Type Ia Supernovae:

Three Not So Easy Pieces

Ignition
Propagation
Light Curve

Progenitor

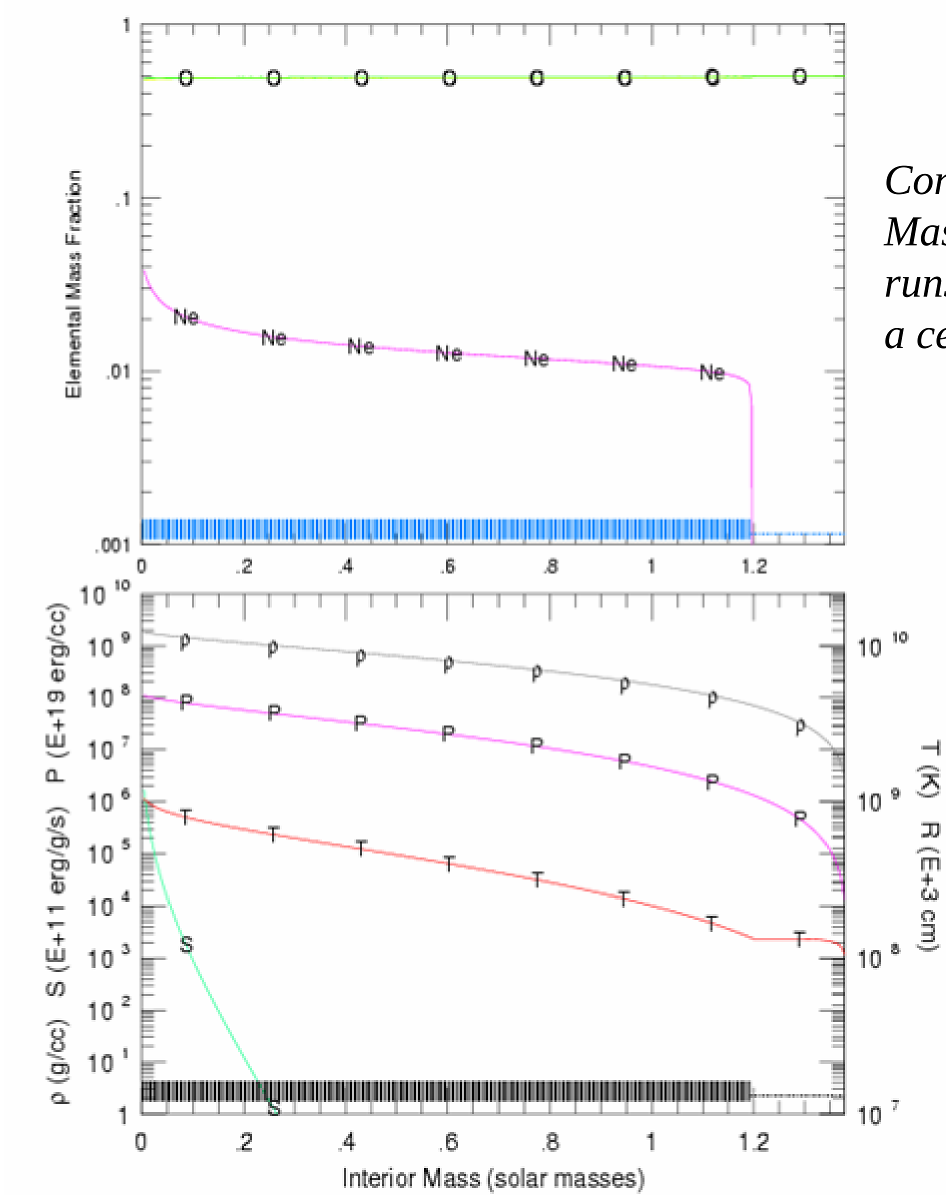
Hoyle and Fowler (1960)
Arnett (1968, 1969)
Nomoto, Sugimoto, & Neo (1976)

Ignition occurs as the *highly screened* carbon fusion reaction begins to generate energy faster than neutrino losses can carry it away.

At a given temperature, the plasma neutrino losses first rise with density and then decline when $\hbar\omega_p > kT$.

$$\text{As } \rho \rightarrow 3\times10^9 \text{ gm cm}^{-3}; \quad T \approx 3\times10^8 \text{ K}$$

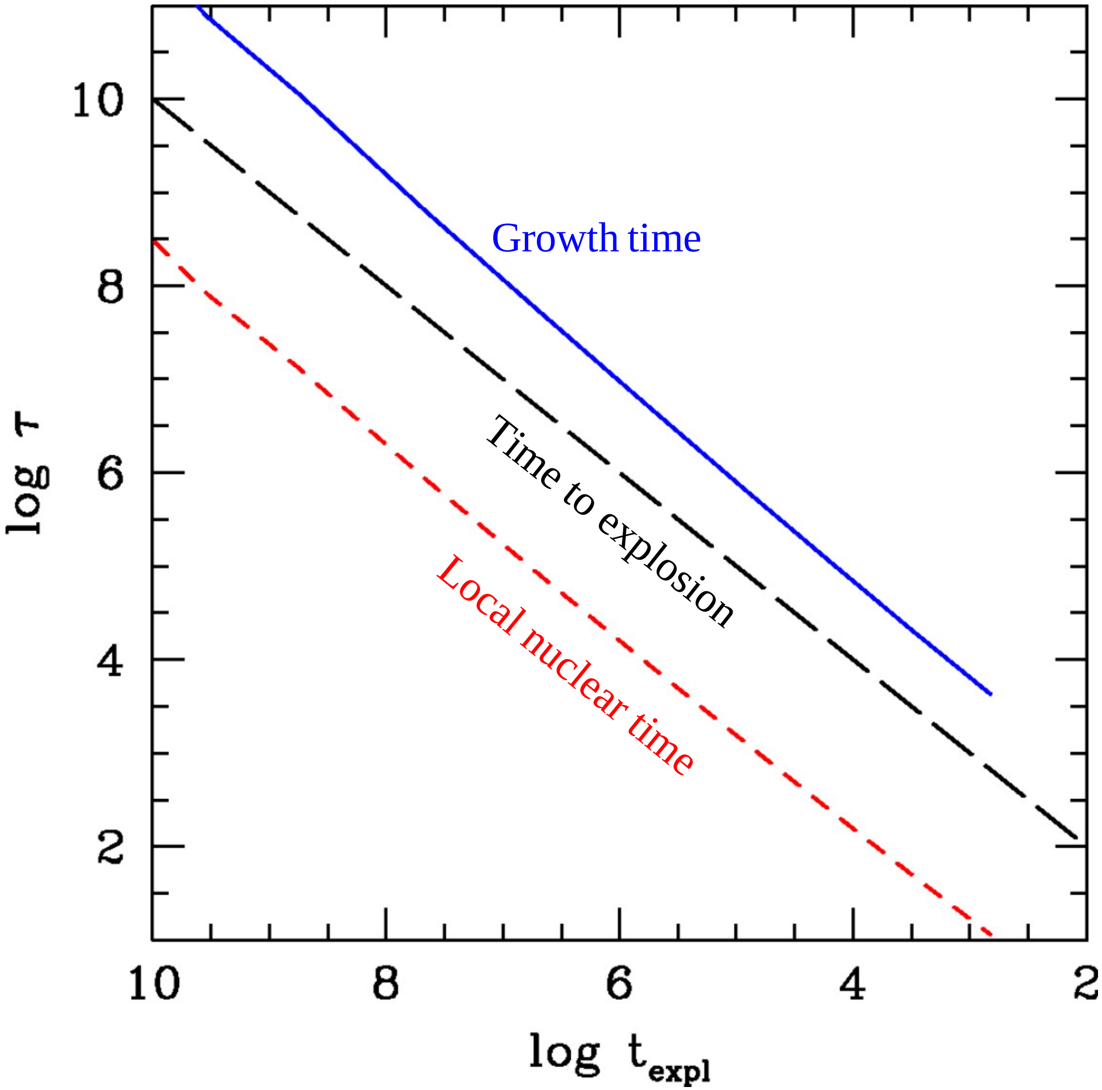
$$S_{nuc}\,(^{12}C + ^{12}C) \geq S_\nu\,(\text{plasma}); \qquad M \approx 1.38\ M_{sun}$$



Conditions in a Chandrasekhar Mass white dwarf as its center runs away – following about a century of convection.

Vertical bars denote convective regions

Pulsational Stability



- White dwarf is pulsationally unstable throughout carbon burning (500 years)
- Pulsational period 2 s
- $\Gamma = 4/3$, $\varepsilon_{nuc} = CT^{23}$
- Most of energy goes into heating the white dwarf
- ***Growth time of the pulsations never catches up with the runaway time***
- Would have interesting consequences if it did.

