The Evolution and Explosion of Massive Stars

Cornell Physics Colloquium, February 25, 2002

see also *Reviews of Modern Physics*, S. E. Woosley, A. Heger, and T. A. Weaver, in press (2002)

http://www.supersci.org

Supernovae:

Make brilliant fireworks

Produce most of the heavy elements

Leave behind exotic neutron stars and black holes

Stir the interstellar and intergalactic media

(Massive) stars are gravitationally confined thermonuclear reactors.

For a star supported by ideal gas pressure, density scales as temperature cubed:

Hydrostatic equilibrium requires that

$$\frac{dP}{dr} = \frac{GM\rho}{r^2}$$

hence the central pressure

$$P \propto \frac{M\rho}{R}$$

but

$$R \propto (\frac{M}{\rho})^{1/3}$$

from which it follows

$$P \propto M^{2/3}\rho^{4/3}$$

and

$$\frac{P^3}{\rho^4} \propto M^2$$

and for an ideal gas with P $= N_A(\rho/\mu)kT$

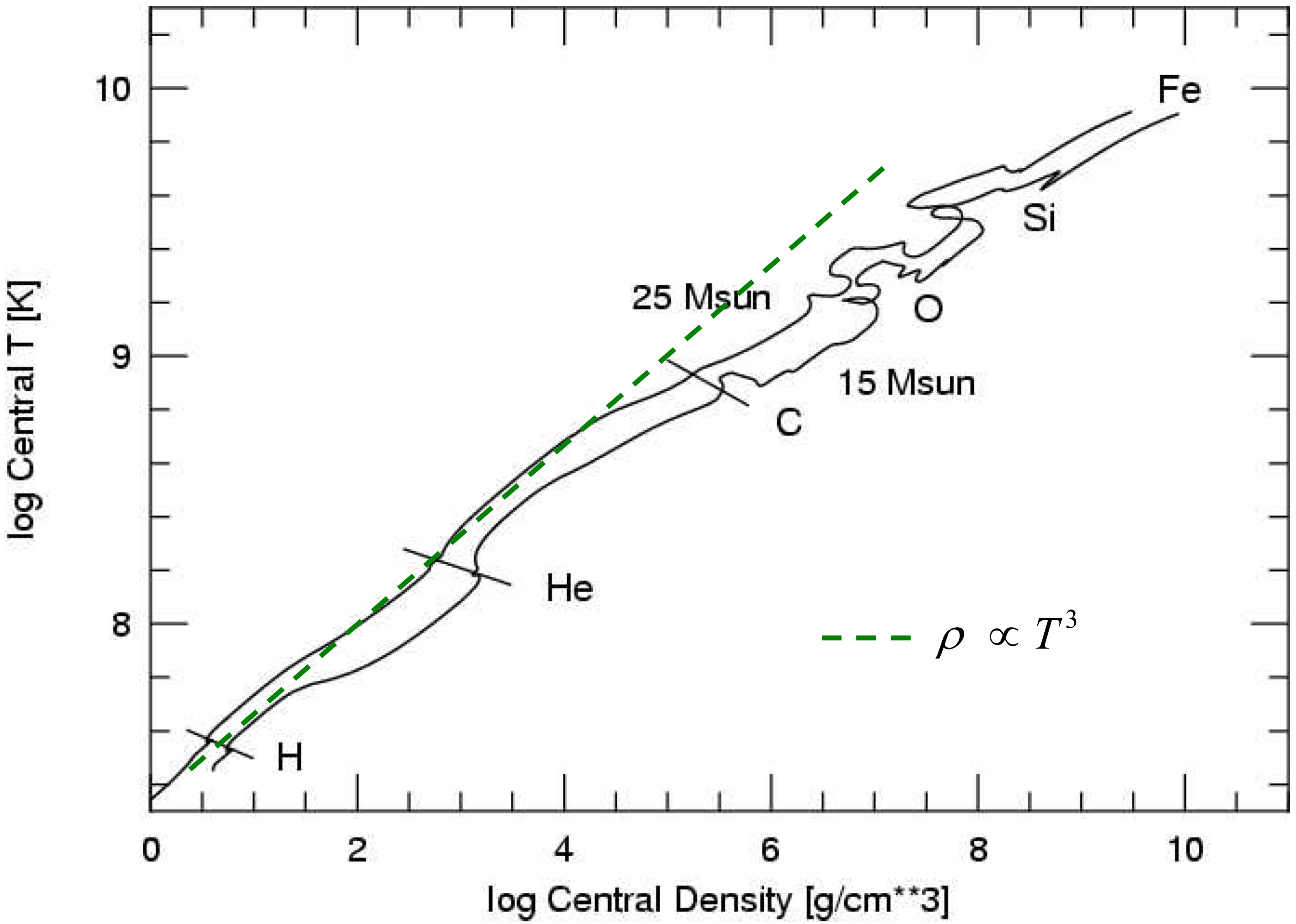
$$\frac{T^3}{\rho} \propto M^2$$

For a star of constant mass supported by ideal gas pressure, as contraction raises the density the temperature will also increase as the cube root of the density. For a given temperature, stars of lower mass will have higher density.

In fact, for stars lighter than about 8 solar masses
the central regions reach a density where the
star can be supported by the quantum mechanical
crowding of the electrons (degeneracy pressure),
before the ignition temperature of carbon (8×10^8 K)

Such stars, e.g., the sun, end their lives as white dwarf
stars after ejecting part of their outer layers as a
planetary nebula.

For more massive stars though...



Advanced Nuclear Burning Stages
(e.g., 20 solar masses)

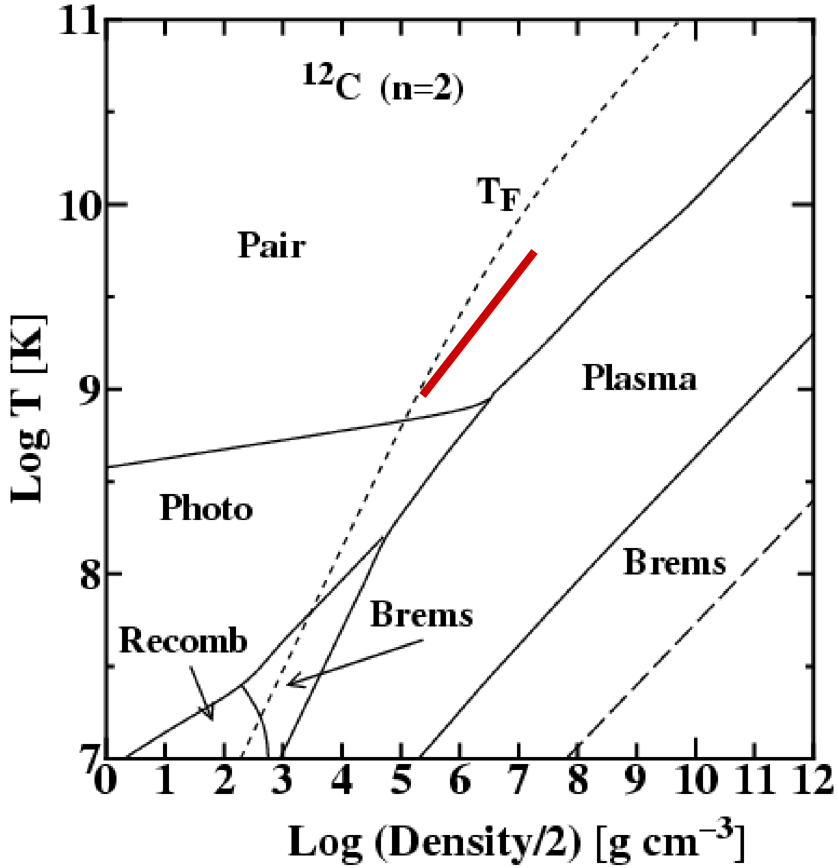
Fuel	Main Product	Secondary Products	Temp (10^9 K)	Time (yr)
H	He	^{14}N	0.02	10^7
He	C,O	^{18}O, ^{22}Ne s- process	0.2	10^6
C	Ne, Mg	Na	0.8	10^3
Ne	O, Mg	Al, P	1.5	3
O	Si, S	Cl, Ar K, Ca	2.0	0.8
Si	Fe	Ti, V, Cr Mn, Co, Ni	3.5	1 week

Neutrino Losses

The evolution of the interior of massive stars after helium burning (i.e., during carbon, neon, oxygen, and silicon burning) is governed by *pair neutrino losses.* These losses are highly sensitive to the temperature.

$$e^+ + e^- \rightarrow \nu + \bar{\nu}$$

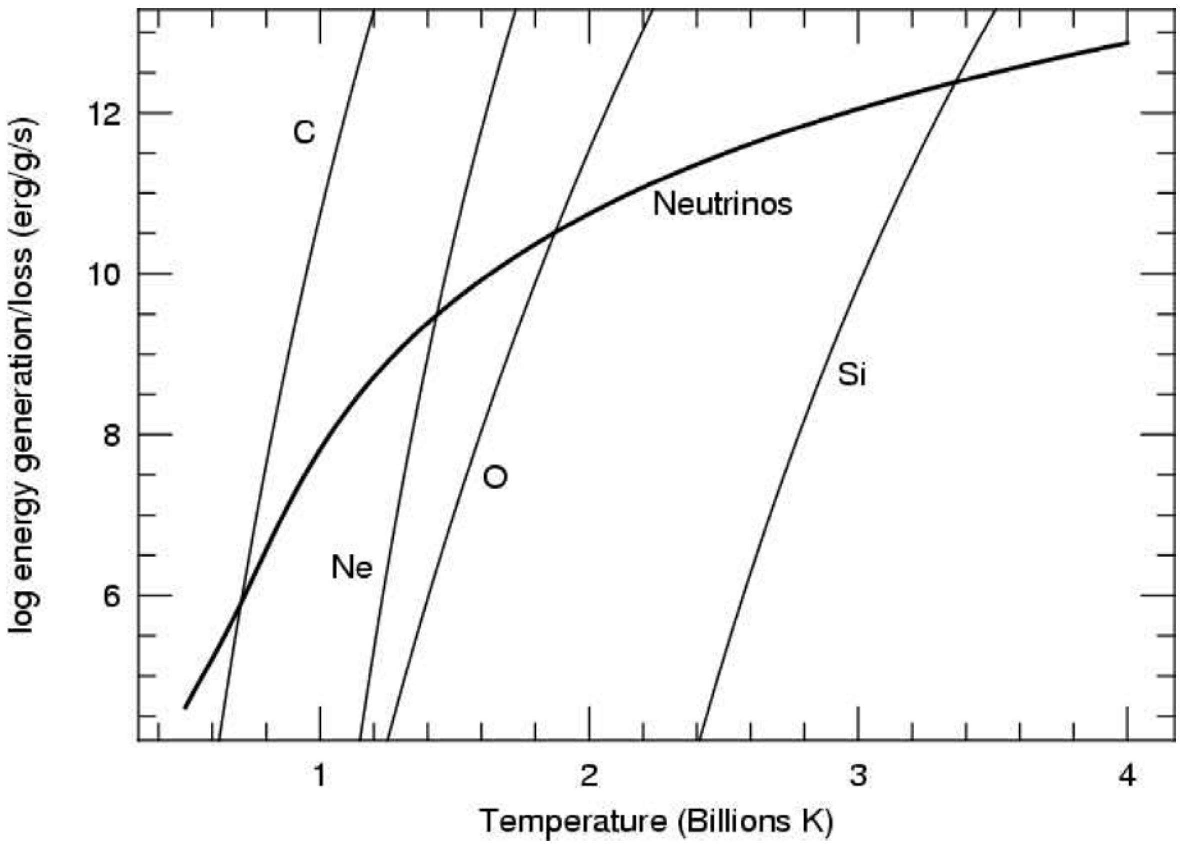
$$rate \propto T^9$$



Itoh et al 1996, *ApJS,* **102**, 411, see also
Beaudet, Petrosian, & Salpeter 1967, *ApJ*, **147**, 122

The advanced burning stages of massive stars occur
in a state of nearly balanced power with energy generation
from nuclear fusion balancing neutrino losses to pair annihilation

Assuming
$\rho \propto T^3$
since the
main sequence



Such a plot yields the correct burning temperature to good accuracy

Burning Stages in the Life of a Massive Star

hydrogen burning						
M_{initial}	T	ρ	M	L	R	τ
$M_\odot$	10^7 K	g cm^{-3}	$M_\odot$	$10^3\ L_\odot$	$R_\odot$	Myr
1	1.57	153	1.00	0.001	1.00	~1,100
15	3.53	5.81	14.9	28.0	6.75	11.1
20	3.69	4.53	19.7	62.6	8.03	8.13
25	3.81	3.81	24.5	110	9.17	6.70
75	4.26	1.99	67.3	916	21.3	3.16

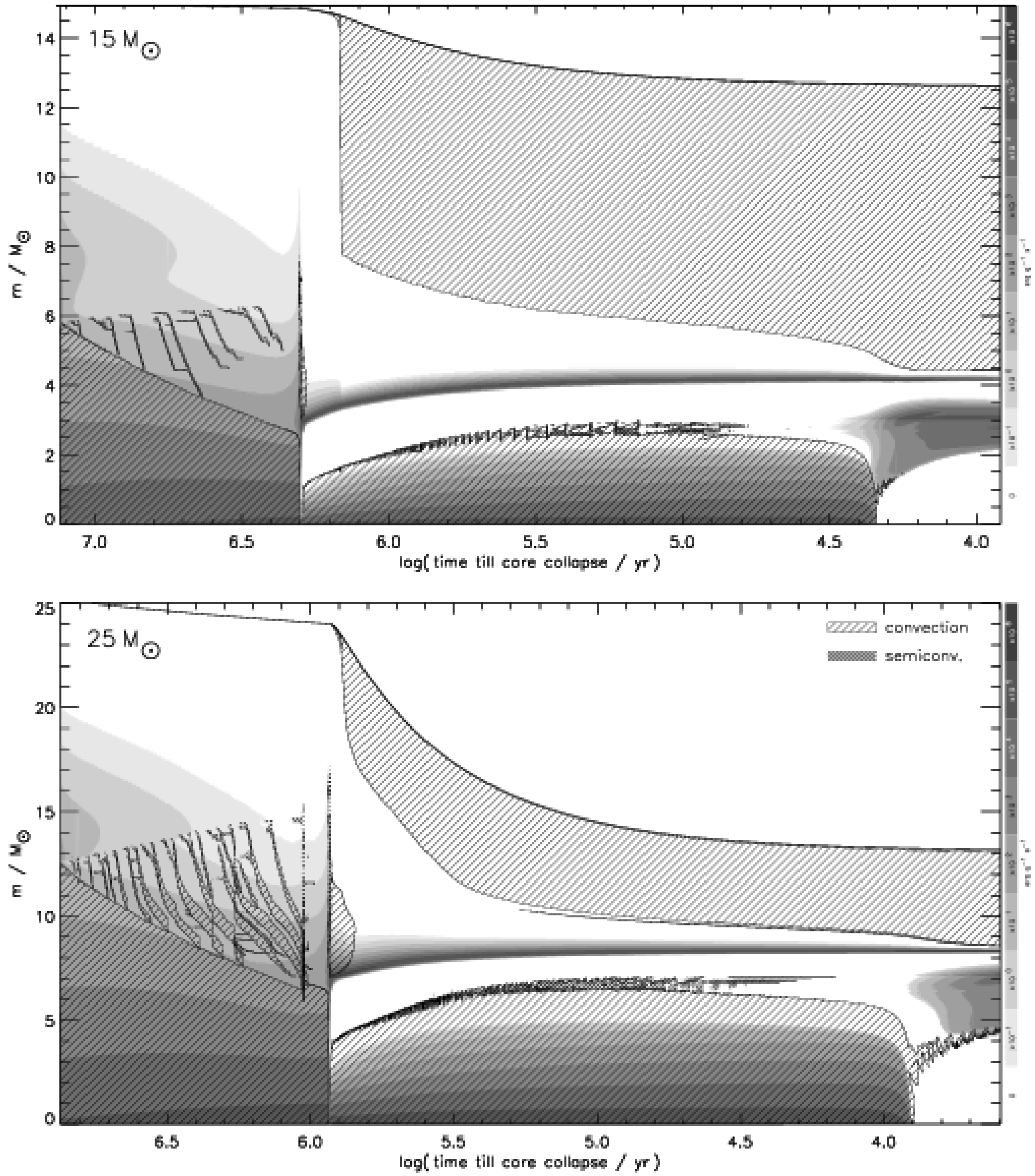
helium burning						
M_{initial}	T	ρ	M	L	R	τ
$M_\odot$	10^8 K	10^3 g cm^{-3}	$M_\odot$	$10^3\ L_\odot$	$R_\odot$	Myr
1	1.25	20	0.71	0.044	~ 100	110
15	1.78	1.39	14.3	41.3	461	1.97
20	1.88	0.968	18.6	102	649	1.17
25	1.96	0.762	19.6	182	1,030	0.839
75	2.10	0.490	16.1	384	1.17	0.478

carbon burning						
M_{initial}	T	ρ	M	L	R	τ
$M_\odot$	10^8 K	10^5 g cm^{-3}	$M_\odot$	$10^3\ L_\odot$	$R_\odot$	kyr
15	8.34	2.39	12.6	83.3	803	2.03
20	8.70	1.70	14.7	143	1,070	0.976
25	8.41	1.29	12.5	245	1,390	0.522
75	8.68	1.39	6.37	164	0.644	1.07

neon burning						
M_{initial}	T	ρ	M	L	R	τ
$M_\odot$	10^9 K	10^6 g cm^{-3}	$M_\odot$	$10^3\ L_\odot$	$R_\odot$	yr
15	1.63	7.24	12.6	86.5	821	0.732
20	1.57	3.10	14.7	147	1,090	0.599
25	1.57	3.95	12.5	246	1,400	0.891
75	1.62	5.21	6.36	167	0.715	0.569

