

Turbulent Flames in Type Ia Supernovae

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Flame instabilities play a dominant role in accelerating the burning front to a large fraction of the speed of sound in a Type Ia supernova. We present three-dimensional numerical simulations of Rayleigh-Taylor (RT) unstable, turbulent flames and reacting bubbles. A low Mach number hydrodynamics method is used, freeing us from the harsh timestep restrictions imposed by sound waves. We fully resolve the thermal structure of the flame and its reaction zone, eliminating the need for a flame model. We compute detailed diagnostics of the turbulence and discuss the flame characteristics as it transitions from the flamelet to the distributed burning regimes.

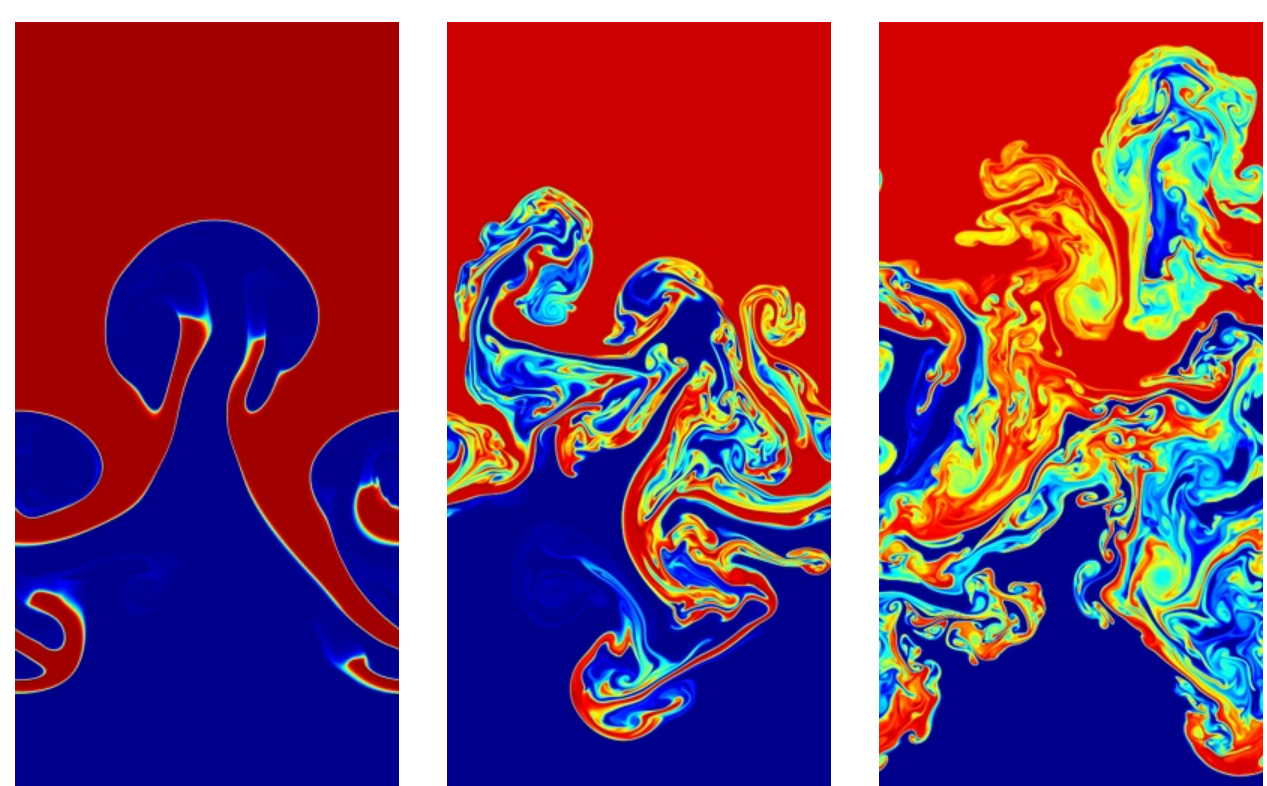
Our flames are very subsonic and out of the reach of fully compressible codes. We use a low Mach number formulation of the Navier-Stokes equations, where the pressure is decomposed into a thermodynamic, p_o , and an $O(M^2)$ dynamic component, π :

