Unsteadiness of Shock Wave / Turbulent Boundary Layer Interactions

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Acknowledgements

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Sponsor: AFOSR and ARO

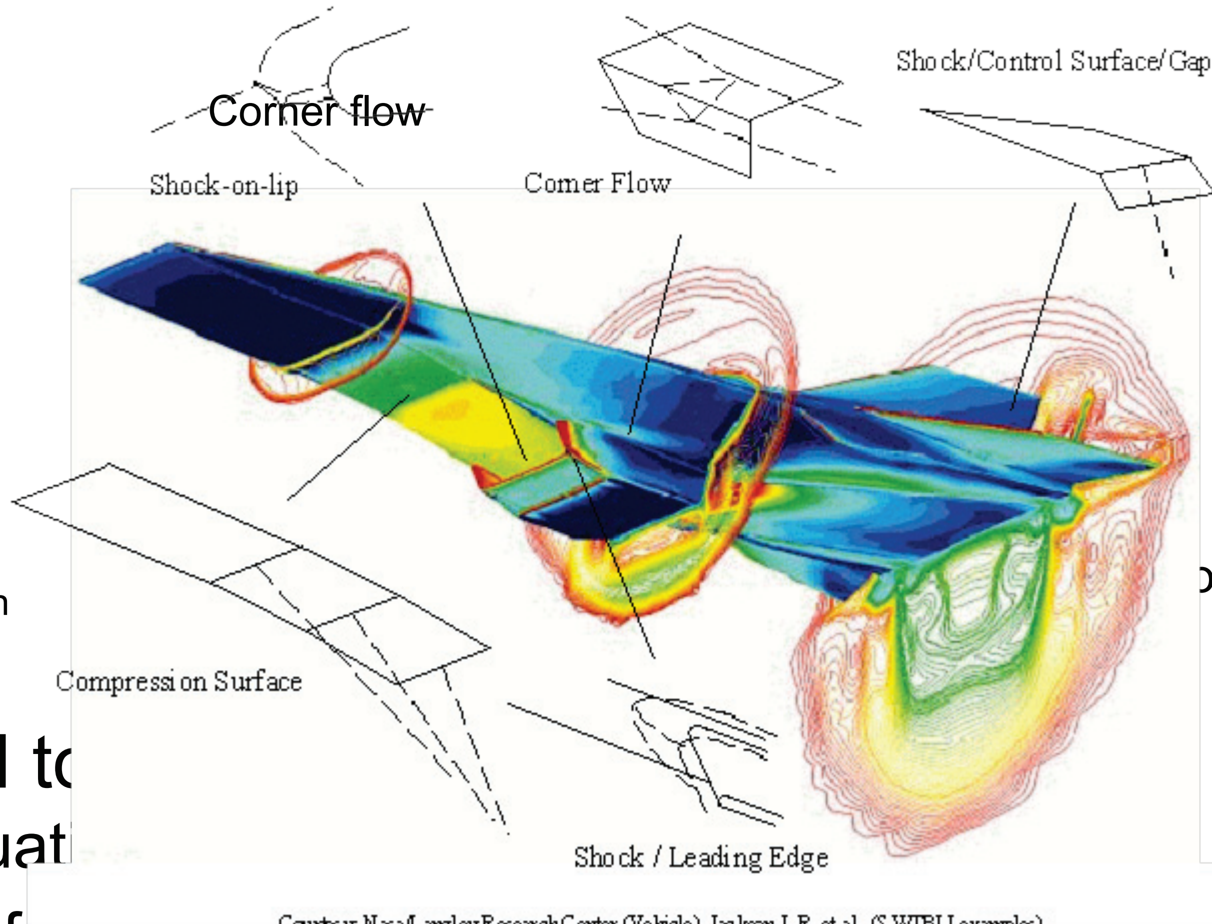
Shock Interactions

- Common feature of high-speed flight

Control surface

Shock-impingement on lip

Corner flow



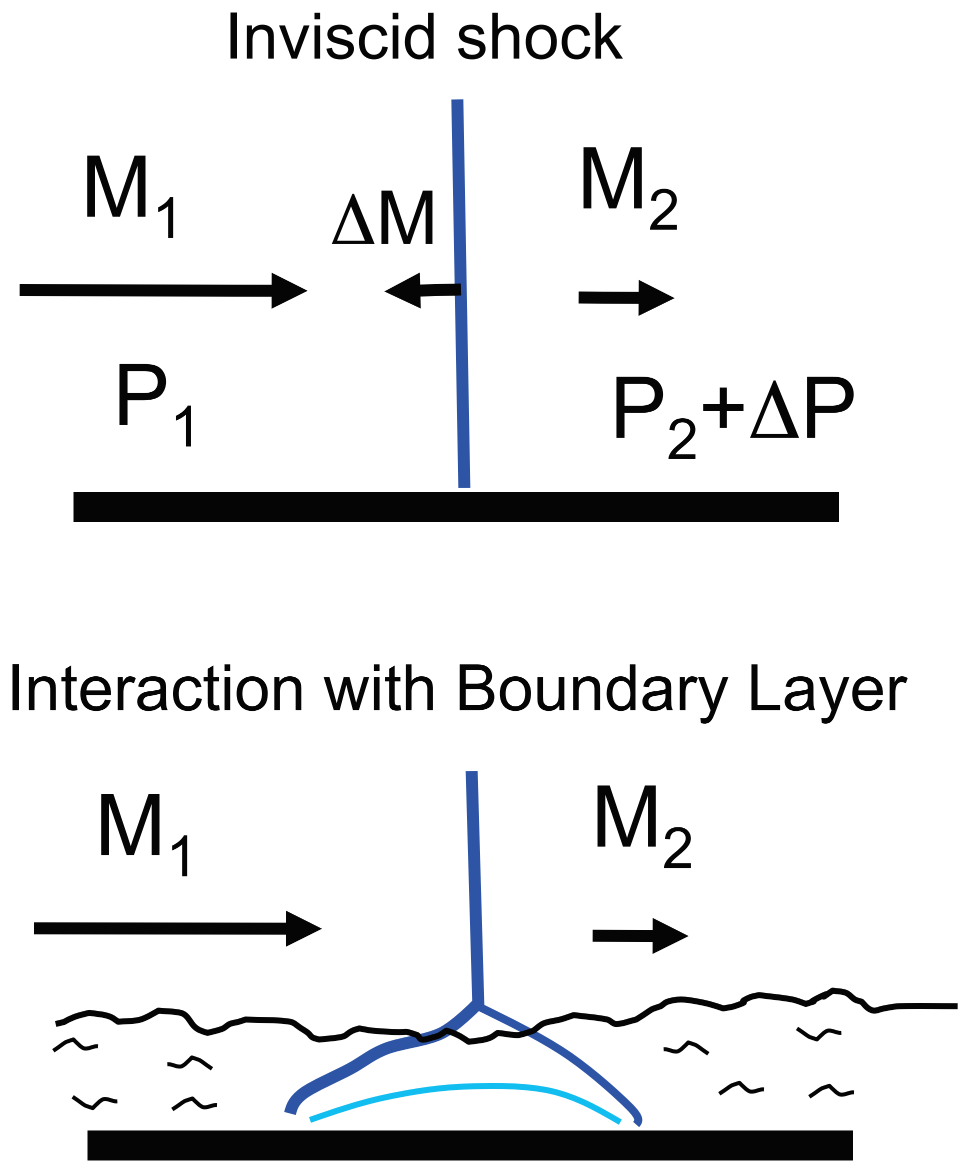
Compression surface

of

- SWBLIs lead to
  - High fluctuati
  - Structural fatigue of panels
  - Inlet instability and unstart

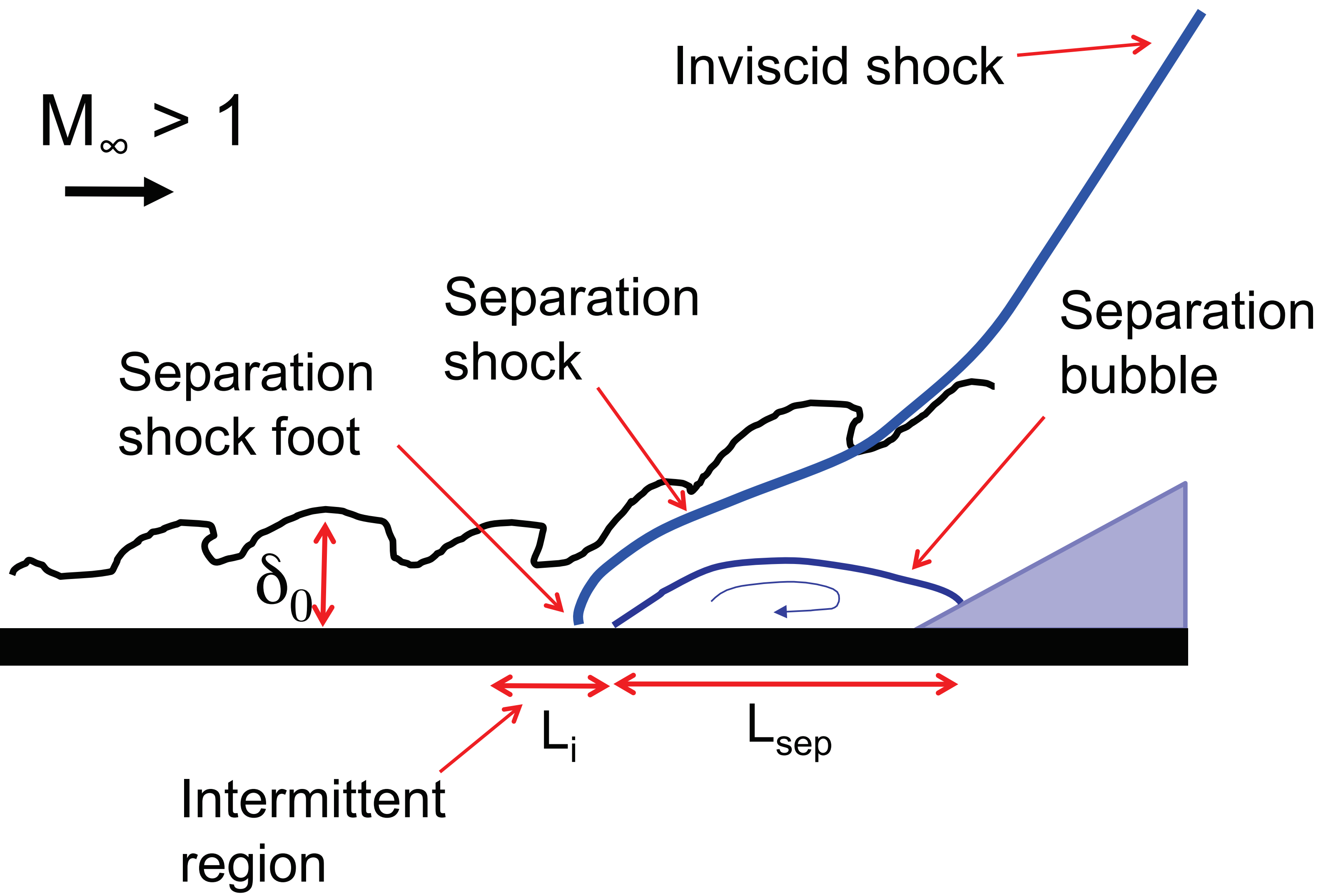
Shock Motion

- Stationary normal shock
  - Shock strength $P_2/P_1 = f(M_1)$
- Shocks will move owing to changing upstream / downstream conditions



