Tracking coherent structures in massive-separated and turbulent flows

Melissa Green
Syracuse University
(but really: Matt Rockwood and Yangzi Huang)

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Recurrence, Self-Organization, and the Dynamics of Turbulence
Kavli Institute for Theoretical Physics, 12 January 2017

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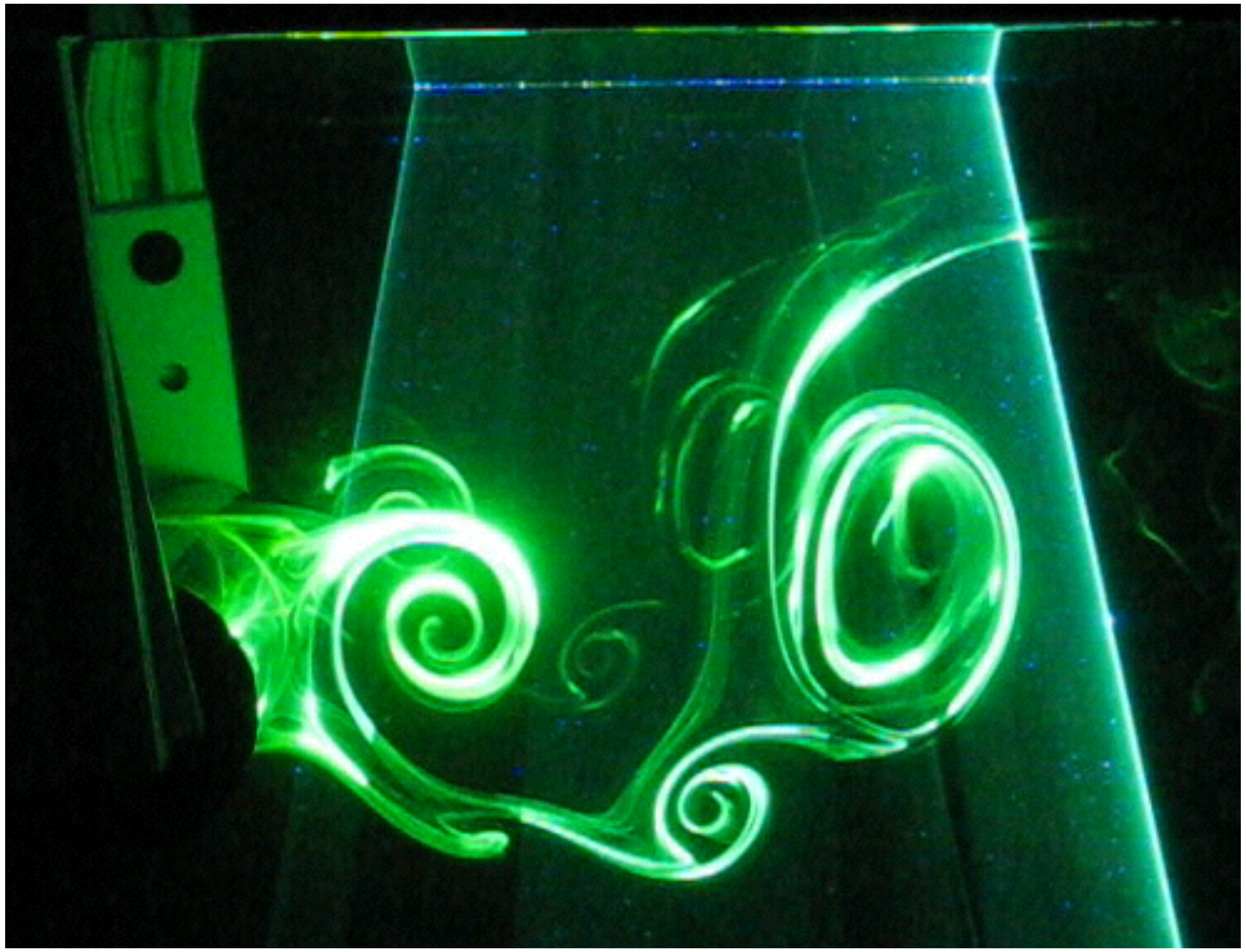
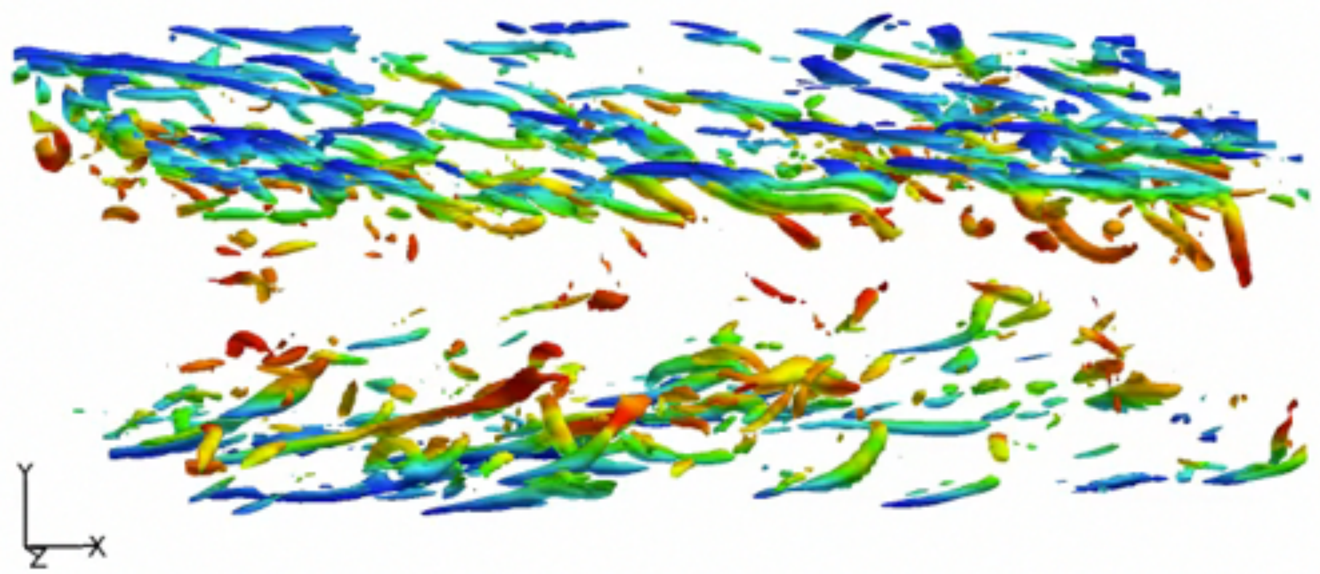
- How do we measure/detect/analyze vortices causing the forces in vortex-dominated and unsteady (and maybe turbulent?) flow fields?

- Lagrangian quantities: define a coherent structure from distinctions in material transport



- Cylinder in cross flow
  - Vortex dynamics (unsteady shedding)
  - Comparison with force/pressure

- 3D turbulent channel
  - Vortex tracking (structure velocity)



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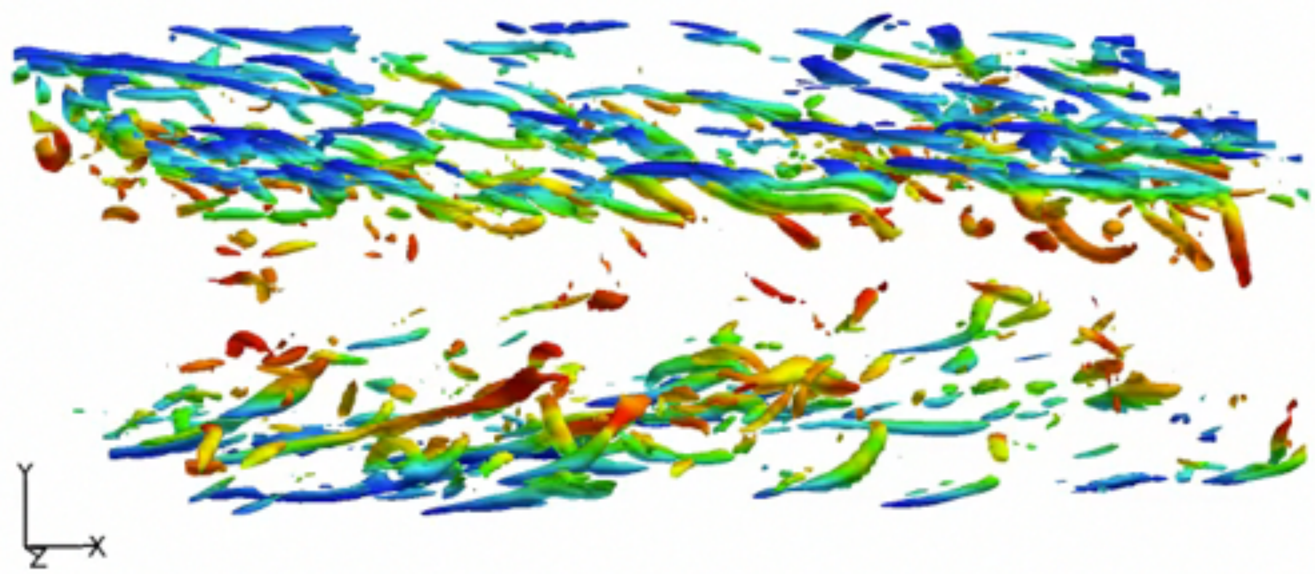

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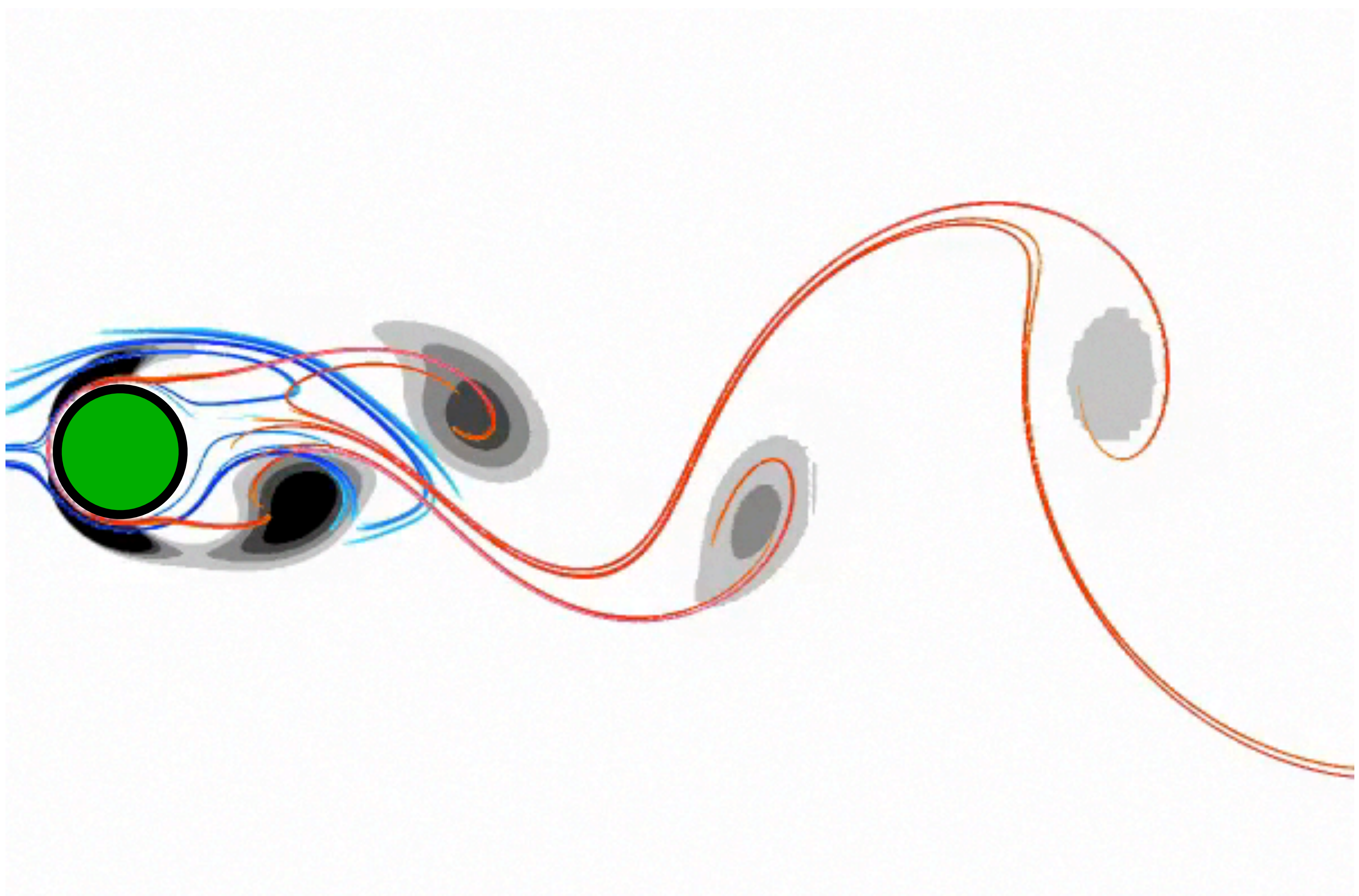
vortex shedding from cylinder in cross-flow

2D, Re=100, Immersed boundary calculation
(thanks to P. Munday, K. Taira, FSU)

Q

nFTLE

pFTLE



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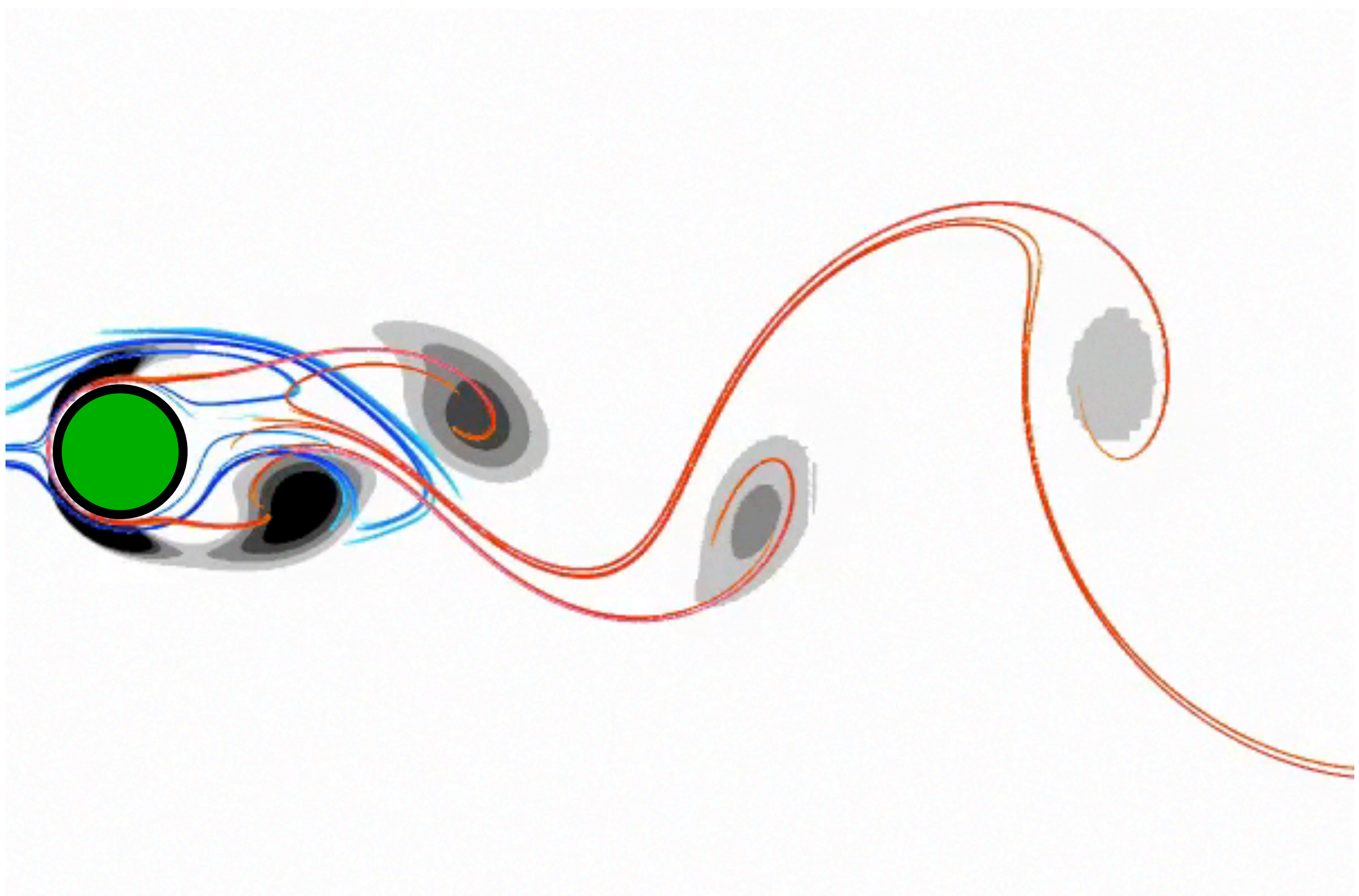

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finite-time Lyapunov exponent

(Haller 2002, among others)

Flowmap (vector)

$$\phi_t^{t+T}(\mathbf{x}) : \mathbf{x}(t) \mapsto \mathbf{x}(t+T)$$

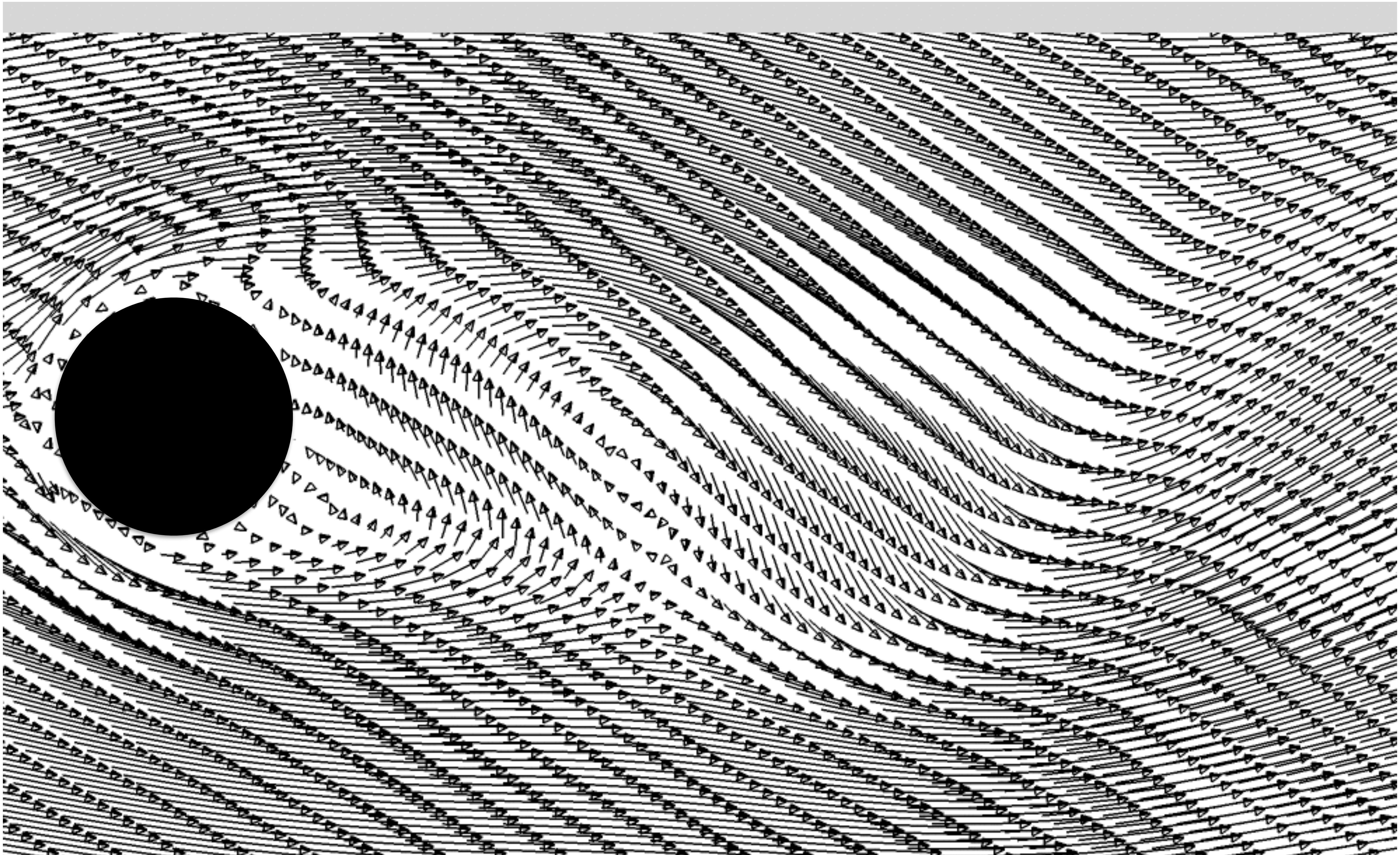
Coefficient of expansion (scalar)

Cauchy-Green deformation tensor (*nxn* tensor, *n* is dimension of flow field)

$$\sigma_t^T = \lambda_{max}\left(\left[\frac{d\phi_t^{t+T}(\mathbf{x})}{d\mathbf{x}}\right]^* \left[\frac{d\phi_t^{t+T}(\mathbf{x})}{d\mathbf{x}}\right]\right)$$

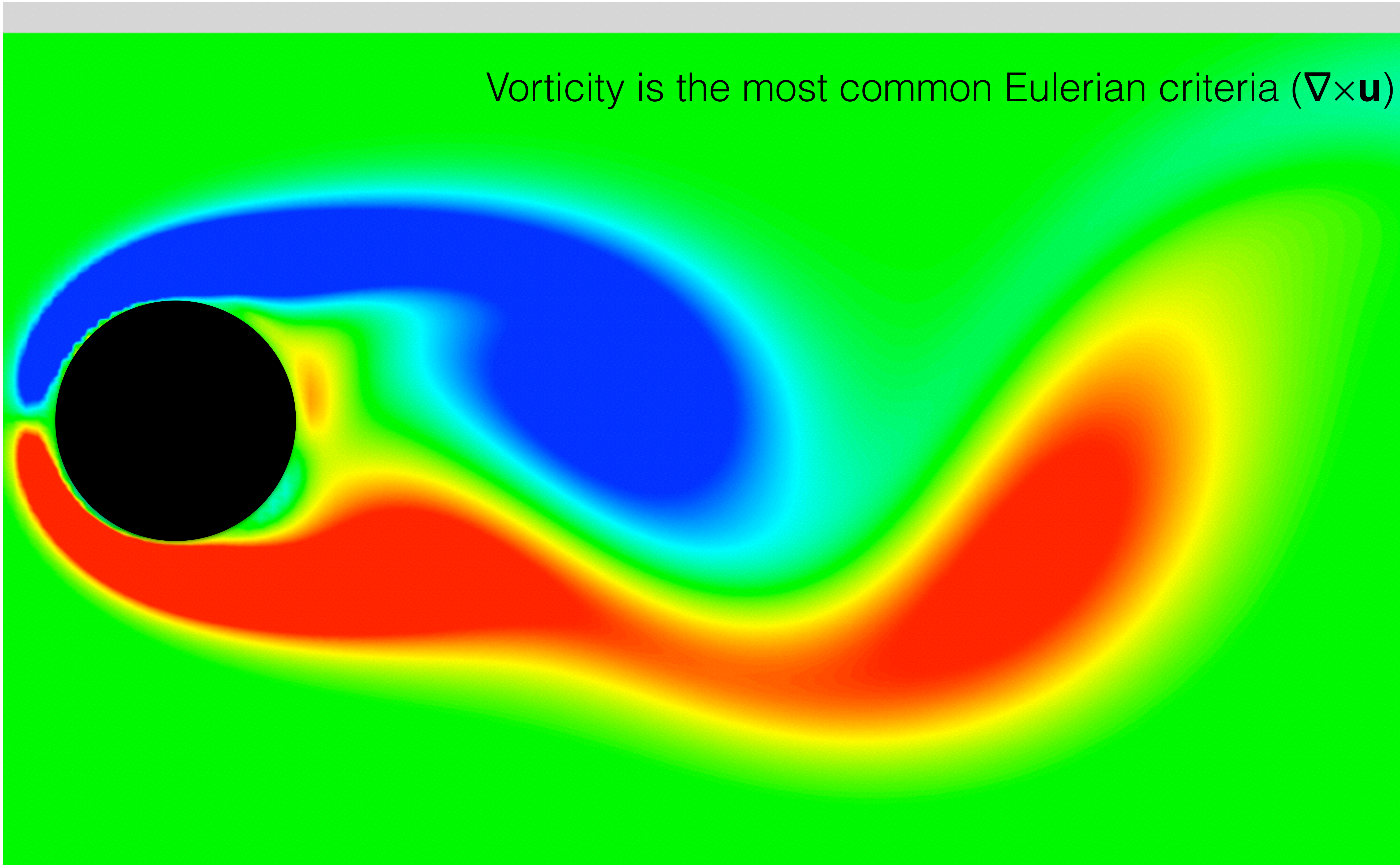
$$FTLE_T(x,t) = \frac{1}{2T}\log \sigma_t^T$$

many data sets start with a velocity field



This is numerical data, but we can also acquire velocity fields from experiments: particle image velocimetry

Eulerian: take gradients of the velocity field



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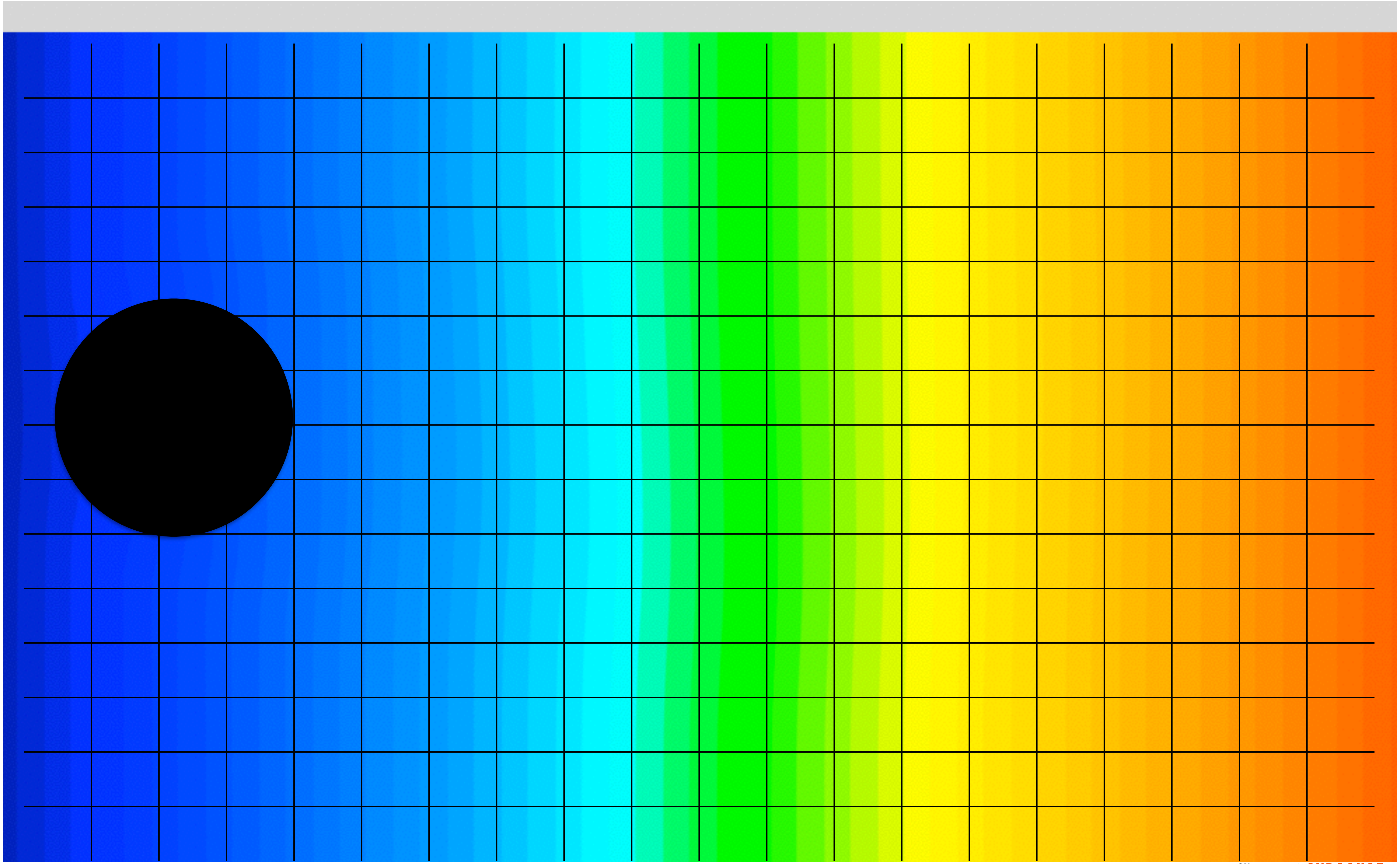
Lagrangian: calculate quantities along fluid trajectories



