On Streak Breakdown in Bypass Transition

Philipp Schlatter[a]

Rick de Lange[b], **Luca Brandt**[a], **Dan Henningson**[a]

[a] **Linné Flow Centre,** KTH Mechanics, Sweden
[b] **TU Eindhoven**, The Netherlands

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Outline

- Introduction & Background
  - Laminar-turbulent transition
  - Streaks and bypass transition
- Streak Breakdown in Bypass Transition
  - Streak impulse responses (linear / nonlinear)
  - Two-mode model
  - DNS of bypass transition
  - Turbulent Boundary Layers?
- Conclusions

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Introduction: Transition to Turbulence

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Classical Transition

Low levels of free-stream turbulence (<1%)

→ exponential growth of TS and secondary instability

$E \propto \exp(2|\alpha_i|x)$

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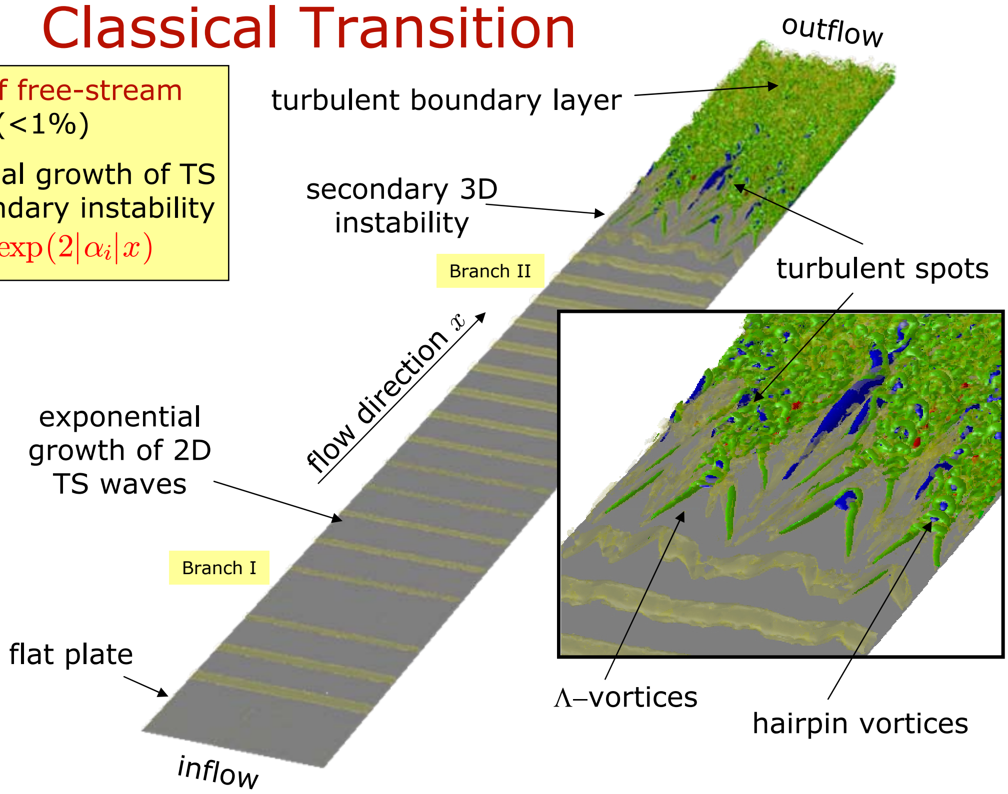

high velocity
low velocity
contours of λ_2

Bypass Transition

High levels of free-stream turbulence (>1%)

→ exponential growth of TS waves is "bypassed"

$E \propto Tu^2 Re_x$

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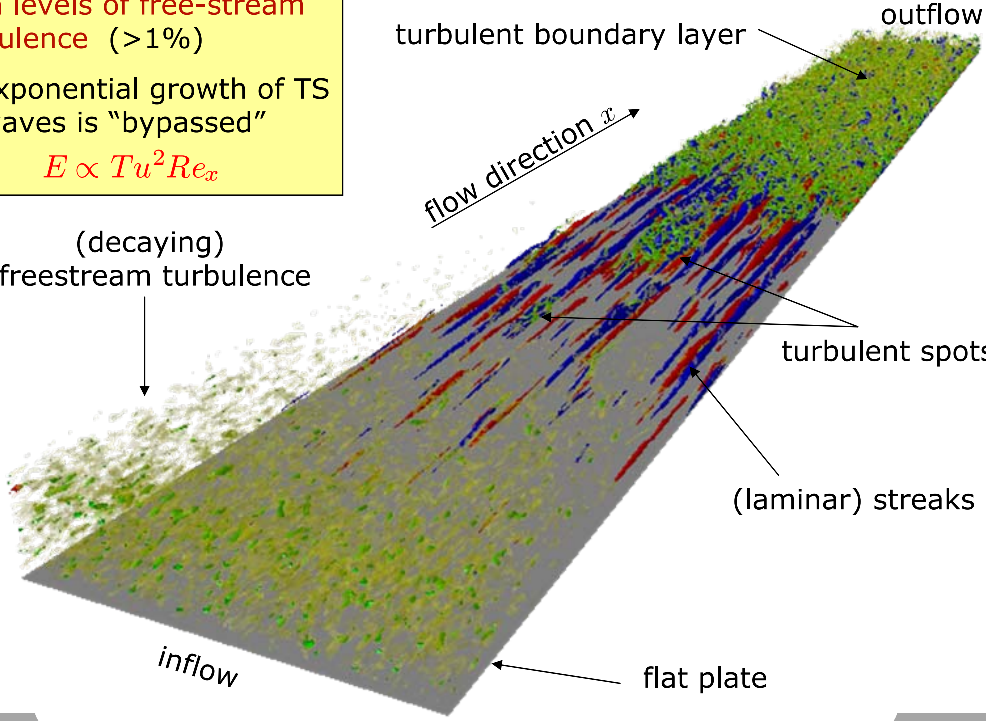

high velocity
low velocity
contours of λ_2

Bypass Transition

- Freestream turbulence induces streaks, which break down to turbulent spots due to secondary instability

