Rocket science, shock waves and video games

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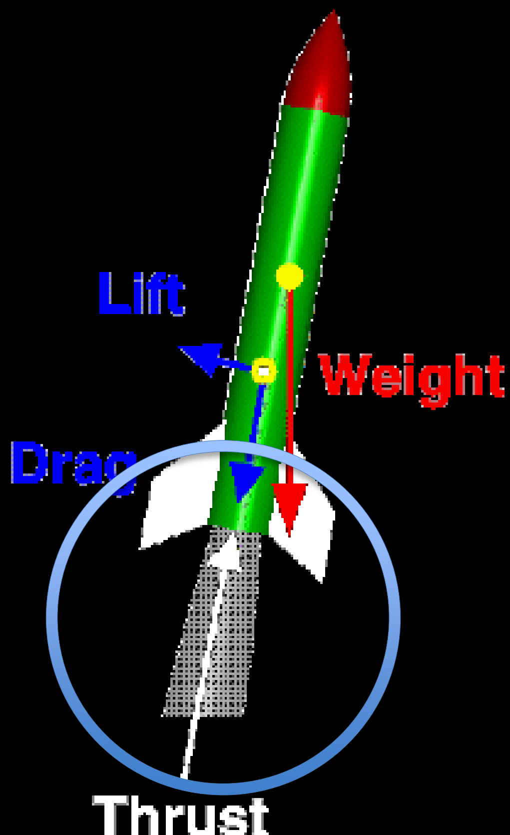
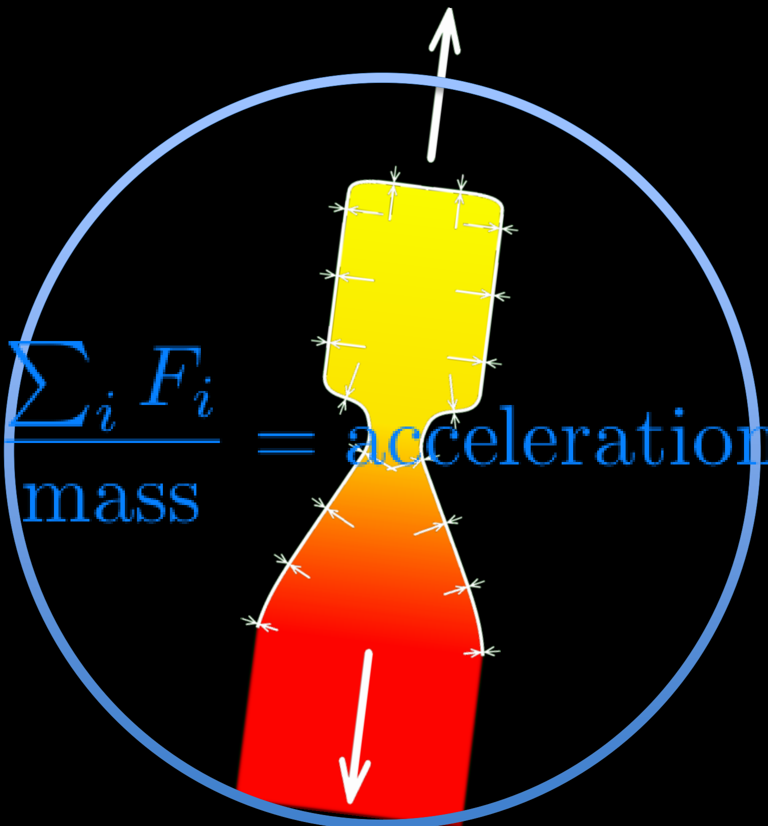
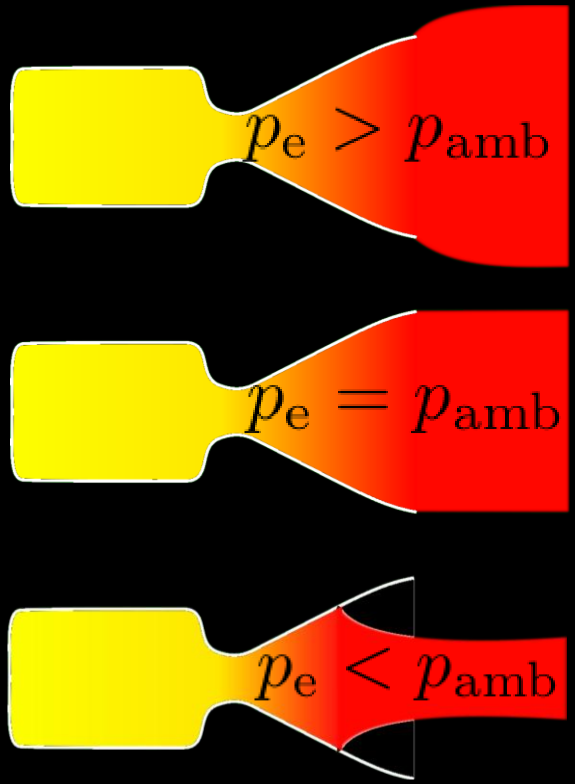
Rocket science in a nutshell