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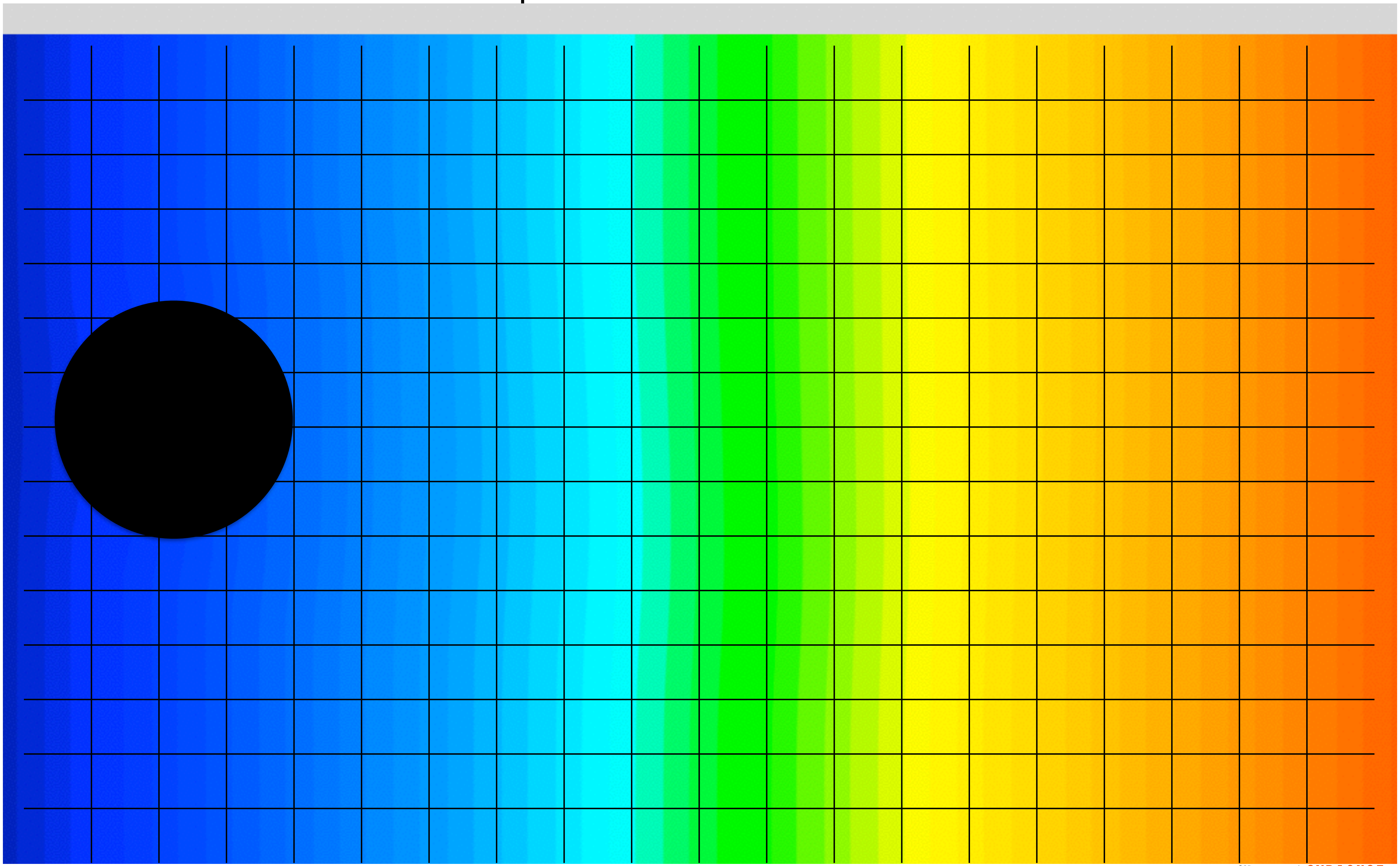
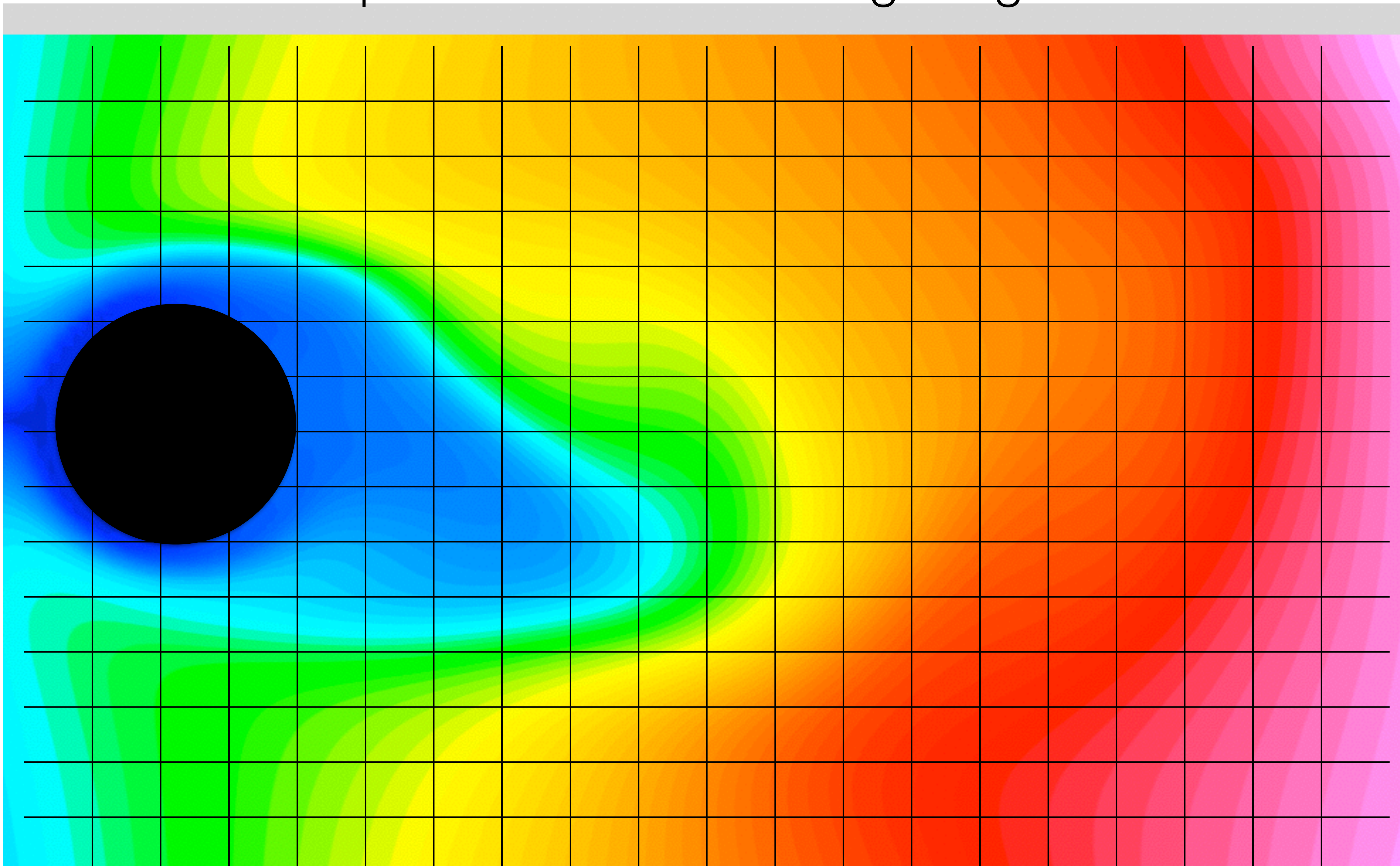
initialize a fluid trajectory at each grid point, keep track of x-location



x-location of trajectories at t_0

integrate fluid trajectories in time
update x-location on original grid



x-location of trajectories at $t_1 > t_0$

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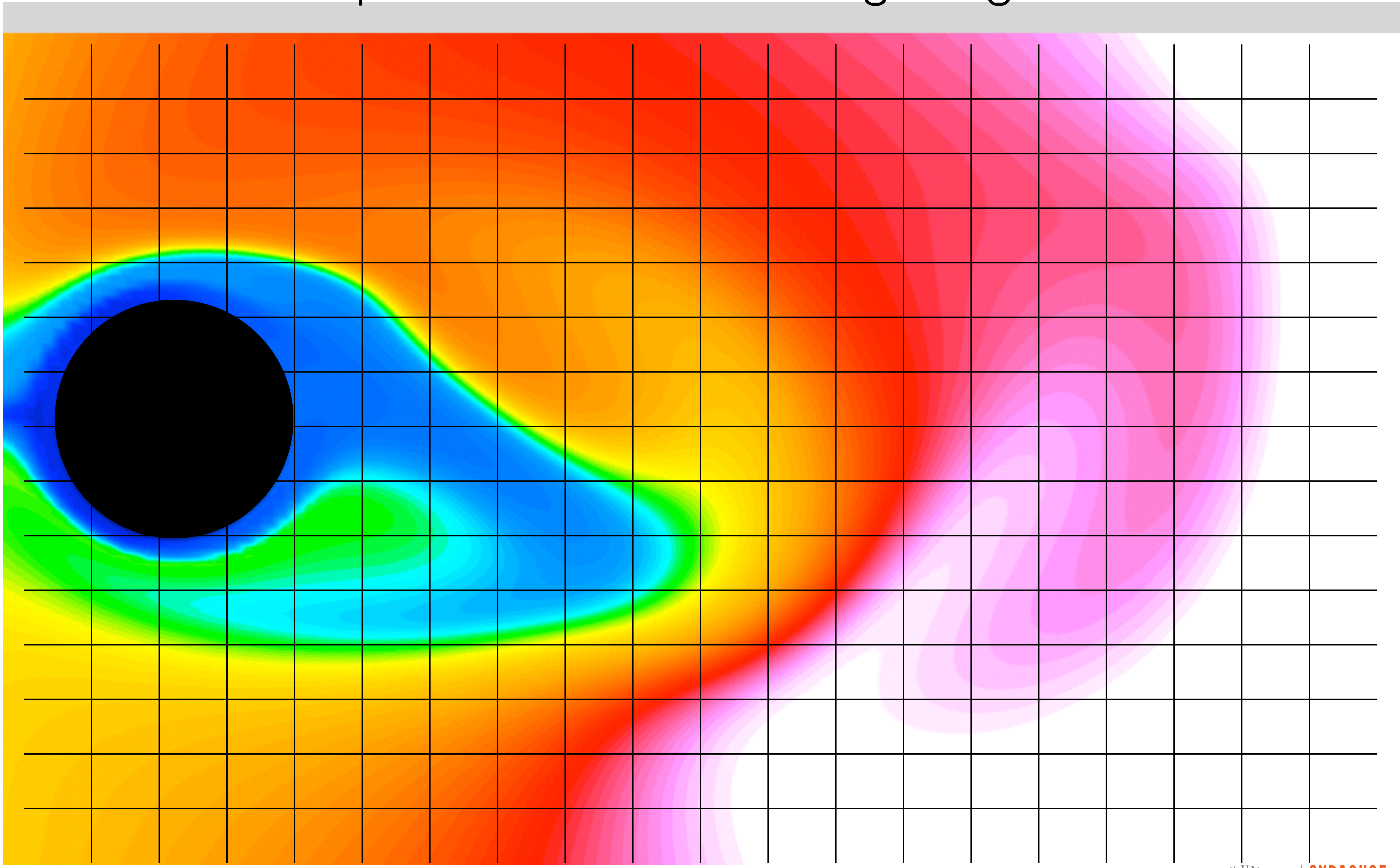
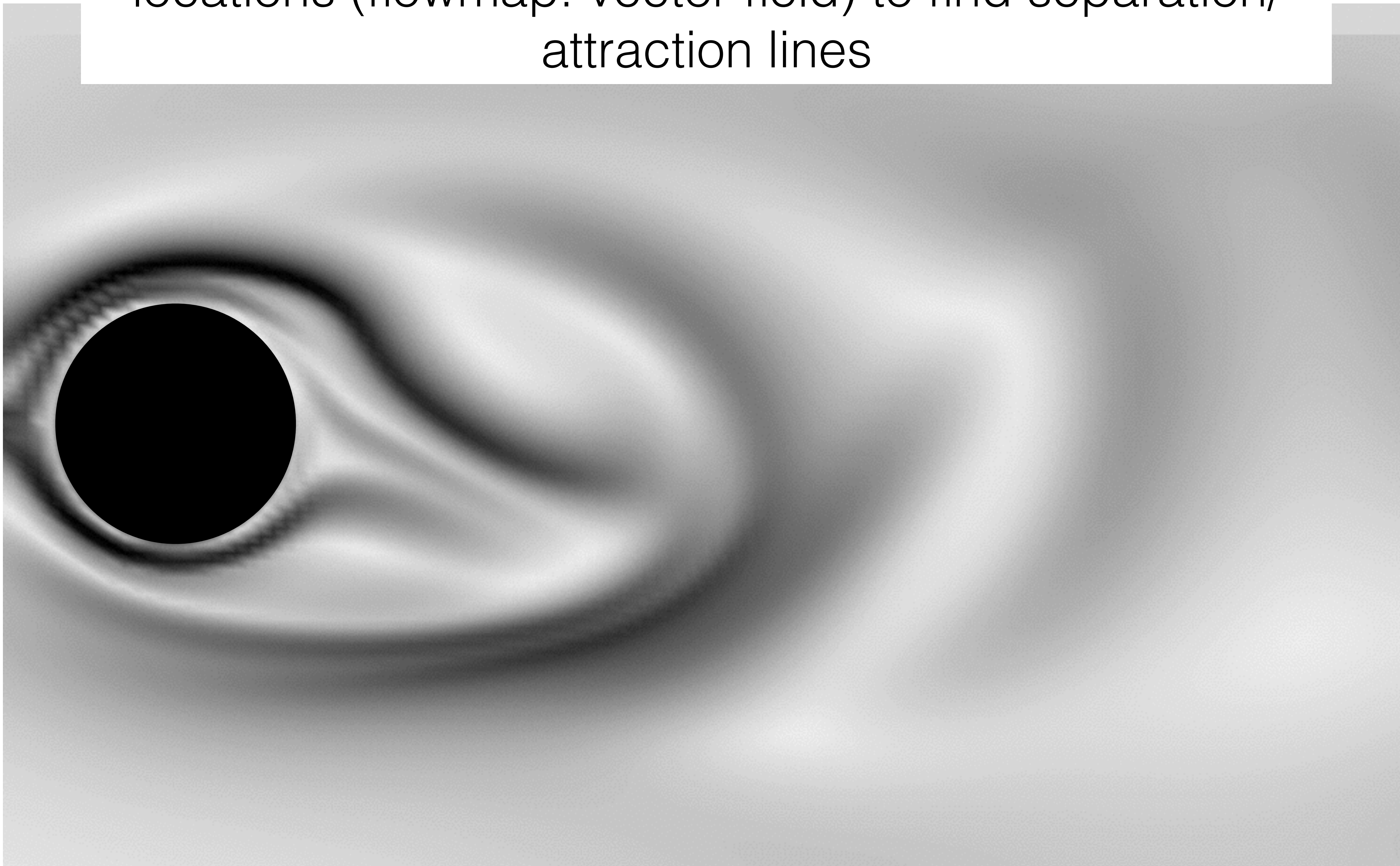
integrate fluid trajectories in time
update x-location on original grid



x-location of trajectories at $t_2 > t_1 > t_0$

FTLE from gradient of integrated fluid trajectory final locations (flowmap: vector field) to find separation/ attraction lines



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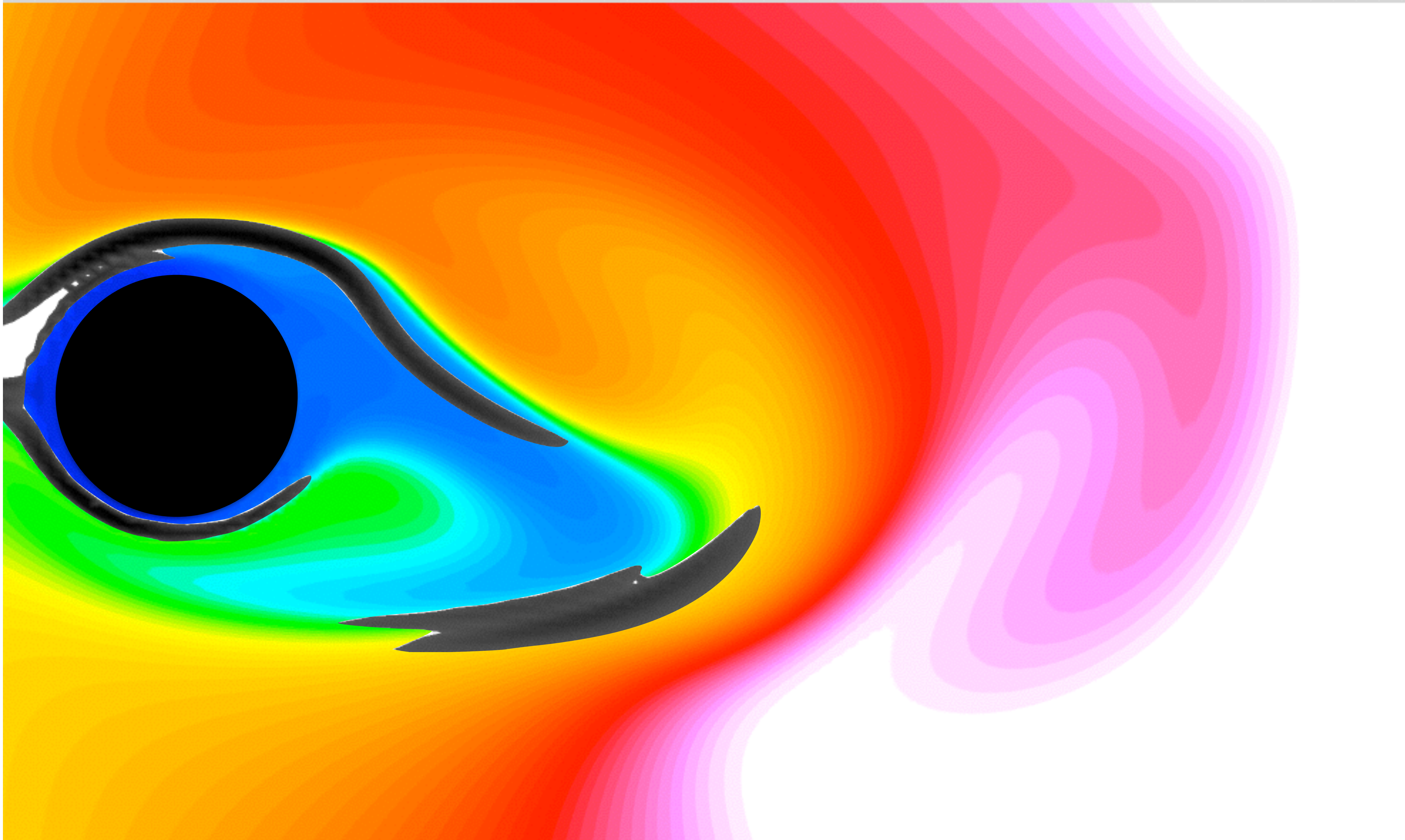
a Lagrangian coherent structure is the ridge of the FTLE field, shows where trajectories sharply behave differently



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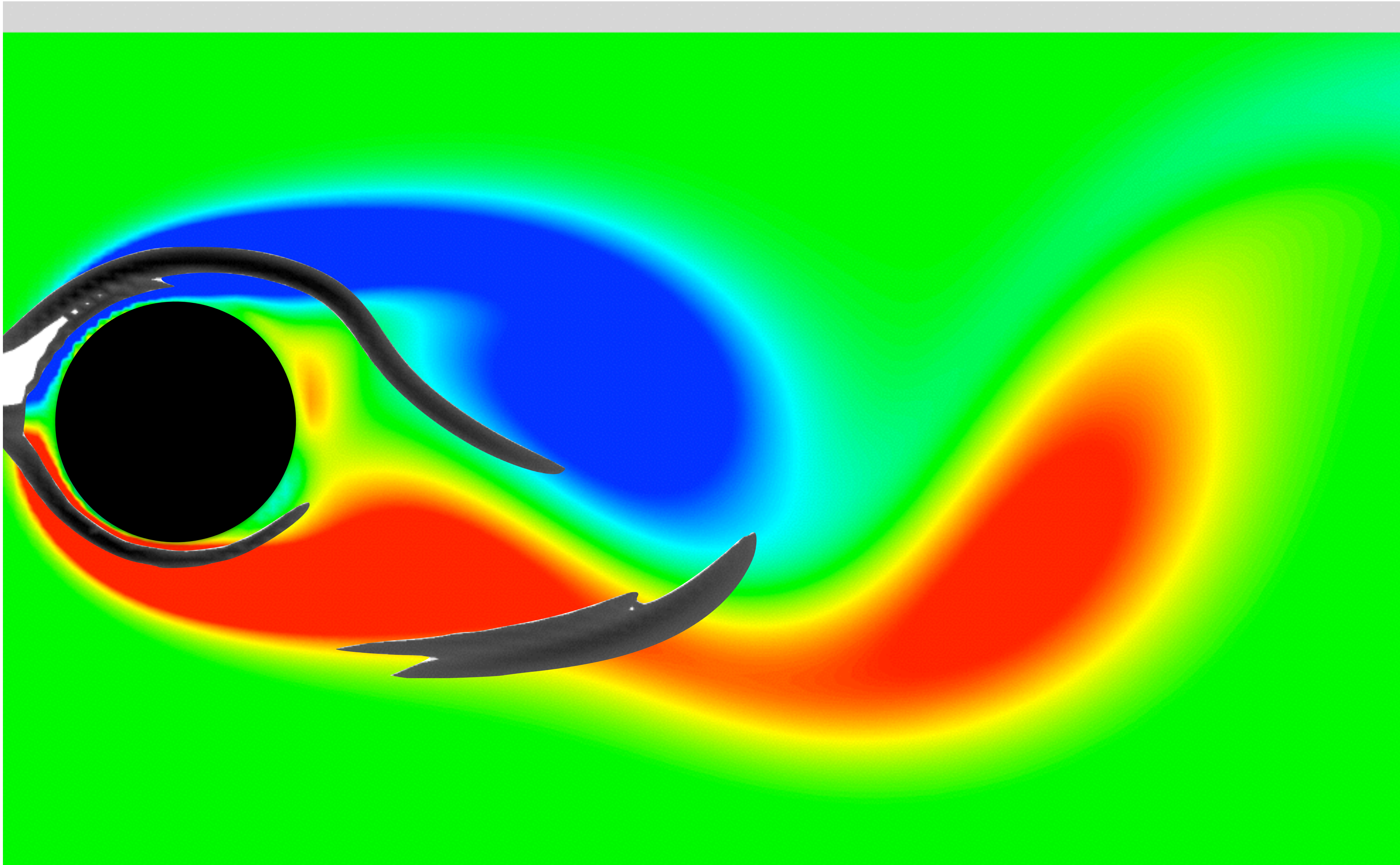
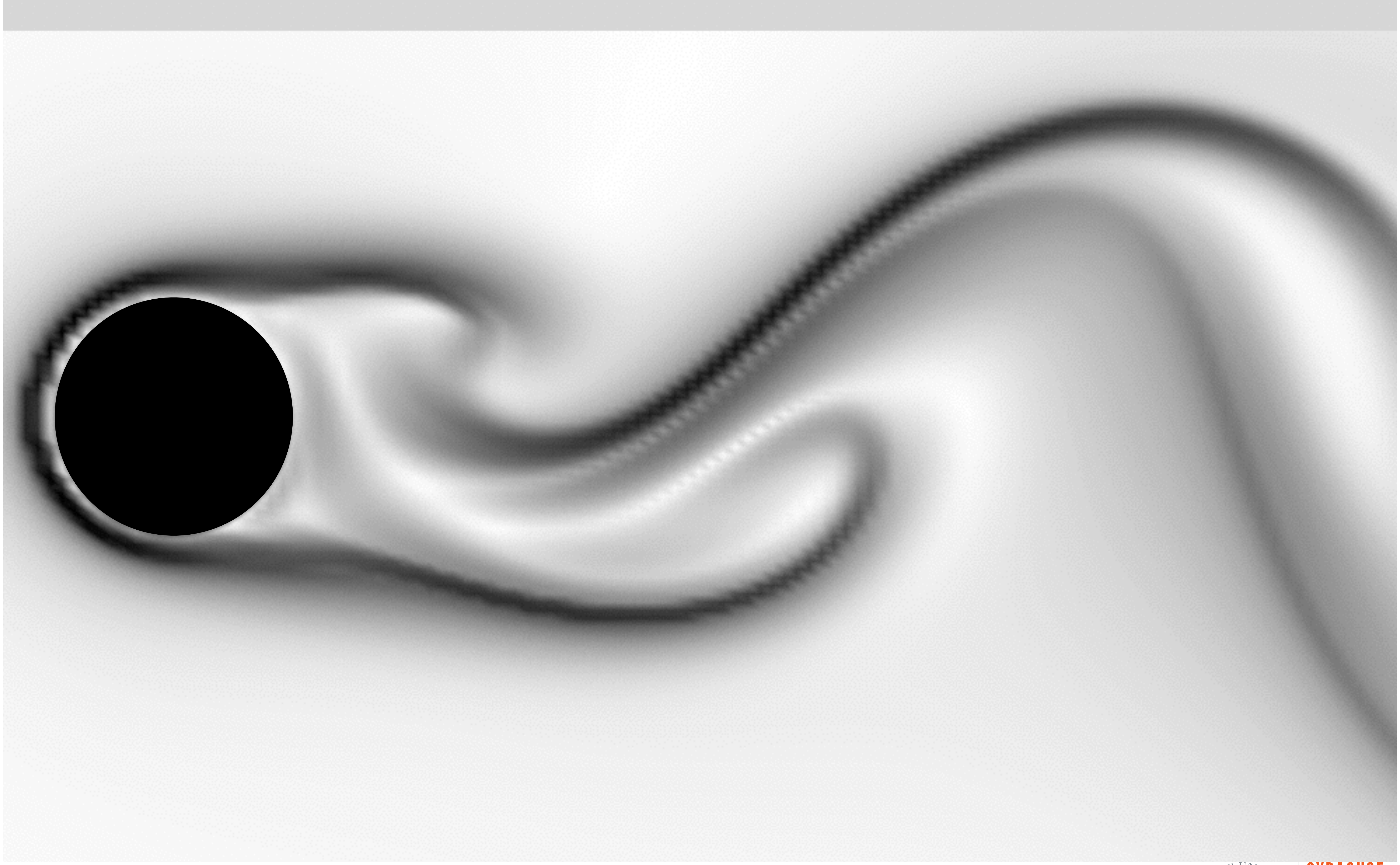
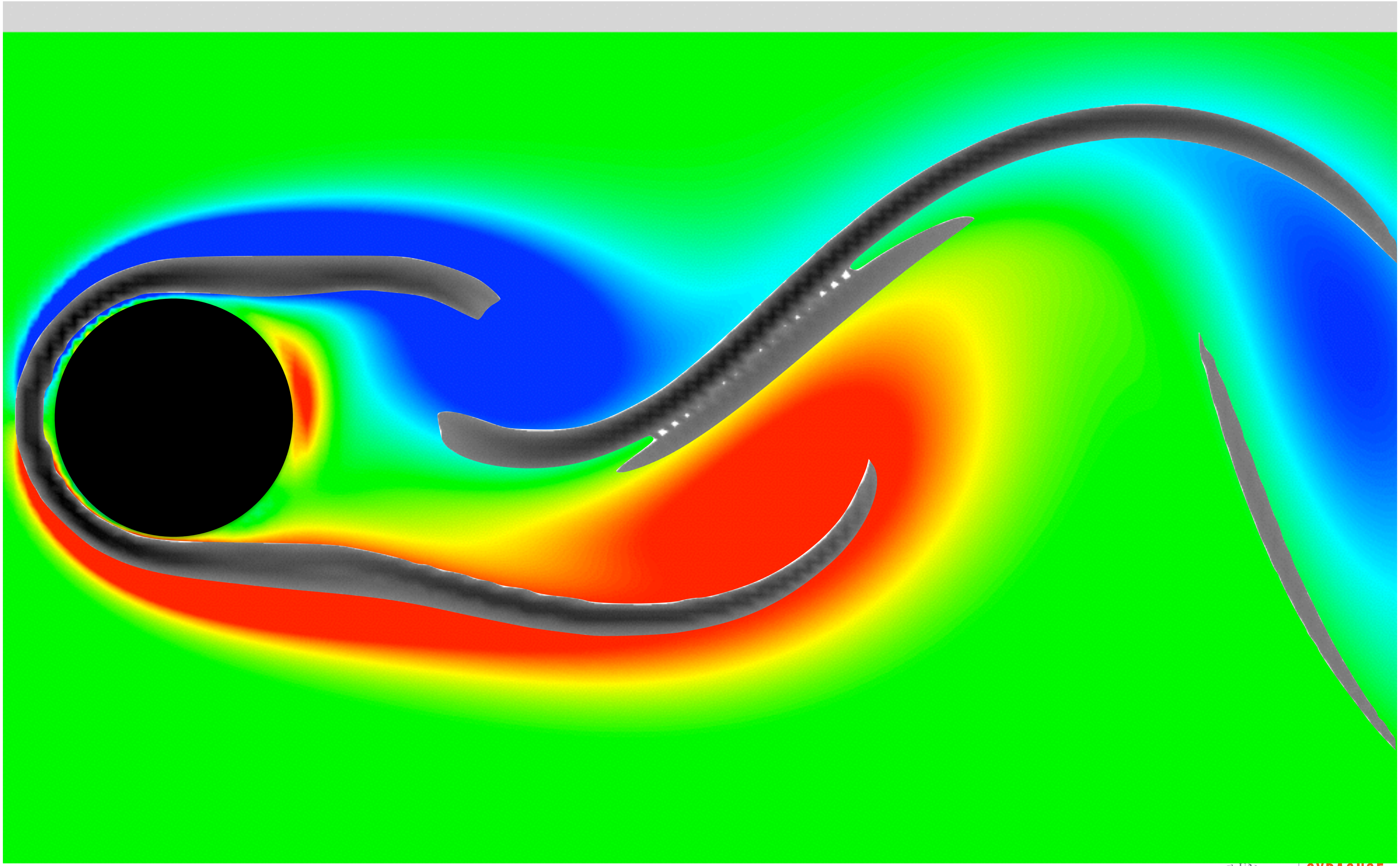
and they do a good job of distinguishing among vortices



can also watch fluid trajectories in backward time to get a negative-time FTLE field



nFTLE are attracting lines - look just like flow visualization



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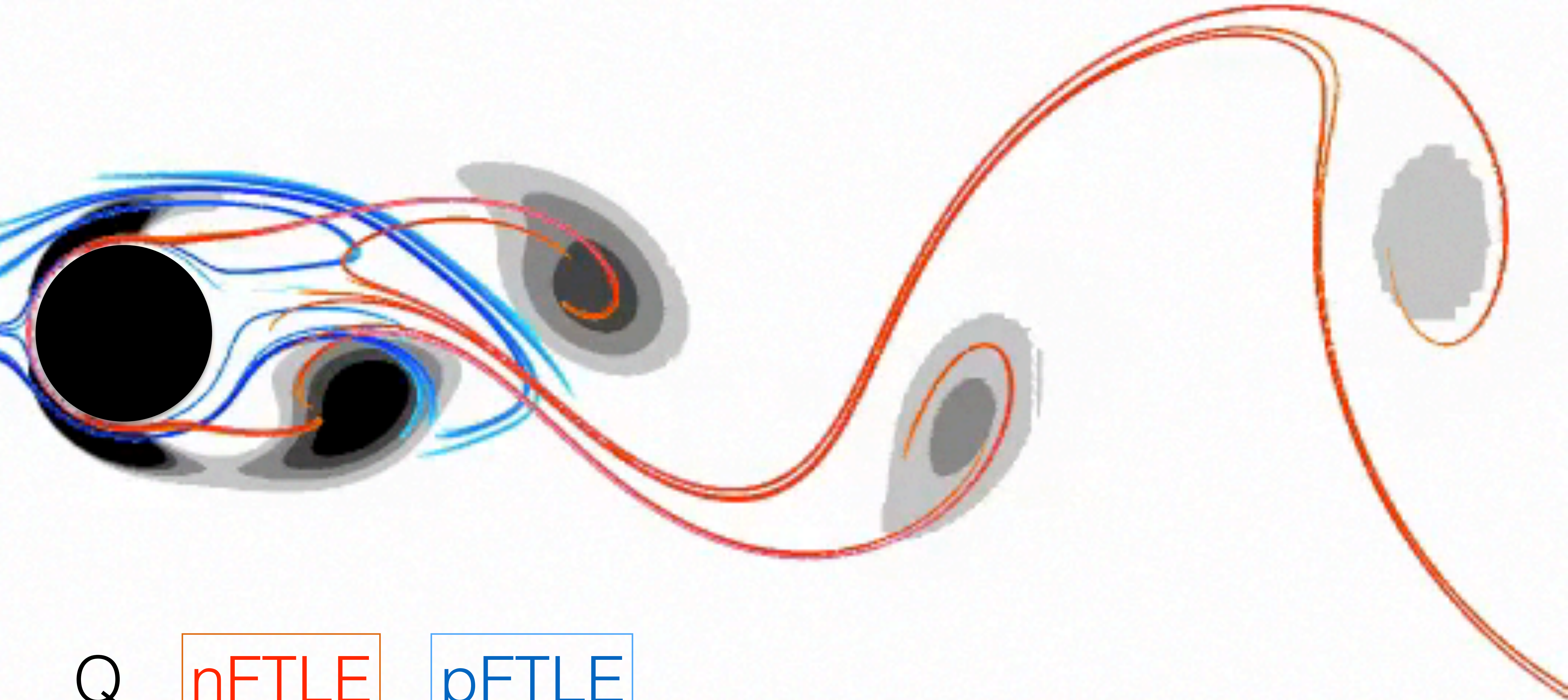
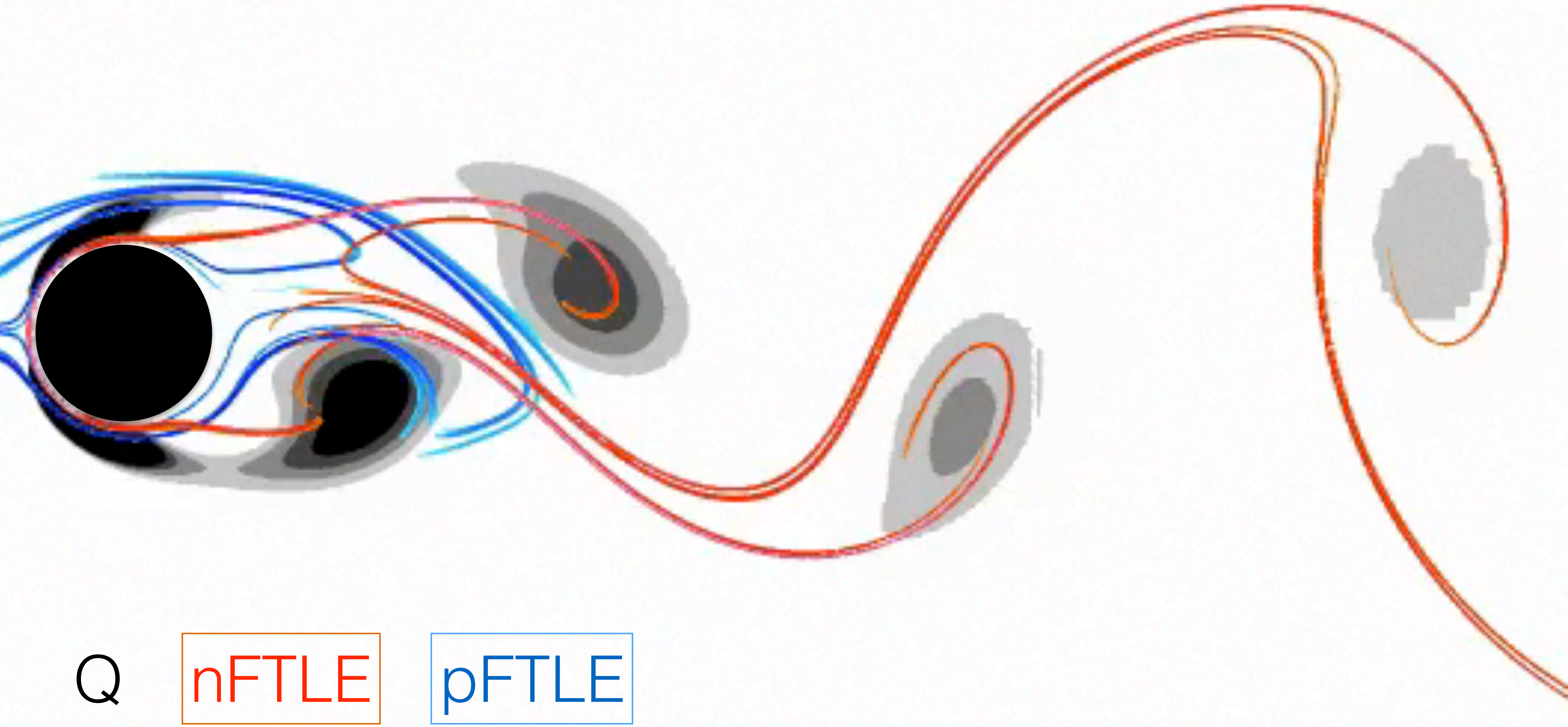


