Small Scale Anisotropy and other results in Turbulent Shear-less Mixing

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Politecnico di Torino

The Nature of Turbulence Program
Kavli Insitute, University of California Santa Barbara, March 24, 2011.

Step onset from an initial uniform distribution of turbulent energy

12^{th} European Turbulence Conference, Marburg, September 2009

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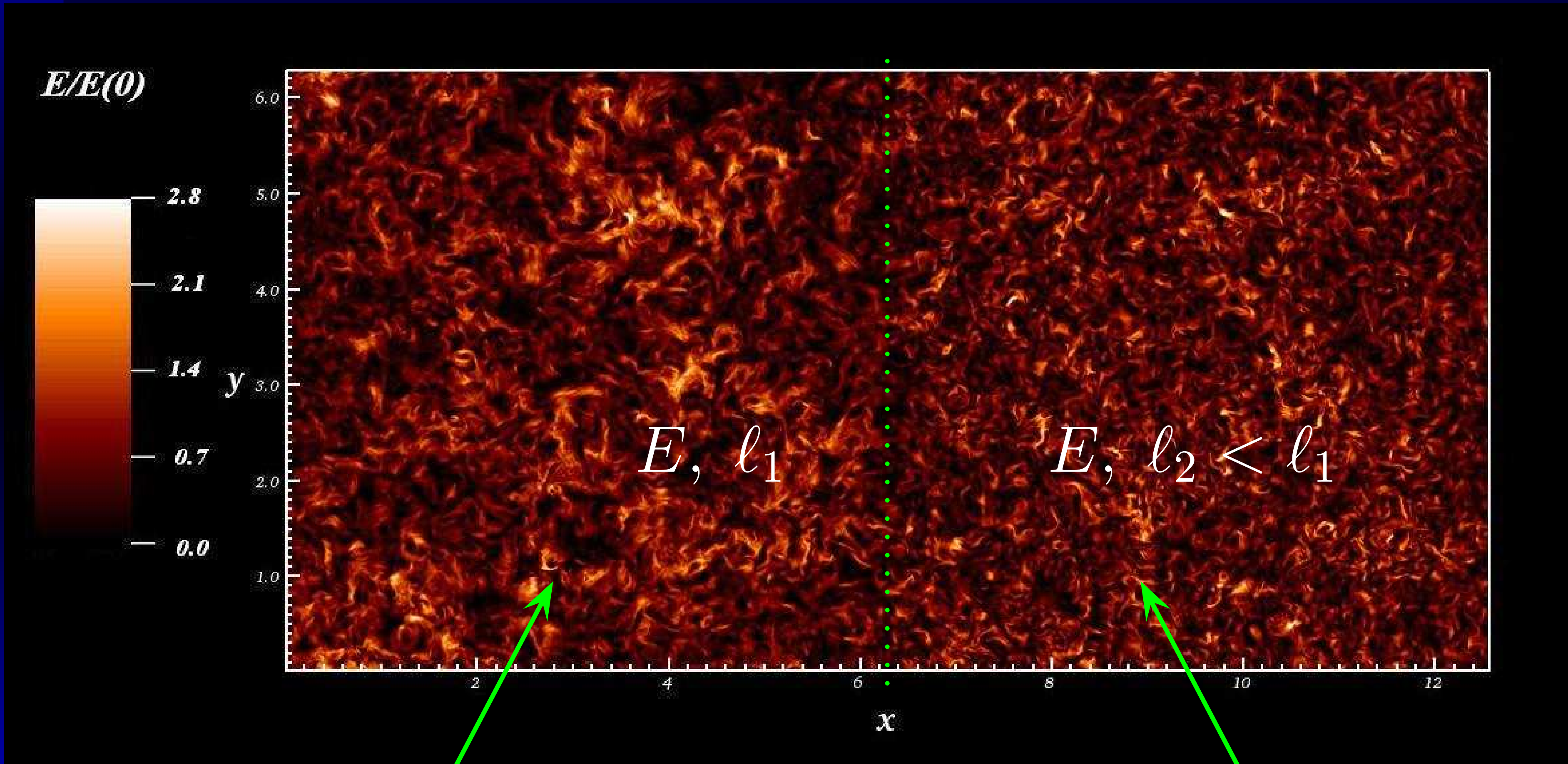
An integral scale gradient introduced in a uniform kinetic energy distribution can generate:

- an energy gradient
- a highly intermittent layer

Flow Configuration

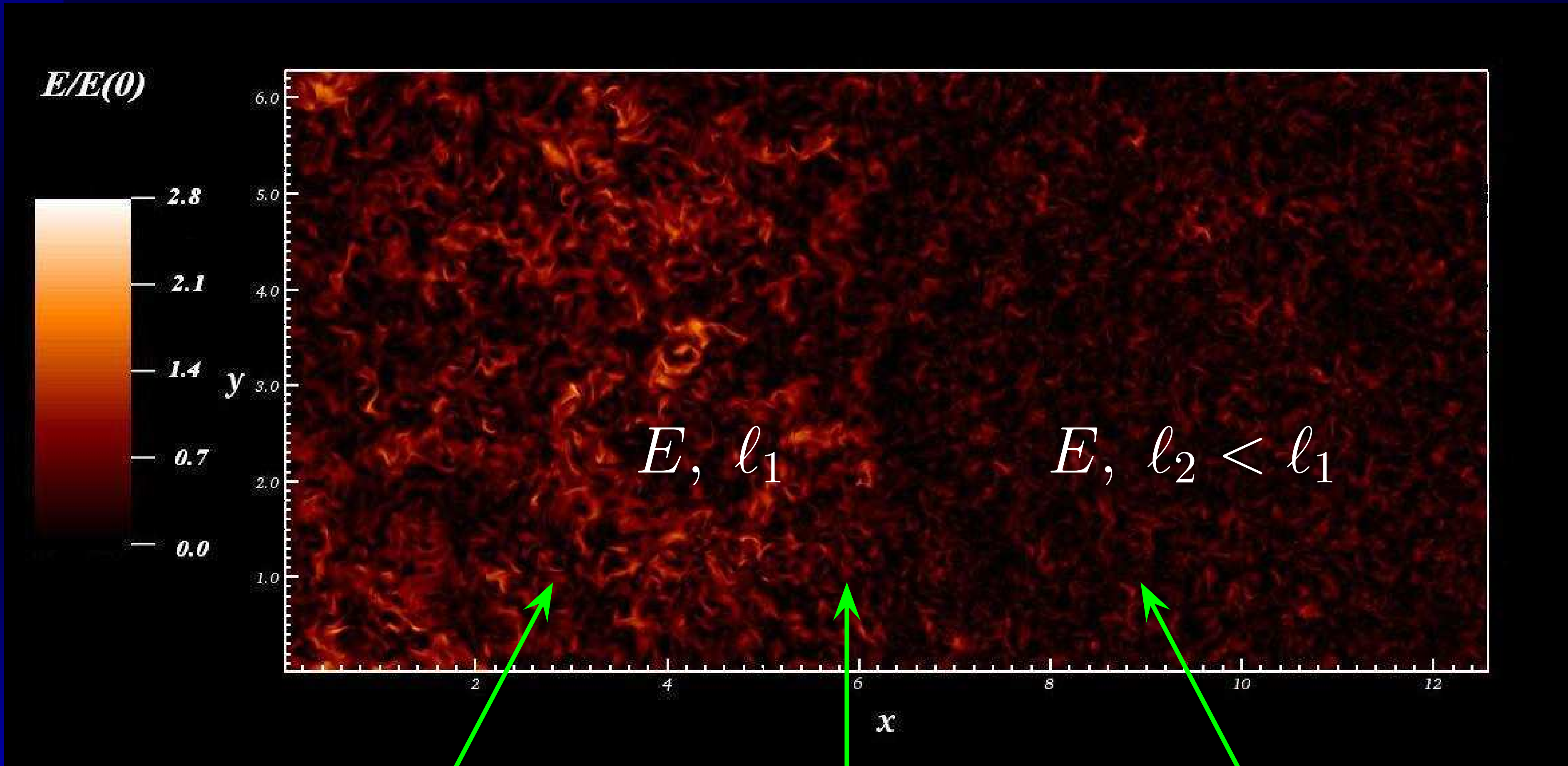
Initially uniform turbulent kinetic energy:



1-Larger scale turbulence   2-Smaller scale turbulence

Flow Configuration

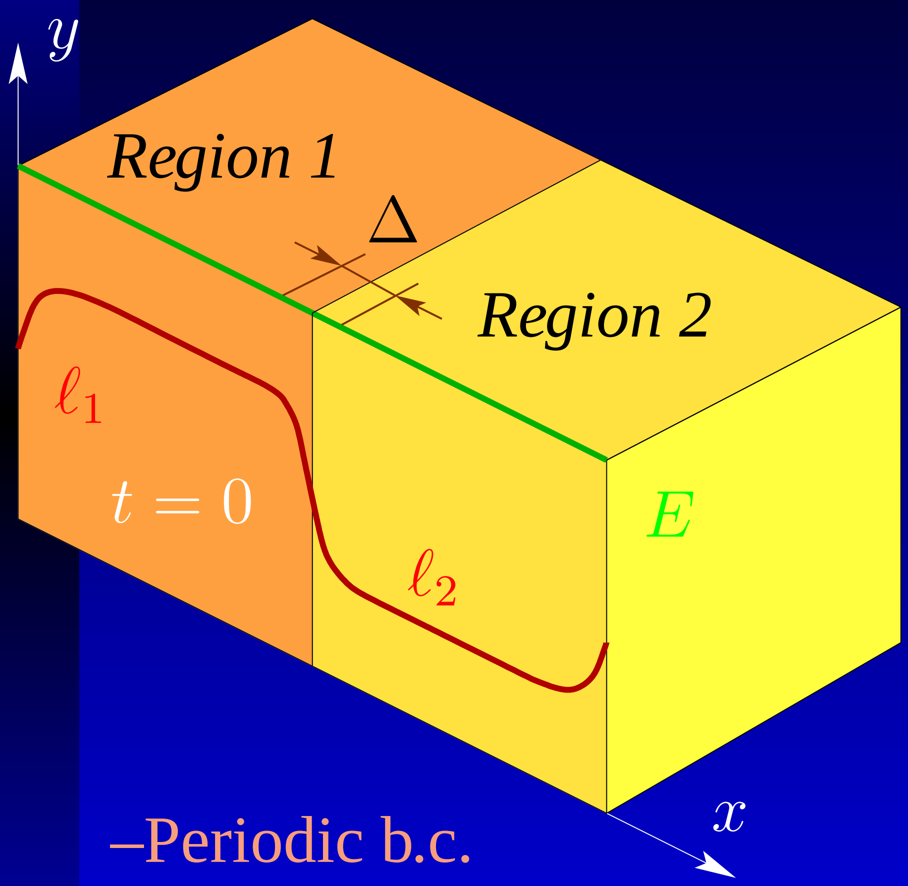
Initially uniform turbulent kinetic energy:



1-Larger scale turbulence 2-Smaller scale turbulence

Shearless mixing layer

Method

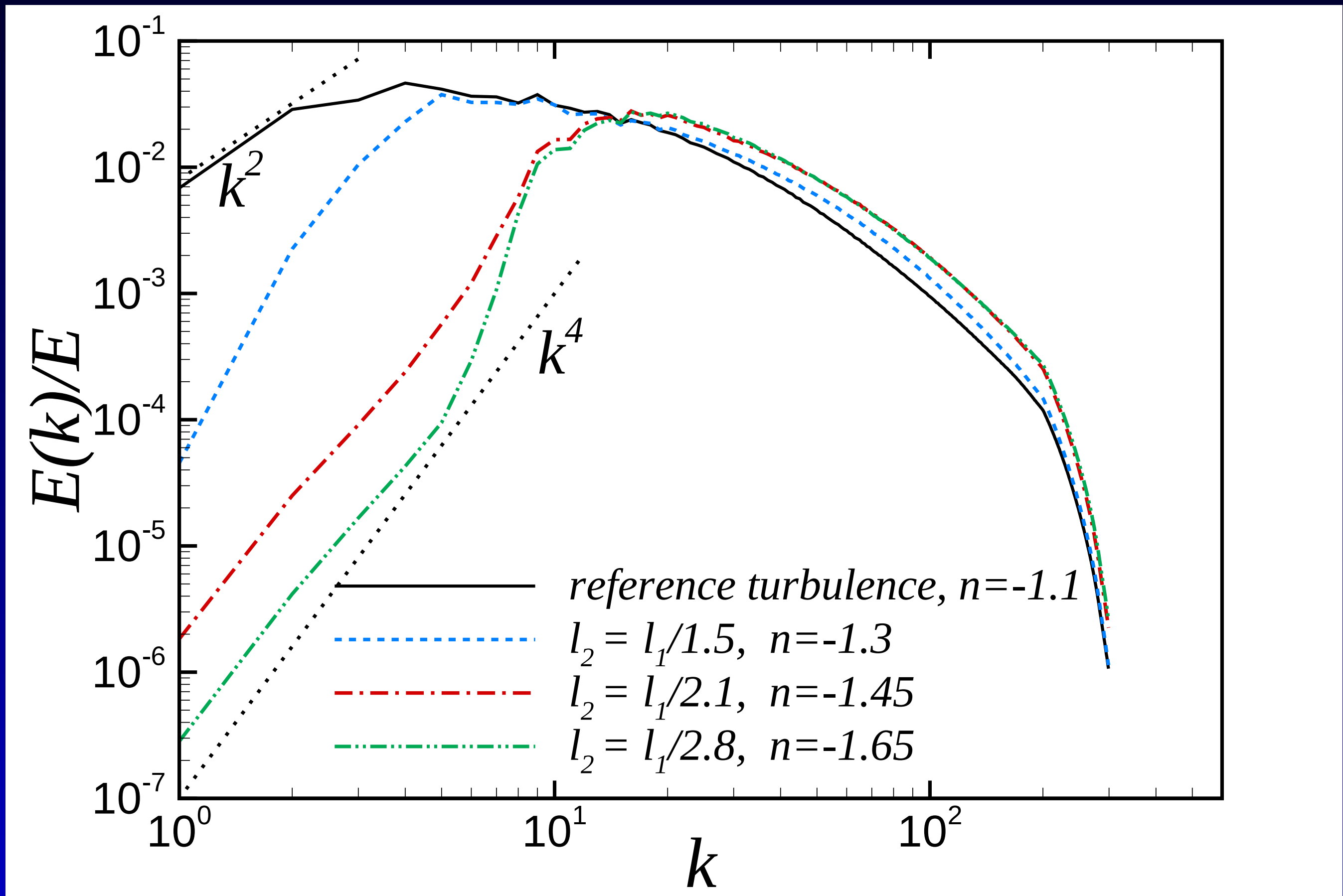


–Periodic b.c.

–Temporal decay

- **DNS**:
  - $Re_\lambda = 150$
  - parallelepiped domain, $2\pi \times 2\pi \times 4\pi$
  - $600^2 \times 1200$ grid points
  - Fourier-Galerkin pseudospectral space discretization
  - explicit RK-4 time integration

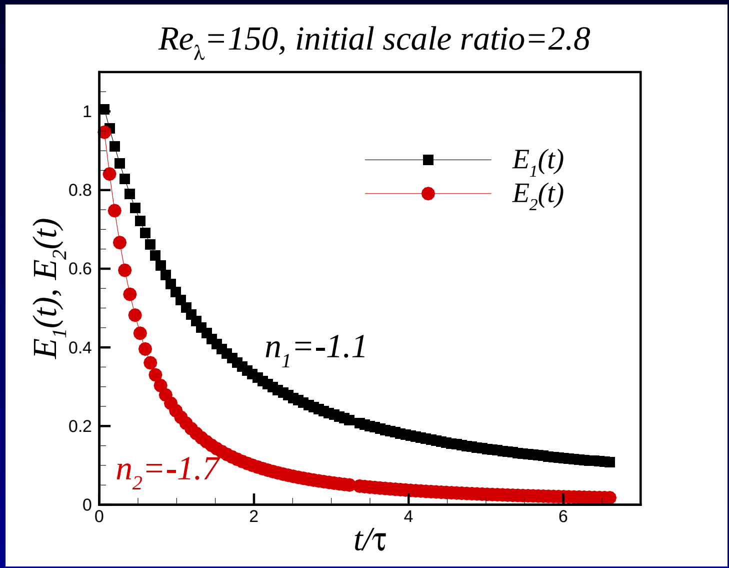
Initial energy spectra

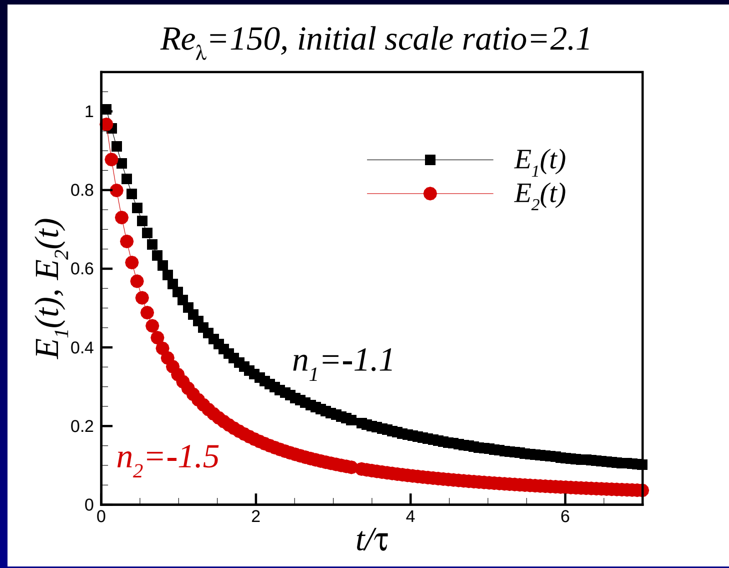


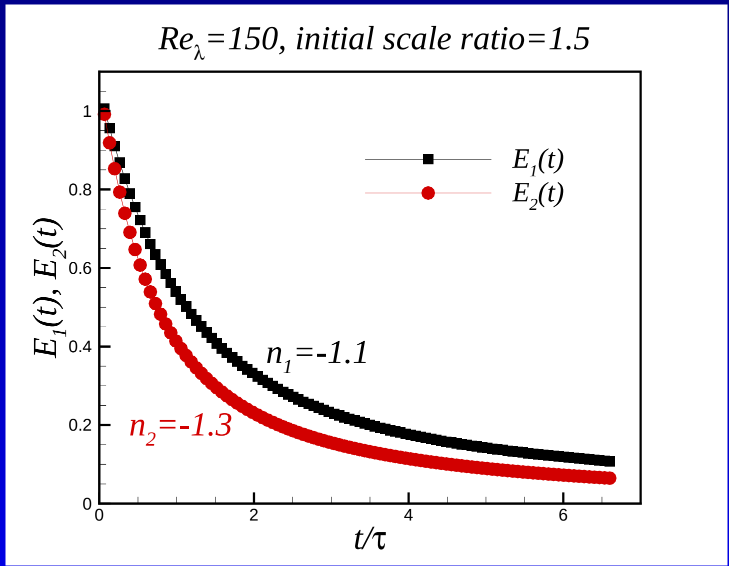
Field 1 $\longrightarrow$ larger integral scale

Field 2 $\longrightarrow$ smaller integral scale

Turbulent kinetic energy decay

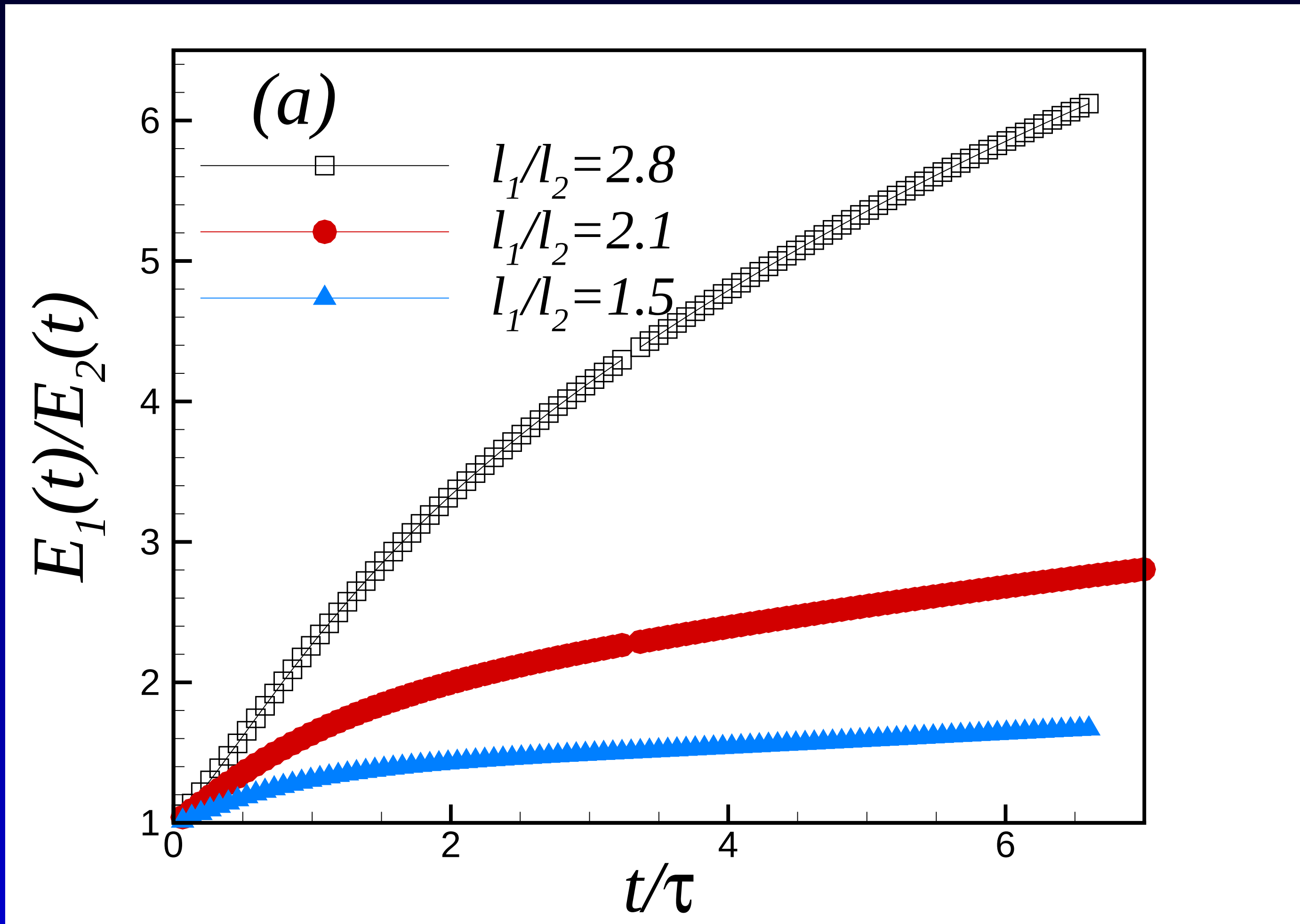






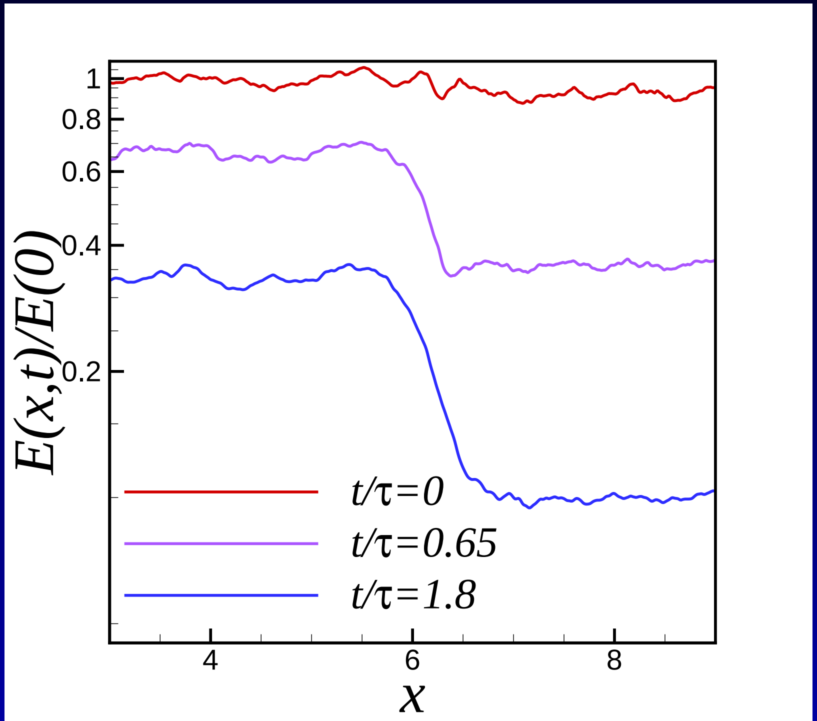
Homogenous turbulence with smaller scale decays faster
$\Rightarrow$ a kinetic energy gradient is generated

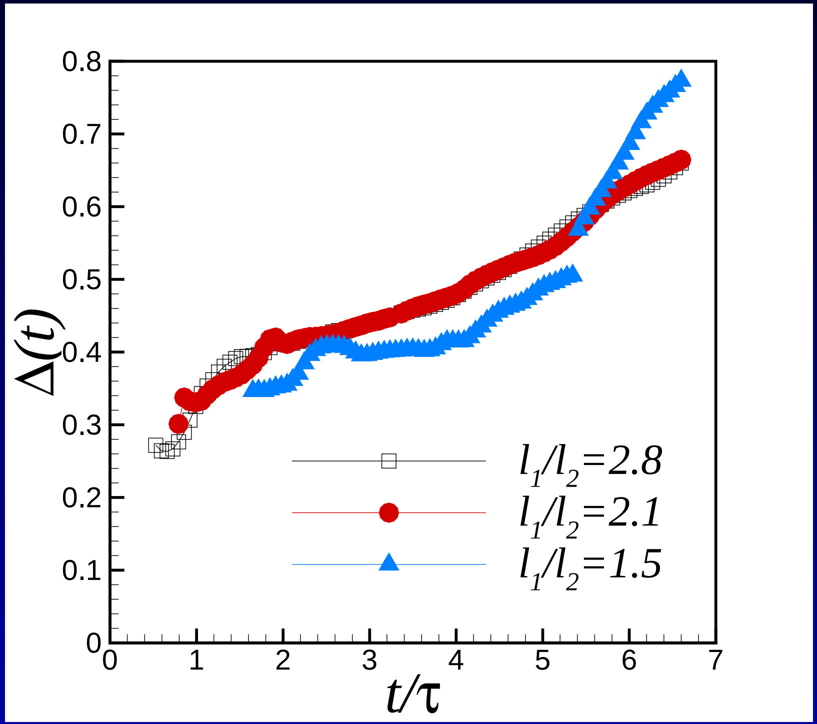
Energy Ratio



Time evolution of the energy ratio E_1/E_2.

