

# Route to Spatiotemporal Complexity of Two-Dimensional Patterns in a Liquid Crystal Light Valve with Optical Feedback

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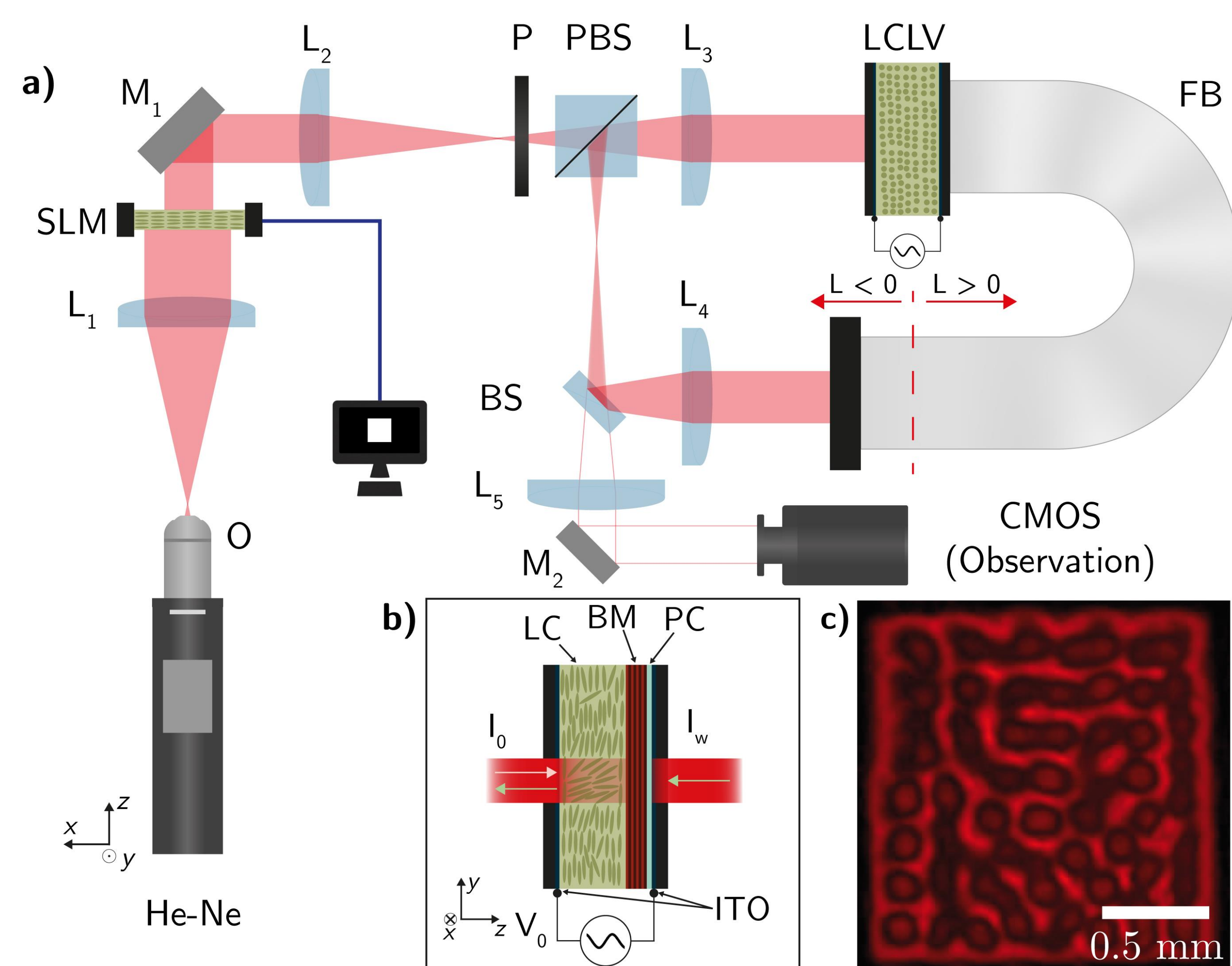
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Pattern formation and its spatiotemporal complexity have significantly been studied in different systems out of equilibrium, such as nonlinear optics, chemistry, ecology, and biology. However, the complex behavior of two-dimensional patterns is not yet fully understood. We use a Liquid Crystal Light Valve (LCLV) with Optical Feedback to characterize the transition, or route, to spatiotemporal complexity of the patterns formed in this system. A universal model of pattern formation, derived from the LCLV simultaneously close to the nascent of bistability and a spatial instability, Lifshitz point, is numerically integrated to obtain the theoretical route to spatiotemporal complexity. The studied complexity of the experimental and theoretical patterns is characterized via the computation of the Largest Lyapunov Exponent and Spatial Permutation Entropy.