Q nFTLE pFTLE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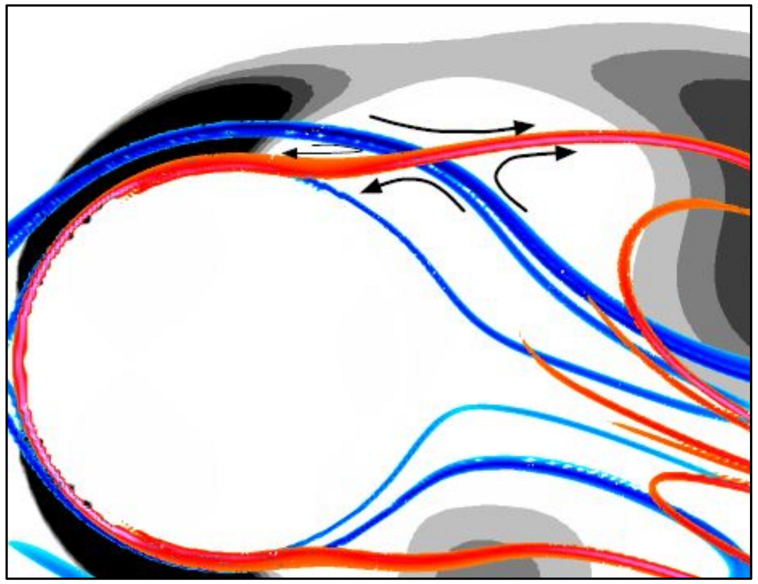

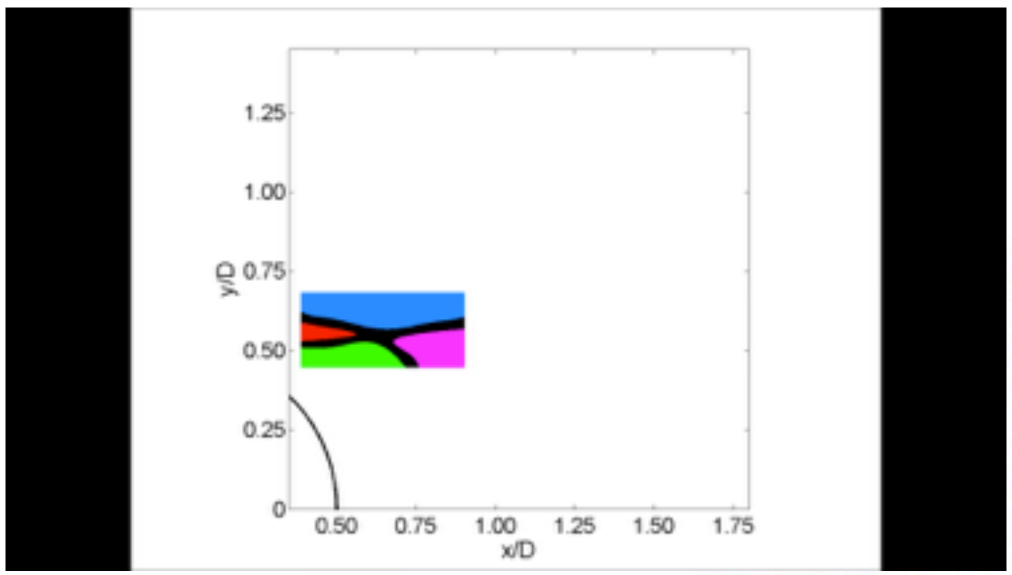

- Non-parallel intersections of negative-time and positive-time FTLE ridges act as saddle points in the flow field
- Saddle sits on, and then separates from cylinder surface at shedding

Q

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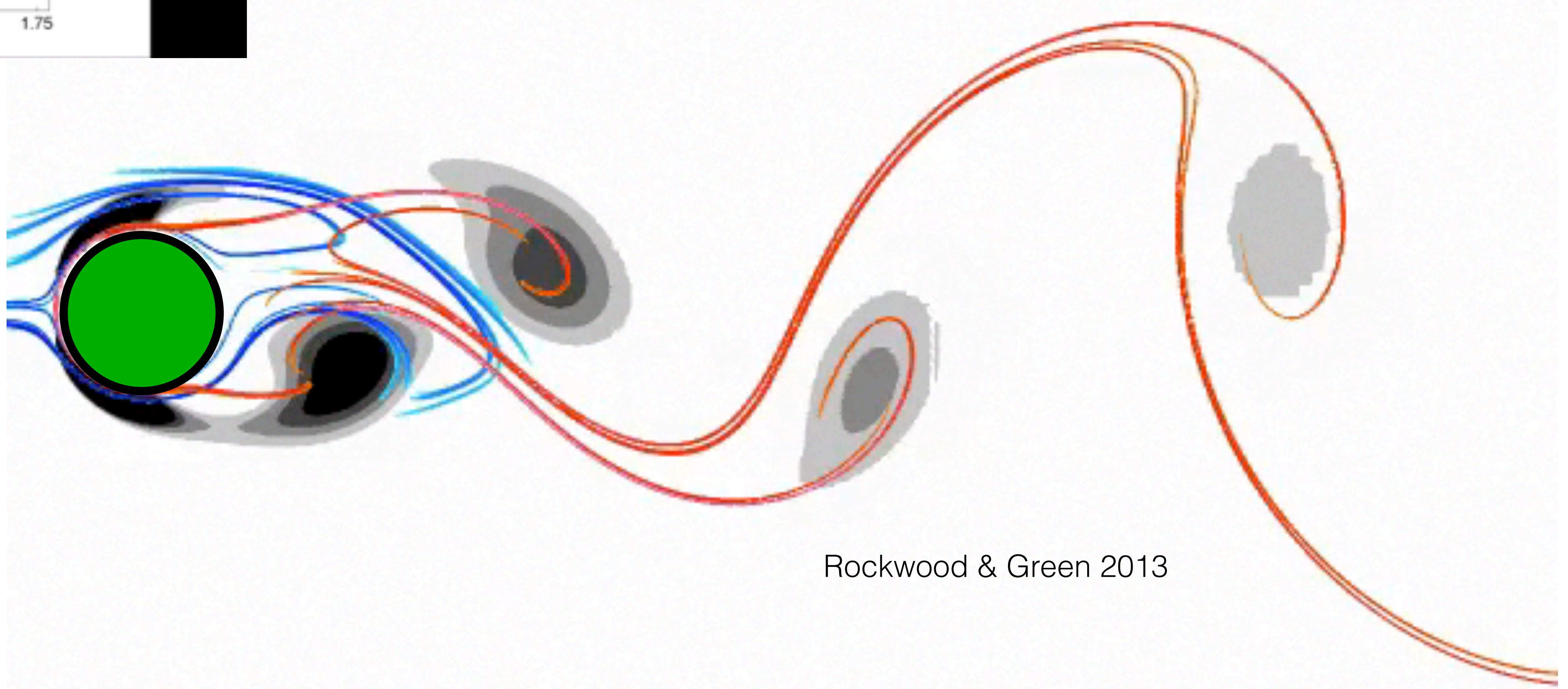

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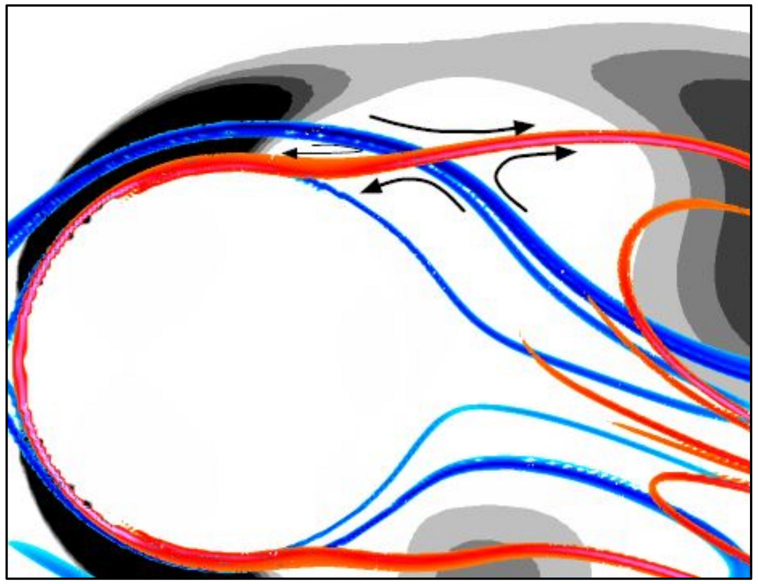

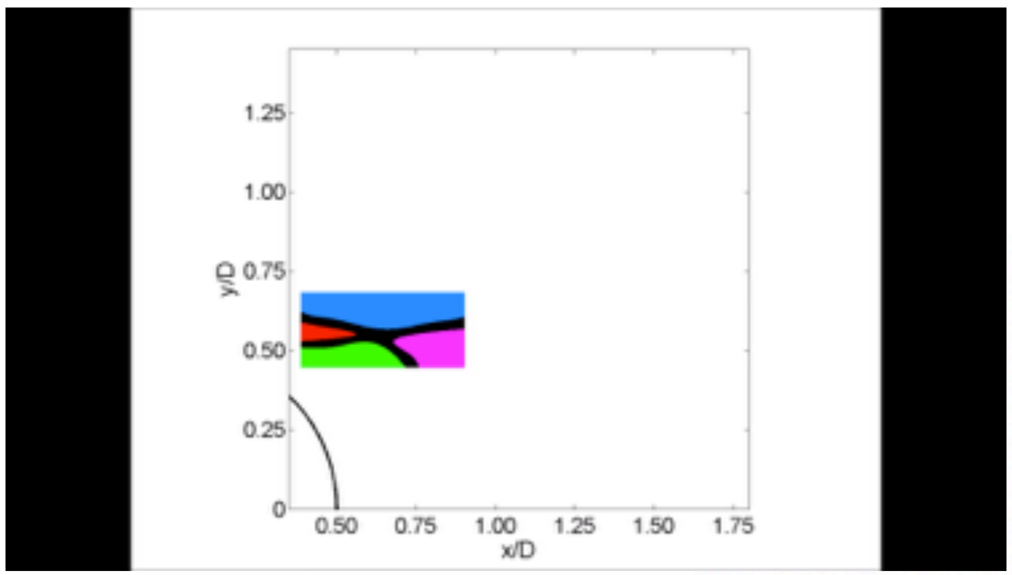

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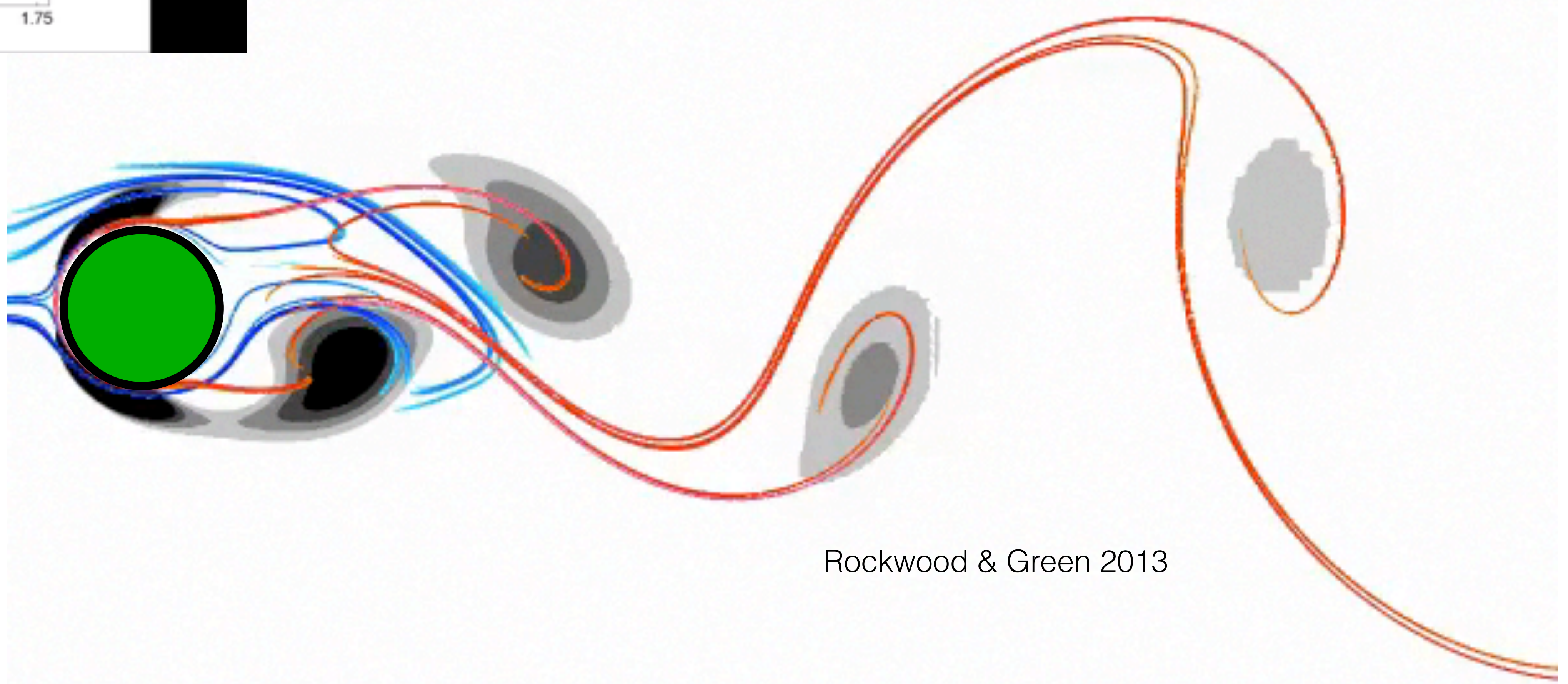

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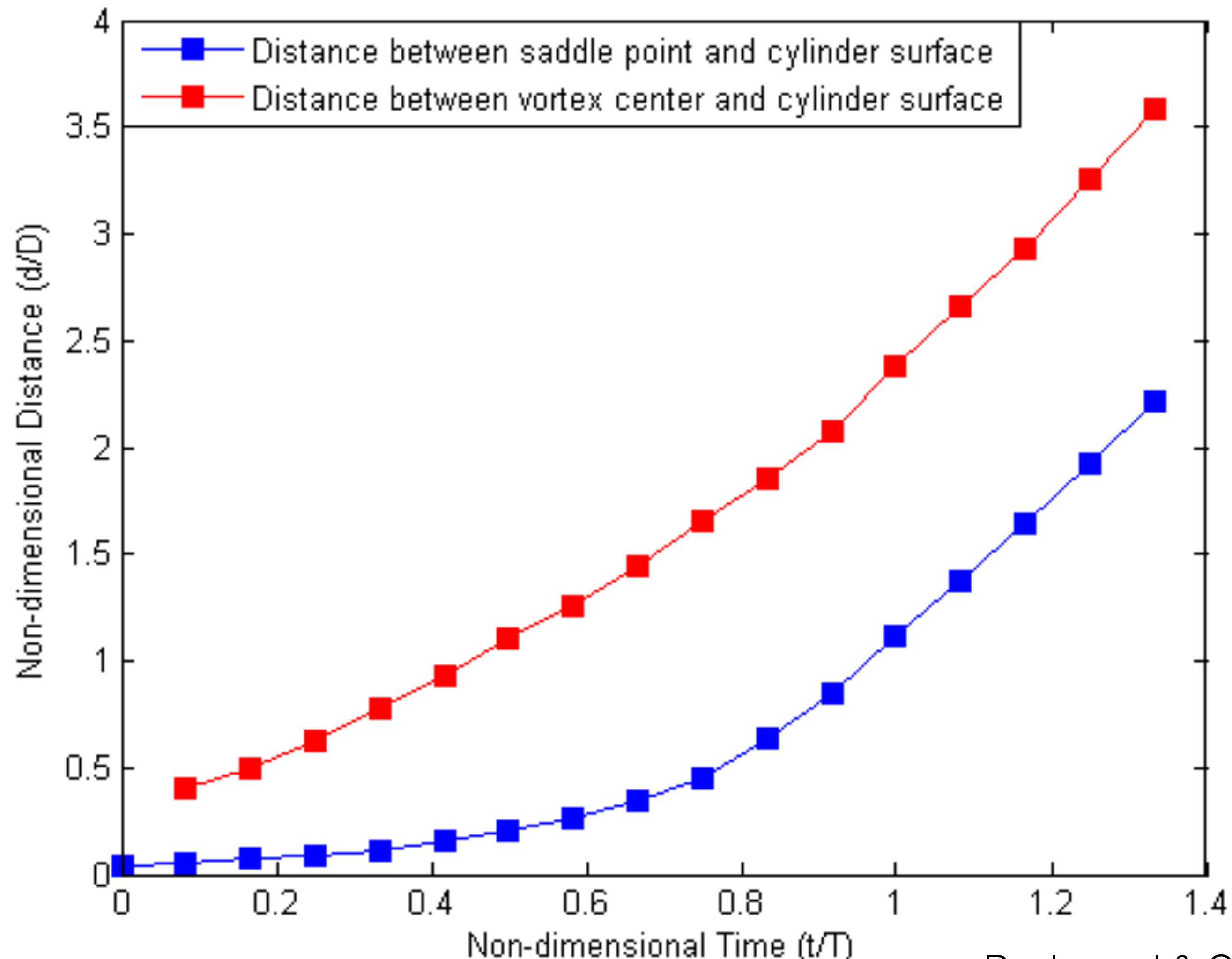
objective shedding ID?



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- “Vortex center” is point of max *Q*
- Two distinct phases evident in tracking saddle
  - Slow phase while vortex still forming, still attached
  - Acceleration to convection speed as vortex sheds

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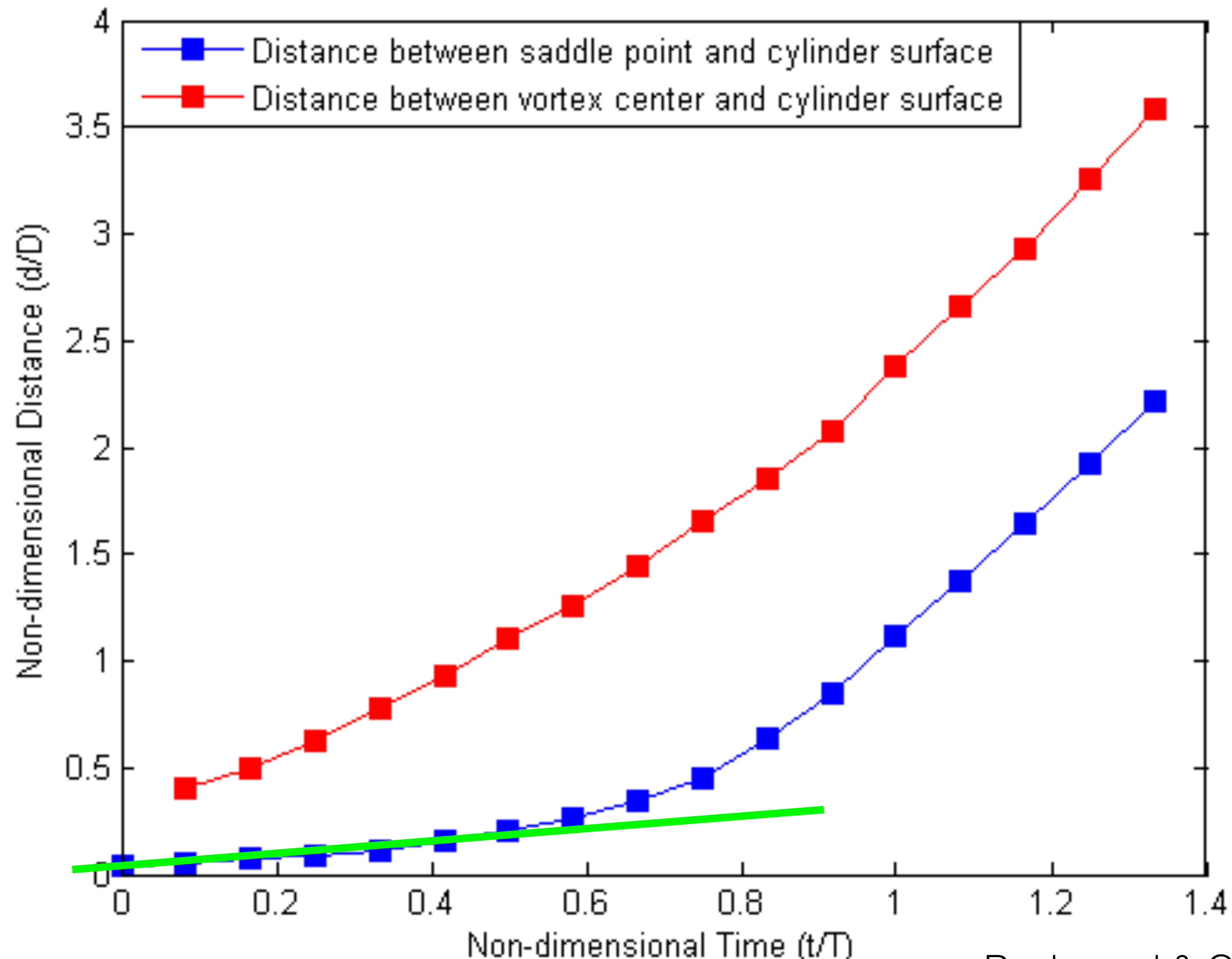

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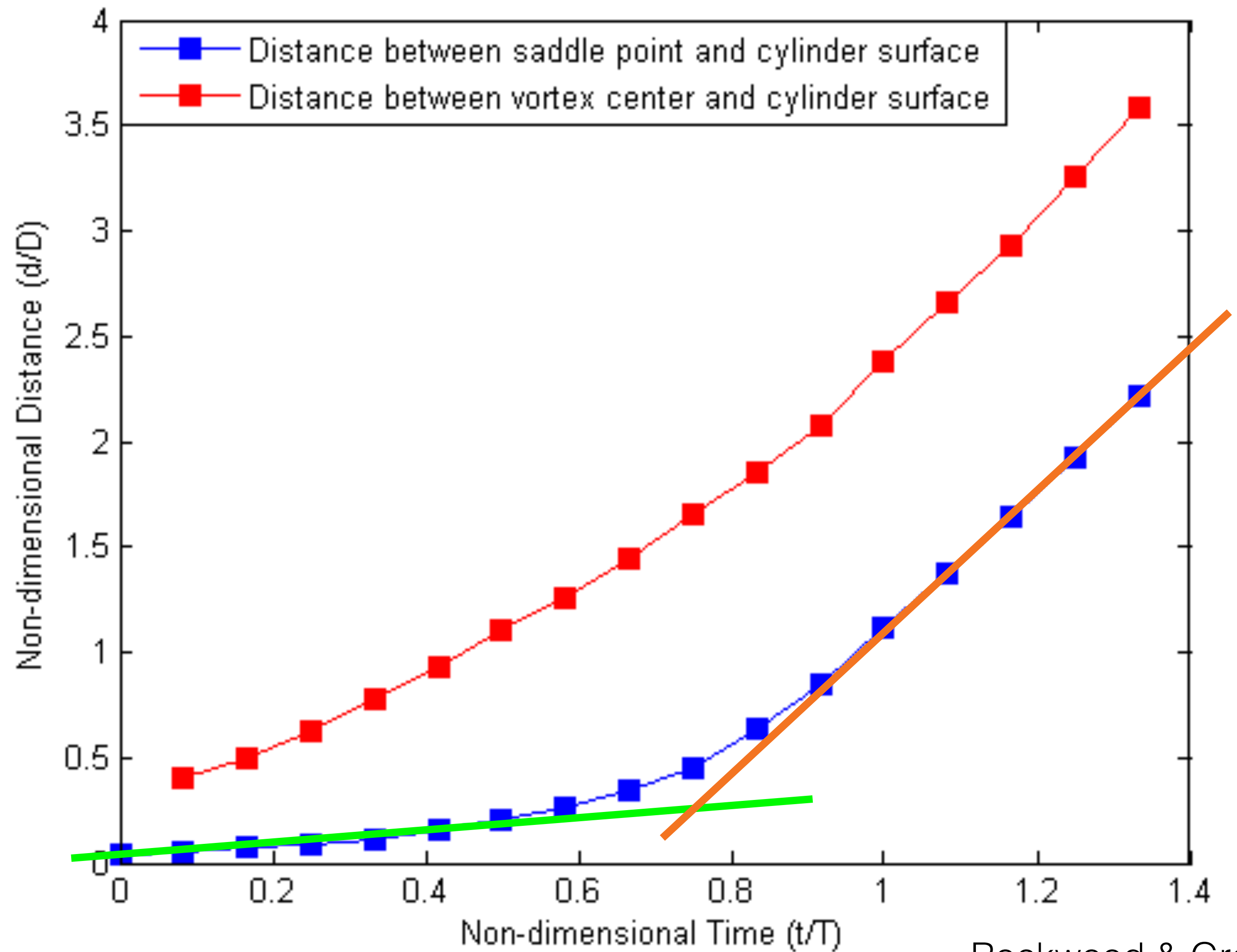

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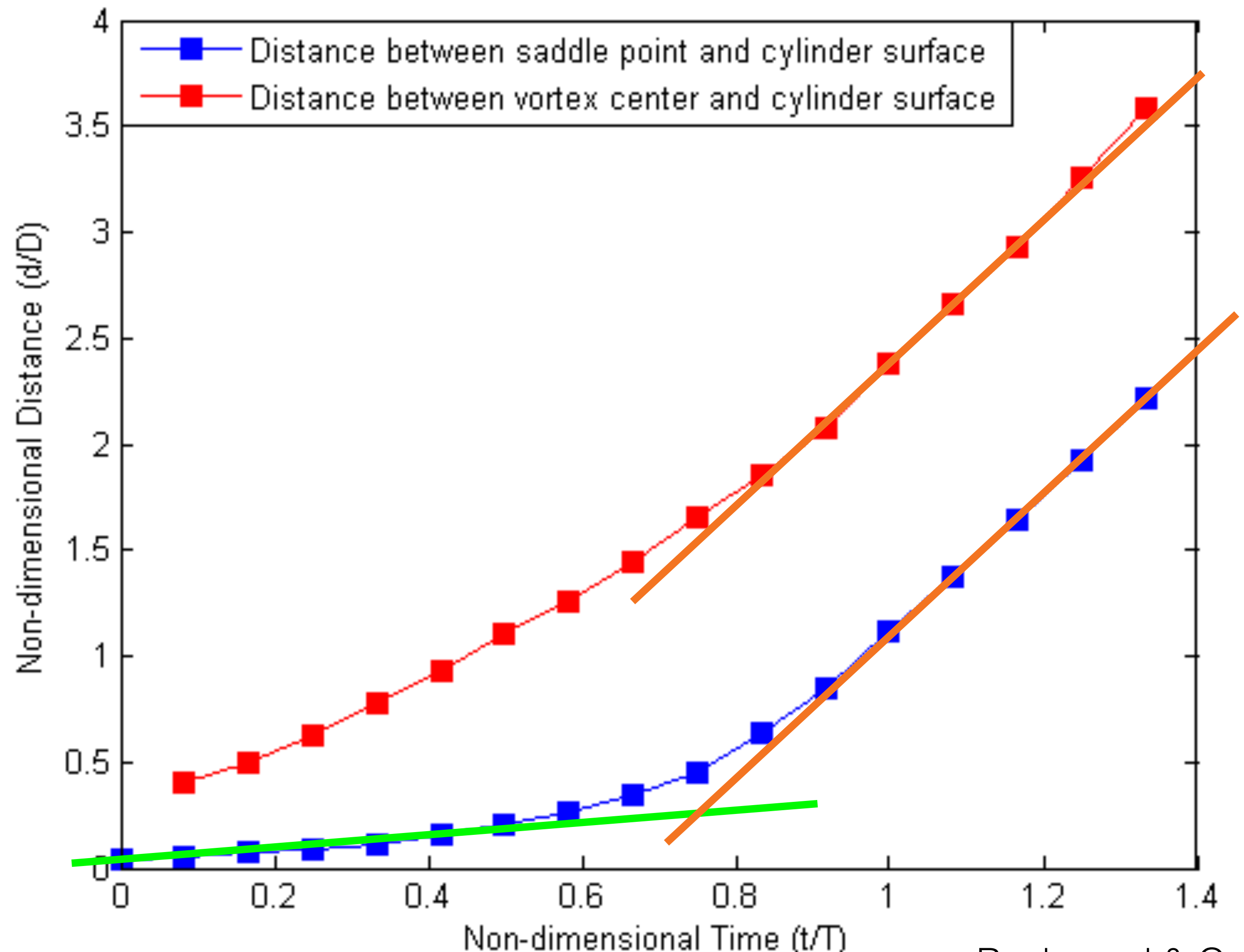

