Stellar explosions are multi-physics problems—modeling them requires the coordinated input of gravity solvers, reaction networks, transport, and hydrodynamics together with microphysics recipes to describe the physics of matter under extreme conditions. Furthermore, these models involve following a wide range of spatial and temporal scales, which puts tough demands on simulation codes. We developed the codes Maestro and Castro to meet the computational challenges of these problems. Maestro uses a low Mach number formulation of the hydrodynamics to efficiently model convection. Castro solves the fully compressible radiation hydrodynamics equations to capture the explosive phases of stellar phenomena. Both codes share the same microphysics and use the AMReX library to provide adaptive mesh refinement and manage the parallelism.

**AMReX**

- **Block structured AMR**
  - Domain divided into varying sized rectangular patches
  - AMReX managed the grid and parallelization
  - Domain codes write kernels that operate on a patch.
  - User-defined tagging criteria for refinement
- **C++/Fortran library
- Hybrid parallelism model based on MPI and OpenMP
  - Coarse-grained distribution of grid patches to nodes using MPI
  - OpenMP threads work within grids
  - Either threading of loops over zones or logical tiling of grids
- Efficient cell-centered and node-centered geometric multigrid solvers provided
- Nightly regression test of all the codes
- Extensive performance and memory profiling tools built-in
- Portability: AMReX-based codes (including Maestro and Castro) run on anything from a laptop to the latest supercomputers
- GPU offloading in development
- Visualization with yt and Visit

**Open development model**

- Open development repositories—all codes are freely available on github
- Planning / review through github issues and pull requests
- Extensive User’s Guides and mailing lists are provided to help new users

**Applications**

- Maestro calculations of the convection occurring in the first generation mass outflow of a Type Ia supernova. The radial velocity profile for typical layers in the interior of a Type Ia supernova is shown, comparing the Mach number to the radius.
- Castro simulation of the inspiral and merger of two white dwarfs, as a model of Type Ia supernovae. The best fit model for Type Ia supernovae is shown with a white dwarf and a neutron star.
- Castro simulation of a buoyant meridional flow in a rotating, stratified, shear layer, which is driven by the non-axisymmetric forces acting on the bottom of the layer.
- Maestro low Mach number hydro (Zingale et al. 2004a,b; Zingale et al. 2005; Morales et al. 2015)
  - Reformulation of compressible Euler equations
  - Return compressibility effects due to heating and stratification
  - Asymptotic expansion in Mach number decomposes pressure into thermodynamic and dynamic parts
  - General equation of state supported
  - Hydrostatic equilibrium analytically enforced:
  \[
  \nabla \rho \approx \rho g
  \]
  - Elliptic constraint on velocity field:
  \[
  n^2 \left( \frac{\partial u}{\partial x} \right)^2 = \frac{1}{\rho g} \left( \frac{\partial \rho}{\partial x} \right)
  \]
  - \( \rho \) is a density-like variable that captures atmospheric stratification
  - S represents reactions and external heating sources
  - Self-consistent evolution of base state
  - Time-step based on bulk fluid velocity, not sound speed
  - Brings ideas from the atmospheric, combustion, and applied math communities to nuclear astrophysics

**Solution methodology**

- Unsplit PPM advection
- Implicit thermal diffusion (solved via multigrid)
- Approximate projection enforces continuity of temperatures (cell-centered and node-centered multigrid)
- Strang-splitting for reactions

**Shared Microphysics**

- https://github.com/StarKiller-astro/Microphysics/
  - Common EOS and reaction networks appropriate for stellar hydrodynamics
  - Reaction righthand side decoupled from integration method
  - JINA ReactLib interface via pynucastro

**Future developments**

- Maestro:
  - Port to C++ framework
  - Rapid rotation
  - Higher-order accuracy
- Castro:
  - New hydrodynamics solvers / MHD
  - Improved coupling of reactions, hydrodynamics, and gravity
- Microphysics infrastructure:
  - GPU acceleration of EOS and reactions

**Castro: compressible radiation hydro**

- 1-, 2-, and 3-dimensional unsplit, 2nd-order hydrodynamics
- Multigroup flux-limited diffusion radiation hydrodynamics, including terms to O(\(v/c\))
- Adaptive mesh refinement with sub-cycling in time: Jumps of 2x and 4x between levels
- Arbitrary equation of state
- General nuclear reaction networks
- Explicit thermal diffusion
- Full Poisson gravity (with isolated boundary conditions), conservative flux formulation
- Rotation (in the co-rotating frame) in 2-d axisymmetric and 3-d
- Ability to restart from a Maestro calculation to bring it into the compressible regime

**Parallel performance**

- Maestro strong scaling on OLCF Titan for pure hydro (more w/ real EOS). The different colors represent different base resolutions. Runs are done with jumps of 2x and 4x in refinement and show excellent strong scaling across all processor counts. (Right) Castro strong scaling on OLCF Titan for a hydro + Poisson gravity model for Type Ia supernovae. (Zingale et al. 2013, Jacobs et al. 2016, used OLCF Titan)
- Maestro strong scaling on NERSC Edison and OLCF Titan. Two different problem sizes are shown, demonstrating good scaling to high core counts. The turn off at the end at OLCF is from crossing NUMA nodes.

- Castro: compressible radiation hydro
  - 1-, 2-, and 3-dimensional unsplit, 2nd-order hydrodynamics
  - Multigroup flux-limited diffusion radiation hydrodynamics, including terms to O(\(v/c\))
  - Adaptive mesh refinement with sub-cycling in time: Jumps of 2x and 4x between levels
  - Arbitrary equation of state
  - General nuclear reaction networks
  - Explicit thermal diffusion
  - Full Poisson gravity (with isolated boundary conditions), conservative flux formulation
  - Rotation (in the co-rotating frame) in 2-d axisymmetric and 3-d
  - Ability to restart from a Maestro calculation to bring it into the compressible regime

**Visualizations**

- Castro simulation of the inspiral and merger of two white dwarfs, as a model of a Type Ia supernova. The best fit model for Type Ia supernovae is shown with a white dwarf and a neutron star.
- Maestro simulation of the implosion of a white dwarf and the resulting thermonuclear explosion during a Type Ia supernova.
- Castro simulation of a buoyant meridional flow in a rotating, stratified, shear layer, which is driven by the non-axisymmetric forces acting on the bottom of the layer.
- Maestro simulation of connection in the accreted helium layer on a white dwarf, showing the radial velocity (red = outflow; blue = inflow). Three different models are shown: (top) a 0.8 \(M_\odot\) white dwarf with a 0.04 \(M_\odot\) He layer; (middle) a 1.4 \(M_\odot\) white dwarf with a 0.04 \(M_\odot\) He layer; and (bottom) a 2.0 \(M_\odot\) white dwarf with a 0.02 \(M_\odot\) He layer.
- Maestro: compressible radiation hydro (Zingale et al. 2005, Morales et al. 2015, used OLCF Titan)
- Castro: compressible radiation hydro (Zingale et al. 2004a,b; Zingale et al. 2005; Morales et al. 2015)

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**NVIDIA**

- GPU acceleration of EOS and reactions

**OLCF**

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**Stony Brook University**

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**Simulations Codes for Astrophysical Reaction Flows**

- https://github.com/StarKiller-astro/Microphysics/

**Arrangement of text and layout**

- The text is arranged in a natural reading order, with sections and sub-sections clearly defined.
- Figures and tables are placed adjacent to the text they illustrate.

**Resources**

- For more information, visit the project websites:
  - https://github.com/StarKiller-astro/Microphysics/
  - https://github.com/StarKiller-astro/AMReX-Astro