CASTRO simulations of supernovae

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Motivation

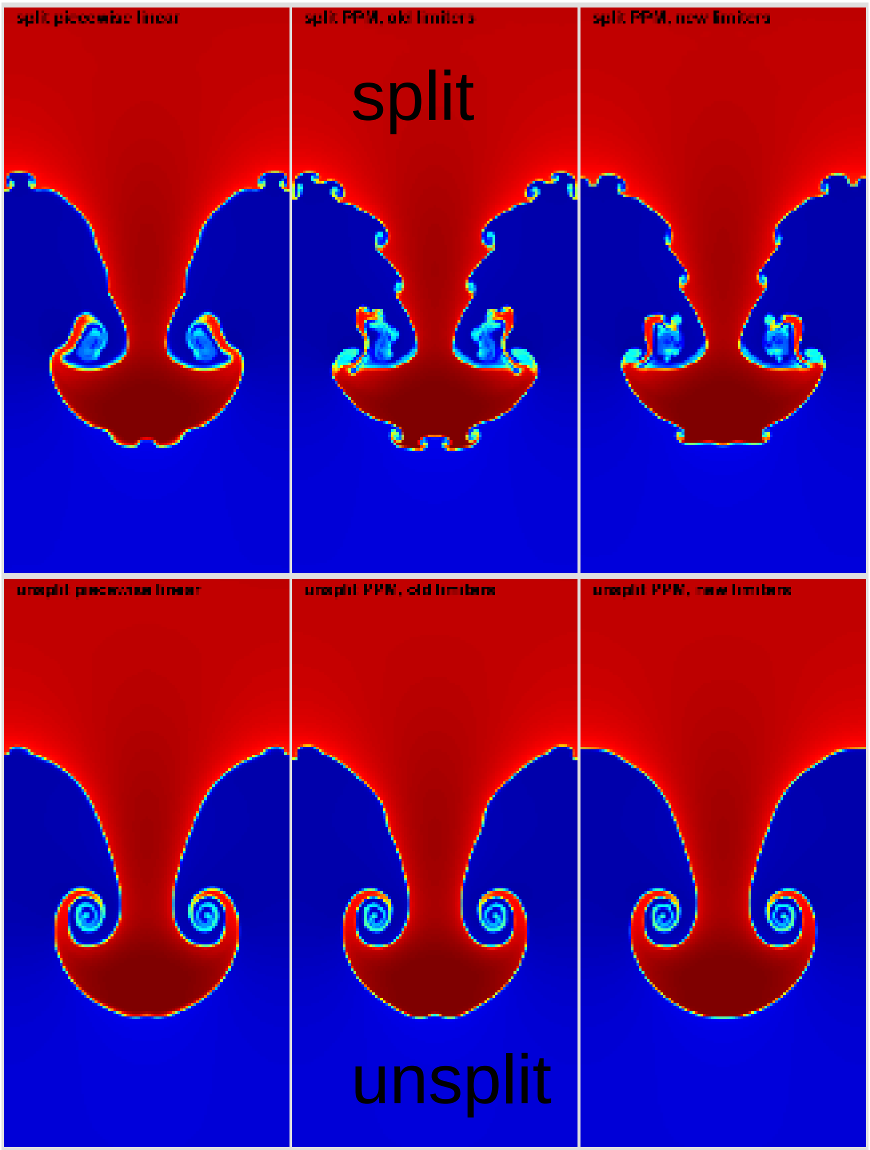
Deriving accurate light curves and nucleosynthetic yields for primordial SNe requires modeling mixing

- How much mixing takes place in primordial core-collapse supernovae, and how might this effect the nucleosynthesis and lightcurves?
- Matching these nucleosynthetic yields to observations of abundance patterns in metal-poor halo stars may tell us about the IMF and explosion energies of the first SNe
- Does Rayleigh-Taylor-driven mixing occur in PISNe?
- If it does, how much mixing takes place?

Overview

- the CASTRO code
- 3D and 2D simulations of primordial core-collapse supernovae
- 2D simulations of pair-instability supernovae
- comparison of our results with observations of SN 2007bi
- Conclusions

Castro



Finite volume, block structured adaptive mesh refinement (AMR) code for astrophysical phenomena

– System of advection-reaction-diffusion equations

– Modular equation of state

– Modular reaction network

– Massively parallel-- CASTRO scales to 200K+ cores

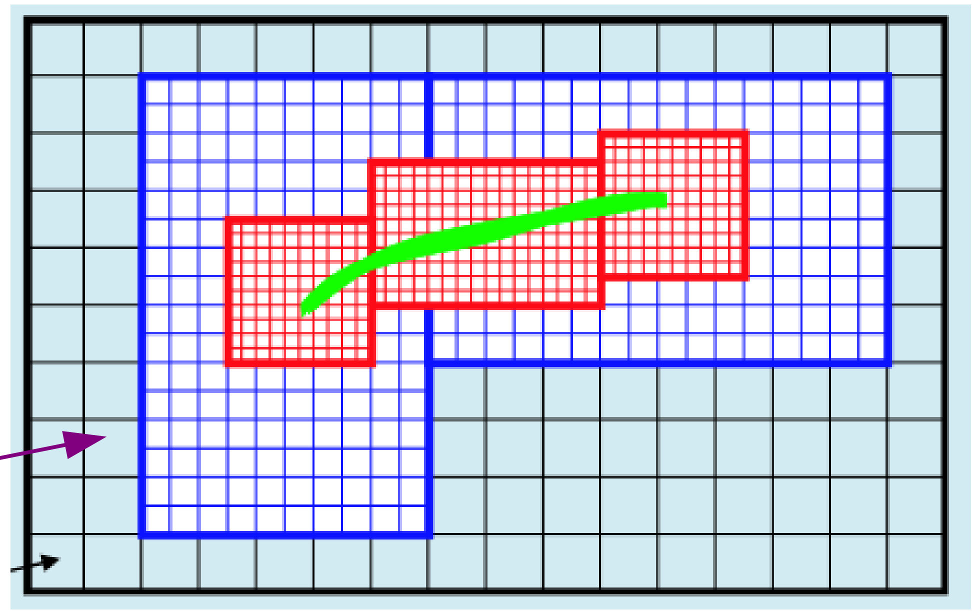
- CASTRO is a general compressible code

Almgren et al. 2010

Slide credit: Andy Nonaka

General Framework

Finite Volume: solution in each Cartesian cell represents the average over the cell



ρ, $\boldsymbol{u}$, T, E, etc.

AMR: block-structured approach with logically rectangular grids

Slide credit: Andy Nonaka

Software overview

BoxLib software framework provides set of tools for finite-volume block-structured AMR applications

– C++ / Fortran90 – Subcycling in time

Parallel I/O

– Peak I/O at NERSC (approx 13 GB/s) is comparable with NERSC benchmarks

Hierarchical programming model – Hybrid MPI/OpenMP approach.

Slide credit: Andy Nonaka

CASTRO overview

Standard compressible equations of motion:

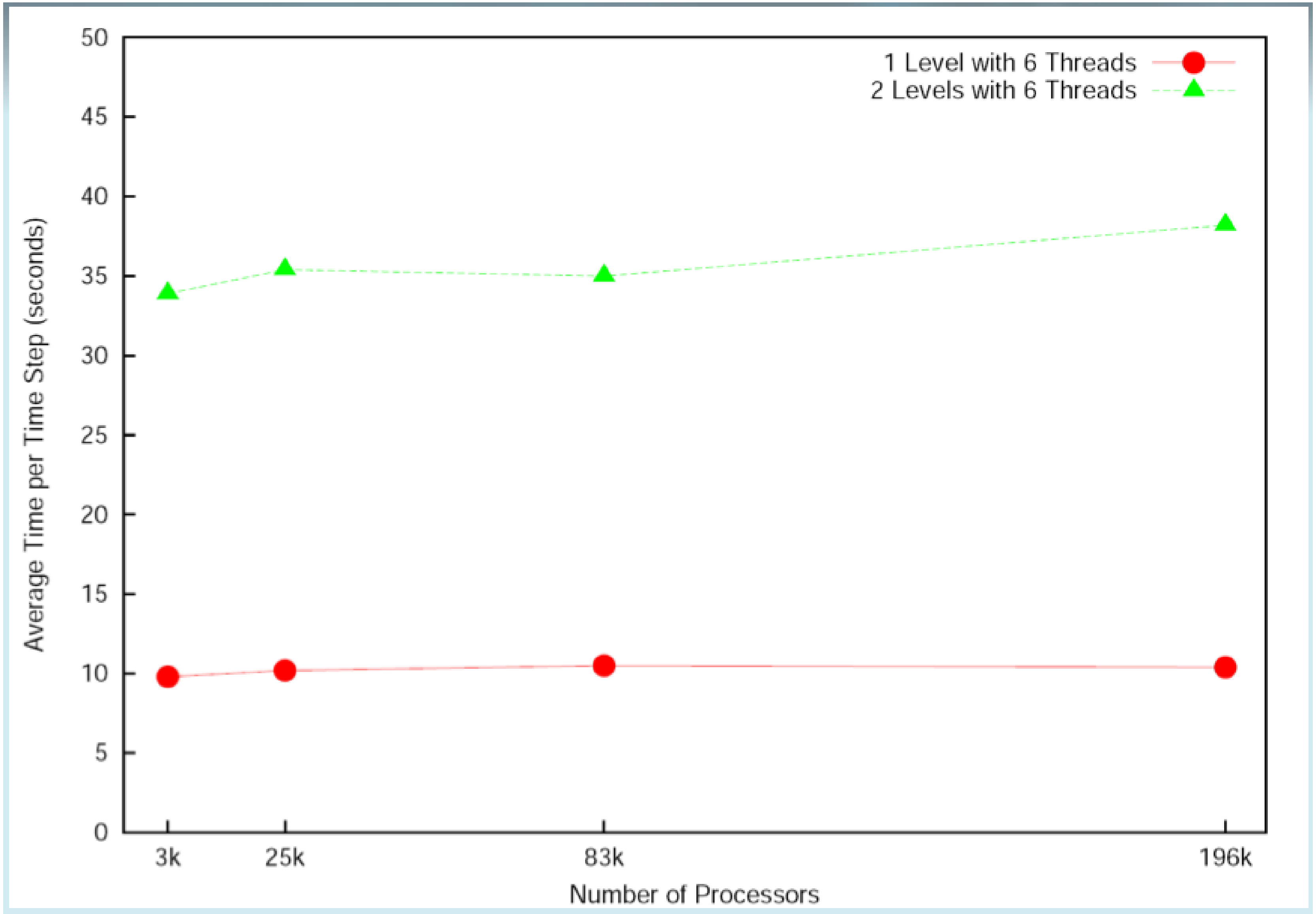
$$
\begin{aligned}
\frac{\partial(\rho X_k)}{\partial t} &= -\nabla\cdot(\rho X_k \mathbf{u}) + \rho\dot{\omega}_k \\
\frac{\partial(\rho \mathbf{u})}{\partial t} &= -\nabla\cdot(\rho \mathbf{u}\mathbf{u}) - \nabla p + \rho\mathbf{g} \\
\frac{\partial(\rho E)}{\partial t} &= -\nabla\cdot(\rho \mathbf{u} E + p\mathbf{u}) + \rho\mathbf{u}\cdot\mathbf{g} + \nabla\cdot k_{\mathrm{th}}\nabla T + \rho H
\end{aligned}
$$

- Advection (Godunov method) and reactions (stiff ODE solver) require little communication.
- Semi-implicit thermal diffusion and self-gravity (Poisson equation) are optional.

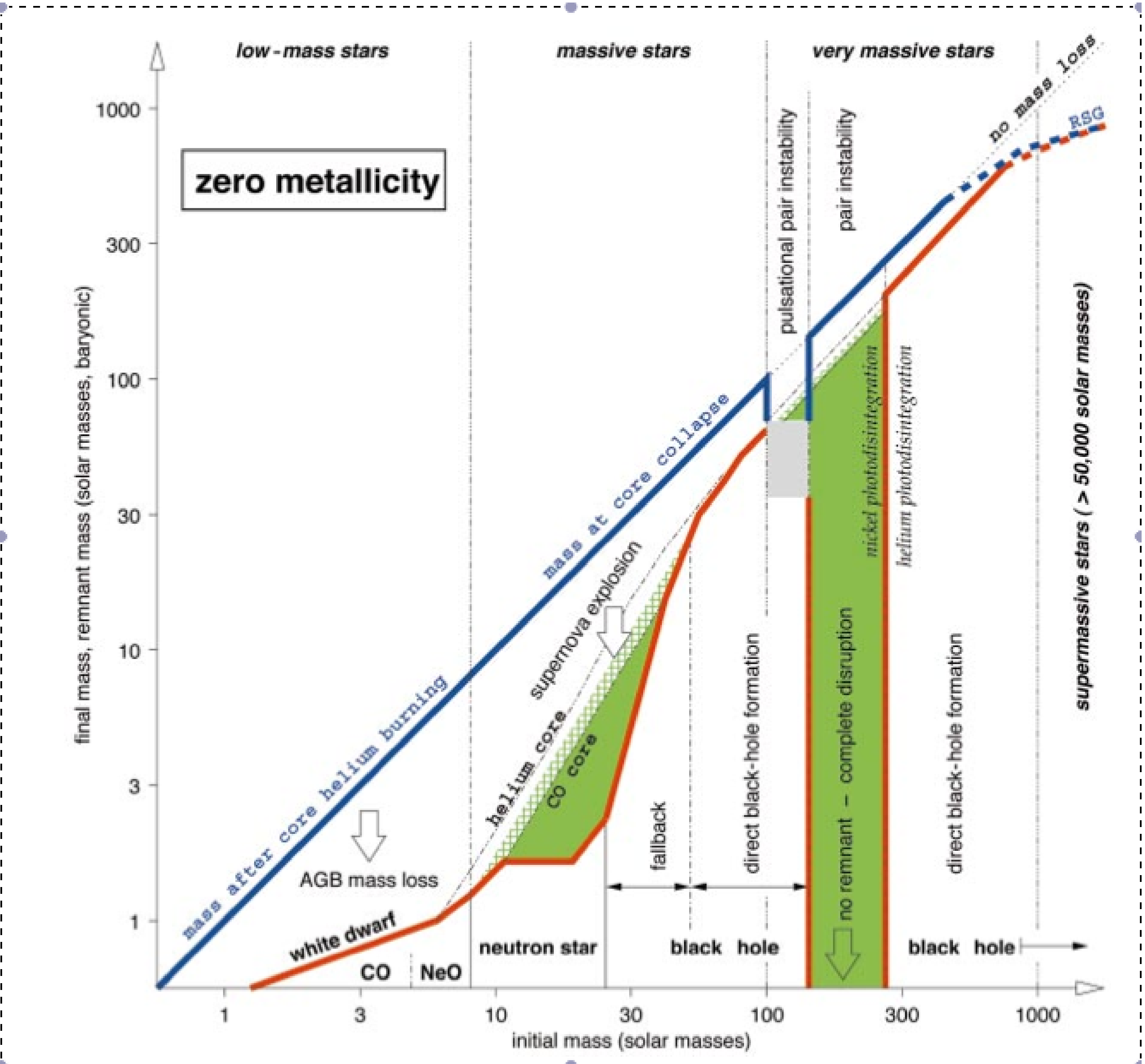
– Using a monopole gravity approximation and explicit thermal diffusion, CASTRO scales to 200K+ cores.

