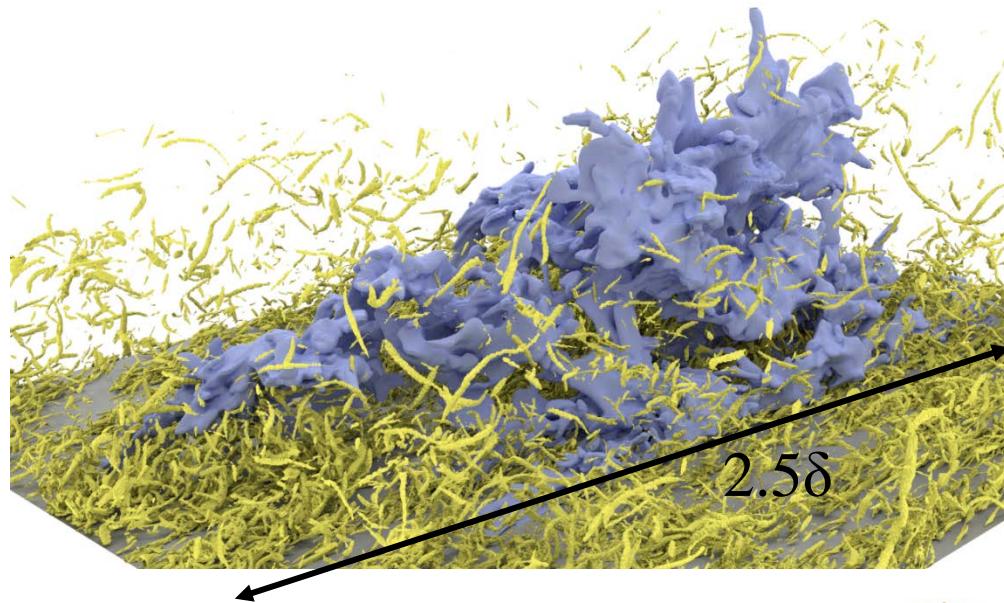


The power of data: Exploring turbulence with a computer

Javier Jiménez & al.
School of Aeronautics, Madrid



TBL: $Re_\tau=1800$, $u'^+=2$
J.A. Sillero (2014)



Laminar



Turbulent



Slow, Small

Fast, Large

Laminar



Turbulent

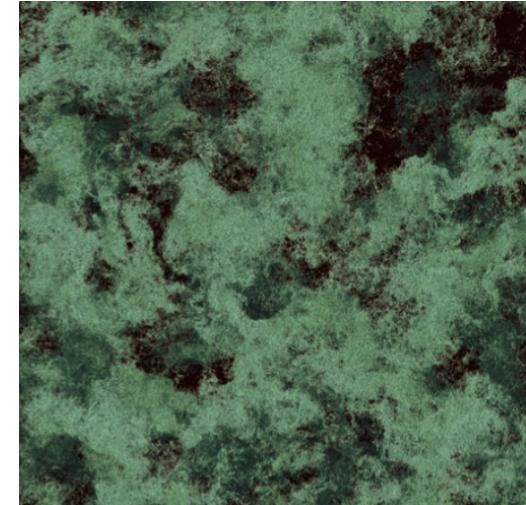
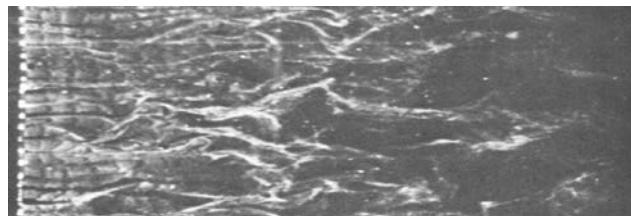
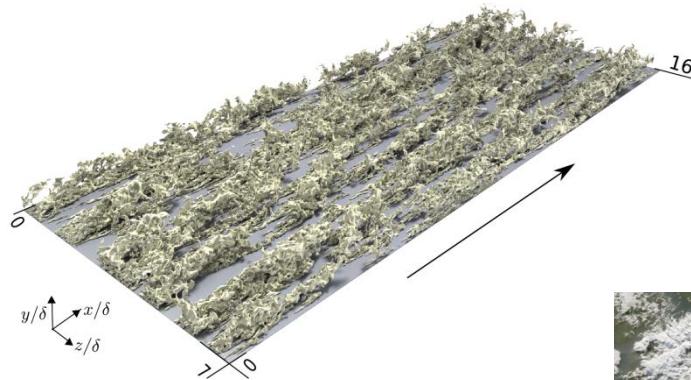


Slow, Small

Fast, Large

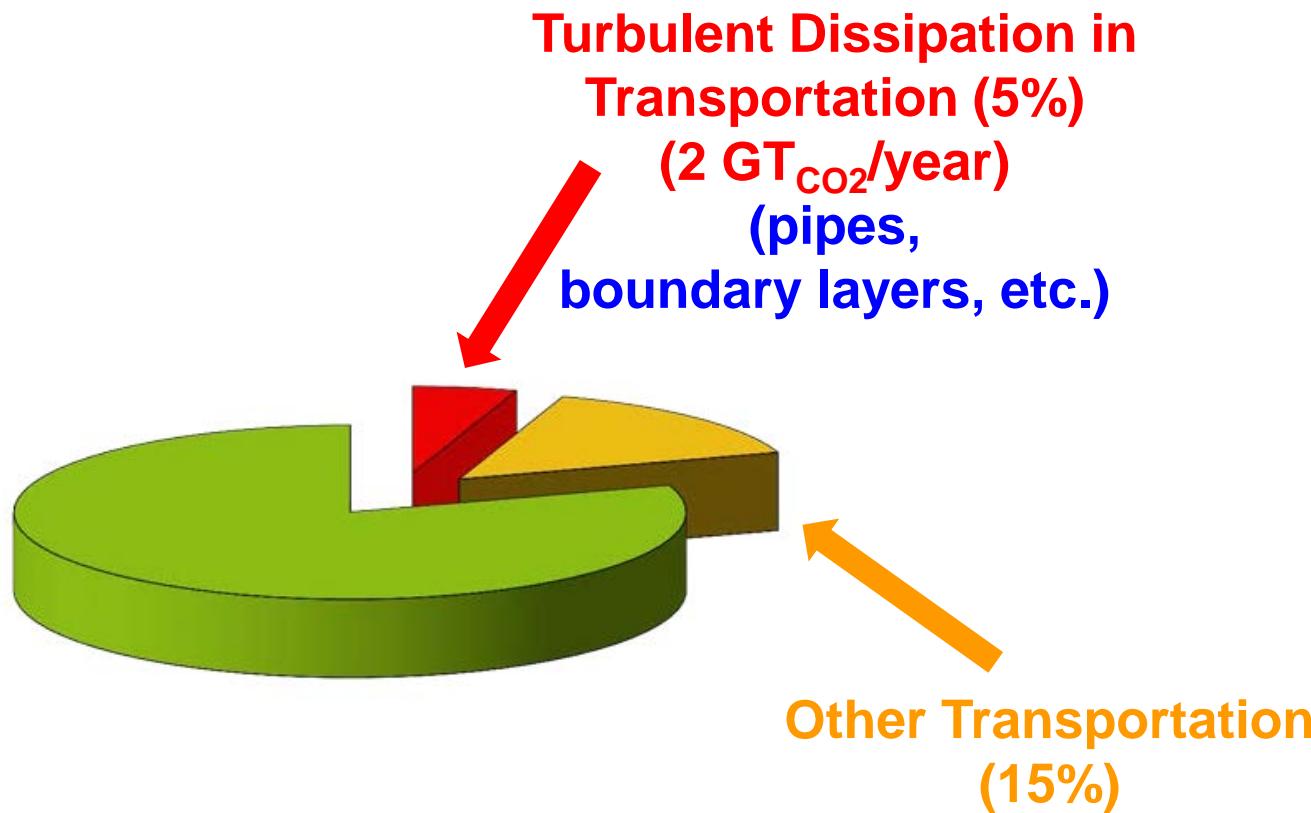
$$Re = U L/v = \text{inertial/viscous}$$

Turbulence is Everywhere



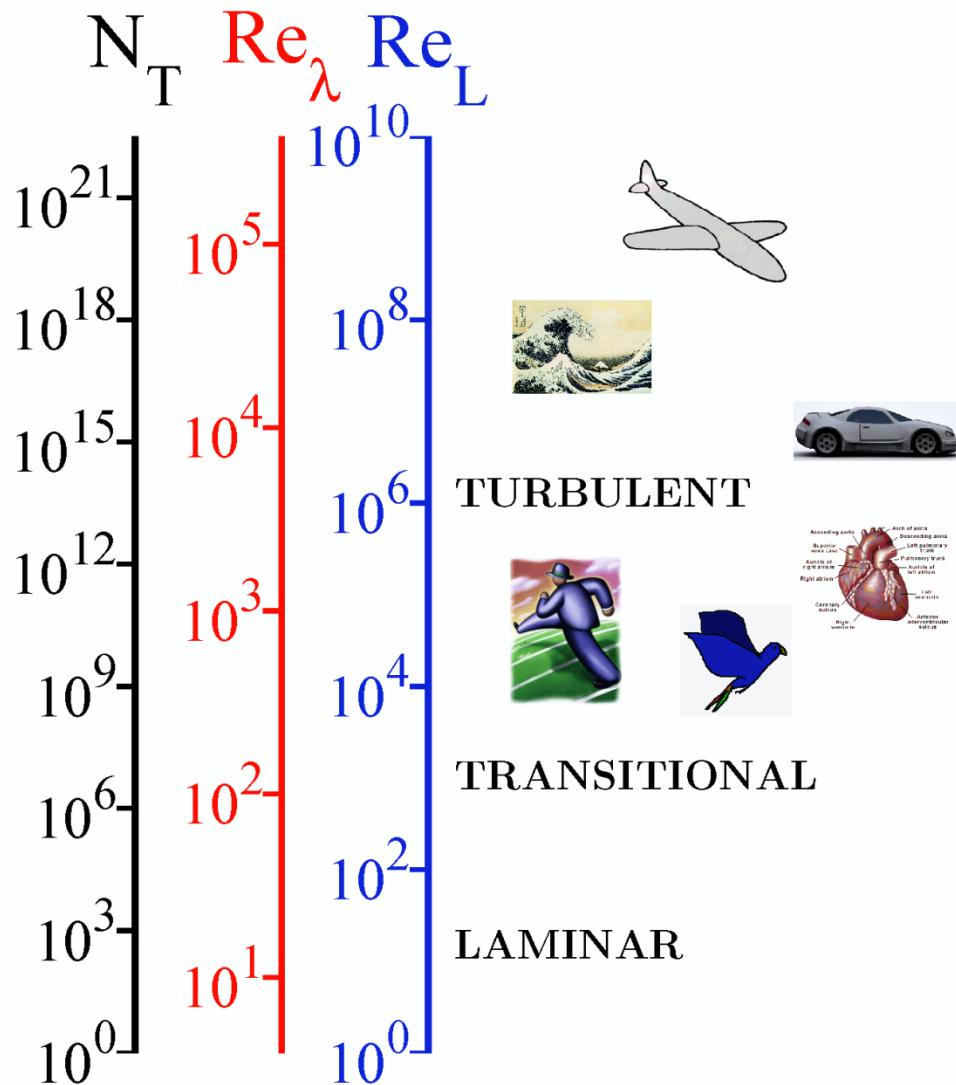
Turbulence is **Expensive**

World Energy Use

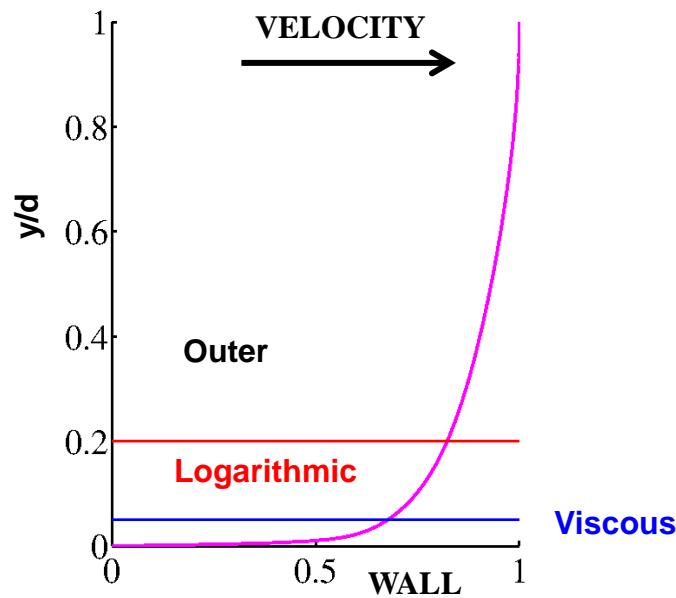


Turbulence is Large

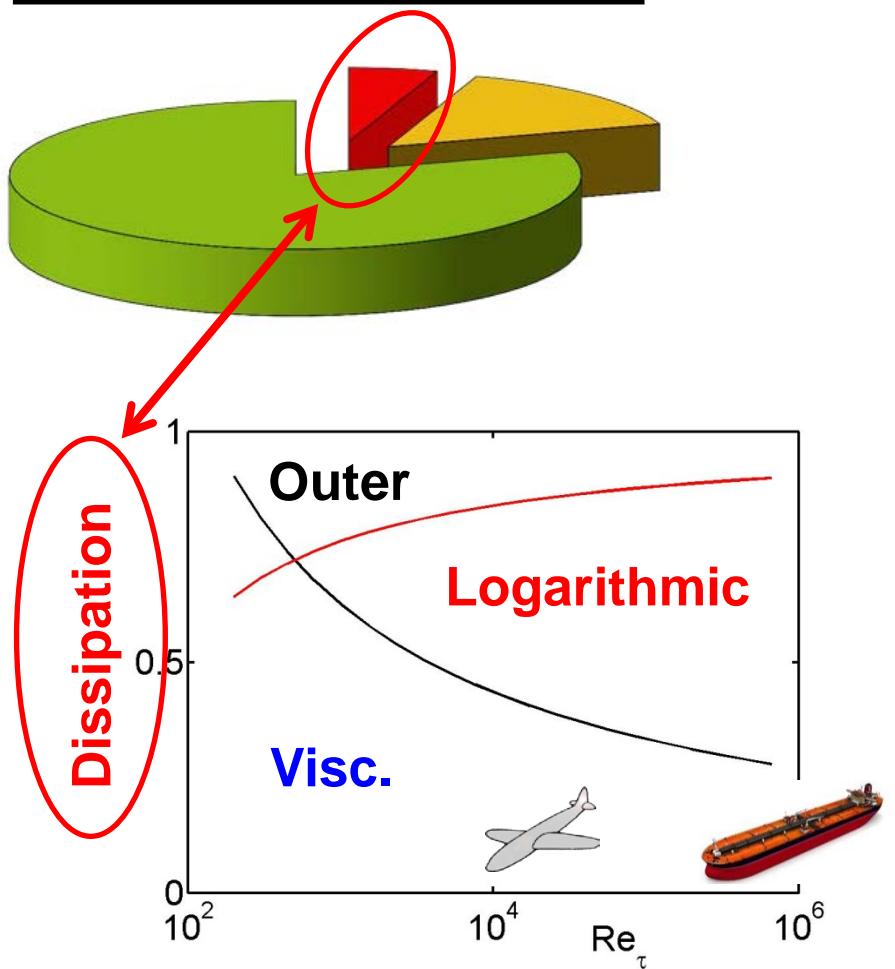
Degrees of Freedom



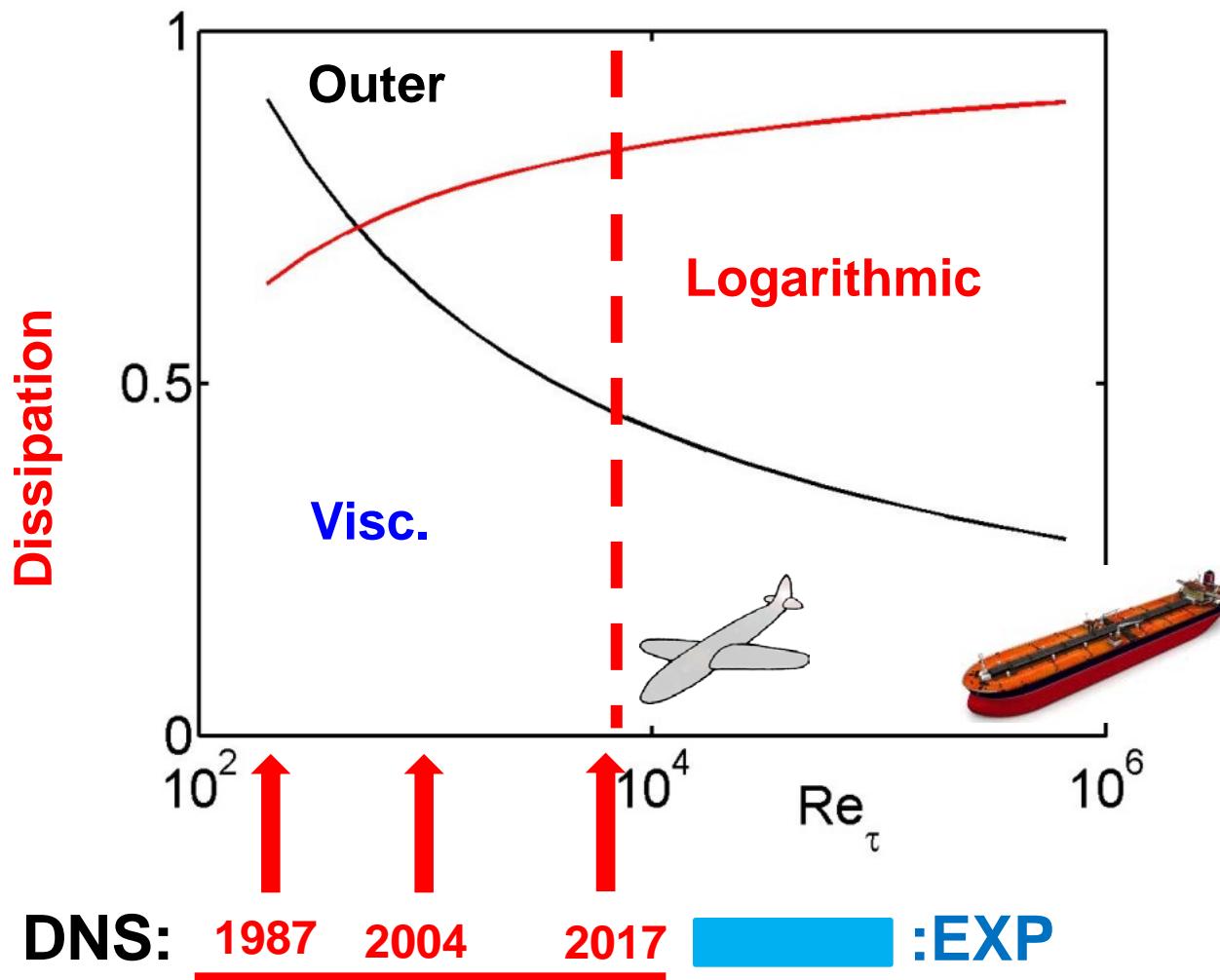
Where is dissipation happening?



