Laminar-Turbulent Boundary-Layer Transition on a Flared Cone at Mach 6

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This work was supported by AFOSR Grant FA9550-15-1-0265 monitored by Dr. Ivett Leyva. Computer time was provided by the US Army Engineering Research and Development Center (ERDC) under the Department of Defense (DOD) High Performance Computing Modernization Program (HPCMP)

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How crazy do things get when you go really fast?

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Outline

Introduction

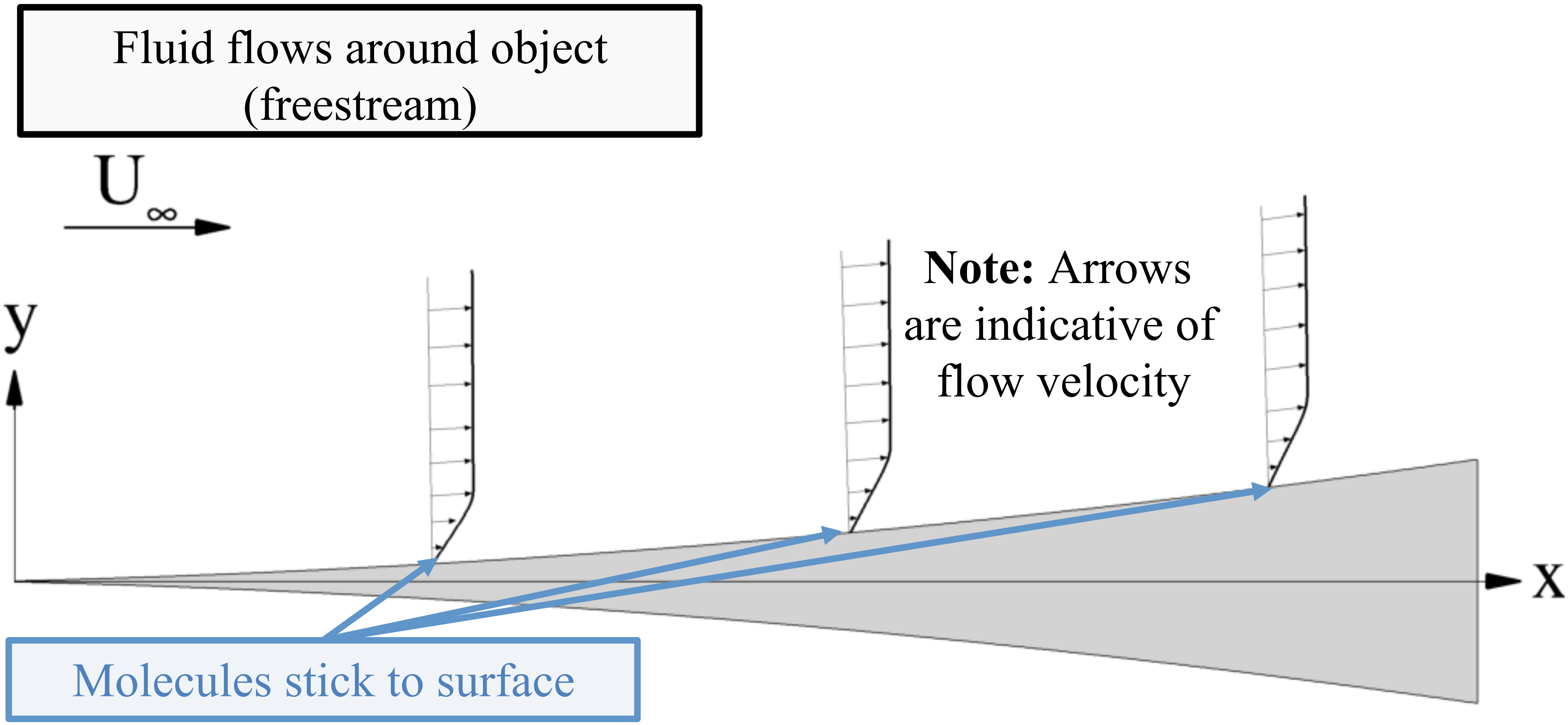
Geometry, Conditions and Simulation Strategy

Primary Wave

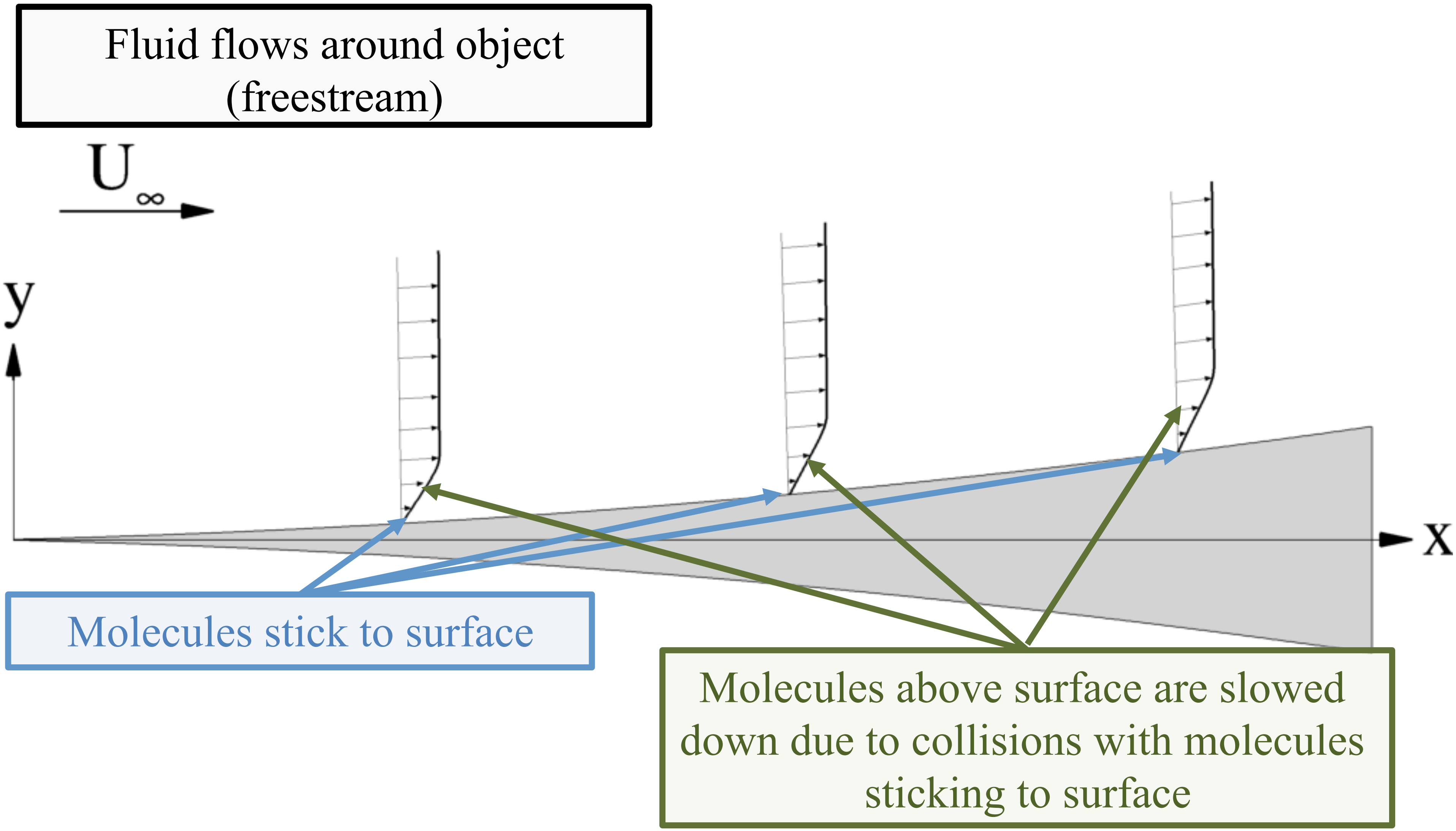
Secondary Instability

Fundamental Breakdown

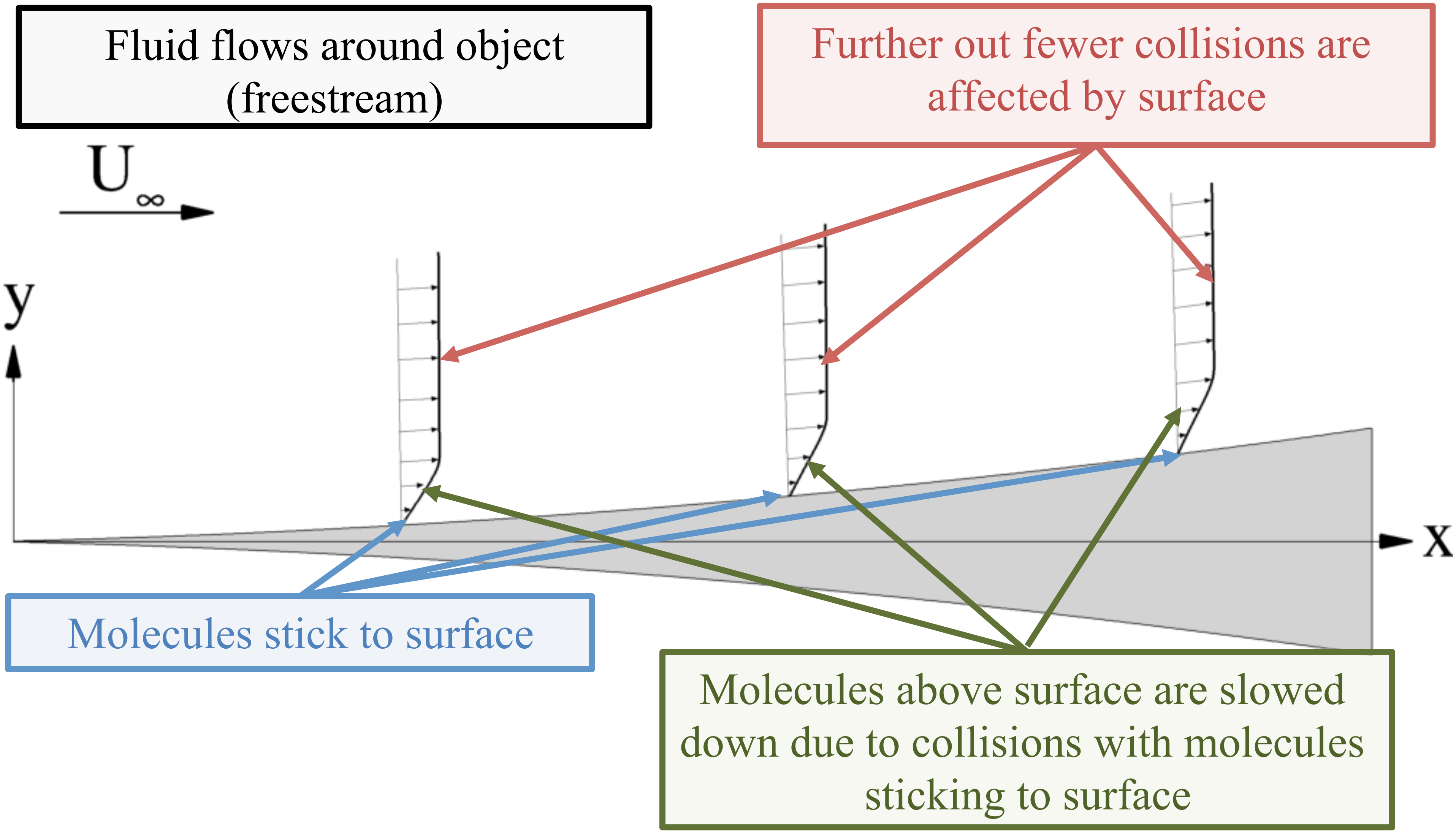
Boundary layer concept



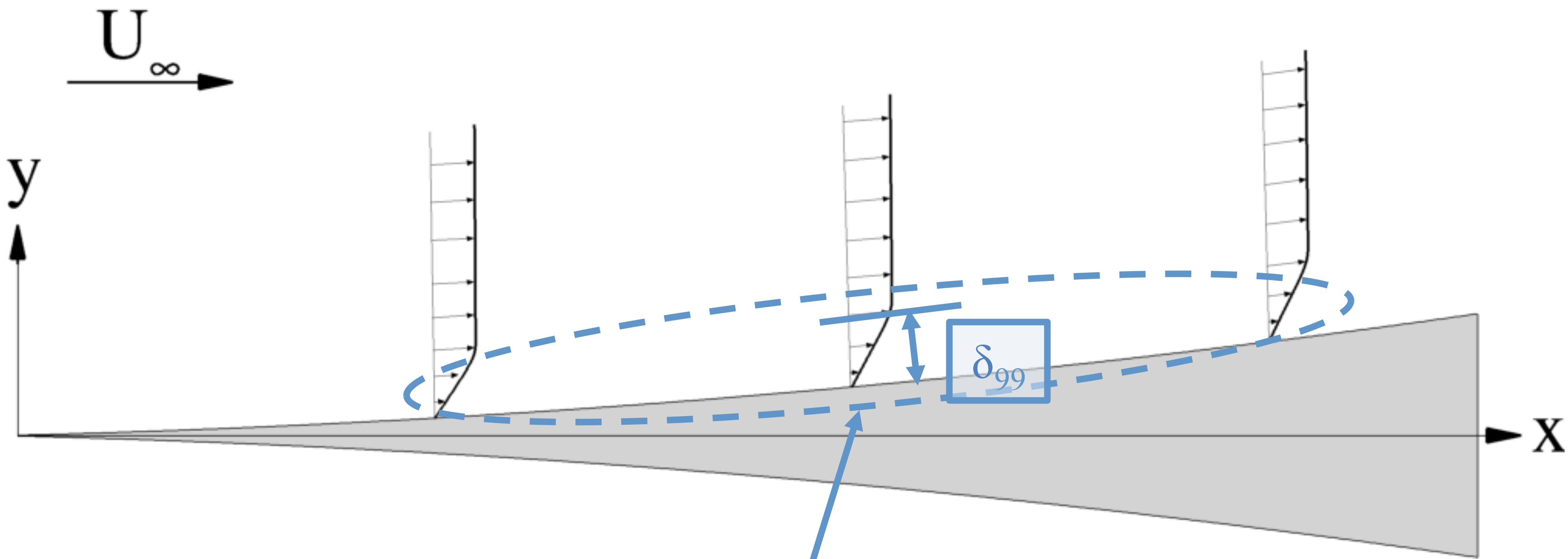
Boundary layer concept



Boundary layer concept



Boundary layer concept

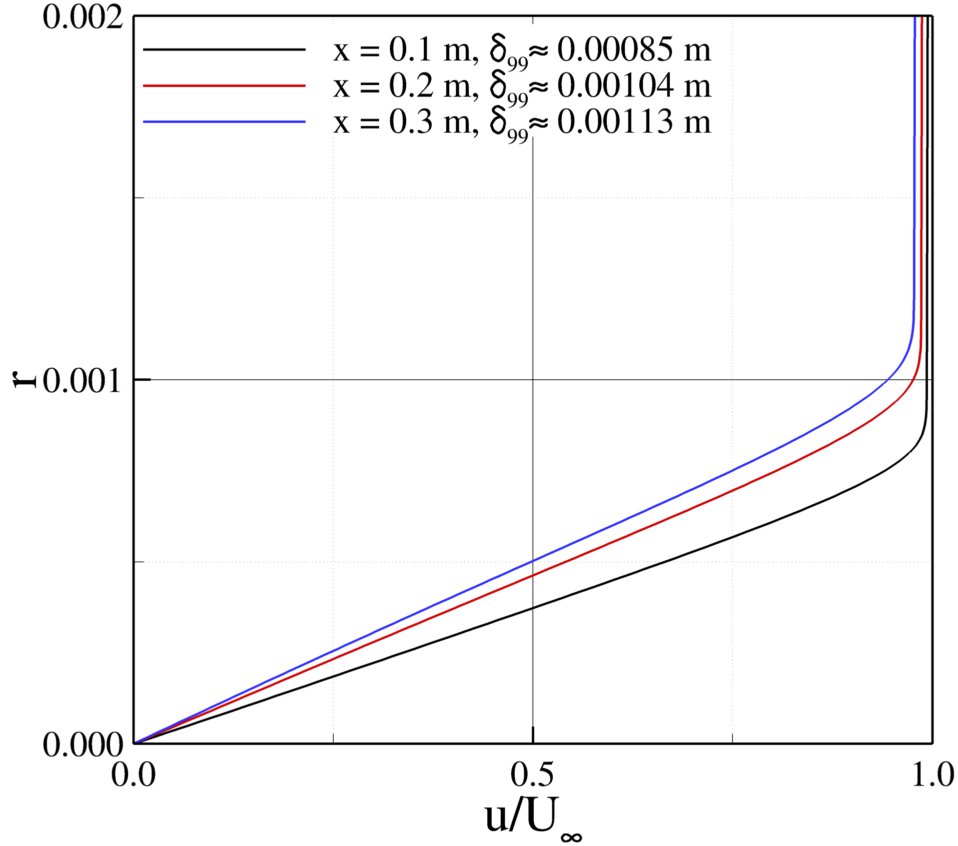


This creates a thin layer near the object called the boundary layer

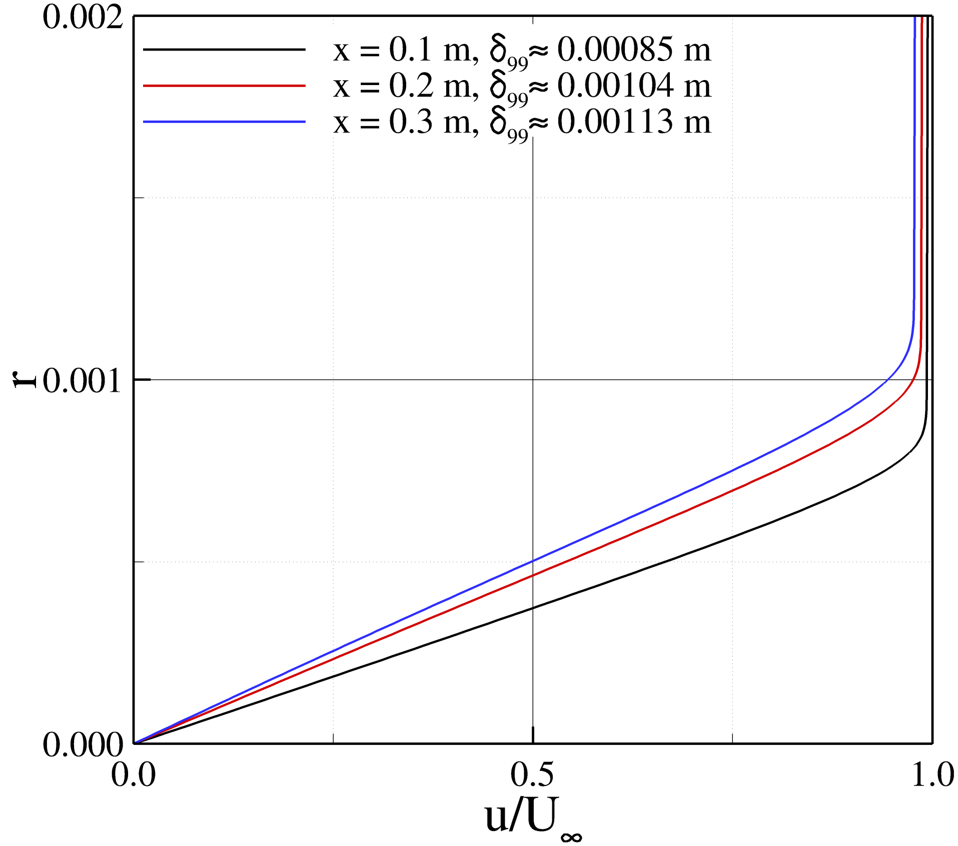
Note: this schematic is not drawn to scale

Boundary layer concept

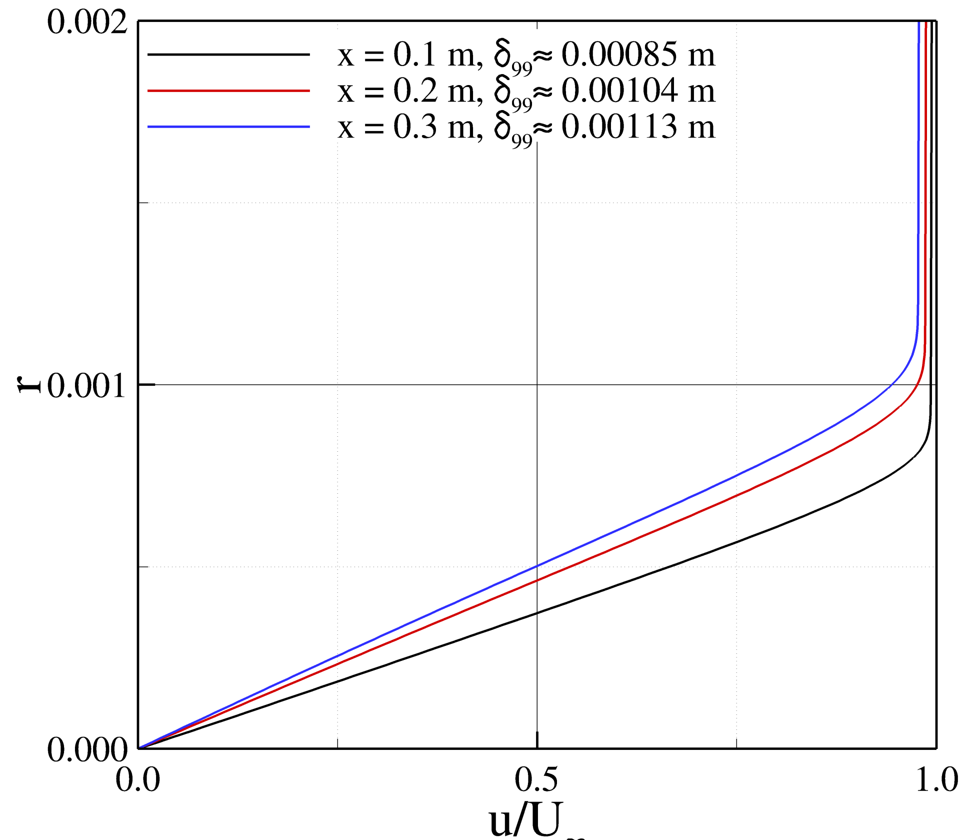
- What is the boundary layer scale (how thick is it)?
- Depends on the flow conditions
- Example: M = 6, Re_1 = 10.82e6 1/m
- $\delta_{99} = O(0.001\ m)$
- Can we relate that to a scale we can grasp?



Boundary layer concept



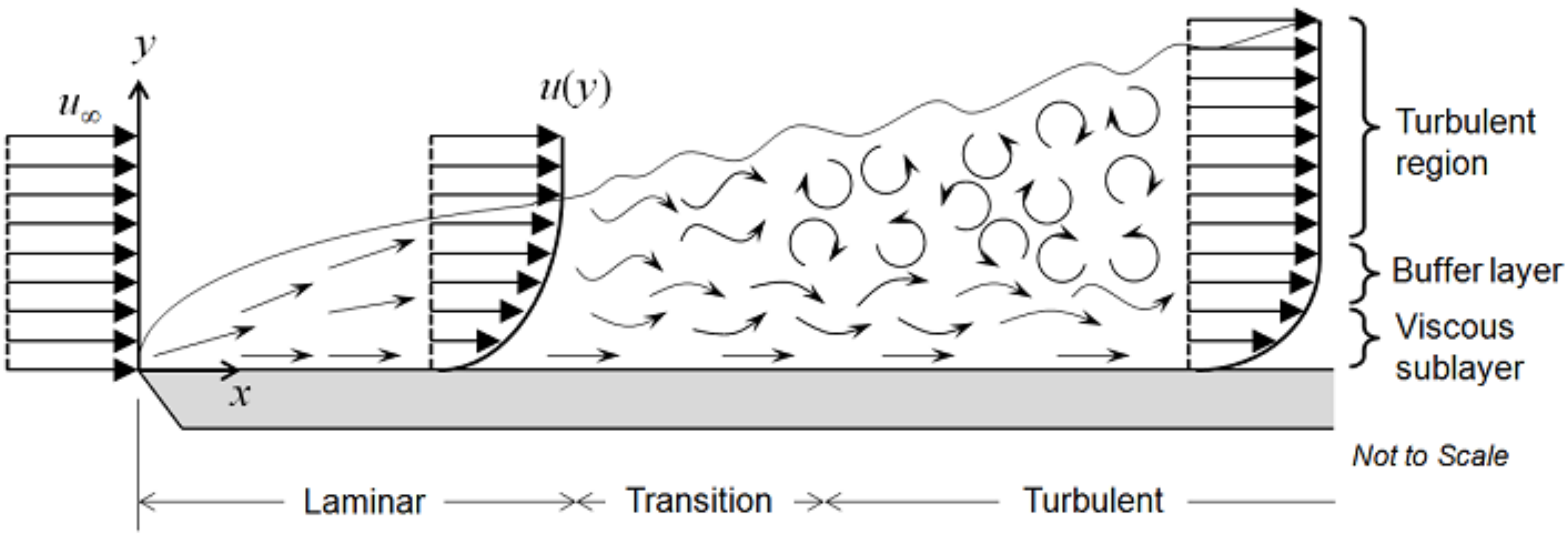
Boundary layer concept



Lego Batman is about 48 times as tall as the boundary layer in our case

What is laminar-turbulent transition?

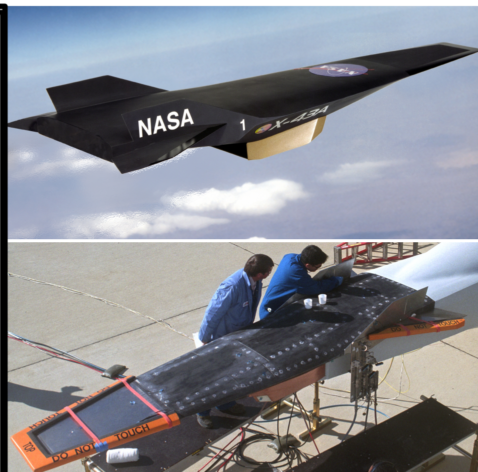
- Laminar flow: “smooth”, “ordered” flow
- Turbulent flow: “chaotic” flow, random fluctuations



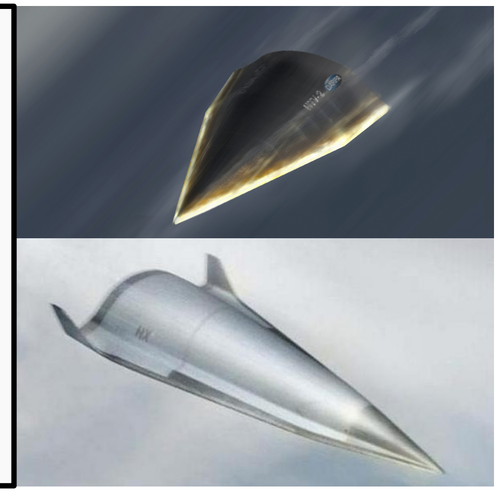
Why hypersonic transition?

