



Topological spin textures in chiral magnets: from 2D to 3D

Jiadong Zang

Department of Physics and Astronomy, University of New Hampshire, Durham, NH 03824



Program Scope

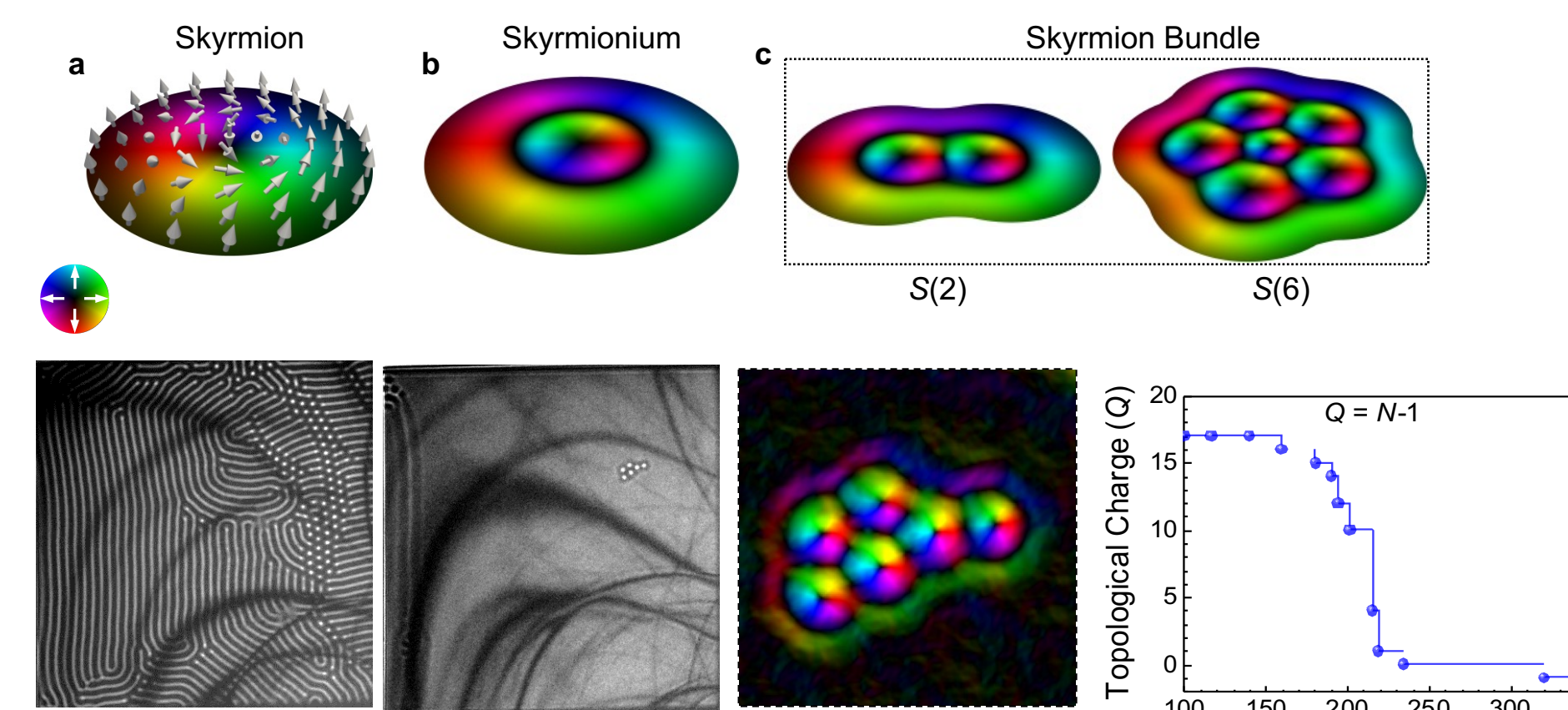
This grant award focuses on the study of both fundamental physical property and material realization of magnetic spin textures with nontrivial topology. It consists of three major part:

- Novel Skyrmionic textures and their dynamics. A zoo of skyrmion-like topological spin textures can be enabled in chiral magnets, and their controlled current driven dynamics can be designed through simulations.
- Investigating transport signatures of spin textures. Topological Hall effect (THE) has been widely used for identifying skyrmions. We have identified THE in various systems. Alternative mechanisms to THE-like feature have been proposed.
- Unlocking 3D topological hopfion textures. Energy landscape, transport signature, and novel dynamics of hopfions will be discussed.