Baraffe, Heger, & Woosley ApJ, 615, 378 (2004)

Ignition Conditions

Last "good convective model" is when the central temperature has risen to 7 – 8 x 10^8 K

Pressure scale height: 400 km

Convective speed: 50 km s^{-1}

Nuclear time scale: ~10^2 s

Binding energy: 4 x 10^{50} erg

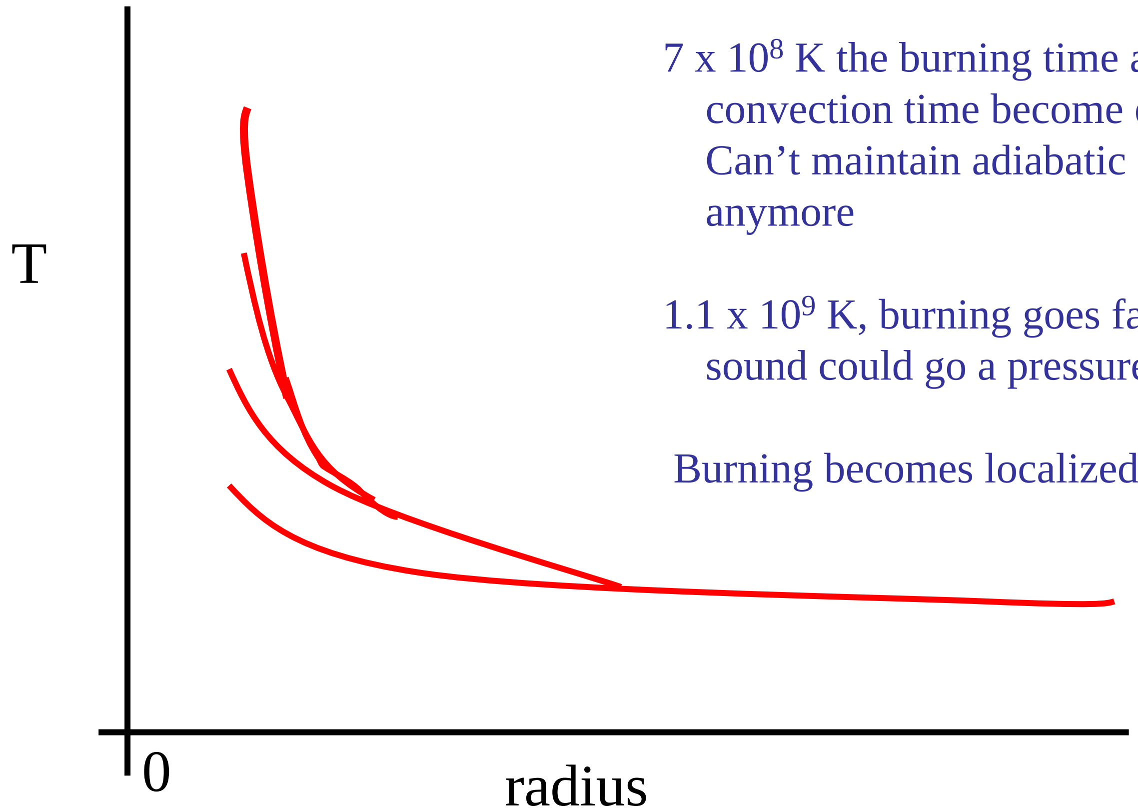
Convective time scale: ~10^2 s

Density: 2.5 x 10^9 g cm^{-3}

In 1D

Convection for 100 years, then formation of a thin flame sheet.

<u>Note that at:</u>



- 7 x 10^8 K the burning time and convection time become equal. Can't maintain adiabatic gradient anymore

- 1.1 x 10^9 K, burning goes faster than sound could go a pressure scale height

- Burning becomes localized

$$S_{nuc} \propto T^{23}$$

Ignition

The crucial unsolved problem in modeling Type Ia supernovae.

- One point or many (how many?)
- One side or isotropic?
- One time or continuous for 1 second?

Key physics:

- The probability density function for the temperature fluctuations and the spatial and temporal correlation functions
- The symmetry of convection with a point energy source
- How things scale as the Rayleigh number approaches infinity
- The role of rotation

Energy Generation Rate

$$S_{nuc} \approx 2.8\times10^{13} \left(\frac{T_8}{7}\right)^{23} \left(\frac{\rho_9}{2}\right)^{3.3} \ \text{erg g}^{-1}\ \text{s}^{-1}$$

Heat Capacity

$$C_P = 9.1\times 10^{14} + \frac{8.6\times10^{13}\,T_8}{\rho_9^{1/3}} + \frac{3.0\times10^{9}\ T_8^3}{\rho_9} \ \text{erg g}^{-1}\ (10^8\ \text{K})^{-1}$$

ions electrons radiation

Adiabatic Temperature Gradient

$$T(r) \approx T_o \left(1 - 0.0185\left(\frac{\rho_{o,9}}{2}\right)^{2/3} r_7^2\right)$$

Luminosity

$$L \approx 5.0 \times 10^{44} \text{ erg s}^{-1} \left(\frac{\rho_{o,9}}{2}\right)^{4.3} \left(\frac{T_{o,8}}{7}\right)^{23}$$

mostly goes into heating the star, the rest into expansion

Dimensionless expansion coefficient

$$\delta_P = -\left(\frac{\partial \ln \rho}{\partial \ln T}\right)_P \approx 0.019 \frac{T}{\rho} \approx 0.007$$

gas must get very hot to expand just a little

From Mixing Length Theory

$$v_{ML} \approx \left(\frac{2g\,\Delta\rho}{\rho}\right) l^{1/2} \approx \left(\frac{4G\delta_P\,L}{3C_P\,T}\right) \approx 40 \text{ km s}^{-1} \left(\frac{T_{o,8}}{7}\right)^{7} \left(\frac{\rho_9}{2}\right)^{1.4}$$

Temperature fluctuations to carry L

$$\left(\frac{\Delta T}{T}\right) \approx \frac{v_{ML}^2}{2gl\delta_P} \approx 0.005\left(\frac{\rho_9}{2}\right)^{2.1}\left(\frac{T_{o,8}}{7}\right)^{14} \qquad \frac{\Delta\rho}{\rho} \approx 4\times 10^{-5}$$

Dimensionless Measures

$$Ra = \frac{g\, l^3\, C_P\, \delta_P\, \Delta T}{T\eta\sigma} \approx 10^{25}$$

Dimensionless temperature gradient

$$Pr = \frac{C_P \eta}{\sigma} \approx 4\times 10^{-3}$$

momentum transport/heat conduction

$$Re = \frac{\rho v_{ML}\, l}{\eta} \approx 10^{14}$$

inertial forces/viscous forces

$$Nu = \frac{\phi l}{\sigma \Delta T} \approx 3\times 10^{11}$$

total heat transport/conduction

$$L_{Kol} = l\ \mathrm{Re}^{-3/4} \approx 3\times 10^{-4}\ \mathrm{cm}$$

$\eta = viscosity$ $\qquad$ $\sigma = conductivity$

If ignition occurs for matter flowing through the stellar center with speed v ignition will occur when the integral

$$\int \left[\left(\frac{dT}{dr} \right)_{exp} + \frac{S_{nuc}}{C_P \, v} \right] dr$$

nb. diverges at r = 0 if v(0) = 0. i.e., it ignites in the center.

diverges. Here, from the adiabatic approximation for the temperature gradient

$$\left(\frac{dT}{dr} \right)_{exp} \approx -0.037 \; T_c \left(\frac{\rho_9}{2} \right)^{2/3} r_7$$

The solution depends on the assumed velocity structure in the core but for v between 50 and 100 km s^{-1}, ignition will occur when the average central temperature is in the range

$T_{ign} = 7.7 - 7.9 \times 10^8$ K.

at r ~ 100 km

Woosley, Wunsch, and Kuhlen (2003)
Wunsch and Woosley (2004)

Three-Dimensional Models of Ignition

Kuhlen, Woosley, and Glatzmaier (2003)

Use Kepler 1D model as a first approximation to the background state. Follow perturbations using anelastic hydrodynamics in 3D

(Glatzmaier, 1984, J. Comp. Phys).

238 Chebyshev polynomials in r direction

85 spherical harmonics in θ

42 spherical harmonics in ϕ

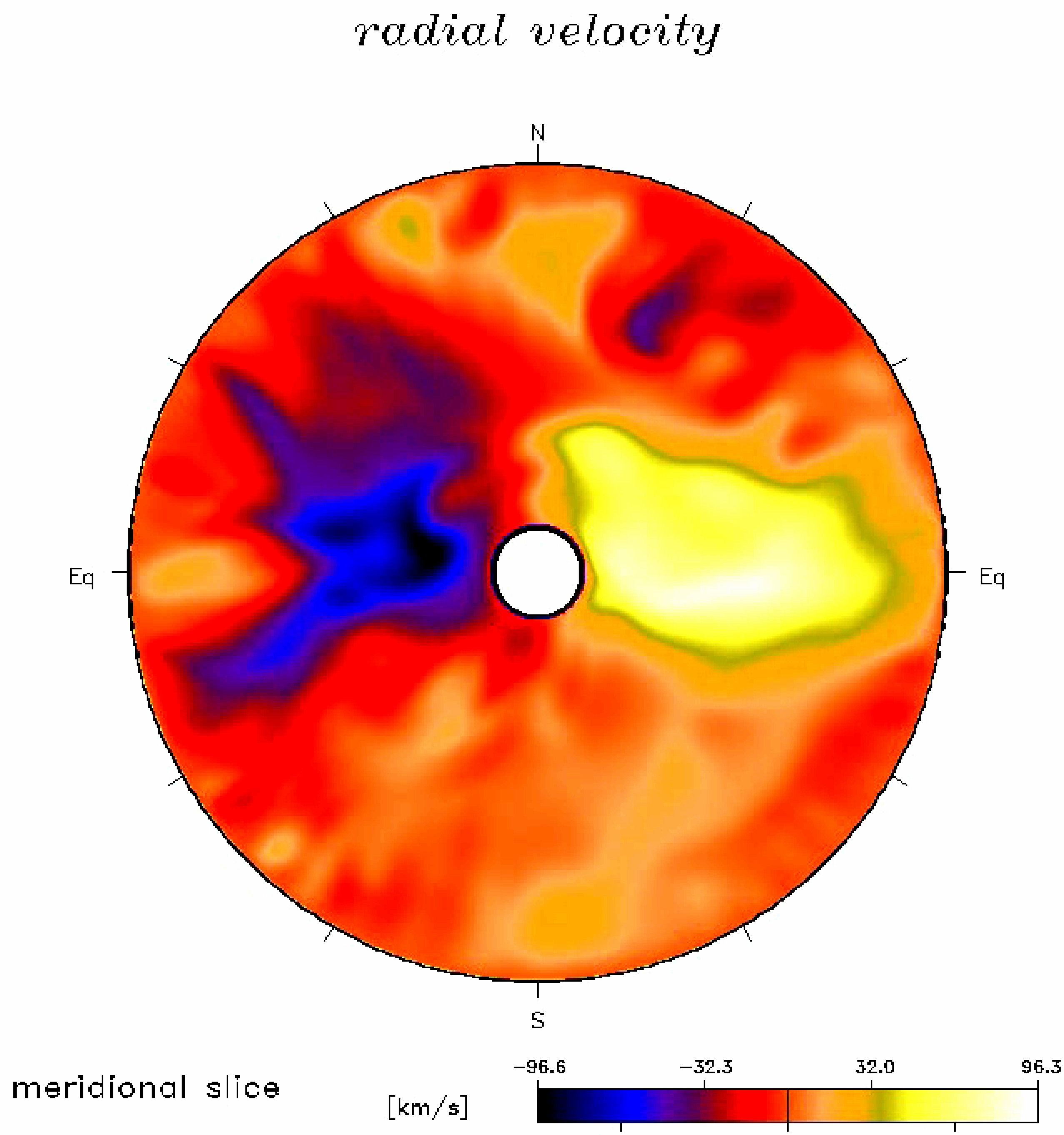
inner boundry at 55 km, about 0.001 solar masses

