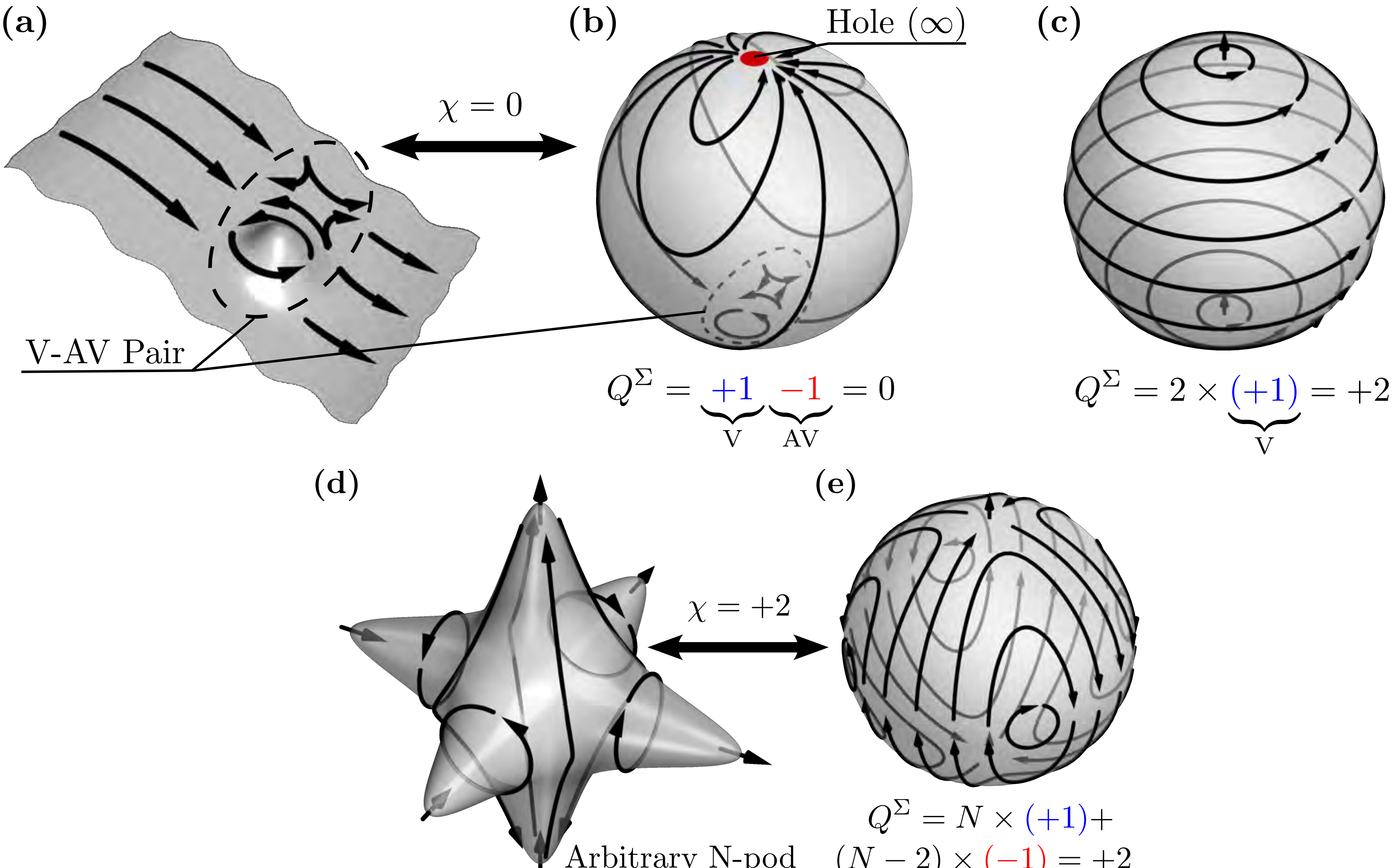
Smeikal et al., *Nat. Phys.* (2018)

High-order vorticity in soft magnetic wireframes

O. M. Volkov, O. V. Pylypovskyi, F. Porrati, F. Kronast, J. A. Fernandez-Roldan, A. Kakay, A. Kuprava, S. Barth, F. N. Rybakov, O. Eriksson, S. Lamb-Camarena, P. Makushko, M.-A. Mawass, S. Shakeel, O. V. Dobrovolskiy, M. Huth, and D. Makarov

