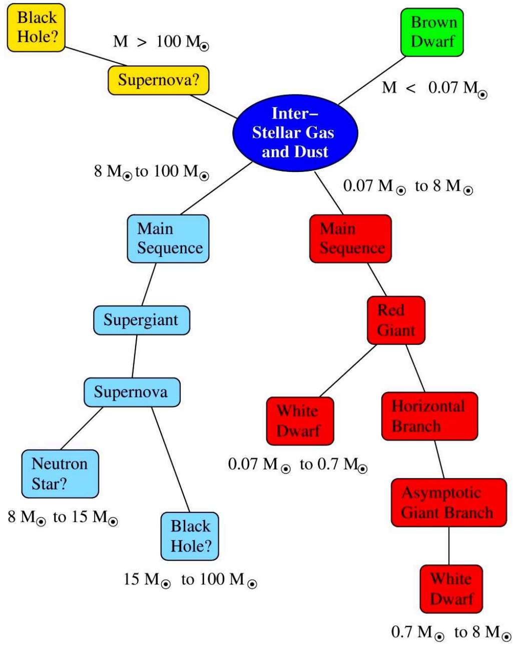
Core Collapse Supernovae

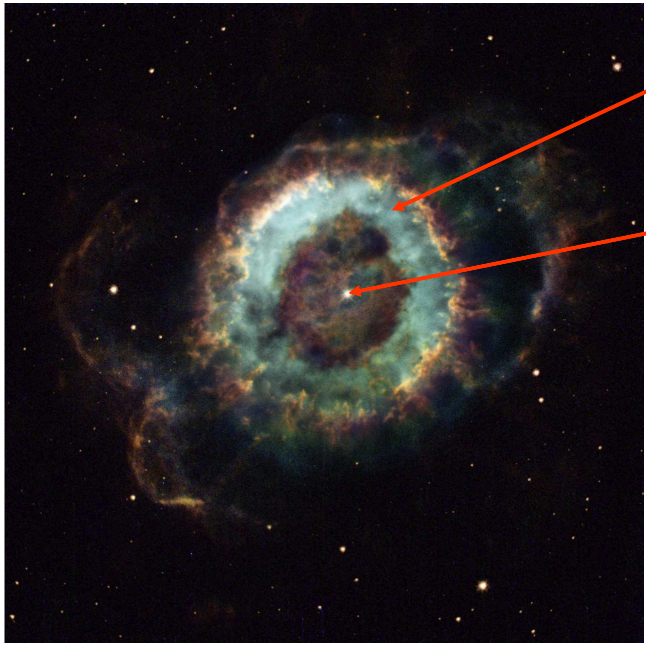
- Explosions of Massive Stars
- Explosive Nucleosynthesis
- Remnants: Neutron stars and Black Holes

Literature: Iliadis, Chap.5.5
Rolfs & Rodney: Cauldrons in the Cosmos, chap. 8 and 9

A Summary of Stellar Evolution



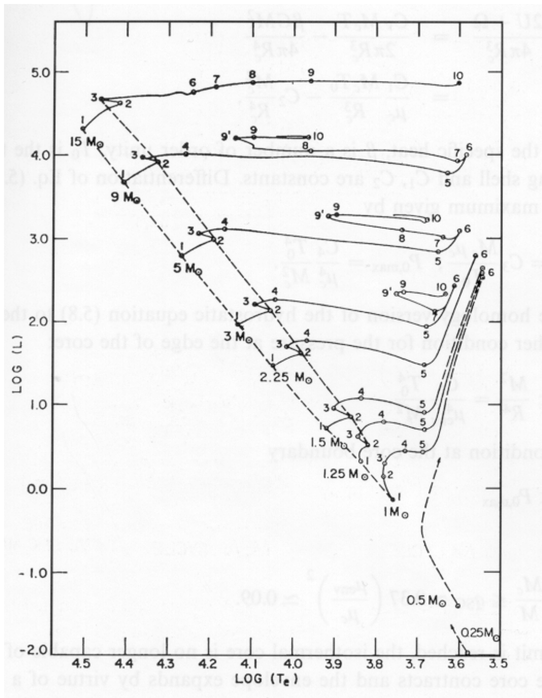
Death of a low mass star: a “Planetary Nebula”



Envelope of star blown into space

And here’s the core !
a “white dwarf”

image: HST
Little Ghost Nebula
distance 2-5 kLy
blue: OIII
green: HII
red: NII



Zero Age Main Sequence (ZAMS): “1”

End of Main Sequence: “2”
(from Kippenhahn & Weigelt, Stellar Structure & Evolution)

Summary: Main Products of Hydrostatic Burning

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	4 H → ^4He (CNO)
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	3 He^4 → ^{12}C; $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	^{12}C + ^{12}C
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$; $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	^{16}O + ^{16}O
Si	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)$…

Summary: Stellar Evolution Stages

hydrogen burning

$M_{initial}$ $M_\odot$	T 10^7 K	ρ g cm^{-3}	M $M_\odot$	L $10^3 L_\odot$	R $R_\odot$	τ 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

$M_{initial}$ $M_\odot$	T 10^8 K	ρ 10^3 g cm^{-3}	M $M_\odot$	L $10^3 L_\odot$	R $R_\odot$	τ 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

$M_{initial}$ $M_\odot$	T 10^8 K	ρ 10^5 g cm^{-3}	M $M_\odot$	L $10^3 L_\odot$	R $R_\odot$	τ 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

$M_{initial}$ $M_\odot$	T 10^9 K	ρ 10^6 g cm^{-3}	M $M_\odot$	L $10^3 L_\odot$	R $R_\odot$	τ 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

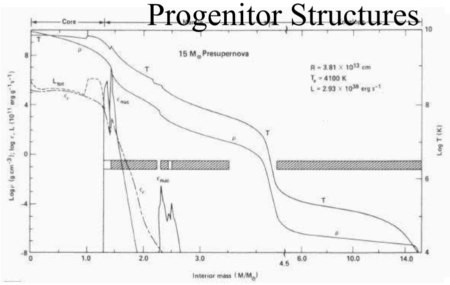
$M_{initial}$ $M_\odot$	T 10^9 K	ρ 10^6 g cm^{-3}	M $M_\odot$	L $10^3 L_\odot$	R $R_\odot$	τ yr
15	1.94	6.66	12.6	86.6	821	2.58
20	1.98	5.55	14.7	147	1,090	1.25
25	2.09	3.60	12.5	246	1,400	0.402
75	2.04	4.70	6.36	172	0.756	0.908

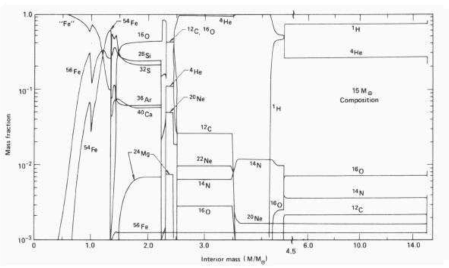
silicon burning

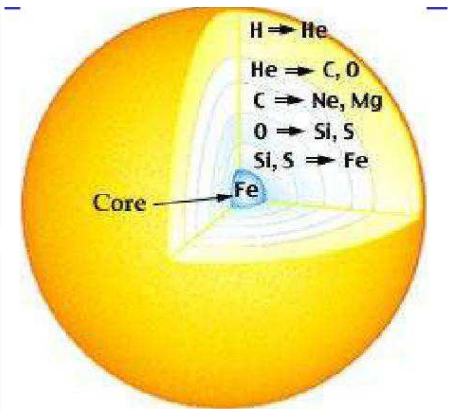
$M_{initial}$ $M_\odot$	T 10^9 K	ρ 10^7 g cm^{-3}	M $M_\odot$	L $10^3 L_\odot$	R $R_\odot$	τ d
15	3.34	4.26	12.6	86.5	821	18.3
20	3.34	4.26	14.7	147	1,090	11.5
25	3.65	3.01	12.5	246	1,400	0.733
75	3.55	3.73	6.36	173	0.755	2.09

Next: Exploding Stars /Supernovae

Progenitor Structures

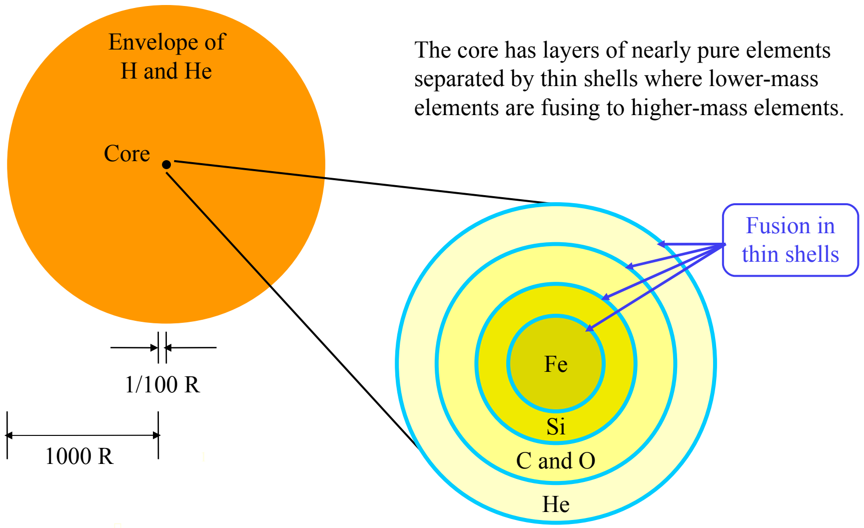






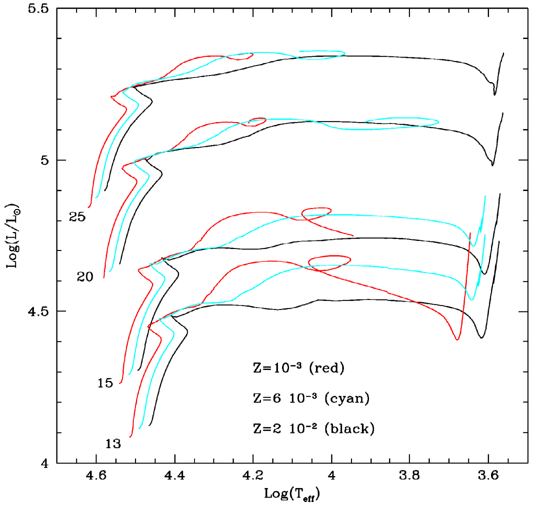
Internal Structure of a Type II Supernova Just Before Its Core Collapses and It Explodes

The core has layers of nearly pure elements separated by thin shells where lower-mass elements are fusing to higher-mass elements.