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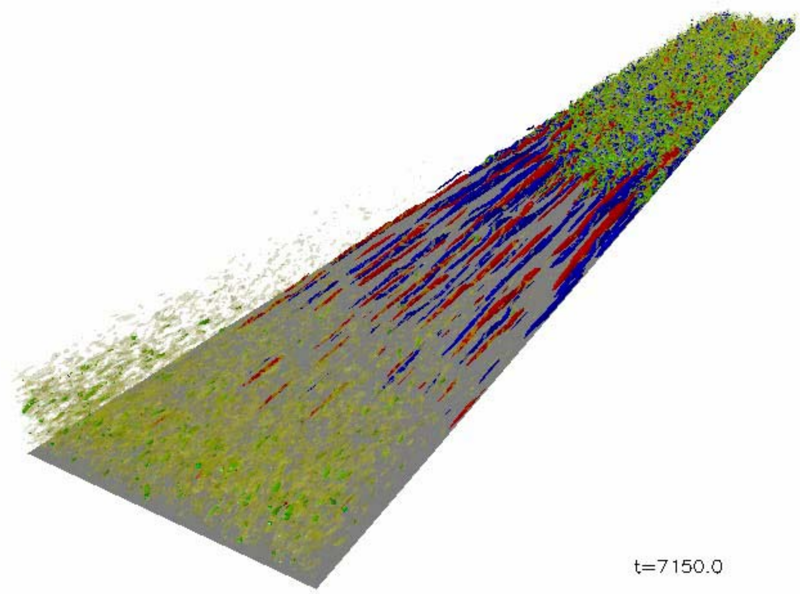


high velocity
low velocity
contours of λ_2

Bypass Transition

moderate to high levels of free-stream turbulence

Matsubara & Alfredsson 2001

Non-modal growth of streaks
↓
Secondary instability of streaks
↓
Turbulent spots
↓
Turbulence

Jacobs & Durbin 2000 Simulations of bypass transition, J. Fluid Mech. 428, 185-212.

Matsubara & Alfredsson 2001 Disturbance growth in boundary layers subject to free-stream turbulence, J. Fluid Mech. 430, 149-168.

Brandt, Schlatter & Henningson 2004 Transition in boundary layers subject to free-stream turbulence, J. Fluid Mech. 517, 167-198.

Durbin & Wu 2007 Transition beneath vortical disturbances, Ann. Rev. Fluid Mech. 39, 107-128.

Mans, de Lange & van Steenhoven 2007 Sinuous breakdown in a flat plate boundary layer exposed to free-stream turbulence, Phys. Fluids 19, 088101.

SIG-33, Genova, October 2008

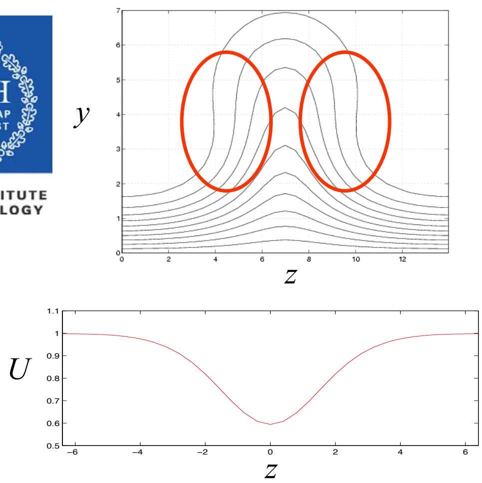
Bypass Transition: Secondary Instability

Antisymmetric sinuous instability:

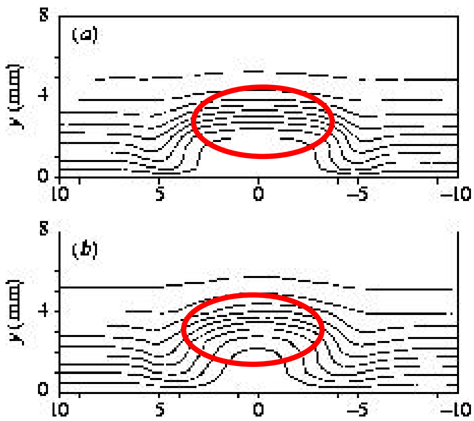
Driven by the streak spanwise shear

Symmetric varicose instability:

Driven by the streak wall-normal shear

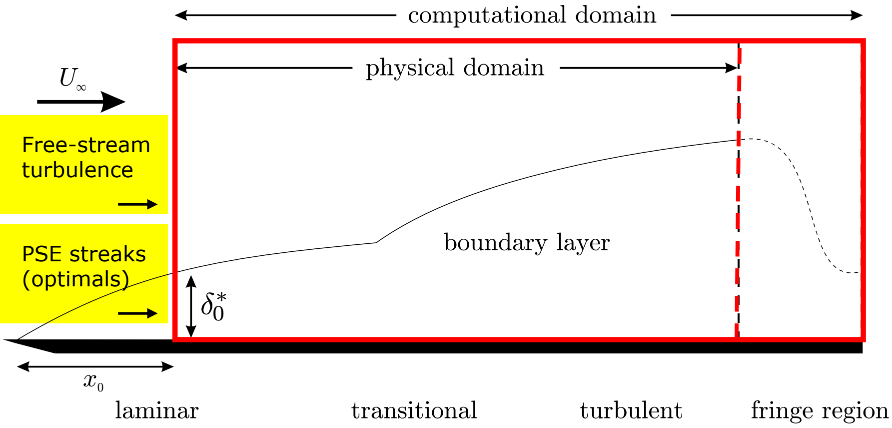


Andersson et al., *JFM* (2001)



Asai, Minagawa & Nishioka, *JFM* (2002)

Numerical Setup



- Fully spectral method: Fourier/Chebyshev tau method
- Periodic boundary condition in the wall-parallel directions, no-slip at lower wall, Neumann conditions at upper boundary.
- Fringe region (volume force) to enforce laminar Blasius inflow condition with superimposed free-stream turbulence / streaks
- Code SIMSON parallelised using MPI (Chevalier *et al.* 2007)

On Streak Breakdown in Bypass Transition

Schlatter, Brandt, de Lange & Henningson, Phys. Fluids 2008

Streak Breakdown

- Eindhoven experiments and KTH simulations show both sinuous and varicose breakdown
- Is this secondary instability of streaks?

