Compressibility Effects in Turbulence: Revisited

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AERONAUTICS AND ASTRONAUTICS, AND

MECHANICAL ENGINEERING

B. Olson, J. Larsson, I. Bermejo Moreno, J. Freund, P. Moin

Ack: AFOSR, ONR, NASA, SciDac

Happy 70th Sreeni !

Int. Symposium on *Turbulence from Angstroms to Light Years*,
ICTS, Bangalore, Jan 21-25 2018

Outline

A Glimpse of compressibility effects on Turbulence

Fundamental Picture

More Recent Studies

- Homogeneous Turbulence
- Shock-Turbulence Interaction
- Variable density/variable property effects

Summary and Open Issues

- Physics and Modeling
- DNS/LES

Annu. Rev. Fluid Mech. 1994. 26 : 211–54

COMPRESSIBILITY EFFECTS ON TURBULENCE

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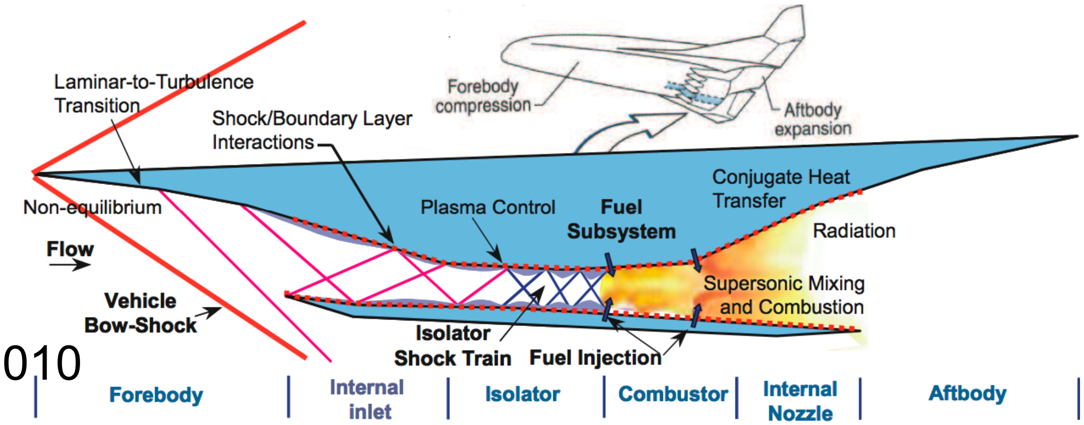
KEY WORDS: shock-turbulence interaction, supersonic mixing, turbulence modeling

A Glimpse of compressibility effects on Turbulence

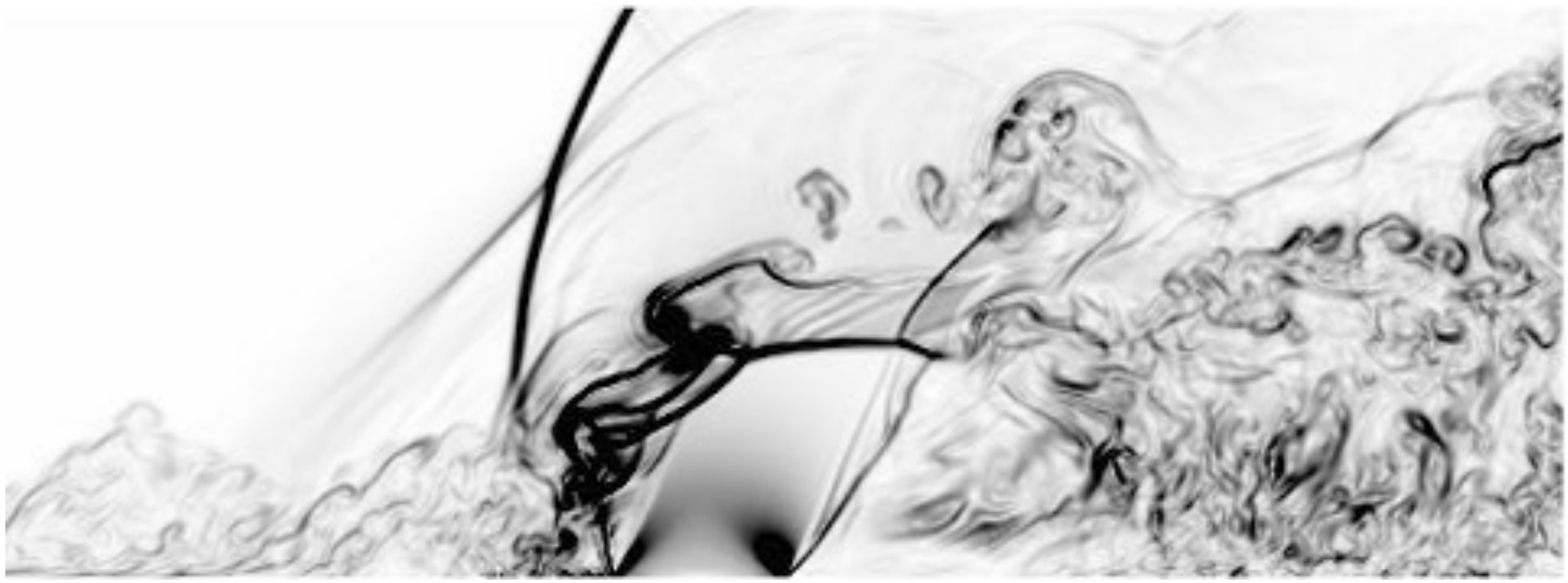
Supersonic mixing -- Scramjet

Supersonic/Hypersonic Turbulent Boundary layers – High speed Aerodynamics

Shock-Turbulence interaction -- High speed Aerodynamics



Kawai & Lele, AIAA J, vol 48, 2010

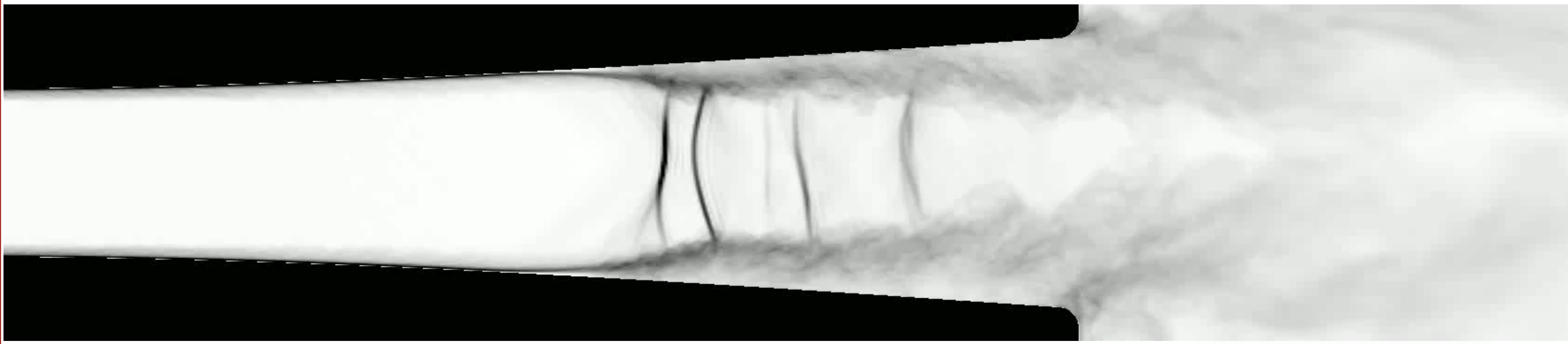


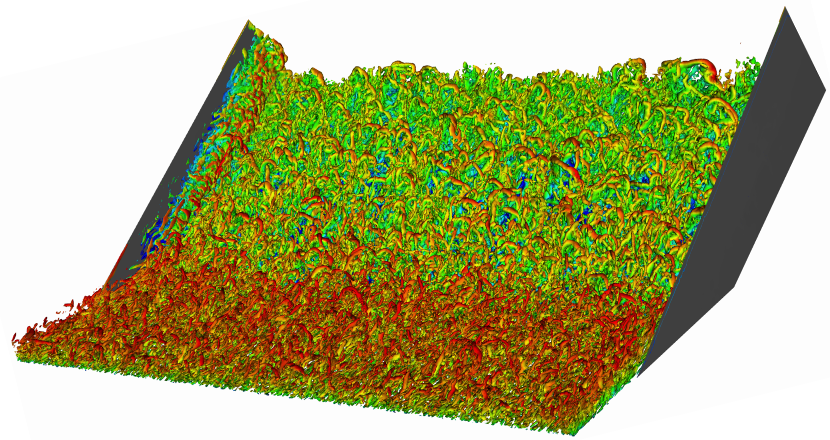
Shock-induced Separation

- ❖ Shock-induced separation
- ❖ Shock-induced unsteadiness

Olson & Lele AIAA 2011-3908

Over-expanded Planar Nozzle





3D Shock-Turbulent Boundary Layer Interaction

Compression ramp with fence

Dawson & Lele, AIAA 2015-1518

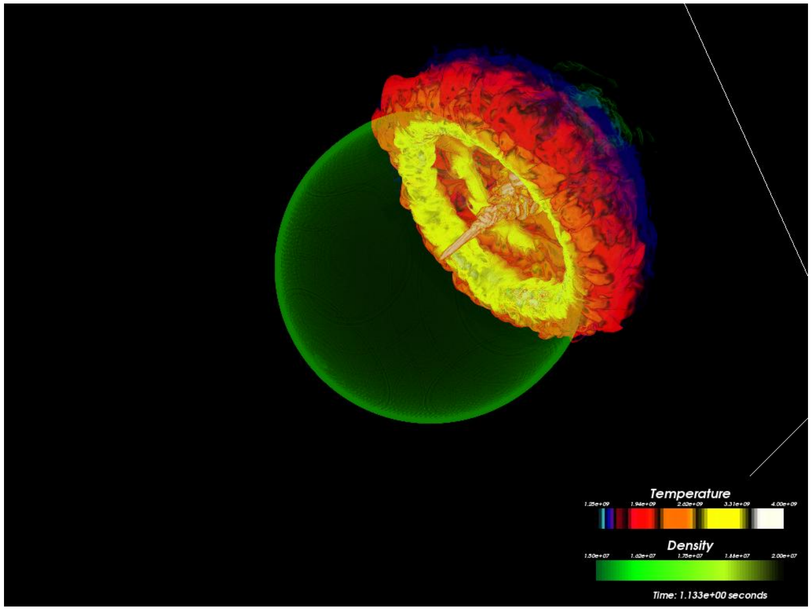
A Glimpse of compressibility effects on Turbulence

Solar convection

Supernova collapse

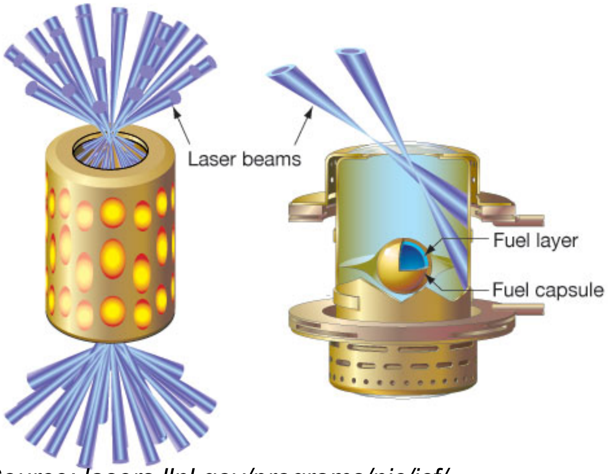
Intersteller density fluctuations

Inertial confinement fusion



Source: flash.uchicago.edu

Supernova explosion



Source: lasers.llnl.gov/programs/nic/icf/

Inertial confinement fusion by shock-induced implosion of a deuterium/tritium capsule

Compressibility Effects on Turbulence - Fundamentals

Three Modes of fluctuations   Yaglom (1948), Moyal (1952), Kovasznay (1953)

- **Vortical mode** or Gust Mode -- Solenoidal velocity, no pressure or density variations
- **Acoustic mode** – No vorticity, irrotational velocity, pressure, density fluctuation-isentropic
- **Entropic mode** – No velocity or pressure, density and temperature fluctuations

Linearized modes of uniform state
Evolve independently at first order in amplitude
  mode coupling: due to mean gradients and nonlinearity

Incompressible turbulence – Nonlinearly interacting vortical modes
Not just gust modes; (incompressible) Pressure effects (non-locality) important

Variable density turbulence (low M reacting flow, low M mixing)
Compressible turbulence – density of fluid parcel changes in response to pressure
  Low M_t -- Pseudo sound (Ristorcelli, 1997) Enslaved dilatational motions