Theoretical developments in this project are also supported by intensive experimental collaborations.

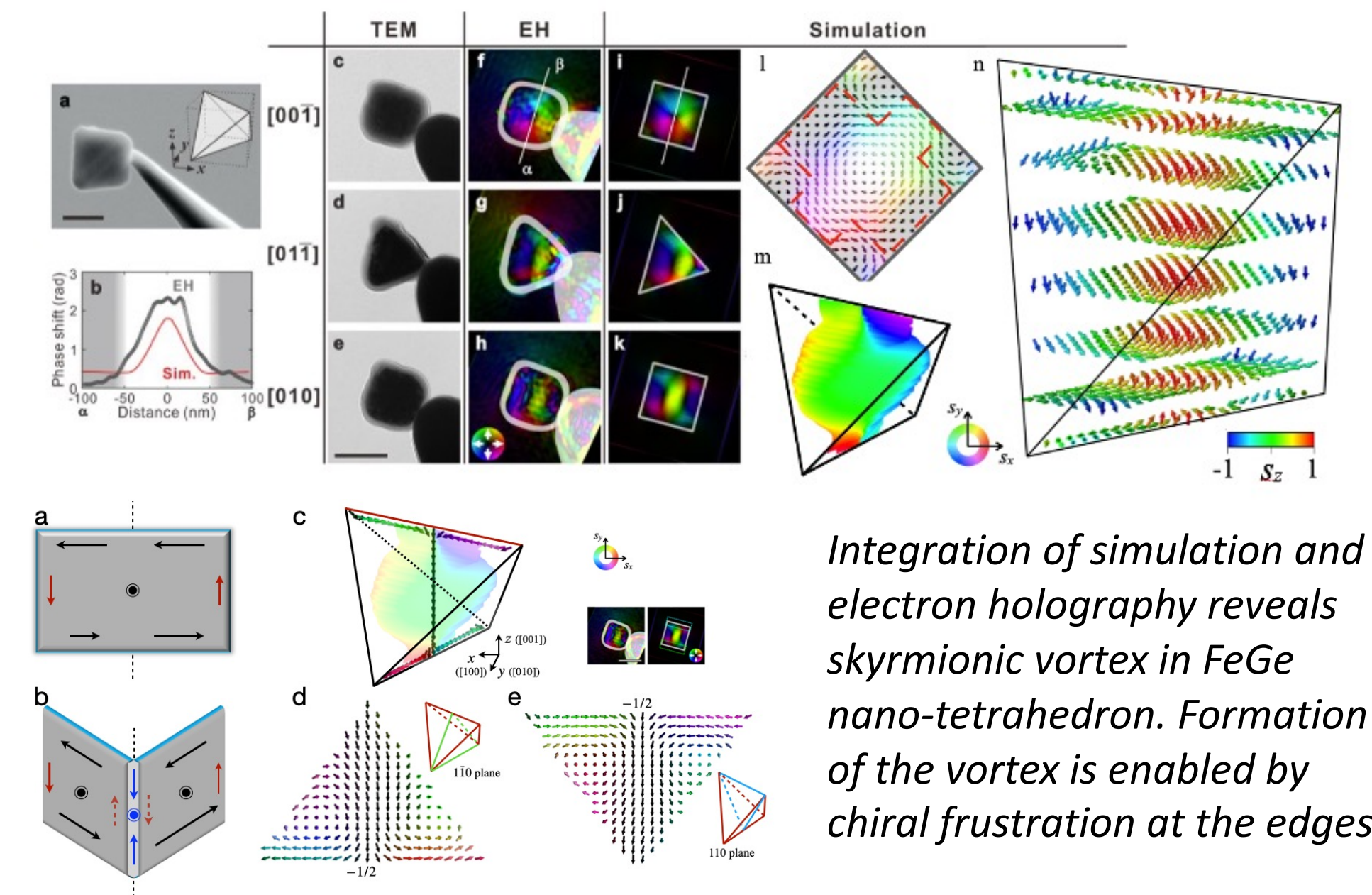
Novel Skyrmionic Textures

From skyrmionium to skyrmion bundles



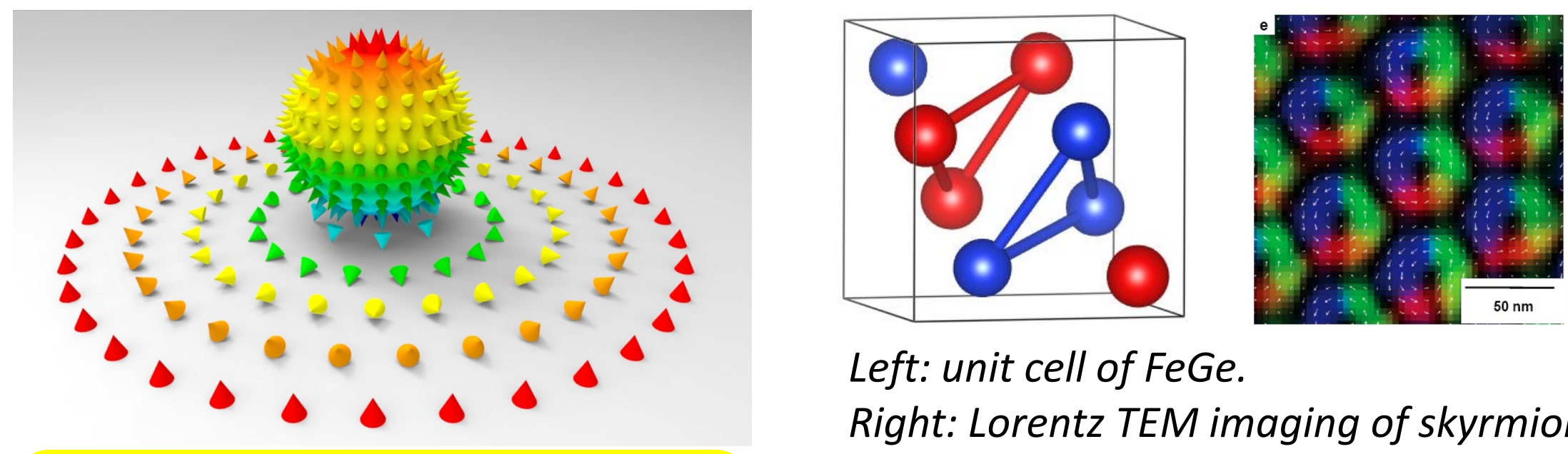
Numerical simulation indicates stable skyrmionium and skyrmion bundle states in chiral magnets. Experimental realization shows cascading topological charge transition in skyrmion bundles

Skyrmionic vortex in chiral tetrahedron



Magnetic Skyrmion

Magnetic skyrmion is a nanostructured spin texture in which magnetic moments point in all directions wrapping a unit sphere. There exists one-to-one correspondence between a skyrmion and a unit sphere. It has been realized in chiral magnets such as MnSi and FeGe.