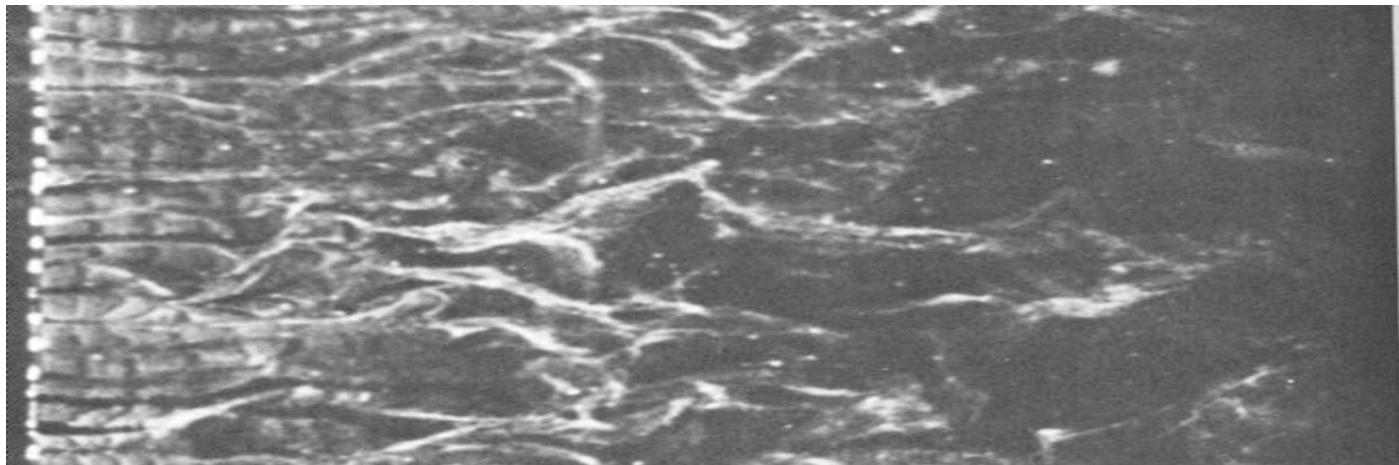
World Energy Use



Where are we now? (Re)



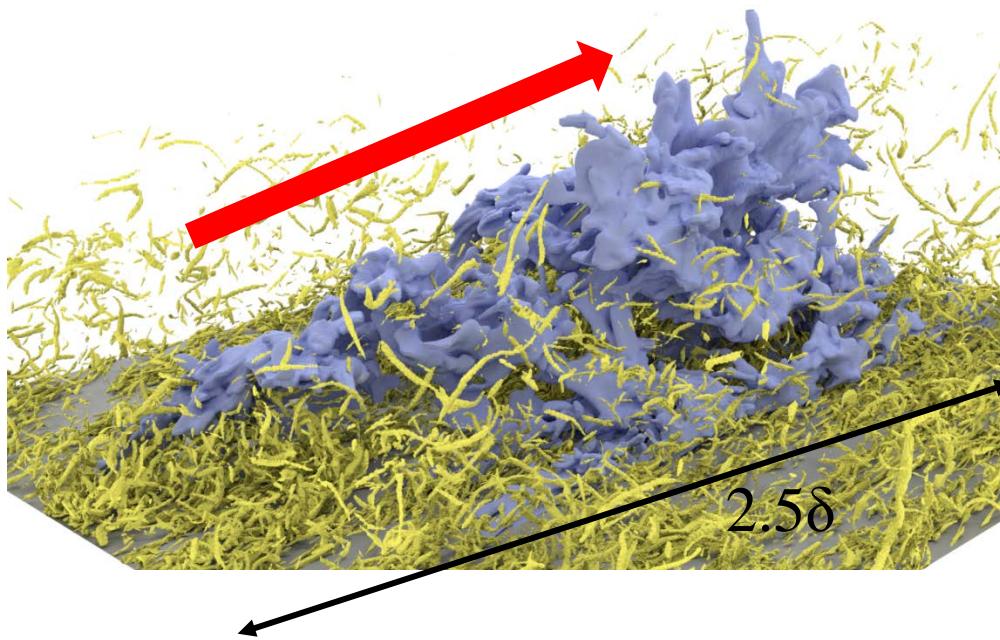
Wall Turbulence in the 1960's



Streaks, Sweeps, Ejections ..

Kline et al. (1967)

Wall Turbulence in 2014

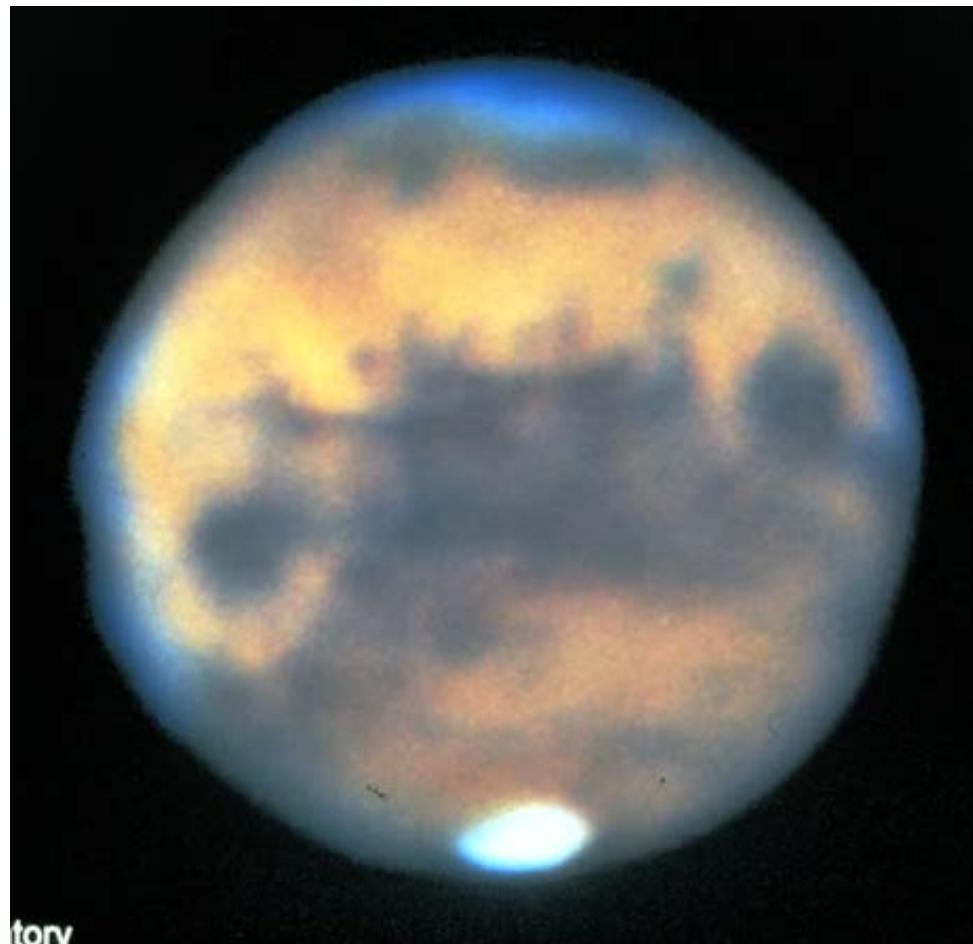


TBL: $\text{Re}_\tau=1800$, $u'^+=2$
J.A. Sillero (2014)

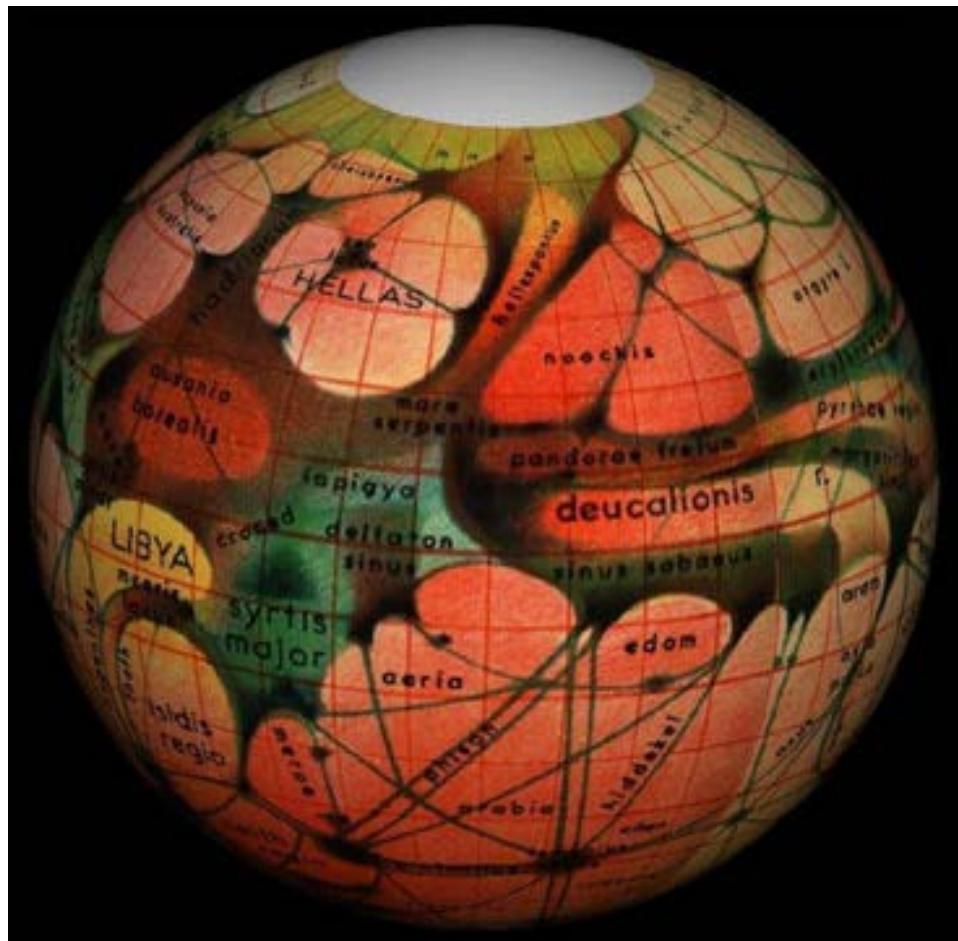
Turbulence

- Before 1990s: **Data-driven**
- After 1990s: **Analysis-driven**

Mars in the 1950's



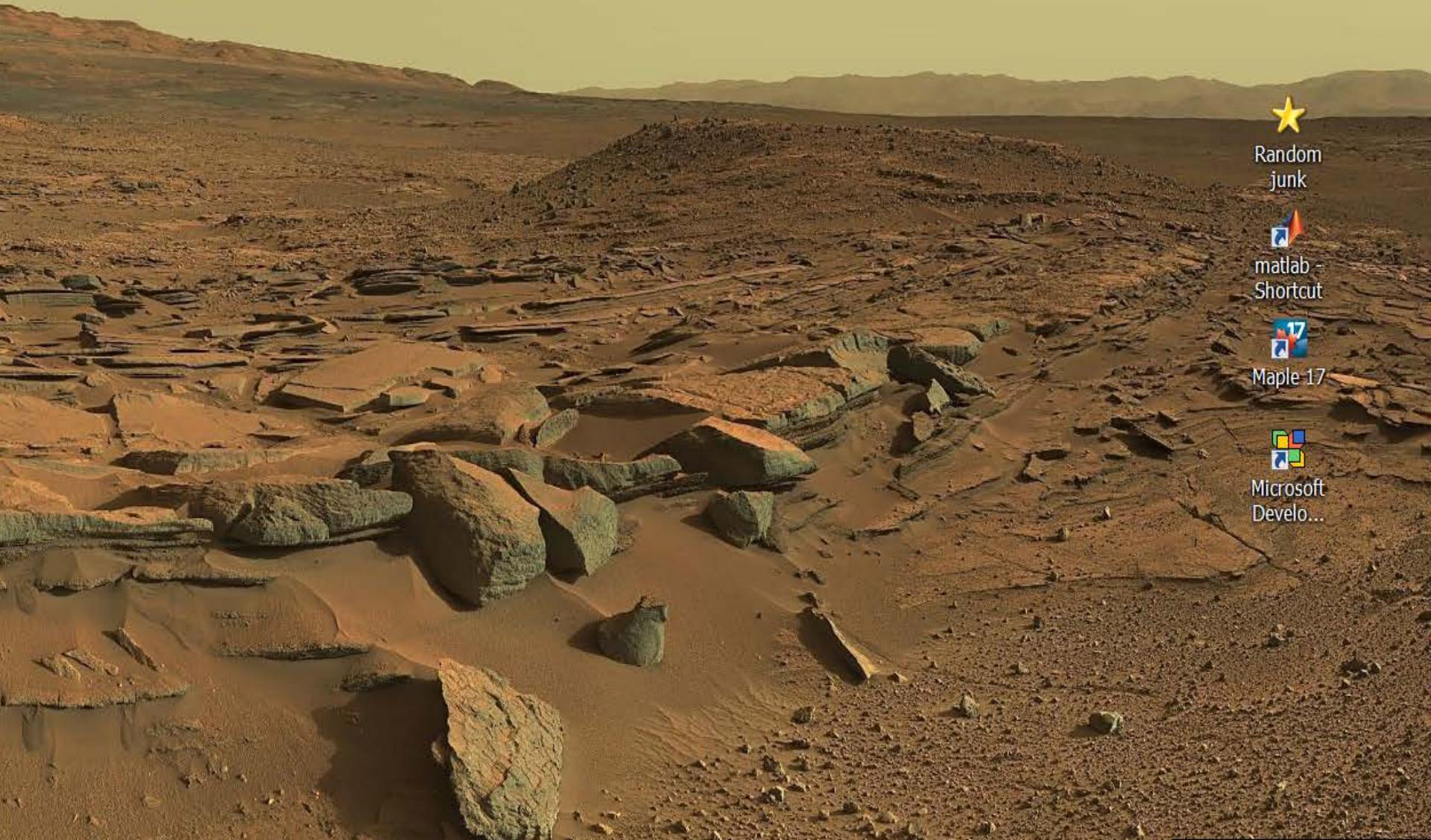
Mars in the 1950's





Comm...
Prompt

Mars in the 2010's





Comm...
Prompt

Mars in the 2010's



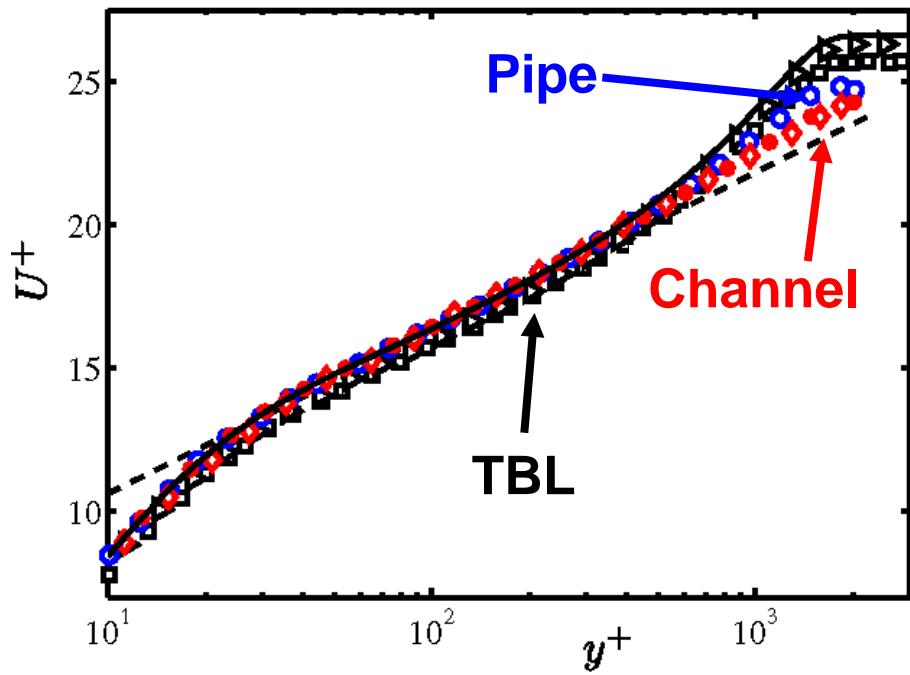
Example #1:

Turbulence in ‘1D’

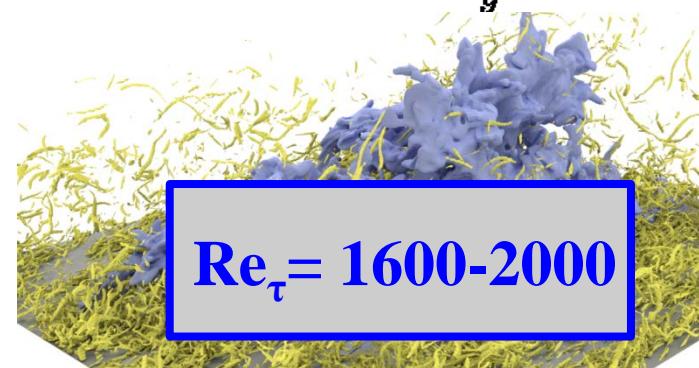
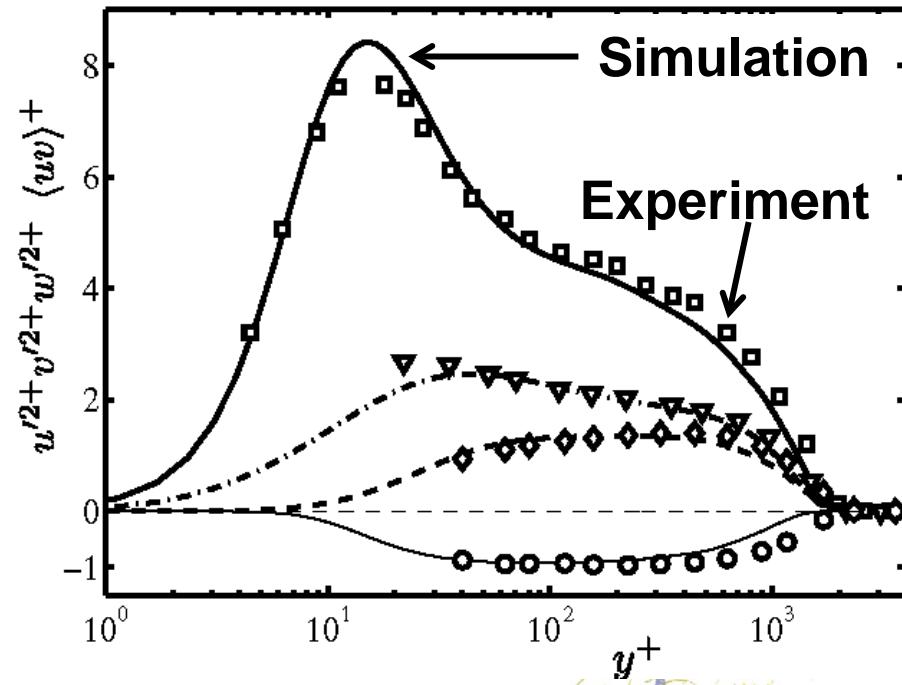
One-point statistics

