Lecture 13

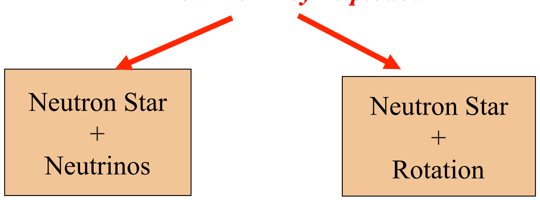
Presupernova Models, Core Collapse and Bounce

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 ..."

Chadwick discovered the neutron in 1932 though the idea of a neutral massive particle had been around since Rutherford, 1920.

When Massive Stars Die, How Do They Explode?



Colgate and White (1966)
Arnett
Wilson
Bethe
Janka
Burrows
Fryer
Mezzacappa
etc.

Hoyle (1946)
Fowler and Hoyle (1964)
LeBlanc and Wilson (1970)
Ostriker and Gunn (1971)
Bisnovatyi-Kogan (1971)
Meier
Wheeler
Usov
Thompson
Burrows

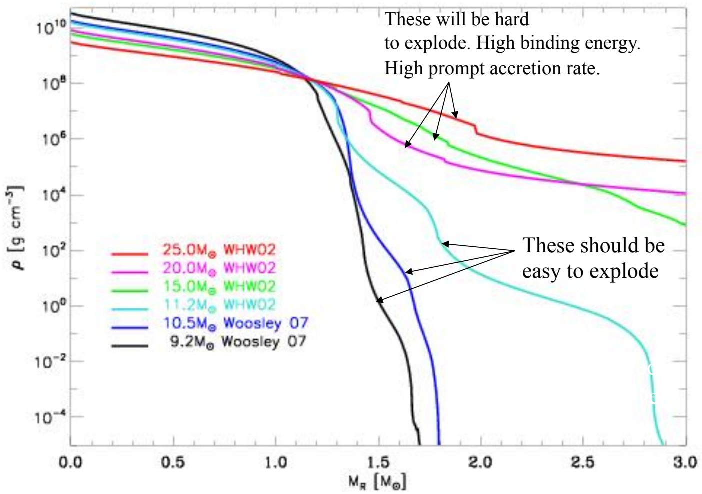
How the star dies is determined by its properties at birth – its mass, composition, rotation rate, and binary membership.

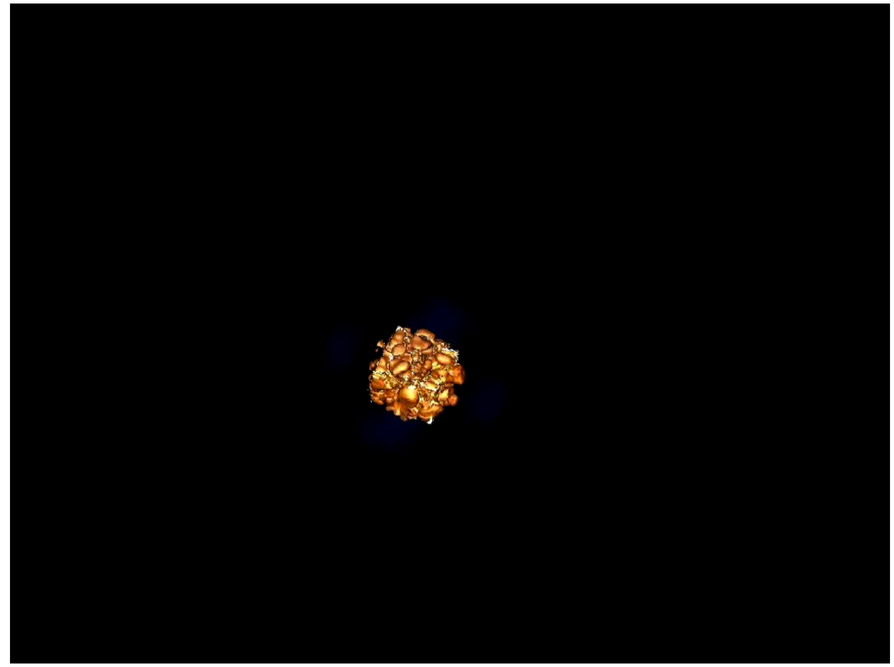
Mass affects the "central engine" by determining the density structure in the inner few solar masses of the presupernova star.

$$P_c \sim \frac{GM\rho}{R} \Rightarrow \frac{T_c^3}{\rho_c} \propto \mu^3 M^2 \quad \text{(for an ideal gas)}$$

$$S = \text{const} + \ln \frac{N_A k}{\mu}\frac{T^{3/2}}{\rho} + \frac{4a}{3}\frac{T^3}{\rho} \quad \text{(heavier stars have higher entropy)}$$

Density Profiles of Supernova Progenitor Cores





O'Connor and Ott, *ApJ*, **730**, 70, (2011)

Characterize possibility of a neutrino powered explosion based upon the compactness parameter, ζ,

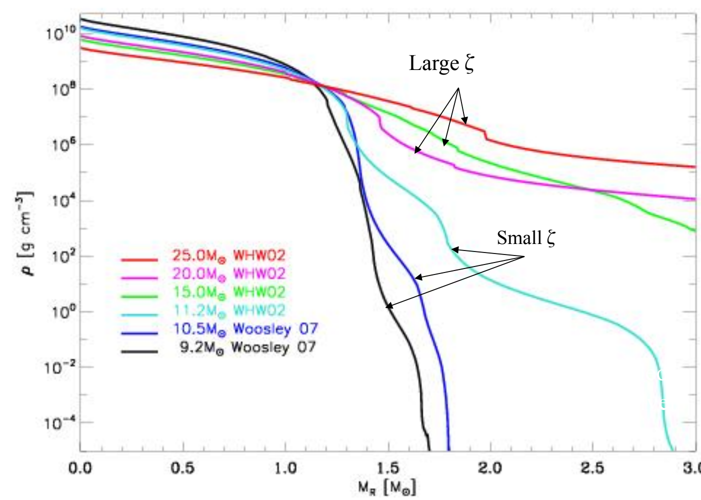
$$\xi_M = \frac{2.5}{R(M_{bary} = 2.5 M_\odot)/1000\ \mathrm{km}}\Bigg|_{t-bounce}$$

If ζ is big, R is small and the 2.5 solar mass point lies close in. The star is hard to explode. Based upon a series of 1D models they find stars with ζ over 0.45 are particularly difficult to explode.

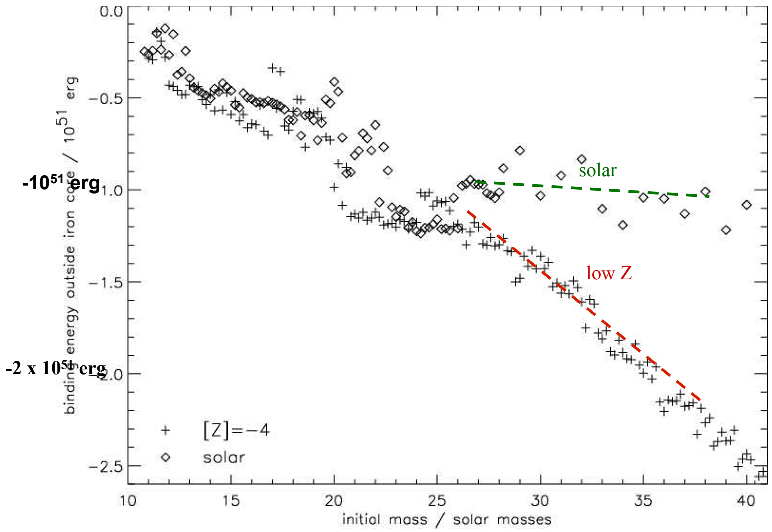
$$\xi(\text{explosion}) < 0.45$$

maybe too high – 0.25?