- Transition leads to significant increases in skin-friction and heat loads
- Prediction of transition necessary for safe design and operation

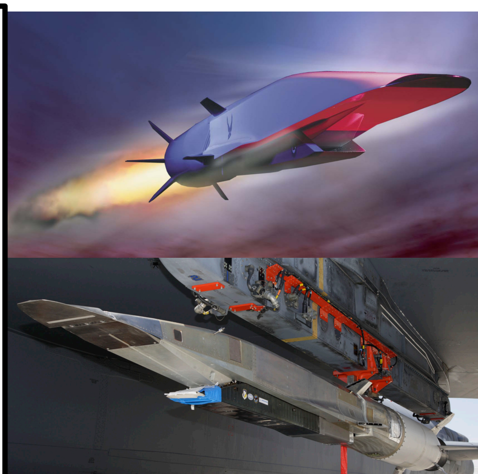
X-43:
- Test flights reaching M ≈ 7 (4600 mph) and M ≈ 9.5 (6600 mph)



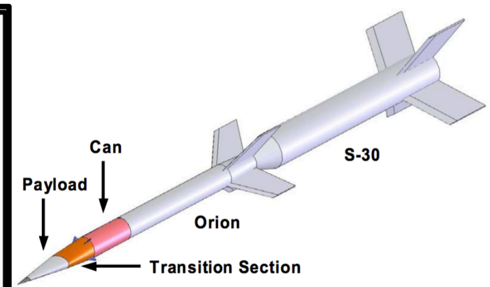
HTV-2:
- Planned to fly at M = 20
- Unsuccessful tests



X-51:
- Test flights reaching M = 5 (3300 mph)

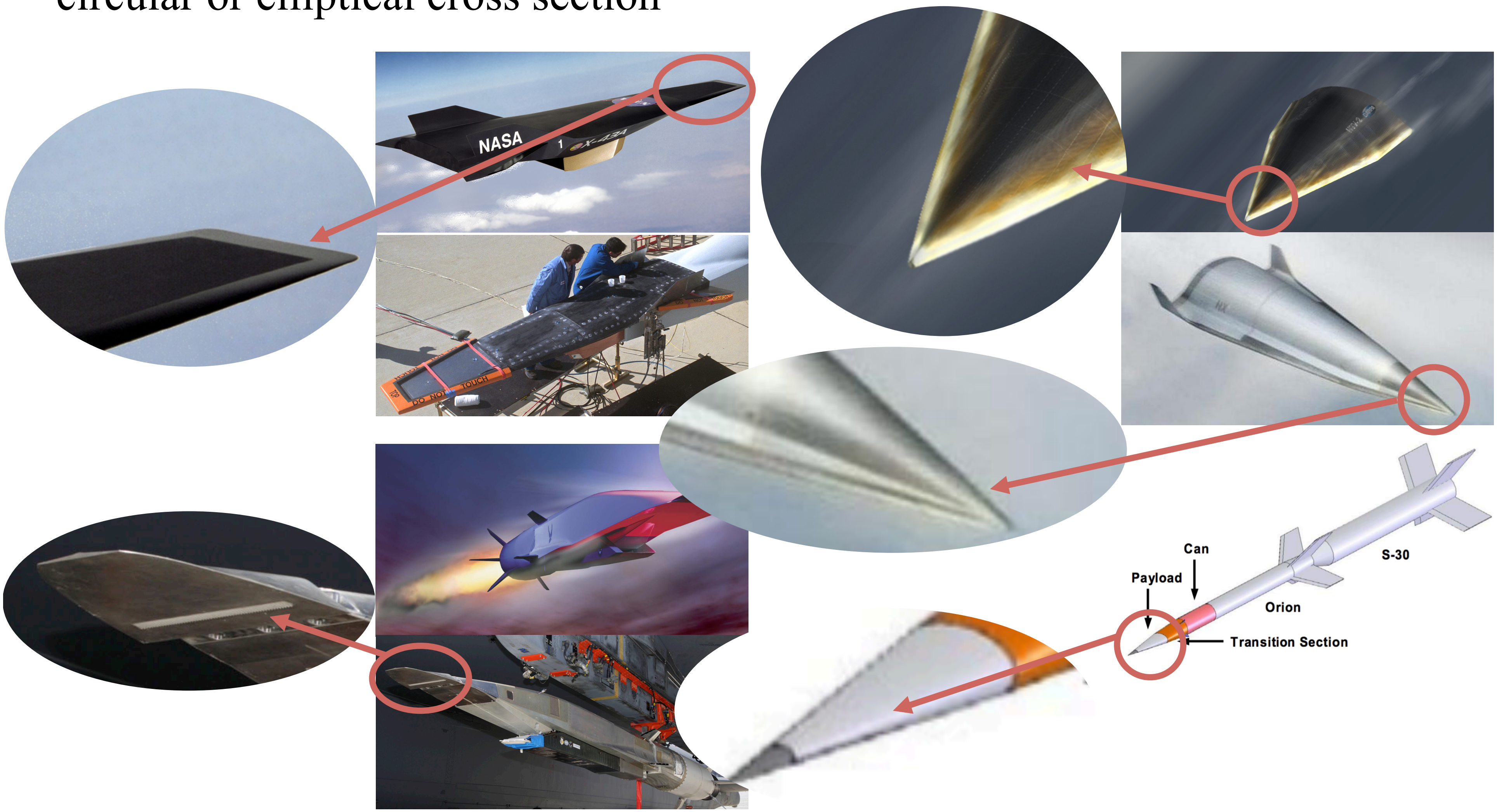


HiFIRE:
- Ongoing project to test hypersonic technology
- Reached M ≈ 6-8 (4500-6100 mph)



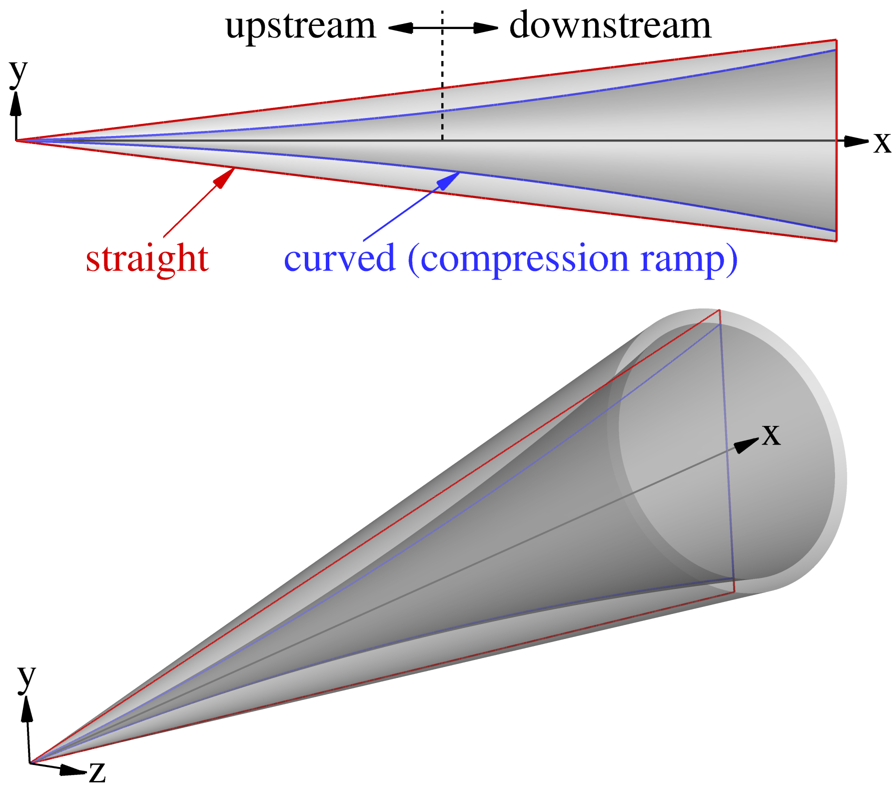
Why cones?

- Forebodies of hypersonic vehicles are more or less wedges or cones with circular or elliptical cross section

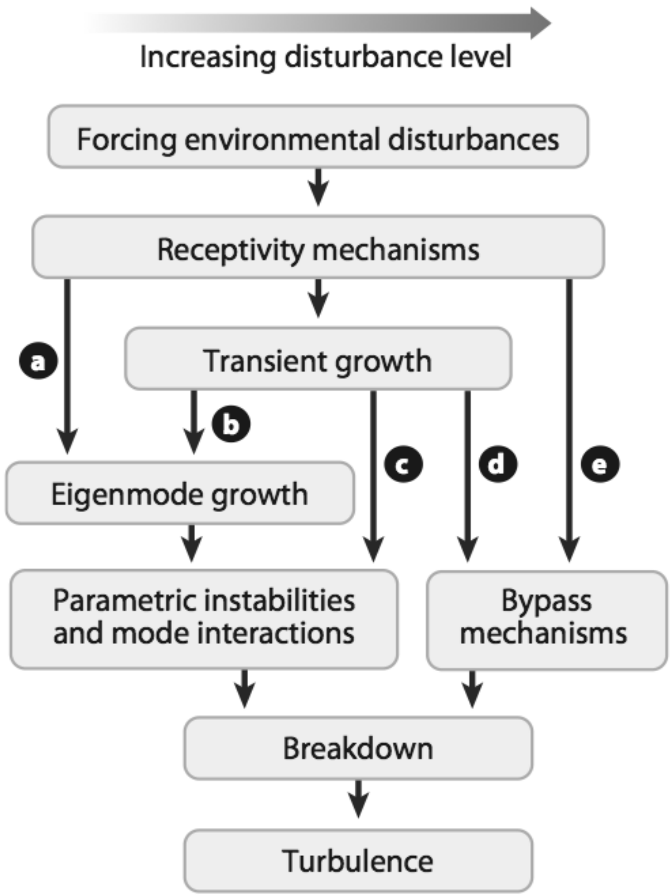


What is a flared cone?

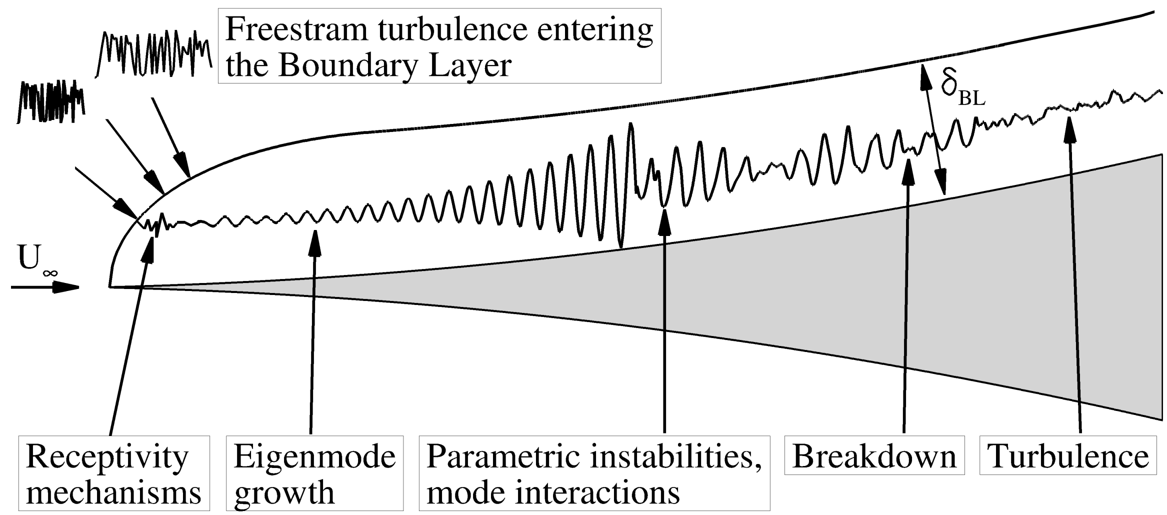
- Experimental test sections are limited in size
- Transition region in high speed flows can be very long
- Move transition region upstream (accelerate transition) by applying flare



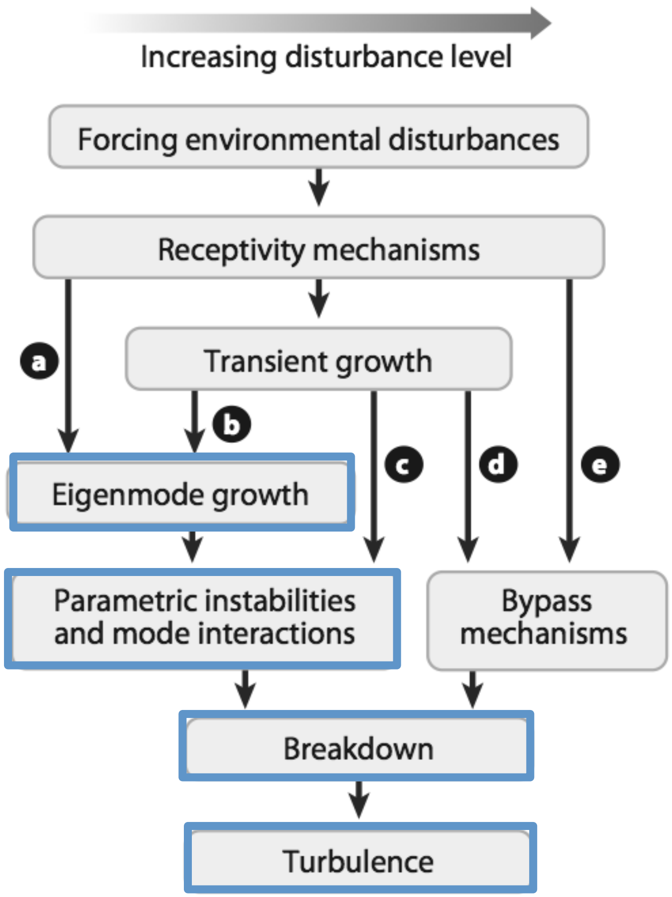
Paths to Transition

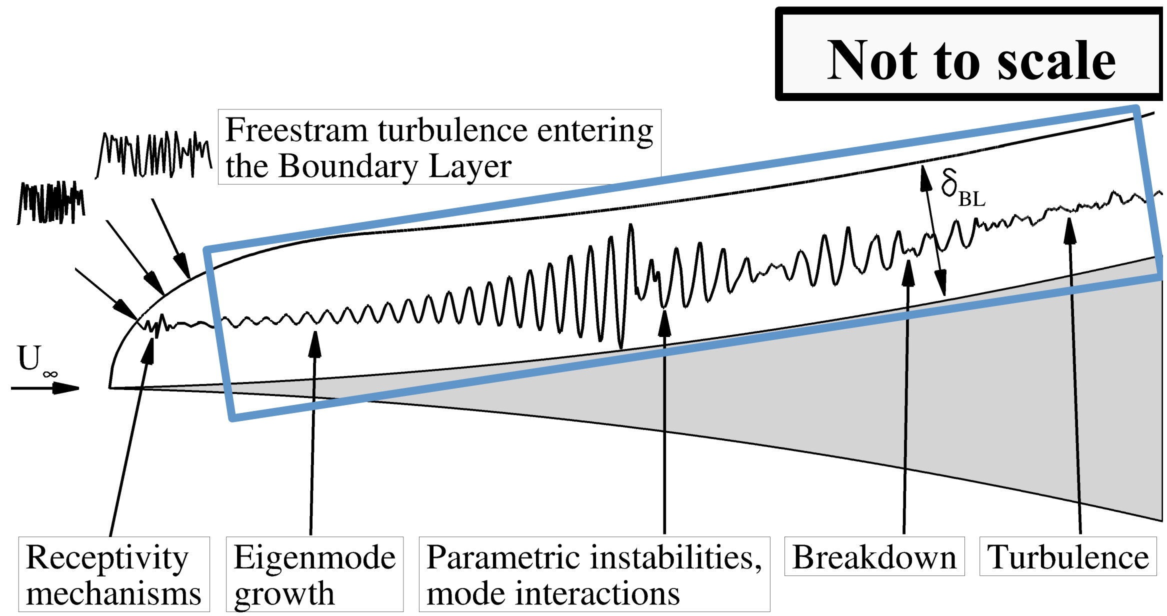


Not to scale



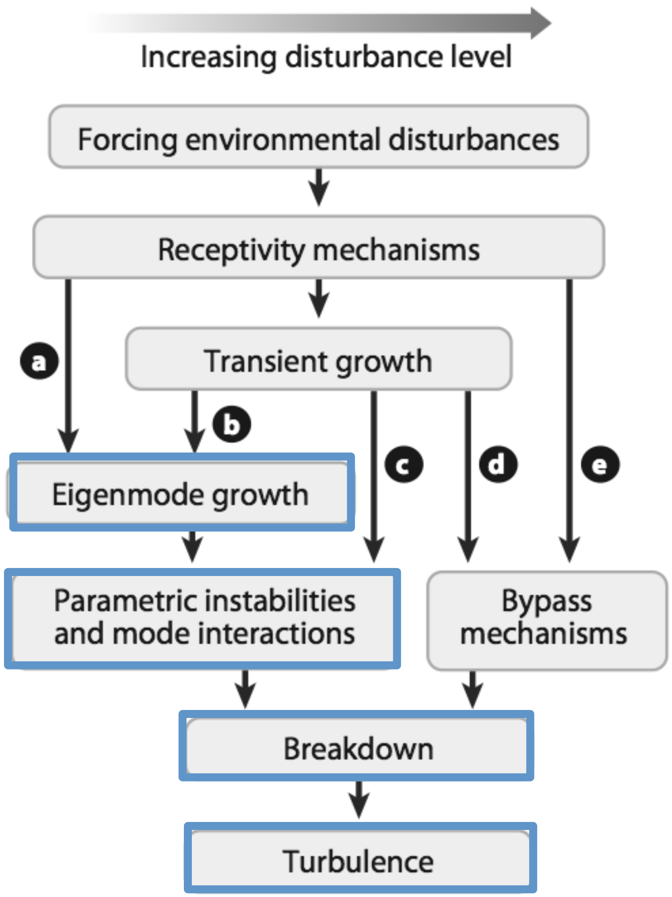
Paths to Transition

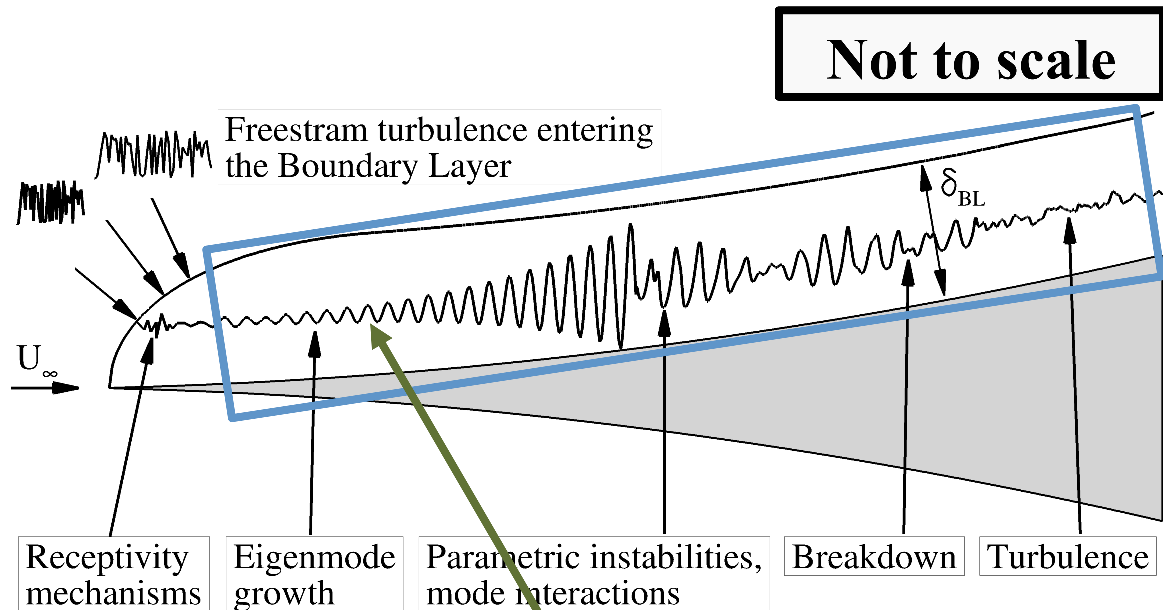




We will be focusing on path a (excluding receptivity)

Paths to Transition



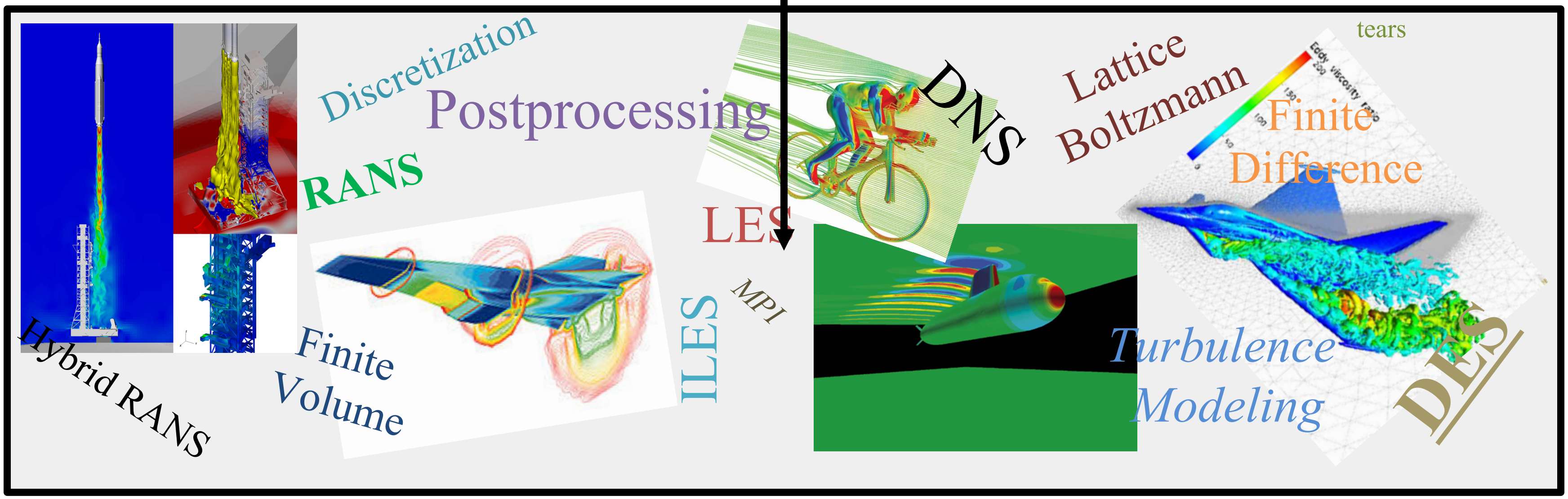


We need a disturbance wave in the boundary layer to transition the flow

We will be focusing on path a (excluding receptivity)

What do we actually do?

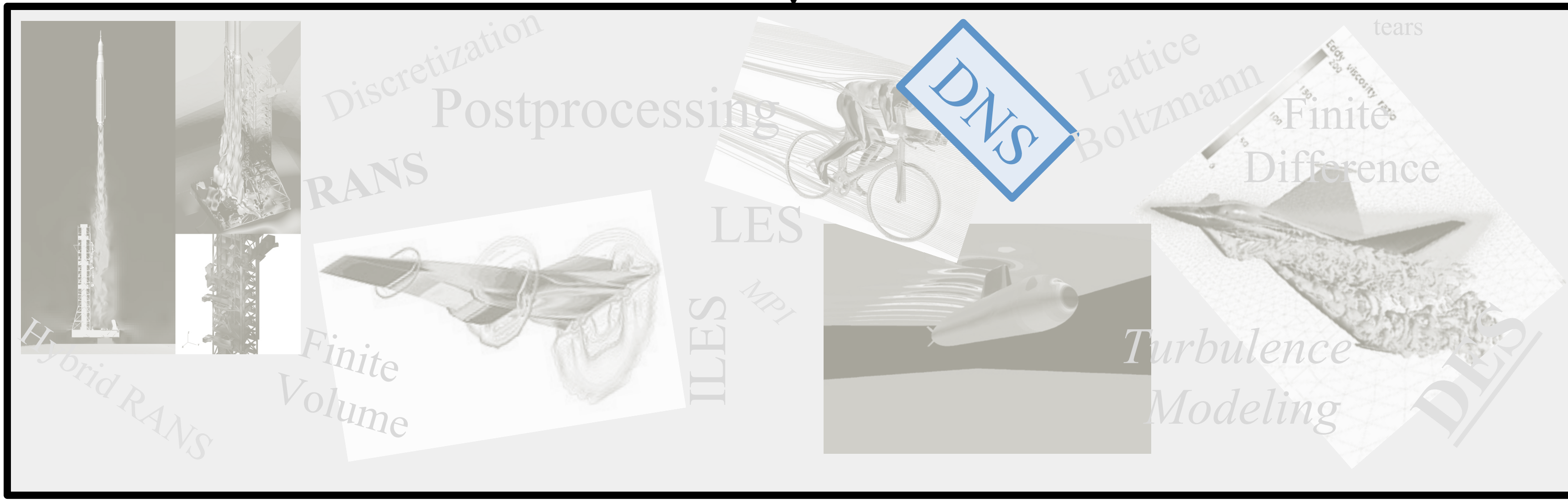
Computational Fluid Dynamics (CFD)



- Lots of variety and different flavors
- Which methods are best suited depends on the problem you are solving

What do we actually do?

Computational Fluid Dynamics (CFD)



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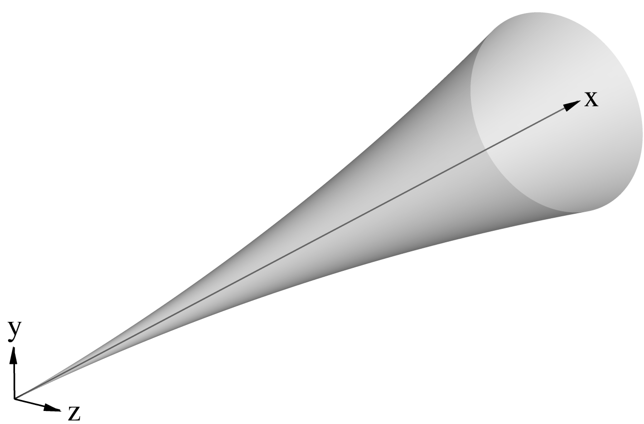
What do we actually do?

DNS = Direct Numerical Simulations

- Numerical solution of the compressible Navier-Stokes Equations

Geometry



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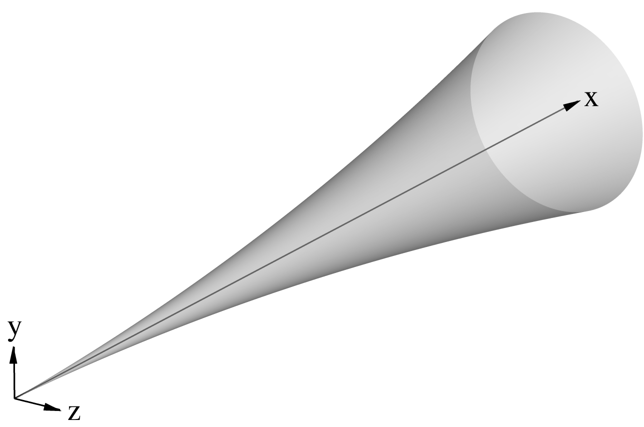
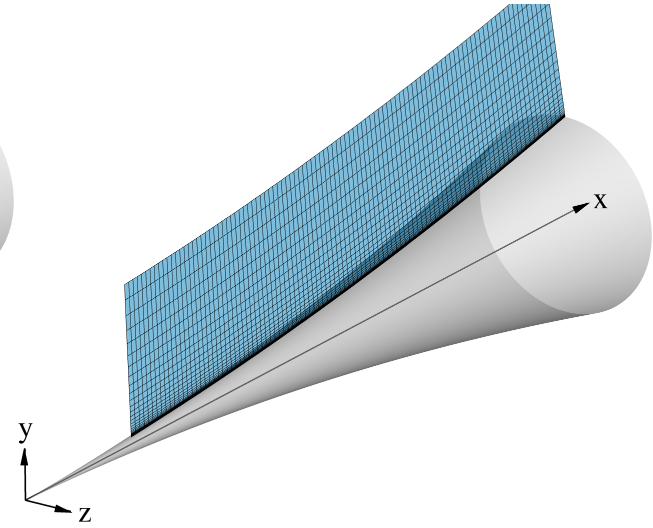
Geometry → **Grid**





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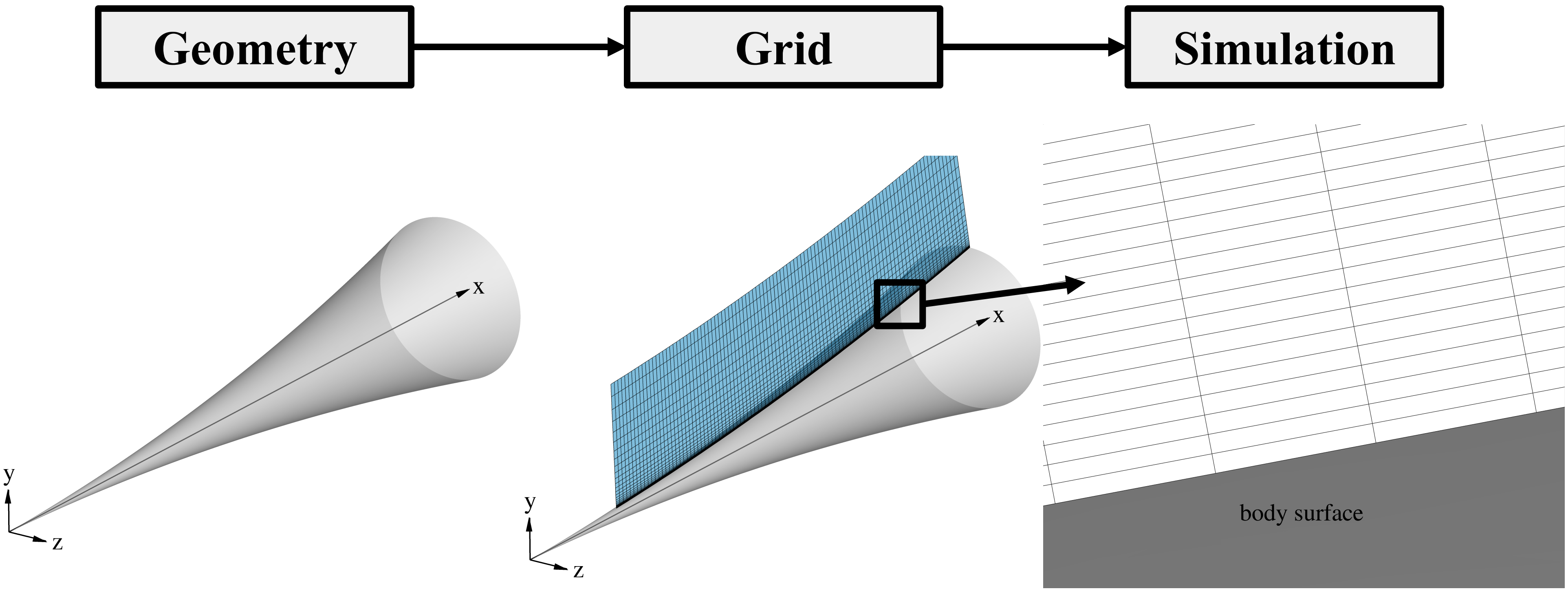
- Numerical solution of the compressible Navier-Stokes Equations

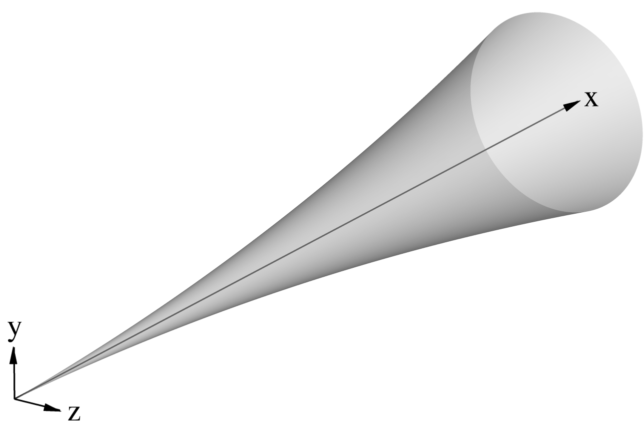


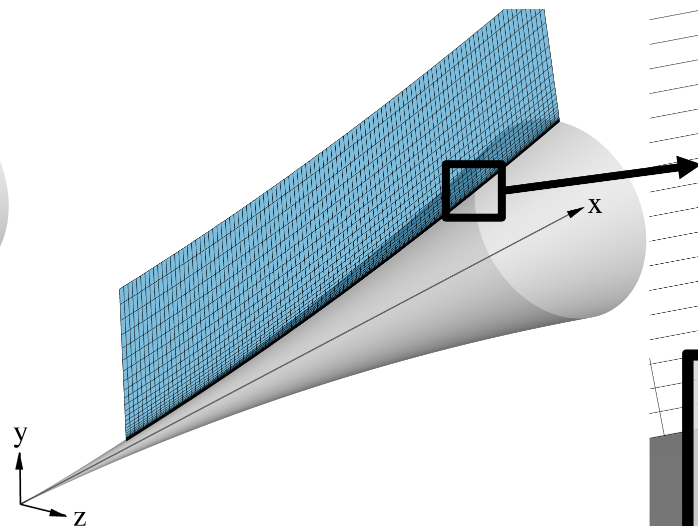
What do we actually do?