Topological Charge

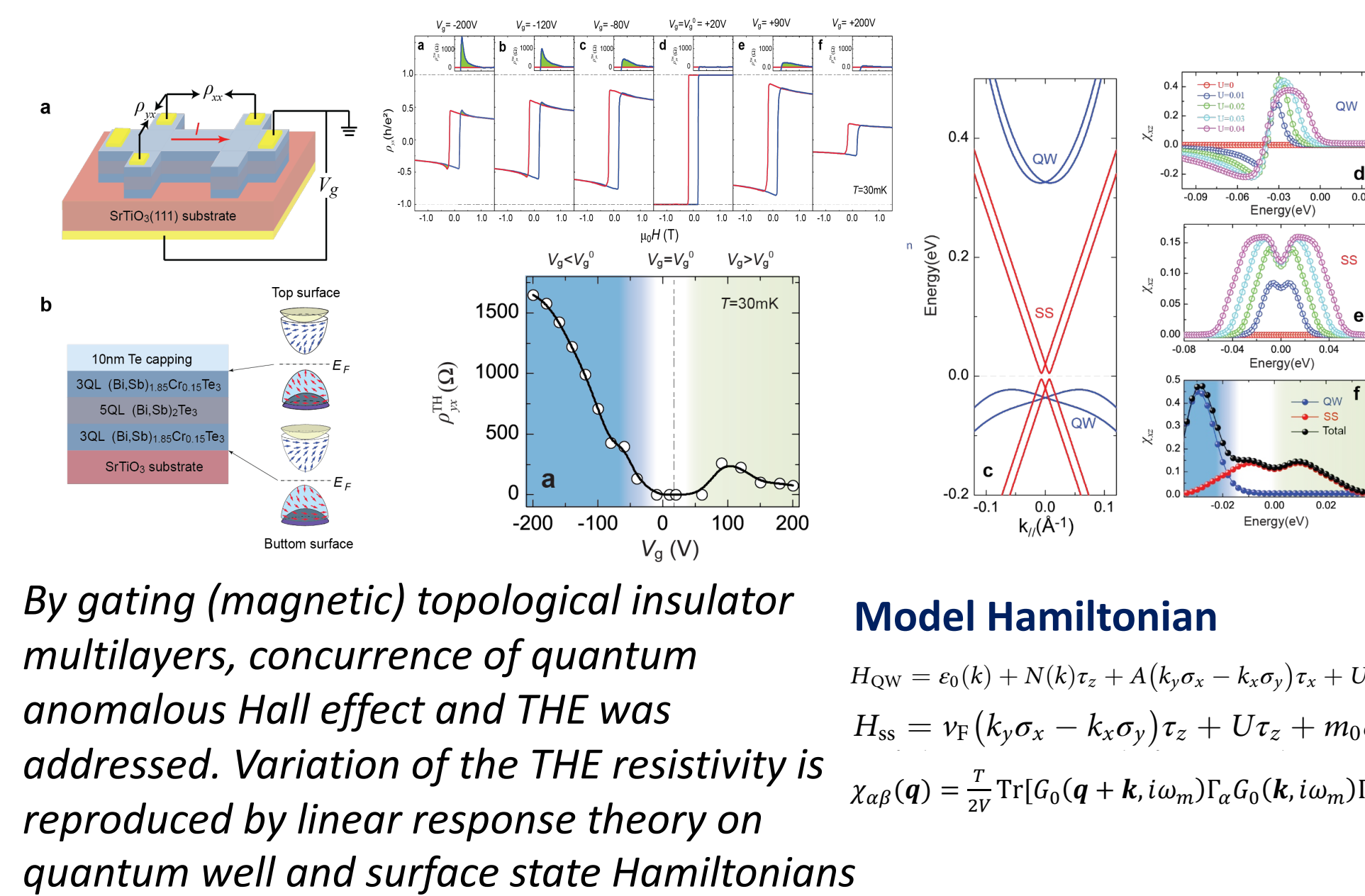
$$Q = \frac{1}{4\pi} \int \mathbf{n} \cdot (\partial_x \mathbf{n} \times \partial_y \mathbf{n}) d^2x$$

Minimal Hamiltonian of chiral magnet

$$H = \sum_{\langle i,j \rangle} -J S_i \cdot S_j + D_{ij} \cdot (S_i \times S_j) - \sum_l H \cdot S_l$$

