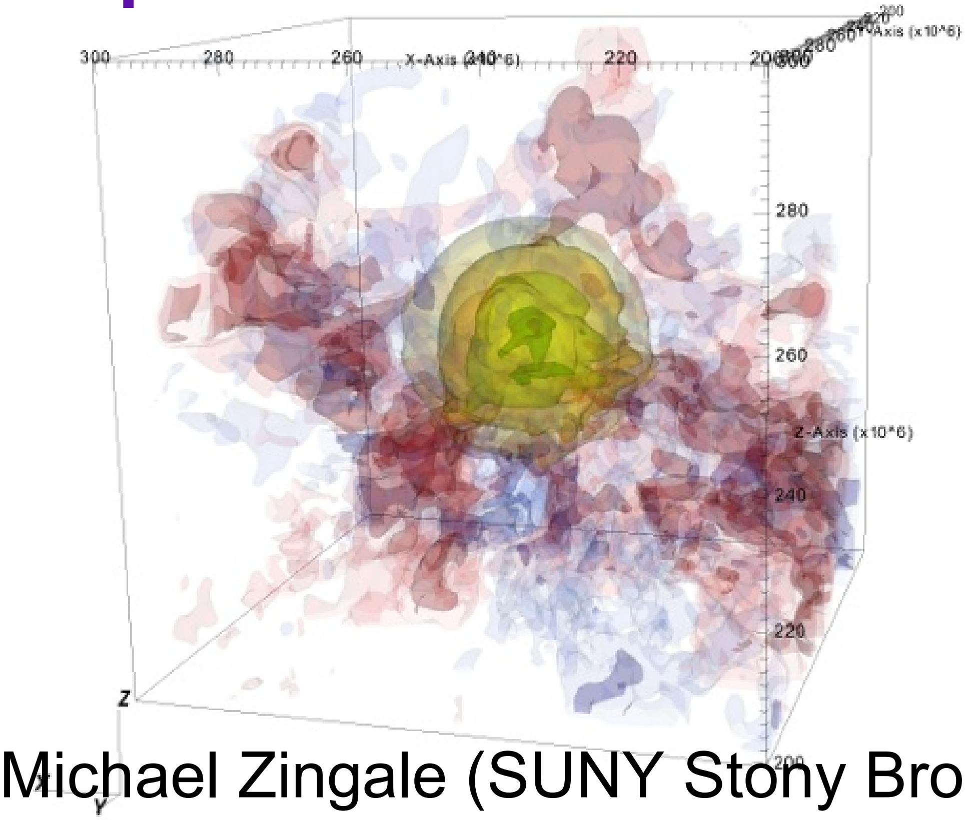
The Challenges of Modeling Explosive Phenomena



Michael Zingale (SUNY Stony Brook)

in collaboration with

Ann Almgren, Andy Aspden, Andy Nonaka, John Bell (LBL),

Alan Calder, Brendan Krueger, Chris Malone (Stony Brook),

Stan Woosley (UCSC)

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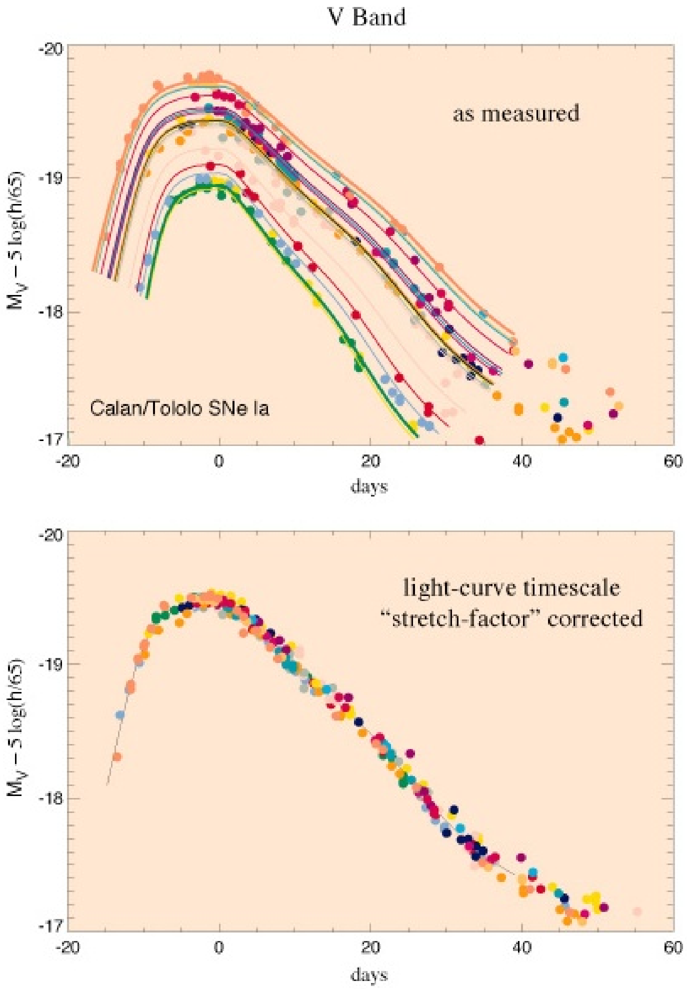
Convection in Astrophysics

- 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

Type Ia Supernovae Observations

- Bright as host galaxy, L ~10^{43} erg s^{-1}
- Large amounts of ^{56}Ni produced
  - Radioactivity powers the lightcurve



Phillips (1993), Perlmutter et al. (1997)

SN 1994D (High-Z SN Search team)

- No H seen in spectra, but strong Si, Ca, and Fe lines
- Occur in old stellar populations
- Lightcurve is robust
  - Variations can be corrected for via a single parameter function.
  - SNe Ia act as standard candles.

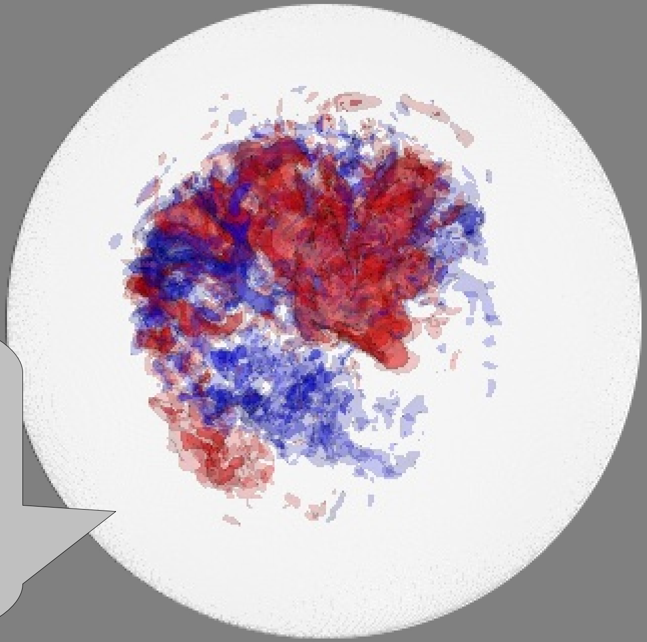
Type Ia Supernovae

(single-degenerate scenario)

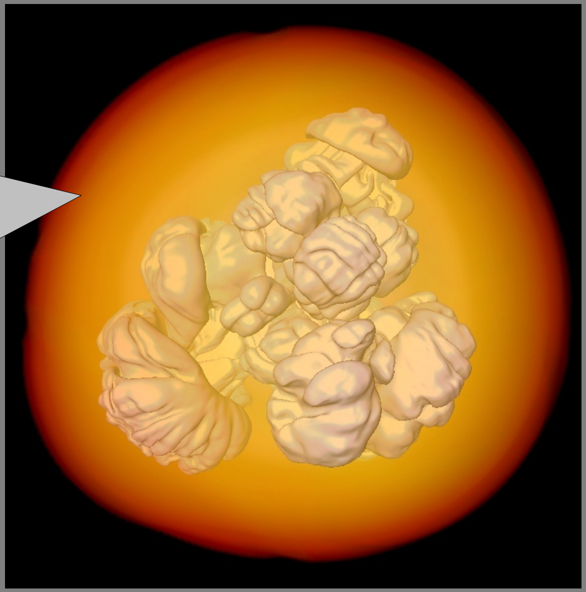
(David A. Hardy & PPARC)

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)

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

SN 1994D (High-Z SN Search team)

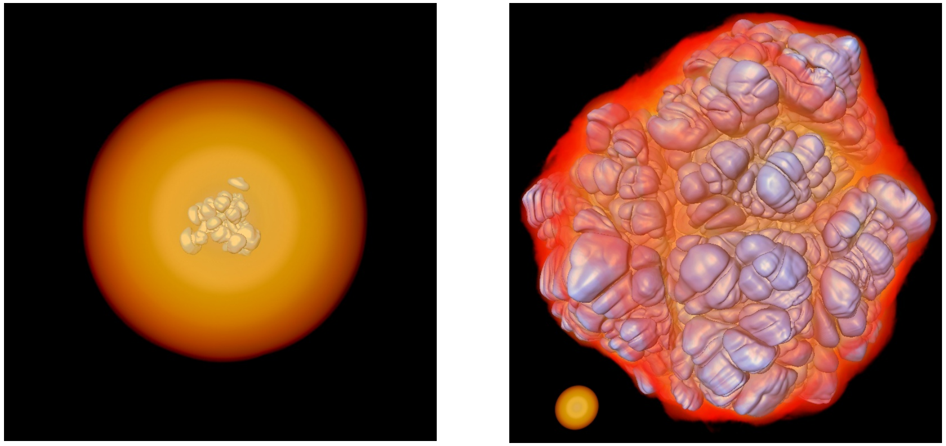
Outstanding Questions in SNe Ia

- What is the progenitor?
  - Alternate models exist, including the merger of two white dwarfs
- Does the burning front remain subsonic or does it transition to a detonation?
  - A late time transition to a supersonic burning front (detonation) appears to give the best match to observations. Turbulence likely plays a key role in this transition.
- What are the initial conditions?
  - Variations in the spatial and temporal distribution of hot spots gives different explosion outcomes (Gracia-Senz & Bravo 2005, Plewa et al. 2004, Roepke et al. 2007, ...)
- 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.