$$\begin{aligned}\frac{\partial(\rho U)}{\partial t} + \nabla \cdot (\rho U U) &= -\nabla \pi + \rho \vec{g} , \\ \frac{\partial(\rho h)}{\partial t} + \nabla \cdot (\rho U h) &= \nabla \cdot (\lambda \nabla T) - \sum_k \rho q_k \dot{\omega}_k , \\ \frac{\partial(\rho X_k)}{\partial t} + \nabla \cdot (\rho U X_k) &= \rho \dot{\omega}_k .\end{aligned}$$

Taking the pressure to be constant along particle paths leads to a constraint similar to that in incompressible flows, but incorporating the heat release from reactions and thermal diffusion:

$$\nabla \cdot U = \frac{1}{\rho \frac{\partial p}{\partial \rho}} \left(\frac{1}{\rho c_p} \frac{\partial p}{\partial T} \left(\nabla \cdot \lambda \nabla T - \sum_k \rho \left(q_k + \frac{\partial h}{\partial X_k} \right) \dot{\omega}_k \right) + \sum_k \frac{\partial p}{\partial X_k} \dot{\omega}_k \right)$$

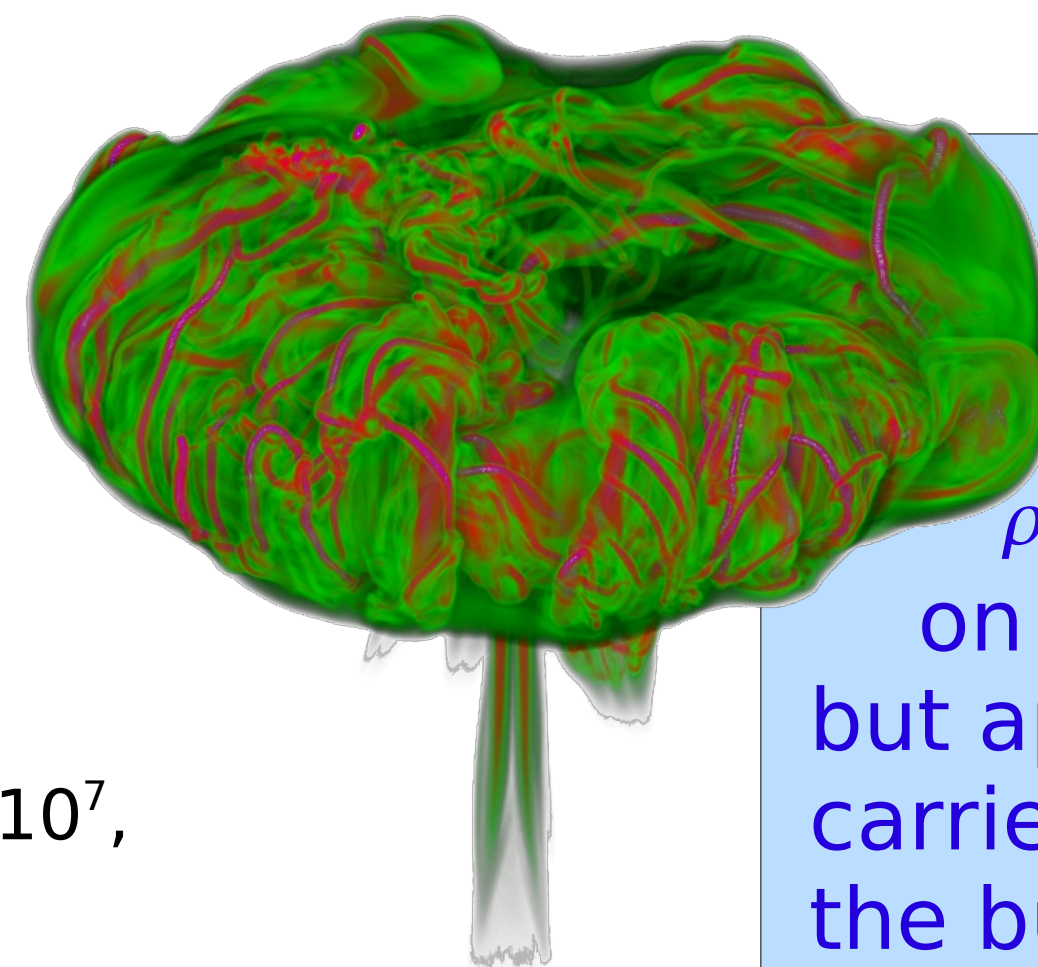
The result is a method that filters out soundwaves, allowing for much larger timesteps than a fully compressible code [1].