Diversity of Progenitor

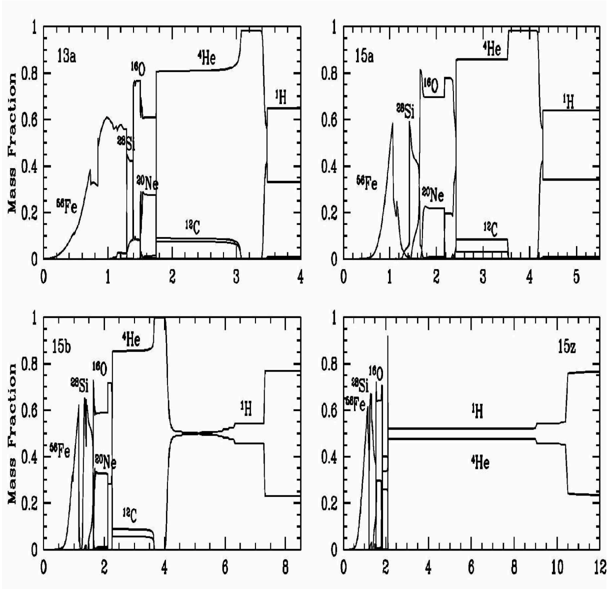
Example: HR-Diagram for various Masses & Metallicities



- RSG/ BSG depends on the H-shell burning (inner boundary of H-rich layer
- Stars tend to end as BSG for low metallicity
- Final BSG is 'more likely' for higher masses
- Z= 0 = > BSG for all M

Final Chemical Structure of the Progenitors

Effect of M(MS) and Z on the core structure



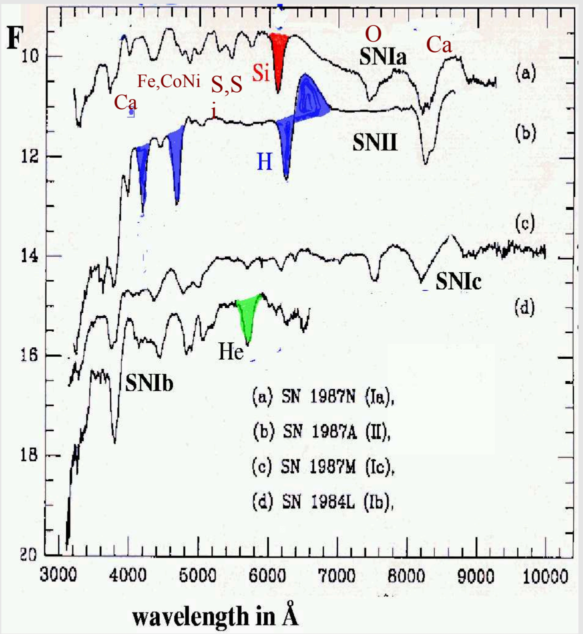
Solar abundance: __a
Z=1E-3 : __b
Z= 0 : __z

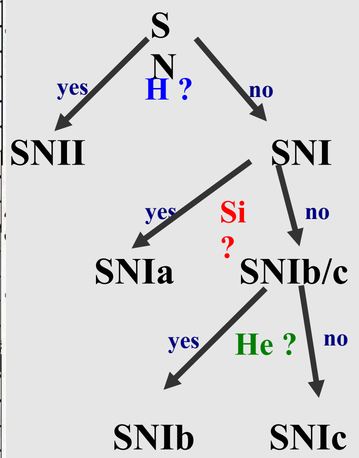
Core masses: 1.8 - 8 Mo

Uncertainties:

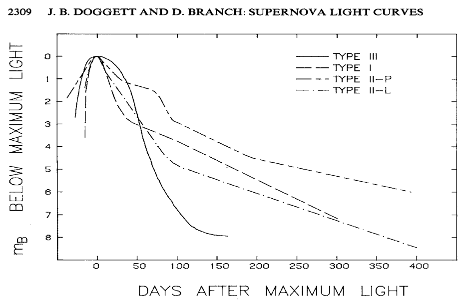
Core structure depends on
- turbulence/ convection (mixing lengths/ overshooting
- nuclear reaction rates (e.g. 12C(α ,γ)16O)

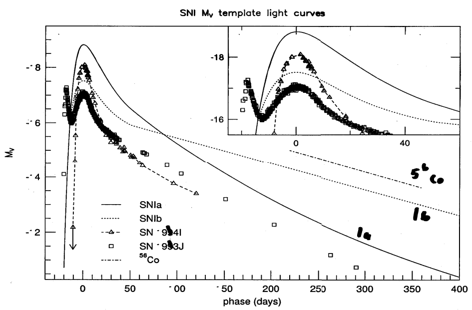
Classification of Supernovae by Spectra at Maximum





Light Curves of Supernovae





Schematic LCs of various types

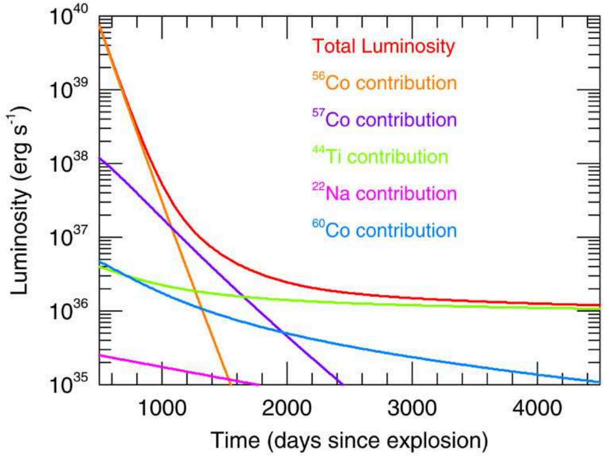
I) only SNIa are thermonuclear

II) **SNII: (H-spectra)**
- a) Different shapes
  - SNII-P: extended plateau
  - SNII-L: linear decline
- b) Rise times t(V):
  - 20d (e.g. SN1993j) and 80d (SN1987A)
- c) Brightness at maximum
  - -16.5m (1987A) to -20m (SN1979c)

III) **SNIb: (H-deficient spectra, but He)**
- a) Rise times are about 15 to 25 days
- b) Brightness at maximum(-17m ..-19m)

IV) SNIc:**(H- and He deficient spectra)**
- a) Different shapes (with and without Co tail)
- b) Rise times t(V): 15 to 25d (e.g. SN94I)
- c) Brightness at maximum -17m (SN94I) to -19.3m (SN98bw/ hypernova)

There is another effect that extends SN light curves: Radioactive decay !



→ Radioactive isotopes are produced during the explosion

→ there is explosive nucleosynthesis !

Endpoints of stellar evolution

The end of stellar evolution is an inert core of spent fuel that cannot maintain gas pressure to balance gravity

Such a core can be balanced against gravitational collapse by electron degeneracy pressure IF the total mass is less than the Chandrasekhar mass limit:

Chandrasekhar Mass:

Only if the mass of a inert core is less than Chandrasekhar Mass M

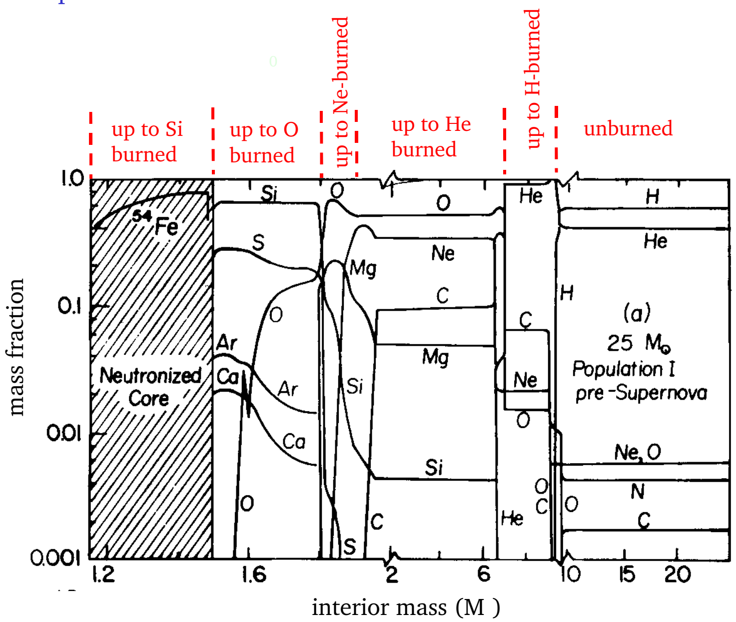
$$M_{Ch} \approx 5.85\, Y_e^2 M_{\odot}$$

Electron degeneracy pressure can prevent gravitational collapse

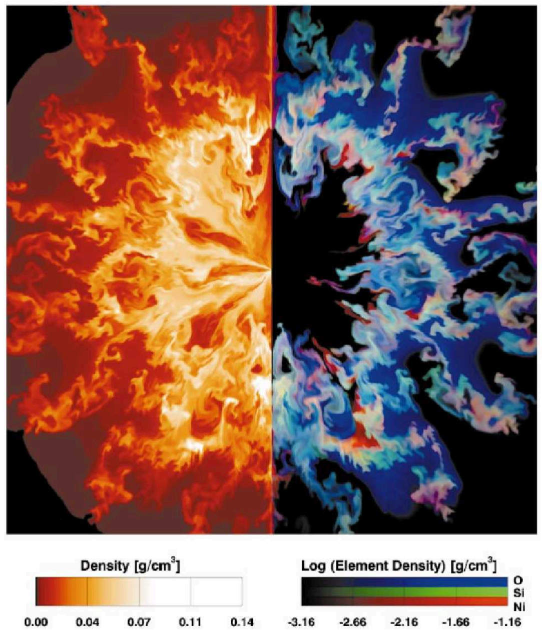
In more massive cores electrons become relativistic and gravitational collapse occurs (then p~n instead of p~n).

For N=Z M =1.46 M

Final composition of a 25 M star:

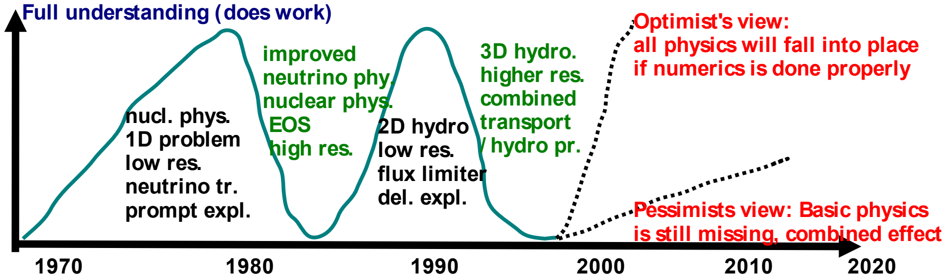


The "mass zones" in "reality":

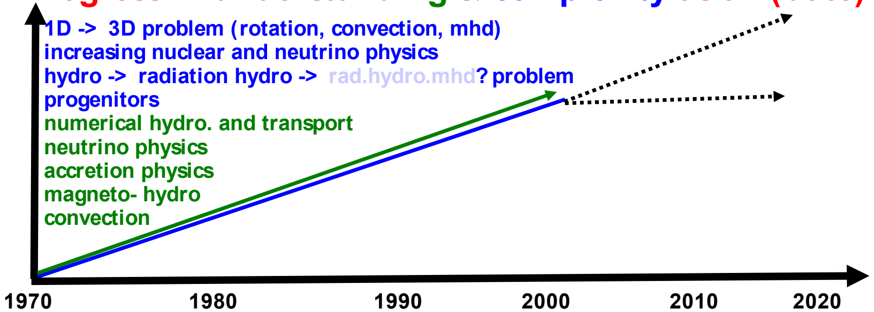


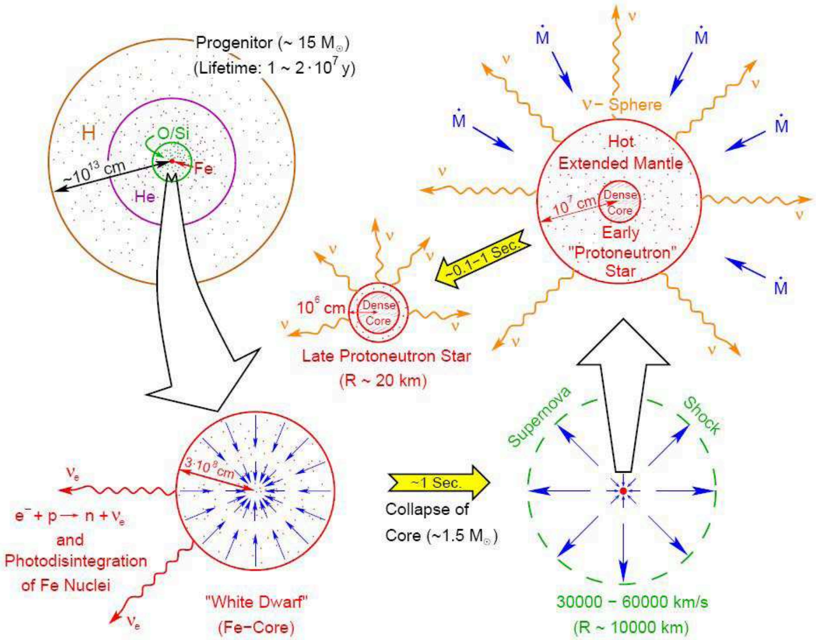
1170s after explosion, 2.2Mio km width, after Kifonidis et al. Ap.J.Lett. 531 (2000) 123L

