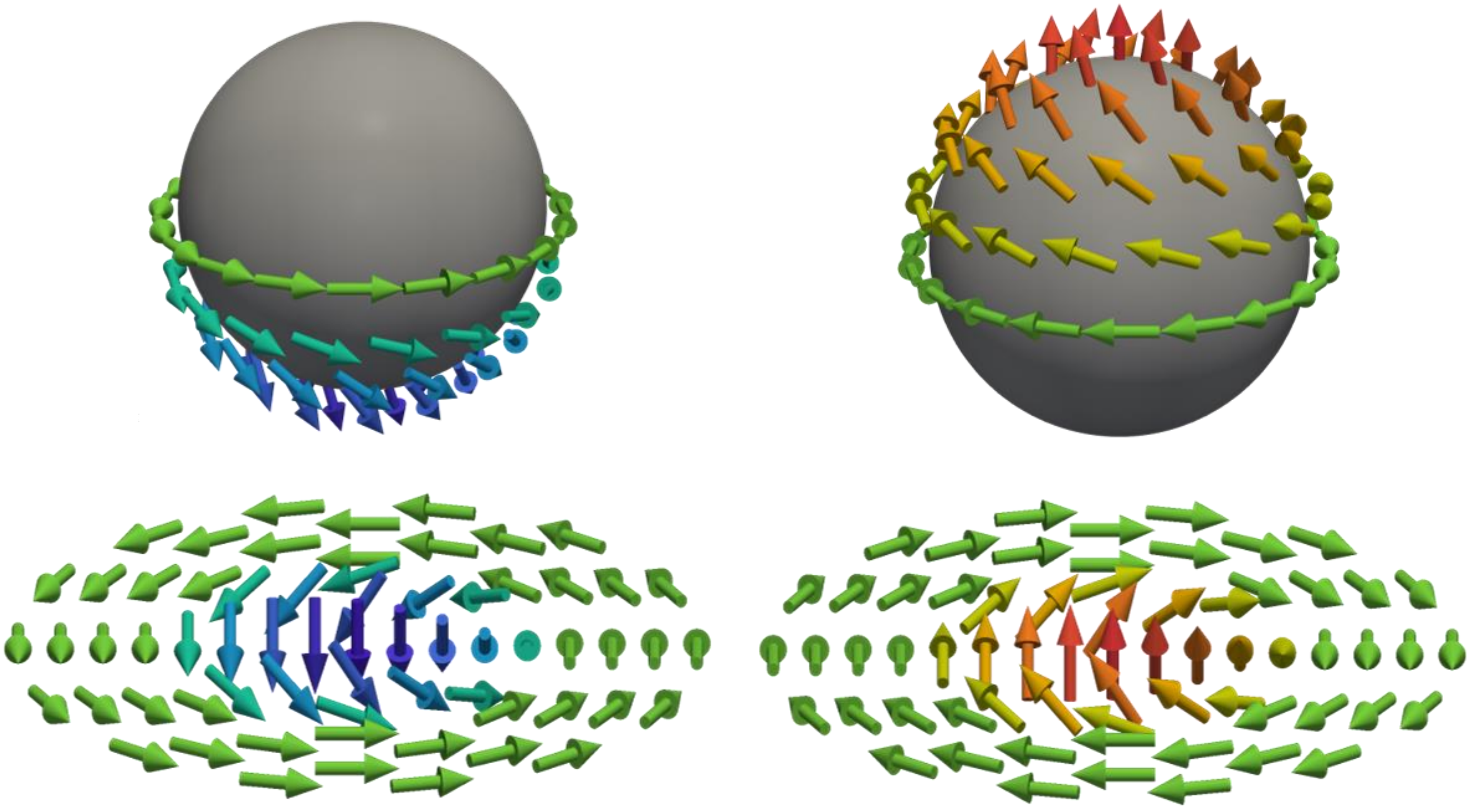
Exploring topological magnetic excitations with combined μ^+SR, site calculations and simulation



Tom Lancaster
Durham University, UK

Contemp. Phys. **60**, 246 (2019)

Acknowledgements

Funding: EPSRC (UK)

PSI: Thomas Hicken, Zaher Salman, Andreas Suter, Thomas Prokscha, Zurab Guguchia

Durham: Nathan Bentley, Theo Breeze, Matjaž Gomilšek, Kévin Franke, Peter Hatton, Murray Wilson, Zac Hawkhead

ISIS: Francis Pratt

Oxford: Ben Huddart, Stephen Blundell, Thorsten Hesjedal

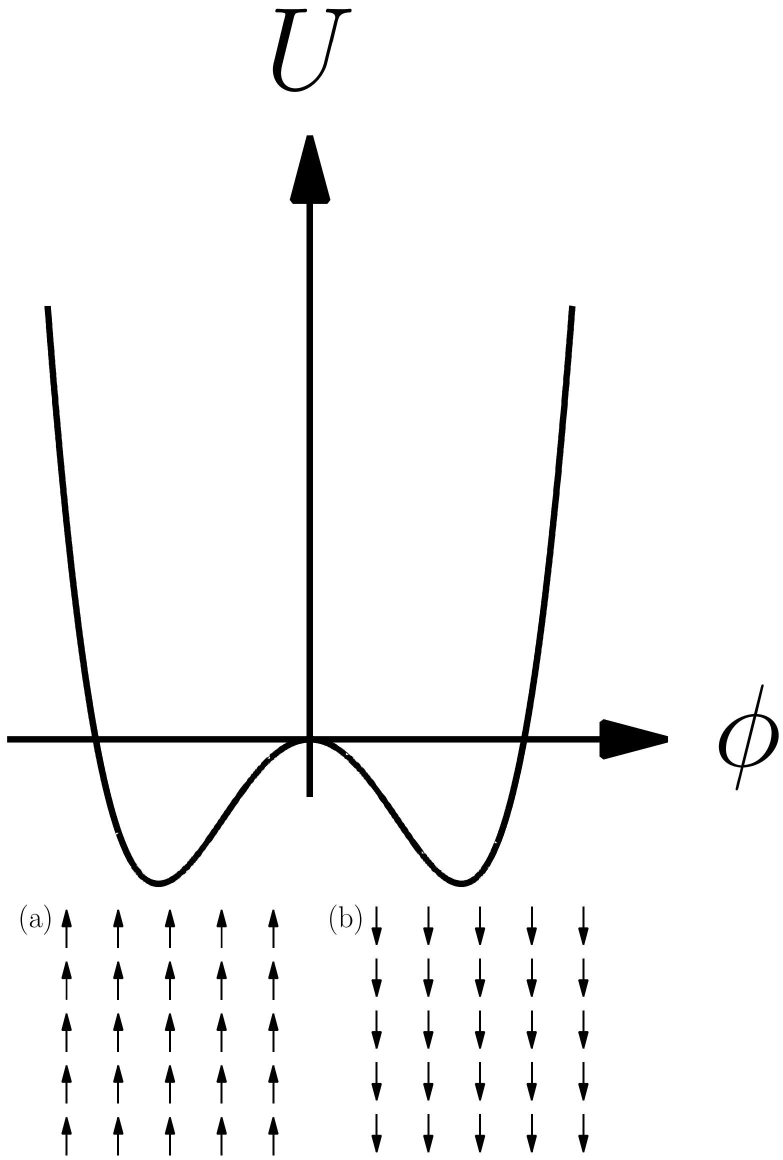
Warwick: Geetha Balakrishnan, Daniel Mayoh

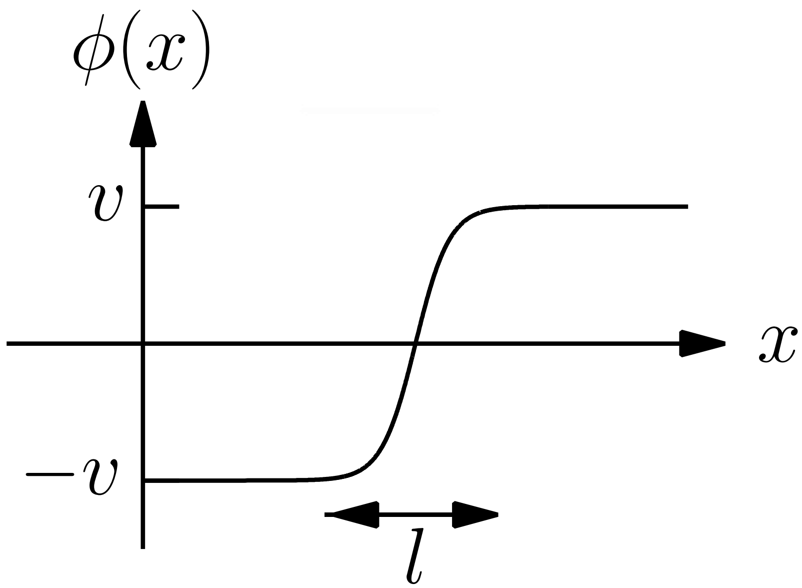
Throw a stone into some water…

… the energy dissipates away.

Some waves aren’t like this

Symmetry breaking and topology



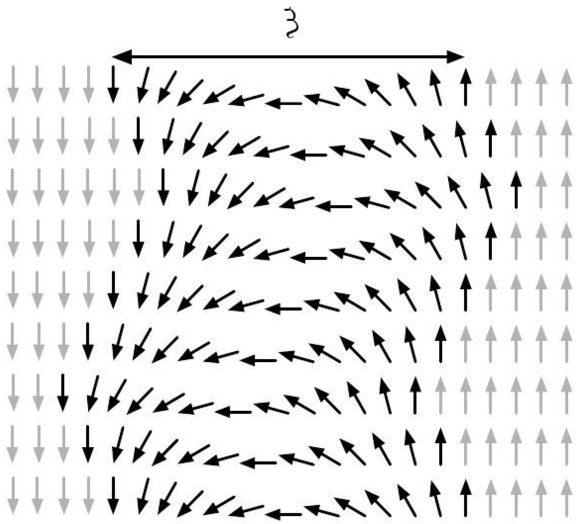


This is a domain wall

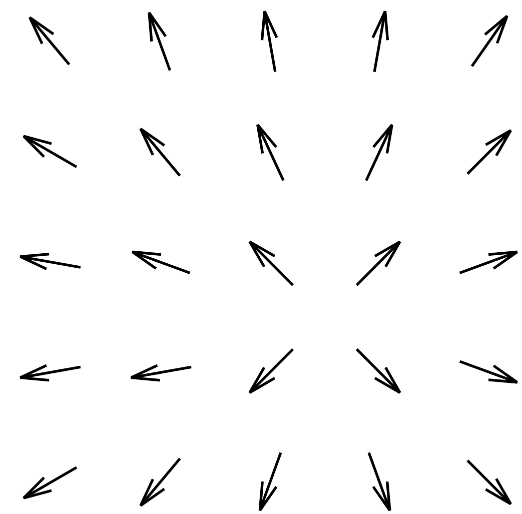
Lives in different ground states at infinity

Topological excitations in magnets:

Walls

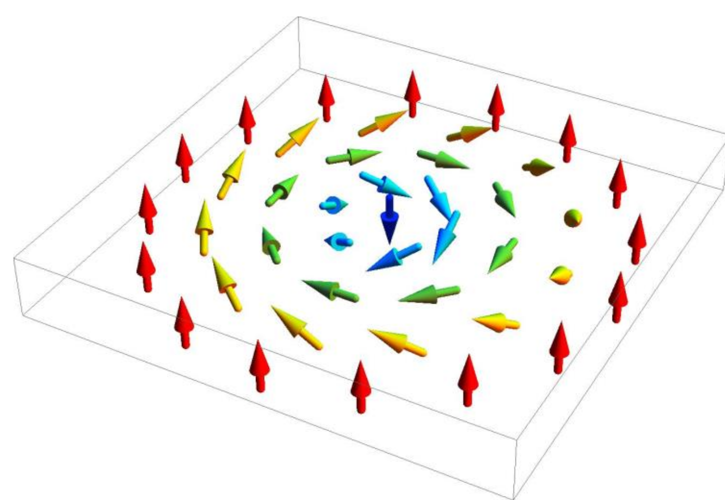


Vortices



Monopoles

Skyrmions



Topology on diverse energy scales: computational strategies

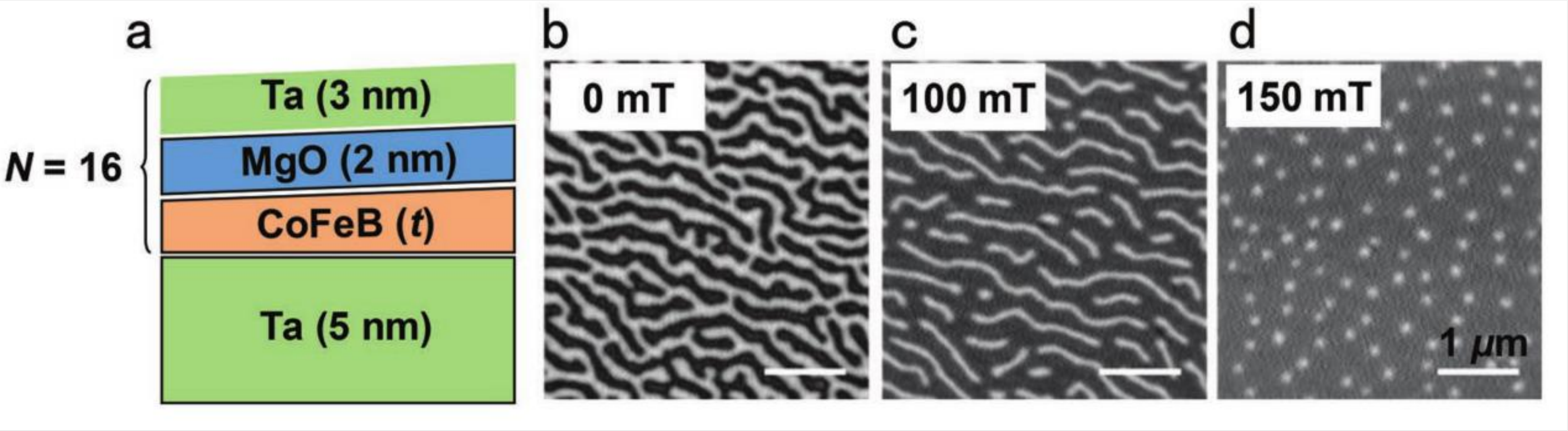
1. Depth dependence in thin magnetic films:
micromagnetics

