4. Compressible flows

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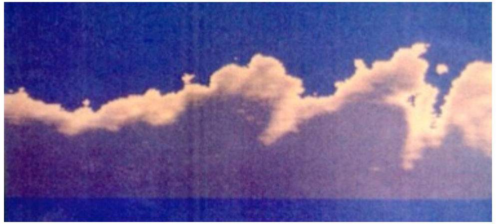
Les Houches School of Physics

ÉCOLE DE PHYSIQUE DES HOUCHES

High speed flows

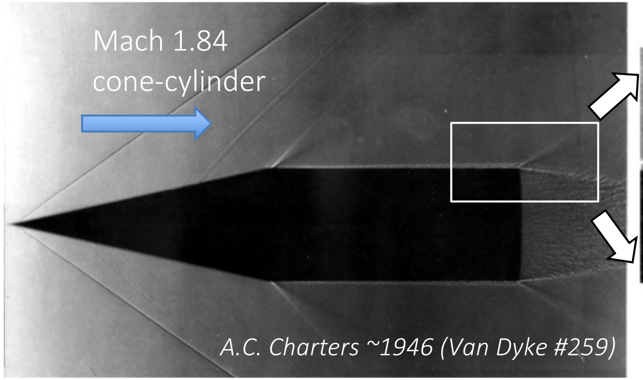
Turbulent boundary layer

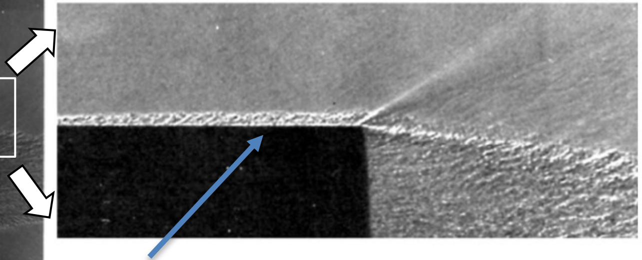
Smith 1989 (Mach 2.5)



Side view

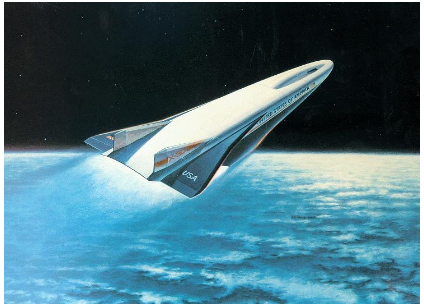
Plan view



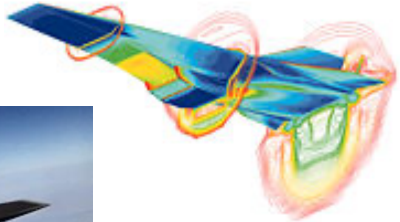


Turbulent boundary layer

Space Shuttle (first flight 1981)

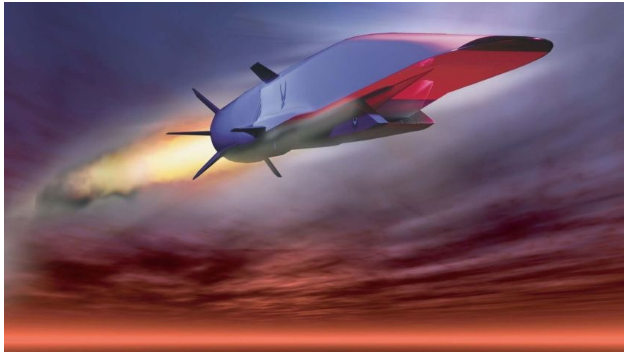


NASP X-30 (proposed 1986)

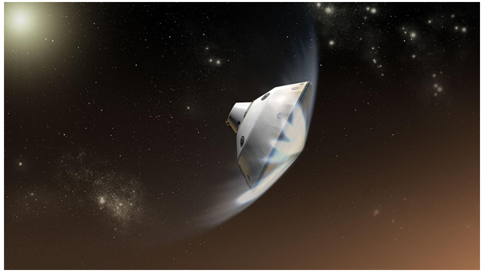


NASA X-43A/Hyper-X (first flight 2004)

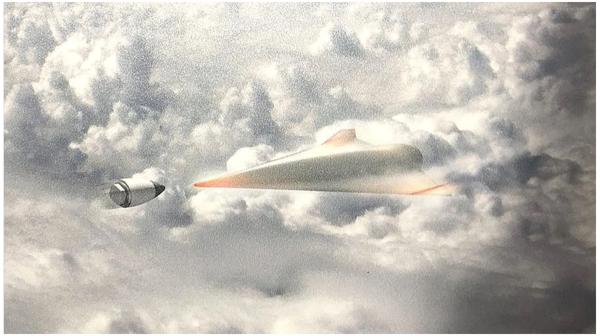
AF X-37B (first flight 2010)



Boeing X-51A Waverider (first flight 2010)

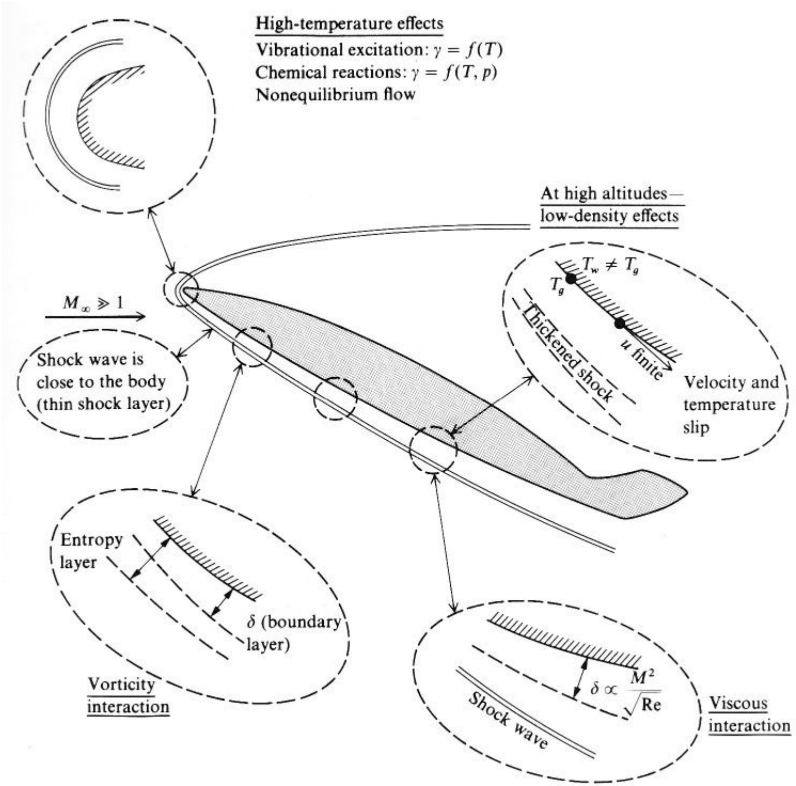


Curiosity Mars probe (2012)

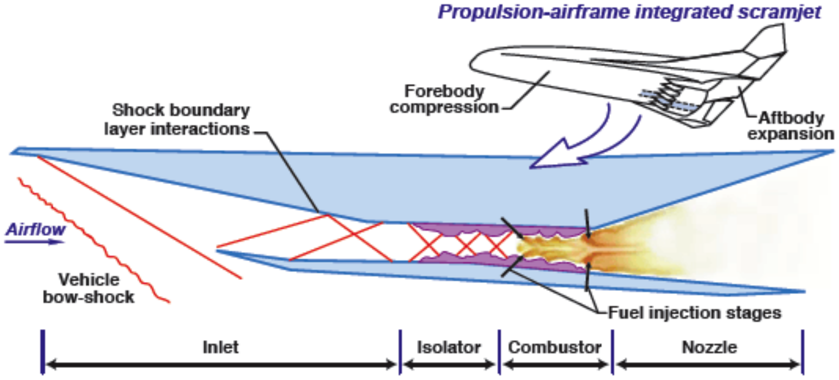


DARPA Glide Breaker

Hypersonic vehicle flow fields



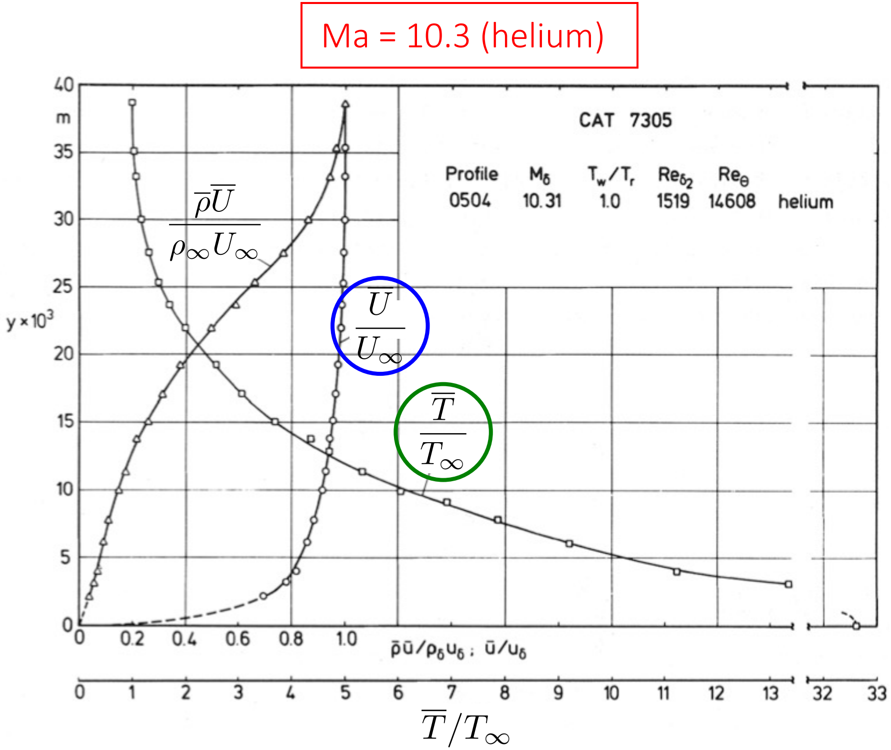
(Anderson, 1989)



(NASA)

(Aerojet Rocketdyne)

Mean flow in high-speed boundary layers

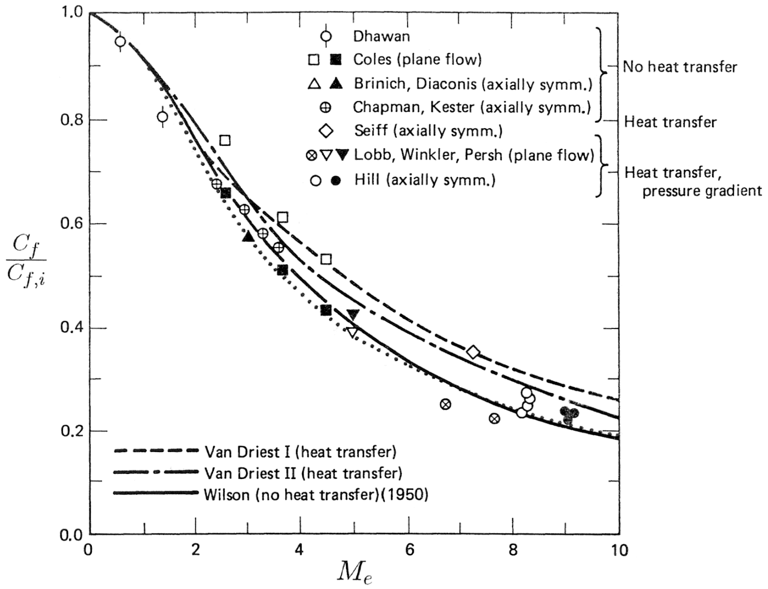


- Mean velocity profile looks similar to that in incompressible flow but scales differently
- Temperature increases near the wall
- Density decreases near the wall
- Need to account for density changes

Watson et al. (1973); Fernholz & Finley (1980)

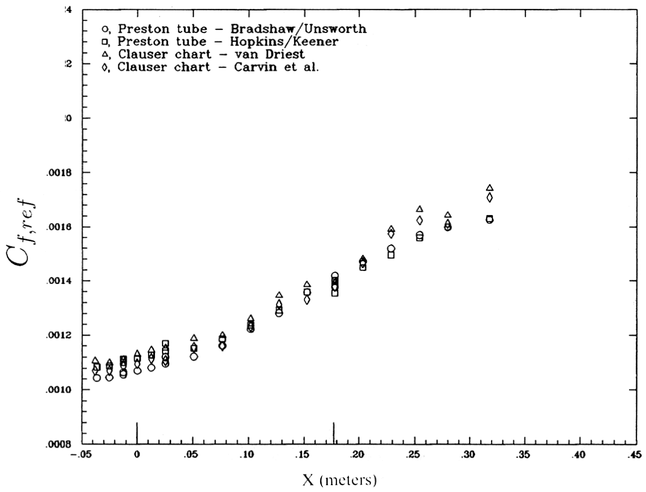
Skin friction

Zero pressure gradient



ρ_w decreases with Mach number

Adverse pressure gradient



ρ_w increases with compression

Compressible turbulent flows and Reynolds number

- In a compressible flow, we have a choice of Reynolds numbers
- Friction Reynolds number

$$Re_\tau = \frac{\delta}{\nu_w / u_\tau} = \frac{\delta u_\tau}{\nu_w}$$

- Momentum thickness Reynolds number (freestream viscosity or wall viscosity)

$$Re_\theta = \frac{U_e \theta}{\nu_e} \qquad Re_{\theta_w} = \frac{U_e \theta}{\nu_w} \qquad (Re_\theta > 200\, Re_{\theta_w} \text{ for Mach 10 helium flow})$$

$$Re_{\delta_2} = \frac{\text{highest momentum flux}}{\text{highest shear stress}} = \frac{\rho_e U_e \theta}{\mu_w}$$

$$(Re_\theta > 10\, Re_{\delta_2} \text{ for Mach 10 helium flow})$$

- The inner layer thickness relative to the boundary layer thickness increases with Ma

Compressible turbulent flows and time scales

- The friction Reynolds number is often interpreted as a ratio of length scales
- What about time scales?

- Outer time scale: $\dfrac{\delta}{U_\infty}$ Inner time scale: $\dfrac{\nu_w}{u_\tau^2}$

- Ratio outer to inner: $R_\tau = \dfrac{u_\tau}{U_\infty}\left(\dfrac{\delta u_\tau}{\nu_w}\right) = \sqrt{\dfrac{C_f}{2}} Re_\tau$

- Time scale ratio decreases with Mach number

What do we know or expect for the mean flow?

1. van Driest transformation collapses the mean velocity profile onto the incompressible form of the log law, and the incompressible form of the wake

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- In the overlap between the inner and outer scaling, we have a log-law
- Best expressed as

$$\frac{\partial \overline{U}}{\partial y} = \frac{\sqrt{\tau_w/\rho}}{\kappa y}$$

velocity scale

length scale

- Hence:

$$U_{VD} = \int_{U_1}^{U} \sqrt{\frac{T_w}{T}} dU = \int_{U_1}^{U} d\left(\frac{U}{u^*}\right)$$

where $u^* = u_\tau \sqrt{(\rho_w/\rho)}$

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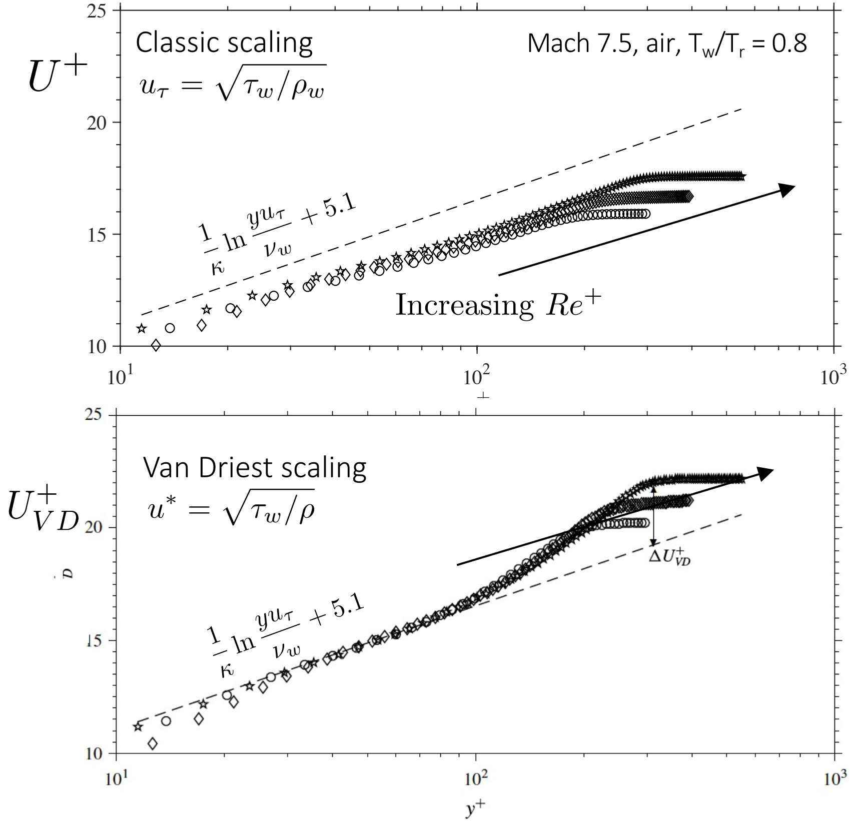
(See also Lee, Helm, Martin, Williams 2023)

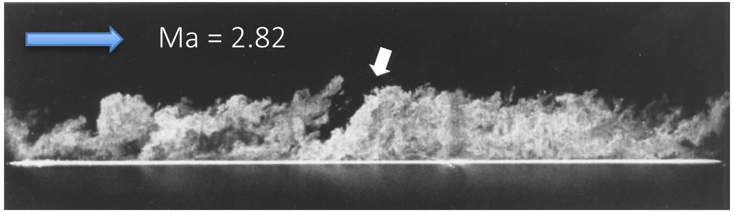


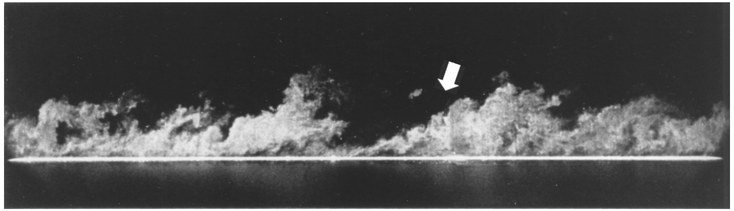
Williams, Sahoo, Baumgartner & Smits (2018)

What do we know or expect for the turbulence?