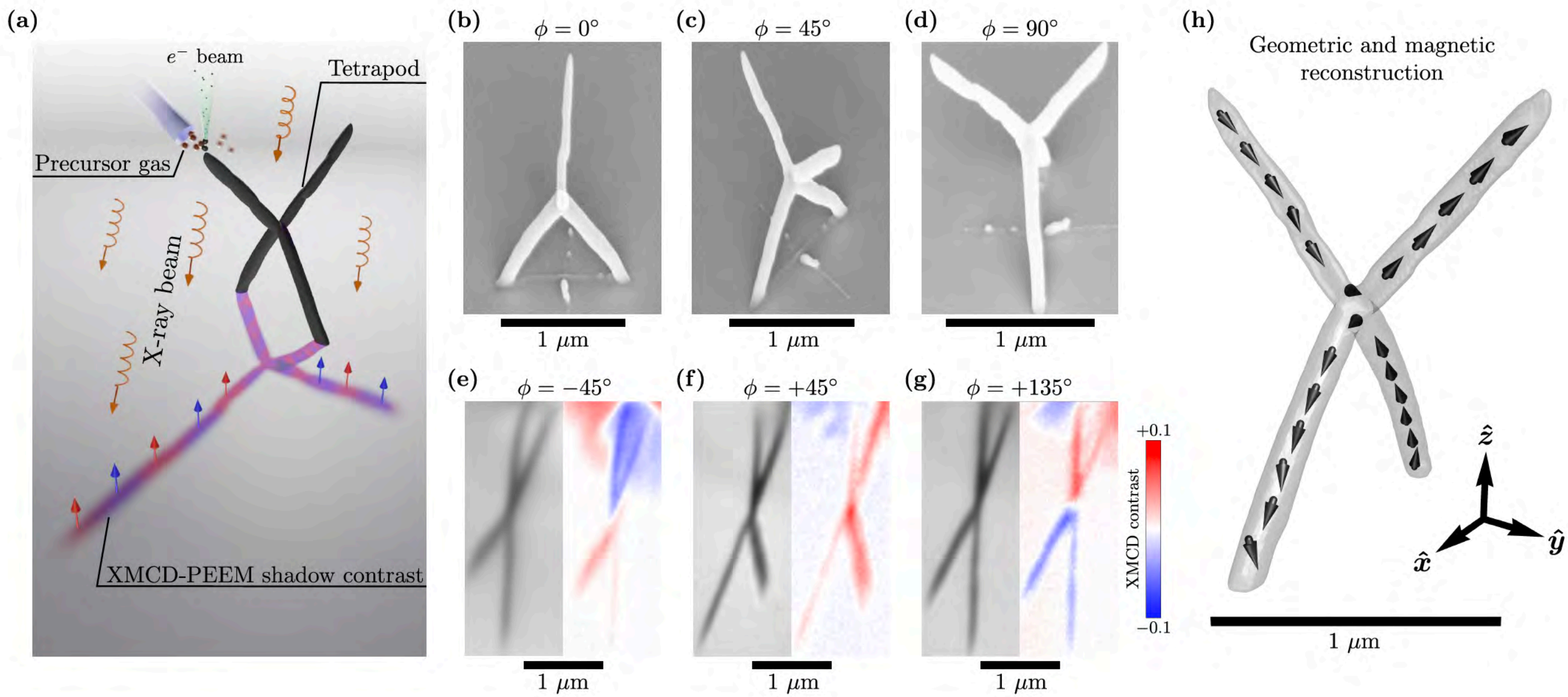
Nature Communications **15**, 2193 (2024)

