NORDITA-FLOW Turbulent Boundary Layers, Stockholm
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Turbulent Spots and Separation Bubbles in High-Speed Boundary Layers

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Work carried out in collaboration with:
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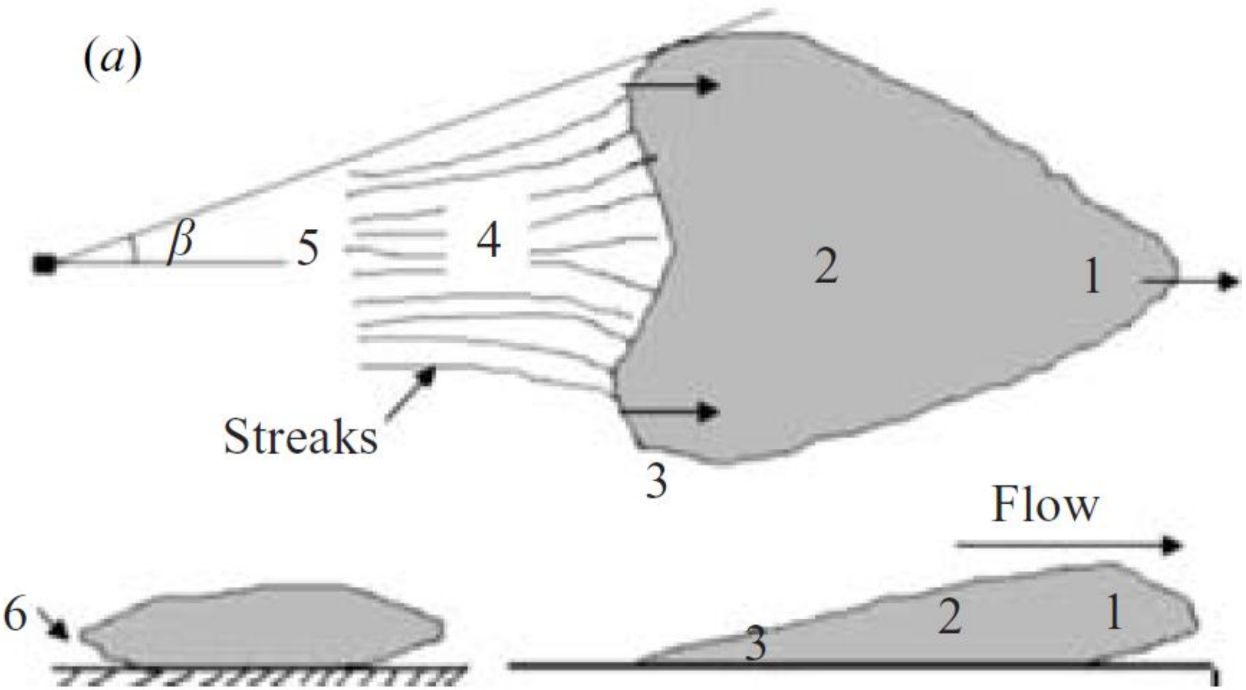
Outline of talk

- Turbulent spots
  - Why are spreading angles so sensitive to Mach number?
  - Relationship to stripes?
- Shock-induced turbulent separation bubble
  - What causes the observed low frequency unsteadiness? Candidate mechanisms:
    - Upstream boundary layer superstructures
    - Internal global mode; forced response
    - Convective or acoustic feedback loops

Spots

- Experiment
  - Emmons (1951)
    - Morkovin: `suddenly everyone was seeing spots'
  - Wygnanski (JFM 78); Cantwell (JFM 87); Tillmark & Alfredsson (JFM 235)
- Simulations
  - Henningson & Kim (JFM 228) ; Singer (PF8); Jacobs & Durbin (JFM 428)
  - Compressible: Krishnan & Sandham (2006,2007) ; Jocksch & Kleiser (2008), Redford et al (2010)

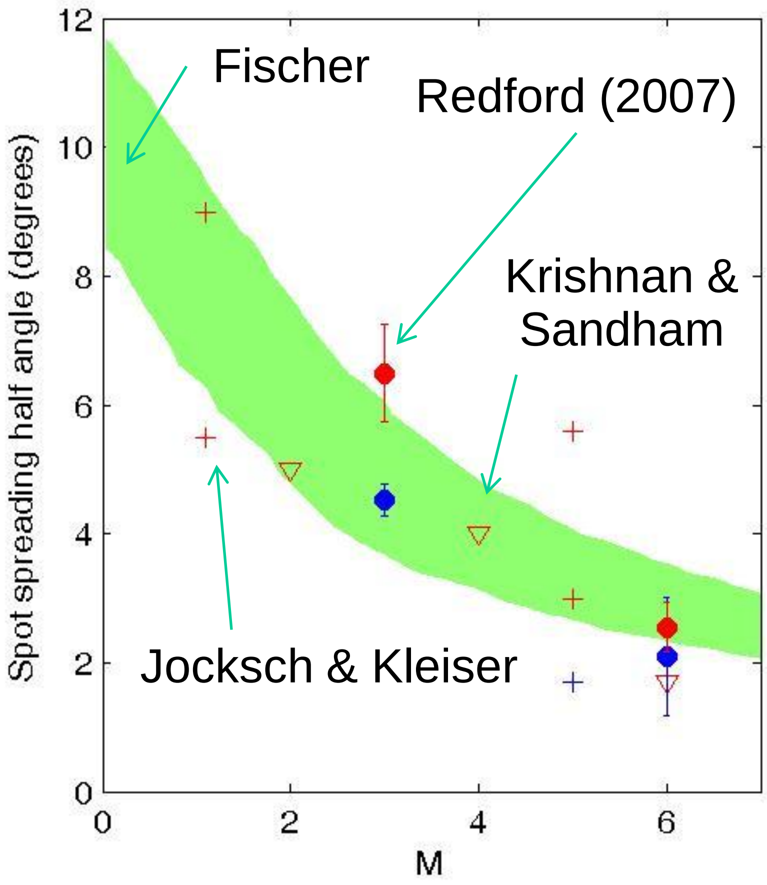


1) Front overhang, 2) Turbulent core, 3) Lateral wingtip, 4) Calmed region, 5) Lateral spreading half-angle, 6) Spanwise overhang.

Leading edge convects at ~85% U_e, trailing edge convects at ~50% U_e

Spot spreading angle

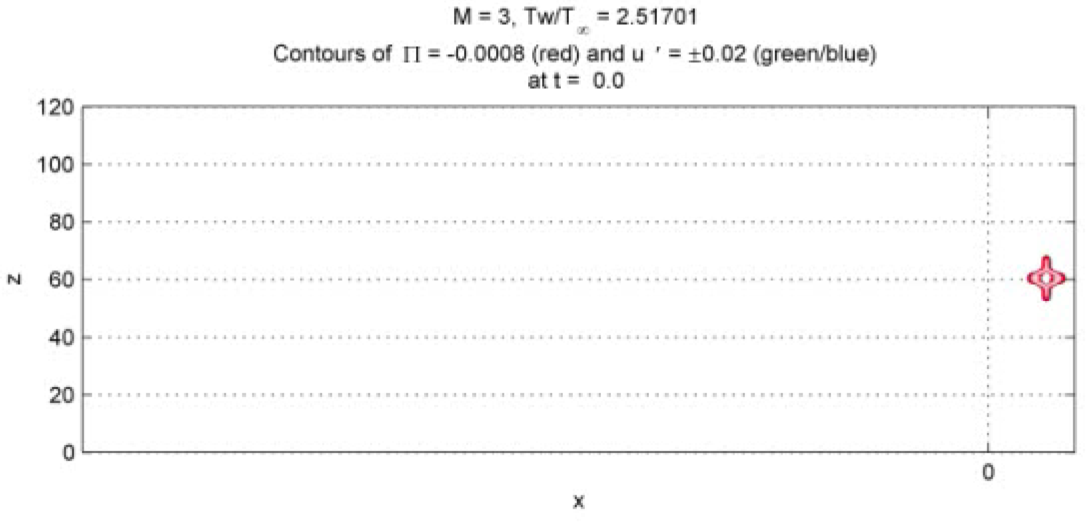
- Spreading angle
  - Reduces strongly with Mach number
  - Cold wall reduces the spread angle by 20-30%
- Measurement variation
  - Jocksch & Kleiser studied Reynolds number effects
  - Differences in measurement techniques



