

Practical concerns of using FTLE with experimental data

Melissa A. Green
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FTLE in vortex-dominated fluid flows

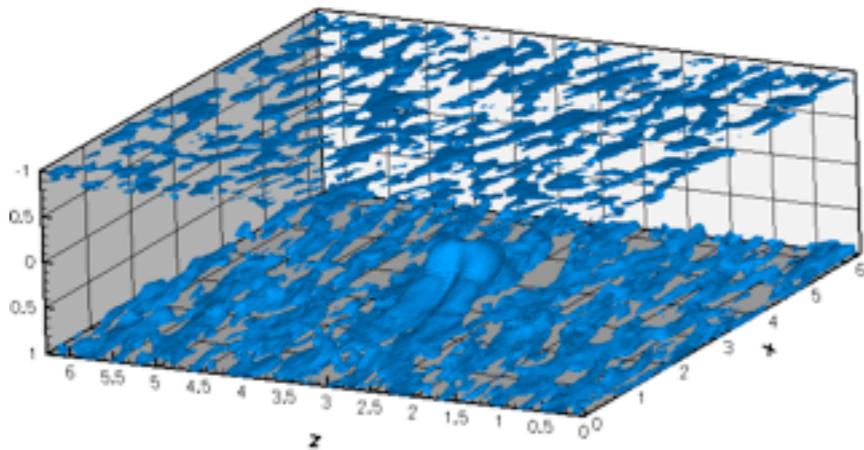
- Attracting and repelling lines (nLCS, pLCS) used to depict flow inside/outside vortices (vortex boundaries)
- Vortex generation, evolution, breakdown
- Correlate LCS with force, efficiency (drag, thrust, performance)

Vortex “breaking” and generation

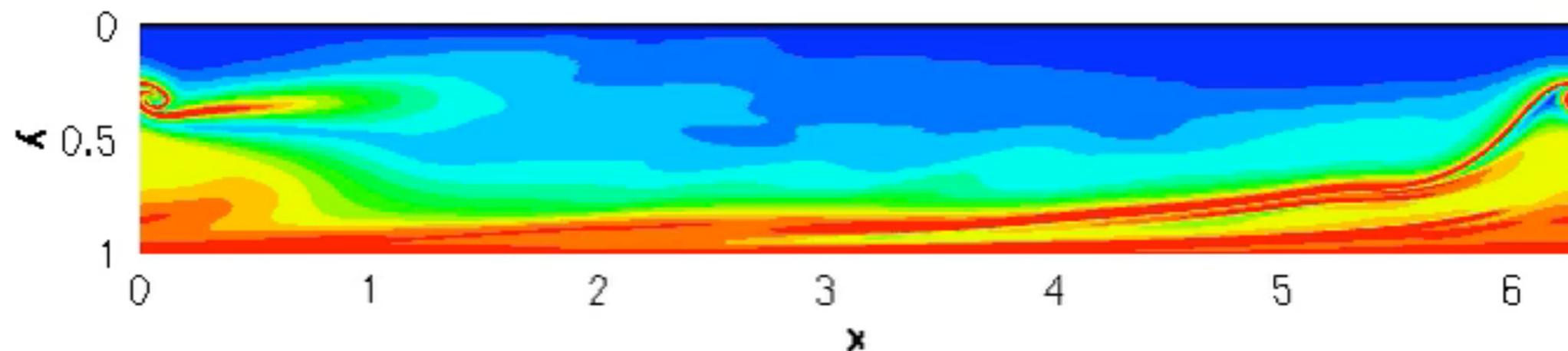


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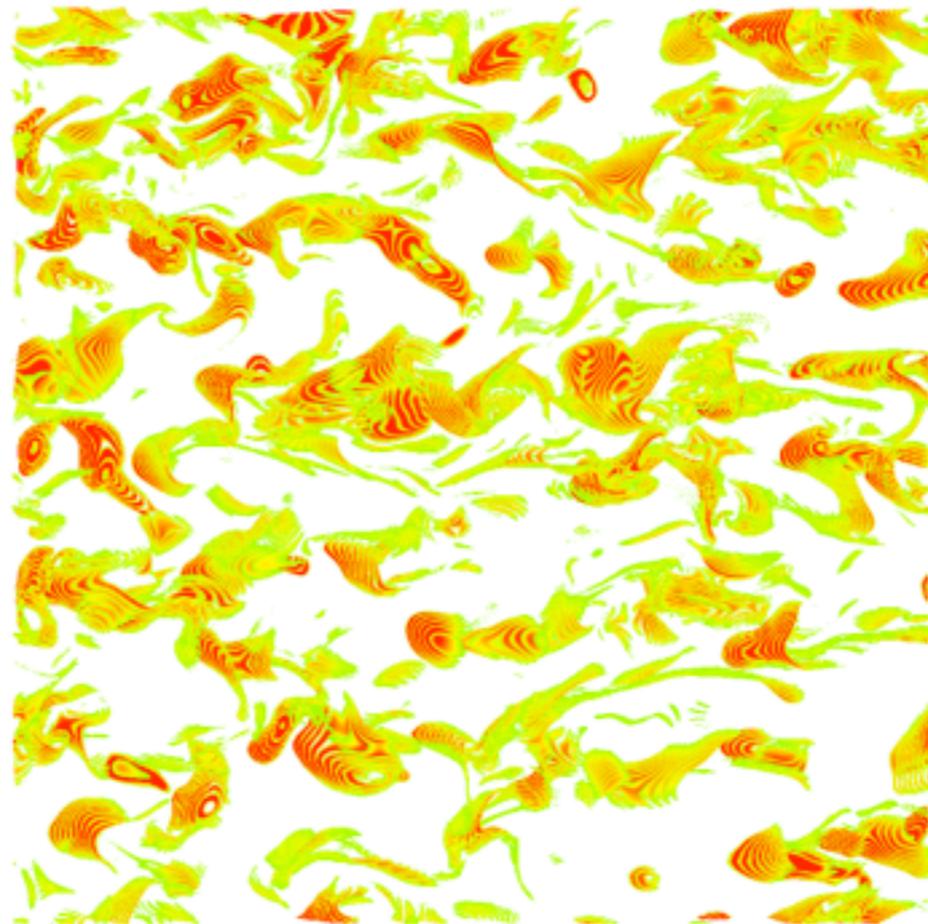


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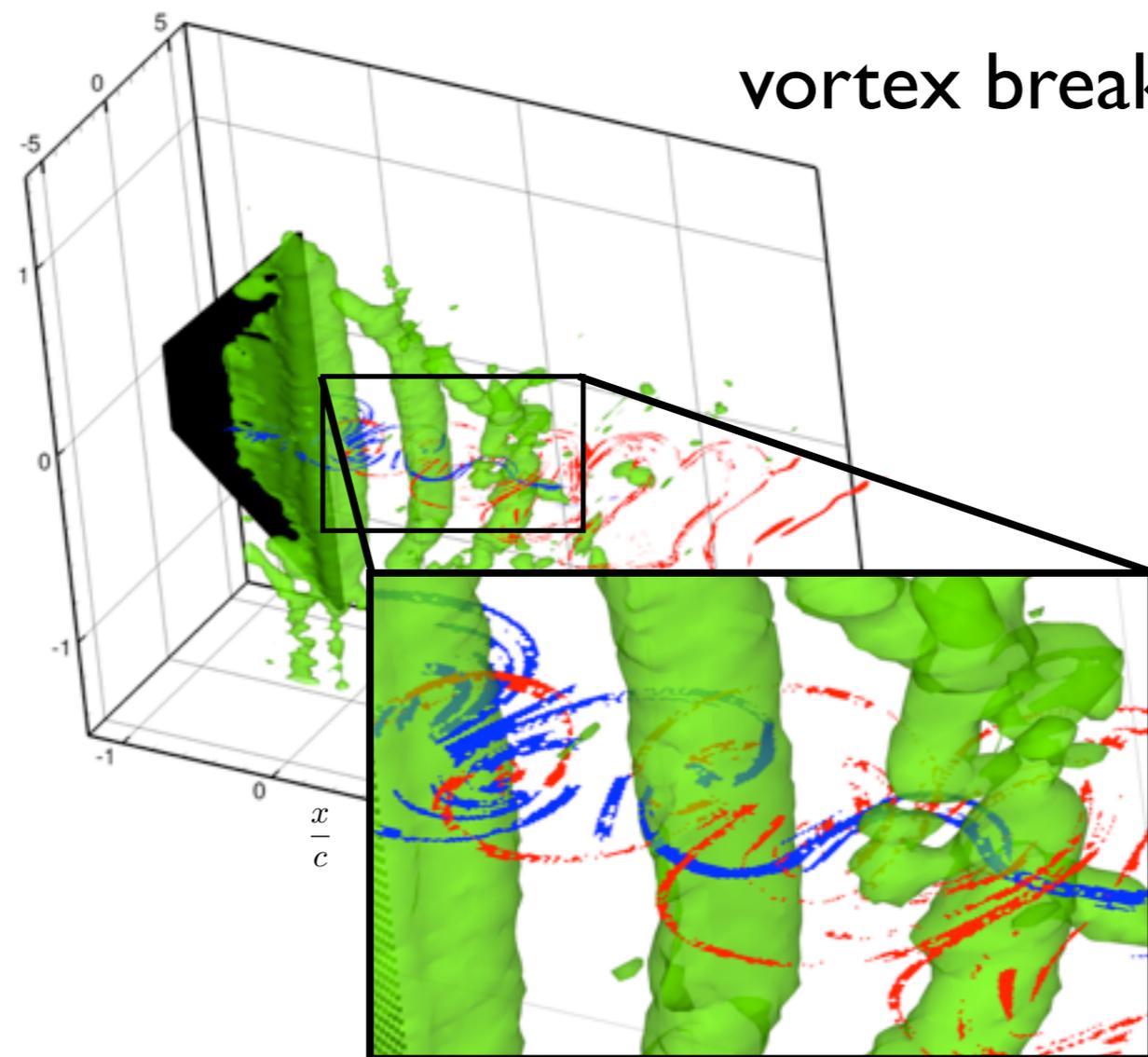


structure tracking, statistics



FTLE in vortex-dominated fluid flows

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vortex breakdown, splitting wake

FTLE in vortex-dominated fluid flows

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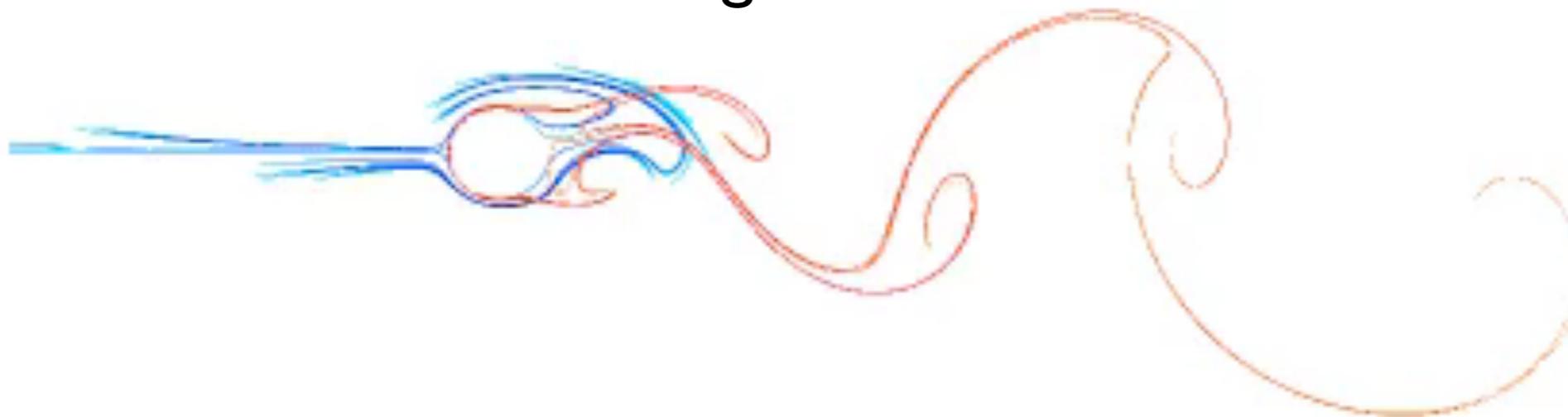
vortex creation, shedding



FTLE in vortex-dominated fluid flows

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vortex creation, shedding



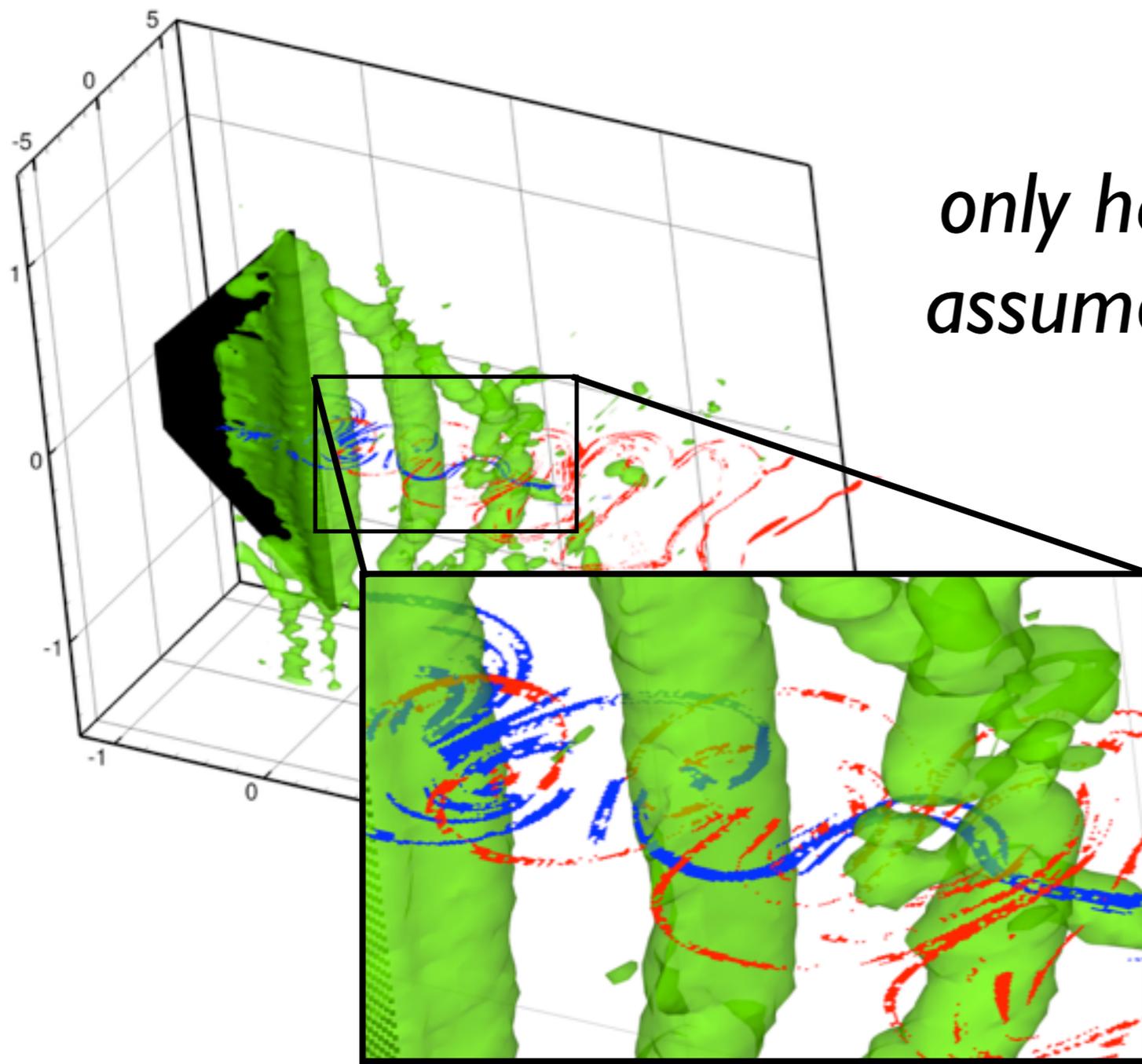
we love FTLE because it looks like flow visualization!



Practical matters

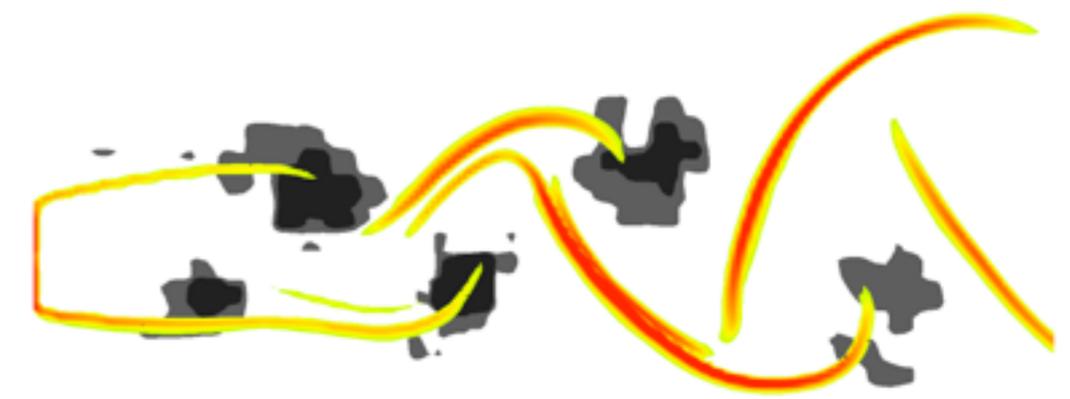
- Flow map calculations (particle integration)
- Easy to implement with **numerical** data - full resolution available in space and time
- Potentially useful with **experimental** data
 - More difficult to get time resolution with hardware, especially in faster flows with multiple length/time scales
 - Most experimental velocity fields from Particle Image Velocimetry (PIV)
 - Planar, 2-component: most common (and cheapest)
 - Planar, 3-component: stereoscopic PIV, not as cheap, becoming more common
 - Volume, 3-component: tomographic, holographic, \$\$\$, not as great with time-resolution





*only had 2-component PIV,
assumed small core flow at
midspan...*

$\frac{x}{c}$



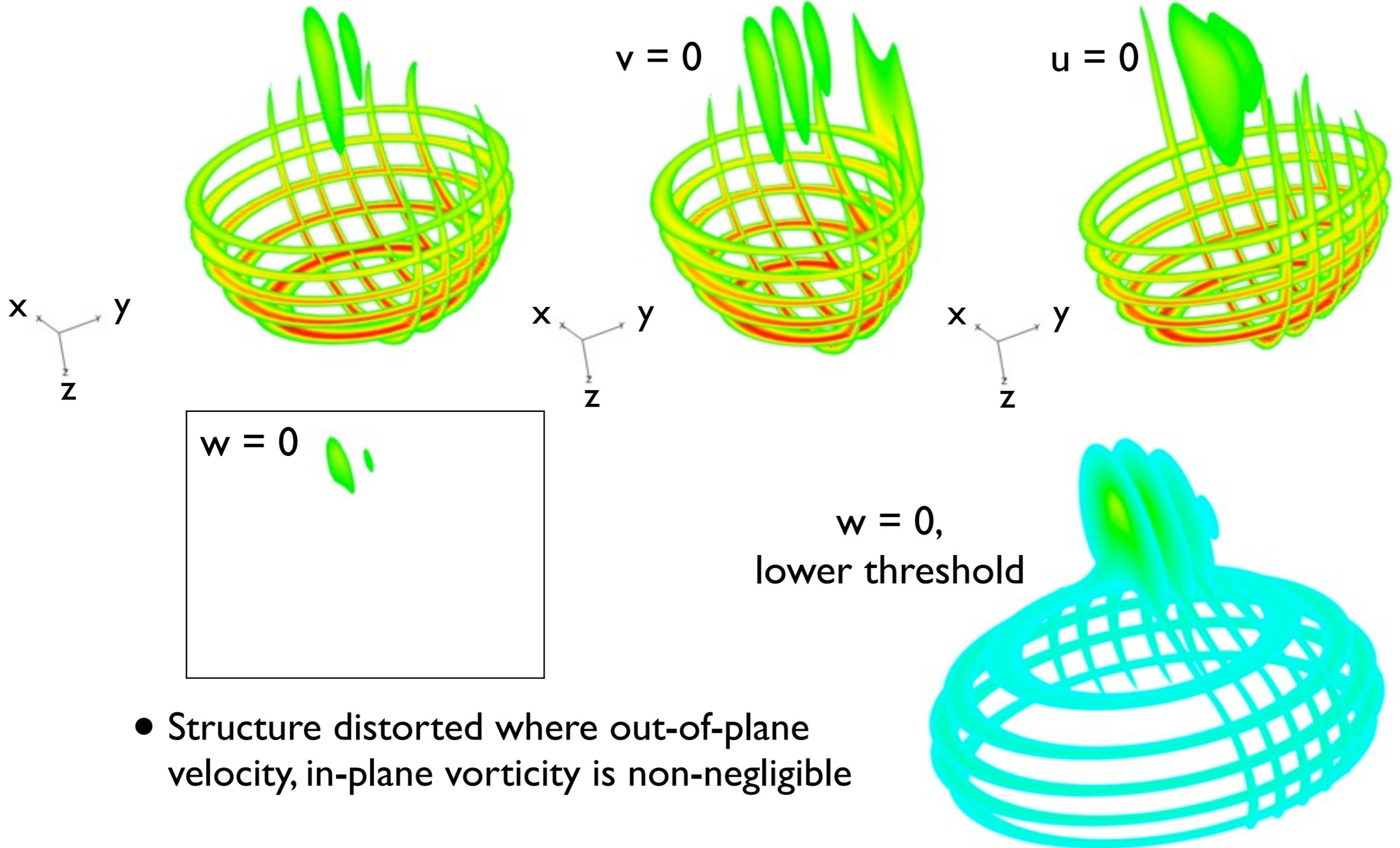
*PIV system has time resolution of
4 Hz for cylinder experiments*



