Skyrmions: From 3D chiral magnets to 2D oxide interfaces

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1. SB, J. Rowland, O. Erten & M. Randeria, Phys. Rev. X **4**, 031045 (2014).

2. J. Rowland, SB & M. Randeria, Phys. Rev. B (Rapid) **93**, 020404 (2016).

3. SB, O. Erten & M. Randeria, Nature Physics **9**, 626 (2013).

Chiral magnetism

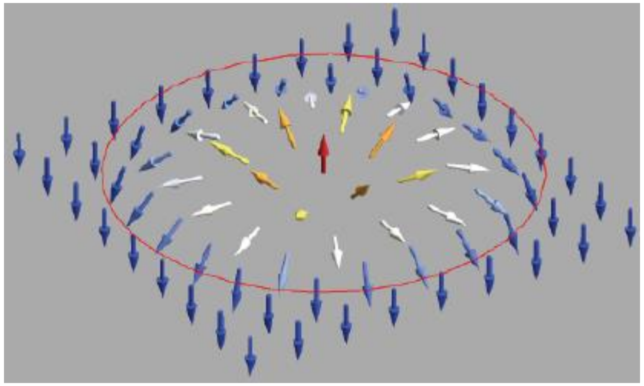
Chiral Dzyaloshinskii-Moriya (DM) exchange

$\boldsymbol{D}_{ij}.(\boldsymbol{S}_i \times \boldsymbol{S}_j)$ $D\boldsymbol{m}.(\nabla \times \boldsymbol{m})$

Broken inversion, e.g. $(x, y, z) \not\rightarrow (-x, -y, -z)$

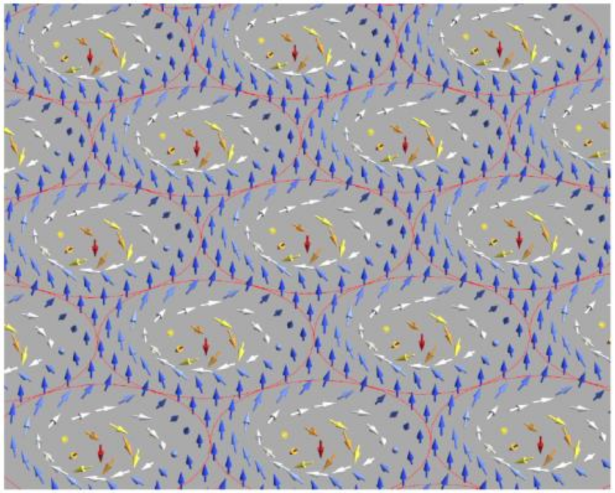
→ "Chiral magnets"

Skyrmions



Topological spin texture

Skyrmion crystal (SkX)

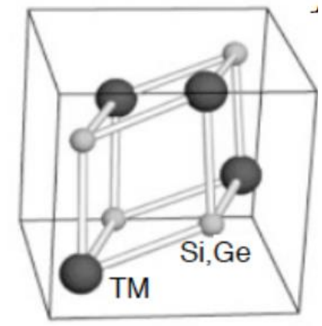


Conventional 3D chiral magnets

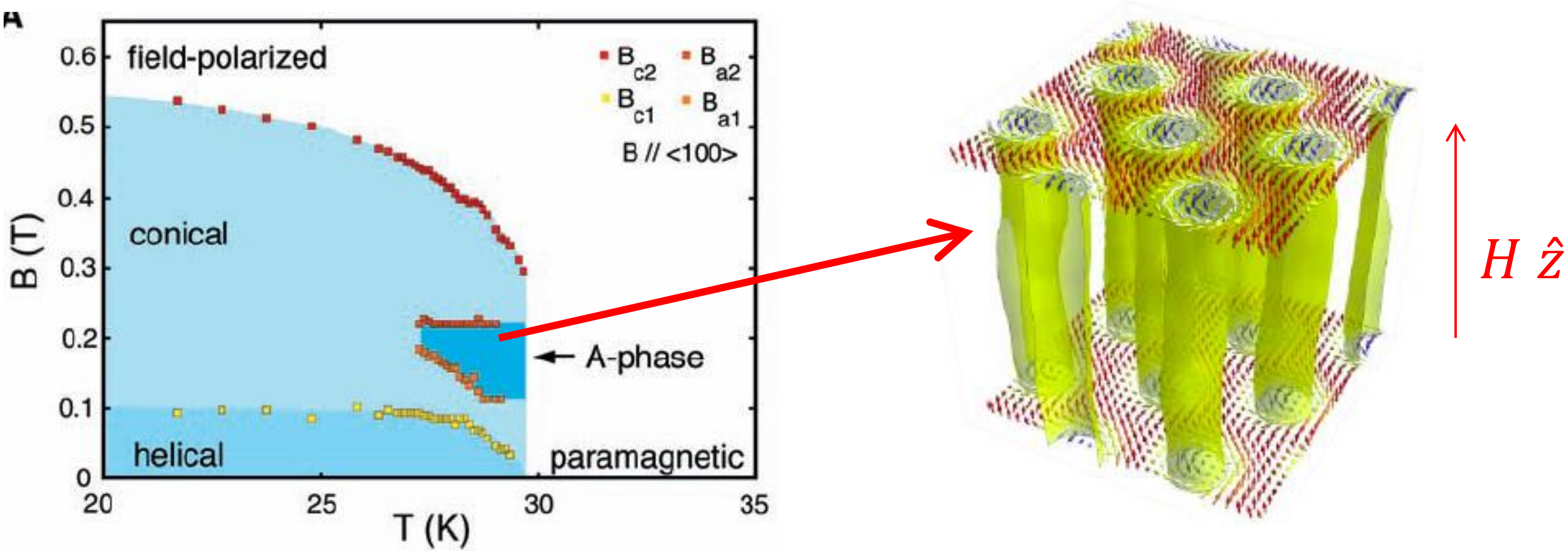
- Non-centrosymmetric crystals

  Cubic crystals <u>without</u> bulk inversion symmetry

Metals: MnSi, $Fe_{1-x}Co_xSi$, FeGe, …
Insulators: Cu_2OSeO_3



B20: no inversion center

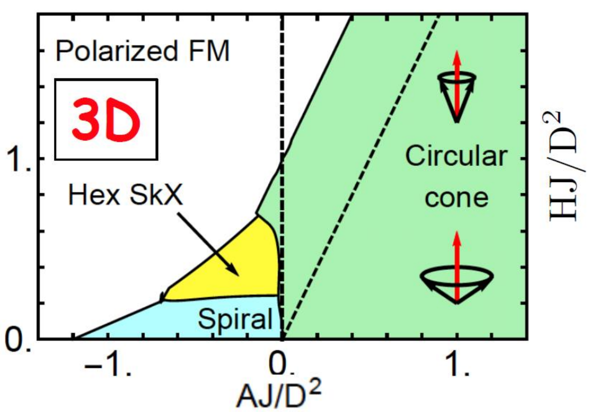


Skyrmion crystal – Narrow region in the phase diagram at finite temperature

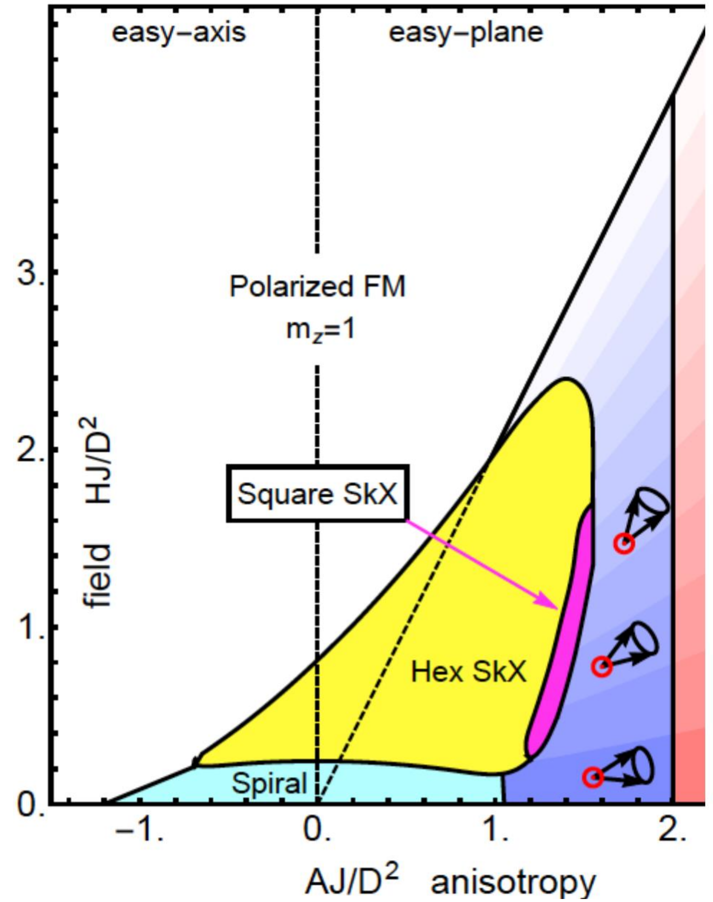
How to enhance the stability of skyrmion phases?

e.g. SkX ground state.

By tuning materials, dimensionality, ...
→ Phenomenological and microscopic understanding of the mechanism for stability

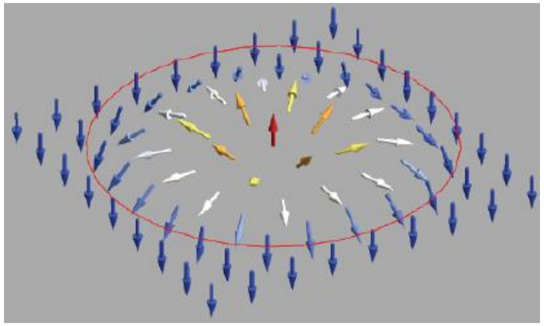


Dimensionality
and/or
Symmetry



→“Uncover” much richer phase diagram
e.g. Transition between SkX phases

Broader motivation



Magnetic Skyrmions: Topological spin texture

- {Condensed matter physics} ∩ {Topology}

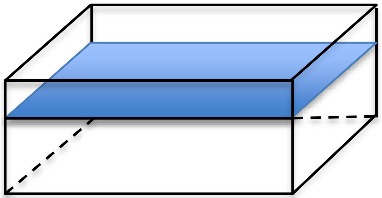
Topological phenomena – "Emergent electromagnetism"
→ Topological Hall effect, spin transfer torque, skyrmion-flow Hall effect

- Interplay of magnetism and spin-orbit coupling (SOC)
→ New materials, Novel magnetic phases

- Long-wavelength structures ⟷ "Soft" condensed matter
∩
in ⟷ "Hard" condensed matter
Correlated quantum materials

Outline

- Skyrmions and chiral magnetism.
- Skyrmion materials and properties.
- How to stabilize skyrmion phases?
  System with broken mirror symmetry ($z \not\to -z$)
  → Much richer skyrmion phase diagram
- Conclusions and outlook.



Outline

- Skyrmions and chiral magnetism.

