The search for the *r*-process in explosions of massive stars

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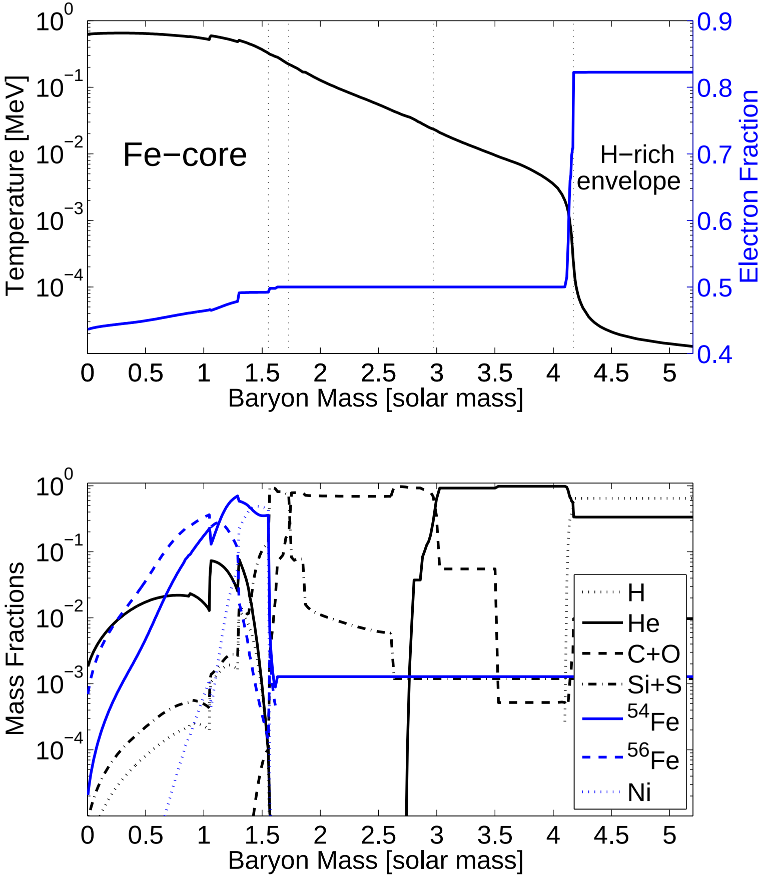
EMMI - EFS Workshop on Neutron-Rich Nuclei, RIKEN Wako
June 16 - 18, 2010

The origin of heavy elements in the Universe: massive stars

Pre-collapse models: core collapse progenitors

Figure: Non-rotating 15(12.64) $M_{\odot}$ progenitor [a]



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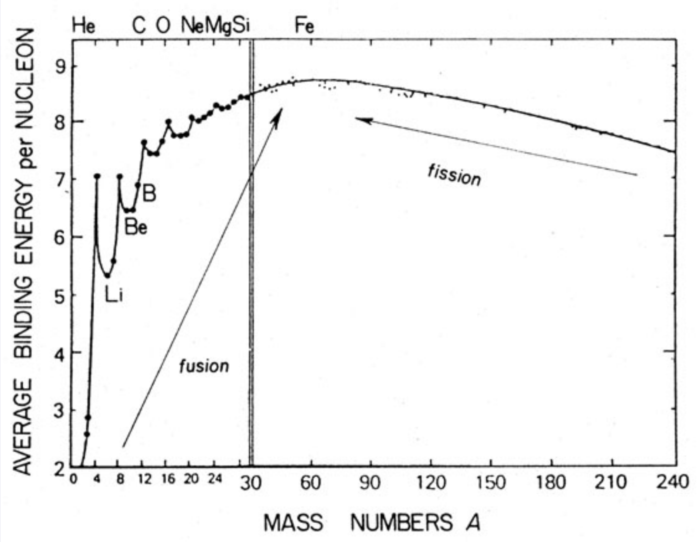
[a] Woosley et al.(2002).

- Stars more massive than 8 $M_{\odot}$
- Onion-like shape due to the nuclear burning history
- High central temperatures ($T \geq 0.1$ MeV)
- Extended 'Fe'-core (1.4 - 1.9 $M_{\odot}$) during Si-burning



- Nuclear burning stops, nuclear statistical equilibrium

$$T \simeq 0.5 \text{ MeV}$$

- Origin of heavier elements, e.g. *r*-process elements

  explosive environments

- Requirement: consistent modeling of all phases

  (i.e. Fe-core collapse, bounce, explosion)

Outline

General relativistic radiation hydrodynamics in spherical symmetry

The concept

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

$$\nabla_\nu T^{\mu\nu} = 0$$

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

3. The (specific) neutrino distribution function

$$F_\nu(t, a, \mu = \cos\theta, E) = \frac{f_\nu(t, a, \mu, E)}{\rho}$$

4. The neutrino (energy) moments

$$\begin{aligned} J &= \frac{2\pi}{(h c)^3} \int_{-1}^{+1} d\mu \int_0^\infty E^3 dE\, F_\nu(t, a, \mu, E) \\ H &= \frac{2\pi}{(h c)^3} \int_{-1}^{+1} \mu d\mu \int_0^\infty E^3 dE\, F_\nu(t, a, \mu, E) \\ K &= \frac{2\pi}{(h c)^3} \int_{-1}^{+1} \mu^2 d\mu \int_0^\infty E^3 dE\, F_\nu(t, a, \mu, E) \end{aligned}$$

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[a] Misner & Sharp (1964), Liebendörfer et al. (2001a,b, 2004)

Why spherical symmetry?

