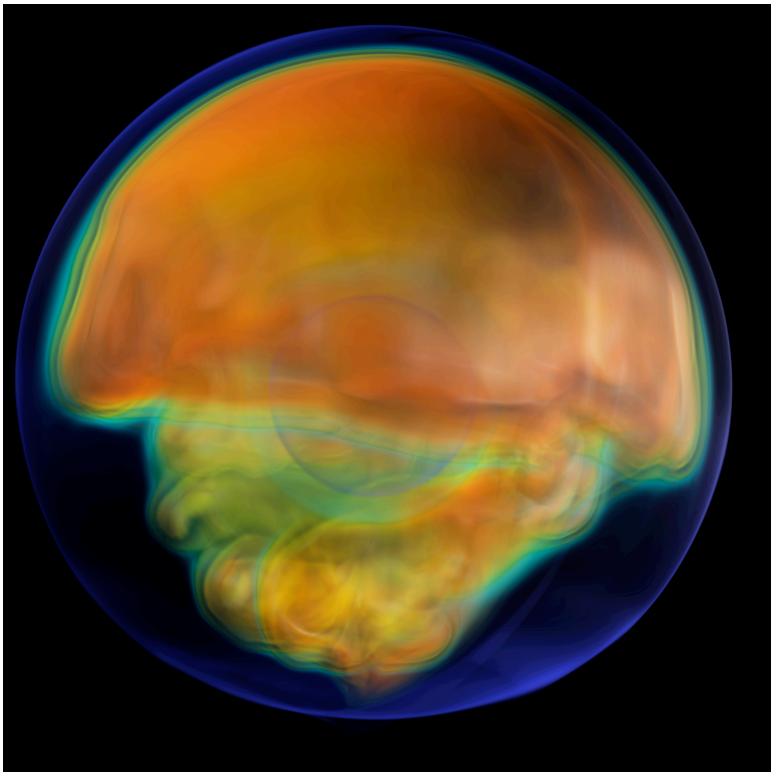
The First Four-Dimensional Core Collapse Supernova Simulations [with 3 spatial dimensions and 1 neutrino spectral (energy) dimension]



Rendering of the matter entropy in the core of a massive star at approximately 100 milliseconds following core bounce. Multidimensional fluid effects, coupled to heating and cooling via neutrino emission and absorption, have served to form large, asymmetric structures in the flow. Much of this complicated flow pattern occurs between the surface of the nascent neutron star at the heart of the star and the position of the original supernova shock (demarcated by the faint blue circle near the edge of the figure). These simulations–the first of their kind–have already consumed tens of millions of cpu-hours on leadership computing platforms and will require tens of millions of additional cpu-hours to follow the evolution out to the requisite one second of physical time. They are being performed by the ORNL-led CHIMERA collaboration, which includes researchers from Florida Atlantic University, NCSU, and ORNL.

Decades of core-collapse supernova simulations have led to a challenging proposition for the eventual description of the explosion mechanism and the associated phenomenology. It is now known that three-dimensional hydrodynamics in general relativistic gravity must be coupled to nuclear kinetics capable of accurate estimation of energy release and compositional changes and to spectral neutrino transport of all flavors of neutrinos in order to reliably determine the nature of the explosion mechanism. Moreover, the inclusion of neutrino masses and oscillations, as well as magnetic fields–both potentially important effects–serve to render the problem even more difficult. All of these effects, familiar in some sense from the earlier life of the star, here operate on very short (millisecond) time scales and at extremes in density (as high as three to four times nuclear matter density) and neutron richness (the ratio of protons to neutrons in the matter can be several times smaller than what is accessible in terrestrial experiments). The rich interplay of all these physical phenomenon in core-collapse supernovae ultimately leads to the realization that only through simulation will we be able to fully disentangle all their effects and arrive at a full understanding of these massive stellar explosions. The relative complexity of all this physics also means that the requisite physical fidelity for these simulations will only be realized at the exascale.