Project DisCo: Physics-based discovery of coherent structures in spatiotemporal systems

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Big Data Summit 2018

Project DisCo

John Travolta in 'Saturday Night Fever' (Paramount)

- The Science Problem
- The Theory
- The Computation
- The Unsupervised Ladder
- The HPC Challenge

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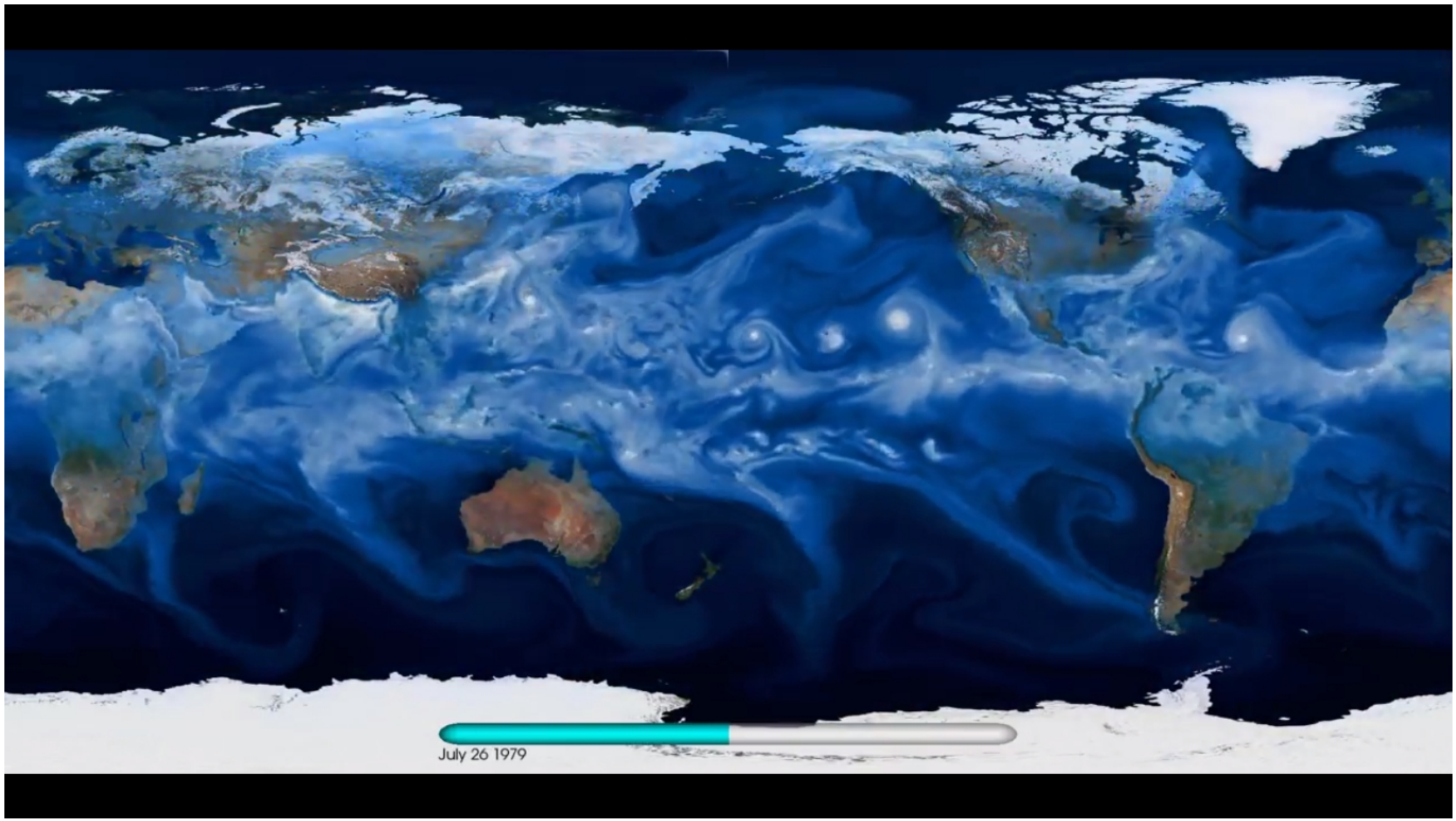
on track for SC'19 Gordon Bell submission