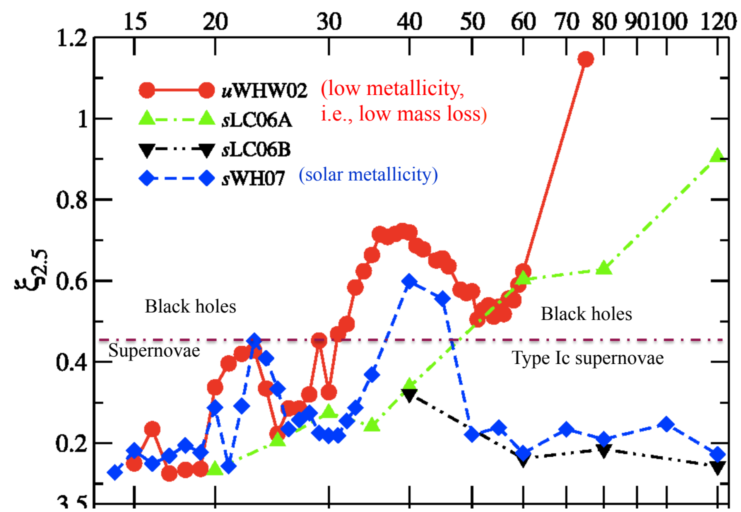
Density Profiles of Supernova Progenitor Cores



Gravitational Binding Energy of the Presupernova Star Outside the Iron Core.

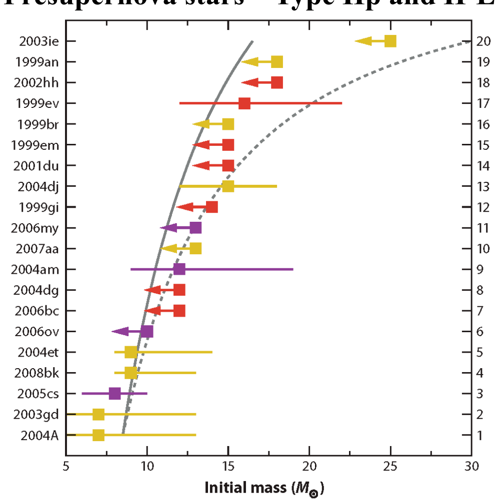


O'Connor and Ott (2011)



Results up here sensitive to poorly known mass loss rates

Presupernova stars – Type IIp and II-L

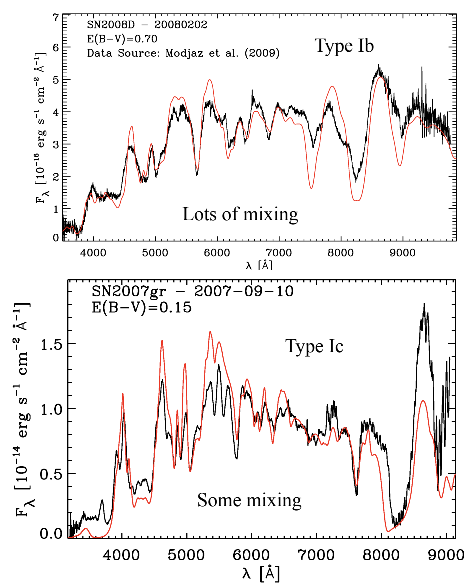


Smartt, 2009
ARAA

Progenitors heavier than 20 solar masses excluded at the 95% condidence level.

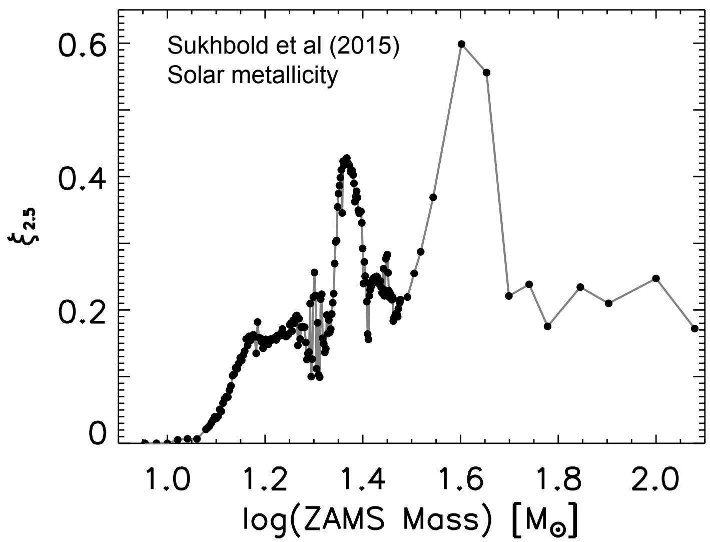
The solid line is for a Salpeter IMF with a maximum mass of 16.5 solar masses. The dashed line is a Salpeter IMF with a maximum of 35 solar masses

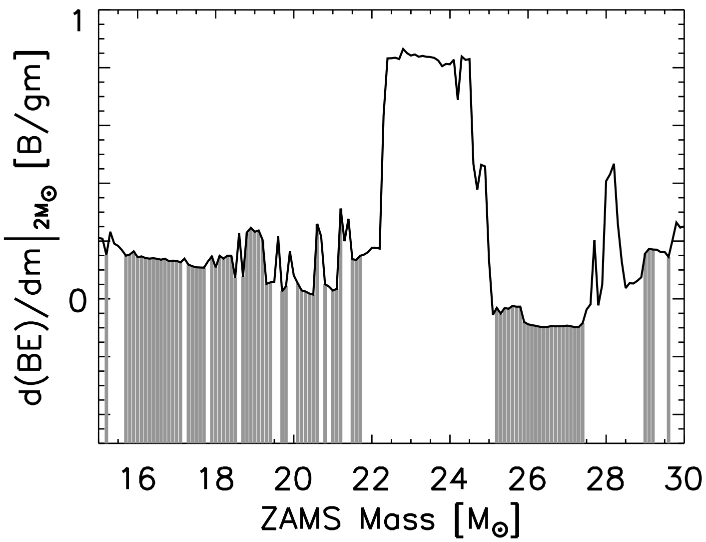
What About Type Ib and Ic Supernovae?

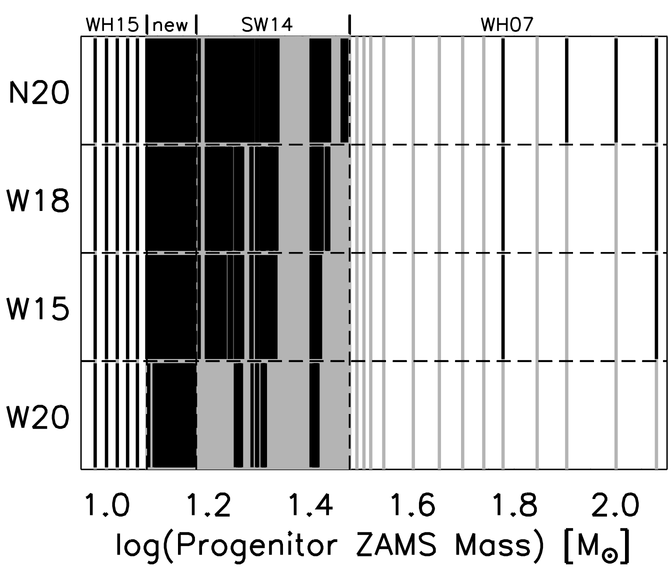


The two models on the left are both derived from a 5.1 helium star that originated from a binary pair in which each star was lighter than 20 solar masses (Yoon, Langer and Woosley 2010)

Dessart, Hillier, Li, & Woosley (2012) .







