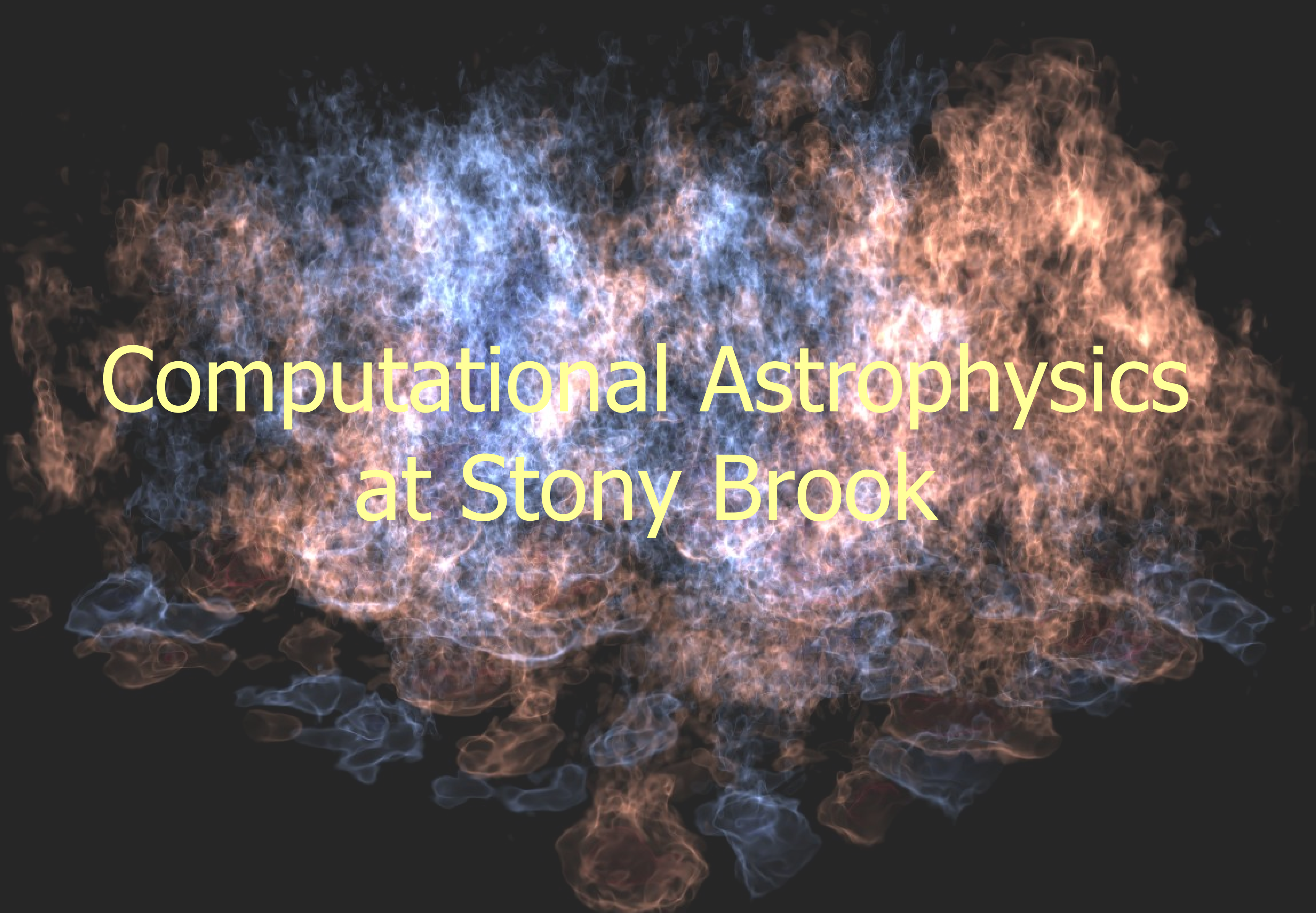
Computational Astrophysics at Stony Brook