1. Strong gravitational fields
2. Relativistic matter outflow

→ Relativistic effects

3. Accurate neutrino transport
4. Simulation times > 10 s

(beyond state-of-the-art multi-D modeling)

The co-moving coordinate system

$$(t, a, \theta, \phi)$$

(eigentime, baryon mass, 2-sphere of radius $r(t, a)$)

The metric functions

$\alpha(t, a)$ (lapse function)

$$\Gamma(t, a) = \sqrt{1 - 2m/r + u^2}$$

with matter velocity $u = \frac{\partial r}{\alpha \partial t}$

Three flavour Boltzmann neutrino transport

$$dF_\nu/dt \qquad \left(\nu = \{\nu_e, \bar{\nu}_e, \nu_{\mu/\tau}, \bar{\nu}_{\mu/\tau}\}\right)$$

$$\begin{aligned}
\frac{\partial F}{\alpha \partial t}(\mu, E) &= \frac{\mu}{\alpha}\frac{\partial}{\partial a}\left(4\pi r^2 \alpha \rho F\right) \\
&+ \Gamma\left(\frac{1}{r} - \frac{1}{\alpha}\frac{\partial \alpha}{\partial r}\right)\frac{\partial}{\partial \mu}\left[\left(1-\mu^2\right)F\right] \\
&+ \left(\frac{\partial \ln \rho}{\alpha \partial t} + \frac{3u}{r}\right)\frac{\partial}{\partial \mu}\left[\mu\left(1-\mu^2\right)F\right] \\
&- \mu\Gamma\frac{1}{\alpha}\frac{\partial \alpha}{\partial r}\frac{1}{E^2}\frac{\partial}{\partial E}\left(E^3 F\right) \\
&+ \left[\mu^2\left(\frac{\partial \ln \rho}{\alpha \partial t} + \frac{3u}{r}\right) - \frac{u}{r}\right]\frac{1}{E^2}\frac{\partial}{\partial E}\left(E^3 F\right) \\
&+ \frac{j}{\rho} - \tilde{\chi}F \\
&+ \frac{1}{c}\frac{E^2}{h^3c^3}\int d\mu' R_{IS}(\mu', \mu, E)F(\mu', E) - \frac{1}{c}\frac{E^2 F(\mu, E)}{h^3c^3}\int d\mu' R_{IS}(\mu, \mu', E) \\
&+ \frac{1}{c}\frac{1}{h^3c^3}\left(\frac{1}{\rho} - F(\mu, E)\right)\int dE' E'^2 d\mu' R^{in}_{NES}(\mu, \mu', E, E')F(\mu', E') \\
&- \frac{1}{c}\frac{1}{h^3c^3}F(\mu, E)\int dE' E'^2 d\mu' R^{out}_{NES}(\mu, \mu', E, E')\left(\frac{1}{\rho} - F(\mu', E')\right)
\end{aligned}$$

The collision term

(2a) Electronic charged current reactions

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

$e^+ + n \rightleftharpoons p + \bar{\nu}_e$

$e^- + \langle A, Z\rangle \rightleftharpoons \langle A, Z-1\rangle + \nu_e$

(2b) Neutral current reactions

$e^- + e^+ \rightleftharpoons \nu + \bar{\nu}$

$N + N \rightleftharpoons N + N + \nu + \bar{\nu}$

$\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau}$

$\nu + e^{-/+} \rightleftharpoons \nu' + e^{-/+}$

$\nu + N \rightleftharpoons \nu + N$ (iso-energetic)

Lepton number conservation:

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

↓

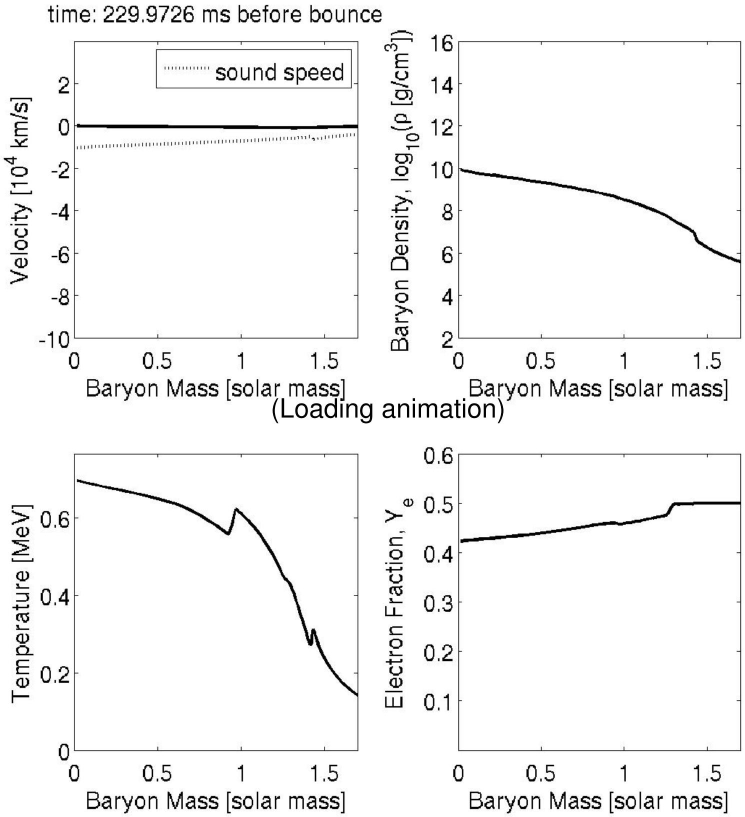
The equation for the neutrino number:

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

Evolution of the electron fraction

$$\frac{\partial Y_e}{\partial t} = -\frac{2\pi m_B c}{(h\,c)^3}\int_{-1}^{+1} d\mu \int_0^\infty E^2 dE (j - \tilde{\chi}F)$$

