Uncovering spatiotemporal coherence in living and non-living matter

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Physics 191

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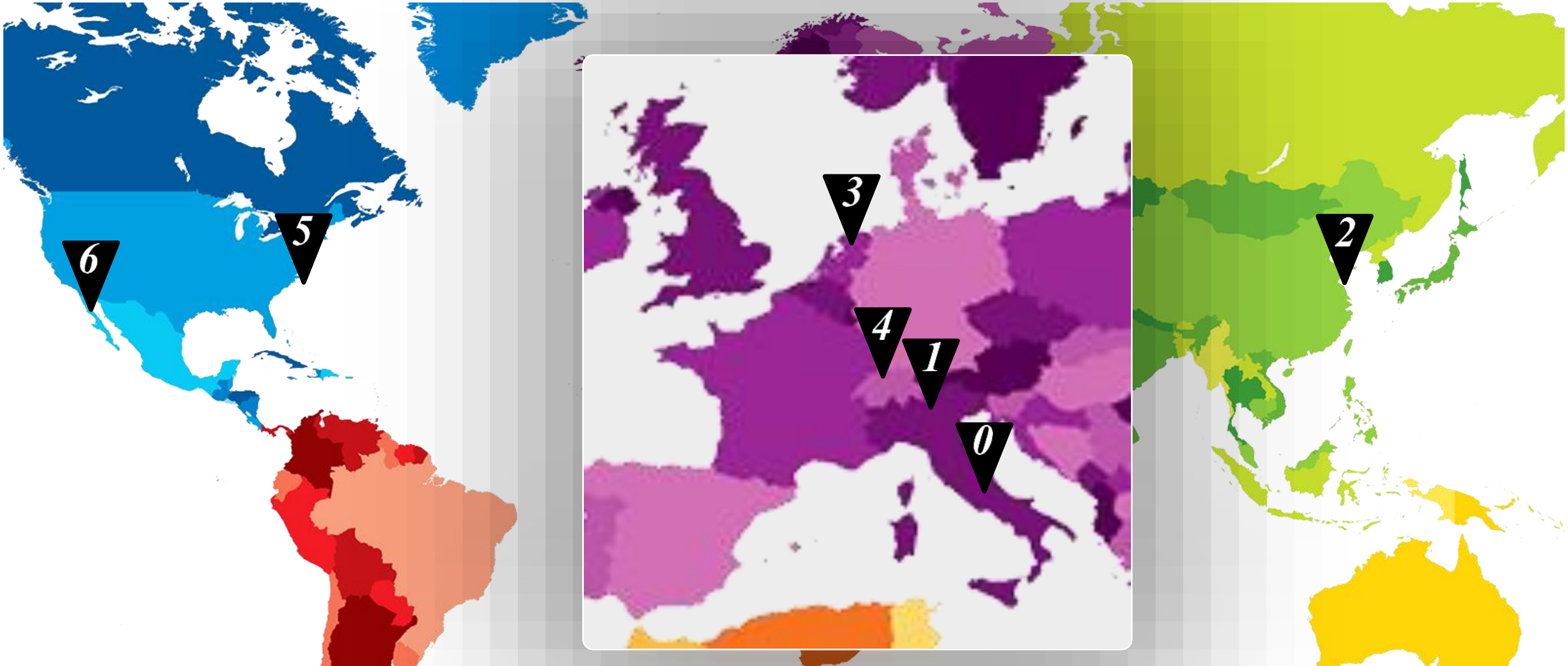
About me

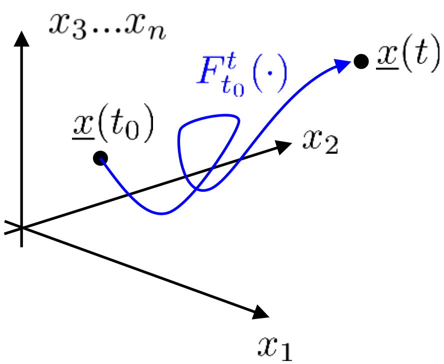


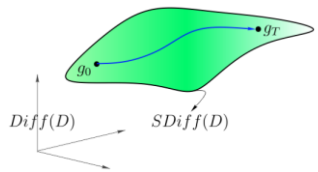
0. Torrevecchia Teatina (Italy)

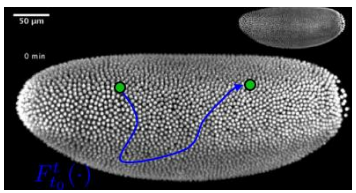
1. Milan - B.Sc., M.Sc. Politecnico di Milano	**2007-2012**
2. Shanghai - Tongji University	**2008-2009**
3. The Netherlands - TU-Delft University	**2011-2012**
4. Switzerland - ETH Zurich	**2014-2017**
5. Boston - Harvard University	**2017-2020**
6. San Diego - UCSD	**2020 -**

Motivation

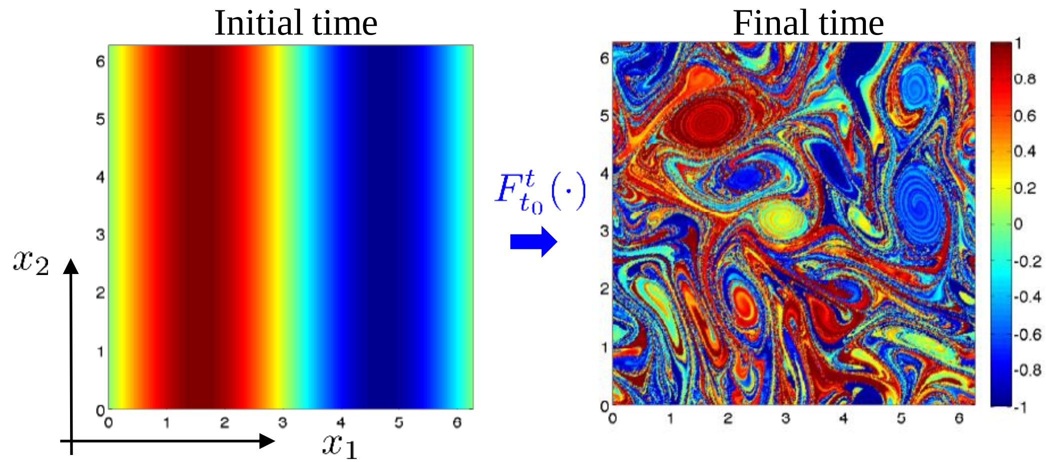
Dynamical System = Phase space + Evolution Rule





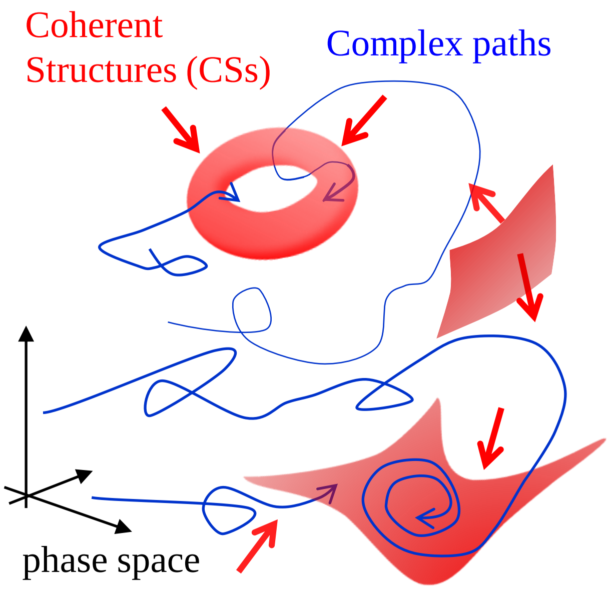


Chaotic System

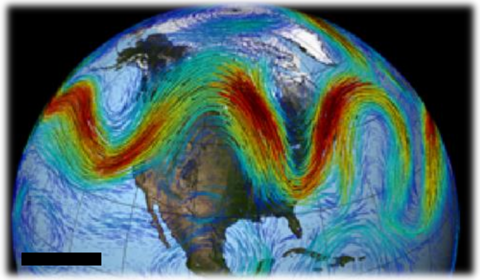


Q: The skeleton of observed trajectory patterns?