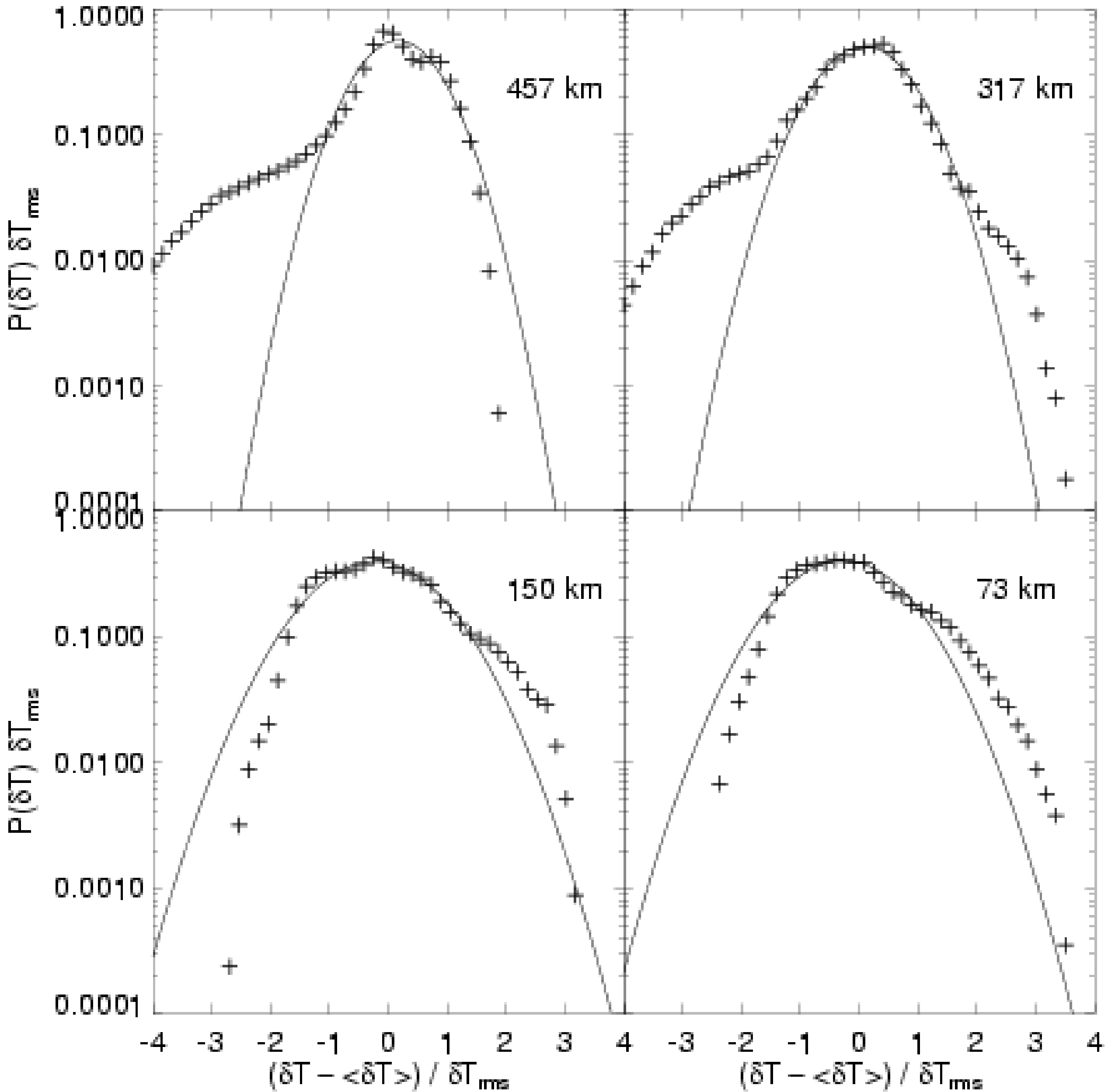
outer boundry at 500 km, approximate extent of convection

central density 2.5×10^9 g cm^{-3}

central temperature 7.0×10^8 K

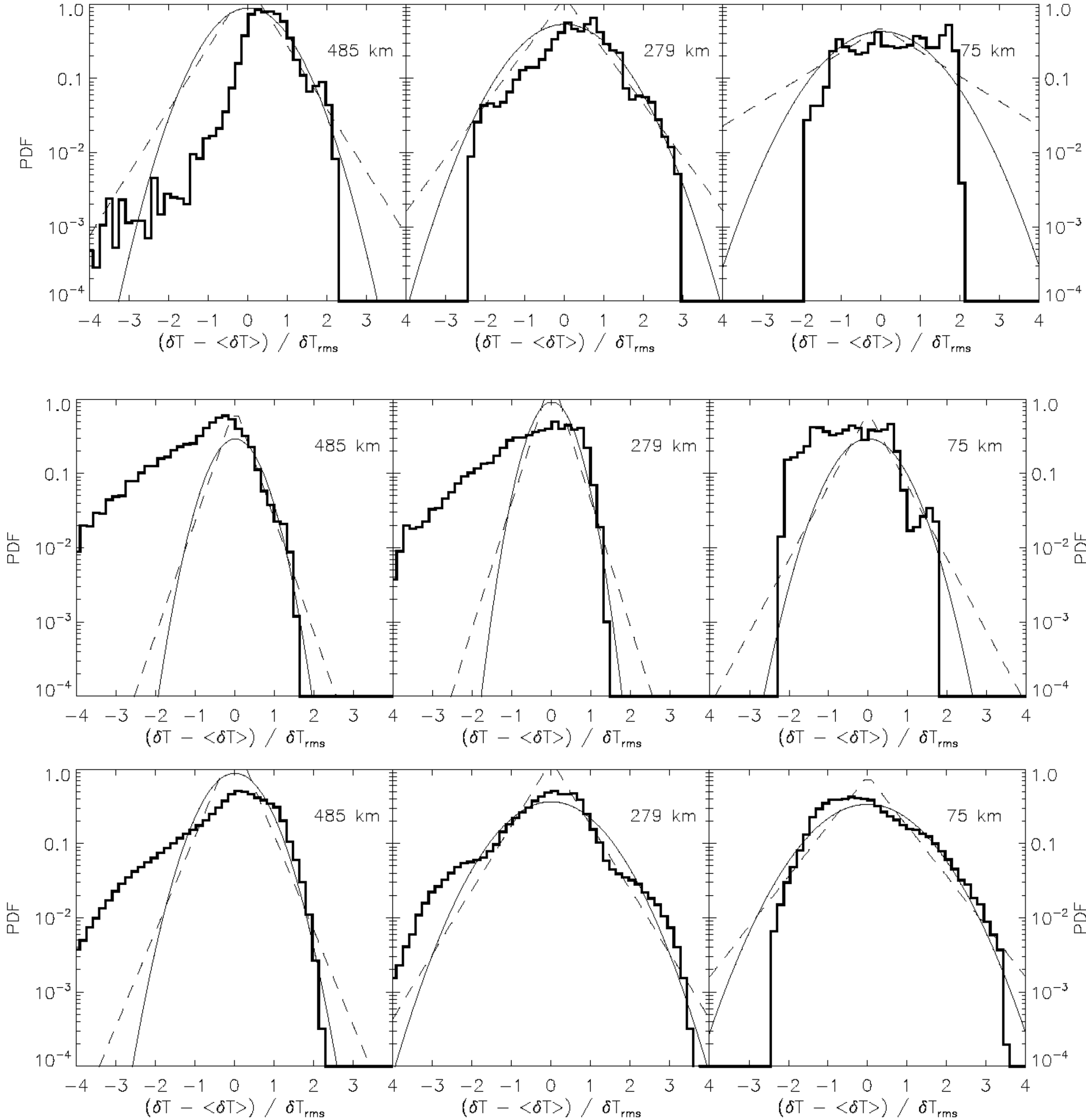
highest velocity on grid 180 km s^{-1}


radial velocity
N
Eq
Eq
S
meridional slice
[km/s]
−96.6
−32.3
32.0
96.3



Kuhlen, Woosley, and Glatzmaier (in prep)

See also Wunsch and Woosley (2004)