Fe-core collapse and bounces



- Pressure loss $\begin{cases} \text{Photodisintegration} \\ \text{Electron captures} \end{cases}$

$$\begin{aligned} e^- + p &\rightarrow n + \nu_e, \\ e^- + \langle A, Z \rangle &\rightarrow \langle A, Z-1 \rangle + \nu_e \end{aligned}$$

⟶ Deleptonisation and contraction

The electron fraction:

$$\boxed{Y_p = \frac{n_p}{n_B} \equiv Y_e := Y_{e^-} - Y_{e^+}}$$

- Adiabatic collapse:

$\begin{cases} \rho \text{ and } T \text{ increase} \\ \text{Super-sonic vs. sub-sonic collapse} \\ \text{Nuclear densities: collapse halts} \end{cases}$

$$\rho \simeq 3 - 4 \times 10^{14} \text{ g/cm}^3$$

⟶ The core bounces back:

Formation of a Shock wave

- Size of the bouncing core[a] $\sim Y_e^2$

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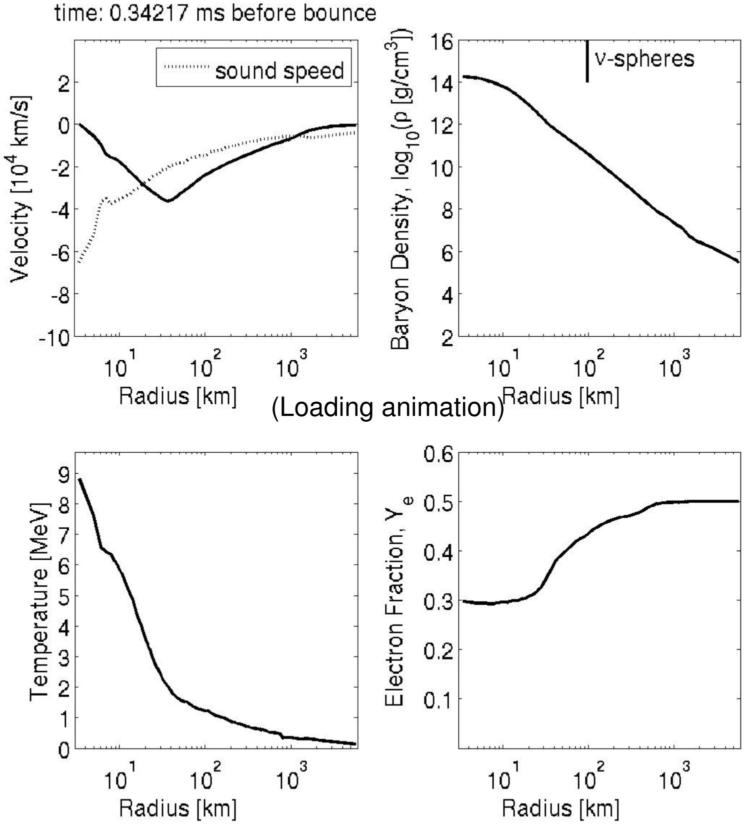
[a] Goldreich & Weber (1980)

The early post-bounce phase



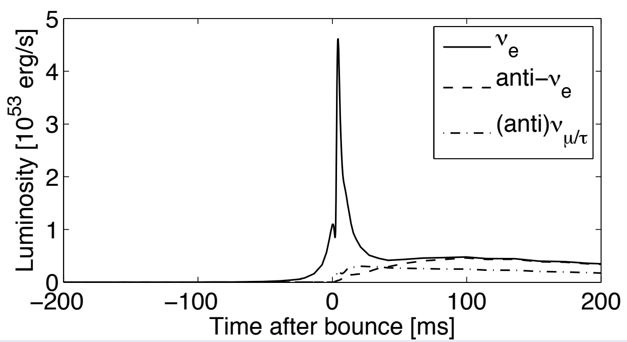
(Loading animation)

Sources of energy loss

1. Dissociation of heavy nuclei ($\sim$ 8 MeV/n_B)
2. Neutrino escape $4 - 5 \times 10^{53}$ erg/s

   (deleptonisation, $Y_e \simeq 0.1$ near ν-spheres)

Figure: Neutrino luminosities



(The deleptonisation burst)

⟶ The Standing Accretion Shock (SAS)

