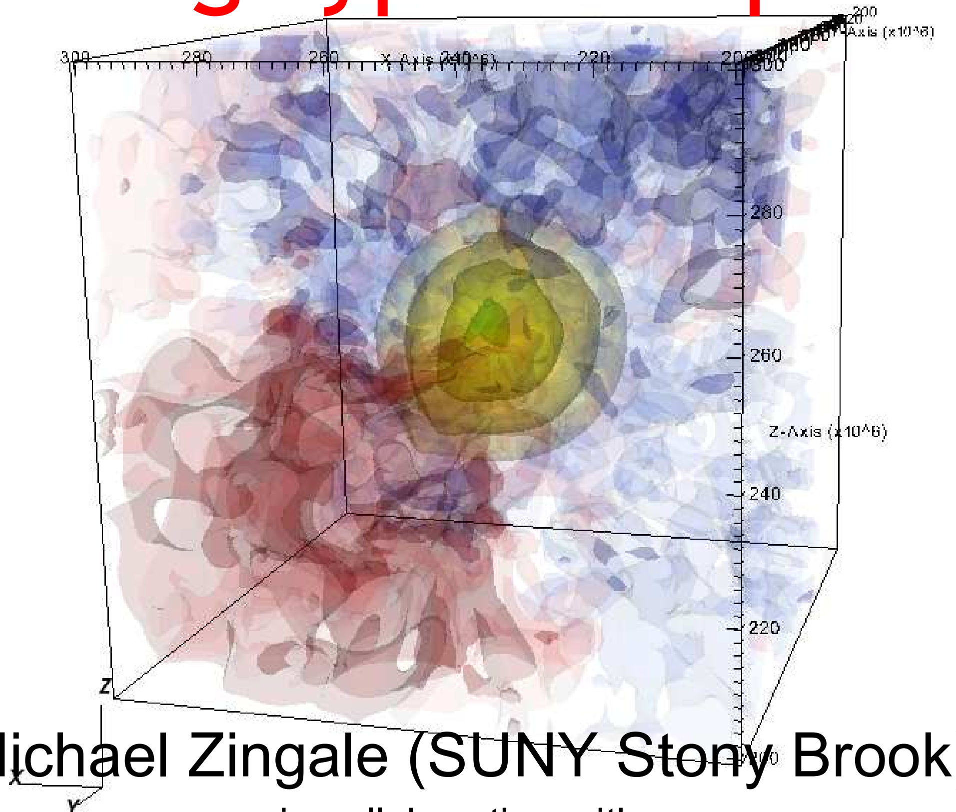
Multi-dimensional models of convection preceding type Ia supernovae



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Type Ia Supernovae

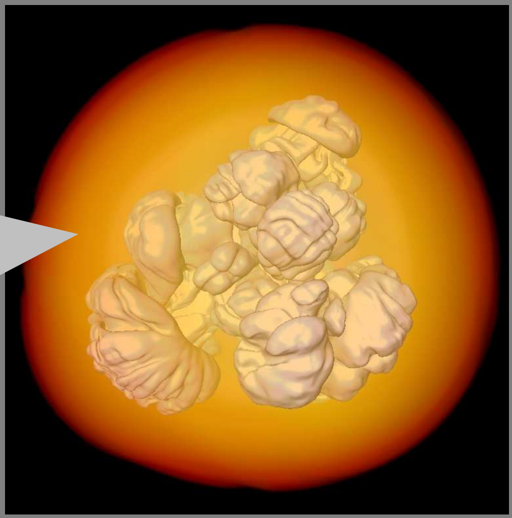
(single-degenerate scenario)

(David A. Hardy & PPARC)

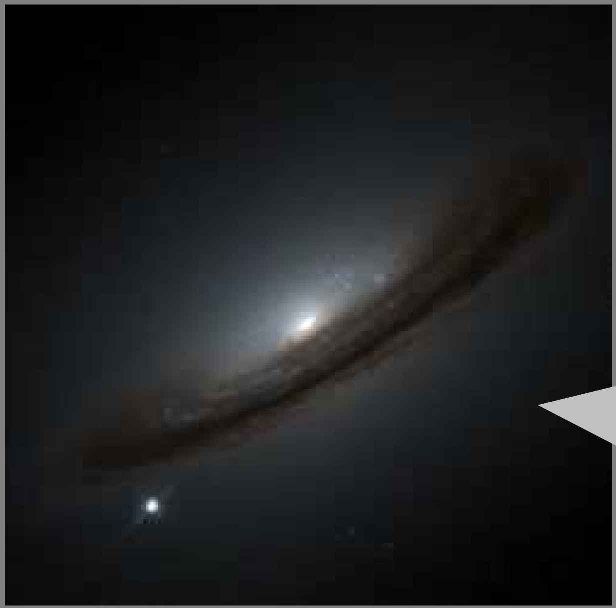
1 Accretion from binary companion. Grows to M_{ch}

2 "Smoldering" phase—central T rises → flame born

3 Flame propagation. Initially subsonic, but detonation transition?



(Roepke and Hillebrandt 2005)