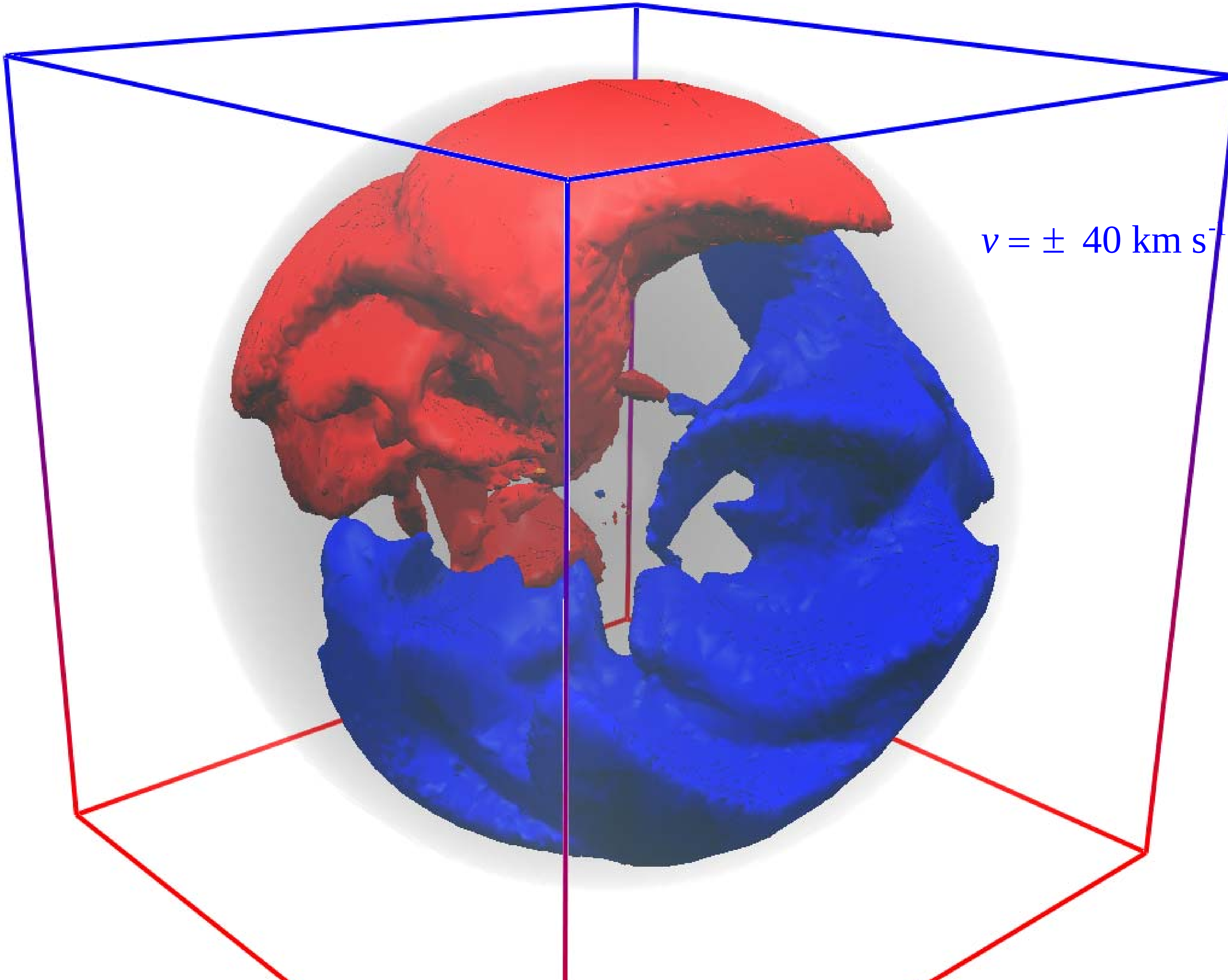


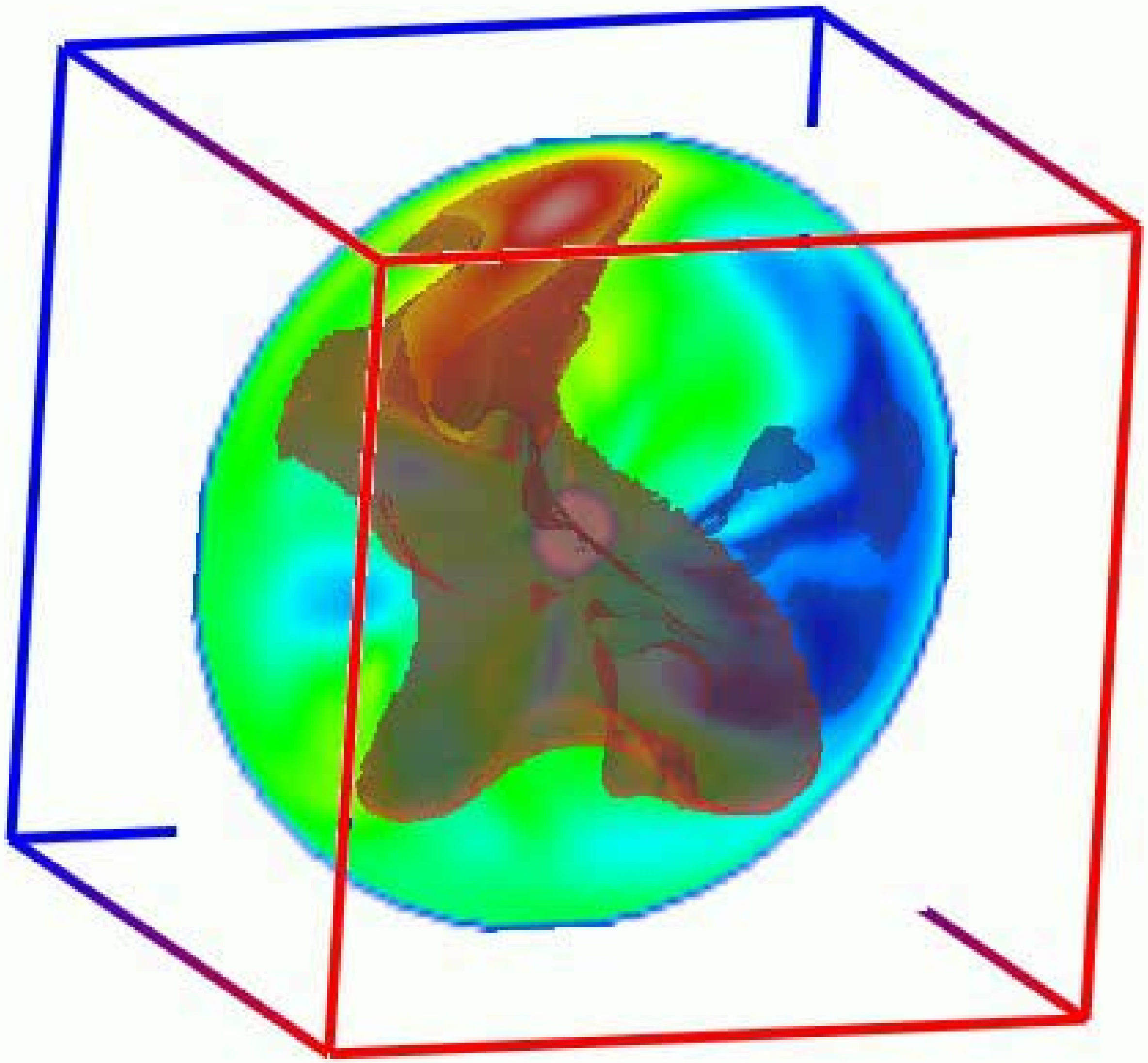
7 seconds of data

up

down

total


v = ± 40 km s



$T_{9c} = 7.0$

$Ra \sim 10^7$

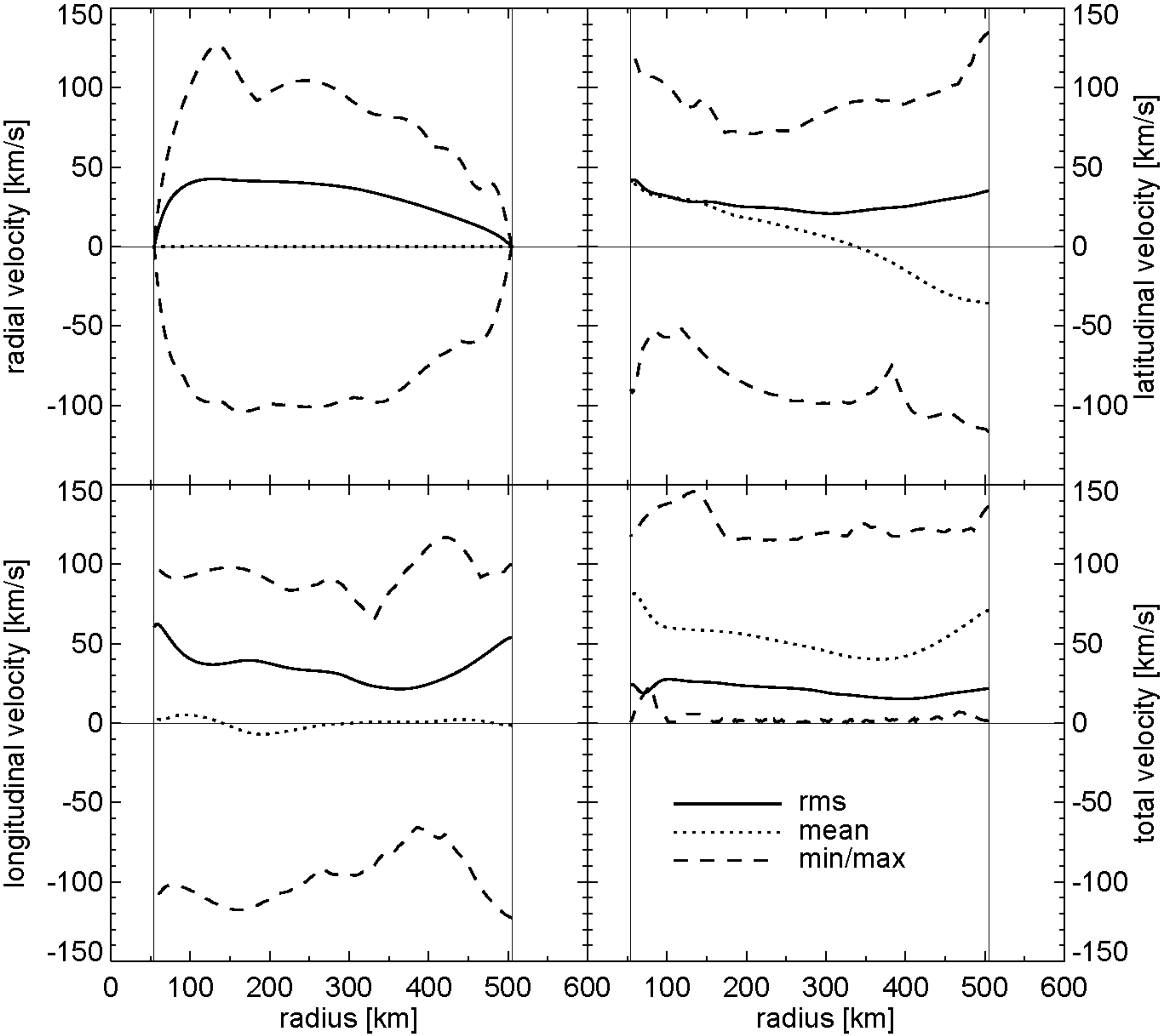
$n = 238$

42 orders in θ

38 orders in φ

70 s of star time

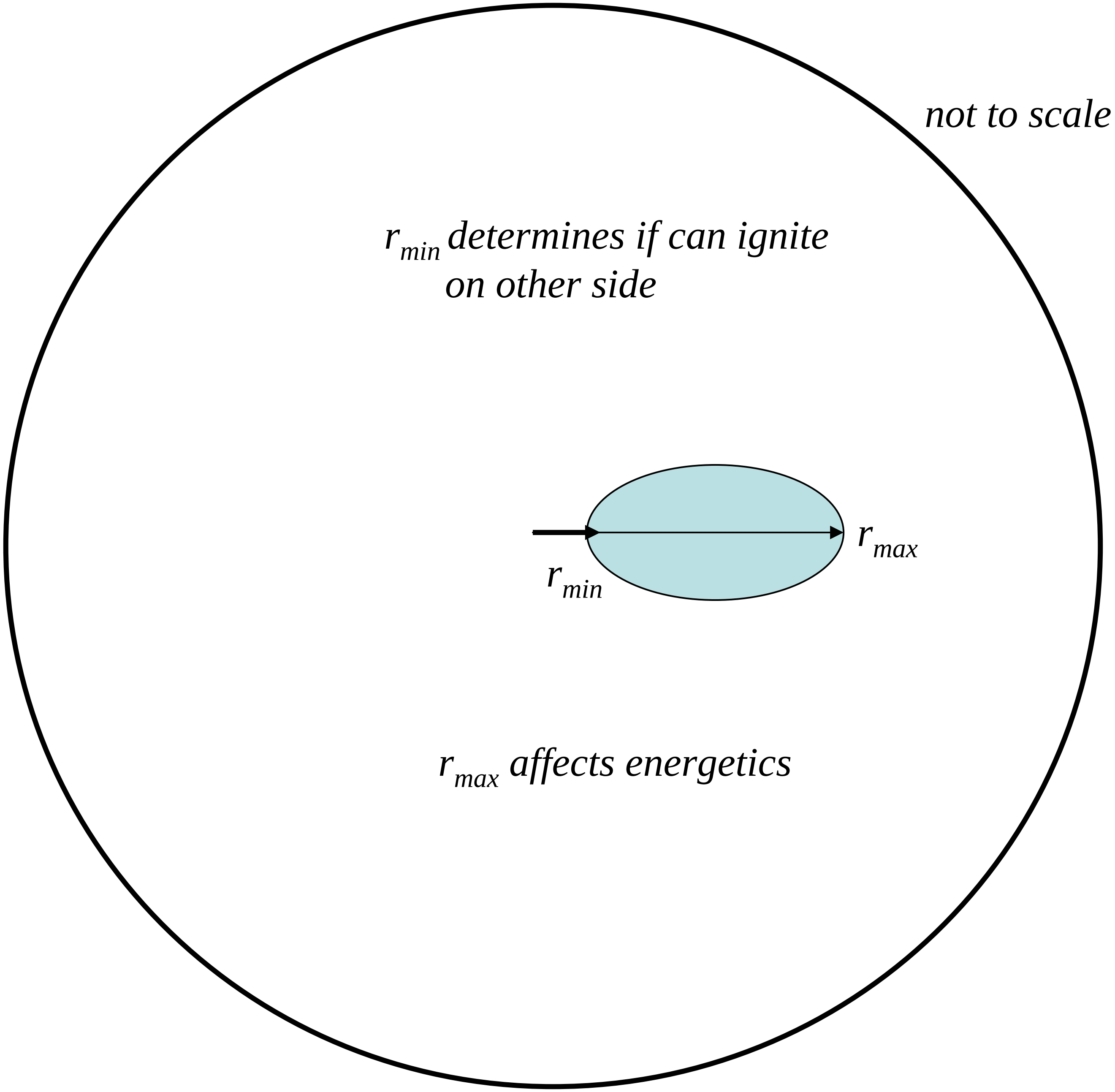
Kuhlen, Woosley, and Glatzmaier (2005)



radial velocity [km/s]
latitudinal velocity [km/s]
longitudinal velocity [km/s]
total velocity [km/s]
radius [km]
radius [km]
rms
mean
min/max

A possible implication is that the supernova ignites preferentially on one side at one or more points. But what is the spatial and temporal distribution of these points?

nb. they do not all ignite at once!



not to scale
r_{min} determines if can ignite on other side
r_{max}
r_{min}
r_{max} affects energetics

r_{min} determines whether ignition propagates to other side

$$\frac{r_{crit}}{v_{eff}} = \sqrt{\frac{2\, r_{crit}}{g_{eff}\, \alpha}} \approx \sqrt{\frac{1}{50\,\alpha}} \Rightarrow r_{crit} \approx 20-40\,\mathrm{km}$$

$$\alpha = 0.1-0.7 \qquad v_{eff} = \mathrm{Max}\{\mathrm{v}_{\mathrm{cond}}, v_{turb}\} \sim 100\,\mathrm{km\ s^{-1}}$$

$$g_{eff} \approx 10^9 \left(\frac{r}{10^7\,\mathrm{cm}} \right) = 100\, r$$

Are all ignition points advected out of the core by the fluid flow or do some stay behind to seed burning on the other side?

Conclusions

(Kuhlen, Woosley, and Glatzmaier, 2003)

- ***Ignition physics is central to understanding how SN Ia explode and is probably the cause of some unpredictable diversity in SN Ia properties.***

- Most of the white dwarf will have a turbulent kinetic energy of order 10^{14} erg g^{-1} *before* the explosion. This sets a lower bound on the flame propagation speed.

- Ignition probably occurs off-center and at multiple points and times, and it may also be grossly asymmetric.

- There may be ways out of this

  Kraichnan (1962) regime at high Rayleigh number

  Rotation

  Surface detonation?

Flame Propagation

- The flame is born a deflagration at ρ_c = 2.5x 10^9 gm cm^{-3}.
  Does a transition to detonation occur at $\rho \sim 10^7$ gm cm^{-3} ?