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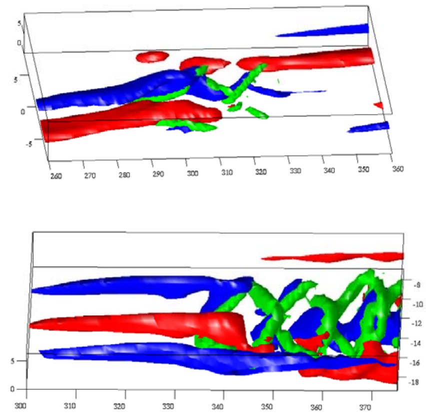
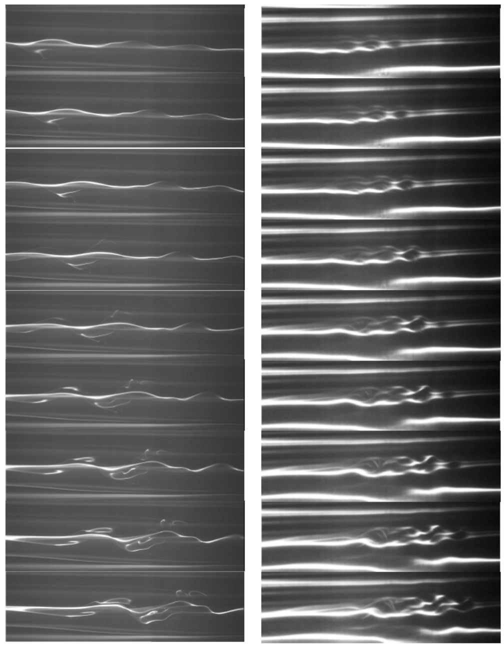


Brandt, Schlatter & Henningson 2004



Mans, de Lange & van Steenhoven 2007

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Nonlinear saturated streaks

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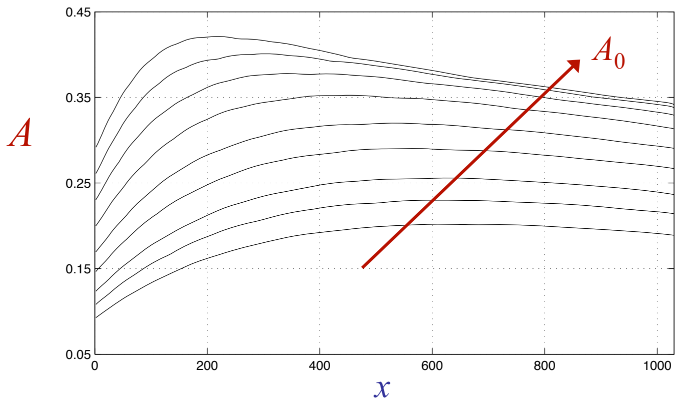


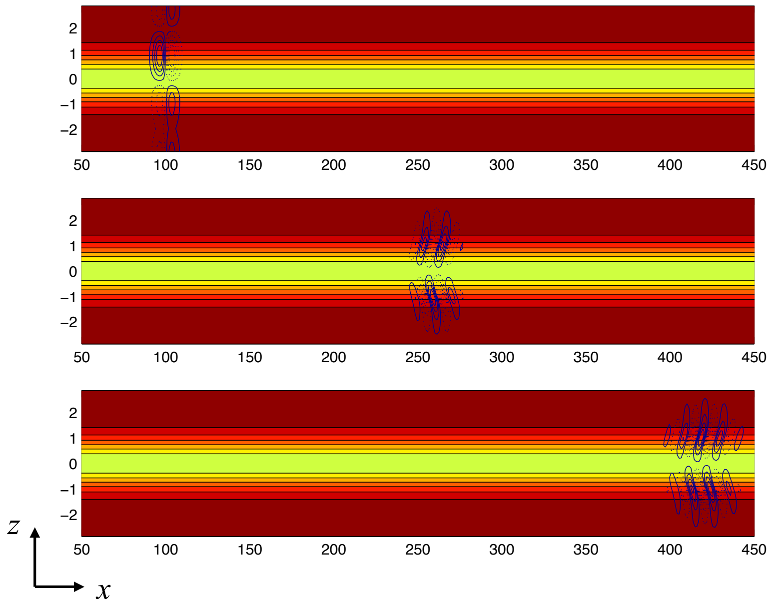
$$A(x) = \frac{1}{2}\left[\max_{y,z}(U - U_B) - \min_{y,z}(U - U_B)\right]$$

Optimal perturbations used as inflow conditions with different initial amplitudes A_0 in DNS

Brandt & Henningson 2002

Impulse response using DNS on frozen streak

Fundamental modes: A=0.36, X=630.



Brandt, Cossu, Chomaz, Huerre & Henningson 2003

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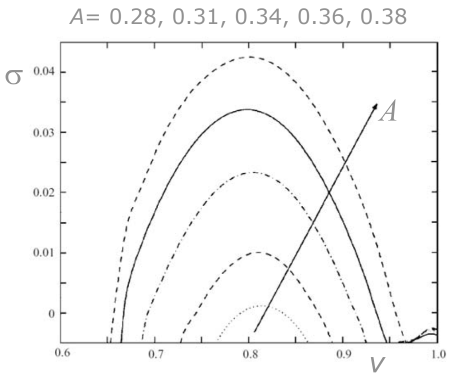
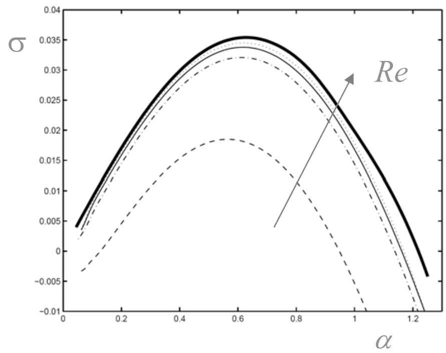
Streak impulse response