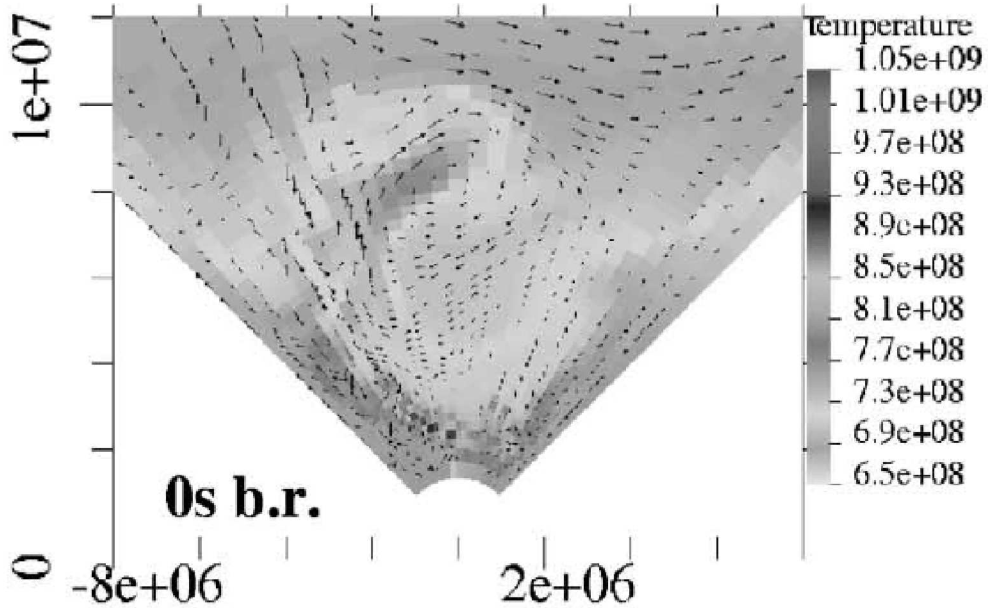
SN 1994D (High-Z SN Search team)

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

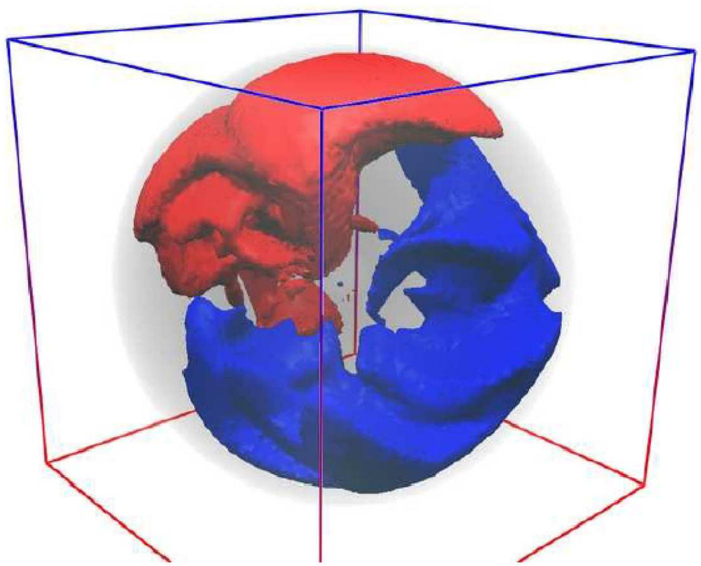
See also posters by Stony Brook colleagues Calder, Jackson, and Krueger

Previous 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. 2006)

◀ 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.

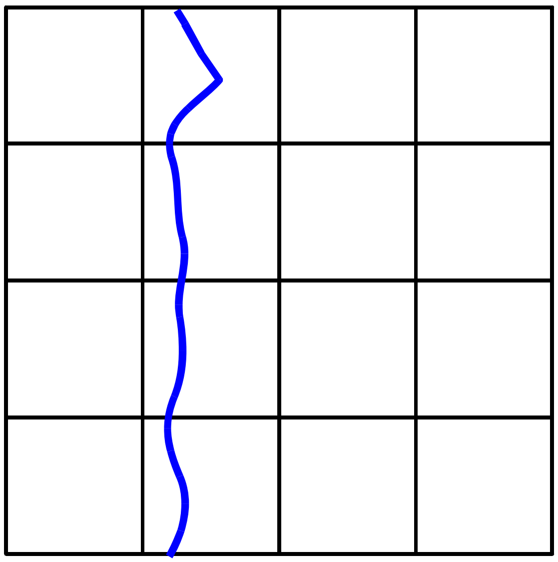
No previous calculations have modeled the entire star.

With rare exception, explosion calculations begin with zero velocity.

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 $M \ll 1$ this is

$$\Delta t = \min\left\{\frac{\Delta x}{c}\frac{1}{1+|M|}\right\} \approx \frac{\Delta x}{c}$$

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?

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
Nonaka, Almgren, Bell, Lijeski, Malone & Zingale 2010, ApjS, 188, 358

Reformulation of compressible Euler equations

- Retain compressibility due to local heating and stratification.
- Pressure is decomposed into thermodynamic and dynamic components, $p(\mathbf{x},t) = p_0(r,t) + M^2\pi(\mathbf{x},t)$
- 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