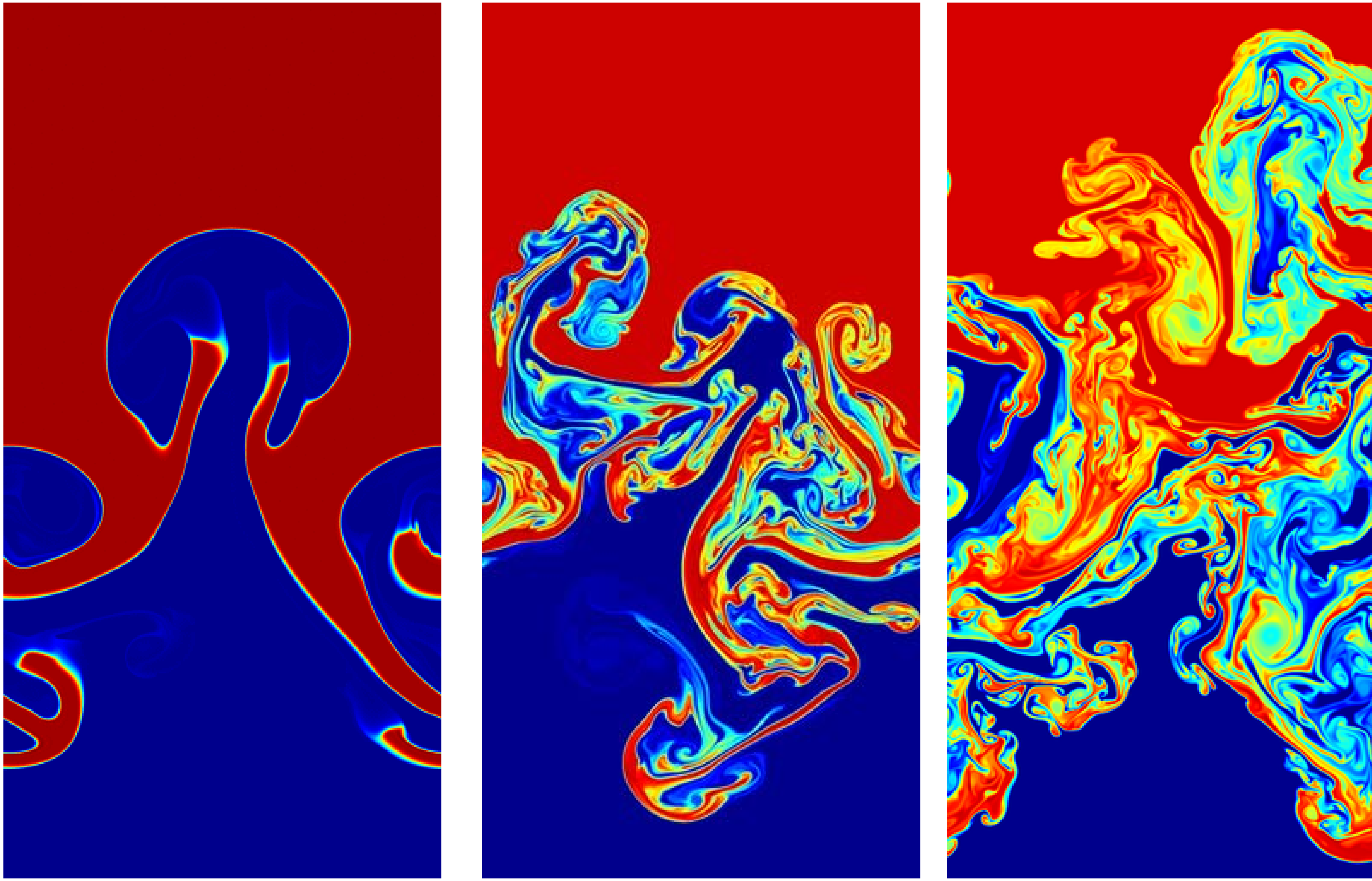
  Probably not if the only physics included is the RT instability on the grid. It still might be possible for sufficiently energetic turbulence to provoke a transition on small scales. (Zingale et al. 2004, 2005)

  Effects of off center ignition and break out still being explored (Plewa et al 2004)

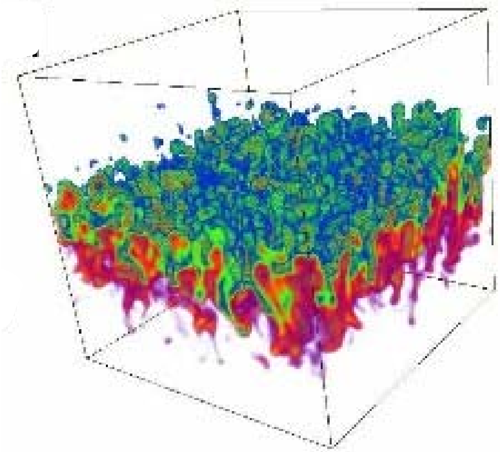
- How to correctly represent the effects of turbulence generated by the RT instability on large scales on the subgrid flame propagation?

  A purely local RT model is inadequate. Must include turbulent cascade from above (Niemeyer, Hillebrandt et al).

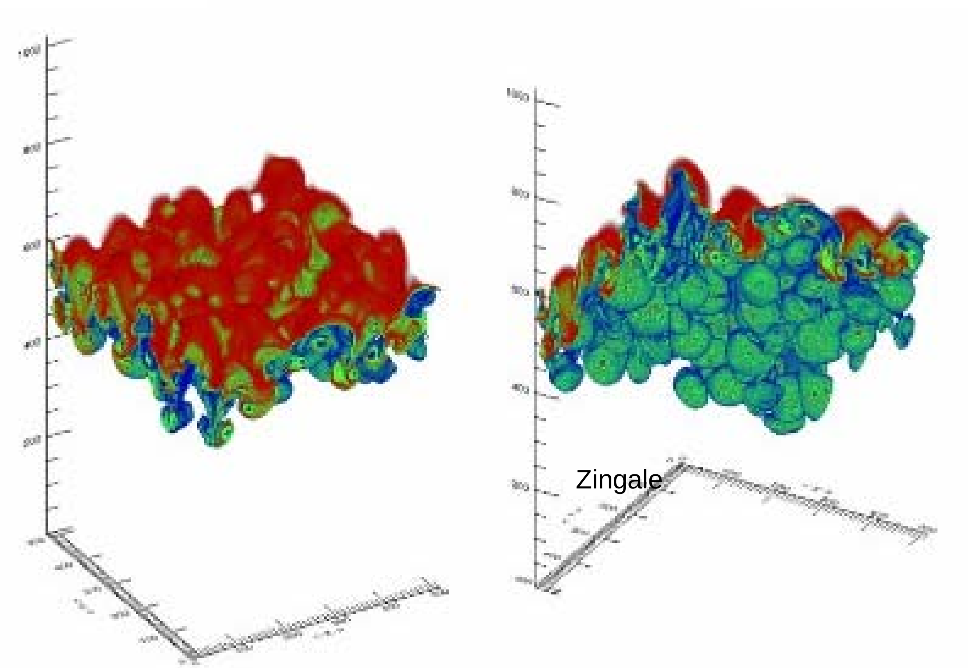
- Issues of resolution and “back propagation”.



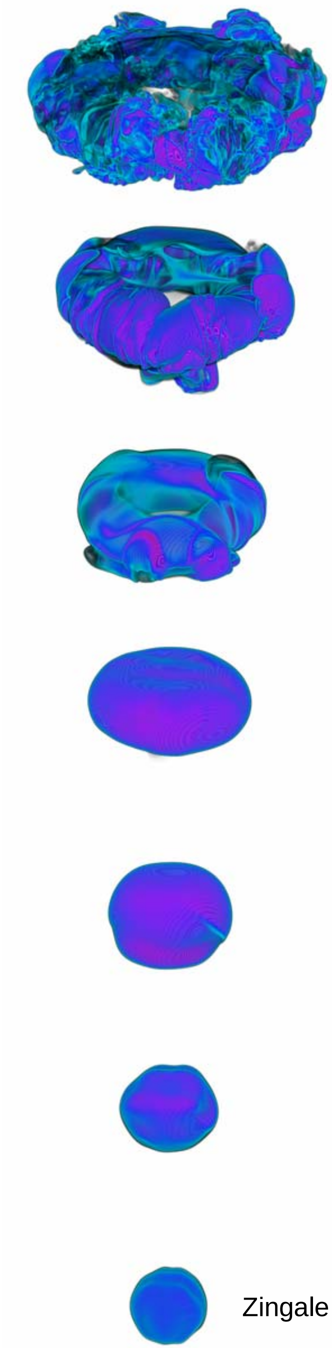
1.5 x 10^7 1.0 x 10^7 0.667 x 10^7



Calder et al. (2002)



or

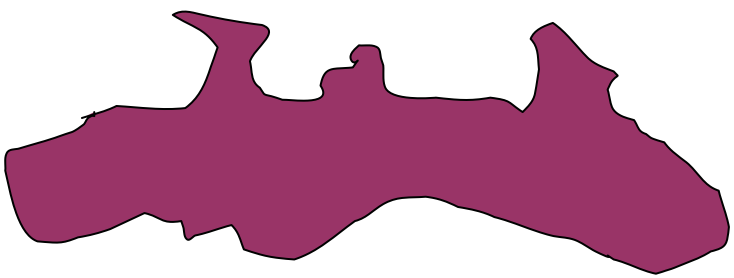


?

Bubbles and planes

How many bubbles and how do they spread?

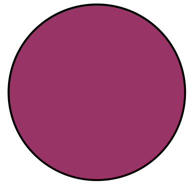
$$v \approx 0.1\, g_{eff}\ t$$



Sharp-Wheeler

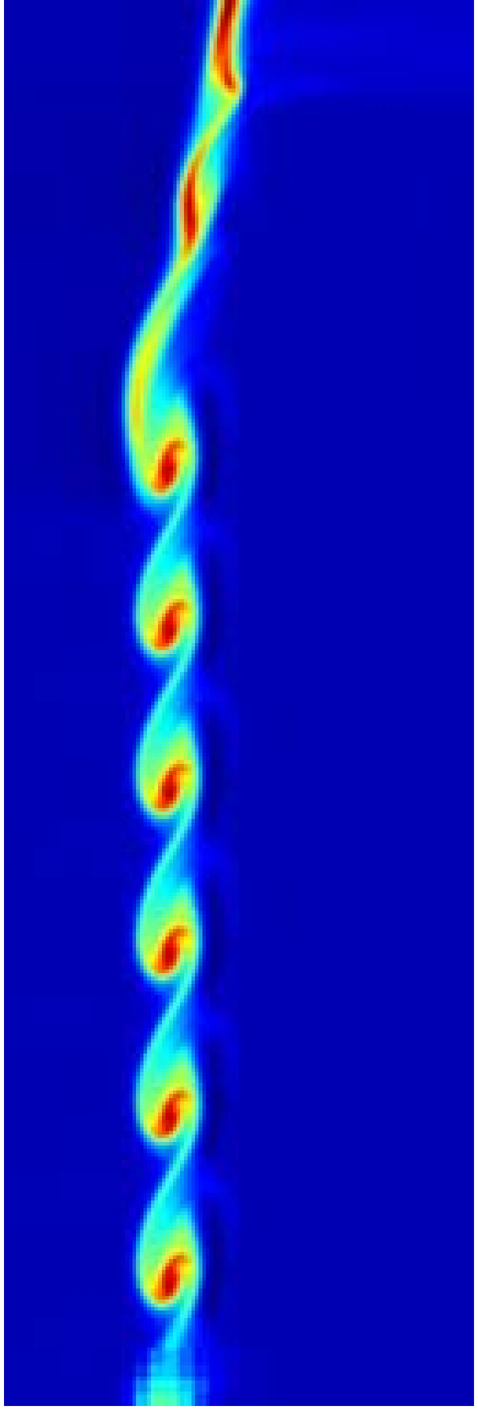
This probably won't make it to the surface