Summary – Reasonable Expectations For Most Core-Collapse Supernovae

- Whether a given star will blow up by neutrino transport depends sensitively on the presupernova structure – on its mass. Even more so than the details of the collapse calculation
- The masses of stars that explode may not be a simply connected set
- Stars around 10 solar masses (+- 1 say) will be very easy to explode
- Typical supernovae (SN IIp) are the result of neutrino energy transport in stars with main sequence masses 8 to ~19 solar masses.
- Rotation may boost the explosion and mixing of supernovae coming from (rapidly rotating) stars above 20 solar masses, but many/most stars above ~20 solar masses become black holes.
- There is an island of “compact” pre-supernova stars at around 30 solar masses that might be exploded by unboosted neutrino transport

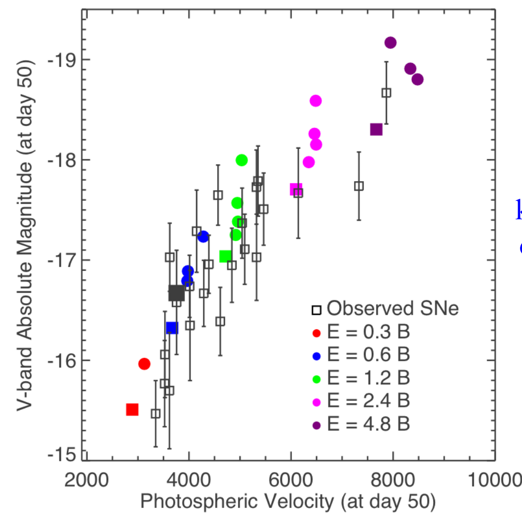
Continued

- Supernovae with explosion energies over 3 x 10^{51} probably do not come from unboosted neutrino transport.

$$\text{Explosion E} \sim \text{BE}_{n*} \times (\text{fraction in } \nu_e\bar{\nu}_e) \times (\frac{\tau_{\exp}}{\tau_{KH}}) \times (\text{Deposition efficiency})$$

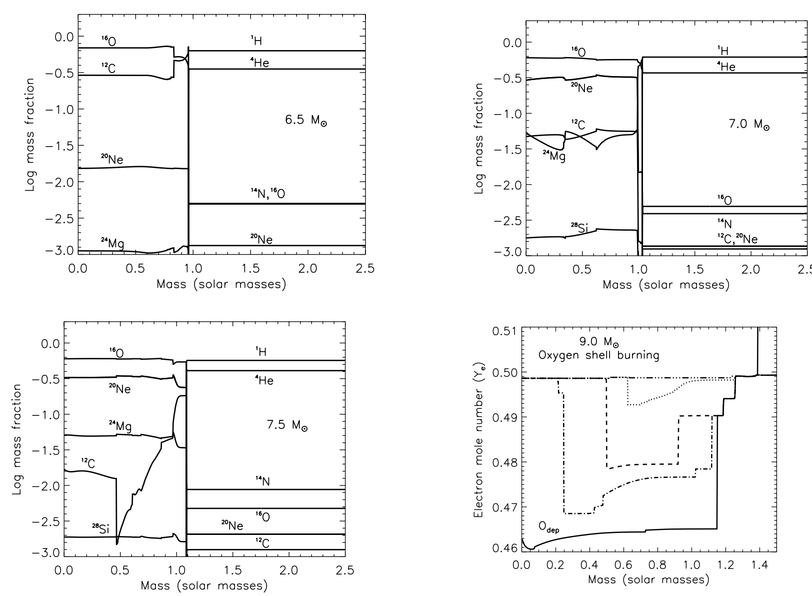
$$\sim 3\times10^{53}\text{ erg}\left(\frac{1}{3}\right)\left(\frac{1}{10}\right)(0.1) \sim 10^{51}\text{ erg}$$

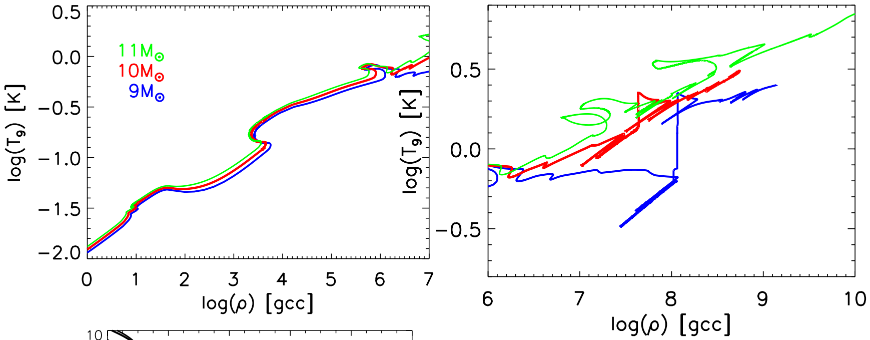
Kasen and Woosley (2009)

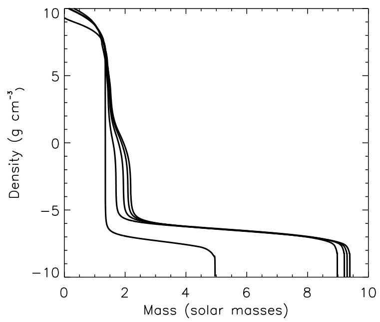


Observationally
The typical SN IIp has kinetic energy at infinity of 6 x 10^{50} erg, but with a wide spread.

Specific Cases in Greater Detail







Left: Presupernova density profiles of stars with mass 8.75, 9.25, 9.5, 9.6, and 9.7 solar masses. These are essentially white dwarfs inside of loosely bound envelopes. They should explode easily