Transition to Distributed Burning

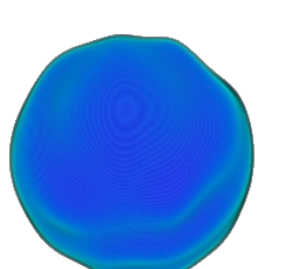
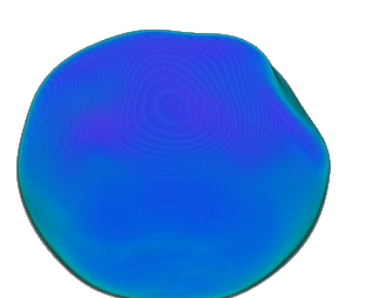
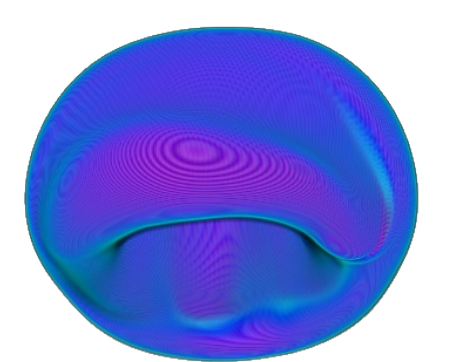
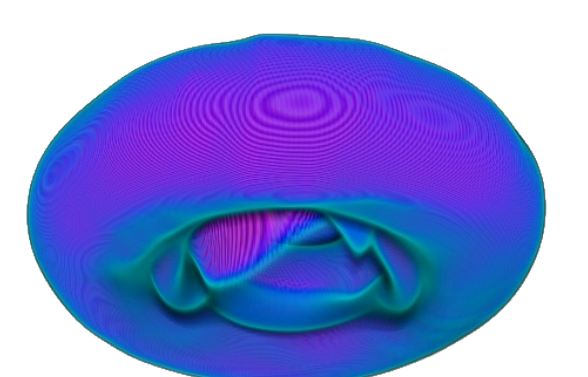
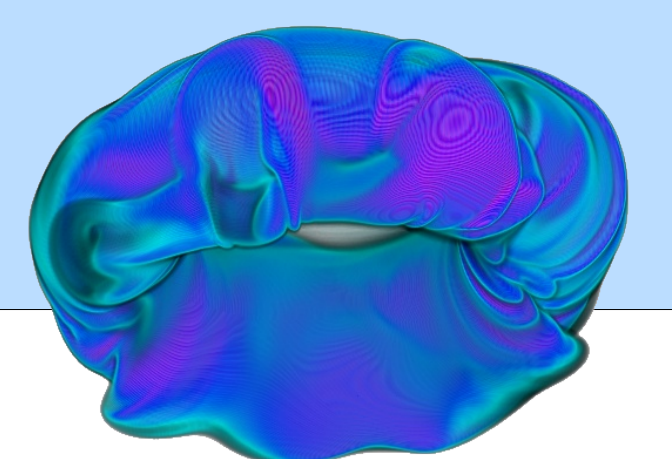
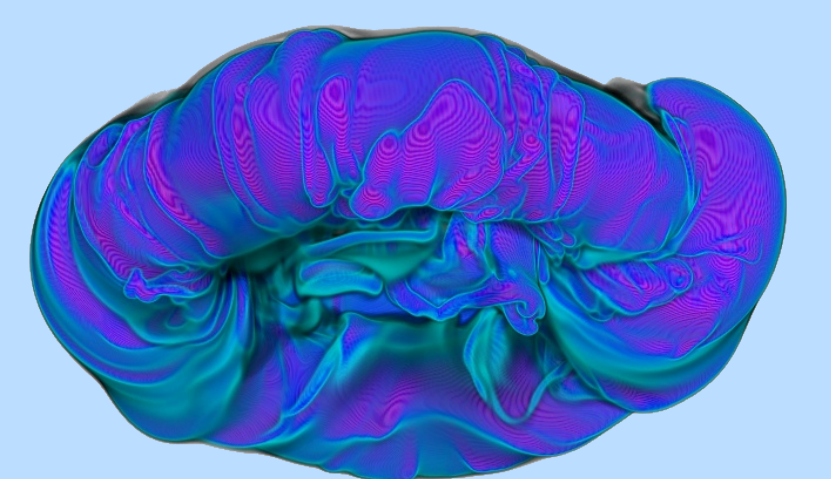
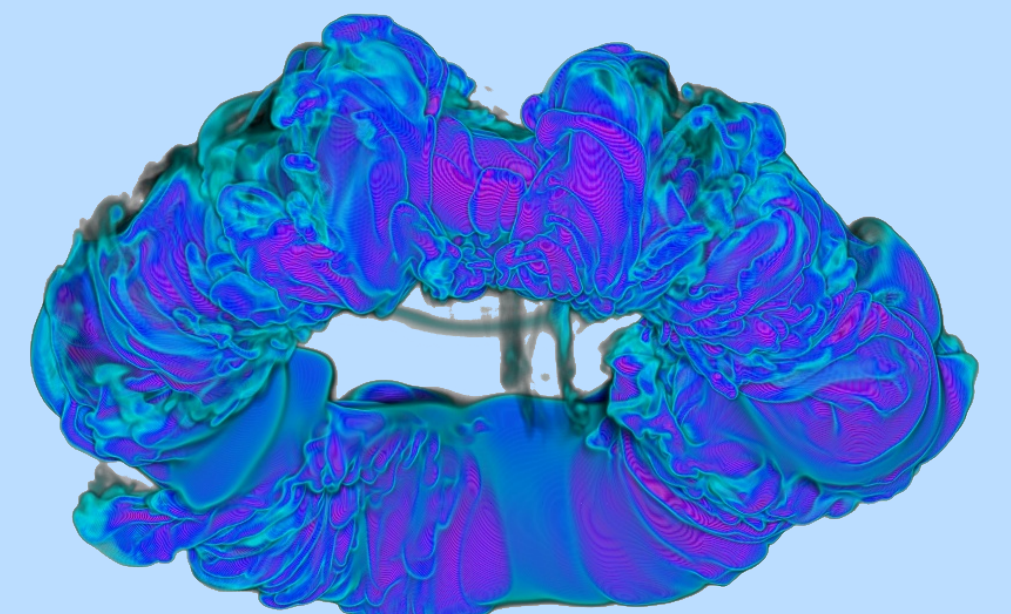
Two-dimensional Rayleigh-Taylor unstable flames at 1.5×10^7 , 10^7 , and 6.67×10^6 g cm⁻³ (left).

We demonstrated for the first time the transition to distributed burning as the Rayleigh-Taylor (RT) unstable flame encounters lower densities in the white dwarf [2]. At high densities, the burning is vigorous enough to suppress the growth of the RT instability, leading to a well defined flame, with a sharp interface separating the fuel and ash—a hallmark of the flamelet regime. At low densities, the burning slows, and the RT instability can grow on scales smaller than the flame itself, breaking down the thermal structure of the flame. This is the distributed burning regime. This transition occurs at $\sim 10^7$ g cm⁻³ in 2-D simulations.