$$\frac{\sum_i F_i}{\text{mass}} = \text{acceleration}$$

Pressure in nozzle plume affects rocket performance



Under-expanded flow
(high altitude)

Ideally-expanded flow

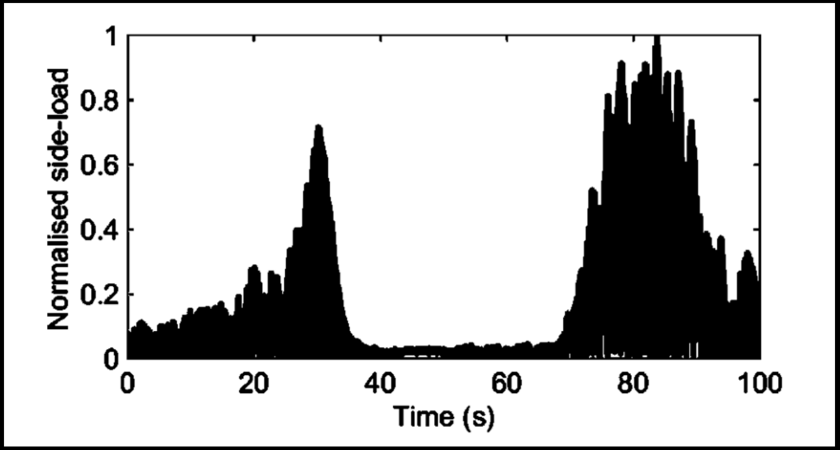
Over-expanded flow
(low altitude)

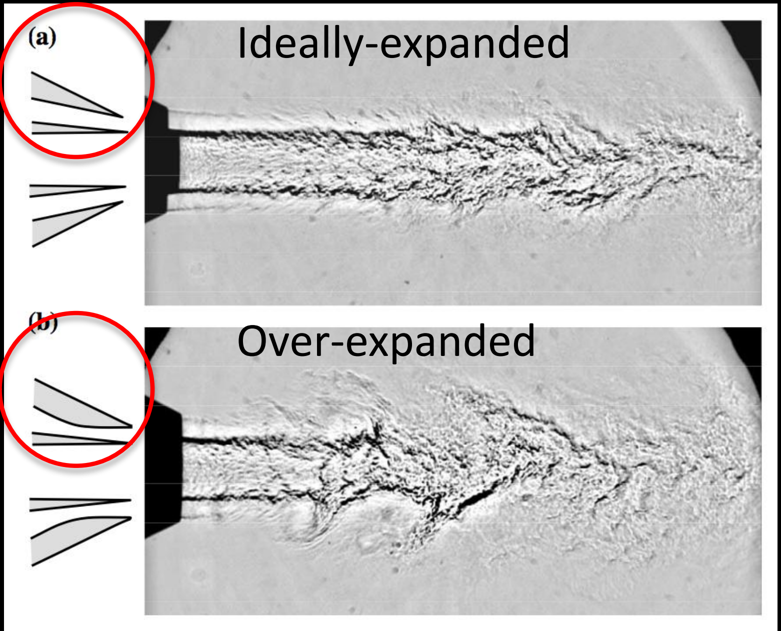
Over-expansion leads to shock waves

- "Mach disks"
  - External flow
- Shock turbulent boundary layer (STBL) interaction
  - Internal flow