Slide credit: Andy Nonaka

CASTRO weak scaling

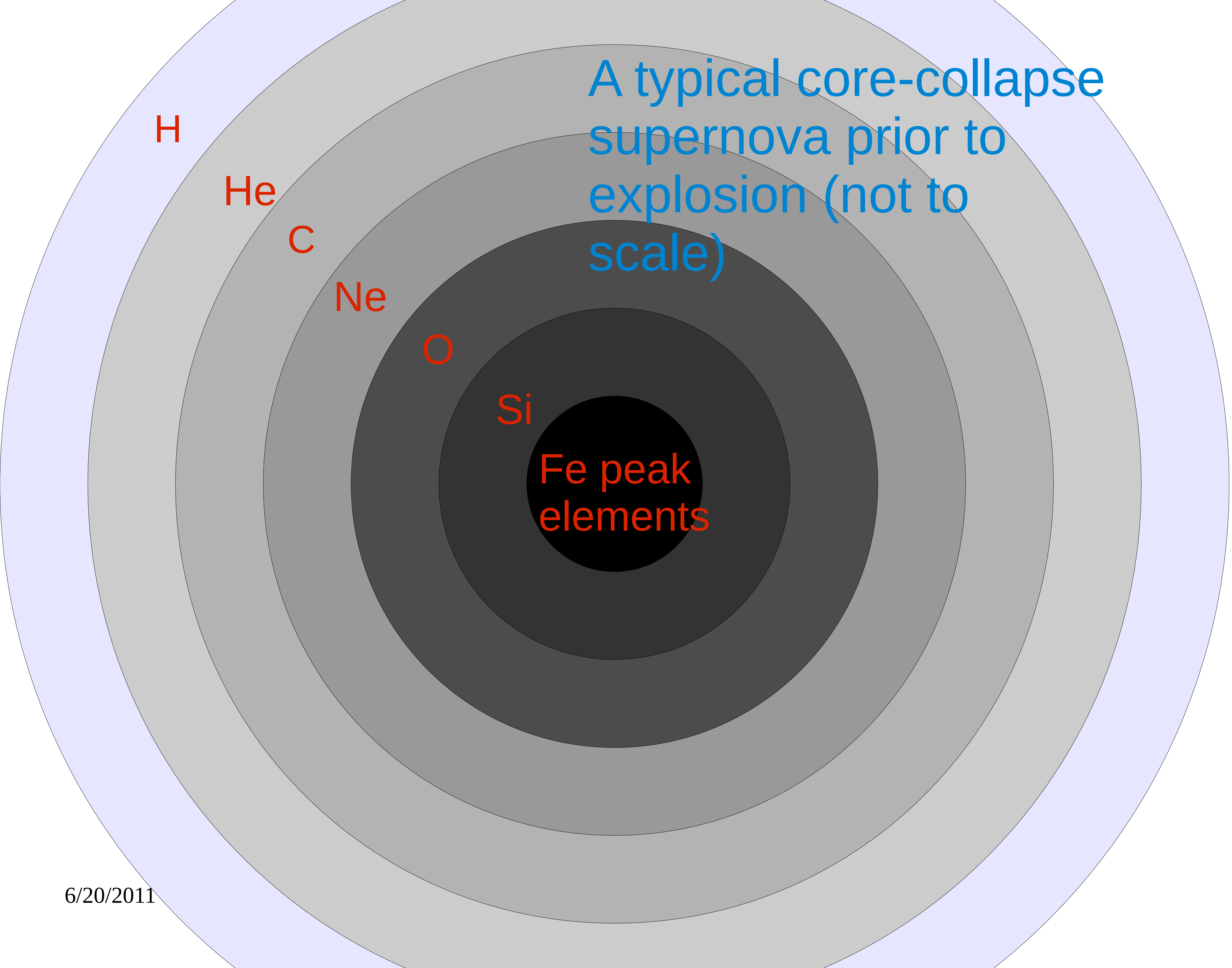


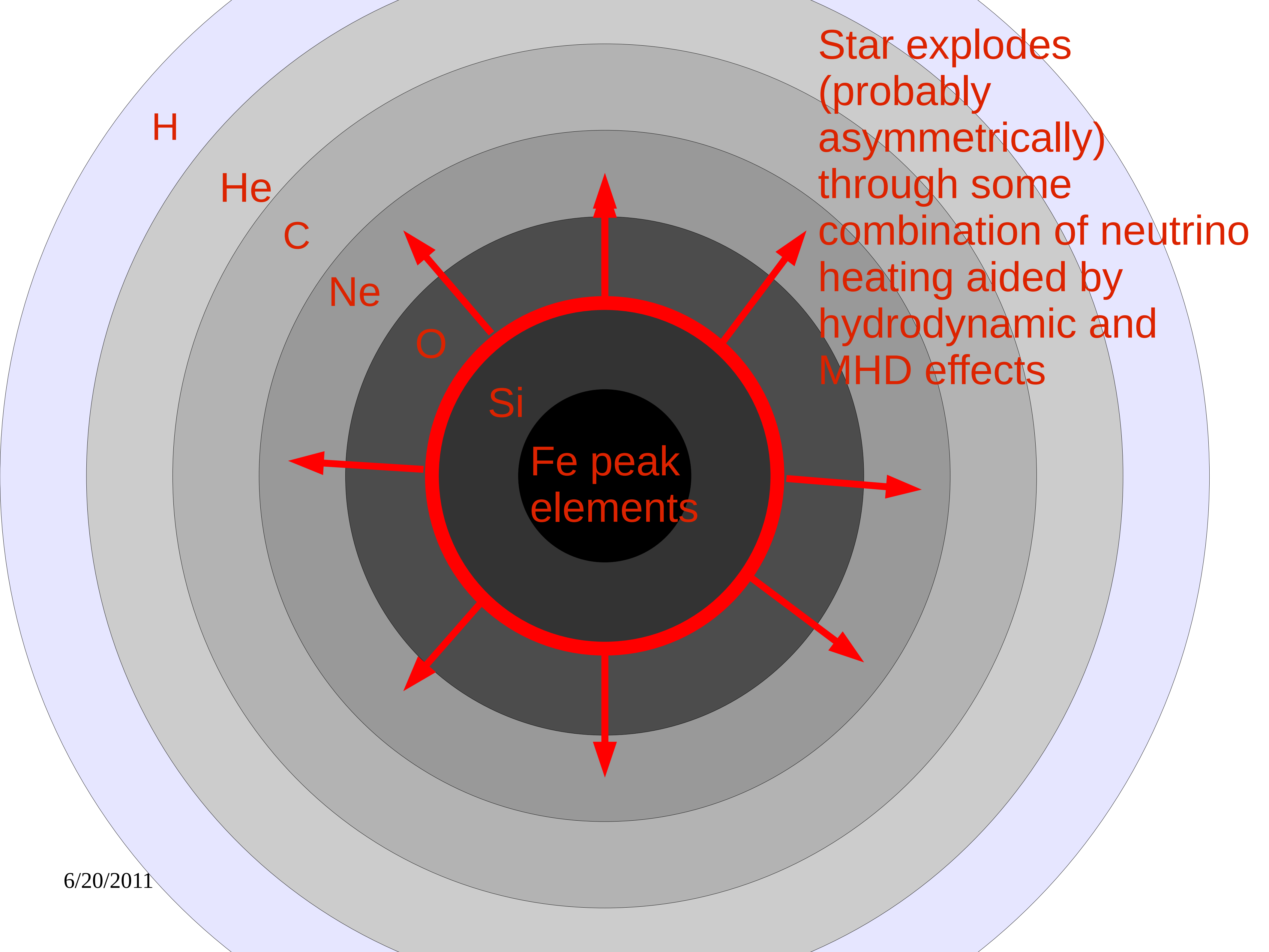
Woosley, Heger, and Weaver 2002



- CC SNe in the 10-50 Msun range
- PISNe more massive:150-250 solar masses
- PISNe explosion method understood—explosion energies not put in by hand

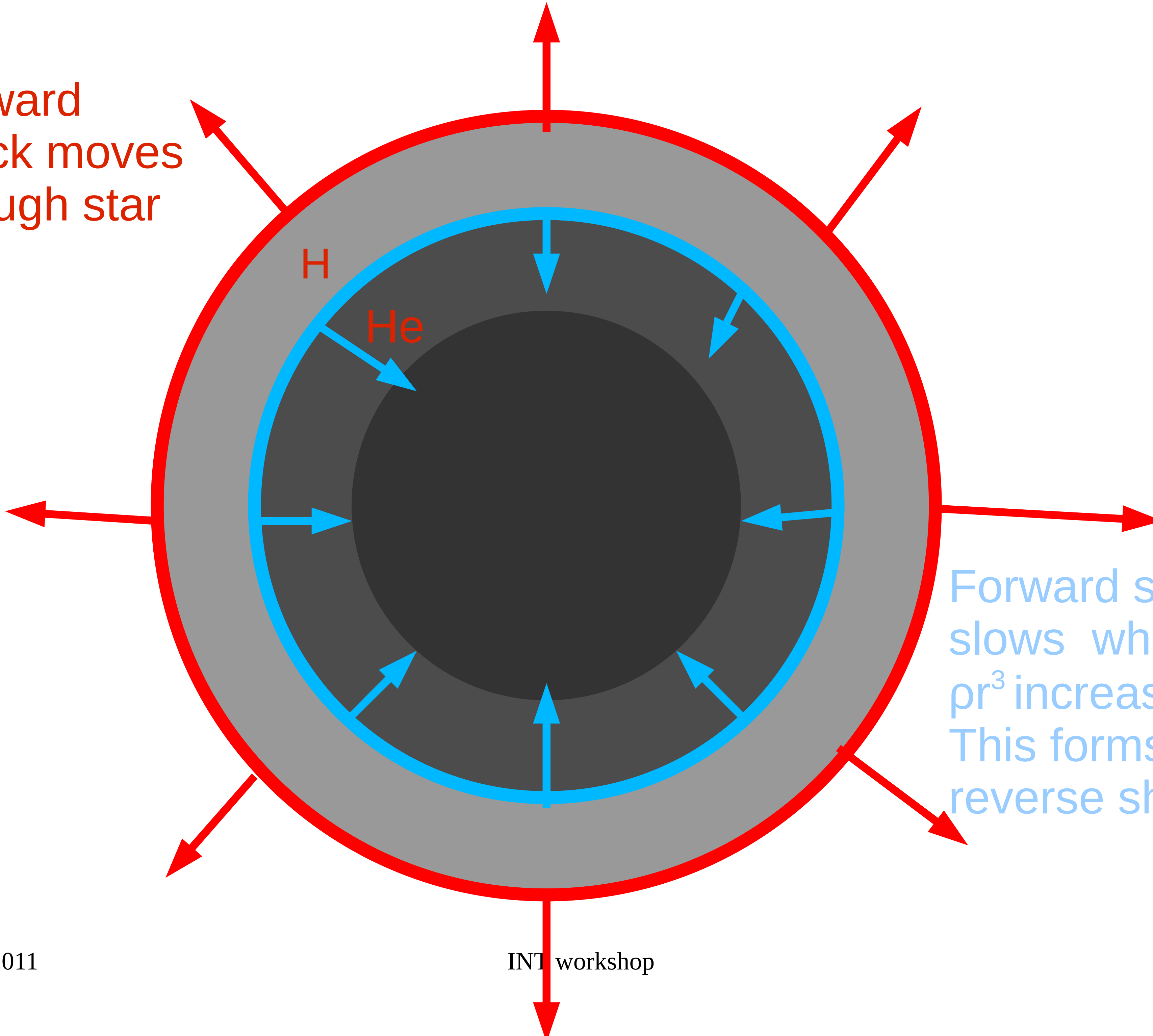
A typical core-collapse supernova prior to explosion (not to scale)





Star explodes (probably asymmetrically) through some combination of neutrino heating aided by hydrodynamic and MHD effects
H
He
C
Ne
O
Si
Fe peak elements

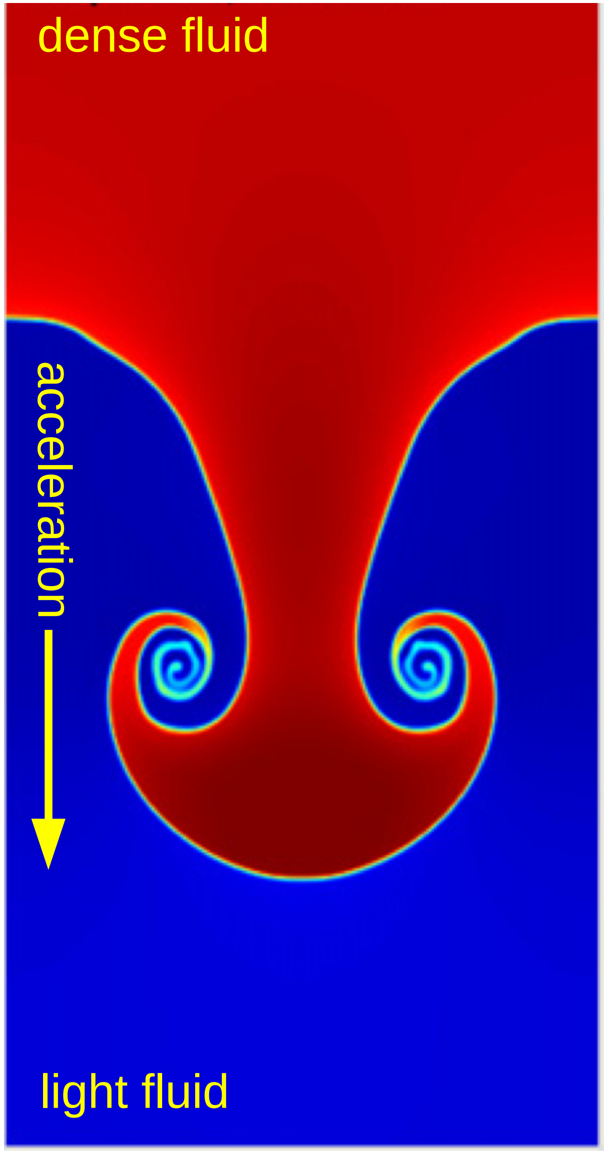
Forward shock moves through star



Forward shock slows where ρr^3 increases. This forms the reverse shock.

the Rayleigh-Taylor instability

- Occurs when density and acceleration gradients are opposed
- At late times, mixed region height $\approx \alpha A g t^2$, where $A \equiv (\rho^2 - \rho^1)/(\rho^2 + \rho^1)$



