CORE COLLAPSE SUPERNOVAE IN THE QCD PHASE DIAGRAM

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Outline

Motivation

The Fundamental Forces of Nature in Core Collapse Supernovae

Gravity

1. General relativity
2. Ideal fluid dynamics
3. Strong gravitational fields
4. Relativistic matter velocities
5. Time dilation $\rightarrow \infty$

$$\alpha(\vec{x}, t) \in [0, 1]$$

(Lapse function)

Electromagnetism

1. Charged particles (protons, ions)
2. Magneto-hydrodynamics
3. Initial B-field: 10^{9-10} G
4. Magnetars ($B \simeq 10^{15}$ G)

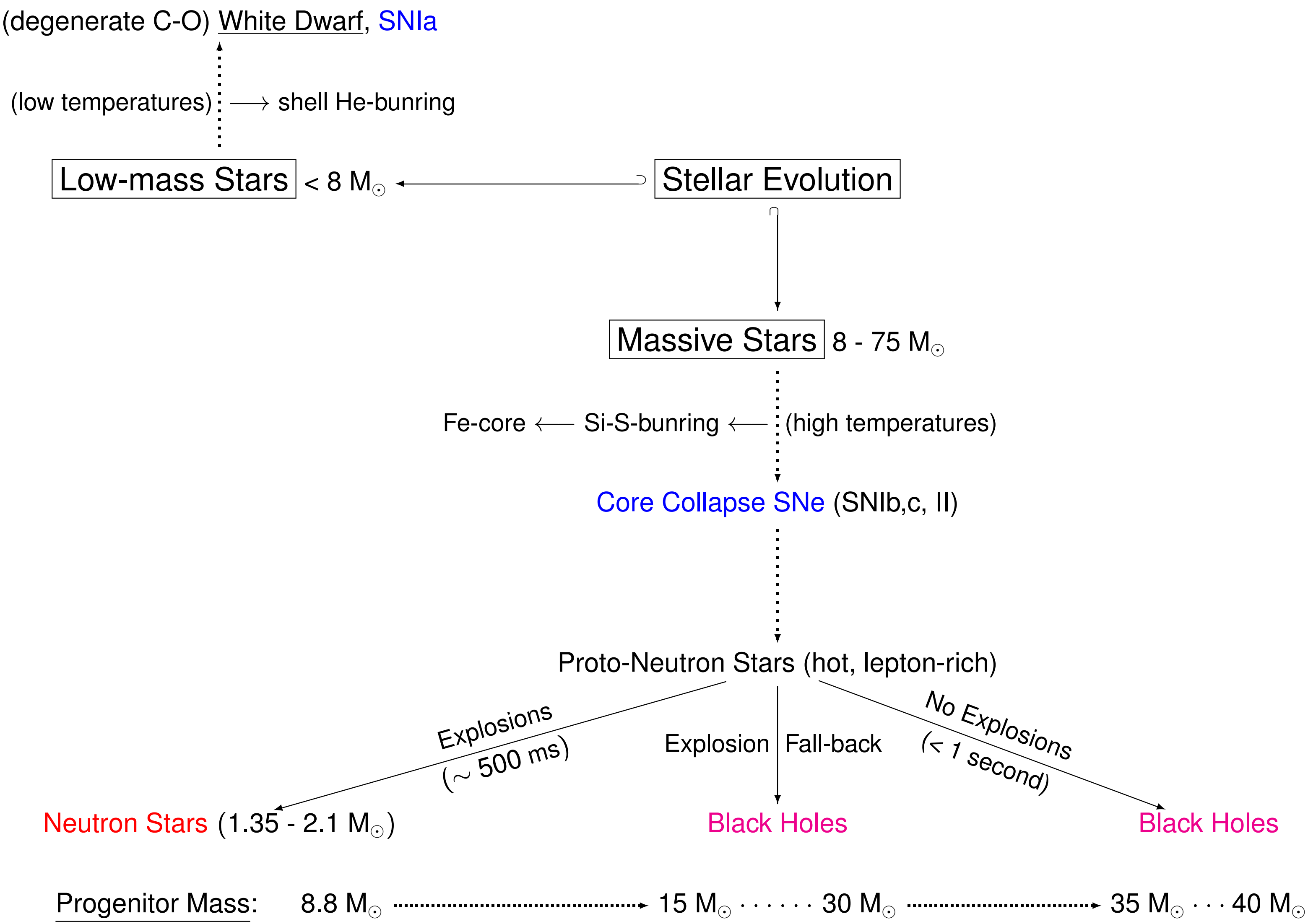
Weak interactions

1. $\nu' s$ (mass-less ultra-relativistic fermions)
   $$f_\nu(t, \vec{x}, \vec{p})$$
2. Radiation transport (Boltzmann transport)
   $$\frac{df_\nu(t, \vec{x}, \vec{p})}{dt} = \Omega(f_\nu)$$
3. Diffusion/free-streeming (neutrino mean free path)

