

Frequency-Domain Simulation of Magnonic Band Structures

Chensong Hua (华辰松) and Weichao Yu (余伟超)

22110190020@m.fudan.edu.cn

Institute for Nanoelectronic devices and Quantum computing, Fudan University, Shanghai 200433, China.

Abstract: We have developed a new approach for COMSOL Multiphysics to simulate the band structures of spin waves in periodical waveguides called magnonic crystals, by applying Floquet boundary conditions to a unit cell. This approach is compatible with the Maxwell equations to calculate dipolar spin wave dispersions and do spincavtronics tasks. New phenomena such as topological edge states and non-Hermitian phases can be discovered with this tool.

Time-Domain Simulation

The dynamics of spin waves can be illustrated by the Landau-Lifshitz-Gilbert (LLG) equation, where the effective field includes external magnetic field, exchange interaction, anisotropy, Dzyaloshinskii-Moriya interaction (DMI) etc. Micromagnetic simulation is performed by COMSOL Multiphysics (Finite Elements Method).

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t}$$

$$\mathbf{H}_{\text{eff}} = \mathbf{H}_{\text{ext}} + A \nabla^2 \mathbf{m} + K m_z \hat{\mathbf{e}}_z + D[(\nabla \cdot \mathbf{m}) \hat{\mathbf{e}}_z - \nabla m_z]$$

Frequency-Domain Simulation

Hypotheses of linearization: Bloch Theorem & Floquet Boundary:

$$\mathbf{m} = \mathbf{m}_0 + \delta \mathbf{m} e^{i\omega t} \quad \delta \mathbf{m}(\mathbf{r} + \mathbf{R}) = \delta \mathbf{m}(\mathbf{r}) \cdot e^{-i\mathbf{k}_F \cdot \mathbf{R}}$$

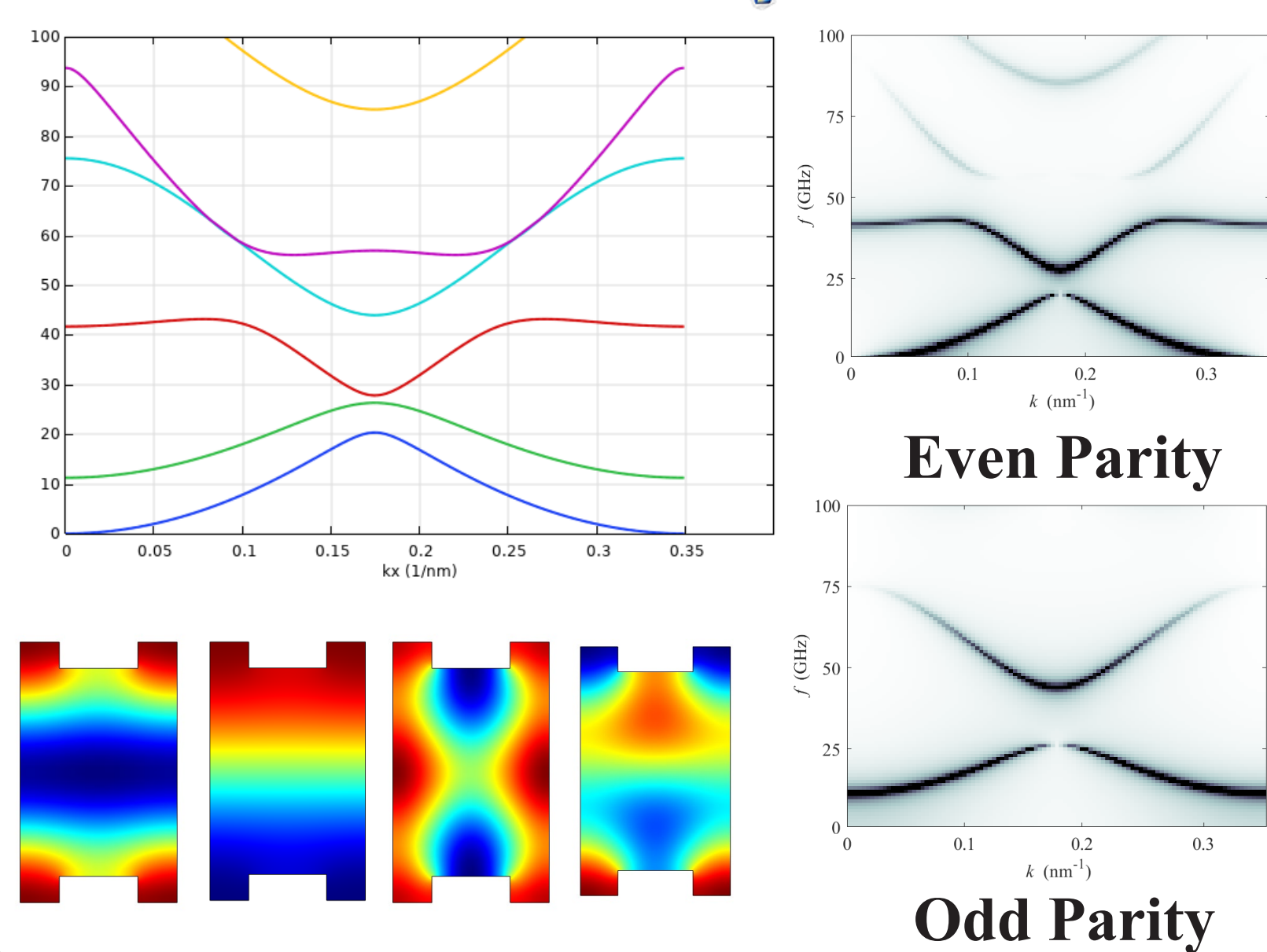
$$\mathbf{H}_{\text{eff}} = \mathbf{h}_0^{\text{eff}} + \delta \mathbf{h}^{\text{eff}} e^{i\omega t} \quad \delta \mathbf{m}_{\text{dst}} = \delta \mathbf{m}_{\text{src}} e^{-i\mathbf{k}_F \cdot (\mathbf{r}_{\text{dst}} - \mathbf{r}_{\text{src}})}$$