Motivation



Atmospheric Flows

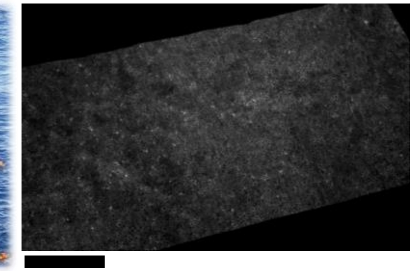


1000 km

Oceanic flows

50 m

Embryogenesis



200 μm

CSs = spatiotemporal organizers of complex systems

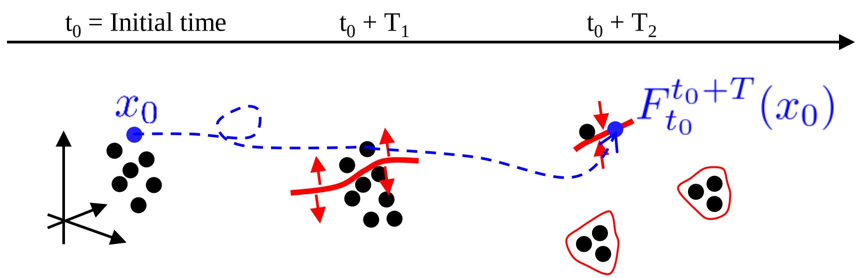
Why

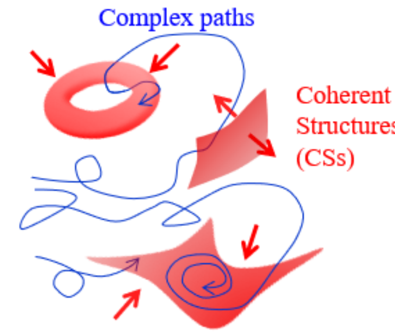
- Data-driven prediction
- Scale Free
- Mechanistic principles unknown

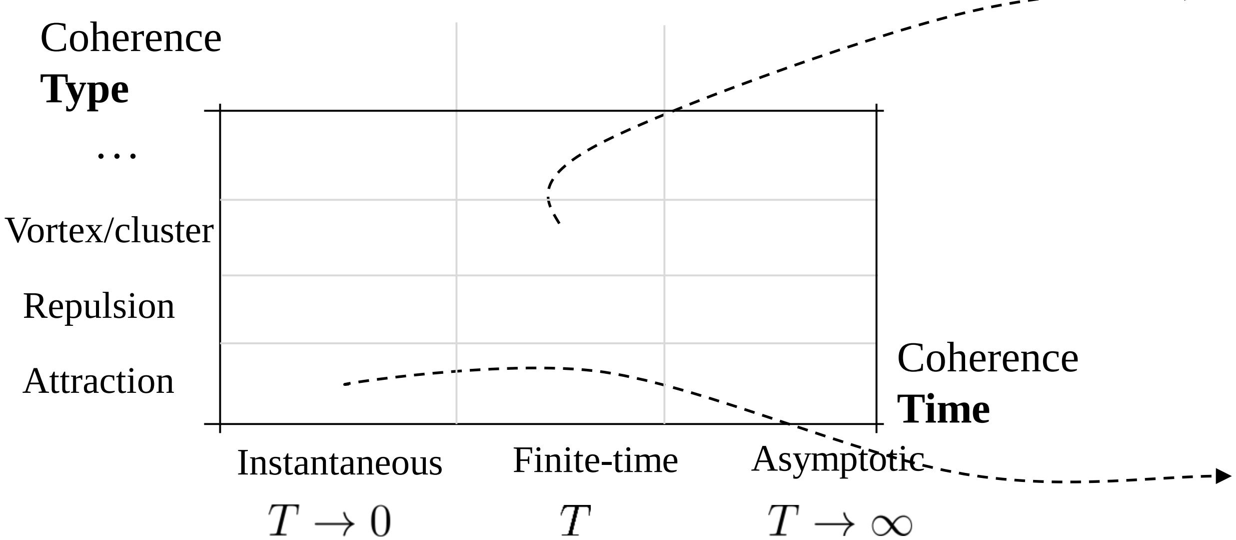
Challenges

- Finite-time datasets
- General time-dependent dynamical systems

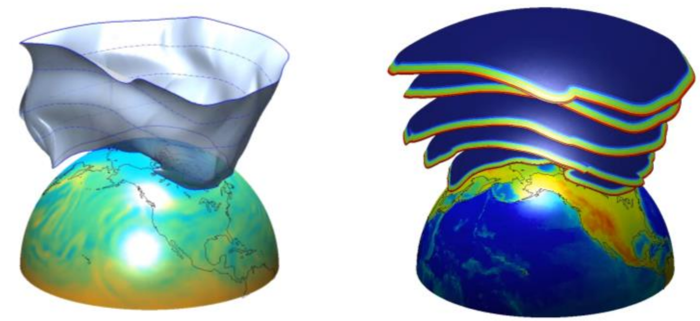
Classification of Coherent Structures (CSs)







Coherent vortex boundaries

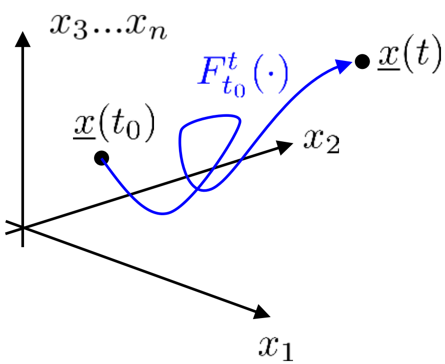


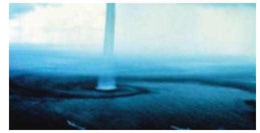
M.S. et al. 74 (11) **J. Atm. Sci.**, (2017)

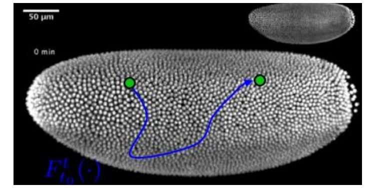
Short-term attractors

M.S. et al. **Nature Comm.** (2020)

How to define Coherent Structures?

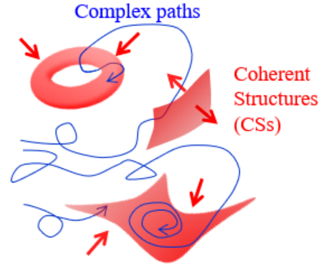






- Define a coherence principle (physics-biology-engineering…)
- Intrinsic quantities (mathematics)
- Seek extremizers (mathematics)

Outline



1. CSs and in Search and Rescue at sea

2. CSs in embryonic development

3. Available projects

Ex1: Hazard Responses

Search and Rescue

Oil spill

Challenges:

- Limited search assets
- Quick response (~ 6h in SAR)