Strong interactions

1. The state of matter
2. $T \in [10^6, 10^{13}]$ K $\left(T \in [10^{-3}, 10^3] \text{ MeV}\right)$
3. $\rho \in [1, 10^{15}]$ g/cm^3 $\left(n_B \in [10^{-16}, 0.6] \text{ fm}^{-3}\right)$
4. Isospin asymmetry $\left(Y_e = \frac{n_p}{n_B} \in [0, 0.6]\right)$
5. Time-dependent nuclear reaction
6. Hot and dense nuclear matter

The Global Picture: The Fate of Massive Stars



The Physics of Core Collapse Supernovae

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

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

		matter	microphysics
T^{tt}	$=$	$\rho(1+e$	$+ \quad)$
$T^{ta} = T^{at}$	$=$		
T^{aa}	$=$	p	$+$
$T^{\theta\theta} = T^{\phi\phi}$	$=$	p	$+$

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

The co-moving reference frame

$(t,\ a)$ (eigentime, baryon mass)

$(\theta,\ \phi)$ (2-sphere of radius $r(t,a)$)

The metric functions

$$G_{\mu\nu} = R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} = 8\kappa T_{\mu\nu} \qquad \text{(Einstein equation)}$$

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

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

$$u = \frac{\partial r}{\alpha \partial t} \qquad \text{(matter velocity)}$$

$m(t,a)$ (gravitational mass)

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

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

3. The neutrino distribution functions

$$F_\nu\,(t, \vec{x}, \vec{v})$$

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

Boltzmann neutrino transport

$$\begin{aligned}
\frac{dF_\nu(t,\vec{x},\vec{v})}{dt} &= \\
&= \frac{\partial F_\nu}{\partial t} + \frac{\partial F_\nu}{\partial \vec{x}}\frac{\partial \vec{x}}{\partial t} + \frac{\partial F_\nu}{\partial \vec{v}}\frac{\partial \vec{v}}{\partial t} \quad \Big\}\ \text{Transport} \\
'' &='' \left(p^\mu \frac{\partial F_\nu}{\partial x^\mu} - \Gamma^\mu_{\nu\tau} p^\nu p^\tau \frac{\partial F_\nu}{\partial p^\mu}\right) \\
&= \left.\frac{dF_\nu}{dt}\right|_{\text{collisions}} \equiv \Omega\,(F_\nu) \quad \Big\}\ \text{Collisions}
\end{aligned}$$

The neutrino moments / moment equations

$$\begin{aligned}
n^\mu(x) &= \int_{-\infty}^{\infty} d^3p\; p^\mu\; F(x,\mathbf{p}) \\
\varepsilon^{\mu\nu} &= \int_{-\infty}^{\infty} d^3p\; p^\mu\; p^\nu\; F(x,\mathbf{p})
\end{aligned}$$

$$\begin{aligned}
\int_{-\infty}^{\infty} d^3p \left(p^\mu \frac{\partial F_\nu}{\partial x^\mu} - \Gamma^\mu_{\nu\tau} p^\nu p^\tau \frac{\partial F_\nu}{\partial p^\mu}\right) &= \nabla_\mu n^\mu(x) \\
&= \int_{-\infty}^{\infty} d^3p\; \Omega\,(F_\nu) \\
\int_{-\infty}^{\infty} d^3p\, p^\delta \left(p^\mu \frac{\partial F_\nu}{\partial x^\mu} - \Gamma^\mu_{\nu\tau} p^\nu p^\tau \frac{\partial F_\nu}{\partial p^\mu}\right) &= \nabla_\mu \varepsilon^{\mu\delta}(x) \\
&= \int_{-\infty}^{\infty} d^3p\, p^\delta\; \Omega\,(F_\nu)
\end{aligned}$$

General Relativistic Radiation Hydrodynamics in Spherical Symmetry

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

$$\begin{array}{rcccc}
 & & \text{matter} & & \text{microphysics} \\
\hline
T^{tt} & = & \rho(1+e & + & J) \\
T^{ta} = T^{at} & = & & & \rho H \\
T^{aa} & = & p & + & \rho K \\
T^{\theta\theta} = T^{\phi\phi} & = & p & + & \frac{1}{2}\rho(J-K)
\end{array}$$

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

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

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

Three Flavor Boltzmann Neutrino Transport in Spherical Symmetry

dF_ν/dt: $\left(\nu = \{\nu_e, \bar\nu_e, \nu_{\mu/\tau}, \bar\nu_{\mu/\tau}\}\right)$

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

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:

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

$\downarrow$

The equation for the neutrino number:

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

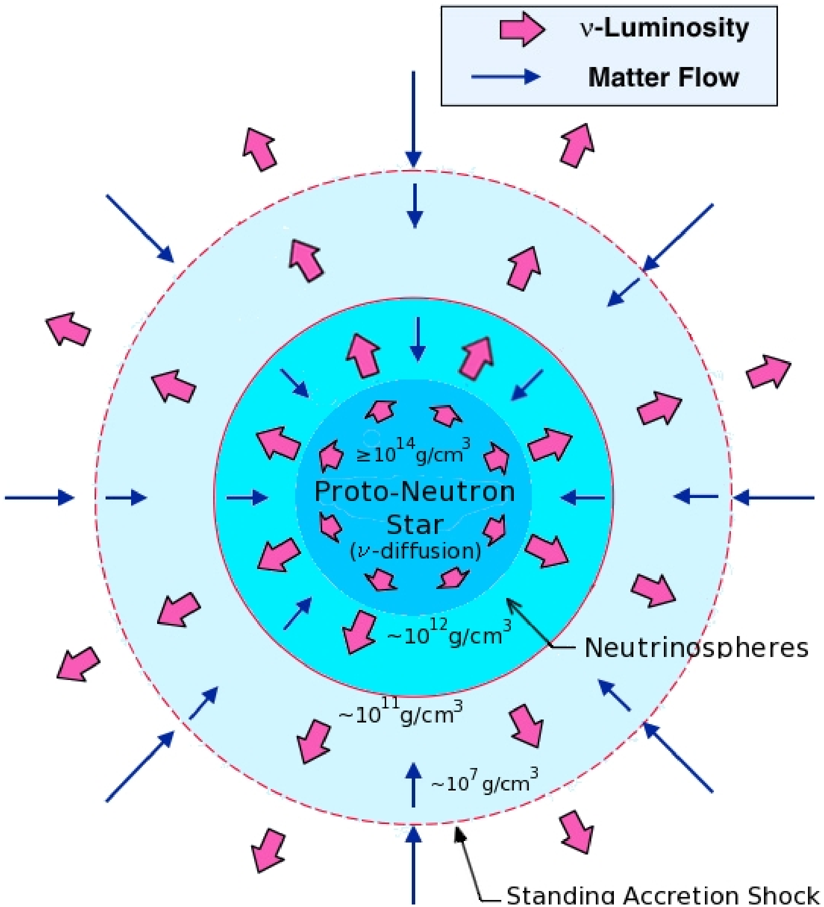
Evolution of the electron fraction

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

The Neutrino Observables

$$L_\nu = 4\pi r^2 \rho \, \frac{2\pi c}{(hc)^3} \int_{-1}^{+1} \mu \, d\mu \int_0^\infty E^3 \, dE \; F_\nu(t, a, \mu, E)$$

$$\langle E_\nu(t,a) \rangle_{\rm rms} = \sqrt{\frac{\int_{-1}^{+1} d\mu \int_0^\infty E^4 \, dE \; F_\nu(t,a,\mu,E)}{\int_{-1}^{+1} d\mu \int_0^\infty E^2 \, dE \; F_\nu(t,a,\mu,E)}}$$



Definition: Neutrinosphere

In the transition from a dense and for neutrinos opaque regime to a (semi-)transparent environment, the neutrino flavor $\{\nu_e, \bar{\nu}_e, \nu_{\mu/\tau}, \bar{\nu}_{\mu/\tau}\}$ and energy E dependent sphere of last scattering is defined via the optical depth as follows

$$\tau(E) := \frac{r}{\lambda(E)} \equiv \frac{2}{3}, \qquad (1)$$

where λ is the neutrino energy dependent total neutrino transport mean free path and r is the distance to the center.

$$\lambda = \lambda_{\nu_e n} + \lambda_{\bar{\nu}_e p} + \lambda_{\nu N} + \lambda_{\nu e^\pm} + \lambda_{\nu\bar{\nu}}$$

Remark

1. The neutrinospheres are typically expressed via the radii R_ν, obtained from the energy integration of (1).
2. Due to the different reactions contributing to the different flavors, the following hierarchy holds

$$R_{\nu_e} > R_{\bar{\nu}_e} > R_{\nu_{\mu/\tau}} > R_{\bar{\nu}_{\mu/\tau}}.$$

3. From expression (1) follows, inside R_ν neutrinos are trapped (diffusion) where outside R_ν neutrinos can be considered free-streaming.

The Equation of State in Core Collapse Supernova Simulations

The different regimes: the baryons

1. $\boxed{T \leq 0.5 \text{ MeV}}$ (time-dependent nuclear reactions)

   The nuclear abundances $n_i = \rho Y_i / m_B$

   (n, p, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{6}Li, . . . ,^{12}C, . . . , ^{54}Fe, ^{56}Fe, ^{56}Ni, ^{60}Zn)

$$\frac{\partial n_i}{\partial t} = \frac{m_B}{\rho}\frac{\partial Y_i}{\partial t} = \frac{m_B}{\rho}\sum_j N^i_j \lambda_j Y_j + \sum_{j,k} \frac{N^i_{j,k}}{1+\delta_{jk}} \langle \sigma v \rangle_{j,k} Y_j Y_k .$$