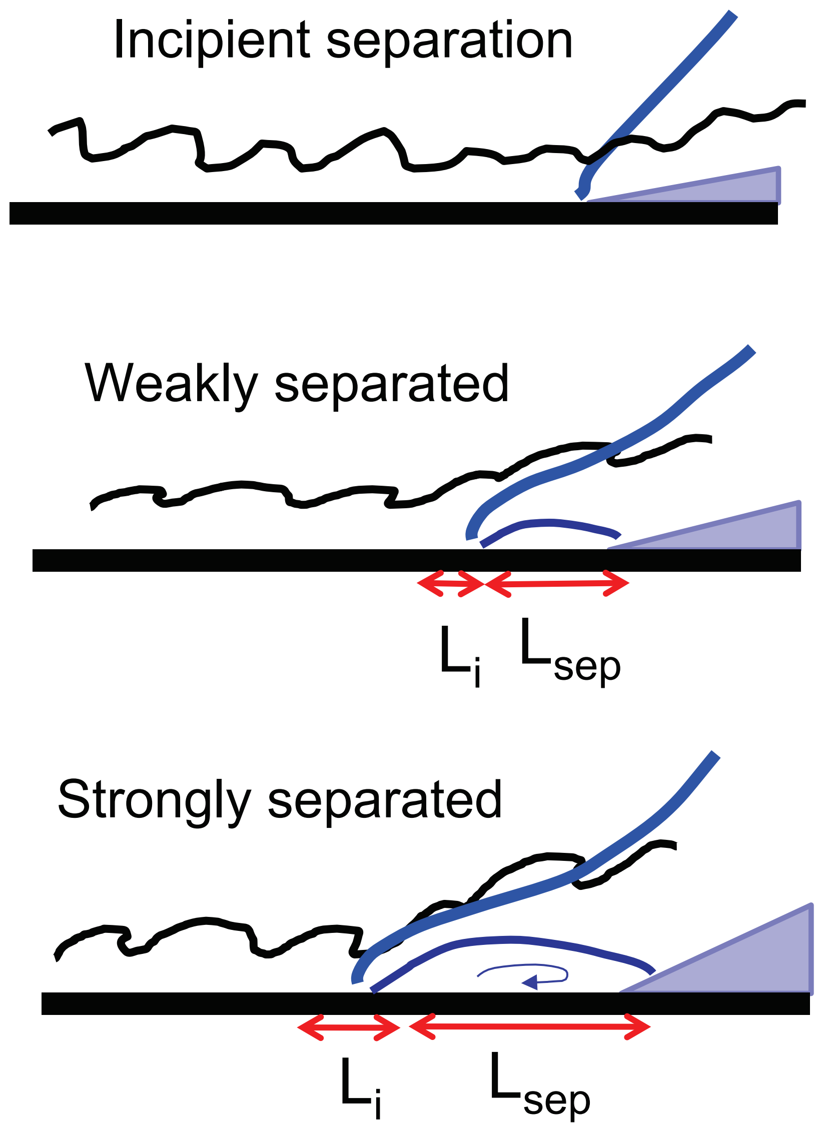
SWBLI – Flow Structure

Compression Ramp Interaction



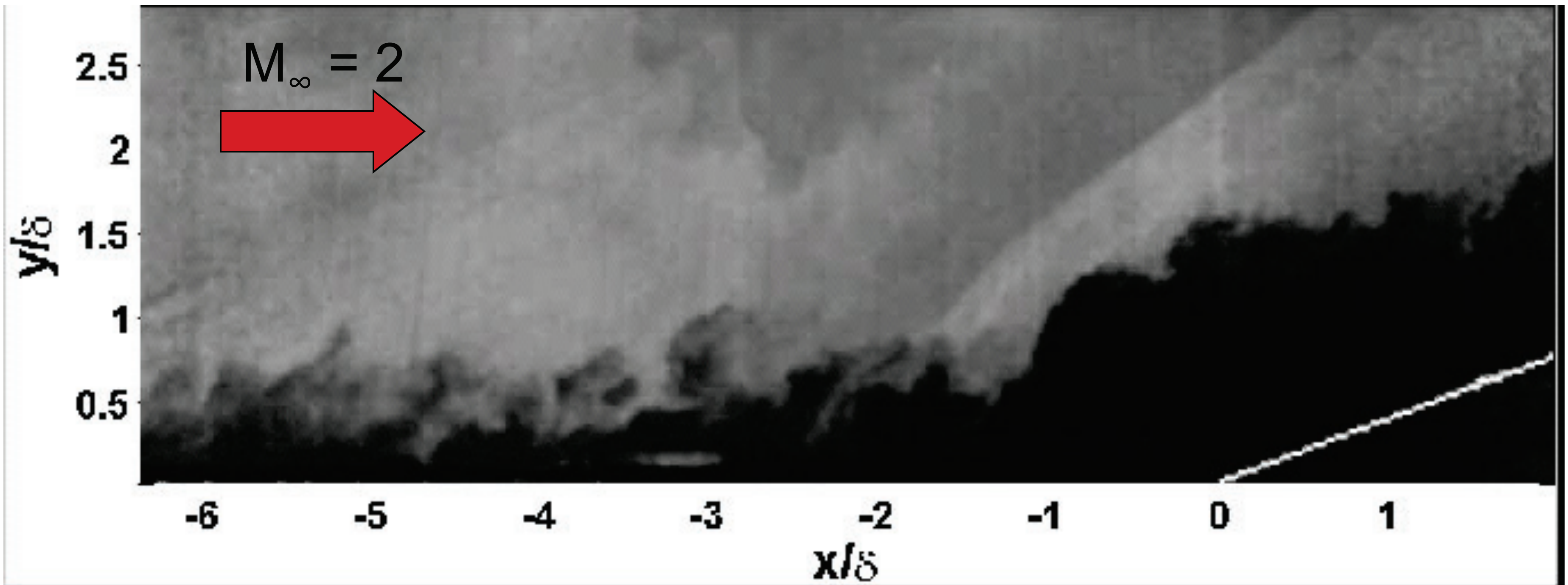
SWBLI – Interaction Strength

- As interaction strengthens
  - Separated flow scale increases, L_{sep}
  - Intermittent region length increases, L_i
  - Characteristic shock foot frequency decreases
  - Separation shock rides on top of the separation bubble



SWTBLI Unsteadiness

10 kHz planar laser scattering (PLS) of a Mach 2 compression ramp SWTBLI (Wagner, U. Texas)



- Dominant boundary layer frequency: $O(U_\infty/\delta_0)$
- Dominant shock foot motion frequency: $O(0.01\ U_\infty/\delta_0)$

SWBLI Unsteadiness

Same movie low-pass filtered to 1 kHz

Source of Separated Flow Unsteadiness?

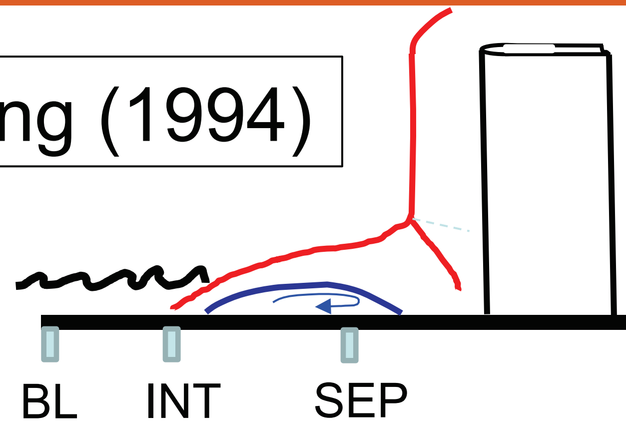
- Most investigators have emphasized one of two mechanisms
  - Forcing by upstream turbulent boundary layer
  - Global instability intrinsic to separated flow

Source of Unsteadiness:

Forcing by Upstream Turbulent Boundary Layer

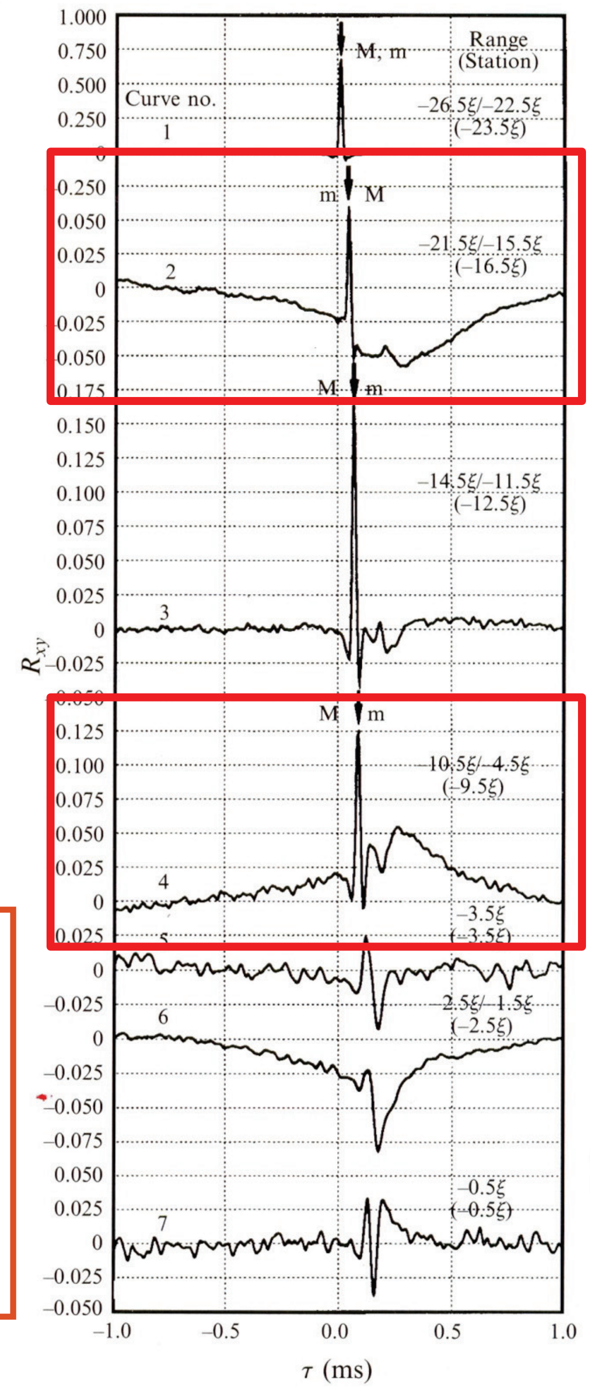
Mach 5 Blunt Fins

Brusniak & Dolling (1994)



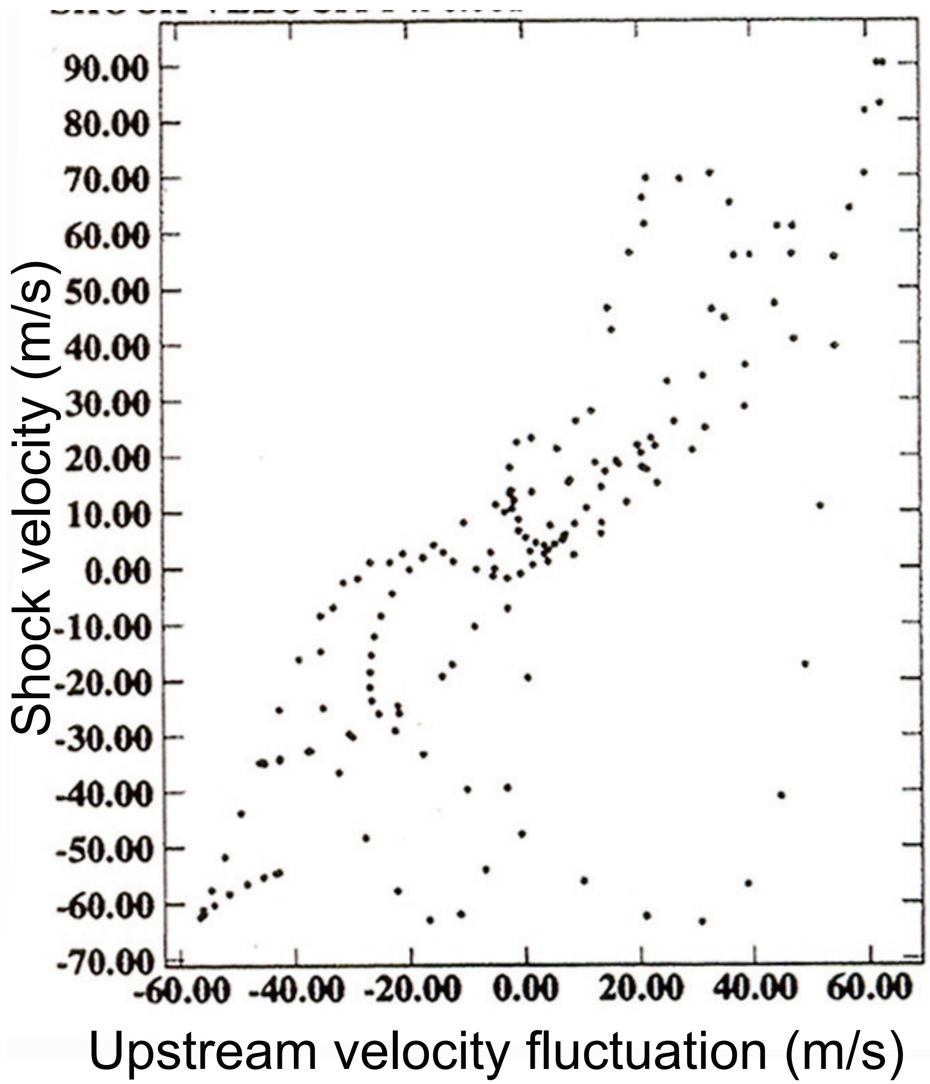
- Correlations obtained between:
  - BL and INT: BL precedes
  - BL and SEP: BL precedes

"The most obvious result is that a correlation *does* exist between signals from under the incoming undisturbed boundary-layer flow and both the intermittent and separated flow regions."



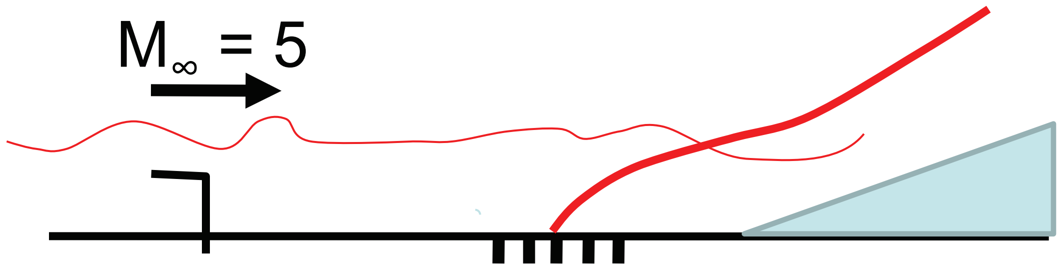
VLES of a Mach 3 Compression Ramp

- Hunt & Nixon (1995) were first to compute unsteady SWBLI
  - Very large-eddy simulation of Dolling & Murphy (1983) experiment
  - Showed shock foot nearly linearly correlated with upstream velocity fluctuations



Source of Low-Frequency Unsteadiness?