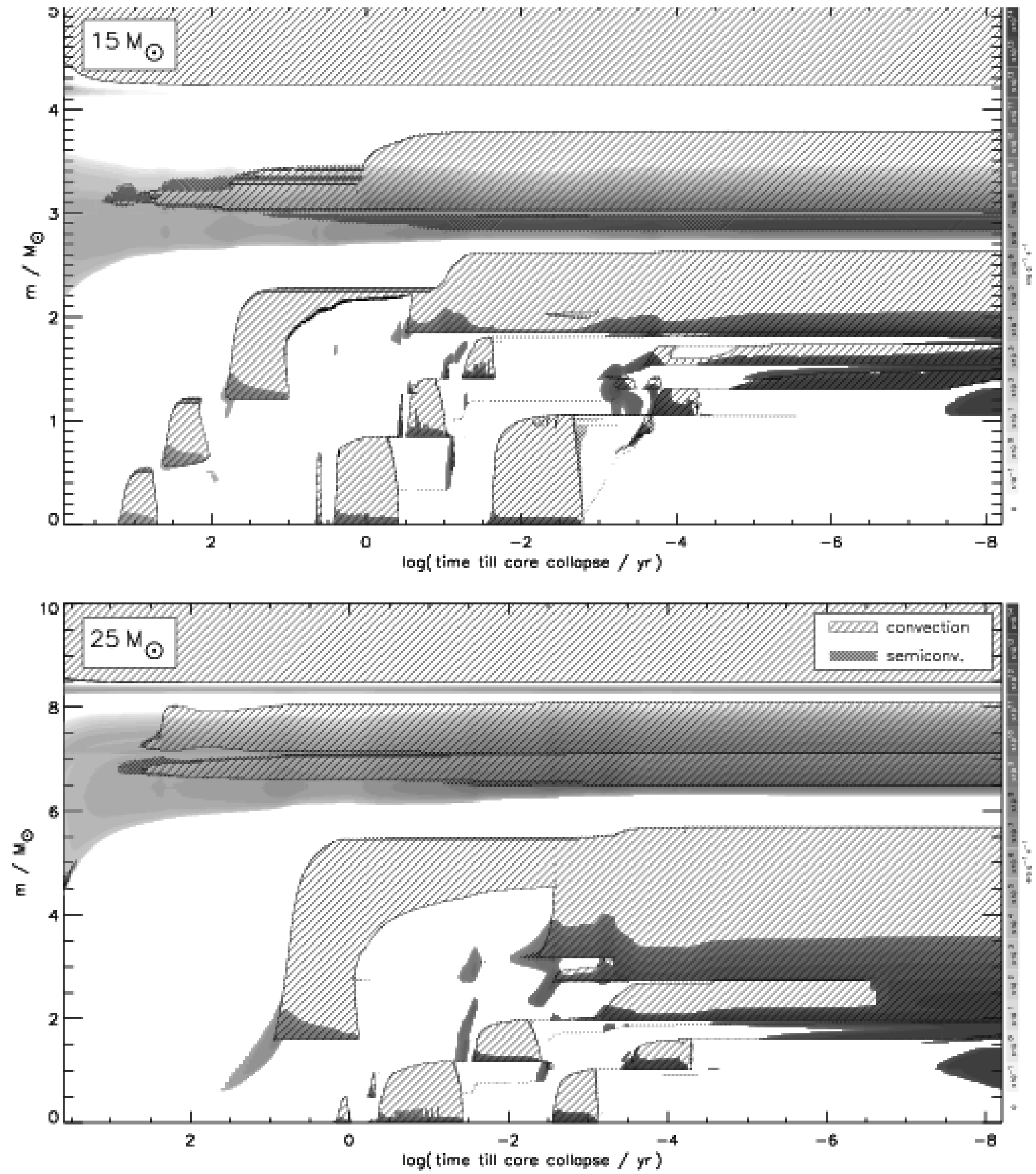
oxygen burning						
M_{initial}	T	ρ	M	L	R	τ
$M_\odot$	10^9 K	10^6 g cm^{-3}	$M_\odot$	$10^3\ L_\odot$	$R_\odot$	yr
15	1.94	6.66	12.6	86.6	821	2.58
20	1.98	5.55	14.7	147	1,090	1.25
25	2.09	3.60	12.5	246	1,400	0.402
75	2.04	4.70	6.36	172	0.756	0.908

silicon burning						
M_{initial}	T	ρ	M	L	R	τ
$M_\odot$	10^9 K	10^7 g cm^{-3}	$M_\odot$	$10^3\ L_\odot$	$R_\odot$	d
15	3.34	4.26	12.6	86.5	821	18.3
20	3.34	4.26	14.7	147	1,090	11.5
25	3.65	3.01	12.5	246	1,400	0.733
75	3.55	3.73	6.36	173	0.755	2.09



The three greatest uncertainties in modeling the presupernova evolution of massive stars are:

- Convection and convective boundaries
- Rotation
- Mass loss (especially the metallicity dependence)



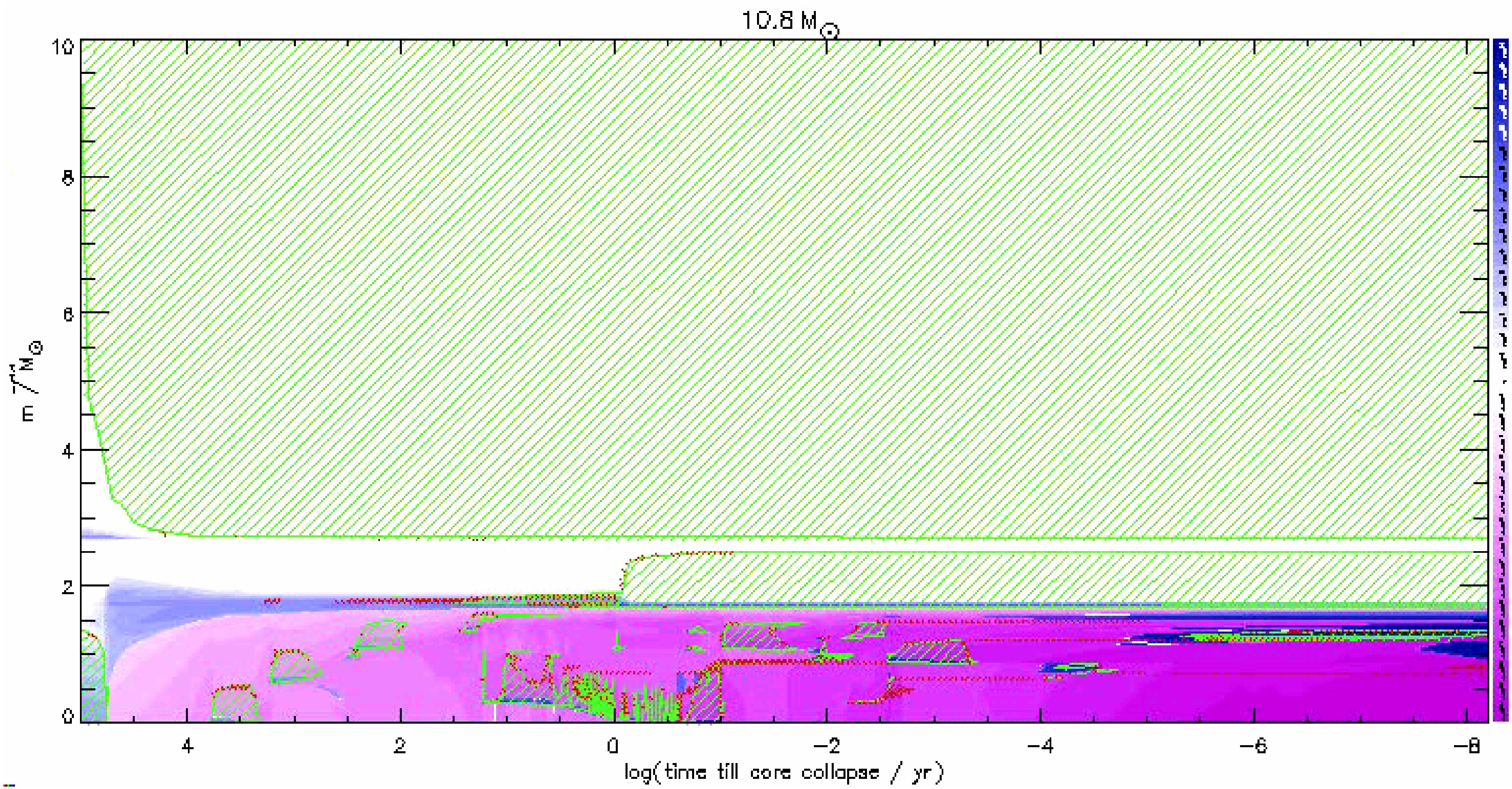
The advanced burning stages are characterized by multiple phases of core and shell burning. The nature and number of such phases varies with the mass of the star.

Each shell burning episode affects the distribution of entropy inside the helium core and the final state of the star (e.g., iron core mass) can be non-monotonic and, to some extent, chaotic.

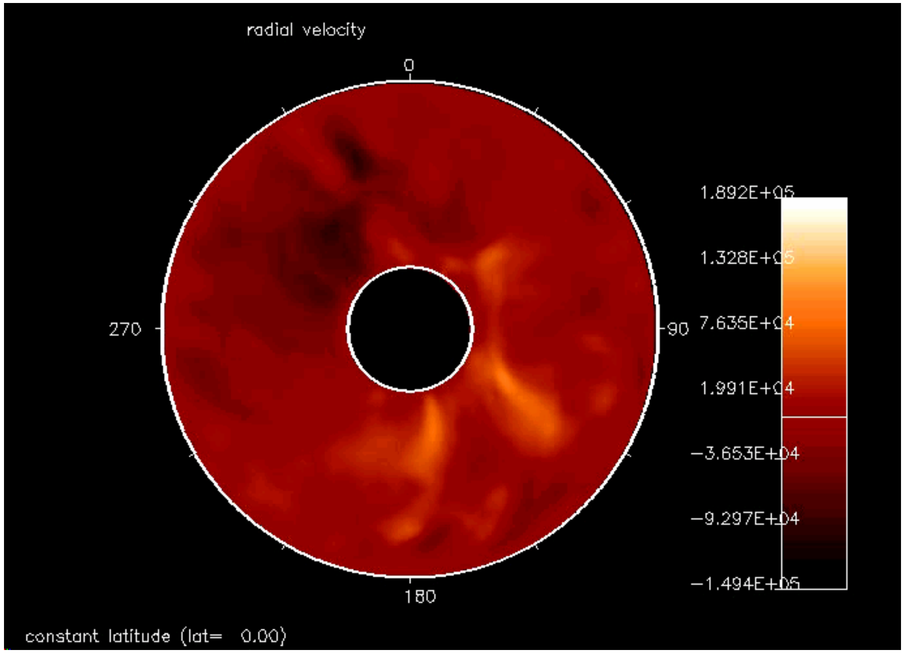
Neutrino losses are higher and the central carbon abundance lower in stars of higher mass.

This movies shows the variation of the convective structure post-helium burning as the mass of the main sequence star is varied.

For this choice of $^{12}C(a,g)^{16}O$ rate, carbon ceases to generate sufficient heat to cause central convection in stars above about 20 solar masses.

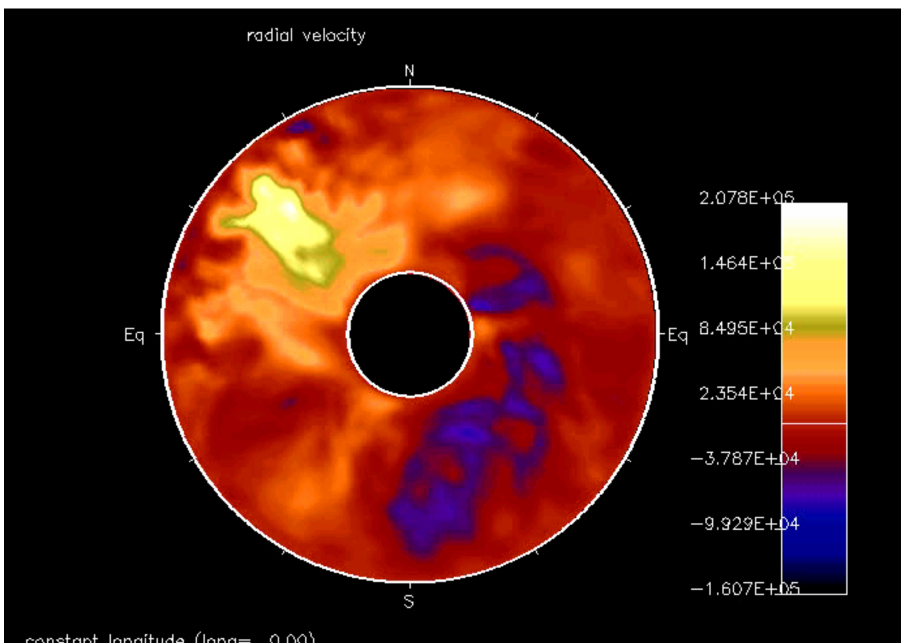


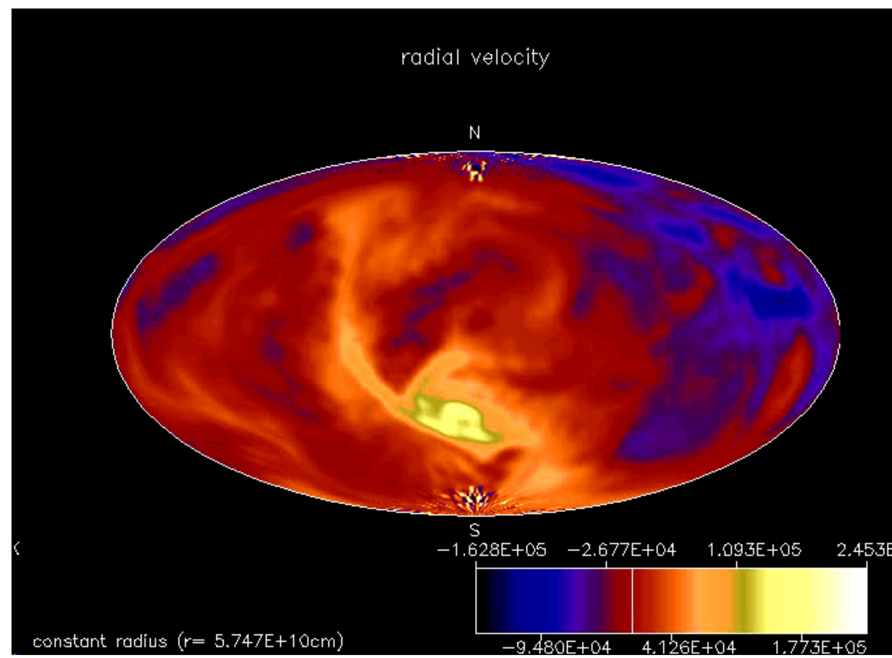
convective and nuclear time scales comparable beyond here



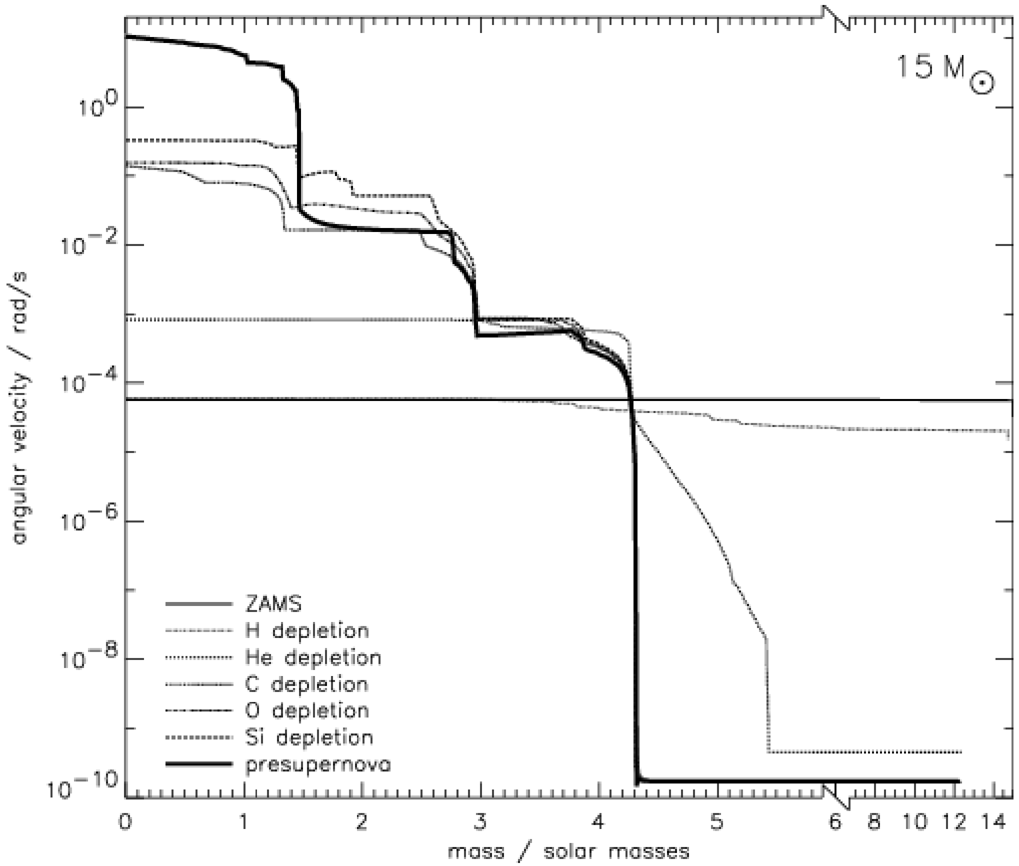
Kuhlen, Woosley, and Glatzmaier are exploring the physics of stellar convection using 3D anelastic hydrodynamics.

The model shown is a 15 solar mass star half way through hydrogen burning. For now the models are not rotating, but the code includes rotation and B-fields. (Previously used to simulate the Earth's dynamo).





Evolution Including Rotation



Numerical Method

1D implicit hydrodynamic stellar evolution code

\+ centrifugal forces
(Kippenhahn & Thomas 1970, Endal & Sophia 1976)

\+ Lagrange coordinate → equipotential surfaces

\+ angular momentum as local variable

mixing in diffusion approximation

$$\frac{\partial x_i}{\partial t} = \frac{\partial}{\partial m}\left[\left(4\pi r^2\rho\right)^2 D\frac{\partial x_i}{\partial m}\right] + \dot{x}_{i,\mathrm{nuc}}$$

$$\frac{\partial \omega}{\partial t} = \frac{1}{i}\frac{\partial}{\partial m}\left[\left(4\pi r^2\rho\right)^2 i\nu\frac{\partial \omega}{\partial m}\right] - 2\omega\frac{\dot{r}}{r}\underbrace{\left(\frac{1}{2}\frac{\mathrm{d}\ln i}{\mathrm{d}\ln r}\right)}_{\approx 1}$$

diffusion coefficient accounts for

- \+ convection
- \+ semiconvection
- \+ dynamical shear
- \+ secular shear
- \+ Goldreich-Schubert-Fricke instability
- \+ Eddington-Sweet circulation
- \+ Solberg-Høiland instability

(Endal & Sophia 1978,
Pinsonneault, Kawaler, Sophia, Demarque 1989)

Heger, Langer, and Woosley (2000), *ApJ*, **528**, 368

First Results from Rotating Stars Including Magnetic Fields

This study is based on a description of the action of magnetic fields in the stellar interior by Henk Spruit (March 2001, priv. com.)