The concept of neutrino-driven explosions in theory

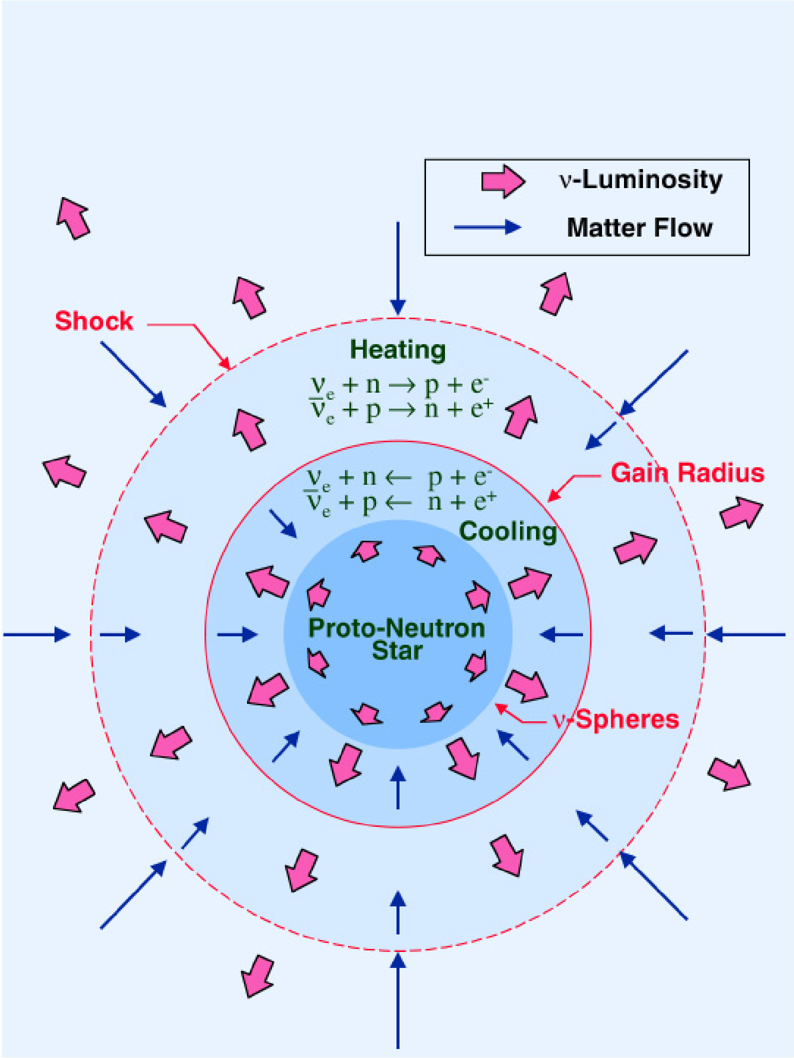


Figure: S. Bruenn

Charged current reactions: heating/cooling

$$\begin{aligned} e^- + p &\rightleftharpoons n + \nu_e, \\ e^+ + n &\rightleftharpoons p + \bar{\nu}_e, \end{aligned}$$

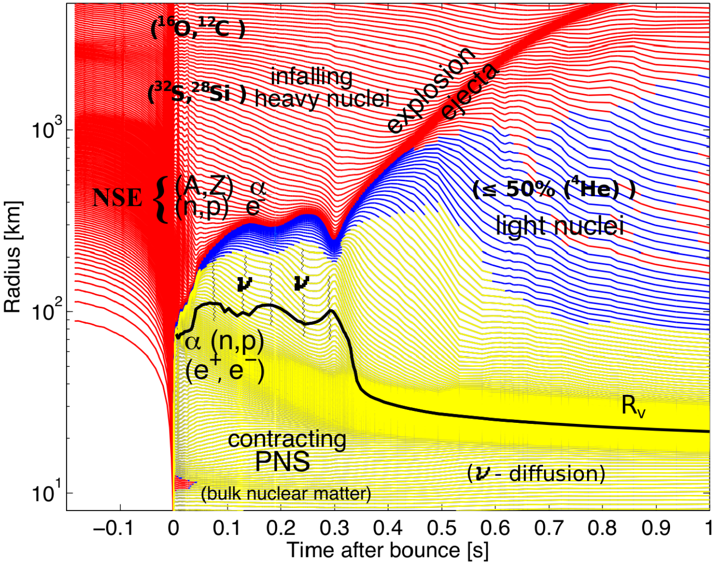


Figure: Evolution of selected mass trajectories.

Neutral current reactions: thermalisation

$$\text{scattering} \left\{ \begin{array}{l} \nu + N \rightleftharpoons \nu + N \qquad (N = n, p)\,, \\[1em] \nu + e^\pm \rightleftharpoons \nu + e^\pm, \end{array} \right.$$

The concept of neutrino-driven explosions in simulations

Spherical symmetry

1. 8.8 $M_\odot$ O-Ne-Mg-core [a] [b] [c]
   - Steep density gradient
   - ν-heating timescale $\sim$ 10 ms
   - Nuclear energy deposition
2. $\geq$9 $M_\odot$ Fe-cores
   - ν-heating timescale $\sim$ 100 ms
   - ν-heating not efficient enough

$\longrightarrow$ No explosions !

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[a] Kitaura et al. (2006)
[b] Fischer et al. (2009)
[c] Nomoto (1983,1984,1987)

Multi-dimensional models

1. Rotation,convection,fluid instabilities
2. More efficient ν-heating
3. Low $E_{\text{explosion}} \simeq 0.5 \times 10^{51}$ erg
4. ν-transport approximations[a]

