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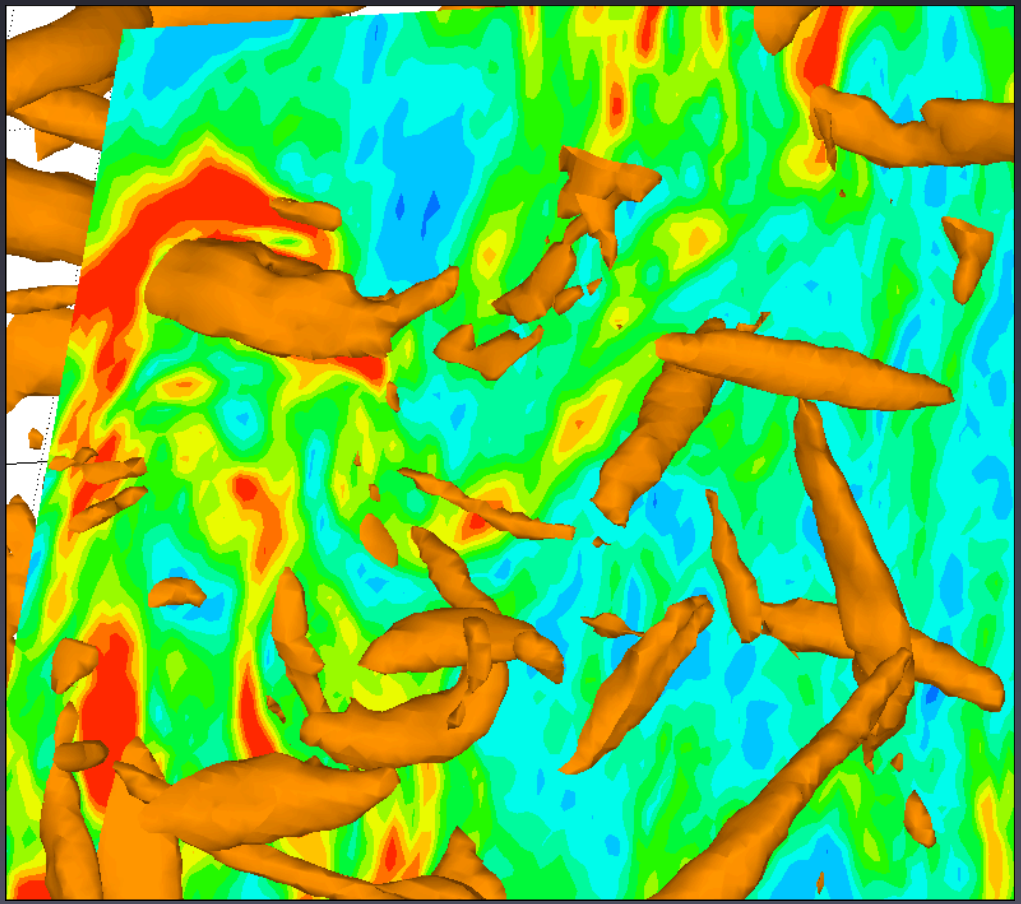
The fine scale features of turbulent shear flows

O.R.H. Buxton

Department of Aeronautics, Imperial College London



Acknowledgements : EPSRC grant number EP/FO56206/1; Doctoral Training Account; HECToR RAP; RAeS Centenary Grant

Introduction

"The most important unsolved problem of classical physics" [RICHARD FEYNMAN]

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- Most engineering flows are turbulent

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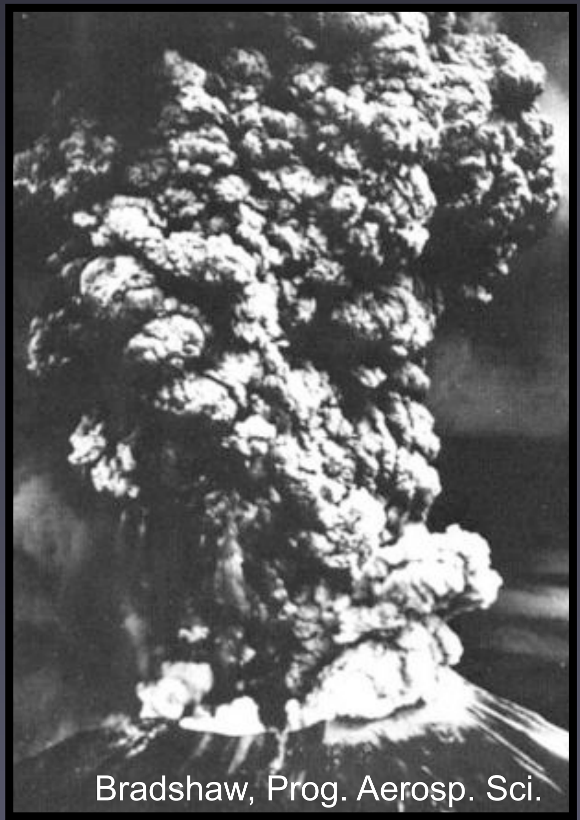
- Multi scale problem
  - Temporally and spatially



Bradshaw, Prog. Aerosp. Sci.

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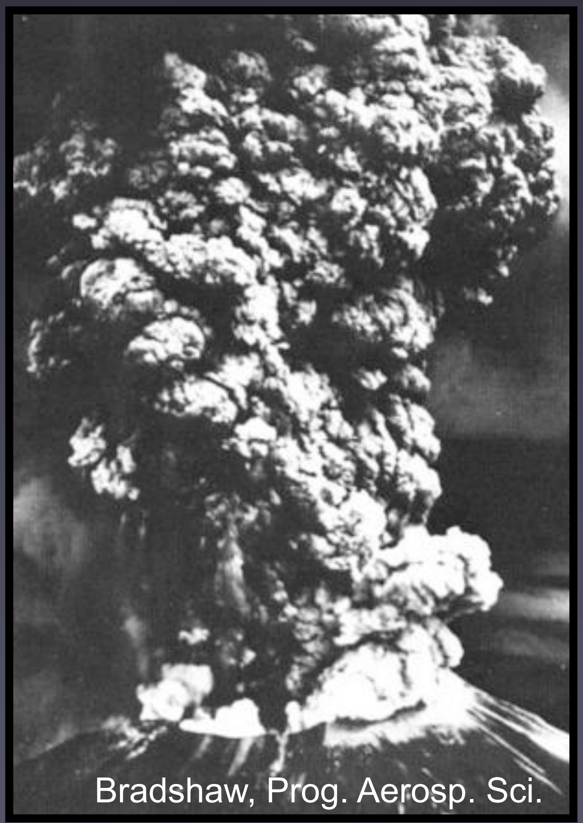

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"The most important unsolved problem of classical physics" [RICHARD FEYNMAN]

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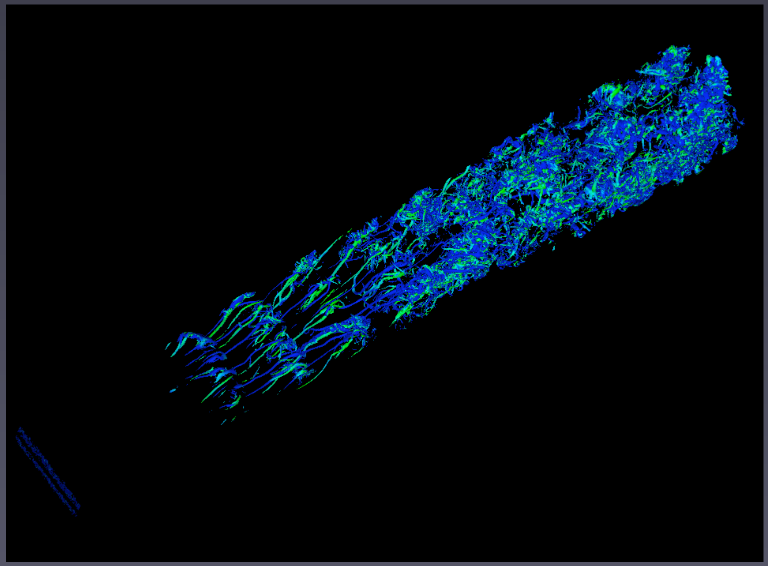
- Fine scales responsible for dissipation
  - Kinetic energy lost due to molecular diffusion and is responsible for drag
  - Dispersion and mixing



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  - High spatial resolution required to compute / measure them $\eta = \left(\nu^3/\langle\epsilon\rangle\right)^{1/4}$

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- Models of fine scales required for LES

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Scope of the study

Is the interaction between large and fine scales "universal"?

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Is the interaction between large and fine scales "universal"?

- TKE transferred along the energy cascade from large to fine scales [RICHARDSON 1926; KOLMOGOROV 1941]
  - Large scales contain most of the energy (velocities)
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- Requires multi-scale data resolving large and fine scales for different turbulent flows
    - Far field of planar 2D mixing layer at different Reynolds numbers

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- Requires multi-scale data resolving large and fine scales for different turbulent flows
  - Far field of planar 2D mixing layer at different Reynolds numbers
- Examine multi-scale interaction of fine-scales conditioned on large scales
  - Convection velocities
  - Probability density functions pdfs

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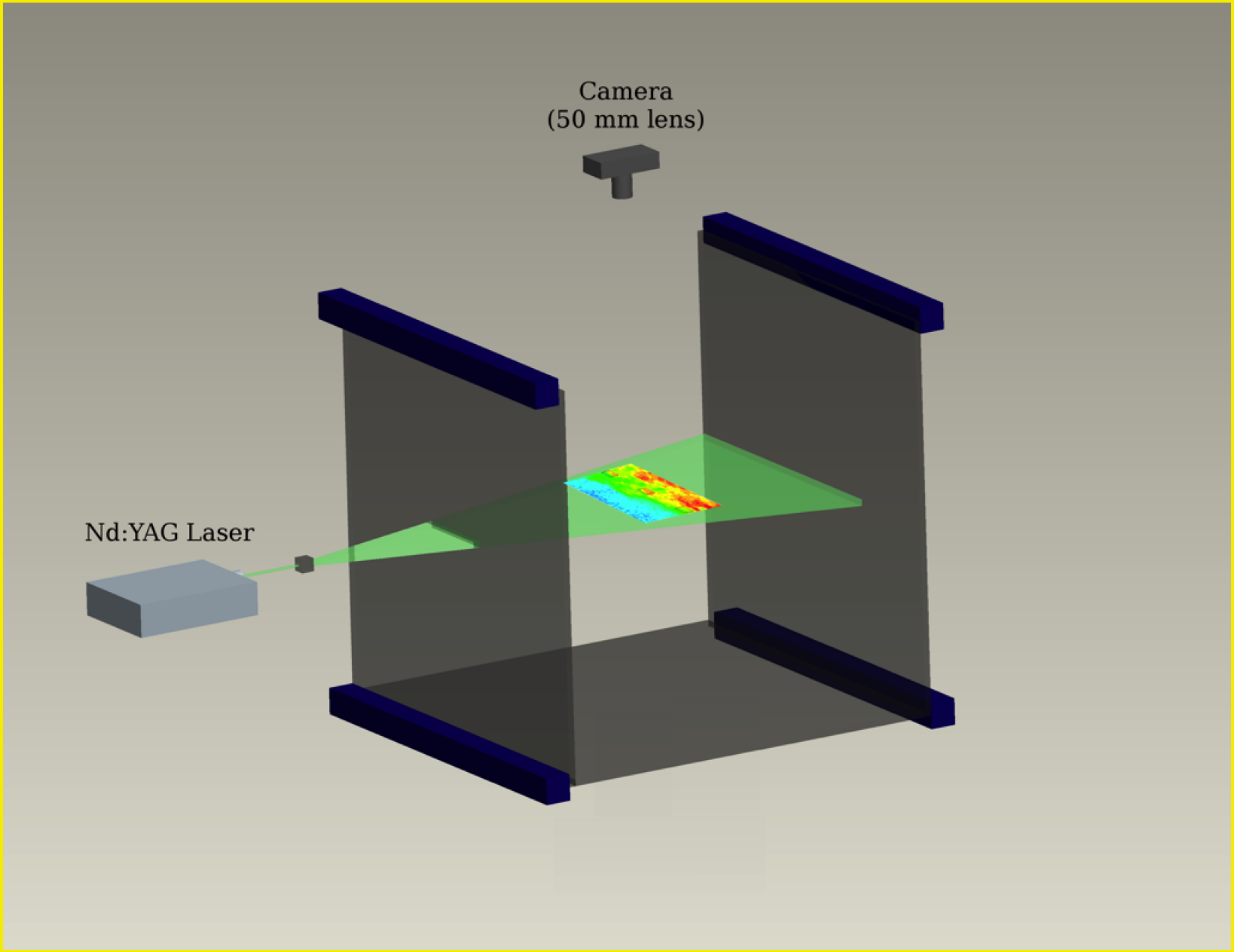
PIV



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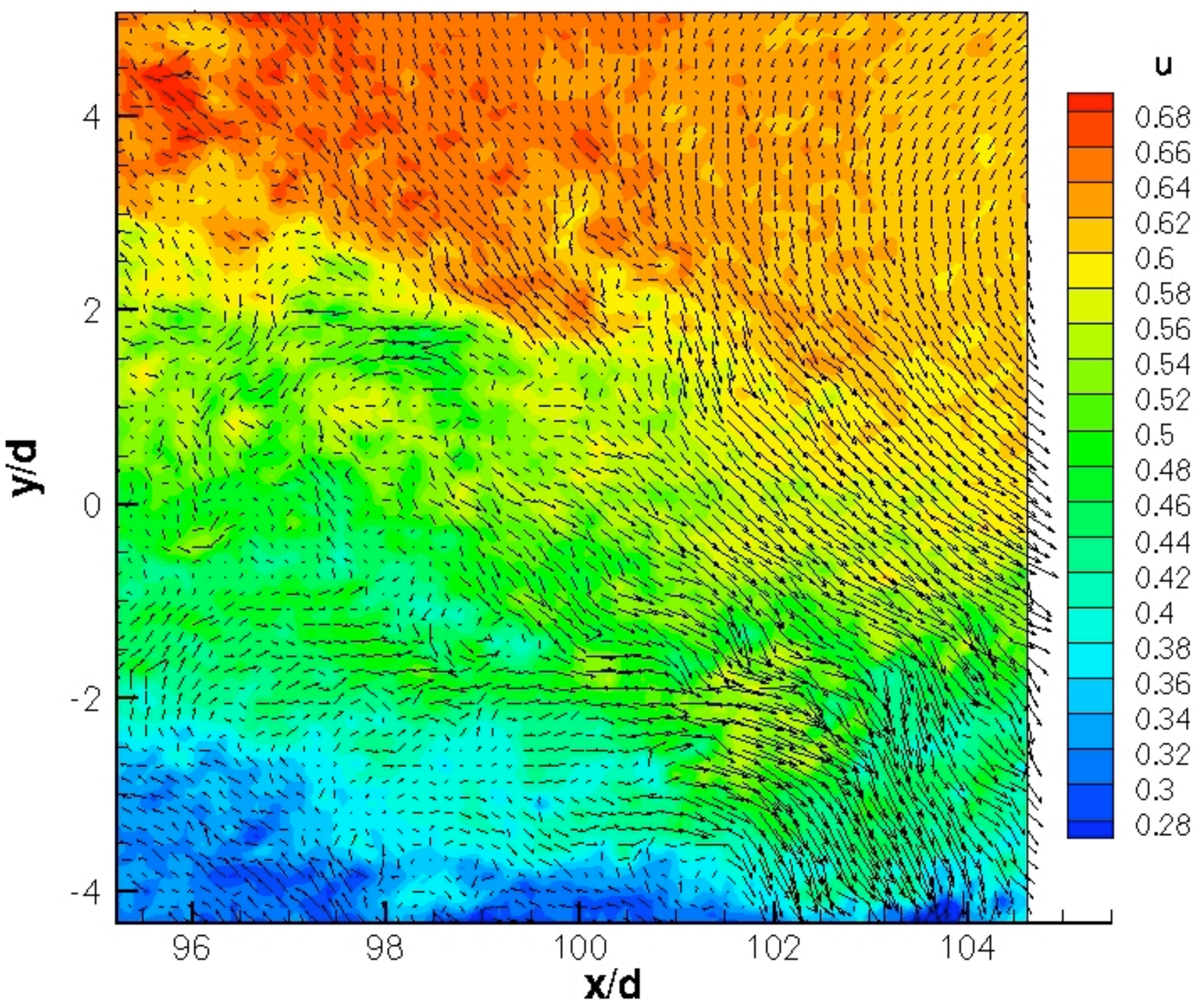
Planar mixing layer



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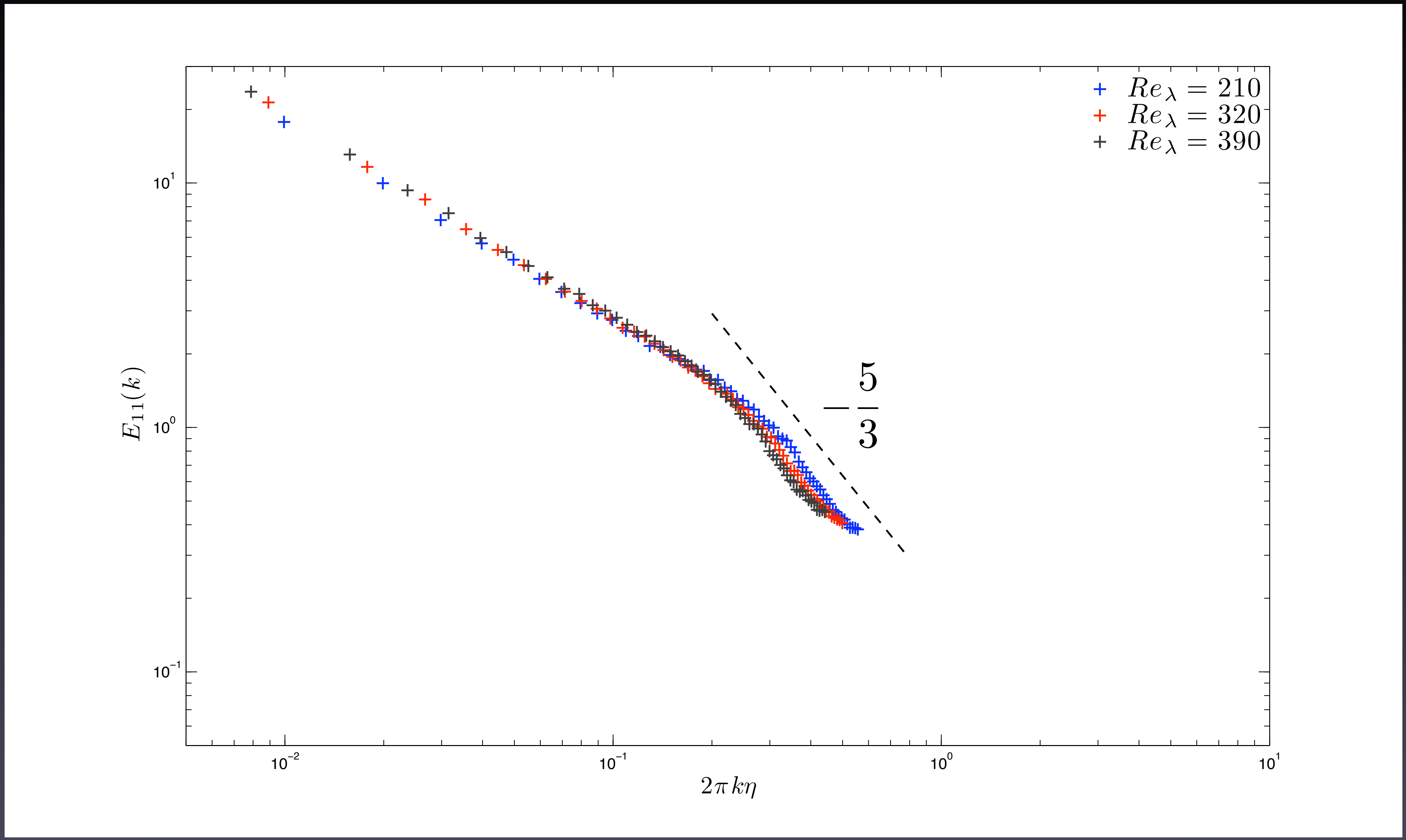

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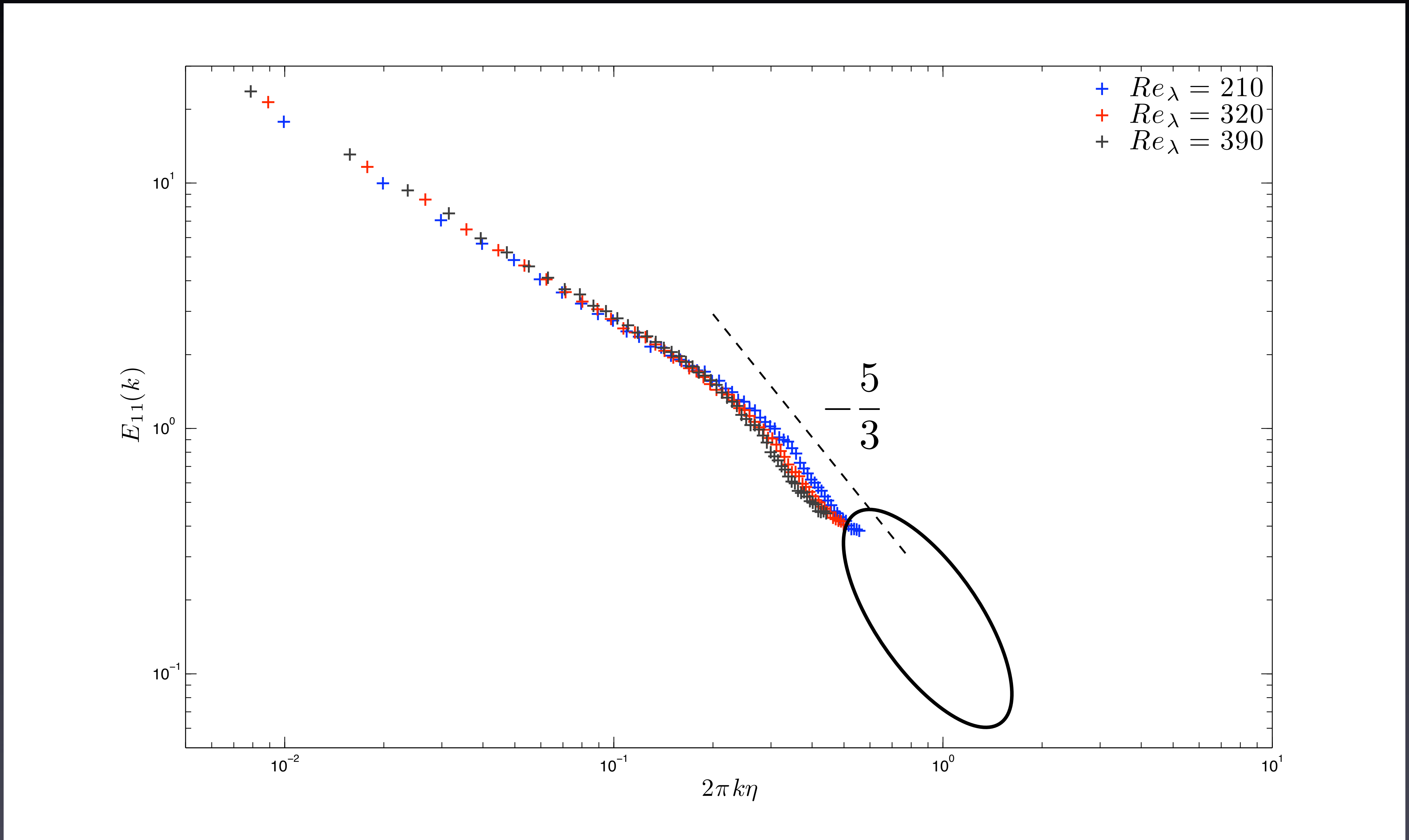

- What about the energy content of the fine-scales?