Spot evolution

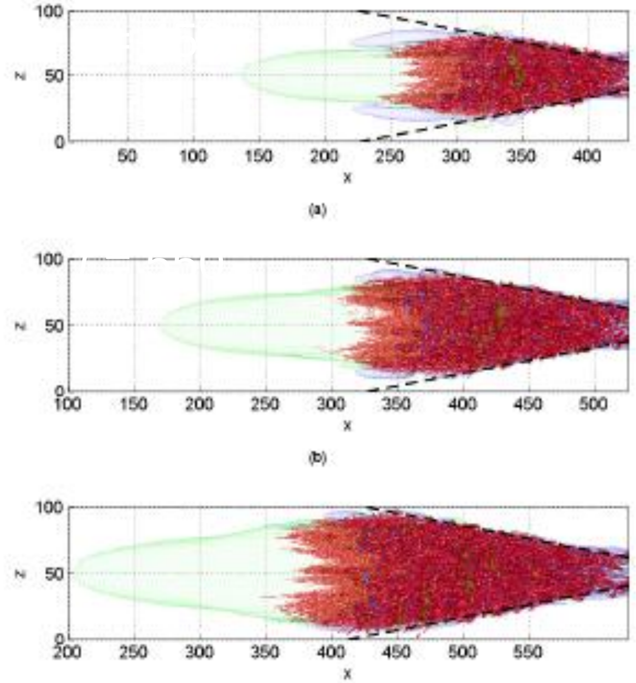
Red=second invariant (vortices)
Green=positive u'(e.g. the calmed region)
Blue=negative u' (low speed region)

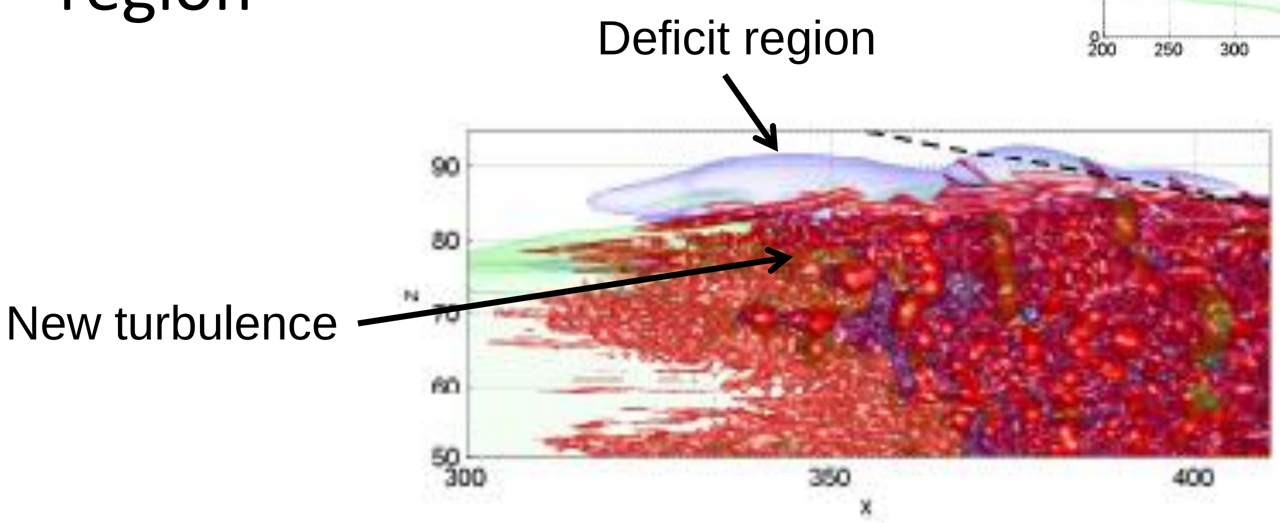
M=3 adiabatic wall temperature case



Spot growth

- Turbulence is created at the wing tip
  - Destabilisation at wing tip
- Turbulence at the front and rear of the spot is convected
- Stable streaks in the calmed region

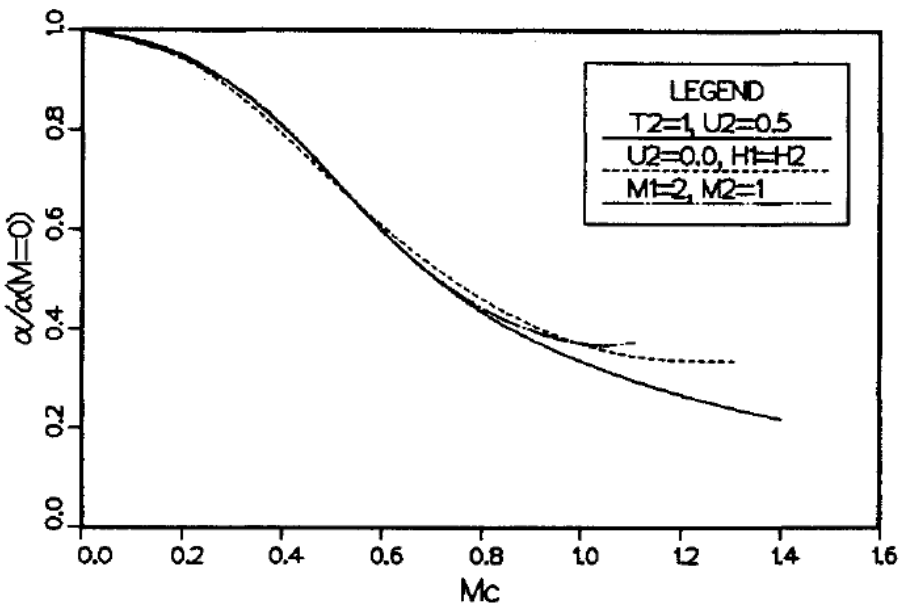




Why are spot so strongly affected by compressibility?

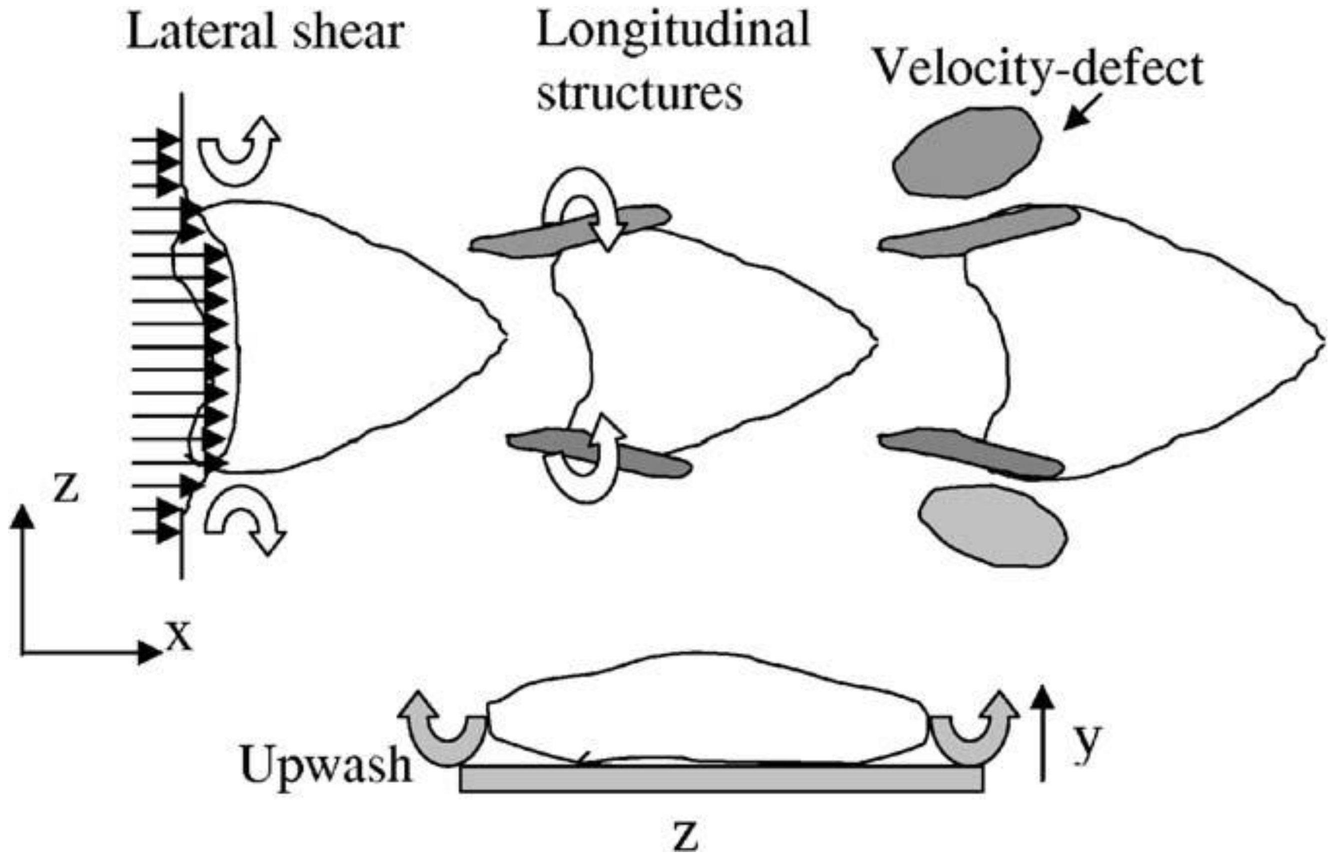
- Turbulent boundary layer exhibits low compressibility effects at least up to Mach 5
- Not a density effect
- Possible analogy with mixing layer – strong reduction of free-shear layer instability with Mach number
- Tip destabilisation (lift-up and lateral jets) seems to be key, but 3D base flow not amenable to analysis

