Study of unsteady shock motion in shock/turbulence interaction

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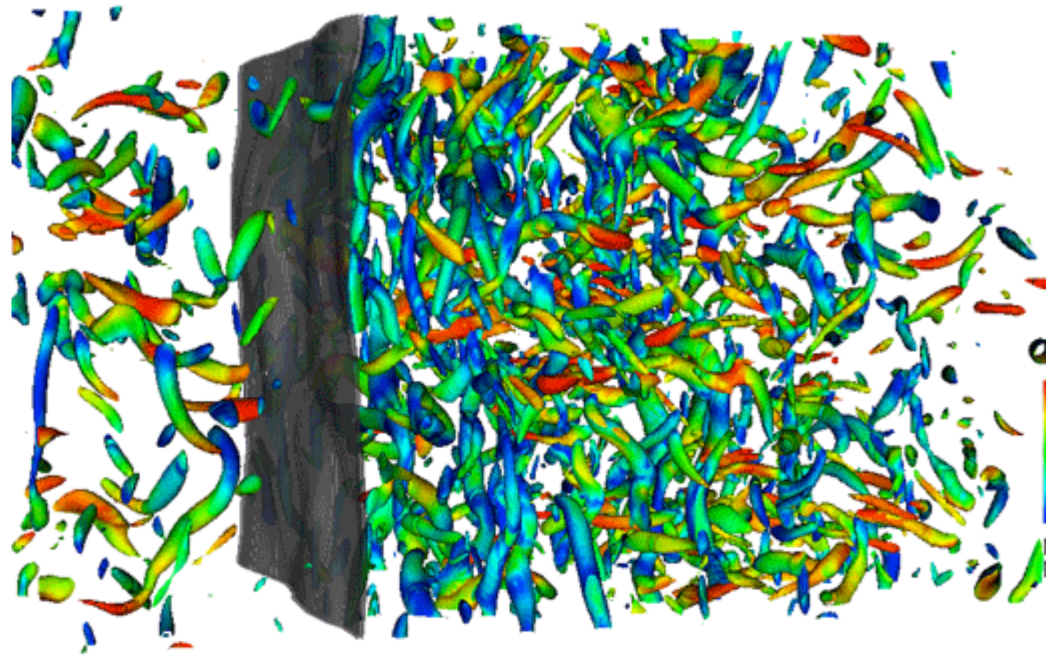
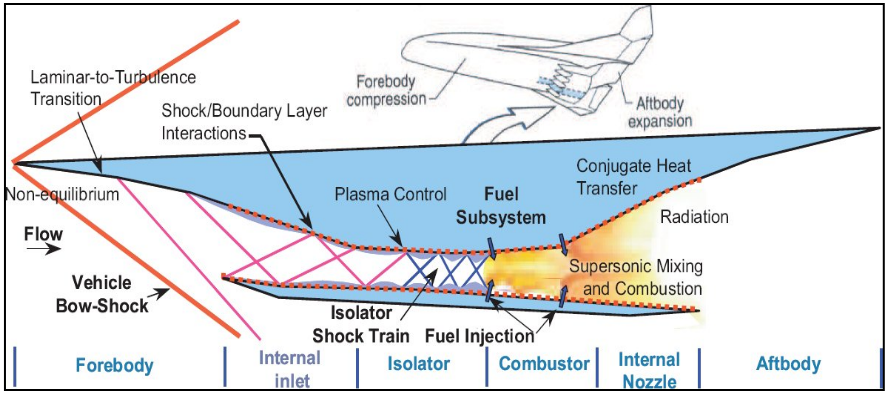


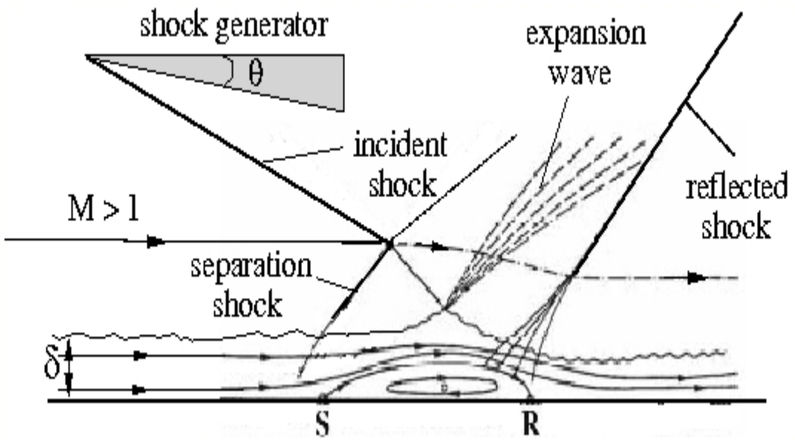
Larsson *et al*. JFM 2013

Motivation

- Shock wave boundary layer interaction (SBLI)
- High speed flow applications
- Increased heating and pressure loads
- Better flow control methodologies and novel aerospace vehicle designs