Shock motion in nozzle is unsteady

- plume mixing
- spurious side loads





Experiment to find source of unsteadiness

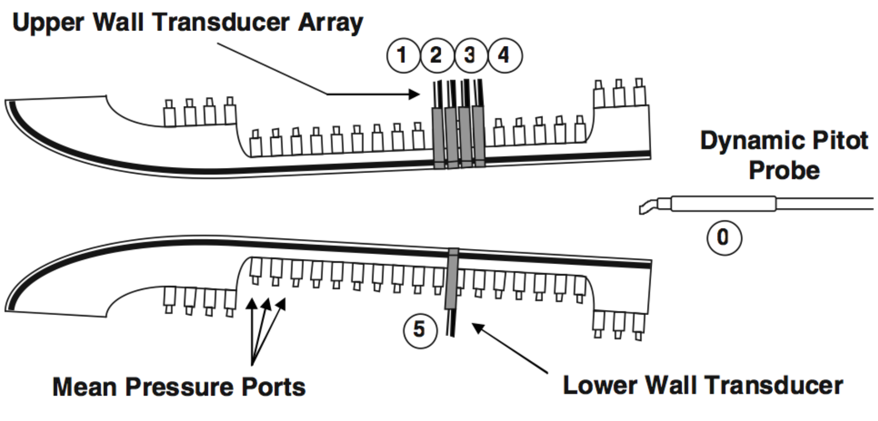
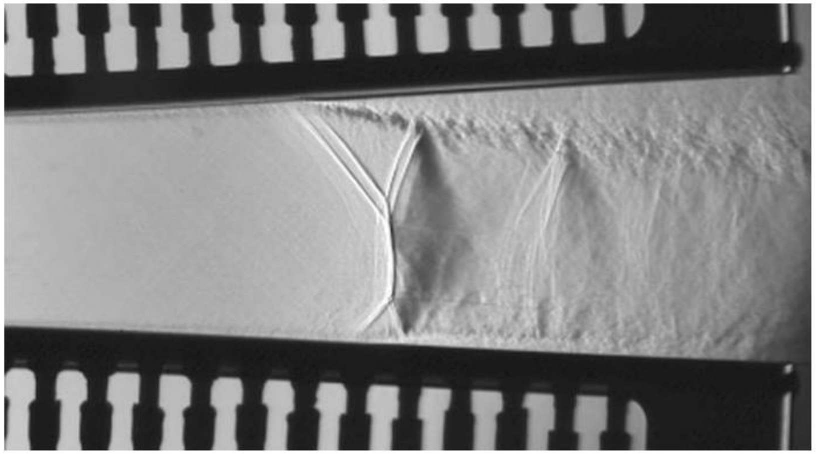


FIG. 8. Diagnostic setup of nozzle.



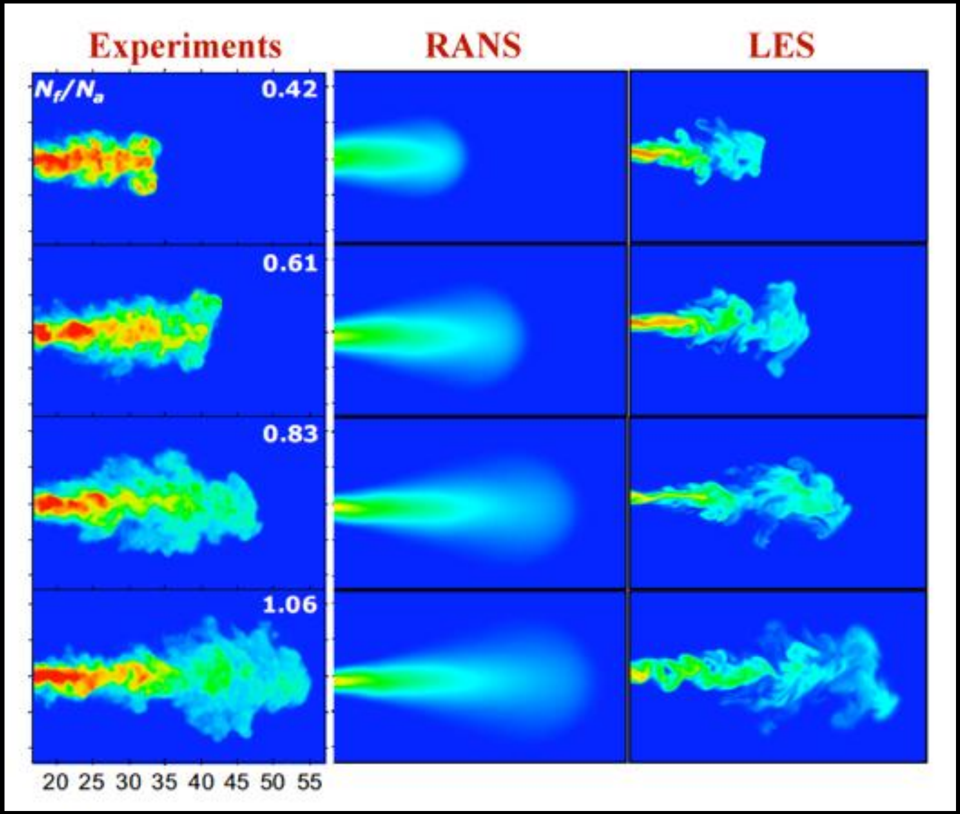
Questions remain

- Turbulent boundary layer
- Side loads
- Mechanism for the coupling between shock and shear layer

