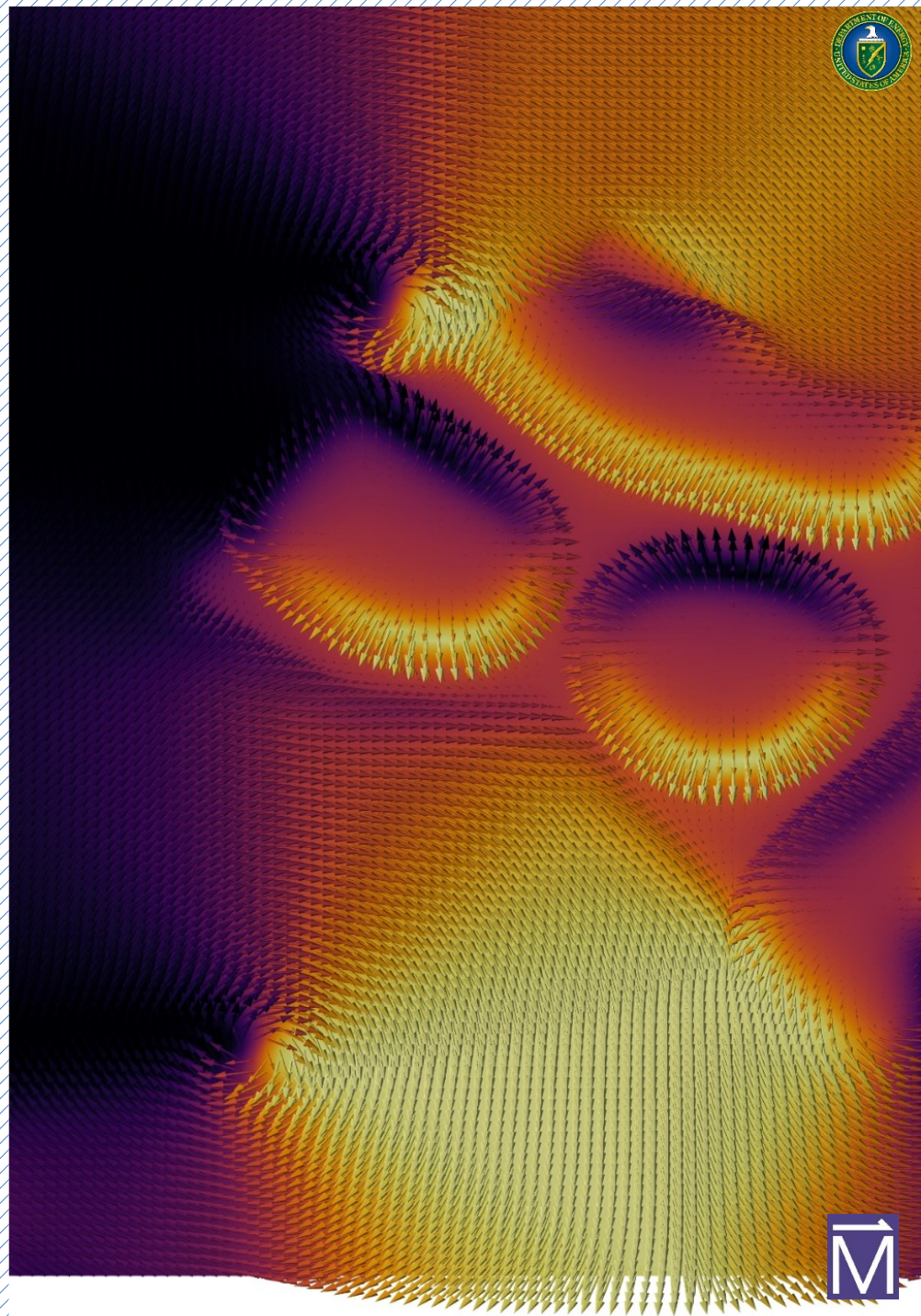
Novel type of topological transport in inversion symmetric ferromagnets

Luis Balicas

A Quantum Universe in a Crystal: Symmetry and Topology across the Correlation Spectrum (qcrystal23).
KITP – Santa Barbara
04/20/2023

J. Macy *et al.*, Appl. Phys. Rev. **8**, 041401 (2021)
B. W. Casas *et al.*, Adv. Mater. **35**, 2212087 (2023)



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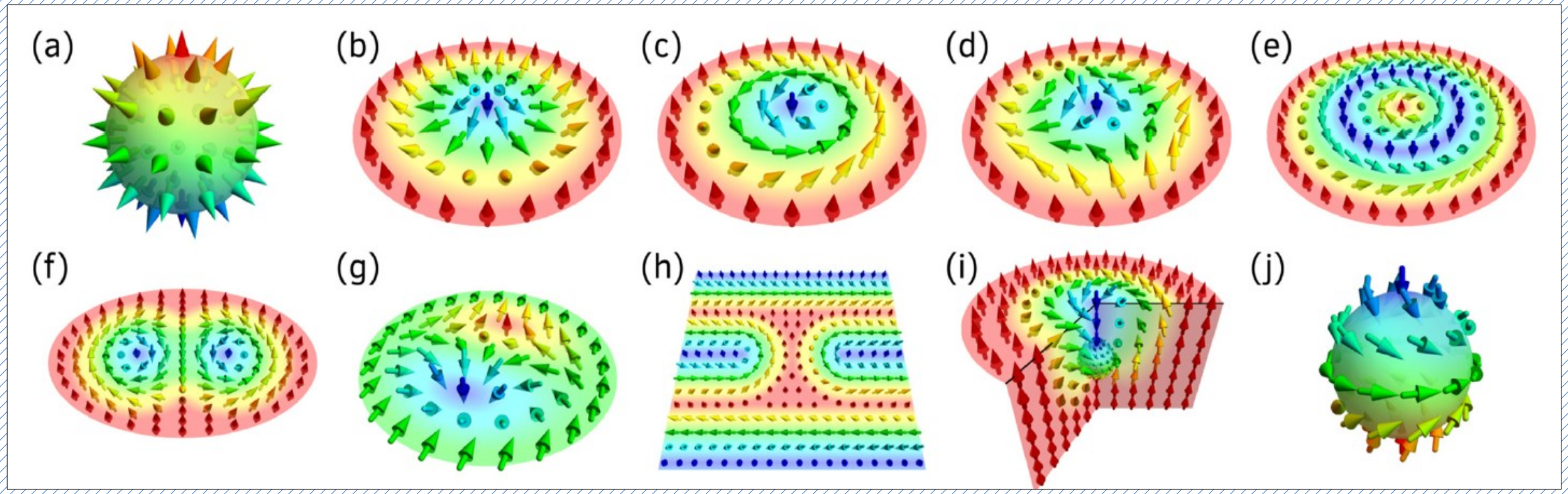
Outline:

1. Very Brief introduction to topological spin textures
2. The $Fe_{3-x}GeTe_2$ compound and its complex spin textures
3. Unconventional topological transport

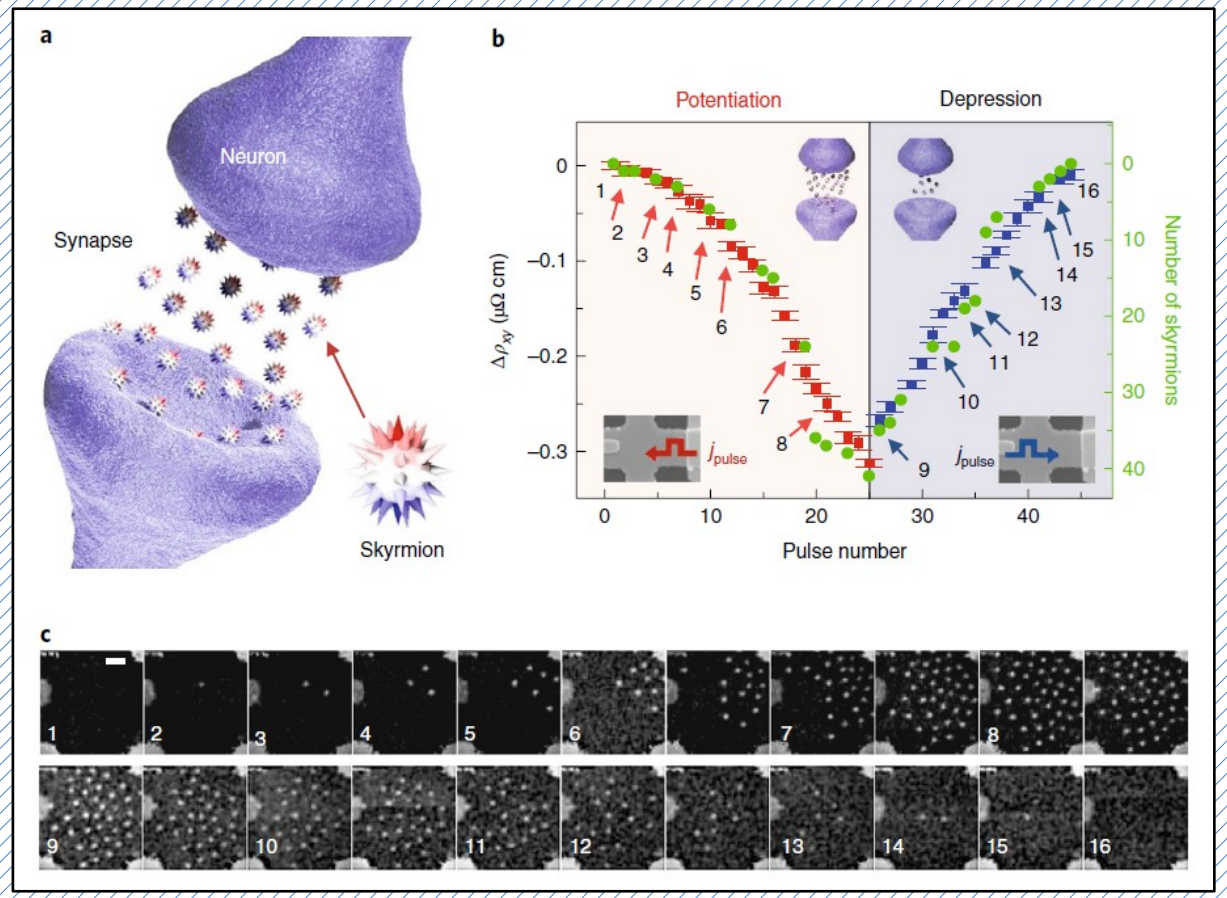
4. Very Brief introduction to $Fe_{5-x}GeTe_2$
5. Conventional and unconventional topological Hall-effect
6. Lorentz microscopy: merons and skyrmions
7. Conclusions

Topological spin textures



Zoo of (topological) spin textures with different winding numbers.
(a) Hedgehog, (b) Néel-type skyrmion, (c) Bloch-type skyrmion, (d) antiskyrmion, (e) skyrmionium, (f) biskyrmion, (g) example of an in-plane skyrmion, (h) skyrmion in helical background, (i) chiral bobber, (j) combed anti-hedgehog formed around the Bloch point in panel (i).
The winding number for (b)–(d), (g), and (h) is $|W| = 1$ and for (f) it is $|W| = 2$ and (e) is topologically trivial

Computing schemes based on skyrmionics



K. M. Song *et al.*, Nat. Electron. **3**, 148 (2020)

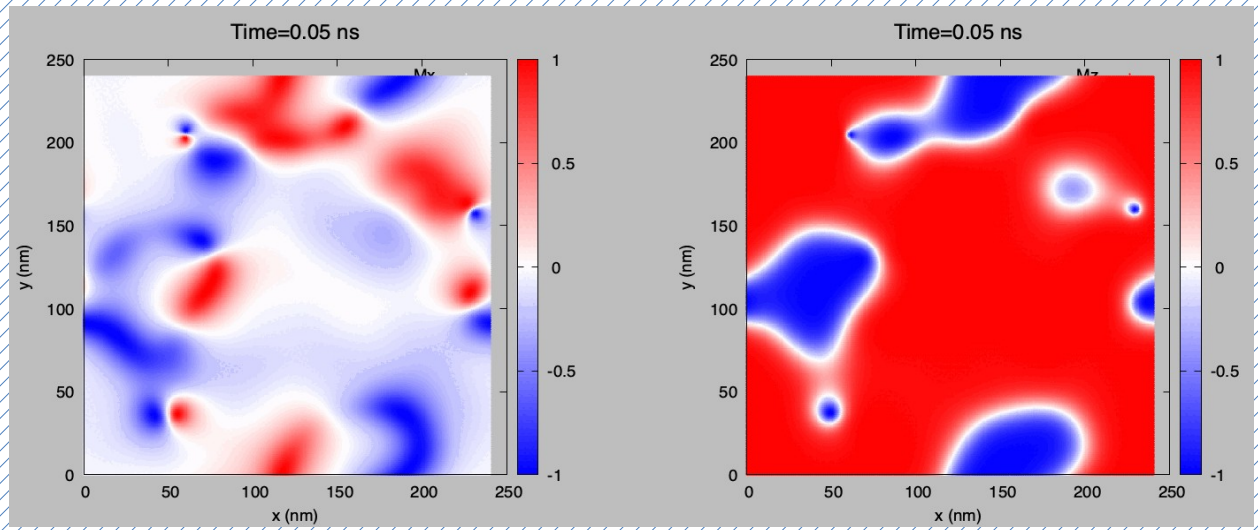
i) Magnetic memories for temporal computing,
Vakili, H. *et al.*, IEEE J. 6, 107 (2020)

ii) Reconfigurable skyrmionic logic,
Luo, S. *et al*. Nano Lett. 18, 1180 (2018)

iii) Skyrmion based decorrelators for stochastic computing,
Pinna, D. *et al.*, Phys. Rev. Appl. **9**, 064018 (2018).

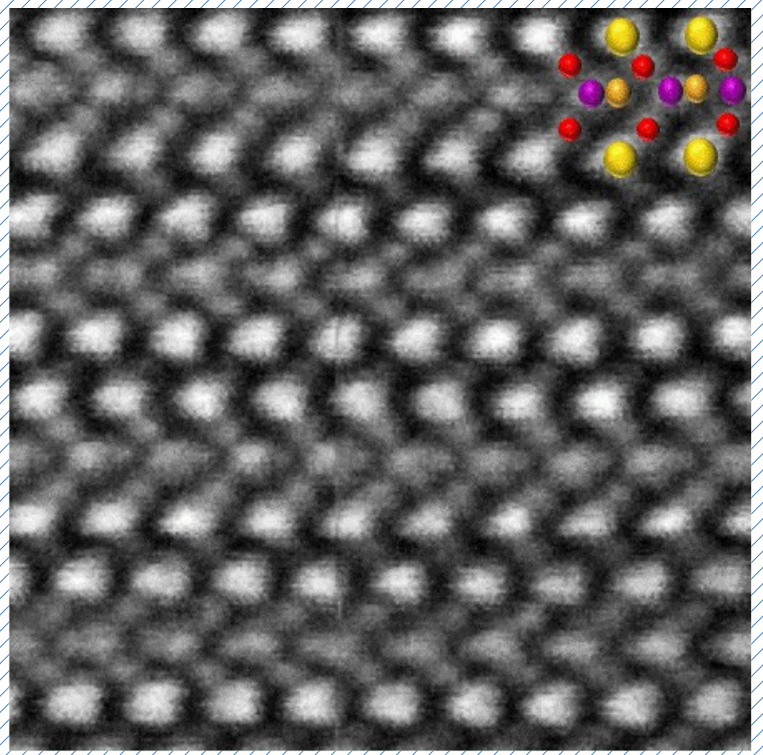
iv) High density reservoir computing using skyrmions
Bourianoff, G. *et al.*, AIP Adv. **8**, 055602 (2018).

v) Skyrmion based quantum computation
C. Psaroudaki *et al.*, PRL **127**, 067201 (2021)



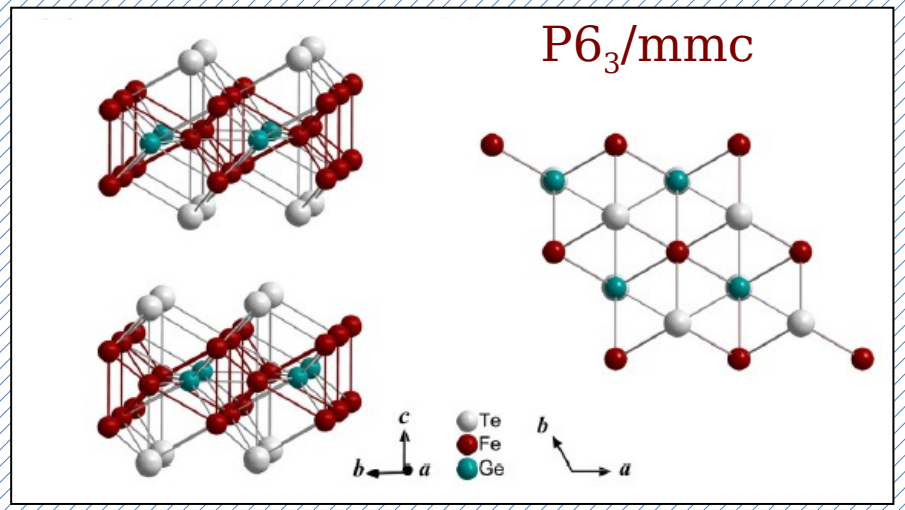
Courtesy of E. J. G. Santos

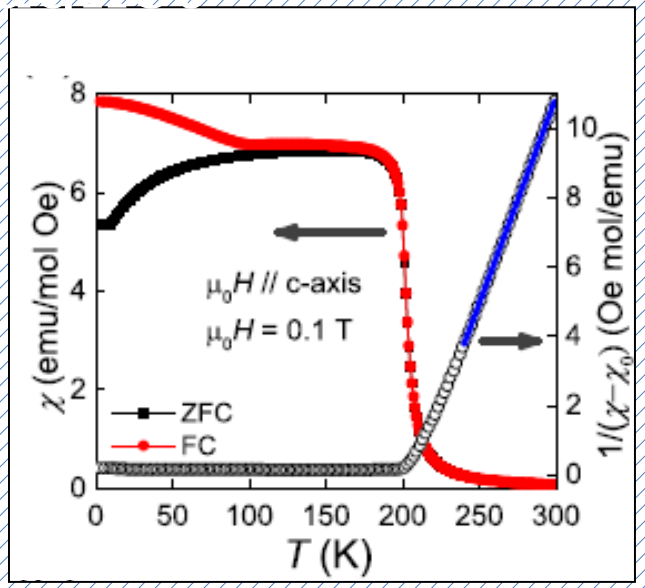
$Fe_{3-x}GeTe_2$



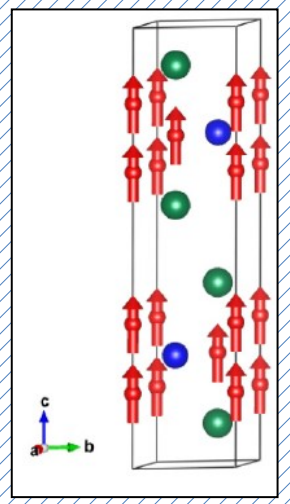
J. Macy *et al.*, Appl. Phys. Rev. **8**, 041401 (2021)