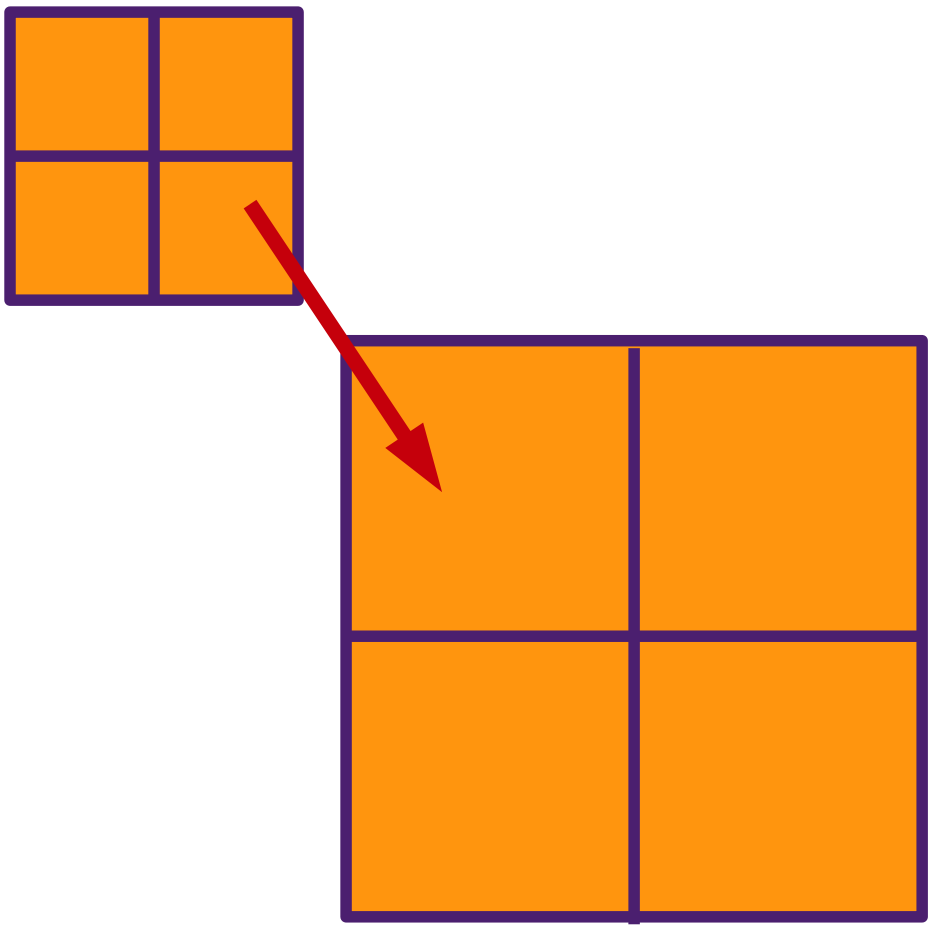
Almgren et al. 2010

Simulations of CC SNe

Joggerst et al. 2010a, 2010b

- 3D: 3 models: 15 M_{sun}, 1.2 β explosion models at zero, 10^{-4} Z_{sun}, and solar metallicity
- 2D: 36 primordial models at 15, 25, and 40 solar masses, zero and 10^{-4} Z_{sun} metallicity, 3 explosion energies (0.6, 1.2, and 2.4 β) and 2 rotation rates
- octant (3D) or quadrant (2D) modeled
- Followed in 2D axisymmetric or 3D Cartesian geometry

3D simulation setup



Original grid 128^n, with 2 levels of refinement

- Simulations enlarged when shock neared outer edge of grid
- 1 octant modeled

CC SNe: methodology

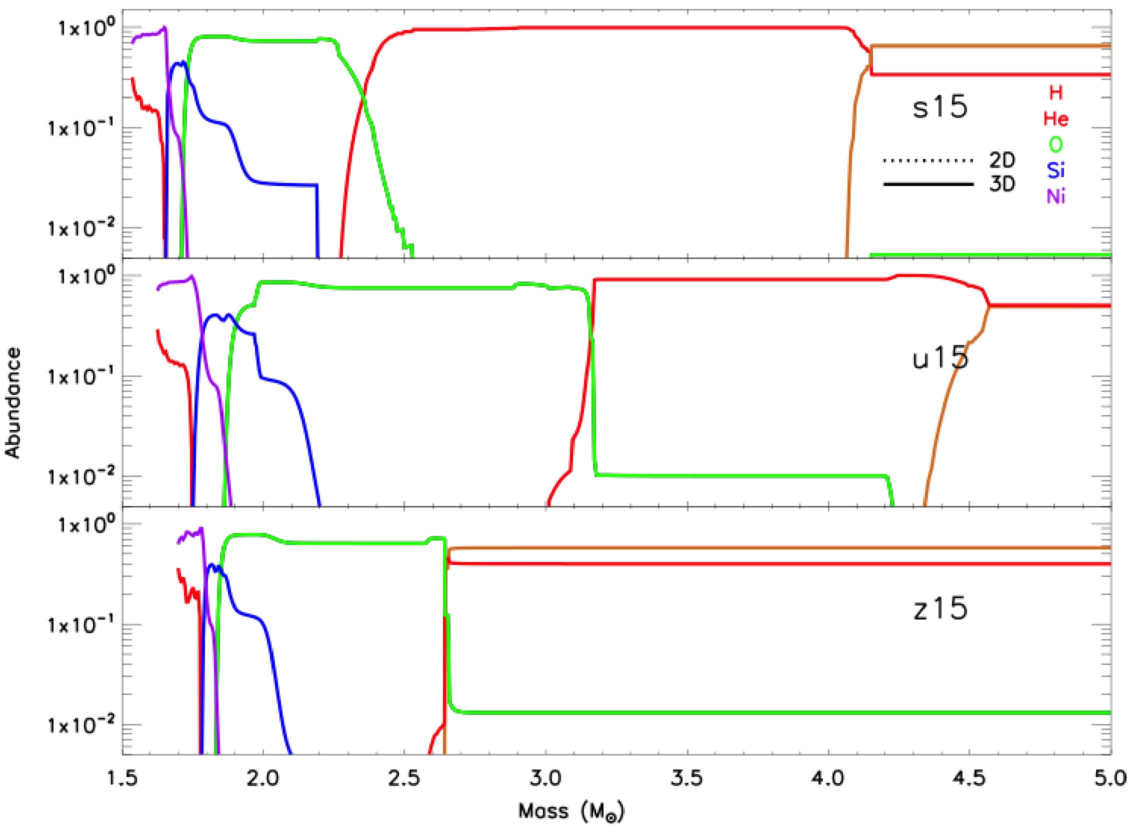
initial models

- simulations initialized from Kepler models that were evolved to the point of collapse, then exploded with a piston at the base of the oxygen shell
- Kepler models mapped to multiple dimensions after nuclear burning had ceased
- explosions are spherically symmetric
- perturbations arise from the grid

simulation setup

- self gravity, using a radial approximation
- heating from ^{56}Ni decay
- perfect gas with radiation EOS, with radiation component dropped in less dense regions
- zero-gradient inner boundary

Three models used for 3D simulations with CASTRO

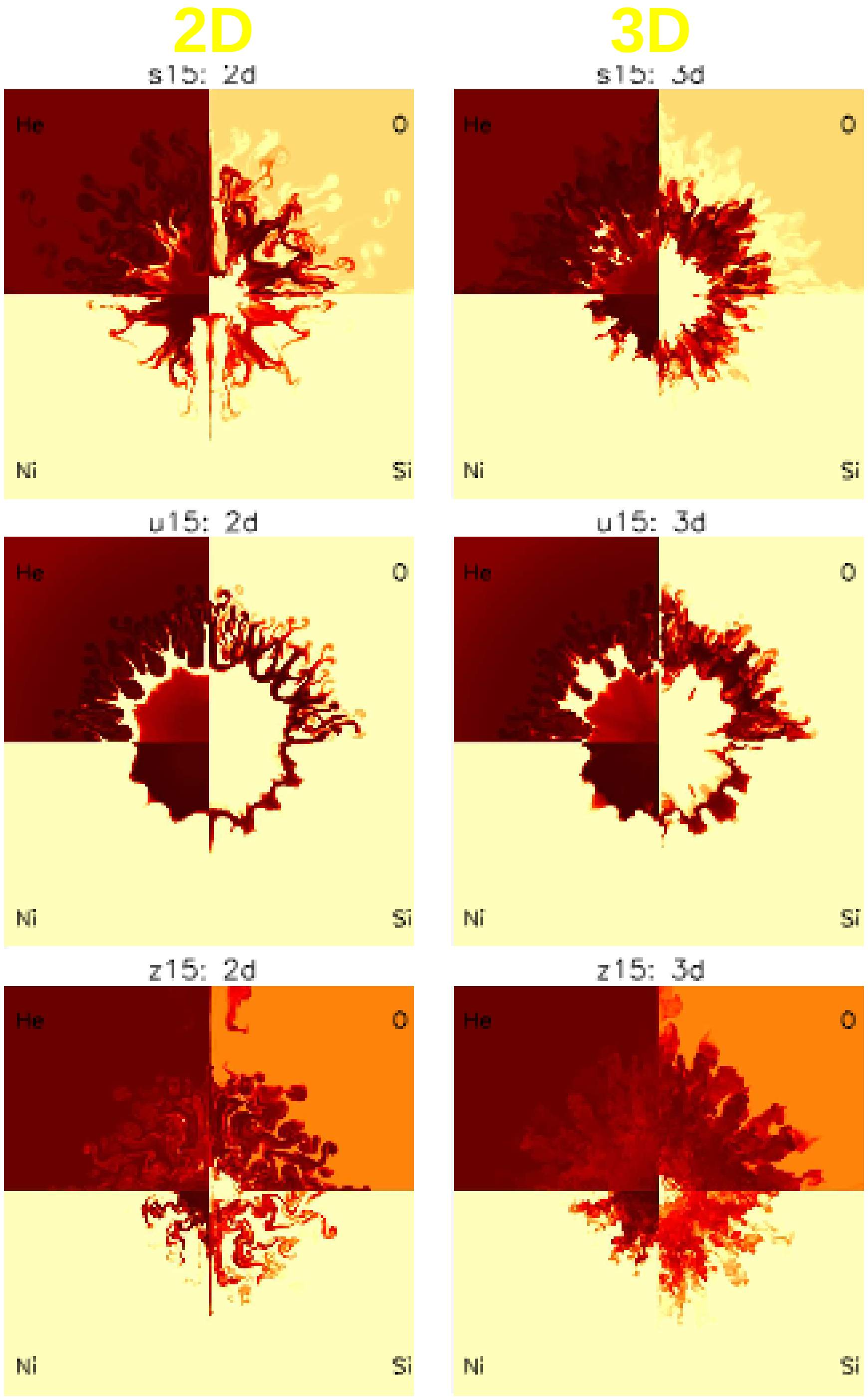


Joggerst et al. 2010b

- S15 and z15 die as red giants
- U15 dies as a blue giant
- Z15 lacks a helium shell because of convection

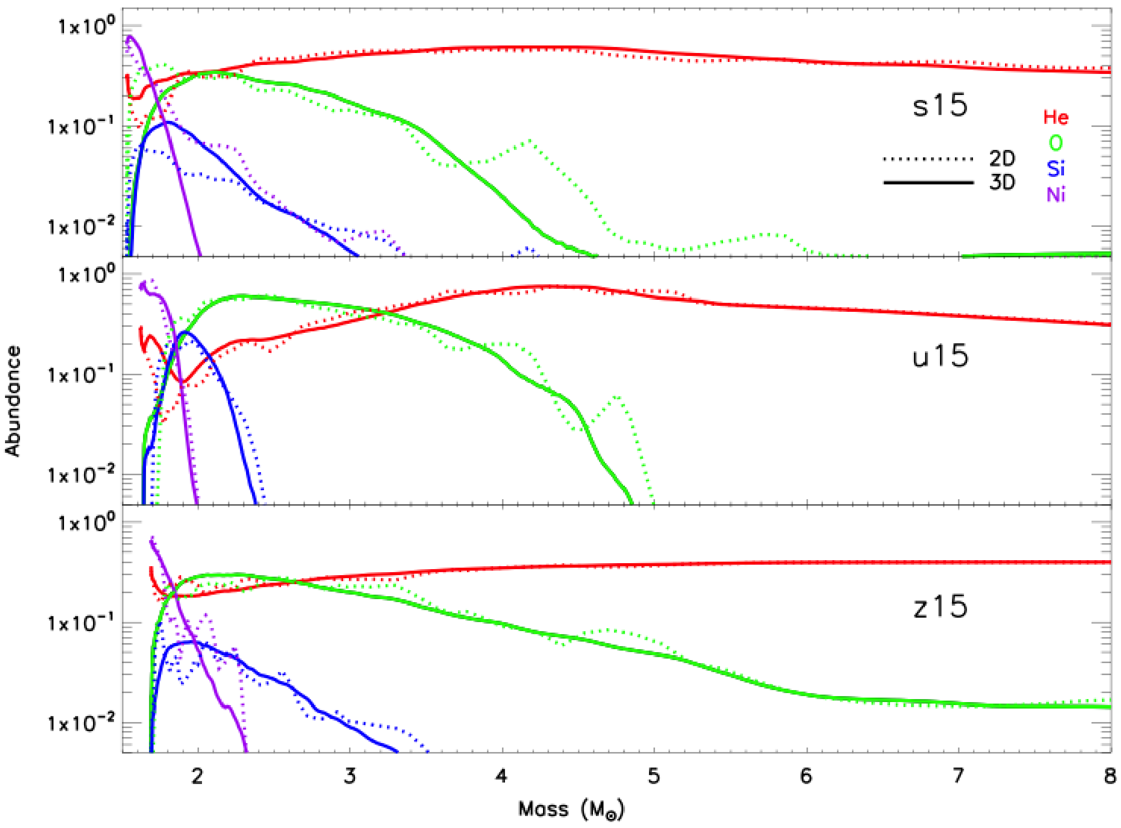
2D vs. 3D

- Shape of instabilities slightly different in 2D vs 3D
- 3D more mixed, but the width of the mixed region is essentially the same
- RT fingers have interacted with one another



