From protoneutron stars to hybrid stars
Exploring the QCD phase transition in core collapse supernovae

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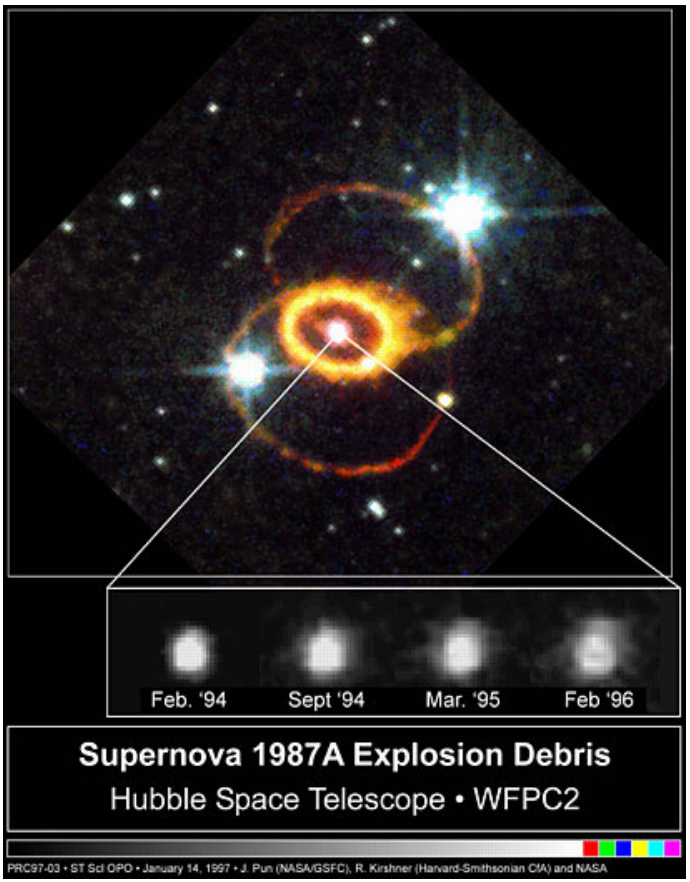
CSQCD II, May 2009

The end of a stellar life

Core collapse supernovae: progenitor stars more massive then 8.8 $M_\odot$



Direct supernova observables

- The explosion ejecta/energy $\sim 10^{51}$ erg
- The remnant/NS kick
- Explosive nucleosynthesis
- Asymmetry of the explosion

Indirect supernova observables

- Gamma-ray bursts (unknown mechanism)
- Gravitational waves (difficult to detect)
- Neutrino signal

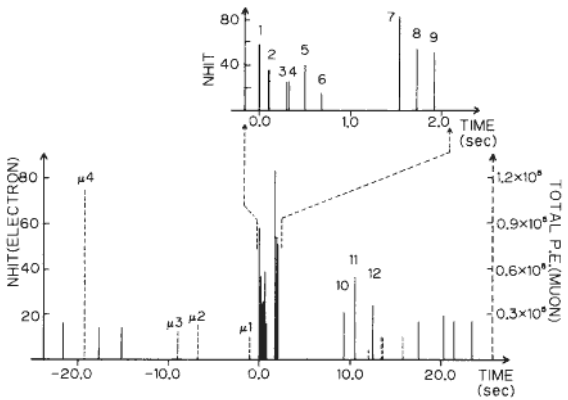
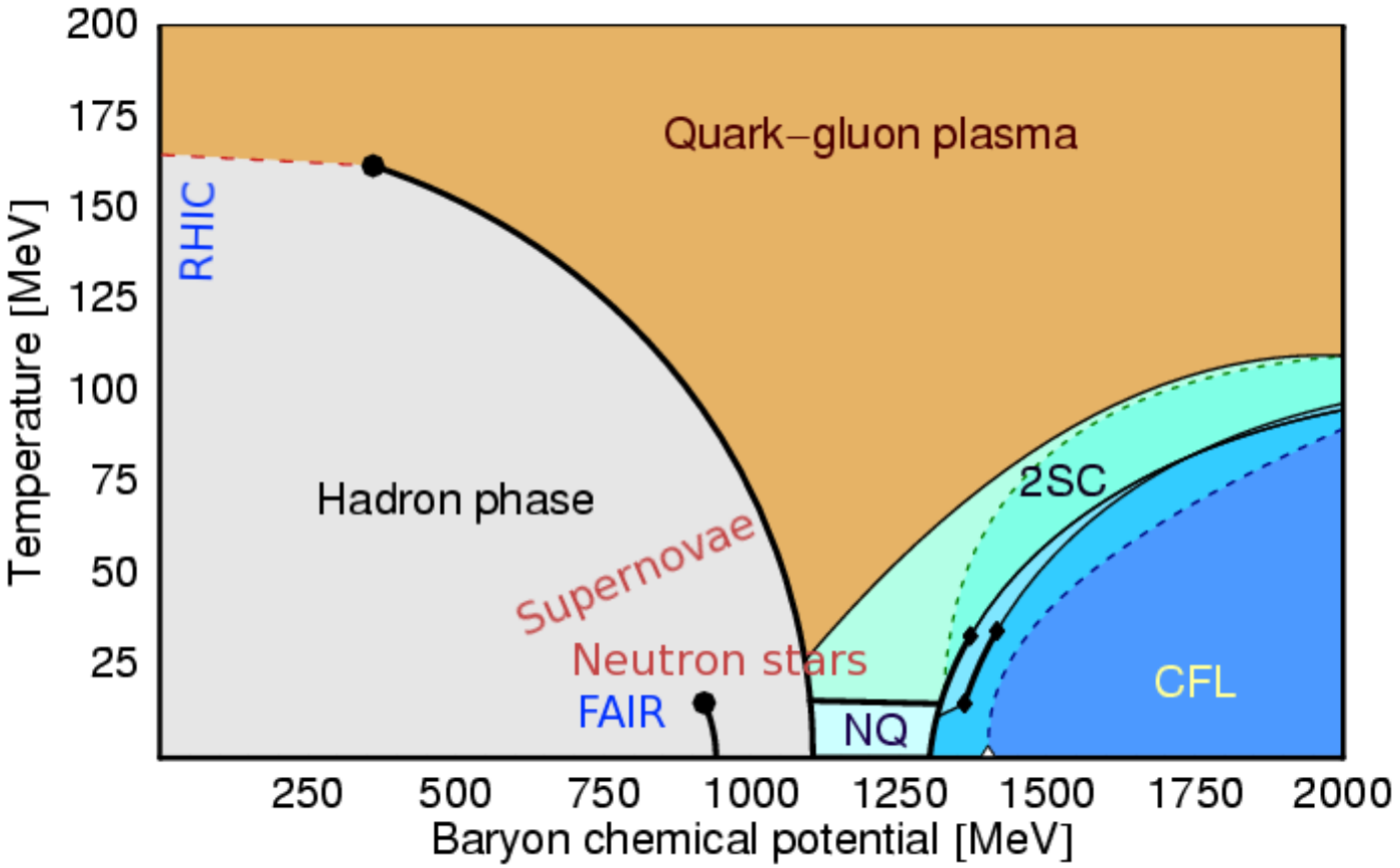


Figure: SN1987A, Hirata et al. 1987

Unification of the 4 fundamental forces
(gravity, electro-magnetism, weak- and strong interactions)

Supernovae as laboratories for matter under extreme conditions


Quark−gluon plasma
RHIC
Hadron phase
Supernovae
Neutron stars
FAIR
2SC
NQ
CFL
Temperature [MeV]
200
175
150
125
100
75
50
25
250
500
750
1000
1250
1500
1750
2000
Baryon chemical potential [MeV]

Outline

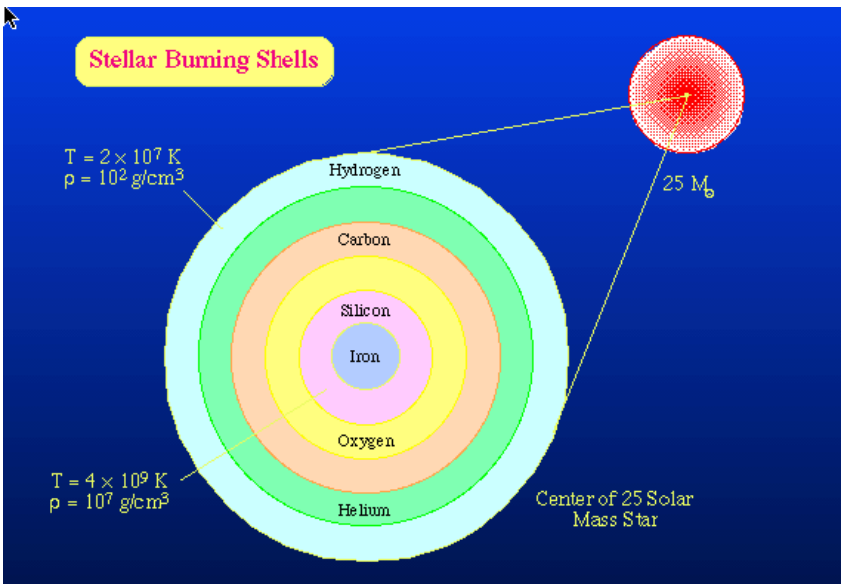
1. Core collapse supernovae
2. Modelling core collapse supernovae in spherical symmetry
3. The equation of state
4. QCD phase transition in core collapse supernovae

collaborators:

Irina Sagert
Giuseppe Pagliara
Matthias Hempel
Jürgen Schaffner-Bielich
Fredrik Sandin
David Blaschke

Phase 0: The progenitor stage

Onion-like structure



1) The final stage of nuclear burning (^{60}Zn, ^{56}Ni, $^{52-56}$Fe)

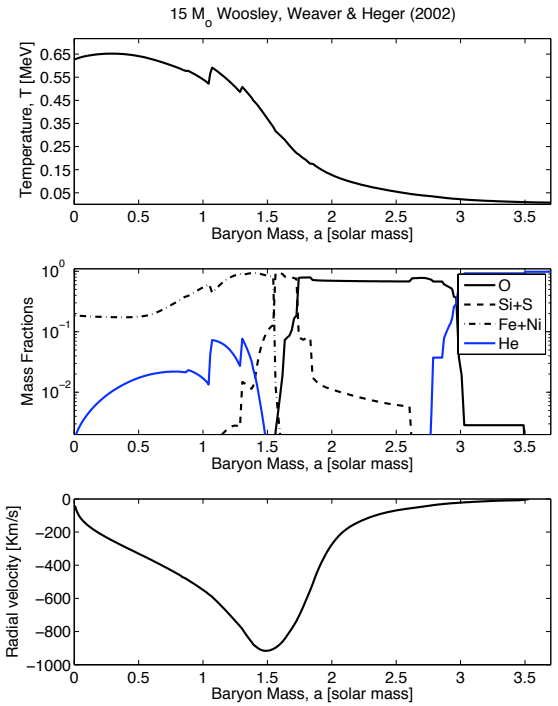
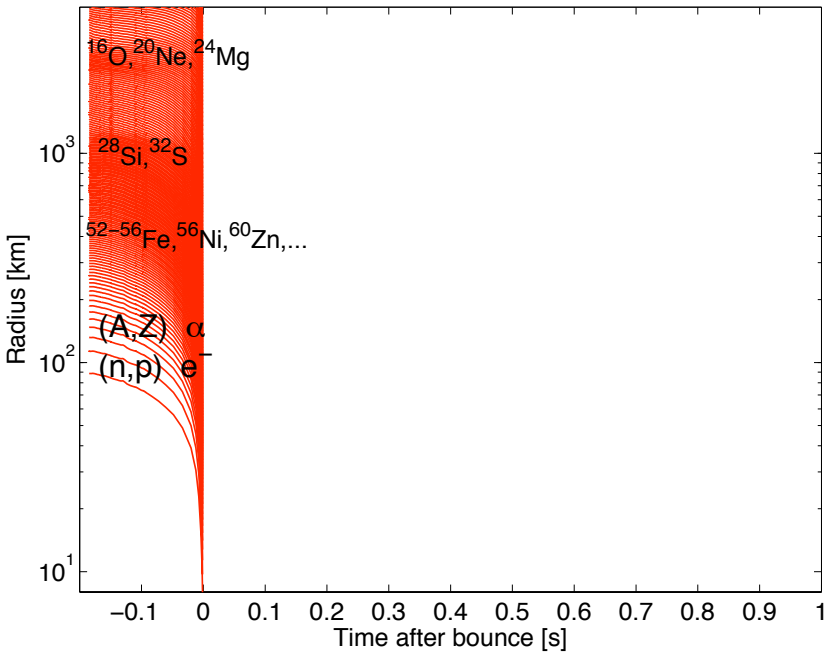