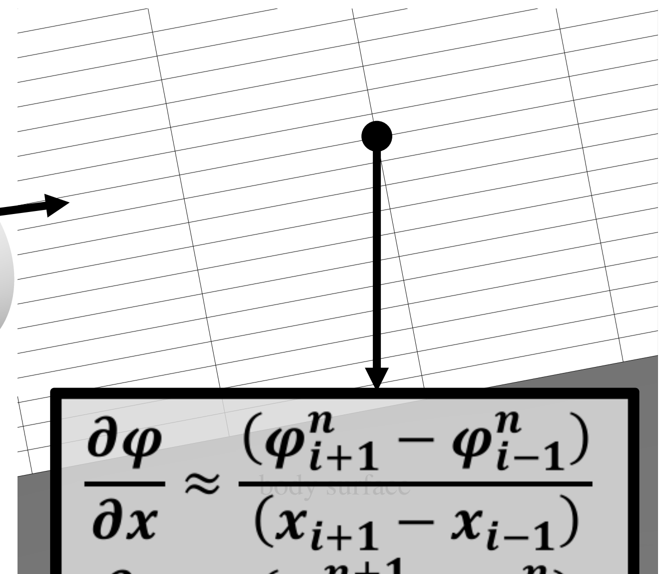
DNS = Direct Numerical Simulations

- Numerical solution of the compressible Navier-Stokes Equations

Geometry → **Grid** → **Simulation**







$$\frac{\partial \varphi}{\partial x} \approx \frac{(\varphi_{i+1}^{n} - \varphi_{i-1}^{n})}{(x_{i+1} - x_{i-1})}$$

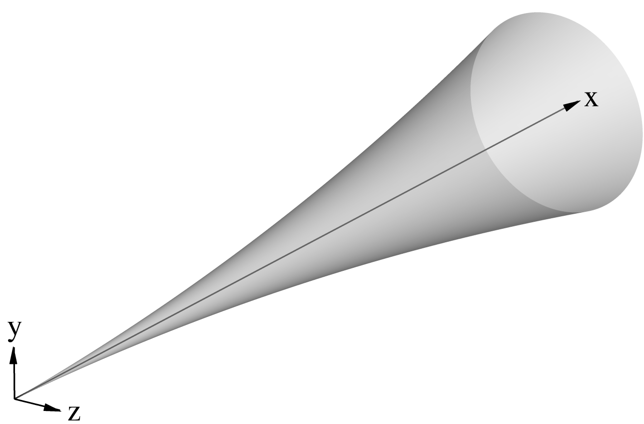
$$\frac{\partial \varphi}{\partial t} \approx \frac{(\varphi_{i}^{n+1} - \varphi_{i}^{n})}{(t^{n+1} - t^{n})}$$

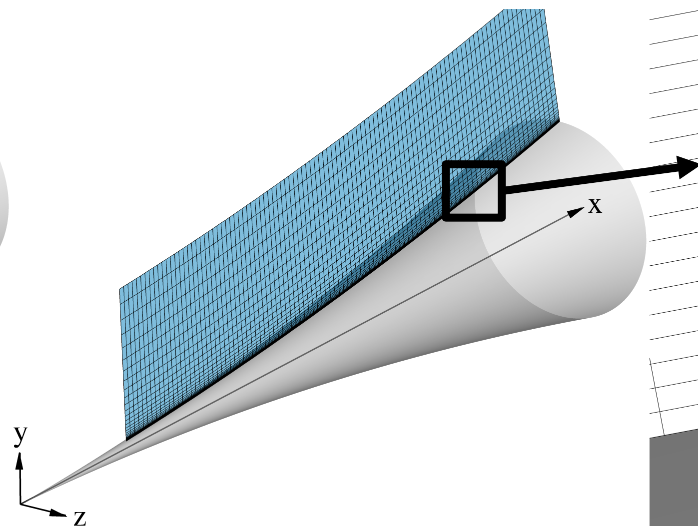
What do we actually do?

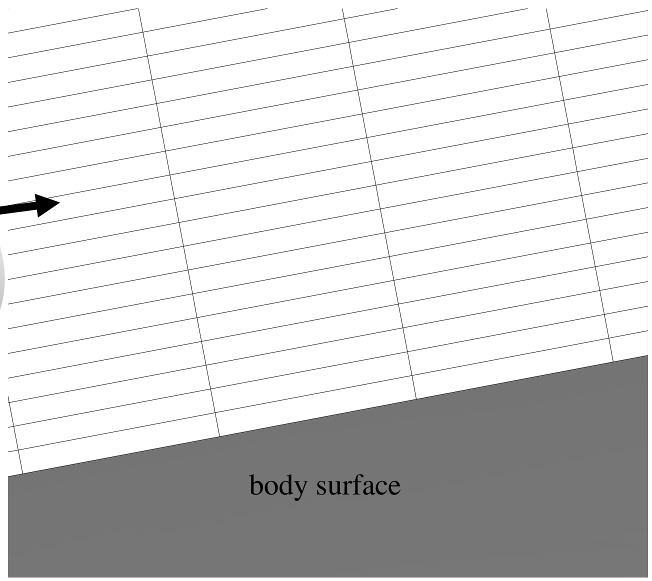
DNS = Direct Numerical Simulations

- Numerical solution of the compressible Navier-Stokes Equations

Geometry → **Grid** → **Simulation**





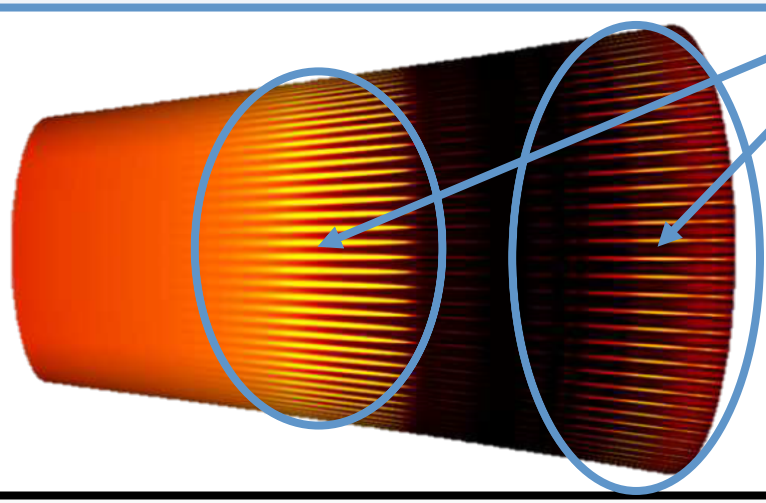


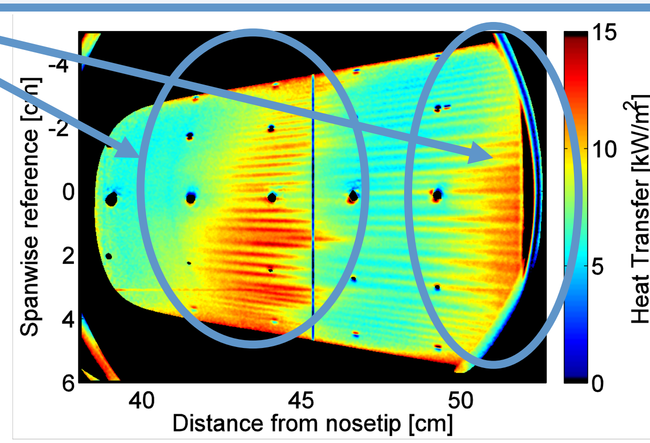
Basically we crunch a lot of numbers and then try to do science

Motivation/Goals of this research

- Hot streaks observed in both simulation and experiment (similar patterns)
- Investigate underlying physical mechanisms responsible for steak pattern
- Why do streaks appear, disappear and reappear?

'hot' streaks (large local heat fluxes) may compromise structural integrity of hypersonic flight vehicle





CFD (U of A, J. Sivasubramanian)

Experiment (Purdue, BAM6QT, B. Chynoweth)

Outline

Introduction

Geometry, Conditions and Simulation Strategy

Primary Wave

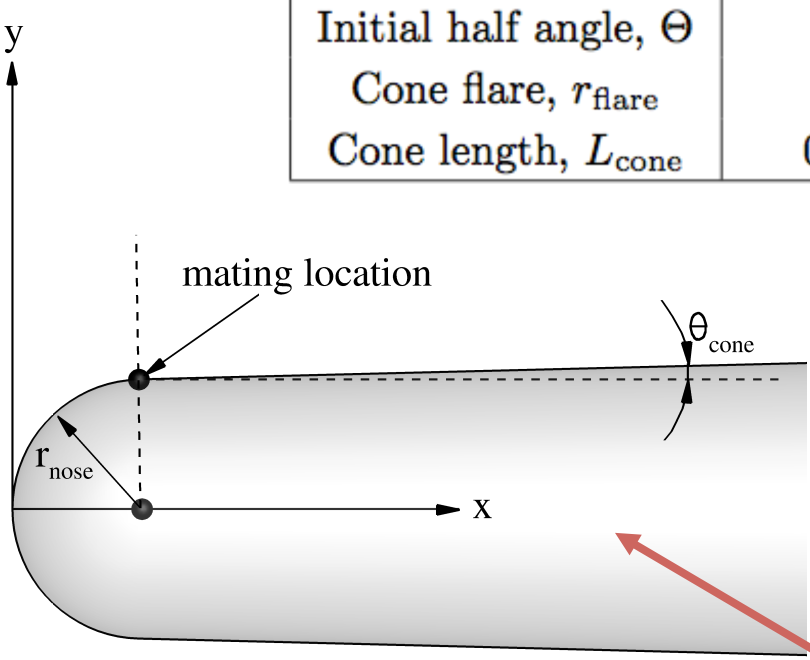
Secondary Instability

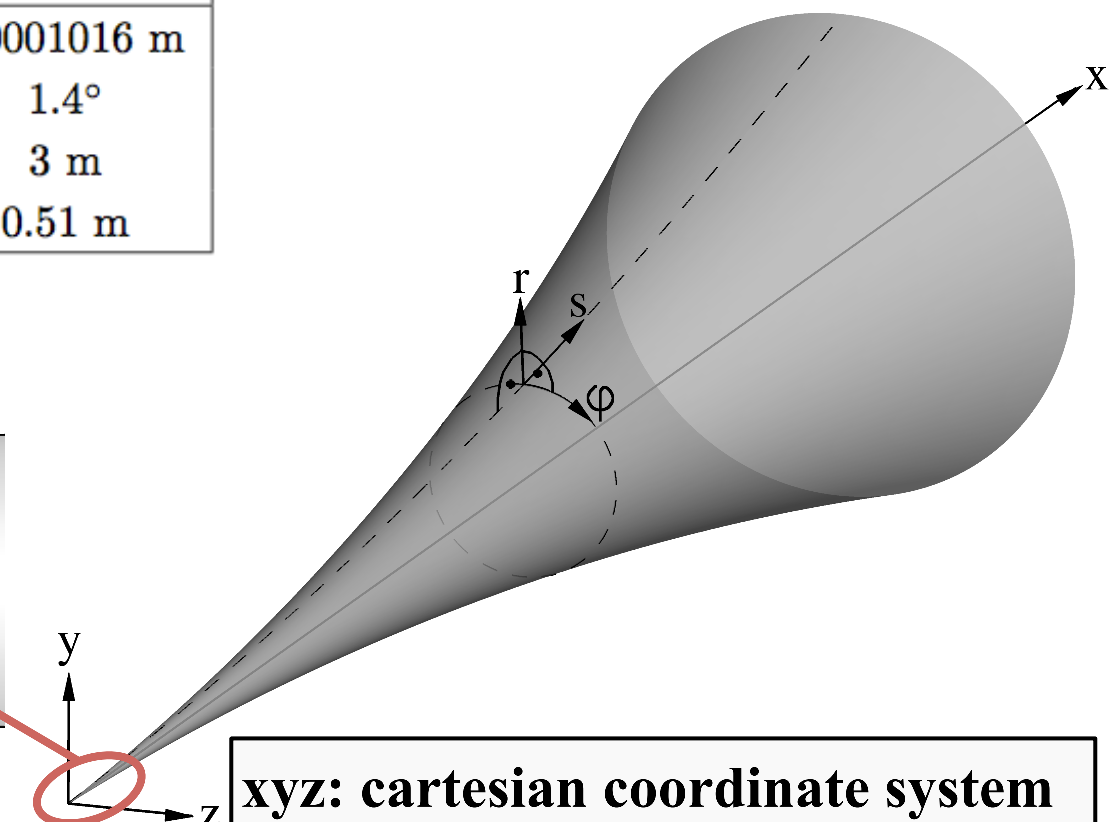
Fundamental Breakdown

Flared Cone Geometry

- Same flared cone geometry as used for the most recent experiments in the Boeing/AFOSR Mach 6 Quiet Tunnel (BAM6QT) at Purdue

Parameter	Value
Nose radius, r_{nose}	0.0001016 m
Initial half angle, Θ	1.4°
Cone flare, r_{flare}	3 m
Cone length, L_{cone}	0.51 m



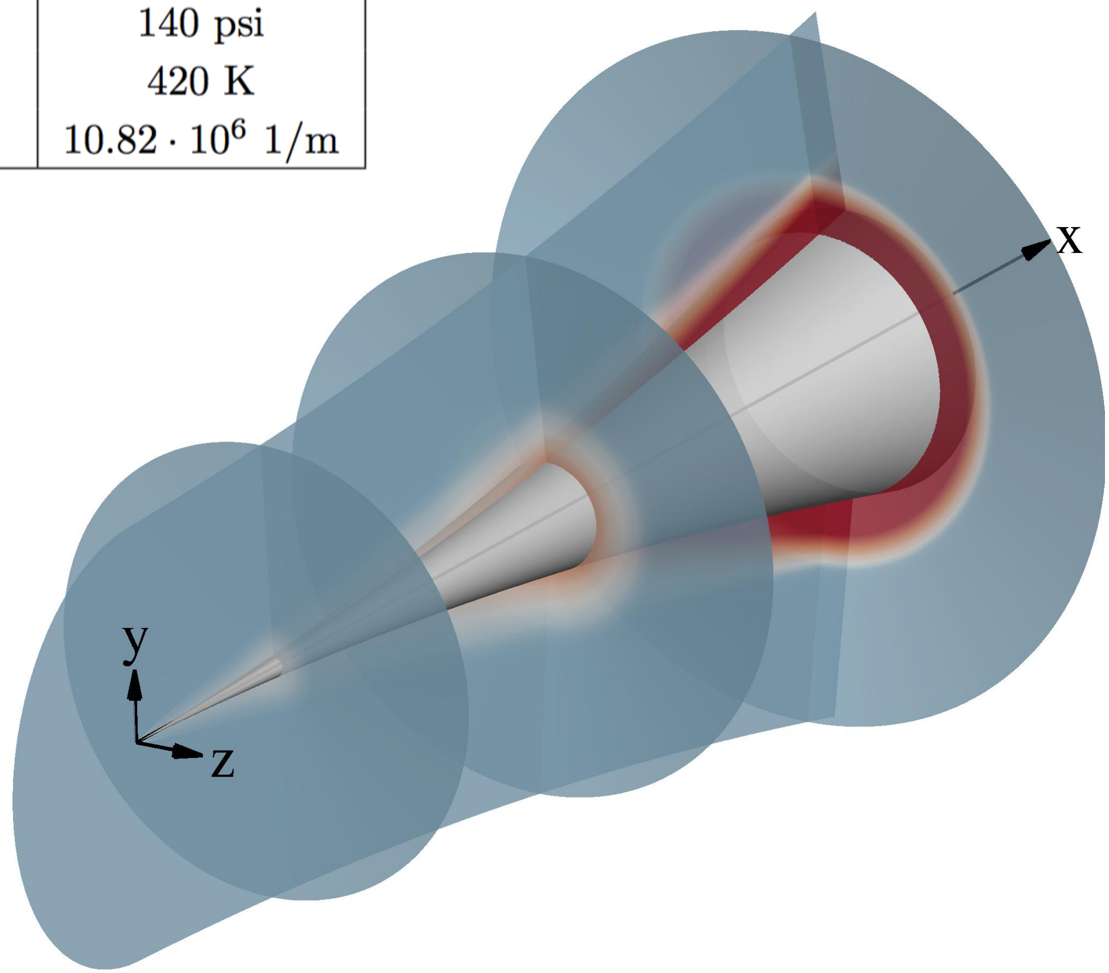


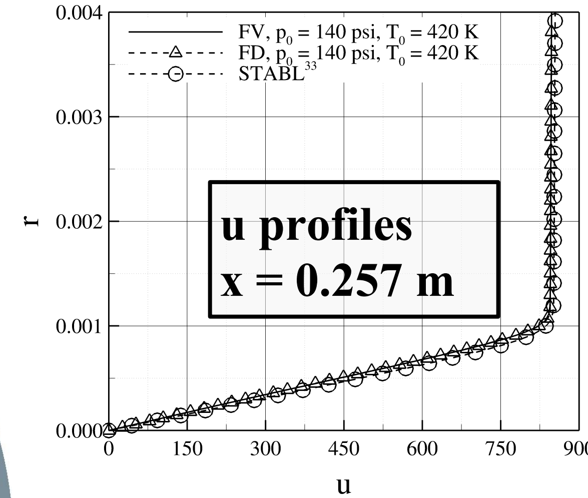
xyz: cartesian coordinate system
srφ: body coordinate system

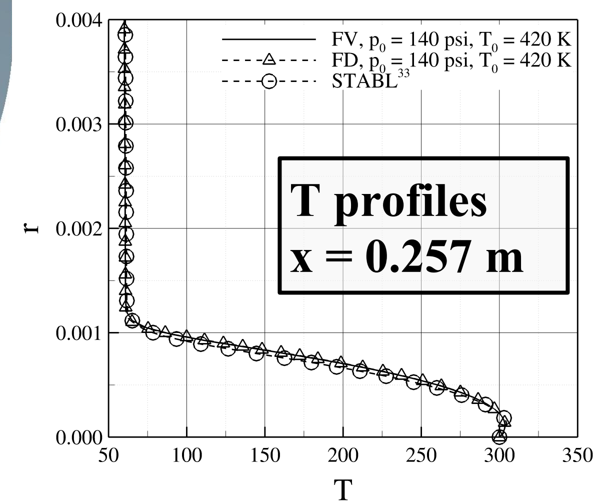
Flow Conditions

- Conditions of the most recent experiments in the BAM6QT

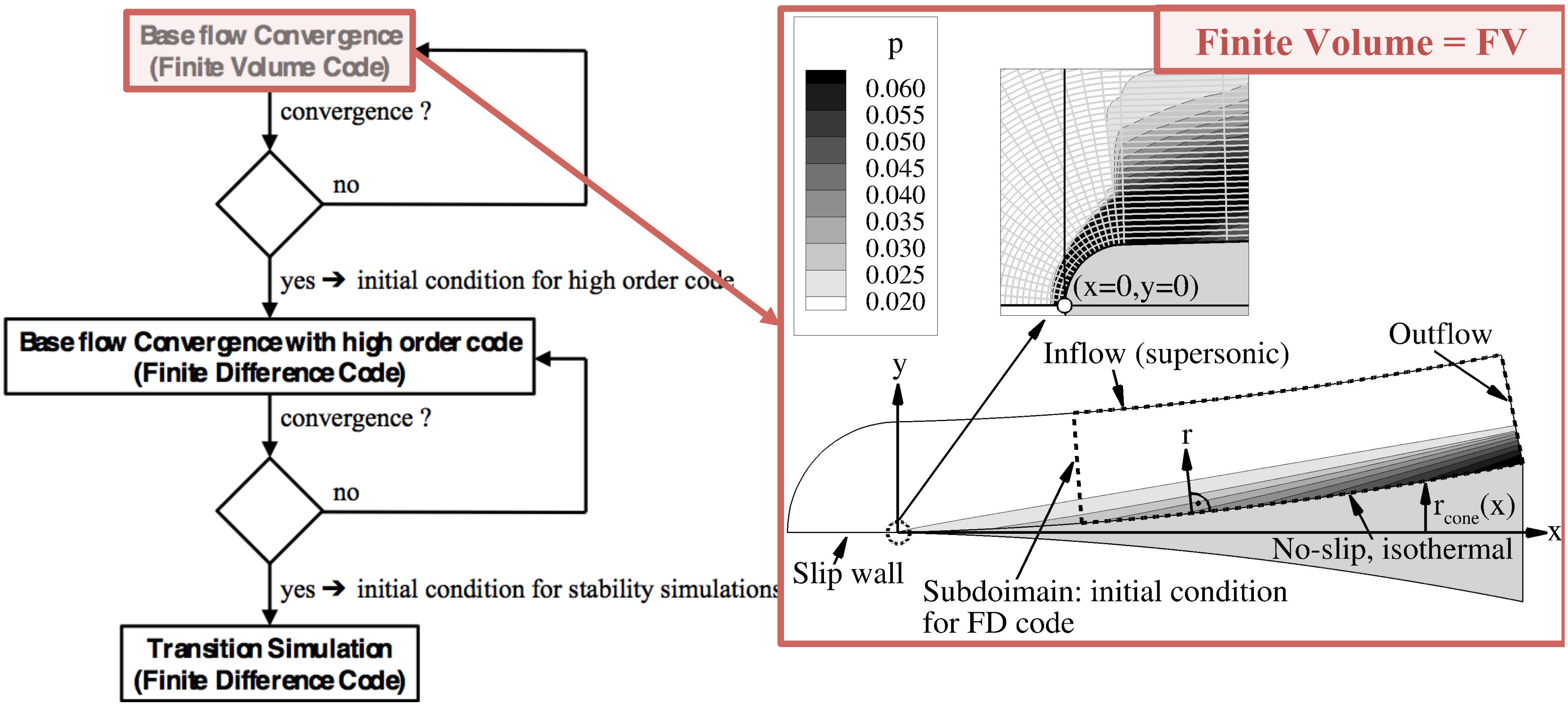
Parameter	Value
p_0	140 psi
T_0	420 K
Re_1	$10.82 \cdot 10^6$ 1/m





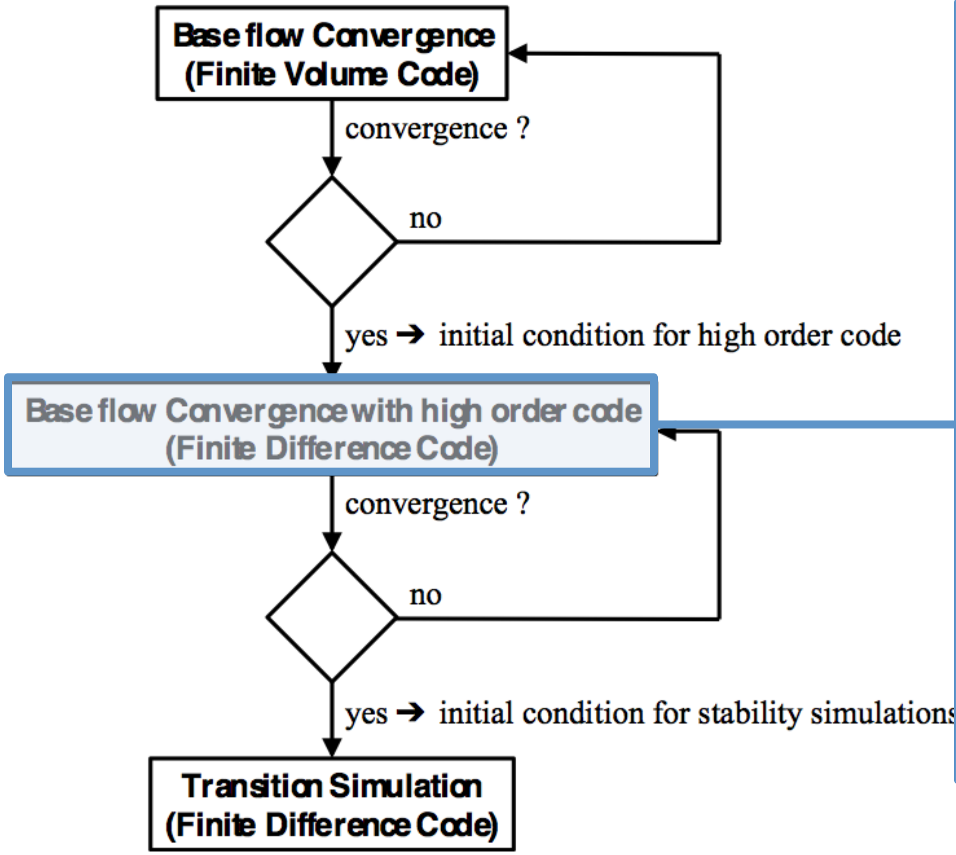


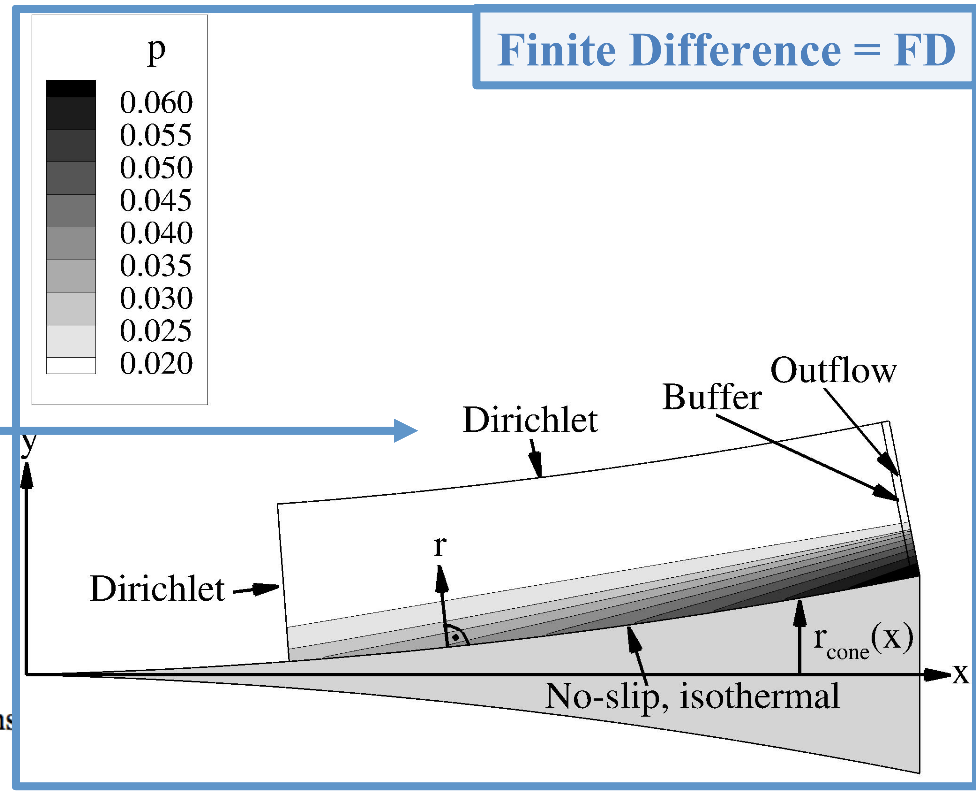
Simulation Strategy: Step 1/3



- Nose of the cone included in the computational domain
- Lower order scheme (numerically more stable but less accurate)