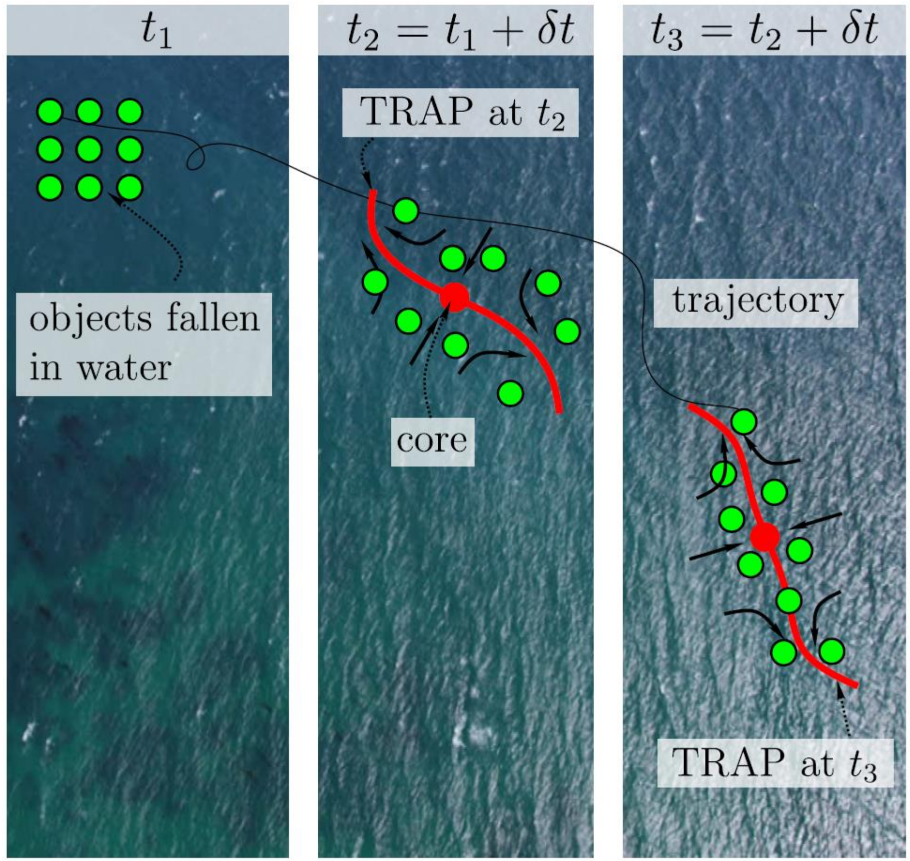
Q: Short-term attractors?

Short-term attractors during Search and Rescue operations

Fluid particles:

$$\dot{\mathbf{x}} = \mathbf{v}(\mathbf{x}, t)$$

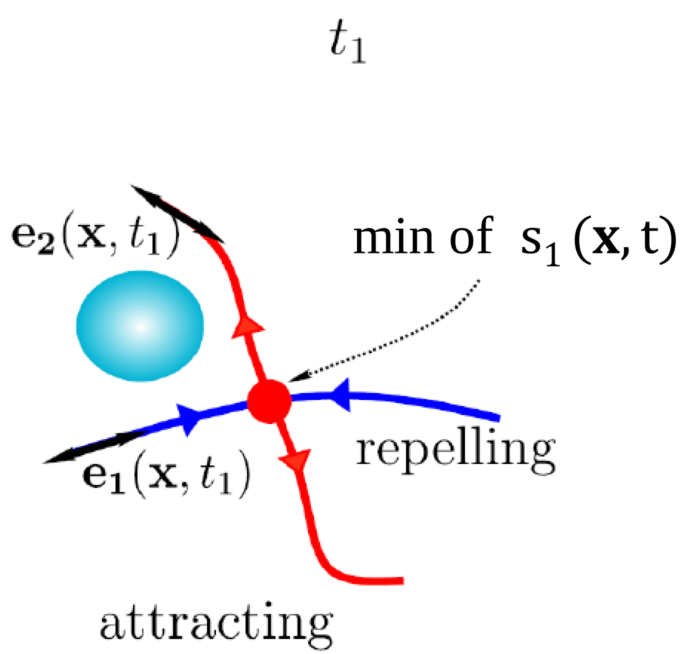
TRansient Attracting Profiles (TRAPs)



TRansient Attracting Profiles (TRAPs)

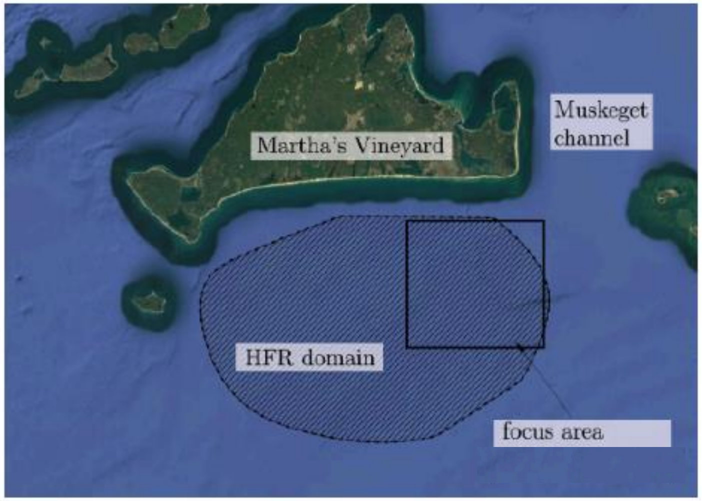
Theorem:

- Instantaneously most attracting curves
- Computable from the Eulerian rate-of-strain tensor $\mathbf{S}(\mathbf{x},t)$
- Tangent to the dominant eigenvector $\mathbf{e}_2(\mathbf{x},t)$:
- Starting from minima of the smallest eigenvalue $s_1(\mathbf{x},t)$



M. Serra & G. Haller, *Objective Eulerian Coherent Structures*, Chaos, (2016)

Field experiments tools

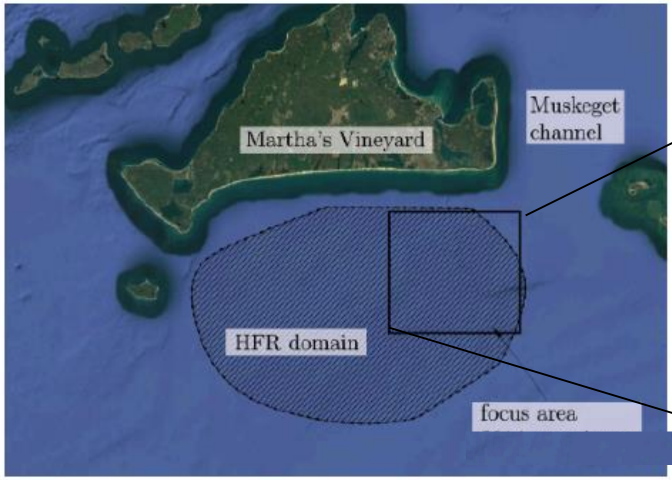


Strategy:

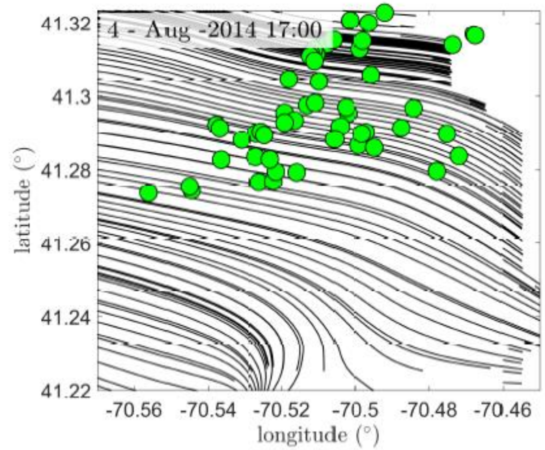
1. Surface velocity field *(input to U. S. Coast Guard)*
2. Compute TRAPs
3. Deploy Drifter and Manikins *(GPS tracked position)*
4. Do TRAPs predict Drifters and Manikins motion? [Video]

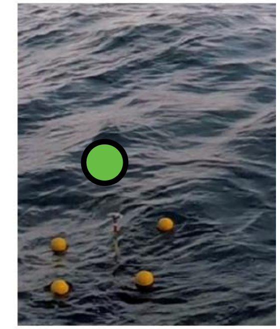
M. Serra et al. *Search and rescue at sea aided by hidden flow structures*, 11, 2525 (2020), **Nature Communications**

