Modeling the Early Phases of Type Ia Supernovae

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in collaboration with

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Convection in Astrophysics

- Evolution of many stellar systems dominated by convective transport of energy
  - Supernovae (both thermonuclear and gravitational)
  - X-ray bursts and novae (thermonuclear explosion of accreted material on a surface of compact object)
  - General stellar evolution, including post main-sequence evolution of massive stars
- Often the convection is highly subsonic
  - Challenging for traditional astrophysical hydrodynamics codes
- New algorithms are needed for efficient simulation of convective astrophysical flows

Low Mach Hydrodynamics

- With explicit timestepping, information cannot propagate more than one zone per step

$$\Delta t = \min \left\{ \frac{\Delta x}{|u| + c} \right\}$$

- For M ≪ 1 :

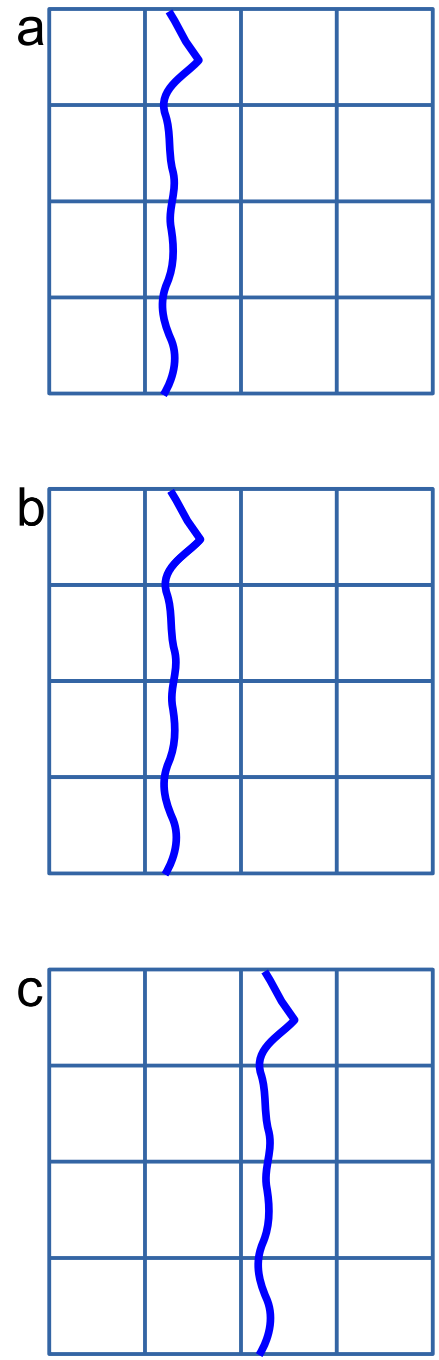
$$\Delta t \approx \frac{\Delta x}{c}$$

- We want:

$$\Delta t \approx \frac{\Delta x}{|u|}$$

- For very low Mach number flows, it takes ~ 1/M timesteps for a fluid element to move more than one zone—can't we do better?

▶ A Mach 0.01 front moving to the right (a) initially, (b) after 1 step, (c) after 100 steps.



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

Outstanding Questions in SNe Ia

- General consensus: thermonuclear explosion of a carbon/oxygen white dwarf
- What is the progenitor?
  - Diversity of observations suggests multiple progenitor channels
  - Single white dwarf or merging white dwarf?
  - Chandra or sub-Chandra mass?
- Single degenerate channel:
  - What are the initial conditions?
  - Does the burning front remain subsonic?
- Double degenerates:
  - Can we avoid the accretion induced collapse?
  - Can we get an explosion that looks like a SNe Ia?
- What is the physical basis for the width-luminosity relationship in the lightcurve?
  - Some variation in the explosion is needed to account for the diversity in explosions.

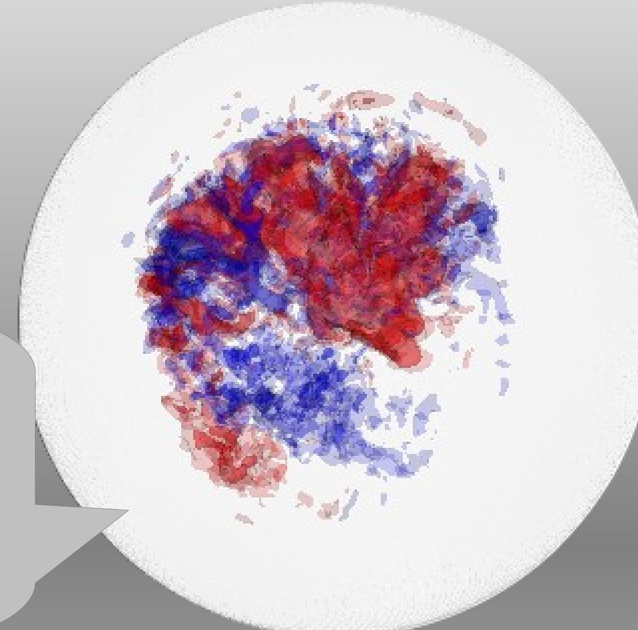
No single code can address all of these questions

Type Ia Supernovae

(Chandra-mass single-degenerate scenario)

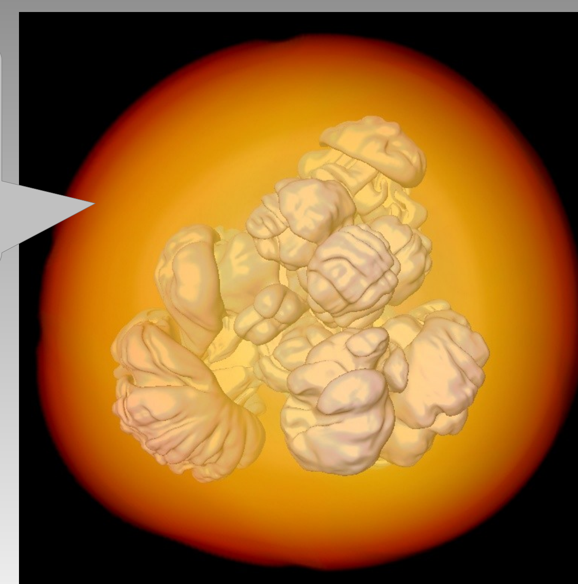
(David A. Hardy & PPARC)