Magnetization mapping for compact manifolds



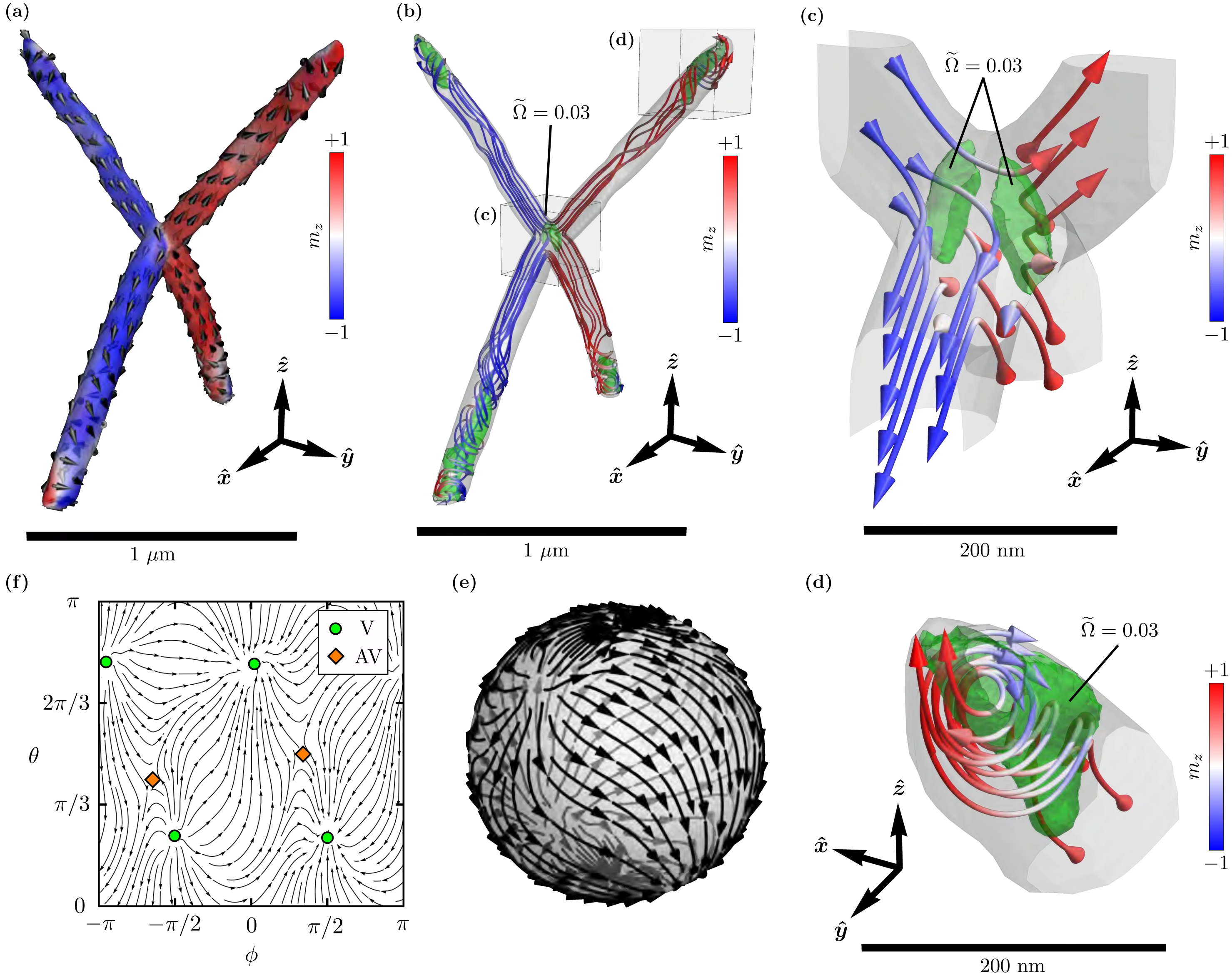
O. Volkov, DM et al., *Nature Communications* **15**, 2193 (2024)