Each of these questions requires a unique code.

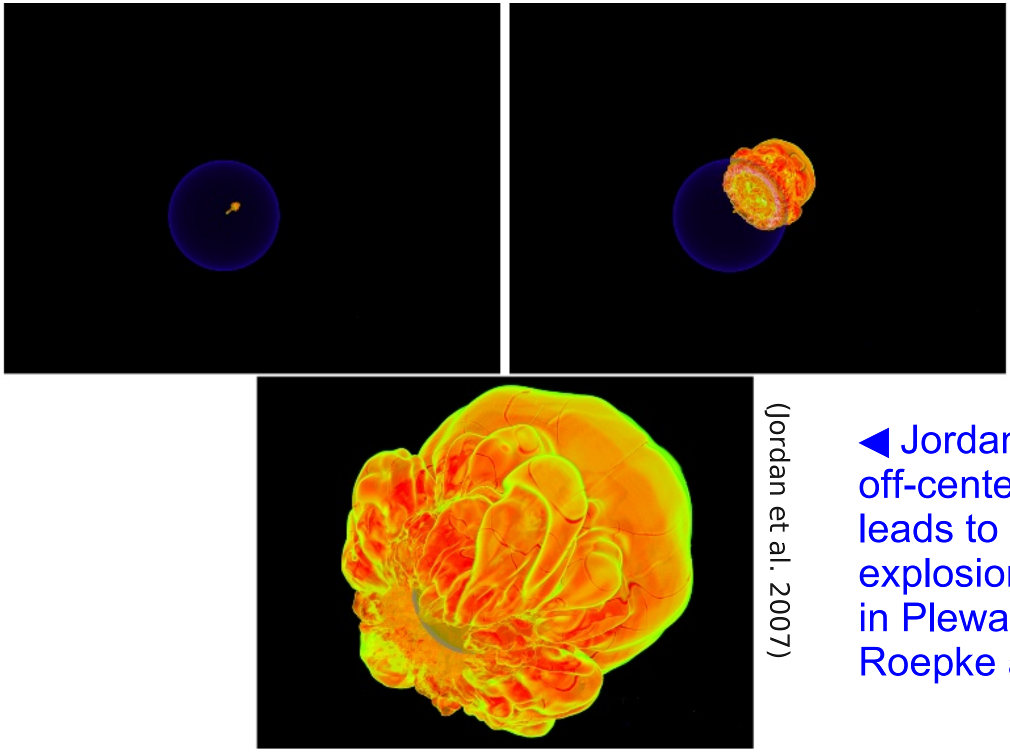
Why Study Ignition?

▼ Roepke and Hillebrandt: ignition seeds in many points distributed around the center.



(Roepke and Hillebrandt 2005)

- Explosion outcome very sensitive to spatial and temporal distribution of initial flames (ignition points)
  - Single point on/off-center vs. multi-point explored by various groups
- Majority of explosion calculations begin with no initial velocity field



(Jordan et al. 2007)

◀ Jordan et al. 2007: Single off-centered ignition point leads to very asymmetric explosion. Also discussed in Plewa et al. 2004, Roepke and Woosley 2006.

... what does nature do?

Multidimensional Simulations

- Nature is 3-d
  - Convection driven by nuclear energy release
  - Fluid instabilities / turbulence
  - Localized burning/runaway
  - Rotation
- Challenging simulations
  - Large computing / memory requirements
  - Making sense of enormous amounts of data
- SNe Ia begin with periods of low speed convection driven by nuclear energy release
  - Requires ability to model the domain for long timescales
- Requires a different algorithmic approach than those traditionally used in astrophysics

Simulating Low Mach Phenomena

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

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

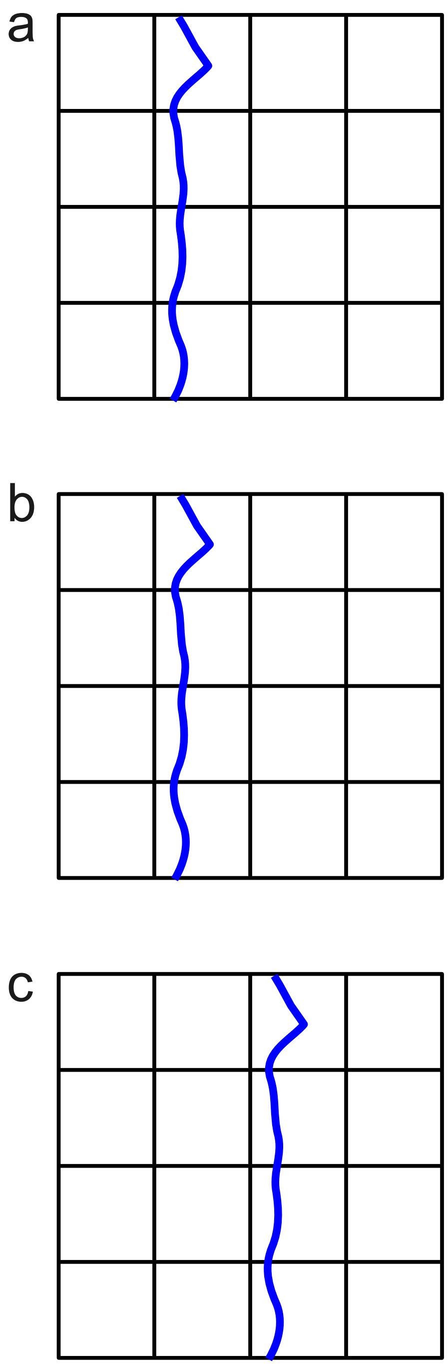
For $M \equiv |u|/c \ll 1$ this is

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

We would like to have

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

For very low Mach number flows, it takes $\sim 1/M$ 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 Number Hydrodynamics

Almgren, Bell, Rendleman, & Zingale 2006 ApJ, 637, 922
Almgren, Bell, Rendleman, & Zingale 2006, ApJ, 649, 927
Almgren, Bell, Nonaka, & Zingale 2008, ApJ, 684, 449

- 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:

$$\nabla p_0 = \rho_0 g$$

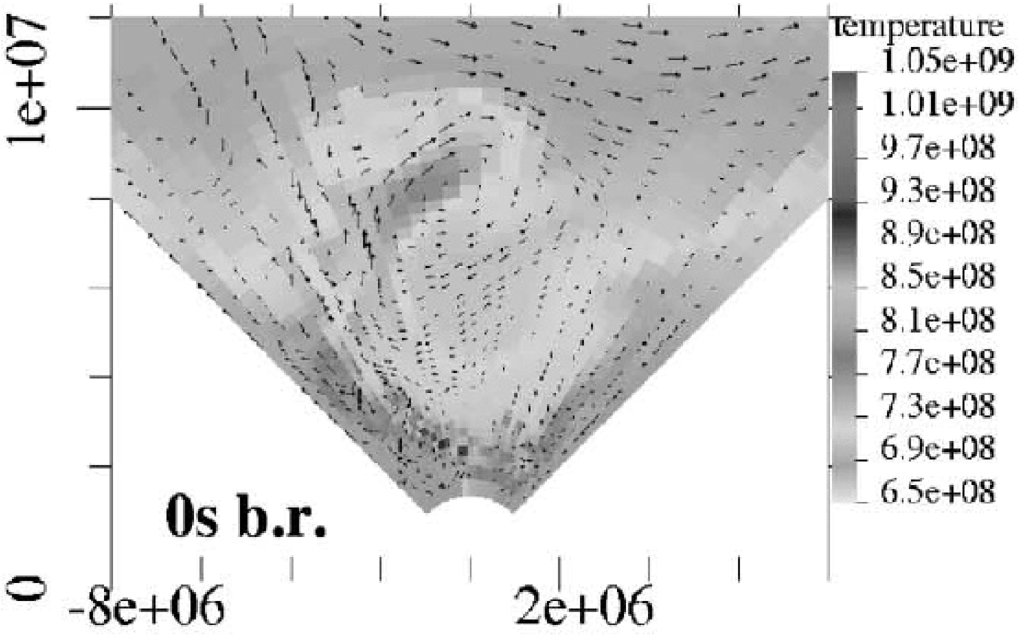
- Elliptic constraint on velocity field

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

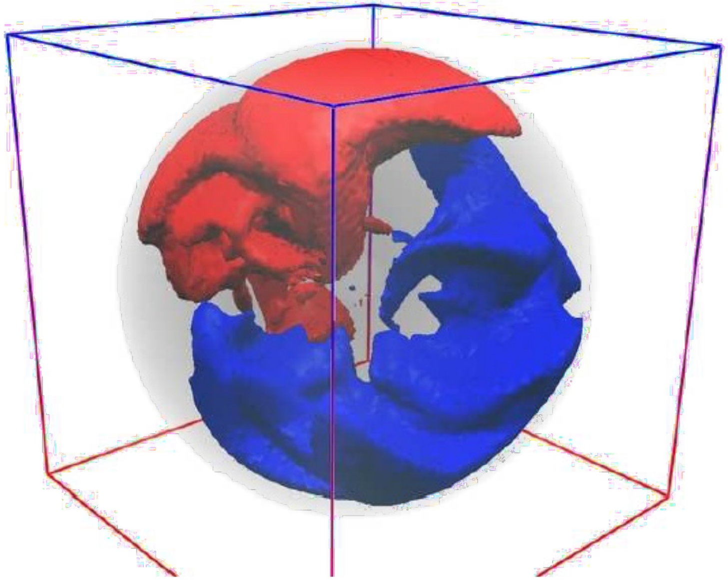
  - β_0 is a density-like variable
  - S represents heating sources
- Timestep based on bulk fluid velocity, not sound speed
- Weak scaling to ~100,000 processors

Previous SNe Ia Convection Calculations

▶ Hoflich and Stein modeled a 2-d wedge using an implicit code. Found flow caused compression near the center. Suggested ignition near the center.



(Hoflich and Stein 2002)



◀ Kuhlen et al. modeled the convectively unstable region, with the very center cut out. The observed a characteristic dipole feature and suggested that off-center ignition was likely.

(Kuhlen et al. 2006)

No previous calculations have modeled the entire star.

Computational Demands

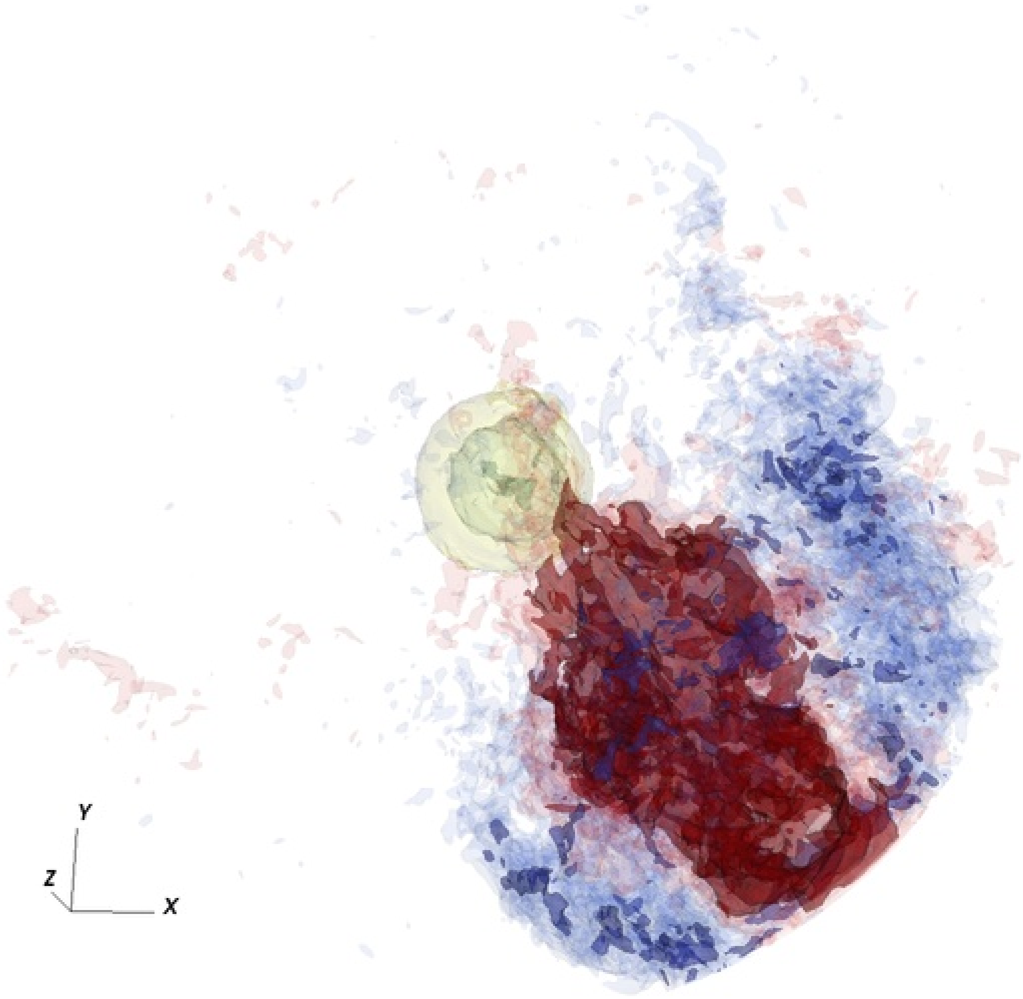
- Computer time measured in CPU-hours
- Single 384^3 run: ~1 million CPU-hours
- Single 576^3 run: ~7 million CPU-hours
  - 10368 processors (1728 MPI tasks × 6 OpenMP threads/MPI task)
  - 2100 plotfiles, each 18 GB in size = ~40 TB of data for a single run

► The OLCF Cray XT5 jaguarpf machine at ORNL. This machine has 224,000 cores and is currently ranked #2 on the Top500 list.

Pre-SNe Ia Convection: Dipole Convection

Zingale, Almgren, Bell, Nonaka, & Woosley 2009,, ApJ, 704, 196.
Nonaka, Aspden, Zingale, Almgren, Bell, & Woosley 2011, in preparation

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

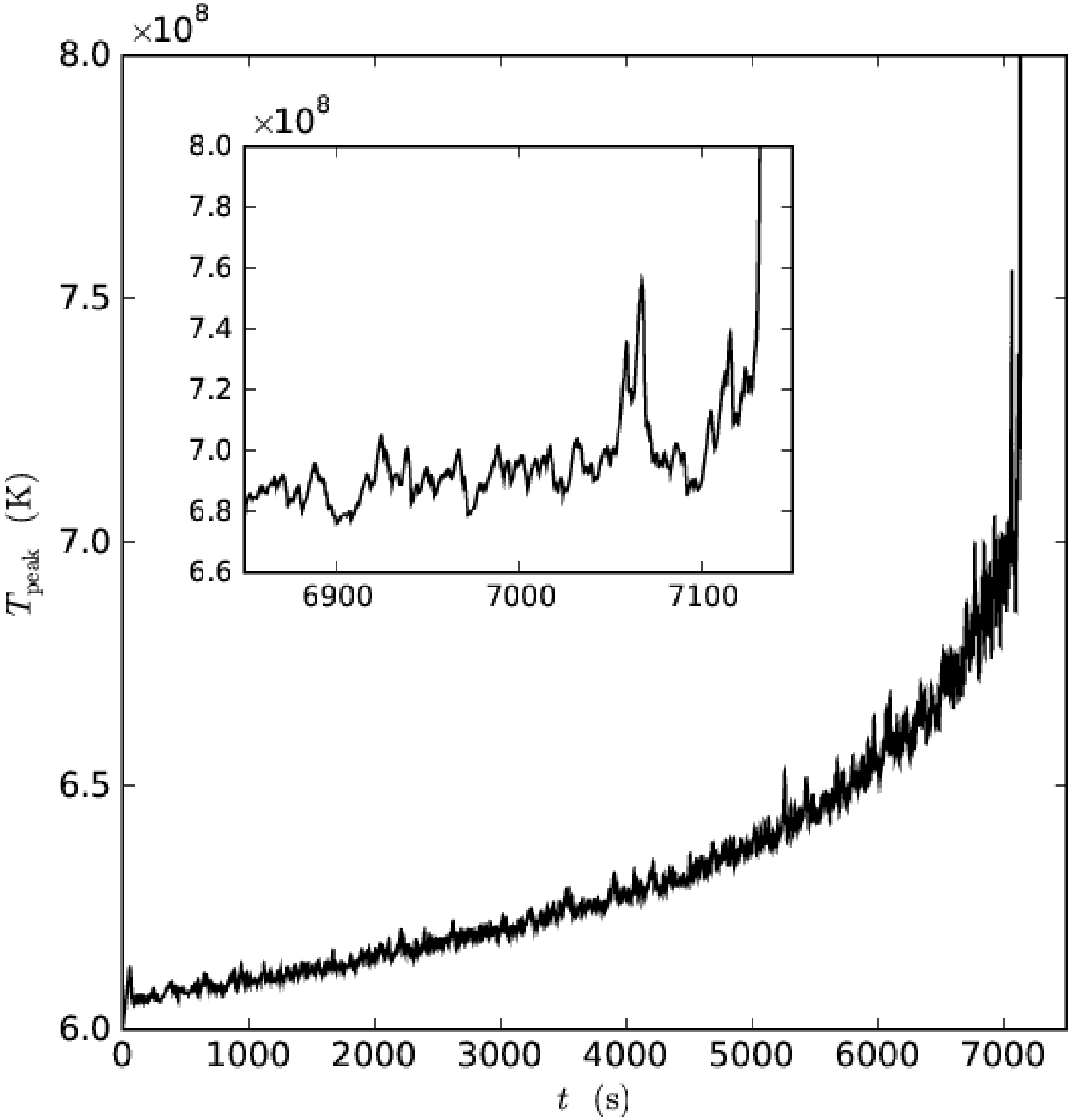


Radial velocity field (red = outflow; blue = inflow) in an 1152^3 non-rotating WD simulation.