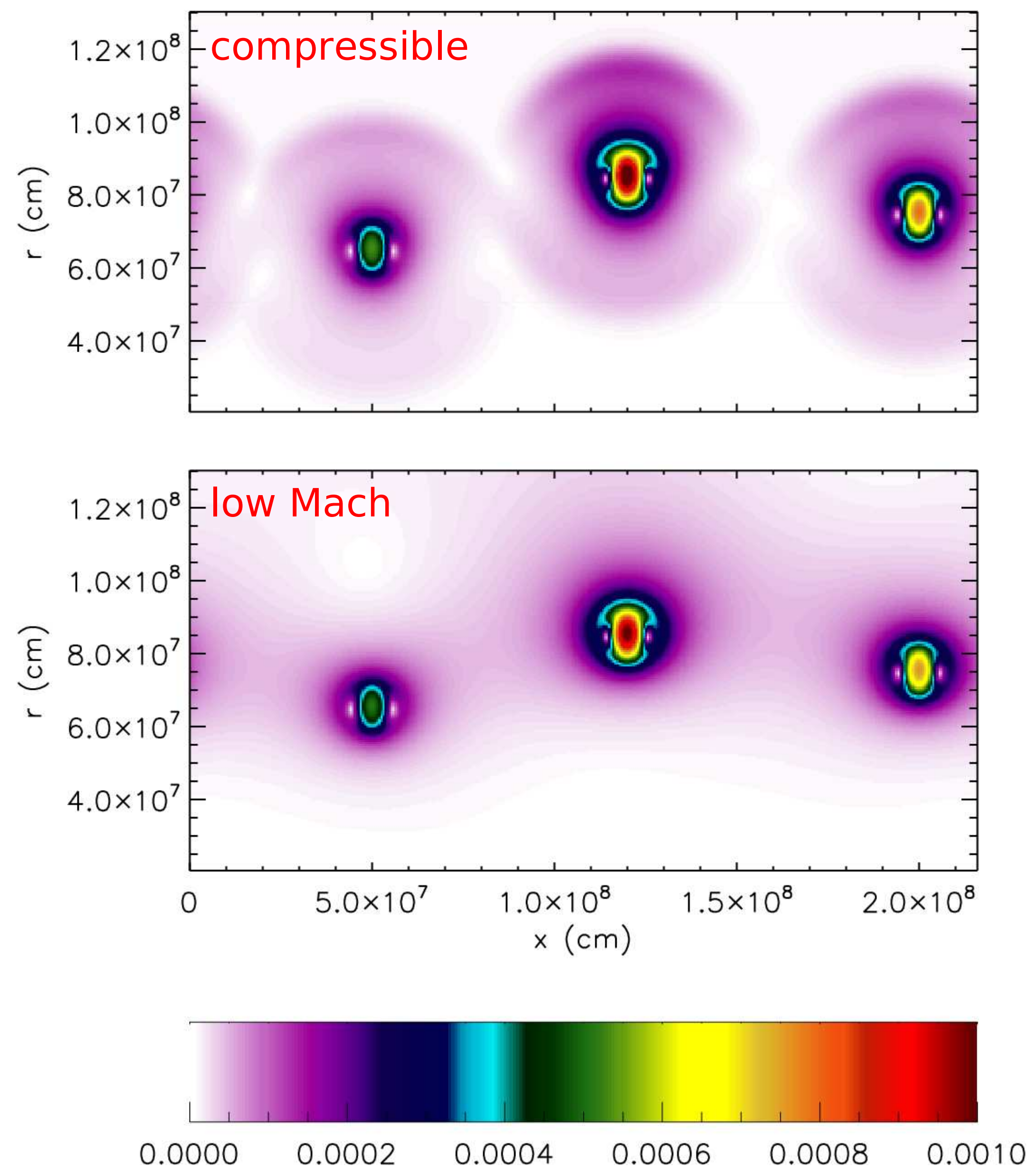
Time step based on bulk fluid velocity, not sound speed

Weak scaling to ~10^5 processors

Filtering Soundwaves

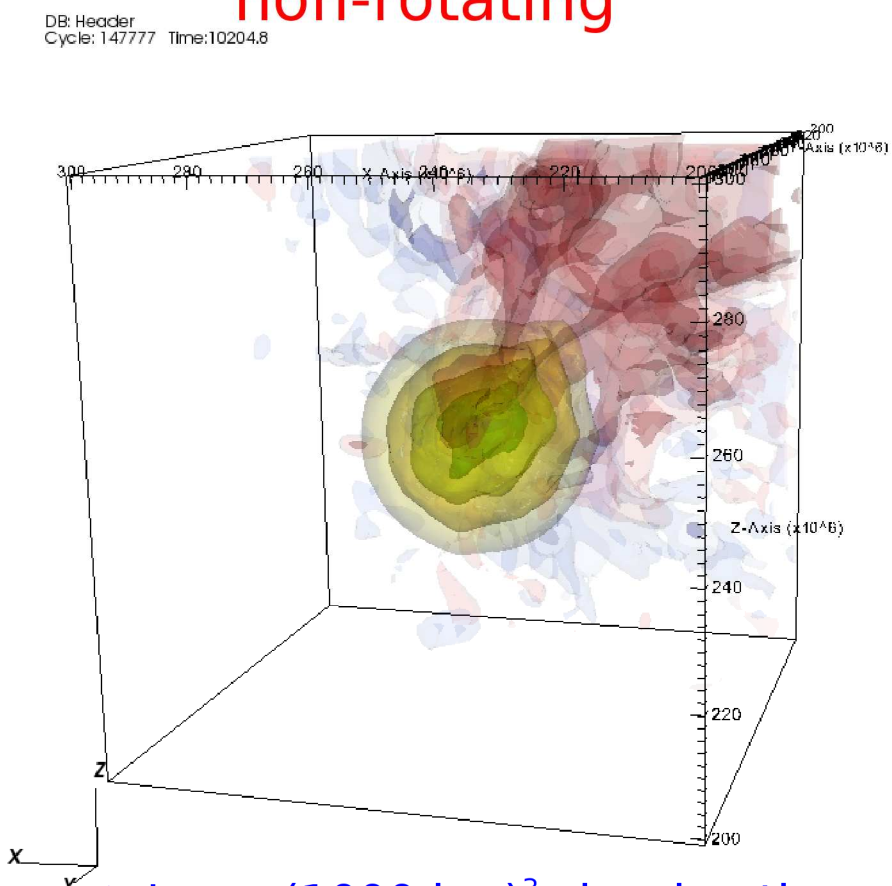
Almgren, Bell, Nonaka, & Zingale 2009 CiSE, 11, 2, 24.