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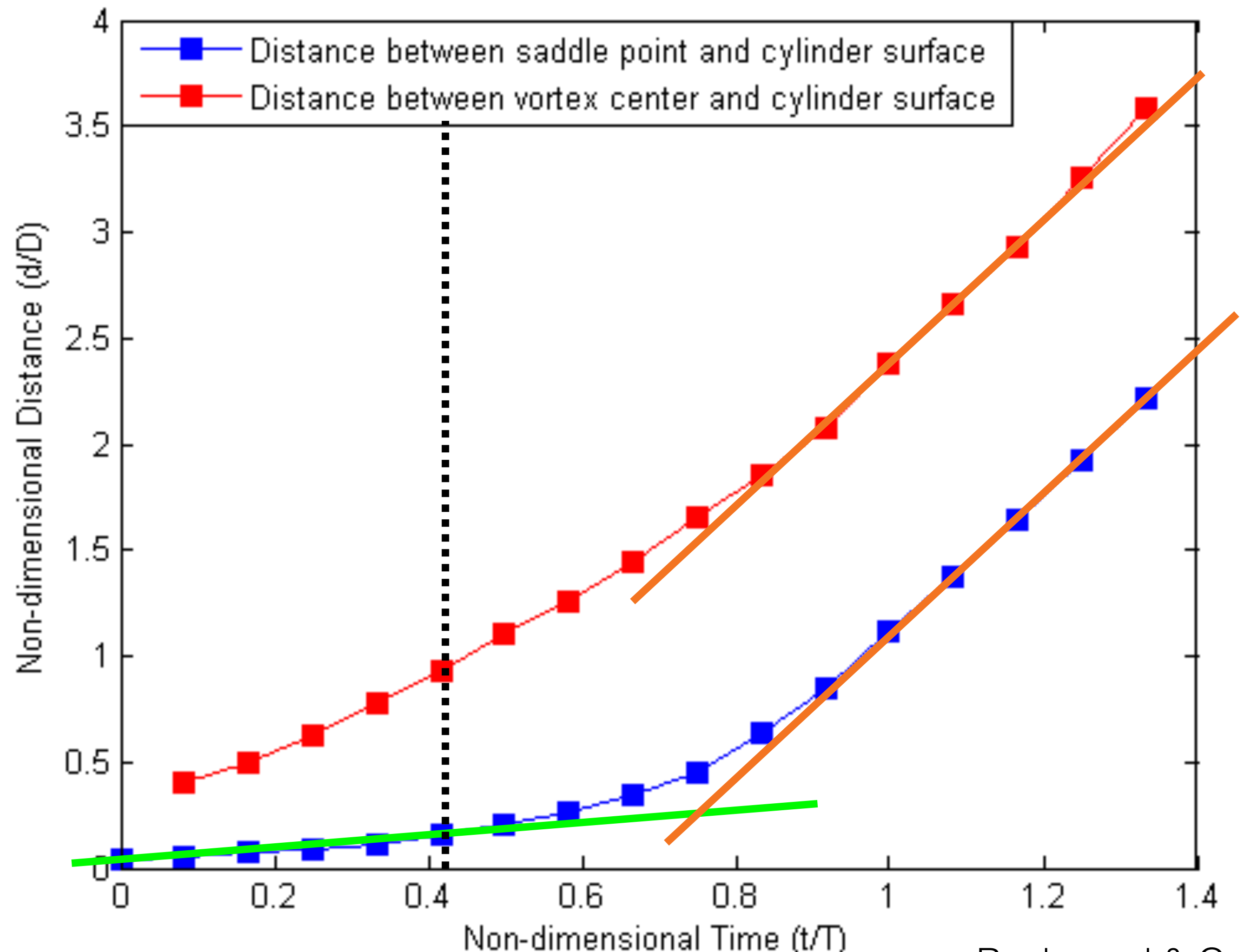

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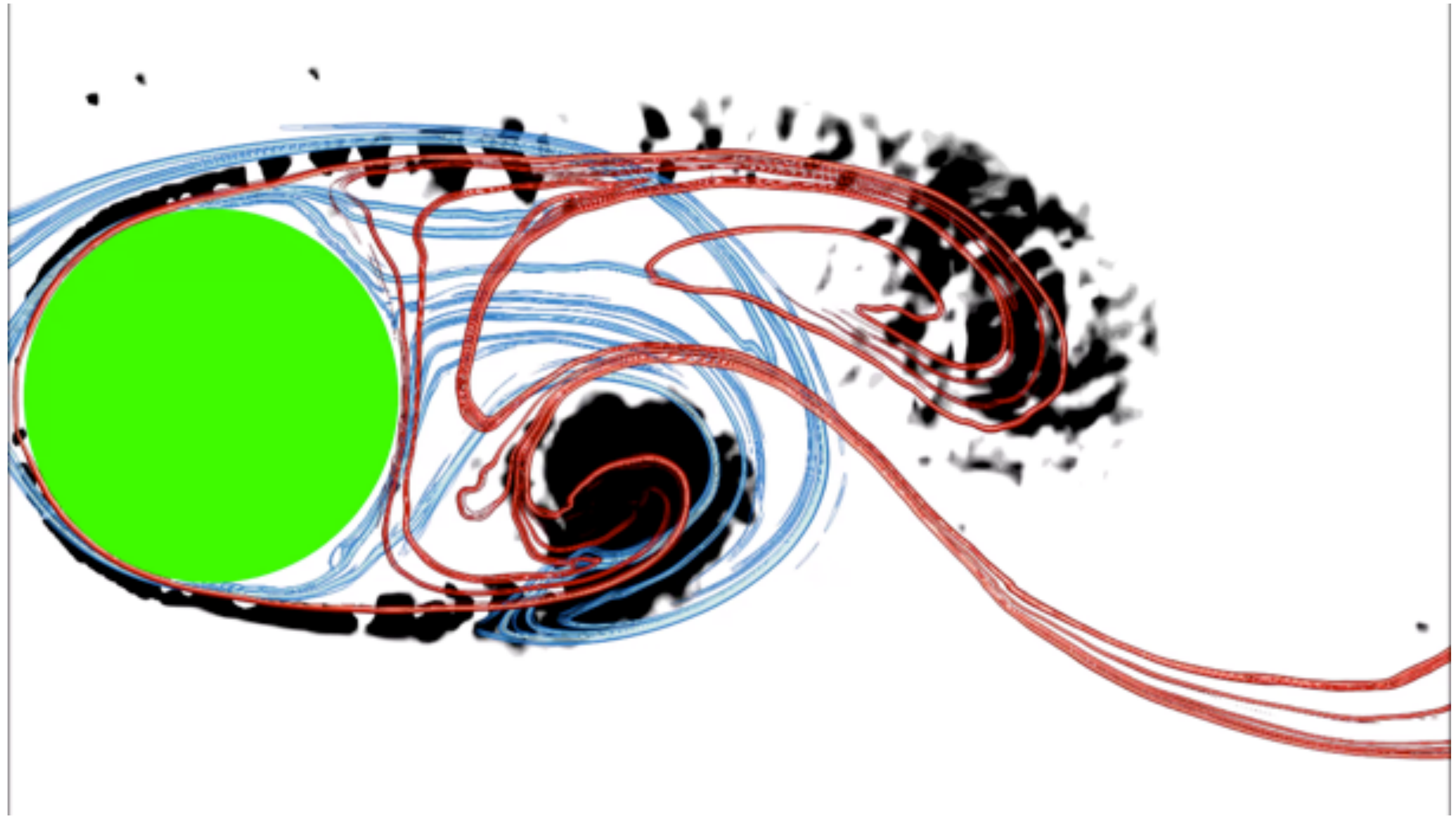
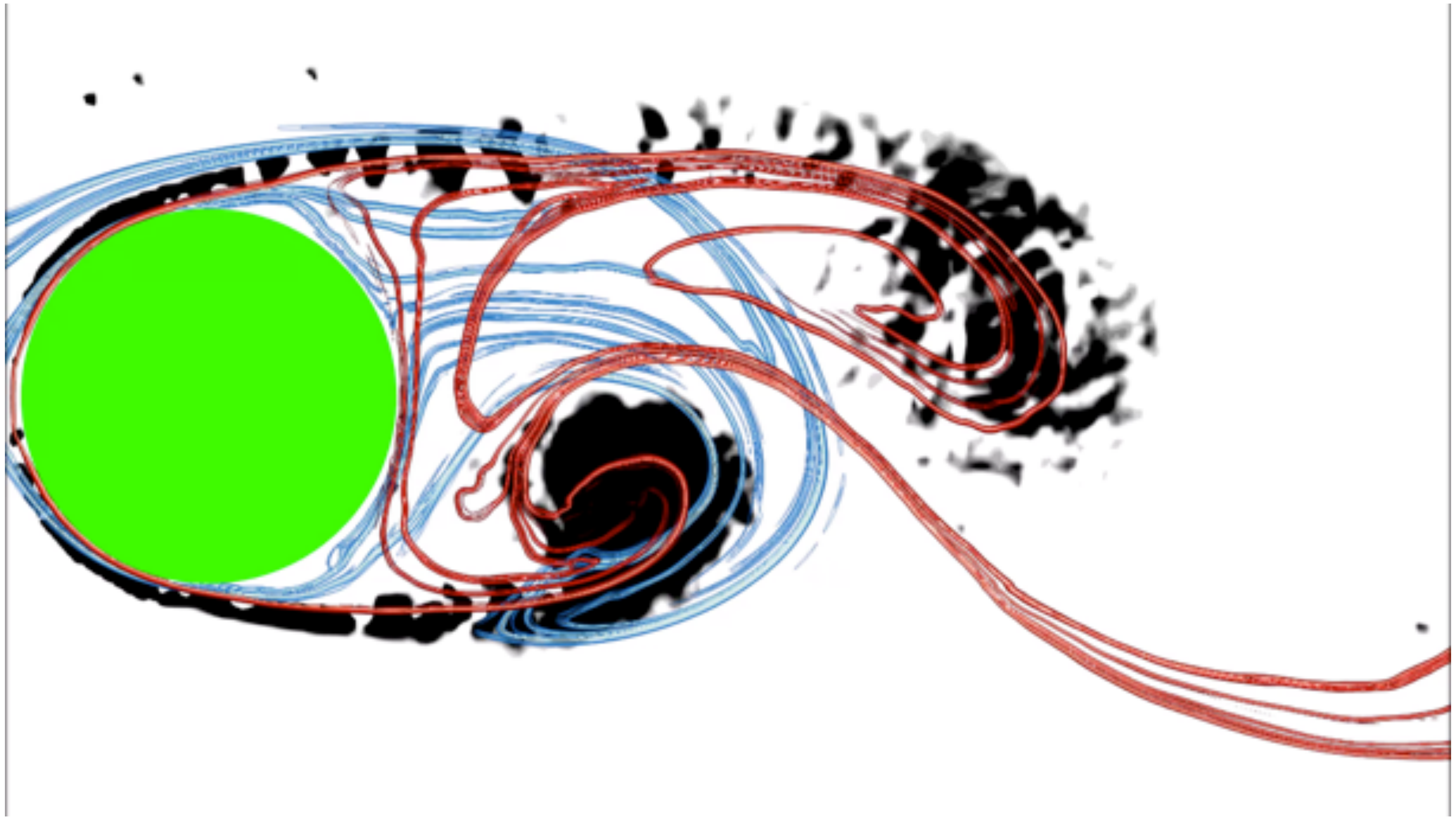
matching with experimental data



- Experimental PIV data, Syracuse CoE water tunnel facility
- Re = 19000
- Phase averaged by pressure transducer at 70°
- See similar saddle point departure
- Some differences in general structure shape (but same features)

matching with experimental data



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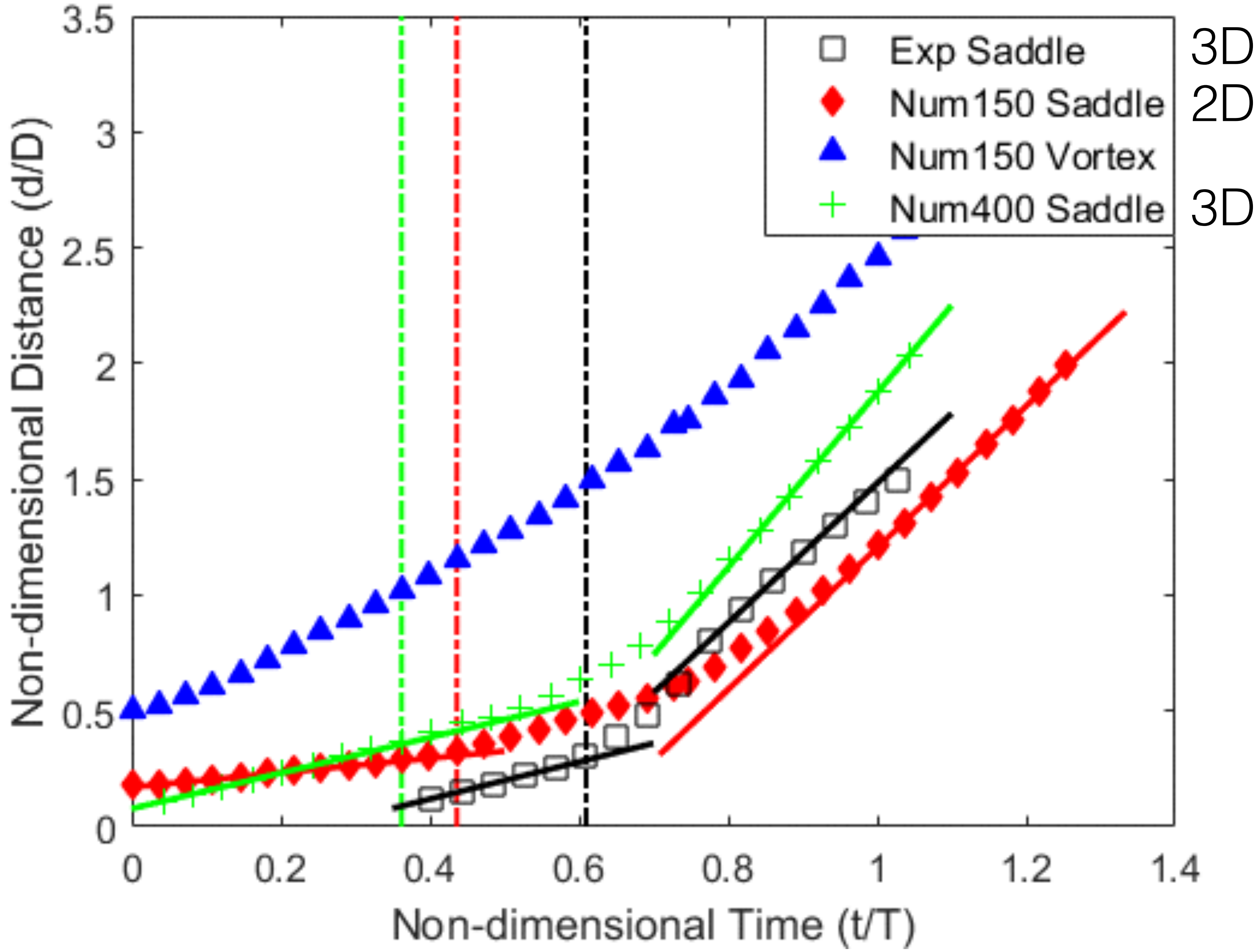
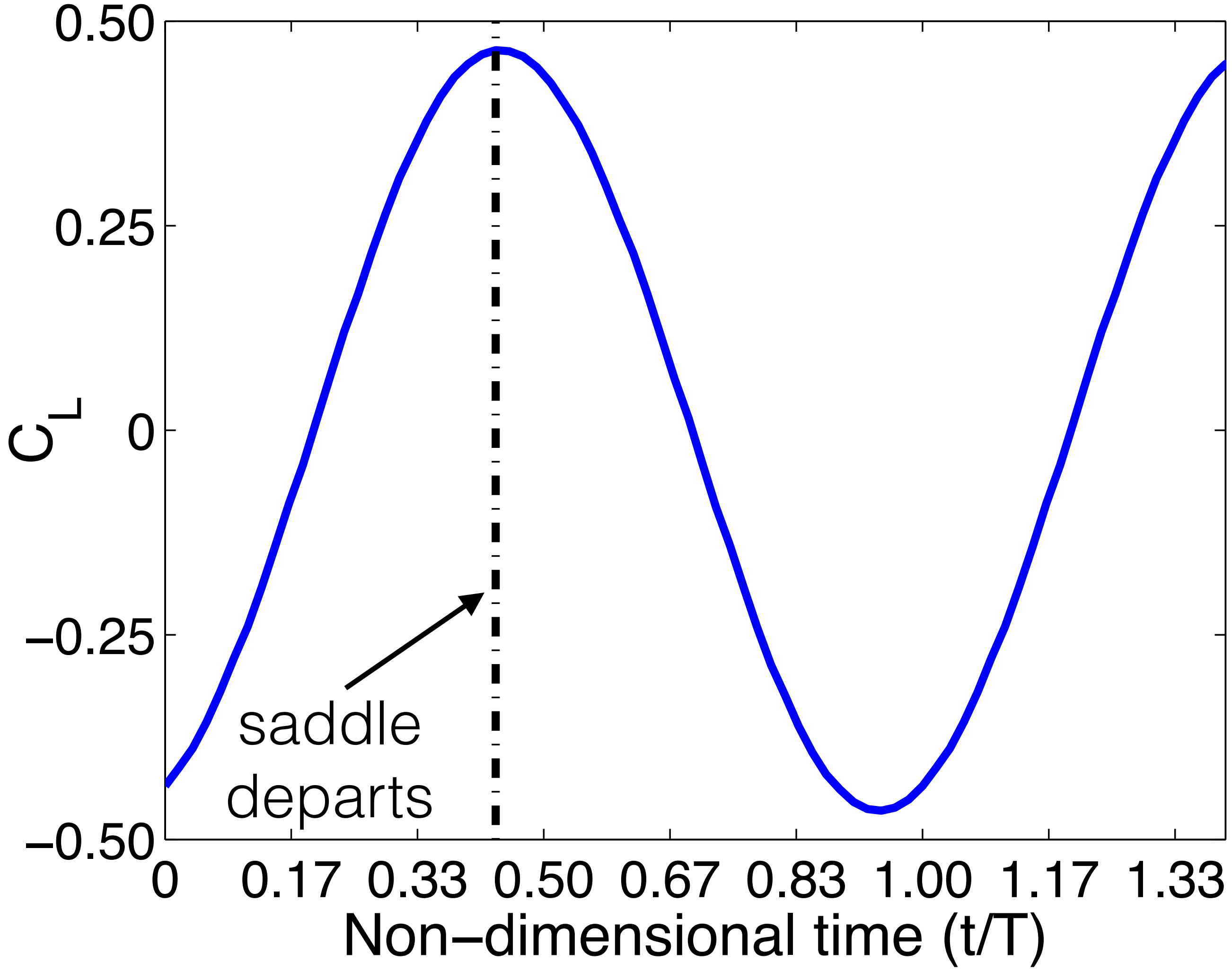
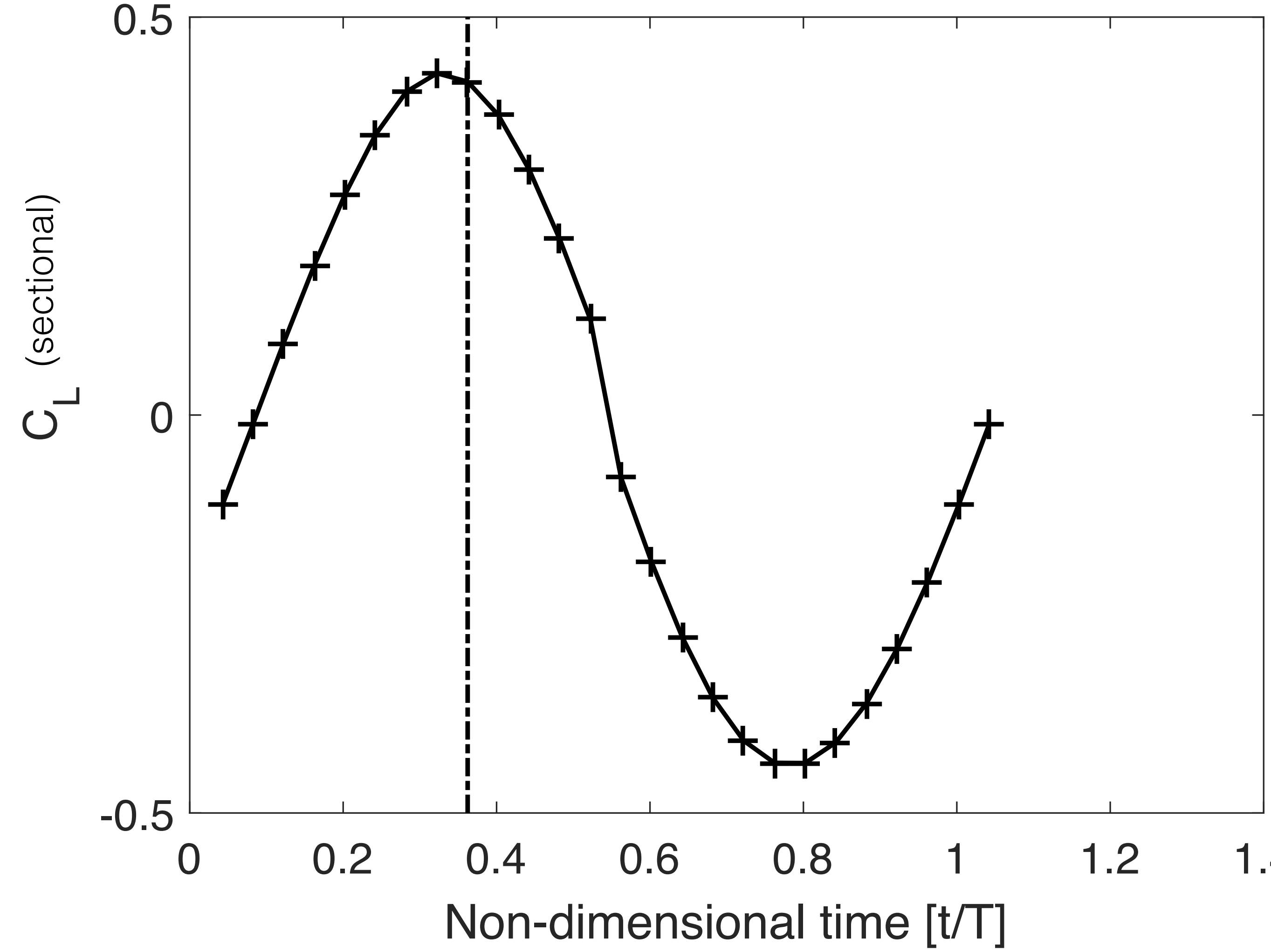


Behavior of the diagnostic (following LCS saddles) is consistent across Re, experimental/numerical

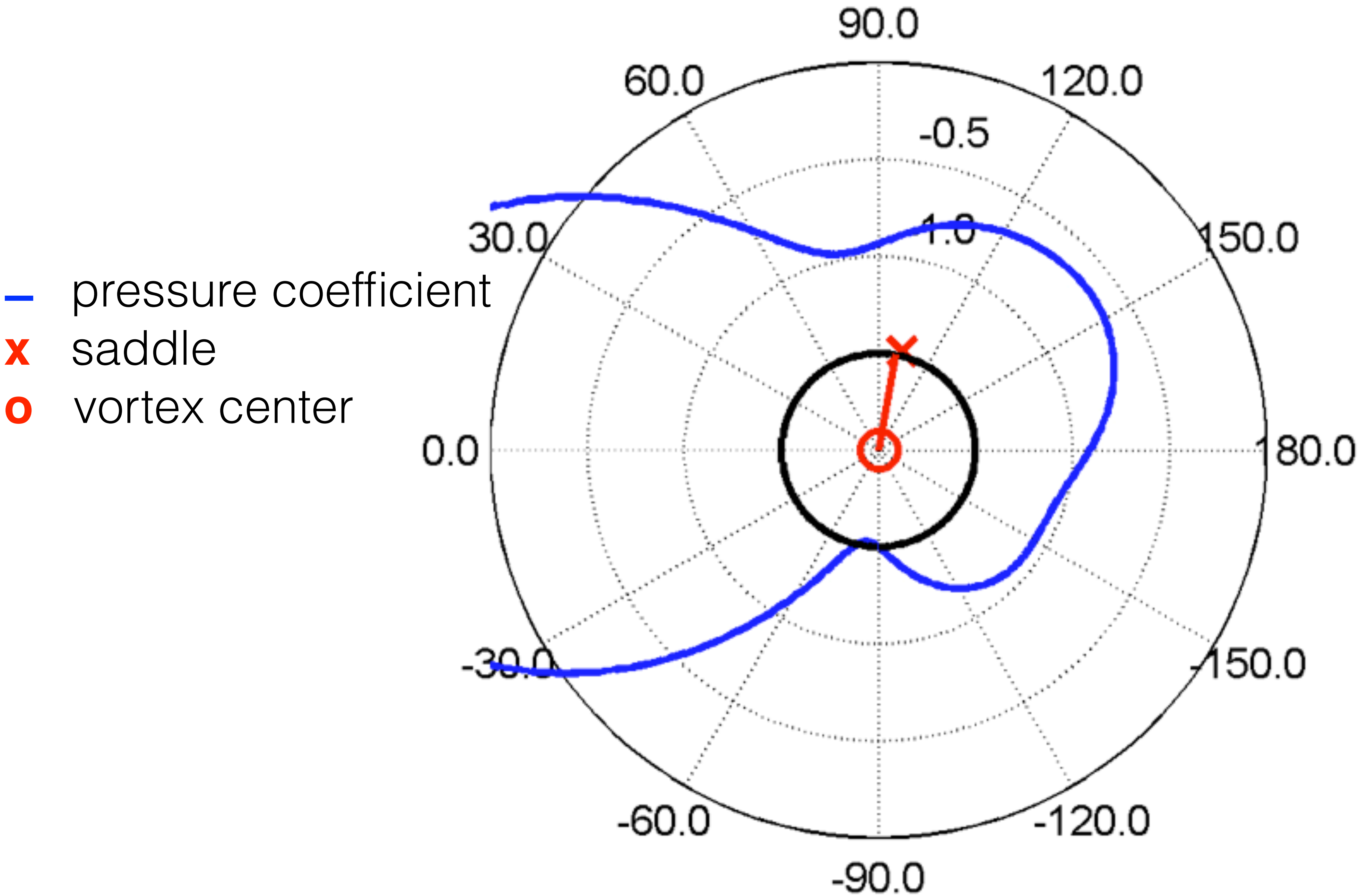




Re=150 numerical data

Re=400 numerical data

Max lift (vertical force) on the cylinder coincides with the saddle point departure timing



Compare with the pressure distribution on the cylinder surface

What locations will see maximum pressure fluctuations?

