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3D Core-collapse Supernova Simulations

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Overview

The mechanism by which the cores of massive stars as they die launch supernova explosions has been studied for many years but has not been unambiguously determined

At the confluence of nuclear, particle, and gravitational physics, and a numerical challenge of the first order, this puzzle has confounded theorists in no small measure due to its complexity. Some of this complexity is due to its multidimensional character—the dynamics experiences many hydrodynamic instabilities, and the explosions are not spherical

Hence, the associated computational complexity of multidimensional simulations has retarded progress, but with the recent advent of fast and large parallel computers, the multidimensional character of core-collapse supernovae may soon be captured. Whereas in the past, 1D and 2D simulations could be performed, 3D simulation capabilities are emerging.

CASTRO – 3D AMR, multigroup radiation-hydrodynamic supernova code

- 2nd-order, Eulerian, unsplit, compressible hydro
- PPM and piecewise-linear methodologies
- Multi-grid Poisson solver for gravity
- Multi-component advection scheme with reactions
- Adaptive Mesh Refinement (AMR) – flow control, memory management, grid generation
- Block-structured hierarchical grids
- Sub-cycles in time (multiple time-stepping – coarse, fine)
- Sophisticated synchronization algorithm
- BoxLib software infrastructure, with functionality for serial distributed and shared memory architectures
- 1D (Cartesian, cylindrical, spherical); 2D (Cartesian, cylindrical); 3D (Cartesian)
- Transport is a conservative implementation of the mixed-frame method of Hubeny & Burrows (2007), with v/c terms and inelastic scattering
- Uses scalable linear solvers (e.g., hypre) with high-performance preconditioners that feature parallel multigrid and Krylov-based iterative methods
- Developers: John Bell, Ann Almgren, Louis Howell, Mike Singer, Jason Nordhaus, Adam Burrows – LBNL, LLNL, Princeton

CASTRO

- Explored the dependence on spatial dimension of the viability of the neutrino heating mechanism of core-collapse supernova explosions.

- CASTRO (Compressible ASTROphysics) is a general compressible code
  - New multi-D radiation-hydrodynamics code
  - Finite Volume, Adaptive mesh refinement (AMR) with sub-cycling in time
  - Advection: 2nd order, unsplit piecewise-linear or PPM
  - Radiation: multi-group flux limited diffusion
  - Gravity: Monopole or multi-grid Poisson solve
  - System of advection-reaction-diffusion equations
  - Scales to 200K+ cores

CASTRO Overview

- **Solve the fully compressible equations of hydrodynamics**

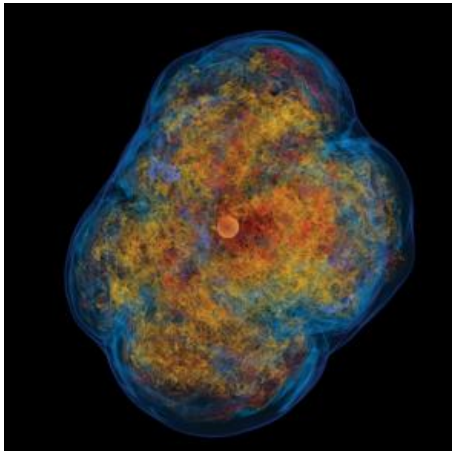
$$\partial t \rho = -\nabla \cdot (\rho u)$$

$$\partial t (\rho u) = -\nabla \cdot (\rho uu) - \nabla p + \rho g$$

$$\partial t (\rho E) = -\nabla \cdot (\rho u E) + pu + \rho u \cdot g + \rho(H - C) ,$$