- Elliptic constraint → instantaneous acoustic equilibriation
  - Numerical experiments show strong agreement with compressible codes for M < 0.3

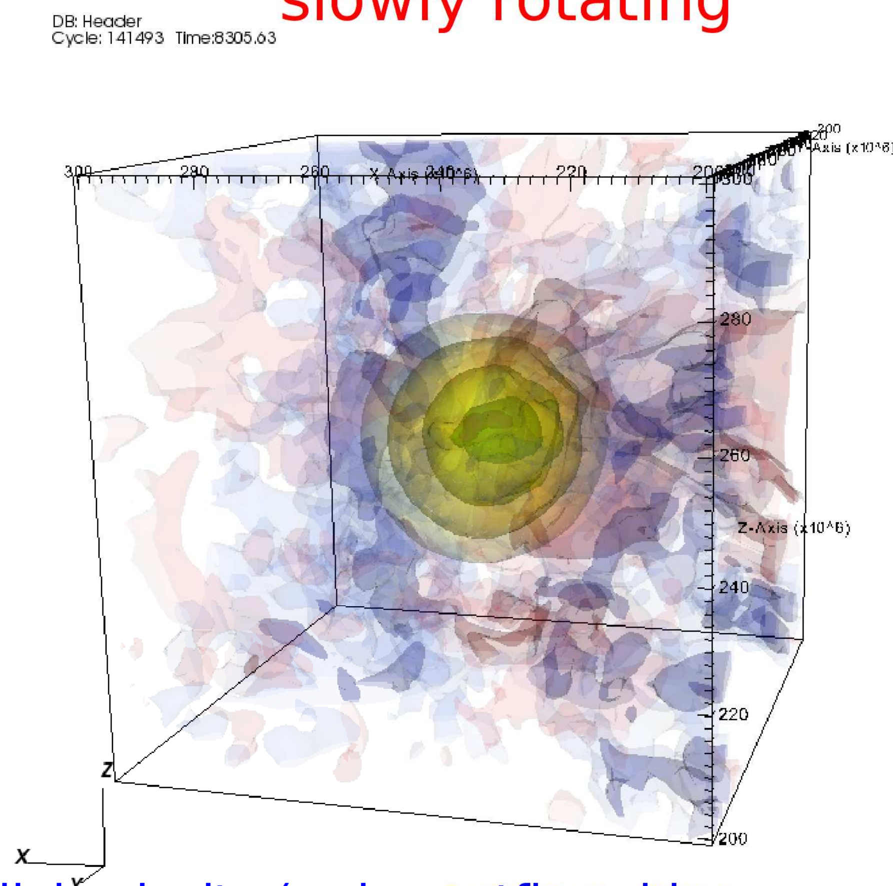


At the moment of ignition...

non-rotating



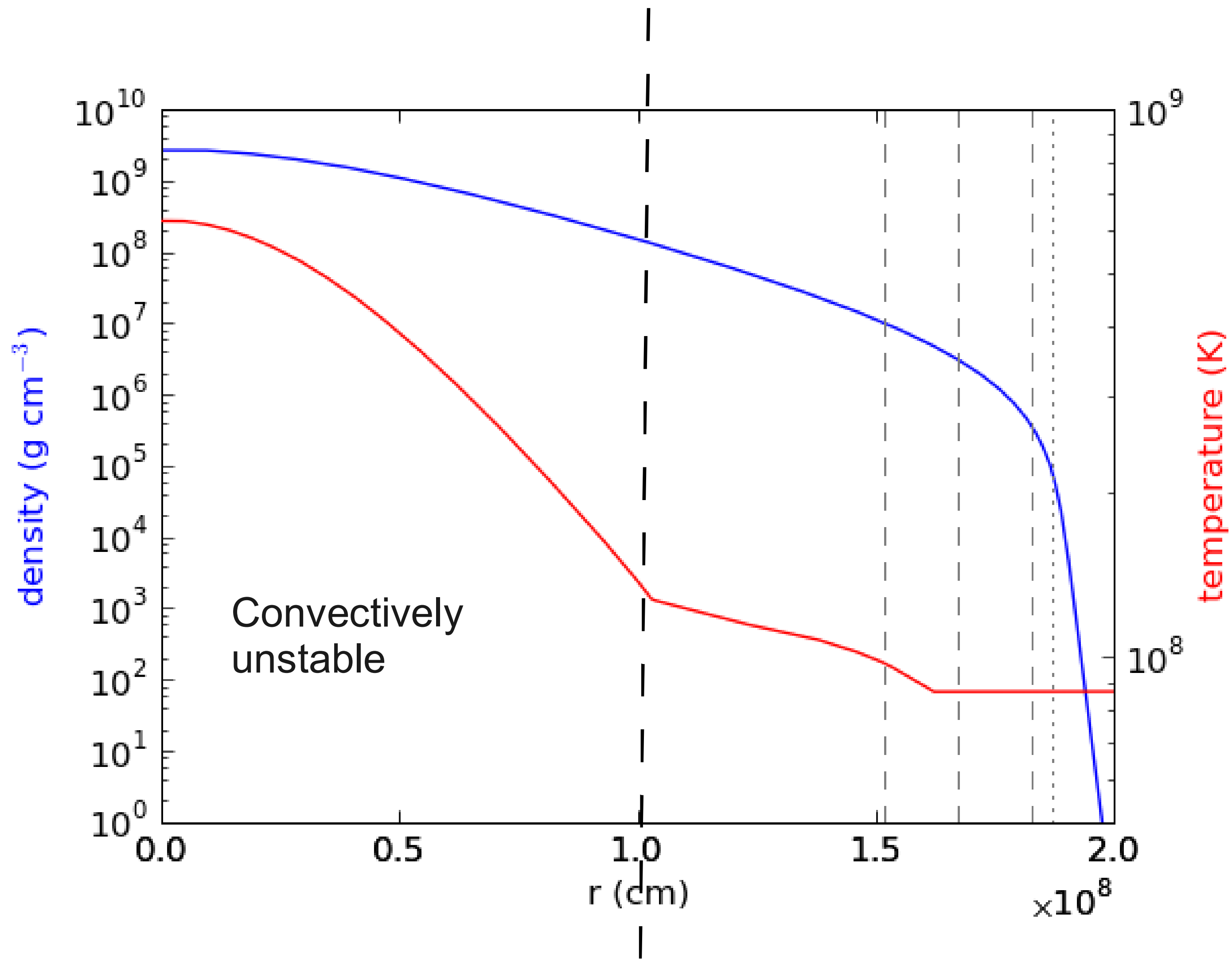
slowly rotating



▲ Inner (1000 km)^3 showing the radial velocity (red = outflow; blue = inflow), and nuclear energy generation rate (yellow to green to purple, log spaced).