$Fe_{3-x}GeTe_2$: a layered ferromagnet

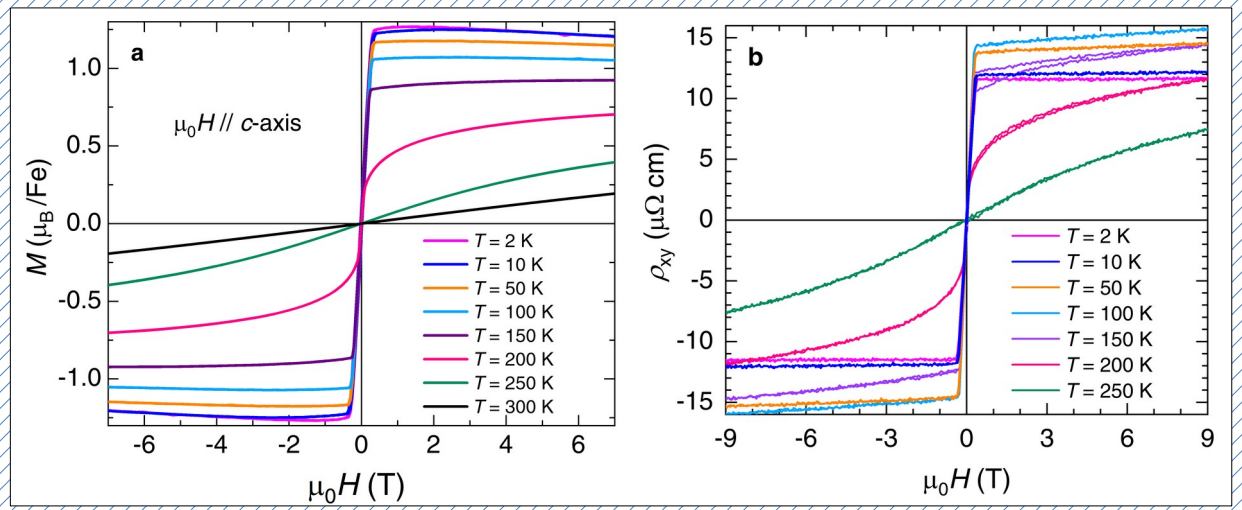




Y. Wang *et al.* PRB **96**, 134428 (2017)



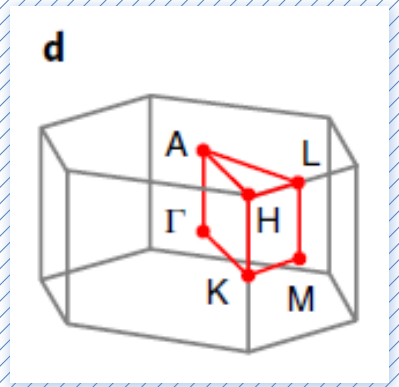
May *et al.*,
PRB **93**, 014411 (2016)

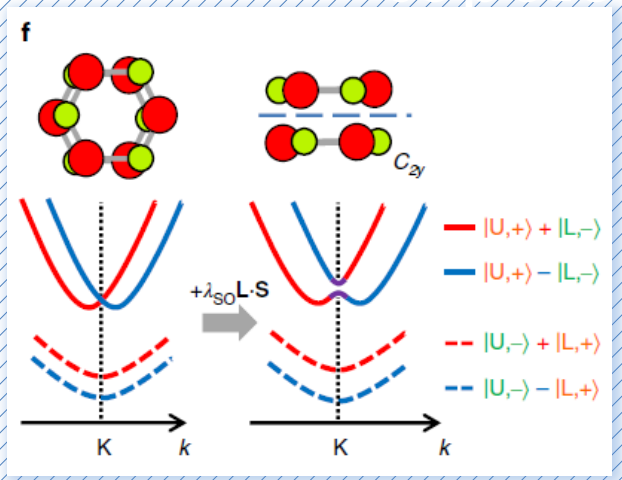


K. Kim *et al.*, Nat. Mater. **17**, 794 (2018)

$$\rho_{xy} = R_0\mu_0H + R_sM$$

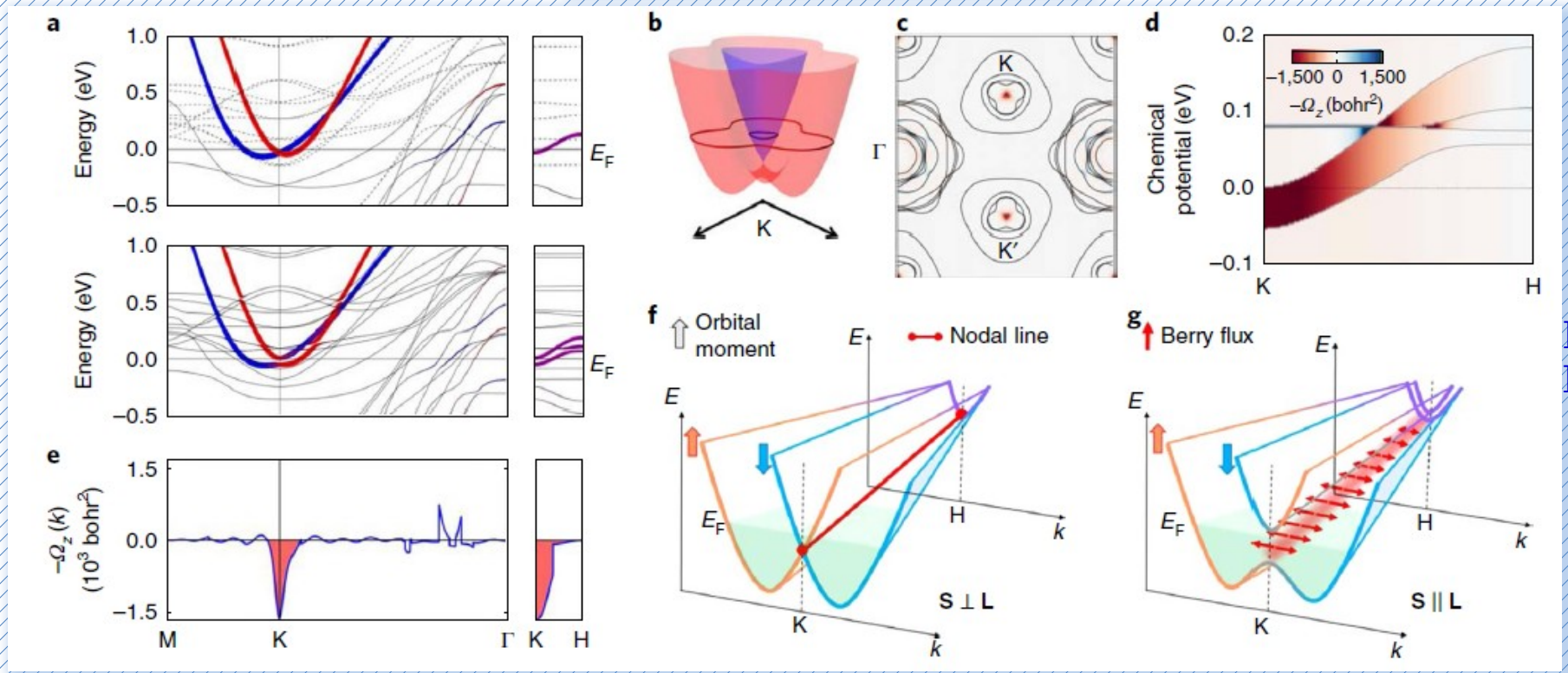
Anomalous Hall in Fe_3GeTe_2: Role for electronic topology?





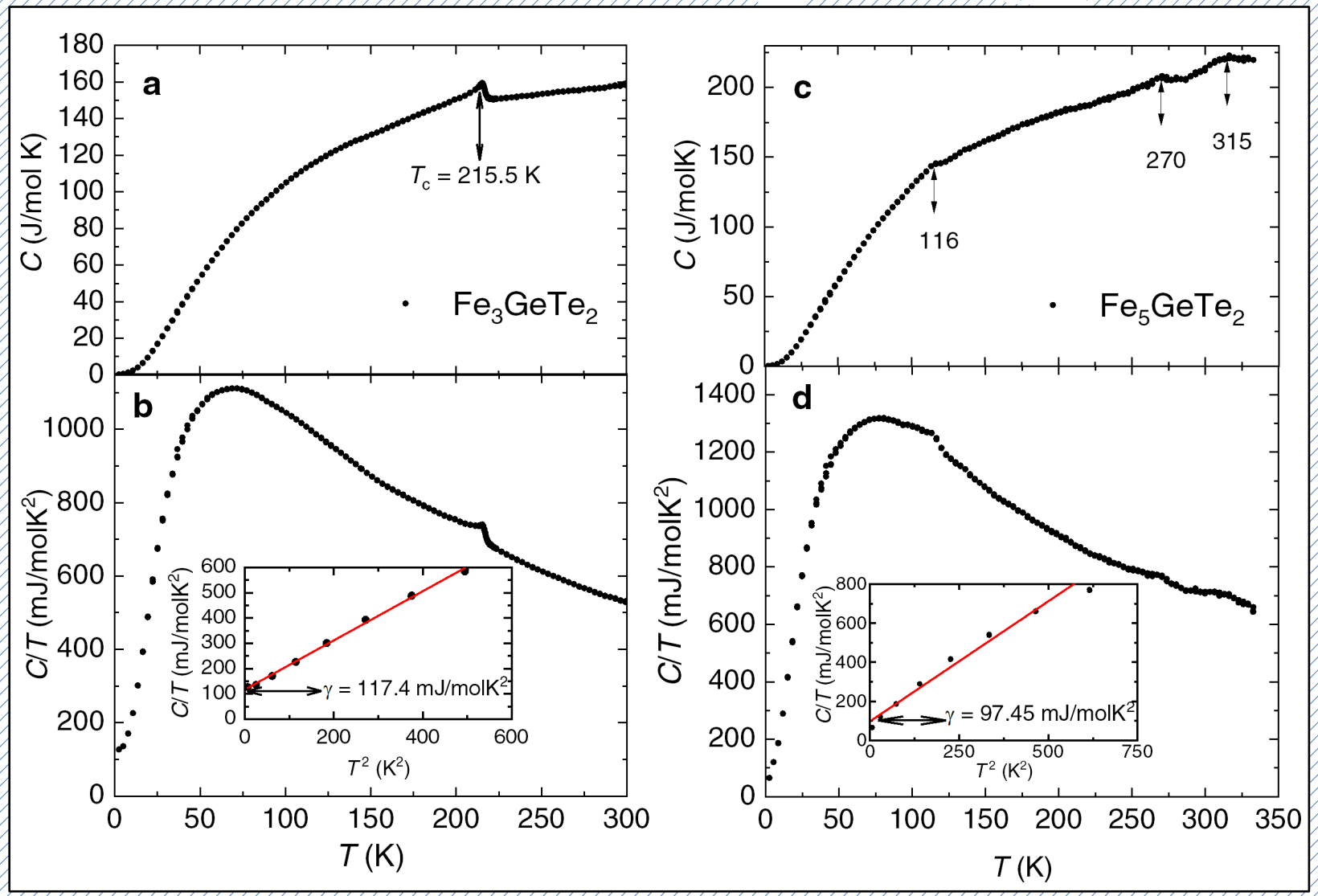
$$\boldsymbol{A}_n(\boldsymbol{R}) = i\langle n(\boldsymbol{R})|\nabla_{\boldsymbol{R}}|n(\boldsymbol{R})\rangle$$

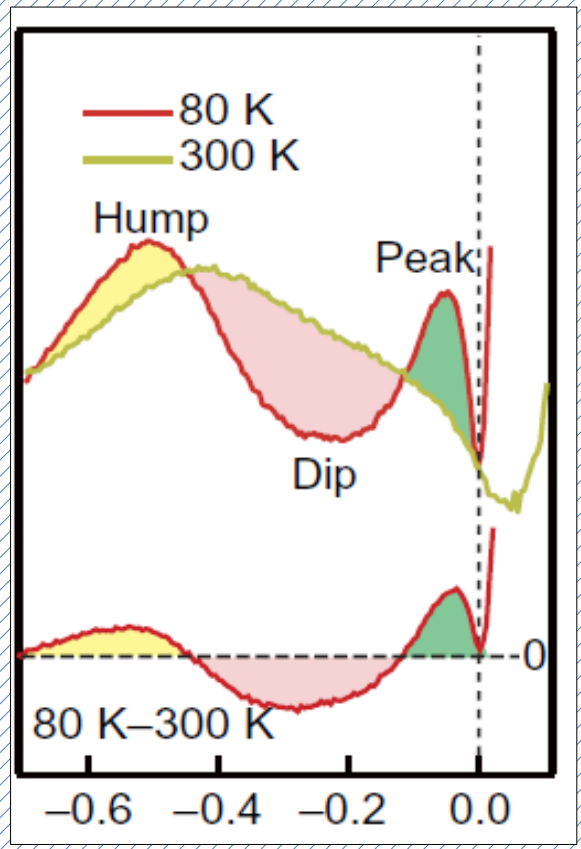
$$\mathrm{Wn}(\mathrm{R}) = \boldsymbol{\nabla R} \times \boldsymbol{An}(\boldsymbol{R}) \Longrightarrow \gamma n = \int_S d\mathbf{S}.\mathrm{Wn}(\mathrm{R})$$



K. Kim *et al.*,
Nat. Mater. **17**, 794 (2018)

Fe_3GeTe_2: a layered heavy-fermion ferromagnet

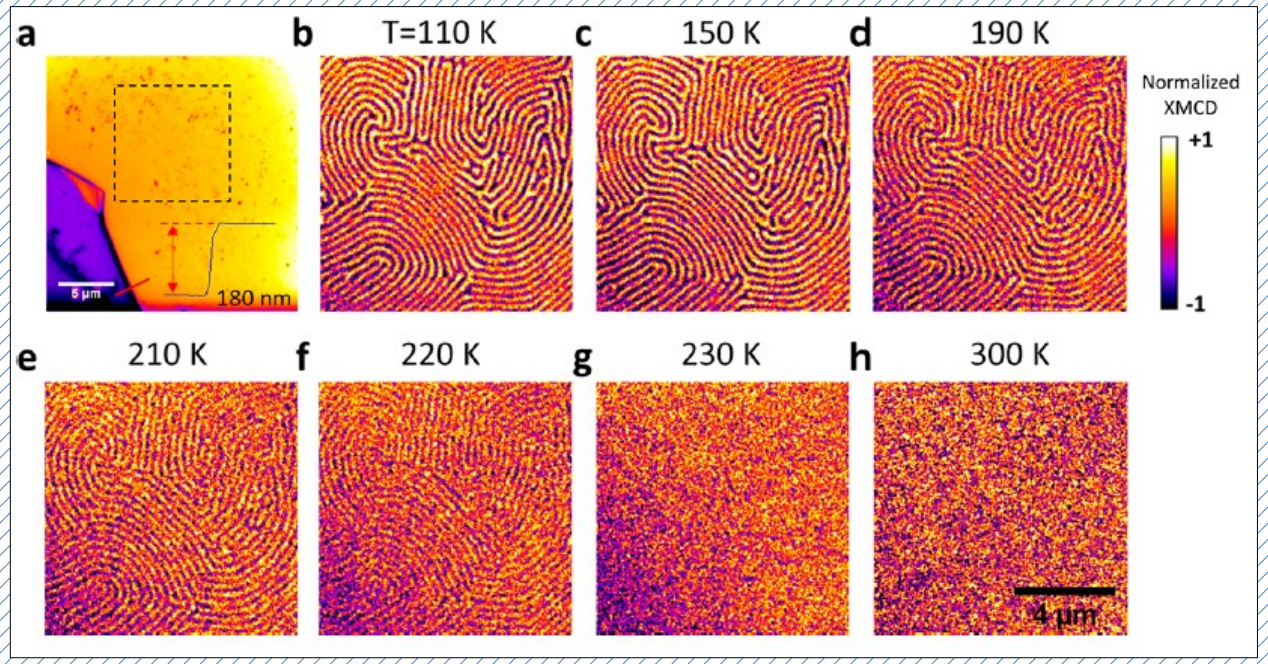




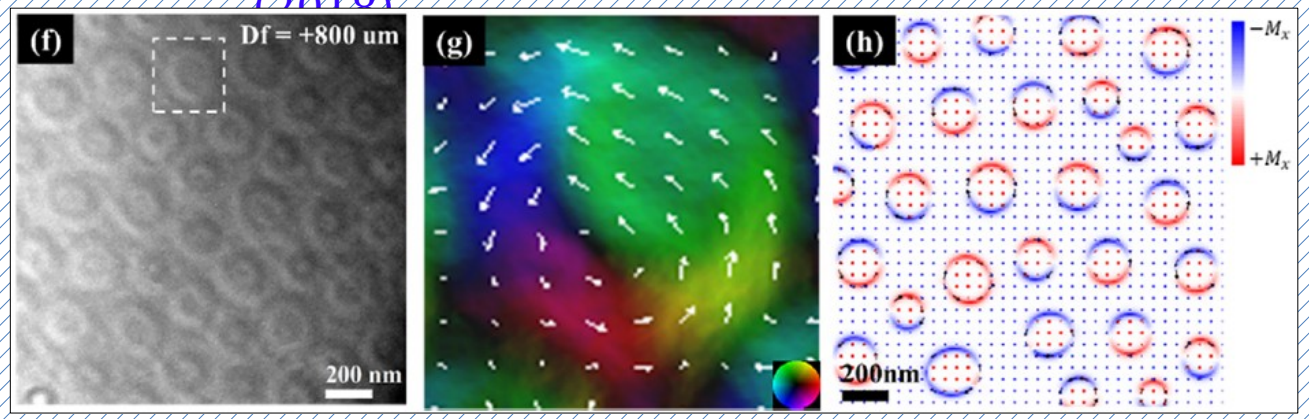
Zhang *et al.*, Sci. Adv. **4**: eaao6791 (2018)

J. Macy *et al.*, Appl. Phys. Rev. **8**, 041401 (2021)

Complex spin textures in $Fe_{3-x}GeTe_2$



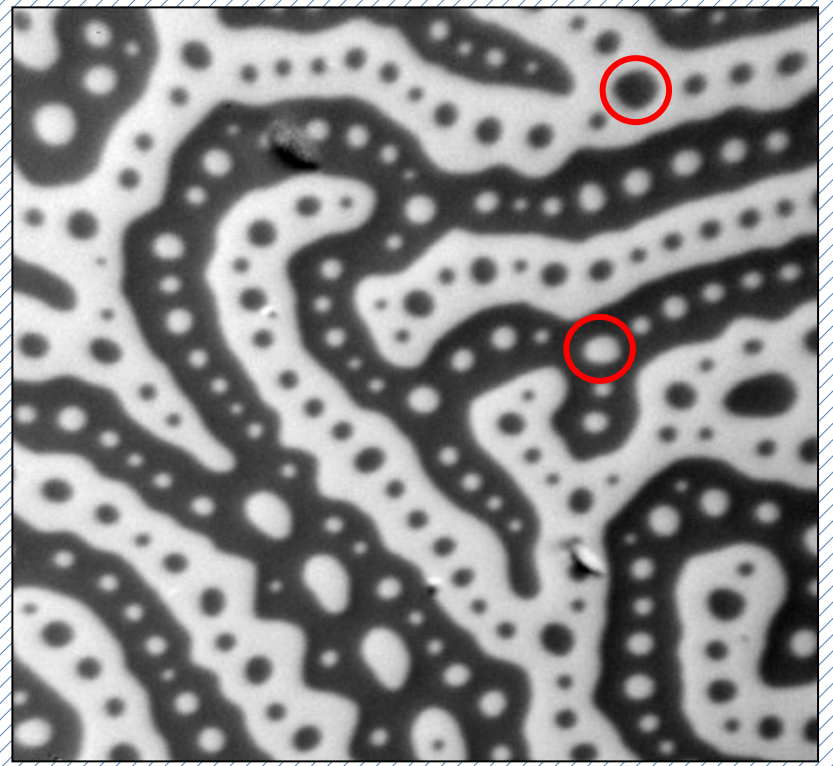
Li *et al.*, Nano Lett. **18**, 5974 (2018)