One-point Statistics Boundary Layers

Mean Velocity

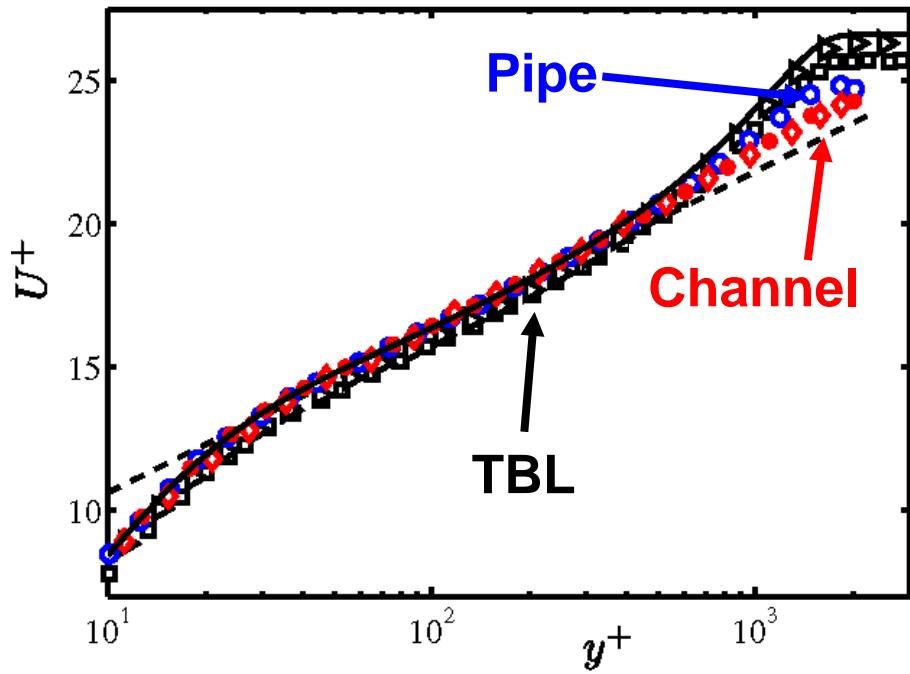


Fluctuations

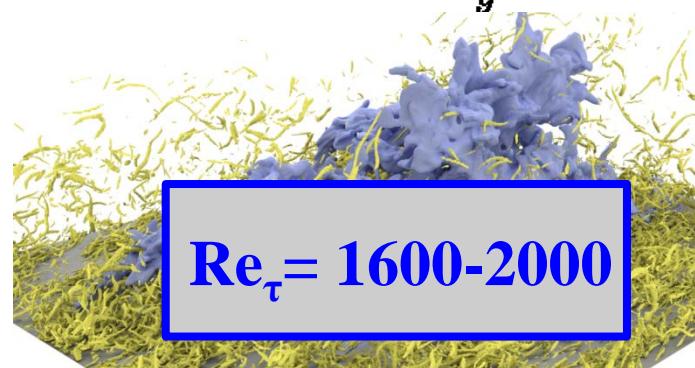
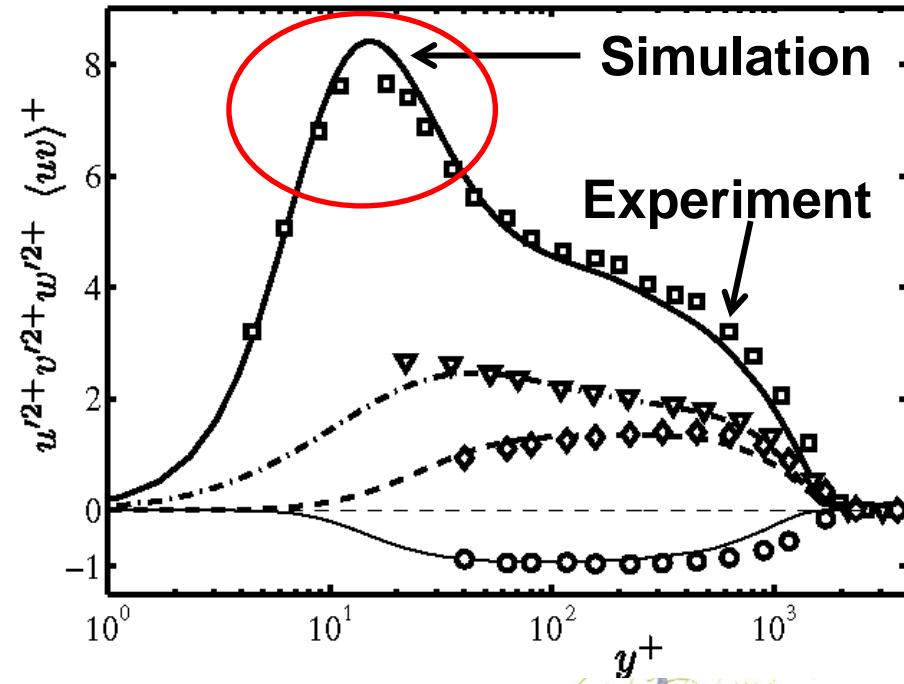


One-point Statistics Boundary Layers

Mean Velocity

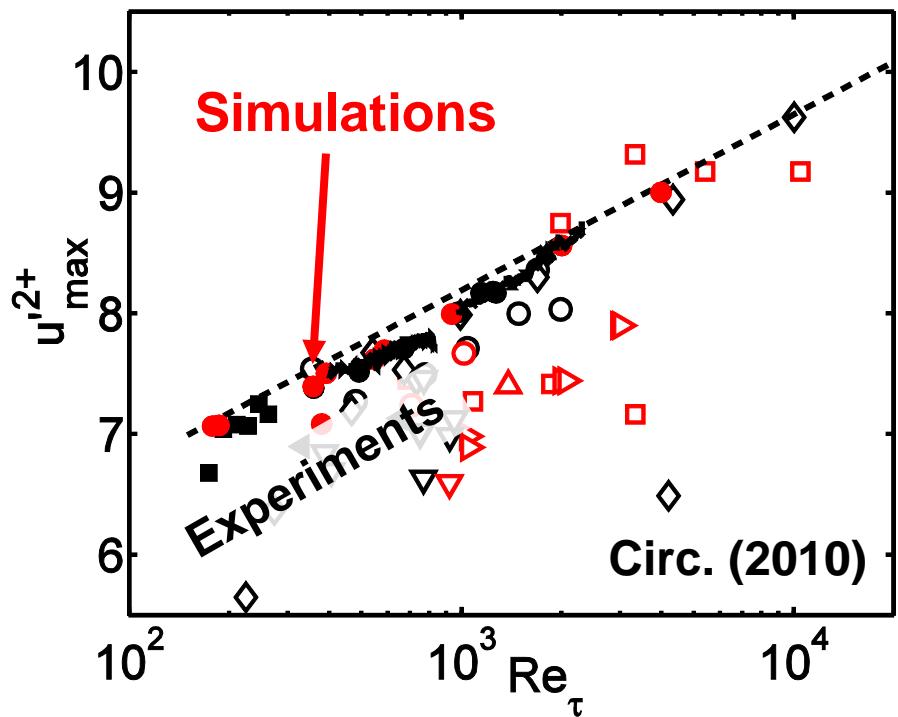


Fluctuations

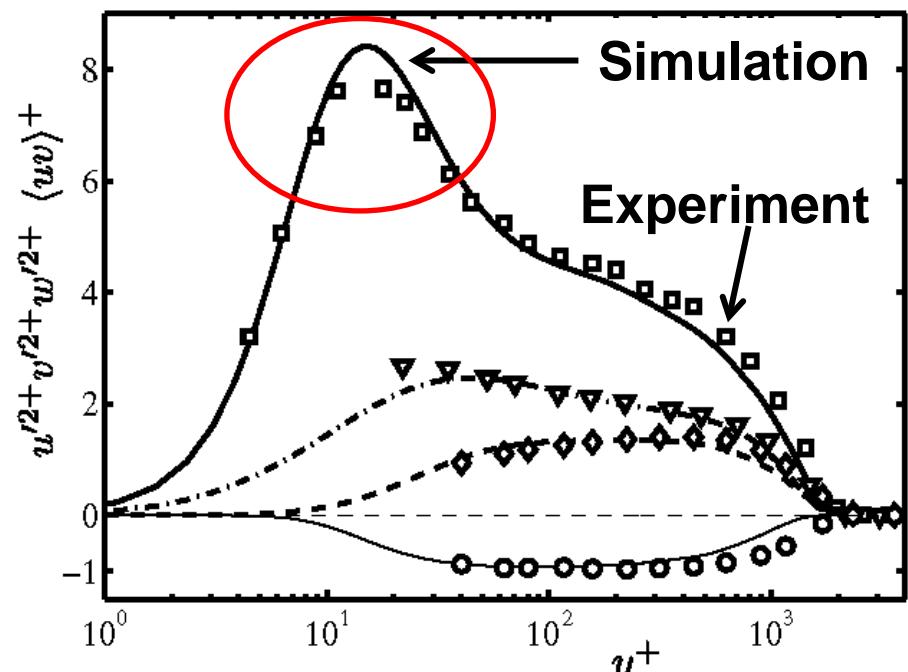


One-point Statistics Wall-bounded Flows

Maximum Fluctuations

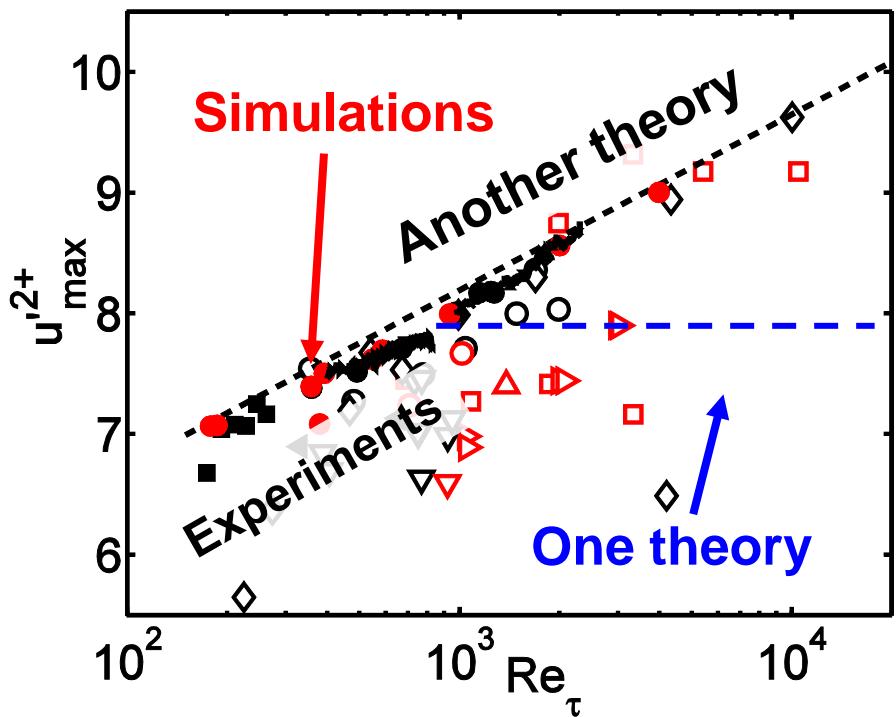


Fluctuations

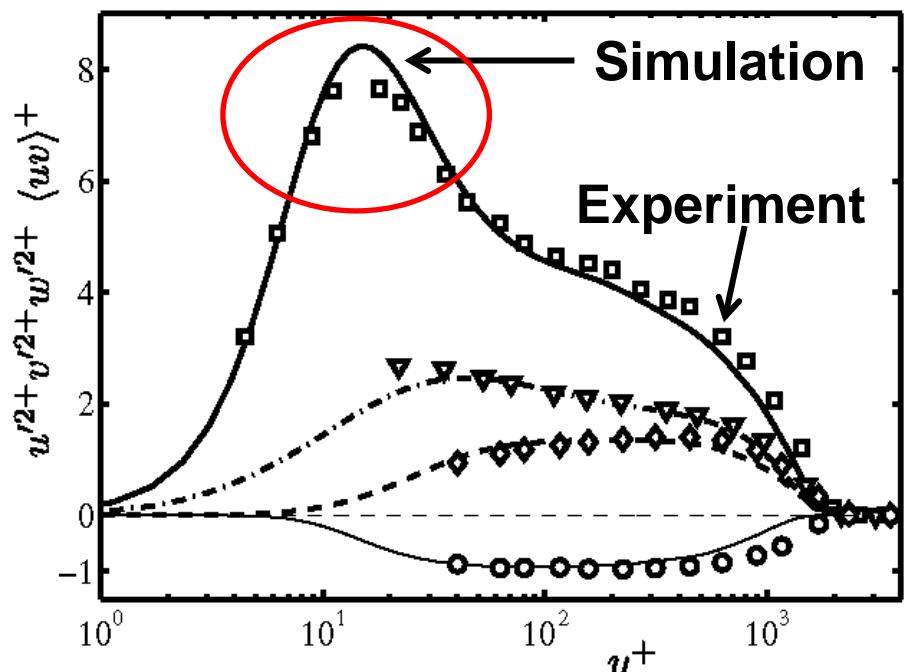


One-point Statistics Wall-bounded Flows

Maximum Fluctuations

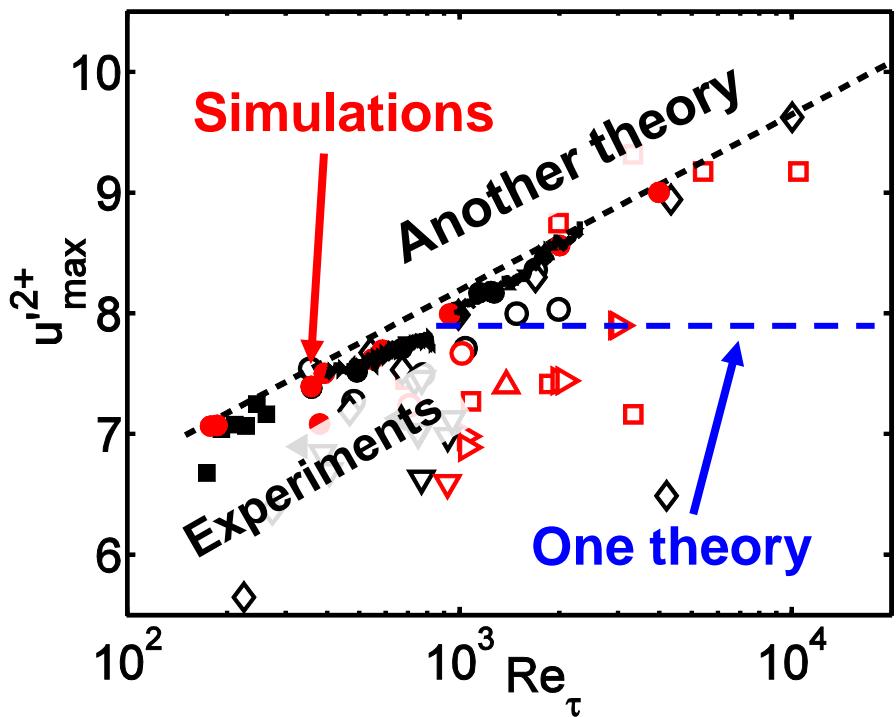


Fluctuations

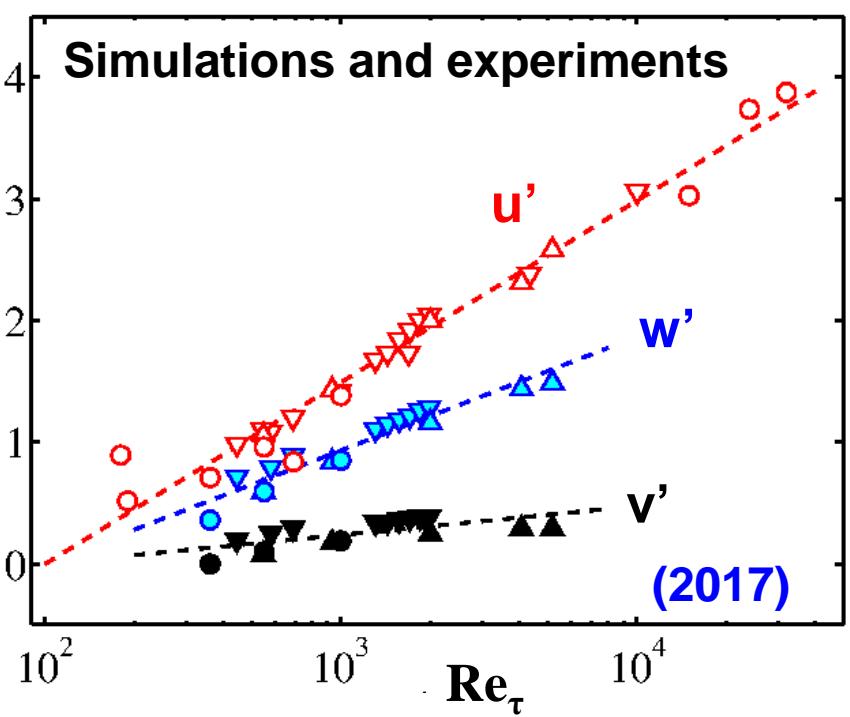


One-point Statistics Wall-bounded Flows

Maximum Fluctuations



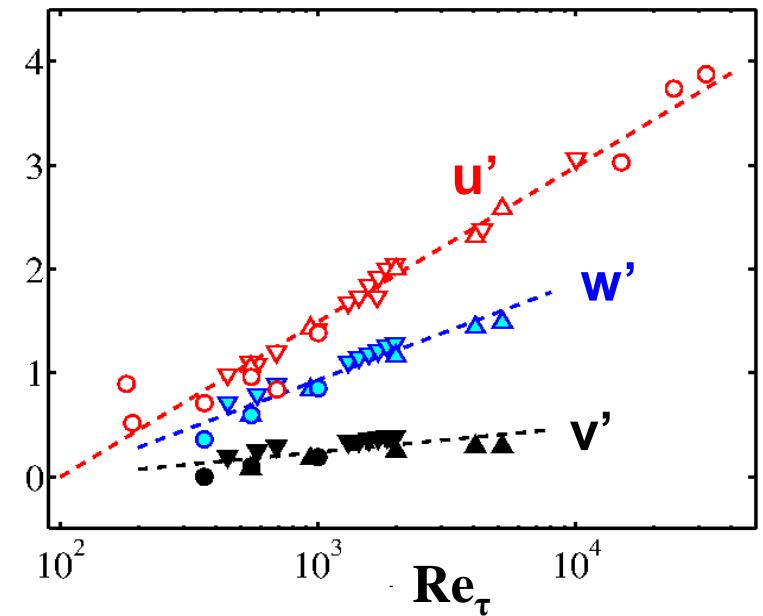
Maximum Fluctuations



One-point Statistics

Wall-bounded Flows

- 1D turbulence
- ~150 Mcpu/BGh
- ~30 TB
- Public unrestricted access
- Highly used