Temporal growth rate σ traveling at velocity v





- Streak instability is convective!
- Group velocity ≈ 0.8
- Growth rate approaches invicid limit as Re increases

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Secondary instability structures

- Non-linear development of impulse response on spatially evolving streak
- Vortex structures at breakdown similar to breakdown under FST

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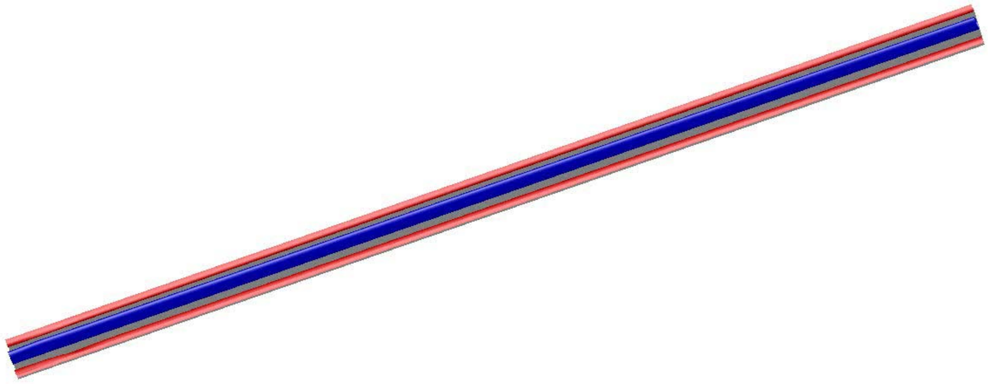

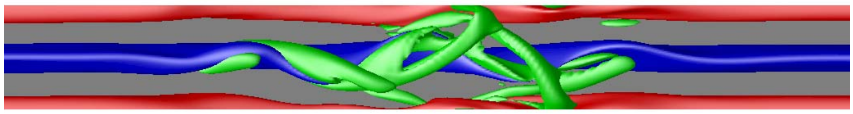

high velocity
low velocity
contours of λ_2

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Comparison of impulse and bypass structure

- Oscillations of low speed streaks in non-linear impulse strikingly similar to spot precursors in bypass transition
- Streak breakdown caused by secondary instability

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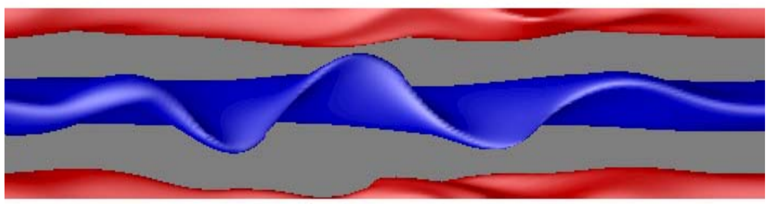

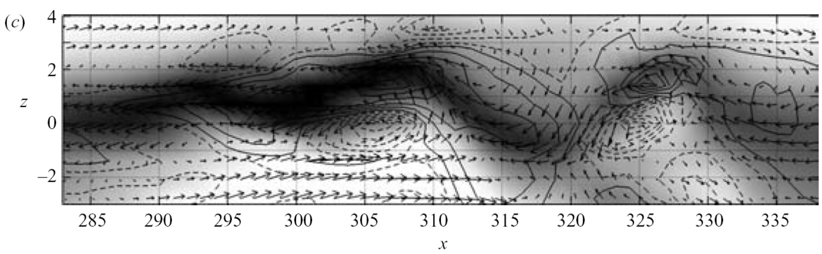

(DNS of Bypass Transition)

Two-Mode Model (Zaki&Durbin)

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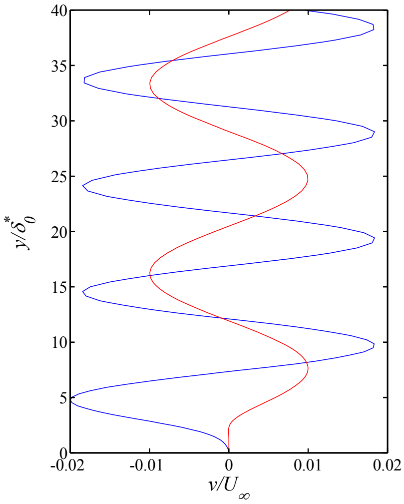
- Simple model of bypass transition starting with interacting continuous spectrum modes
- Low-frequency penetrating mode & high-freq. non-penetrating mode (streak + secondary instability)
- Initial conditions with $v_{\rm rms}$ 2%

$$u_{in} = U_B + u_1 e^{i(\pm\beta_1 z - \omega_1 t)} + u_2 e^{i(\pm\beta_2 z - \omega_2 t + \phi)}$$

Ref.: Zaki & Durbin, JFM 2005



Two-Mode Model

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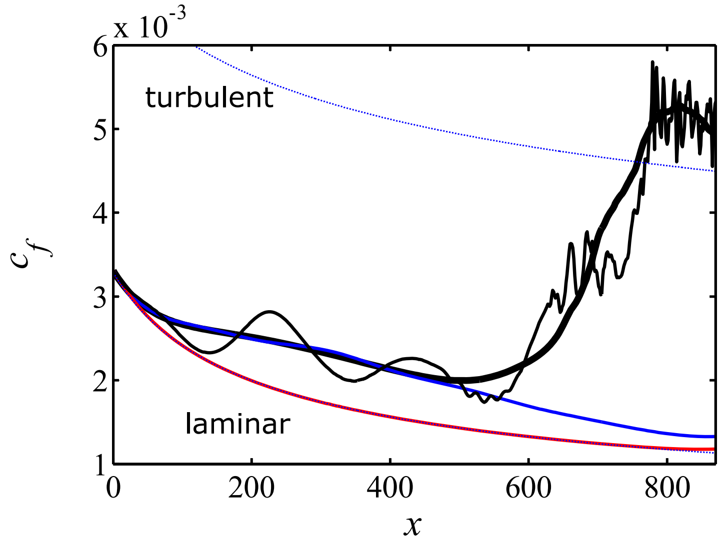


Transition only if two modes are present!