2. Anisotropic skyrmion phases:
muon sites and single crystal measurements

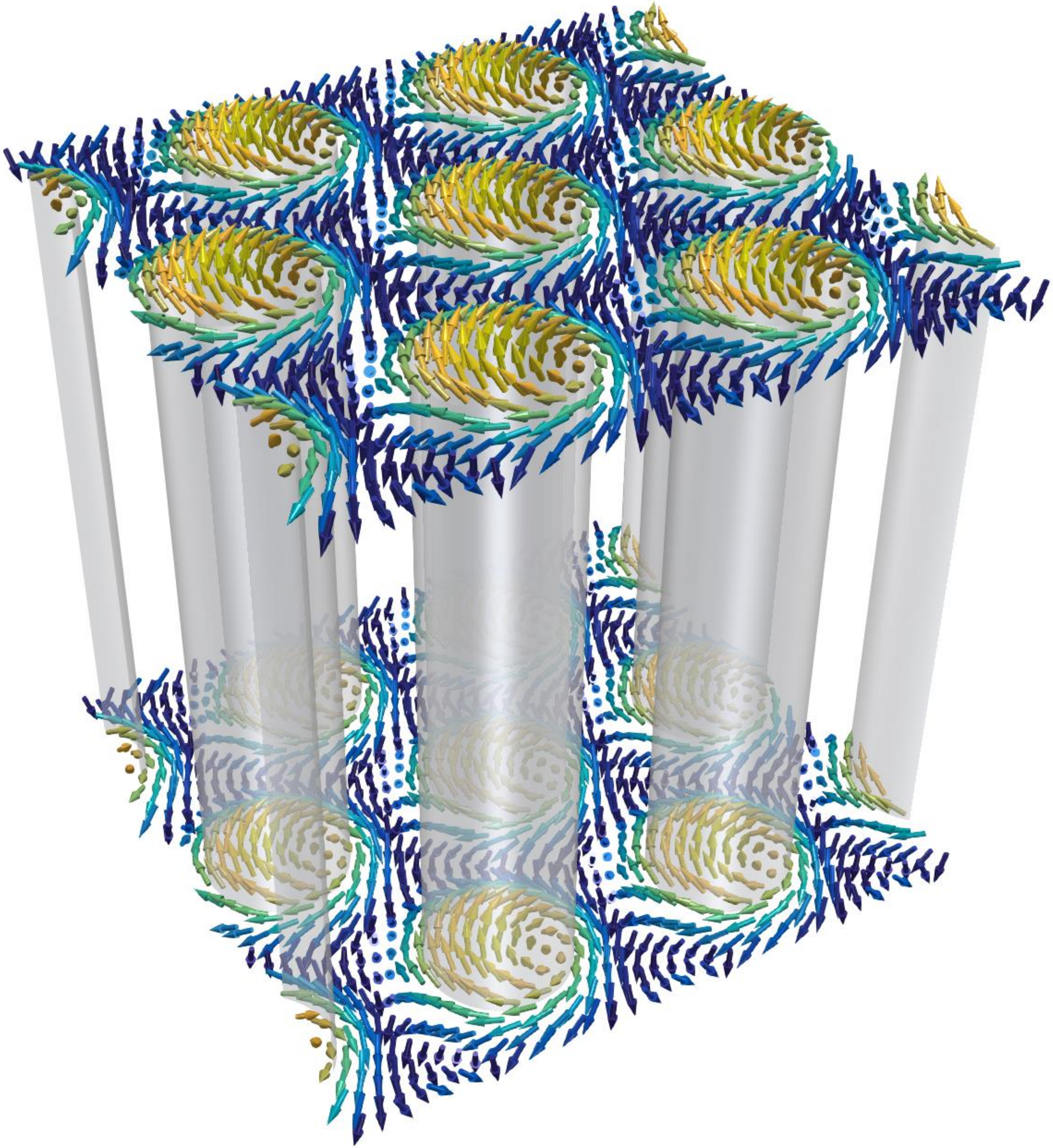
3. Transition metal dichalcogenides:
electronic band structure

Message: this is unlocked by muon site determination

Part 1: Depth dependence in skyrmion- hosting Ta/[CoFeB/MgO/Ta]$_{16}$



L. Liu *et al.*, Adv. Mater **31,** 1807683 (2019)
TJH *et al.*, Phys Rev B **109,** 134423 (2024)



What leads to topological magnetic states?

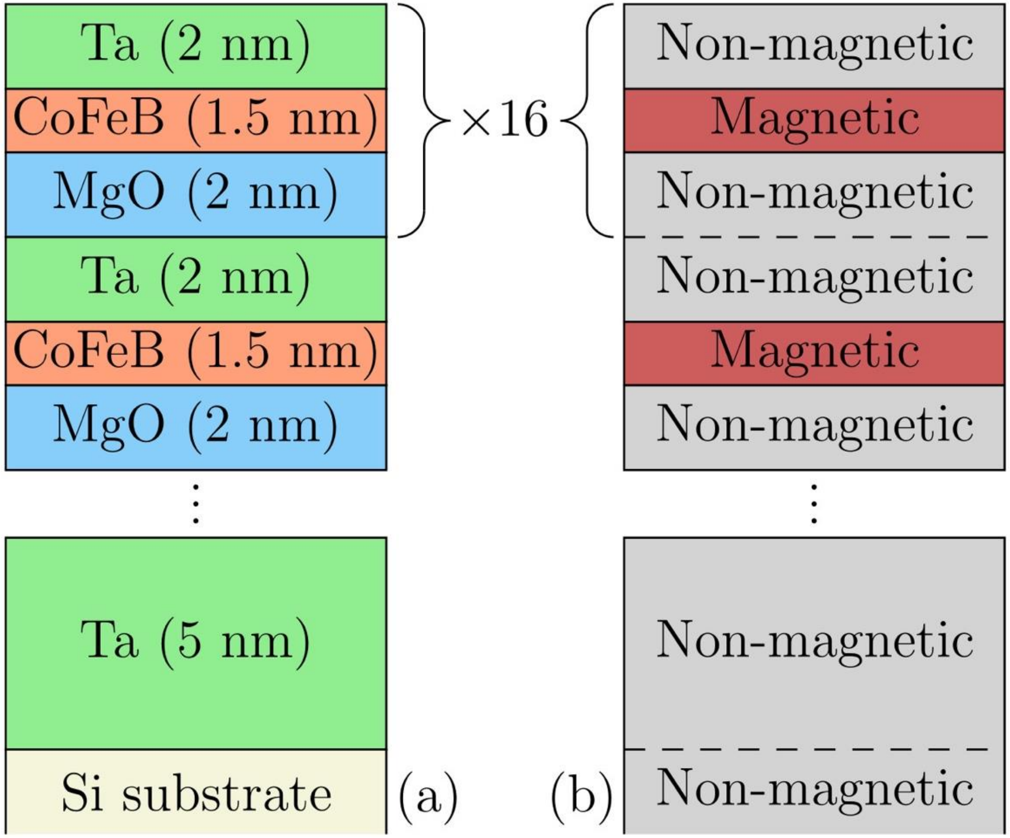
Three ingredients in an effective Hamiltonian

- Exchange interaction, *J*
- Dzyaloshinskii-Moriya interaction, ***D***
- Single-ion anisotropy
- Applied magnetic field, ***B***

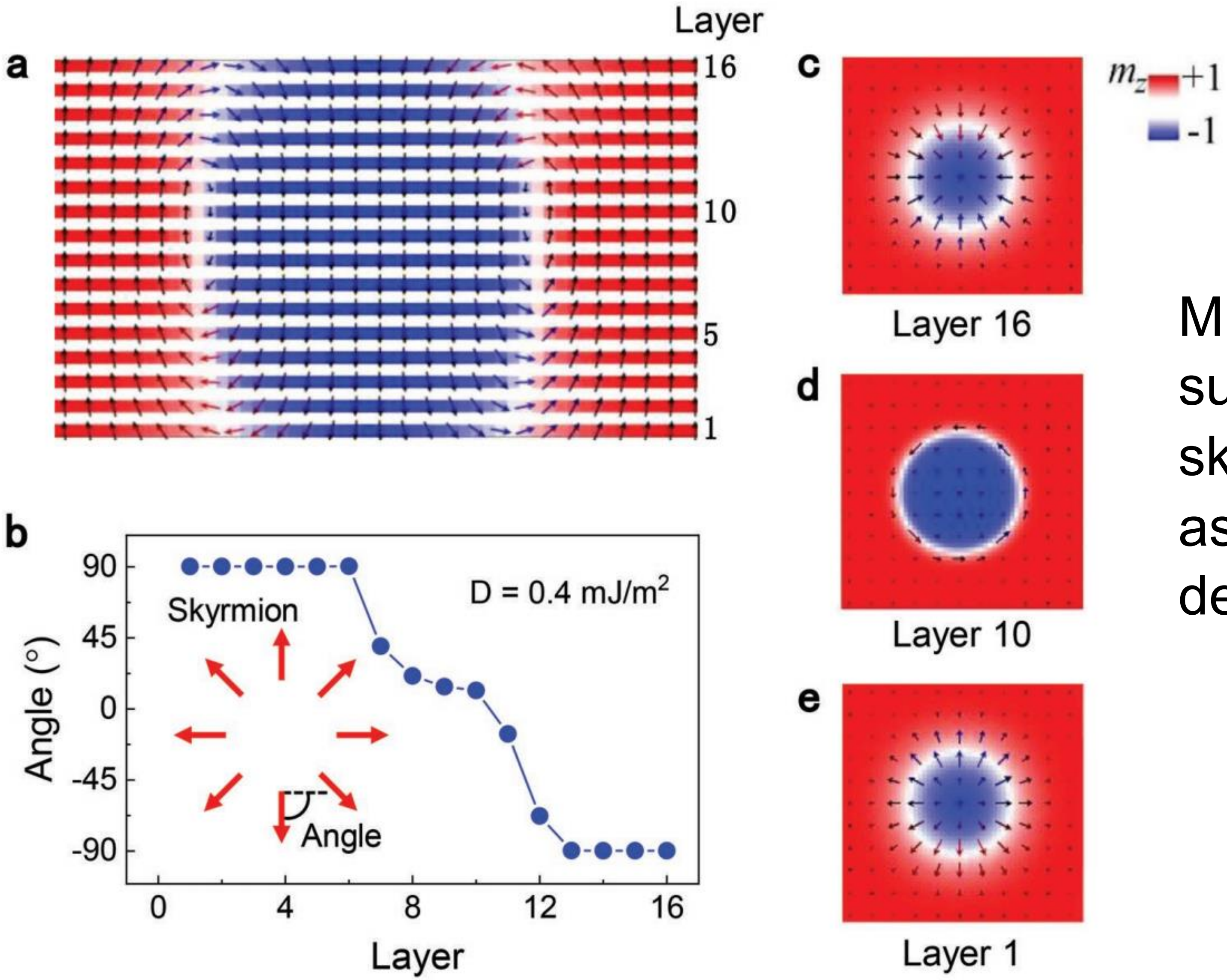
$$\mathcal{H} = \underbrace{-J\sum_{ij}\boldsymbol{S}_i\cdot\boldsymbol{S}_j}_{\text{Align spins}} + \underbrace{\sum_{ij}\boldsymbol{D}\cdot\left(\boldsymbol{S}_i\times\boldsymbol{S}_j\right)}_{\text{twist spins}} + \underbrace{g\boldsymbol{S}\cdot\boldsymbol{B}}_{\text{Stabilise}}$$

Interpretation in micromagnetics

$$H = -A\boldsymbol{m}\cdot\boldsymbol{\nabla}^2\boldsymbol{m} + D\left(\boldsymbol{m}\cdot\boldsymbol{\nabla}m_z - m_z\boldsymbol{\nabla}\cdot\boldsymbol{m}\right) - K\left(\boldsymbol{m}\cdot\boldsymbol{u}\right)^2 - \frac{1}{2}\mu_0 M_s \boldsymbol{m}\cdot\boldsymbol{H}_d$$