$$v \approx 0.7\, g_{eff}\ t$$



sphere

This probably will

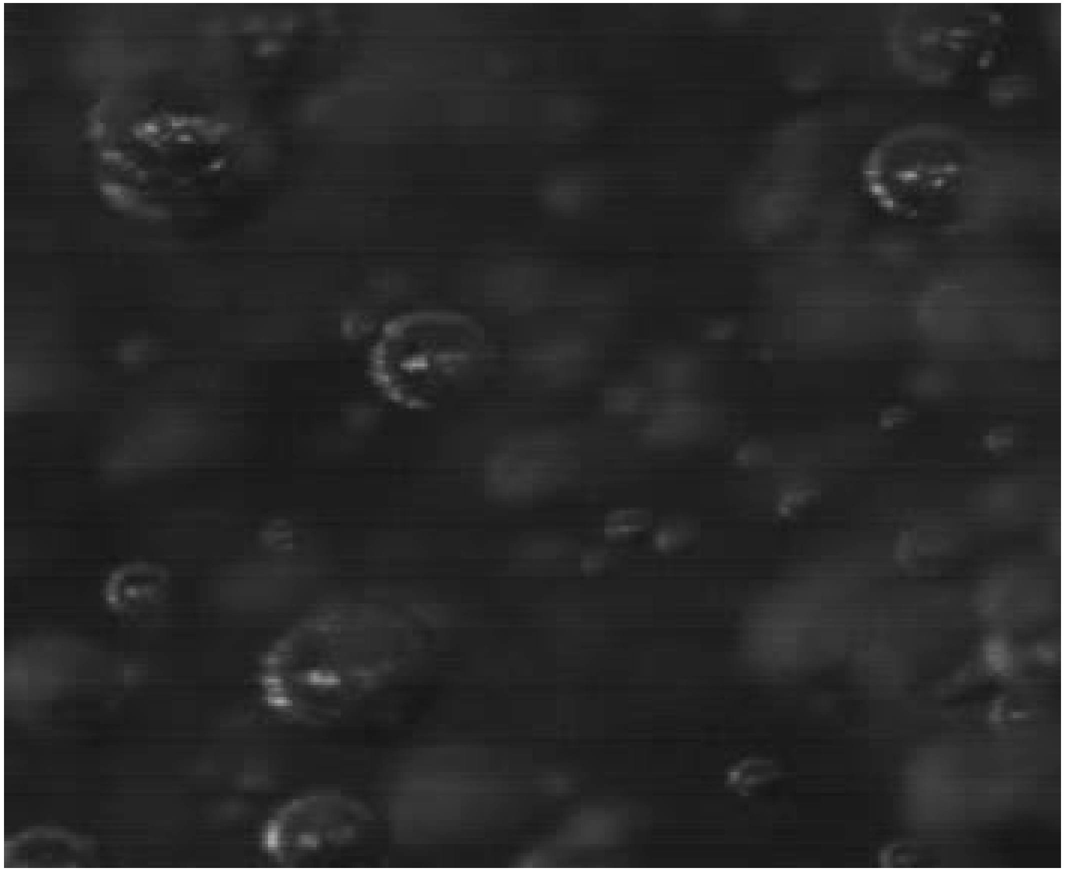


Are lateral spreading and backwards propagation correctly included?

Zingale (2005)

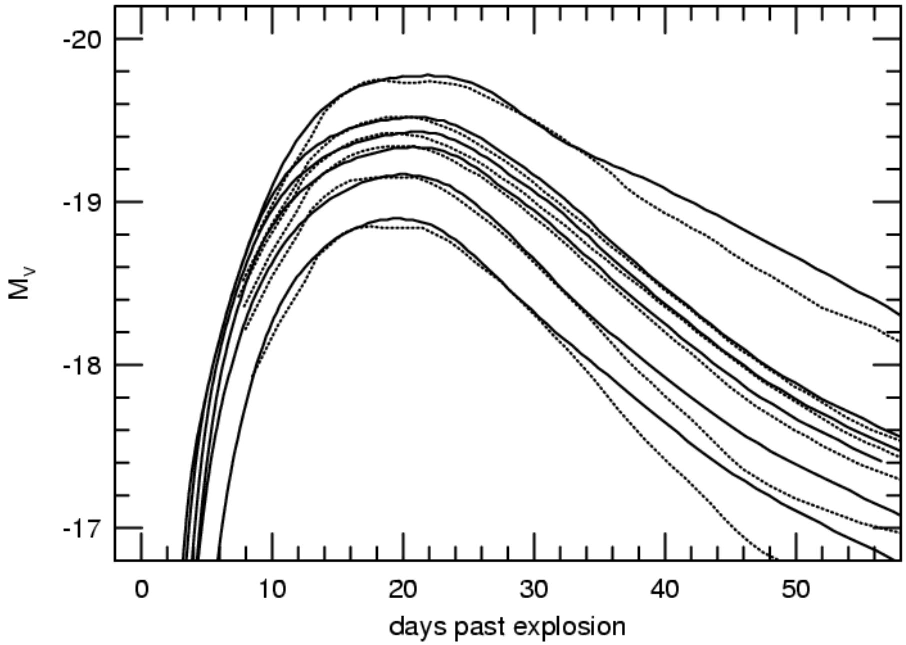
Shear velocity = 10 x laminar speed
small shear width

<u>The Guinness Effect</u>



Big bubbles move up;
little bubbles move down.

The Phillips Effect



Left – a single supernova model (energy, density structure, etc) in which only the mass of ^{56}Ni has been varied. Also shown are the standard template of light curves displaying the width-luminosity relation.

Pinto & Eastman, (2001), *New Astron,*

Light Curves

What matters?

- The mass of ^{56}Ni -- contributes explosion energy, radioactive energy, and opacity.

- The mass of ^{54}Fe, ^{58}Ni, and other stable members of the iron group -- contribute opacity and explosion energy, but no radioactive energy.

- The mass of SiSArCa -- contribute to the explosion energy, but not the opacity or radioactive energy.

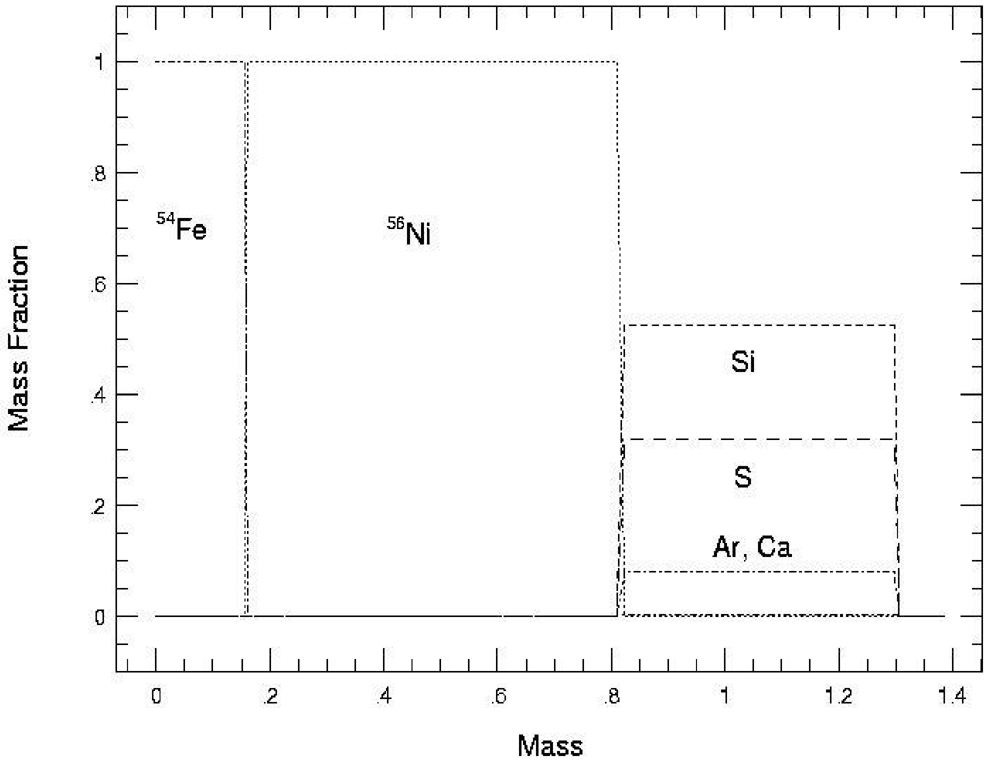
- The explosion energy -- depends on the ignition density (hence accretion rate) and C/O ratio as well as all the above masses.