Ding *et al.*, Nano Lett. **20**, 868 (2020)

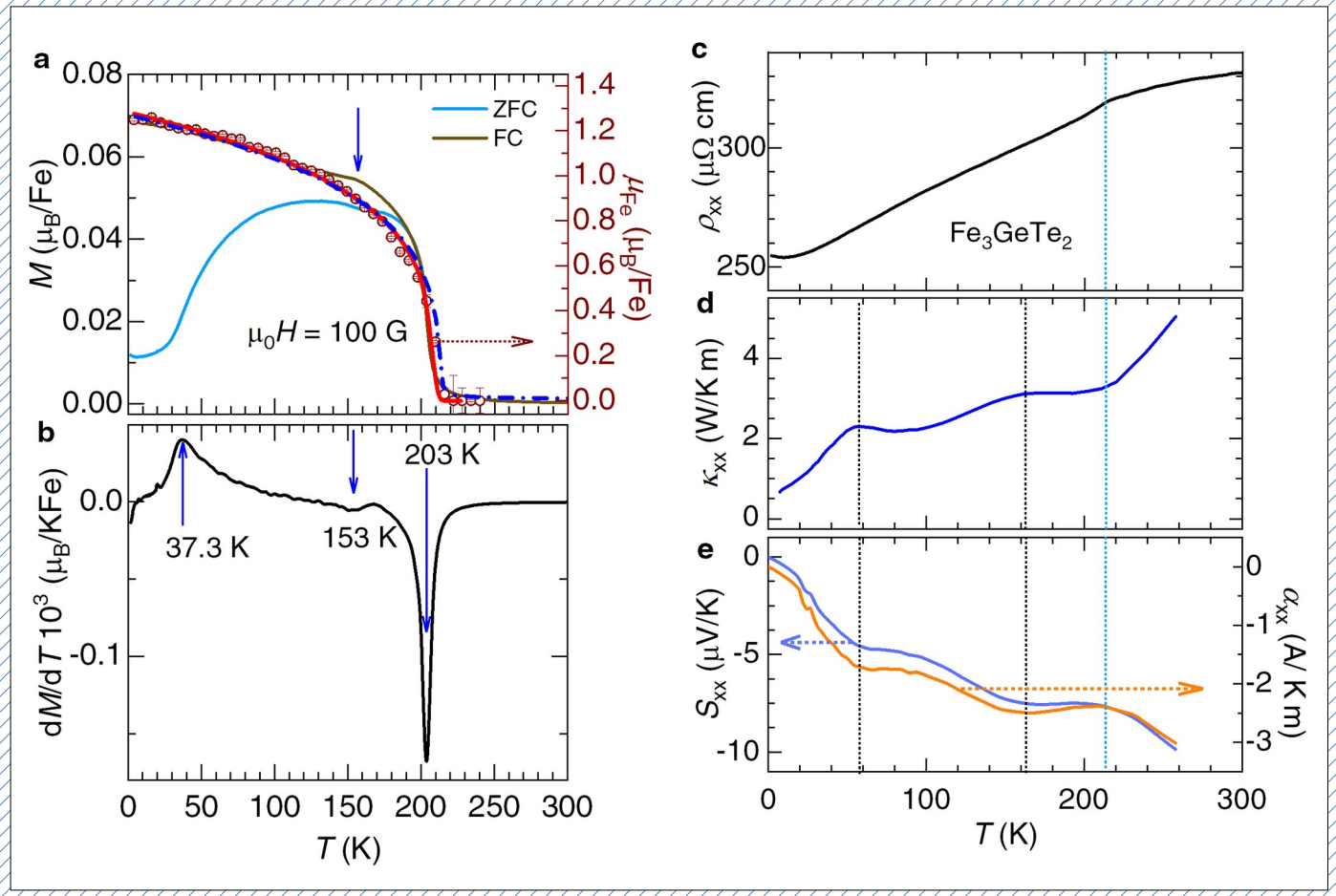
$\mu_0 H = 0$ T

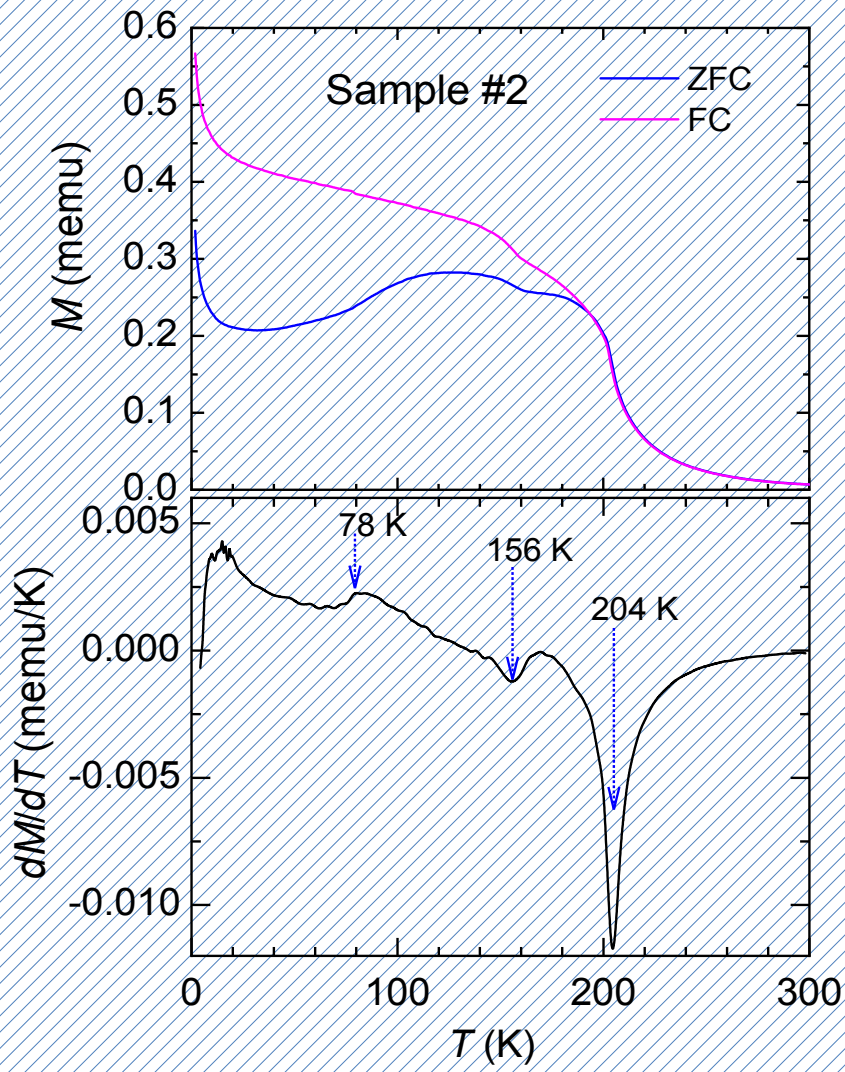
20 μm



unpublished

Magnetization, transport and neutrons

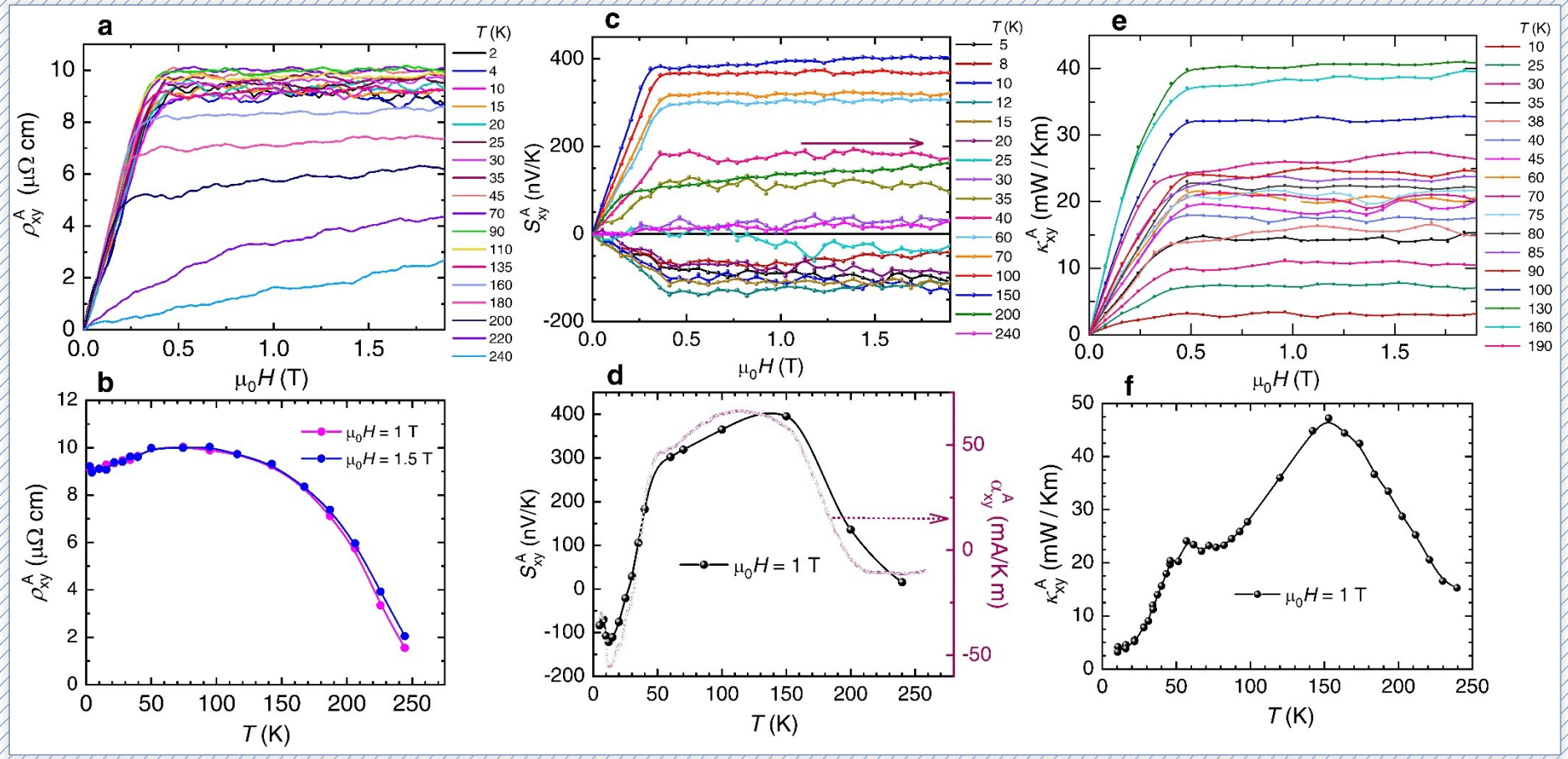




$$k_{xx} = \frac{j_{Qx}}{\nabla T_x}$$

J. Macy *et al.*, Appl. Phys. Rev. **8**, 041401 (2021)

Interplay between electronic topology and spin textures



$$r_{xy}^{A} = \frac{w E_y}{I_x} t$$

$$S_{xy}^{A} = \frac{w E_y}{\nabla T_x}$$

$$k_{xy}^{A} = \frac{j_{Qx}}{\nabla T_y}$$

$$r_{xy}^{A} = SHM\, \rho_{xx}^{n}$$

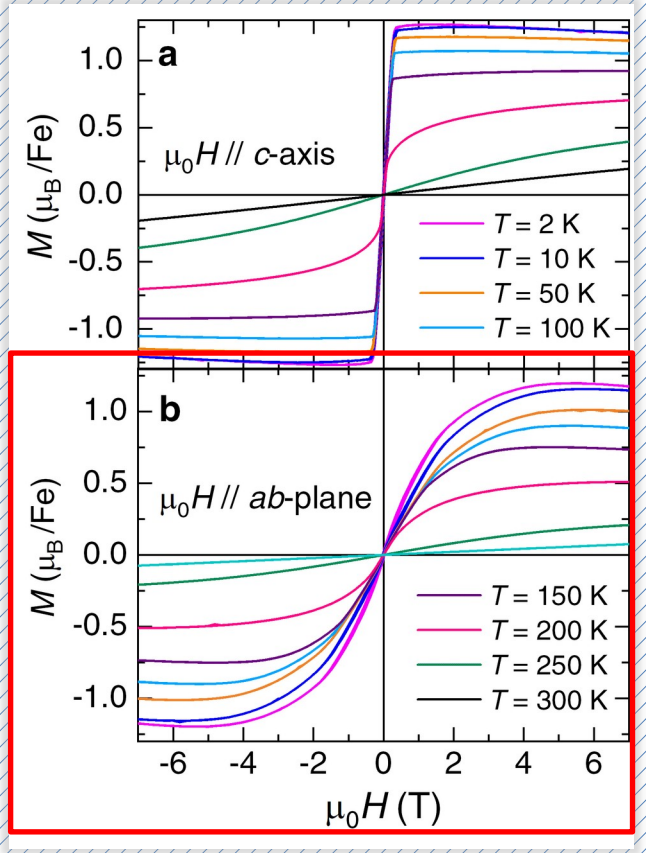
$$S_{xy}^{A} = \frac{\alpha_{xy}\sigma_{xx} - \alpha_{xx}\sigma_{xy}}{\sigma_{xx}^{2} + \sigma_{xy}^{2}}$$

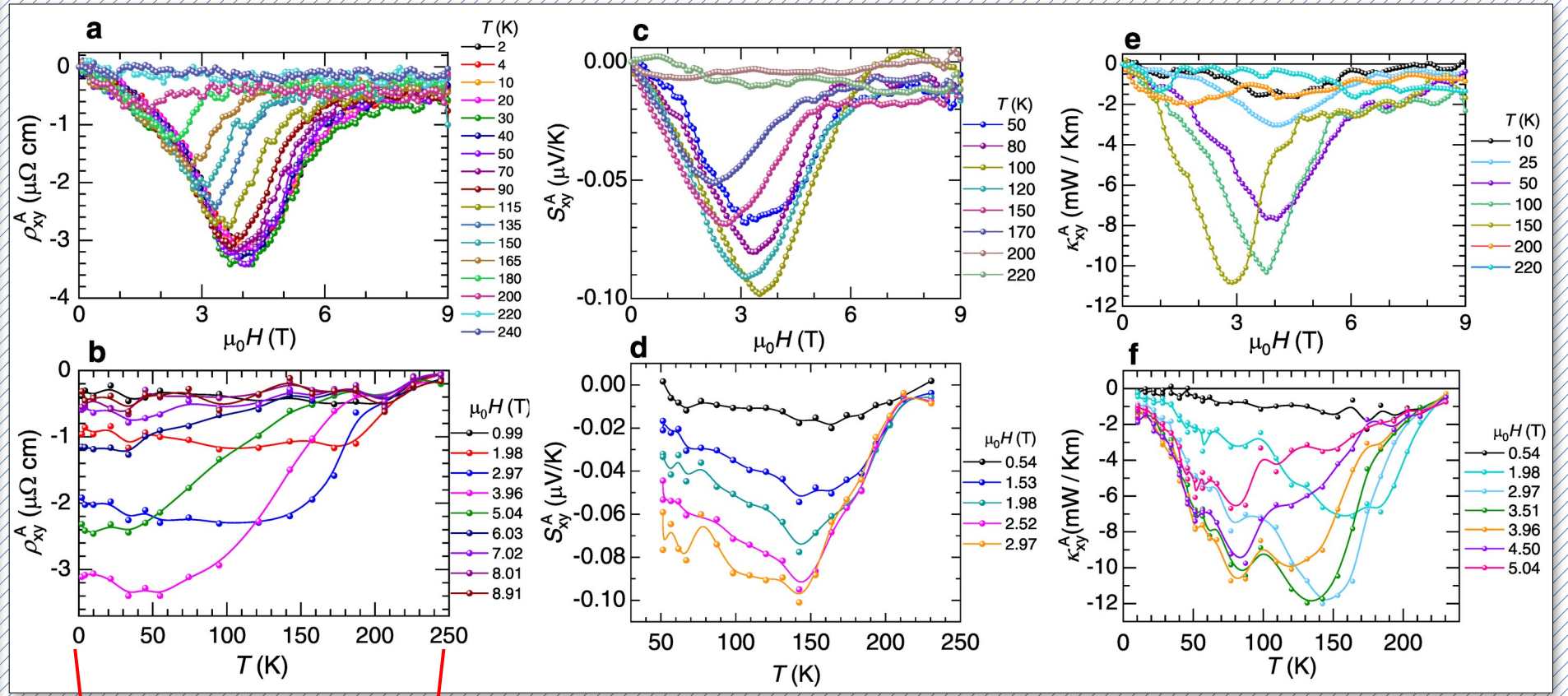
$$\sigma_{xy}^{A} = -\frac{\rho_{xy}^{A}}{(\rho_{xx})^{2} + (\rho_{xy}^{A})^{2}}$$

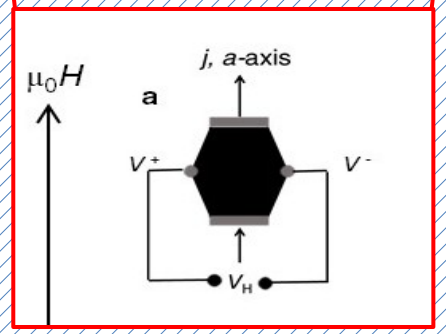
$$\alpha_{xy} = \frac{e k_B}{\hbar} \sum_{n} \int_{FS} \frac{d^3k}{(2\pi)^3} \Omega^{z}(\boldsymbol{k}) s(\boldsymbol{k})$$