Stony Brook Computational Astro

- Broad interests:
  - *Stellar explosions*: Type Ia supernovae, X-ray bursts, novae, …
  - *Radiation hydro*: black widow pulsar, exoplanetary heating
  - *Algorithmic development*: low speed solvers
- Faculty:
  - Alan Calder
  - Jim Lattimer
  - Doug Swesty
  - Mike Zingale
- Grads:
  - Sheridan Curley
  - Adam Jacobs
  - Max Katz
  - Don Willcox

Simulation Codes

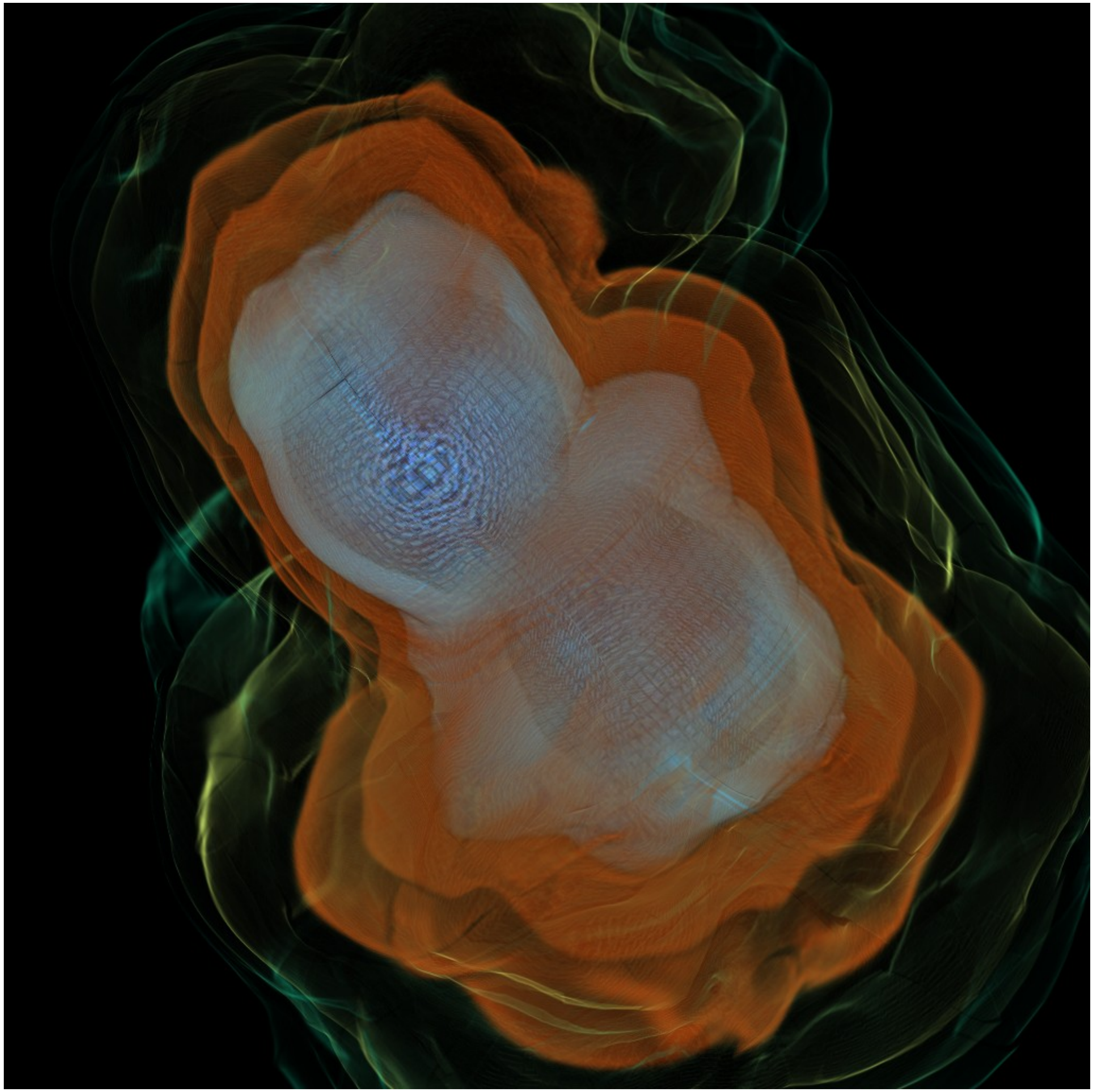
- Generally, we work on developing patch-based adaptive mesh refinement codes
- Castro: AMR compressible radiation hydrodynamics
  - Developed in collaboration with CCSE/LBNL
  - Built on BoxLib (C++/Fortran)
- Flash: AMR compressible hydrodynamics
  - Developed by Chicago Flash Center—Calder and Zingale are former members
- Maestro: low Mach number hydrodynamics
  - Developed in collaboration with CCSE/LBNL
  - Built on BoxLib (Fortran 2003)
- V2D: 2-d multigroup neutrino rad hydro code
  - Solves first law of thermodynamics in place of total energy eq
  - Uses a generalized tabular EOS
  - Swesty & Myra