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  System with broken mirror symmetry ($z \nrightarrow -z$)

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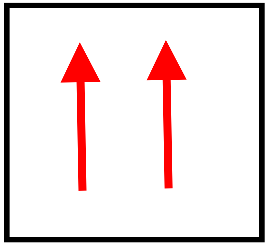
Chiral magnetism : DM term

○ Magnetism → magnetic exchange (isotropic)
(Local moments)

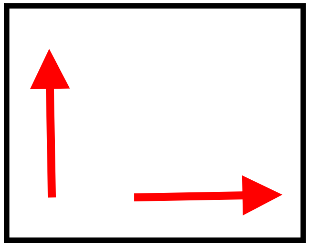
$$\mathcal{H}_J = -J\boldsymbol{S}_i \cdot \boldsymbol{S}_j$$



○ Broken inversion e.g. $(x, y, z) \not\rightarrow (-x, -y, -z)$

→ Chiral Dzyaloshinskii-Moriya exchange

$$\mathcal{H}_{DM} = \boldsymbol{D}_{ij} . (\boldsymbol{S}_i \times \boldsymbol{S}_j)$$



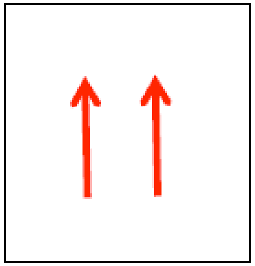
Symmetry → Direction of $\boldsymbol{D}$ vectors

Microscopics → Magnitude of $\boldsymbol{D}$ vectors

$J \gg D \propto \alpha$ ← Spin-orbit coupling strength

Spin textures

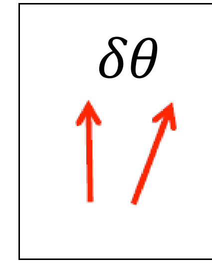
$J > 0$



$$-J\, \boldsymbol{S}_i . \boldsymbol{S}_j \sim -J \cos\delta\theta \sim J\delta\theta^2/2$$

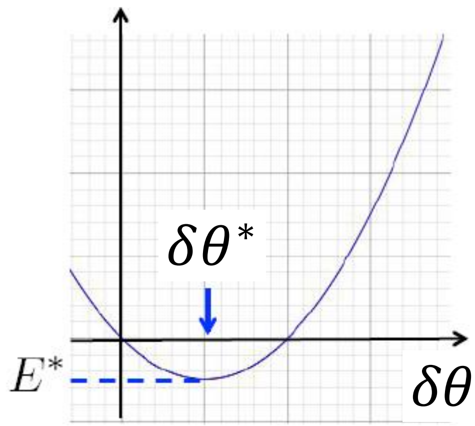
$$-\boldsymbol{D}.\left(\boldsymbol{S}_i \times \boldsymbol{S}_j\right) \sim -D \sin\delta\theta \sim -D\delta\theta$$

Twist



Pitch

$\delta\theta^* = D/J$



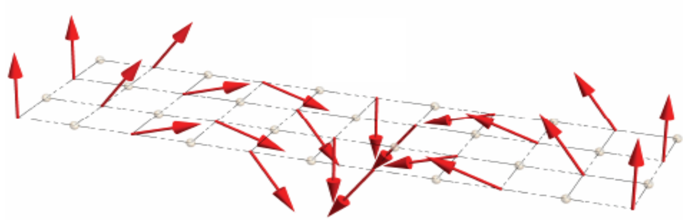
$E^* = -D^2/2J$

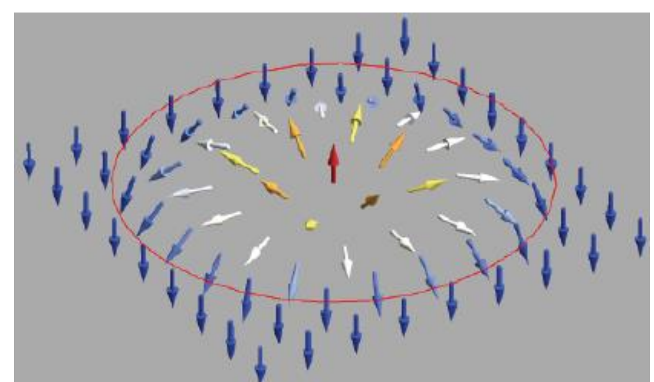
→ Length scale

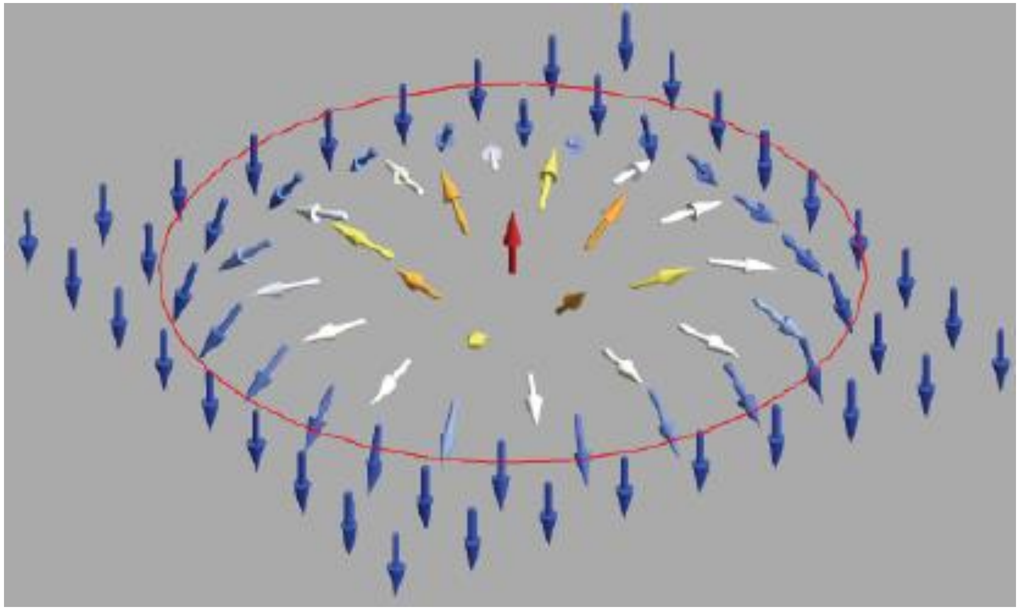
$L_D = \left(\frac{J}{D}\right) a \gg a$

Skyrmions

Spiral



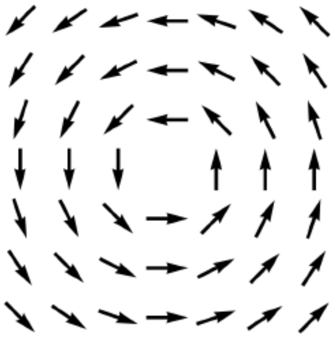




What is skyrmion?

Skyrmion → A topological soliton

Example: Vortex in superfluid



The first use of a topological soliton to model a particle

"A unified field theory of mesons and baryons"
Nuclear Physics 31, 556 (1962)

T. H. R. Skyrme
(1922 – 1987)

Skyrmions in condensed matter:

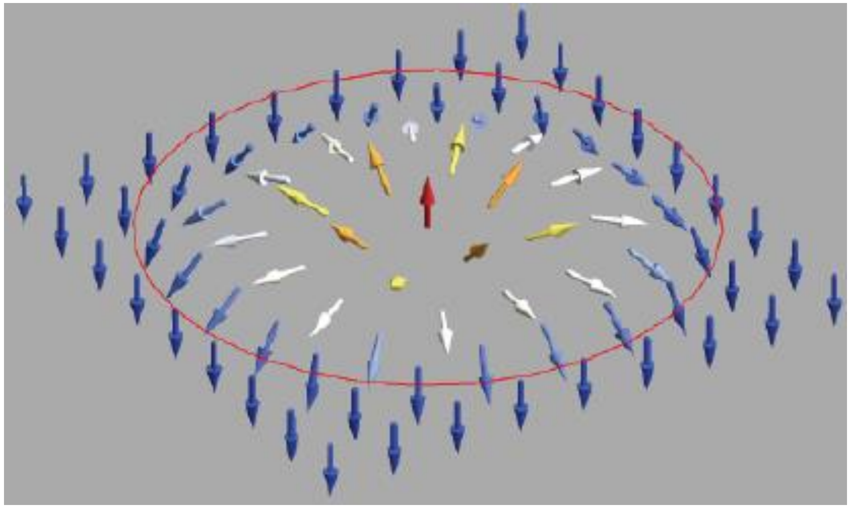
- Liquid crystals
- Quantum Hall effect
- Spinor Bose condensates
- Cold atoms with synthetic gauge fields
- Magnetic materials*

→ Chiral magnets

* Belavin-Polyakov solution for metastable state in 2D Heisenberg model

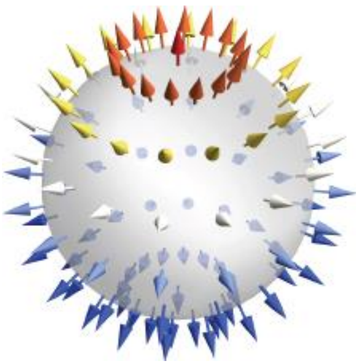
Magnetic Skyrmions

Texture in local magnetization $\hat{\boldsymbol{m}}(\boldsymbol{r})$



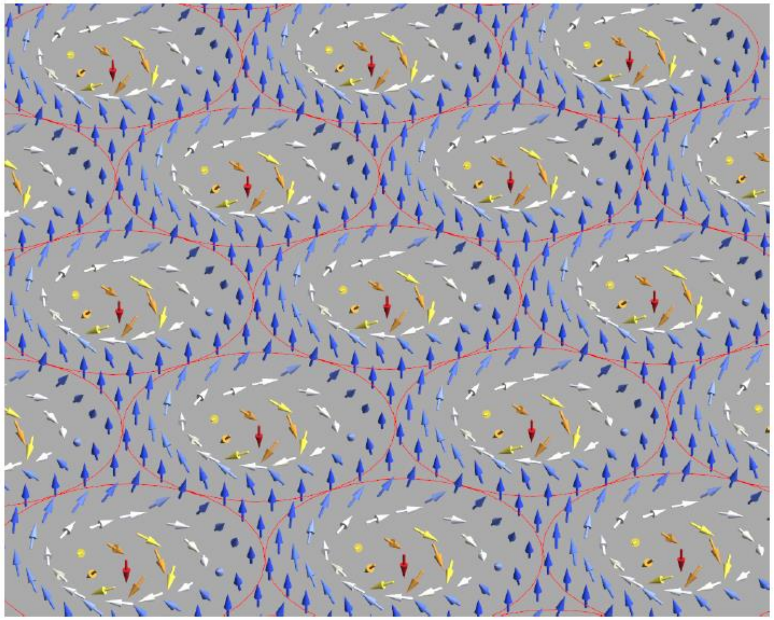
(Hedgehog or Ne'el skyrmion)

"Hedgehog"



Wrapping of unit sphere in spin space

$$\Pi_2(S^2) = \mathbb{Z}$$



Skyrmion crystal (SkX)

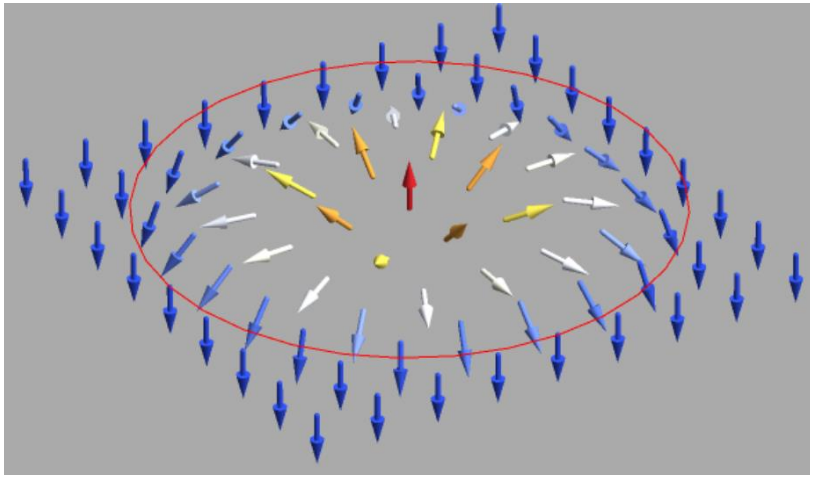
Topological charge

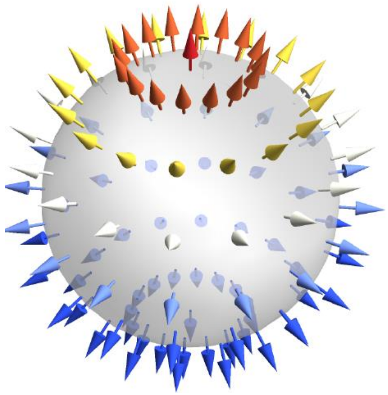
$$N_{sk} = \int d^2r\, \chi(\boldsymbol{r})$$
$$= 0, \pm 1, \pm 2, \ldots$$