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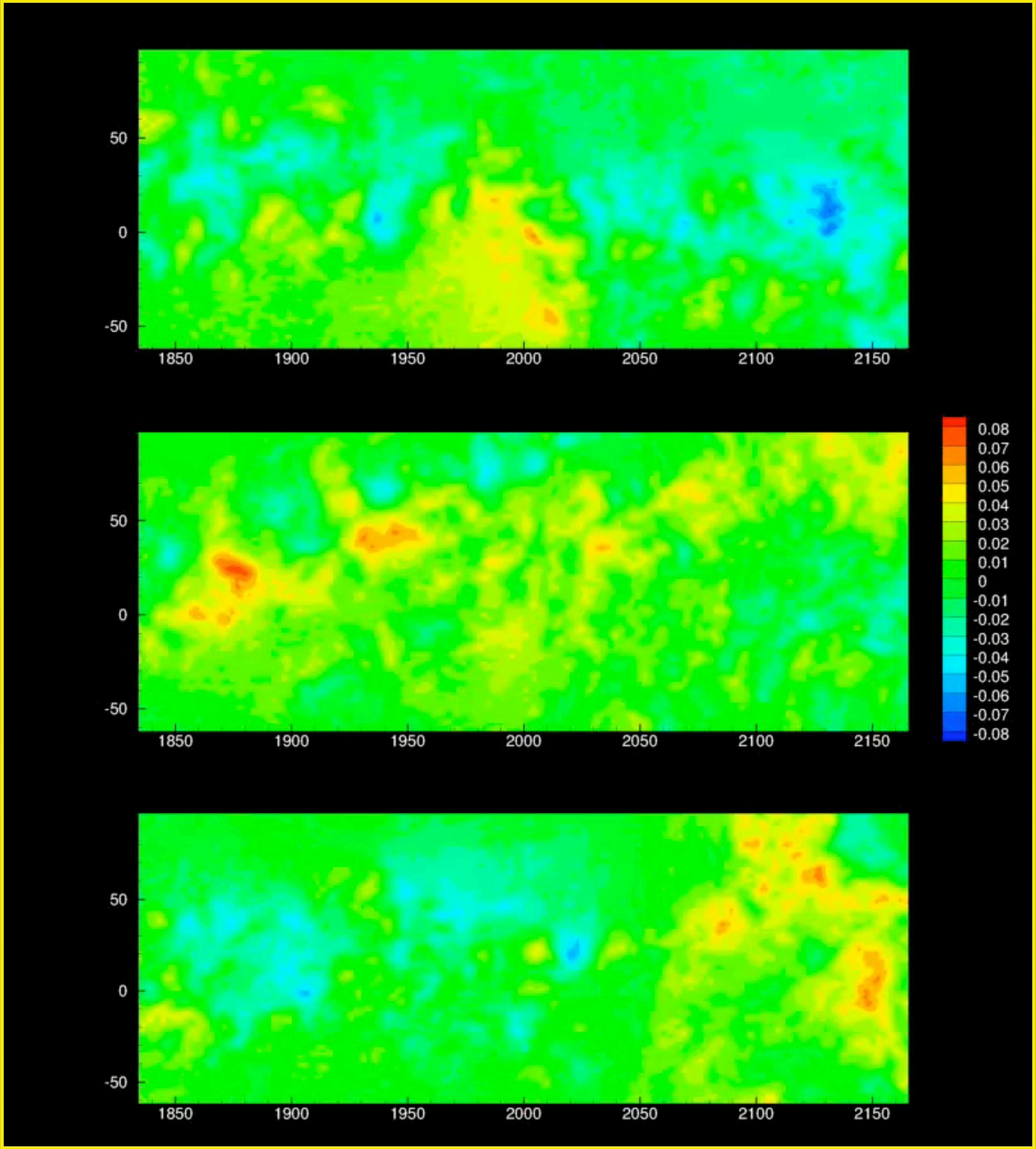

u_1'

$Re_\lambda = 210$

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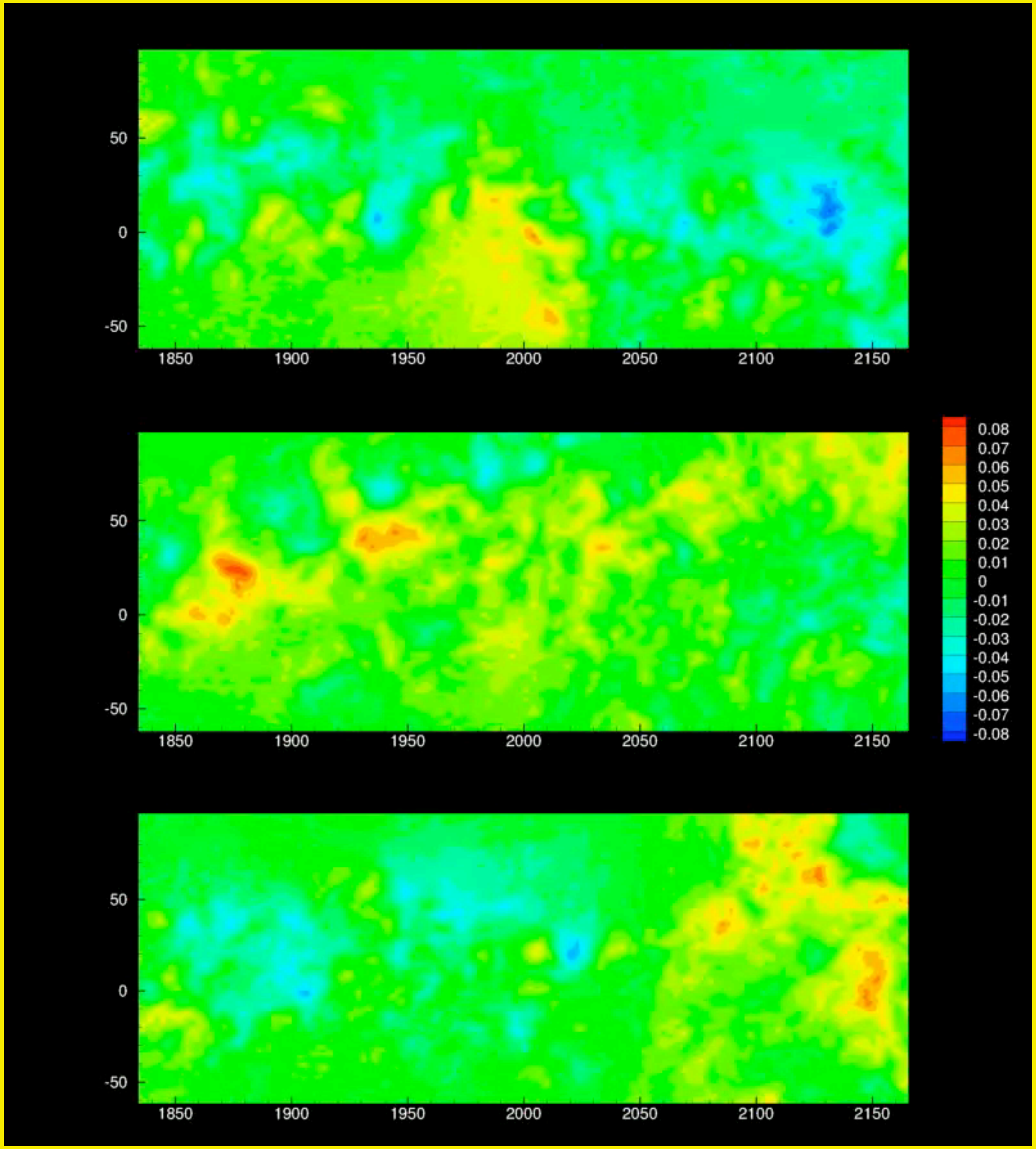
Planar mixing layer



$u_1^{'}$

$Re_\lambda = 210$

- Evidently multi-scale

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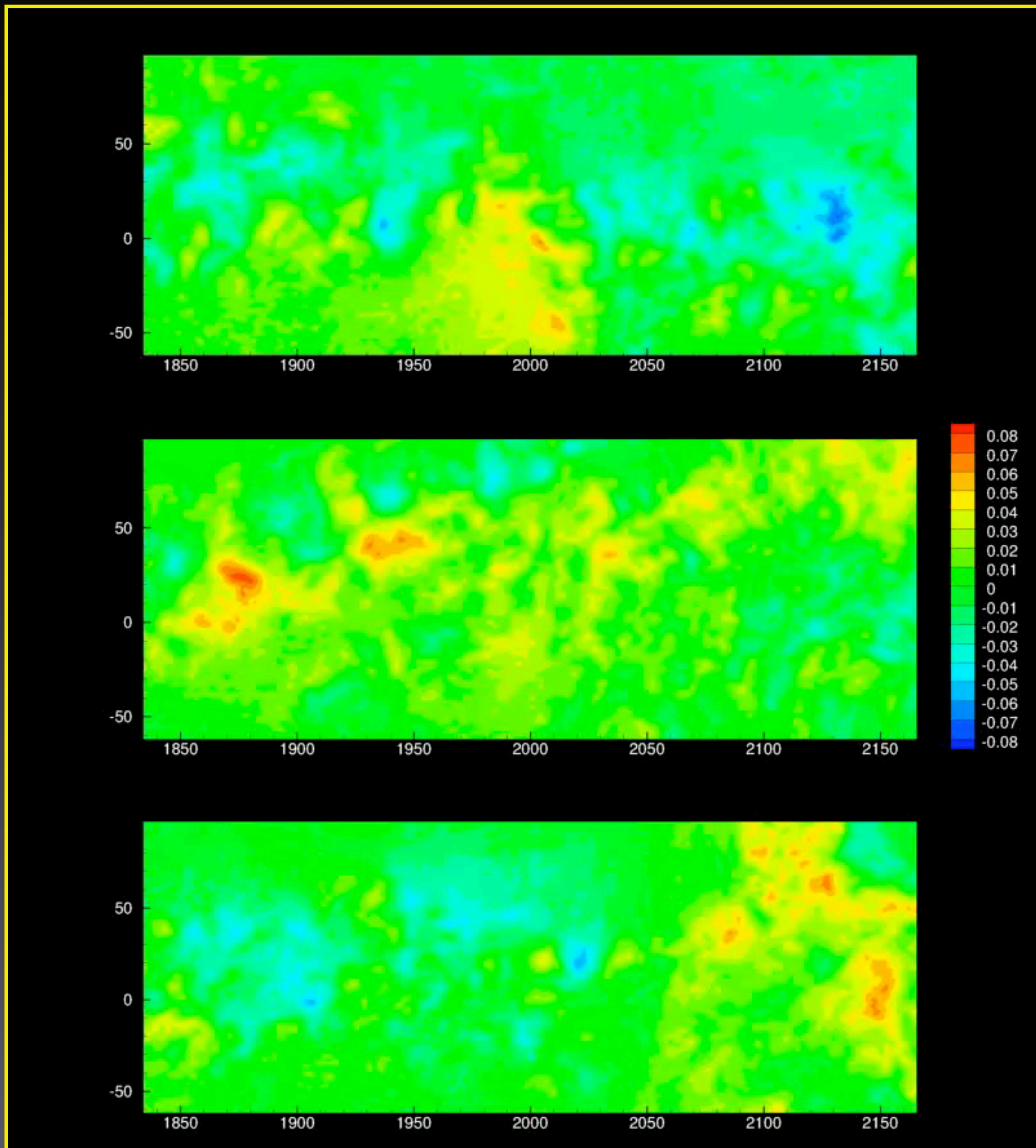
Planar mixing layer



$u_1^{'}$

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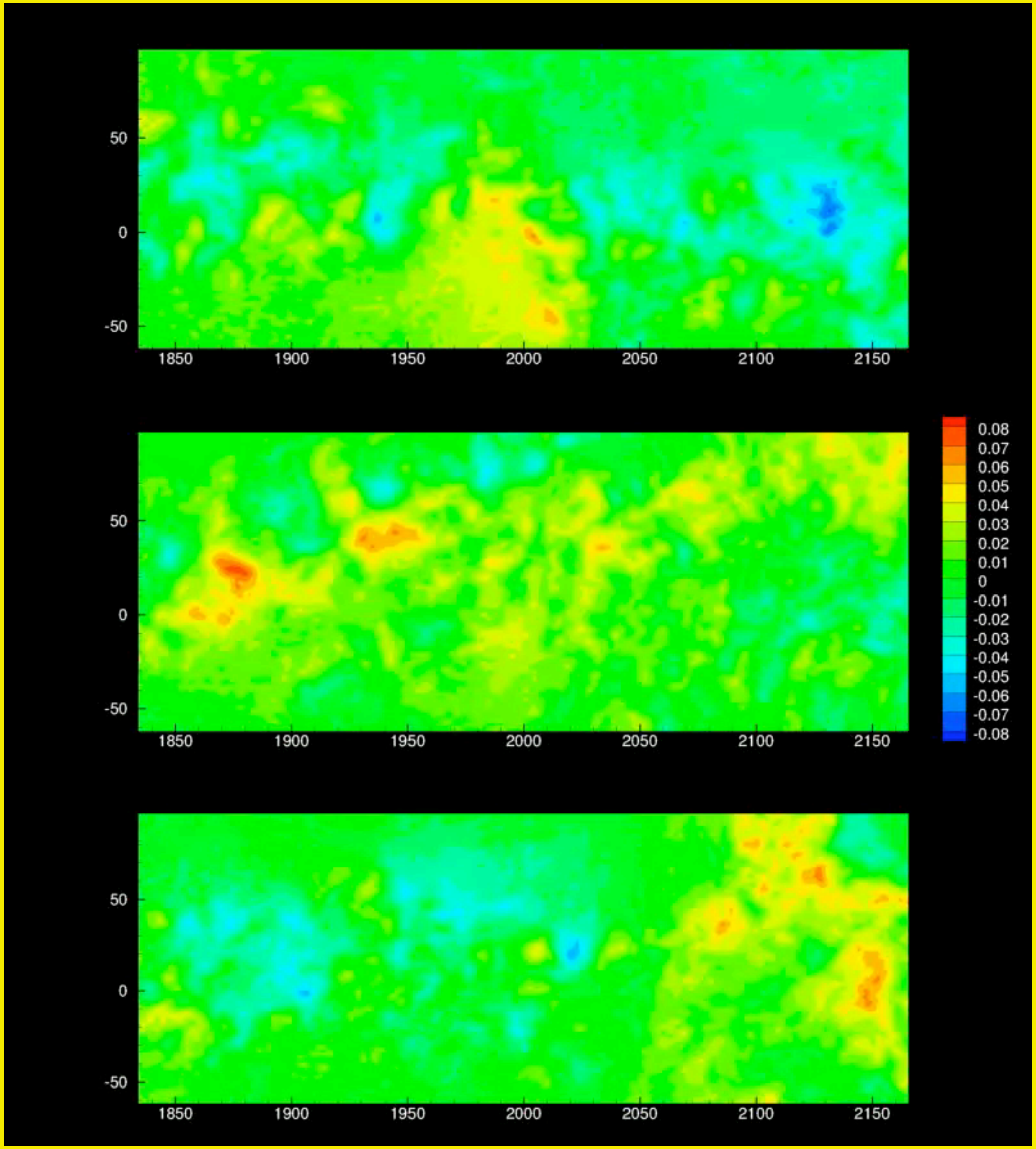
- Evidently multi-scale
- Convection velocities obtained by cross correlation

Planar mixing layer



$u_1^{'}$

$Re_\lambda = 210$

- Evidently multi-scale
- Convection velocities obtained by cross correlation
- Is the convection velocity scale dependent?

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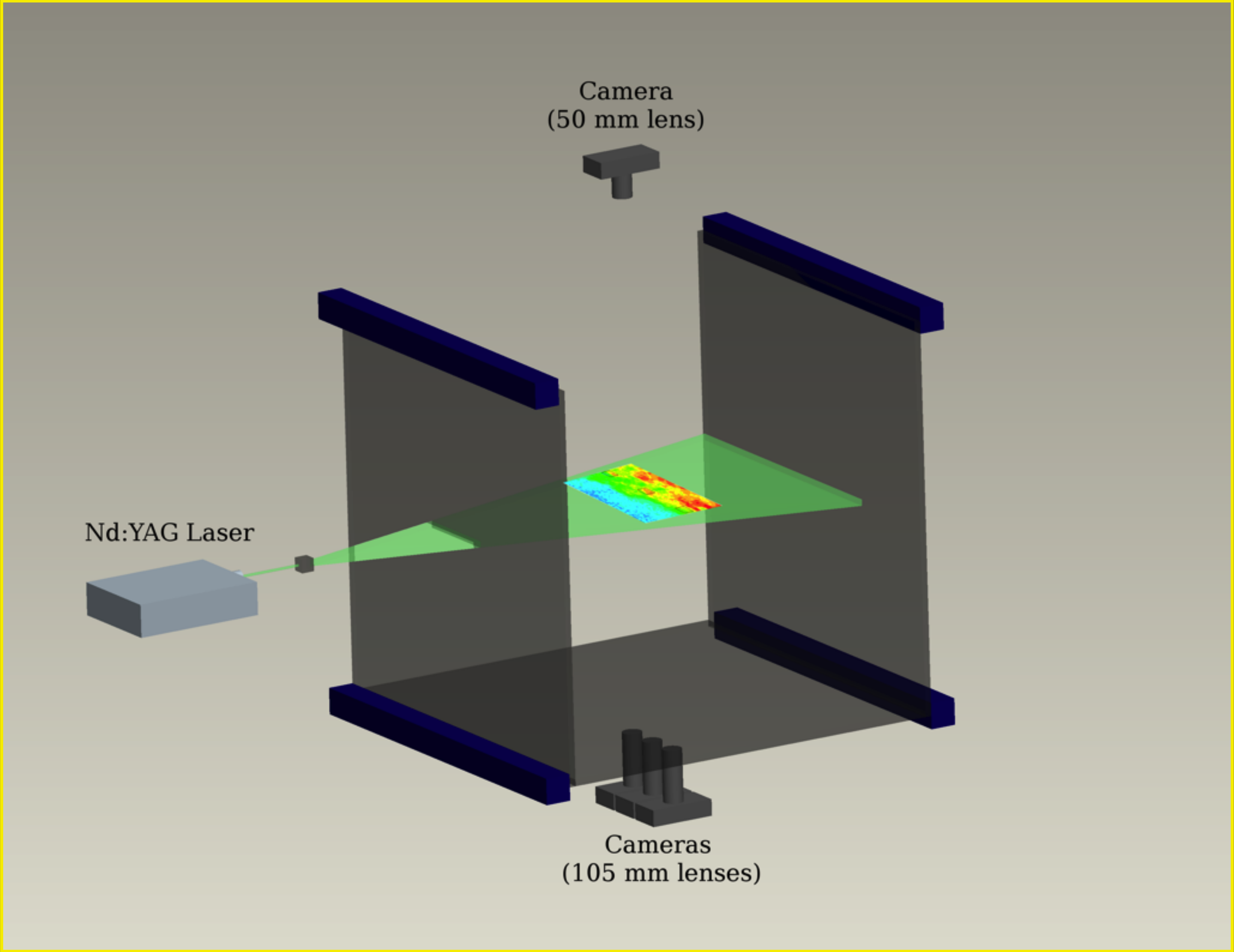
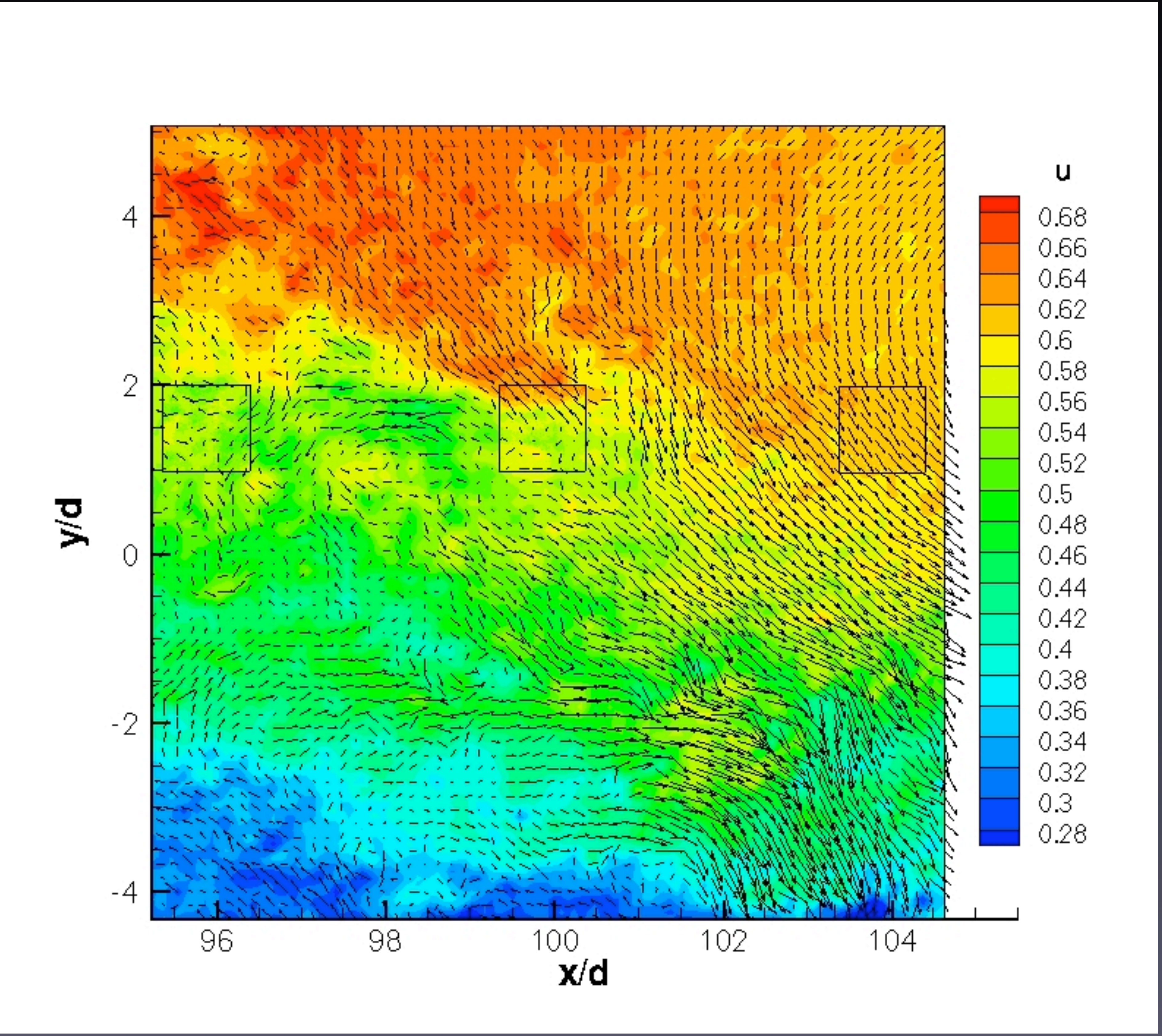
Synchronised multi-scale PIV