Castro

- Fully compressible AMR radiation hydrodynamics code
  - Gray and MG FLD radiation
  - Unsplit PPM hydrodynamics solver
  - Arbitrary reaction network and equation of state
  - Self gravity (Poisson via MG) with isolated, periodic, Dirichlet/Neumann BCs
  - Jumps of 2 and 4x between levels and AMR subcycling
  - Ability to restart from a Maestro calculation
- Freely available:
  - Main Castro: https://github.com/BoxLib-Codes/Castro
  - Radiation module: https://github.com/BoxLib-Codes/CastroRadiation

Castro WD Mergers

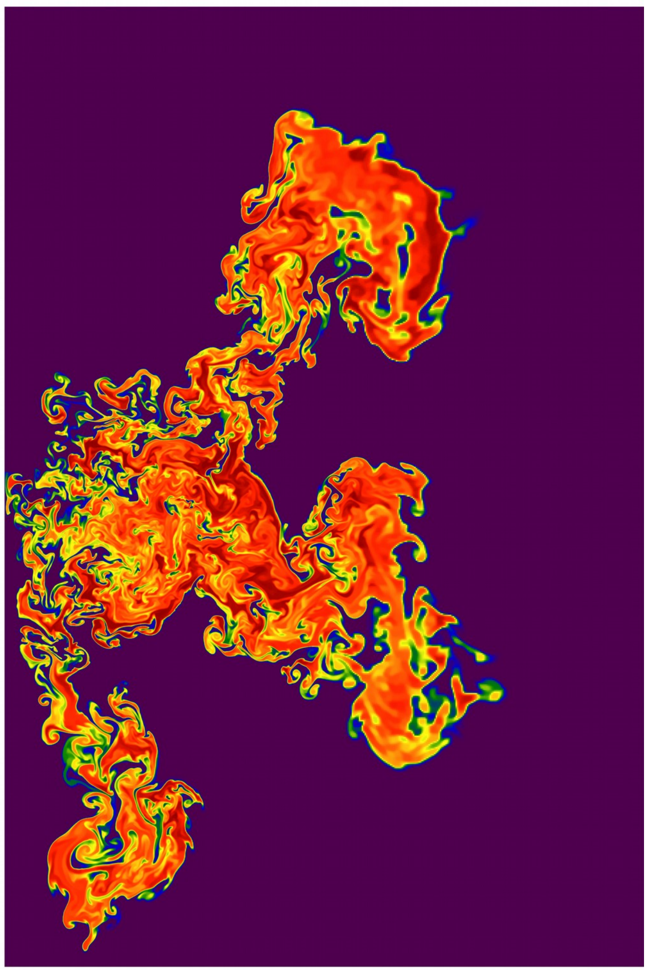
- Currently modeling the inspiral and merger of two white dwarfs