Topological charge density

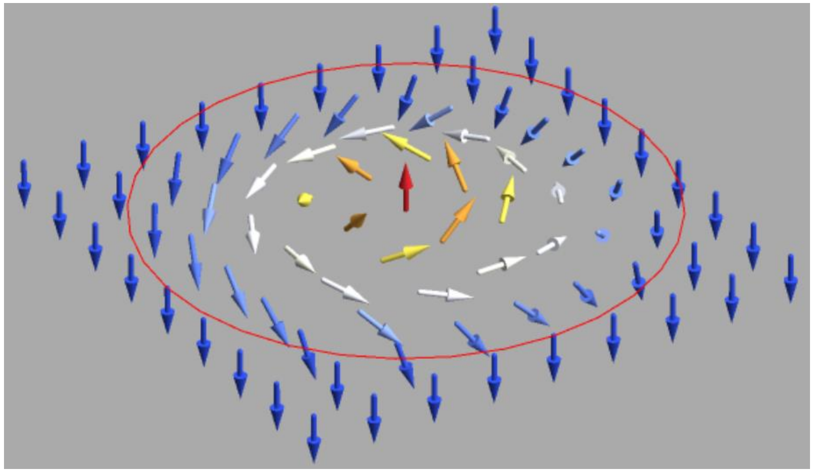
$$\chi(\boldsymbol{r}) = \frac{1}{4\pi}\, \hat{\boldsymbol{m}}.\left(\partial_x \hat{\boldsymbol{m}} \times \partial_y \hat{\boldsymbol{m}}\right)$$

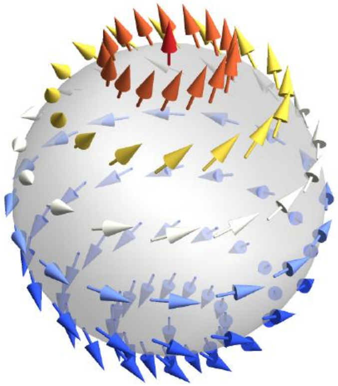
Different types of skyrmions





Hedgehog or Ne'el skyrmion





Vortex or Bloch skyrmion

Outline

- Skyrmions and chiral magnetism.
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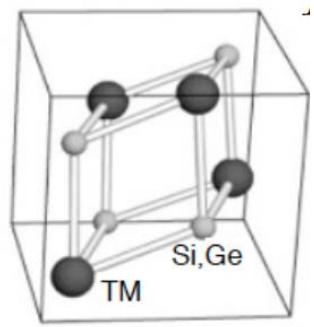
- How to stabilize skyrmion phases?
  - System with broken mirror symmetry ($z \not\to -z$)
  - → Much richer skyrmion phase diagram
- Conclusions and outlook.

Skyrmions in 3D chiral magnets

- Non-centrosymmetric crystals

  Cubic crystals without bulk inversion symmetry



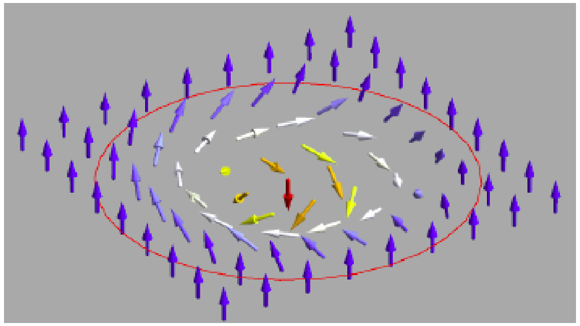
B20: no inversion center

Metals: MnSi, $Fe_{1-x}Co_xSi$, FeGe, …
Insulators: Cu_2OSeO_3

$(x, y, z) \not\rightarrow (-x, -y, -z)$

DM interaction

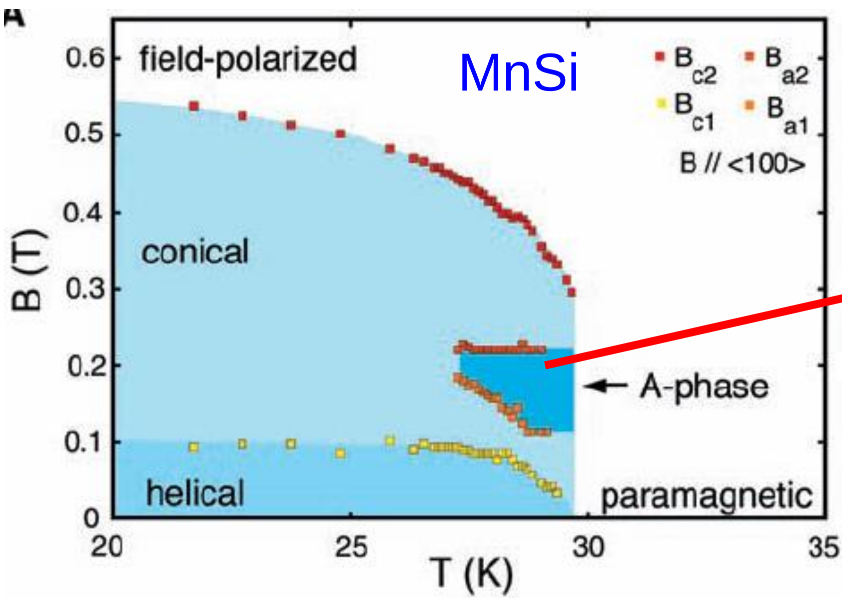
$D\boldsymbol{m}.(\nabla \times \boldsymbol{m})$



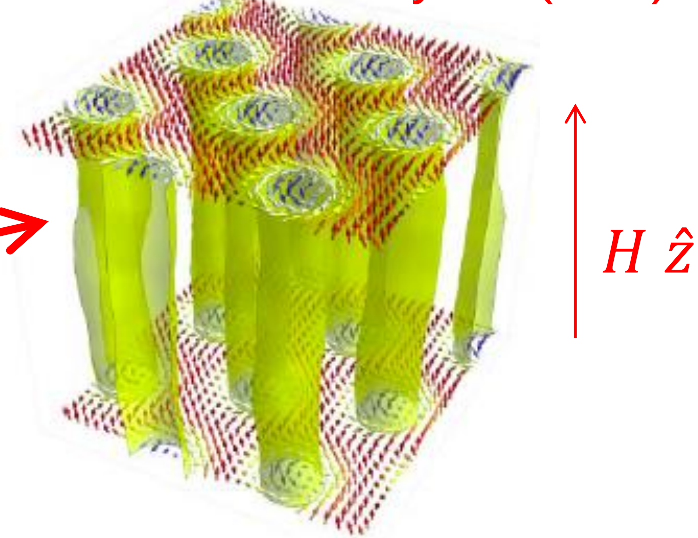
Vortex or Bloch skyrmion

Experiments: C. Pfleiderer, Y. Tokura, ..
Theory: A. Bogdanov, N. Nagaosa, A. Rosch, A. Vishwanath, C. Batista …

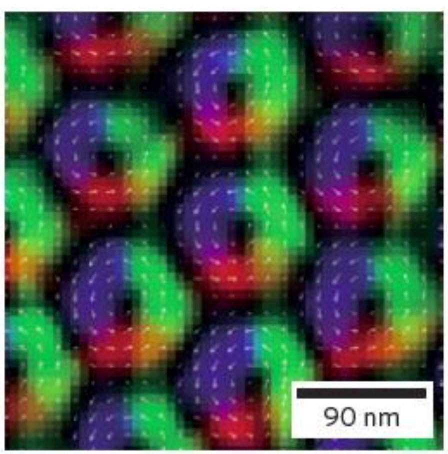
Observation of skyrmions



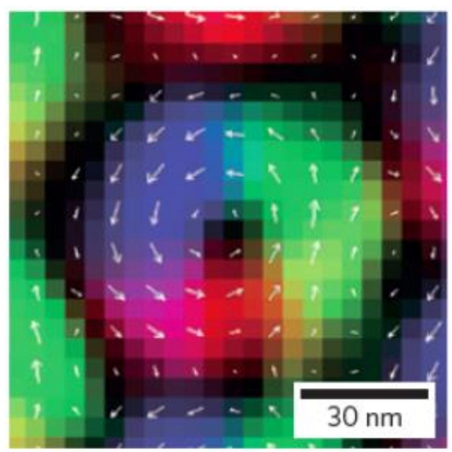
Skyrmion crystal (SkX)



Real-space observation of skyrmion



FeCoSi

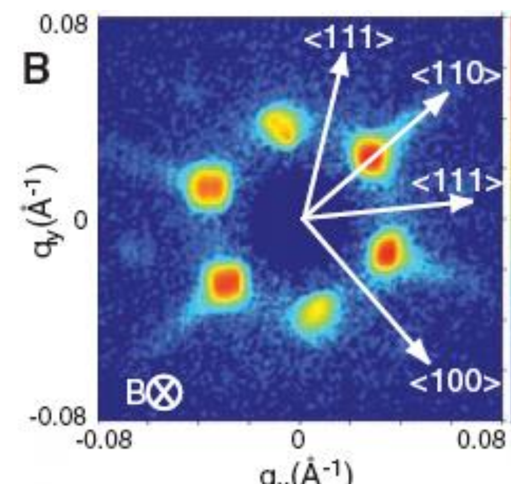


Lorentz TEM

Tokura group

Yu et al., Nature (2010)

Neutron Scattering



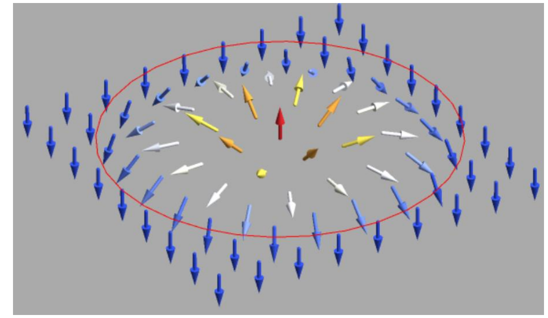
S. Mühlbauer, et al. Science (2009).

Chiral magnetic materials with broken surface inversion/mirror

$z \not\to -z$

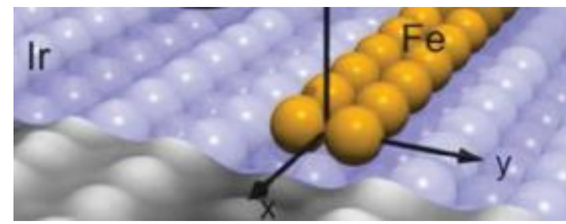
DM interaction

$D\boldsymbol{m}.((\hat{\mathbf{z}} \times \boldsymbol{\nabla}) \times \boldsymbol{m})$



Hedgehog or Ne'el skyrmion

- Magnetic monolayer on metals with large spin-orbit coupling.



Bode et al, Nature (2007);Romming et al., Science (2013))

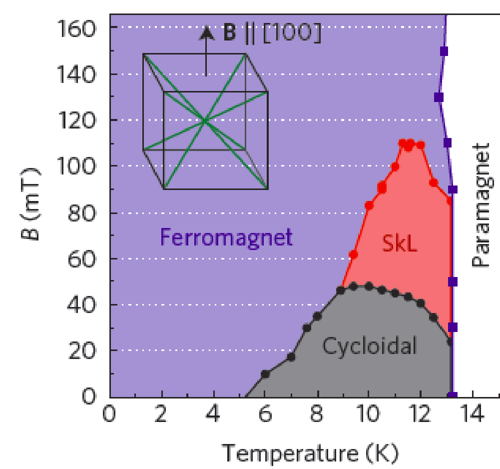
- Multilayers with interfacial DM interactions, room temperature skyrmion.