   $\longrightarrow$ Maxwell-Boltzmann gas + nuclear binding energy [a]

2. $\boxed{T > 0.5 \text{ MeV}}$ (nuclear statistical equilibrium, NSE)

- Compressible liquid-drop model incl. surface effects [b]
- RMF (TM1) and Thomas-Fermi approximation [c]
- The composition: (single nucleus approximation)

  (n, p, ^{4}He, $\langle A, Z \rangle$)

- Compressibilities, symmetry energies:

  ((180, 220, 375), 29.3 MeV)[b], (281, 36.9 MeV)[c]

[a] Thielemann et al. (2004), Audi et al. (2003)
[b] Lattimer and Swesty (1991)
[c] Shen et al. (1998)

Non-baryonic contributions

((e^-, e^+), γ, ion-ion-correlations) [a]

[a] Timmes and Arnett (1999)

The independent variables

T (e), n_B, Y_p

The EoS output

hydrodynamics: p, s, e

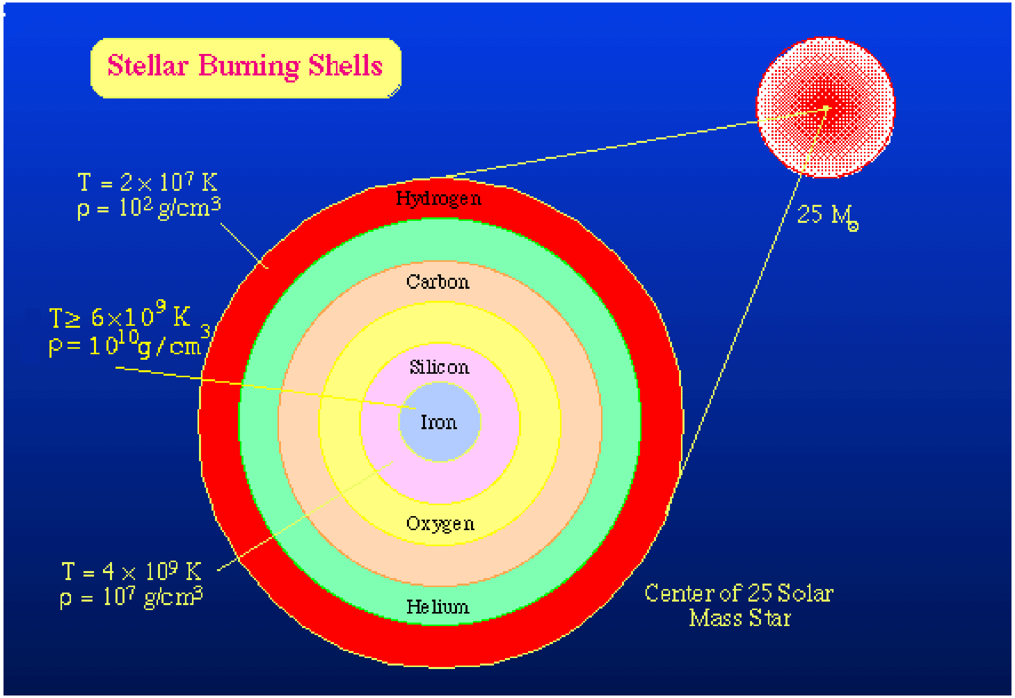
neutrino transport:

μ_n, μ_p, μ_e, X_n, X_p, $X_{\langle A,Z \rangle}$

(weak interactions)