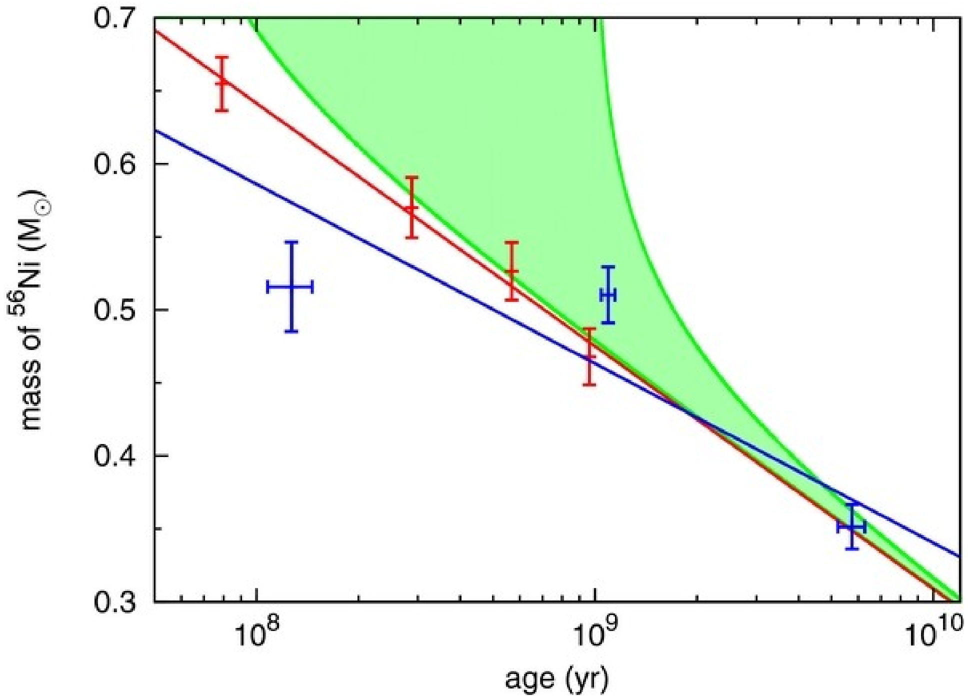
All the source code, setup files, etc., are freely available online on github

Flash SNe Ia Explosions

- Flash is used for SNe Ia explosion models
  - flame model + network allow for deflagrations

