Complex turbulence interaction using massively parallel direct numerical simulations

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Motivation & computational challenge

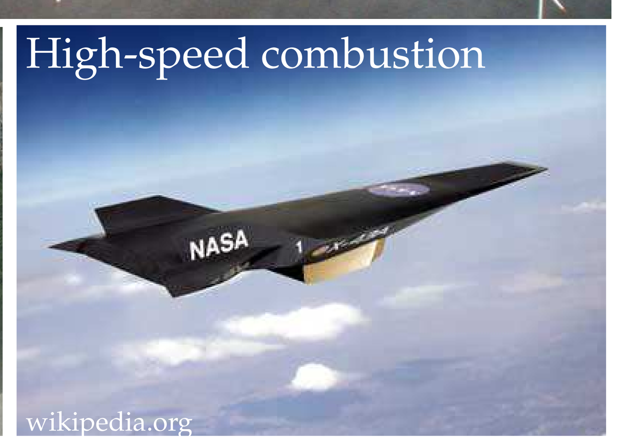
Most flows of practical interest are turbulent

- High Reynolds numbers (Re) with wide range of spatial and temporal scales

$$Re = \frac{uL}{\nu} \propto R_\lambda^2$$

$\boldsymbol{u}$: characteristic velocity
$\boldsymbol{L}$: characteristic length
$\boldsymbol{\nu}$: kinematic viscosity
$\boldsymbol{R_\lambda}$: Taylor's Reynolds number

Controlling turbulence: improved energy efficiency



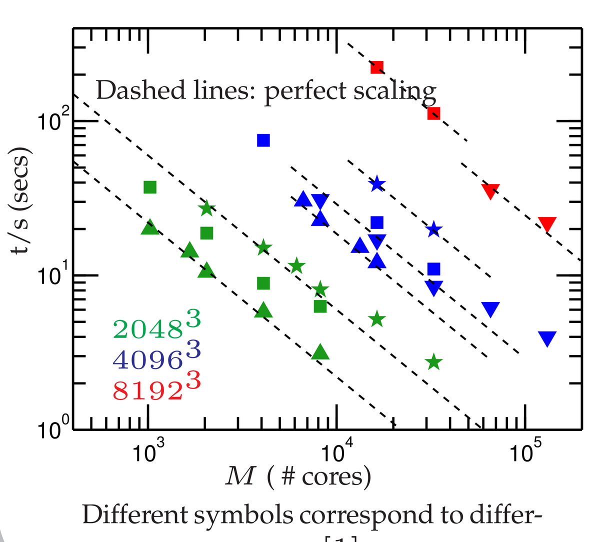
How do we study turbulence?

Resolving all scales: extreme computational cost

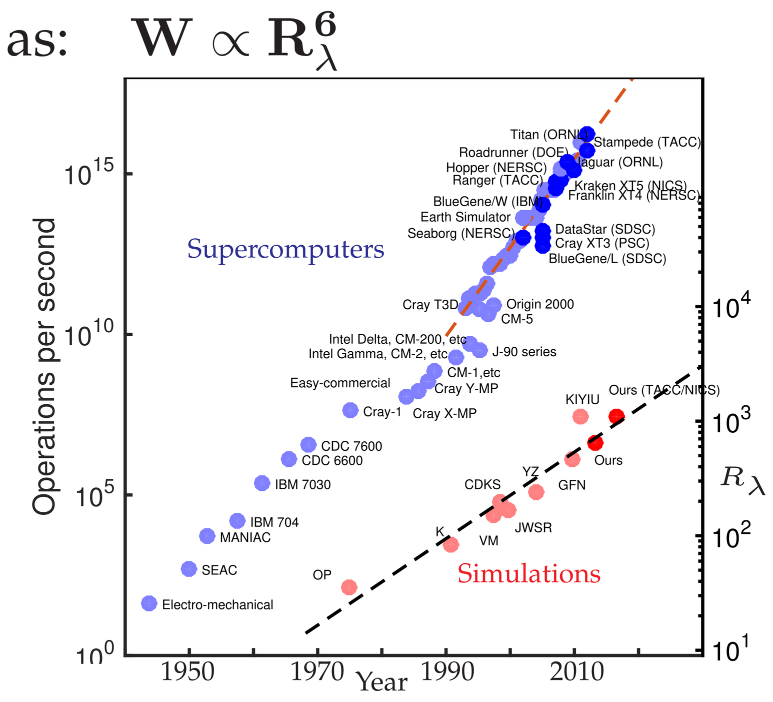
Domain $> \boldsymbol{L}$: Integral length scale (largest scale)