Perceived status of the SN problem as a function of time

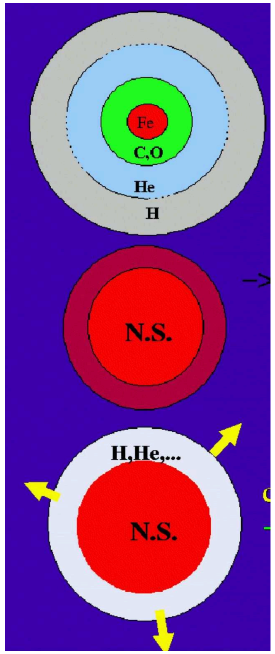


Progress in understanding & complexity as a F(date)





SN-Scenario: Core Collapse of Star > 8 Mo



Example: 12Mo< M(MS)

a) Final stellar structure with 10Ro< R< 1000Ro (SNII)
   0.2 to 2 Ro for CO-core (SNIc)
b) Hot Fe core is supported by partially degenerate electrons
   electron capture and photo-disintegration of heavy nuclei
=> Collapse of Fe core and formation of a proto neutron star

- released potential energy : 1E53 erg
- collapse time scale : 1 sec
- radius of hot neutron star: 100 to 200 km

Most of the energy is lost by neutrino cooling over 10-60 sec.

c) Ejection of the envelope
- about 1.5 ..2.5E51 erg are deposited in the envelope
- envelope becomes unbound (E(pot)= 5E50erg)

Problems and complications:
a) No self-consistent model for the ejection.
Mechanisms include shock driven, neutrino driven, MHD,...
b) Properties of remnants, i.e. Neutron star vs. Black Hole
c) Initial boundary, i.e. stellar structure, mass loss etc.

C) Scenarios for core collapse SNII, Ib,Ic (M > 8Mo)

I) Initial collapse phase

a) 8 Mo < M < 10..12 Mo
1) Central, non-degenerate C-burning -> degenerate O,Ne,Mg core grows(Mcore<M(Ch))
2) Further growing by C-shell burning
3) Electron capture on Mg and Ne reduced pressure due to electrons (part. deg.)
   and M(Ch) decreases (due to change in mean molecular weight) -> collapse starts
4) Explosive O and Si burning set in

b) M > 10..12 Mo: hydrostatic burning up to Fe -> electron capture + collapse starts

II) Γ < 4/3 (rel. deg. electron gas + electron capture) [e + p -> n + ν (e)]

Inner region is a n=3 polytrope: M(r)=M(r/R) -> dv/dr=v(R)r/R ->homologous collapse

III) rho > 3E11 ... 1E12 g/ccm -> trapping of neutrinos

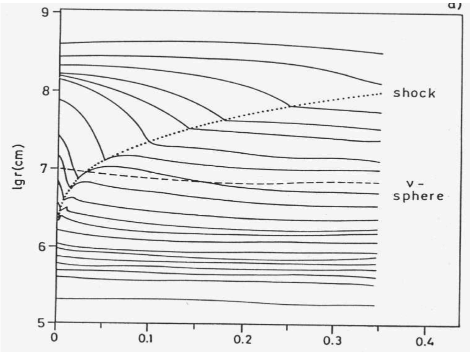
IV) Neutonization: e + p <=> n + ν (e), and formation of a proto-neutron star

V) Collapse stops (formation of a hot proto-neutron star supported by deg. n +p)

Rebounce of infalling material (E(kin)=(4-8)E51erg
a shock front is formed
Temperature in shock front > 5E9K -> dissoziation of Fe
=> energy loss 8E18erg/g = 1.6E52erg/Mo
=> shock stalls

Prompt explosion does not work !!!

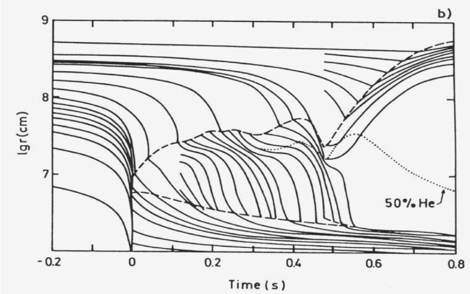
C:Senarios: numerical simulations of the core bounce i



Model for a 20 Mo star

(Hillebrandt 1987, High energy phenoma in massive stars, ed. Pacini, Reidel, p. 73)

- shock stalls -> prompt explosion does not work for massive stars
- neutrinos are not effective

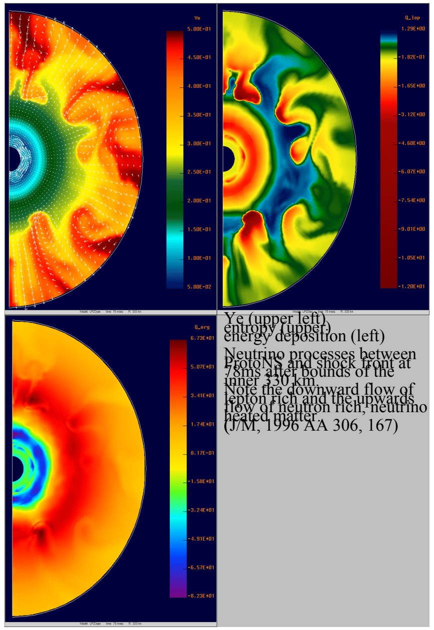


Model for a 25 Mo star

(Wilson, 1985, Numerical Astrophysics, eds. Centrella et al., Jones & Barlett, p.145

- envelope is ejected by a neutrino driven explosion

Solution: Neutrino driven explosions? (Burrows, Herant, Mueller/ Janka



Example: Neutrino processes between the proto-neutron-star and the stalled shock wave

Large scale convection brings in low entropy, high density material to the region of neutrino coupling behind the shock -> more efficient mechanism to gain energy from neutrinos

Very promising till the middle of the 90th but, currently, no group gets strong explosions.

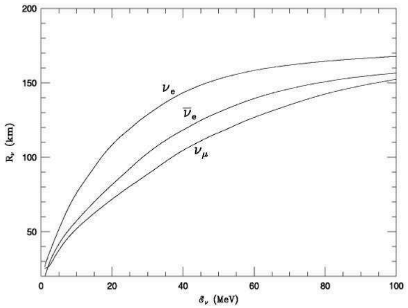
Problems:

- high resolution
- change from 2 to 3-D calculations
  (3-D convection favors small Eddi's which are less effective for transport)
- approximations in neutrino transport
- neutrino cross sections
- equation of state

THIS MECHANISM MAY STILL WORK

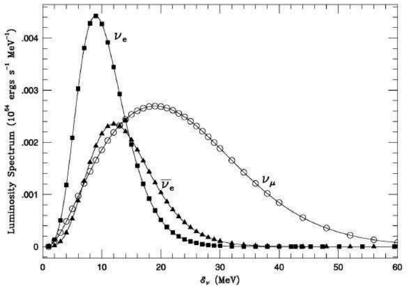
Influence of the neutrino properties

(Example: Burrows et al. 2000, ApJ 539, 865)



Location of the neutrino sphere for various flavors and energies

Rem.: Cross section depends on the flavor and energy



Neutrino luminosity for various flavors and energies

- **cooling of the NS depends on the EOS**
- **production of neutrinos depend on nuclear physics**
- **energy deposition depends on the cross section and emission from the NS**

Advances in neutrino transport

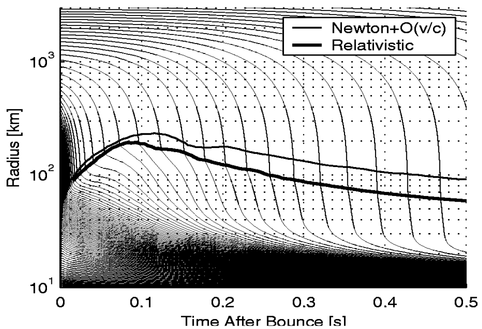
Classical approach: Flux limited diffusion

Different groups get very different answers

Rem.: Result depends sensitively on the flux limiter and the treatment of neutrinos

Now: Full solution of the radiation transport equation for multi-groups, including relativistic terms and in spherical coordinates (and various groups get quantitative similar solutions, e.g. Liebendoerfer et al. 2001, Burrows et al. 2000, Rampp et al. 2000)

Start of multi-D RT (in diffusion approximation, e.g. Lichtenstedt et al., 2000)



(from Liebendoerfer et al. 2001)

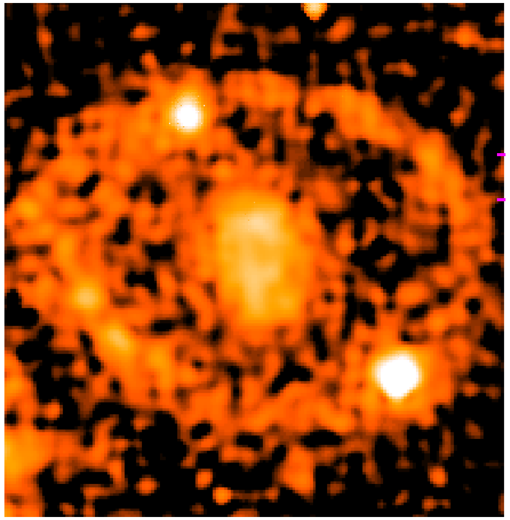
- **Spherical collapse in 1D of a core of a 13 Mo**
- **No explosion**

Results: No explosion in 1-D or multi-D + flux limiter

Hope: Multi-D may solve the problem

Direct Images of SN1987A (SINS-team)

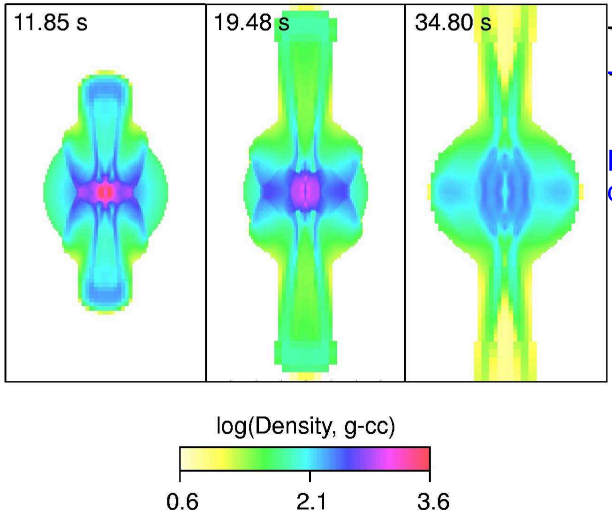
(see L. Wang et al. 2002, ApJ Letter, submitted)



HST image taken in 2000 June 11 (with filter F439W)