1 Accretion from binary companion. Grows to M_{ch}



2 “Smoldering” phase—central T rises → flame born

3 Flame propagation. Initially subsonic, but detonation transition?



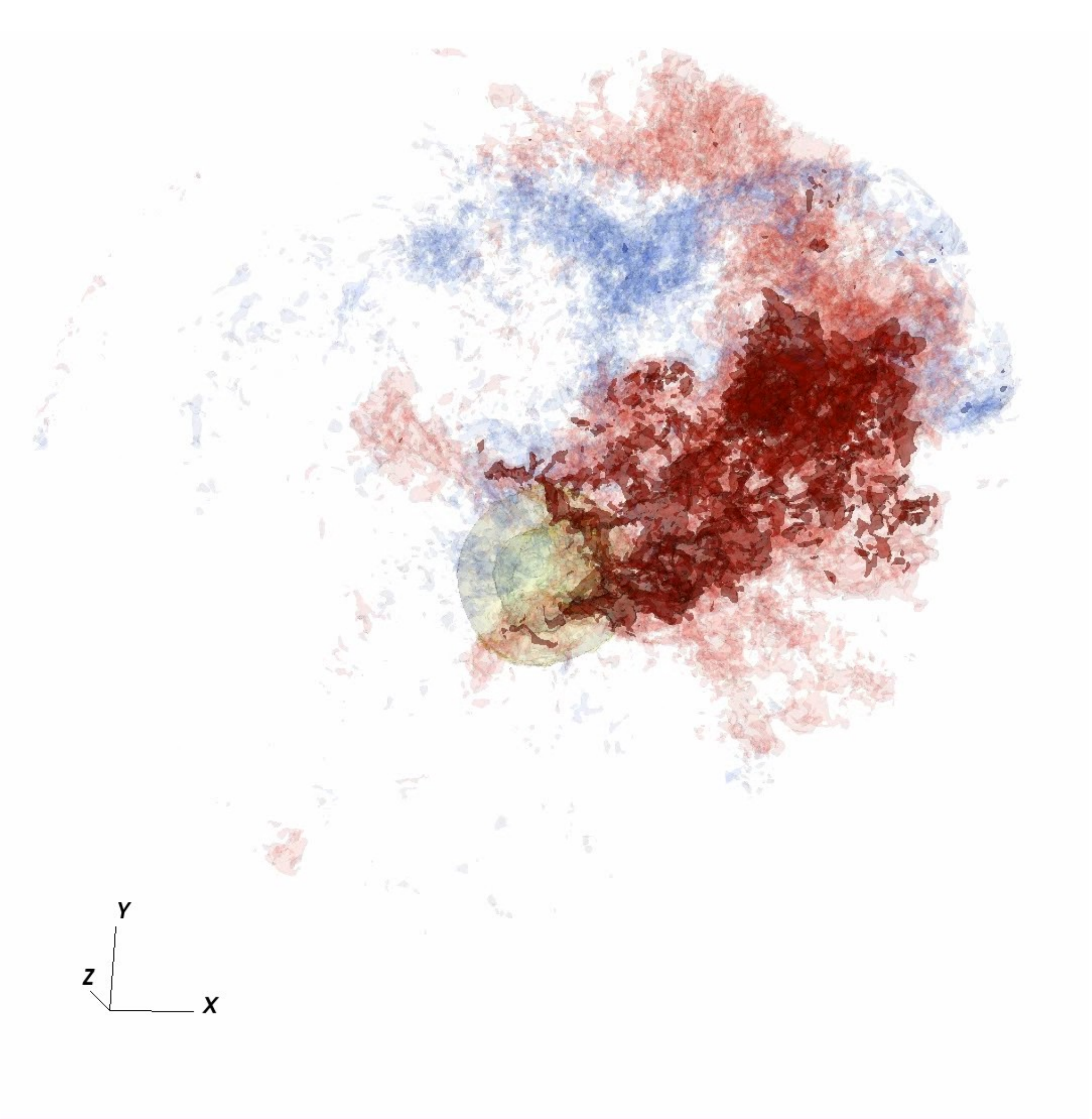
(Roepke and Hillebrandt 2005)

SN 1994D (High-Z SN Search team)