The Science Problem

Unsupervised detection (segmentation) of spatiotemporal structures in climate



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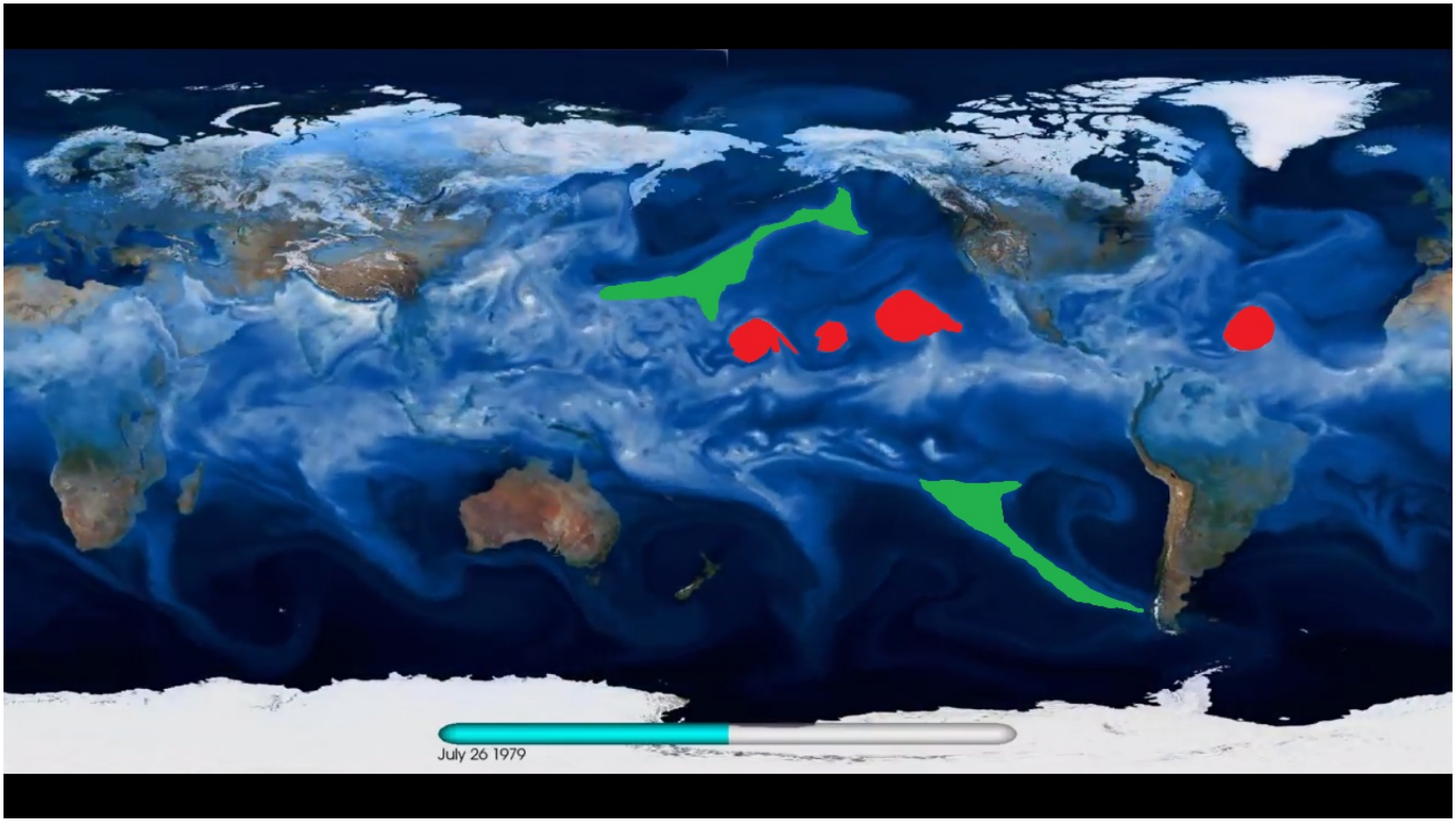