Mixing layer linear growth rate vs. convective Mach number

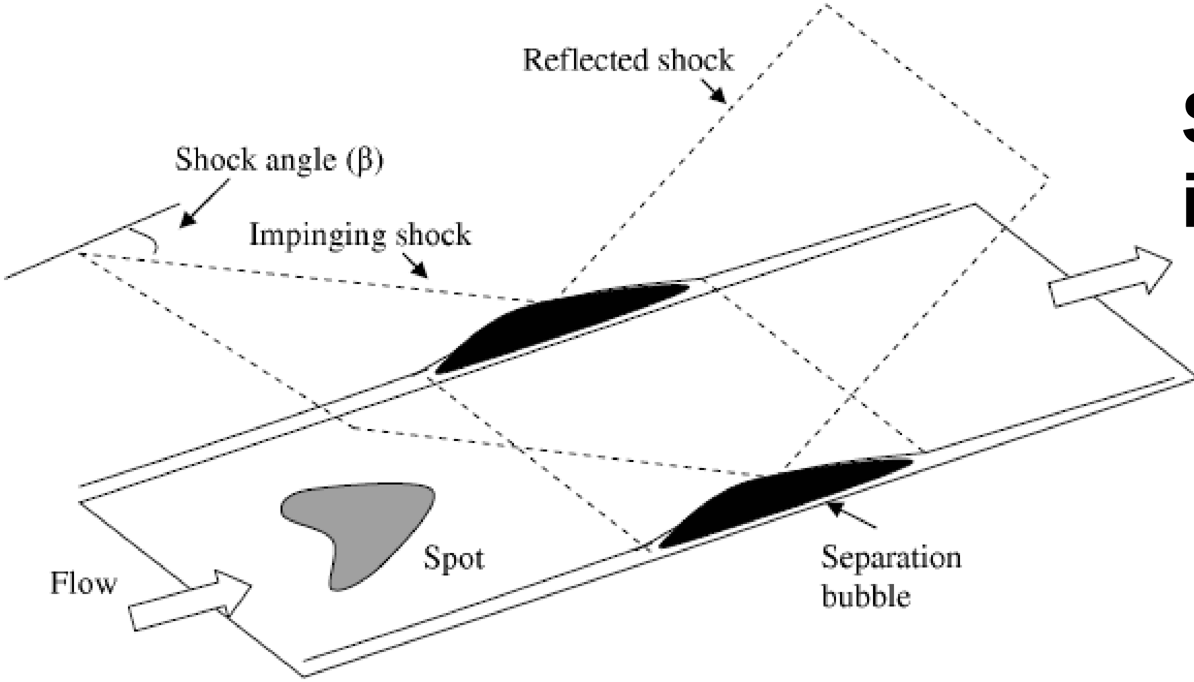


$$M_c = \frac{U_1 - U_2}{a_1 + a_2}$$

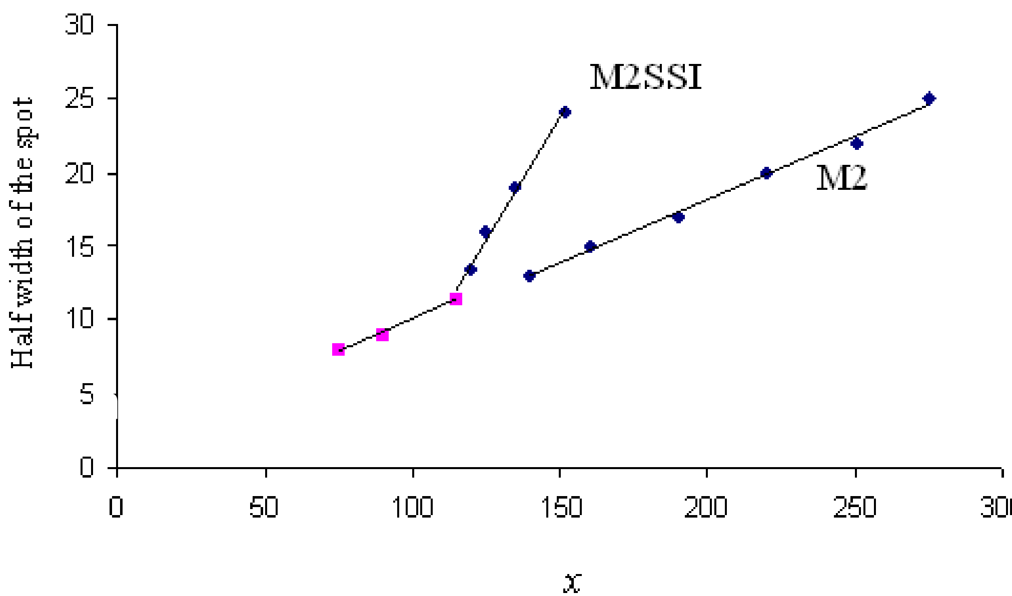
Possible growth mechanism



Shock-spot interaction



Enhanced spot growth with higher spanwise velocity change



Relation to stripes?

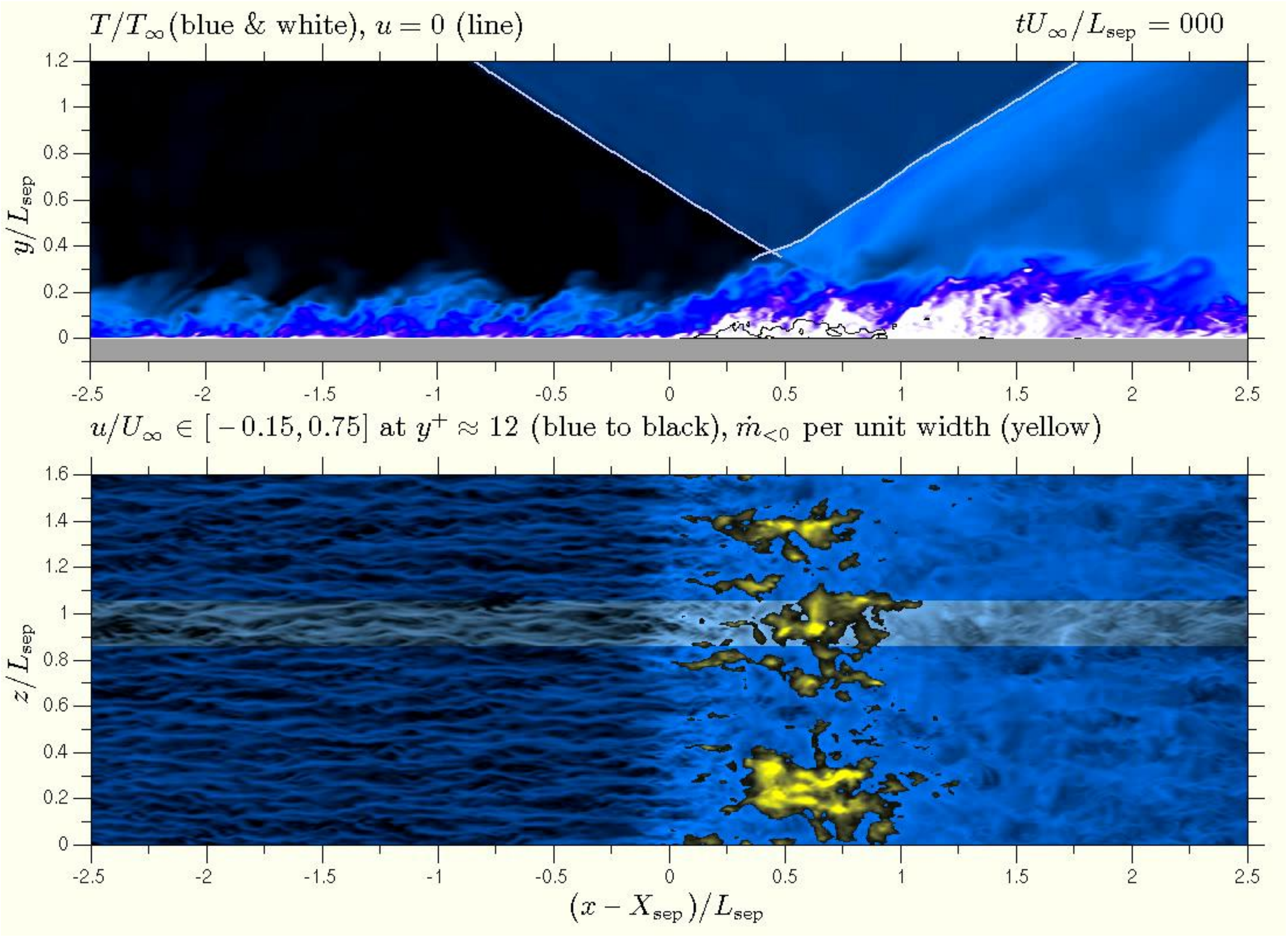
Picture from DSH (2010)