Topological Hall Effect in Topological Matters

Crossover from THE to QAHE



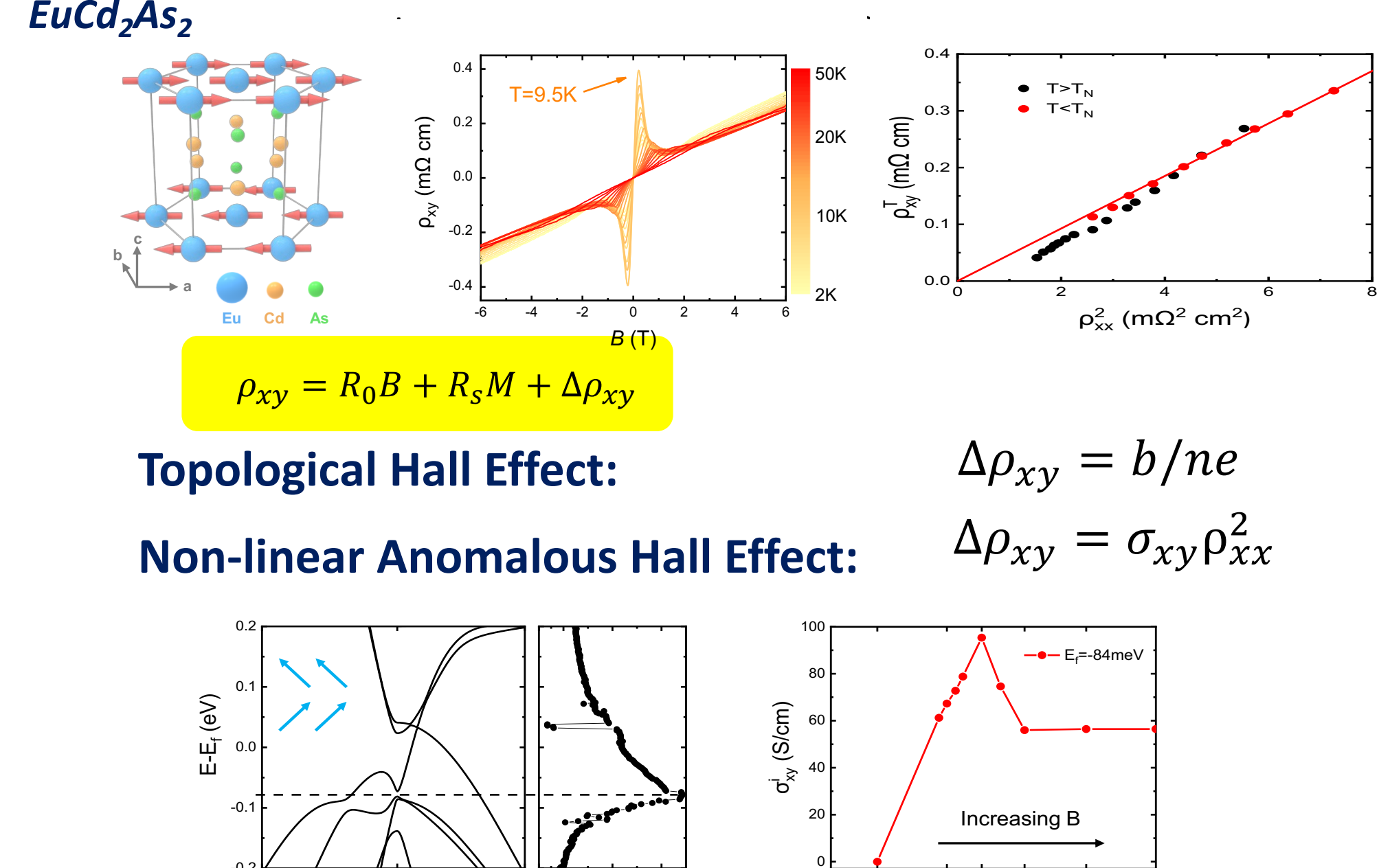
Model Hamiltonian

$$H_{2D} = \epsilon_0(k) + N(k)\tau_z + A(k_x\sigma_x - k_y\sigma_y)\tau_x + U\tau_x$$

$$H_{3D} = v_F(k_y\sigma_x - k_x\sigma_y)\tau_z + U\tau_z + m_0\sigma_x$$

$$\chi_{\alpha\beta}(q) = \frac{\tau}{2\pi} \text{Tr} [G_0(q+k, i\omega_n) S_\alpha G_0(k, i\omega_n) \Gamma_\beta]$$