  Moreau-Luchaire et al., Nature Nano (2016)

- New 3D skyrmion material with broken mirror

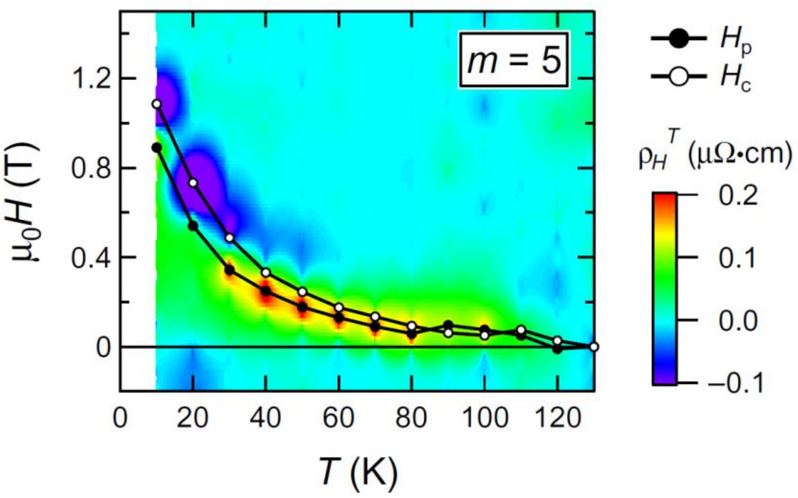
  Polar magnetic semiconductor GaV_4S_8

  Kézsmárki et al, Nature Mat. (2015)



- Oxide interfaces → broken surface inversion and large Rashba SOC

$SrRuO_3/SrIrO_3$ Matsuno et al., Sci. Adv. (2016)



← Topological Hall effect

Potential candidates – Oxide Interfaces with magnetism

$LaAlO_3/SrTiO_3$ (?) – SB, Erten & Randeria, Nature Phys. (2013)
SB, Rowland, Erten & Randeria, PRX (2014)
Li, Liu & Balents., PRL (2014)

$GdTiO_3/SrTiO_3$ – Robust magnetism and large Rashba SOC
Expt: Moetakef et al., PRX (2012).
DFT: H. Banerjee, SB, M. Randeria & T. Saha-Dasgupta, Sci. Rep. (2015)

And may be many more ……..

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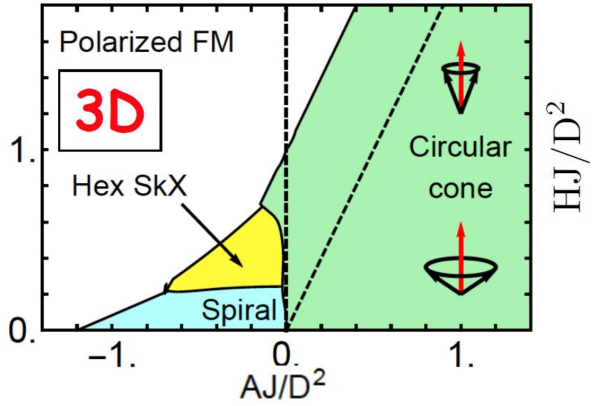
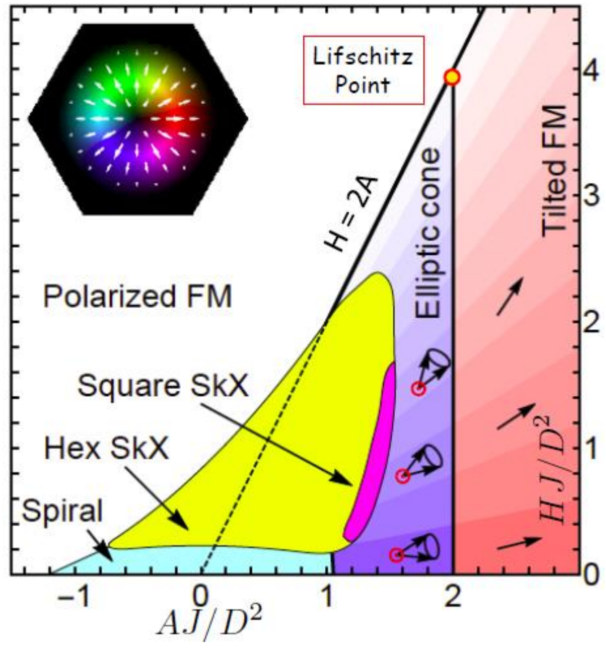
- How to stabilize skyrmion phases?
  System with broken mirror symmetry ($z \nrightarrow -z$)
  → Much richer skyrmion phase diagram
- Conclusions and outlook.



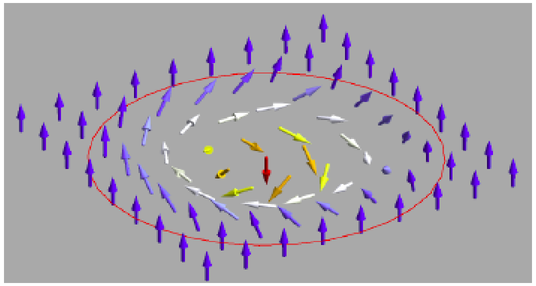


Form of DM interaction $\boldsymbol{D}_{ij} \cdot (\boldsymbol{S}_i \times \boldsymbol{S}_j)$

Symmetry → Direction of DM vector
SOC → Magnitude of DM

- Broken bulk inversion $\boldsymbol{r} \nrightarrow -\boldsymbol{r}$
  "Dresselhaus SOC"

  → $\widehat{\boldsymbol{D}}^{D}_{ij} = \widehat{\boldsymbol{r}}_{ij} \quad \rightarrow \quad D_D \boldsymbol{m} . (\nabla \times \boldsymbol{m})$



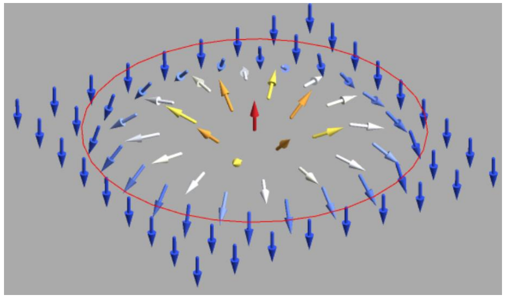
Bloch skyrmion

- Broken surface inversion/mirror

  $z \nrightarrow -z$

  Rashba SOC

  → $\widehat{\boldsymbol{D}}^{R}_{ij} = \widehat{\boldsymbol{z}} \times \widehat{\boldsymbol{r}}_{ij} \quad \rightarrow \quad D_R \boldsymbol{m} . ((\widehat{\boldsymbol{z}} \times \nabla) \times \boldsymbol{m})$



Ne'el skyrmion

Length scale, $L_D = (J/D)a \gg a$ → Continuum field theory

$T = 0$ constraint $\boldsymbol{m}^2(\boldsymbol{r}) = 1$

$$\mathcal{F}[m(r)] = \frac{J}{2}|\nabla m|^2$$ Isotropic FM exchange

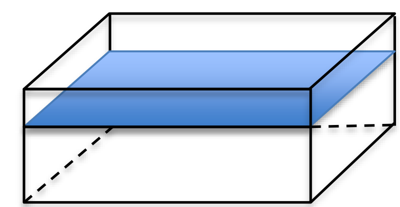
+ DM terms — Dzyaloshinskii-Moriya

$$+ A\, m_z^2$$ Anisotropy

$$-H\, m_z$$ Magnetic field

A>0 Easy plane
A<0 Easy axis

Anisotropy axis,
Mirror plane ⊥ $H\ \hat{z}$



Origin of anisotropy:

$$A = A_s + A_c$$

A_s , single-ion + dipolar

Rashba SOC → $A_c \simeq D^2/2J$, Kitaev-compass anisotropy, always energetically comparable to DM

SB, Rowland, Erten & Randeria, PRX (2014)

→T=0 Phase diagram as a function of

- Field HJ/D^2
- Anisotropy AJ/D^2

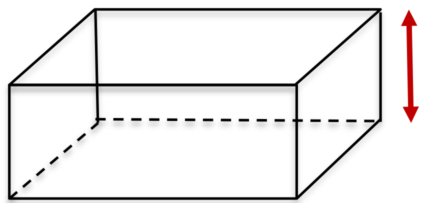
Minimize $\mathcal{F}$ with the constraint $\boldsymbol{m}^2(\boldsymbol{r}) = 1$

→ Optimal $\boldsymbol{m}(\boldsymbol{r})$

- Variational calculations (analytical)
- Conjugate gradient minimization (numerical)

3D systems -- Bulk or film with thickness $\gg (J/D)a$

→ Periodic boundary condition in x, y, z



2D systems -- thickness $\ll (J/D)a$

3D systems with broken mirror symmetry

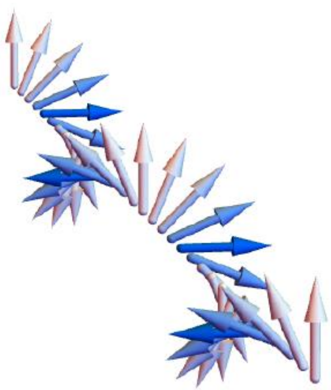
→ no z variation

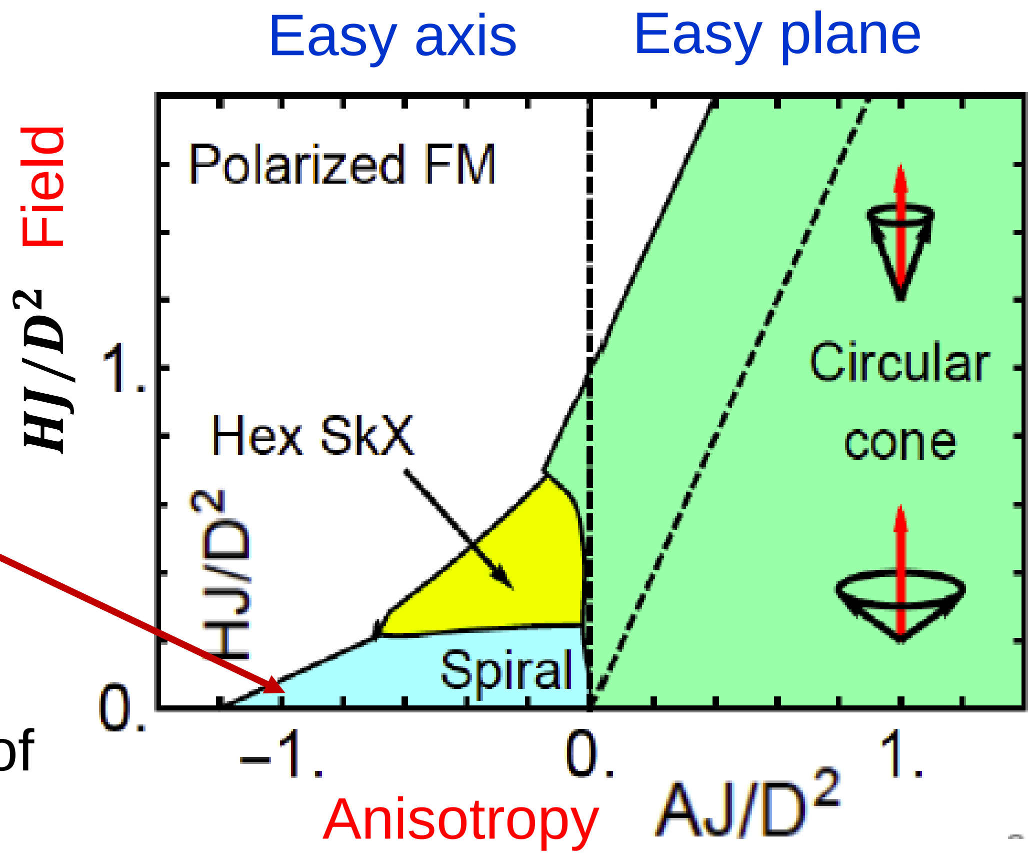
Broken bulk inversion and/or broken surface inversion/mirror