Synchronised multi-scale PIV



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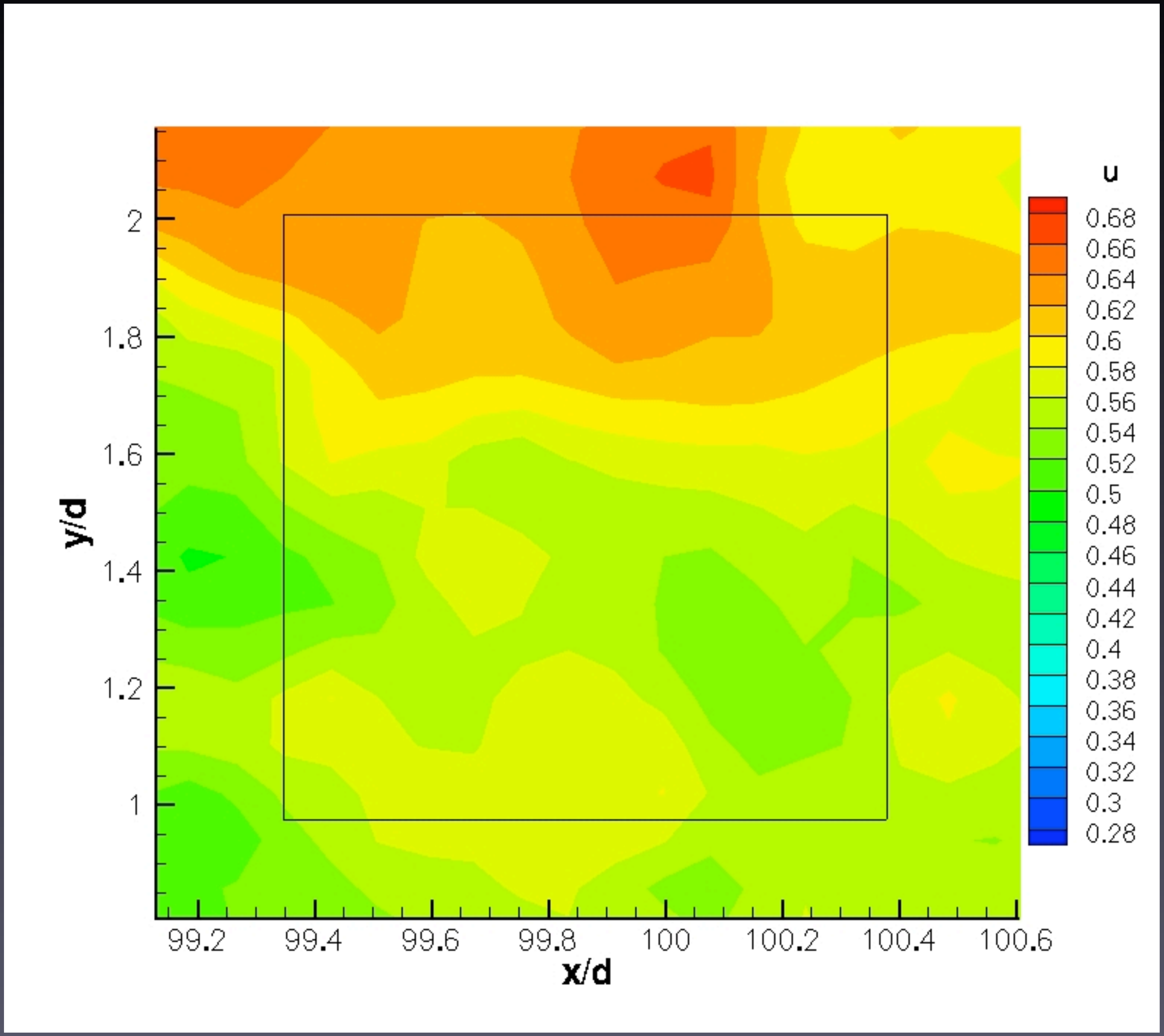
Planar mixing layer



- Adjacent vectors separated by 1.62 mm (resolution = 3.24 mm, 50% overlap)
  - 5.6η
  - 0.2λ

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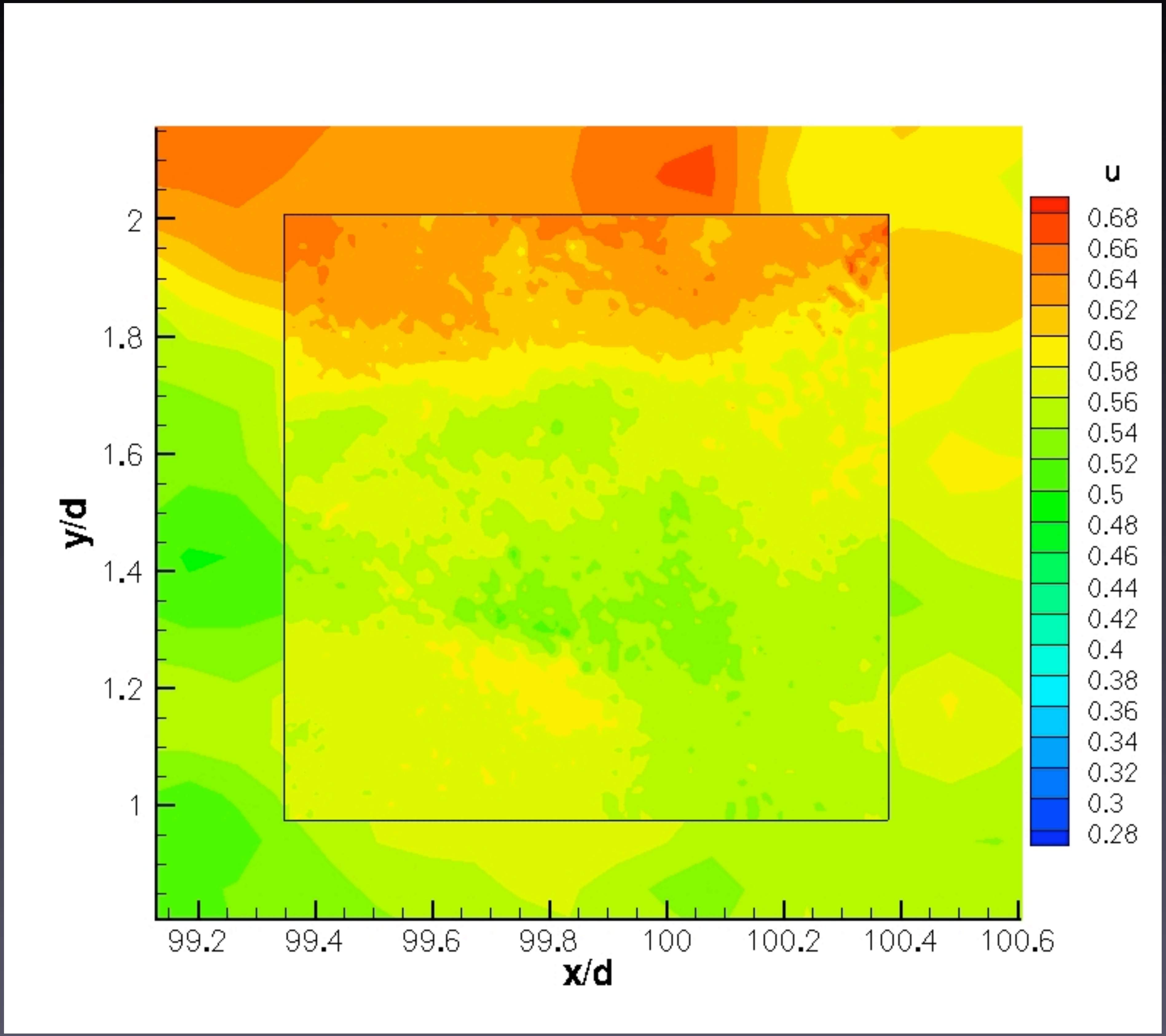
Planar mixing layer



- Adjacent vectors separated by 0.18 mm (resolution = 0.36 mm, 50% overlap)
  - 0.62η
  - 0.02λ

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Planar mixing layer

- Probability density function for $|u^{'}| > \sqrt{\langle u'^2 \rangle}$

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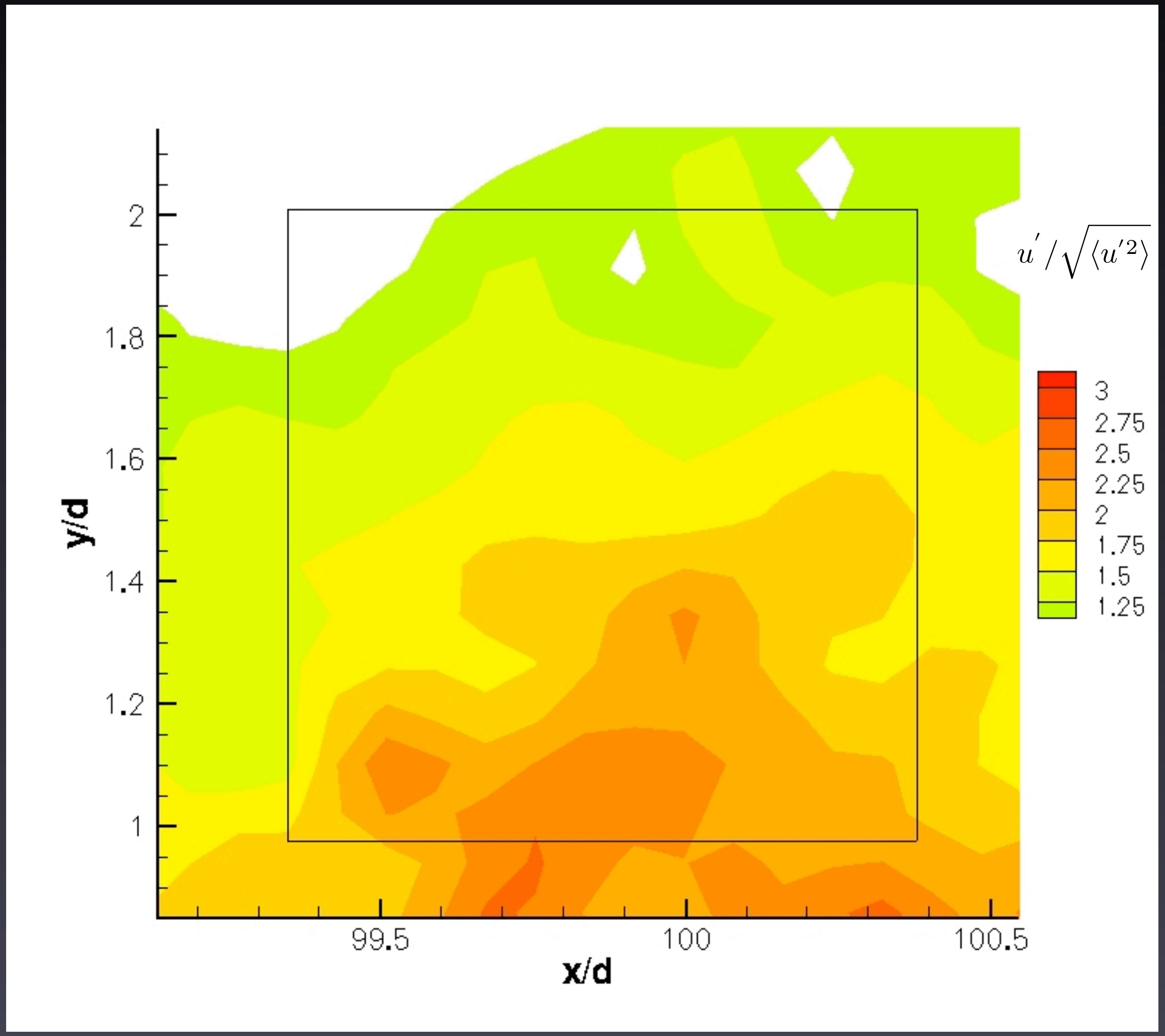
Planar mixing layer



- Probability density function for $|u^{'}| > \sqrt{\langle u'^2 \rangle}$
- Colouring cut off for $u^{'} < \sqrt{\langle u'^2 \rangle}$

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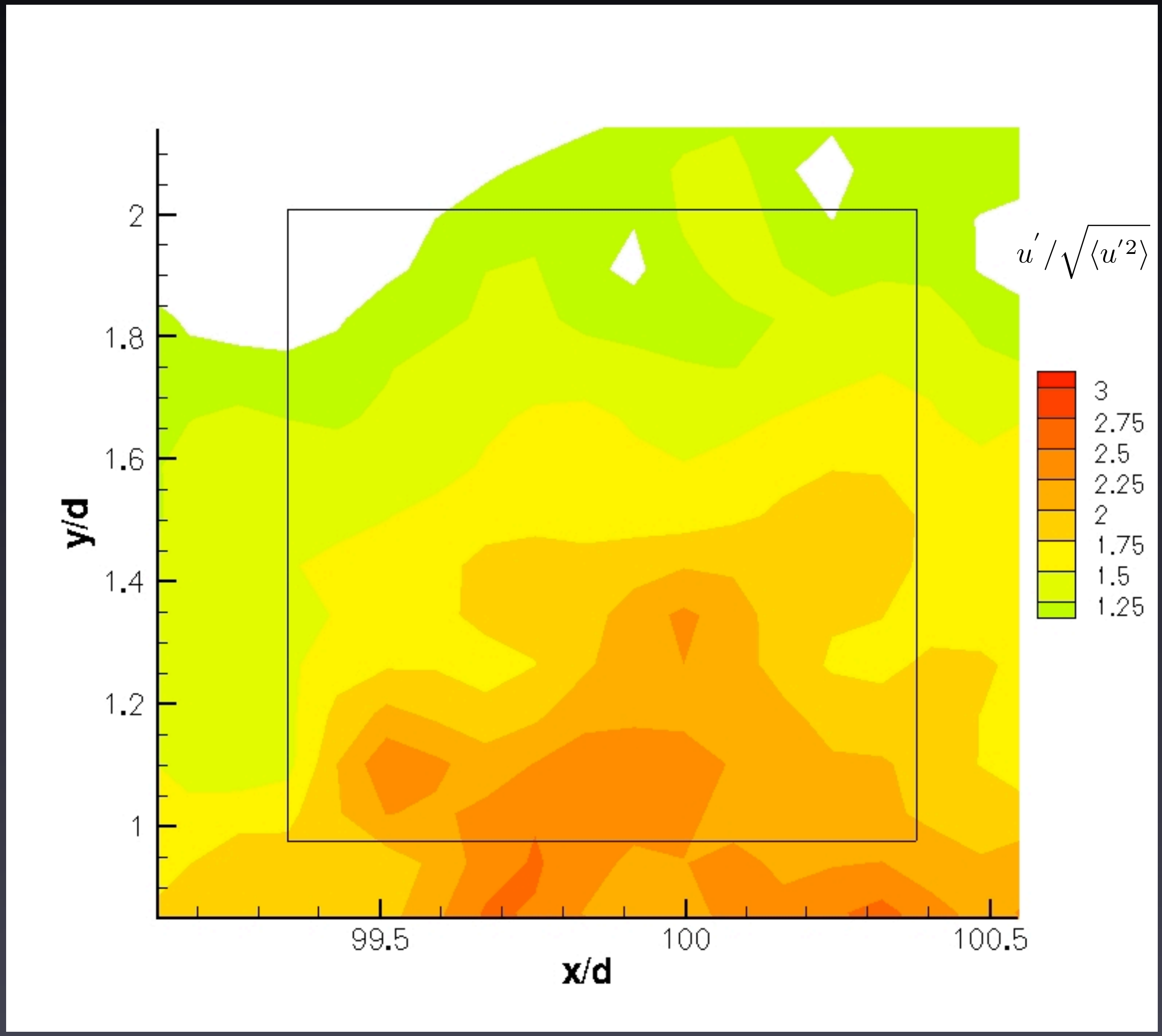
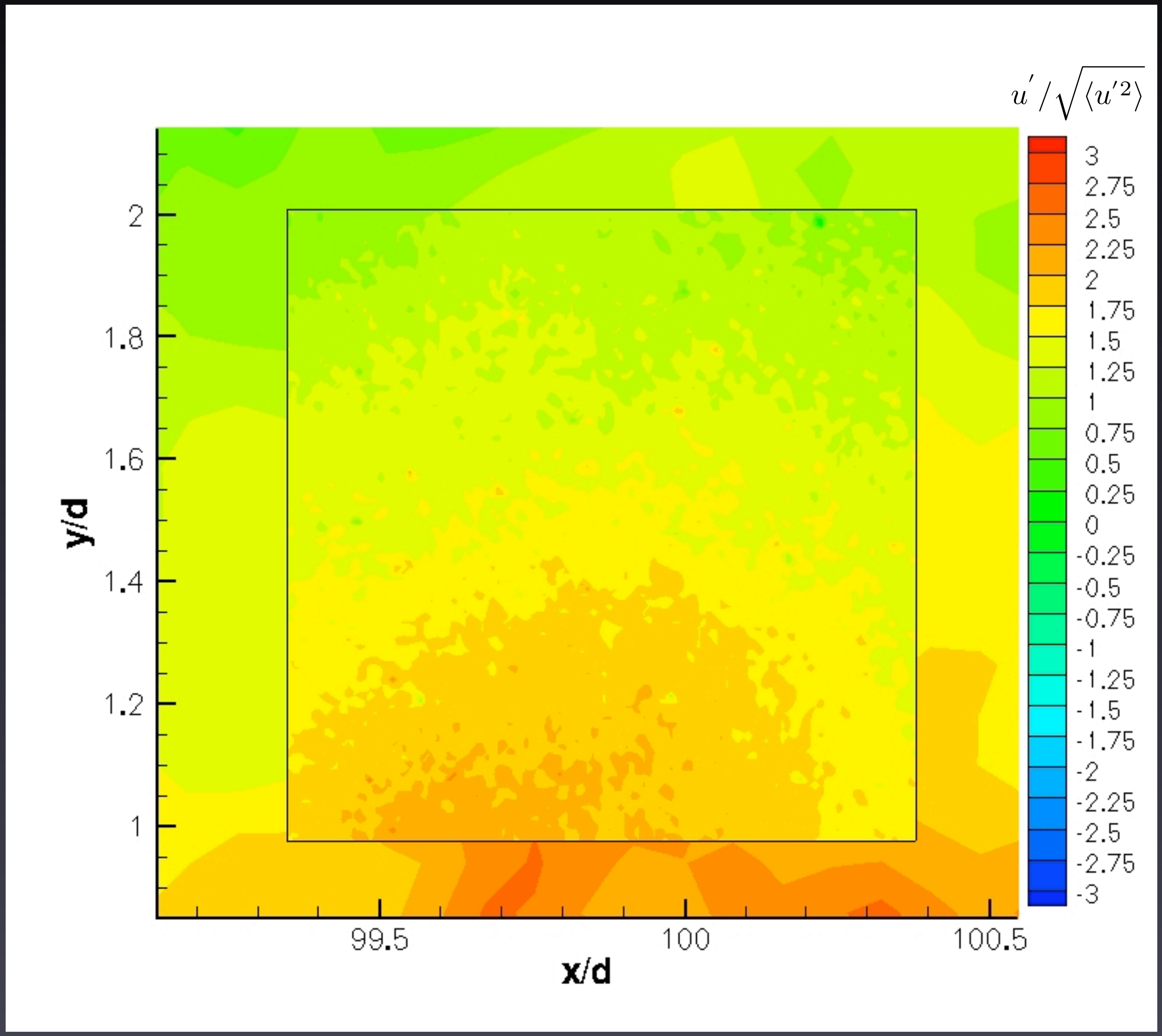
Planar mixing layer





- Probability density function for $|u^{'}| > \sqrt{\langle u'^2 \rangle}$
- Colouring cut off for $u^{'} < \sqrt{\langle u'^2 \rangle}$
- Now use small scale data to produce conditional pdf