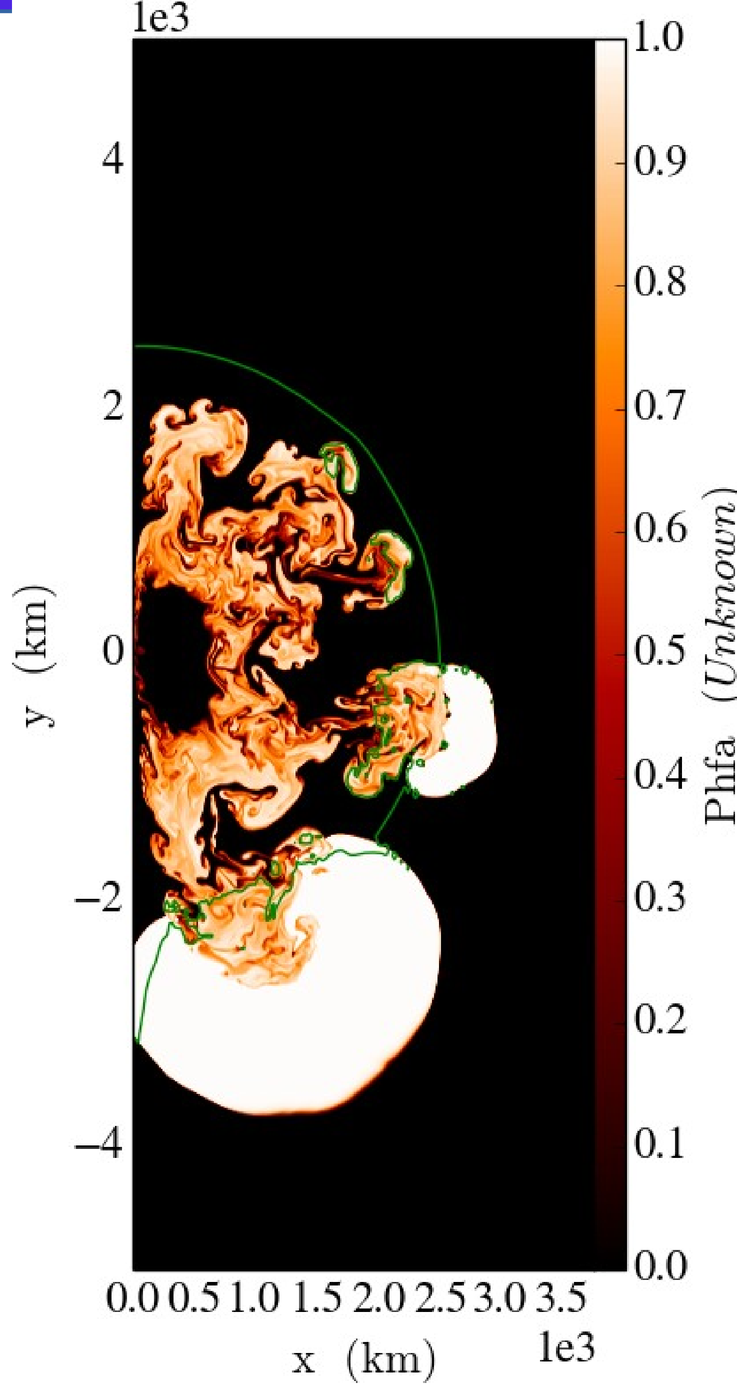


Rising fireball during the deflagration phase of an SNe Ia in the DDT paradigm



^{56}Ni mass synthesized in an explosion (red points and fit) as a function of progenitor age (red curve) where age is measured as the cooling time of the WD before accretion. The green region represents a range of main sequence lifetimes that could be added to give the age as the "delay time" from star formation. The blue points and fit are the observational results of Neill et al (2009). While the slope is different, the trend is in the same direction.

Flash SNe Ia Explosions



A deflagration ignited on a shell rises to the meet the deflagration-to-detonation density (green contour) and the resulting detonation fronts begin to consume the star. Unburned fuel (C, Ne) is shown in black, and ash (Mg, O) in white.

Maestro: Low Mach Hydro

- Reformulation of compressible Euler equations
  - Retain compressibility effects due to heating and stratification
  - Asymptotic expansion in Mach number decomposes pressure into thermodynamic and dynamic parts
  - Analytically enforce hydrostatic equilibrium through base state:

$$\nabla p_0 = \rho_0 g$$

- Elliptic constraint on velocity field:

$$\nabla \cdot (\beta_0 \mathbf{U}) = \beta_0 \left(S - \frac{1}{\bar{\Gamma}_1 p_0} \frac{\partial p_0}{\partial t} \right)$$

  - β_0 is a density-like variable
  - S represents heating sources
- Self-consistent evolution of base state
- Timestep based on bulk fluid velocity, not sound speed
- Brings ideas from the atmospheric, combustion, and applied math communities to nuclear astrophysics