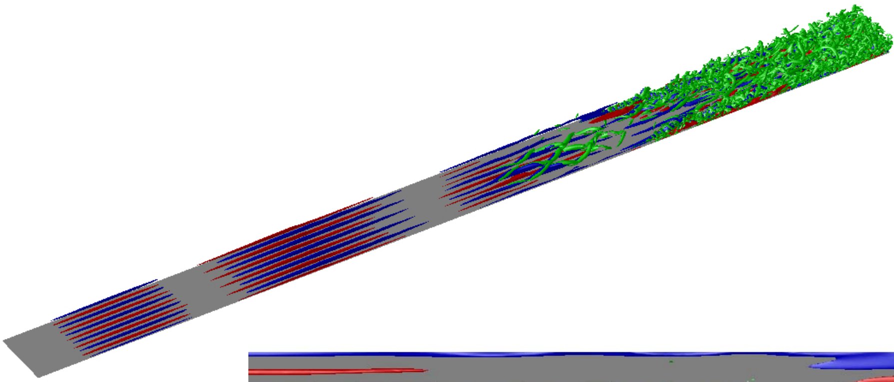
non-penetrating — two modes

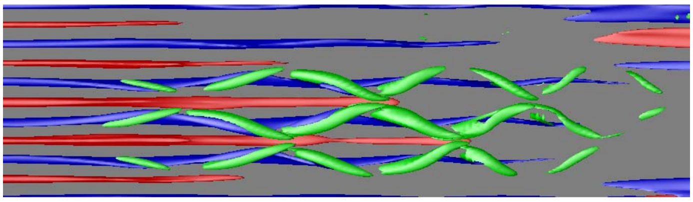
penetrating — (instantaneous)

Ref.: Zaki & Durbin, JFM 2005

Breakdown in model simulation

- 3D structures show subharmonic sinuous breakdown
- Vortical structures above oscillating low-speed streak





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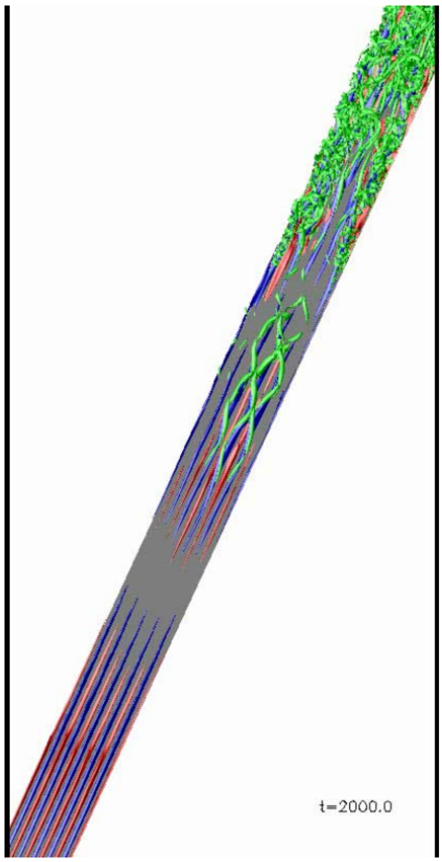
Breakdown in model simulation



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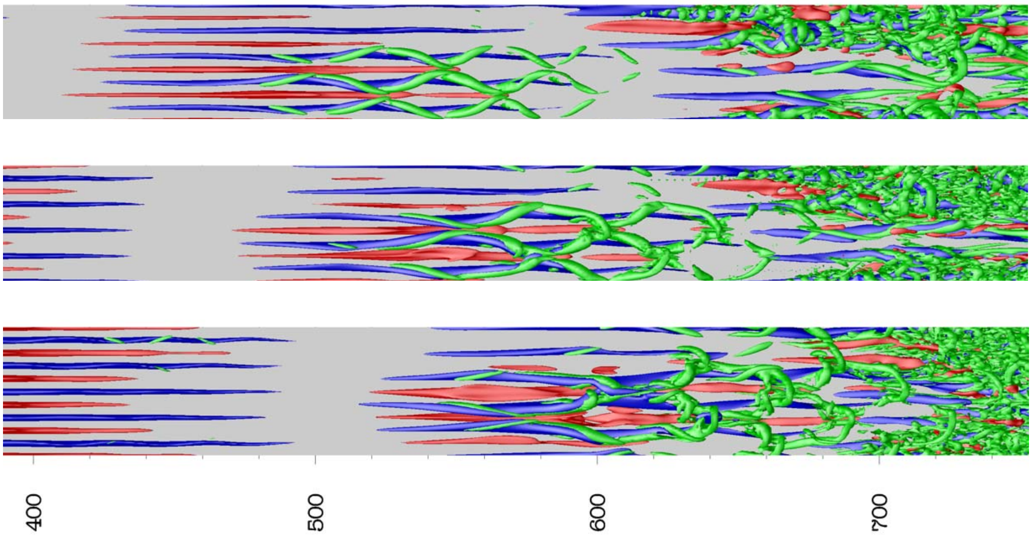
high velocity
low velocity
contours of λ_2

Breakdown in model simulation

- Top view of flow structure at three time instants



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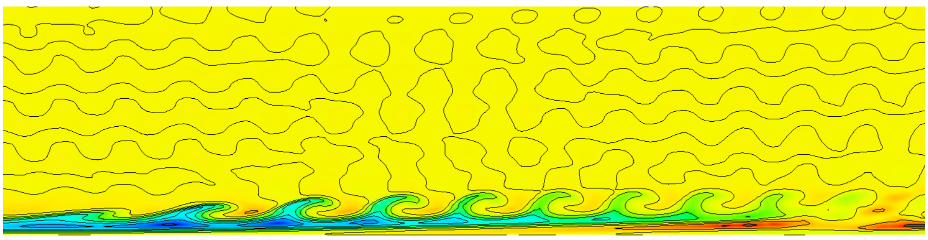
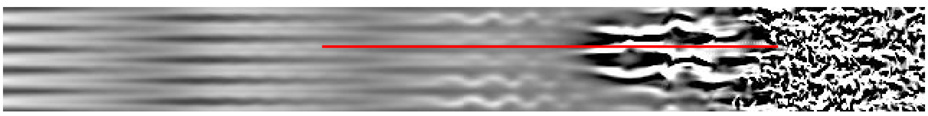
2D cut of breakdown in model