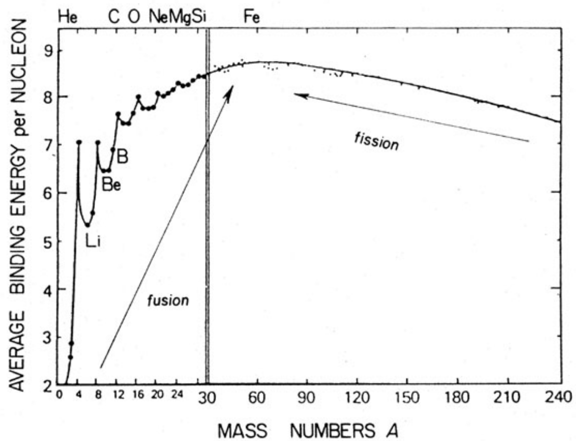
Core Collapse Supernova Phenomenology

The End of Stellar Evolution of Massive Stars



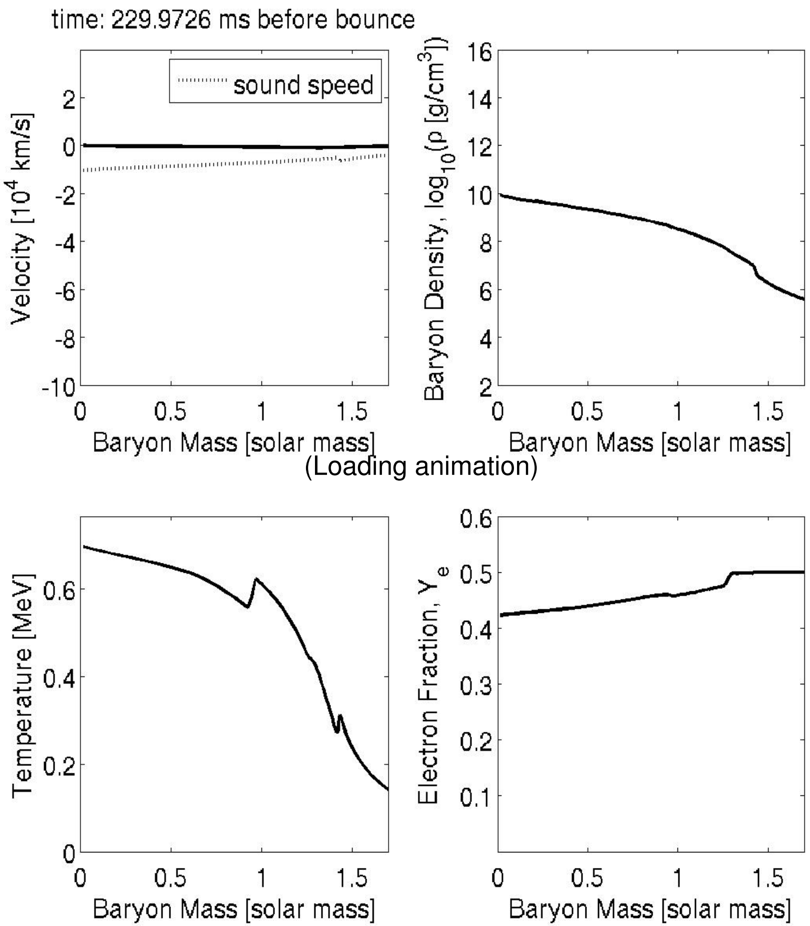
- Onion-like shape
  (due to the nuclear burning history of the stars)
- The most stable elements: ^{56}Fe, ^{56}Ni
  (largest binding energy per nucleon)
- The origin of heavier elements ?

$^{232-238}$U, $^{238-244}$Pu, $^{202-208}$Pb



The Fe-core Collapse and Bounce

Figure: 15 $M_\odot$ [a]



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1. Pressure loss { Photodisintegration / Electron captures }

$$e^- + p \rightarrow n + \nu_e,$$
$$e^- + \langle A, Z\rangle \rightarrow \langle A, Z-1\rangle + \nu_e$$

⟶ Deleptonization and contraction

The electron fraction:

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

2. Adiabatic collapse:
   - T and ρ increase
   - Y_e decreases
3. Nuclear densities: collapse halts

$$\rho \simeq 3-4 \times 10^{14}\ \mathrm{g/cm^3} (\simeq 0.18 - 0.24\ \mathrm{fm^{-3}})$$

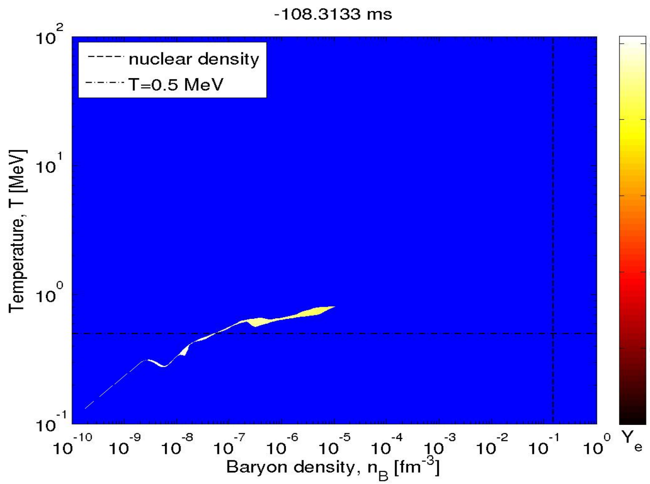
(Dissociated nuclear matter)

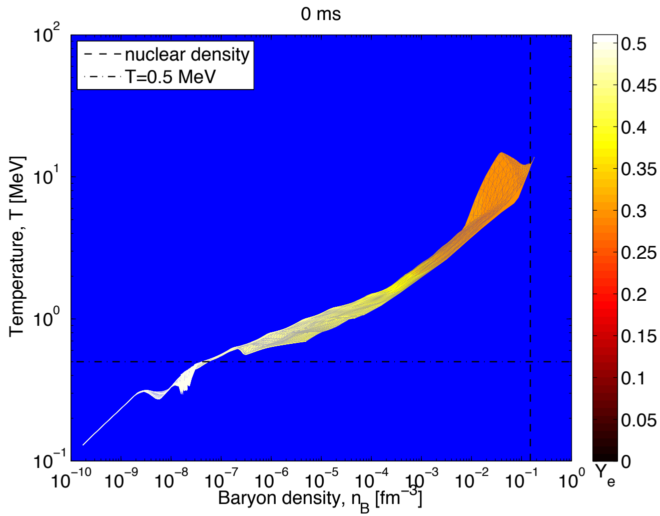
⟶ The core bounces back: Shock wave

4. Formation of the protoneutron star (PNS)

[a] Woosley, Heger & Weaver (2002)