LLG equation in frequency domain after Fourier transform:

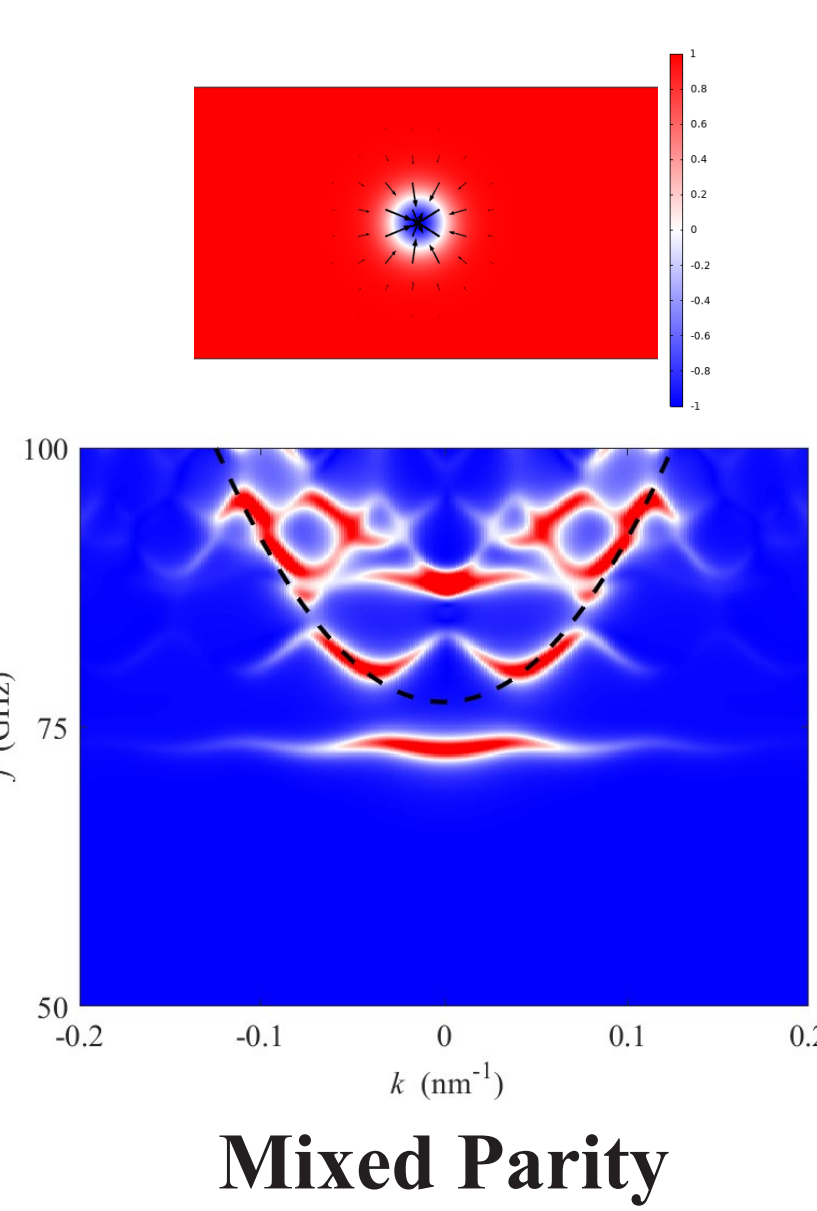
$$i\omega \delta \mathbf{m} = -\gamma \mathbf{m}_0 \times \delta \mathbf{h}^{\text{eff}} - \gamma \delta \mathbf{m} \times \mathbf{h}_0^{\text{eff}} + i\omega \alpha \mathbf{m} \times \delta \mathbf{m}$$

Magnonic band structures can be obtained by applying the method of eigenfrequency analysis or frequency scanning.