Field Experiment

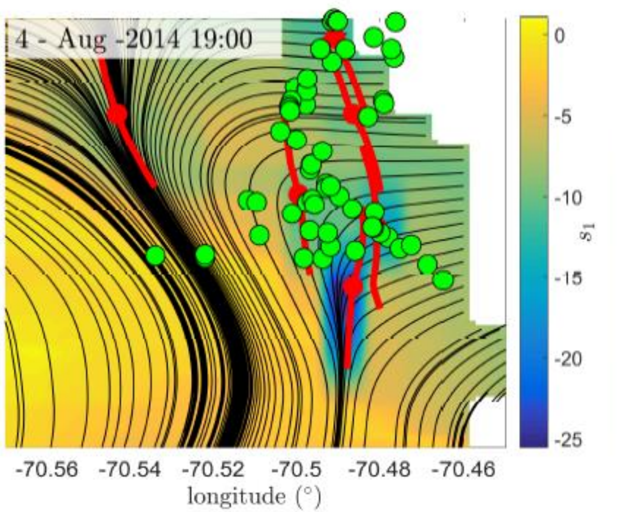


70 drifters emulate **people fallen in water with uncertain initial position**





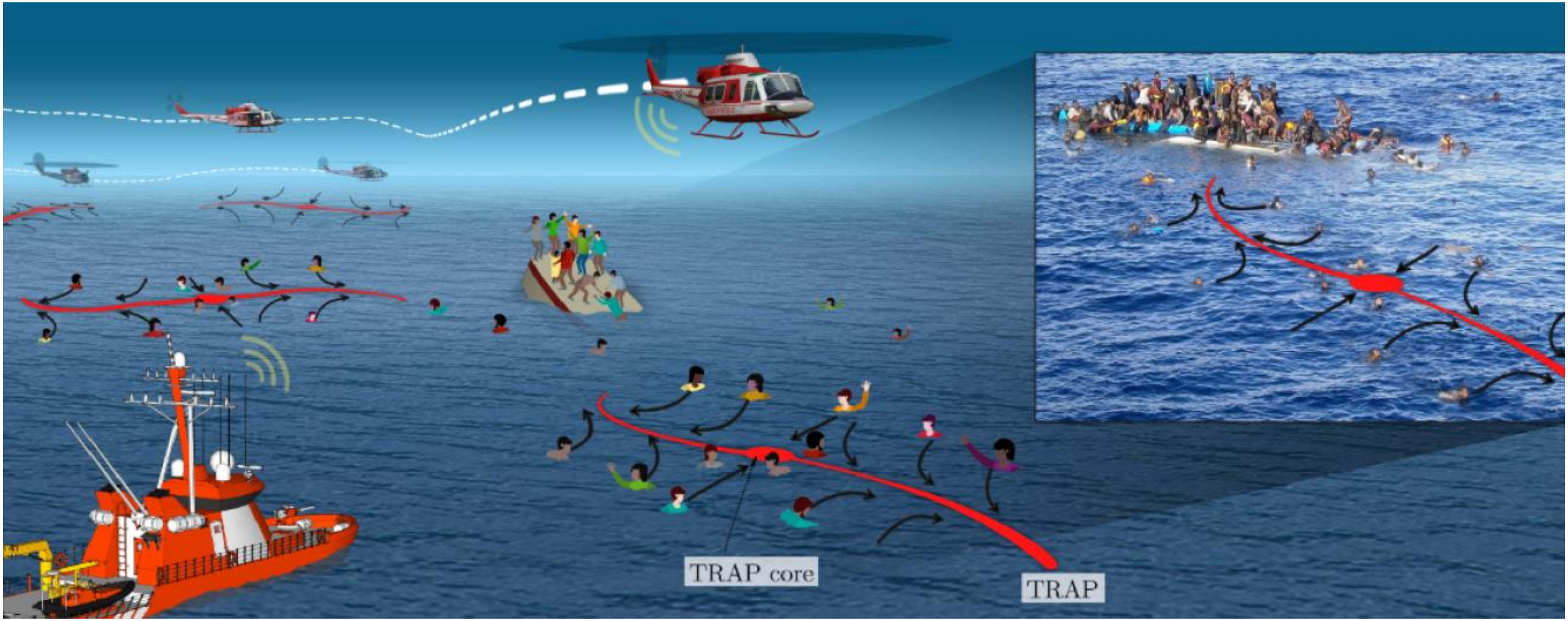
After 2h



TRAPs predict the motion of floating objects

M. Serra et al. *Search and rescue at sea aided by hidden flow structures*, 11, 2525 (2020), **Nature Communications**

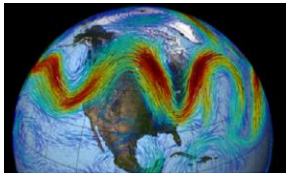
Summary



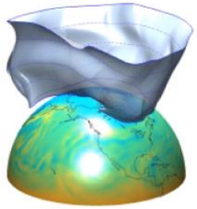
- Fluid-based TRAPs = short-term attractors of general floating objects
- 1D curves (optimal for search assets allocation)
- Robust to uncertainties
- Quick to compute
- Hidden

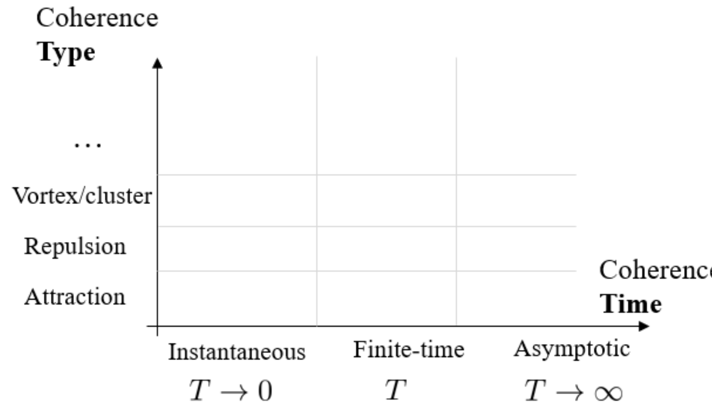
Different types of Coherence

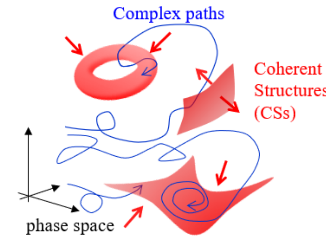
Jet-type structures



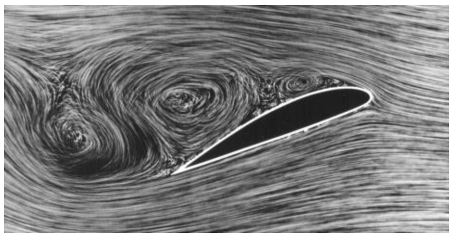
Vortex-type structures

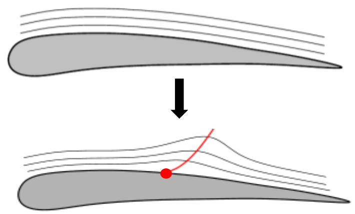






Curvature-based structures (high folding deformations)





...

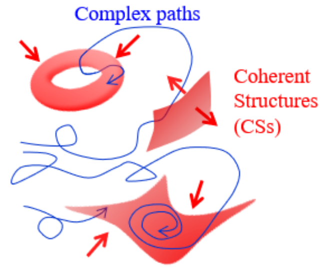
M.S. & G. Haller, *Objective Eulerian Coherent Structures*, **Chaos**, (2016)
M.S. & G. Haller, *Forecasting Long-Lived Lagrangian Vortices from their Objective Eulerian Footprints*, **J. Fluid Mech.**, (2017)
M.S. & G. Haller, *Efficient Computation of Null Geodesics with Applications to Coherent Vortex Detection*, **Proc. Roy. Soc. A**, (2017)
M.S., P. Sathe, F. Beron-Vera & G. Haller, *Uncovering the edge of the Polar Vortex*, **J. Atm. Sci.**, (2017)
S. Katsanoulis, M. Farazmand, **M. S.** & G. Haller, *Vortex boundaries as barriers to diffusive vorticity transport in two-dimensional flows*, **PRF** (2020)
M.S., J. Vetel & G. Haller, *Exact theory of material spike formation in flow separation*, in press, **J. Fluid Mech.**, (2018)
M.S., S. Crouzat, G. Simon, J. Vetel & G. Haller, *Material spike formation in highly unsteady separated flows*, 883 A30, **J. Fluid Mech.** (2020)
B. Klose, **M.S.** & G. Jacobs, *The Kinematics of Lagrangian Flow Separation in External Aerodynamics*, in press, **AIAA Journal** (2020)
P. Nolan, **M. S.** and S. Ross, *Finite-time Lyapunov exponents in the instantaneous limit and material transport*, **Nonlinear Dynamics** (2020)