4 Explosion! Lightcurve powered by Ni decay. Width / luminosity relation.

Dipole Convection

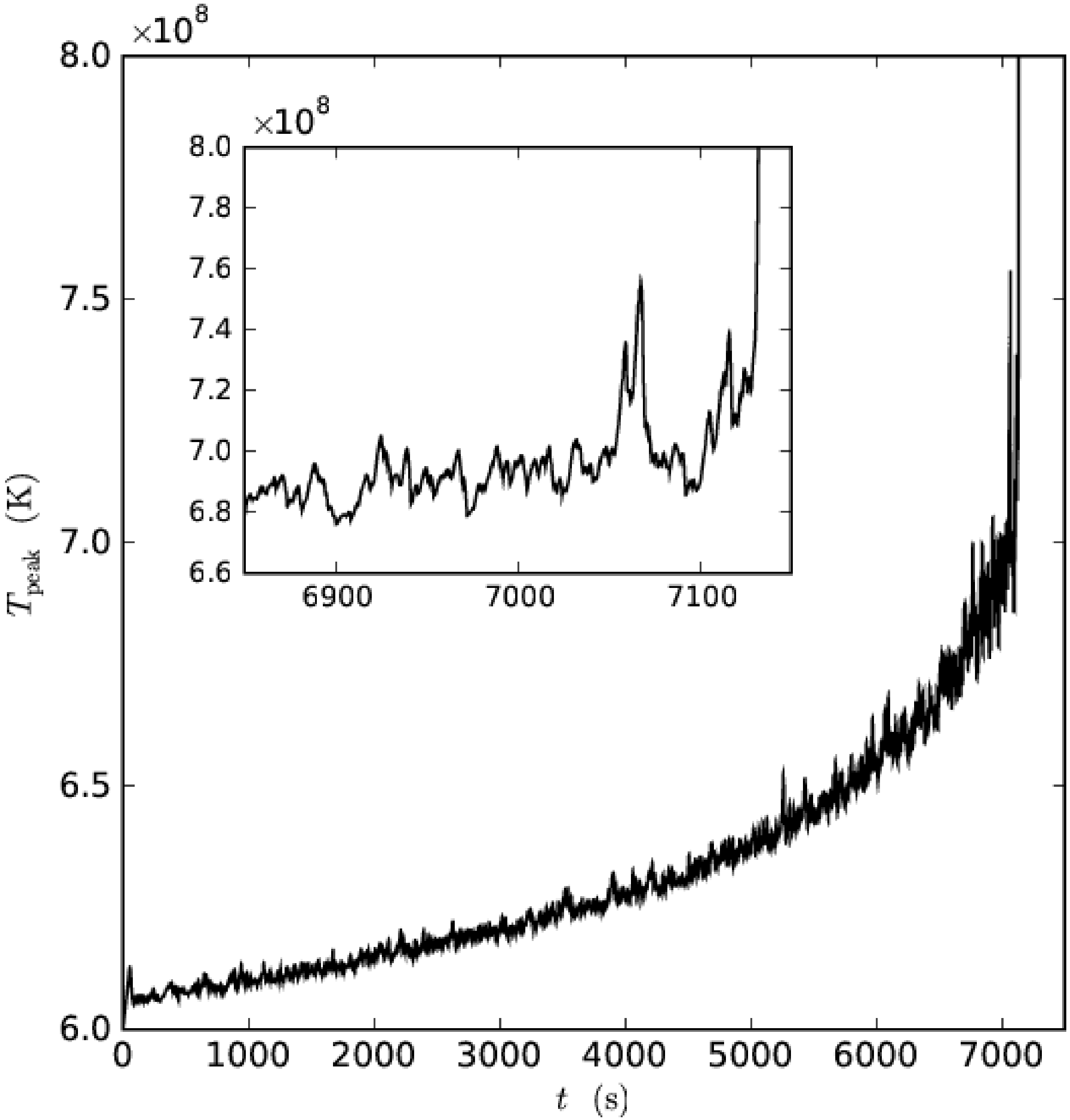
- Dipole feature seen in previous calculations better described as a jet
  - Asymmetry in radial velocity field
- Direction changes rapidly



Radial velocity field (red = outflow; blue = inflow) in an 1152^3 non-rotating WD simulation.

Nonlinear Runaway

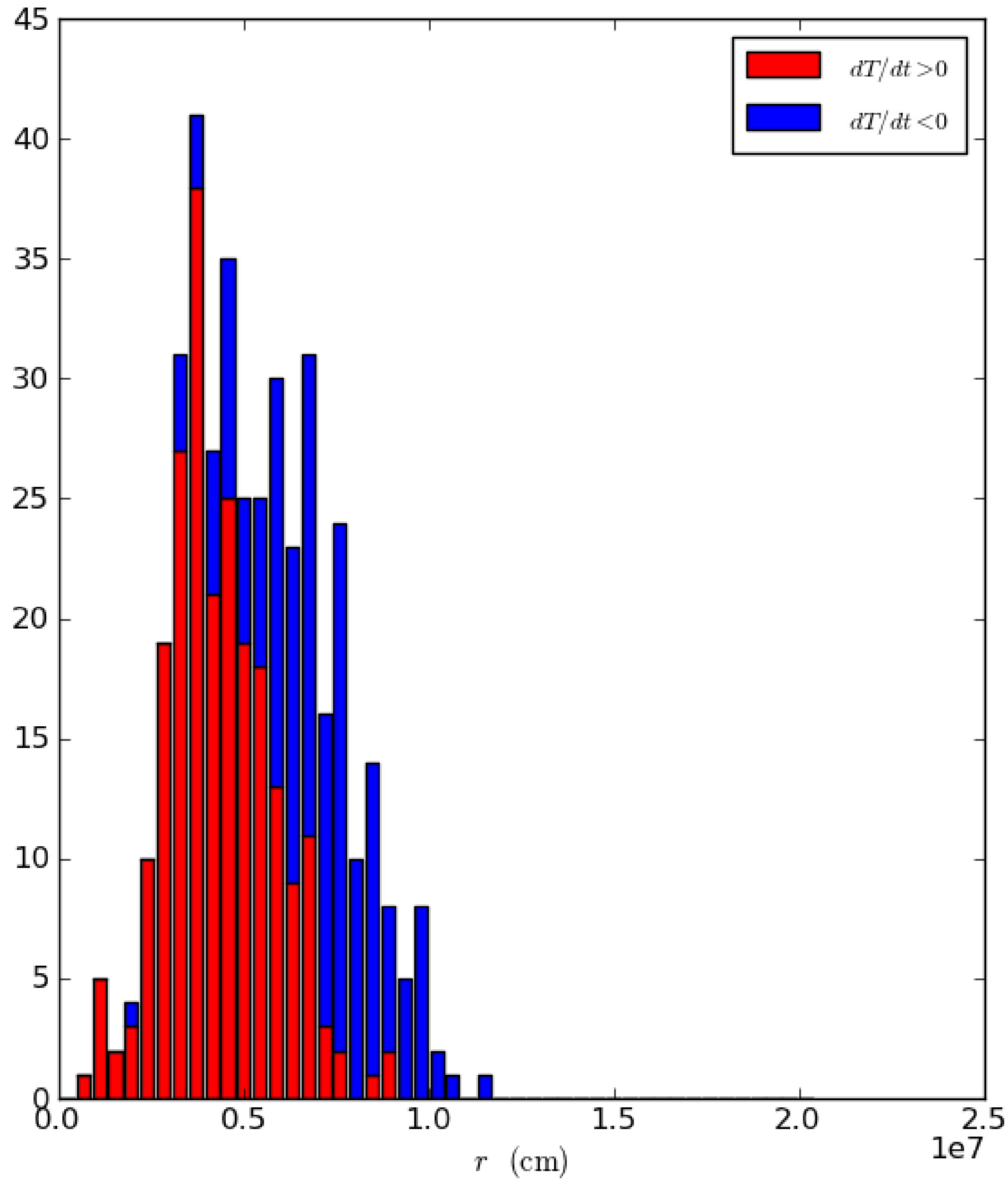
- Temperature increase nonlinear
  - Ignition occurs as T crosses 8 x 10^8 K
  - “Failed” hotspots seen toward the end.