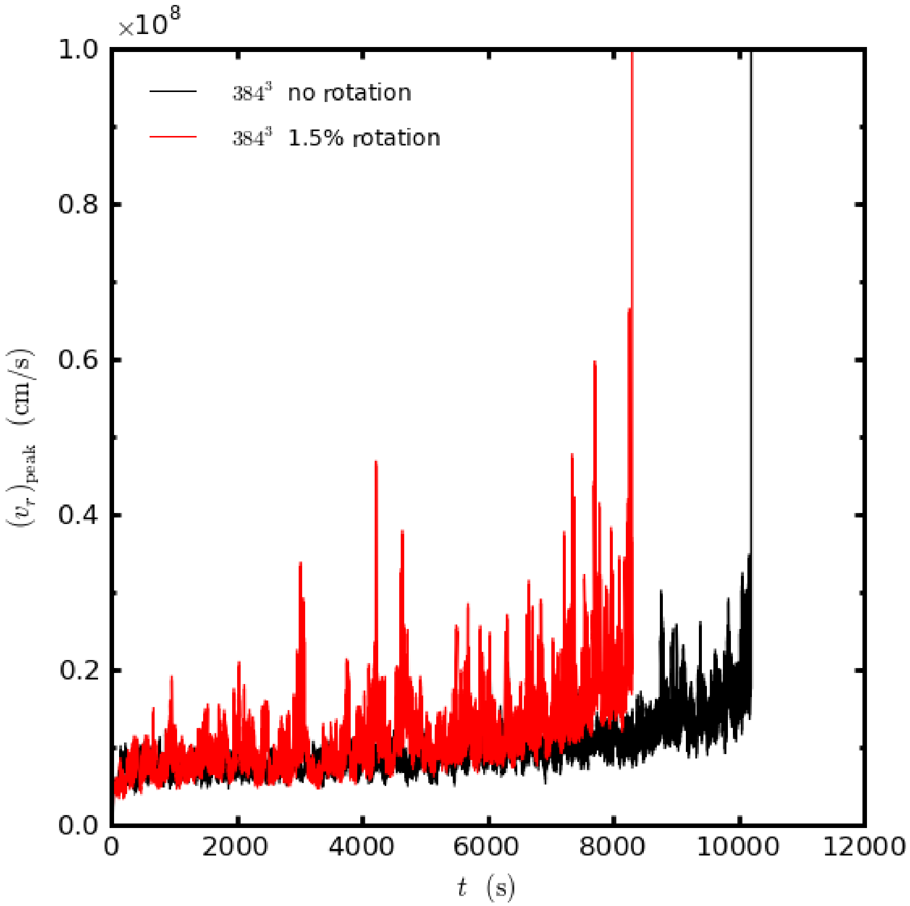
Energy generation (yellow to green contours) is strongly peaked—ignition is localized.

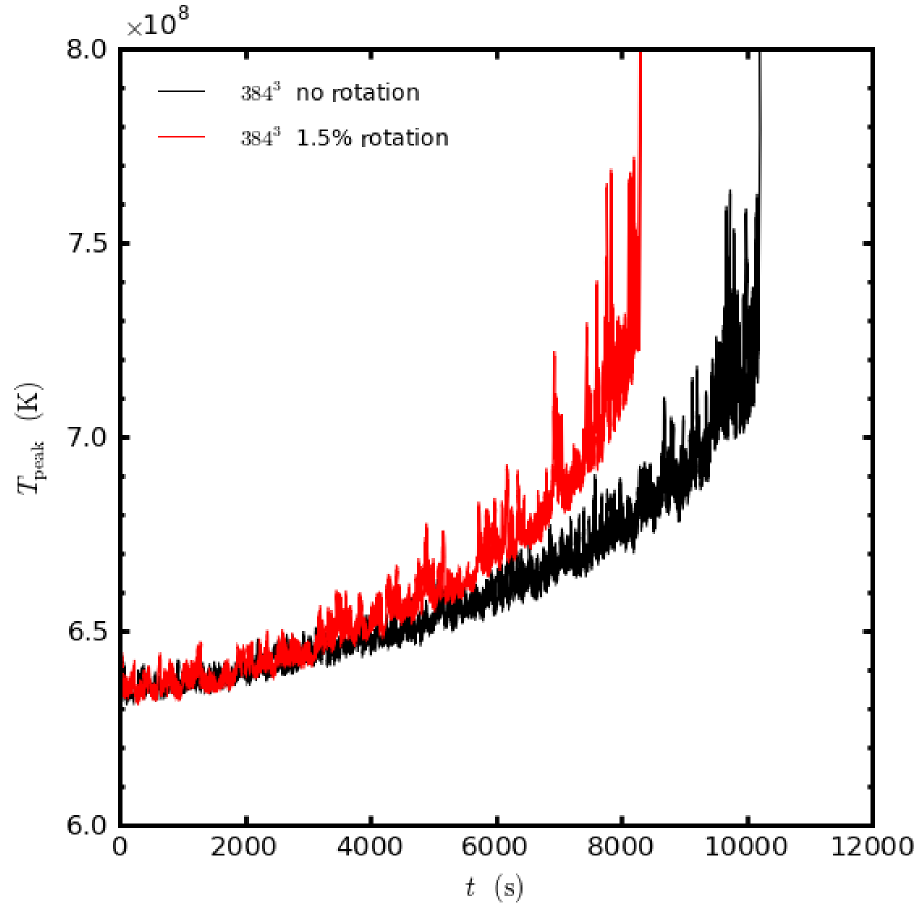
White Dwarf Initial Model



Rotating vs. Non-rotating

Zingale et al. 2010, in preparation.