Turn to computational science to elucidate the physics

High-fidelity CFD approach

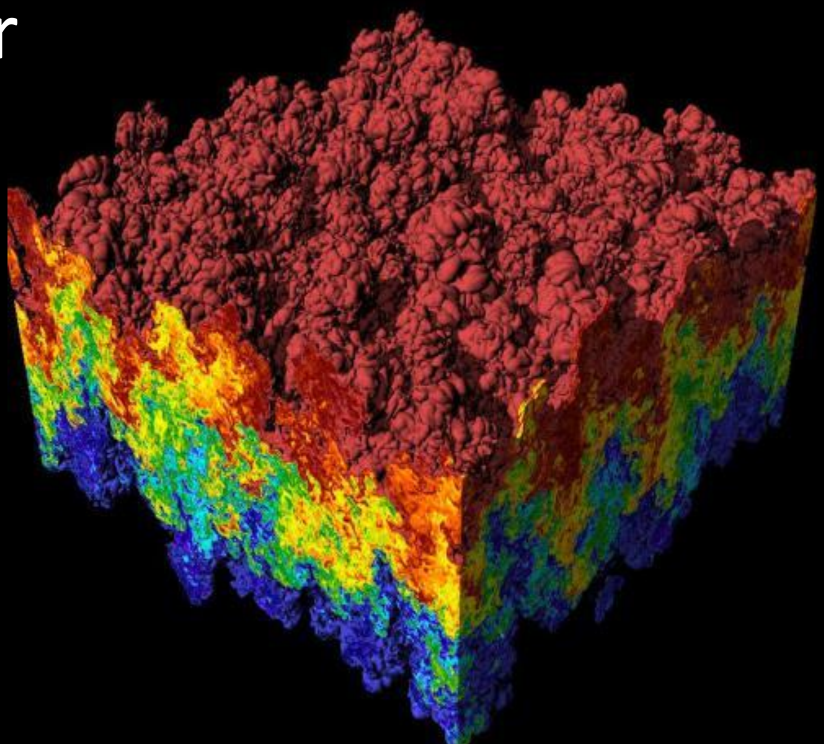
- Large-eddy simulation (LES) methodology
- Comp. Expensive



Jet plume showing example of difference between experiment (left), RANS (center) and LES (right).

The Miranda Code

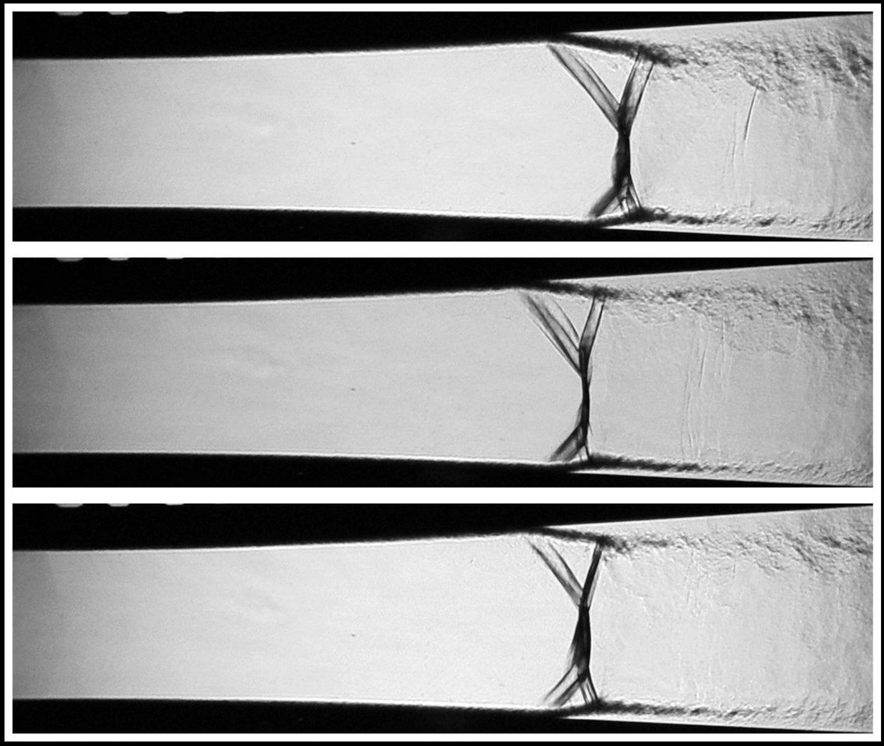
- Developed at Lawrence Livermore National Lab
  - Used for astrophysics research (Rayleigh-Taylor)
- Scales well on large clusters 32k
- High order



