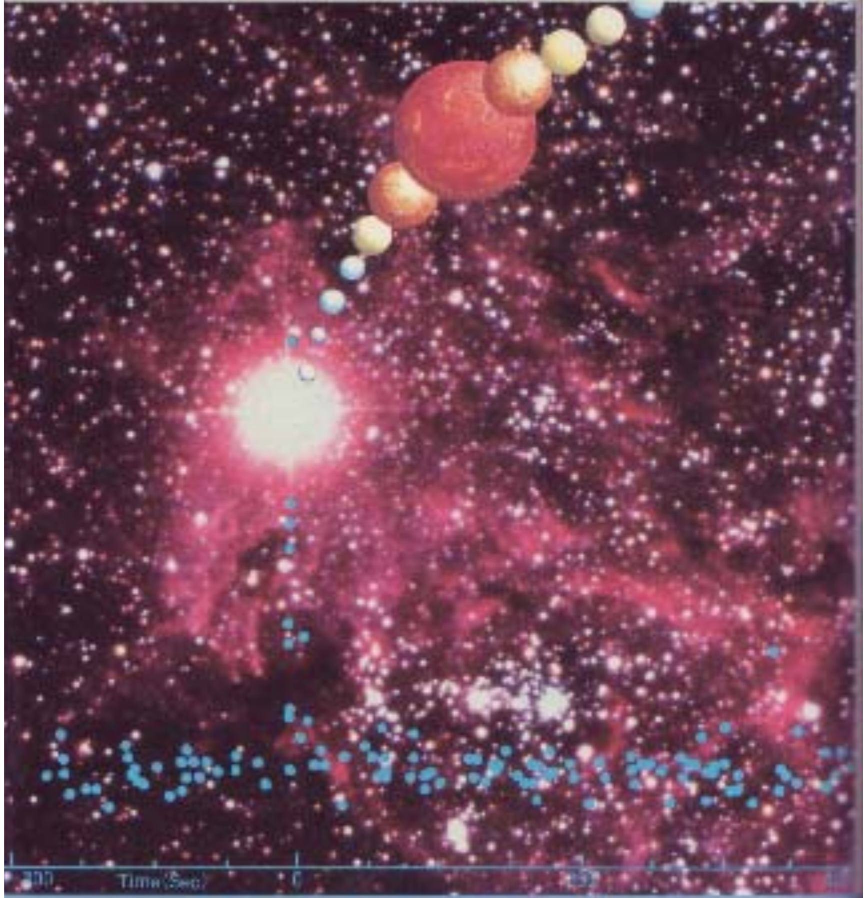

Happy Birthday Ken!

超新星1987Aに挑む

壮烈な星の最期をさぐる

野本陽代／野本憲一＝監修



BLUE BACKS

How Do Massive Stars Die (and Explode)?

When Massive Stars Die, How Do They Explode?

a question that is at
least 65 years old
(Baade and Zwicky 1939)

Neutron Star + Neutrinos

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

+Vibrations? Burrows

Neutron Star + Rotation

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

Black Hole + Rotation

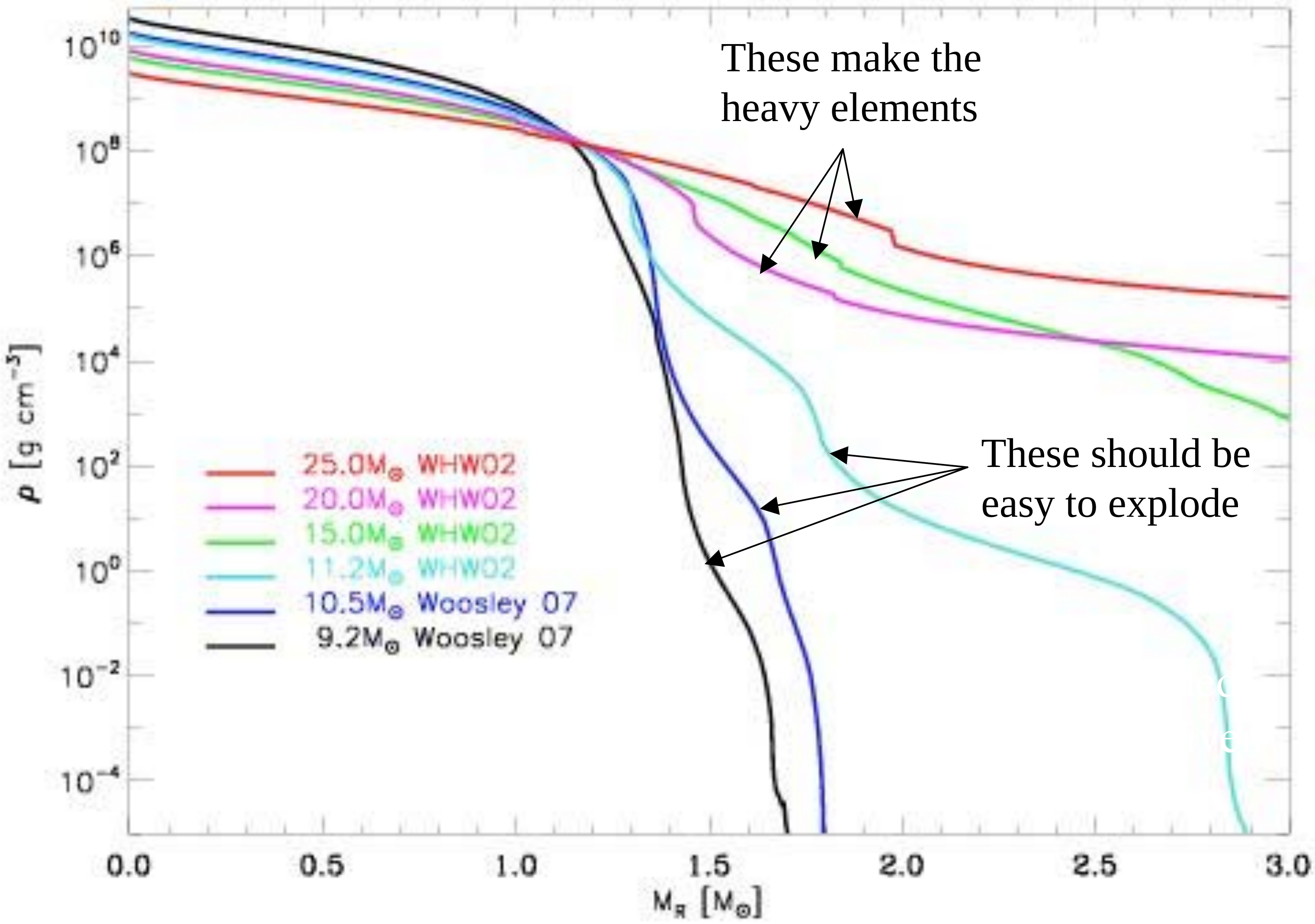
Bodenheimer and Woosley (1983)
Woosley (1993)
MacFadyen and Woosley (1999)
Narayan and Piran (2004)
etc

All of the above?

The death of a star and how it may potentially explode is most sensitive to:

- *The density structure surrounding the iron core*
- *The rotation rate of the core and that material*

Density Profiles of Supernova Progenitor Cores



These make the heavy elements

These should be easy to explode

図６－１　人間と地球の素材は超新星が作り出した。

Stars of different masses, metallicities and binary histories will also differ in central rotation rate.

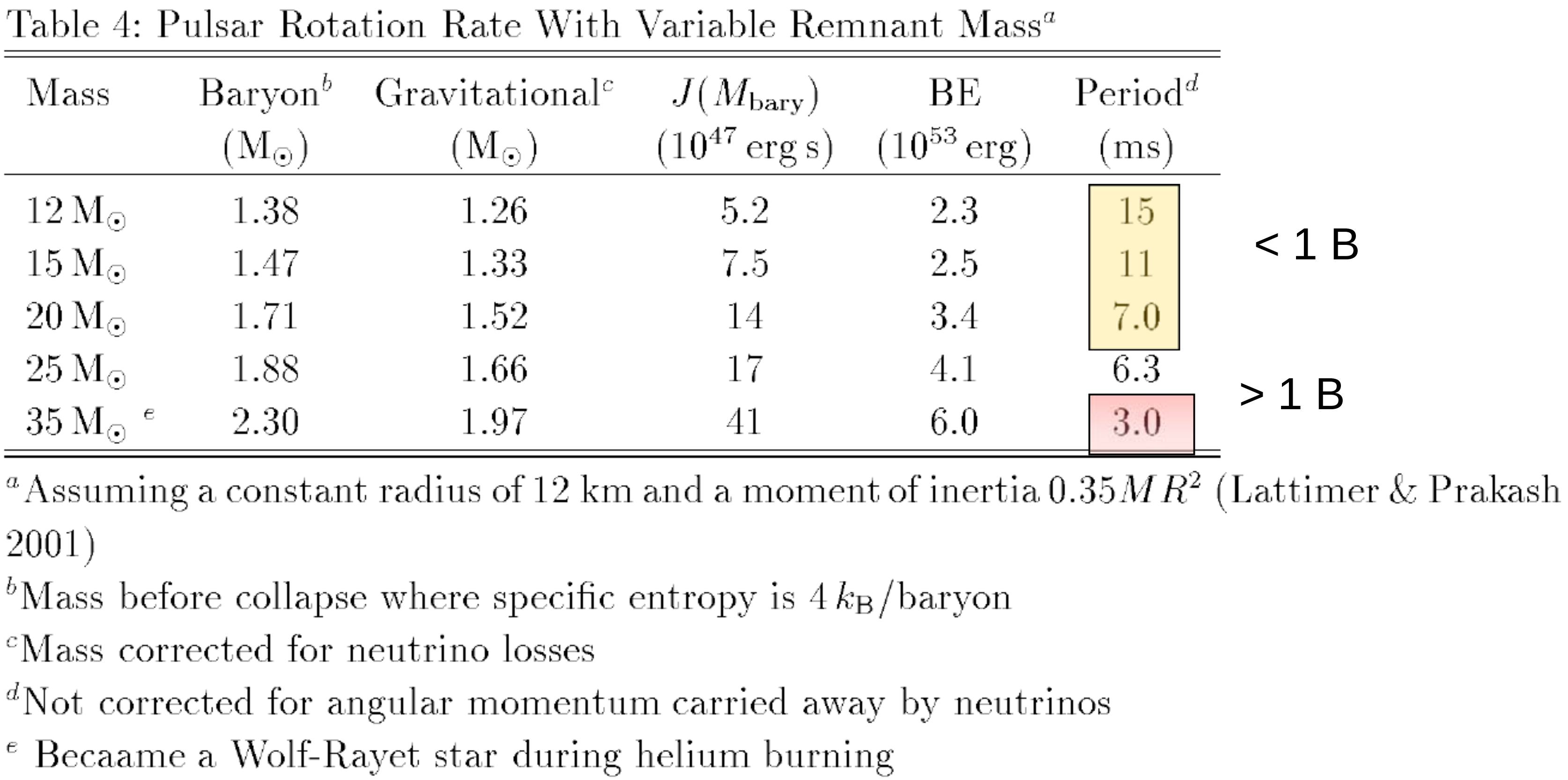


Table 4: Pulsar Rotation Rate With Variable Remnant Mass[a]