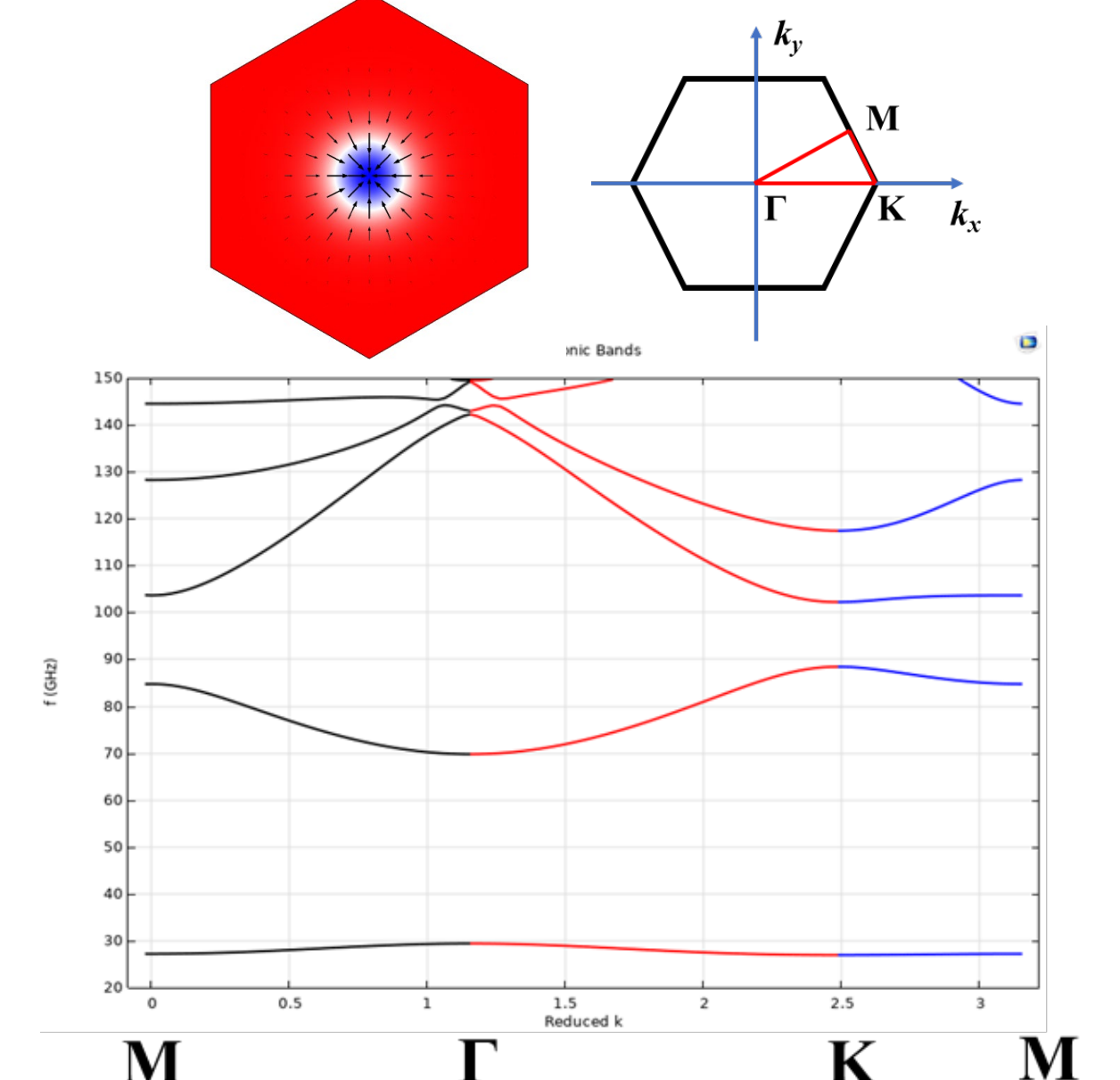
1D Width-Modulated Crystal



1D Skyrmion Chain



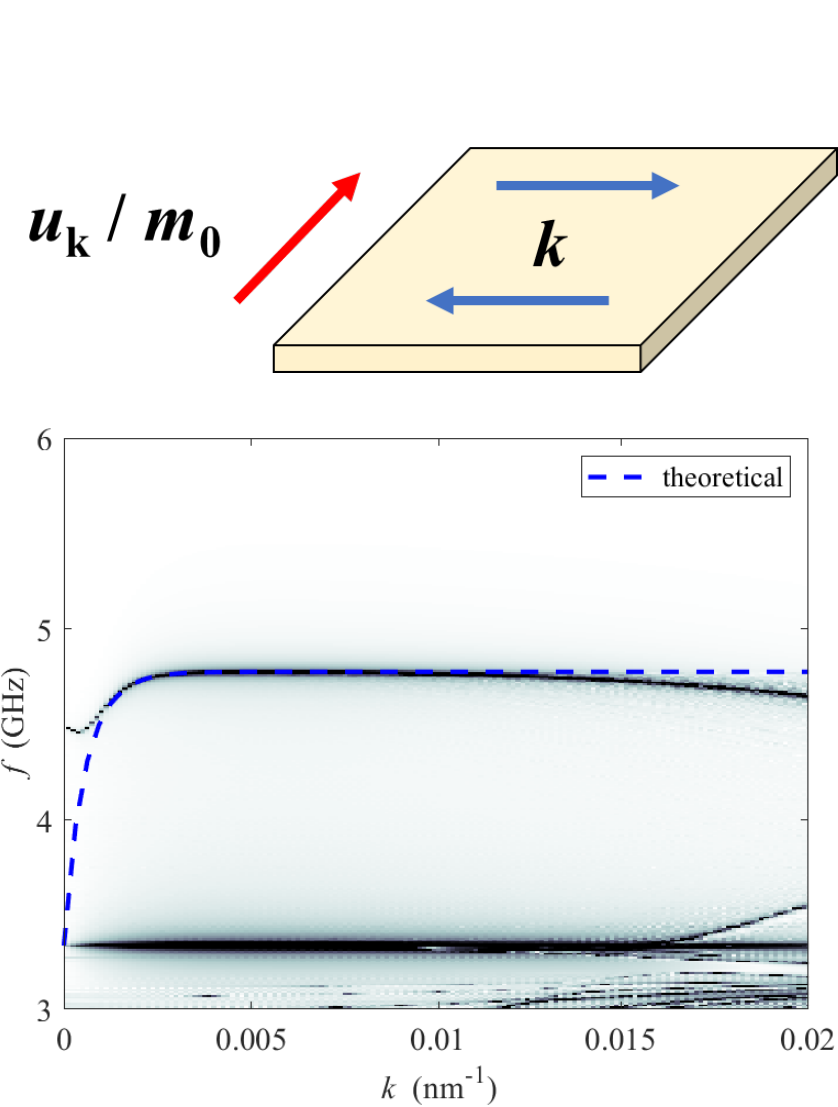
2D Skyrmion Crystal (SkX)