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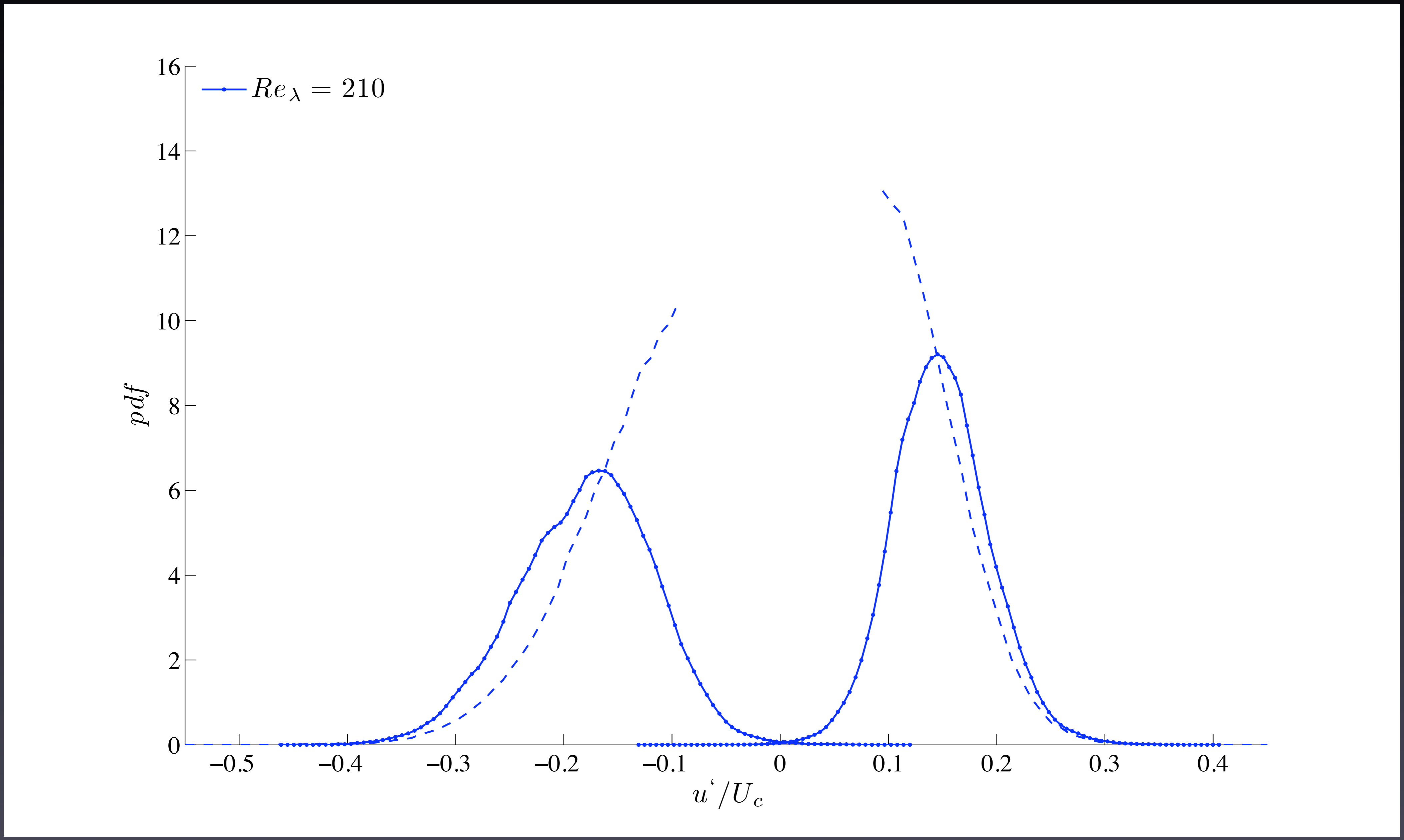
Planar mixing layer



- Probability density function for $|u^{'}| > \sqrt{\langle u'^2 \rangle}$
  - Dashed line : large scale information
  - Solid line : proportion of $1 - e^{-2}$ of large scale information exceeds threshold

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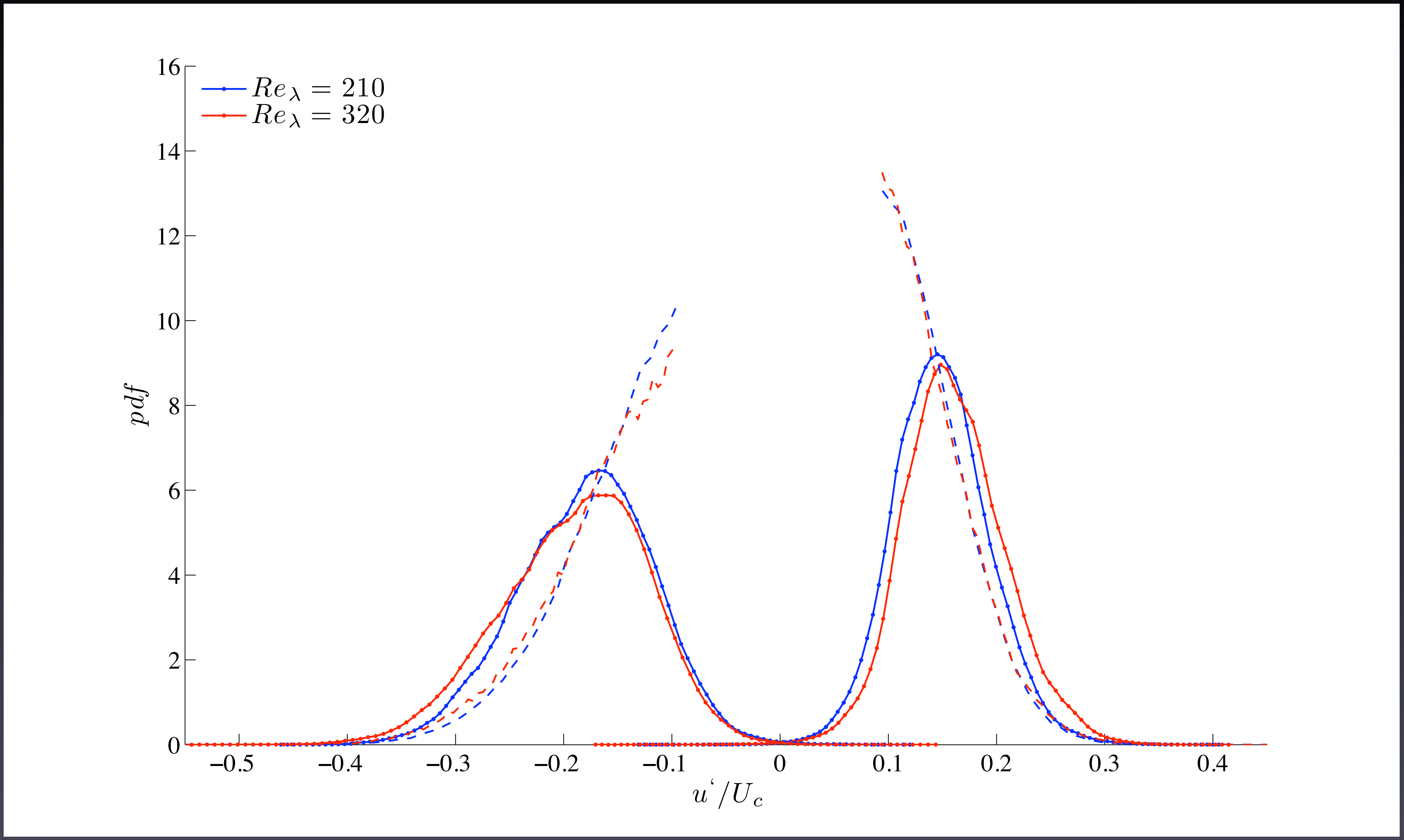
Planar mixing layer



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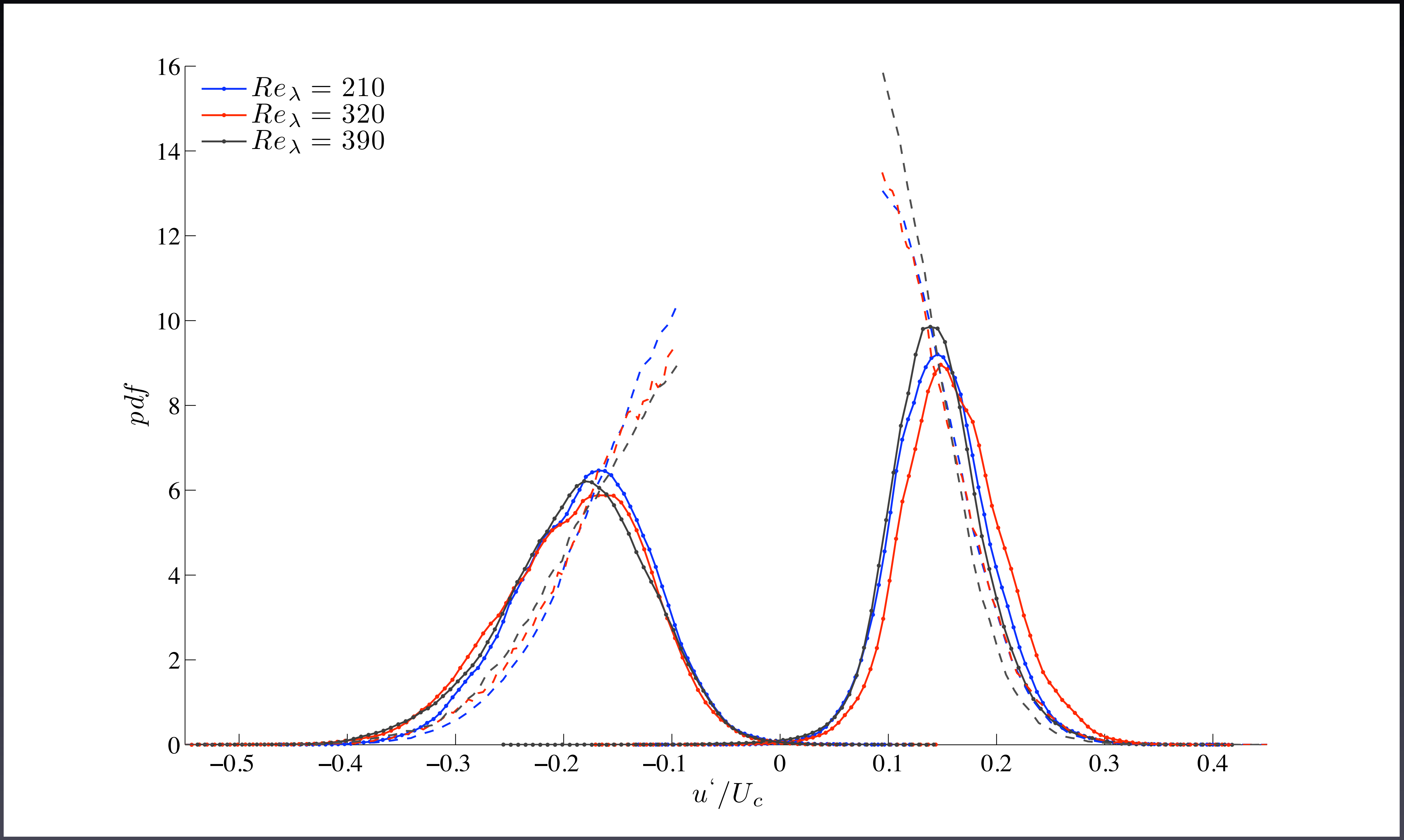

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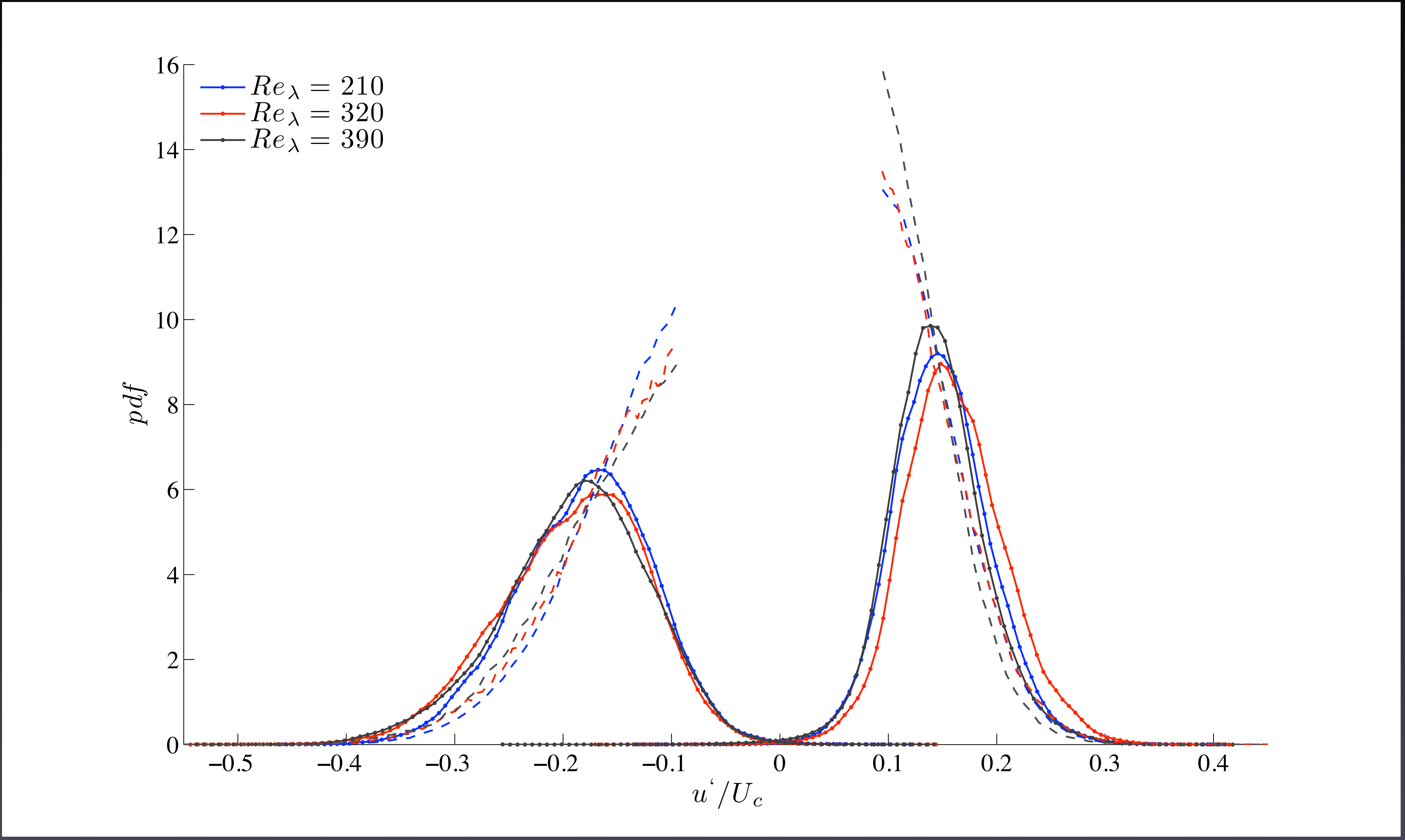
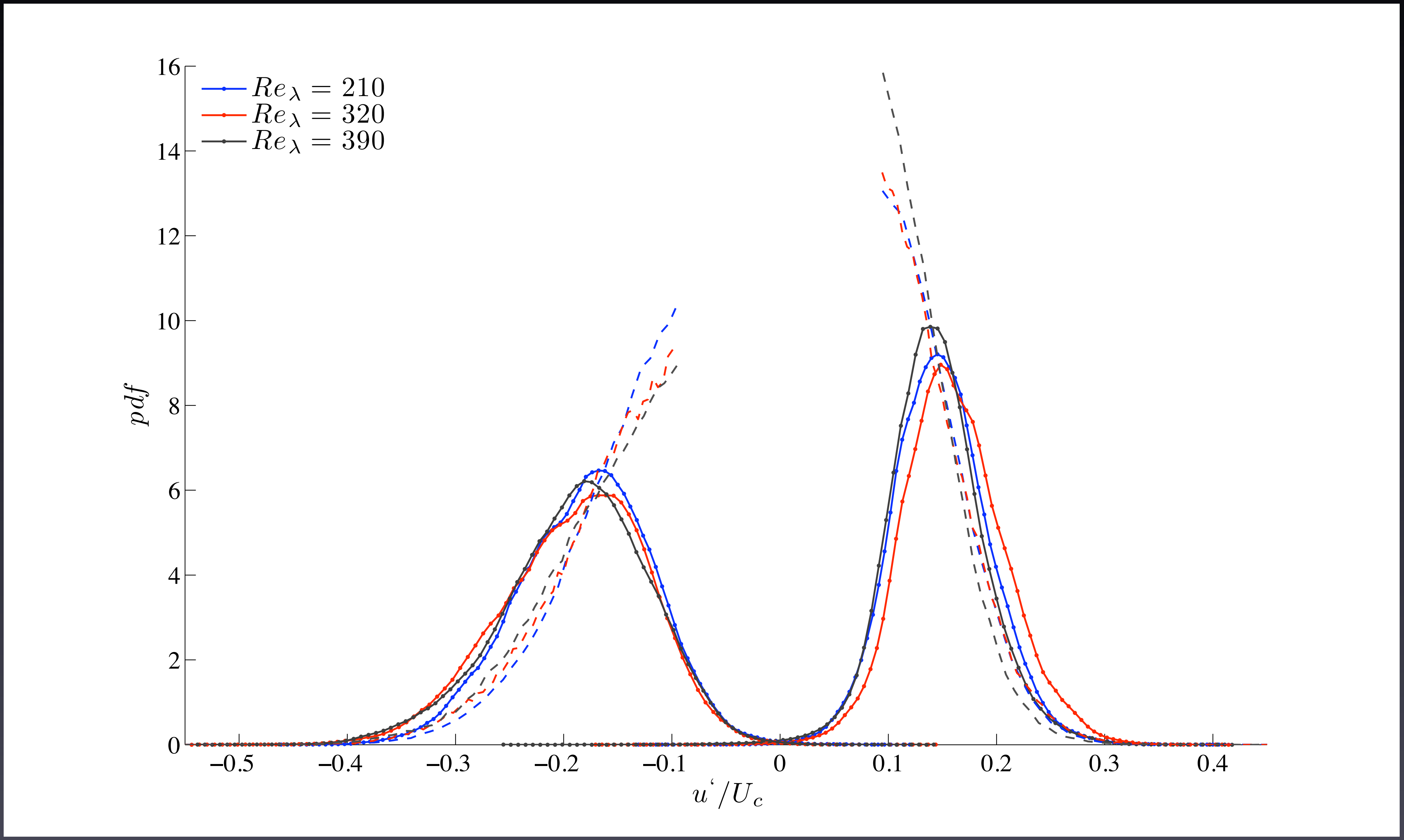


- Different behaviour for positive and negative fluctuations
  - Longer tails for negative fluctuations

Planar mixing layer



- Different behaviour for positive and negative fluctuations
  - Longer tails for negative fluctuations
- Reynolds number effect?

Three dimensional data

3D data allows examination of velocity gradient quantities

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Three dimensional data

3D data allows examination of velocity gradient quantities

$$D_{ij} = \frac{\partial u_i}{\partial x_j} = S_{ij} + \Omega_{ij}$$

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Three dimensional data

3D data allows examination of velocity gradient quantities

$$D_{ij} = \frac{\partial u_i}{\partial x_j} = S_{ij} + \Omega_{ij}$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

Dissipation (ϵ)

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Three dimensional data

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Dissipation (ϵ)

$$\Omega_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right)$$

Enstrophy (ω^2)

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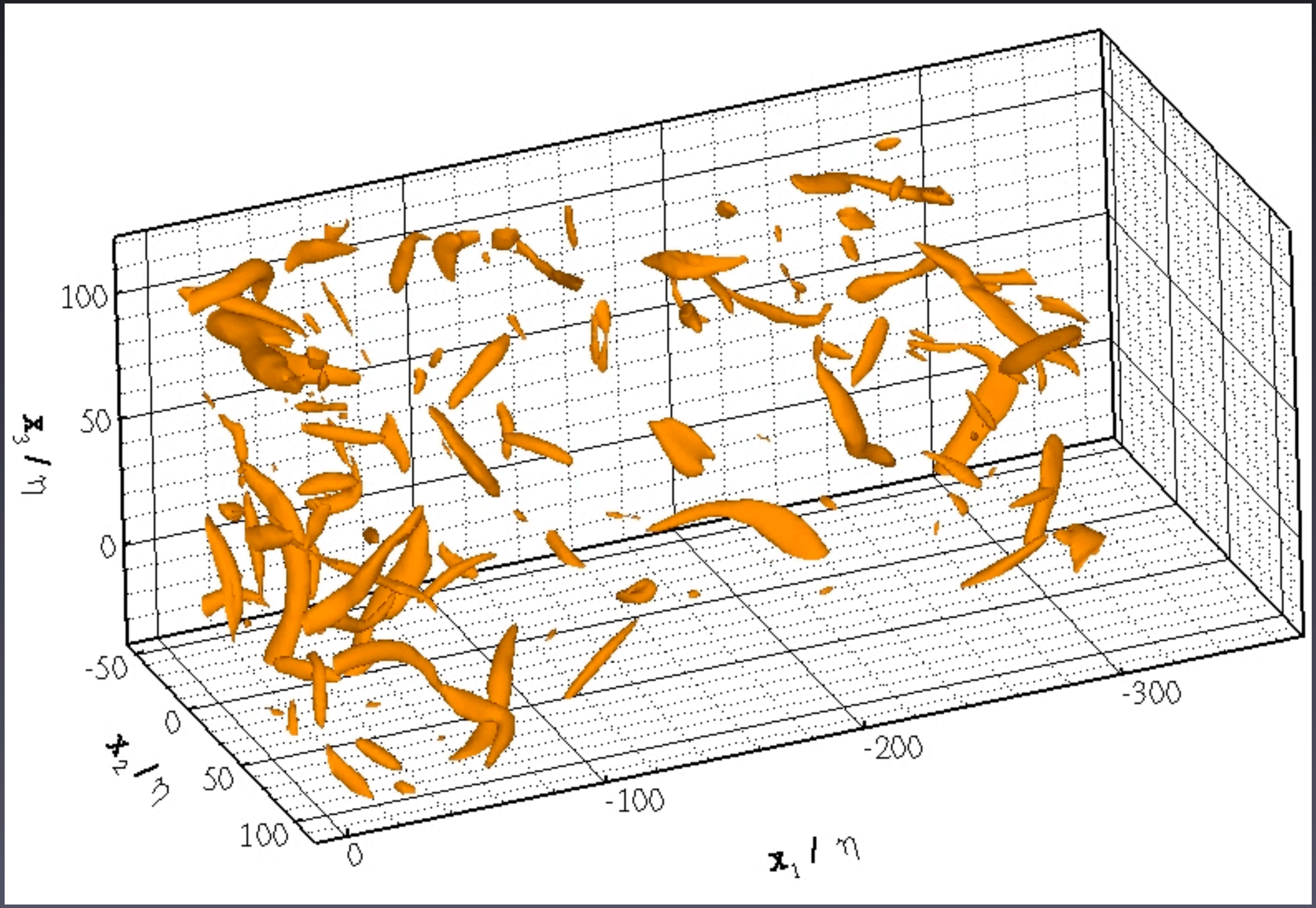
Turbulent axisymmetric jet

$$\Omega_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right)$$



$$\omega^2 = 75.0\mathrm{s}^{-1} = 3.55\langle\omega^2\rangle$$

- Isosurfaces of enstrophy (rotation dominated)