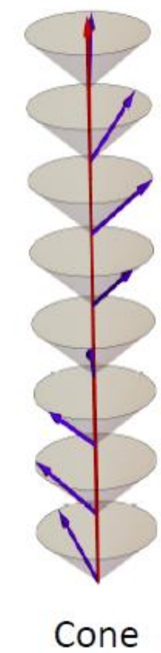
3D with broken bulk inversion

$T = 0$

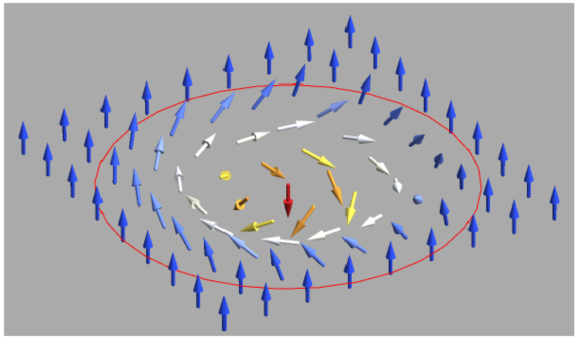
Helical or
Bloch spiral







Hexagonal crystal of
Bloch skyrmion



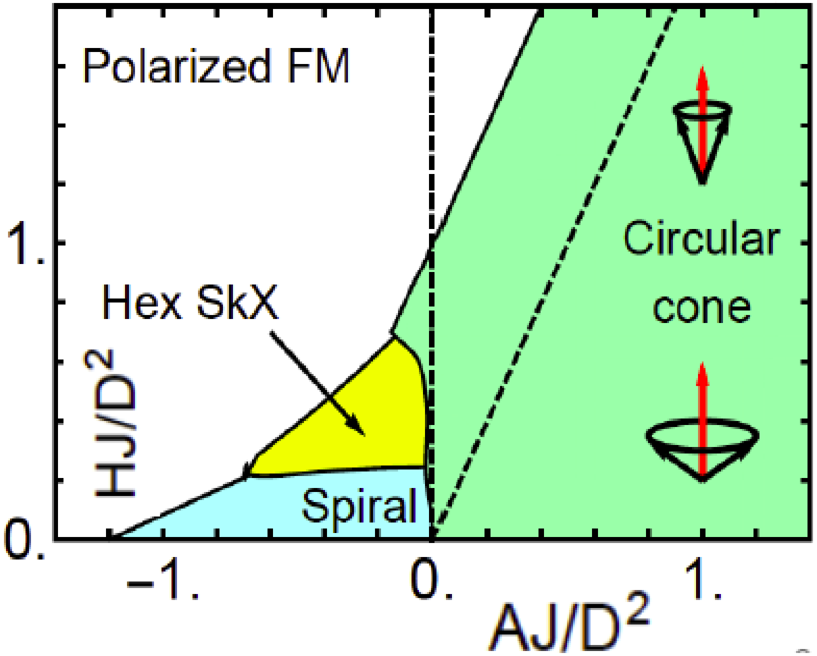
Conventional chiral magnet e.g. MnSi

Wilson et al., PRB (2014)

Conventional chiral magnets

Broken bulk inversion

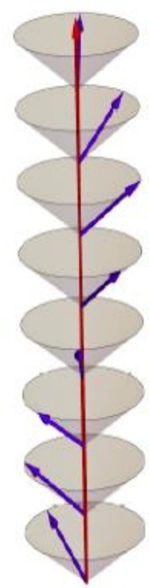
$(x, y, z) \to (-x, -y, -z)$



DM

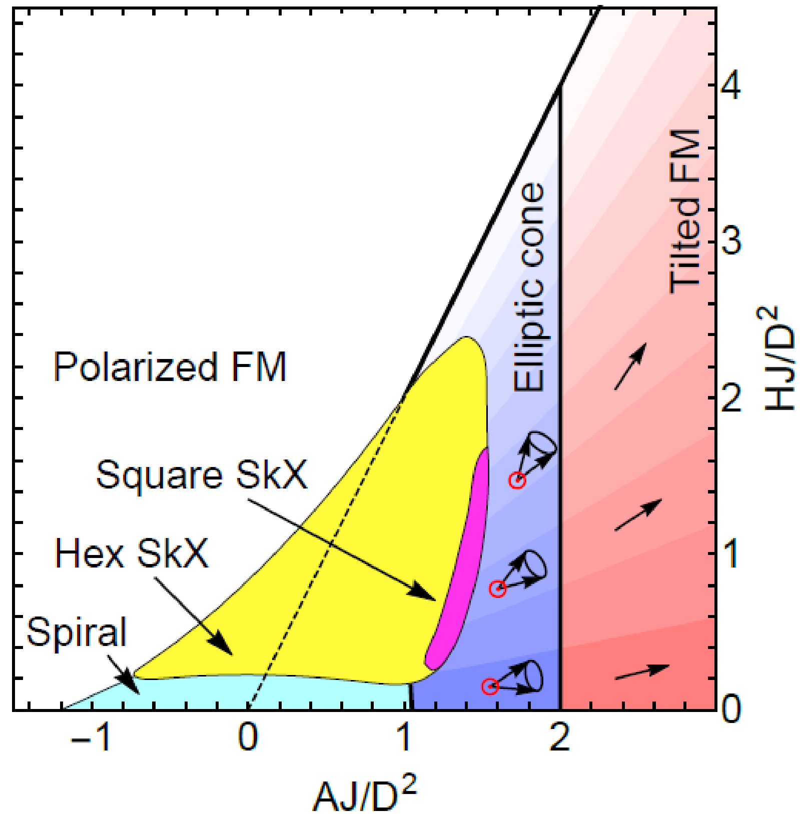
$D\boldsymbol{m}.(\nabla \times \boldsymbol{m})$

- Cone phase dominates.
- Twist in 3 directions.



Chiral magnets with Rashba SOC

Broken $z \to -z$

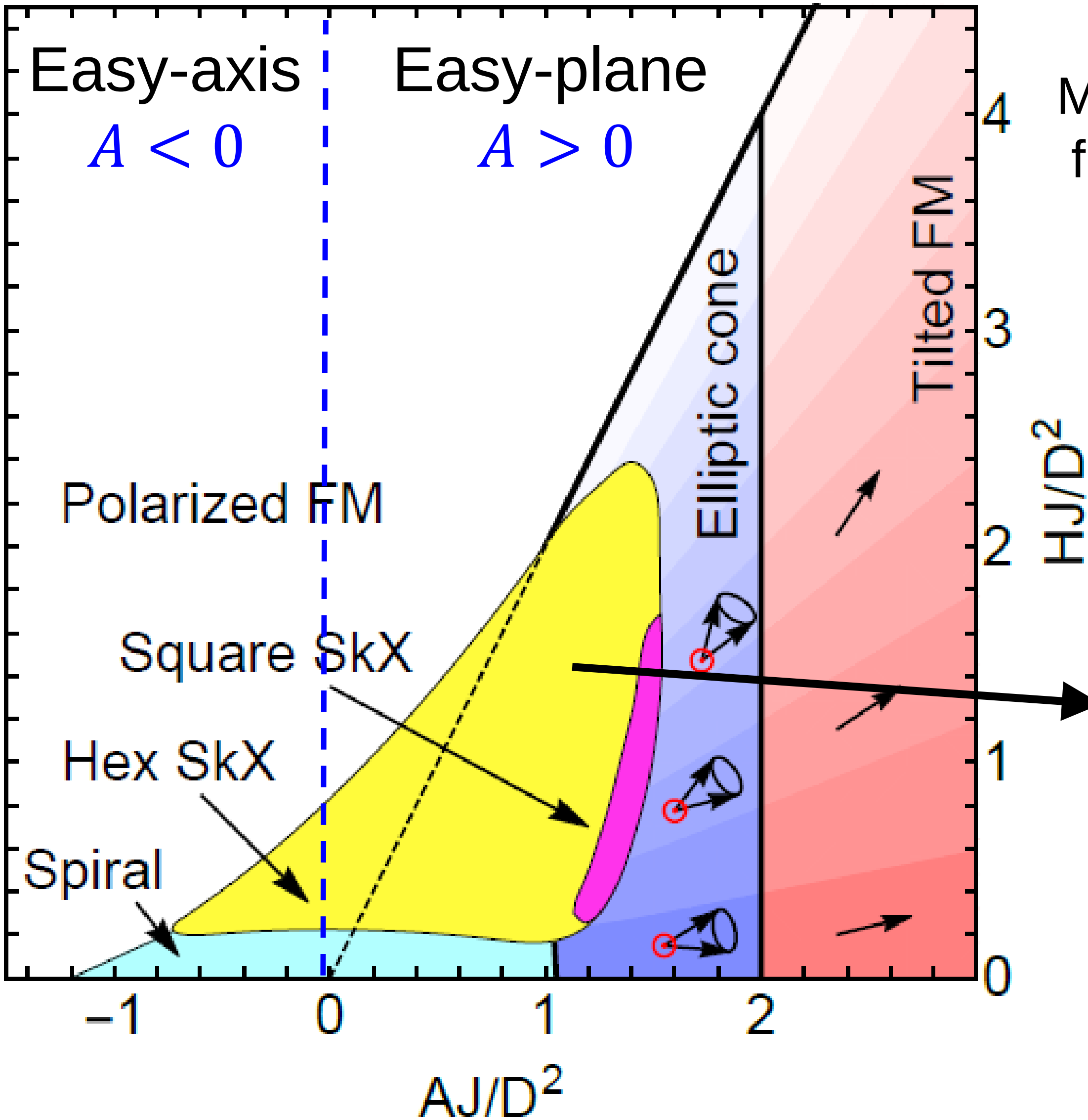


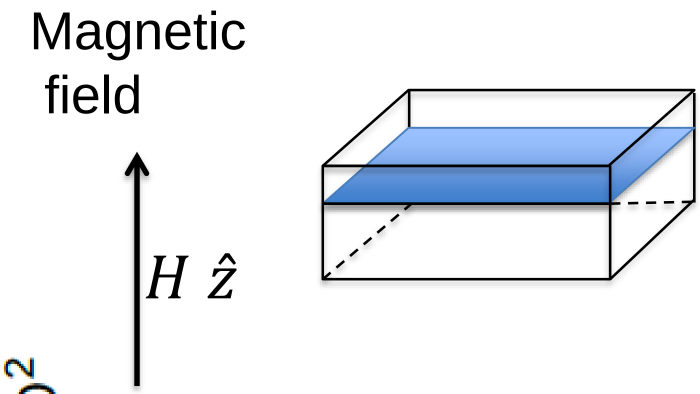
DM

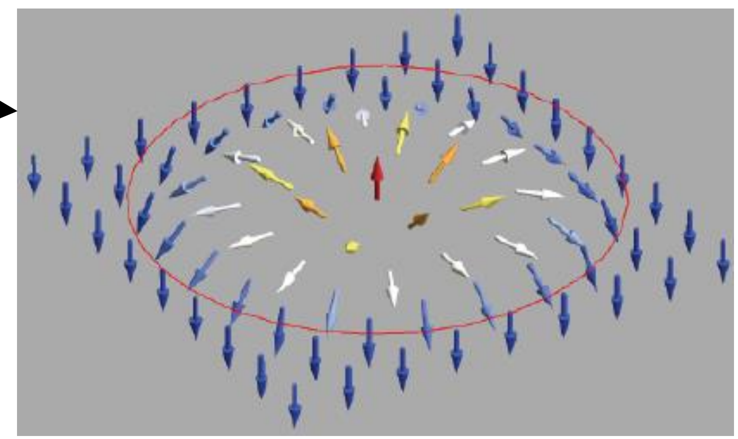
$D\boldsymbol{m}.((\hat{\boldsymbol{z}} \times \boldsymbol{\nabla}) \times \boldsymbol{m})$

- No cone phase even in 3D with broken mirror.