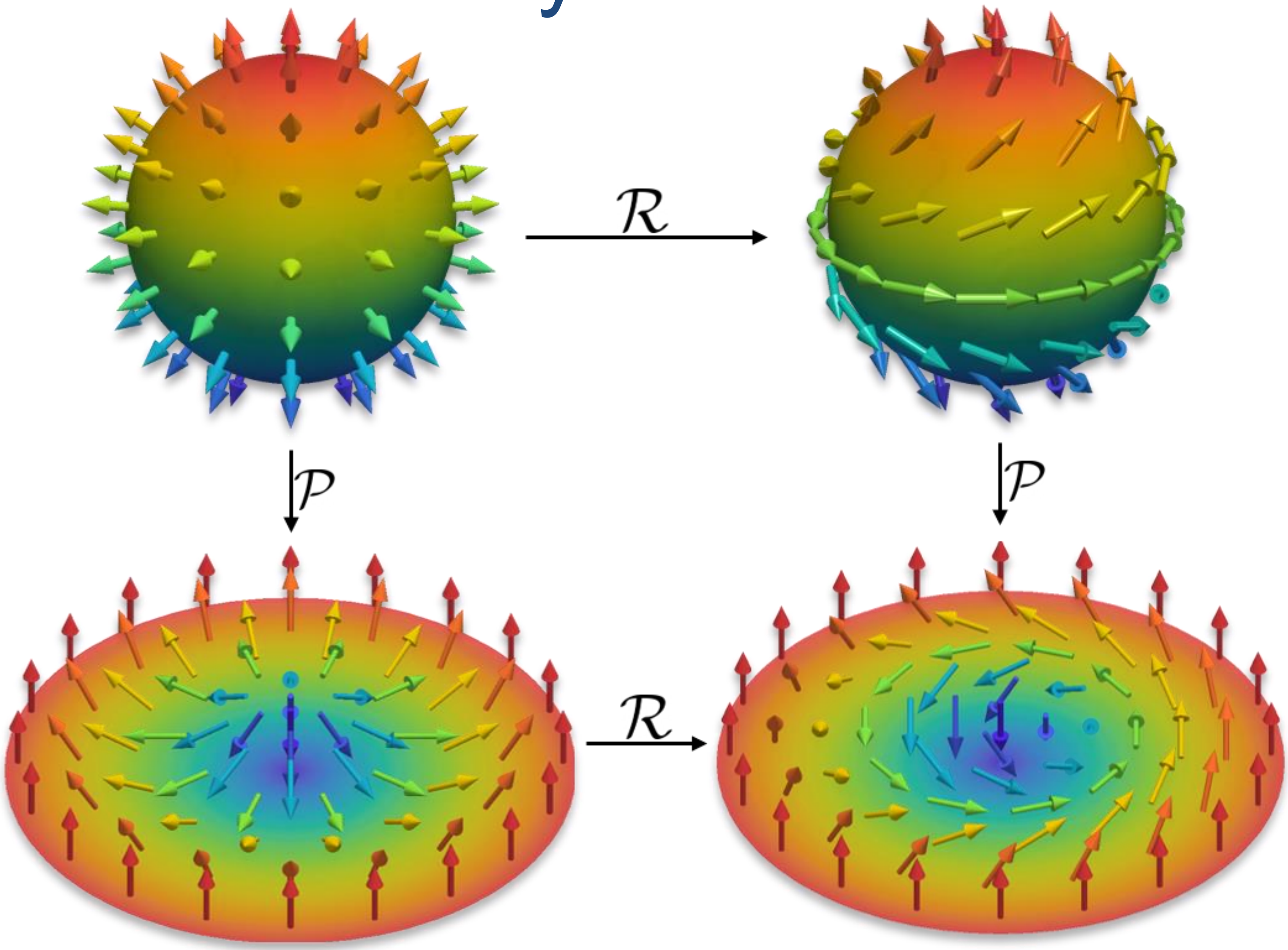
Multilayer skyrmion system
Ta/[CoFeB/MgO/Ta]$_{16}$



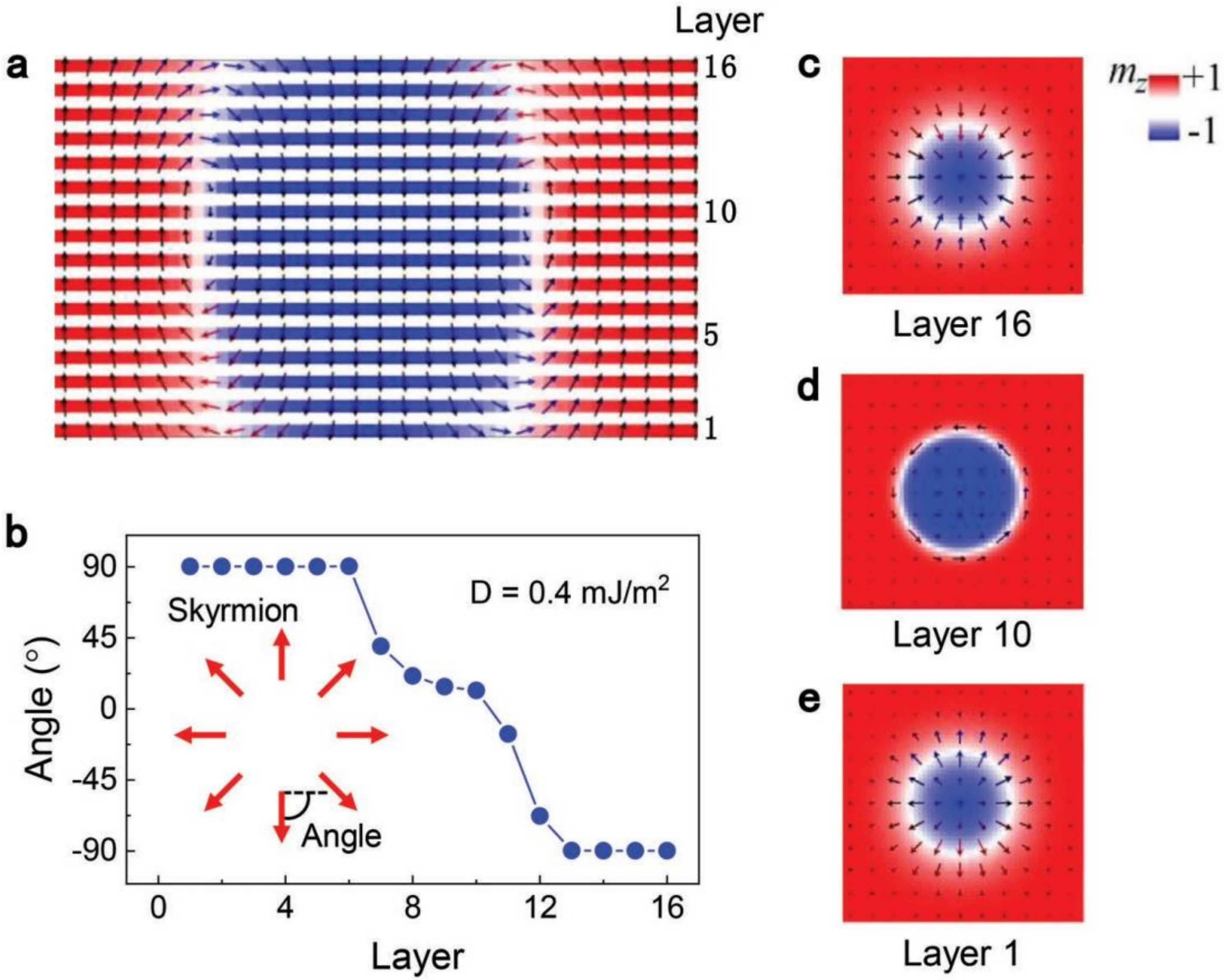
Micromagnetics suggest the skyrmions change as a function of depth

Contemp. Phys. **60**, 246 (2019)

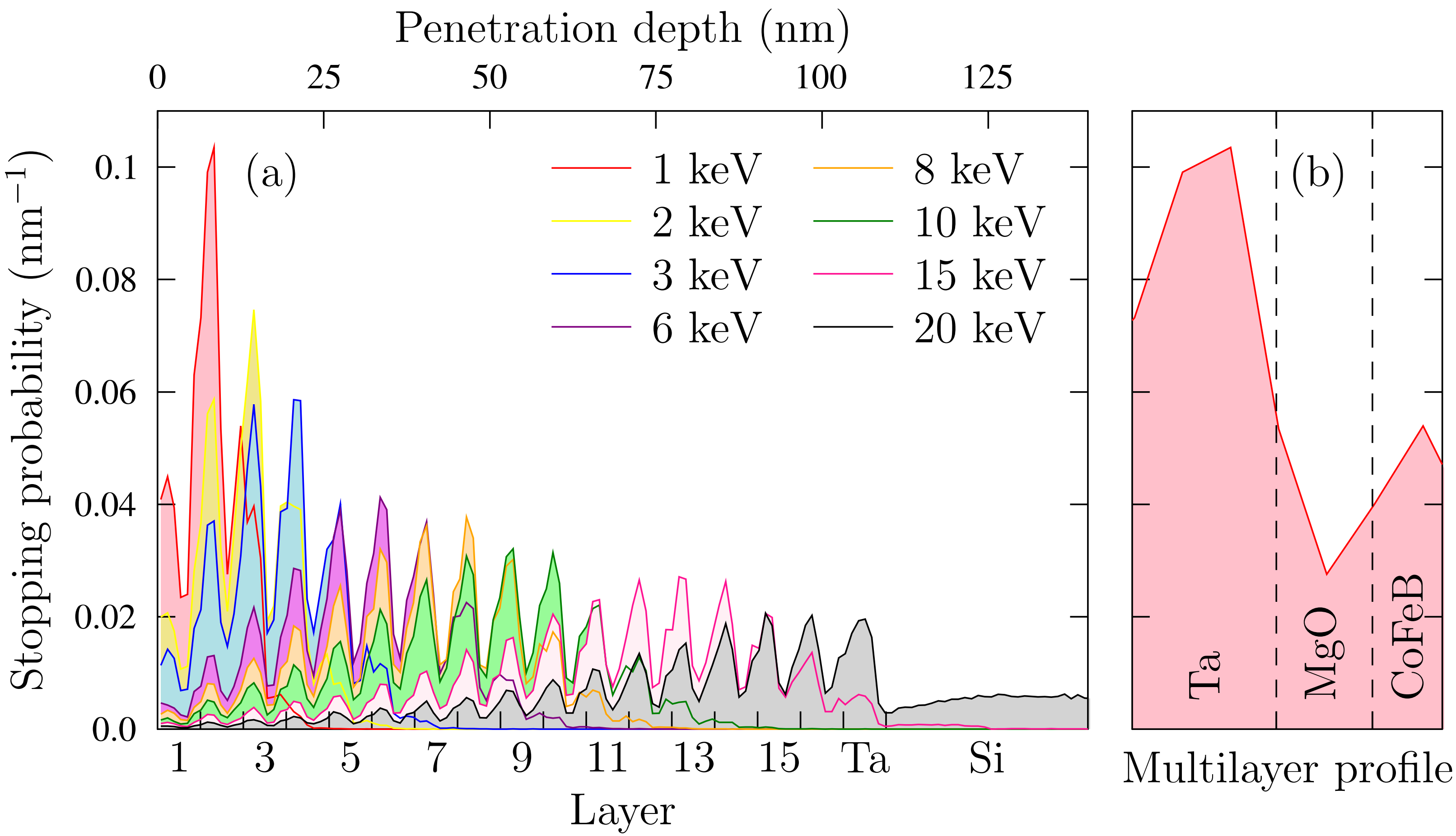
Skyrmions



Can we test this prediction?