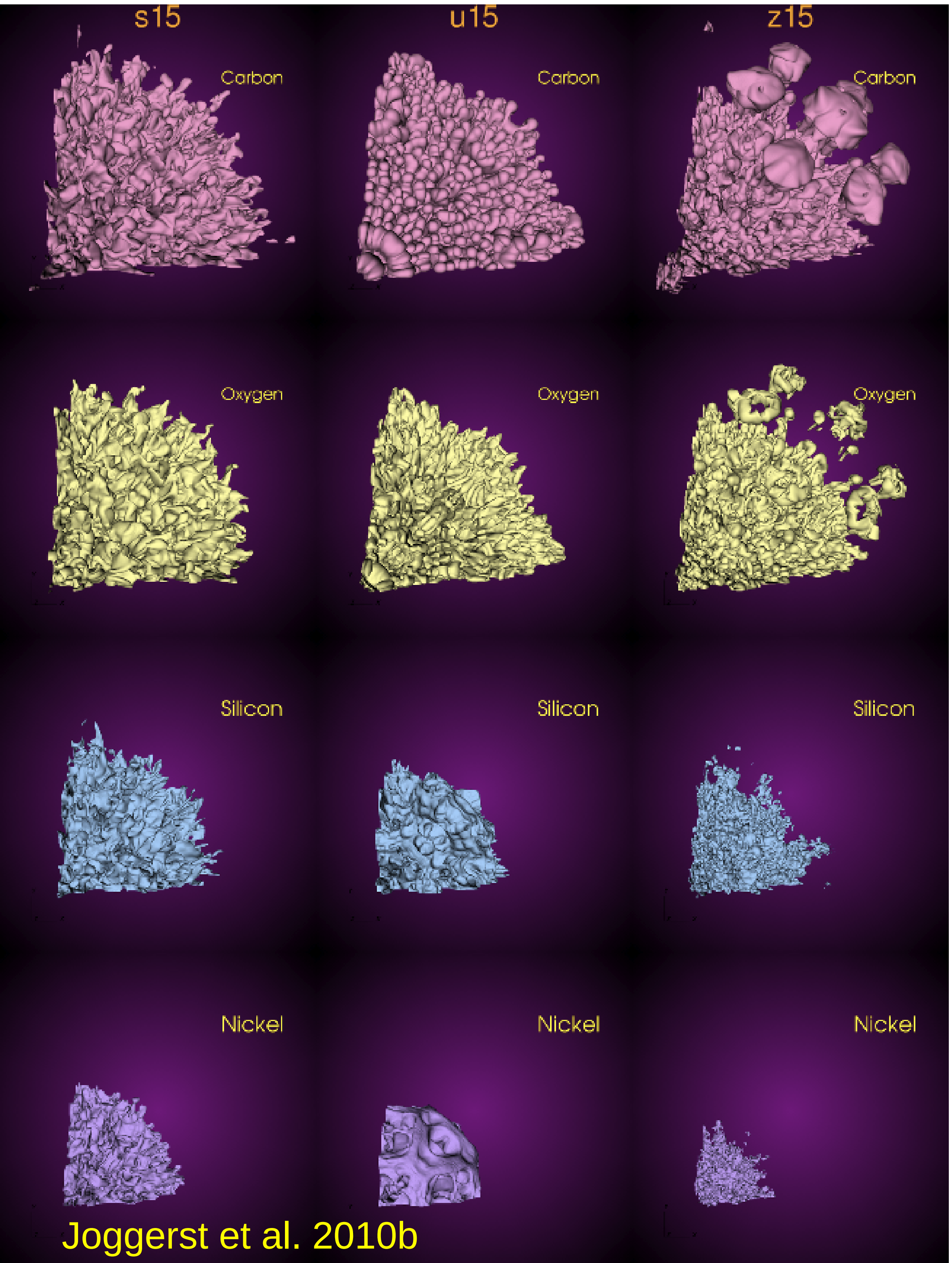
Joggerst et al. 2010b

Abundance Vs Mass



Joggerst et al. 2010b

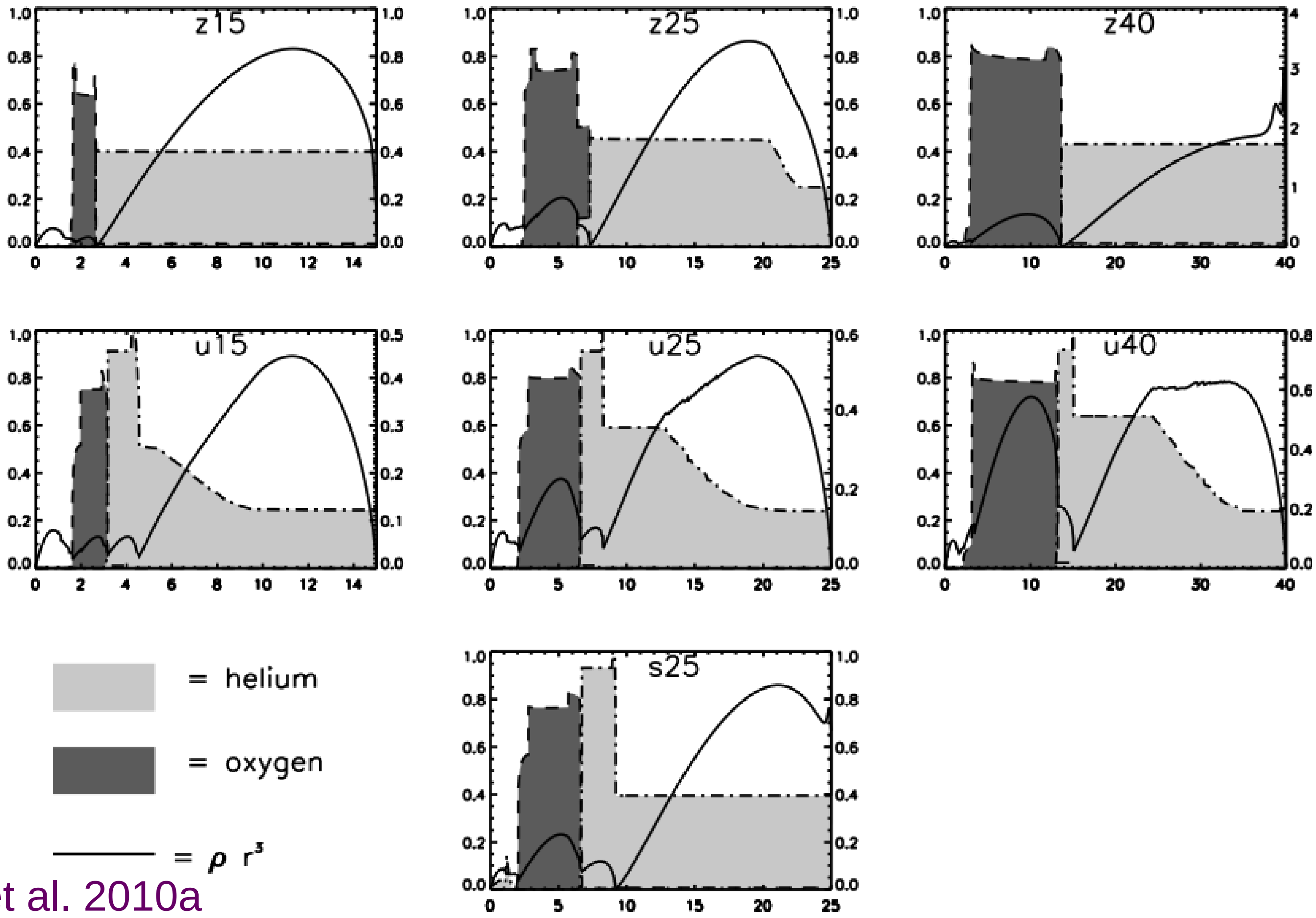
- Width of mixed region the same between 2D and 3D
- 2D is bumpier than 3D—reflects transition to turbulence; better sampling



3D renderings

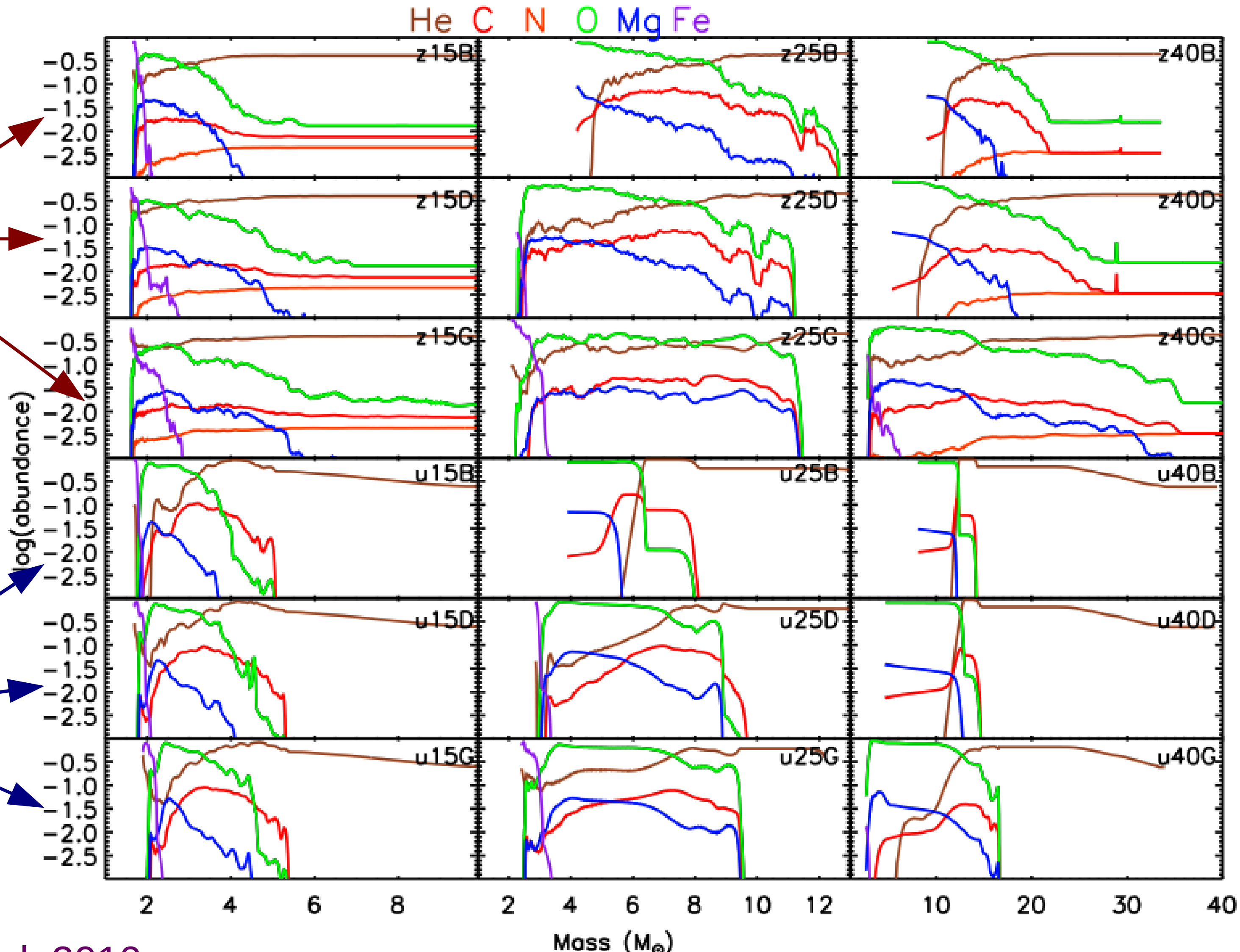
- Z15 shows broken-off clumps
- U15 is the least mixed
- Heavy elements don't penetrate lighter layers

Primordial CC supernovae: initial models



Joggerst et al. 2010a

Primordial CC SNe: abundance vs mass after mixing



Red stars show more mixing

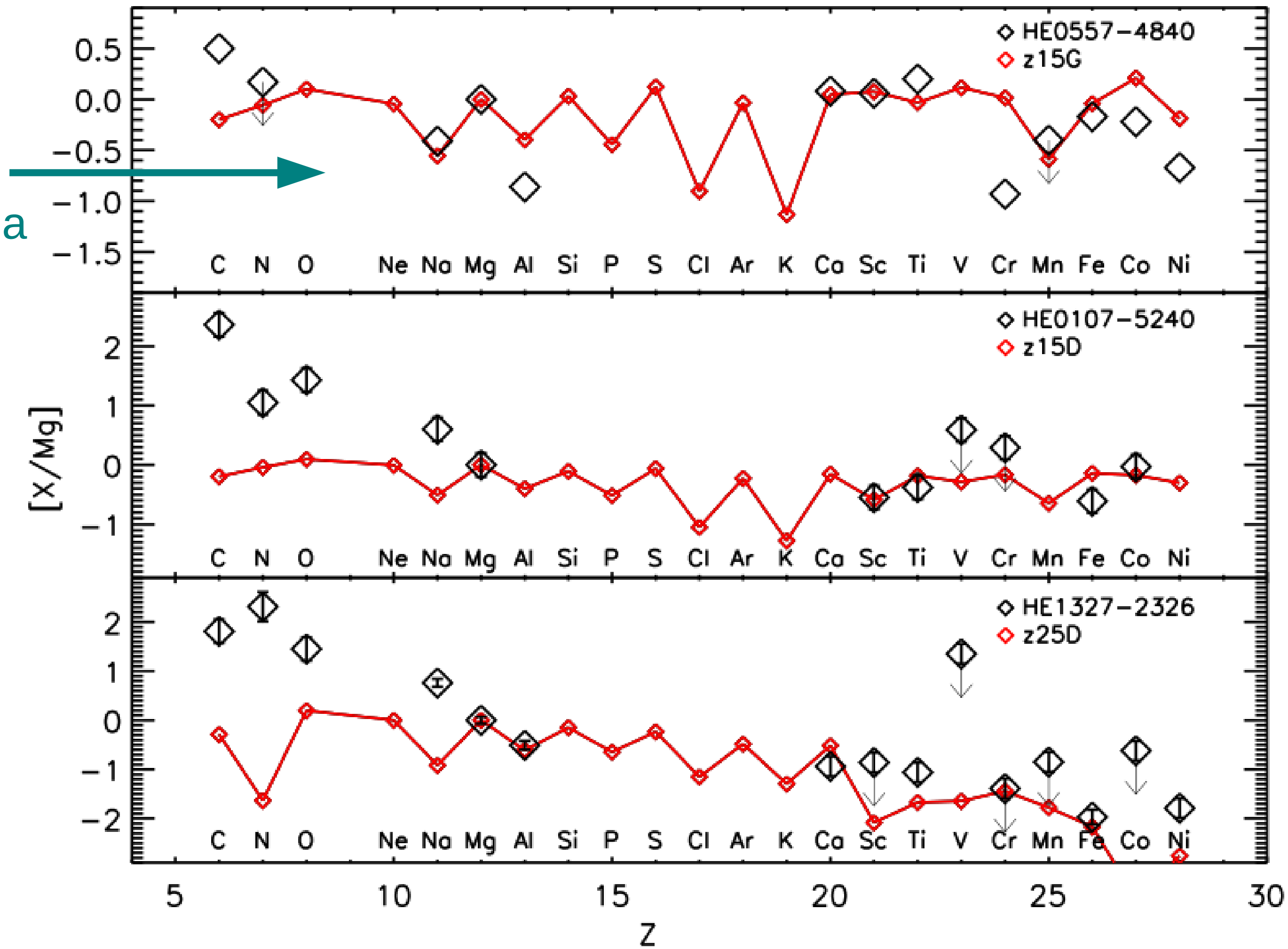
Blue stars show less

Mixing increases with explosion energy

Joggerst et al. 2010a

Nucleosynthetic yields compared to the abundances of the three most iron-poor stars