- Simulations: Barkley & Tuckerman (2008); Duguet, Schlatter & Henningson (2010) etc.
- Calmed regions present, as are found behind an isolated spot
- Same mechanism, different Reynolds number regimes? Also sensitive to the geometry

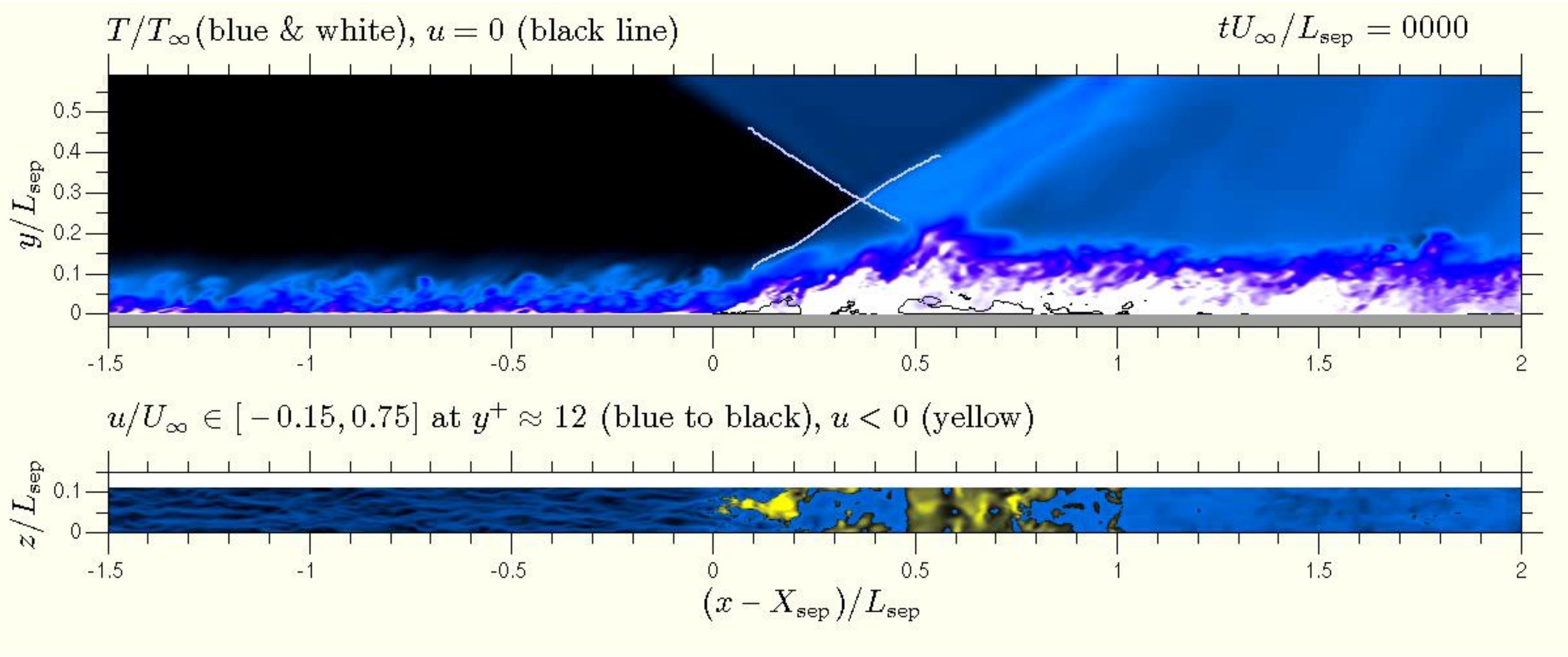
Shock impingement Touber & Sandham 2009a,b