Nonlinear anomalous Hall effect



Conclusions

- Skyrmion textures with arbitrary topological charges can be generated. In chiral magnet nanoparticles chiral frustration at the sample edges are important.
- Topological Hall effect can be induced in topological matters, but special care must be taken. It could be nonlinear anomalous Hall effect from field-induced band evolution.
- Magnetic hopfion is a new class of 3D topological texture. Its recent realization might lead to more exciting research. It has novel current driven dynamics owing to its 3D nature.

Future Plans

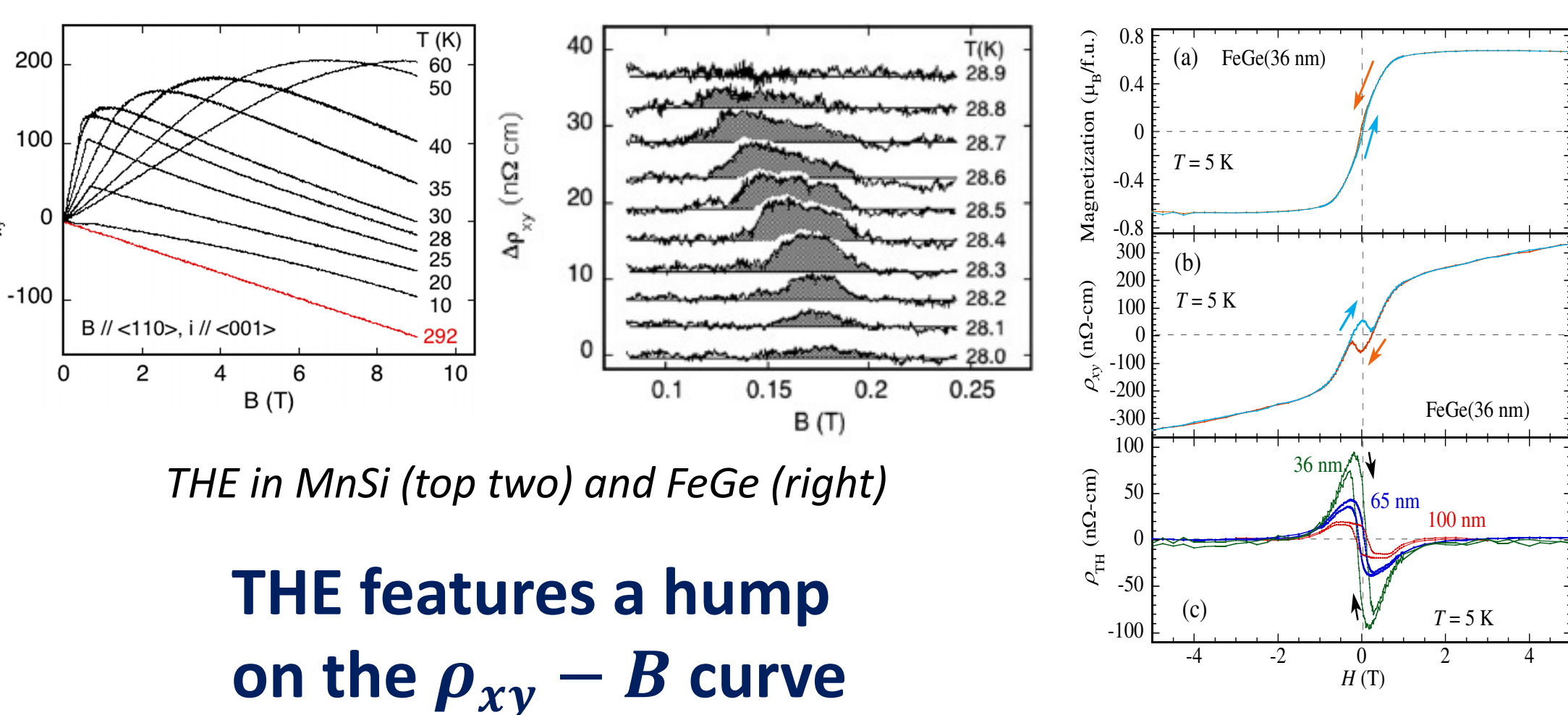
- Exploration of other exotic topological spin textures, especially the composites of skyrmions, Bloch points, helical stripes, and merons.
- Developing 3D magnetic imaging as a special example of inverse problem in general. Using advanced algorithm such as machine learning.
- Clarifying topological Hall effect in various systems. Studying transport signatures of topological textures.