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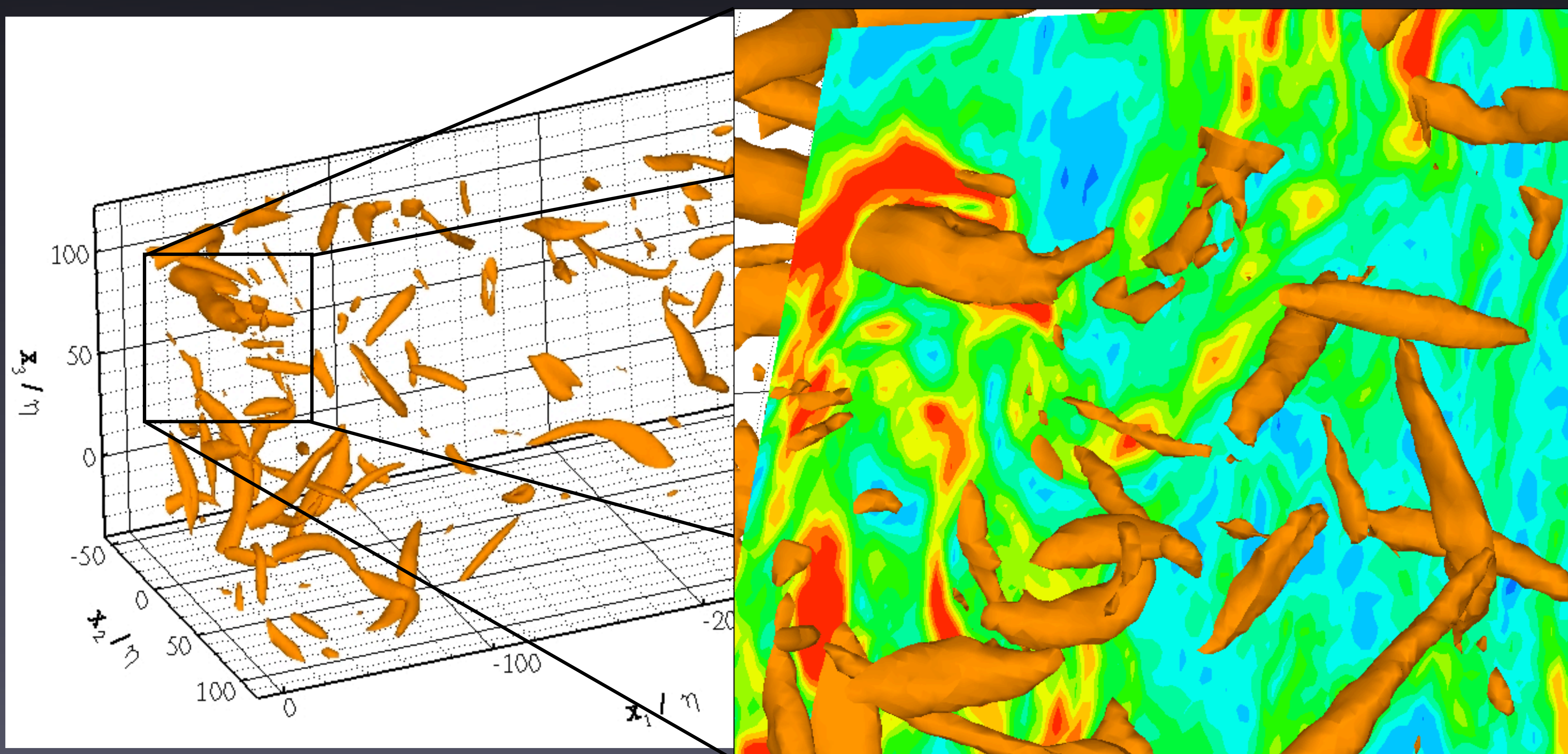
Turbulent axisymmetric jet

$$\Omega_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right) \qquad S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

- Contours of dissipation (strain dominated)



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Three dimensional data

"Interaction between strain and rotation intrinsic to the very nature of three dimensional turbulence" [TENNEKES & LUMLEY 1972]

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Three dimensional data

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$$\frac{1}{2}\frac{\mathrm{D}\omega^2}{\mathrm{D}t} = \omega_i S_{ij}\omega_j + \nu\nabla^2\omega_i$$

$$\frac{1}{2}\frac{\mathrm{D}\frac{\epsilon}{2\nu}}{\mathrm{D}t} = -S_{ij}S_{jk}S_{ki} - \frac{1}{4}\omega_i S_{ij}\omega_j - S_{ij}\frac{\partial^2 p}{\partial x_i \partial x_j} + \nu S_{ij}\nabla^2 S_{ij}$$

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- Quantity $\omega_i S_{ij}\omega_j$ is the rate of enstrophy amplification

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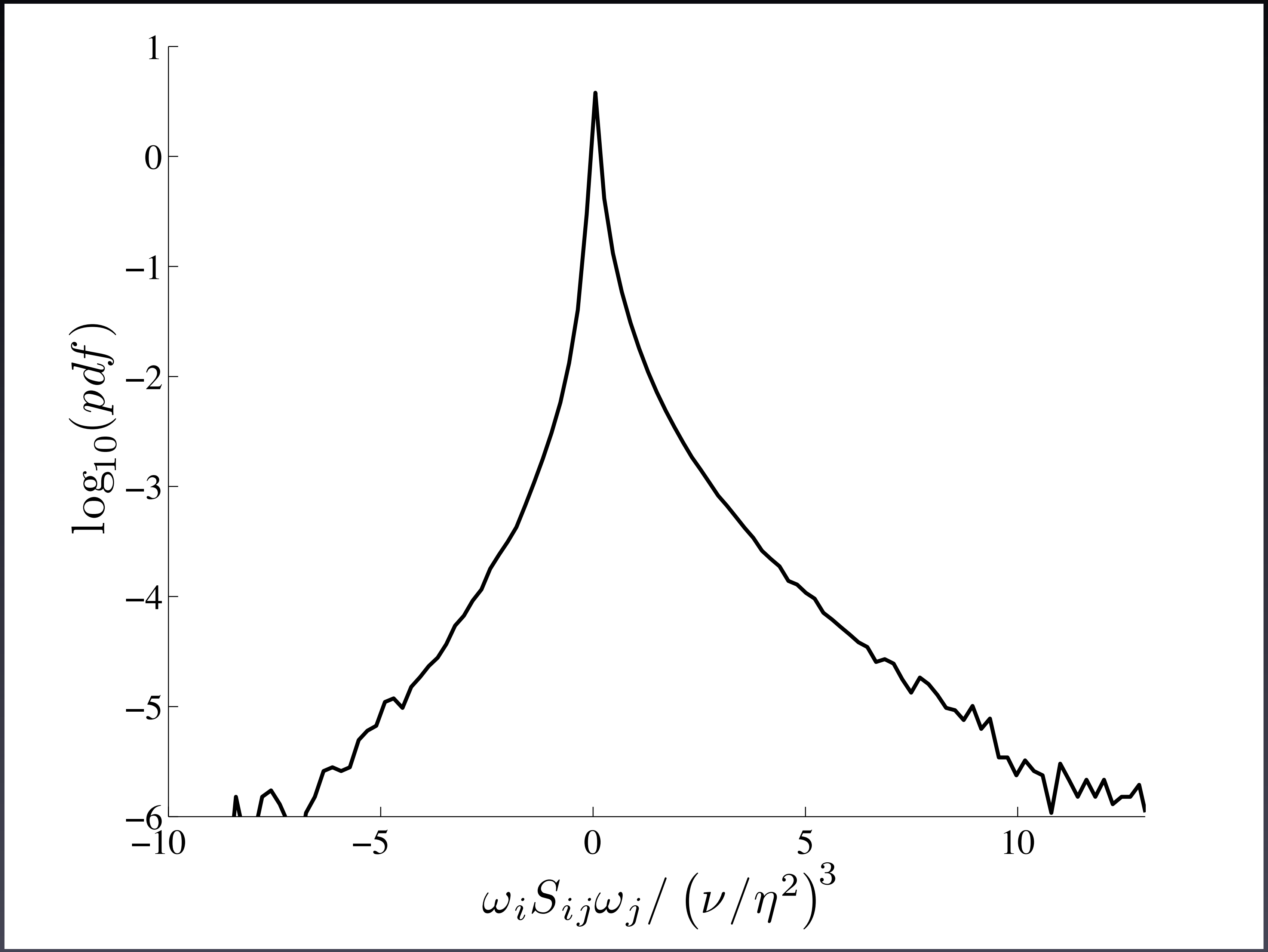
Turbulent axisymmetric jet



- Enstrophy amplification favoured over attenuation
  - $\langle \omega_i S_{ij} \omega_j \rangle = 0.07 \left(\nu/\eta^2\right)^3$
  - 71% of data points enstrophy amplifying

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Three dimensional data

"Interaction between strain and rotation intrinsic to the very nature of three dimensional turbulence" [TENNEKES & LUMLEY 1972]

$$\frac{1}{2}\frac{\mathrm{D}\omega^2}{\mathrm{D}t} = \omega_i S_{ij} \omega_j + \nu \nabla^2 \omega_i$$

$$\frac{1}{2}\frac{\mathrm{D}\frac{\epsilon}{2\nu}}{\mathrm{D}t} = -S_{ij}S_{jk}S_{ki} - \frac{1}{4}\omega_i S_{ij} \omega_j - S_{ij}\frac{\partial^2 p}{\partial x_i \partial x_j} + \nu S_{ij} \nabla^2 S_{ij}$$

- Quantity $\omega_i S_{ij} \omega_j$ is the rate of enstrophy amplification
- Excellent metric for examining the interaction between strain-rate and rotation : $\omega_i S_{ij} \omega_j = \omega^2 s_i \left(\hat{e}_i \cdot \hat{\omega}\right)^2$

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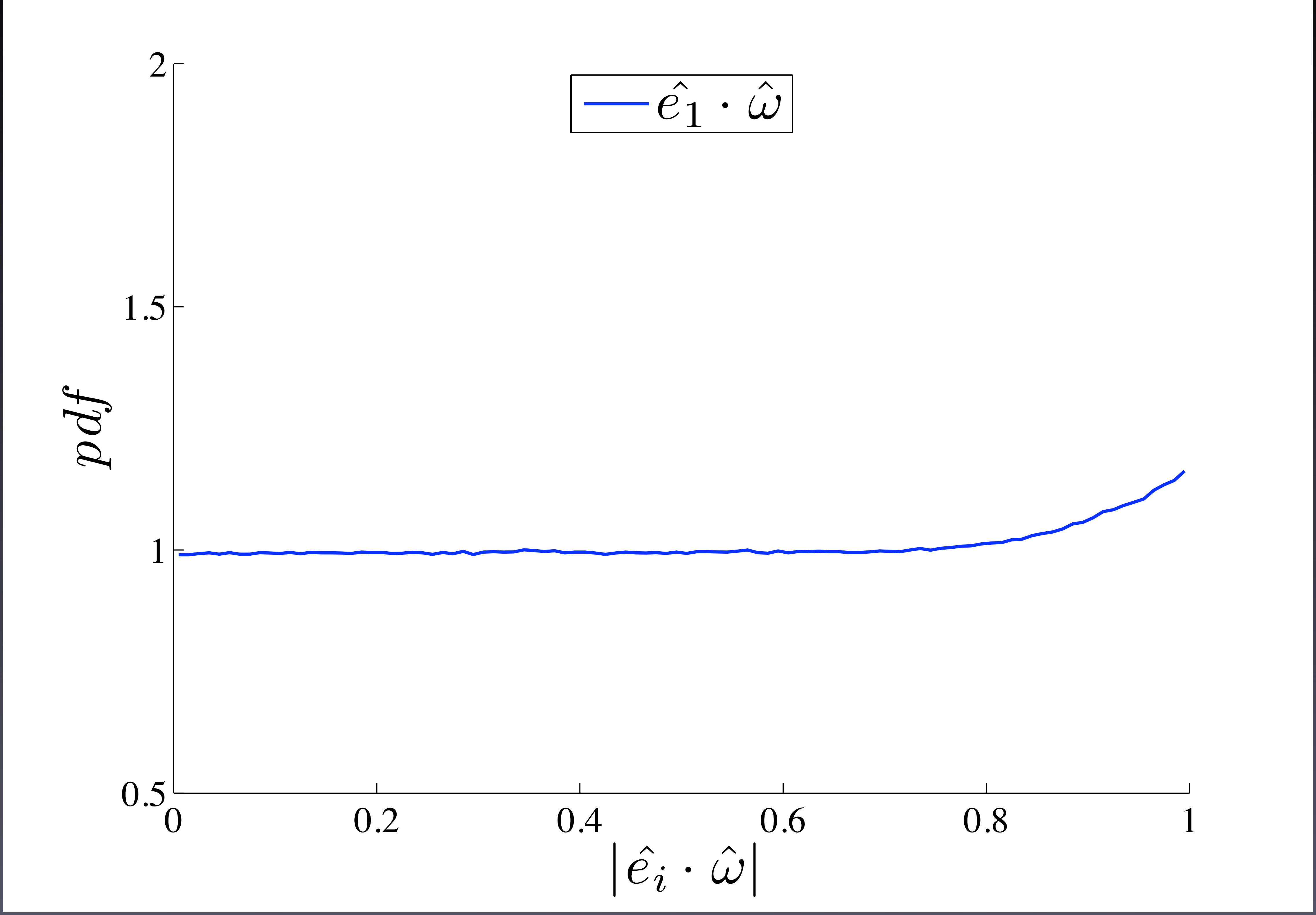
Planar mixing layer



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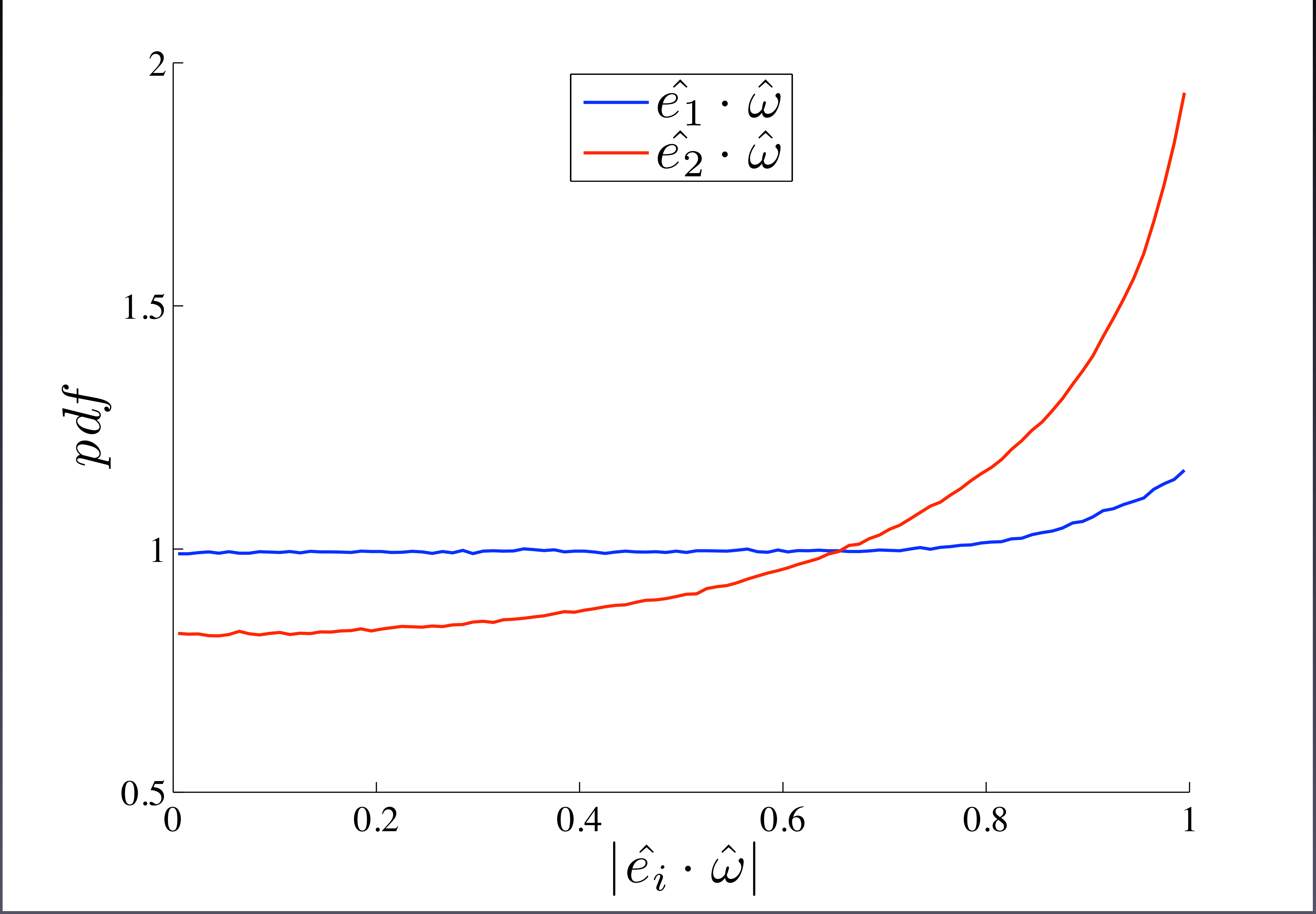

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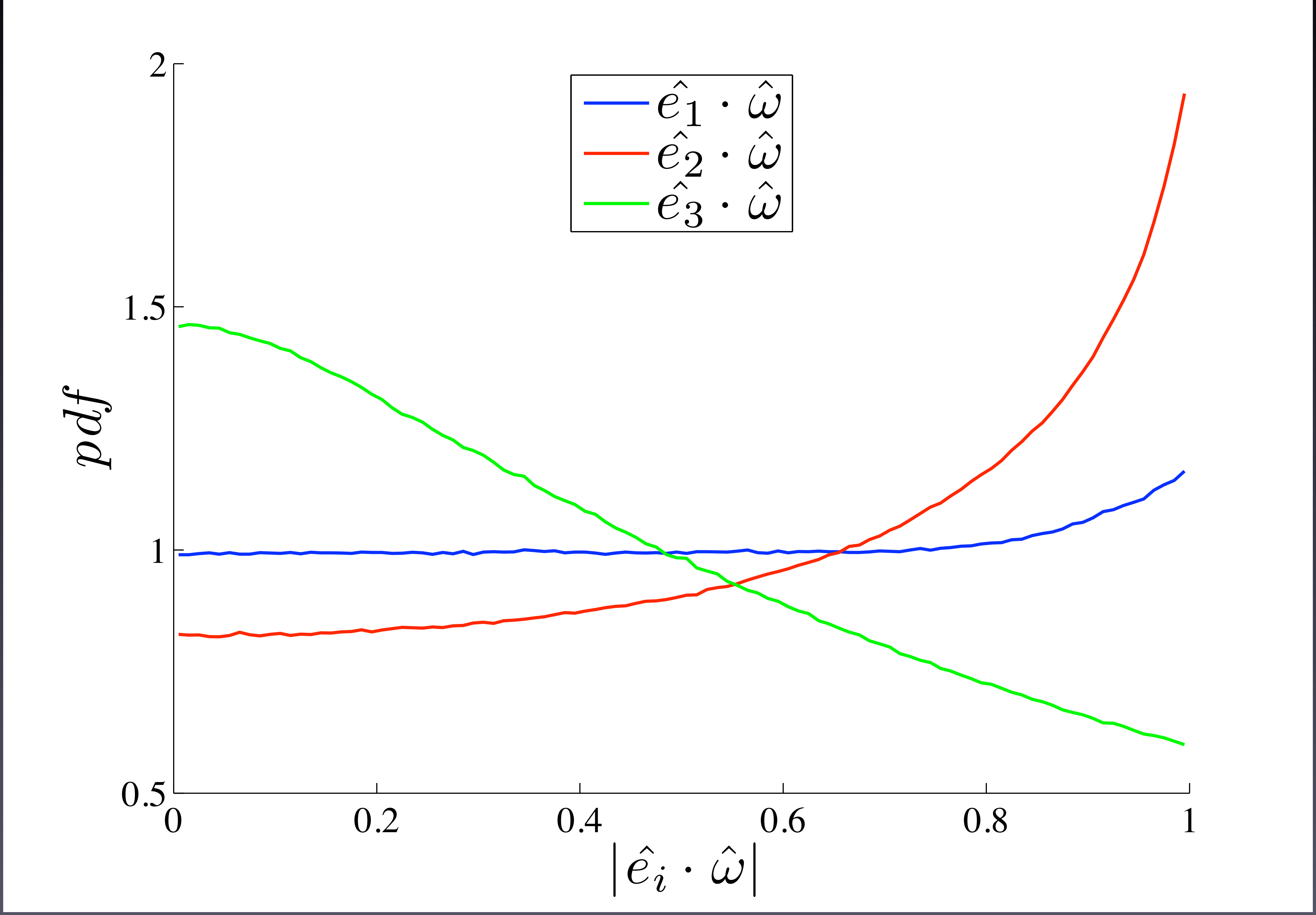
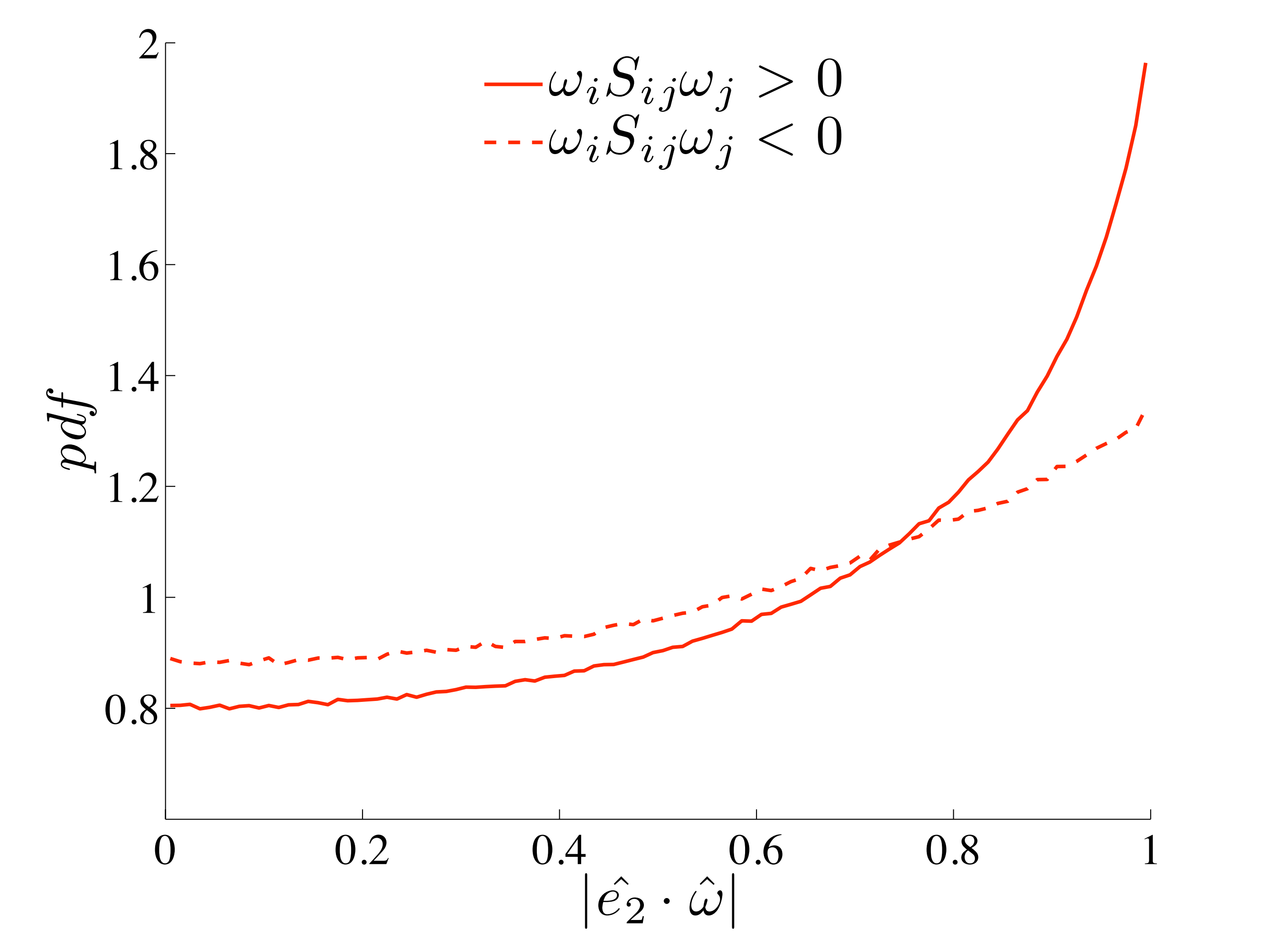