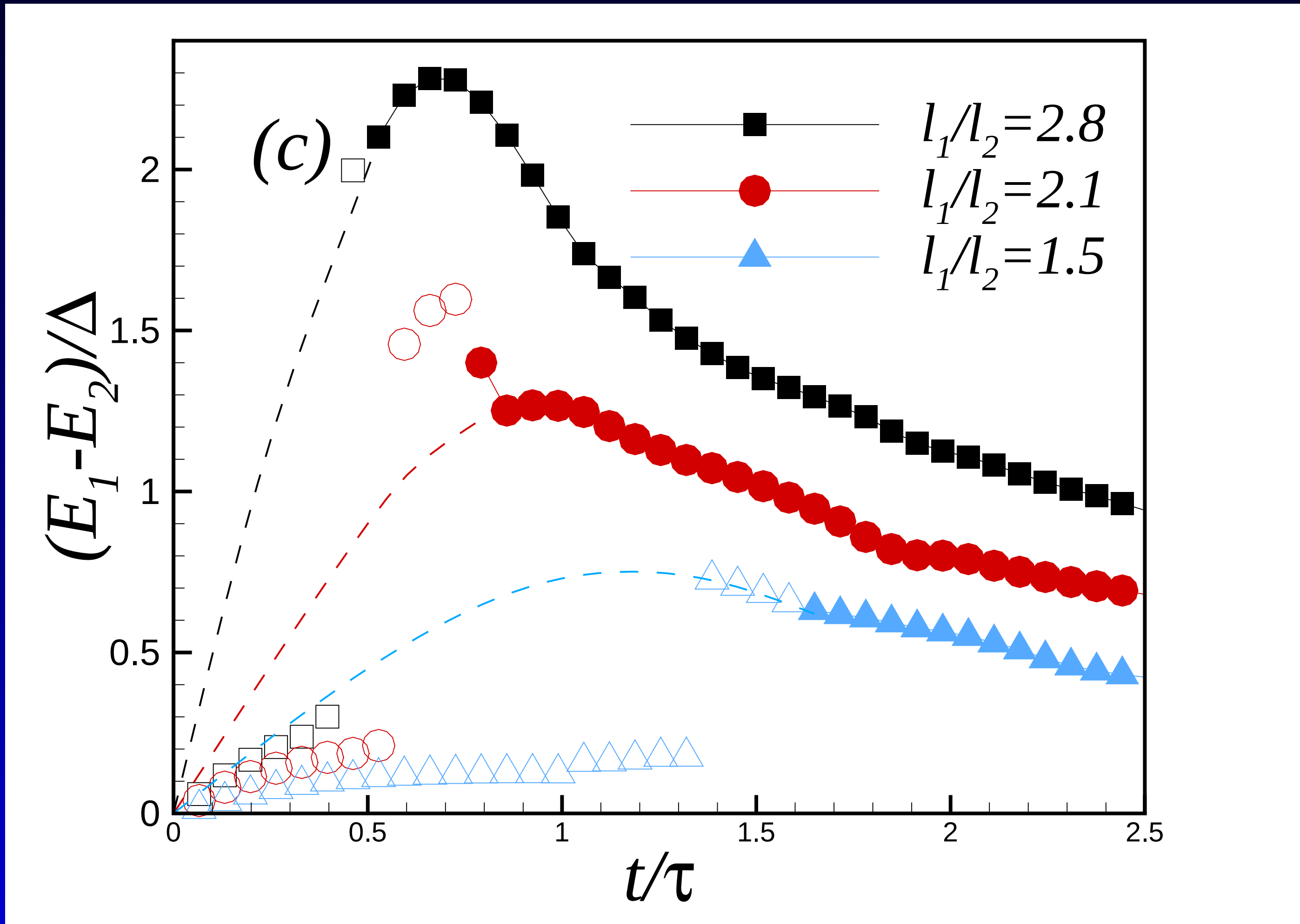
Mixing layer thickness $\Delta(t)$





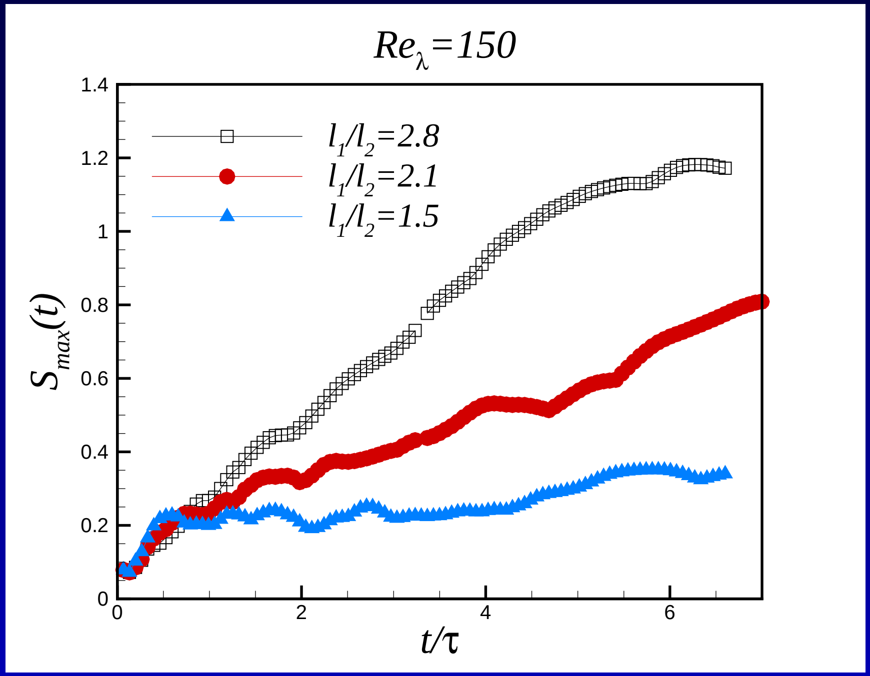
τ = initial eddy turnover time

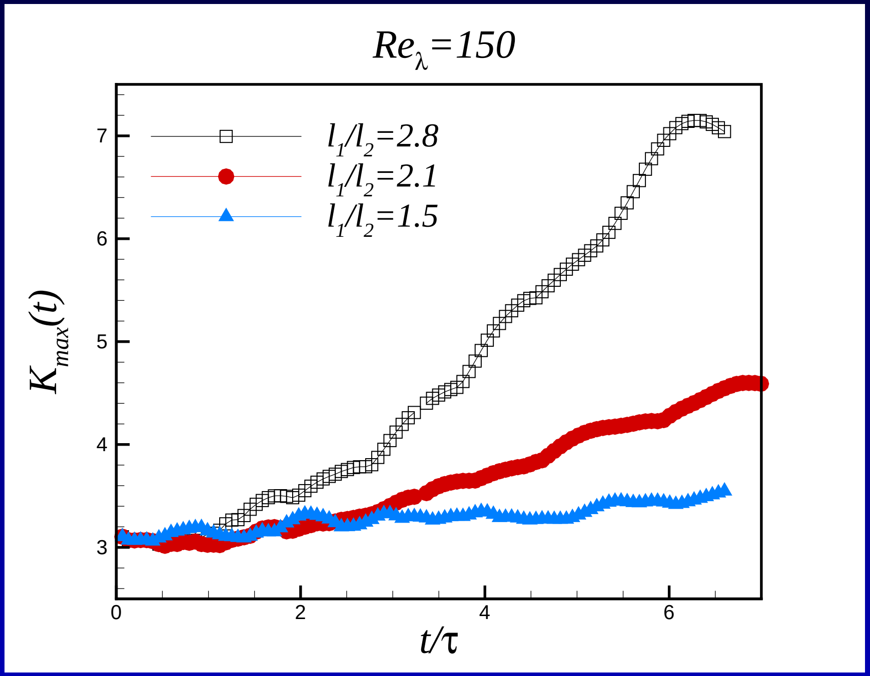
Kinetic energy gradient



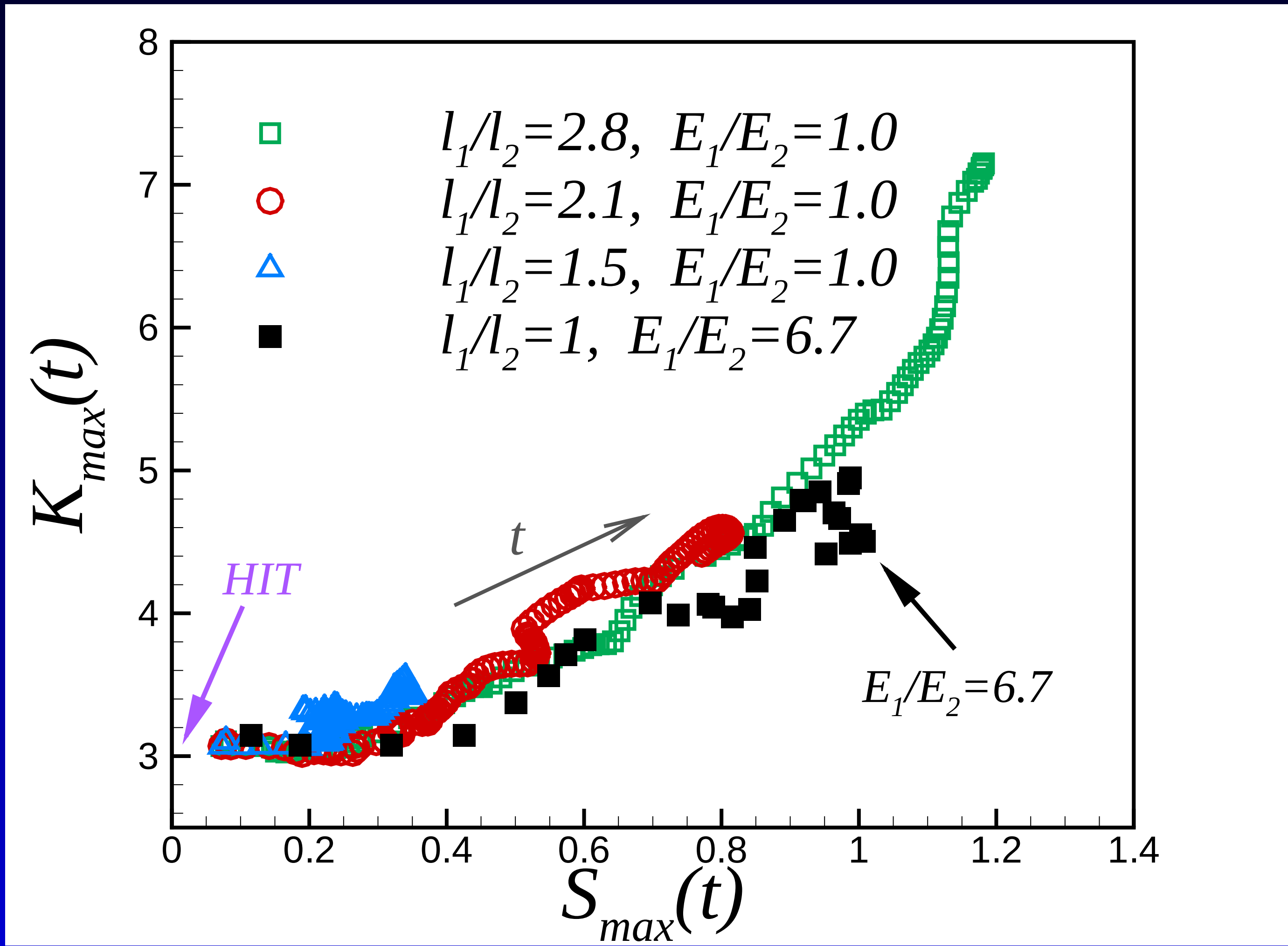
Mixing layer intermittency

Velocity skewness and kurtosis, component in the inhomogeneous direction: maximum in the mixing layer



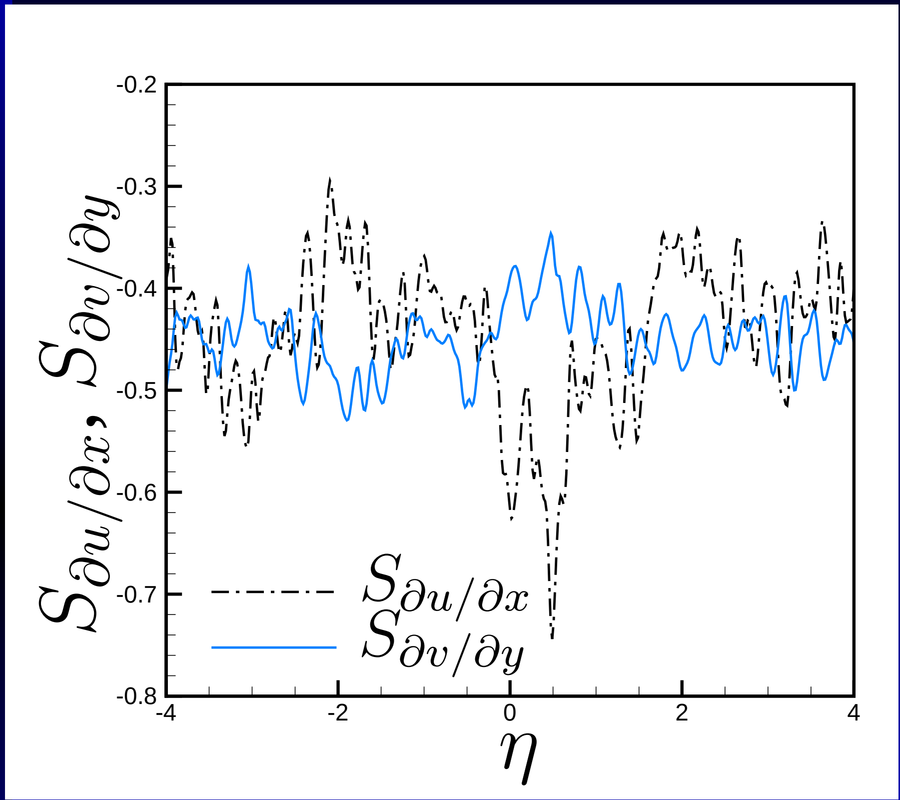


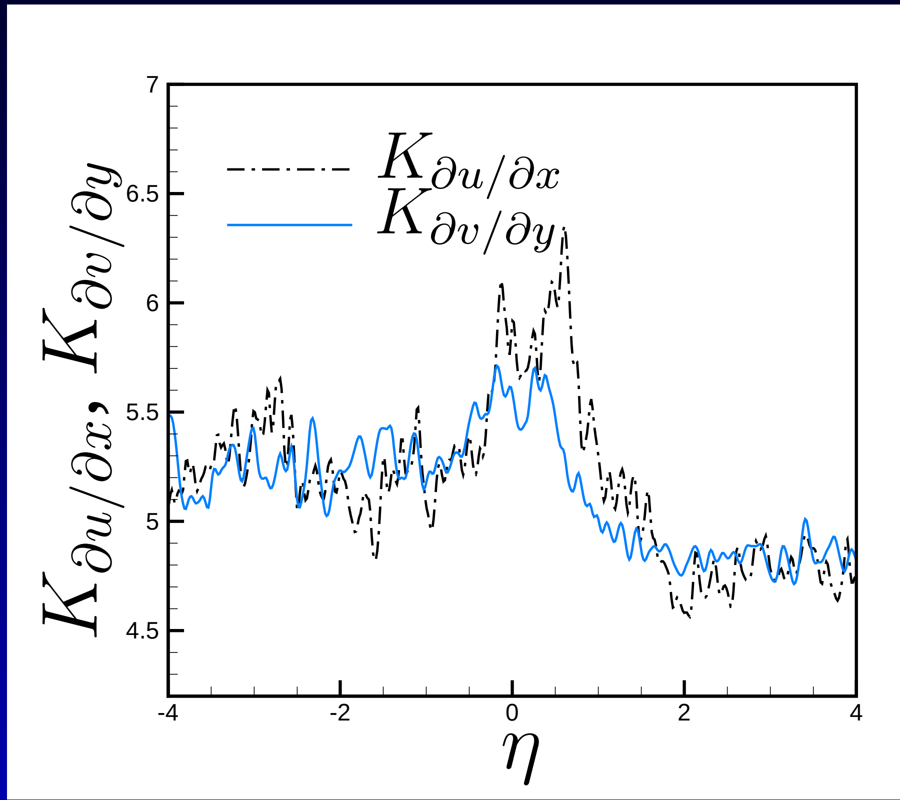
Intermittency



A scale gradient can generate more intermittency than an energy gradient in presence of a uniform scale

Longitudinal derivatives





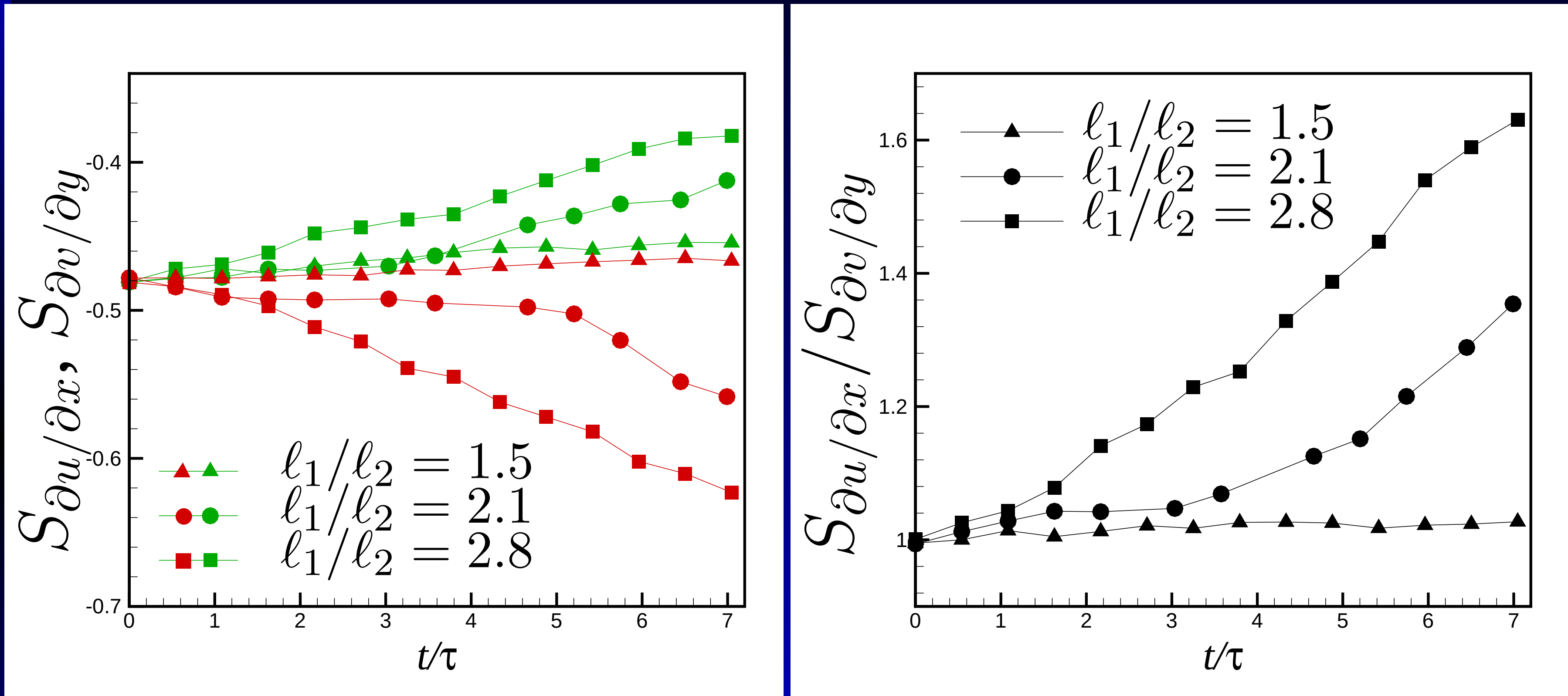
Spatial distribution of longitudinal moments,

$\eta = x/\Delta$,

x, u in the inhomogenous direction,

y, v in homogenous directions.

Longitudinal derivatives



Anisotropy is propagated to small scales.

Conclusions

Simulations of a flow with an homogenous energy and an integral scale gradient show:

- an integral scale inhomogeneity generates an energy gradient
- the decay exponent of turbulent flow with the same initial energy depends on their integral scale $\Rightarrow$ the smaller the scale, the faster the decay.
- intermittency can be higher than that generated by an energy gradient and a uniform scale
- anisotropy and intermittency quickly spread to small scales.

Small scale anisotropy induced by a spatial variation of the integral scale

Euromech Colloquium 512, Torino, October 2009

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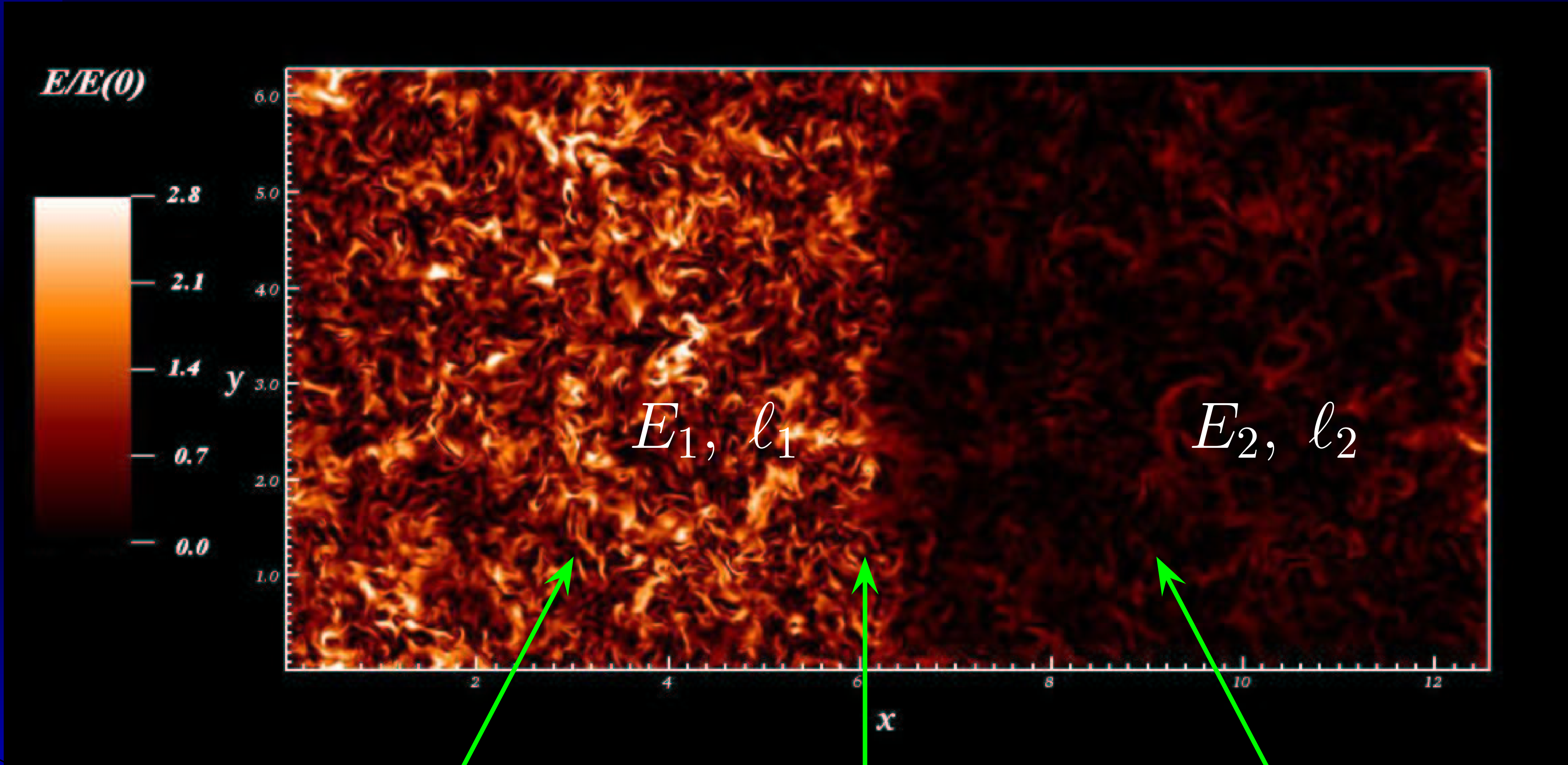
Turbulent shearless mixing