Side view

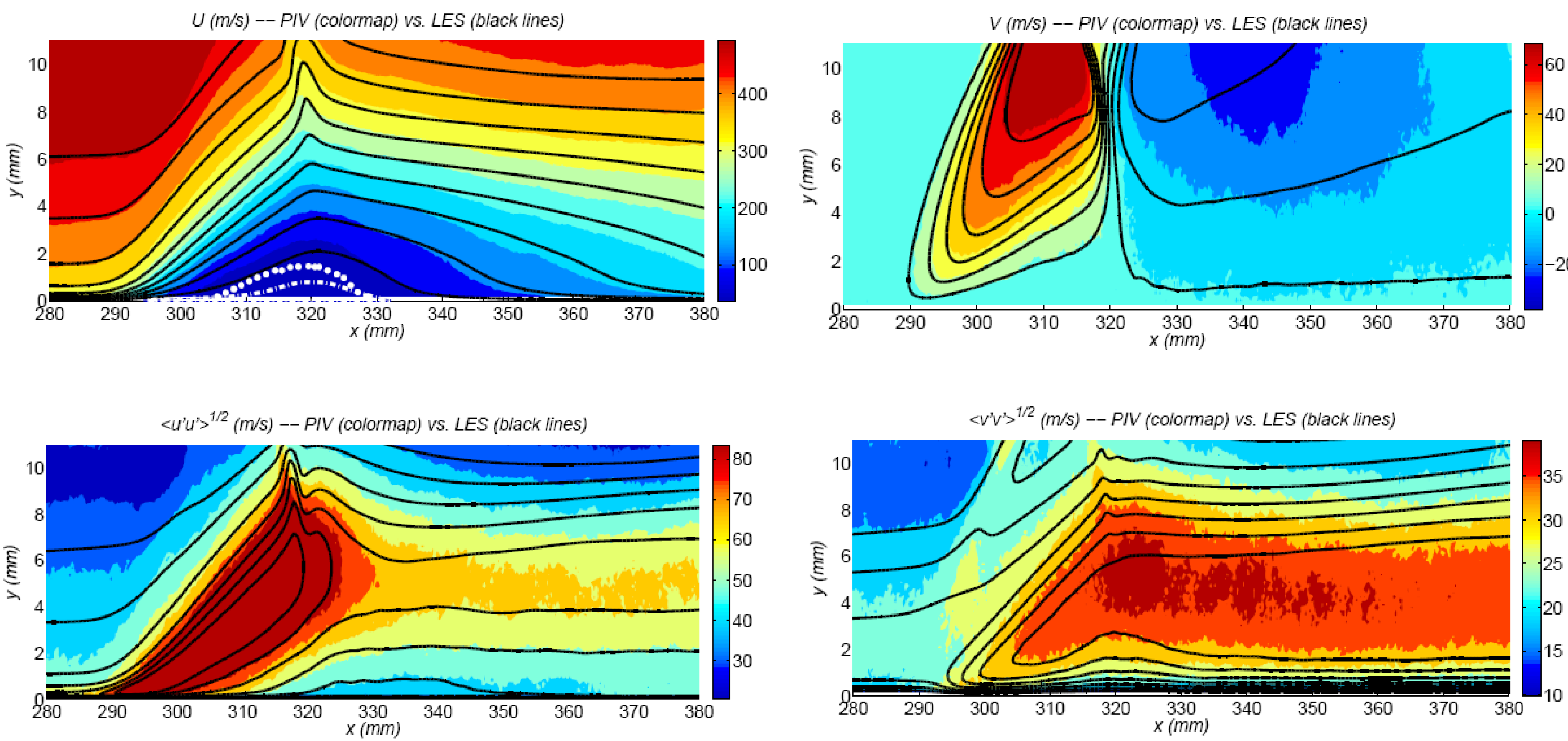
Top view



Faster visualisation in narrow box shows low frequency clearly

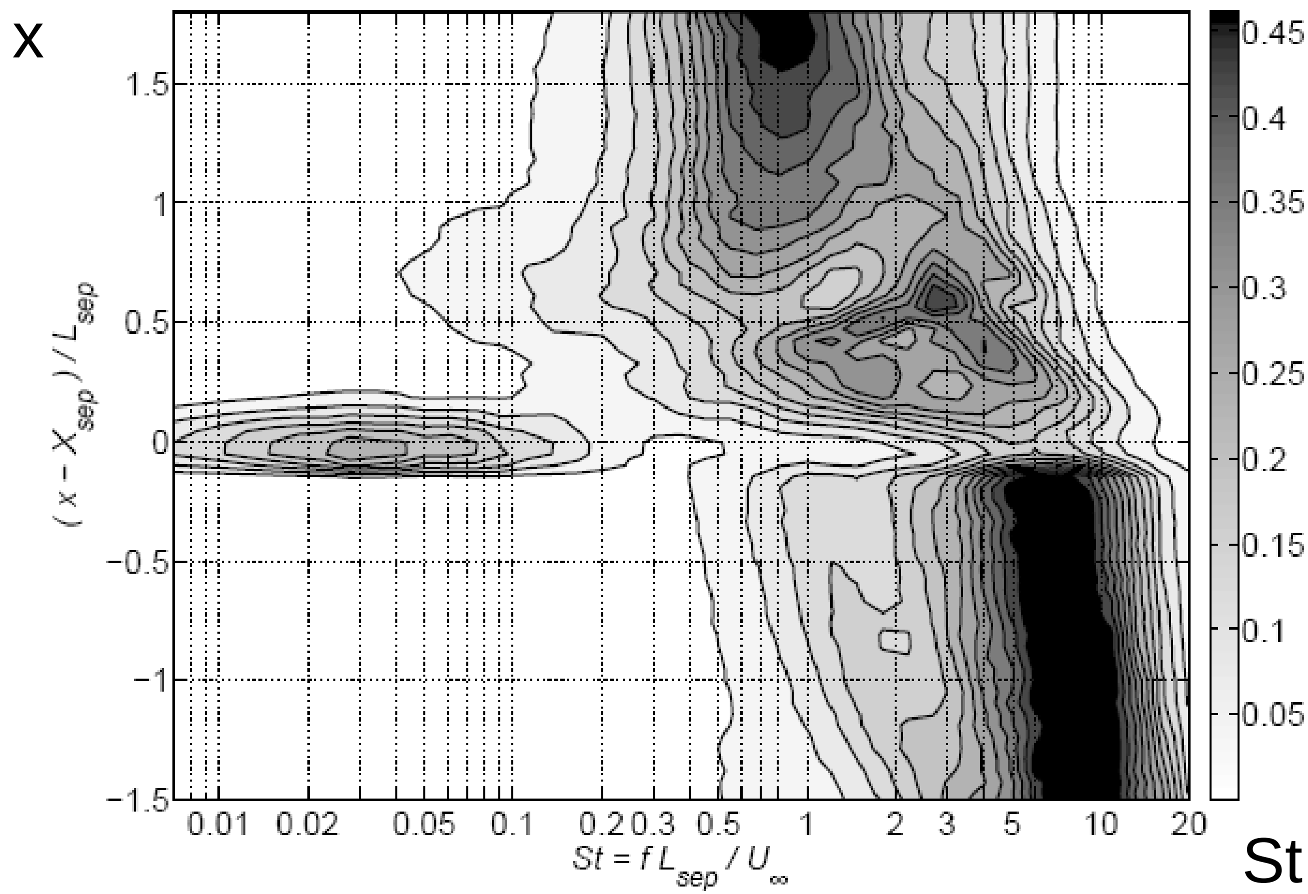


LES (wide domain) vs PIV (Dupont et al)



LES (x,y,z): N=451x81x361 L=71.9x11.2x19 (δ_{1i}) Δ^{+}=40,1.6,13.5

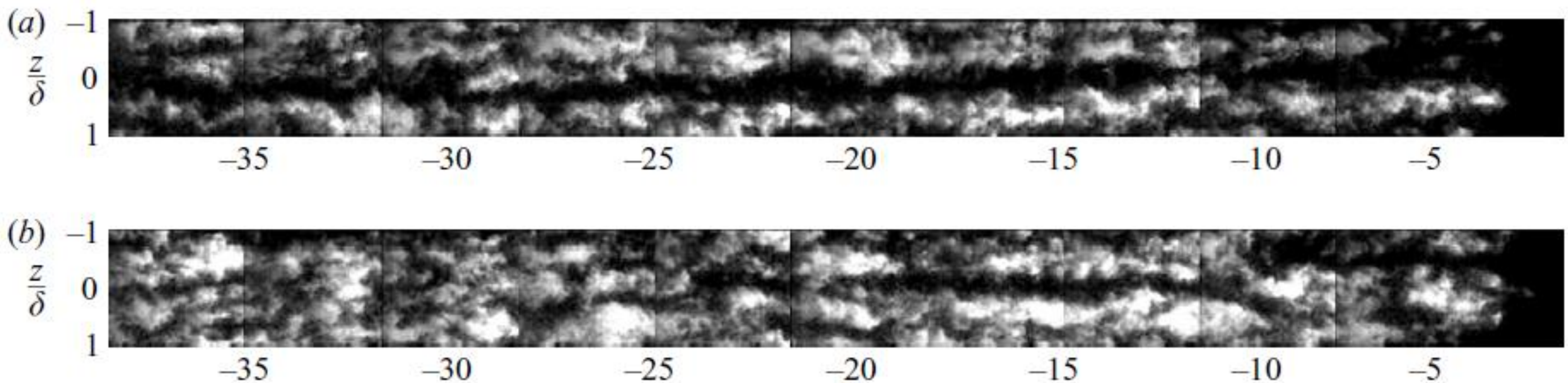
Spatial variation of the premultiplied power spectrum of wall pressure



low-f is spatially confined to the foot of the reflected shock

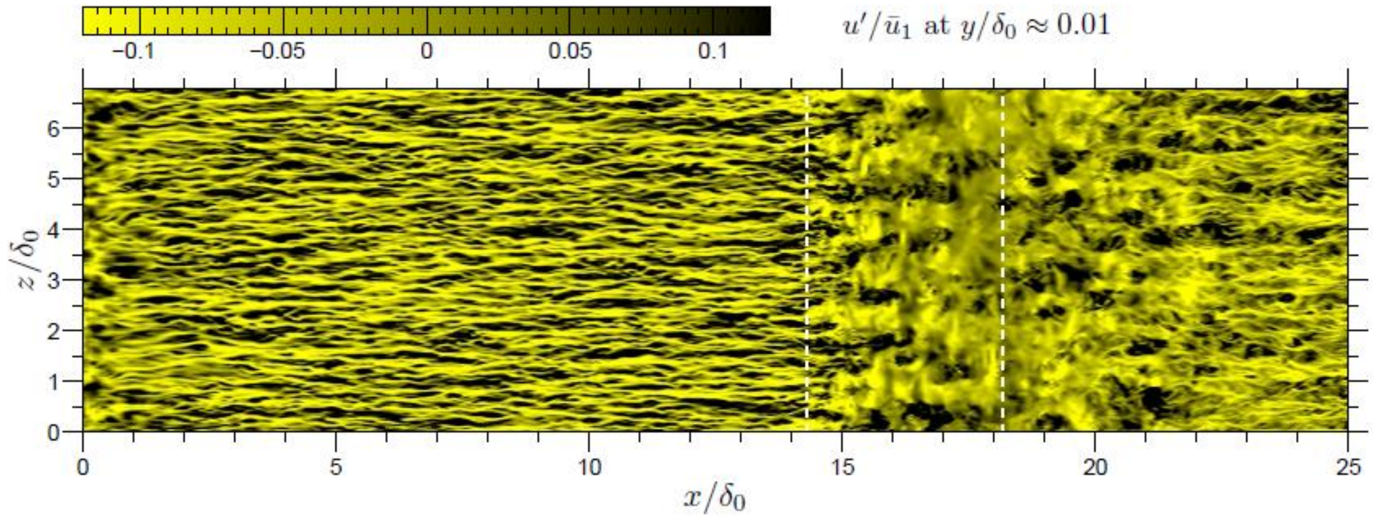
Upstream superstructures?

- Ganapathisubramani et al (2007): L=30-40δ structures observed in upstream boundary layer and correlated with unsteady shock movement
- Such structures are absent from the LES which still gives low-f oscillation, consistent with experiment
- Present interpretation: upstream structures exist in some facilities, but not necessary to understand the low-f motions
- Origin of L=30-40 δ structures?