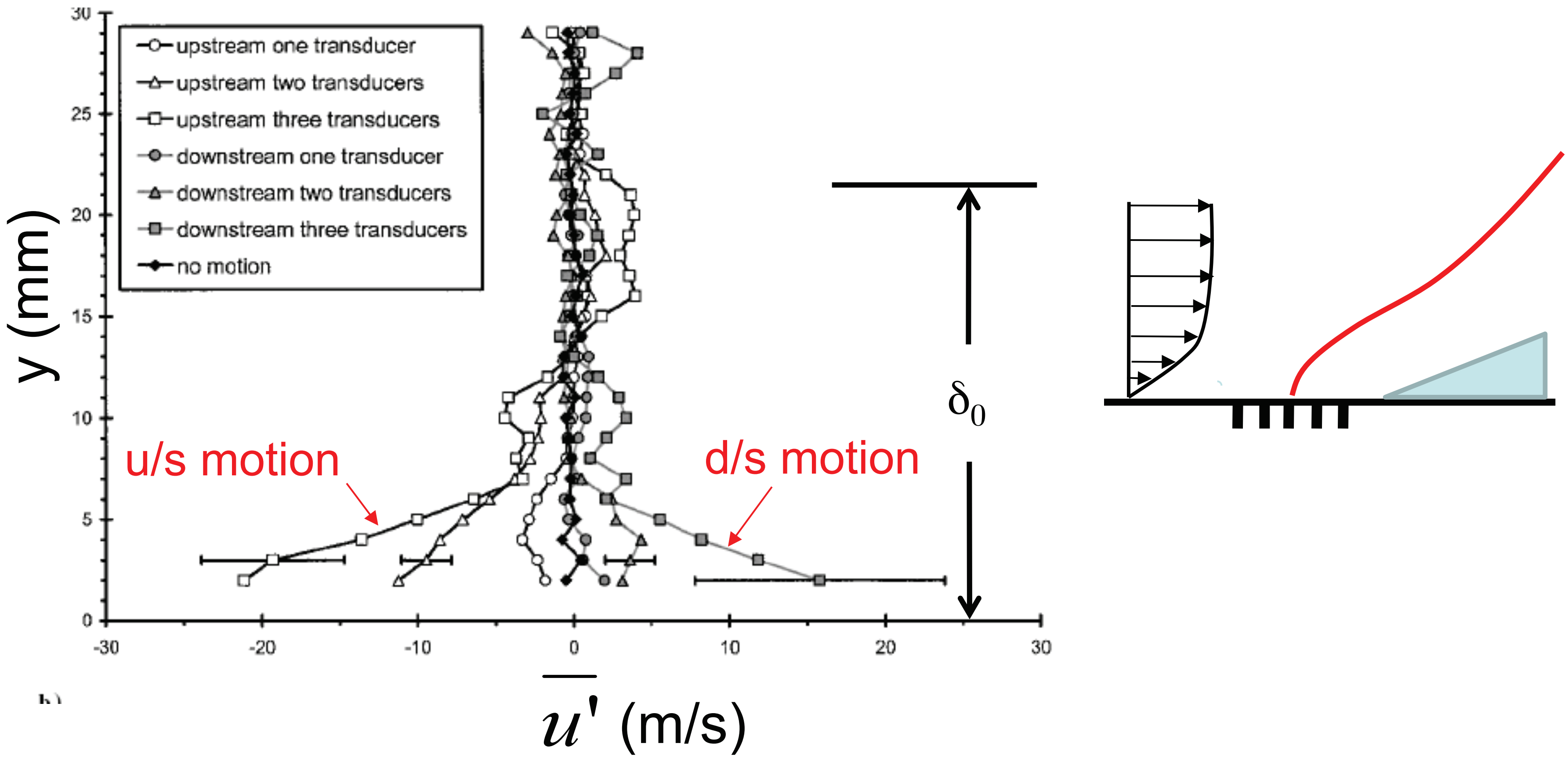
- Rises/falls in Pitot pressure in upstream boundary layer were correlated with shock-foot motion
  (McClure & Dolling, 1992; Unalmis & Dolling, 1994)
- Characteristic structures 20δ to 40δ long



- They argued for a thickening/thinning mechanism
  - Thickening BL → shock foot moves upstream
  - Thinning BL → shock foot moves downstream

Mach 5 Compression Ramp Interaction

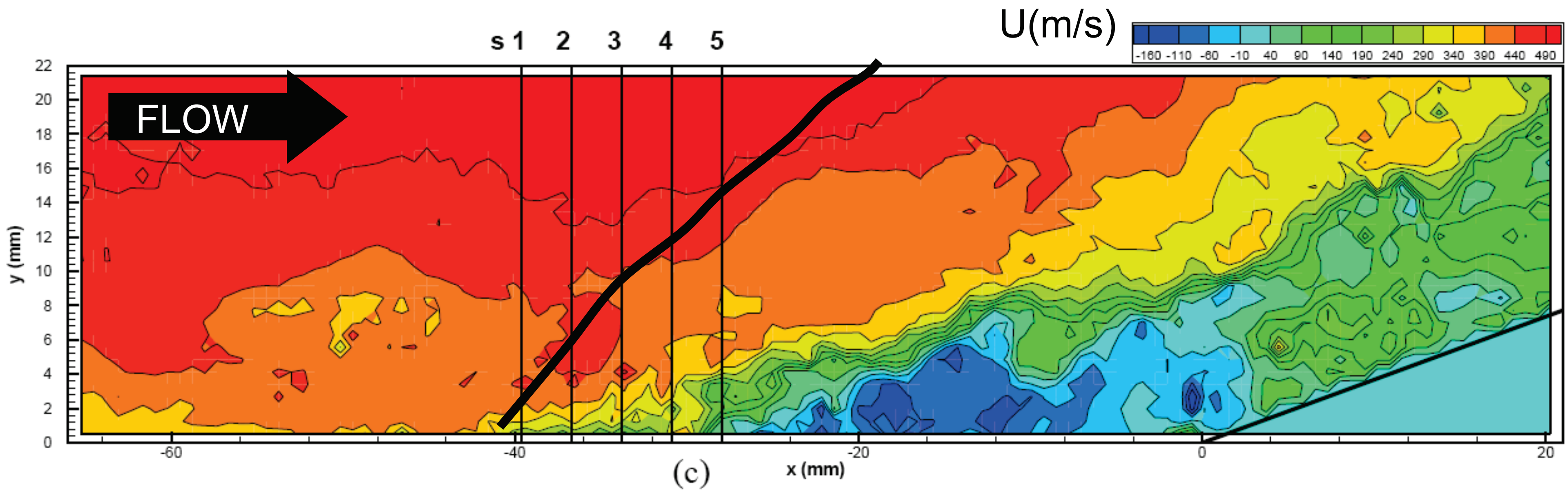
Simultaneous PIV and wall-pressure (Beresh et al. 2002)



- No thickening / thinning mechanism observed
- Correlation of shock ***motion*** with fluctuations in lower part of boundary layer

Mach 2 Compression Interaction

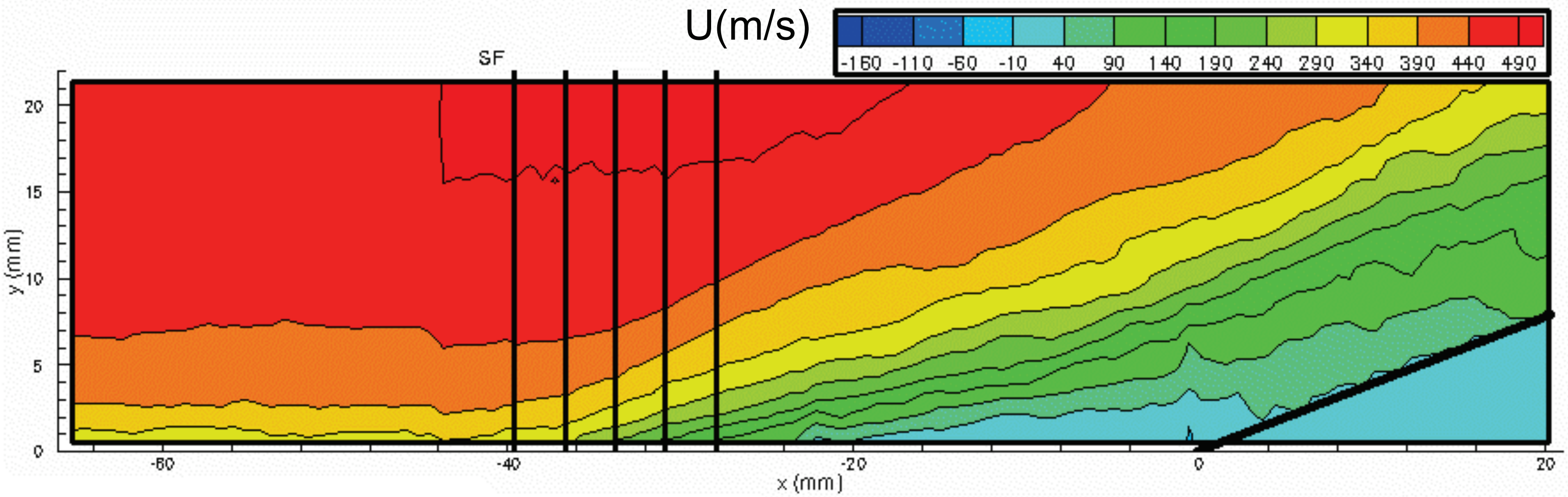
- Wide-field PIV gives global flowfield of Mach 2 compression ramp interactions



Hou (2002)

Conditionally-Averaged Velocity Fields

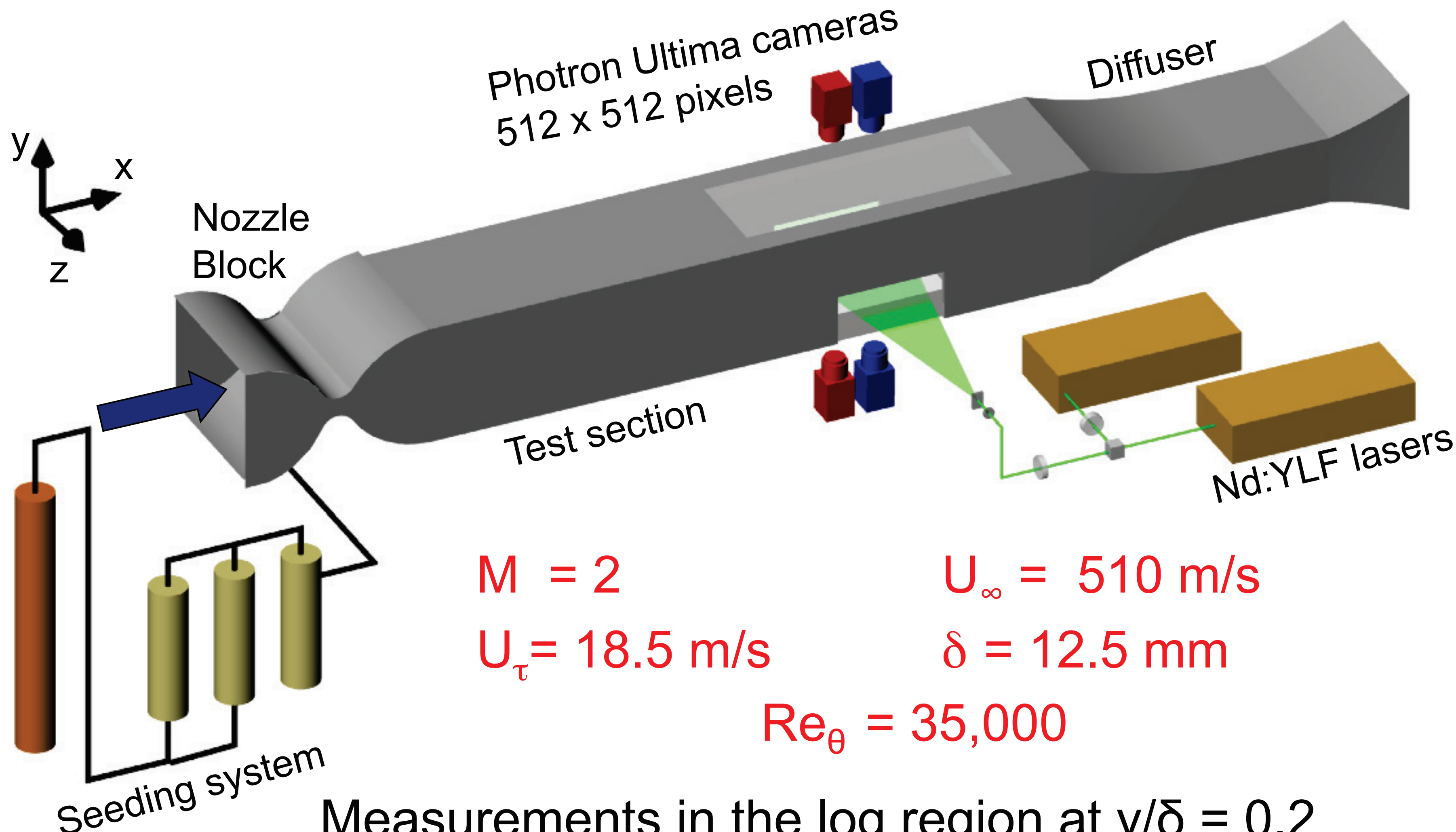
Hou (2002)



- Separation shock responds to breathing of separated flow
- Clear correlation of separated flow scale with upstream boundary layer thickness

Characterization of Upstream Mach 2 Boundary Layer

6 kHz Plan-View PIV



$M = 2$

$U_\infty = 510$ m/s

$U_\tau = 18.5$ m/s

$\delta = 12.5$ mm

$Re_\theta = 35{,}000$

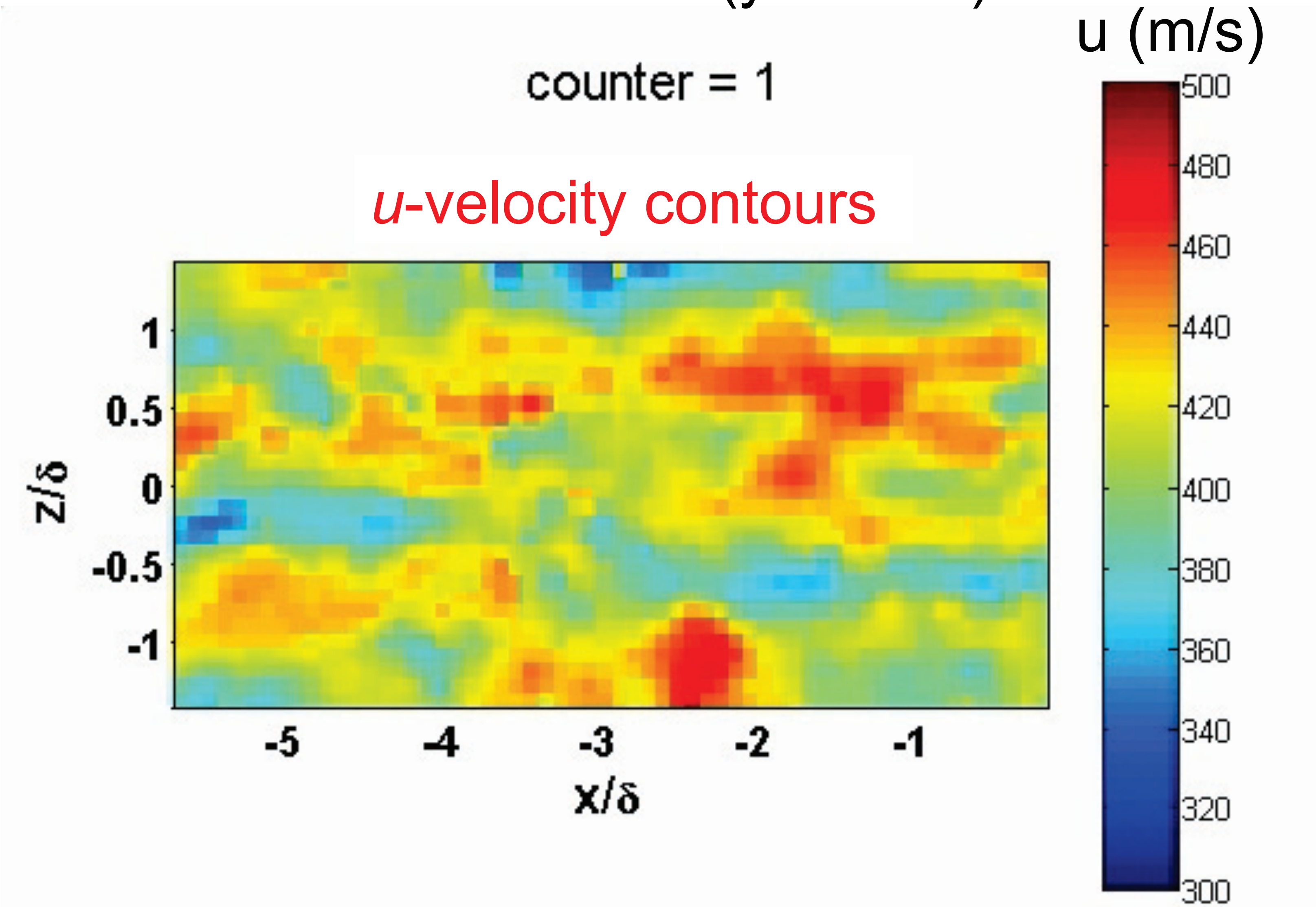
20 nm TiO_2 particles

Measurements in the log region at $y/\delta = 0.2$

Field of view (between two camera pairs): $6\delta \times 3\delta$

High-Speed Plan View PIV

6 kHz PIV Movie (y/δ = 0.2)