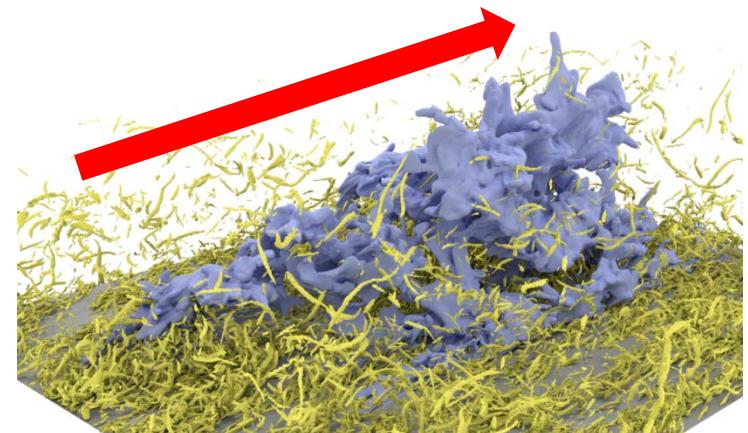
Turbulence in ‘(3+1)D’ (geometry + time)

**Coherent structures
in wall-bounded flows**

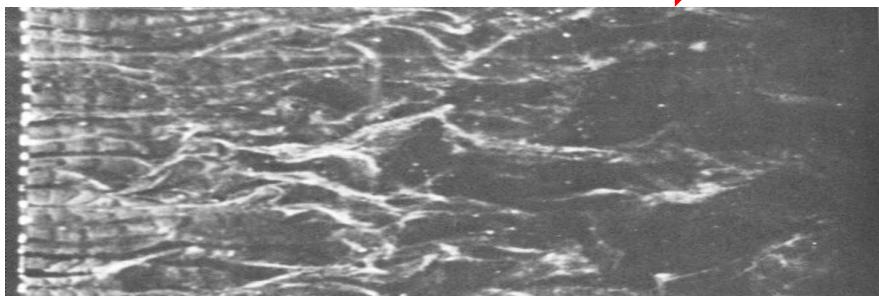
Turbulence Structures

$$\partial_t \text{structure} = f(\text{structure}) + \dots$$

- **Strong**
- **Dynamics**
- **Observable**
- **Relevant**



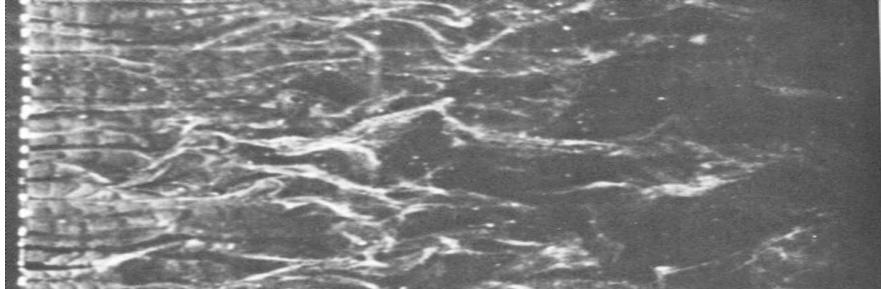
What do we know about WBT Structures?



Kline et al. (1967)

Streaks, Sweeps, Ejections ..

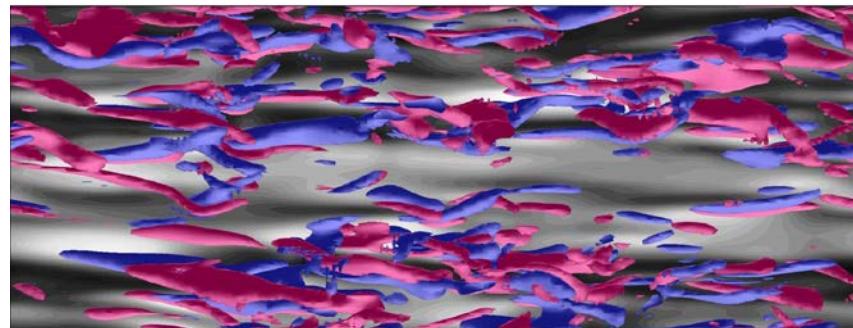
What do we know about WBT Structures?



Kline et al. (1967)

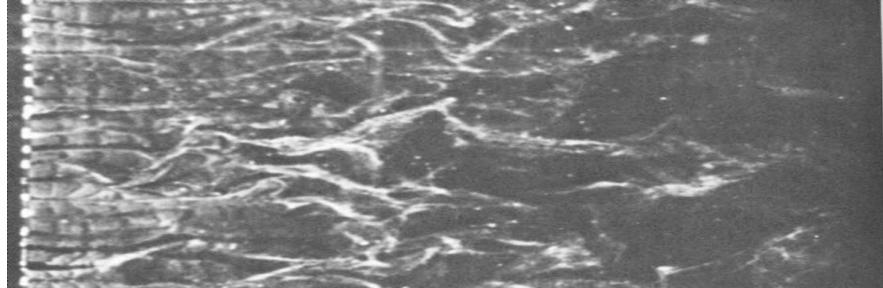
Streaks, Sweeps, Ejections ..

Velocity Streaks,
Vortices



Kim, Moin, Moser
(1987)

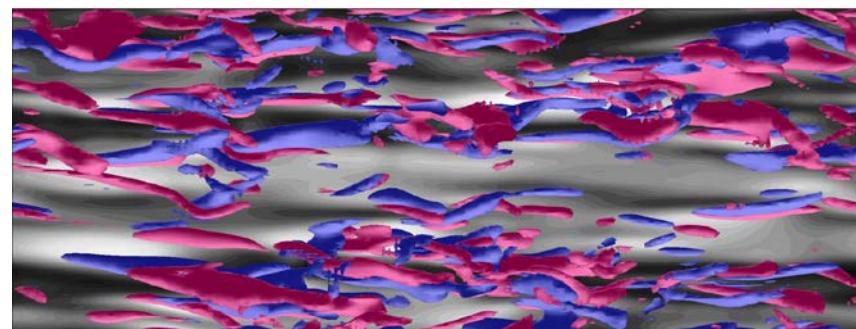
What do we know about WBT Structures?



Kline et al. (1967)

Streaks, Sweeps, Ejections ..

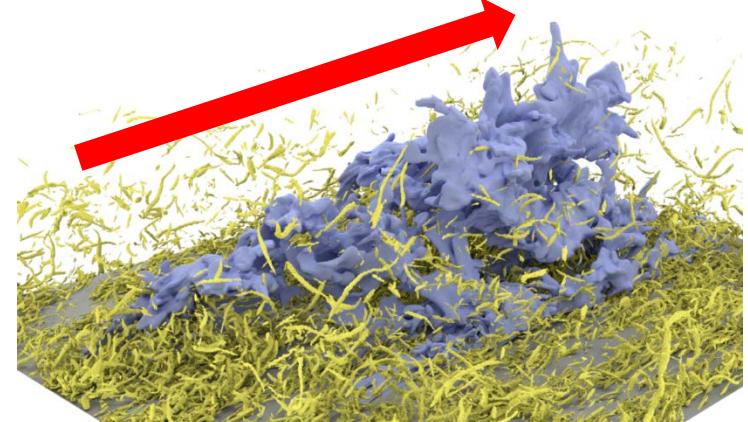
Velocity Streaks,
Vortices



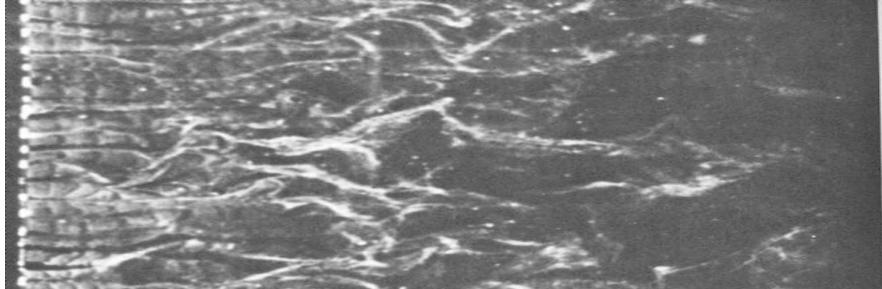
Kim, Moin, Moser
(1987)

Sillero, Jimenez, Moser (2014)

“everything”

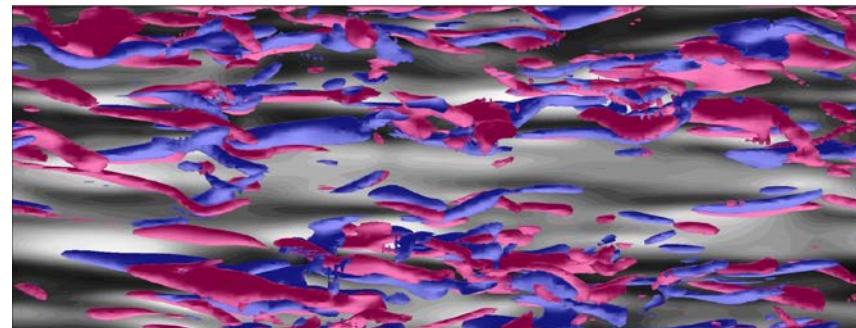


Structures of Wall-Bounded Turbulence

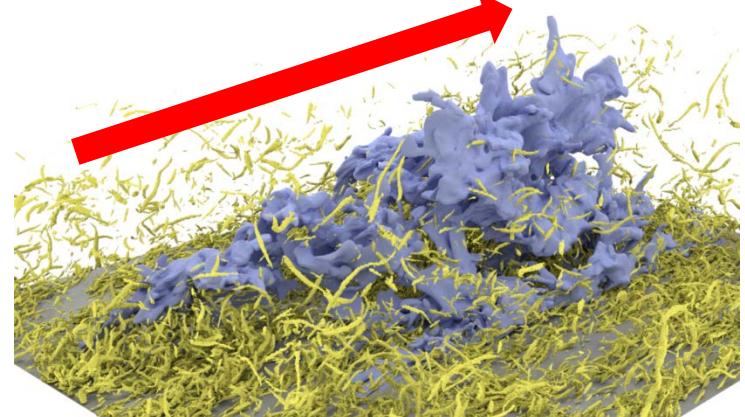


1987
(streaks, vortices)
What does it do?

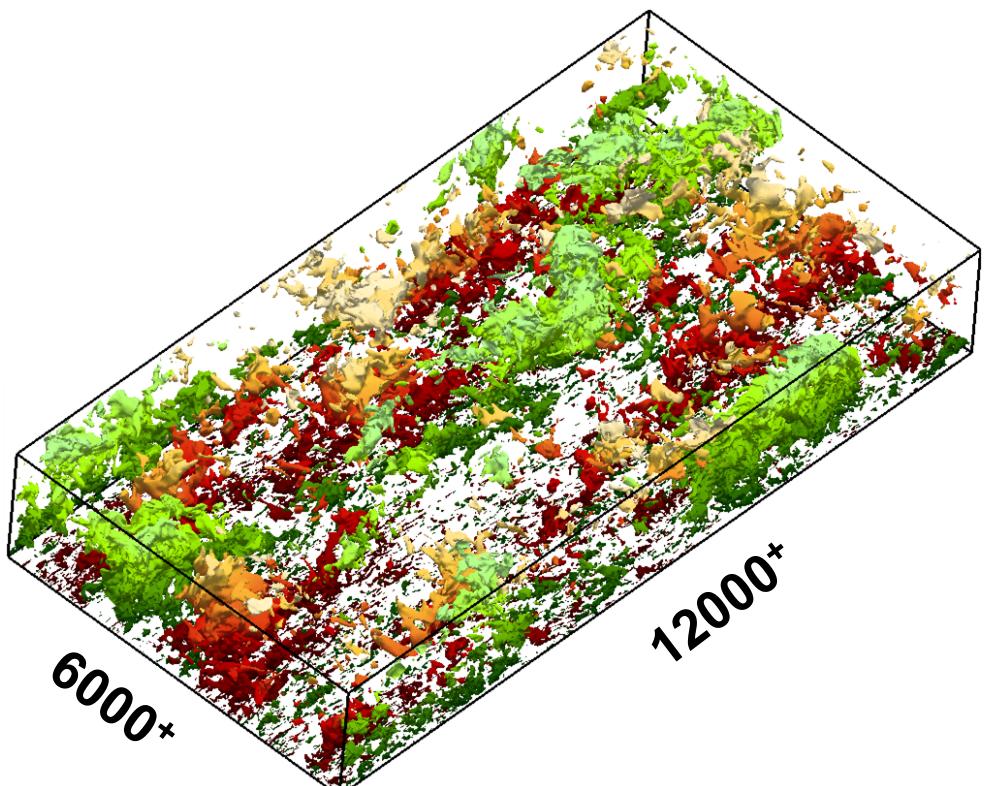
1967
(there is something there)
What is it?



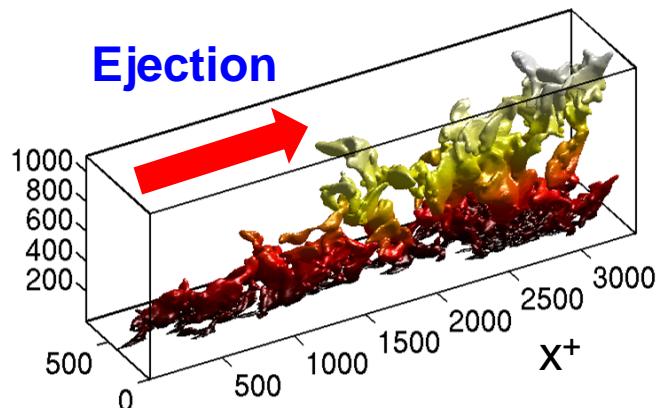
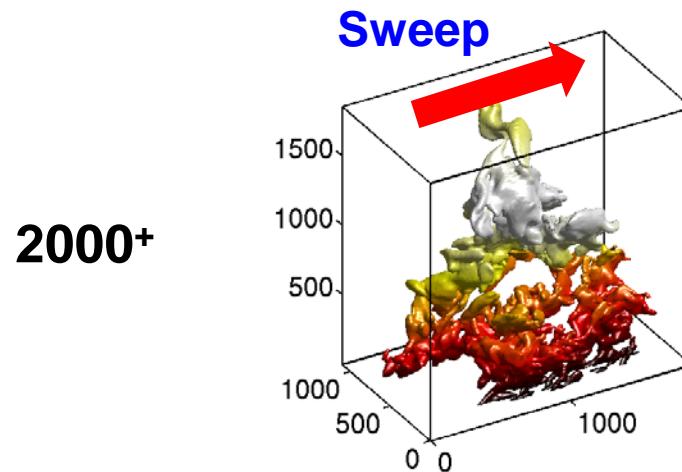
2016
(we know “everything”)
What is the question?



Momentum (\mathbf{uv}) Structures of the Logarithmic layer



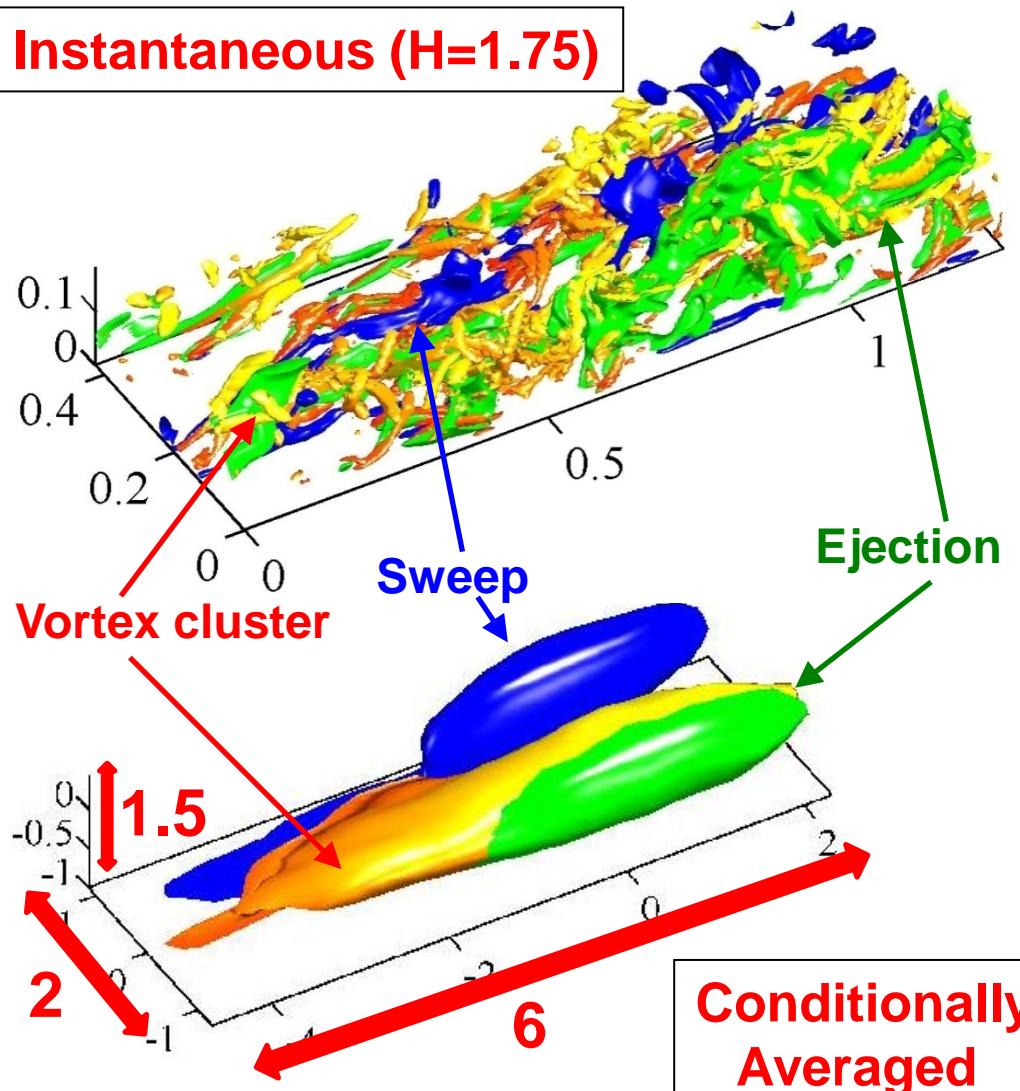
$$-uv > 1.75 u'v'$$



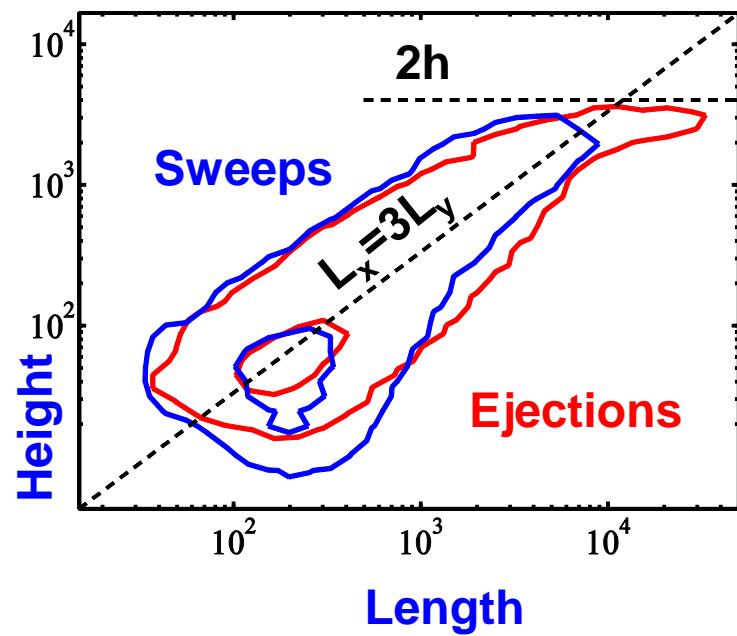
Channel: $Re_\tau = 2000$. A. Lozano-Durán