Only one extremely metal-poor star can be fit acceptably by a single model



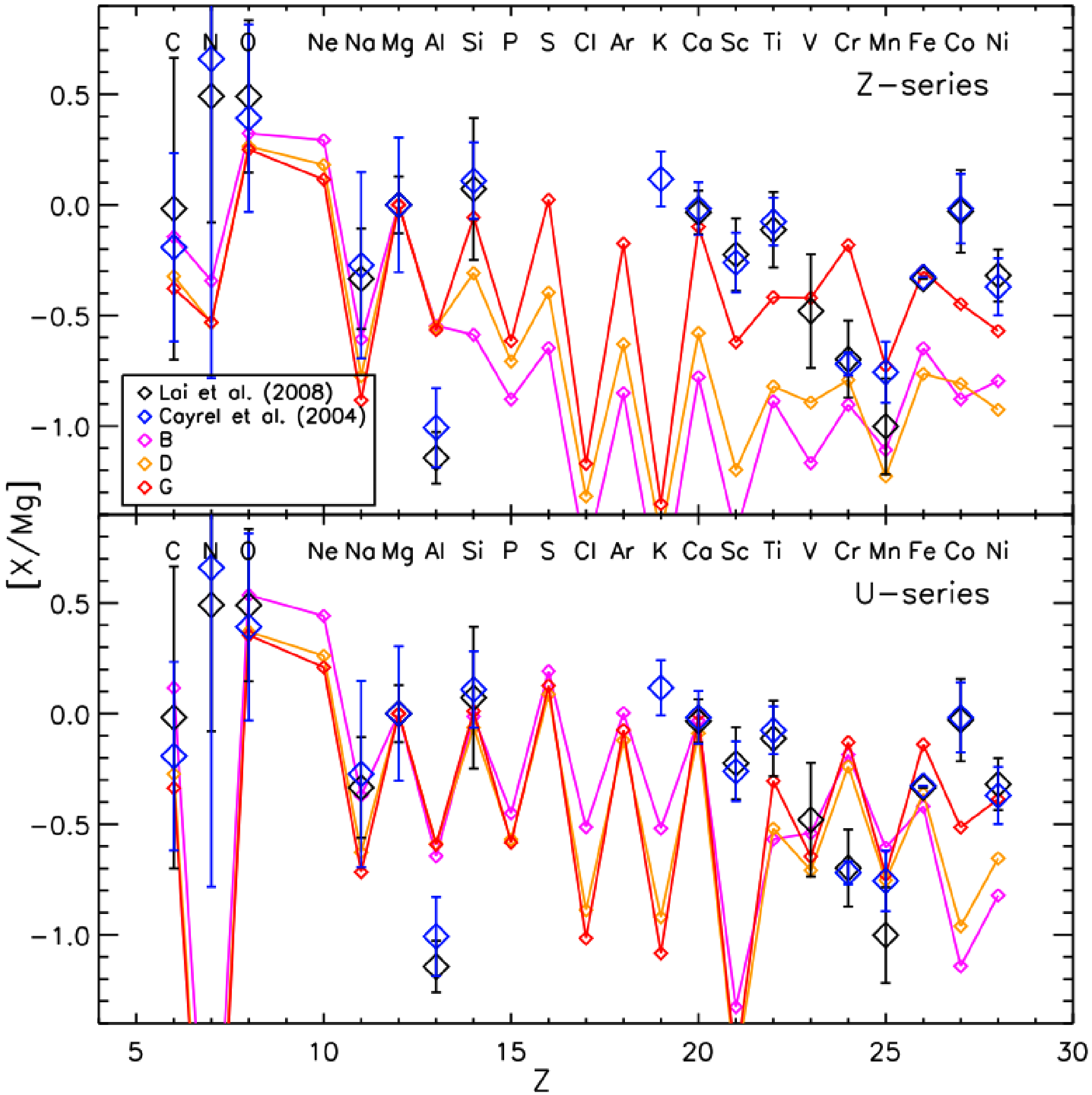
Joggerst et al. 2010a

Nucleosynthetic yields compared to the abundances of EMP stars

Diamonds: averages of observed abundances in stars with -4.0>[Fe/H]>-2.5

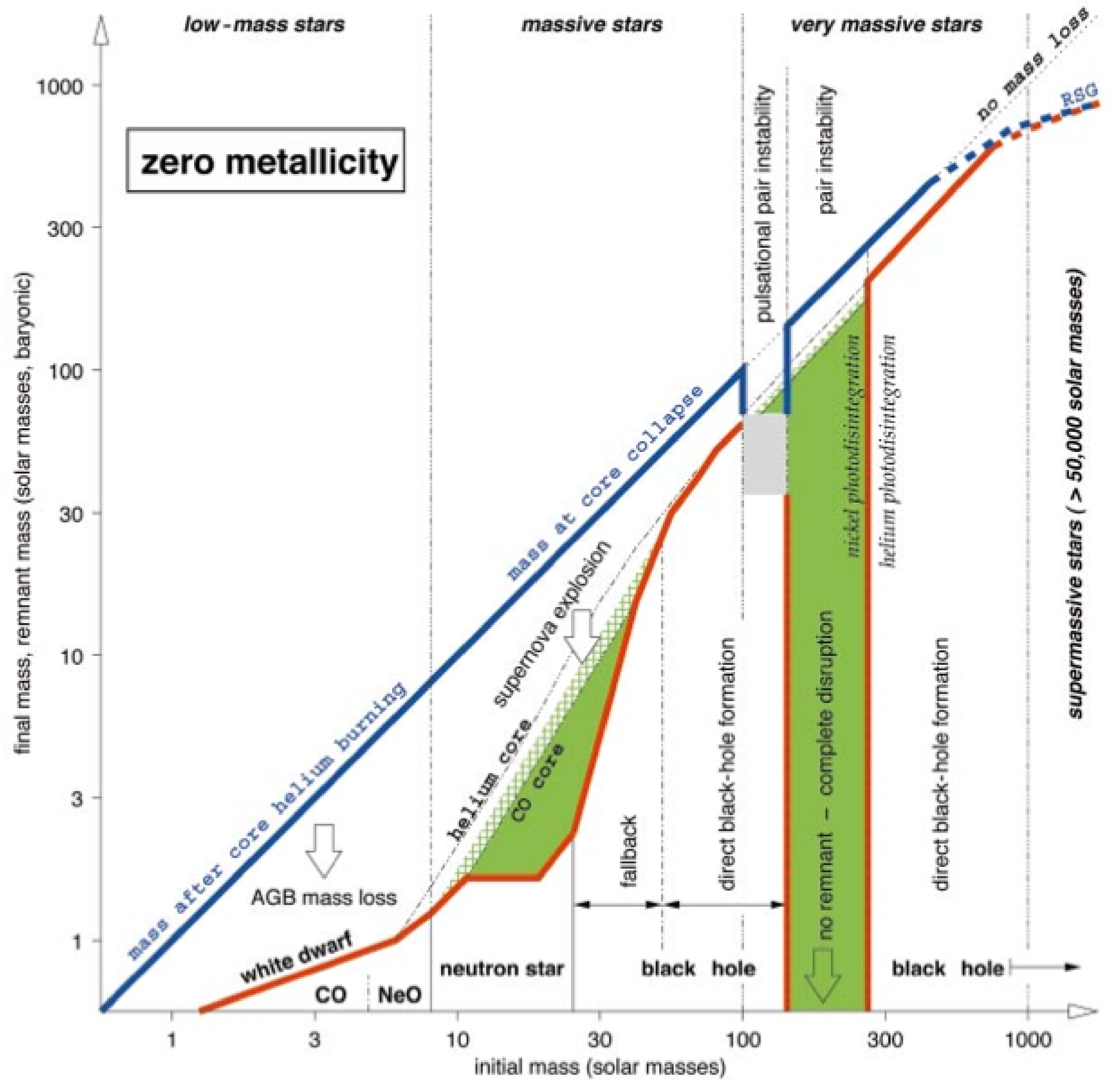
Lines: Salpeter IMF averages over theoretical yields for each explosion energy
Pink: 0.6 β
Orange: 1.2 β
Red: 2.4 β

Red stars (top panel) reproduce these abundance patterns well



Joggerst et al. 2010a

Woosley, Heger, and Weaver 2002



- CC SNe in the 10-50 Msun range
- PISNe more massive:150-250 solar masses
- PISNe explosion method understood—explosion energies not put in by hand

Pair-instability supernovae

- Explosion begins in He cores above 40 M_{sun} when the temperature there exceeds 10^9 K (after He burning)
- Creation of e^+/e^- pairs in the core softens the equation of state (γ falls below 4/3) which induces collapse and instabilty.
- For He cores < 135 M_{sun}, explosive O burning (and Si burning, for more massive cores) halts the collapse and explodes the star.

CC SNe vs PISNe

- 10-140 M_{sun}
- Leave behind remnants
- Explosions not successful in 1D for most models; explosions must be put in by hand
- Experience vigorous RT mixing which significantly changes lightcurve, spectra, and nucleosynthesis

- 140-260 M_{sun}
- No remnant left behind, in general
- 1D explosions emerge from models; energies and geometries well determined
- Mixing thought to occur, but not well investigated.

Observational signatures of PISNe

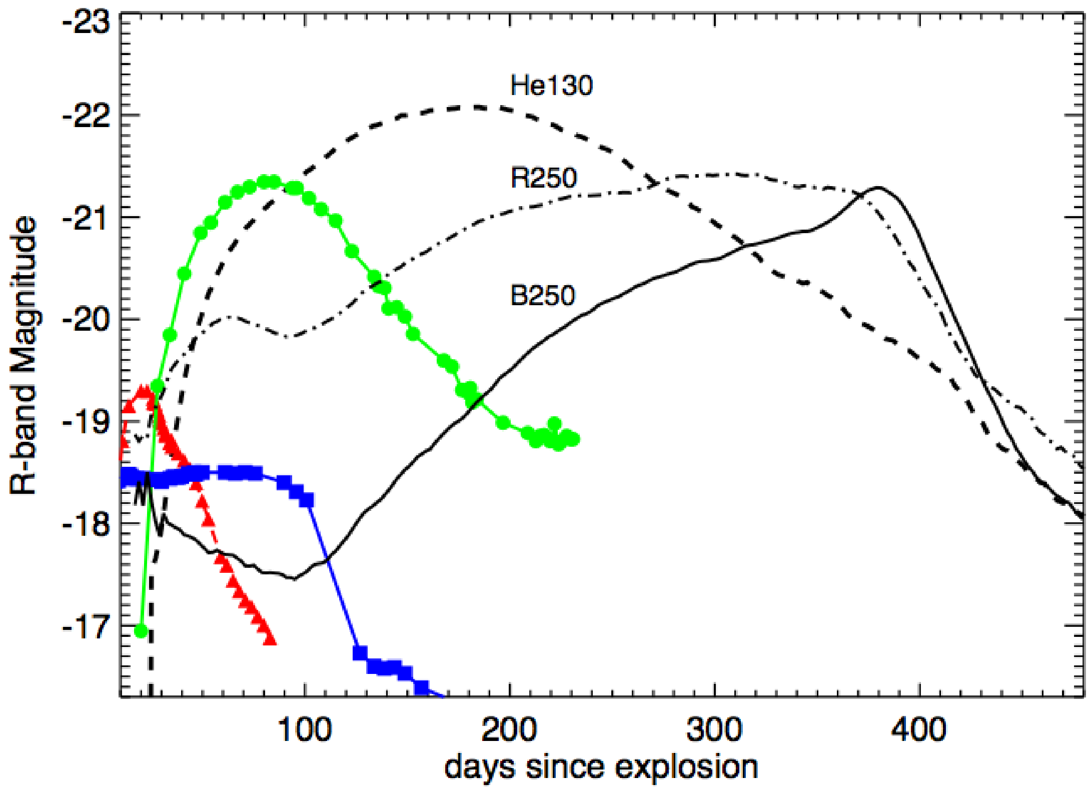
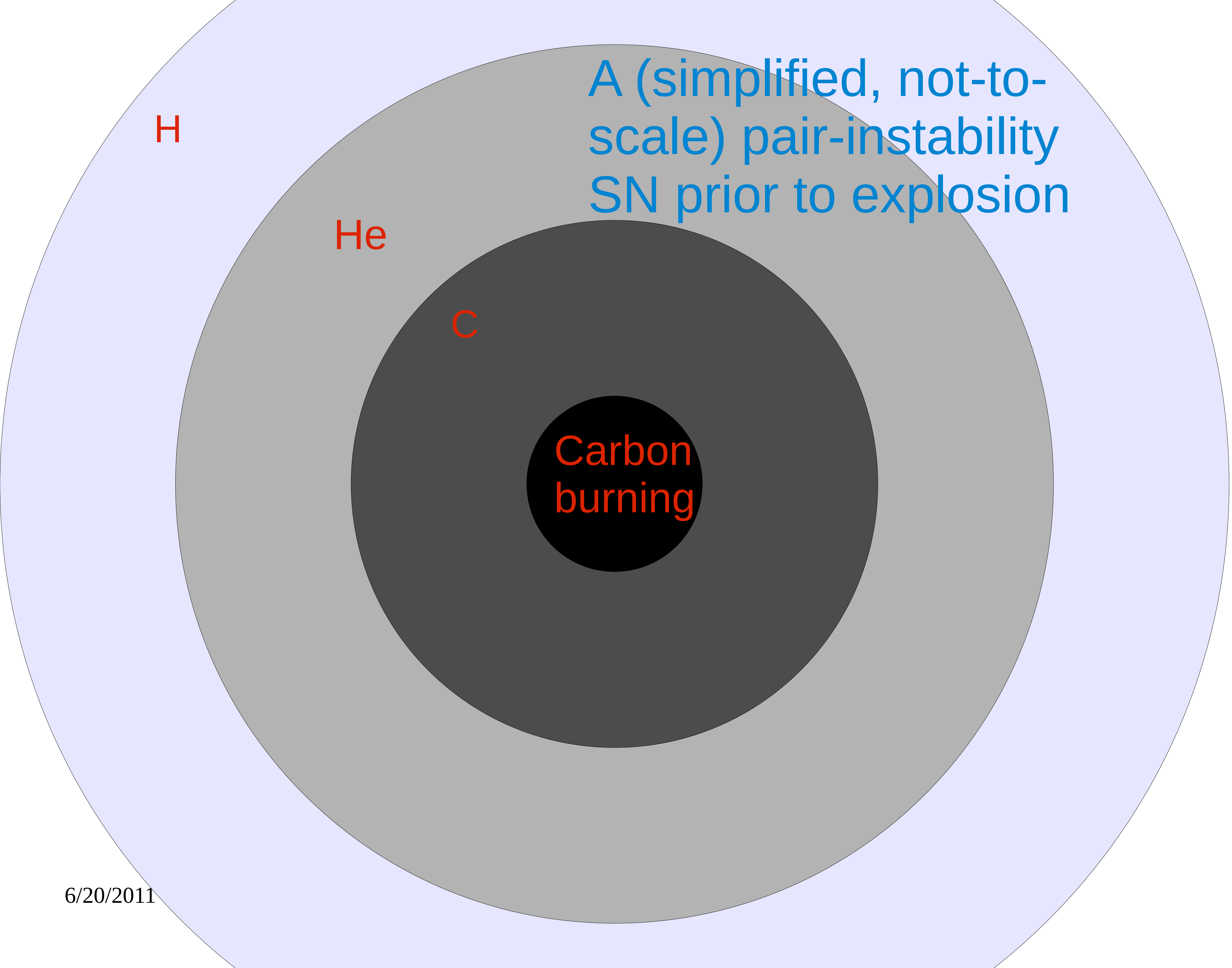