Grid Spacing $< \boldsymbol{\eta}$: Kolmogorov microscale (smallest scale)

Computational work scales as: $\mathbf{W} \propto \mathbf{R}_\lambda^6$



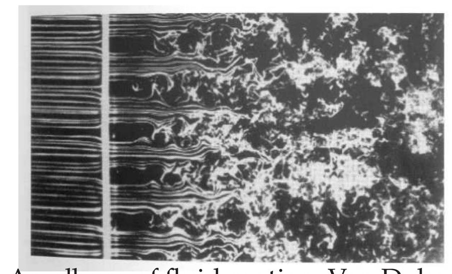
Different symbols correspond to different supercomputers[1]



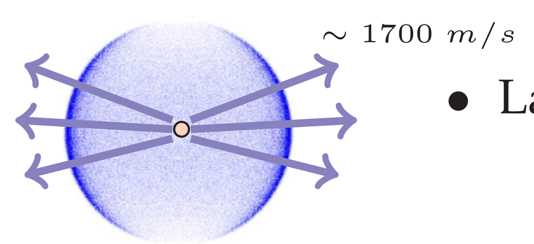
Turbulence control: generation and mitigation

How can turbulence be generated or controlled?

- Classical approach: grid turbulence
- **New method: laser-controlled turbulence**[2,4]



An album of fluid motion, Van Dyke



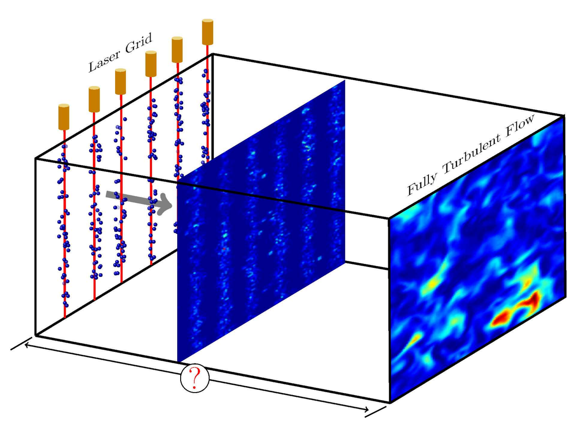
Cl atoms arising from 355 nm photo-dissociation of Cl2 (Courtesy of Dr. Simon North)

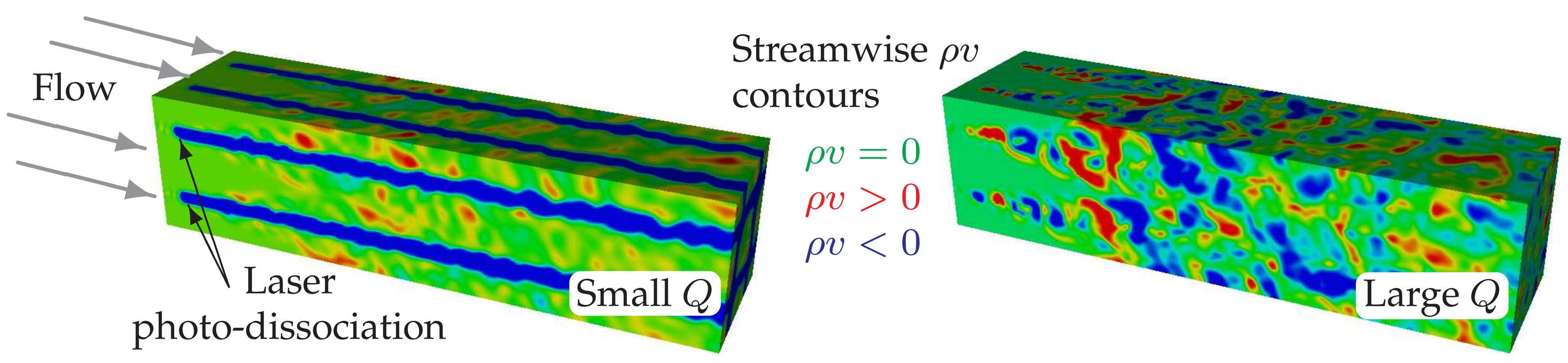
- Lasers can photo-dissociate molecules
  - Fragments with very large velocities + TNE[3]