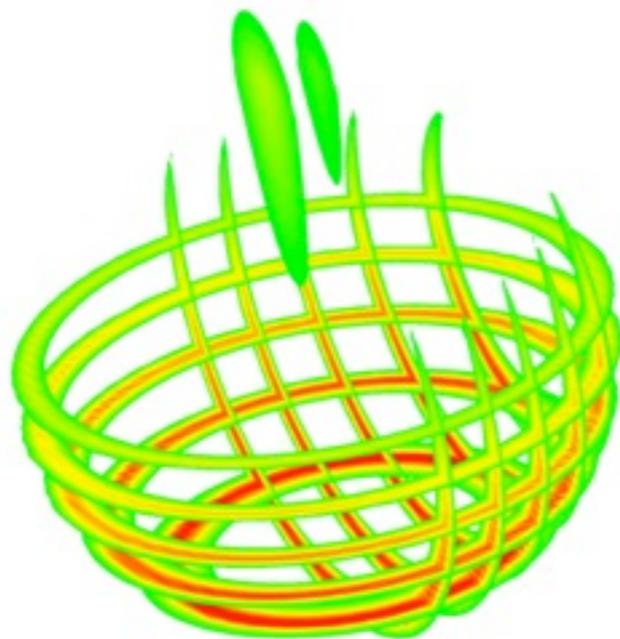
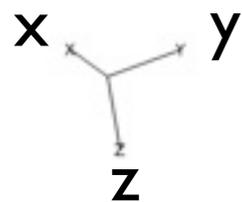
- “Dangers” of naive approaches
- 2D data of a 3D flow field
 - Hill’s spherical vortex
 - Turbulent channel simulation
- Degrading time resolution
 - Turbulent channel simulation
- Lots of pretty pictures of bad results



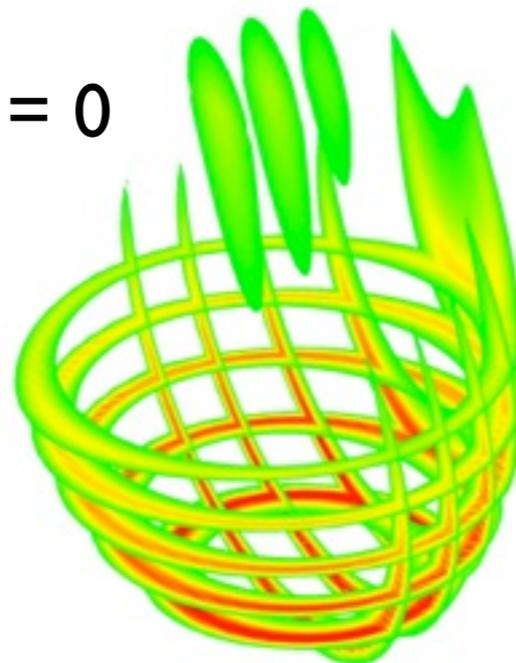
2D/3D - Hill's spherical vortex



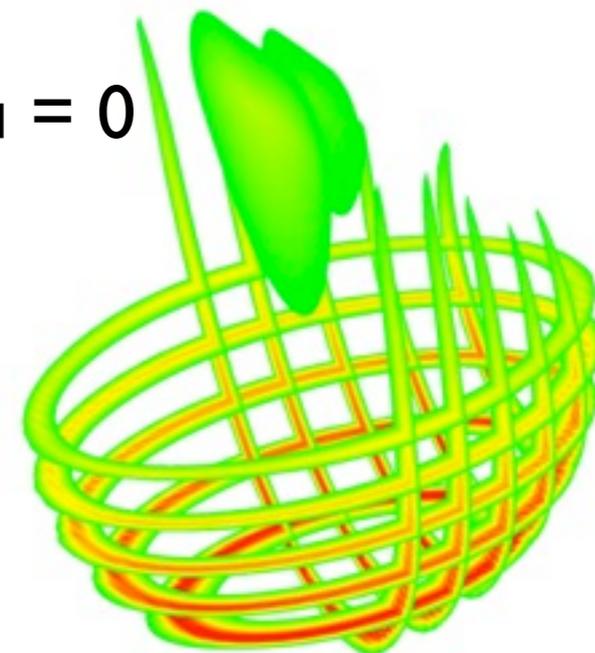
- Structure distorted where out-of-plane velocity, in-plane vorticity is non-negligible
- In some cases, structures missed almost altogether



$v = 0$



$u = 0$



inside vortex

$$u = \alpha z x / 5$$

$$v = \alpha z y / 5$$

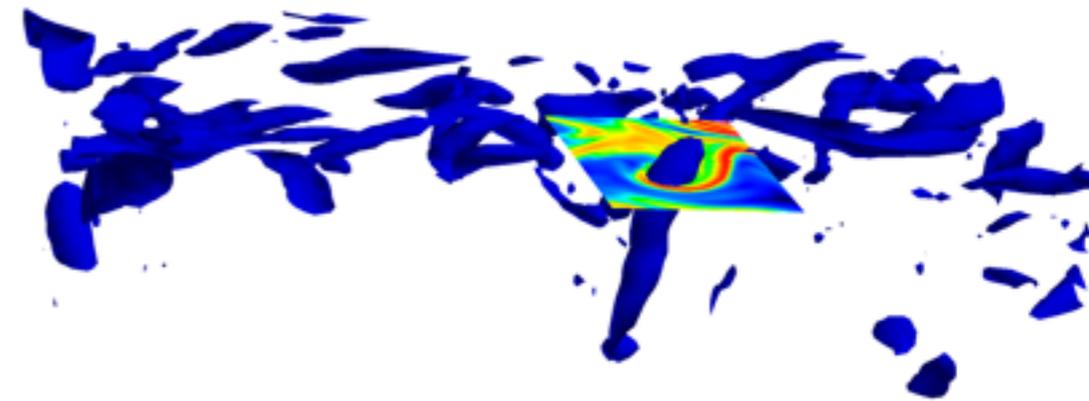
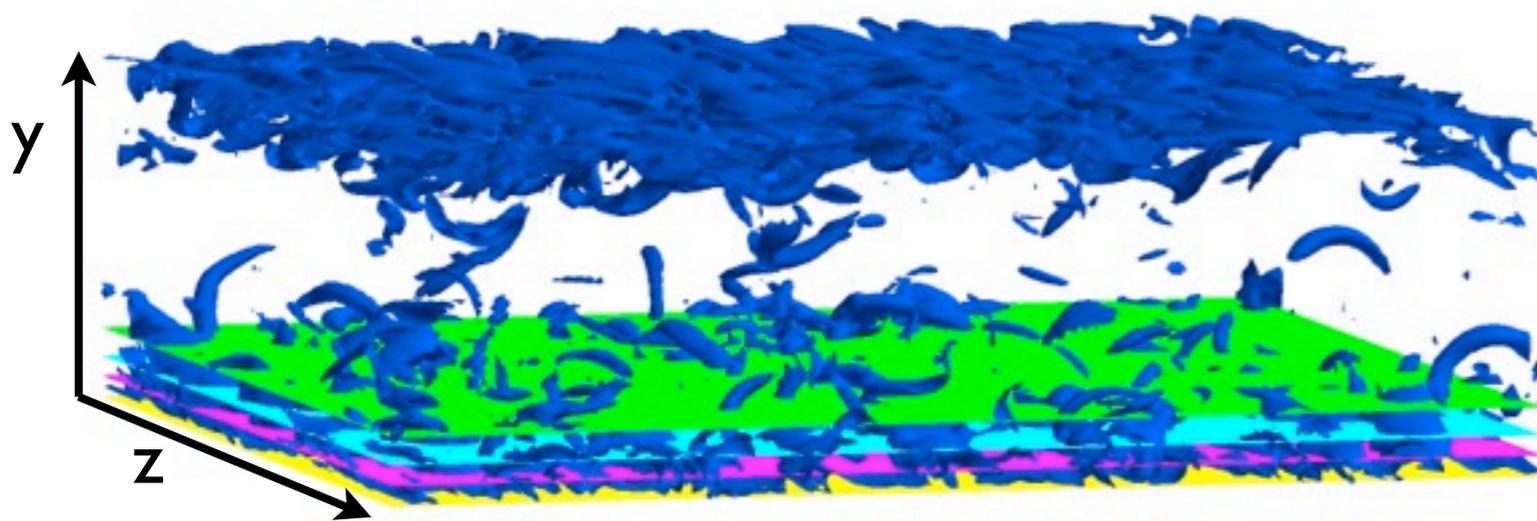
$$w = \alpha / 5 (1 - z^2 - 2x^2 - 2y^2)$$

- For $v=0$, should see no difference in xz plane ($v=0$ by equations anyway)
- Largest expected v at high y, z - should see effects in yz plane
- Divergence everywhere just function of z (not helpful)
- In-plane vorticity also large where there are issues
 - For $v=0$, $\omega_x = dw/dy - dv/dz = -\alpha y$, $\omega_z = 0$
 - For $u=0$, $\omega_y = du/dz - dw/dx = \alpha x$, $\omega_z = 0$



Dimensionality issues - turbulent channel DNS

- DNS of a turbulent channel ($Re_\tau=180$, same as Green et al. 2007, from Kim et al. 1987)
- Calculate nFTLE in 2D planes
 - Use full volume of three-component data - let particle trajectories fly
 - Use only in-plane velocities, assume $v=0$ (simulated 2D PIV)



Rockwood & Green, APS 2012

$y^+=11$

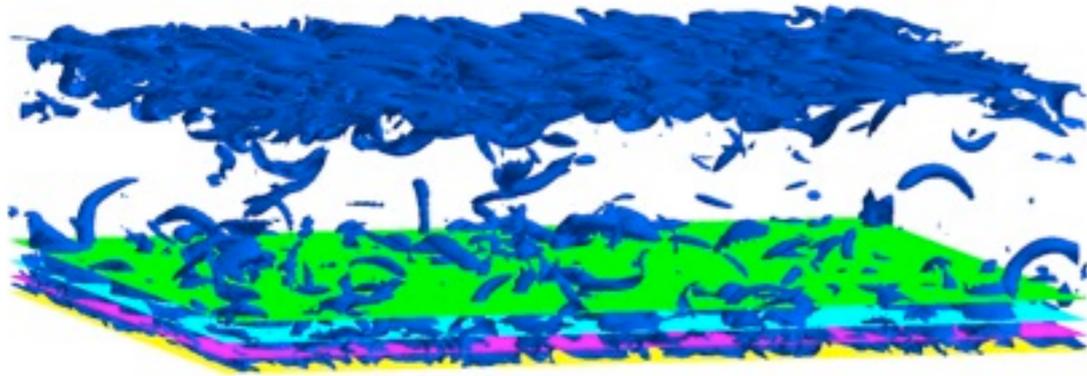
$y^+=30$

$y^+=50$

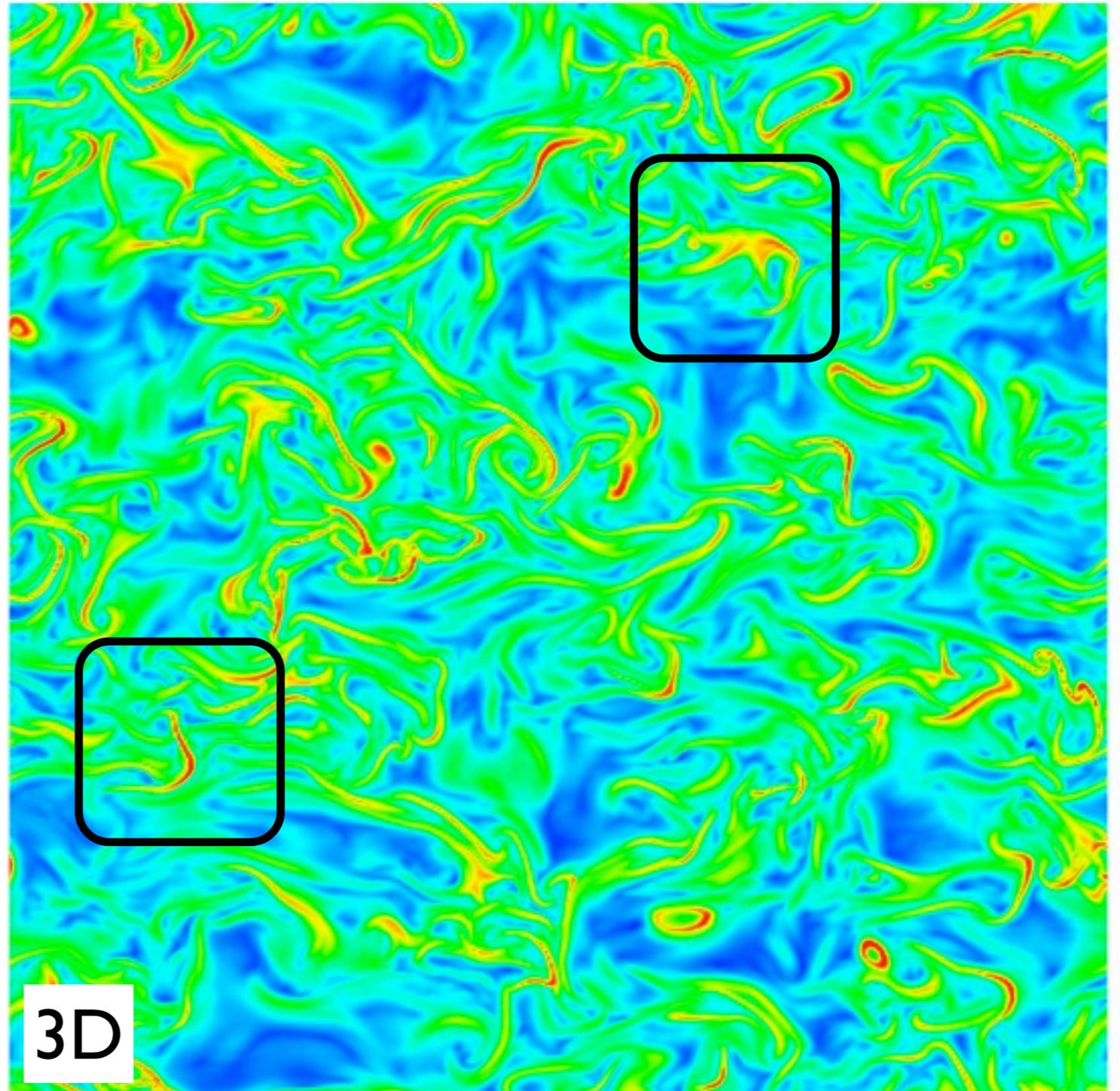
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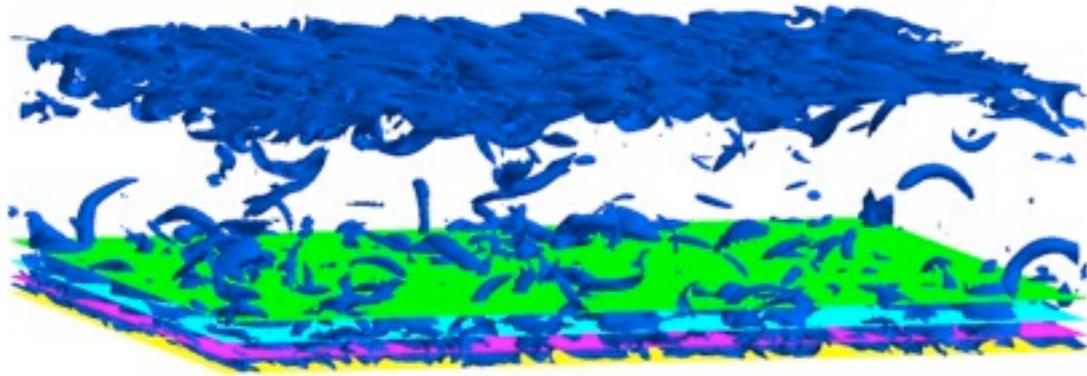


- Clear loss of detail in 2D nFTLE
- Not just a matter of filtering out smaller scales, important qualitative differences

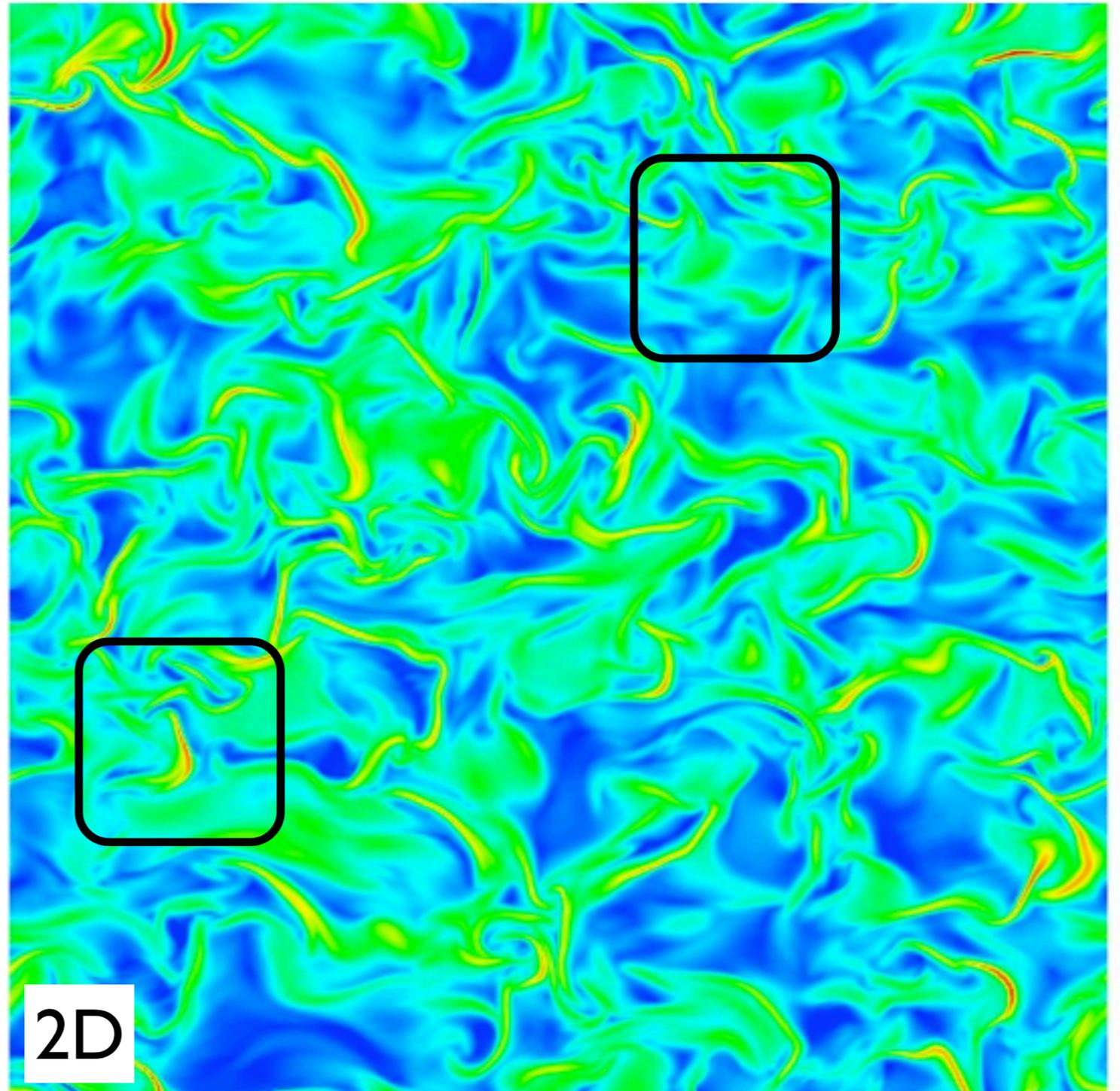


3D

$$y^+ = 76$$

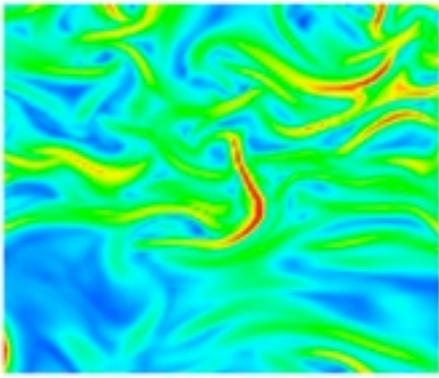


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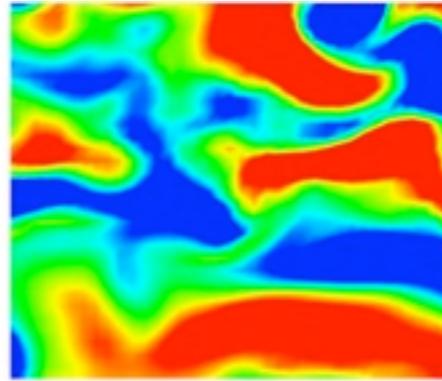
2D