## Experimental setup

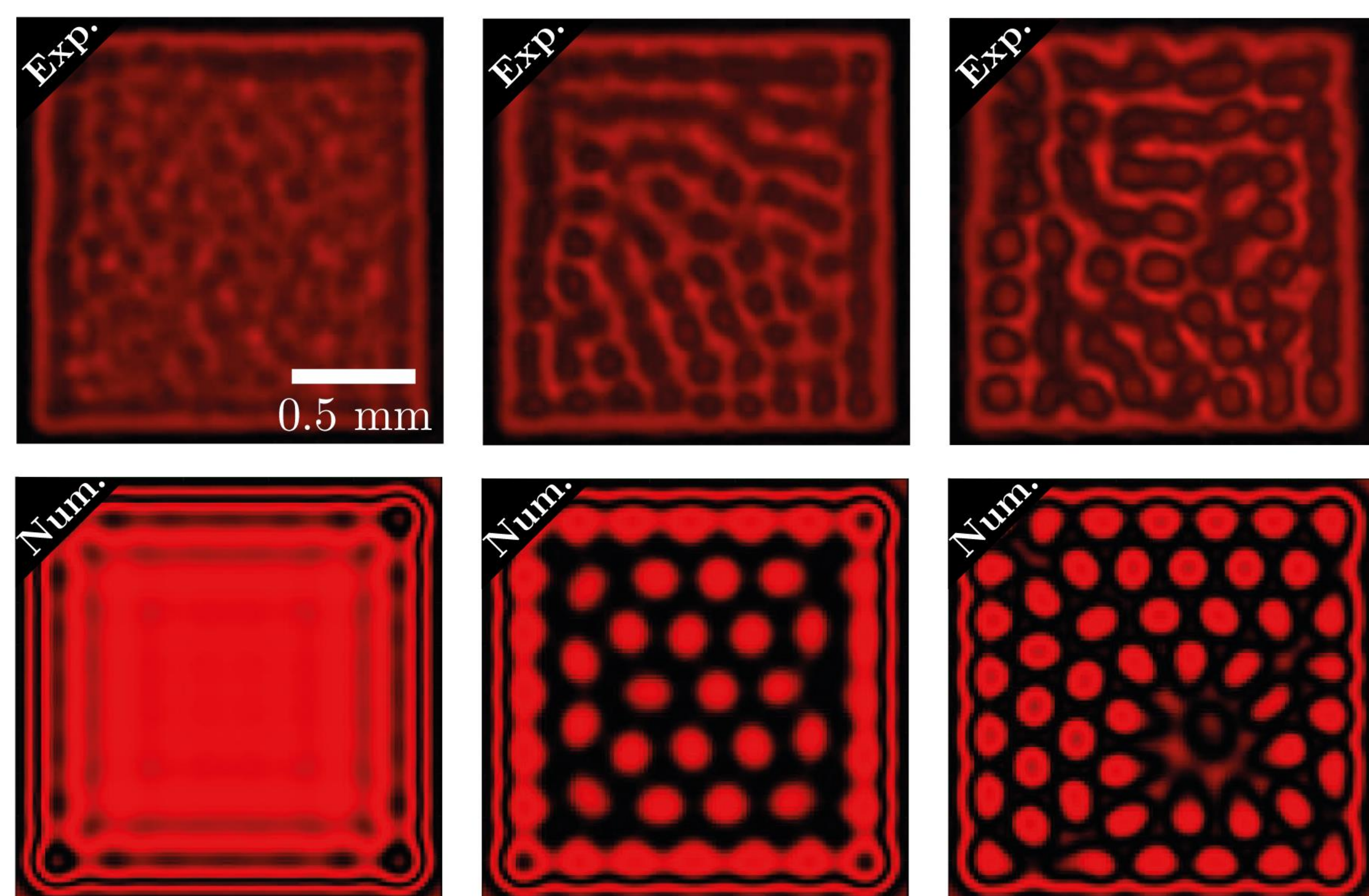


**Figure 1:** Liquid Crystal Light Valve (LCLV) with Optical Feedback. **a)** Schematic representation of the experimental setup. He-Ne accounts for a Helium-Neon laser. O is an optical objective,  $L_i$  stands for Lens ( $i=\{1,2,3,4\}$ ), SLM is a spatial light modulator, P is a  $\lambda/2$  polarizer, PBS is a polarizer beam splitter, BS is a beam splitter, FB is an optical fiber bundle, M stands for mirror and CMOS accounts for a complementary metal-oxide-semiconductor camera. **b)** Schematic representation of the LCLV. LC accounts for the liquid crystal layer, BM is a Bragg mirror, PC is a photoconductive layer, ITO are transparent indium tin oxide electrodes,  $V_0$  is the driving voltage,  $I_0$  is the laser intensity and  $I_w$  is the writing intensity after passing through the LCLV. **c)** Snapshot of a recorded solution.

## Theoretical model

The **Non-Variational Turing-Swift-Hohenberg equation** can be derived [1]:

$$\partial_t u = \eta + \mu u - u^3 + \nu \nabla^2 u - \nabla^4 u + \kappa u \nabla^2 u + c(\nabla u)^2$$