Initial Mass ($M_\odot$)	Final Mass ($M_\odot$)	Helium Core Mass ($M_\odot$)	CO Core Mass ($M_\odot$)	Si Core Mass ($M_\odot$)	Fe Core Mass ($M_\odot$)	BE Envel (-10^{47} erg)	BE O-shell (-10^{49} erg)	Outcome
6.5	6.38	0.960	0.960	-	-	2.0[b]	-	CO WD
7.0	6.79	1.033	1.033	-	-	2.1[b]	-	OC WD
7.5	6.96	1.088	1.088	-	-	1.8[b]	-	ONe WD/EC SN
8.0	7.76	1.171	1.171	-	-	1.2[b]	-	"
8.5	8.28	1.271	1.271	-	-	2.3[b]	-	"
8.75	8.51	1.345	1.345	-	-	1.1[b]	-	"
9.0	8.75	1.386	1.386	1.356	1.255	2.1	-	Conv O-Flame SN
9.25	8.98	1.699	1.449	1.360	1.261	2.0	3.7	"
9.3	9.02	1.766	1.459	1.371	1.295	2.0	3.6	Si-Flash SN
9.4A[c]	9.11	1.862	1.475	1.377	1.297	2.1	4.4	Si-Defl. SN
9.4E[c]	9.11	1.862	1.475	1.335	1.259	2.1	4.4	Si-Defl. SN
9.5	9.21	1.944	1.592	1.387	1.287	2.2	4.2	Si-Flash SN
9.6	9.30	2.094	1.528	1.400	1.302	2.1	7.0	"
9.7	9.39	2.183	1.546	1.412	1.305	2.2	7.4	"
9.8A[c]	9.48	2.281	1.564	1.409	1.316	2.1	7.3	Si Defl. SN
9.8E[c]	9.48	2.281	1.564	1.269	1.215	2.1	7.3	"
9.9A[c]	9.58	2.356	1.588	1.415	1.349	2.2	8.4	"
9.9E[c]	9.58	2.356	1.597	1.302	1.231	2.2	8.4	"
10.0A[c]	9.69	2.448	1.612	1.430	1.362	2.0	10	"
10.0E[c]	9.69	2.448	1.626	1.311	1.232	2.0	10	"
10.1C[c]	9.79	2.484	1.634	1.427	1.354	2.0	10	"
10.1E[c]	9.79	2.484	1.657	1.336	1.256	2.0	10	"
10.2C[c]	9.89	2.545	1.655	1.427	1.363	2.0	12	"
10.2E[c]	9.89	2.545	1.638	1.370	1.296	2.0	12	"
10.3D[c]	10.00	2.591	1.670	1.438	1.336	2.0	9.3	"
10.3E[c]	10.00	2.591	1.645	1.363	1.260	2.0	9.3	"
10.4	10.09	2.634	1.684	1.477	1.353	2.0	9.9	Ordinary SN
10.5	10.19	2.666	1.709	1.477	1.355	2.0	11	"
11	10.68	2.797	1.780	1.545	1.411	2.8	7.3	"
11.5	10.81	2.740	1.757	1.487	1.375	2.7	12.5	"
12.0	10.93	3.103	1.997	1.636	1.290	3.7	12.2	"

ELECTRON-CAPTURE SUPERNOVAE

e.g., $M_\alpha = 2.2\ M_\odot$ i.e., main sequence mass $\approx 9\ M_\odot$ (Nomoto et al)

O, Ne, Mg core develops - residual of carbon burning, but not hot enough to ignite Ne or O burning. Degenerate core (may) grow by thin helium shell burning. $M \rightarrow 1.375\ M_\odot$ if envelope not lost

$^{24}Mg(e^-,\nu_e)^{24}Na$, $^{20}Ne(e^-,\nu_e)^{20}Na$ reduce Y_e hence $\rho \uparrow$

runaway collapse

At about 2×10^{10} g cm^{-3}, ignite oxygen burning, but matter is already falling in rapidly. Very degenerate runaway. Burn to iron group but $kT < \varepsilon_{Fermi}$. No appreciable overpressure. Instead capture electrons on Fe group nuclei. Collapse accelerates.

Oxygen burning continues, but in a thin shell through which matter is falling supersonically. Collapse continues to nuclear density without ever having formed a large iron core.

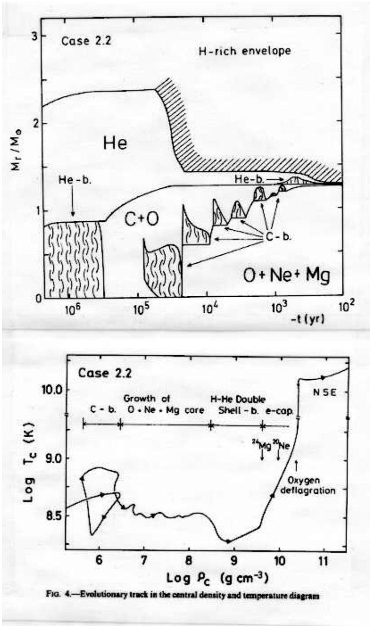
Original model due to Miyaji et al (1980). Studied many times since.

A similar evolution may occur for accreting Ne-O white dwarfs (or very rapidly accreting CO-white dwarfs) in binary systems - an alternate outcome to Type Ia supernovae. This phenomena in a binary is generally referred to as "Accretion Induced Collapse (AIC)".

Once the collapse is well underway, the outcome does not vary appreciably from what one would expect for a collapsing iron core of the same (zero temperature Chandrasekhar) mass.

The energy release from oxygen burning and silicon burning is small compared with the gravitational potential at which the burning occurs

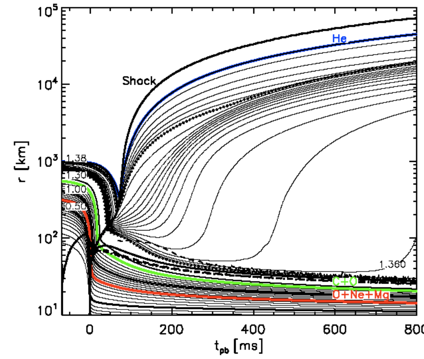
Miyaji et al, *PASJ*, **32**, 303 (1980)
Nomoto, *ApJ*, **277**, 791(1984)
Nomoto, *ApJ*, **322**, 206 (1987)
Mayle and Wilson, *ApJ*, **334**, 909 (1988)
Baron et al, *ApJ*, **320**, 304, (1987)



$M_{MS} \approx 8.5\ M_\odot$

$M_{He} \approx 2.2\ M_\odot$

Nomoto, *ApJ*, **322**, 206, (1987)



Kitaura, Janka, and Hillebrandt (2006) using 2.2 solar mass He core from Nomoto (1984, 1987)

Explosion ~10^{50} erg, basically the neutrino wind. Very little Ni or heavy elements ejected.

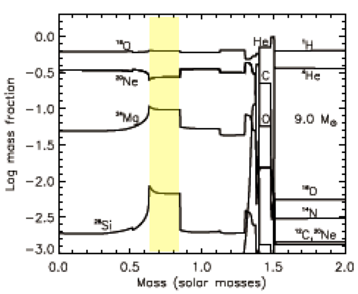
Faint supernova(?)

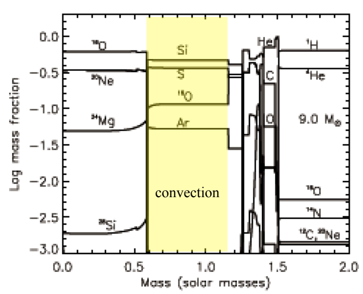
*Star of ~ 10 solar masses suggested as progenitor of the Crab nebula by Nomoto et al. (1982, Nature, **299**, 803)*

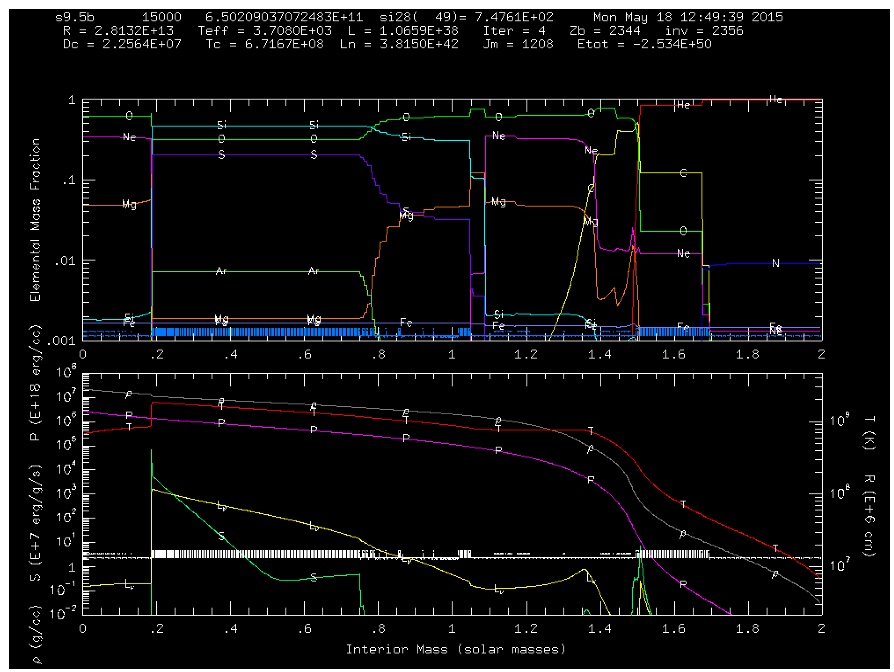
Observed for Crab: KE = 0.6 to 1.5 x 10^{50} erg in 4.6+- 1.8 solar masses of ejecta (Davidson and Fesen 1985)

