Lecture 14

Neutrino-Powered Explosions, Rotation, and Mixing

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.

For the next 30 years little progress was made though there were speculations:

Hoyle (1946) - *supernovae are due to a rotational bounce!!*

Hoyle and Fowler (1960) – *Type I supernovae are due to* the explosions of white dwarf stars

Fowler and Hoyle (1964) – *other supernovae are due to thermonuclear burning in massive stars – aided by rotation and magnetic fields*

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

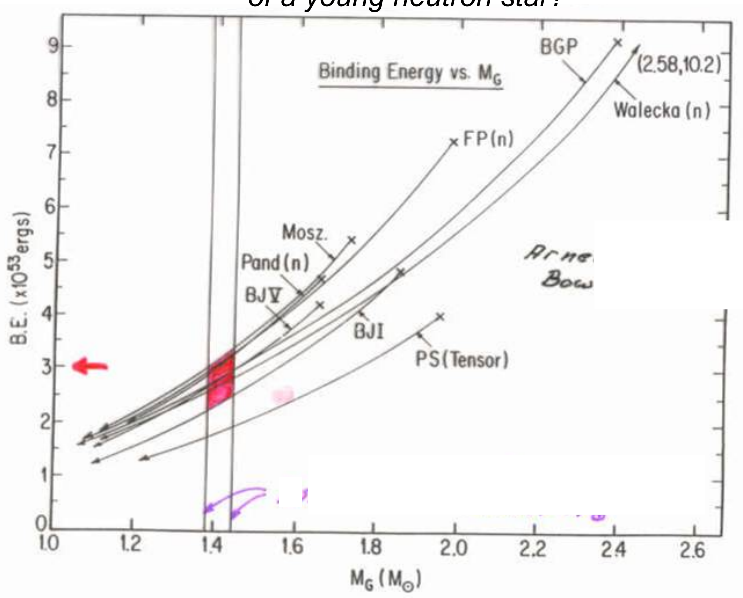
ABSTRACT

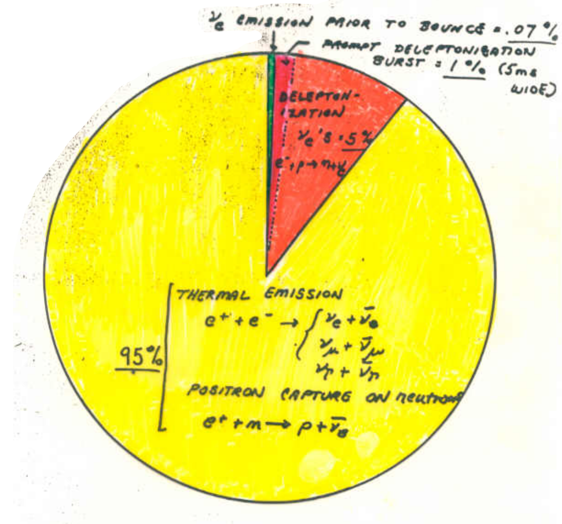
We regard the release of gravitational energy attending a dynamic change in configuration to be the primary energy source in supernovae explosions. Although we were initially inspired by and agree in detail with the mechanism for initiating gravitational instability proposed by Burbidge, Burbidge, Fowler, 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

Preliminary: *The neutrino emission of a young neutron star?*





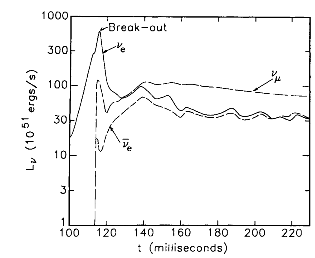


FIG. 1.—Emergent neutrino luminosities from the period just prior to core bounce (at 112.6 ms) to ~100 ms after bounce. The curves are for electron

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 μ - and τ - neutrinos are hotter than the electron neutrinos.

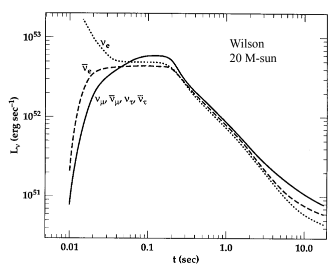


FIG. 2.—Neutrino luminosity L_ν for the six neutrino types as labeled as a function of time in the 20 $M_\odot$ supernova model.

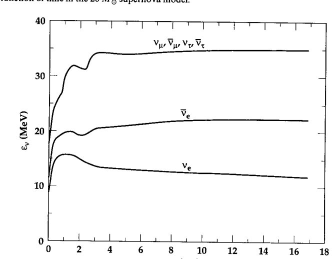


FIG. 3.—Mean neutrino energy ϵ_ν weighted by the square of the neutrino energy for the six neutrino types as a function of time in the 20 $M_\odot$ supernova model.

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

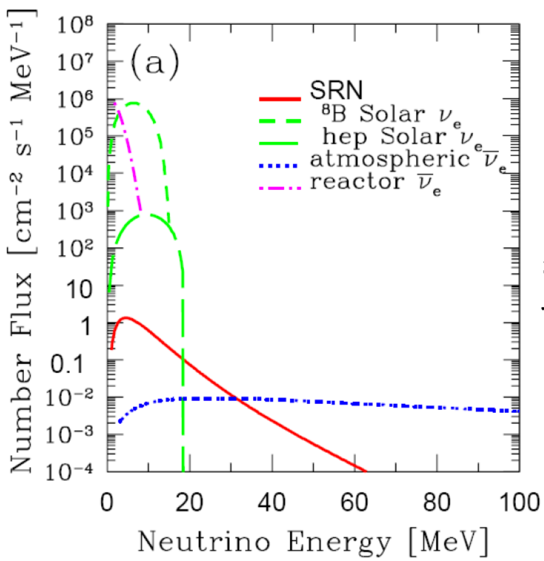
Cosmological Neutrino Flux

Ando, 2004, *ApJ*, **607**, 20

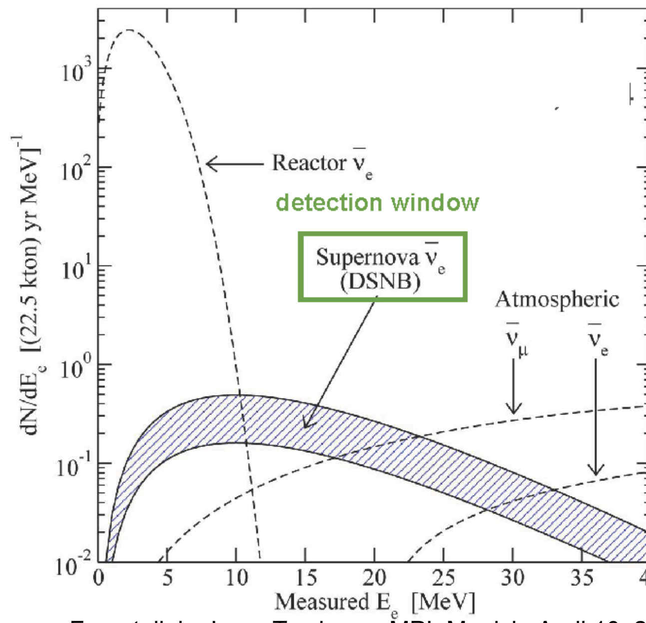
TABLE 2
FLUX AND EVENT RATE OF SUPERNOVA RELIC NEUTRINOS