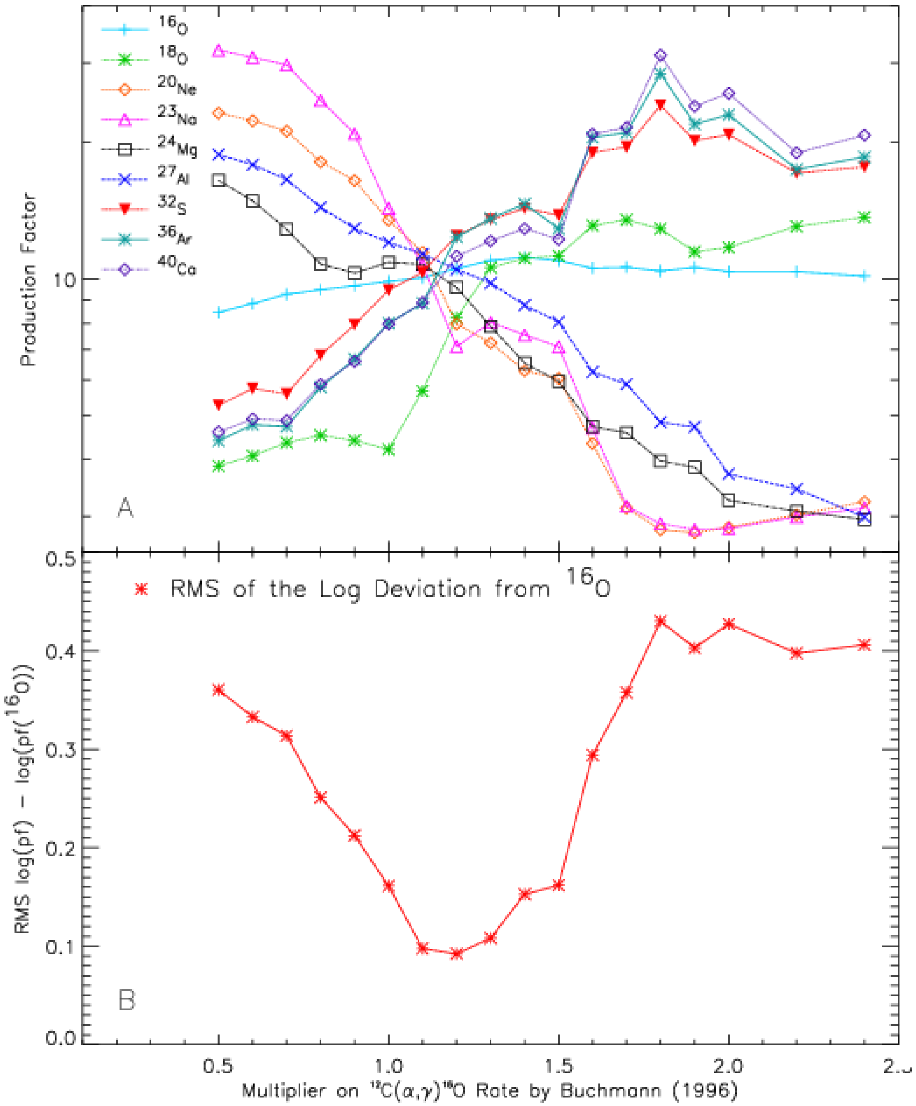
note models "b" (with B-fields) and "e" (without)

model	mass $M_\odot$	J erg s	P ms	M_{Y_e} $M_\odot$	J_{Y_e} erg s
m15b	15	1.093×10^{48}	7.65	1.373	9.148×10^{47}
m15c	15	1.185×10^{48}	7.05	1.311	8.131×10^{47}
m15e	15	3.989×10^{49}	0.21	1.328	3.199×10^{49}
m20b	20	1.519×10^{48}	5.50	1.640	1.580×10^{48}
m20c	20	1.569×10^{48}	5.32	1.560	1.474×10^{48}
m20e	20	4.061×10^{49}	0.21	1.600	4.007×10^{49}
m25a	25	2.175×10^{48}	3.84	1.831	2.664×10^{48}
m25b	25	2.097×10^{48}	3.99	1.745	2.441×10^{48}
m25c	25	2.947×10^{48}	2.84	1.449	2.351×10^{48}
m25d	25	1.204×10^{48}	6.94	1.730	1.370×10^{48}
m25e	25	4.137×10^{49}	0.20	1.815	4.875×10^{49}

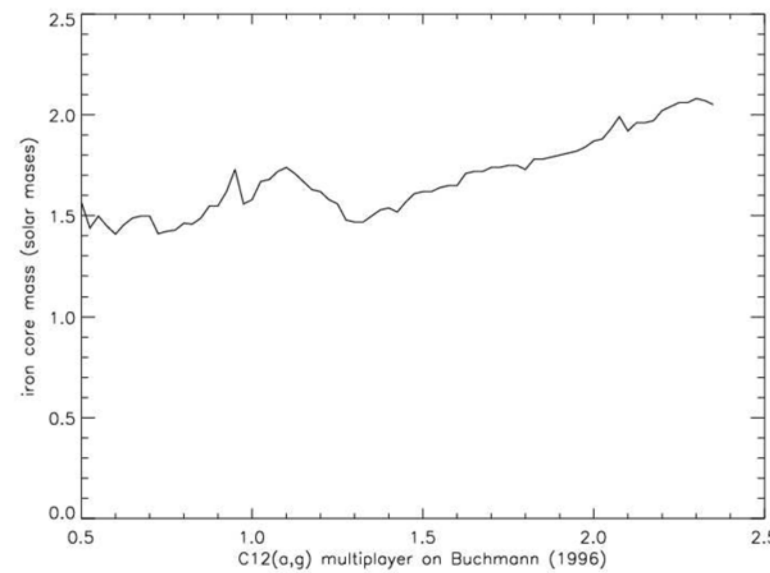
Heger, Woosley, & Spruit, in prep. for *ApJ*

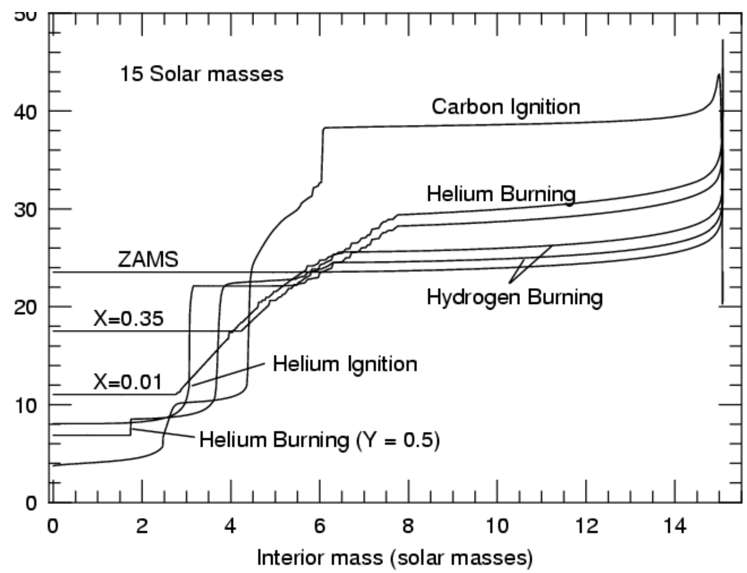
Spruit, (2001), *A&A*, **381**, 923

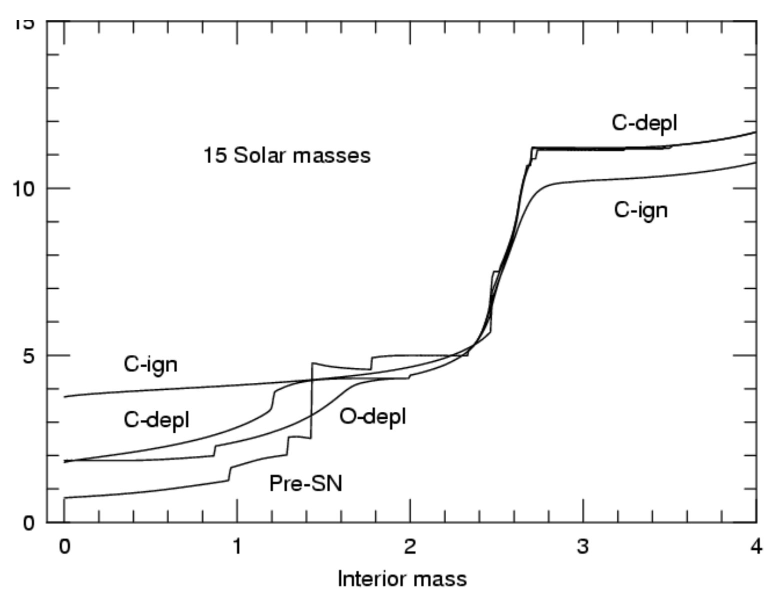
$^{12}C(\alpha,\gamma)^{16}O$



Uncertainties in key reaction rates affect not only the nucleosynthesis but the explosion itself







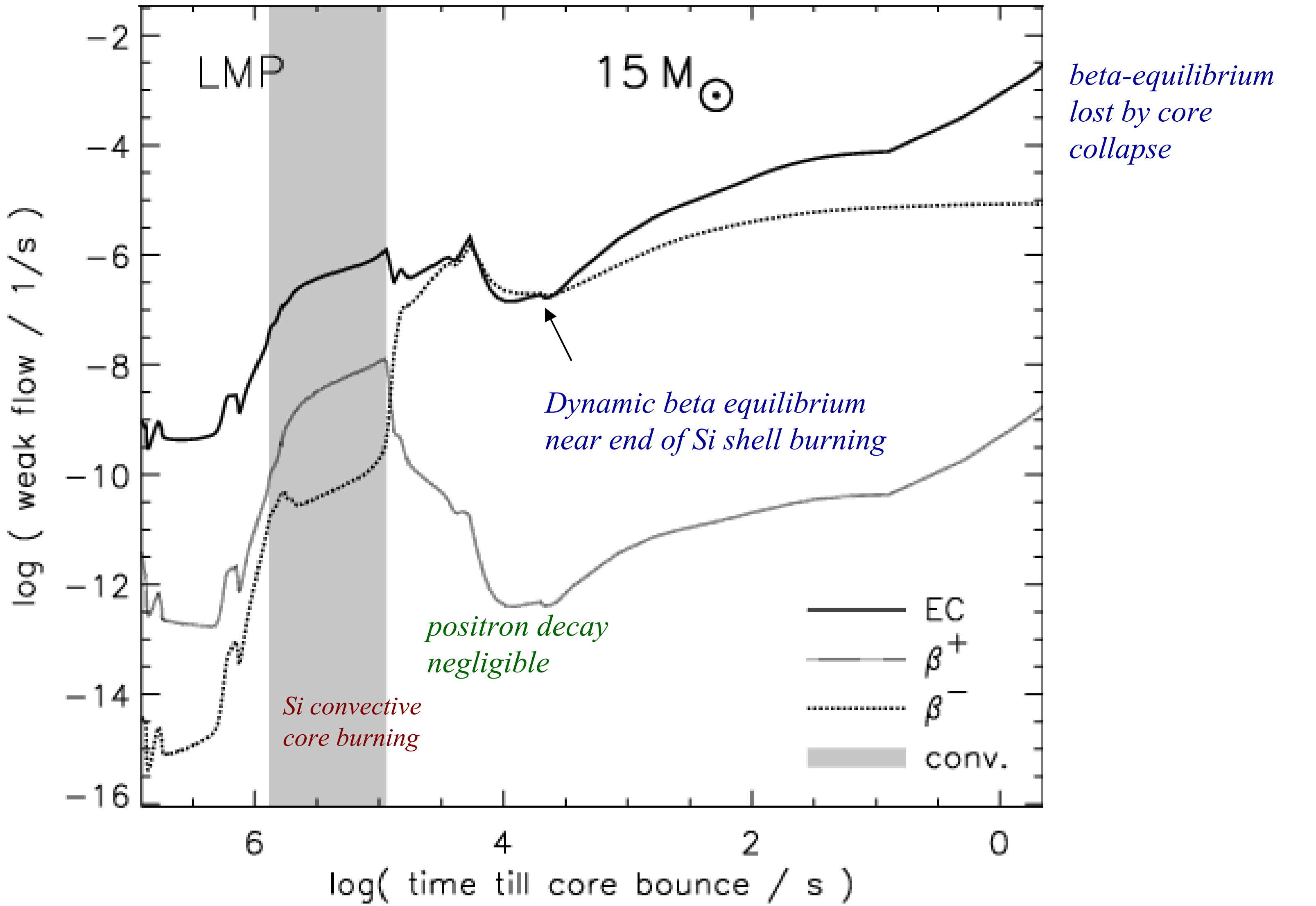
With each progressive burning stage the central entropy decreases. Red giant formation leads to an increased entropy in the outer hydrogen envelope.

The decrease in central entropy is accompanied by an *increase* in degeneracy so that in its later (post-carbon) burning stages the idea of a Chandrasekhar Mass has some meaning.

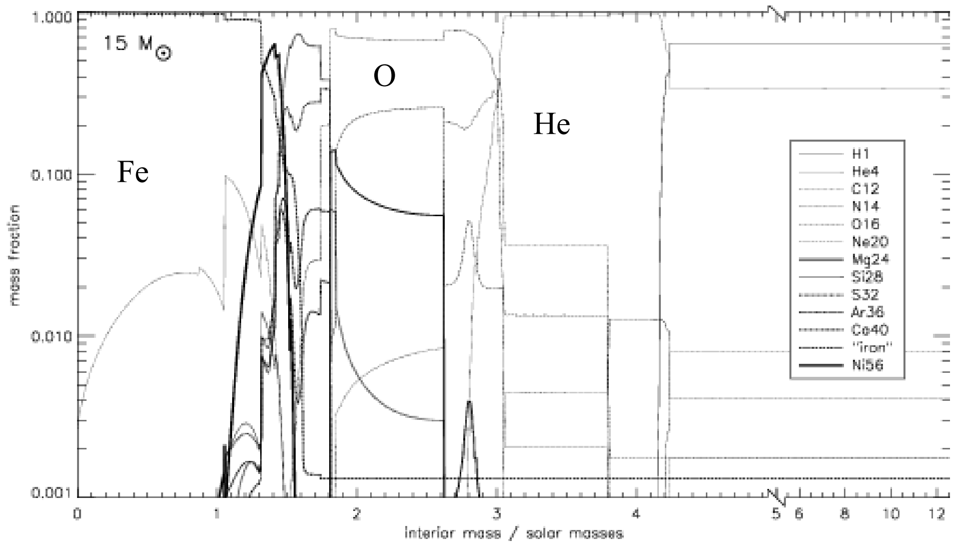
Ultimately the iron core that forms is not too dissimilar to the Chandrasekhar Mass but with corrections for:

a) composition
b) thermal content
c) Coulomb effects
d) finite boundary pressure

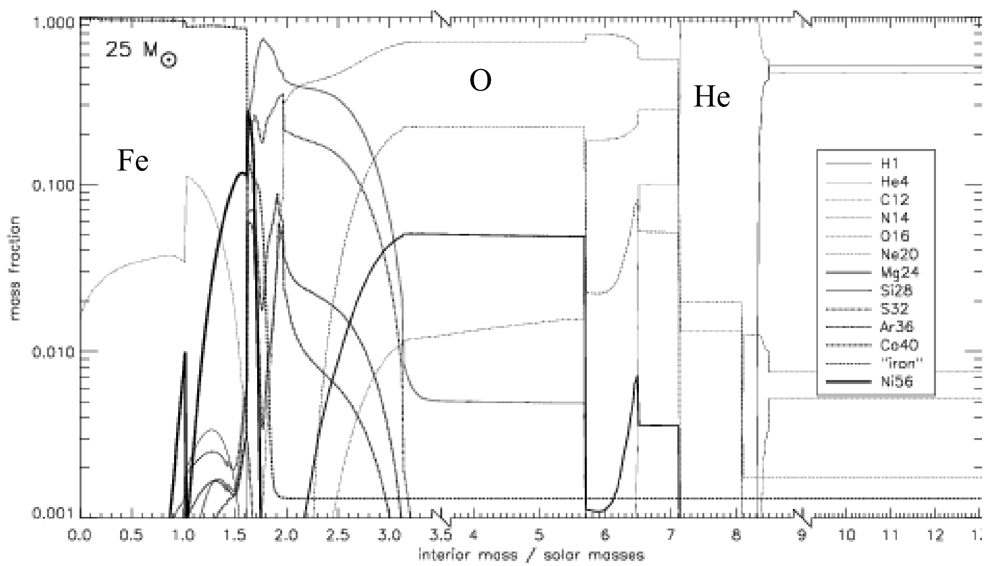
Weak interactions are important:



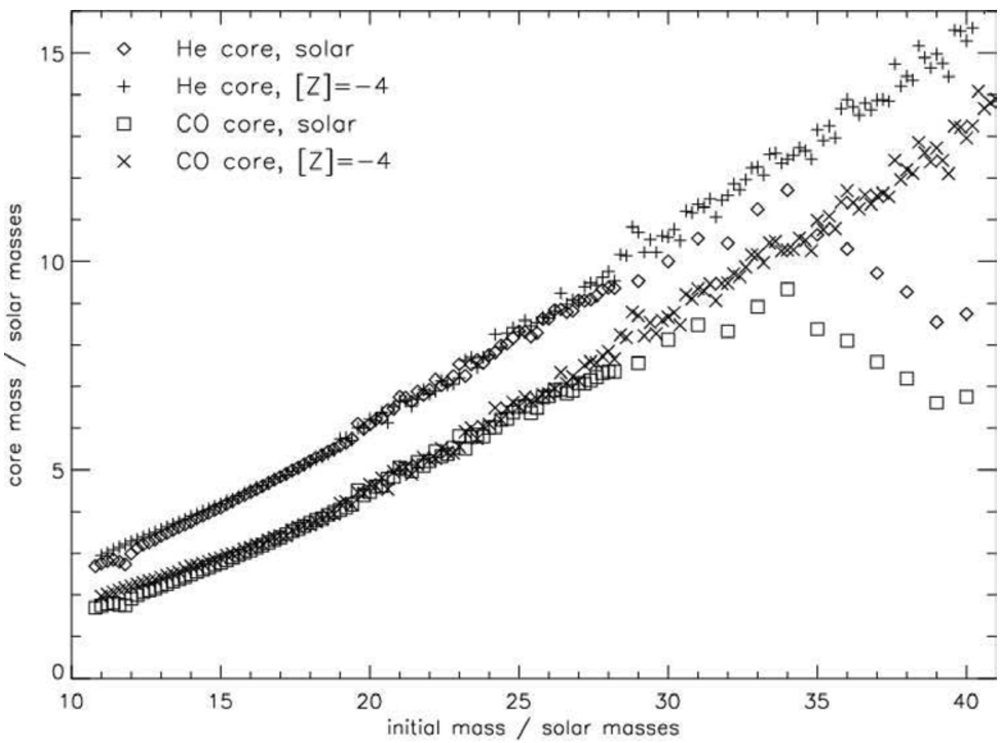
Presupernova composition structure



Stars of higher mass have larger helium cores and thicker shells of heavy elements outside an iron core of relatively constant mass.