Ignition Radius Likelihood

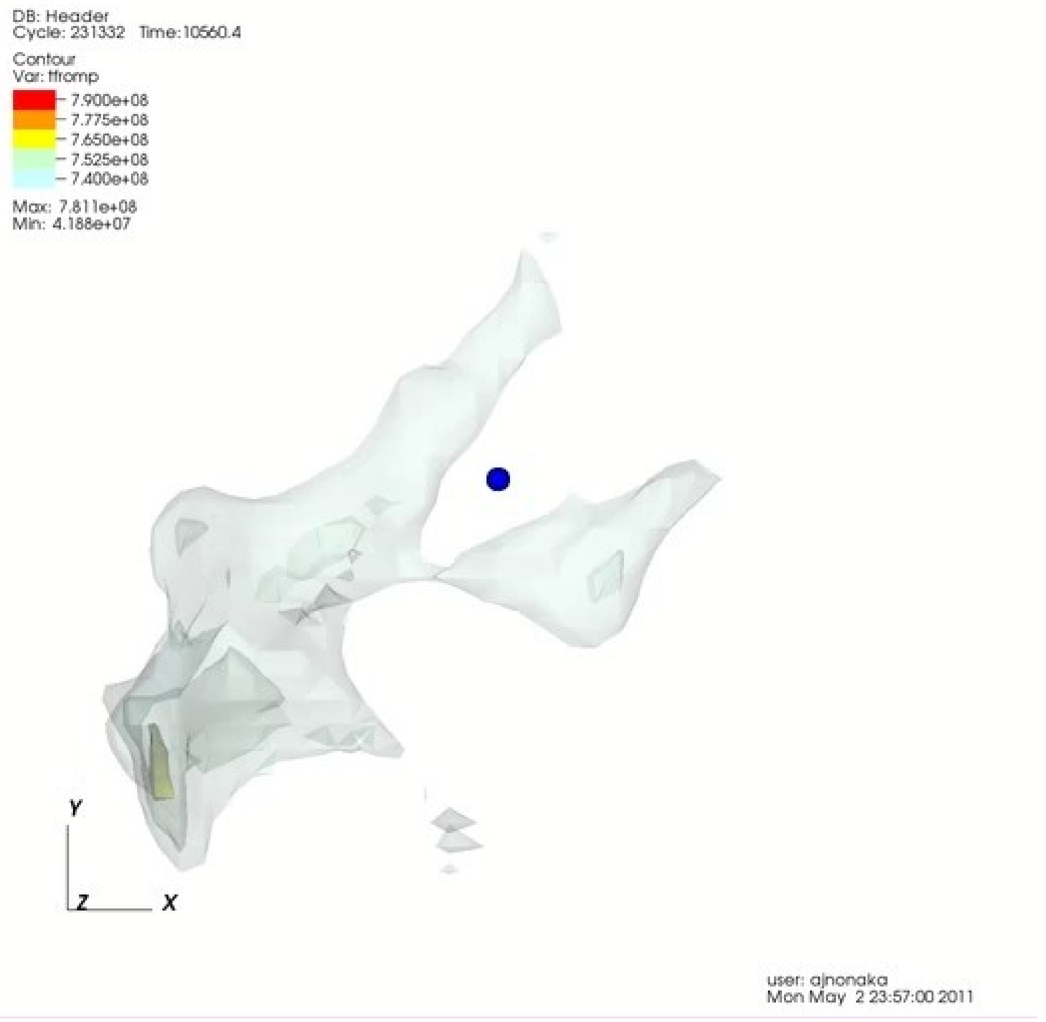
- Distribution of likely ignition locations
  - Average hotspot radius over 1 s intervals
  - Consider final 200 s of evolution
- Vast majority of hotspots are moving outward from the center
- Off-center ignition likely

► Histogram of likely ignition radii from 576^3 non-rotating model. Hotspot radii are averaged into 1 s intervals and colored by sign of temperature change



Multiple Ignition?