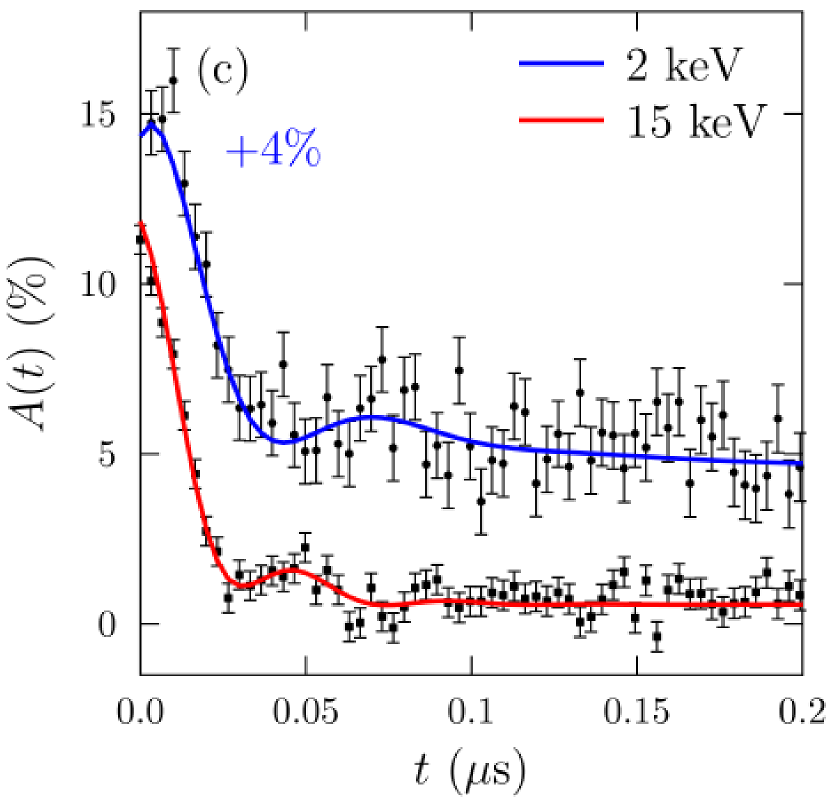


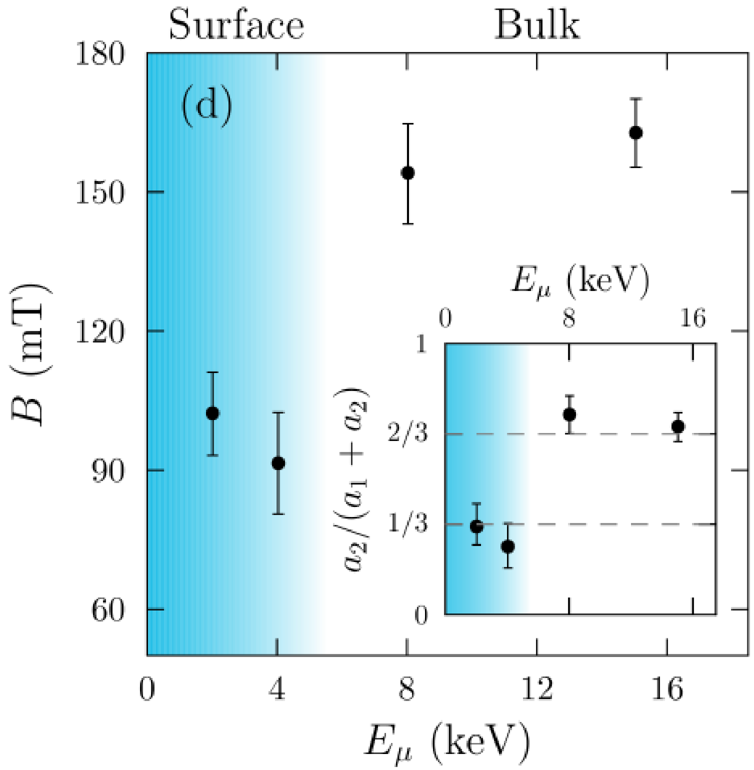
LEM measurements



Rule of thumb: approximately 1 keV per multilayer

ZF LE results





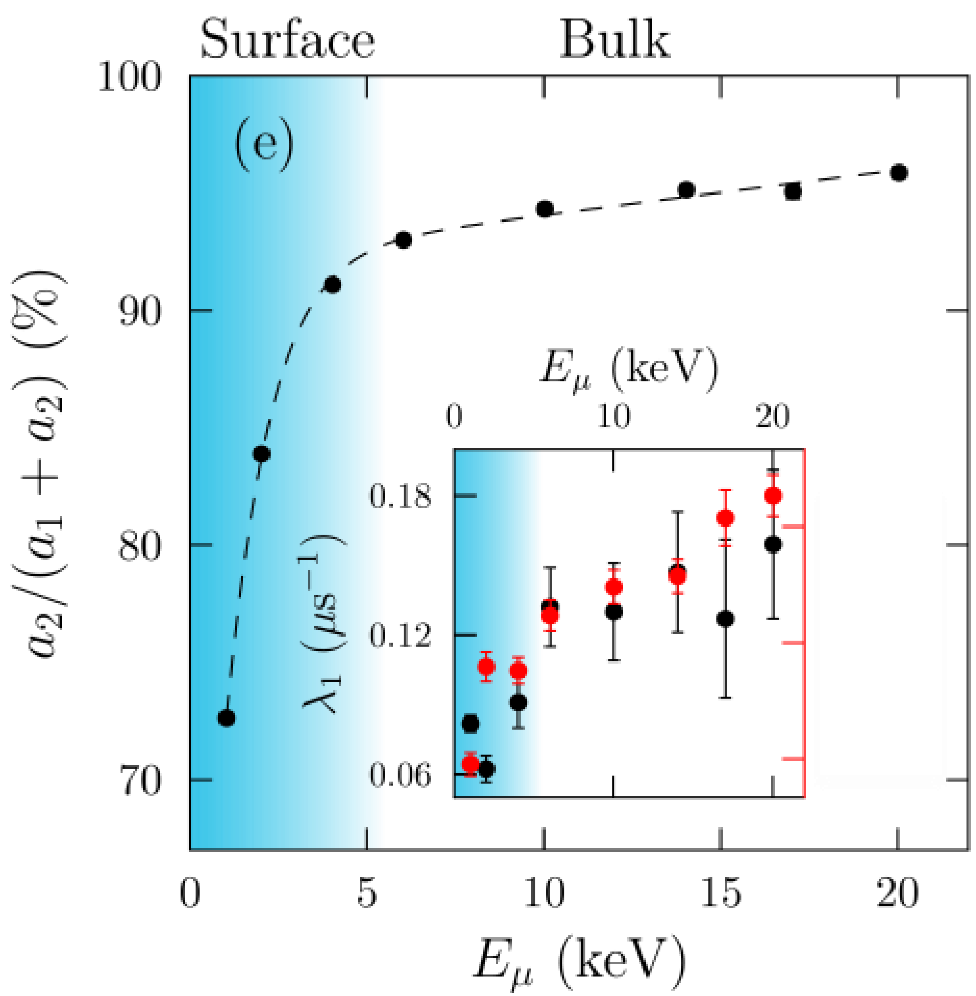
Change in the magnetic structure suggested below layer 5

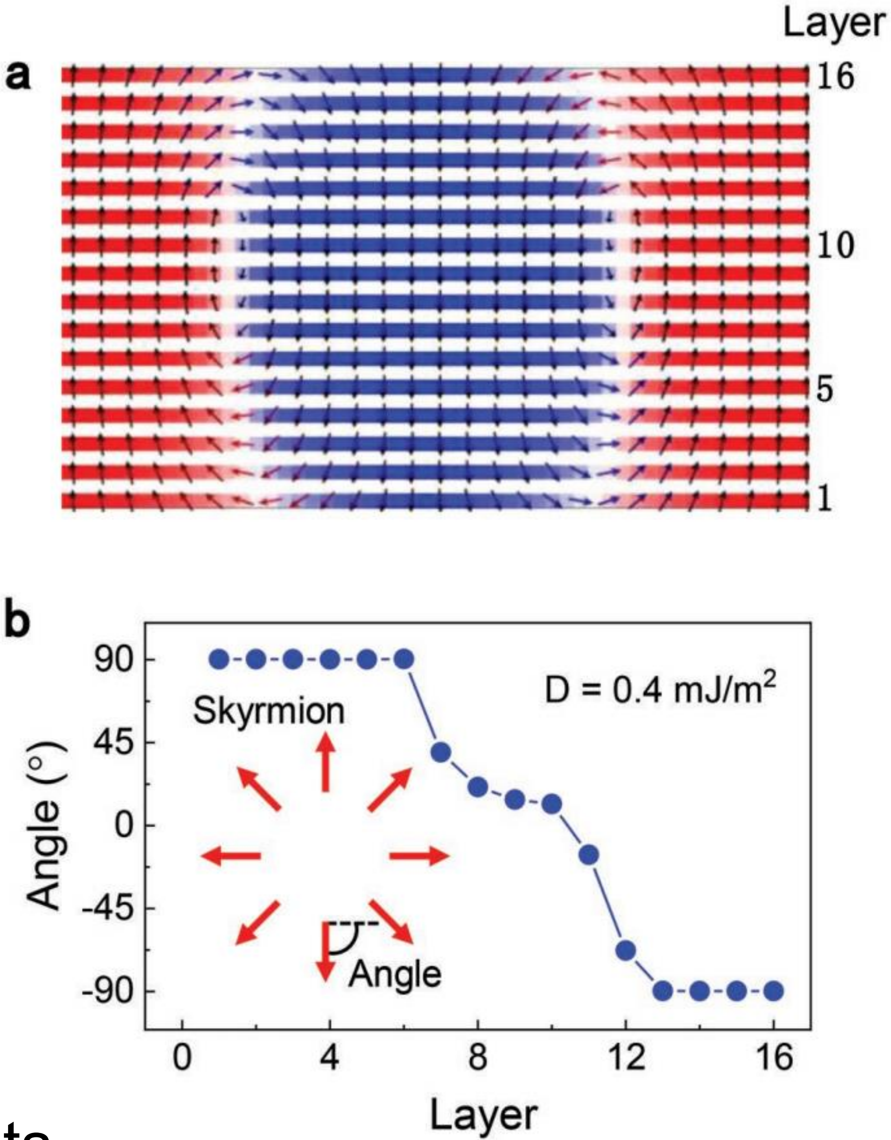
Underlying magnetic state: disordered domain walls

TJ Hicken *et al.*, Phys Rev B **109,** 134423 (2024)

TJ Hicken *et al*., Phys Rev B **109,** 134423 (2024)

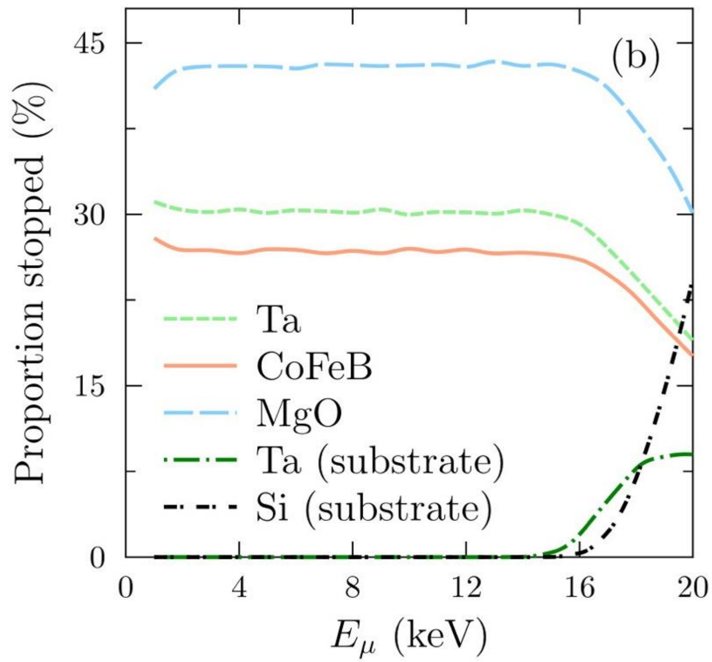
LEM results





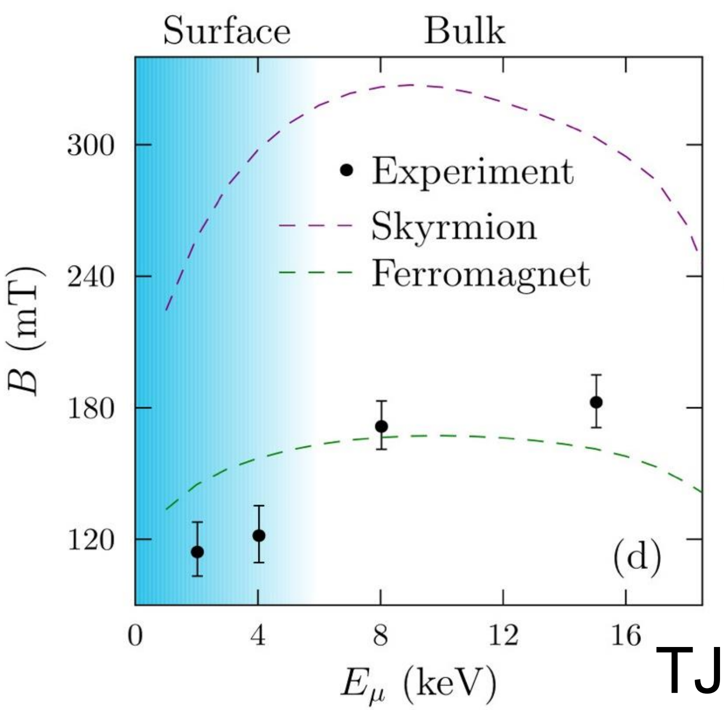
Same effect seen in wTF measurements, showing change around layer 5

Interpretation of muon result



$$H = -A\boldsymbol{m}\cdot\boldsymbol{\nabla}^2\boldsymbol{m} + D\left(\boldsymbol{m}\cdot\boldsymbol{\nabla}m_z - m_z\boldsymbol{\nabla}\cdot\boldsymbol{m}\right) - K\left(\boldsymbol{m}\cdot\boldsymbol{u}\right)^2 - \frac{1}{2}\mu_0 M_s\boldsymbol{m}\cdot\boldsymbol{H}_d$$

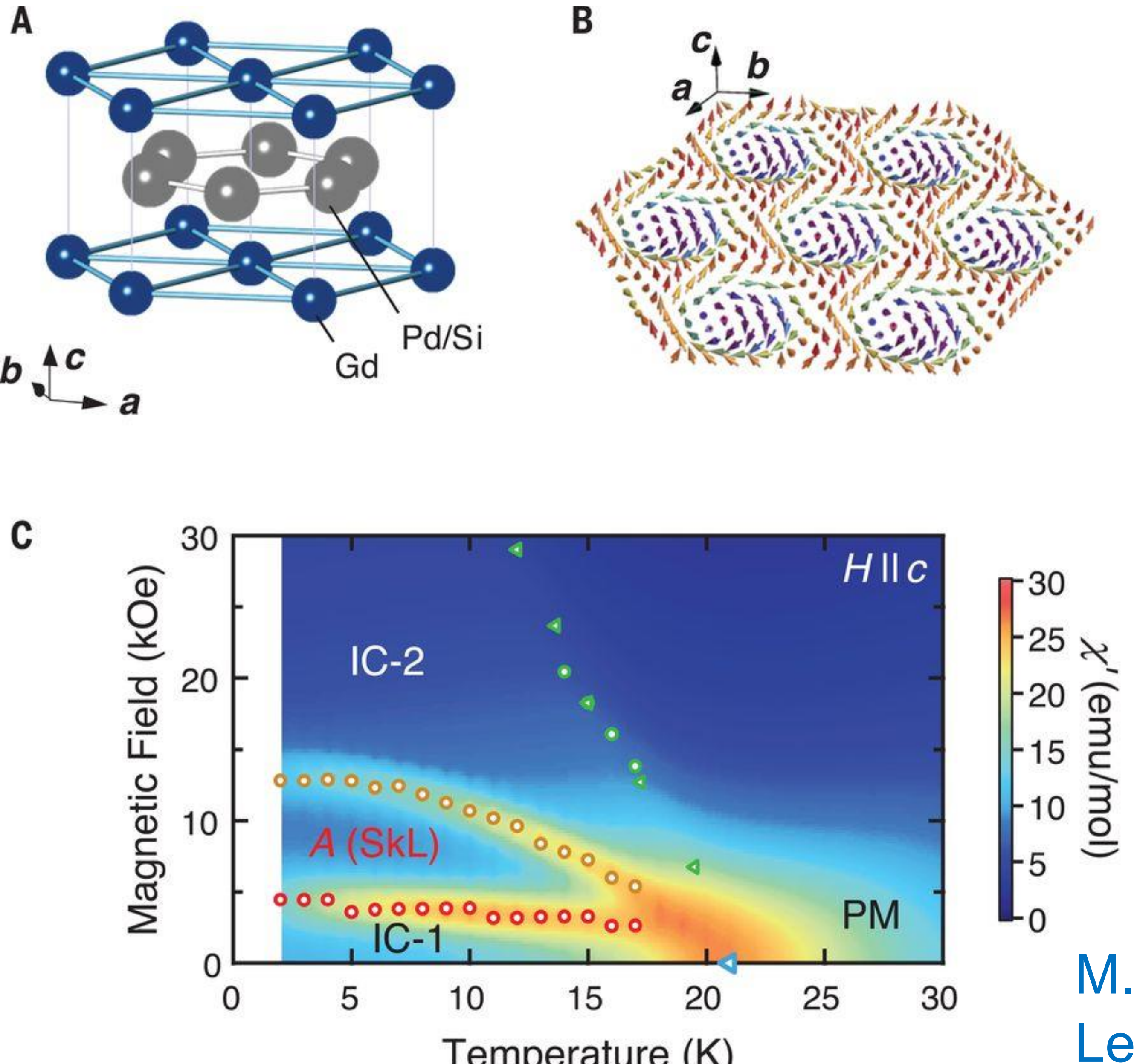
Oscillations from muons in nonmagnetic layers,