Two sources of energy (kinetic and internal):

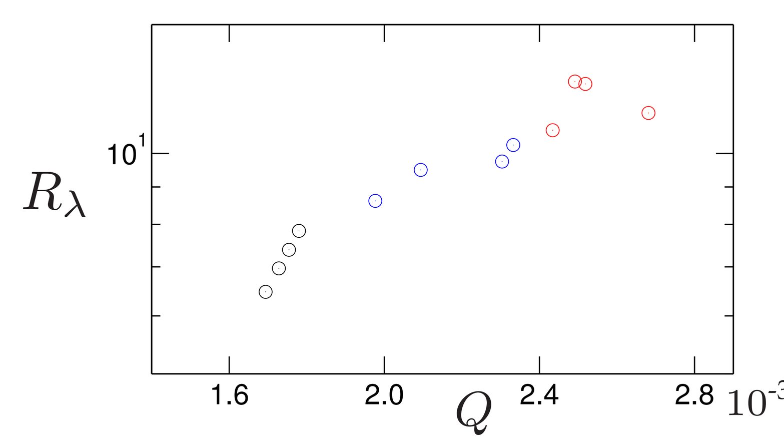
$$\Delta K_l = \frac{\sum(\mathbf{u}_l^2 - \mathbf{u}_0^2)}{\sum \mathbf{u_0}^2}, \qquad \Delta e_l = \frac{\sum e_l}{\sum e_0}$$

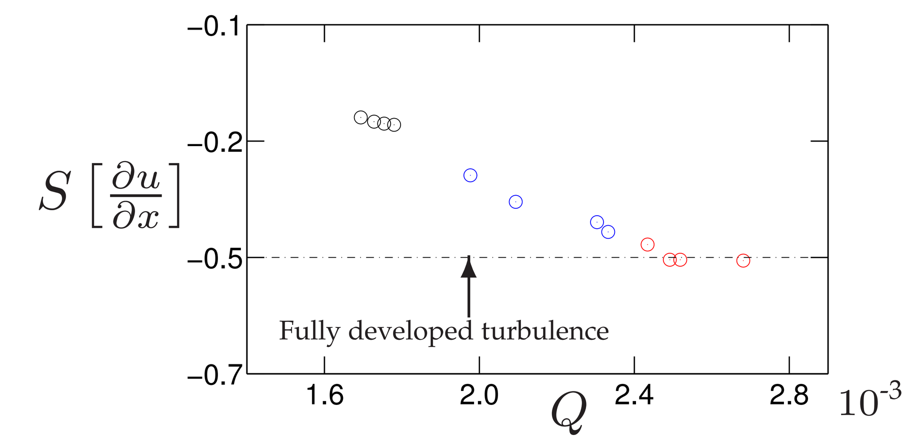
Relative importance parameter: $Q = \frac{\Delta K_l}{\Delta e_l}$





Qualitatively different evolution: Q controls turbulence





- Small Q: increased viscosity (high T) reduces turbulence
- Large Q: triggers turbulence