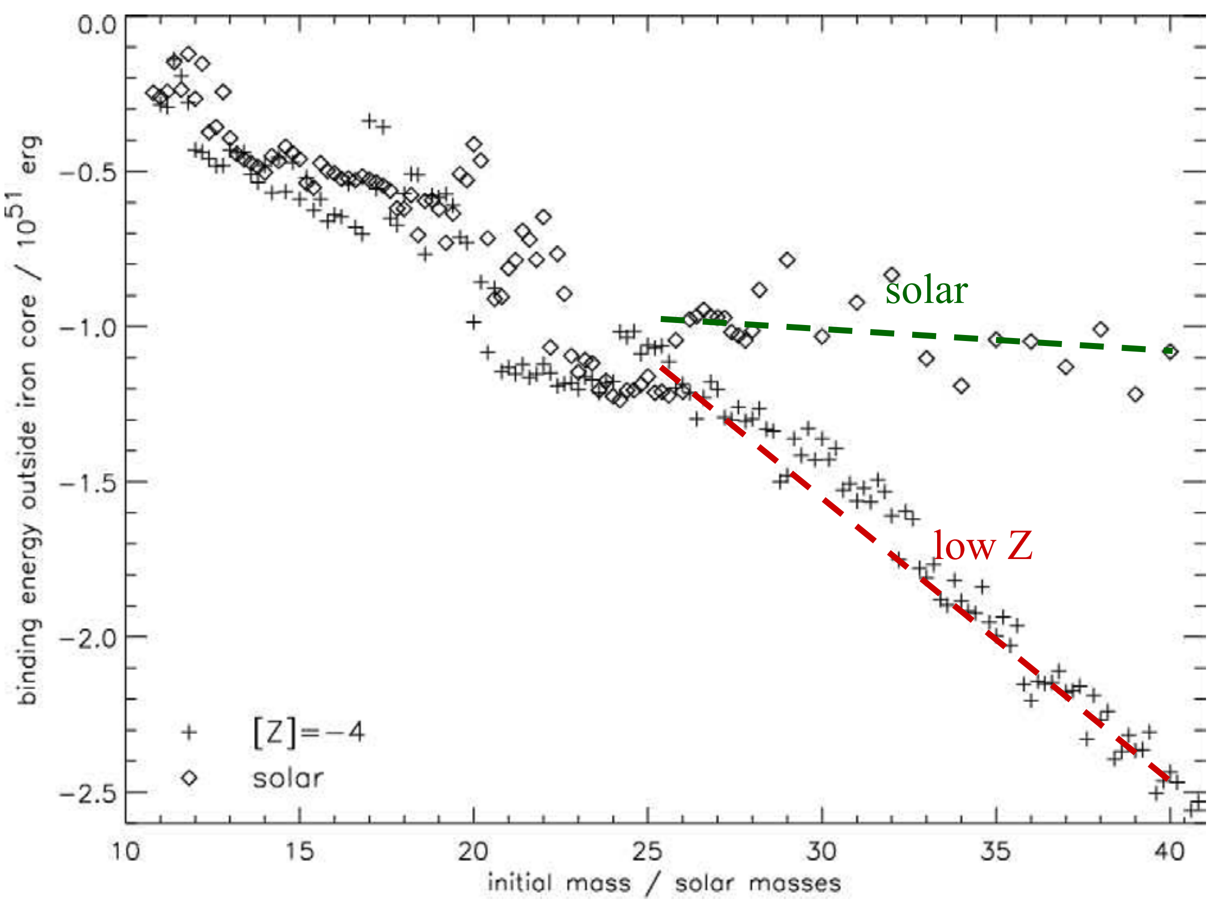
Note that due to mass loss the 15 and 25 solar mass main sequence stars have almost the same mass whne they die.



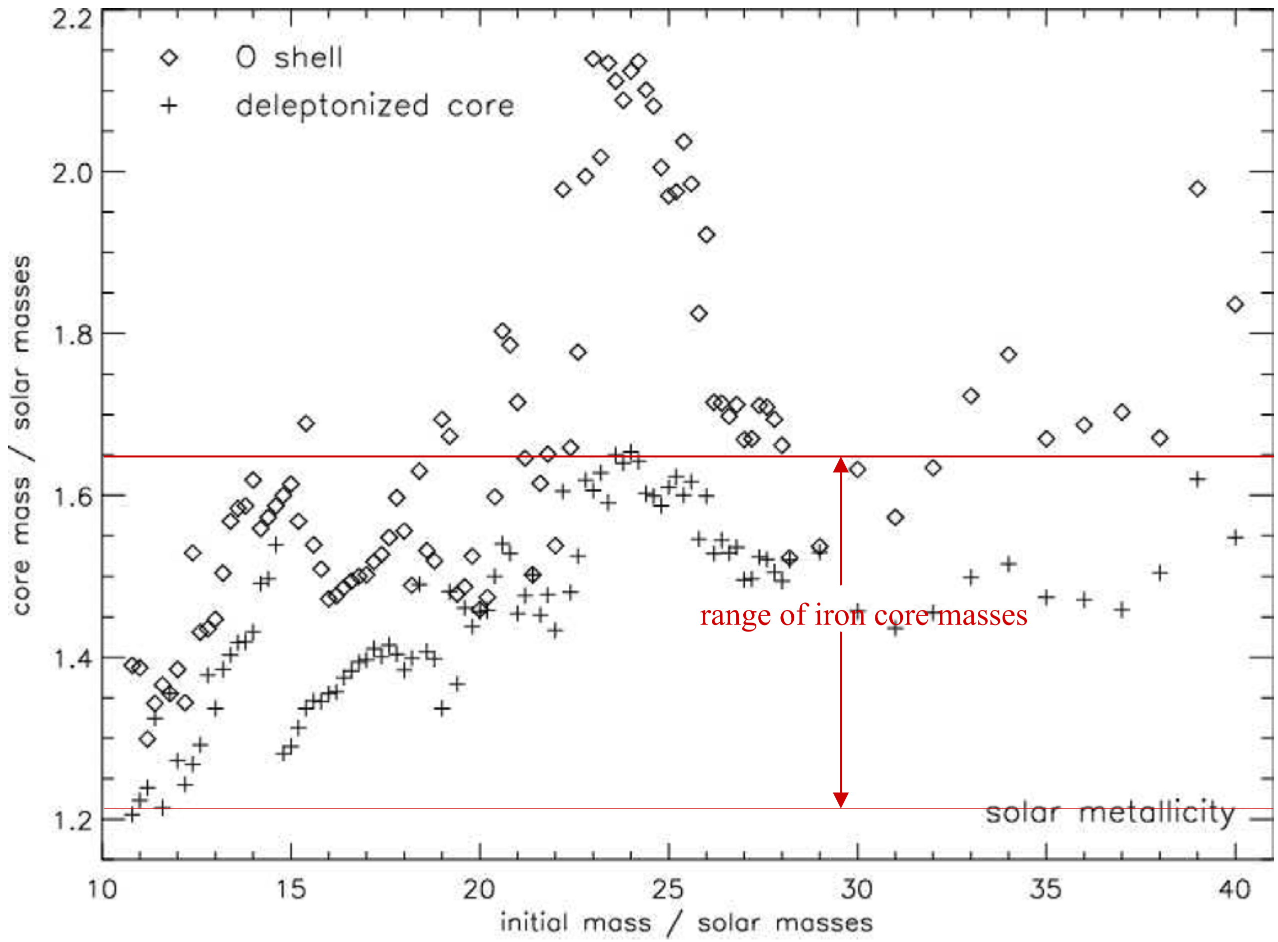
The helium core is that part of the star that has burned up all its hydrogen when the star finally dies. The CO core is the part that has burned up all the helium.

Low metallicity stars can have larger helium and CO cores when they die because the mass loss is reduced. The maximum helium core mass for a single star of solar metallicity is about 12 solar masses.

Gravitational Binding Energy of the Presupernova Star



This is just the binding energy outside the iron core. Bigger stars are more tightly bound and will be harder to explode. The effect is more pronounced in metal-deficient stars.



The iron core mass is a (nucleosynthetic) lower limit to the baryonic mass of the neutron star. A large entropy jump characterizes the base of the oxygen shell and may provide a natural location for the mass cut. Naively the baryonic mass of the remnant may be between these two – but this is very crude and ignores fall back. Above some remnant mass (1,7? 2.2?) a black hole will result. For the most abundant supernovae (10 to 20 solar masses) the range of iron core masses is1.2 to 1.55 solar masses. For the oxygen shell it is 1.3 to 1.7. From these numbers subtract about 15% for neutrino losses. Across all masses the iron core varies only from 1.2 to 1.65 solar masses.

Thorsett and Chakrabarty, (1999), *ApJ*, **512**, 288

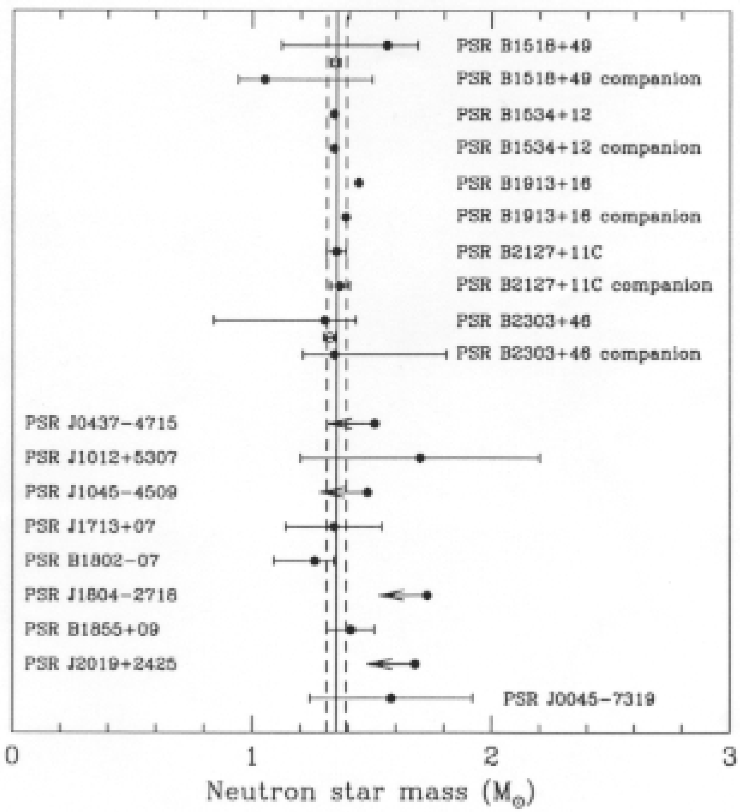


FIG. 5.—Neutron star masses from observations of radio pulsar systems. All error bars indicate central 68% confidence limits, except upper limits are one-sided 95% confidence limits. Five double neutron star systems are shown at the top of the diagram. In two cases, the average neutron star mass in a system is known with much better accuracy than the individual masses; these average masses are indicated with open circles. Eight neutron star–white dwarf binaries are shown in the center of the diagram, and one neutron star–main-sequence star binary is shown at bottom. Vertical lines are drawn at $m = 1.35 \pm 0.04\ M_\odot$.

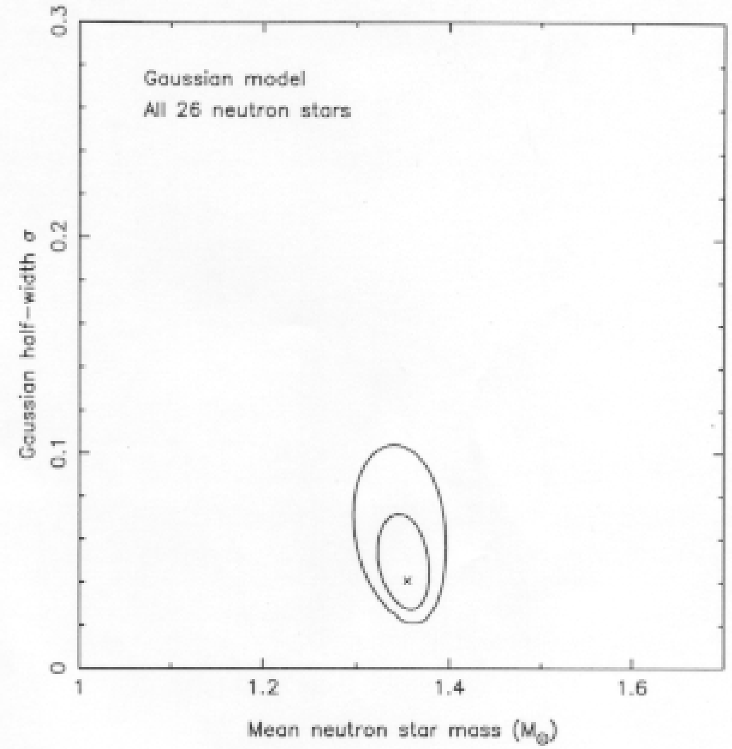
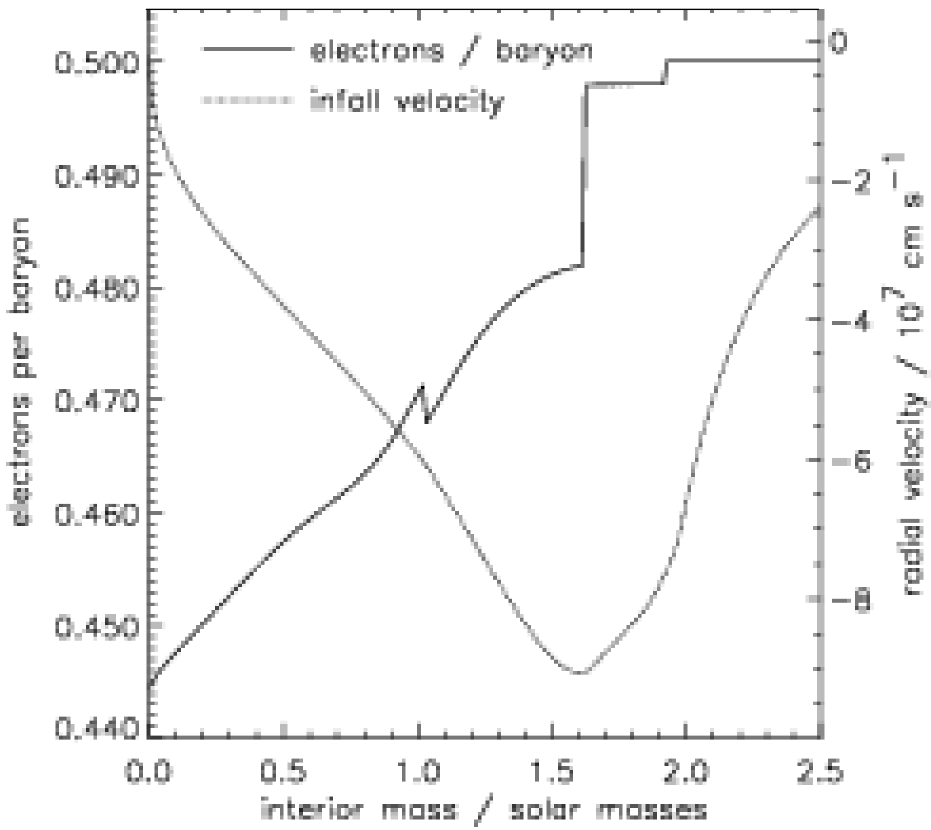


FIG. 2.—Maximum likelihood estimate of the mean and standard deviation, $\hat{m}$ and σ, of a Gaussian neutron star mass distribution. The maximum likelihood solution is marked with a cross, and contours indicate 68% and 95% confidence regions.

Observations indicate a narrow range of gravitational masses of 1.3 – 1.4 solar masses.

Effects of binary membership?
Maximum neutron star mass (Bethe-Brown)?
Small number statistics?



Owing to a combination of neutrino losses, electron capture, and photodisintegration, the iron core collapses.

(note by the way the low value of Y_e and its large variation; the zero entropy Chandrasekhar Mass would be far less than 1.4 solar masses. The agreement of average neutron star masses with this value is a coincidence.)

Baade and Zwicky, *Proceedings of the National Academy of Sciences,* (1934)

"With all reserve we advance the view that a supernova represents the transition of an ordinary star into a neutron star consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed much more closely than ordinary nuclei and electrons, the gravitational packing energy in a cold neutron star may become very large, and under certain conditions, may far exceed the ordinary nuclear packing fractions ..."

The explosion is mediated by neutrino energy transport ....

THE HYDRODYNAMIC BEHAVIOR OF SUPERNOVAE EXPLOSIONS*

STIRLING A. COLGATE AND RICHARD H. WHITE
Lawrence Radiation Laboratory, University of California, Livermore, California
Received June 29, 1965

ABSTRACT

We regard the release of gravitational energy attending a dynamic change in configuration to be the primary energy source in supernovae explosions. Although we were initially inspired by and agree in detail with the mechanism for initiating gravitational instability proposed by Burbidge, Burbidge, Fowler, and Hoyle, we find that the dynamical implosion is so violent that an energy many times greater than the available thermonuclear energy is released from the star's core and transferred to the star's mantle in a supernova explosion. The energy released corresponds to the change in gravitational potential of the unstable imploding core; the transfer of energy takes place by the emission and deposition of neutrinos.

Colgate and White, (1966), *ApJ*, **143,** 626

see also

Arnett, (1966), *Canadian J Phys*, **44,** 2553

Wilson, (1971), *ApJ*, **163**, 209

But there were fundamental problems in the 1960's and early 1970's that precluded a physically complete description

- Lack of realistic progenitor models
- Neglect of weak neutral currents
- Uncertainty in the equation of state at super-nuclear densities
- Inability to do multi-dimensional models

1.C

Nuclear Physics **A324** (1979) 487–533 © *North-Holland Publishing Co., Amsterdam*

EQUATION OF STATE IN THE GRAVITATIONAL COLLAPSE OF STARS

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Received 12 February 1979

Abstract: The equation of state in stellar collapse is derived from simple considerations, the crucial ingredient being that the entropy per nucleon remains small, of the order of unity (in units of k), during the entire collapse. In the early regime, $\rho \sim 10^{10}$–10^{13} g/cm^3, nuclei partially dissolve into α-particles and neutrons; the α-particles go back into the nuclei at higher densities. At the higher densities, nuclei are preserved right up to nuclear matter densities, at which point the nucleons are squeezed out of the nuclei. The low entropy per nucleon prevents the appearance of drip nucleons, which would add greatly to the net entropy.

We find that electrons are captured by nuclei, the capture on free protons being negligible in

BBAL 1979

- The explosion was low entropy
- Heat capacity of excited states kept temperature low
- Collapse continues to nuclear density and beyond
- Bounce on the nuclear repulsive force
- Possible strong hydrodynamic explosion
- Entropy an important concept

Type-II Supernovae from Prompt Explosions

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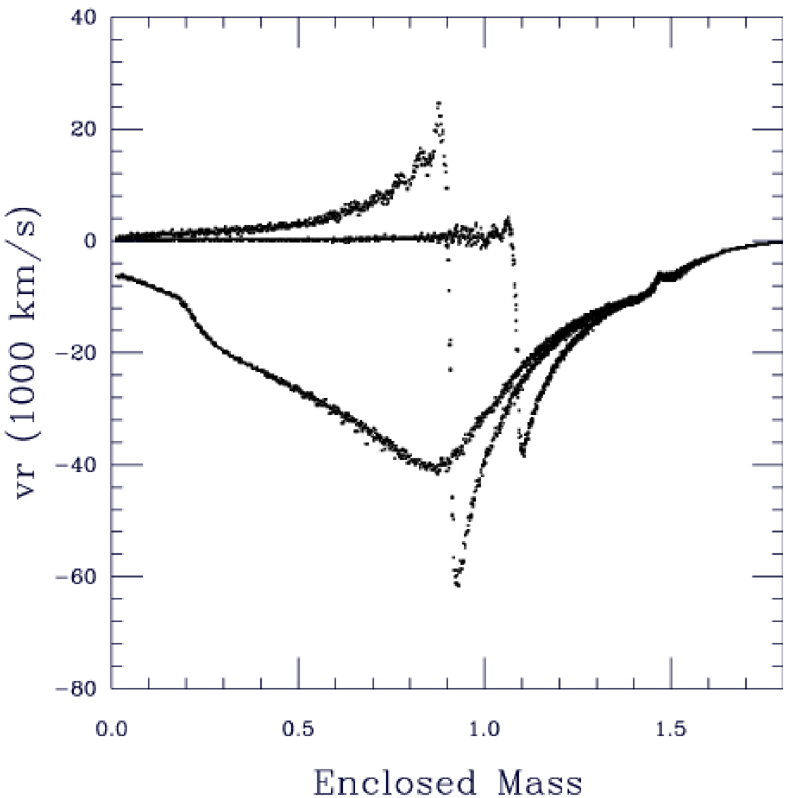
(Received 22 May 1987)

Evidence is cited that supernova 1987A involved a large explosion energy, $\simeq(2-3)\times10^{51}$ ergs. Such a large explosion energy has not come from delayed shocks to date, nor is it likely to. Improved physics in the presupernova evolution, especially the inclusion of Coulomb interactions, has brought the iron-core mass down by $\gtrsim 0.1 M_\odot$ in the $13 M_\odot$ star which has recently been evolved. We find that supernova explosion energies up to 3×10^{51} ergs can be obtained by the prompt-explosion mechanism, provided that a somewhat soft equation of state is used at supranuclear densities.