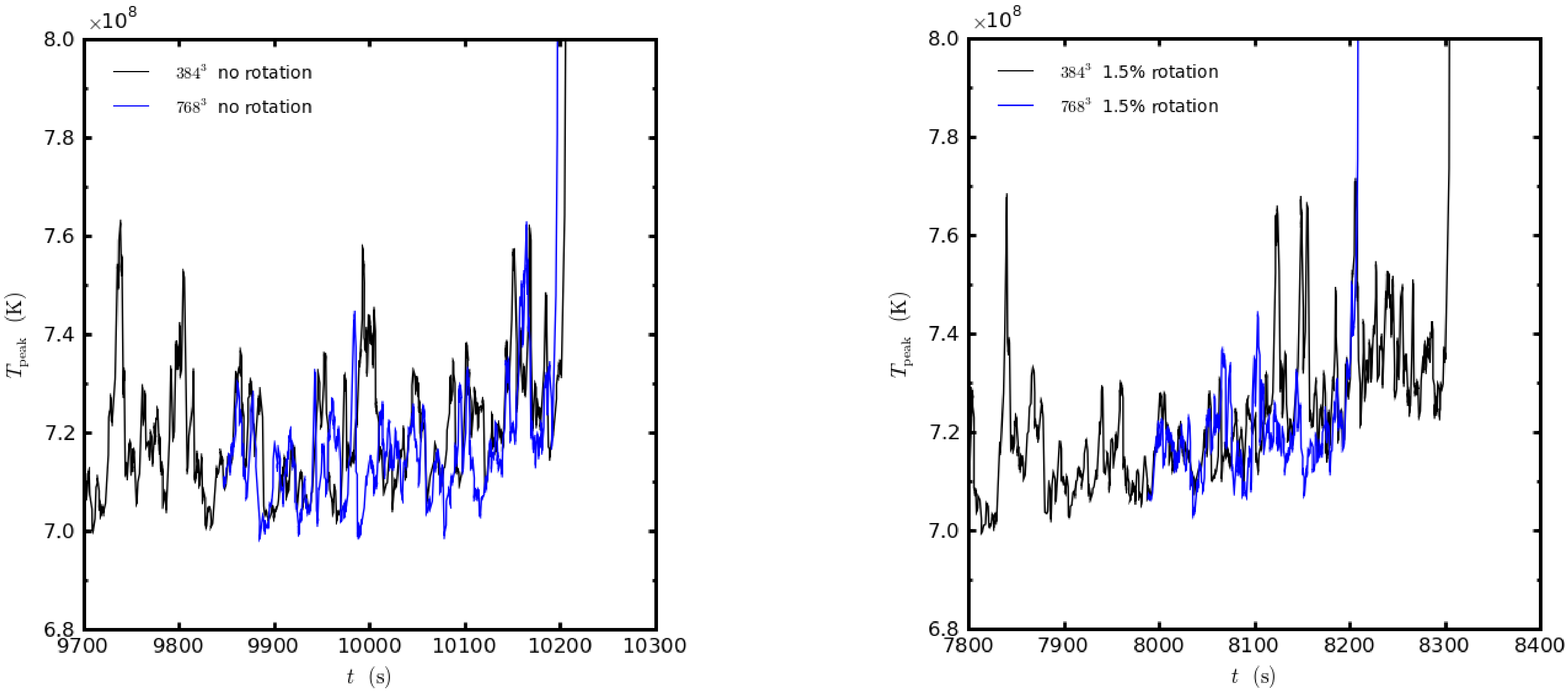


Rotating model has stronger velocity fluctations...

...and ignites sooner

AMR: Improving Resolution

Zingale et al. 2010, in preparation.