2. **Mach number effects act only through the mean density (temperature) variation, and effects due to density fluctuations (shocklets, for example) are negligible even at high Mach number**

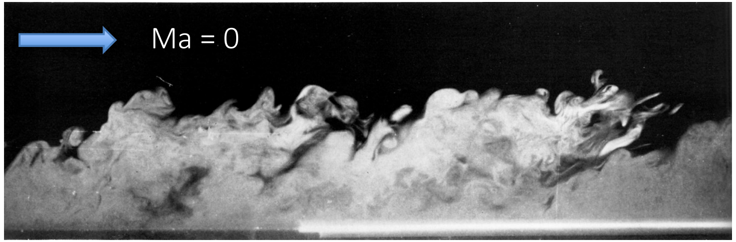
Mie scattering from acetone droplets





Smith (1989); Smith & Smits (1995)

Smoke flow visualization



Falco (1977)

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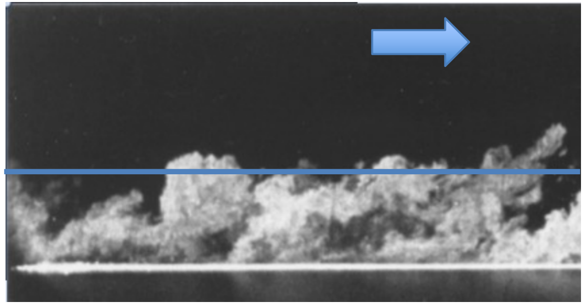
Rayleigh scattering (FRS):

- Scattering from particles with d < λ
- ~10 nm clusters of H_2O, condensed in nozzle from naturally occurring water in air supply, or
- ~10 nm clusters of CO_2, condensed in nozzle from CO_2 gas injected upstream (Miles & Forkey 1991)

$$\frac{y}{\delta} = 0.72$$



Mach 2.9, Re_θ =78,000

Side view

Plan view

Scaling the turbulence

3. Morkovin scaling collapses the turbulent stress profiles onto the incompressible data, at least for the overlap region and the outer flow

FRS – Baumgartner et al. (1997) ; PLIF - Delo & Smits 1997)

Scaling the turbulence

3. **Morkovin scaling collapses the turbulent stress profiles onto the incompressible data, at least for the overlap region and the outer flow**

Morkovin's hypothesis (1961):

- "The essential dynamics of these shear flows will follow the incompressible pattern"

$$u_\tau = \sqrt{\tau_w/\rho_w}$$

$$\Downarrow$$

$$u^* = \sqrt{\tau_w/\rho}$$

FRS – Baumgartner et al. (1997) ; PLIF - Delo & Smits 1997)

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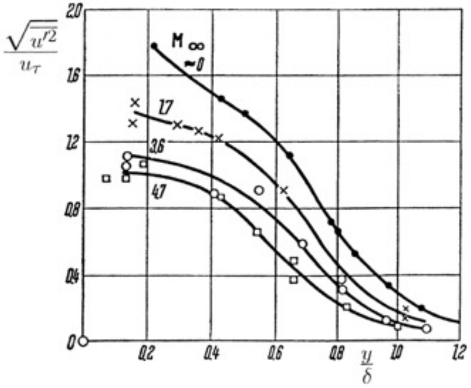
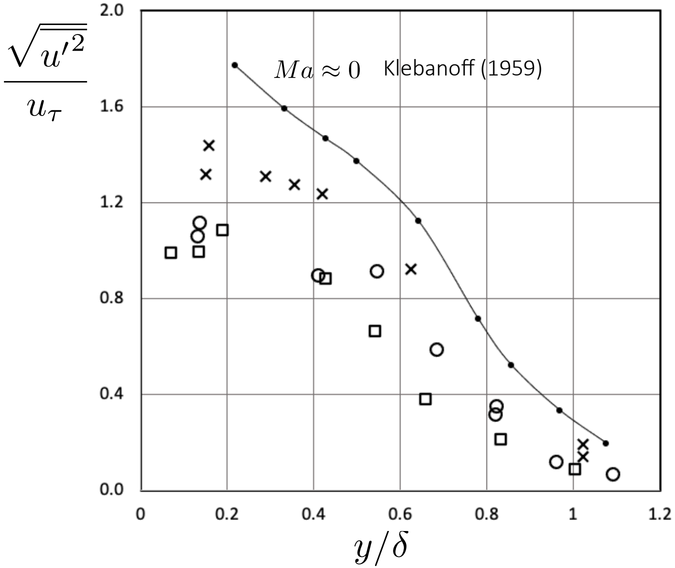
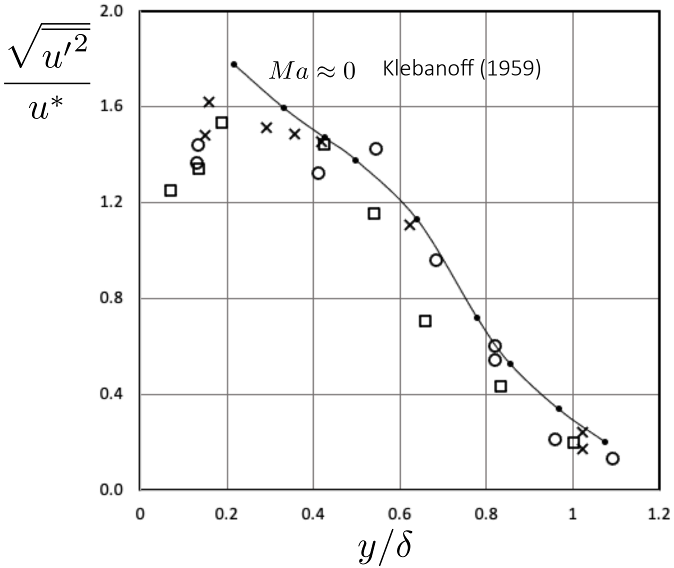


Classic scaling



Morkovin scaling

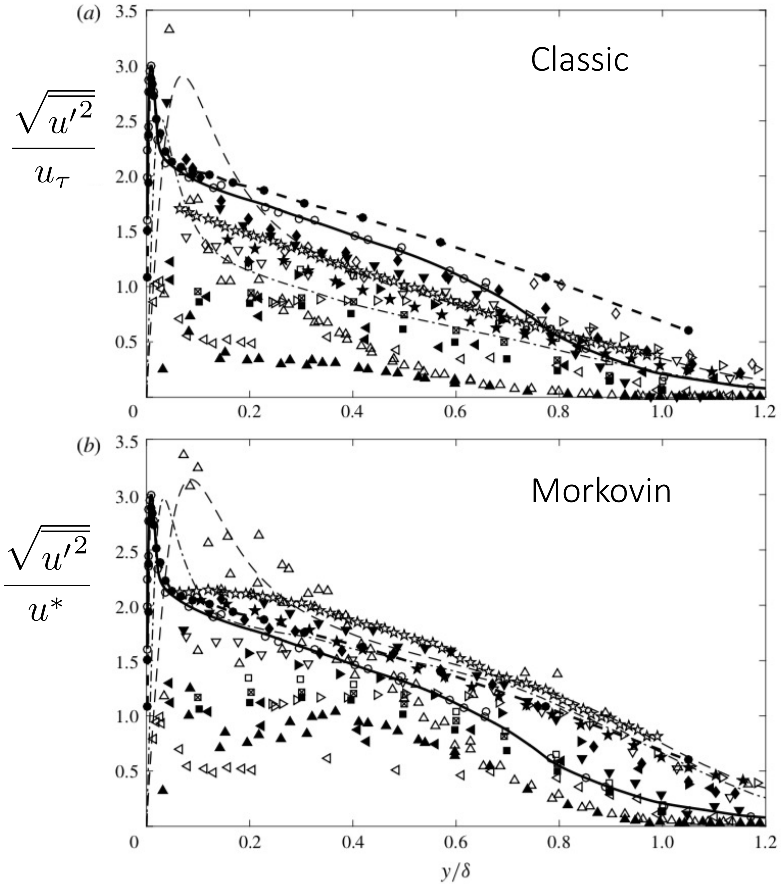


Historical record

Including all experimental data, up to Ma = 11, obscures any conclusion

Previous hot-wire measurements often suffer from

- inadequate frequency response
- mixed-mode response/calibration
- inadequate spatial resolution.



Williams, Sahoo, Baumgartner & Smits (2018)

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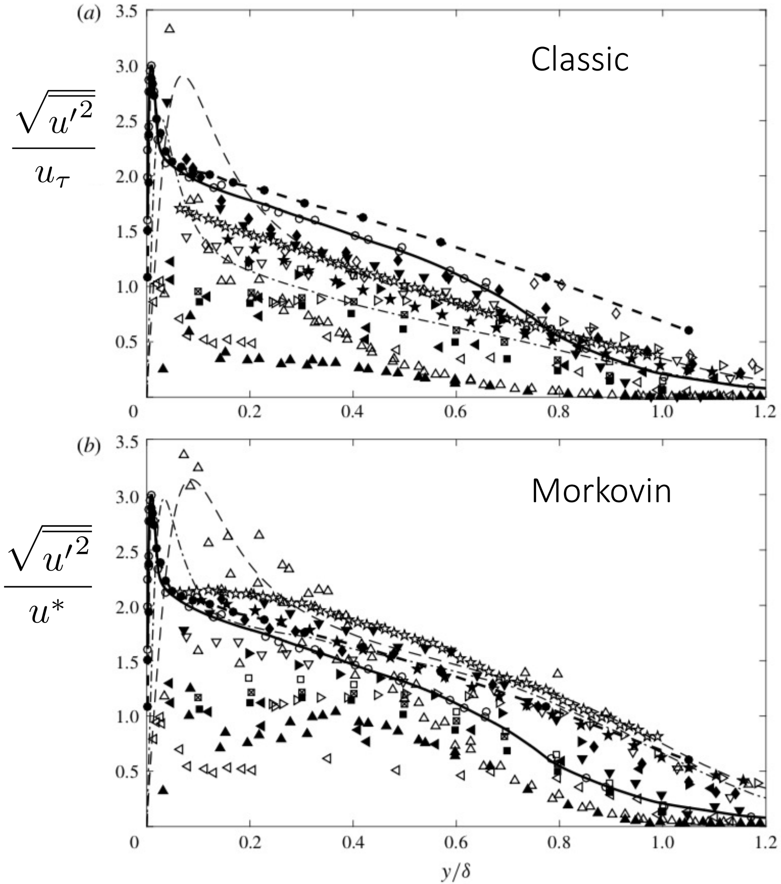
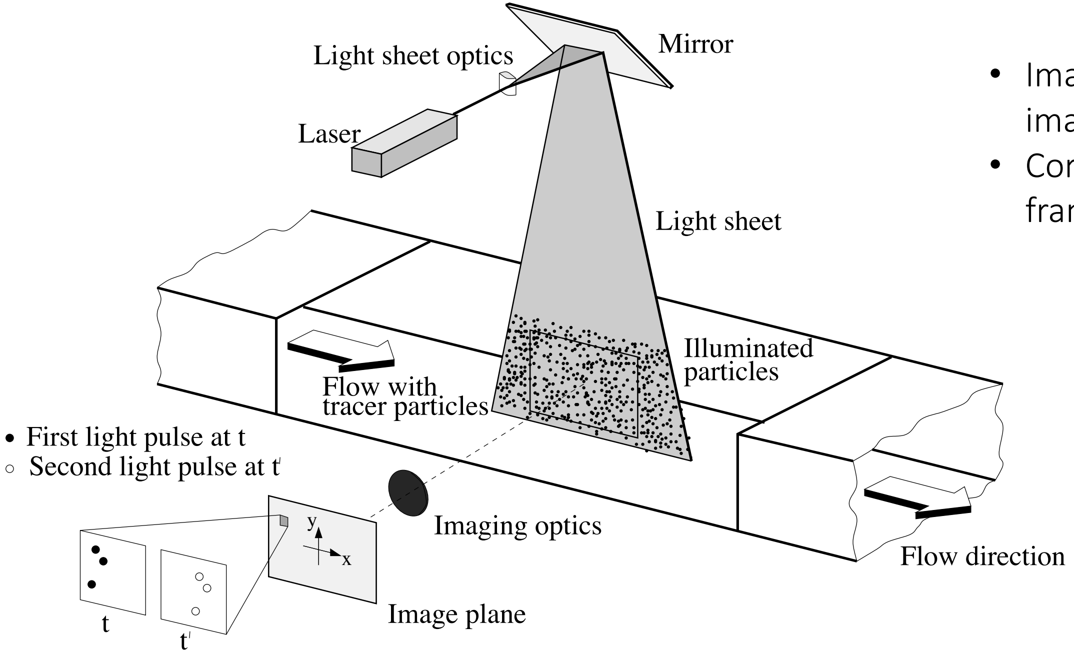
What about PIV at high Mach number?



Williams, Sahoo, Baumgartner & Smits (2018)

Particle image velocimetry



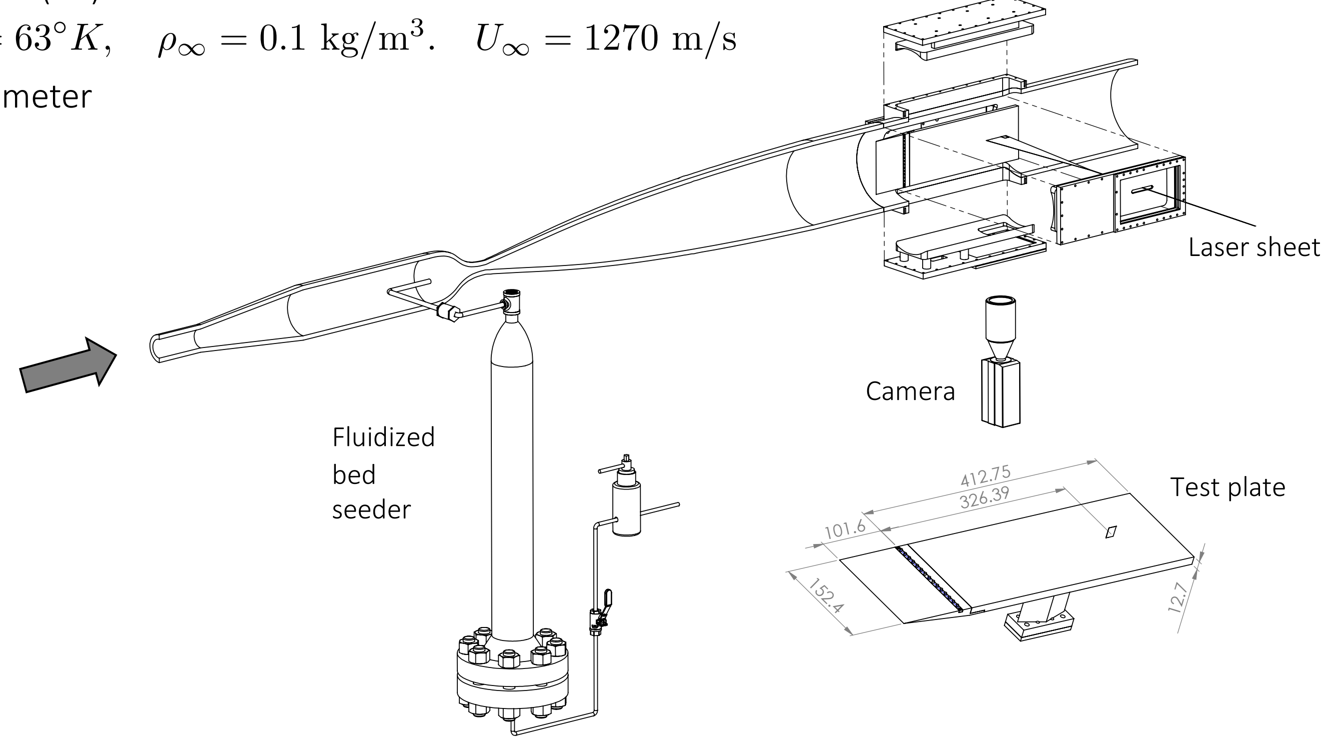
- Image particles using a laser and a fast, two-image camera
- Correlate motion of particles in successive frames

- Direct measure of velocity
- Provides spatial information
- Particles need to follow the flow

Raffel (2007)

Mach 8 wind tunnel

- Low enthalpy, perfect gas (air) Mach 8 wind tunnel
  $T_0 = 870^\circ K, \quad T_\infty = 63^\circ K, \quad \rho_\infty = 0.1\ \mathrm{kg/m^3}. \quad U_\infty = 1270\ \mathrm{m/s}$
- TiO_2 particles, 2 μm diameter



Williams, Nguyen, Schreyer & Smits (2015)

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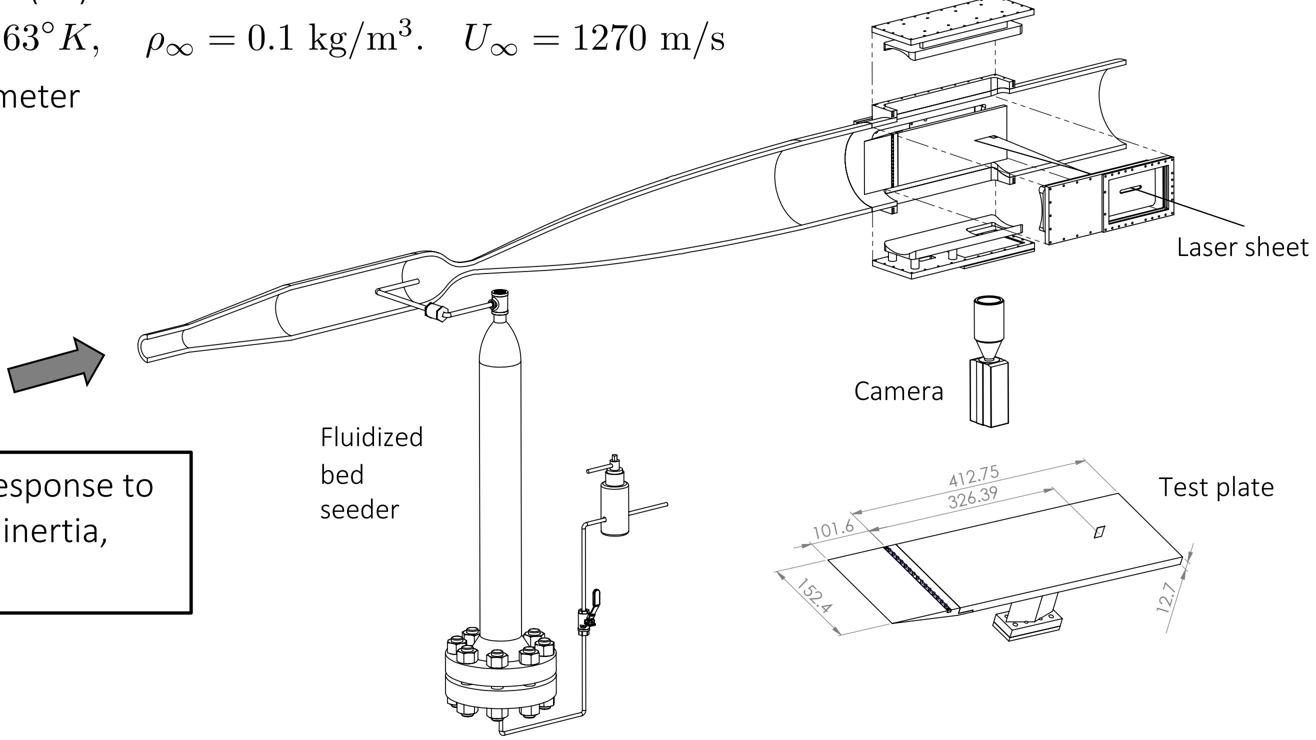
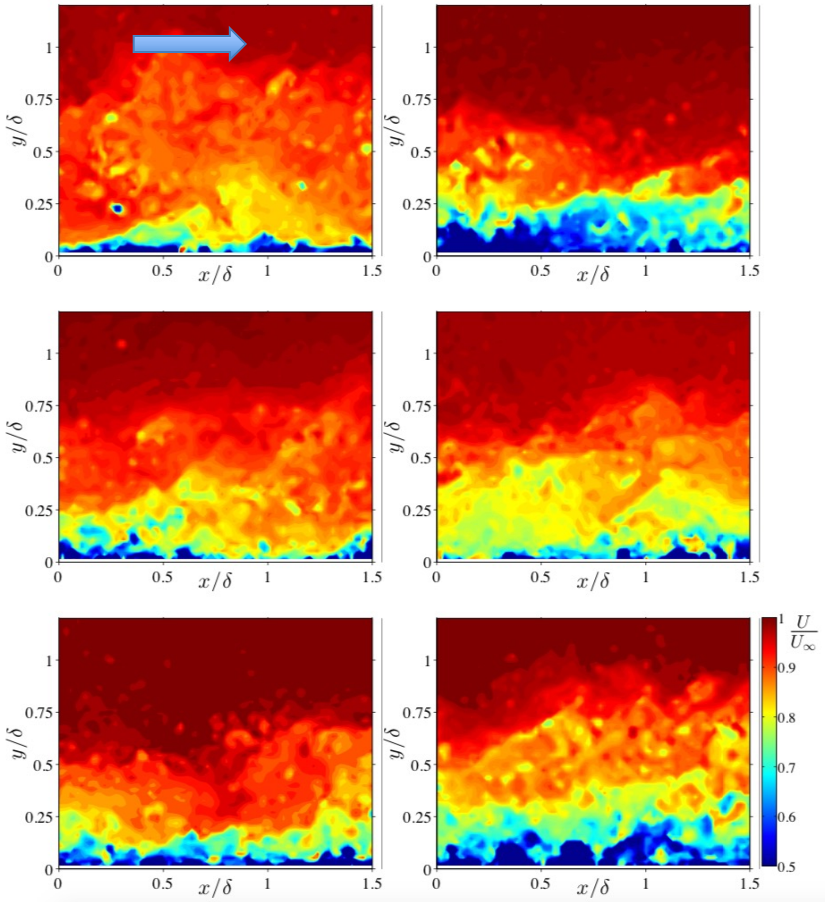
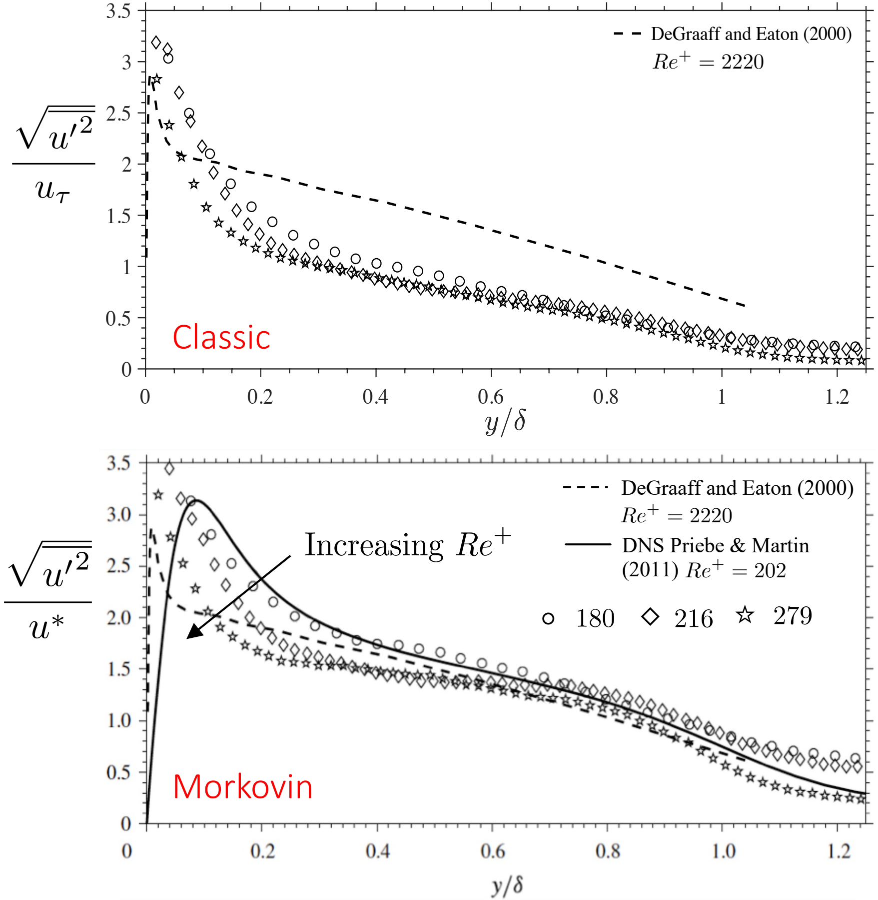