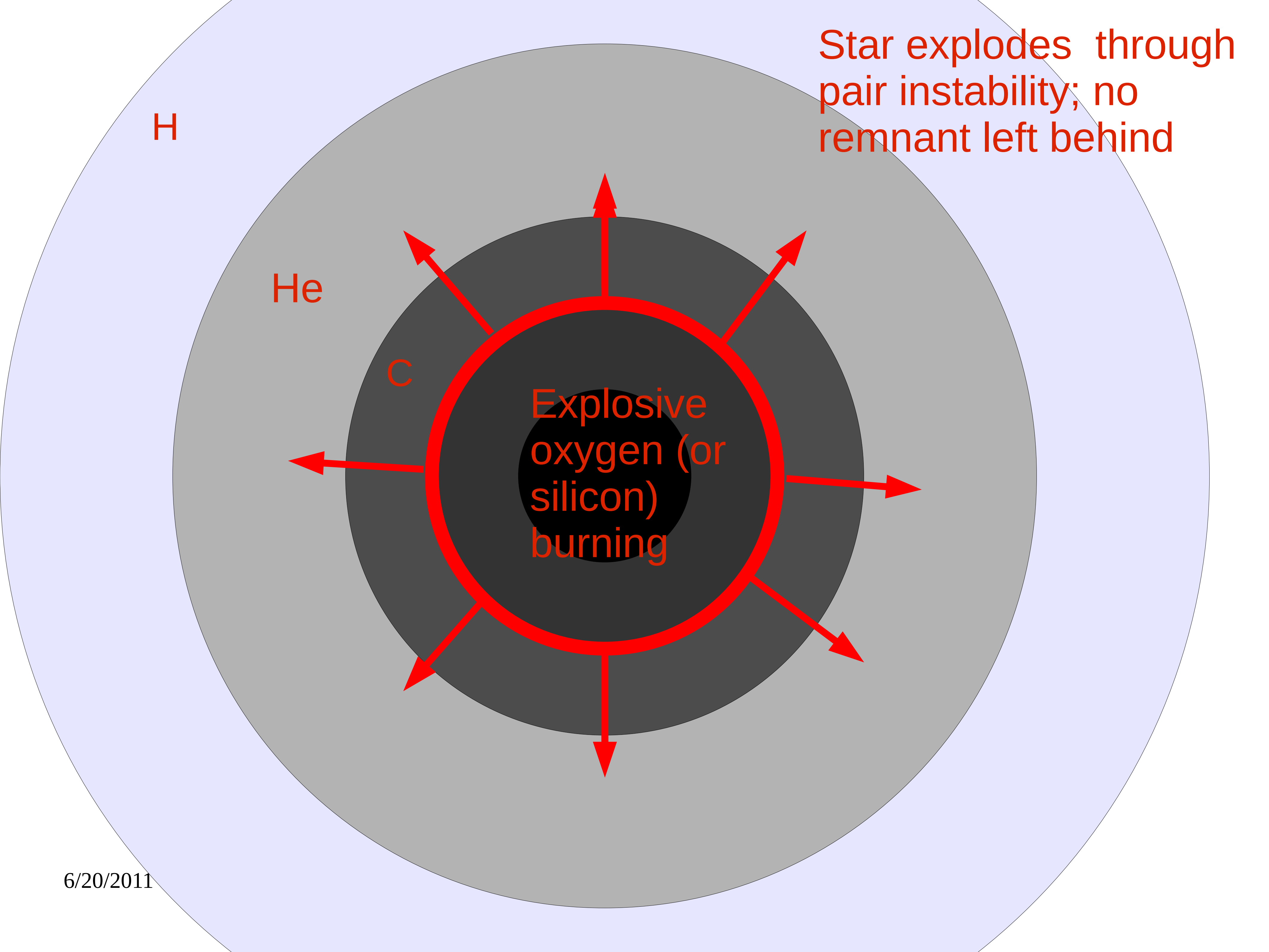
FIG. 6.— Synthetic R-band light curves (at $z = 0$) of bright PI SN models – R250 (dashed-dot), B250 (solid), and He130 (dashed) – compared to observations of a normal Type Ia supernova SN 2001el (red triangles, Krisciunas et al. 2003) a normal Type IIP supernova SN 1999em (blue squares, Leonard et al. 2002) and the over-luminous core-collapse event SN 2006gy (green circles, Smith et al. 2006).

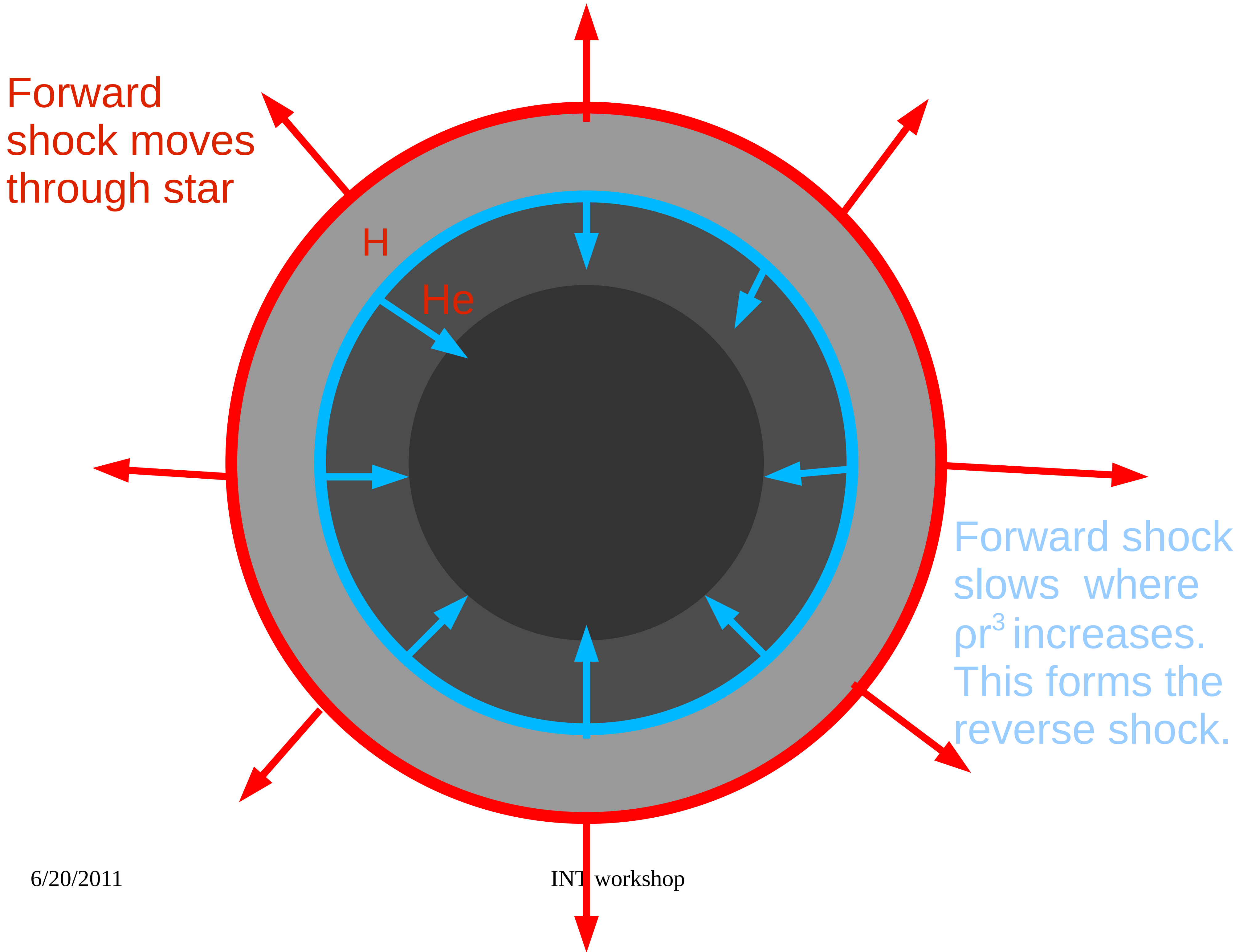
- Brighter peak luminosity
- Light curve of longer duration
- Morphology of light curve depends on envelope of the progenitor star

Kasen, Woosley, and Heger (2011)

A (simplified, not-to-scale) pair-instability SN prior to explosion




Star explodes through
pair instability; no
remnant left behind
H
He
C
Explosive
oxygen (or
silicon)
burning


Forward
shock moves
through star
H
He
Forward shock
slows where
ρr3 increases.
This forms the
reverse shock.

2D PISNe study

Joggerst and Whalen 2011

- Models taken from KEPLER runs 20 s after explosion
- 9 models: 175,200,225, and 250 Msun at zero and 150, 175, 200, 225, and 250 Msun 10^{-4} Z_{sun} metallicity
- 1 quadrant (2D) modeled
- 1024^2 resolution, with up to 4 levels of refinement
- Up to 12 grid enlargements

PISNe simulations: methodology

initial models

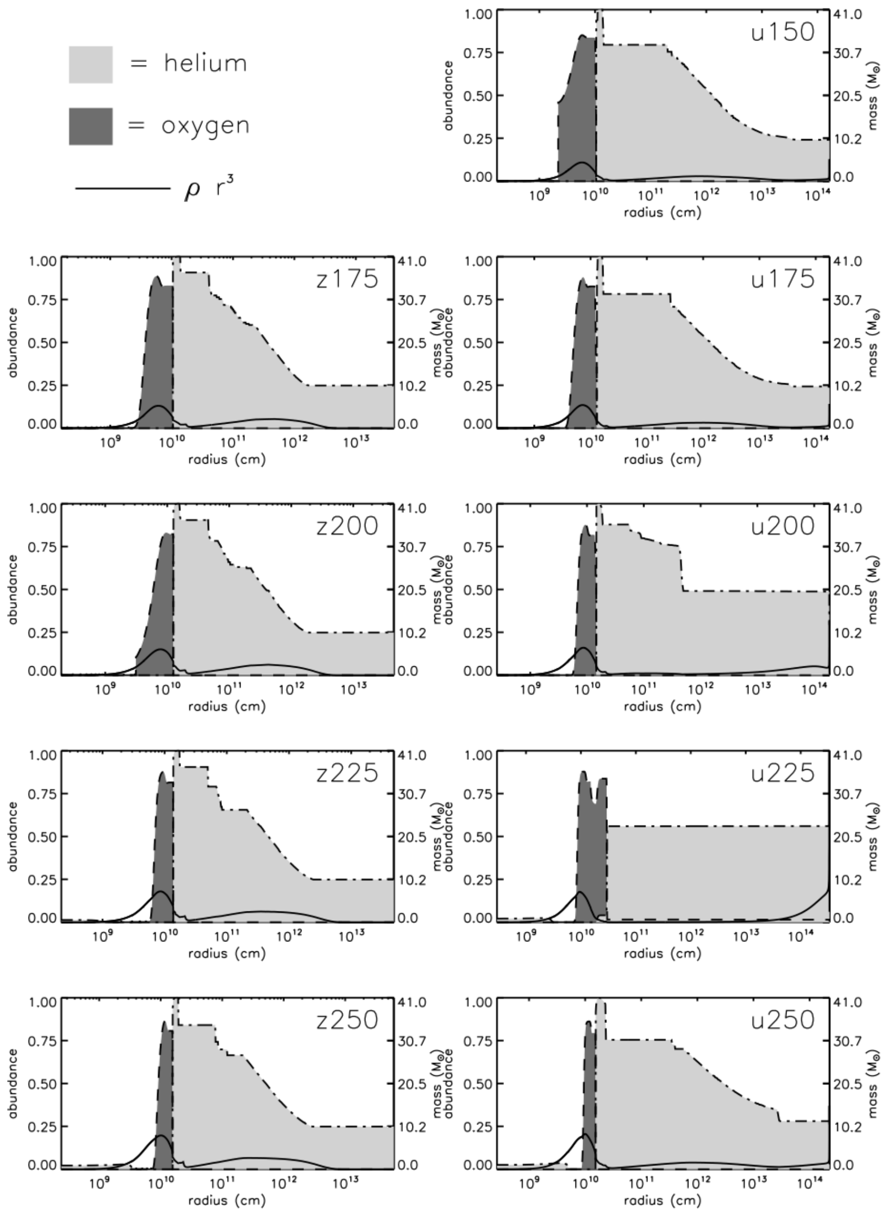
- Simulations initialized from 1D Kepler models evolved through all stable stages of nuclear burning to 20 seconds past explosion, when nuclear burning had ceased
- Explosions are spherically symmetric and their energies arise from models; they are not put in by hand
- perturbations arise from the grid

simulation setup

- self gravity, using a radial approximation
- heating from ^{56}Ni decay
- Helmholz EOS used for first ~1000 seconds
- perfect gas with radiation EOS, with radiation component dropped in less dense regions used after ~1000 seconds
-

initial models

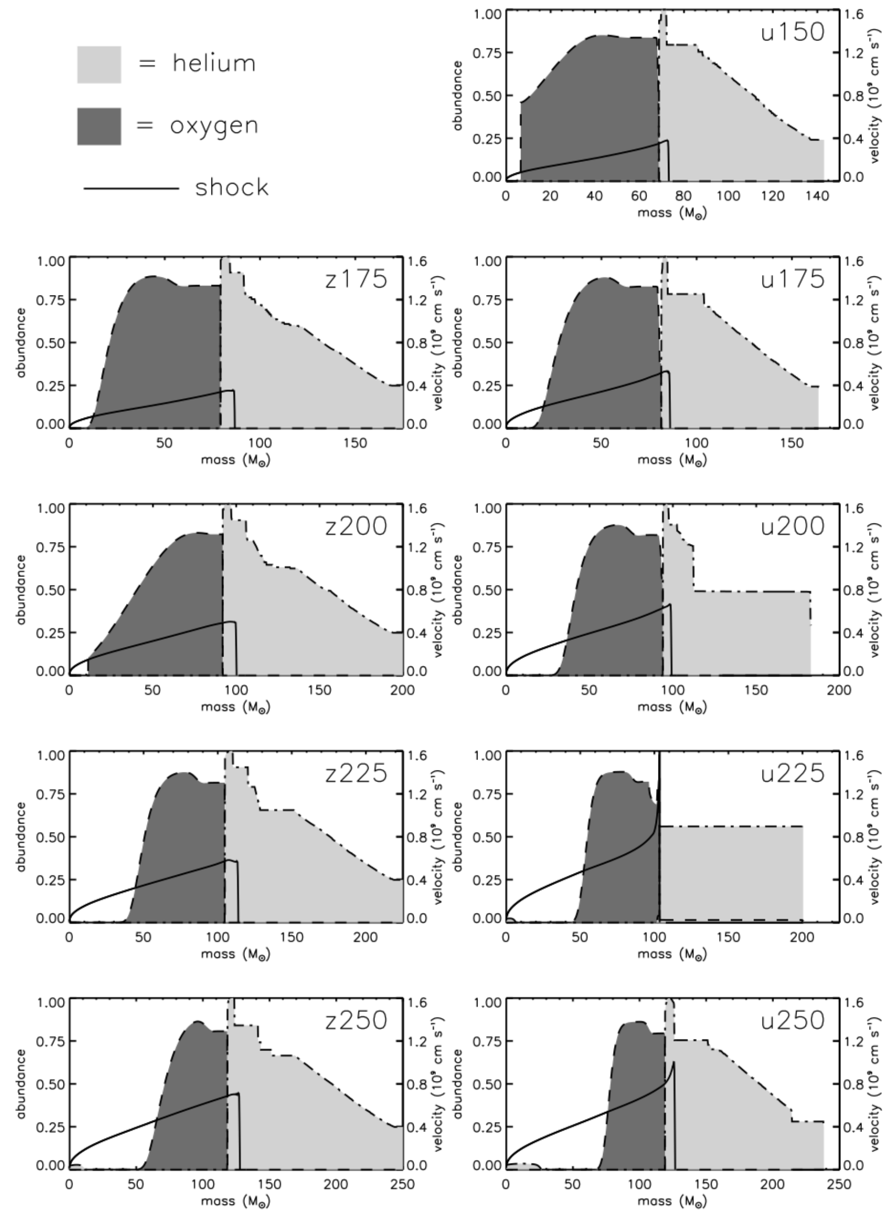
Joggerst and Whalen (2011)