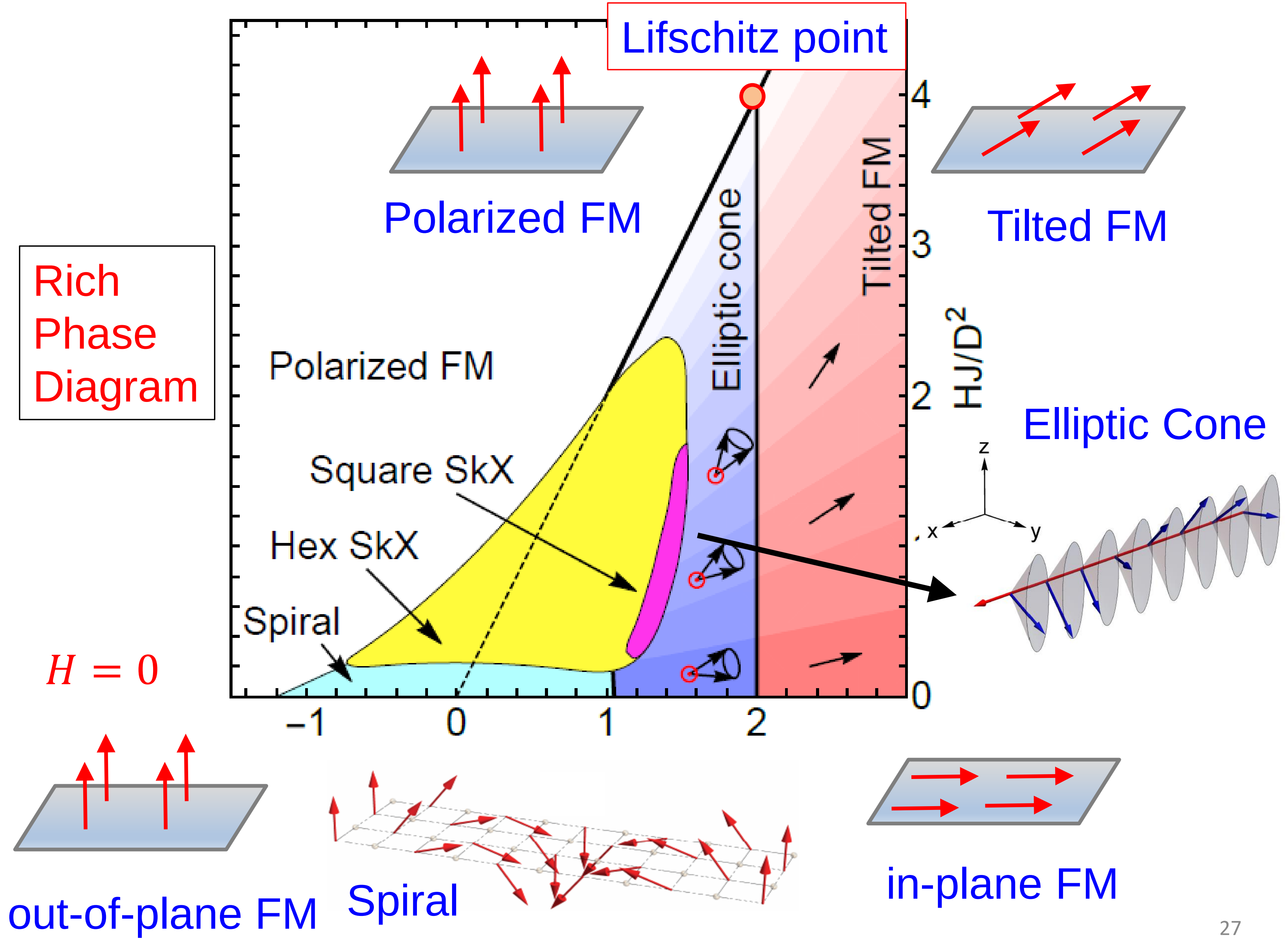
Phase Diagram







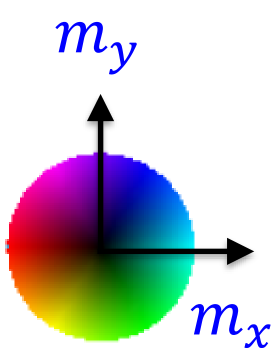
→ Very large region of stable skyrmion crystal (SkX) phase

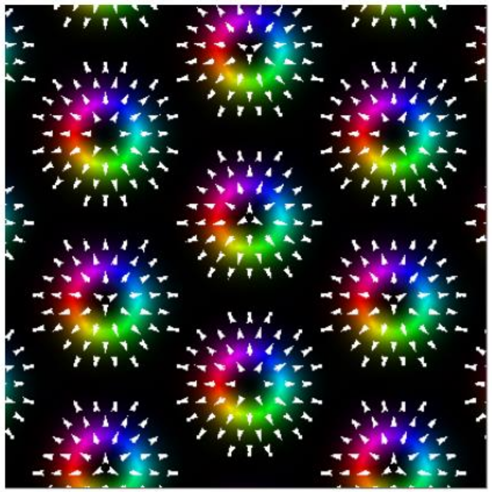


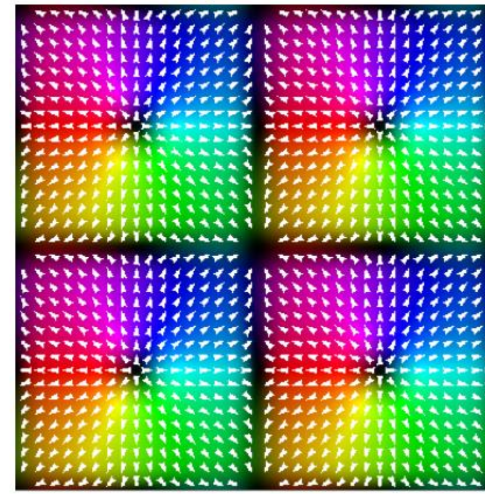
Lifschitz point
Polarized FM
Tilted FM
Rich Phase Diagram
Polarized FM
Elliptic cone
Tilted FM
Square SkX
Hex SkX
Spiral
HJ/D²
Elliptic Cone
z
x
y
H = 0
−1
0
1
2
0
2
3
4
out-of-plane FM
Spiral
in-plane FM

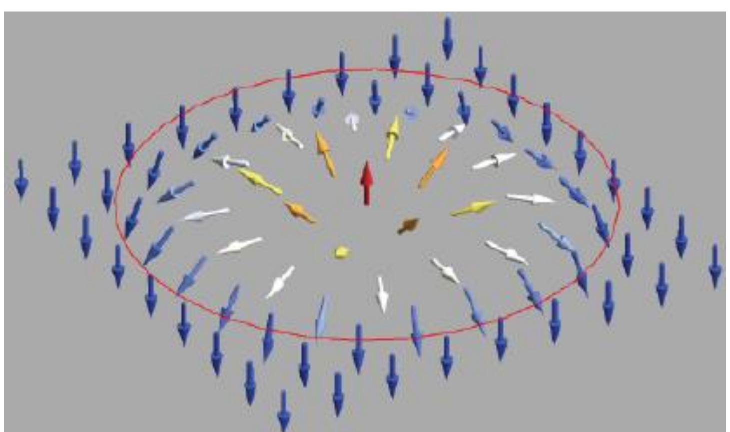
Skyrmion crystal phases

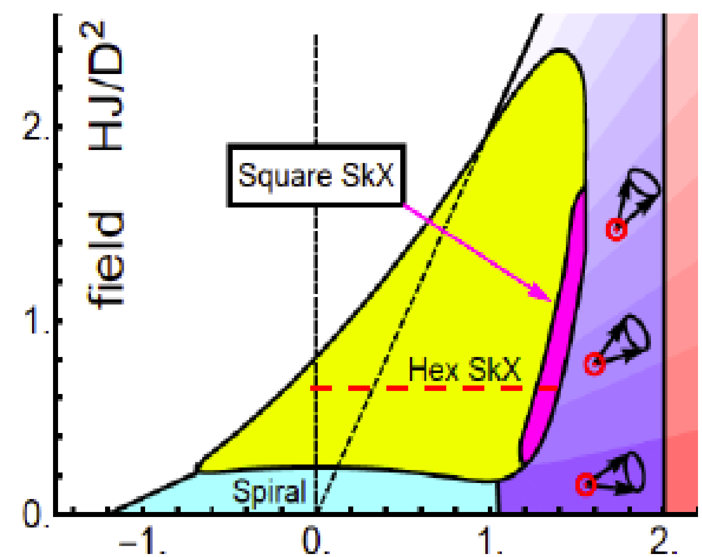
Hexagonal SkX → Square SkX transition tuned by anisotropy







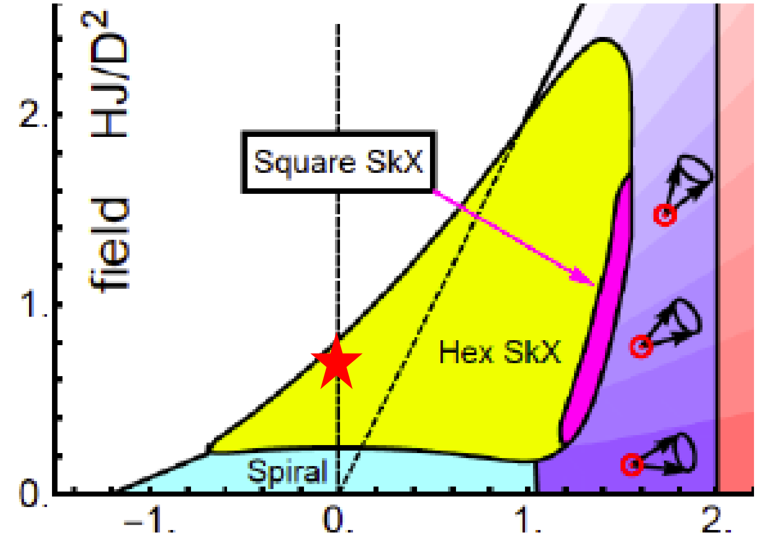


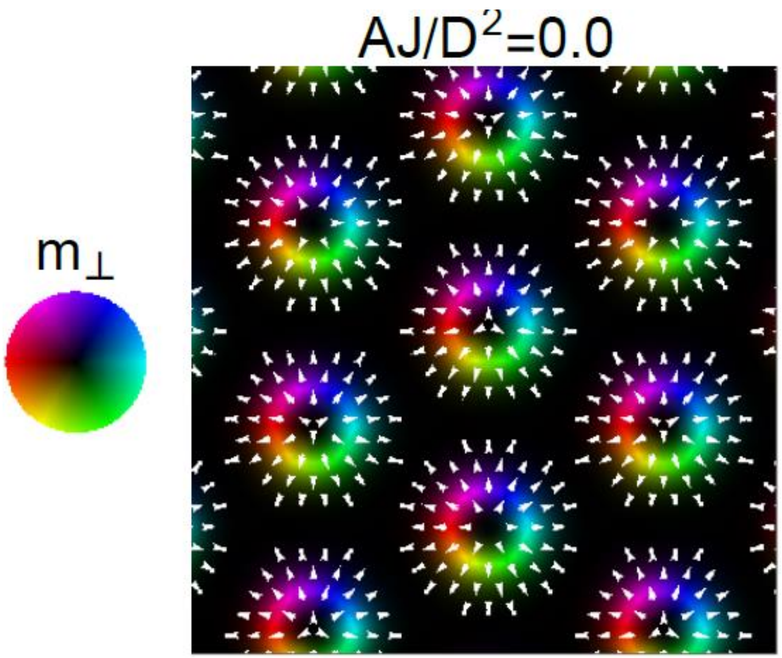


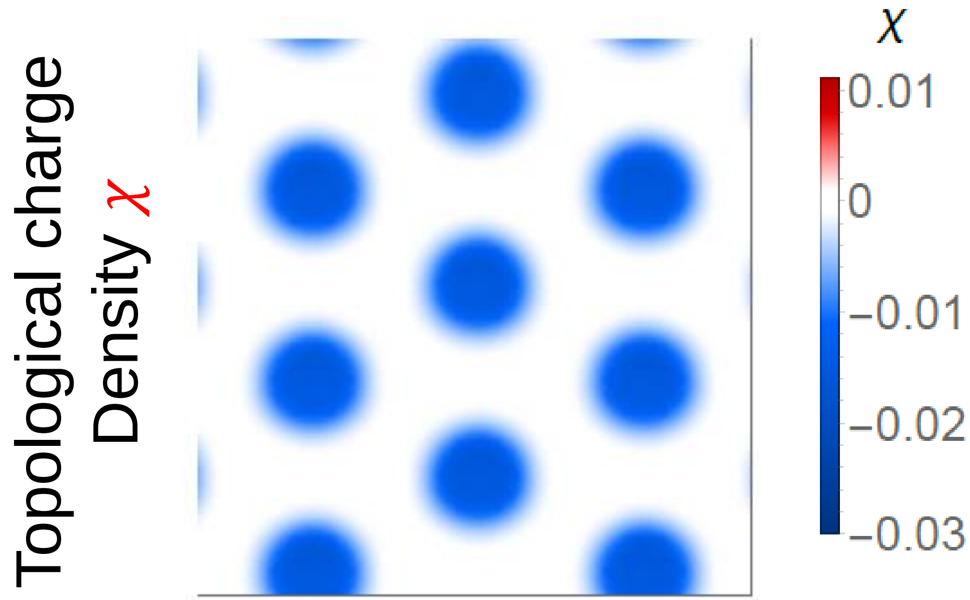
“Conventional” Hexagonal Skyrmion crystal