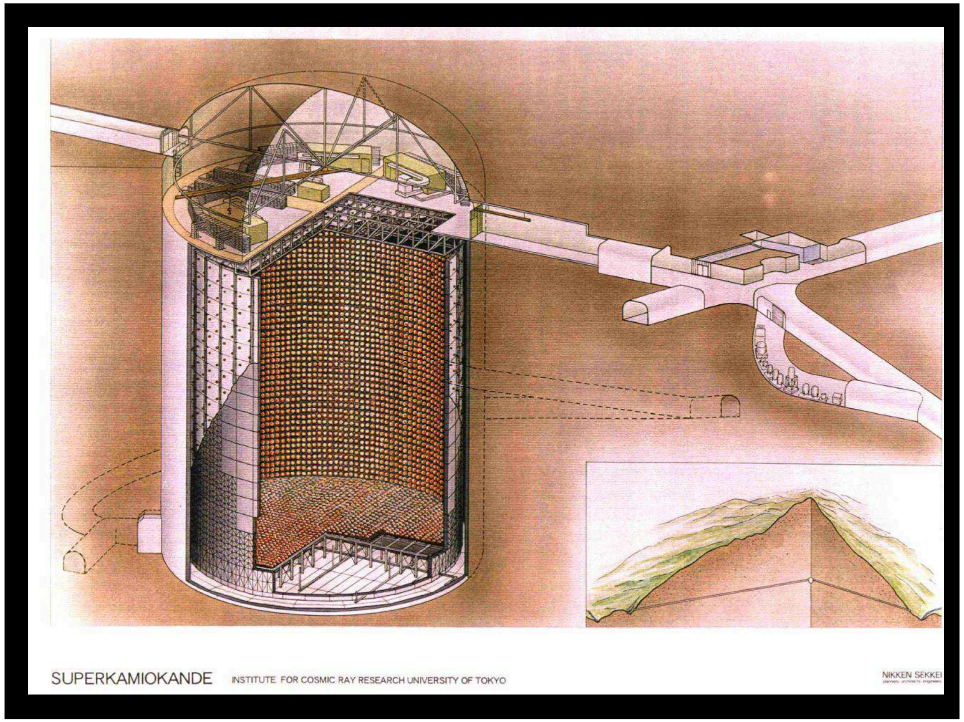
- Common axis for outer ring and inner debris
- Asphericity increases from about 10 % (from P) to a factor of 2

Density structure after jet has penetrated the star

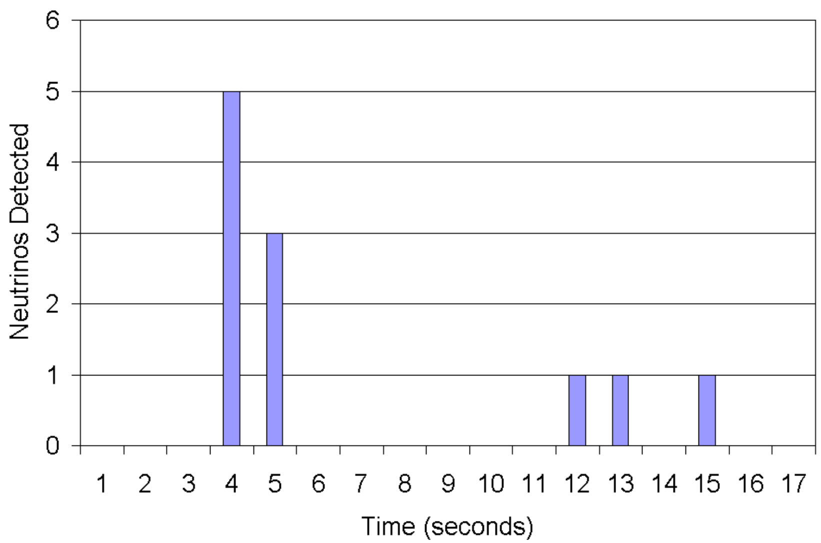


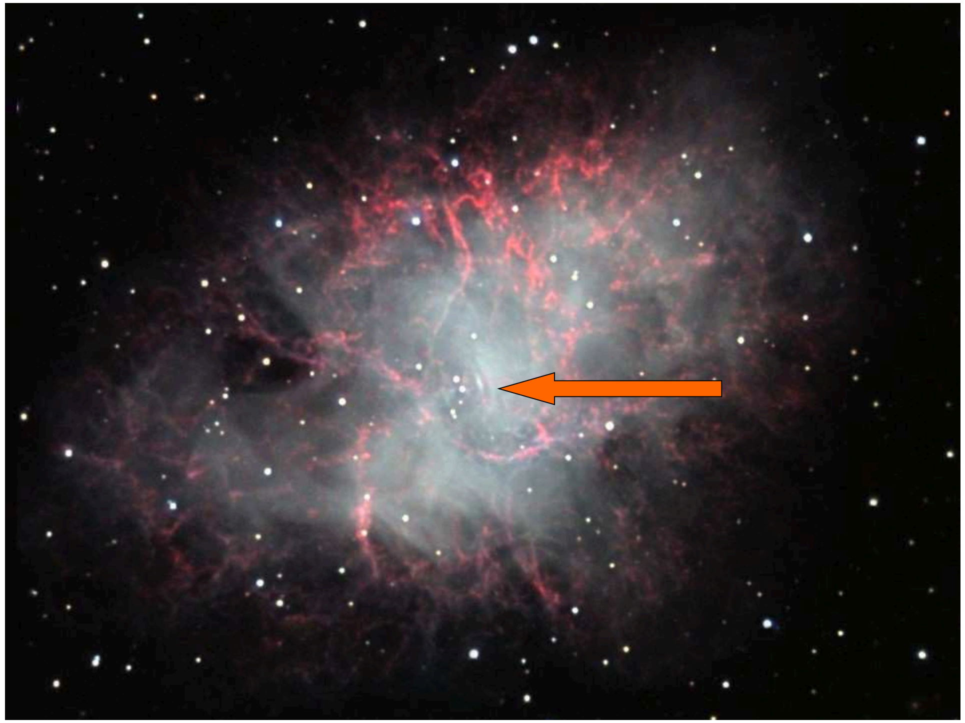
- Domains: y= 11.25E10cm
- log (rho) = 0.6 ... 3.6

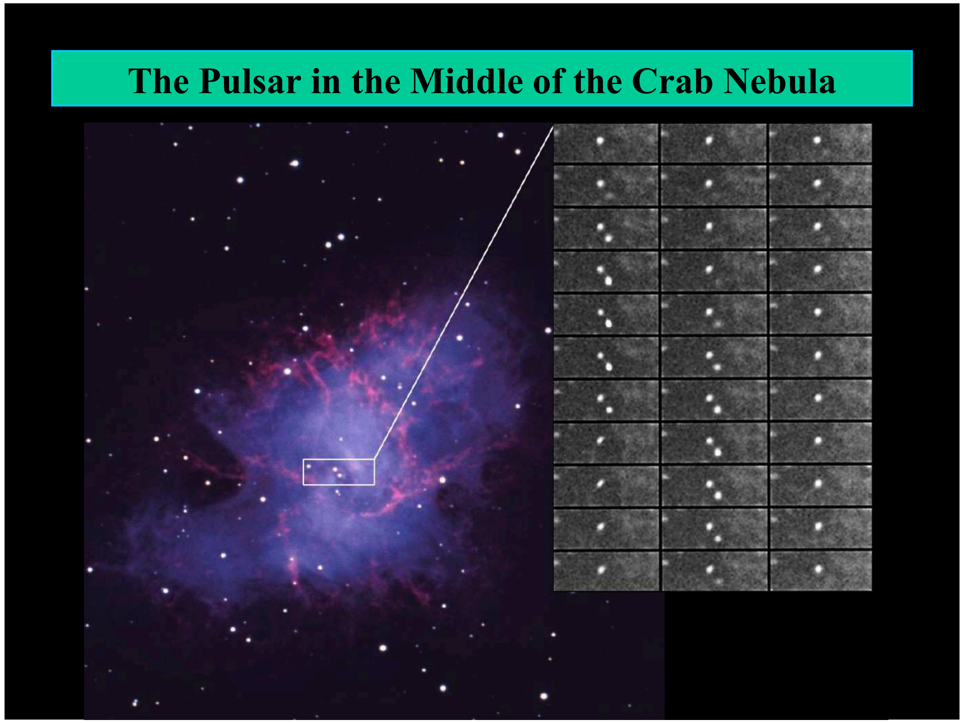
Efficiency for energy deposition ≈ 20 %



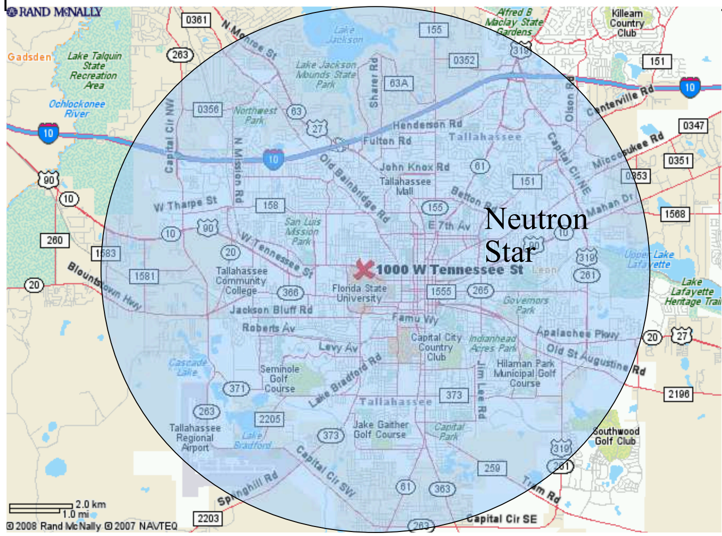
Neutrinos Detected from Supernova 1987a







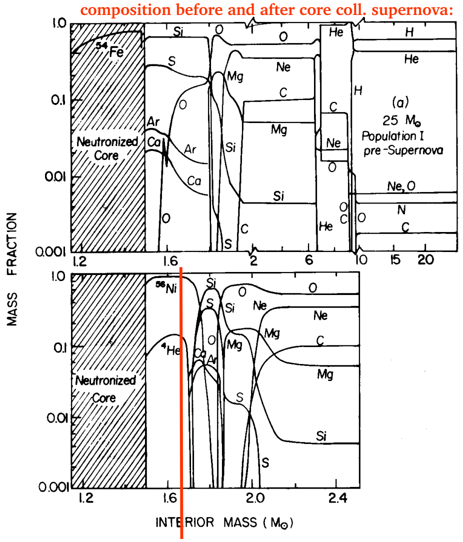
The Size of a Neutron Star Compared to Tallahassee



Explosive Nucleosynthesis

Shock wave rips through star and compresses and heats all mass regions

composition before and after core coll. supernova:



mass cut somewhere here

not ejected | ejected

Explosive C-Si burning

- similar final products
- BUT weak interactions unimportant for >= Si burning (but key in core !!!)\
- BUT somewhat higher temperatures
- BUT Ne, C incomplete
  (lots of unburned material)

Explosive Si burning:

Deepest layer: full NSE Si → Ni

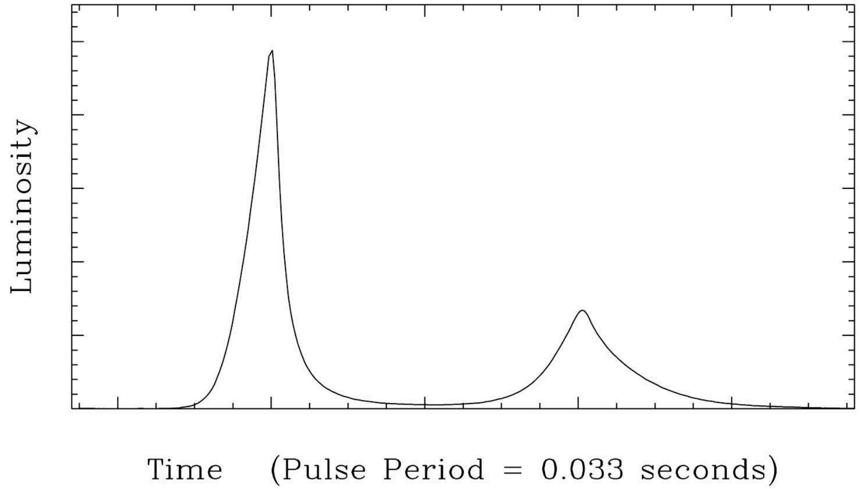
Further out: α -rich freezeout

- density low, time short → 3α cannot keep up and α drop out of NSE
  (but a lot are made from 2p+2n !)
- result: after freezeout lots of α !
  fuse slower – once one C is made
-

33

quickly captures more

The Light Curve of the Crab Pulsar



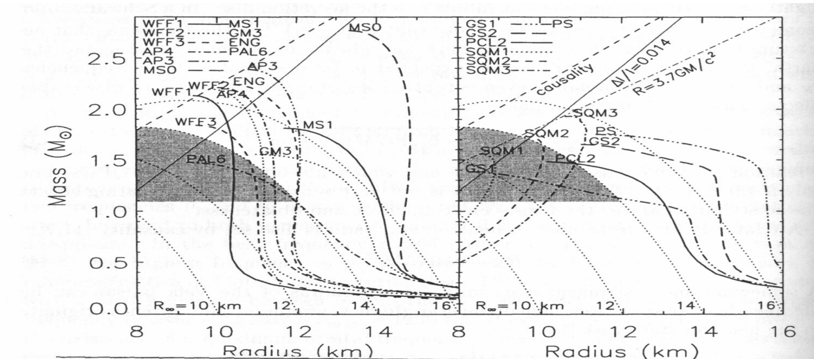
The Rotation Periods of Some Selected Pulsars

Pulsar	Rotation Period (Seconds)	Rotation Rate (Rotations/Sec)
PSR 1845–19	4.3	1/4
PSR 0329+54	0.71	1.4
Crab Pulsar	0.033	30
PSR 0437–47	0.0058	175
PSR 1937+20	0.0016	640

B) Remnants: Neutron Star vs. Black Holes

The equation of state at high densities (from Lattimer, 2001, AIP 556, 205)

Influence of the EOS on the mass and radius of a neutron star



Symbol	Reference	Approach	Composition
FP	[5]	Variational	np
PS	[20]	Potential	$n\pi^0$
WFF(1-3)	[32]	Variational	np
AP(1-4)	[1]	Variational	np
MS(1-3)	[15]	Field Theoretical	np
MPA(1-2)	[16]	Dirac-Brueckner HF	np
ENG	[4]	Dirac-Brueckner HF	np
PAL(1-6)	[21]	Schematic Potential	np
GM(1-3)	[6]	Field Theoretical	npH
GS(1-2)	[8]	Field Theoretical	npK
PCL(1-2)	[22]	Field Theoretical	npHQ
SQM(1-3)	[22]	Quark Matter	Q (u, d, s)

- R(NS) is 11 to 16 km
- structure depends on the EOS
- M(NS) < 1.4 to 2.2 Mo

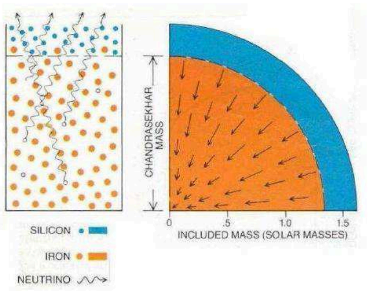
Neutron star masses seem to cluster around 1.4Mo Black hole masses from SRT

Object	Mass Range (Mo)	Source
A062000	3.3 to 13.6	Froning et al. 2001
J1118+480	6.0 to 7.7?	Wagner et al. 2001
GS J112468	4.5 to 6.1	Bailyn et al. 1998
4U 154347	2.7 to 7.5	Orosz et al. 1998
GRO J165540	5.5 to 7.9	Shahbaz et al. 1999
J1819.32525	8.7 to 11.7	Orosz et al. 2001
GS 2000+25	5.5 to 8.6	Ioannou et al. 2002
GS 2023+338	7.0 to 9.5	Sanwal et al. 1996 Casares & Charles 1994

The masses of J0422+32 and H1705?25 are not reliable but are sometimes included in tables (Rob)

Remark: Is there a mass gap between NS and BH ?
Attention: Possible selection effect for SRTs! The mass gap may reflect the mass of the progenitor at time of the explosion (if system looses more than ½ of its mass it becomes unbound)

The Core Collapse Phase



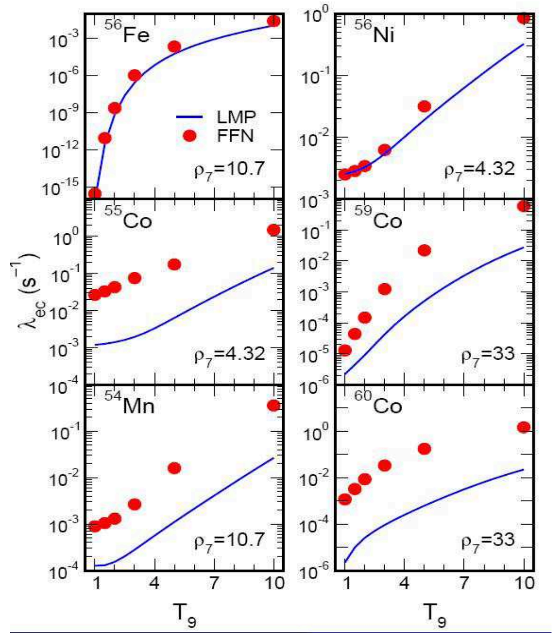
- $T = 0.1$–0.8 MeV, $\rho = 10^7$–10^{10} g cm^{-3}. Composition of iron group nuclei (A = 45–65)
- Important processes:
  - electron capture: $e^- + (N,Z) \rightarrow (N+1, Z-1) + \nu_e$
  - β^- decay: $(N,Z) \rightarrow (N-1, Z+1) + e^- + \bar{\nu}_e$
- Dominated by allowed transitions (Fermi and Gamow-Teller)

Nucleosynthesis in Core Collapse Supernovae

- Explosions of Massive Stars
- Explosive Nucleosynthesis
- Remnants: Neutron stars and Black Holes

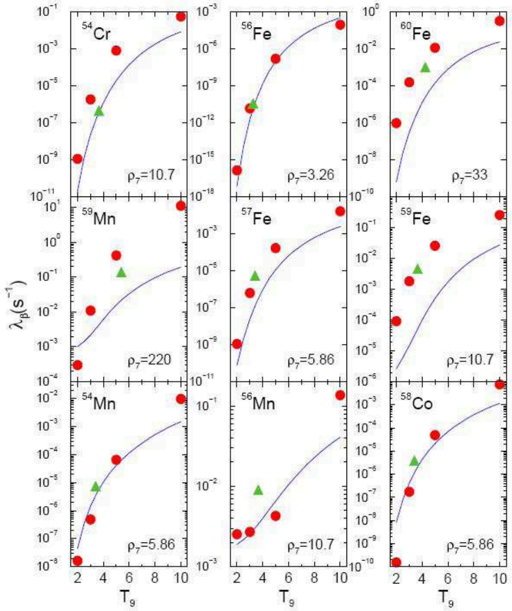
Literature: Iliadis, Chap.5.5
Rolfs & Rodney: Cauldrons in the Cosmos, chap. 8 and 9

Electron Capture Rates: Fuller Fowler Newman vs. Shell Model



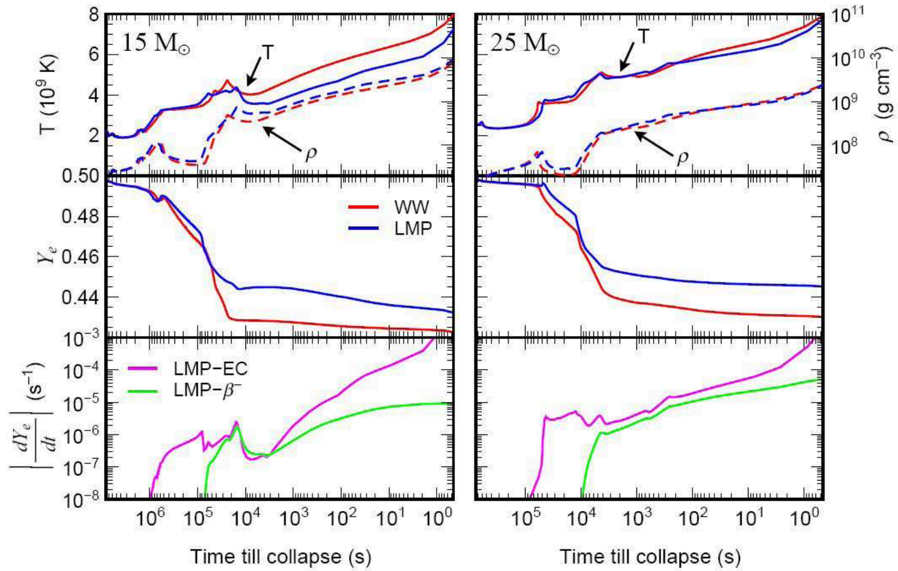
FFN: Independent Particle Picture
(FFN 1985)
Shell-Model (blue line)

Beta-decay rates (

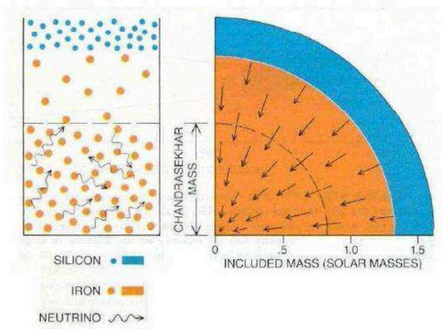


Influence of the weak reaction rates during the collapse

(A. Heger *et al.*, 2001)



Important Processes during the Collapse Phase



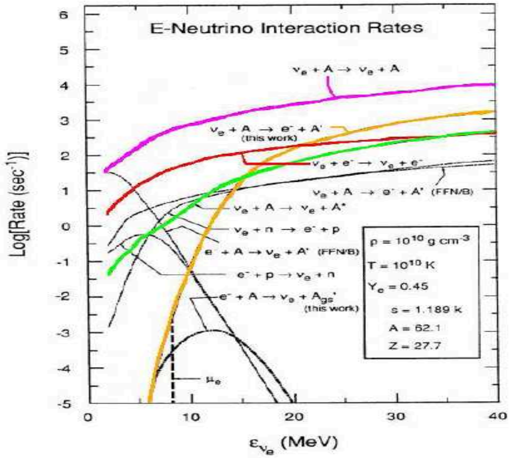
Important processes:

- Neutrino transport (Boltzmann equation):
  $\nu + A \rightleftarrows \nu + A$ (trapping)
  $\nu + e^- \rightleftarrows \nu + e^-$ (thermalization)

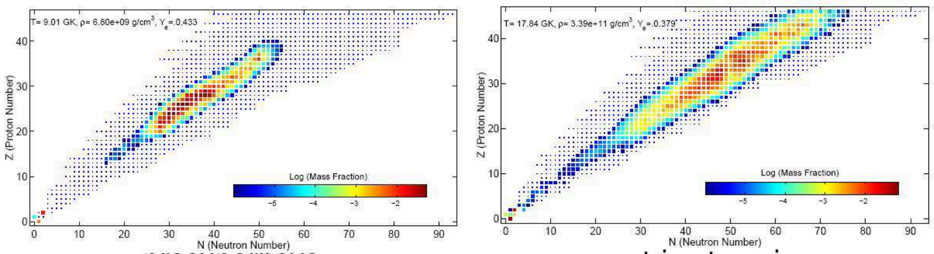
  cross sections $\sim E_\nu^2$
- electron capture on protons:
  $e^- + p \rightleftarrows n + \nu_e$