$Re_\lambda = 150,\ E_1/E_2 = 6.6,\ t/\tau = 0.92$



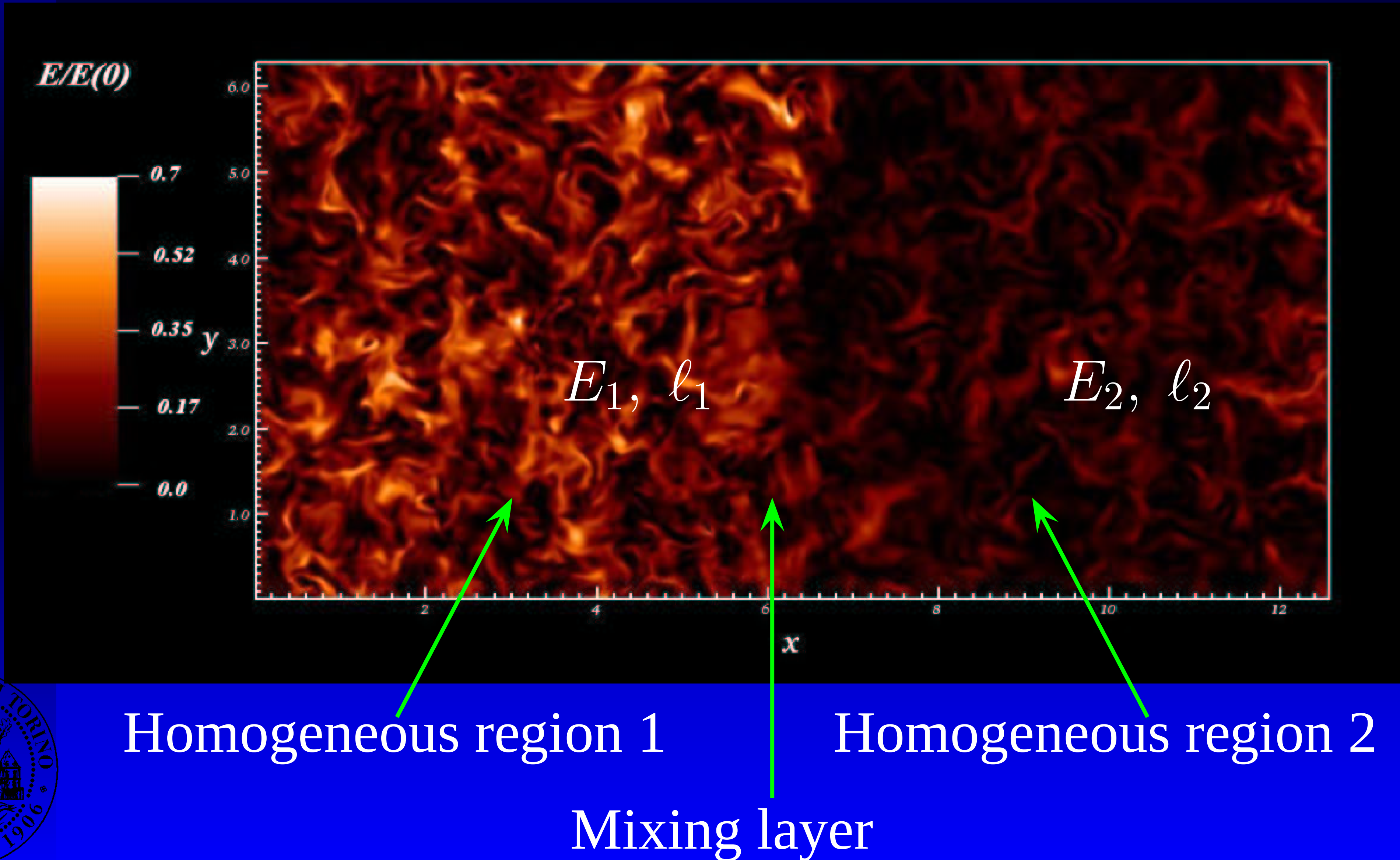
Homogeneous region 1

Homogeneous region 2

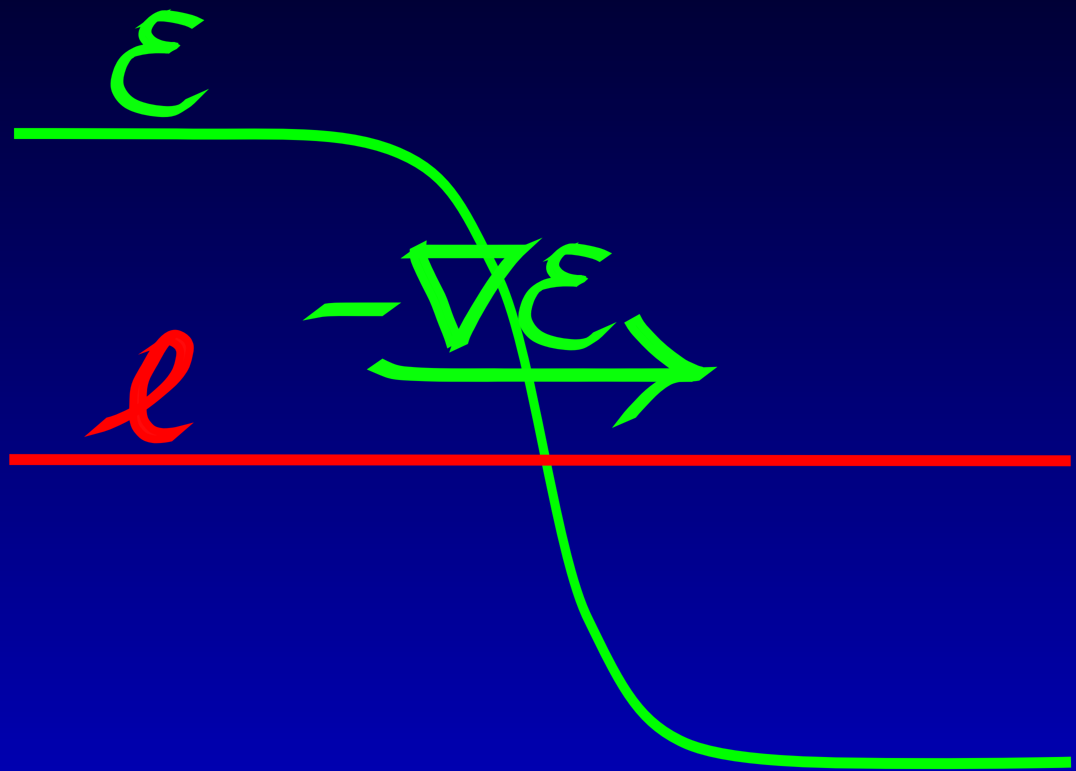
Mixing layer

Turbulent shearless mixing

$Re_\lambda = 150$, $E_1/E_2 = 6.6$, $t/\tau = 6.7$

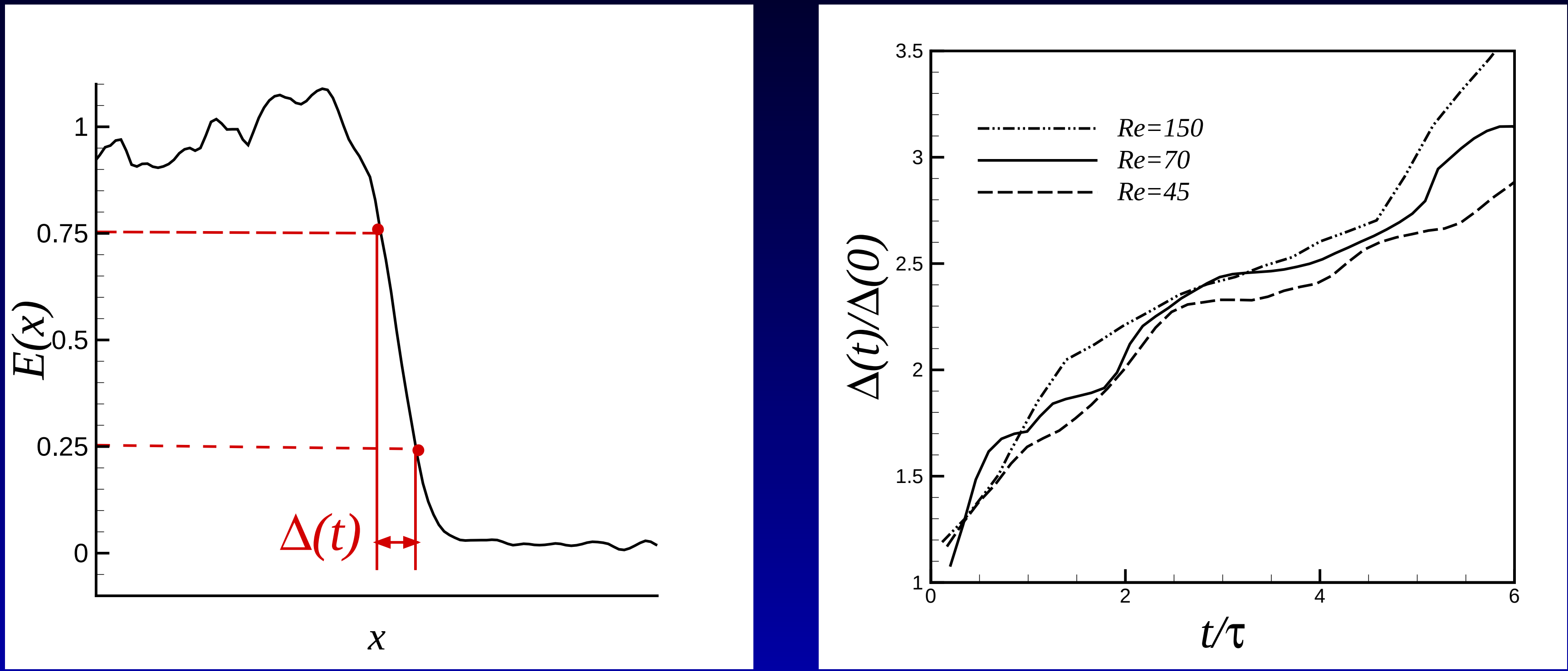


1-Gradient of energy



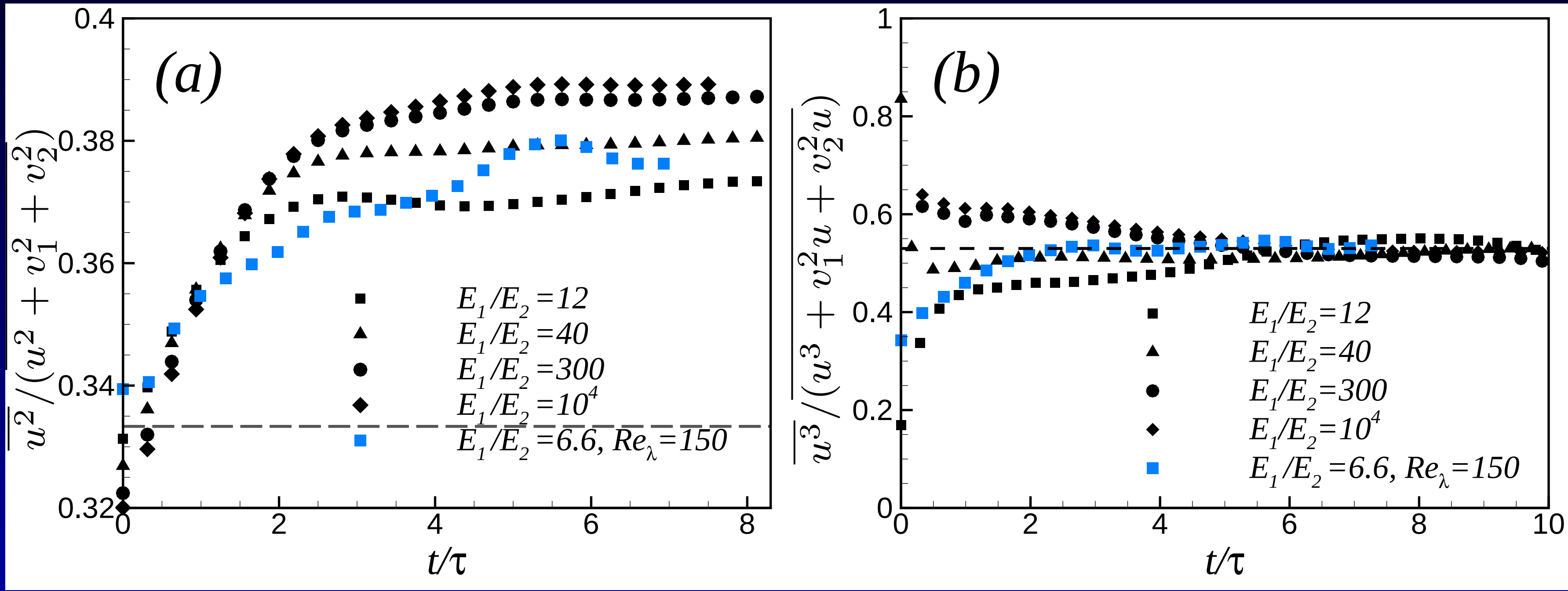
Gradient of energy, uniform integral scale

Mixing layer thickness, $E_1/E_2 = 6.7$



$\Delta(t)$ is the mixing layer thickness, defined from the kinetic energy distribution, see *JFM* 2006, $\Delta \sim t^{0.45}$.

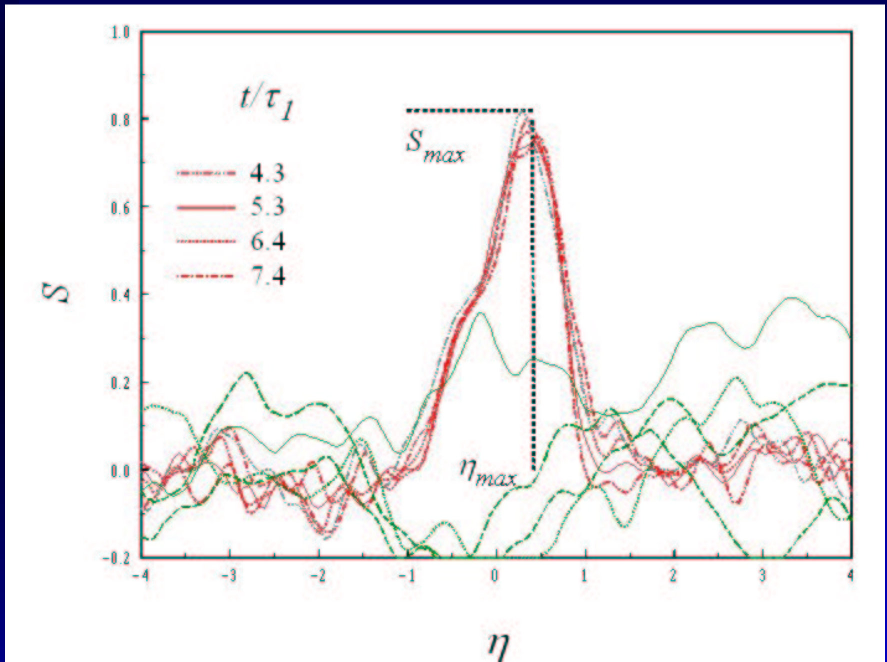
Velocity moments, large scale anisotropy

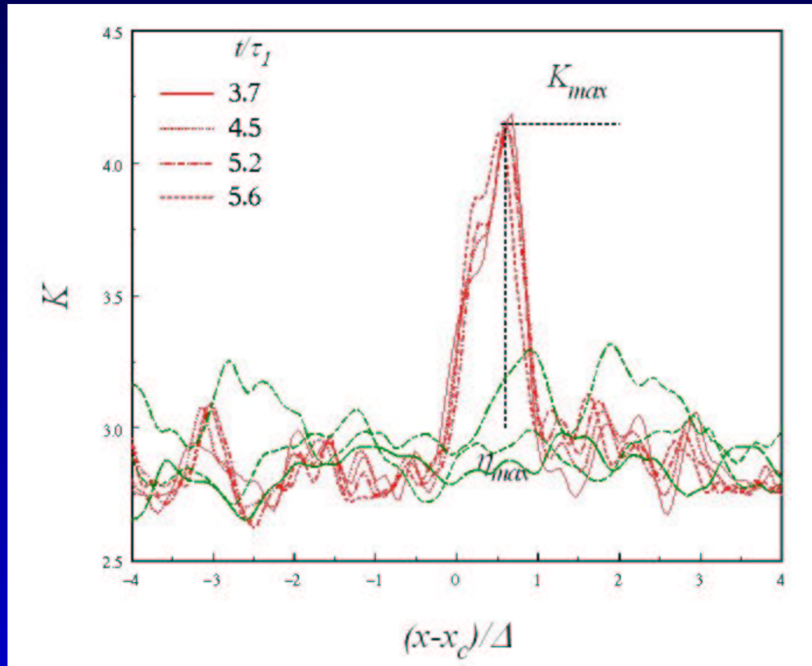


Velocity moments, large scale intermittency

$Re_\lambda = 45$, $E_1/E_2 = 6.7$, $\ell_1/\ell_2 = 1$

$S = \overline{u^3}/\overline{u^2}^{3/2}$ $S = \overline{v^3}/\overline{v^2}^{3/2}$, $K = \overline{u^4}/\overline{u^2}^2$ $K = \overline{v^4}/\overline{v^2}^2$





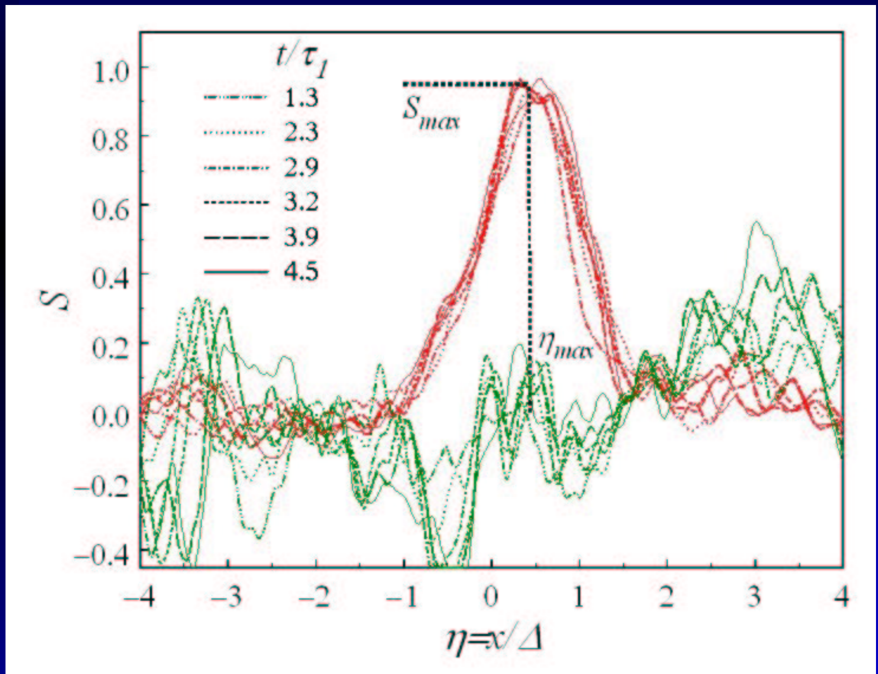
u, x in the mixing direction

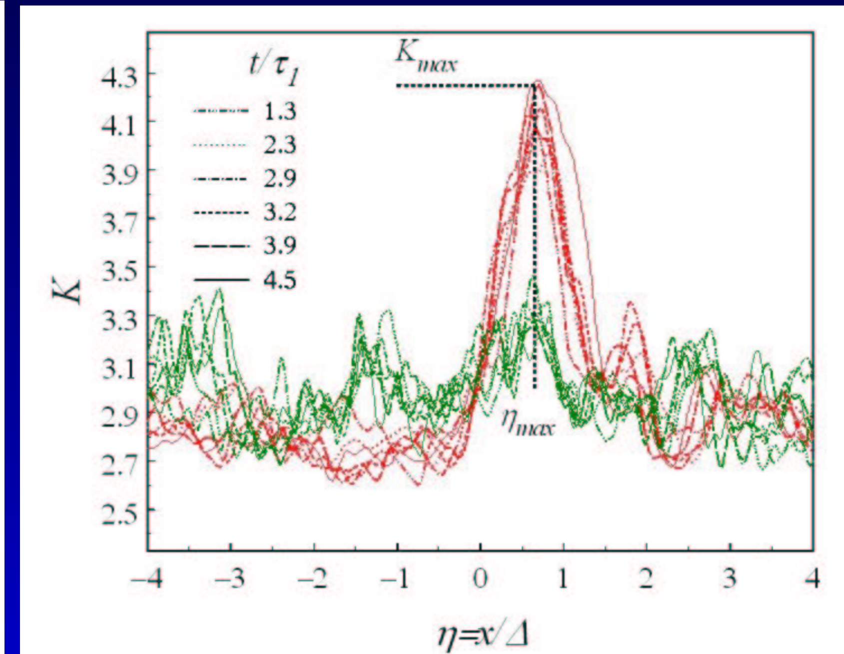
v, y normal to the mixing direction

Velocity moments, large scale intermittency

$Re_\lambda = 150$, $E_1/E_2 = 6.7$, $\ell_1/\ell_2 = 1$

$S = \overline{u^3}/\overline{u^2}^{3/2}$ $S = \overline{v^3}/\overline{v^2}^{3/2}$, $K = \overline{u^4}/\overline{u^2}^2$ $K = \overline{v^4}/\overline{v^2}^2$



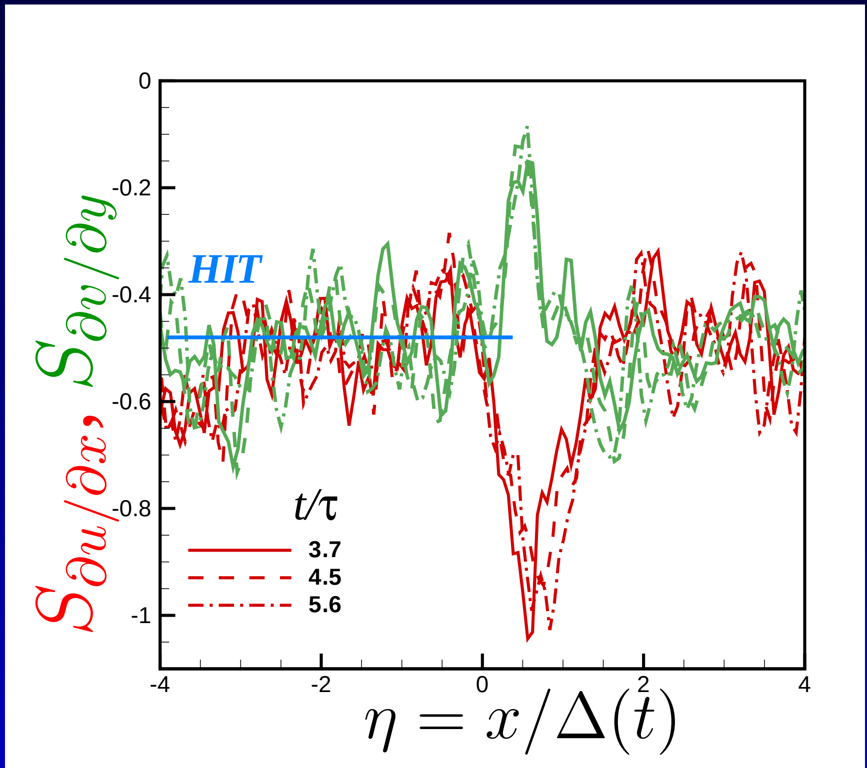


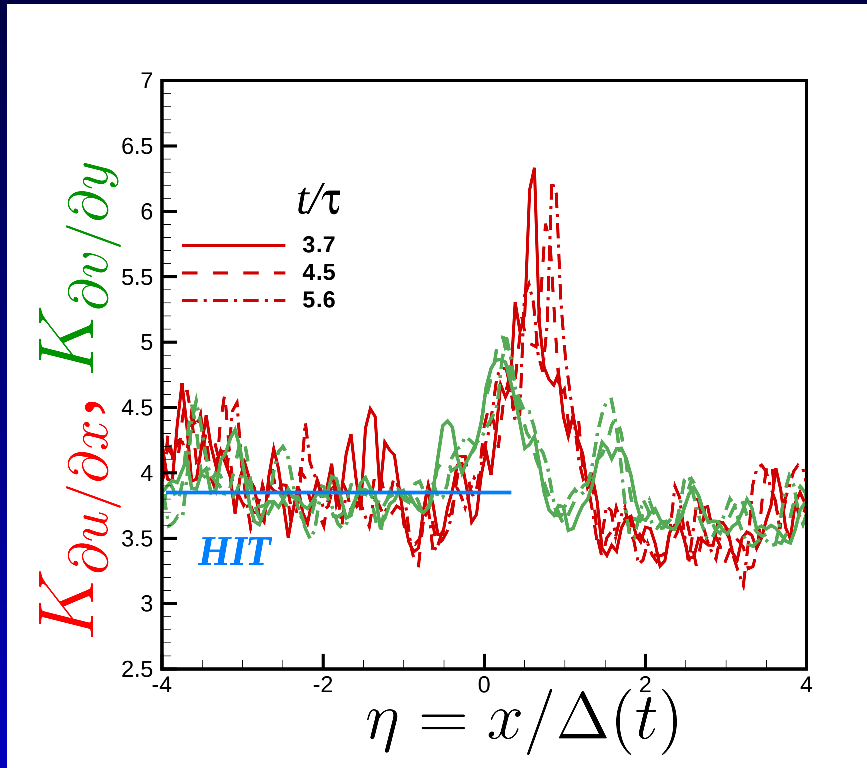
u, x in the mixing direction

v, y normal to the mixing direction

Small scale intermittency

$Re_\lambda = 45$, $E_1/E_2 = 6.7$, $\ell_1/\ell_2 = 1$

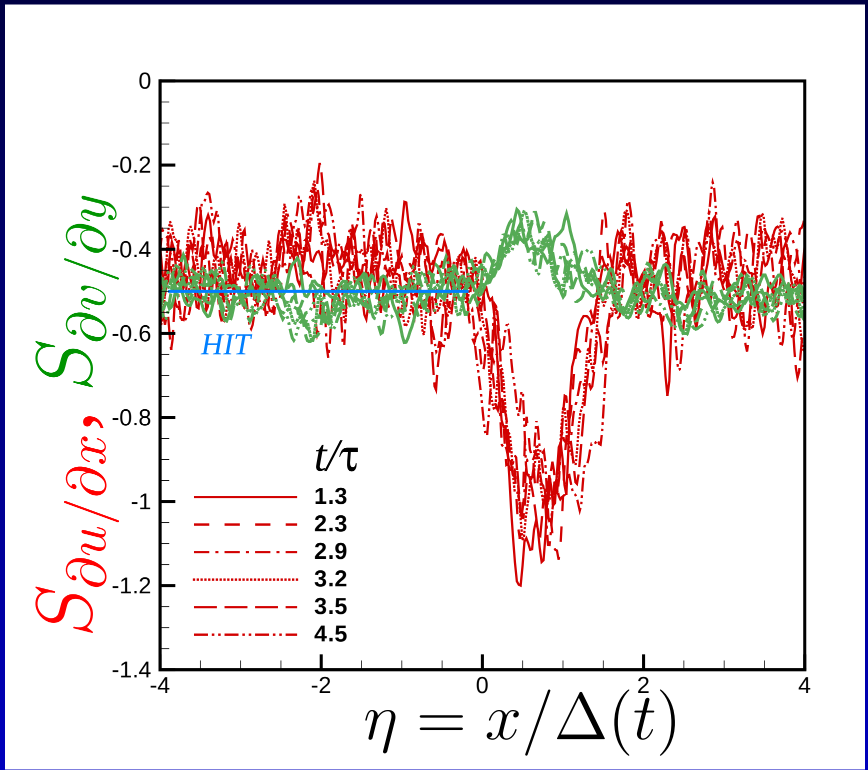


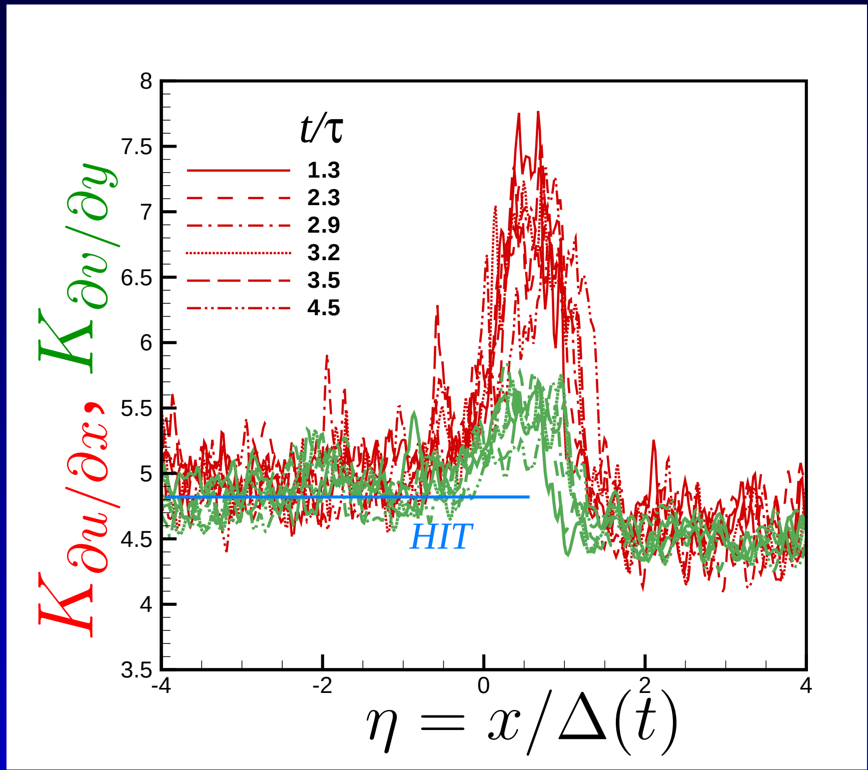


η is the dimensionless coordinate along the mixing
$\Delta(t)$ is the mixing half-width

