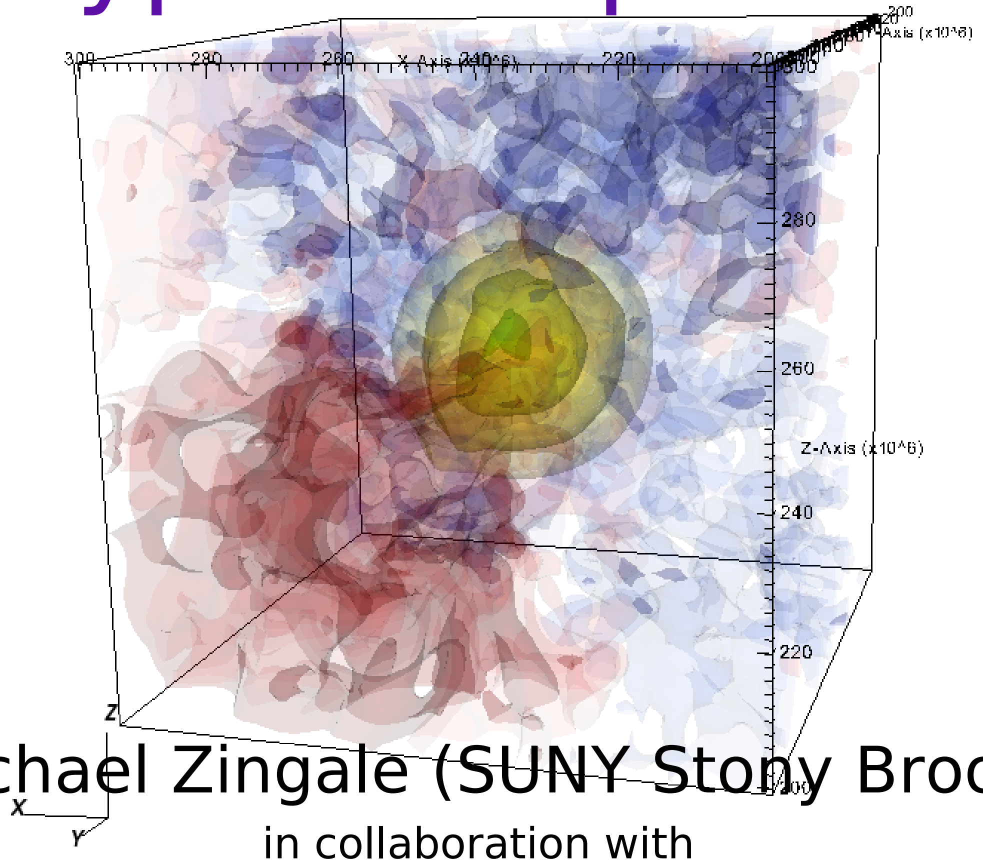
Modeling Convection and Ignition in Type Ia Supernovae



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in collaboration with

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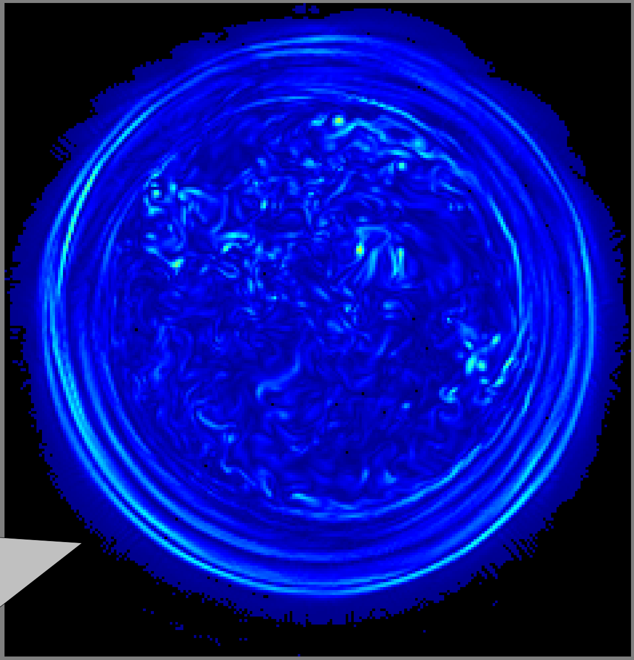
Type Ia Supernovae

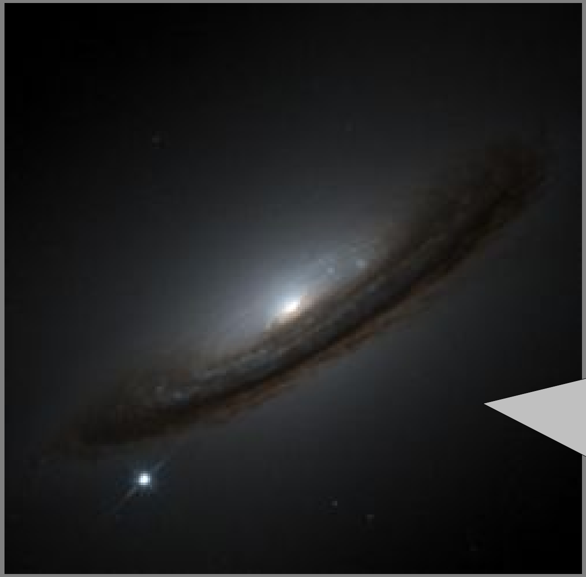
(single-degenerate scenario)

(David A. Hardy & PPARC)

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

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

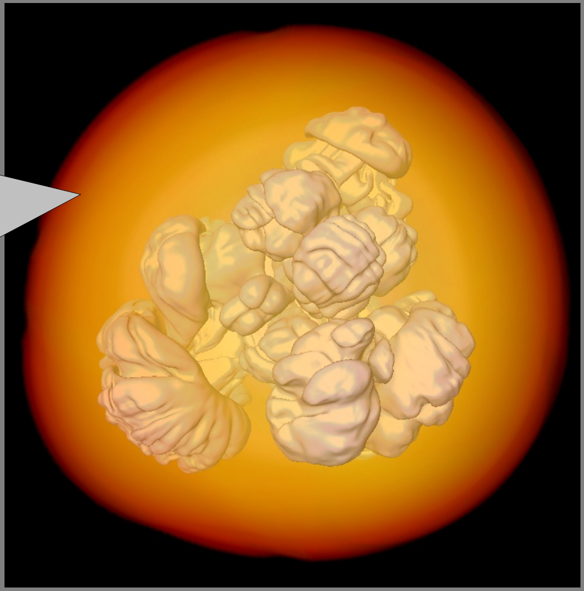




SN 1994D (High-Z SN Search team)