Pre-SNe Ia Convection: Runaway

Zingale, Almgren, Bell, Nonaka, & Woosley 2009, ApJ, 704, 196.

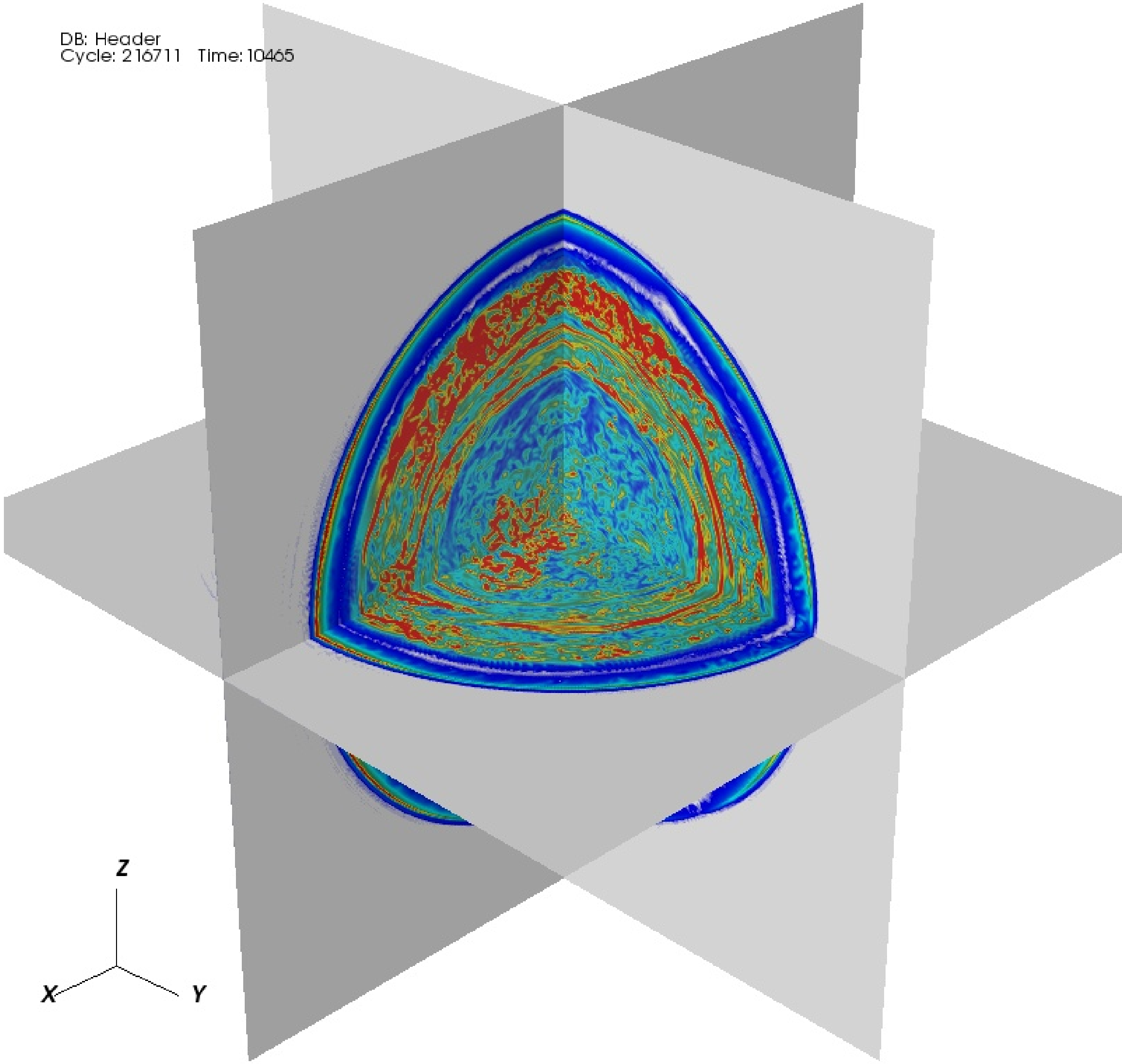
- Temperature increase nonlinear
  - Ignition occurs as T crosses 8 x 10^8 K
  - “Failed” hotspots seen toward the end.



Pre-SNe Ia Convection: Shear Layer

Zingale, Nonaka, Almgren, Bell, Malone, Woosley 2011, accepted to ApJ

- Clear separation between the convecting and stable regions
- Persists up to ignition
  - Strong shearing here will greatly affect the flame evolution

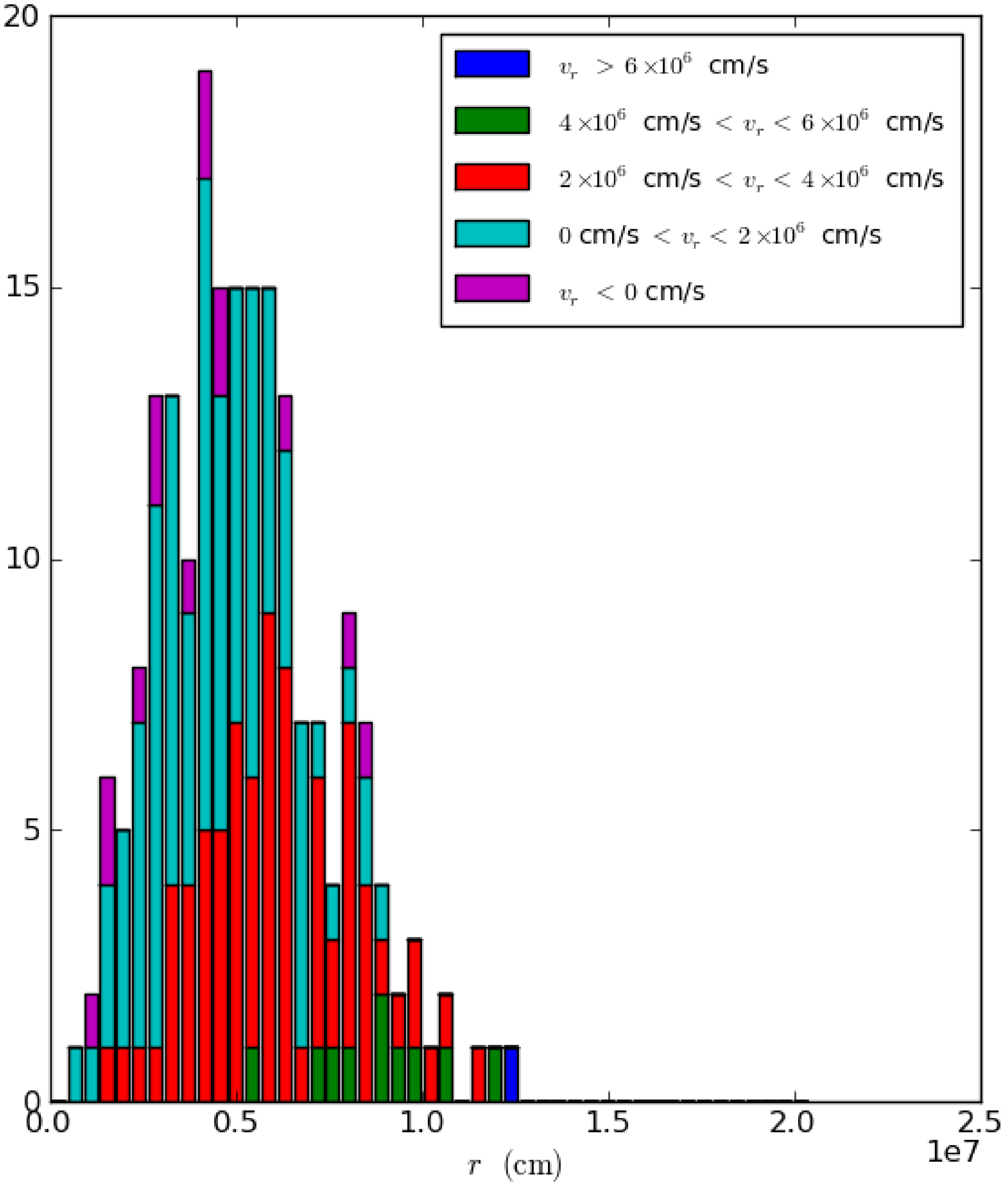


Vorticity field in a non-rotating model.