- Need to model particle response to get good results (include inertia, compressibility, and slip)

Williams, Nguyen, Schreyer & Smits (2015)

PIV results Ma =7.5





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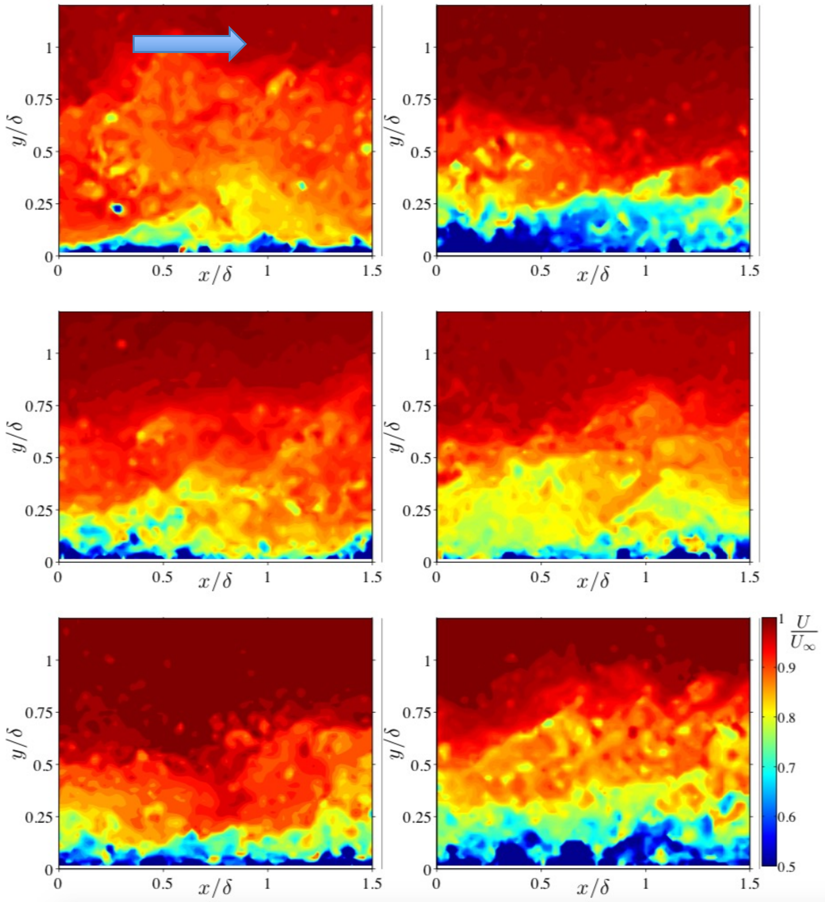
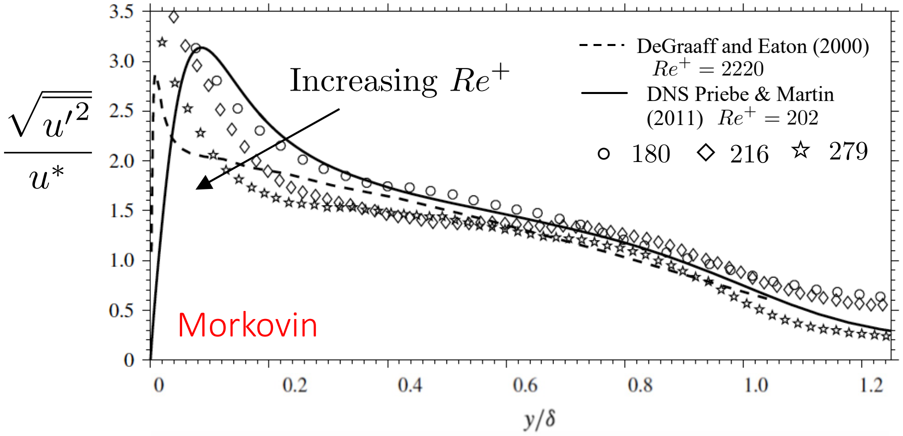
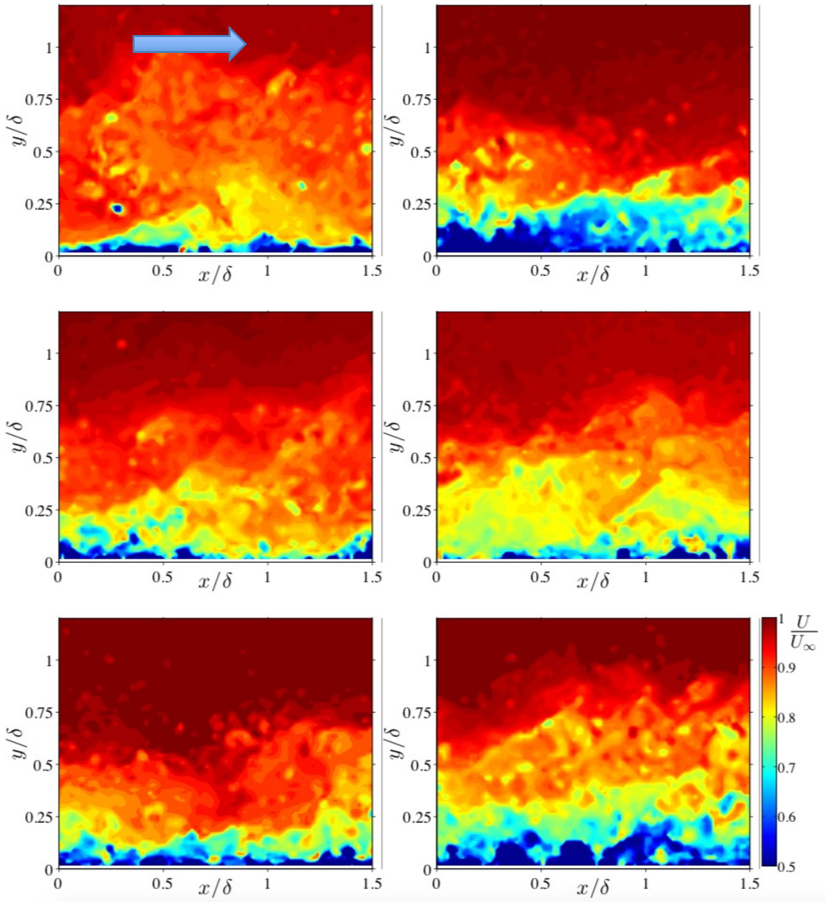


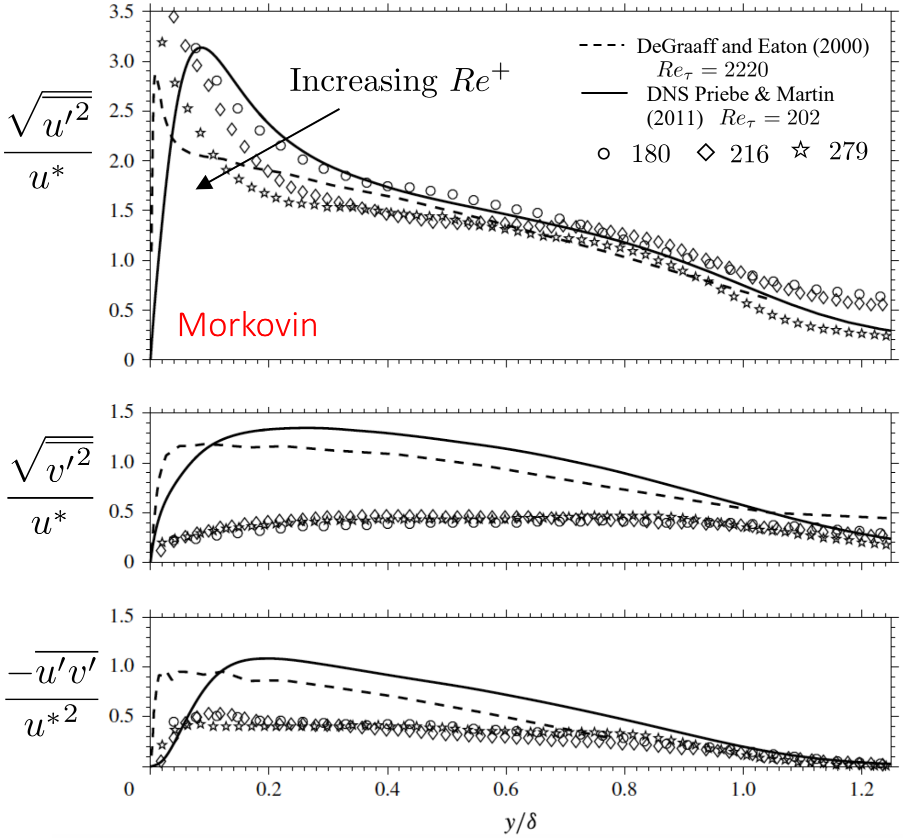


- Results agree well with DNS at the same Reynolds number
- Show the expected behavior with increasing Reynolds number
- Support Morkovin scaling
- But…

Williams, Sahoo, Baumgartner & Smits (2018)

PIV results Ma =7.5





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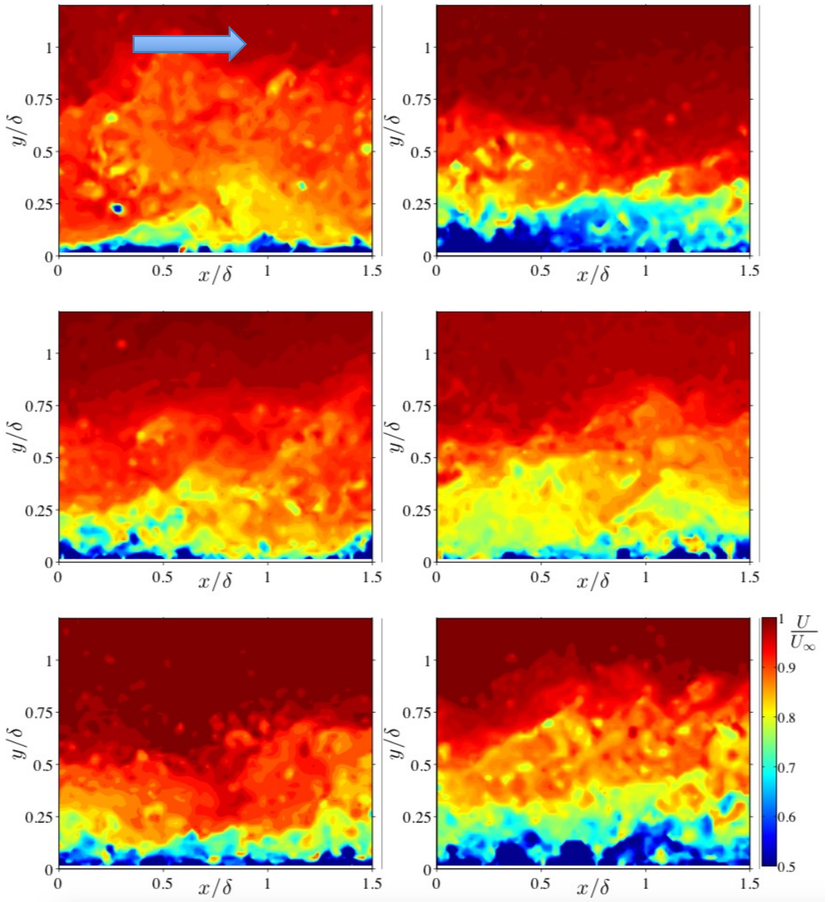
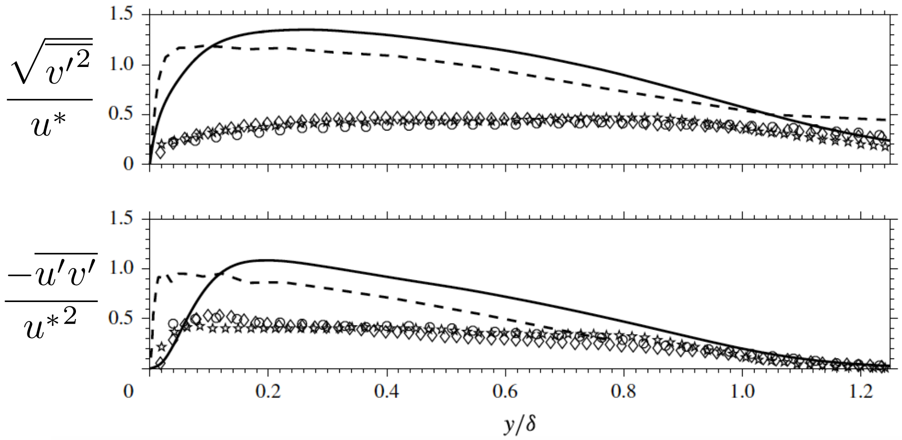
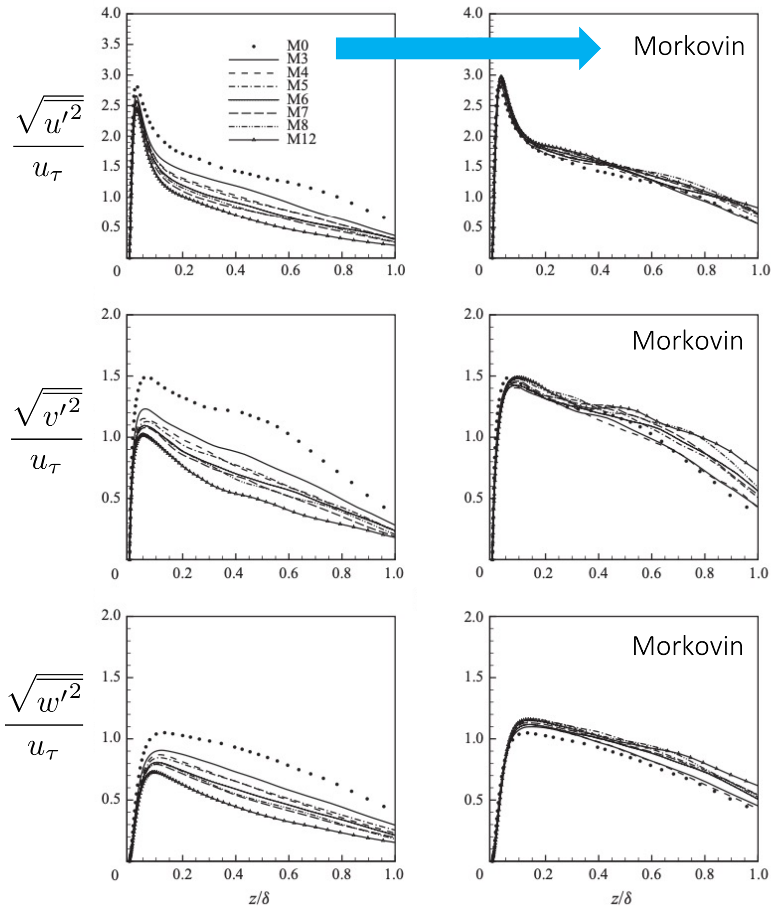


- It is very difficult to measure the wall-normal component v'
- This is a general result for all experimental methods and almost all experiments



What about DNS?