Model	W_s	ρ_{trap}	$Y_{L,f}$	$\frac{\rho_c^{\max}}{\rho_0(0.33)}$	E_{shock}	E_{lost}
43	29.3	0.4	0.390	4.1	1.7	3.4
59	29.3	1.0	0.365	4.1	...	4.6
61	29.3	0.4	0.390	4.1	1.9	4.9
62	36.0	1.0	0.385	4.1	2.1	2.1
63	34.0	1.0	0.375	4.1	1.4	4.6



Death of the shock in a star of 15 solar masses.

The shock is born at the edge of the "homologous core" near 0.7 solar masses. Initially the bounce gives it positive kinetic energy, but for each 0.1 solar masses it traverses and photodisintegrates about 10^{51} erg of energy is lost. Additional energy is lost as the shock moves to low densities, $\rho \approx 10^{11}$ gm cm^{-3}, to neutrinos.

After about 10 ms the once powerful shock has stagnated and become an accretion shock.

THE ASTROPHYSICAL JOURNAL, **295**: 14–23, 1985 August 1

REVIVAL OF A STALLED SUPERNOVA SHOCK BY NEUTRINO HEATING*

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Received 1984 March 23; accepted 1985 February 5

ABSTRACT

We analyze the mechanism for revival of a stalled supernova shock found by one of us (J. R. W.) in a computation. Neutrinos from the hot, inner core of the supernova are absorbed in the outer layers, and although only about 0.1% of their energy is so absorbed, this is enough to eject the outer part of the star and leave only enough mass to form a neutron star. The neutrino absorption is independent of the density of material. After the shock recedes to some extent, neutrino heating establishes a sufficient pressure gradient to push the material beyond about 150 km outward, while the material further in falls rapidly toward the core. This makes the density near 150 km decrease spectacularly, creating a quasi-vacuum in which the pressure is mainly carried by radiation. This is a perfect condition to make the internal energy of the matter sufficient to escape from the gravitational attraction of the star. The net energy of the outgoing shock is about 4×10^{50} ergs.

Subject headings: neutrinos — shock waves — stars: supernovae

* See also conference proceedings by Wilson (1982)

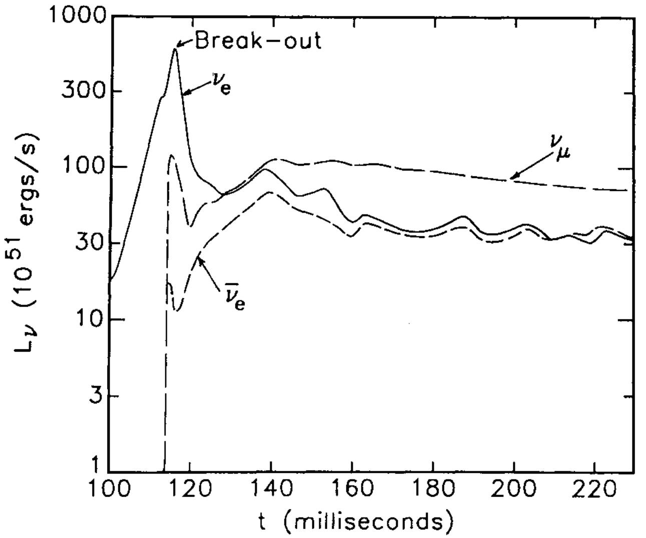


FIG. 1.—Emergent neutrino luminosities from the period just prior to core bounce (at 112.6 ms) to ~100 ms after bounce. The curves are for electron

Myra and Burrows, (1990), *ApJ*, **364**, 222

Neutrino luminosities of order $10^{52.5}$ are maintained for several seconds after an initial burst from shock break out.

At late times the luminosities in each flavor are comparable though the mu and tau neutrinos are hotter than the electron neutrinos.

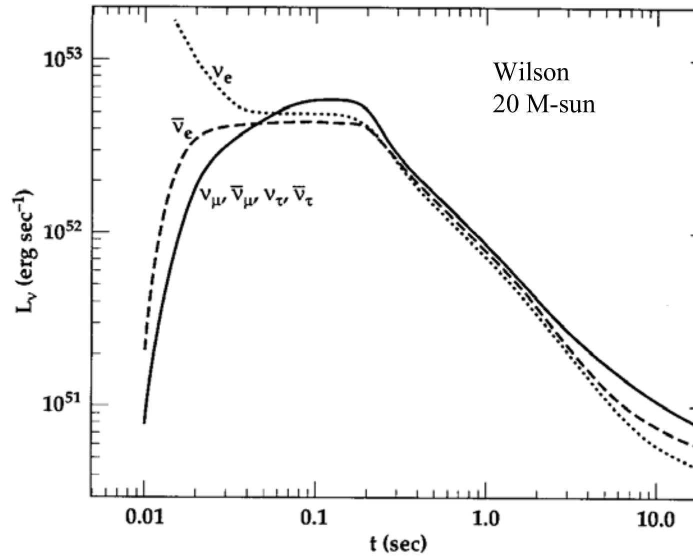


FIG. 2.—Neutrino luminosity L_ν for the six neutrino types as labeled as a function of time in the 20 $M_\odot$ supernova model.

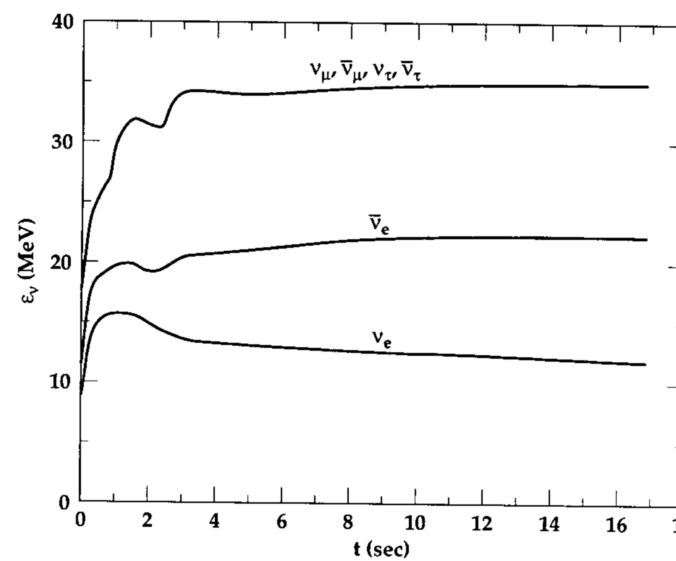
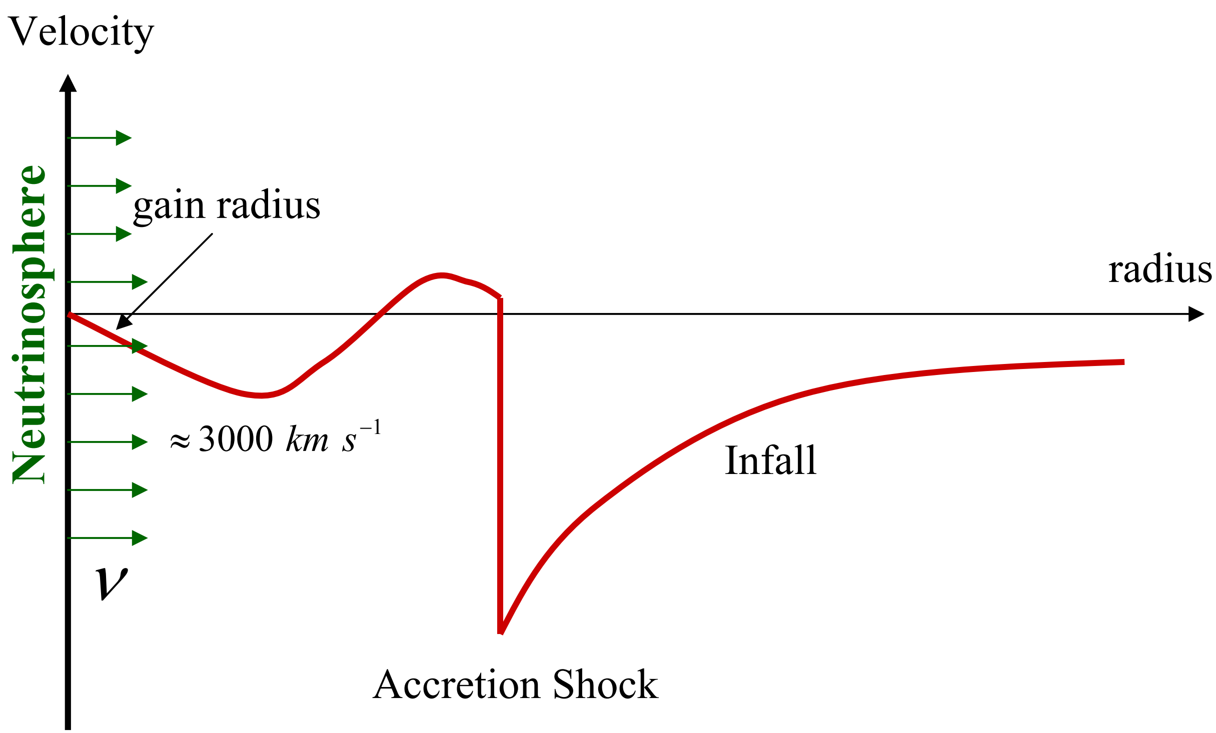
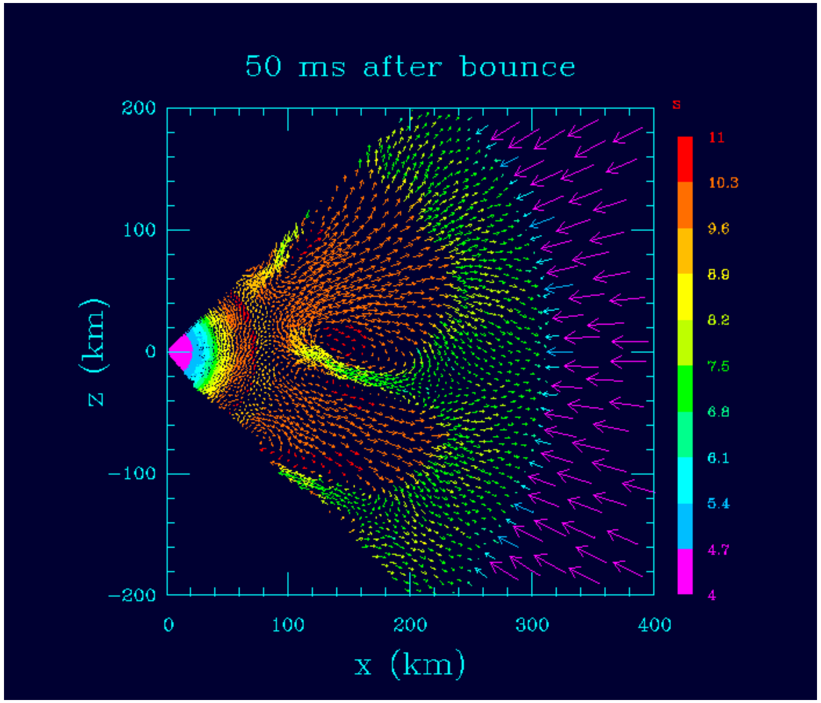


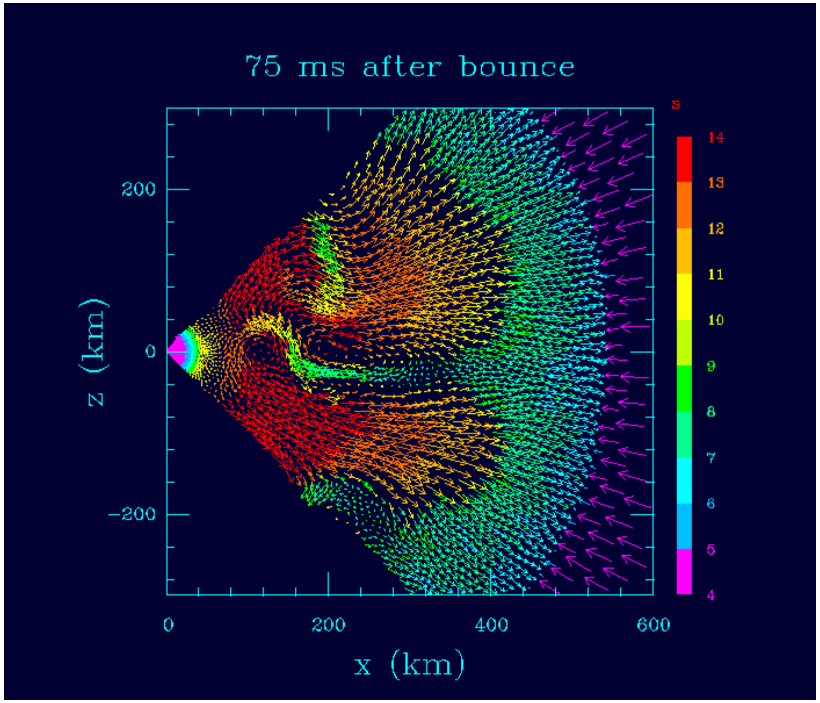
FIG. 3.—Mean neutrino energy ϵ_ν weighted by the square of the neutrino energy for the six neutrino types as a function of time in the 20 $M_\odot$ supernova model.

Woosley et al. (1994), *ApJ*,, **433,** 229



Inside the shock, matter is in approximate hydrostatic equilibrium. Inside the gain radius there is net energy loss to neutrinos. Outside there is net energy gain from neutrino deposition. At any one time there is about 0.1 solar masses in the gain region absorbing a few percent of the neutrino luminosity.





Herant and Woosley, 1995. 15 solar mass star.
successful explosion.
(see also Herant, Benz, & Colgate (1992), *ApJ*, **395**, 642)

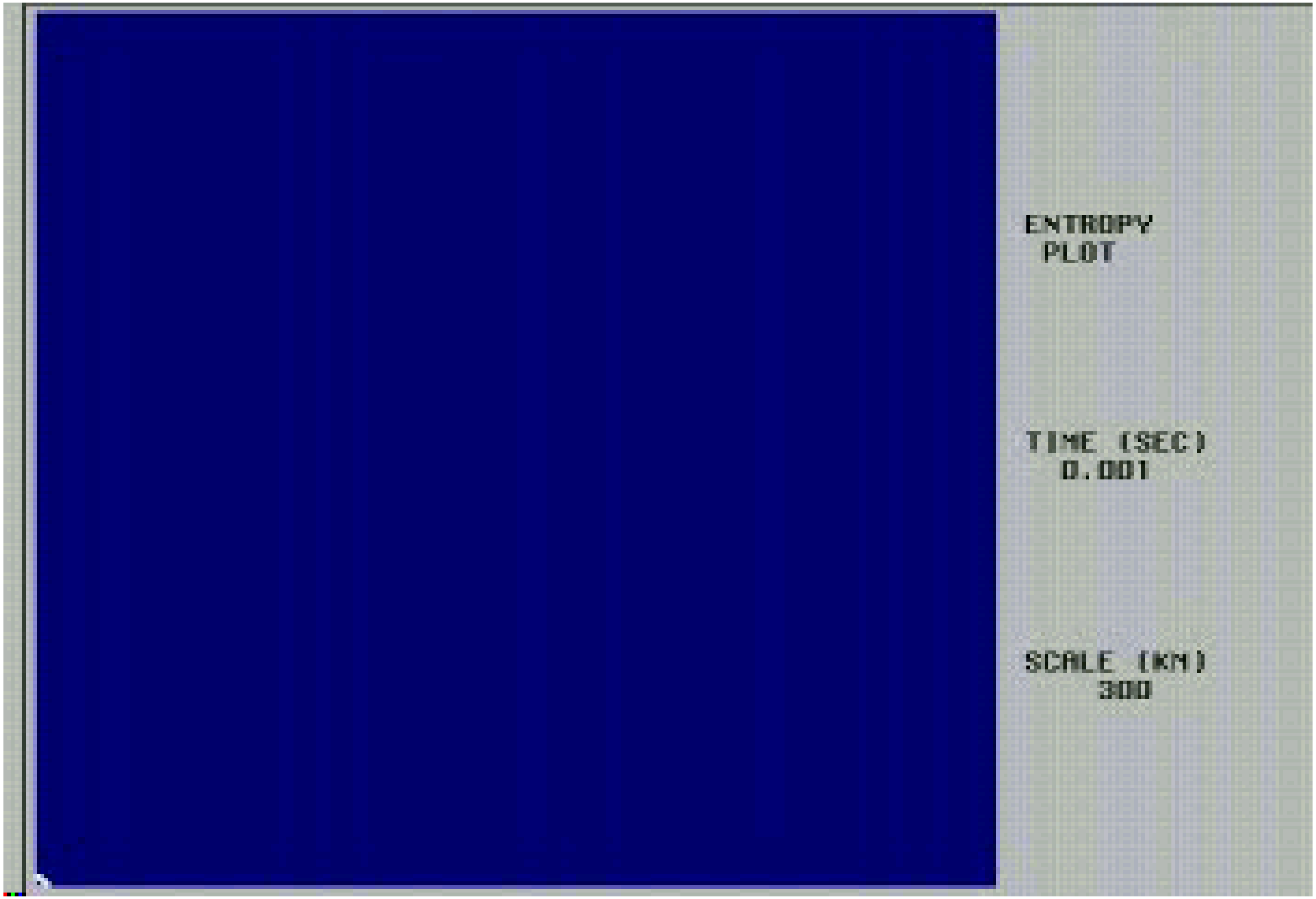
Beneficial Aspects of Convection

- Increased luminosity from beneath the neutrinosphere
- Cooling of the gain radius and increased neutrino absorption
- Transport of energy to regions far from the neutrinosphere (i.e., to where the shock is)

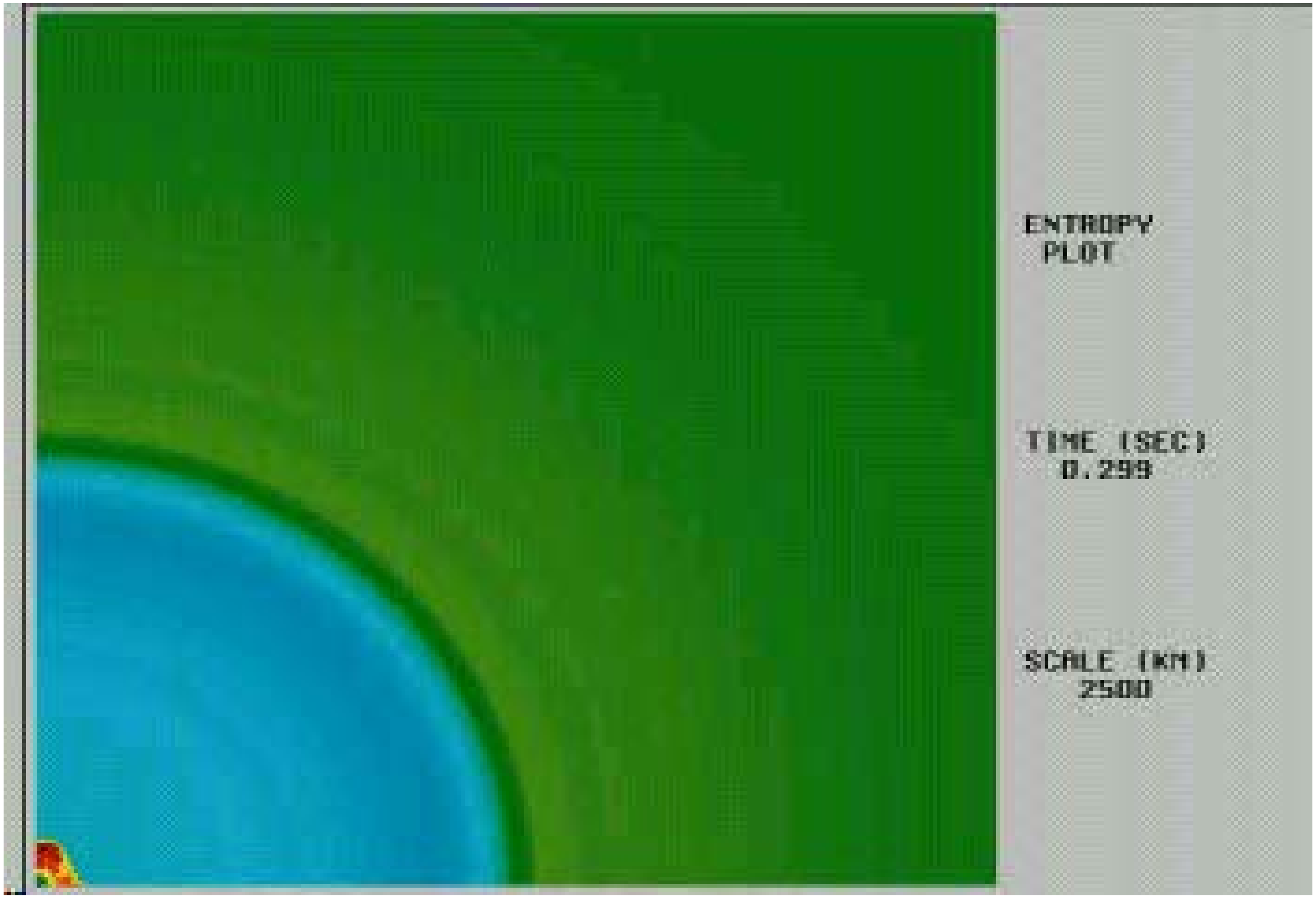
Also Helpful

- Decline in the accretion rate and accompanying ram pressure as time passes
- A shock that stalls at a large radius
- Accretion sustaining a high neutrino luminosity as time passes (able to continue at some angles in multi-D calculations even as the explosion develops).