Taylor's Hypothesis applied to PIV results

Successive vector fields displaced in the streamwise direction by $\Delta x = -kU_c\Delta t$ ($\Delta t = 166\ \mu s$, $U_c = 0.9U_\infty$, k = integer)

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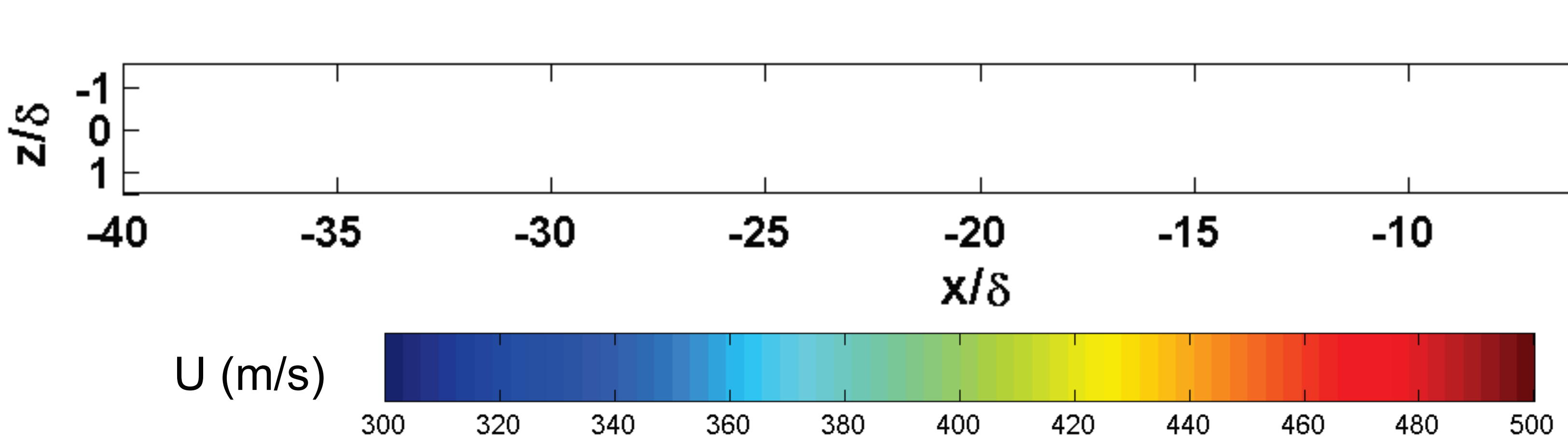

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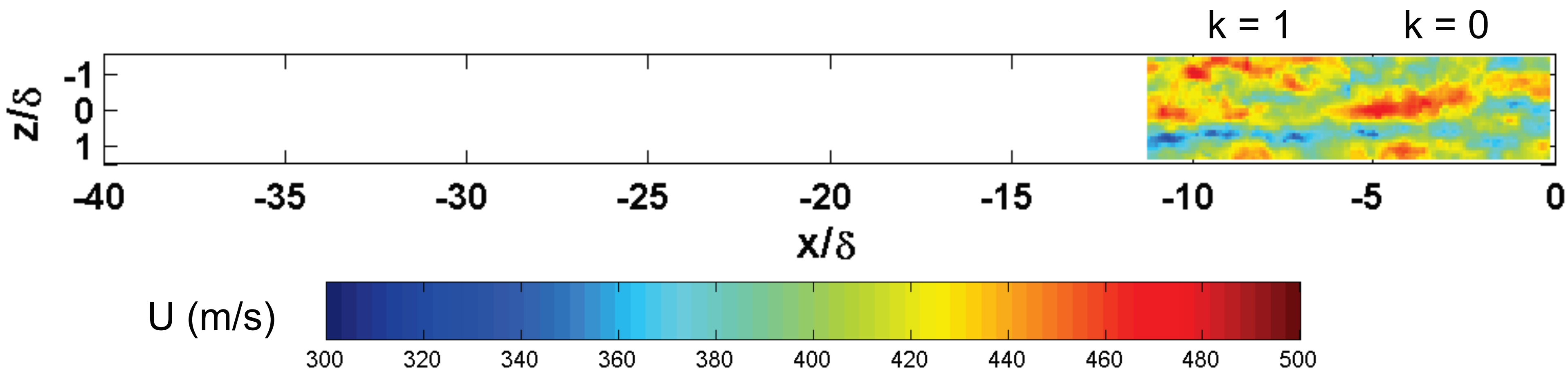

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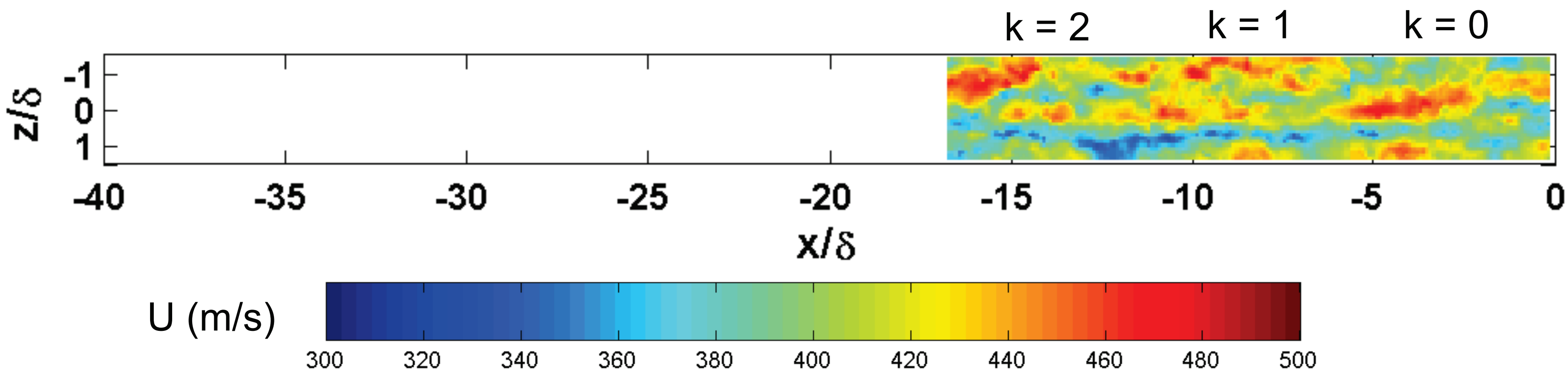

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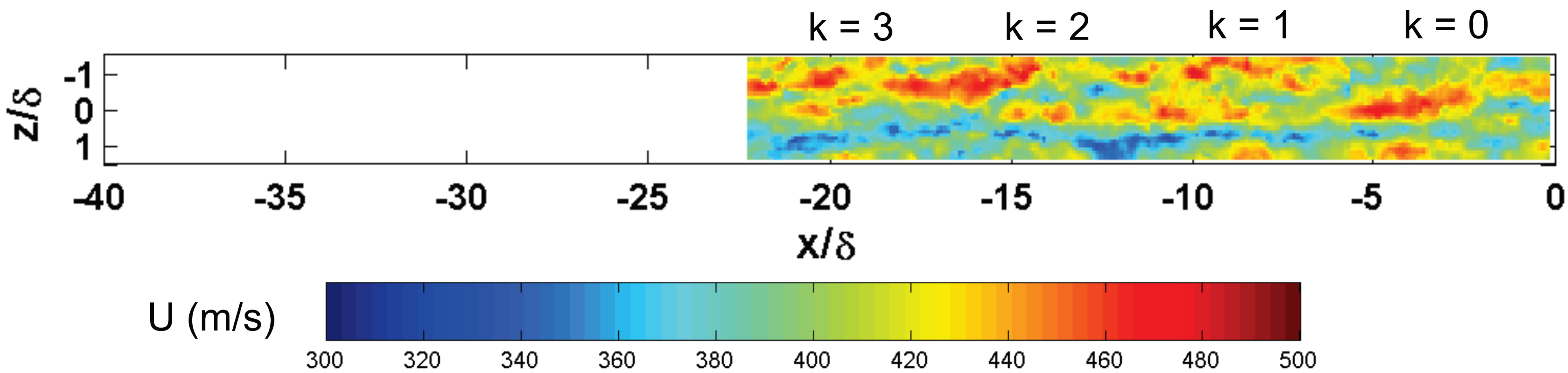

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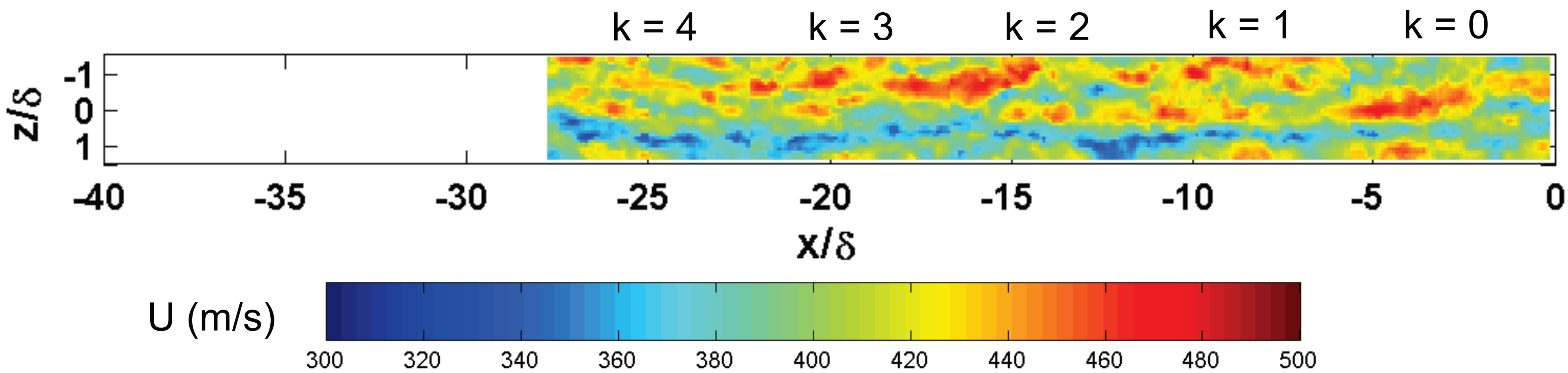

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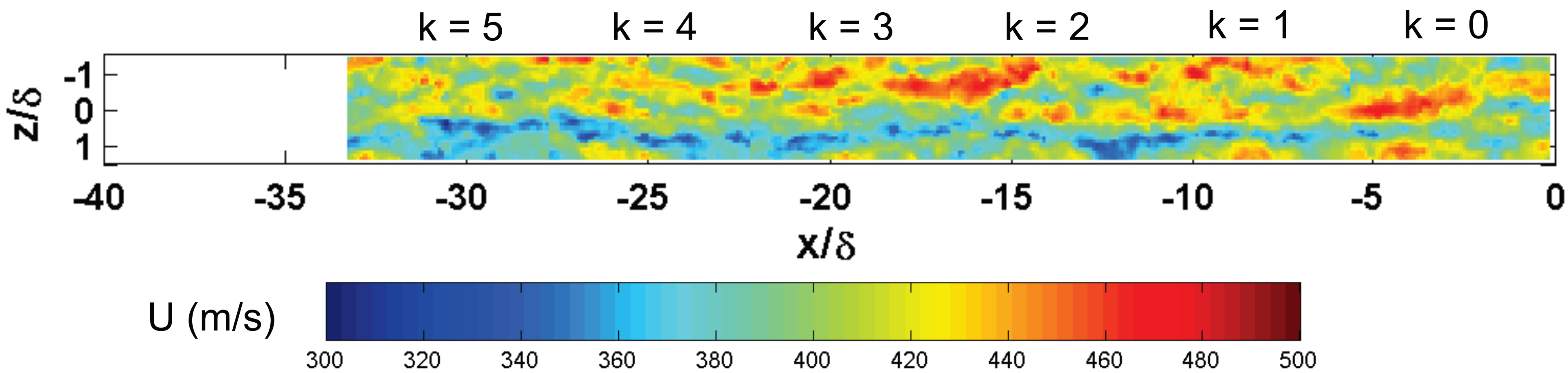