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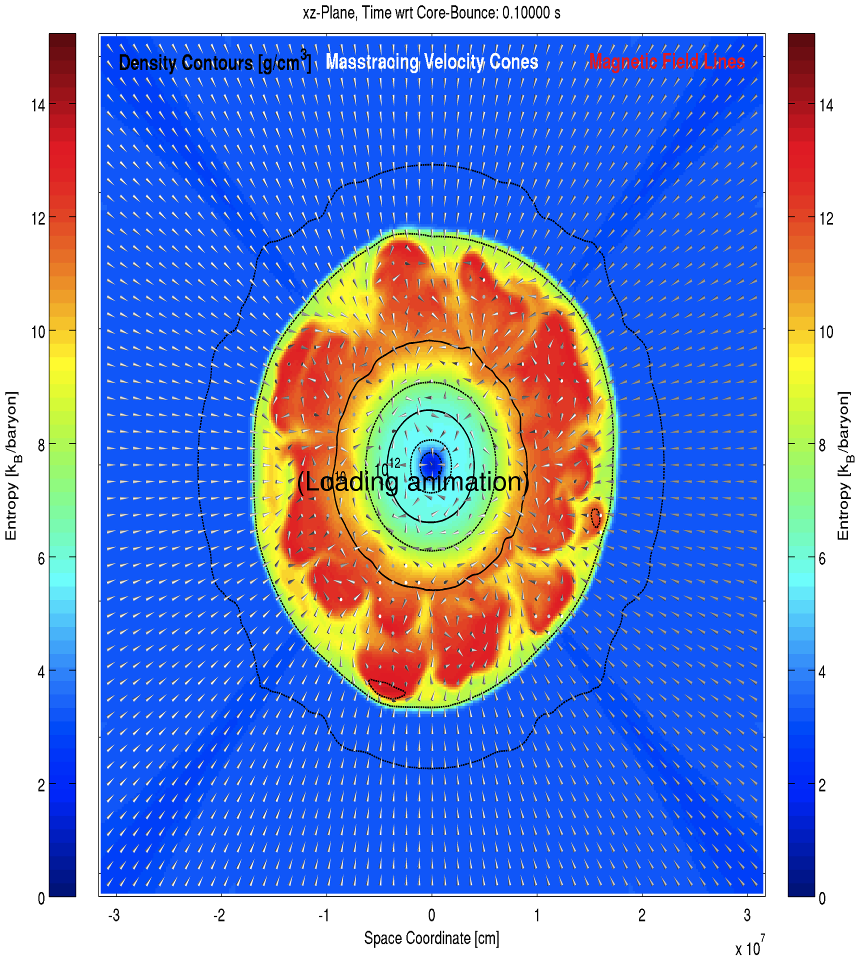
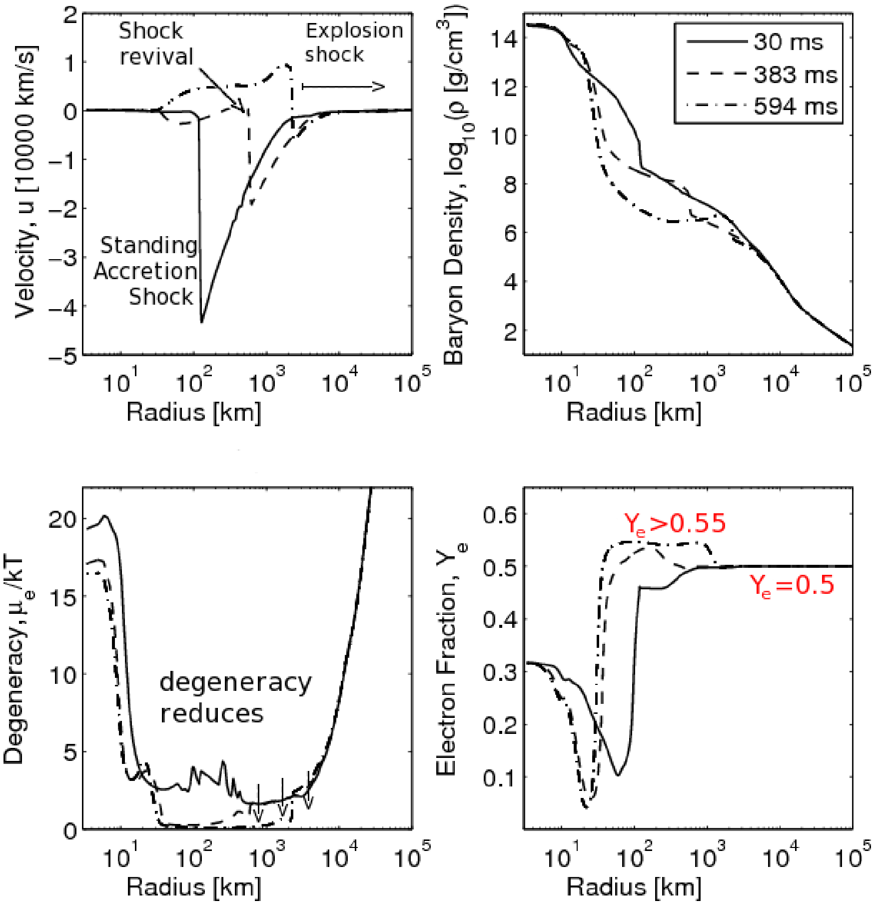
[a] Burrows (1995, 2006) (acoustic mechanism), MacFaden & Woosley (1999) (magneto-rotational), Blondin & Mezzacappa (2003) (MGFL, SASI), Bruenn et al. (2009) (MGFL, nucl. reaction network), Kotake et al. (2005) (SASI, GW), Foglizo et al. (2007) (SASI), Marek & Janka (2009) (ray-by-ray)

15 $M_\odot$ Liebendörfer & Whitehouse (3D-MHD-IDSA, in preparation)



Neutrino driven explosions in spherical symmetry and the early explosion ejecta

Figure: The initial explosion phase, 10.8 $M_\odot$ progenitor model.



Enhanced neutrino heating

- Neutrino heating [a] not efficient to drive explosions

→ Increased neutrino opacity and emissivity

$$e^- + p \rightleftharpoons n + \nu_e, \quad e^+ + n \rightleftharpoons p + \bar{\nu}_e$$

(in the region of low density and high entropy, i.e. outside the neutrinospheres !)

Shock revival and Explosion

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[a] Bruenn (1985) + N-N-Bremsstrahlung

The initial proton-to-baryon ratio of the ejecta

- Shock propagation outwards
- Composition given by the progenitor model

→ Shock heating: reduced degeneracy and hence

$$Y_e \simeq 0.54 - 0.57$$

(General agreement between different groups [a])

Does the initially proton-rich material become neutron-rich at later times ∼ 10 seconds ?