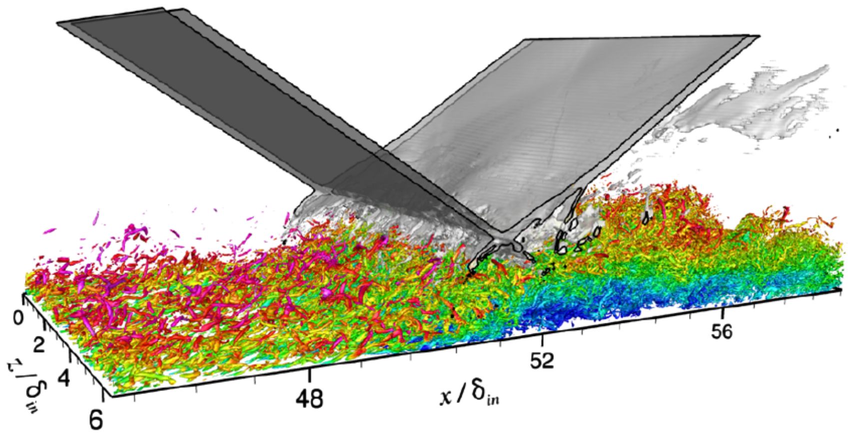


Stanford FPCE Group



SBLI – Physics

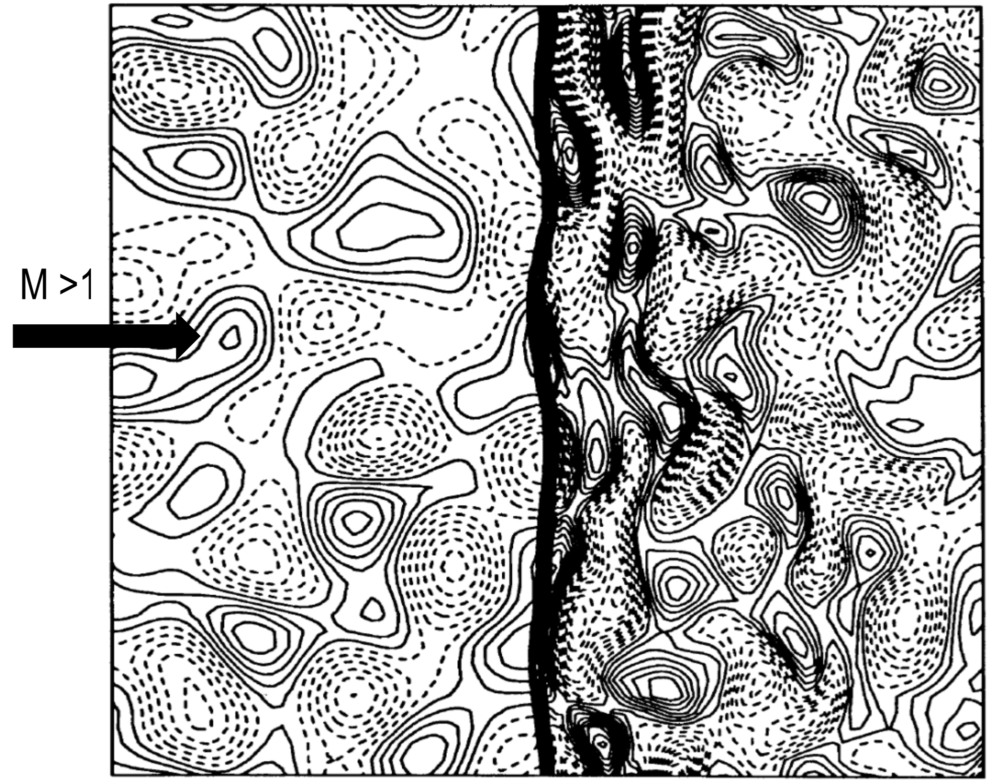
- Shock unsteadiness – important physics
- Fluctuating heat and pressure loads
- Mechanisms of shock unsteadiness
  - incoming turbulent boundary layer (Ganapathisubramani *et al.*, 2007)
  - ‘breathing ‘ of separation bubble (Wu and Martin, 2008 and Priebe and Martin, 2012)



Pirozzoli and Bernardini, AIAA 2011

Model problem

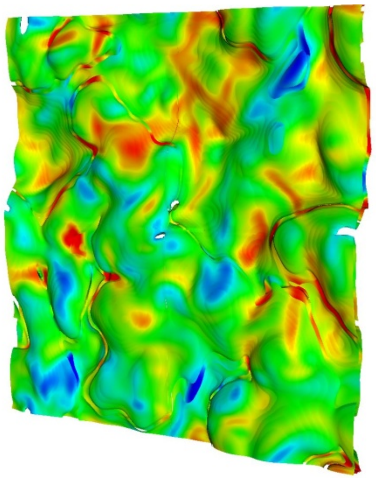
- Isotropic turbulence interacting with shock
  - DNS:
    Lee *et al.* 1993, 1997
    Jamme *et al.* 2002
    Larsson *et al.* 2009, 2013
  - Theoretical:
    Ribner 1953, 1954
    Cambon *et al.* 1993
    Mahesh *et al.* 1996
    Donzis 2012
  - Experimental:
    Hesselink &Sturtevant 1988
    Barre et al. 1996
    Andreopoulos et al. 2000

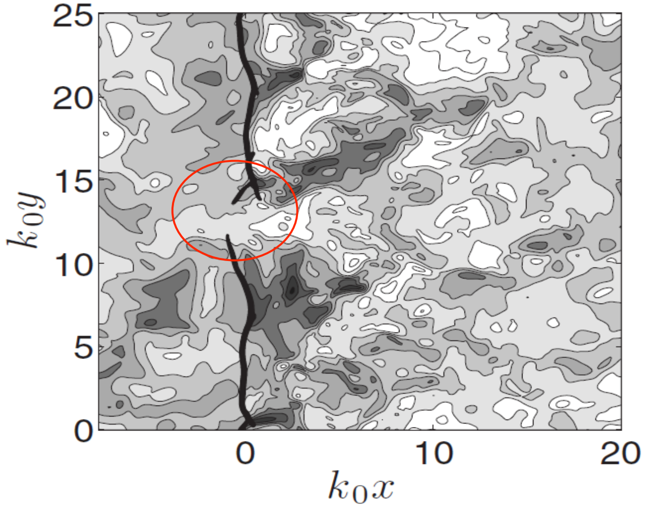


Lee *et al*. JFM 1993

Shock holes

- Region of smooth compression
- Criteria for shock holes in 3D (Donzis 2012, Larsson et al 2013)
  - $M_t \geq 0.6$ (M-1)
- Equivalent criteria in 1D
  - $u' / a \geq 0.35$ (M-1)
- Zank *et al*., 2002 – Destabilization of 1D Burgers' shock (> 5% turbulence)