Neutrino Reactions during Collapse

Bruenn and Haxton (1991)
based on results for ^{56}Fe

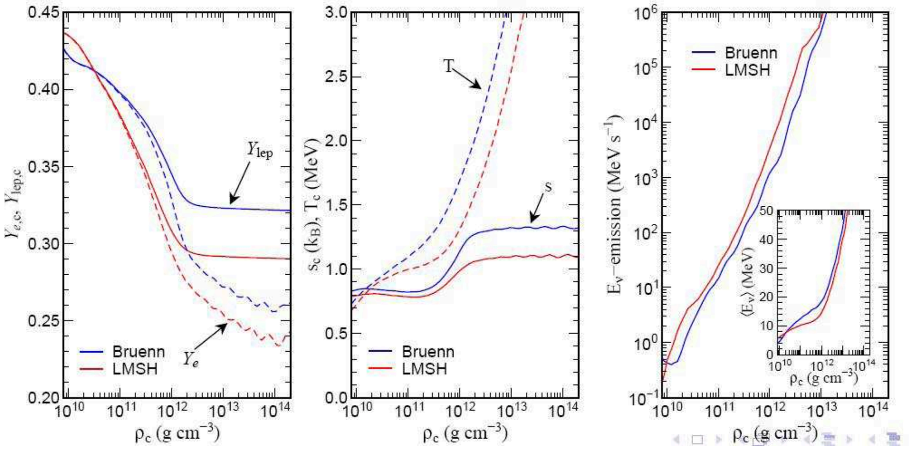


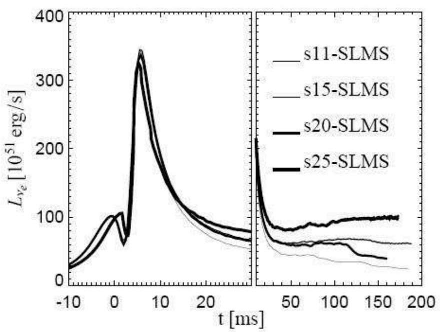
Change of Abundances During the Collapse



presupernova neutrino trapping

With Rampp & Janka (General Relativistic model)
15 $M_\odot$ presupernova model from A. Heger & S. Woosley





Models for Nucleosynthesis in CC Supernovae

Production of elements depends on nuclear vs. hydro-timescales

Problem: No consistent mechanism for ejection of envelope
However, we need to know the time evolution
of **density,** temperature & neutrino flux

Approach:

- Take a stellar model at the end of stellar evolution
- Estimate neutrino flux (1E53 erg go into neutrinos)
- Add explosion energy of 1 to 3 foe as variable at the outer edge of the Iron core.
- Calculate the propagation of the shock front.
- Add a cutoff in mass, i.e. which fraction goes into the neutron star.

Example: 15 & 25 Mo stars

(e.g.Woosley & Weaver, 1995, ApJ 101, 181; Umeda et al. 2009. ApJ 692, 1517)

Shock Propagation

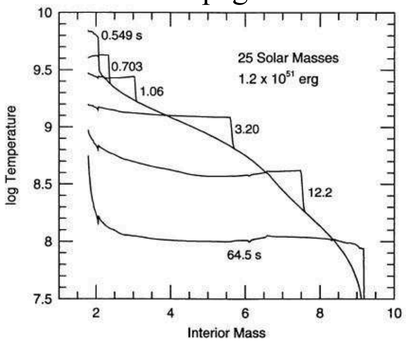
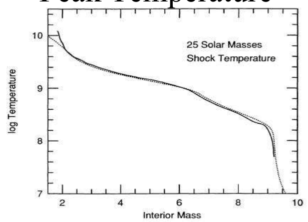


FIG. 8.—Temperature structure as the shock propagates through the mantle and helium core of a 25 $M_\odot$ solar metallicity model. The kinetic energy of all ejecta at infinity is 1.2×10^{51} ergs. Curves are labeled by the time in seconds at which each is sampled. Note the presence, except near the collapsed core, of large nearly isothermal regions behind the shock.

Peak Temperature



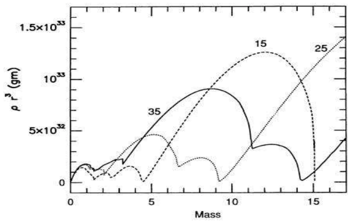
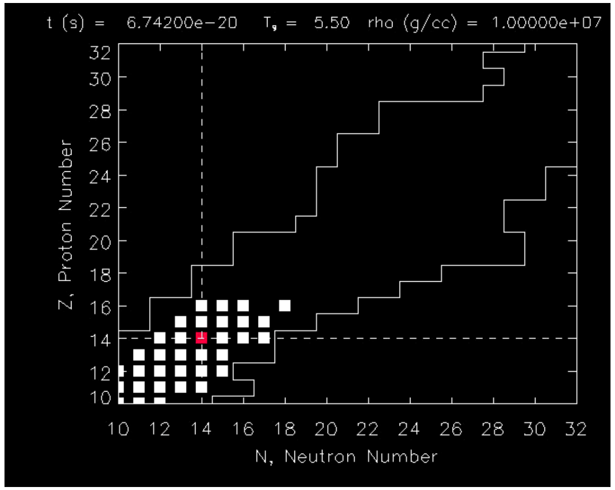


FIG. 1.—Distribution of density times radius cubed (ρr^3) in presupernova stars of 15, 25, and 35 $M_\odot$ of solar metallicity. The helium core masses for these stars are 4.2, 9.2, and 14.2 $M_\odot$, respectively.

- NSE abundances go to He
He-rich freezeout

The alpha-rich freezeout (B. Mayers/Clemson)



Main Processes for Explosive Nucleosynthesis:

- Explosive O and Si-burning (alpha-capture)
- Neutrino reactions

Example: Neutrino irradiation in He-layer

^{4}He (ν_x,ν_x' p) ^{3}H(α,γ)^{7}Li

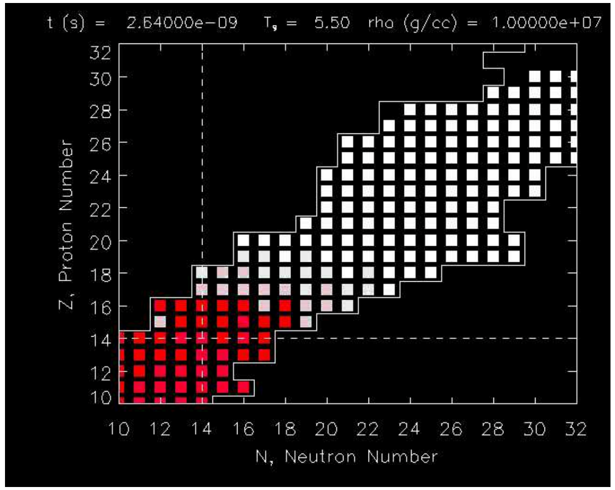
- Alpha-rich freezeout:

a) Nucleii are heated by shock (low-density, high T => NSE and He-rich

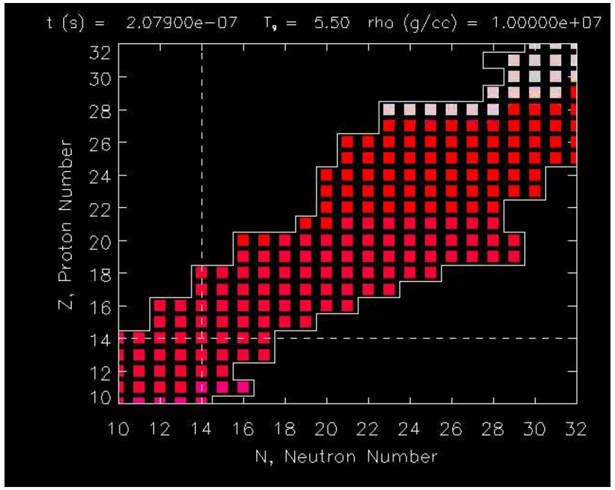
b) Expansion and cooling → production of heavy nucleii, decays & weak reactions

Movie from Brad Meyers' Clemson

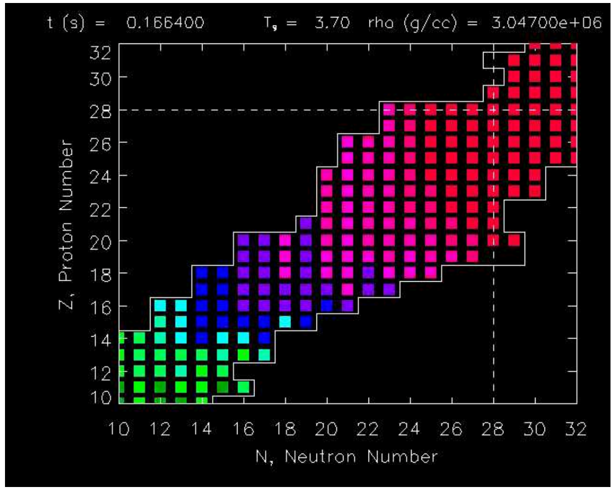
The alpha-rich freezeout (B. Mayers/Clemson)



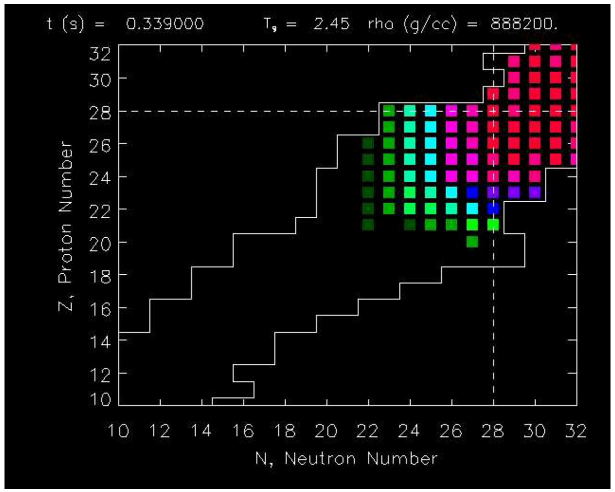
The alpha-rich freezeout (B. Mayers/Clemson)



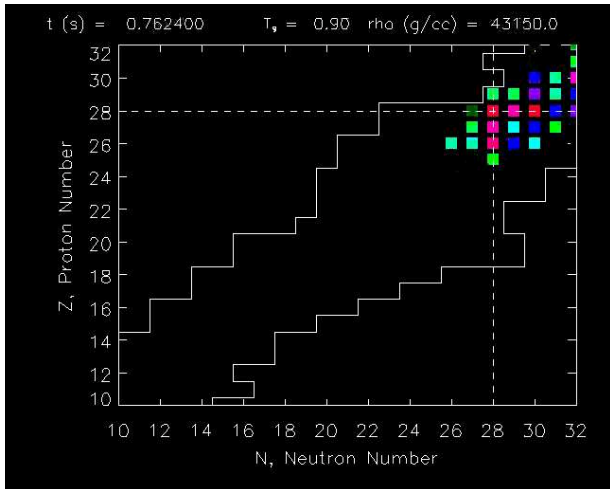
The alpha-rich freezeout (B. Mayers/Clemson)



The alpha-rich freezeout (B. Mayers/Clemson)



The alpha-rich freezeout (B. Mayers/Clemson)