Detection of Transient instabilities

B. Klose*, **M.S*.** & G. Jacobs, *Objective early identification of kinematic instabilities in shear flows*, under review, **J. Fluid Mech.**

- **Observed coherent patterns →** seek their exact **mathematical construct**
- **Computable from experimental data** (no mechanistic models needed)
- **Coherence principles in Biology?** attraction, repulsion, synchronization…

Outline



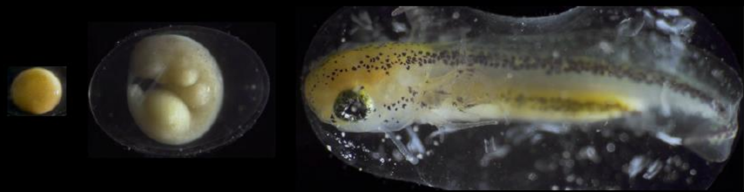
1. CSs and in Search and Rescue at sea

2. CSs in embryonic development

3. Available projects

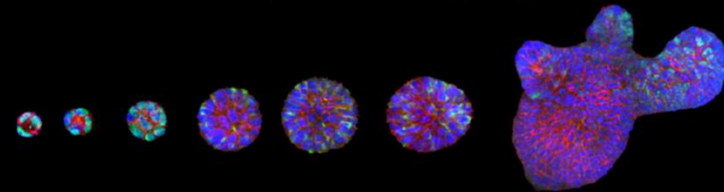
Ex2: Spatiotemporal coherence in living matter - Morphogenesis

Animal Morphogenesis



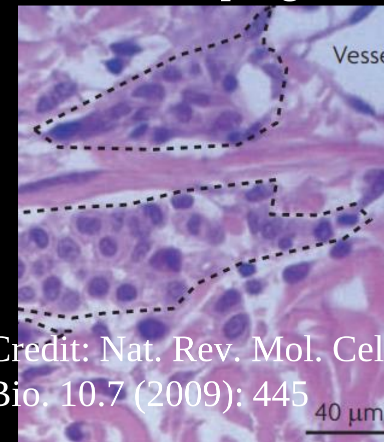
Credit: Jan van Ijken

Intestinal **Organoid Morphogenesis**

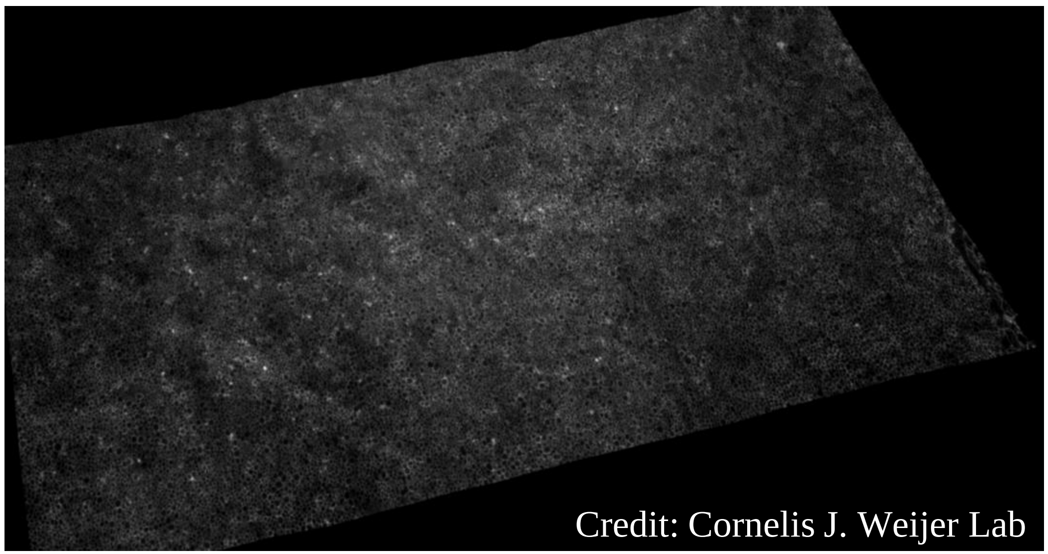


Credit: Liberali lab, *Nature* **569**, 66–72 (2019)

Cancer Morphogenesis



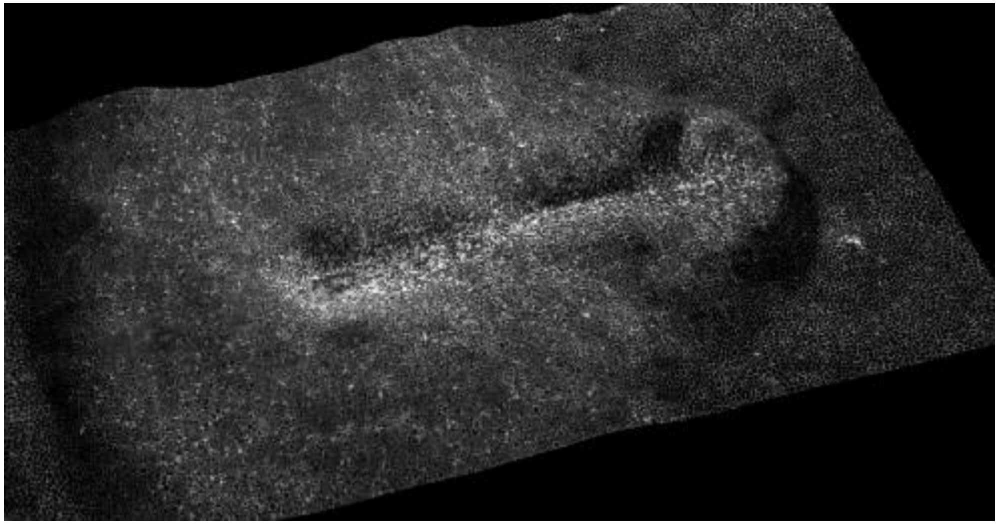
Credit: Nat. Rev. Mol. Cell Bio. 10.7 (2009): 445