Attached Sweeps and Ejections

Instantaneous ($H=1.75$)



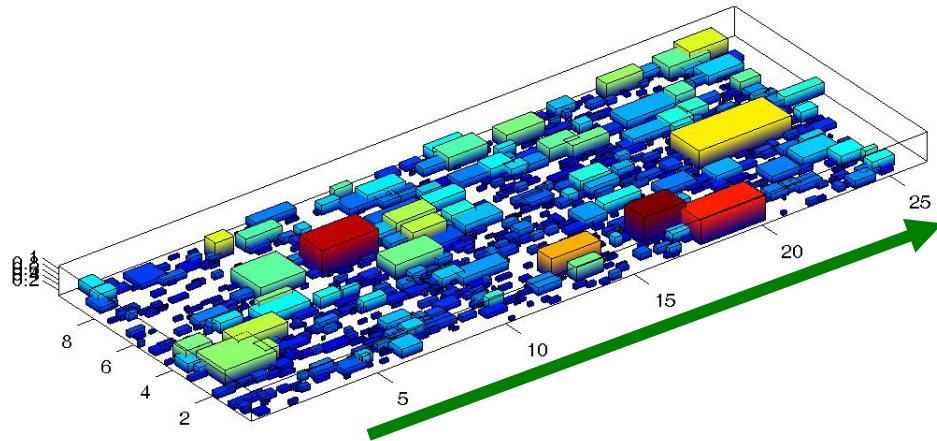
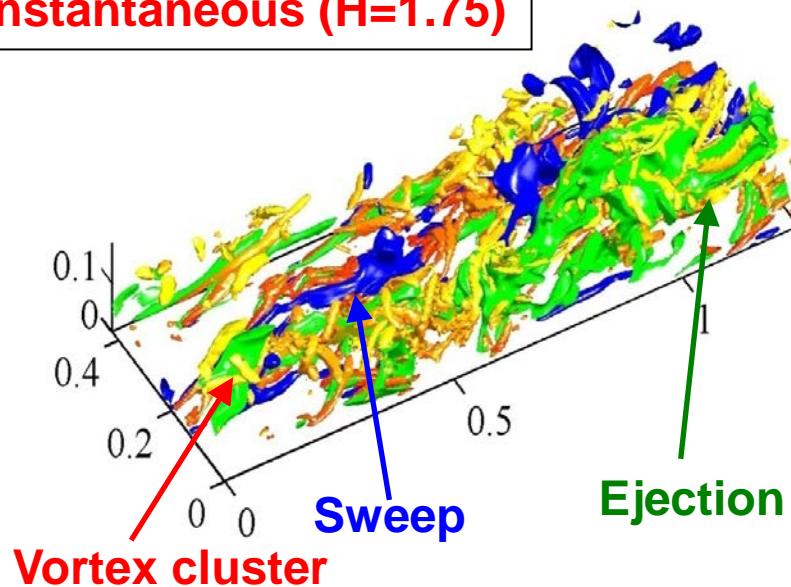
Momentum Transfer
is self-similar



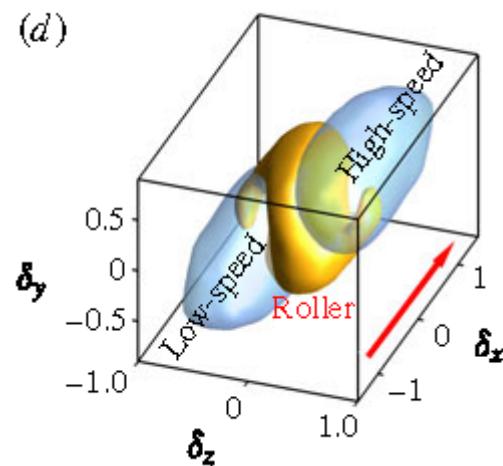
Lozano-Duran, Flores & J (2012)

Attached Sweeps and Ejections cover the wall

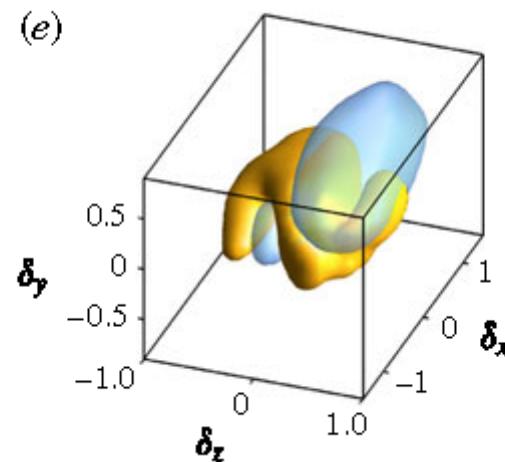
Instantaneous ($H=1.75$)



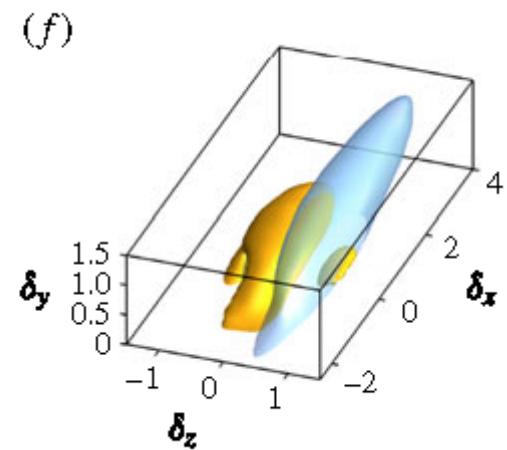
They are in most Shear Flows



No wall



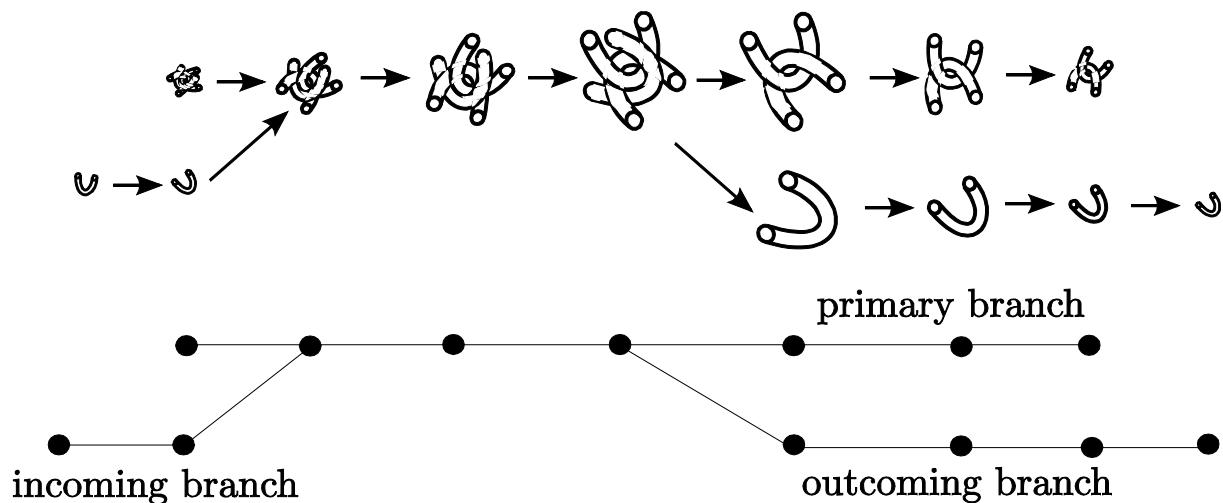
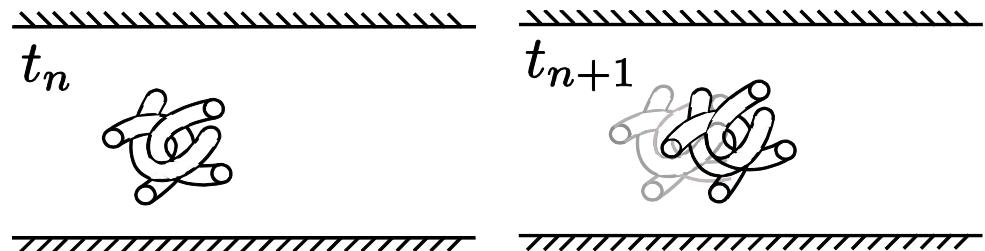
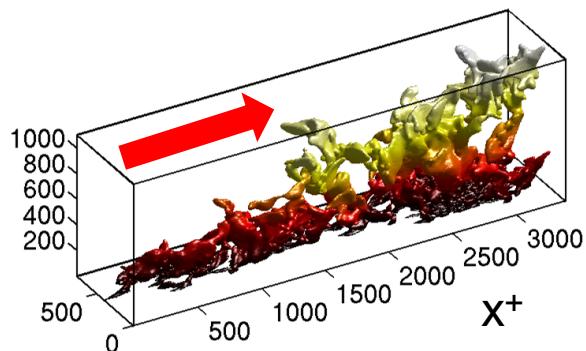
Far from wall



Attached to wall

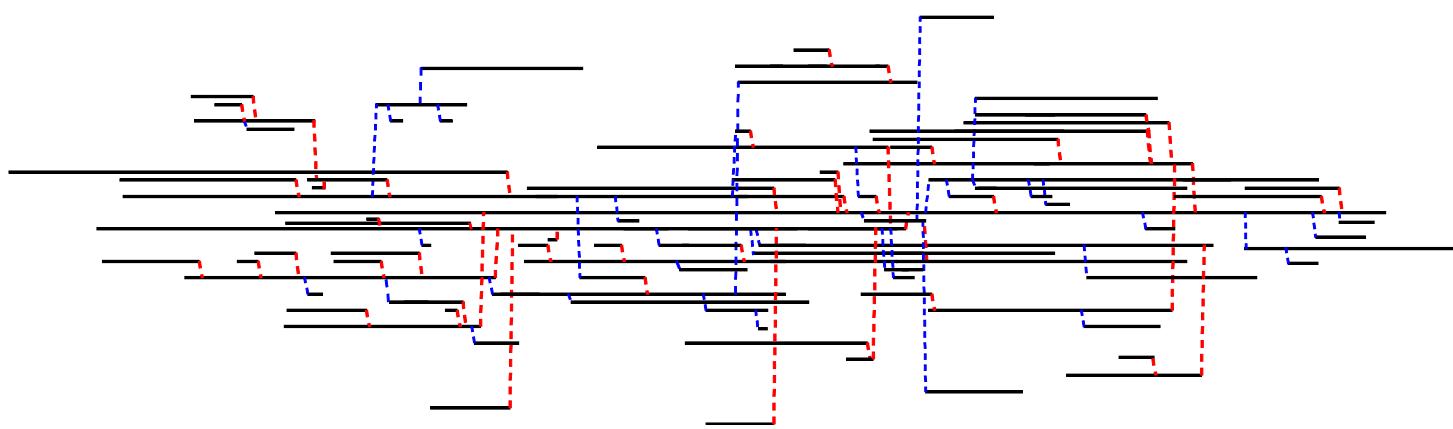
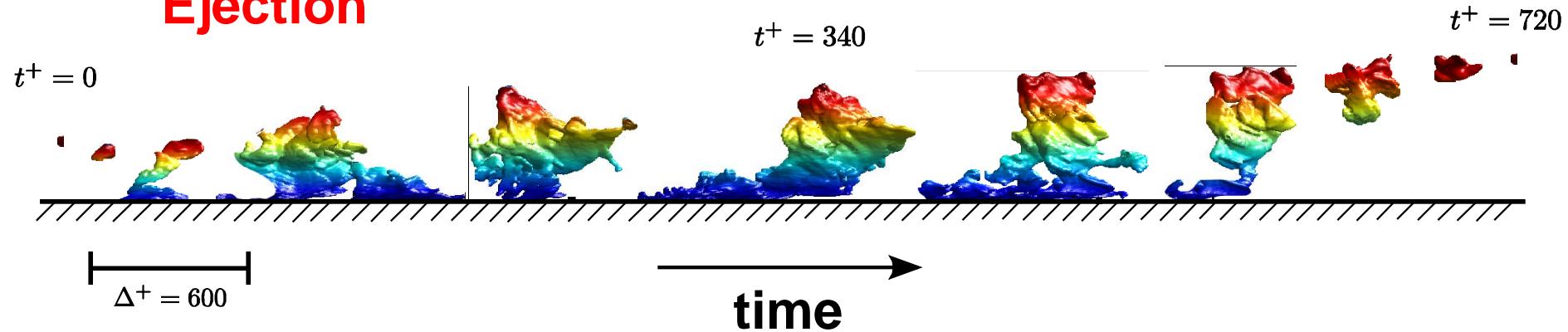
Del Alamo & al (2006), Lozano & al (2012), Dong & al (2017), ...

Tracking Eddies in Time



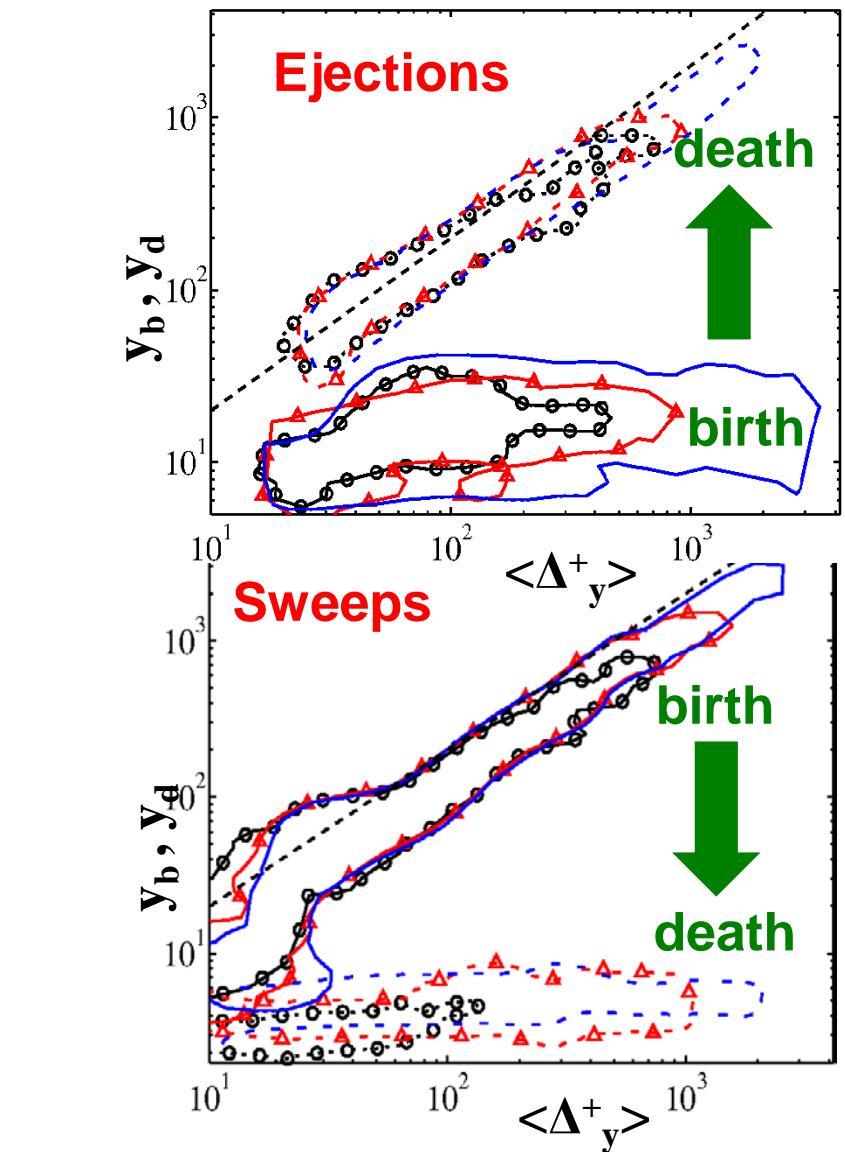
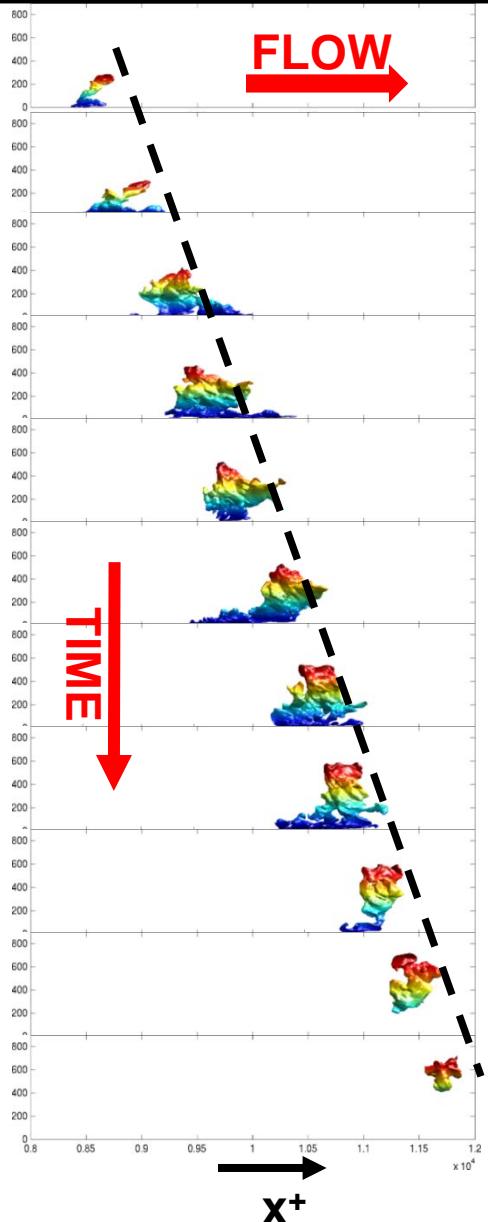
Tracking in Time