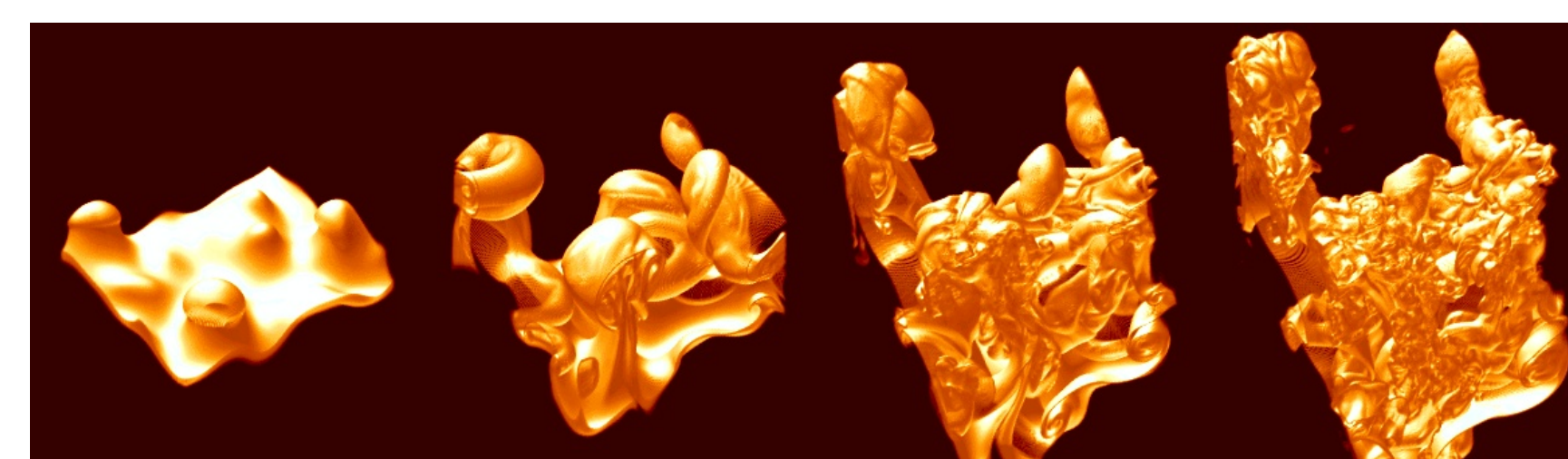
Reactive Bubbles

Preliminary results of a 3-D reactive bubble, at $\rho = 1.5 \times 10^7$ g cm⁻³, (vorticity on left, ash mass on right). This density is far from ignition conditions, but approachable by DNS. Over 200 million zones are carried. At late times a hole develops in the center of the bubble, due to the strong shear, but at higher densities the faster reaction rate may suppress this. Also apparent is the growth of small scale structure on the sides of the bubble, only seen in high resolution runs. As the bubble becomes more turbulent, it may be possible to shed sparks and ignite other regions of the star. Large scale simulations employing flame models would likely wash this away, perhaps missing a key component in the ignition process.