Pre-SNe Ia Convection:
Ignition Radius Likelihood

Zingale, Nonaka, Almgren, Bell, Malone, Woosley 2011, accepted to ApJ

- 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

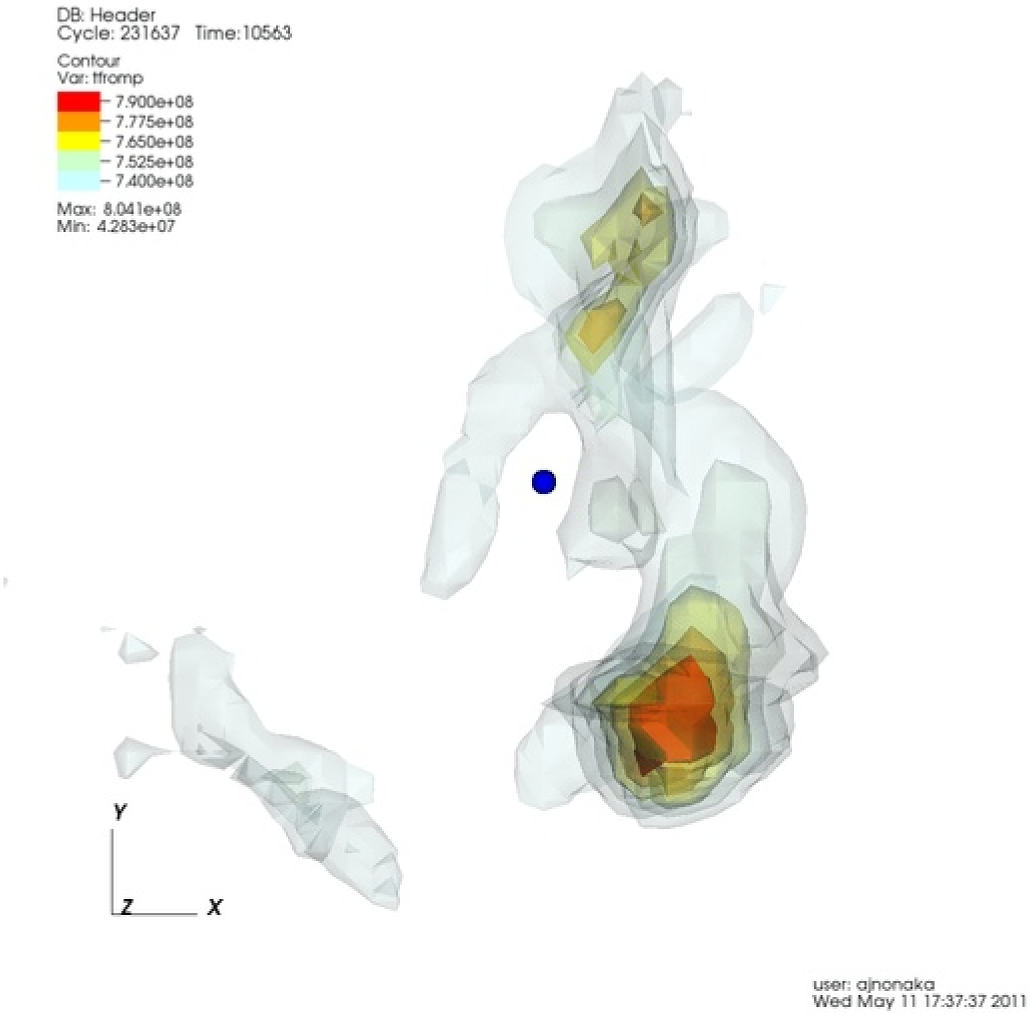


► Histogram of likely ignition radii from 576^3 non-rotating model. Hotspot radii are averaged into 1 s intervals and colored by radial velocity.

Pre-SNe Ia Convection: Multiple Ignition?

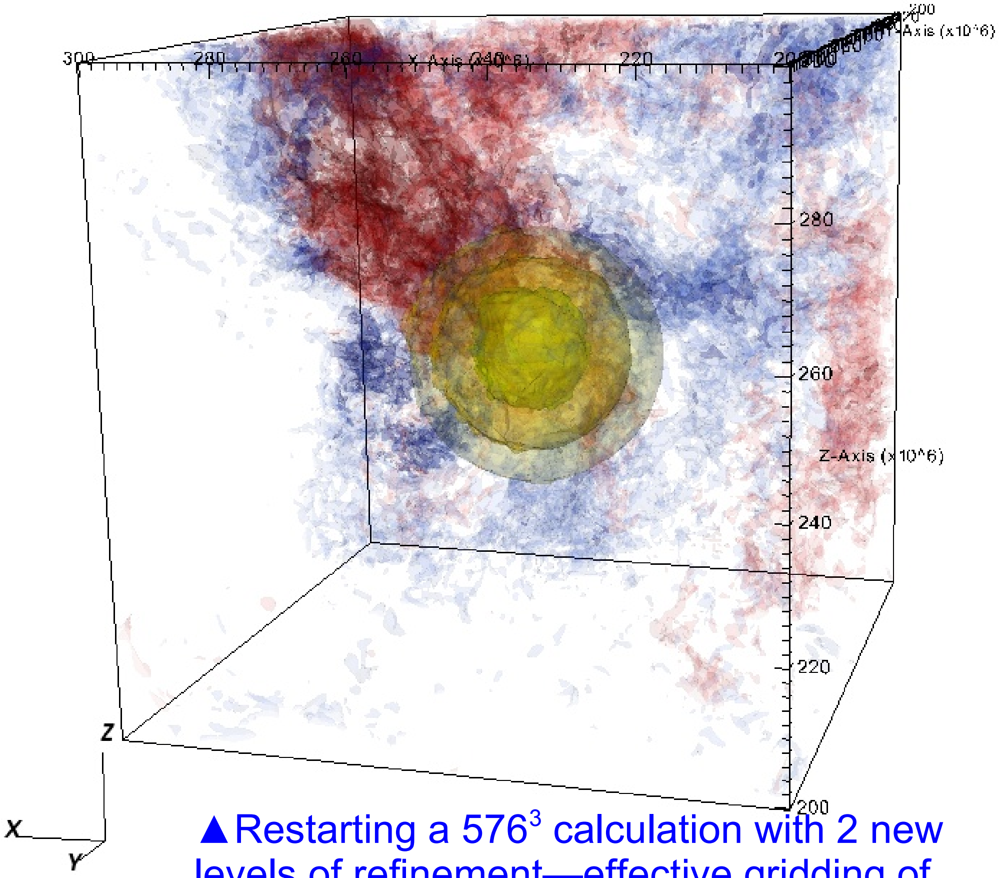
Nonaka, Aspden, Zingale, Almgren, Bell, Woosley 2011, in preparation

- 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.