Topological Hall Effect (THE)

Emergent Magnetic Field

$$b = \left(\frac{\hbar}{2e}\right) \mathbf{n} \cdot (\partial_x \mathbf{n} \times \partial_y \mathbf{n})$$

Emergent magnetic field induces Hall effect of itinerant electrons



Magnetic Hopfion

- 3D topological spin texture, no singularity
- Equal S_z contours form a torus plane
- Two arbitrary equal spin contours linked with each other

Construction of a hopfion

$$\mathbb{R}^3 \rightarrow S^3 \rightarrow S^2$$

$$\psi_1 = \frac{2x}{1+r^2}, \psi_2 = \frac{2y}{1+r^2}, \psi_3 = \frac{2z}{1+r^2}, \psi_4 = \frac{1-r^2}{1+r^2}$$

$$|\chi\rangle = \begin{pmatrix} \psi_1 + i\psi_2 \\ \psi_3 + i\psi_4 \end{pmatrix}, \mathbf{n} = \langle \chi | \sigma | \chi \rangle$$

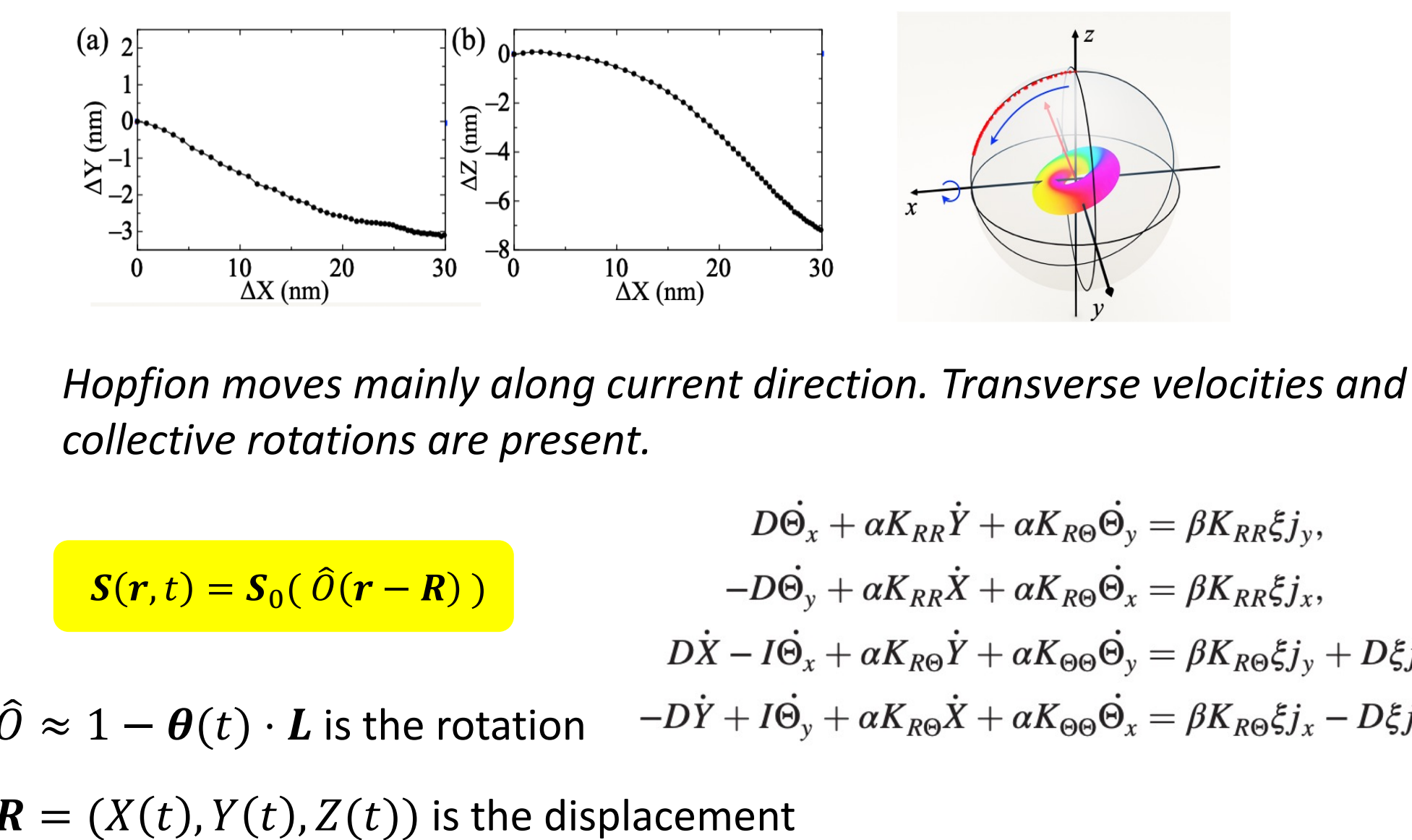
$$Q_H = \frac{1}{8\pi^2} \int d^3r \epsilon_{\alpha\beta\gamma} \psi_\alpha \partial_\beta \psi_\gamma / \psi_4^2 = \frac{1}{8\pi^2} \int \mathbf{B} \cdot \mathbf{A}$$

Prediction of magnetic hopfion



Current driven hopfion dynamics