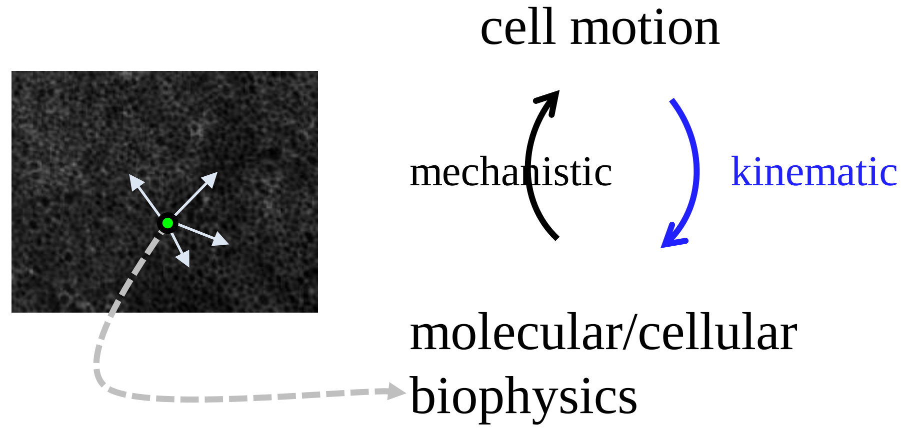


Credit: Cornelis J. Weijer Lab

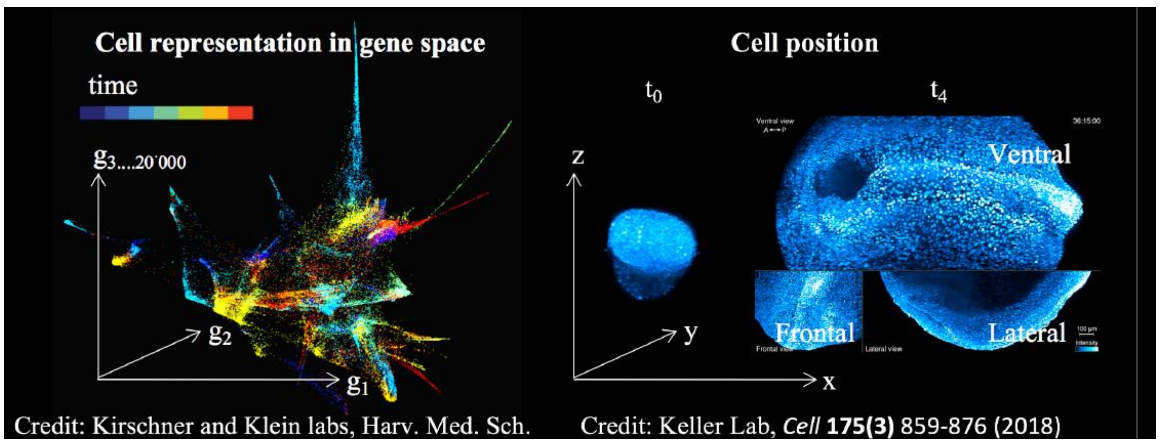
Q: when do cells become fated during development?

When do cells became fated?





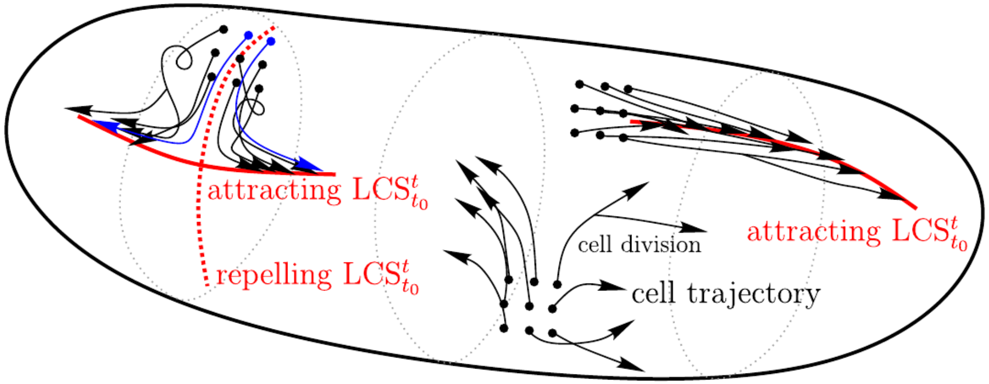
Phase space of developmental cell trajectories?



- Cell velocities and trajectories in position space are easily accessible

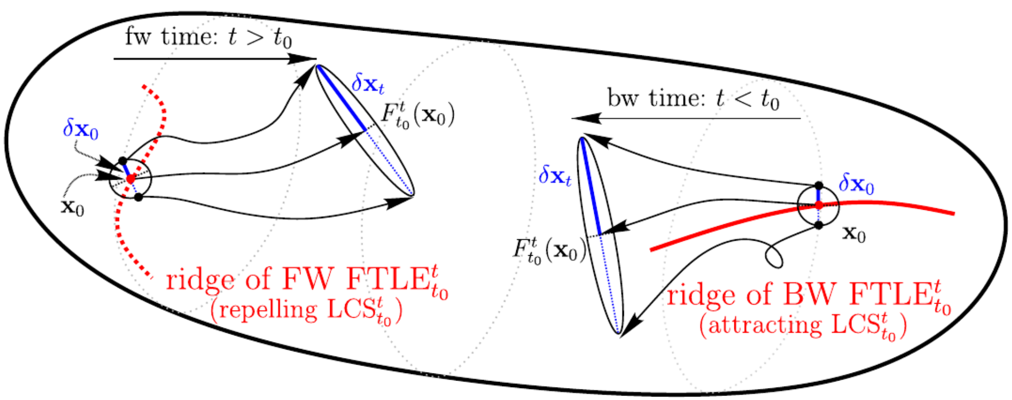
Q: is there a footprint of cell fate acquisition in cell position data?

Dynamic Morphoskeleton = Attracting and Repelling Coherent Structures



- Centerpieces of cell patterns
- Time scales, exact spatial location

Finite-time Lyapunov Exponent (FTLE)



$$\mathbf{F}^t_{t_0}(\mathbf{x}_0) = \mathbf{x}_0 + \int_{t_0}^{t} \mathbf{v}(\mathbf{F}^{\tau}_{t_0}(\mathbf{x}_0), \tau)\; d\tau$$

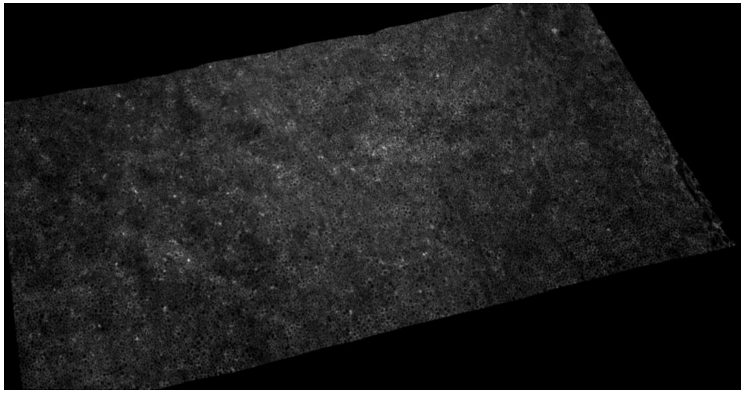
$$\mathbf{C}^t_{t_0}(\mathbf{x}_0) = [\nabla \mathbf{F}^t_{t_0}(\mathbf{x}_0)]^{\top} \nabla \mathbf{F}^t_{t_0}(\mathbf{x}_0)$$

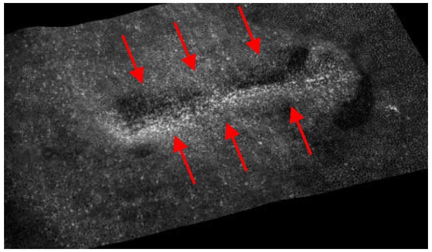
$$FTLE^t_{t_0}(\mathbf{x}_0) = \frac{1}{\underbrace{|t - t_0|}_{T}} \ln \left(\max_{\delta \mathbf{x}_0} \frac{|\overbrace{\nabla \mathbf{F}^t_{t_0}(\mathbf{x}_0)\delta \mathbf{x}_0}^{\delta \mathbf{x}_t}|}{|\delta \mathbf{x}_0|} \right) = \frac{1}{2|T|} \ln\left(\lambda_2(\mathbf{x}_0)\right)$$

- Scalar field
- **Finite-time deformation**

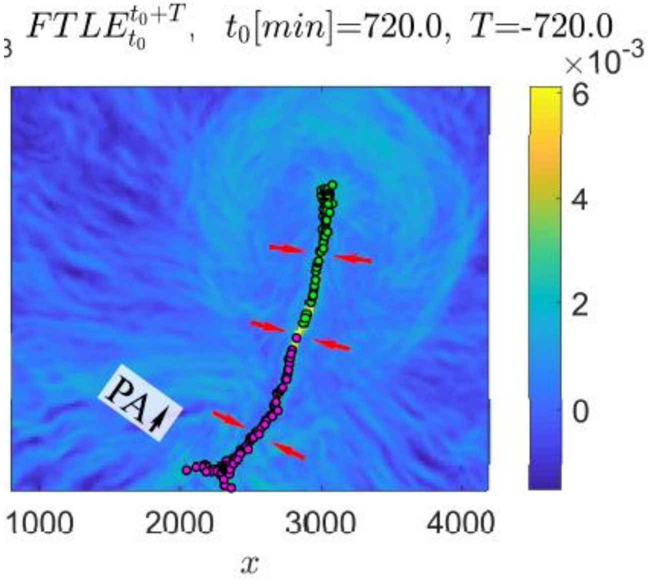
M. S., S. Streichan, M. Chuaid, C.J. Weijerd and L. Mahadevan, *Dynamic morphoskeletons in development*, **PNAS** (2020)