Topological charge density

$$\chi(\boldsymbol{r}) = \frac{1}{4\pi}\,\widehat{\boldsymbol{m}}.\left(\partial_x\widehat{\boldsymbol{m}} \times \partial_y\widehat{\boldsymbol{m}}\right)$$

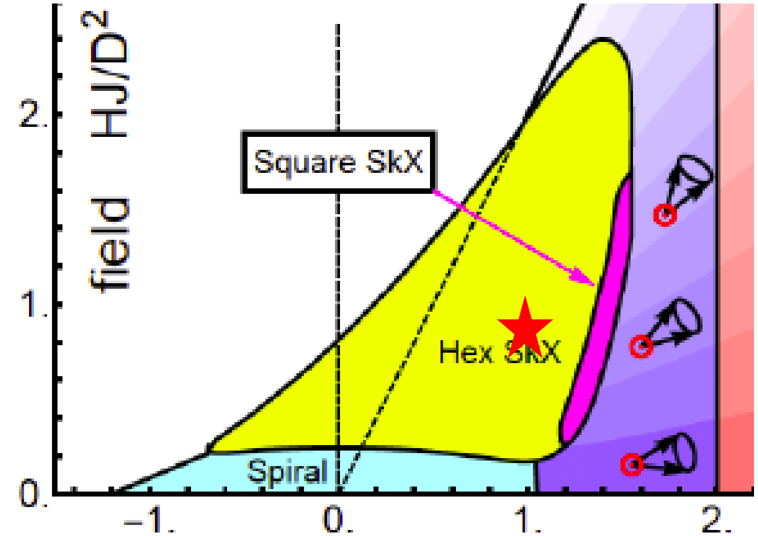






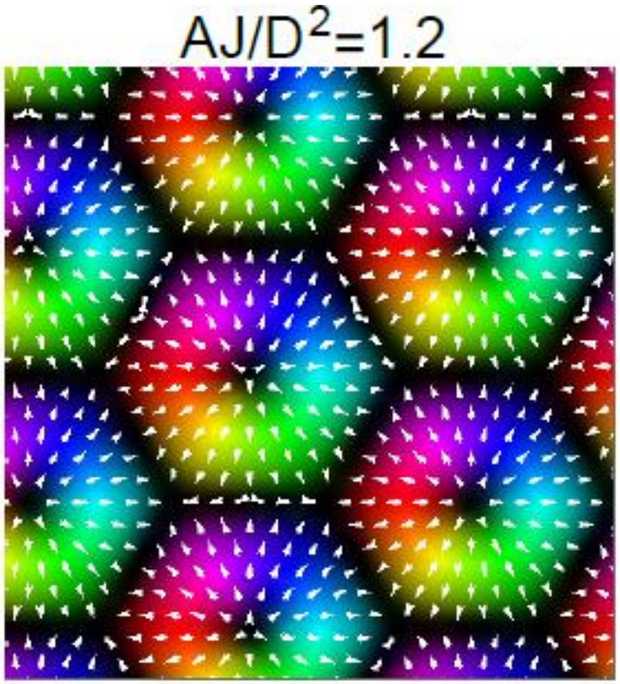
Topological charge, $N_{sk} = \int_{u.c.} d^2r\,\chi(r) = -1$

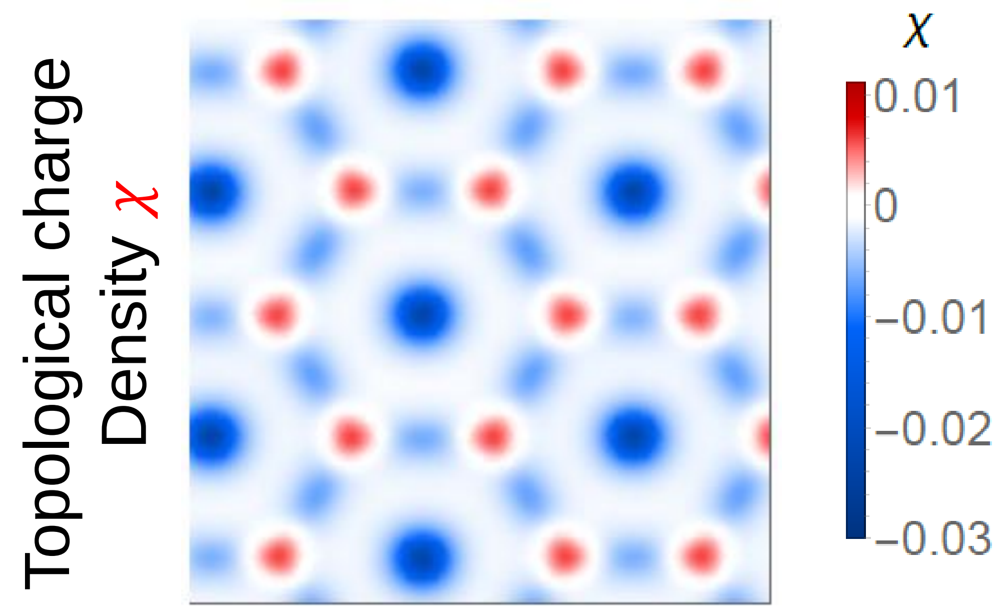
"Vortex-antivortex" Skyrmion crystal



Topological charge density

$$\chi(\boldsymbol{r}) = \frac{1}{4\pi}\,\hat{\boldsymbol{m}}.\left(\partial_x\hat{\boldsymbol{m}} \times \partial_y\hat{\boldsymbol{m}}\right)$$



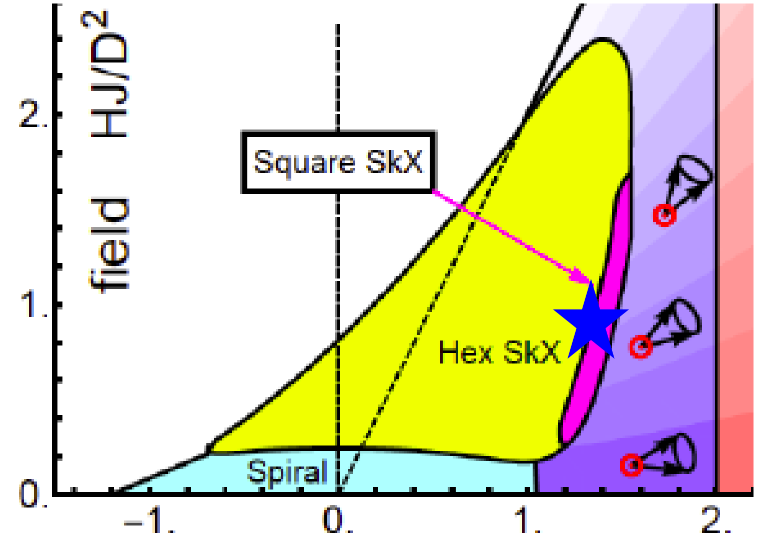


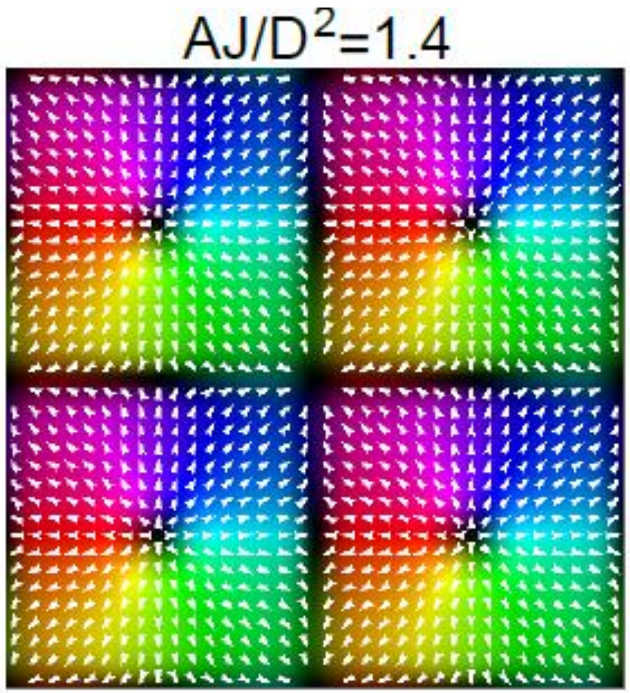
Topological charge, $N_{sk} = \int_{u.c.} d^2r\, \chi(r) = -1$

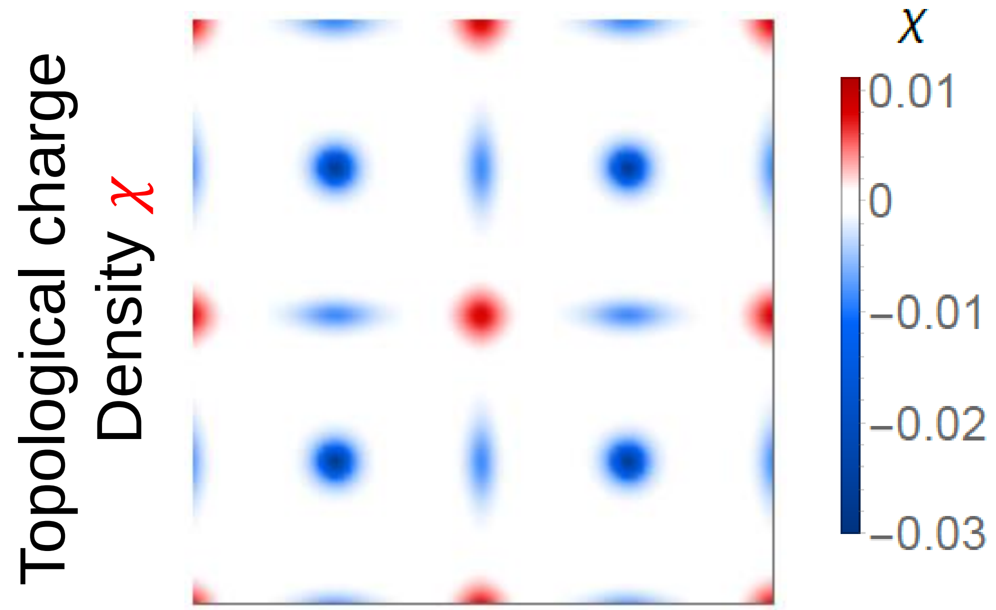
Square Skyrmion crystal

Topological charge density

$$\chi(\boldsymbol{r}) = \frac{1}{4\pi}\,\widehat{\boldsymbol{m}}.\left(\partial_x\widehat{\boldsymbol{m}} \times \partial_y\widehat{\boldsymbol{m}}\right)$$