		Flux (cm^{-2} s^{-1})			Event Rate [(22.5 kton yr)$^{-1}$]	
Model	Redshift Range	Total	$E_\nu > 11.3$ MeV	$E_\nu > 19.3$ MeV	$E_e > 10$ MeV	$E_e > 18$ MeV
		Normal Mass Hierarchy				
LL..................	Total	11.7	2.3	0.46	2.3	1.0
	$0 < z < 1$[a]	4.1 (35.3)	1.6 (70.9)	0.39 (85.2)	1.7 (77.5)	0.9 (87.5)
	$1 < z < 2$[a]	4.9 (42.0)	0.6 (26.3)	0.06 (14.0)	0.5 (20.6)	0.1 (11.9)
	$2 < z < 3$[a]	1.8 (15.1)	0.1 (2.5)	0.0 (0.7)	0.0 (1.7)	0.0 (0.5)
	$3 < z < 4$[a]	0.6 (5.3)	0.0 (0.2)	0.0 (0.0)	0.0 (0.1)	0.0 (0.0)
	$4 < z < 5$[a]	0.2 (2.1)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
TBP	Total	16.1	1.3	0.14	0.97	0.25
KRJ	Total	12.7	2.0	0.28	1.7	0.53

LL = Livermore group (1998); TBP = Thompson, Burrows and Pinto (2003); KRJ = Keil, Raffelt, and Janka (2003)



S. Ando and K. Sato, New J. Phys. 6:170, 2004.



From talk by Irene Tamborra, MPI, Munich, April 10, 2013

DSNB Detection Perspectives

The DSNB has not been observed yet. Most stringent limit is from Super-Kamiokande (SK):

$$\phi_{\bar{\nu}_e} \leq 2.8 - 3.0\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$ for E > 17.3 MeV

Concept	energy window (MeV)	detection processes	experiment (location)	fiducial mass (kt)	events per year
H_2O	19.3 - 30 [17.3 – 30]	$\bar{\nu}_e\,(p,n)e^+$	SK (Japan)	22.5	0.25 - 1.40
		$\nu_e\,(^{16}O,X)e^-$	DUSEL WC (USA)	300	3.3 - 18.7
		$\bar{\nu}_e\,(^{16}O,X)e^+$	MEMPHYS (Europe)	440	4.9 - 27.5
		$\nu_w(e^-,e^-)\nu_w$	Hyper-K (Japan)	500	5.5 - 31.2
		$\nu_w(p,p)\nu_w$	Deep-TITAND (Japan)	5 10^3	55 - 312
		$\nu_w(^{16}O,X)\nu_w$			
$H_2O + Gd$	11.3 - 30	same as H_2O	GADZOOKS (Japan)	22.5	0.97 - 2.8
			DUSEL WC+Gd	300	12.9 - 37.2
			MEMPHYS+Gd	440	18.9 - 54.6
			Hyper-K+Gd	500	21.5 - 62.0
Scintillator	$\sim 8 - 30$	$\bar{\nu}_e\,(p,n)e^+$	LENA (Europe)	50	1.9 - 5.4
		$\nu_e\,(^{12}C,X)e^-$	Hano Hano (USA)	10	0.3 - 1.1
		$\bar{\nu}_e\,(^{12}C,X)e^+$			
		$\nu_w(e^-,e^-)\nu_w$			
		$\nu_w(p,p)\nu_w$			
		$\nu_w(^{12}C,X)\nu_w$			
Argon	$\sim 18 - 30$	$\nu_e\,(^{40}Ar,X)e^-$	LANNDD (USA)	< 100	< 3.3
		$\bar{\nu}_e\,(^{40}Ar,X)e^+$	GLACIER (Europe)	100	0.9 - 3.3
		$\nu_w(e^-,e^-)\nu_w$			
		$\nu_w(^{40}Ar,X)\nu_w$			

From talk by Irene Tamborra, MPI, Munich, April 10, 2013

NEUTRINO BURST OBSERVED FEBRUARY 23, 1987

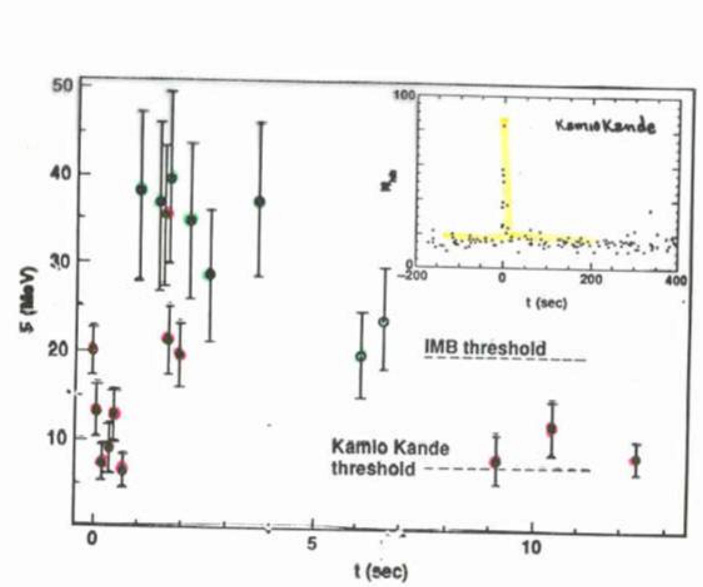
- Originated from SN 1987A in the Large Magellanic Cloud, 55 kpc distant. First signal from supernova (supernova detected optically, neutrino data then searched).
- Detected in 3 locations - IMB - Cleveland; Kamiokande - Japan; and Baksan - USSR.
- Observed at Kamiokande and IMB* - 19 neutrino events, energies 8 to 40 MeV. Inferred neutrino temperature - 5 MeV. Total neutrino energy inferred at LMC - 2 to 5 x 10^{53} erg. Duration about 10 s with most emission during first 3 s.
- Neutrino flux at Earth about 5 × 10^{10} cm^{-2} s^{-1}.
- Observed coming through the Earth!
- Arrival at same time as light puts limits on neutrino mass (very small)

K II 2140 tons H_2O
IMB 6400 tons "

Cerenkov radiation from

$\bar{\nu}$(p,n)e$^+$ - dominates
ν(e$^-$,e$^-$)n - relativistic e
all flavors ν

less than solar neutrino flux but neutrinos more energetic individually.



At densities above nuclear, the coherent scattering cross section (see last lecture) is no longer appropriate. One instead has scattering and absorption on individual neutrons and protons.

Scattering: $\kappa_{\nu s} \approx 1.0\times10^{-20}\left(\frac{E_\nu}{\text{MeV}}\right)^2 \text{ cm}^2\text{ gm}^{-1}$

Absorption: $\kappa_{\nu a} \approx 4\kappa_{\nu s}$

The actual neutrino energy needs to be obtained from a simulation but is at least tens of MeV. Take 50 MeV for the example here. Then $\kappa_\nu \sim 10^{-16}\text{ cm}^2\text{ g}^{-1}$. Gives $l_{mfp} \sim$ 1 m and $\tau_{diff} \sim$ few seconds.

Neutrino Burst Properties:

$$E_{tot} \sim \frac{3}{5}\frac{GM^2}{R} \qquad M = 1.5\ M_\odot$$

$$\sim 3\times10^{53}\text{ erg} \qquad R = 10\text{ km}$$

emitted roughly equally in $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau$, and $\bar{\nu}_\tau$

Time scale

$$\tau_{Diff} \sim \left(\frac{R^2}{l\,c}\right) \qquad l = \frac{1}{\kappa_\nu \rho}$$

$\kappa_\nu \sim 10^{-16}\text{ cm}^2\text{ gm}^{-1}$ for $\varepsilon_\nu =$ 50 MeV (next page)

$\rho \sim 3\times10^{14}\text{ gm cm}^{-3} \quad \Rightarrow \quad l \sim$ 30 cm $\qquad$ R ~ 20 km

$$\tau_{Diff} \sim \left(\frac{(2\times10^6)^2}{30\bullet 3\times10^{10}}\right) \sim 5\text{ sec}$$

Very approximate

Temperature:

$$L_\nu \approx \frac{E_{tot}}{6\tau_{Diff}} \approx 10^{52}\text{ erg s}^{-1}\text{ per flavor}$$

$$\approx \frac{7}{16}\left(4\pi\sigma R_\nu^2 T_\nu^4\right) \Rightarrow T_\nu \approx 4.5\text{ MeV}$$

for $R_\nu \approx$ 20 km and $\tau_\nu = 3$ sec

Actually $\bar{R}_\nu$ is a little bit smaller and τ_{Diff} is a little bit longer but 4.5 MeV is about right.