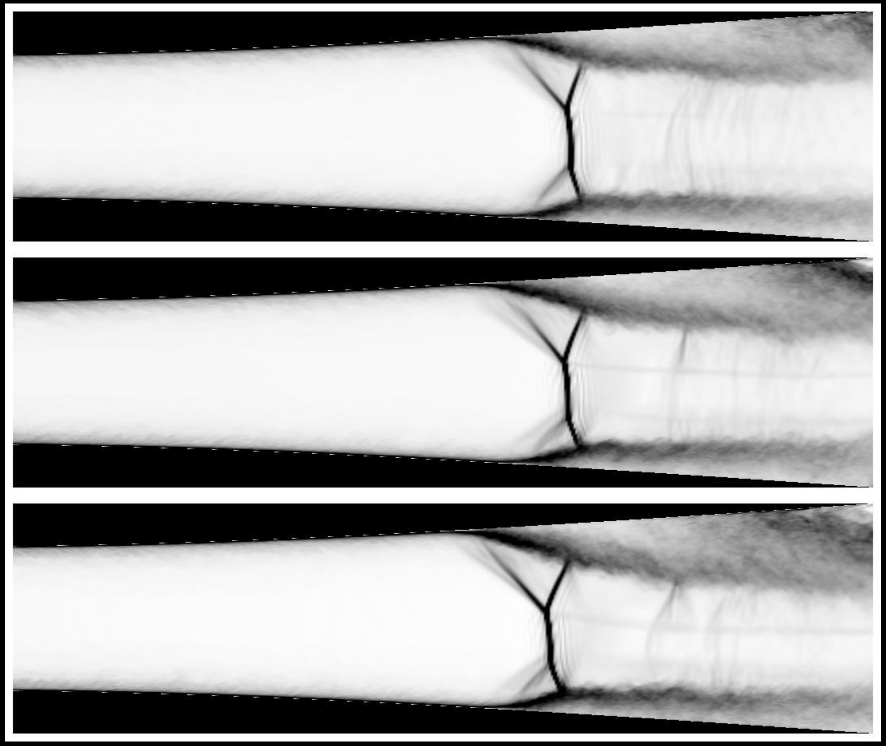
Results of LES calculations

- Ran 3 meshes
  - 8, 30, 150 Million grid points
- LLNL “hera” and “atlas” (max 4096 cpus)
- ~ 5 Million CPU Hrs
- ~ 20 TB of raw data

Instantaneous density field



Experiment



Simulation

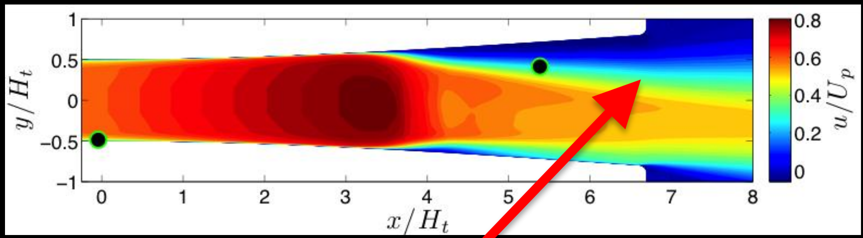
*Exp. is actual Schlieren.