Experimental realization of soft magnetic tetrapod



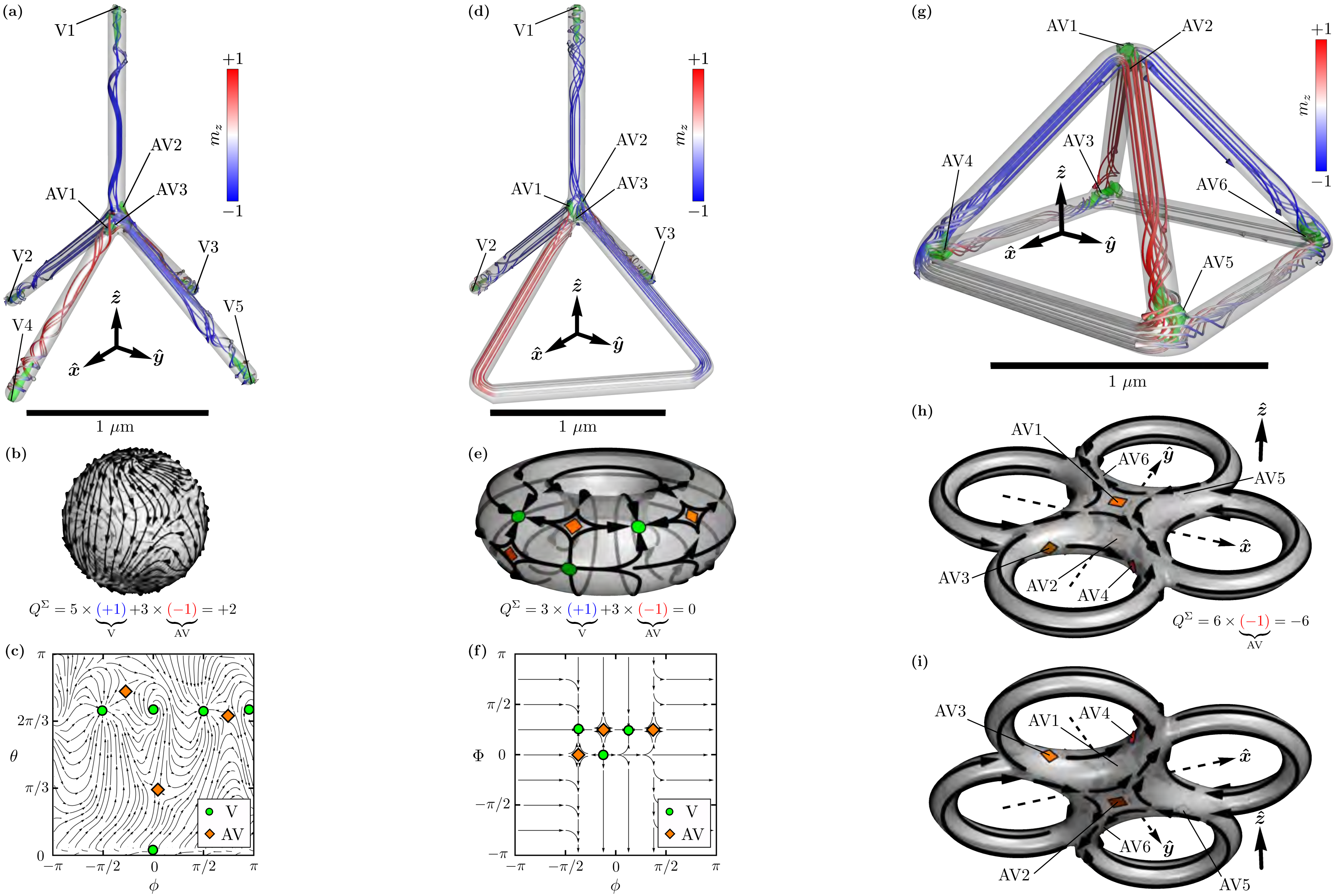
O. Volkov, DM et al., *Nature Communications* **15**, 2193 (2024)