The Theory: Computational Mechanics

Think of this as a *physics-based* machine learning technique

Segmentation achieved through use of *local causal states*

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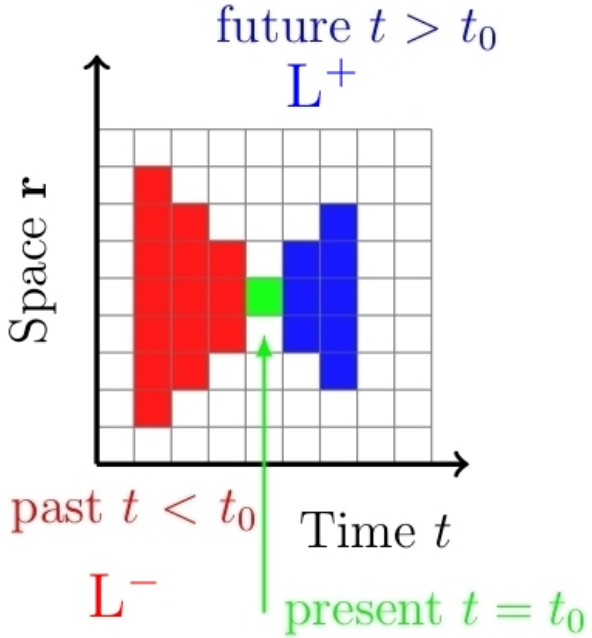
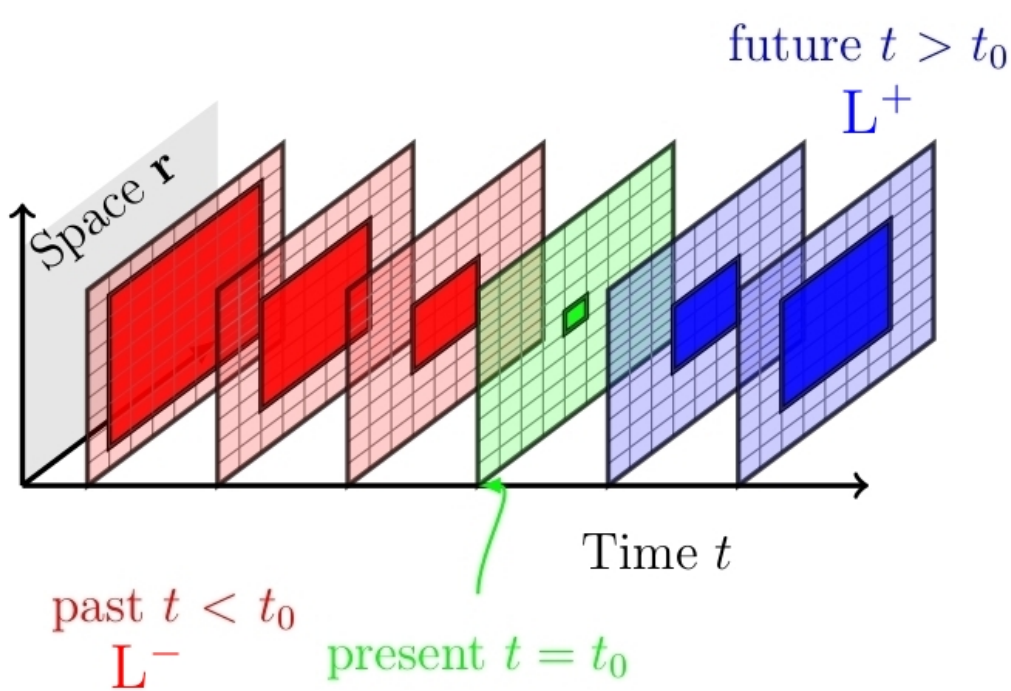
Segmentation achieved through use of *local causal states*

Causal states defined through the *causal equivalence relation*

$$\text{past}_i \sim_\epsilon \text{past}_j \iff \Pr(\text{Future}|\text{past}_i) = \Pr(\text{Future}|\text{past}_j)$$

Lightcones used as local notions of past and future





The Computation

Goal - reconstruction of *causal equivalence relation* from data

$$\ell_i^- \sim_\epsilon \ell_j^- \iff \Pr\left(\mathtt{L}^+|\ell_i^-\right) = \Pr\left(\mathtt{L}^+|\ell_j^-\right)$$

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- Training
  1. Reconstruct morph$(\ell_i^-) = \Pr\left(\mathtt{L}^+|\ell_i^-\right)$
     - extract $\left(\ell^-, \ell^+\right)$ pairs from sample fields
     - for real-valued fields, need to cluster space of lightcones

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  2. Cluster together pasts with same morph - resulting clusters are *local causal states*
     - gives ϵ-map; $\epsilon(\ell_i^-) = \xi_{\ell_i^-} = \{\ell_j^- \ : \ \ell_j^- \sim_\epsilon \ell_i^-\}$

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- Inference
  1. Use ϵ-map to perform *causal filtering*; $\mathbf{x} \to \mathcal{S} = \epsilon(\mathbf{x})$
     - *Segmentation* semantics from structural properties of $\mathcal{S}$