Sensitive to ferromagnetic regions between domain walls

TJ Hicken *et al*., Phys Rev B **109,** 134423 (2024)

Part 2: Anisotropy in Gd_2PdSi_3



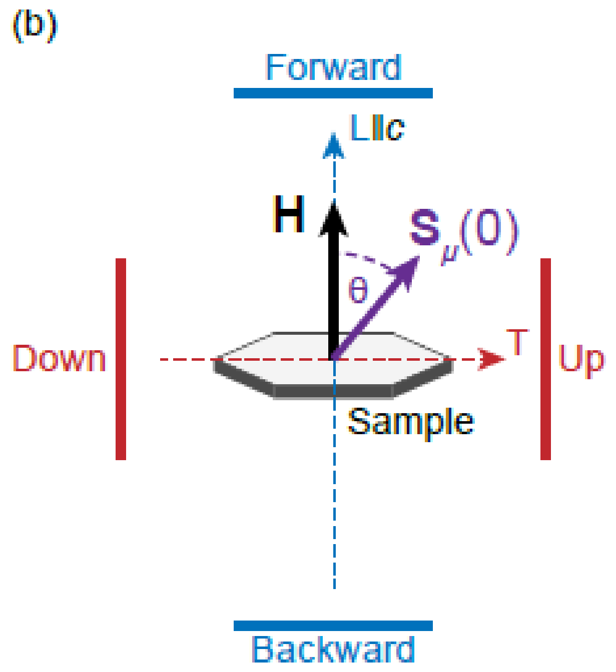
Centrosymmetric skyrmion host

Claims of frustration-induced skyrmions

No consensus on formation mechanism

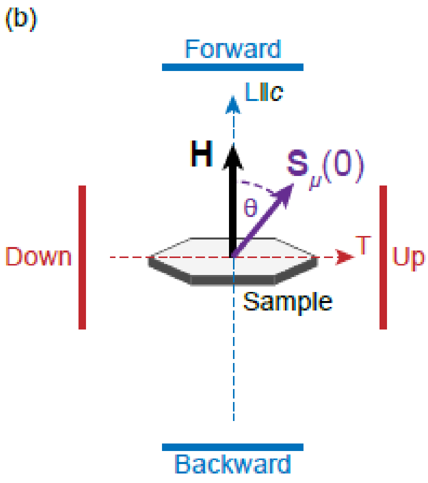
M. Gomilsek *et al.*, Phys. Rev. Lett. **134**, 046702 (2025)

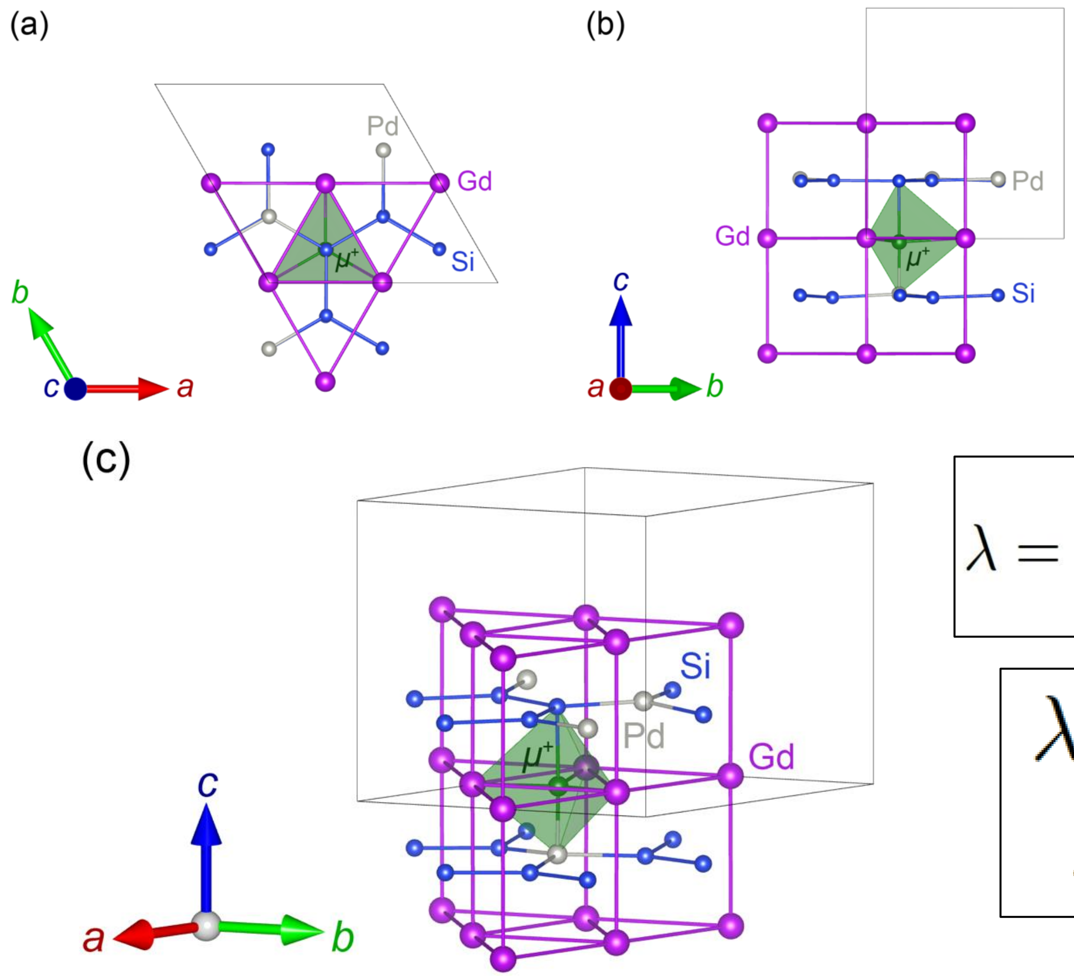
Single-crystal measurements are the key…



Spin rotator measurements using GPS at PSI

Combined with muon sites…



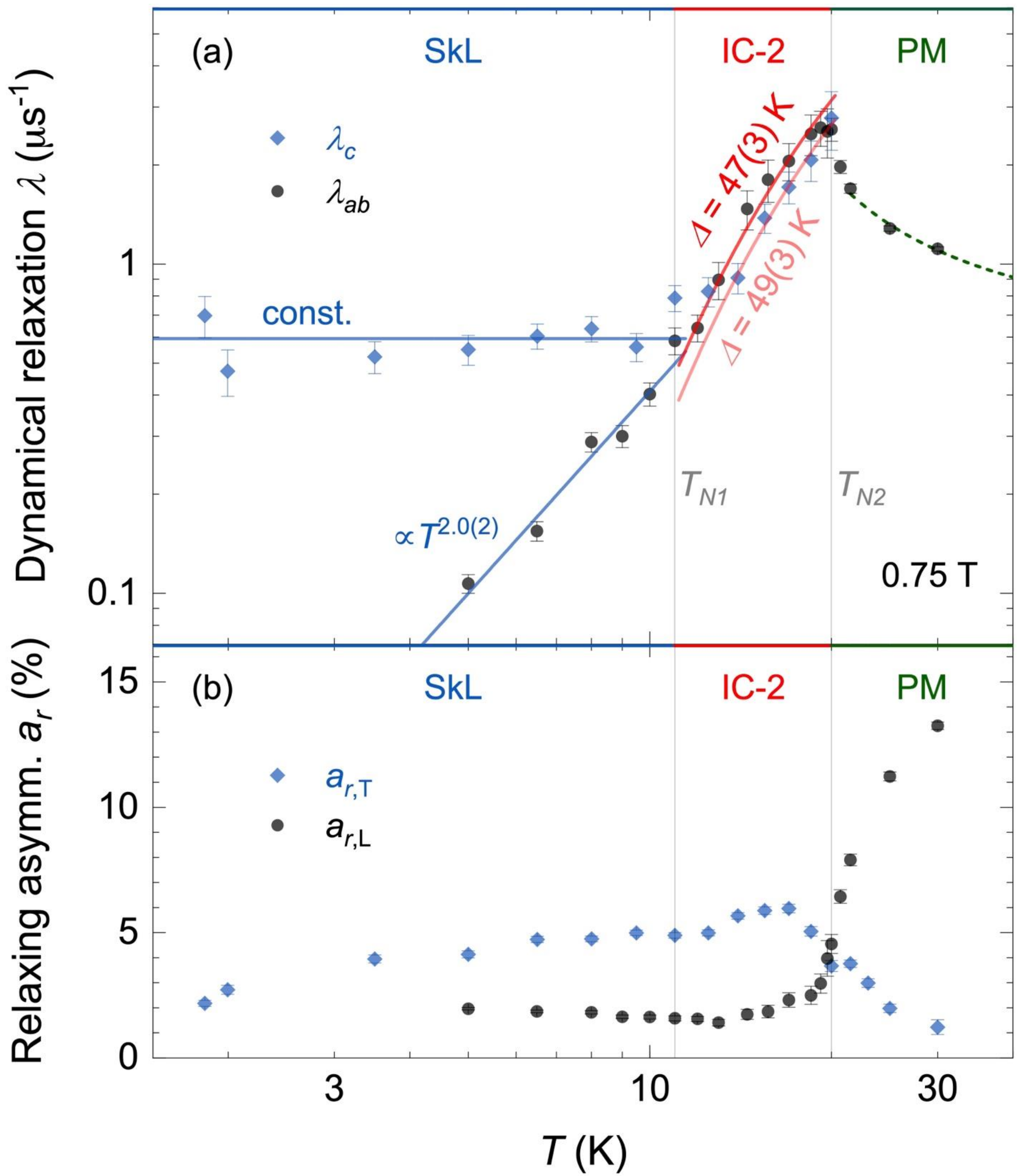


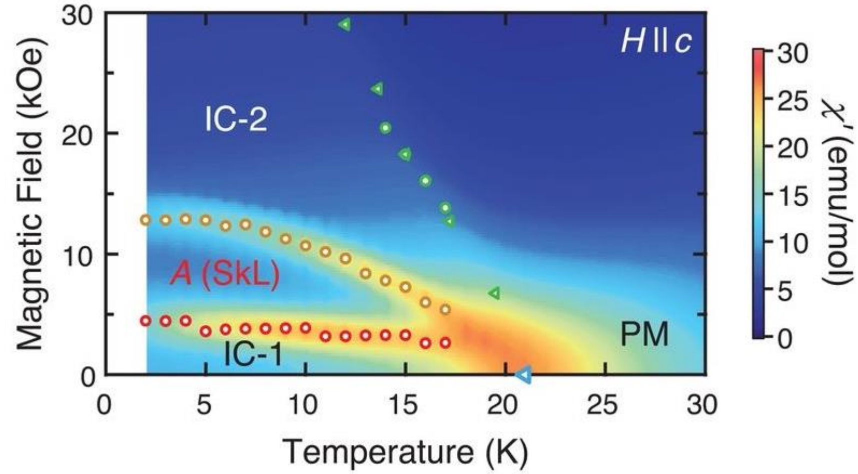
$$\lambda = \int_0^\infty \cos(\omega_0 t)[\Phi_{xx}(t) + \Phi_{yy}(t)]\,dt$$

$$\lambda_{ab} = \lambda_L/2$$
$$\lambda_c = \lambda_T - \lambda_L/2$$

In-/out-of-plane Gd^{3+} spin ⇒in-/out-of-plane magnetic field at muon site

Role of anisotropy in Gd_2PdSi_3





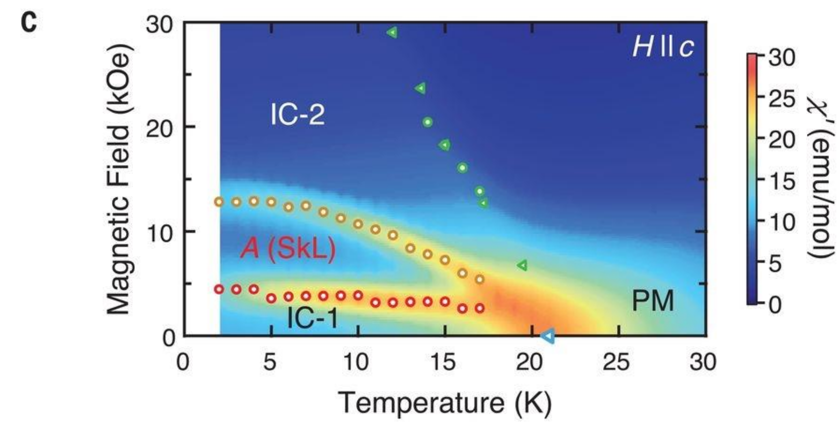
Skyrmion phase: highly anisotropic.