- Mixing

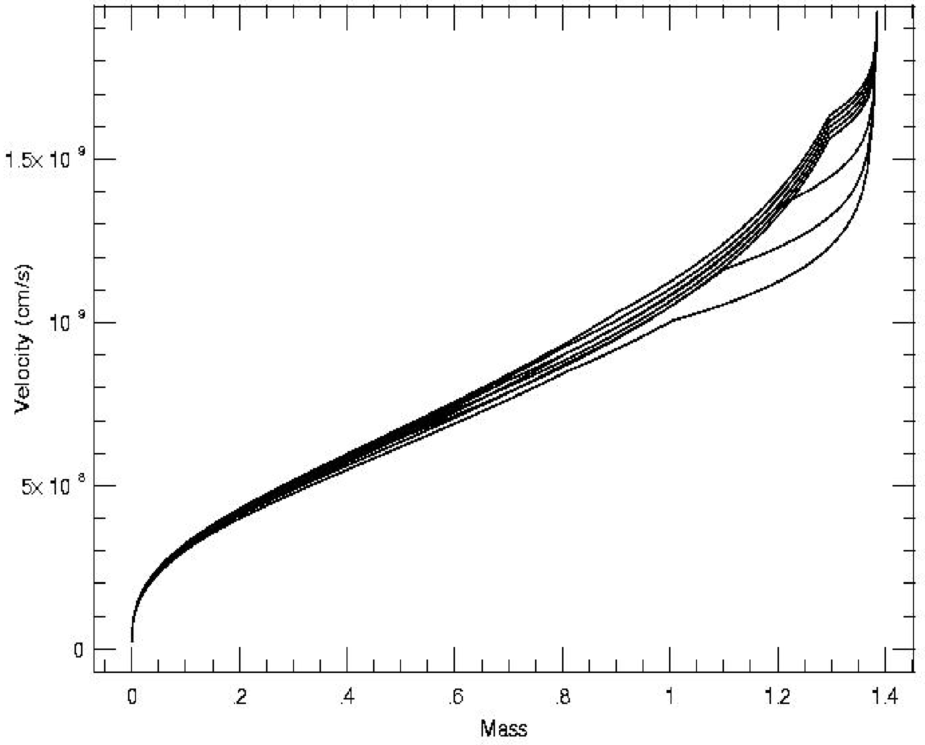
An idealized model

Assume a starting mass of 1.38 solar masses, a central density of 2 x 10^9 g cm^{-3} and a C/O ratio of 1::2

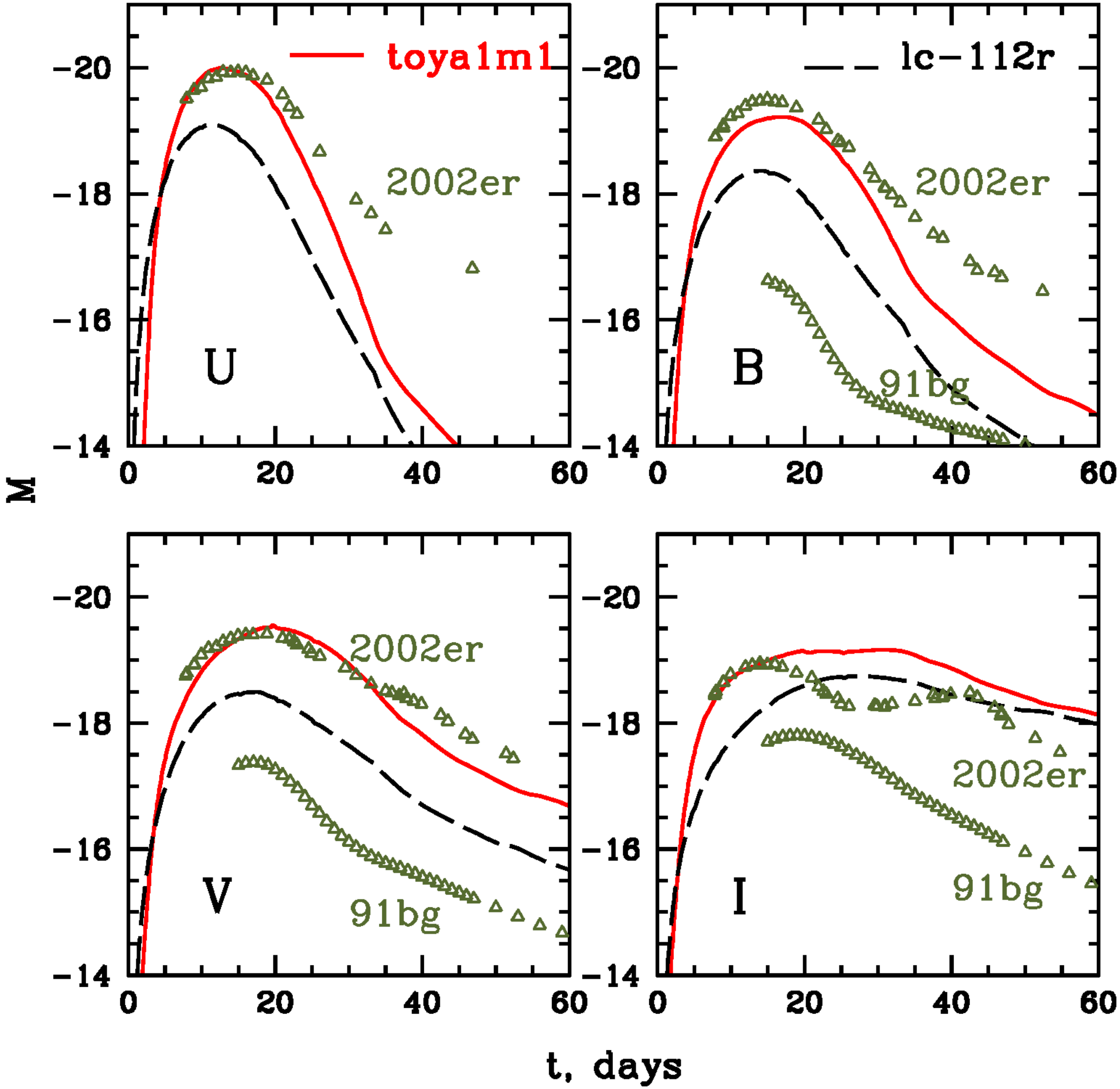
For a given starting density, the final composition (three variables, plus mixing) then defines the model.

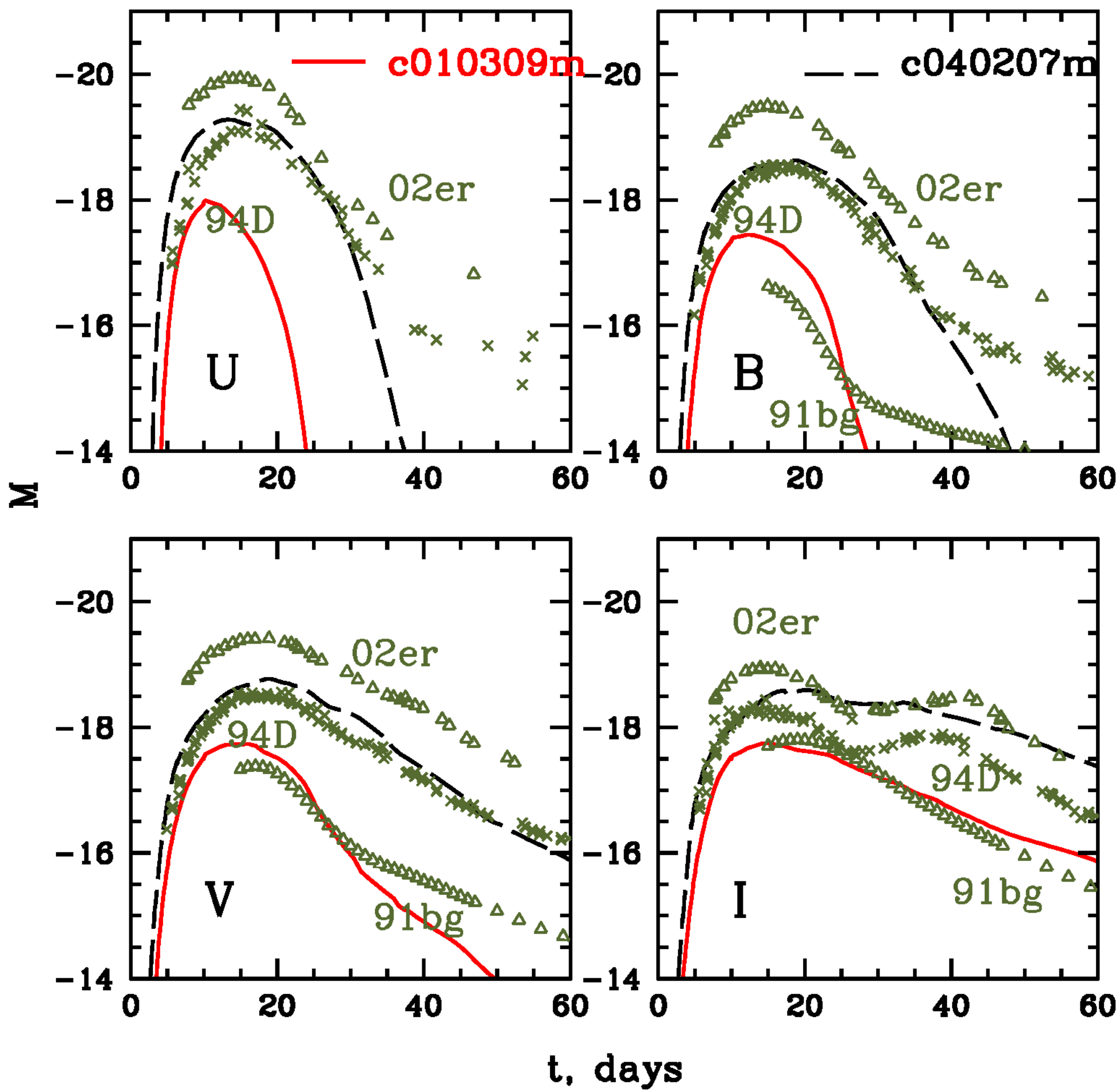


The final velocity distribution is not very sensitive to how the energy is deposited (especially for the iron containing region).



Blinnikov, Sorokina, and Woosley (2005)





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