3D

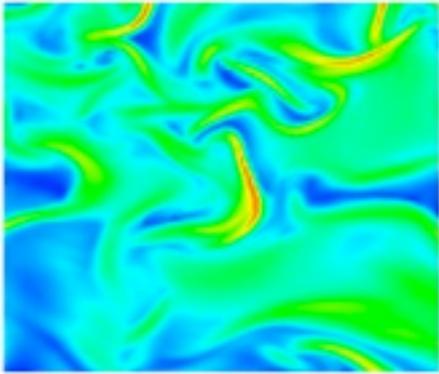


“Good”
match

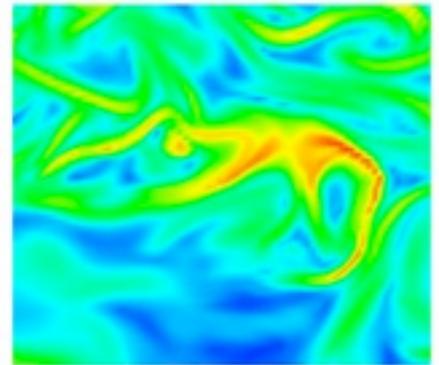
v



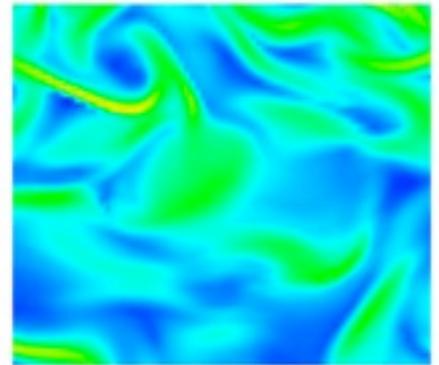
2D



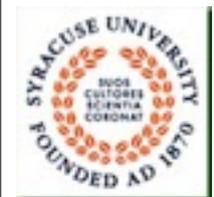
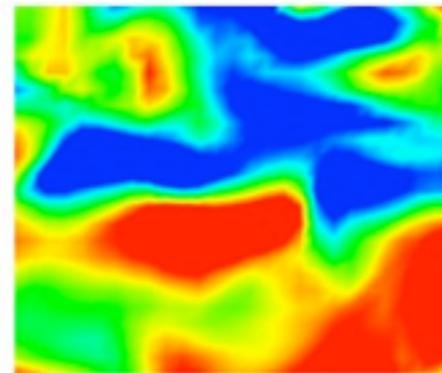
3D



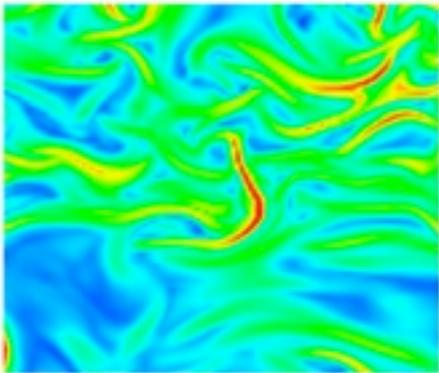
2D



Not-so-
good

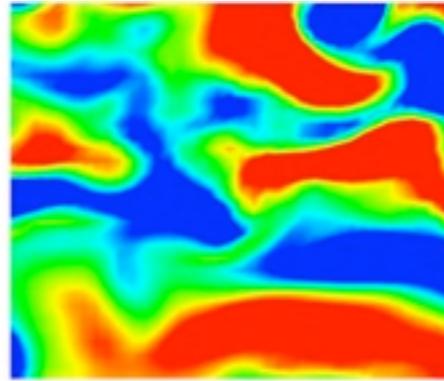


3D

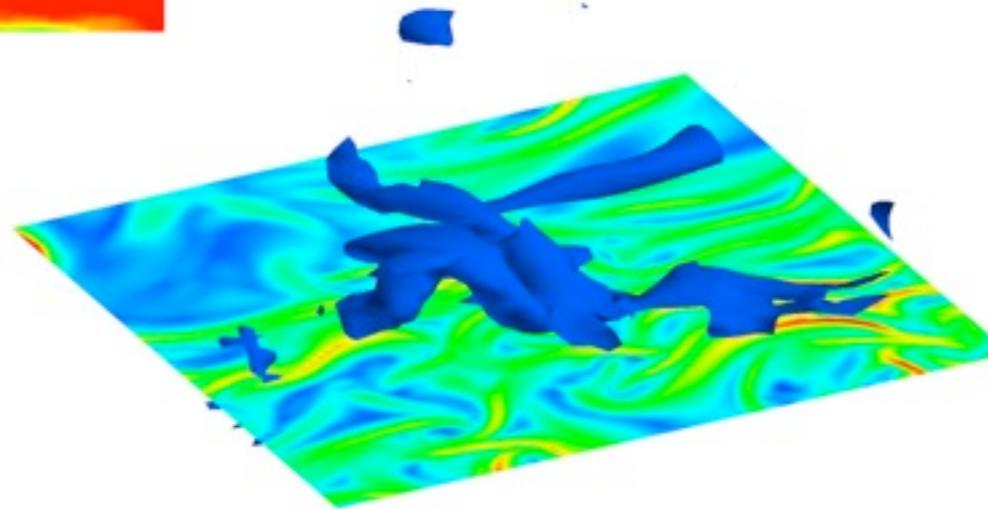
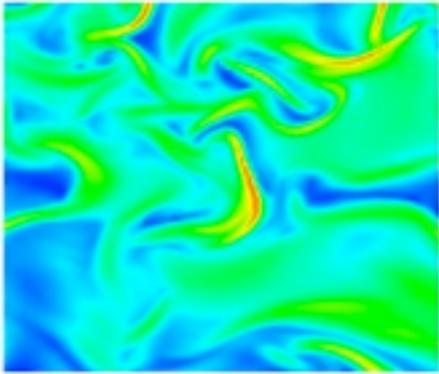


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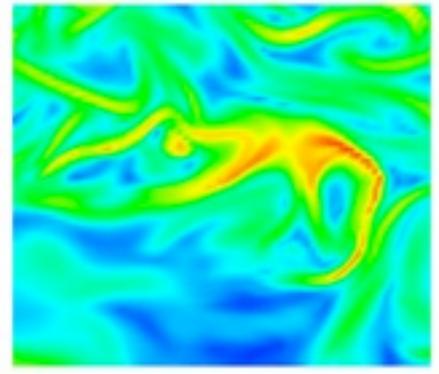
V



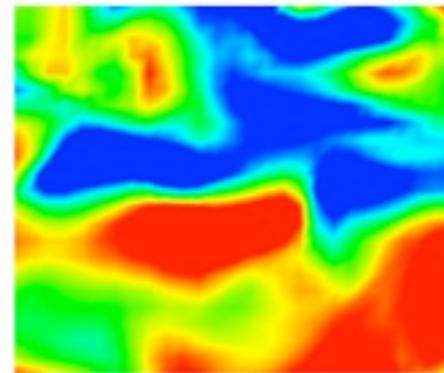
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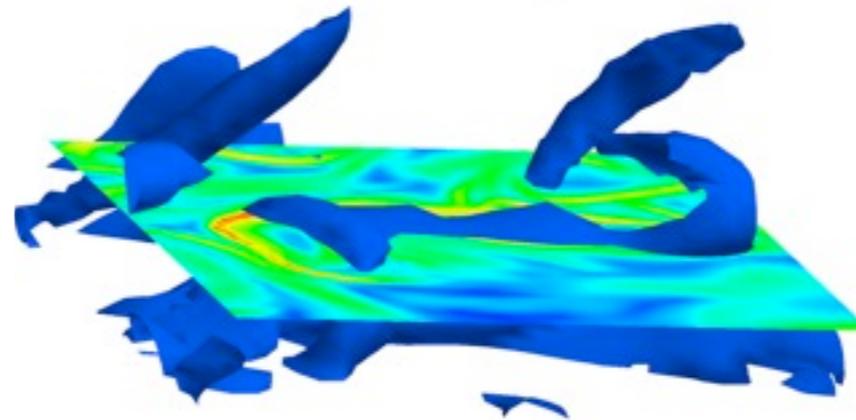
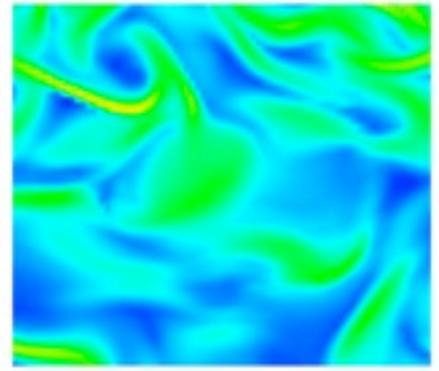
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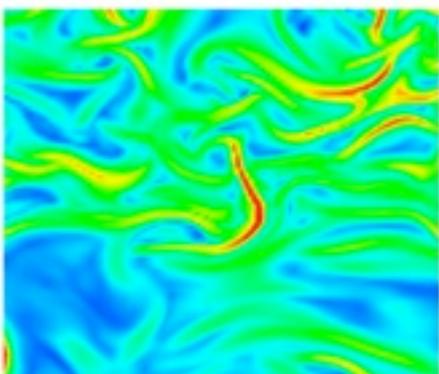
Not-so-
good



2D

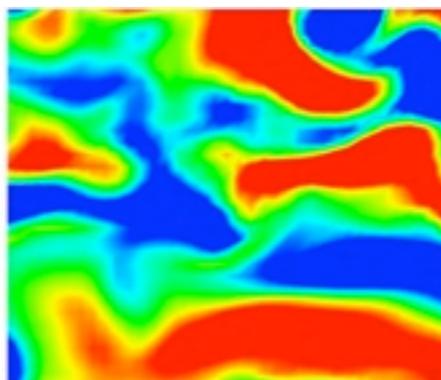


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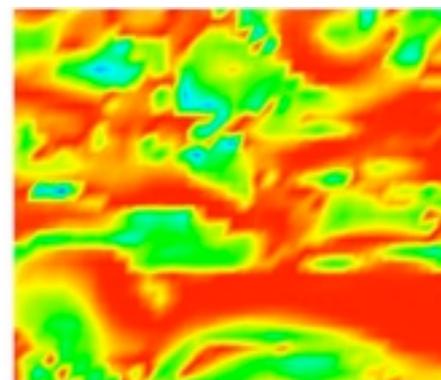


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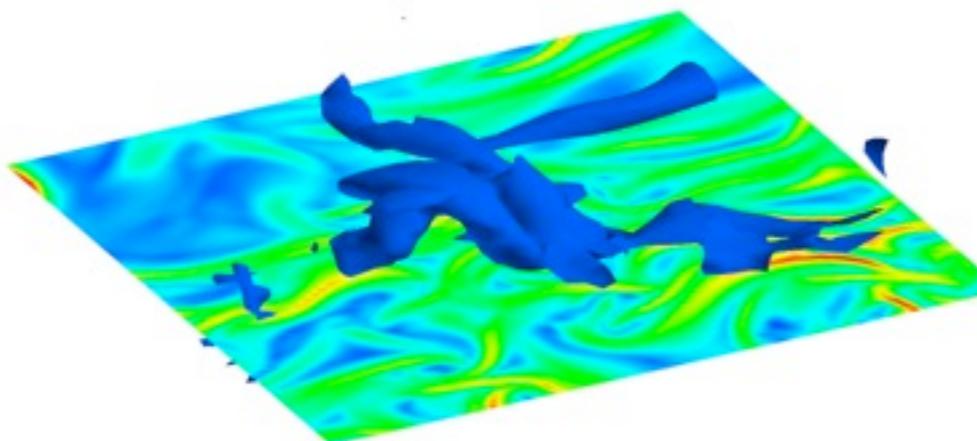
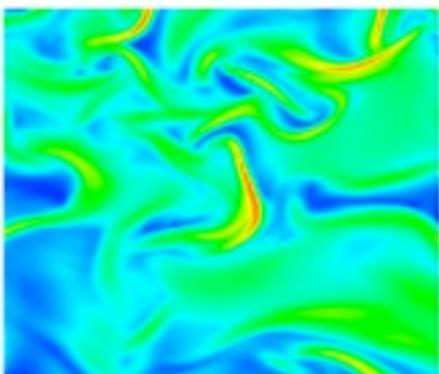
v



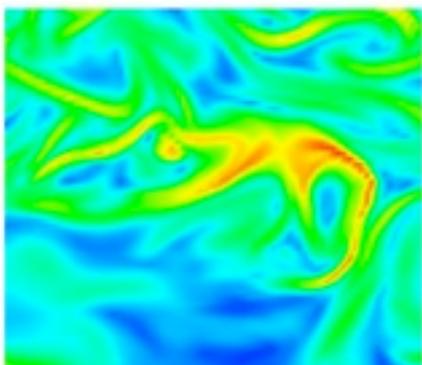
$$\sqrt{\frac{\omega_x^2 + \omega_z^2}{\omega^2}}$$



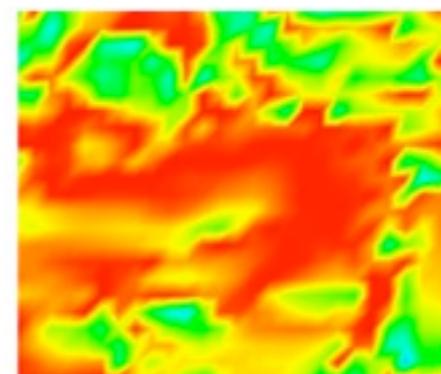
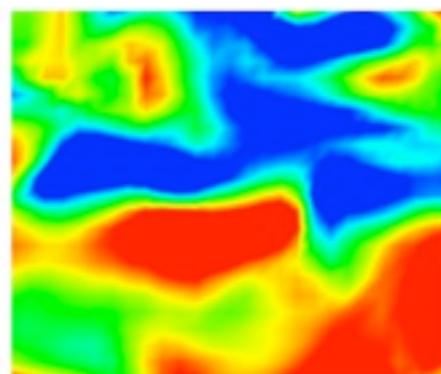
2D



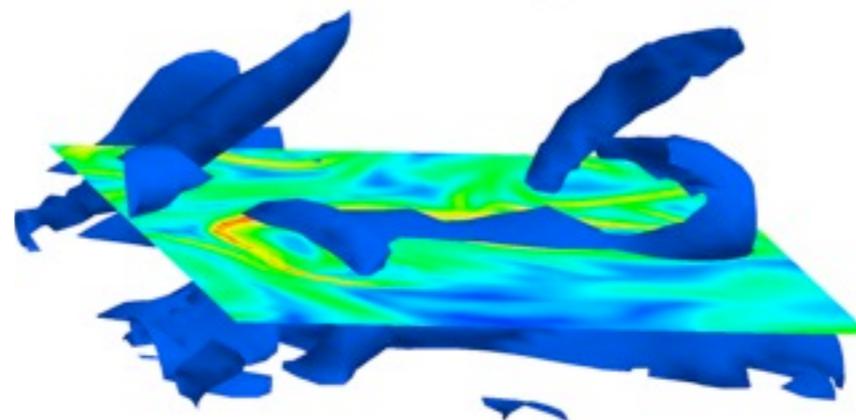
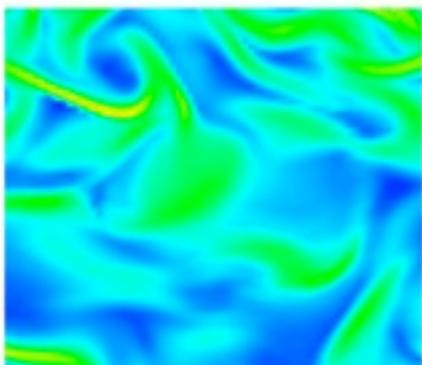
3D



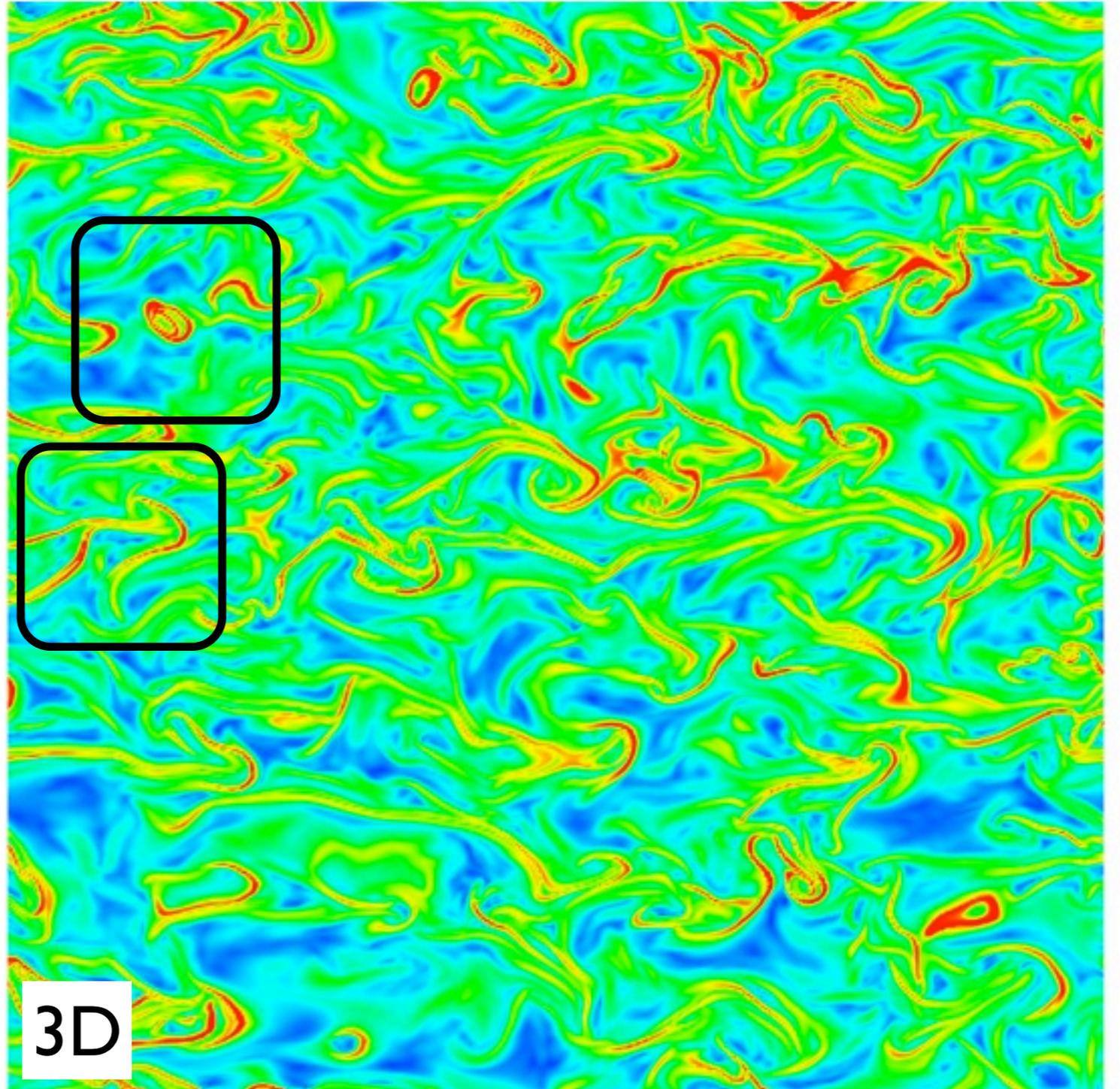
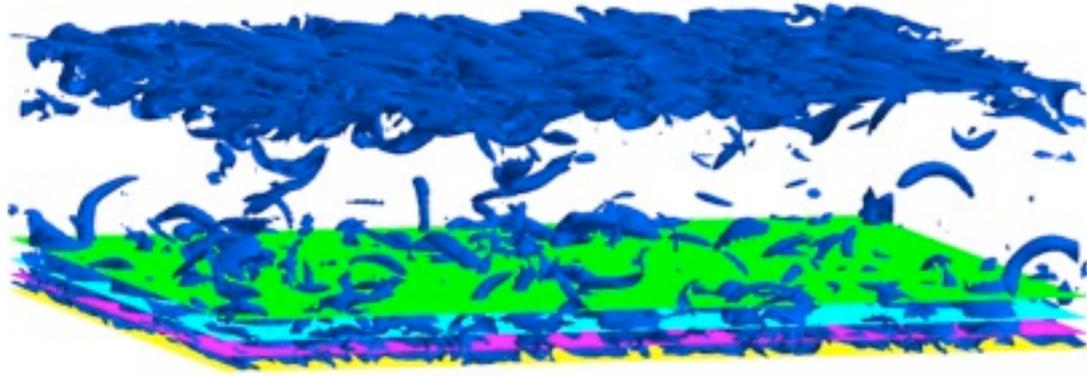
Not-so-
good