Ejection



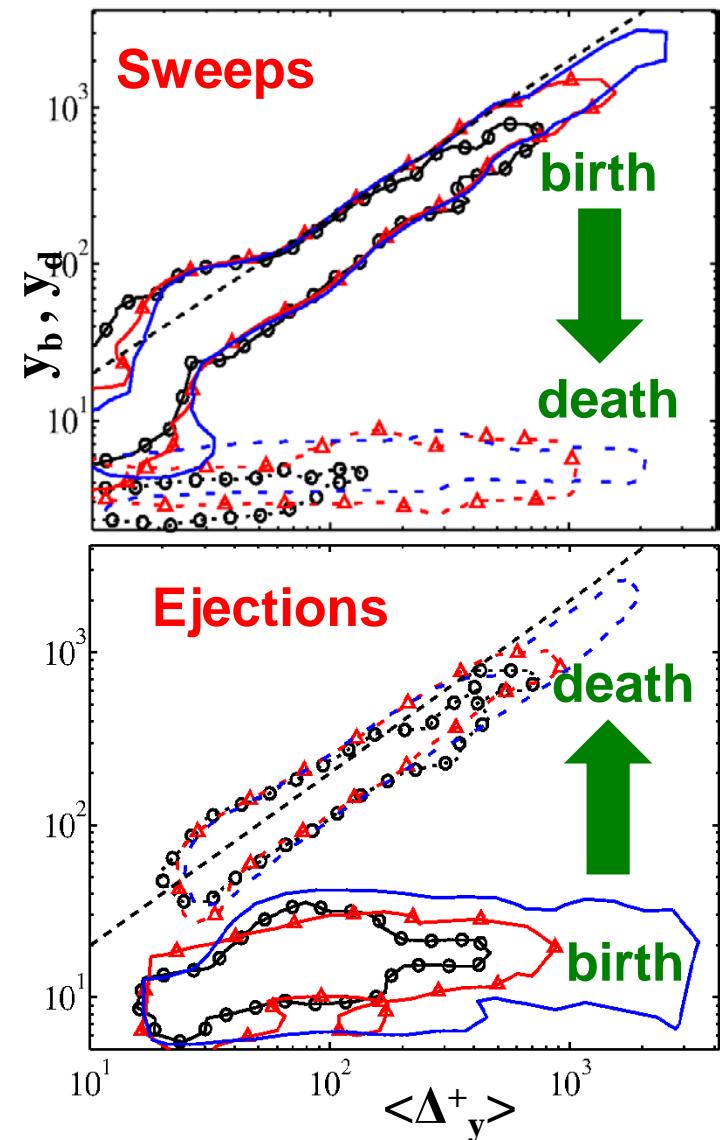
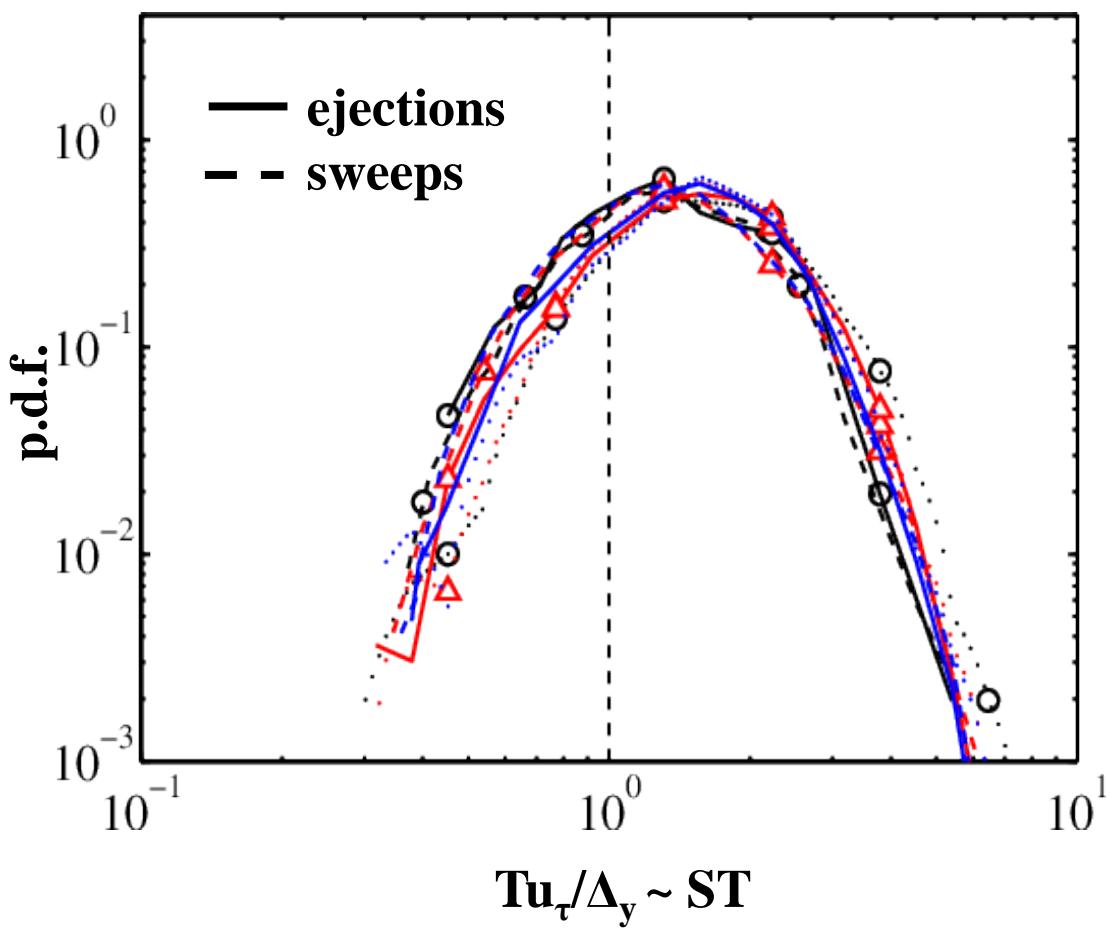
Tracking in Time

Ejection



Channel: $Re_\tau = 4200$. A. Lozano-Durán

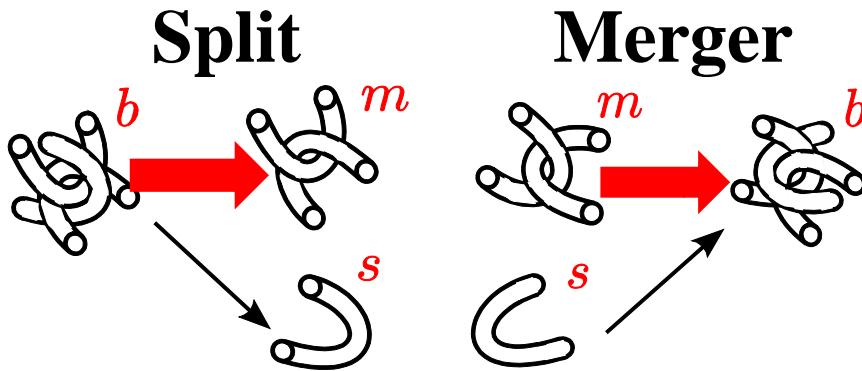
Lifetimes: Attached Sweeps and Ejections



Channels: $Re_\tau = 950-4200$

Lozano-Durán & J (2014)

Splits and Mergers



$$V_b \approx V_m + V_s$$

$$\Delta V_{\text{BRANCH}} = \Sigma |\Delta V| \approx \Sigma V_s$$

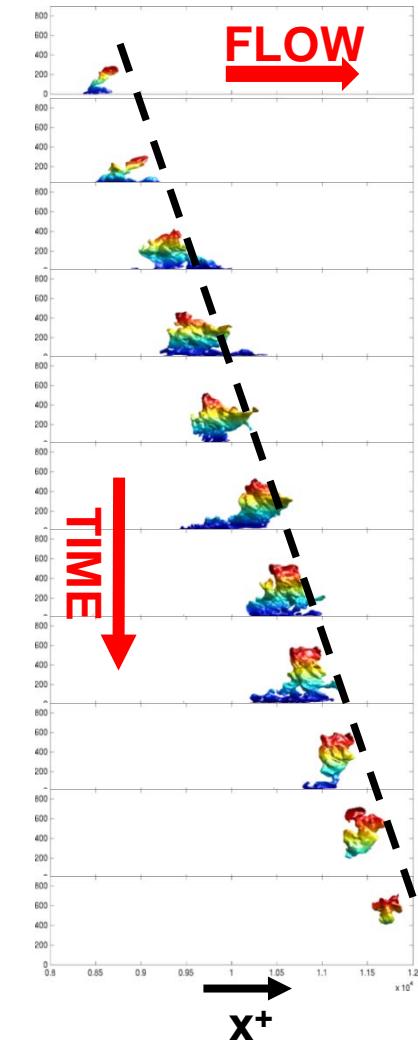
$\Delta y/\eta$	Inertial Growth	Smooth Growth
0-50	0%	100%
50-200	28%	72%
200-400	54%	46%
>400	94%	6%

$Re_\tau = 4200$; “detached”

Lozano-Durán & J (2014)

Structures in Wall-bounded Flows

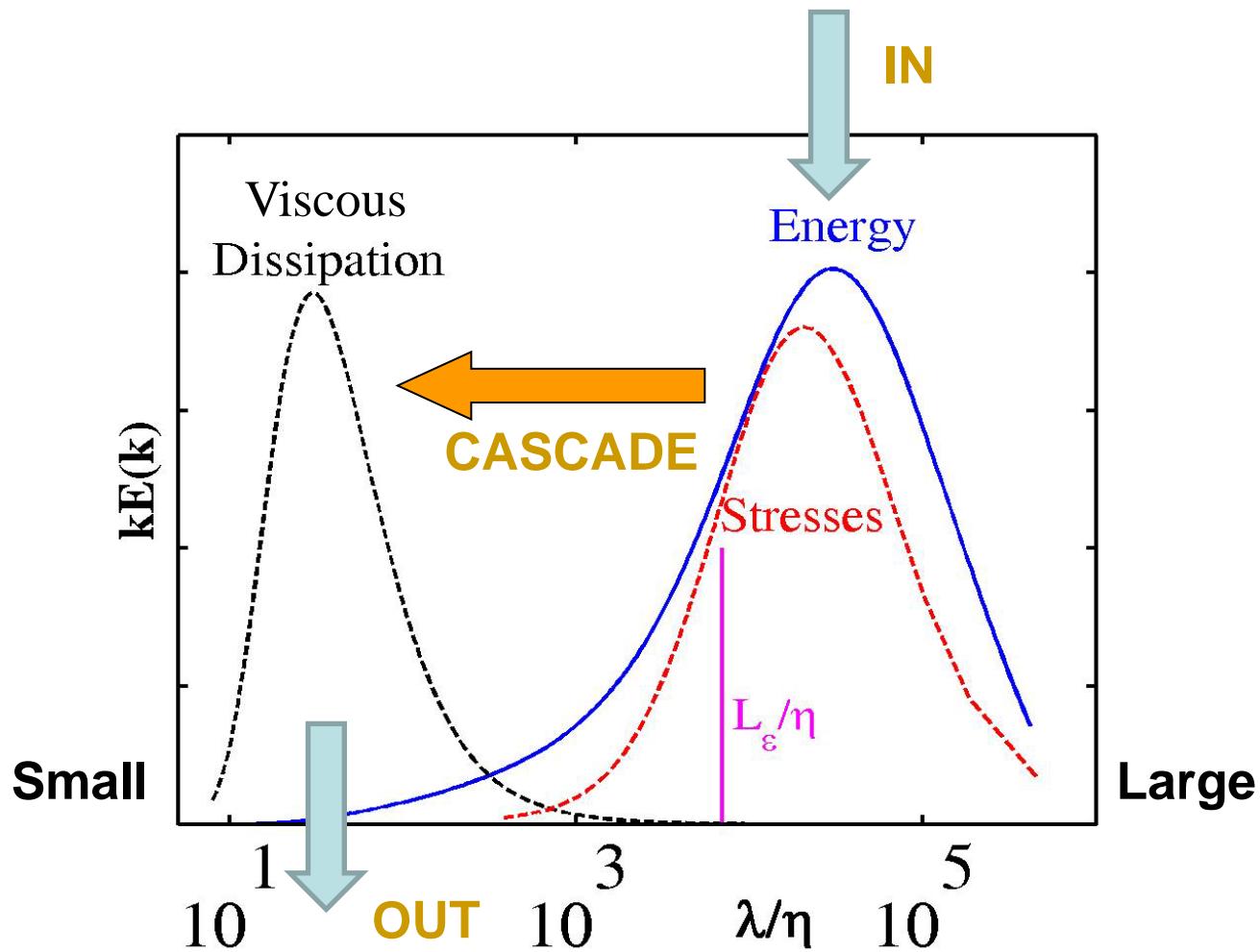
- (3+1)D turbulence
- ~30 Mcpu/‘various’
- ~20 TB (raw) + 150 TB (processed)
- ~ 10^4 files
- Public ‘restricted’ access
- Software is highly used



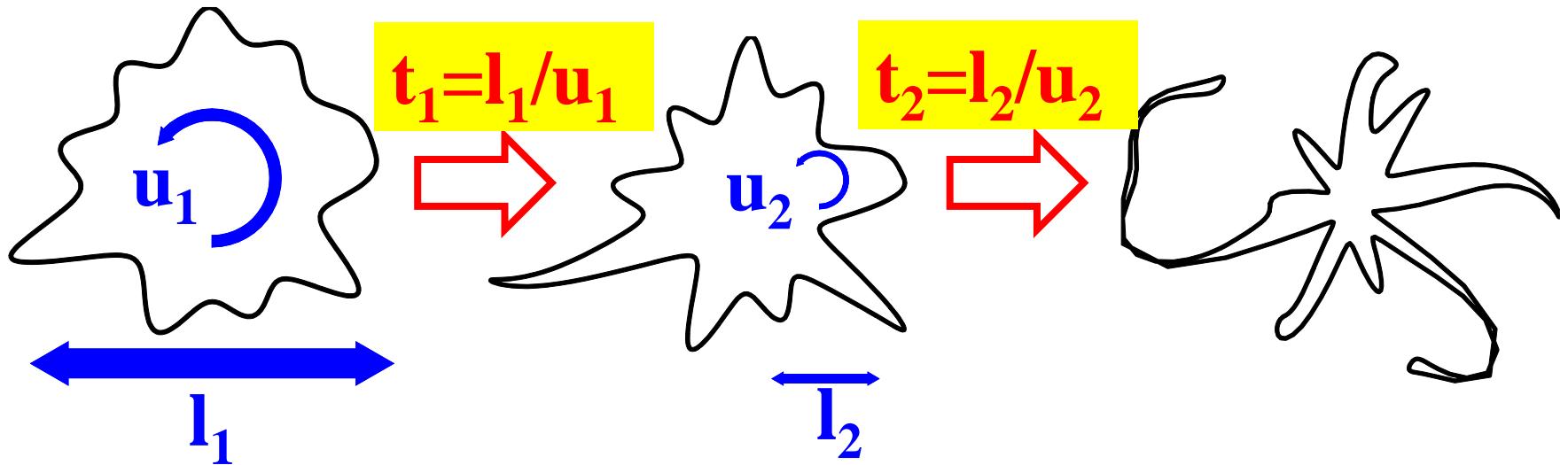
Turbulence in (1+1)D (scale + time)

The energy cascade

The turbulence cascade



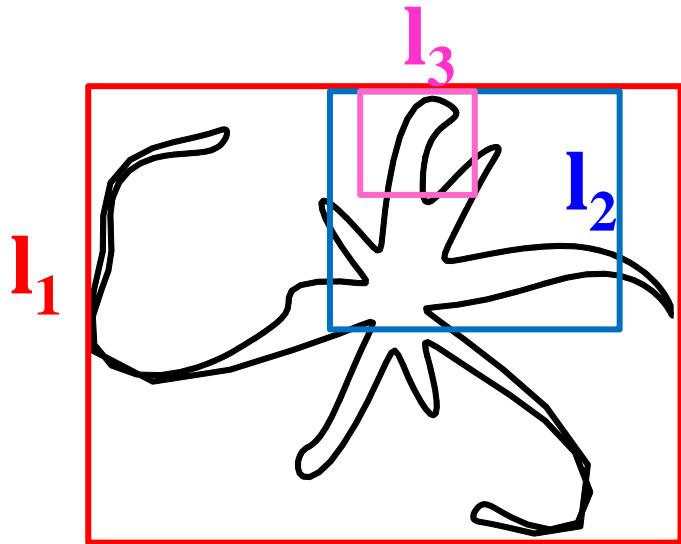
The Obukhov energy cascade



$$u_1^2/t_1 = u_2^2/t_2 = u_j^3/l_j = \varepsilon$$

$$u = (\varepsilon l)^{1/3}$$

The Kolmogorov energy cascade

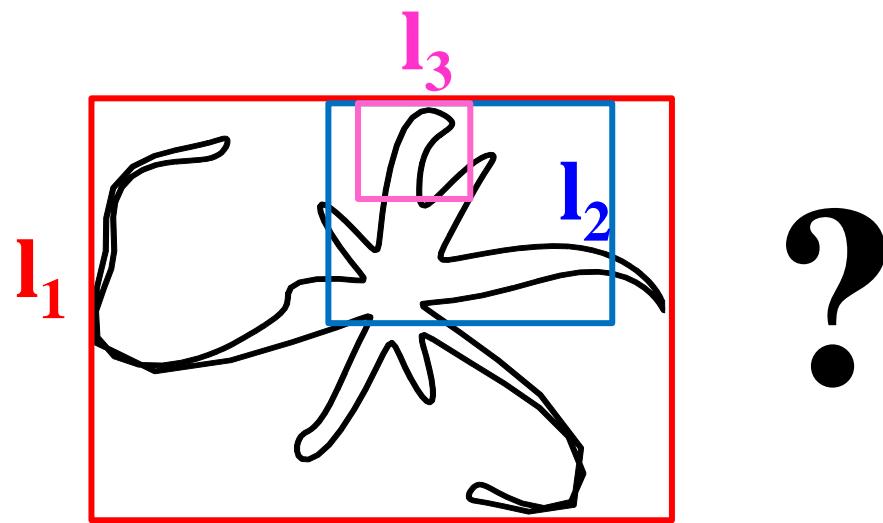
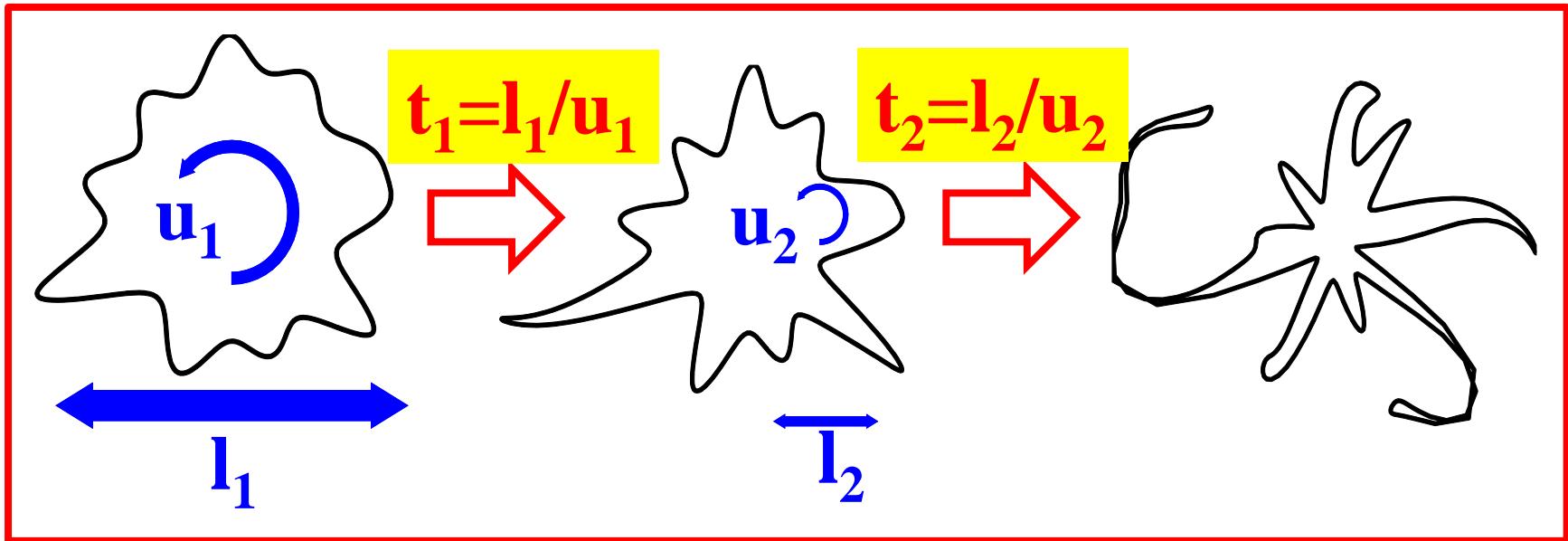