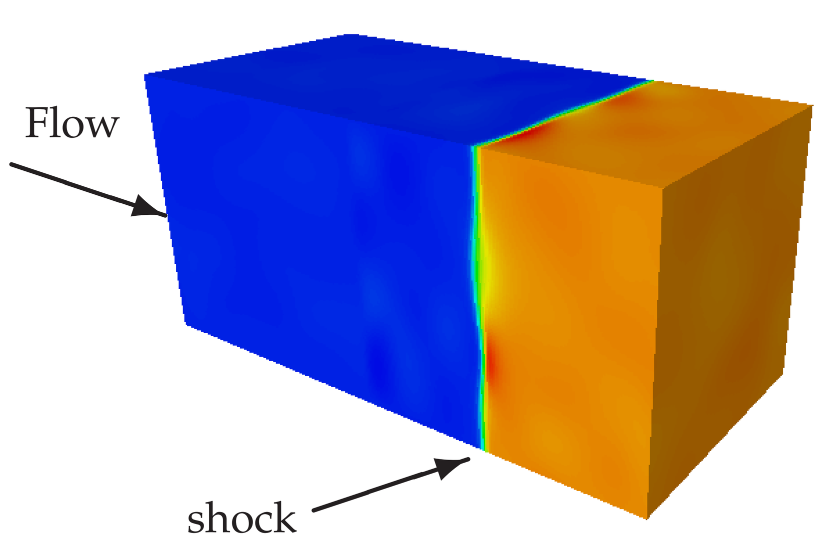
Studying complex systems with high Q: extreme computational cost

Shock turbulence interaction

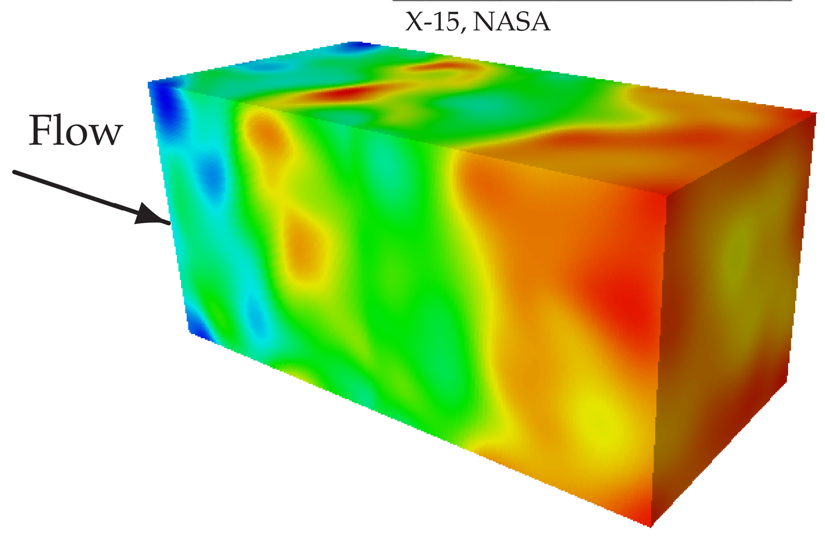
When turbulent flows pass through a shock:

- Turbulence characteristics change
- Shock structure weakened
- Thermodynamic quantities $\neq f(M_1)$
- Rankine-Hugoint relations no longer applicable

X-15, NASA



Wrinkled regime (weak incoming turbulence)