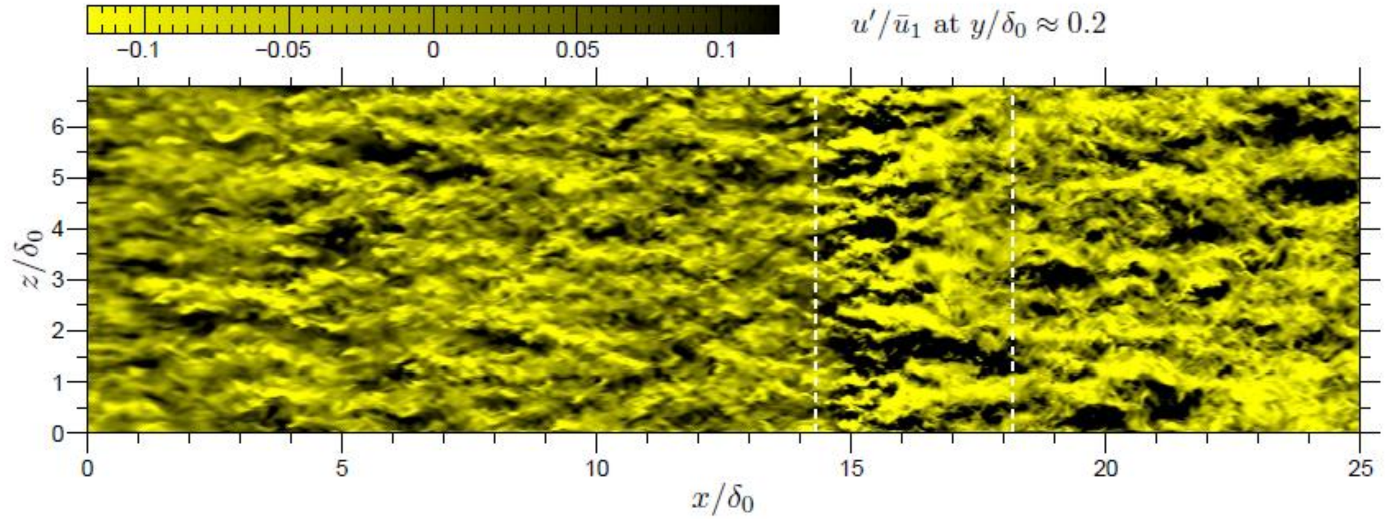
Streamwise velocity perturbation field

y/δ_0=0.01



(a) at $y^+ \approx 12$, $u_c/\bar{u}_1 \approx 0.35$

y/δ_0=0.2

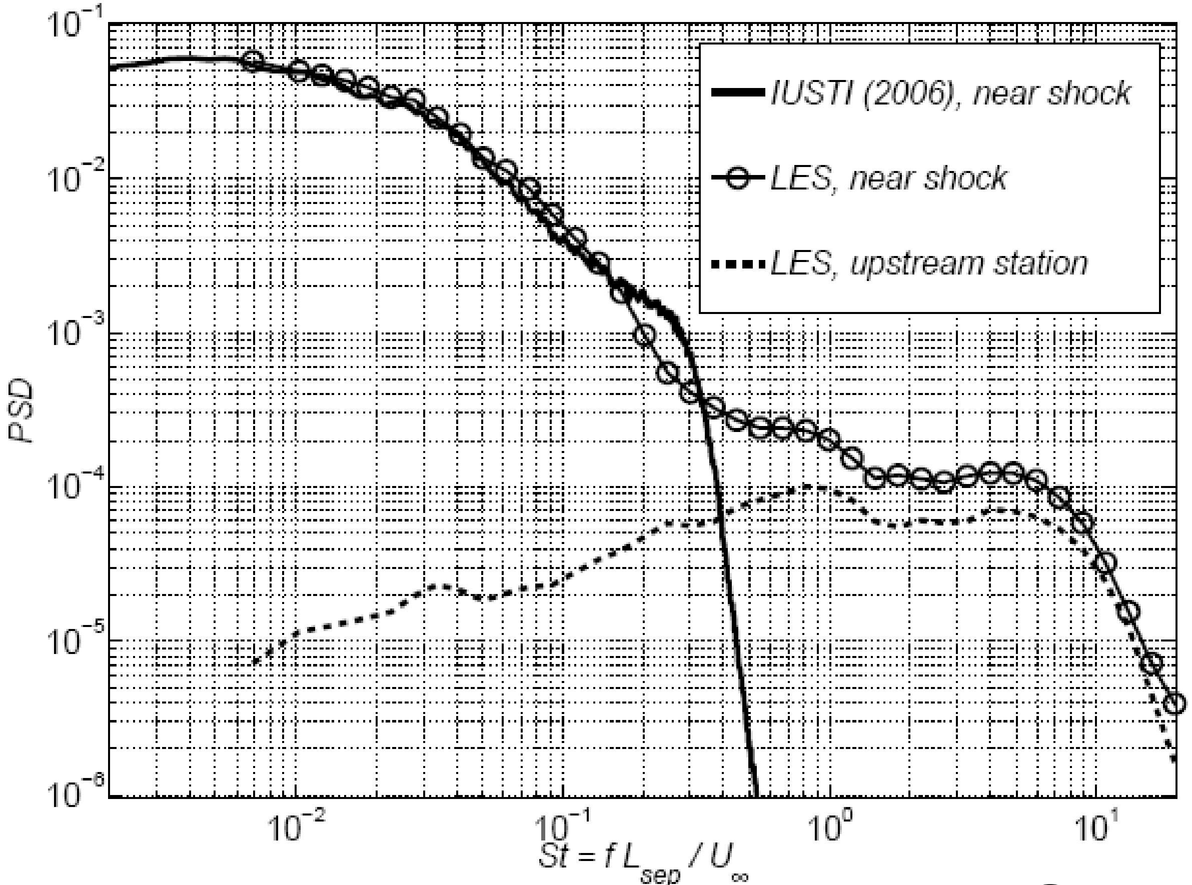


(b) at $y/\delta_0 \approx 0.2$, $u_c/\bar{u}_1 \approx 0.73$

Digital filter
inflow method

Power spectrum of wall pressure under reflected shock foot

Power spectral density



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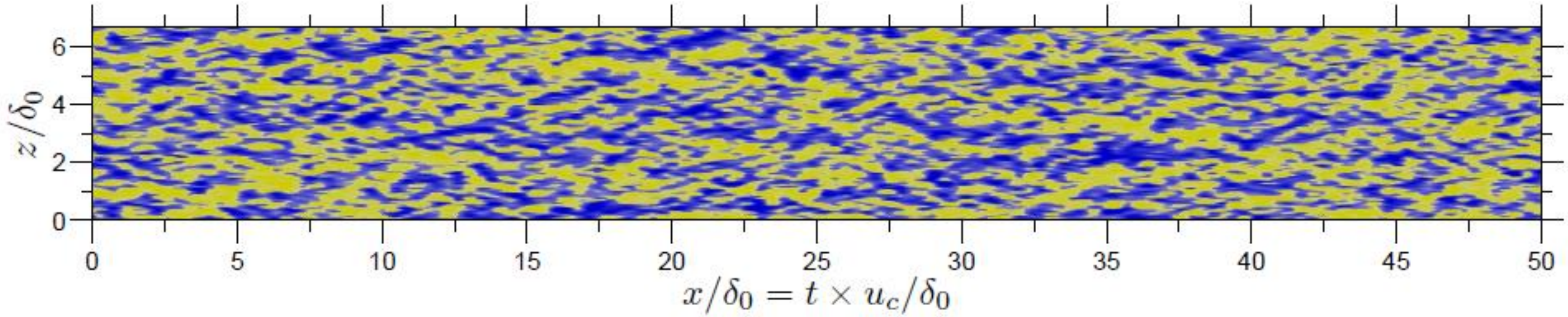
Long structures reconstructed from time series at fixed points

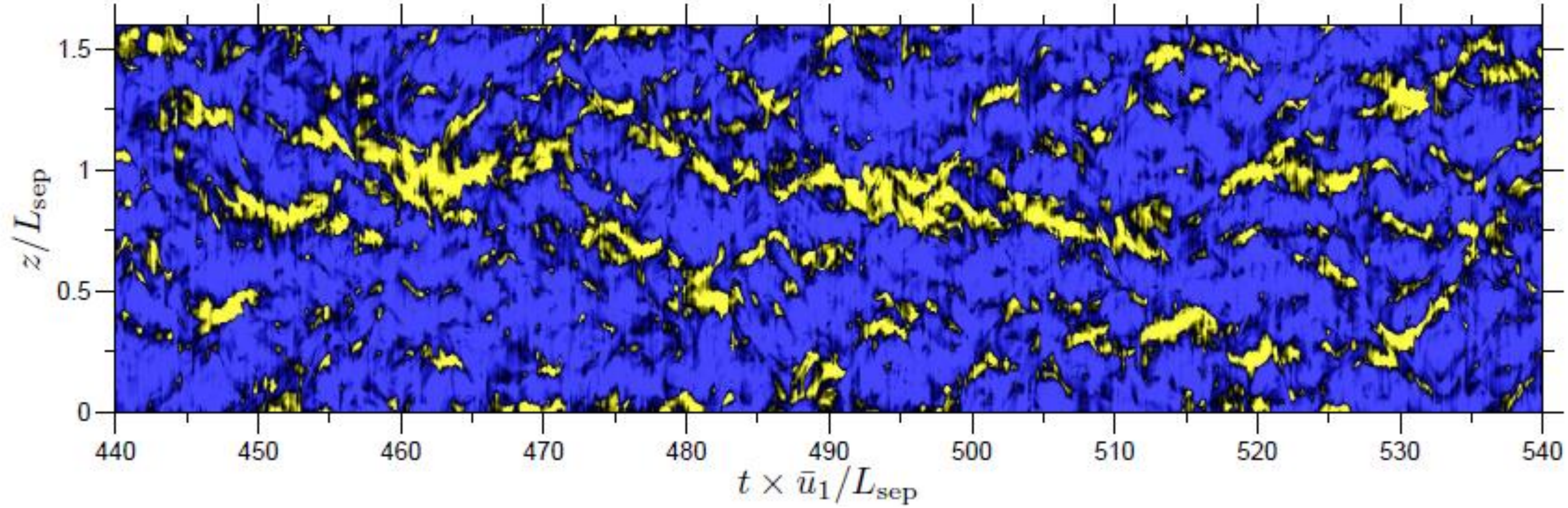
Upstream boundary layer (y/δ_0=0.2)