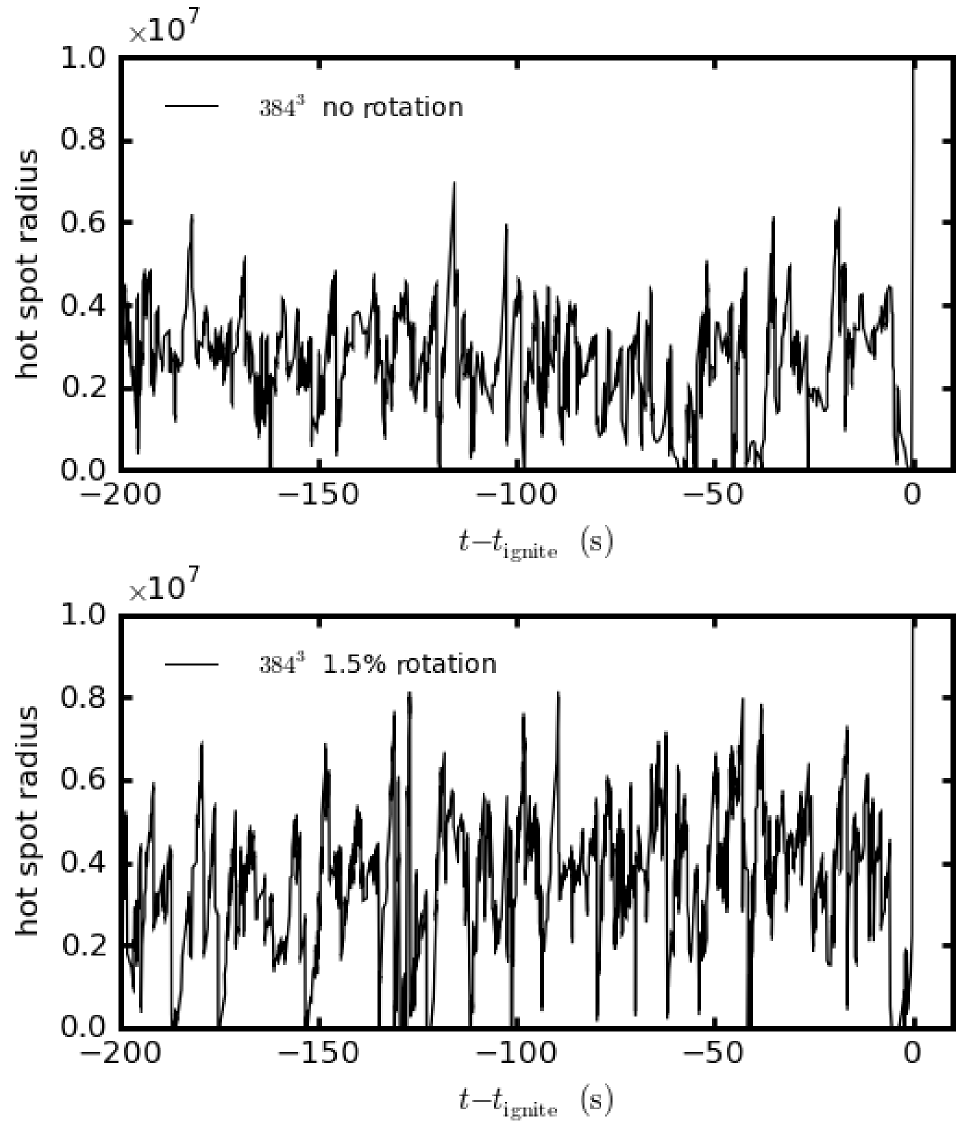


- Adding a level of refinement late in the evolution appears well-behaved.

Strongly Non-linear Ignition

Zingale et al. 2010, in preparation.

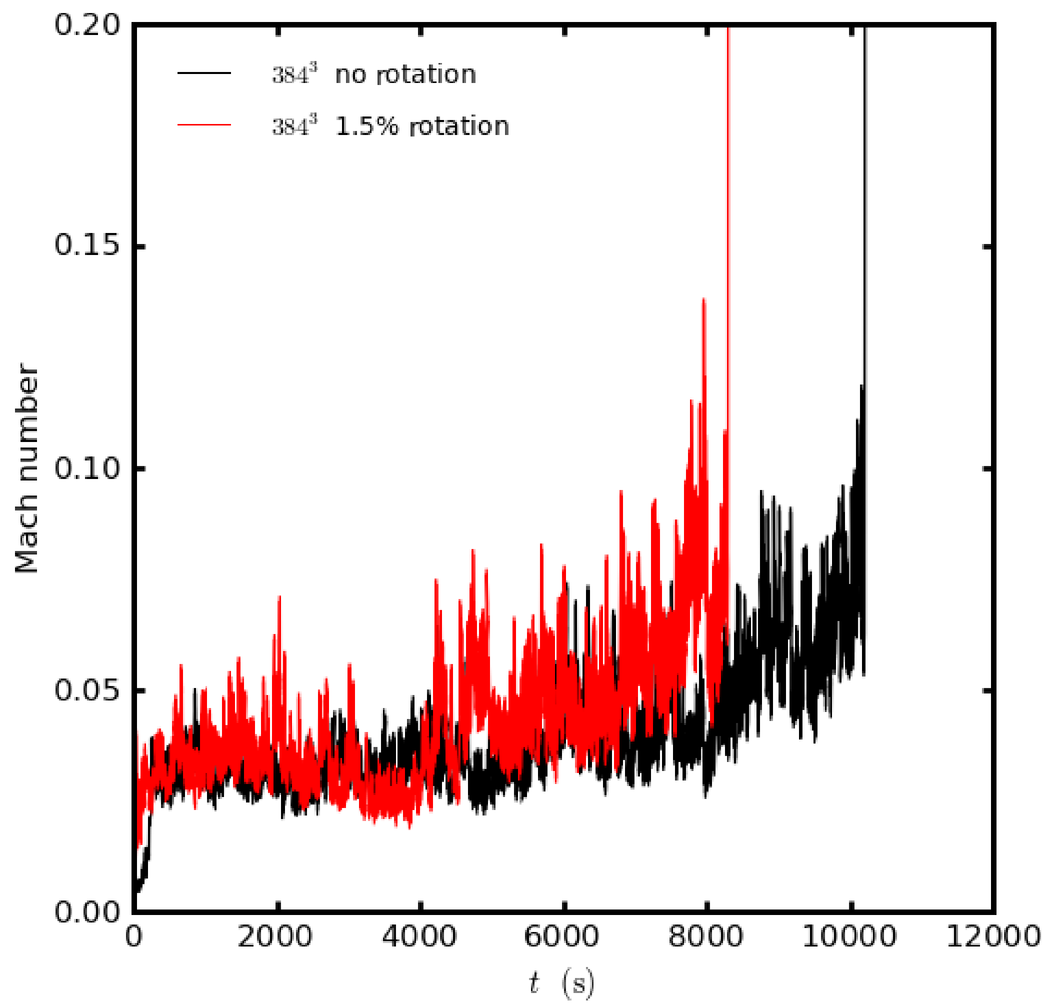
- Radius of hot spot fluctuates widely up until ignition
- “Second ignition” currently not captured.



In the Low-Mach Regime...

Zingale et al. 2010, in preparation.