- DNS of turbulent boundary layers
- (small box DNS, ~10δ, bigger box results soon)
- Matched Reynolds numbers (570 < Re^+ < 377)
- 0.3 < Ma < 11.9
- 1 < T_w/T_∞ < 28

Profiles collapse in Morkovin scaling, for all three components, even at Ma = 12

Duan, Beekman & Martin (2011)

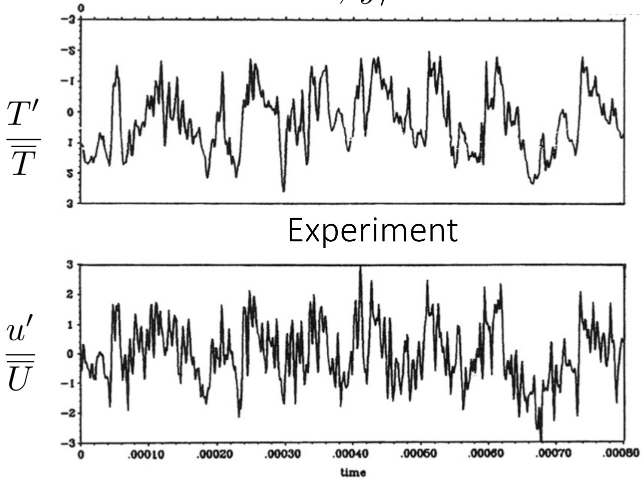
Strong Reynolds Analogy between temperature and velocity

One-dimensional energy equation: $$h_0 = h + \tfrac{1}{2}U^2$$

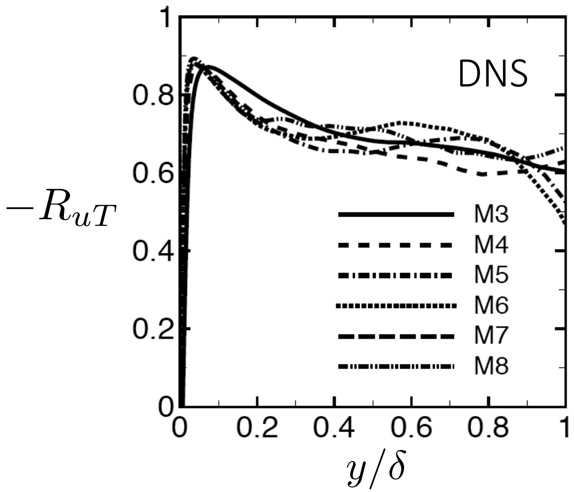
Perfect gas with $T_0' = 0 \longrightarrow$ $$\frac{T_{rms}}{\overline{T}} = (\gamma - 1)M^2 \frac{u_{rms}}{\overline{U}},$$

$$R_{uT} = \frac{\overline{u'T'}}{u_{rms}T_{rms}} = -1$$

Mach 2.9, $y/\delta = 0.6$



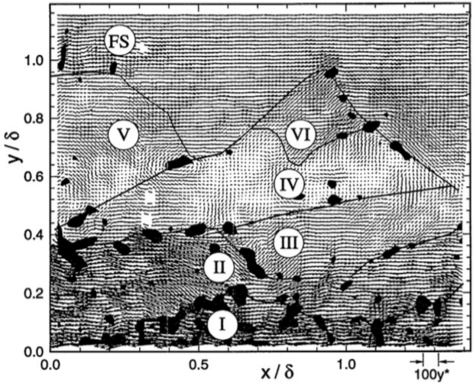
Smith & Smits (1993)



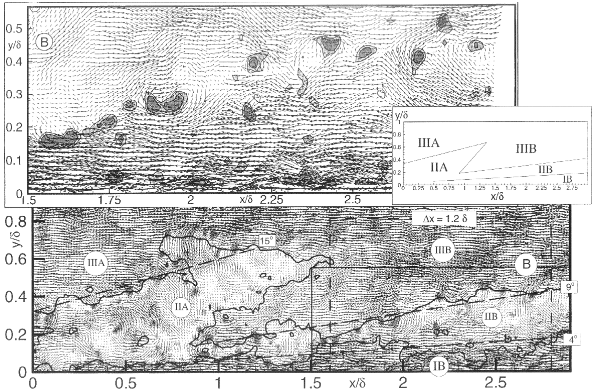
Wu & Martin (2004)

Unform momentum zones (UMZ)

$Re^{+} \approx 2600$



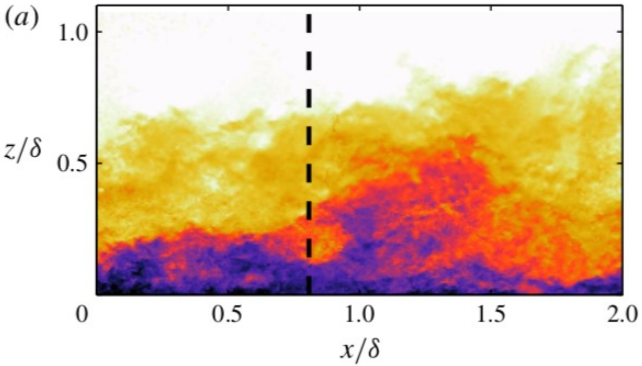
Meinhart & Adrian (1995)

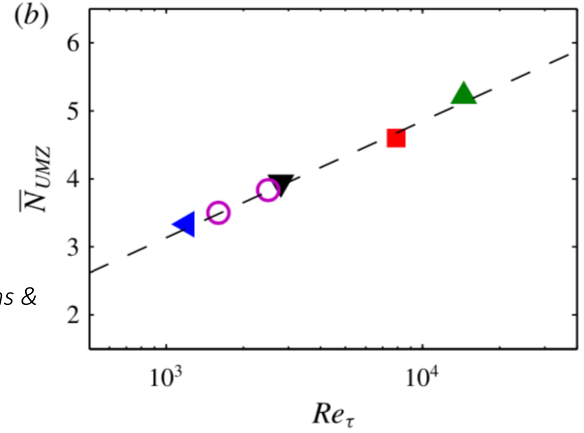


Adrian, Meinhart & Tomkins (1999)

- Number of UMZ's scales logarithmically with Re⁺
- But not as fast as the number of hierarchies

$Re^{+} \approx 8000$





de Silva, Hutchins & Marusic (2016)

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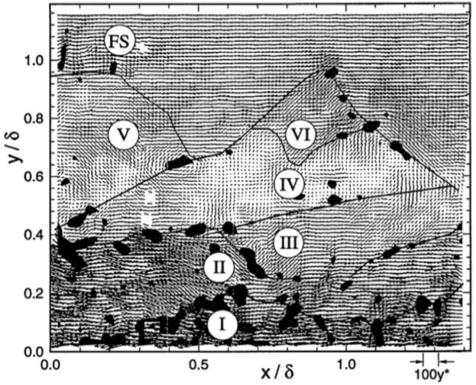
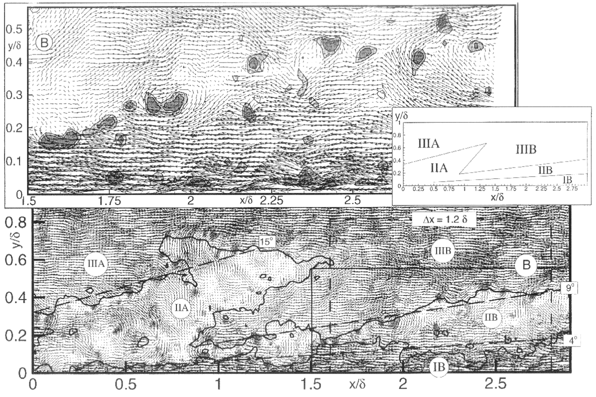


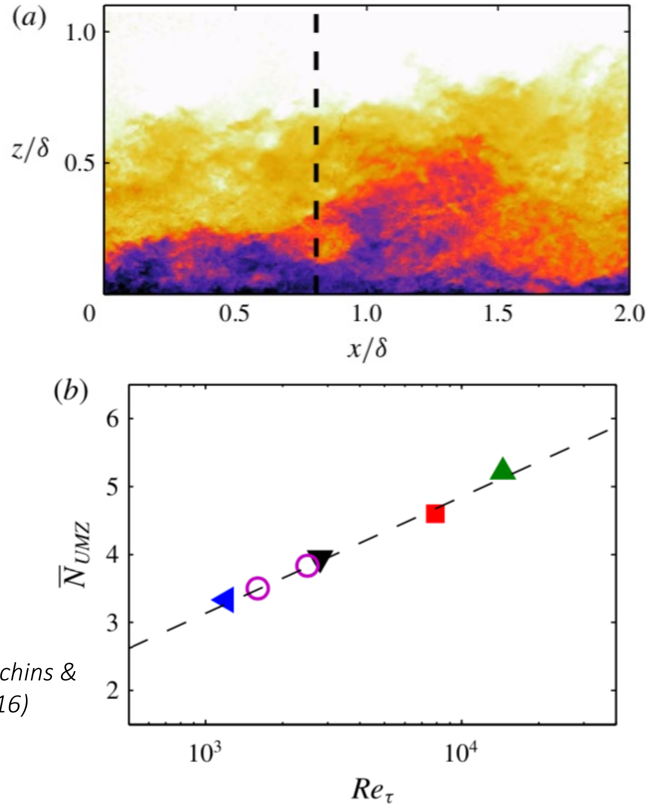
Meinhart & Adrian (1995)



Adrian, Meinhart & Tomkins (1999)

Incompressible flow
Mach = 0

$Re_\tau \approx 8000$



de Silva, Hutchins & Marusic (2016)

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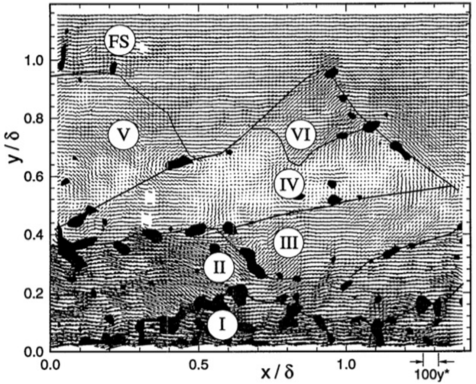
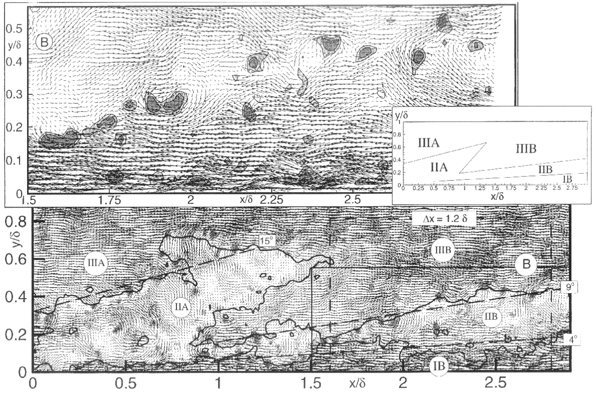


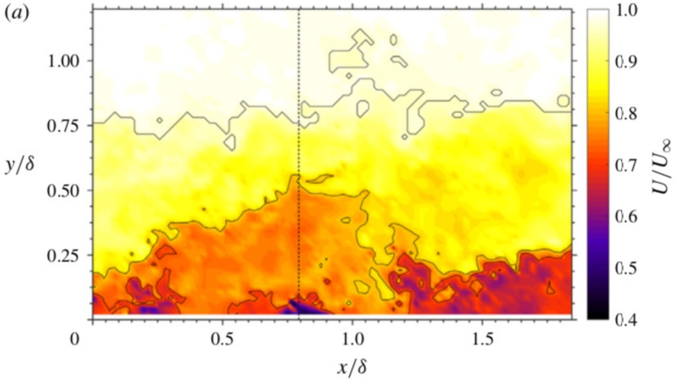
Meinhart & Adrian (1995)

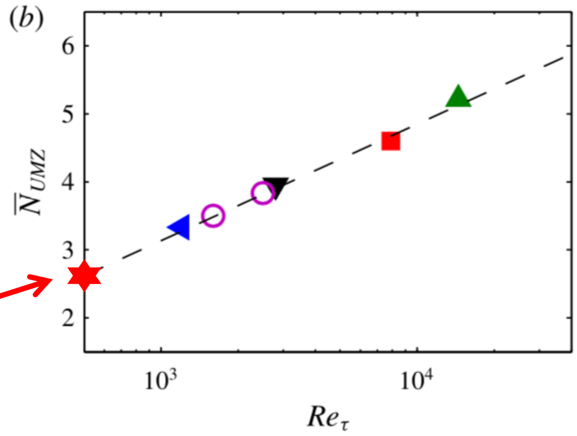


Adrian, Meinhart & Tomkins (1999)

Hypersonic flow
Mach 7.5

$Re_\tau \approx 280$



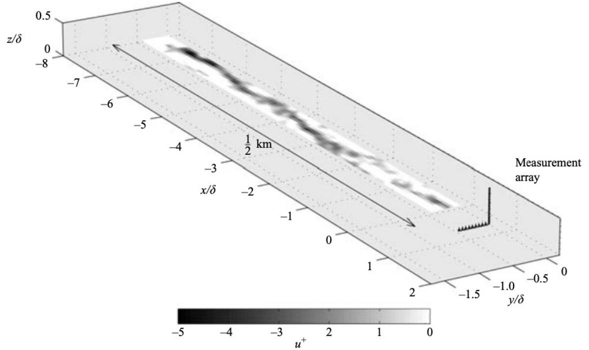


Mach 7.5

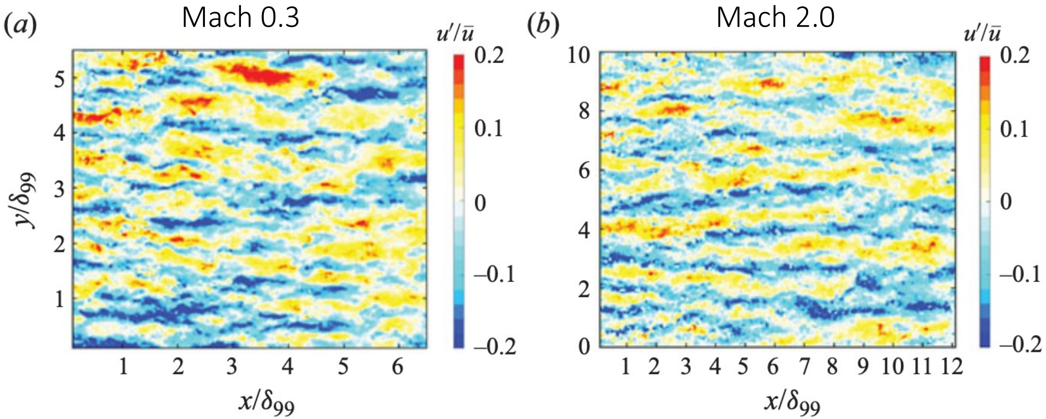
Williams, Sahoo, Baumgartner & Smits (2018)

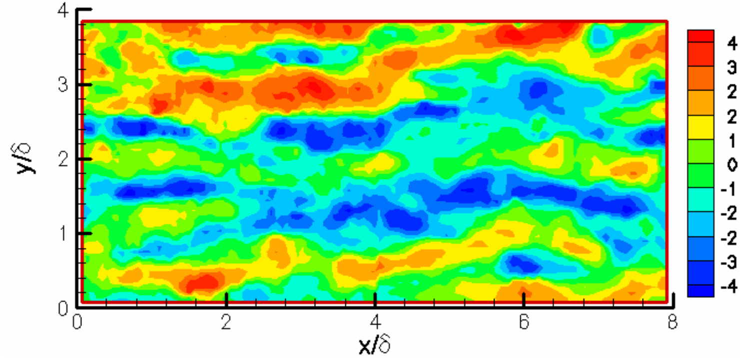
Superstructures (VLSMs)

Atmospheric boundary layer
Hutchins & Marusic (2007)

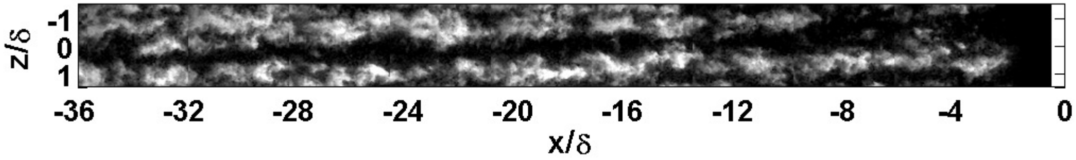


Spanwise spacing ≈δ (may increase with Mach number (*Bross et al. 2021)*





Mach 2
Ganapathisubramani, et al. (2006)



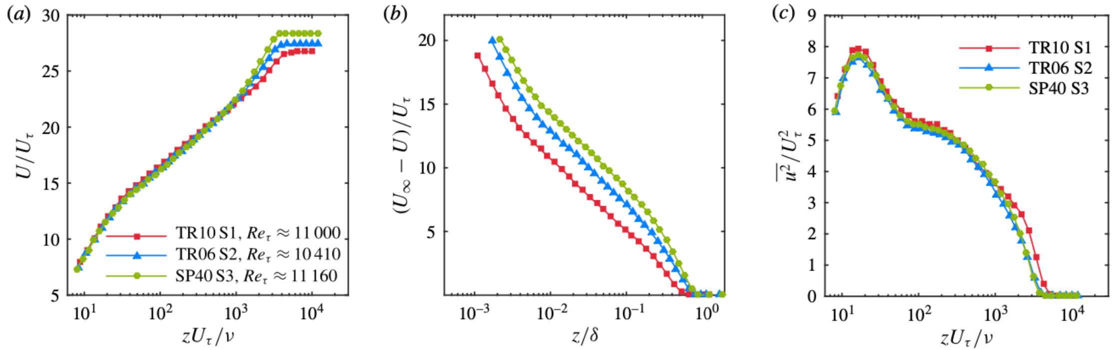
Beyond flat plate boundary layers

- Van Driest and Morkovin work well for flat plate boundary layers

- What about "real" world effects?
  - Tripping effects
  - Transitional effects
  - Surface curvature
  - Görtler vortices

- What about complex flows?
  - Shock wave boundary layer interactions
  - Superstructures
  - Görtler vortices

Tripping effects



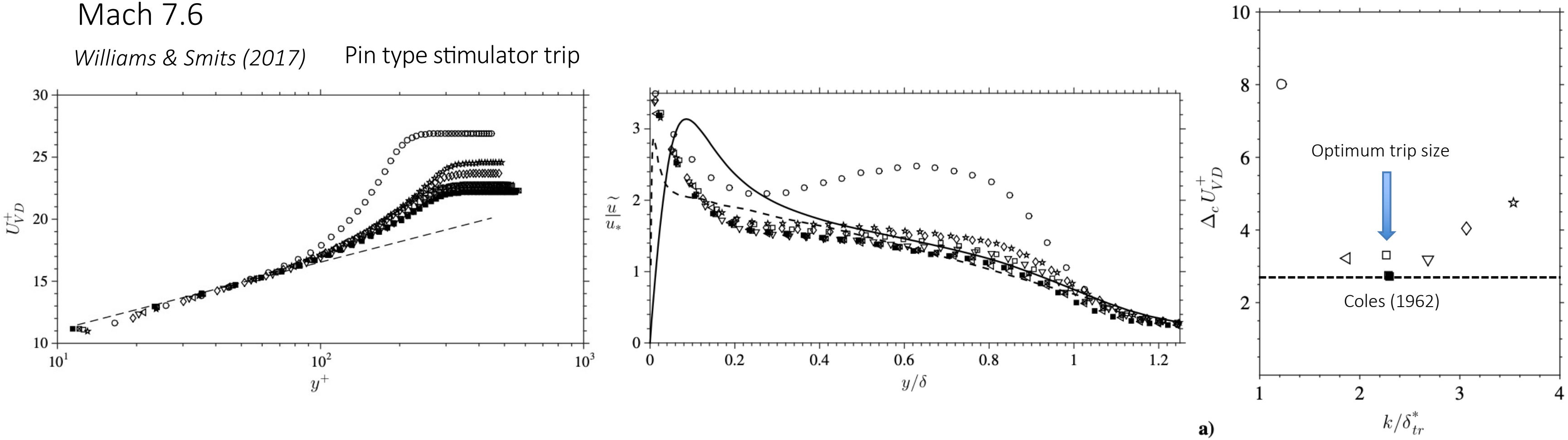
Subsonic flow

Marusic et al. (2015)