Figure: The progenitor

Phase 1: The collapse phase



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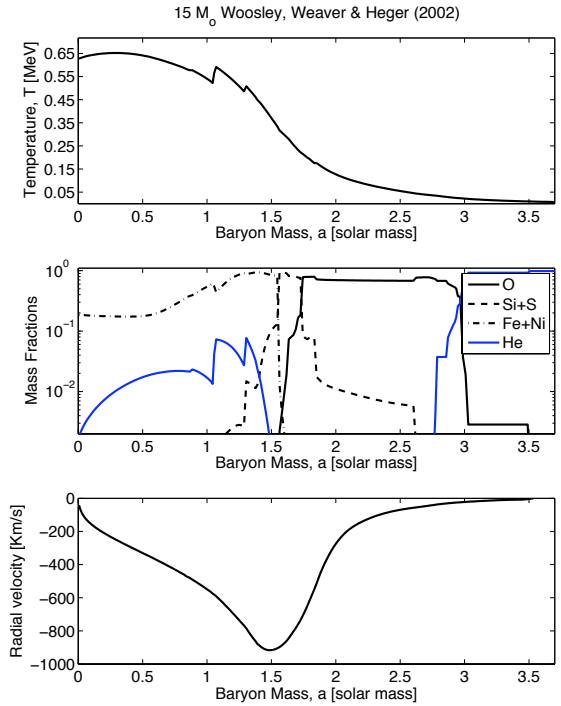


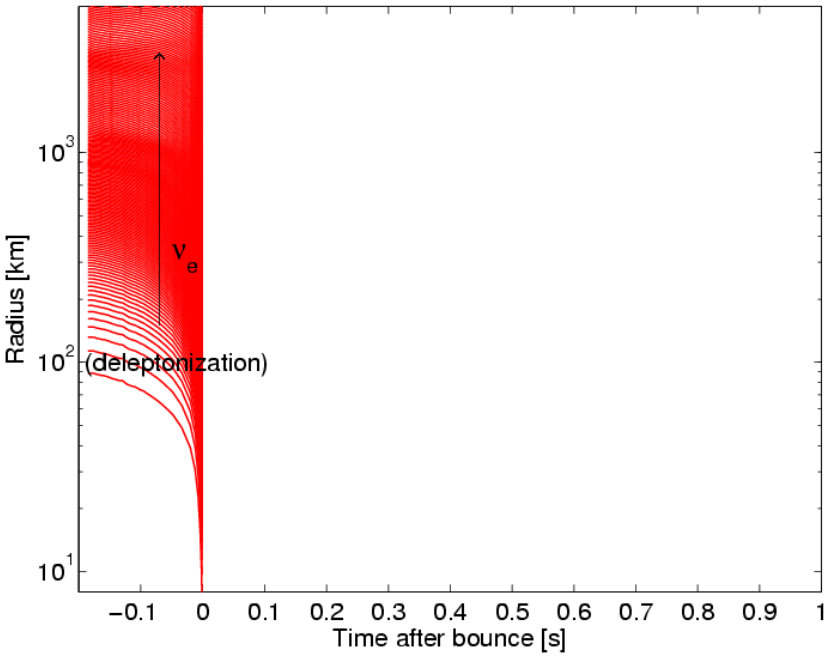
Figure: The progenitor

2) Pressure loss and Collapse due to:

2a) Photodisintegration of heavy nuclei

2b) Electron captures

Phase 1: The collapse phase



Deleptonization: the electron fraction Y_e decreases

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

$$e^- + (A, Z) \rightarrow (A, Z-1) + \nu_e$$

Note: $\rho \simeq 10^{12}$ g/cm^3 (Neutrino transport!)

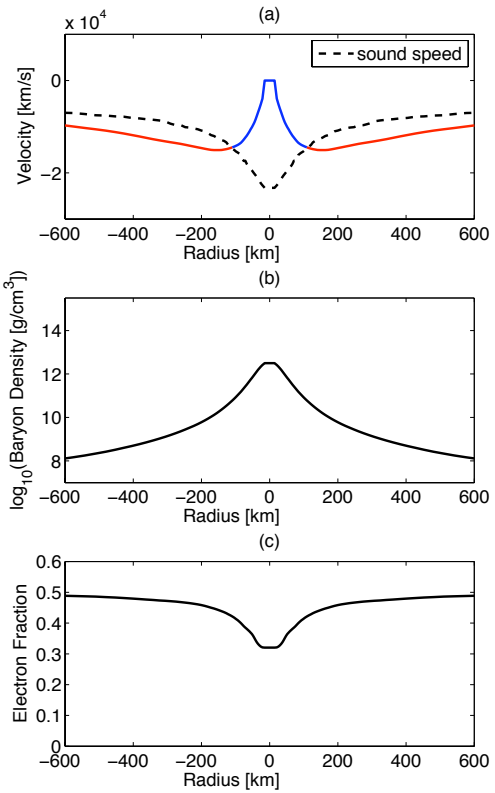


Figure: Radial profiles of the collapse phase

Phase 2: The core bounce

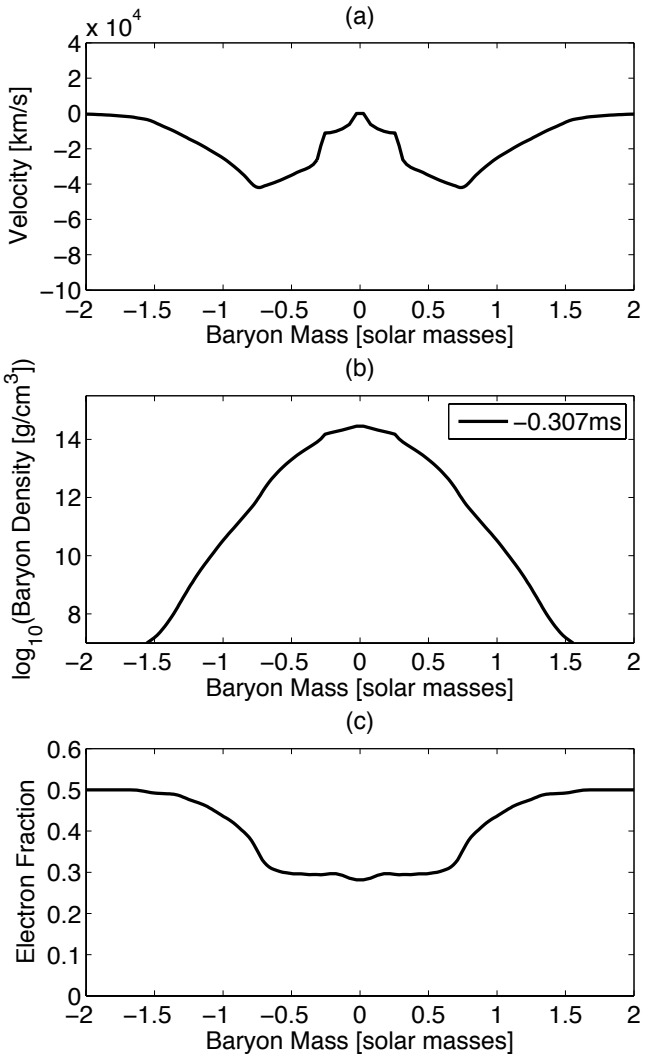


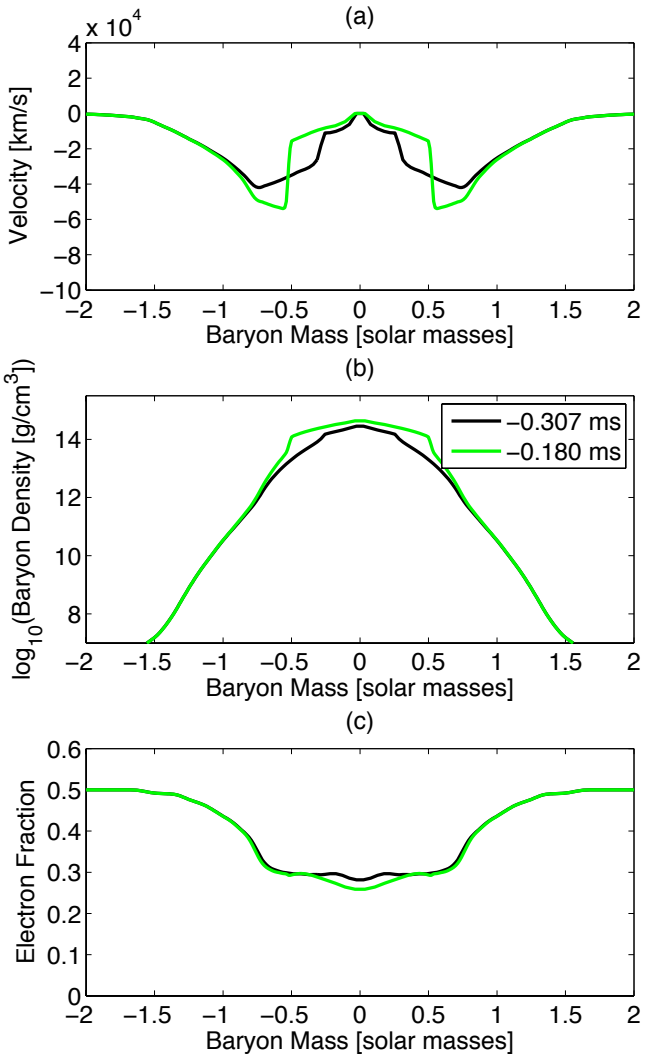
Figure: Radial profiles of the core bounce with respect to mass

1. Collapse halts at nuclear saturation density

$$n_B \simeq 0.11 - 0.13 \text{ fm}^{-3}$$
$$\rho \simeq 2 - 4 \times 10^{14} \text{ g/cm}^3$$

2. Formation of a stagnation wave

Phase 2: The core bounce



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3. Propagation of the stagnation wave