Coincide with saddle departure

Full flow field evolution (*of interest)* reduced to one red “x”

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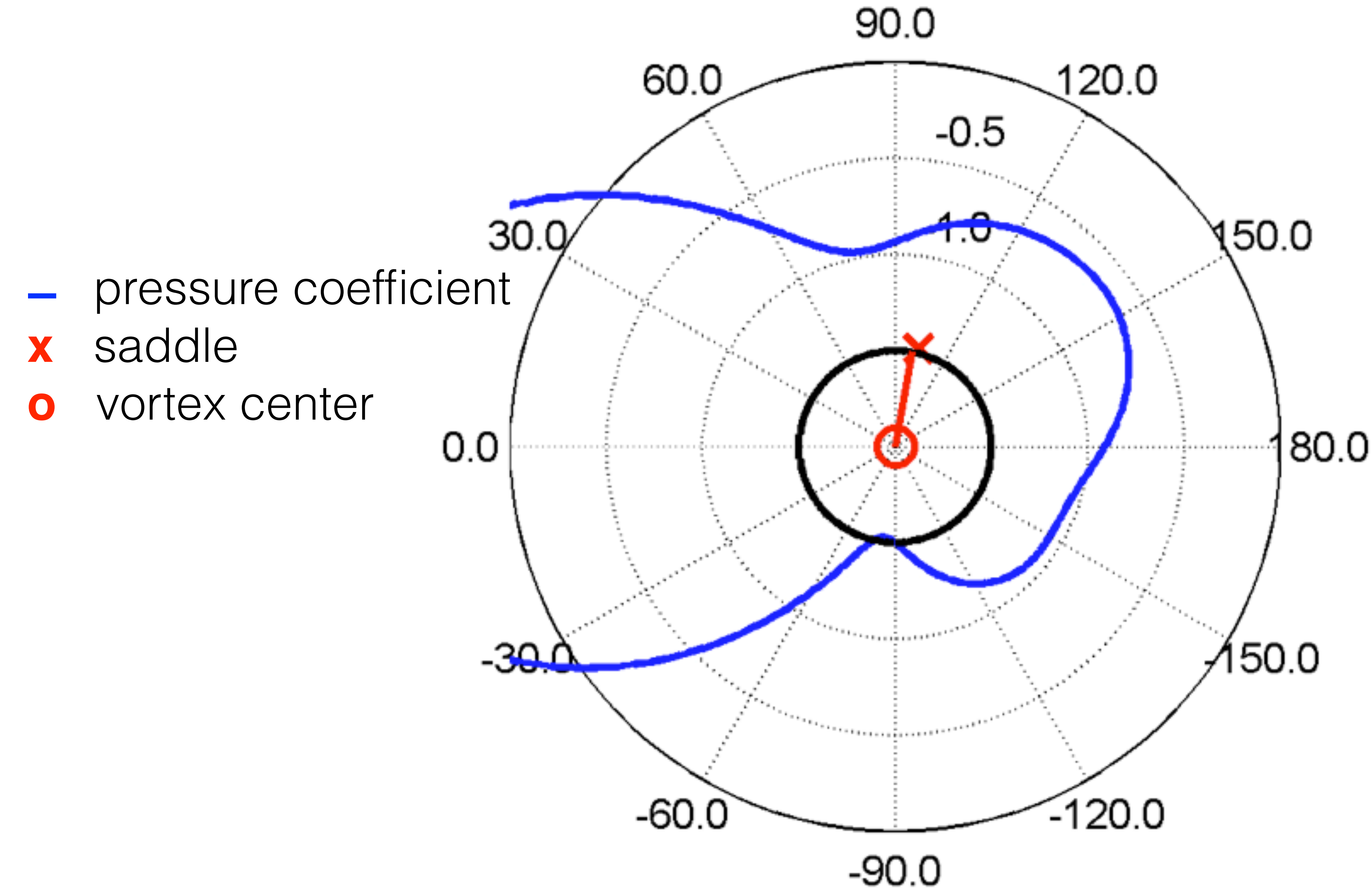

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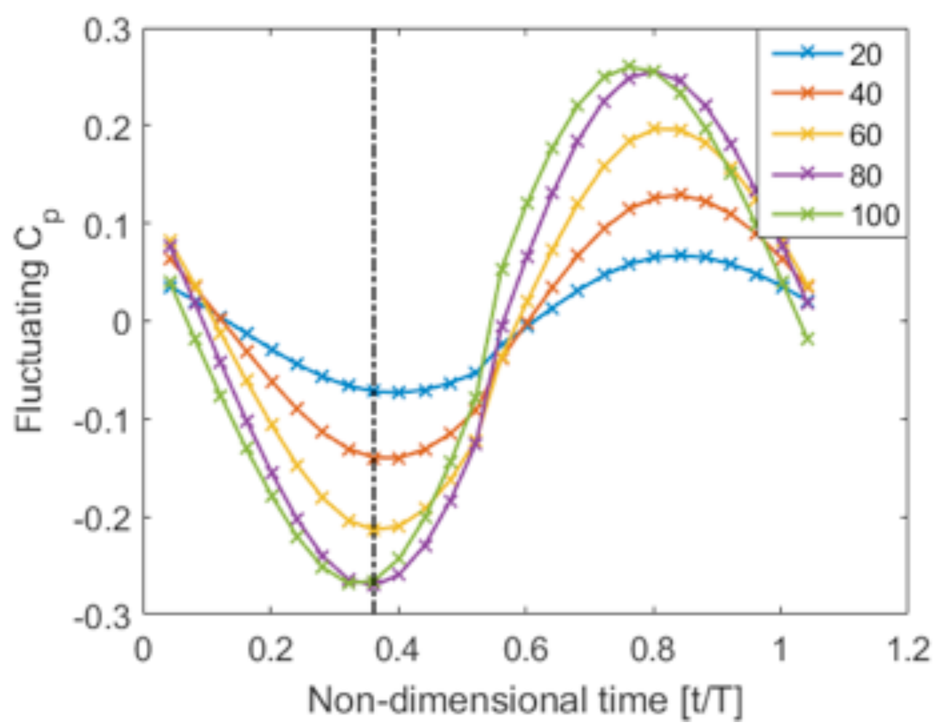
Coincide with saddle departure

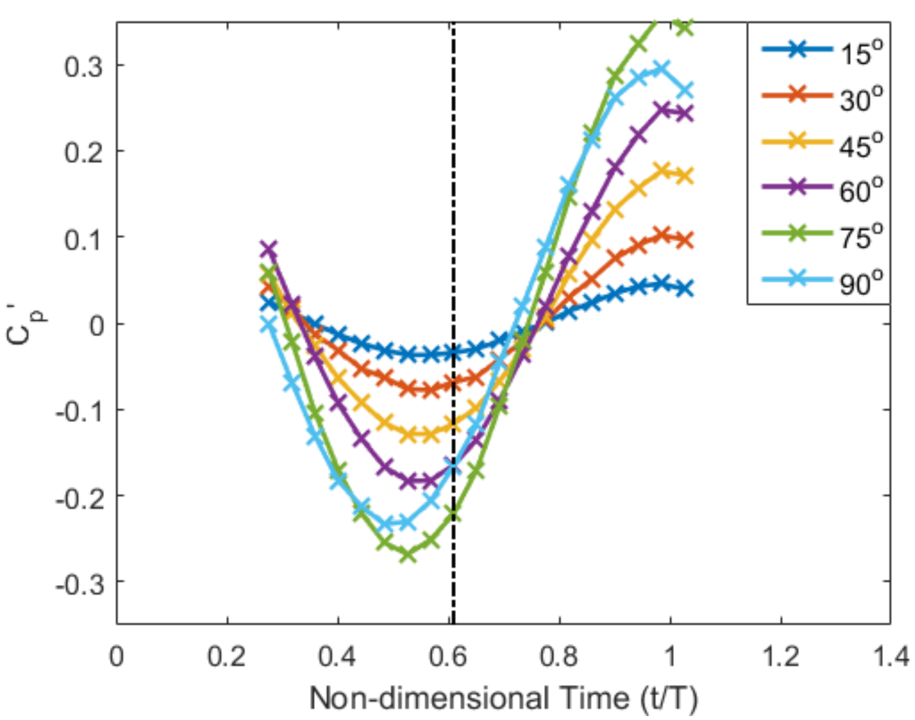
Full flow field evolution (*of interest)* reduced to one red “x”

- Distinct behavior of Lagrangian saddle at time of vortex shedding
- Surface pressure behavior shows shedding coinciding with pressure minima/ peak vertical force
- Can we use pressure signals on the surface to infer the behavior of the shedding wake?
    - Preliminary data from *Re*=400 3D numerical solution and *Re*=19000 experimental data indicate potentially yes

Re=400, num

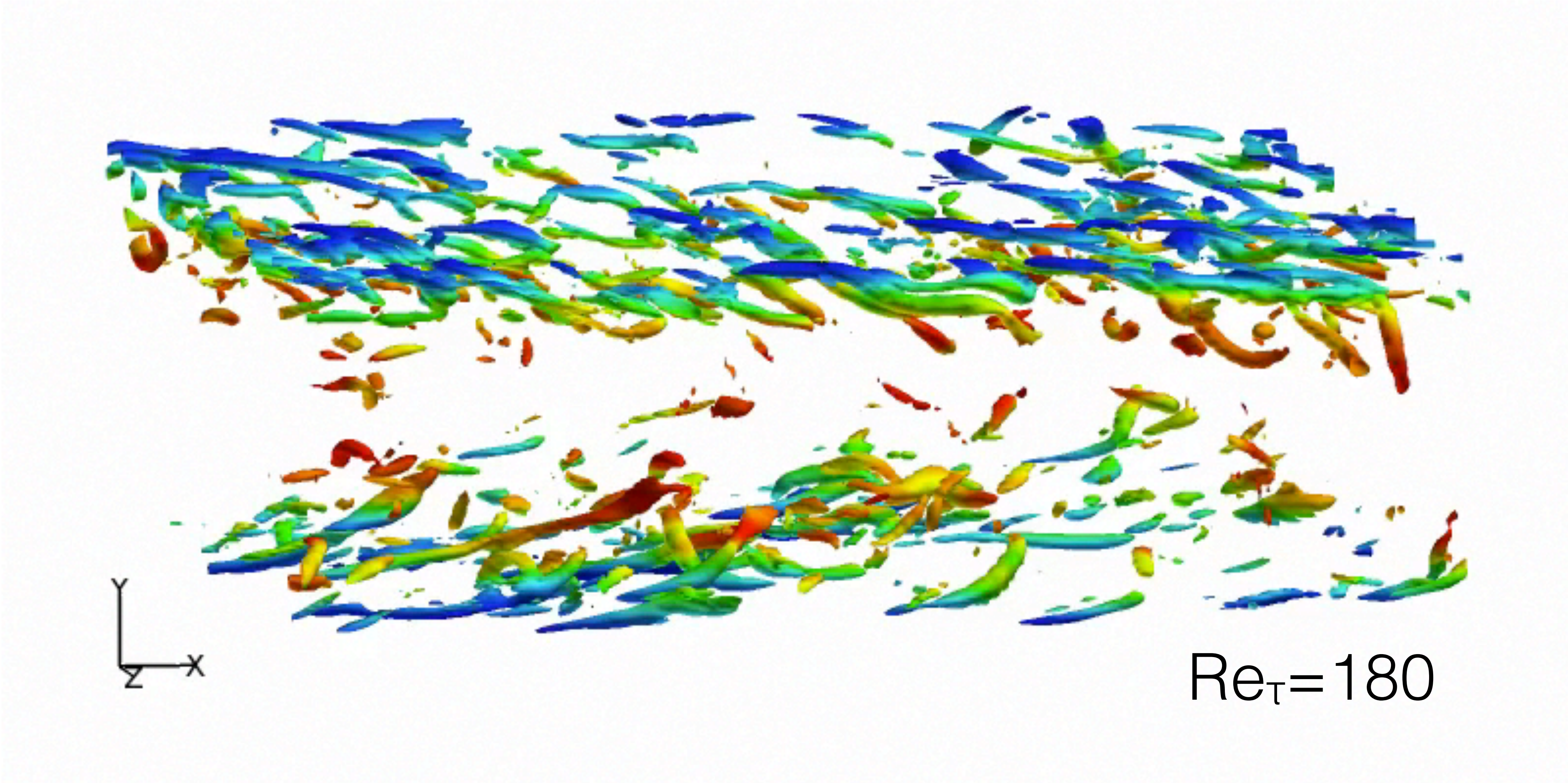


Re=19000, exp



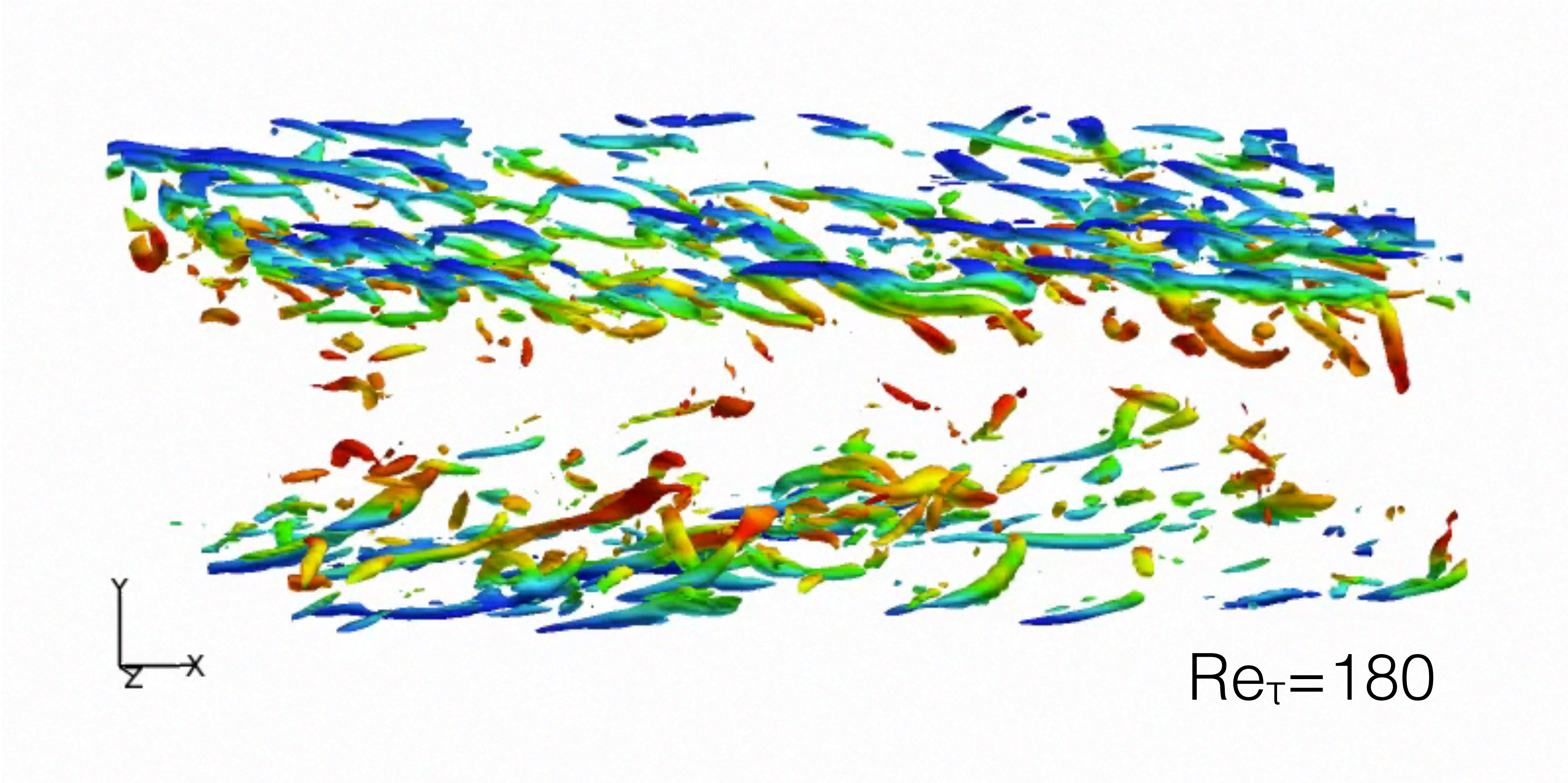
- Can we find/track similar coherent structures in 3D turbulence?

turbulent channel simulation



- Simulation based on Kim, Moin, Moser 1987
- Structure generation and evolution in 3D space and time
- How do LCS saddles do at tracking structures here?

turbulent channel simulation



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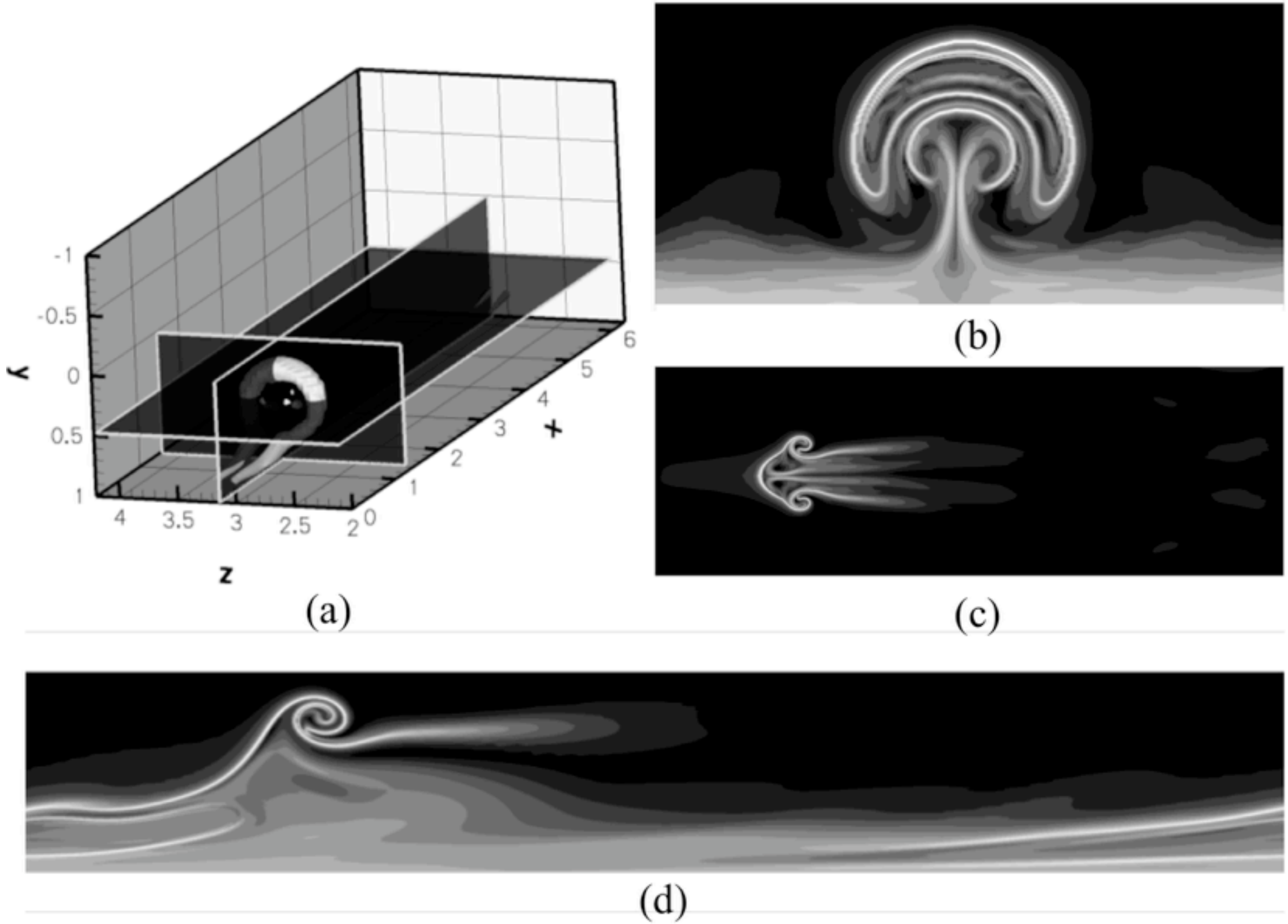
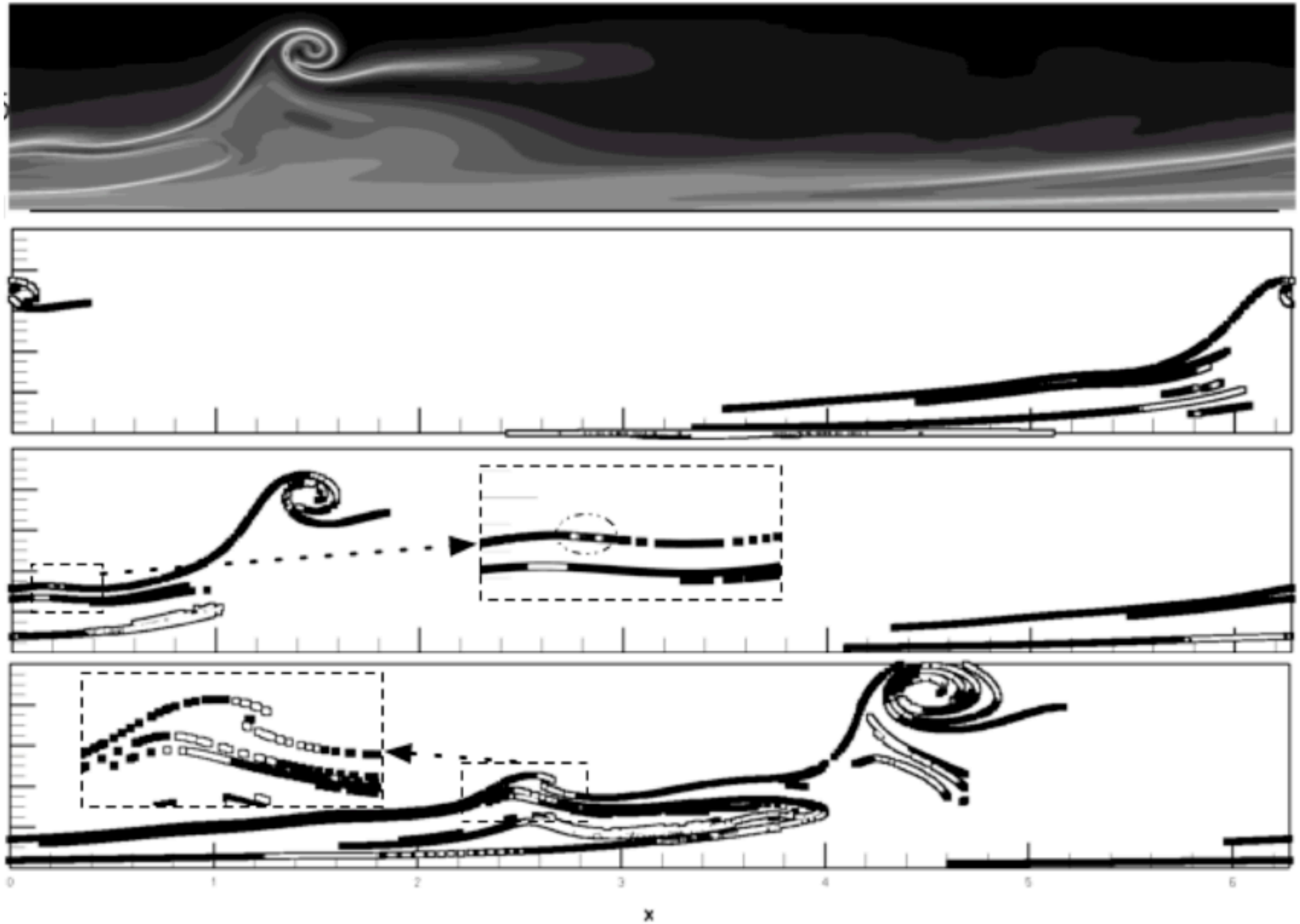
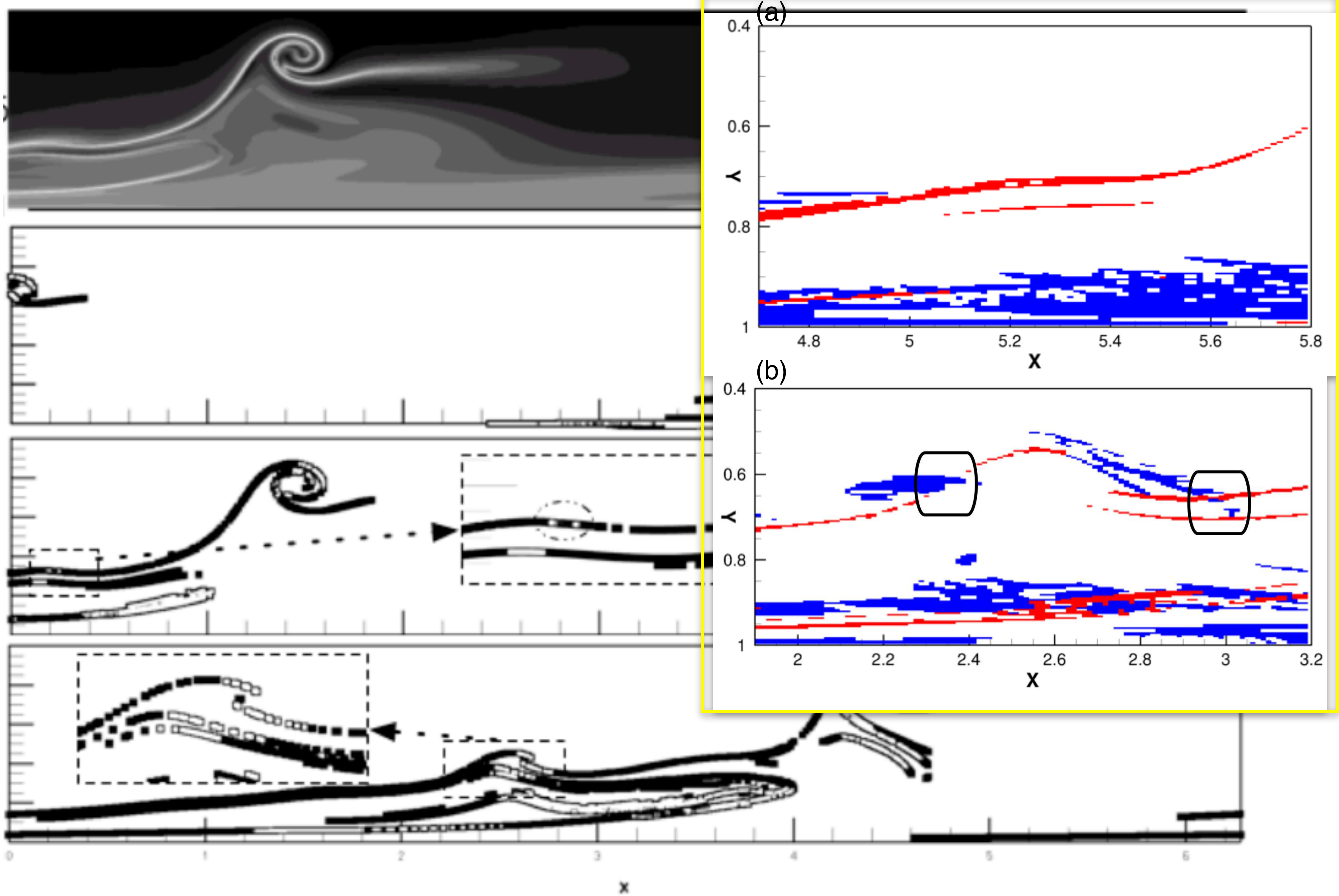
- But first, a little history…



nFTLE (Green et al. 2007) on isolated hairpin (Zhou et al. 1999)



Loss of “hyperbolicity” along nFTLE ridge showed where secondary vortex would emerge (Green et al. 2007)



That was actually correlated with the appearance of pFTLE ridges and saddles (Green et al. 2010)

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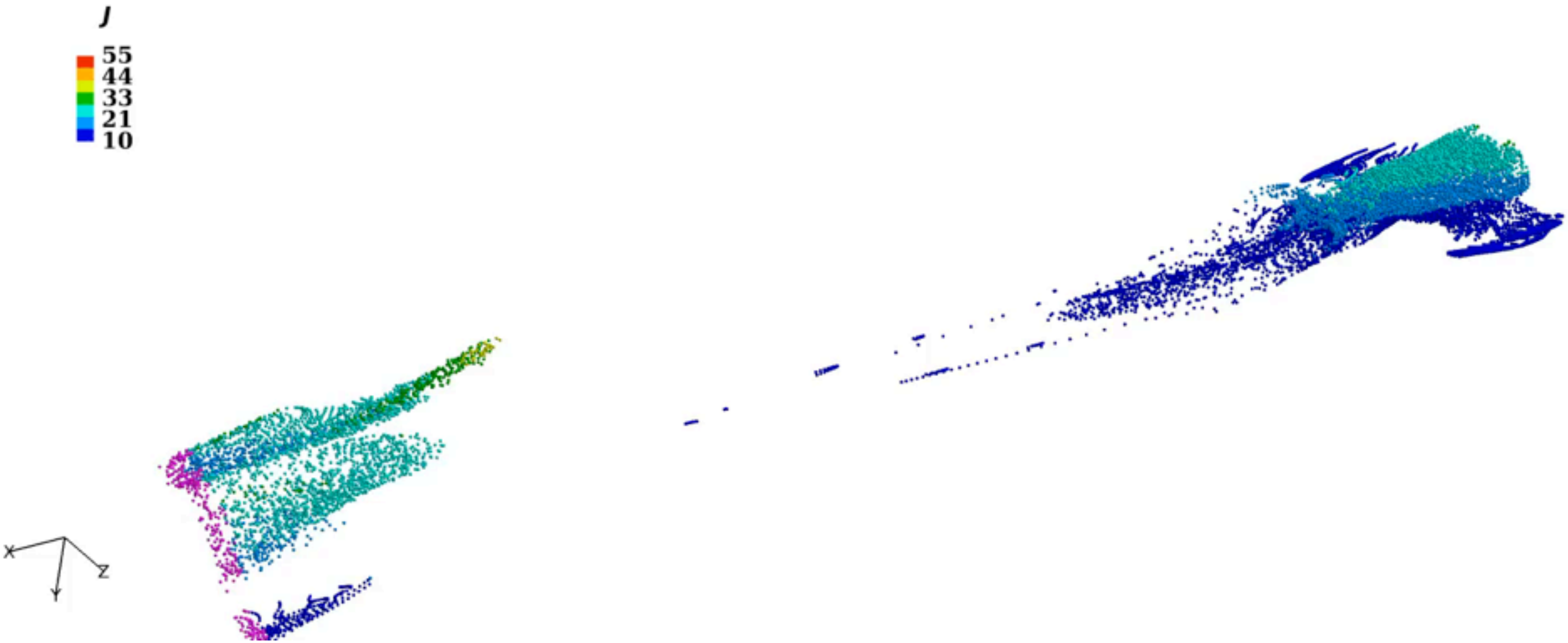
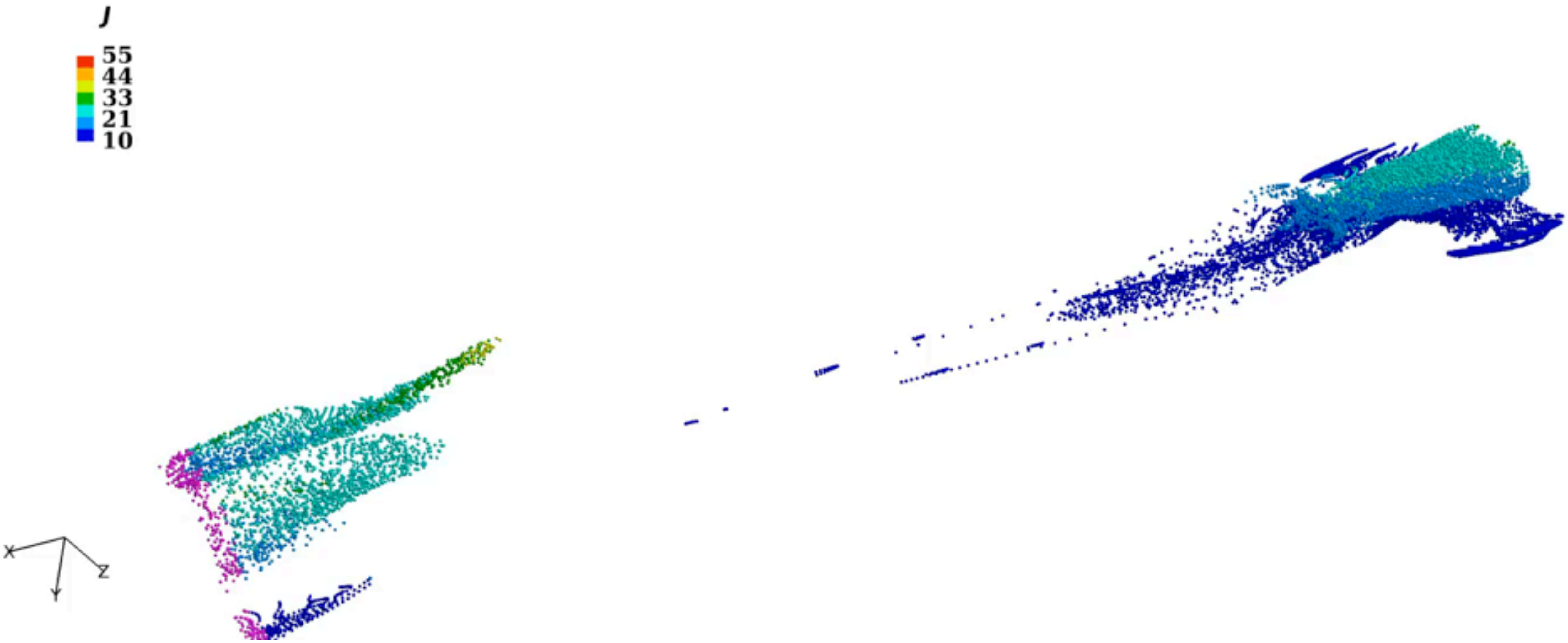


Have more recently looked at new Lagrangian methods to identify fluid that is contained within secondary hairpin

Can we connect it with wall signatures in pressure, shear, etc?