J. Macy *et al.*, APR **8**, 041401 (20

Novel topological transport for $\mu \parallel \mu_0 H$





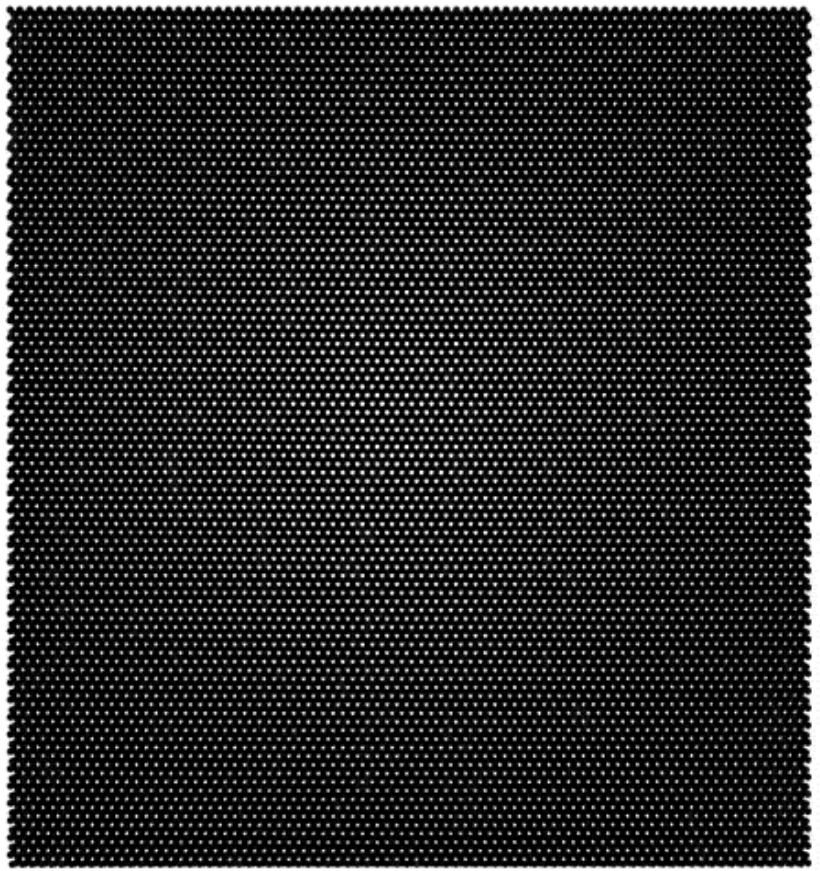


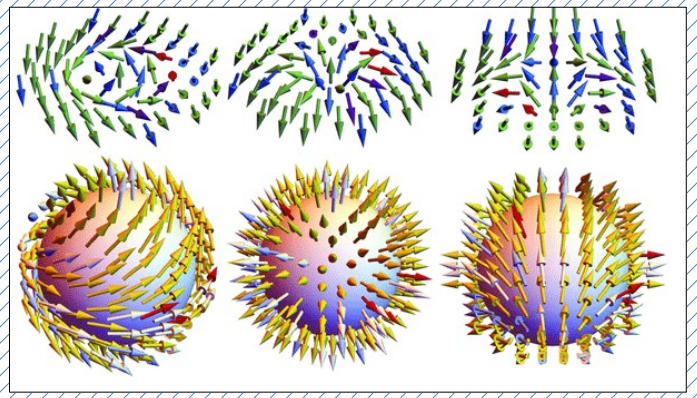
$$\chi_{i,j,k} = \boldsymbol{S}_i \cdot (\boldsymbol{S}_j \times \boldsymbol{S}_k)$$

J. Macy *et al.*, APR **8**, 041401 (2021)

MC simulations

$$H = -\frac{1}{2}\sum_{i,j} \boldsymbol{S}_i^{\alpha}\, \boldsymbol{\mathcal{J}}_{i,j}^{\alpha,\beta}\, \boldsymbol{S}_j^{\beta} - \frac{1}{2}\sum_{i,j} K_{ij}\left(\boldsymbol{S}_i \cdot \boldsymbol{S}_j\right)^2 - \frac{1}{2}\sum_{i} D_i\left(\boldsymbol{S}_i \cdot \boldsymbol{e}\right)^2 - -\frac{1}{2}\sum_{i} \mu_i\left(\boldsymbol{S}_i \cdot \boldsymbol{B}\right)$$



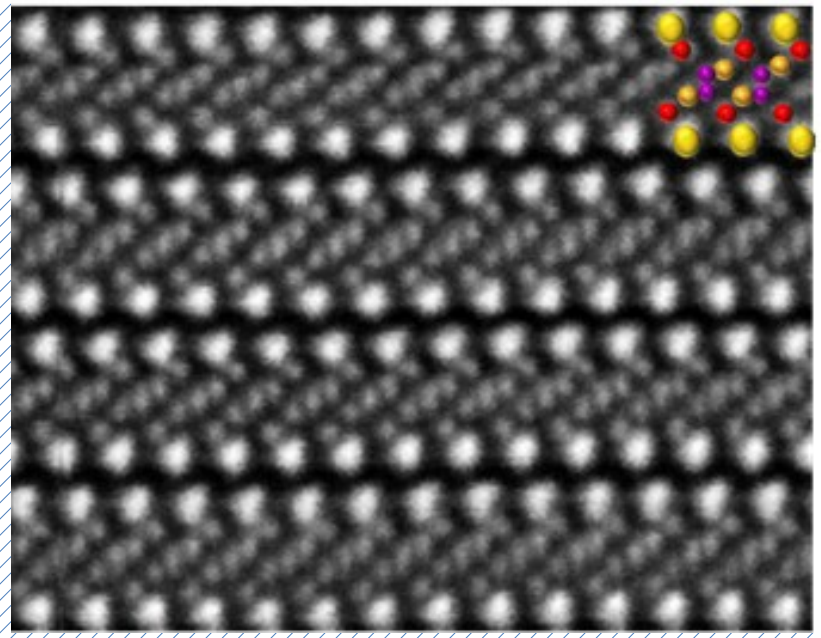


$$n = \frac{1}{4\pi}\int dx\,dy\, \boldsymbol{m} \cdot \left(\frac{\partial \boldsymbol{m}}{\partial x} \times \frac{\partial \boldsymbol{m}}{\partial y}\right)$$

K. Everschor-Sitte *et al.*,
J. Appl. Phys. **124**, 240901 (2018)

J. Macy *et al.*, APR **8**, 041401 (2021)

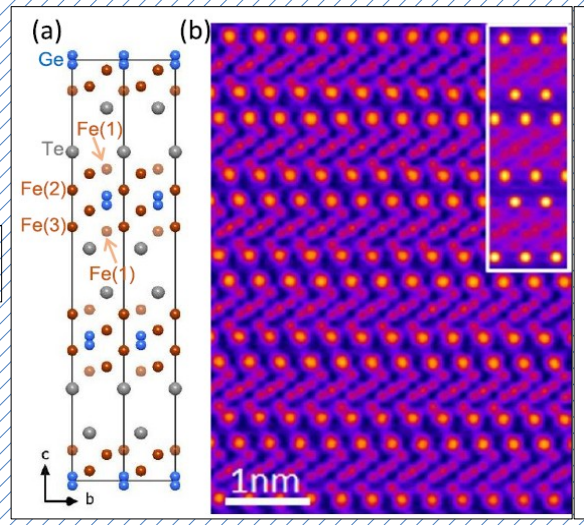
$Fe_{5-x}GeTe_2$ and its doped variants

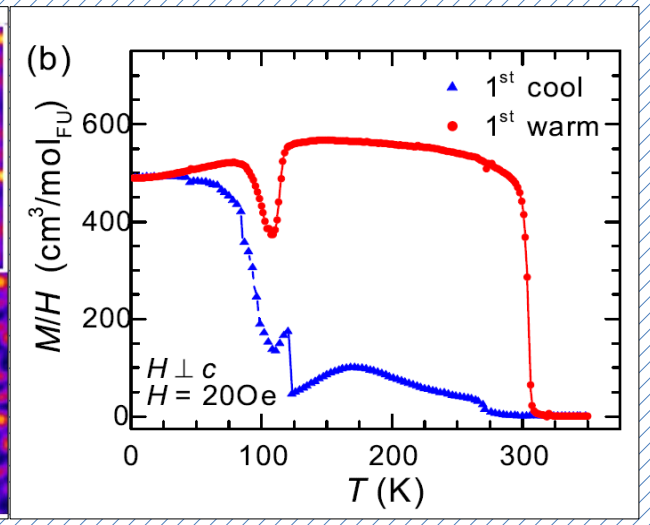


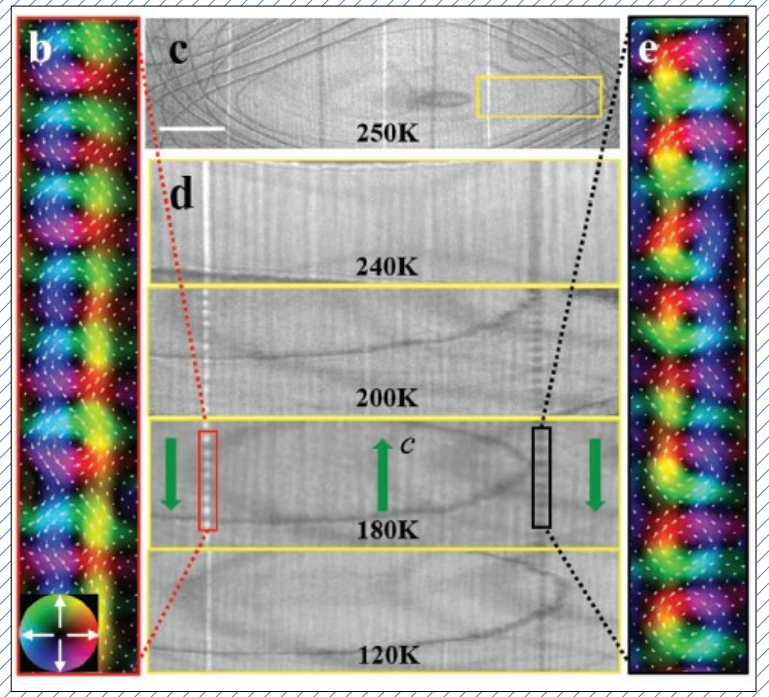
B. W. Casas *et al.*, Adv. Mater. **35**, 2212087 (2023)

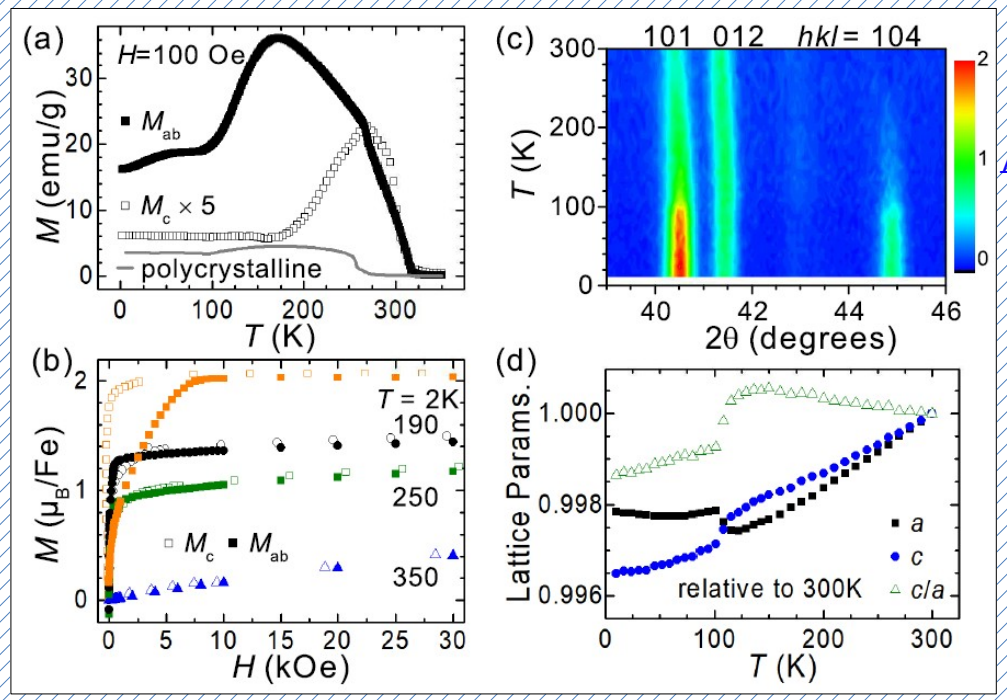
Introduction to $Fe_{5-x}GeTe_2$

R-3m

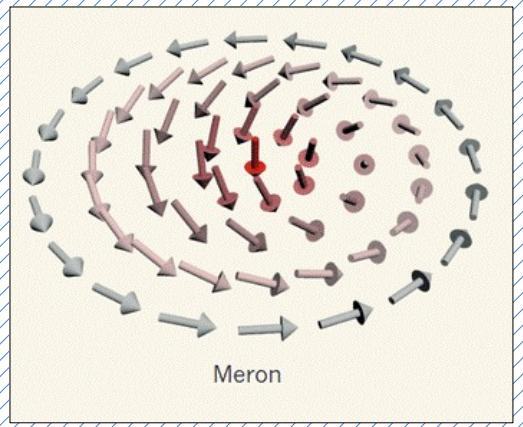


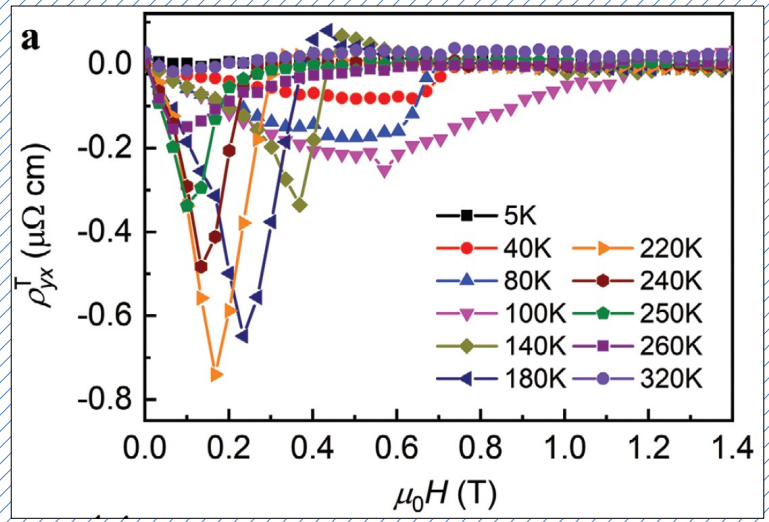






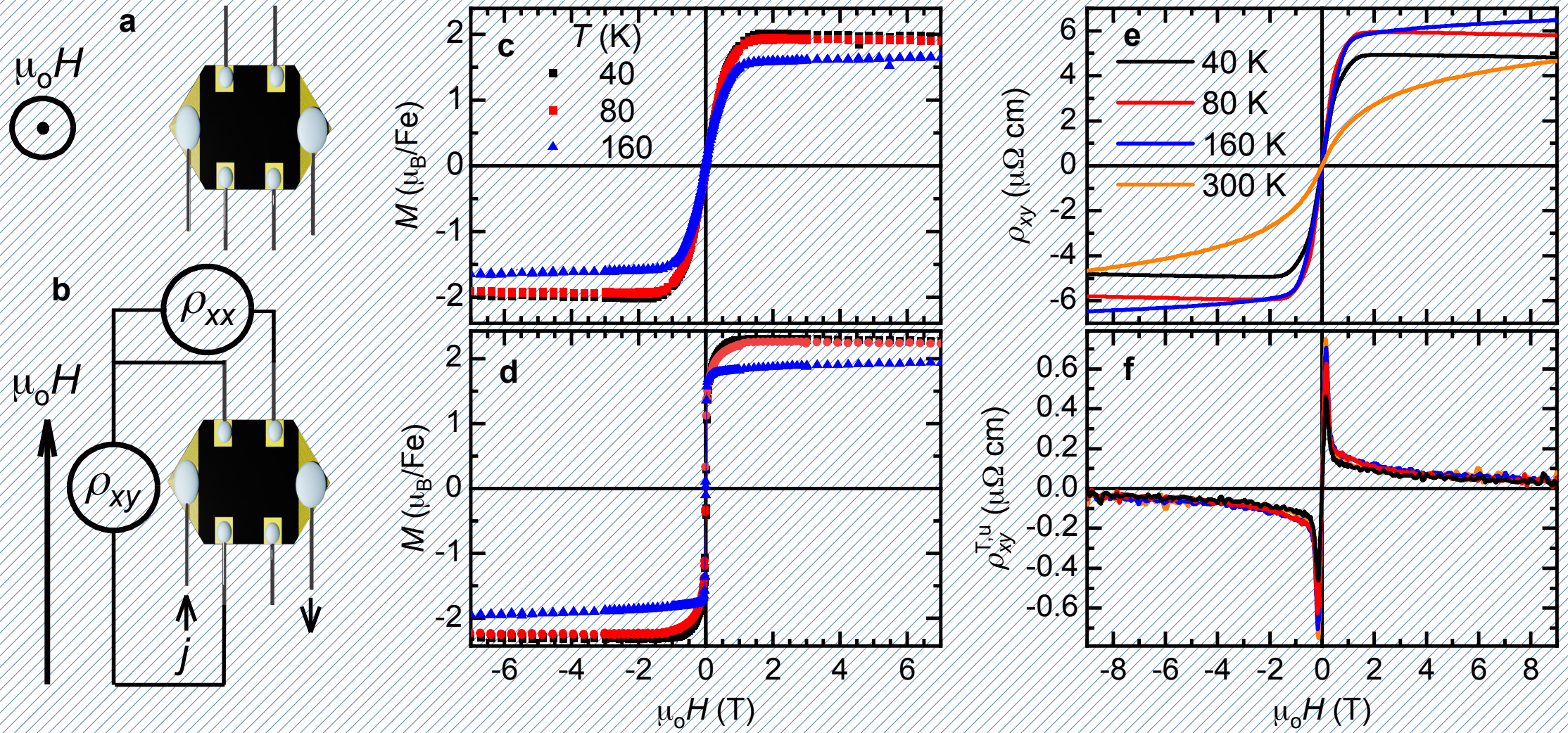
A. F. May *et al.*,
ACS Nano **13**, 4436 (2019)





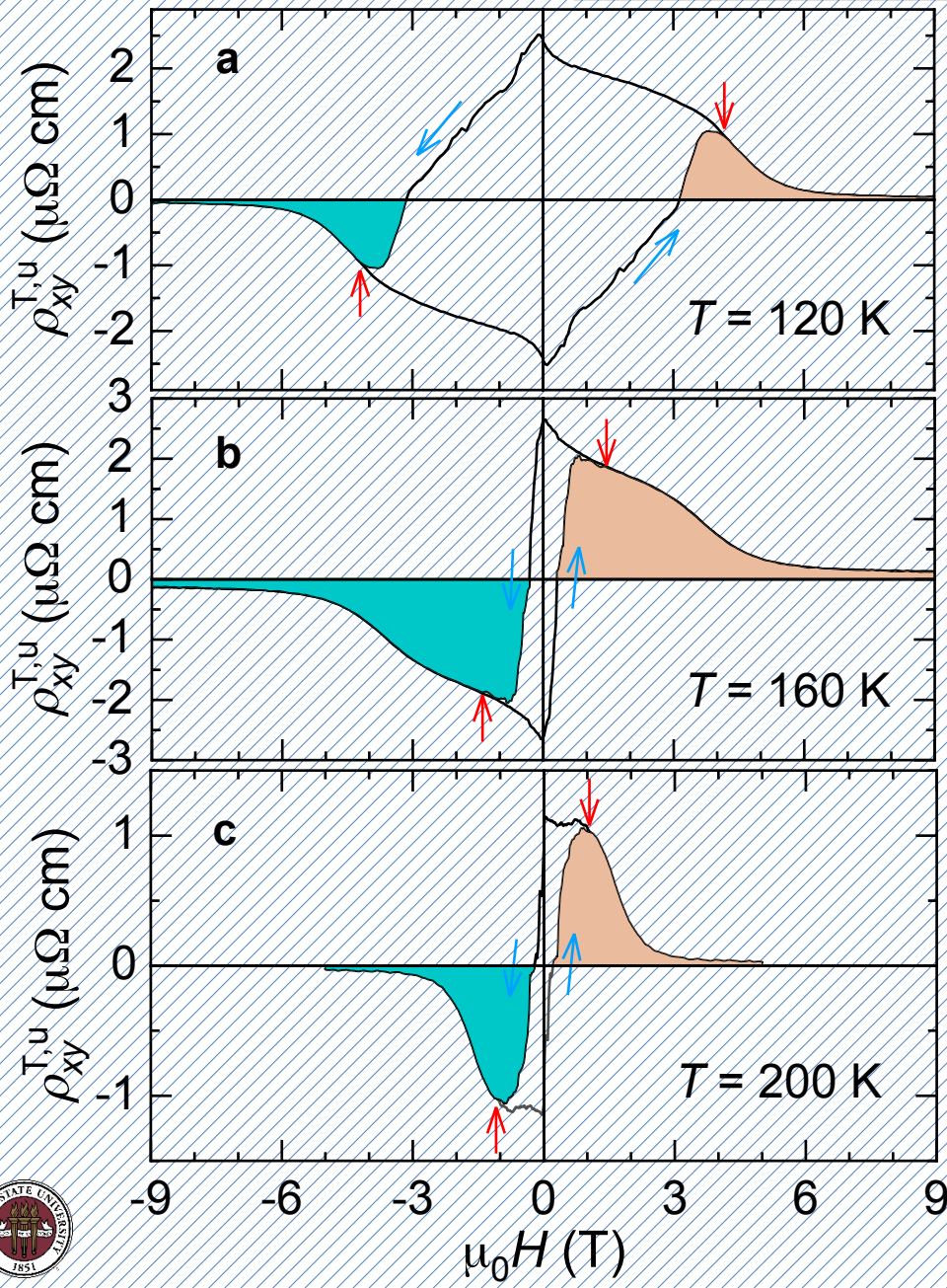
Y. Gao *et al.*, Adv. Mater. **32**, 2005228