3 Flame propagation. Initially subsonic, but detonation transition?

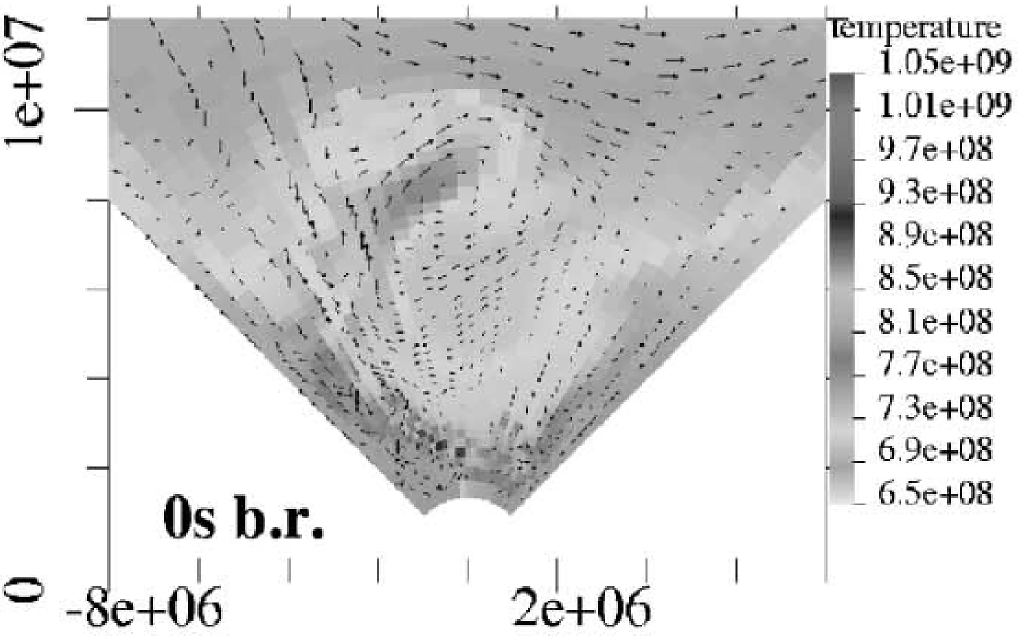
4 Explosion! Lightcurve powered by Ni decay. Width / luminosity relation.



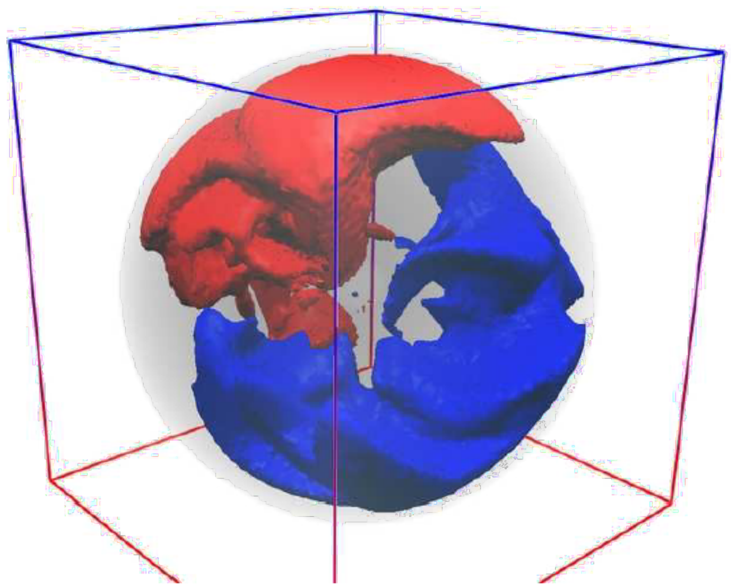
(Roepke and Hillebrandt 2005)

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.

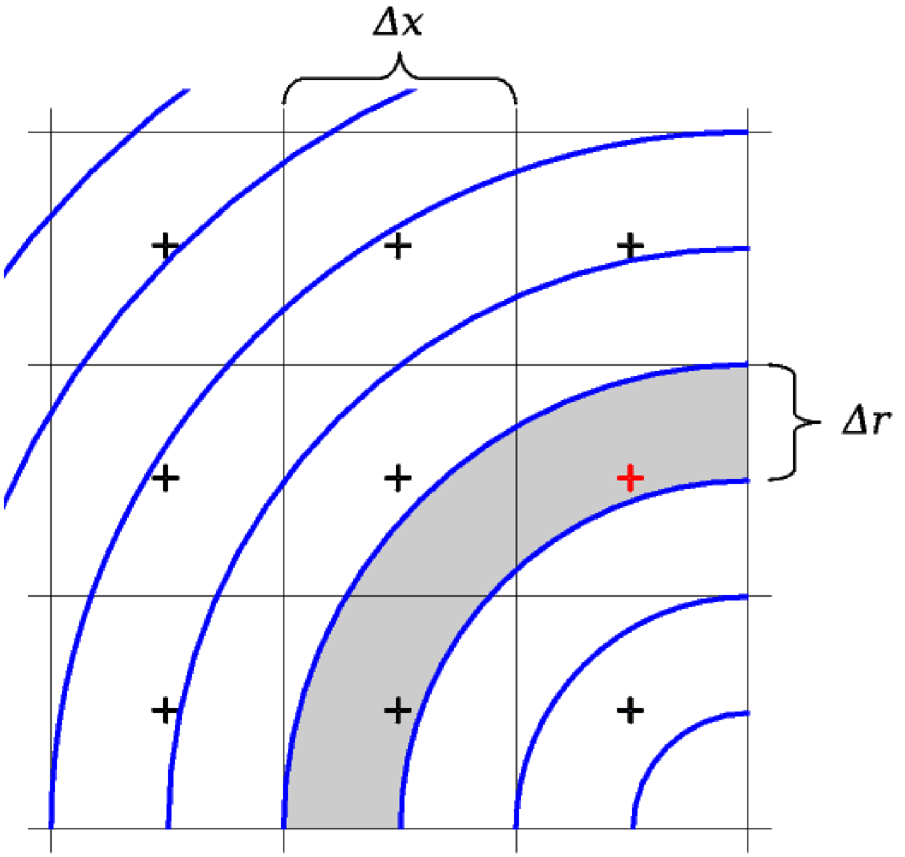
No previous calculations have modeled the entire star.

With rare exception, explosion calculations begin with zero velocity.