Small scale intermittency

$$Re_\lambda = 150,\ E_1/E_2 = 6.7,\ \ell_1/\ell_2 = 1$$

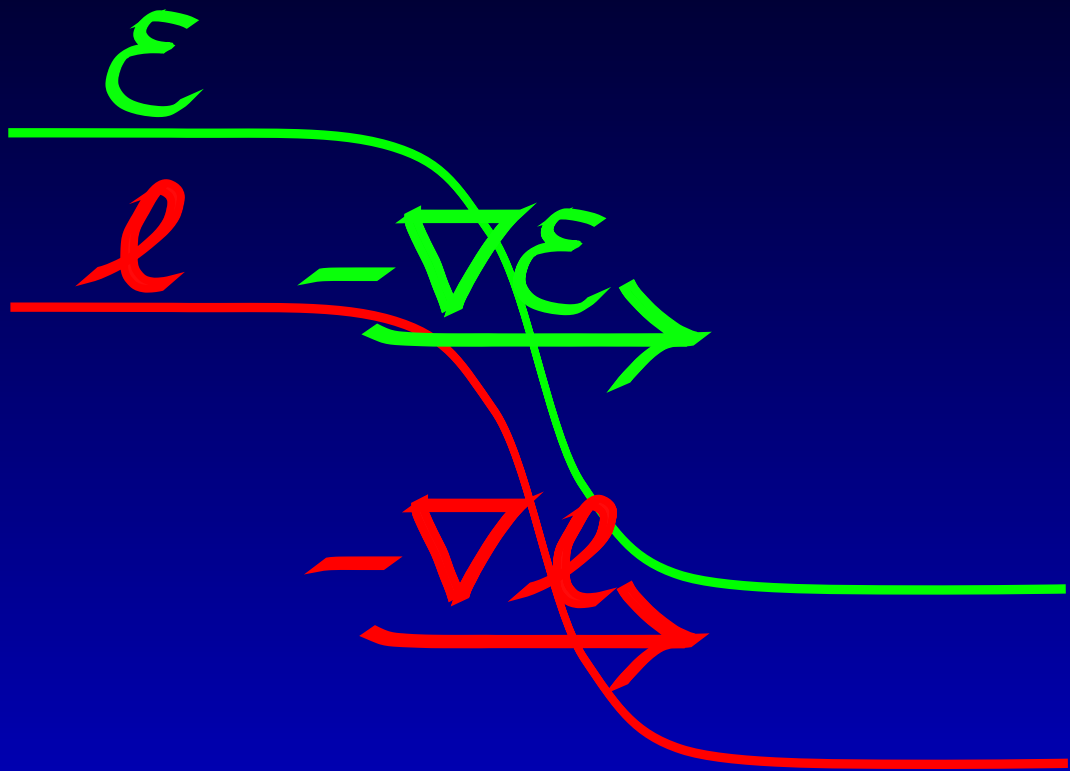




η is the dimensionless coordinate along the mixing

$\Delta(t)$ is the mixing half-width

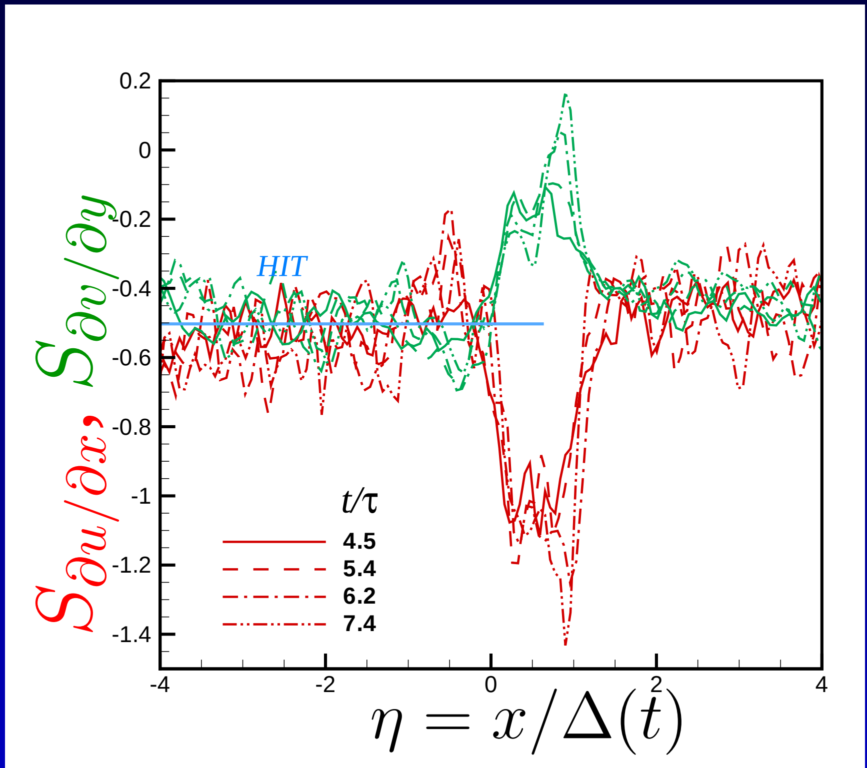
2-Concurrent gradients

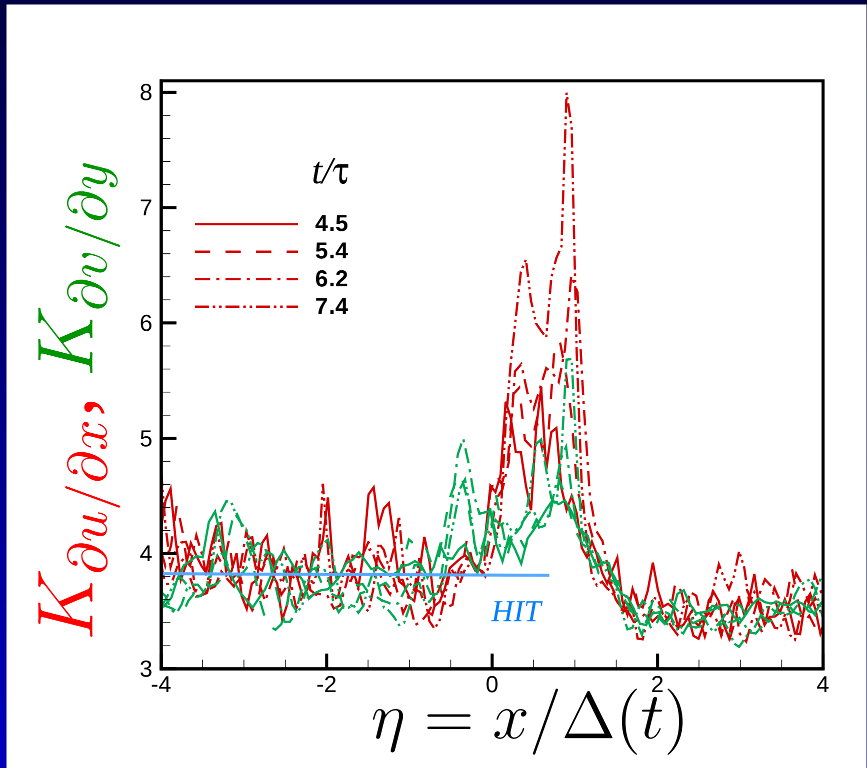


Concurrent gradients of energy and scale

Small scale intermittency

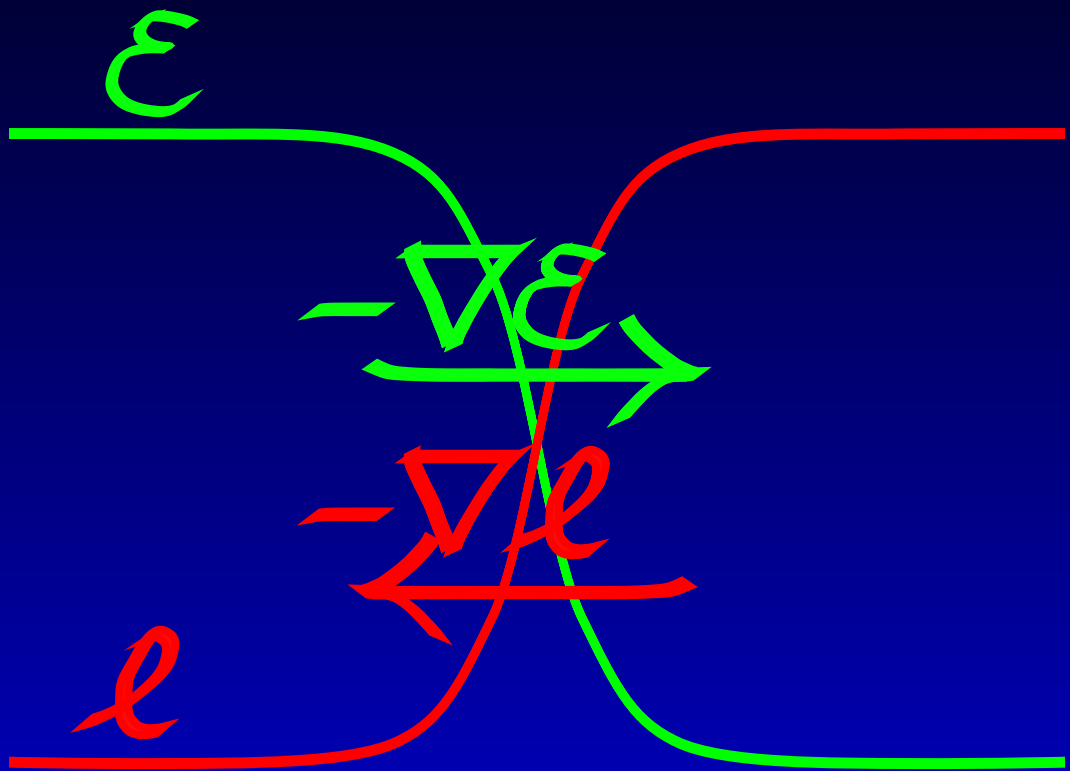
$Re_\lambda = 45$, $E_1/E_2 = 6.7$, $\ell_1/\ell_2 = 2.1$





η is the dimensionless coordinate along the mixing
$\Delta(t)$ is the mixing half-width

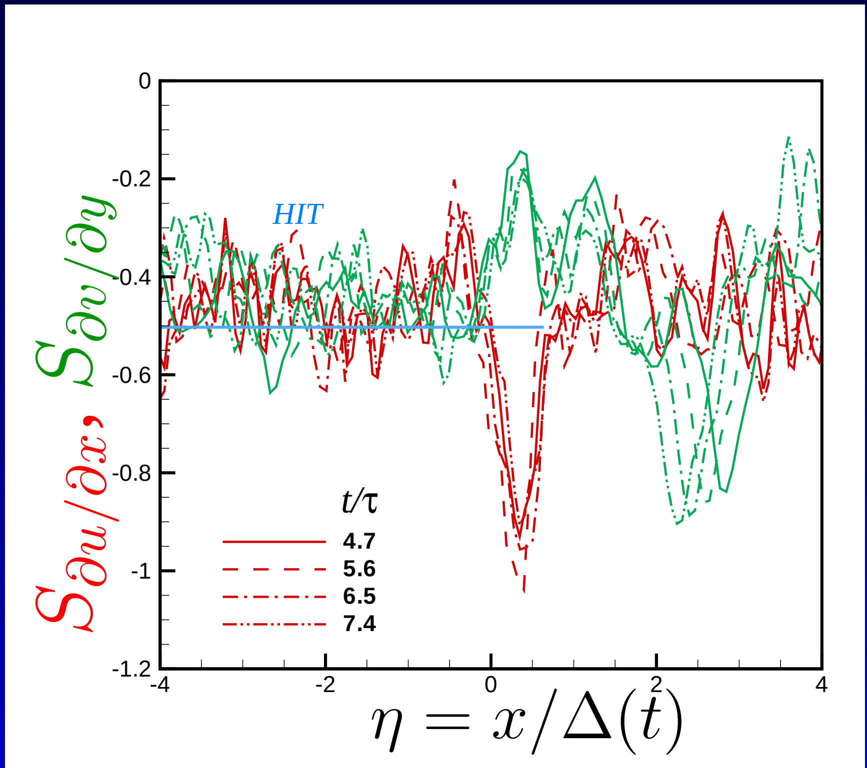
3-Opposite gradients

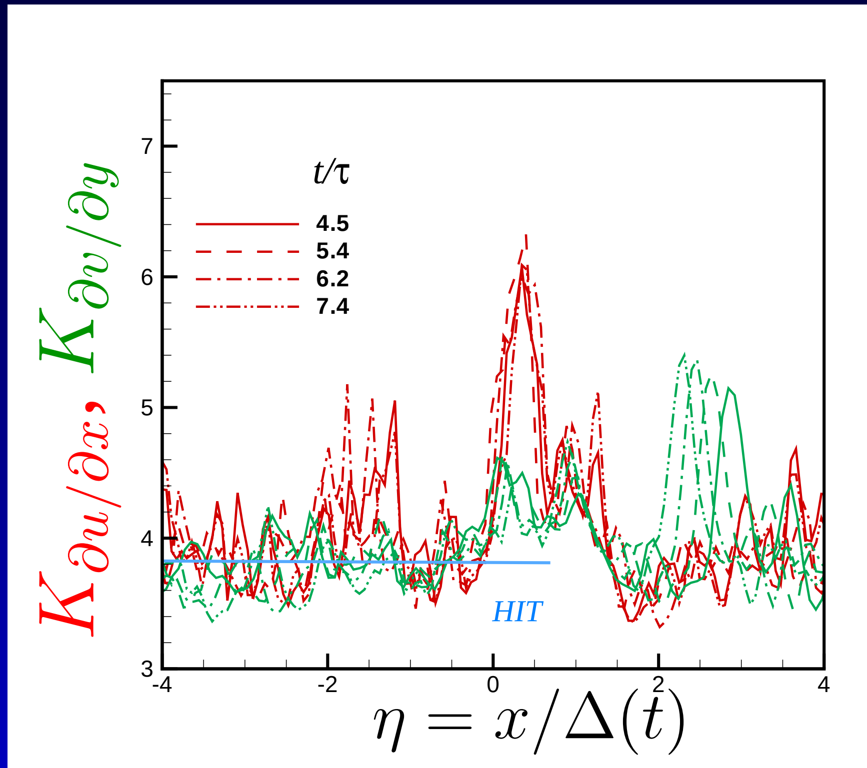


Opposite gradients of energy and integral scale

Small scale intermittency: higher moments

$Re_\lambda = 45$, $E_1/E_2 = 6.5$, $\ell_1/\ell_2 = 0.6$

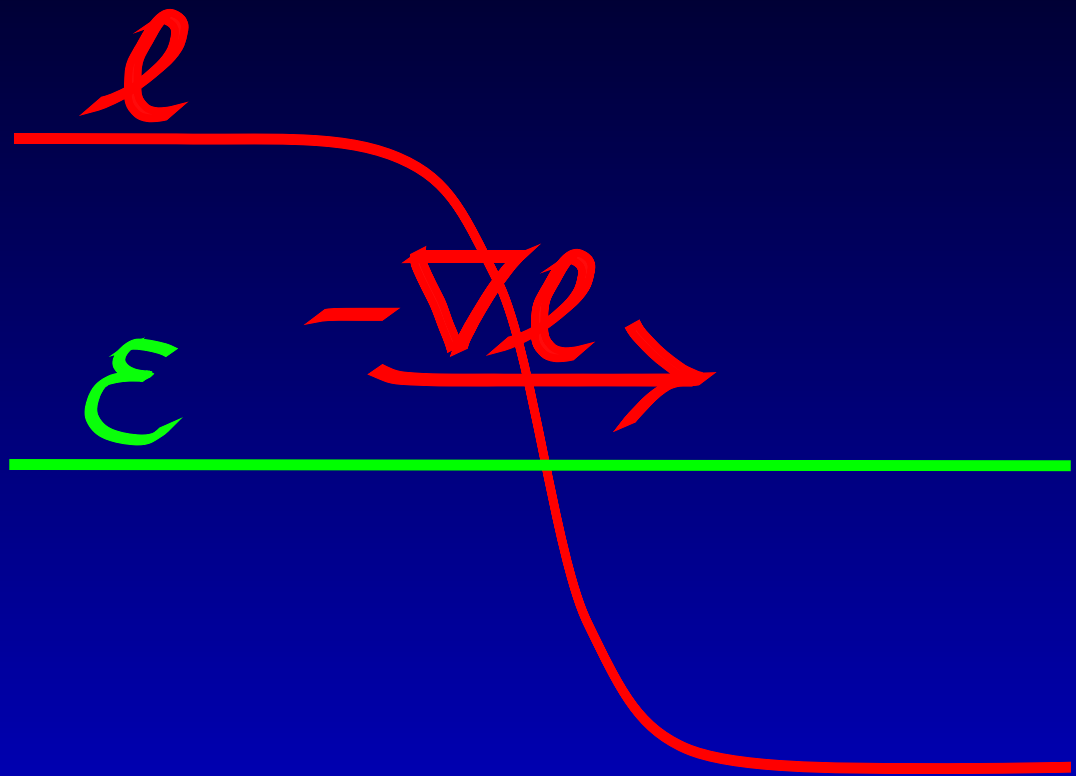




η is the dimensionless coordinate along the mixing

$\Delta(t)$ is the mixing half-width

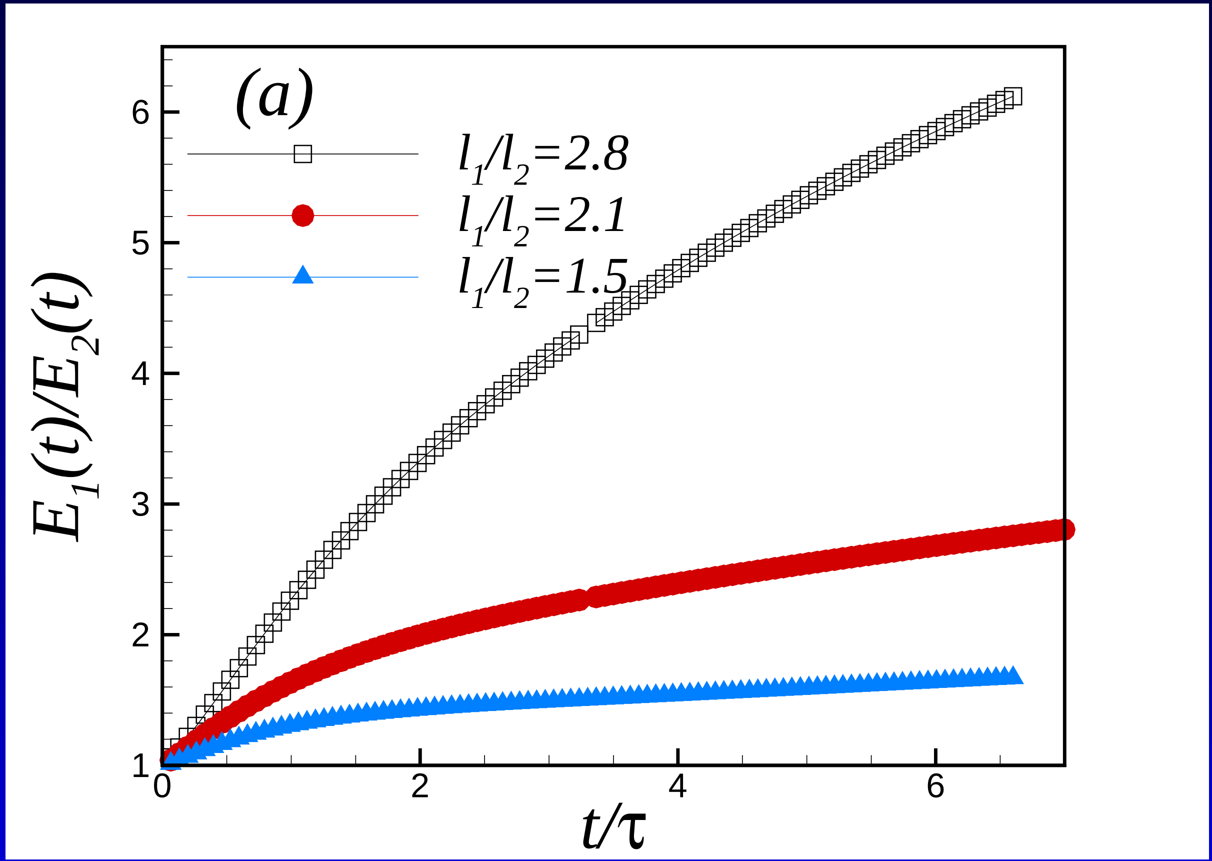
4-Gradient of integral scale



Gradient of integral scale, initially uniform energy

Energy ratio

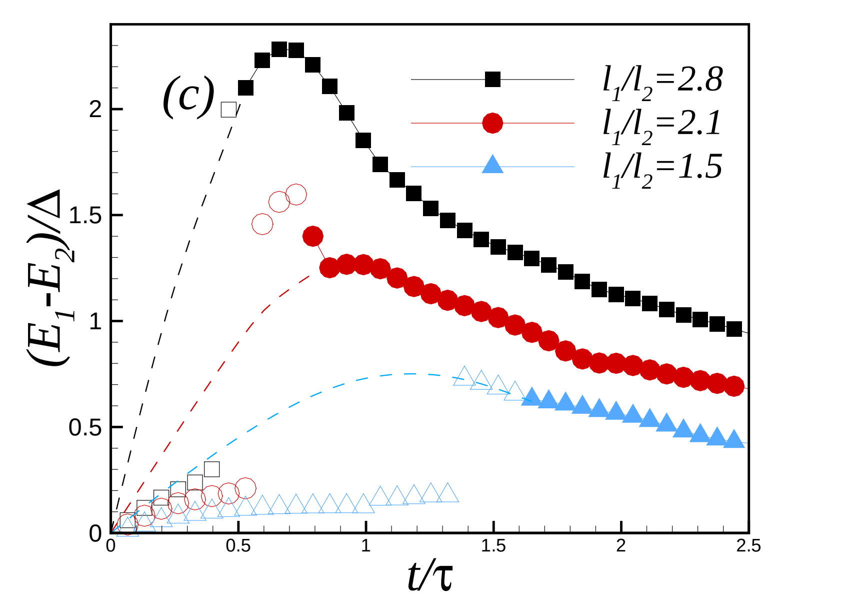
Different decay rates ⇒ kinetic energy does not remain constant:

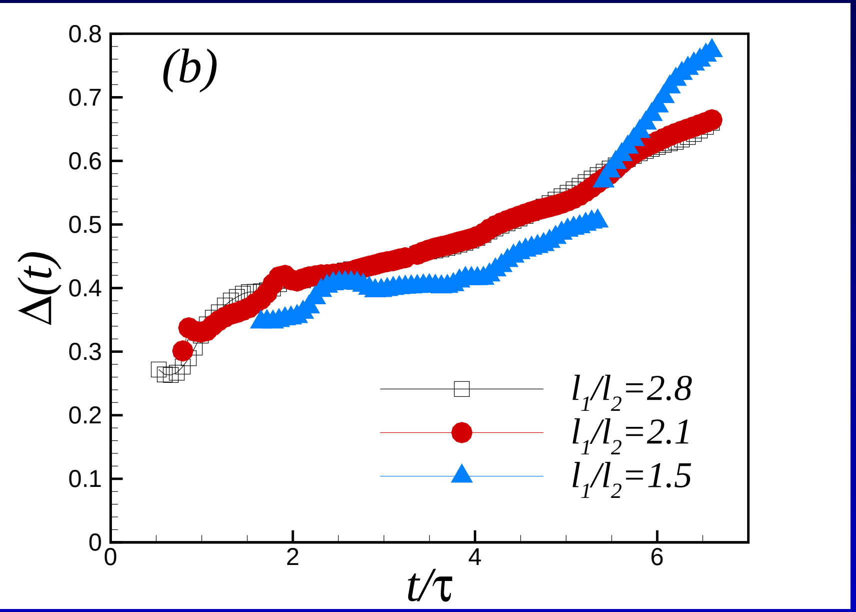


⇒ a concurrent energy gradient is generated

Kinetic energy gradient

Kinetic energy gradient and mixing layer thickness

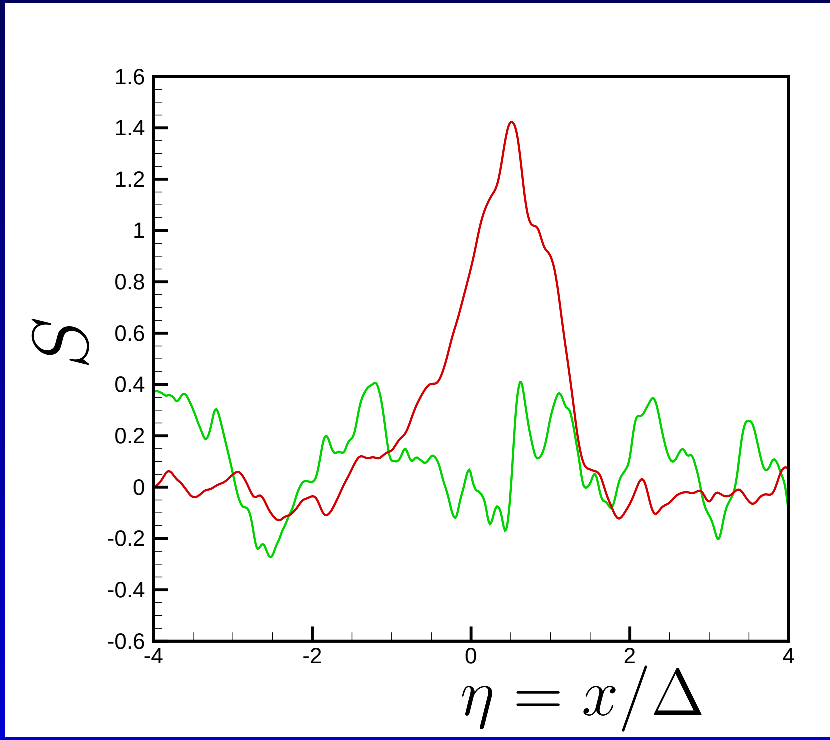


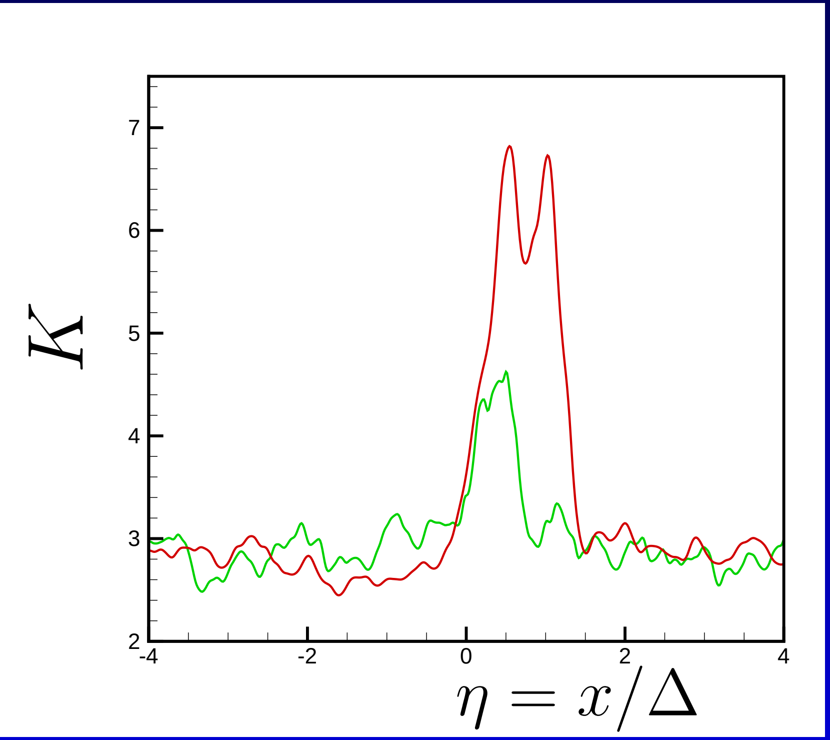


Velocity moments, large scale intermittency

$Re_\lambda = 150$, $E_1/E_2 = 6.7$, $\ell_1/\ell_2 = 2.8$, $t/\tau = 6.8$

$S = \overline{u^3}/\overline{u^2}^{3/2}$ $S = \overline{v^3}/\overline{v^2}^{3/2}$ $K = \overline{u^4}/\overline{u^2}^{2}$ $K = \overline{v^4}/\overline{v^2}^{2}$