L=5δ_0 approx



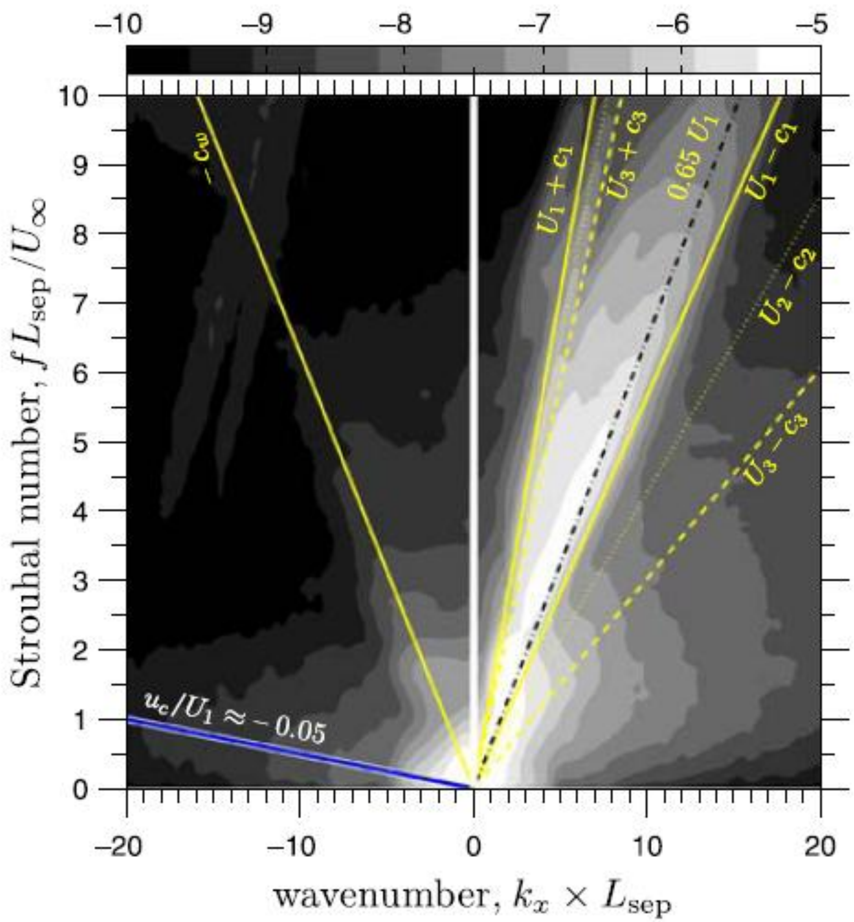
Separation zone

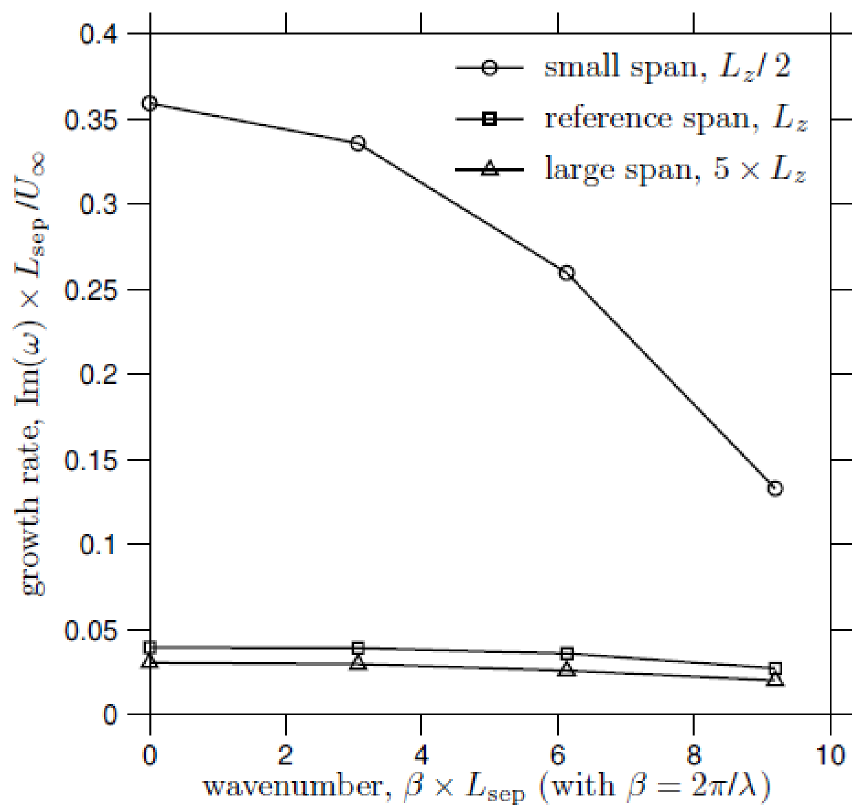
L=50δ_0 (approx)



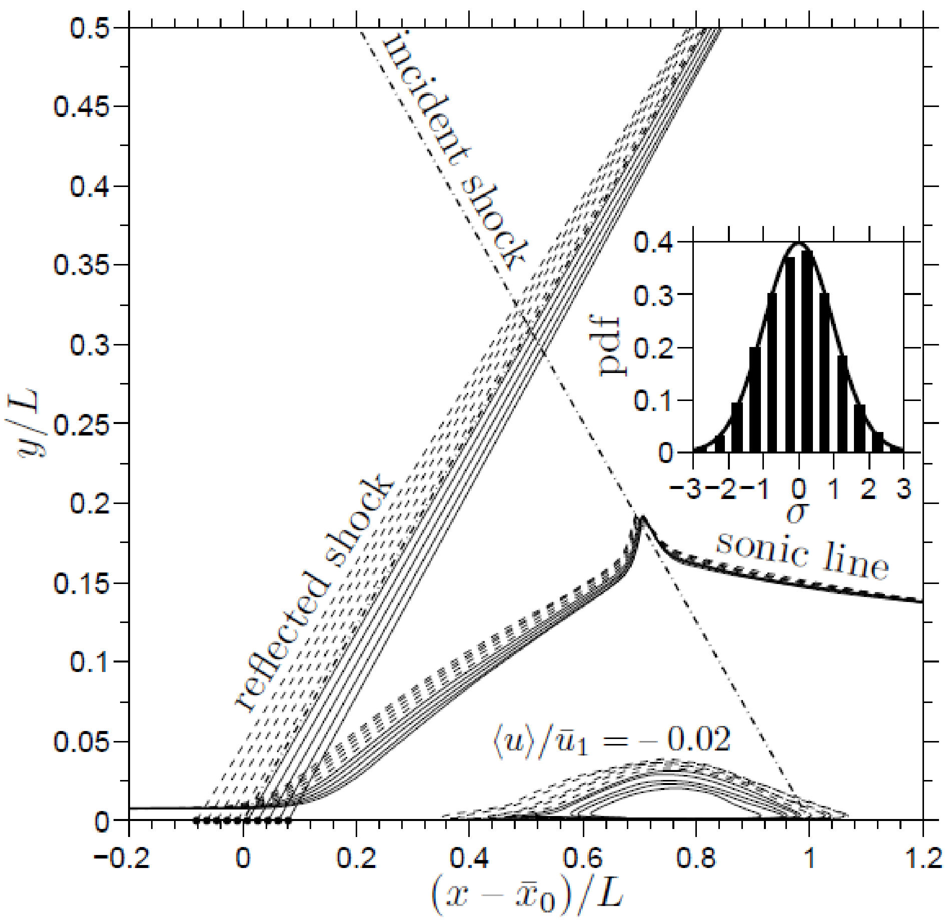
Convective or acoustic feedback loops; global modes?