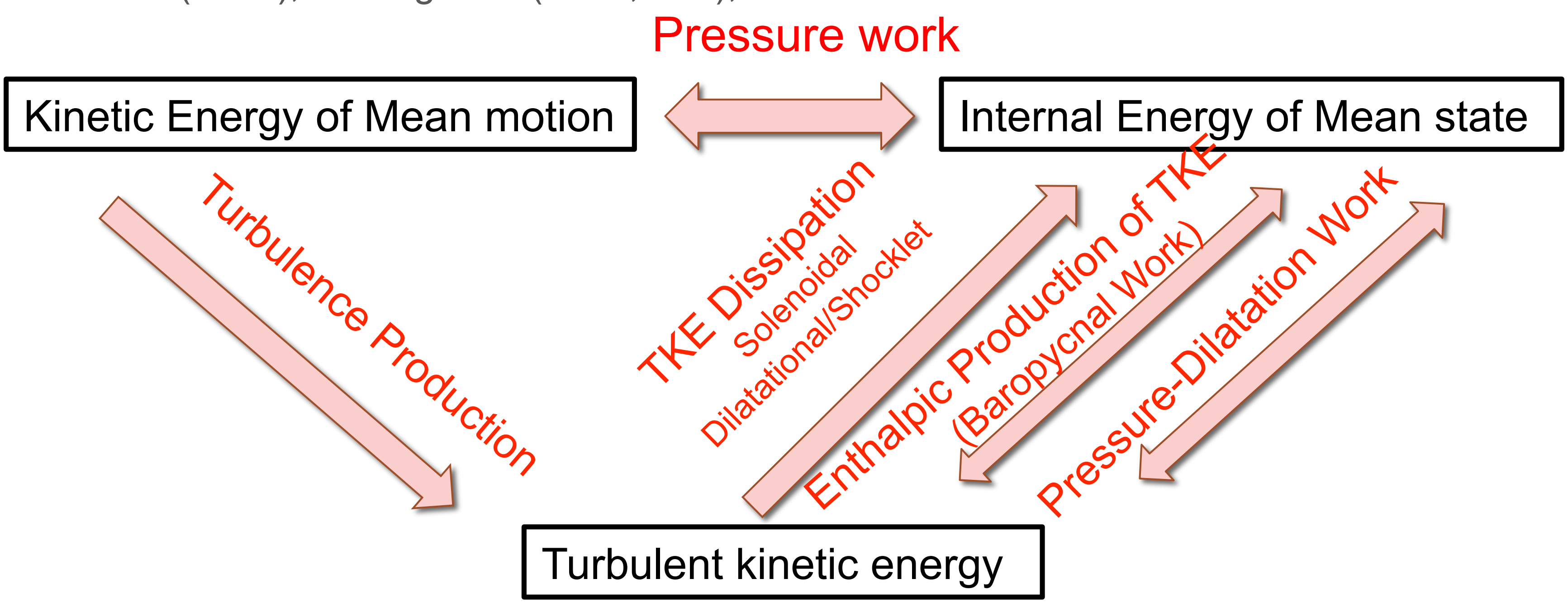
Linearized modes of non-uniform state ? Linear stability analysis; non-linear interactions
Primary Instability → Secondary Instability → Transition to turbulence
Useful framework but not well suited for broadband turbulence dynamics
  global modes/DMD/POD useful for modeling large-scale dynamics

Compressibility Effects on Turbulence - Fundamentals

Decomposition of variables: **Favre decomposition** (mass weighted velocity) (define)

Energy Transfer pathways (coupling of momentum with thermodynamics)

Favre (1965), Huang et al (1995,JFM), ….



Compressibility Effects on Turbulence - Fundamentals

Dimensionless parameters -- summary

Relative/Convective Mach Number M_c , M_r $= (U_1 - U_2)/(C_1 + C_2)$

Turbulence Mach Number $M_t = q/C$

Gradient/Deformation Mach Number $M_g = SL/C = (L/C) / (1/S) = L / (C/S)$

Friction Mach Number $M_T = u_T / C$

Mixing Layer $u_T / \Delta U \sim 0.2$; Boundary Layer $u_T / U_\infty \sim 1/25$

So for TBL require M_∞ which is at least 5 times larger than mixing layers for significant compressibility effects

In practice, even at $M_\infty = 10$ intrinsic compressibility effects seem absent! Why ?

Intense aerodynamic heating in supersonic/hypersonic TBL →

Very low density and high viscosity near the wall

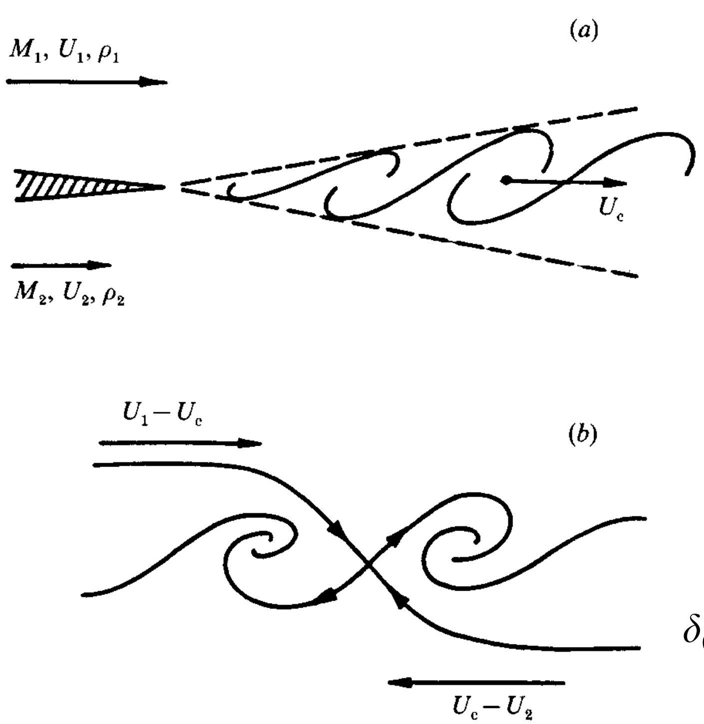
Compressibility Effects on Turbulence - Fundamentals

Flow Physics of Supersonic Mixing -- Observations I

Suppression of mechanical mixing

Brown & Roshko (1974), Bogdonoff (1983), Papamoschou & Roshko (1986)

D. Papamoschou and A. Roshko



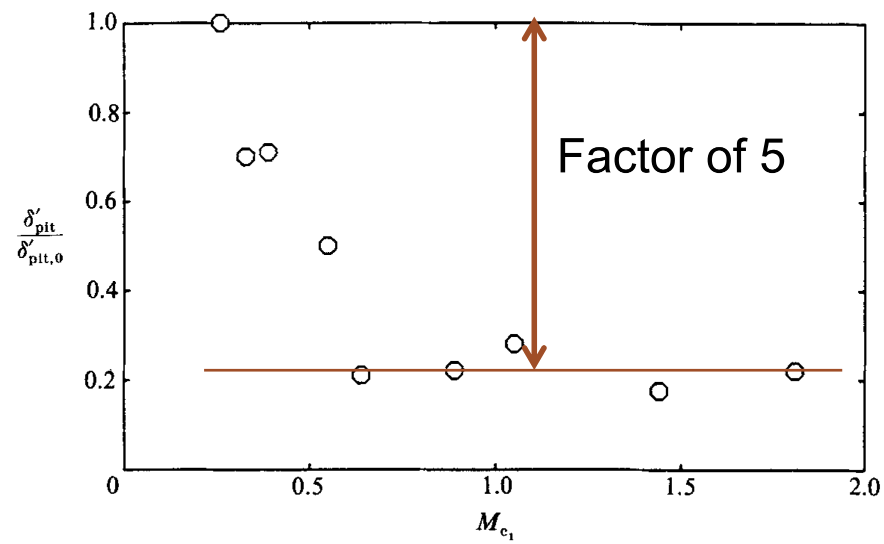


FIGURE 16. Normalized Pitot-thickness growth versus M_{c_1}.

$$\delta_0'(x;r,s) \simeq C_\delta \frac{(1-r)(1+s^{1/2})}{2(1+s^{1/2}r)} \left\{ 1 - \frac{(1-s^{1/2})/(1+s^{1/2})}{1+2.9(1+r)/(1-r)} \right\},$$

$$M_c = (U_1 - U_2)/(C_1 + C_2)$$

Compressibility Effects on Turbulence - Fundamentals

Flow Physics of Supersonic Mixing -- Observations II

Explanations/Hypotheses

Dilatational/Shocklet dissipation Zeman (1990), Sarkar et al (1991)

Damping via Acoustic Radiation

Suppression of linear instability
Sandham & Reynolds (1990), Ragab & Wu (1989), Grosch & Jackson (1989), Lu & Lele (1993)

Turbulence structure change Vreman et al (1996), Pantano & Sarkar (2002)

Sonic Eddy Hypothesis Briedenthal (1992) AIAA J.

Compressibility Effects on Turbulence - Fundamentals

Flow Physics of Supersonic Mixing -- Observations III

Freund, Lele & Moin, JFM (2003)

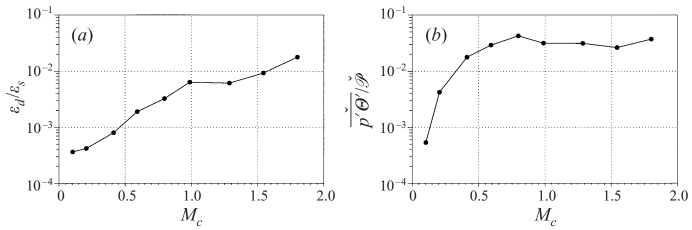


FIGURE 21. (*a*) Ratio of dilatational to solenoidal dissipation and (*b*) ratio of integrated pressure dilatation to the integrated production.

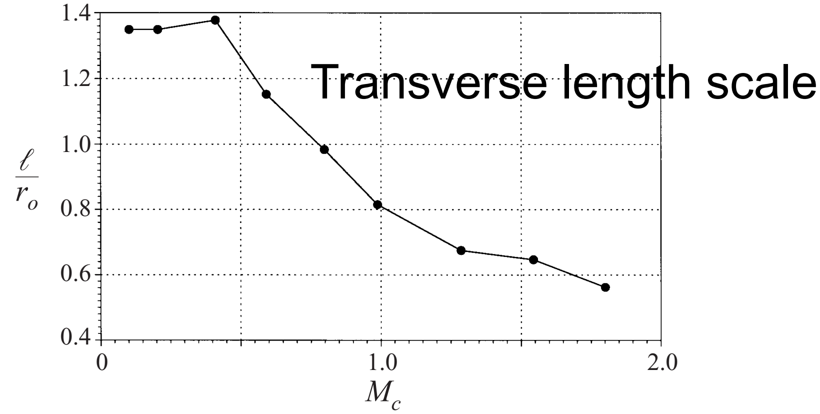
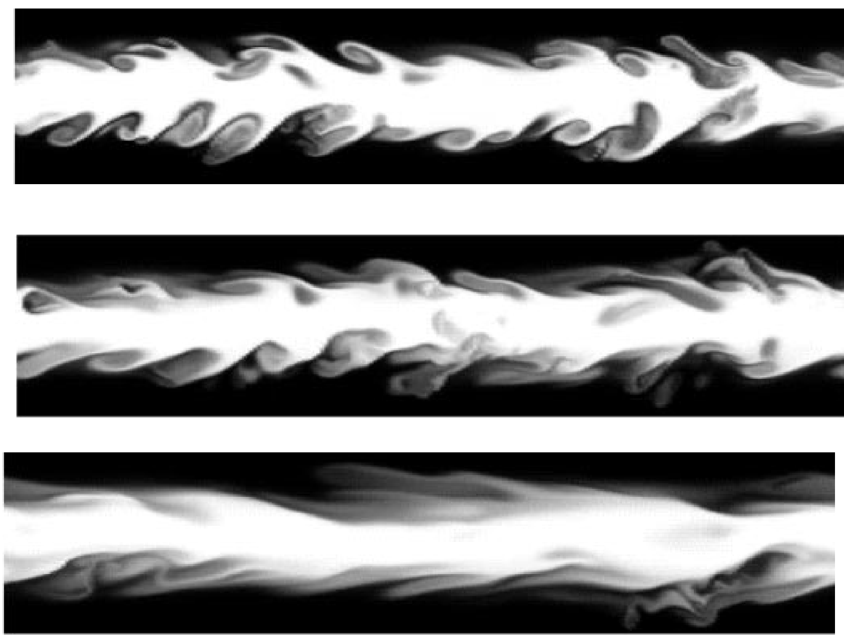


FIGURE 6. Transverse large-eddy lengthscale.



$M_c = 0.2$

$M_c = 1.0$

$M_c = 1.9$

Passive tracer cuts

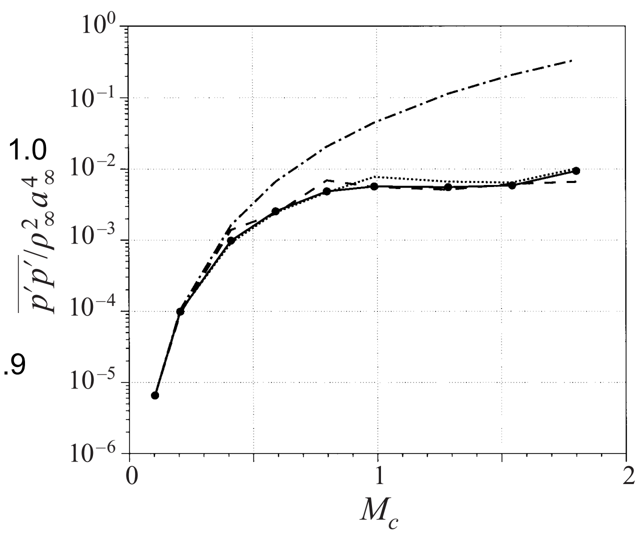


FIGURE 30. 'Un-normalized' pressure fluctuations at $r = r_o$: —●—, from the simulatic ---, $\sim M_g^4$ from (6.4); ······, $\sim M_{t_r}^4$ from (6.5); —·—, $\sim U_j^4$ (see text).