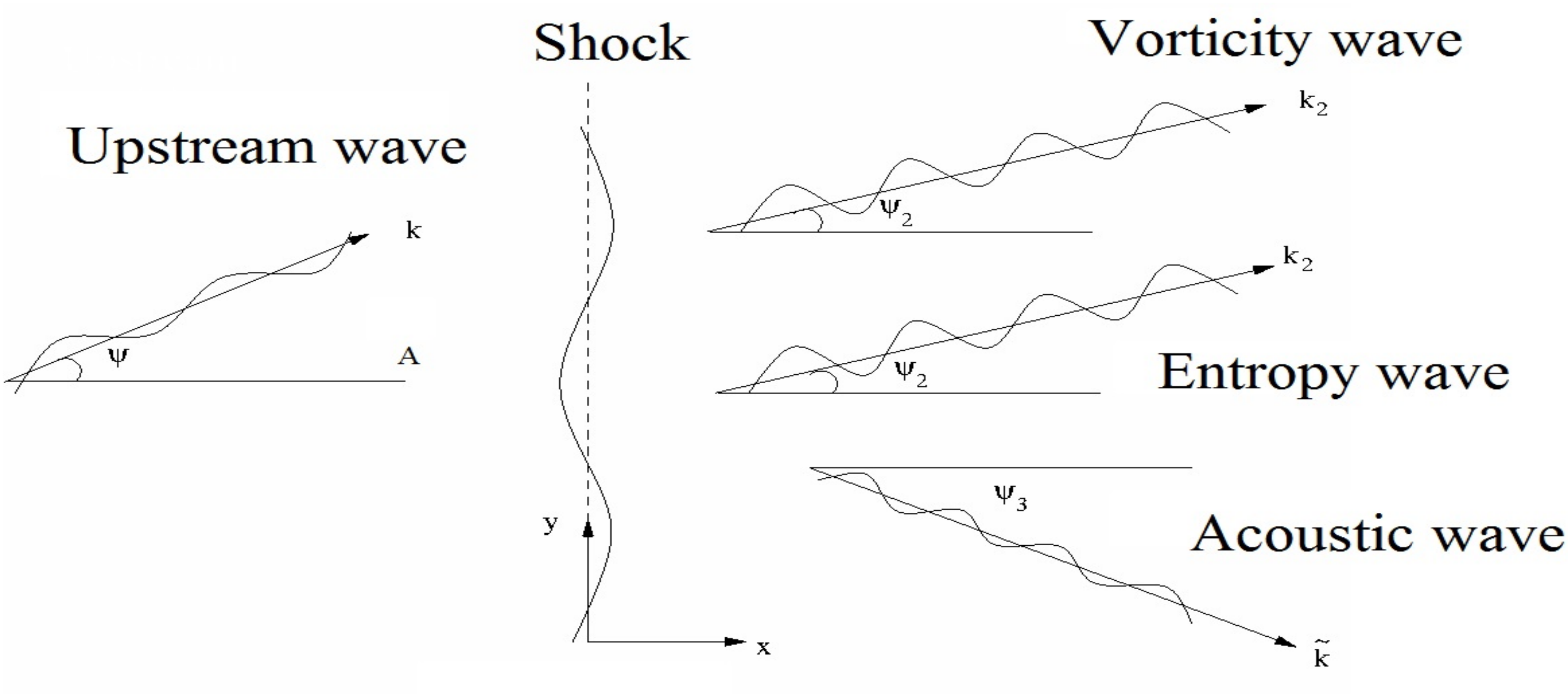


Larsson *et al*. PoF 2009

Objectives of current work

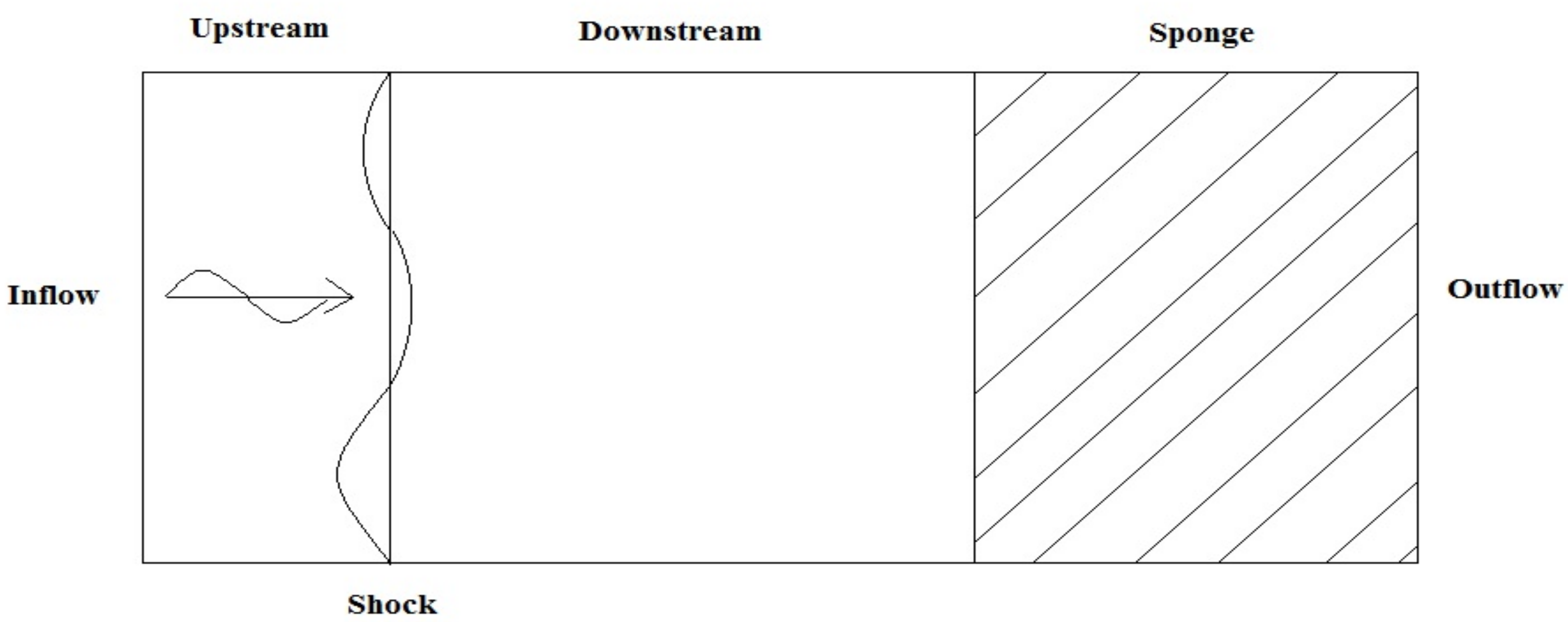
- Can one-dimensional (1D) Euler shock be broken using either single mode or broadband perturbations?
  - Effects of turbulence on shock
- Can 3D shock turbulence interaction be replicated in 1D environment?
  - Comparison of shock statistics – correlations
  - Qualitative understanding – multi–dimensional phenomena?

Linear Interaction Analysis (Ribner 53, 54)



- Turbulence decomposed into three modes (Kovasznay, 1953)
- Linear superposition of modes (in the linear limit) as solution

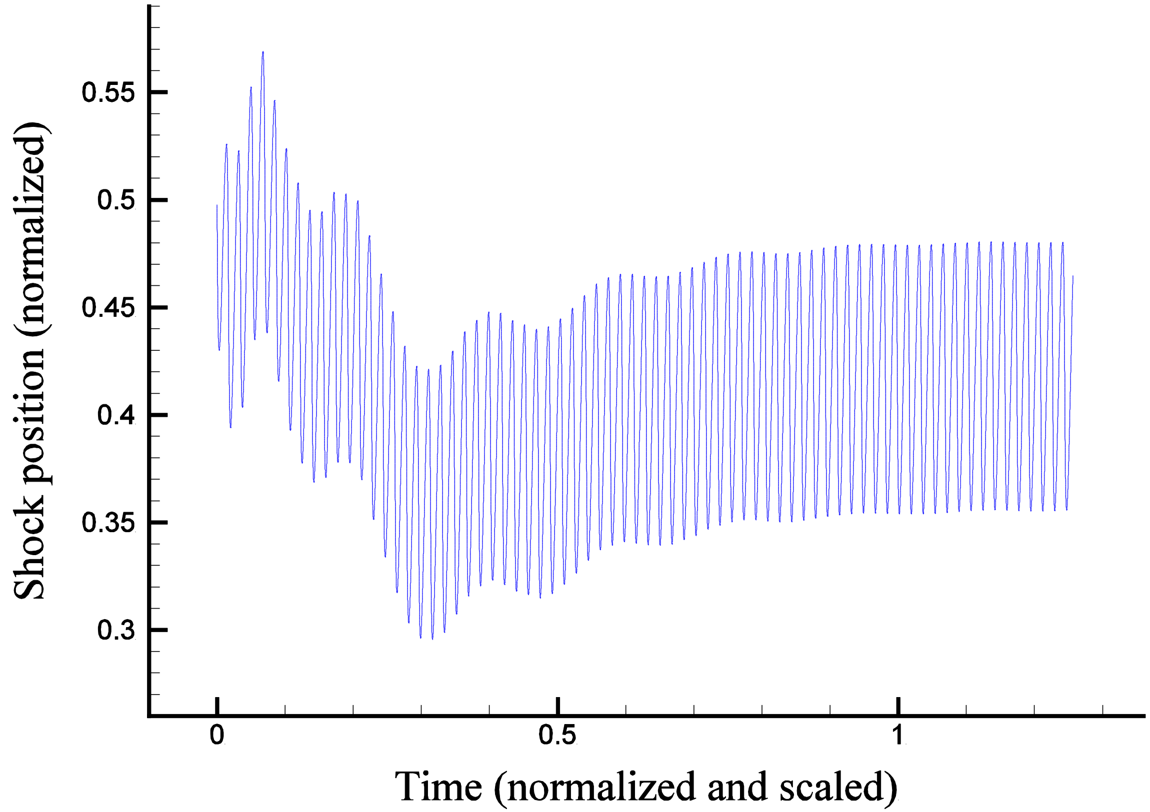
Numerical method



- Euler equations of mass, momentum and energy (1D only)
- Sinusoidal fluctuations superposed at inflow