The Fe-Core Collapse and Bounce in the Phasediagram





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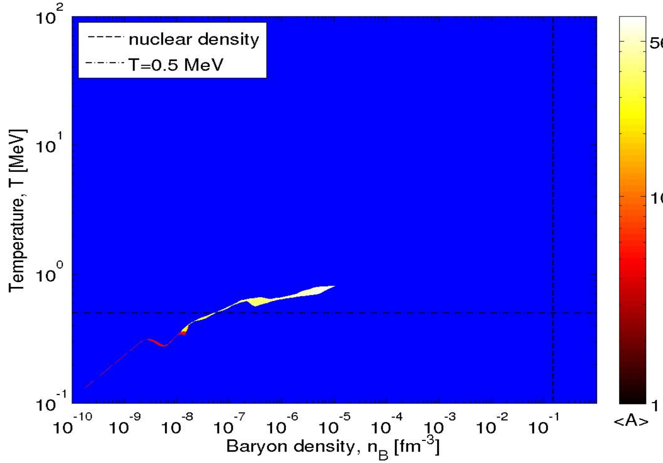
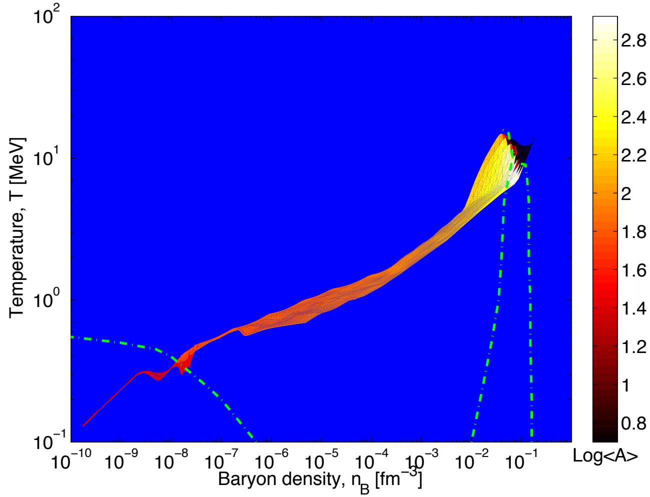
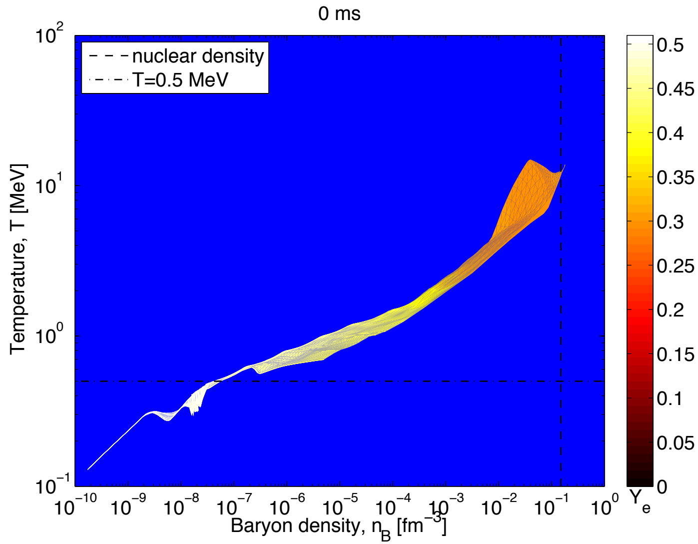
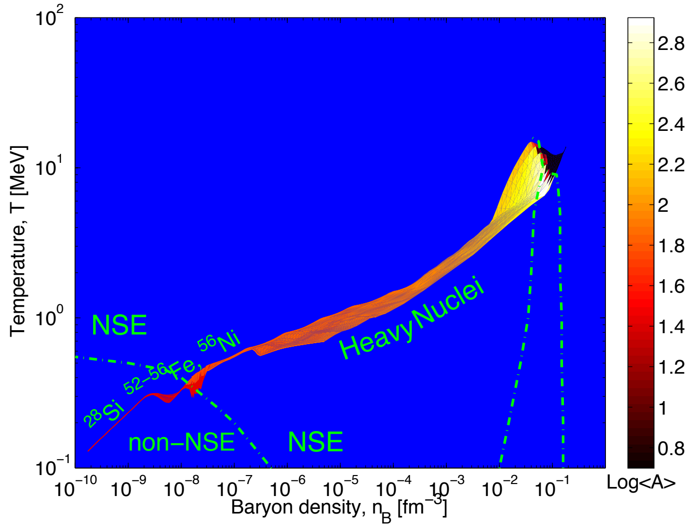




