Entropy-driven processes in optics and photonics

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The role of entropy as a driving force is foundational across thermodynamics, yet its operational significance in optical systems has remained largely unexplored. In this talk, I will present a unified framework—optical thermodynamics—that establishes entropy as a governing principle for the evolution, control, and manipulation of light in complex photonic systems. This perspective reveals that many seemingly disparate optical phenomena can be understood as manifestations of entropy-driven processes, even in the absence of conventional material equilibration.

Central to this framework is the recognition that structured optical fields, particularly in multimode and nonlinear environments, possess a well-defined thermodynamic description in which entropy can be engineered and harnessed. Building on this foundation, I will highlight three recent advances that collectively demonstrate the predictive and generative power of this approach.

First, I will discuss the concept of universal routing of light (Nature Photonics, 2025), where the flow of optical energy across high-dimensional mode spaces is shown to follow entropy gradients, enabling deterministic redistribution of light without relying on conventional index-based guidance. This work establishes a new paradigm for controlling light in complex media through entropy landscape design.

Second, I will present the experimental realization of an optical Joule–Thomson expansion (Nature Physics), where spectral and spatial degrees of freedom undergo a transformation analogous to thermodynamic expansion, leading to cooling or heating of optical distributions depending on the system's initial state. This result provides a direct bridge between classical thermodynamic processes and purely optical dynamics.

Finally, I will discuss the observation of negative optical temperatures (Science), arising in bounded optical state spaces where population inversion leads to entropy decreasing with increasing energy. This regime enables counterintuitive behavior, including the reversal of conventional energy flow directions, and opens new avenues for manipulating light beyond equilibrium constraints.

Taken together, these results establish entropy not merely as a descriptive quantity, but as a functional resource in optics. By elevating entropy to a design principle, optical thermodynamics offers a new lens through which to understand and engineer complex photonic systems, with implications ranging from beam combining and nonlinear optics to information processing and fundamental studies of irreversibility in wave systems.