Primitive streak formation in chicken embryo





Attractor at final time

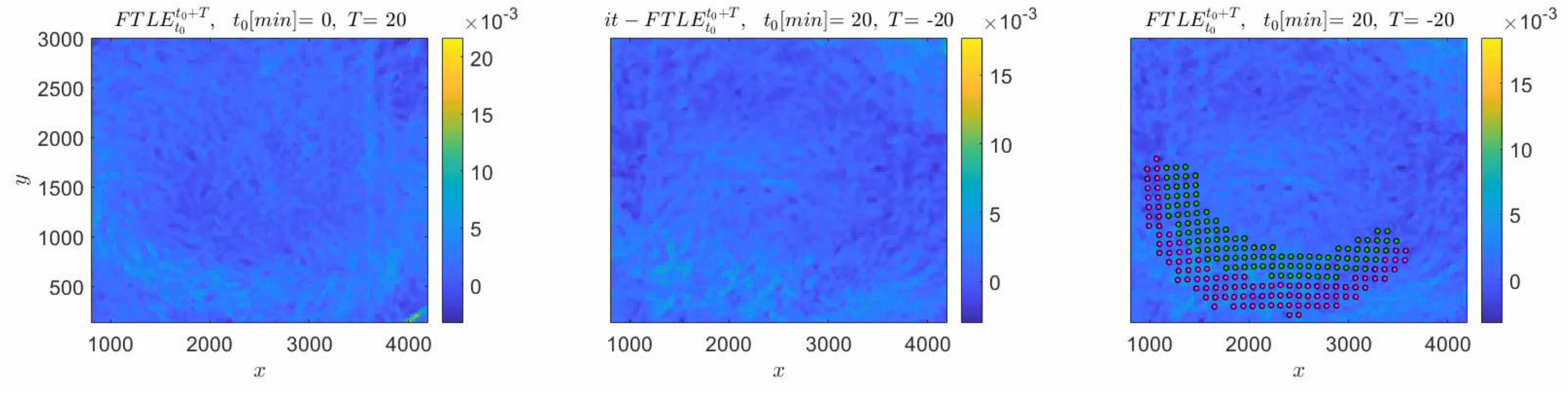


- **When do attractors and repellers form?**

M. S., S. Streichan, M. Chuaid, C.J. Weijerd and L. Mahadevan, *Dynamic morphoskeletons in development*, **PNAS** (2020)

Primitive streak formation in chicken embryo

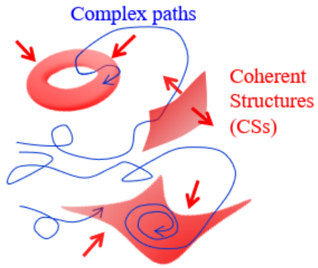
Repellers at initial time | **Domain of attraction at initial time** | **Attractor at final time**



- **Footprint of cell fate specification from positional CSs**
- **Hidden to conventional tools**

M. S., S. Streichan, M. Chuaid, C.J. Weijerd and L. Mahadevan, *Dynamic morphoskeletons in development*, **PNAS** (2020)

Outline



1. CSs and in Search and Rescue at sea

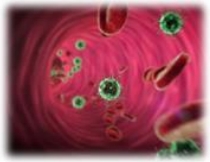
2. CSs in embryonic development

3. Available projects

Available projects

1. Predicting, Sensing and controlling CSs of Microorganisms in dilute suspensions

tumor cells in blood



swimming bacteria

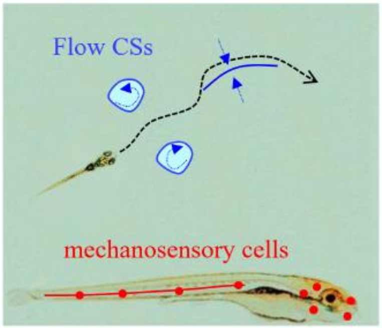
Ambient flow velocity

$$\dot{\boldsymbol{x}}_{\boldsymbol{f}} = \boldsymbol{v}_{\boldsymbol{f}}(\boldsymbol{x}_{\boldsymbol{f}}, t)$$

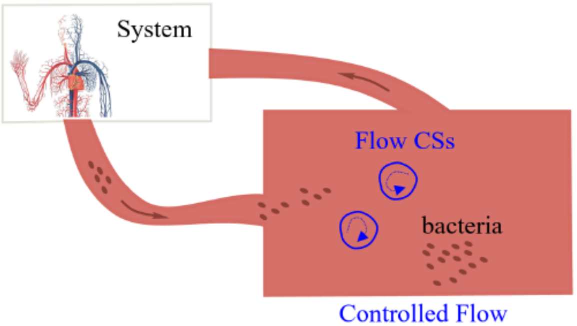
Microorganism/particle velocity

$$\begin{cases} \dot{\boldsymbol{x}}_{\boldsymbol{p}} = \boldsymbol{v}_{\boldsymbol{f}}(\boldsymbol{x}_{\boldsymbol{p}}, t) + \epsilon \boldsymbol{f}(\boldsymbol{p}, \text{shape}, \text{density ratio}...) + \boldsymbol{\xi}_{\boldsymbol{T}} \\ \dot{\boldsymbol{p}} = \sum_i \boldsymbol{g}_i(\boldsymbol{x}_{\boldsymbol{p}}, t, \text{taxis}_i, \text{shape}, \text{density ratio}, ...) + \boldsymbol{\xi}_{\boldsymbol{R}} \end{cases}$$

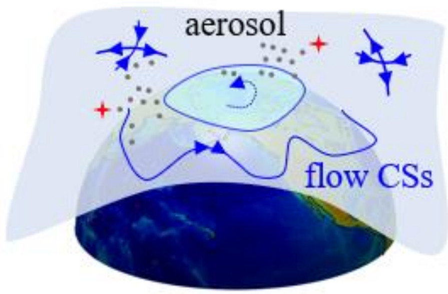
Sensing



Control

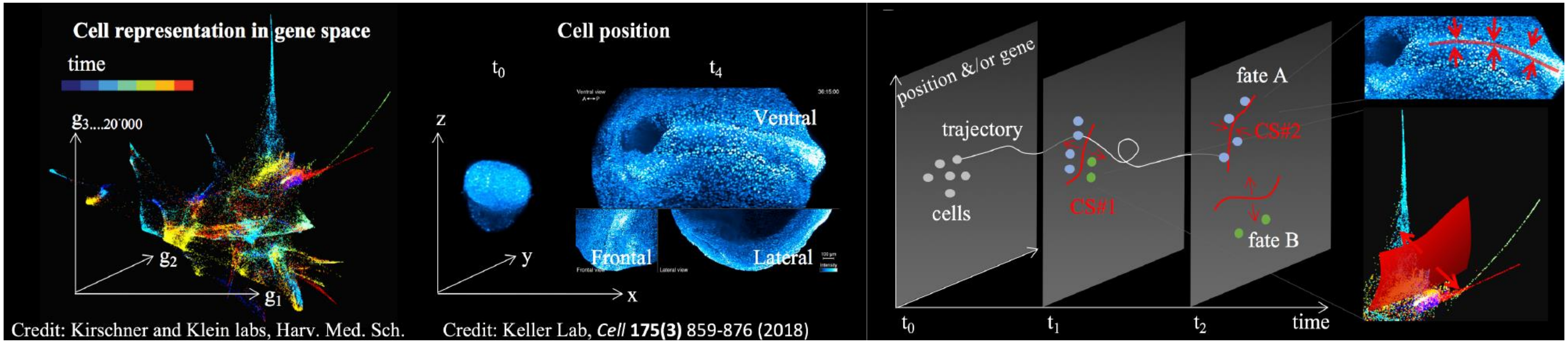


Prediction

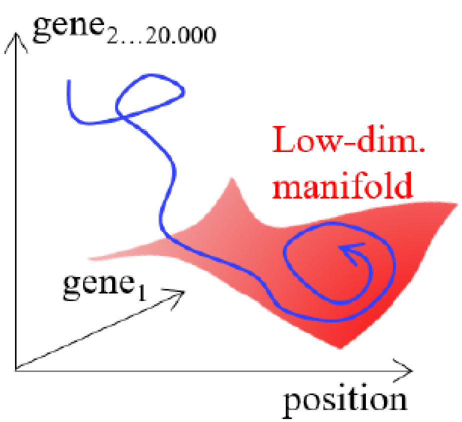


- **Sensing:** How do microorganisms navigate complex environments?
- **Learning** the **locomotion taxis** of microorganisms **from data**
- **Control** bacteria\tumor exosomes exploiting the known interactions with ambient flow