Unconventional THE in $Fe_{5-x}GeTe_2$

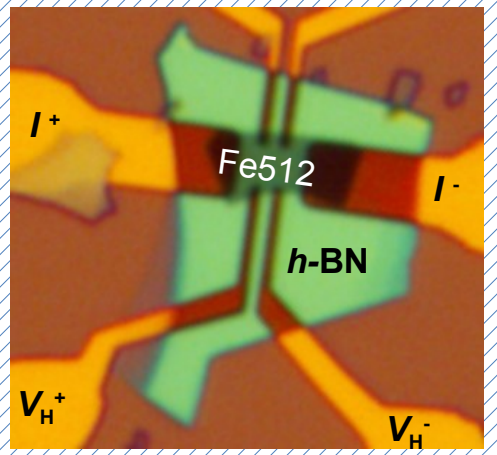


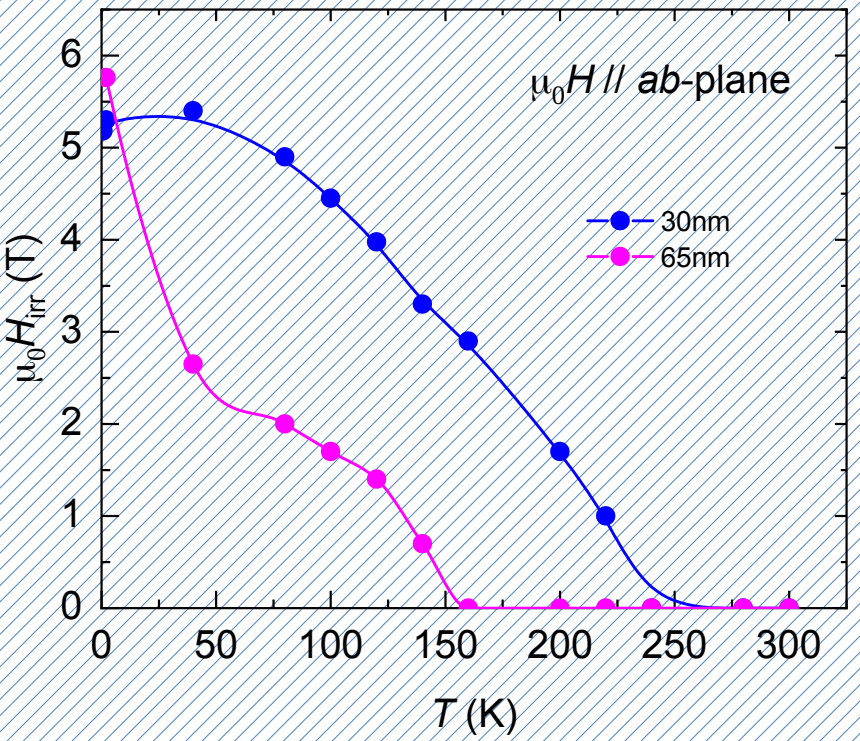
B. W. Casas *et al.*, Adv. Mater. **35**, 2212087 (2023).

Large irreversibility exfoliated samples



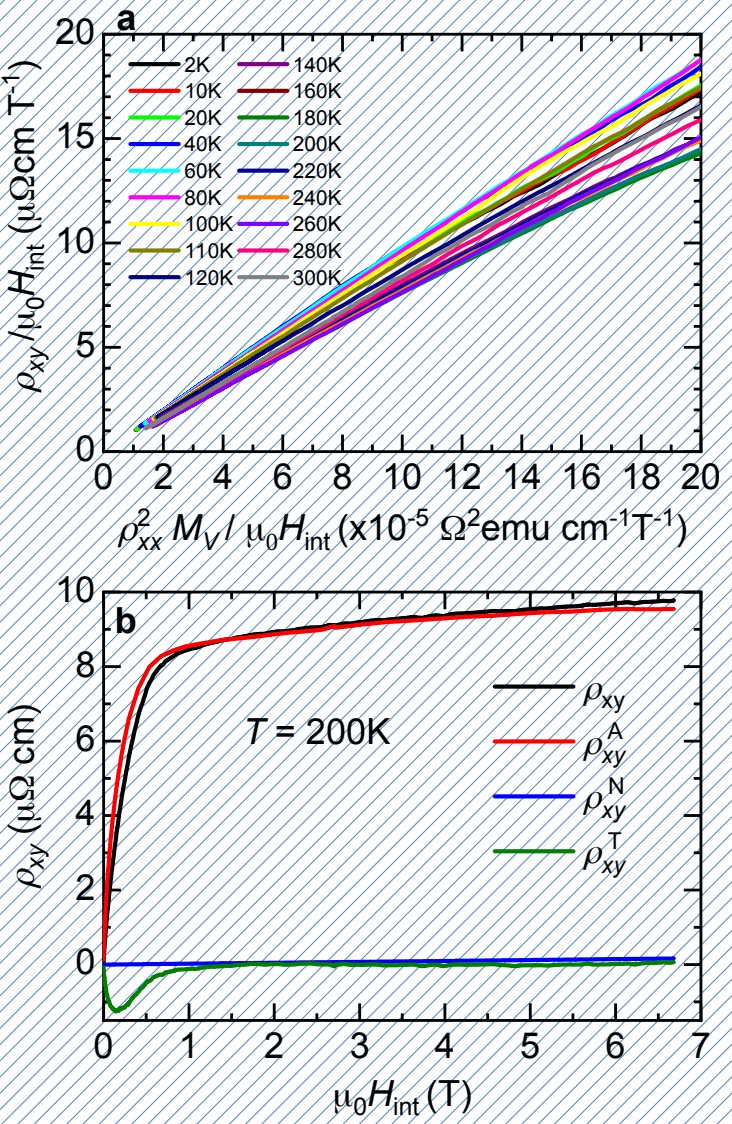
Casas *et al.*,
Adv. Mater. **35**,
2212087 (2023).

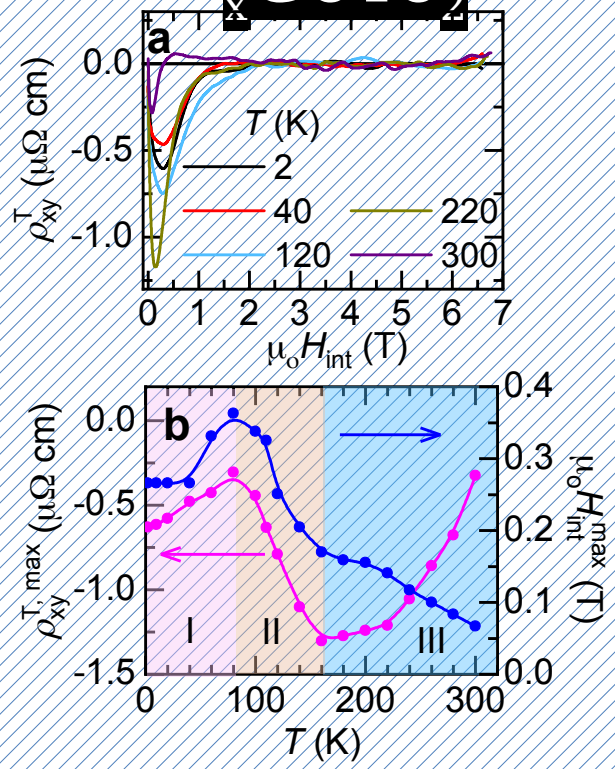


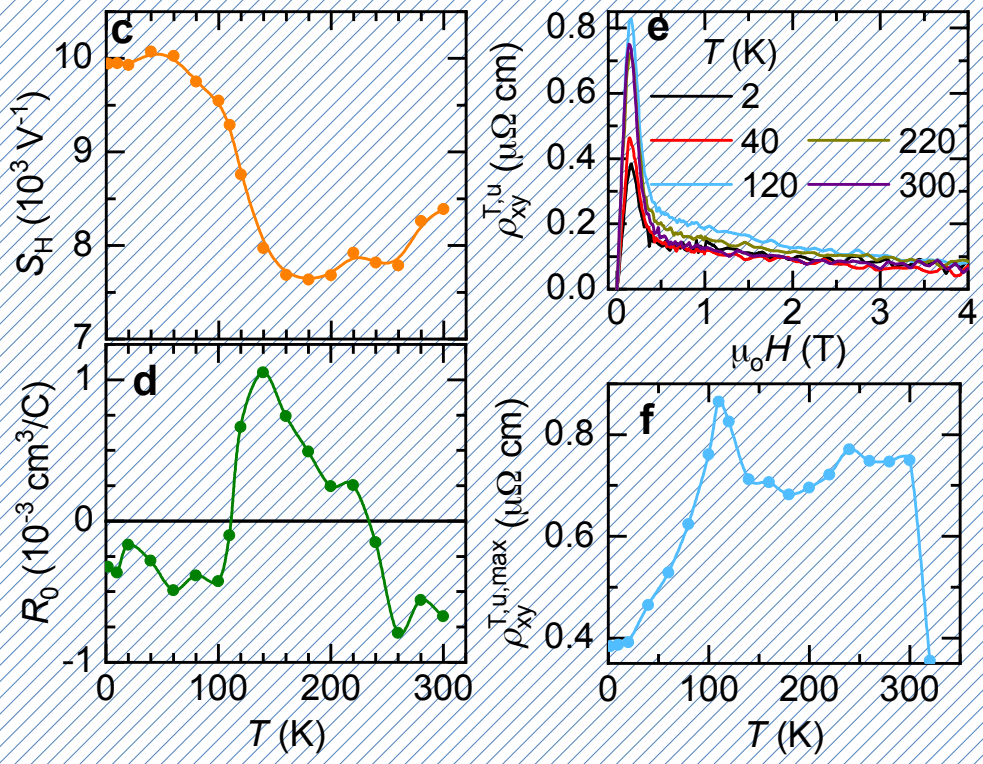


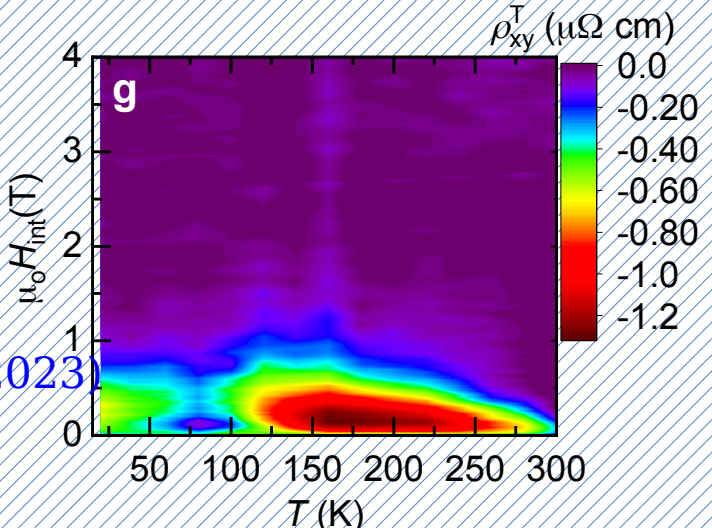
A. Moon *et al.* (Unpublished).

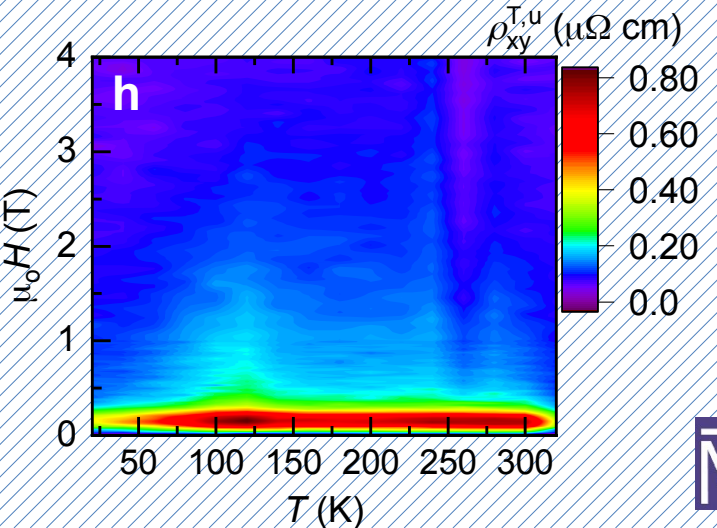
Conventional and Unconventional THE in $Fe_{5-x}GeTe_2$







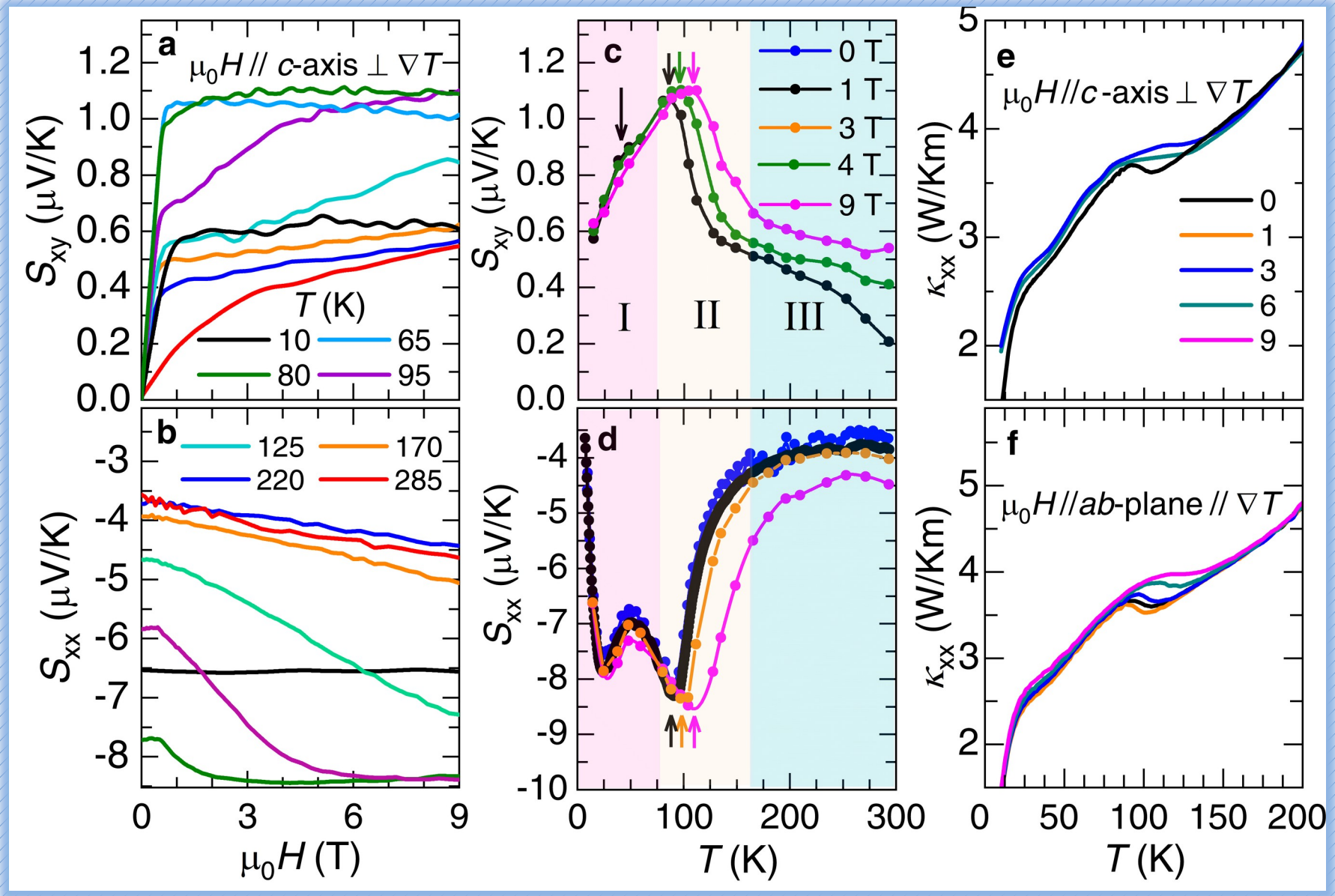




. W. Casas *et al.*, Adv. Mater. **35**, 2212087 (2023)

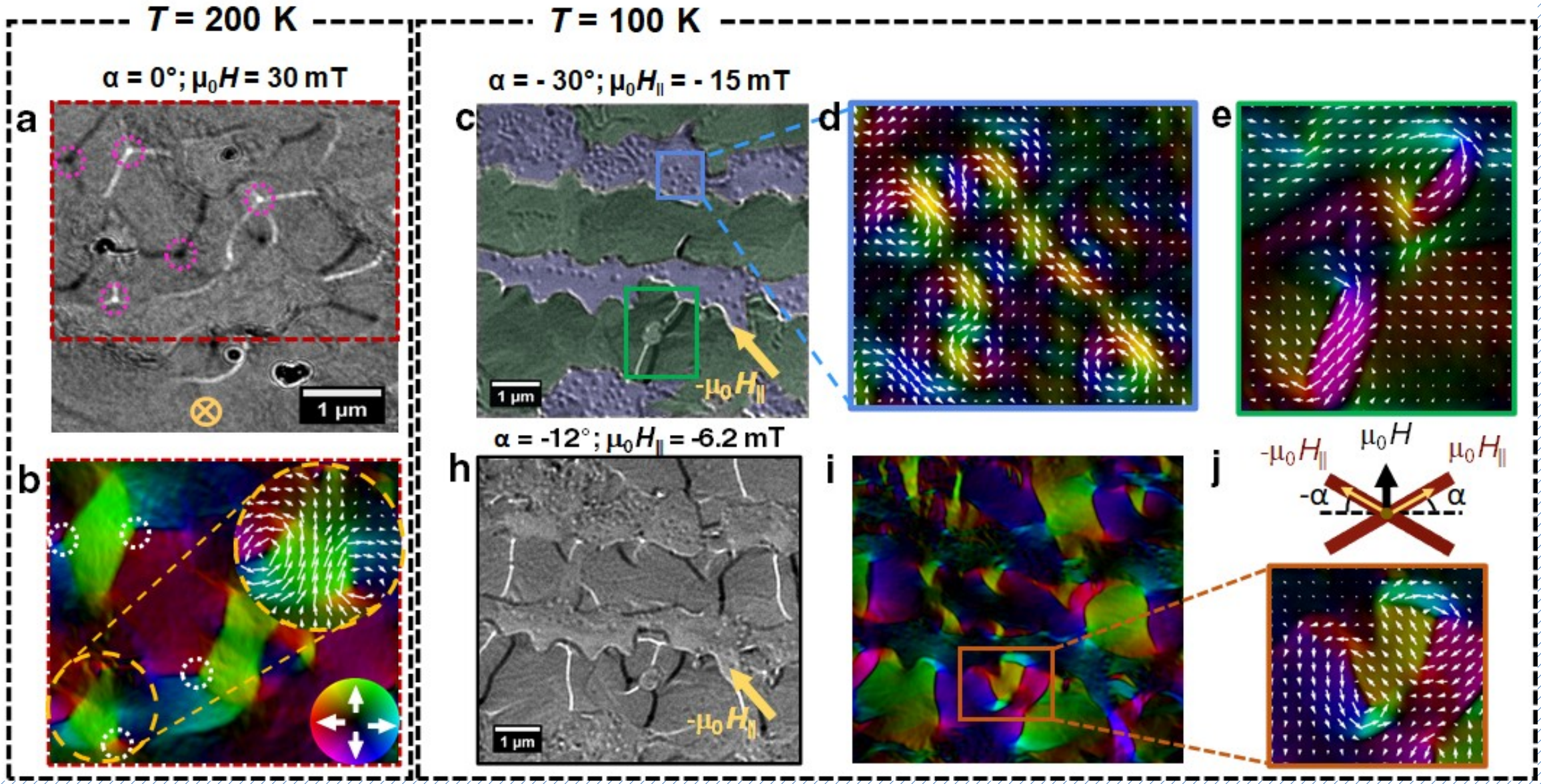
See also, G. Kimbell *et al.*, Commun. Mater. **3**, 19 (2022)