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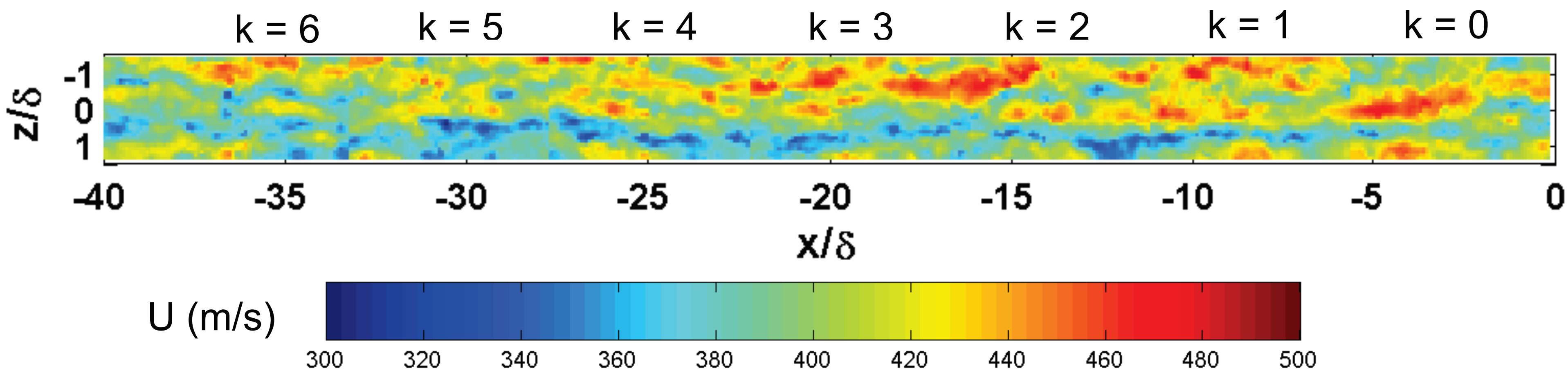

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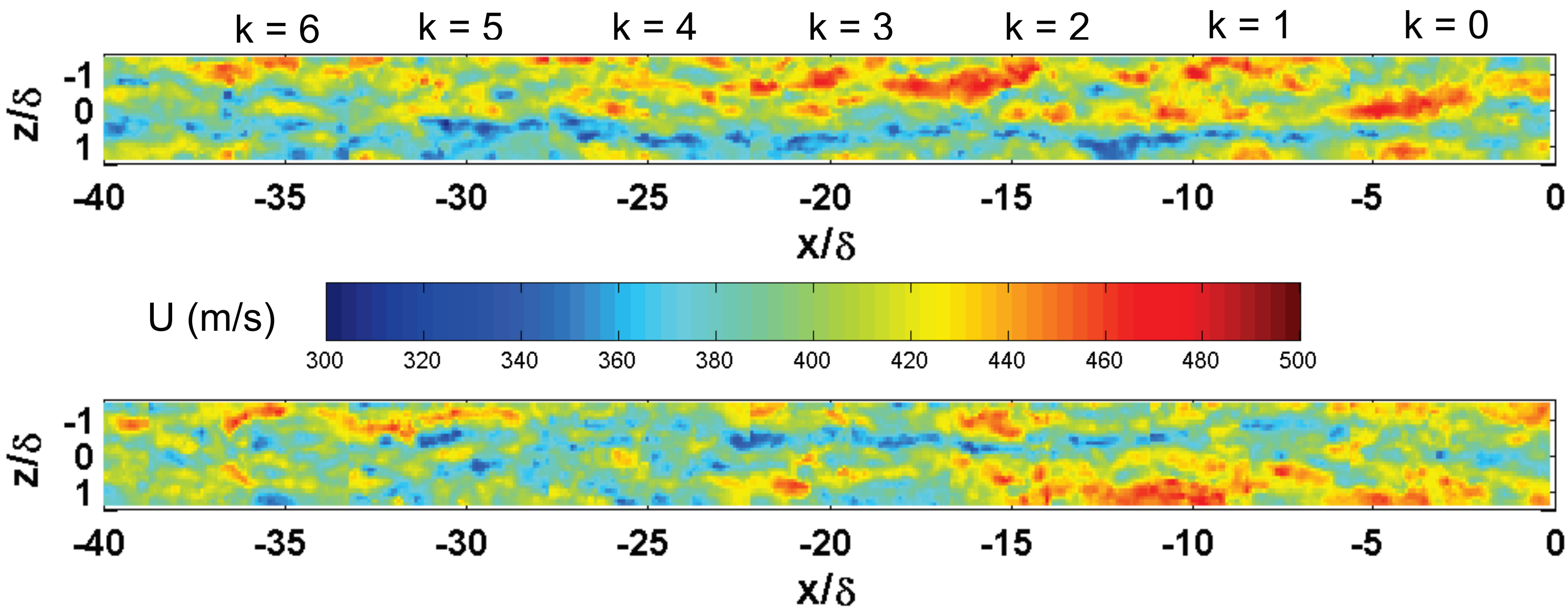

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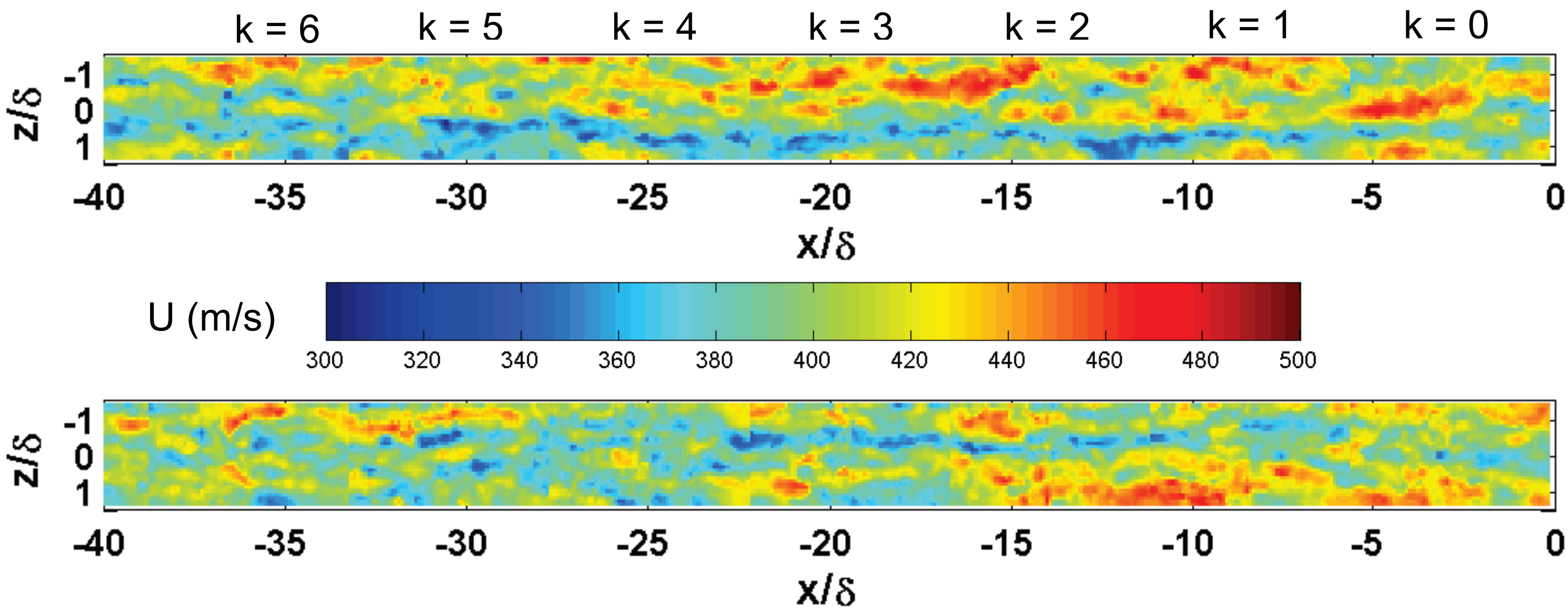
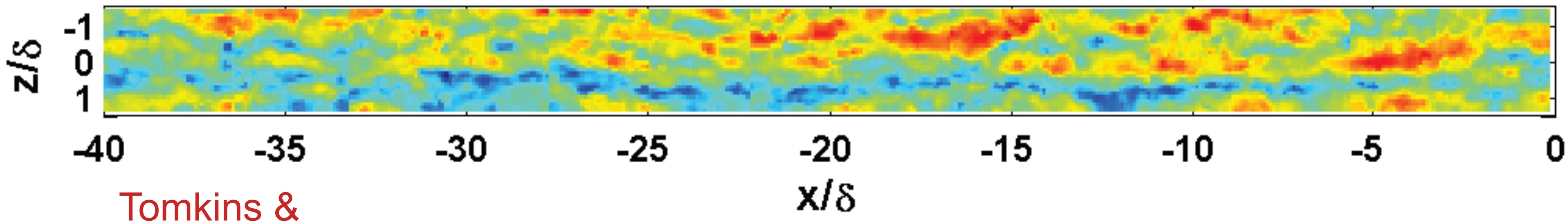
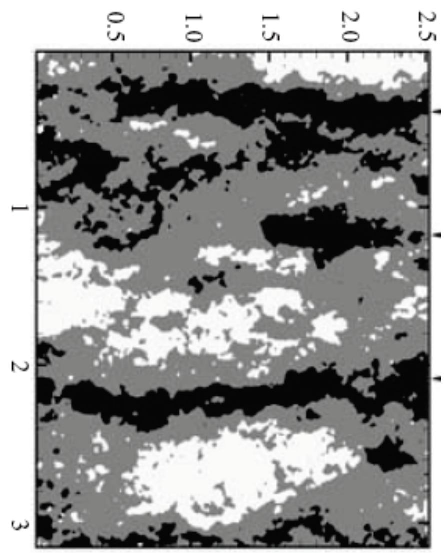


Superstructures

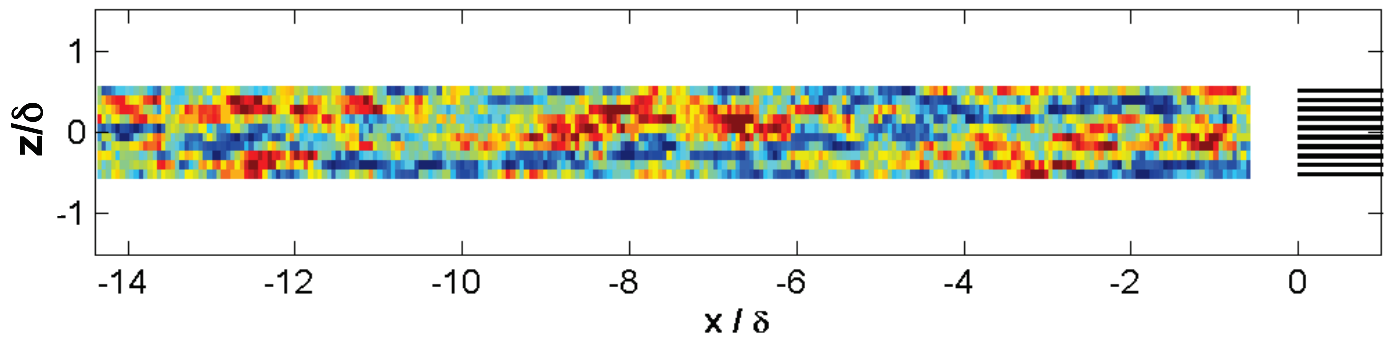


Tomkins & Adrian (2003)



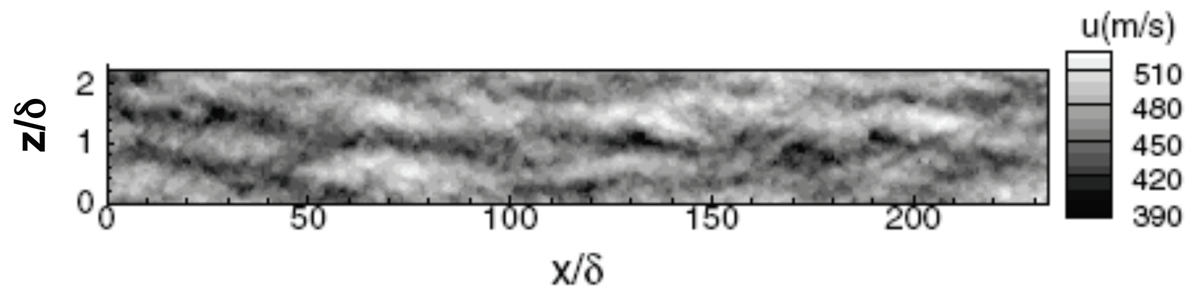
Incompressible boundary layer at comparable wall-normal location

Hutchins, Ganapathisubramani, Marusic (2004)



Mach 3 boundary layer at comparable wall-normal location

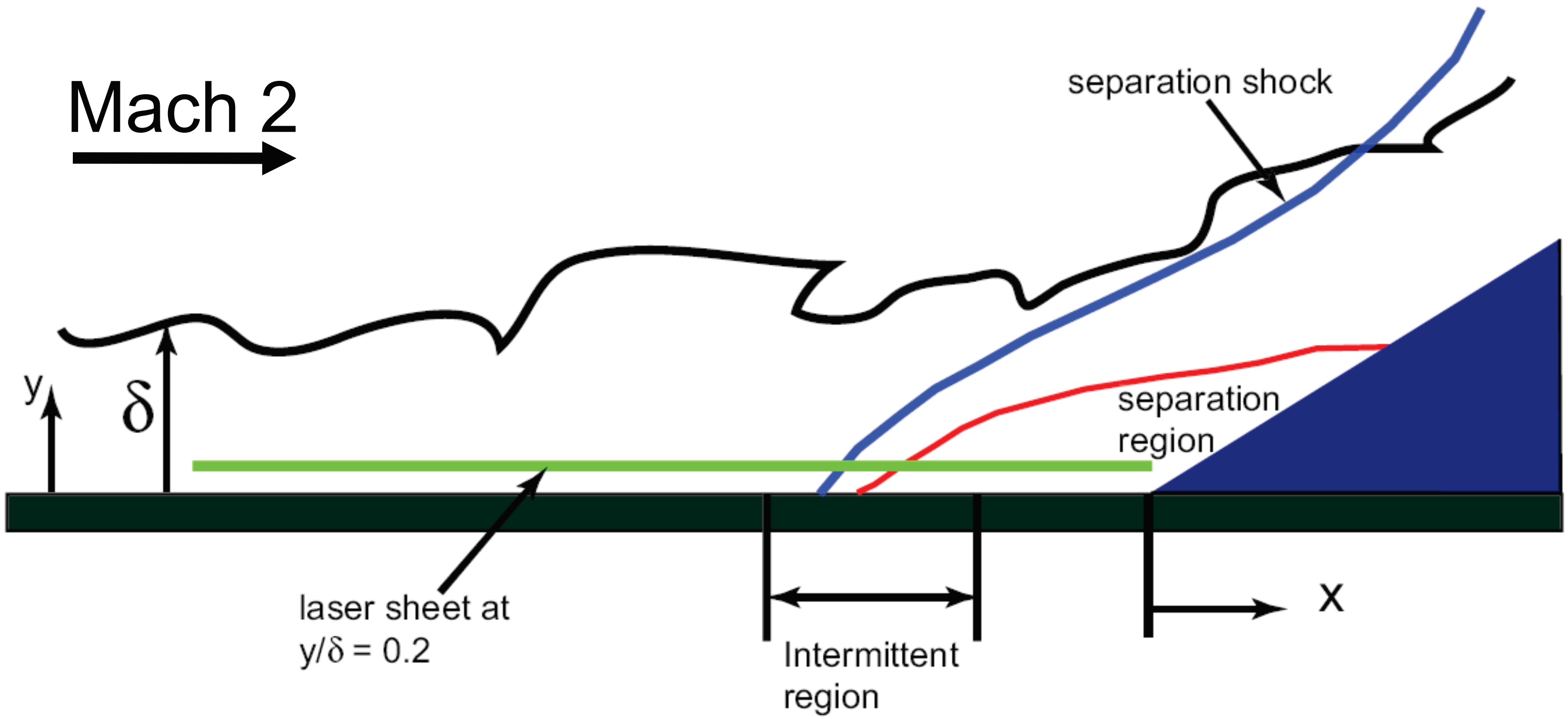
Wu & Martin (2007)