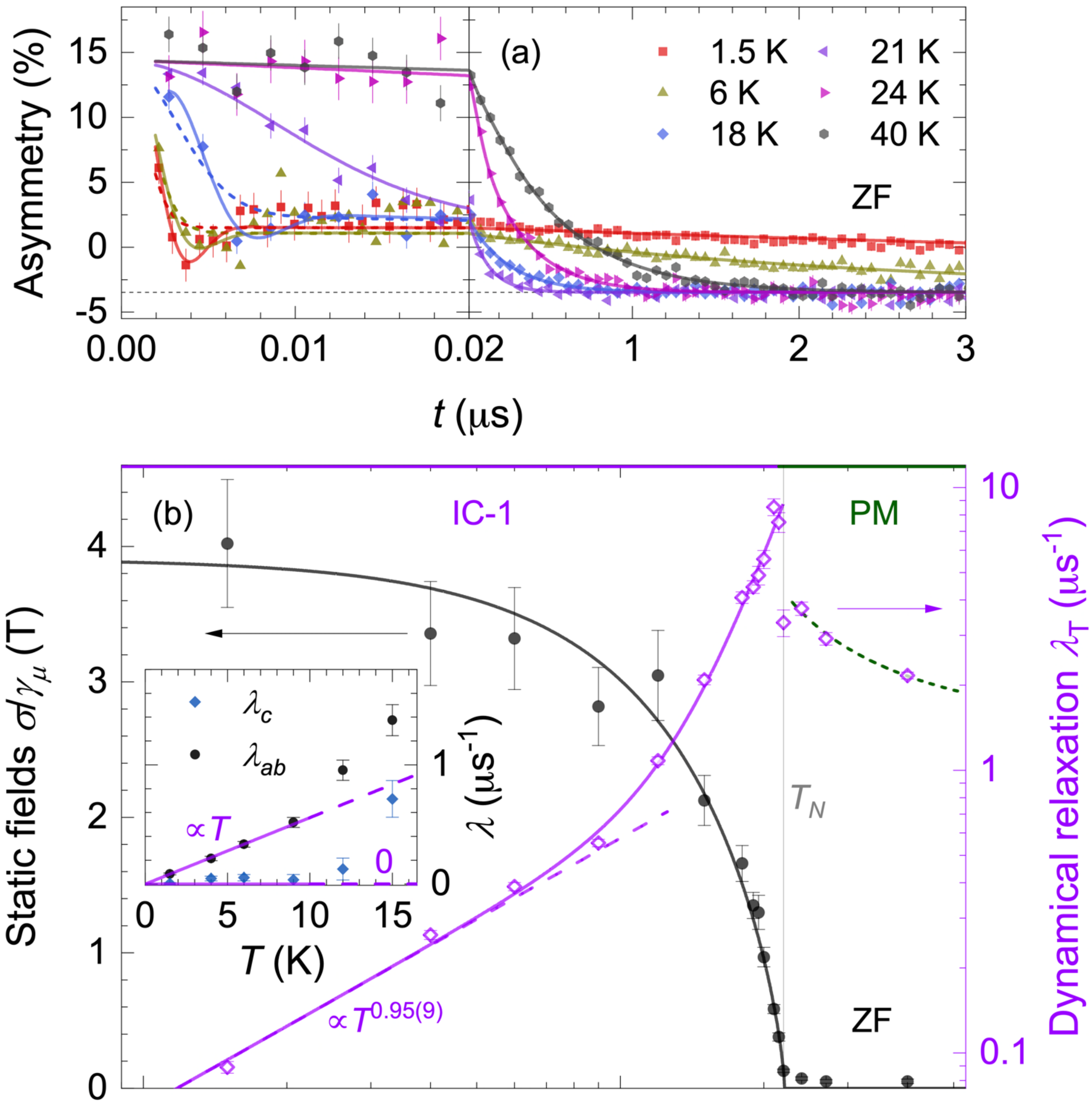
Out-of-plane fluctuations are dominant

Message: anisotropy crucial

Role of anisotropy in Gd_2PdSi_3

M. Gomilsek *et al.*, Phys. Rev. Lett. **134**, 046702 (2025)





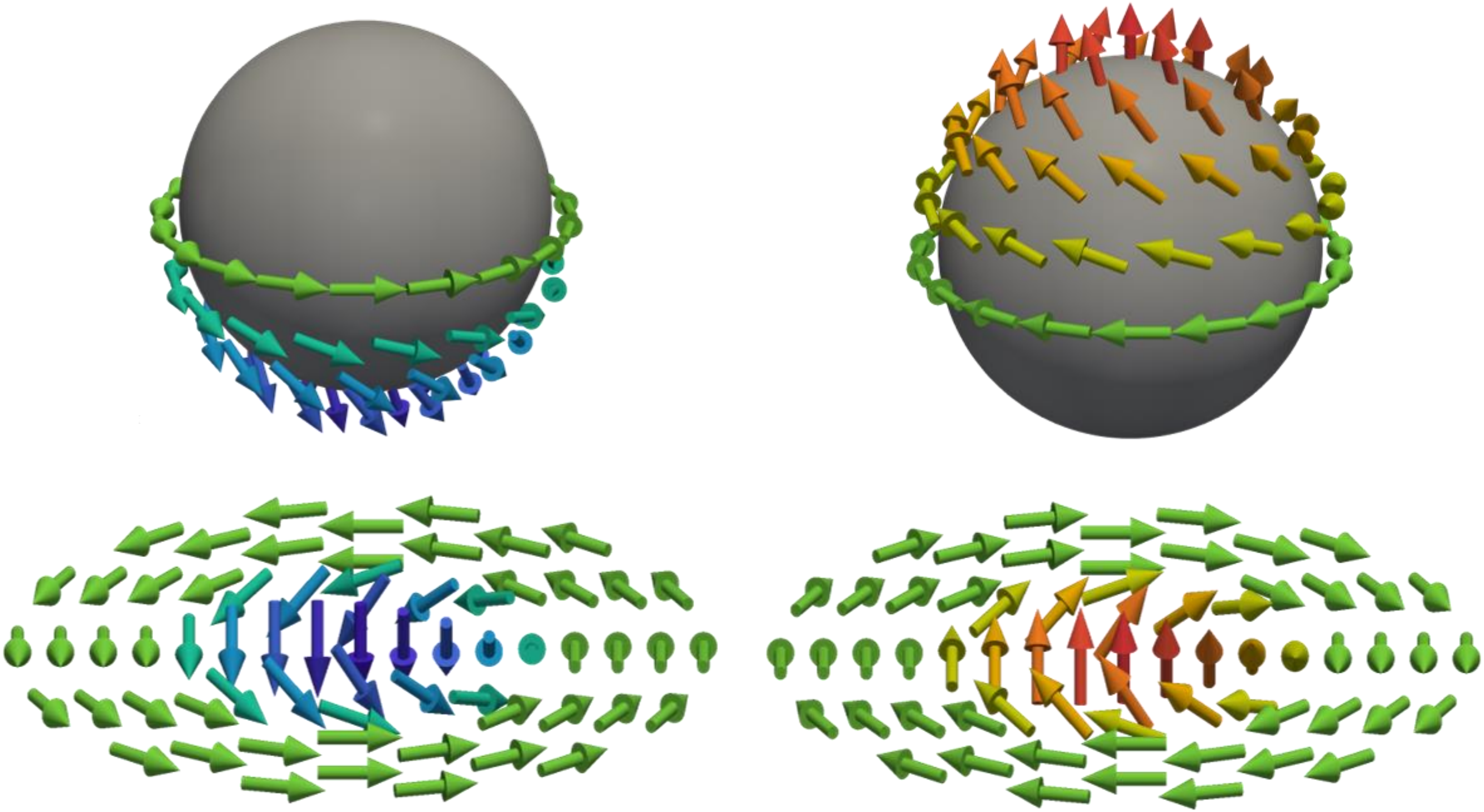
IC1 phase – unknown structure

Relaxation is very anisotropic

Implies a mult-q magnetic structure (e.g. merons)

M. Gomilsek *et al*., Phys. Rev. Lett. **134**, 046702 (2025)

Merons

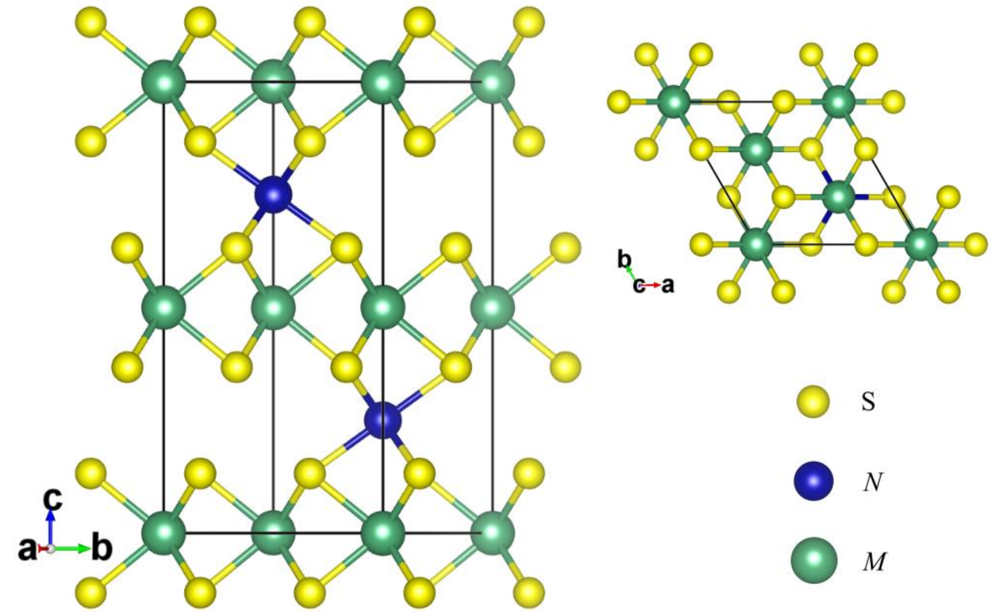


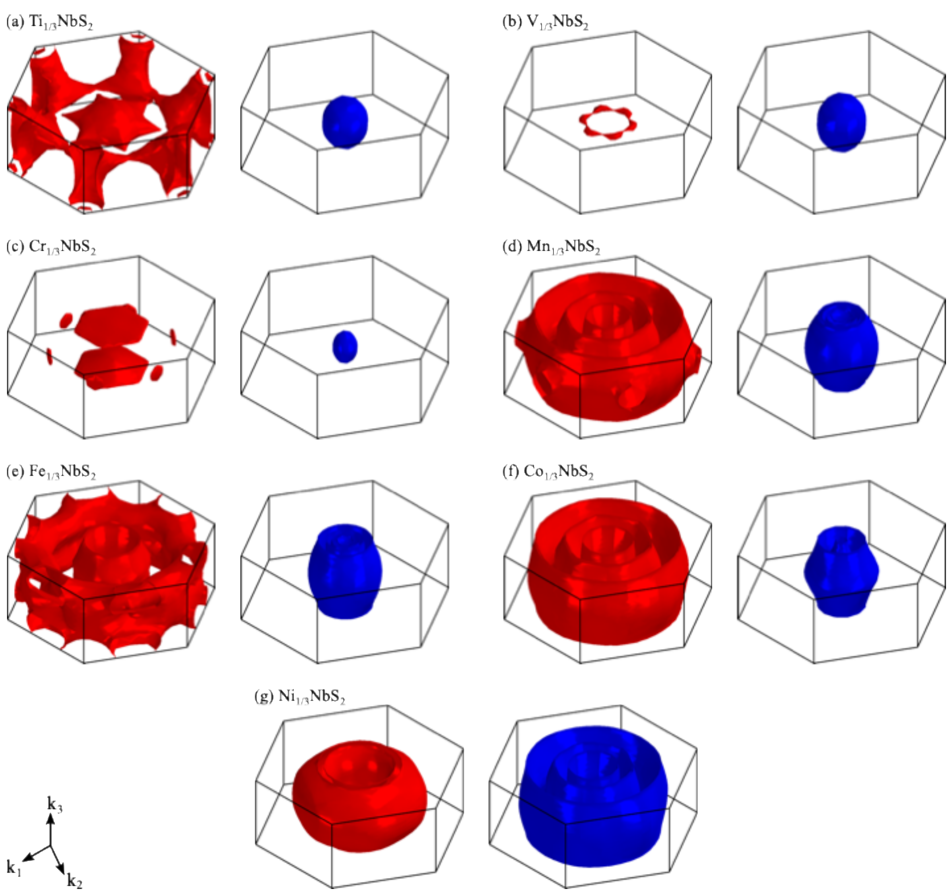
See Murray Wilson's talk at the end of the week