Available projects

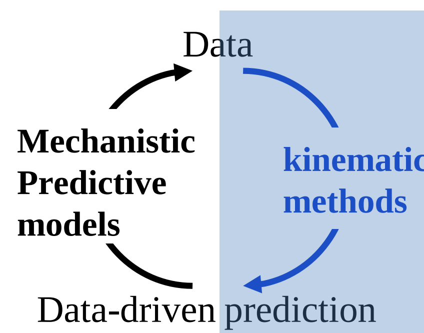


2. CSs and dimensionality reduction in gene + position space

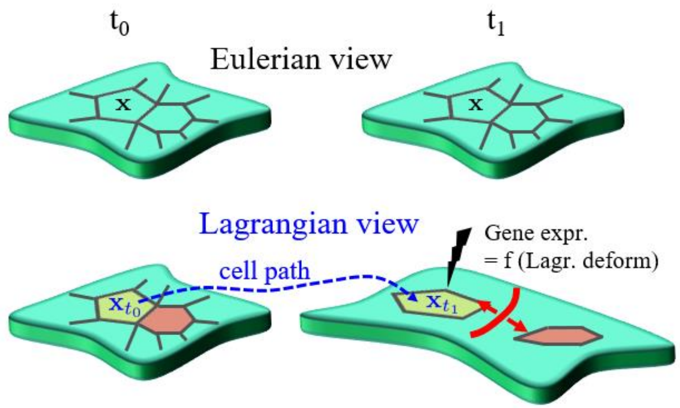


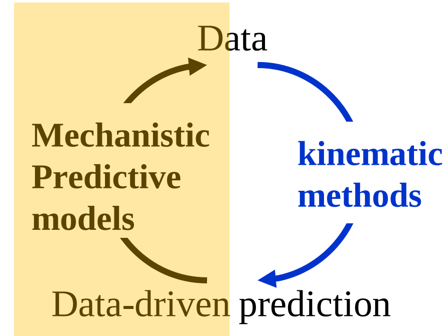
- Coherence principle: Positional proximity + synchronous gene expressions

→ Data-driven discovery of the relevant biophysical mechanisms



3. Mechanistic predictive models





$$\begin{cases} \frac{D\boldsymbol{v}}{Dt} = -p\boldsymbol{I} + \mu\boldsymbol{\nabla}^2\boldsymbol{v} + \boldsymbol{F}_a \\ \frac{D\boldsymbol{F}_a}{Dt} = \boldsymbol{f}(\overbrace{\text{Euler. quantities}}^{\text{upstream genes...}}, \overbrace{\text{Lagrang. quantities}}^{\text{Tissue deformations...}}) \end{cases}$$

- $\boldsymbol{f}$ is typically unknown → **learn part of the model from data**
  (Nonlinear system identification / physics-aware machine learning)

→ Coordinated cell motion with no centralized controller

Active matter models

$$\rho\frac{D}{Dt}\mathbf{v} = -\nabla p + \eta\nabla^2\mathbf{v} + \nabla\cdot[\sigma^e + \sigma^a]$$

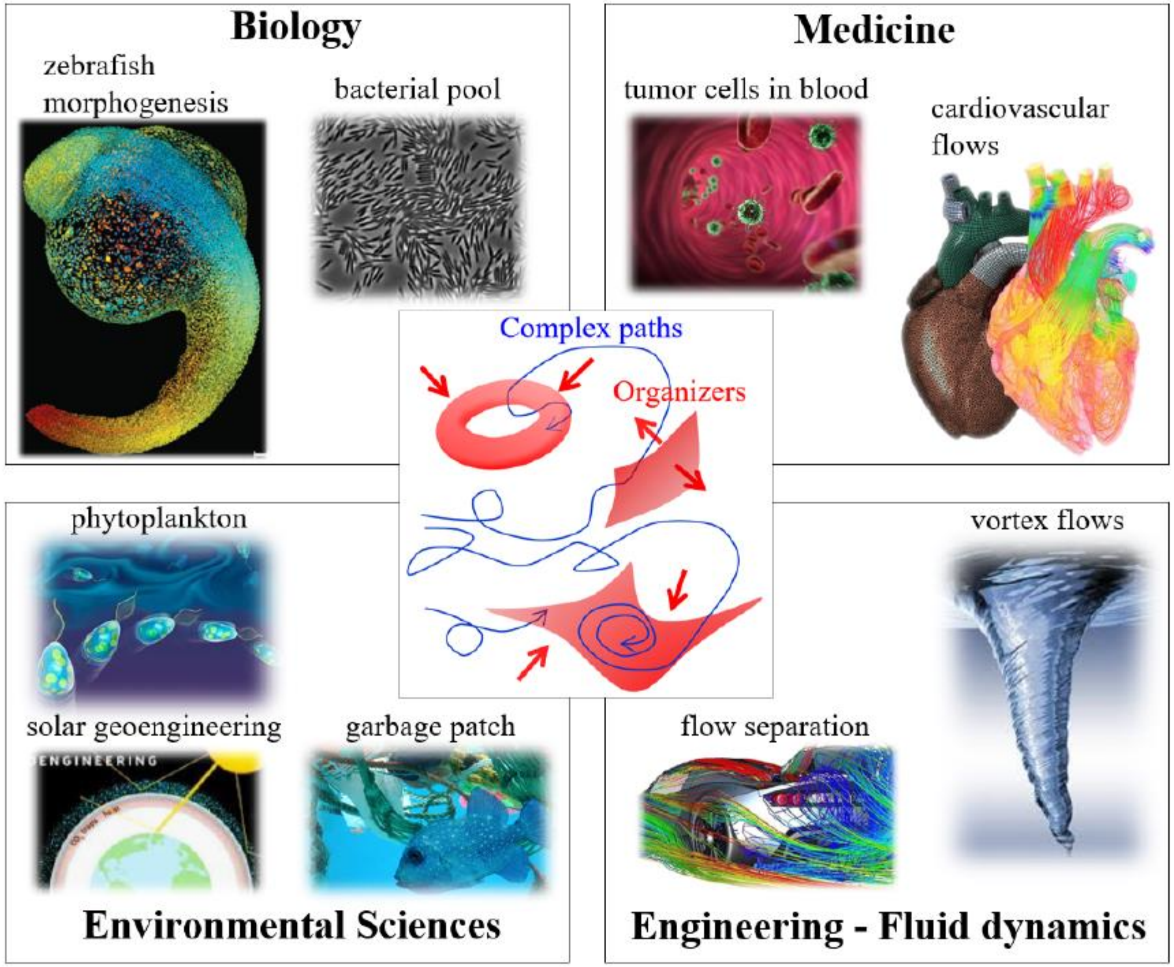
$$\frac{D}{Dt}\mathbf{Q} = \lambda S\mathbf{D} + \mathbf{Q}\mathbf{\Omega} - \mathbf{\Omega}\mathbf{Q} + \gamma^{-1}\mathbf{H}$$

$$\mathbf{Q} = S(\mathbf{n}\otimes\mathbf{n} - \mathbf{I}/2)$$

M. S., L. Lemma, L. Giomi, Z. Dogic and L. Mahadevan, *Transport, mixing and deformation in active nematics*, (preprint) ←

P. Nolan, **M. S.** and S. Ross, *Finite-time Lyapunov exponents in the instantaneous limit and material transport*, **Nonlinear Dynamics** (2020)

Thank you



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