P40 grit sandpaper, 6mm and 10 mm threaded rod, matched $Re_\tau \approx 11000$

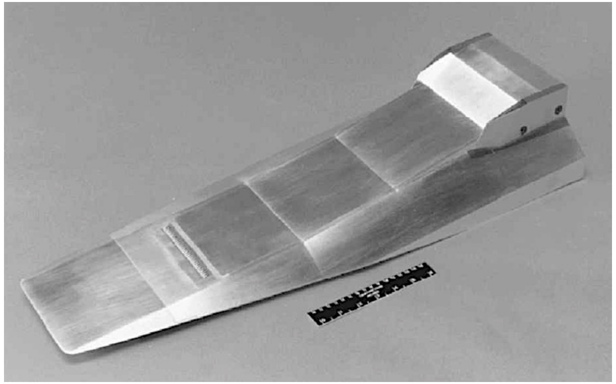
Mach 7.6

Williams & Smits (2017) Pin type stimulator trip

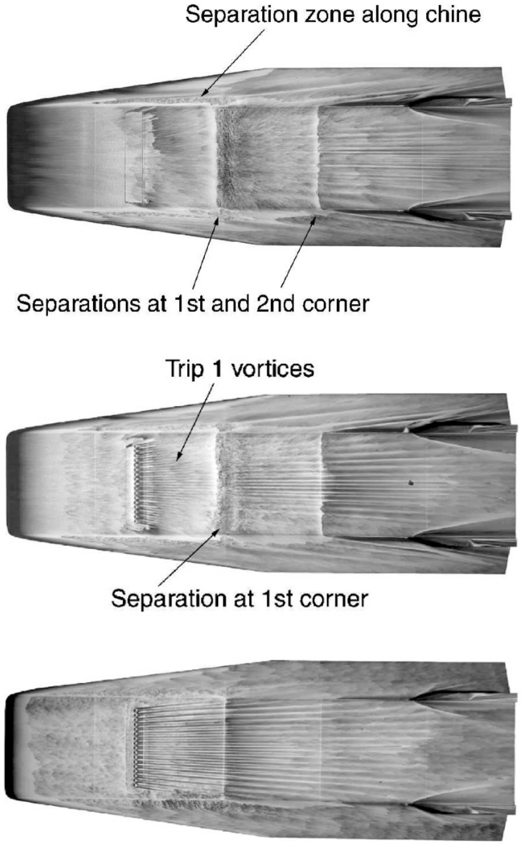


Tripping effects

- Hyper-X tripping at Mach 6, α = 2°



Berry et al. (2001)



No trip

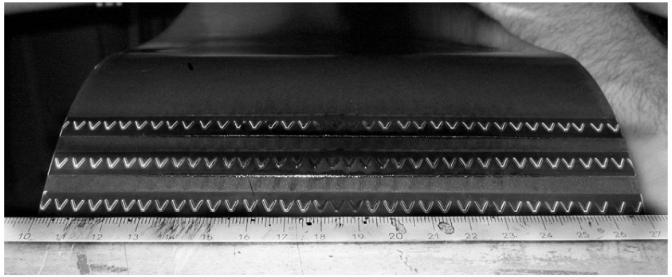
Critical roughness

Effective roughness

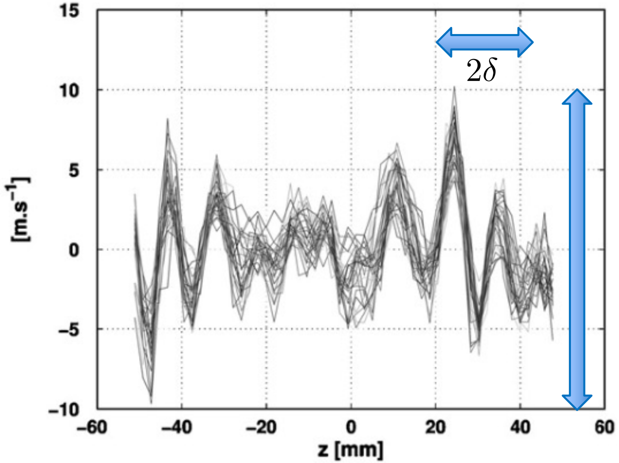
Upstream history effects

- Periodic roughness upstream of the throat at Mach 2.3

- Vortex generation in subsonic flow
  - Subsonic experiment, following development of streamwise vortices on a wind tunnel wall
  - TG vortices form in the contraction, with $\lambda \approx 2\delta$, persisting into the working section through transition
  - As the boundary layer grows, the vortices appear to pair so as to maintain $\lambda \approx 2\delta$, so their number decreases with downstream distance



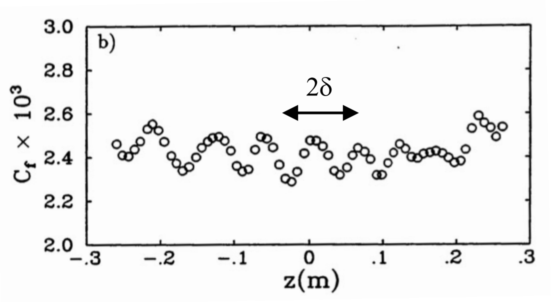
d = 5 mm



δ = 11 mm

$\approx u_\tau$

Mach 2.3



Smith (1993)

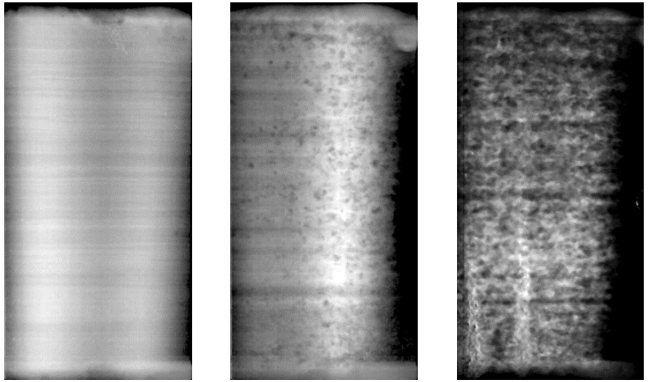
$Re_\tau = 4100$

Dussauge & Piponniau (2008)

Transitional structures in boundary layers

No tripping

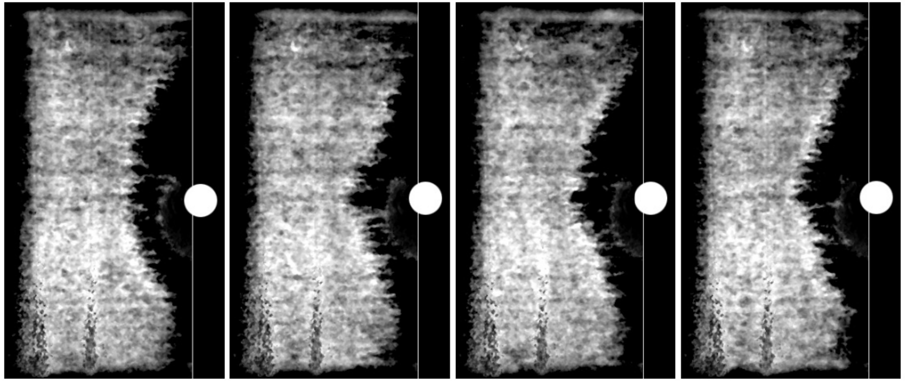
M = 5, upstream boundary layer



Laminar Transitional Turbulent

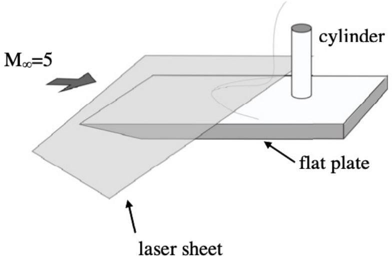
No tripping

M = 5, upstream of SWBLI



- Organized, longitudinal structures in turbulent boundary layer appear to originate at specific spanwise locations
- Long-lasting

- Organized, longitudinal structures ripple the separation line ahead of cylinder interaction

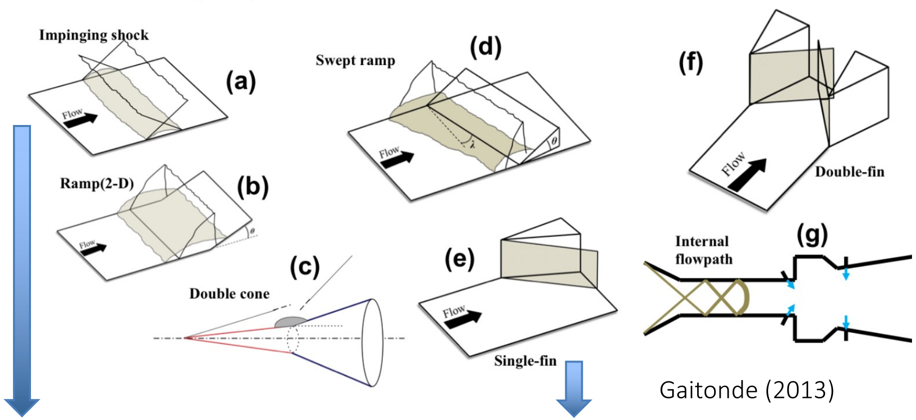


Murphree et al. (2006)

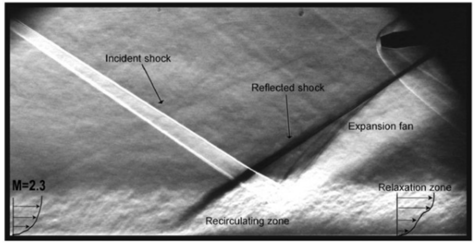
Shock-wave boundary layer interactions (SWBLI)

- Pressure gradient
- Shock-induced separation
- Streamline curvature effects
- Transverse curvature effects
- Upstream history effects, initial conditions
- Reynolds number effects
- Unsteadiness
- Three-dimensionality
- Asymmetry

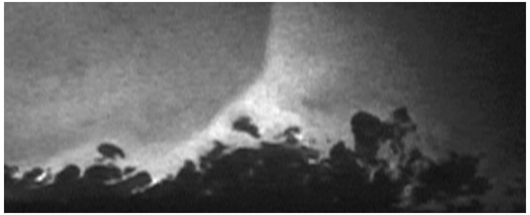
Dolling 2001; Délery & Dussauge 2009; Babinsky & Harvey 2011; Gaitonde 2015



Gaitonde (2013)



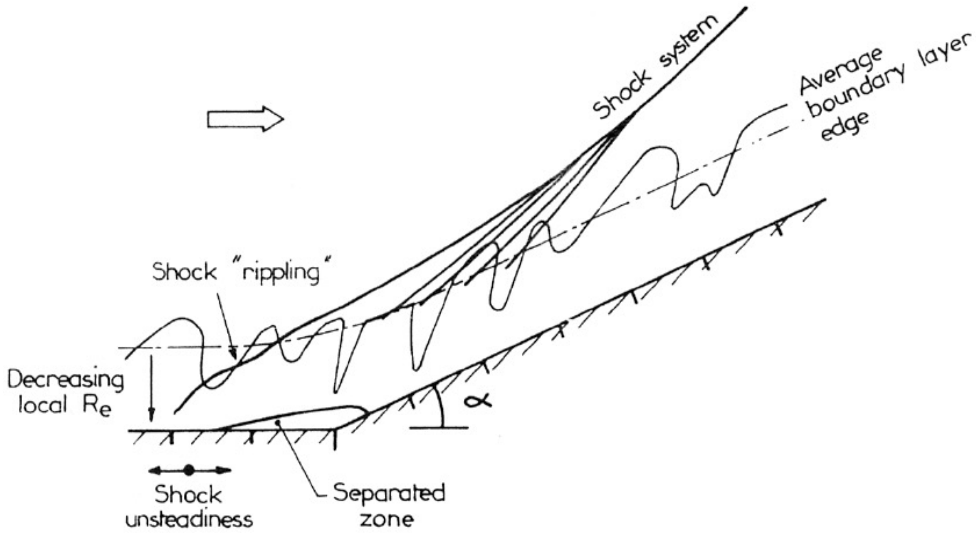
Dupont et al. (2005) 9.5º reflected shock at Mach 2.3



Bookey et al. (2001) 10º sharp fin at Mach 8

Shock-wave boundary layer interactions (SWBLI)

- Intense shock unsteadiness
- Shock splits and ripples
- Strong shocks lead to separation
- Shock interacts with boundary layer to amplify turbulence
- Peaks occur in friction and heat transfer



Unsteadiness of SWBLI and superstructures

- Shock motion in SWBLI increases with shock strength
- Can lead to severe unsteady pressure and heat loading
- In unseparated flows, VLSM + TG vortices
- In separated flows, VLSM + shear layer instability + TG vortices

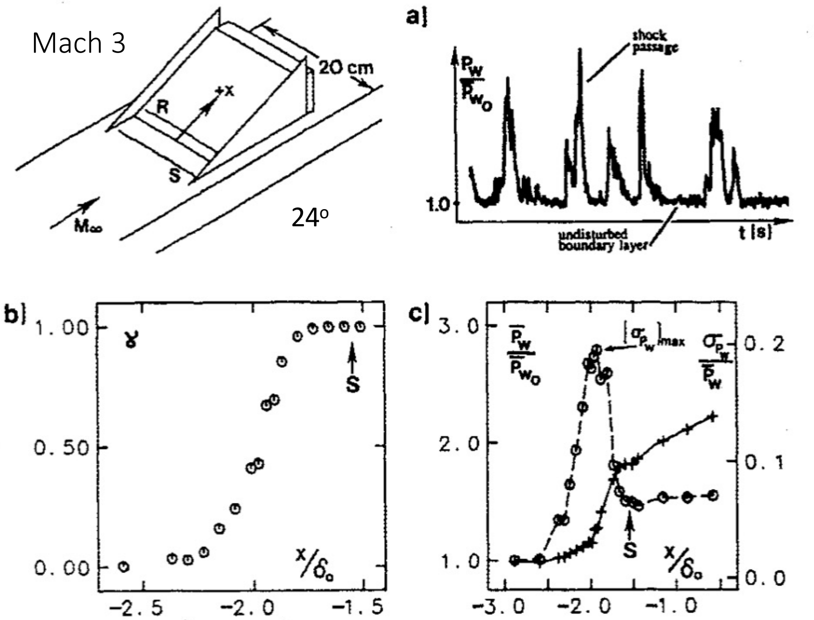


Fig. 1 Typical separated compression ramp flowfield surface properties: a) pressure signal near separation; b) intermittency; and c) mean wall pressure and standard deviation distributions.[3]

Dolling & Or (1985)

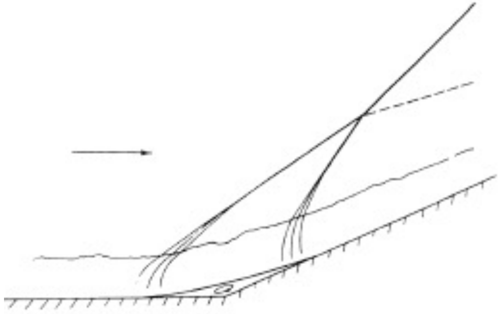
side view

plan view

SWBLI at Mach 2.5

500 KHz sequential images of using FRS (Miles et al.)

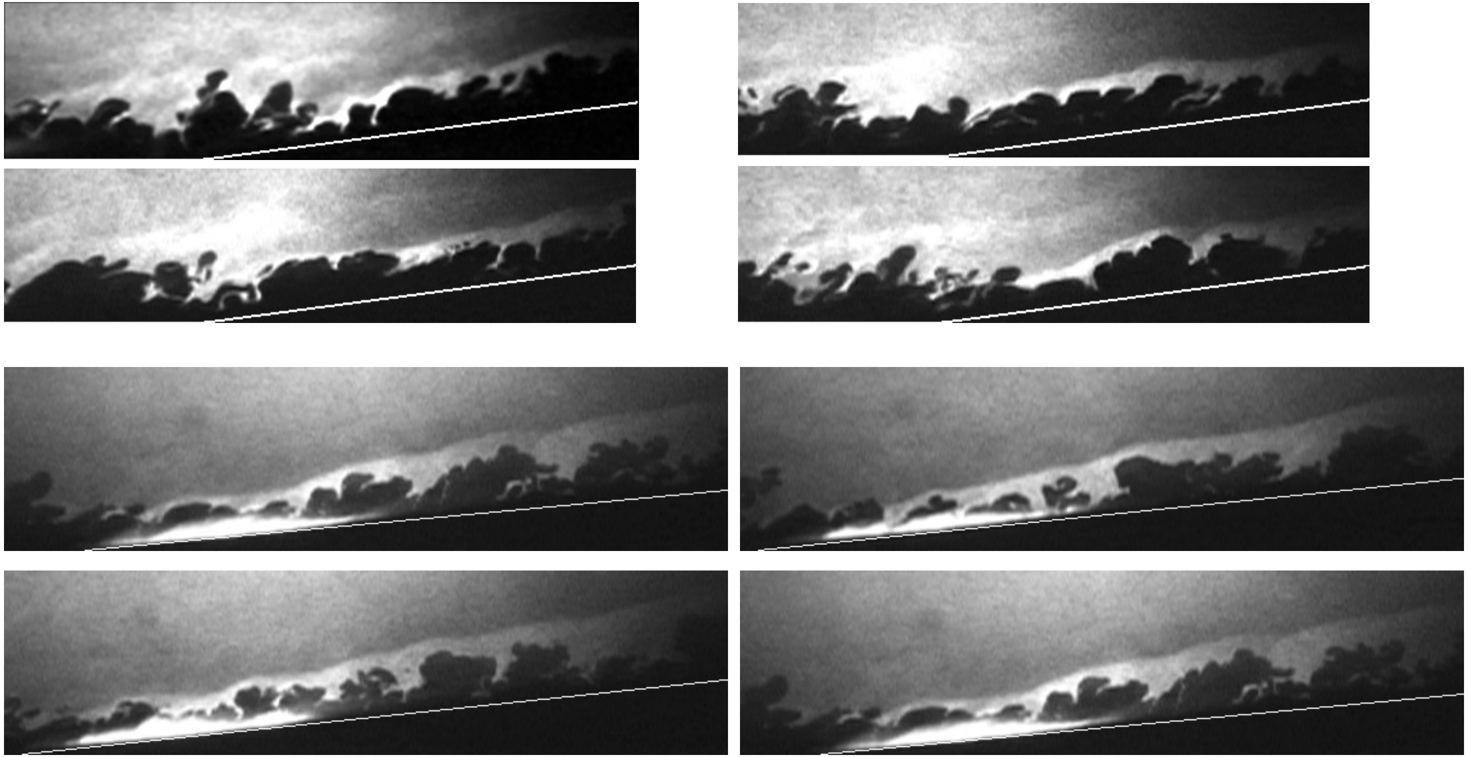
MHz rate pulse-burst laser, coupled with MHz rate CCD framing camera (PSI)



FRS visualizations 8^{o} compression corner at Ma = 7.2

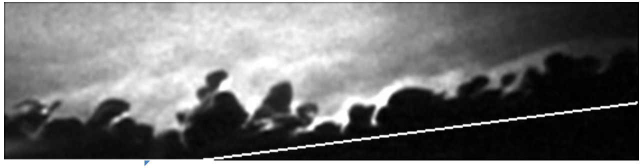
Filtered Rayleigh Scattering

Images are 6.5 x 1.8δ (δ = 11 mm)

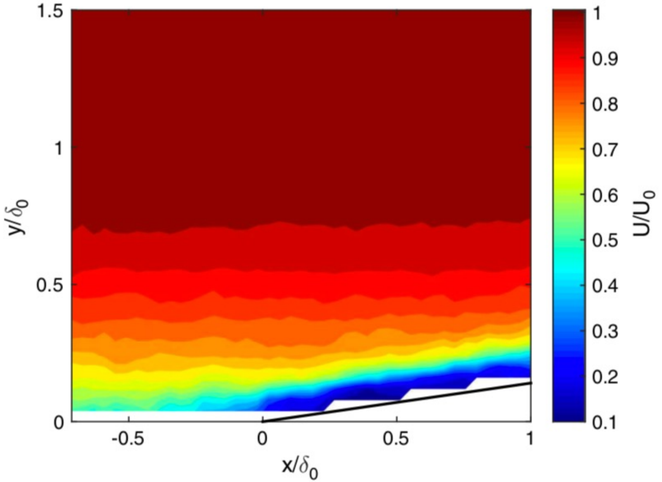


Bookey, Wyckham, Smits & Martin, AIAA 2005

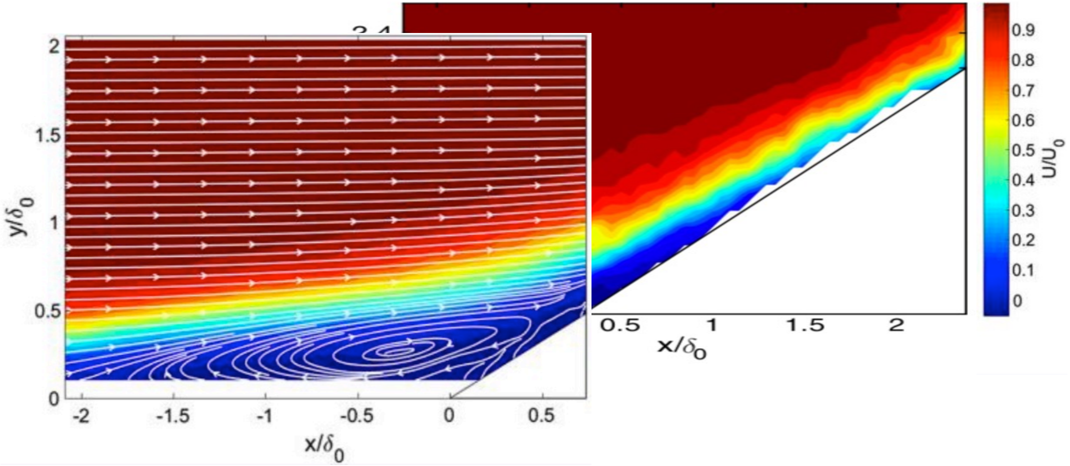
PIV data for 8° and 33° compression corners at Ma = 7.2