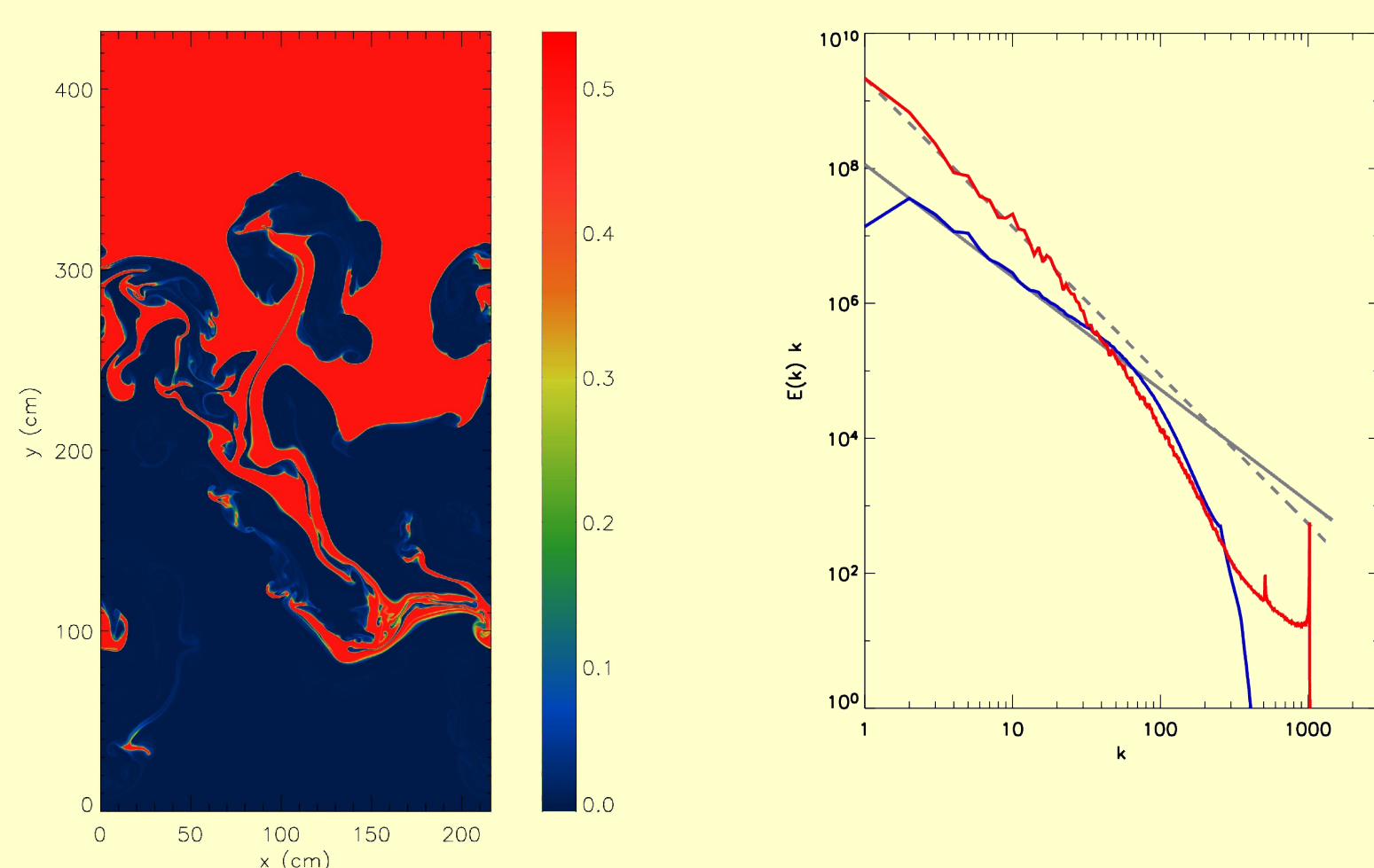