Part 3: $M_{1/3}NbS_2$

Flexible series of TMDCs

Rich range of magnetism across the series

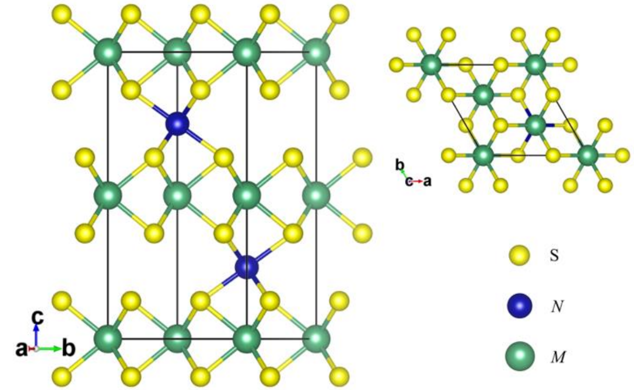


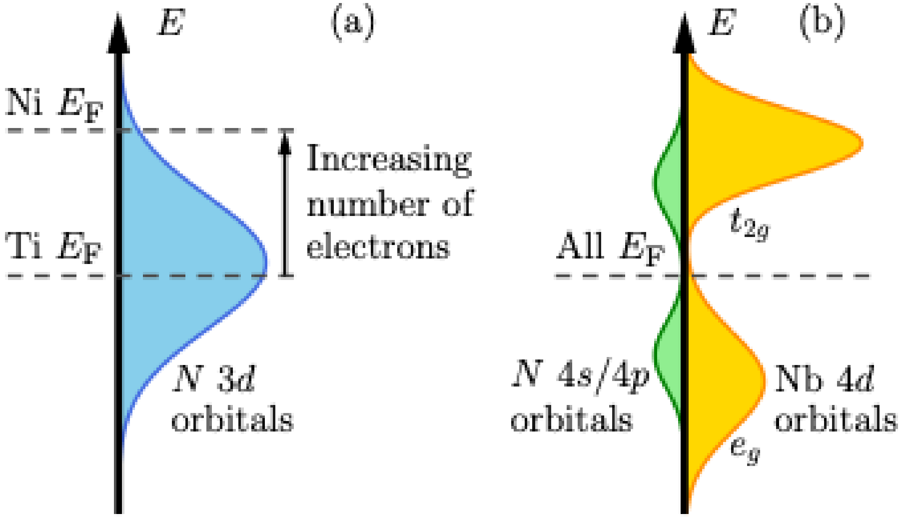


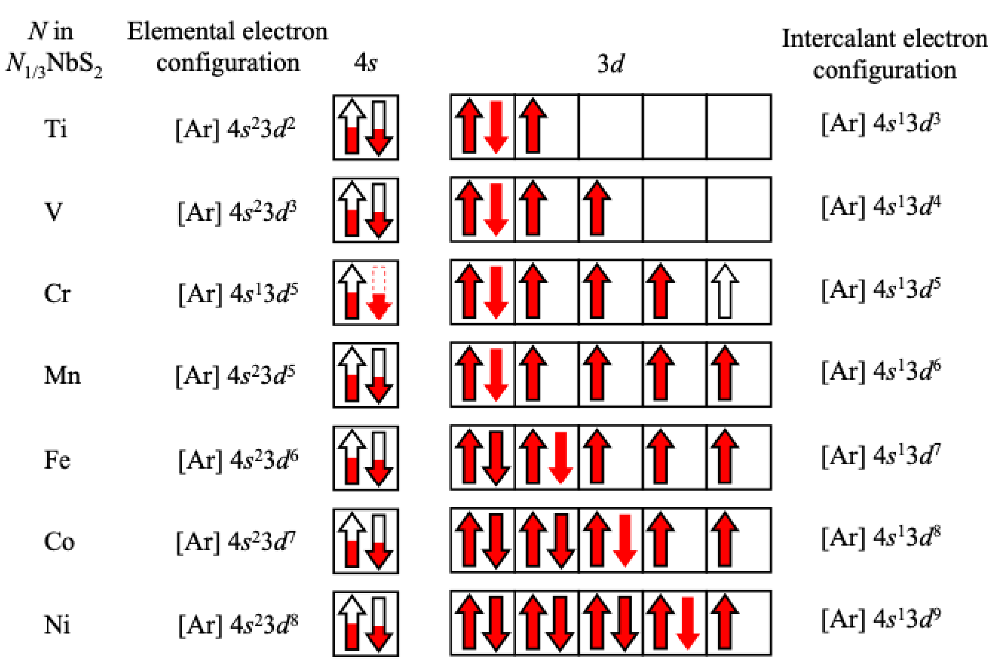
The main features of the magnetism follow from filling rigid NbS_2 bands

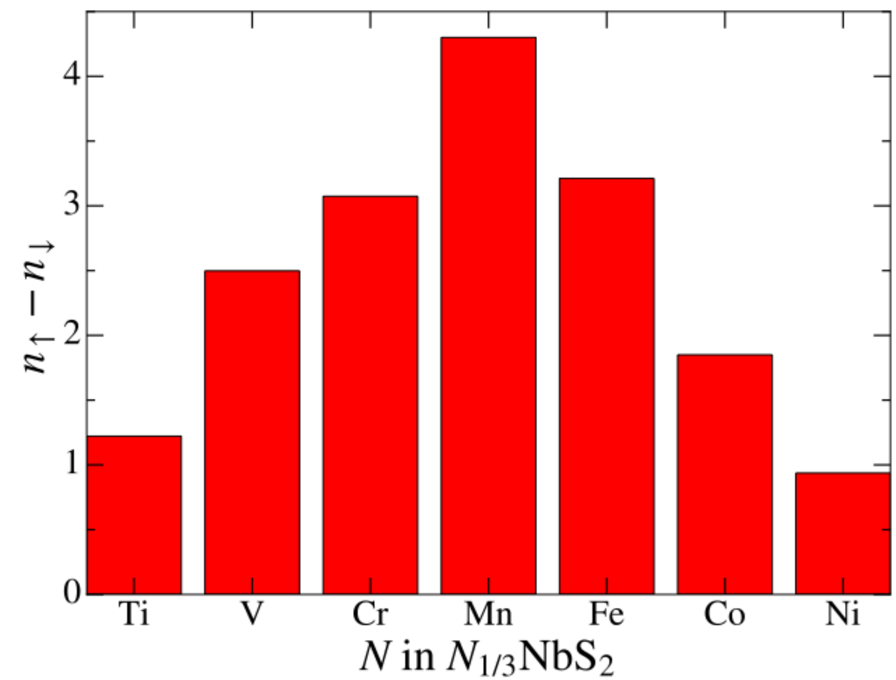
N.P. Bentley et al., 2506.06111

Electronic structure (DFT)



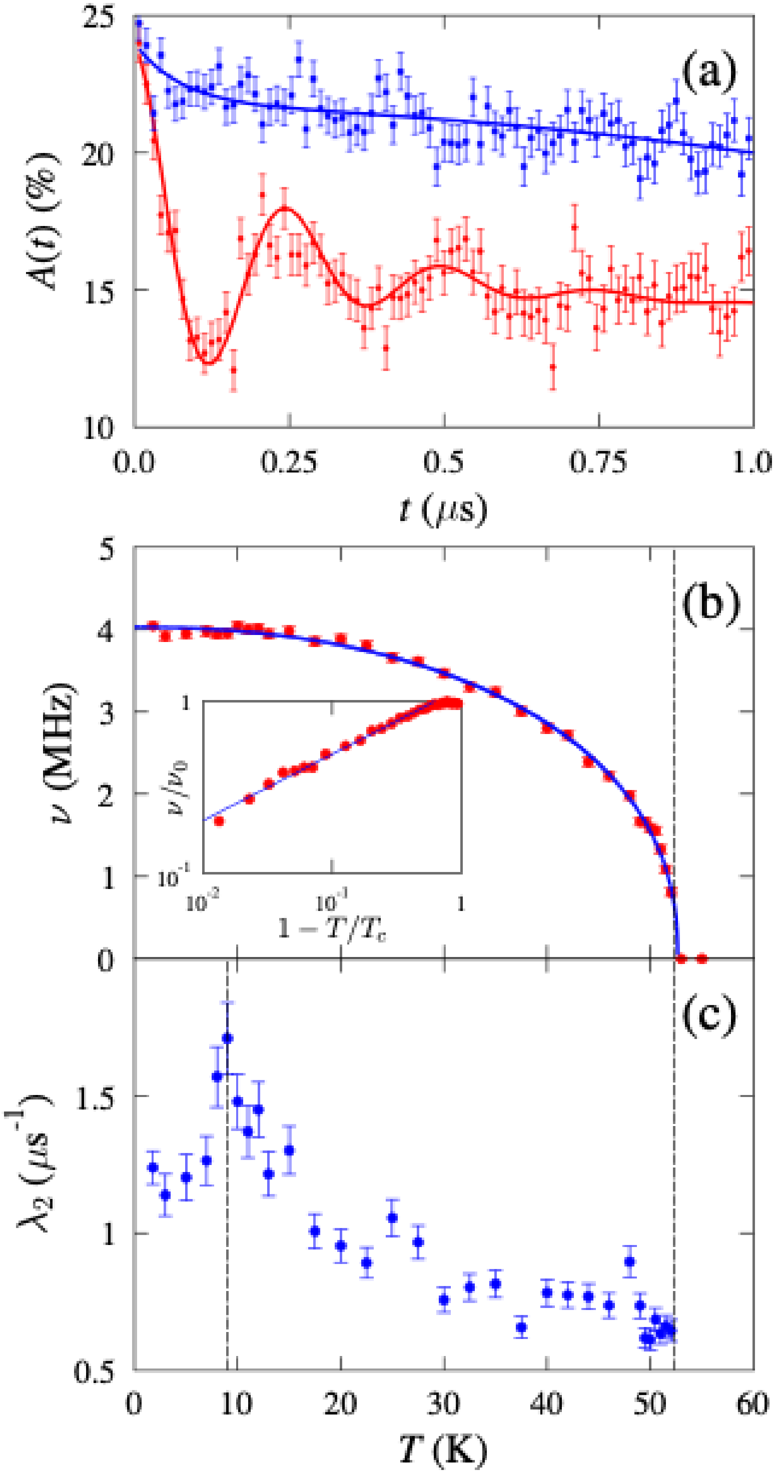






DFT gives the main features, but not the details

$V_{1/3}NbS_2$



Band structure gives big picture

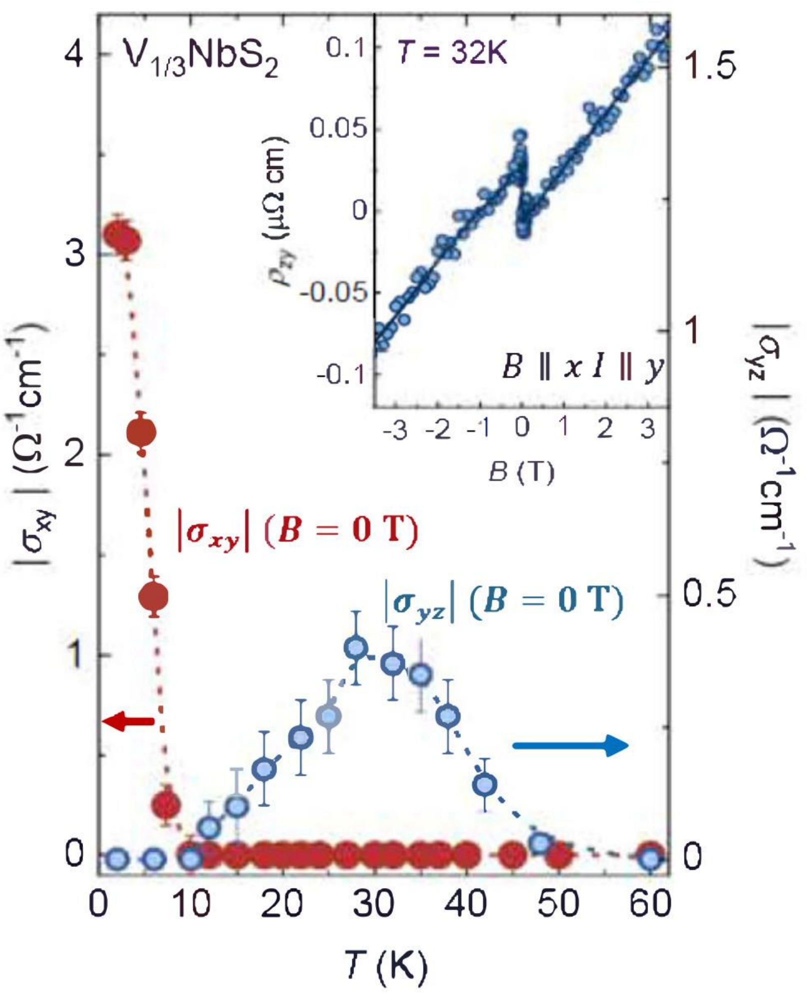
Experiment provided the subtleties

Longitudinal relaxation shows pronounced peak at 10 K.

A feature is seen at this temperature in magnetization and in neutron diffraction

N.P. Bentley et al., 2506.06111

$V_{1/3}NbS_2$: some recent speculation



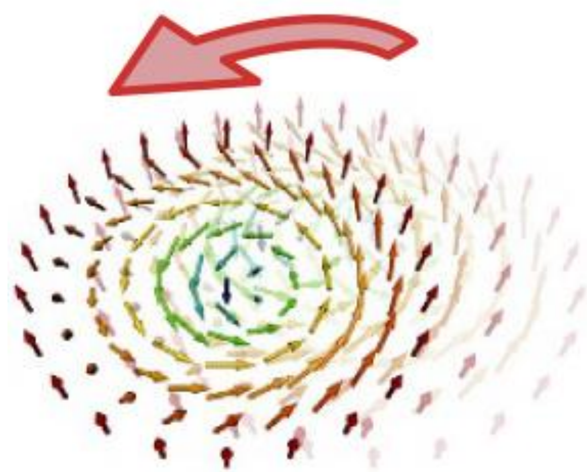
Spontaneous AHE seen below 10 K

Coincides with region of NFL behaviour

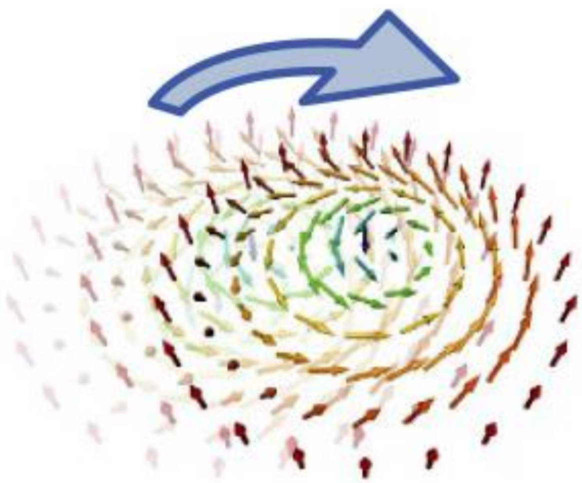
Speculation about formation of domain-wall topological excitations

Ray *et al*., Nat. Commun., **16** 3532 (2025)

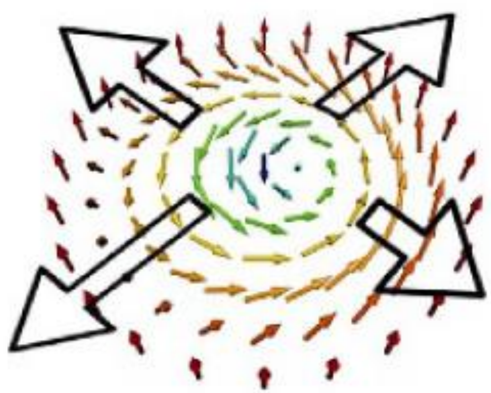
We can see topological excitations through their dynamics