Mass	Baryon[b] ($M_\odot$)	Gravitational[c] ($M_\odot$)	$J(M_{\mathrm{bary}})$ (10^{47} erg s)	BE (10^{53} erg)	Period[d] (ms)
12 $M_\odot$	1.38	1.26	5.2	2.3	15
15 $M_\odot$	1.47	1.33	7.5	2.5	11
20 $M_\odot$	1.71	1.52	14	3.4	7.0
25 $M_\odot$	1.88	1.66	17	4.1	6.3
35 $M_\odot$ [e]	2.30	1.97	41	6.0	3.0

[a] Assuming a constant radius of 12 km and a moment of inertia $0.35MR^2$ (Lattimer & Prakash 2001)

[b] Mass before collapse where specific entropy is $4\,k_{\mathrm{B}}$/baryon

[c] Mass corrected for neutrino losses

[d] Not corrected for angular momentum carried away by neutrinos

[e] Becaame a Wolf-Rayet star during helium burning

< 1 B

> 1 B

Heger, Woosley, & Spruit (2004) using magnetic torques as derived in Spruit (2002)

7 – 12 $M_\odot$ Stars

Poelarends, Herwig, Langer and Heger (2007ab, in prep)

Ignite carbon burning	7.25 $M_\odot$
Heaviest to lose envelope by winds and thermal pulses	9.0 $M_\odot$
Ignite Ne and O burning	9.25 $M_\odot$
Range of e-capture NeO SNe	9.0 - 9.25 $M_\odot$

Expected number 4%; Maximum number 20%

Larger percentage at lower metallicity

12 $M_\odot$ Model has binding 1 x 10^{50} erg
external to 1.7 $M_\odot$ baryon; 1 x 10^{49} erg
external to 2.6 $M_\odot$

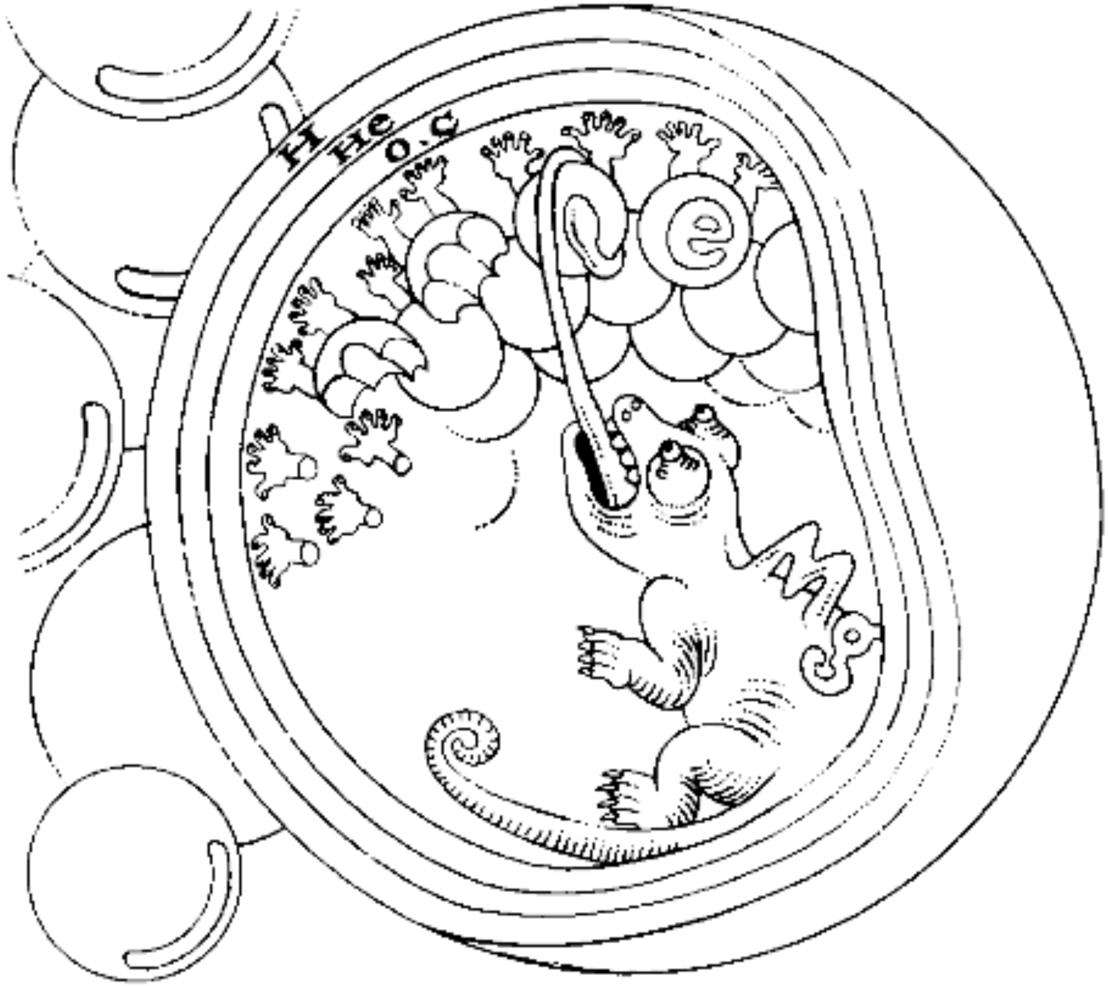
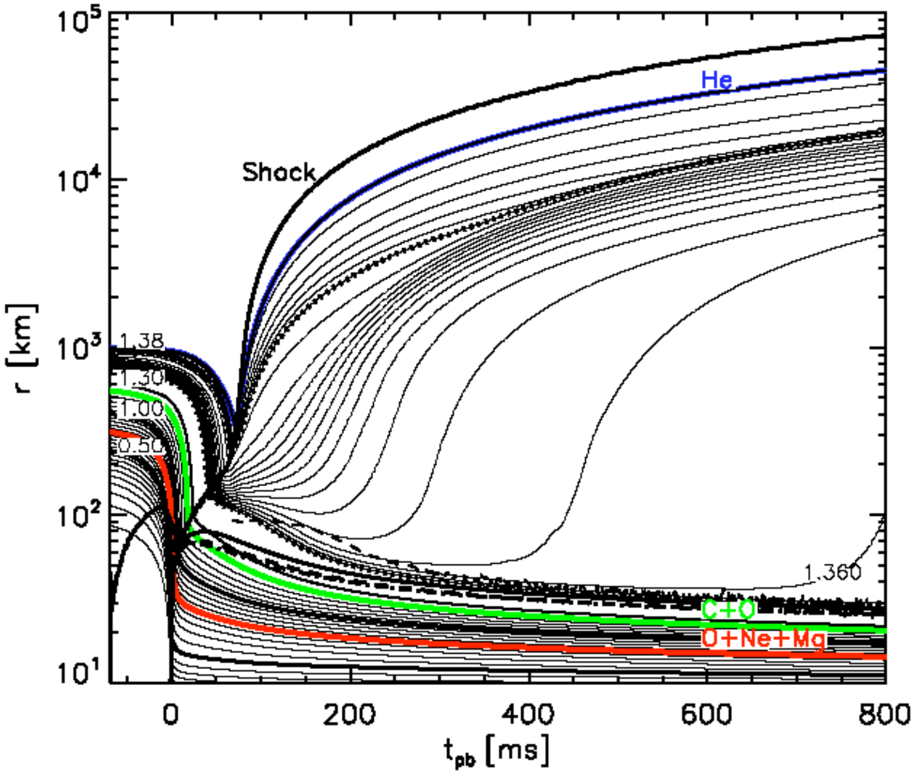


図3－4　質量が太陽の10倍までの星では、重力を支えていた電子がマグネシウムに吸収されて重力崩壊を起こす。



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)

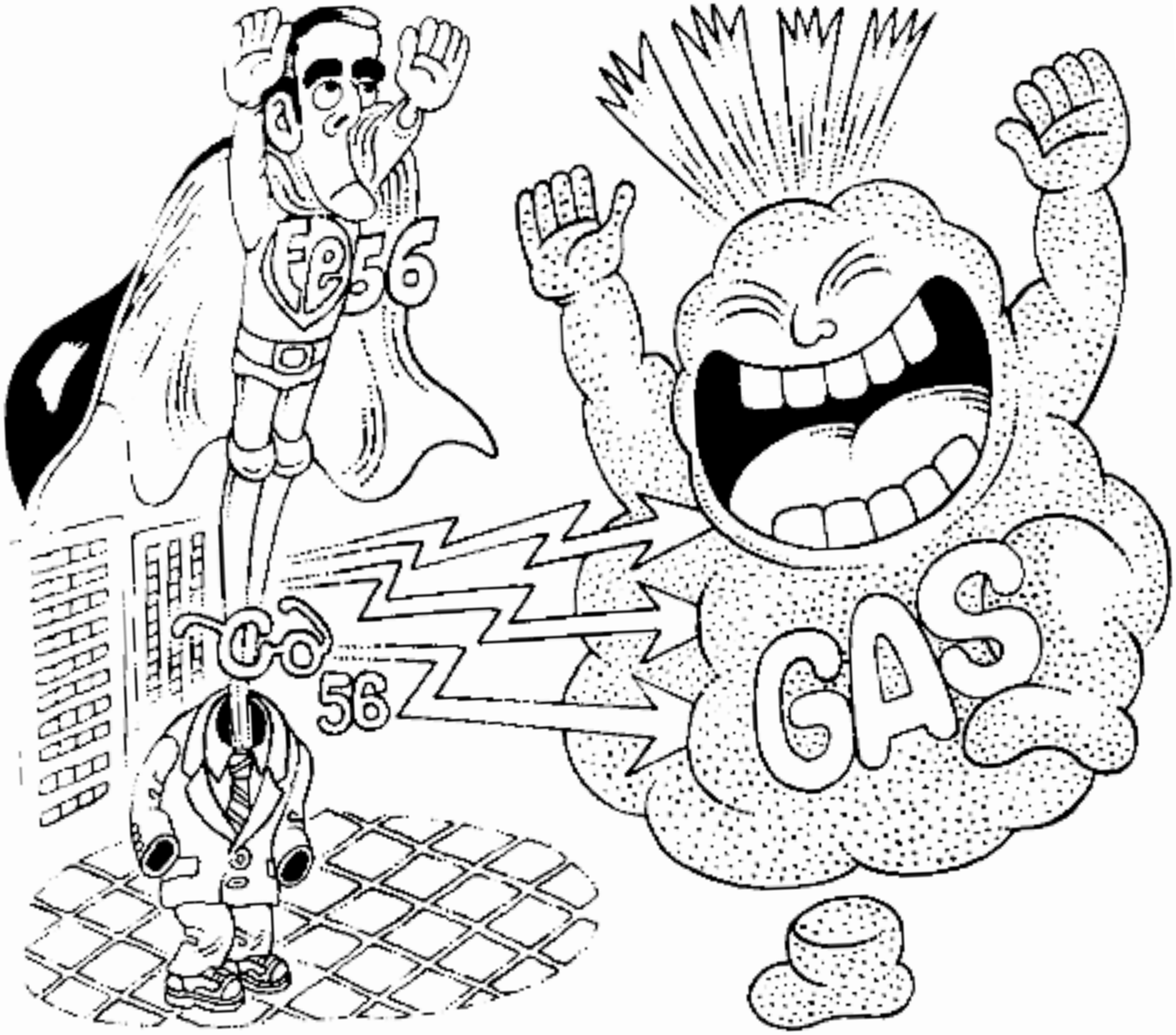
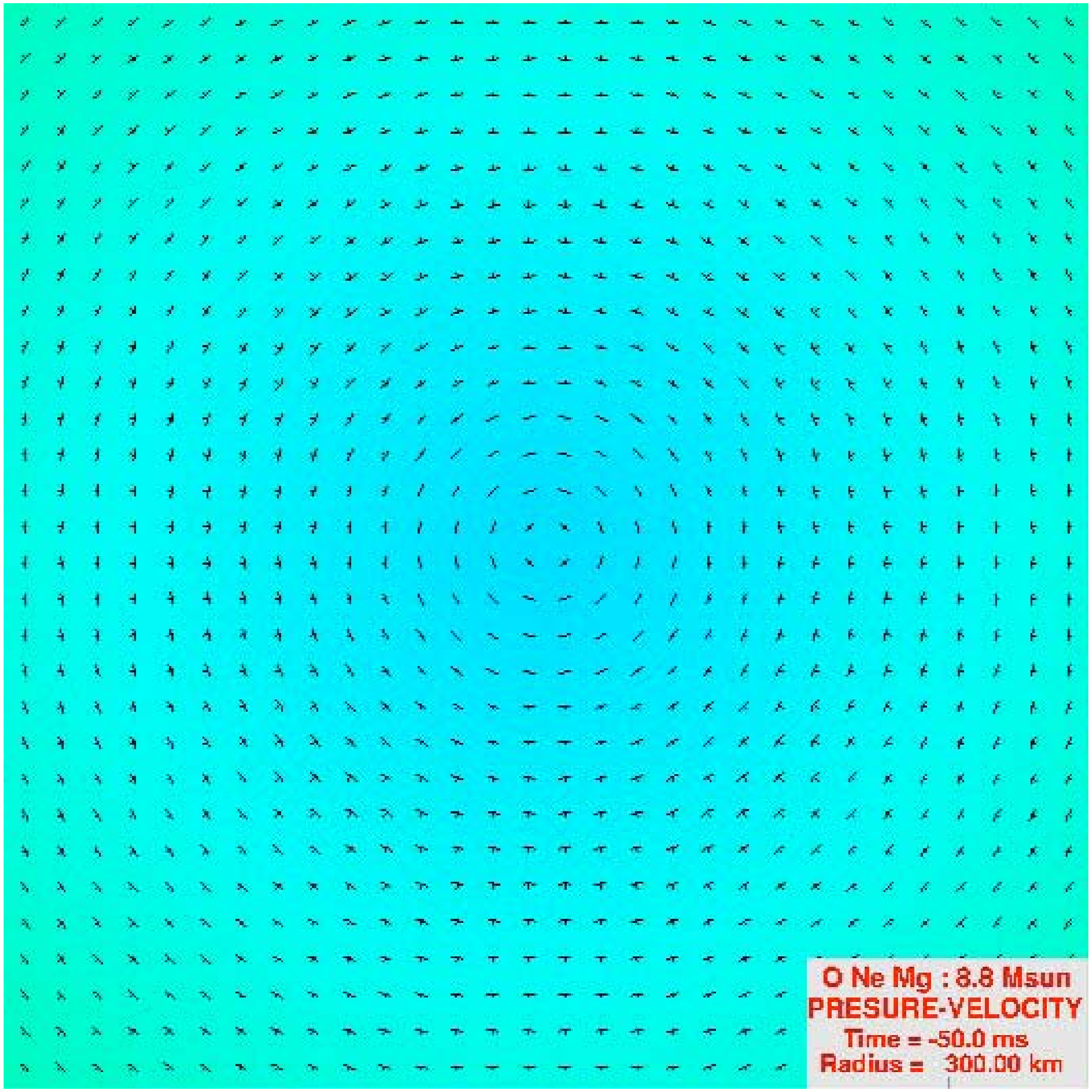