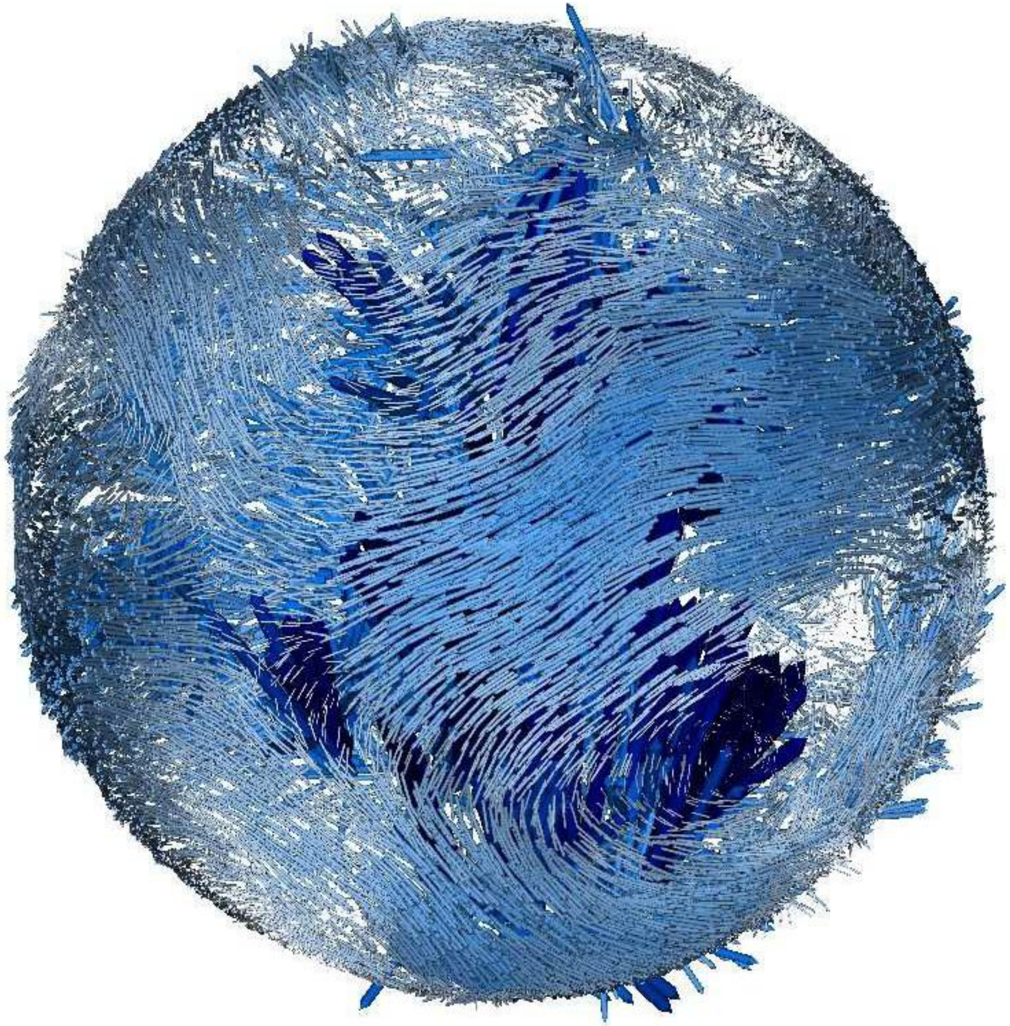
where ρ, T, p, g, and u are the fluid density, temperature, pressure, gravitational acceleration, and velocity.

- **Advection (Godunov method) and reactions (stiff ODE solver) require little communication.**