The Unsupervised Ladder

No labeled data – no error metric to optimize

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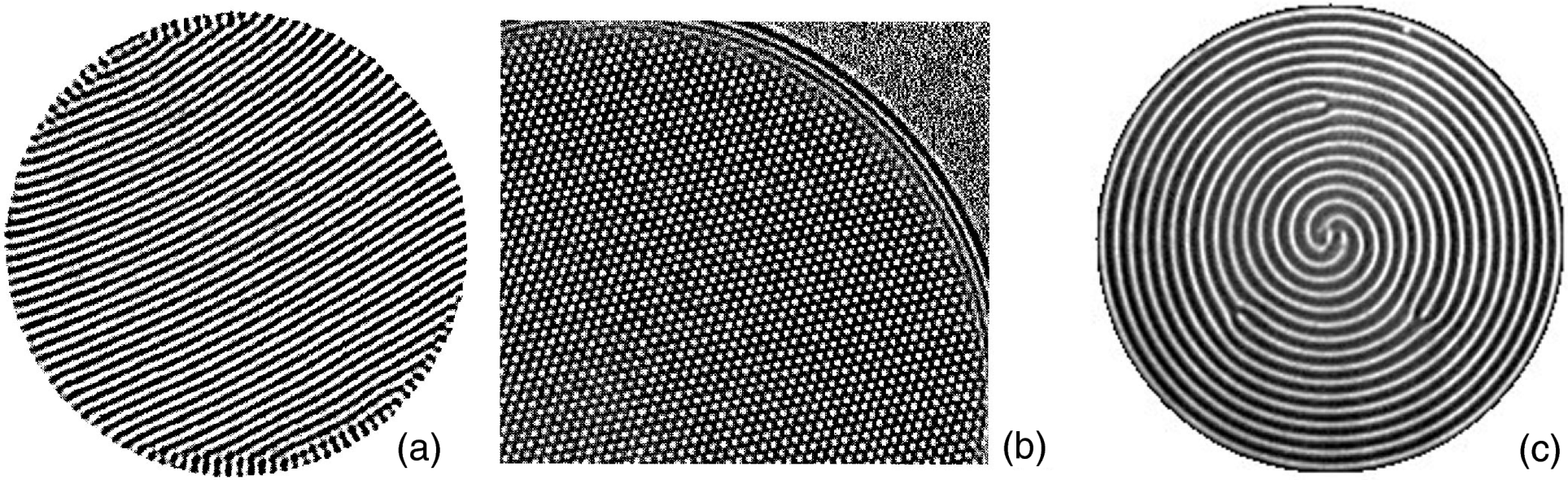
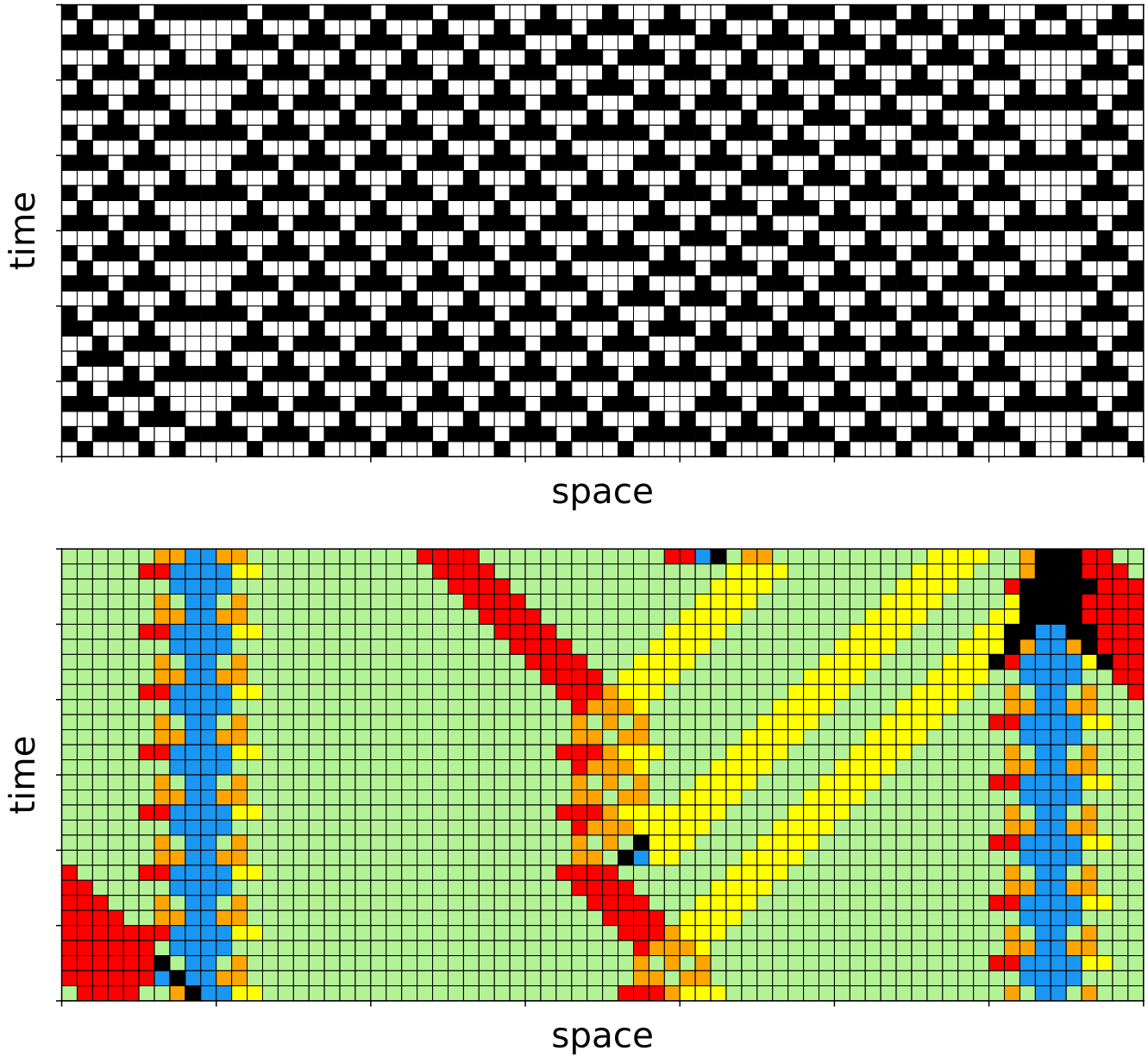
Built from physical theory