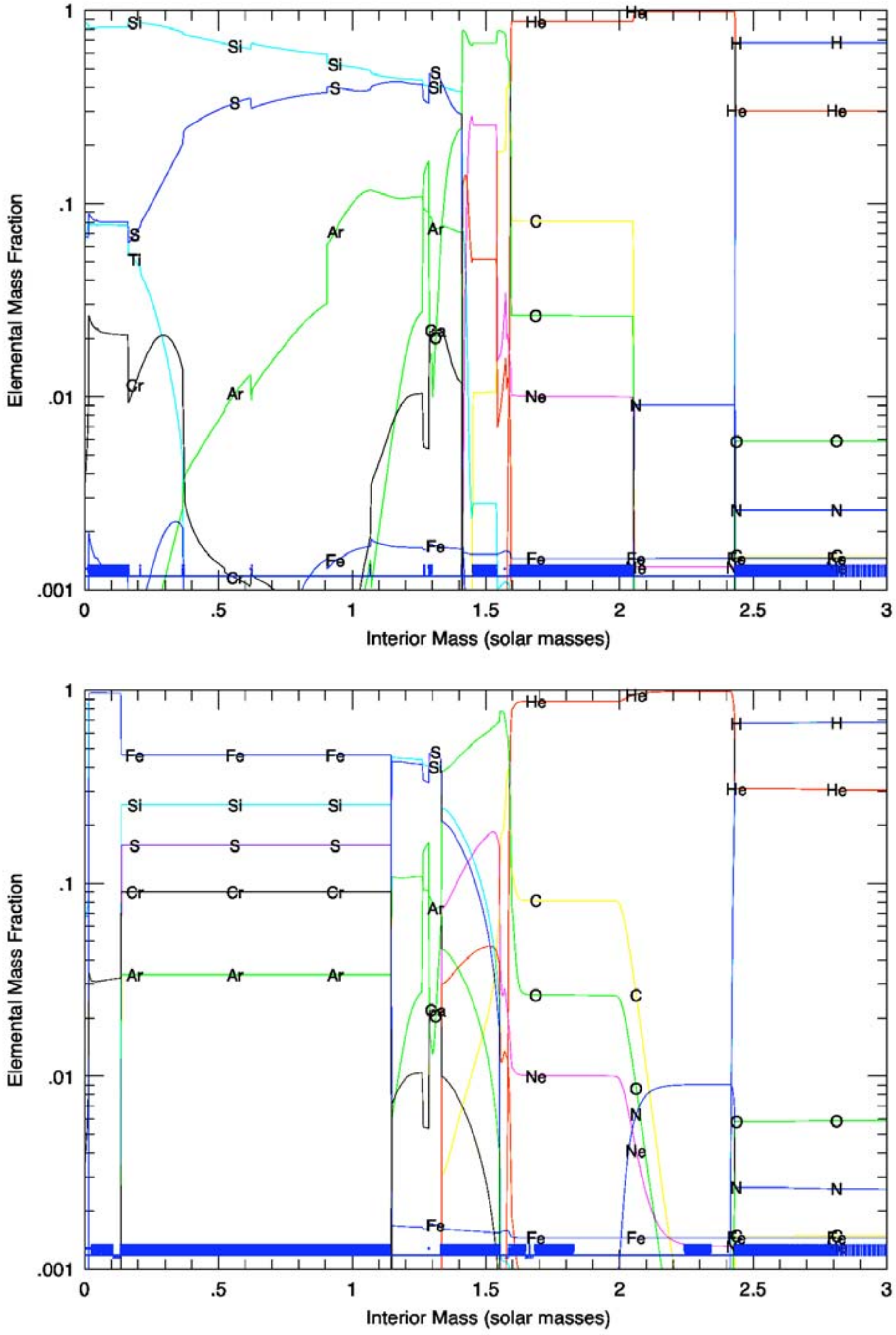
図7－4　超新星1987Aの熱源は？

8.8-Solar mass Progenitor of Nomoto: Neutrino-driven Wind Explosion



Dessart, Burrows et al. 2007;

Burrows 1987



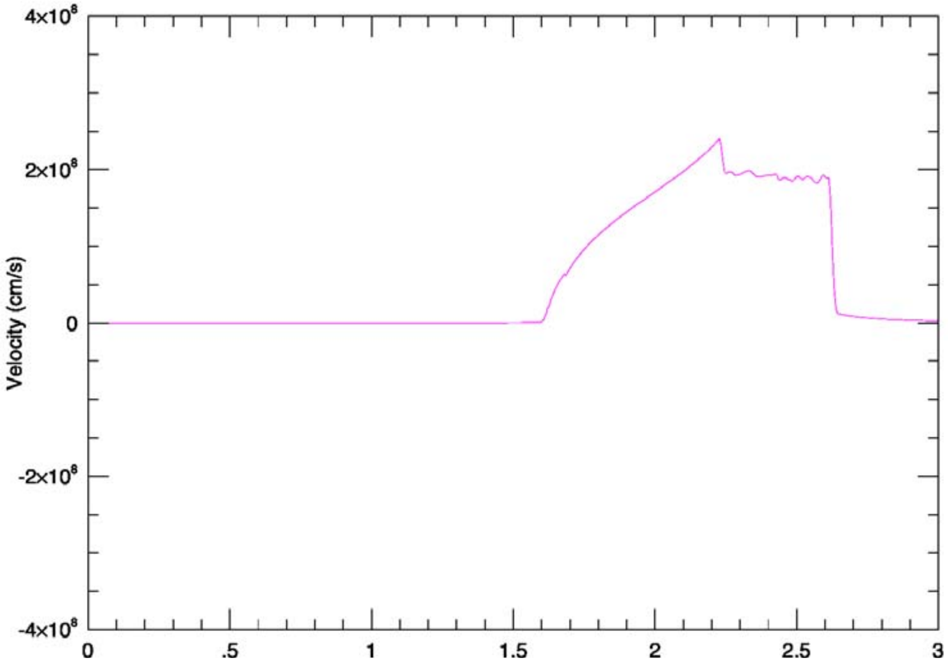
$10\ M_\odot$ Woosley and Heger (2007)

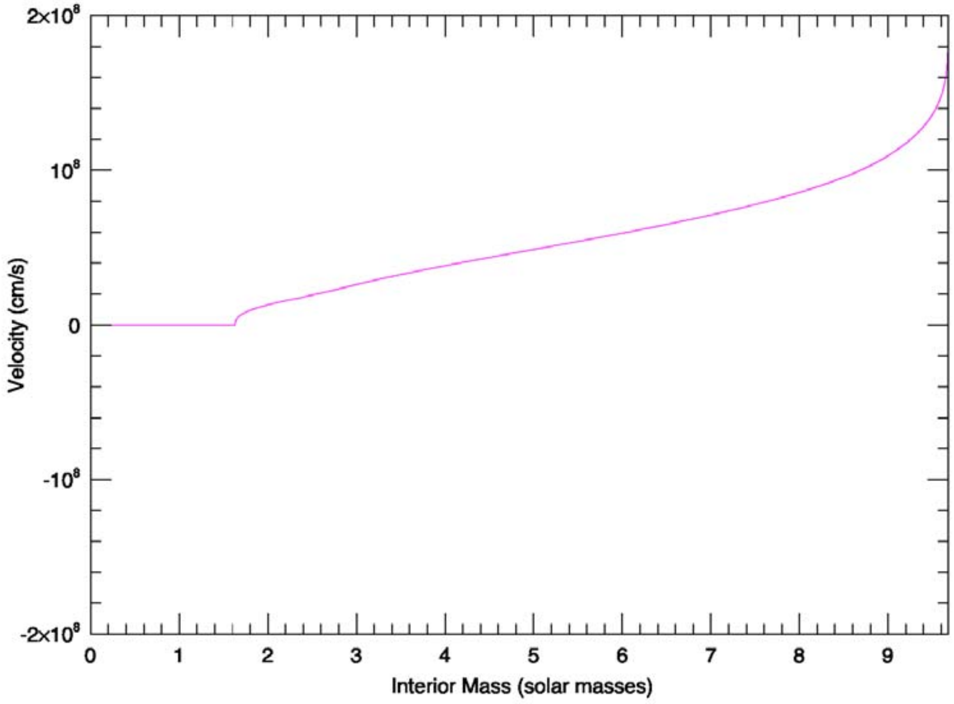
Fine zoning and careful treatment of nuclear physics (250 isotope network)

Ignition at 5×10^8 g cm^{-3} in a core of almost pure ^{30}Si ($Y_e = 0.46$).