Compressibility Effects on Turbulence - Fundamentals

Absence of significant effects in Supersonic/Hypersonic TBLs

Morkovin (1962), Bradshaw (1977), Smits & Dussauge (1986)

DNS Duan & Martin, JFM (2011)

$$U^+_{\mathrm{VD}} = \int_0^{u^+} \left(\frac{\bar{\rho}}{\rho_w}\right)^{1/2} du^+,$$

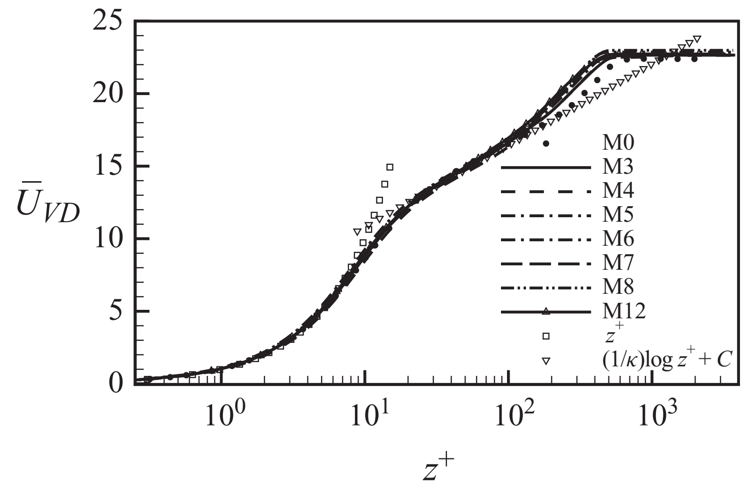


FIGURE 4. Van Driest transformed velocity for different free-stream Mach number cases.

Direct numerical simulation of hypersonic turbulent boundary layers 247

Case	M_δ	ρ_δ (kg m^{-3})	T_δ (K)	T_w/T_δ	Re_θ	Re_τ	$Re_{\delta 2}$	θ (mm)	H	δ (mm)
M0	0.30	0.0900	220.0	1.00	1514.7.6	569.9	1515.2	2.76	1.41	23.0
M3	2.97	0.0910	219.9	2.51	3028.6	486.9	1586.7	0.619	5.09	8.85
M4	3.98	0.0902	219.2	3.83	4093.7	438.2	1587.4	0.658	8.01	12.0
M5	4.90	0.0962	224.4	5.31	4931.7	416.5	1578.0	0.682	11.29	15.1
M6	5.81	0.0990	230.7	7.02	5775.1	412.8	1582.2	0.730	15.4	19.7
M7	6.89	0.0929	224.2	9.49	7207.3	391.7	1586.4	0.838	20.2	28.1
M8	7.70	0.0990	232.8	11.2	7508.3	397.5	1577.5	0.861	24.2	31.8
M12	11.93	0.0906	228.0	27.6	11356.4	376.8	1577.5	1.33	46.1	84.7

TABLE 1. Dimensional boundary-layer edge and wall parameters for the DNS database.

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Compressibility Effects on Turbulence - Fundamentals

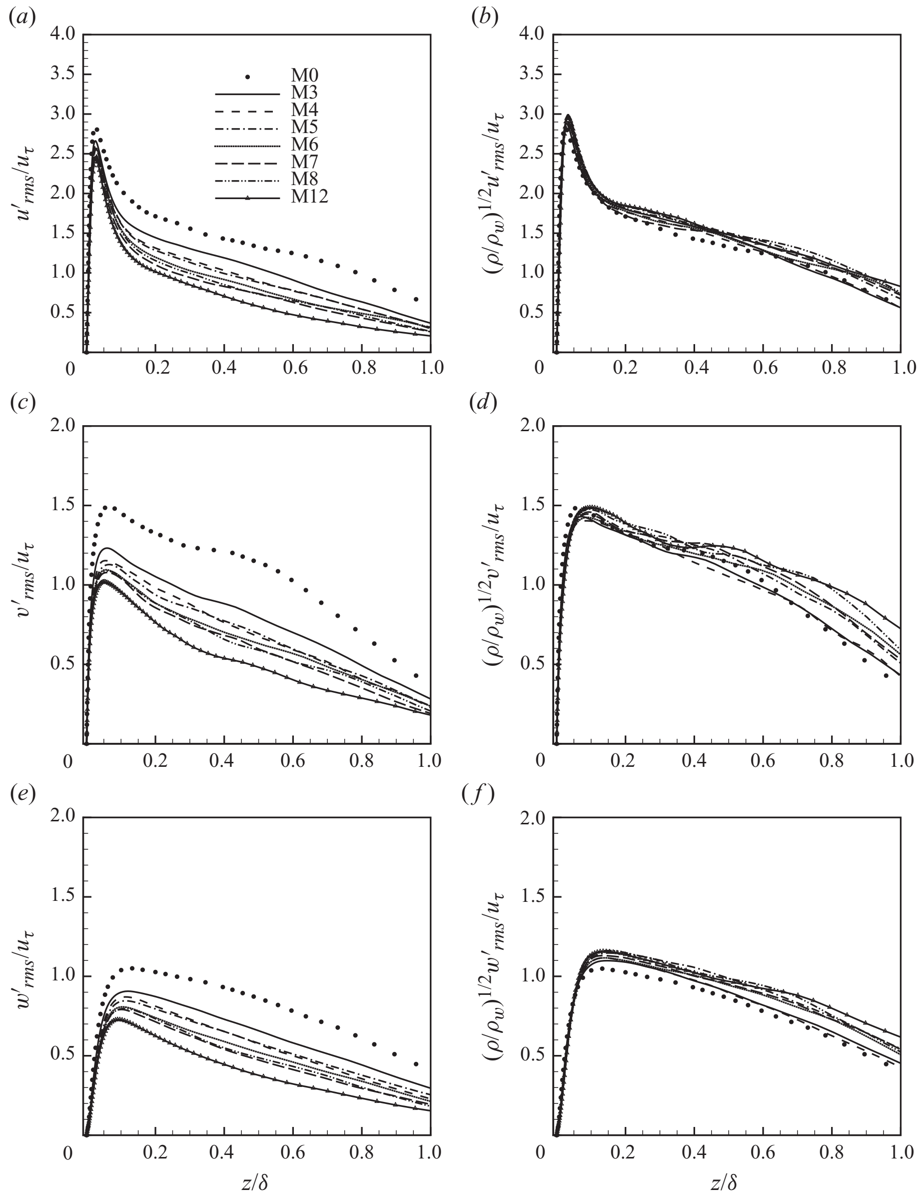

FIGURE 6. Turbulence intensities and density-weighted turbulence intensities of the (a, b) streamwise, (c, d) spanwise and (e, f) wall-normal fluctuating velocity components for different free-stream Mach number cases.

Local density scaling

DNS

Duan & Martin, JFM (2011)

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Compressibility Effects : Homogeneous Turbulence

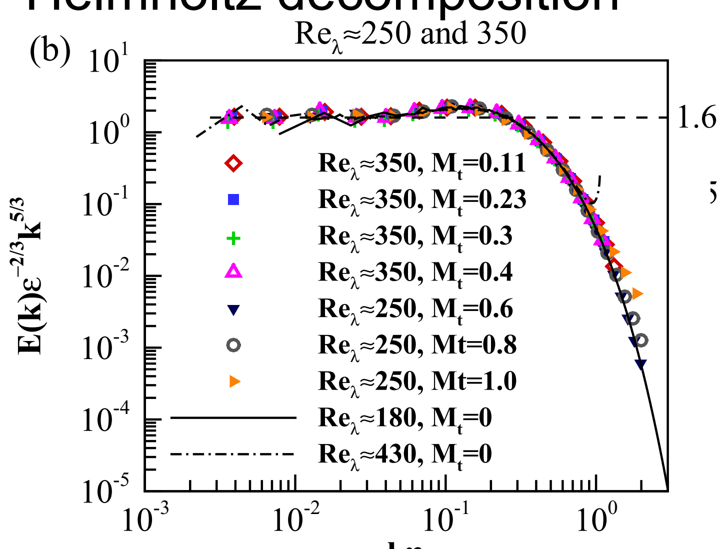
Spectral behavior

HIT Decaying and solenoidal forcing

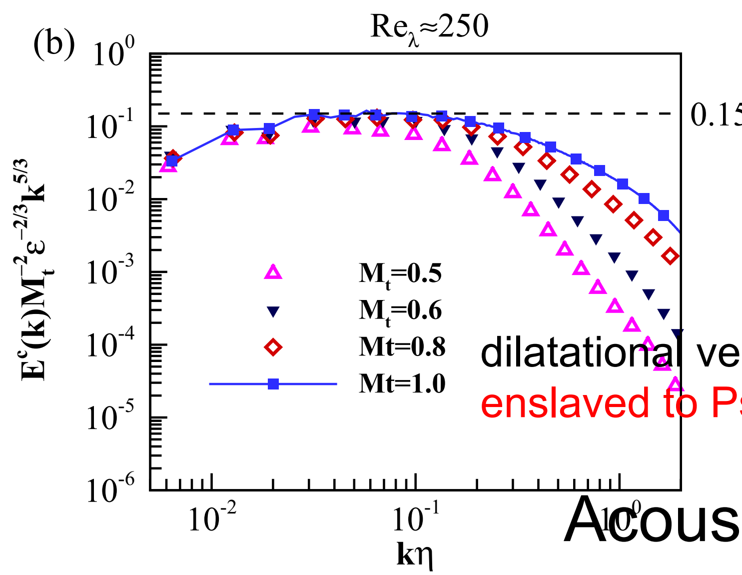
Aluie (2011), Kritsuk et al (2013), Donzis & Jagannathan JFM (2013), Others

Wang, Gotoh & Watanabe PRF (2017)

Helmholtz decomposition



Kolmogorov scaling



dilatational velocity at high k
enslaved to Pseudo sound

Acoustic scaling

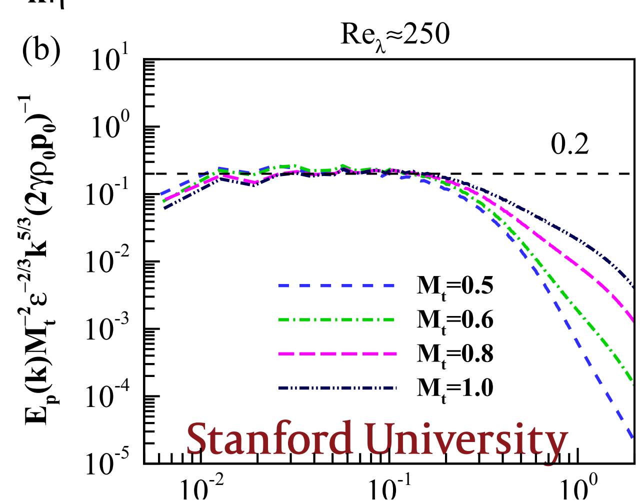


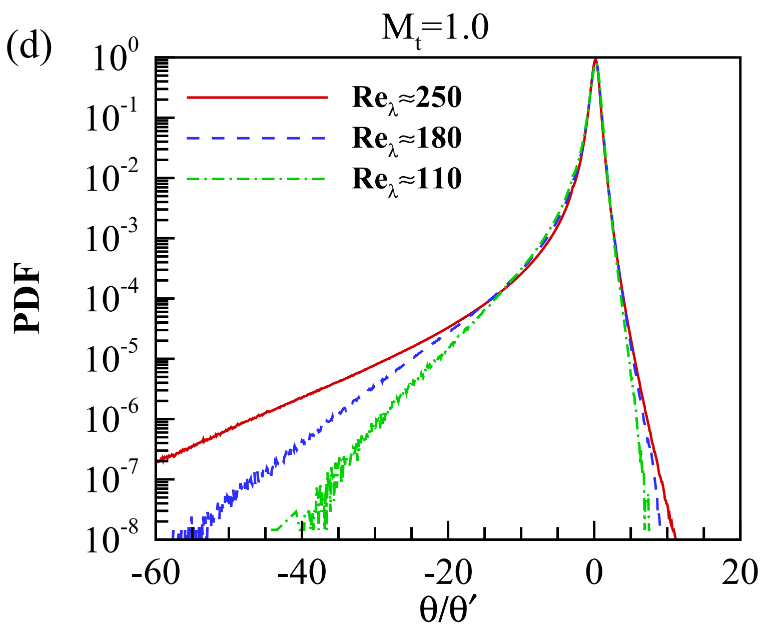
TABLE III. Simulation parameters and resulting flow statistics for 1024^3 grid resolution.