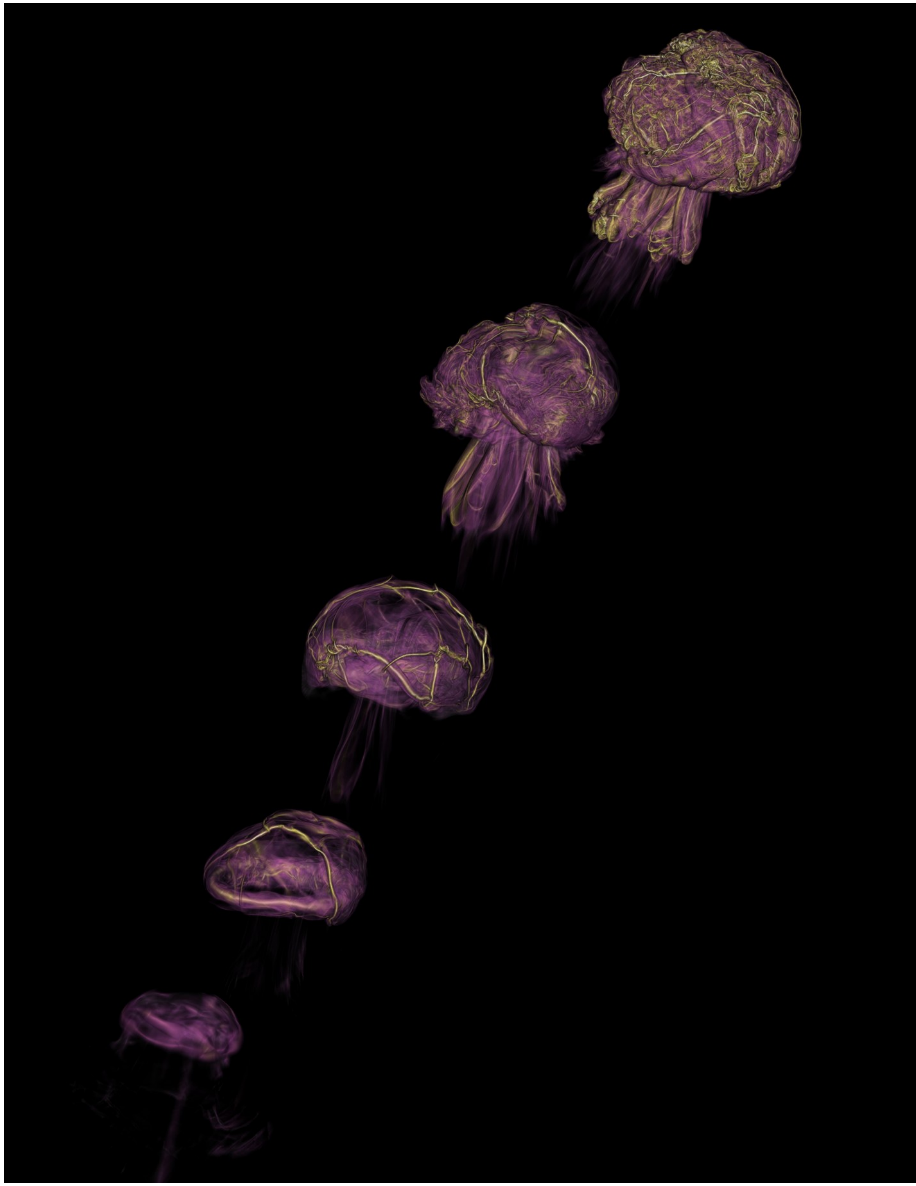
- Disable burning in a hot spot once it ignites to allow further evolution
- Second hot spot is not present over a short timescale
- Single-point, off-center ignition most likely.



On To Explosion...

- Mach number gets large (ignition): restart in our compressible code, Castro
  - Same underlying BoxLib discretization
  - Same microphysics
  - Solves the fully compressible Euler equations using an unsplit PPM method
- Basic findings:
  - Off-center ignition: background turbulence doesn't strongly affect flame propagation.
  - Central ignition: convective turbulence can push the flame off-center.
  - Single-degenerate model almost always produces an asymmetric explosion
  - Single spot = small amount of burned mass = less expansion = higher density when DDT occurs

Castro (including MGFLD radiation solver) is freely available at: https://github.com/BoxLib-Codes)



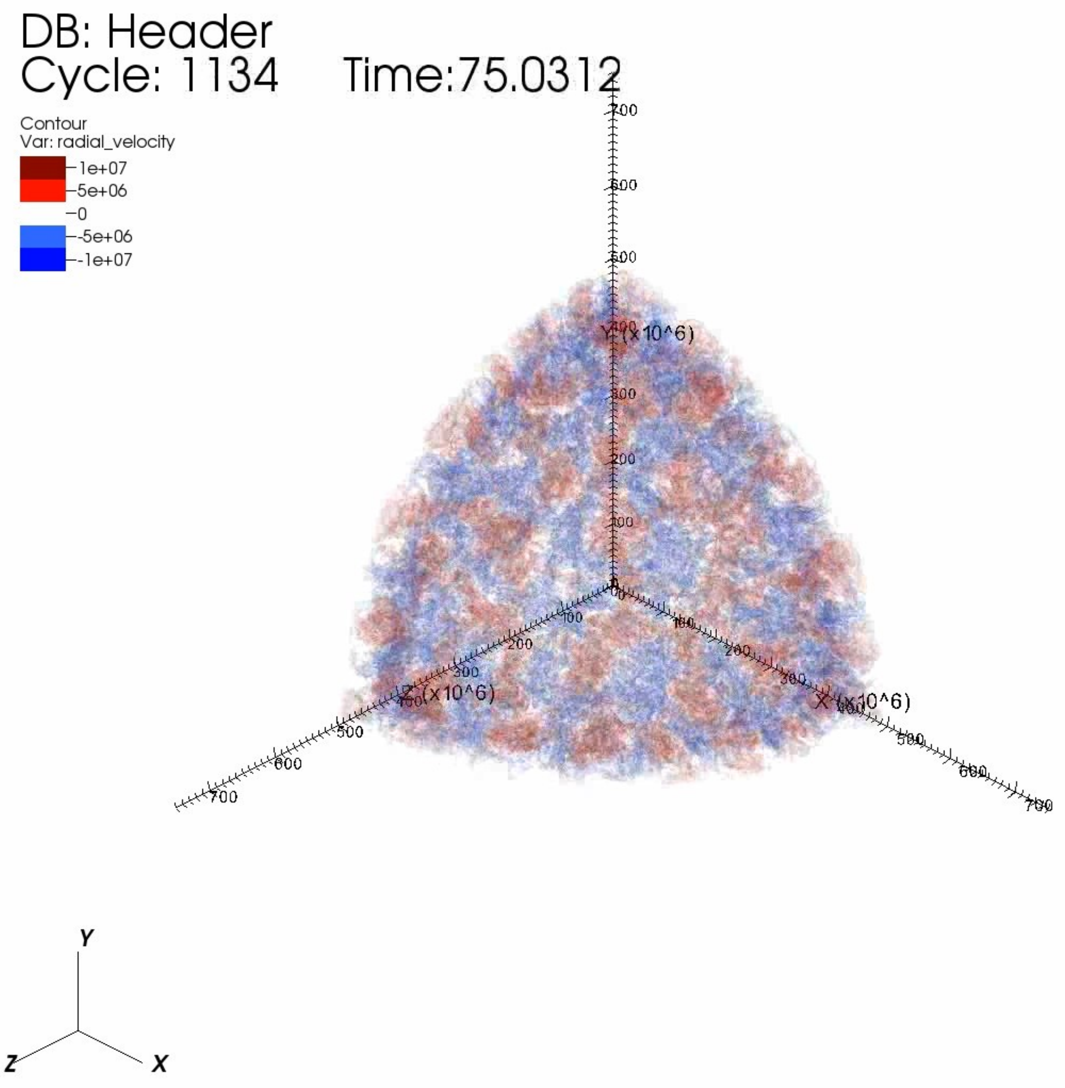
(Malone et al. 2014)