2D



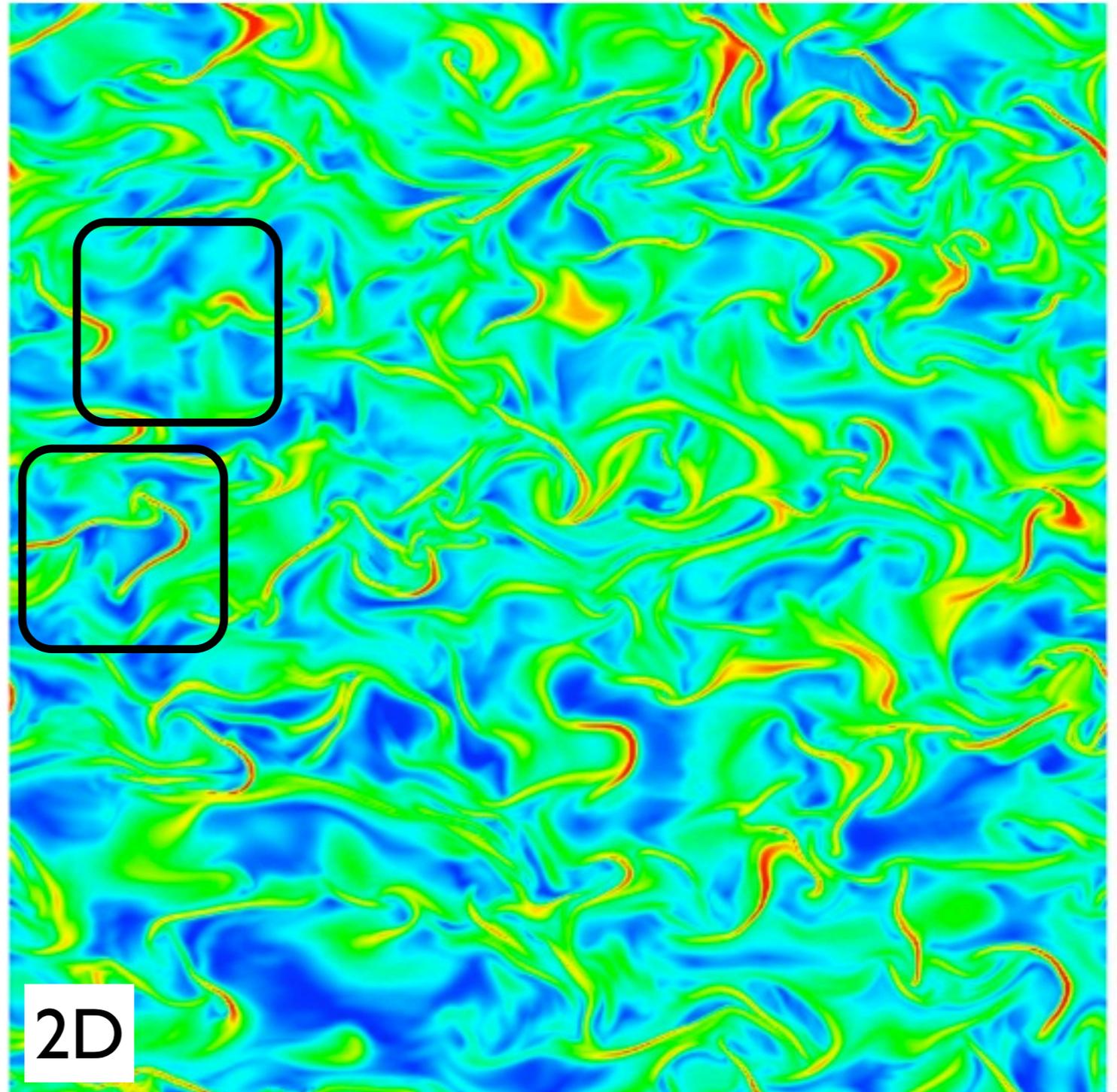
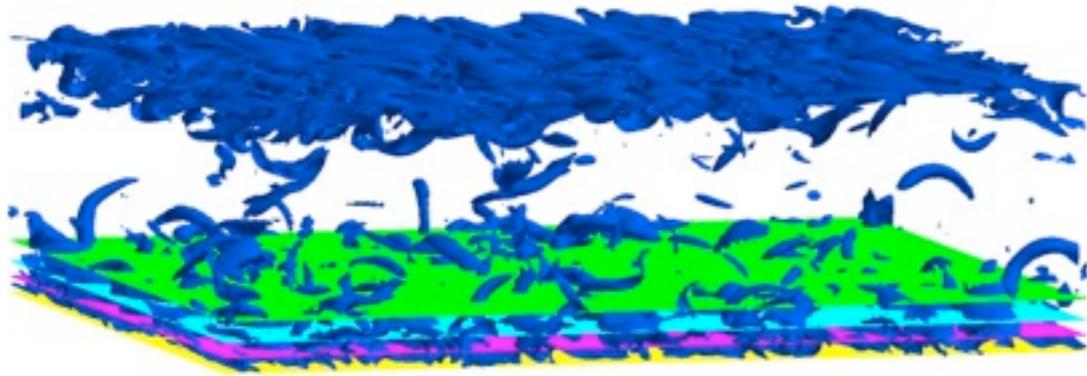
$$y^+ = 50$$



3D



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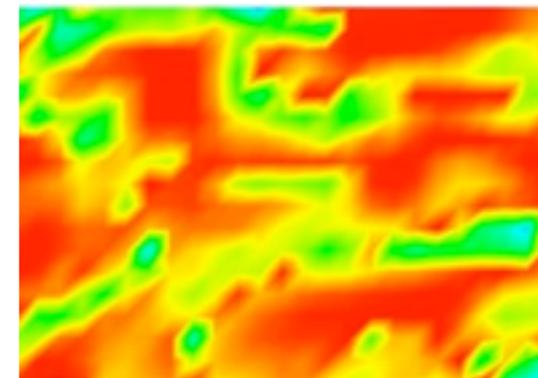
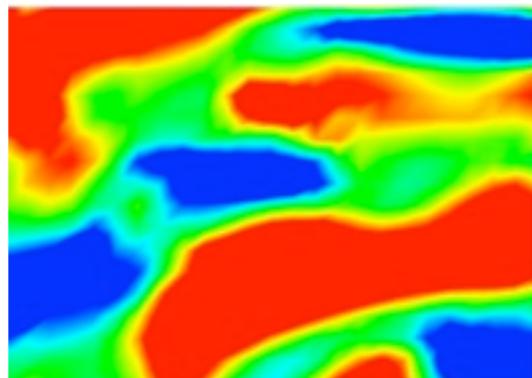
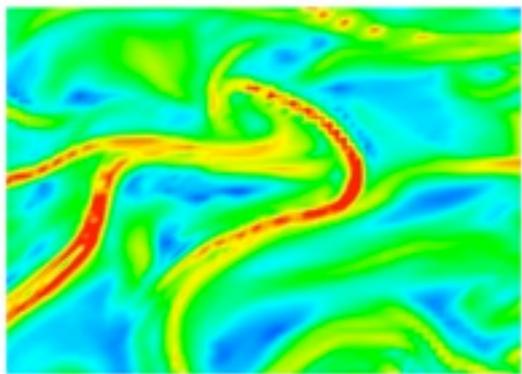
2D



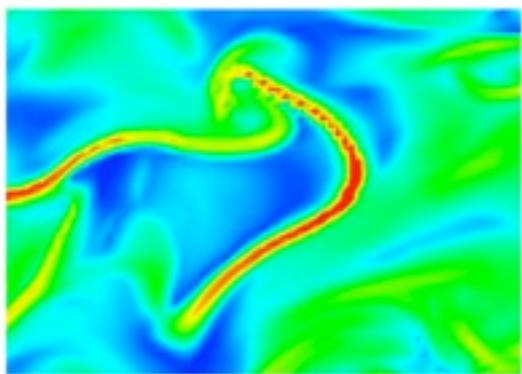
$$\sqrt{\frac{\omega_x^2 + \omega_z^2}{\omega^2}}$$

v

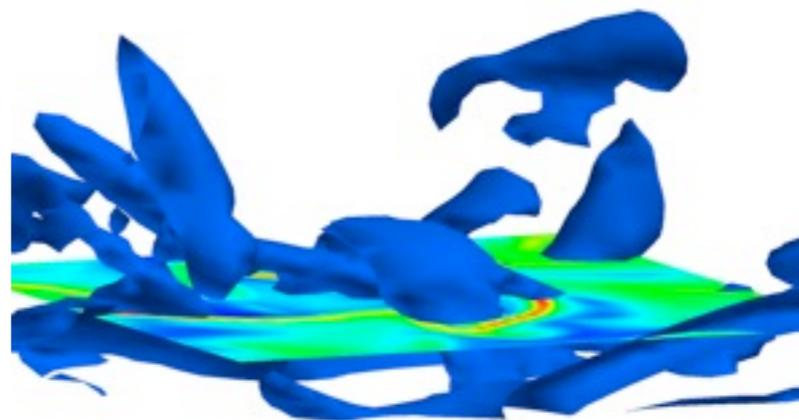
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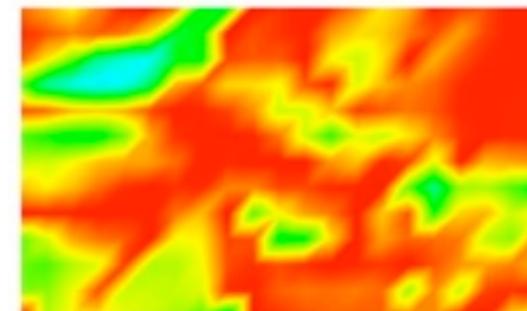
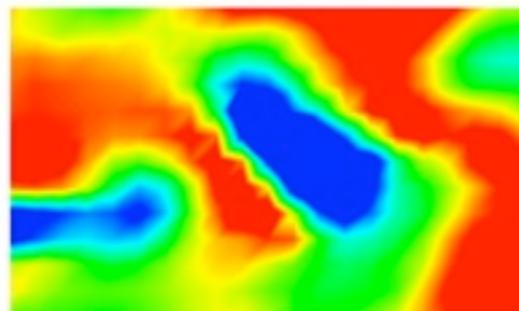
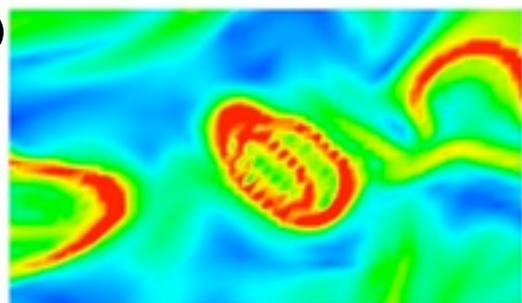
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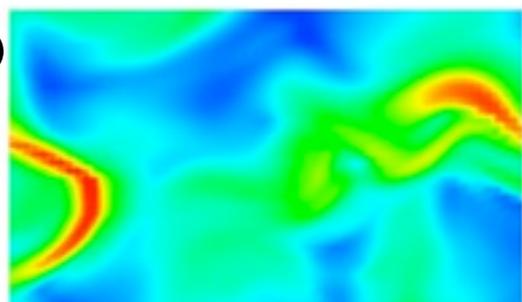
“Good”
match



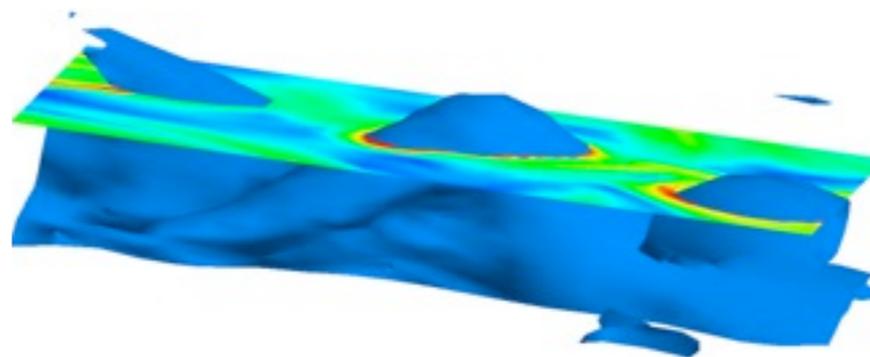
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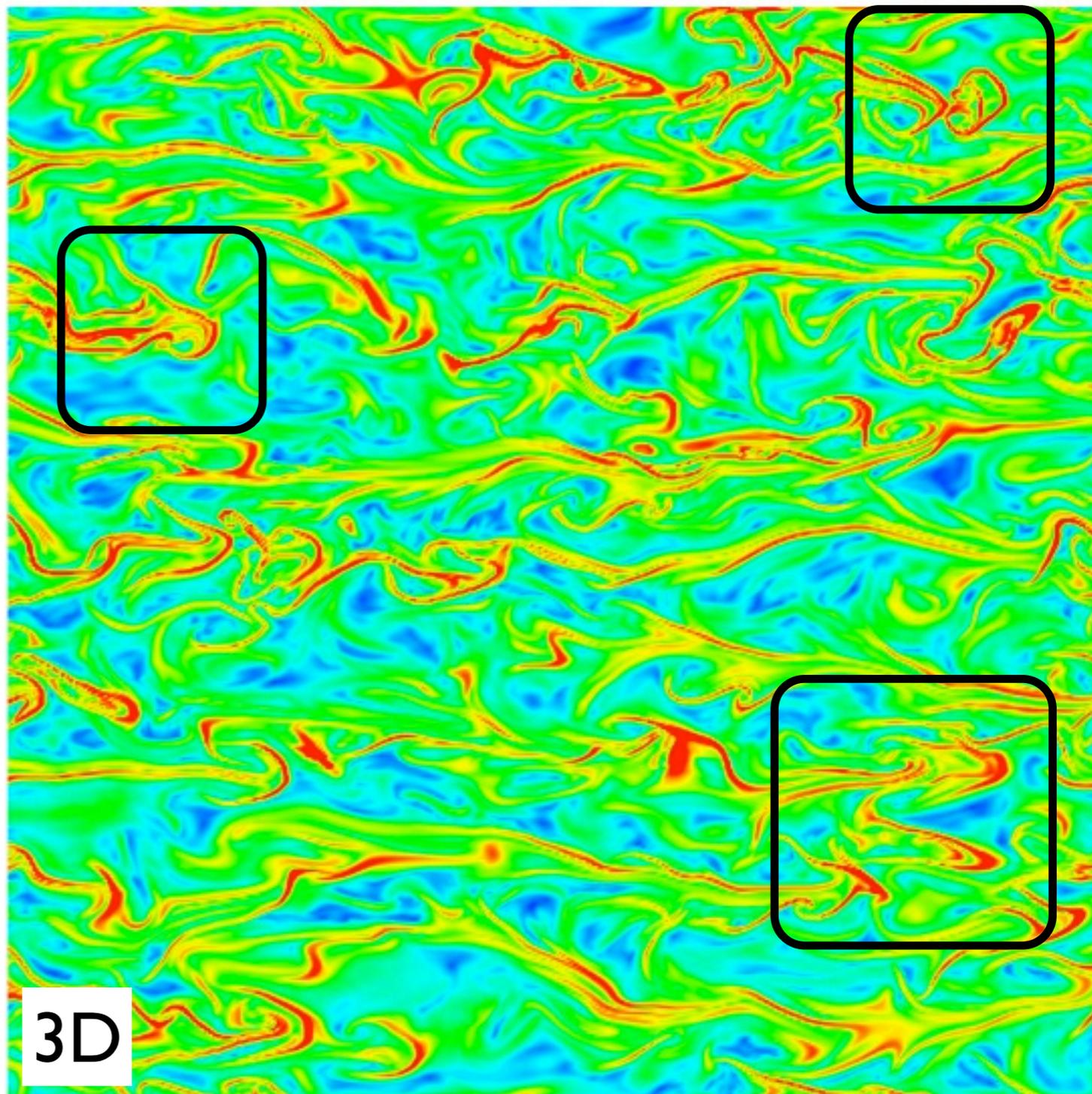
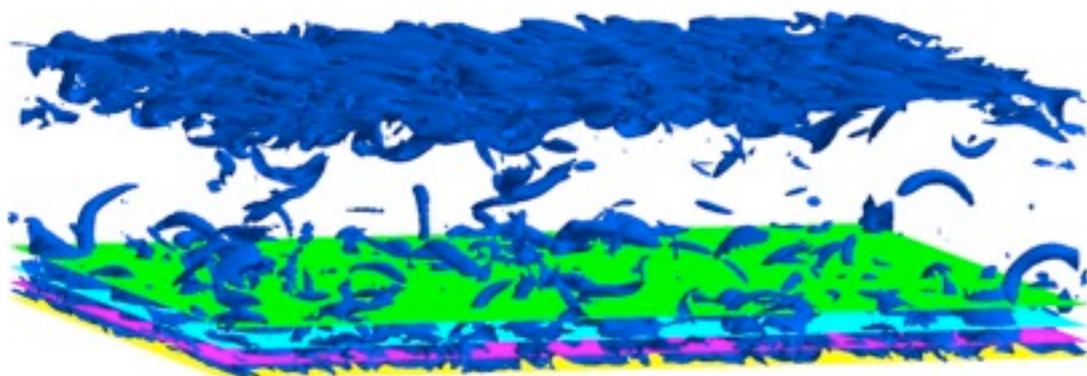
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Not-so-good