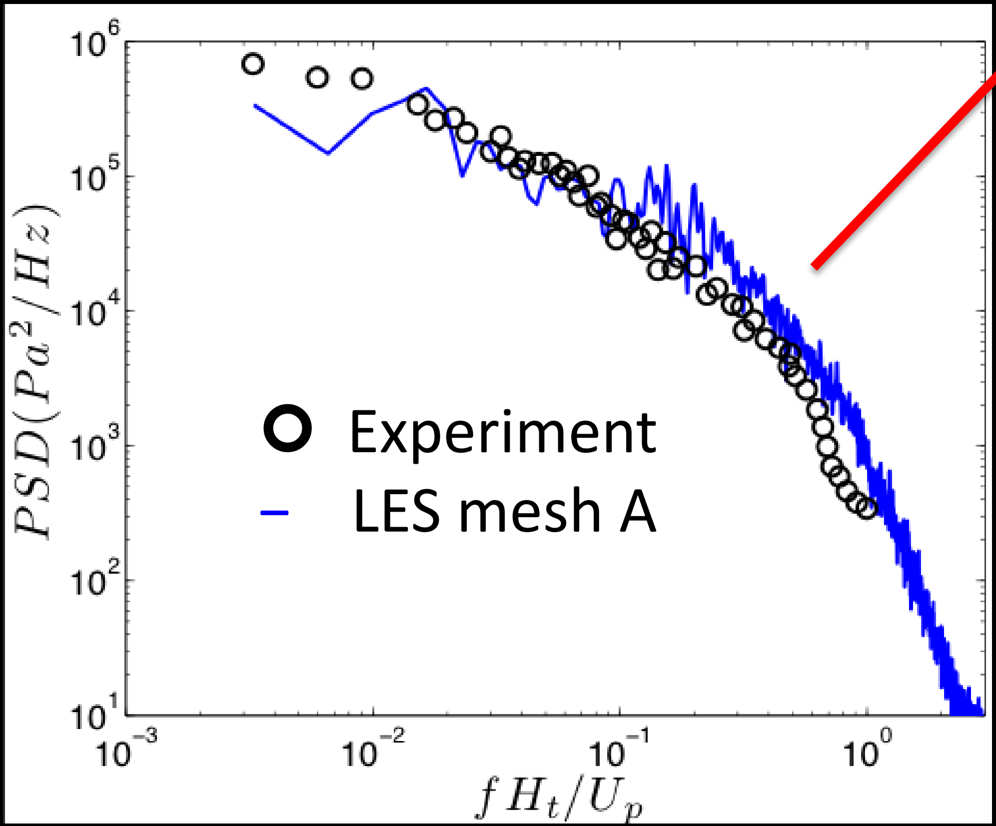
*Sim. is $\int_z \|\nabla \rho\| \mathrm{dz}$