Mapping

Zingale, Almgren, Bell, Nonaka, & Woosley 2009, ApJ, 704, 196
Nonaka, Almgren, Bell, Lijewski, Malone, & Zingale 2010, ApJS, 188, 358

- Spherical star
  - 1-d hydrostatic radial base state $\nabla p_0 = -\rho_0 g \mathbf{e}_r$
  - 3-d Cartesian full state
  - Not aligned
- Cartesian grid eliminates coordinate singularities
- Mapping needed
  - Best results with $\Delta r < \Delta x$

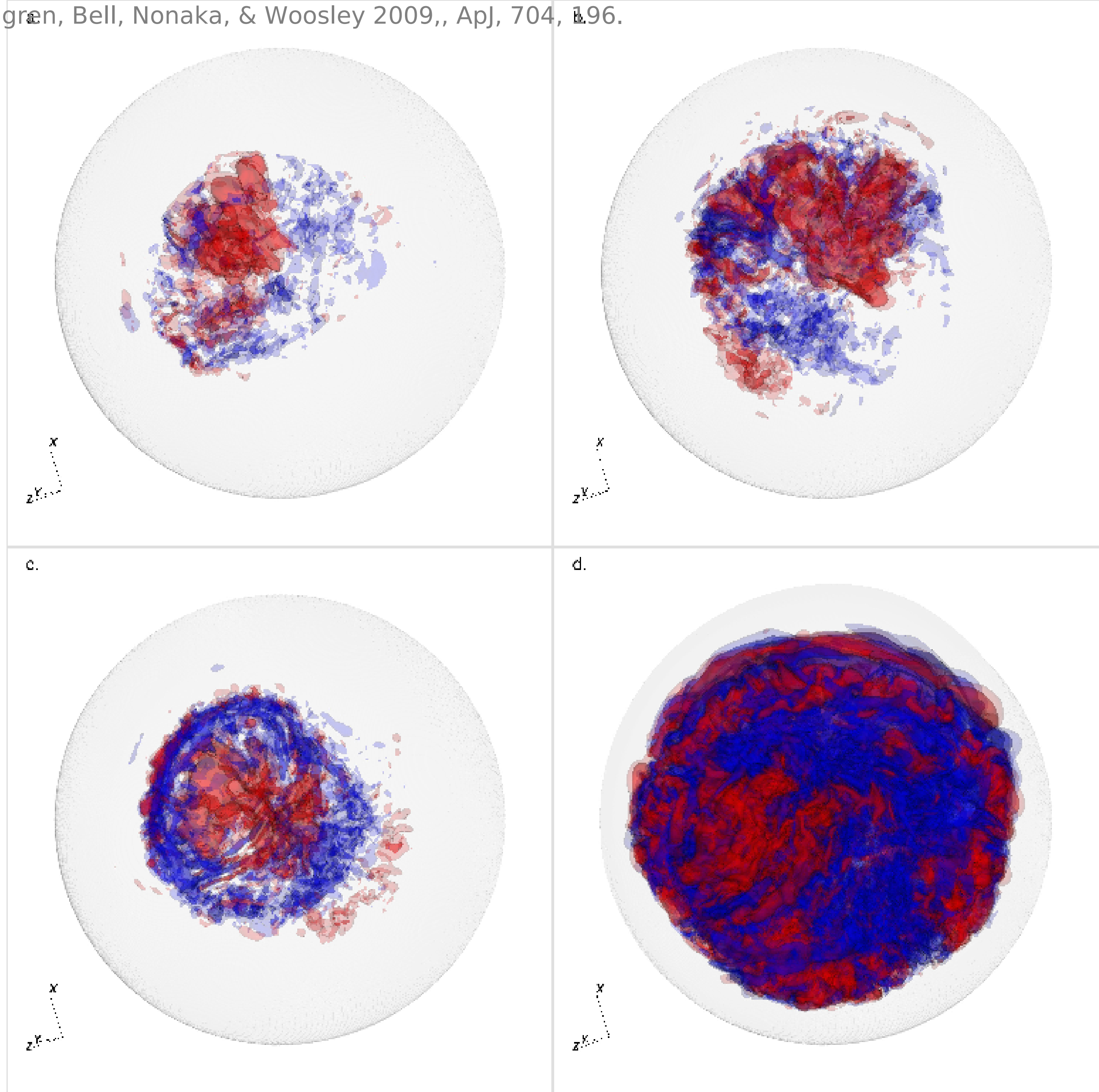


WD Convection: Initial Study

Dipole Convection

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

- Recover dipole feature seen in previous calculations
  - Asymmetry in radial velocity field
- Direction of dipole changes rapidly

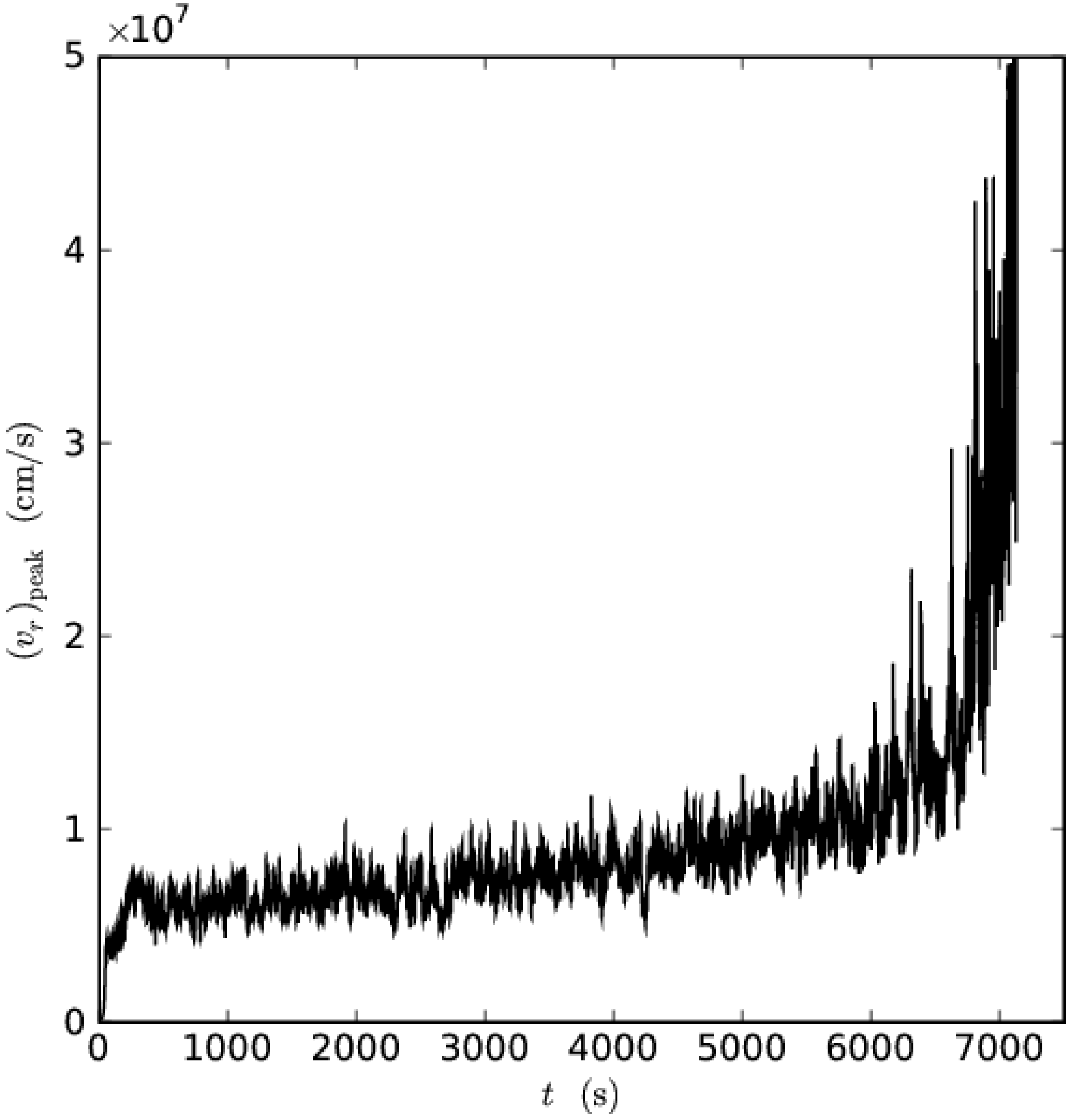


WD Convection: Initial Study

Convective Speeds

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

- Radial velocities ~ 10^7 cm/s imply convective turnover time of ~ 20 s.
  - Same magnitude as initial laminar flame speed.
- Explosion model calculations need to model the initial flow.