A victory for theory

Back to supernovae:

There were fundamental problems in the late 1960's and early 1970's that precluded a physically complete description:

- Lack of realistic progenitor models (addressed in the 80s)
- Primitive radiation transport or none
- Neglect of weak neutral currents – discovered 1974
- Uncertainty in the equation of state at super-nuclear densities (started to be addressed in the 80s)
- Inability to do realistic multi-dimensional models - the current frontier
- Missing fundamental physics (still discussed – flavor mixing?)

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

EQUATION OF STATE IN THE GRAVITATIONAL COLLAPSE OF STARS

H. A. BETHE†
The Niels Bohr Institute, DK-2100 Copenhagen Ø, Denmark
and
G. E. BROWN††, J. APPLEGATE†† and J. M. LATTIMER‡
NORDITA, DK-2100 Copenhagen Ø, Denmark

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 - no longer believed

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

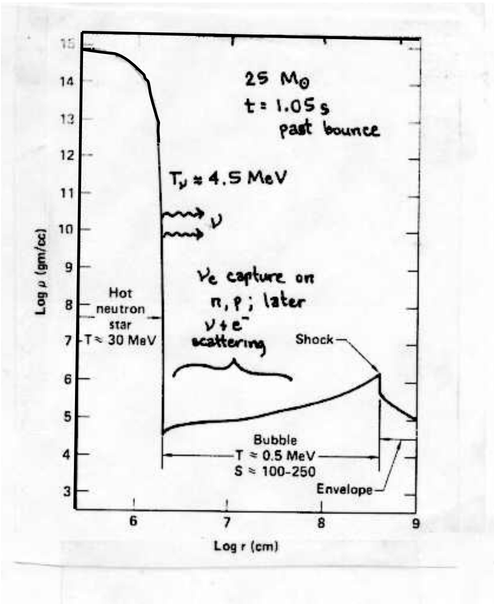
REVIVAL OF A STALLED SUPERNOVA SHOCK BY NEUTRINO HEATING*

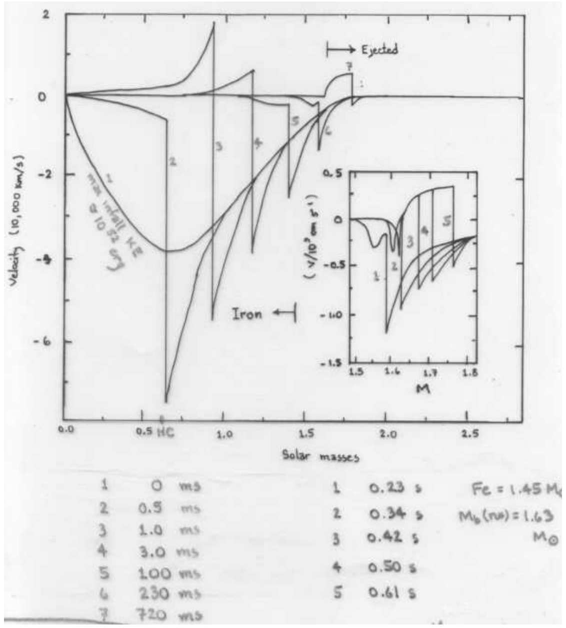
HANS A. BETHE
Laboratory of Nuclear Studies, Cornell University
AND
JAMES R. WILSON
Lawrence Livermore National Laboratory
Received 1984 March 23; accepted 1985 February 5

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)



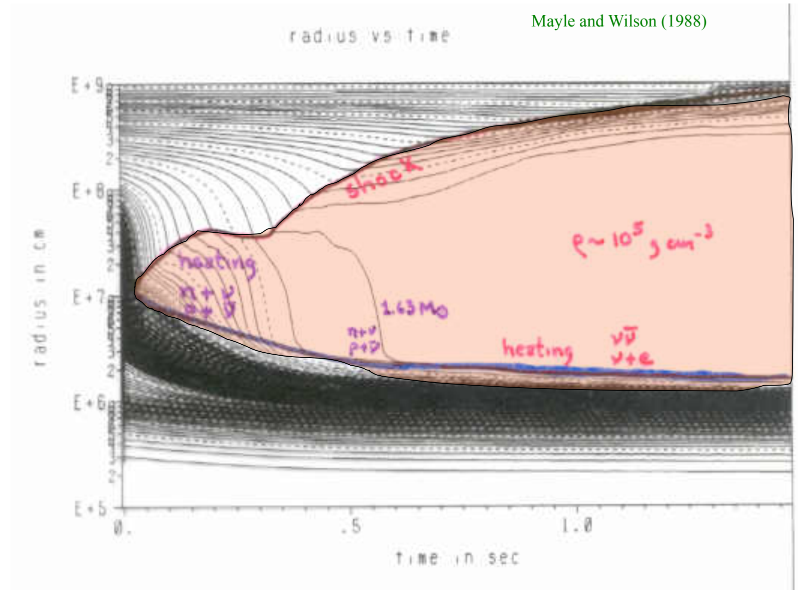


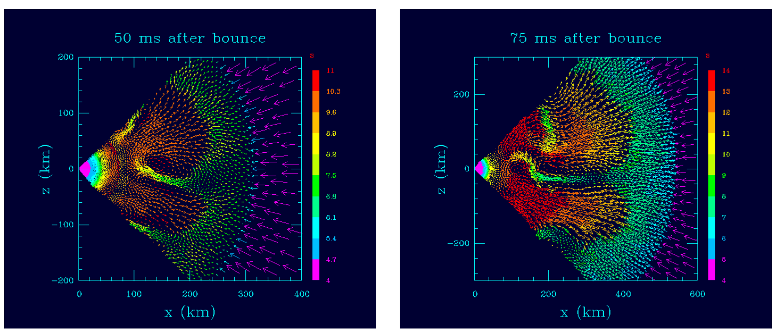
20 Solar Masses

Mayle and Wilson (1988)

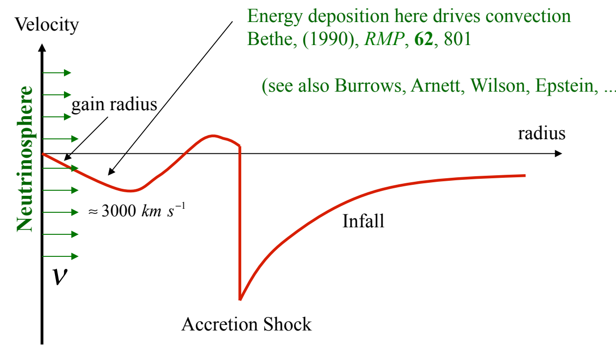
$r_{bounce} = 5.5 \times 10^{14}$ g cm^{-3}