Magnetization textures with high-order vorticity



O. Volkov, DM et al., *Nature Communications* **15**, 2193 (2024)

Wireframes of different Euler characteristic



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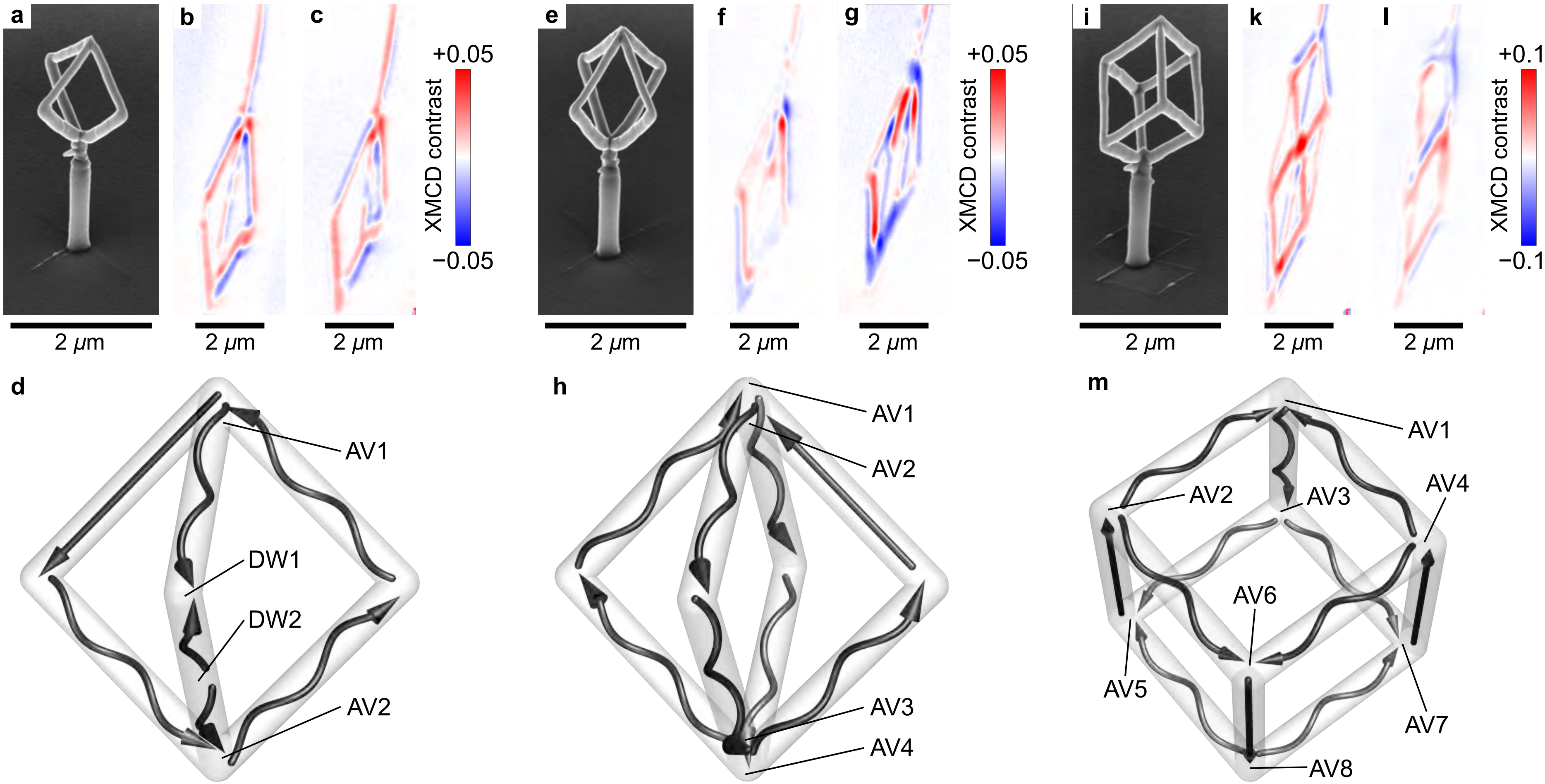
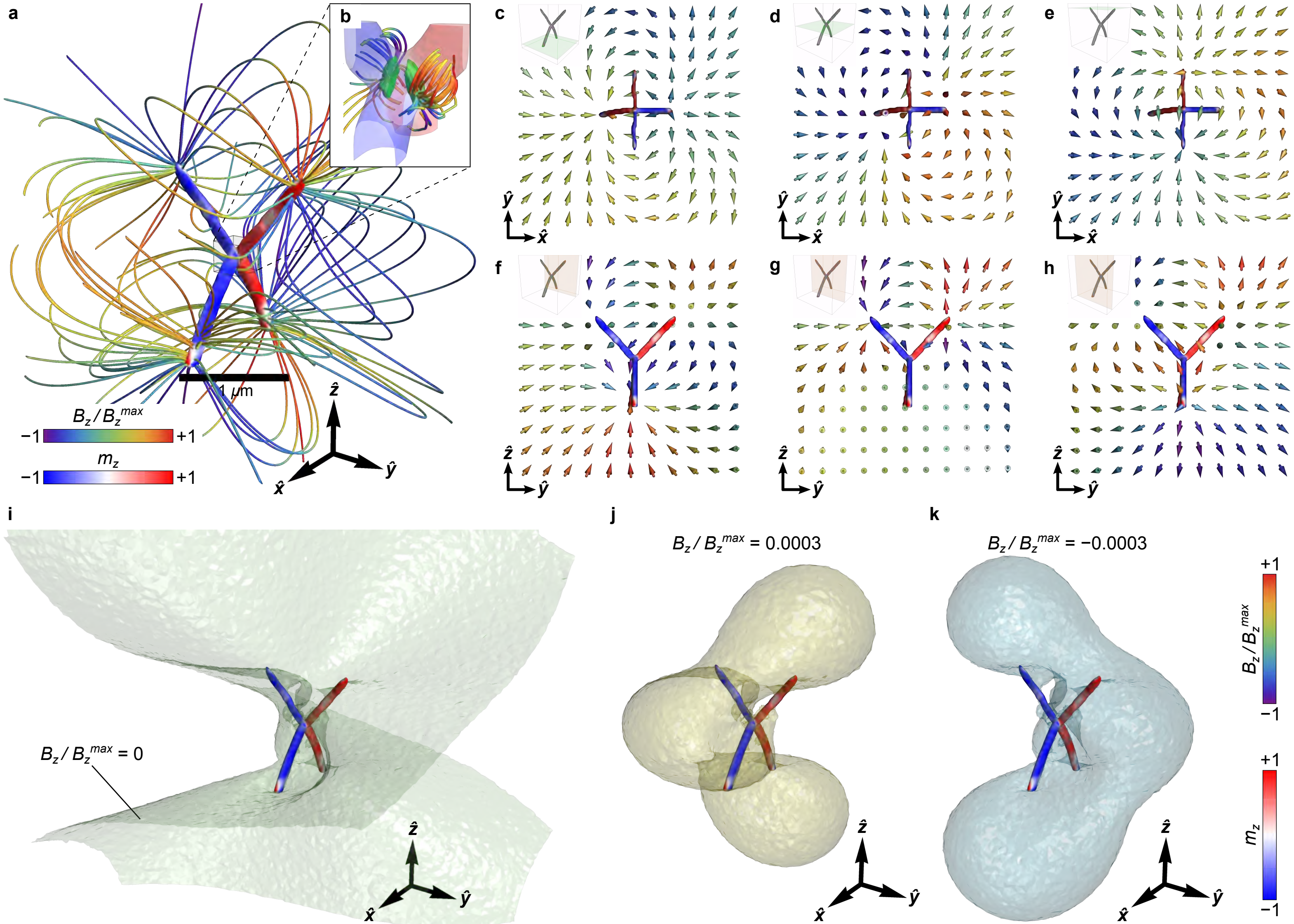
Wireframes of different Euler characteristic