Outflow conditions: minimize shock drift and spurious noise

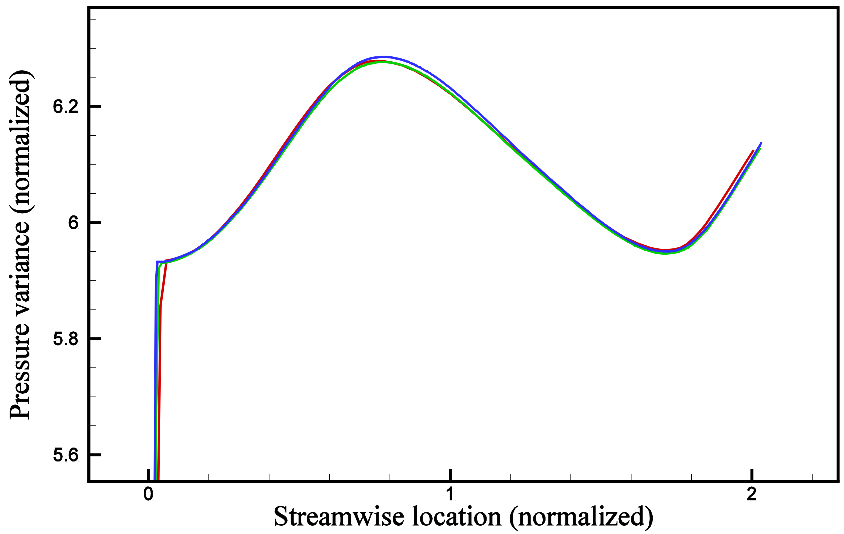
- Sponge region – minimize spurious reflections
- Shock drift velocity < 1% upstream mean velocity



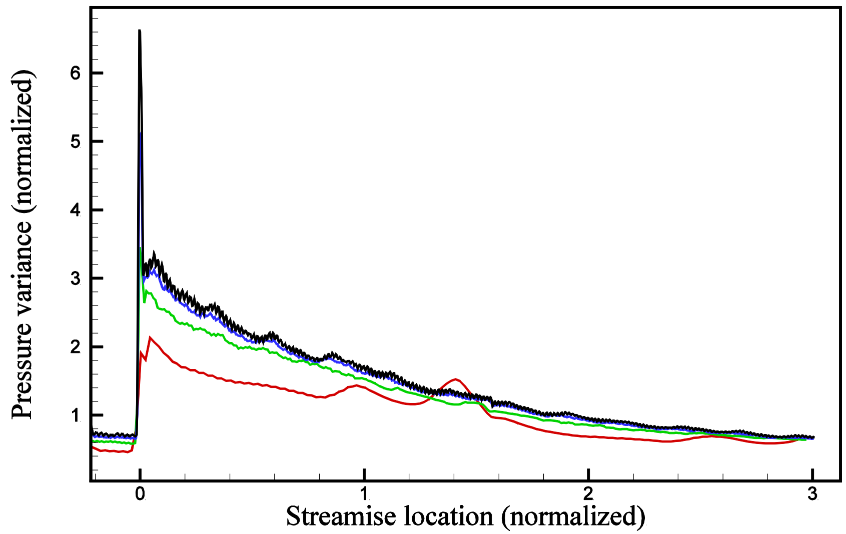
Variation of shock position for a high amplitude single mode entropy wave interacting with a shock wave

Error analysis – Grid convergence

Combination of acoustic/vorticity/entropy



Broadband of acoustic waves



Color	Red	Green	Blue	Black
Grid size	π/50	π/100	π/200	π/400

Error analysis – Sponge convergence

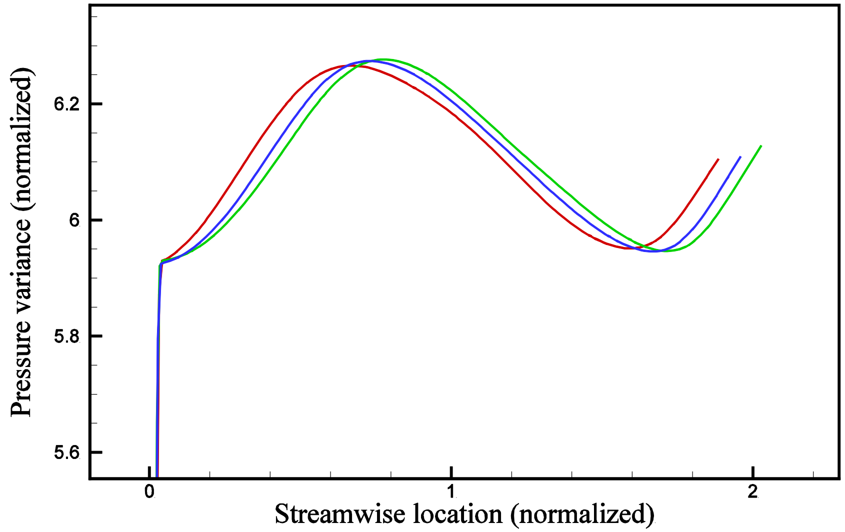
- Sponge region – prevent reflections from outflow

$$-\sigma_{sp}\left(\frac{x-x_{sp}}{L_{sp}}\right)^2 (q - q_{\text{target}})$$

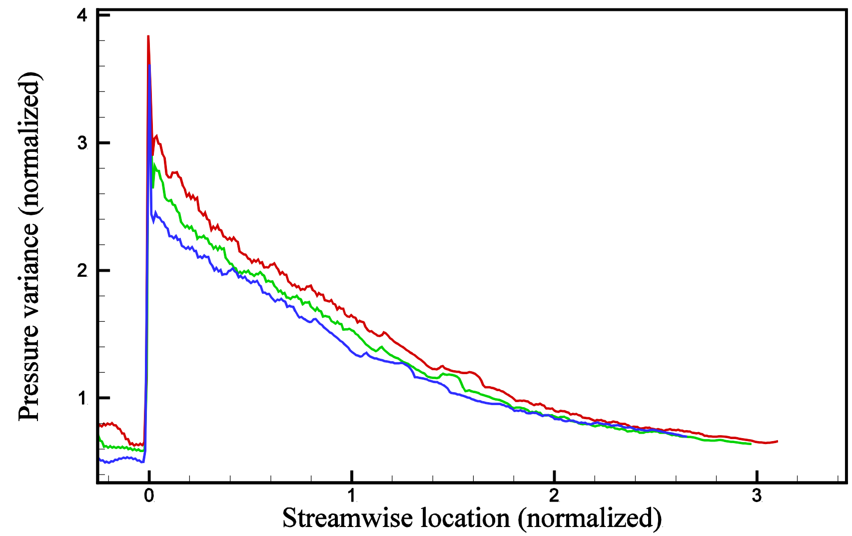
- Reflection coefficient from end of the sponge
  - $\alpha_d \sim \sigma_{sp} L_{sp}$
- Reflection coefficient from inside the sponge
  - $\alpha_r \sim 1 / \sigma_{sp}$
- Coefficients are independent but not the parameters