Thermal transport



B. W. Casas *et al.*, Adv. Mater. **35**, 2212087 (2023)

L-TEM: coexistence between merons and skyrmions



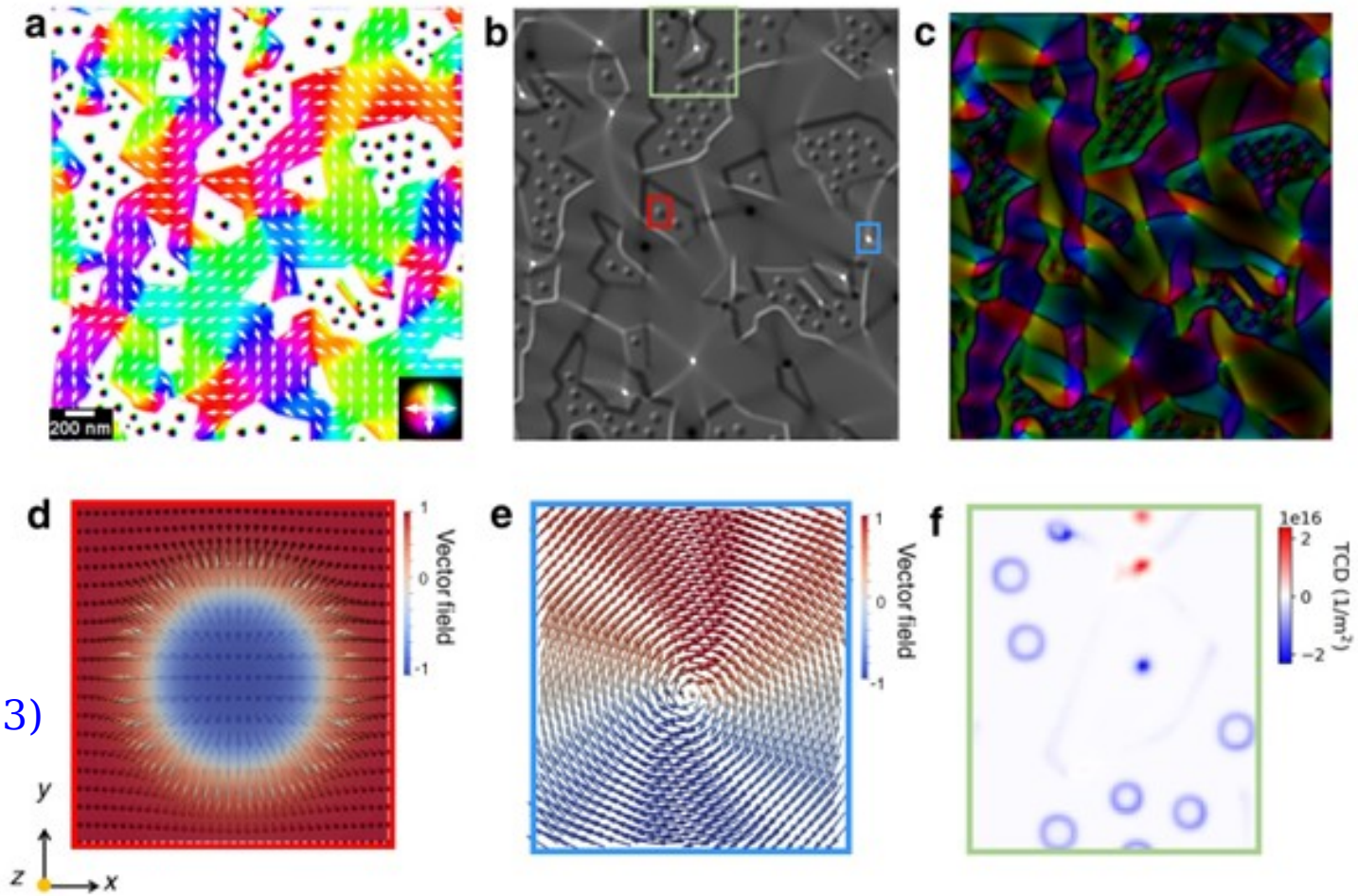
B. W. Casas *et al.*, Adv. Mater. **35**, 2212087 (2023).

Micromagnetic simulations via Mumax3

- In different regions, strong in-plane uniaxial anisotropy along the *x*-axis. Remaining regions have out-of-plane anisotropy leading to interfacial DMI.
- Spatially uniform exchange constant $J = 1 \times 10^{-11}$ J/m.
- Formation of in-plane domains (with vortices) and skyrmions in remaining regions.

Simulated LTEM

Grain-like regions
Voronoi tessellation
Magnetic domains



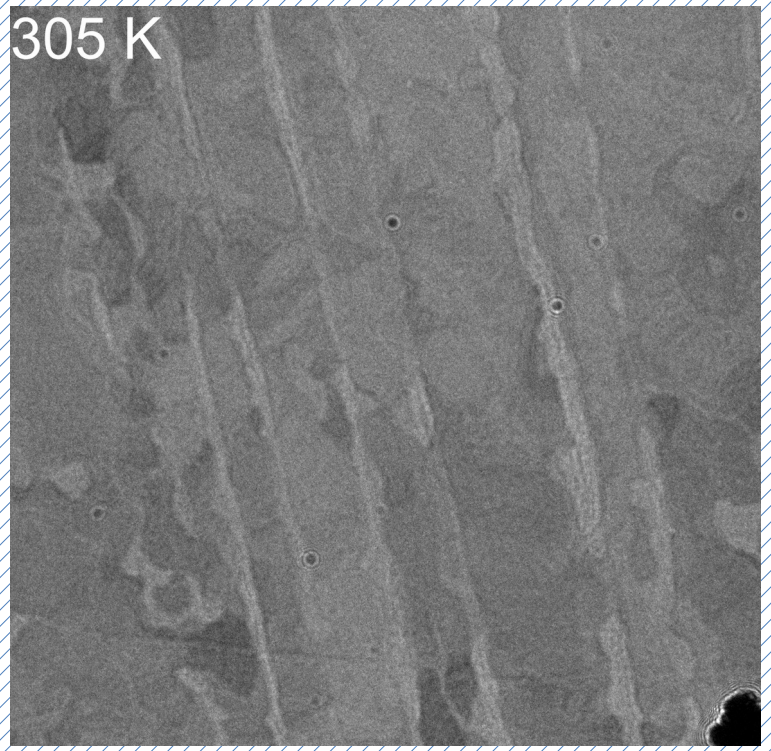
imulated Magnetic induction maps

Topological charge density

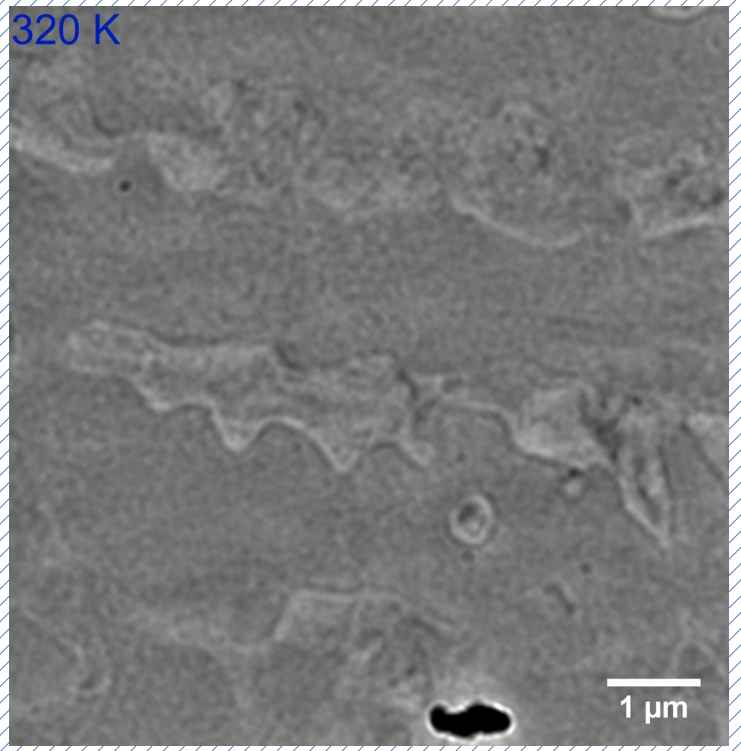
. W. Casas *et al.*,
dv. Mater. **35**, 2212087 (2023)

Evolution of domains as a function of T and $\mu_0 H$

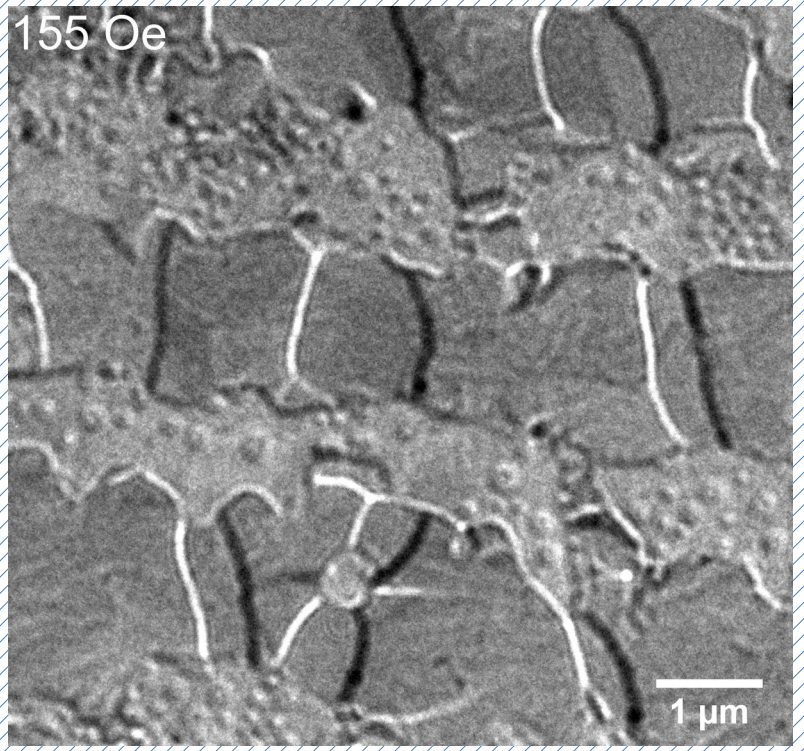
$\mu_0 H$ = "0 G"



$\mu_0 H$ = 300 G



T = 100 K



$\mu_0 H$ ⊗

$-\mu_0 H_{\parallel}$

α = -16.5°

B. W. Casas *et al.*,
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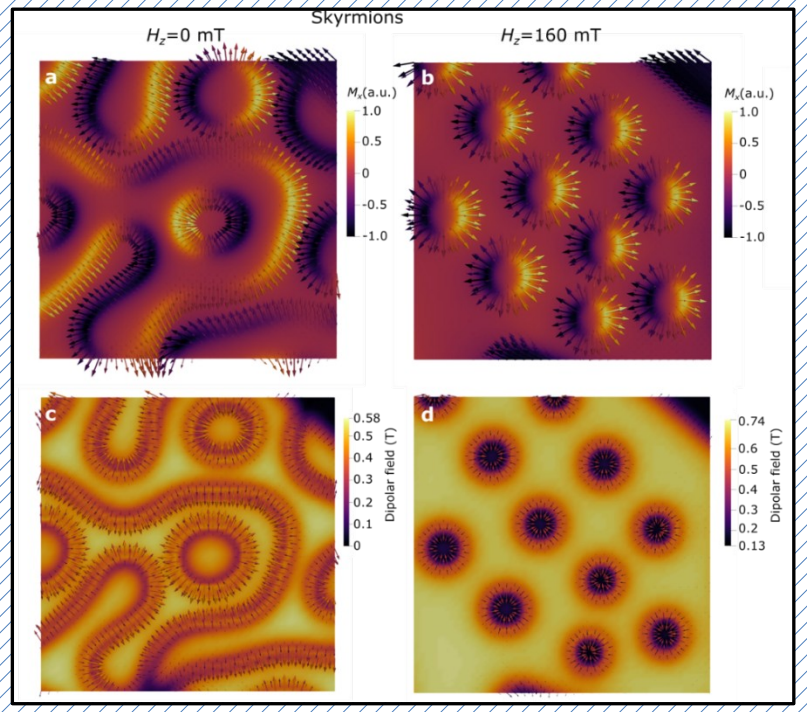
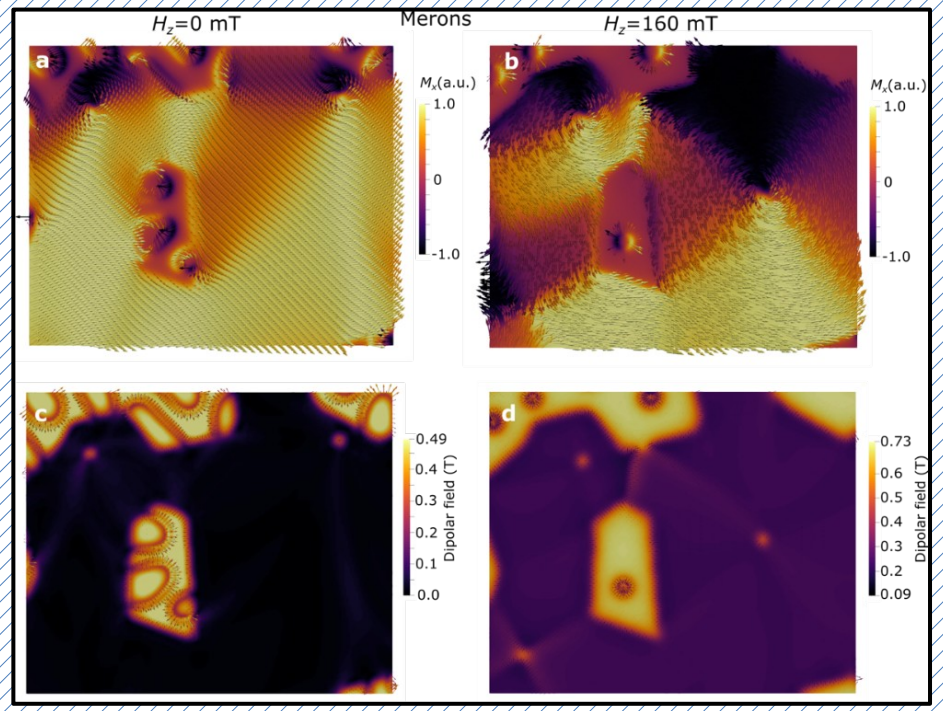
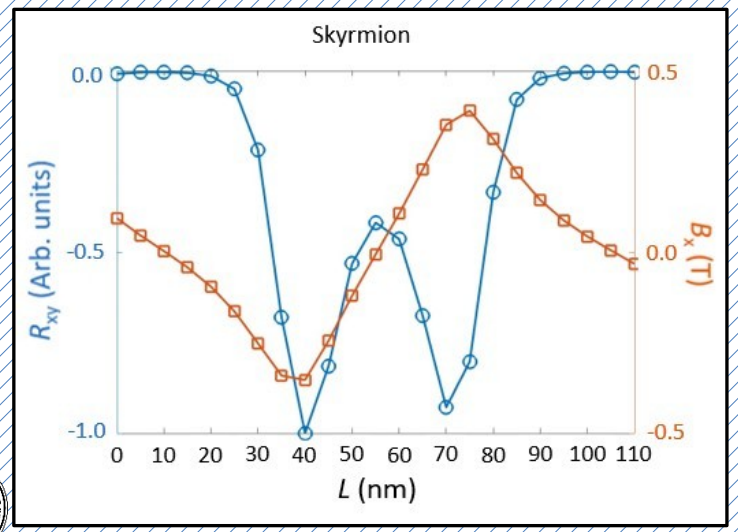
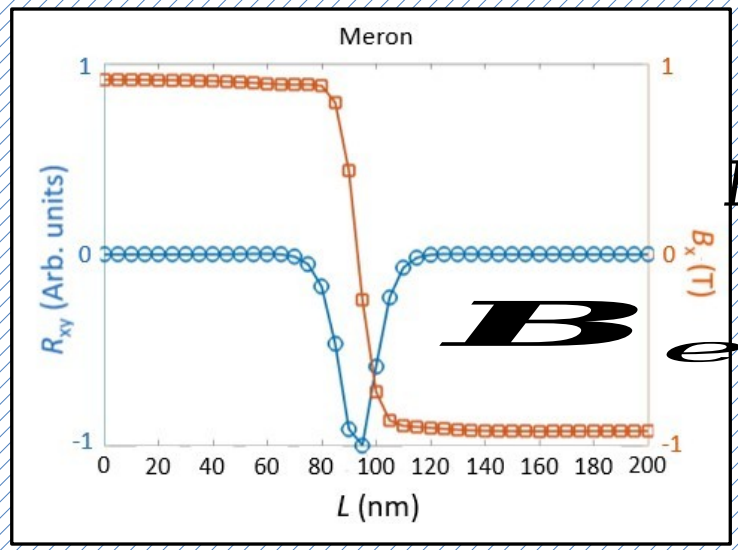
Dipolar fields and their contribution to the Hall response