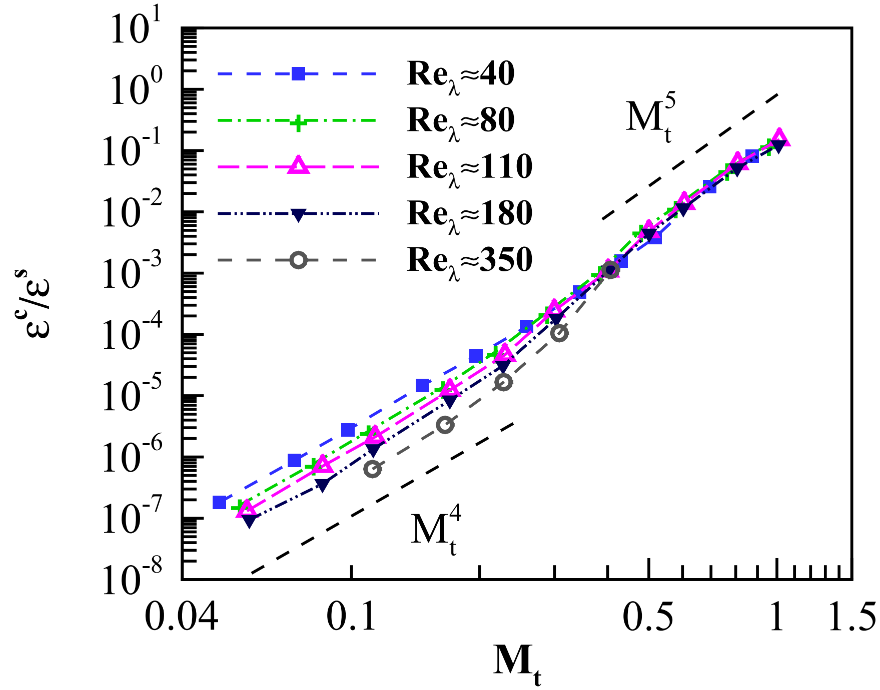
Resolution	Re_λ	M_t	$\eta/\Delta x$	L_I/η	λ/η	S_3	$D = \epsilon L_I/(u'/\sqrt{3})^3$
1024^3	350	0.11	0.64	371	36.5	−0.55	0.41
1024^3	355	0.17	0.64	374	36.8	−0.55	0.43
1024^3	369	0.23	0.62	382	37.7	−0.56	0.41
1024^3	361	0.30	0.58	395	37.4	−0.55	0.44
1024^3	365	0.40	0.59	390	37.6	−0.54	0.43
1024^3	253	0.51	1.00	233	31.2	−0.53	0.44
1024^3	262	0.60	1.02	231	31.6	−0.53	0.42
1024^3	261	0.79	1.05	229	30.9	−0.83	0.41
1024^3	250	1.02	1.04	226	29.1	−1.95	0.42

Compressibility Effects : Homogeneous Turbulence

Shocklets & Dissipation

Lee et al (1991), Samtany et al. (2001), **Wang et al PRF (2017)**



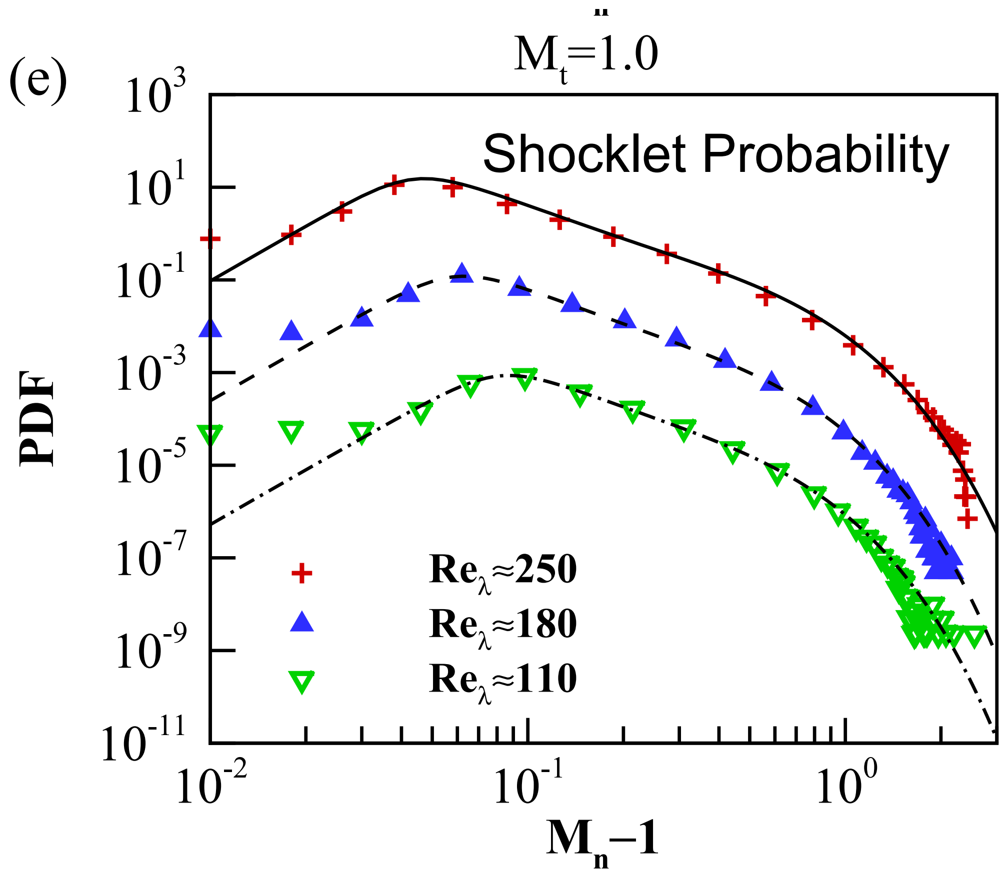


$$\epsilon^c/\epsilon^s \sim M_t^4 \mathrm{Re}_L^{-1} \log(\mathrm{Re}_L),$$

Compressibility Effects : Homogeneous Turbulence

Shocklets & Dissipation

Lee et al (1991), Samtany et al. (2001), **Wang et al PRF (2017)**



$$P(M_n - 1) = C_1 \exp\left[-\frac{M_n - 1}{\beta_2}\right]\left[1 + \left(\frac{M_n - 1}{M_n^{\exp} - 1}\right)^{-\beta_1}\right]\left[1 + \left(\frac{M_n - 1}{\beta_3}\right)^{-\beta_1 - 4}\right]^{-1},$$

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Canonical shock/turbulence interaction

Isotropic turbulence passing through a normal shock in a perfect gas

Isolates the core interaction between turbulence and shock

Parameters:

M_1, M_t, Re_t

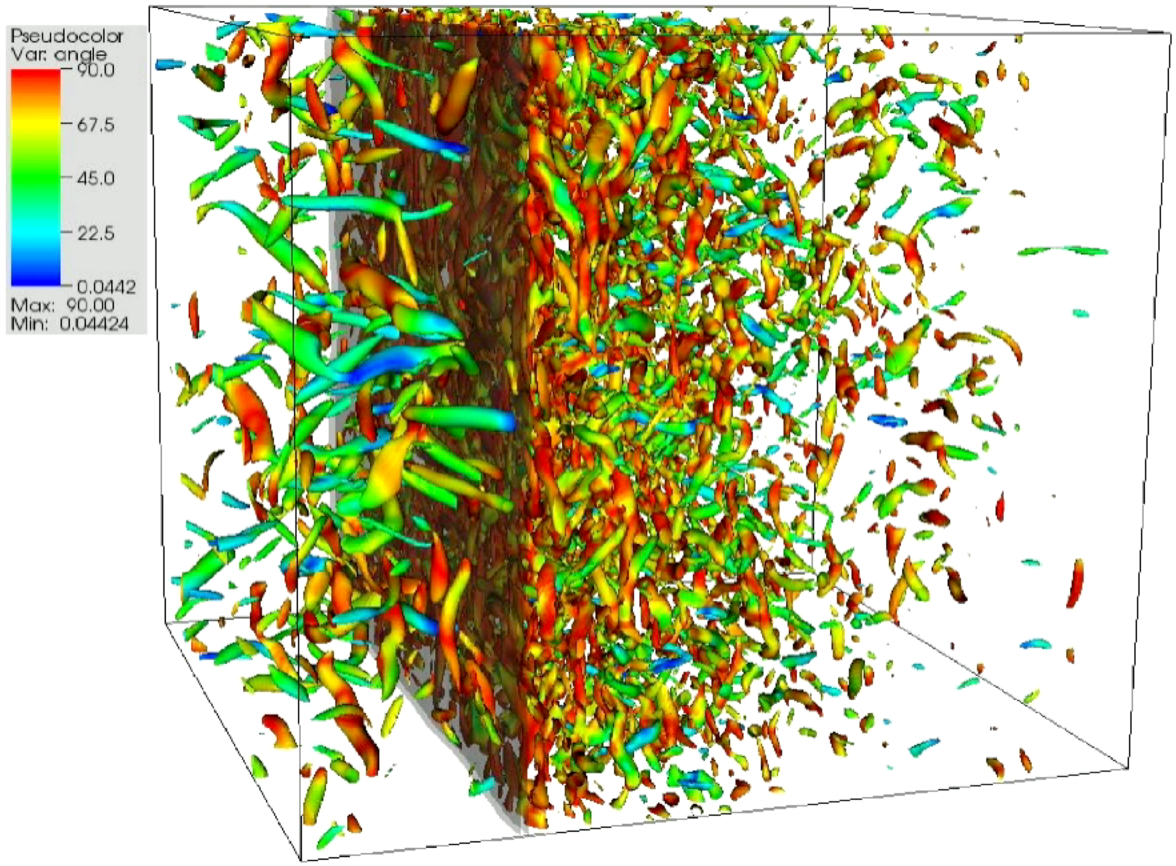
Entropy fluctuations

Acoustic fluctuations

δ_{shock}/L

Real-gas effects

Eddies visualized by Q-criterion, colored by angle vorticity from x_1. Shock visualized by dilatation contour.



From Larsson & Lele, Phys. Fluids, 2009

Larsson, Bermejo-Moreno & Lele, JFM, 2013

Difference compared to previous studies

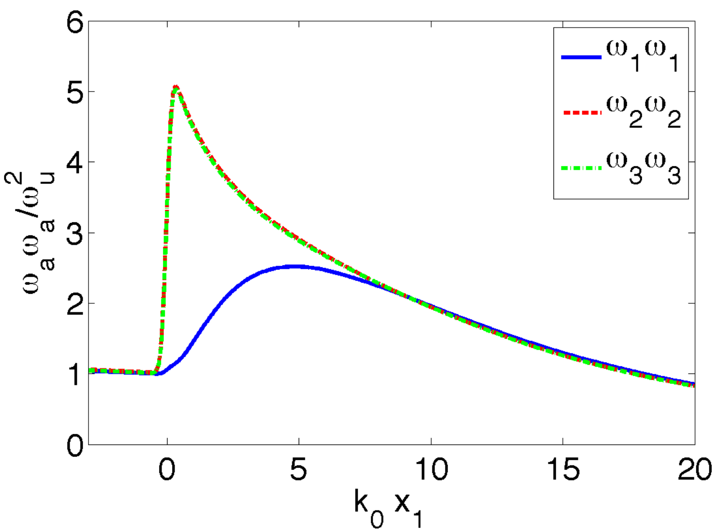
Past studies: Re_λ = 20 on 129*64^2 grids (Lee et al, 1993, 1997, Mahesh et al, 1997)

Present: Re_λ = 40 on 1040*384^2 grid; Re_λ = 60 on 1675*512^2 grid; Re_λ = 74 on 2234*1024^2 grids

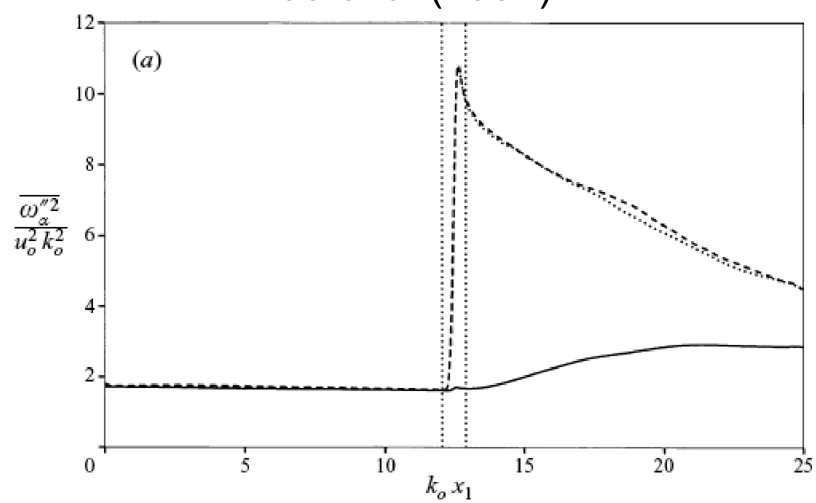
Return to local (small-scale) isotropy in present DNS, but not in past work