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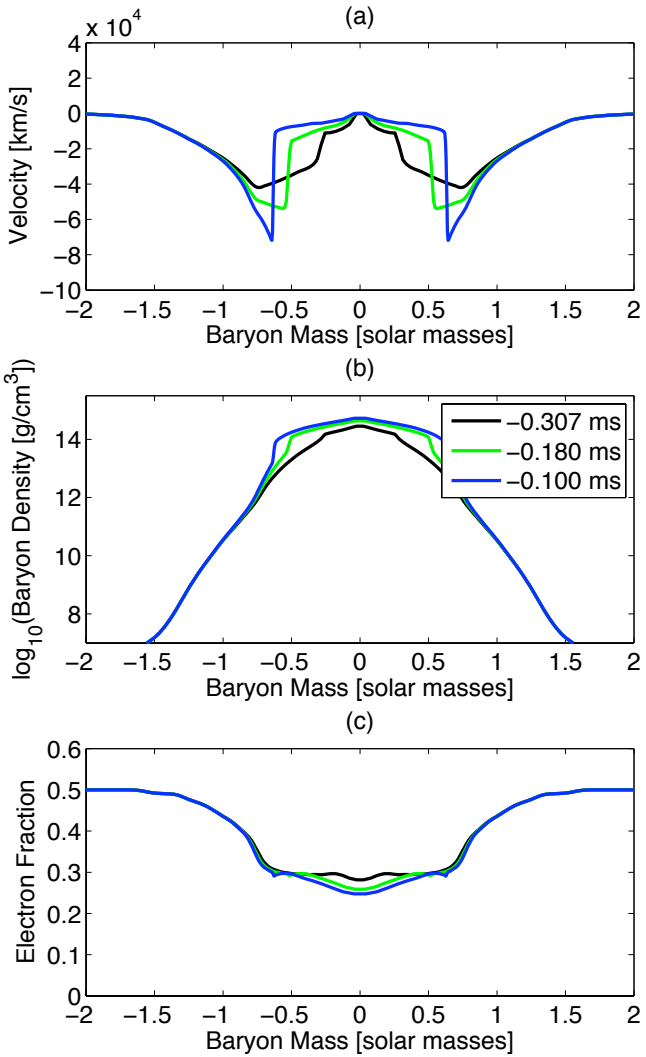

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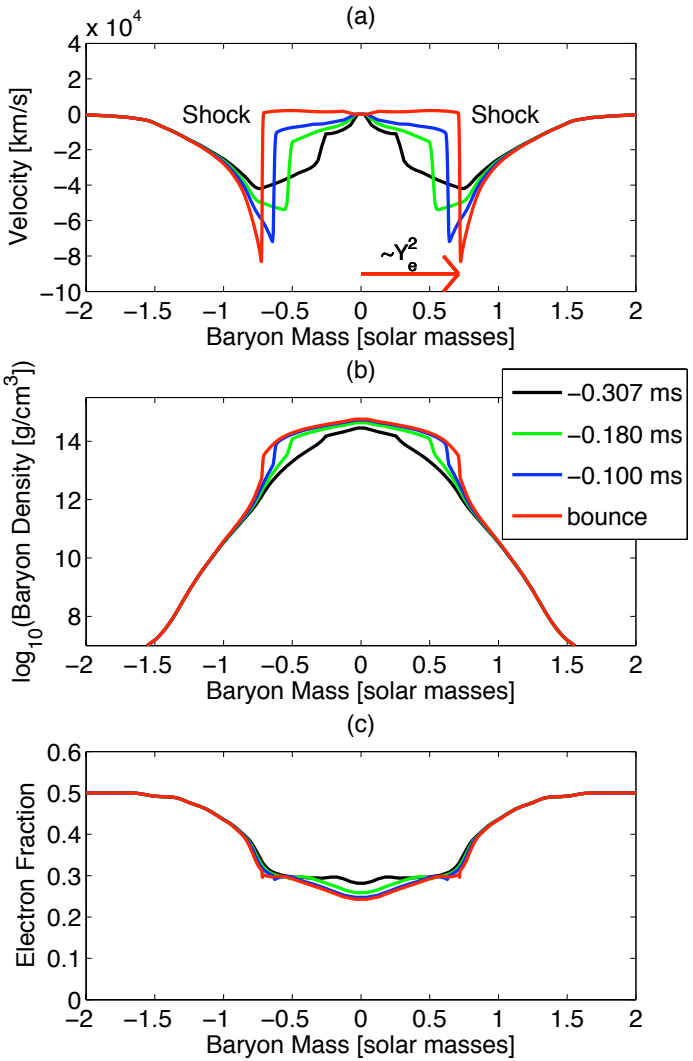

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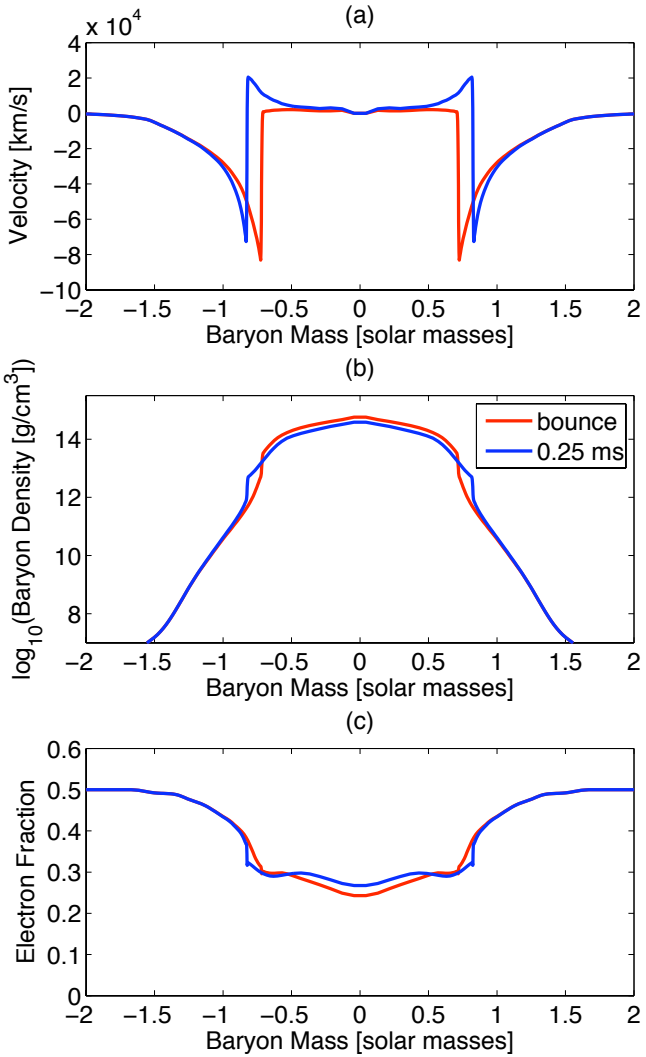
2. Formation of a stagnation wave
3. Propagation of the stagnation wave
4. $\rightarrow$ shock wave

   Remark: the size of the bouncing core[a]

$$M_{\text{core}} = (\kappa/\kappa_0)^{3/2} M_0, \kappa = \frac{\hbar c}{4}(3\pi^2)^{\frac{1}{3}} \left(\frac{Y_e}{m_B}\right)^{\frac{4}{3}}$$

[a] Goldreich & Weber 1980

Phase 2: The core bounce



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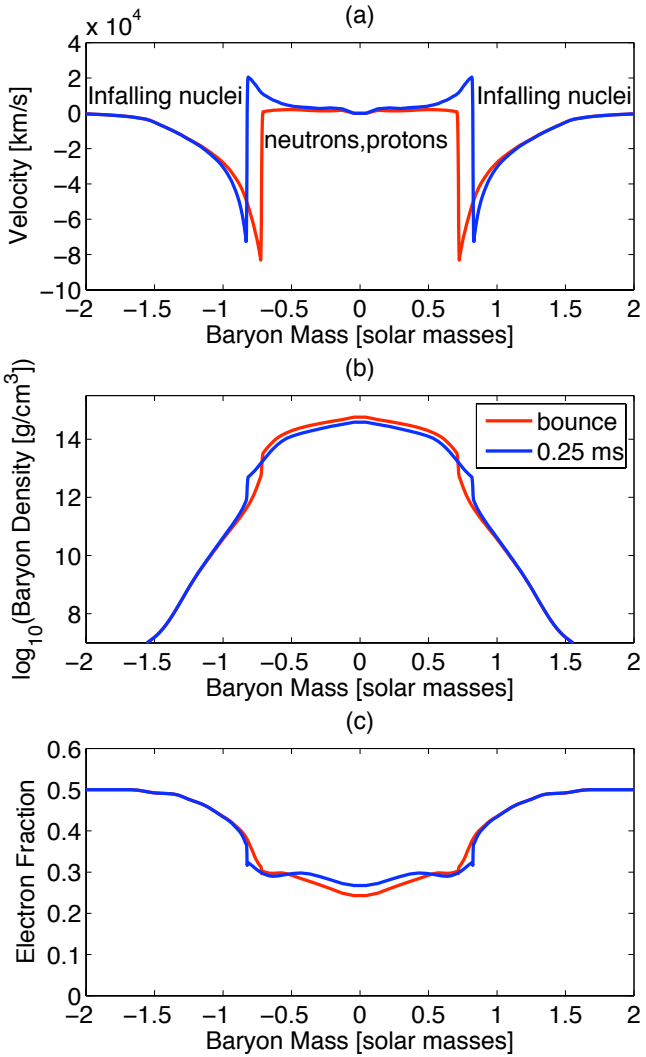
5. Shock acceleration

[a] Goldreich & Weber 1980

Phase 2: The core bounce



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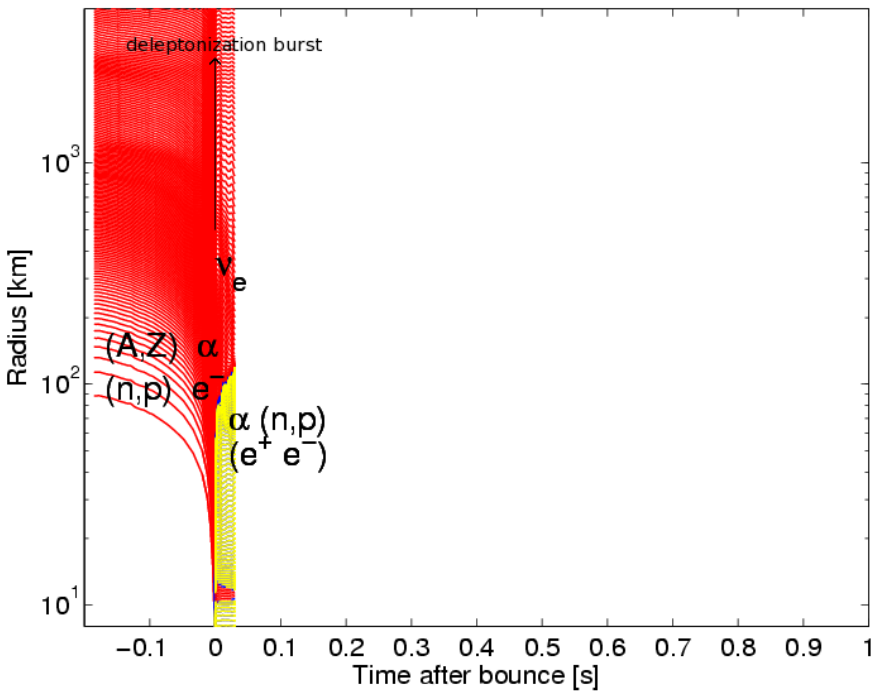
5. Dynamic shock vs. dissociation of nuclei