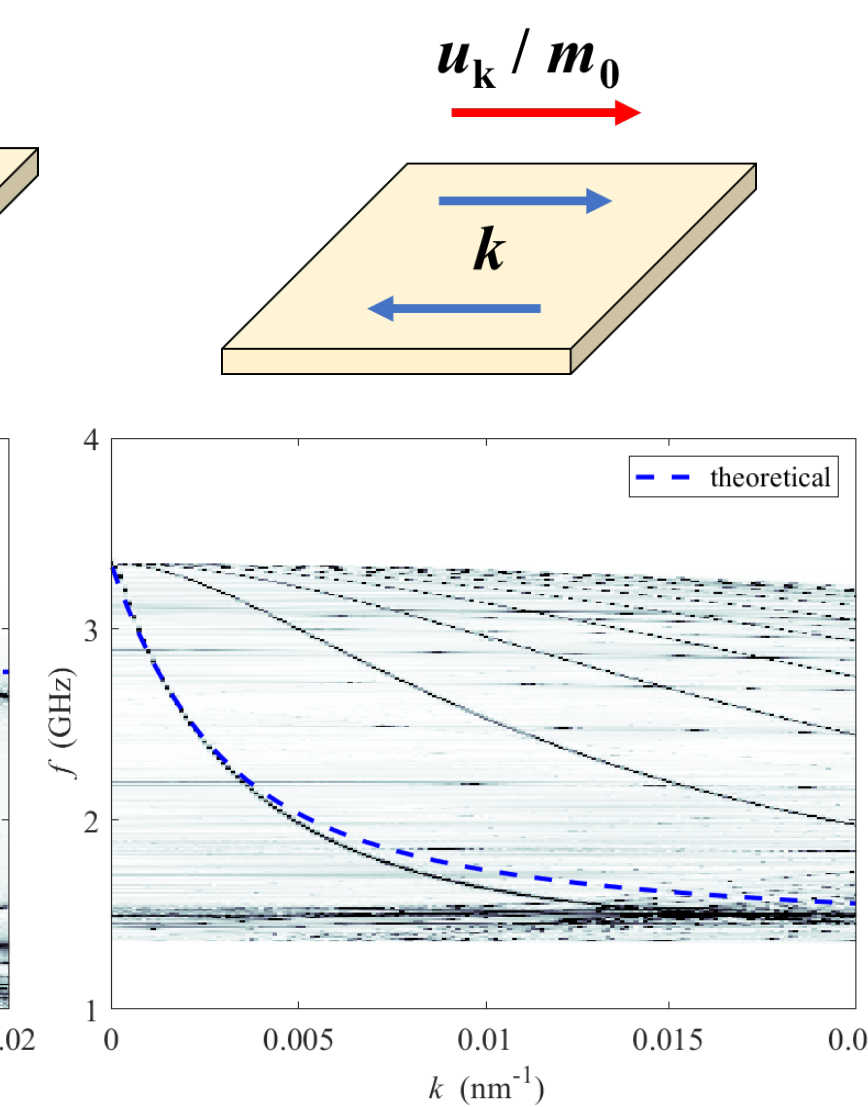
Coupling with Magnetostatics

$$\nabla \cdot \delta \mathbf{b} = 0 \quad \nabla \times \delta \mathbf{h} = 0 \quad \longleftrightarrow \quad \delta \mathbf{b} = \mu_0 (\delta \mathbf{h} + M_s \delta \mathbf{m}) \quad \longleftrightarrow \quad \nabla \times (\nabla \times \delta \mathbf{h}) - (i\sigma\omega - \epsilon\omega^2) \delta \mathbf{b} = 0$$