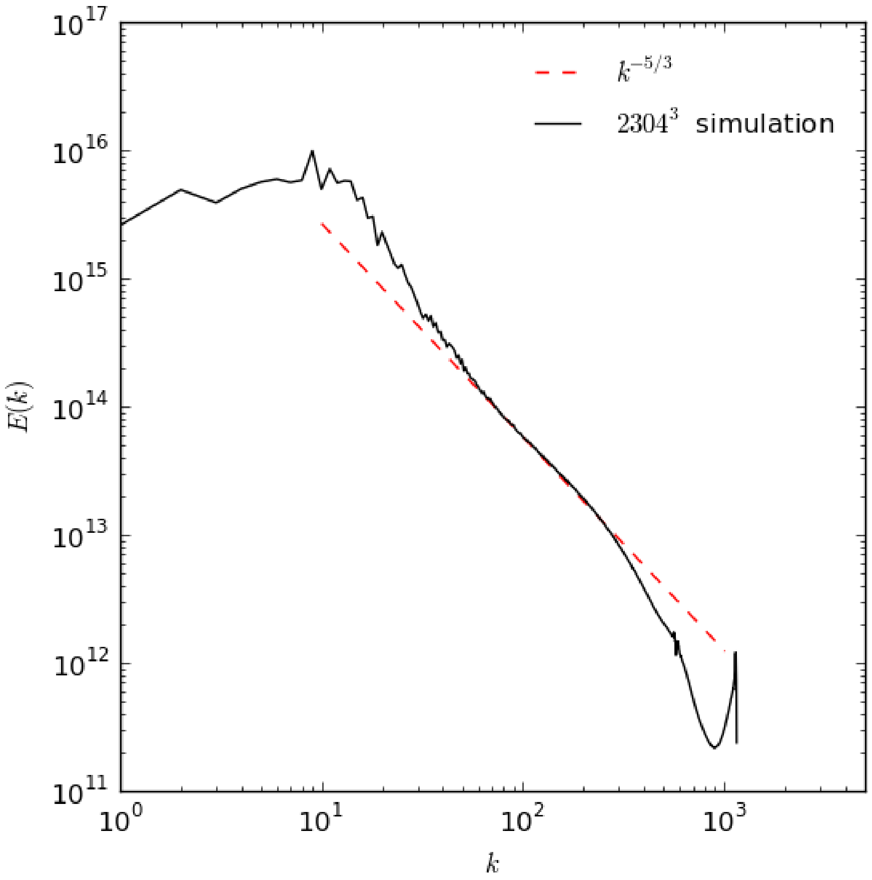


Current Work: Turbulent Properties

Nonaka, Aspden, Zingale, Almgren, Bell, Woosley 2011, in preparation



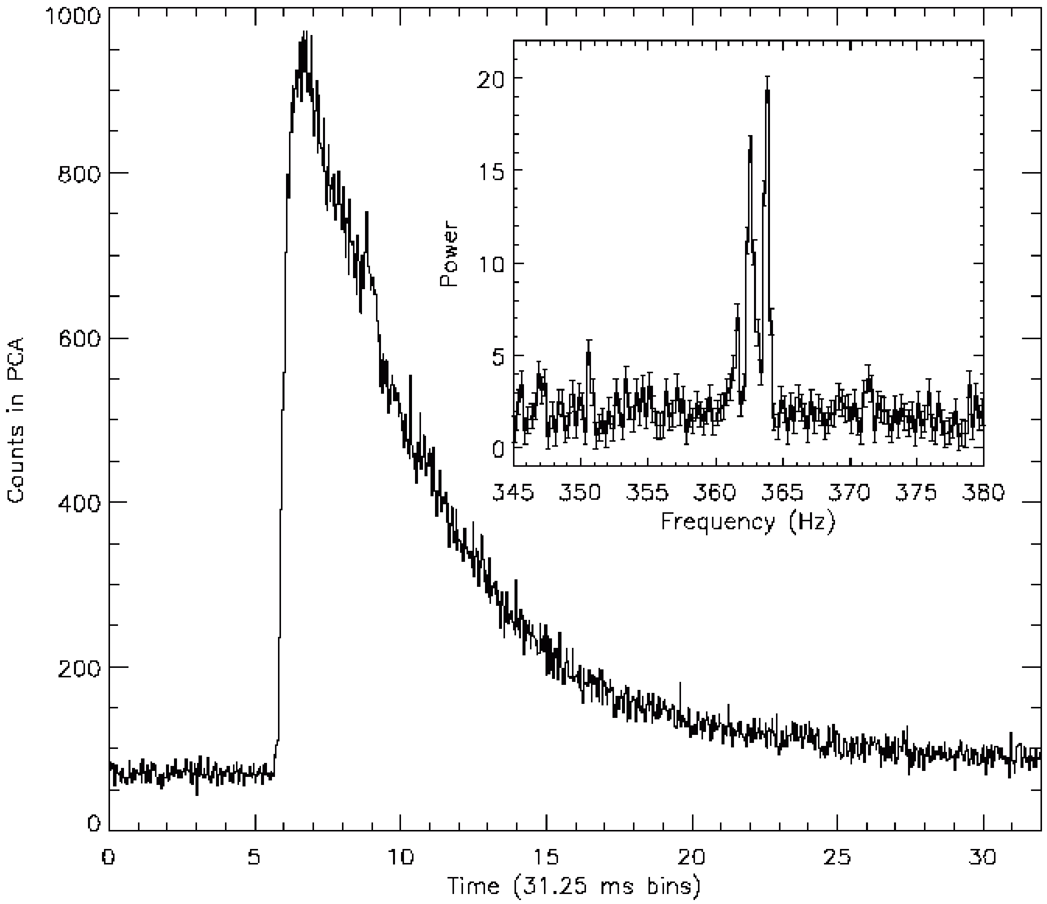
▲Restarting a 576^3 calculation with 2 new levels of refinement—effective gridding of 2304^3 (~2 km resolution)



- High resolution simulations show a well-resolved turbulent cascade
- Integral scale large/turbulent intensity small → turbulence unlikely to affect flame propagation.
- Velocities in stable region are much higher/shearing.

X-ray Bursts

- Thermonuclear runaway in thin accreted H/He layer on surface of a neutron star
- Accretion timescale ~ hours to days
- Runaway timescale ~ seconds
- > 70 sources known, some with 10s or more individual bursts.
- Potential site for rp-process nucleosynthesis



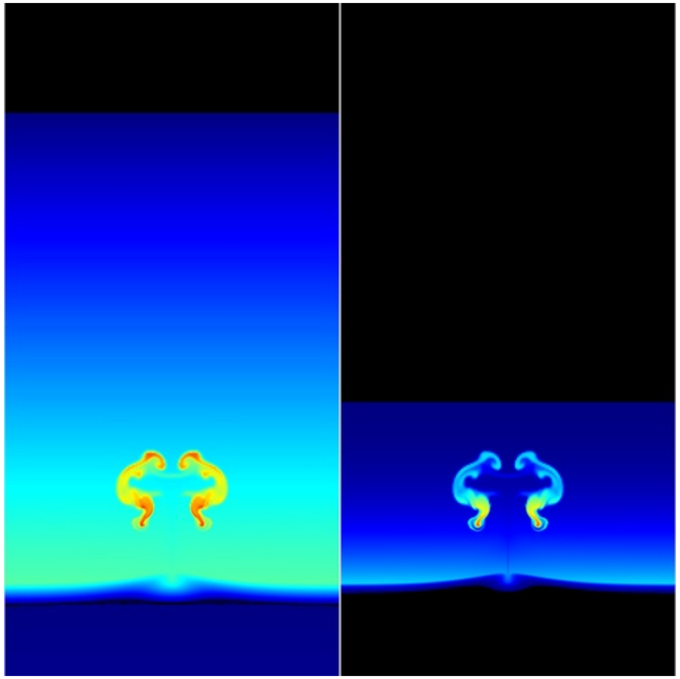
Strohmayer et al., 1996, ApJ, 469:L9

Outstanding Questions in XRBs

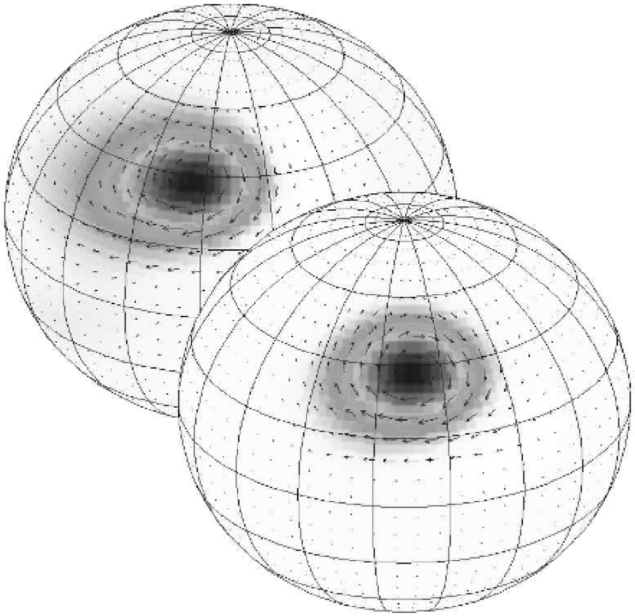
- How does the fuel spread over the surface?
- How does the ignition begin?
- Is the burning localized?
- Does convection modify the nucleosynthesis?
- What are the effects of rotation?
- Does convection bring ash to the surface?

Localization

- Accreted layer not degenerate enough to localize a hot spot
  - Fizzles out, maybe stirs
  - Similar to nova (Shankar & Arnett 1994)



MAESTRO simulation ($L = 3.84$ m, $\Delta x = 0.5$ cm) evolved to $t = 1.5 \times 10^{-5}$ s showing dissiapation of a hot spot (initial $T = 10^{9}$ K) in a He NS accreted layer. Temperature is shown on the left, nuclear energy generation rate is shown on the right.



(Adapted from Strohmayer and Bildsten 2003)

Fig. 3.13. Initial evolution of a burning hot spot ignited off the equator as seen in a frame rotating with the neutron star. Velocity vectors show the circulation of the fluid induced by the Coriolis forces. The hot spot expands due to burning and drifts west-southwest because of the latitude dependence of the Coriolis force (after Spitkovsky, Levin & Ushomirsky 2002).

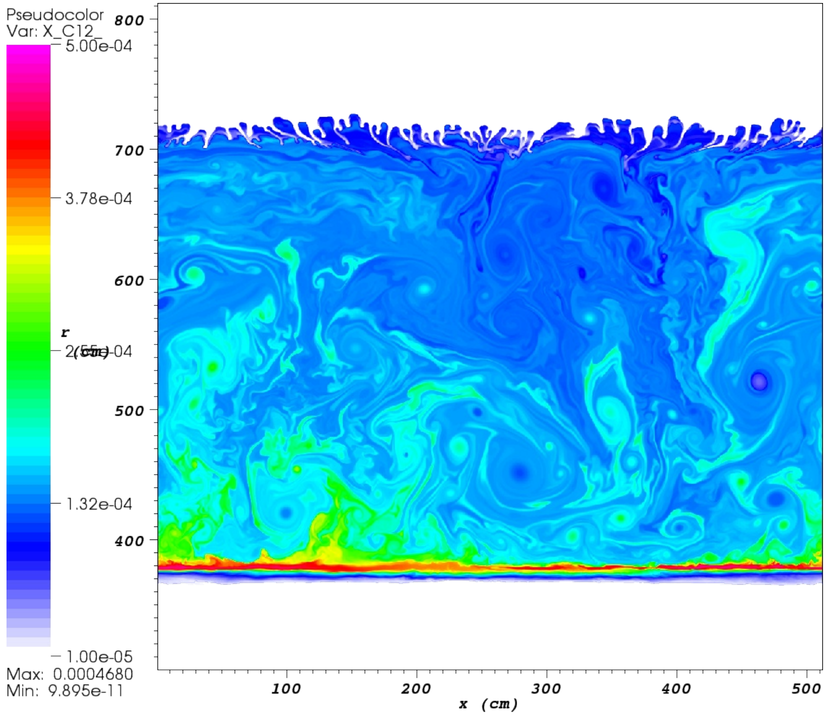
- Spitkovsky et al. (2001)
  - Shallow-water calculations of spreading on NS
  - Coriolis force balances lateral spreading of burning front
  - Simplified vertical structure