sub-Chandra SNe Ia Models

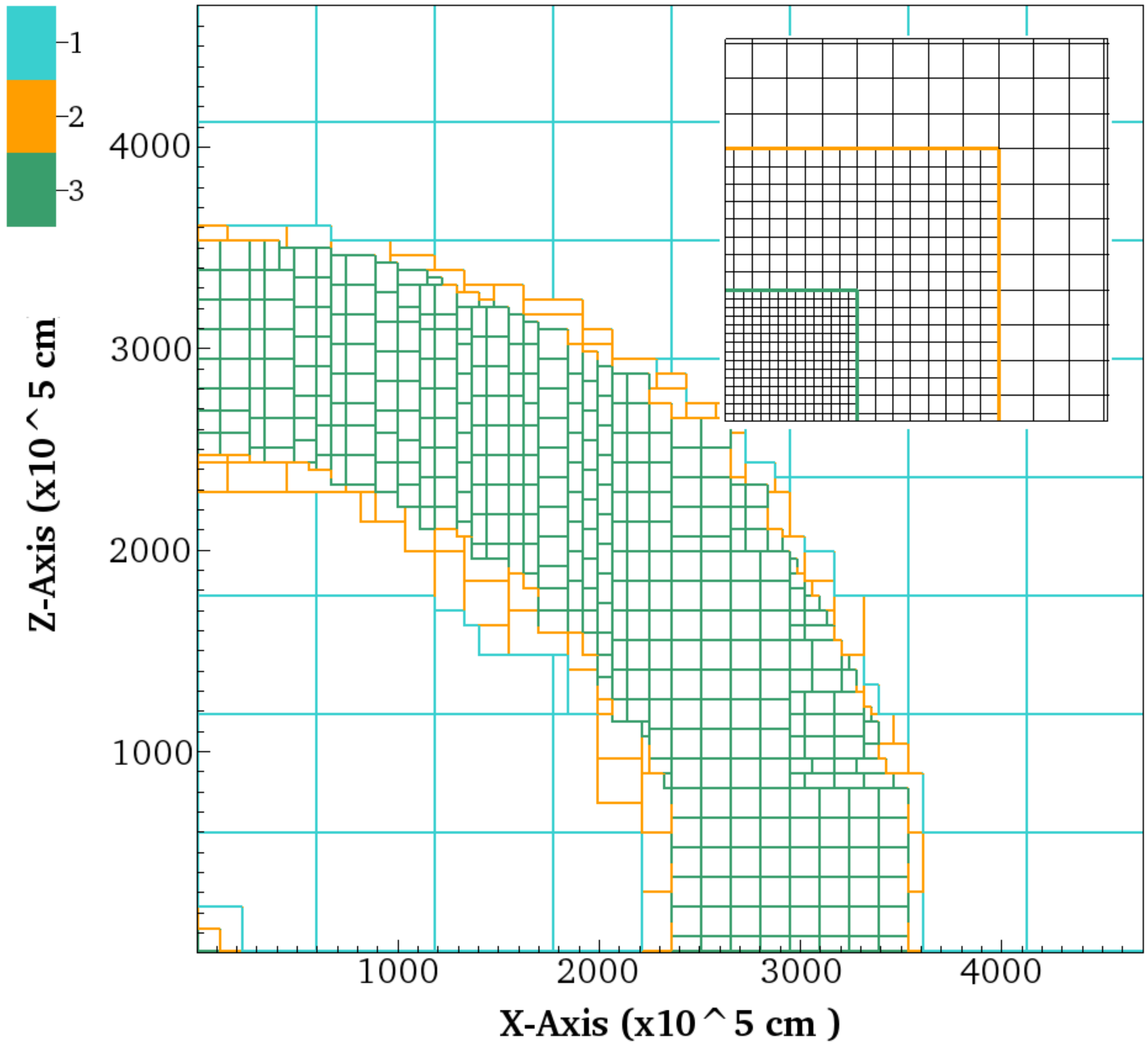
- Basic idea:
  - Burning begins in an accreted helium layer on the surface of a low(er) mass white dwarf
  - Detonation
- How does the burning transfer to the C/O core?
  - Edge lit: direct propagation of detonation across interface. May require ignition at altitude
  - Double detonation: compression wave converges at core, ignites second detonation at the center of the WD
- Main problem: how much surface He is too much?
- Potential progenitors: Iax class SNe (Foley et al. 2013)
  - Lower velocity, lower peak magnitude, hot photosphere
- Our focus:
  - What does the ignition in the He layer look like?
  - What variety of outcomes can we expect for different masses?

Convective Structure

- Cellular/granular pattern forums
- Length scale seems converged with resolution
- Hot spots rise up and expand
- Potentially multiple hot spots simultaneously