8° corner

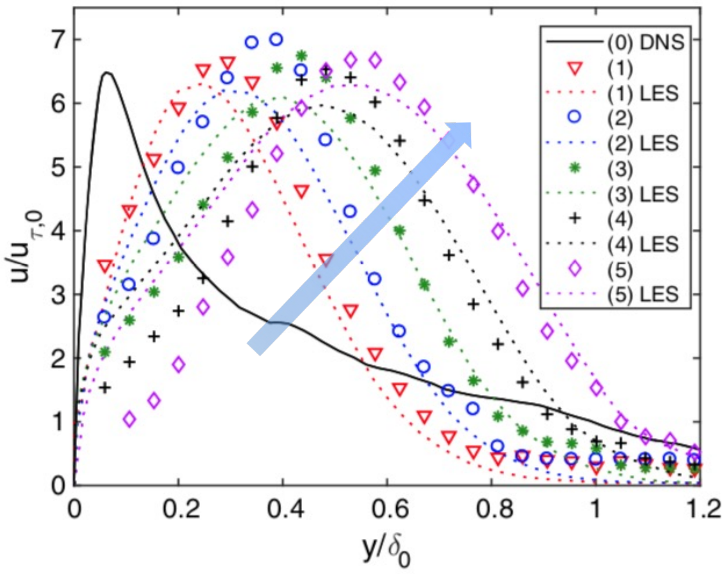


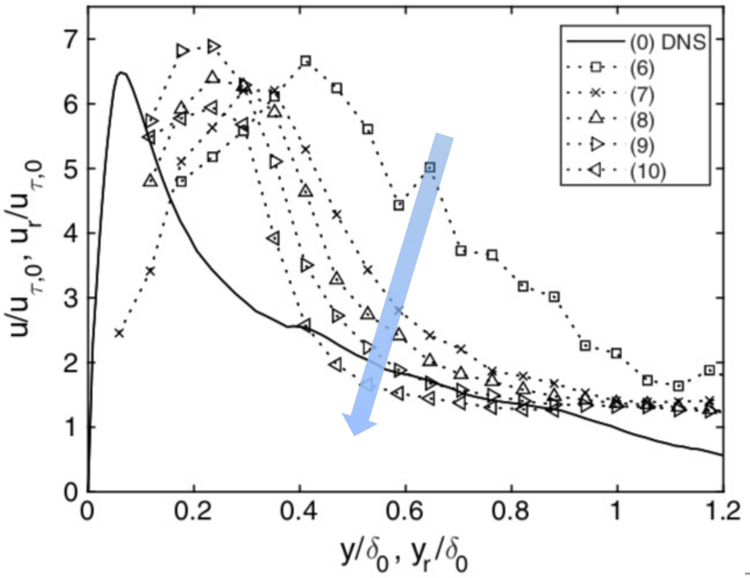
33° corner



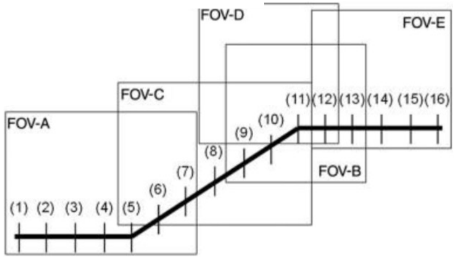
Schreyer, Sahoo, Williams & Smits, AIAAJ 2018

PIV data for 33^o compression corner at Ma = 7.2

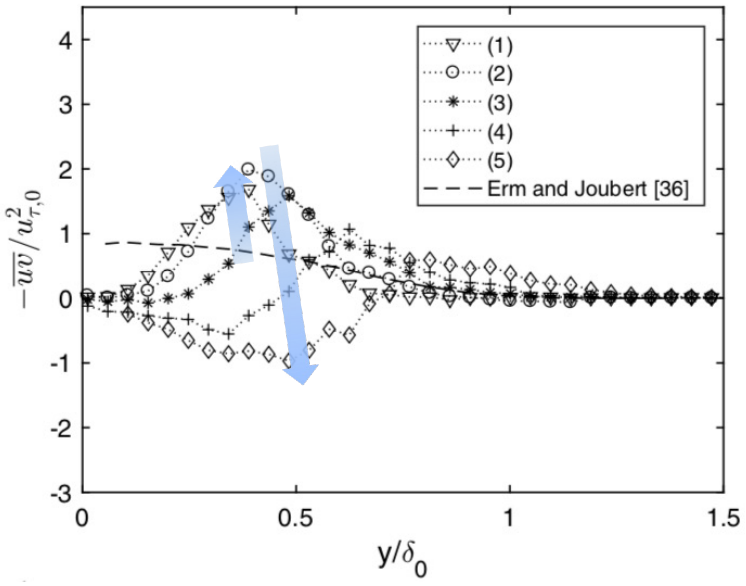


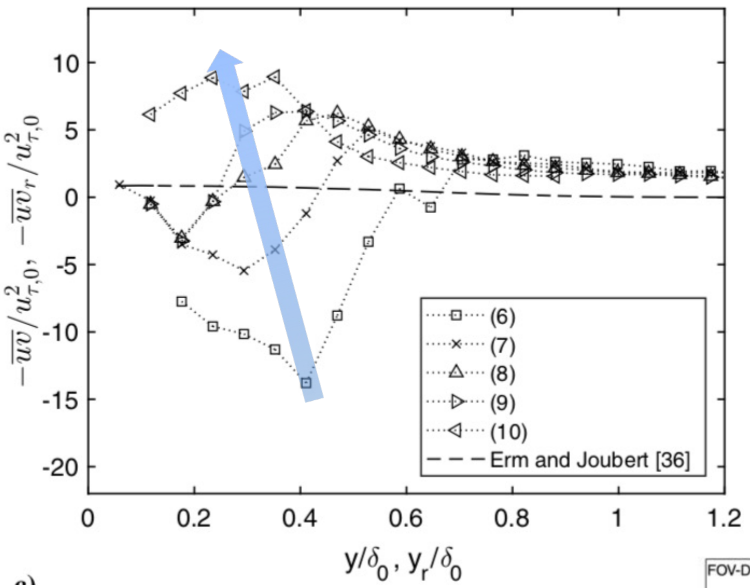


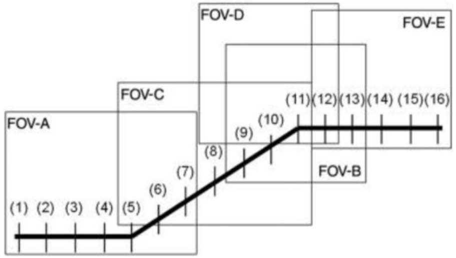
- Progressively larger amplification through the shock
- Morkovin scaling no longer works



PIV data for 33° compression corner at Ma = 7.2

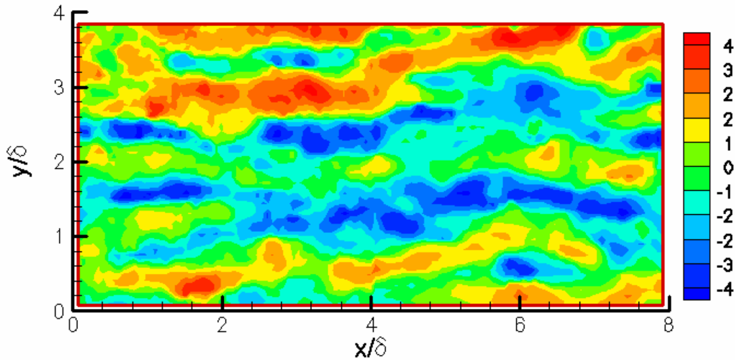






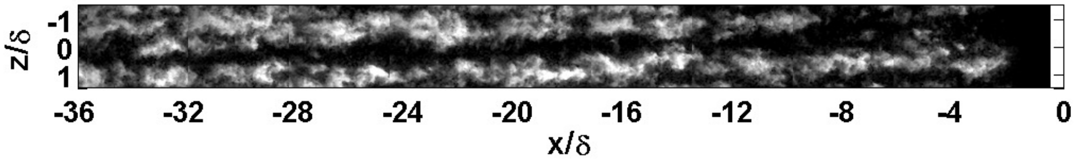
- Progressively larger amplification through the shock
- Morkovin scaling no longer works

Superstructures in supersonic flows



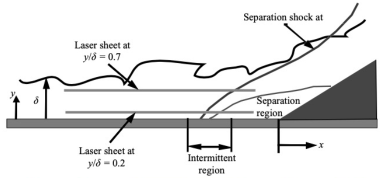
Mach 2 flat plate boundary layer

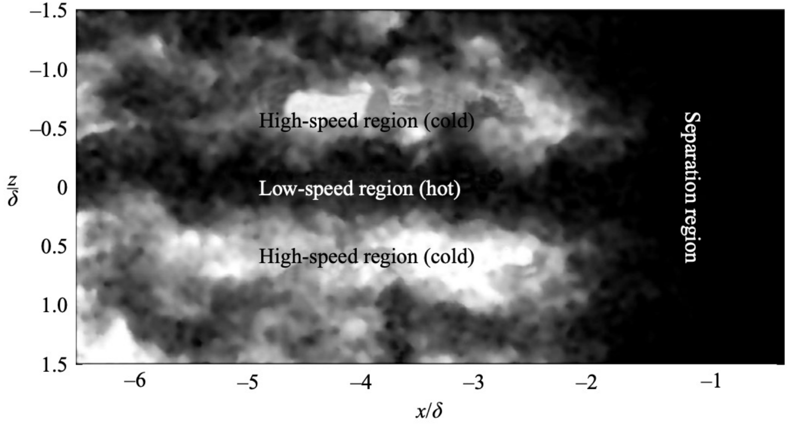
Ganapathisubramani, et al. (2006; 2007)

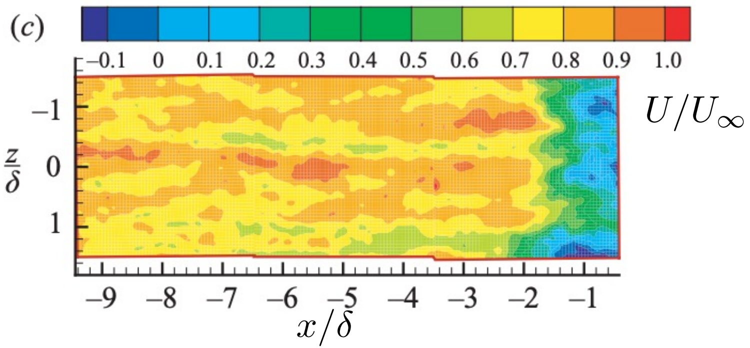


Mach 2 compression ramp 20°

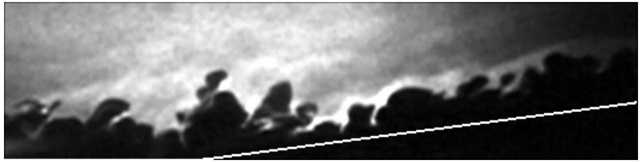
Ganapathisubramani, et al. (2007)





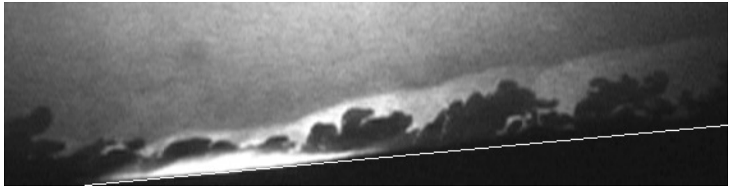


Superstructures and SWBLI

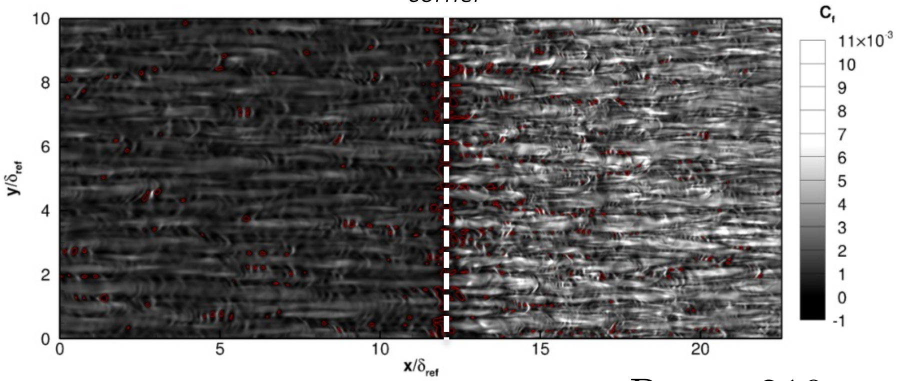


$Re_\tau = 400$

FRS

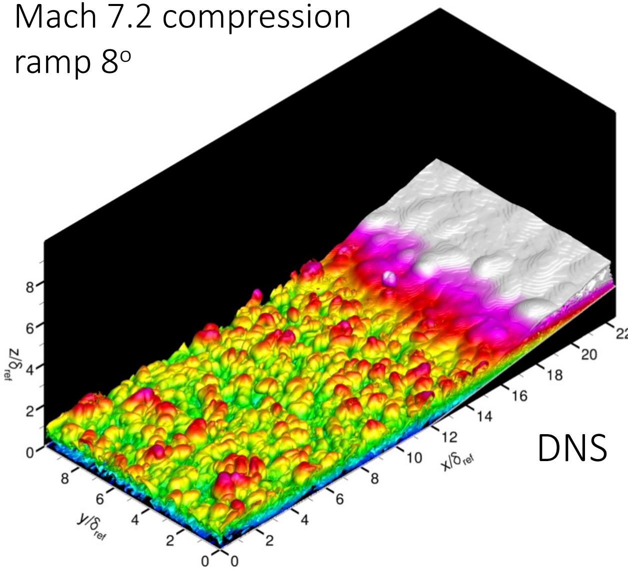


Ma = 7.2



$Re_\tau = 210$

Mach 7.2 compression ramp 8°



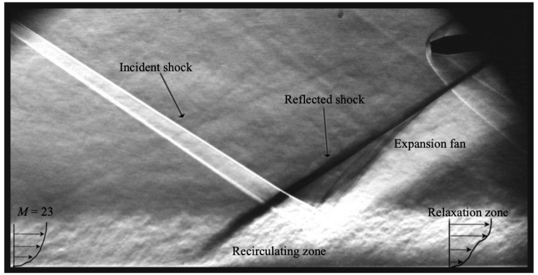
DNS

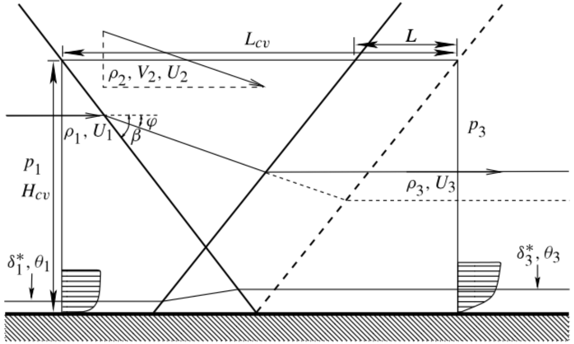
Superstructures modulate the shock and cause unsteadiness (unseparated flows)

Bookey et al. (2005); Schreyer et al. (2011); Priebe & Martin (2021)

Unsteadiness of separated SWBLI

- Shock motion and unsteadiness in SWBLI increases with shock strength
- In unseparated flows, the superstructures appear to be the prime cause of the shock motion (relatively high frequencies)
- In separated flows, there is a large-scale, slow pulsation of the separation bubble (relatively low frequencies)
- Pulsation related to the entrainment of fluid into the mixing layer feeding the separation bubble
- Leads to a mass balance model of SWBLI interactions and a separation criterion based on Ma, Re, and turning angle

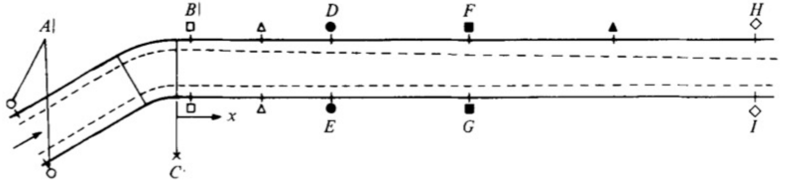


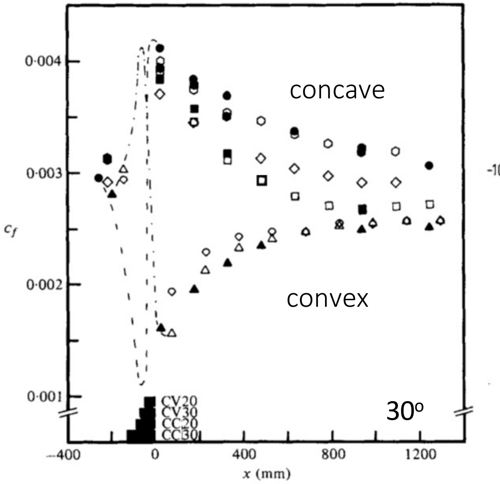


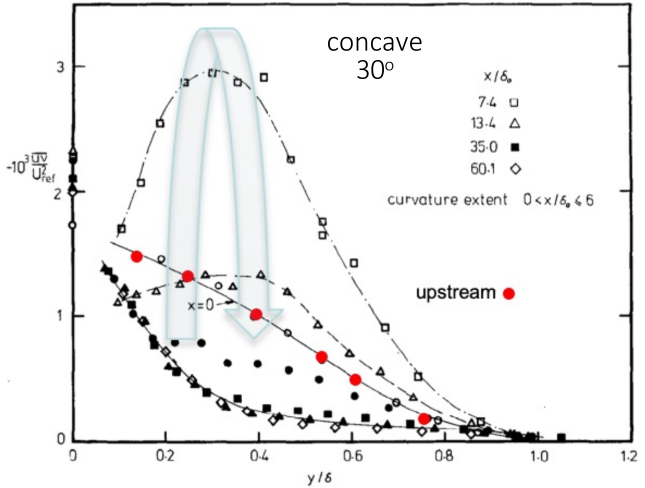
Souverein et al. (2009, 2013); Piponniau et al. (2009)

Concave streamline curvature and Görtler vortices

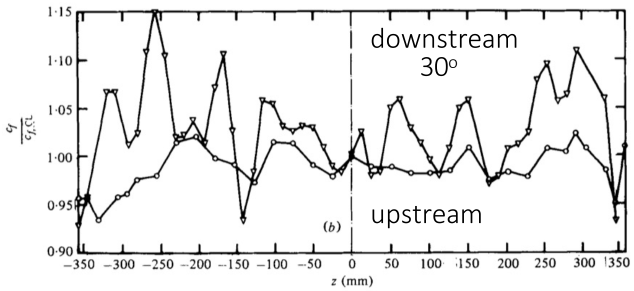
Effect of short regions of curvature on turbulent boundary layers