B. W. Casas *et al.*,
Adv. Mater. **35**, 2212087 (2023





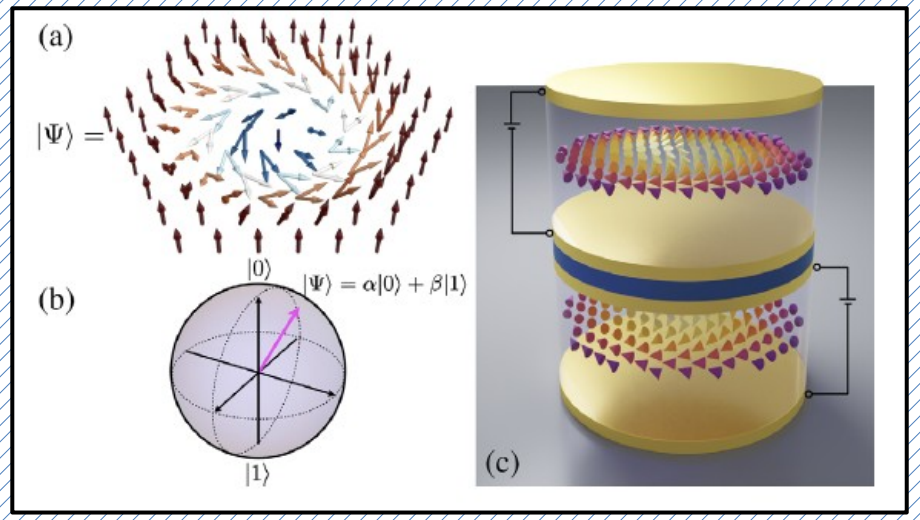
$$R_{xy} \propto \int_{-y_0}^{y_0} \int_{-x_0}^{x_0} N_{Sk}(x, -x'\, y - y')\, dx'\, dy$$

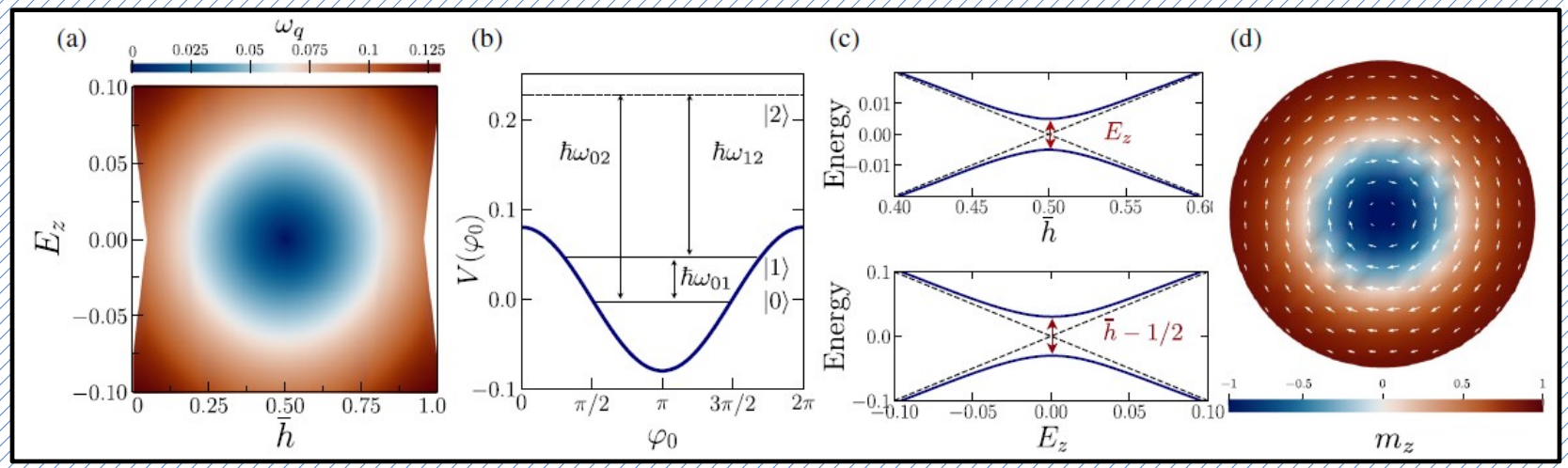
$$B_{em} \propto N_{Sk}$$

Summary

- A novel type of topological transport associated to complex non-coplanar spin textures $Fe_{n-x}GeTe_2$
- Fe512: coexistence of merons with skyrmions in the presence of global inversion symmetry
- High T_c, can be grown in large area: do these materials represent a new paradigm for skyrmionics? Beginning of Meronics?

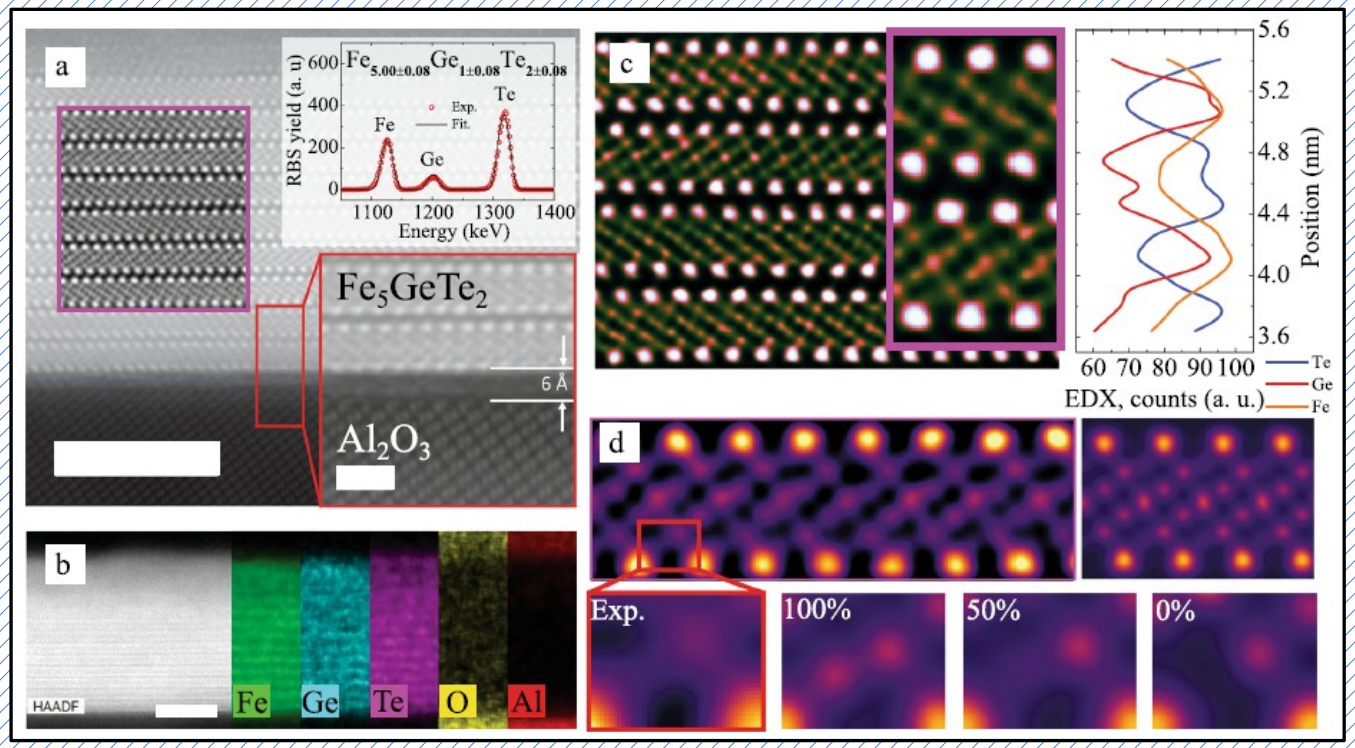
Qubits based on skyrmions in frustrated magnets?

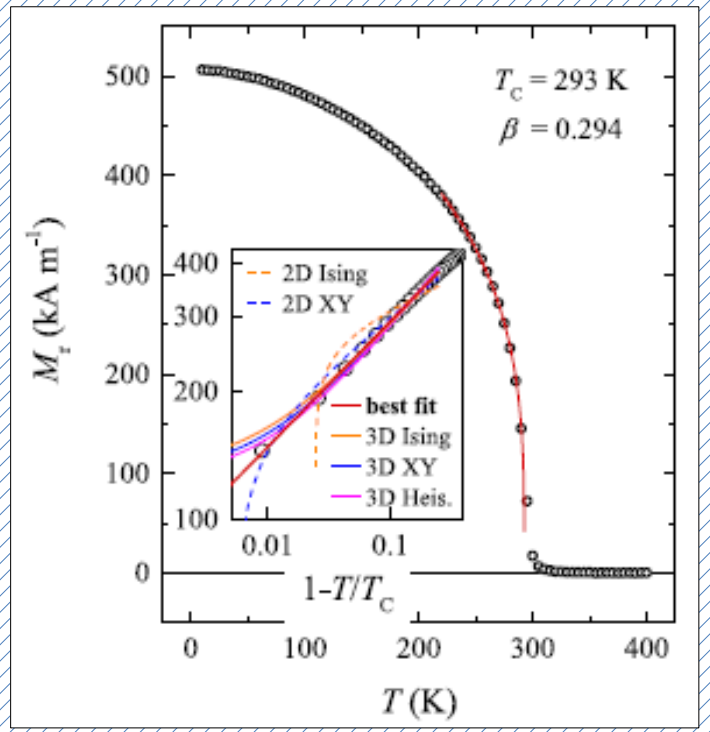




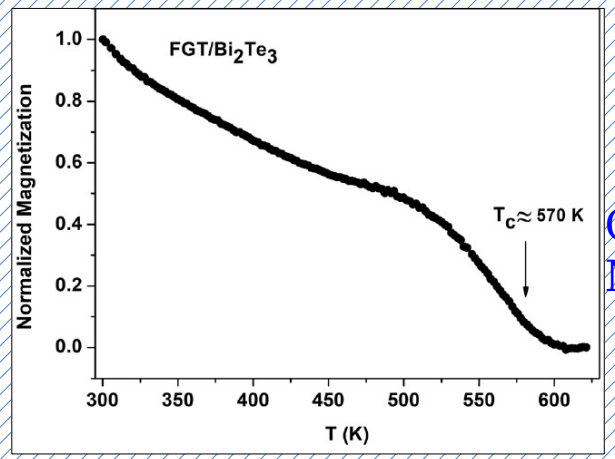
C. Psaroudaki *et al.*, PRL **127**, 067201 (2021)

Large area growth via molecular beam epitaxy

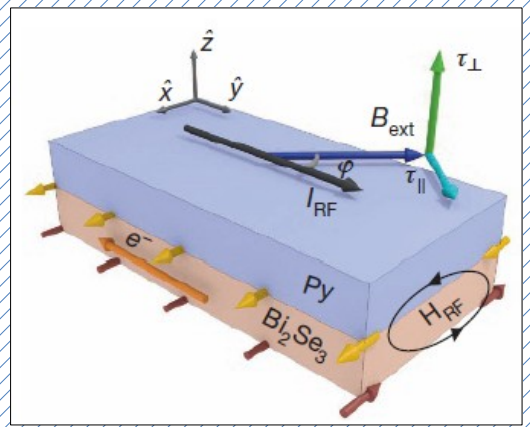




Ribeiro *et al.*, npj 2D Mater. Appl. **6**, 10 (2022)

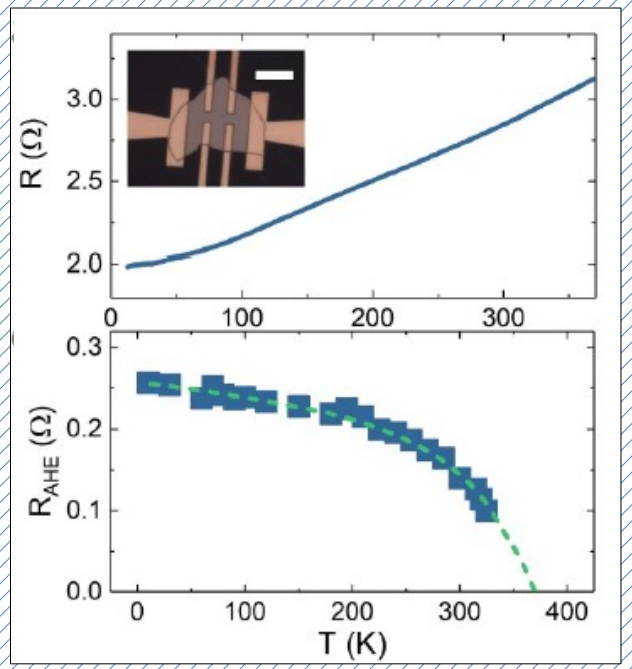


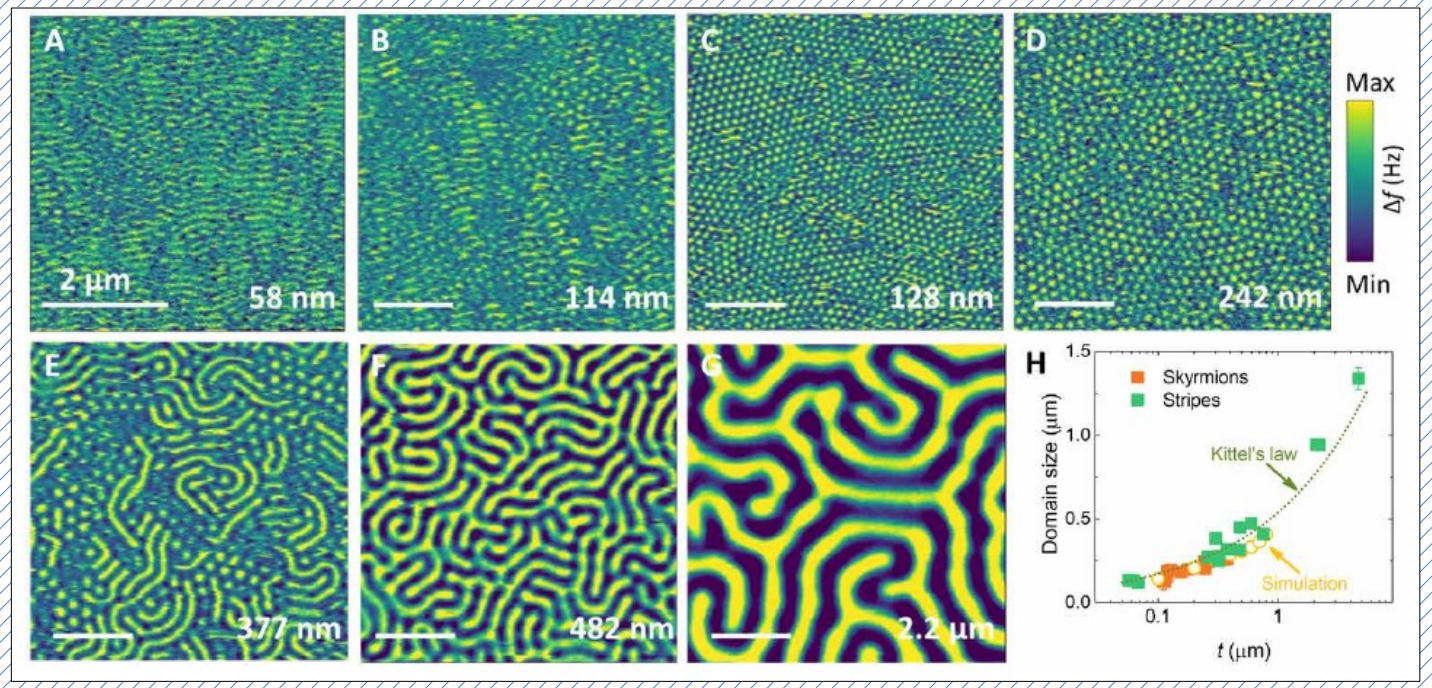
Georgopoulou-Kotsaki et *al.*, Nanoscale **15**, 2223 (2023)

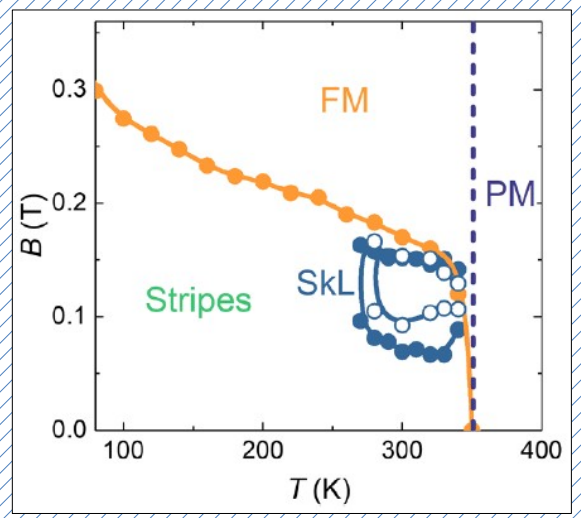


Mellnik *et al.*, Nature **511**, 449 (2014)

Skyrmions at room T in $(Fe_{0.5}Co_{0.5})_{5-x}GeTe_2$







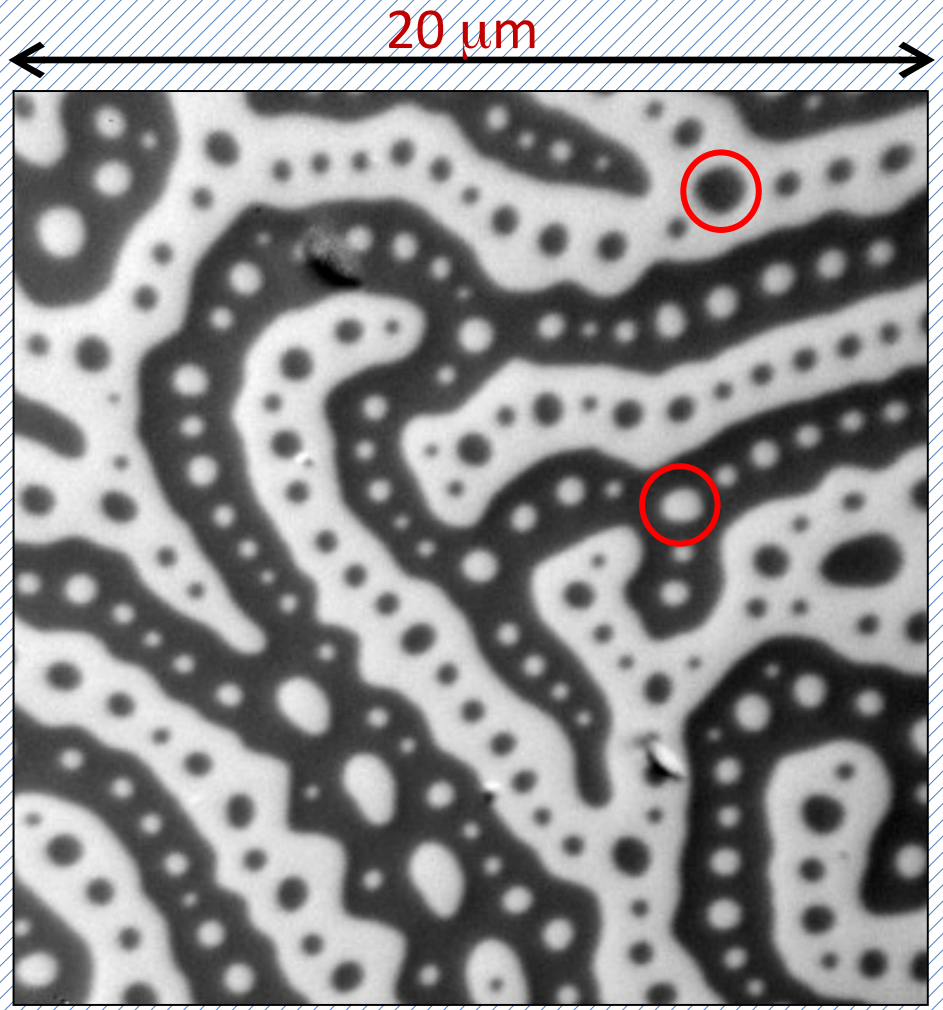
Zhang *et al.*, Sci. Adv. **8**, eabm7103 (2022