The Fe-Core Collapse and Bounce in the Phasediagram





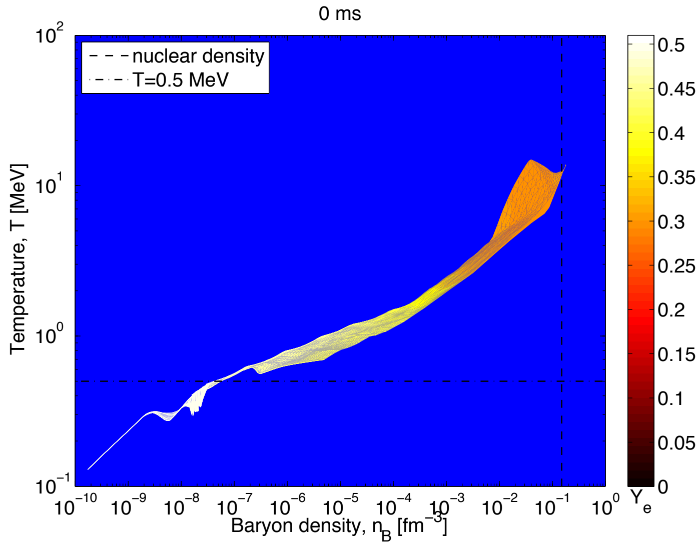
The different phases

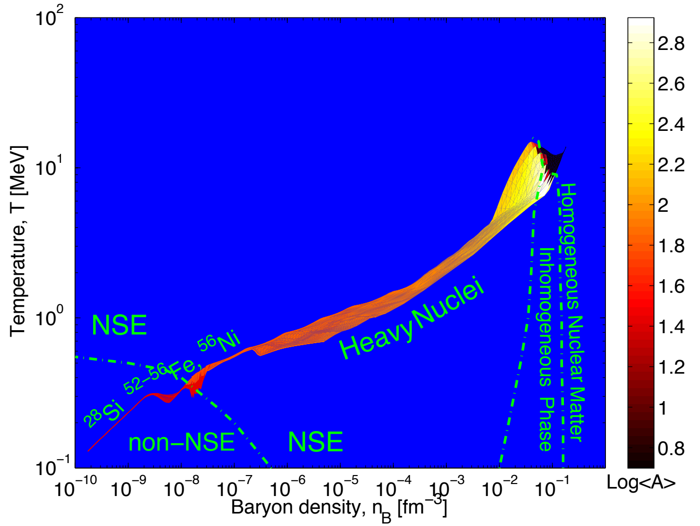
1. $T \leq 0.5$ MeV (non-NSE)
   - Time-dependent nuclear reactions (^{12}C, ^{16}O, ^{28}Si, ^{32}S)
   - Heavy nuclei up to ^{56}Fe and ^{56}Ni
2. $T > 0.5$ MeV (NSE)

   (nuclear statistical equilibrium)
3. $T \simeq 2$ MeV, $n_B \simeq 10^{-3}$
   - heavy nuclei $\langle A \rangle \geq 200$
   - $x_{\langle A,Z \rangle}$ decreases, $x_{\text{light cluster}}$, x_n, x_p increase
4. Y_e reduces: nuclei become neutron-rich

⟶ The neutron drip line ($n_B \simeq 10^{-3}$ fm^{-3})

The Fe-Core Collapse and Bounce in the Phasediagram





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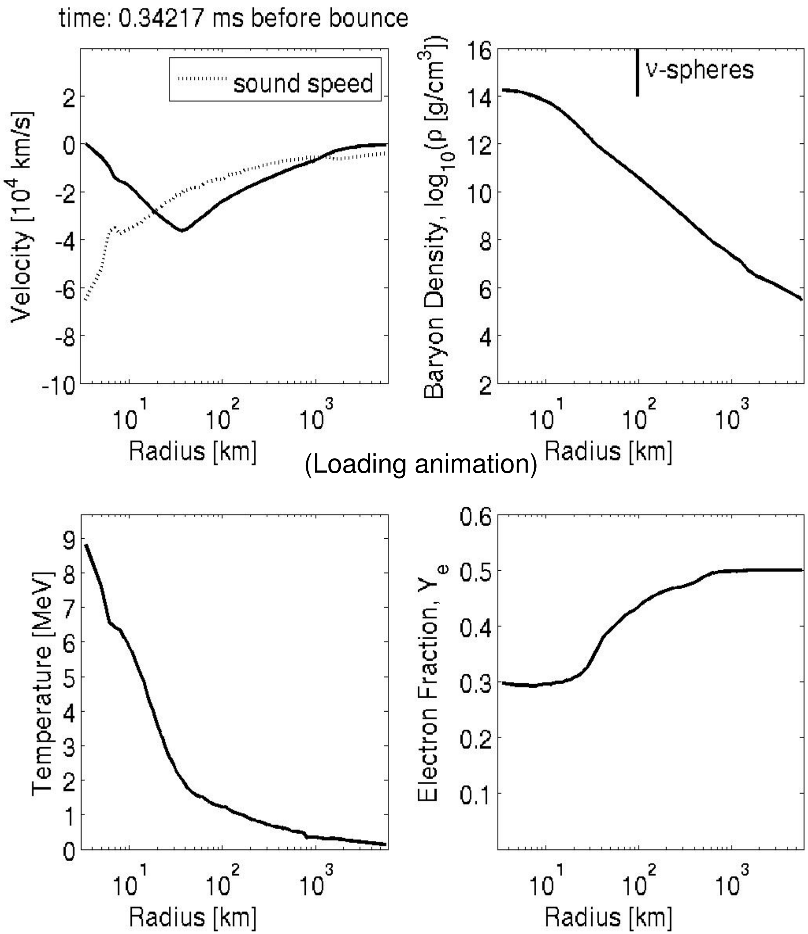
→ The neutron drip line ($n_B \simeq 10^{-3}$ fm^{-3})