Unsteady shock movie

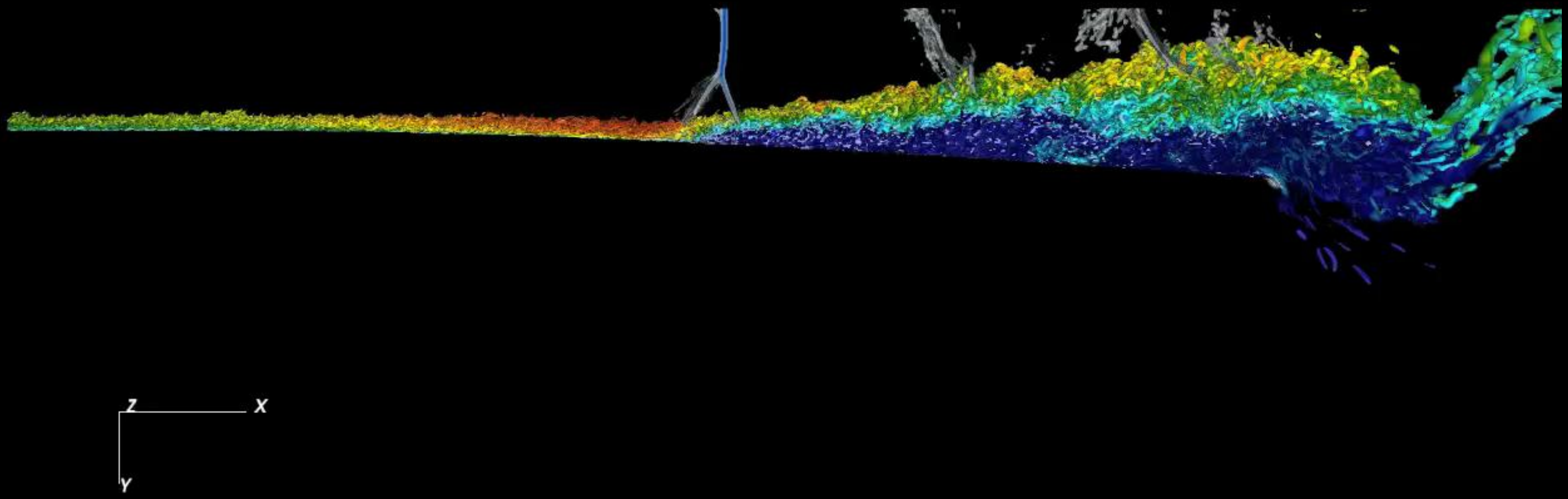
Broad range of spatiotemporal scales

- Power spectral density show large range of time scales in shear layer



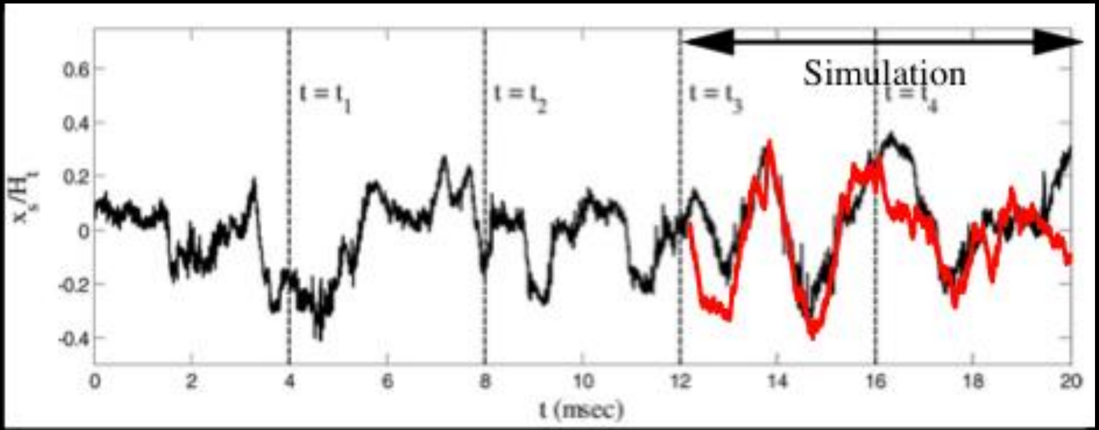


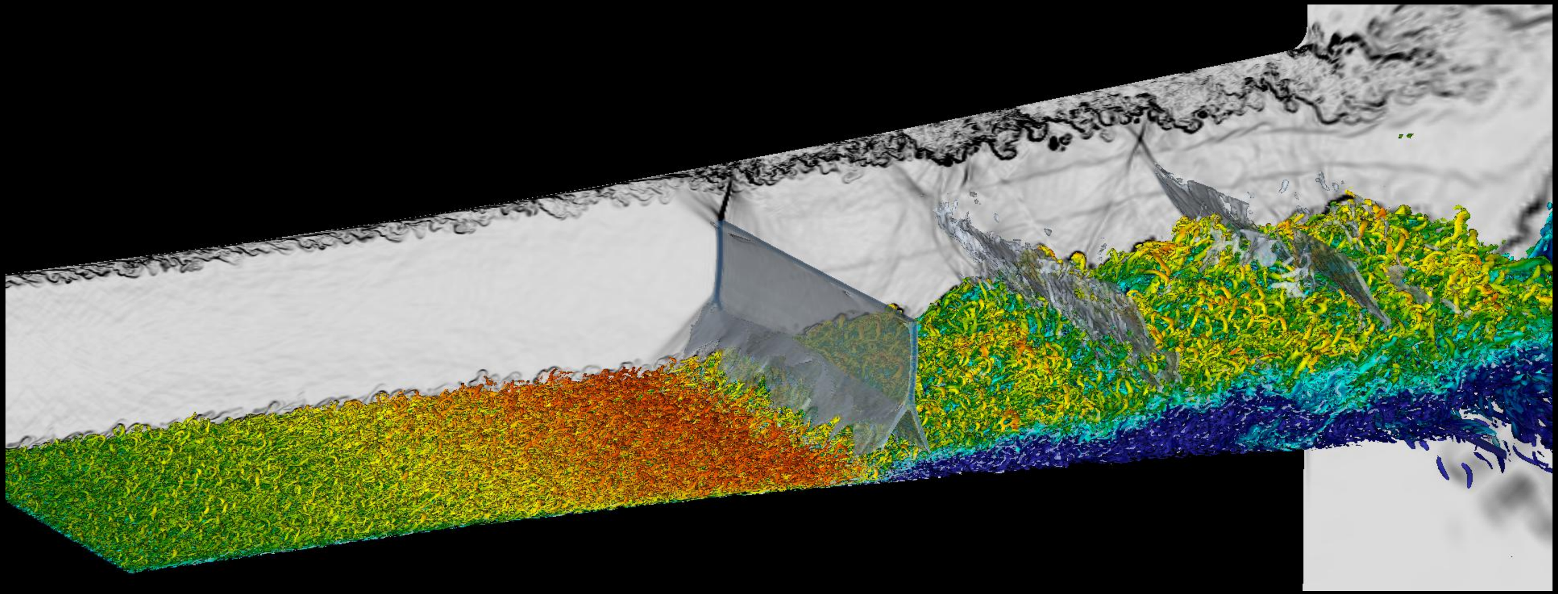
Turbulent boundary layer movie



Small time step = Long wait

- High Reynolds number flow (>1e5)
- CFL limits time step
- O(1e6) time steps needed

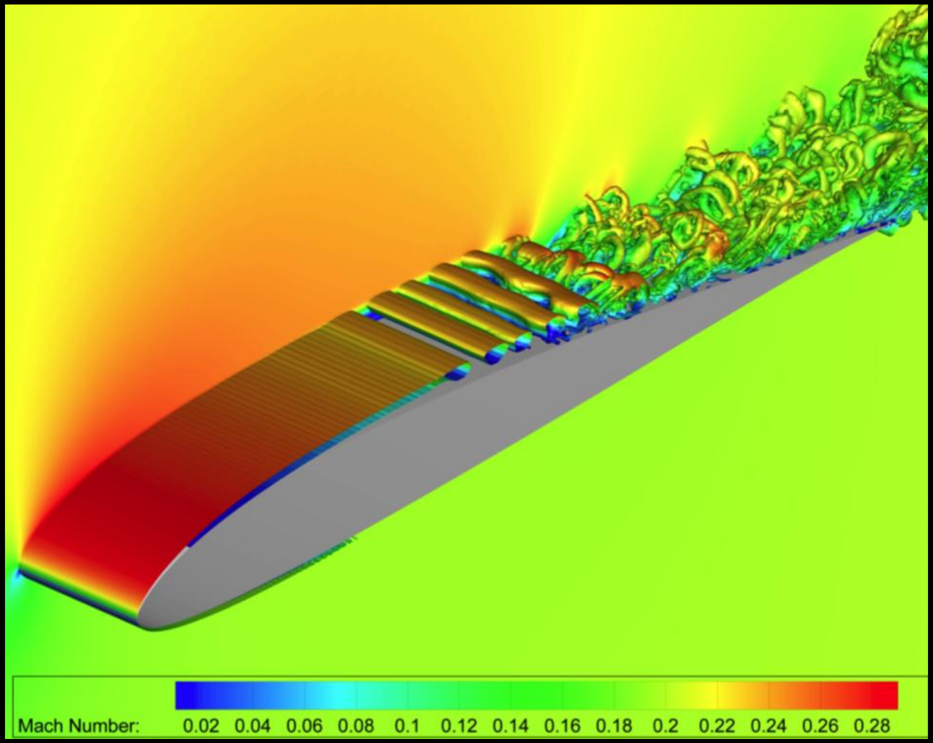




Reduce wall time or bust

- An unfinished solution is no solution
- Wall time per time step must be minimized
- GPUs offer affordable alternative to large scale CPU cluster

LES speedup example



- Re = 60,000
- 16 Tesla C2070 cards
- 13.6x speed-up over CPU (32 Xenon procs.)
- CPU 102hrs
- GPU 15hrs

*Castonguay and Jameson et. al., AIAA-2011-3229
Stanford University

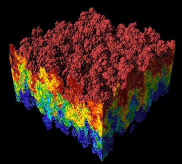
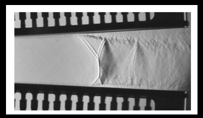
Throughput is scheme dependent

- .135 sec/dt (90% eff) GPU 4th order Spectral Diff.
- .918 sec/dt CPU 4th order Spectral Diff.
- 3-5 sec/dt (90% eff) CPU 10th order Finite Diff.

Physics, Reynolds number

Time to Solution = [sec/dt] x [N time steps]

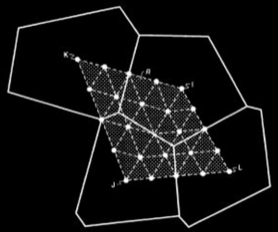
"Codesign" for performance

Physics

Numerics

Architecture



$$\nabla^2$$

Summary and Looking forward

- High Reynolds number LES
  - expensive
  - worthwhile
- GPU can make simulations viable for smaller clusters
- “Codesigned” software needed for optimal performance