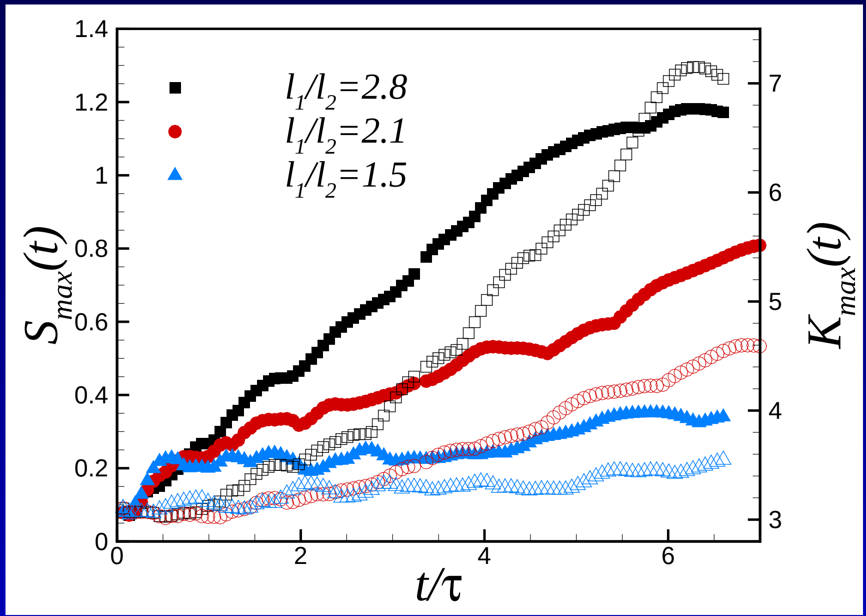


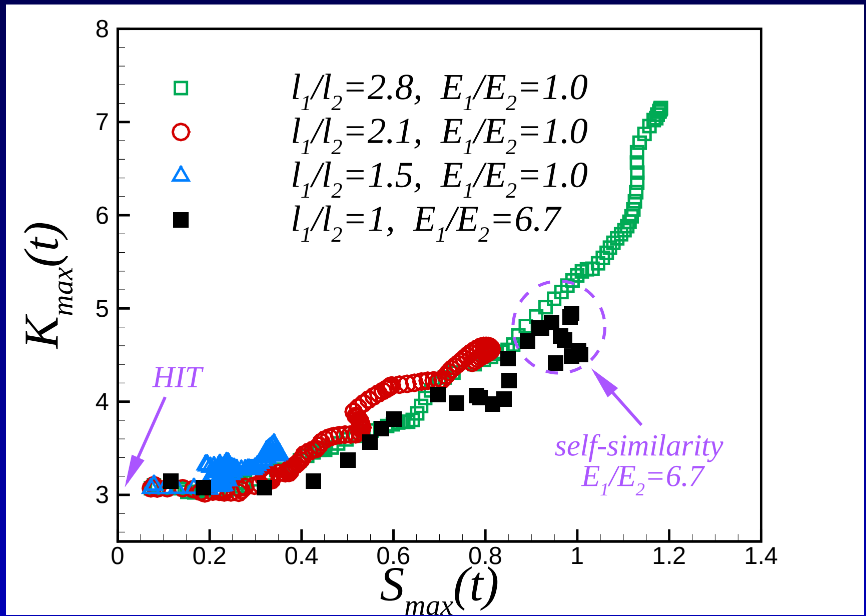
u, x in the mixing direction

v, y normal to the mixing direction

Large scale intermittency

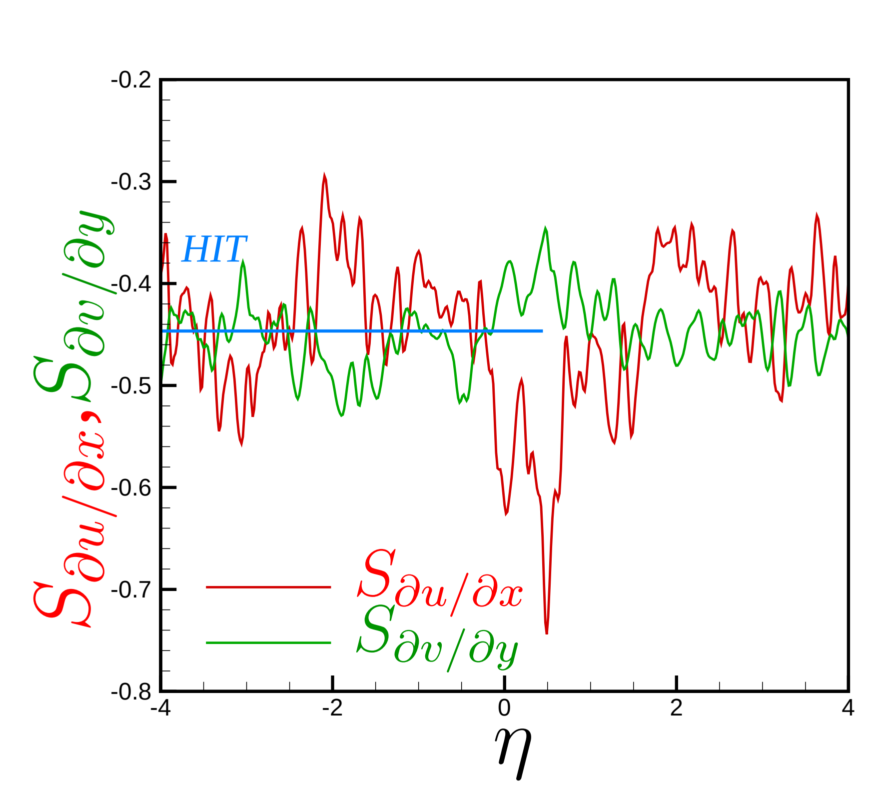
Velocity skewness and kurtosis, component in the inhomogeneous direction: maximum in the mixing layer

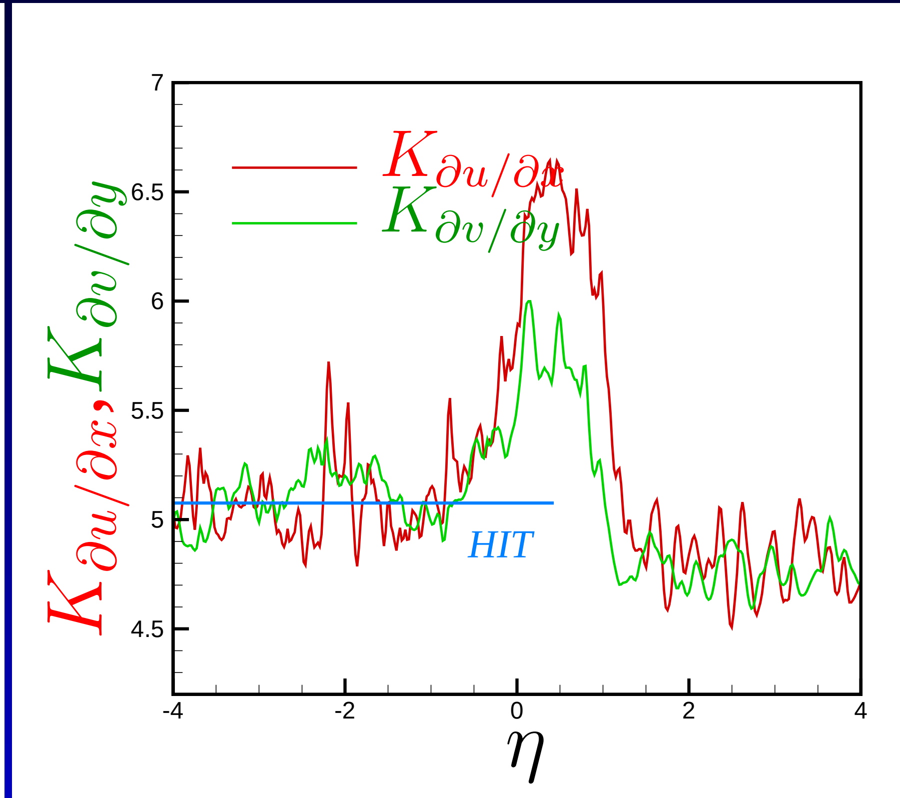




Small scale intermittency

$Re_\lambda = 150,\ E_1/E_2 = 1,\ \ell_1/\ell_2 = 2.8,\ t/\tau = 6.7$



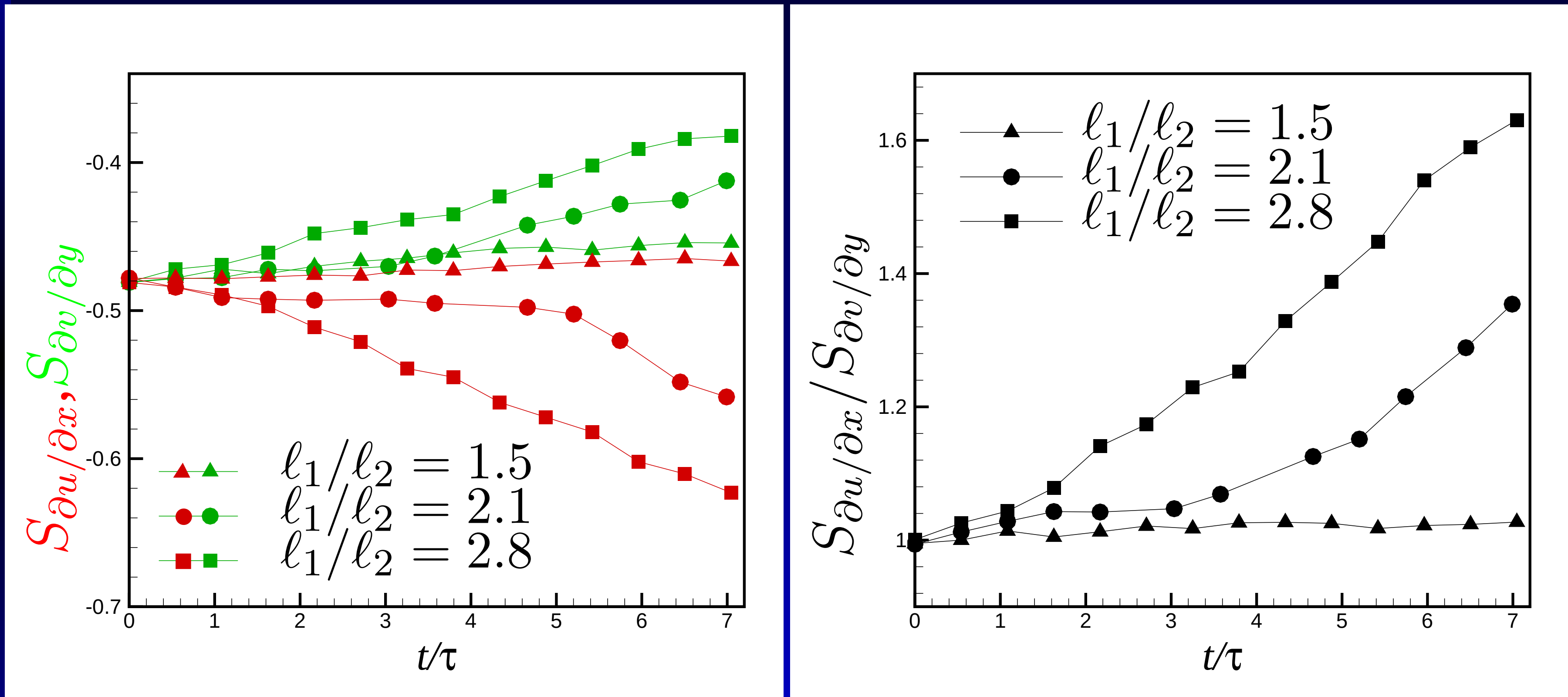


Spatial distribution of longitudinal moments,

$\eta = x/\Delta,$

Small scale anisotropy: skewness

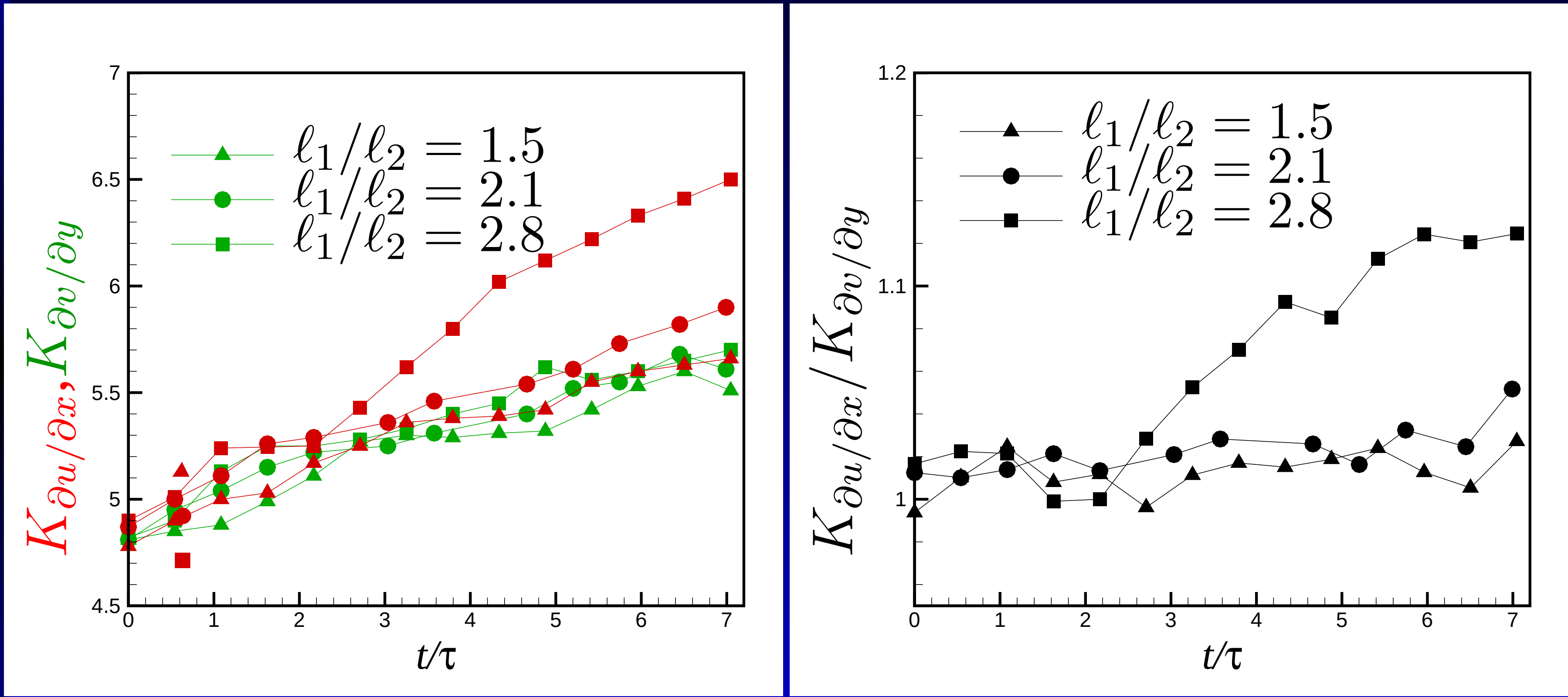
$Re_\lambda = 150$, $E_1/E_2 = 1$, $\ell_1/\ell_2 = 2.8$:



Anisotropy is propagated to small scales.

Small scale anisotropy: kurtosis

$Re_\lambda = 150$, $E_1/E_2 = 1$, $\ell_1/\ell_2 = 2.8$:

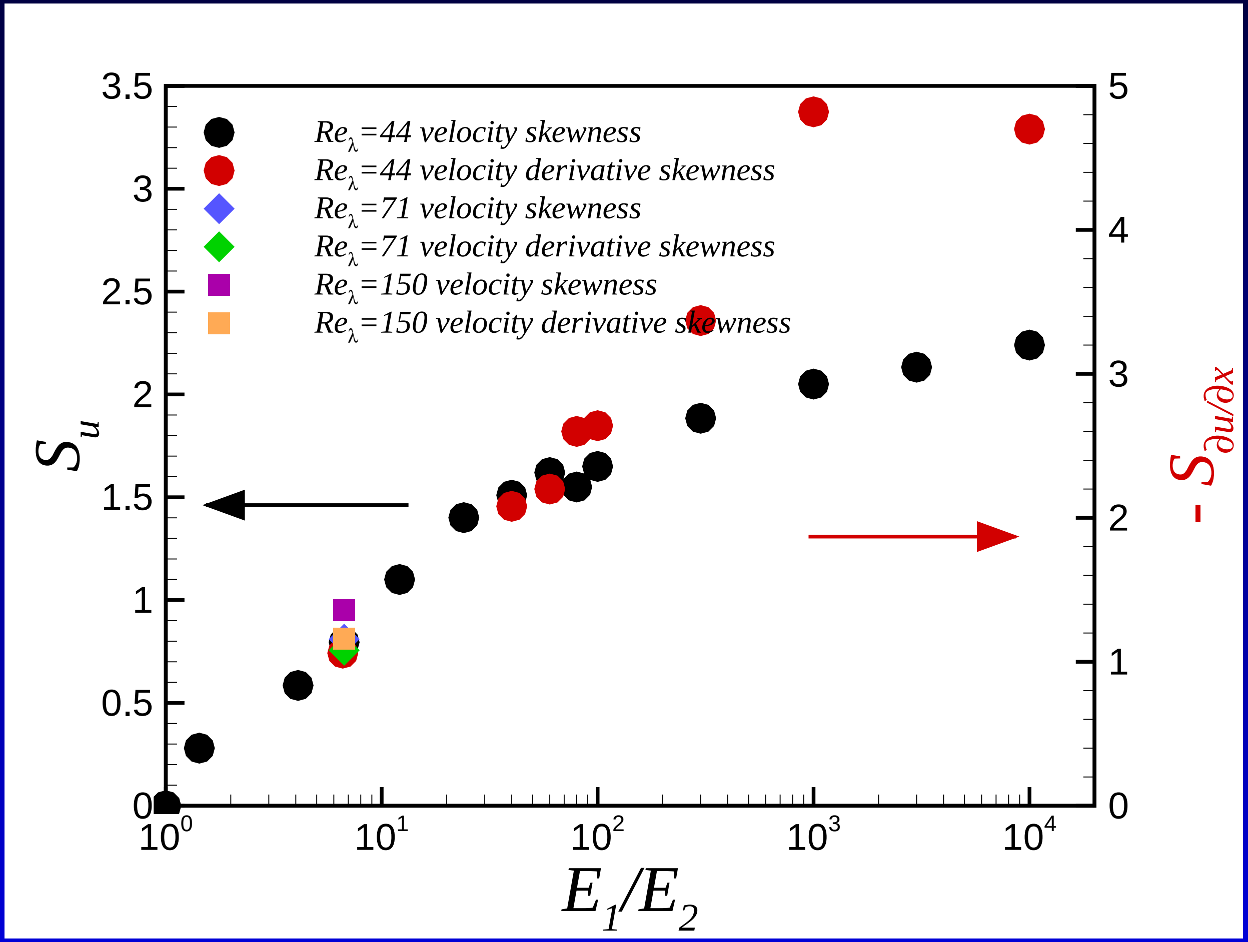


Anisotropy is propagated to small scales.

Asymptote for $E_1/E_2 \to +\infty$

Skewness:

velocity

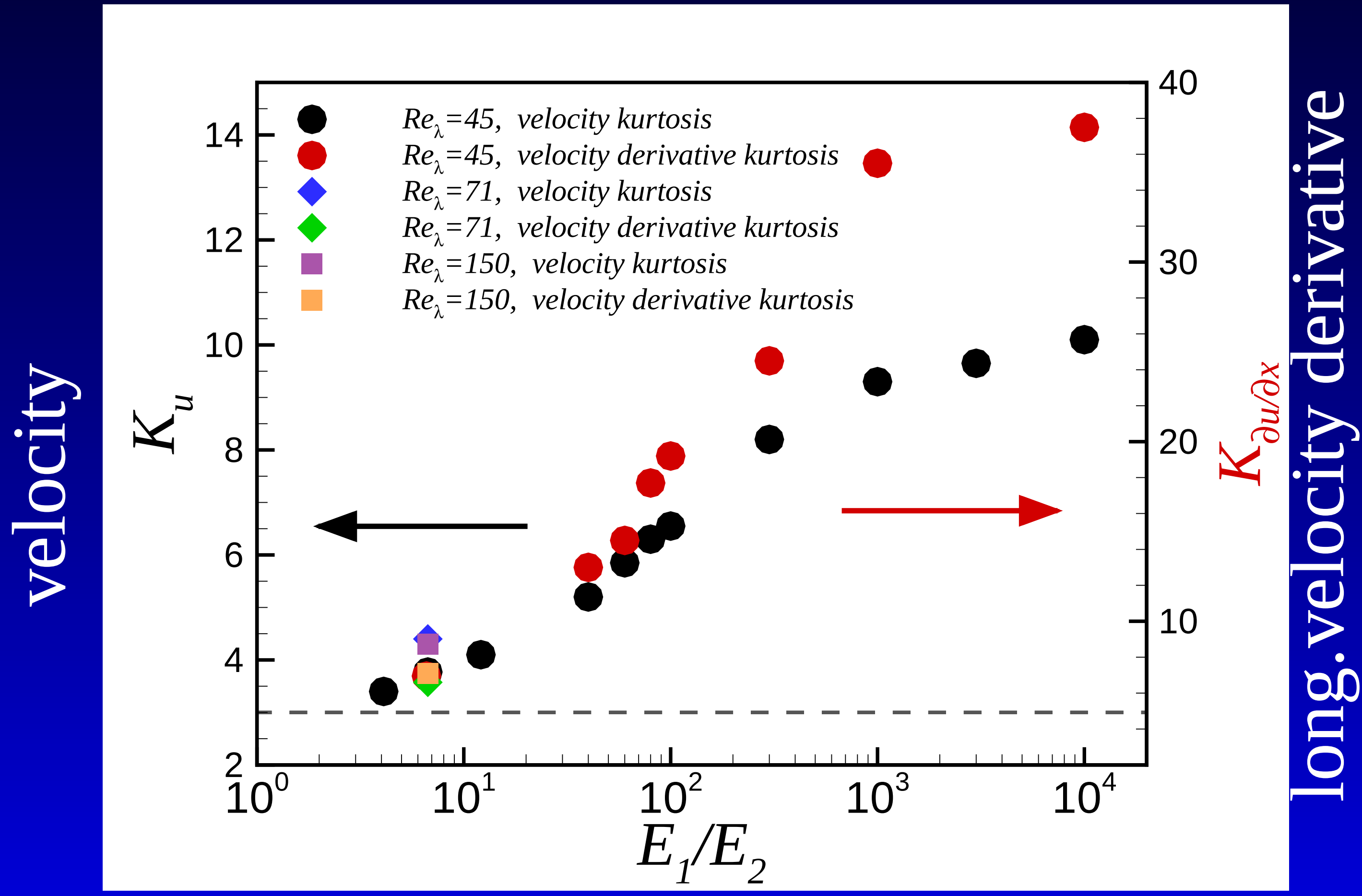


long.velocity derivative

u, x in the mixing direction

Asymptote for $E_1/E_2 \to +\infty$

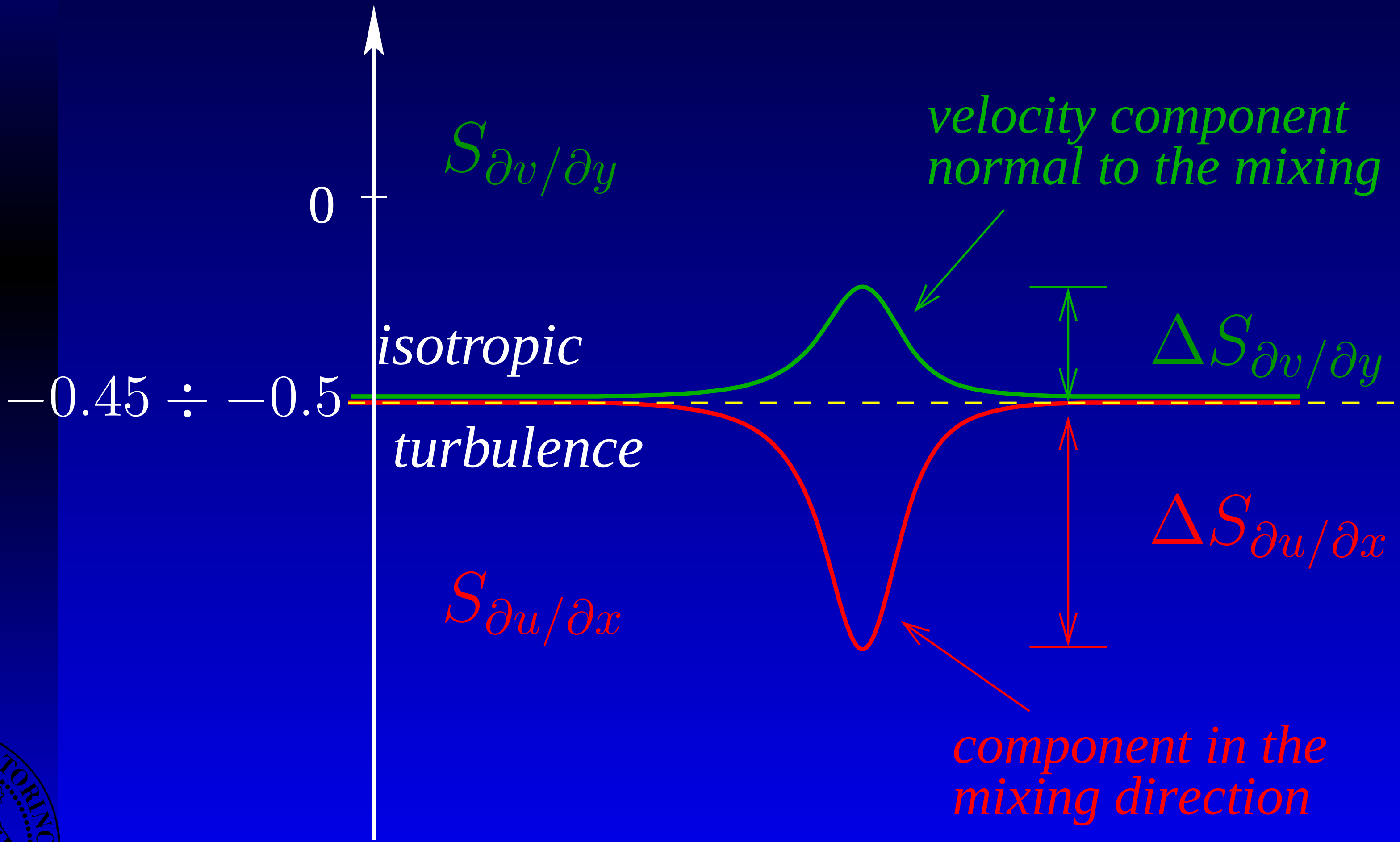
Kurtosis:



u, x in the mixing direction

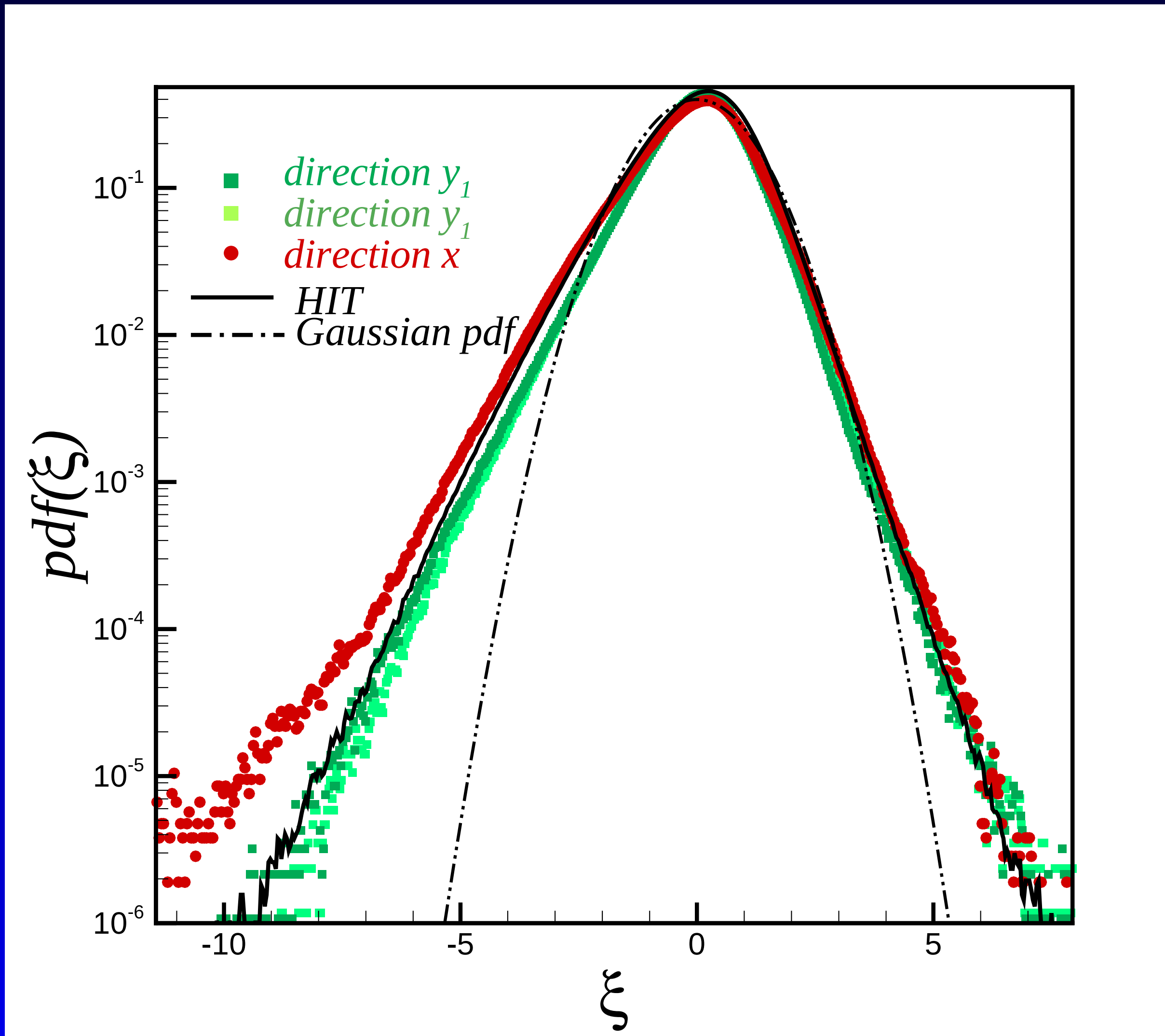
Longitudinal derivatives

Scheme of the general behaviour for the longitudinal *skewness*



Probability density function

$Re_\lambda = 150,\ E_1/E_2 = 6.7,\ t/\tau = 4.0$:



$$\xi = \frac{\partial u_i}{\partial x_i} \Big/ \overline{\left(\frac{\partial u_i}{\partial x_i}\right)^2}^{\frac{1}{2}}$$

$$i = y_1,\ y_2,\ x$$

Large scales: main features of velocity statistics

- *HIGH INTERMITTENCY* function of:
  - gradient of turbulent kinetic energy
  - gradient of integral scale

- *ANISOTROPY* mild on the second order moments

  high for higher moments (anisotropy ratio equal to 2 for the 3rd and 1.5 for the 4th order moments) slightly increasing with Re

Small scales: main features of velocity derivative statistics

- *HIGH INTERMITTENCY* function of:
  - gradient of turbulent kinetic energy
  - gradient of integral scale
  - much more intense than that of the large scales

- *ANISOTROPY* mild on the second order moments

  high for higher moments (anisotropy ratio up to 10 for the 3rd order moment and 2 for the 4th moment) slightly decreasing with Re

Conclusions

Simulations of a flow with an homogenous energy and an integral scale gradient show:

- an integral scale inhomogeneity generates an energy gradient
- the decay exponent of turbulent flow with the same initial energy depends on their integral scale $\Rightarrow$ smaller the scale, faster the decay.
- intermittency generated in the mixing layer can be higher than generated by an energy gradient and a uniform scale
- anisotropy and intermittency spread to small scales.

Decay exponent of large and small scales in isotropic turbulence

Euromech Colloquium 512, Torino, October 2009

Michele Iovieno, Daniela Tordella

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Politecnico di Torino,
Corso Duca degli Abruzzi 24, 10129 Torino, Italy

Motivation

- Verify the dependence of the decay exponent of homogeneous turbulence from the initial conditions.
- check the role of the small scales during the decay

State of art

Speziale - Bernard 1992, self-preserving decay: all correlations scale with the Taylor microscale:

$$B_{LL}(r) = \overline{u'^2} f\left(\frac{r}{L}\right)$$

$$B_{LLL}(r) = \overline{u'^2}^{\frac{3}{2}} g\left(\frac{r}{L}\right)$$

- $L = \lambda(t)$
- decay exponent asymptotes -1
- all length scales proportional to λ during the decay
- derivative skewness S = constant.

State of art

George 1992: equilibrium hypothesis, relaxed constraint on triple correlations:

$$\partial_t E(k,t) = T(k,t) - \nu k^2 E(k,t)$$

$$\begin{aligned} E(k,t) &\approx \overline{u'^2}\lambda f(k\lambda,*) \\ T(k,t) &\approx \frac{\nu\overline{u'^2}}{\lambda} g(k\lambda,*) \end{aligned}$$

- power-law decay determined by the initial conditions (initial Re_λ)
- $S\,Re_\lambda = \text{const}$

Experiments

Lavoje et al., *JFM* 2007, grid turbulence

Antonia et al., *J.Turb.* 2003, grid turbulence

Antonia, Orlandi *PoF* 2003, dns

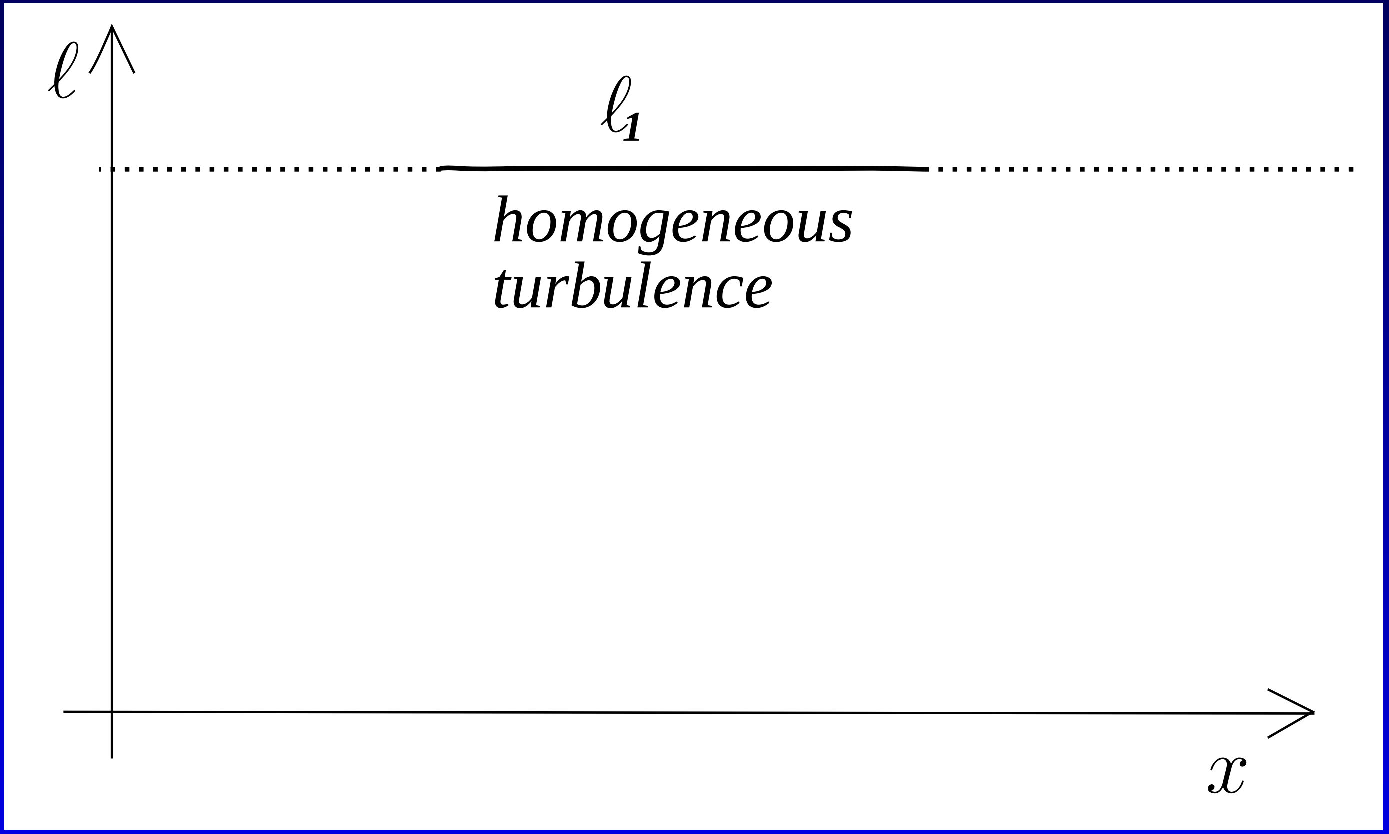
Antonia, Orlandi *JFM* 2004, dns

Mansour, Wray, *PoF* 1994, dns

etc.

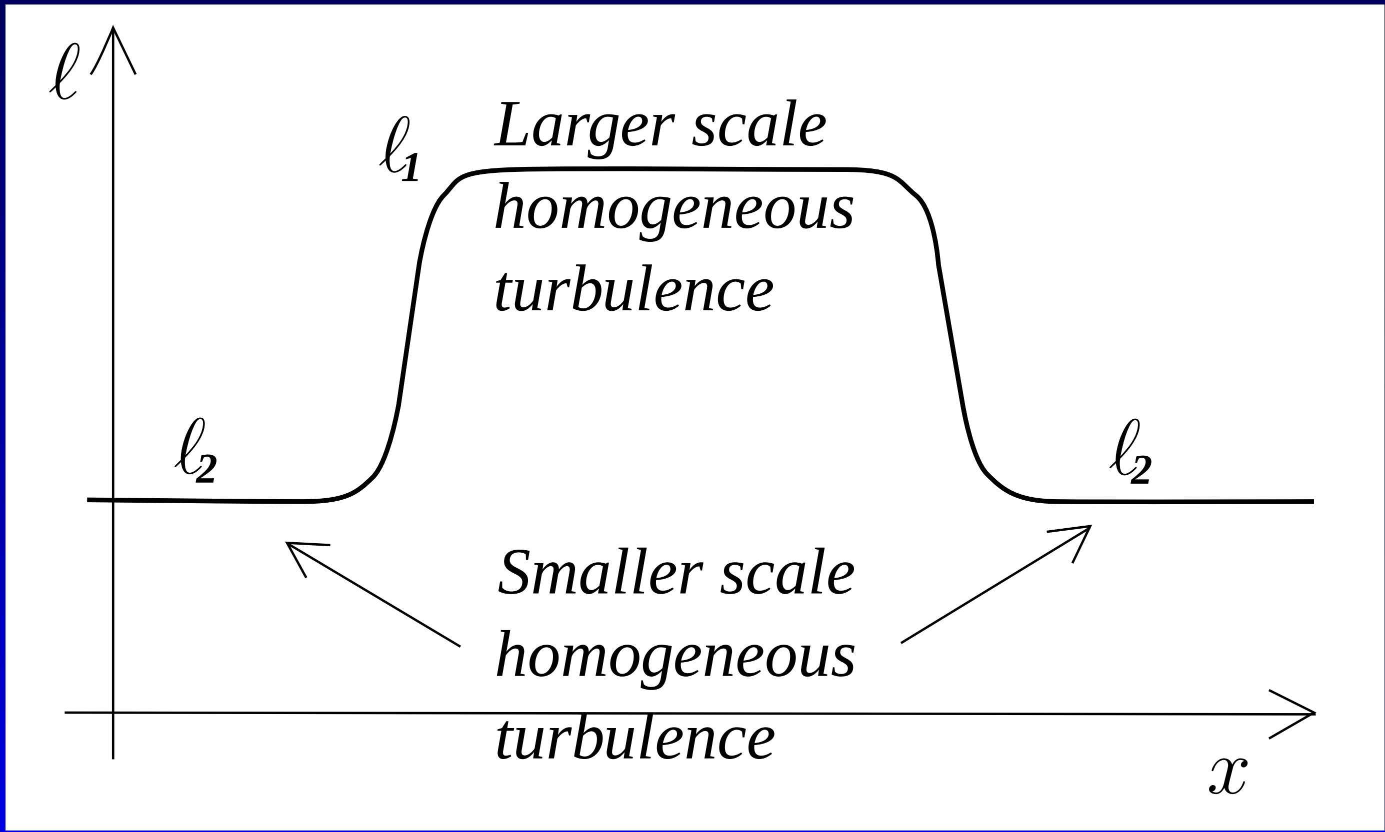
Flow configuration

We follow the time decay of two homogeneous turbulent flows with the same initial kinetic energy but different scales:



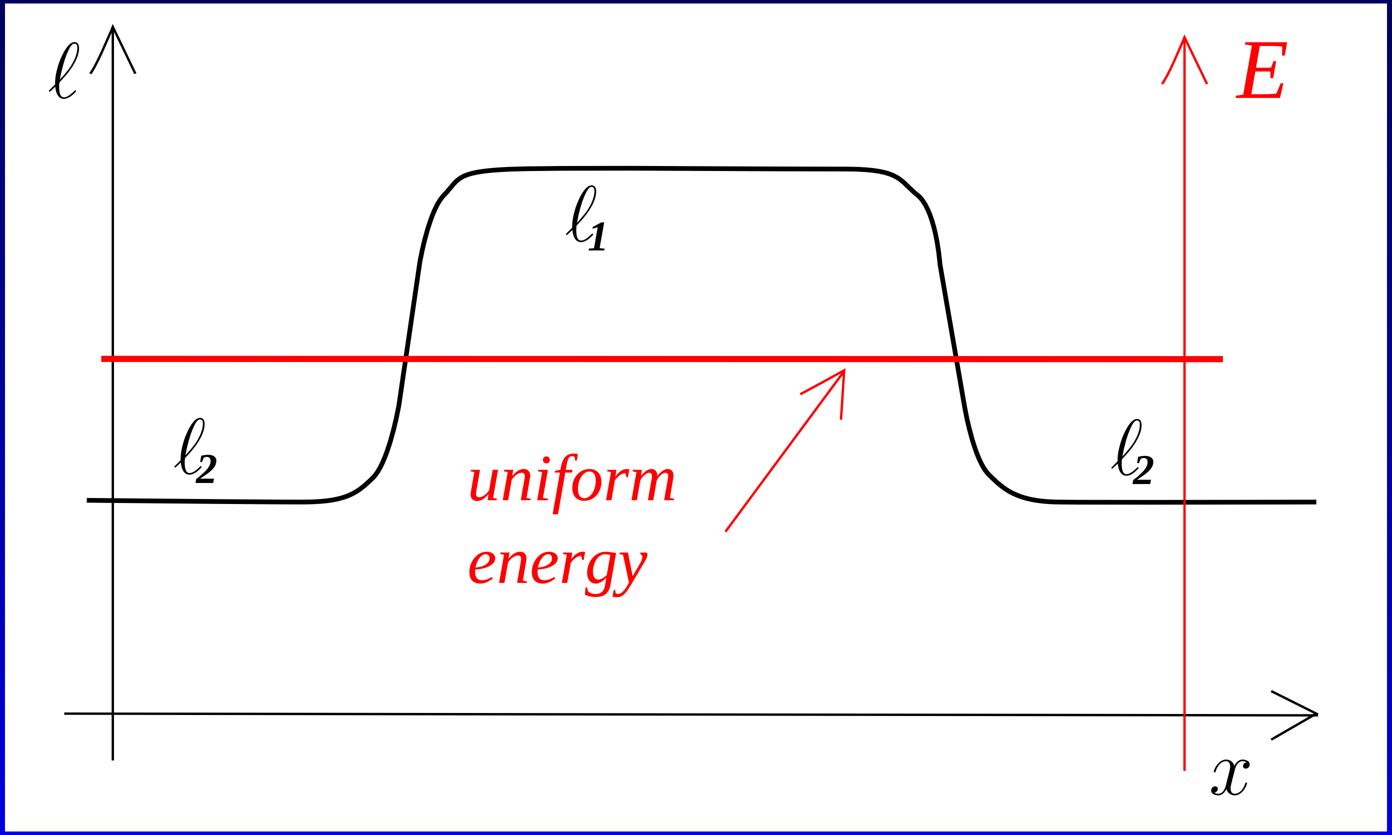
Flow configuration

We follow the time decay of two homogeneous turbulent flows with the same initial kinetic energy but different scales:

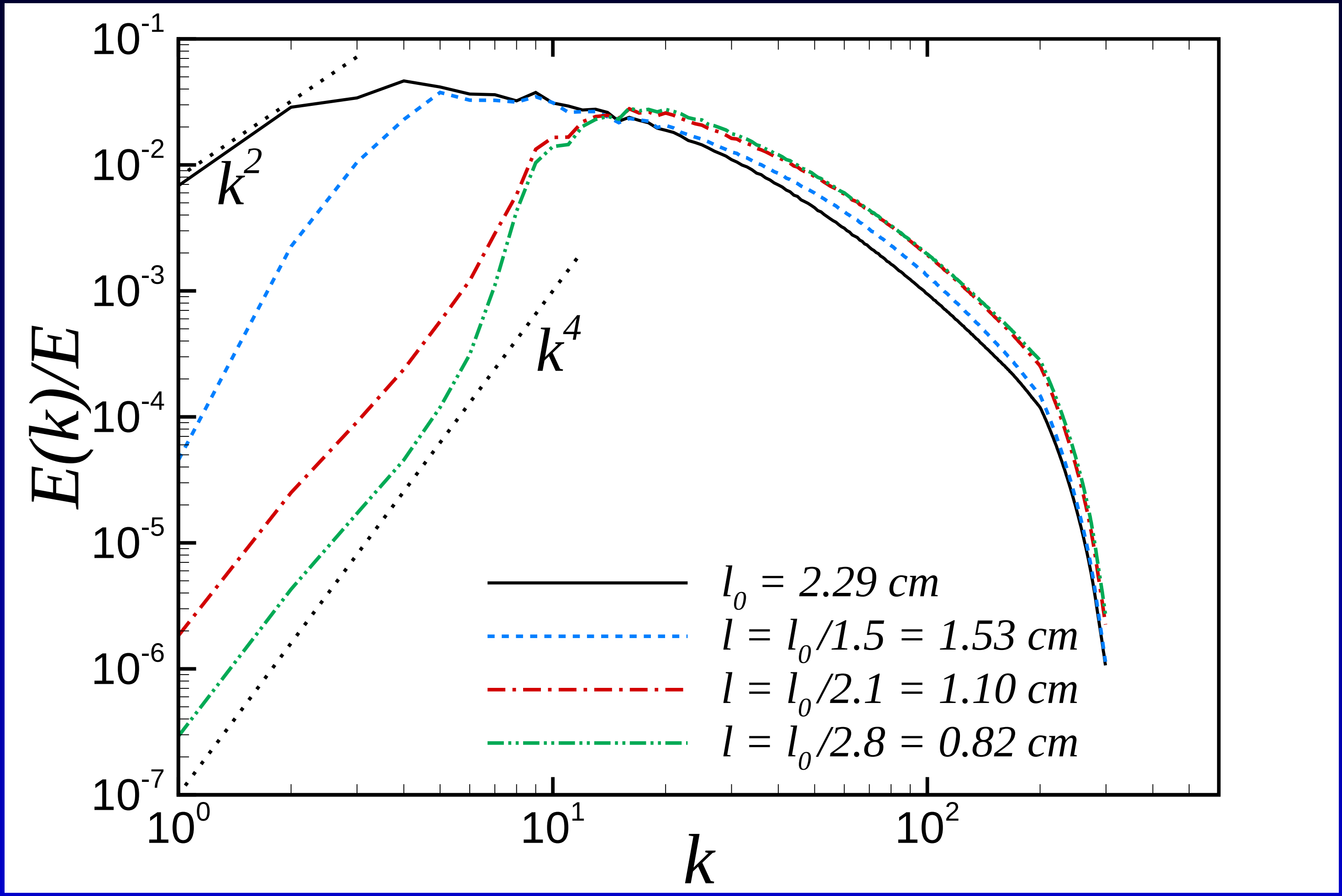


Flow configuration

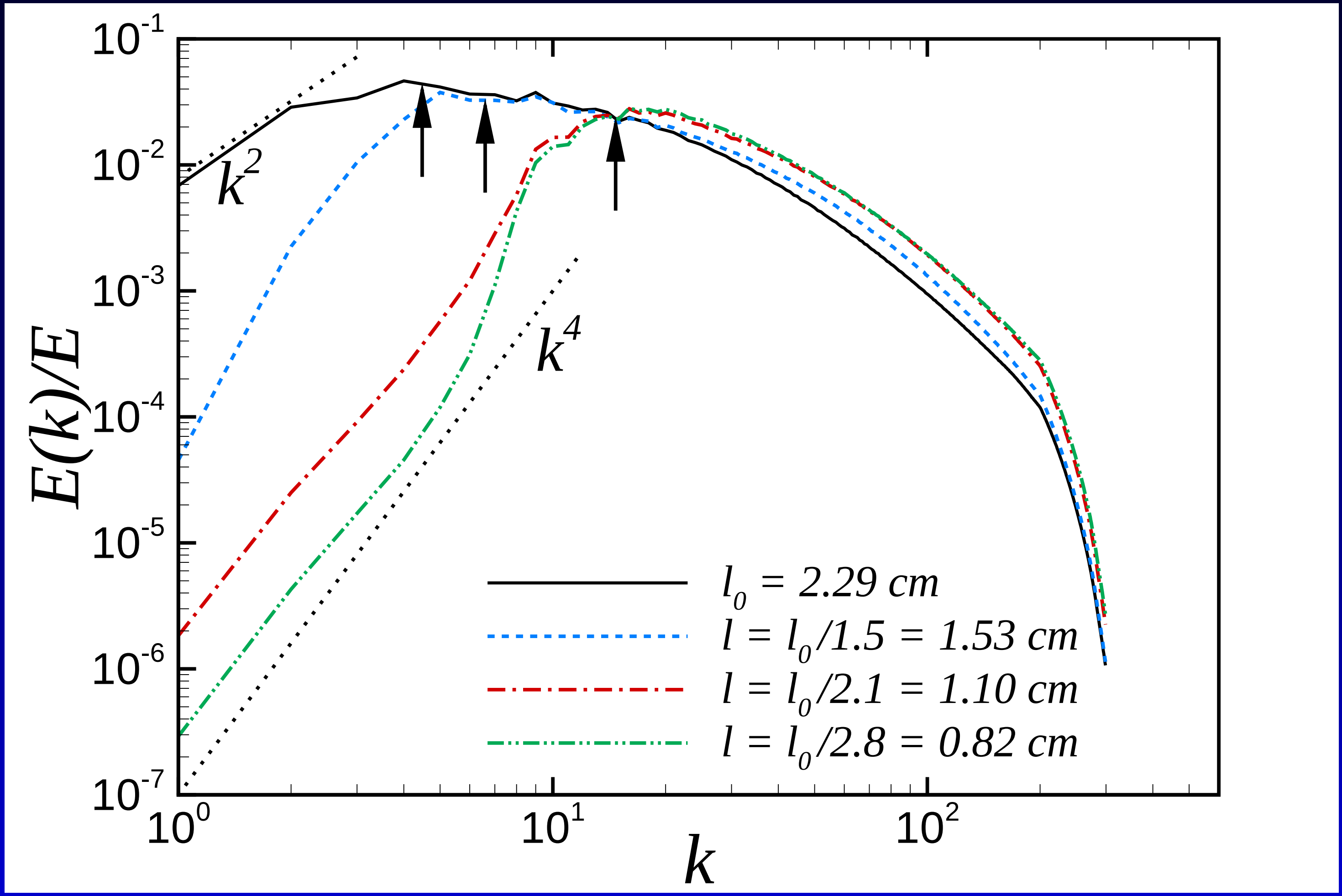
We follow the time decay of two homogeneous turbulent flows with the same initial kinetic energy but different scales:



Initial energy spectra

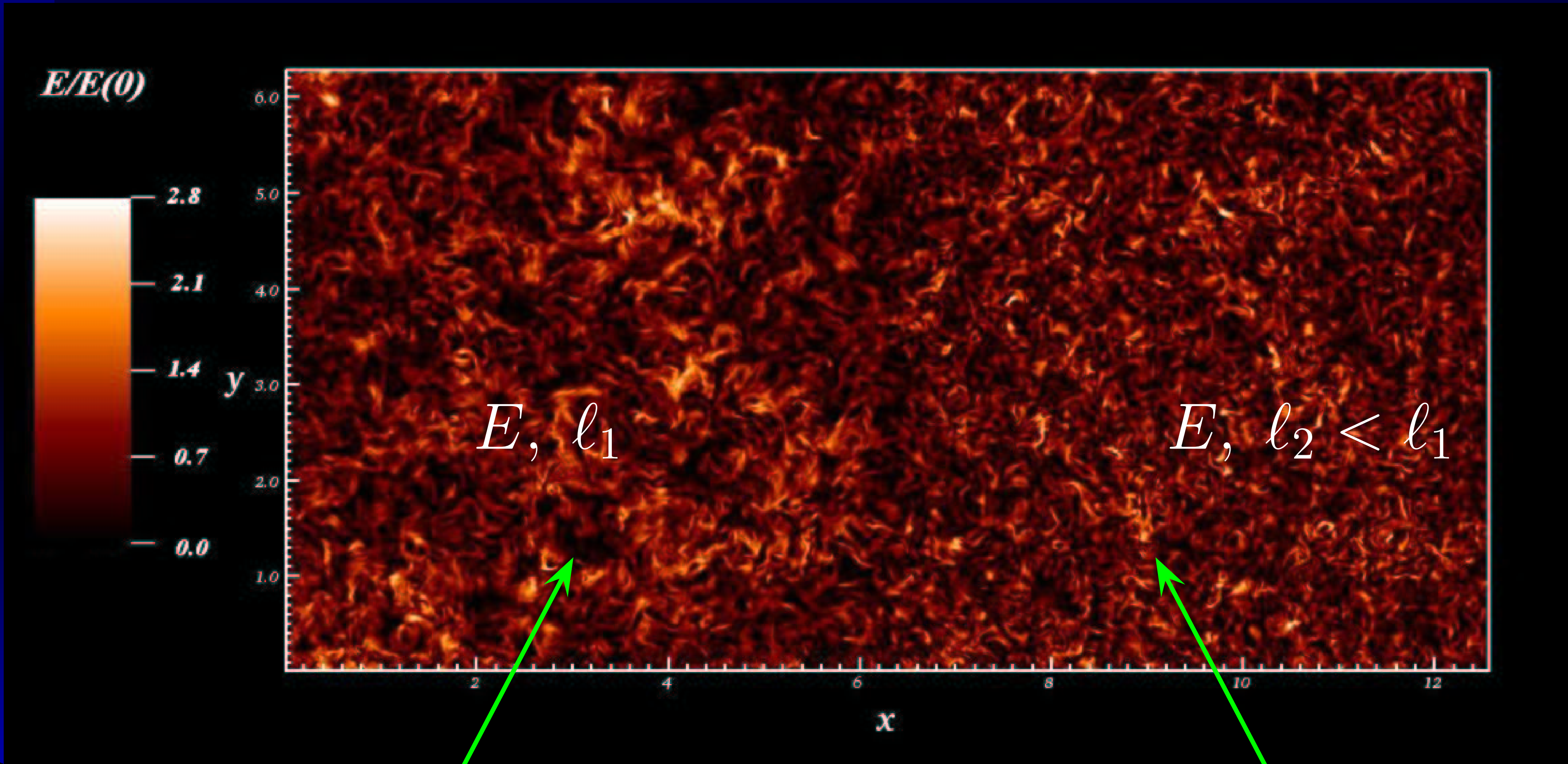


Initial energy spectra



Flow configuration

$Re_\lambda = 150,\, E_1 = E_2,\, \ell_1 > \ell_2,\, t/\tau = 0$

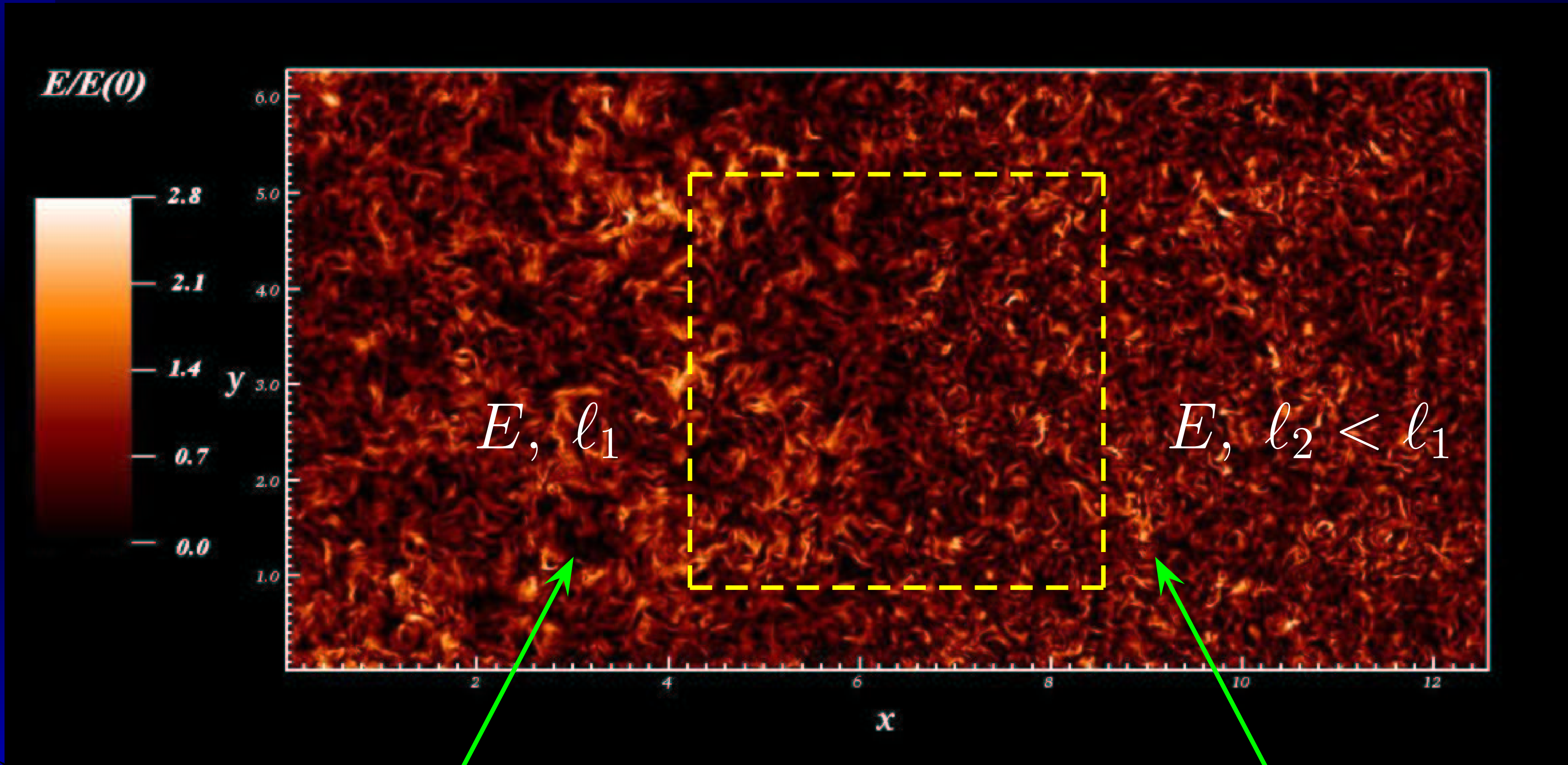


Larger integral scale

Smaller integral scale

Flow configuration

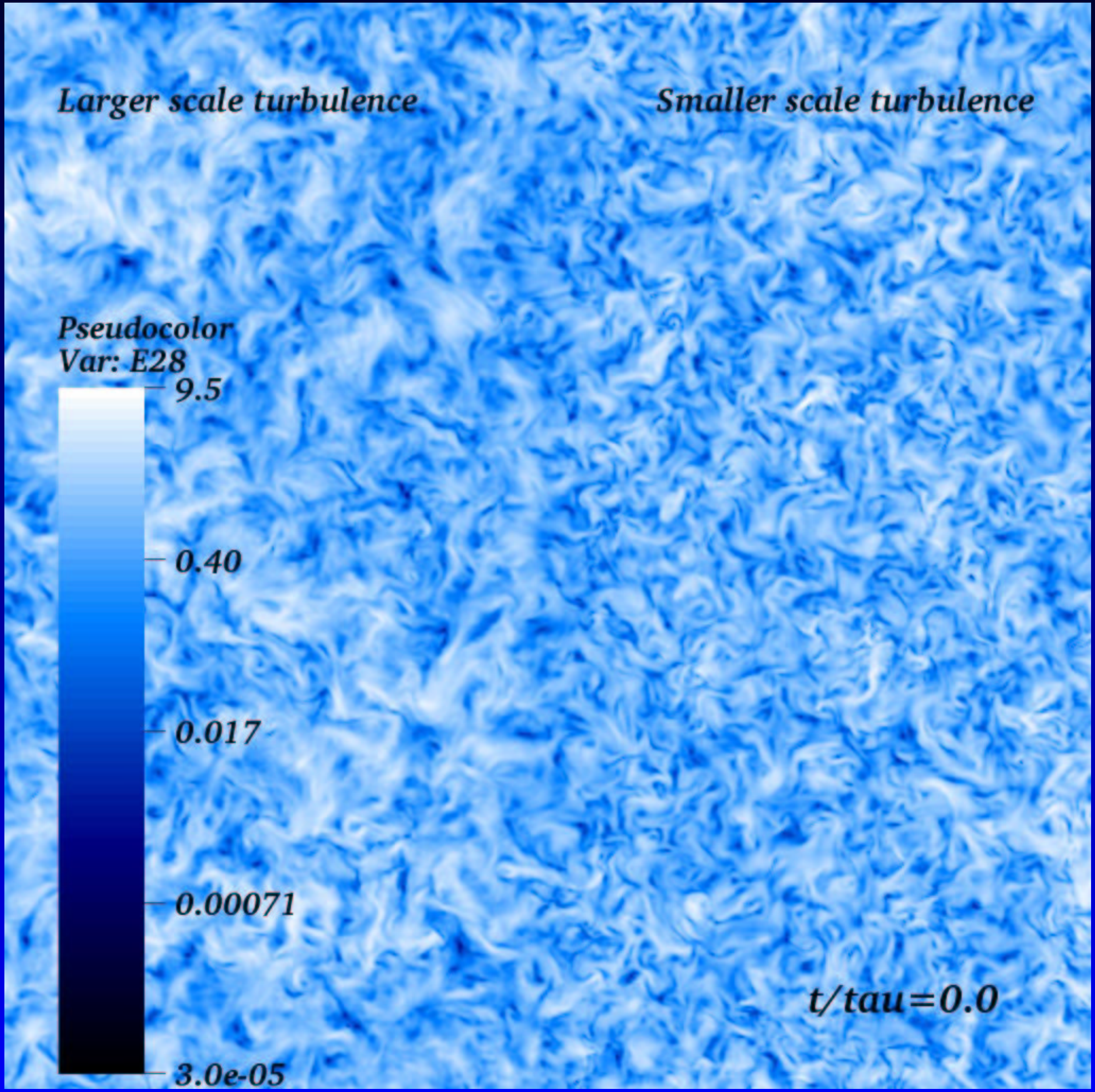
$Re_\lambda = 150,\ E_1 = E_2,\ \ell_1 > \ell_2,\ t/\tau = 0$



Larger integral scale

Smaller integral scale

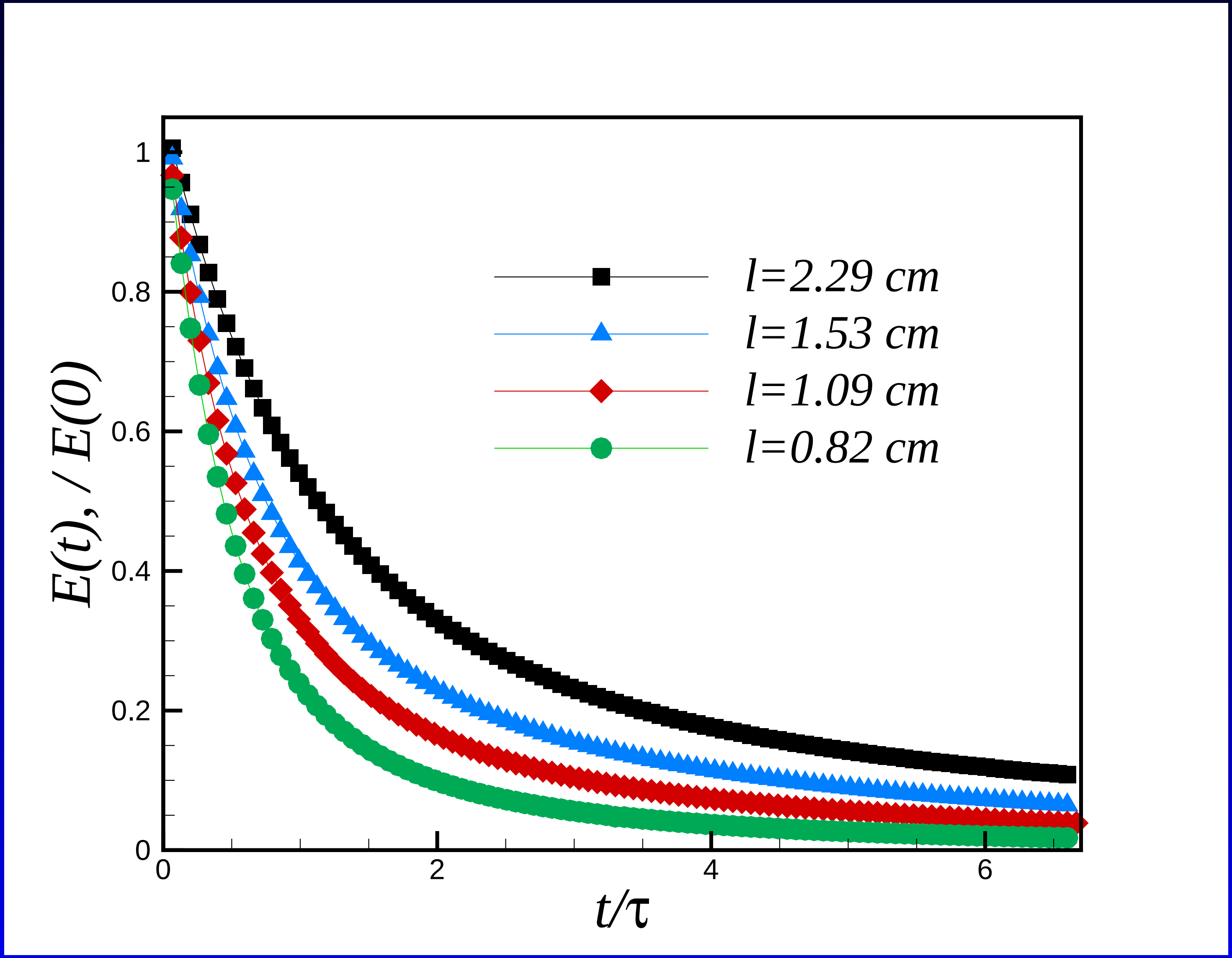
Flow configuration



$Re_\lambda = 150$
$E_1 = E_2$
$\ell_1/\ell_2 = 2.8$
$t/\tau = 0$

Movie: $E(t)$

Turbulent kinetic energy decay



Large and small scale decay

Turbulent kinetic energy is divided into a large-scale and a small-scale content:

$$E_S(t) = \int_0^{k_s} E(k,t)\mathrm{d}k$$

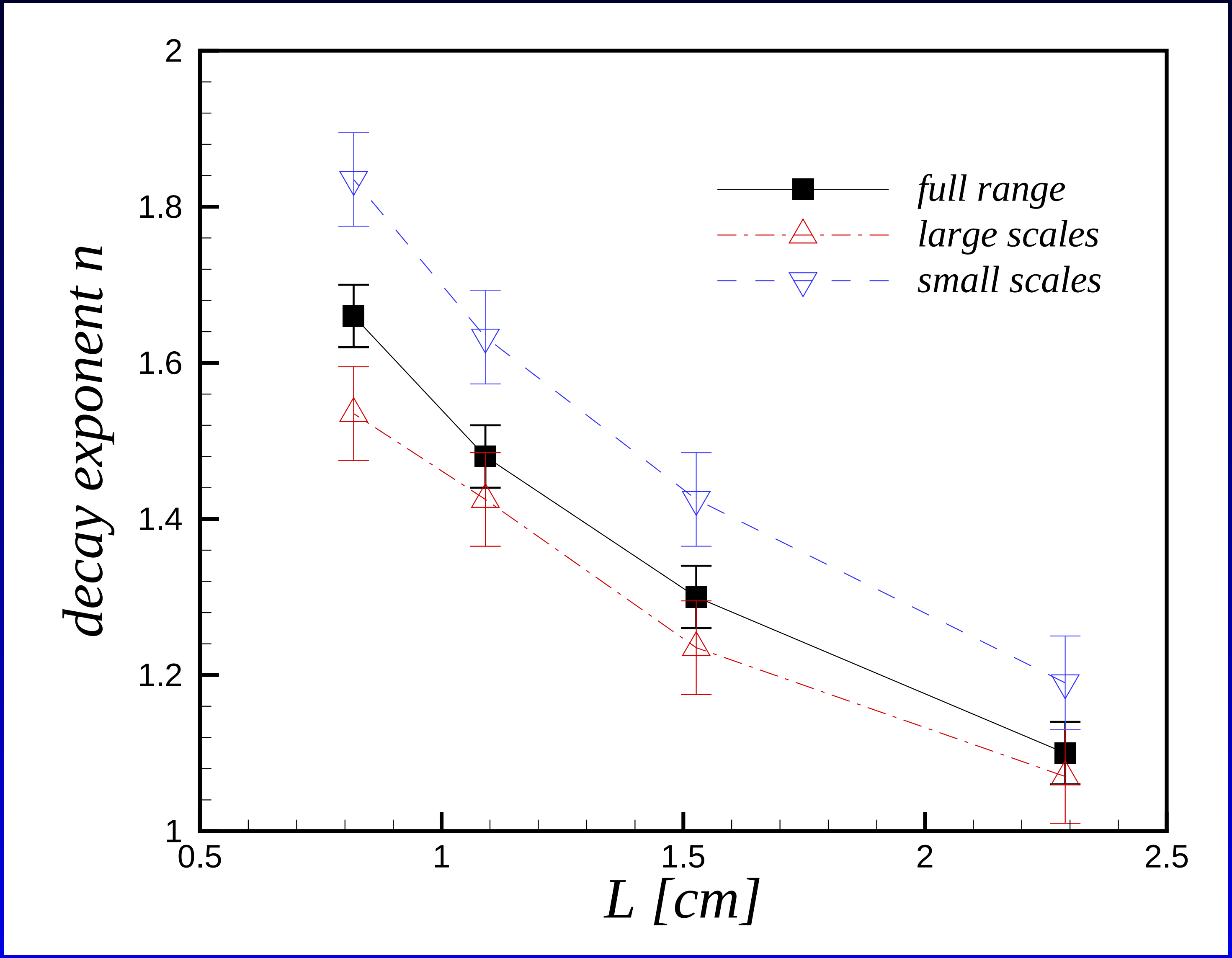
and

$$E_L(t) = \int_{k_s}^{+\infty} E(k,t)\mathrm{d}k$$

k_s is chosen so that

$$E_L(0) = 0,6E$$
$$E_S(0) = 0.4E$$

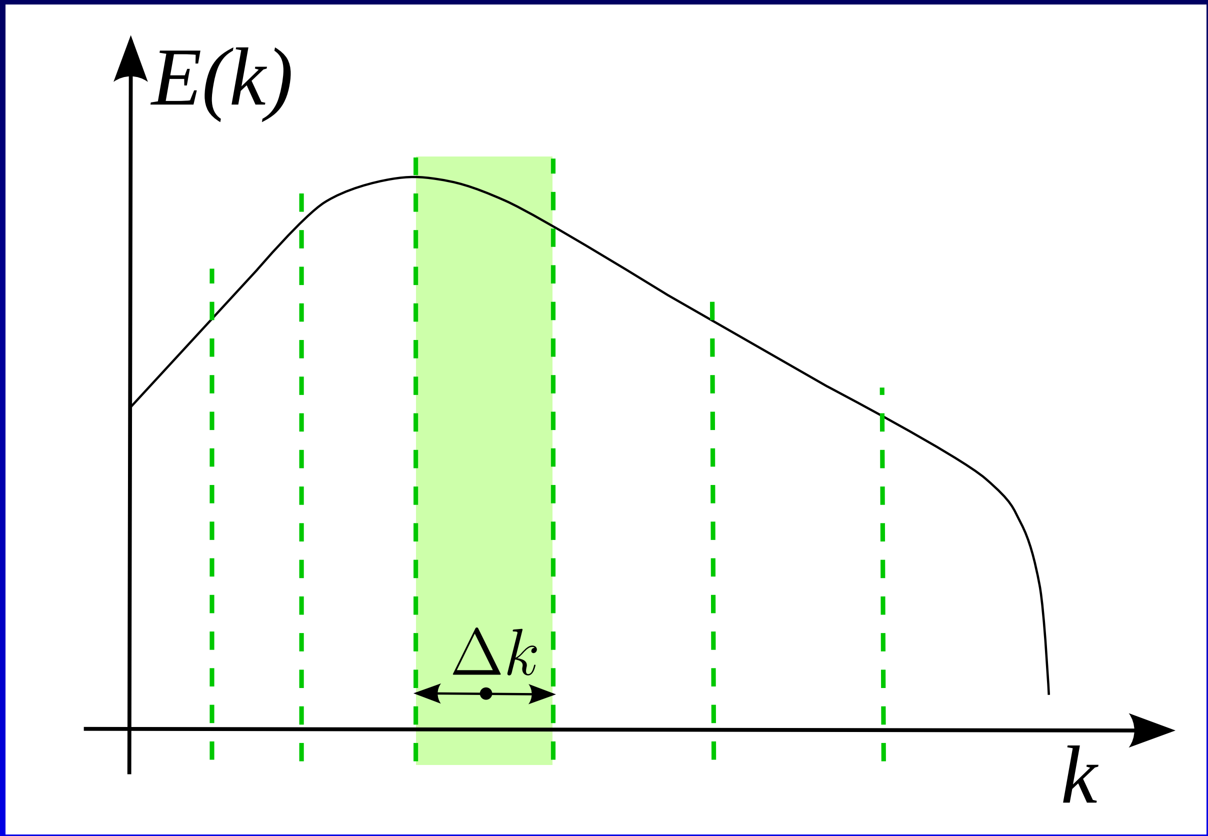
Decay exponent



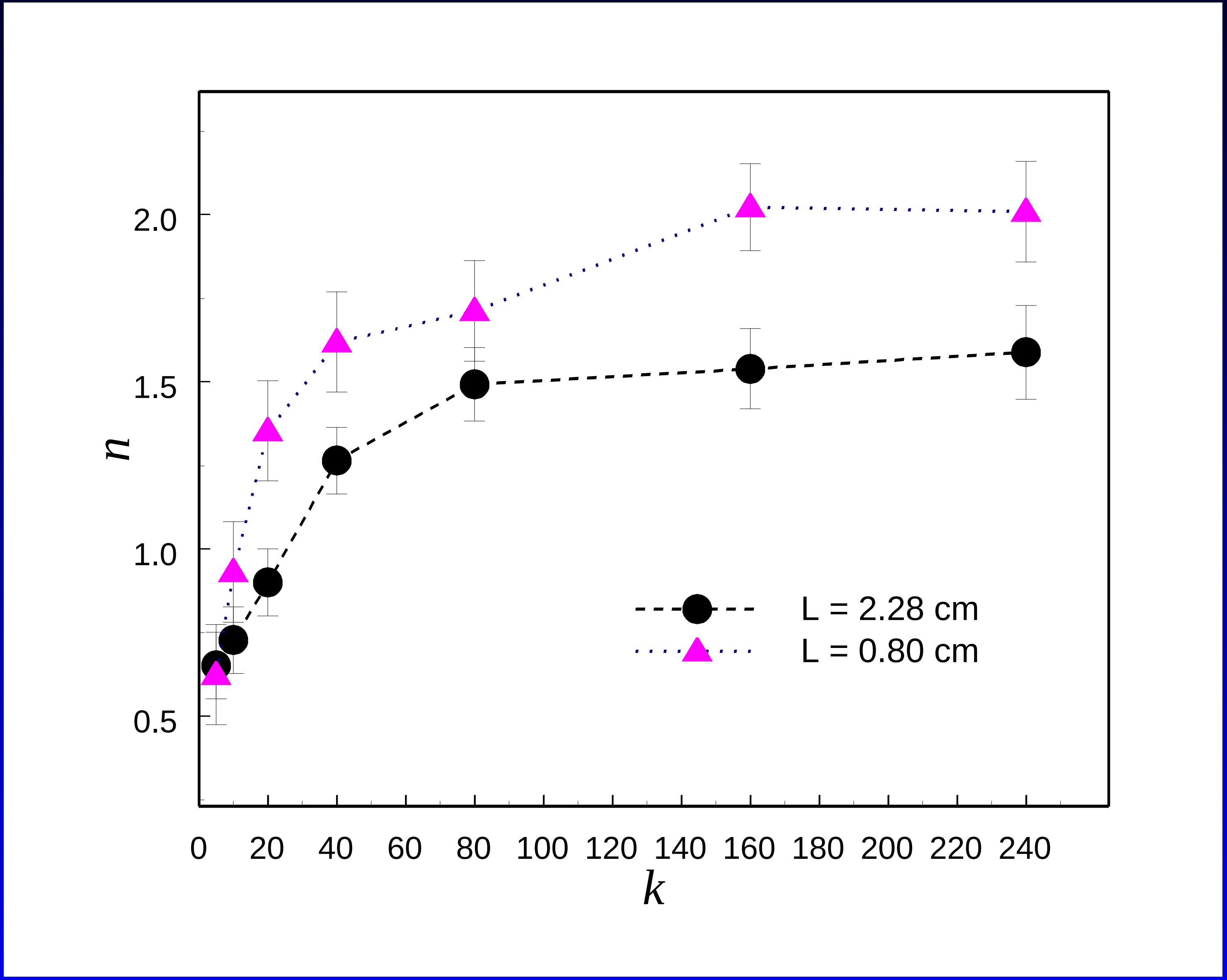
Scale by scale exponent

We measure the decay exponent scale by scale:

$$E(k,t) \approx t^{-n(k)}$$

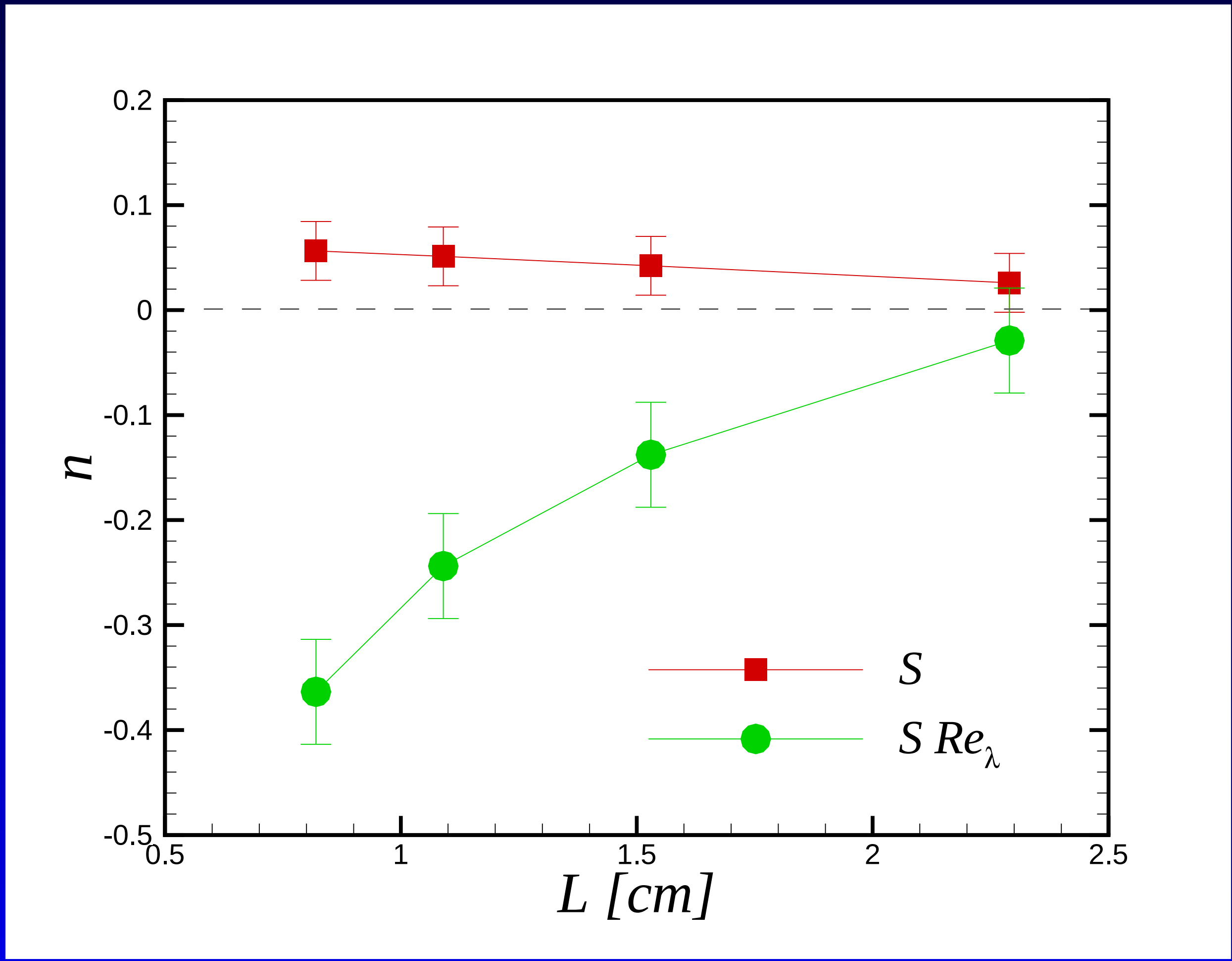


Scale by scale exponent



Derivative skewness

$$S_{\partial u/\partial x} \sim t^a, \qquad S_{\partial u/\partial x} Re_\lambda \sim t^b$$