Very degenerate but not so degenerate as a Ia.
$T \sim 2.5 \times 10^9$ at runaway.
Peak $T = 6 \times 10^9$ K.

Total nuclear energy liberated 3×10^{50} erg





Thermonuclear supernova!

Final kinetic energy
3.7 x 10^{49} erg

L ~ 3 - 10 x 10^{40} erg/s for ~ 1 year.

Typical ejection speeds
few x 10^{7} cm s^{-1}.

Leaves 1.63 solar masses

One year later, SN of about 10^{50} erg inside 8 solar masses of ejecta already at 10^{15} cm.

Results for stars near 10 solar masses

Mass	He core	CO core	Fe core	comment
9.2	1.69	1.43	1.22	envelope intact
10	2.2	1.58	1.29	envelope ejected
10.5	2.47	1.68	1.29	envelope ejected

Caveat: Multi-D effects not explored!

What about rotation?

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 the 10 solar mass star when it collapsed was
7×10^{47} erg s

This corresponds to a pulsar period of 11 ms, about half of what the Crab is believed to have been born with.

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

The explosion of the Crab SN was not (initially) powered by rotation and fall back was minimal.

This is consistent with what is estimated for young pulsars

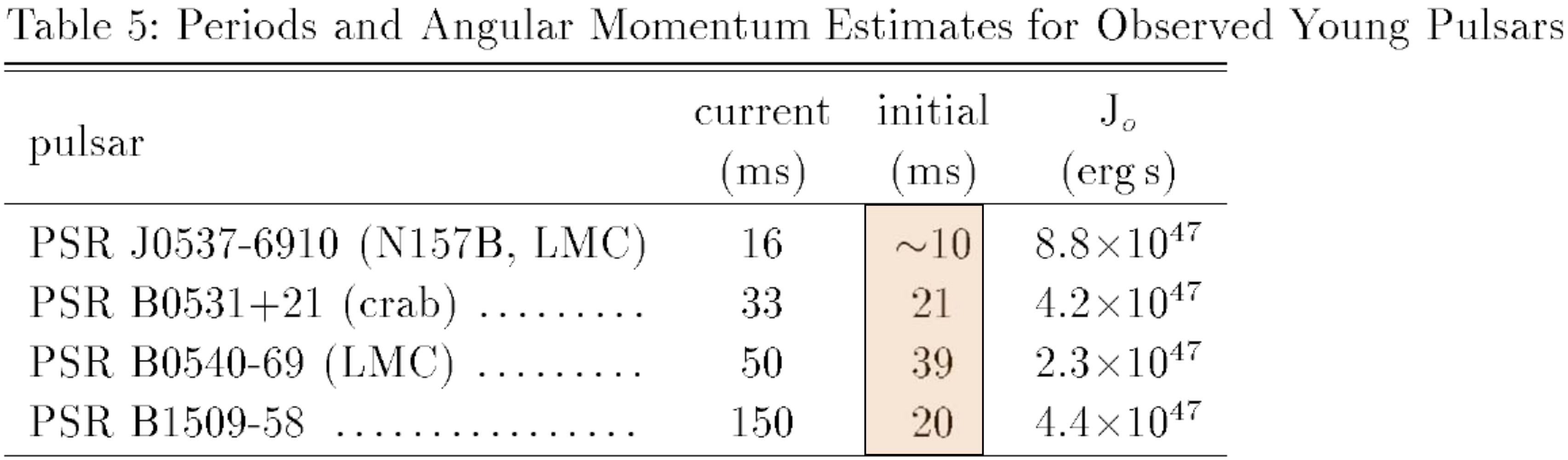


Table 5: Periods and Angular Momentum Estimates for Observed Young Pulsars

pulsar	current (ms)	initial (ms)	J_o (erg s)
PSR J0537-6910 (N157B, LMC)	16	$\sim$10	8.8×10^{47}
PSR B0531+21 (crab)	33	21	4.2×10^{47}
PSR B0540-69 (LMC)	50	39	2.3×10^{47}
PSR B1509-58	150	20	4.4×10^{47}

So, one could put together a consistent picture …

Stellar evolution including approximate magnetic torques gives slow rotation for common supernova progenitors.

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times 2 ?

Heger, Woosley, & Spruit (2004) using magnetic torques as derived in Spruit (2002)

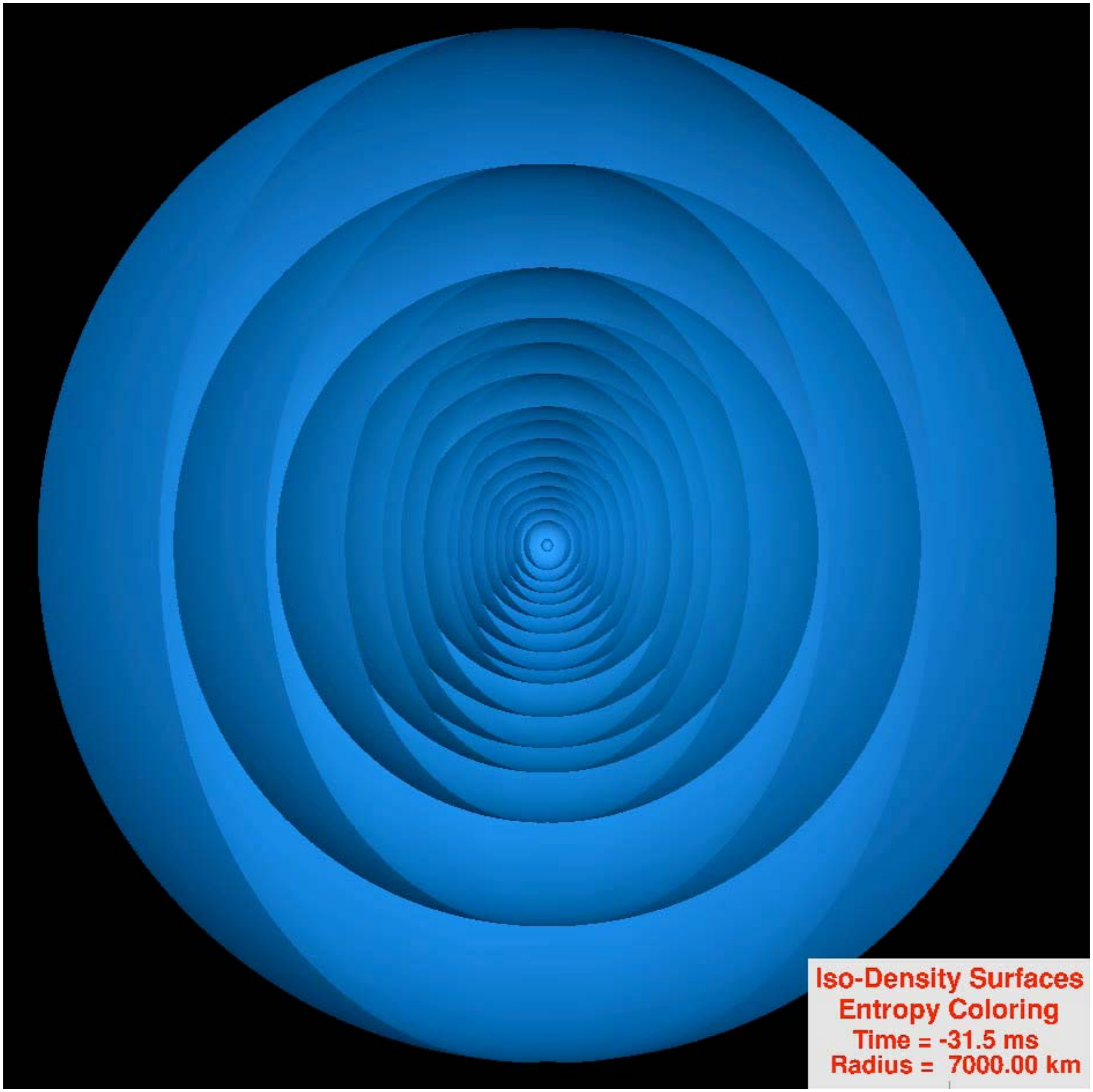
Implication:

Rotation unimportant in the initial explosion of the Crab (though clearly important now)

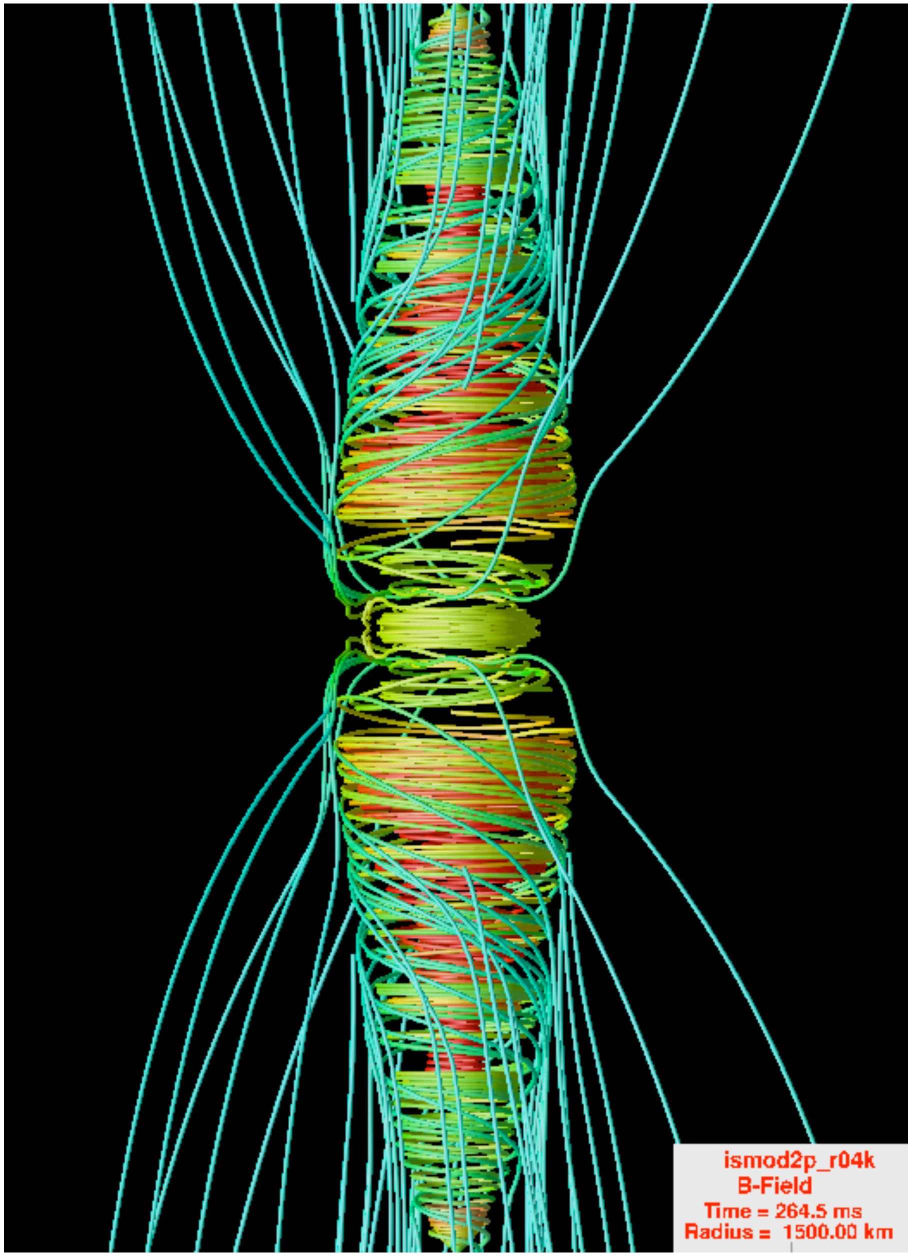
Speculation:

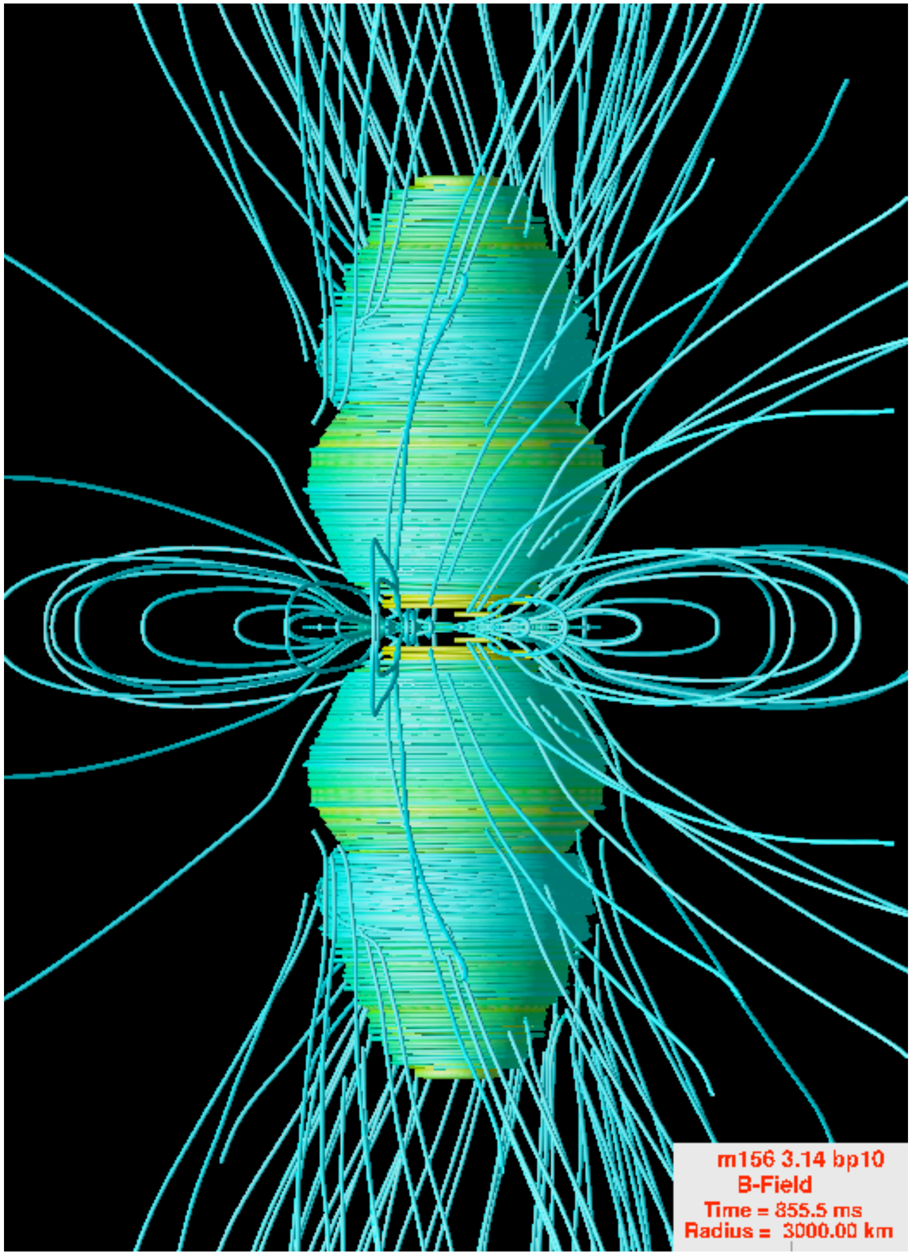
Rotation also unimportant in other models where Heger, Woosley, and Spruit calculated a period of ~10 ms, i.e., up to about 25 solar masses.

15 Solar masses – explodes with an energy of order 10^{51} erg.


Iso-Density Surfaces
Entropy Coloring
Time = -31.5 ms
Radius = 7000.00 km

But what about magnetars, black holes and gamma-ray bursts?


ismod2p_r04k
B-Field
Time = 264.5 ms
Radius = 1500.00 km


m156 3.14 bp10
B-Field
Time = 855.5 ms
Radius = 3000.00 km

What are the Magnetar Progenitors?

Muno, M, 2006, astroph 0611589

makes a compelling case that at least three magnetars have originated from stars with masses greater than 30 solar masses on the main sequence.

e.g, the star cluster Westerland 1 with a turn off mass of ~ 40 solar masses contains CXOU J164710.2-455216, an anomalous XRP and a source of soft gamma-ray bursts.

Birth rate of magnetars = 10% SN rate
(Kouveliotou 1994; Gaensler et al (1999, 2005)

GRB rate = 0.5% SN rate

Not every magnetar birth makes a bright GRB (maybe only the extreme cases do and in stars with no envelopes - or GRBs are something else - collapsars?)

But maybe….

Rotation and B-fields are important in about 10% of massive star deaths and neutrinos (or vibrations) power the rest.

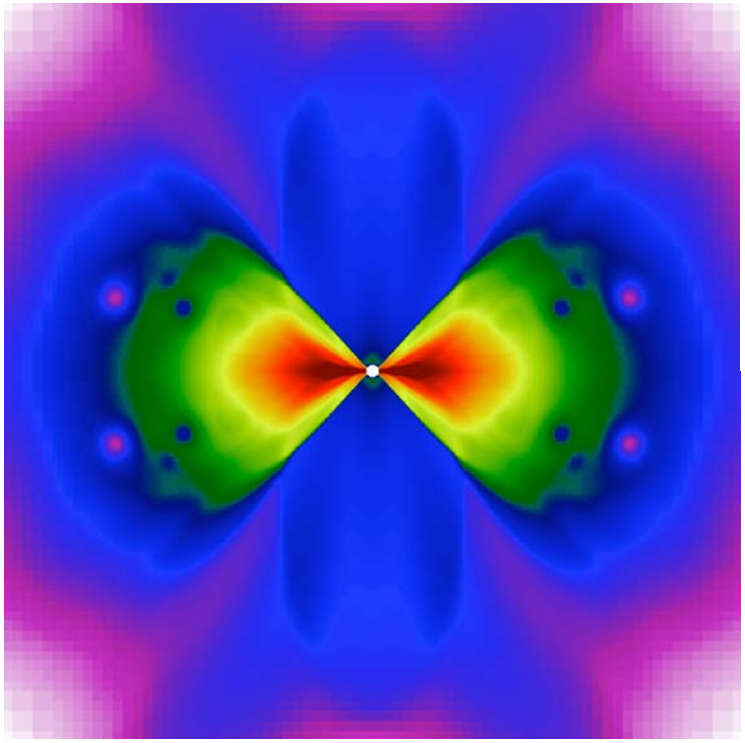
Conversely, one would expect about 10% of all supernovae to be anomalous in some fashion - not just the ones with the GRBs.

HYPERNOVAE !!?!

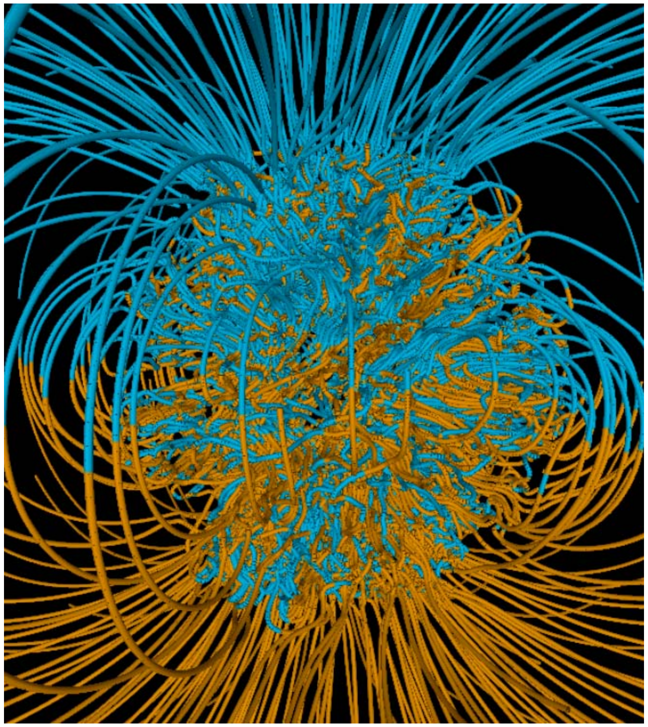
But what about the GRBs?

Today, there are two principal models being discussed for GRBs of the "long-soft" variety:

- The collapsar model
- The millisecond magnetar

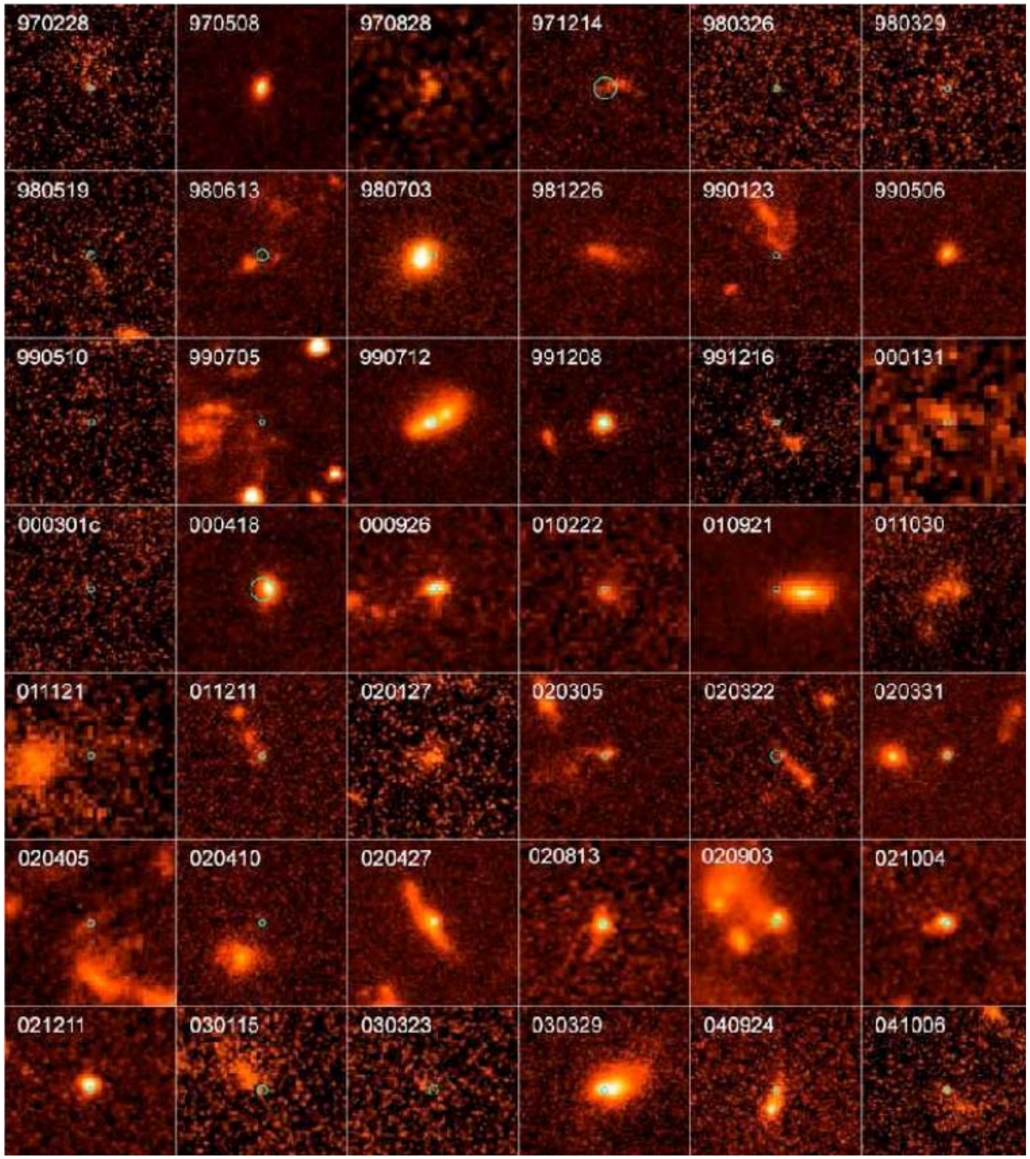


MacFadyen and Zhang (2005)



Glatzmaier

LS-GRBs occur in star-forming regions



Fruchter et al (2006)
Nature.

The green circles show GRB locations to an accuracy of 0.15 arc sec.

Conclusion: *GRBs trace star formation even more than the average core-collapse supernova. They are thus to be associated with the most massive stars. They also occur in young, small, star forming galaxies that might be metal poor.*

Need iron core rotation at death to correspond to a pulsar of < 5 ms period if rotation and B-fields are to give a a supernova with energy > 1 B. Need a period of ~ 2 ms or less to make classical GRBs. This is much faster than observed in common pulsars.

Total rotational kinetic energy for a neutron star

$$E_{\mathrm{rot}} \sim 2 \times 10^{52}\,(1\ \mathrm{ms/P})^2\ (10\ \mathrm{km/R})^2\ \mathrm{erg}$$

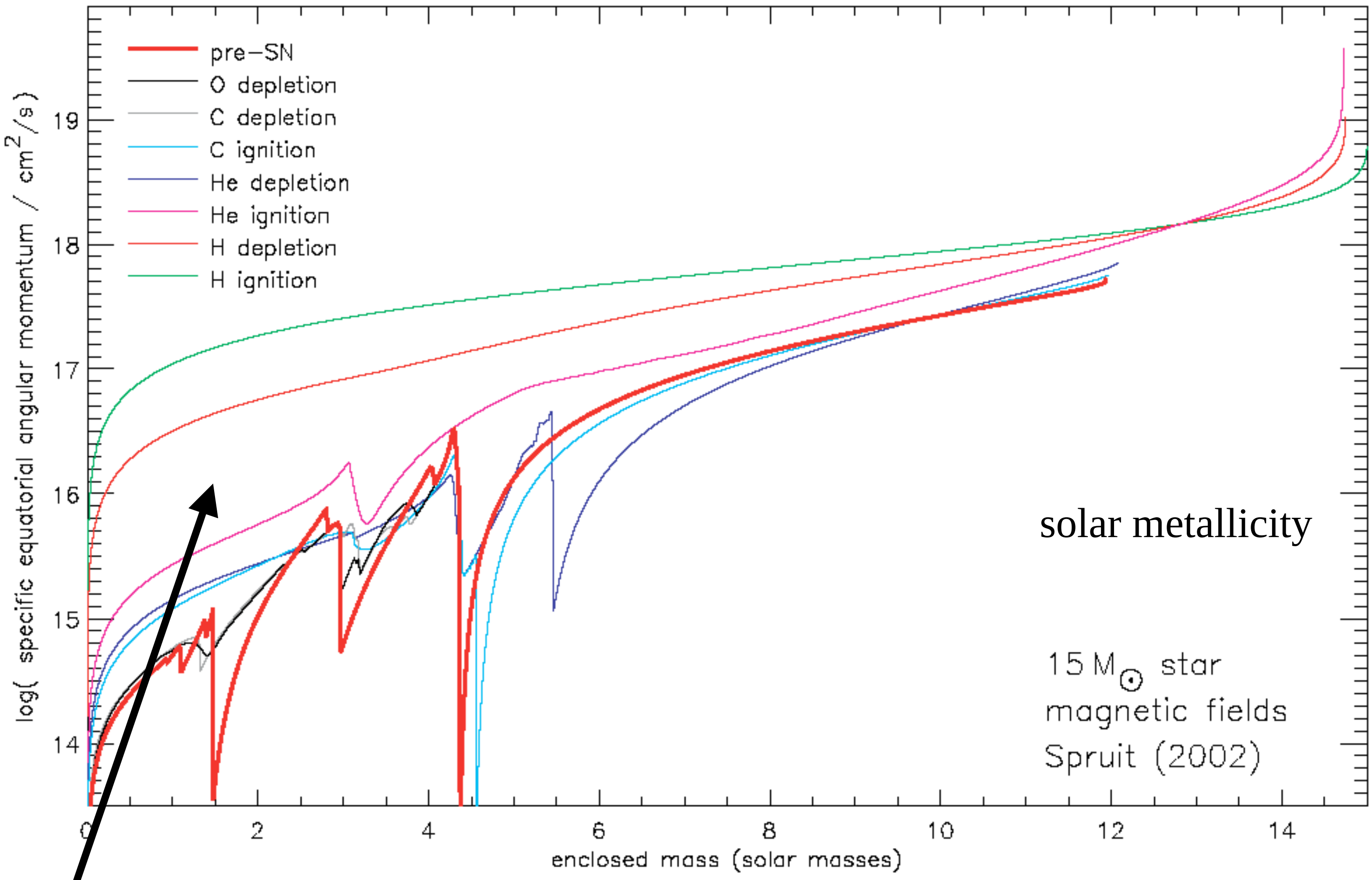
$$\mathrm{j} = R^2\Omega \sim 6 \times 10^{15}\,(P_{-3}^{-1}R_6^2)\ \mathrm{cm^2\ s^{-1}}\ \ \mathrm{at\ M} \approx 1.4\,\mathrm{M}_\odot$$

For the last stable orbit around a black hole in the collapsar model (i.e., the minimum j to make a disk)

$$j_{LSO} = 2\sqrt{3}\ GM/c = 4.6\times10^{16}\ M_{BH}/3M_\odot\ \mathrm{cm^2\ s^{-1}} \qquad \text{non-rotating}$$

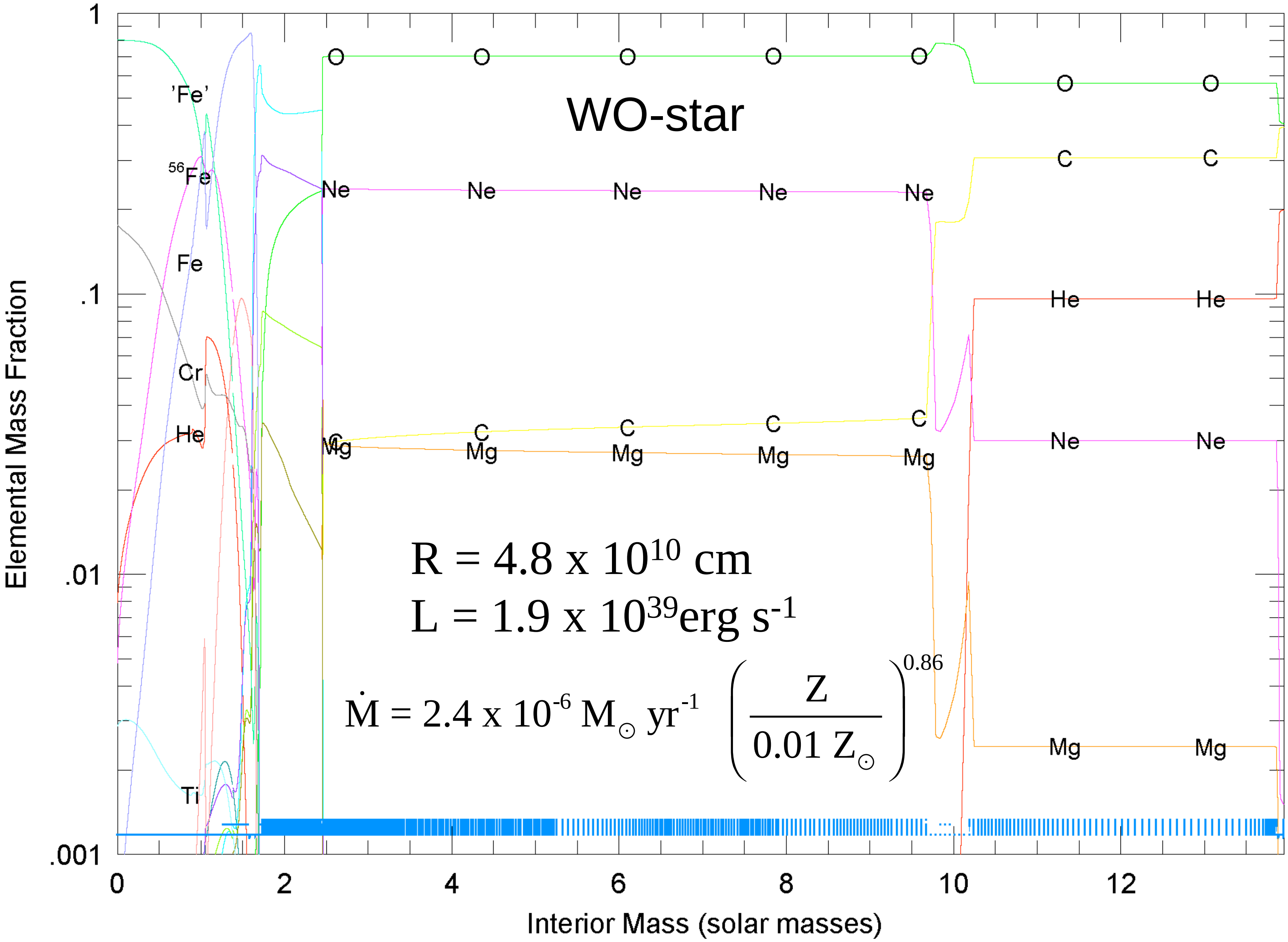
$$j_{LSO} = 2/\sqrt{3}\ GM/c = 1.5\times10^{16}\ M_{BH}/3M_\odot\ \mathrm{cm^2\ s^{-1}} \qquad \text{Kerr}\quad a = 1$$

It is somewhat easier to produce a magnetar model!



Much of the spin down occurs as the star evolves from H depletion to He ignition, i.e. forming a red supergiant. Early removal of the envelope helps but then must endure WR mass loss.