Counterclockwise

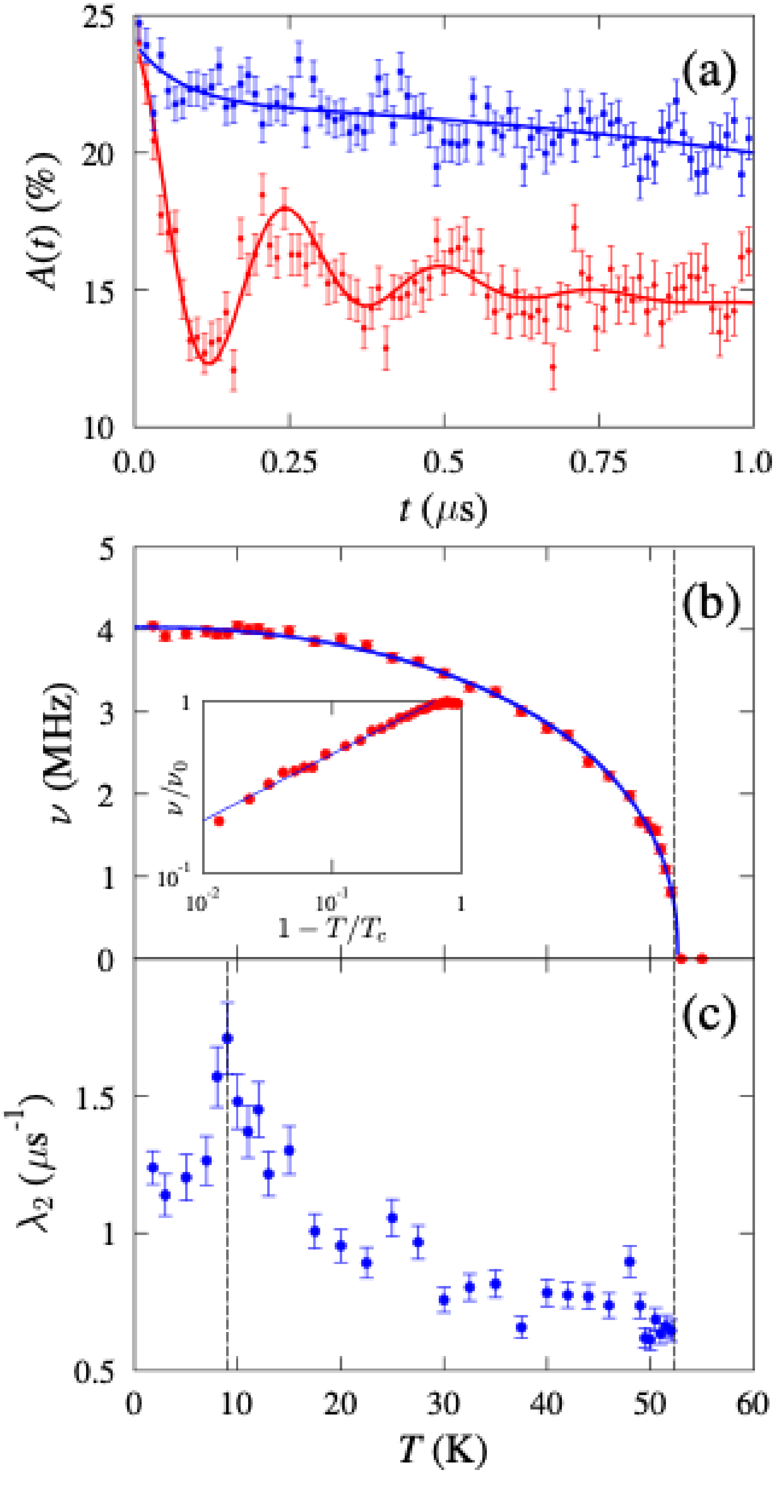


Clockwise

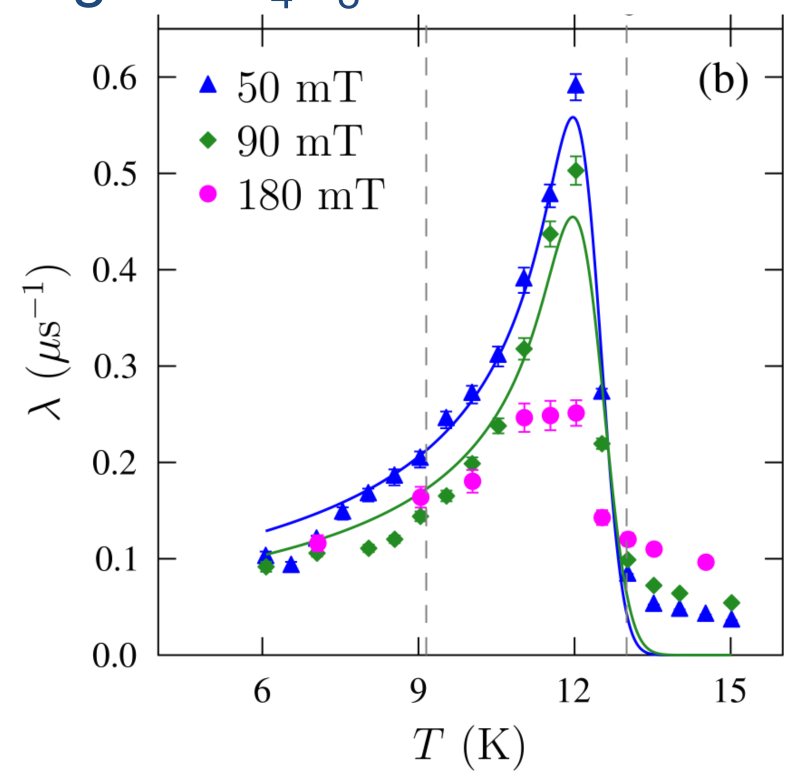


Breathing

$V_{1/3}NbS_2$



Can compare with other cases where skyrmions are observed: e.g. GaV_4S_8



N.P. Bentley et al., 2506.06111

Summary

- Topology gives us an organizing principle to understand low-dimensional magnetism
- Phenomena operate across energy scales, necessitating different computational strategies
- Allows insight into depth dependence, anisotropic magnetism and the search for new excitations

Acknowledgements

Funding: EPSRC (UK)

PSI: Thomas Hicken, Zaher Salman, Andreas Suter, Thomas Prokscha, Zurab Guguchia

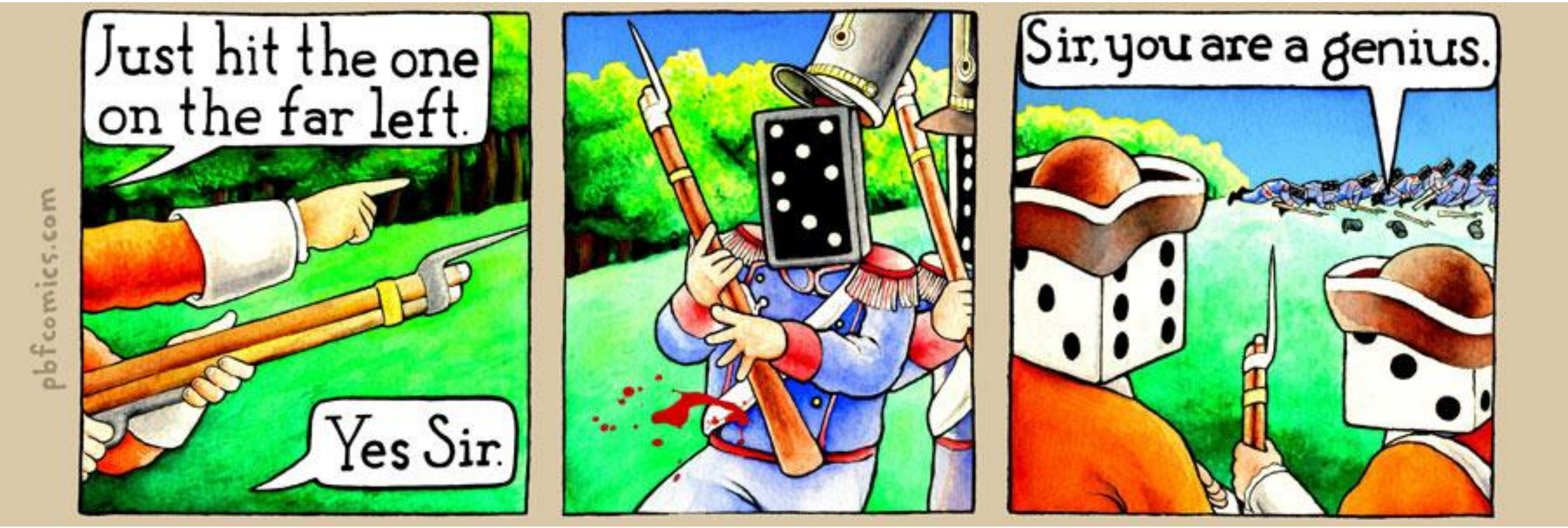
Durham: Nathan Bentley, Theo Breeze, Matjaž Gomilšek, Kévin Franke, Peter Hatton, Murray Wilson, Zac Hawkhead

ISIS: Francis Pratt

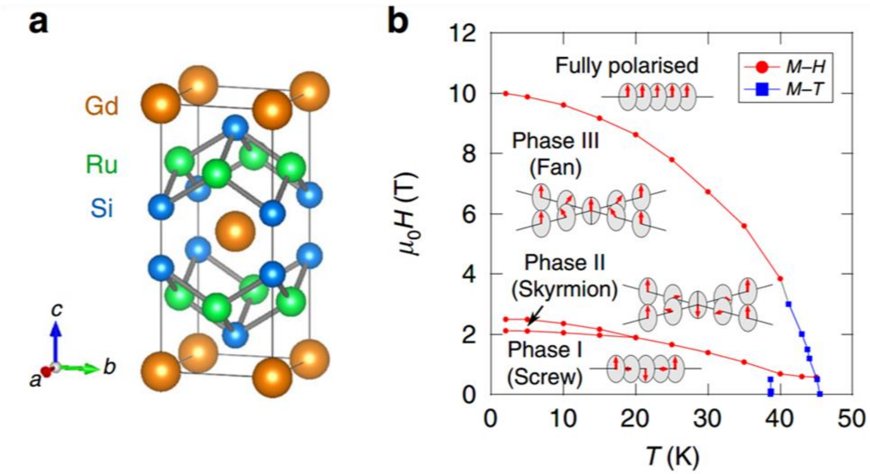
Oxford: Ben Huddart, Stephen Blundell, Thorsten Hesjedal

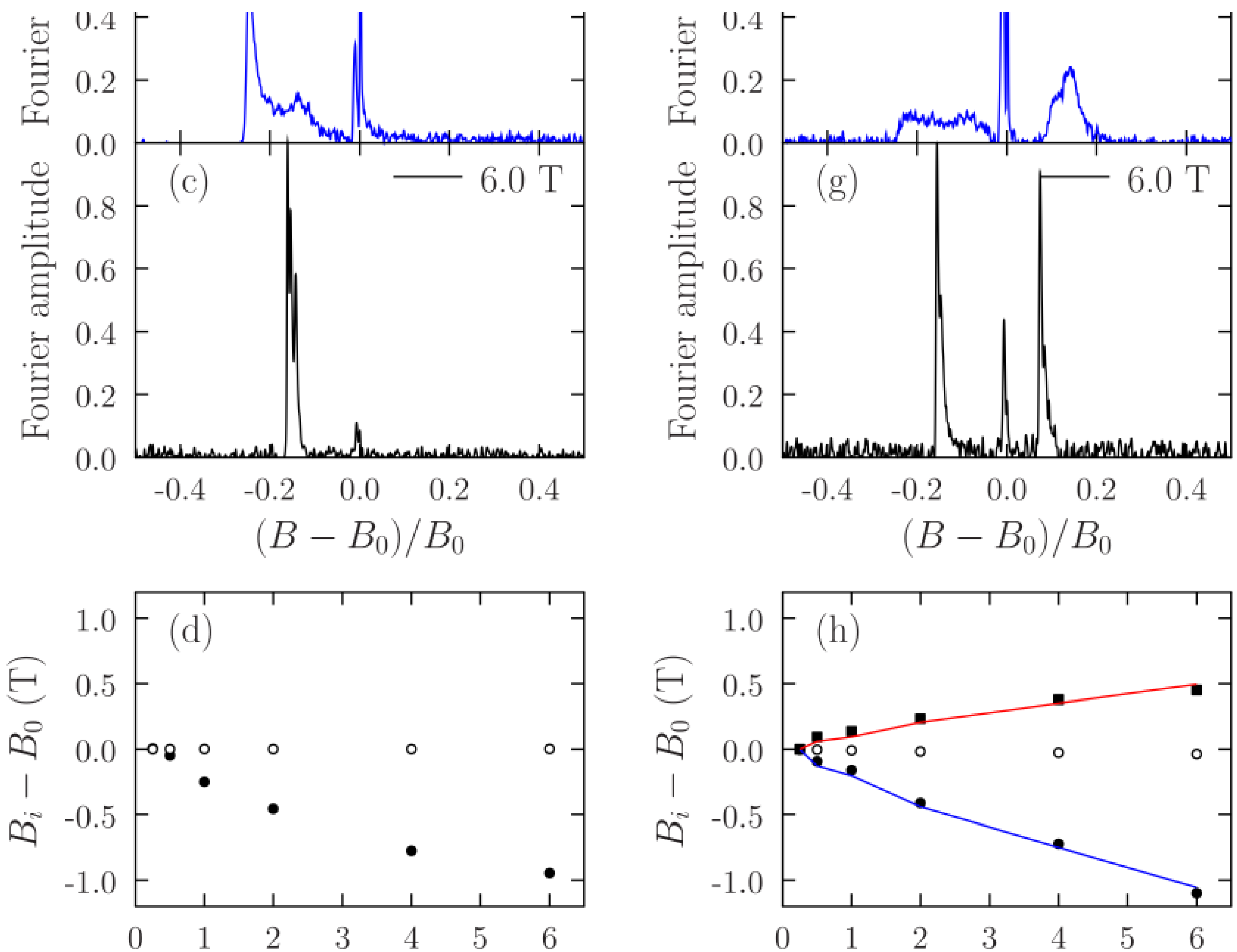
Warwick: Geetha Balakrishnan, Daniel Mayoh

Questions


pbfcomics.com
Just hit the one on the far left.
Yes Sir.
Sir, you are a genius.

$GdRu_2Si_2$





Fitting the trends implies a negative hyperfine contribution at the muon site

This suggests an RKKY mechanism in this material

There have been claims that RKKY stabilizes skyrmions in this system