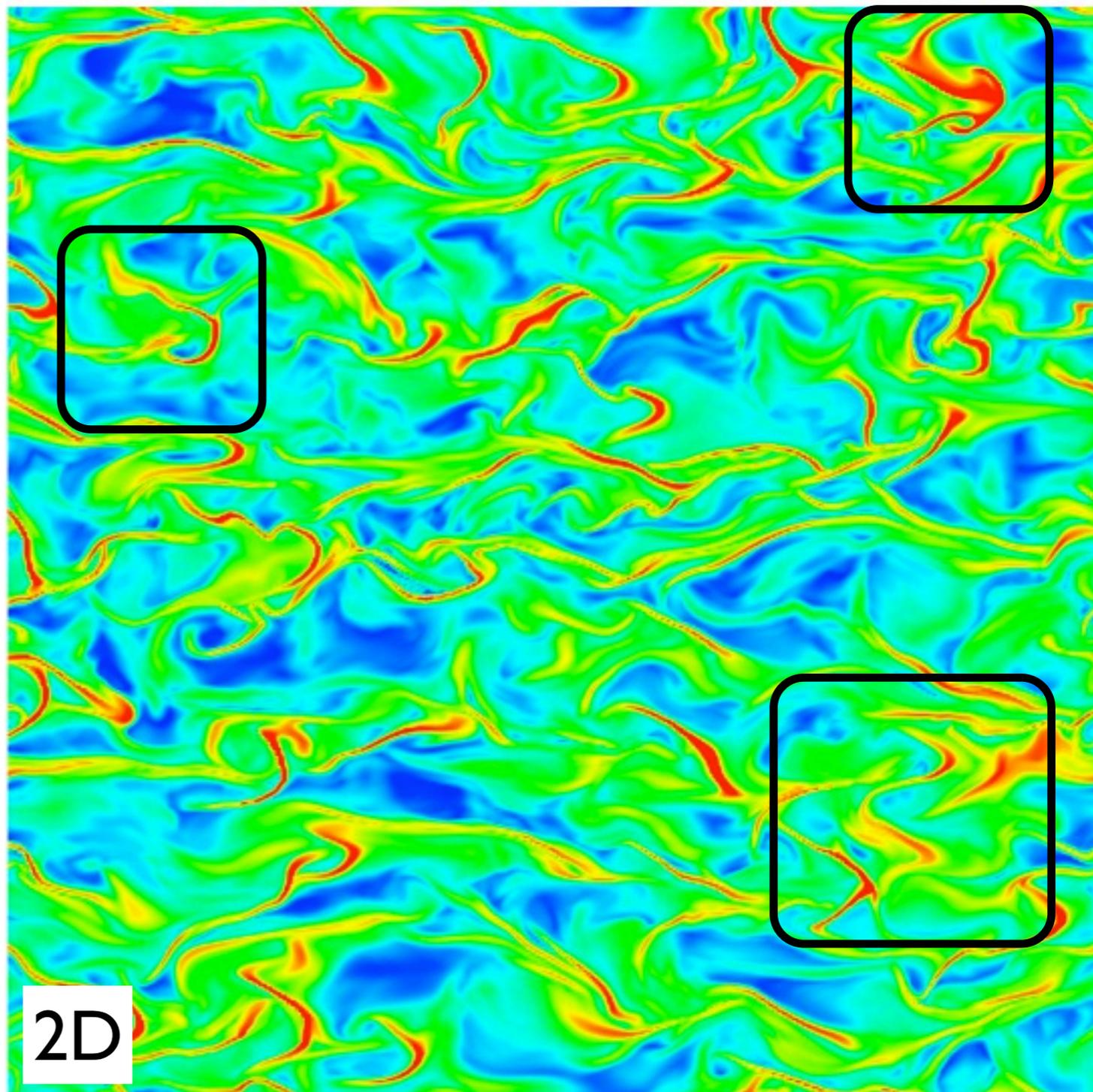
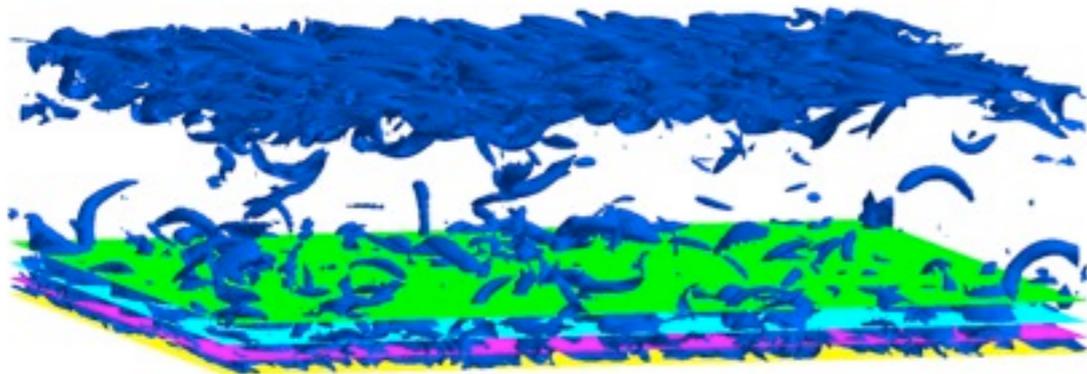
$$y^+ = 30$$



3D



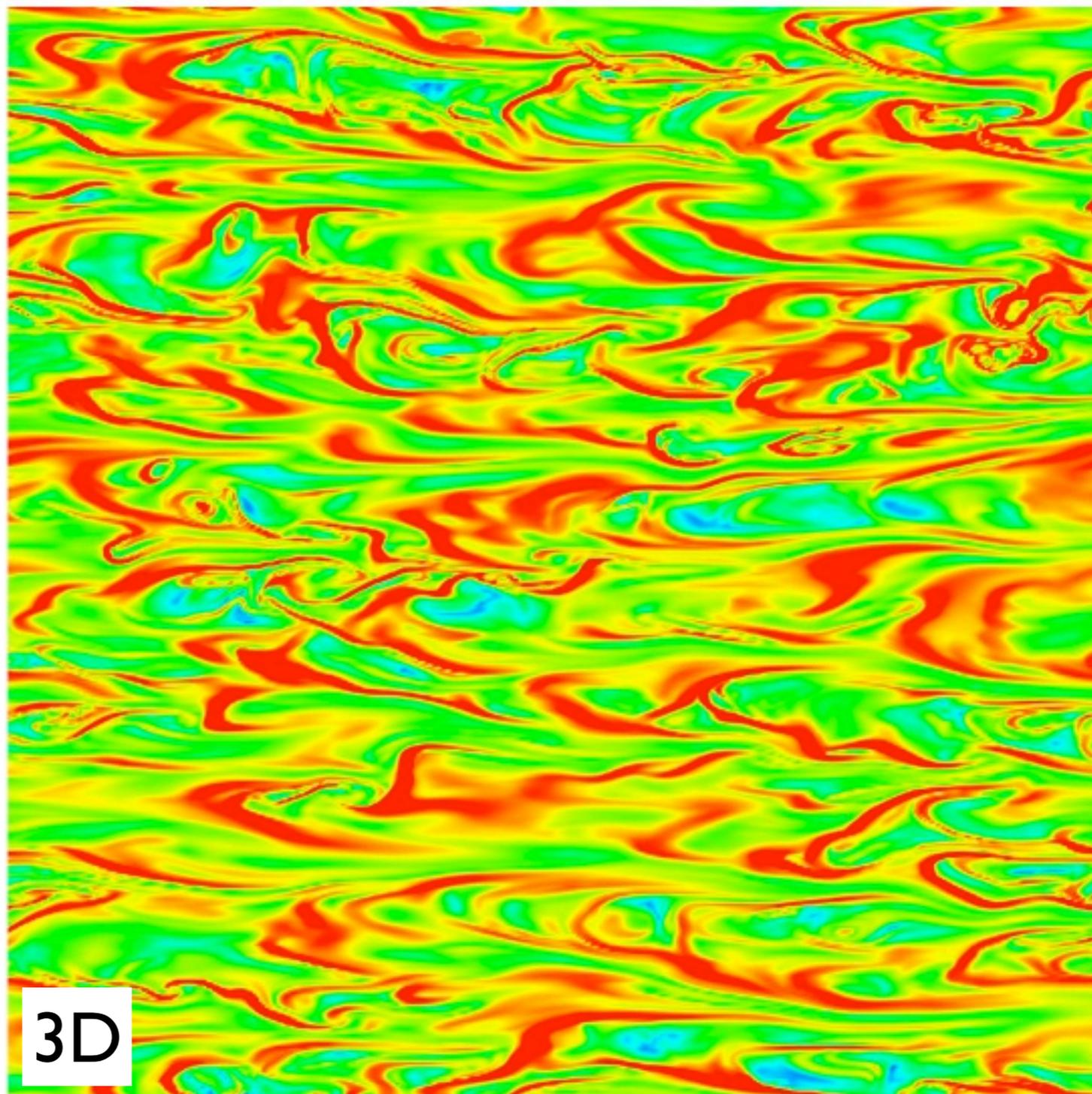
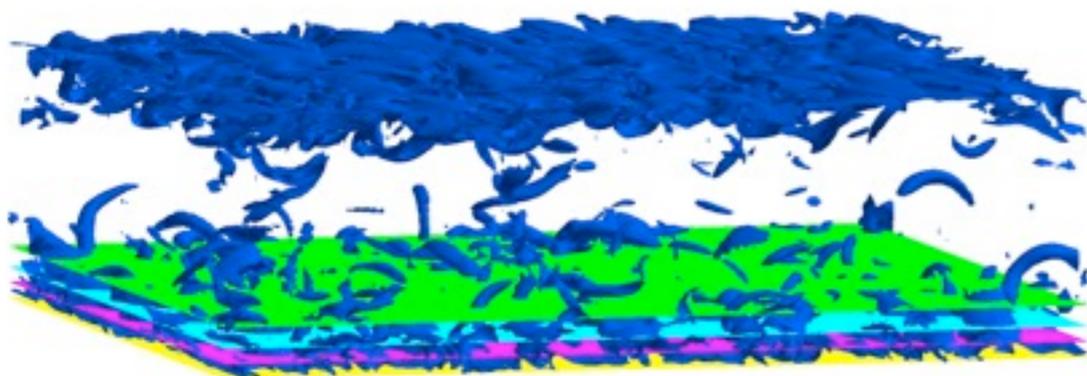
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2D



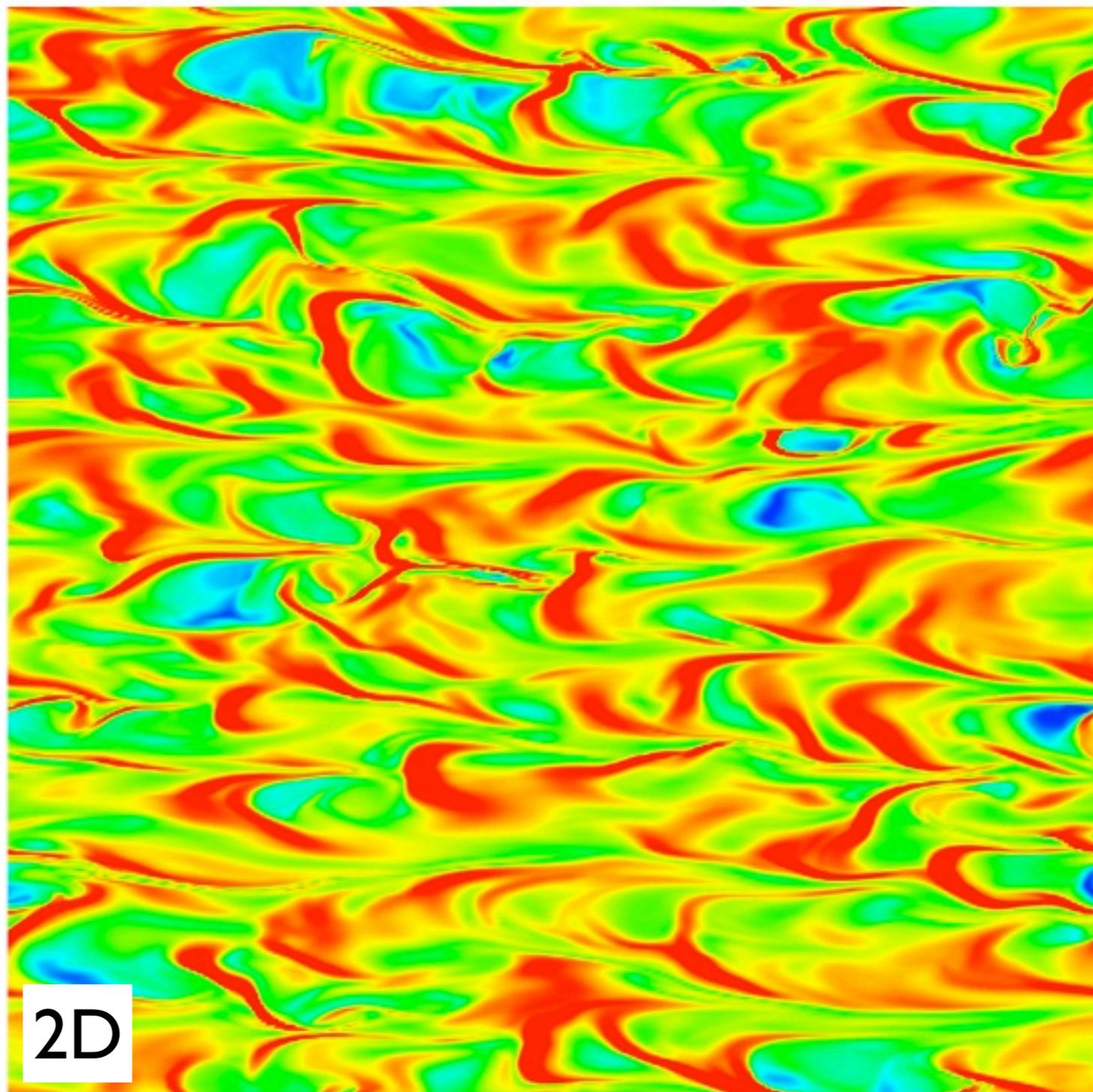
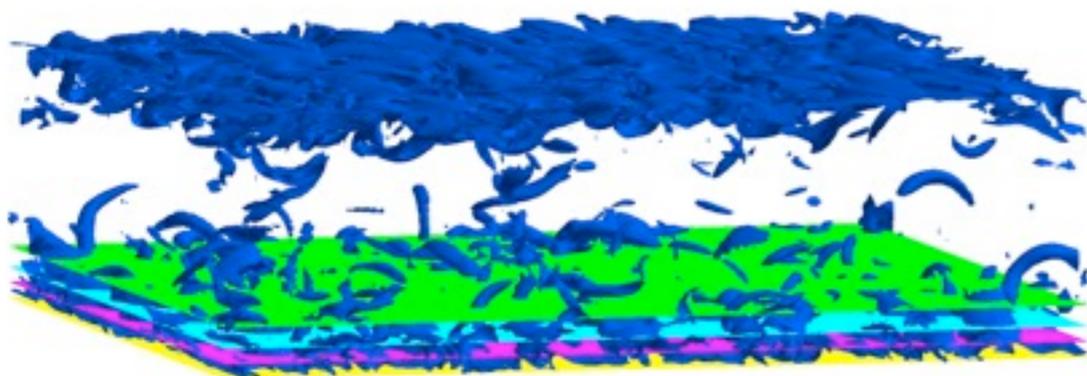
$$y^+ = 11$$



3D



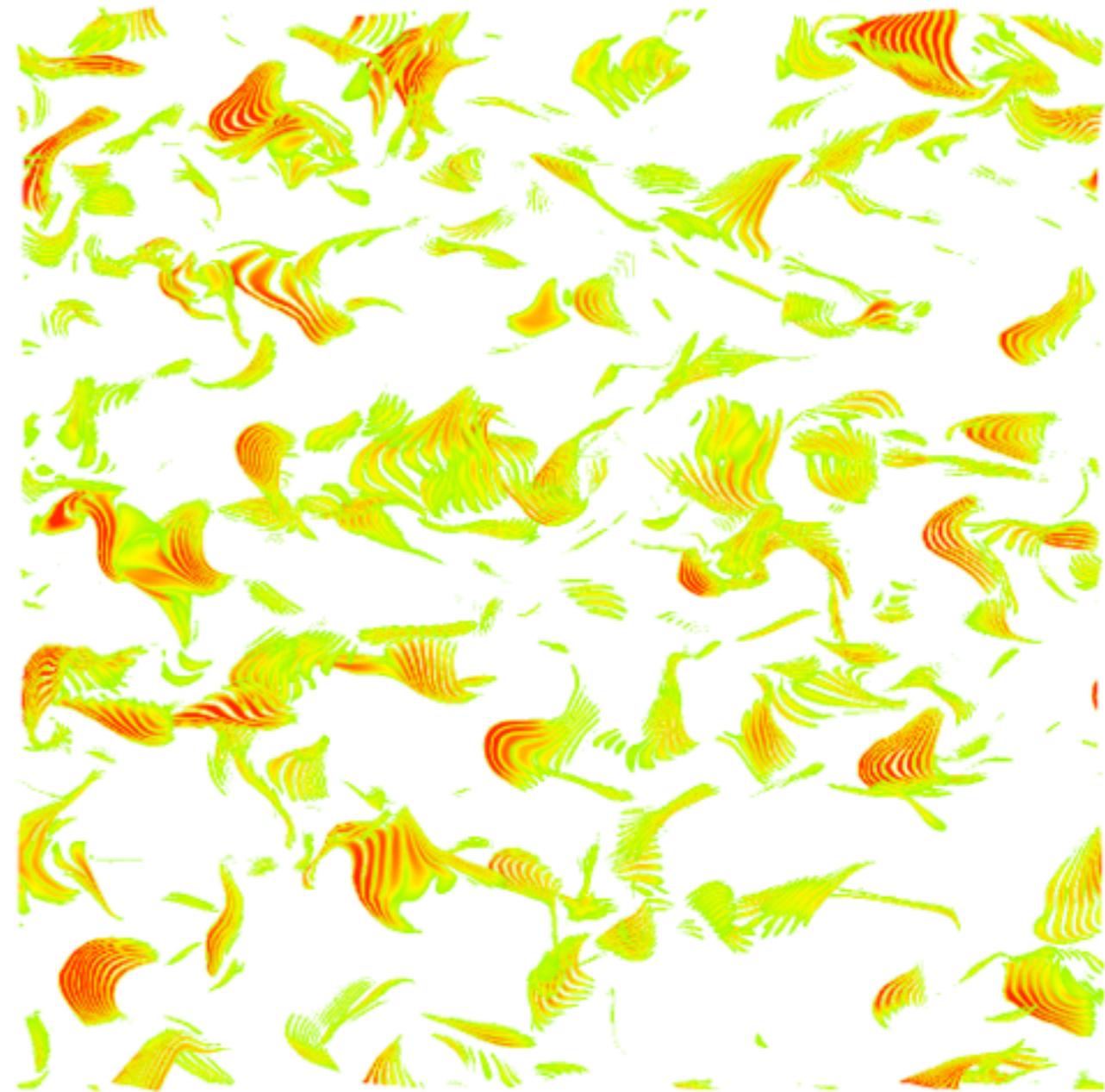
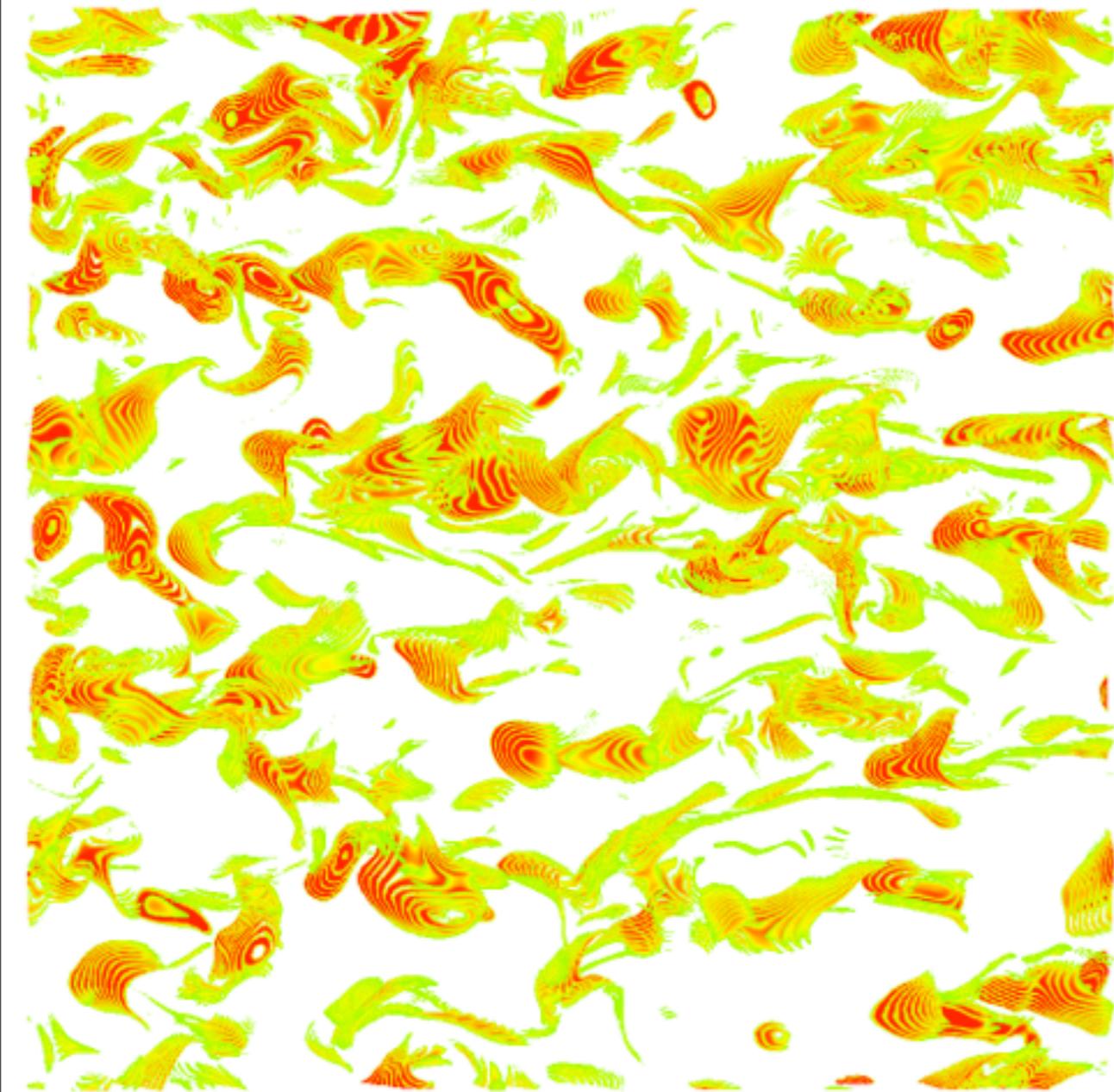
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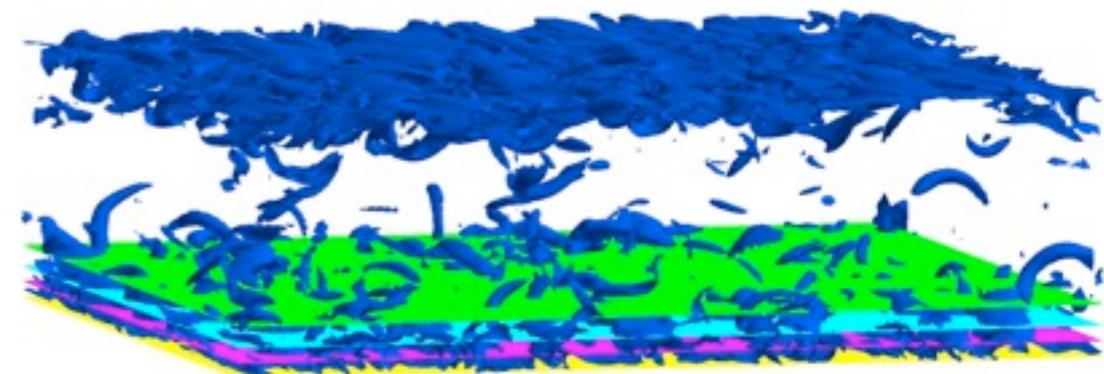
2D