- validation established using physical principles

broken symmetry

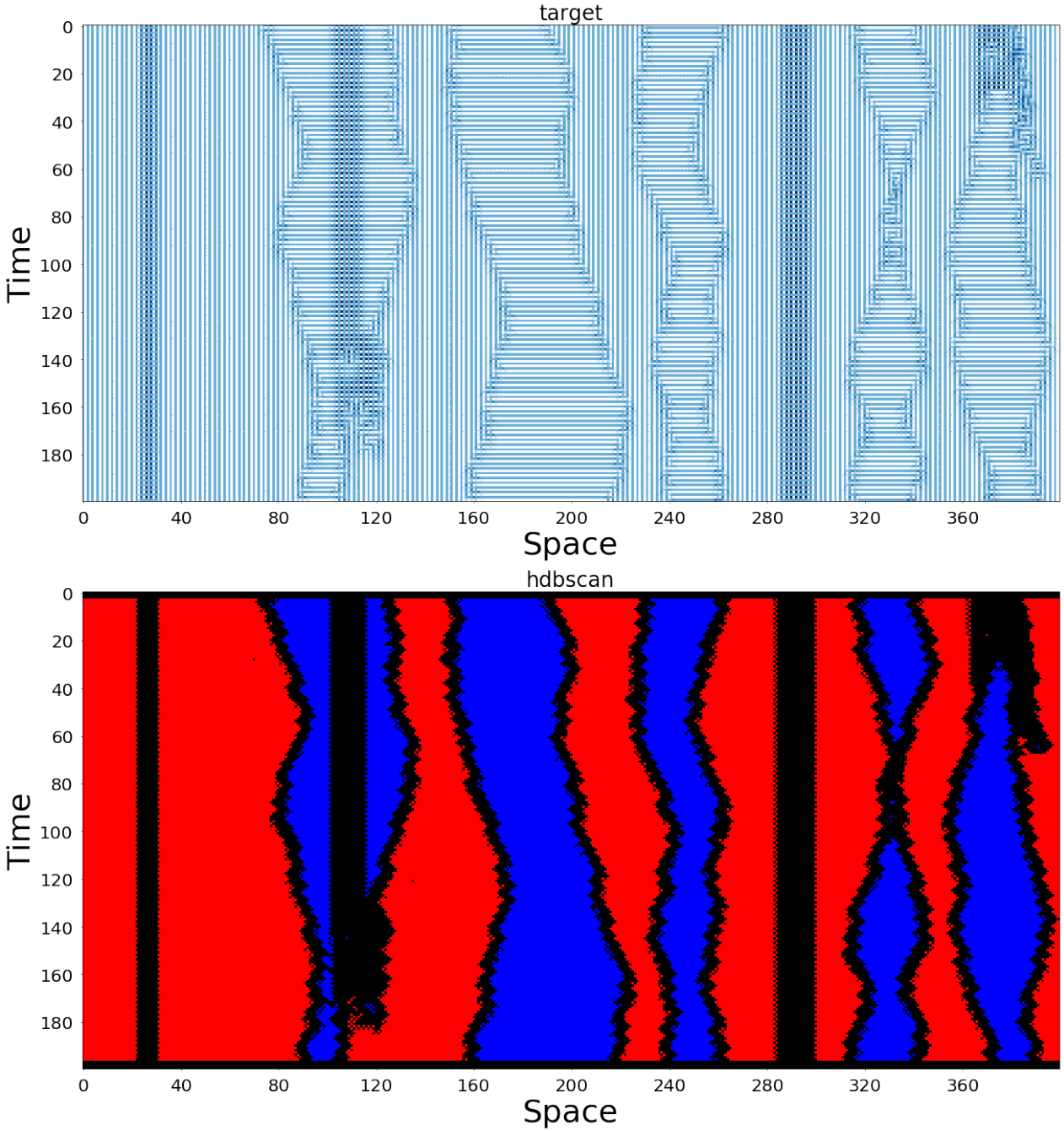


Step 1 – Cellular Automata

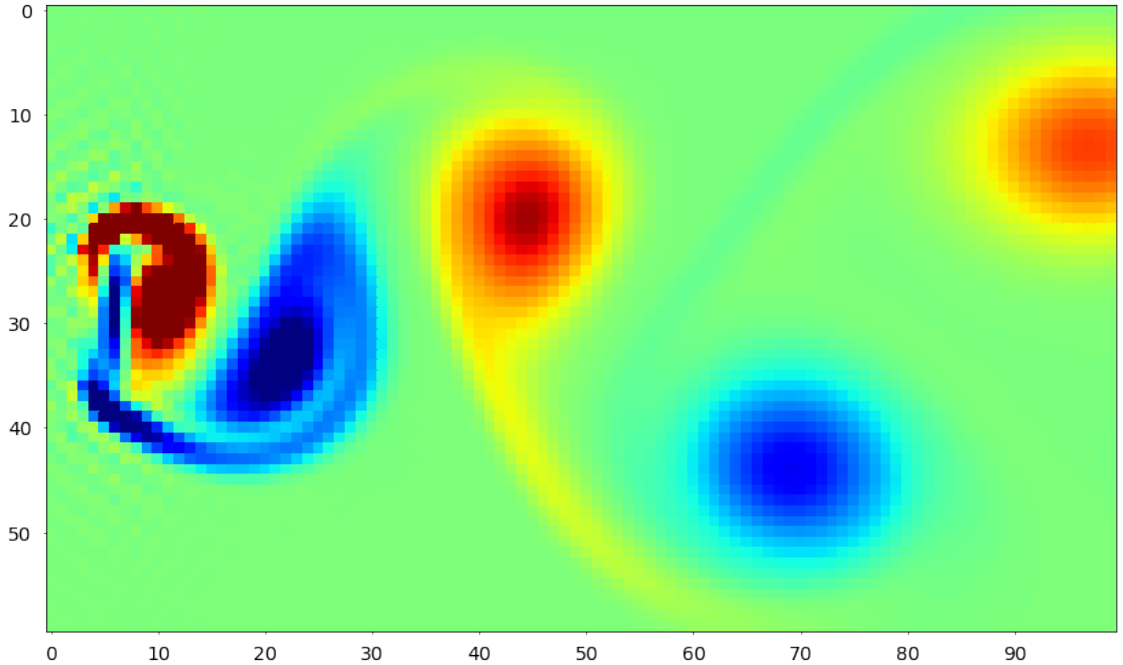


A. Rupe and J.P. Crutchfield (2018). Local Causal States and Discrete Coherent Structures. arXiv preprint arXiv:1801.00515.