Error analysis – Sponge convergence

Combination of acoustic/vorticity/entropy



Broadband of acoustic waves



Color	Length	Strength	Normalized α_r	Normalized α_d
Red	1 π	2.0	1	1
Green	4 π	1.0	2	2
Blue	16 π	0.5	4	4

Results

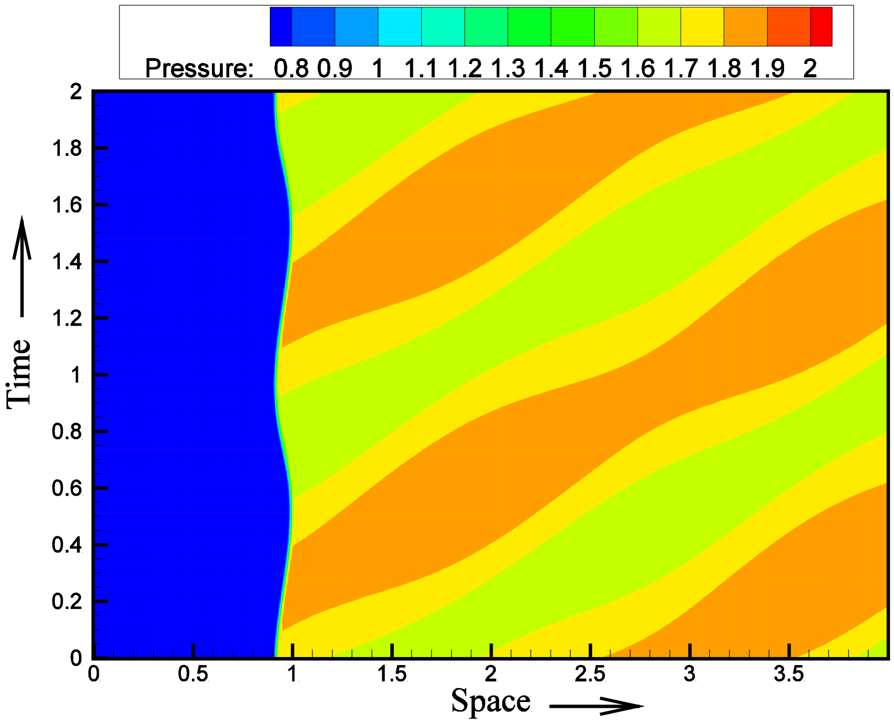
Breaking the shock

Wave mode	**Fluctuation amplitude**	u_{rms} / a
Entropy single mode	10% 30% 50% 80%	
Right moving acoustic single mode	10% 30% 50% 80%	0.071 0.214 0.357 0.571
Right moving acoustic broadband		0.15 0.225 0.3
Left moving acoustic broadband		0.15 0.225 0.3

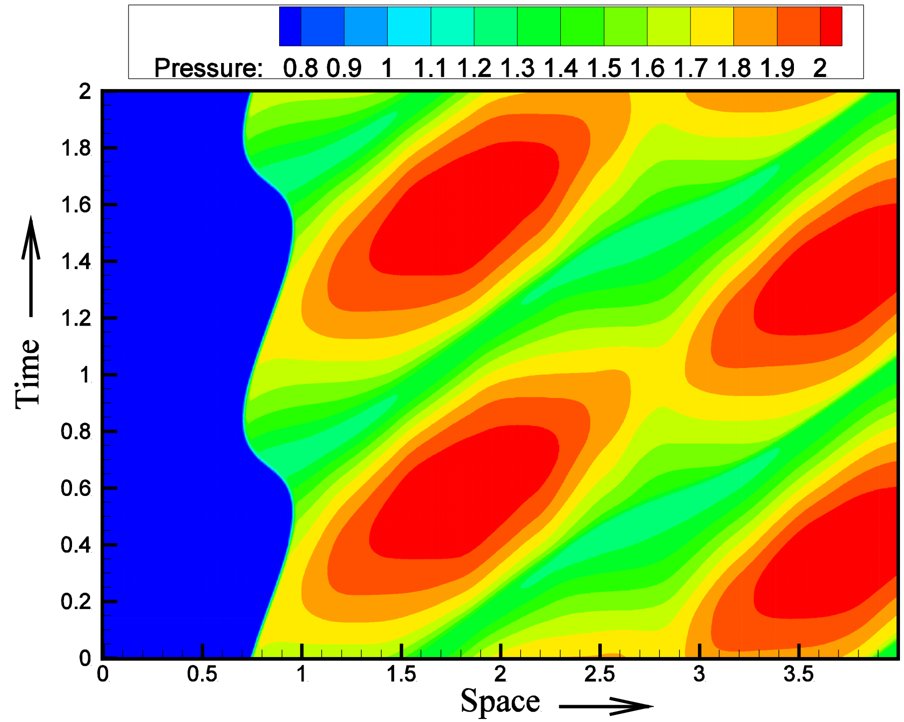
Shock breaking criteria $u_{rms}/a \sim 0.175$ for M 1.5 normal shock [Donzis (2012) Larsson et al. (2013)] is exceeded in the cases

Can a single mode entropy wave break the shock?