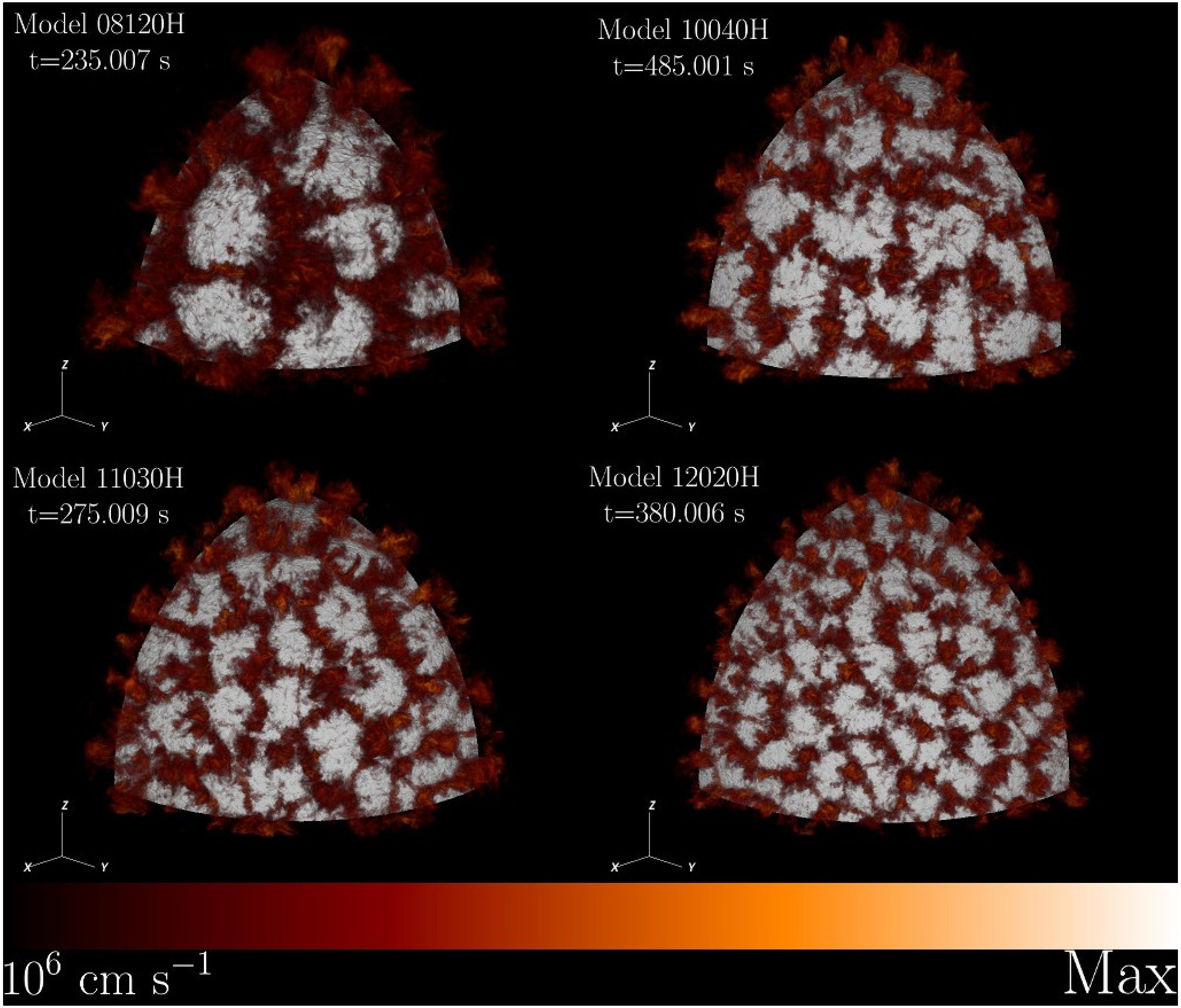
Maestro: Low Mach Hydro

- Solved via a fraction step method:
  - Advection terms handled with an unsplit Godunov method
  - Diffusion (if used) via an implicit solve with multigrid
  - Constraint enforced via projection, solved via multigrid
  - Reactions via Strang-splitting
  - Overall second-order in space and time
- Supports a general equation of state
  - Includes some recent ideas on energy conservation in low Mach systems with general equations of state
- Supports arbitrary reaction networks
  - Multiple species advected
  - New coupling mode (SDC) underway
- Lagrangian tracer particles
- MPI + OpenMP hybrid approach to parallelism via BoxLib

