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Bulk-spatiotemporal Vortex Correspondence at Photonic Topological Critical Points

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Bulk–boundary correspondence is one of the most important effects in topological physics, establishing a bridge connecting abstract topological properties of bulk materials to boundary transport phenomena. Traditionally, boundary effects predicted by the bulk–boundary correspondence are largely confined to near-field edge states or higher-order localized states. However, there exists another class of topological principles, the bulk-scattering correspondence, which reveals that the bulk topology of topological insulators or topological semimetals also determines their far-field reflection behavior. In a recent work [1], we discovered a novel topological correspondence, termed the bulk–spatiotemporal vortex correspondence, in a new class of optical zero-refractive-index media called gyromagnetic double-zero-index metamaterials (GDZIMs). GDZIM always emerges at a spin-1/2 Dirac point of a topological phase transition. We discover that a spatiotemporal reflection vortex singularity is always anchored to the Dirac point of the metamaterial, with the vortex charge being determined by the topological invariant leap across the phase transition. This new correspondence extends the protected boundary effects into the time domain and characterizes topological phase-transition points, setting it apart from any pre-existing bulk–boundary or bulk-scattering correspondences. Based on this correspondence, we demonstrate a mechanism to deterministically generate optical spatiotemporal vortex pulses with a firmly fixed central frequency and momentum, hence showing ultra-robustness. Our findings uncover connections between zero-refractive-index photonics, topological photonics, and singular optics, which would enable the manipulation of spacetime topological light fields using the inherent topology of extreme-parameter metamaterials.

Reference:

[1] R.-Y. Zhang, X. Cui, Y.-S. Zeng, J. Chen, W. Liu, M. Wang, D. Wang, Z.-Q. Zhang, N. Wang, G.-B. Wu and C. T. Chan, Nature 641 1142 (2025).