30% fluctuations



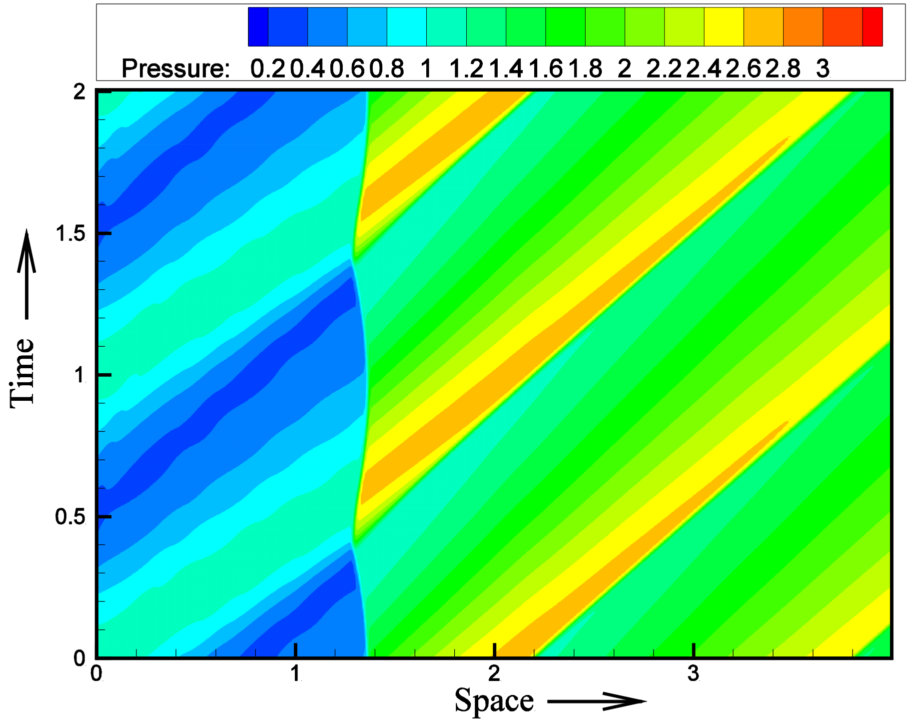
80% fluctuations



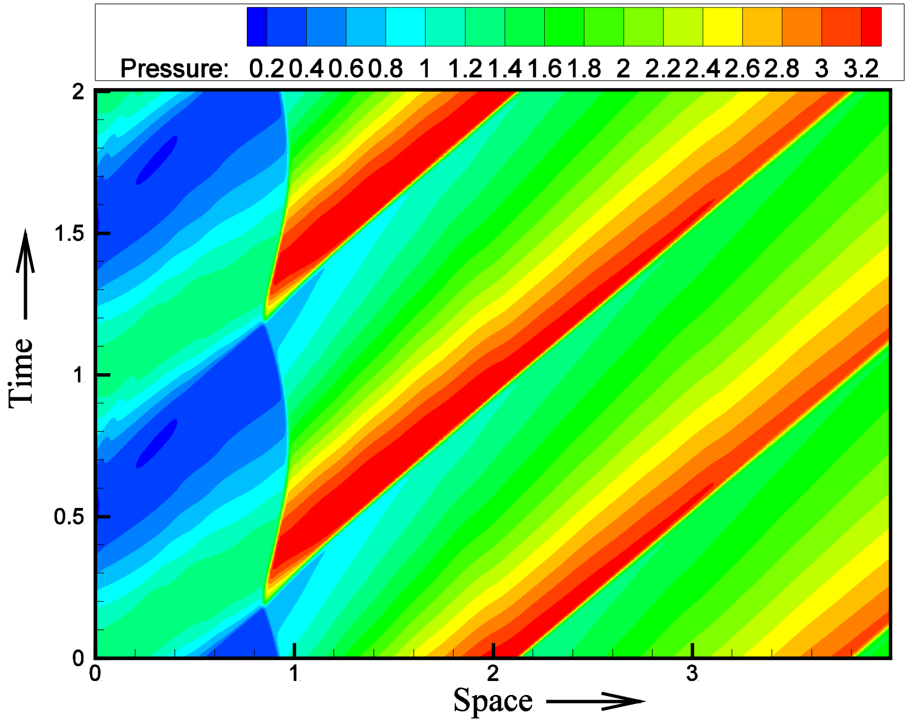
Clear distinct wavy line – jumps are identifiable

Can a single mode acoustic wave break the shock?

50% fluctuations



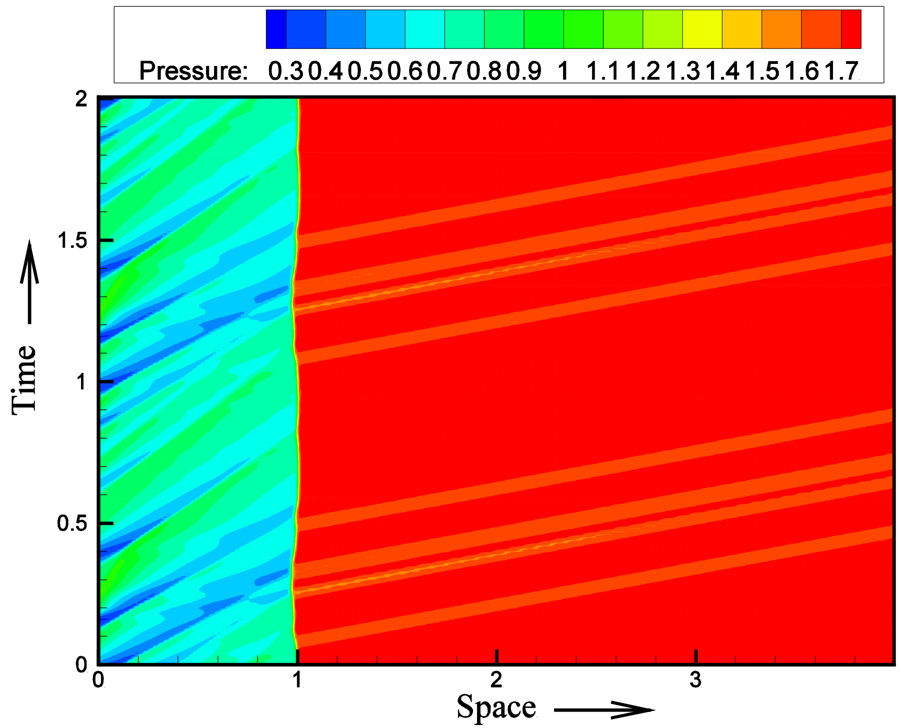
80% fluctuations



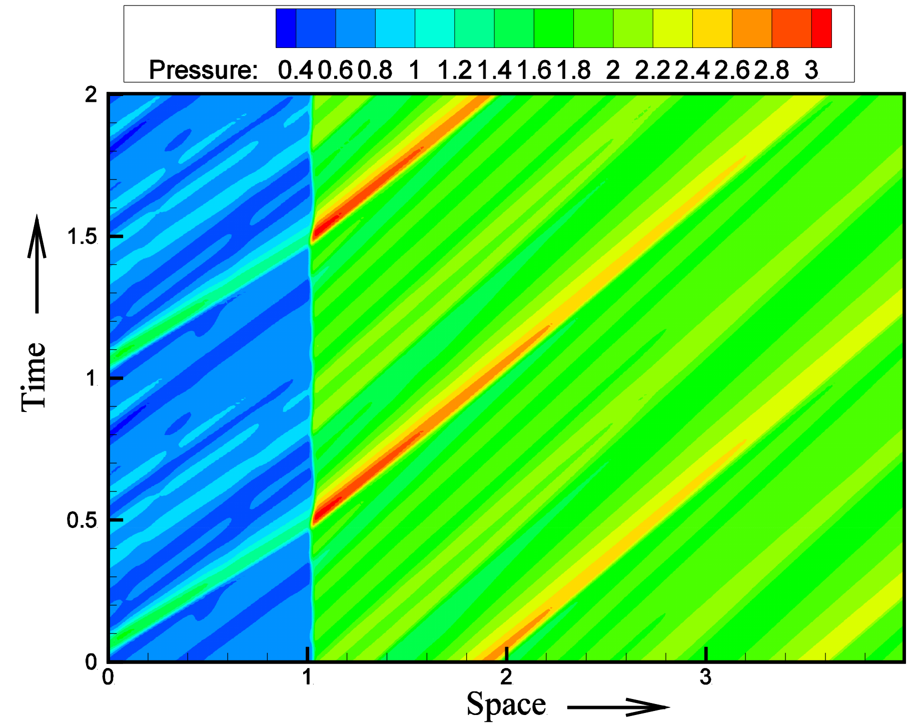
Sharp jump in pressure is identifiable

Can acoustic broadband waves break the shock?