Vorticity redistribution is a nonlinear process

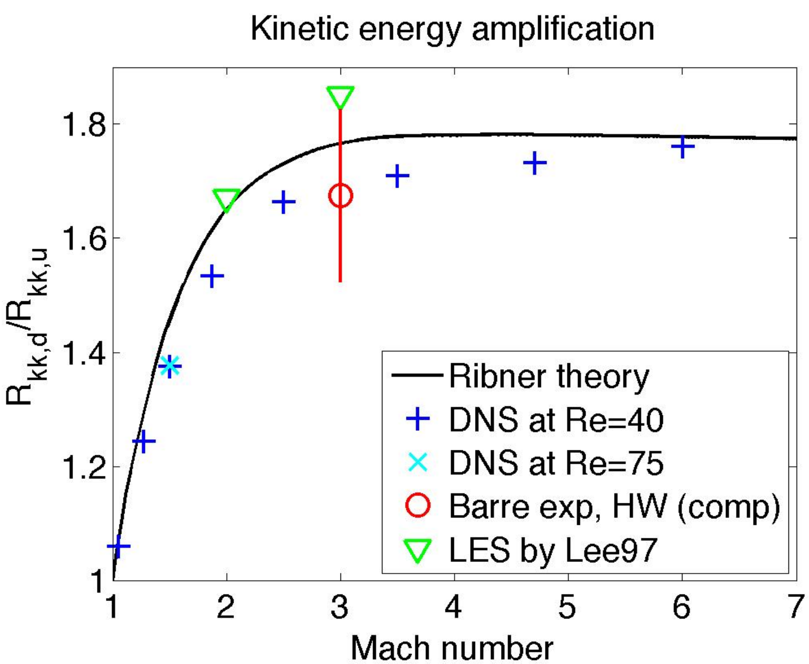
Past work did not fully capture these processes due to lack of grid resolution

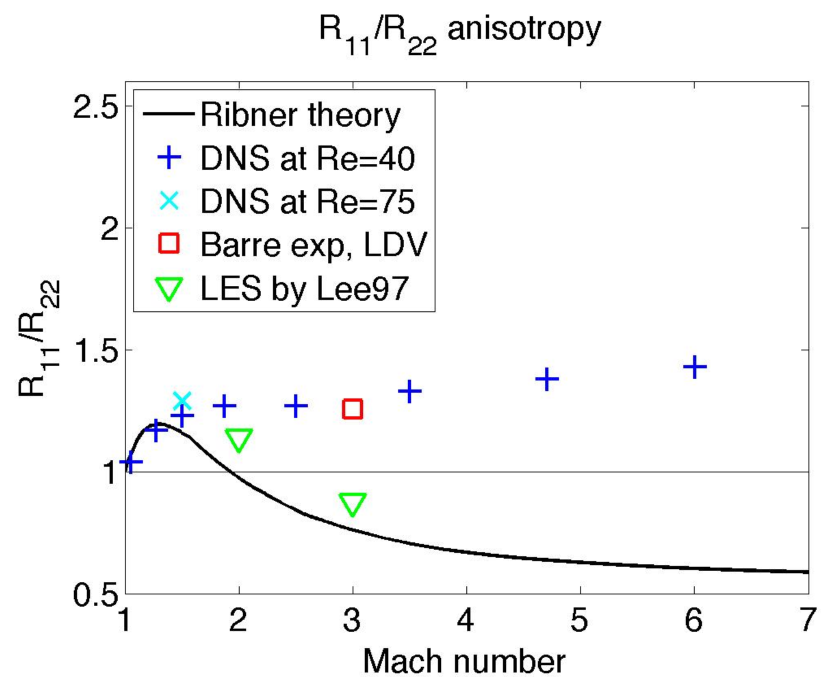


Lee et al (1997)



Reynolds stresses: amplification across shock





Linear theory predicts TKE amplification correctly, but misses the return to isotropy of small-scale turbulence and (post-shock) Reynolds stress anisotropy

Also see, Donzis (2012) Phys. Fluids and Ryu & Livescu (2014) JFM
Also K. Sinha and collaborators

Shock motion and approach flow at $(M,M_t) = (1.50,0.38)$

Contours of streamwise velocity scaled by upstream speed of sound (colors)

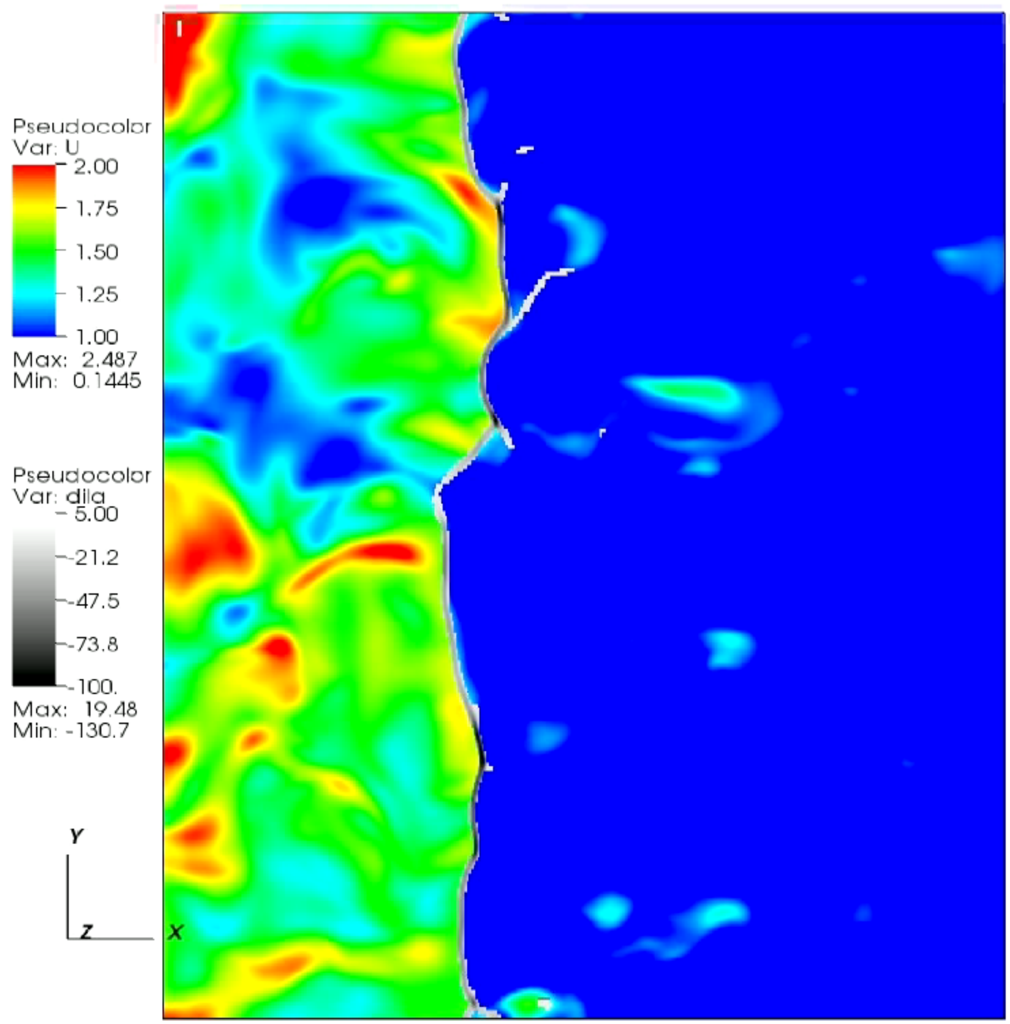
Contours of dilatation at shock (gray scale)

u' > 0:

- "pushed back" shock
- strong shock (high compression)

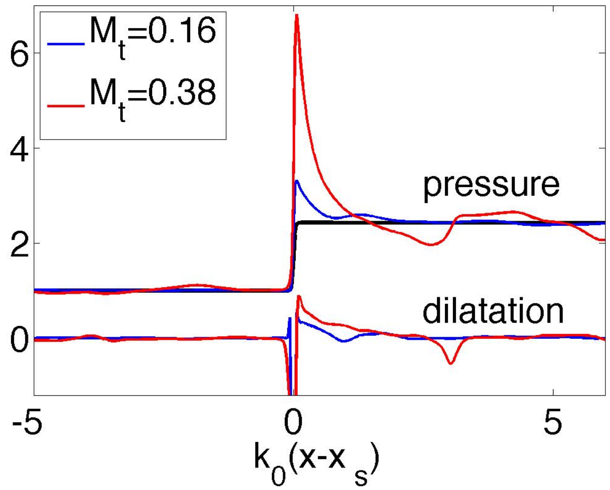
u' < 0:

- "pushed forward" shock
- weak shock (low compression)

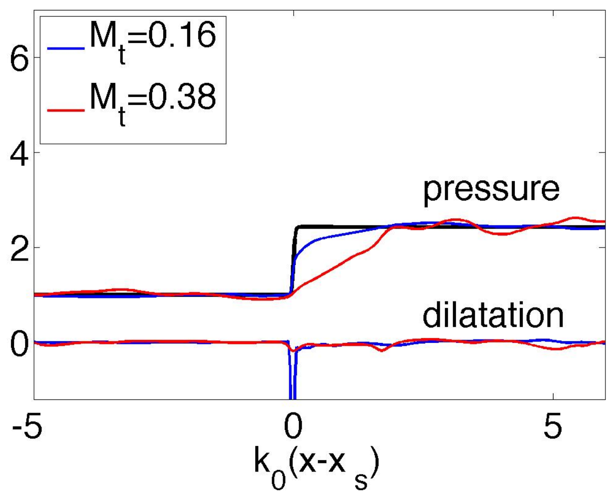


Instantaneous profiles through shock

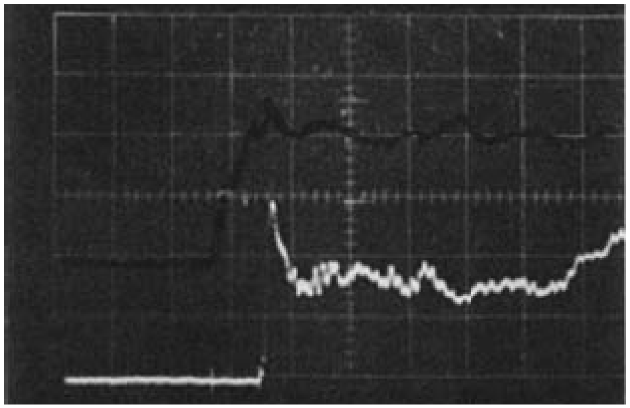
Peaked profiles at M = 1.50

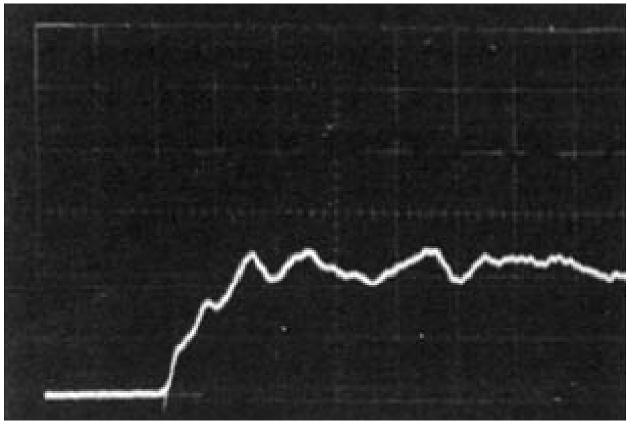


Rounded profiles at M = 1.50



Hesselink & Sturtevant (JFM 1988): "Peaked" and "rounded" pressure profiles for shock propagating through random medium at M <= 1.1





Source: Hesselink & Sturtevant, JFM 1988

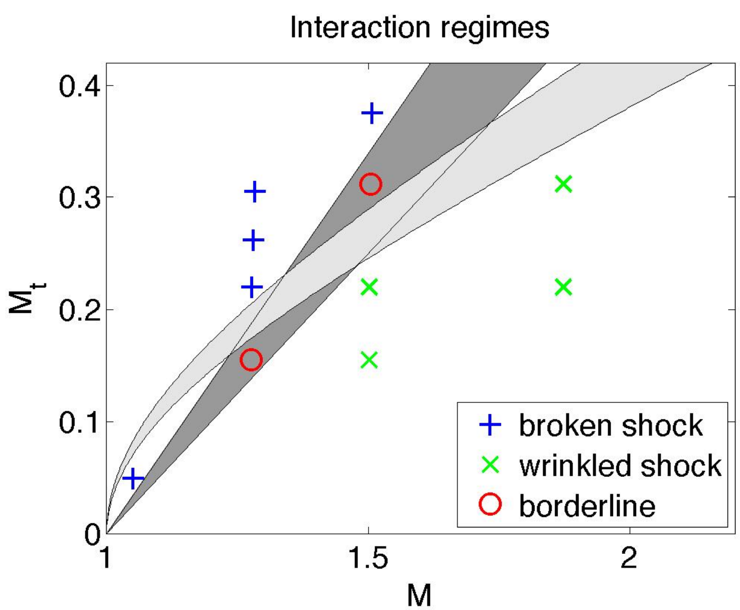
Interaction regimes

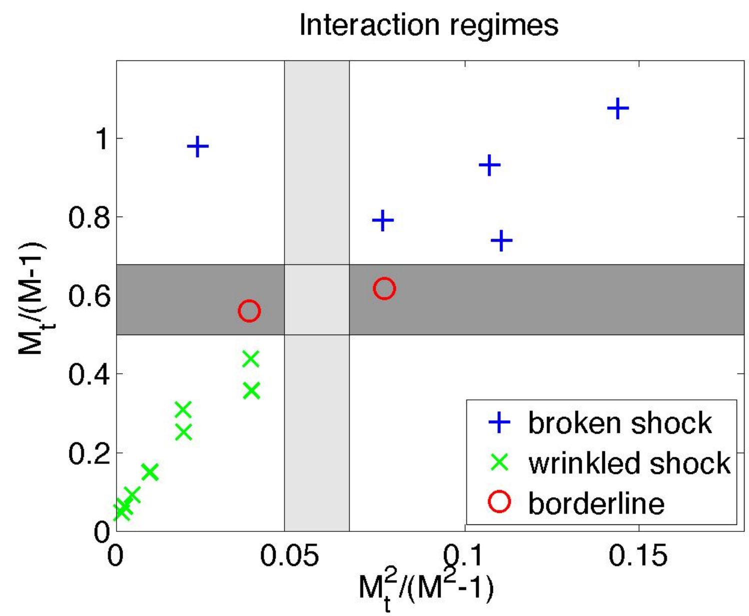
"Broken shock" regime -- existence of smooth (isentropic) profiles through shock

"Wrinkled shock" regime -- every local interaction has a clear shock

Under what conditions can "broken shock" regime be expected?