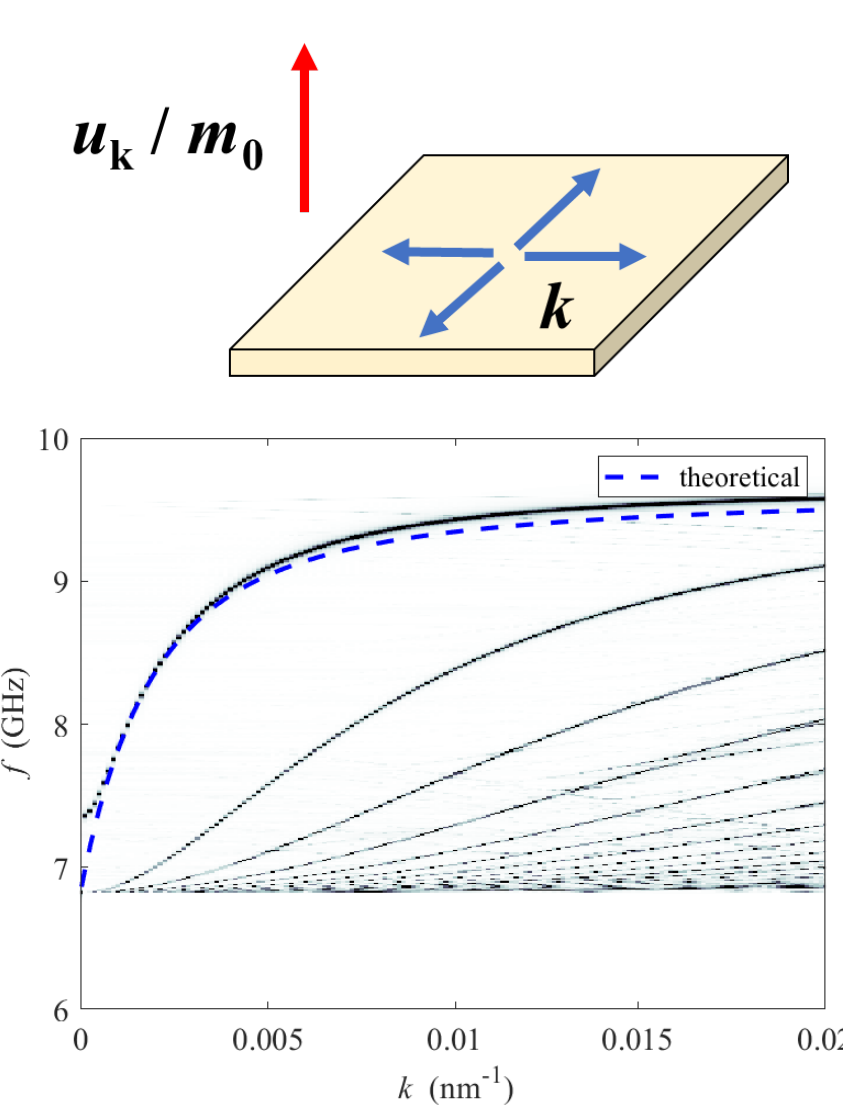
Surface Wave



Backward Volume Wave

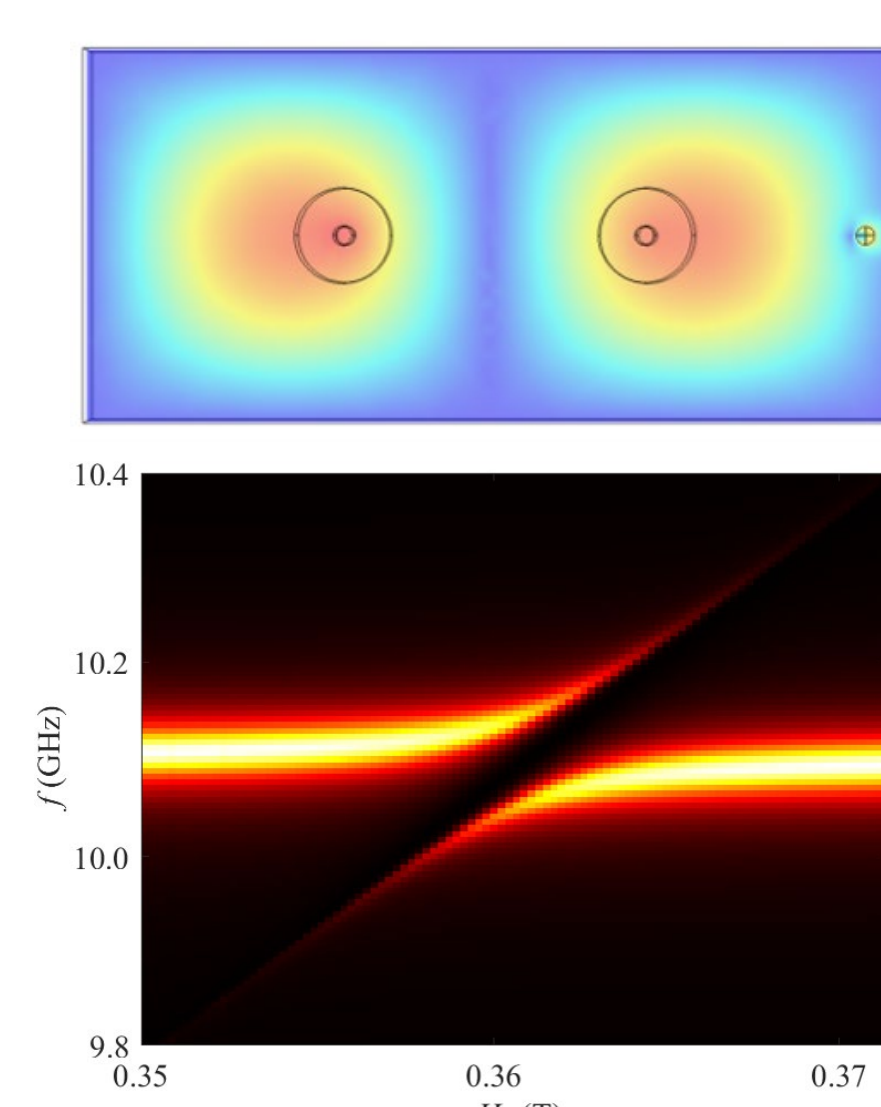


Forward Volume Wave

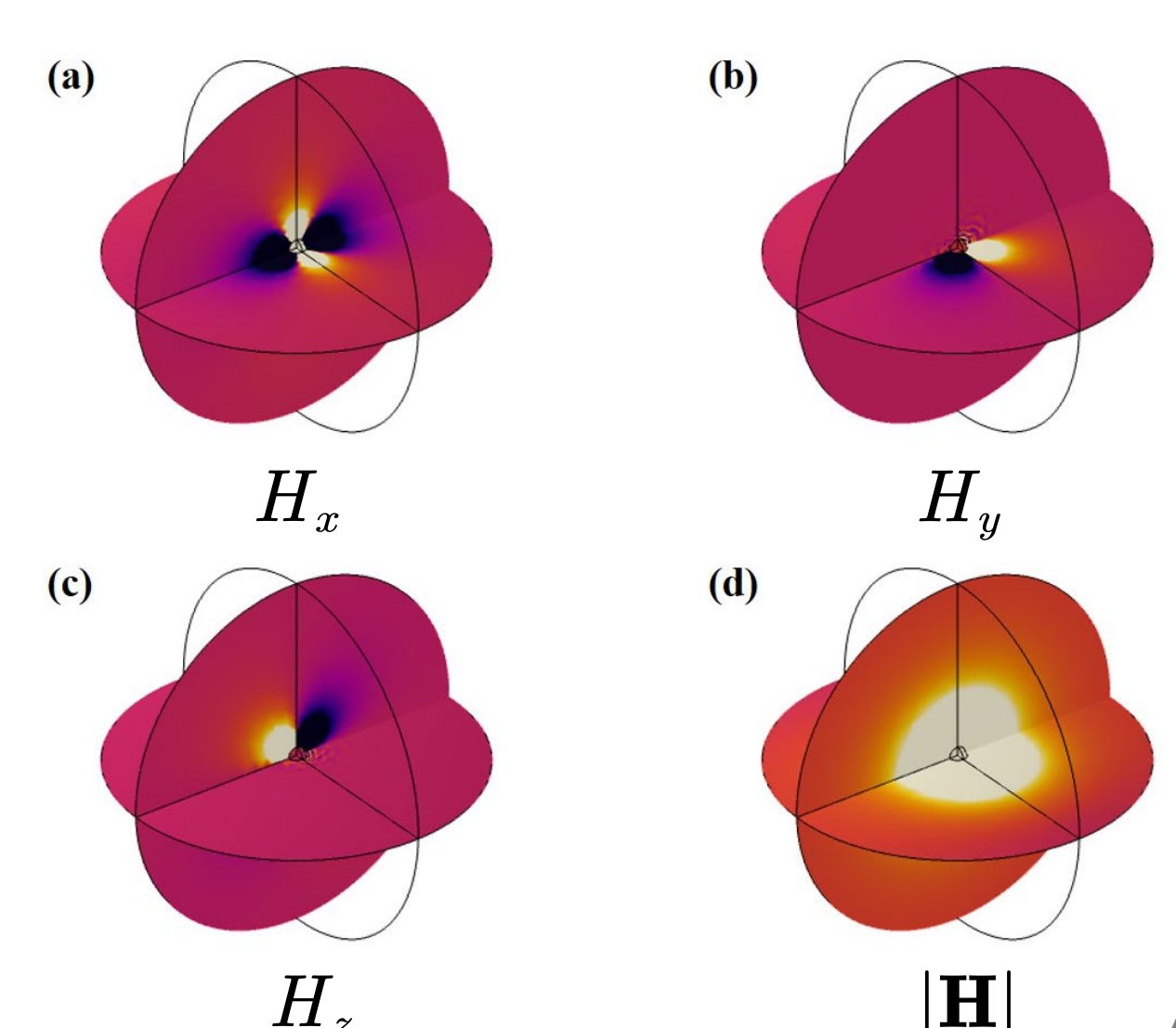


Coupling with Electromagnetic Waves