Left moving – 20%



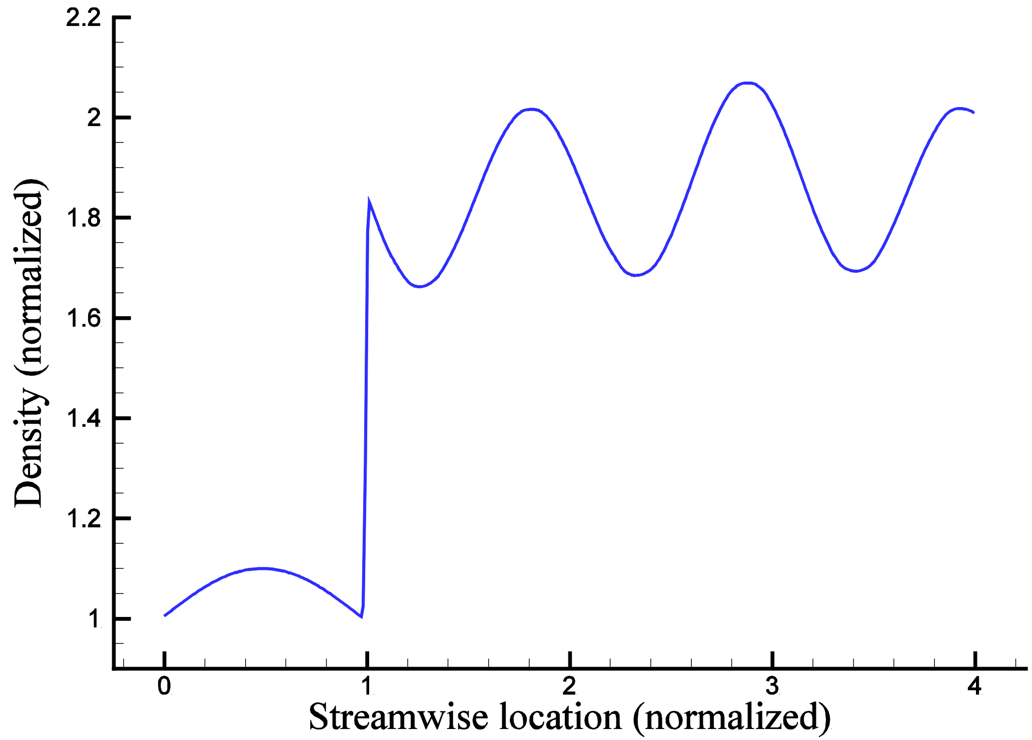
Right moving – 20%



Intact shock for higher intensities in velocity field

Replicate 3D features in 1D interactions

- DNS database of 3D shock turbulence interaction
  - Re_λ 40, M 1.5 and M_t 0.16
- Corresponds to 10% fluctuation levels for planar waves



Sinusoidal single mode entropy wave interacting with a shock giving rise to sinusoidal fluctuations downstream

Cases and terminologies

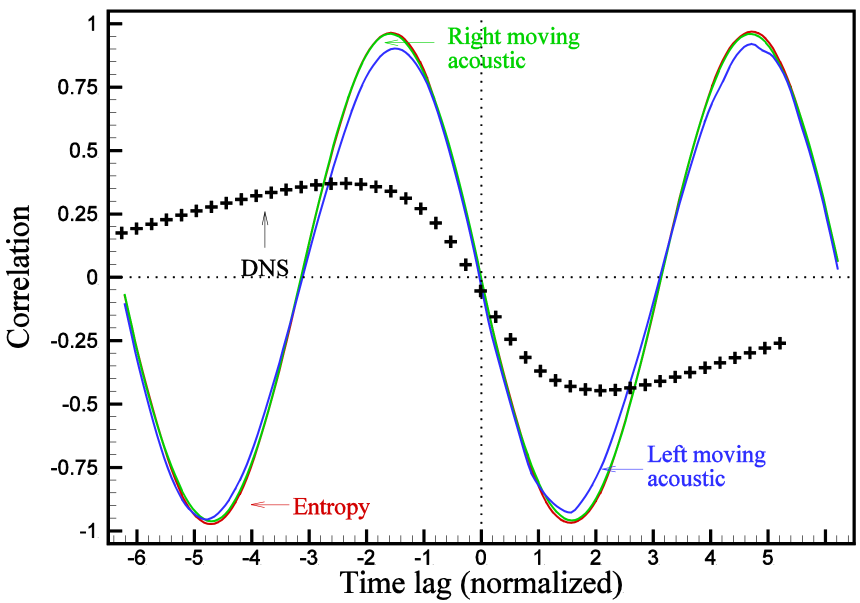
- Shock position – using half pressure rise and linear interpolation
- Shock strength (θ) – using jump in density values from just upstream and downstream of shock

Wave mode	Fluctuation amplitude	u_{rms} / a
Entropy single mode	10%	
Right moving acoustic single mode	10%	0.071
Left moving acoustic single mode	10%	0.071
Right moving acoustic broadband		0.15
Left moving acoustic broadband		0.15

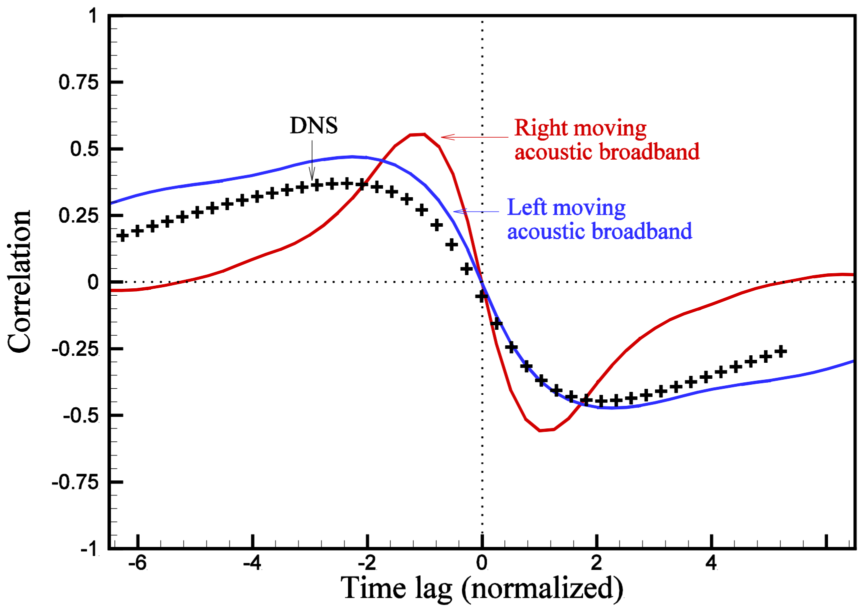
Correlations of shock speed (u'_s) with shock position (x'_s)

- Zero correlation at zero time lag is observed in all cases – shock position is integral of shock speed
- Positive shock speed – pushed back shock