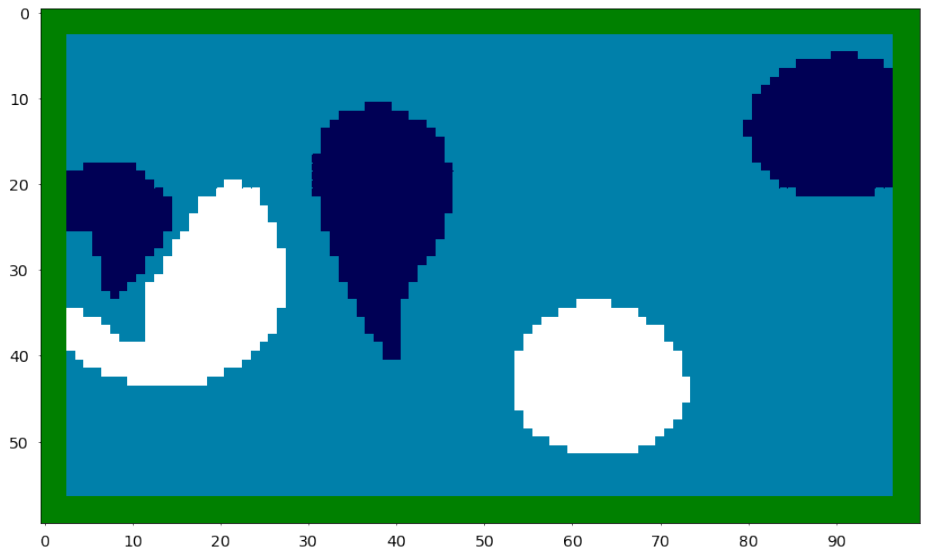
Step 2 – Coupled Map Lattices



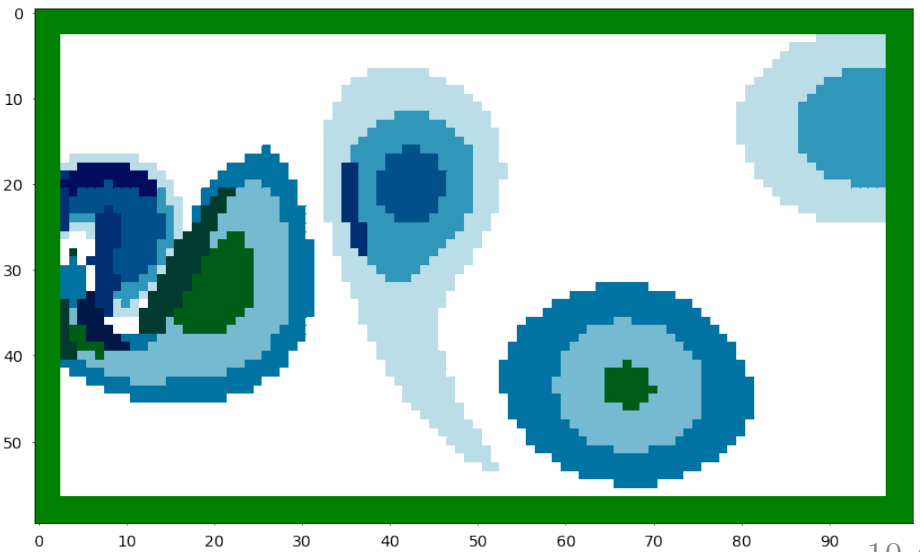
Step 3 – Vortex Shedding



K = 3

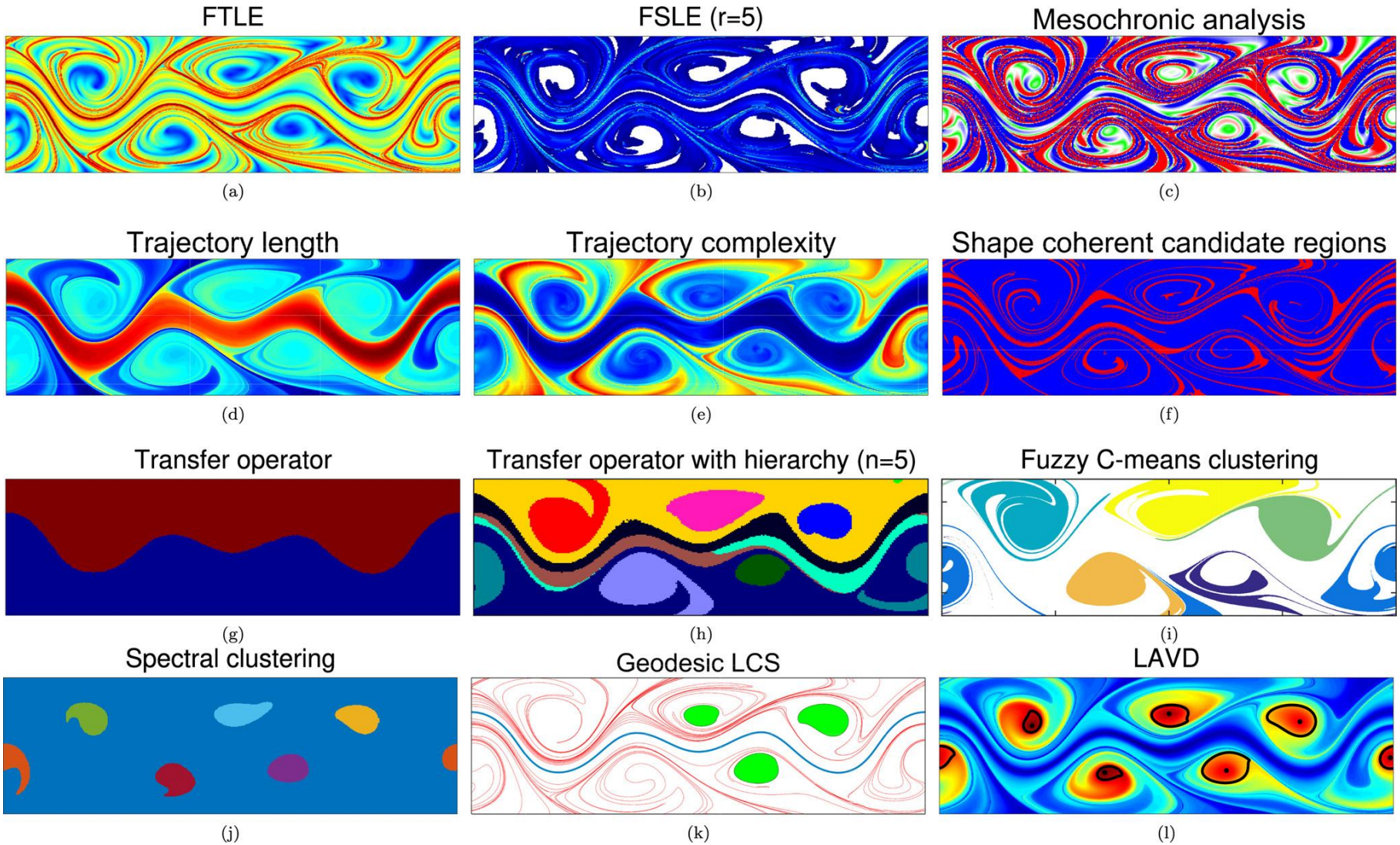


K = 11



Step 4 – Bickley Jet

Candidate data set for SC'19 GB submission



Hadjighasem, A., Farazmand, M., Blazevski, D., Froyland, G., & Haller, G. (2017). A critical comparison of Lagrangian methods for coherent structure detection. Chaos: An Interdisciplinary Journal of Nonlinear Science, 27(5), 053104.