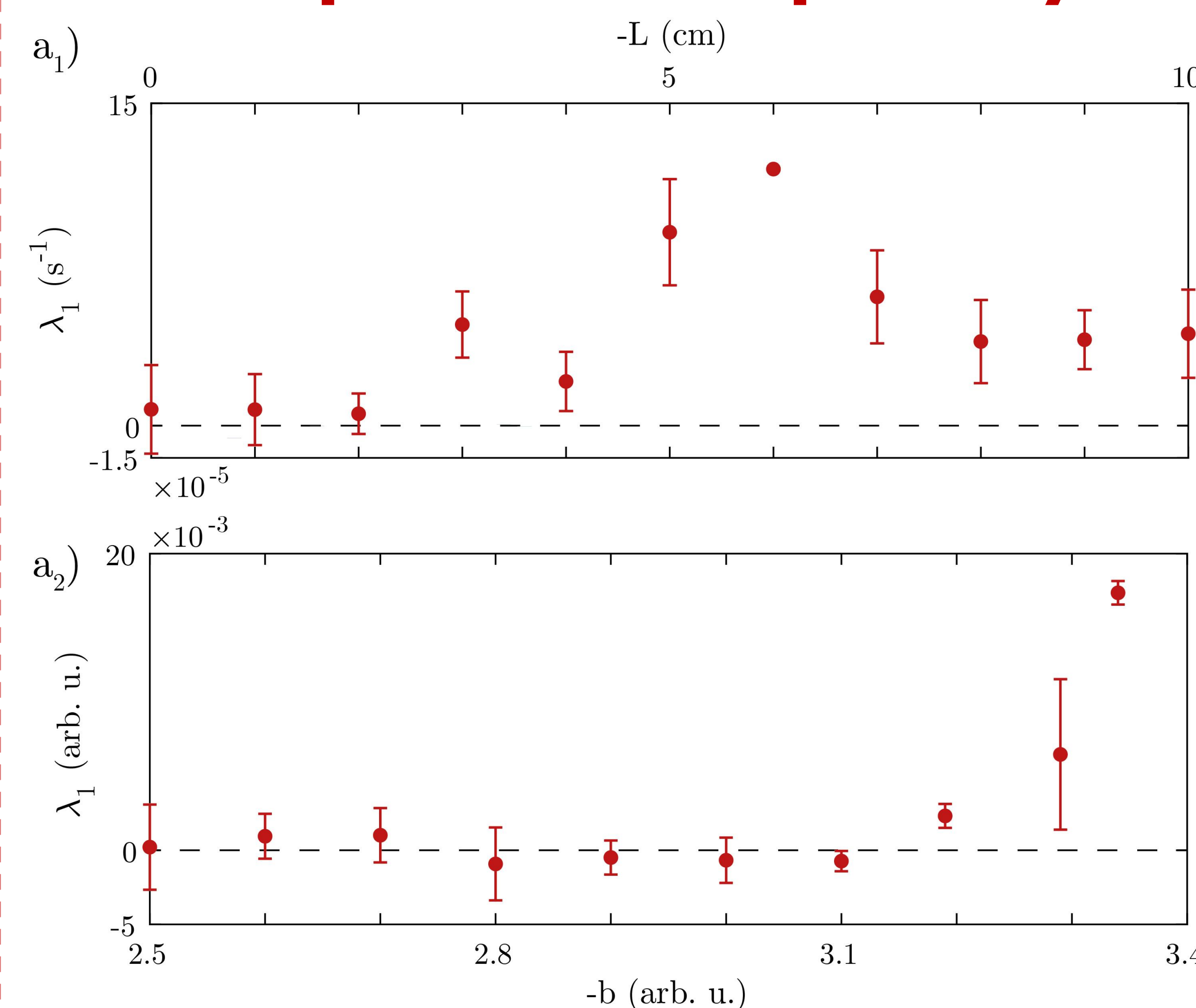
**Figure 2:** Characteristic solutions of the system. Top panel shows the liquid crystal light valve results. Bottom panel shows the numerical simulations of the Turing-Swift-Hohenberg Equation.