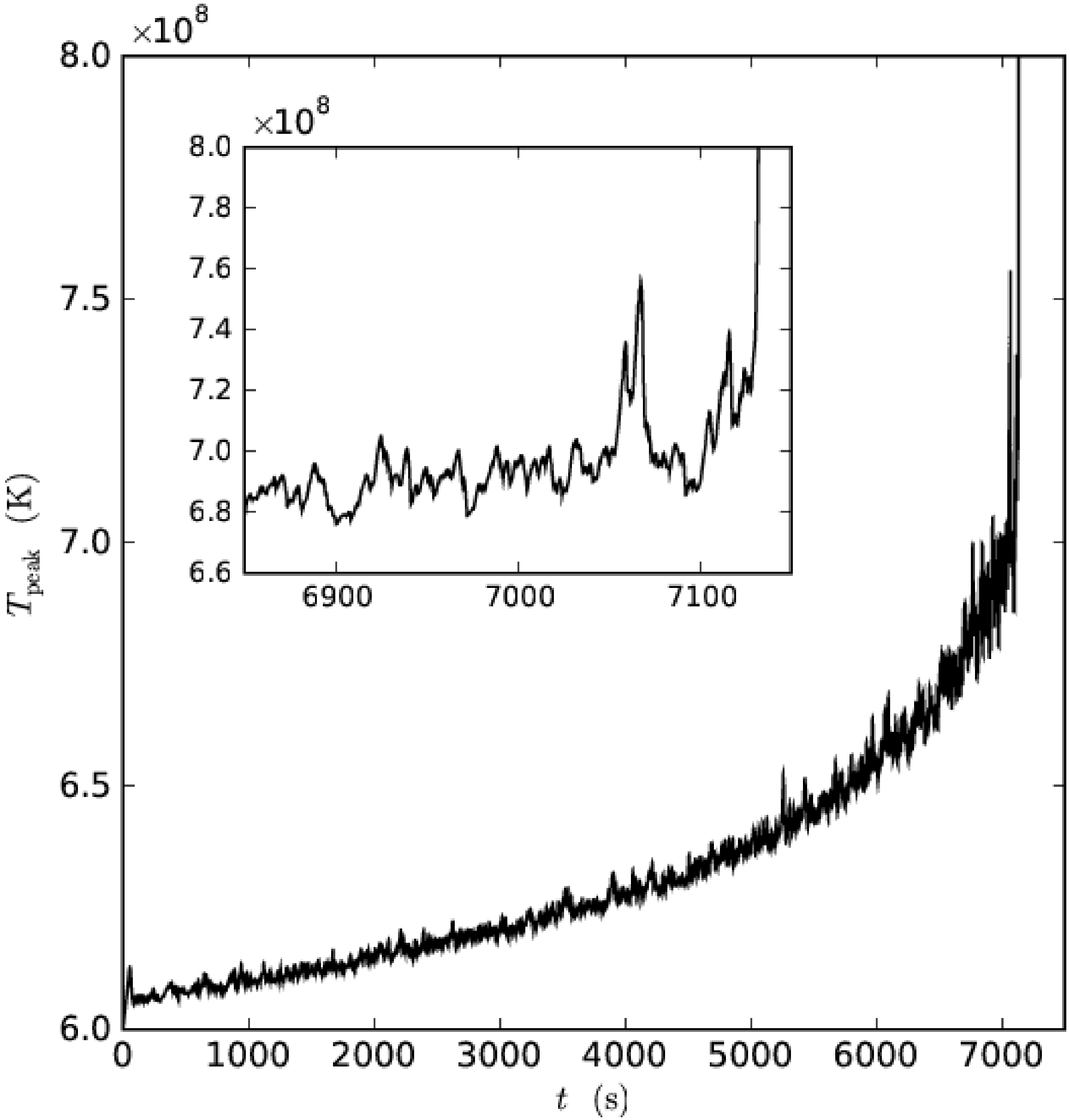


WD Convection: Initial Study

Runaway

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

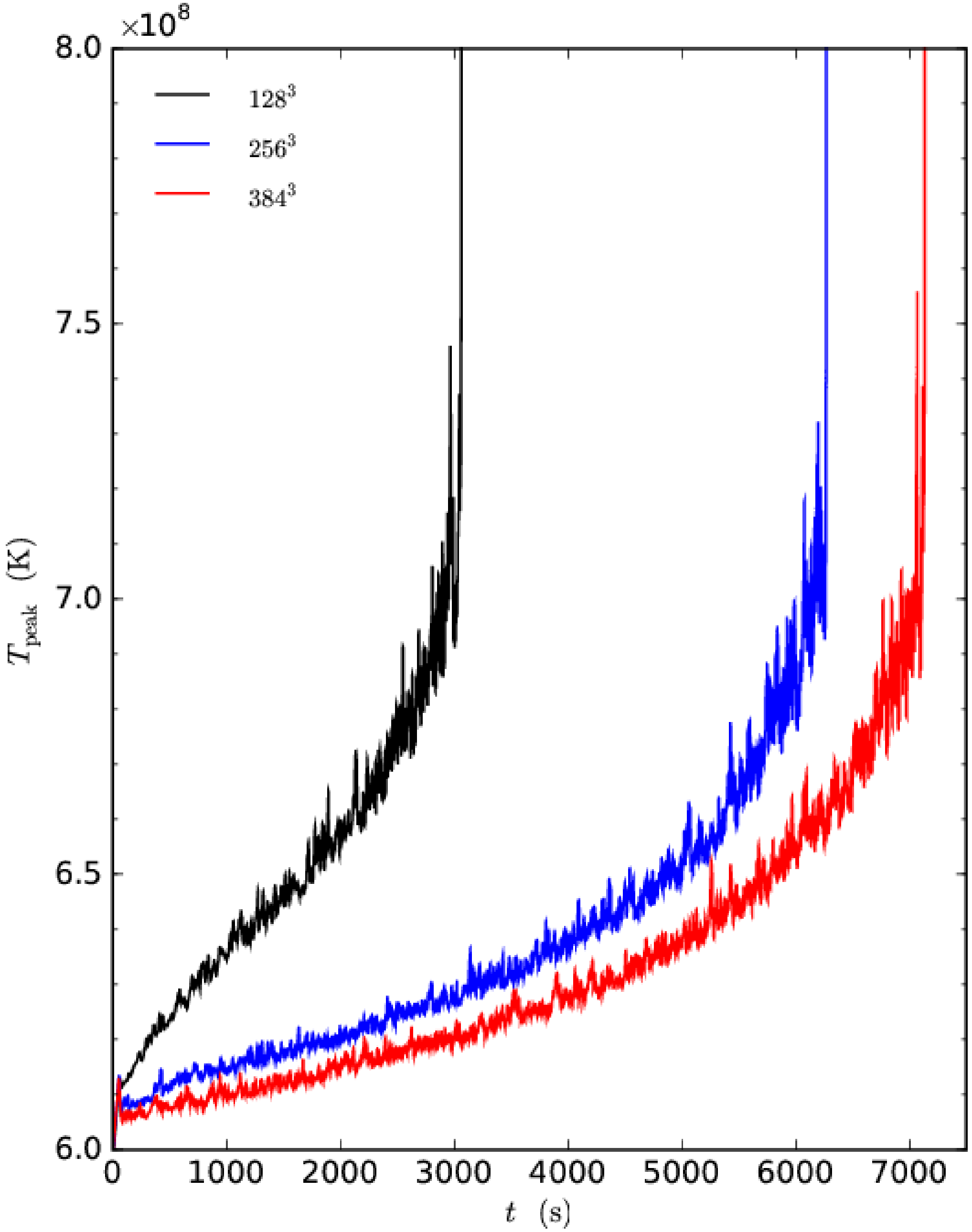
- Temperature increase nonlinear
  - Ignition occurs as T crosses 8 x 10^8 K
  - “Failed” hotspots seen toward the end.