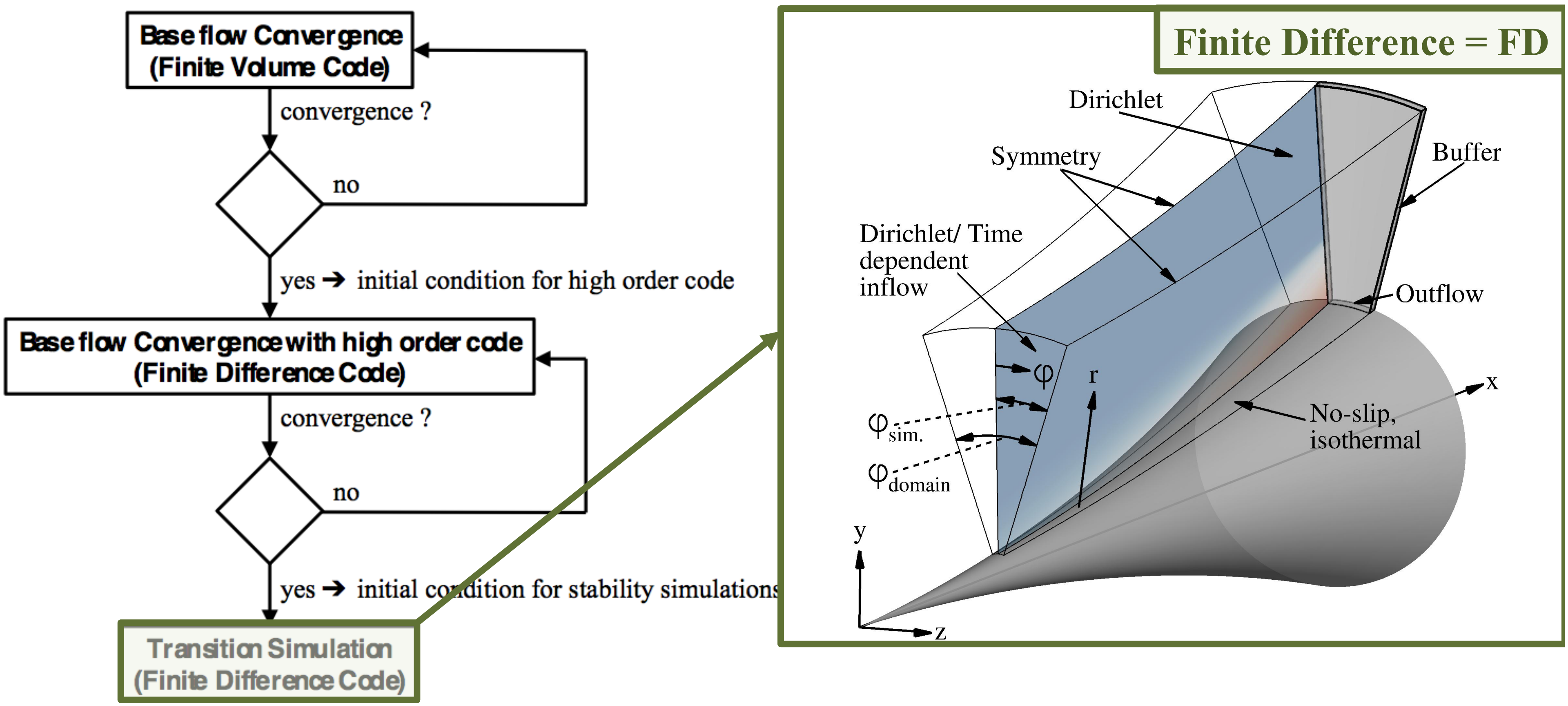
Simulation Strategy: Step 2/3



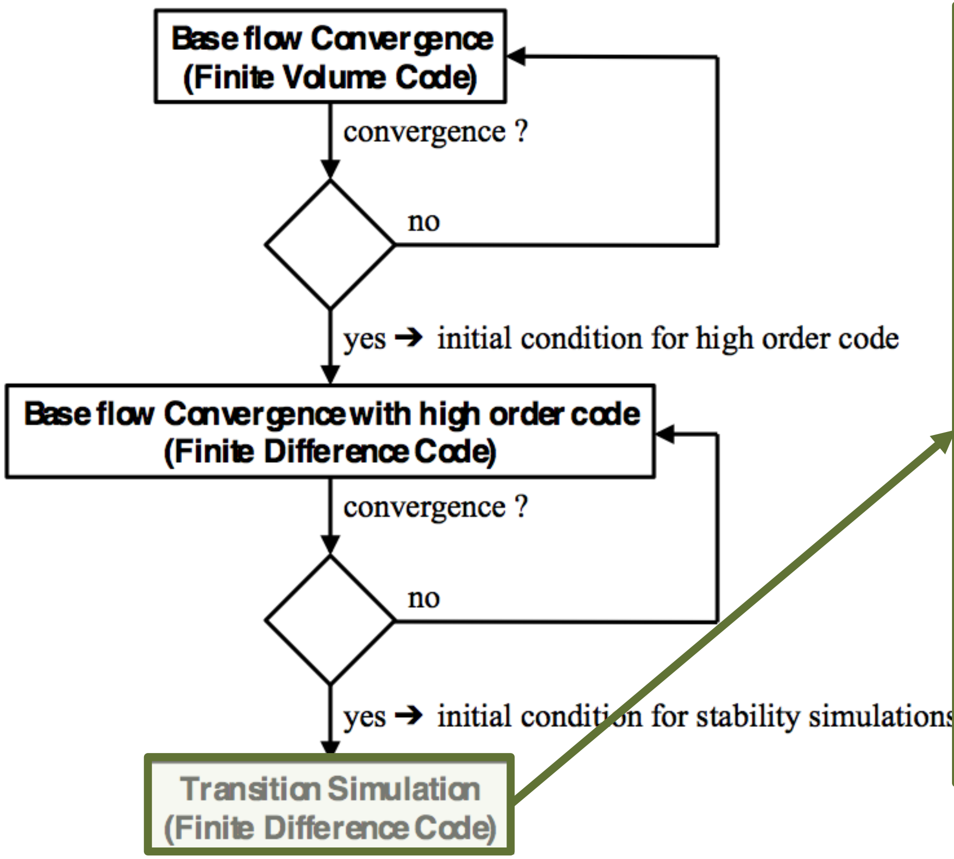


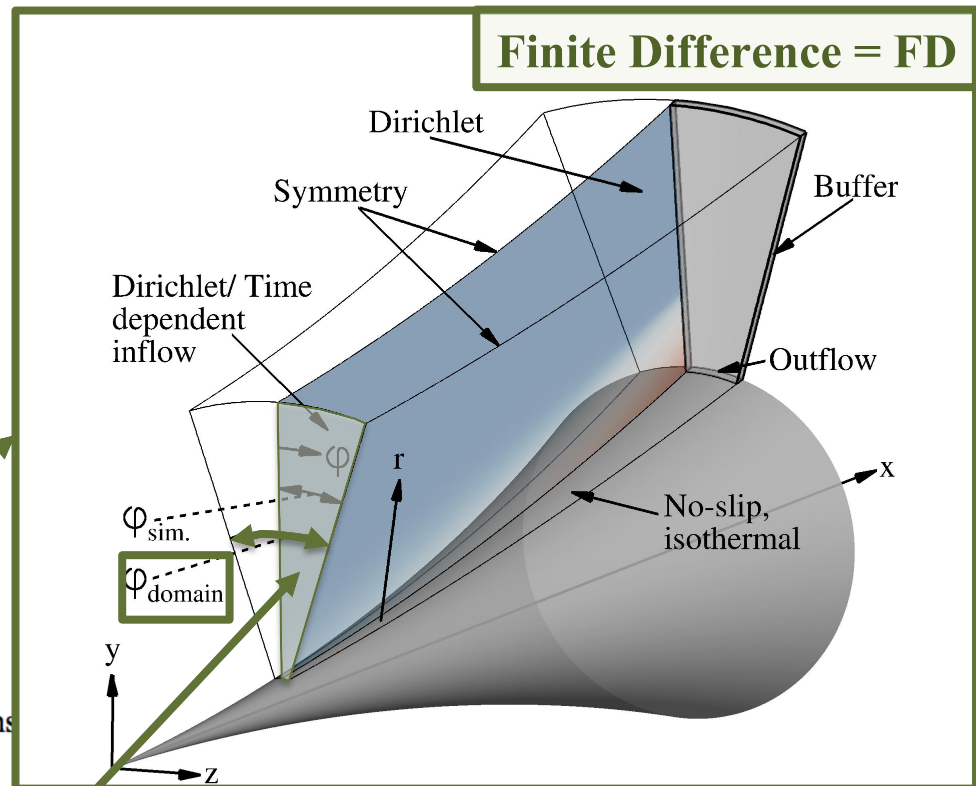
- Nose not included
- Higher order scheme (more accurate, numerically more "expensive")

Simulation Strategy: Step 3/3



Simulation Strategy: Step 3/3

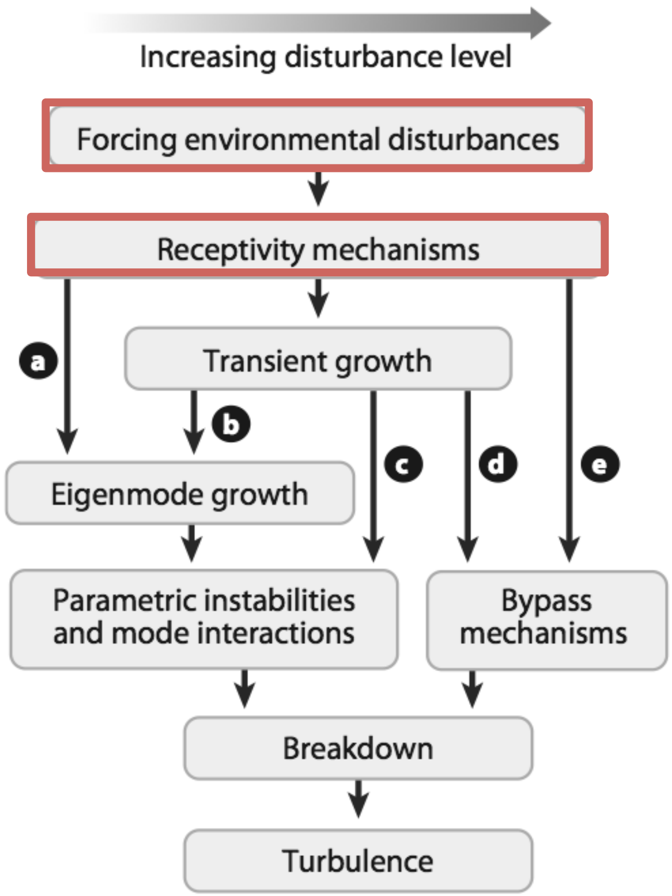


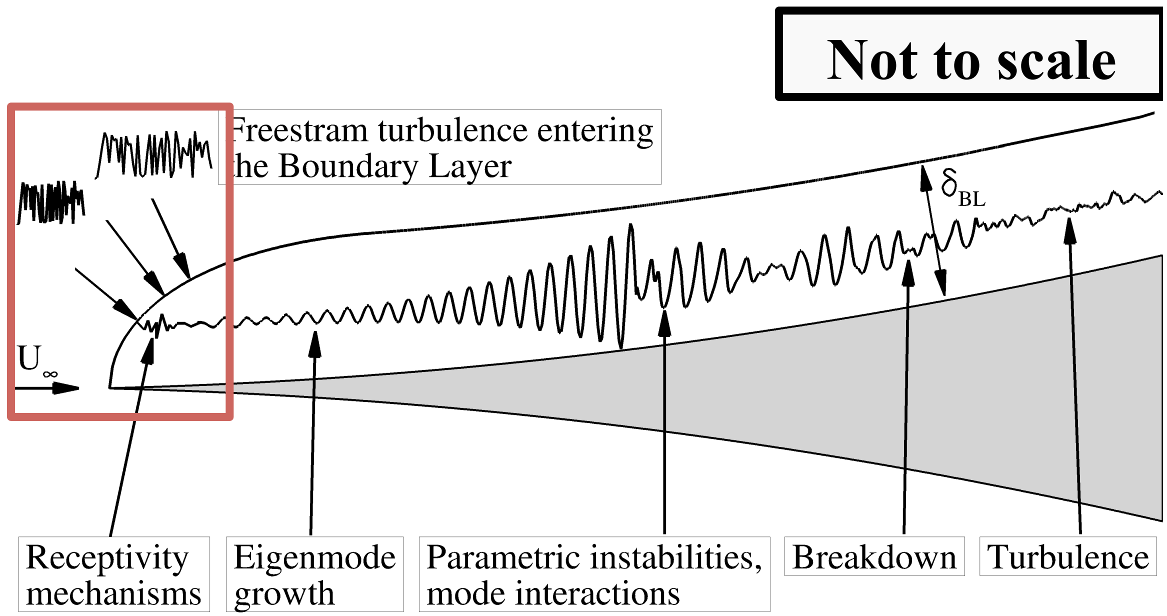


Note: We only simulate a small "wedge" of the cone

Define domain wave number: $k_{c,domain} = 2\pi/\varphi_{domain}$

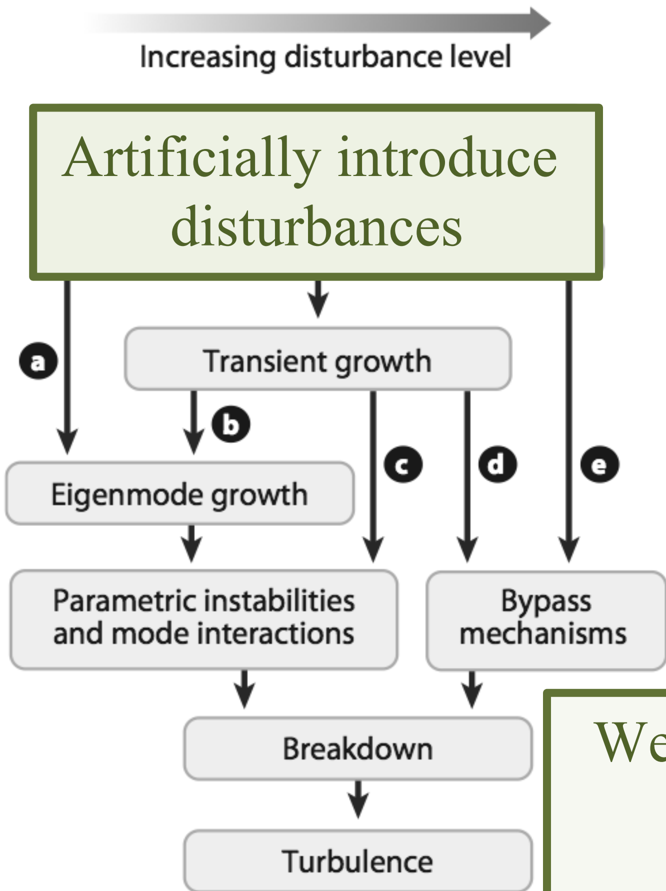
Where do the disturbances come from?





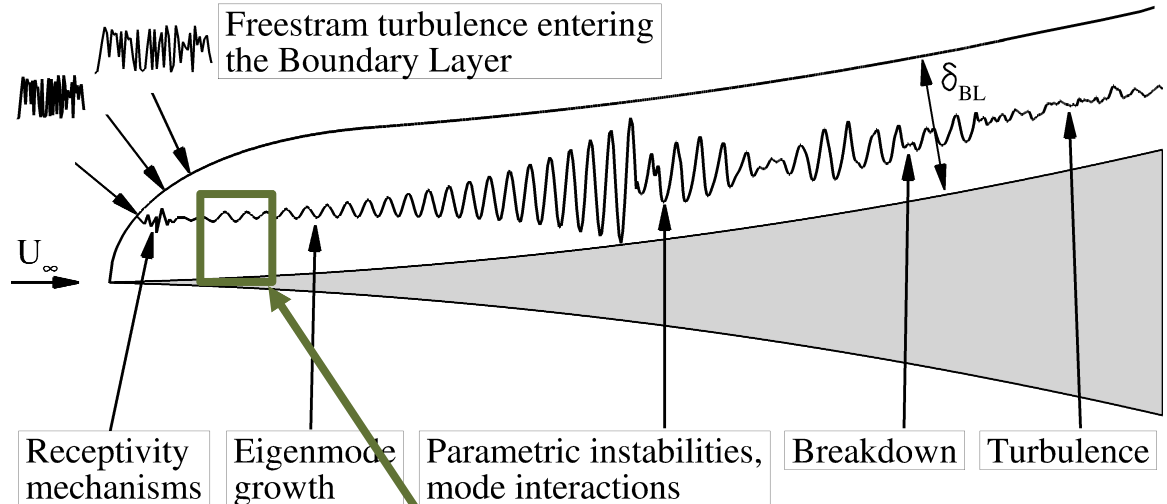
Recall: Omitting environmental disturbances and the receptivity mechanisms. How do disturbances get into the Boundary Layer in the simulations?

Where do the disturbances come from?



Artificially introduce disturbances

Not to scale



We force ("seed") them artificially in the boundary layer

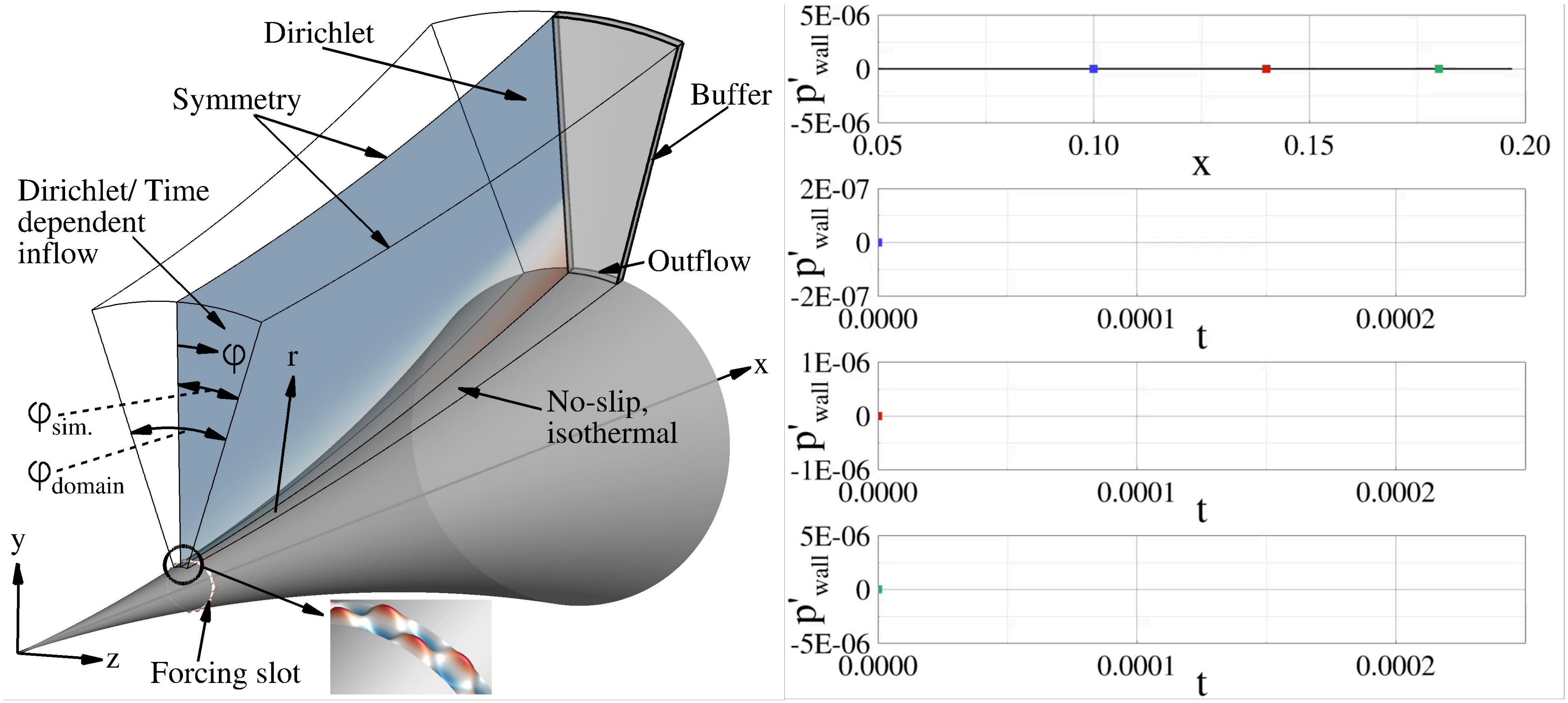
⇒We use **2** different strategies to do this

Strategy 1: Continuous forcing

Strategy 2: Pulse forcing

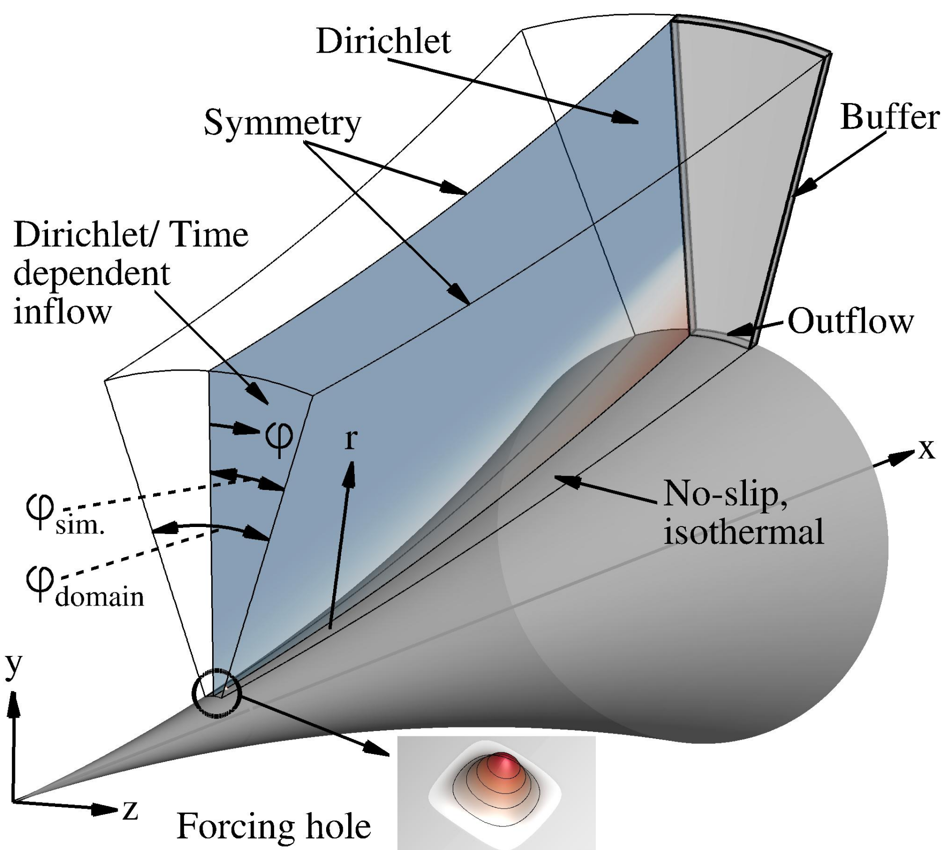
Strategy 1: Continuous forcing

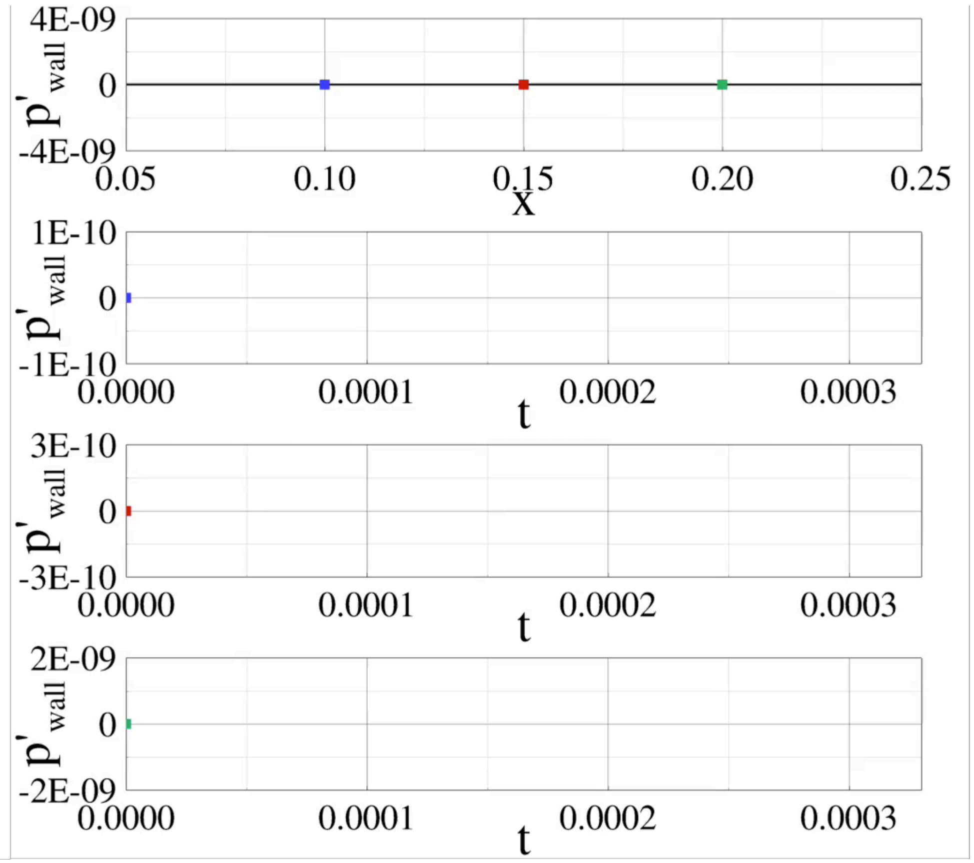
- Disturbances are forced at all times (continuously)
- A “controlled” set of frequencies is introduced



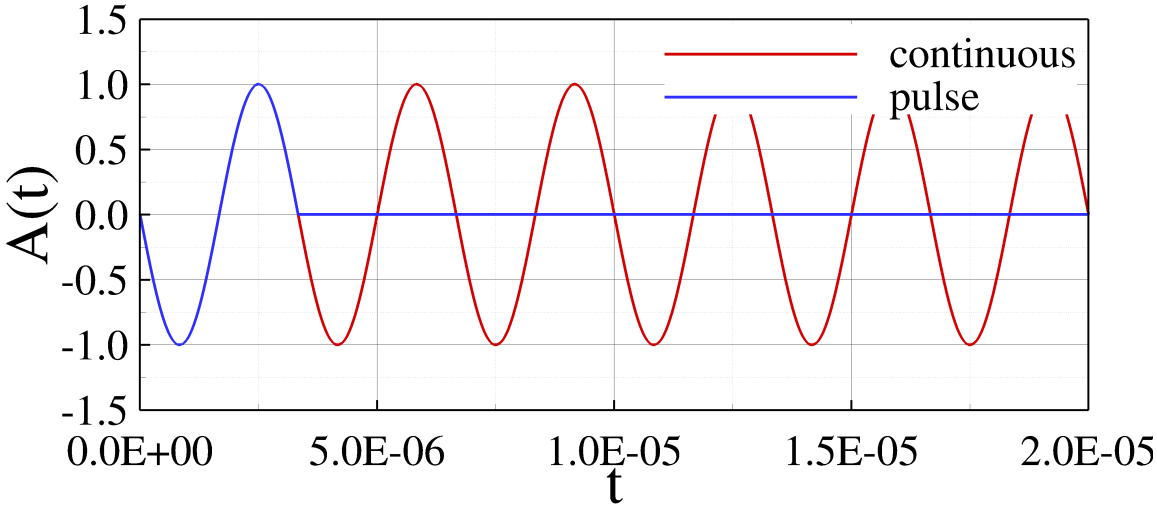
Strategy 2: Pulse forcing

- Disturbances are forced for a short duration
- A wide range of frequencies is introduced

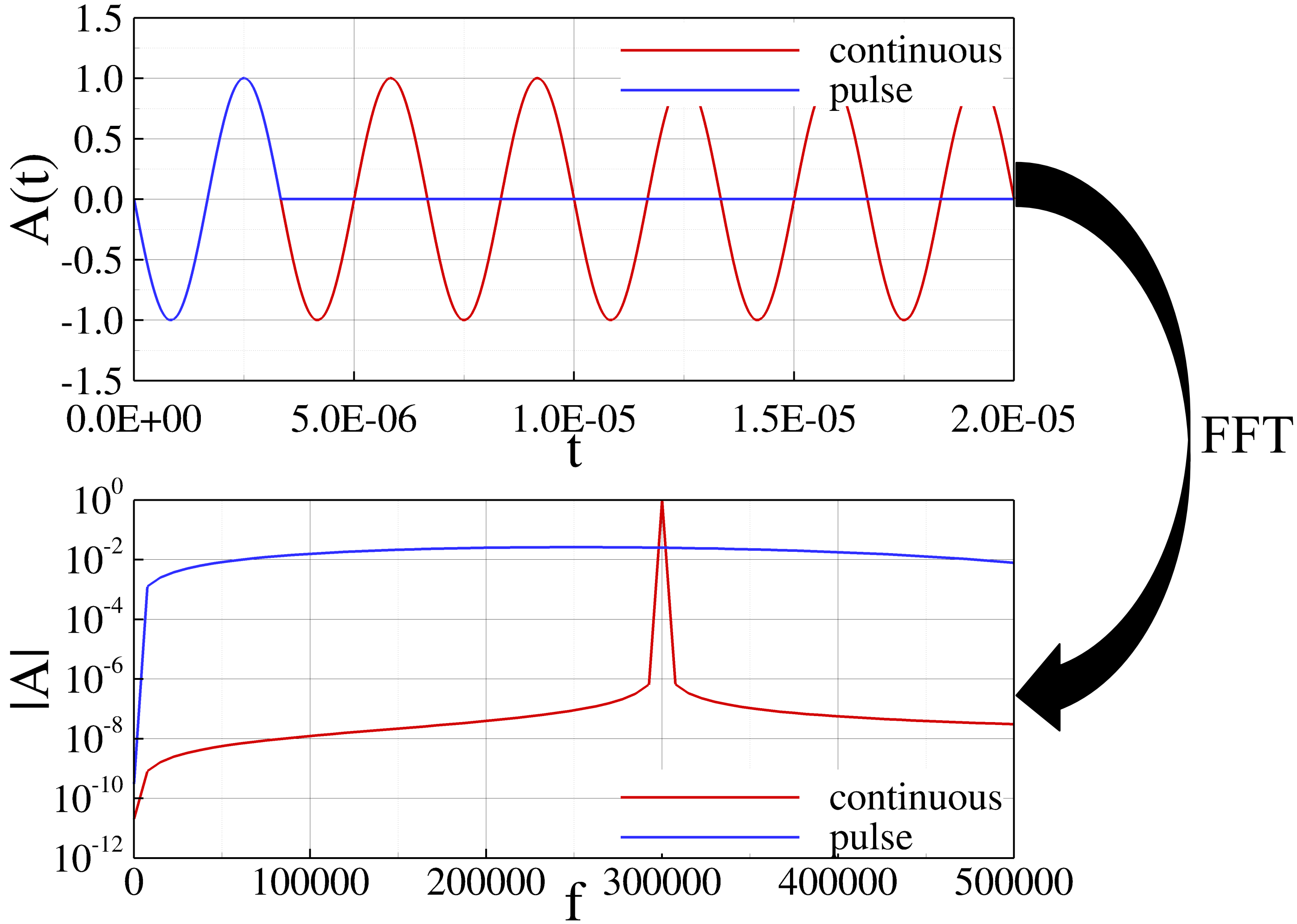




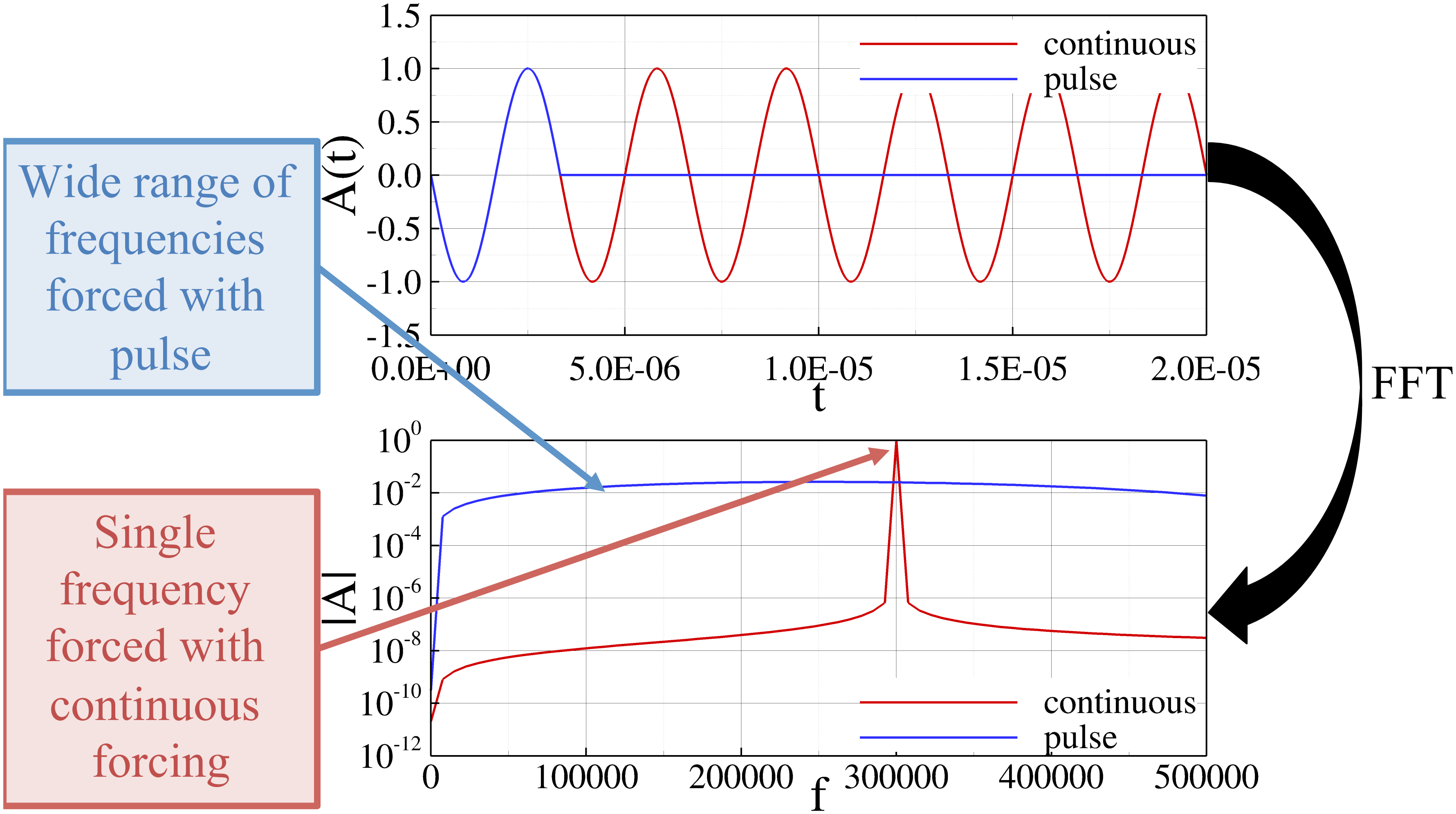
Continuous vs. Pulse forcing



Continuous vs. Pulse forcing



Continuous vs. Pulse forcing



- Note: with continuous forcing we can accurately control the frequency of the disturbance waves that are introduced

How to initiate laminar-turbulent transition?