Turbulent axisymmetric jet



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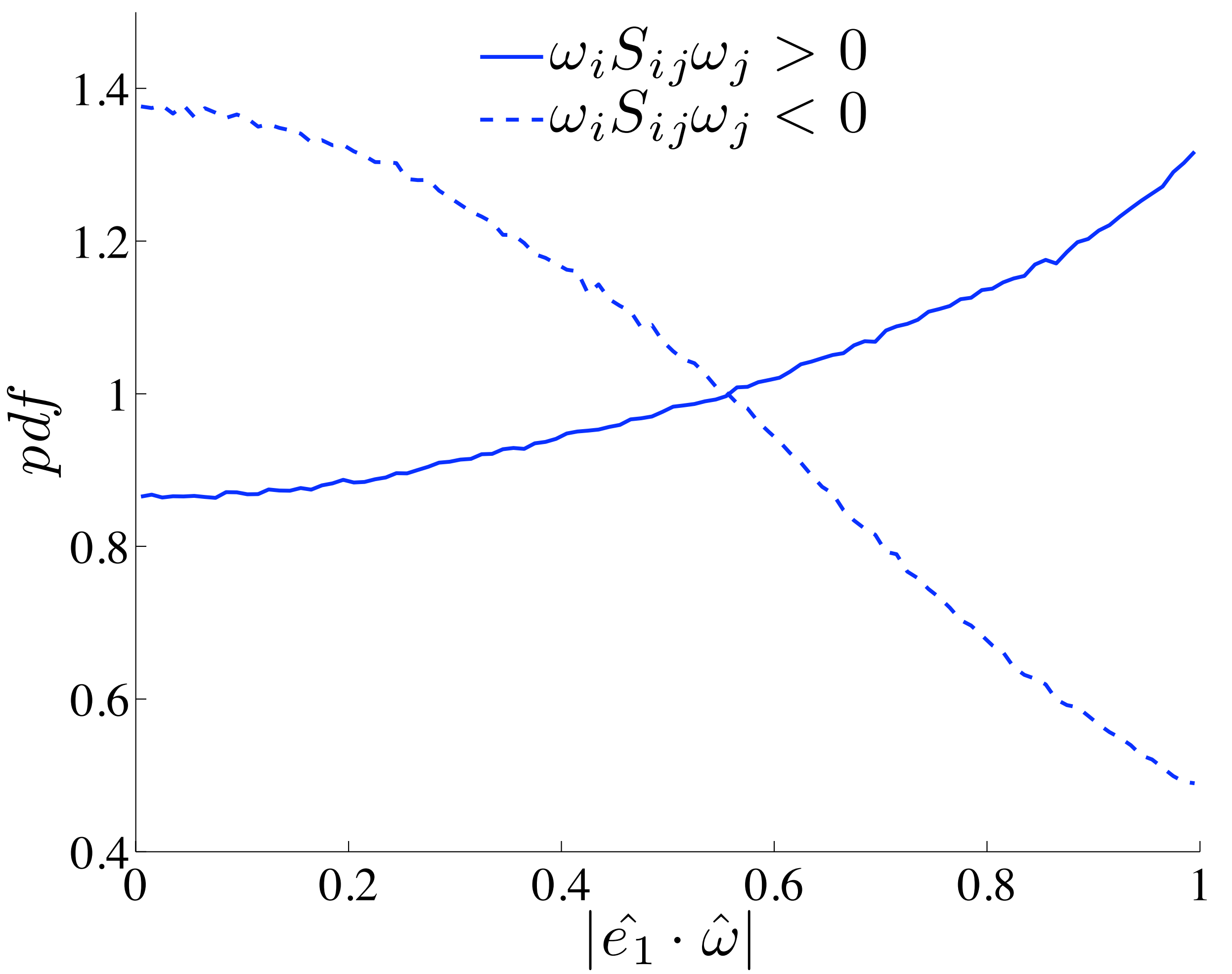
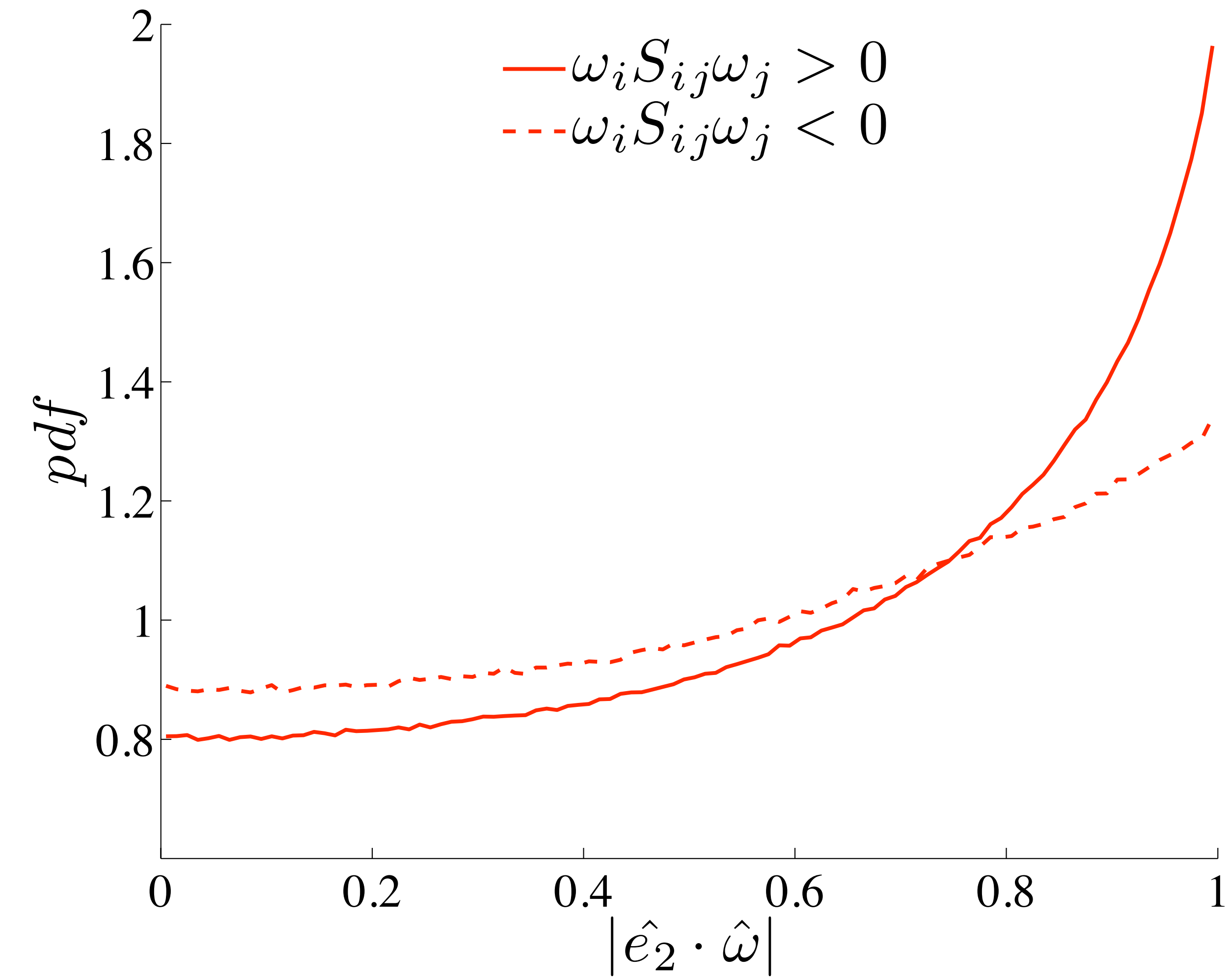
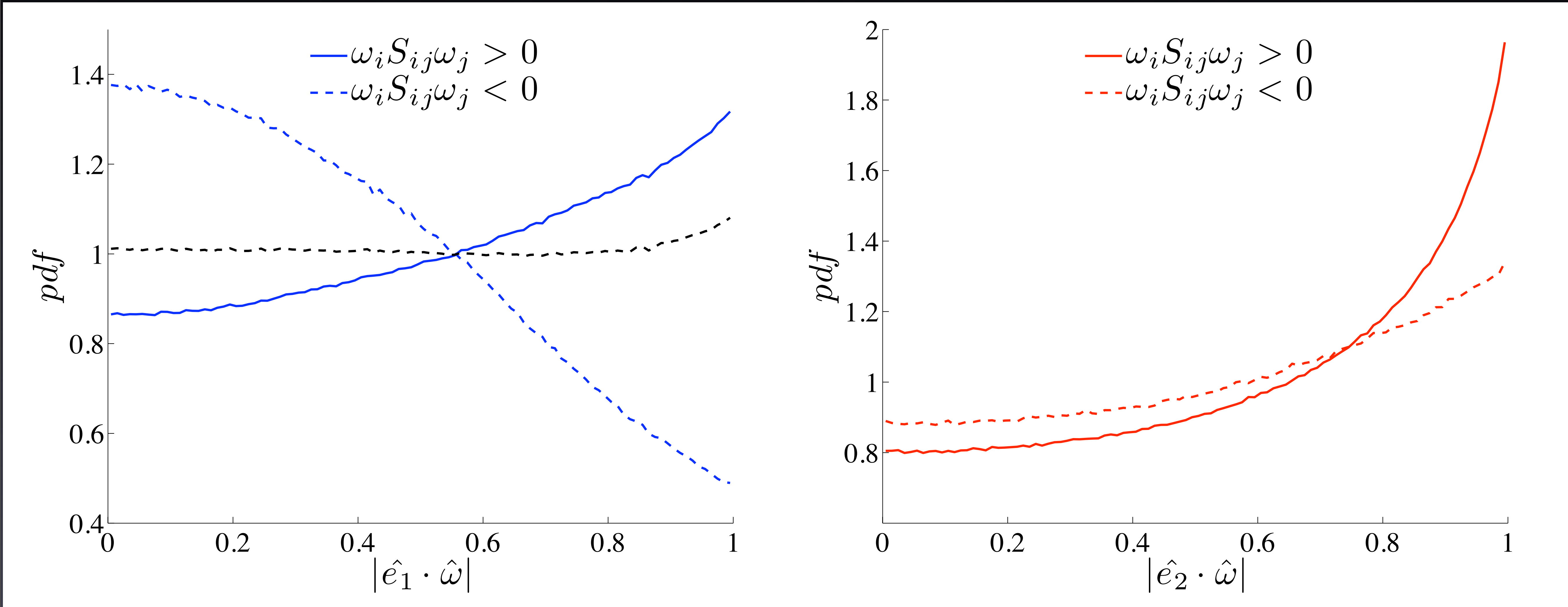
Turbulent axisymmetric jet





- Alignment between $\hat{e_1}$ and $\hat{\omega}$ crucial to enstrophy production rate
  - parallel = enstrophy production
  - perpendicular = enstrophy destruction

Turbulent axisymmetric jet



- Alignment between $\hat{e_1}$ and $\hat{\omega}$ crucial to enstrophy production rate
  - parallel = enstrophy production
  - perpendicular = enstrophy destruction

“Traditional” $|\hat{e_1} \cdot \hat{\omega}|$ pdf the summation of enstrophy producing and enstrophy destroying data points

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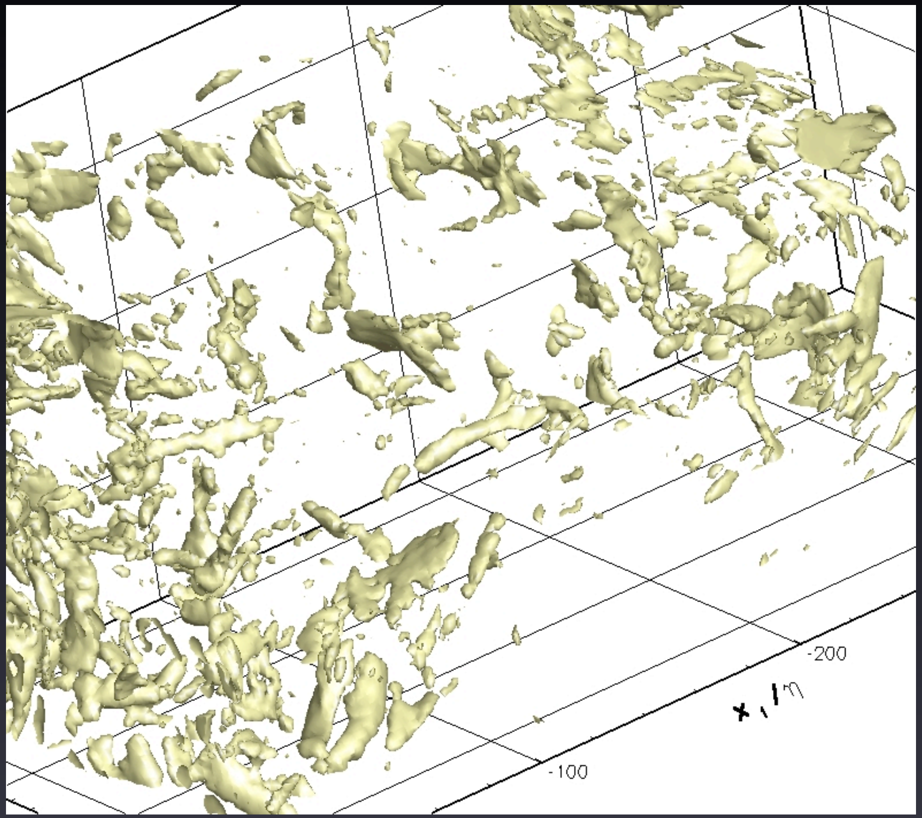
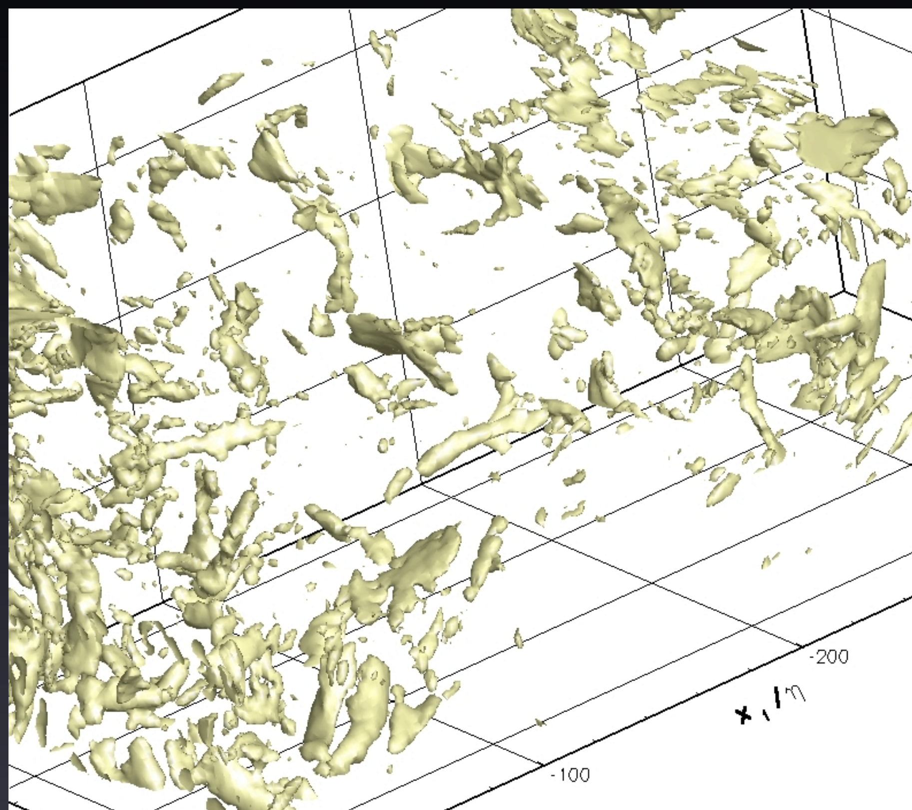
Turbulent axisymmetric jet



$$\omega_i S_{ij} \omega_j > 0$$

- Predominantly “sheet-like”

Turbulent axisymmetric jet



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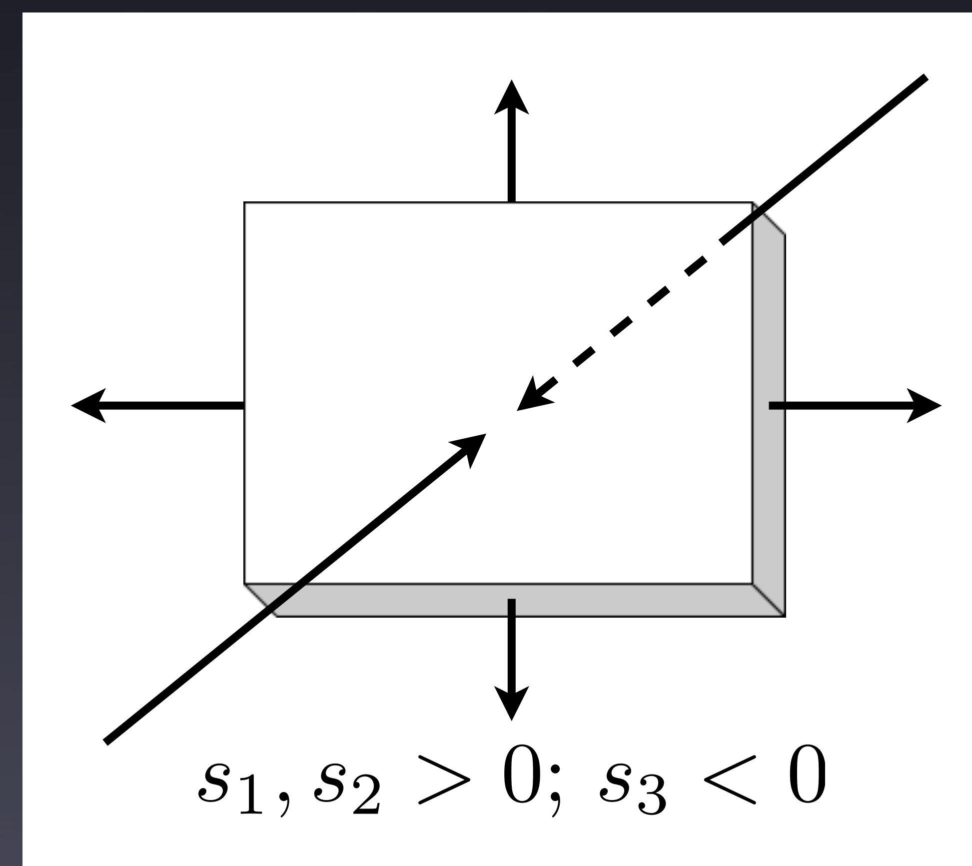