Explosion energy at 3.6 s
3×10^{50} erg



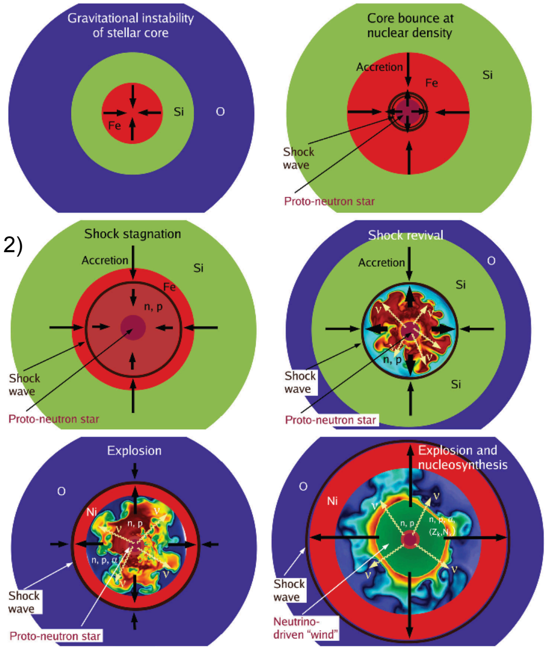


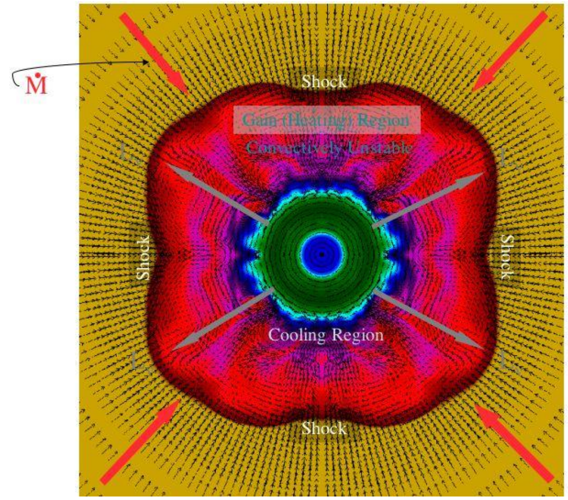
Herant and Woosley, 1995. 15 solar mass star.
successful explosion.
(see also Herant, Benz, & Colgate (1992), *ApJ*, **395**, 642)



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.

Janka et al (2012)
PTEP.



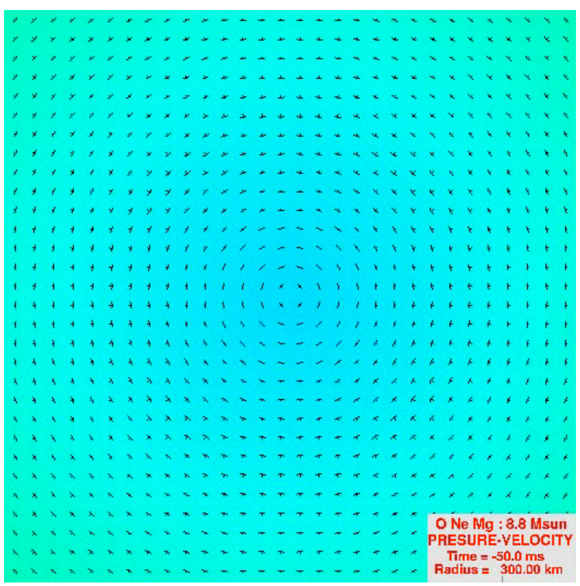


Burrows (2005)

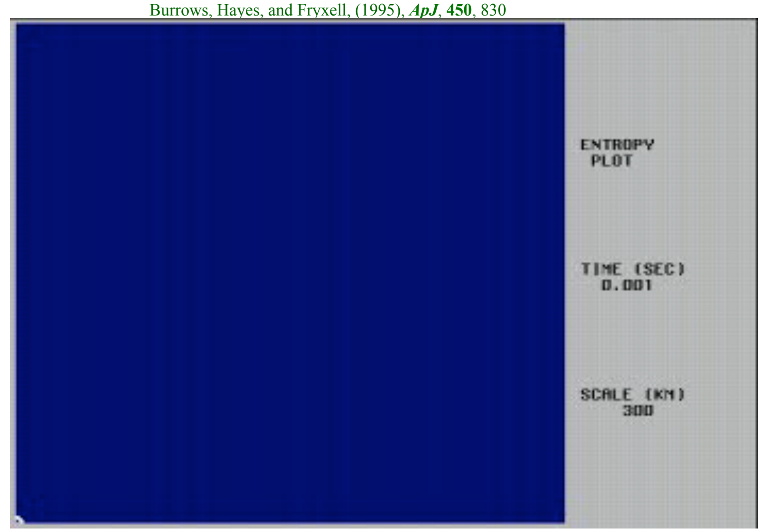
8.8-Solar mass Progenitor of Nomoto: Neutrino-driven Wind Explosion

Burrows et al ,
2007, AIPC,
937, 370

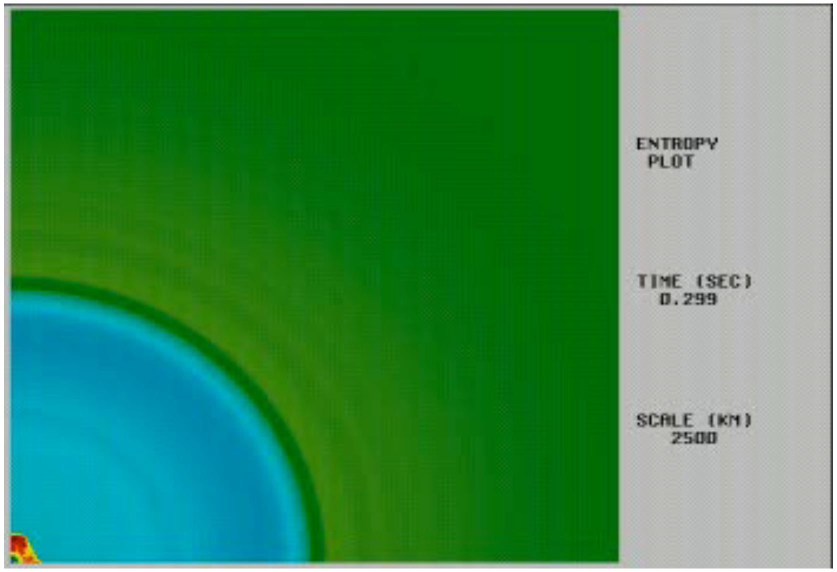
Explosion energy
$\leq 10^{50}$ erg



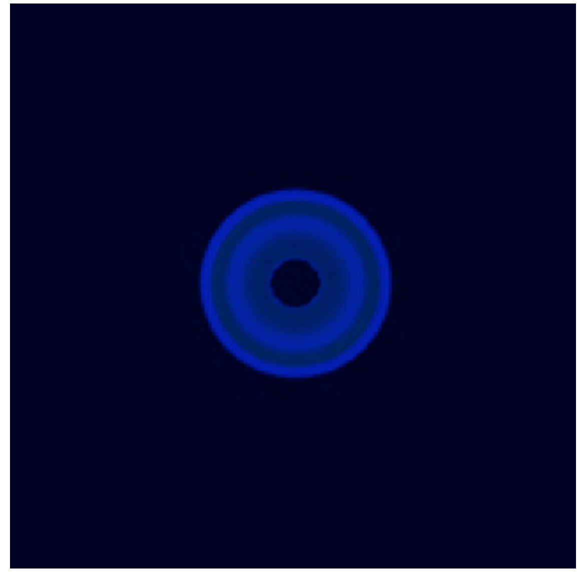
Burrows, Hayes, and Fryxell, (1995), ***ApJ***, **450**, 830