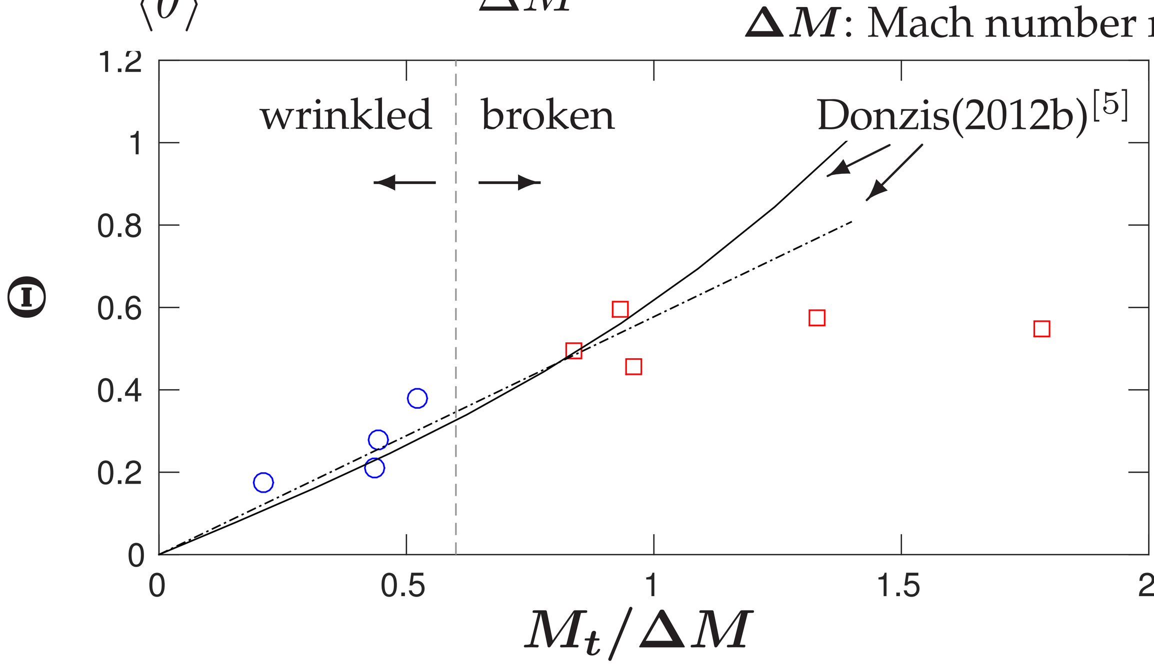


Broken regime (strong incoming turbulence)

Shock structure quantification:

$$\Theta \equiv \frac{\langle(\tilde{\theta} - \langle\tilde{\theta}\rangle)^2\rangle^{1/2}}{\langle\tilde{\theta}\rangle} \approx f\left(\frac{M_t}{\Delta M}\right)$$

$\tilde{\boldsymbol{\theta}}$: local min $(\mathbf{div}\,\vec{\boldsymbol{V}})$
$\boldsymbol{M_t}$: turbulent Mach number
$\boldsymbol{\Delta M}$: Mach number minus unity



- Turbulence effects on shock are significant and quantifiable
- High computational cost in broken regime due to turbulence strength

Impact

- Controlling turbulence can drastically improve efficiency, reduce drag and friction losses
  - Energy generating technologies, wind farms and hydroelectric turbines
  - Commercial aircraft, hypersonic vehicles
- Novel techniques for shock structure analysis due to shock turbulence interaction
- Understanding interactions can significantly lead to better flow control
  - Accurate calculation of turbulent shock jumps
  - Turbulent characteristics predictable

References & Acknowledgements

[1] Donzis, D., Yeung, P., and Pekurovsky, D., 2008, "Turbulence Simulations on $O(10^4)$ Processors", TeraGrid 2008.

[2] Maqui, A. and Donzis, D., 2014, "Generation of compressible turbulence using lasers as sources of intense energy", American Physical Society-DFD 2014 Conference.

[3] Donzis, D. and Maqui, A., 2016, "Statistically steady states of turbulence in thermal equilibrium and non-equilibrium", J. Fluid Mech., 797.

[4] Maqui, A. and Donzis, D., 2016, "Turbulence generation through intense kinetic energy sources", Phys. Fluids, 28.

[5] Donzis, D., 2012, "Shock structure in shock-turbulence interactions", Phys. Fluids, 24.

Acknowledgements:

NSF and AFOSR for financial support and TAMU High Performance Research Computing, XSEDE, ORNL, ANL, NERSC for computer time