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{B}^{eff} + \frac{\alpha}{M} \mathbf{M} \times \frac{d\mathbf{M}}{dt} + \frac{pa^3}{2eM} (\mathbf{j} \cdot \nabla) \mathbf{M} - \frac{pa^3\beta}{2eM^2} \mathbf{M} \times (\mathbf{j} \cdot \nabla) \mathbf{M}$$



Acknowledgements

This work was supported by the Office of Basic Energy Sciences, Division of Materials Sciences and Engineering, U.S. Department of Energy, under Award No. DE-SC0020221.

References

1. J. Tang, Y. Wu, W. Wang, L. Kong, B. Lv, W. Wei, J. Zang, M. Tian, H. Du, *Nature Nanotechnology*, 16, 1086 (2021).
2. K. Niitsu, Y. Liu, A. Booth, X. Yu, N. Mathur, M. Stolt, D. Shindo, S. Jin, J. Zang, N. Nagaosa, Y. Tokura, *Nature Materials* 21, 305 (2022).
3. J. Jiang, et. al, *Nature Materials*, 19, 732 (2020)
4. X. Cao, J. X. Yu, P. Leng, C. Yi, Y. Yang, S. Liu, L. Kong, Z. Li, X. Dong, Y. Shi, J. Zang, F. Xiu, *Physical Review Research* 4, 023100 (2022).
5. Y. Liu, R. K. Lake, J. Zang, *Phys. Rev. B* 98, 174437 (2018)
6. Y. Liu, W. Hou, X. Han, J. Zang, *Phys. Rev. Lett.* 124, 127204 (2020)