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



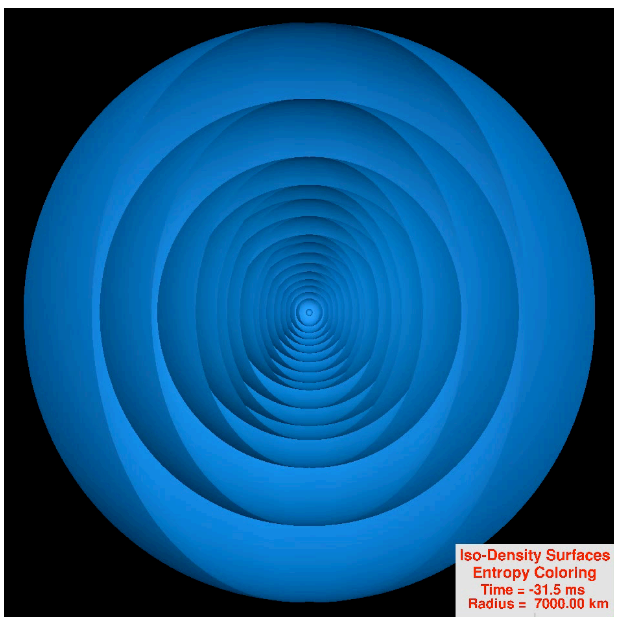
At 408 ms, KE = 0.42 foe, stored dissociation energy is 0.38 foe, and the total explosion energy is still growing at 4.4 foe/s

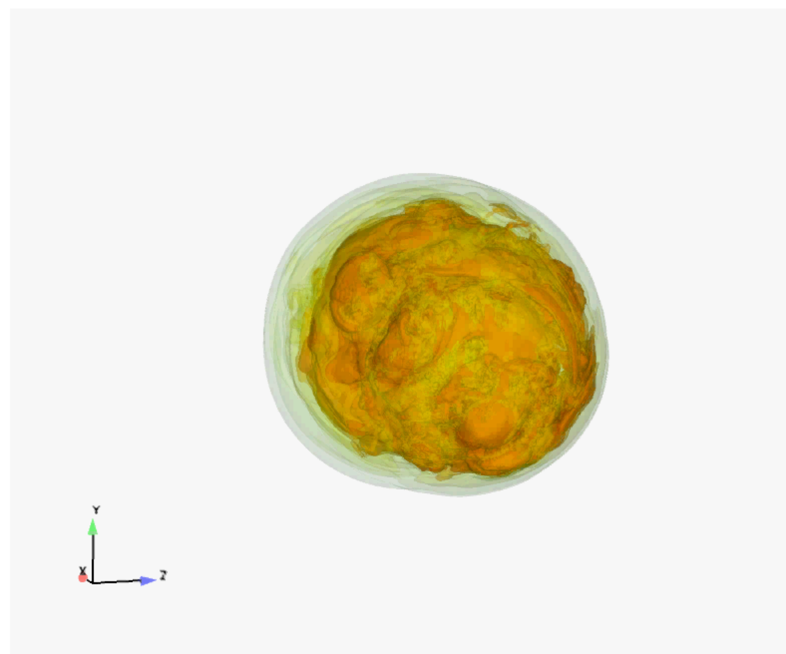


Mezzacappa et al. (1998), *ApJ*, **495**, 911.

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

No explosion.



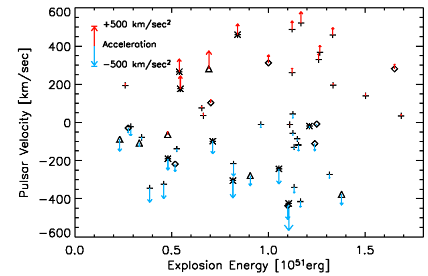


<u>Beneficial Aspects of Convection</u>

- Increased luminosity from beneath the neutrinosphere
- Turbulent motion is an extra source of pressure
- Transport of energy to regions far from the neutrinosphere (i.e., to where the shock is)

<u>Also Helpful</u>

- 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).



Scheck et al. (2004)

Figure 1: Neutron star velocities and accelerations at one second after core bounce for a sample of simulations [4]. Different symbols denote different progenitor stars.

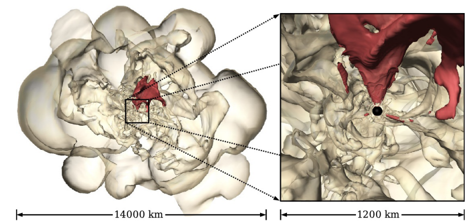
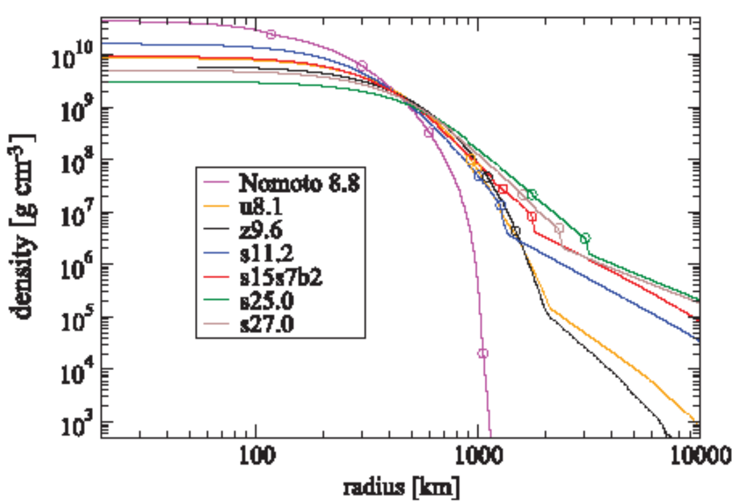
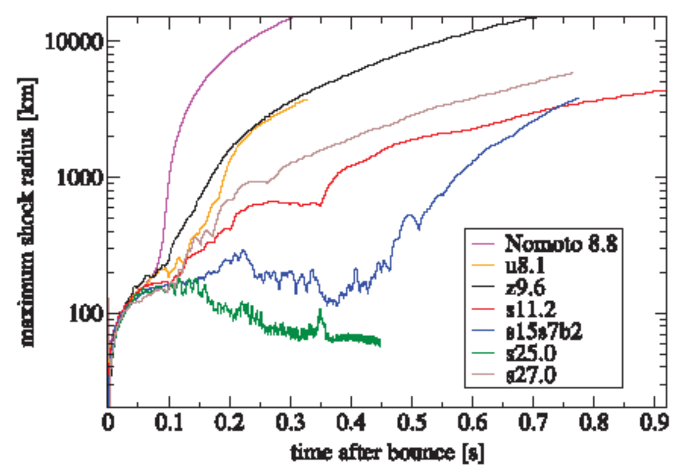


Figure 2: Three-dimensional simulation [7] one second after core bounce. The bright structure is a surface of constant proton-to-neutron ratio which roughly marks the outer boundaries of the neutrino-heated high-entropy bubbles. The dark surface, blown up in the right figure, is defined by a constant value for the mass flux per unit area and defines a downflow of matter towards the neutron star, the surface of which is indicated by the black sphere (corresponding to a density of 10^{11}g/cm^3).