[a] Goldreich & Weber 1980

Phase 2: The core bounce



1. Collapse halts at nuclear saturation density
2. Formation of a stagnation wave

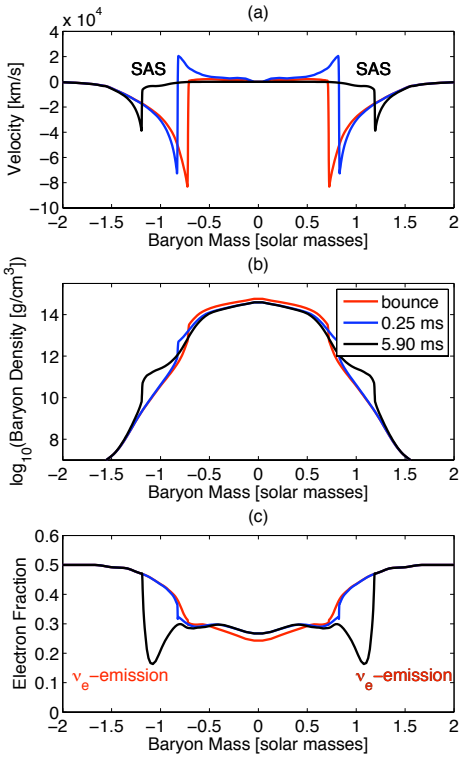
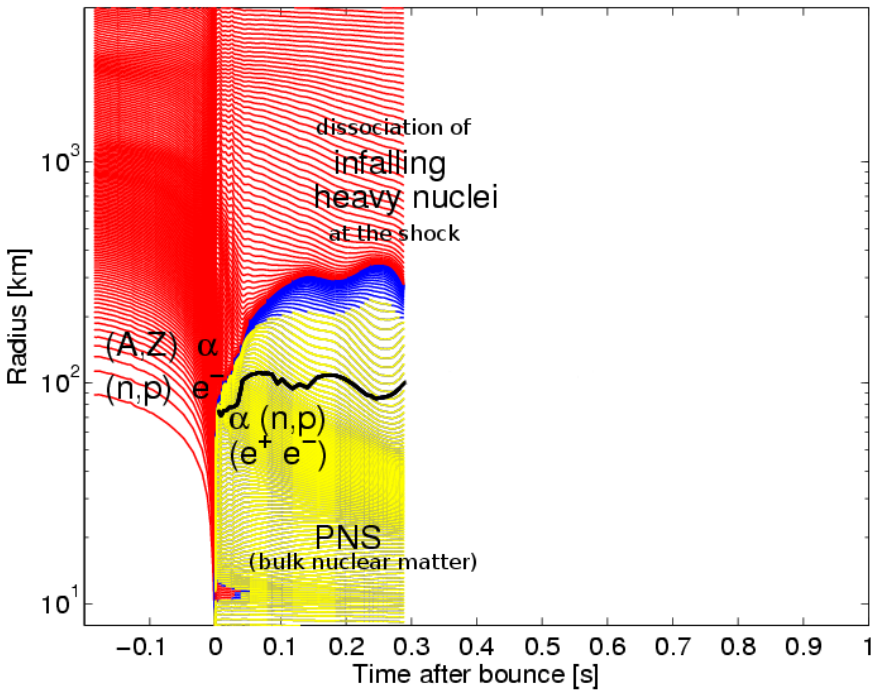


Figure: The core bounce

3. →shock wave
4. dynamic shock wave vs. infalling matter
5. Additional electron captures: neutrino burst

Phase 2: The core bounce



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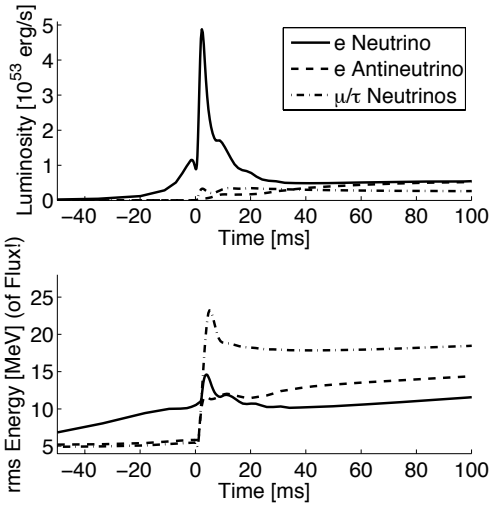
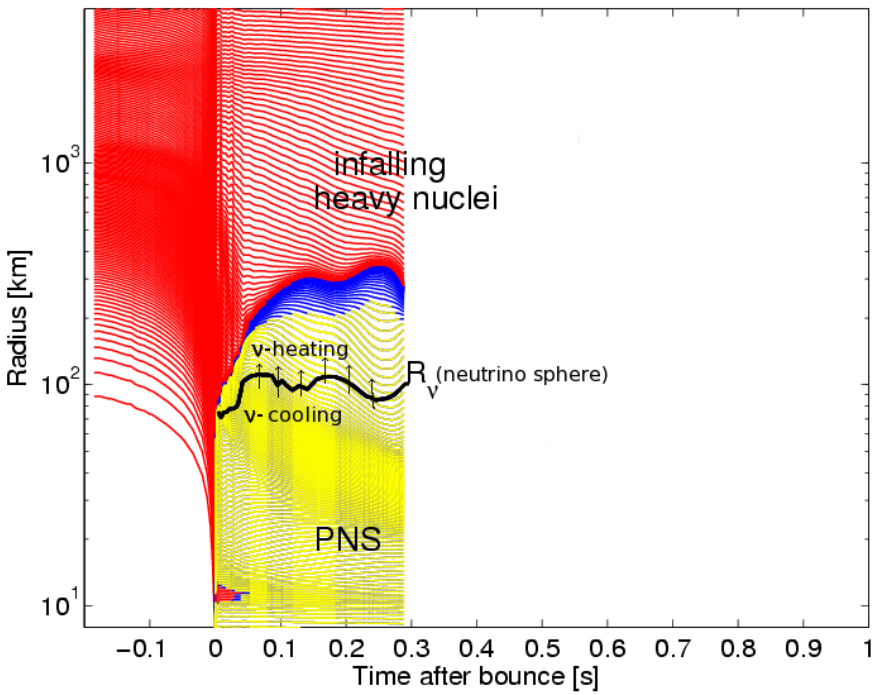


Figure: The deleptonization burst

3. → shock wave
4. dynamic shock wave vs. infalling matter
5. Additional electron captures: neutrino burst (several $\sim 10^{53}$ erg/s)

→ no prompt explosion

Phase 3: post bounce/accretion phase



$$L_\nu = (L_{\text{accretion}}, L_{\text{diffusion}}) = \left(-\frac{GM}{r}\frac{dM}{dt}\Big|_{R_\nu}, 4\pi r^2 c\, u_\nu\Big|_{R_\nu} \right)$$

The neutrino reactions [a]

1. Electronic charged current reactions
   $e^- + p \leftrightarrow n + \nu_e$
   $e^+ + n \leftrightarrow p + \overline{\nu}_e$
   $e^- + (A, Z) \leftrightarrow (A, Z-1) + \nu_e$
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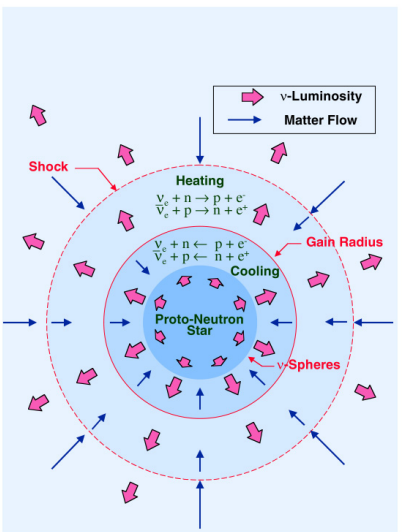
   $\nu + N \leftrightarrow \nu + N$
   $\nu + (A, Z) \leftrightarrow \nu + (A, Z)$



[a] Shinder & Shapiro 1982,Bruenn & Haxton 1991,Wilson & Mayle 1993

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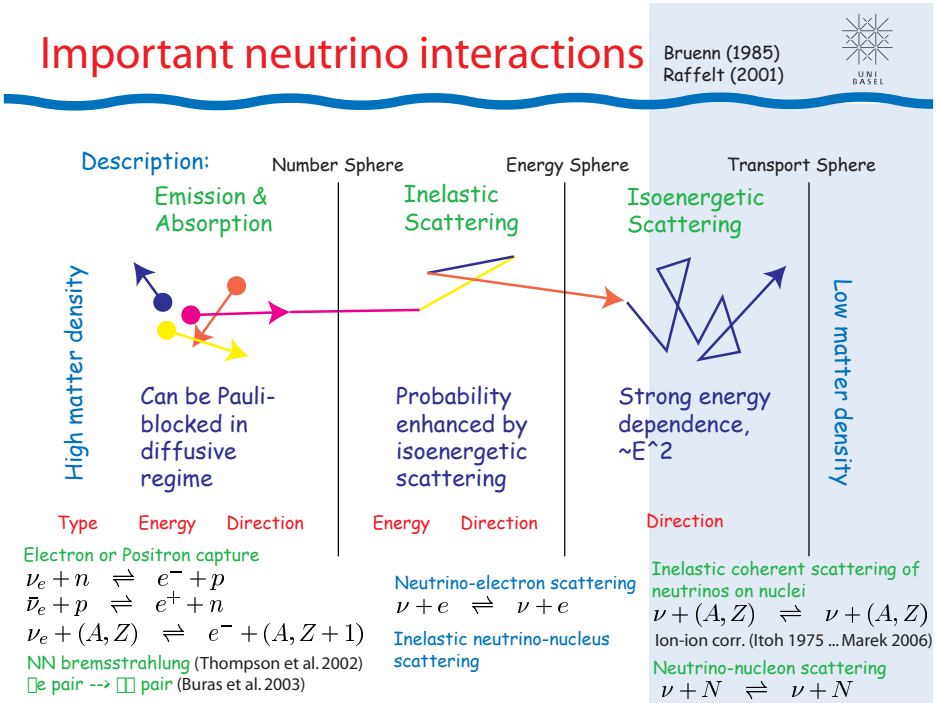

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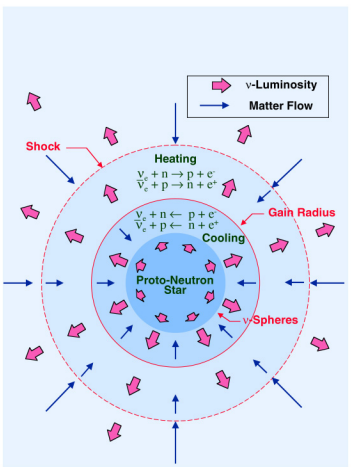

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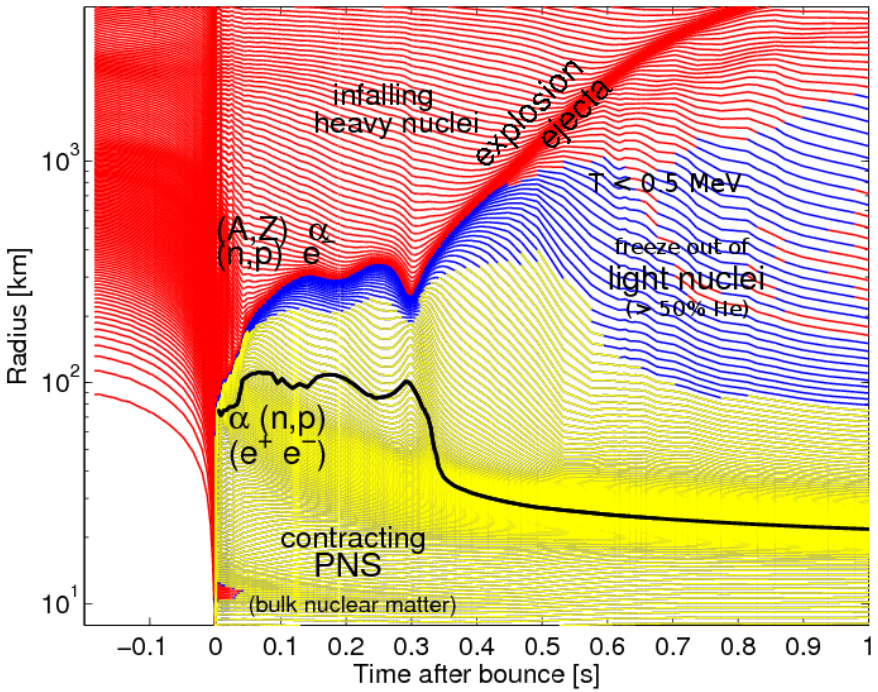
Phase 4: (neutrino driven) explosion