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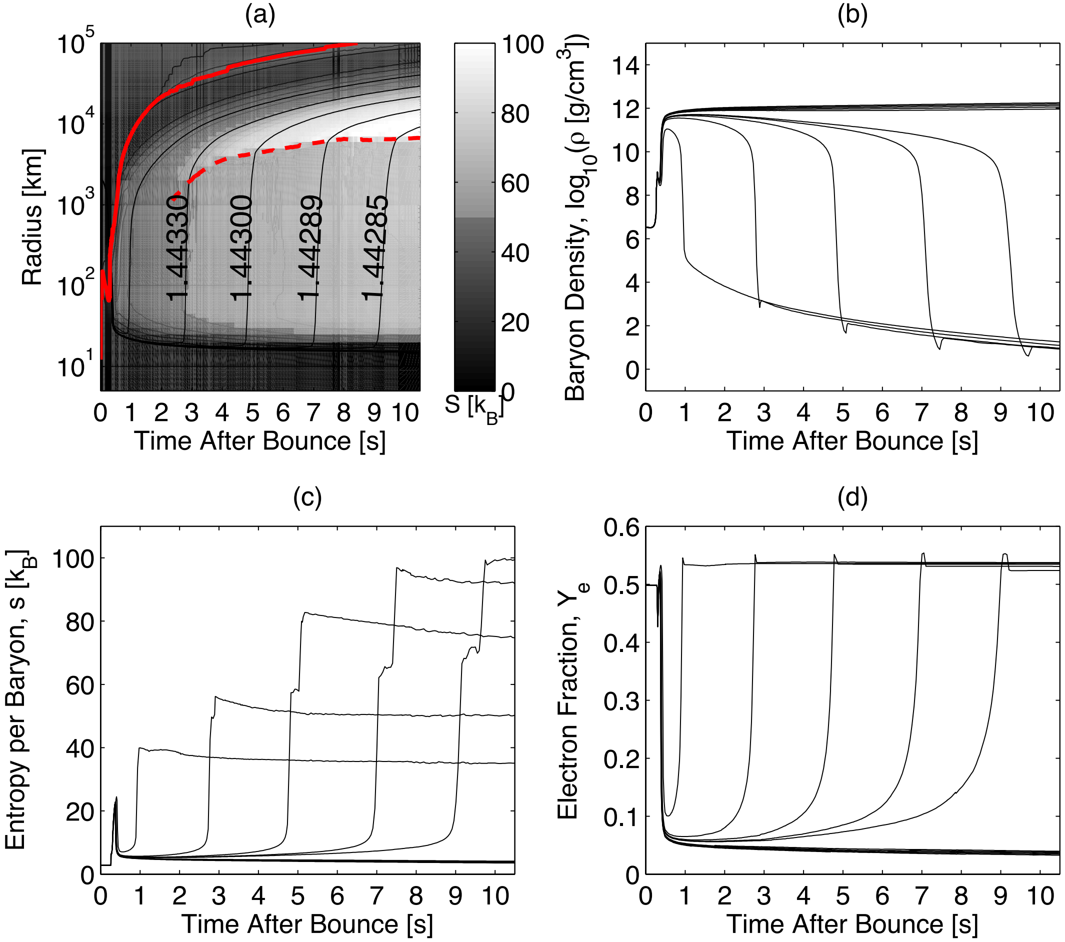
[a] Qian & Woosley (1996), Liebendörfer et al.(2001), Ramp & Janka (2000)*, Janka et al.(2002), Liebendörfer et al.(2003), Thompson, Borrows & Pinto (2003)**, Buras & Janka (2006)†, Marek & Janka (2009)†

Evolution of selected mass trajectories in the neutrino driven wind



No *r*-process

1. Direct explosion ejecta[a]

   $Y_e > 0.5$

2. ν-driven wind:

   - Initial 'slow' expansion $\sim$ s
   - Rapid acceleration $\sim$ 100 ms
   - Wind termination shock [b]
   - Y_e : 0.05 $\longrightarrow$ 0.53 – 0.56
   - Entropies $\simeq$ 40 – 100 k_B/n_B
   - simulation times $>$ 10 seconds

$\longrightarrow$ $Y_e \simeq 0.52 - 0.54$

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[a] Fröhlich et al. (2006a,b,c)
[b] Arcones et al. (2008)

The equation of state

The different thermodynamic regimes, the baryons

1. $T \leq 0.5$ MeV: (time-dependent nuclear reactions)
   - Nuclear reaction network[a]
   - Nuclear abundances used: (n, p, ^{3}He, ^{4}He, ^{12}C,...,^{56}Ni)
2. $T > 0.5$ MeV: (nuclear statistical equilibrium, NSE)
   - RMF (TM1) and Thomas-Fermi approximation
   - (n, p, ^{4}He, $\langle A, Z \rangle$) (single nucleus approximation) [b] [c]
   - Incompressibility, asymmetry energy $(281, 36.9$ MeV)

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[a] Thielemann et al.(2004)
[b] Lattimer & Swesty (1991), Shen et al. (1998)
[c] Typel et al. (2009), Hempel & Schaffner-Bielich (2010)

On top of the baryon contributions

(e^-, e^+), γ, ion-ion-correlations [a] and ν's

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[a] Timmes & Arnett (1999)