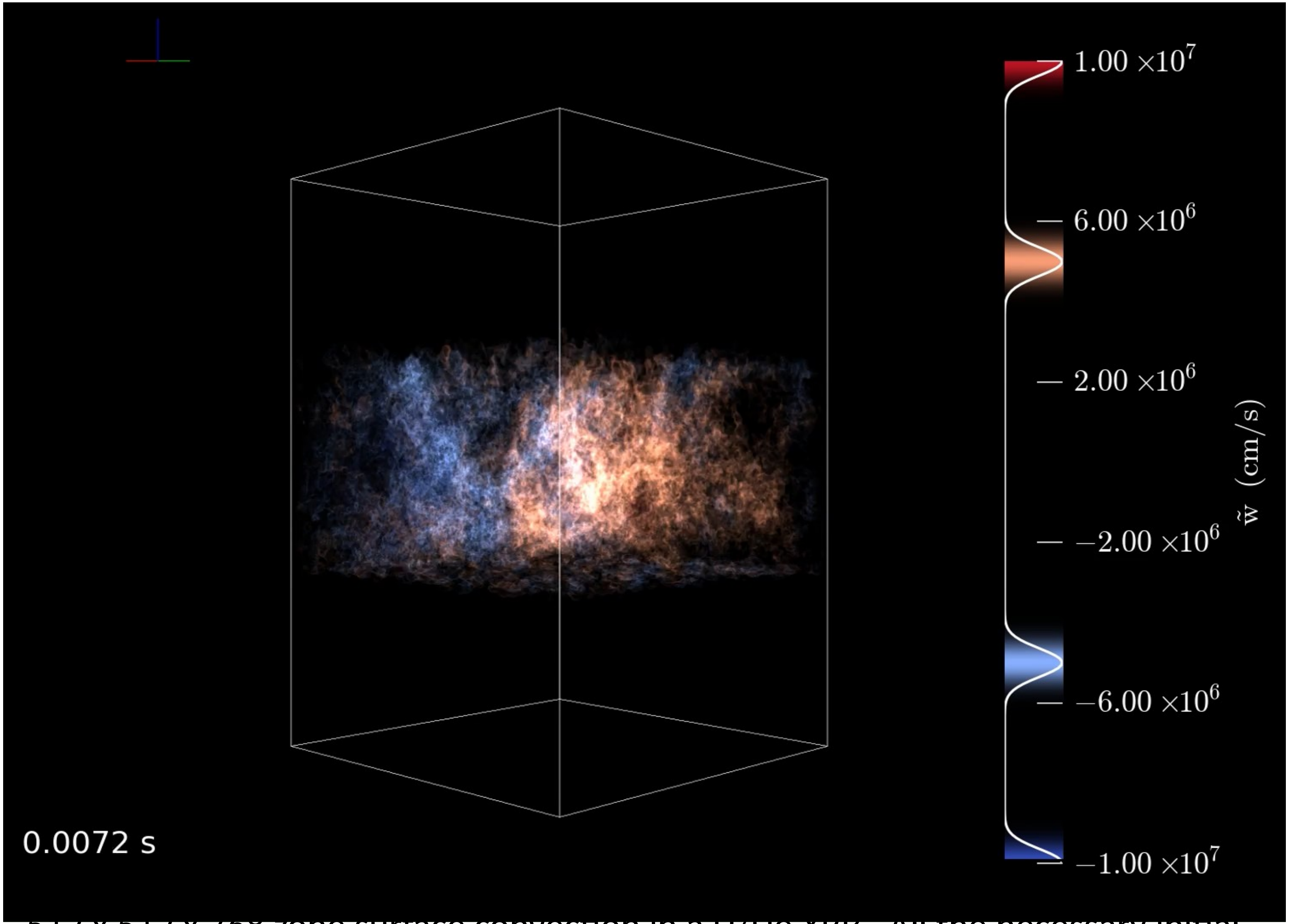
Community Support

- Maestro is a large code
  - Publicly available at: `https://github.com/BoxLib-Codes/MAESTRO`
  - > 300 page users guide
  - E-mail support list
- Potential applications in astrophysics include:
  - Classical novae
  - URCA process in white dwarfs
  - Proto-neutron star cooling
  - Core convection in massive stars
  - Shell burning in evolved stars
  - Multidimensional core-collapse SNe progenitor models
  - Convection in exoplanetary interiors

Maestro sub-Chandra SNe Ia



Maestro X-ray Bursts



512 x 512 x 768 zone surface convection in a H/He XRB. All the necessary initial models, microphysics, inputs files, initialization routines, etc. for this problem are distributed with Maestro