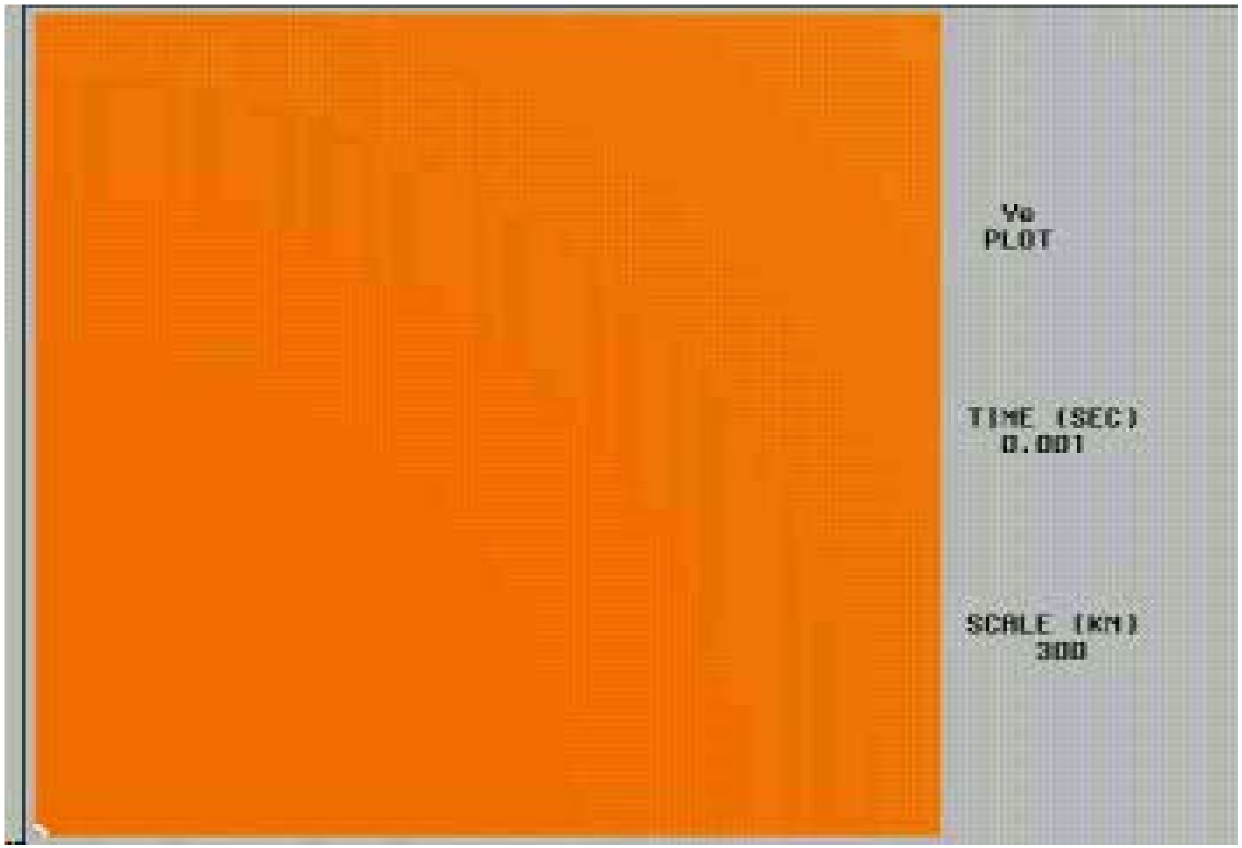
Burrows, Hayes, and Fryxell, (1995), ***ApJ***, **450**, 830

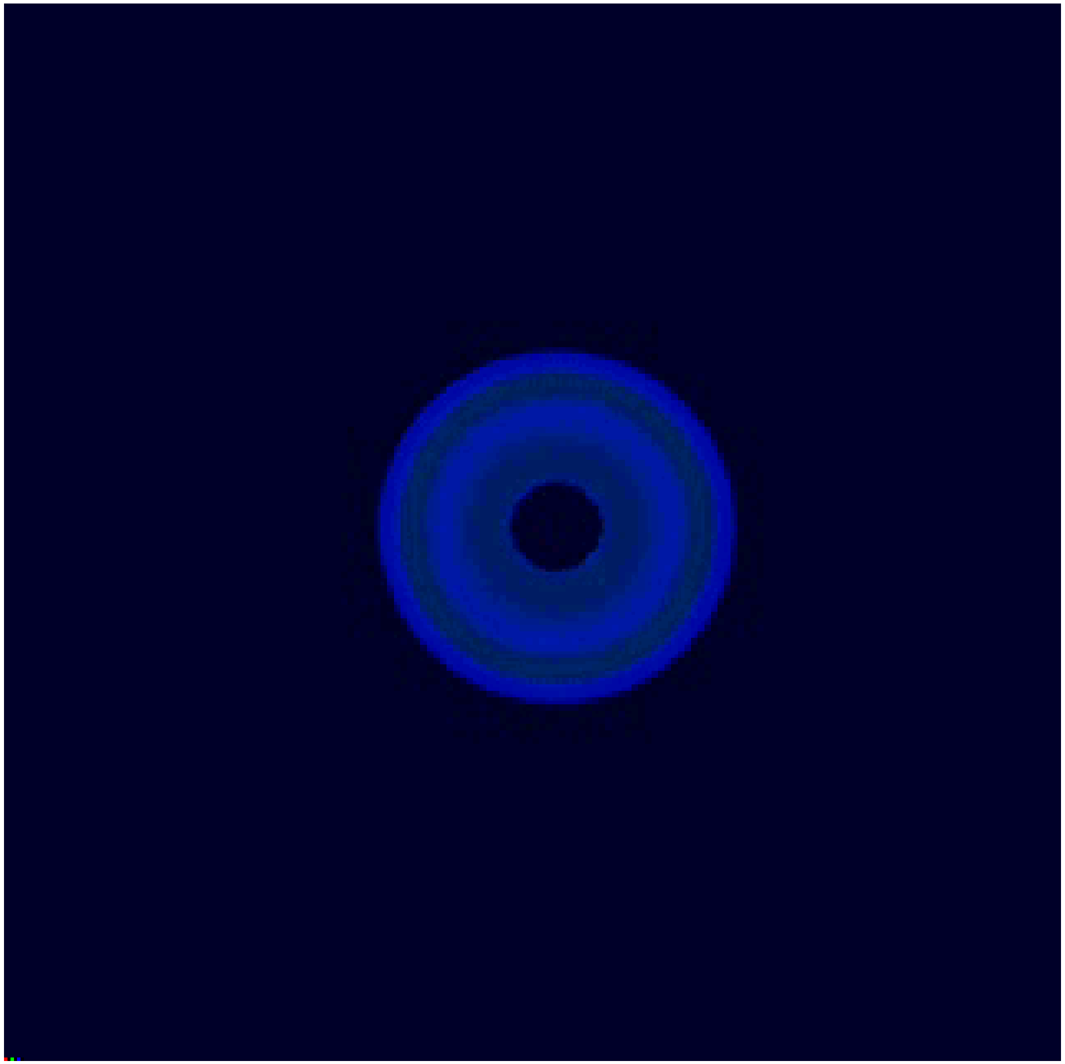


15 Solar masses – exploded with an energy of order 10^{51} erg.
see also Janka and Mueller, (1996), *A&A*, **306**, 167



At 408 ms, KE = 0.42 foe, stored dissociation energy is 0.38 foe, and the total explosion energy is still growing at 4.4 foe/s


Ye
PLOT
TIME (SEC)
0.001
SCALE (KM)
300



Mezzacappa et al. (1998), *ApJ*, **495**, 911.

Using 15 solar mass progenitor WW95. Run for 500 ms.
1D flux limited multi-group neutrino transport coupled to 2D hydro.

No explosion.

Generic Problems with "Successful" Explosions

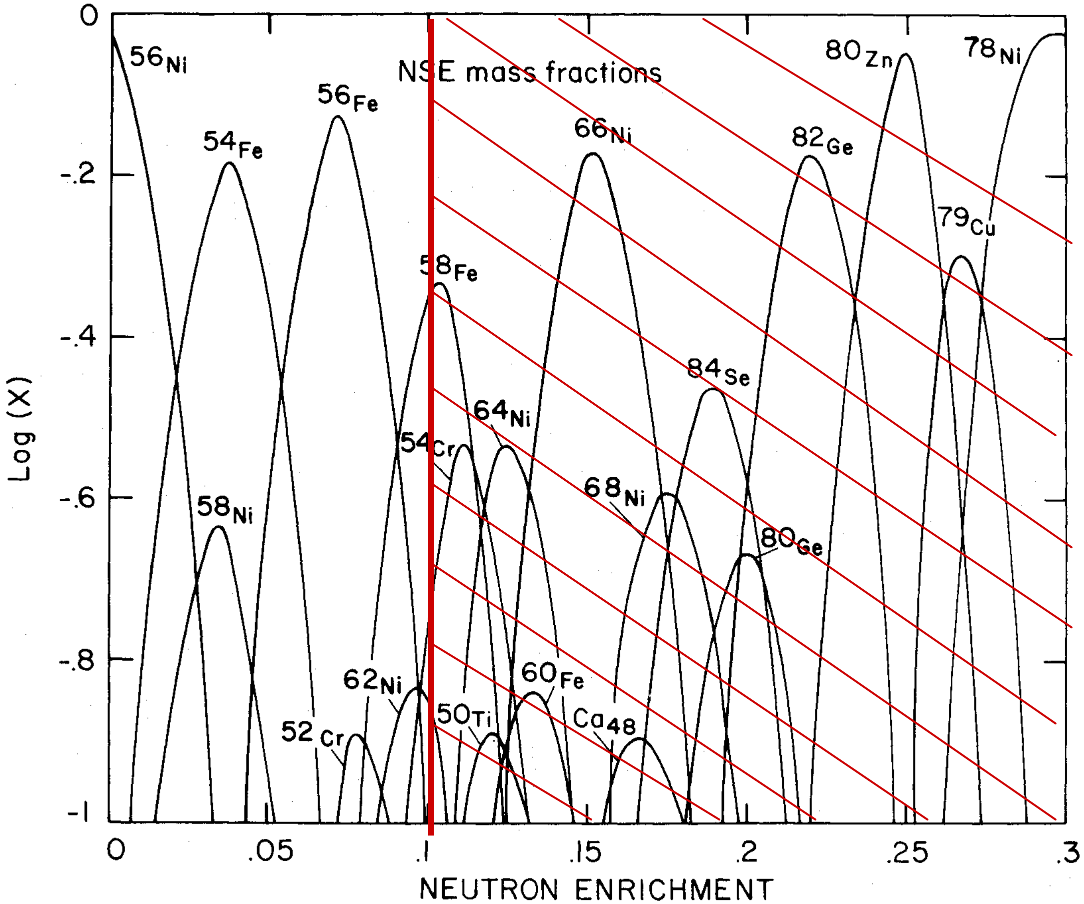
- Leave neutron star masses that are too low – about 1.1 solar masses
- Eject too much neutron-rich material – about 0.1 solar masses of Y_e below 0.45. Sr, Y, Zr
- May be too energetic

perhaps because ....

- Neutrino transport not handled well in multi-D models
- Most models 2D so far; need 3D
- May be under-resolved

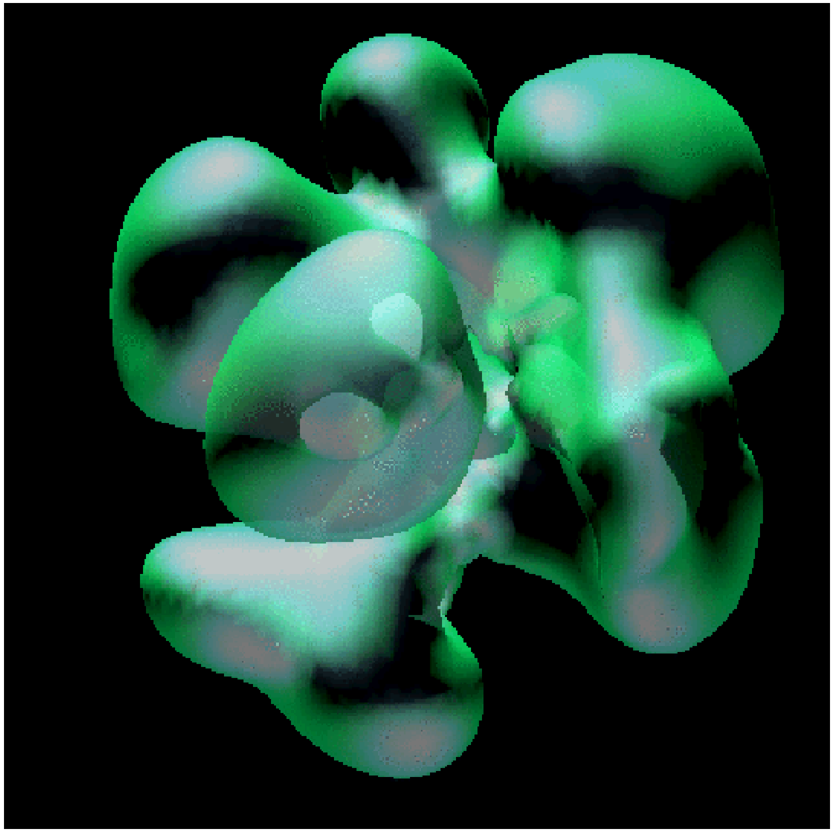
In nuclear statistical equilibrium the abundances of nuclei are very sensitive to the degree of neutronization as measured by Y_e. For Y_e below 0.45, the abundant species in nse are very rare in nature.

$Y_e = 0.45$



$$Y_e = (1 - \eta)/2$$

Hartmann, Woosley, and El Eid (1985), *ApJ,* **297**, 837



The box is 1000 km across.

First three-dimensional calculation of a core-collapse 15 solar mass supernova.

This figure shows the iso-velocity contours (1000 km/s) 60 ms after core bounce in a collapsing massive star. Calculated by Fryer and Warren at LANL using SPH (300,000 particles).

Resolution is poor and the neutrinos were treated artificially (trapped or freely streaming, no gray region), but such calculations will be used to guide our further code development.

300,000 particles	1.15 Msun remnant	2.9 foe
1,000,000 “	1.15 “	2.8 foe – 600,000 particles in convection zone
3,000,000 “	in progress	

Conclusions here

- There is controversy here that will not be settled by democracy, but by better calculations that

  a) Include good to excellent multi-angle multi-group neutrino transport
  b) Are three dimensional

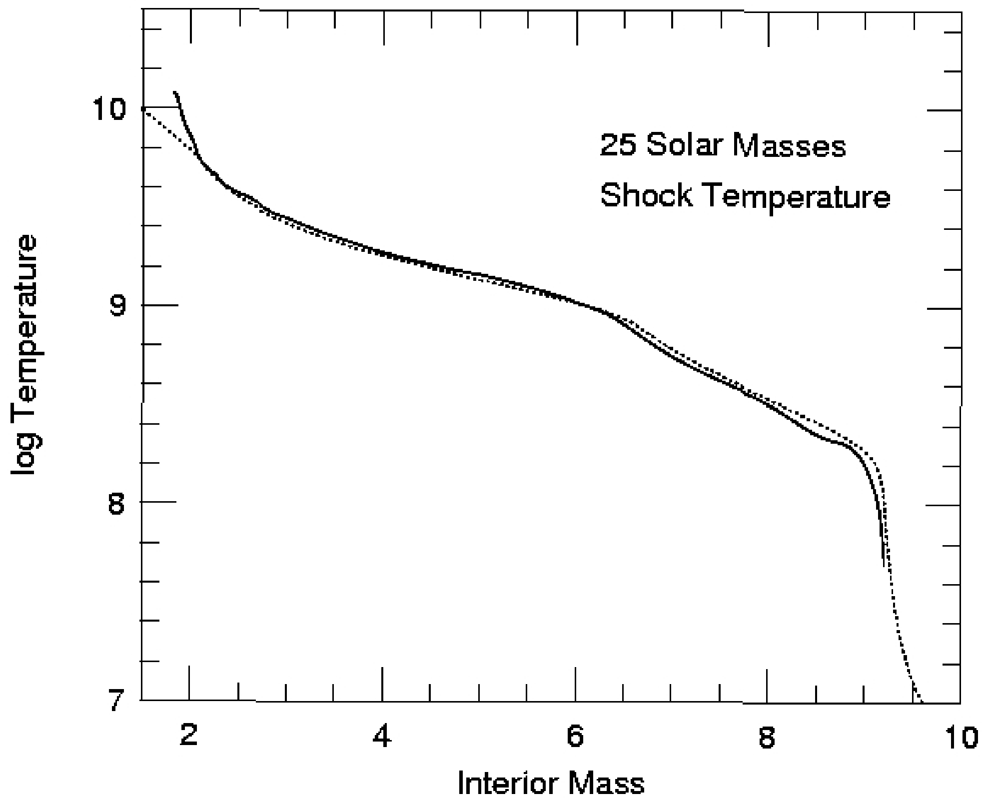
  these will be computationally intensive but can be done.