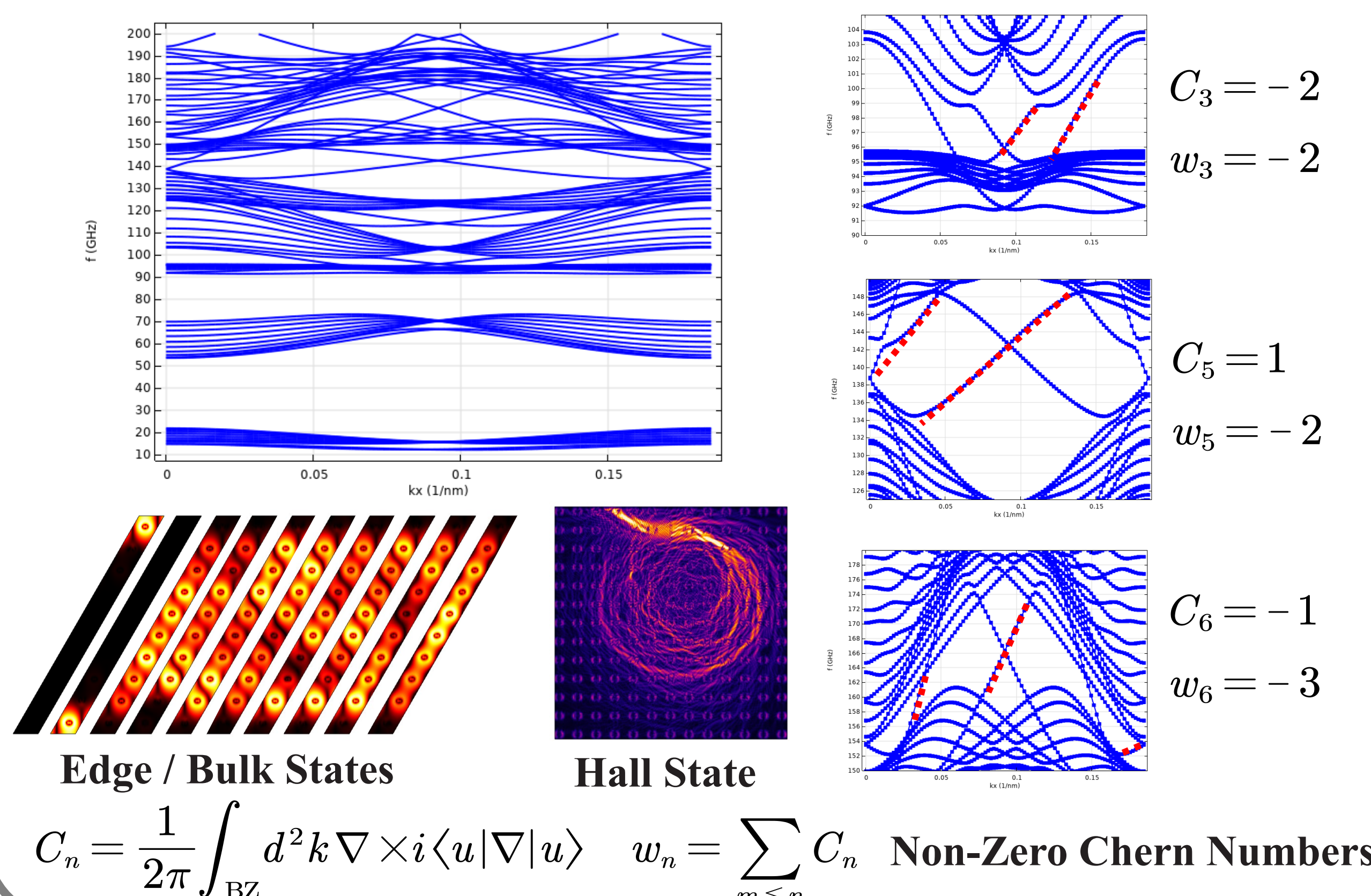
Cavity Photon-Magnon Interaction



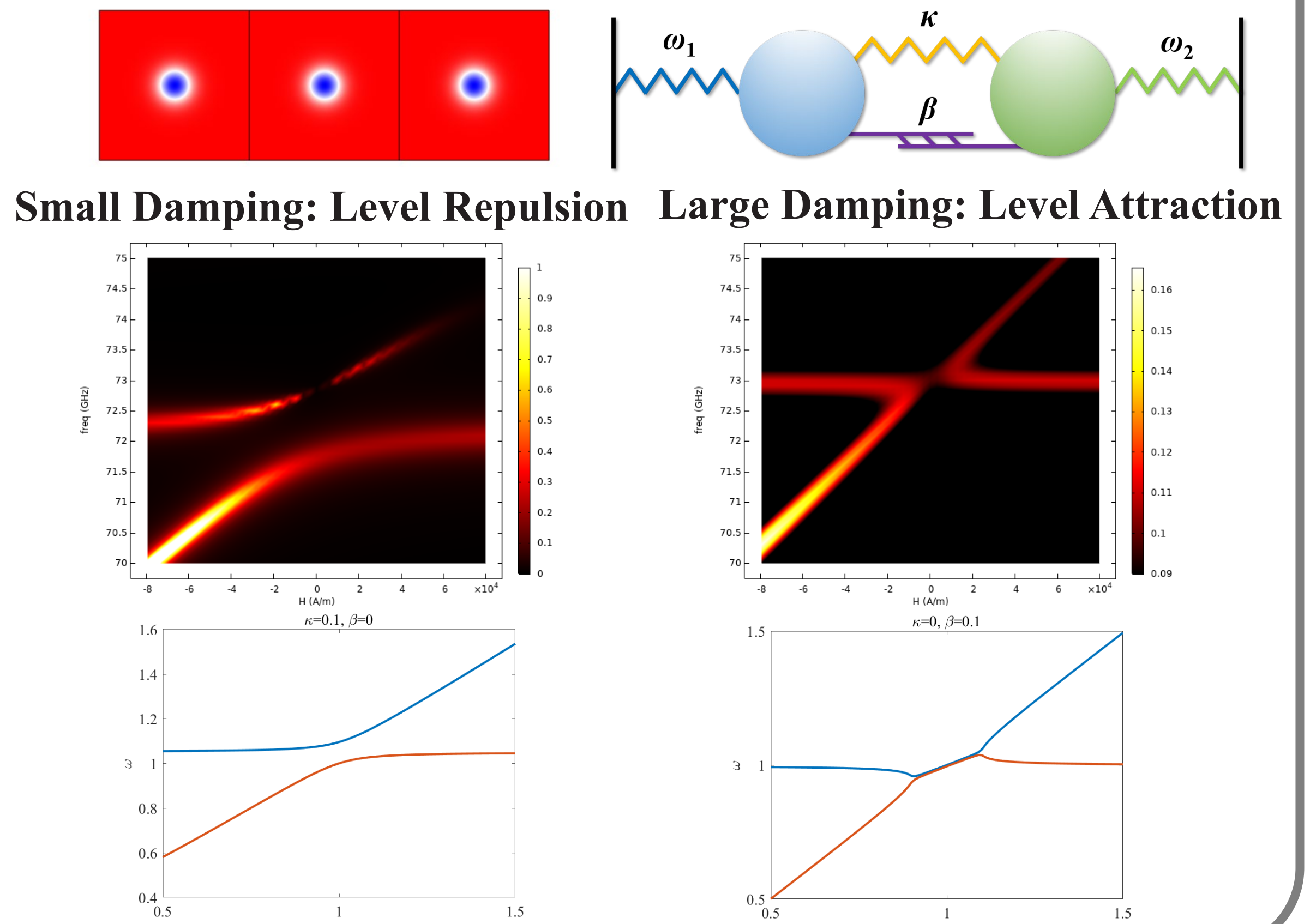
Spin Radiation



Topologically Non-Trivial Edge States in SkX



Non-Hermitian Skyrmionic Phase Transition



Reference

- [1] J. Zhang *et al.*, AIP Adv. **13**, 055108 (2023).
 [2] K.-S. Lee, D.-S. Han, and S.-K. Kim, Phys Rev Lett **102**, 127202 (2009).
 [3] F. Ma *et al.*, Nano Lett. **15**, 4029 (2015).
 [4] K. Xie, L. Zhang, and F. Ma, J. Appl. Phys. **130**, 153901 (2021).
 [5] D. D. Stancil and A. Prabhakar, *Spin Waves: Theory and Applications* (Springer, 2009).
 [6] W. Yu *et al.*, Phys Rev Lett **123**, 227201 (2019).