WD Convection: Initial Study
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



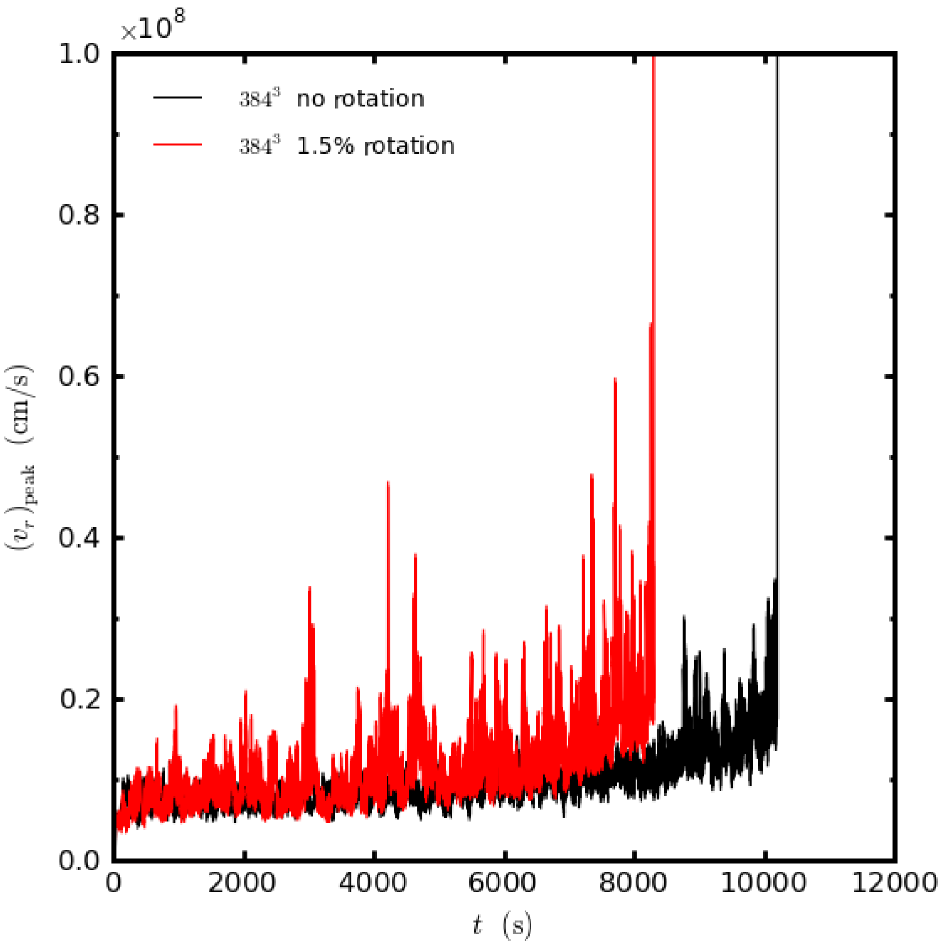
Improved Calculations

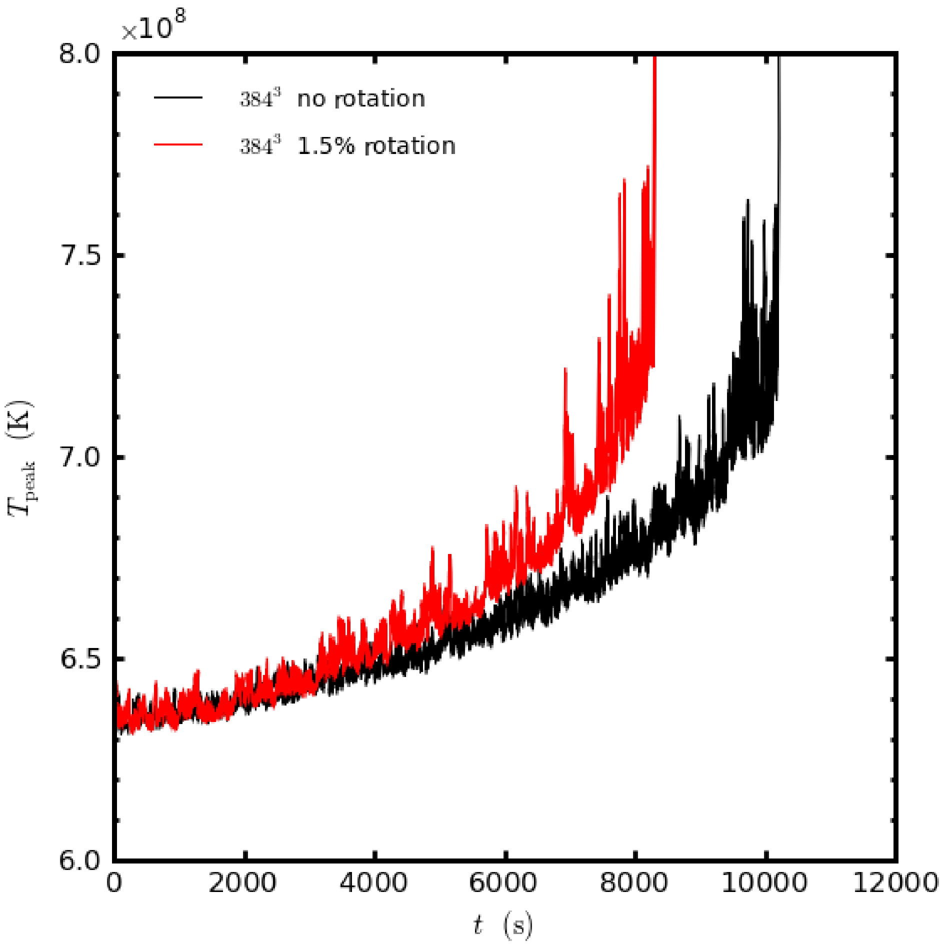
- New energetics
- PPM advection
- Base state evolution
- Rotation
- Better coupling between base state and full state