- 2D cut resembles Kelvin-Helmholtz instability
- Claimed by Durbin & Wu to be responsible for breakdown in recent Annu. Rev. Fluid Mech. (2007)
- Sinuous oscillations claimed to be artifact of plotting





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DNS Structures

- DNS of bypass transition
  (re-run of simulation by
  Brandt, Schlatter & Henningson, 2004)

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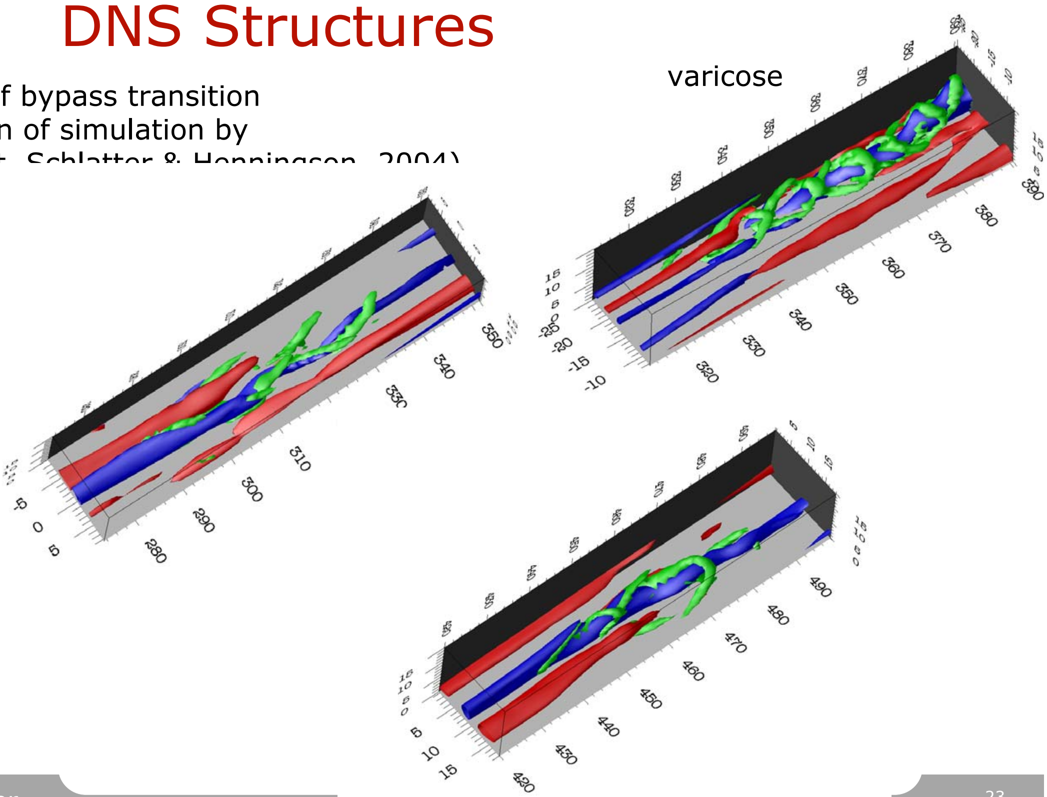

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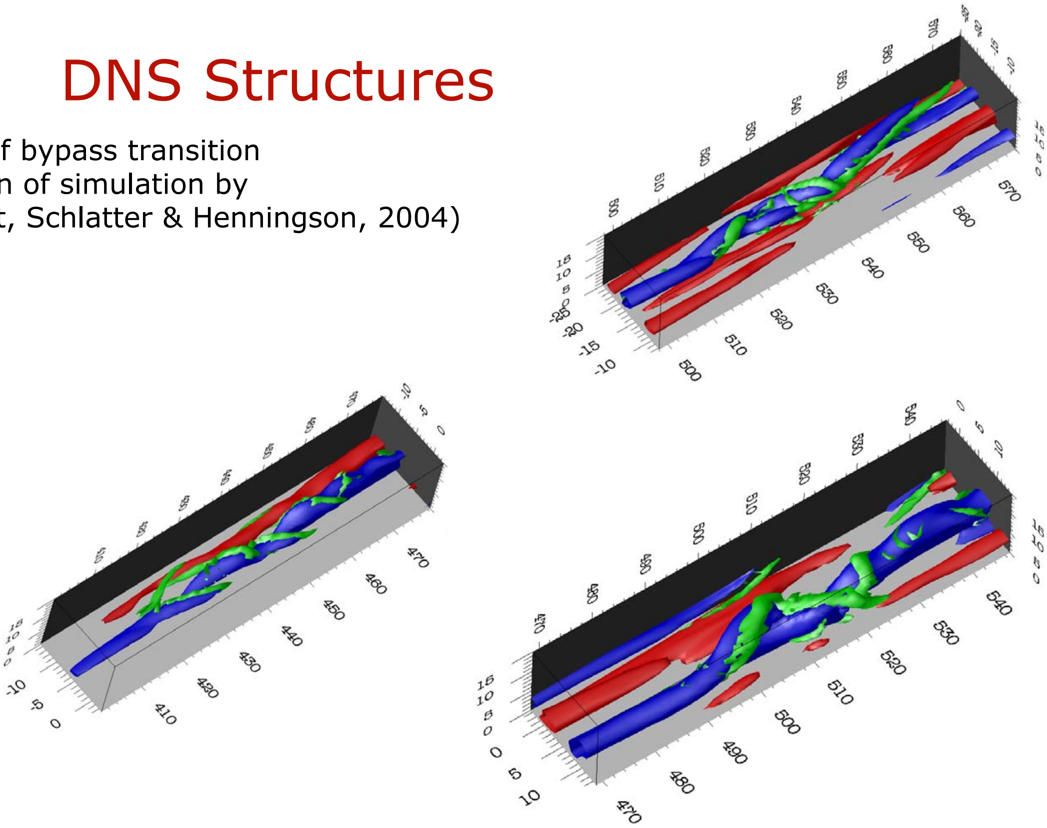
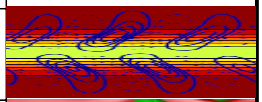
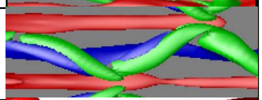
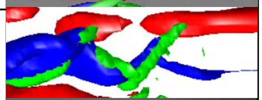
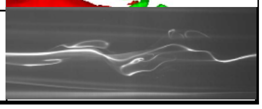