O. Volkov, DM et al., *Nature Communications* **15**, 2193 (2024)

Magnetic stray field textures

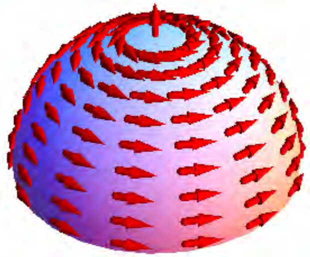


O. Volkov, DM et al., *Nature Communications* **15**, 2193 (2024)

Instead of summary

Impact of curvature on a magnetic system

Cylindrical surfaces



Spherical surfaces

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

Induced anisotropy responses:

$$\mathscr{E}_{ex}^A = \boldsymbol{\Gamma}^2 + \sin^2\theta \boldsymbol{\Omega}^2 + \cos^2\theta (\partial_\varphi \boldsymbol{\Gamma})^2$$

Quadratic in curvature

Induced chiral responses:

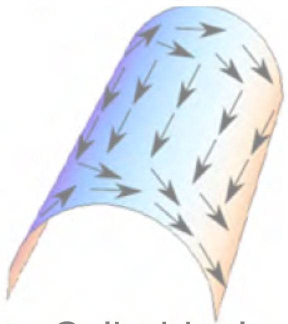
$$\mathscr{E}_{ex}^D = D_{\alpha\beta\gamma} m_\beta \nabla_\gamma m_\alpha, \quad D_{\alpha\beta\gamma} = -D_{\beta\alpha\gamma}$$