- z models more compact than u models
- $\rho\ r^3$ shown as solid black line
- scaled to maximum value in model u225
- $\rho\ r^3$ increases more in u200 and u225; these should have a stronger reverse shock

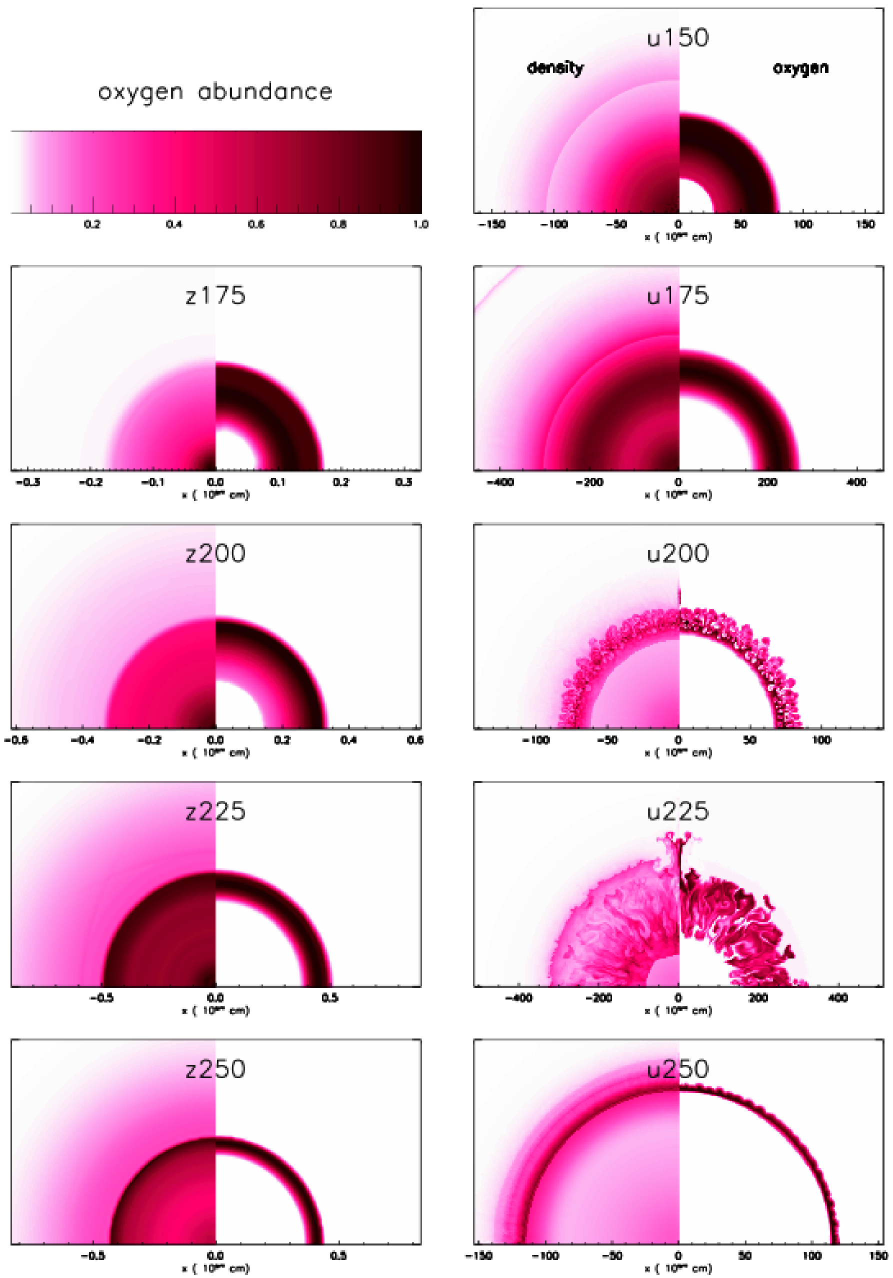
position of shock

- Shock shown as solid black line
- Scaled to maximum value in u225
- At time of mapping to 2D, shock is just past the base of the helium layer



Joggerst and Whalen (2011)

final state of models

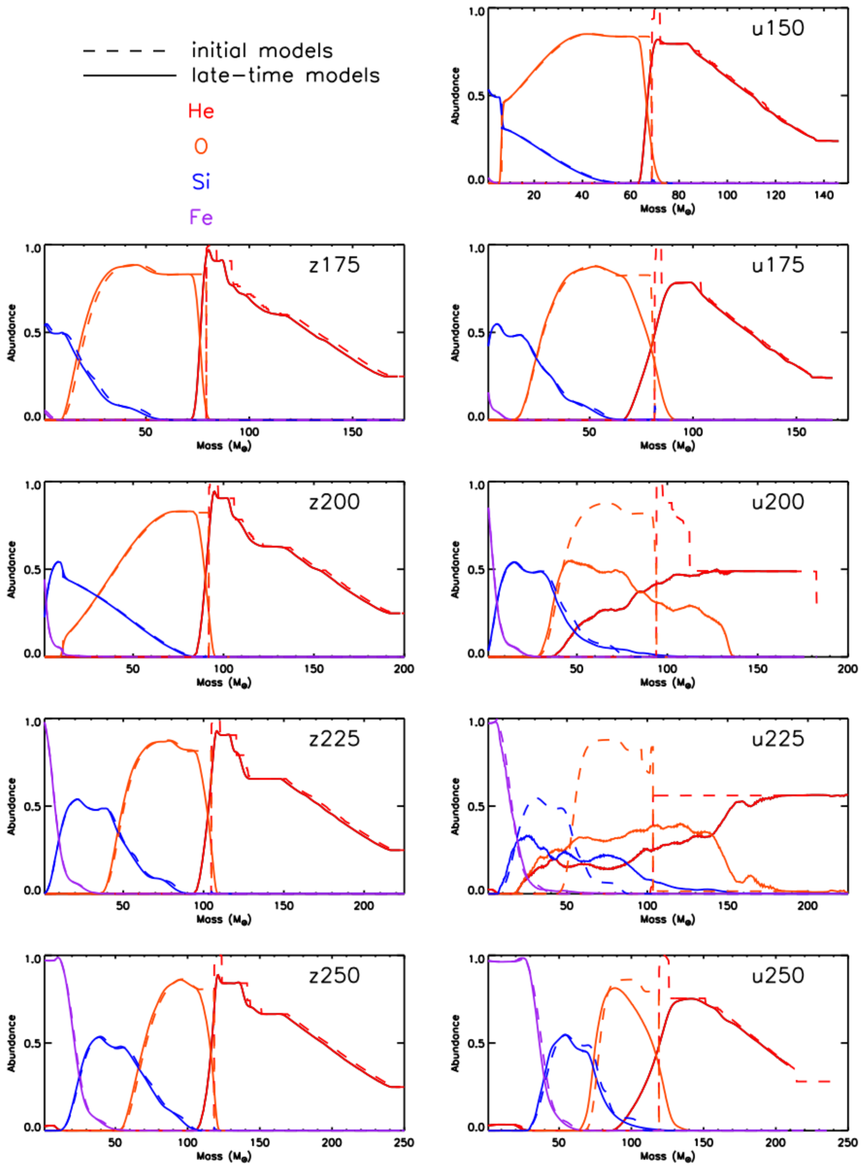


- density scaled to individual models
- a dense shell forms in models > 200 Msun
- RT instability occurs only in models with steep increase in ρr^3 at the outer edge: u200 and u225, and slightly in u250

Joggerst and Whalen (2011)

' workshop

radial averages



- Slight differences between initial and final models in simulations that experience no mixing caused by numerical diffusion
- Nickel remains undisturbed and is not mixed to outer parts of star in all models

Joggerst and Whalen (2011)

Our results are robust

- 3D simulations unlikely to show RT instability in 2D simulations where RT instability is absent.
- the explosion energy and geometry arise from models themselves, and are not put in by hand as they are in CC models
- our models span the expected range in shape and mass for PISNe

convection before explosion

energy generation rate at the top of the oxygen shell in a 150 M_{sun} star 60 seconds after maximum compression

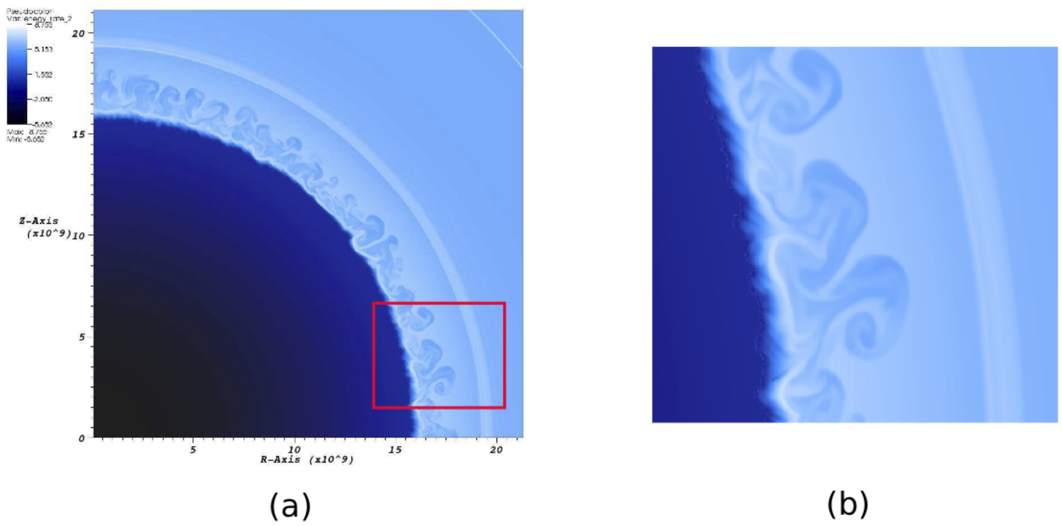


Figure 2: Energy generation rate

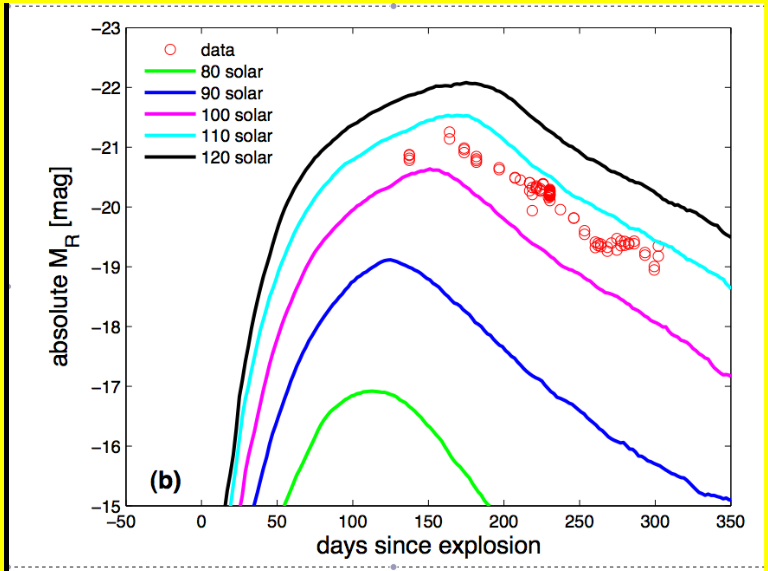
Chen and Heger 2010

- Rayleigh-Taylor instability occurs due to oxygen burning during the explosion
- these fingers will seed later instabilities that occur in the wake of the explosion

Implications for cosmology

- The lack of mixing in PISNe could provide a way to differentiate Pop III core-collapse supernova light curves from Pop III PISNe light curves
- An unmixed star might enrich the surrounding halo differently than a mixed star, though how important PISNe were to early metal enrichment is debatable

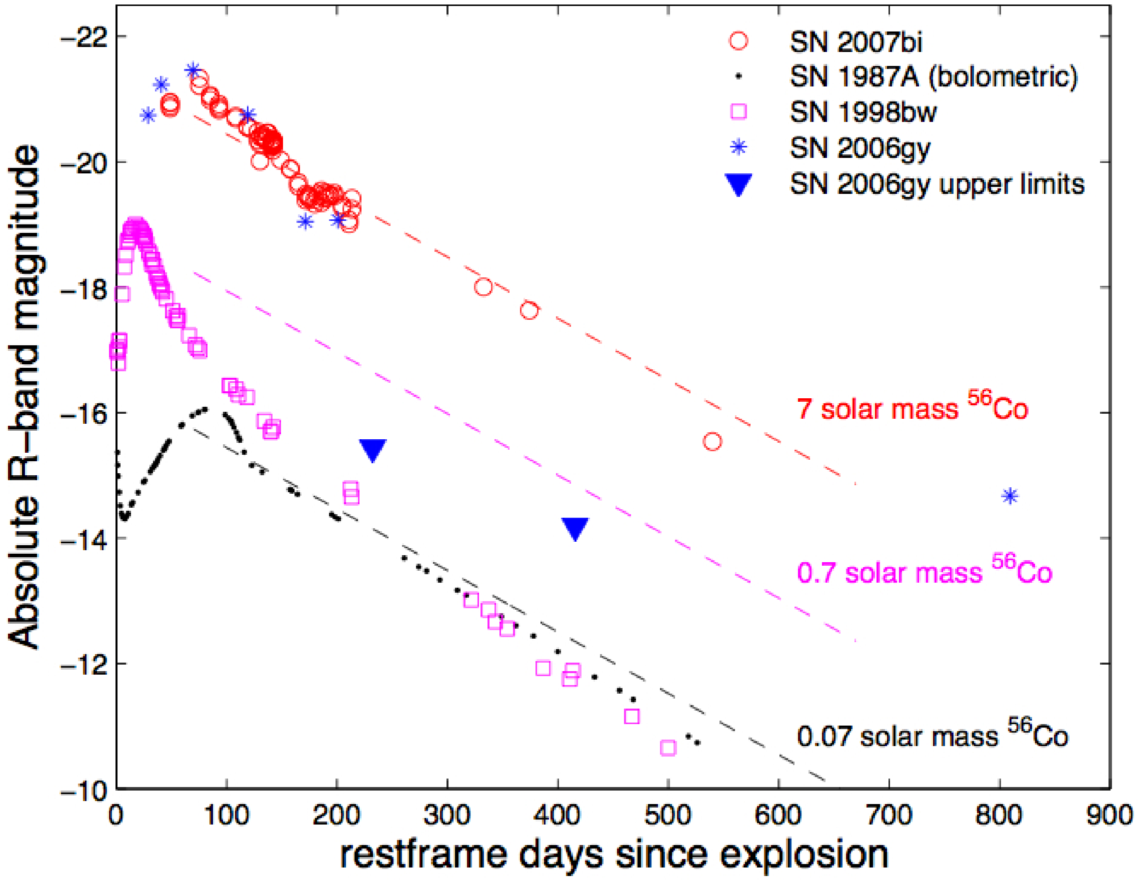
2007bi: a PISNe?