Big whorls have
small whorls ... (Richardson 1922)

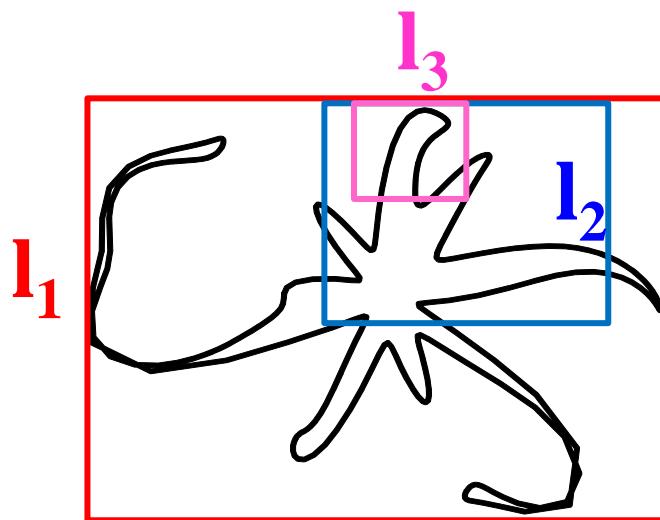
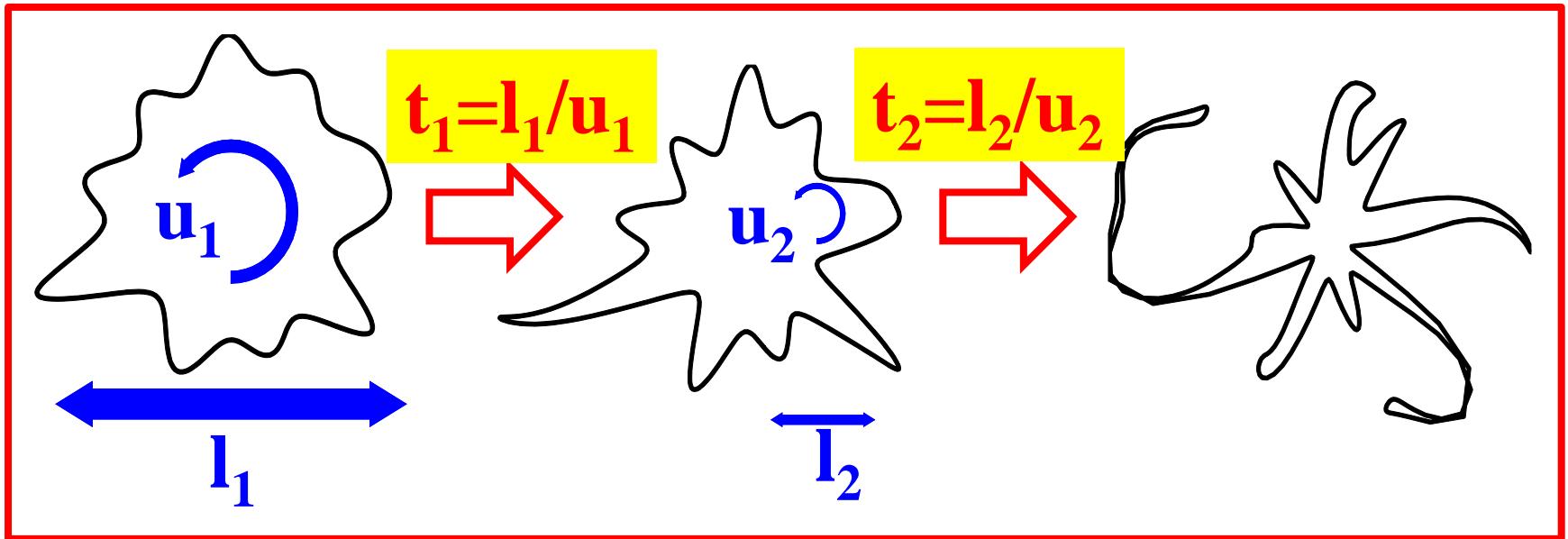
$$\partial_r(\Delta u^3) = -4\varepsilon/5 \quad (\text{Kolmogorov 1941})$$

$$u = (\varepsilon l)^{1/3}$$

Which is the real cascade?



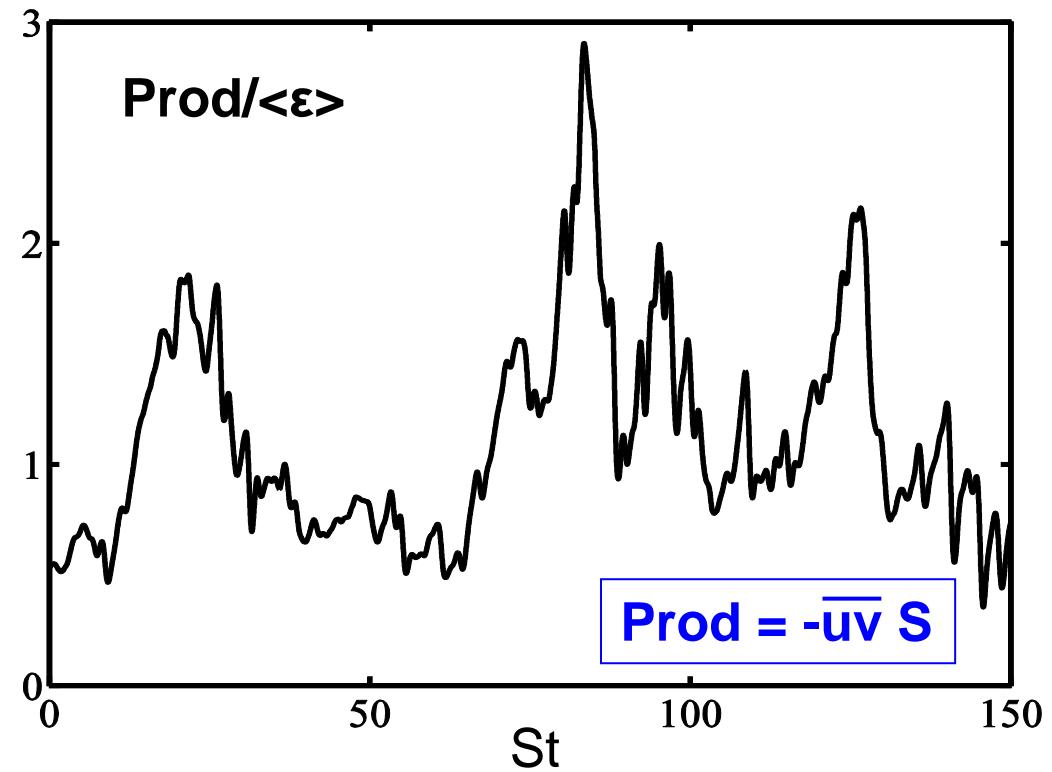
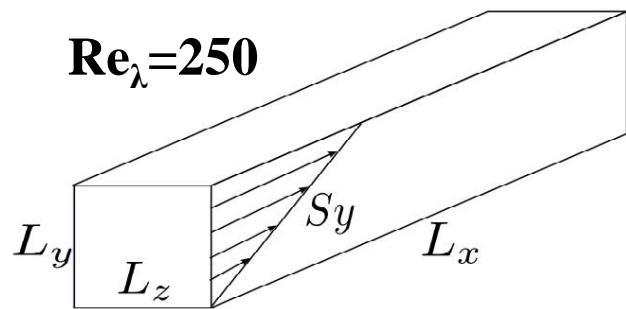
Why should we care?



LES,
Control, etc.

The energy cascade

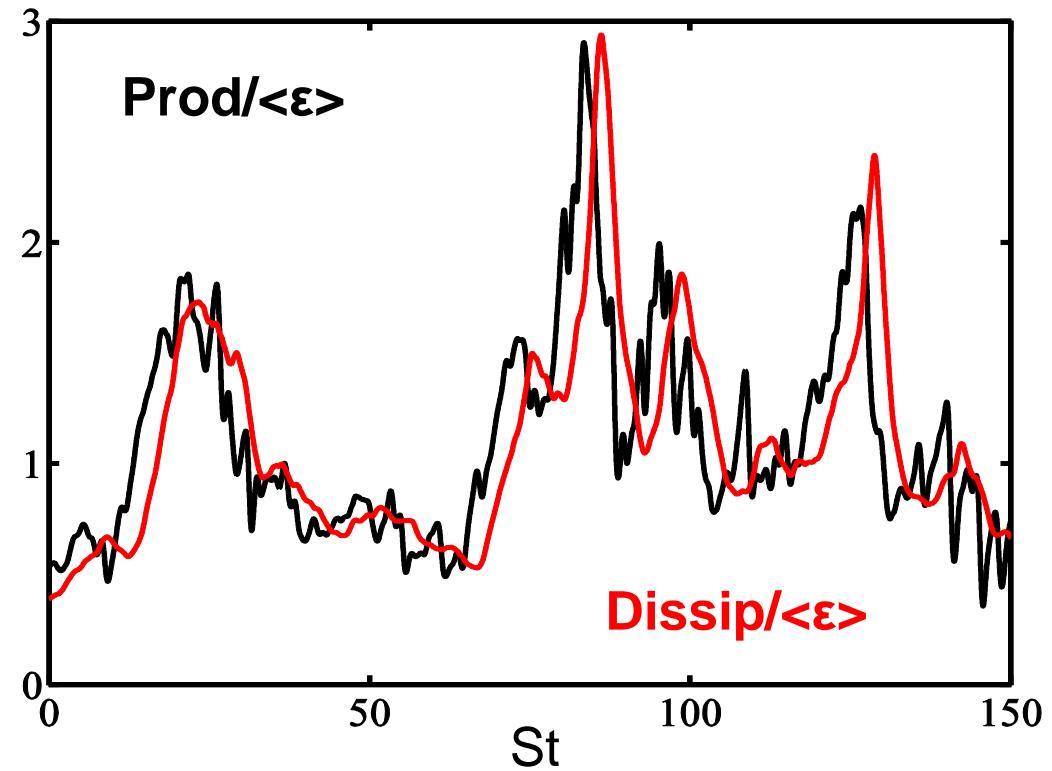
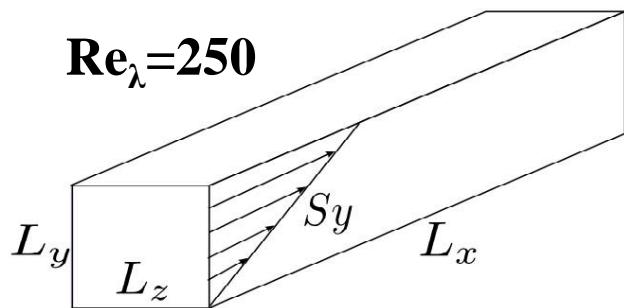
Homogeneous Shear Turbulence



The energy cascade takes time

Large to Small

Homogeneous Shear Flow

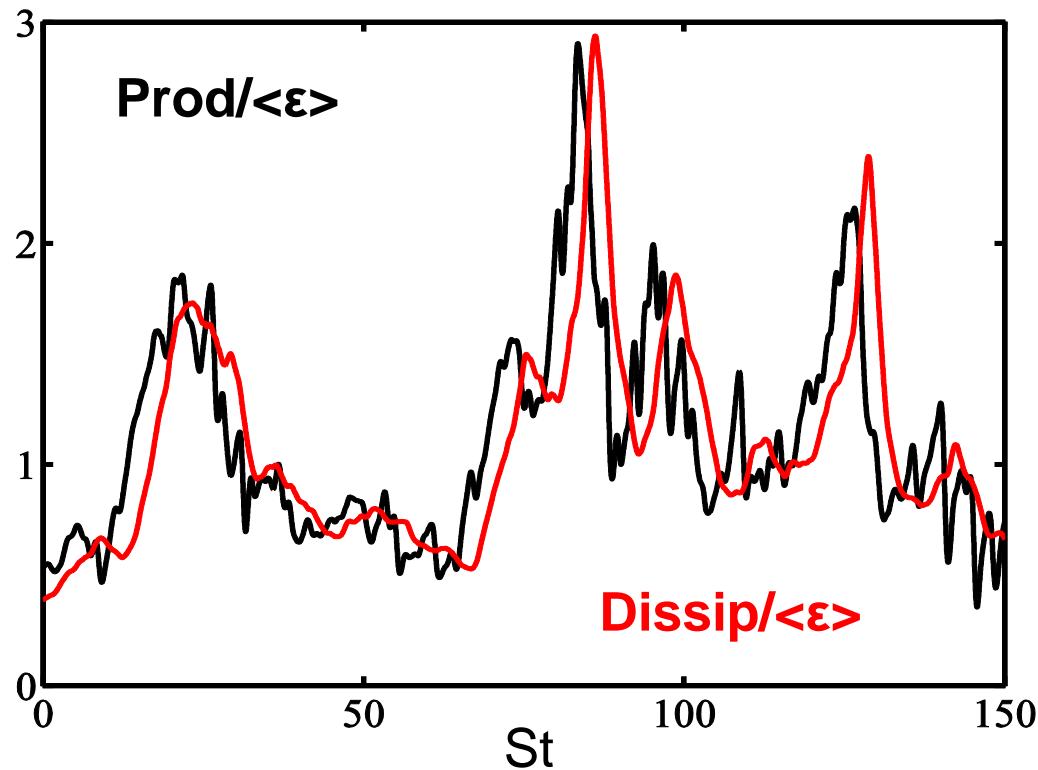
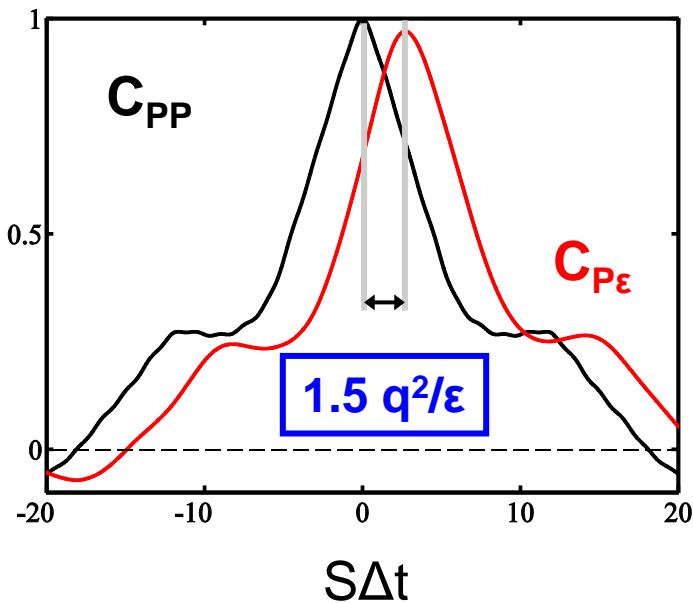


The energy cascade takes time

Large to Small

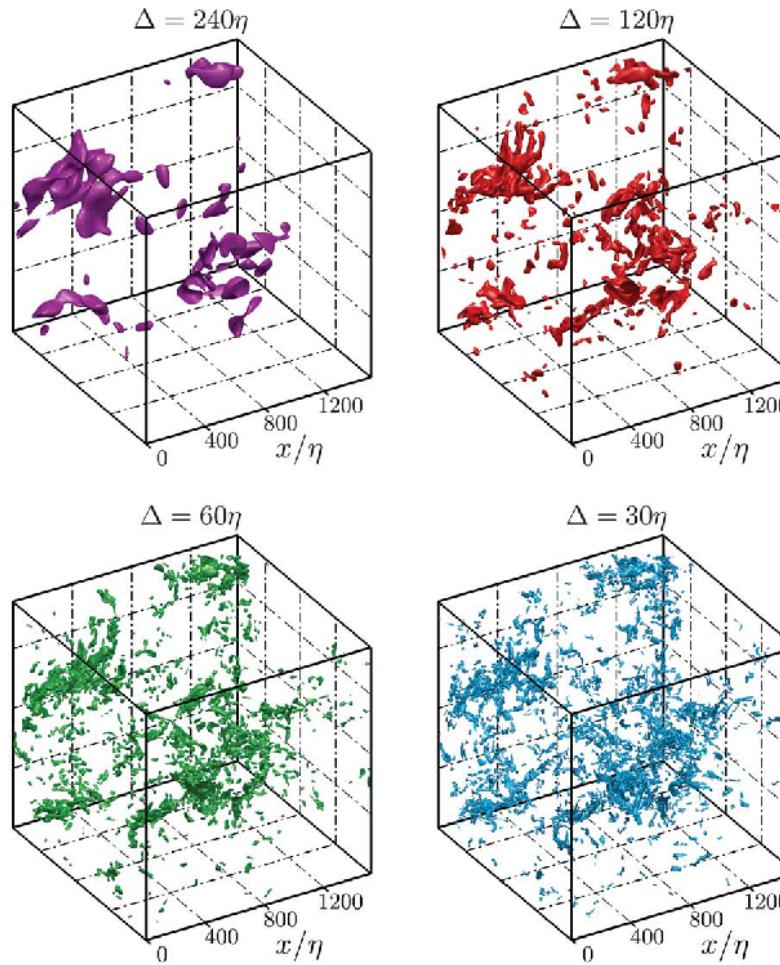
Homogeneous Shear Turbulence

Temporal cross-correl.