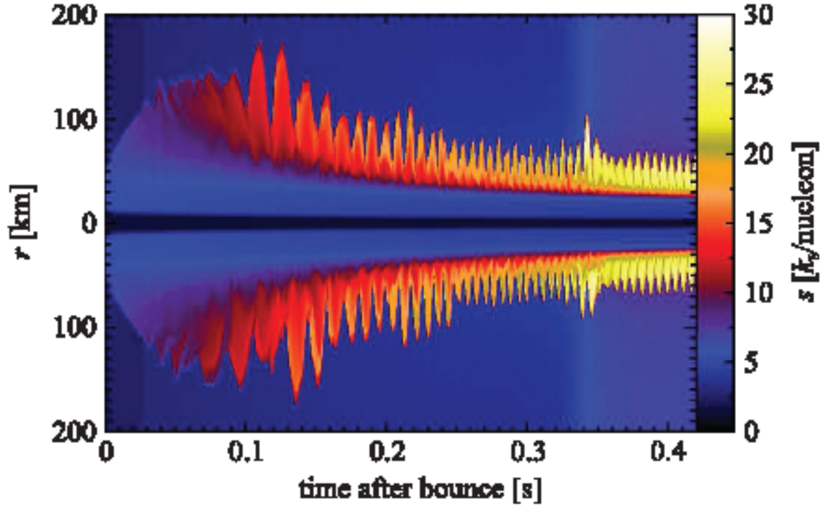


Janka et al. 2012, *Prog. Theor. Exp. Phys.*, 01A309



Weak explosions for all 6 models in 2D except for 25 solar masses

Janka et al (2012)   25 solar masses – note SASI



Two plots for north and south polar regions

Outcome sensitive to resolution and initial perturbations – Couch and Ott (2015)

THE ASTROPHYSICAL JOURNAL, 799:5 (12pp), 2015 January 20 COUCH & OTT

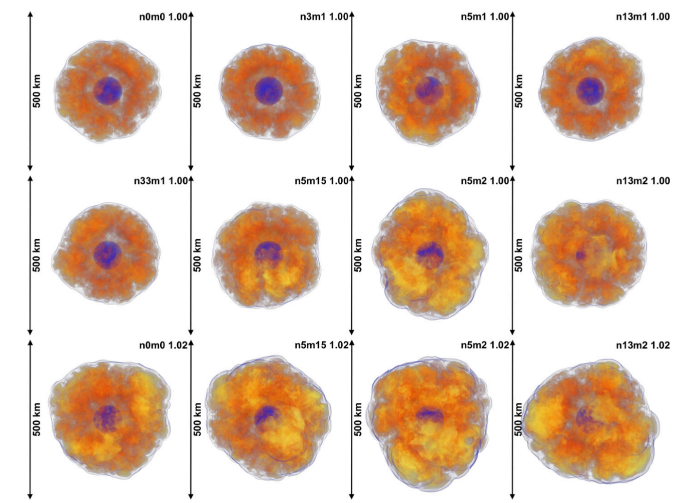


Figure 1. Volume renderings of specific entropy for several of the 3D simulations at 150 ms after bounce. Darker, red colors correspond to specific entropies of $\sim 14\, k_B$ baryon^{-1} while lighter, yellow colors correspond to entropies of $\sim 18\, k_B$ baryon^{-1}. The blue colors, which highlight the shock surface and the lower-entropy cooling region near the protoneutron star, correspond to specific entropies of $\sim 5\, k_B$ baryon^{-1}. Models with stronger perturbations show higher specific entropies in the gain layer and a greater shock extension. This is a result of the stronger turbulence and concomitant higher neutrino heating efficiency and turbulent pressure in these models.

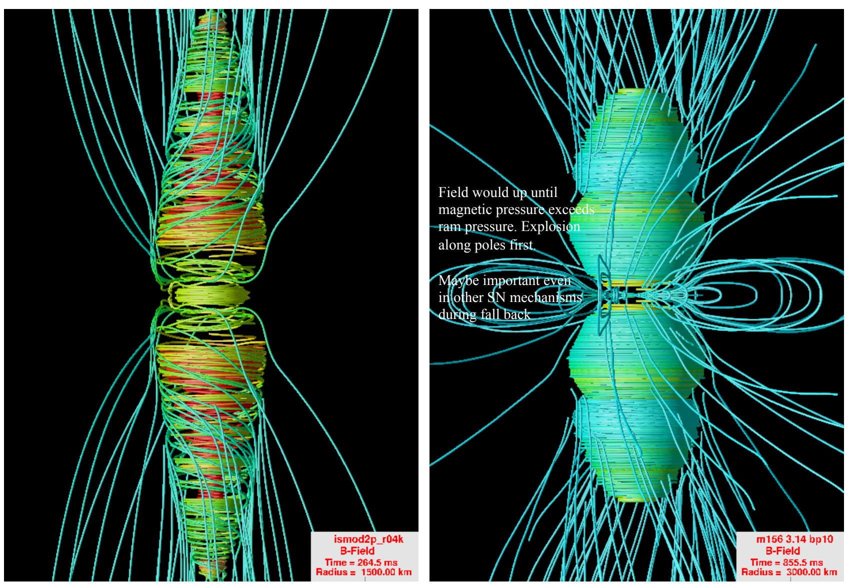
Challenges

- Tough physics – nuclear EOS, neutrino opacities
- Tough problem computationally – must be 3D (convection is important). 6 flavors of neutrinos out of thermal equilibrium (thick to thin region crucial). Must be follwoed with multi-energy group and multi-angles
- Magnetic fields and rotation may be important
- If a black hole forms, problem must be done using relativistic (magnto-)hydrodynamics (general relativity, special relativity, magnetohydrodynamics)

When Massive Stars Die, How Do They Explode?

Neutron Star + Neutrinos	Neutron Star + Rotation	Black Hole + Rotation
Colgate and White (1966) Arnett Wilson Bethe Janka Herant 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 etc	Bodenheimer and Woosley (1983) Woosley (1993) MacFadyen and Woosley (1999) Narayan (2004) ***All of the above?***
10	20	35 $M_\odot$

The answer depends on the mass of the core of helium and heavy elements when the star dies and on its angular momentum distribution.



Burrows et al 2007, *ApJ*, **664**, 416

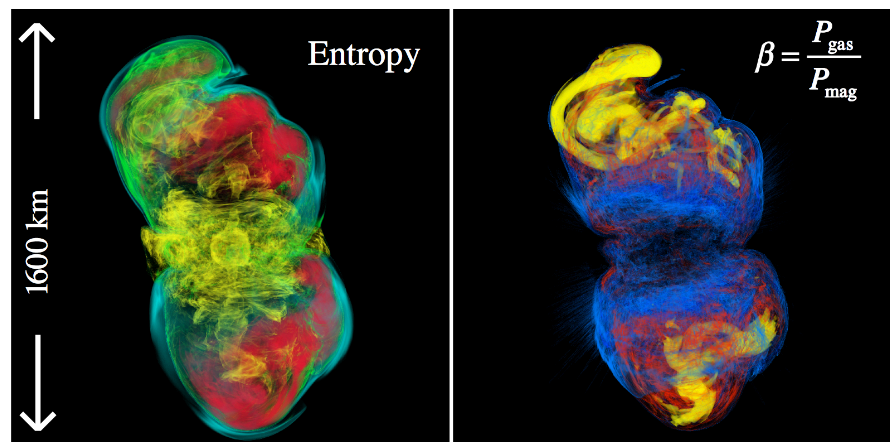
Rotationally Powered Models

Common theme:

Need iron core rotation at death to correspond to a pulsar of < 5 ms period if rotation and B-fields are to matter. This is much faster than observed in common pulsars.

A concern:

If calculate the presupernova evolution with the same efficient magnetic field generating algorithms as used in some core collapse simulations, will it be rotating at all?