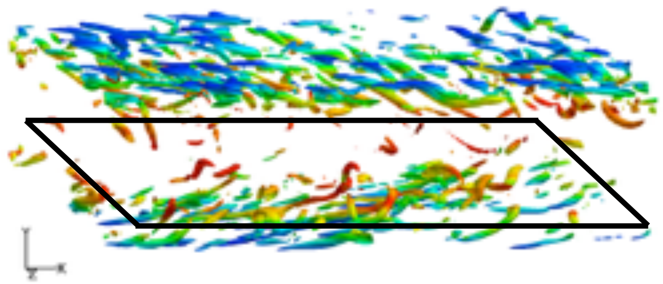


Have more recently looked at new Lagrangian methods to identify fluid that is contained within secondary hairpin
Can we connect it with wall signatures in pressure, shear, etc?

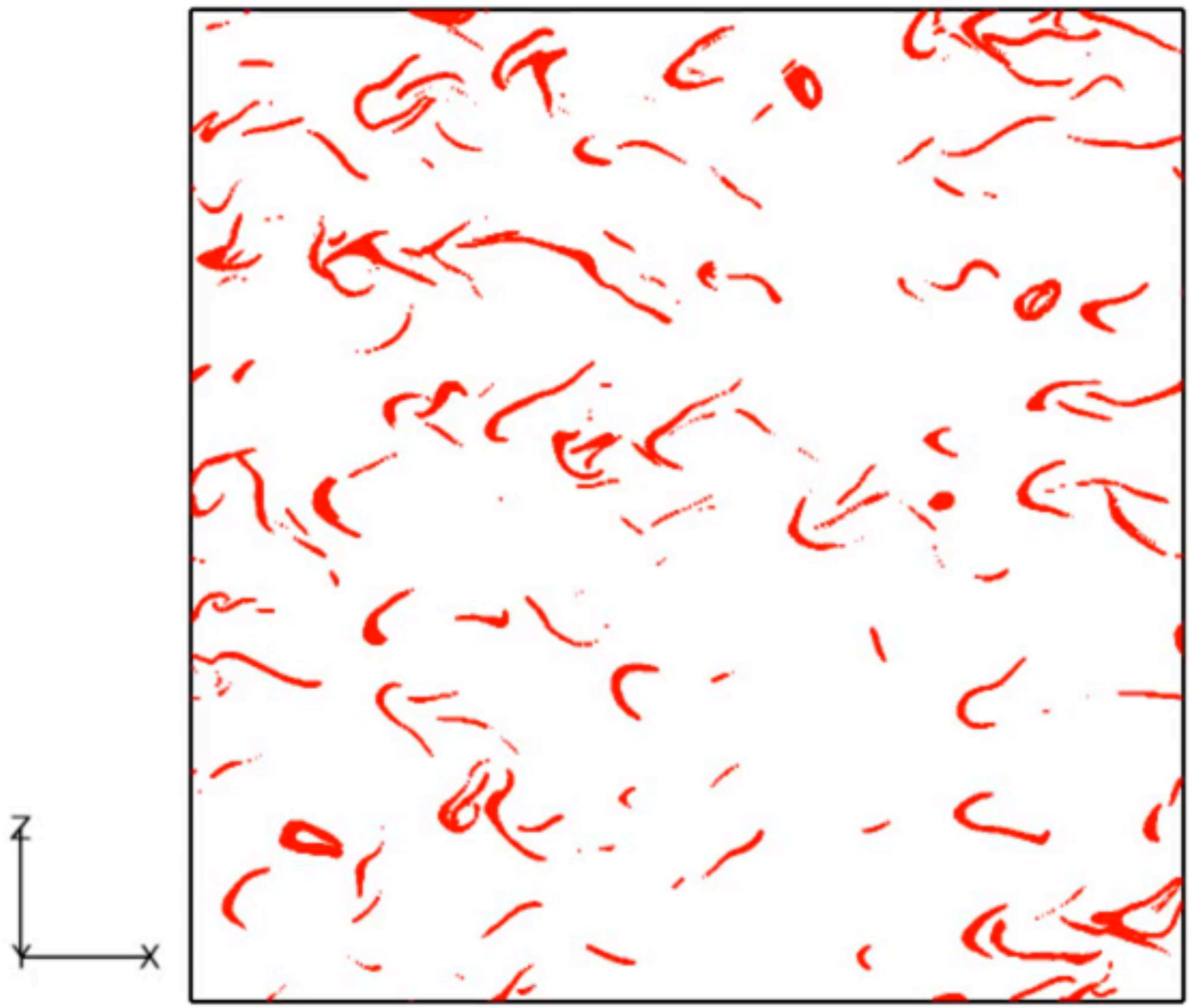
- Not yet
  - Difficult to separate material from close to the wall and the material in the hairpin
  - Constant entrainment and detrainment

- Not yet
    - Difficult to separate material from close to the wall and the material in the hairpin
    - Constant entrainment and detrainment

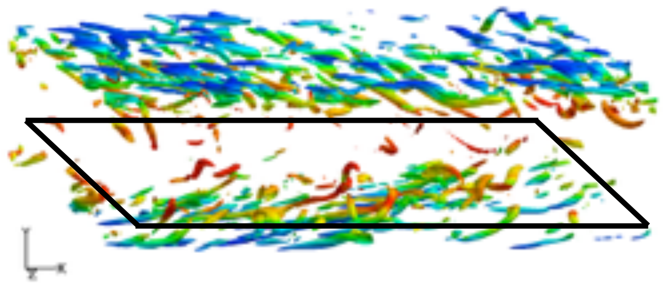
- Still, do these features of the Lagrangian FTLE field have any meaning in 3D turbulence?
- What happens when we look for saddles?



nFTLE



For now, just tracking in the 2D plane ($y^+=50$)



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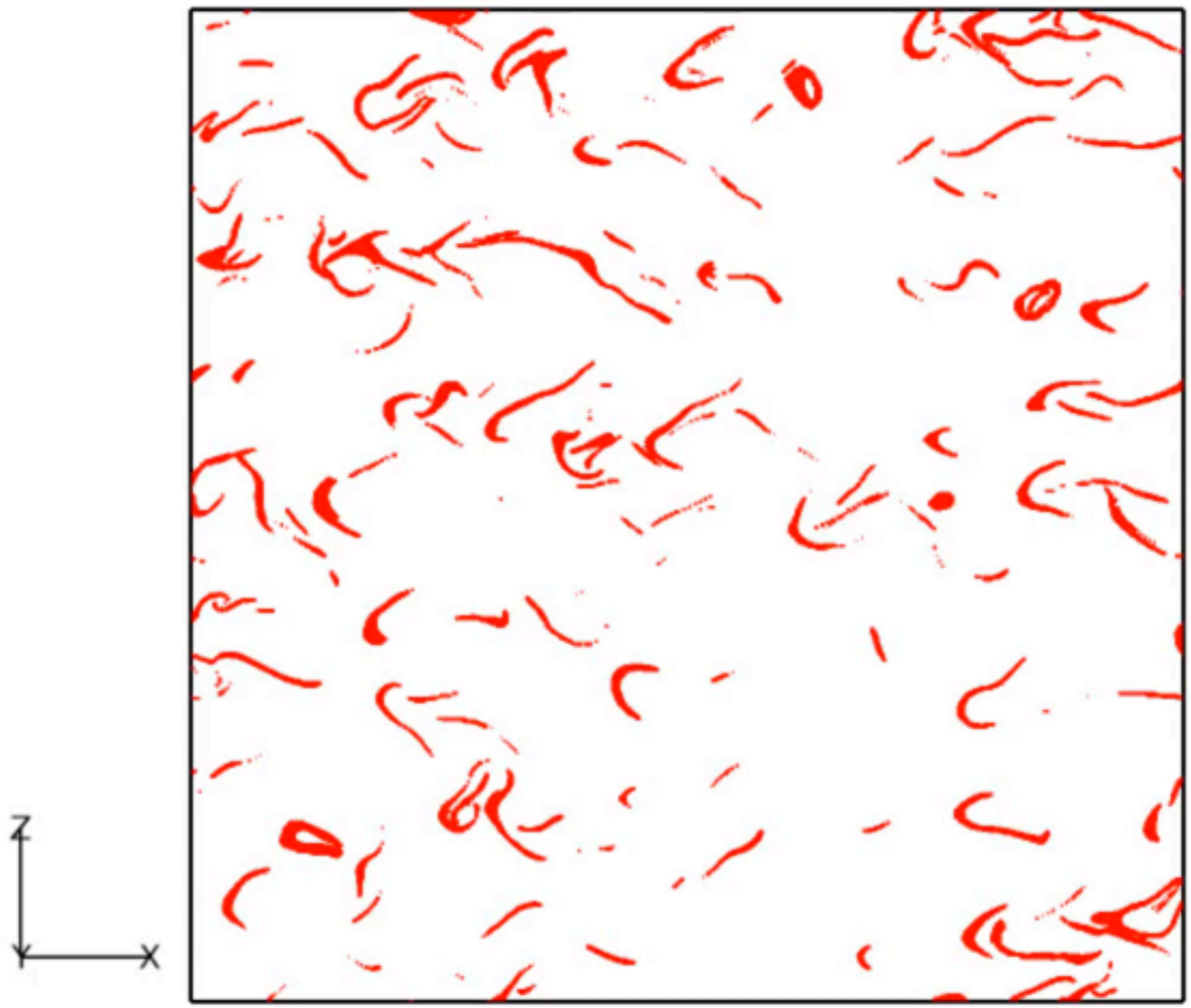

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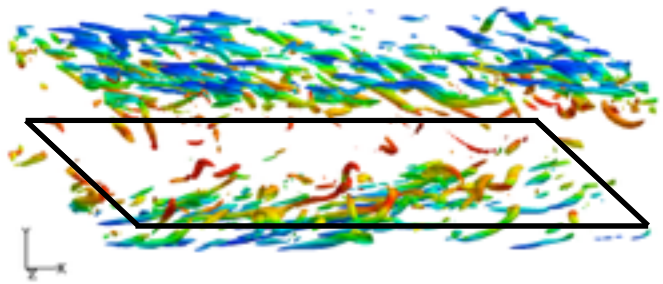
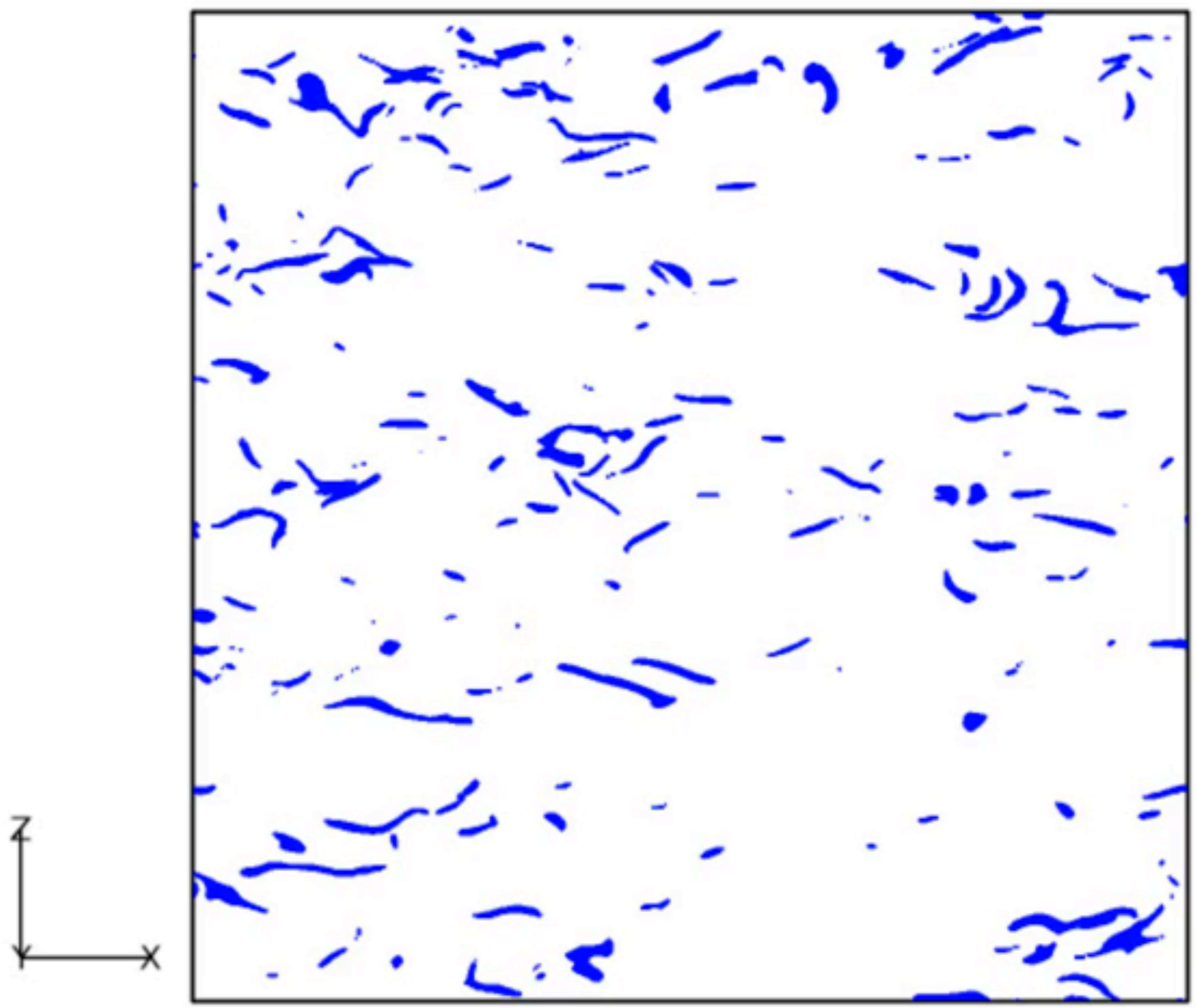


pFTLE



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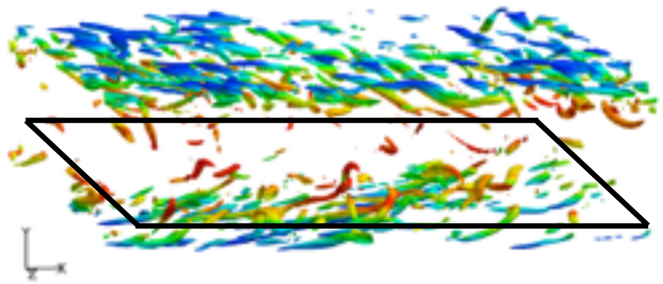

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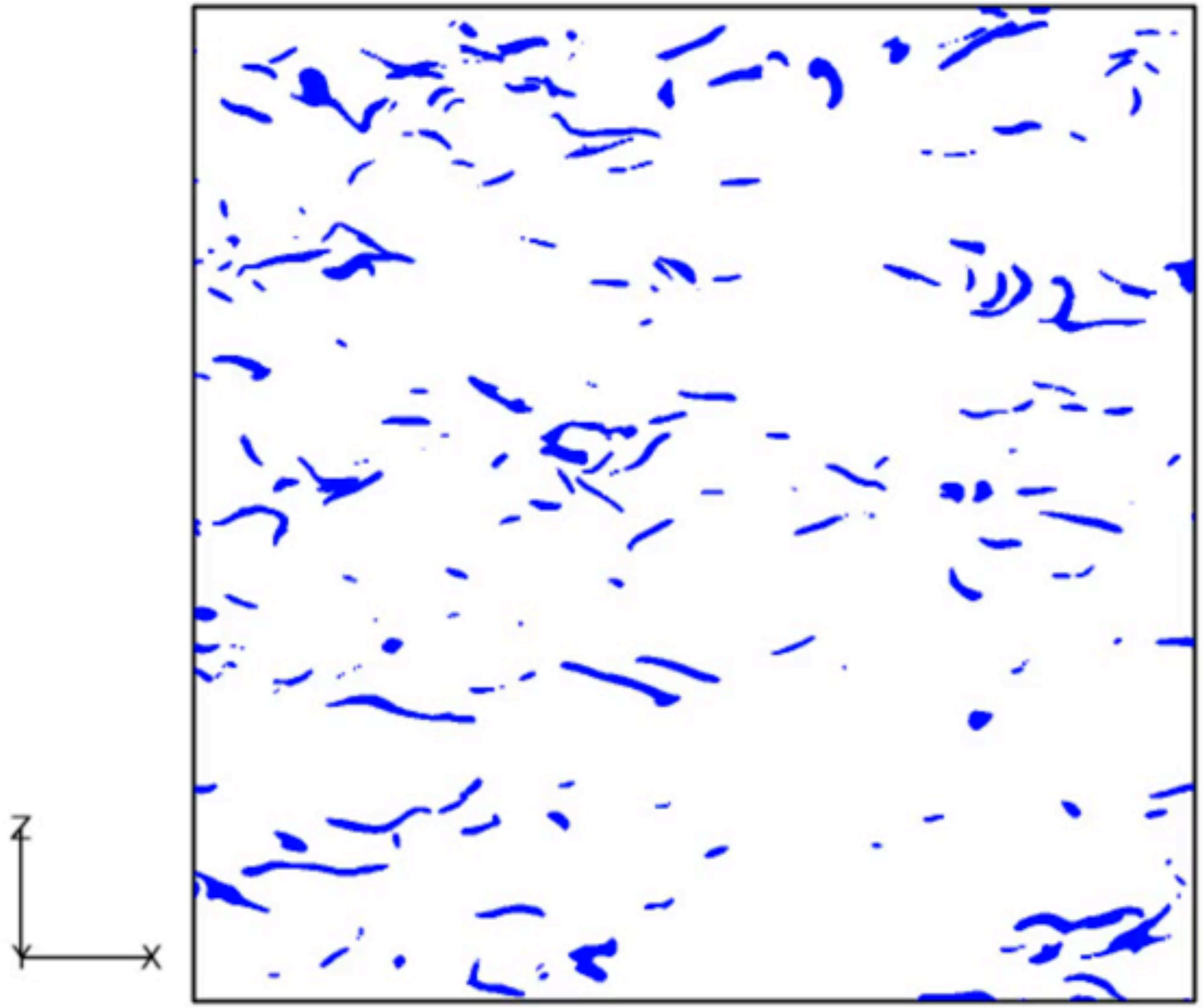

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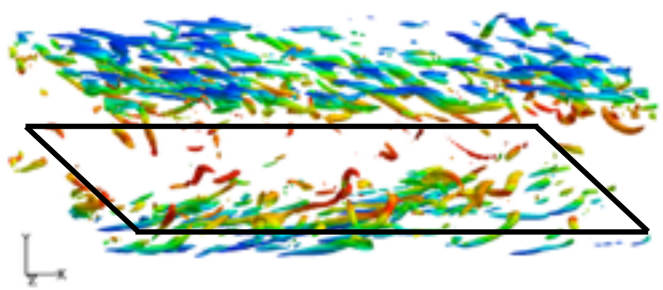
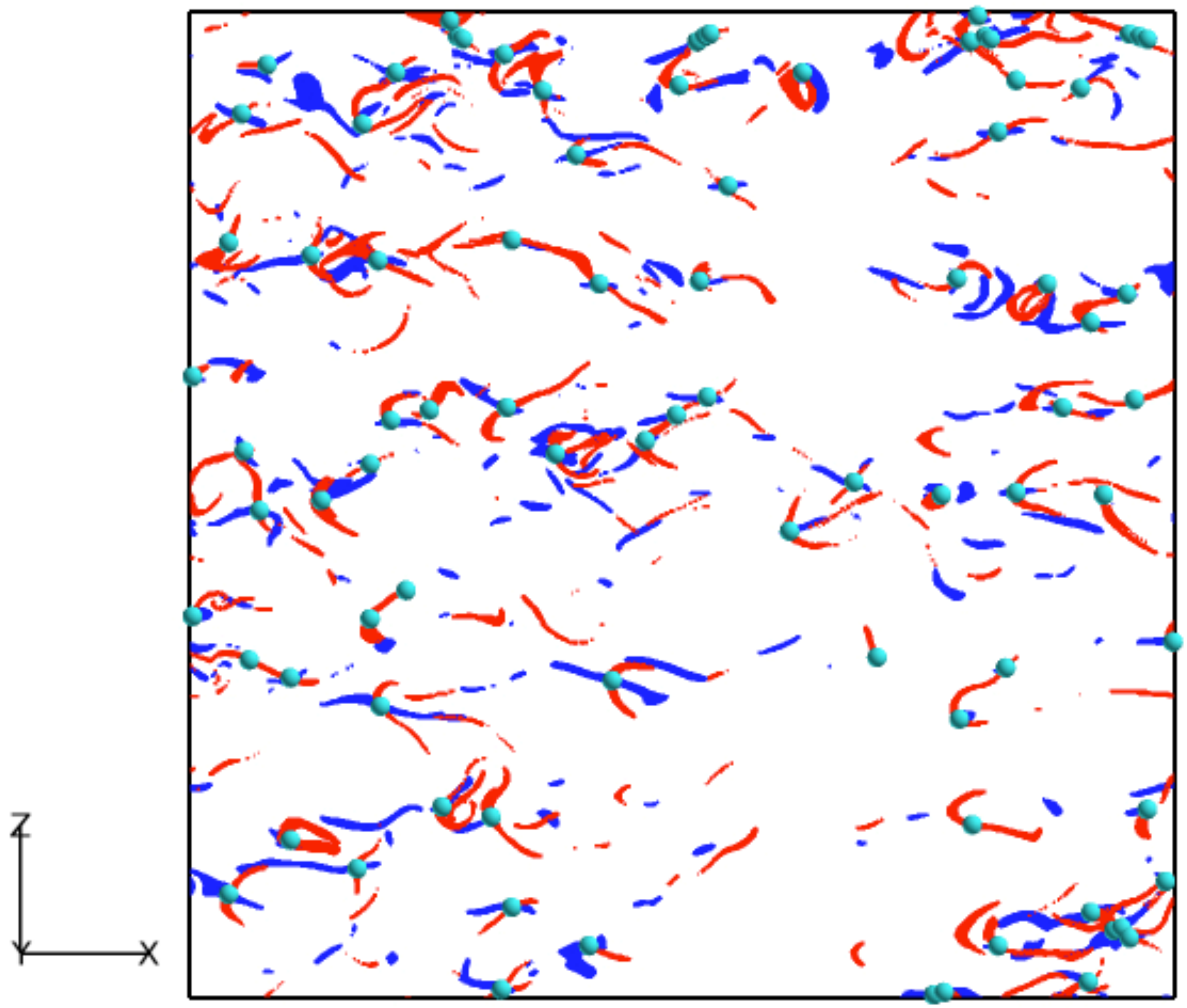
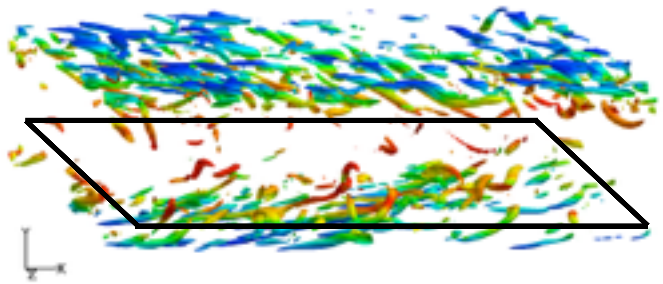


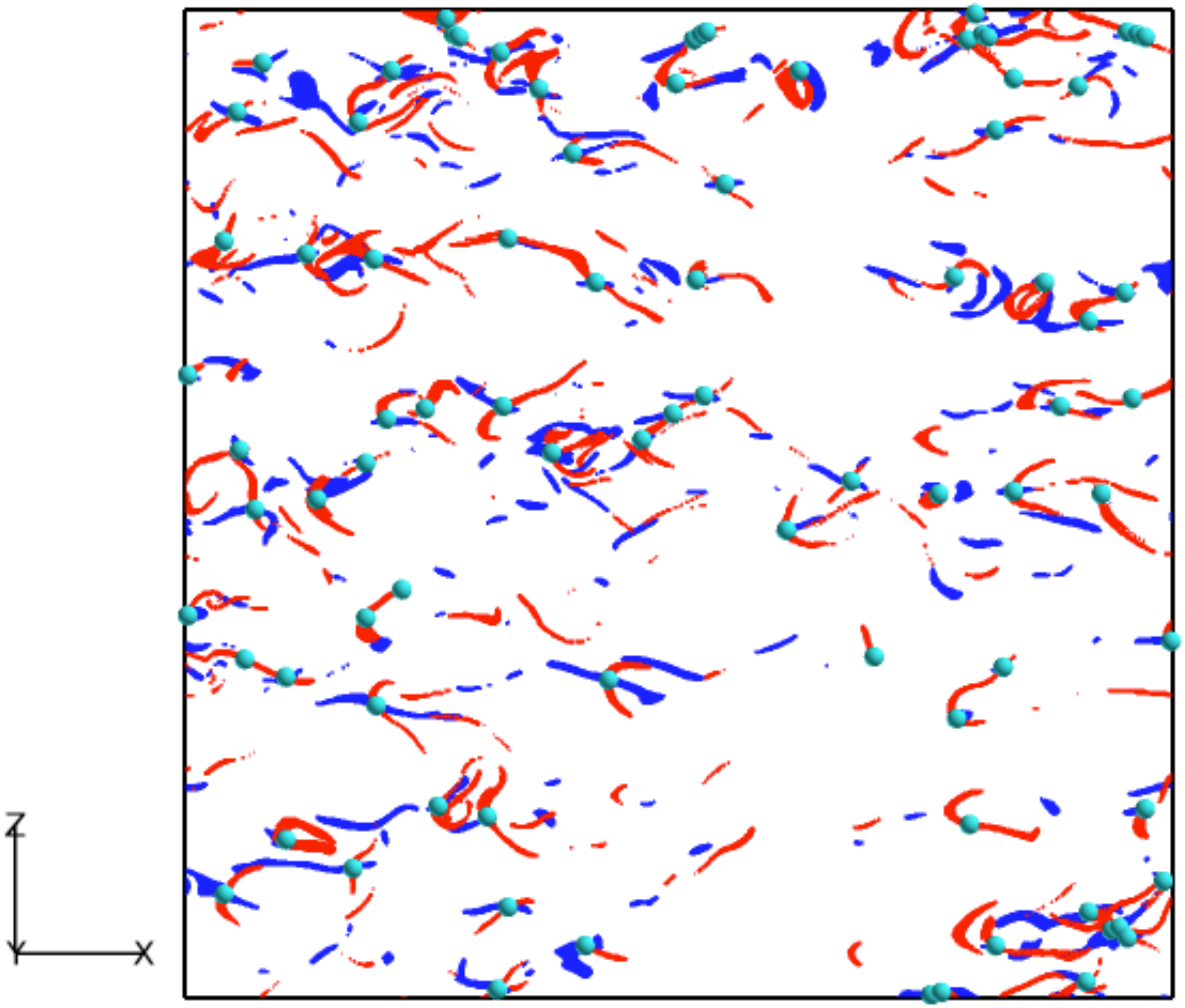
nFTLE, pFTLE, saddles



For now, just tracking in the 2D plane (y^+=50)

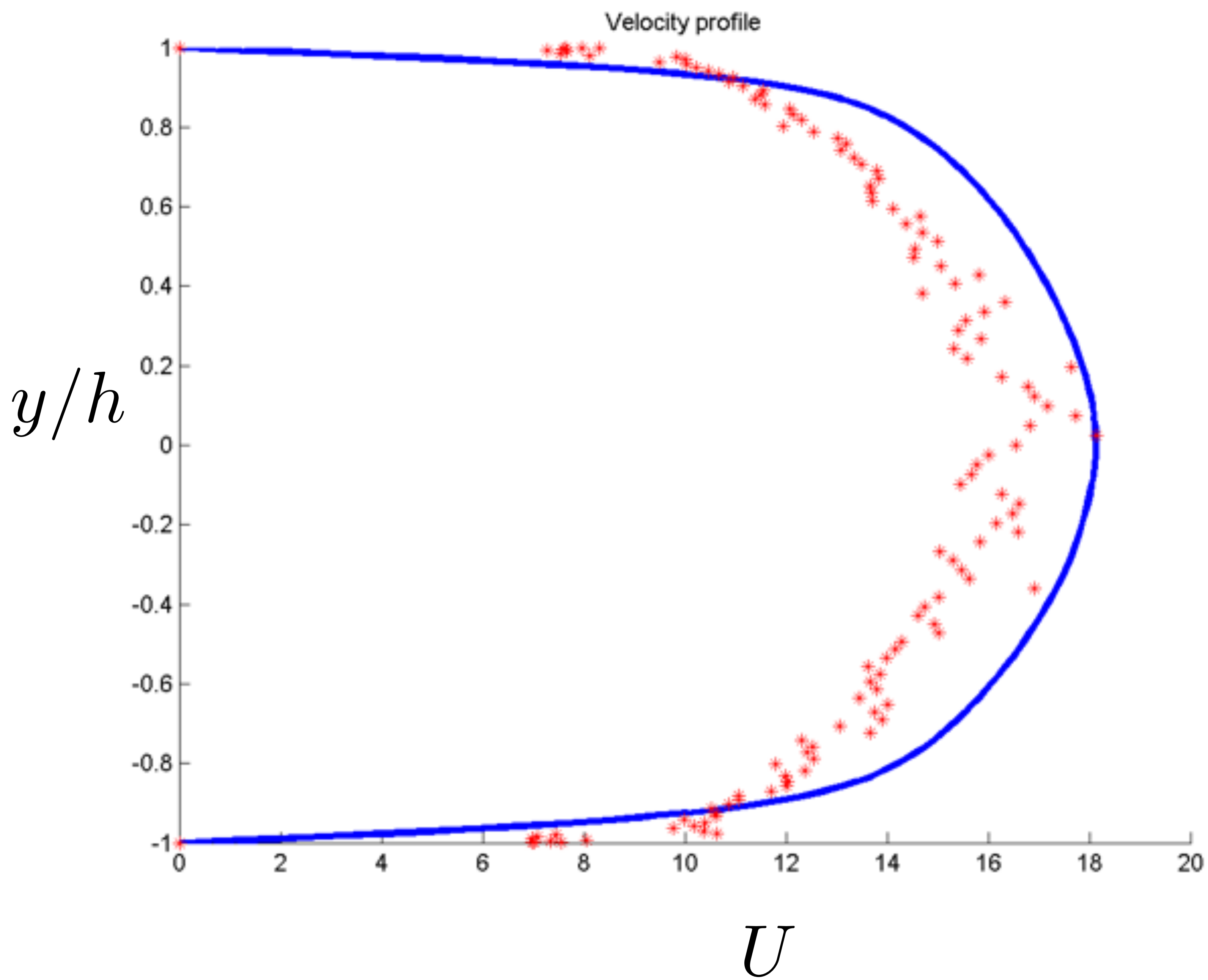


nFTLE, pFTLE, saddles



For now, just tracking in the 2D plane (y^+=50)

- Can start to compare structure velocity (as determined from saddles) to turbulent flow properties (mean velocity profile)
- Same trend as seen in Kim & Hussain, 1993