Comparison of secondary instability characteristics

Sinuous instability	*Wavelength* [δ^*]	*Growthrate* [U_∞/δ^*]	*Propagation velocity* [U_∞]	*Visualization*
Inviscid instability	10.4	0.035		
Linear impulse response	10.4	0.032	0.65 –0.8– 0.95	
Non-linear impulse	11	0.025	0.55 –0.8– 0.95	
Zaki-Durbin model	20		0.55 –0.85– 0.95	
KTH simulations	7 - 11		0.85	
TU/e experiments	9 - 16	0.01	0.8	

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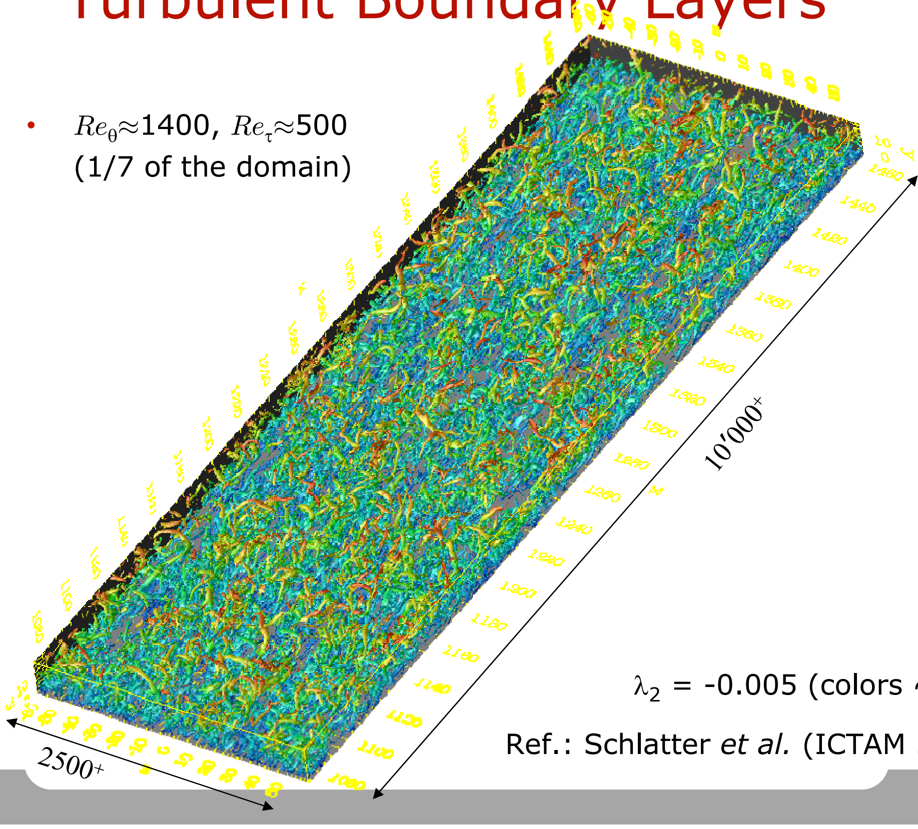
Turbulent Boundary Layers

- $Re_\theta \approx 1400$, $Re_\tau \approx 500$ (1/7 of the domain)



λ_2 = -0.005 (colors ~y)

Ref.: Schlatter *et al.* (ICTAM 2008)

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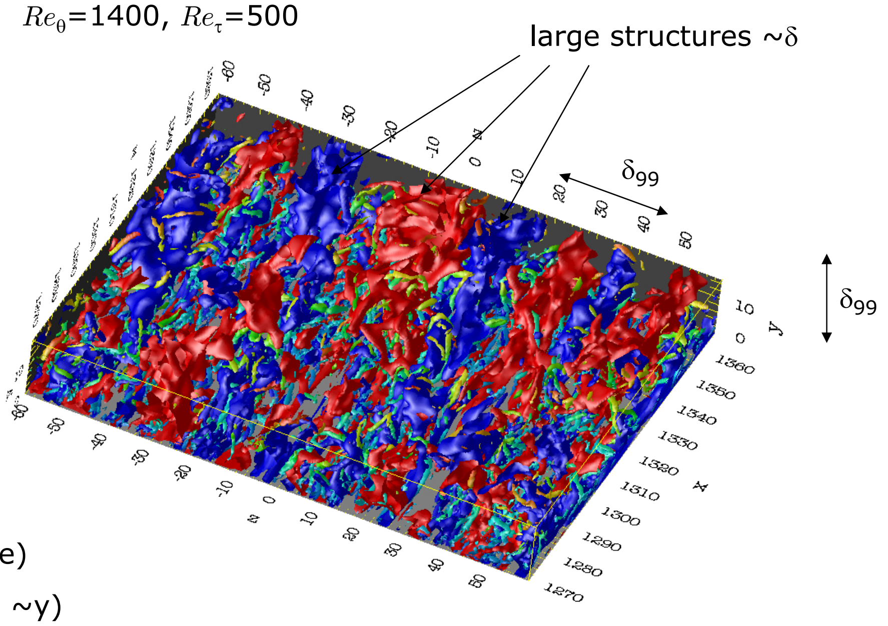
Turbulent Boundary Layer