PIV Imaging of Mach 2 Compression Ramp Interactions

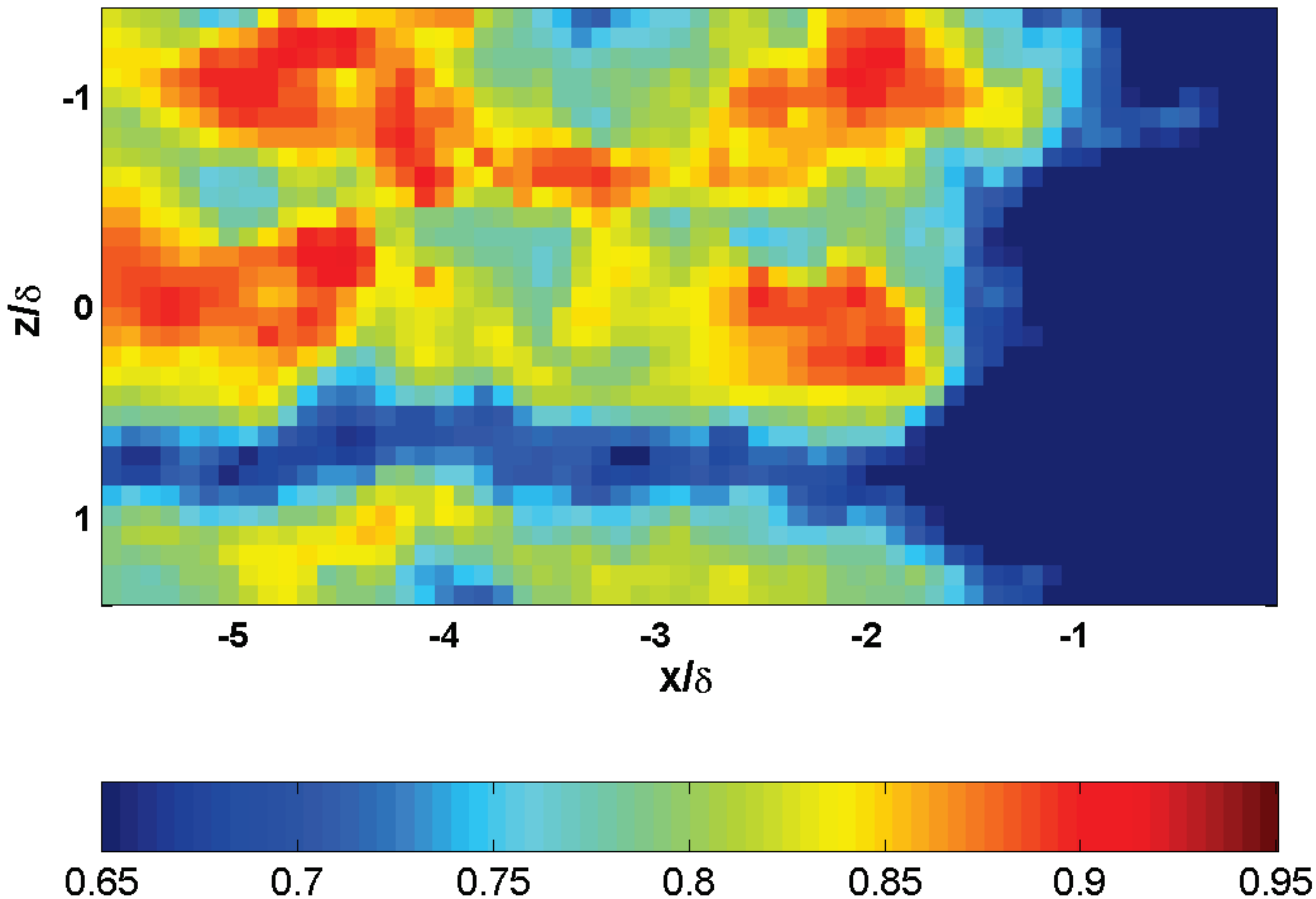
Mach 2 Compression Ramp Interactions

We now consider SWTBLI generated by a 20^o compression ramp in a Mach 2 flow



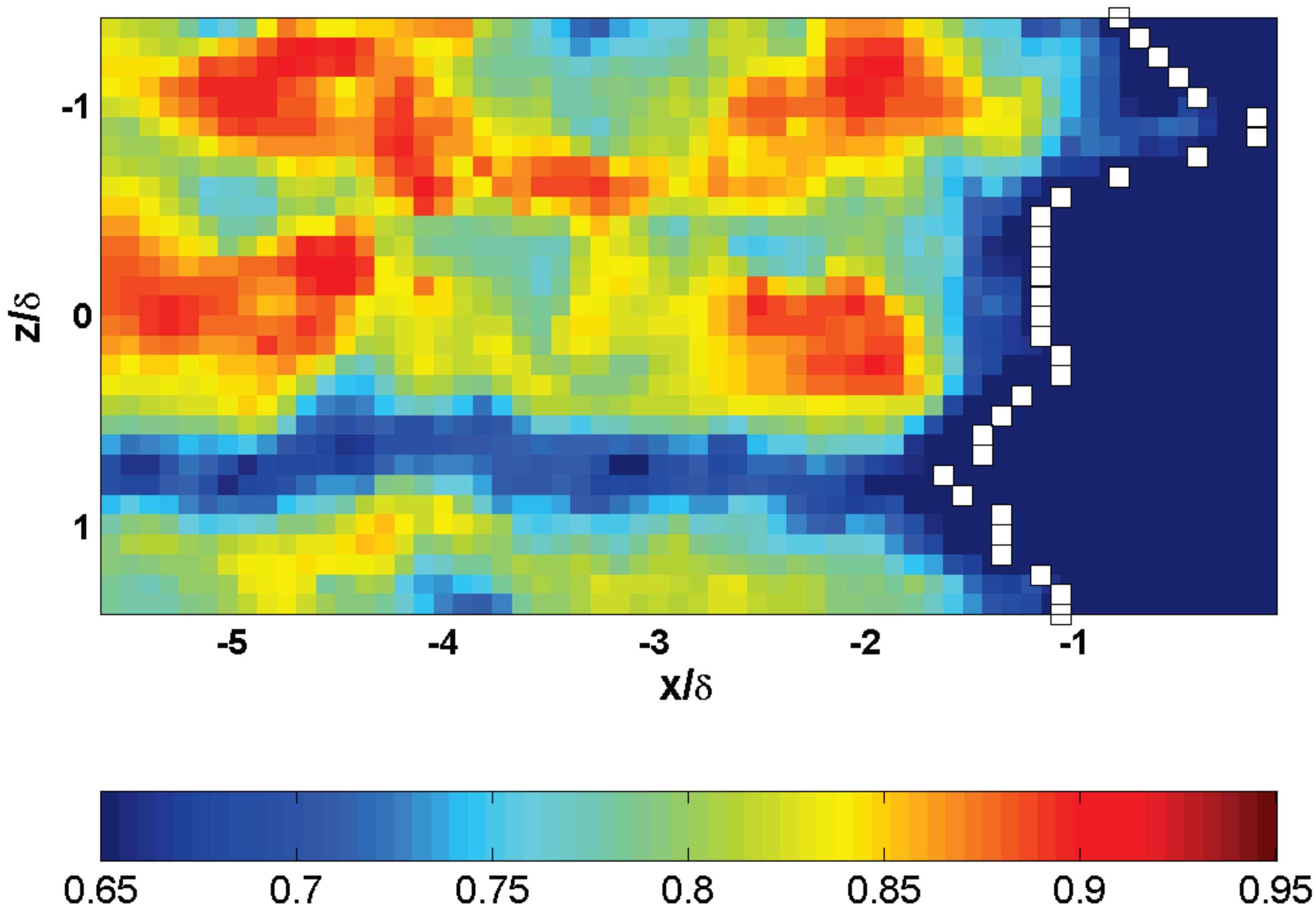
Correlation Analysis

Objective is to correlate upstream velocity fluctuations with location of separated flow surrogate