Improved Calculations

Rotating vs. Non-rotating

Zingale et al. 2010, in preparation.





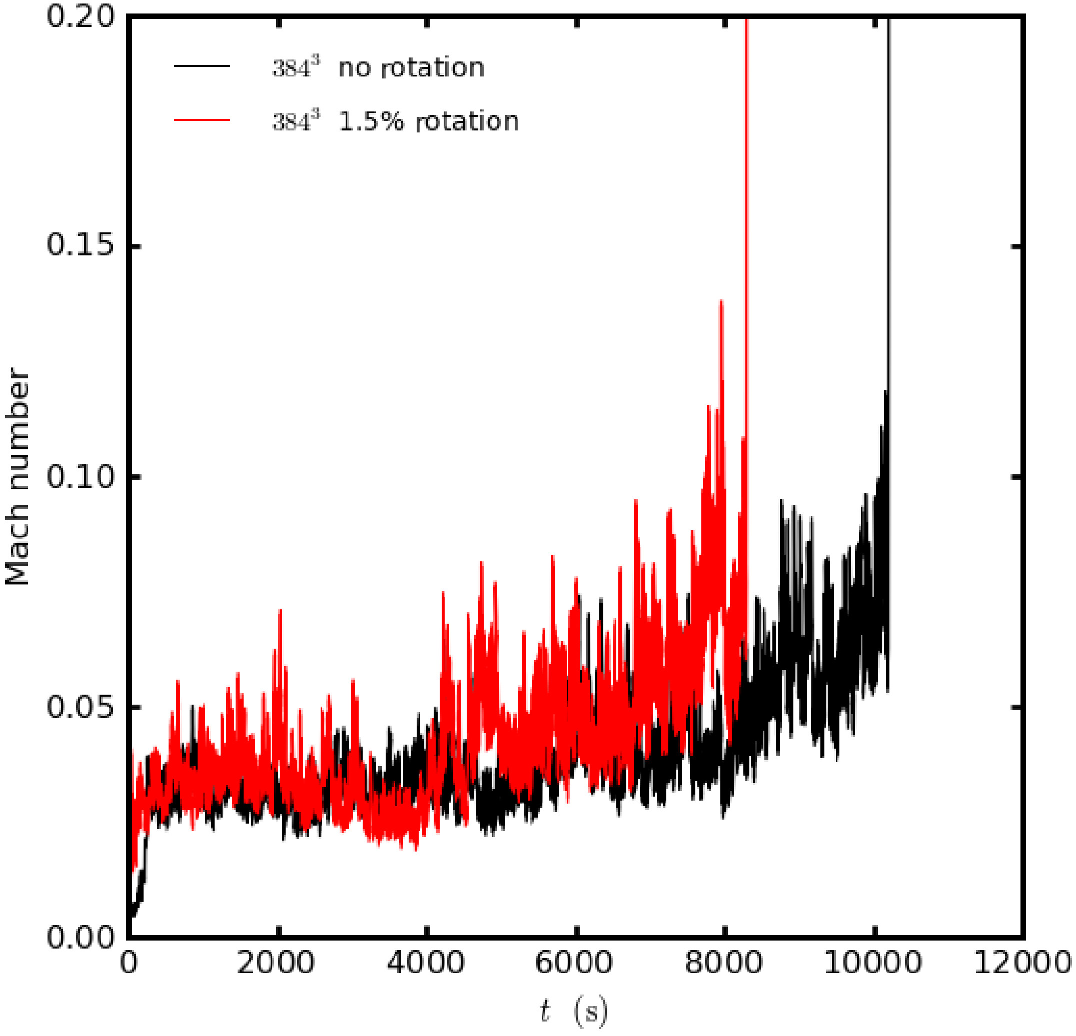
Rotating model has stronger velocity fluctations...

...and ignites sooner

Improved Calculations
Rotating vs. Non-rotating

Zingale et al. 2010, in preparation.

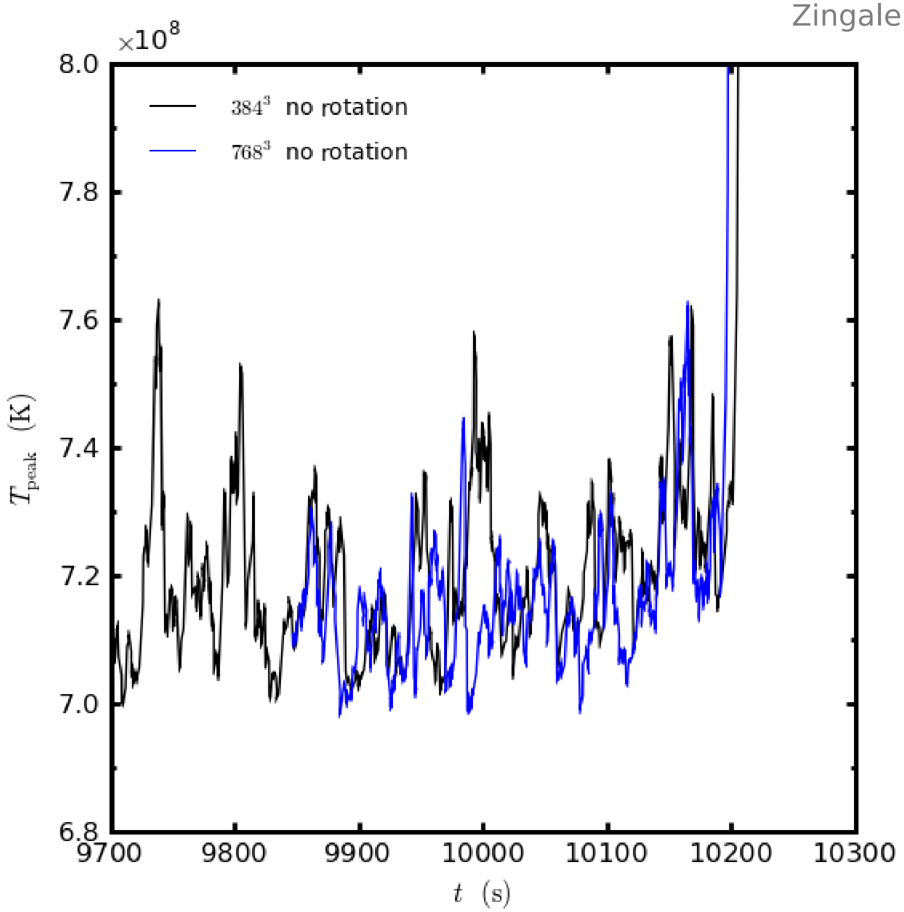
- Both models in low-Mach number regime up until ignition
  - Maximum Mach number is in outer stable region