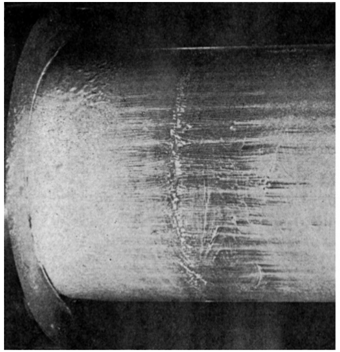


- Convex curvature is stabilizing
  - Expected to promote separation
  - Slow recovery
- Concave curvature is destabilizing
  - Expected to delay separation
  - Non-monotonic flow recovery
  - Appearance of TG vortices

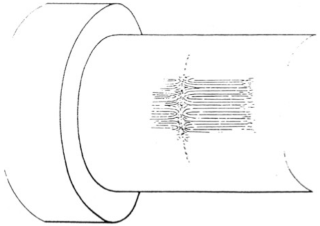


Smits, Young & Bradshaw (1979)

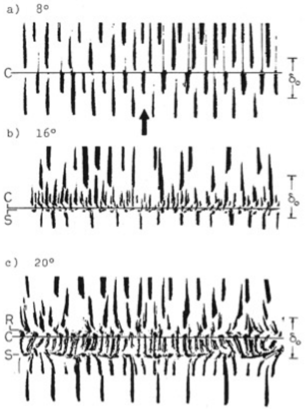
Concave streamline curvature and Görtler vortices



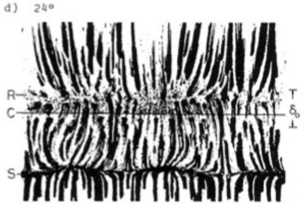
Mach 3.2

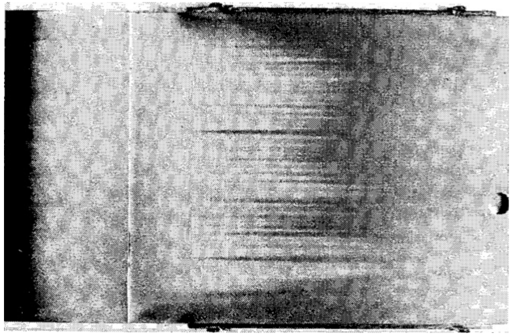


Roshko & Thomke (1966)
Shamroth & MacDonald (1970)



SWBLI Mach 2.9, 8^o to 24^o
Settles et al. (1979)





Mach 5.8

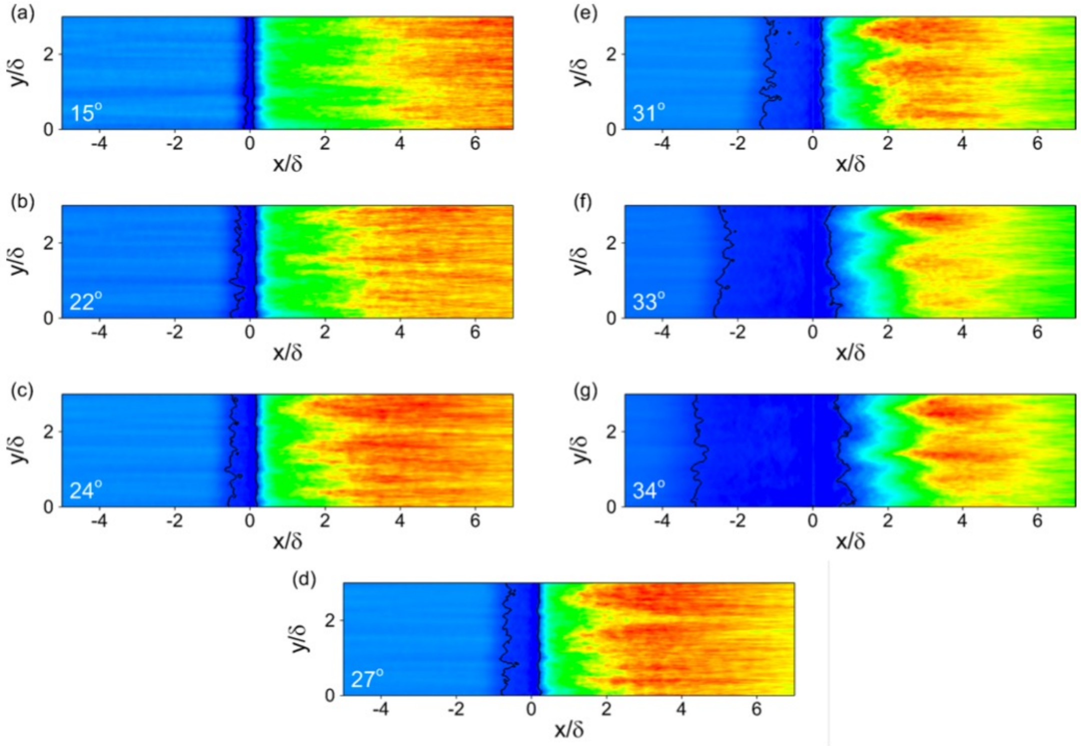
Ginoux (1971)

$$\lambda = 2 - 3\delta$$

"Therefore, although one can conceive that orderly arrays of pairs of counter-rotating vortices of the Gortler type, existing in the free shear layers as a result of streamline curvature, imply this type of flow attachment, one can also conceive that vortices are being developed as a result of this being the only possible type of attachment in the presence of any weak initial disturbance in the approaching boundary layer." (Ginoux 1971)

Superstructures and separated SWBLI

Ma = 10 $Re_\tau = 460$

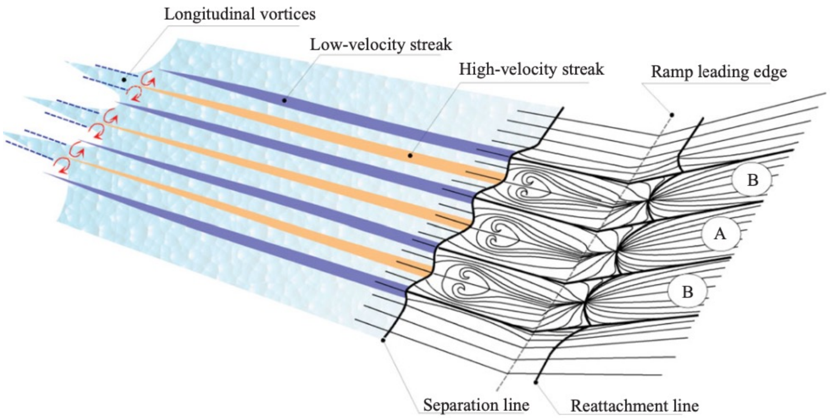


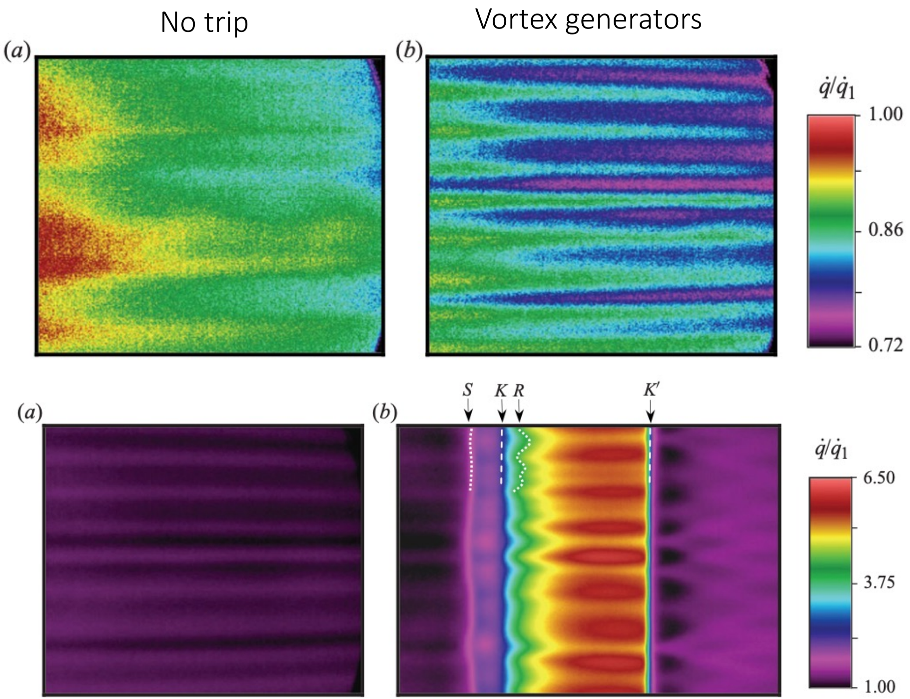
Turbulent boundary layer compression ramp interactions (LES)

Helm & Martin (2021)

Schulein & Tromifov 2011 (Mach 5)

- Longitudinal vortices, initiated at the leading edge, survive for long distances, $O(10^4 h)$
- The total number, dimension and type of installed vortex generators define the number of vortex pairs generated downstream



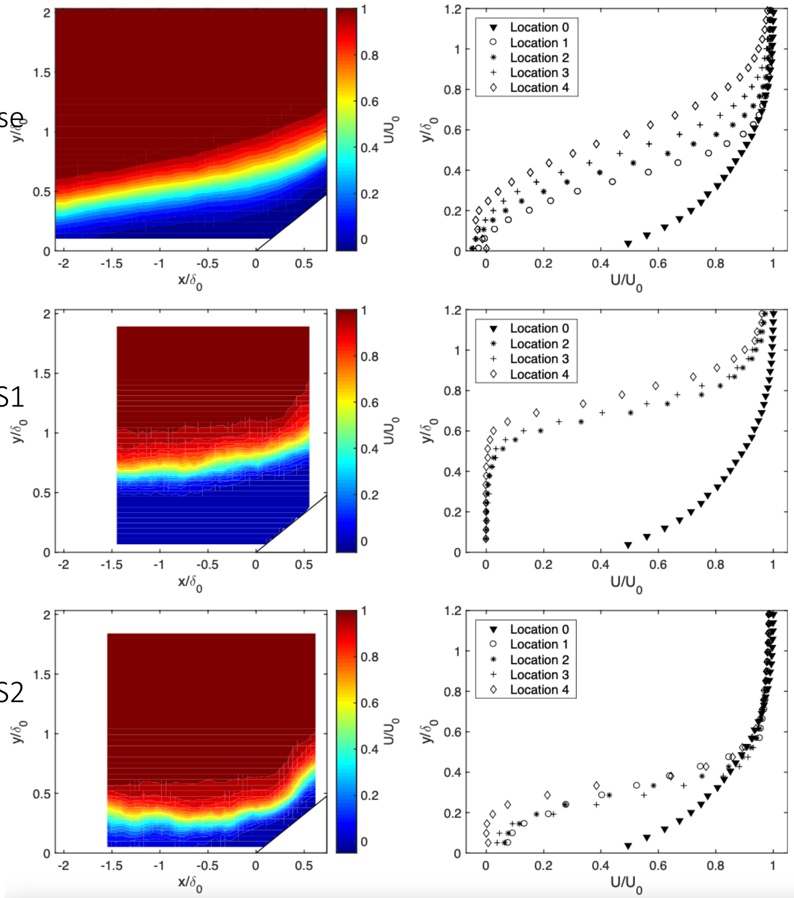


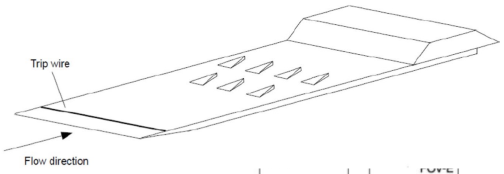
VG control for 33° compression corner at Ma = 7.2

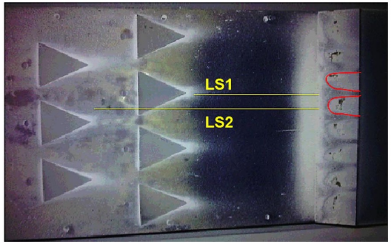
Base case (no VG)

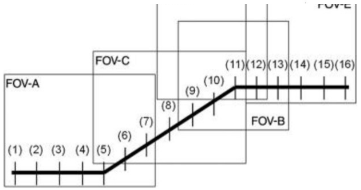
Along LS1

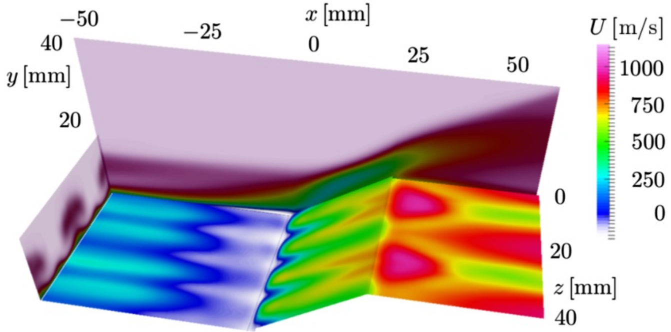
Along LS2







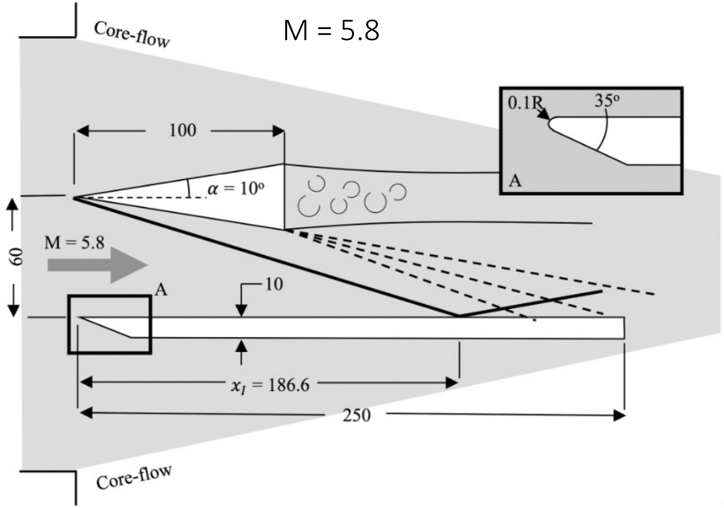


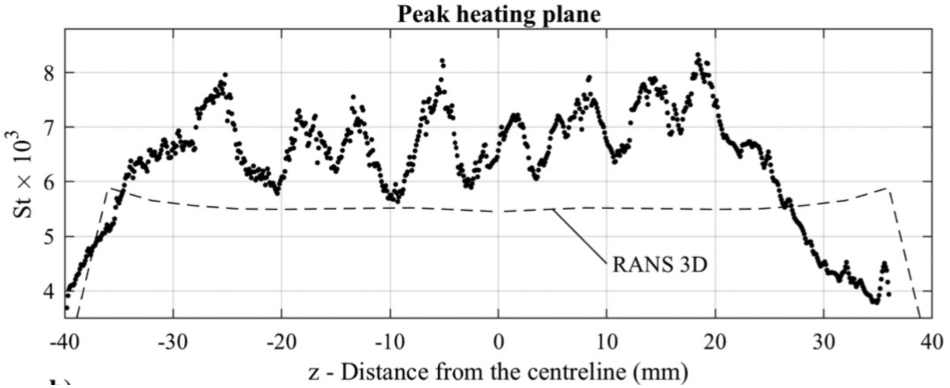


LES

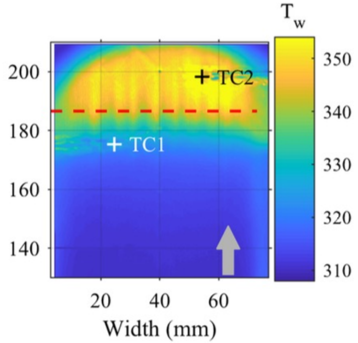
Schreyer et al. (2016, 2021)

Separation by reflected shock Mach 5.8





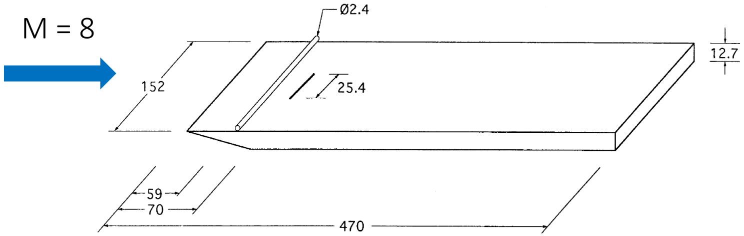
Currao et al. (2020)

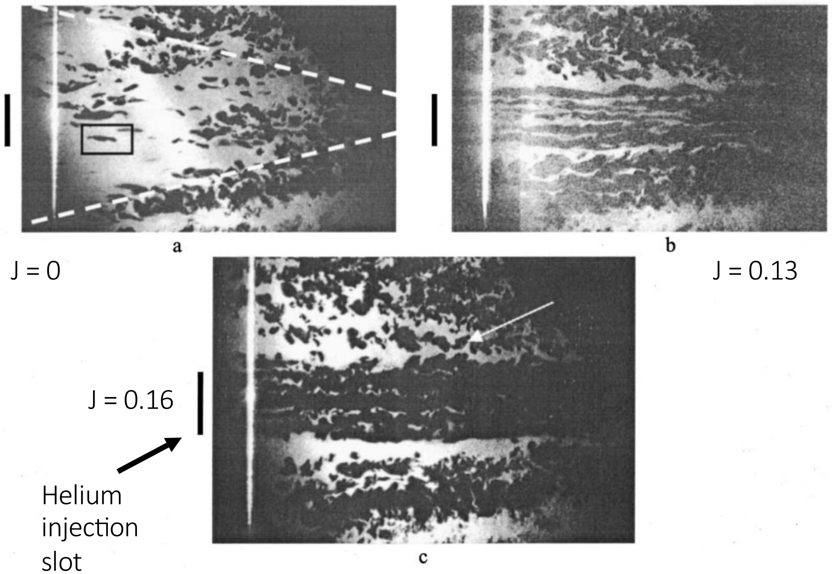


Temperature plan view

- Boundary layer transitions to turbulent on shock impingement
- Taylor-Görtler vortices form almost immediately
- Heat flux varies by ±15%
- Missed by RANS

Helium injection in Mach 8 turbulent boundary layer





$$J = \frac{(\rho U^2)_{inj}}{(\rho U^2)_\infty} = \frac{(\gamma p M^2)_{inj}}{(\gamma p M^2)_\infty}$$

- Organized, longitudinal structures in turbulent boundary layer are formed in region of helium injection
- Taylor-Görtler vortices due to concave curvature caused by injection

Auvity et al. (2001)

Görtler number

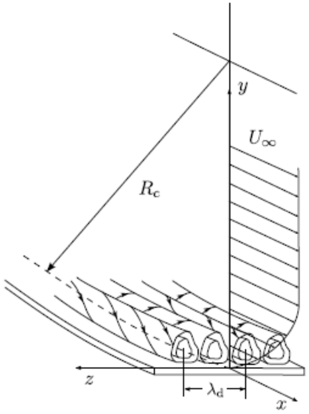
- Taylor-Görtler vortices in laminar, incompressible flows with concave streamline curvature are seen to occur when (Liepmann, Schlichting, Dryden)

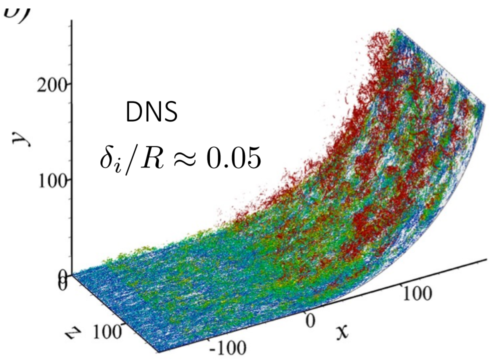
$$G_\theta = Re_\theta \sqrt{\frac{\theta}{R}} \;\; > [6, 9]$$

- For turbulent, incompressible flows with concave streamline curvature, Tani (1962) suggested

$$G_\theta = \frac{U_\infty \theta}{\nu_T}\sqrt{\frac{\theta}{R}} = \frac{55}{H}\sqrt{\frac{\theta}{R}} \;\; > [\approx 4]$$

$$\text{with} \quad \nu_T = 0.018\, U_\infty \delta^* \quad \text{(Clauser)}$$





You et al. (2021)

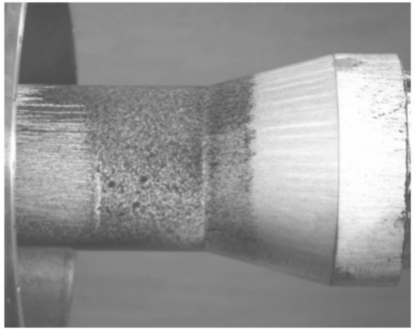
- For turbulent, compressible flows with concave streamline curvature, Smits & Dussauge (2006) suggested incorporating compressible forms of H and θ
- For a given δ, H increases faster than θ decreases with M, so the Görtler number decreases with M
- Boundary layers more stable to concave curvature

$$\text{still holds with} \quad \nu_T \propto U_\infty \delta_i^* \quad \text{(Maise \& McDonald)}$$

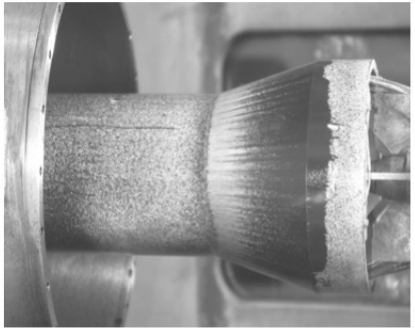
Are these simple ideas correct?