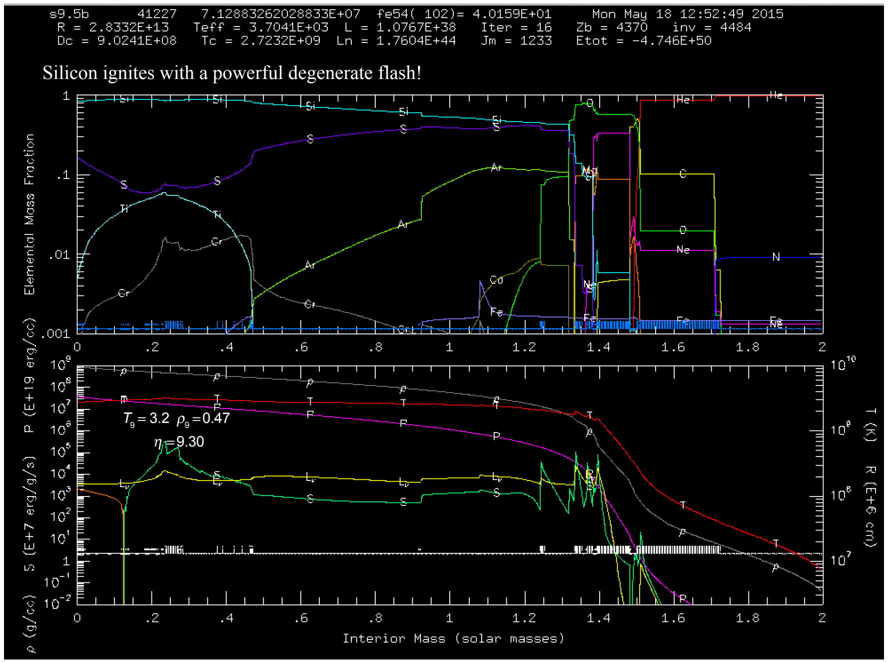
"FLAME" STARS (9.0 – 10.5 Solar Masses)

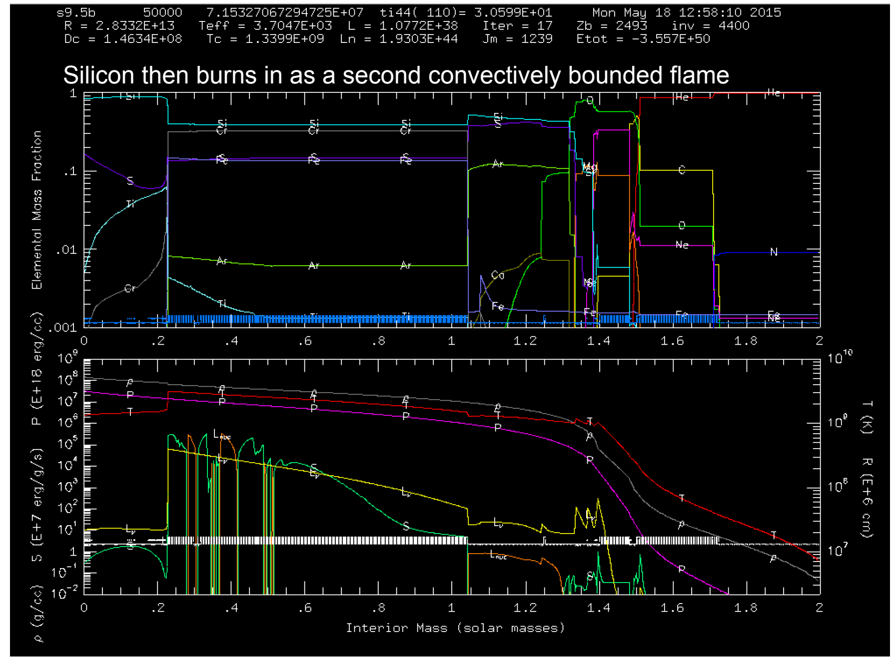
Due to plasma neutrino losses which increase rapidly with the density, a temperature inversion develops. Neon, oxygen and silicon burning ignite off center and burn inwards in "convectively bounded flames".