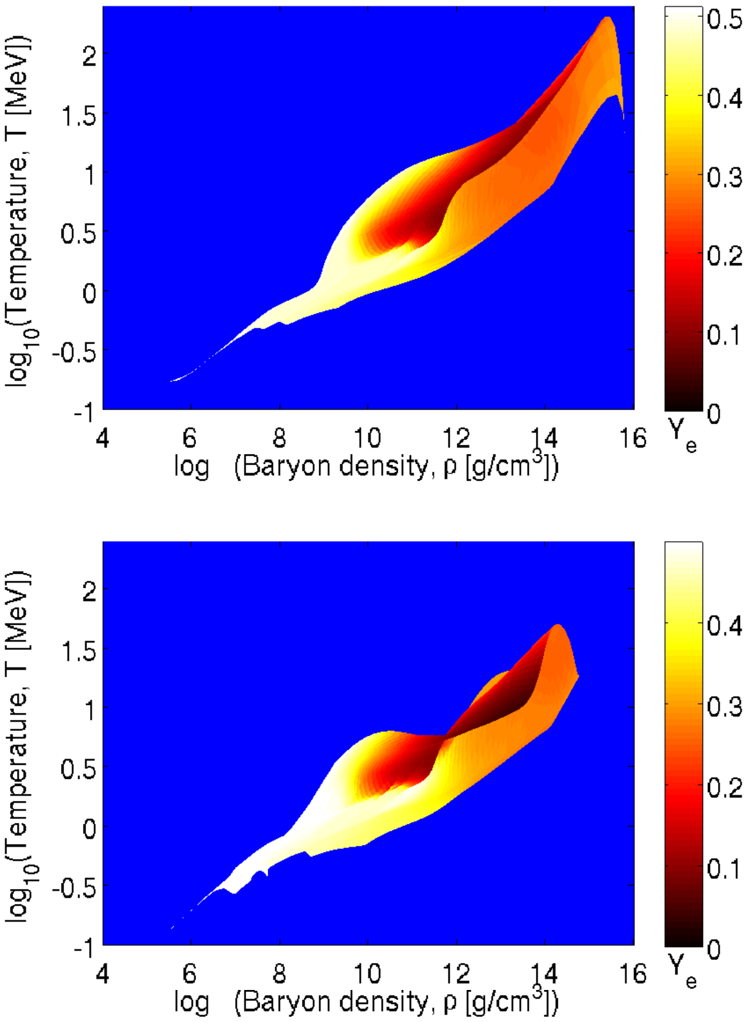
Conditions for the quark hadron phase transition

1. $T \simeq 10 - 100$ MeV, $Y_e \simeq 0.2 - 0.3$, $n_B \simeq n_0$
2. T- and Y_e-dependent critical density, $n_c = n_c(T, Y_e)$
3. Critical density close to nuclear saturation density

$$n_c = 0.12 - 0.24 \text{ fm}^{-3} \ (2 - 4 \times 10^{14} \text{ g/cm}^3)$$

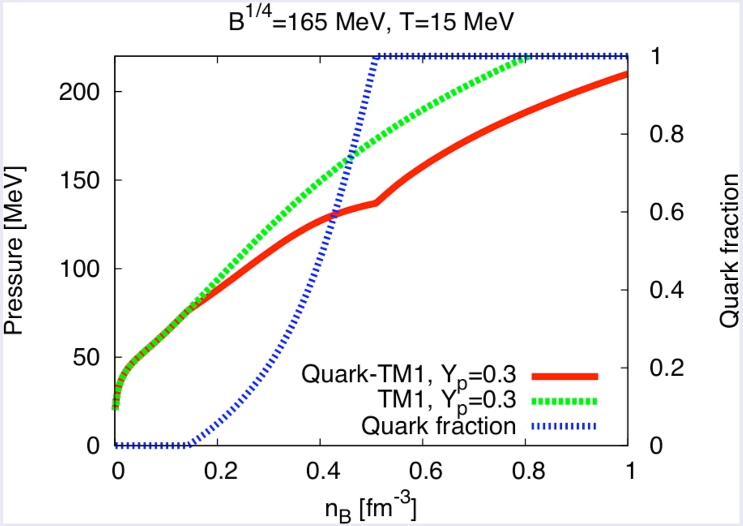
The quark hadron phase transition in simulations of massive stars?

Figure: 40 $M_\odot$ (top) and 15 $M_\odot$ (bottom)