Effects of the Neutrino Irradiation on the Nucleosynthesis

TABLE 4

25 $M_\odot$ EXPLOSION WITH AND WITHOUT NEUTRINO IRRADIATION

Isotope	w/o ν	with ν $T_\nu = 8$	with ν $T_\nu = 6$	Isotope	w/o ν	with ν $T_\nu = 8$	with ν $T_\nu = 6$
^{7}Li*	2.13E-08	7.31E-07	2.81E-07	^{40}K	3.13E-06	3.44E-06	3.31E-06
^{10}B	2.51E-09	2.75E-09	2.58E-09	^{41}K	2.74E-05	3.04E-05	2.96E-05
^{11}B*	1.18E-08	2.35E-06	1.03E-06	^{43}Ca	6.36E-06	8.39E-06	7.92E-06
^{15}N*	3.39E-05	2.33E-04	1.29E-04	^{45}Sc	4.20E-06	6.18E-06	5.00E-06
^{19}F*	3.53E-05	1.48E-04	9.15E-05	^{47}Ti	9.98E-06	1.18E-05	1.11E-05
^{21}Ne	5.84E-04	6.41E-04	6.08E-04	^{50}V	2.21E-07	2.93E-07	2.94E-07
^{22}Na*	1.59E-06	3.43E-06	2.57E-06	^{51}V	3.65E-05	6.51E-05	5.40E-05
^{26}Al	9.38E-05	1.29E-04	1.14E-04	^{53}Cr	3.65E-04	4.17E-04	3.96E-04
^{31}P	2.78E-03	3.18E-03	3.02E-03	^{54}Cr	3.39E-05	4.17E-05	4.18E-05
^{33}S	5.61E-04	6.60E-04	6.18E-04	^{55}Mn	1.37E-03	2.33E-03	1.86E-03
^{35}Cl	4.28E-04	7.01E-04	5.80E-04	^{57}Fe	1.30E-02	1.43E-02	1.42E-02
^{39}K	3.79E-04	5.39E-04	4.65E-04	^{59}Co	8.31E-04	1.54E-03	1.16E-03

Sensitivity to Assumes Mass Cut on Element Production

TABLE 8

SENSITIVITY[a] TO MASS CUT (25 $M_\odot$ EJECTA[b])

Isotope	Piston ($M_\odot$)	Piston Production	Eject ($M_\odot$)	Eject Production
^{4}He	8.657(0)	1.35	8.637(0)	1.36
^{33}S	6.63(-4)	8.81	6.57(-4)	8.85
^{35}Cl	7.02(-4)	11.9	7.01(-4)	12.0
^{39}K	5.38(-4)	6.63	5.16(-4)	6.45
^{41}K	3.04(-5)	4.95	2.93(-5)	4.83
^{40}Ca	1.68(-2)	12.0	1.67(-2)	12.1
^{42}Ca	1.48(-4)	15.1	1.46(-4)	15.1
^{43}Ca	8.29(-6)	3.96	5.71(-6)	2.76
^{44}Ca	2.04(-4)	6.12	6.68(-5)	2.03
^{45}Sc	6.28(-6)	6.91	4.42(-6)	4.93
^{46}Ti	5.80(-5)	11.1	5.61(-5)	10.9
^{47}Ti	1.17(-5)	2.41	8.13(-6)	1.69
^{48}Ti	4.91(-4)	9.79	2.43(-4)	4.89
^{49}Ti	3.12(-5)	8.17	2.58(-5)	6.85
^{51}V	6.52(-5)	7.41	6.29(-5)	7.24
^{52}Cr	3.82(-3)	11.0	3.49(-3)	10.2
^{53}Cr	4.18(-4)	10.4	4.09(-4)	10.3
^{55}Mn	2.34(-3)	7.54	1.91(-3)	6.23
^{56}Fe	3.73(-1)	13.7	1.55(-1)	5.74
^{57}Fe	1.44(-2)	21.5	4.25(-3)	6.46
^{58}Fe	9.46(-4)	11.0	9.26(-4)	10.9
^{59}Co	1.54(-3)	19.6	5.90(-4)	7.61
^{58}Ni	3.25(-2)	28.1	5.28(-3)	4.63
^{60}Ni	9.05(-3)	19.8	2.39(-3)	5.29
^{61}Ni	9.33(-4)	46.5	3.35(-4)	16.9
^{62}Ni	6.20(-3)	95.7	1.10(-3)	17.2
^{63}Cu	3.87(-4)	28.8	3.48(-4)	26.2
^{65}Cu	2.48(-4)	40.1	2.45(-4)	40.1
^{64}Zn	1.16(-4)	5.00	7.65(-5)	3.34
^{66}Zn	4.64(-4)	33.8	3.46(-4)	25.5
^{67}Zn	9.12(-5)	44.5	9.08(-5)	44.9

[a] Only those ejecta whose production factor changes by more than 0.1% are given.
[b] Piston was at 1.78 $M_\odot$; ejecta were external to 2.07 $M_\odot$.

Results of Explosive Nucleosynthesis

TABLE 7

NUCLEOSYNTHESIS—PRESUPERNOVA AND POST-EXPLOSION IN S25A

Isotope	PreSN	Post SN	Isotope	PreSN	PostSN
^{1}H	9.40(0)	9.40(0)	^{41}K	3.26(-5)	2.93(-5)
^{2}H	9.81(-5)	9.81(-5)	^{40}Ca	5.76(-3)	1.67(-2)
^{3}He	6.29(-4)	6.29(-4)	^{42}Ca	2.93(-4)	1.46(-4)
^{4}He	8.63(0)	8.64(0)	^{43}Ca	4.59(-6)	5.71(-6)
^{6}Li	1.41(-9)	1.41(-9)	^{44}Ca	3.91(-5)	6.68(-5)
^{7}Li	2.12(-8)	7.44(-7)	^{46}Ca	8.30(-7)	8.90(-7)
^{9}Be	3.78(-10)	3.84(-10)	^{48}Ca	2.95(-6)	2.89(-6)
^{10}B	2.51(-9)	2.76(-9)	^{45}Sc	3.93(-6)	4.42(-6)
^{11}B	1.08(-8)	2.40(-6)	^{46}Ti	4.63(-5)	5.61(-5)
^{12}C	3.25(-1)	3.21(-1)	^{47}Ti	6.45(-6)	8.13(-6)
^{13}C	1.45(-3)	1.45(-3)	^{48}Ti	4.20(-5)	2.42(-4)
^{14}N	7.93(-2)	7.93(-2)	^{49}Ti	8.41(-6)	2.58(-5)
^{15}N	3.31(-5)	2.33(-4)	^{50}Ti	1.60(-5)	1.59(-5)
^{16}O	3.45(0)	3.25(0)	^{50}V	8.10(-8)	2.93(-7)
^{17}O	1.01(-3)	1.01(-3)	^{51}V	1.03(-5)	6.29(-5)
^{18}O	2.72(-3)	2.52(-3)	^{50}Cr	3.22(-5)	2.09(-4)
^{19}F	3.59(-5)	1.33(-4)	^{52}Cr	2.86(-4)	3.49(-3)
^{20}Ne	4.86(-1)	3.94(-1)	^{53}Cr	3.54(-5)	4.09(-4)
^{21}Ne	5.27(-4)	6.29(-4)	^{54}Cr	3.49(-5)	4.16(-5)
^{22}Ne	4.81(-2)	4.76(-2)	^{55}Mn	2.78(-4)	1.91(-3)
^{23}Na	1.40(-2)	1.08(-2)	^{54}Fe	1.33(-3)	1.64(-2)
^{24}Mg	1.04(-1)	1.06(-1)	^{56}Fe	2.18(-2)	1.55(-1)
^{25}Mg	2.77(-2)	2.39(-2)	^{57}Fe	8.74(-4)	4.25(-3)
^{26}Mg	3.82(-2)	3.26(-2)	^{58}Fe	8.86(-4)	9.26(-4)
^{27}Al	2.59(-2)	2.44(-2)	^{59}Co	4.21(-4)	5.90(-4)
^{28}Si	2.37(-1)	3.15(-1)	^{58}Ni	9.04(-4)	5.28(-3)
^{29}Si	8.50(-3)	1.15(-2)	^{60}Ni	1.50(-3)	2.39(-3)
^{30}Si	5.16(-3)	1.26(-2)	^{61}Ni	2.51(-4)	3.35(-4)
^{31}P	2.13(-3)	3.18(-3)	^{62}Ni	5.95(-4)	1.10(-3)
^{32}S	9.82(-2)	1.41(-1)	^{64}Ni	9.22(-4)	9.03(-4)
^{33}S	6.54(-4)	6.57(-4)	^{63}Cu	4.01(-4)	3.48(-4)
^{34}S	1.14(-2)	7.13(-3)	^{65}Cu	2.19(-4)	2.45(-4)
^{36}S	4.20(-5)	4.19(-5)	^{64}Zn	7.13(-5)	7.65(-5)
^{35}Cl	4.82(-4)	7.00(-4)	^{66}Zn	3.46(-4)	3.46(-4)
^{37}Cl	3.01(-4)	2.54(-4)	^{67}Zn	1.08(-4)	9.08(-5)
^{36}Ar	1.32(-2)	2.25(-2)	^{68}Zn	6.50(-4)	6.96(-4)
^{38}Ar	1.09(-2)	4.90(-3)	^{70}Zn	8.56(-6)	1.31(-5)
^{40}Ar	1.59(-5)	1.41(-5)	^{69}Ga	8.98(-5)	1.00(-4)
^{39}K	5.37(-4)	5.16(-4)	^{71}Ga	5.80(-4)	4.92(-4)
^{40}K	3.41(-6)	3.44(-6)	^{70}Ge	8.90(-5)	1.41(-4)

Example: 15 & 25 Mo stars

(e.g.Woosley & Weaver, 1995, ApJ 101, 181; Umeda et al. 2009. ApJ 692, 1517)

Shock Propagation

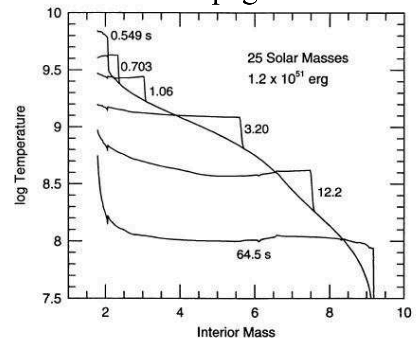
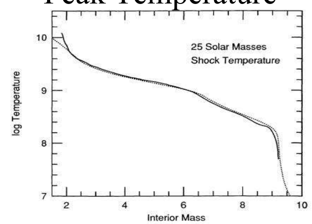


FIG. 8.—Temperature structure as the shock propagates through the mantle and helium core of a 25 $M_\odot$ solar metallicity model. The kinetic energy of all ejecta at infinity is 1.2×10^{51} ergs. Curves are labeled by the time in seconds at which each is sampled. Note the presence, except near the collapsed core, of large nearly isothermal regions behind the shock.

Peak Temperature



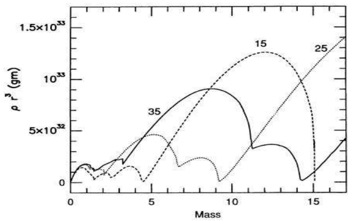


FIG. 1.—Distribution of density times radius cubed (ρr^3) in presupernova stars of 15, 25, and 35 $M_\odot$ of solar metallicity. The helium core masses for these stars are 4.2, 9.2, and 14.2 $M_\odot$, respectively.