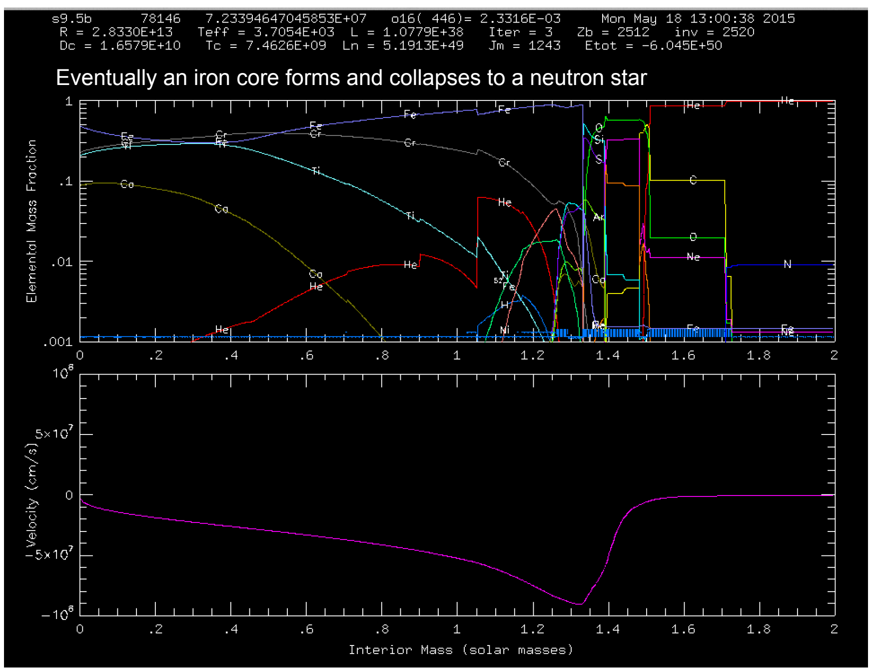


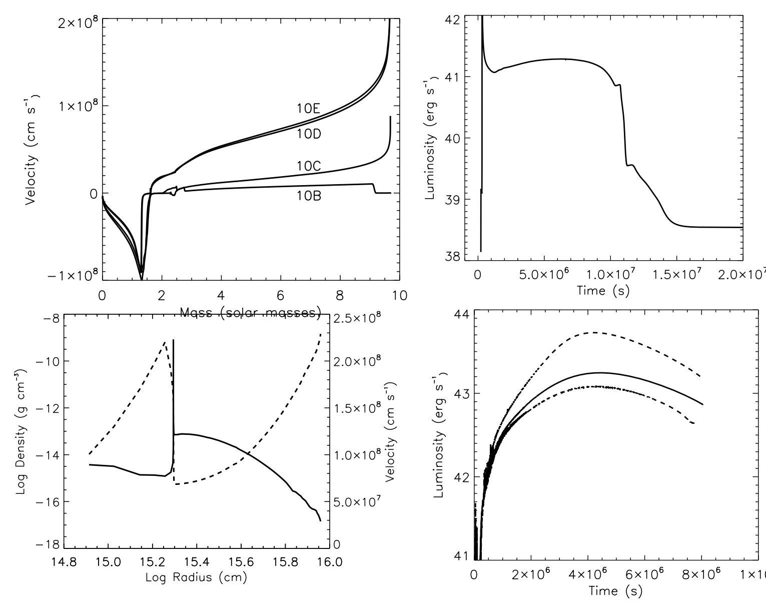





s9.5b 41227 7.12883262028833E+07 fe54(102)= 4.0159E+01 Mon May 18 12:52:49 2015
R = 2.8332E+13 Teff = 3.7041E+03 L = 1.0767E+38 Iter = 16 Zb = 4370 inv = 4484
Dc = 9.0241E+08 Tc = 2.7232E+09 Ln = 1.7604E+44 Jm = 1233 Etot = -4.746E+50
Silicon ignites with a powerful degenerate flash!
Elemental Mass Fraction
ρ (g/cc) S (E+7 erg/g/s) P (E+19 erg/cc)
T (K) R (E+6 cm)
Interior Mass (solar masses)


s9.5b 50000 7.15327067294725E+07 ti44(110)= 3.0599E+01 Mon May 18 12:58:10 2015
R = 2.8332E+13 Teff = 3.7047E+03 L = 1.0772E+38 Iter = 17 Zb = 2493 inv = 4400
Dc = 1.4634E+08 Tc = 1.3399E+09 Ln = 1.9303E+44 Jm = 1239 Etot = -3.557E+50
Silicon then burns in as a second convectively bounded flame
Elemental Mass Fraction
ρ (g/cc) S (E+7 erg/g/s) P (E+18 erg/cc)
T (K) R (E+6 cm)
Interior Mass (solar masses)


s9.5b 78146 7.23394647045853E+07 o16(446)= 2.3316E-03 Mon May 18 13:00:38 2015
R = 2.8330E+13 Teff = 3.7054E+03 L = 1.0779E+38 Iter = 3 Zb = 2512 inv = 2520
Dc = 1.6579E+10 Tc = 7.4626E+09 Ln = 5.1913E+49 Jm = 1243 Etot = -6.045E+50
Eventually an iron core forms and collapses to a neutron star
Elemental Mass Fraction
Velocity (cm/s)
Interior Mass (solar masses)


Velocity (cm s^{-1})
Mass (solar masses)
10E
10D
10C
10B
Luminosity (erg s^{-1})
Time (s)
Log Density (g cm^{-3})
Log Radius (cm)
Velocity (cm s^{-1})
Luminosity (erg s^{-1})
Time (s)

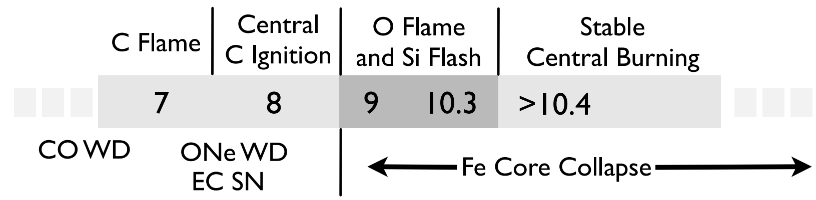
But what about the Crab?

In a calculation that included current approximations to all known mechanisms of angular momentum transport in the study, the final angular momentum in the iron core of a 10 solar mass star when it collapses was
5 x 10^{47} erg s

This corresponds to a pulsar period of 17 ms, just a bit less than the Crab is believed to have been born with.

Spruit (2006) suggests modifications to original model that may result in still slower spins.

Therefore---
The explosion of the Crab SN was probably not (initially) powered by rotation and the explosion was therefore weak. But historical accounts suggest that it was very bright...



Stars 10.5 solar masses and above ignite all post-helium burning stages in their centers without violent flashes (KEPLER)

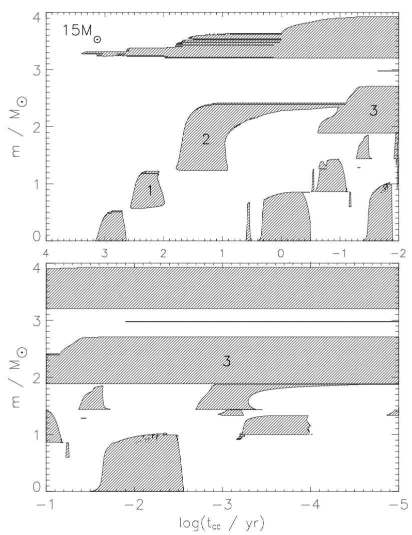


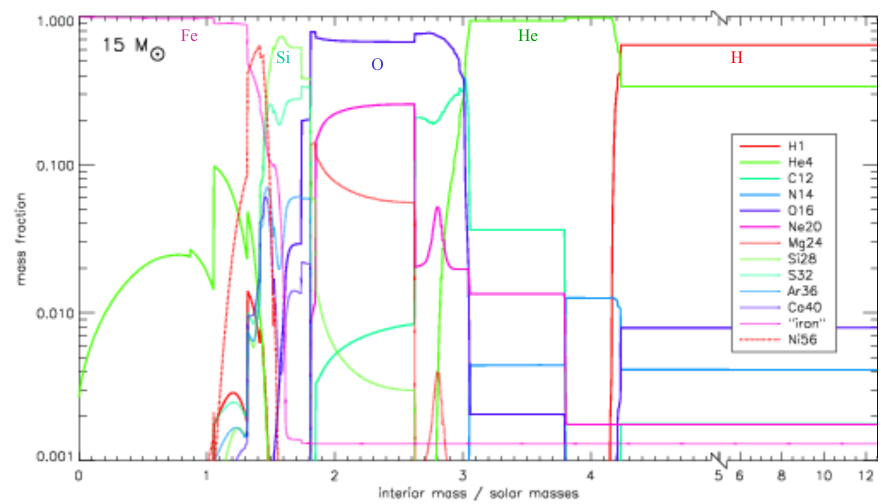
Figure 8. Convective history of a 15 $M_\odot$ model, a typical supernova mass

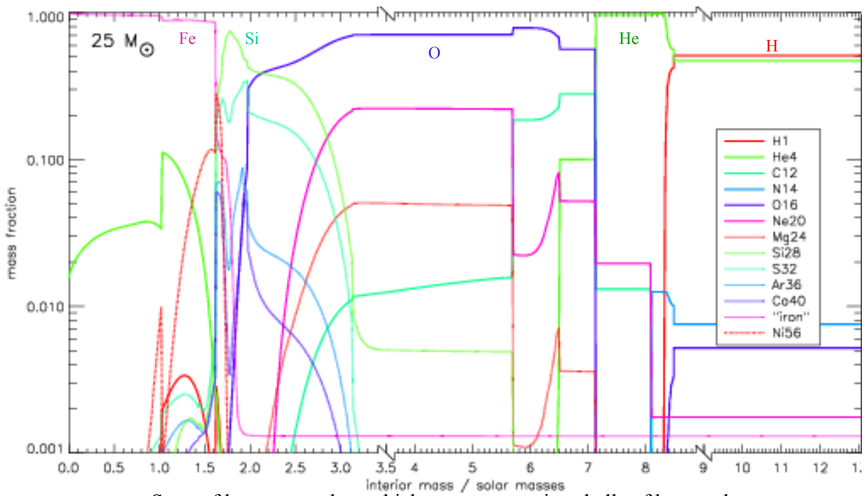
Sukhbold and Woosley (2014)

Top: Carbon, neon, and oxygen burning

Bottom: Silicon burning. x-axis is log time until iron core collapse.