Heger, Woosley, & Spruit (2004)



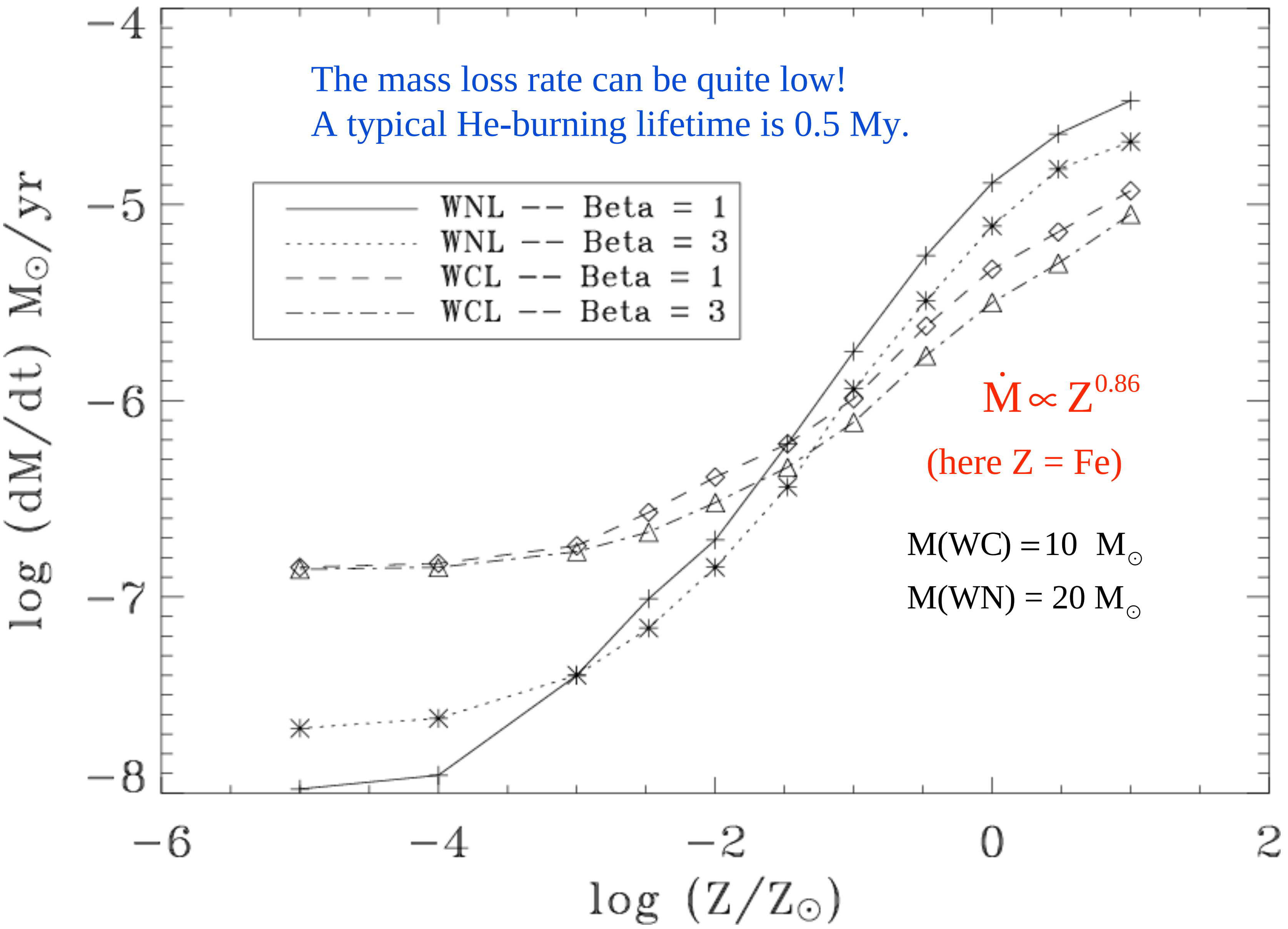
WO-star

$R = 4.8 \times 10^{10}$ cm

$L = 1.9 \times 10^{39}$ erg s^{-1}

$$\dot{M} = 2.4 \times 10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1} \left(\frac{Z}{0.01\ Z_{\odot}} \right)^{0.86}$$

Derived from 16 $M_{\odot}$ star with rapid rotation



The mass loss rate can be quite low!
A typical He-burning lifetime is 0.5 My.

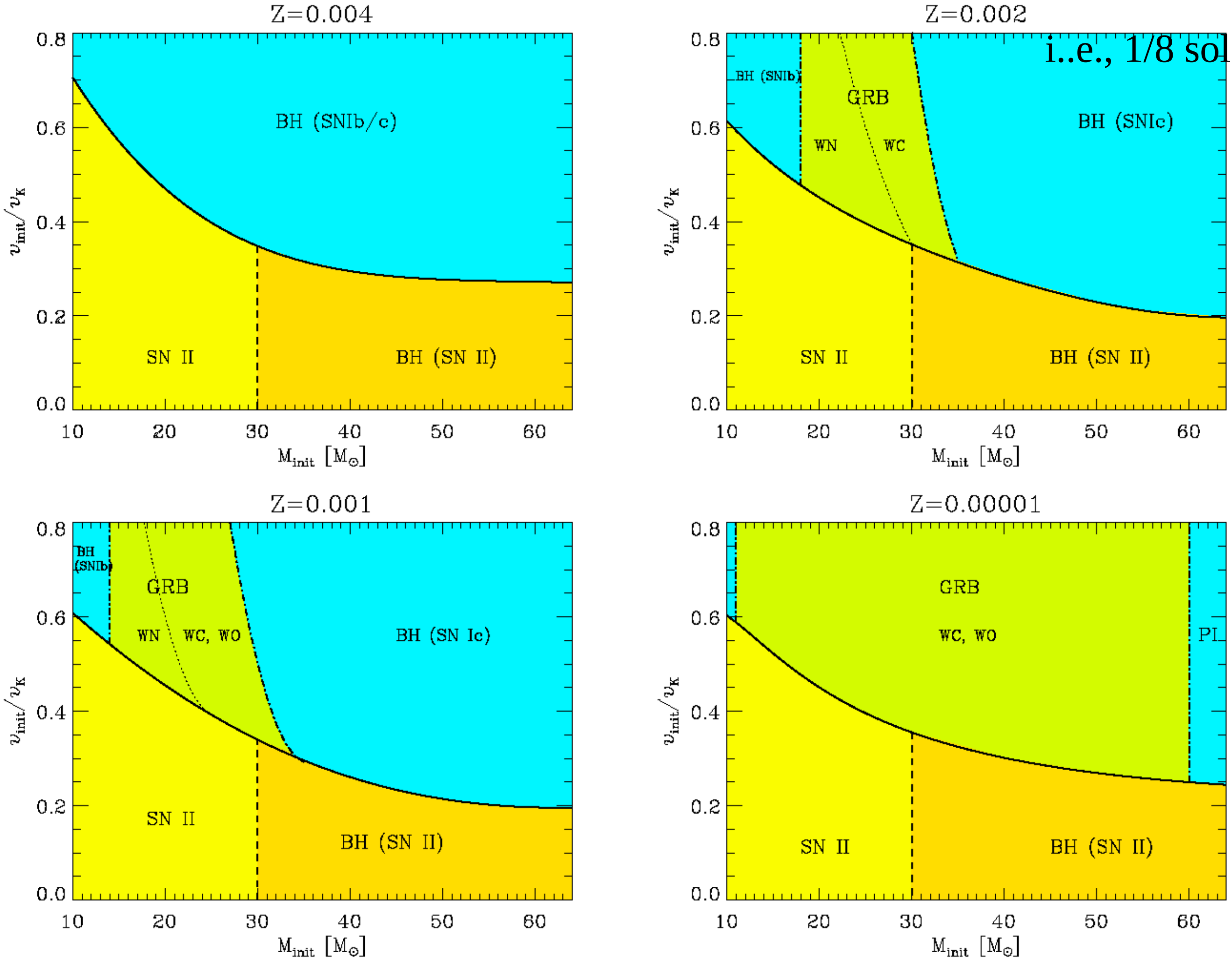
$\dot{M} \propto Z^{0.86}$

(here Z = Fe)

M(WC) = 10 $M_\odot$
M(WN) = 20 $M_\odot$

Theory

Vink & de Koter (A&A, 442, 587, (2005))



i..e., 1/8 solar

Yoon, Langer,
and Norman (2006)

$N_{GRB} / N_{SN} \ll 1\%$

out to redshift 4

saturates at 2% at

redshift 10

Woosley and Heger (2006) find similar results but estimate a higher metallicity threshold (30% solar) and a higher mass cut off for making GRBs.

Caveats:

- Magnetic torques (Spruit) uncertain. Certainly the final angular momentum could be off by a factor of 2.
- Metallicity means iron in the vicinity of the GRB, not CNO averaged over the galaxy
- The mass loss rates of WR stars and their iron dependence are quite uncertain
- If more mass is lost along the polar axis as theory suggests, higher metallicities can be tolerated
- Rotation requirements for making a GRB may have been overestimated - especially for pulsars or collapsars with bigger black holes

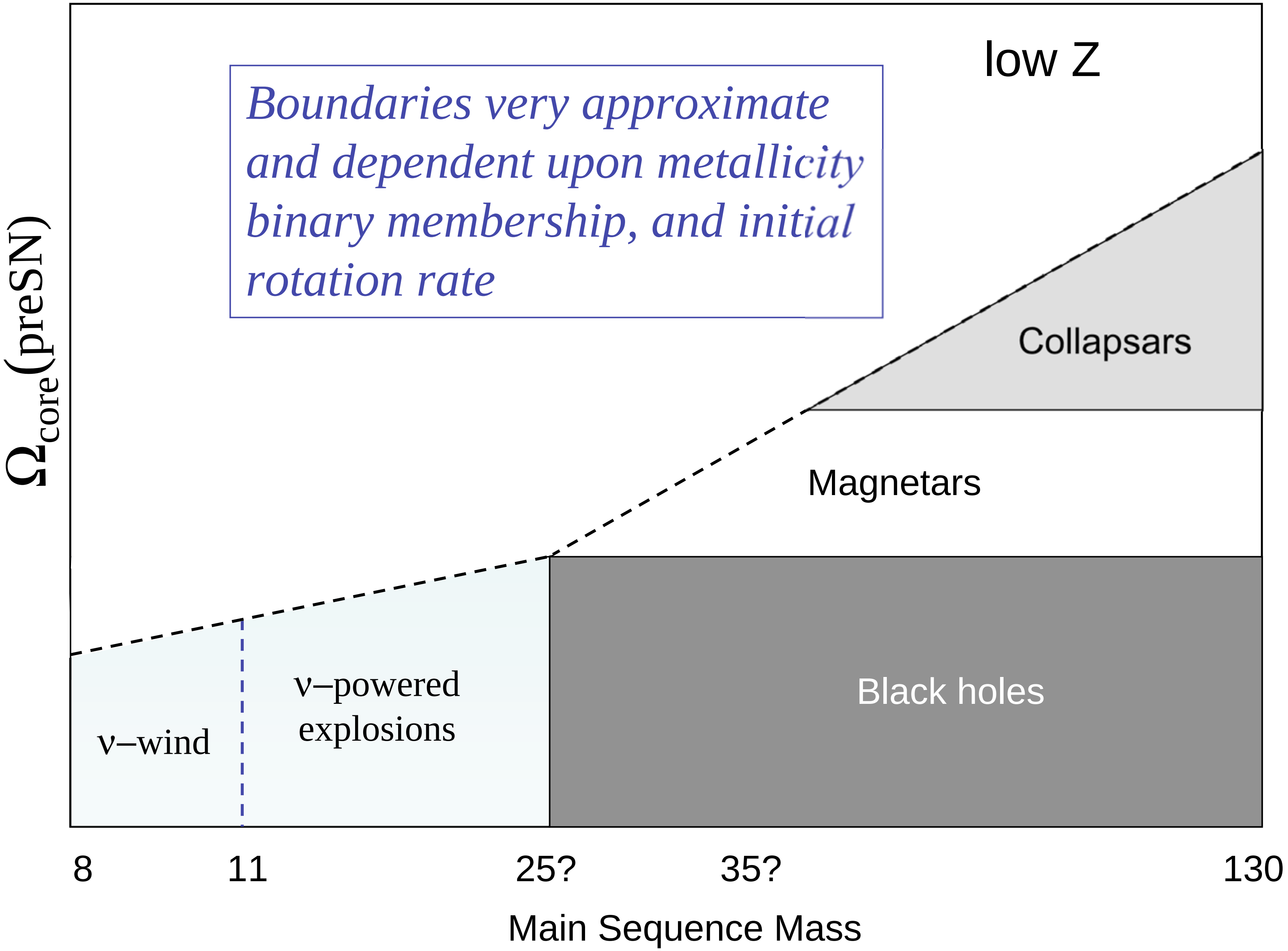
Black Holes

ApJ, **652**, 518 (2006) - McClintock et al.