- We initiate a so called “controlled” breakdown

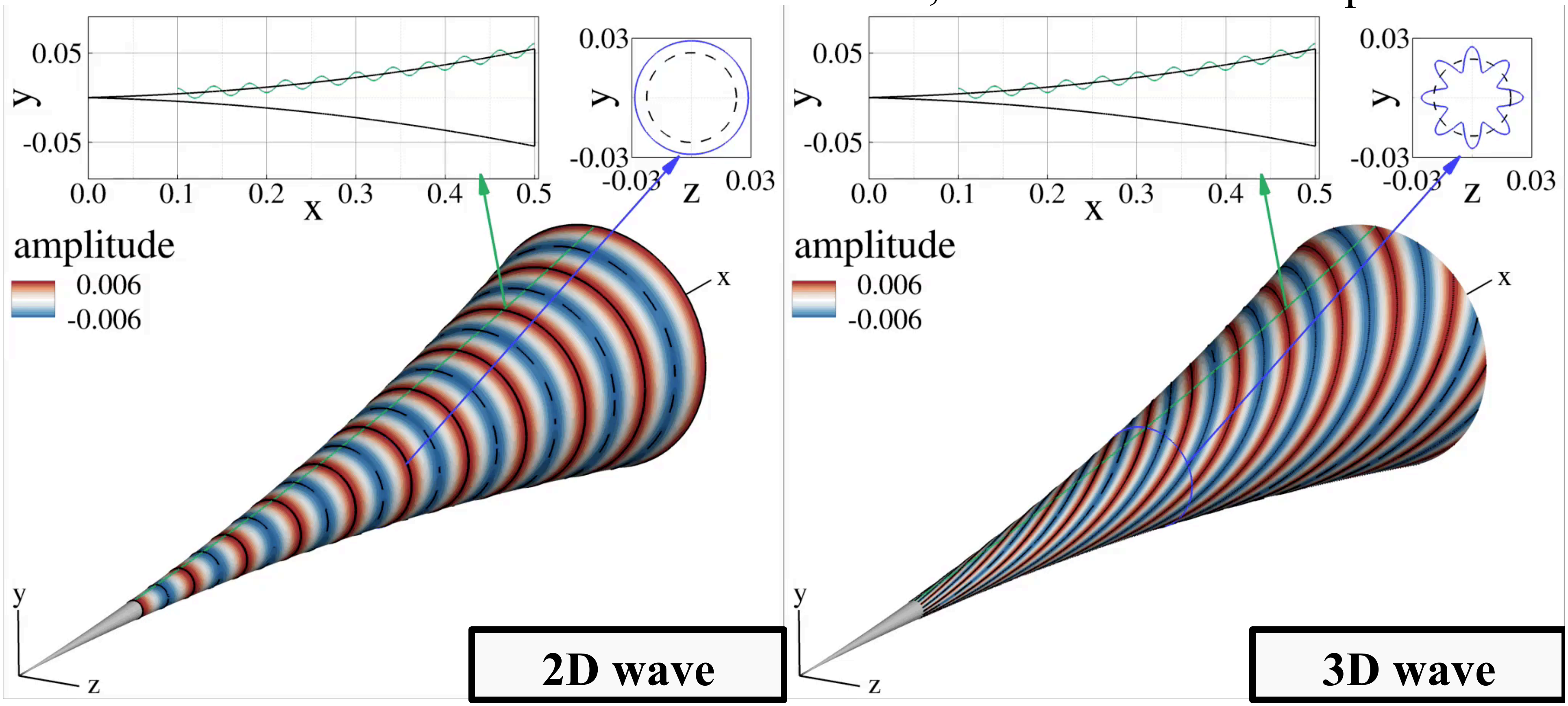
- Through continuous forcing of …
  - a 2D disturbance wave: so-called **primary wave**
  - a 3D disturbance wave: so-called **secondary wave**
  - Both waves have the same frequency f_0 (primary wave frequency)

- This “controlled” breakdown scenario is called the **fundamental resonance scenario**

What are 2D and 3D waves?

- **2D waves:** axisymmetric, wave fronts are orthogonal to x-axis, no modulation in azimuthal direction

- **3D waves:** modulation in azimuthal direction, wave fronts are oblique w.r.t. x



What do we mean by disturbance waves?

- We introduce waves (denoted by a $'$) that "disturb" the laminar base flow

- **Disturbance ansatz:**

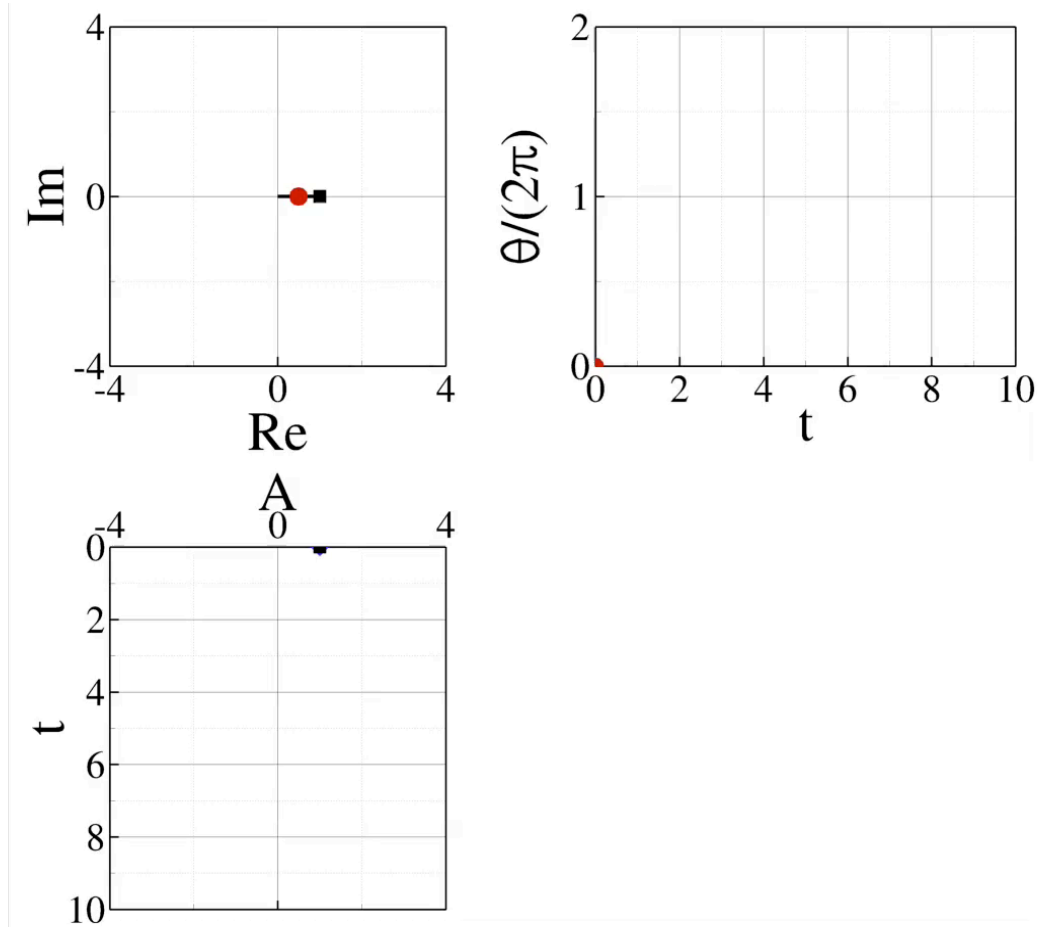
$$\phi = \phi_{\text{base flow}} + \phi'$$

- **Travelling wave ansatz:**

$$\phi' = \phi(y) e^{-\alpha_i x} e^{i(\alpha_r x + \beta_r - \omega_r t)}$$

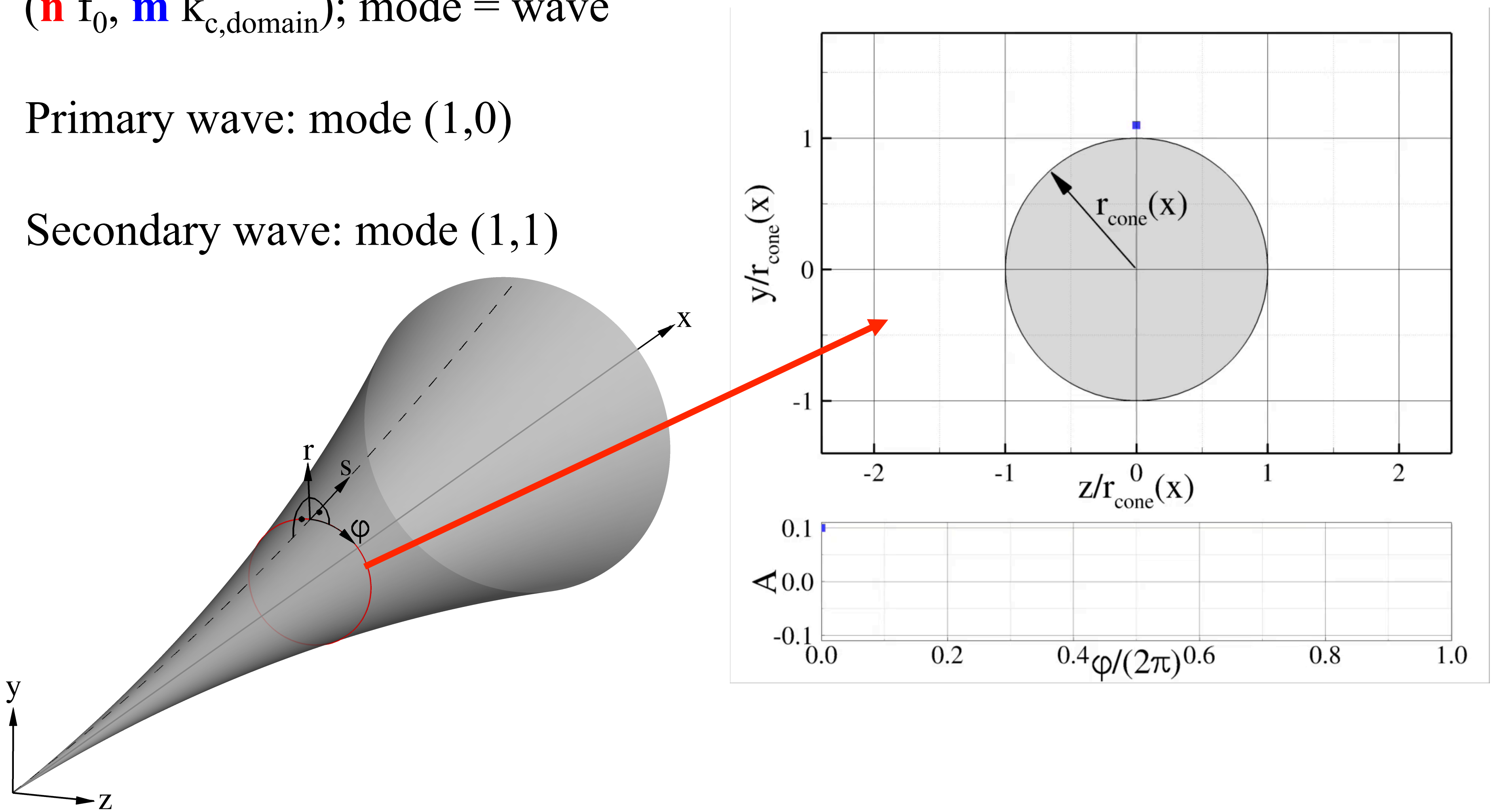
Growing/decaying part

Oscillatory part



Terminology

- mode (**n**,**m**) is shorthand notation for ($\mathbf{n}\ f_0$, $\mathbf{m}\ k_{c,domain}$); mode = wave
- Primary wave: mode (1,0)
- Secondary wave: mode (1,1)



How do we pick the input parameters?

- What do we need?
  1) A primary wave frequency f_0
  2) The wave number k_c of the secondary wave

- How to get f_0?
  Map out linear stability regime by running a pulse simulation
  Discussed in **Primary Wave** part

- How to get k_c of secondary wave?
  Parameter study of fundamental resonance onset
  Discussed in **Secondary Instability** part

Outline

Introduction

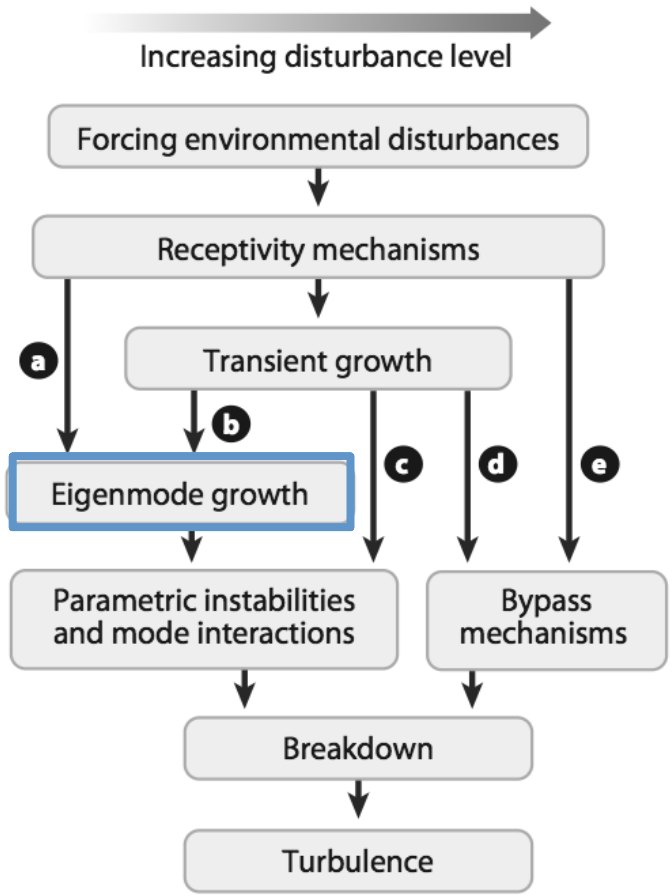
Geometry, Conditions and Simulation Strategy

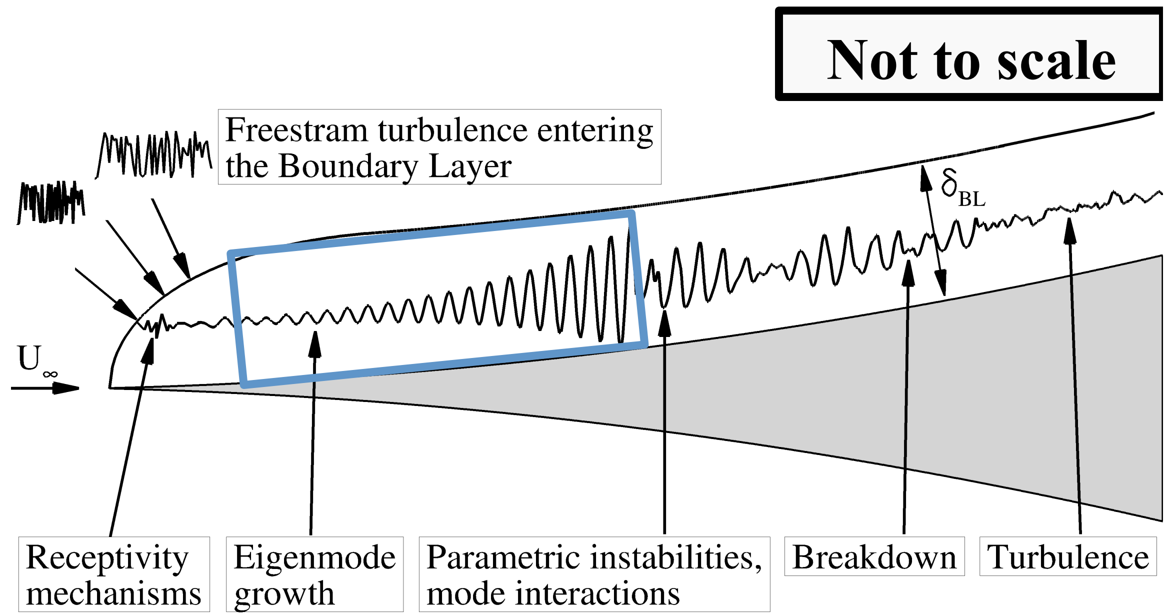
Primary Wave

Secondary Instability

Fundamental Breakdown

Primary Wave



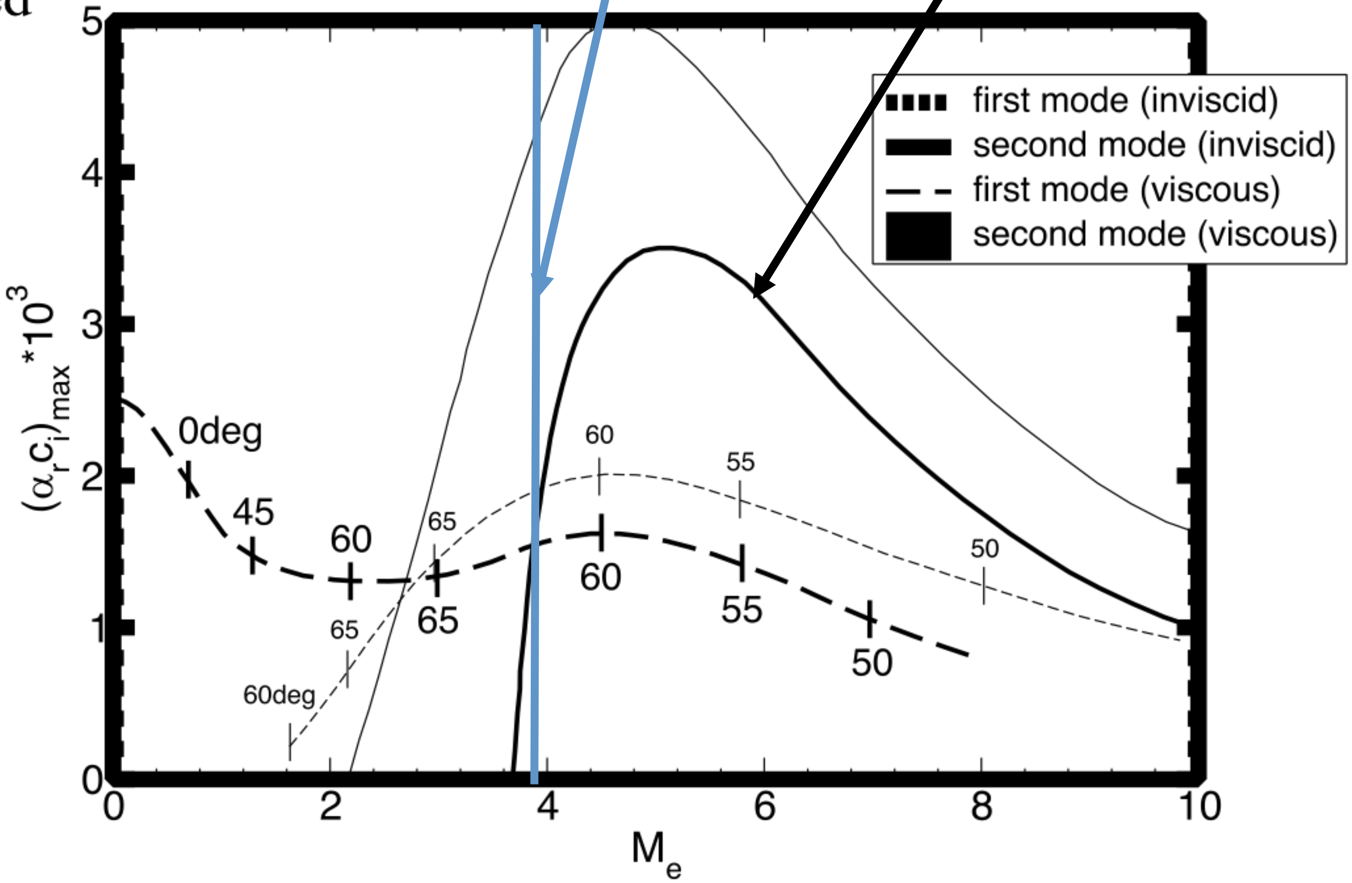


Eigenmode growth – linear behavior

Goal: Find most amplified 2D wave

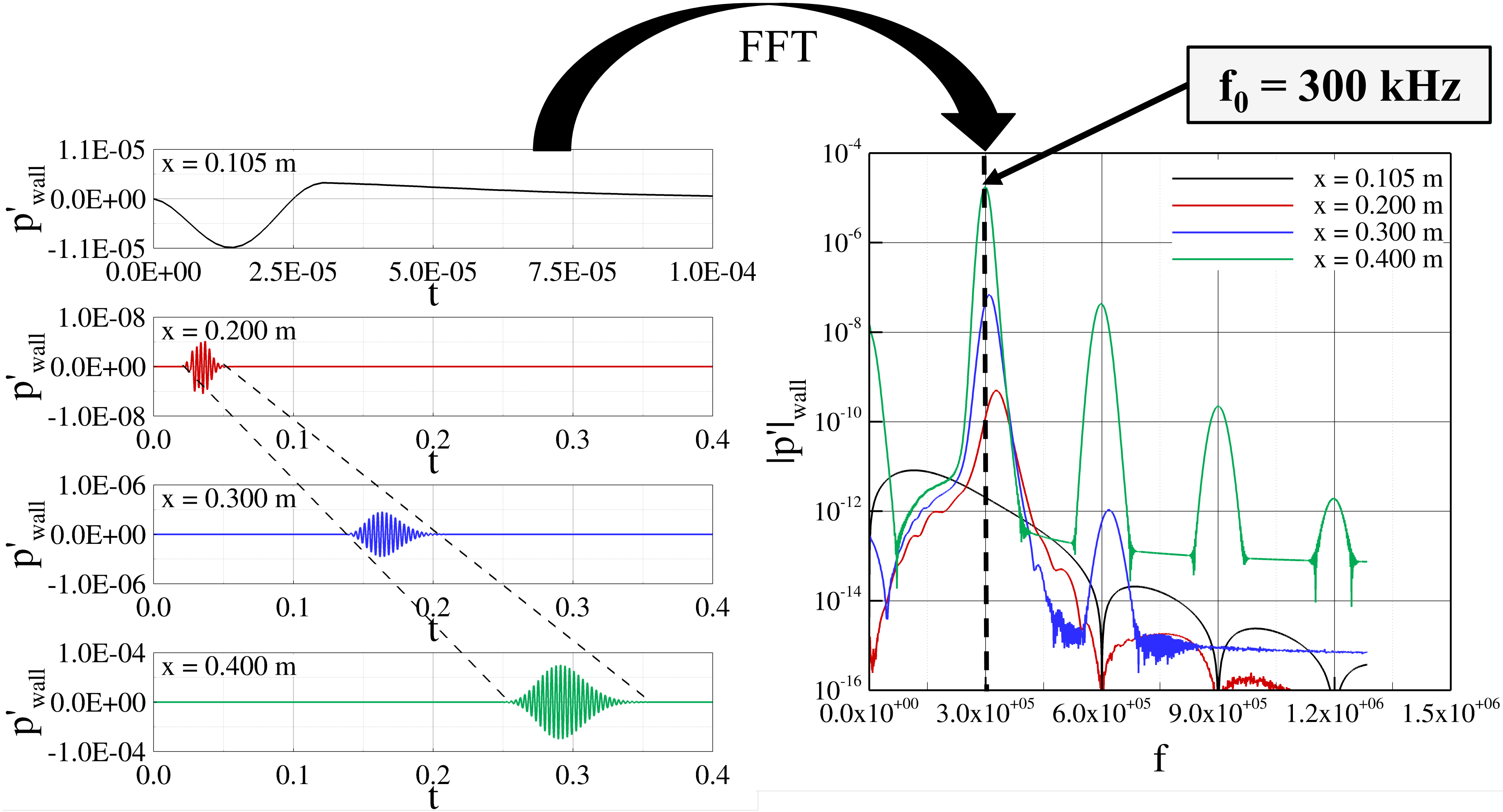
Why 2D wave?

- Extensive research on compressible Linear Stability Theory by L. Mack
- Once we exceed a certain **Mach number (≈ 4)** the **2D modes** are most amplified



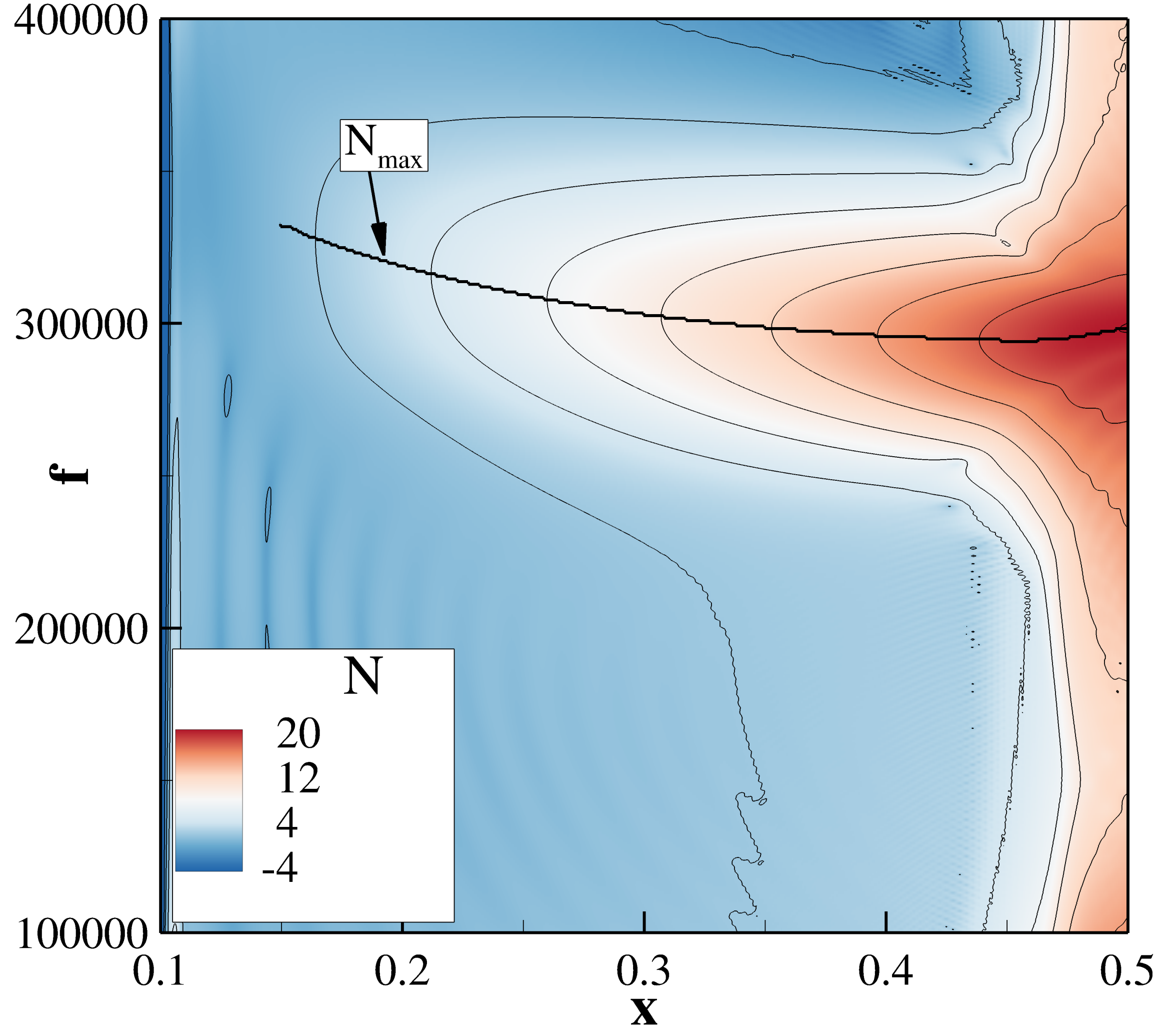
Primary Wave

- Axisymmetric pulse simulations to map out linear stability regime



Primary Wave

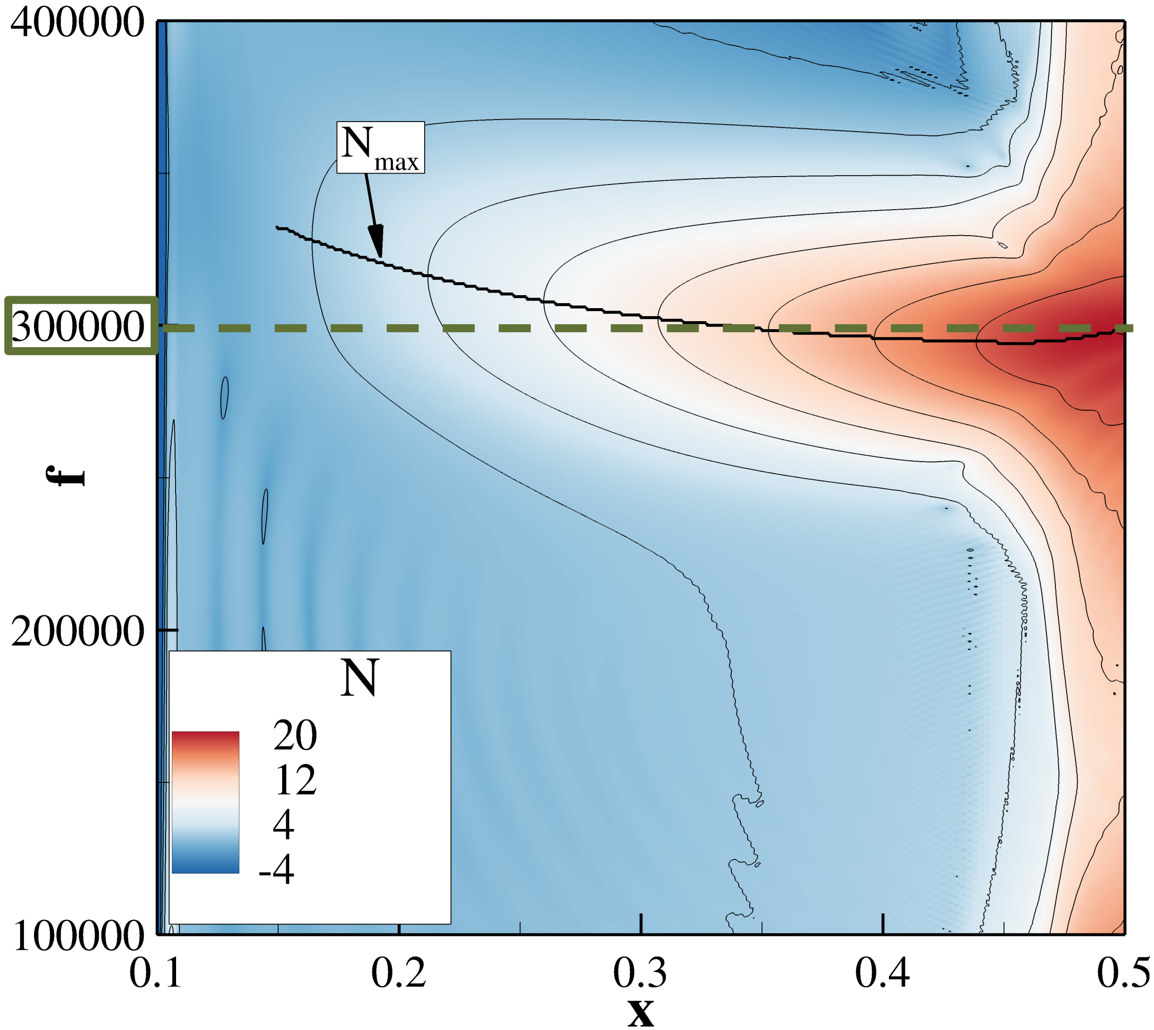
- **Definition:** $N = \ln(A(x)/A(x_0))$, where x_0 is the reference position
- It is a measure of how much a wave grows in downstream direction