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Explosive nucleosynthesis

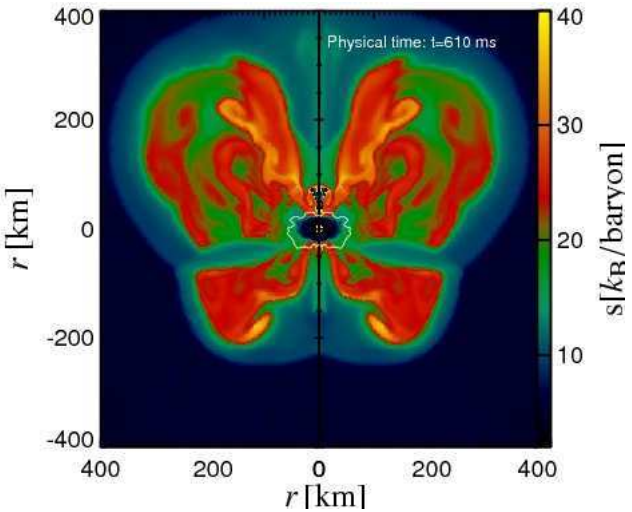
(r, s, p, νp) - process

[a] Shinder & Shapiro 1982,Bruenn & Haxton 1991,Wilson & Mayle 1993

Neutrino driven explosions?

→ No explosions in spherical symmetry
(for progenitors $> 8.8\ M_\odot$, O-Ne-Mg core) [a]

Multi-dimensional effects?
(rotation, convection, fluid instabilities...) [b]



Whitehouse et al. 2008 (3-dimensional, IDSA, in preparation)

→ Neutrino transport approximation
→ Low explosion energies

[a] Kitaura et al. 2006, Nomoto 1984, 1987
[b] Burrows 1995/2006 (acoustic mechanism),
MacFaden & Woosley 1999 (magneto-rotational),
Blondin & Mezzacappa 2003 (MGFL, SASI),
Bruenn et. al. 2006 (MGFL, nucl. reactions),
Kotake et al. 2005 (SASI, GW),
Foglizo et al. 2007 (SASI),
Marek & Janka 2007 (ray-by-ray Boltzmann transport)

General relativistic hydrodynamics in spherical symmetry

1. Space time of a collapsing star: spherically symmetric and non-stationary [a]

$$ds^2 = -\alpha^2 dt^2 + \frac{r'^2}{\Gamma^2} da^2 + r^2(d\theta^2 + sin^2\theta d\phi^2)$$

2. Conservation equations for energy and momentum

$$T^{\mu\nu}_{\ ;\nu} = 0$$

$$T^{tt} = \rho(1 + e+$$

$$T^{ta} = T^{at} =$$

$$T^{aa} = p+$$

$$T^{\theta\theta} = T^{\phi\phi} = p+$$

3. Interactions between the fluid and the radiation field [b]

   neutrino distribution function (phase space): $f(t, a, \mu = \cos\theta, E)$

[a] Misner & Sharp 1964, Liebendörfer et al. 2001a,b
[b] Bruenn 1985, Mezzacappa & Bruenn 1993

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$$T^{\mu\nu}_{\ ;\nu} = 0$$

$$T^{tt} = \rho(1 + e + J)$$
$$T^{ta} = T^{at} = \rho H$$
$$T^{aa} = p + \rho K$$
$$T^{\theta\theta} = T^{\phi\phi} = p + \frac{1}{2}\rho(J - K)$$

3. Interactions between the fluid and the radiation field [b]

   evolution of the specific neutrino distribution function:
   $F(t, a, \mu = \cos\theta, E) = f(t, a, \mu = \cos\theta, E)/\rho$

$$J = \int_{-1}^{+1} d\mu \int_0^\infty E^3 dE\, F(t, a, \mu, E)$$

$$H = \int_{-1}^{+1} \mu d\mu \int_0^\infty E^3 dE\, F(t, a, \mu, E)$$

$$K = \int_{-1}^{+1} \mu^2 d\mu \int_0^\infty E^3 dE\, F(t, a, \mu, E)$$

(2a) Electronic charged current reactions
$e^- + p \leftrightarrow n + \nu_e$
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[b] Bruenn 1985, Mezzacappa & Bruenn 1993

General relativistic radiation hydrodynamics in spherical symmetry

1. Spherically symmetric and non-stationary spacetime [a]

$$ds^2 = -\alpha^2 dt^2 + \frac{r'^2}{\Gamma^2} da^2 + r^2(d\theta^2 + sin^2\theta d\phi^2)$$

2. Conservation equations for energy and momentum

$$T^{\mu\nu}_{\ ;\nu} = 0$$

3. Interactions between the fluid and the radiation field [b]
4. Boltzmann ν-transport: dF/dt

$$\frac{1}{\alpha c}\frac{\partial F}{\partial t} + \frac{\partial(4\pi r^2 \alpha\rho\mu F)}{\alpha\partial a} + \Gamma\left(\frac{1}{r} - \frac{\partial\alpha}{\alpha\partial r}\right)\frac{\partial(1-\mu^2)F}{\partial\mu} +$$

$$\left(\frac{\partial \ln\rho}{\alpha c\partial t} + \frac{3}{r}\frac{u}{c}\right)\frac{\partial\left(\mu(1-\mu^2)F\right)}{\partial\mu} + \left[\mu^2\left(\left(\frac{\partial \ln\rho}{\alpha c\partial t} + \frac{3}{r}\frac{u}{c}\right)\right) - \frac{1}{r}\frac{u}{c} - \mu\Gamma\frac{\partial\alpha}{\alpha\partial r}\right]\frac{1}{E^2}\frac{\partial(E^3F)}{\partial E} =$$

$$= \frac{j}{\rho} - \tilde{\chi}F + \frac{1}{c}\frac{E^2}{h^3c^3}\int d\mu' R_{IS}(\mu', \mu, E)F(\mu', E) - \frac{1}{c}\frac{E^2F(\mu, E)}{h^3c^3}\int d\mu' R_{IS}(\mu, \mu', E)$$

$$+\frac{1}{c}\frac{1}{h^3c^3}\left(\frac{1}{\rho} - F(\mu, E)\right)\int dE' E'^2 d\mu' R^{in}_{NES}(\mu, \mu', E, E')F(\mu', E')$$

$$-\frac{1}{c}\frac{1}{h^3c^3}F(\mu, E)\int dE' E'^2 d\mu' R^{out}_{NES}(\mu, \mu', E, E')\left(\frac{1}{\rho} - F(\mu', E')\right)$$

5. general relativistic treatment and conservation of energy, momentum and lepton number [c]

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[c] Liebendörfer et al. 2004

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3. Interactions between the fluid and the radiation field
4. Boltzmann ν-transport: dF/dt

$$\frac{1}{\alpha c}\frac{\partial F}{\partial t} + \frac{\partial(4\pi r^2 \alpha\rho\mu F)}{\alpha\partial a} + \Gamma\left(\frac{1}{r} - \frac{\partial\alpha}{\alpha\partial r}\right)\frac{\partial(1-\mu^2)F}{\partial\mu} +$$

$$\left(\frac{\partial \ln\rho}{\alpha c\partial t} + \frac{3}{r}\frac{u}{c}\right)\frac{\partial\left(\mu(1-\mu^2)F\right)}{\partial\mu} + \left[\mu^2\left(\left(\frac{\partial \ln\rho}{\alpha c\partial t} + \frac{3}{r}\frac{u}{c}\right)\right) - \frac{1}{r}\frac{u}{c} - \mu\Gamma\frac{\partial\alpha}{\alpha\partial r}\right]\frac{1}{E^2}\frac{\partial(E^3F)}{\partial E} =$$

$$= \frac{j}{\rho} - \tilde{\chi}F + \frac{1}{c}\frac{E^2}{h^3c^3}\int d\mu' R_{IS}(\mu',\mu,E)F(\mu',E) - \frac{1}{c}\frac{E^2F(\mu,E)}{h^3c^3}\int d\mu' R_{IS}(\mu,\mu',E)$$

$$+\frac{1}{c}\frac{1}{h^3c^3}\left(\frac{1}{\rho} - F(\mu,E)\right)\int dE' E'^2 d\mu' R^{in}_{NES}(\mu,\mu',E,E')F(\mu',E')$$

$$-\frac{1}{c}\frac{1}{h^3c^3}F(\mu,E)\int dE' E'^2 d\mu' R^{out}_{NES}(\mu,\mu',E,E')\left(\frac{1}{\rho} - F(\mu',E')\right)$$

5. general relativistic treatment and conservation of energy, momentum and lepton number

$$\frac{\partial Y_{\nu_e}}{\partial t} + 4\pi m_B\frac{\partial\left(r^2N_{\nu_e}\right)}{\partial a} = \frac{2\pi m_B c}{h^3c^3}\int_{-1}^{+1} d\mu\int_0^\infty E^2 dE\,(j - \tilde{\chi}F) \quad \rightarrow \quad \frac{\partial Y_e}{\partial t} = -\frac{2\pi m_B c}{h^3c^3}\int_{-1}^{+1} d\mu\int_0^\infty E^2 dE\,(j - \tilde{\chi}F)$$

(2a) Electronic charged current reactions
$e^- + p \leftrightarrow n + \nu_e$
$e^+ + n \leftrightarrow p + \overline{\nu}_e$

(2b) Neutral current reactions
$e^- + e^+ \leftrightarrow \nu + \overline{\nu}$
$N + N \leftrightarrow N + N + \nu + \overline{\nu}$
$\nu_e + \overline{\nu}_e \leftrightarrow \nu_{\mu/\tau} + \overline{\nu}_{\mu/\tau}$
$\nu + e^{-/+} \leftrightarrow \nu' + e^{-/+}$
$\nu + N \leftrightarrow \nu + N$

$$\frac{\partial Y_L}{\partial t} + 4\pi m_B\frac{\partial\left(r^2N_L\right)}{\partial a} = 0$$
$$\downarrow$$

Hot and dense asymmetric matter [a]

[a](Lattimer & Swesty 1991, Shen et al. 1998, Timmes & Arnett 1999)

The Thermodynamic regimes

1. T < 0.5 MeV : nuclear burning/nuclear reaction network [a]
   for simplicity 14 α-nuclei: ^{4}He . . . ^{56}Ni
   for $Y_e \neq 0.5$: a few off-α nuclei
2. T > 0.5 MeV : nuclei in nuclear statistical equilibrium assumption: $\langle A, Z \rangle$ [b] [c], α, (n,p)
3. dissociated/bulk nuclear matter (n,p)