Single mode waves



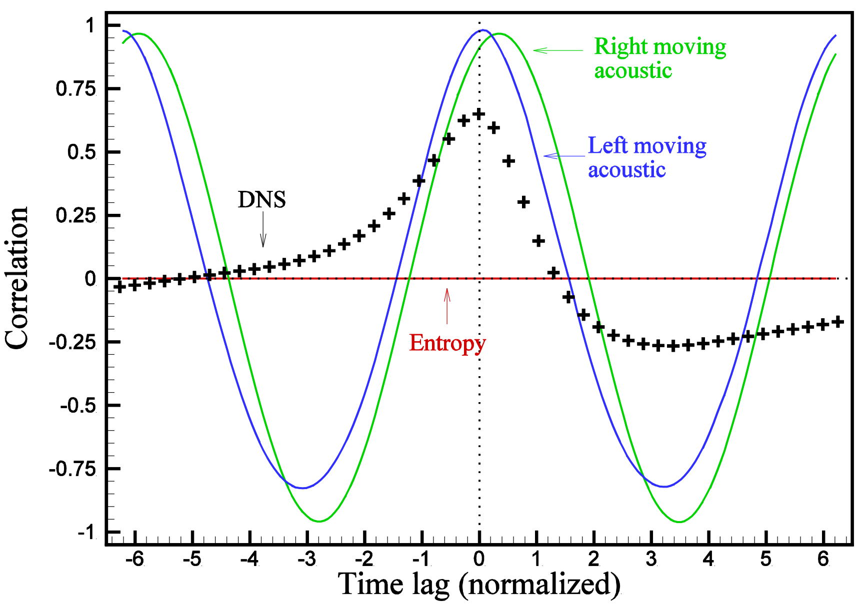
Broadband of waves



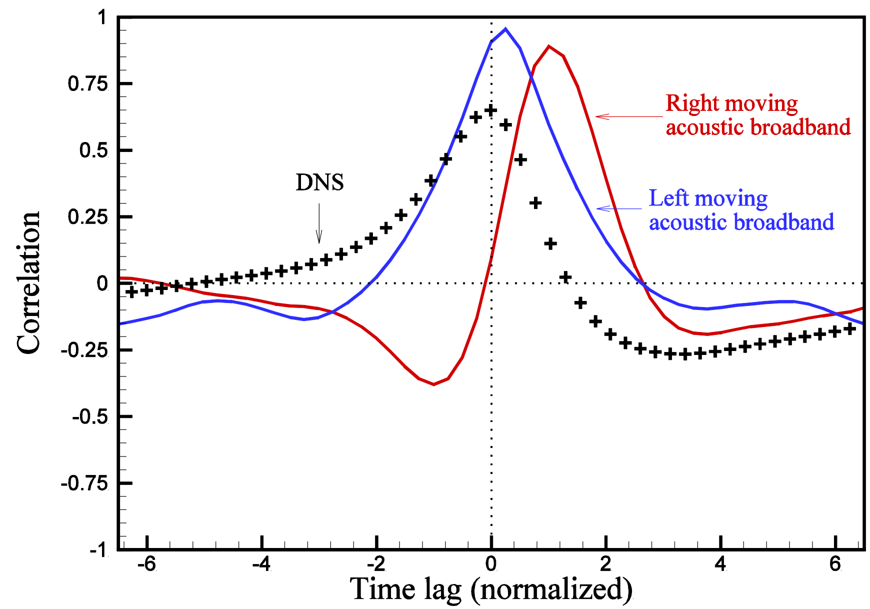
Correlations of shock speed (u'_s) with upstream velocity fluctuations (u'_u)

- Periodic variations with changes in time lag – single mode
- High intensity velocity fluctuations – positive shock speed

Single mode waves



Broadband of waves

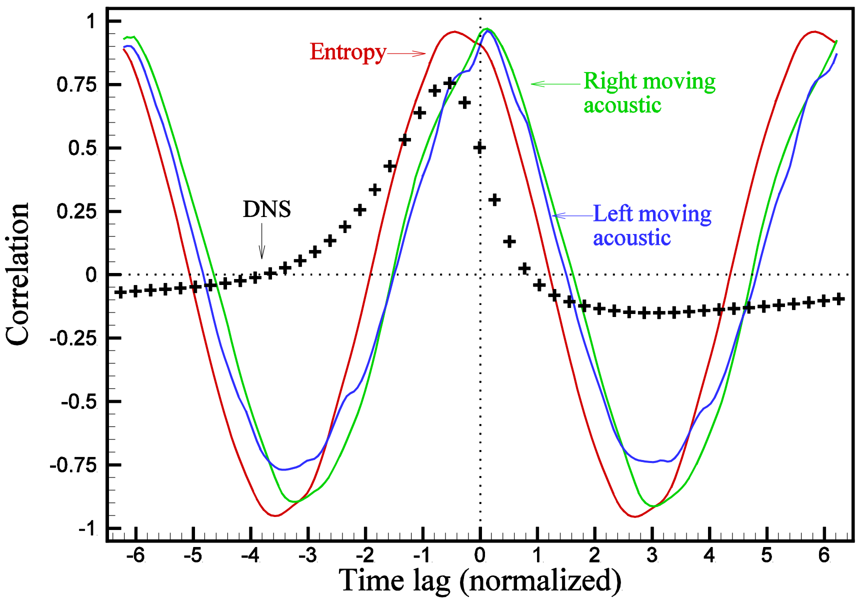


Correlations of shock speed (u'_s) with shock strength (θ')

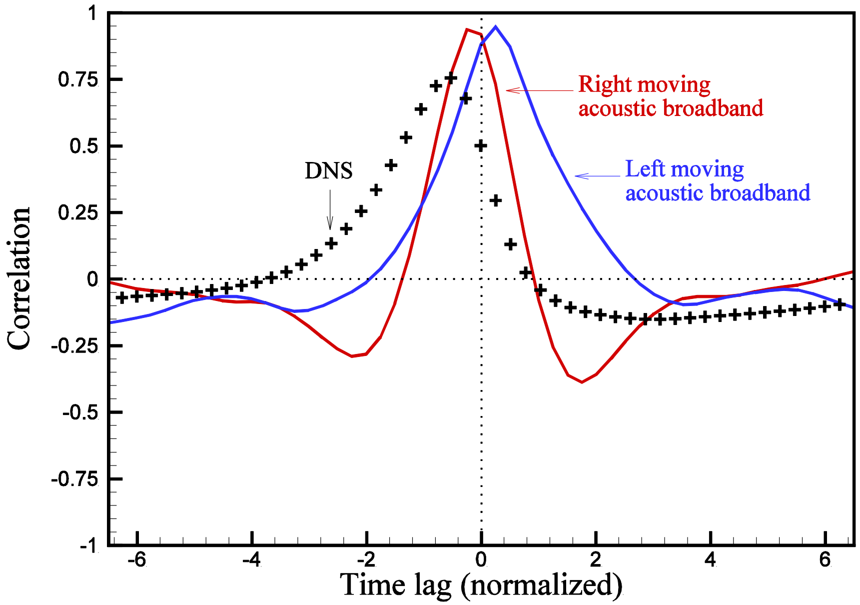
- Negative time lag – positive shock speed followed by stronger shock
  -- negative shock speed followed by weaker shock

- Pushed back shock is stronger

Single mode waves



Broadband of waves



Summary

- 1D Euler shock is very difficult to break even at very high amplitudes
- 1D broadband left moving acoustic waves show similar features as 3D shock turbulence interaction
- Correlations support qualitative difference between 1D cases and 3D cases in terms of shock holes

Thank you
Any questions?