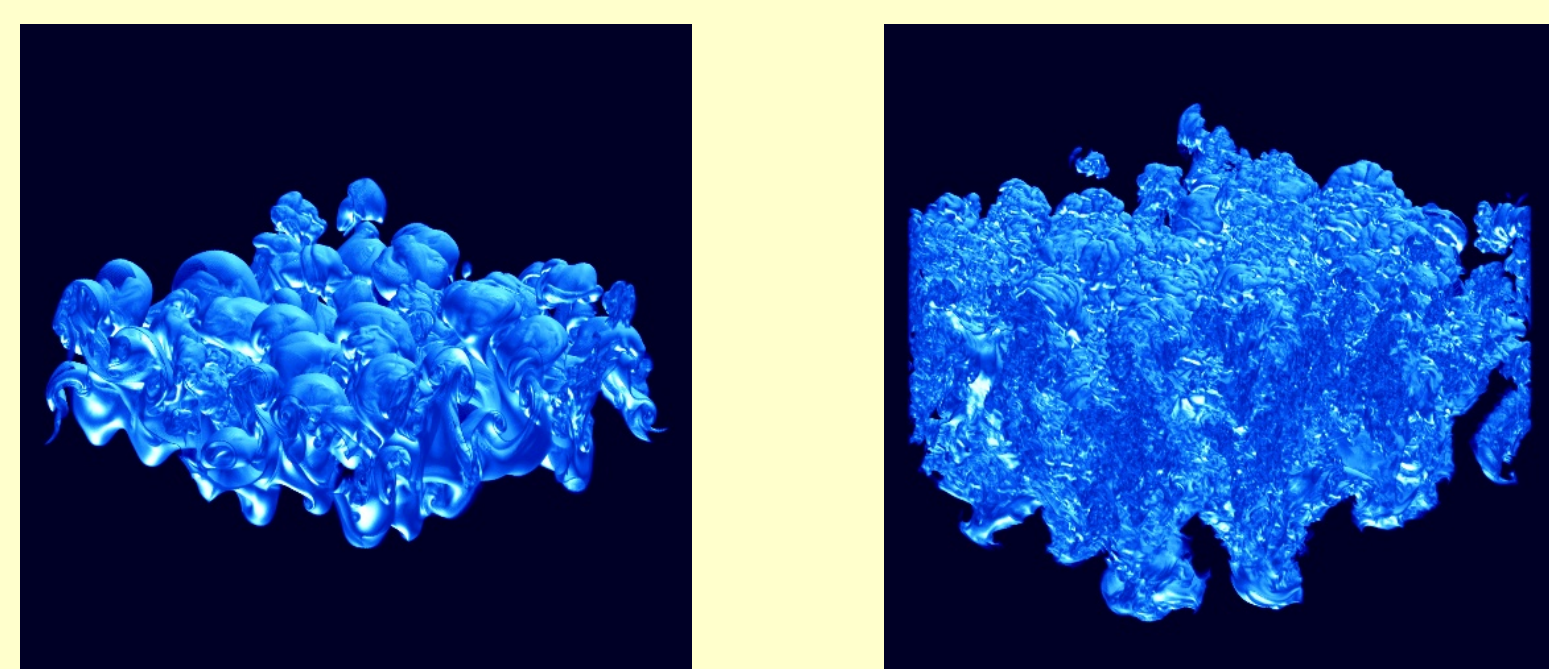