Step 5 – Transitional / Turbulent Flow

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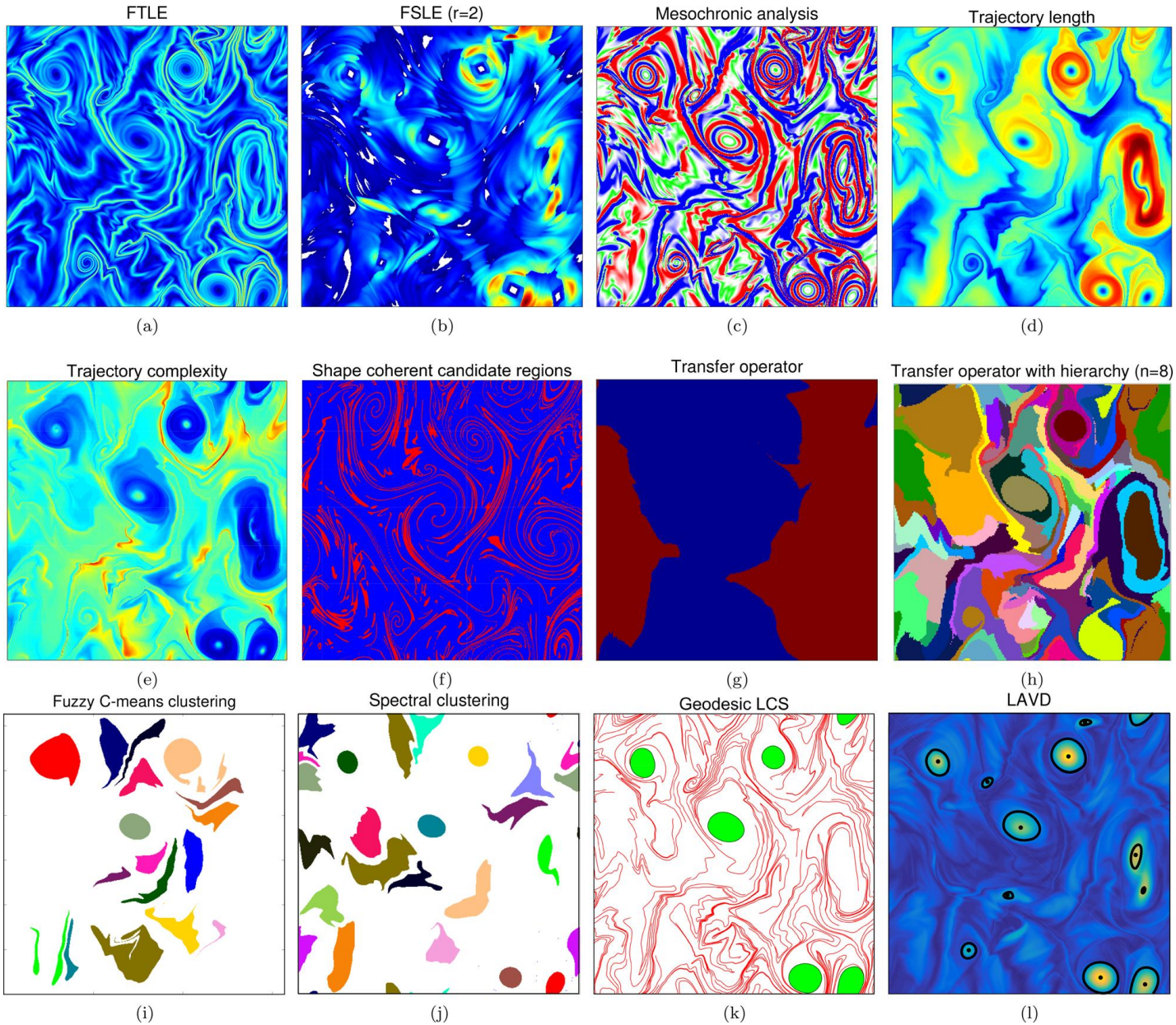

The HPC Challenge

- Clustering very high-dimensional lightcone data
  - kmeans vs dbscan
- Multi-node clustering in Python
- Efficient use of memory

Outcomes

Completed Papers:

- A. Rupe, J.P. Crutchfield, K. Kashinath, and Prabhat (2017). A Physics-Based Approach to Unsupervised Discovery of Coherent Structures in Spatiotemporal Systems, Lyubchich, V., N. C. Oza, A. Rhines, and E. Szekely, eds., 2017: Proceedings of the 7th International Workshop on Climate Informatics: CI 2017. NCAR Technical Note NCAR/TN-536+PROC, 132 pp, doi:10.5065/D6222SH7. arXiv:1709.03184 [physics.flu-dyn]
- A. Rupe and J.P. Crutchfield (2018). Local Causal States and Discrete Coherent Structures. arXiv preprint arXiv:1801.00515.
  - *Accepted for publication* in Chaos: An Interdisciplinary Journal of Nonlinear Science
- A. Rupe and J.P. Crutchfield (2018). Spacetime Symmetries, Invariant Sets, and Additive Sub-Dynamics of Cellular Automata. Preparing for submission.

Planned Manuscripts:

- A. Rupe and J.P. Crutchfield (2018). Spacetime Computational Mechanics.
- Structural Semantics of Local Causal States, Part 1: Contamination.
- Structural Semantics of Local Causal States, Part 2: Coherence Detection.
- Local Causal States and Lagrangian Coherent Structures.

Outcomes

Presentations:

- Seminar – Center for Nonlinear Dynamics, UT Austin, 2016
- Talk – APS Far West Section, 2016
- Poster – AGU Fall Meeting, 2016
- Talk – Dynamics Days, 2017
- Talk – 7th Annual UC Davis Math Conference, 2017
- Poster – 7th International Workshop on Climate Informatics, NCAR, 2017
- Poster – Intel HPC Developer Conference, 2017
- Talk – 70th Annual Meeting of the APS Division of Fluid Dynamics, 2018
- Poster – Dynamics Days, 2018
- Poster – Intel AI Dev
- Talk – Information Engines at the Frontiers of Nanoscale Thermodynamics, Telluride Science Research Center

Thank You!