Correlation Analysis

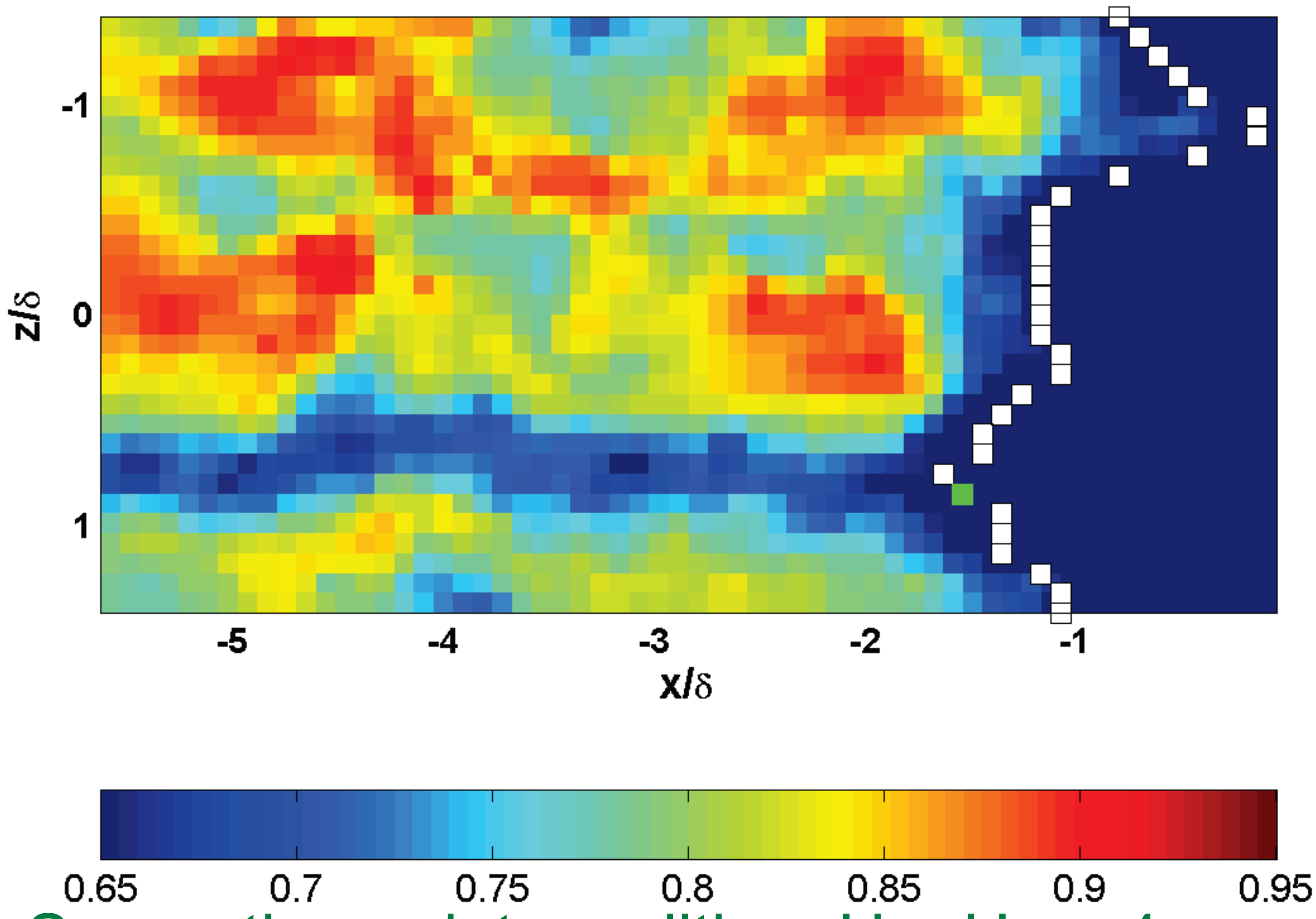
Define separation line surrogate



Separation point condition: $U < U_m - 4\sigma_u$

Correlation Analysis

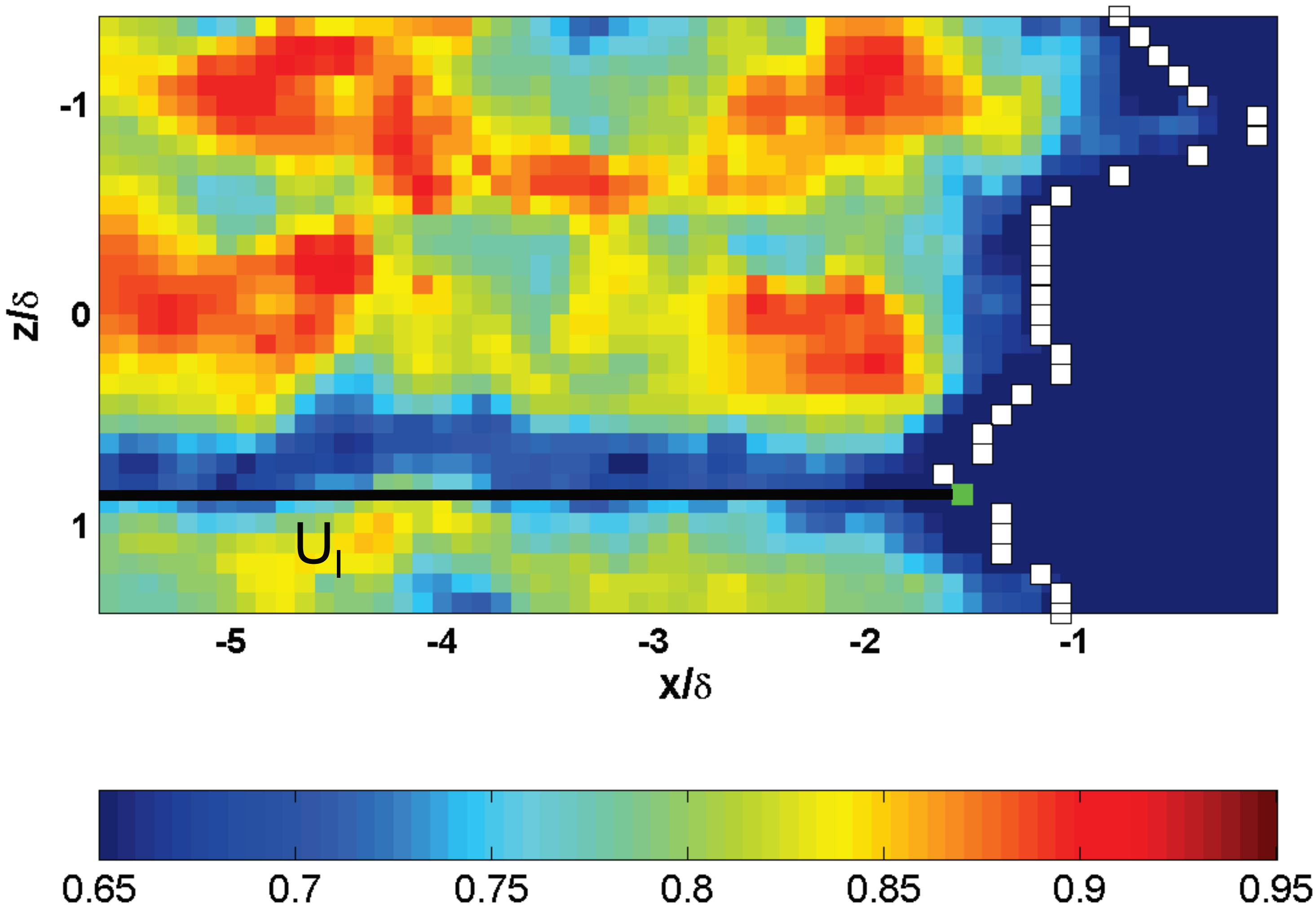
Identify point on separation line



Separation point condition: $U < U_m - 4\sigma_u$

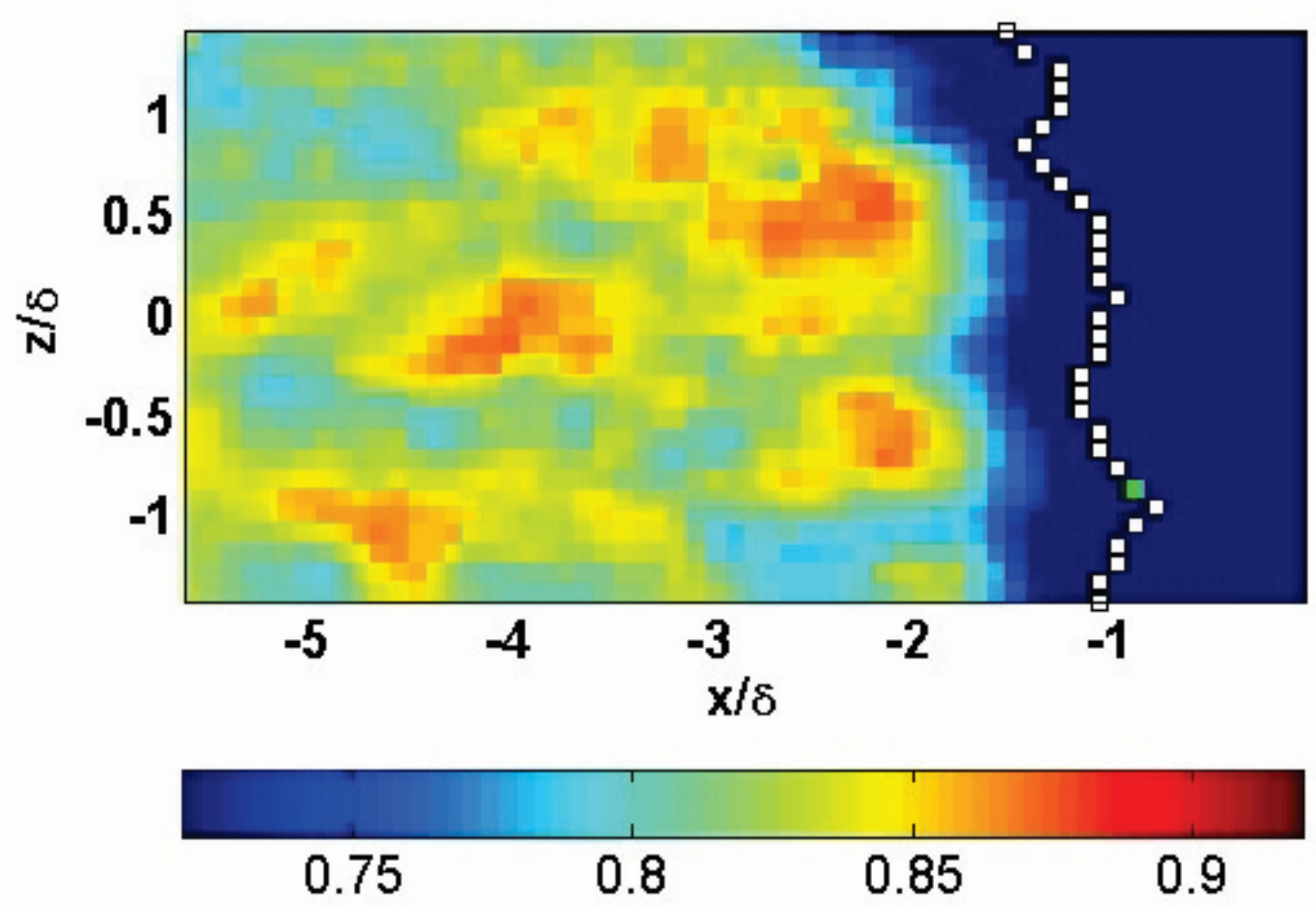
Correlation Analysis

Compute average velocity along line shown



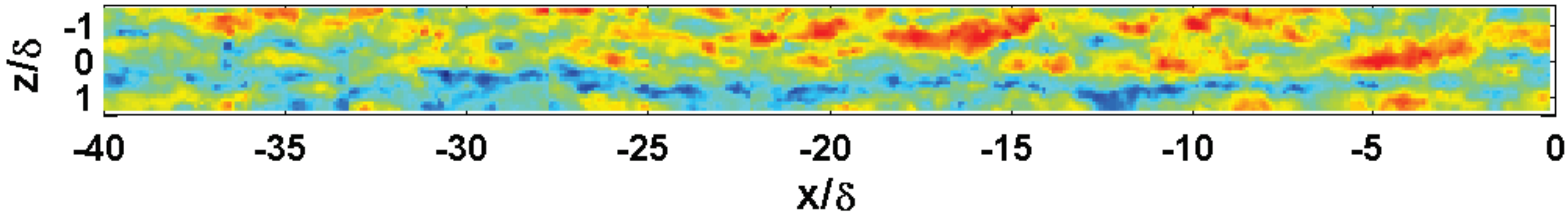
Correlate U_l with x_{sep}

Low-Pass Filtered 6-kHz PIV Movie

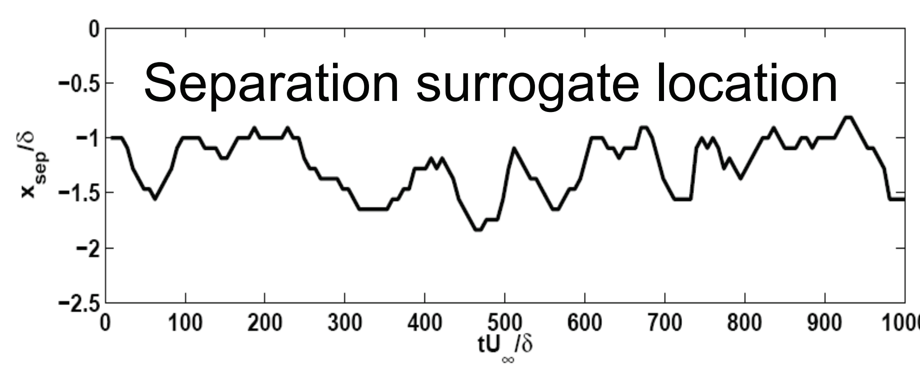


Low-Pass Filtered Data

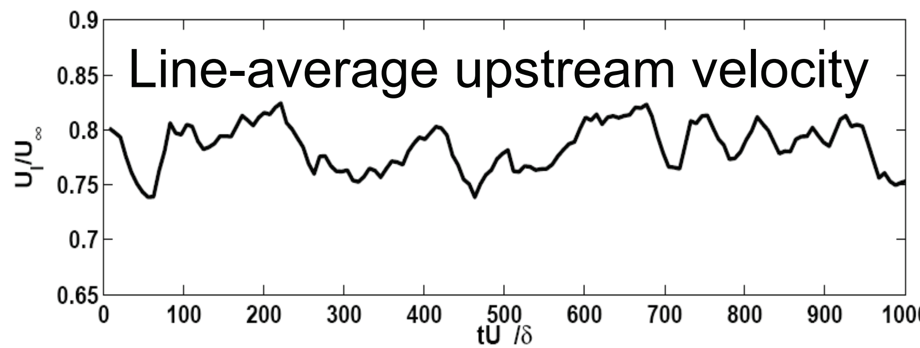
Ganapathisubramani, Clemens, Dolling (2006, 2009)



- Separation line surrogate strongly correlated to **low frequency** upstream fluctuations



(a)

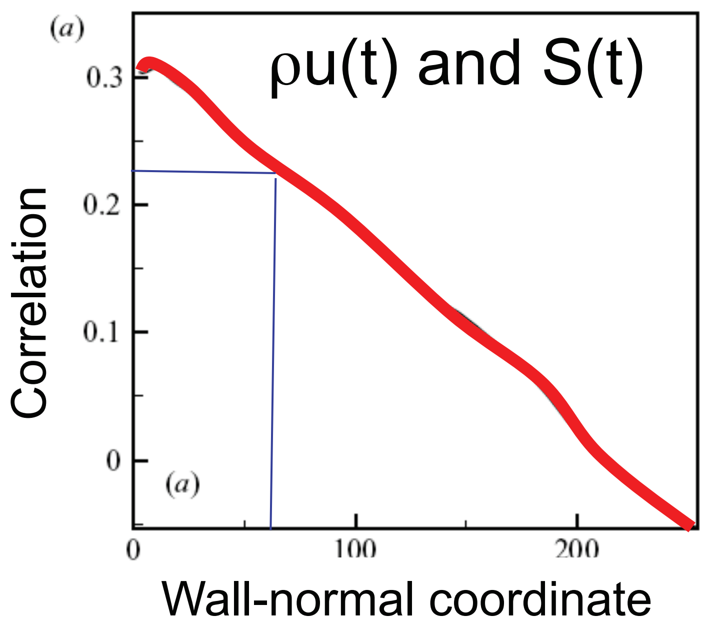


Correlation coefficient = 0.7

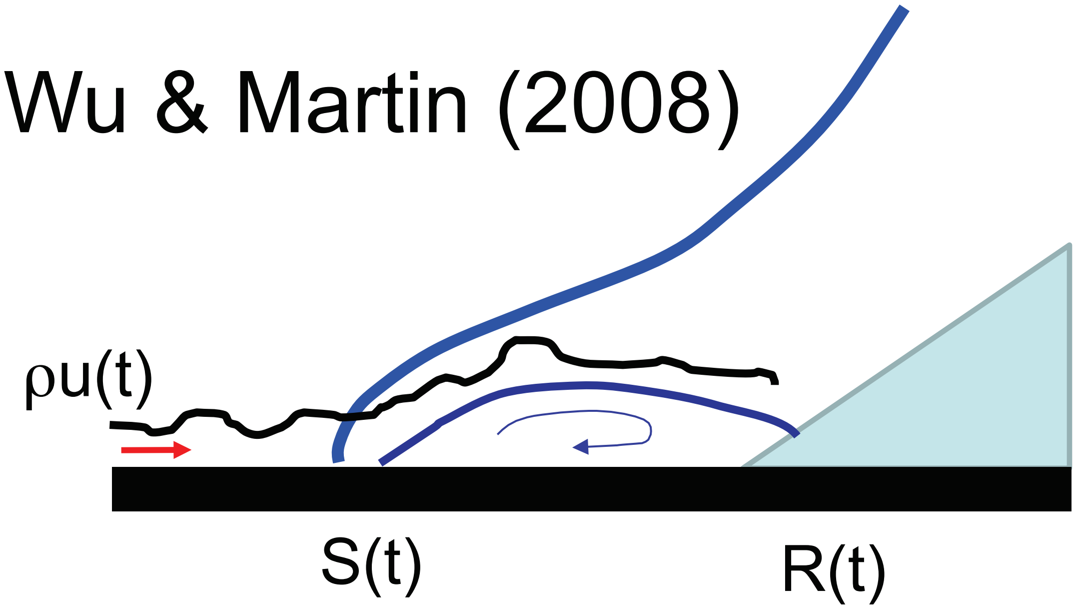
Source of Unsteadiness:

Downstream Mechanism

DNS Mach 3 Compression Ramp



Wu & Martin (2008)



- Correlation at y/δ_0=0.2 only 0.23
- Superstructures cause spanwise undulations of separation line but not large-scale streamwise motion
- Proposed bubble pulsation due to a wake-like instability of the shear layer similar to cavity or backstep flows