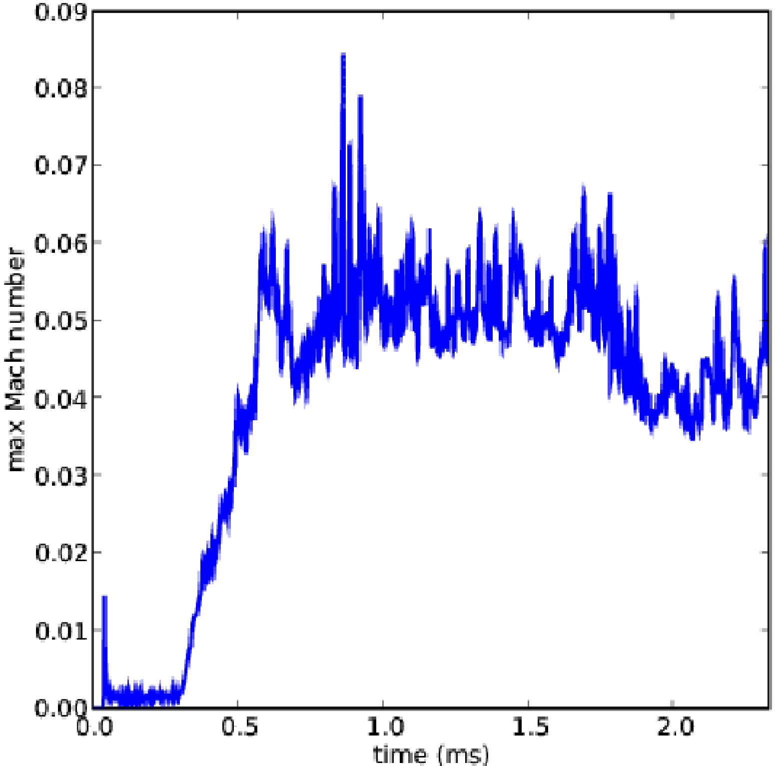
X-ray Burst Modeling

Malone et al. 2011, ApJ, 728, 118

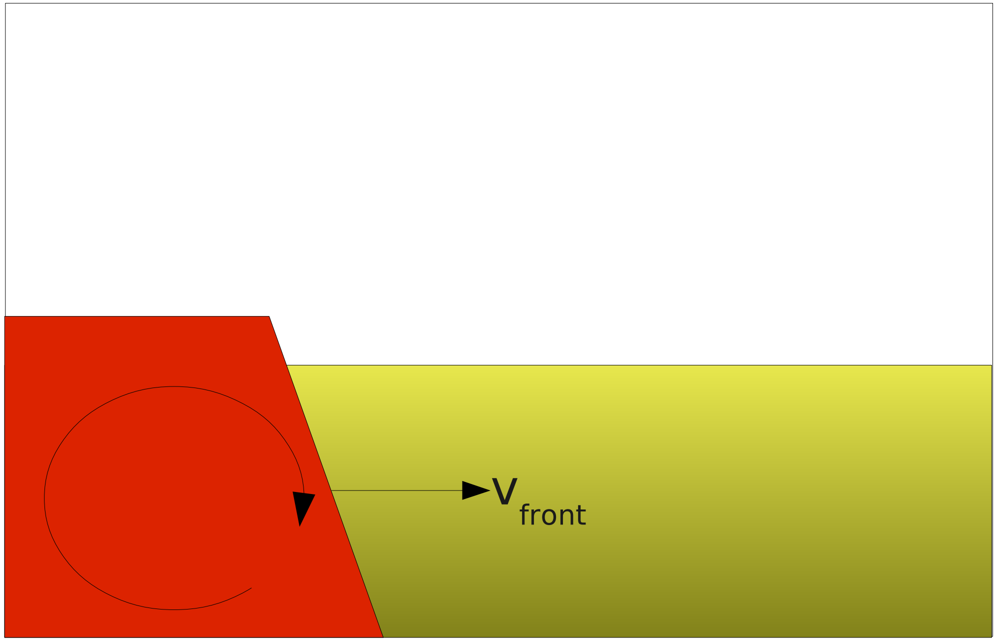
- Pure He layers
  - Convective energy transport develops quickly
  - Resolution requirements much higher than previously thought
  - 2-d simulations challenging. 3-d?
- Mixed H/He bursts underway
  - Nuclear physics more time consuming
  - Steep composition change challenging

▶ Convection in an He layer on a neutron star, modeled by graduate student Chris Malone.





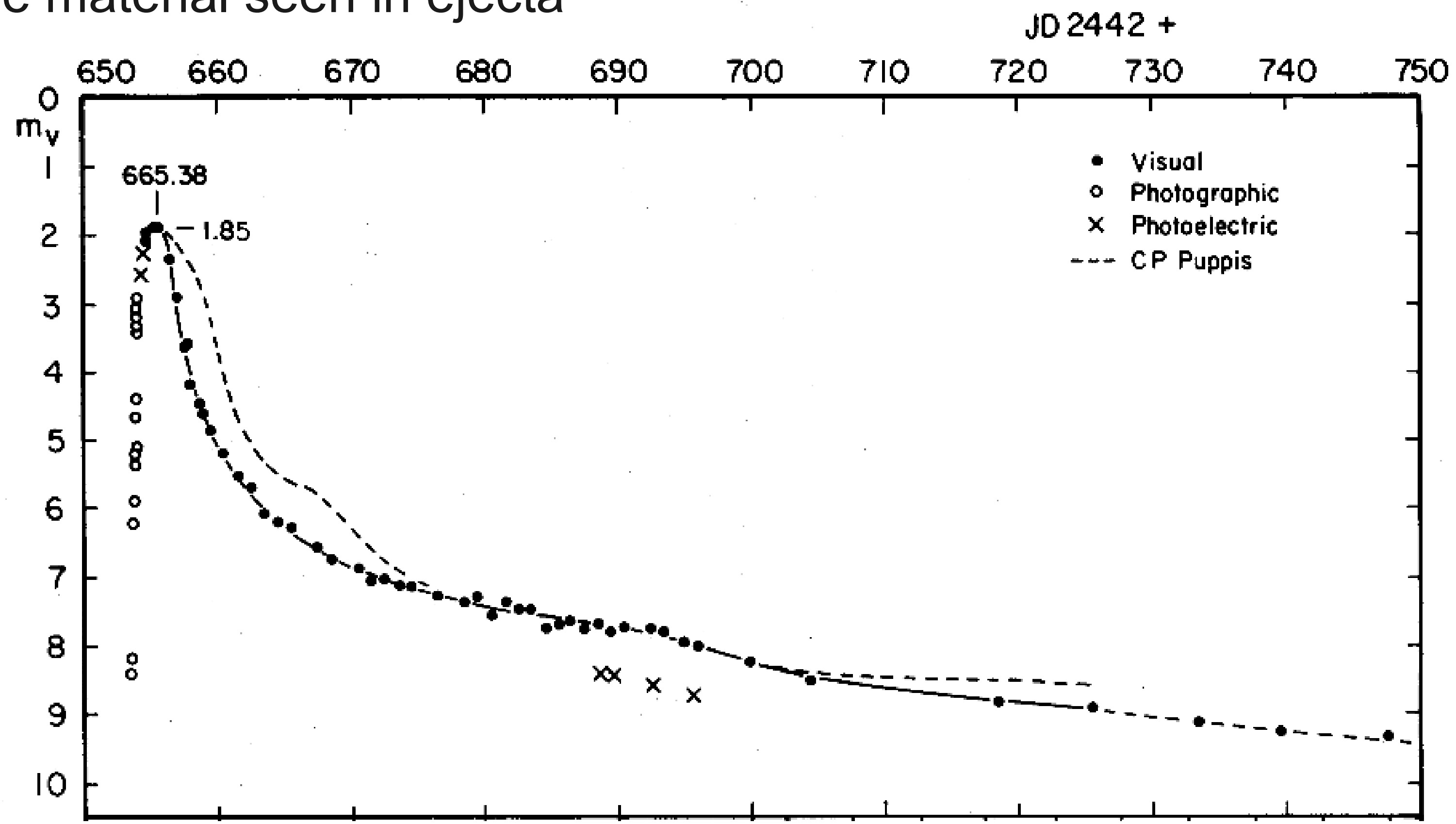
What Can't We Do (Now)?