The independent variables

$$(T,\ Y_e,\ n_B)$$

The output

(p,e,s)

$$(x_n, x_p, x_\alpha, x_{A,Z}, \mu_B, \mu_Q, \mu_e)$$

Figure: 10 $M_\odot$

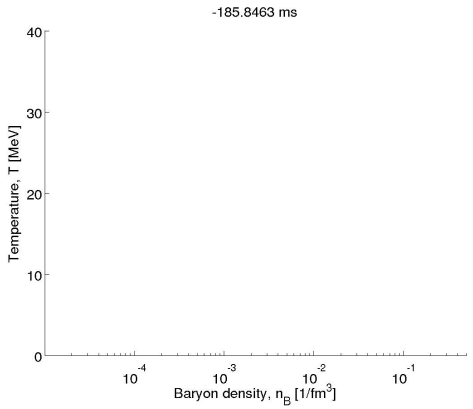
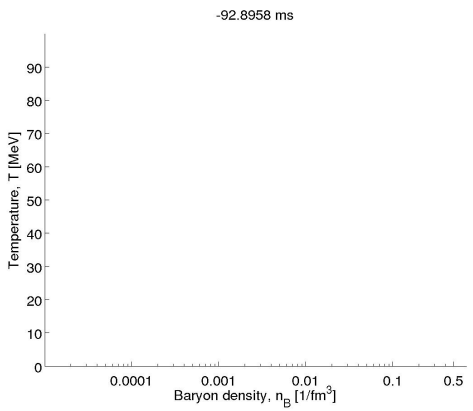


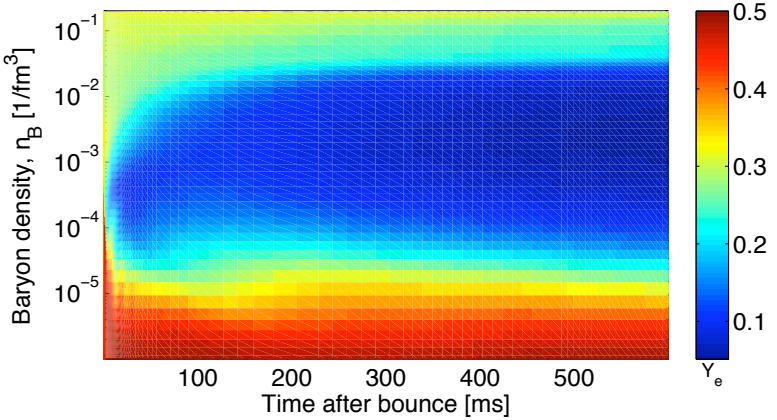
Figure: 40 $M_\odot$

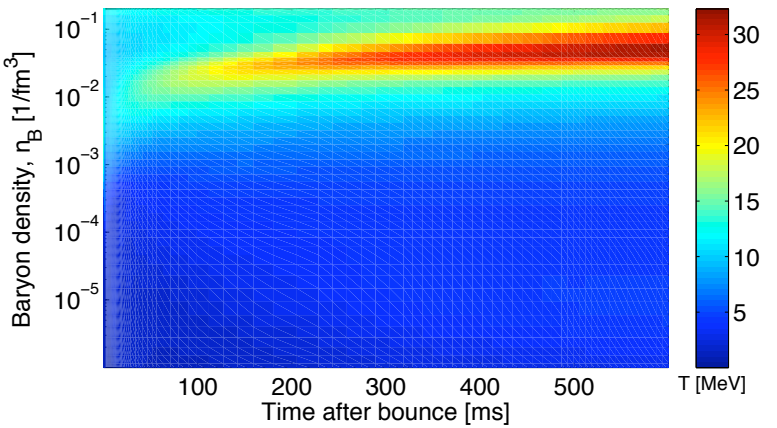


[a] F.-K. Thielemann et al., Basel
[b] M. Hempel, J. Schaffner-Bielich; nuclei distribution (work in progress)
[c] Langanke et al. (2003), Hix et al. (2003)

The EoS

Figure: 10 $M_\odot$





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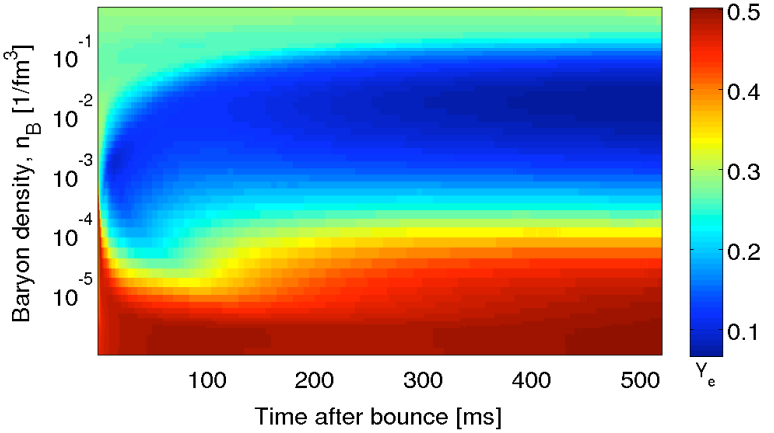
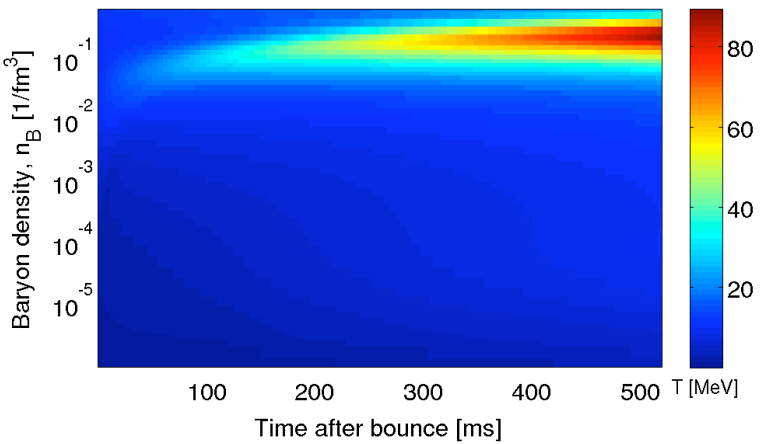




QCD phase transition

1. Density increases above nuclear saturation ($n_B > n_0$)
2. Temperature increases above 30 MeV
3. Asymmetric matter (central $Y_e < 0.3$)

conditions favourable for a phase transition from hadronic matter to 'exotic' (strange, quark) matter

Historic overview:

1 Takahara & Sato 1988: Relation to SN1987A
- parametrized EoS and GR hydrodynamics

2 Gentile et al. 1993: Realistic EoS and GR hydrodynamics
- Formation of a SECOND SHOCK immediately after bounce
- Second shock merges with the first shock
- Possible observable? → No neutrino transport!

3 Nakazato et al. 2008: Realistic EoS and Boltzmann neutrino transport
- very massive progenitors: 100 $M_\odot$ → black hole formation

For the accurate prediction of three-flavor neutrino spectra:
- General relativistic radiation hydrodynamics
- Three flavor Boltzmann neutrino transport

—> Spherical symmetry
- Low (10 $M_\odot$) and intermediate (15 $M_\odot$) mass progenitors[a]

[a] Woosley et al. 2002

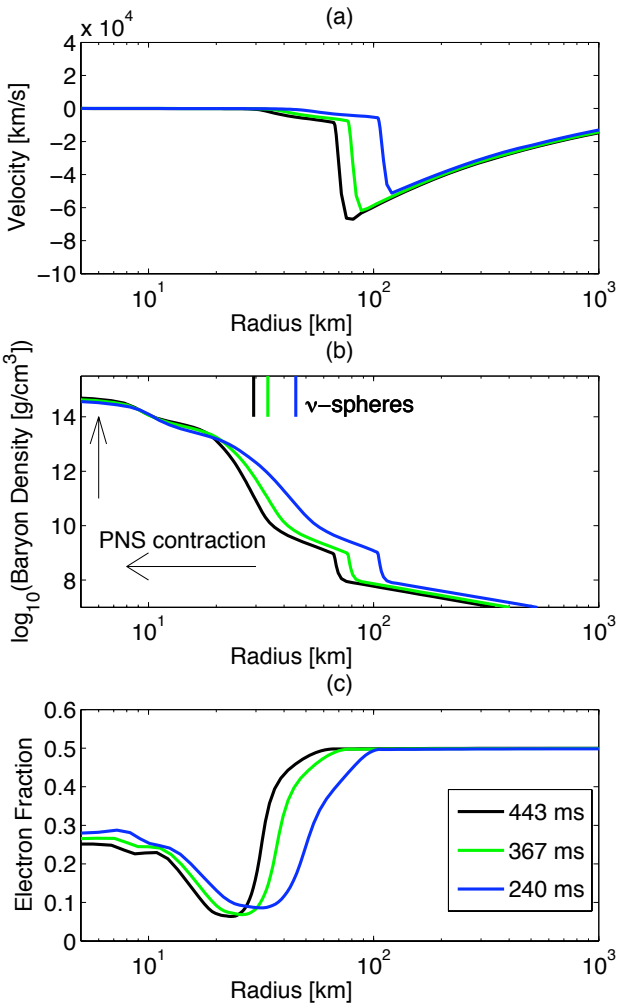


Figure: PNS contraction behavior

The quark EoS: MIT bag model for (u,d,s)-quark matter

1. Early onset of the phase transition
   (a) critical density close to saturation:
   $$n_c \simeq n_0 = 0.11 - 0.13 \text{ fm}^{-3}$$
   (b) density and asymmetry dependent critical density:
   $$n_c = n_c(T, y_e)$$
2. Stable neutron star masses $M_{\text{NS}} > 1.44$ $M_\odot$ (Hulse-Taylor pulsar)
3. No stable (pure) strange quark matter
4. Compatible with heavy ion data

$B_1^{1/4} = 162$ MeV (1.56 $M_\odot$) , $B_2^{1/4} = 165$ MeV (1.50 $M_\odot$)

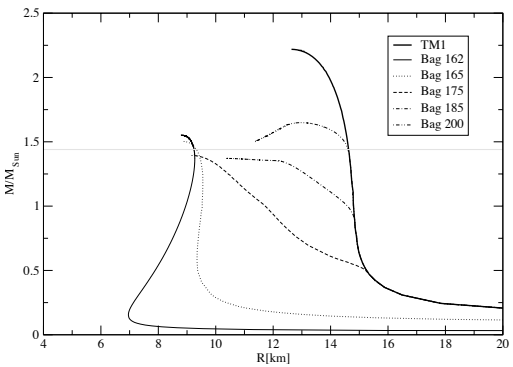


Figure: Mass Radius relation (G. Pagliara, I. Sagert)

5. Construction of the phasetransition using Gibbs
6. Neutrinos are trapped in quark matter phase
   (construct the hadronic chemical potentials from the quark chemical potentials to ensure β-equilibrium)