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

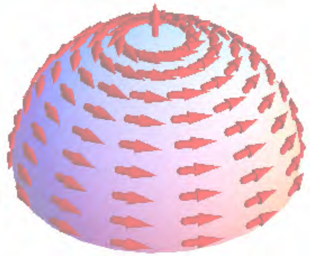
Linear in curvature

Gaididei et al., *PRL* (‘14); Pylypovskyi, DM et al., *PRL* (‘15); Kravchuk, DM et al., *PRL* (‘18); Volkov, DM et al., *PRL* (‘19)…

Impact of curvature on a magnetic system



Cylindrical surfaces



Spherical surfaces

Magnetic interactions in the anisotropic Heisenberg ferromagnet:

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

Exchange energy   Anisotropy energy

New approach to material science

designing magnetic responses by tailoring the geometry of thin films

Induced anisotropy responses:

$$\mathscr{E}_{ex}^{A} = \boldsymbol{\Gamma}^2 + \sin^2\theta \boldsymbol{\Omega}^2 + \cos^2\theta (\partial_\varphi \boldsymbol{\Gamma})^2$$

Quadratic in curvature

Induced chiral responses:

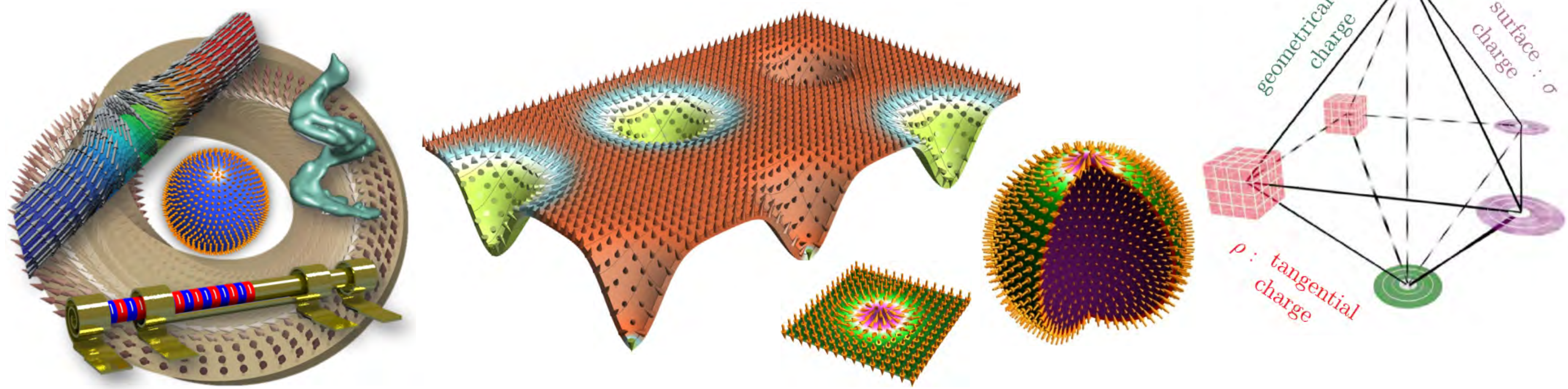
$$\mathscr{E}_{ex}^{D} = D_{\alpha\beta\gamma} m_\beta \nabla_\gamma m_\alpha, \quad D_{\alpha\beta\gamma} = -D_{\beta\alpha\gamma}$$

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

Linear in curvature

Gaididei et al., *PRL* ('14); Pylypovskyi, DM et al., *PRL* ('15); Kravchuk, DM et al., *PRL* ('18); Volkov, DM et al., *PRL* ('19)…

Effects of geometrical curvatures in magnetism

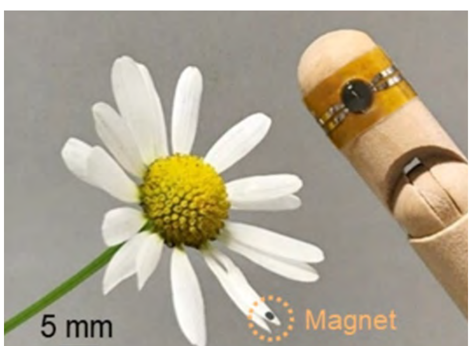


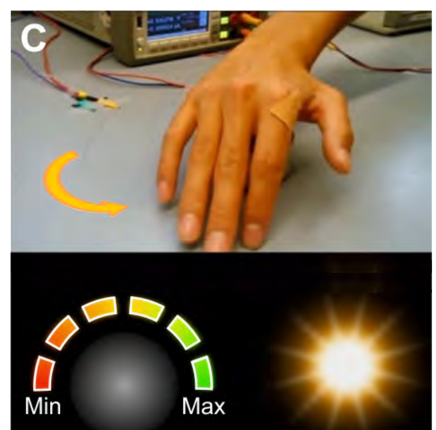
Nature Physics & *Nature Communications* & *Phys. Rev. Lett.* & *Nano Letters* & *Advanced Materials* & *Appl. Phys. Lett.*