- There needs to be better cross comparison among the groups doing the problem

  a) Running the same progenitors
  b) Using as much as possible the same physics (as well as their version of the "best" physics in the different codes
  c) Talking to each other

- My own --- Probably there is nothing wrong with the basic model, but with the codes.

$$4/3\pi\ r^3\sigma\ T^4 = Explosion\ \ energy \approx 10^{51}\ erg$$



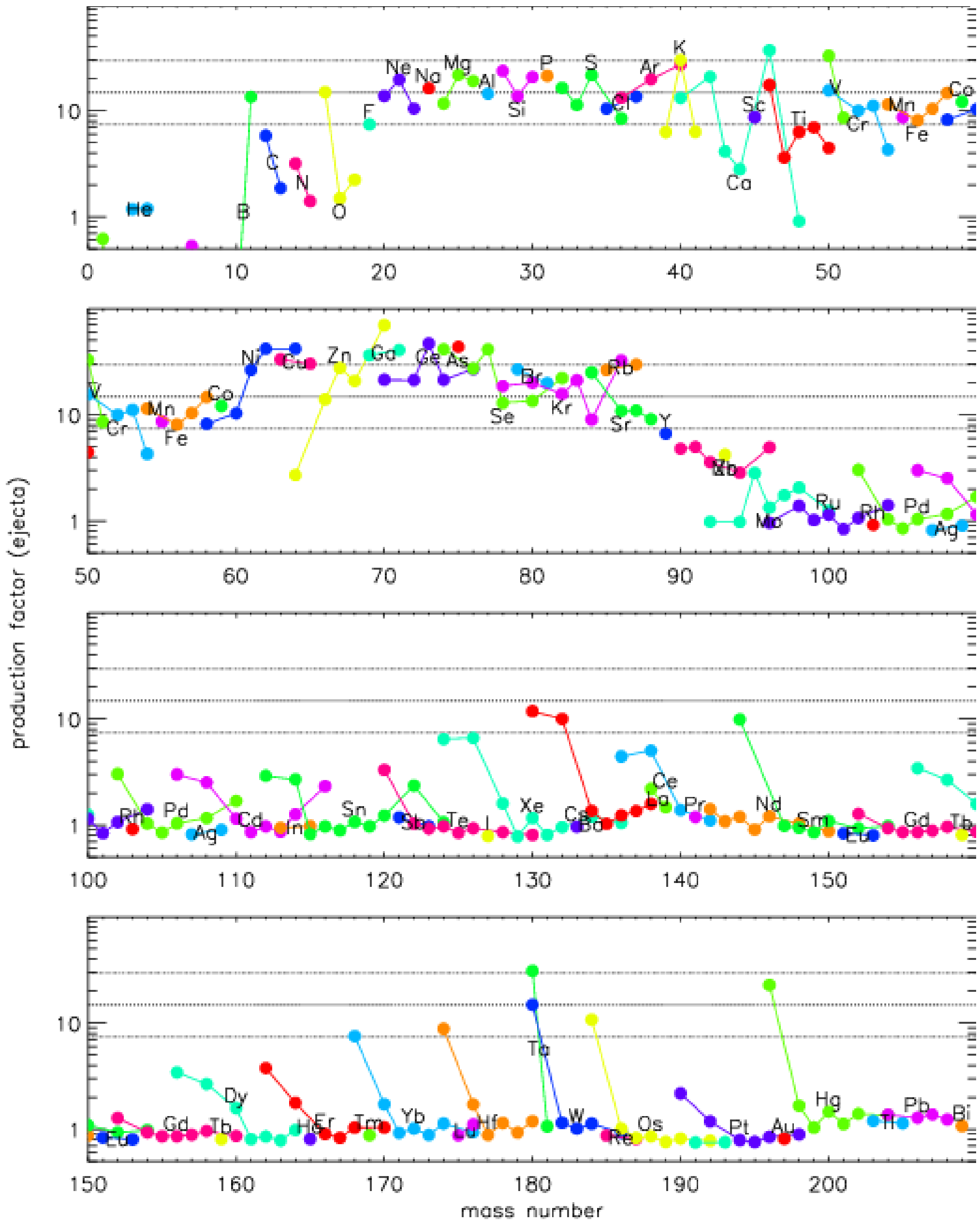
Explosive Nucleosynthesis

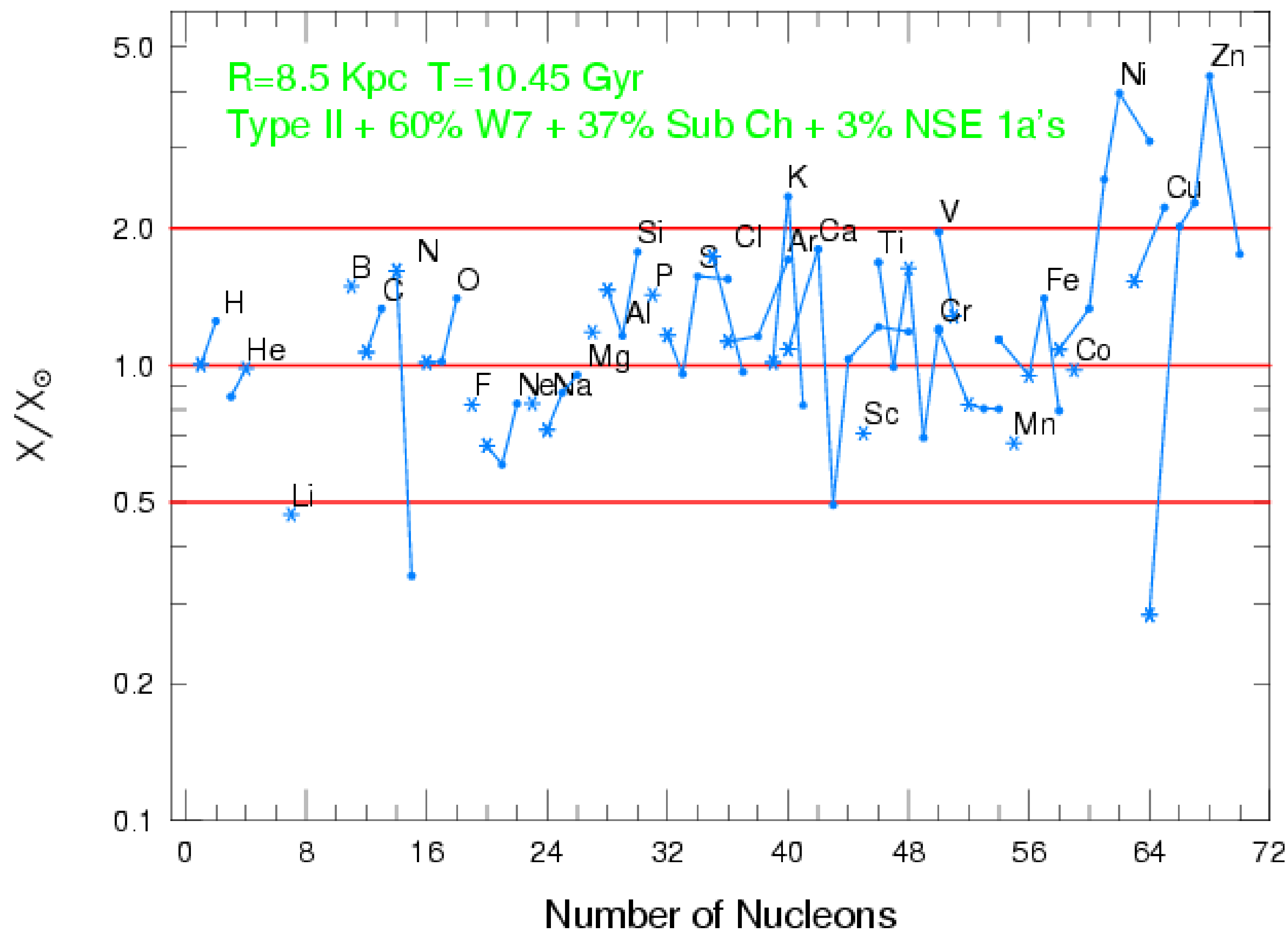
Fuel	Main Product	Secondary Products	Temp (10^9 K)	Time (sec)
Innermost Ejecta	r- process	-	>10 low Y_e	about 1
Si, O	^{56}Ni	Iron group	> 4	0.1
O	Si,S	Cl, Ar K, Ca	3 - 4	1
O, Ne	O, Mg Ne	Na, Al P	2 - 3	5
		p - process ^{11}B, ^{19}F	"	"

25 Solar Masses; Rauscher et al. (2002), ApJ, submitted

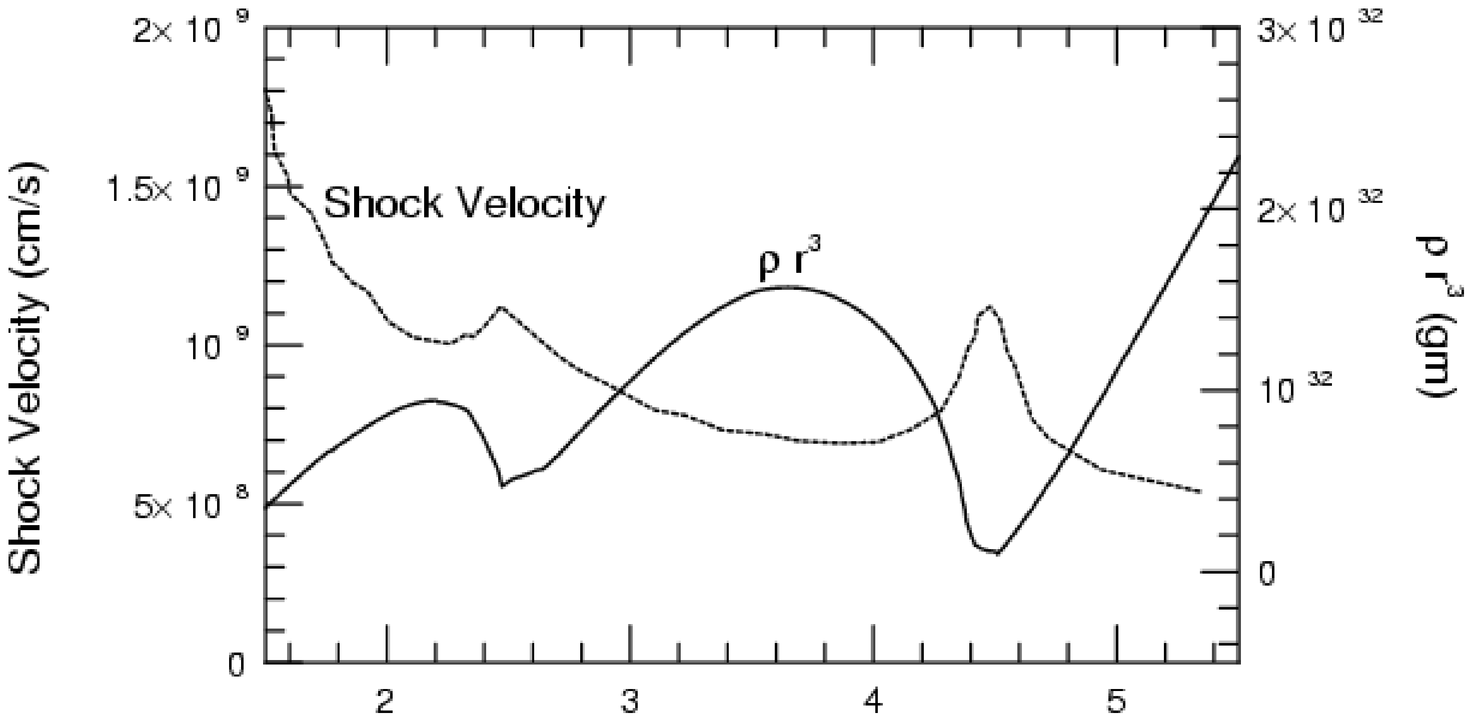
300 such models currently being calculated.

Heger & Woosley





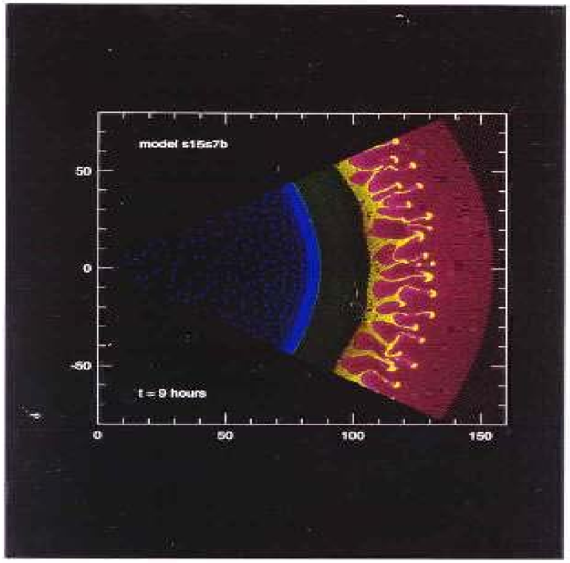
R=8.5 Kpc T=10.45 Gyr
Type II + 60% W7 + 37% Sub Ch + 3% NSE 1a's
X/X⊙
Number of Nucleons
5.0
2.0
1.0
0.5
0.2
0.1
0
8
16
24
32
40
48
56
64
72
H
He
Li
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn



Shock Velocity (cm/s)
2× 10 9
1.5× 10 9
10 9
5× 10 8
0
Shock Velocity
ρ r3
3× 10 32
2× 10 32
10 32
0
ρ r3 (gm)
2
3
4
5

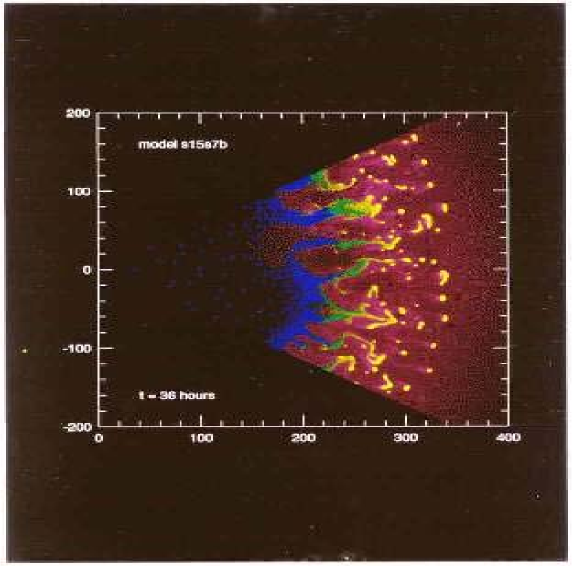
As the expanding helium core runs into the massive, but low density hydrogen envelope, the shock at its boundary decelerates. The deceleration is in opposition to the radially decreasing density gradient of the supernova.

Rayleigh-Taylor instability occurs.



The calculation at the right (Herant and Woosley, ApJ, 1995) shows a 60 degree wedge of a 15 solar mass supernova modeled using SPH and 20,000 particles. At 9 hours and 36 hours, the growth of the non-linear RT instability is apparent.

Red is hydrogen, yellow is helium, green is oxygen, and blue is iron. Radius is in solar radii.



15 Solar Mass Supernova – Herant and Woosley (1994), *ApJ*, **425**, 814

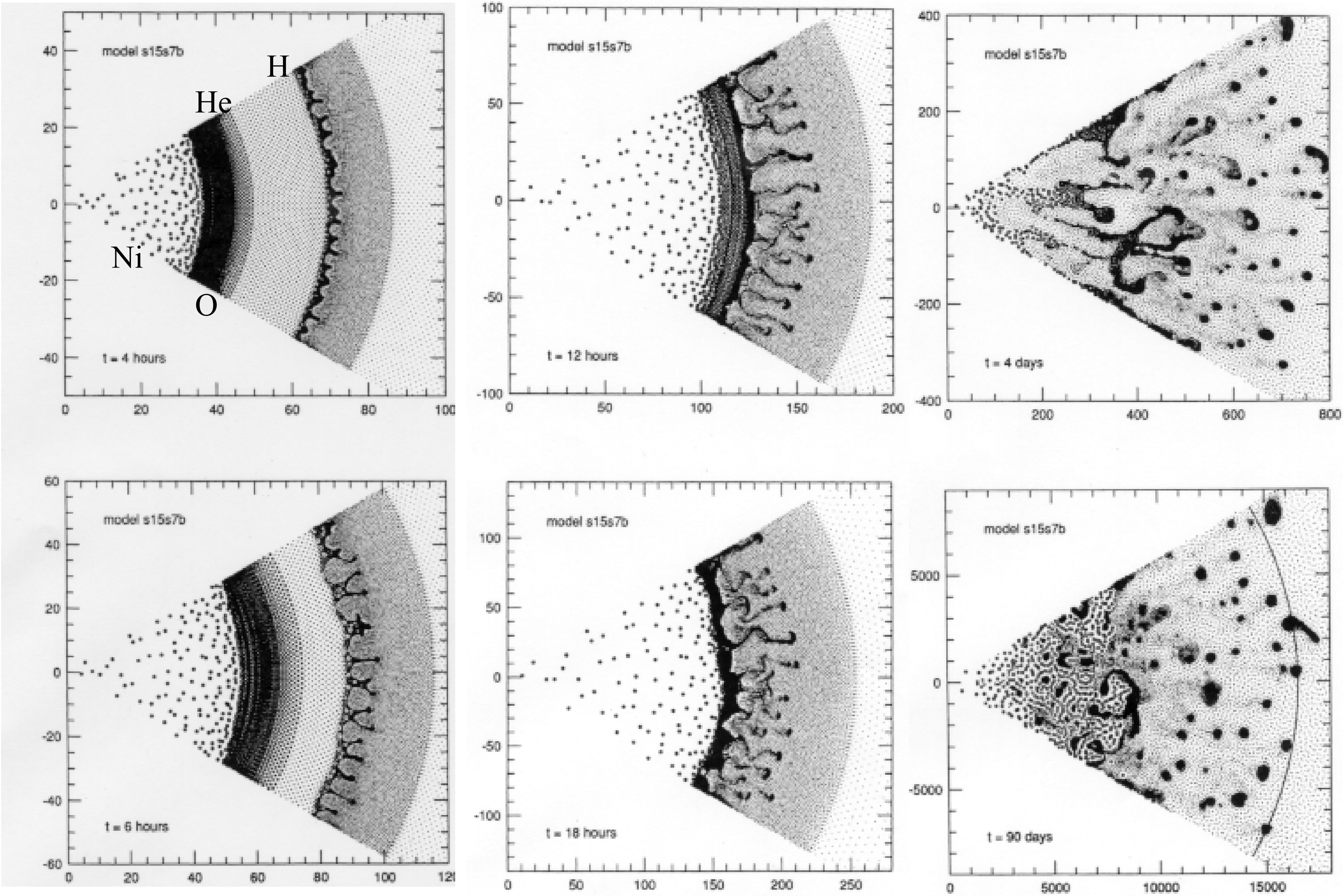
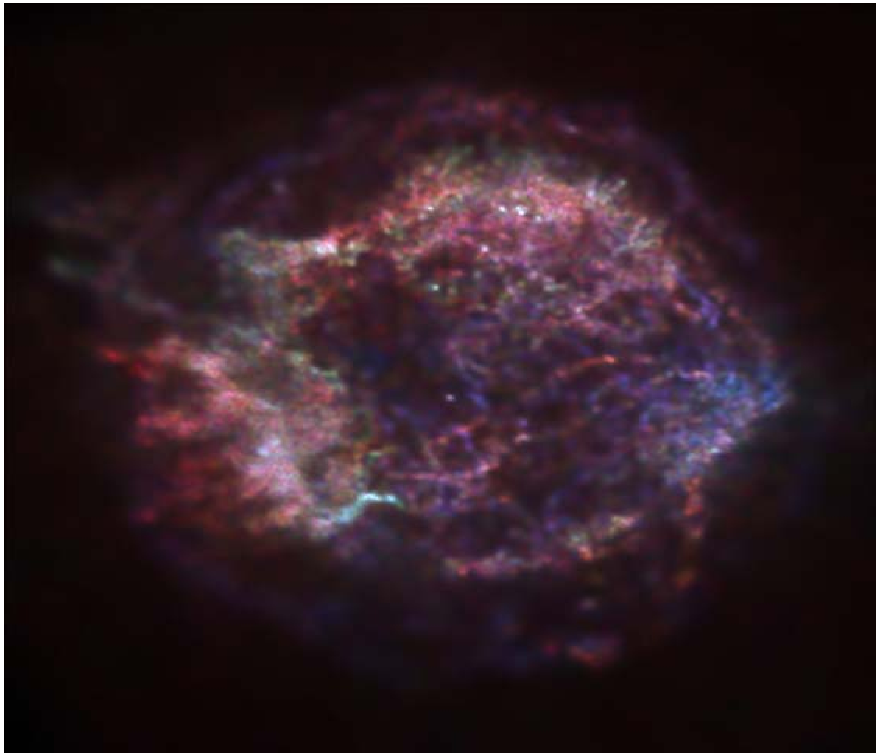
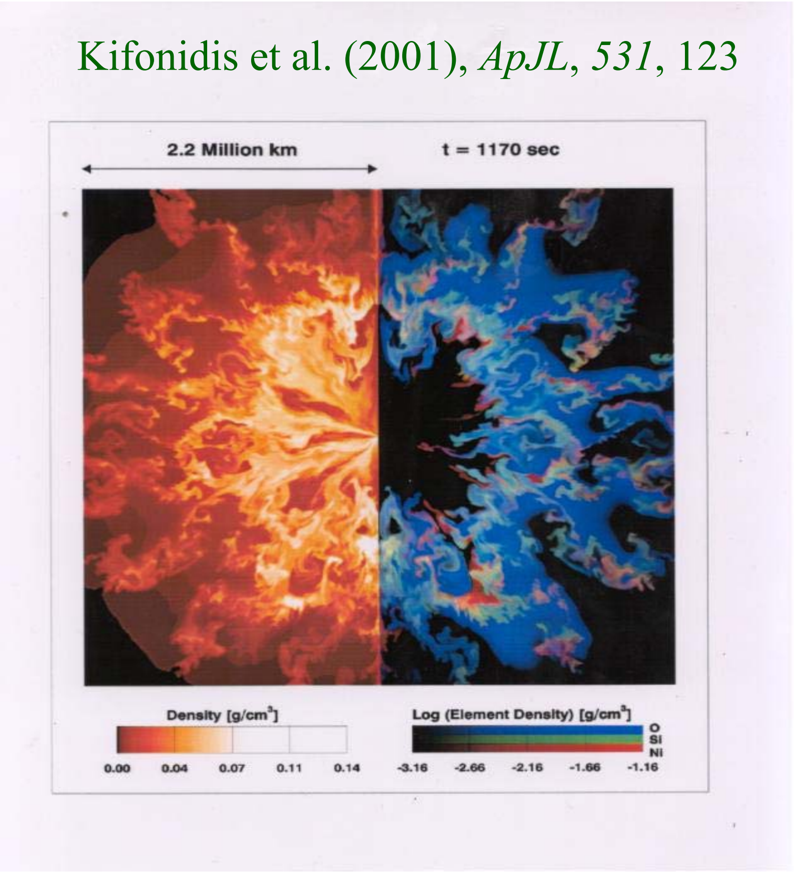