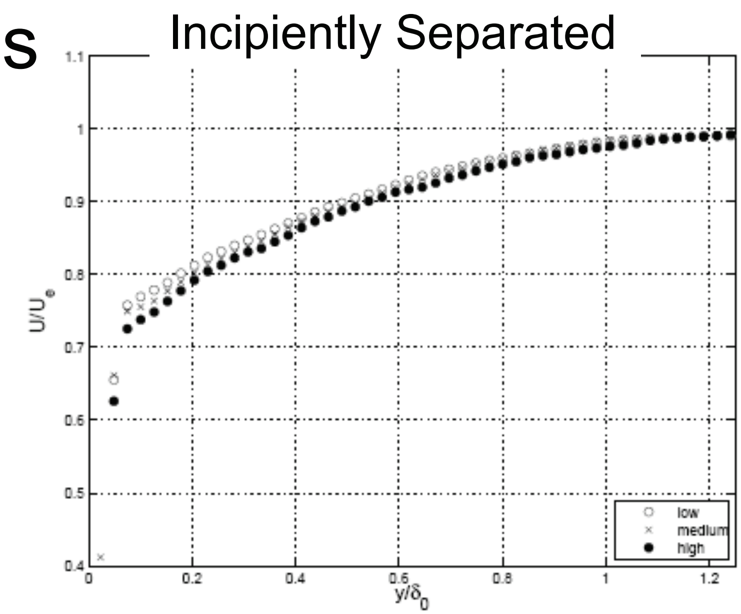
Conditional Boundary Layer Profiles

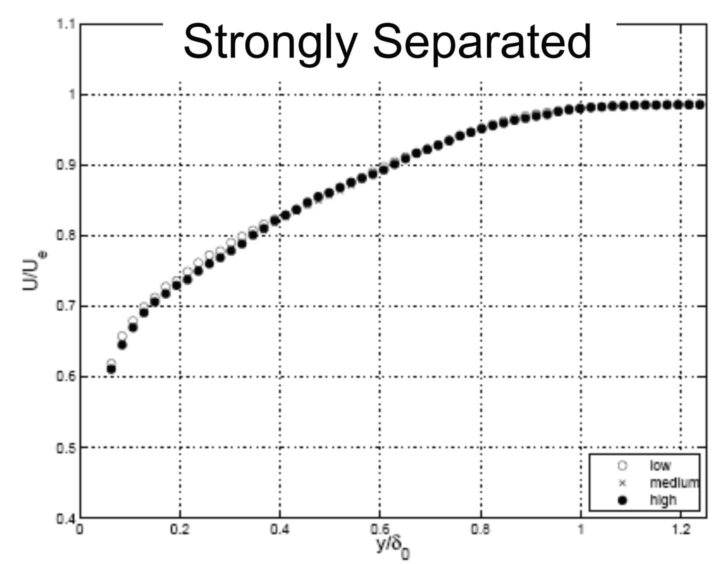
Mach 2 incident-shock interactions

- Piponniau et al. (2009) and Souverein et al. (2009) obtained average velocity profiles conditioned upon separation shock location

- Difference observed in incipiently separated case, not in strongly separated

- Suggests upstream mechanism diminishes with increasing strength of separation

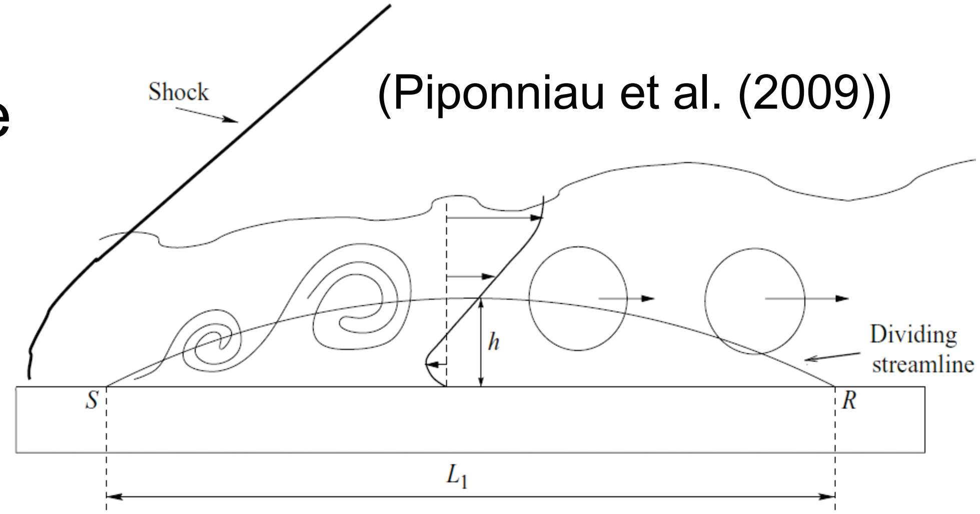




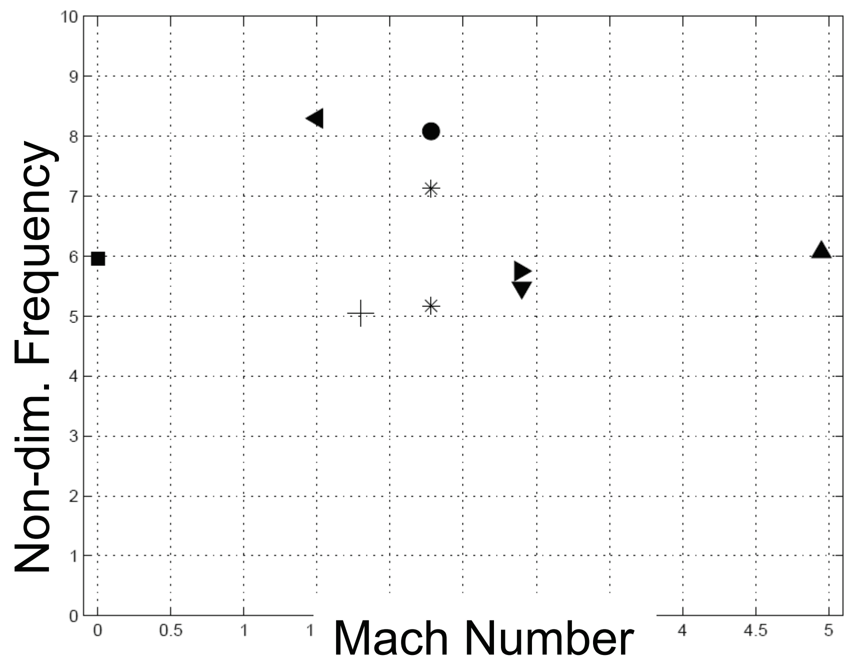
Shear Layer Entrainment Mechanism

- Wu & Martin (2008): shear layer flaps owing to imbalance in (i) the entrainment rate of the shear layer and (ii) the separation bubble re-charge rate near reattachment
- Piponniau et al. (2009) proposed similar model and obtained Strouhal number scaling with Mach number

- Concluded shear layer / bubble instability as a universal mechanism that drives separated flows



(Piponniau et al. (2009))



Can we reconcile these views?

Strength of Interactions

- Dussauge & Piponniau (2008) argued that *incipiently separated* interactions are primarily driven by upstream boundary layer
- Clemens & Narayanaswamy (2009) extended this concept to explore effect of separated flow scale
- Souverein et al. (2009) investigated effect of separated flow scale upstream mechanism

Strength of Interactions

Authors	M	Configuration	Re_θ	L_{sep}/δ_0	US / DS
Dupont et al. (2006)	2.3	impinging shock from 8° shock generator	6900	≈4.3*	DS
Dupont et al. (2006)	2.3	impinging shock from 9.5° shock generator	6900	≈5*	DS
Wu & Martin (2006)	2.9	24° compression corner	2390	4.2	DS
Touber & Sandham (2008)	2.3	impinging shock from 8° shock generator	5900	4.5	DS
Humble et al. (2009)	2.1	impinging shock from 10° shock generator	49000	<1	US
Ganapathisubramani et al. (2006)	2	28° compression corner	35000	2	US
Beresh et al. (2002)	4.95	24° compression corner	35000	2	US
Erengil & Dolling (1993)	4.95	24° compression corner	35000	2	US / DS
Thomas et al. (1994)	1.5	6-12° compression corner	17000	<2	DS
Brusniak and Dolling (1994)	4.95	Blunt fin	31600	≈3	US / DS

Strength of Interactions

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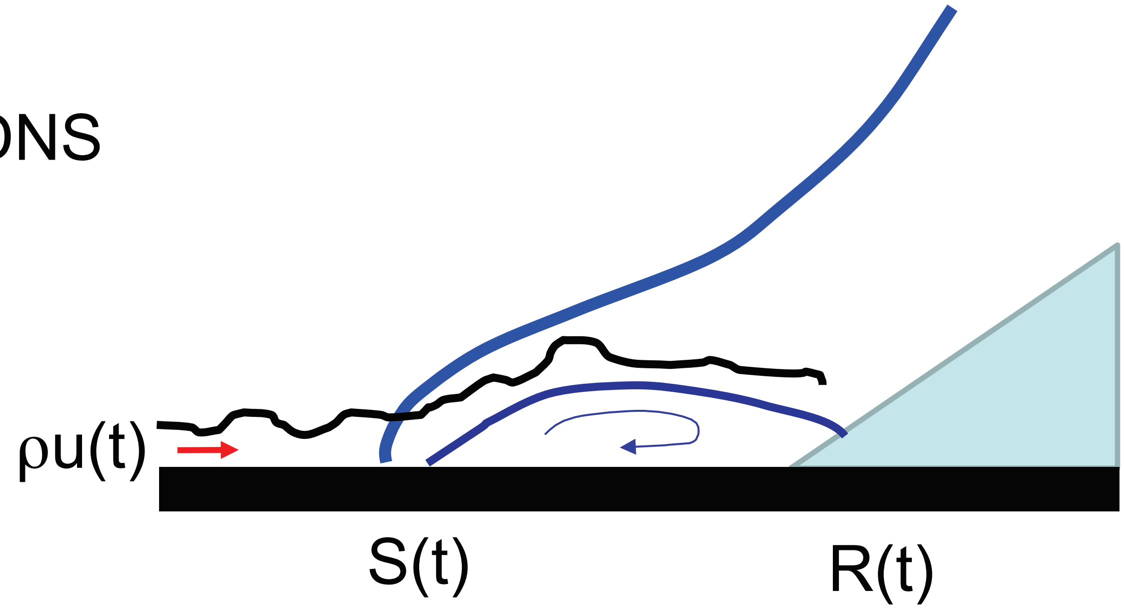
Our View

- 'Upstream-only' or 'downstream-only' mechanisms are too simplistic*
- We argue that both mechanisms are always present in all SBLIs but:
- As separation bubble grows, upstream fluctuations become less effective at moving the separation line
  - Momentum fluctuations cannot overcome pressure rise across separation shock
- The bubble expands / contracts by some sort of large-scale instability (Wu & Martin, 2008; Piponniau et al., 2009)

*Similar (but subtly different) view recently proposed by Dussauge's group (Souverein et al., 2009)

Example of both mechanisms?

Wu & Martin (2008) DNS



Correlation coefficient between ρu(t) and S(t) = 0.3

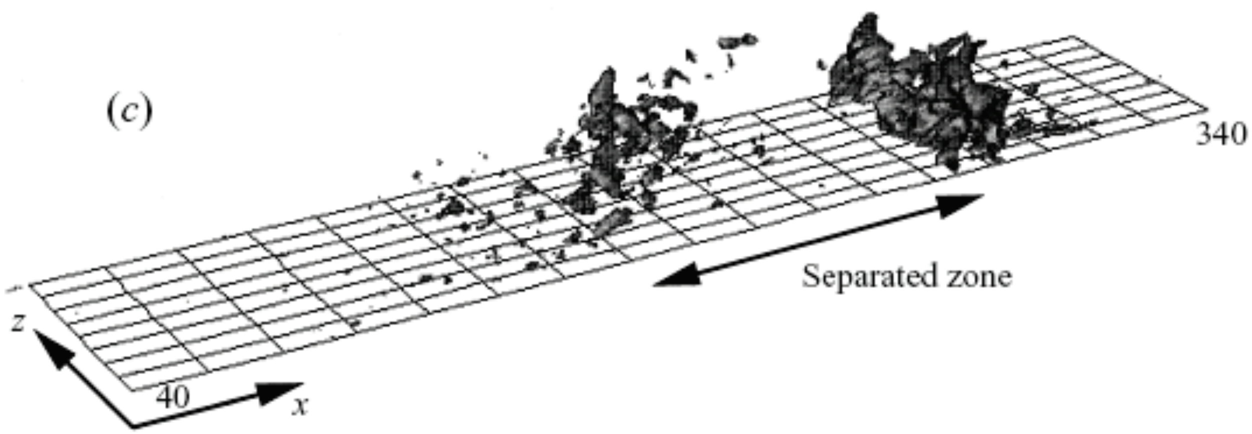
Correlation coefficient between S(t) and R(t) = -0.35

Separation equally affected by upstream and downstream mechanisms?

Is there an upstream role for strong interactions?

Na & Moin (1998): DNS of incompressible separation

- Fluctuations in upstream boundary layer can seed shear layer that grow and cause flapping of separation point
- We see evidence of this in plasma-jet forcing experiments



What about superstructures?

- Most important velocity (momentum) fluctuations are those closest to the wall (Beresh et al., 2002; Wu & Martin, 2008; Na & Moin, 1998)
- Superstructures observed in the log-region likely not as relevant as near-wall shear stress fluctuations
- Superstructures distracted us from looking closer to wall
- We do believe superstructures represent a 'broader truth'
  - Turbulent boundary layers need to exhibit very low frequency content to couple flow instabilities (even in weak interactions)
  - Superstructures do impose their footprint on the wall shear stress (Hutchins & Marusic, 2007)

Conclusions

- We are close to having a comprehensive understanding of unsteadiness of shock-induced turbulent separation
- Interactions will exhibit varying degrees of upstream and downstream effects depending on the scale of separation
- **High-speed vehicles exhibit very high Re and so interactions will likely be intermittently separated**
  - **Practical interactions are likely to remain sensitive to upstream mechanism**