Angle Dependent MG Rad Transport

- A current project is underway to develop a new class of implicit finite-volume methods for angle dependent rad transport & rad hydro

$$\frac{\partial I_\nu}{\partial t} + \mathbf{n}\cdot\nabla I_\nu + I_\nu \int d\nu' \int d\mathbf{n}' \kappa^s_\nu(\mathbf{n},\mathbf{n}') - \int d\nu' \int d\mathbf{n}' \kappa^s(\mathbf{n}',\mathbf{n}) I_{\nu'}(\mathbf{n}') = S_\nu - c\kappa^a_\nu I_\nu$$

- Designed to have correct transport speeds in optically thick, as well as thin, limits
  - Utilizes S_N angular discretization
  - Utilizes time-dependent formal solution of time-dependent rad transfer equation to accurately predict fluxes at cell edge

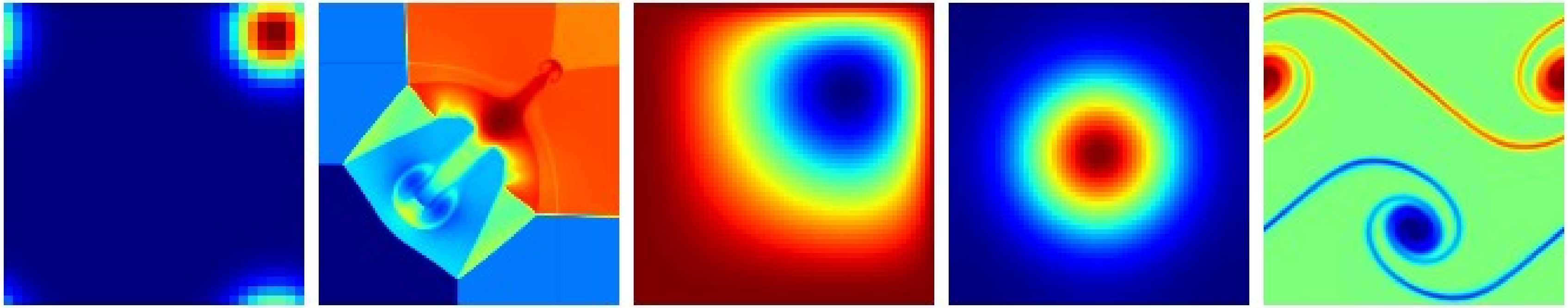
$$I_\nu(\mathbf{x},\mathbf{n}) = \int_0^{s_0} ds' S_\nu(\mathbf{x}-\mathbf{n}s',\mathbf{n}) \exp\left(-\int_0^{s'} ds'' \kappa_\nu(\mathbf{x}-\mathbf{n}s'',\mathbf{n})\right) + I_\nu(\mathbf{x}_s,\mathbf{n}) \exp\left(-\int_0^{s_0} ds'' \kappa_\nu(\mathbf{x}-\mathbf{n}s'',\mathbf{n})\right)$$

  - Includes scattering contributions as well as correctly including source/sink terms in flux calculation
- Utilizes highly scalable Krylov subspace algorithms for linear system solve
- Initial intended application is modeling time-dependent NS atmospheres, e.g. NS atmospheres during bursts

Institute for Advanced Computational Science @ SBU

- 8+ faculty (Physics & Astronomy, Applied Math, CS, SOMAS, Marine Sciences)
  - Hiring now!
- ~1000 core cluster
- Provides student fellowships, some training
- Working toward computational science graduate certificate
  - 1^{st} step: interdisciplinary programs hard
- Alan is happy to talk to anyone who has a similar situation

Pyro: Hydro by Example



- A "python hydro" code designed with clarity in mind to teach students about simulation techniques
- 2-d solvers for:
  - Linear advection
  - Compressible hydrodynamics
  - Elliptic equations (via multigrid)
  - Implicit diffusion
  - Incompressible hydrodynamics
  - Low Mach number atmospheric flows
  - Coming soon: gray flux limited diffusion radiation hydrodynamics
- BSD-3 licensed, up on github: https://github.com/zingale/pyro2

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Current Texts

Computational Hydrodynamics for Astrophysics

PDF version

An introduction to the grid-based methods commonly used for astrophysical simulation, starting with linear advection and developing the methods for the compressible Euler