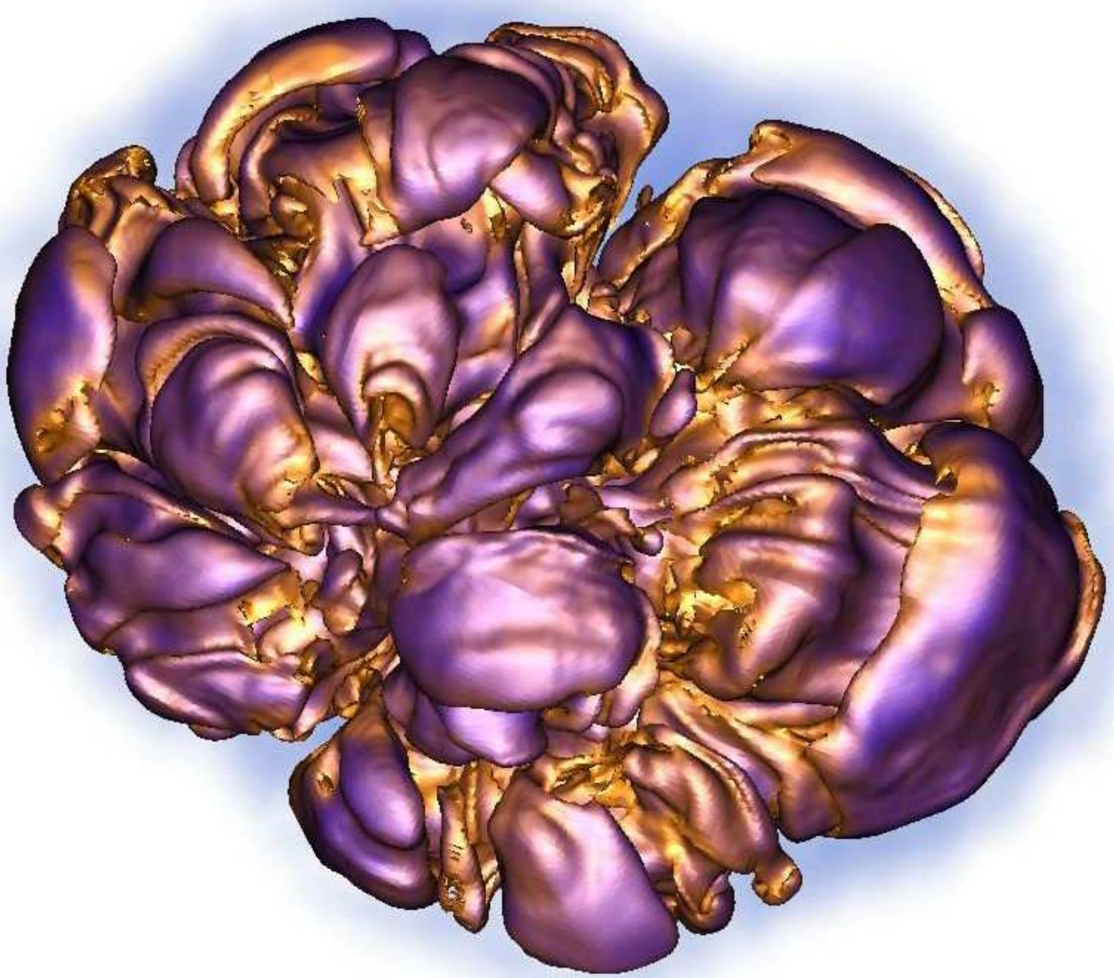


Computationally Intensive Kraken runs

- In 3D, Cartesian domain is a cube of length 10,000 km.
  - Interior to a radius of 200 km, all of our simulations have zones smaller than a kilometer.
  - Exterior to 200 km, the resolution dynamically follows the shock via adaptive grids.
- Total number of grid points is around 10 million
- Number of cores: 16000-32000;
- Memory: ~3 Terabytes total (~100 Megabytes per core);
- 4 simulations; ~1,000,000 CPU-hours per run



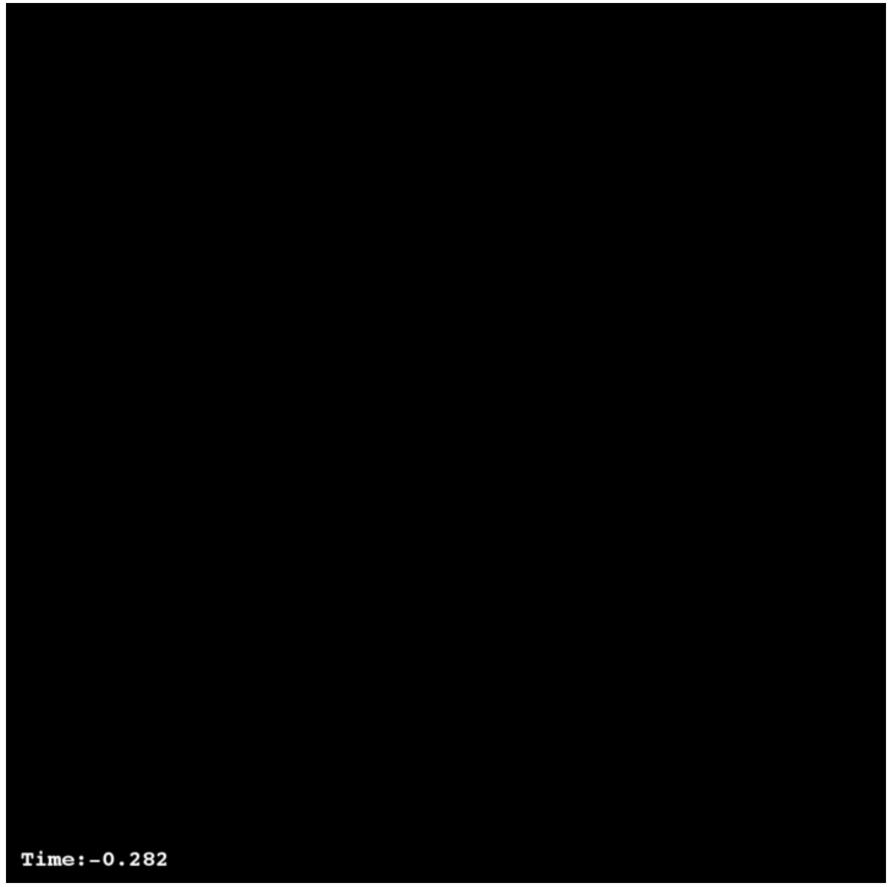
Velocity vector field profile on a spherical shell of radius 90 km towards the end of the simulation (370 ms after core bounce). Both the size and color of the vectors represent the magnitude of the velocity eld, with darker (lighter) shades corresponding to higher (lower) values.