3D, GR-MHD
"Leakage scheme" for neutrinos
Mosta, Ott, et al (2014)
Does not produce explosion or jets during time followed

Assuming the emission of high amplitude ultra-relativistic MHD waves, one has a radiated power

$$P \sim 6 \times 10^{49} \ (1 \text{ ms}/P)^4 \ (B/10^{15} \text{ gauss})^2 \ \text{erg s}^{-1}$$

and a total rotational kinetic energy

$$E_{rot} \sim 4 \times 10^{52} \ (1 \text{ ms}/P)^2 \ (10 \text{ km}/R)^2 \ \text{erg}$$

For magnetic fields to matter one thus needs magnetar-like magnetic fields and rotation periods (for the cold neutron star) of < 5 ms. This is inconsistent with what is seen in common pulsars. Where did the energy go?

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

Mass	Baryon[b] ($M_\odot$)	Gravitational[c] ($M_\odot$)	$J(M_{bary})$ (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 $4\,k_B$/baryon
[c] Mass corrected for neutrino losses
[d] Not corrected for angular momentum carried away by neutrinos
[e] Became a Wolf-Rayet star during helium burning

Magnetic torques as described by Spruit, *A&A*, **381**, 923, (2002)

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	~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}

Aside: Note an interesting trend. Bigger stars are harder to explode using neutrinos because they are more tightly bound and have big iron cores.

But they also rotate faster when they die.

Mixing During the Explosion

The Reverse Shock and Rayleigh-Taylor Instability:

The Sedov solution (adiabatic blast wave)

For $\rho = Ar^{-\omega}$

$$v_{shock} = A^{\frac{1}{\omega-5}} \; E^{\frac{1}{5-\omega}} \; t^{(\omega-3)/(5-\omega)} \qquad \omega < 5$$

$\omega=3 \;\rightarrow\; v_{shock}$ = constant

$\omega<3 \;\rightarrow\; v_{shock}$ slows down

$\omega>3 \;\rightarrow\; v_{shock}$ speeds up

$$R_S = \left(\frac{Et^2}{\alpha A}\right)^{\frac{1}{\nu+2-\omega}}$$

ν = dimension of space

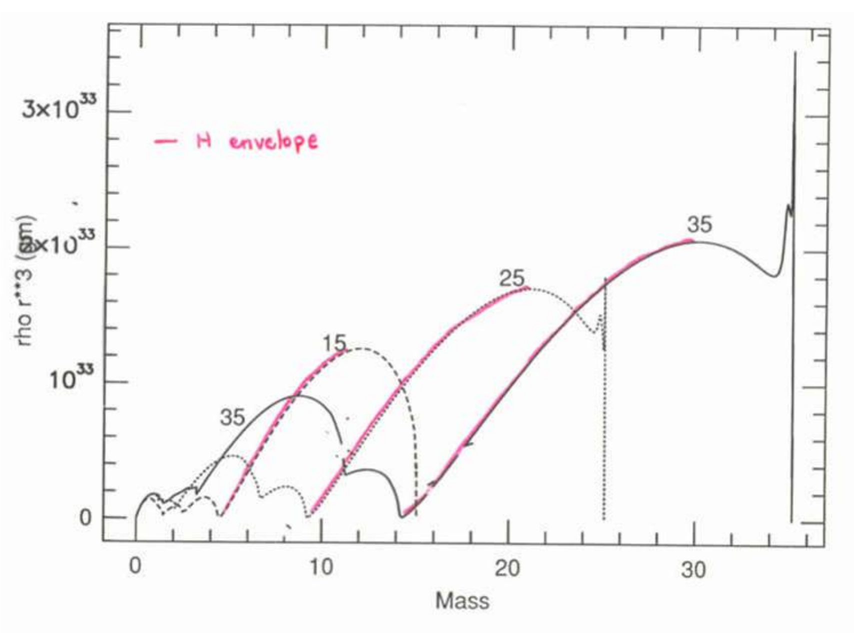
1, 2, or 3

α = const = f(ν)

Korobeinikov (1961)

If ρr^3 increases with radius, the shock will slow down. The information that slowing is occuring will propagate inwards as a decelerating force directed towards the center. This force is in the opposite direction to the density gradient, since the density, even after the explosion, generally decreases for the material farther out.

$\Rightarrow$ Rayleigh-Taylor instability and mixing



Example:

For constant density and an adiabatic blast wave. The constants of the problem are $E_{initial}$ and ρ. We seek a solution $r(t, E_{initial}, \rho)$. Assume that these are the only variables to which r is sensitive.

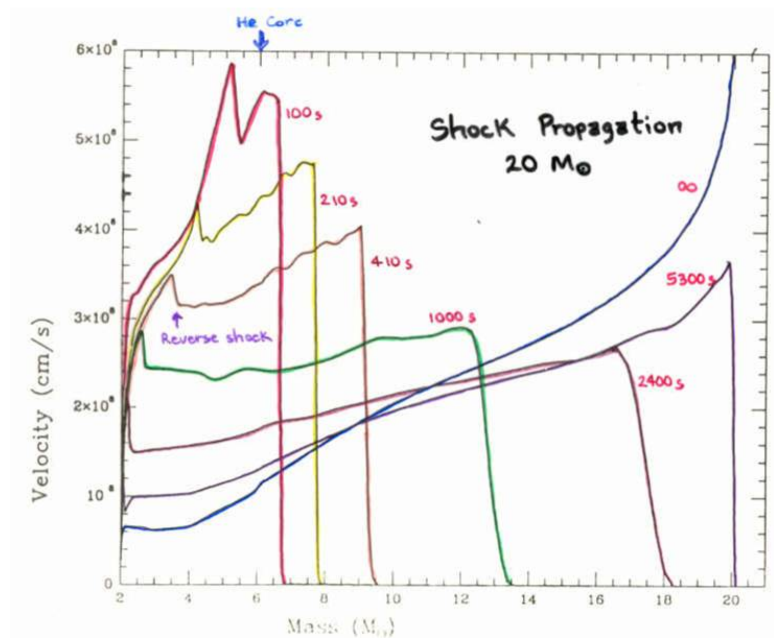
Units E $\quad \dfrac{\text{gm cm}^2}{\text{sec}^2}$

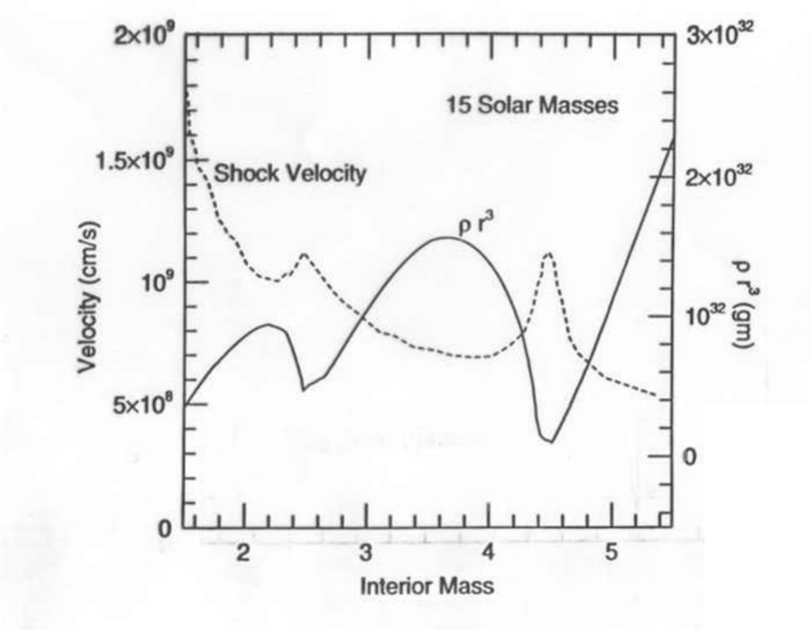
$\rho \quad \dfrac{\text{gm}}{\text{cm}^3}$