Separation on cylinder/flare Mach 5

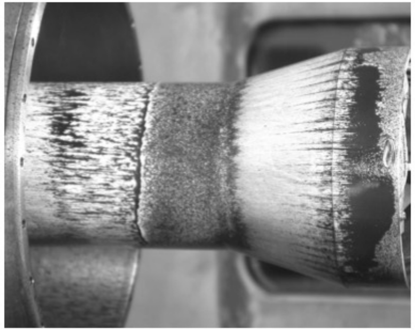
M = 5, axisymmetric flare/cone
Oil flow visualization in natural transition



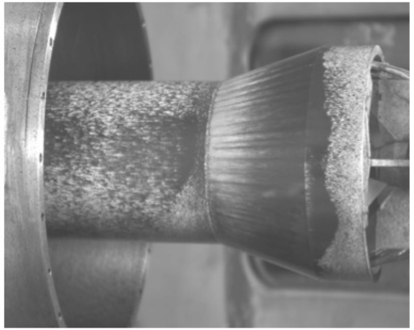
a) $p_{st} = 0.9 \times 10^5$ **Pa,** $Re_L = 0.38 \times 10^6$



c) $p_{st} = 5.4 \times 10^5$ **Pa,** $Re_L = 1.46 \times 10^6$



b) $p_{st} = 2.1 \times 10^5$ **Pa,** $Re_L = 0.67 \times 10^6$



d) $p_{st} = 5.5 \times 10^5$ **Pa,** $Re_L = 1.55 \times 10^6$

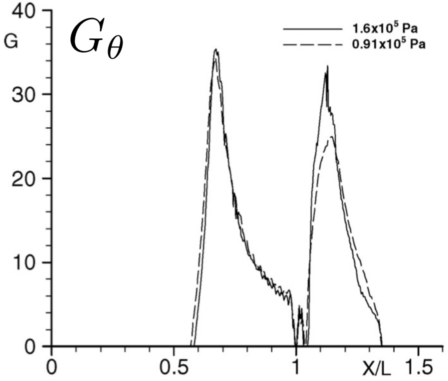
- Taylor-Görtler vortices present in all cases

$$G_\theta = Re_\theta \sqrt{\frac{\theta}{R}}$$

$$G_{\delta^*} = Re_{\delta^*} \sqrt{\frac{\delta^*}{R}} = H^{3/2} G_\theta$$

$$H \approx \left(1 + 0.693(\gamma - 1) M_\infty^2\right) \overline{H} = 20.5 \quad \text{at } M_\infty = 5$$

$$G_{\delta^*} \approx 90 G_\theta$$

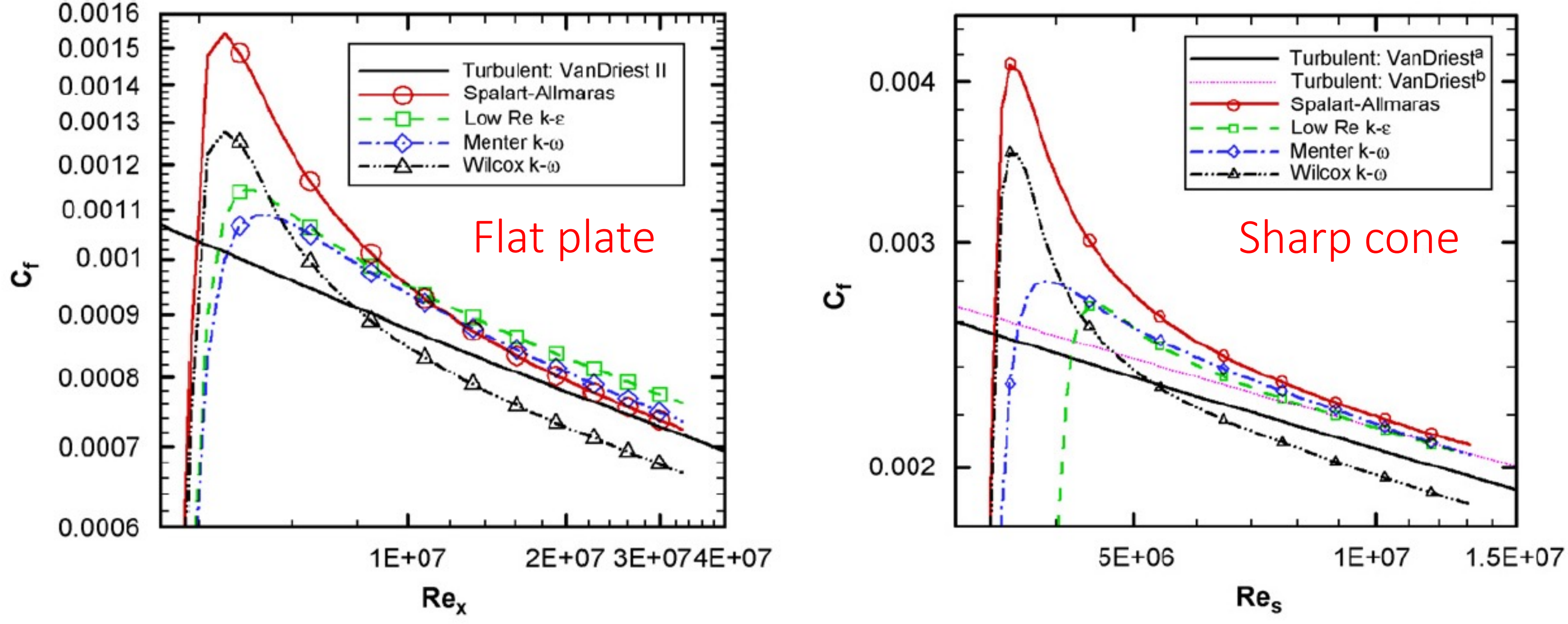


$$Re_L = 0.38 \times 10^6, \\ = 0.68 \times 10^6$$

Benay et al. (2006)

What about turbulence modeling (RANS)?

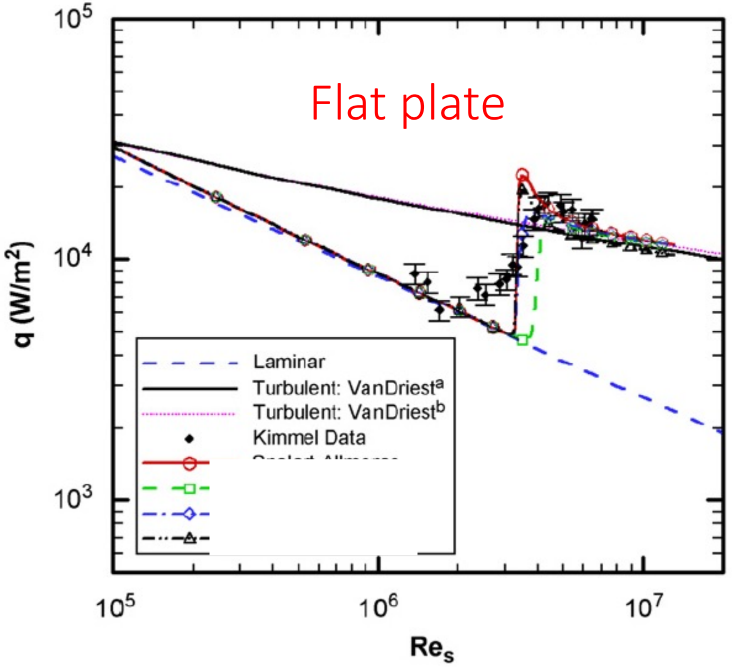
Skin friction at Ma = 8

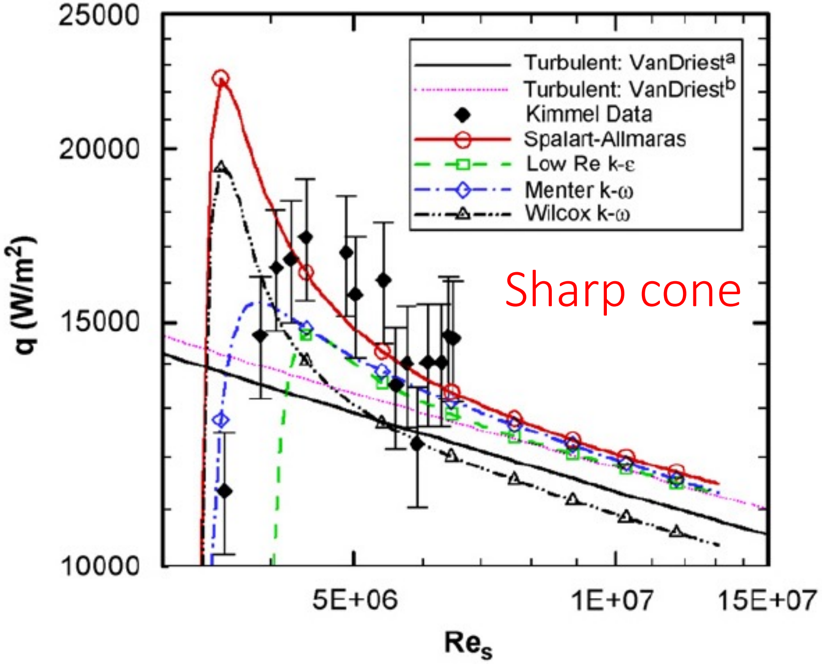


Roy & Blottner (2006)

What about turbulence modeling (RANS)?

Heat transfer at Ma = 8

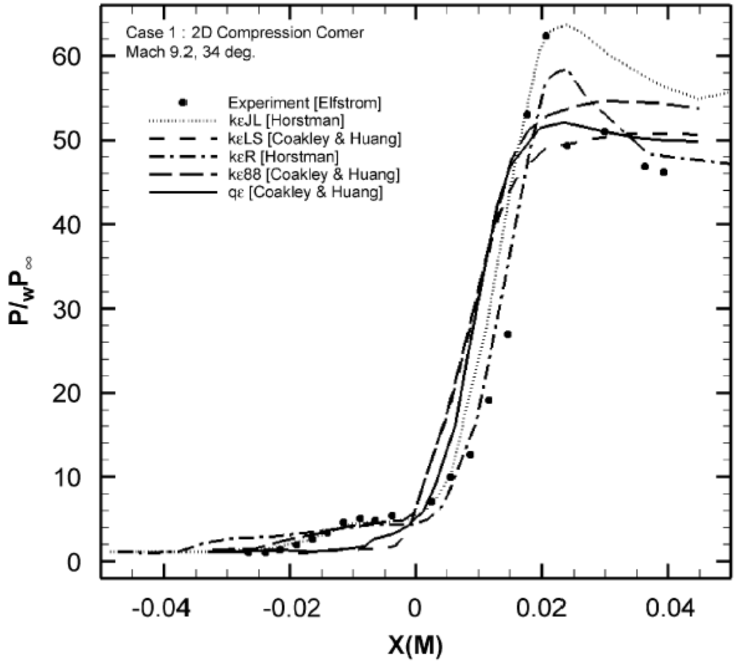




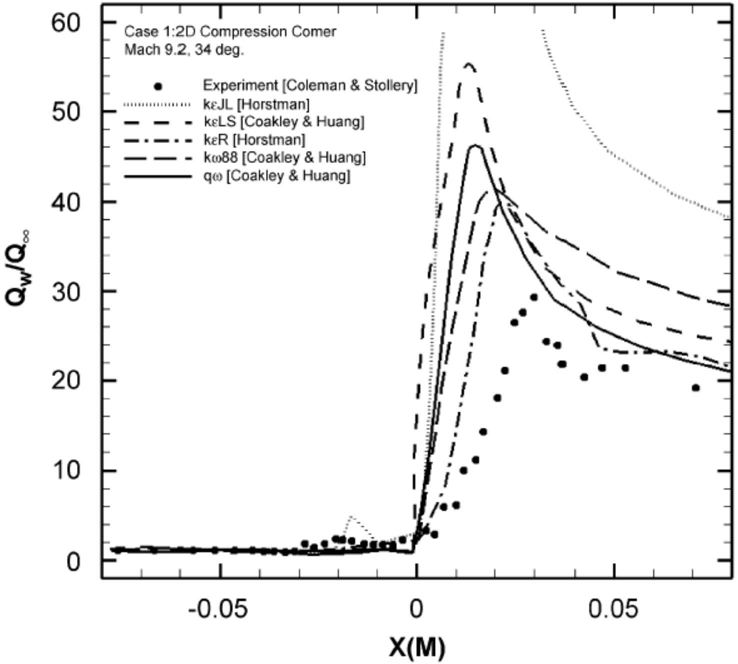
Roy & Blottner (2006)

34° compression corner at Ma = 9.2 (separated)

Wall pressure



Heat transfer



Roy & Blottner (2006)

Summary

- Zero pressure gradient, smooth wall flows appear to follow Van Driest/Morkovin scaling for mean flow and turbulence
- Shock-wave boundary-layer interactions are inherently unsteady, with large fluctuations in wall pressure and heat transfer
- SWBLI can cause very large amplifications of turbulence
- RANS models not reliable for SWBLI, especially at high Mach number

Remarks

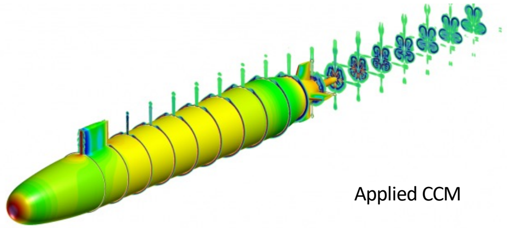
- Increasing Mach number generally coupled with decreasing Reynolds number
  - perfect for DNS (or high-resolution LES)
- High Mach number experiments must be designed for DNS
- Experiment and DNS/LES must be done at the same Reynolds number
- Need to expand our interests to include
  - heat transfer, roughness, film cooling
  - ablation, wall catalysis, pyrolysis, real gas effects, chemistry
  - curvature, pressure gradient, three-dimensionality
- Diagnostics are crucial to everything (understanding, modeling, validation, etc.), especially for turbulence
  - New diagnostics for τ_w' , q' , species, reaction rate?

Opportunities

- Flows with pressure gradients
  - What constitutes a canonical experiment?
  - Is there one or more characteristic parameters?
  - Prediction of separation on smoothly varying surfaces is still a major challenge
  - Data base is scattered, not systematic nor complete
- Turbulence Modelling
  - LES for separated flows well-established
  - RANS-DES easy for fixed separation point, hard for smoothly varying surfaces
  - LES wall functions necessary to make progress – lots of work needed
  - RANS for compressible flows, especially SWBLI (including transonic flows with possible separation)
  - Hypersonic flows
- Reduced order modeling
  - Resolvent analysis (McKeon)
  - Linear models (Gayme)
- Machine learning/AI
  - Can only be effective if there is a large-enough database

Incompressible turbulence

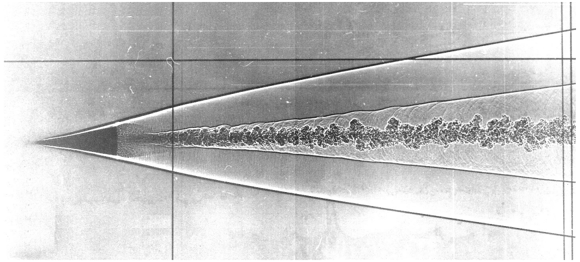
- Canonical turbulent flows
  - Grid turbulence
  - Jets and wakes
  - Fully-developed flows (channel, pipe, Couette, Ekman, Taylor-Couette)
  - Flat plate boundary layers, smooth or rough walls
- Perturbations in boundary conditions
  - Roughness, heat transfer
  - Step changes, impulsive changes
- Pressure gradients
- Complex flows
  - Streamline curvature (convex and concave)
  - Streamline convergence and divergence
  - Rotation (turbulent vortex flows)
  - Stratification (stable or unstable)
- Bodies of revolution (concurrent complex flows)
- Separation
  - Sudden (backward facing step, sharp edges)
  - Gradual (slowly varying flows)
- Flows with chemistry (mixing)
- Noise generation and transmission
- Flow control



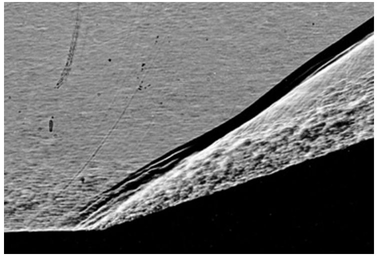
Applied CCM

Compressible turbulence

- Canonical turbulent flows
  - Grid turbulence
  - Jets and wakes
  - Channel, pipe
  - Flat plate boundary layers, smooth or rough walls
- Perturbations in boundary conditions
  - Roughness, heat transfer
  - Step changes, impulsive changes
- Pressure gradients
- Complex flows
  - Streamline curvature (convex and concave)
  - Streamline convergence and divergence
  - Rotation (turbulent vortex flows)
  - Stratification (stable or unstable)
- Separation
  - Sudden (backward facing step, sharp edges)
  - Gradual (slowly varying flows)
- Shock-wave boundary layer interactions (2D and 3D)
- Flows with chemistry
- Noise generation and transmission

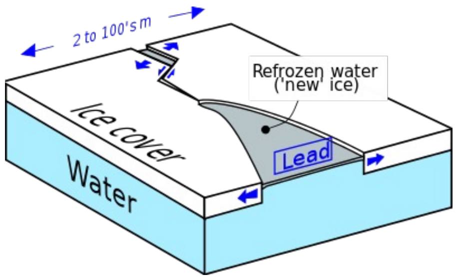


Mach 5.6 (Canning, NASA-Ames)



Some opportunities in turbulence

- Scalar transport
  - Contaminants, food or prey, pheromones
- Two-phase flows
  - Particle/bubble tracking (Lagrangian dynamics)
  - Cloud formation, plankton upwelling
  - Sediment, dust transport
- Atmospheric/geophysical flows
  - Stable (night time), unstable (convective, day time)
  - Rotating flows (Coriolis)
  - Heat, mass and momentum fluxes
  - Step changes (leads and polynyas)
- Stratified turbulence



Experiment, DNS, LES

Golden age of turbulence

Rapidly improving experiment and computation

Democratization of experiment and computation

New facilities, new ideas

Need courage to move beyond canonical flows

Questions?