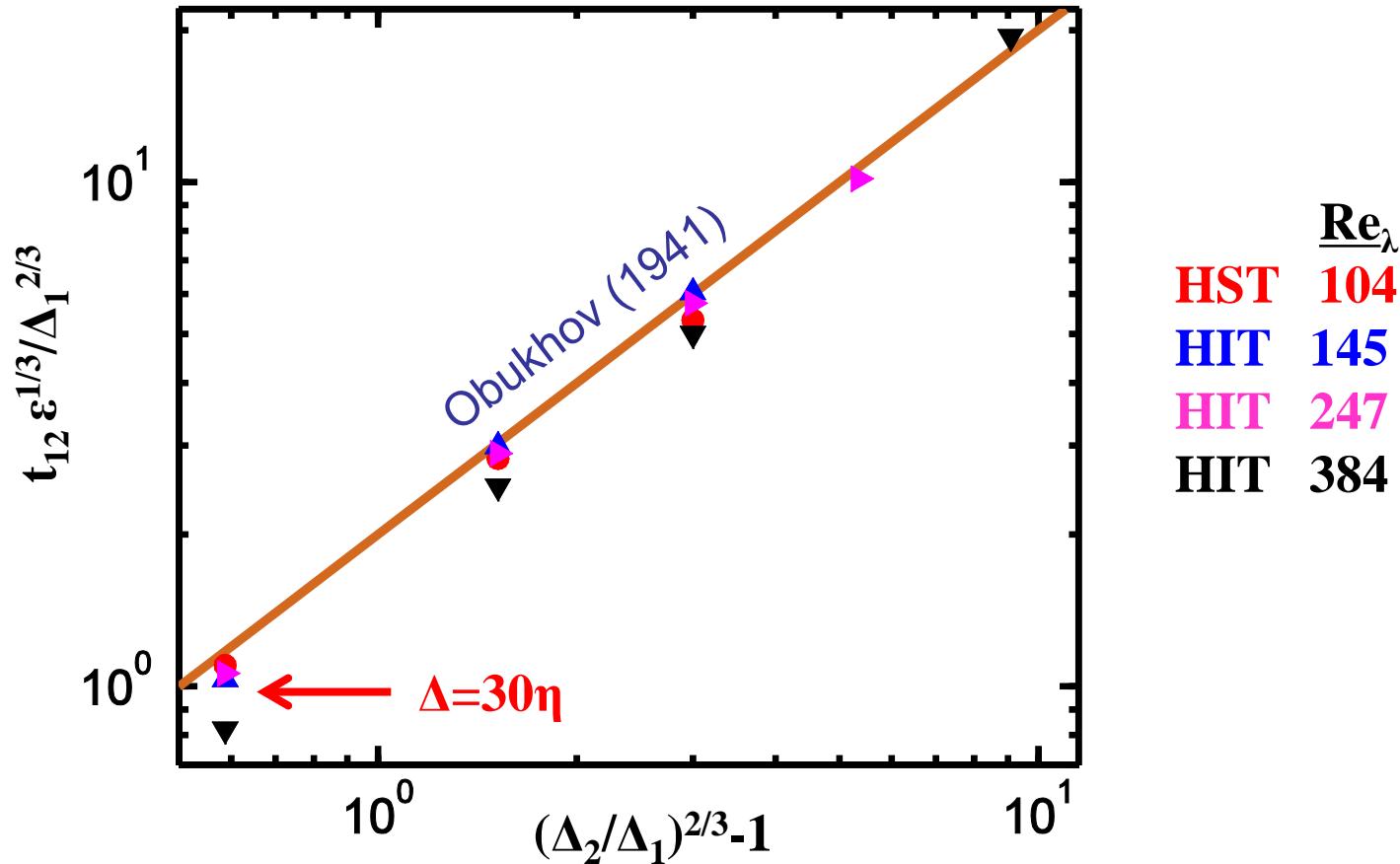


Filter to isolate Scales

**Homogeneous
Isotropic
Turbulence
 $Re_\lambda = 350$**



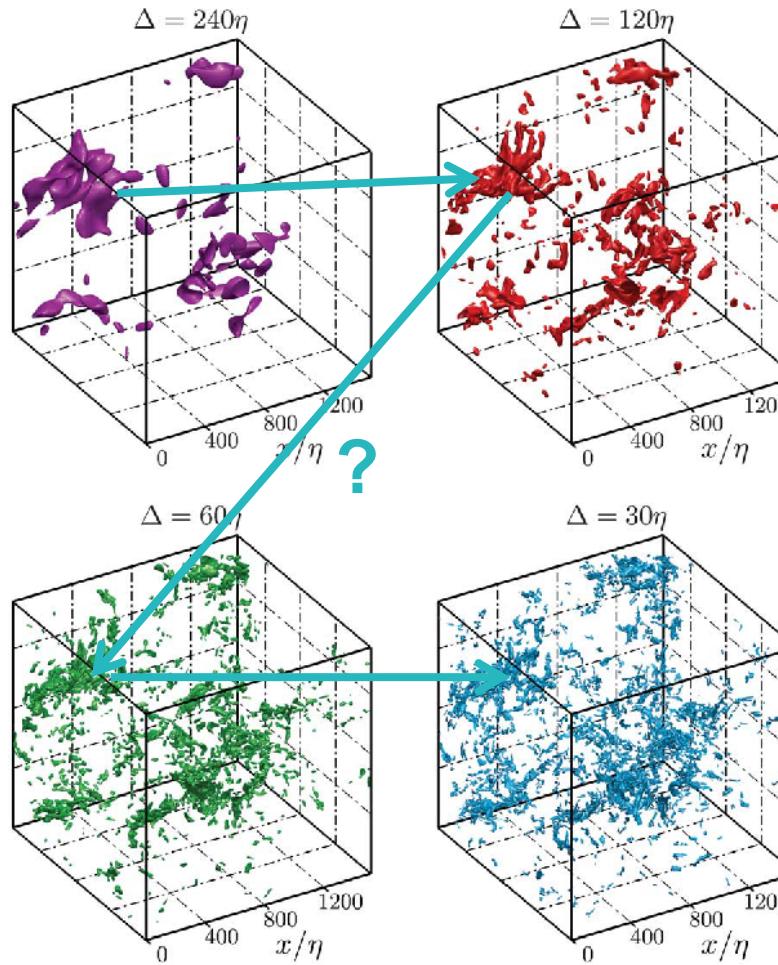
The ‘velocity’ of the cascade



Scale+Position+Time

‘5-D’ turbulence

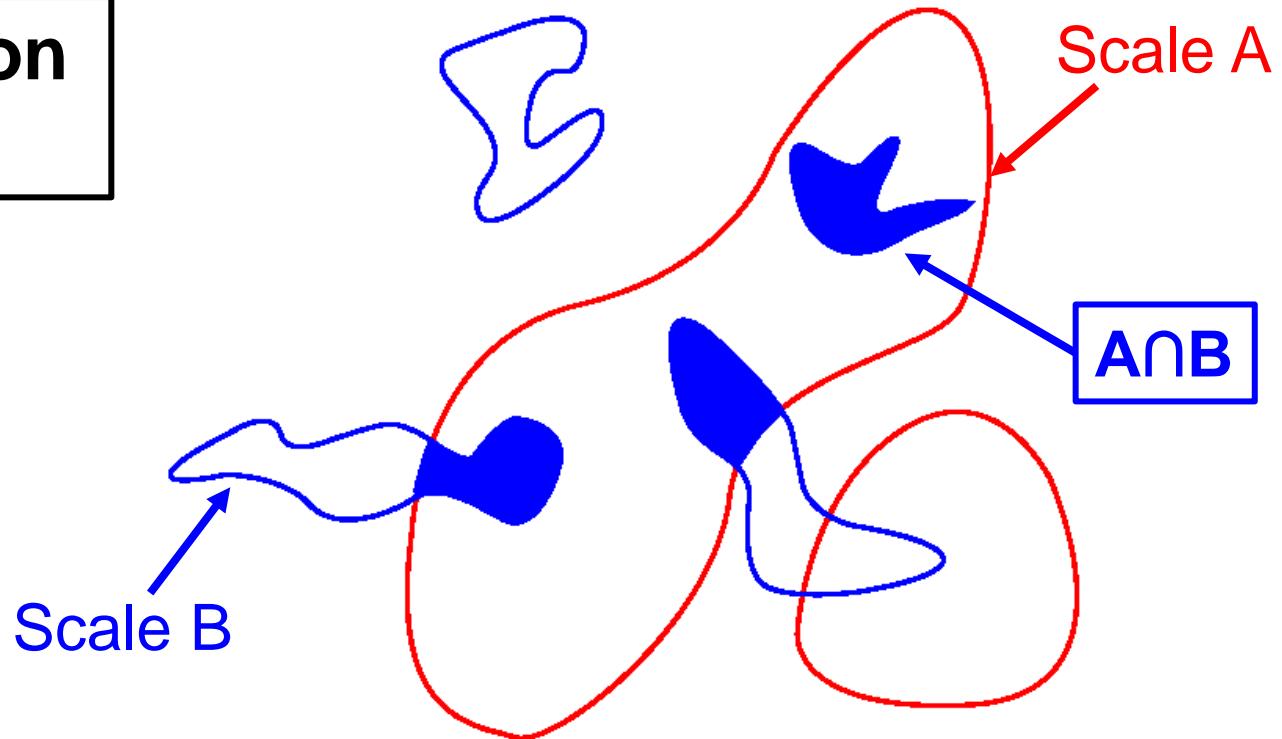
Large \rightarrow Small ✓
but
Is it local in space?



Scale+Position+Time

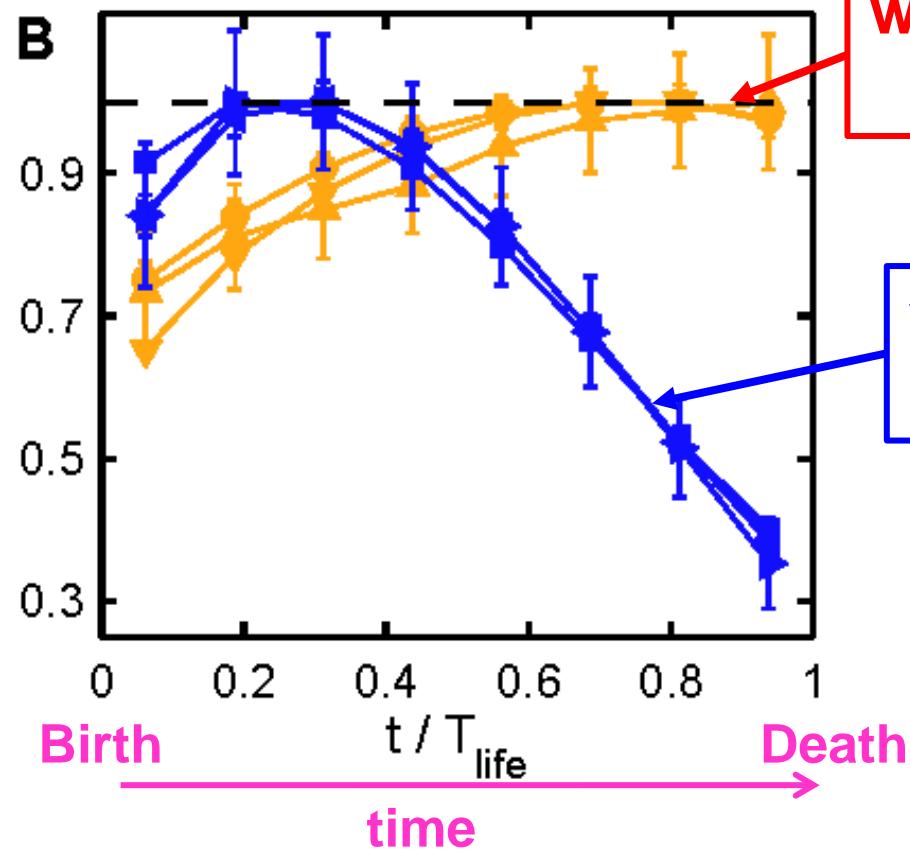
‘5-D’ turbulence

Intersection
ratio



Intersection History

Intersection
ratio

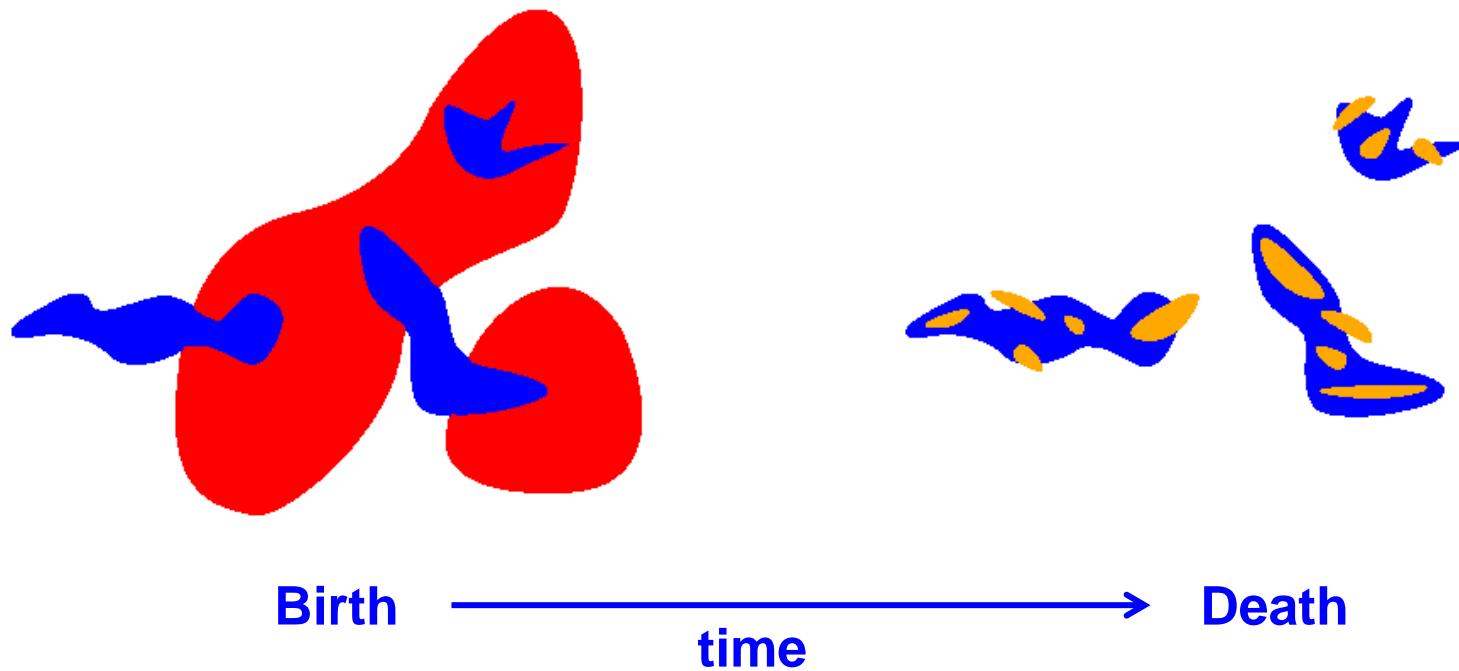


with SMALLER
structures

with LARGER
structures

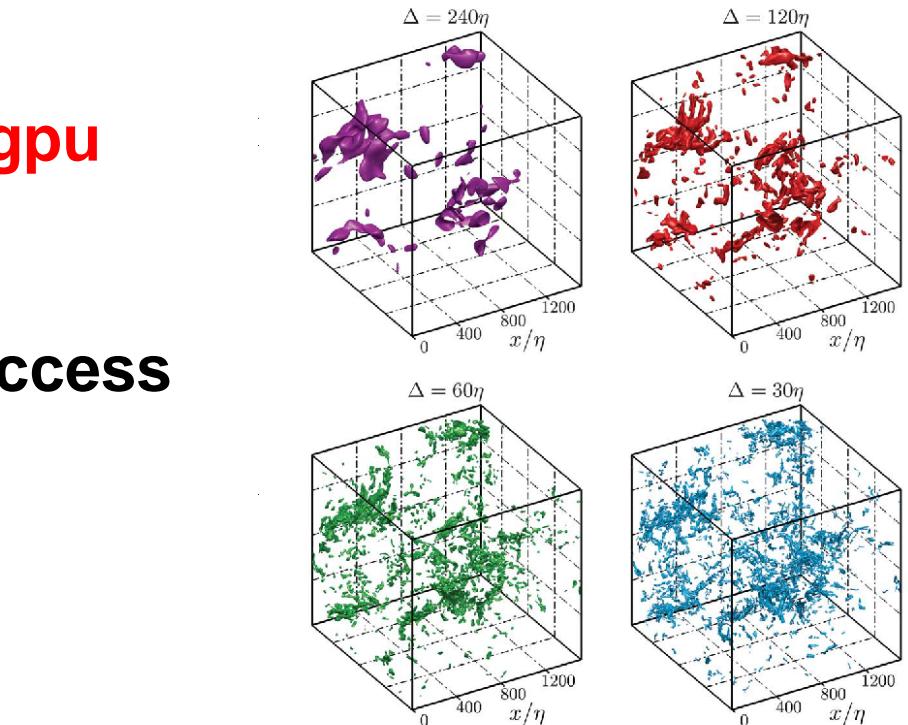
Intersection History

Obukhov, 1941



Scale+Position+**Time** Statistics Homogeneous Flows

- ‘5D’ turbulence
- ~20 Mh/BGQ + 10 Mh/gpu
- ~250 TB
- 25,000 snapshots
- Public ‘unrestricted’ access



Summary

- Turbulence is **hard**, but **not a mystery**
- Thanks to **supercomputers and simulations**
- **Analysis-driven** rather than **Data-driven**

Dimensions	Primary Mcpuh	Archival TB	files
1	150	30	200
3+1	30	170	10^4
3+1+1	30	250	3×10^4
3+1+1	120	100PB -> 250TB	10^4

- **Postprocessing** becoming more important
- **Long-term storage** crucial

Thank you