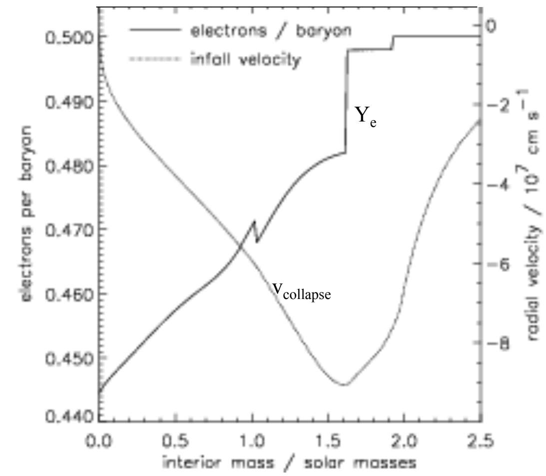
The convective burning shells occur in different places and times for different mass stars and "sculpt" the density structure around the final iron core.





Stars of larger mass have thicker, more massive shells of heavy elements surrounding the iron core when it collapses.

Note that the final masses of the 15 and 25 solar mass main sequence stars are nearly the same – owing to mass loss.



Distribution of collapse velocity and Y_e (solid line) in the inner 2.5 solar masses of a 15 solar mass presupernova star. A collapse speed of 1000 km/s anywhere in the iron core is a working definition of "presupernova". The cusp at about 1.0 solar masses is the extent of convective core silicon burning.

Core Collapse

Once the collapse is fully underway, the time scale becomes very short. The velocity starts at 10^8 cm s^{-1} (definition of the presupernova link) and will build up to at least c/10 = 30,000 km s^{-1} before we are through. Since the iron core only has a radius of 5,000 to 10,000 km, the next 0.2 seconds are going to be very interesting.

Neutrino Trapping

Trapping is chiefly by way of elastic neutral current scattering on heavy nuclei. Freedman, PRD, 9, 1389 (1974) gives the cross section

$$\sigma_{coh} \approx a_0^2\, A^2 \left(\frac{\varepsilon_\nu}{\text{MeV}}\right)^2 \bullet 1.5\times10^{-44}\ \text{cm}^2$$

hence

$a_0 = \sin^2(\theta_W)$ where θ_W is the "Weinberg angle", a measure of the importance of weak neutral currents

$$\kappa_{\text{coh}} \approx a_o^2\, A\, N_A \left(\frac{\varepsilon_\nu}{\text{MeV}}\right)^2 \bullet 1.5\times10^{-44}\ \text{cm}^2\ \text{gm}^{-1}$$

$$= 5.0\times10^{-19}\, a_0^2 \left(\frac{A}{56}\right)\left(\frac{\varepsilon_\nu}{\text{MeV}}\right)^2\ \text{cm}^2\ \text{gm}^{-1}$$

$$\kappa_{coh} = 2.6\times10^{-20}\left(\frac{A}{56}\right)\left(\frac{\varepsilon_\nu}{\text{MeV}}\right)^2\ \text{cm}^2\,\text{gm}^{-1}$$

if one takes $a_0^2 = \sin^4(\theta_W) = (0.229)^2 = 0.0524$

$$\varepsilon_F = 1.11(\rho_7 Y_e)^{1/3} \text{ MeV}$$
$$\sim 20 \text{ MeV at}$$
$$\rho = 10^{11} \text{ g cm}^{-3}$$
$$(\varepsilon_\nu \sim 10-20 \text{ MeV is better})$$

Therefore neutrino trapping will start when

$$\kappa_\nu \rho R \sim 1 \qquad R \sim 10^6 \text{ cm}$$

$$\left(3\times10^{-20}\right)(2)(100)\rho\left(10^6\right) \sim 1 \;\Rightarrow \rho \sim 10^{11} \text{ g cm}^{-3}$$

(for $A \sim 100$)

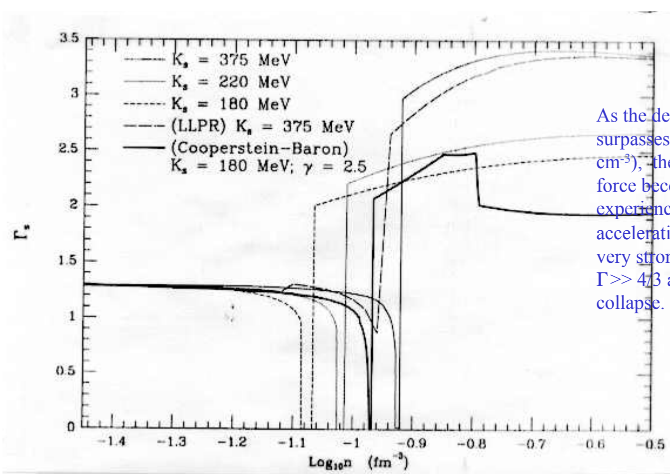
From this point on the neutrinos will not freely stream but, increasingly, will diffuse. Neutrino producing reactions will be inhibited by the filling of neutrino phase space. The total lepton number

$$Y_L = Y_e + Y_\nu$$

will be conserved, not necessarily the individual terms. At the point where trapping occurs $Y_L = Y_e \sim 0.37$. At bounce $Y_e \sim 0.29$; $Y_\nu \sim 0.08$.

Alternatively set $\tau_{diff} = \dfrac{R^2 \kappa \rho}{c}$ to the collapse;

time, ~10 ms. Get $\rho \sim 10^{12}$ (*crude*)



As the density reaches and surpasses nuclear)(2.7 x 10^{14} gm cm^{-3}), the effects of the strong force become important. One first experiences attraction and an acceleration of the collapse, then a very strong repulsion leading to $\Gamma >> 4/3$ and a sudden halt to the collapse.

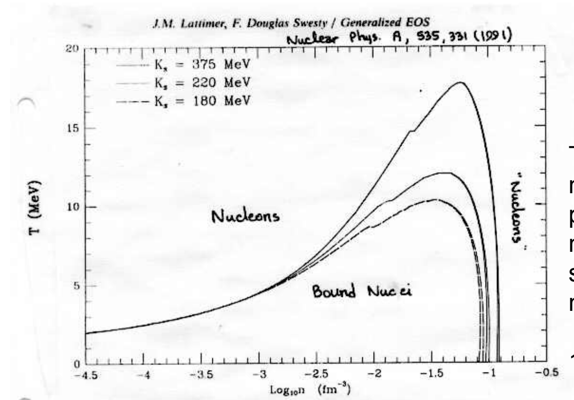
In general, favor the curves K = 220. For densities significantly below nuclear, Γ is due to relativistic positrons and electrons.

Bounce

Up until approximately nuclear density the structural adiabatic index of the collapsing star is governed by the leptons – the electrons and neutrinos, both of which are highly relativistic, hence nearly Γ=4/3.