- Lee et al (1993): $\dfrac{p'_{\mathrm{turb}}}{\Delta p_{\mathrm{shock}}} \sim \dfrac{M_t^2}{M^2-1} \gtrsim \mathrm{const}$
- Present: $\text{finite prob. of } u < c \ \Rightarrow\ \dfrac{M_t}{M-1} \gtrsim \mathrm{const}$ Consistent with Donzis 2013





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Variable Property Effects: density and viscosity change

Semi-local scaling **-- includes scaling of transport eqn** **(recall Laminar BL theory)**

Coleman et al (1995), Patel et al (2016), **Pecnik & Patel JFM (2017)**

$$U^+_{\mathrm{VD}} = \int_0^{u^+} \left(\frac{\bar{\rho}}{\rho_w}\right)^{1/2} du^+, \qquad U^+ = \int_0^{u^+} \left(\frac{\bar{\rho}}{\rho_w}\right)^{1/2} \left[1 + \frac{1}{2}\frac{1}{\bar{\rho}}\frac{d\bar{\rho}}{dy}y - \frac{1}{\bar{\mu}}\frac{d\bar{\mu}}{dy}y\right] du^+,$$

Van Driest Scaling   Trettel & Larsson, PoF 2016

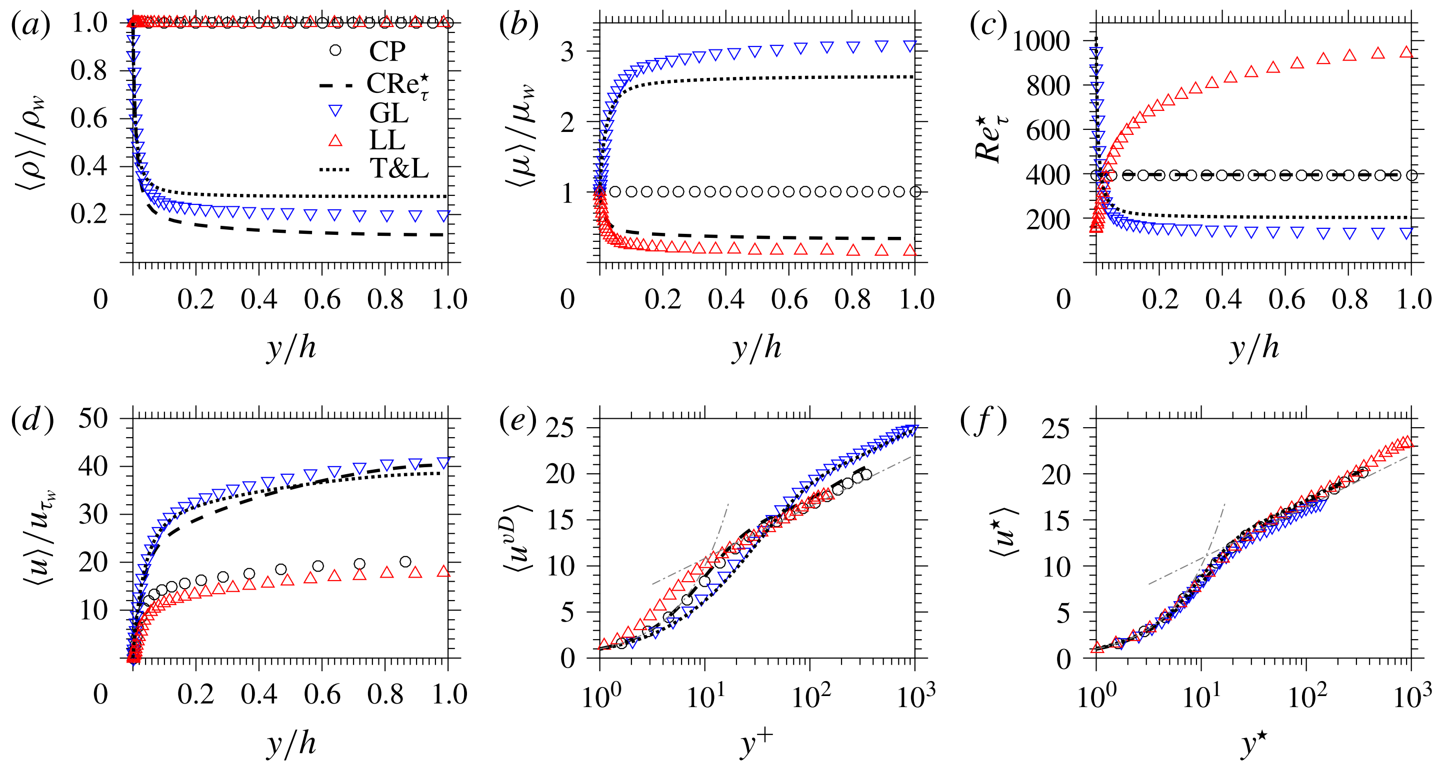

FIGURE 2. Averaged profiles for density (a), viscosity (b), semi-local Reynolds number (c), velocity (d), van Driest transformed velocity (e) and universal velocity scaling (f) for the DNS cases presented in table 1.

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Summary and Open Issues

Physical understanding of compressibility effects has improved

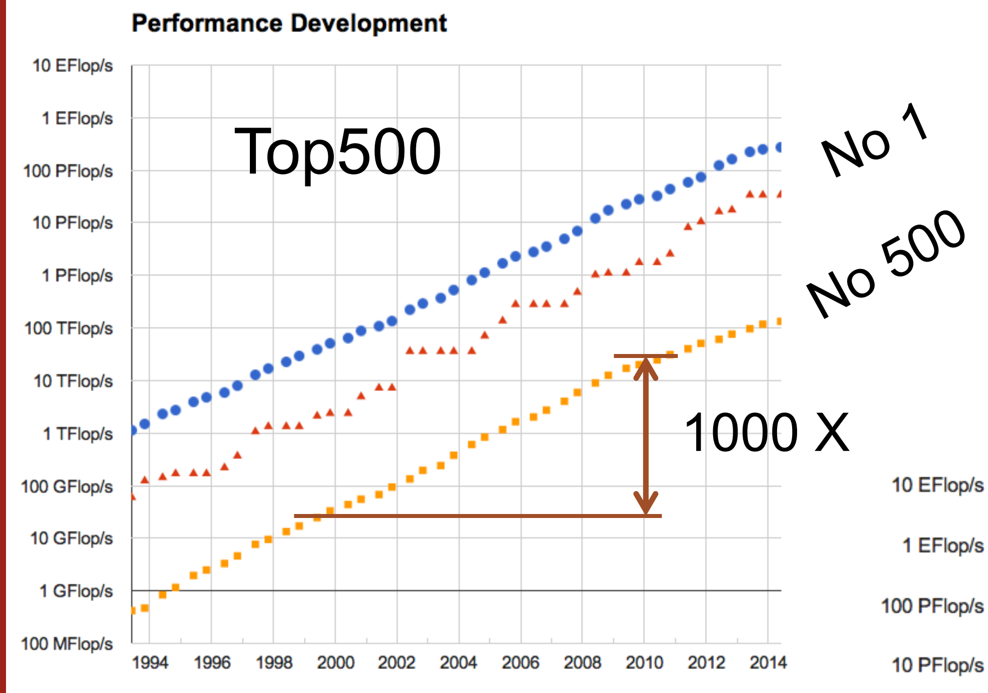
Significant progress in some areas with DNS, LES
(limitations in Re, Many non-dimensional parameters)

Theoretical framework still insufficient
How does acoustic communication impact vortex dynamics?
Engineering models incorporating physics of variable-density and compressibility

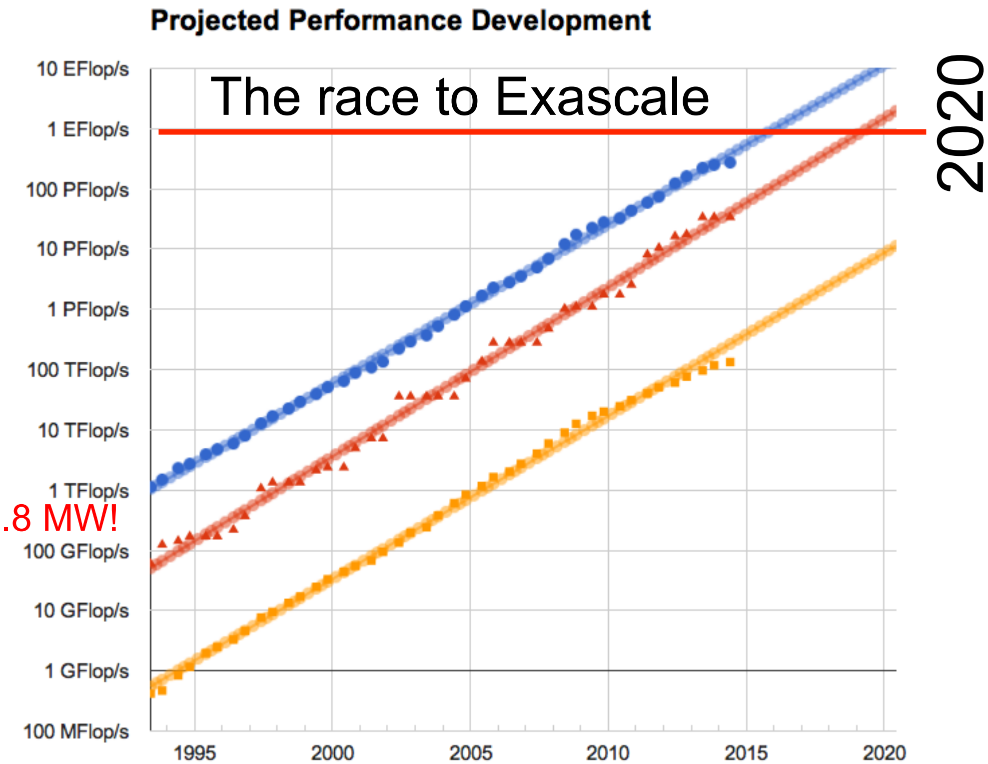
Limited experiments with detailed turbulence measurements

Inflow conditions, boundary conditions (confinement …)
Confirmation of phenomena and scaling laws
observed in idealized simulations

Open Issues: Shape of things to come … ?



HPC Hardware and Software



But this is not Moore's law at IC level
Multicore chips, million cpu's,
hyperthreading, memory hierarchies,…

No 1 system in 2014 with 33.8 petaflops with 17.8 MW!
Need high Flops/watt

Will today's petascale code (MPI+OpenMP) run on exascale system …. probably not!

Need to develop exascale ready computational frameworks

Thank you!

Any questions ?

The Challenge of High Reynolds Numbers

Spatial and temporal bandwidth increases with Re

η/L scales as $Re^{-3/4}$

Computational cost (DNS) scales as $Re^{9/4}$ times $Re^{3/4}$ or Re^{3}

Computational cost Wall resolved LES scales as $Re^{13/7}$

Wall modeled LES reduces the cost to $O(Re)$

Practically the computational cost restricts the resolution which can be afforded and thus the scale bandwidth.

Need for modeling in turbulence simulations relevant to high Re continues

Compressibility Effects on Turbulence - Fundamentals

How to characterize ?

- ❖ Effects on turbulence generation - flow instability and turbulence energetics
- ❖ Effects on turbulence cascade
- ❖ Effects on turbulence dissipation

- ❖ System scale effects (multiple-scale interactions)
  - Radiative damping
  - Flow-acoustic resonance

Choice of variables ?