M = 6
T_0 = 420 K
p_0 = 140 psi

Primary Wave

Choose primary wave frequency f_0 = 300 kHz



$M = 6$
$T_0 = 420$ K
$p_0 = 140$ psi

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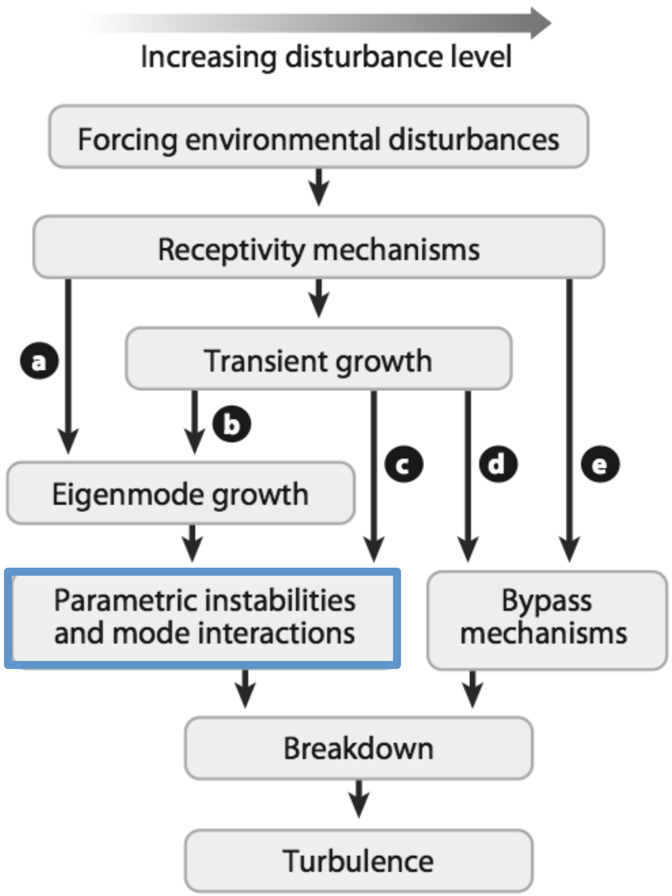
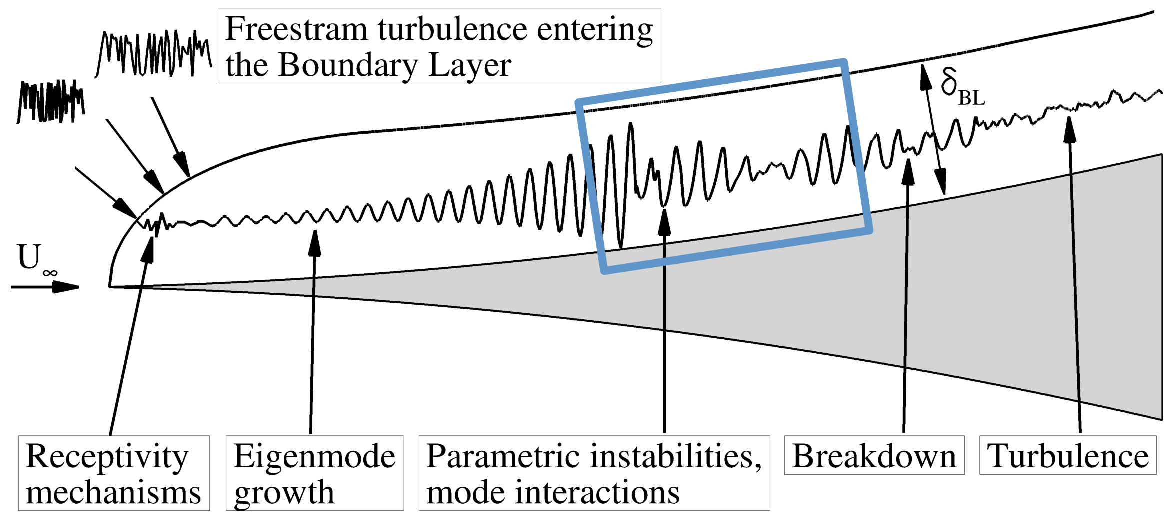
Secondary Instability



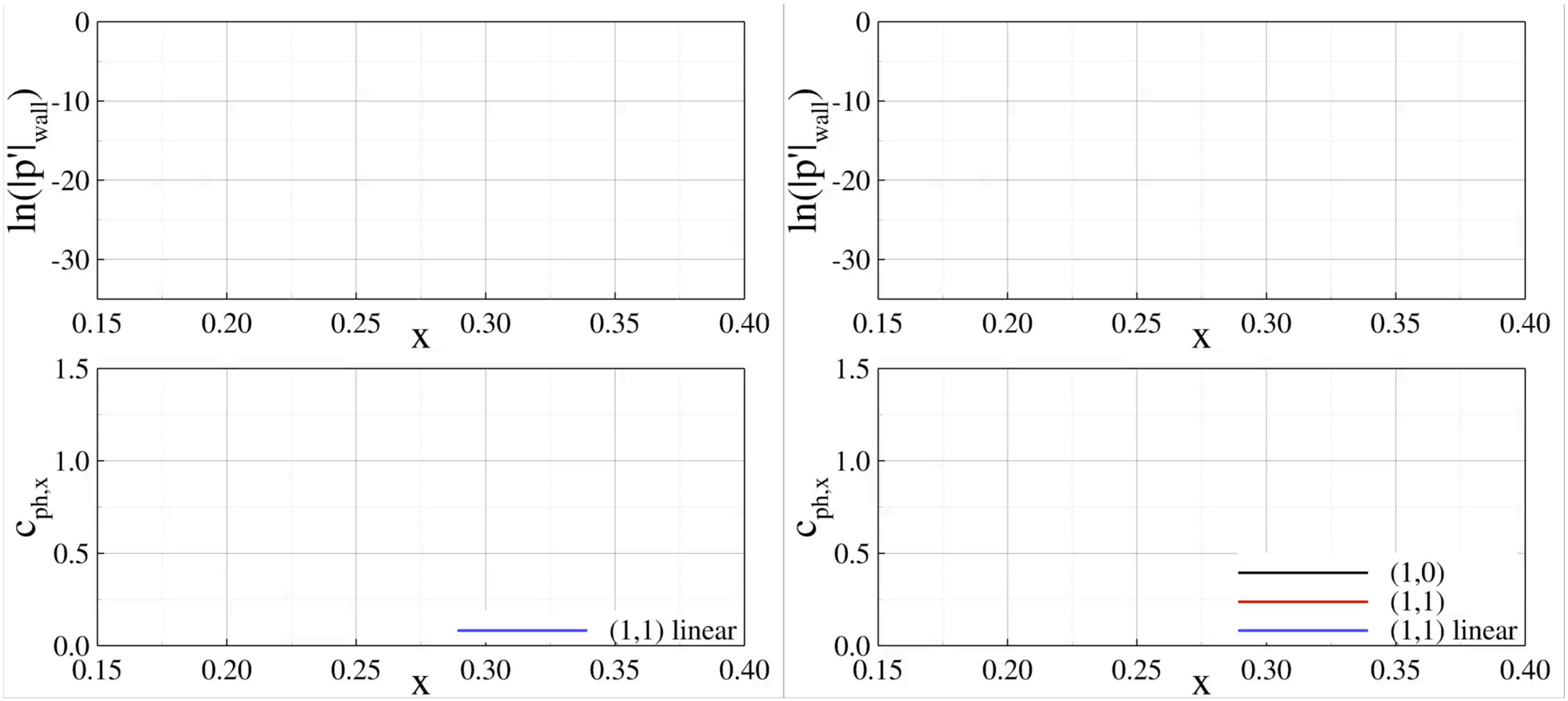


Mode interactions/resonance

Goal: Find 3D wave that experiences strongest growth after resonance

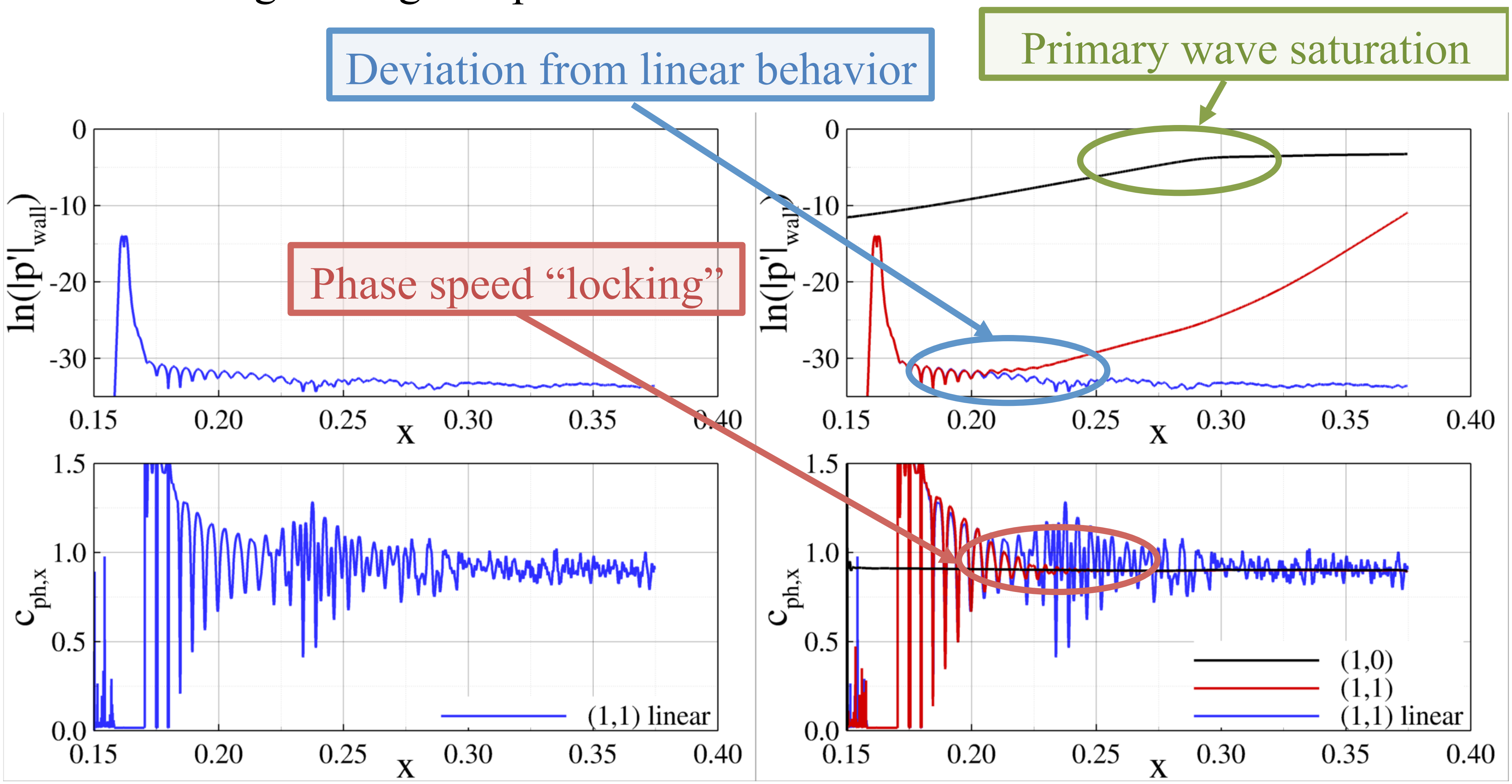
Fundamental Resonance Onset

- How does the behavior of the secondary wave change when force by itself and when forced in the presence of a primary wave



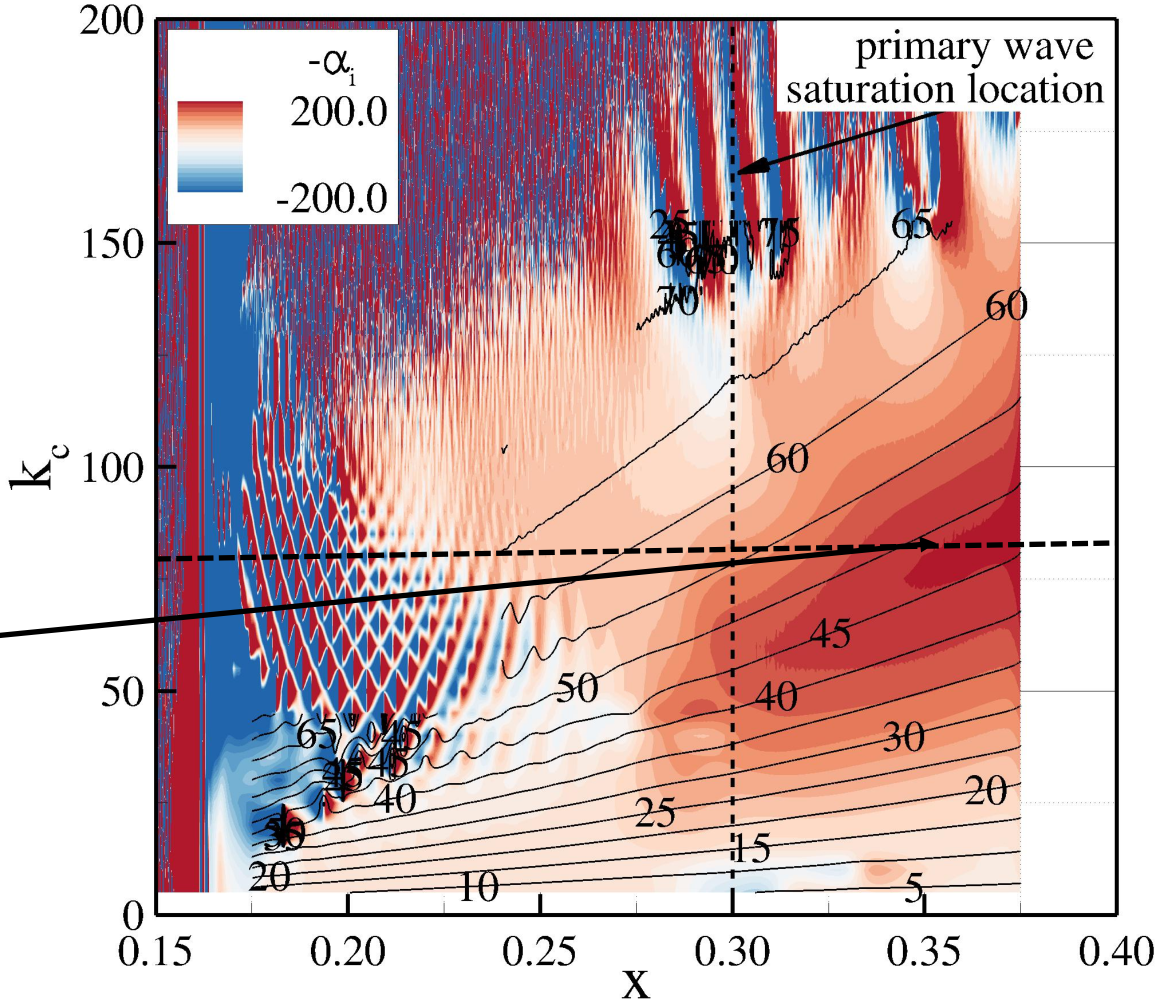
Fundamental Resonance Onset

- The secondary wave experiences strong growth once the primary wave reaches large enough amplitude => fundamental resonance



Growth Rate of Secondary Instability

- k_c of disturbance wave that experiences the strongest secondary growth rate changes in downstream direction
- Strongest secondary growth rate after **fundamental resonance** onset: $\mathbf{k_c \approx 80}$



Parameters for Fundamental Resonance

- Disturbance input for fundamental breakdown simulation

- **Primary wave (1,0):**
  - Frequency = 300 kHz
  - 2D: $k_c = 0$, no modulation in azimuthal direction

- **Secondary wave (1,1):**
  - Frequency = 300 kHz
  - 3D: $k_c = 80$ => 80 wavelengths around the circumference of the cone

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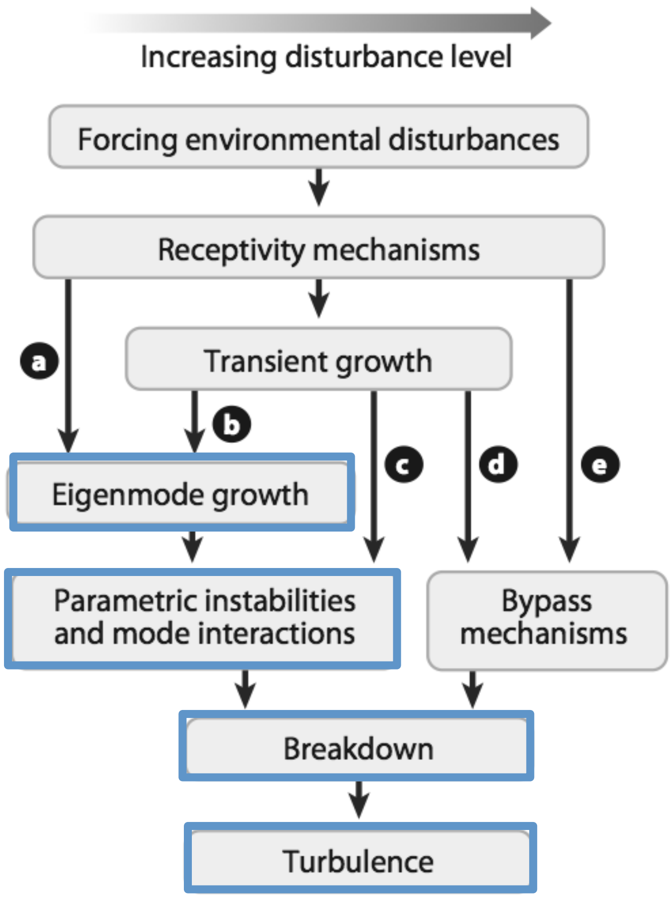
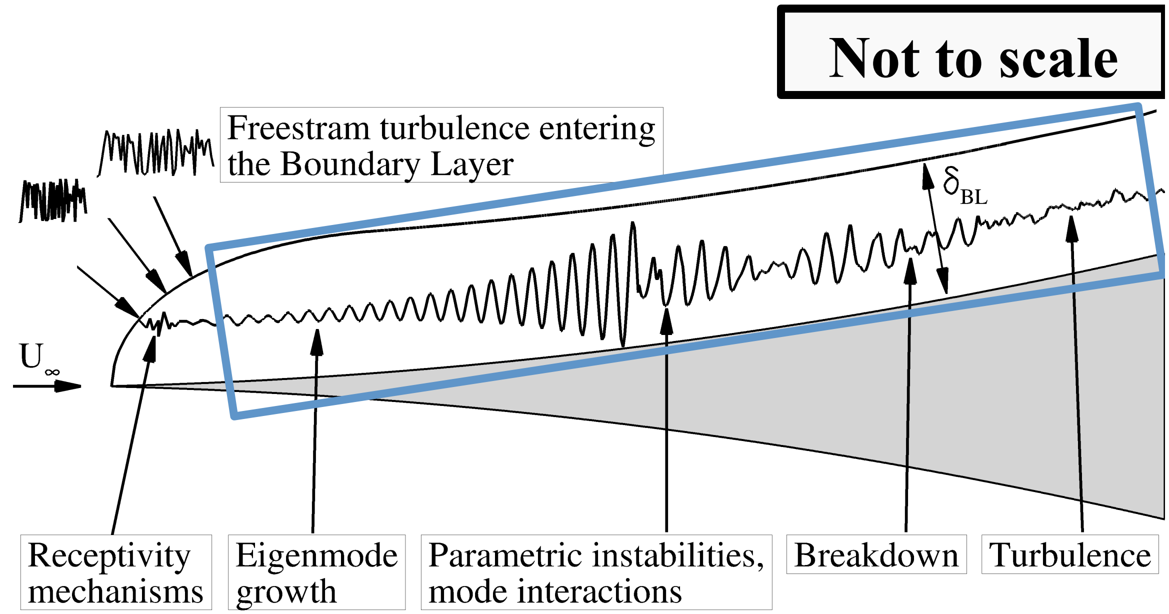
Fundamental Breakdown





All the way from linear growth to breakdown

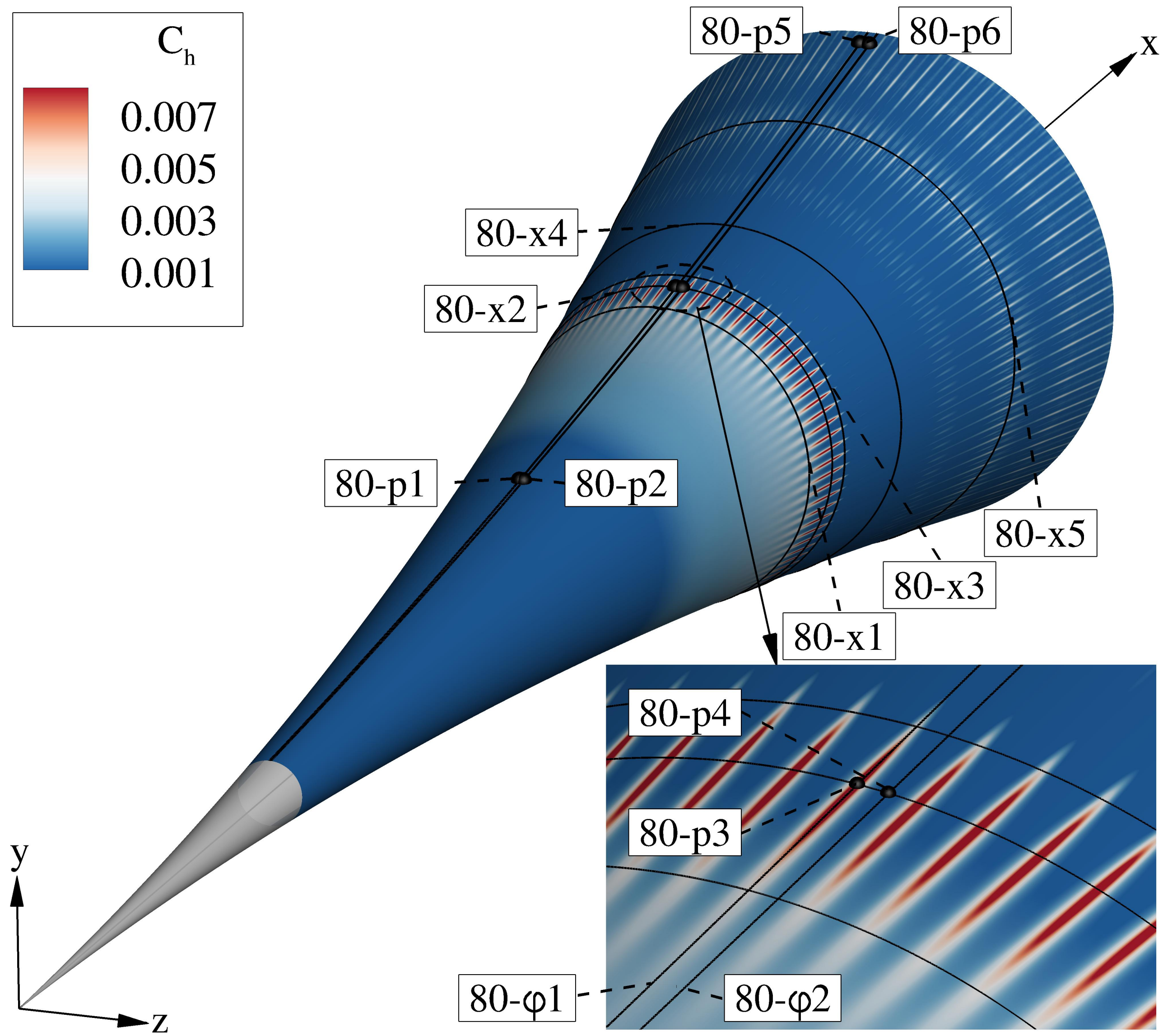
Fundamental Breakdown

- **Conditions:**
  - p_0 = 140 psi
  - T_0 = 420 K
  - $Re_1 = 10.82\ 10^6$ 1/m

- **Primary wave, mode (1,0)**
  - $f_{(1,0)}$ = 300 kHz
  - $k_{c,\ (1,0)}$ = 0 => 2D wave
  - $A_{(1,0)} = 10^{-4}$

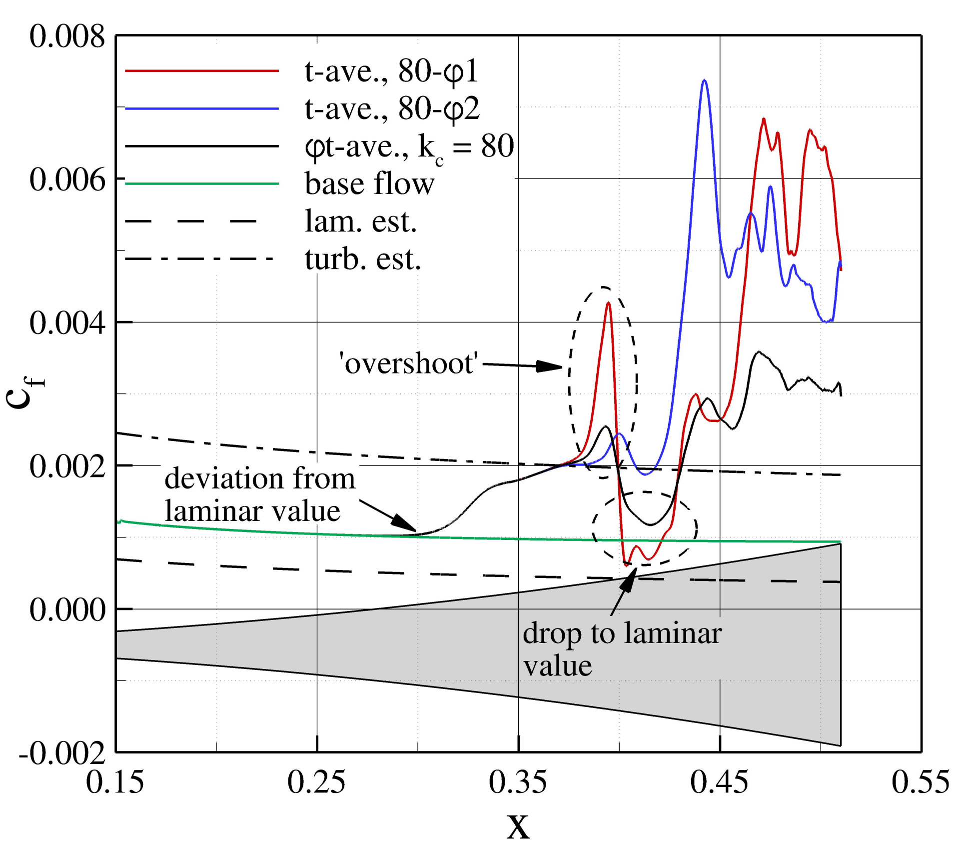
- **Secondary wave, mode (1,1)**
  - $f_{(1,1)}$ = 300 kHz
  - $k_{c(1,1)}$ = 80 => 3D wave
  - $A_{(1,1)} = 10^{-2}$