As nuclear density is approached however, the star first experiences the attactive nuclear force and Γ goes briefly but dramatically below 4/3.

At still higher densities, above ρ_{nuc}, the repulsive hard core nuclear force is encountered and abruptly $\Gamma >> 4/3$.



Phase boundaries between uniform matter and nuclei for the case $Y_e = 0.3$ and for selected values of the incompressibility K_s.

$$\rho = 1.66\times10^{15}\, n(\text{fm}^{-3}) \text{ g cm}^{-3}$$
$$= (N_A 10^{-39})^{-1} \text{ "}$$

Throughout the collapse, nuclei stay, for the most part, bound, but above nuclear density it makes sense to talk of individual nucleons again.

1 MeV = 11.6 billion K

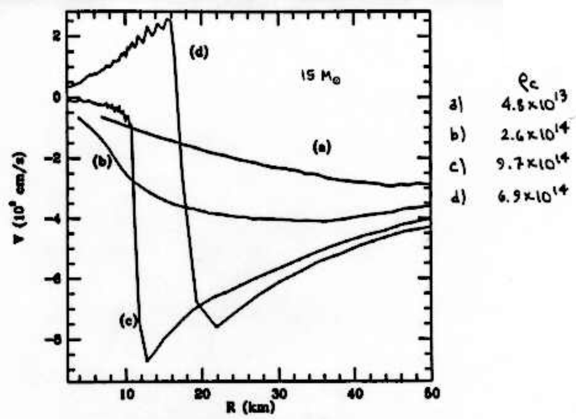


Figure 16: Velocity profiles at various times
The velocity profiles of taken from the collapse of the 15 $M_\odot$ model of Woosley and Weaver (1988). Time (a) is at last good homology, time (b) when the center has gone above nuclear matter density and the homology is broken, time (c) is at maximum scrunch, and time (d) is when the shock wave has been launched.

The portion of the core that collapses together is called the "homologous core". It collapses subsonically (e.g., Goldreich & Weber, *ApJ*, **238**, 991 (1980); Yahil *ApJ*, ***265***, 1047 (1983)). This is also approximately equivalent to the "sonic core".

This part of the core is called homologous because it can be shown that within it, $v_{collapse}$ is proportional to radius. Thus the homologous core collapses in a sef similar fashion. Were $\Gamma = 4/3$ for the entire iron core, the entire core would contract homologously, but because Γ becomes significantly less than 4/3, part of the inner core pulls away from the outer core.

As the center of this inner core approaches and exceeds ρ_{nuc} the resistance of the nuclear force is communicated throughout its volume by sound waves, but not beyond its edge. Thus the outer edge of the homologous core is where the shock is first born. Typically, M_{HC} = 0.6 – 0.8 solar masses.

The larger M_{HC} and the smaller the mass of the iron core, the less dissipation the shock will experience on its way out.

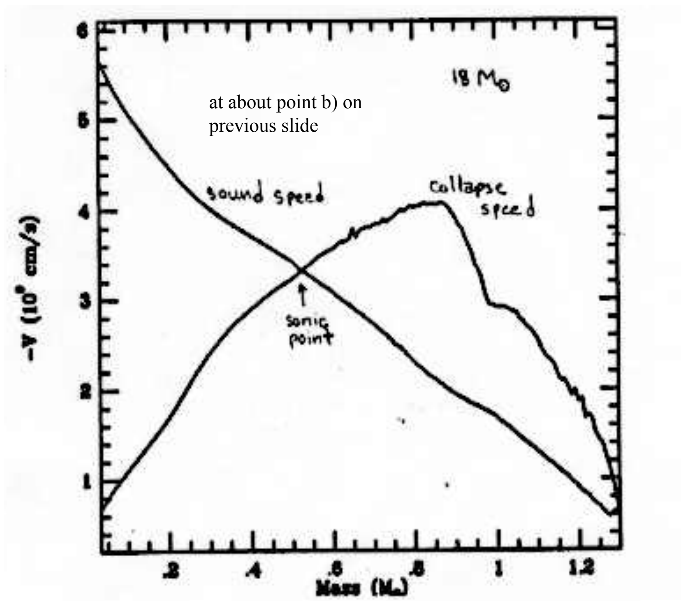


Figure 17: Sonic Point

<u>Factors affecting the mass of the homologous core:</u>

- Y_L – the "lepton number", the sum of neutrino and electron mole numbers after trapping. Larger Y_L gives larger M_{HC} and is more conducive to explosion. Less electron capture, less neutrino escape, larger initial Y_e could raise Y_L.

- GR – General relativistic effects decrease M_{HC}, presumably by strengthening gravity. In one calulation 0.80 solar masses without GR became 0.67 with GR. This may be harmful for explosion but overall GR produces more energetic bounces and this is helpful.

- Neutrino transport – how neutrinos diffuse out of the core and how many flavors are carried in the calculation.

Relevant Physics To Shock Survival

Photodisintegration:

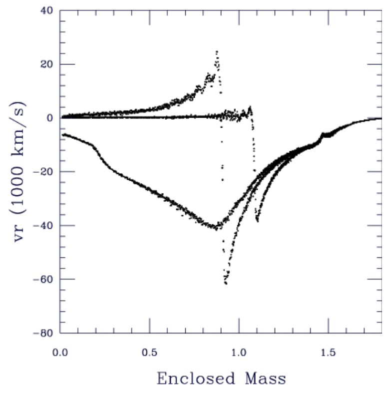
As the shock moves through the outer core, the temperature rises to the point where nuclear statistical equilibrium favors neutrons and protons over bound nuclei or even a-particles

$$q_{nuc}(^{56}Fe \rightarrow 26p, 30n) = 9.65\times10^{17}\left(\frac{492.26\text{ MeV}}{56}\right)$$
$$= 8.5\times10^{18}\text{ erg gm}^{-1}$$
$$= 1.7\times10^{51}\text{ erg}/0.1\ M_\odot$$

Neutrino losses

Especially as the shock passes to densities below 10^{12} g cm^{-3}, neutrino losses from behind the shock can rob it of energy. Since neutrinos of low energy have long mean free paths and escape more easily, reactions that degrade the mean neutrino energy, especially neutrino-electron scattering are quite important. So too is the inclusion of $\mu-$ and $\tau-$flavored neutrinos

It is now generally agreed that the so called "prompt shock mechanism" – worked on extensively by Bethe, Brown, Baron, Cooperstein, and colleagues in the 1980's – does not work. The shock fails and becomes in a short time (< 10 ms) an accretion shock.



Collapse and bounce in a 13 solar mass supernova. Radial velocity vs. enclosed mass at 0.5 ms, +0.2 ms, and 2.0 ms with respect to bounce. The blip at 1.5 solar masses is due to explosive nuclear burning of oxygen in the infall (Herant and Woosley 1996).

The Equation of State and General Relativity

A softer nuclear equation of state is "springier" and gives a larger amplitude bounce and larger energy to the initial shock. General relativity can also help by making the bounce go "deeper".

The "Compactness" of the Presupernova Star

It is relatively easy to blow up stars that have rapid density declines outside of the iron core – e,g, 9 – 11 solar masses

The Dimensionality of the Calculation and the Treatment of ν-Transport

The resources to do realistic 3D calculations are just becoming available

Rotation and Magnetic Fields

Clearly a major factor in making a gamma-ray burst and the supernova that goes with it. How extensive is the mass range where these are important?