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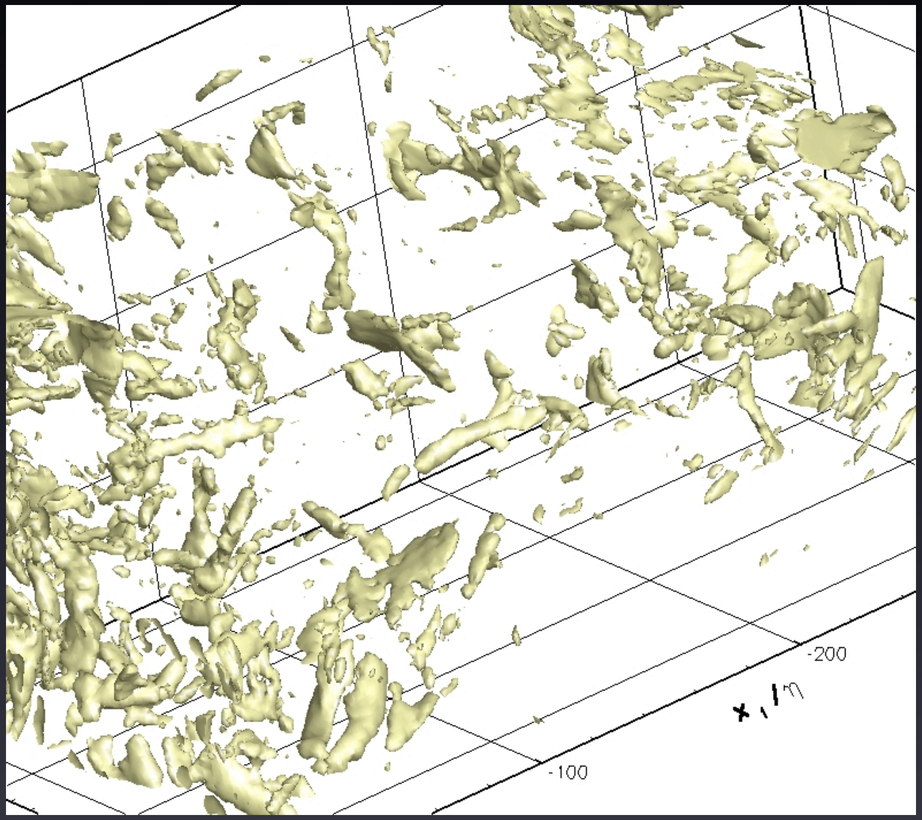
Turbulent axisymmetric jet



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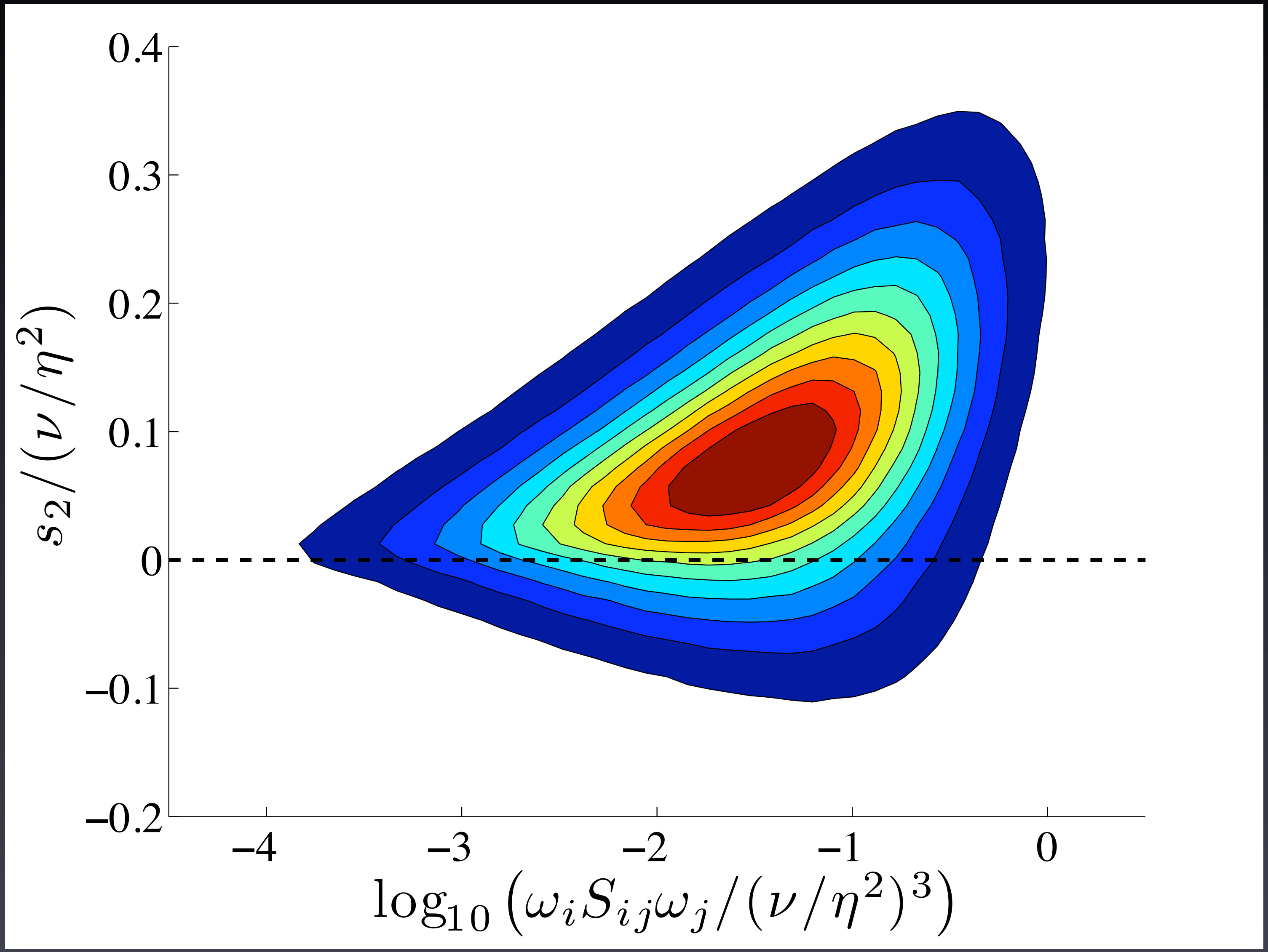

- Positive s_2 favoured over negative
- Particularly for high $\omega_i S_{ij} \omega_j$

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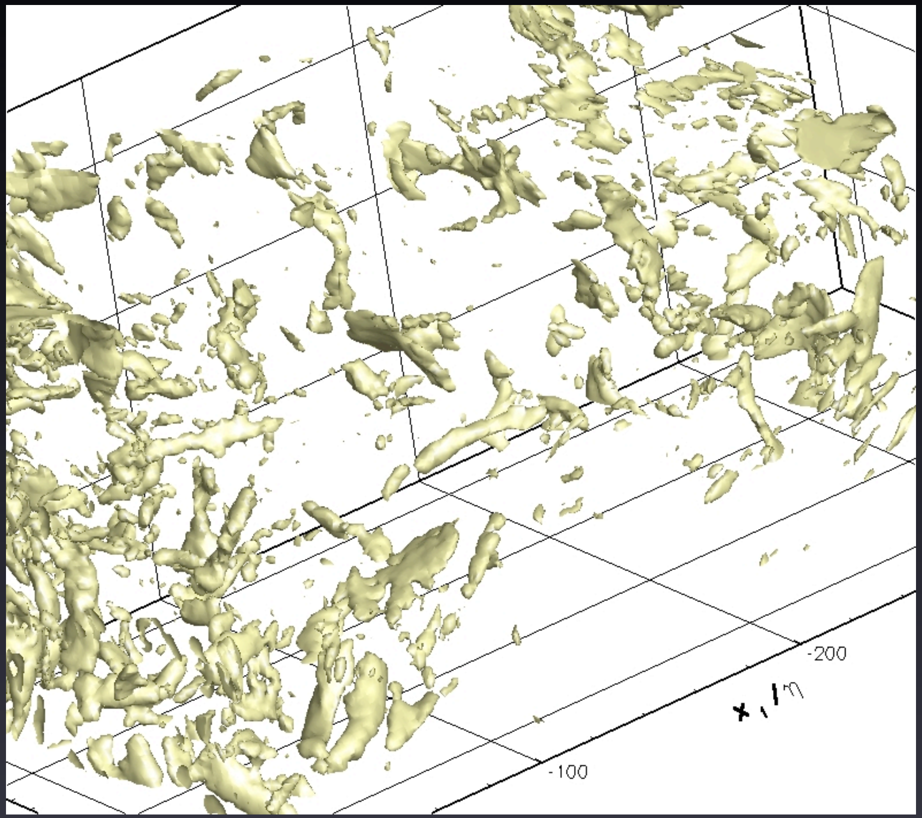
Turbulent axisymmetric jet



$$\omega_i S_{ij} \omega_j > 0$$

- Predominantly "sheet-like"
- Strongly rotational regions favour enstrophy production

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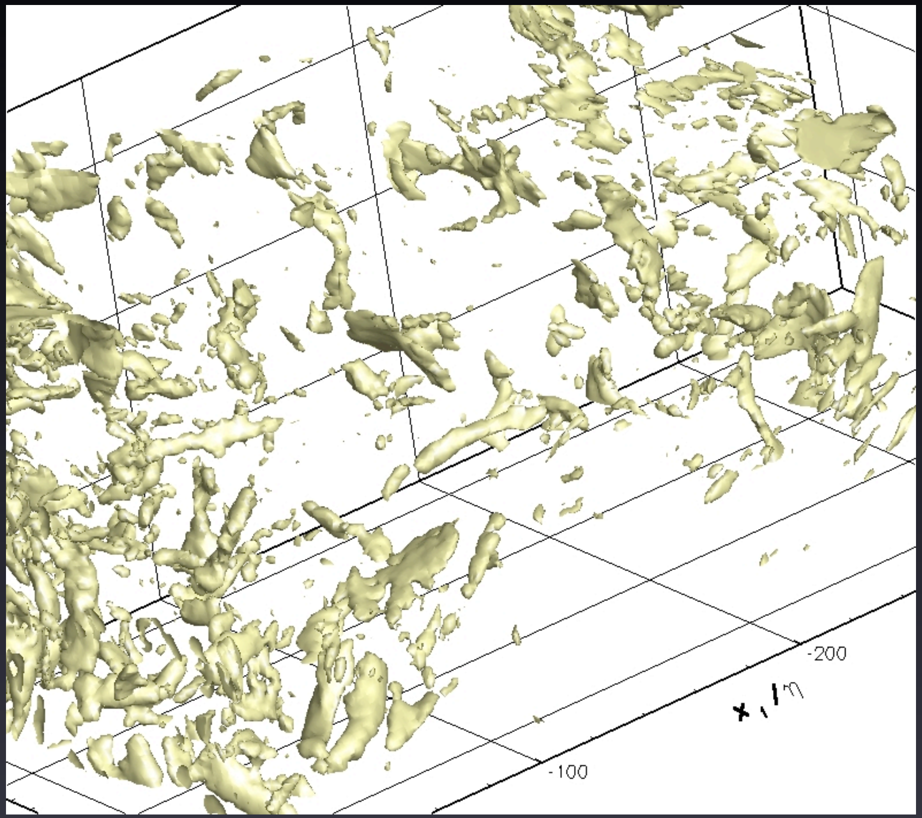
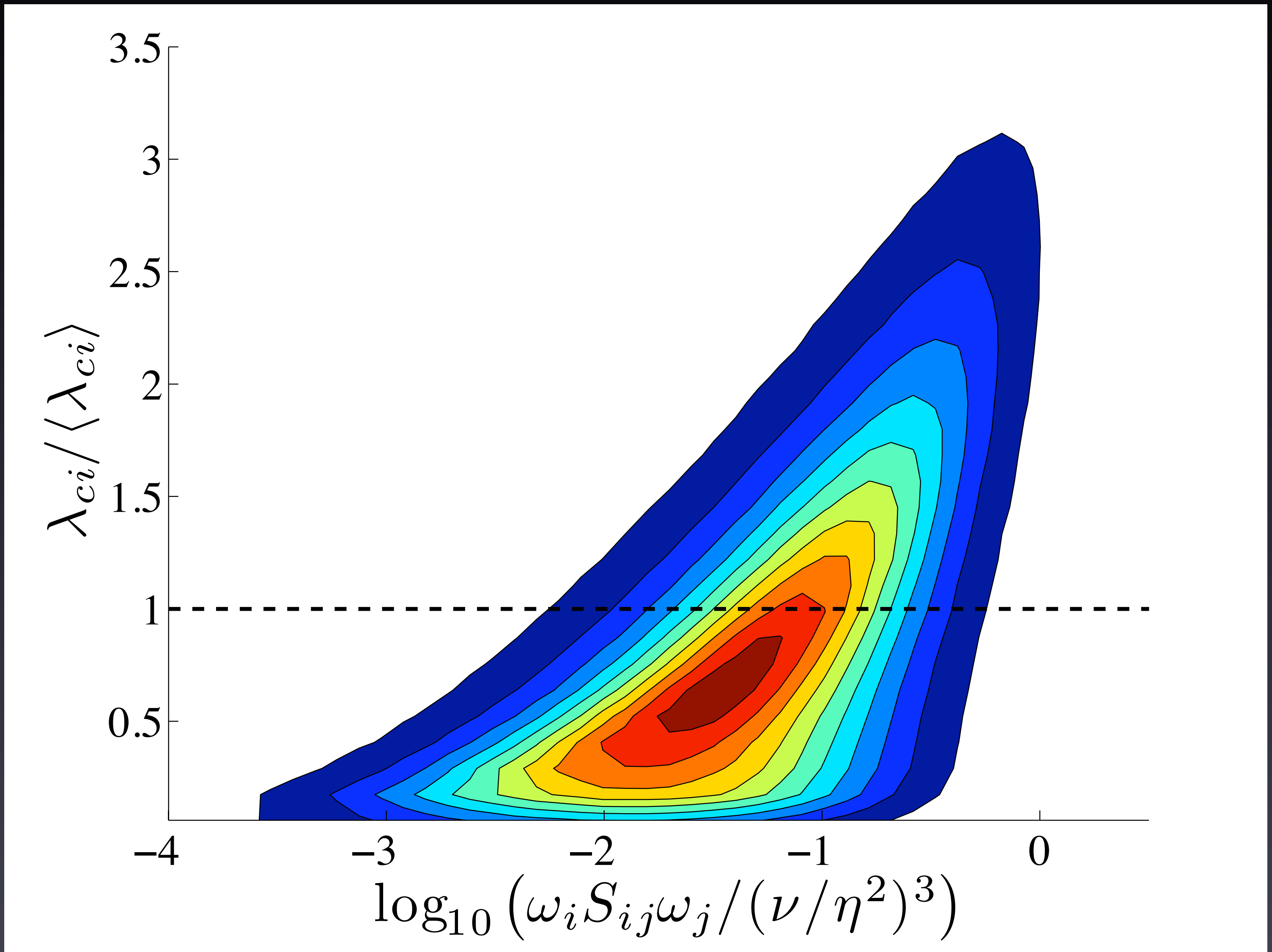
Turbulent axisymmetric jet



$\omega_i S_{ij} \omega_j > 0$



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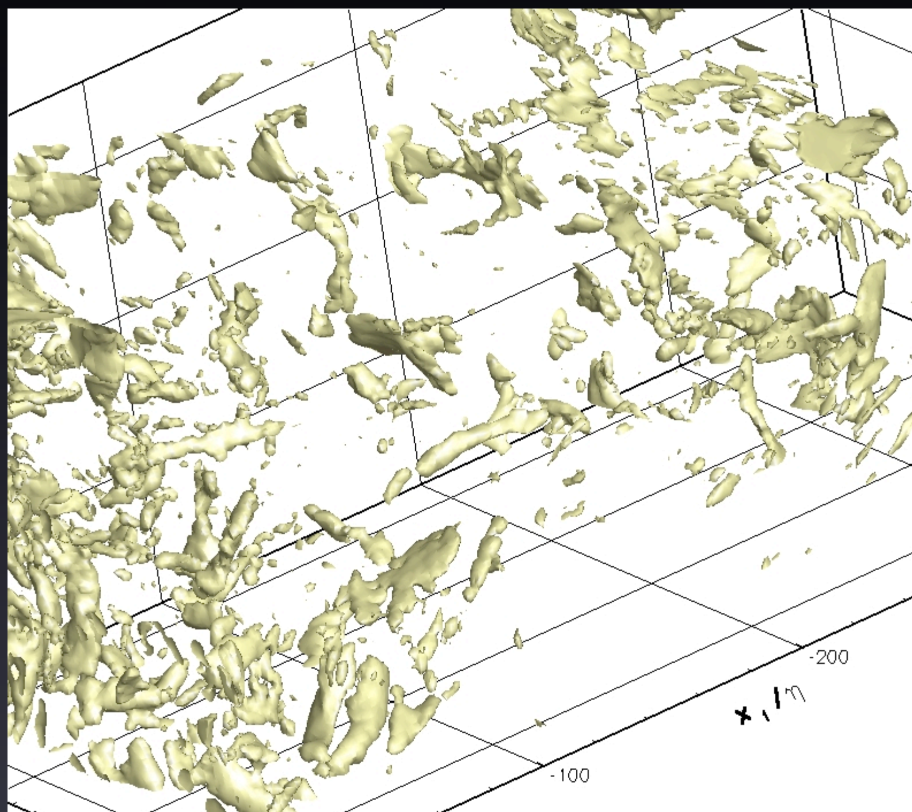
Turbulent axisymmetric jet

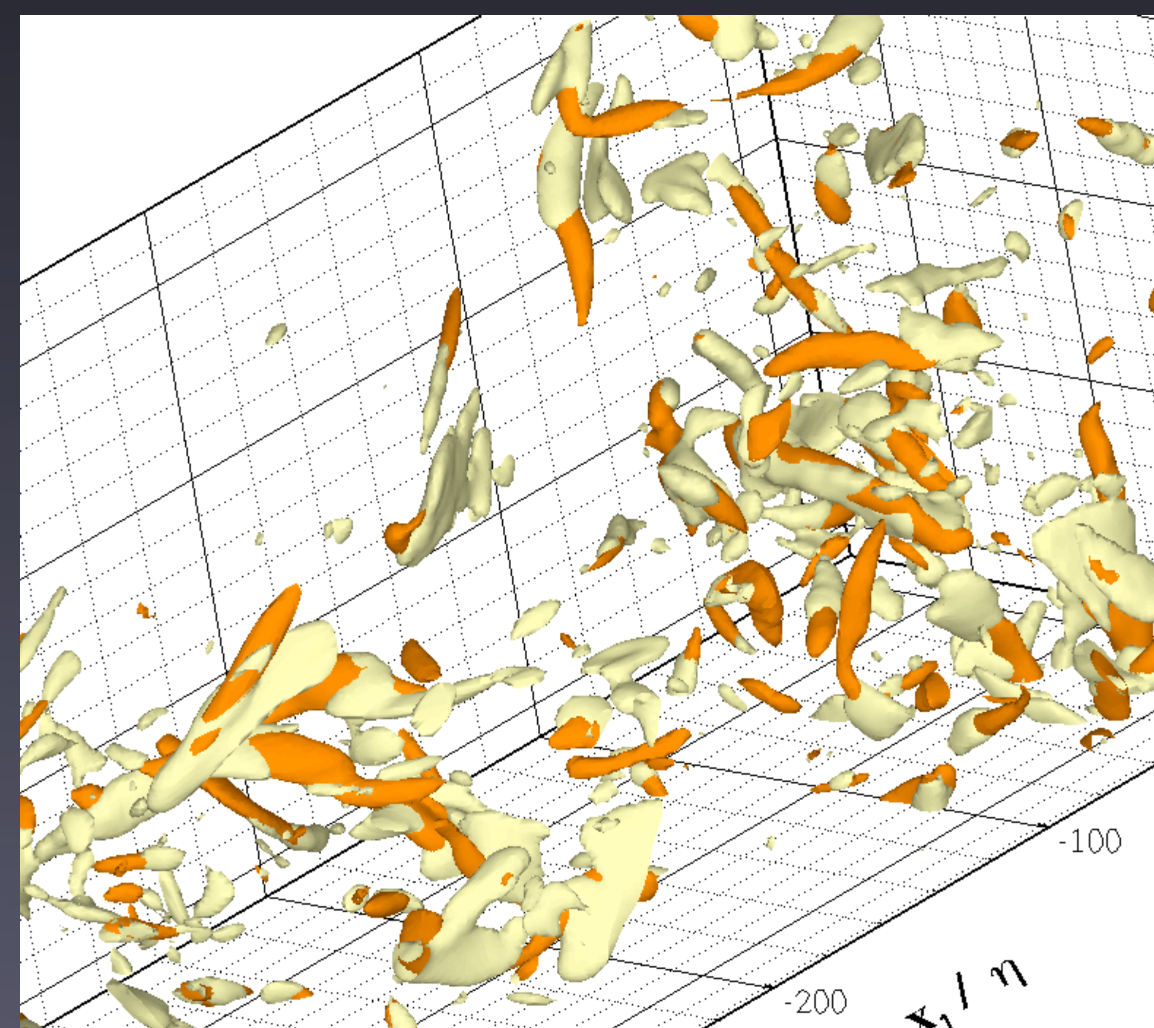


$\omega_i S_{ij} \omega_j > 0$

- Predominantly “sheet-like”
- Strongly rotational regions favour enstrophy production

$$\omega_i S_{ij} \omega_j = 4 \times 10^5 \mathrm{s}^{-3} = 0.96 \left(\nu/\eta^2\right)$$

$$\omega^2 = 75.0 \mathrm{s}^{-1} = 3.55 \langle \omega^2 \rangle$$



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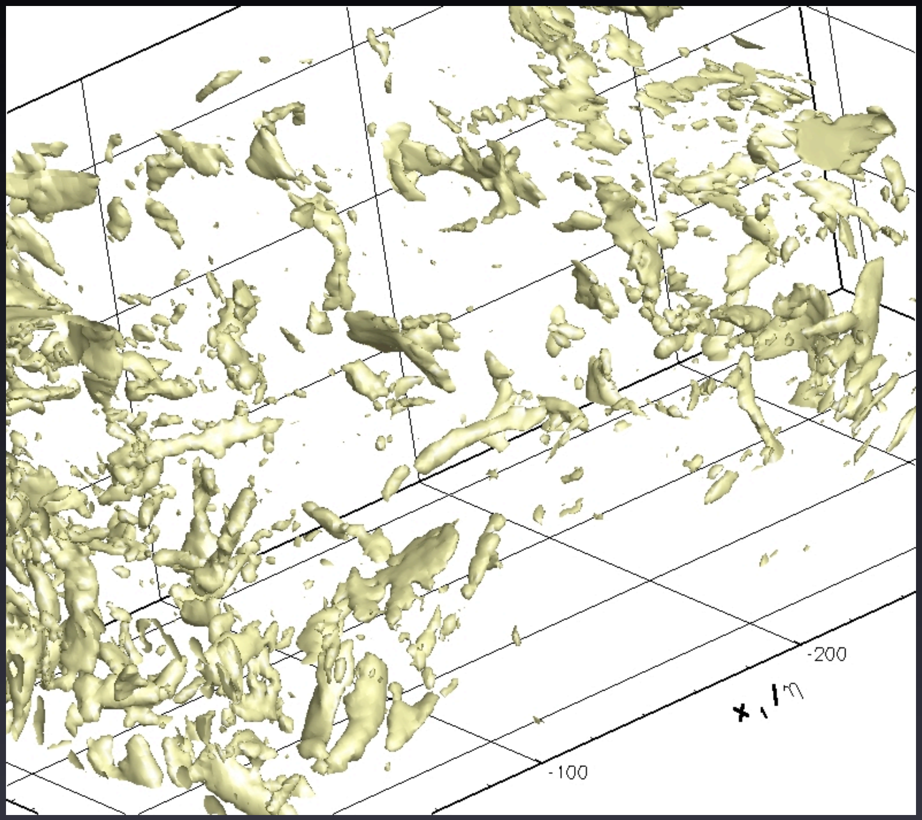
Turbulent axisymmetric jet