full velocity field

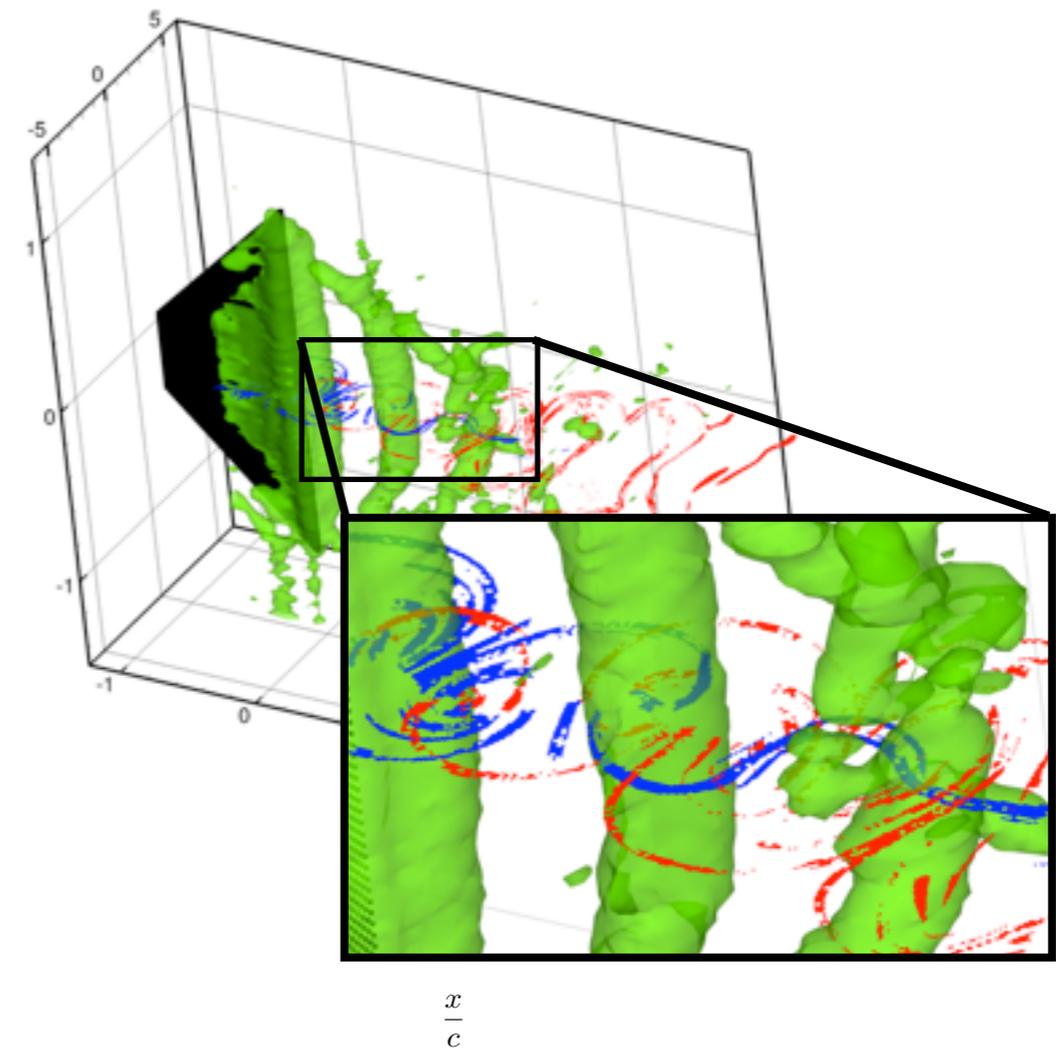
no out of plane velocity



nFTLE ridges at 9 overlapping planes $50 < y^+ < 76$

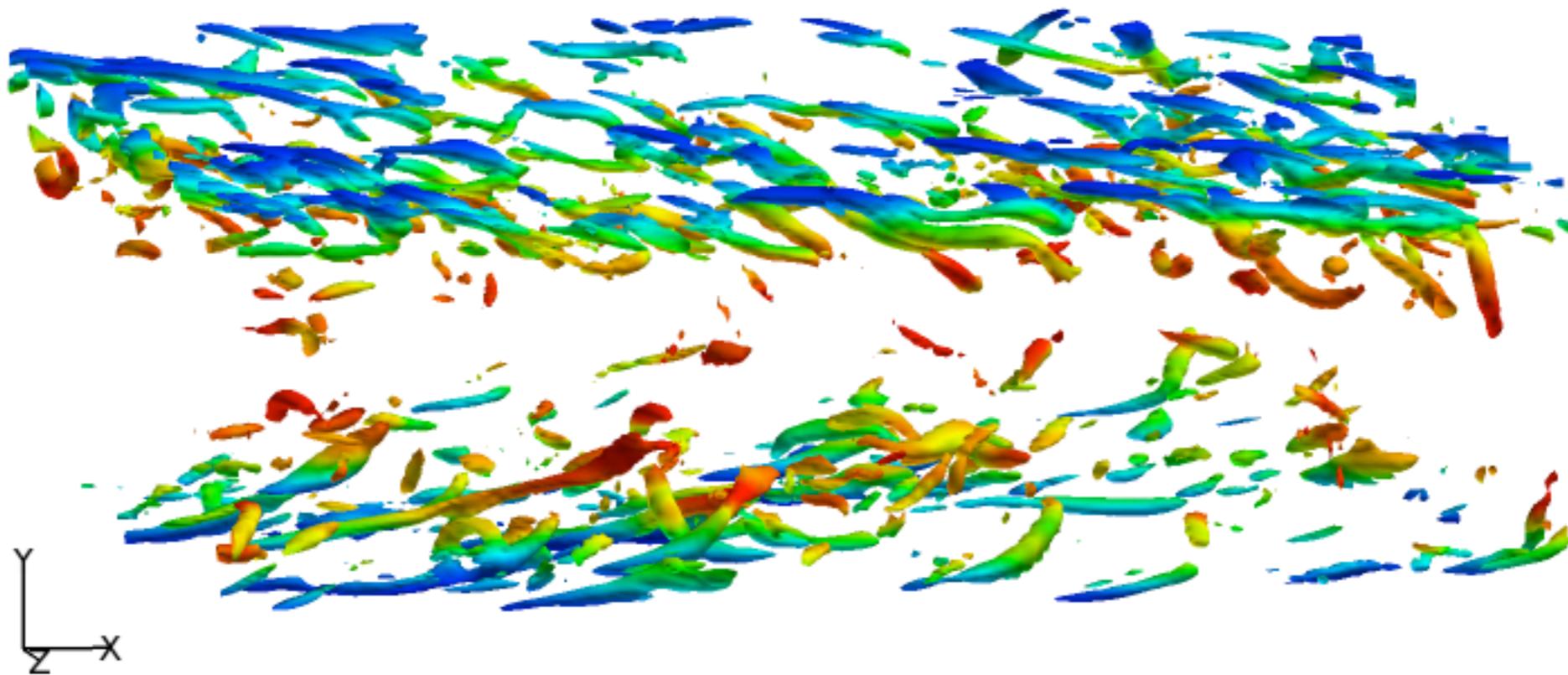


- Two component data in inherently 3D flows can be insufficient for Lagrangian analysis
 - Need better way to measure inaccuracy
- Looking for good metrics - should ultimately only use the limited data we start with
 - Out of plane velocity?
 - In-plane vorticity?
- Structures of interest should be normal to FTLE plane for most reliable LCS results



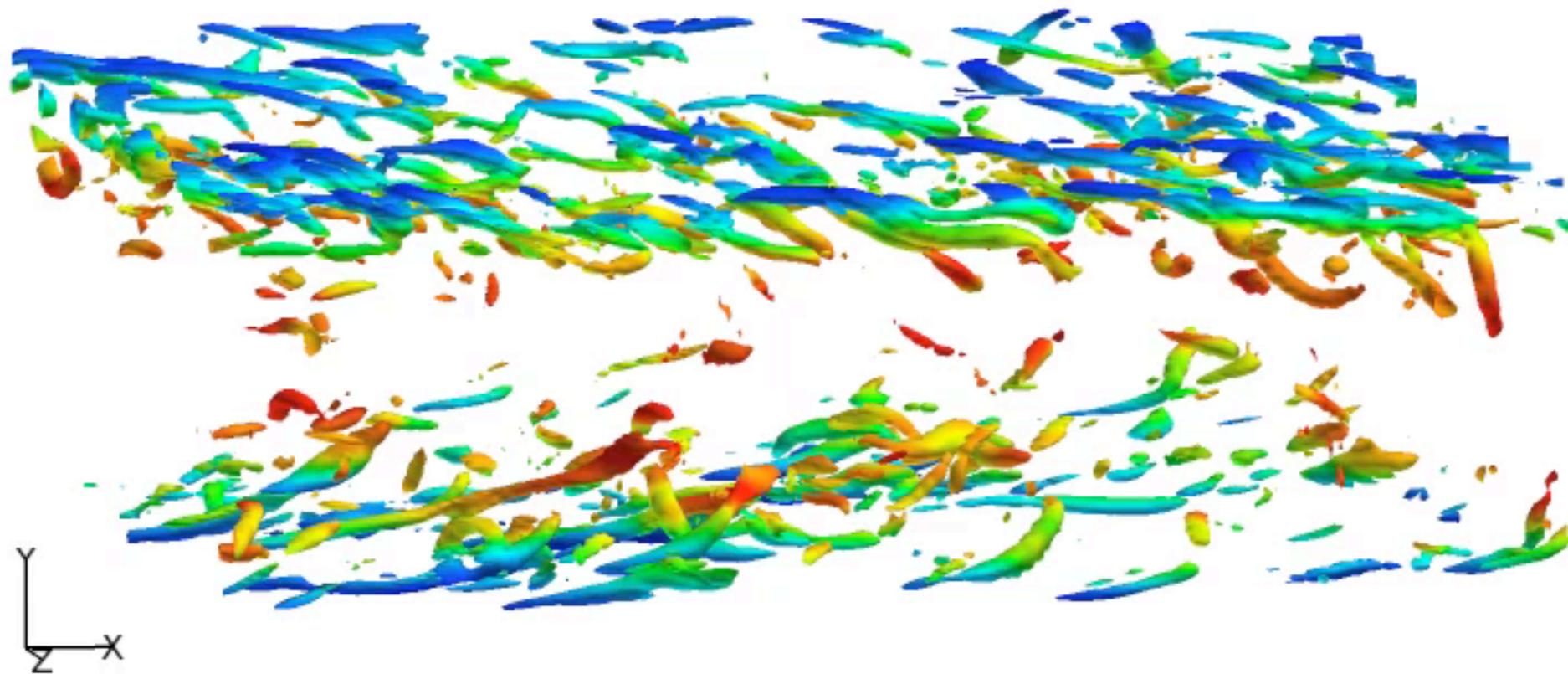
Time resolution of velocity data

- Generally, use approximate velocities to use for intermediate integration calculations (interpolation)
- When the velocity data is far apart in time - what happens to FTLE fields calculated using (poorly) estimated velocity fields?



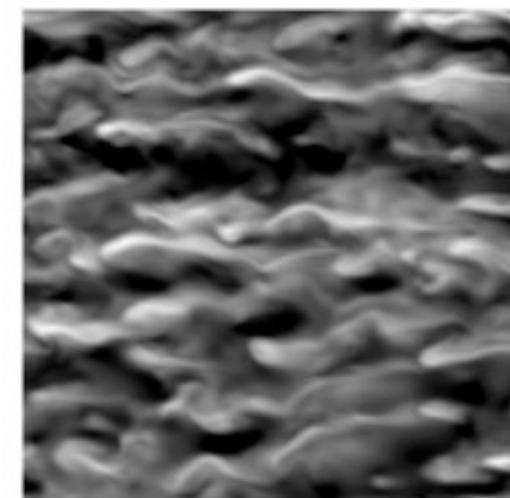
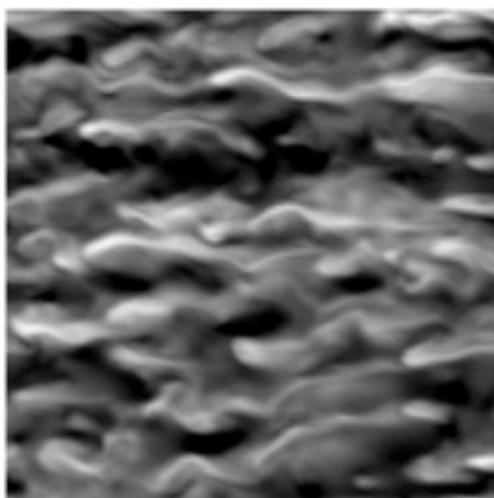
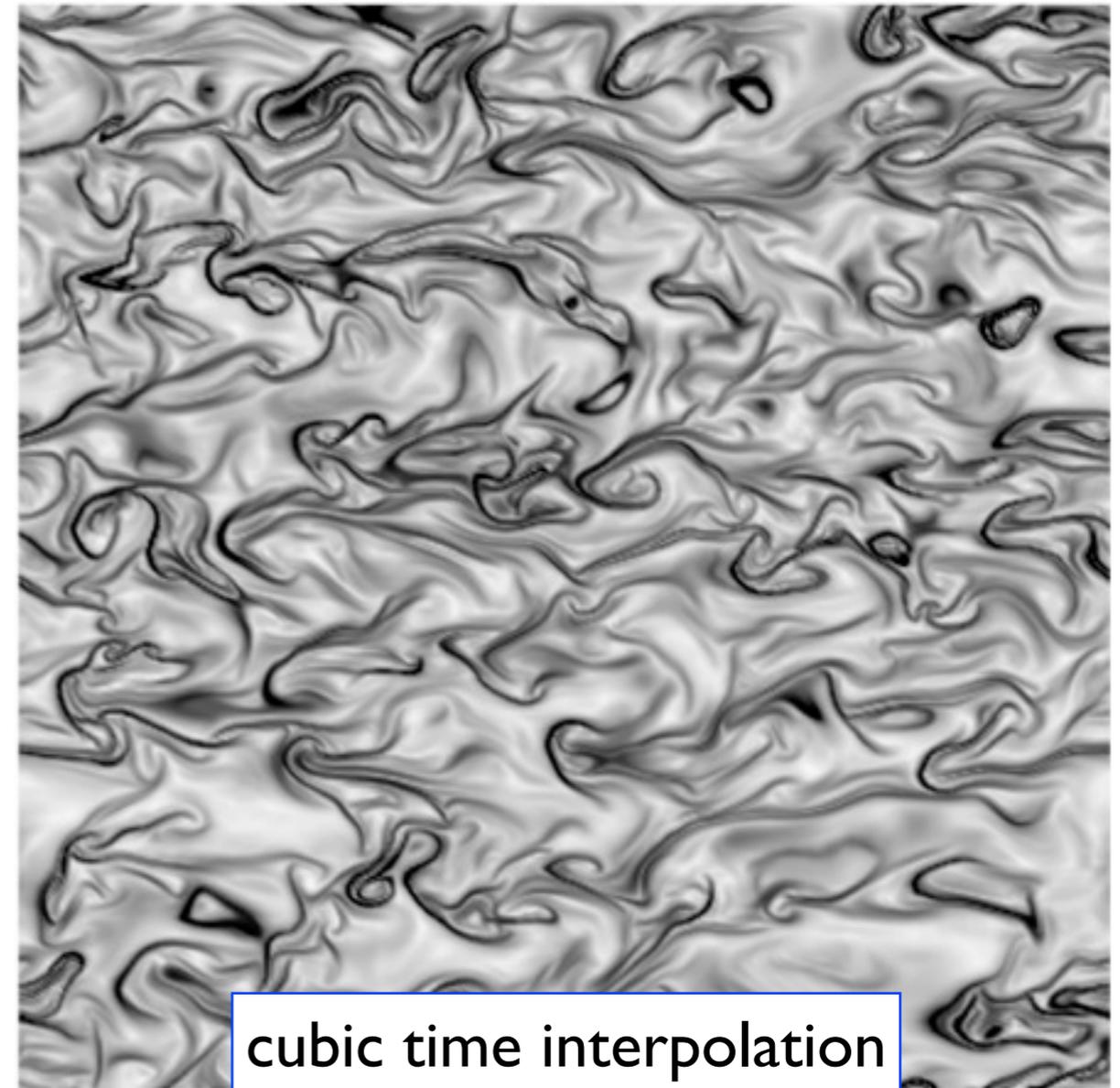
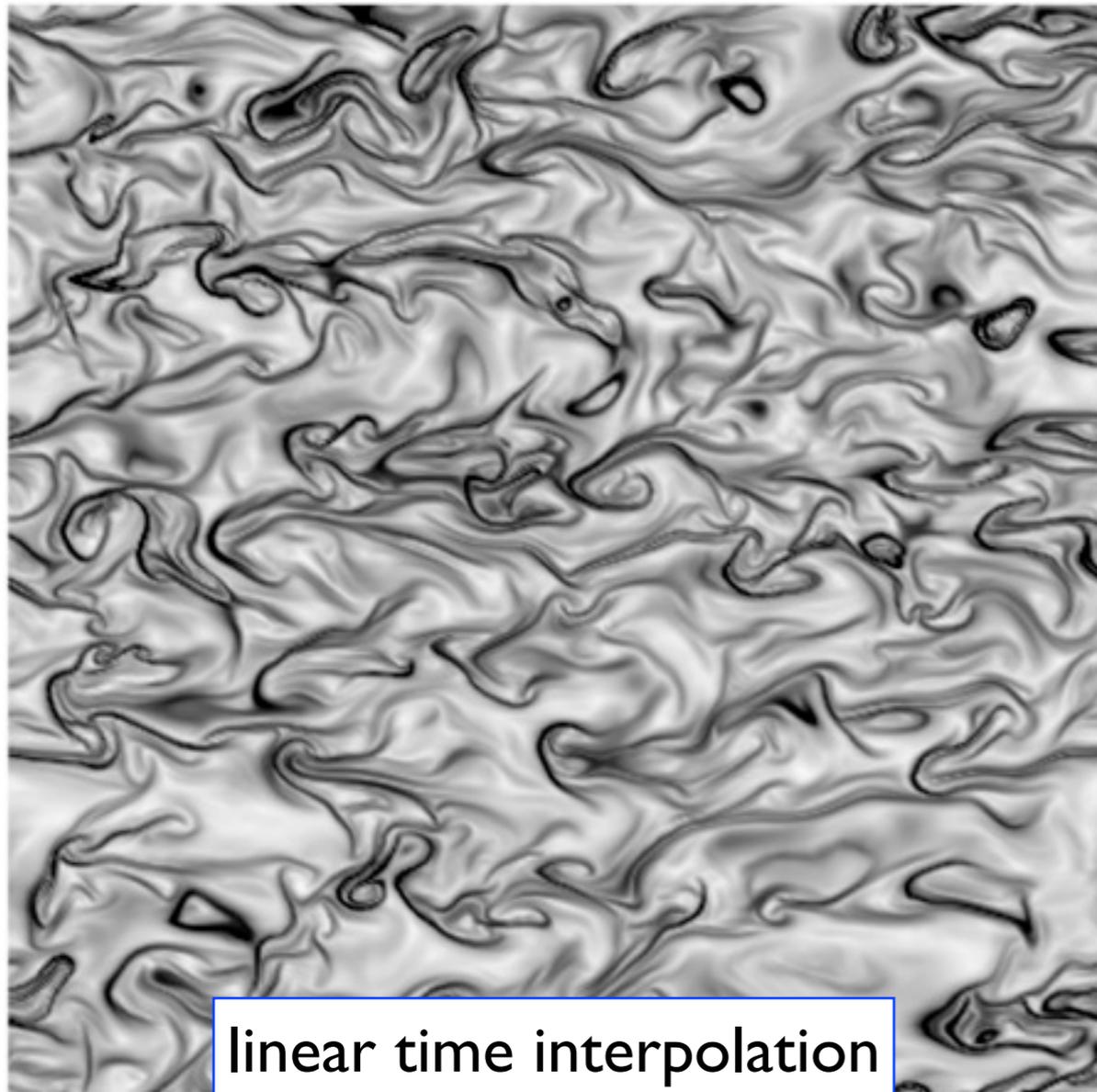
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- When the velocity data is far apart in time - what happens to FTLE fields calculated using (poorly) estimated velocity fields?