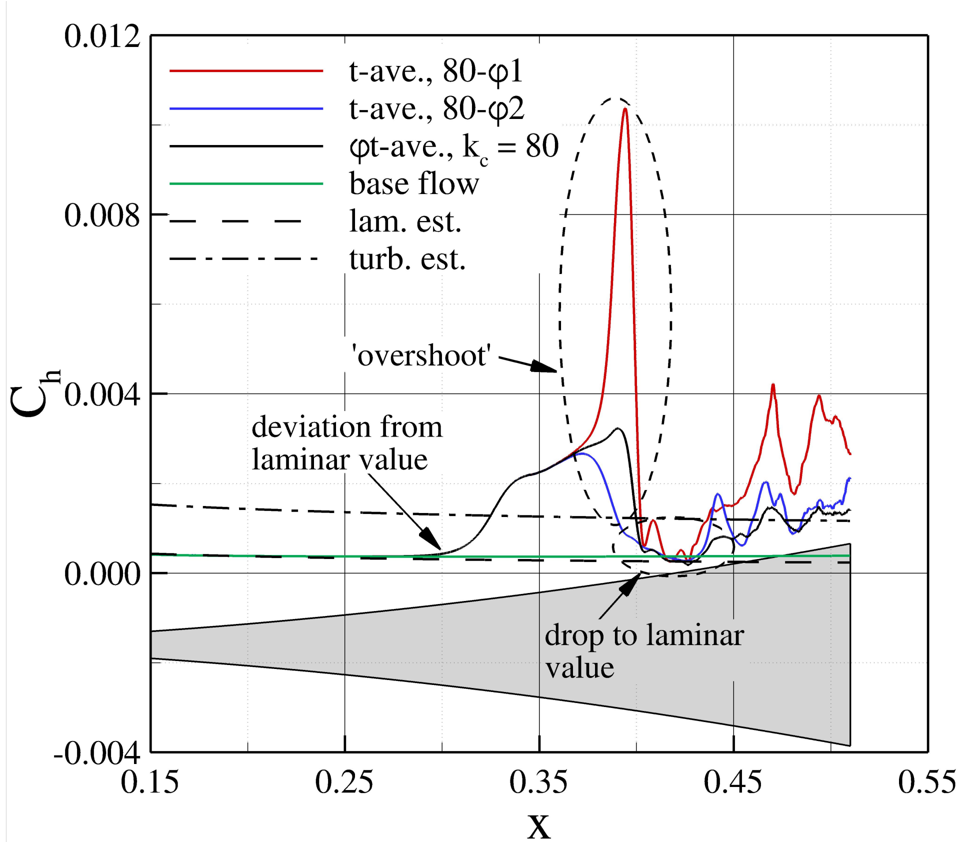
Fundamental Breakdown



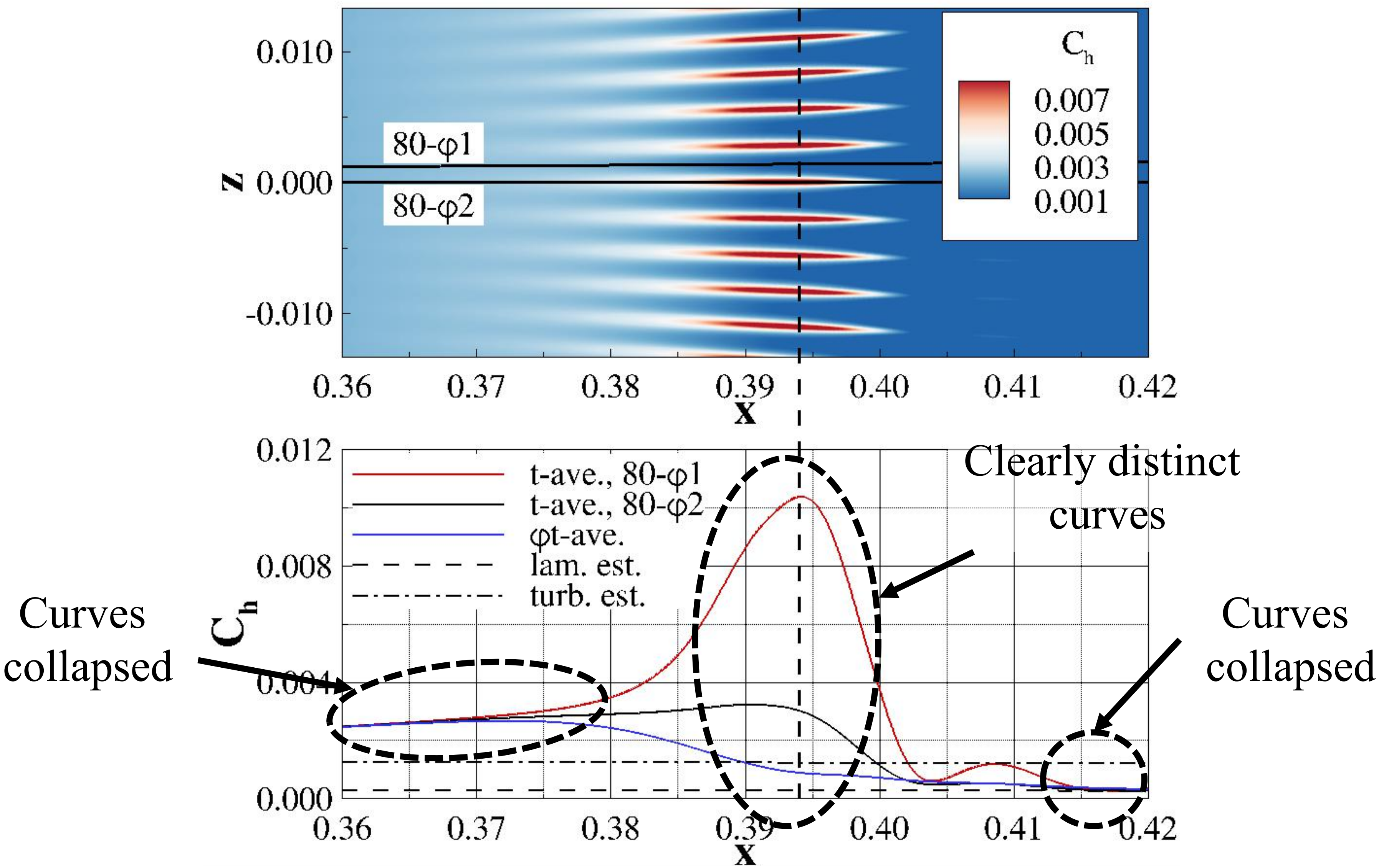
Fundamental Breakdown

- ‘Overshoots’ in Stanton number and skin-friction coefficient compared to turbulent estimate

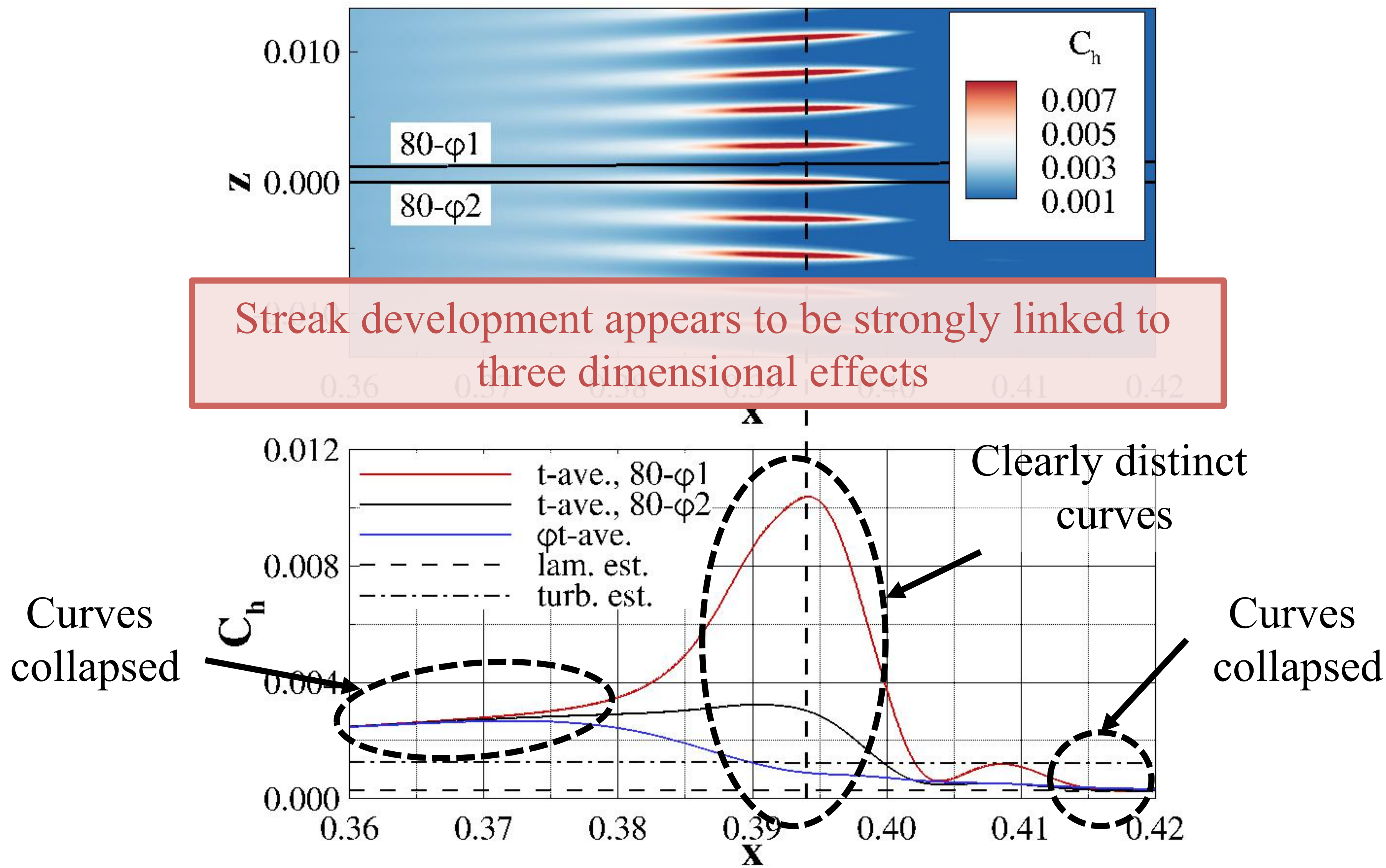




Fundamental Breakdown



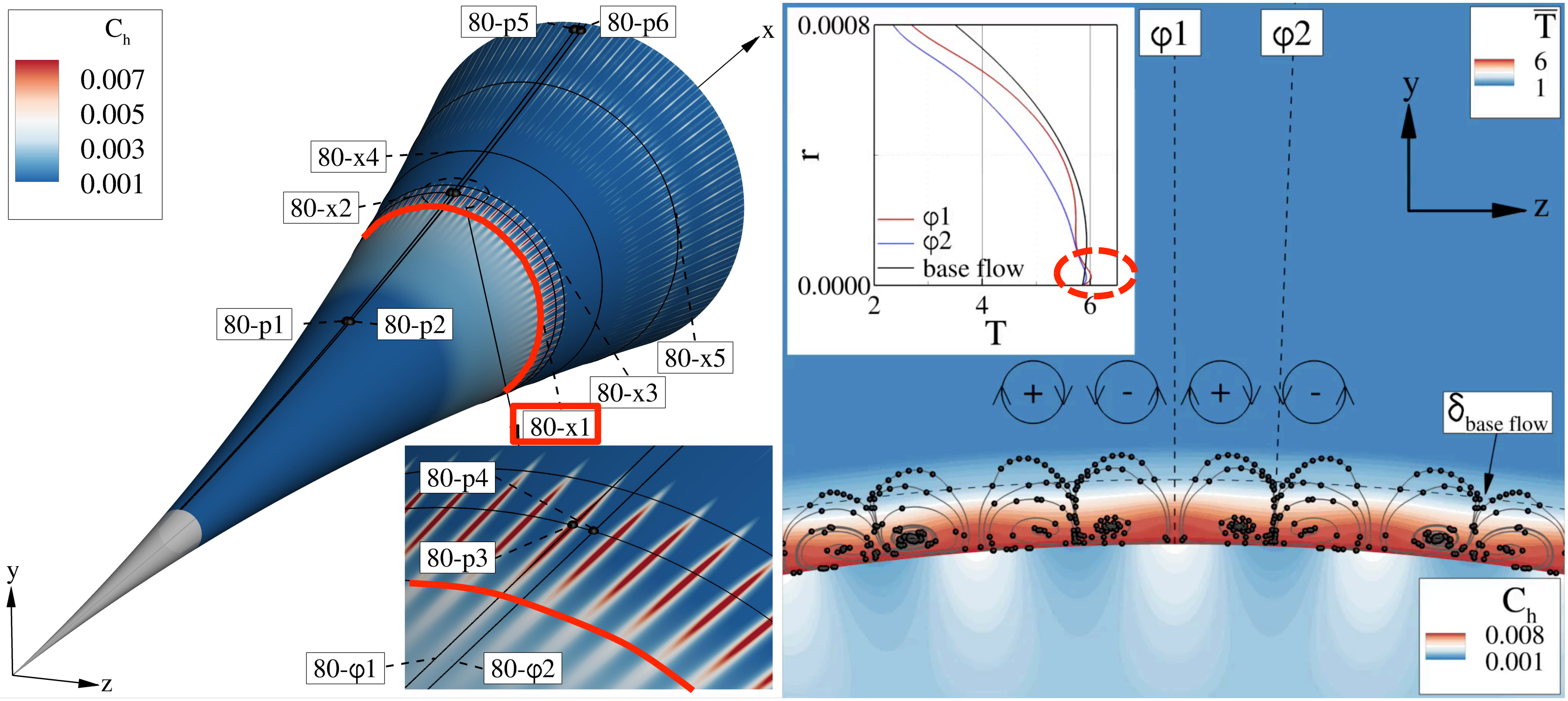
Fundamental Breakdown



Streak development appears to be strongly linked to three dimensional effects

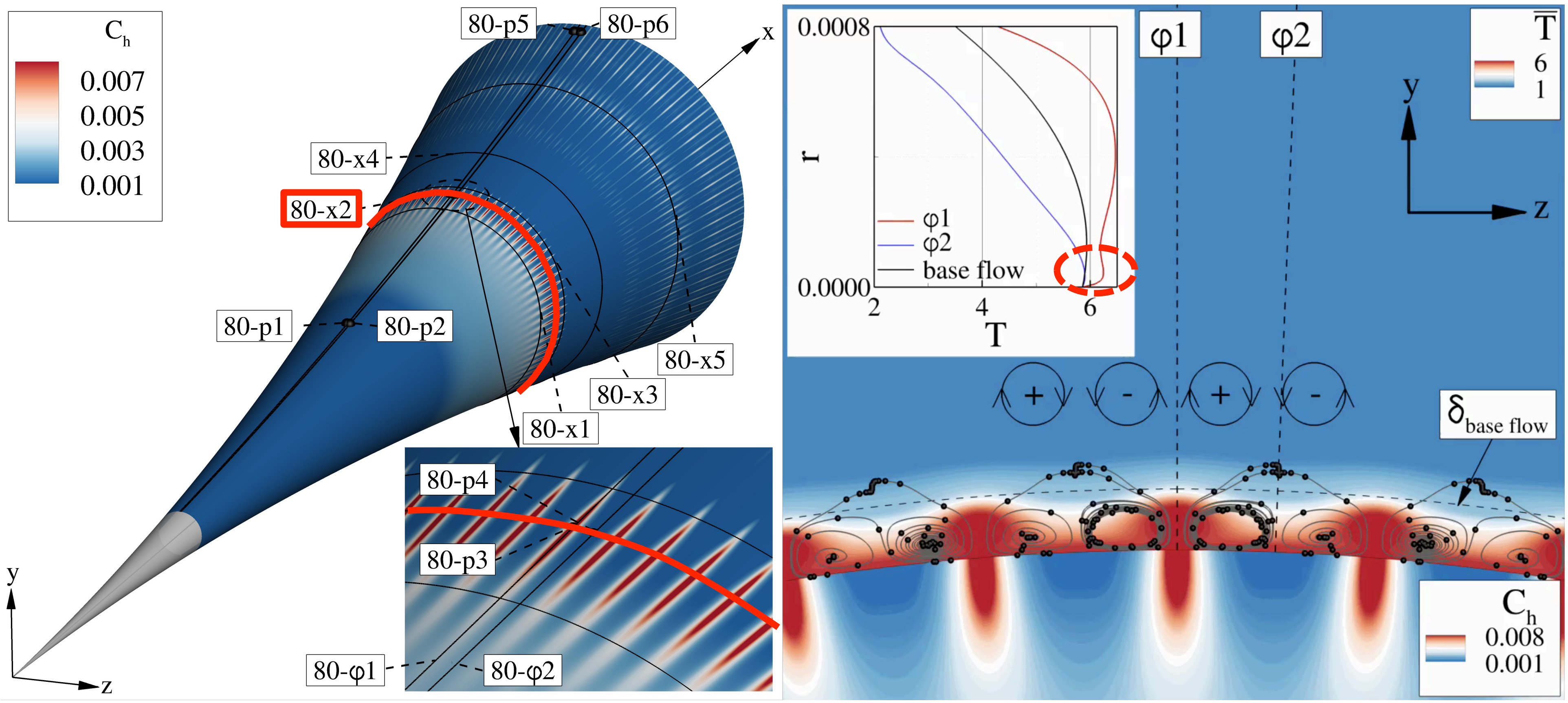
Fundamental Breakdown

- Streaks appear (80-x1)
- Streamwise vortices form when streaks begin to appear



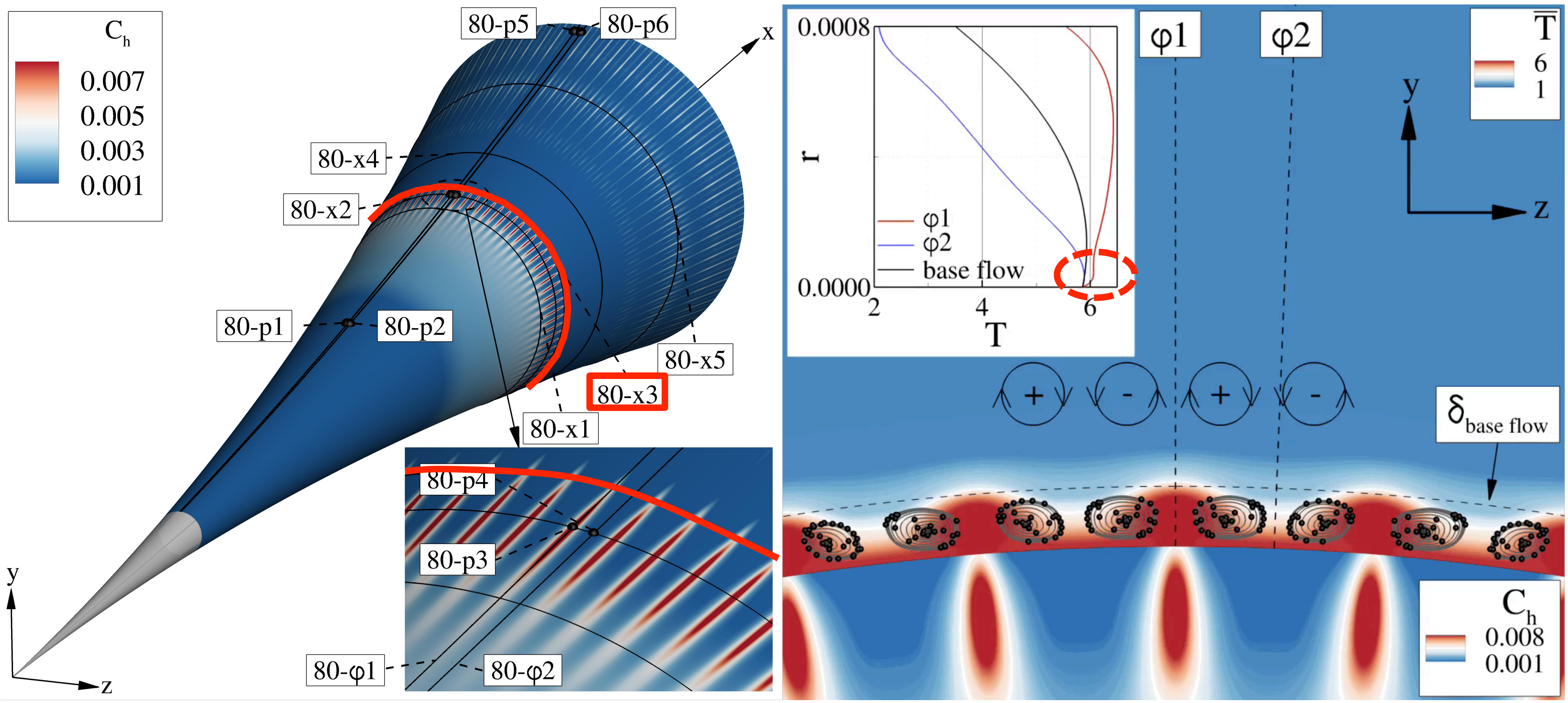
Fundamental Breakdown

- Location where Stanton number becomes maximal (80-x2)



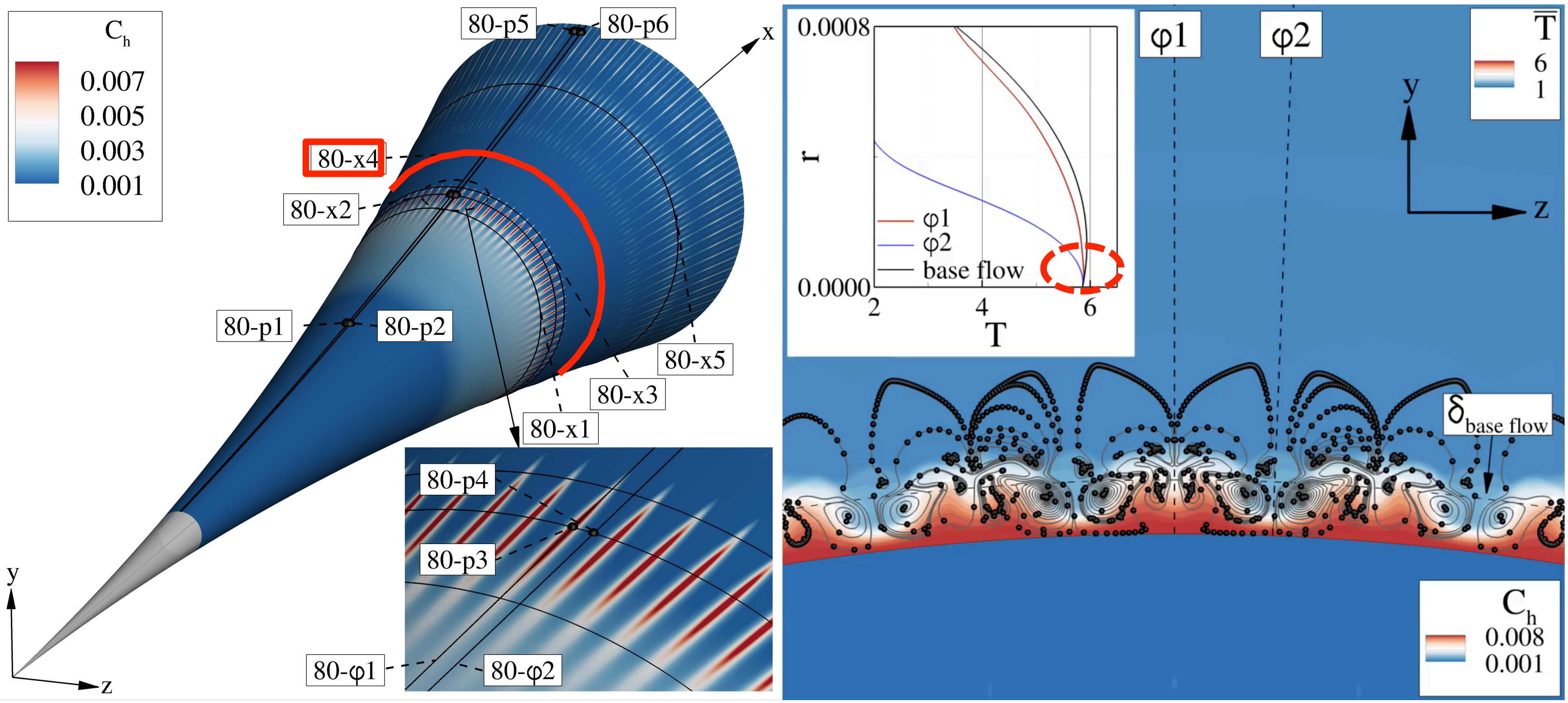
Fundamental Breakdown

- Streaks begin to fade (80-x3)



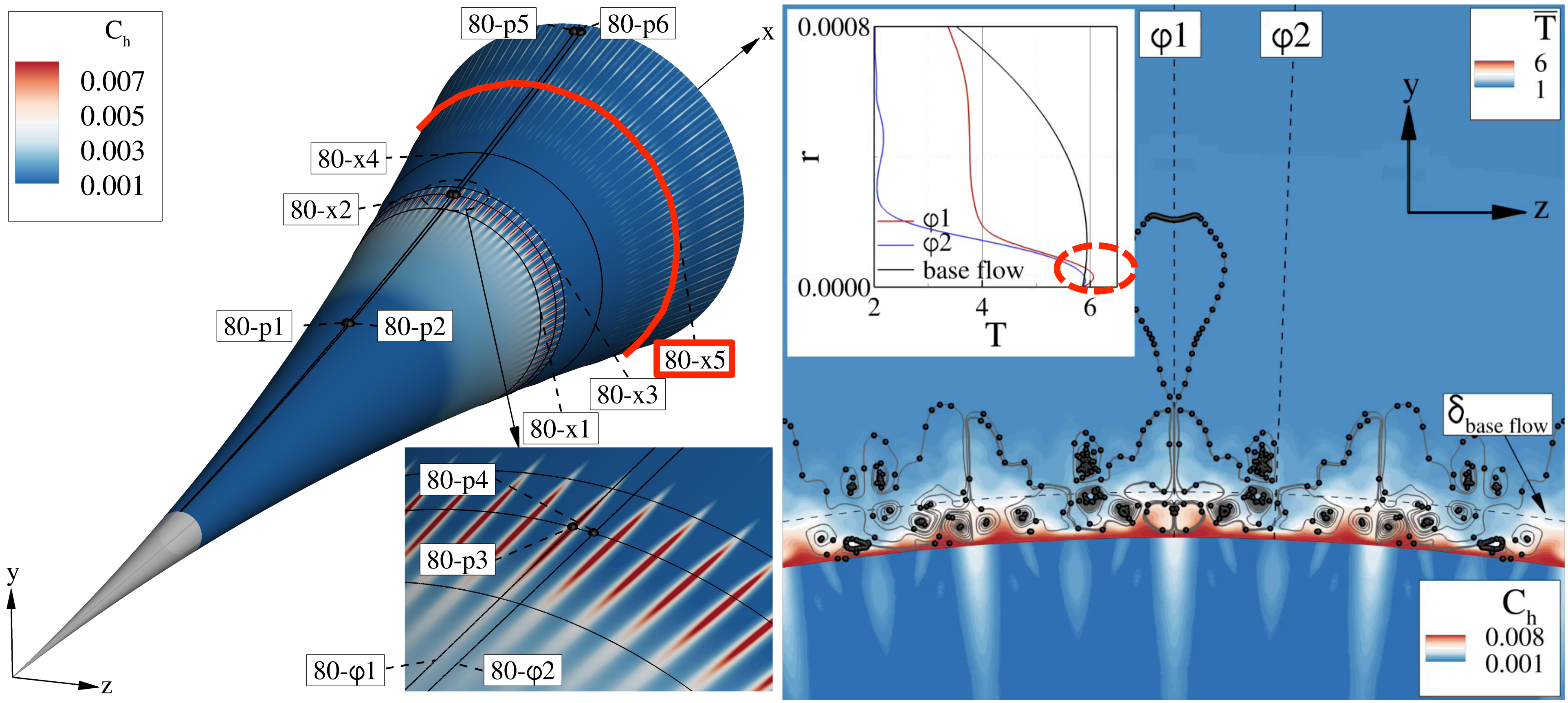
Fundamental Breakdown

- Streaks disappeared (80-x4)



Fundamental Breakdown

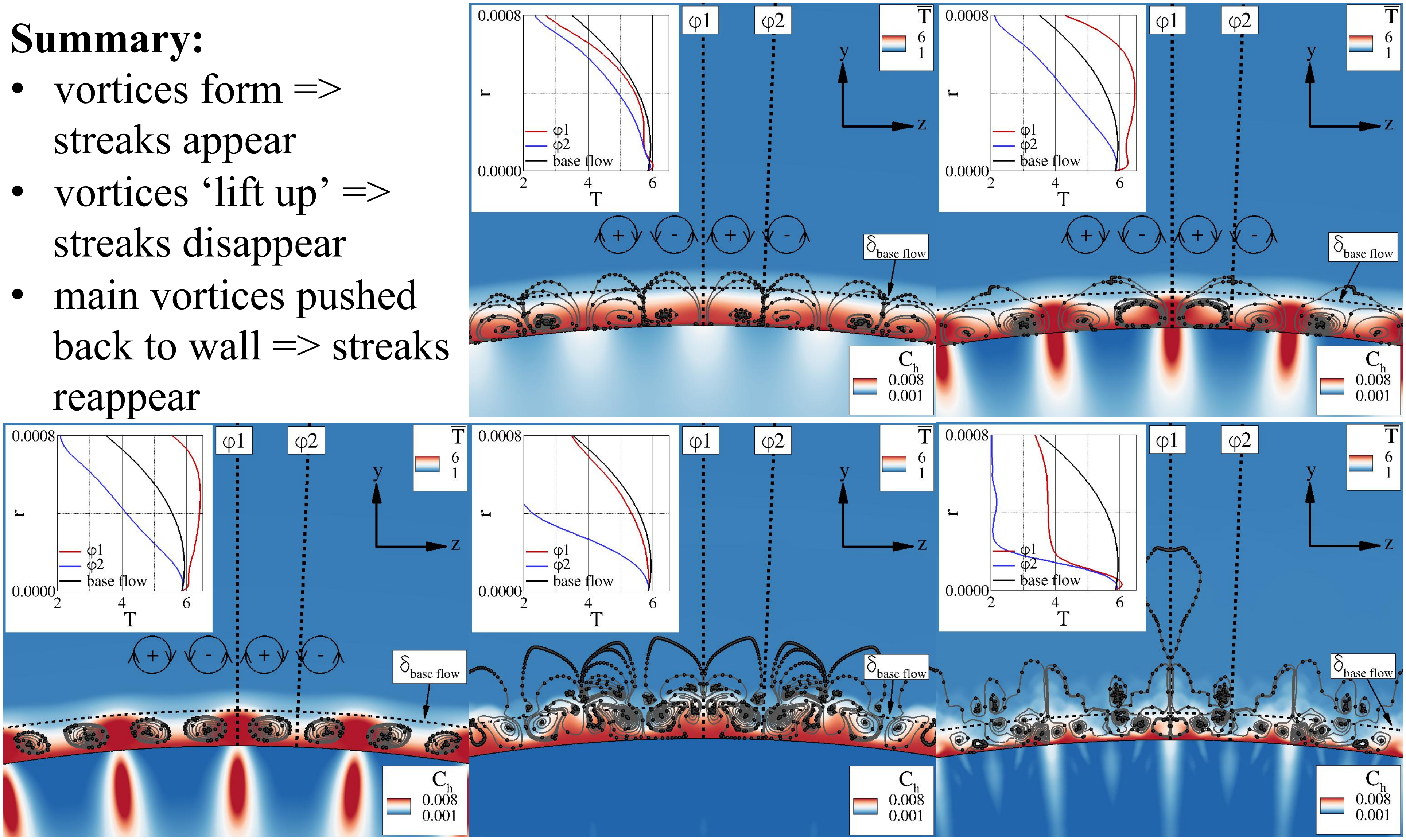
- Streaks reappear (80-x5)