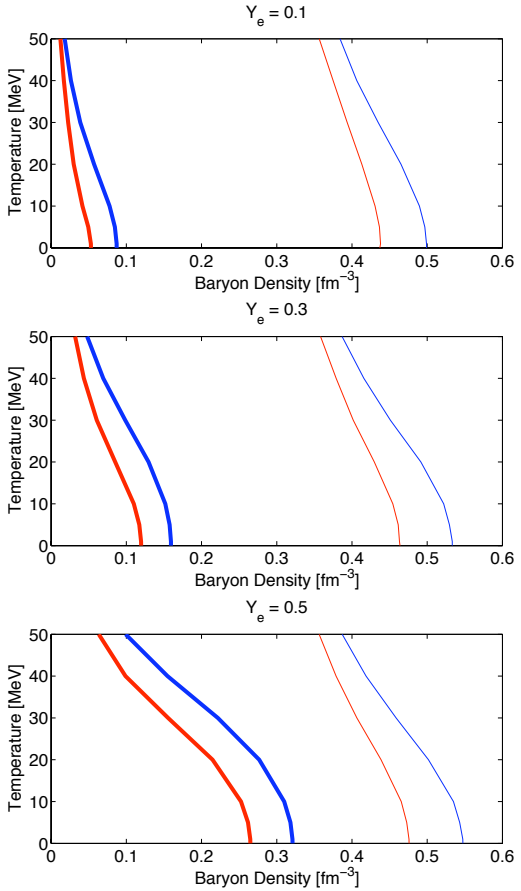
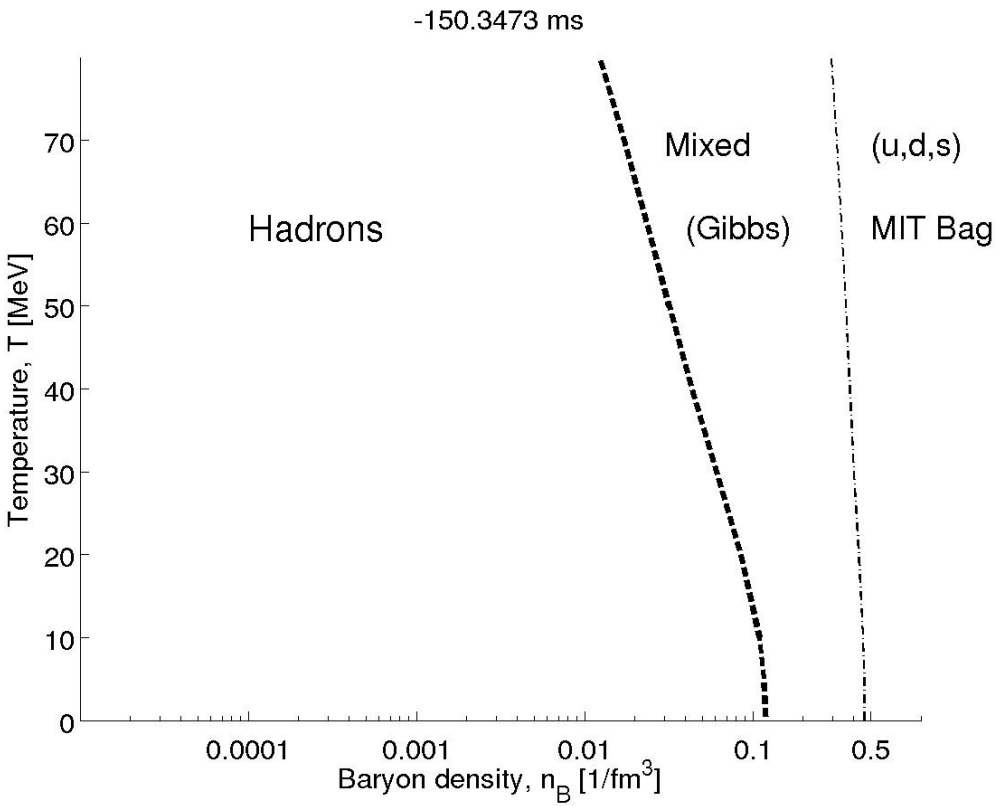


Figure: Phasediagram

onset of the phasetransition (thick lines)
pure quark phase (thin lines)

QCD phase transition

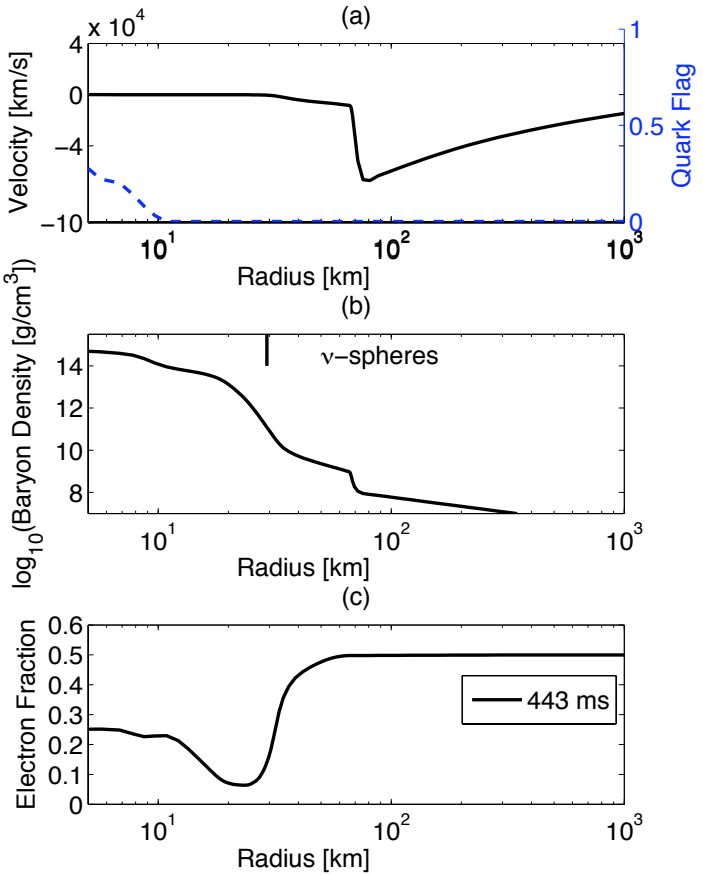
Figure: 10 $M_\odot$



Quark phasetransition during the early postbounce phase

1. Matter converts from the pure hadronic into the mixed quark-hadronic phase
2. the adiabatic index reduces in the mixed phase

$\longrightarrow$ PNS collapse



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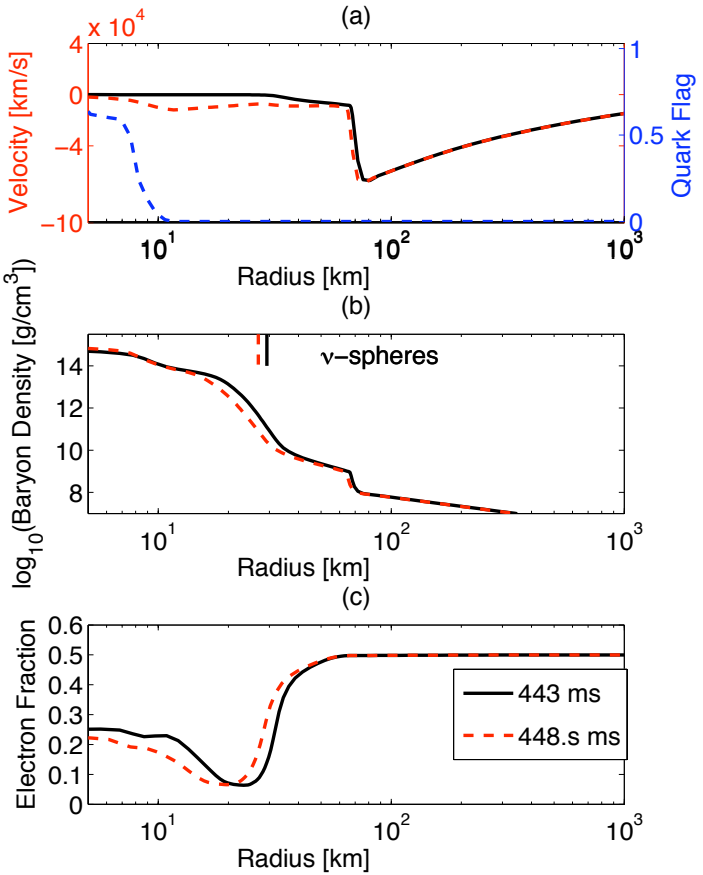

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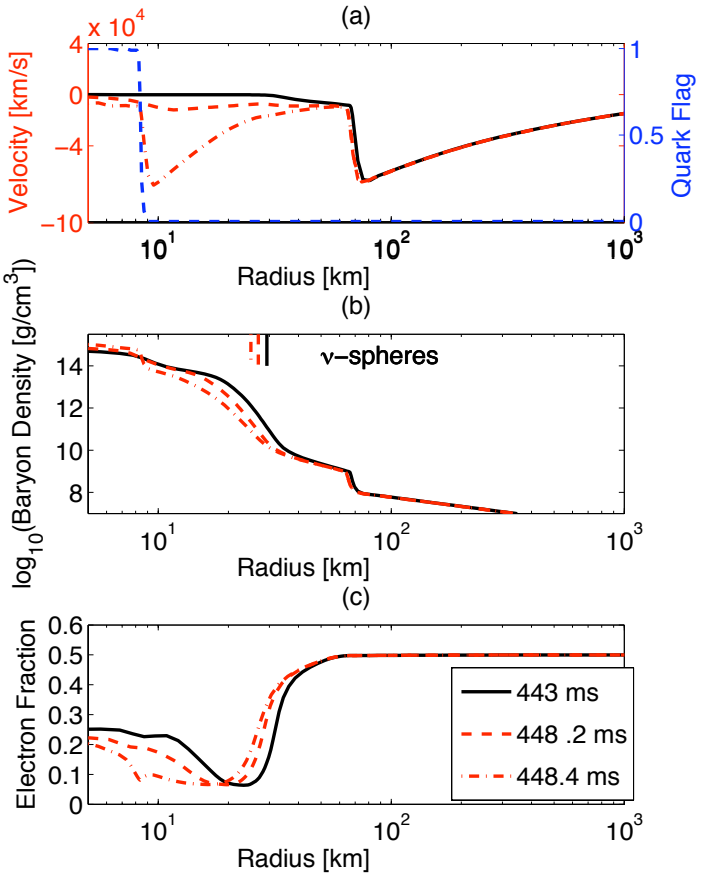

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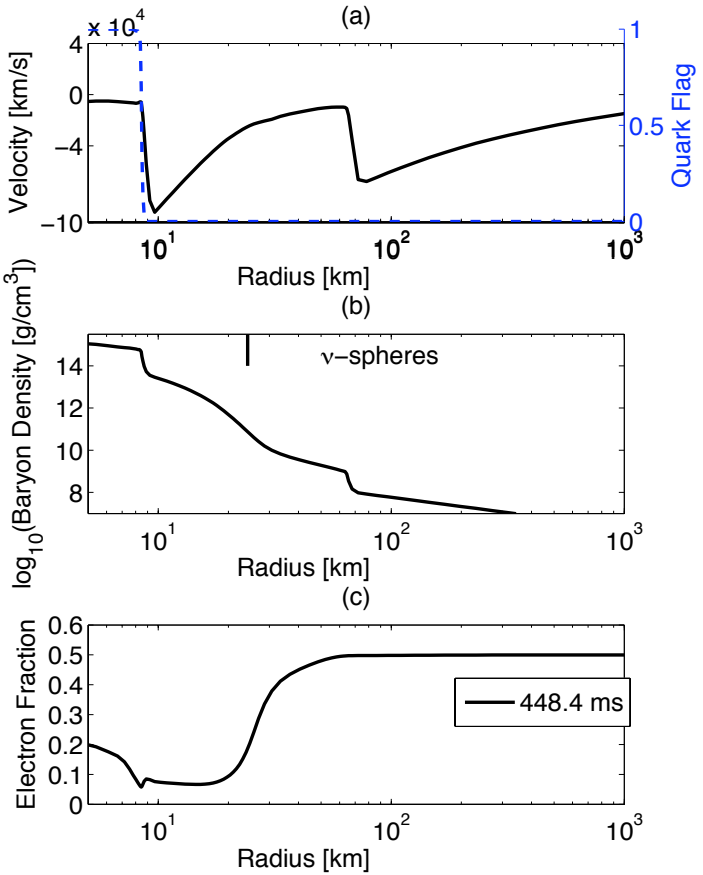
   (similar to the original Fe-core bounce)
6. The stagnation wave meets the supersonically infalling material at the sonic point:

   $\longrightarrow$ Formation of a SECOND SHOCK inside the PNS



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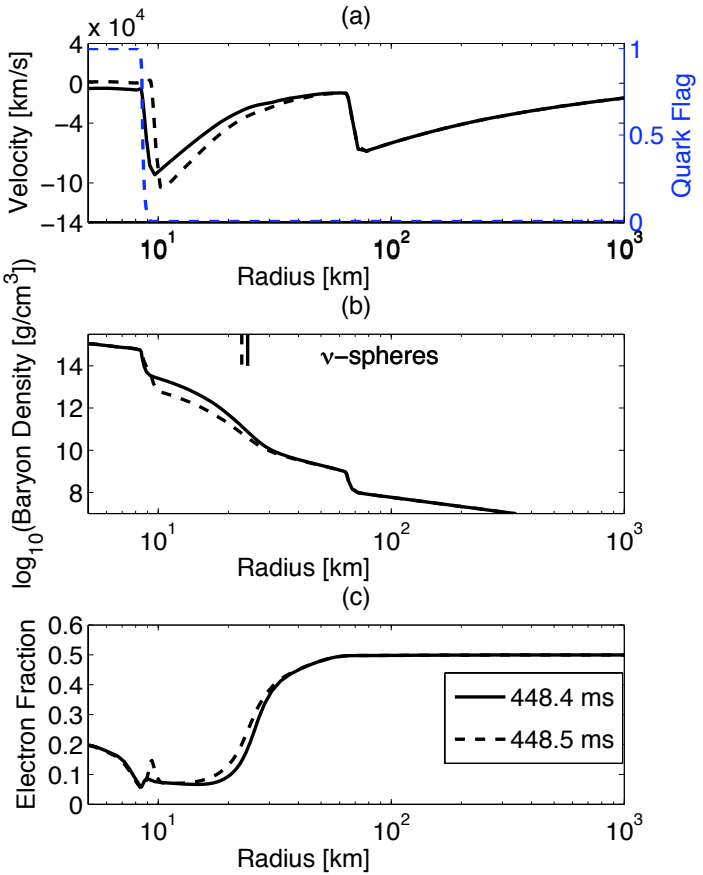

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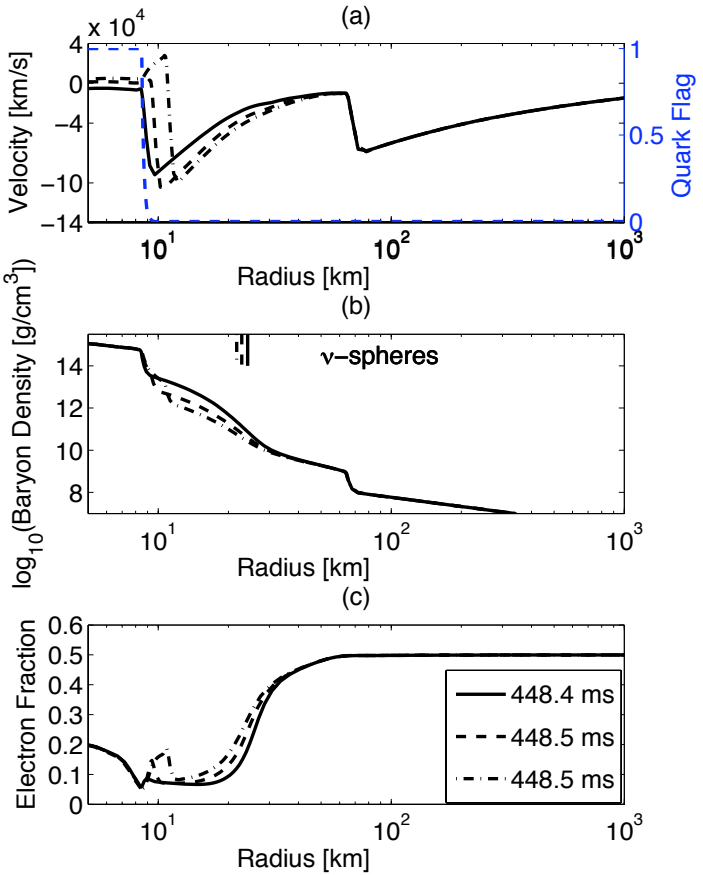

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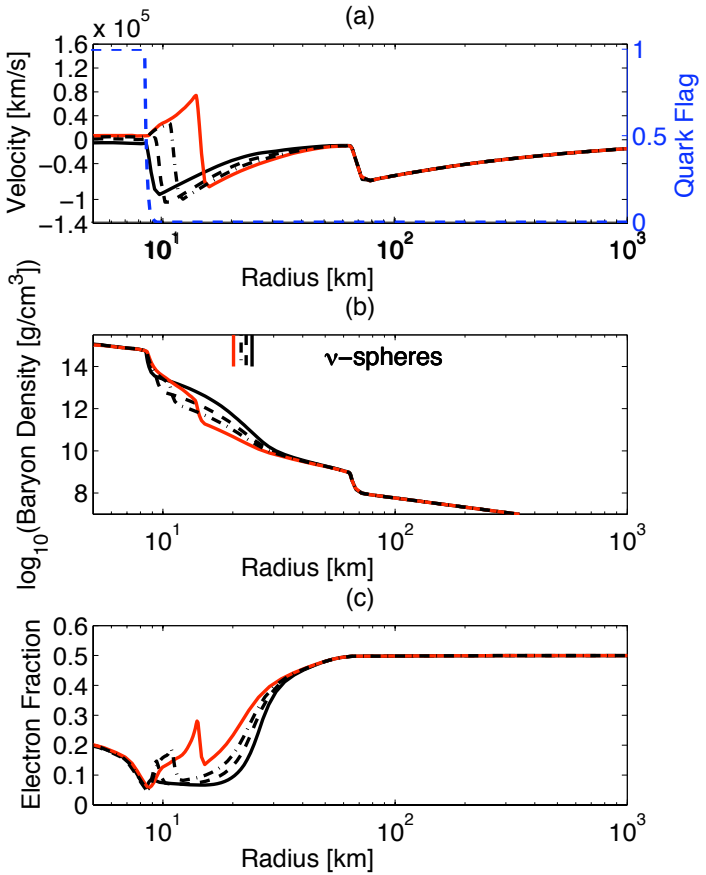
8. The shock turns into a dynamic shock : $P_{ram} = \rho u^2 < P_{thermal}$

(difference to the first shock: no dissociation of infalling material!)



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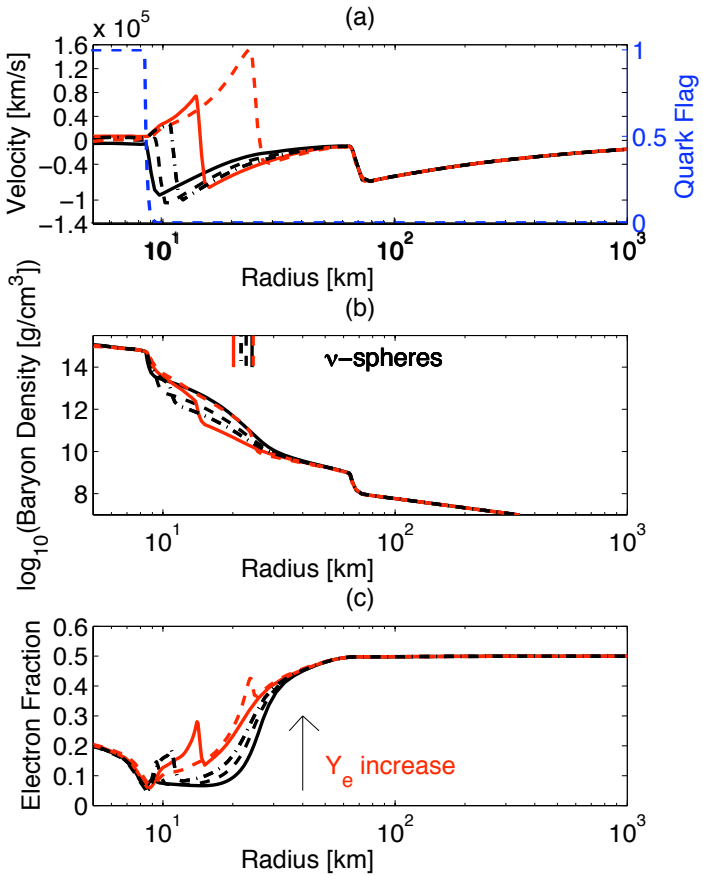
10. Shock propagation over the ν-spheres: 2nd neutrino burst



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10 $M_\odot$ progenitor model

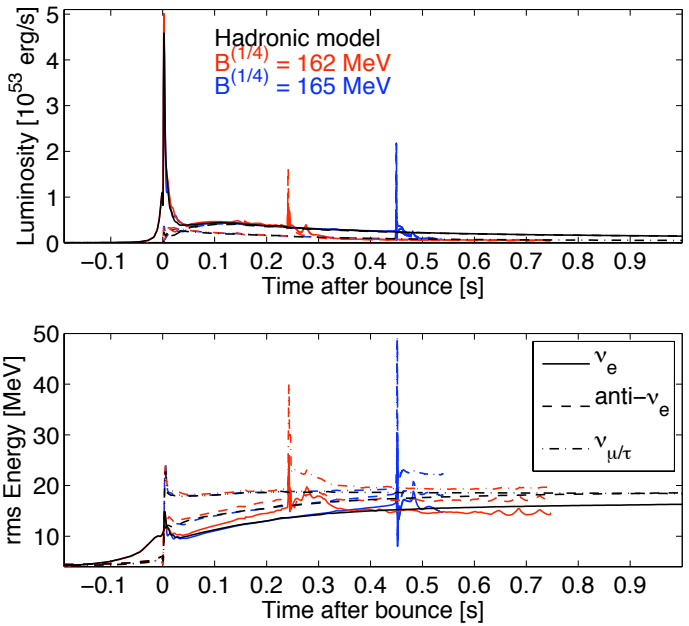

Figure: The second neutrino burst, dominated by $\bar{\nu}_e$ due to the Y_e increase (Sagert et al. 2009)

Summary and Outlook

Summary

1 Investigation of the quark phase transition in core collapse supernovae

1a Spherically symmetric approach/Failed supernova explosion models

1b Constrain the quark model

1c Allow an early onset of the phase transition during the early post bounce phase

2 Confirm the formation of a strong second shock
→ Explosions even in spherical symmetry

Prog. [$M_\odot$]	Quark EoS [MeV]	t_{pb} [ms]	M_Q [$M_\odot$]	M_{mixed} [$M_\odot$]	M_{PNS} [$M_\odot$]	E_{expl} [10^{51} erg]
10	162	255	0.850	0.508	1.440	0.44
10	165	448	1.198	0.161	1.478	1.64
15	162	209	1.146	0.320	1.608	0.42
15	165	330[a]	1.496	0.116	1.700	unknown

3 Release of a second neutrino burst ($\bar{\nu}_e$)
(significant increase in the mean-neutrino energies)

→ detectable by present neutrino measurement facilities (Super-Kamiokande, SNO)?

[a] moment of black hole formation

Outlook

4 Some models eject neutron rich material on fast timescales
→ Favourable conditions for the *r*-process?

5 Different scenarios?

5a Explosion of more massive progenitors vs. black hole formation

5b Weak neutrino-driven explosion and a delayed quark phase transition during fall back

5c multi-dimensional simulations

6 More advanced/improved quark EoS(s)