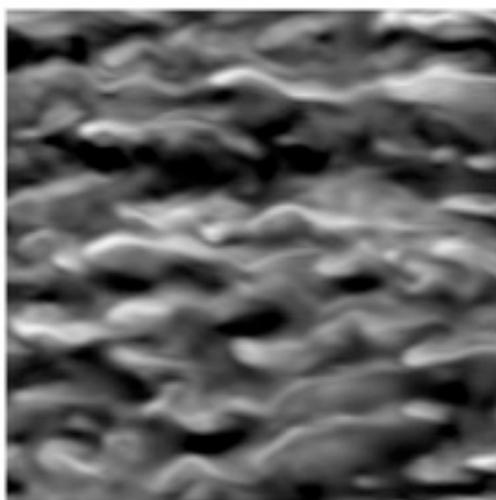
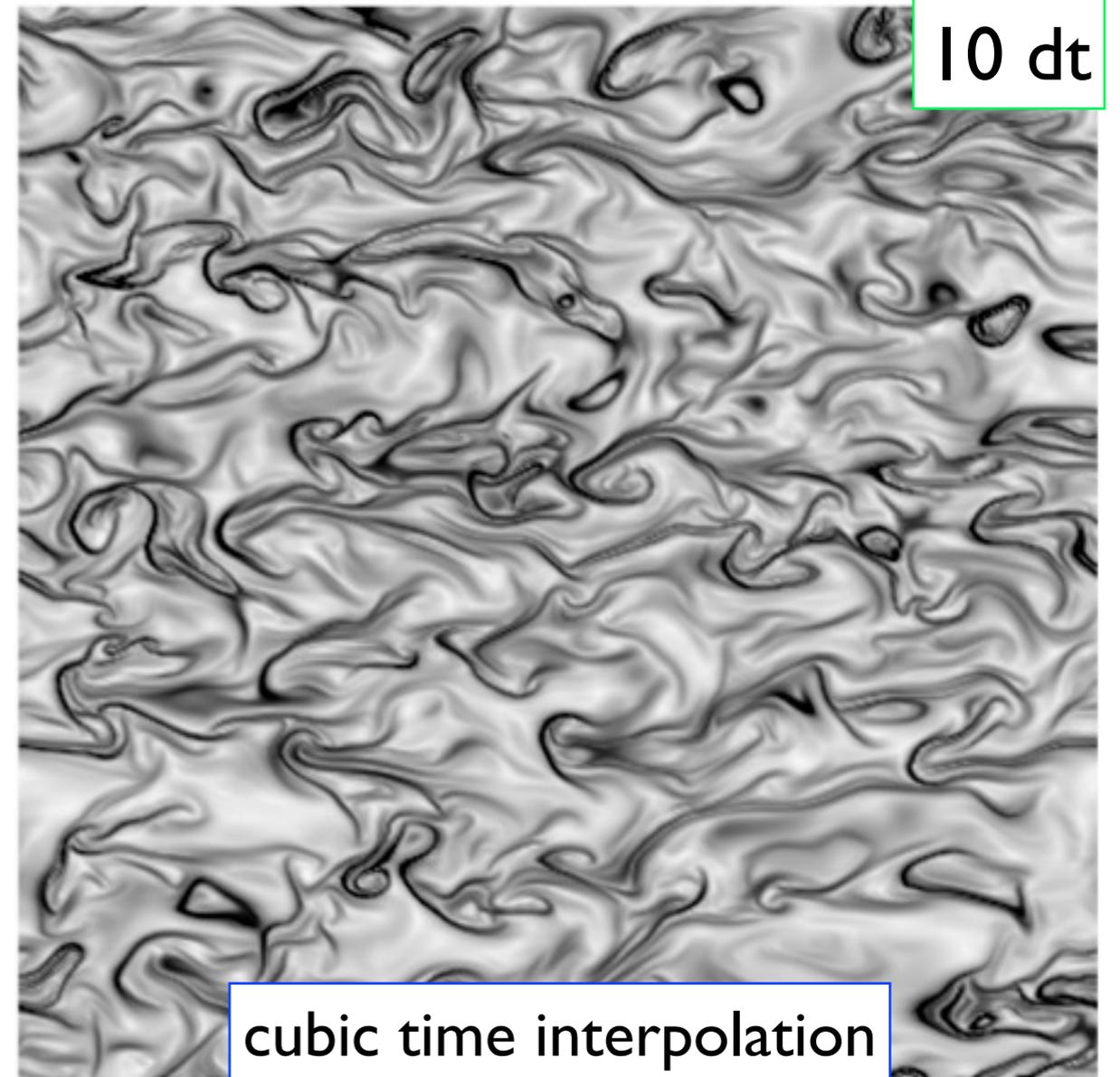
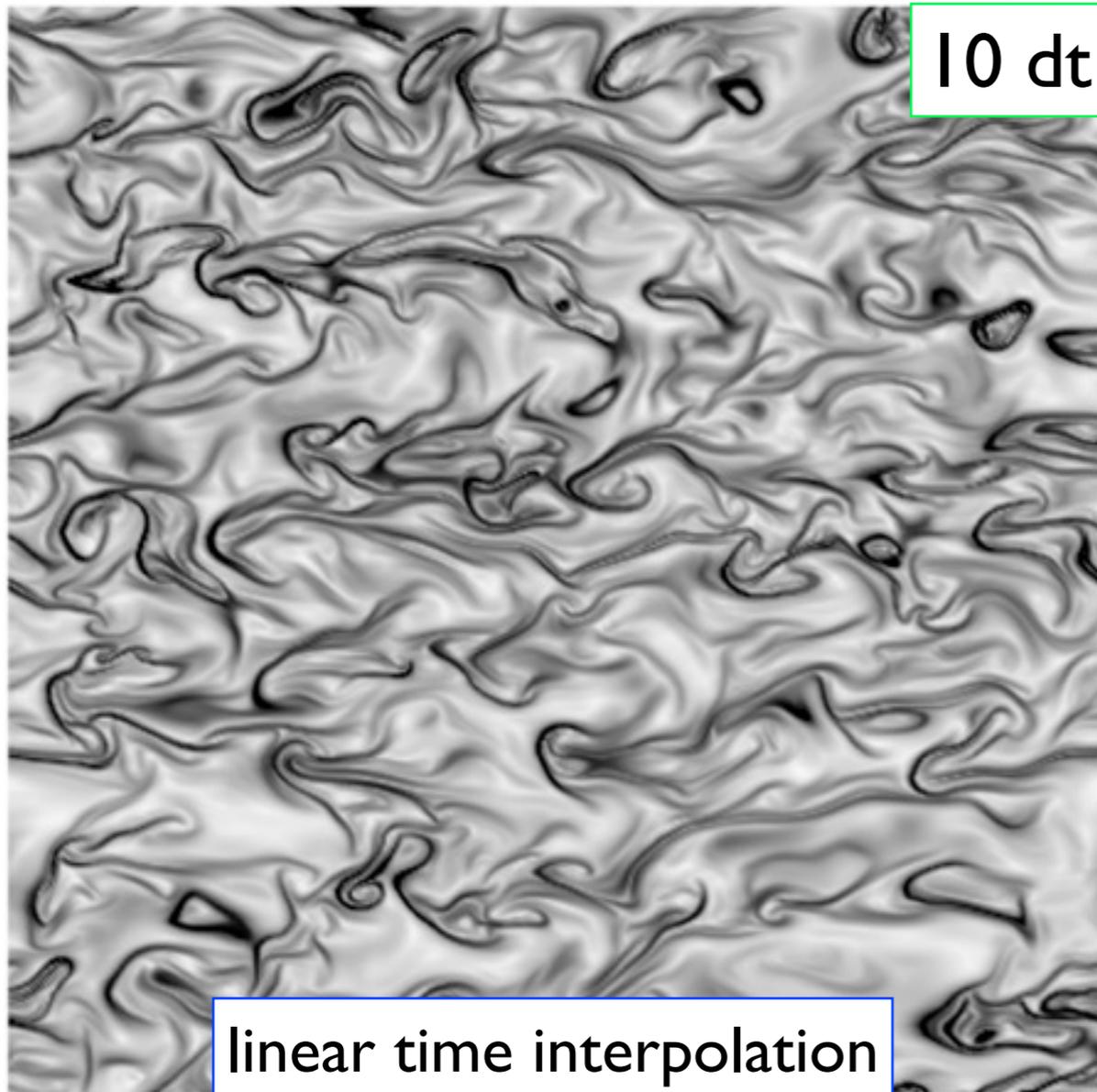


$$dt = 50 \Delta T$$

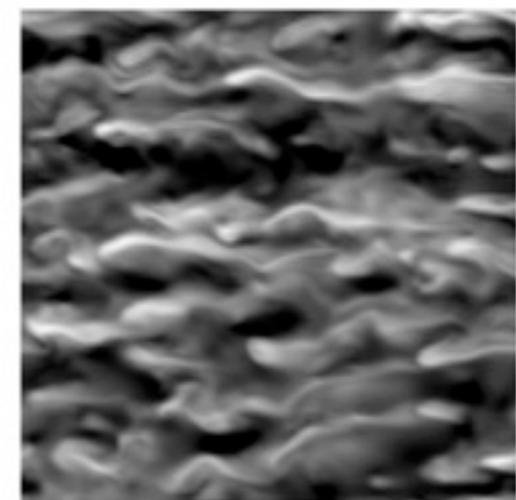
Time resolution issues - turbulent channel



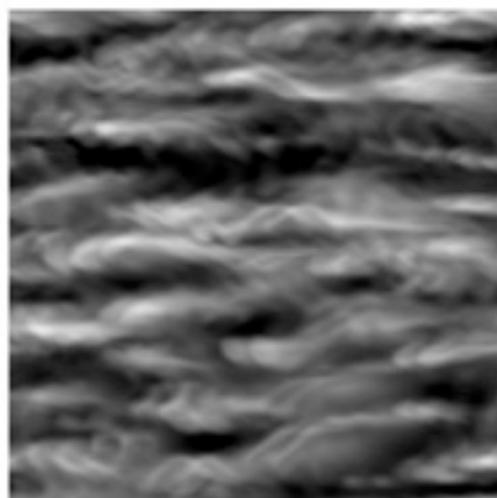
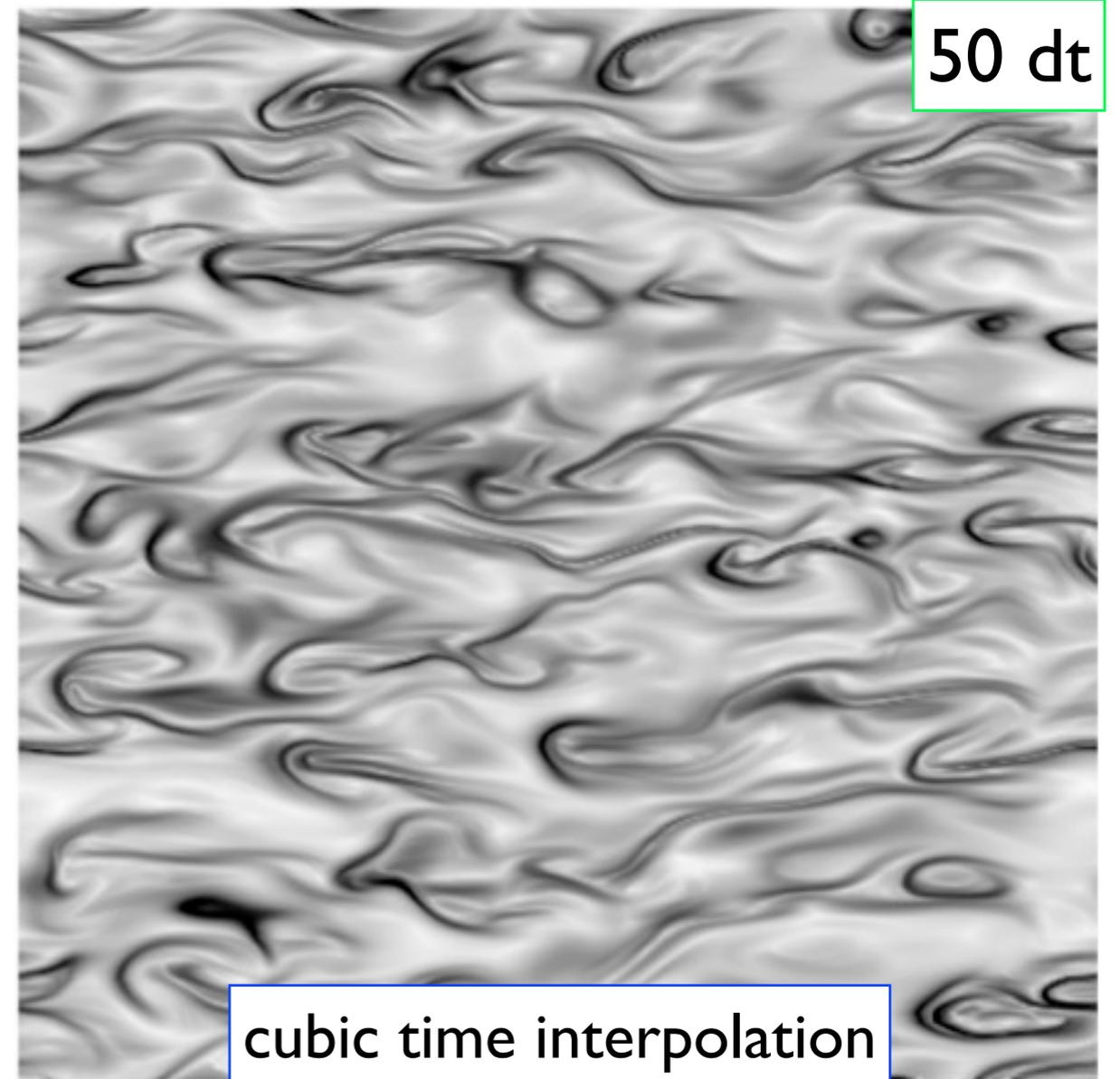
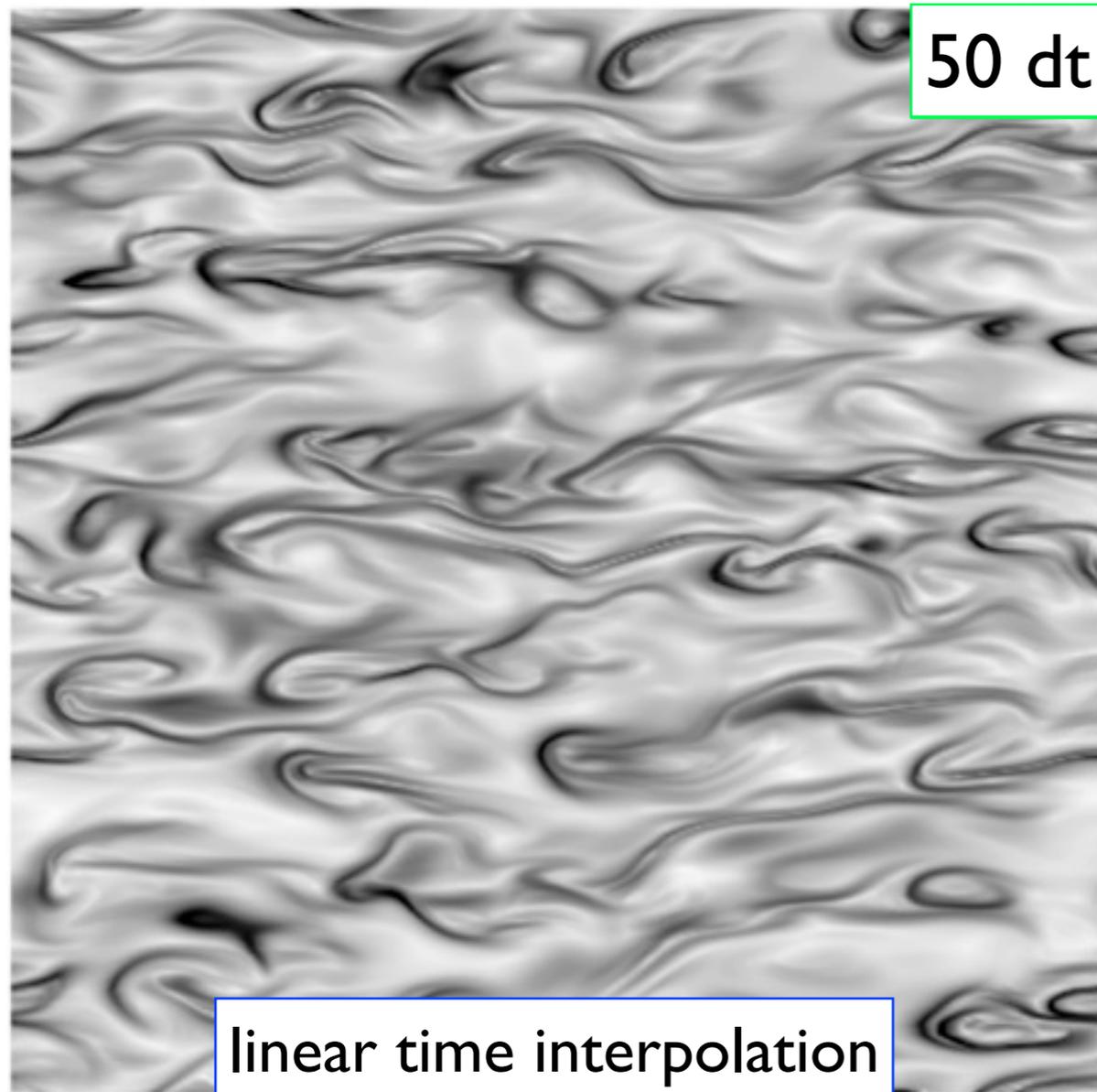
Time resolution issues - turbulent channel