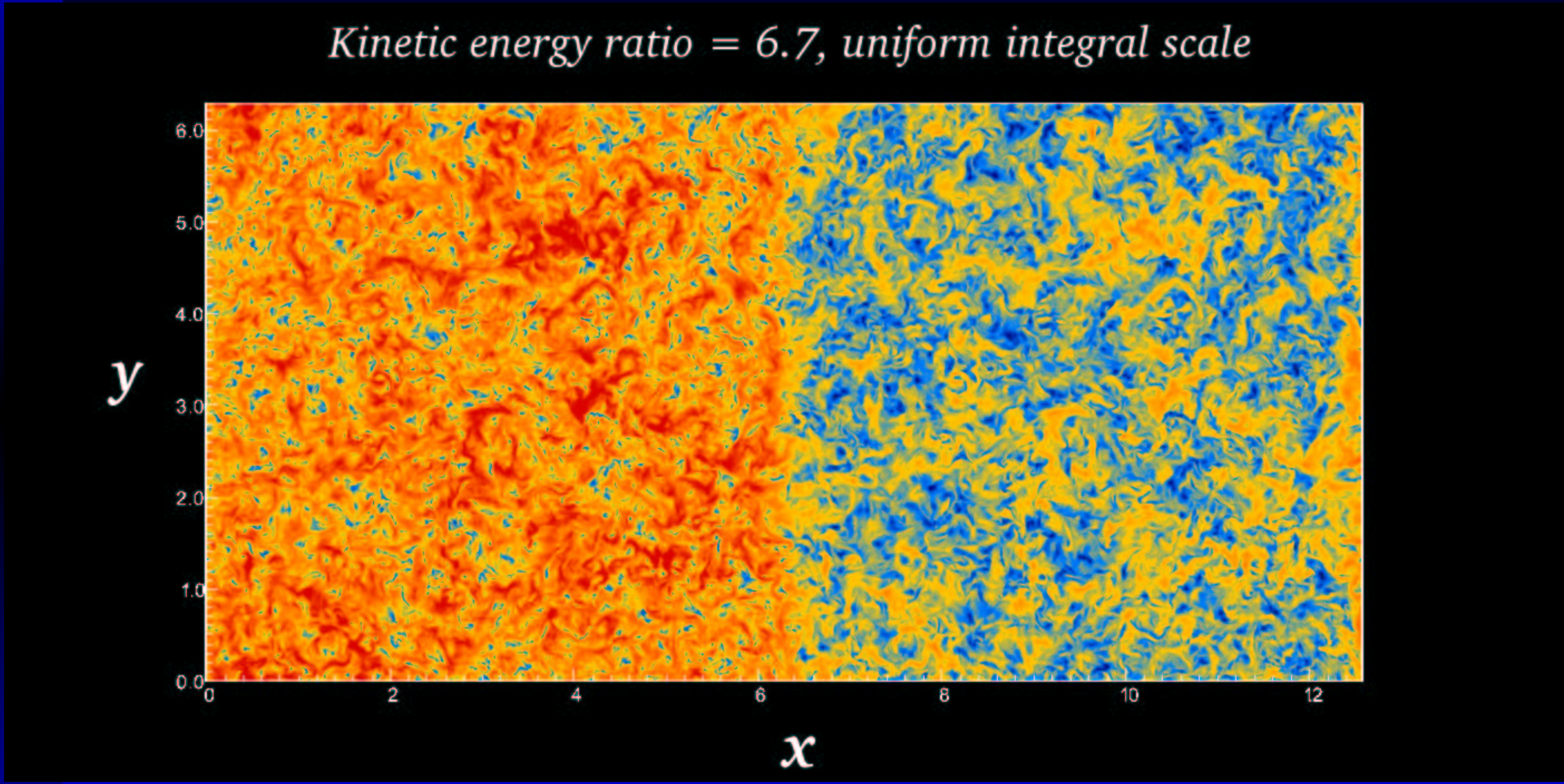


Conclusions

Simple numerical experiments on decaying homogeneous and isotropic turbulence show:

- decay exponent is affected by large and small scale origanizations
- decay exponent is closer to -1 are associated with turbulence where more of the energy is distributed at low wavenumbers
- derivative skewness remains constant

Uniform integral scale



Movie: $E(t)$

Diffusion of a passive scalar across a turbulent energy gradient

M.Iovieno, L.Ducasse, D.Tordella

Politecnico di Torino, Dipartimento di Ingegneria Aeronautica e Spaziale

EFMC 8, Bad Reichenhall, September 2010

Passive scalar

Basic phenomenology

- A passive scalar is a contaminant present in so low concentration that it has no dynamical effect on the fluid motion,
- Turbulence transports and disperses the scalar by making particles follow chaotic trajectories, it stretches and foldes lines of constant concentration, and scalar fluctuations reach the smaller scales.

Passive scalar

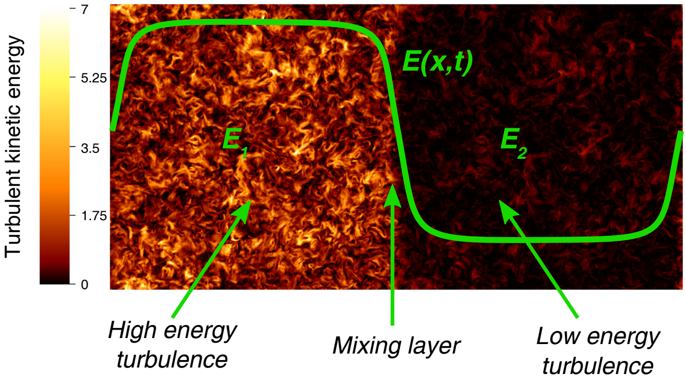
Basic phenomenology

- at large scales:
  - the mean concentration, variance and flux are strongly influenced by the boundary conditions and scalar injection
- at small scales:
  - scalar differences are not gaussian,
  - intermittency observed at inertial range scales as well as at the dissipation scales, with ramp/cliff structures

see, e.g.:
Warhaft *ARFM* 2000,
Shraiman and Siggia, *Nature* 2000,
Gotoh, *PoF* 2006, 2007.

Turbulent shearless mixing

General flow configuration:



periodic boundary condition ⇒ 2 mixing layers

Main features

Shearless mixing layers shows the following properties:

- no gradient of mean velocity, thus no kinetic energy production
- the mixing is generated by the inhomogeneity in the turbulent kinetic energy and integral scale
- the mixing layer becomes very intermittent at both large and small scales (EC-512, 2009)
- the presence of a gradient of energy is a sufficient condition for the onset of intermittency (Phys.Rev.E, 2008, Phys.Rev.Lett, subm.2010)
- 2D and 3D mixings: different asymptotic layer thickness growth exponent

Passive scalar transport

We solve the passive scalar advection-diffusion equation

$$\frac{\partial \vartheta}{\partial t} + u_j \frac{\partial \vartheta}{\partial x_j} = \frac{(-1)^{n+1}}{Re\,Sc} \nabla^{2n} \vartheta$$

for the shearless mixing configuration.

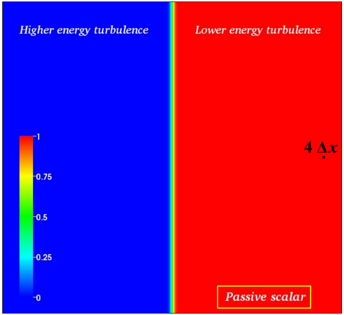
DNS simulations have been performed at $Re_\lambda = 150$ and $Sc = 1$, both in 3D turbulence ($600^2 \times 1200$ grid, $n = 1$) and 2D turbulence (1024^2 grid, $n = 2$).

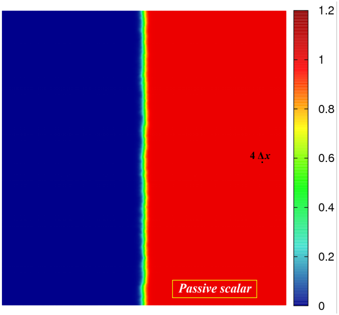
Scheme of the flow

Passive scalar

3D Mixing
($600^2 \times 1200$ grid)

2D Mixing
(1024^2 grid)





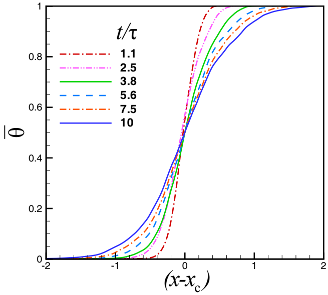
Run 3D Movie

Run 2D Movie

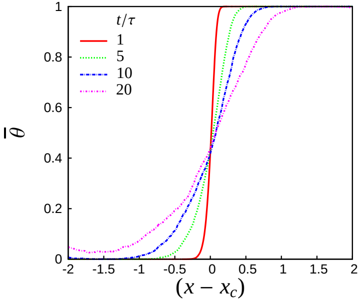
The passive scalar is initially introduced in the low energy turbulent region and diffuses through the mixing layer

Mean Scalar Diffusion

3D Mixing



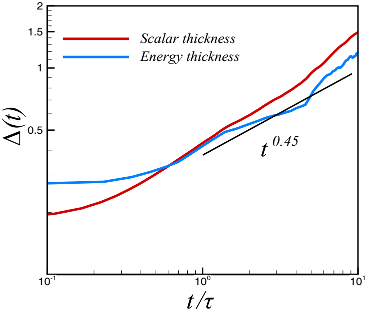
2D Mixing



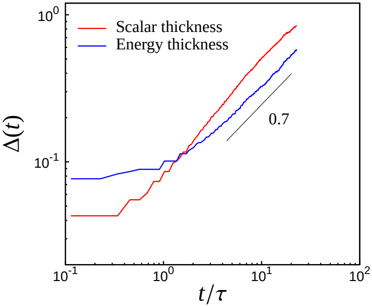
Energy ratio $E_1/E_2 = 6.7$, Schmidt number = 1.

Scalar mixing layer thickness

3D Mixing



2D Mixing

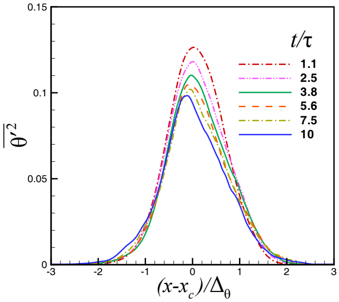


Scalar layer thickness: $\Delta_\vartheta = x_{\vartheta=0.75} - x_{\vartheta=0.25}$

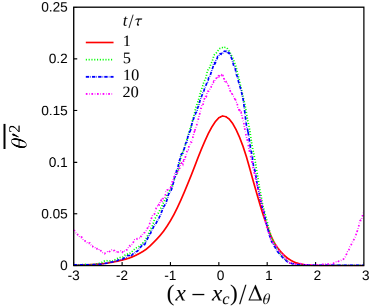
3D mixing: $\Delta_\vartheta \sim t^{0.45}$, 2D mixing: $\Delta_\vartheta \sim t^{0.7}$

Scalar variance

3D Mixing



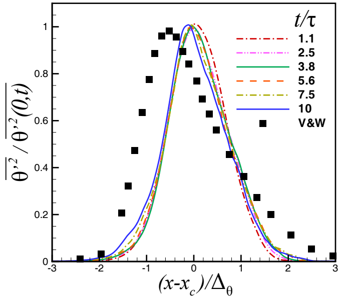
2D Mixing



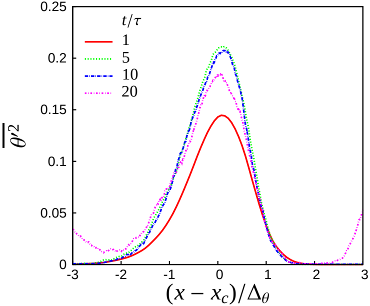
Self-similar distribution, peak shifted toward the high kinetic energy region

Scalar variance

3D Mixing



2D Mixing

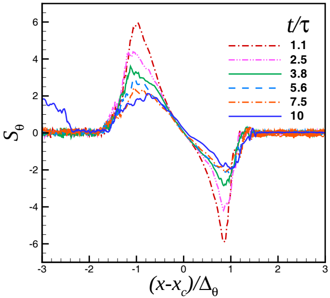


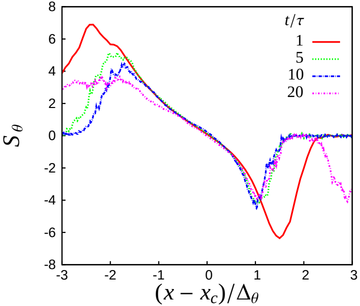
Veeravalli and Warhaft, 1990: laboratory experiment, linear source in the mixing layer centre, data at $x/x_0 = 0.4$ $(t/\tau \approx 4)$.

Scalar skewness

3D Mixing

2D Mixing





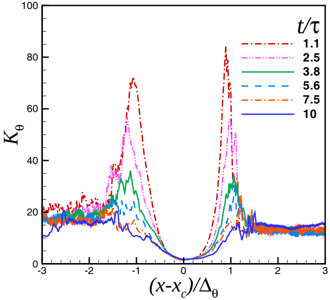
Strong non-gaussian statistic at the mixing layer border

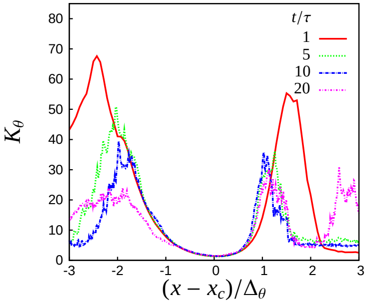
2D: intermittency penetrates more in the direction opposite to the energy gradient.

Scalar kurtosis

3D Mixing

2D Mixing





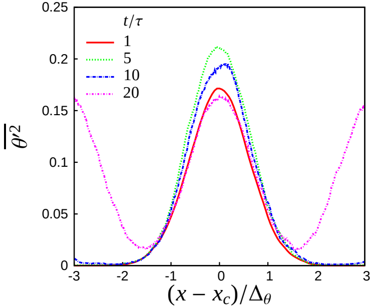
2D: higher asymmetry, wider intermittent region

Intermittency gradually reduces as the mixing procedes

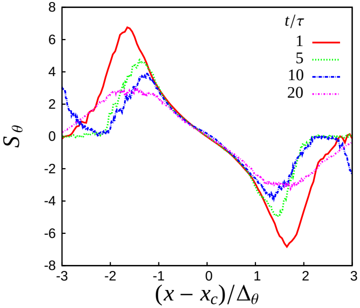
No energy gradient

2D mixing - numerical validation

Scalar variance



Scalar skewness

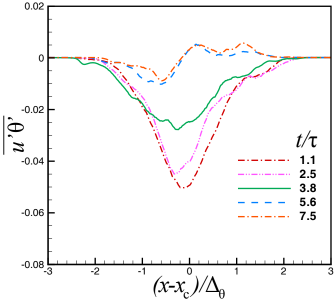


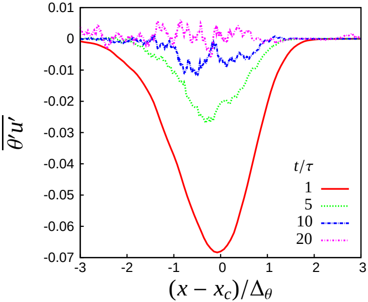
No energy gradient $\Rightarrow$ no asymmetry

Scalar flux

3D Mixing

2D Mixing





$$\overline{u'\vartheta'} \sim 1/\Delta_\vartheta(t)$$

Conclusions

2D/3D Passive scalar diffusion across an energy step:

- all moments profiles are skewed towards the higher kinetic energy region
- self-similar profiles of first and second order moments
- large intermittency and non-gaussian behaviour on both sides of the mixing, even where the scalar flux is small.
- larger asymmetry in moment distributions in 2D mixing
- 2D: no stretching, inverse cascade, long-range interaction which penetrate more against the energy gradient

A measure of turbulent diffusion in two and three dimensions

F. De Santi[1], **L. Ducasse**[1],
J. von Hardenberg[2],
M. Iovieno[1], D. Tordella[1]

[1]Politecnico di Torino, Torino, Italy
[2]Istituto di Scienze dell'Atmosfera e del Clima, CNR, Torino, Italy

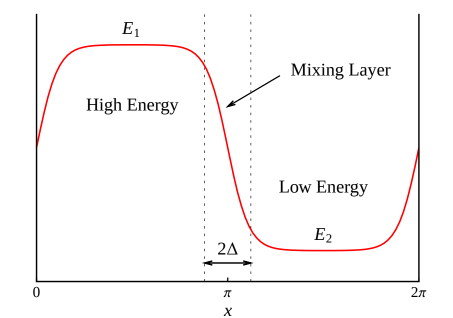
September 14, 2010

European Fluid Mechanics Conference - 8

Presentation of the problem

2 turbulent flows put aside with different kinetic energies :

- a high energy field on the left of energy E_1
- a low energy field on the right of energy E_2



Mixing layer thickness : $\Delta(t)$

$\Delta(0) \approx l$ (integral scale)

$l \approx D/80$

Periodic boundary conditions : 2 mixing layers in the simulation

Presentation of the problem

Main goals :

- Study the turbulent diffusion through the evolution in time of the mixing layer
- Compare 2D and 3D cases

Presentation of the problem

Main goals :

- Study the turbulent diffusion through the evolution in time of the mixing layer
- Compare 2D and 3D cases

Shearless mixing layers show the following properties:

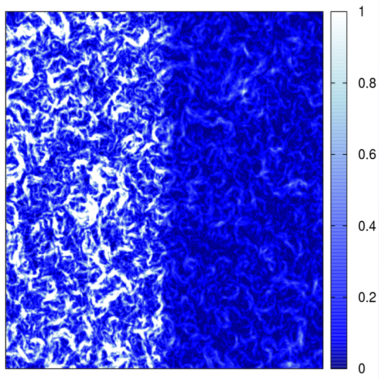
- No gradient of mean velocity → no kinetic energy production
- Mixing generated by the inhomogeneity in the turbulent kinetic energy
- Intermittent behavior at both large and small scales (EC-512, 2009)
- Gradient of energy : sufficient condition for the onset of intermittency (Phys.Rev.E, 2008)
- 2D and 3D mixings → show a very different behaviour

A visualisation

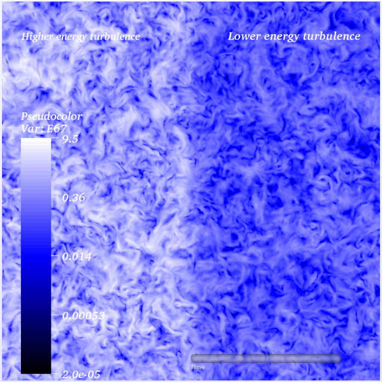
Kinetic energy : evolution in time

Initial energy ratio : $E_1/E_2 = 6.6$

2 D



3 D



Important remarks

Main parameter : Initial energy ratio E_1/E_2

The system has been studied using the values :
$E_1/E_2 = 6.6, 40, 300, 10^4, 10^6$

In the Navier Stokes equation :

$$\partial_t \mathbf{u} + (\mathbf{u} \cdot \nabla)\mathbf{u} = \frac{1}{\rho}\nabla p + (-1)^{p+1}\nu_n \Delta^{2n}\mathbf{u}$$

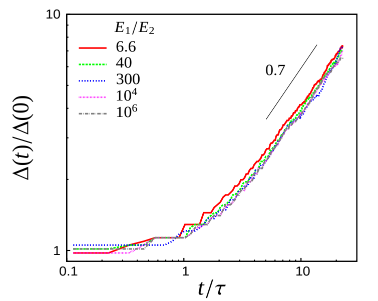
2D : An hyperviscous coefficient ($n = 2$) has been used

3D : The total energy decays faster than in 2D

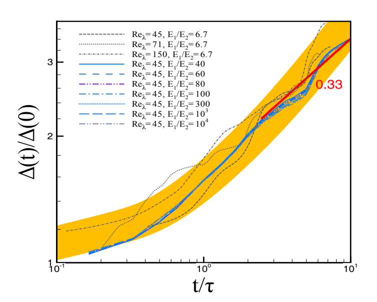
Evolution of the mixing layer

Time evolution of the mixing layer thickness $\Delta(t)$:

2 D



3 D

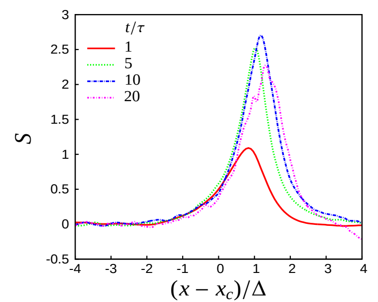


$\Rightarrow$ 2D mixes faster !

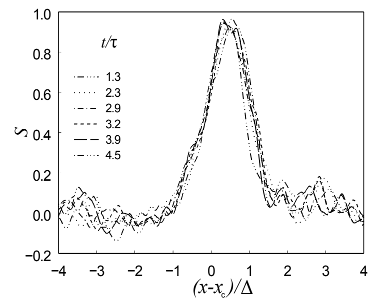
Velocity statistics

Skewness (computed along the homogeneous *y* direction)

2 D



3 D

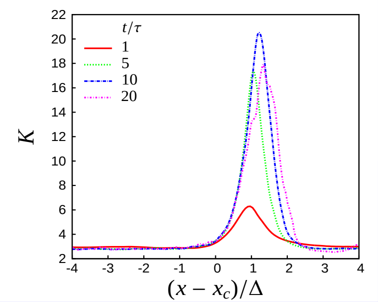


$E_1/E_2 = 10^4$

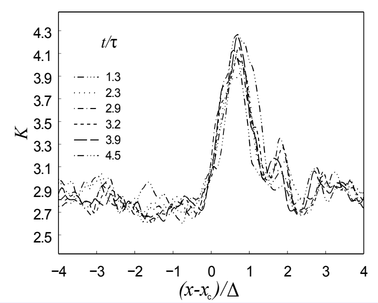
Velocity statistics

Kurtosis (computed along the homogeneous y direction)

2 D



3 D

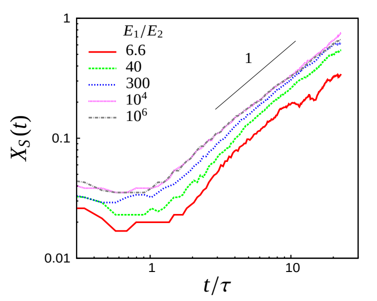


$E_1/E_2 = 10^4$

Velocity statistics

Position of the maximum of skewness X_S

2 D

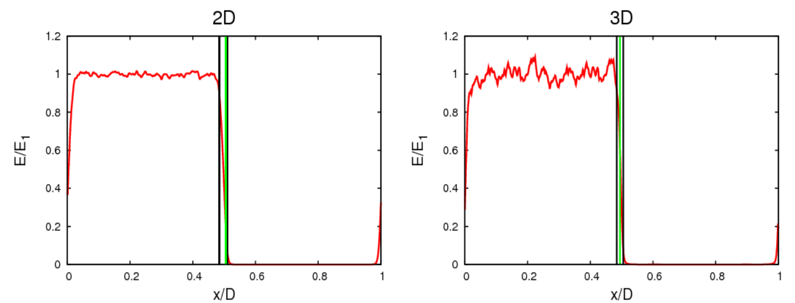


2D $\Rightarrow X_S(t) \propto t$ evolves faster than $\Delta(t) \propto t^{0.7}$

3D $\Rightarrow X_S(t) \propto \Delta(t) \propto t^{0.33}$

Time evolution

Time evolution of the energy profile :



—— Mixing layer
—— Position of the maximum of skewness

Total time in both cases : $\sim 22\,\tau$

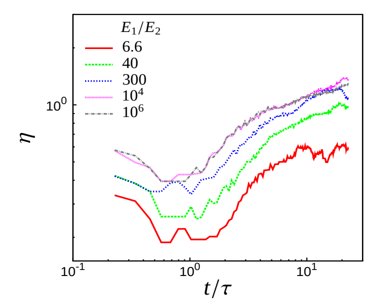
Velocity statistics

Evolution of the penetration $\eta = X_S/\Delta$

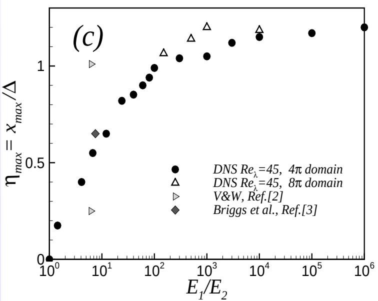
2D $\Rightarrow$ $\eta(t)$ diverges

3D $\Rightarrow$ $\eta(t)$ reaches a constant value : η_{max}

2 D



3 D



Memory

Proposal of a memory measure **as a global quantity referred to its own time derivative**, for example

$$MEM = \frac{\Delta}{\Delta'}$$

2D : $\frac{\mathrm{d}\Delta(\mathrm{t})}{\mathrm{d}t} \sim t^{-0.3}$,   3D : $\frac{\mathrm{d}\Delta(\mathrm{t})}{\mathrm{d}t} \sim t^{-0.67}$

2D : $\mathbf{MEM} = \frac{\mathbf{\Delta(t)}}{\mathbf{\Delta(t)_t}} \sim \mathbf{1.4t}$,   3D : $\mathbf{MEM} = \frac{\mathbf{\Delta(t)}}{\mathbf{\Delta(t)_t}} \sim \mathbf{3t}$

different dimensionality, same trend (qualitative universality?), with a different coefficient

3D has a slightly longer memory than 2D

Conclusions

Comparison between the 2D and 3D situation :

Similarities :

- $\Delta(t)$ evolves asymptotically in time as a power law
- A strong intermittency $\rightarrow$ visible on the high order moments

Differences :

- Mixing is faster in 2D
- No autosimilarity in time in the 2D case

Conclusions

Comparison between the 2D and 3D situation :

Similarities :

- $\Delta(t)$ evolves asymptotically in time as a power law
- A strong intermittency $\rightarrow$ visible on the high order moments

Differences :

- Mixing is faster in 2D
- No autosimilarity in time in the 2D case

Possible explanation :

The evolution of $\Delta(t)$ is essentially led by the large scales
2D$\rightarrow$ energy tends to concentrate to the large scales (inverse cascade)