- NSE abundances go to He
He-rich freezeout

Example of Nucleosynthesis Results for 25Mo

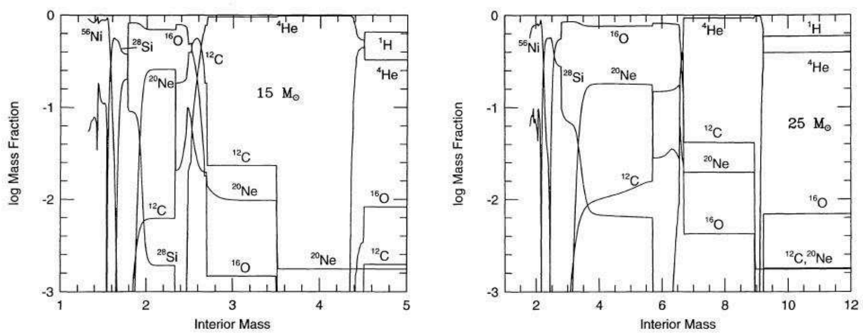


FIG. 10*a* FIG. 10*b*

FIG. 10.—Final mass fractions of the major abundances — ^{1}H, ^{4}He, ^{12}C, ^{16}O, ^{20}Ne, ^{28}Si, and ^{56}Ni—(*a*) the inner 5 $M_{\odot}$ of a 15 $M_{\odot}$ solar metallicity supernova (model S15A); (*b*) the inner 12 $M_{\odot}$ of the ejecta of a 25 $M_{\odot}$ solar metallicity supernova (model S25A). Each had an explosion energy of 1.2 × 10^{51} ergs (Table 3).

Example of Nucleosynthesis Results for 25Mo

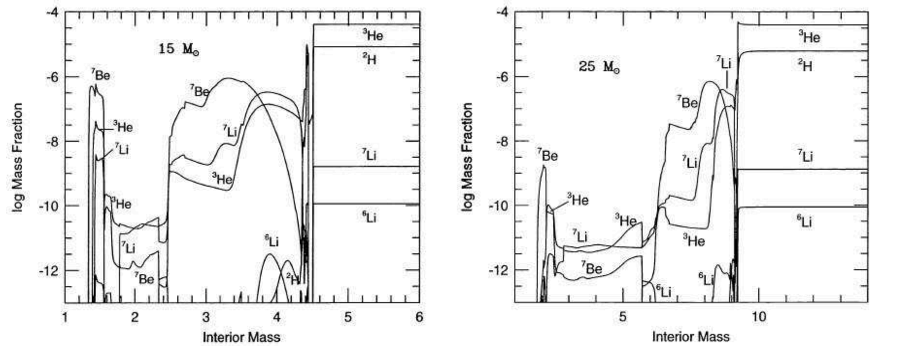


FIG. 11*a* FIG. 11*b*

FIG. 11—Mass fractions of ^{2}H and the isotopes of He and Li and the ^{7}Li progenitor, ^{7}Be in the interior of models S15A(*a*) and S25A(*b*) at a time of 2.5 × 10^{4} s. Note the large production of mass 7 in the helium layer by the neutrino process.

Example of Nucleosynthesis Results for 25Mo

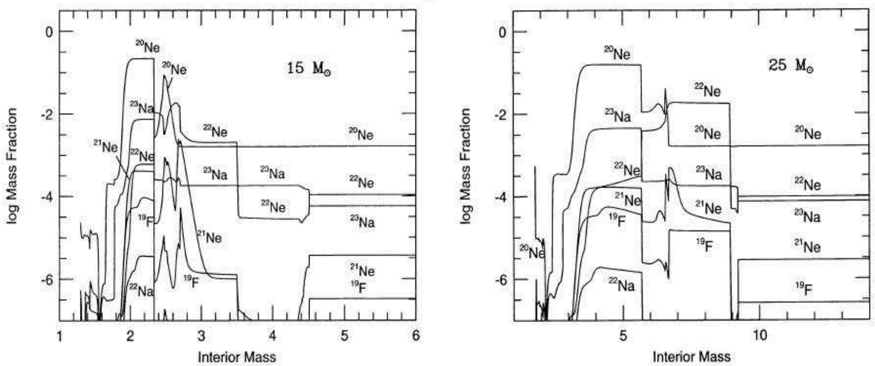


FIG. 14*a* FIG. 14*b*

FIG. 14.—Mass fractions in the interiors of the 15 $M_{\odot}$ (*a*) and 25 $M_{\odot}$ (*b*) explosion of the isotopes of F, Ne, and Na

Example of Nucleosynthesis Results for 25Mo

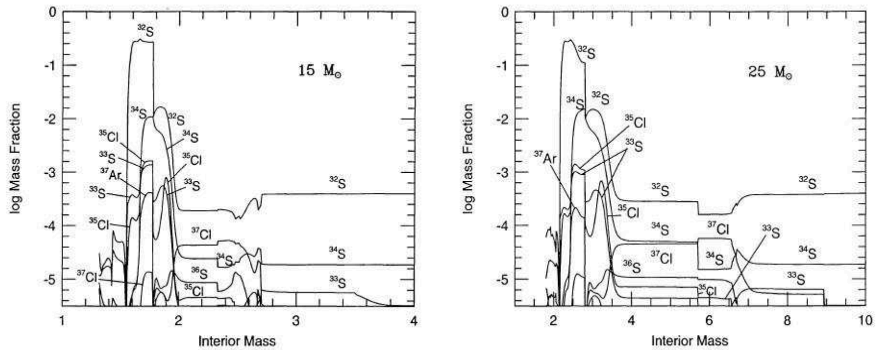


FIG. 17*a* FIG. 17*b*

FIG. 17.—Mass fractions in the interiors of the 15 $M_{\odot}$ (*a*) and 25 $M_{\odot}$ (*b*) explosion of the isotopes of Cl and S and their progenitors

Example of Nucleosynthesis Results for 25Mo

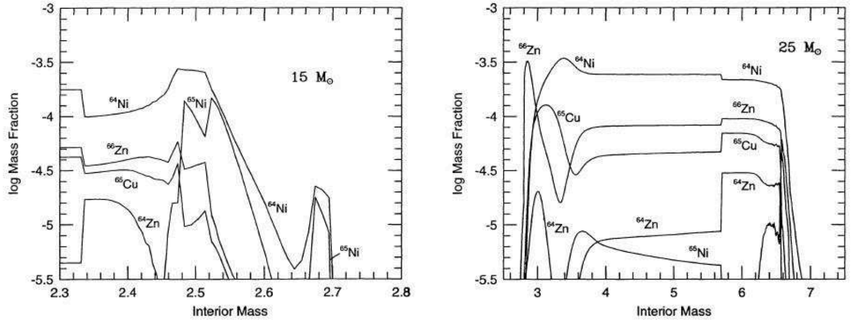


FIG. 32a FIG. 32b

FIG. 32.—Mass fractions in interiors of the 15 $M_{\odot}$ (a) and 25 $M_{\odot}$ (b) explosions of the progenitors of ^{64}Ni, and ^{65}Cu, and ^{66}Zn. Here the plots emphasize those species having substantial production by neutron capture farther out in the star.

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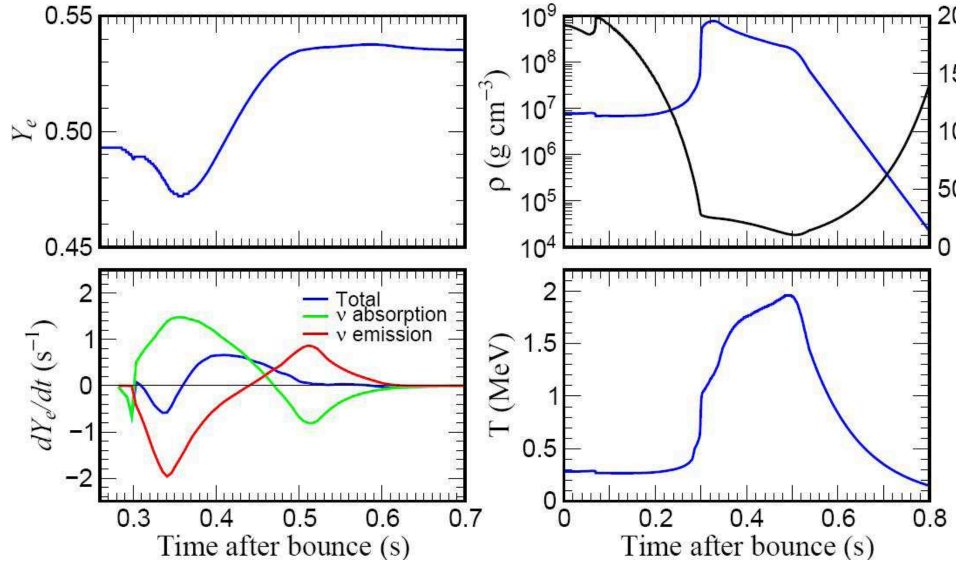
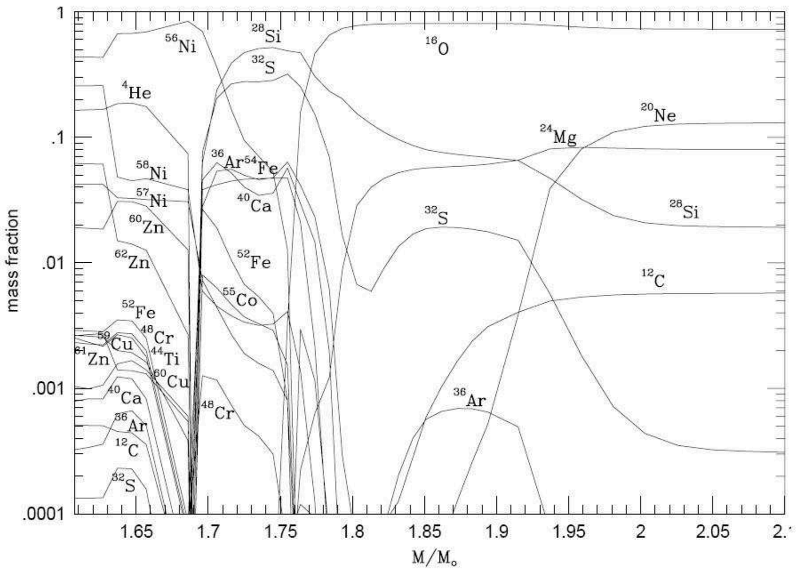
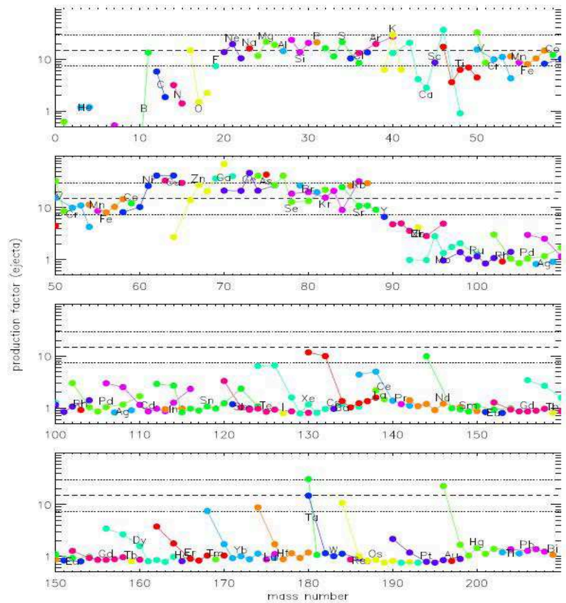


Abundance Distribution for a 23Mo Star with 1fo



- Inner layers, α-rich freeze out.
- Outer layers, explosive Si burning.

Supernova relative to Solar Abundances



Abundances averaged over stars with all masses and a Sapleter IMF

(N(star)~ M^{-3}