3D rendering of an isentropic surface with entropy equal to 10 k_b $baryon^{-1}$. The colormap represents the magnitude of the entropy gradient on the surface, with values increasing going from orange to purple. The surface spans 1600 km and corresponds to a time 380 ms after core bounce.

Early stages of the supernova explosion of the core of a massive star at its death.

Movies show iso-surfaces of entropy near the shock wave, first produced just after the bounce of the collapsing core. The shock begins life stalled and hovers around a radius of 150 kilometers, but soon, due to constant neutrino heating, is reenergized into explosion.

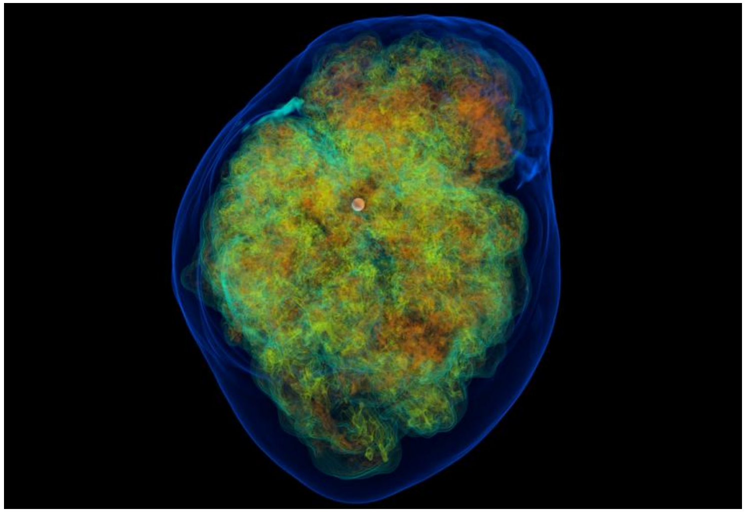


The camera is rotating to present from all sides the turbulent convection that ensues during the stalled phase of the blast and that continues into the explosion phase. The small inner sphere visible in the interior at the end of the movie bounds a region with a density 100 million times that of our Sun's core. This is the proto-neutron star (newly-born pulsar), left behind by the exploding outer region, and has a radius at this stage of only tens of kilometers. The overall scale of the final frames is roughly 2000 kilometers on a side.

The simulation results presented use a fully three-dimensional code CASTRO, which requires on the order of 2 million CPU-hours per run.

On Going and Future Work

- **Finishing 3D multi-group module for CASTRO**
- **Conducting the first-ever such calculations on Kraken and Franklin.**
- **These calculations will be "heroic" if the results are as expected.**
- **These future runs will require significant resources:**
  - **Multi-D supernova simulations are very computational-intensive, requiring for this next generation of simulations ~10-20 million CPU-hours each.**
  - **Need ~ 100 MCPU-hours, if next generation of 3D multi-group simulations proves efficient and successful. The 2D and 1D have already proven out spectacularly.**



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