- Lateral flame propagation w/ resolved nuclear physics
  - Low Mach methods cannot (currently) describe two different scale heights (fuel and ash)
  - Lengthscale for Coriolis force to balance pressure gradient (Rossby length): $L = \sqrt{gH_0/f}$ ~ few km
    - Much bigger domain that we currently use

Novae

- Explosion of surface H layer on white dwarf
  - Similar progenitor system to SNe Ia (but much fainter)
  - Recur when new layer of fuel is accreted (recurrance times of decades to 1000s of years, depending on white dwarf mass)
  - CNO burning required to explain luminosity
  - Core material seen in ejecta



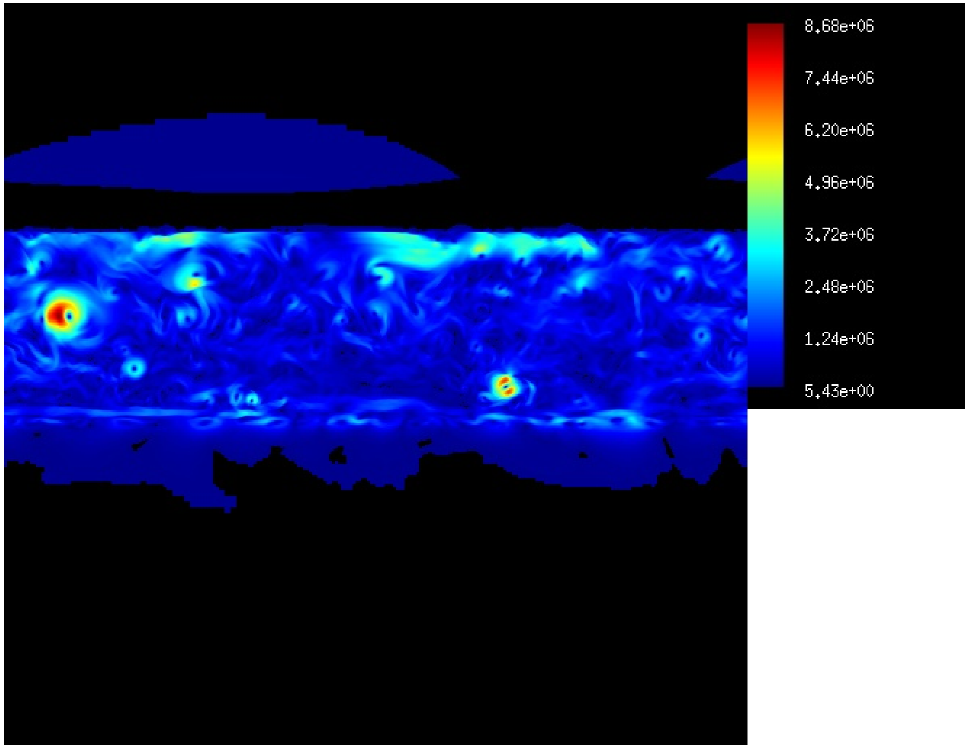
(Young, Corwin, Bryan, and De Vaucouleurs)

Novae

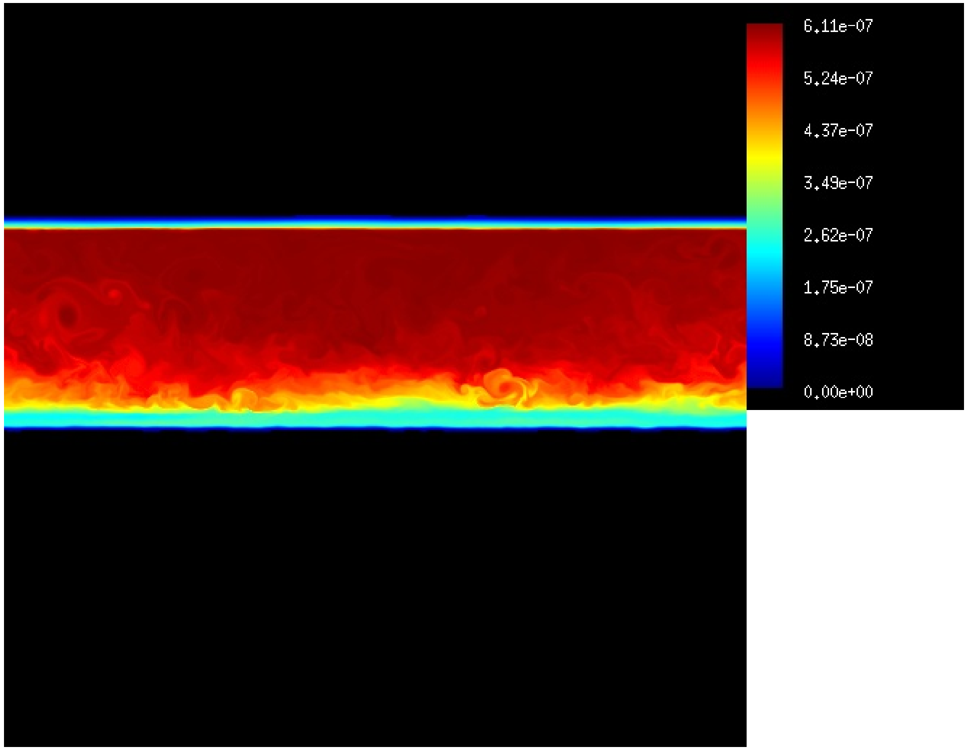
- Biggest issue: dredge-up
  - Underlying C/O needed to catalyze the reaction—enrichment by atleast order-of-magnitude
  - Convection? Shear instabilities during accretion? Mass diffusion? (Livio and Truran 1990)
- Does the WD gain or lose mass as a result of the explosion?
- Can novae be SNe Ia progenitors?

Novae

- Numerical challenges
  - Numerical mixing at base of accretion layer can artifically enhance burning
  - Expansion is significant—needs to be tracked to accurately model dynamics.



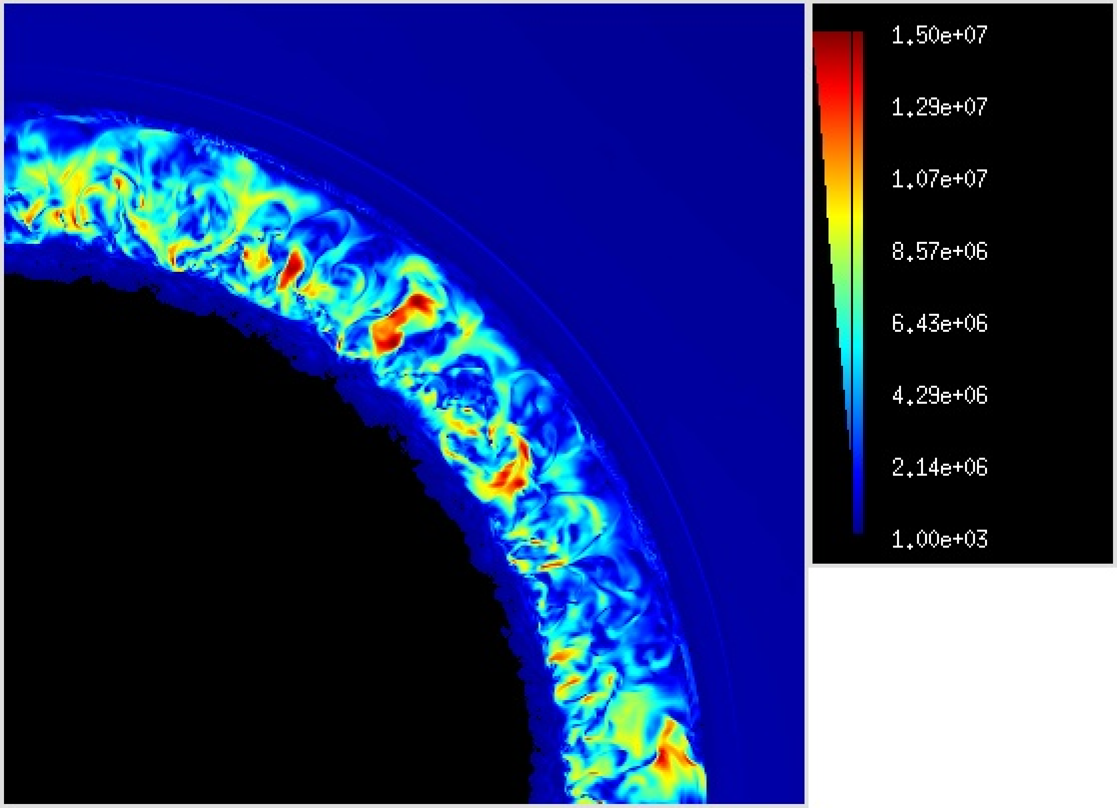
Velocity magnitude



^{15}N abundance

sub-Chandra SNe Ia Models

- Numerical challenges
  - Convective region potentially extends to the “top” of the star—difficult to capture steep gradient.



Slice through 3-d domain of vorticity in He layer on surface of 1.0 $M_\odot$ WD.

Summary / What's Next?

- Modern algorithms / supercomputers can model convective astrophysical flows for many turnover times in 3-d.
  - Requires involvement of many different disciplines: mathematics, computational science, application scientists.
- Convection in pre-SNe Ia white dwarfs:
  - Rapidly changing convective field
  - Range of ignition locations: between central and ~80 km off-center
  - Details of ignition distribution can be learn by looking at late time fluctuations
  - Single-point, off-center ignition likely

Summary / What's Next?

- X-ray bursts
  - Low Mach number hydrodynamics provides an efficient means for modeling convection on neutron stars
  - Exploring mixed H/He burning underway.
- Applications to nova, sub-Chandra SNe Ia ignition, and H core convection in massive stars underway.
- Future Work
  - Addition of long wavelength acoustics to extend range of validity of low Mach number model
  - Work on understanding limits to method
  - Restart ignition calculation in compressible code to follow the subsequent flame evolution.