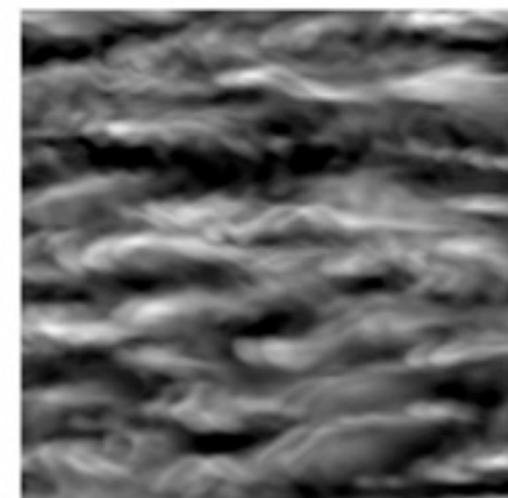
streamwise velocity



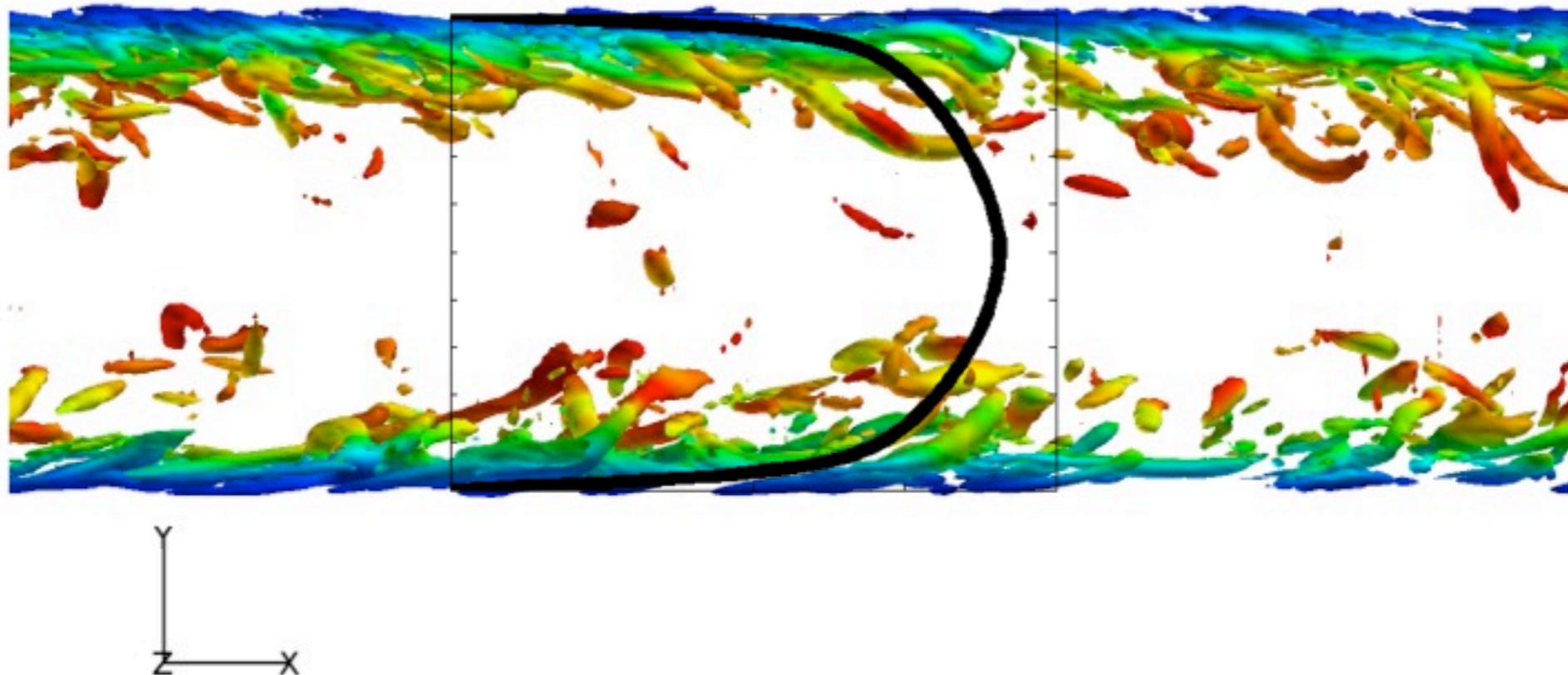
Time resolution issues - turbulent channel



streamwise velocity

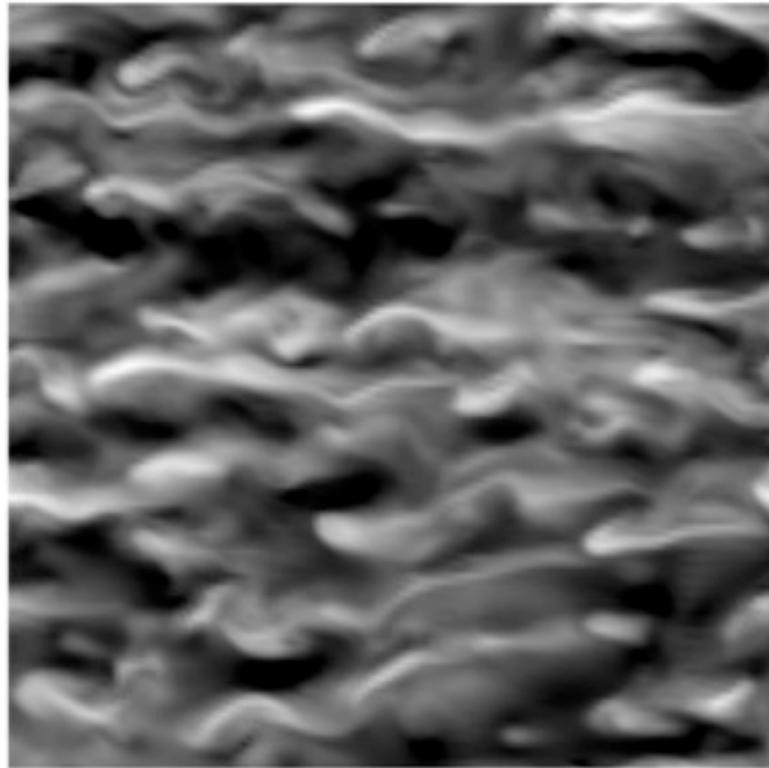


Smarter ways to create intermediate fields

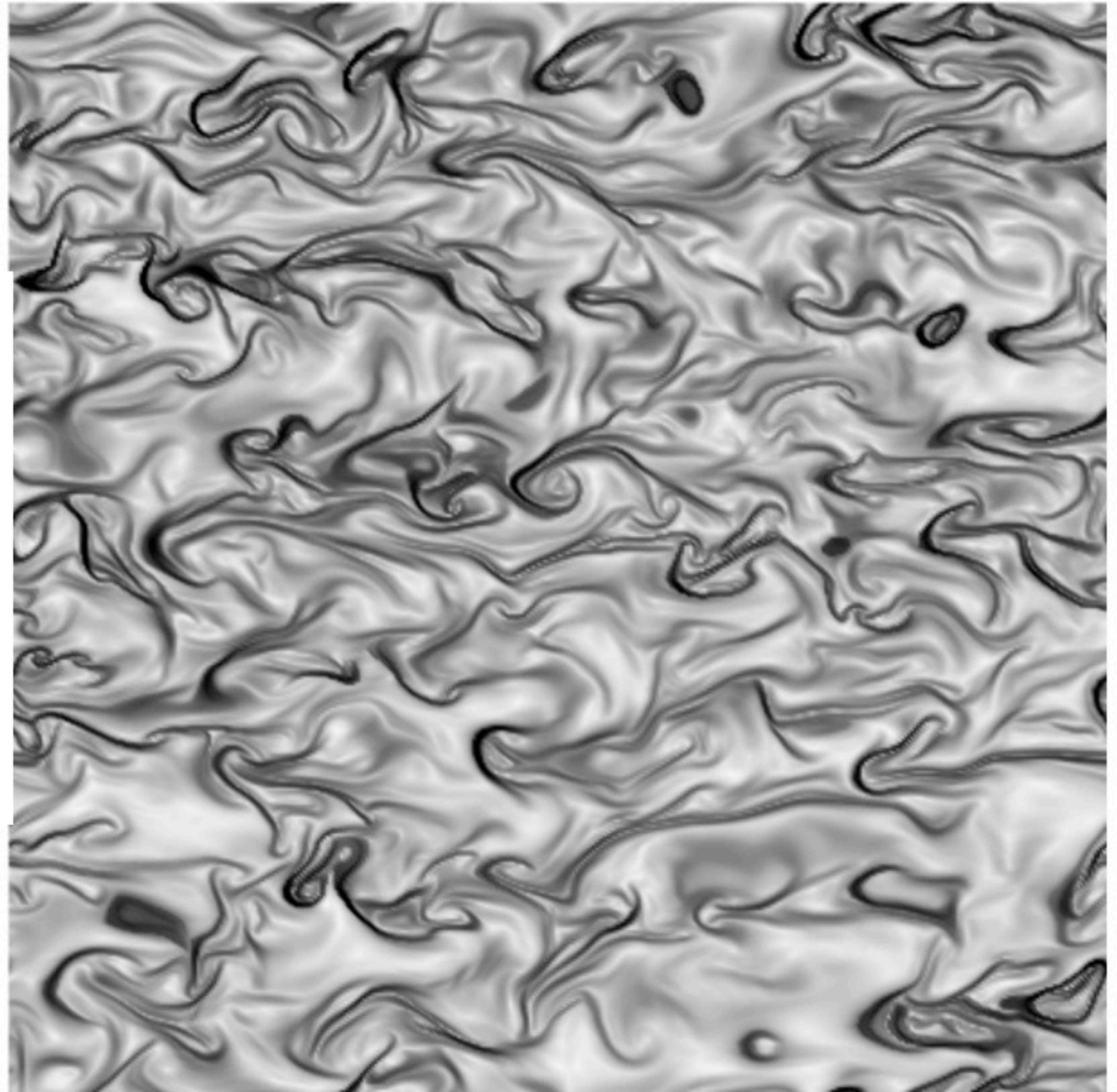


- For turbulent channel, use Taylor's hypothesis (frozen eddy) and shift velocity field by it's mean profile
 - *Advection contributed by turbulent circulations themselves is small and therefore the advection of a field of turbulence past a fixed point can be taken to be entirely due to the mean flow*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

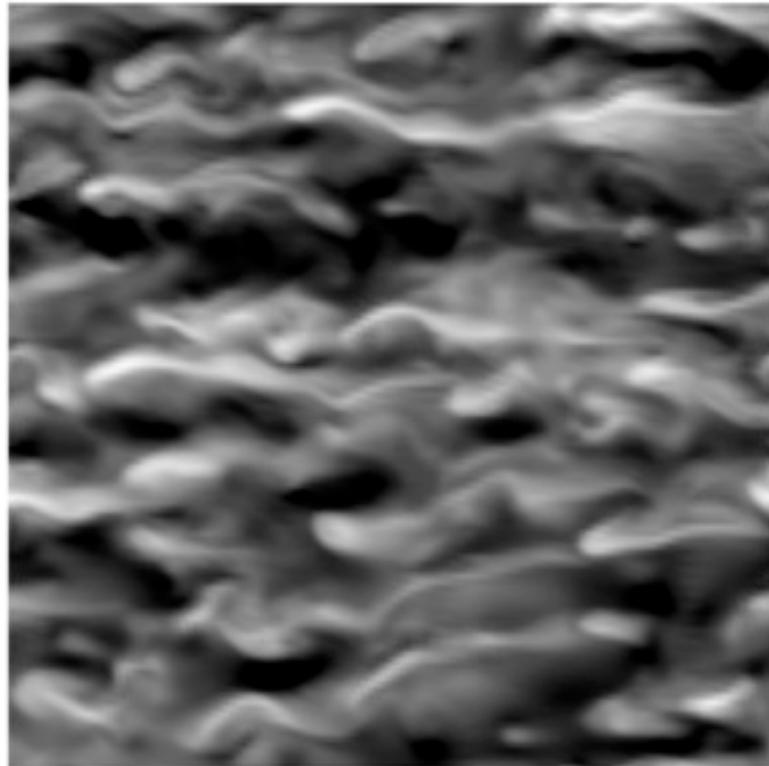
nFTLE using shifted velocity fields



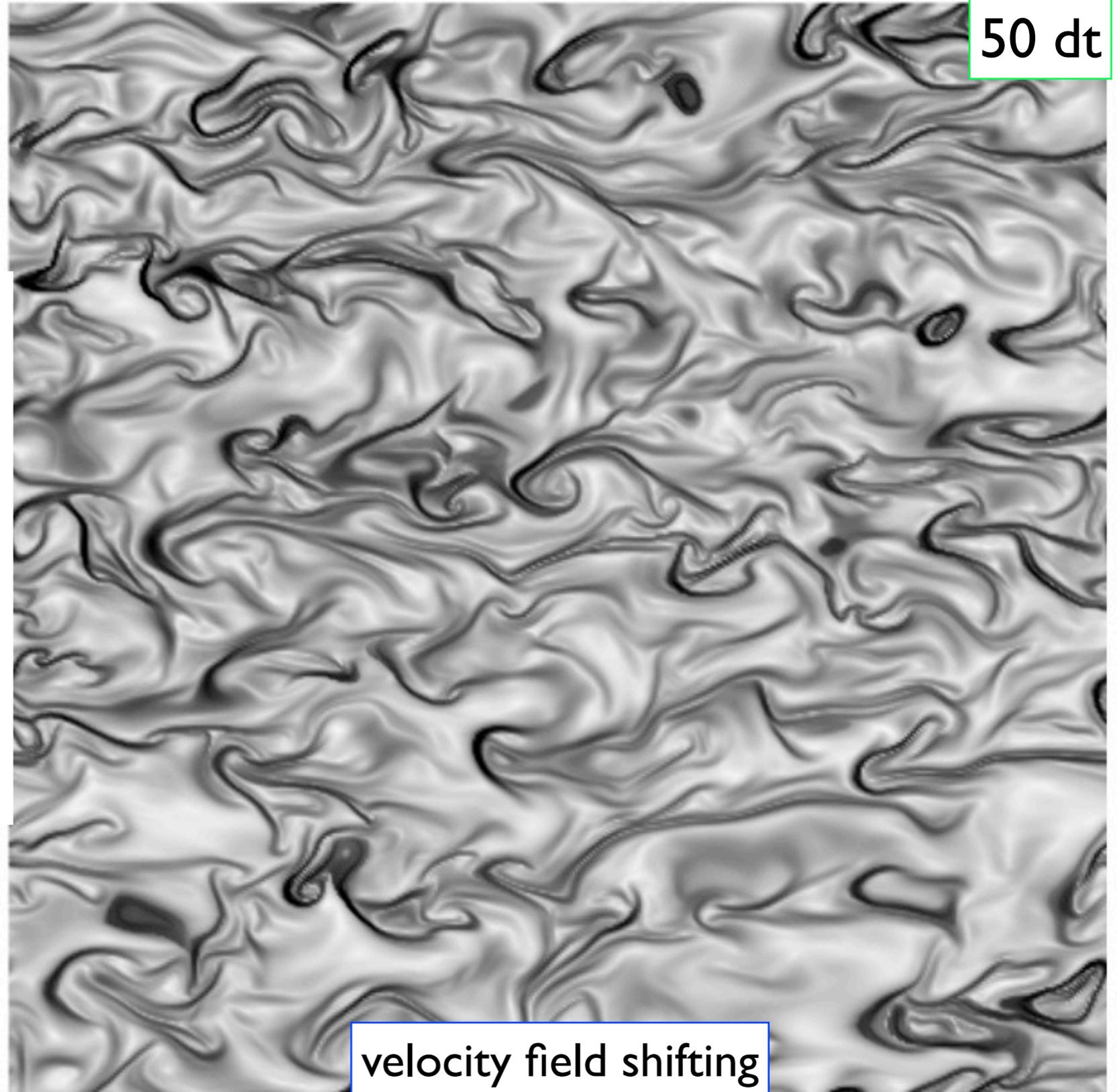
streamwise
velocity



nFTLE using shifted velocity fields



streamwise
velocity

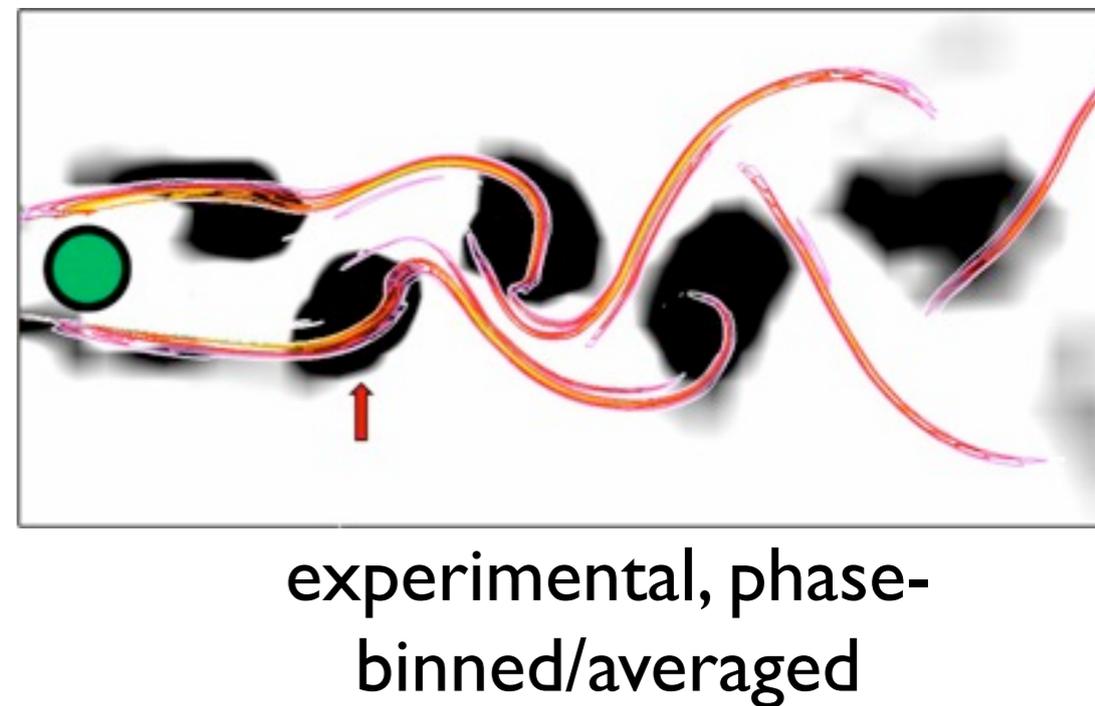
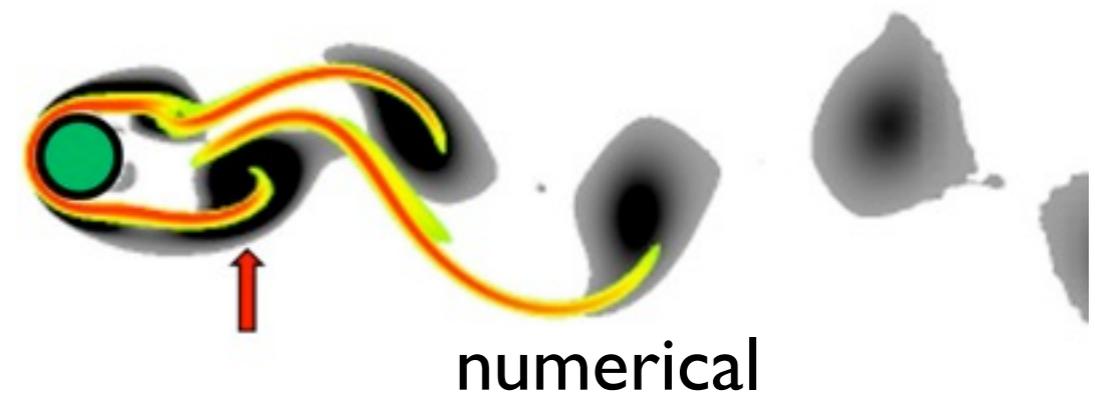


50 dt

velocity field shifting



- Smarter, more flexible models out there (Tu & Rowley, Exp Fluids 2013)
- Still need to be careful about limitations of velocity field estimation scheme - what's it doing to the structures?
- Phase-binning/averaging, loss of vorticity



Summary

- FTLE powerful, but not for use in isolation
- Need to be aware of what general flow behavior will be, need data resolution in time/space/dimension
- How to quantify poor LCS performance?
- What quantities can we use to predict bad LCS performance? (must be available from under-resolved data)

*Thanks: Matthew Rockwood, Thomas Loiselle, Jacob Morrida
Kunihiko Taira (FSU)*