## Introduction

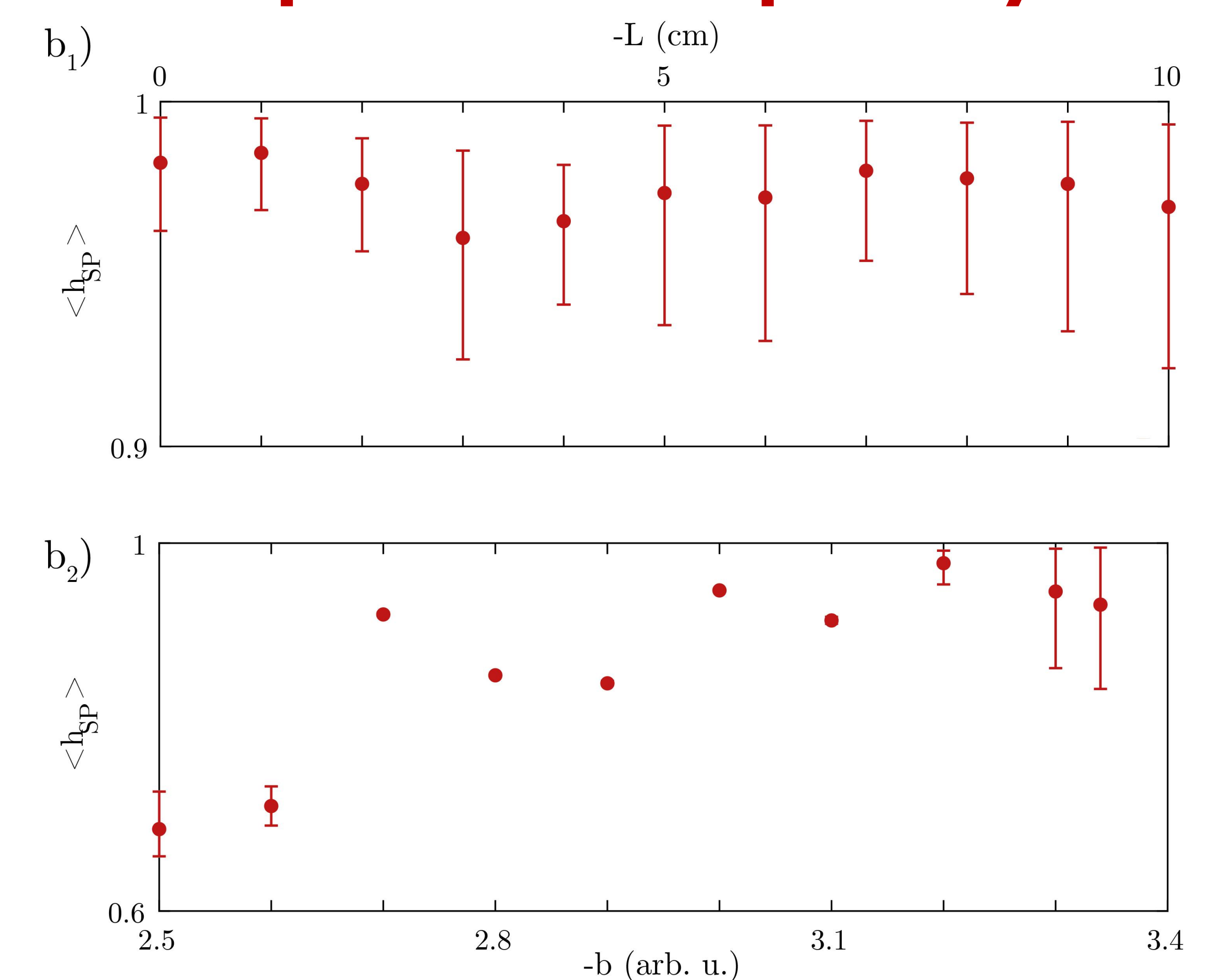
To characterize the emergence of two dimensional spatiotemporal complex optical patterns, we use a **Liquid Crystal Light Valve with optical feedback**, with varying free diffraction  $L$ .

The temporal complexity is characterized by computing the **Largest Lyapunov Exponent** [2], whereas the spatial complexity is characterized by computing the **Spatial Permutation Entropy** [3].

## Temporal complexity



## Spatial complexity



**Figure 3:** Complexity parameters. **a)** Largest Lyapunov Exponent  $\lambda_1$  for varying diffraction length  $L$  and nonlinear diffusion  $b$ . **a<sub>1</sub>)** Experimental data. **a<sub>2</sub>)** Numerical data. The points correspond to the spatial average, and the error bars account for the standard deviation of the data. **b)** Spatial Permutation Entropy  $\langle h_{SP} \rangle$  for varying diffraction length  $L$  and nonlinear diffusion  $b$ . **b<sub>1</sub>)** Experimental data. **b<sub>2</sub>)** Numerical data. The points correspond to the spatial average and the error bars account for the minimum and maximum value obtained.

## Conclusions

The optical patterns exhibit **chaotic dynamics** associated with the increase of the Largest Lyapunov Exponent and **irregular spatial distributions**, associated with a high spatial permutation entropy.

These features were also obtained by integrating a universal model of pattern formation, indicating that these findings are intrinsic of two-dimensional patterns. This shed light on the mechanisms that underlie the formation of complex spatiotemporal patterns in two dimensions.

[1] S. Residori (2005). *Patterns, fronts and structures in a Liquid Crystal Light Valve with optical feedback*, Physics Reports , 416(5-6), 201-272.

[2] M. G. Clerc, G. González-Cortés, V. Odent, and M. Wilson (2016). *Optical textures: characterizing spatiotemporal chaos*, Optics Express, 24(14), 15478-15485.

[3] C. Bandt and B. Pompe (2002). *Permutation Entropy: A Natural Complexity Measure for Time Series*, Physical Review Letters, 88(17), 174102.

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