Thermodynamic **ρ;** log**(ρ); v=1/ρ; p;** log**(p); s** (Entropy)**; B** (Bernoulli enthalpy)

Kinematic U_i; ρU_i; $\sqrt{\rho}\, u_i$; ρ^(1/3) u_i (for spatial scale decomposition)

Compressibility Effects on Turbulence - Fundamentals

Scaling of spectra/structure functions ?

Vortical turbulence -- Kolmogorov scaling

Entropy fluctuations stirred by turbulence

Random nonlinear acoustic field

Random field of shocks

Pressure spectra -- hydrodynamic, pseudo-sound, sound

Density spectra – entropic, acoustic, pseudo-sound

Aeroacoustics

Computational methods for predicting aerodynamic noise

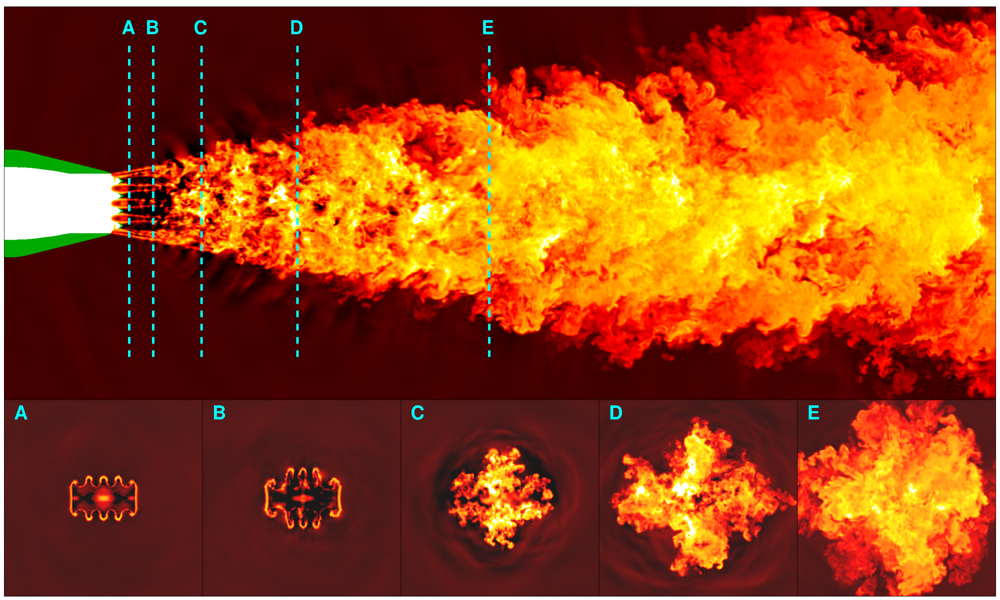
Physics of aerodynamic noise generation

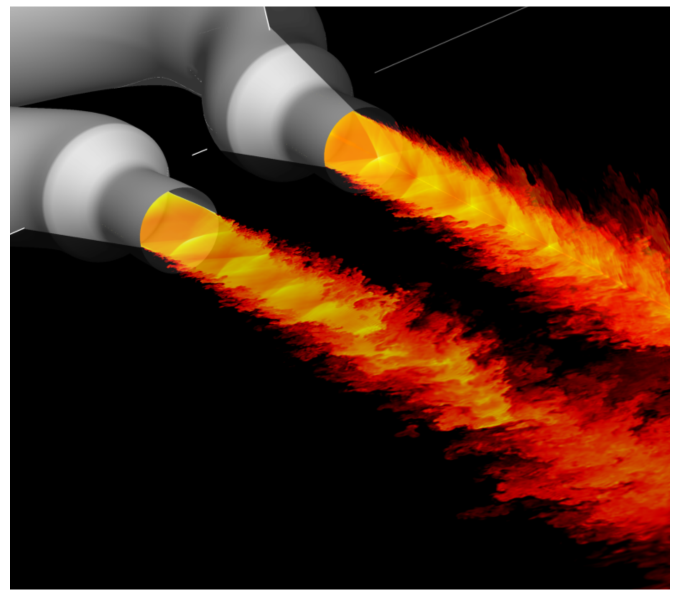
Modeling noise sources and the far-field radiated noise

Supersonic Jet Noise

Noise predictions using accurate LES of noise producing flow

Approximate methods using source models



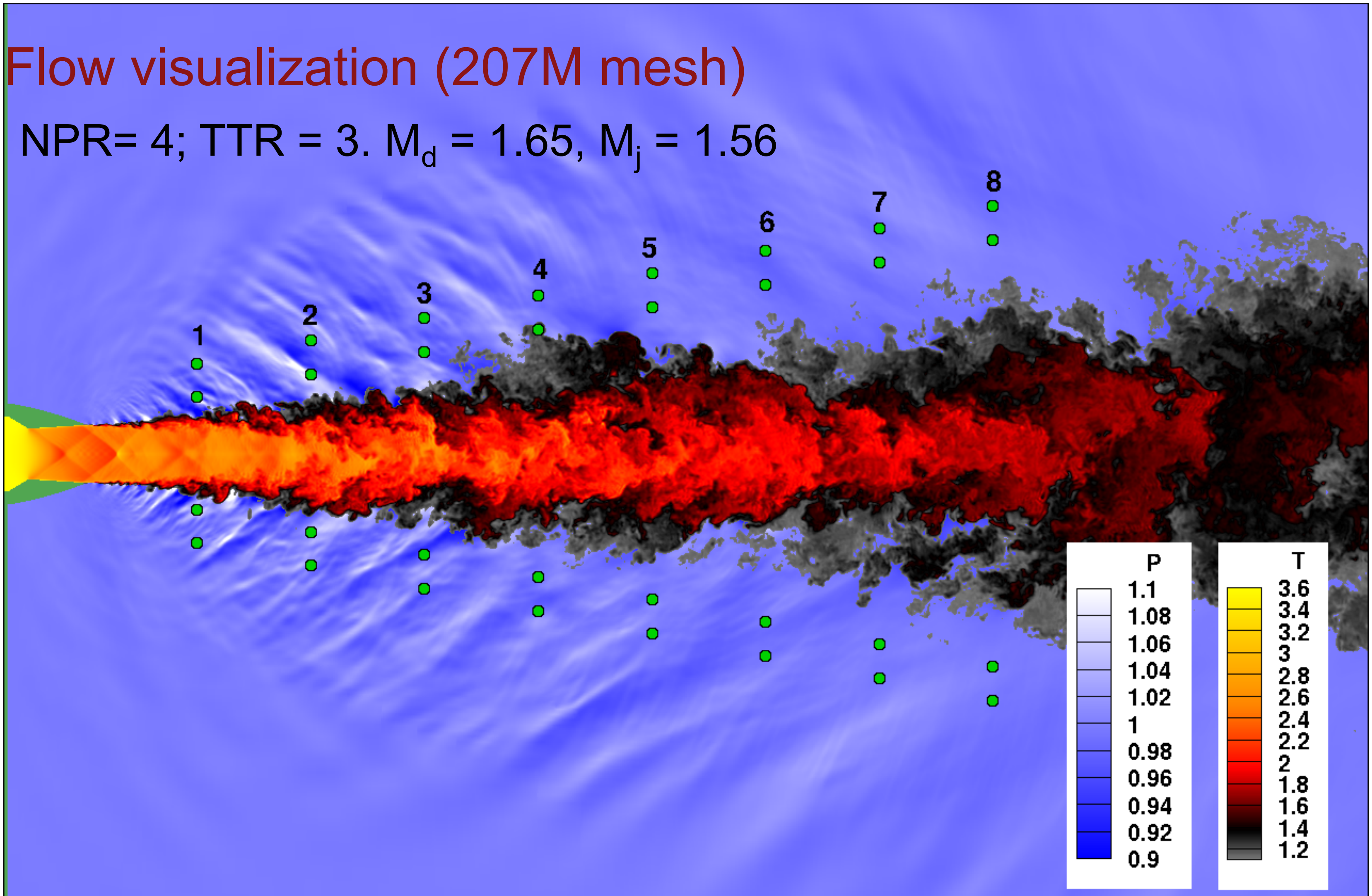


- NASA Nozzle -- NA2C3 geometry (2:1 aspect ratio)
- CharLES solver
- Up to 500M isotropic adaptively refined mesh
- BlueGene/P with up to 160K cores (ALCC program, ANL)

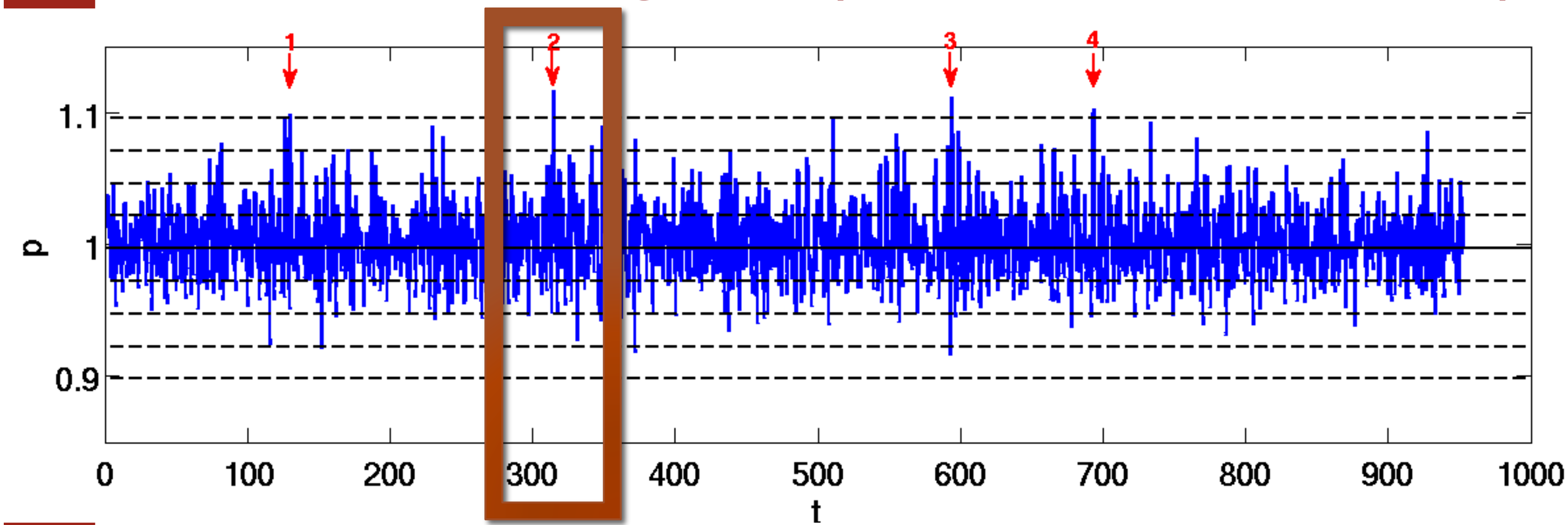
Crackle : Annoying Component of Supersonic Jet Noise (Ffowcs Williams, 1975)
Intermittent, Steep N-wave signature, Skewness

What causes crackle ? Mechanism unknown –source nonlinearity vs non-lin. Propgn.

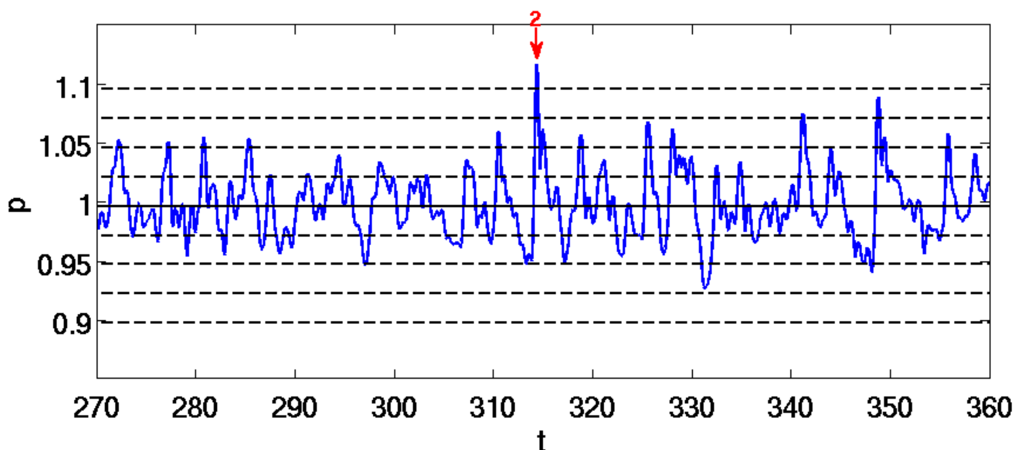
Nichols et. al. 2013, ASME J. Eng. Gas Turbines and Power 213, Vol. 135.