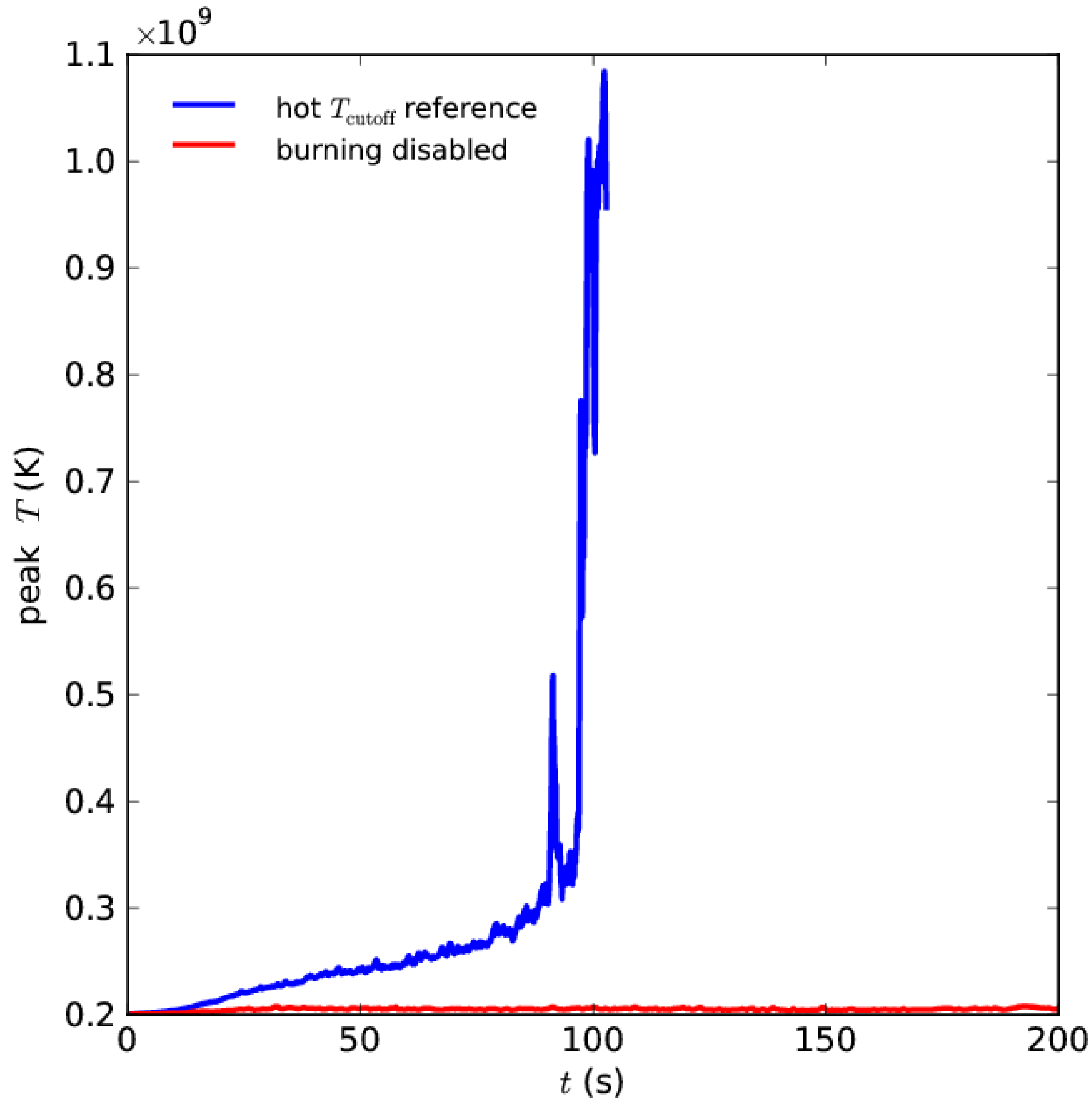


sub-Chandra SNe Ia Models



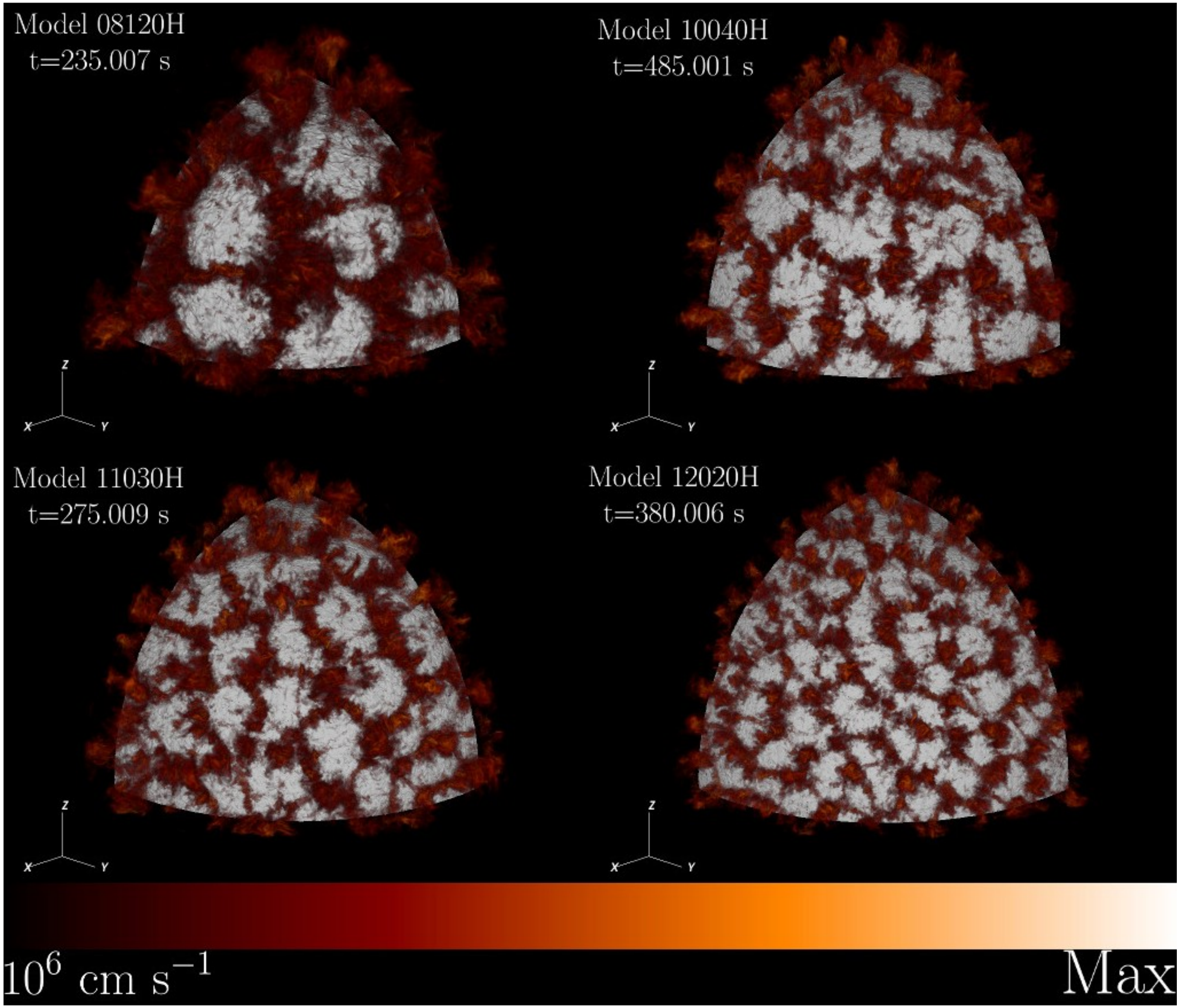
Runaway

- Runaway driven by 3-alpha and $^{12}C(\alpha,\gamma)^{16}O$
  - Next set of calculations will use a bigger network



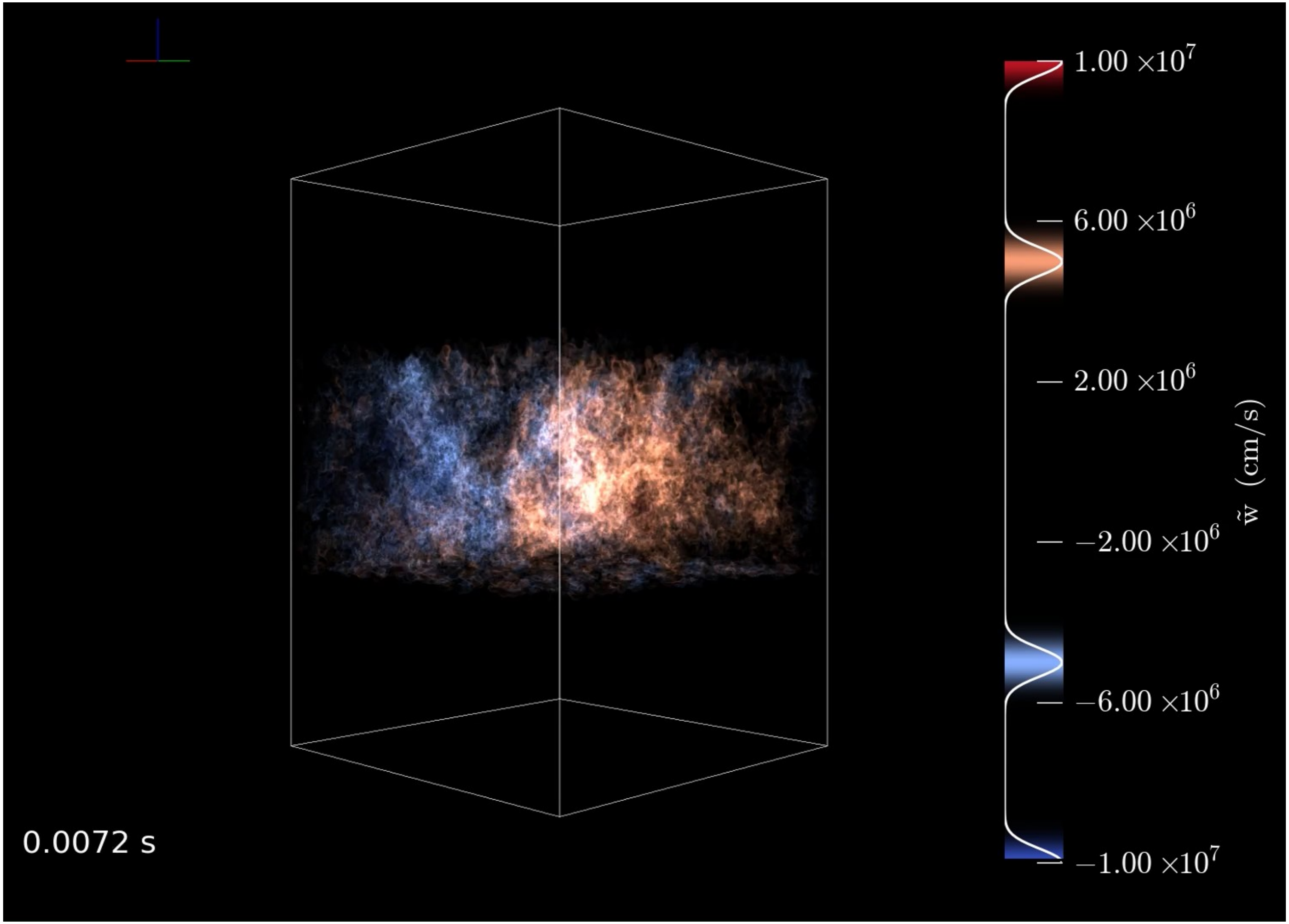
Initial Models Study

- Three types of outcomes
  - Localize runaway on short timescale
  - Nova-like convective burning
  - Quasi-equilibrium (?)



See poster by Adam Jacobs…

X-ray Bursts



All the necessary initial models, microphysics, inputs files, initialization routines, etc. for this problem are distributed with Maestro

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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

Reproducibility

- Simulation codes are complex, ever-changing codes
  - We should all strive to make everything freely available
- Maestro and Castro are freely available on github:
  - https://github.com/BoxLib-Codes
- All Maestro problem setups (SN Ia convection, sub-Ch convection, & XRB) and microphysics are distributed with the code
- Castro (including gray and MGFLD radiation) also available
  - Maestro → Castro restart

Summary/Future

- Modeling SNe (of any progenitor class) requires the cooperation of many different simulation codes focusing on individual phases
- Our SNe Ia results:
  - Chandra SD: single-point, off-center ignition
  - Sub-Ch SD: variety, likely single-point…
- Maestro development directions: acoustics, MHD, rotation, ???
- *Releasing simulation codes / problem files is part of scientific reproducibility*
- Convection calculations in the Chandra regime have now been used as the starting point for the subsequent explosion
- Sub-Chandra calculations will elucidate the conditions at which He ignition takes place and whether a detonation is possible