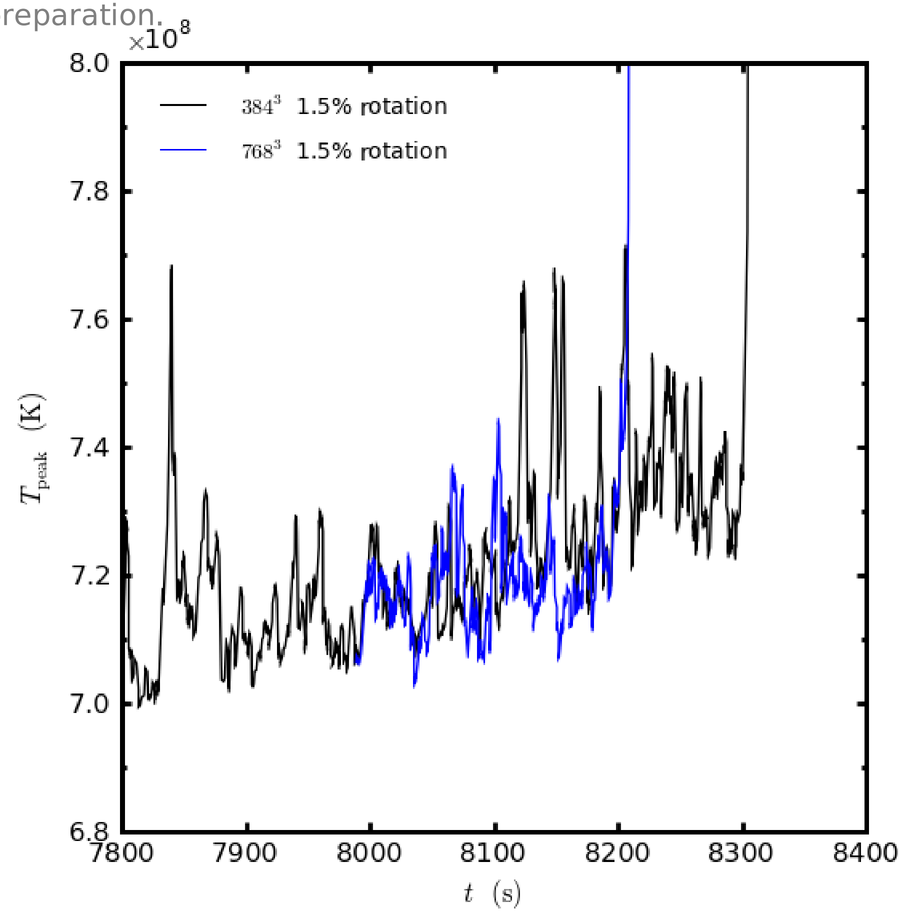


Improved Calculations

AMR: Improving Resolution

Nonaka, Almgren, Bell, Lijewski, Malone, & Zingale 2010, ApJS, 188, 358
Zingale et al. 2010, in preparation.



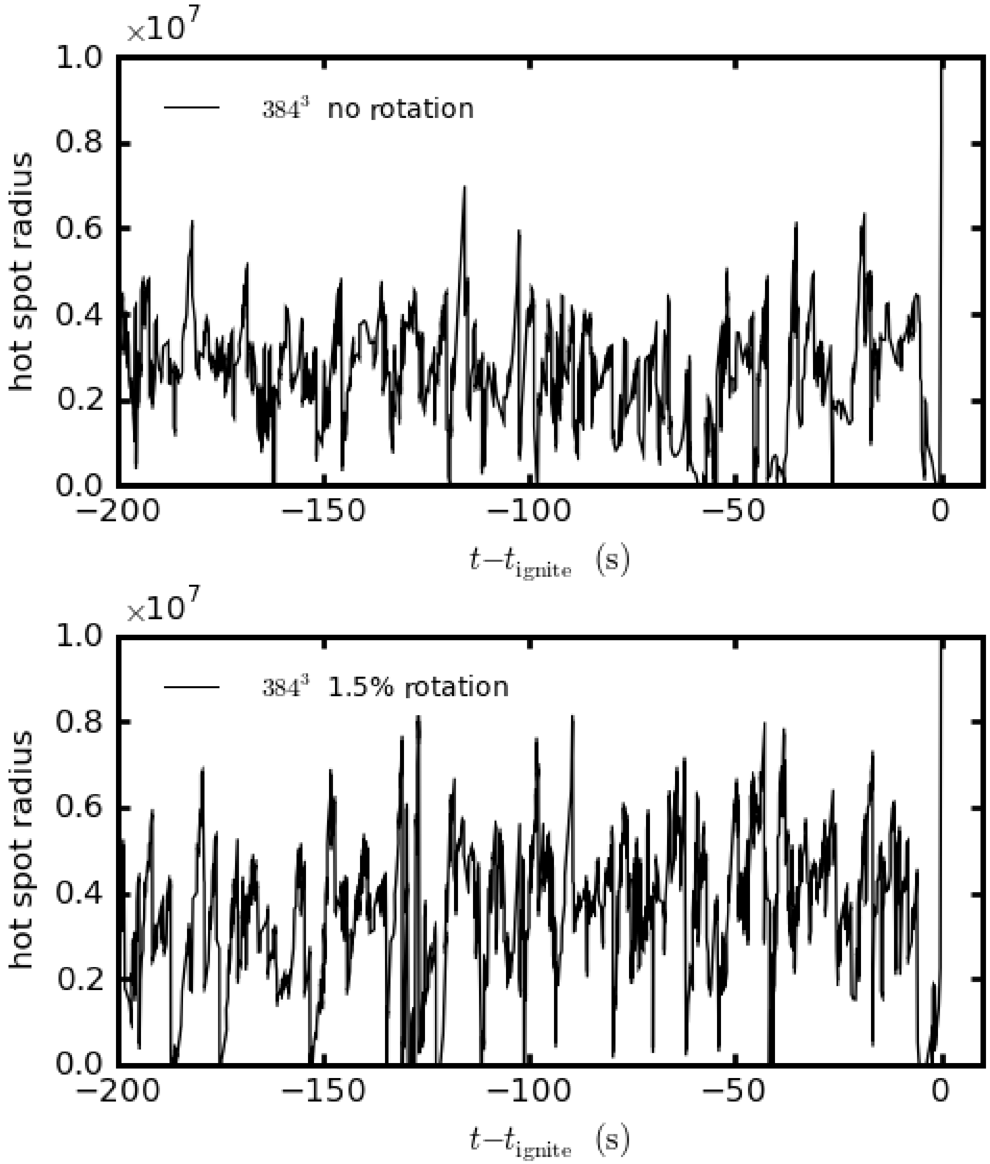


- Adding a level of refinement late in the evolution appears well-behaved.