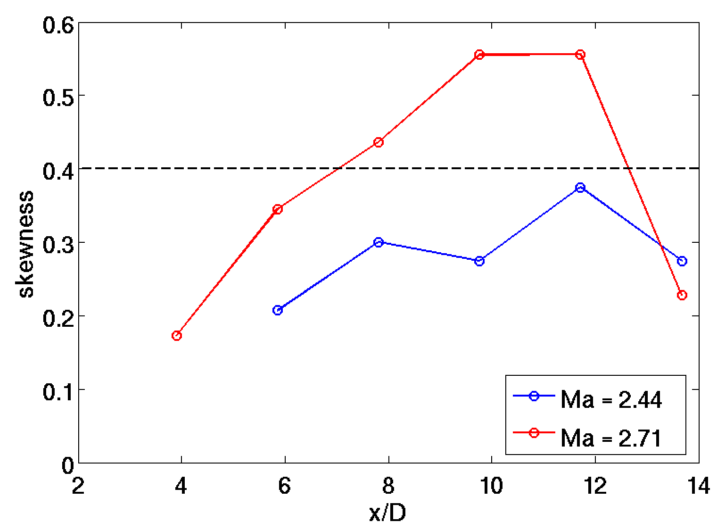


Pressure signal (skewness 0.425)

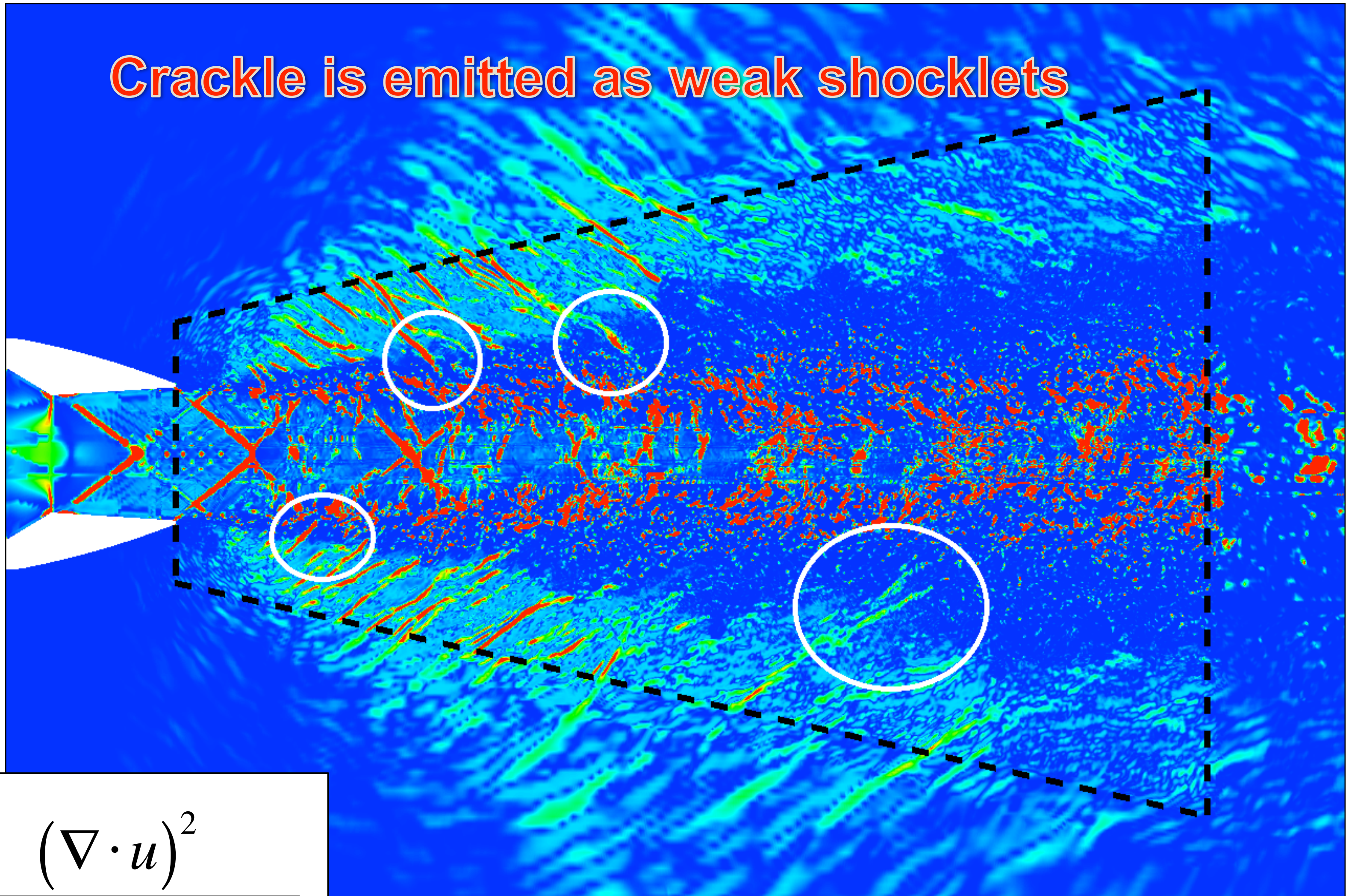


(Zoom)





Shock sensor (207M)



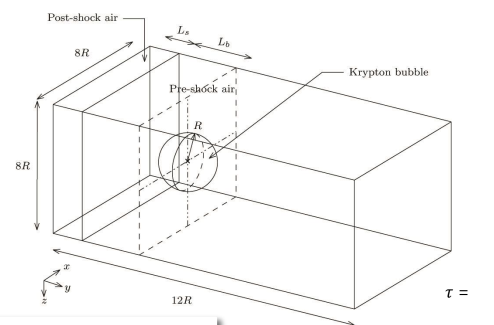
$$\frac{(\nabla \cdot u)^2}{(\nabla \cdot u)^2 + \Omega^2 + \varepsilon}$$

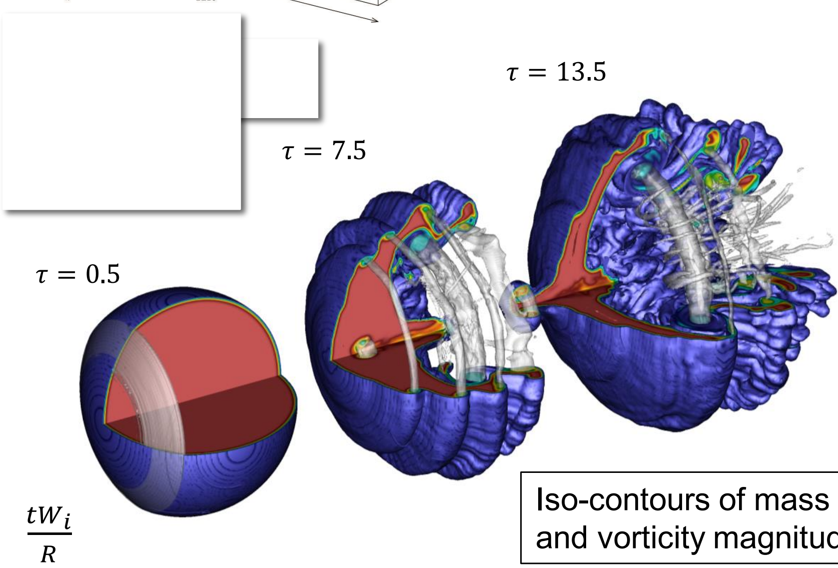
(Ducros et al., 1999; Bhagatwala & Lele, 2009)

Main Research Areas: Fluid Dynamics - Turbulence

› Shock-induced instability and multi-material mixing

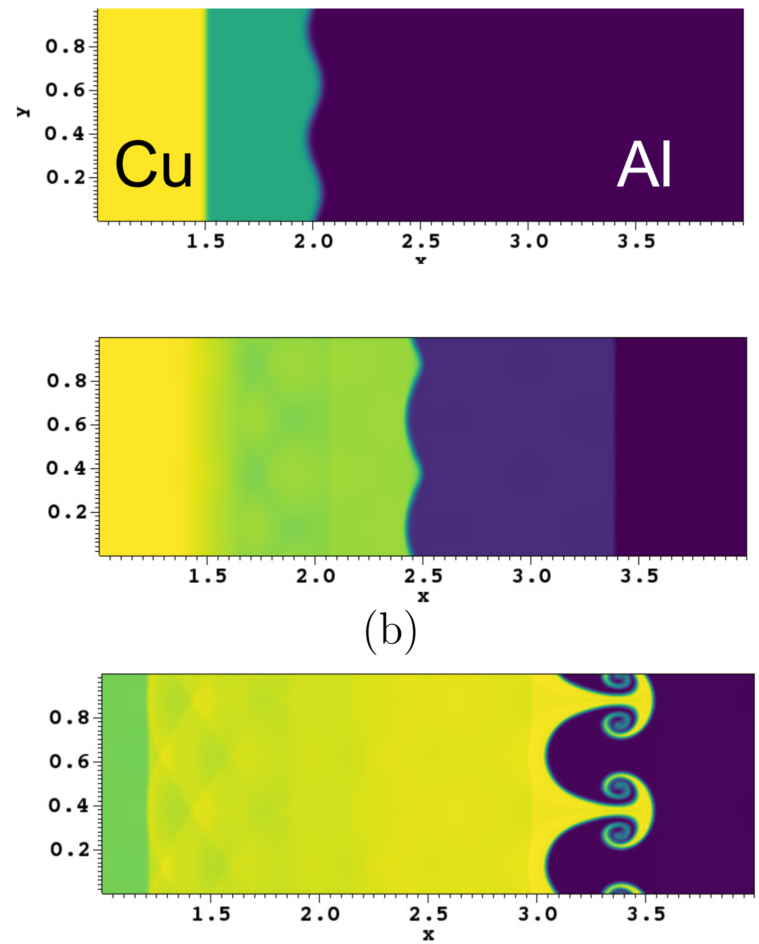
Numerical methods for shocks/interfaces
Non-linear elastic/plastic deformations





Iso-contours of mass fraction and vorticity magnitude

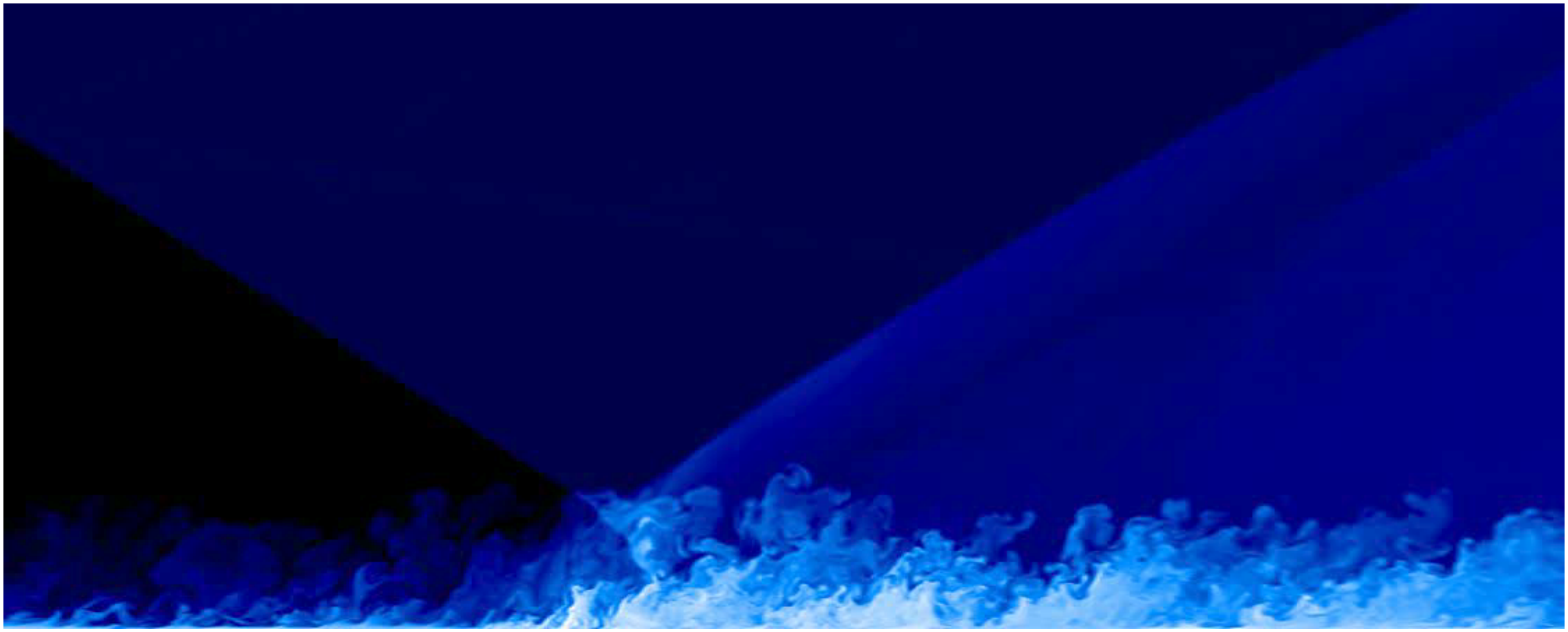
Shock driven instability at solid-solid interface



Compressible turbulence, Shock-Boundary layer Interactions

Capturing shock waves and turbulence

LES results Morgan, Kawai & Lele AIAA 2011-3431, *J. Fluid Mech.* 2013, Vol 729



M = 2.28; Re_θ = 2300; wedge angle = 8 deg Expt: IUSTI, Marseille

Temperature contours