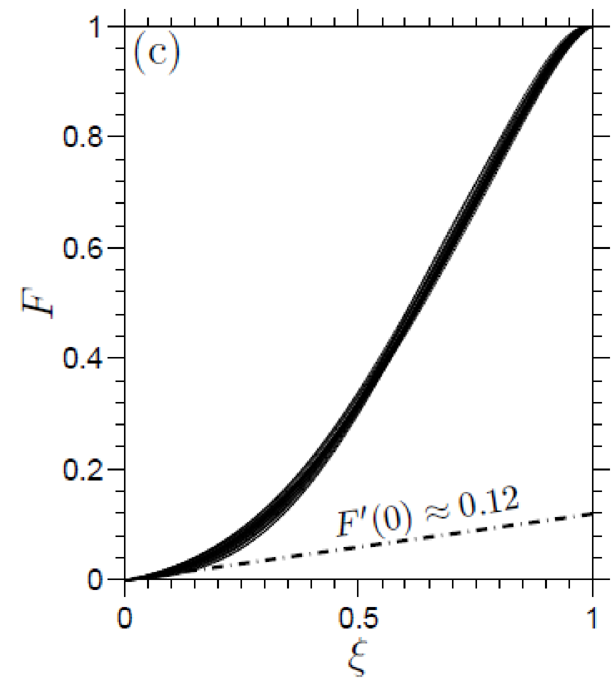
- Pipponiau et al (2009); Pirozzoli & Grasso (2006); Touber & Sandham (2009).





Conditional averages and separation similarity





$$F(\xi) \equiv \frac{\delta_i(\xi) - \delta_i(\xi = 0)}{\Delta_i},$$

$$\Delta_i(t) \equiv \delta_i(\xi = 1) - \delta_i(\xi = 0),$$

Model for the forced response of the reflected shock foot region

- Based on the Momentum integral equation (MIE)
- Formal derivation of Langevin equation, at leading order equivalent to Plotkin's (1975) empirical proposal

$$\dot{\zeta} + \phi\zeta = \psi(t)$$

- Time variation of normalised reflected shock location ζ
- Time constant ϕ depends on mean flow
- Forcing $\psi(t)$ from skin friction variations

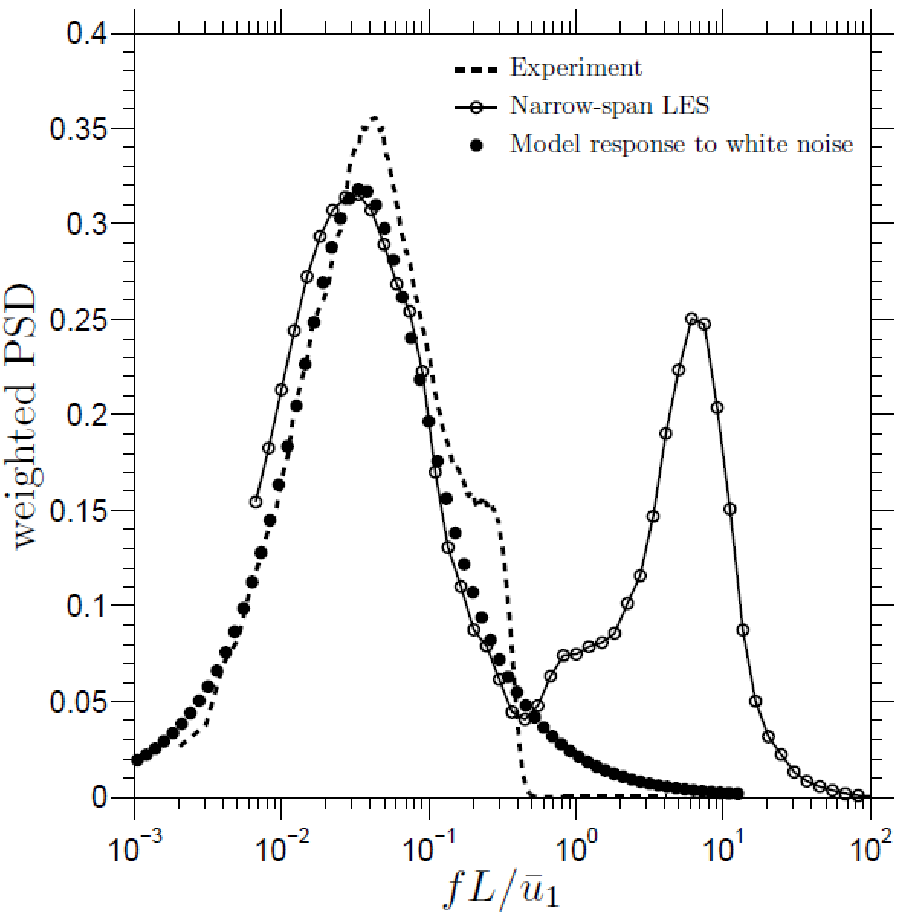
$$\phi = \frac{L}{\Theta_\rho}\left[\frac{1}{2F'(0)}\left(\bar{C}_{f_0}\left(1-k\right) - \frac{l_0}{L}\Lambda\right) - k\tan\beta\left(\kappa_2 + \frac{p_1}{\rho_1 u_1^2}\kappa_p\right)\right]$$

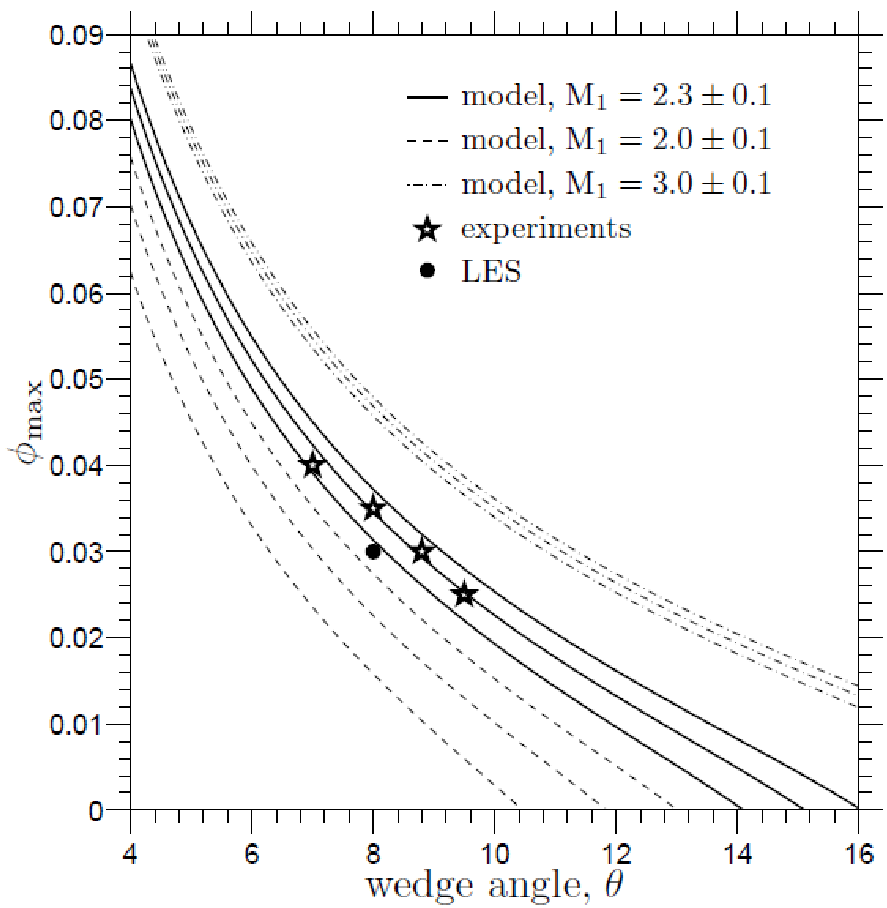
$$\psi(t) = \frac{l_0 C''_{f_0}(t)}{2LF'(0)}.$$

All terms in ϕ can be modelled in terms of upstream conditions and impinging shock angle

Model results

- Model for all terms in agreement with (limited) experiments and LES





Conclusions

- **Turbulent spots**
  - Strong compressibility effect on turbulent spot growth
  - Suggests an instability mechanism driving spot growth (as opposed to lateral turbulent convection)
- **Shock-induced separation**
  - Shock impingement LES show low-frequency unsteadiness in absence of upstream superstructures
  - Global mode only significantly unstable for narrow span simulation
  - Some evidence for upstream feedback
  - Analysis based on unsteady MIE is leading to quantitative predictions that can be checked