- Re_θ=1400, Re_τ=500



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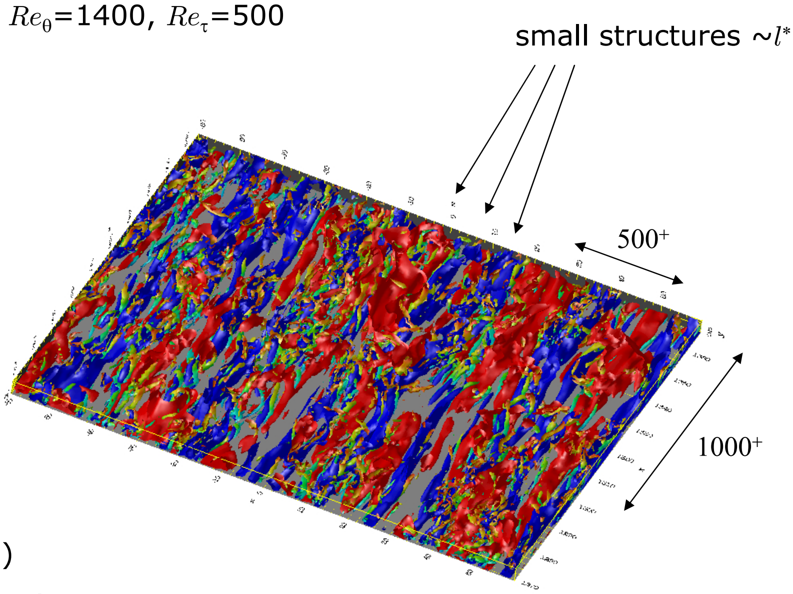
u'=± 0.1 (red/blue)

λ_2 = -0.01 (colors ~y)

Turbulent Boundary Layer

- Re_θ=1400, Re_τ=500



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u'=± 0.1 (red/blue)

λ_2 = -0.01 (colors ~y)

Turbulent Boundary Layer

- Re_θ=1400, Re_τ=500

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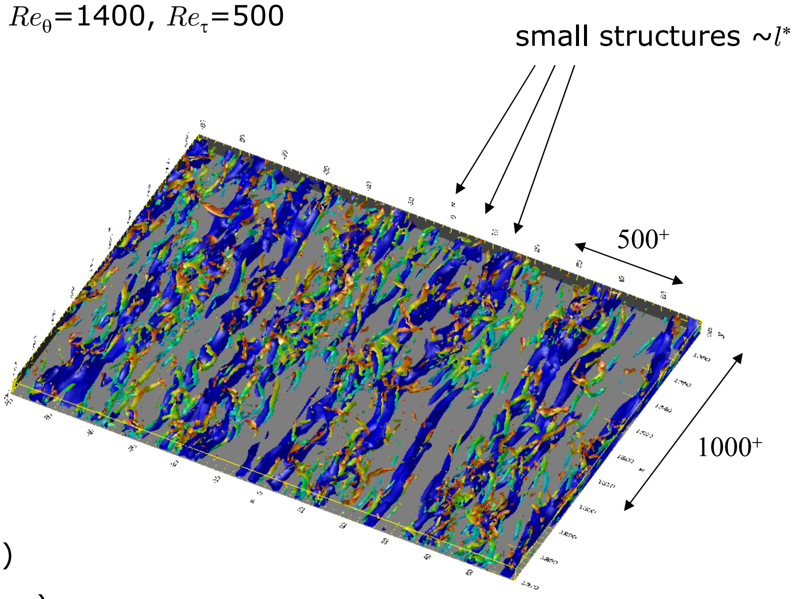

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Turbulent Boundary Layer

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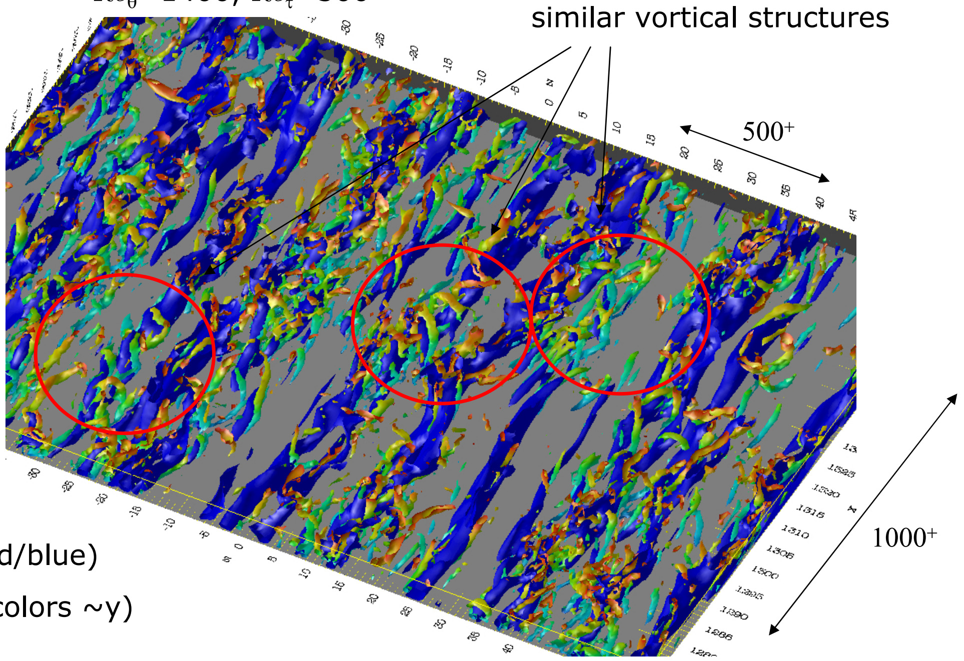

u'=± 0.1 (red/blue)

λ_2 = -0.01 (colors ~y)

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Conclusions

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Conclusions

Streak Breakdown in Bypass Transition:

- ***Sinuous breakdown*** in bypass transition is caused by secondary instability of streaks
- Characteristics of breakdown similar in experiments and simulations of full bypass transition, impulse response and two-mode model
- 2D cuts of 3D simulations could mistakenly be interpreted as evidence of Kelvin-Helmholtz instability

- ***Varicose breakdown*** could be explained by streak interaction (However, sinuous is more common)
- Instability of 3D shear layers formed between the two streaks.
- Significant lower amplitudes at breakdown

→ Connection to turbulent wall flows?

Thank you!