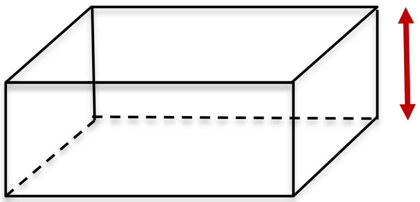




Topological charge, $N_{sk} = \int_{u.c.} d^2r\,\chi(r) = -1$

Systems with both Dresselhaus and Rashba DM terms

$$D_D = D\cos\beta$$
$$D_R = D\sin\beta$$



3D systems: Bulk or film with thickness $\gg (J/D)a$

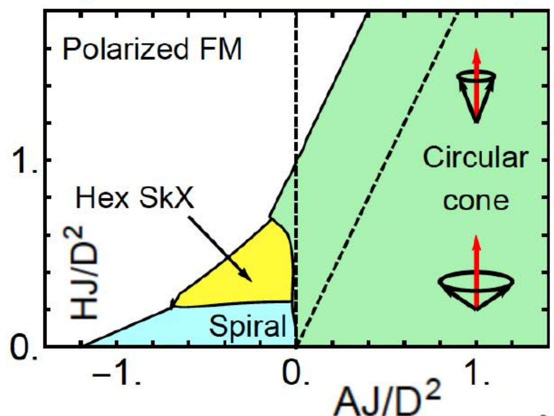
→ periodic boundary condition in x, y, z

e.g. Thick 3D chiral magnets under strain gradient

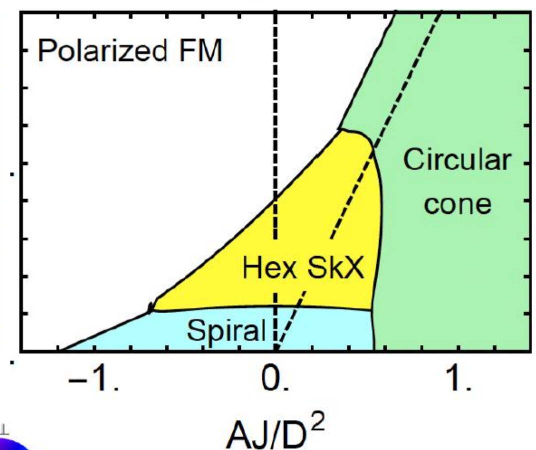
$\mathcal{F}[\boldsymbol{m}(\boldsymbol{r})] = \frac{J}{2}\lvert\boldsymbol{\nabla}\boldsymbol{m}\rvert^2$	Isotropic FM exchange
$+ D\cos\beta\, \boldsymbol{m}.(\nabla \times \boldsymbol{m})$	DM -- Dresselhaus
$+ D\sin\beta\, \boldsymbol{m}.((\hat{\boldsymbol{z}} \times \nabla) \times \boldsymbol{m})$	DM -- Rashba
$+ A\, m_z^2$	Anisotropy
$-H\, m_z$	Magnetic field

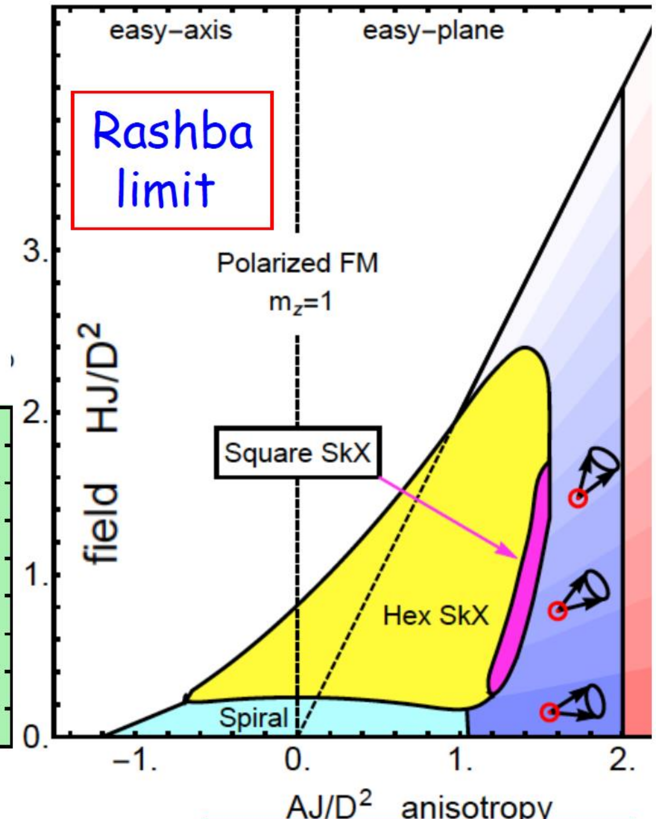
Evolution from Dresselhaus → Rashba

Dresselhaus limit



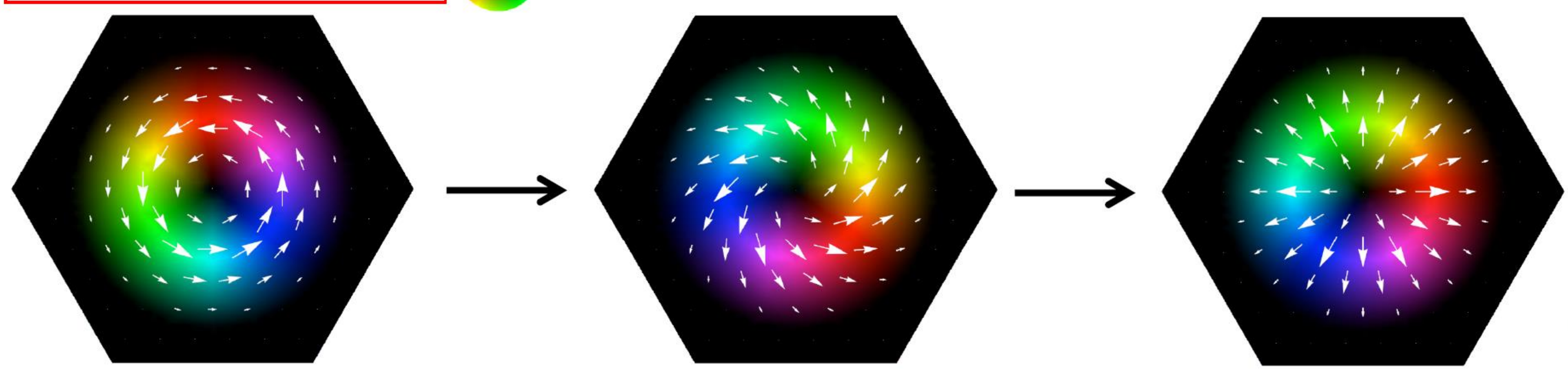
$D_R = D_D$





Vortex-like / Bloch

Hedgehog / Neel



Why care about skyrmions?

→ Metallic chiral magnets

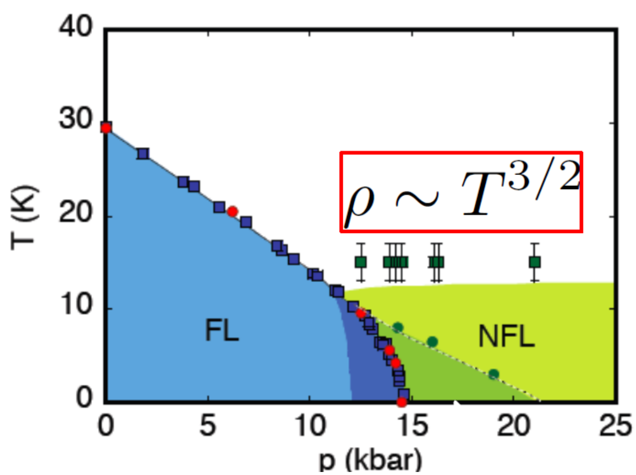
"Emergent electromagnetism"

- Topological Hall effect
- Spin-transfer torque

Manipulation of skyrmion motion by ultrasmall current.

- Low pinning compared to domain walls.

- Non-Fermi liquid phase under pressure



MnSi

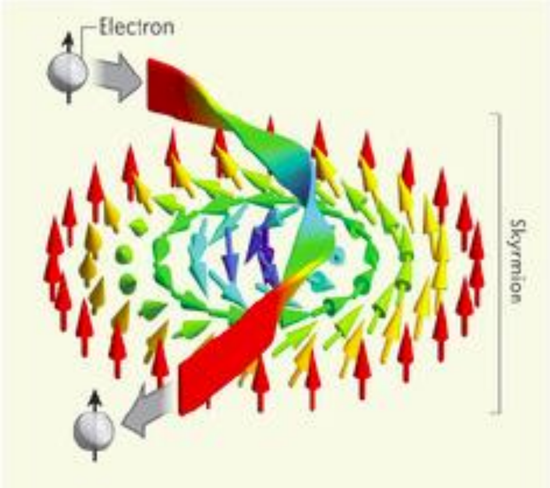
Ritz et al, Nature 497, 231 (2013)

- Real-space Berry phase

→ Emergent magnetic field

$$B_{eff}^{z} \propto \boldsymbol{m}.(\partial_x \boldsymbol{m} \times \partial_y \boldsymbol{m})$$

~100 T for 10 nm skyrmion



Review: Nagaosa &Tokura, Nature Nano (2013)

Conclusions

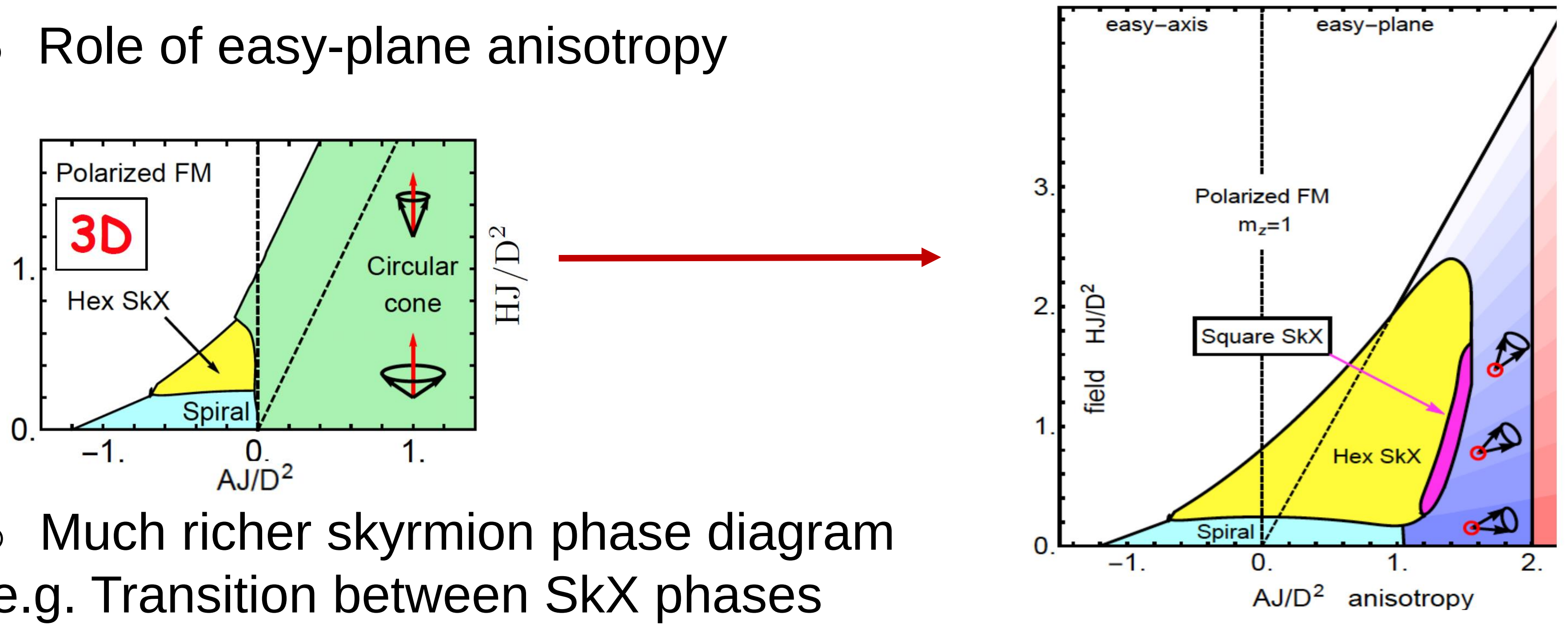
Enhanced stability of skyrmion phases →

3D → 2D

Broken bulk inversion→ broken surface inversion/mirror

“Dresselhaus” SOC → Rashba SOC

- Role of easy-plane anisotropy



- Much richer skyrmion phase diagram

e.g. Transition between SkX phases

Magnetic oxide interfaces

→ Broken surface inversion

→ Large Rashba SOC

Thank you!