$\dfrac{E}{\rho} \quad \dfrac{\text{cm}^5}{\text{sec}^2} \Rightarrow r^5 \propto \dfrac{E}{\rho} t^2$

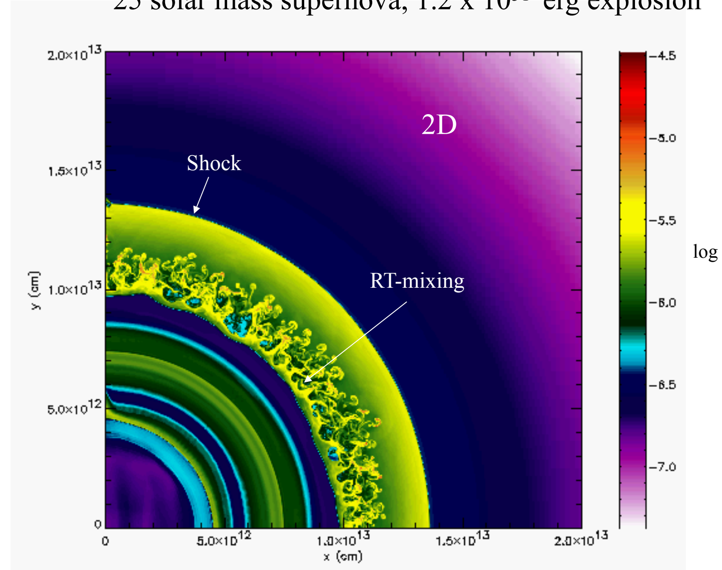
$$r = K\left(\frac{E_{initial}}{\rho}\right)^{1/5} t^{2/5}$$

$$v = \frac{dr}{dt} = \frac{2}{5} K \left(\frac{E_{initial}}{\rho}\right)^{1/5} t^{-3/5}$$ which is our ω=0 case

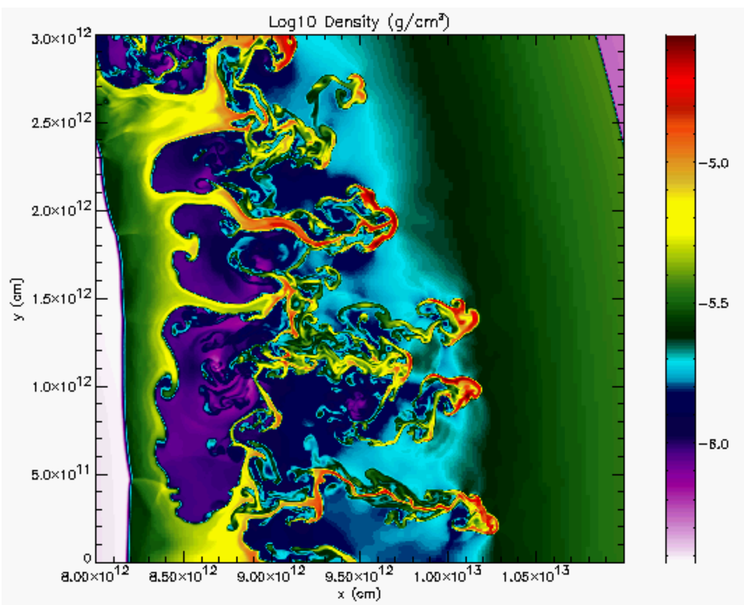




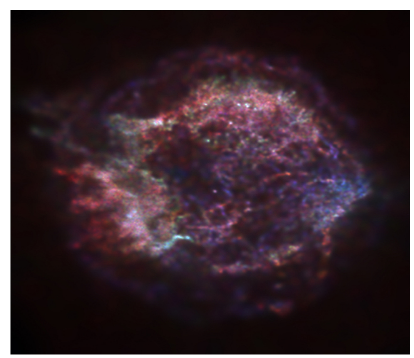
25 solar mass supernova, 1.2 x 10^{51} erg explosion

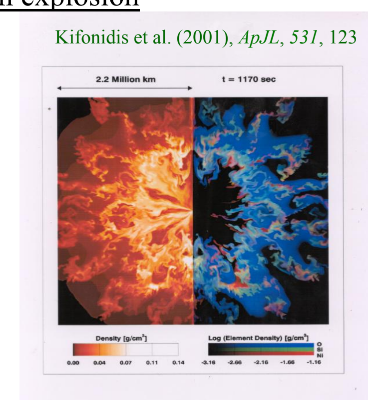


Calculation using modified FLASH code – Zingale & Woosley



Diagnosing an explosion





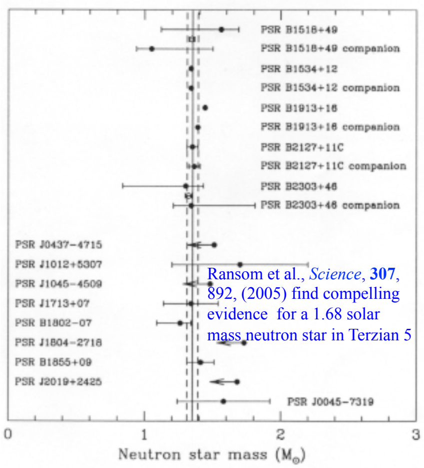
Left - Cas-A SNR as seen by the Chandra Observatory Aug. 19, 1999

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

Neutron star masses (2007):

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



Vertical line is at

$1.35 \pm 0.04\ M_\odot$

If in the models the mass cut is taken at the edge of the iron core the average gravitational mass for for stars in the 10 – 21 solar mass range is (12 models; above this black holes start to form by fall back):

$1.38 \pm 0.16\ M_\odot$

If one instead uses the S = 4 criterion, the average from 10 – 21 solar masses is

$1.45 \pm 0.18\ M_\odot$

From 10 to 27 solar masses the average is

$1.53 \pm 0.22\ M_\odot$

Caveats:
- Binary membership
- Minimum mass neutron star
- Small number statistics

Neutron star masses (2015):

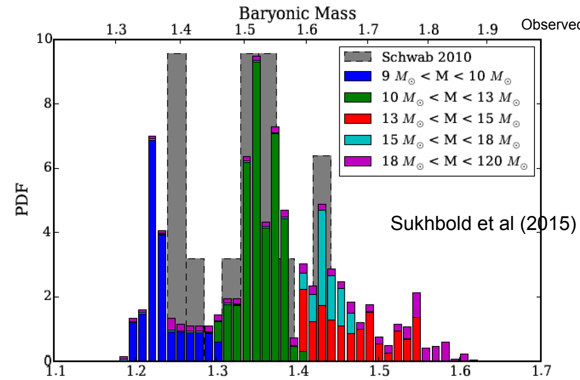


TABLE 2. INTEGRATED STATISTICS (SEE § 4.2 FOR DESCRIPTIONS)

Cal.	$\overline{E}$ (erg)$\times 10^{51}$	$\overline{M_b}$ ($M_\odot$)	$\overline{M_g}$ ($M_\odot$)	$M_{Ni,l}$ ($M_\odot$)	$M_{Ni,u}$ ($M_\odot$)	SN%	(SN> 20)%
W15	0.70×10^{51}	1.539	1.368	0.044	0.055	63	8.7
W18	0.74×10^{51}	1.544	1.368	0.047	0.058	64	10.0
W20	0.60×10^{51}	1.544	1.368	0.049	0.040	49	4.0
N20	0.89×10^{51}	1.543	1.368	0.053	0.071	71	14.8