FIG. 4.—Same as Fig. 2 at yet later times

Diagnosing an explosion



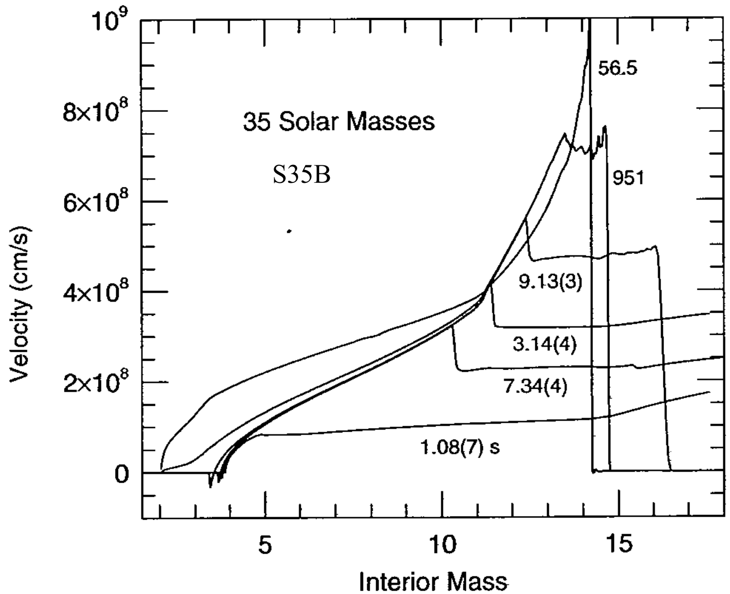


Left - Cas-A SNR as seen by the Chandra Observatory Aug. 19, 1999

The red material on the left outer edge is enriched in iron. The greenish-white region is enriched in silicon. Why are elements made in the middle on the outside?

Right - 2D simulation of explosion and mixing in a massive star - Kifonidis et al, Max Planck Institut fuer Astrophysik

Fallback

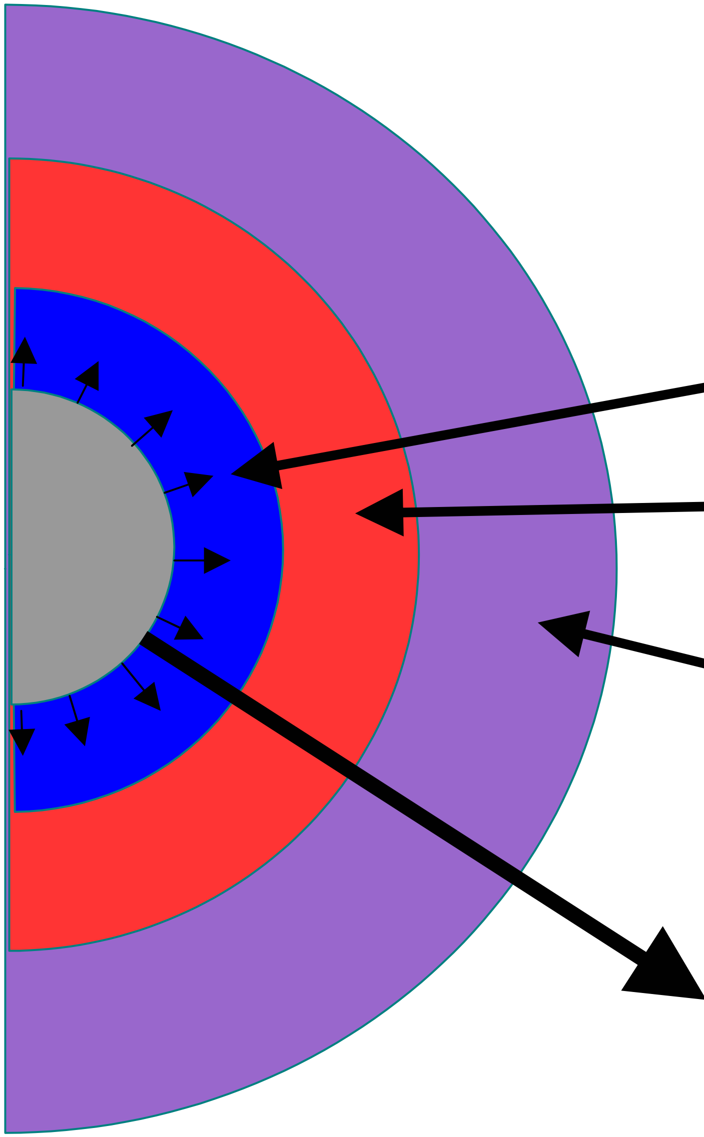


Woosley and Weaver, (1995), *ApJS*, **101**, 181

Mass /Model	Z (/Z$_\odot$)	Fe Core (M$_\odot$)	Piston (M$_\odot$)	M$_9$ (M$_\odot$)	BE$_9$ (10^{50} erg)	α	v_o (10^4 km/s)	Remnant (M$_\odot$) *	KE$_\infty$ (10^{51} erg)	M(^{56}Ni) (M$_\odot$)
S11A	1	1.32	1.32	1.52	0.18	2.52	2.90	1.32	1.29	0.069
S12A	1	1.32	1.32	1.53	0.37	4.04	3.67	1.32	1.17	0.043
S13A	1	1.41	1.41	1.86	0.56	1.06	1.94	1.46	1.31	0.133
S15A	1	1.32	1.29	1.99	1.48	1.09	1.88	1.43	1.22	0.115
S18A	1	1.46	1.42	2.34	2.84	0.46	1.28	1.76	1.17	0.066
S19A	1	1.66	1.66	2.86	4.14	0.35	1.22	1.98	1.19	0.100
S20A	1	1.74	1.74	2.93	5.16	0.35	1.24	2.06	1.17	0.088
S22A	1	1.82	1.82	3.10	7.12	0.50	1.51	2.02	1.47	0.205
S25A	1	1.78	1.78	3.14	9.78	0.47	1.45	2.07	1.18	0.129
S30A	1	1.83	1.83	3.13	10.7	0.35	1.27	4.24	1.13	0
S30B	1	1.83	1.83	3.13	10.7	0.71	1.81	1.94	2.01	0.440
S35A	1	2.03	2.03	3.63	15.9	0.50	1.60	7.38	1.23	0
S35B	1	2.03	2.03	3.63	15.9	0.81	2.04	3.86	1.88	0
S35C	1	2.03	2.03	3.63	15.9	0.95	2.20	2.03	2.22	0.568
S40A	1	1.98	1.98	3.90	20.1	0.64	1.79	10.34	1.19	0
S40B	1	1.98	1.98	3.90	20.1	1.04	2.28	5.45	1.93	0
S40C	1	1.98	1.98	3.90	20.1	1.34	2.59	1.98	2.57	0.691

Fall back and mixing together, plus uncertainties in the explosion energy can really complicate the calculation of nucleosynthesis.

r-Process Site #1: The Neutrino-powered Wind *



Anti-neutrinos are "hotter" than the neutrinos, thus weak equilibrium implies an appreciable neutron excess, typically 60% neutrons, 40% protons

$\bar{\nu}_e + p \rightarrow n + e^+$ * favored

$\nu_e + n \rightarrow p + e^-$

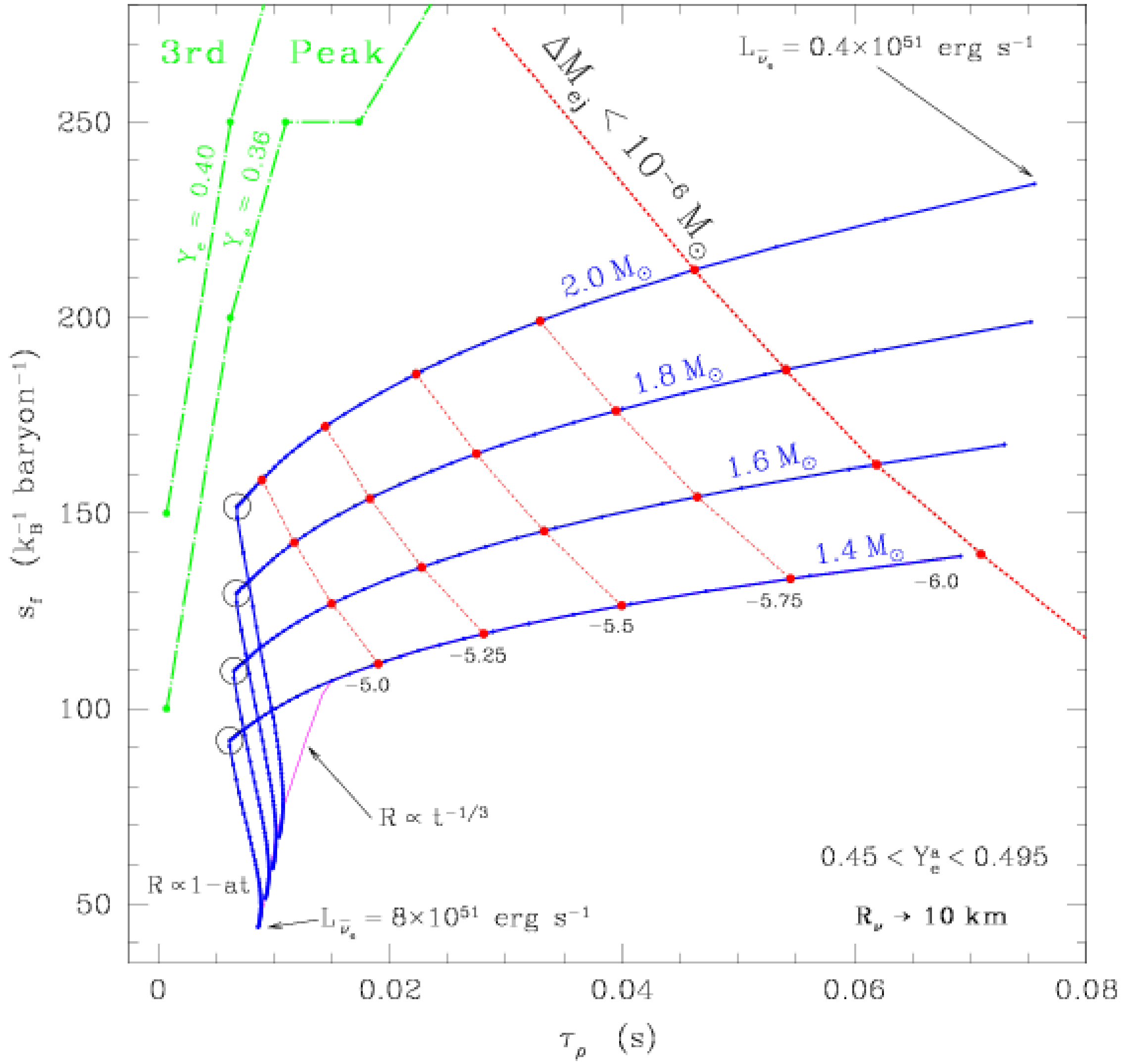
$60n + 40p \rightarrow 20\alpha + 20n$ $\quad T_9 = 5 - 10$

few $\alpha(\alpha n,\gamma)^{12}C(n,\gamma)(\alpha,n)....."Fe"$ $\quad T_9 = 3 - 5$

$"Fe" + 200n \rightarrow$ r – process $\quad T_9 = 1 - 2$

Nucleonic wind, 1 - 10 seconds

Duncan, Shapiro, & Wasserman (1986), *ApJ*, **309**, 141
Woosley et al. (1994), *ApJ*, **433**, 229



Thompson, Burrows, and Meyer, (2001), *ApJ*, **562**, 887

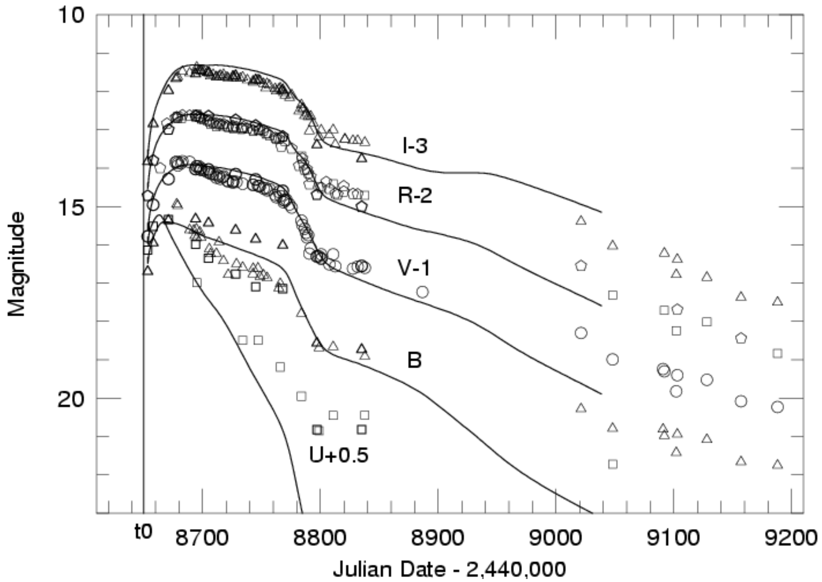
So far the necessary high entropy and short time scale for the r-process is not achieved in realistic models for neutron stars (though small radius helps).

Takahashi, Witti, & Janka *A&A*, (1994), **286**, 857

Qian & Woosley, *ApJ*, (1996), **471**, 331

For typical time scales need entropies > 300.

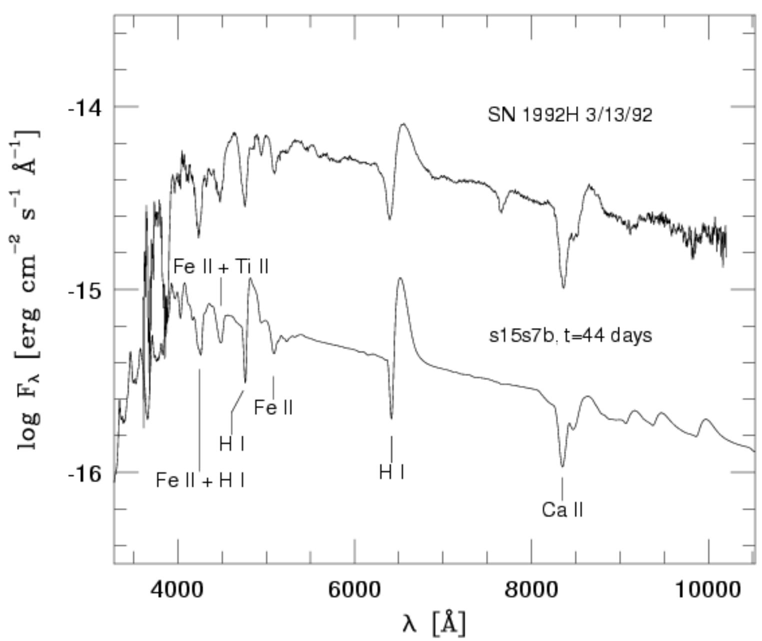
blue lines show contraction from about 20 km then evolution at constant R = 10 km as the luminosity declines.



Eastman, Pinto, & Woosley

The light curves and spectra of Type II supernovae are relatively insensitive to the uncertainties surrounding the explosion mechanism – though they do depend on mixing and the amount of ^{56}Ni that is ejected.

Current models work well



Conclusions

- Models for supernova explosions based on neutrino energy transport appear to work qualitatively. Exact agreement with observations - if possible - will require a new generation of codes and computers.

- Similarly, presupernova evolution is qualitatively understood but there remain important uncertainties with respect to convective boundary layers, the effects of rotation and redistribution of angular momentum, mass loss, and the reaction rate for $^{12}C(ag)^{16}O$

- There also remain a number of unresolved problems in supernova physics including: a) the origin of neutron star "kicks"; b) why some supernovae appear to be deformed; c) the relation between supernovae and gamma-ray bursts; d) the site of the r-process; and more...