The quark hadron phase transition in PNS interiors

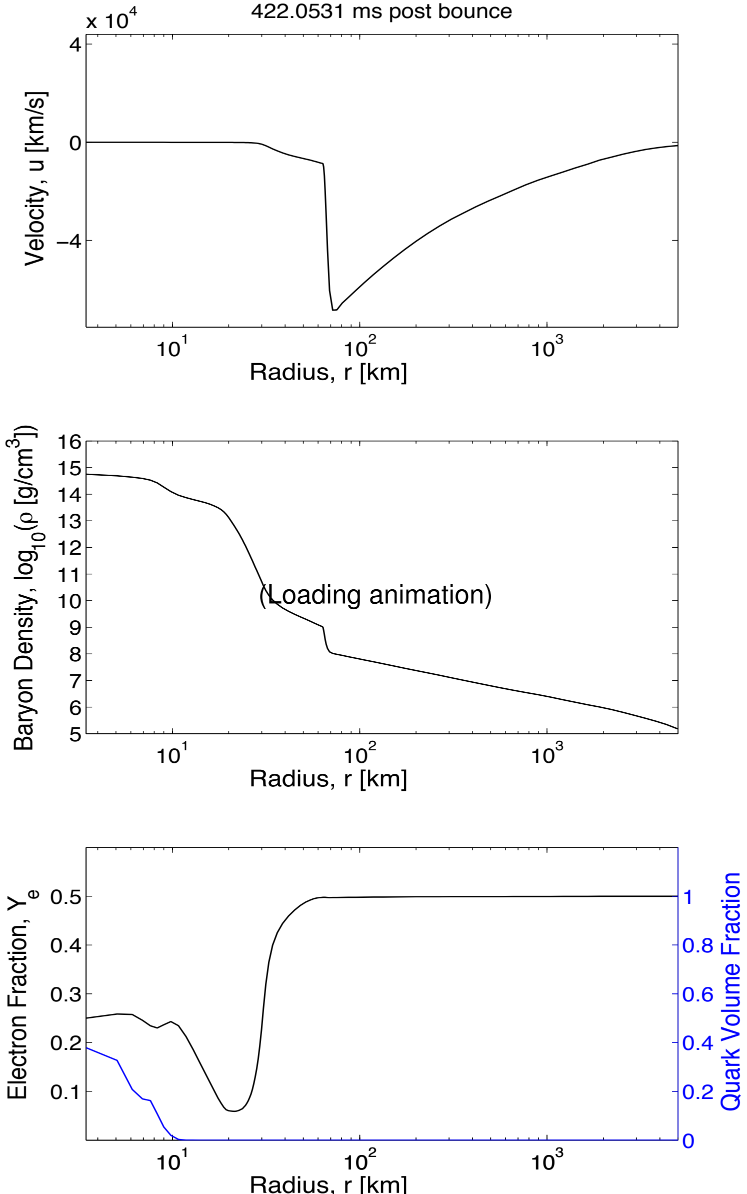
Construction of the quark matter EoS



- The MIT bag model for strange quark matter
- The mixed phase: Gibbs construction

PNS evolution with quarks: collapse

1. Softening of the EoS in the mixed phase
   - PNS collapse
2. Stiffening of the EoS in the pure quark phase
   - Collapse halts
   - Strong hydrodynamic shock wave
   - Shock expansion and acceleration $\longrightarrow$ Explosions ! (even in spherical symmetry)



Results of the quark hadron phase transition

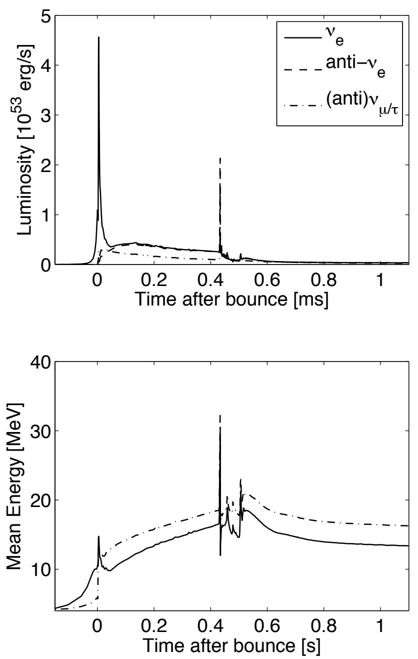
The standard explosion scenario of massive stars:

Conditions indicate a weak *r*-process (if any) in neutrino-driven outflows ⟶ Missing input-physics ???

The neutrino observables

1. No direct signal form the phase transition
2. Shock crossing over the neutrinospheres

⟶ Neutrino burst dominated by $\bar{\nu}_e$



3. Detection of the "QCD-burst" (ICEC,SK)[a]

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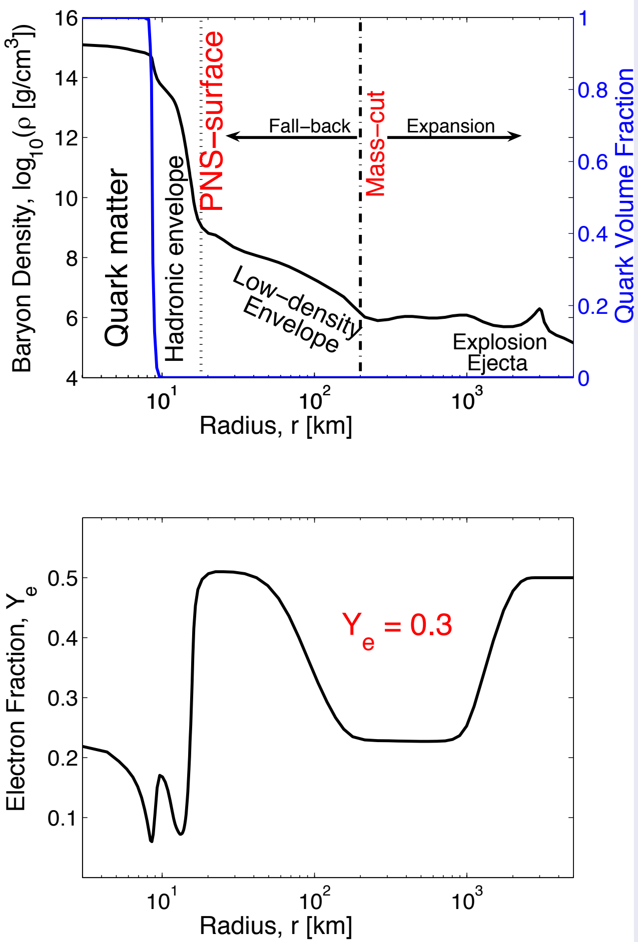
[a] Dasgubta et al. (2010)

QCD degrees of freedom: possible site for the *r*-process



Outlook

The to-do list

1. Improved nuclear physics input
   (ν-hadron physics ($e^{-}-$captures, ν-N-scattering [a]), quark-matter description (PNJL[b]), ν-quark interactions)
2. Detailed explosive nucleosynthesis analysis
3. Alternative scenarios
4. Multi-dimensional models of the quark hadron phase transition
   (gravitational waves[c], rotation, convection, magnetic field[d])

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[a] G.Martinez-Pinedo & K.-H. Langanke

[b] Sandin & Blaschke (2007)

[c] Abdikamalov et al. (2009)

[d] Nobutoshi et al. (2010)

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