Fundamental Breakdown

Summary:

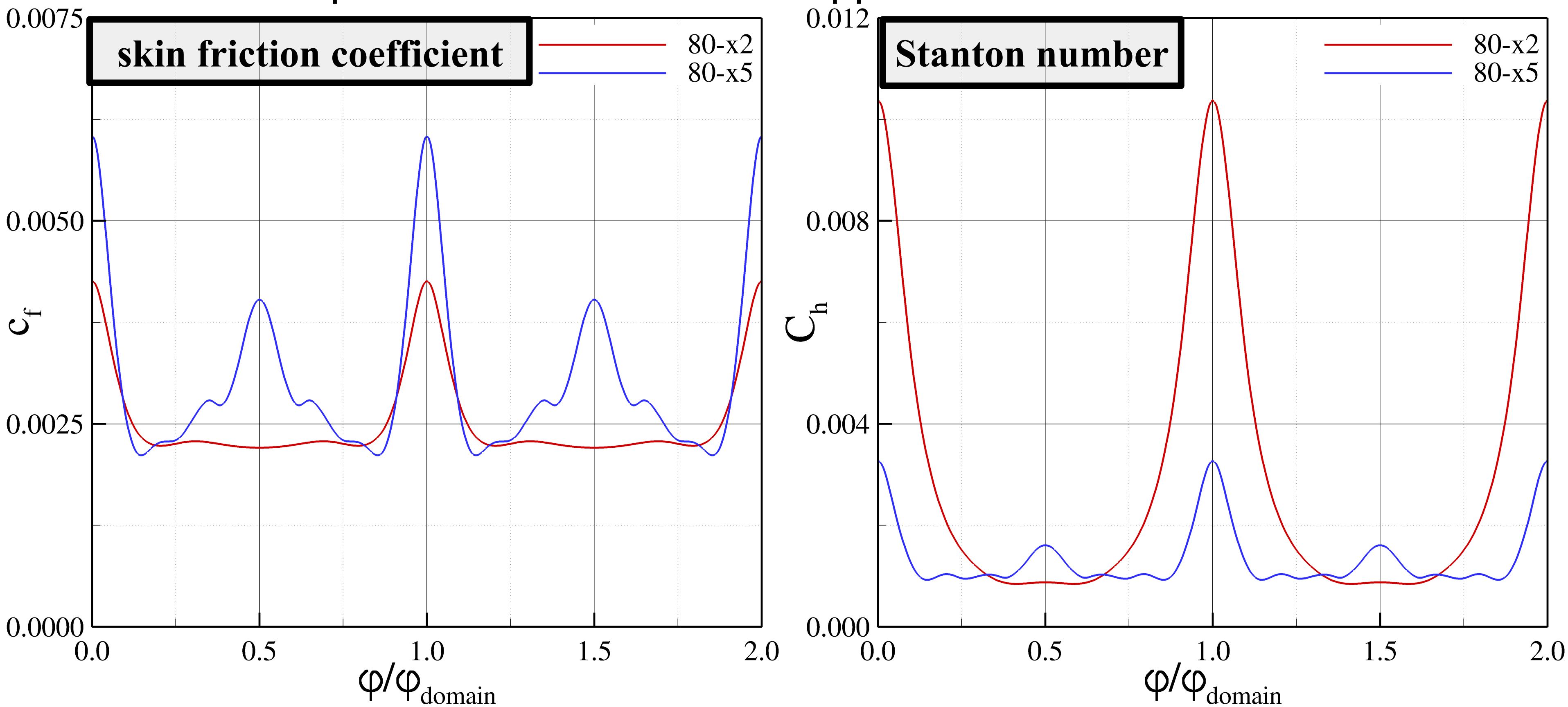
- vortices form => streaks appear
- vortices 'lift up' => streaks disappear
- main vortices pushed back to wall => streaks reappear



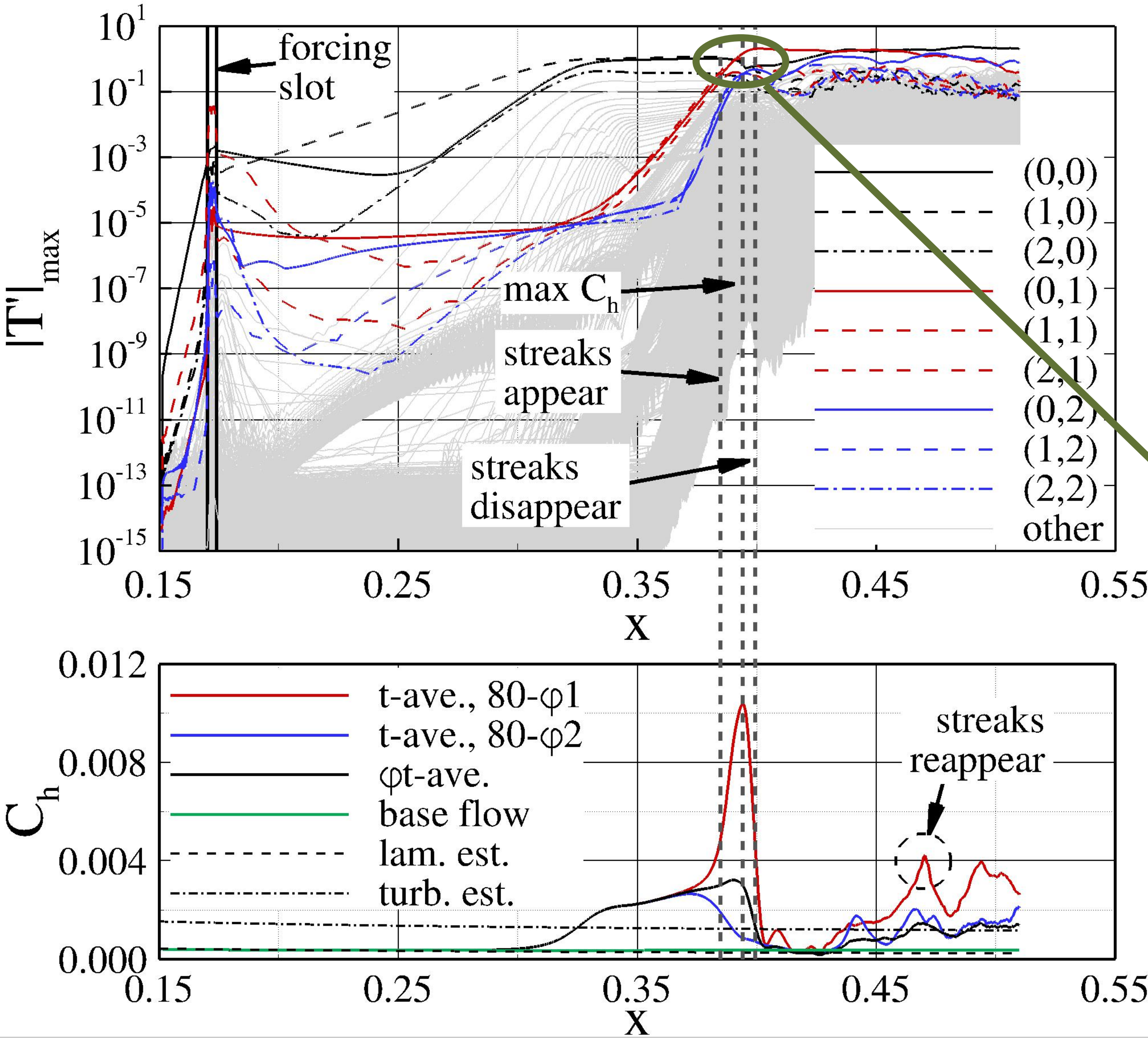
How many streaks are there?

- 80 streaks at position where streaks first appear (corresponding to wave number of secondary wave)

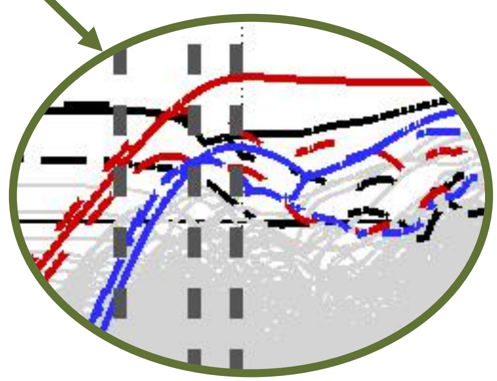
- 160 streaks at position where streaks reappear



Fundamental Breakdown

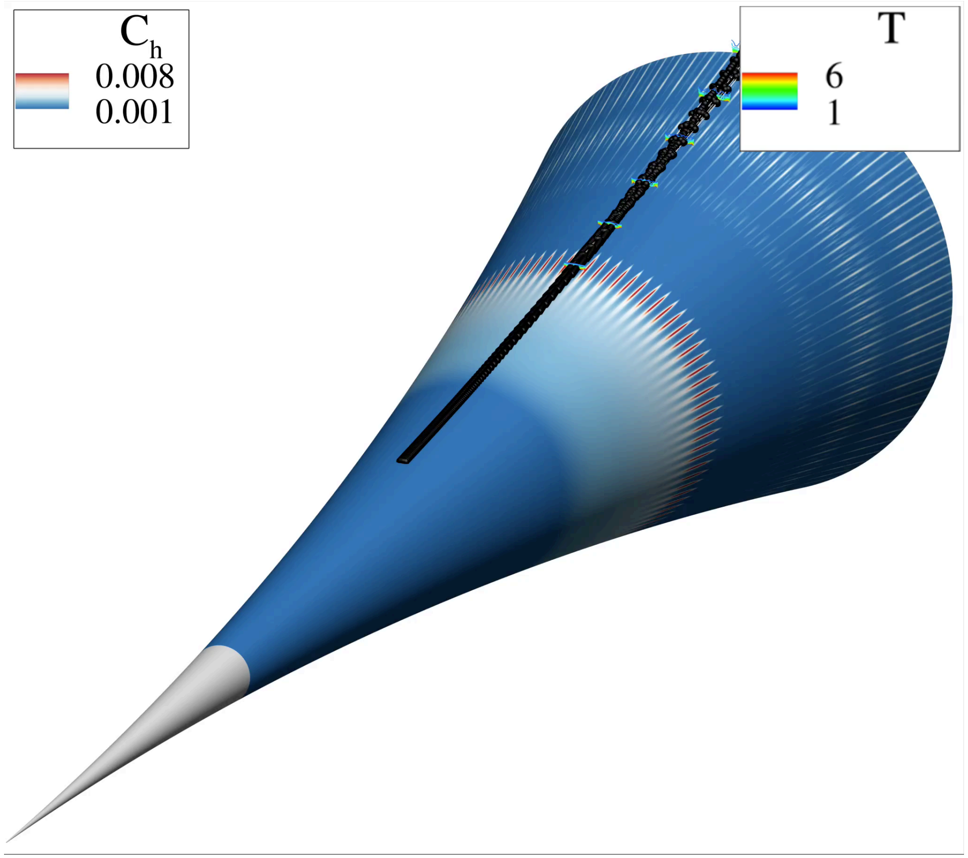


- Mode (0,1) becomes dominant when streaks appear ($|T'|_{max}$)
- Streaks are linked to steady longitudinal vortex modes



Fundamental Breakdown

- How do the streamlines look in 3D?



Fundamental Breakdown

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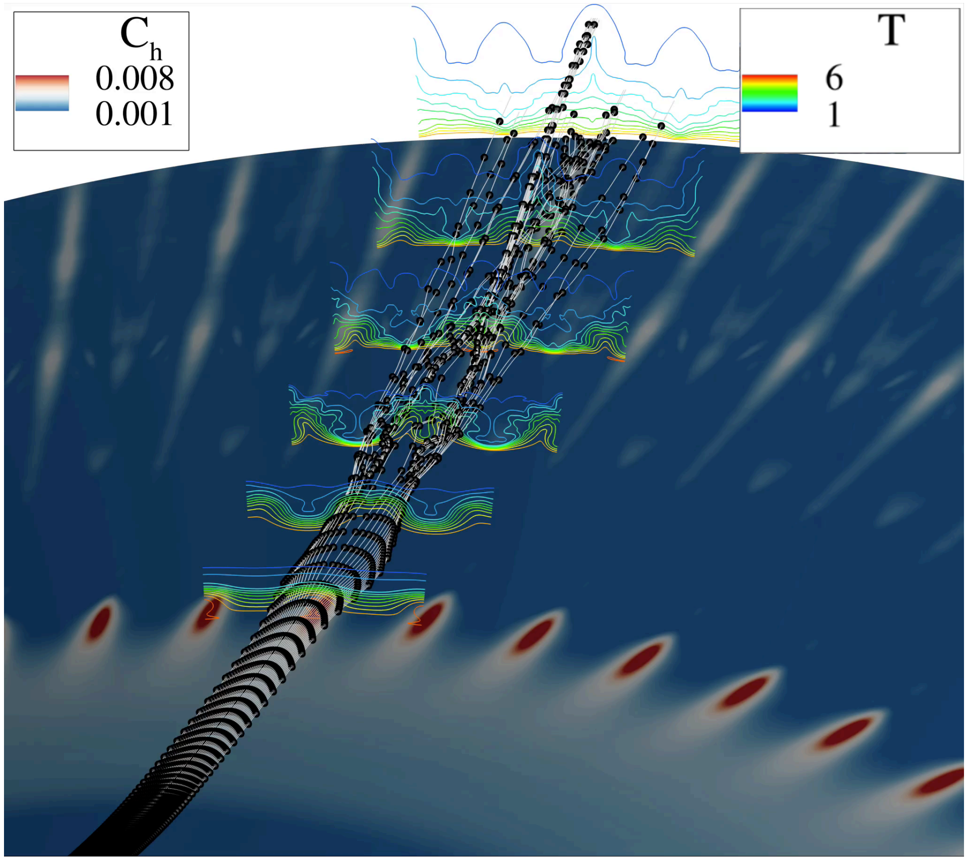
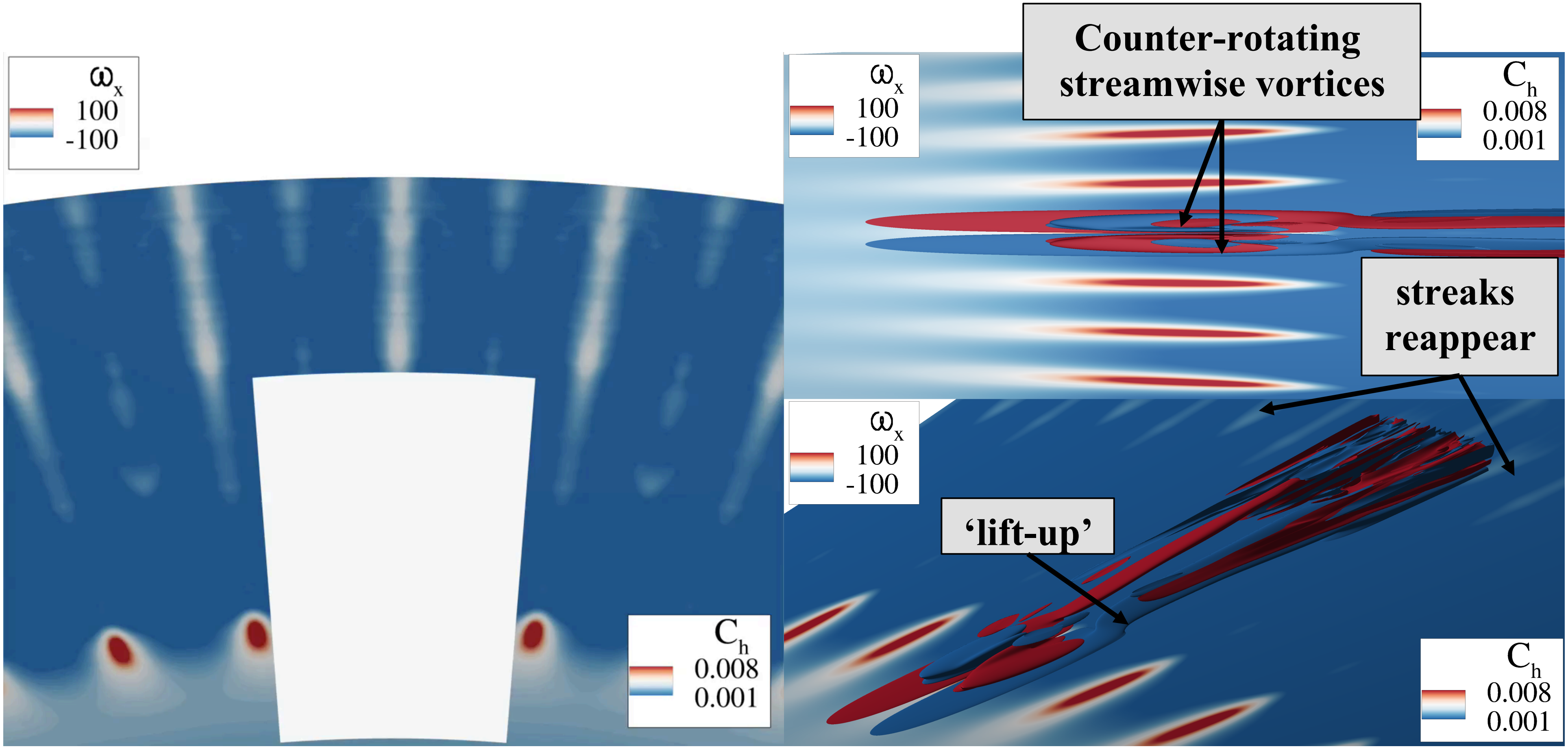


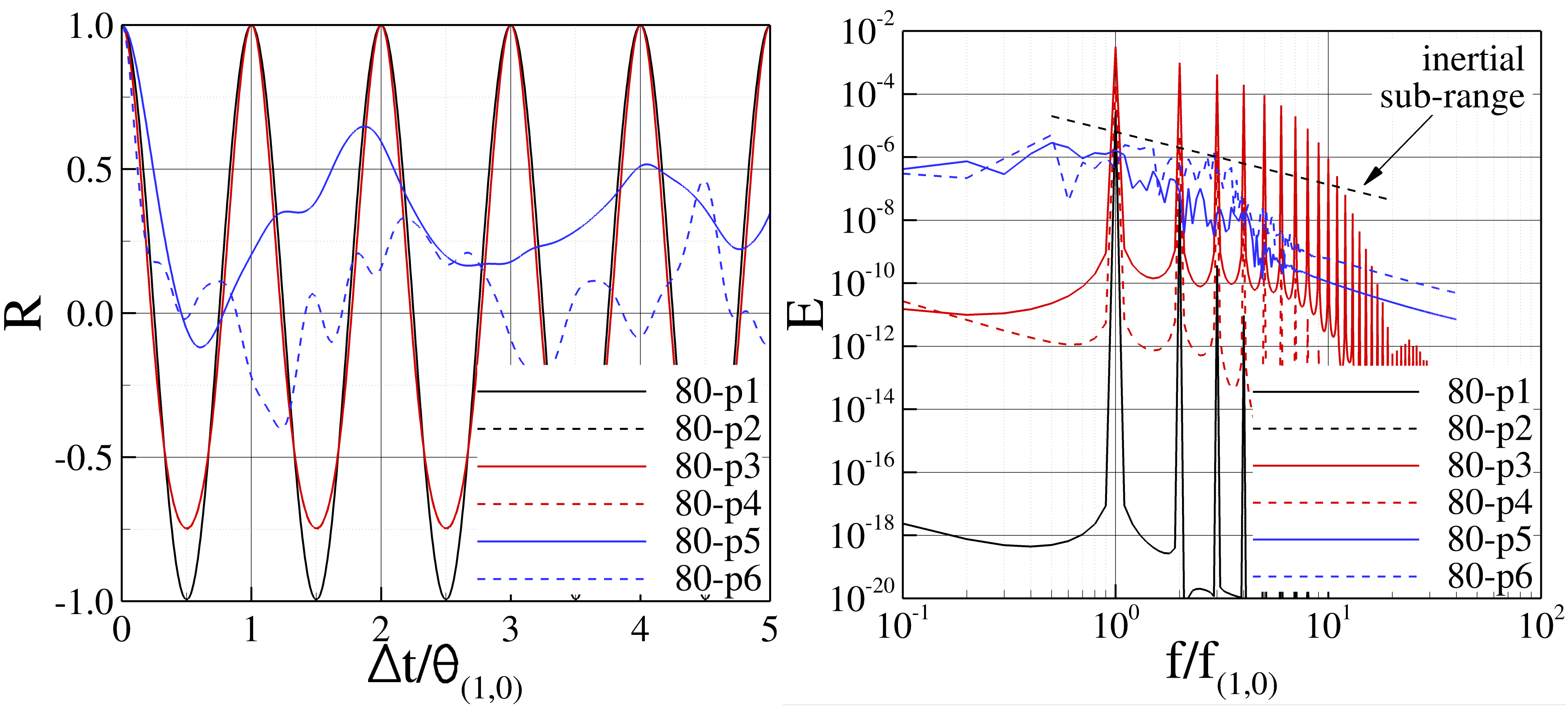
Fundamental Breakdown

- Visualizes streamwise streaks with ω_x'



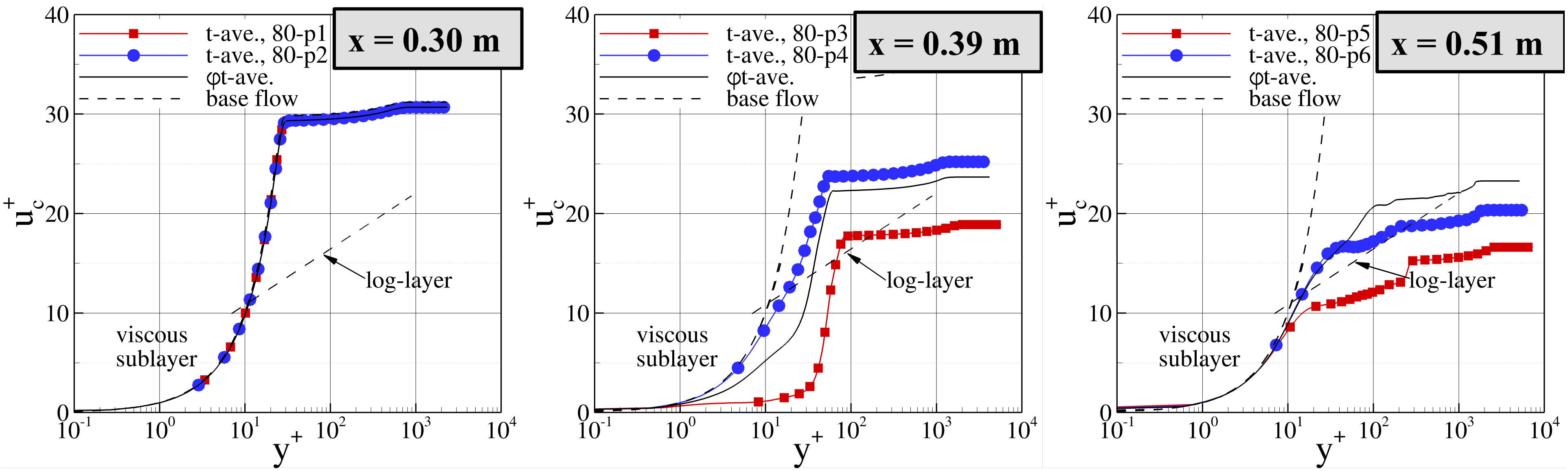
Is the flow turbulent?

- There are different ways to assess if the flow has completely transitioned to turbulence



Is the flow turbulent?

- For a turbulent boundary layer we would expect the so called log-layer to form in the Van Driest transformed velocity profiles



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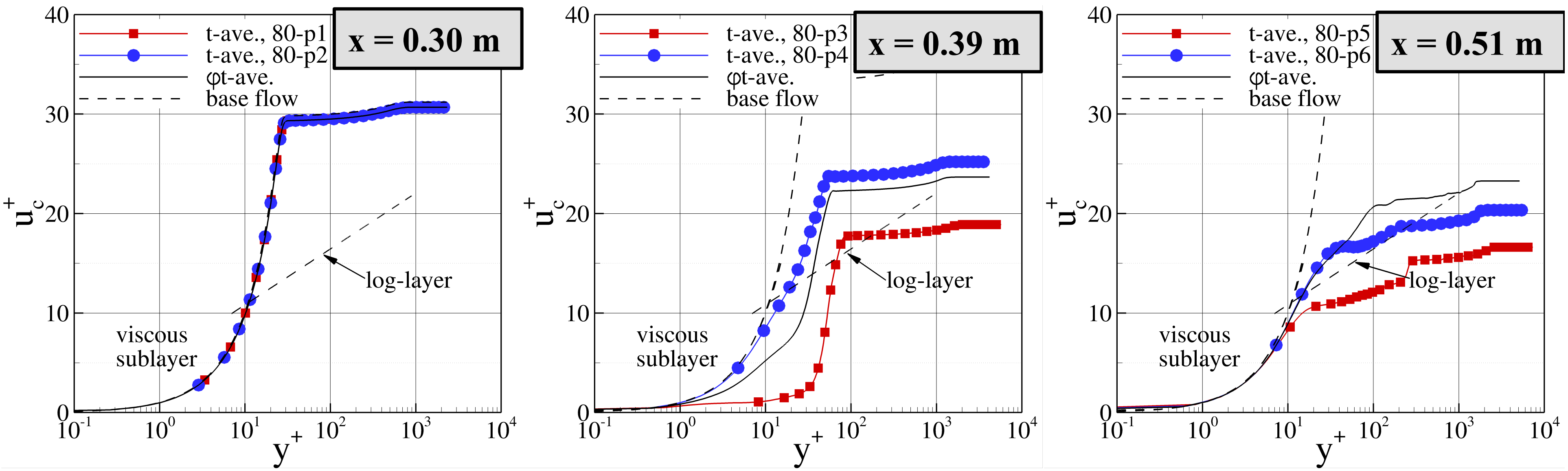
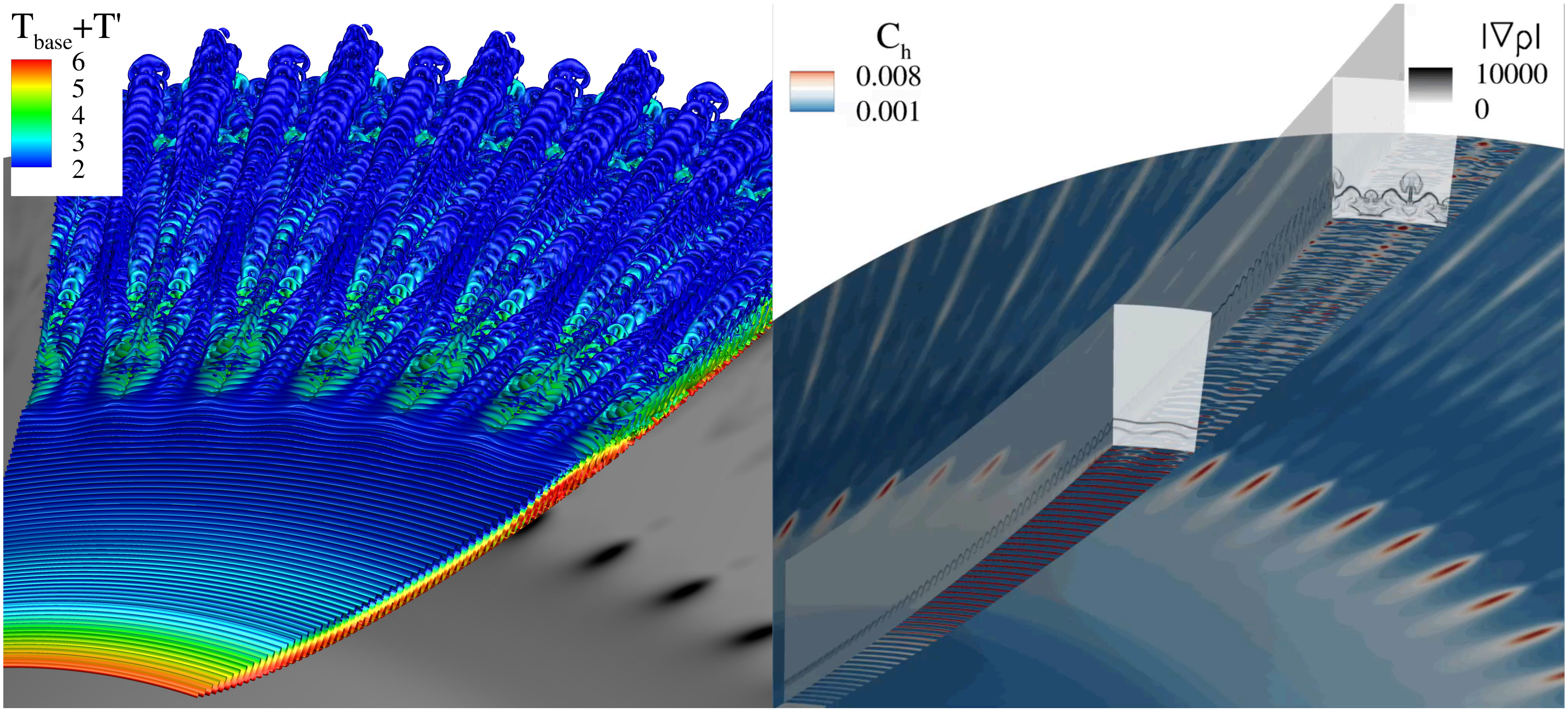


Flow has progressed far into the breakdown regime but doesn't seem to be fully turbulent yet

Fundamental Breakdown



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Summary

Goals of this research:

- Explore and understand underlying physical mechanism(s) of streak development in the nonlinear stages

Findings:

- Largest N-factor for primary wave: $f_0 = 300$ kHz
- Strongest resonance for $k_c = 80$
- Number of streaks in circumferential direction corresponds to azimuthal wave number of dominant secondary wave (80 streaks)
- Streak formation leads to significant overshoot in skin friction and Stanton number
- Streaks are strongly linked to streamwise vortical modes, in particular mode (0,1)

Thank You