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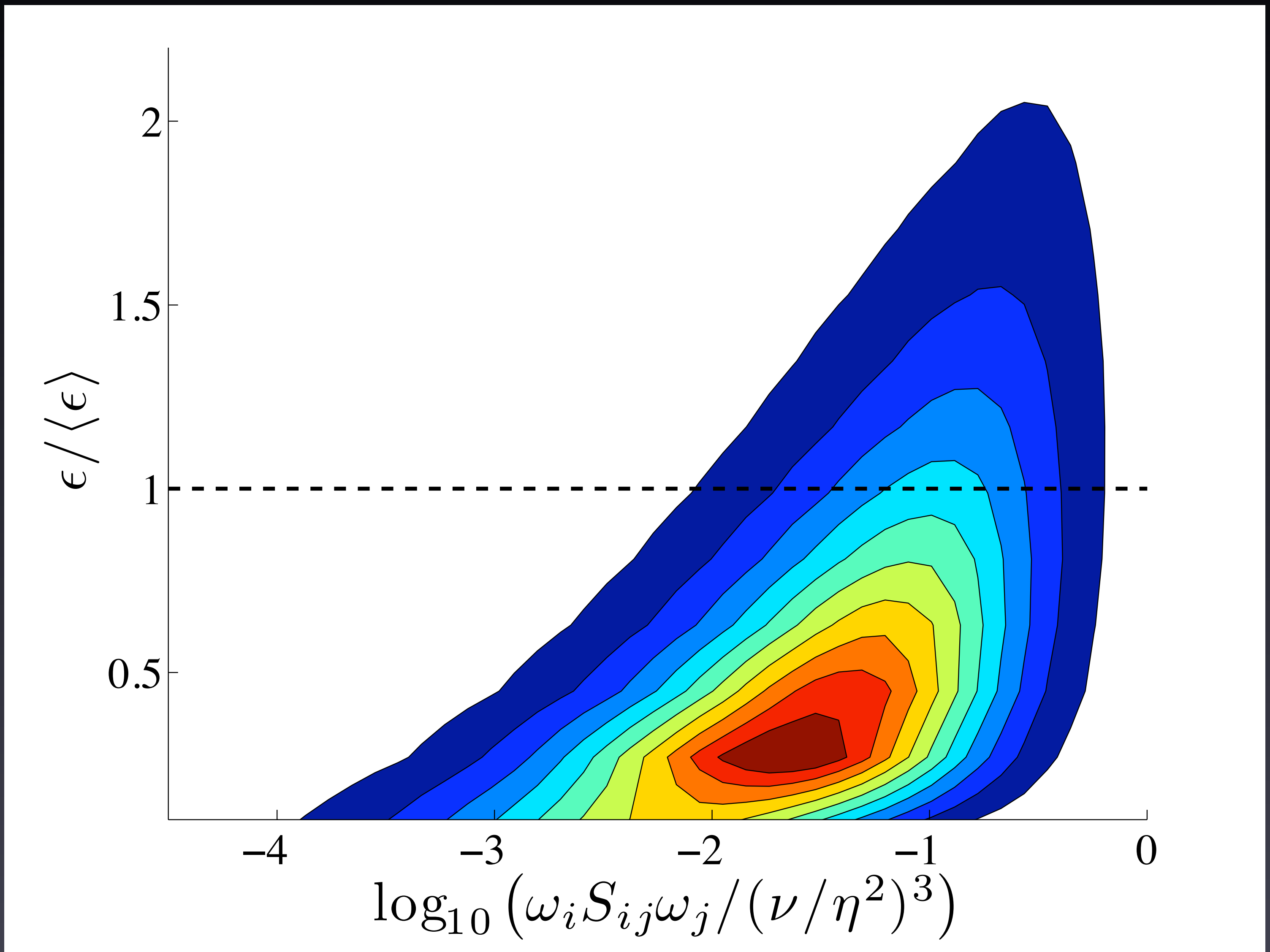

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- Strongly dissipative regions tend to coincide with enstrophy producing regions

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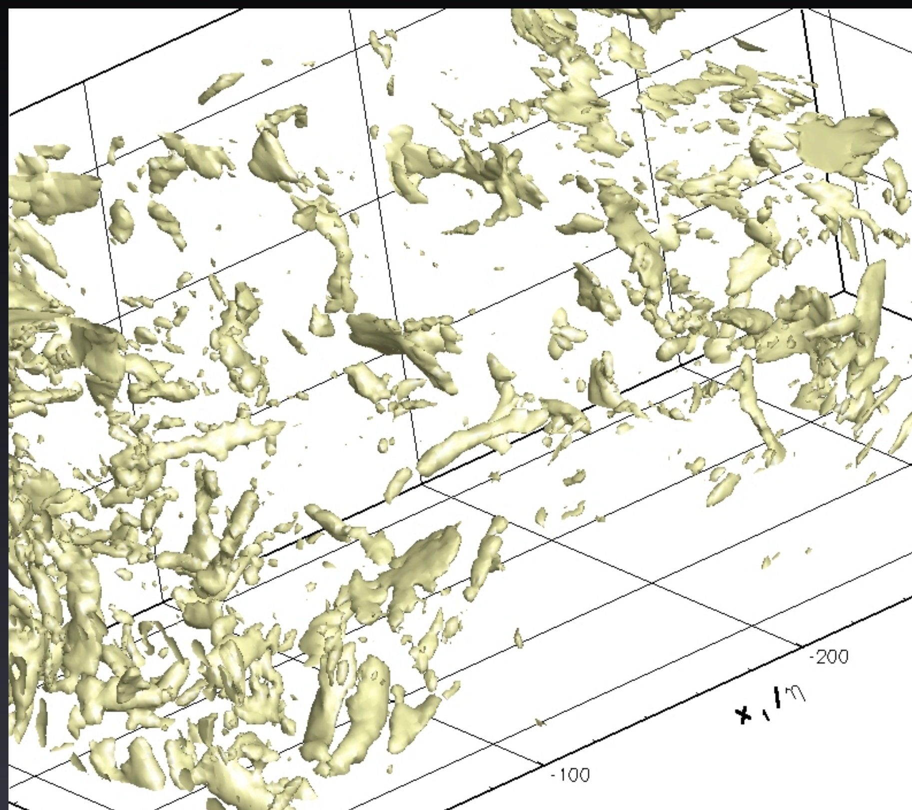

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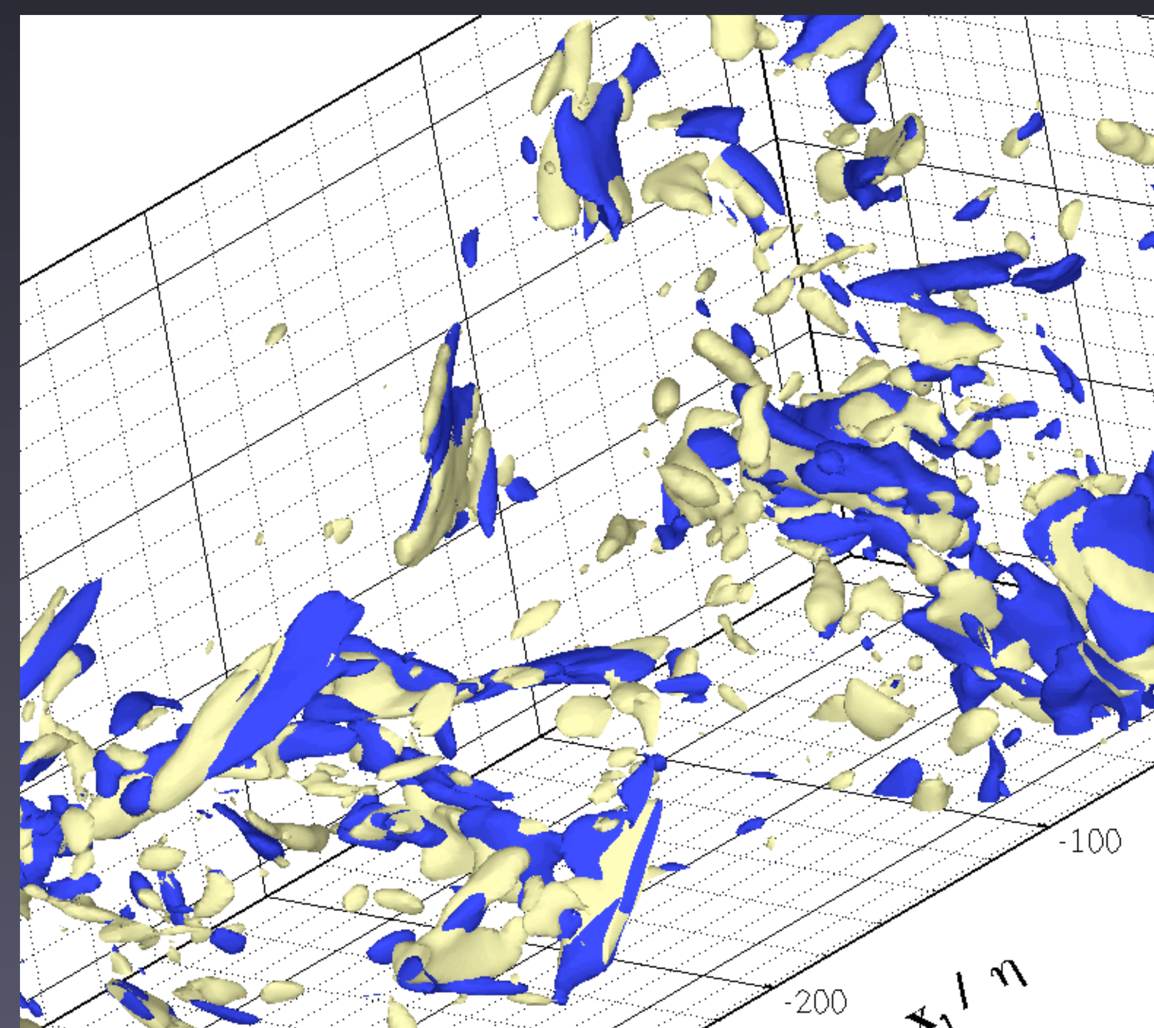
$$\epsilon = 0.24 \mathrm{m}^2 \mathrm{s}^{-3} = 2.86 \langle \epsilon \rangle$$



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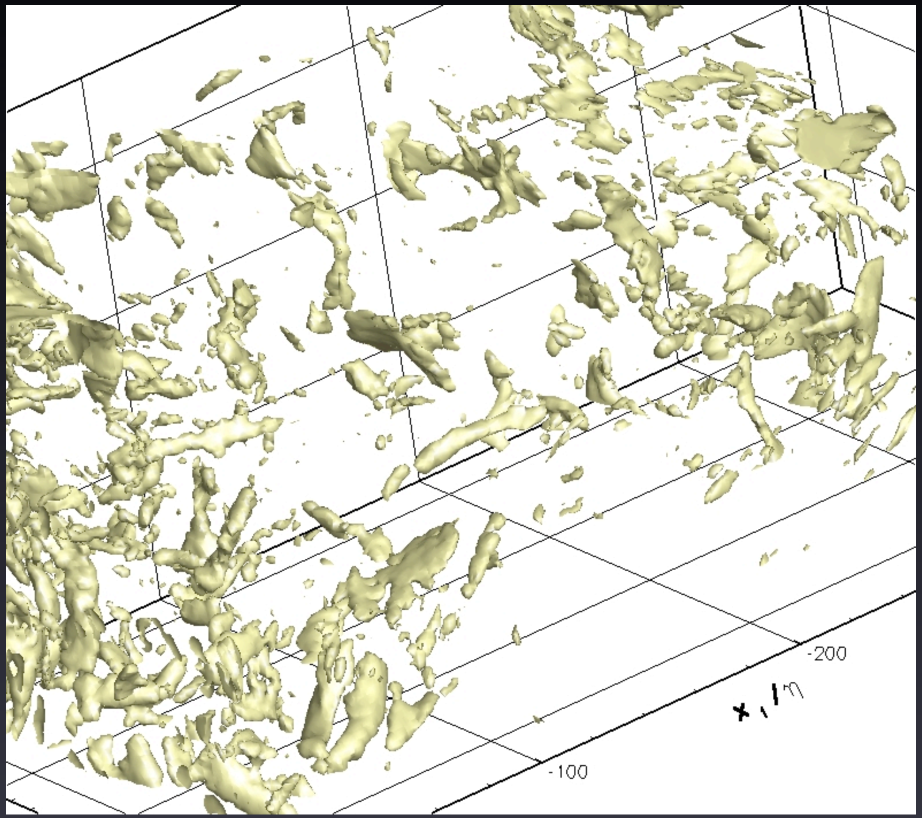

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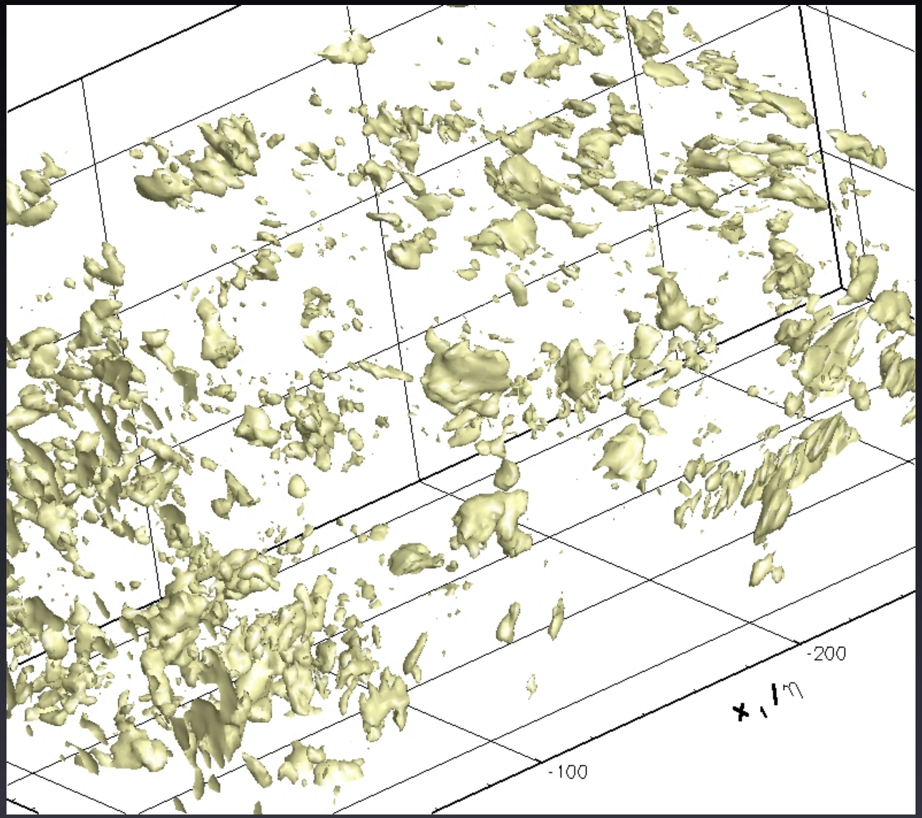

$\omega_i S_{ij} \omega_j < 0$

- Unstructured
- Strongly rotational regions do not favour enstrophy attenuation
- Strongly dissipative regions do not tend to coincide with enstrophy attenuating regions

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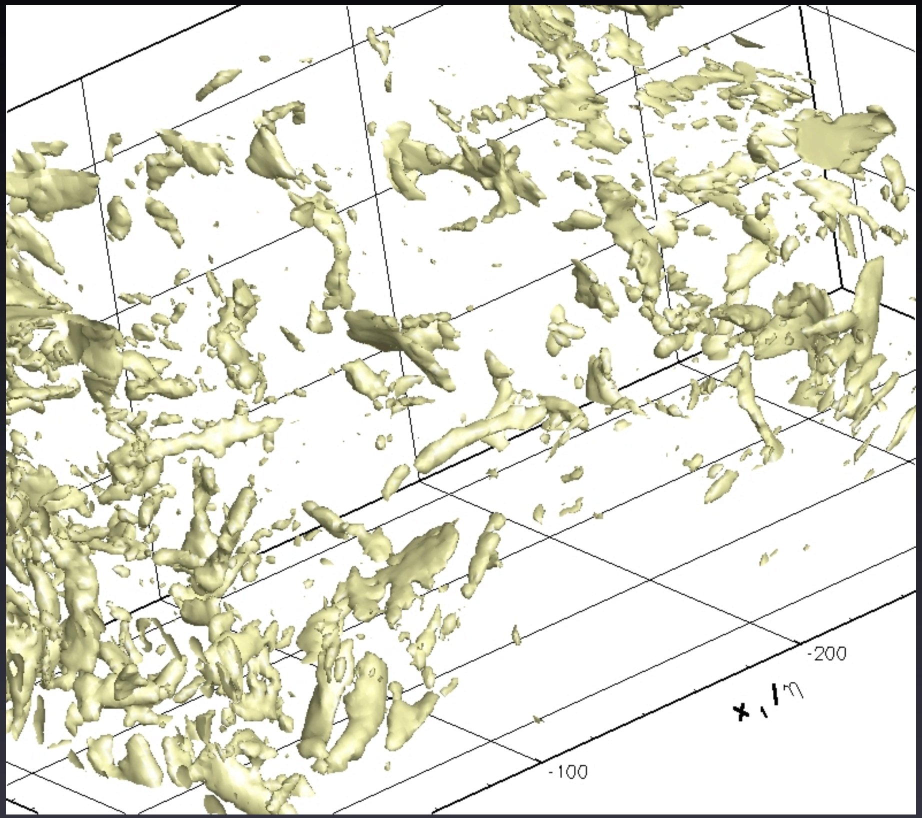
Turbulent axisymmetric jet



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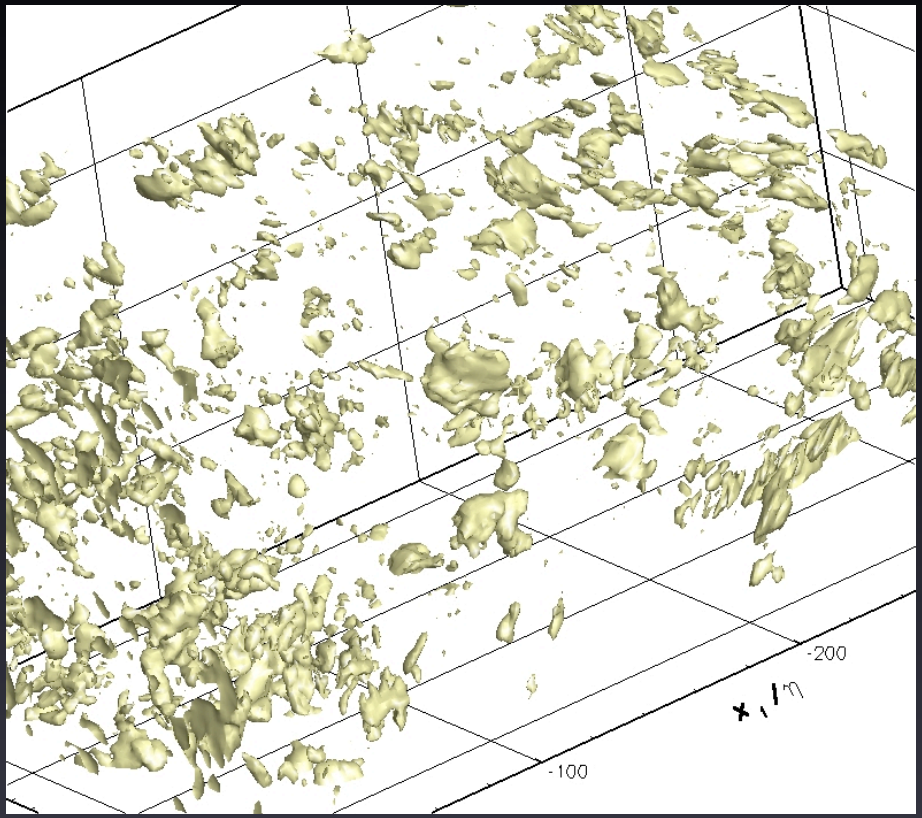

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[BUXTON & GANAPATHISUBRAMANI (2010) *J. Fluid Mech.* ***651*** 483-502]

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Conclusions

- Multi-scale PIV experiment performed in planar mixing layer
  - Asymmetry in fine-scale $pdf\mathrm{s}$ for positive and negative fluctuations
  - Different behaviour for fine-scale $pdf\mathrm{s}$ of positive and negative fluctuations
  - Reynolds number effect?
  - Need to consider power spectral densities for the fine-scales conditioned on large scale fluctuations
  - Are convection velocities scale dependent?

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  - Asymmetry in fine-scale $pdf\mathrm{s}$ for positive and negative fluctuations
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  - Reynolds number effect?
  - Need to consider power spectral densities for the fine-scales conditioned on large scale fluctuations
  - Are convection velocities scale dependent?
- 3D velocity gradient data reveals strain - rotation interaction
  - Interaction directly leads to enstrophy amplification
    - Sustains turbulence in shear flows
  - Look for "universality" of interaction by examining different shear flows

Ongoing / future work

- Volumetric three dimensional velocimetry
  - Fully three dimensional PIV data in a volume
- Dual plane stereoscopic particle image velocimetry
  - Three dimensional velocity and velocity gradient data in a plane
- Direct numerical simulations
  - incompact3d code run on HECToR
- Large eddy simulations
  - streamLES run on HECToR