- Both models in low-Mach number regime up until ignition
  - Maximum Mach number is in outer stable region



Ignition Summary

Table 1. Ignition parameters from different simulations

ID	simulation description	grid[a]	Δx (km)	R_{ignite} (km)	$(v_r)_{\mathrm{ignite}}$[b] (km s^{-1})	source
A	non-rotating WD, $T_c = 6.25 \times 10^8$ K initial model, new energetics, PPM, $\rho_{\mathrm{cutoff}} = 10^5$ g cm^{-3}	384^3	13.0	11.3	0.14	this paper
B	rotating WD (1.5% Keplerian), $T_c = 6.25 \times 10^8$ K initial model, new energetics, PPM, $\rho_{\mathrm{cutoff}} = 10^5$ g cm^{-3}	384^3	13.0	46.4	7.0	this paper
C	rotating WD (3.0% Keplerian), $T_c = 6.25 \times 10^8$ K initial model, new energetics, PPM, $\rho_{\mathrm{cutoff}} = 10^5$ g cm^{-3}	384^3	13.0			this paper
D	restart of simulation A after 9846 s with 1 level of refinement near the center	768^3	6.5	34.9	21.2	this paper
E	restart of simulation B after 7989 s with 1 level of refinement near the center	768^3	6.5	40.5	6.7	this paper
-	non-rotating WD, $T_c = 6 \times 10^8$ K initial model, old energetics, piece-wise linear, $\rho_{\mathrm{cutoff}} = 10^6$ g cm^{-3}	256^3	19.5	32.4	2.9	Zingale et al. (2009)
-	non-rotating WD, $T_c = 6 \times 10^8$ K initial model, old energetics, piece-wise linear, $\rho_{\mathrm{cutoff}} = 3 \times 10^6$ g cm^{-3}	256^3	19.5	84.6	39.0	Zingale et al. (2009)
-	non-rotating WD, $T_c = 6 \times 10^8$ K initial model, old energetics, piece-wise linear, $\rho_{\mathrm{cutoff}} = 3 \times 10^6$ g cm^{-3}	384^3	13.0	21.6	4.8	Zingale et al. (2009)

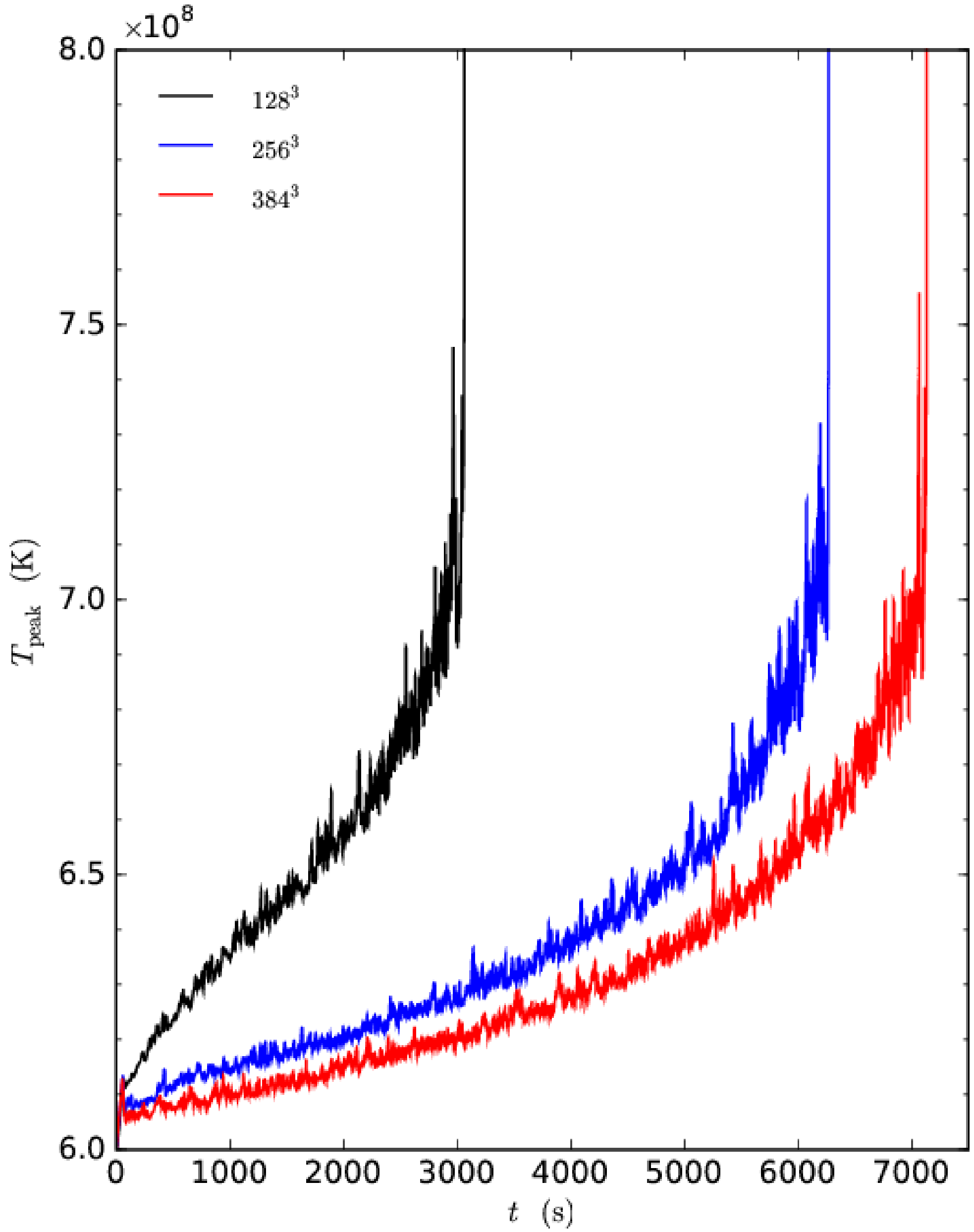
[a]effective resolution (if AMR)

[b]positive values indicate outflow, negative values indicate inflow

Resolution Sensitivity

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

- 128^3, 256^3, 384^3 simulations run with identical parameters
  - Lower resolution ignites earlier
  - Some convergence seen



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.
- Rapidly changing convective field
  - Typical convective velocities ~ laminar flame speed
  - Accurate explosion calculations need a realization of the velocity field
- Range of ignition locations: between central and ~80 km off-center
  - Large parameter study needed to map out distribution of allowed ignition radii
- Acoustics or mapping into a compressible code needed to explore the “second ignition”.
- MAESTRO being applied to X-ray bursts; work just beginning on applications to nova, sub-Chandra SNe Ia ignition, and H core convection in massive stars.