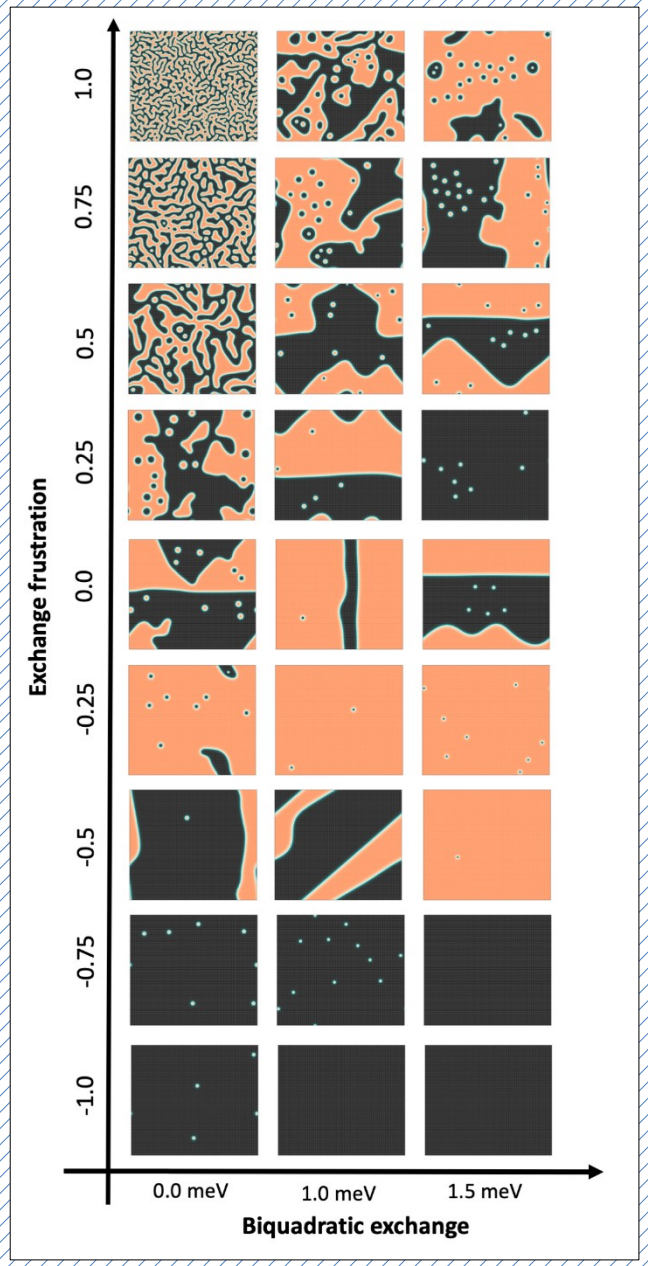
Spin textures from competing interactions

"Bubbles" ranging from 100 to 700 nm

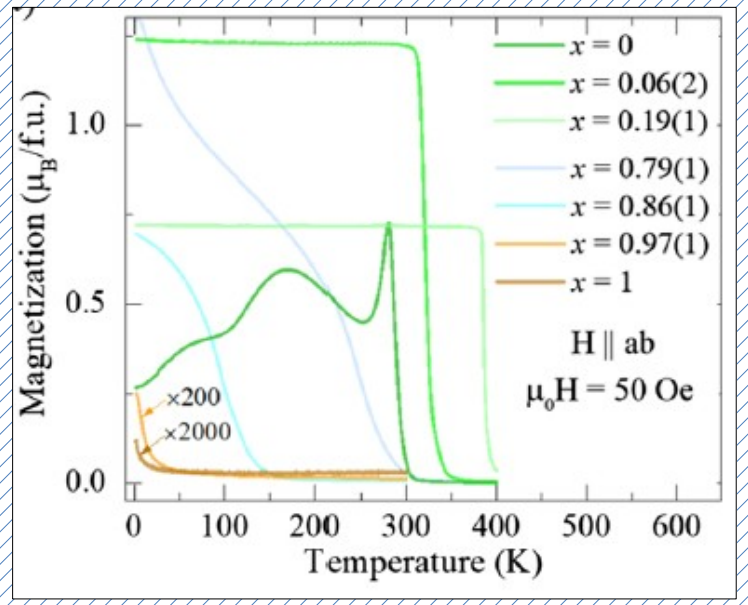
$\mu_0 H \cong 0$ G

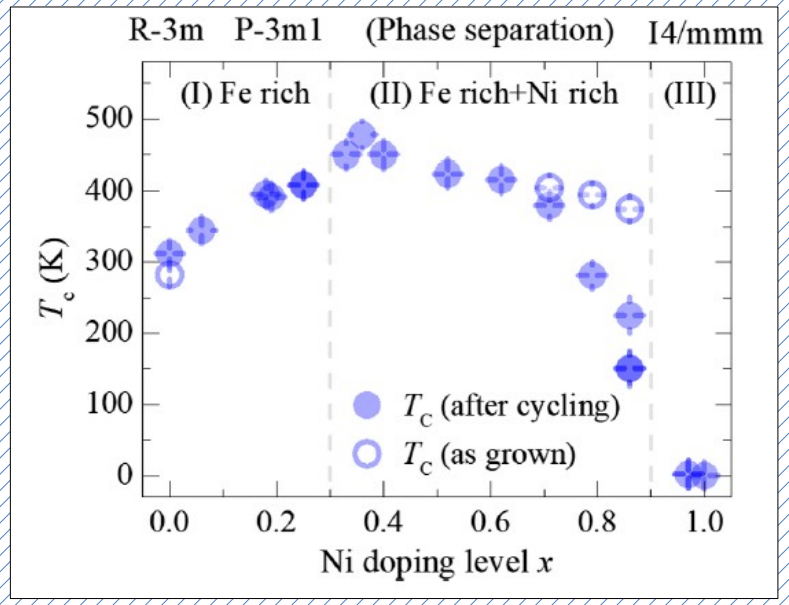
$T = 100$ K



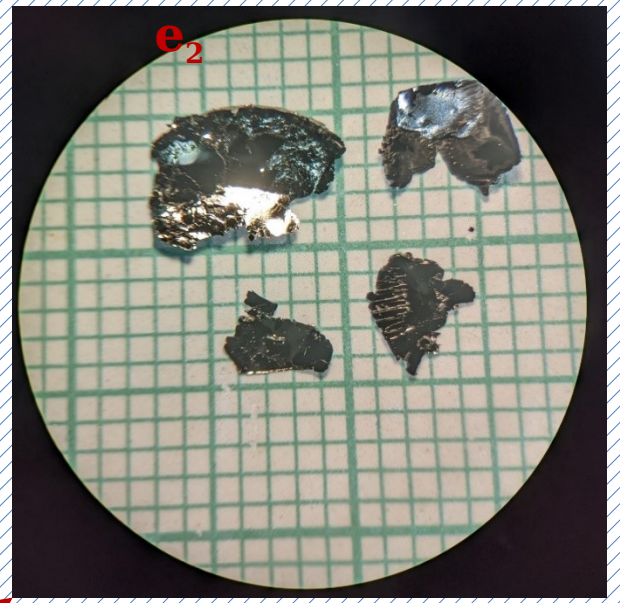


Very high Curie temperatures in $(Fe_\delta Ni_{1-\delta})_{5-x}GeTe_2$

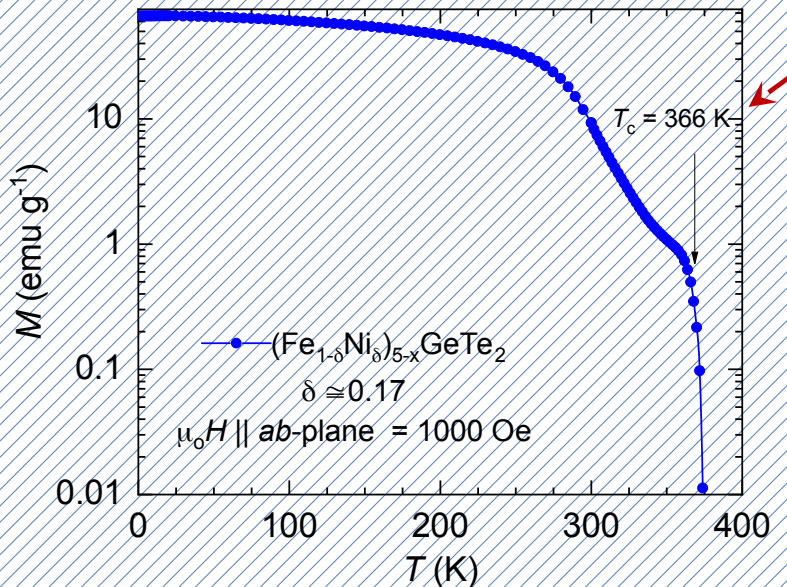




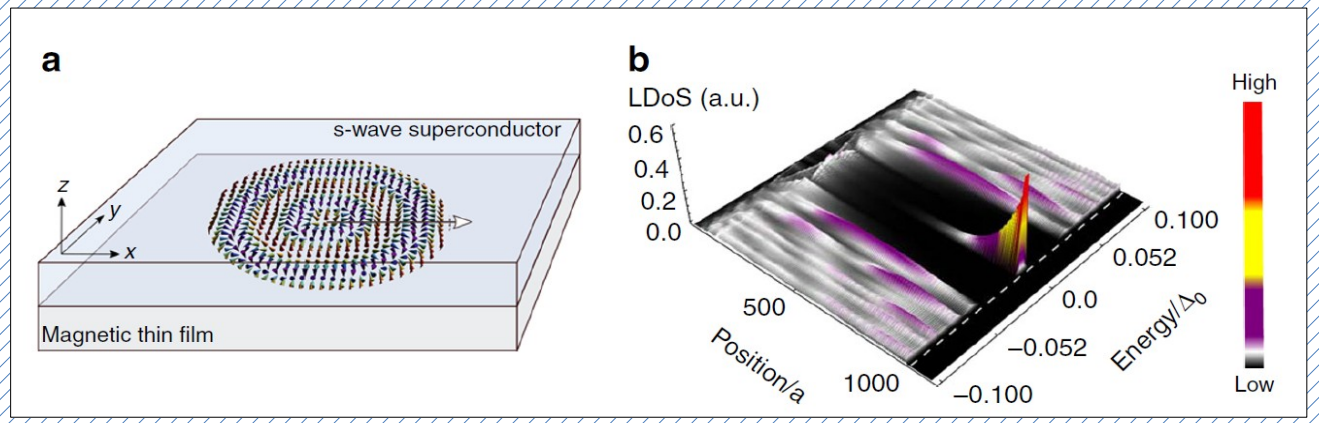
$Fe_{3.95}Ni_{0.67}GeT$



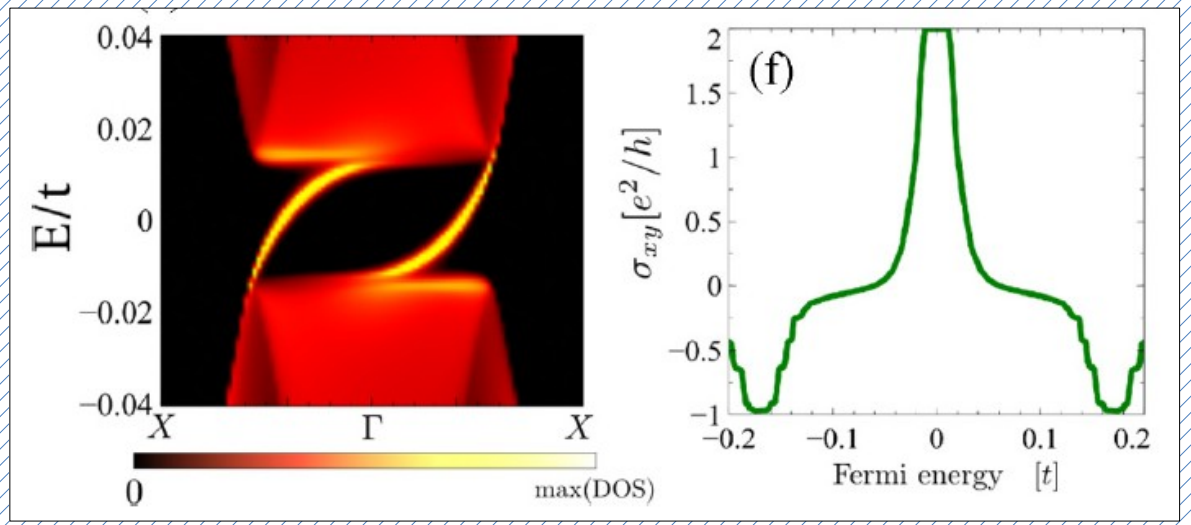
X. Chen *et al.*, PRL **128**, 217203 (2022)



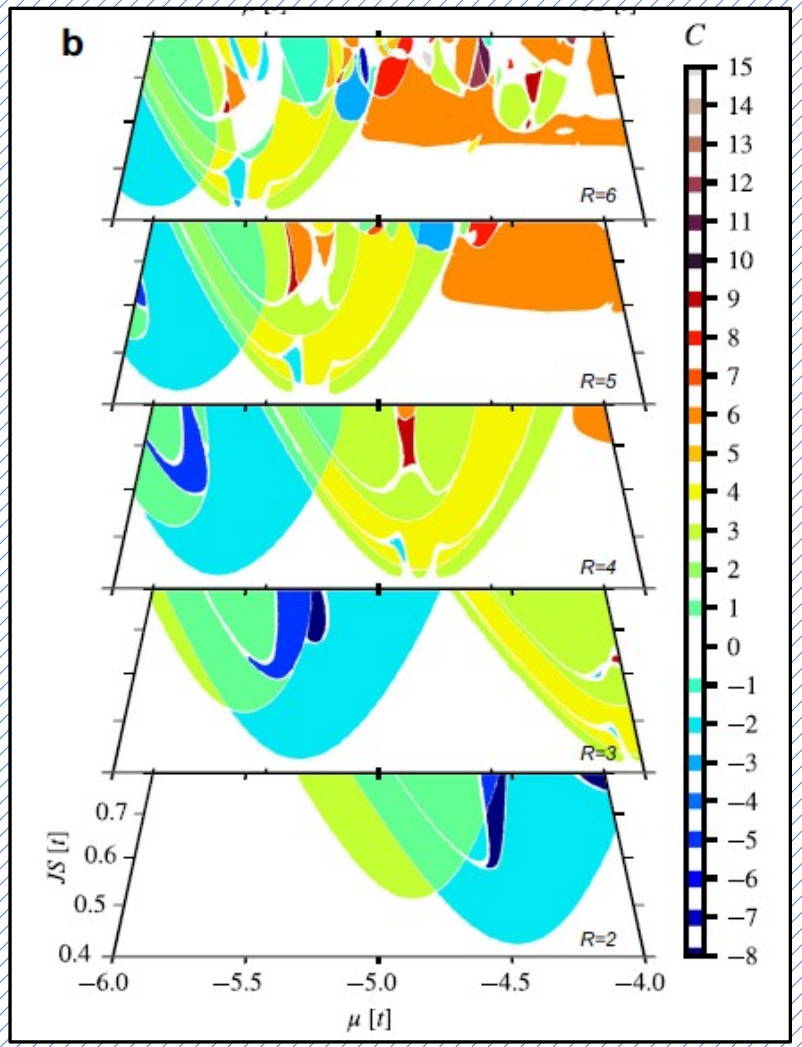
Skyrmions and SC for topological SC? QAH in graphene?



M. Garnier *et al.*, Commun. Phys. **2**: 126 (2019)

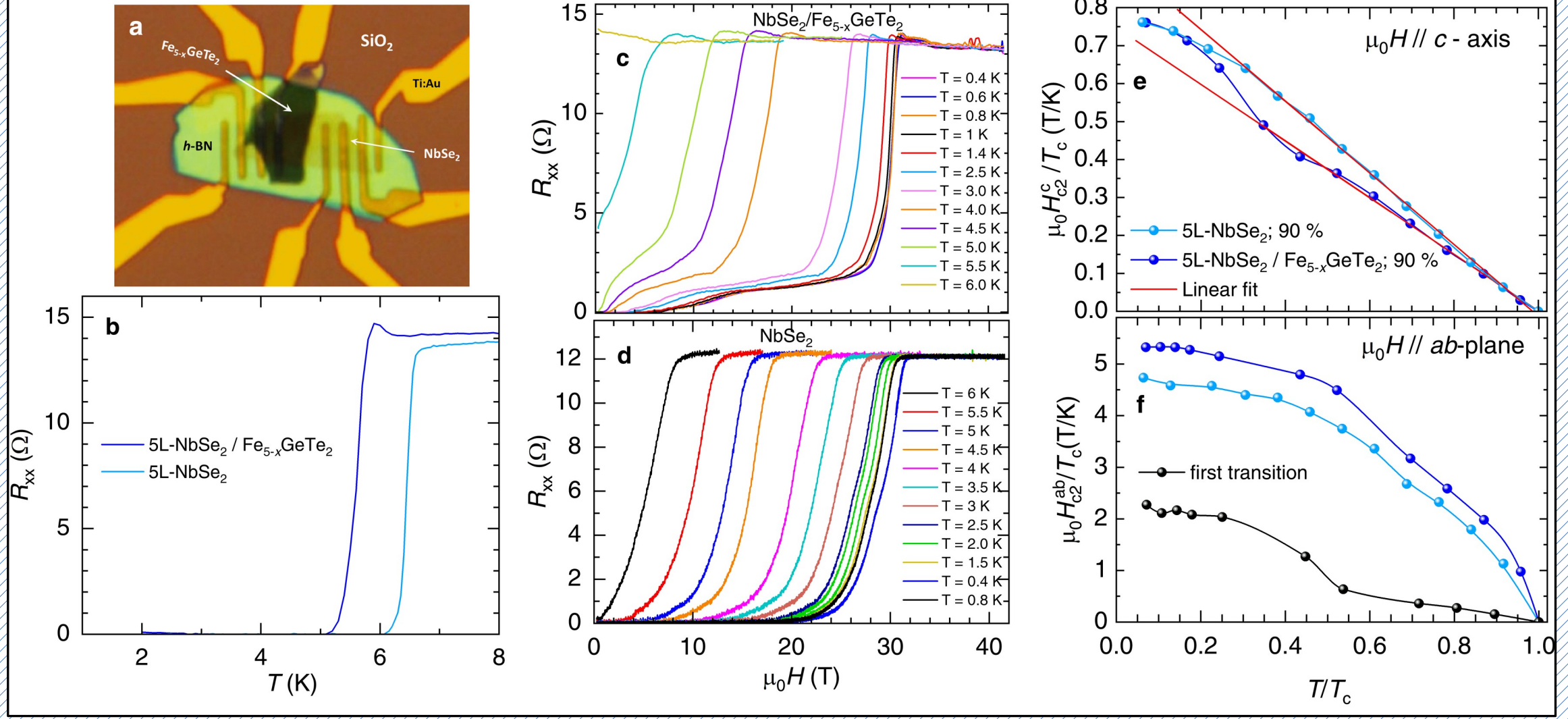


J. L Lado *et al.*, Phys. Rev. B **92**, 115433 (2015)



E. Mascot *et al.*, npj Quantum Mater. **6**, 6 (2021)

Novel superconducting phases in FM/SC heterostructures?



Iron distribution according to EDS