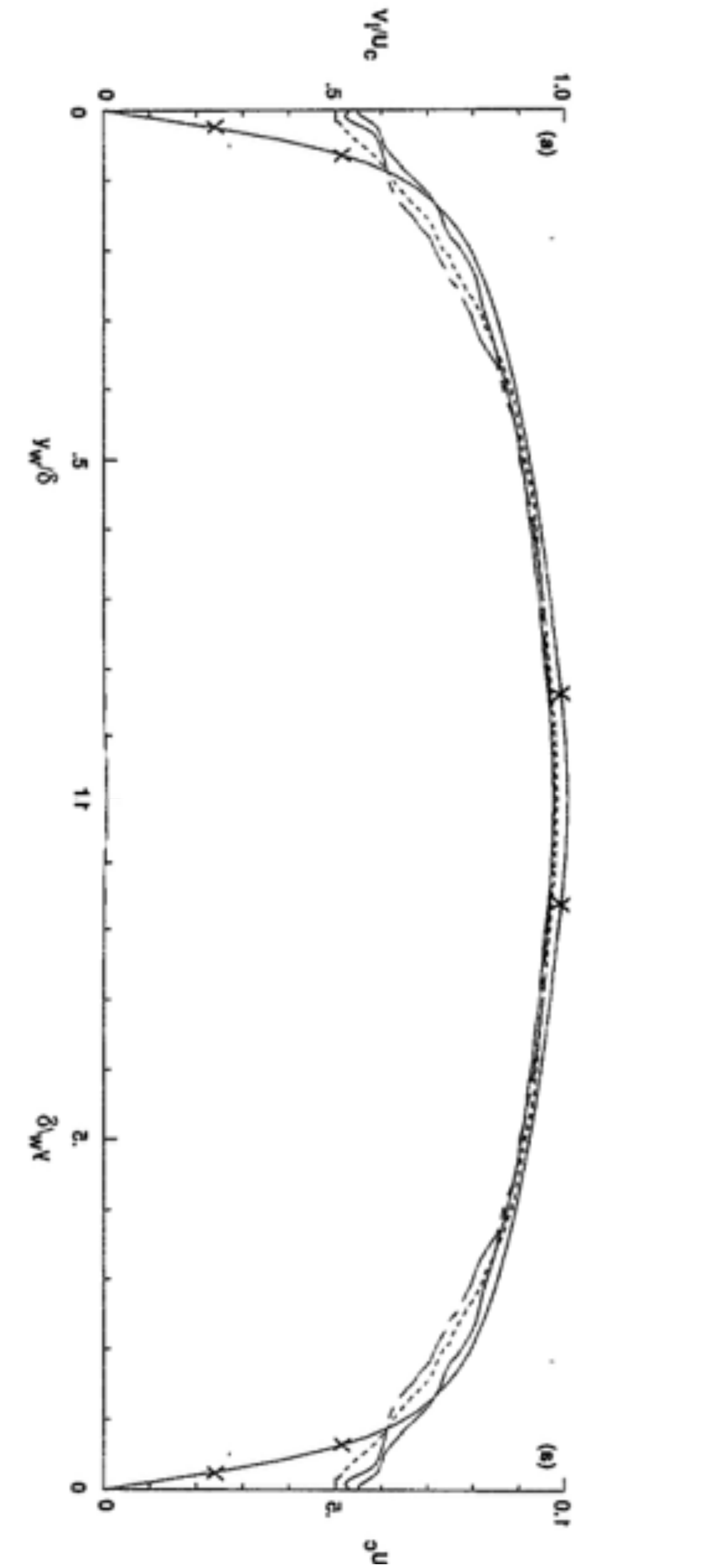
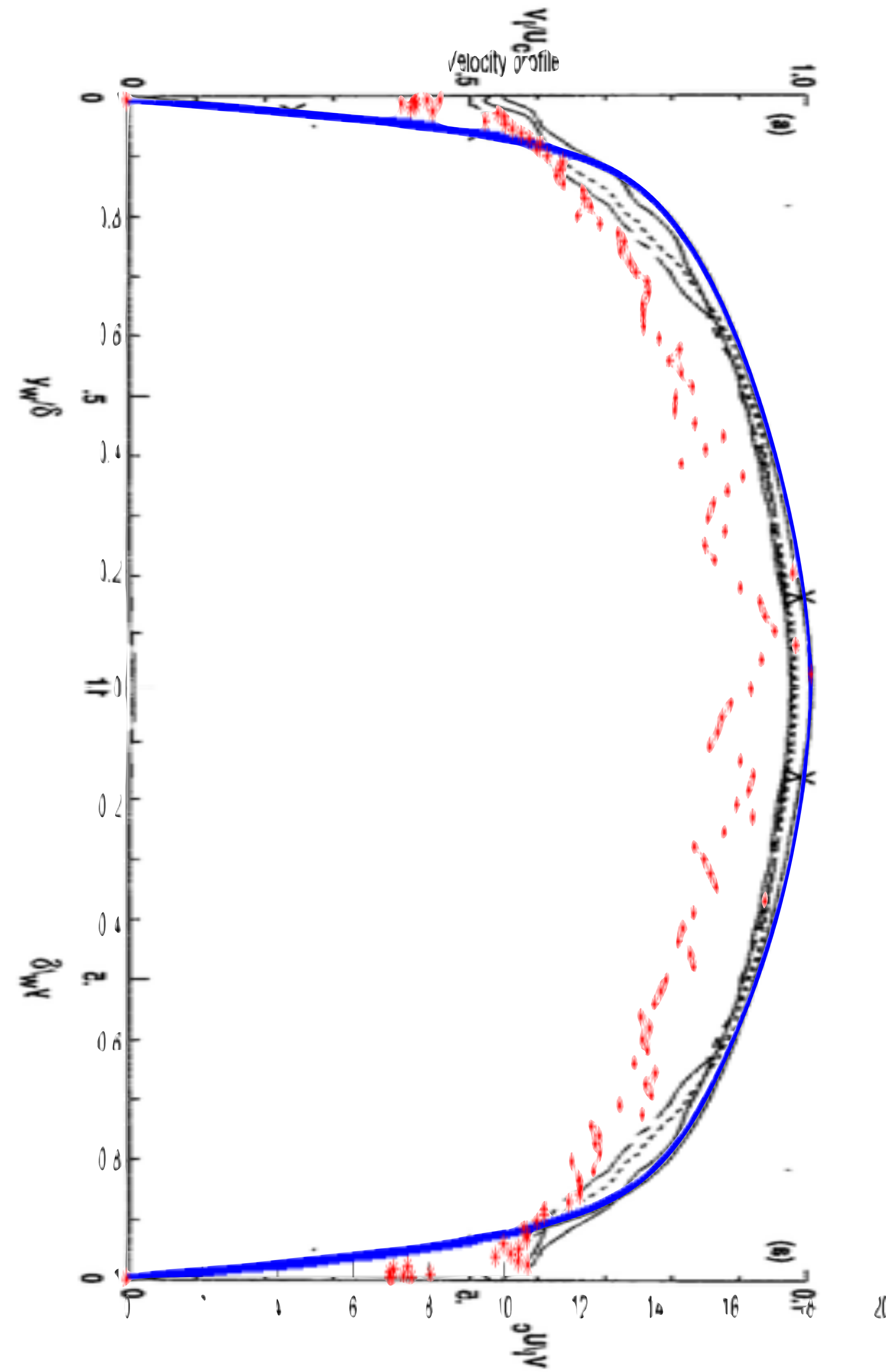


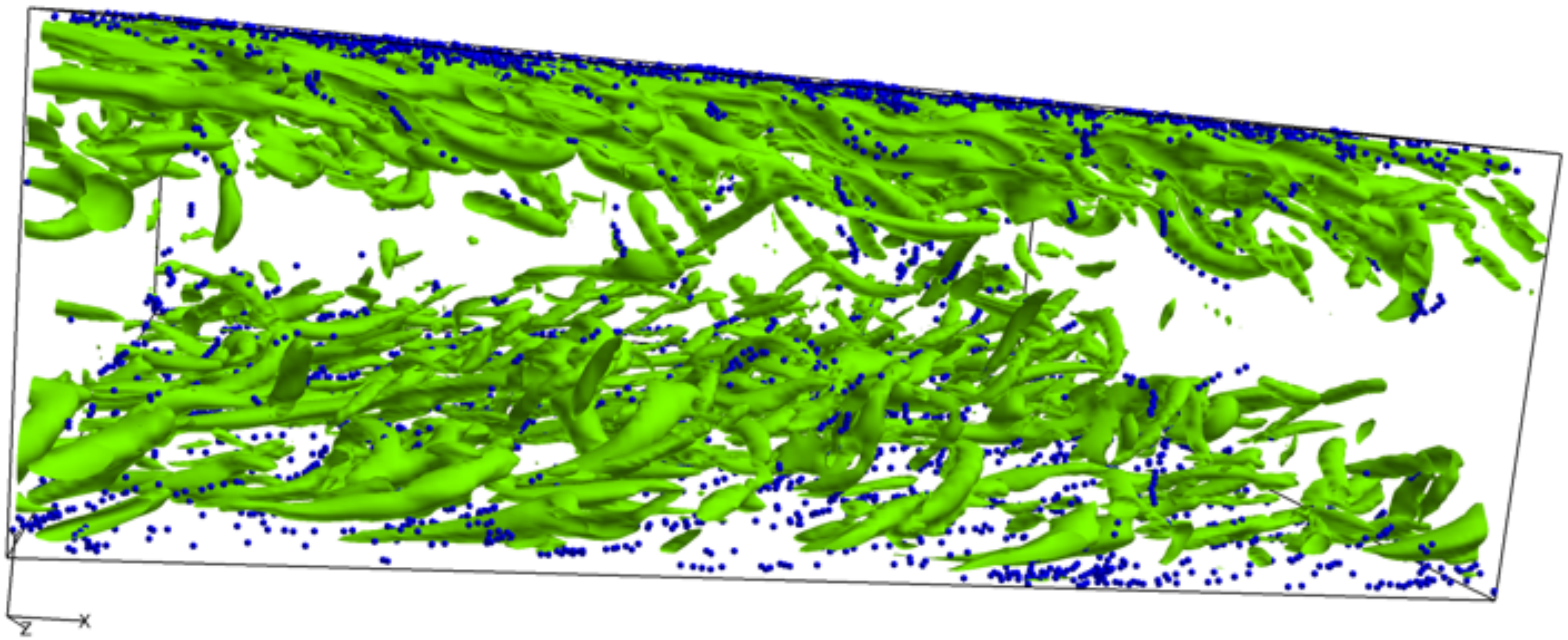
FIG. 2. Propagation velocities for the vorticity perturbations across the channel (a) in global coordinate and (b) in wall coordinate: – ×–, mean; ——, ω_x; - - -, ω_y; – – –, ω_z.

- Point of overlap closer to the wall than earlier work
- New results not statistically converged
    - FTLE not great near the wall
    - Fewer saddles mid-channel



- For now, just tracking in 2D planes (although FTLE calculated with full 3D data)
- LCS are really co-dimension 1 structures - saddles are co-dimension 2. Really curves in 3D space, not as straightforward to track.

- Can we use saddles to identify individual structures to watch dynamics (behavior, lifespan, etc)?
- Can we use correlate saddles (or diagnostics of saddles, saddle distributions) to correlate to wall measurements?



some notes…

- FTLE requires lots of velocity data support to calculate
  - Dimension, spatial resolution, temporal resolution
- Despite previous point, relatively insensitive to velocity field errors
  - Individual particle trajectories are sensitive, but it takes large, persistent errors to affect identification of separatrices in flow field
- Implementation in full turbulence IS tricky
  - Flowmap integration time related to relevant time scale
  - Might be filtering faster time scales, not capturing slower ones

summary

- LCS saddles a different way to identify and track coherent structures
- Need algorithms/software for tracking (especially in 3D)

- Great for flow visualization, but should be a quantitative way to access what we intuit by eye in flow viz
- Looking for quantitative connections between visible vortex dynamics and flow structure, pressure, shear, forces, etc

Thanks: Sam Taira (FSU)

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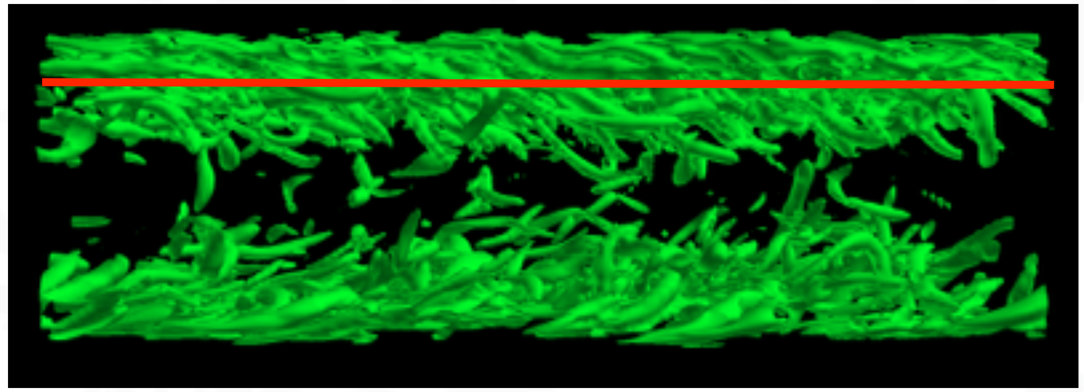
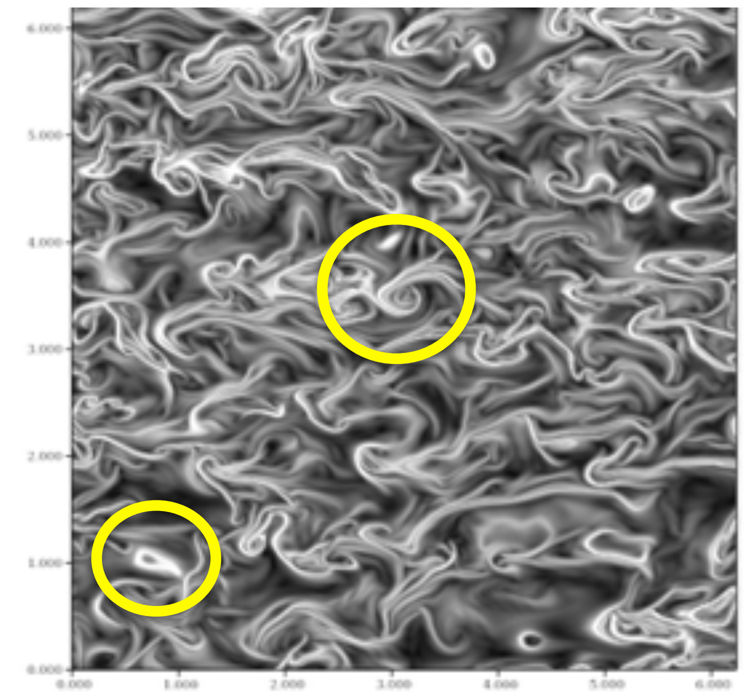
Dimensionality issues

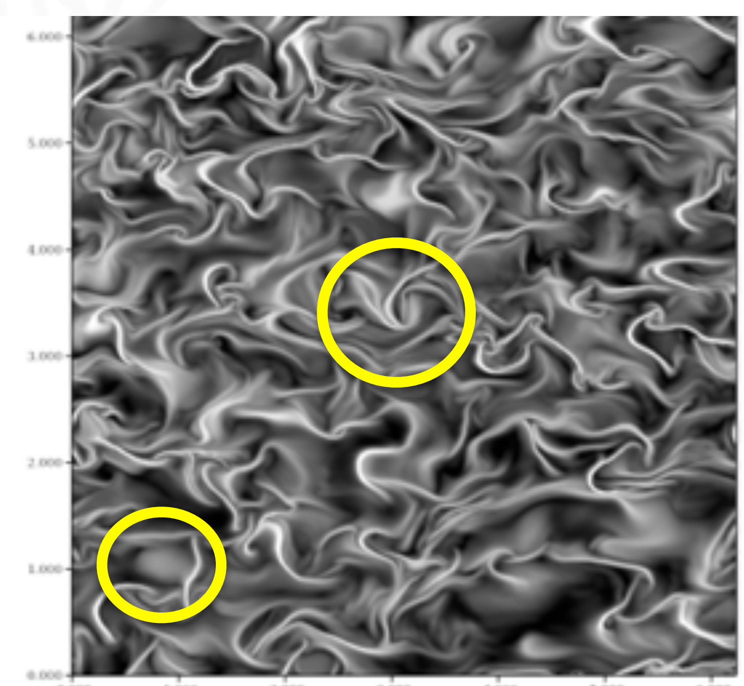
Turbulent channel DNS Re_τ=180



- In experiments, can be difficult to get full volume of 3-component data in 3D flows
- Calculate nFTLE in a plane
  - Use full volume of three-component data - let particle trajectories fly
  - Use only in-plane velocities, assume v=0 (simulated 2D PIV)
- Not just a matter of filtering out smaller scales, important qualitative differences



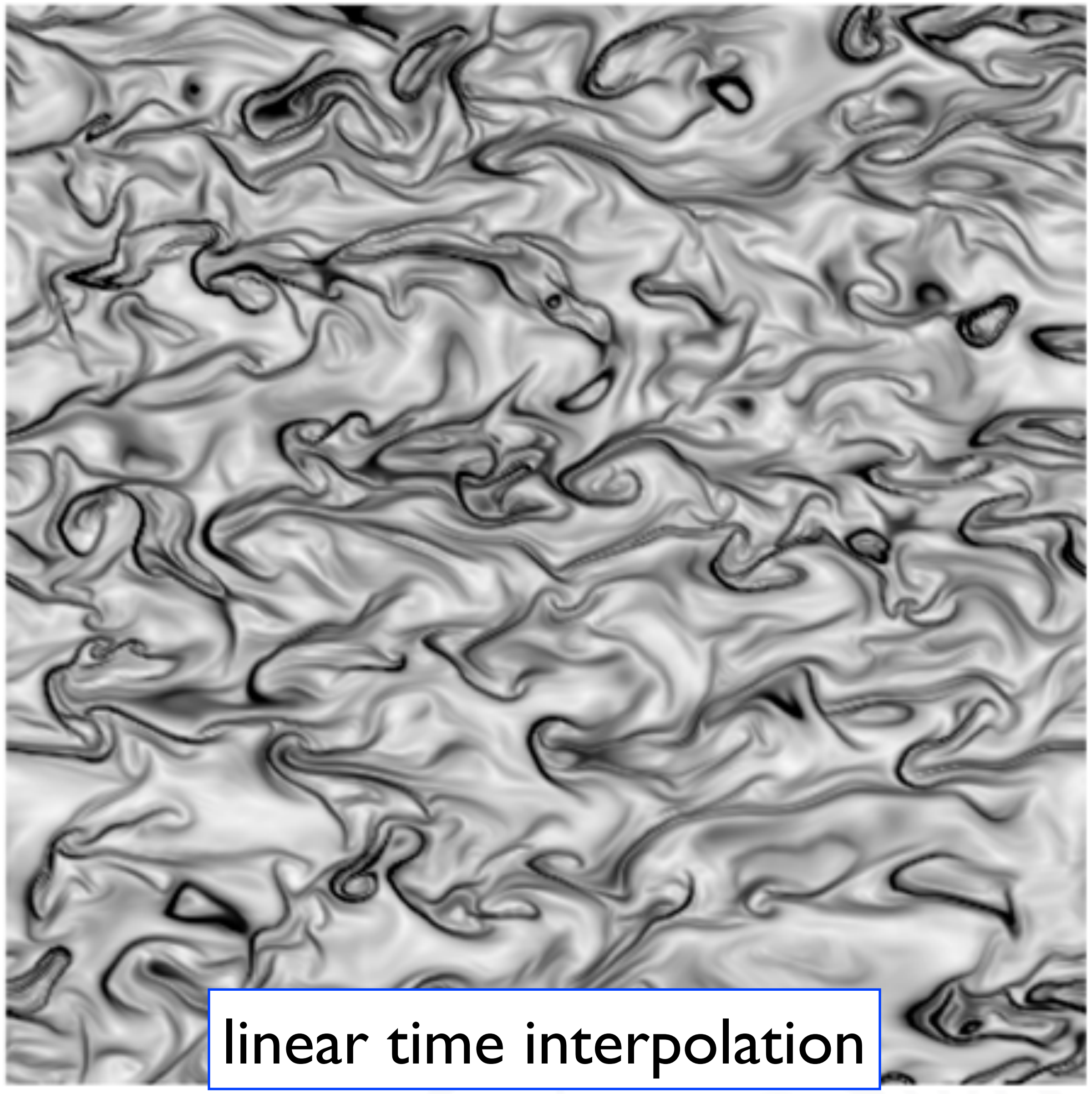
“3D” nFTLE

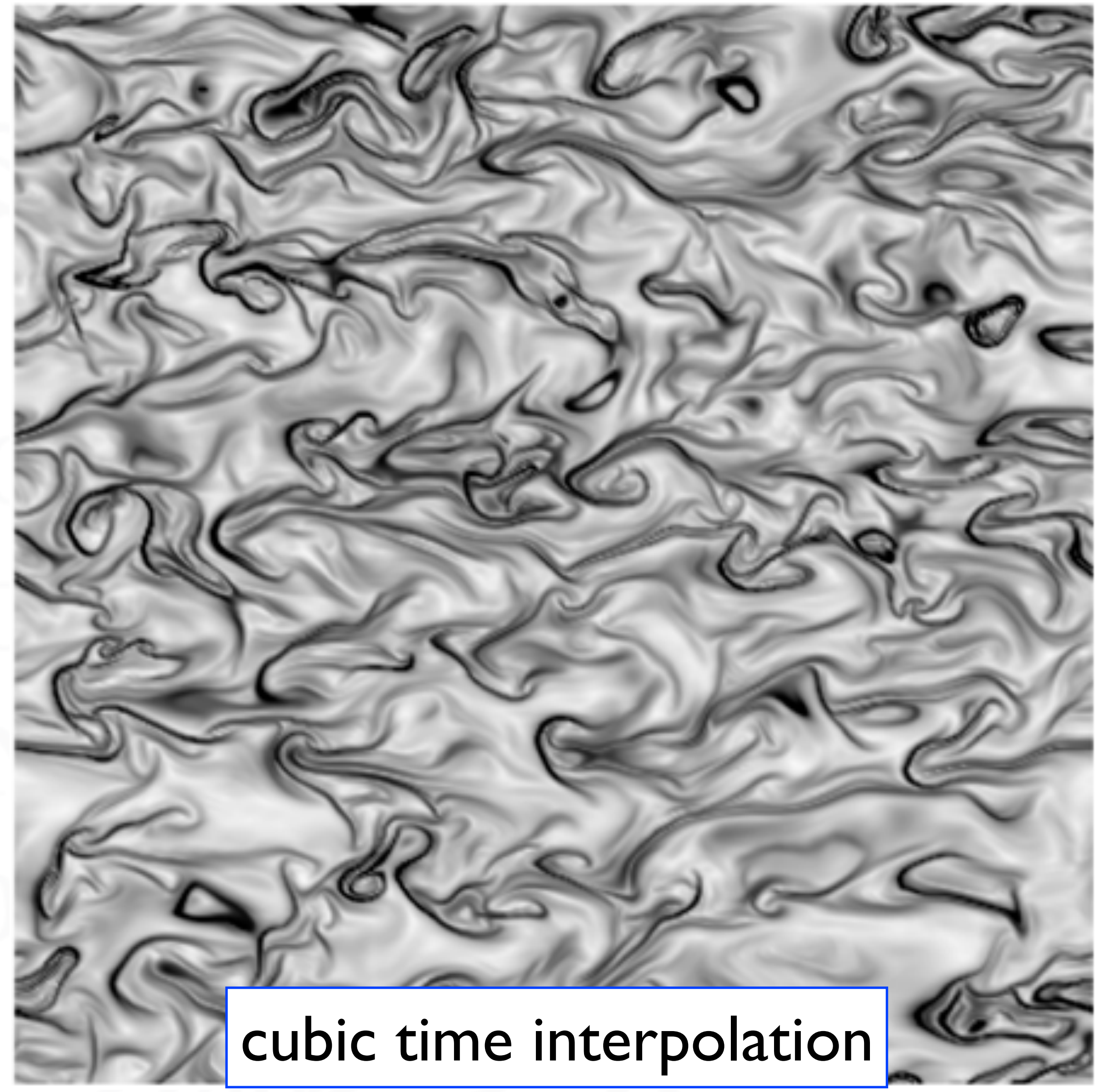


“2D” nFTLE

Rockwood et al., Chaos 2015 (submitted)