Turbulent Thermonuclear Flames

We performed a large 3-D simulation of a RT unstable flame [3], following the evolution to the point where the flame becomes fully turbulent (see left). The turbulence is Kolmogorov in nature and is anisotropic on the large scales (since gravity provides a preferred direction) but becomes isotropic as it cascades down to smaller scales. Interestingly, in 2-D, the turbulence obeys Bolgiano-Obukhov scaling—a potential energy cascade. This difference in scaling makes the density at which the flame transitions into the distributed burning regime dependent on the dimensionality. This was observed directly by comparing our 2-D simulations [2] to this large scale 3-D simulation, which entered the distributed burning regime. This difference demands that flame simulations be run in 3-D. Follow-up calculations, where we feed turbulence into the domain, are underway, and will allow us to examine whether we can attain conditions favorable to a deflagration-detonation transition.



Close-up of a RT unstable flame showing the growth of a few modes and the onset of turbulence.



Volume renderings of the carbon mass fraction for the 3-D RT unstable carbon flame at 1.5×10^7 g cm⁻³ (top row), showing a fully turbulent flame at late times. 2-D RT at the same density (bottom left) in a 4x wider domain. Associated kinetic energy power spectra (bottom right) for the 2-D (red) and 3-D (blue) with corresponding -11/5 and -5/3 power law fits respectively (gray lines).