"Comparison of the observations of SN 2007bi with models calculated before the SN discovery. The curves presented are for various helium cores (masses as indicated) exploding as PISNe, and cover the photospheric phase. The data are well f t by 100– 110M models...." (Gal-Yam et al. 2009)

- Exploding core mass likely around 100 M_{sun}
- Observations well fit by PISN models
- More than 3 M_{sun} of ^{56}Ni synthesized in the explosion
- No H or He lines are seen, making interactions with circumstellar medium a poor explanation for extreme brightness of the event

2007bi is different from other luminous SNe

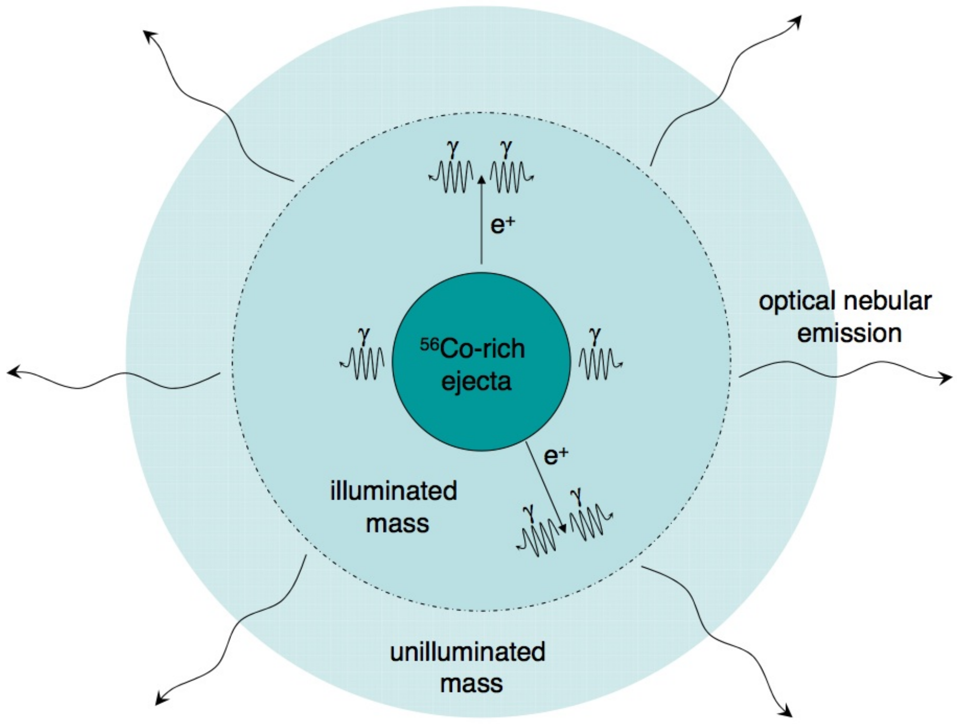


- all other luminous SNe showed evidence for H in their spectra; 2007bi does not
- no strong signatures of interaction with a circumstellar medium.

Gal-Yam et al. (2009)

no mixing in 2007bi?

^{56}Ni appears concentrated in the center of the ejecta:



Gal-Yam et al. (2009)

- light-curve modeling (sensitive to all mass) gives a high mass estimate, while nebular spectroscopic modeling (sensitive only to radioactively enriched material) gives a lower mass estimate
- nebular spectrum appears depleted in C,O, and Mg relative to outer layers of envelope
- lack of He lines: He is almost certainly present, but only appears in the vicinity of ^{56}Ni.

conclusions

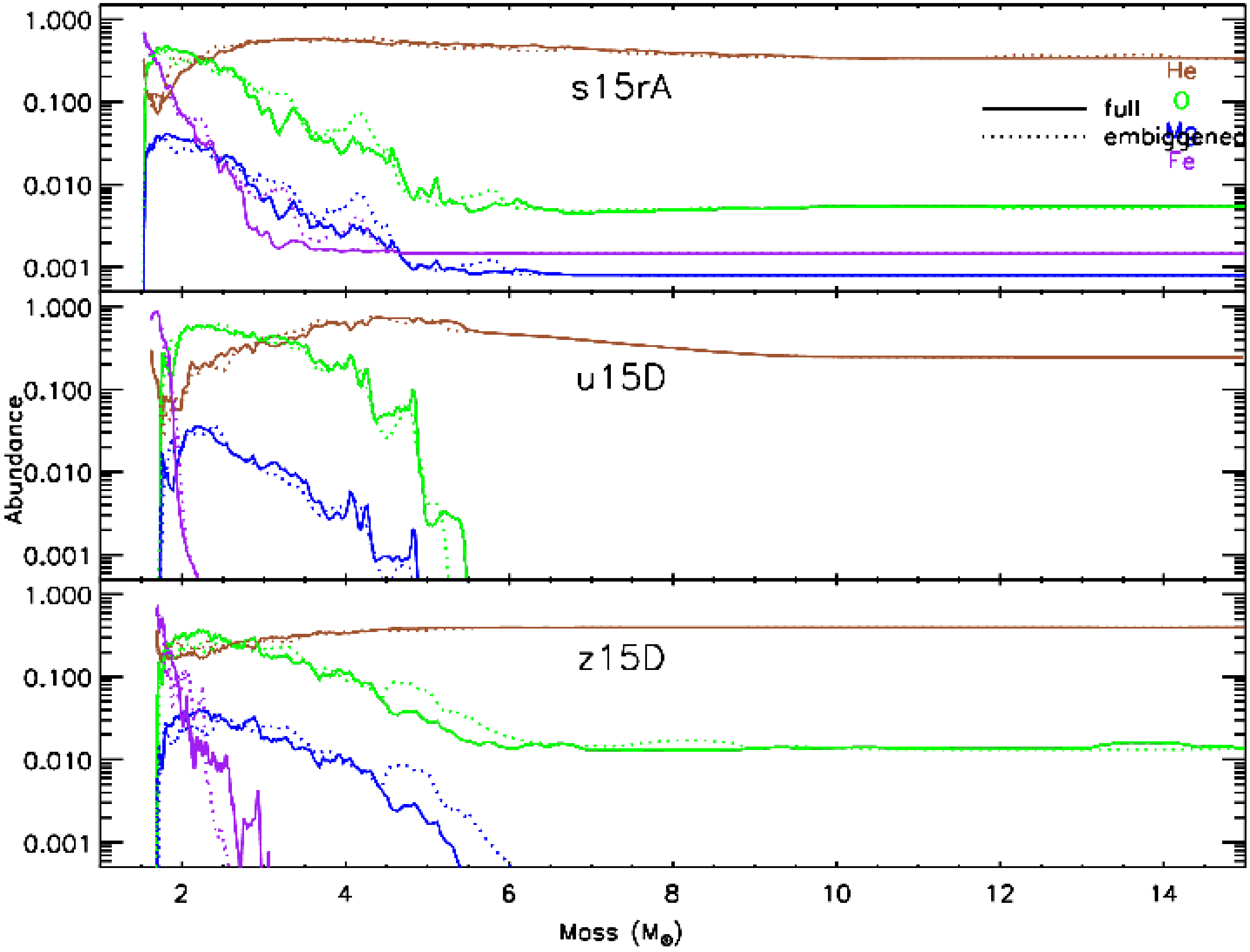
- CASTRO is a mature code that scales to 200k+ cores
- Abundance patterns in metal-poor stars in our halo are well fit by 15-25 solar mass models with explosion energies < 2.4 β
- many PISNe may exhibit very little mixing—since these are spherically symmetric explosions, this is a robust result (insofar as the initial models are correct)
- this may provide a way to distinguish between observations of PISNe and CC SNe in the early universe.
- if SN 2007bi was a PISN, the lack of mixing observed in the star confirms these simulations

additional material

future work

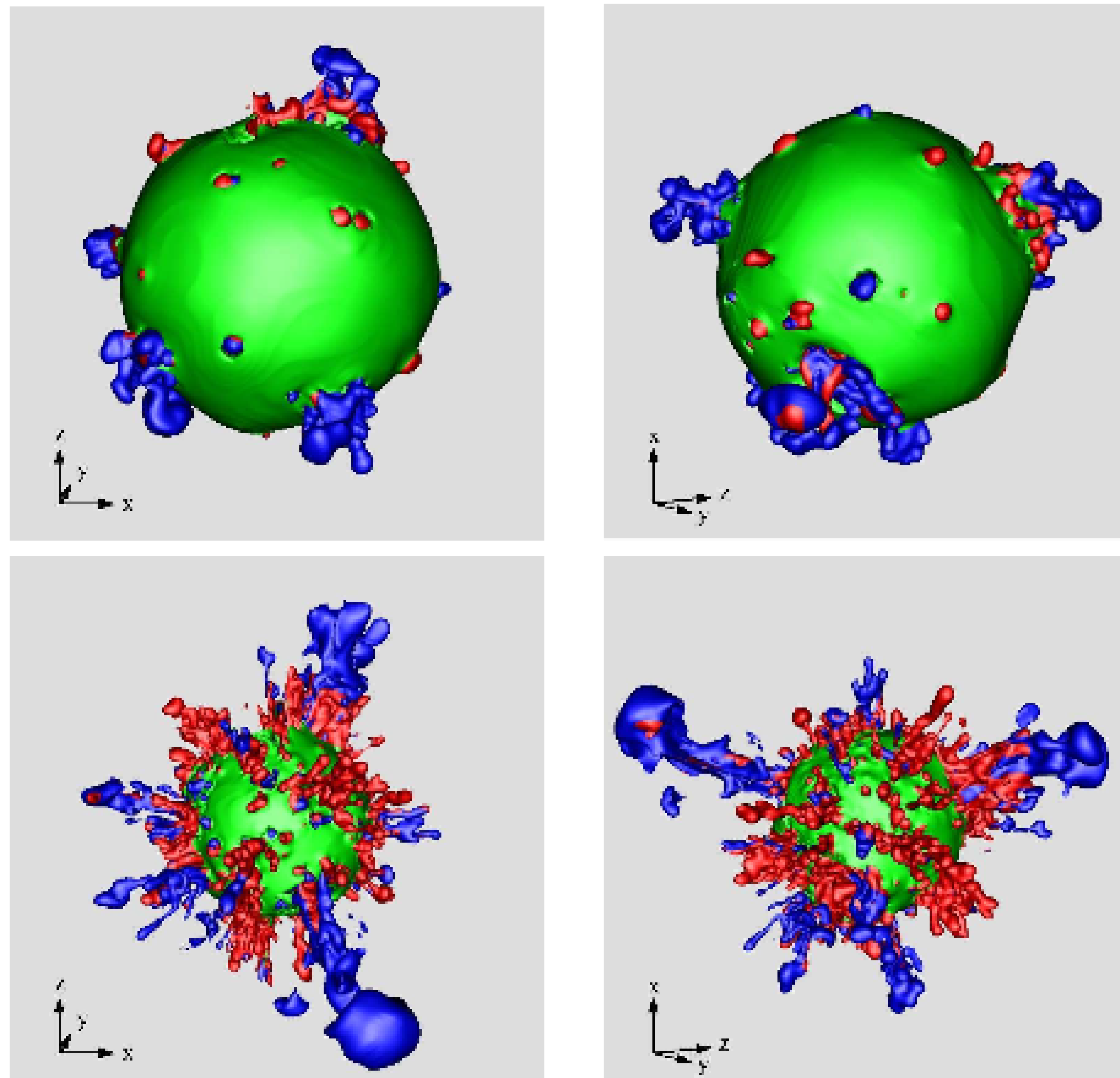
- solar or near-solar metallicity models should be investigated
- convection from nuclear burning before/during the explosion may have an impact on the post-explosion hydrodynamics—see work by Ke-Jung Chen

full vs enlarged simulations



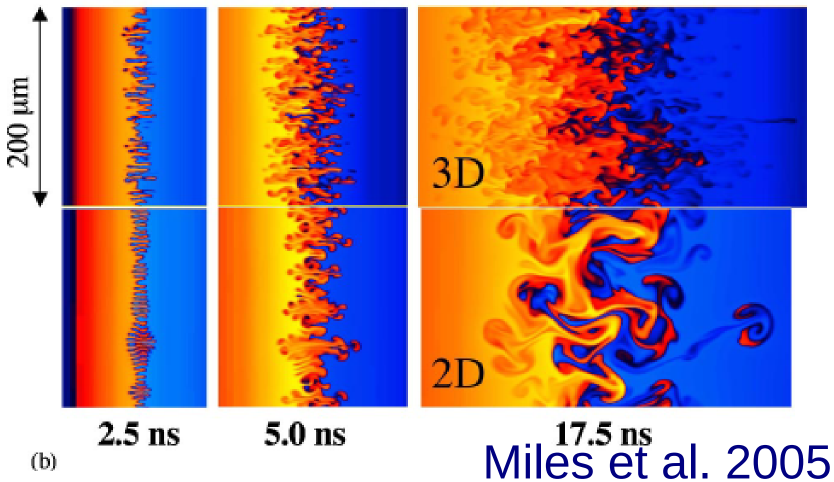
Mixing in an 87A progenitor

- Instabilities grew ~30% faster in 3D than in 2D
- This allowed bubbles of ^{56}Ni to penetrate the He layer
- Little interaction between instabilities



Hammer et al. 2010

why are 2D and 3D so similar?



Miles et al. 2005

large-scale structures do not form through inverse cascade!

- Artificial drag forces in 2D lead to slower growth rate in 2D than 3D initially
- At late times, mixed region height ≈$\alpha A g t^2$, where $A \equiv (\rho^2 - \rho^1)/(\rho^2 + \rho^1)$
- Mixing is more thorough in 3D than 2D, leading to lower A and thus a lower height in 3D relative to 2D