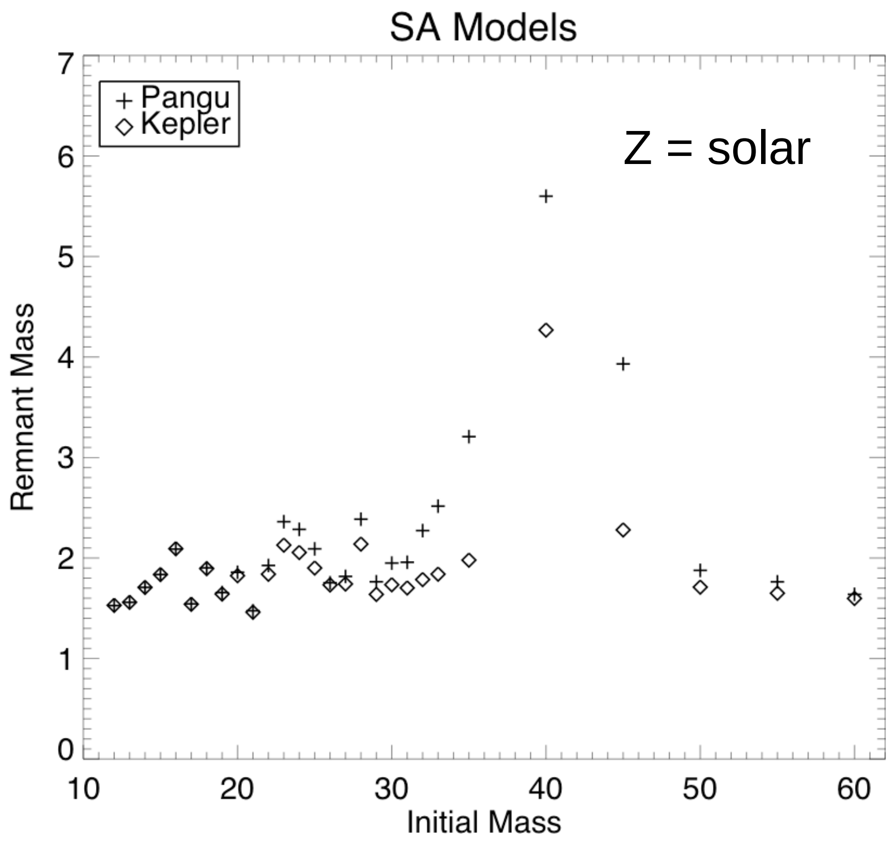
Extreme spin of black hole in microquasar
GRS 1916+105 $a > 0.98$

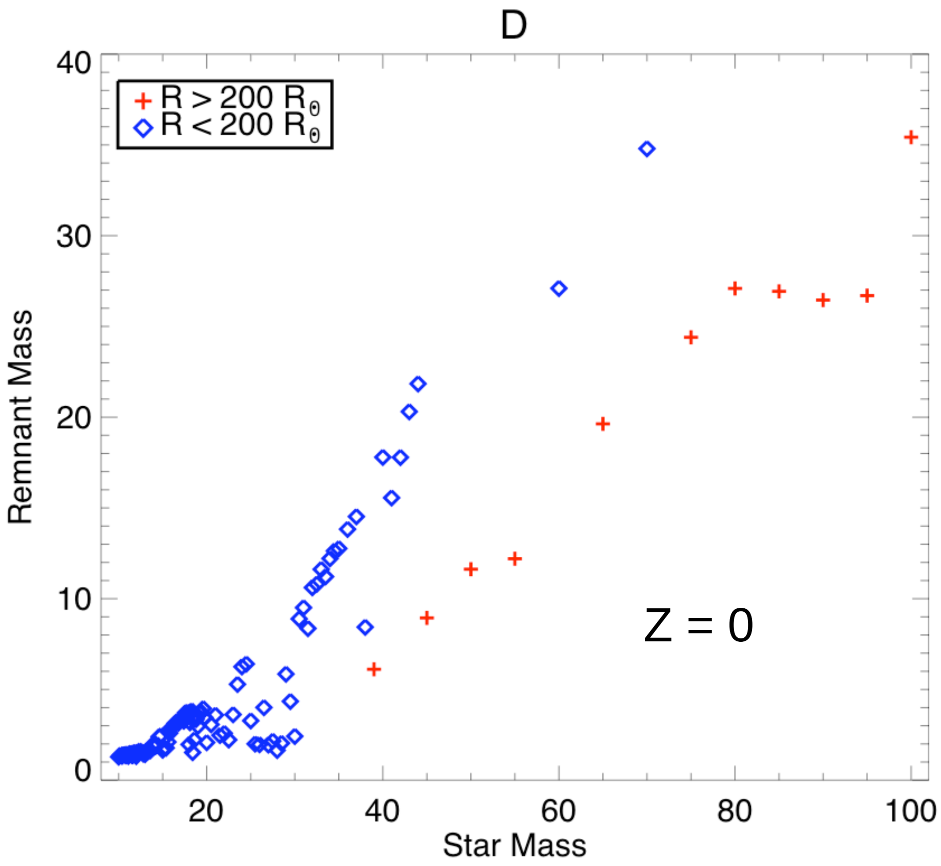
Two others quite high

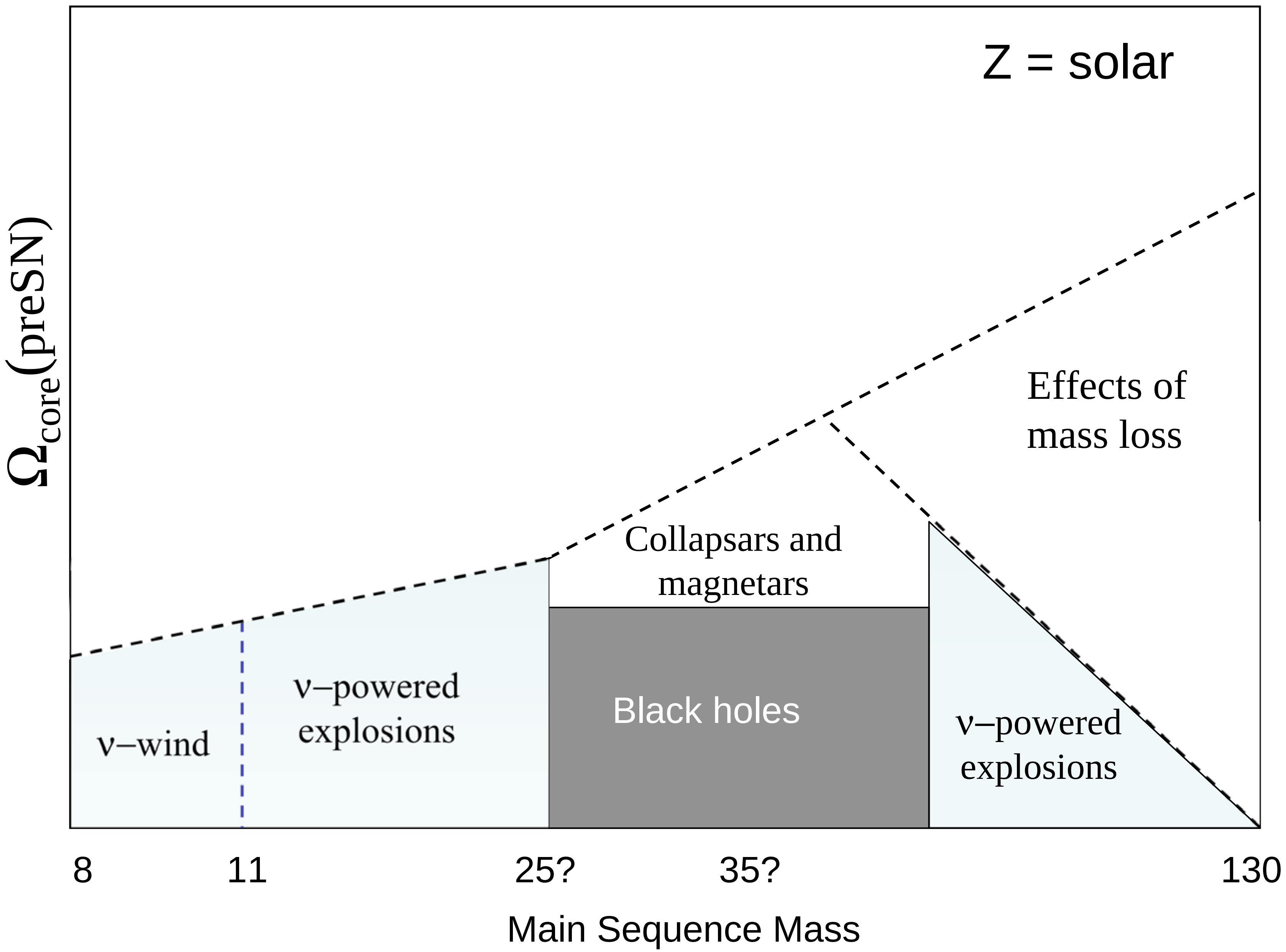
Spin natal, not acquired by later accretion,
but mass ~14 solar masses.


low Z
Boundaries very approximate and dependent upon metallicity binary membership, and initial rotation rate
Collapsars
Magnetars
Black holes
ν–powered explosions
ν–wind
Ω_{core}(preSN)
8
11
25?
35?
130
Main Sequence Mass

Remnant Masses
(no rotation, 1.2 B)






Z = solar
Ω_core(preSN)
Effects of mass loss
Collapsars and magnetars
ν–powered explosions
ν–wind
Black holes
ν–powered explosions
8
11
25?
35?
130
Main Sequence Mass

Conclusions

- Stars of 9.25 to ~12 solar masses could easily make supernovae without any recourse to rotational effects. Probable spin of the neutron star at birth is about 20 ms and this rate may characterize most SN II, Ib and Ic, modulo the effects of fall back

- Magnetars (and GRBs? and black holes?) come from the most massive, most rapidly rotating stars. Rotation and magnetic fields may play a big role in the deaths of ~10% of supernovae

- A better understanding of presupernova evolution with magnetic torques is urgently needed in order to better determine the dividing line