Time resolution issues



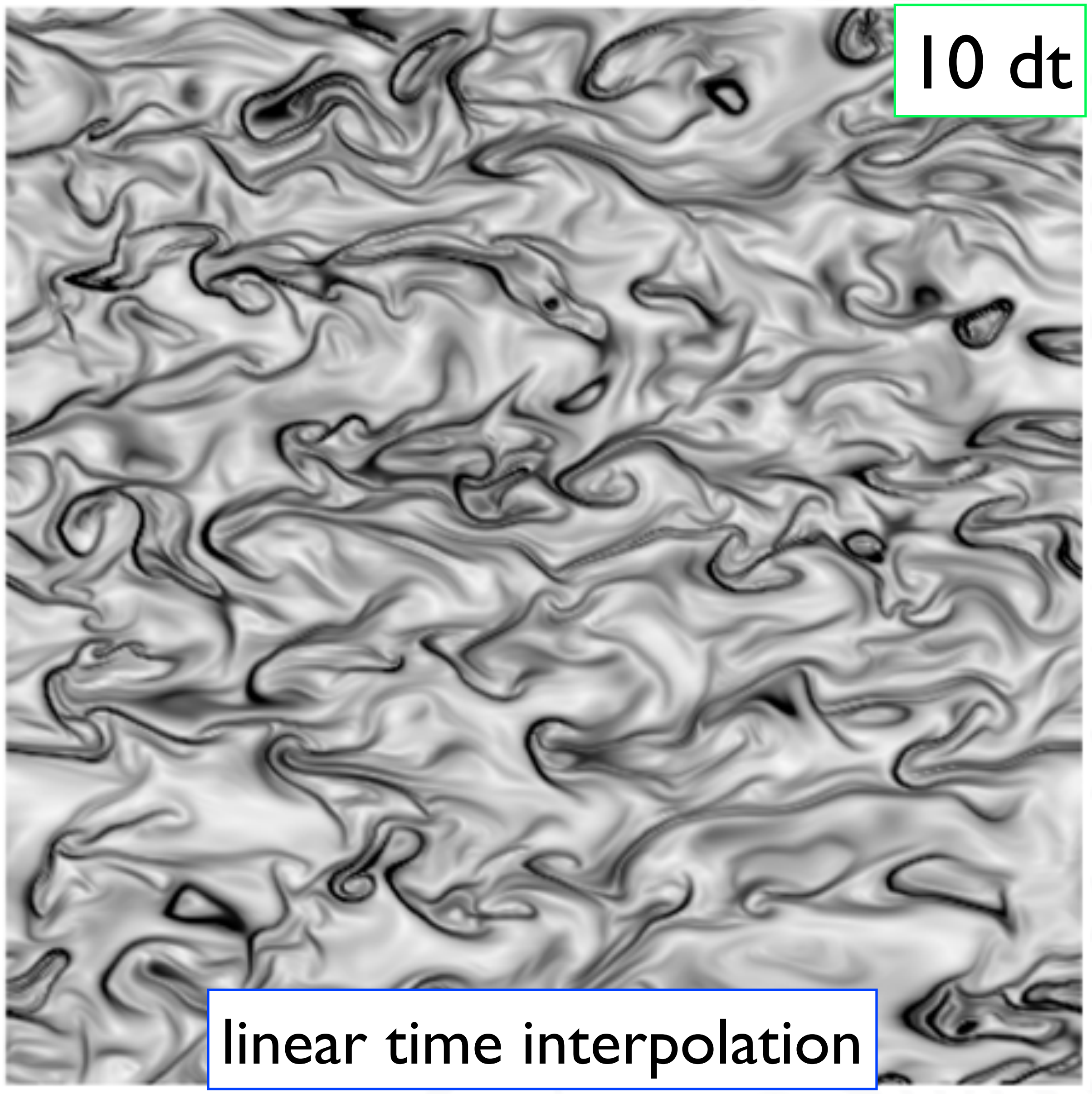


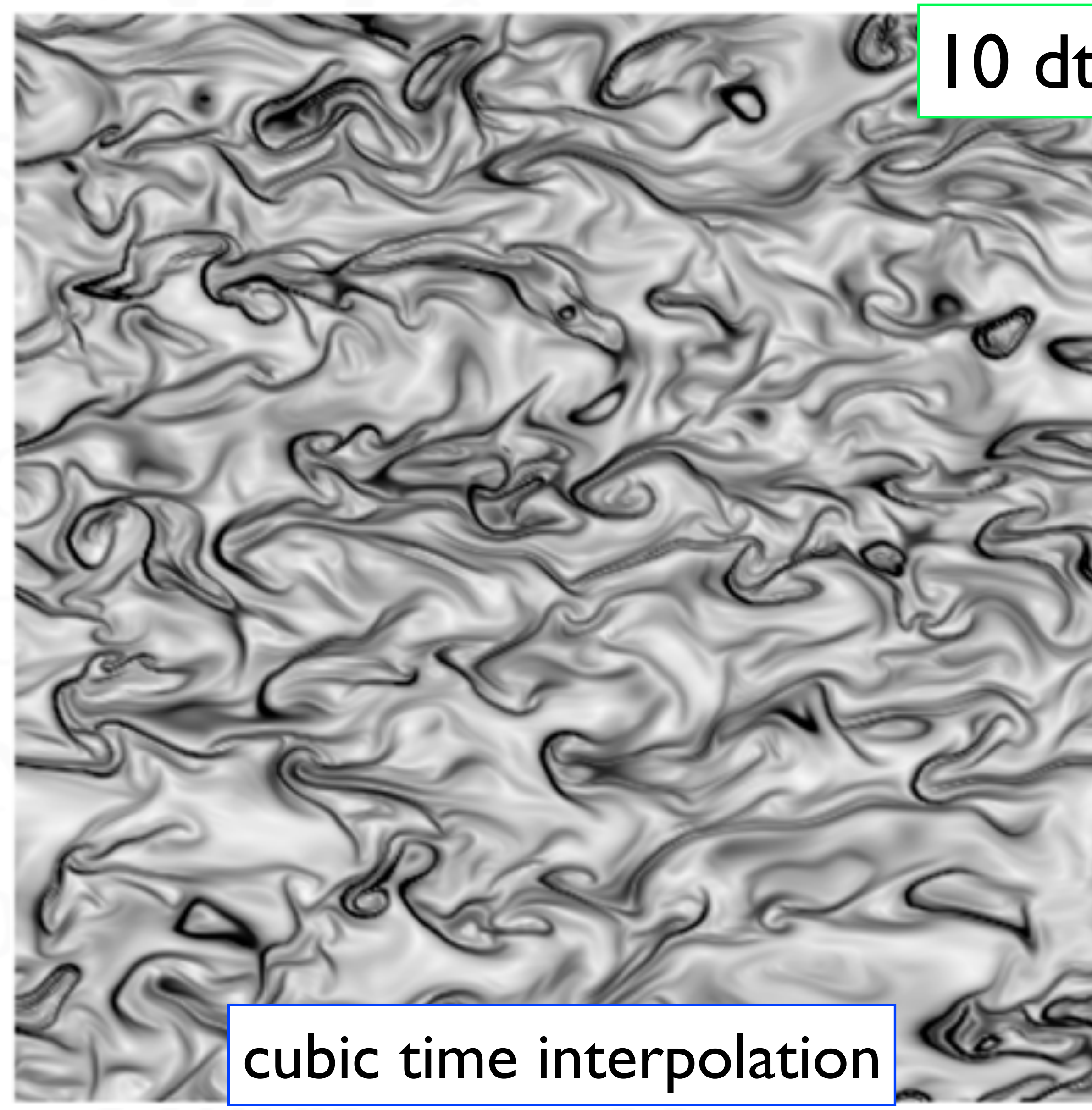
Time resolution issues

linear time interpolation

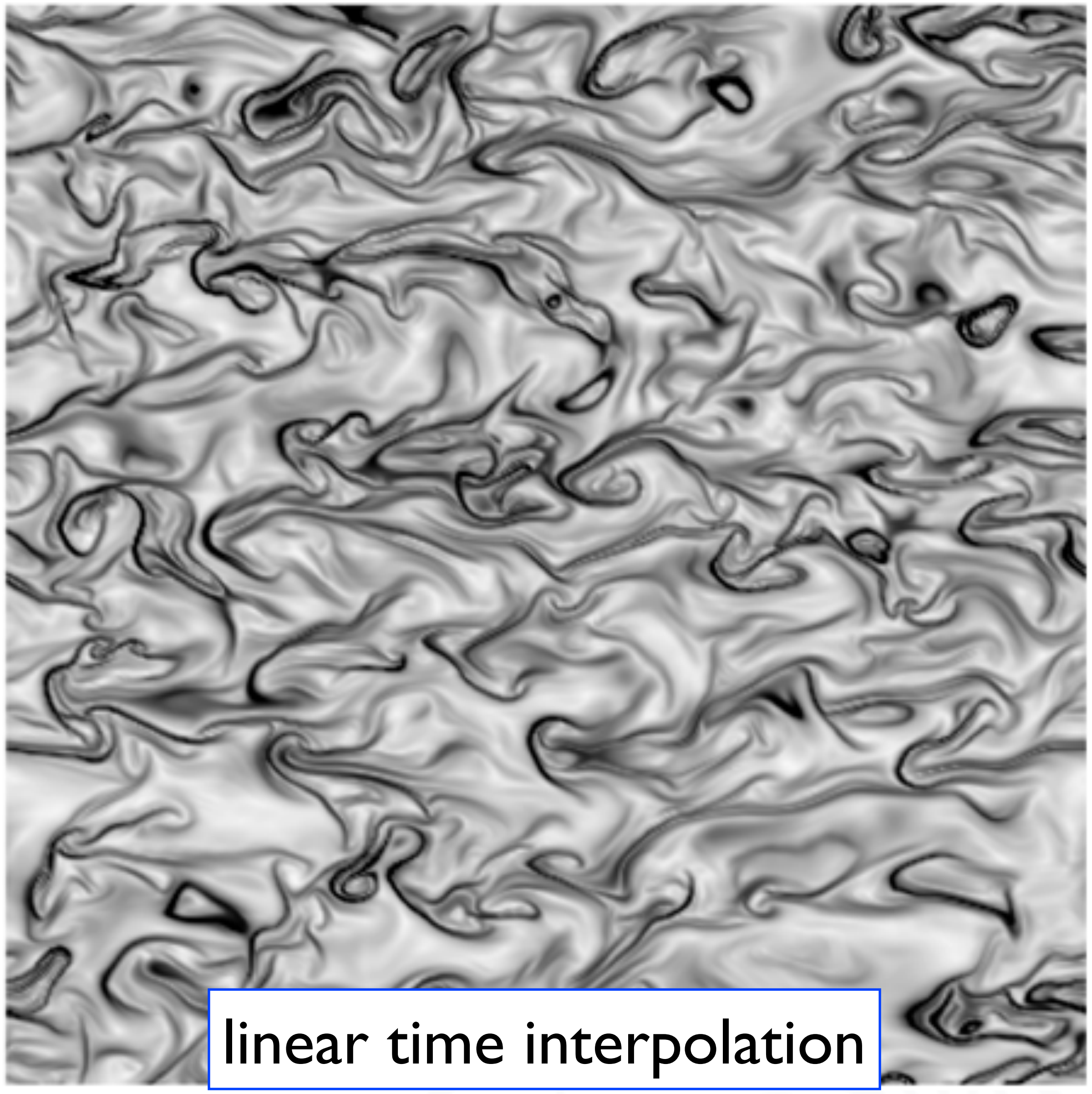
cubic time interpolation

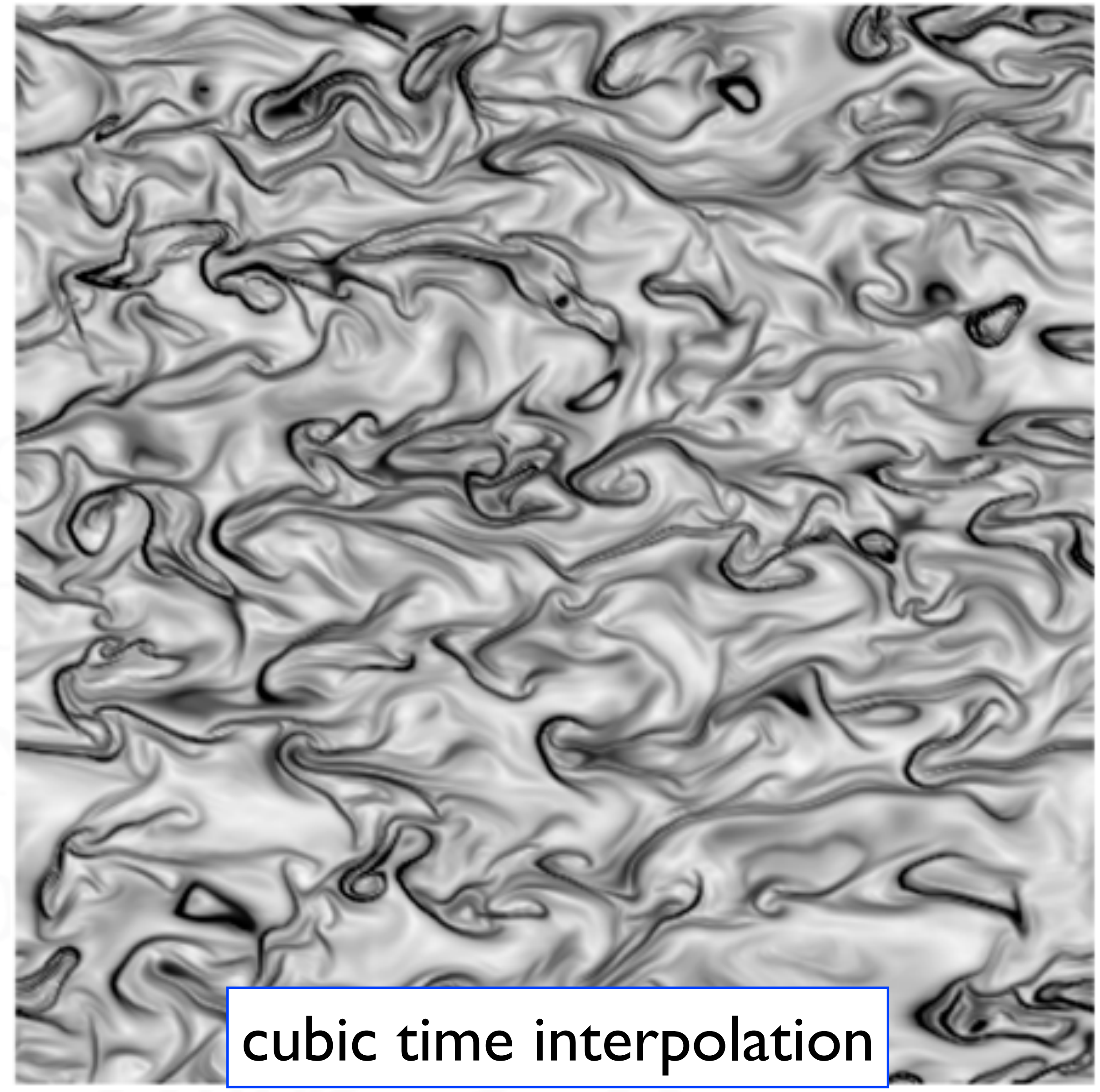
Time resolution issues





Time resolution issues





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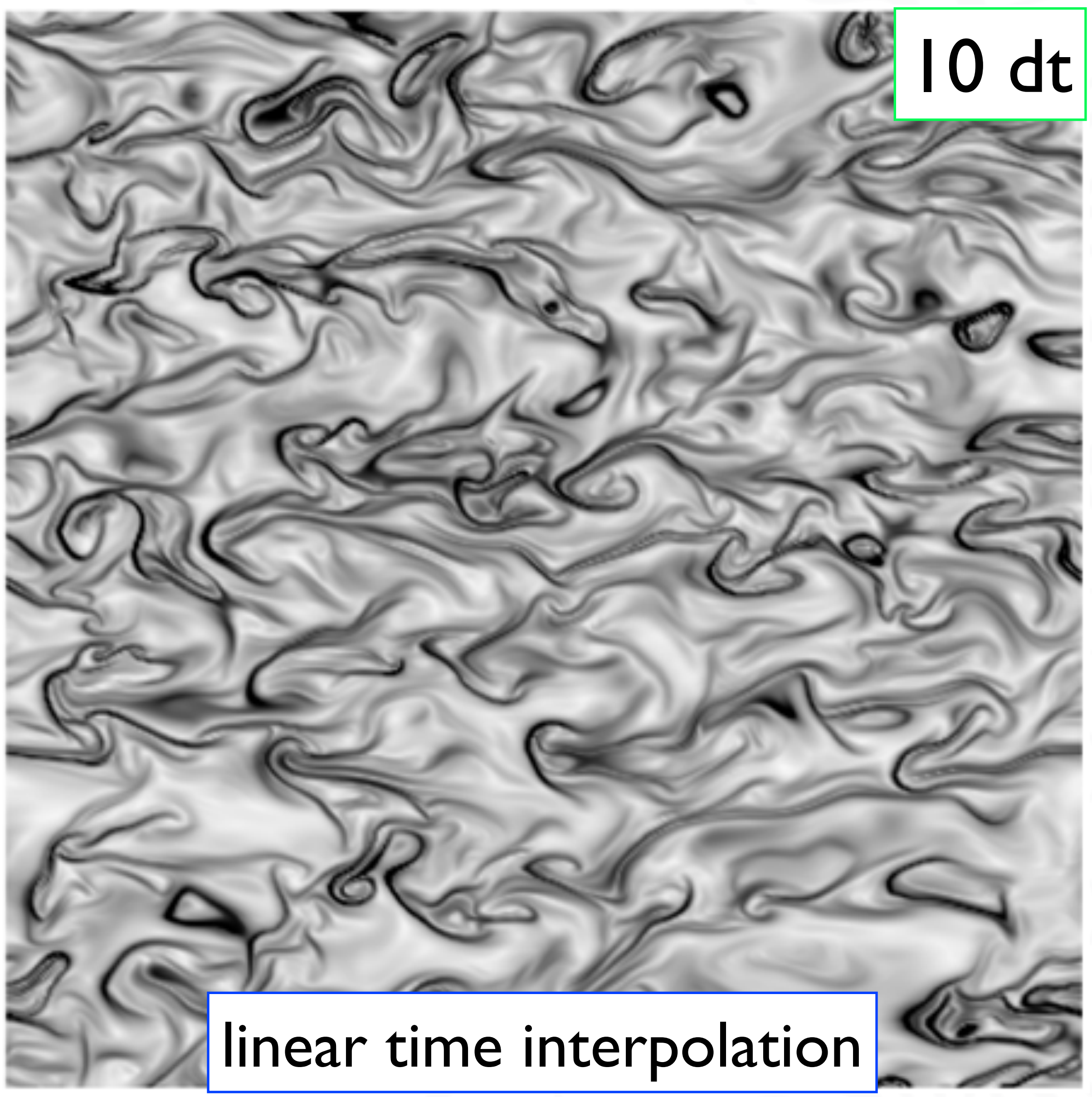
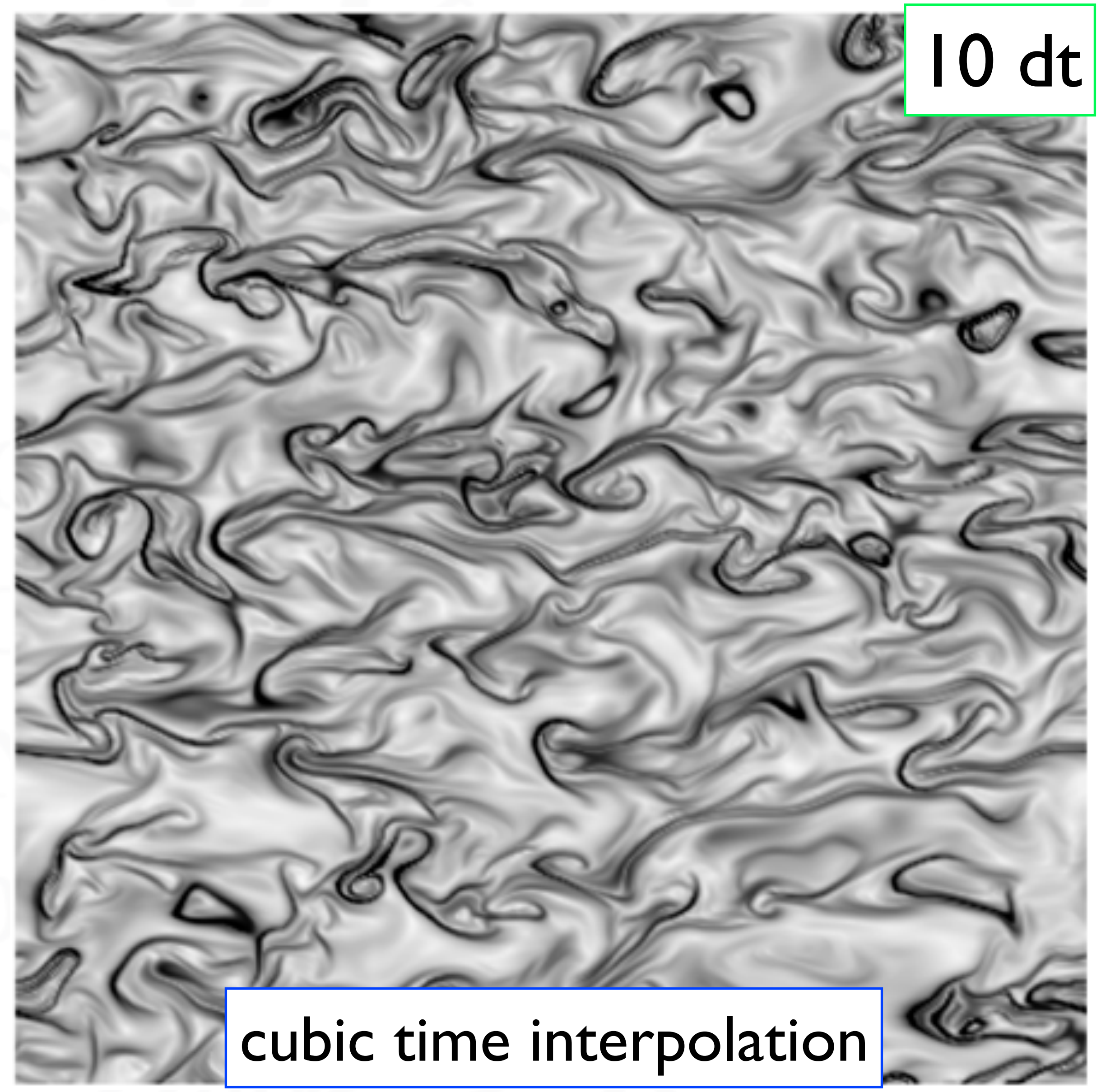
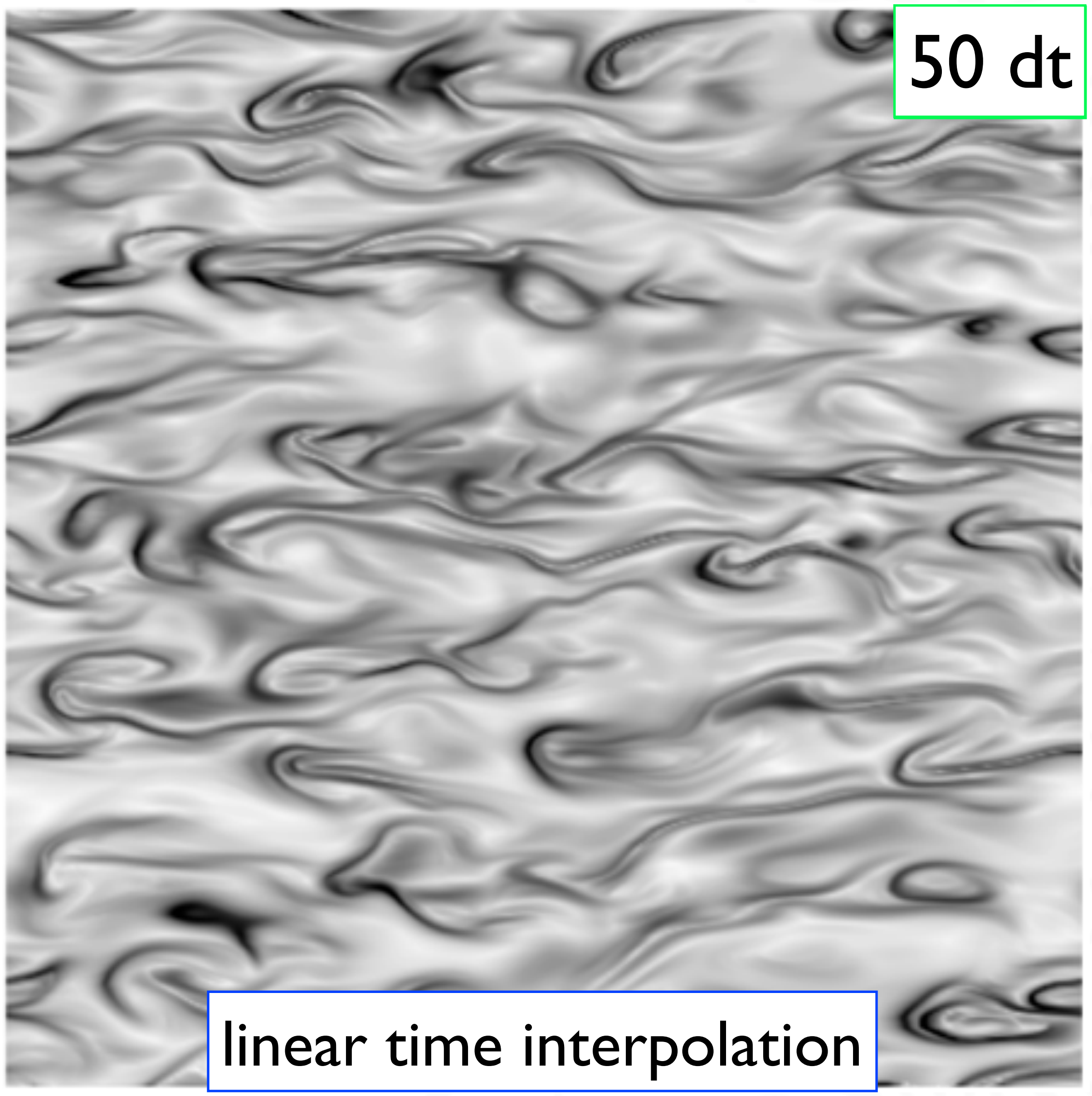
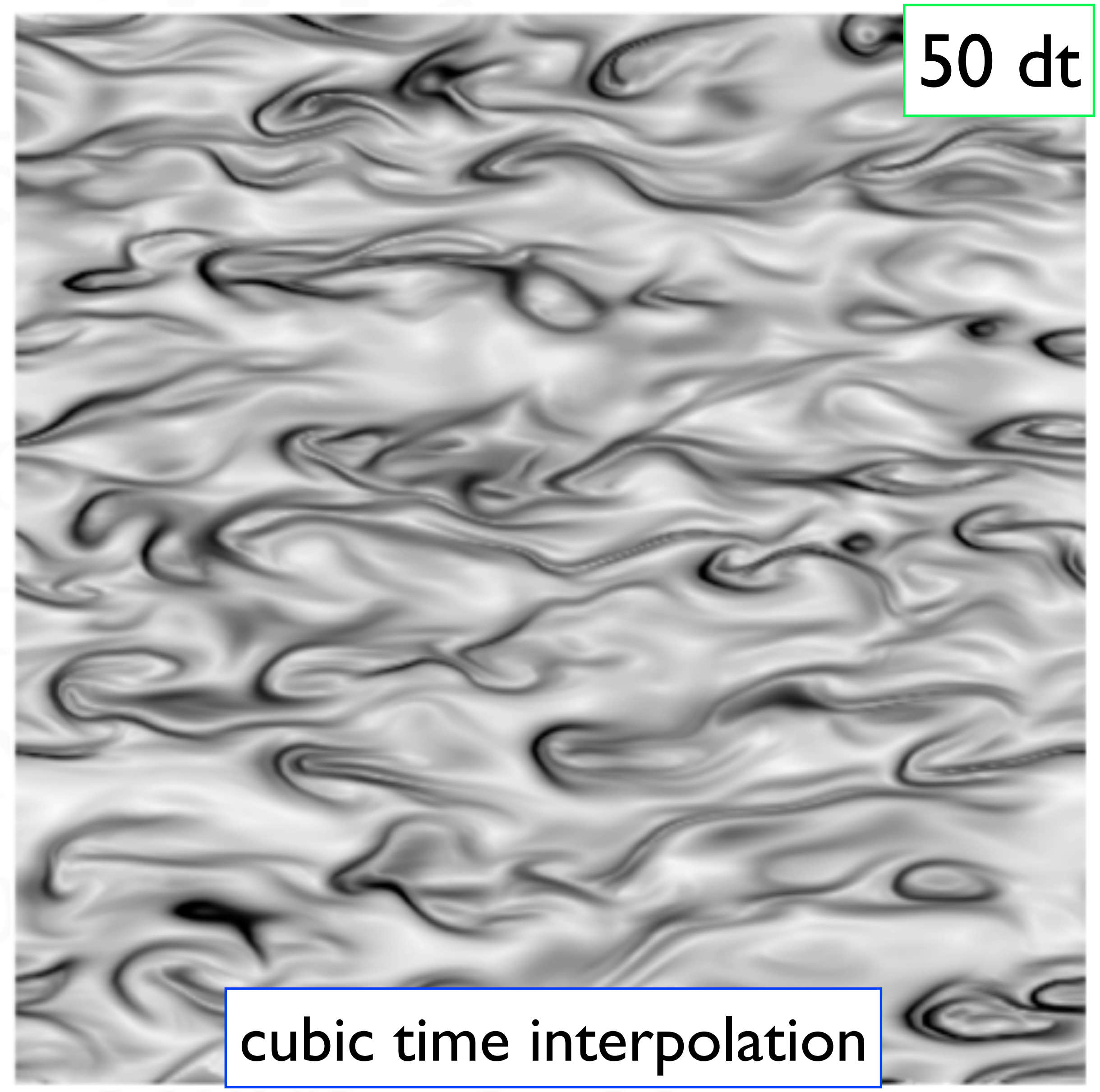




Time resolution issues



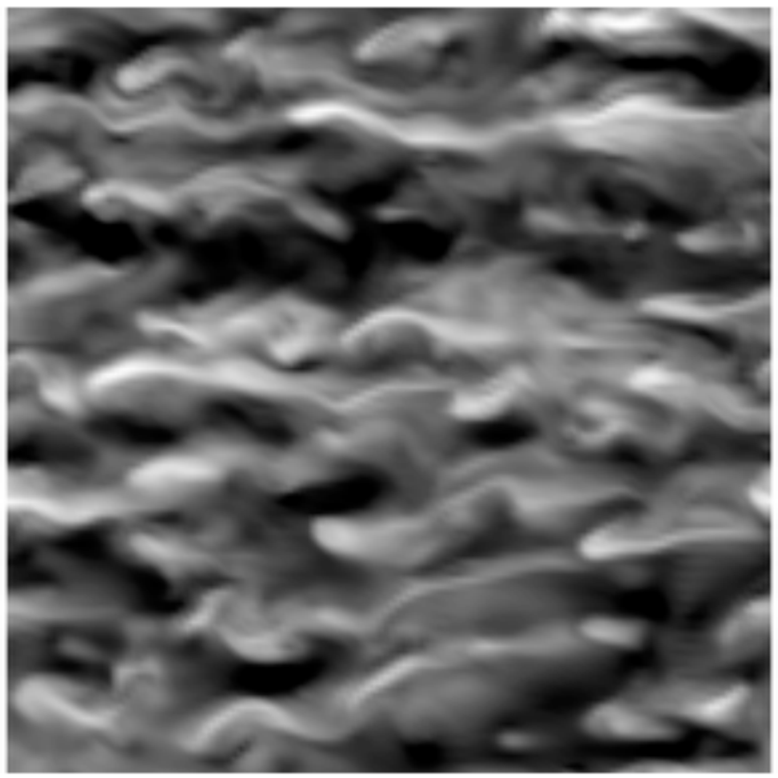


- Cubic splines can be impractical in full 3D space over the whole time of interest
- Is there a smarter way to recreate the intermediate velocity fields?

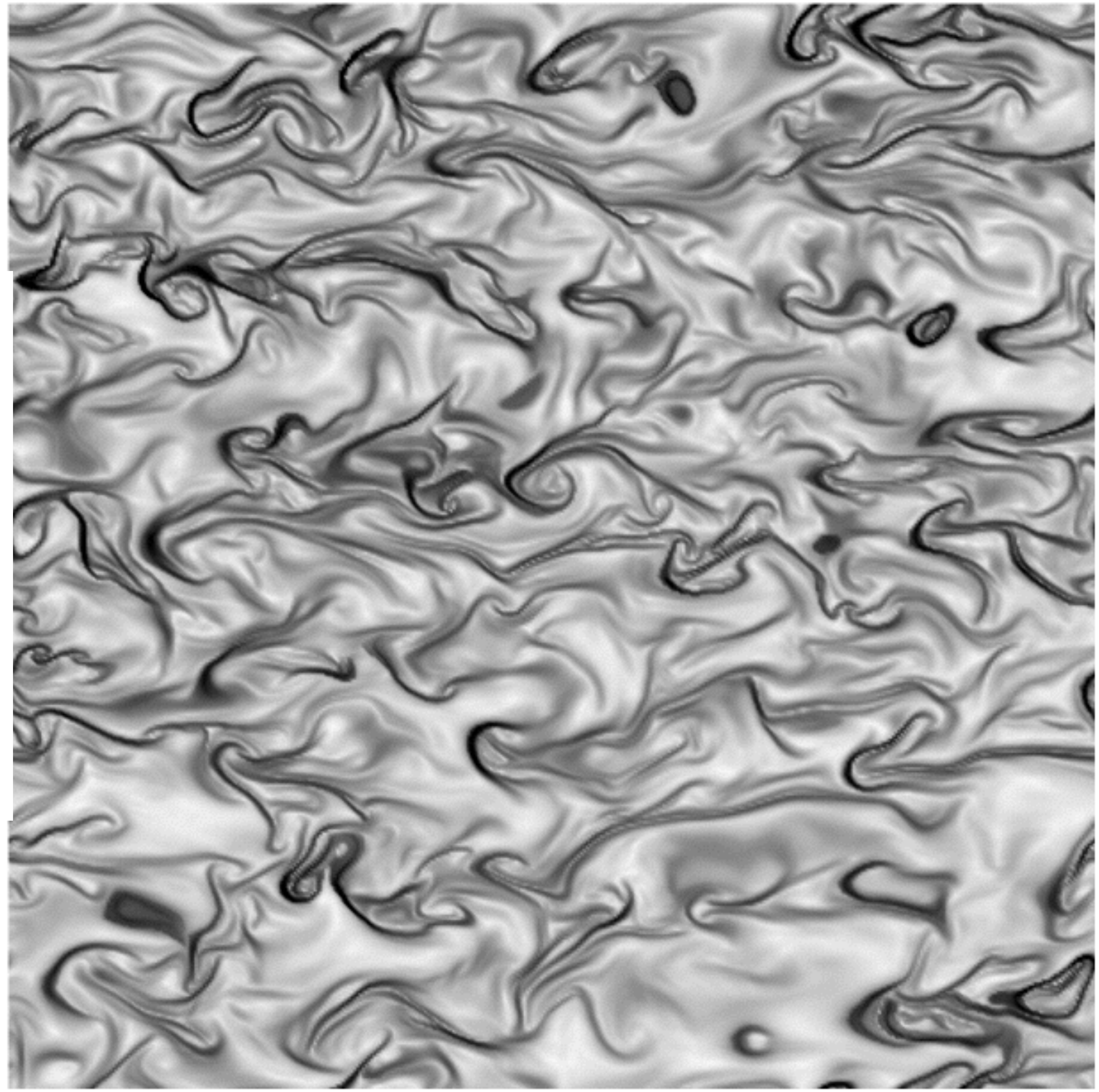
- Cubic splines can be impractical in full 3D space over the whole time of interest
- Is there a smarter way to recreate the intermediate velocity fields?

- For turbulent channel, use Taylor's hypothesis (frozen eddy) and shift velocity field by it's mean profile
  - *Advection contributed by turbulent circulations themselves is small and therefore the advection of a field of turbulence past a fixed point can be taken to be entirely due to the mean flow*
- Instead of interpolating in time, shift velocity field according to the mean velocity profile

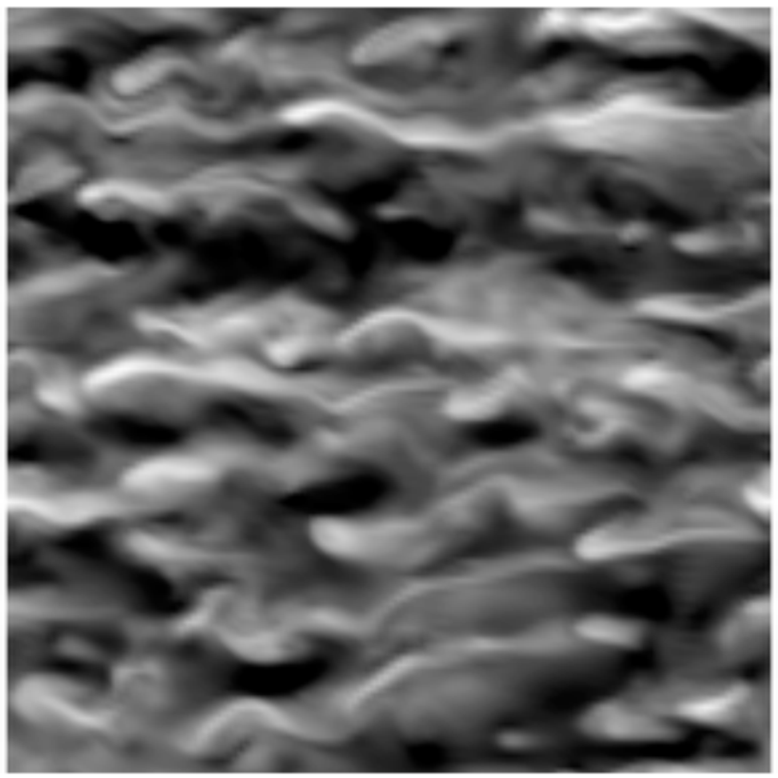
nFTLE using shifted fields



streamwise velocity



nFTLE using shifted fields



streamwise
velocity