Improved Calculations
Strongly Non-linear Ignition

Zingale et al. 2010, in preparation.

- Radius of hot spot fluctuates widely up until ignition



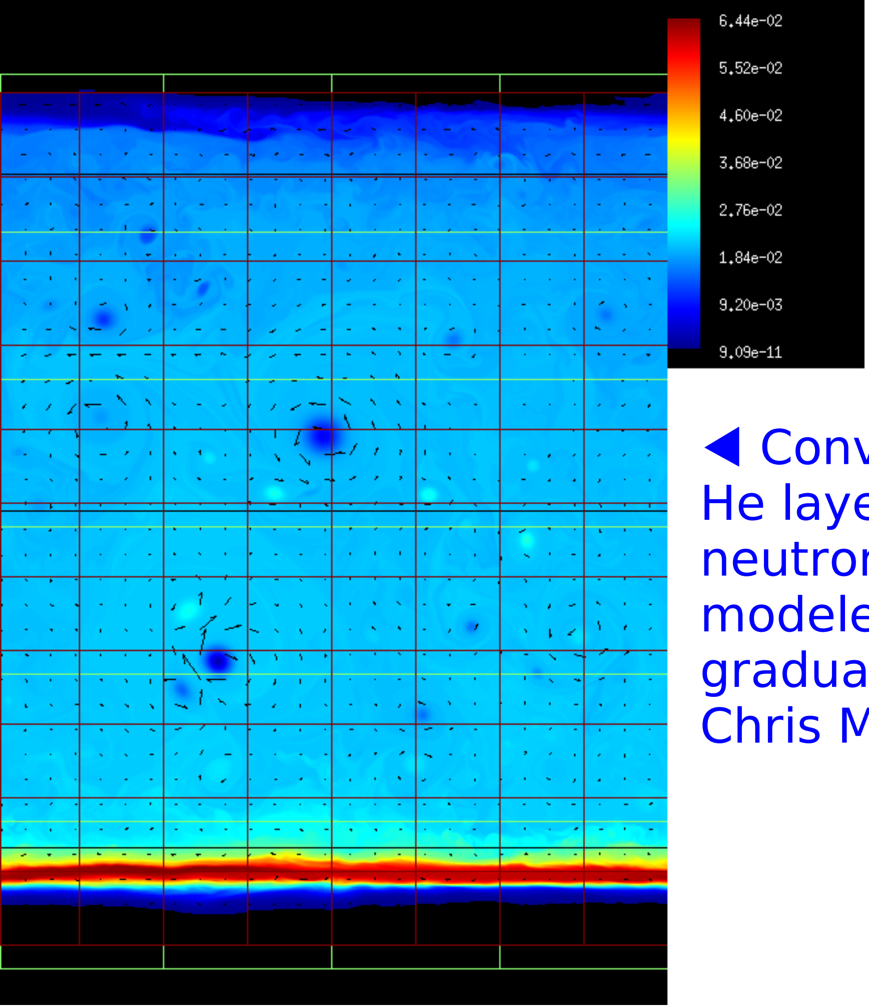
Ignition Summary

Table 1. Ignition parameters from different simulations

ID	simulation description	grid[a]	Δx (km)	$R_{\rm ignite}$ (km)	$(v_r)_{\rm ignite}$[b] (km s^{-1})	source
A	non-rotating WD, $T_c = 6.25 \times 10^8$ K initial model, new energetics, PPM, $\rho_{\rm cutoff} = 10^5$ 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, $\rho_{\rm cutoff} = 10^5$ 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, $\rho_{\rm cutoff} = 10^5$ 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, $\rho_{\rm cutoff} = 10^6$ 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, $\rho_{\rm cutoff} = 3 \times 10^6$ 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, $\rho_{\rm cutoff} = 3 \times 10^6$ g cm^{-3}	384^3	13.0	21.6	4.8	Zingale et al. (2009)

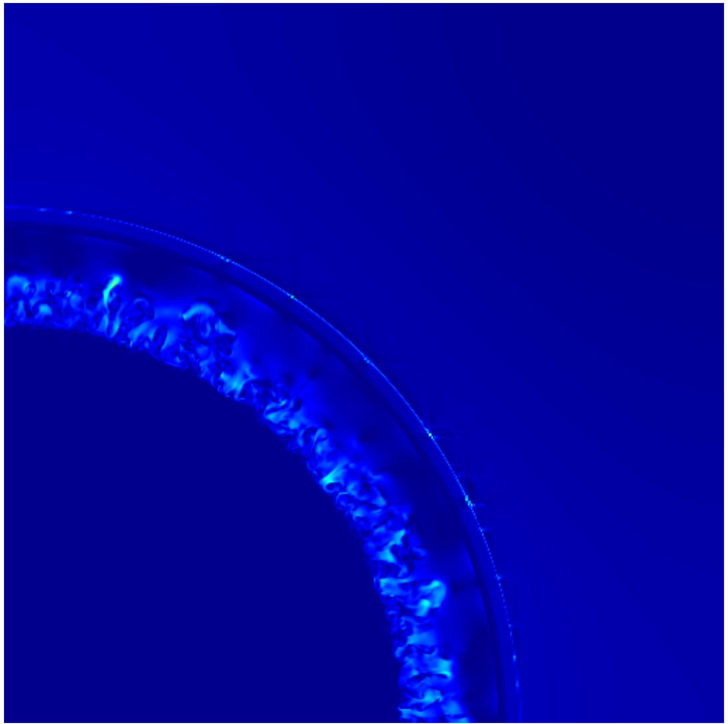
[a]effective resolution (if AMR)

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



- MAESTRO also being used to model:
  - X-ray bursts
    (Chris Malone, SBU)
  - Sub-Chandra Ia models
    (just started)
  - Classical nova
    (Brendan Krueger, SBU, just started)
  - Massive star H convection
    (Candace Gilet, UCB/LBL, just started)

◀ Convection in a He layer on a neutron star. (2-d; modeled by graduate student Chris Malone).



▶ Convection in a He layer on a sub-Chandra mass WD (slice through 3-d domain; very early)

Summary

- Modern algorithms / fast supercomputers are now able to model convective astrophysical flows for many turnover times in full 3-d.
- Rapidly changing convective field
  - Typical convective velocities ~ laminar flame speed
  - Accurate explosion calculations will need a realization of the velocity field
- Maximum Mach number O(0.1) toward very end of calculation (in outer layers)
- Range of ignition locations seen
- 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”.