Curvilinear magnetism: fundamentals and applications

Two sides of the coin: Sensitivity of shapeable sensors is affected by local curvatures

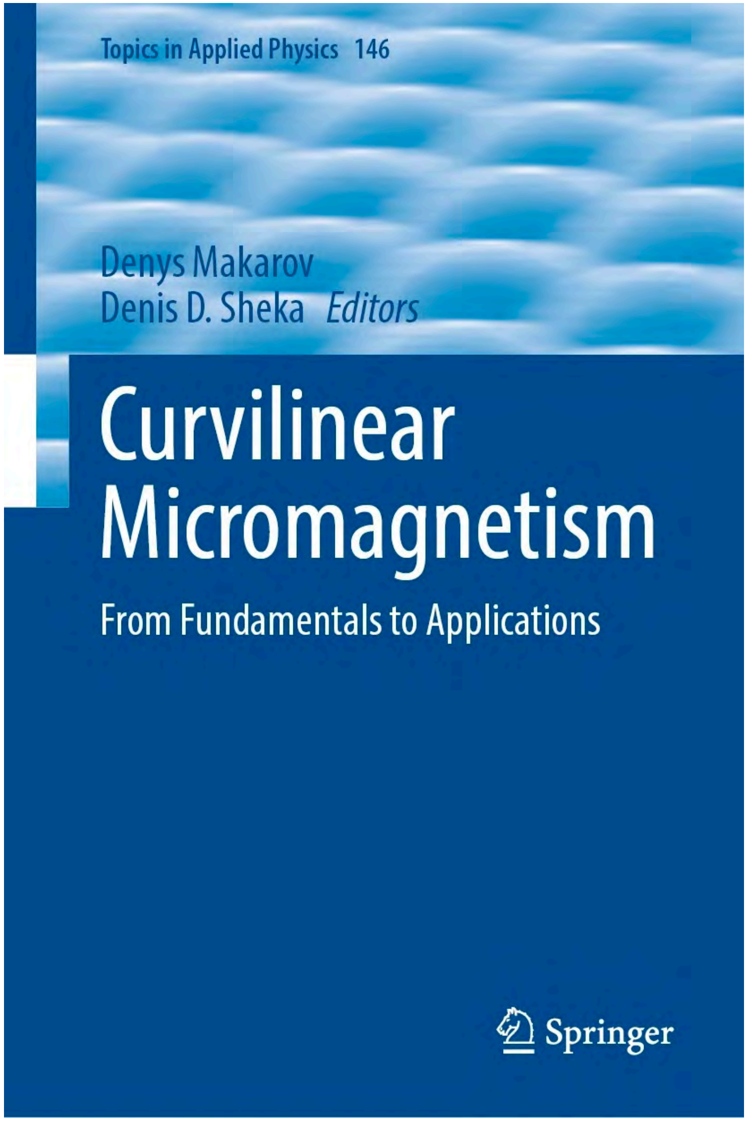
Shapeable magnetoelectronics





Science Advances & *Nature Electronics* & *Nano Letters* & *Advanced Materials* & *Communications Materials* & *Nature Commun.*

Curvilinear micromagnetism



Geometry-Induced Magnetic Effects in Planar Curvilinear Nanosystems
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Effects of Curvature and Torsion on Magnetic Nanowires
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Pages 37-81

Curvilinear Magnetic Shells
Denis D. Sheka, Volodymyr P. Kravchuk, Davide Peddis, Gaspare Varvaro, Michał Krupiński, Manfred Albrecht et al.
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Tubular Geometries
Pedro Landeros, Jorge A. Otálora, Robert Streubel, Attila Kákay
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Geometrically Curved Magnetic Field Sensors for Interactive Electronics
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Thank you for your attention