5. Transition to in-homogeneous nuclear matter

   $$n_B \simeq 10^{-2} \text{ fm}^{-3}$$

   (structure formation: pasta, spaghetti, Swiss-cheese)
6. Homogeneous nuclear matter ($n_B \simeq 0.1$ fm^{-3})

Proto-Neutron Star evolution



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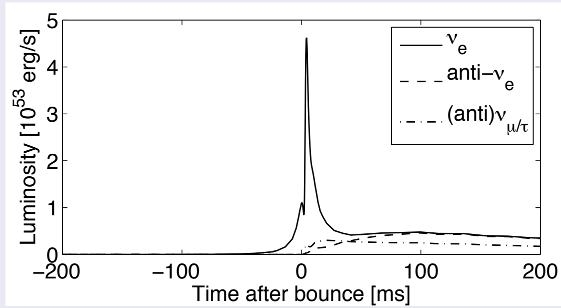
1. Sources of energy loss:
   - Dissociation of heavy nuclei (~ 8 MeV/n_B)
   - Neutrino escape: $4 - 5 \times 10^{53}$ erg/s (deleptonization, $Y_e \simeq 0.1$ near ν-spheres)

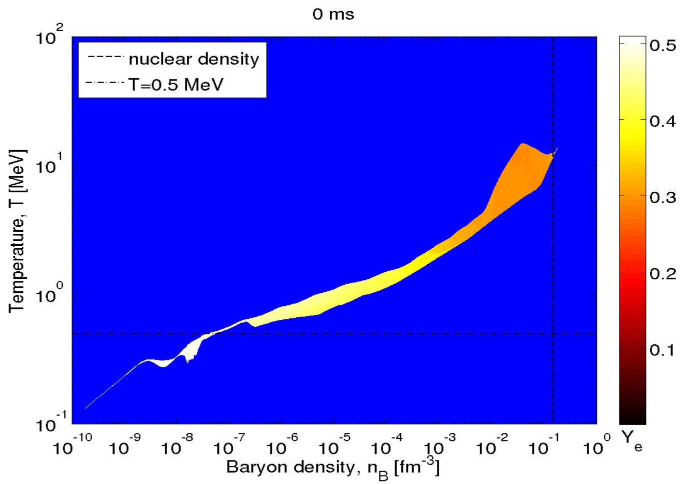
Figure: Neutrino luminosities

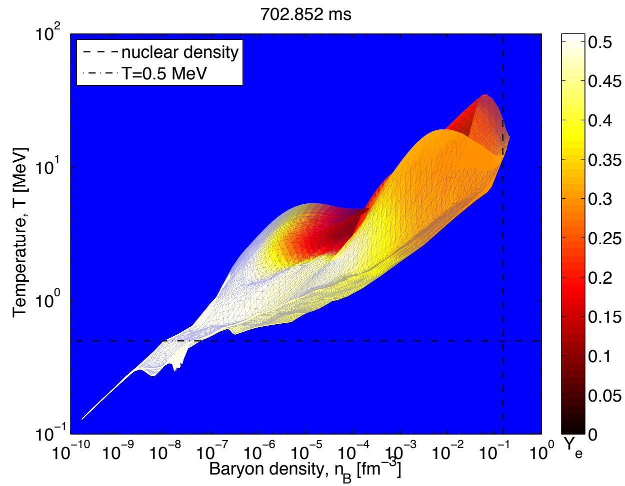


(The deleptonization burst)

2. PNS evolution is given by:
   - Mass accretion vs. ν-heating/cooling
   - PNS compression (timescale ~ 100 ms) (Central T and ρ increase, Y_e decrease)

The Post-Bounce Evolution in the Phasediagram





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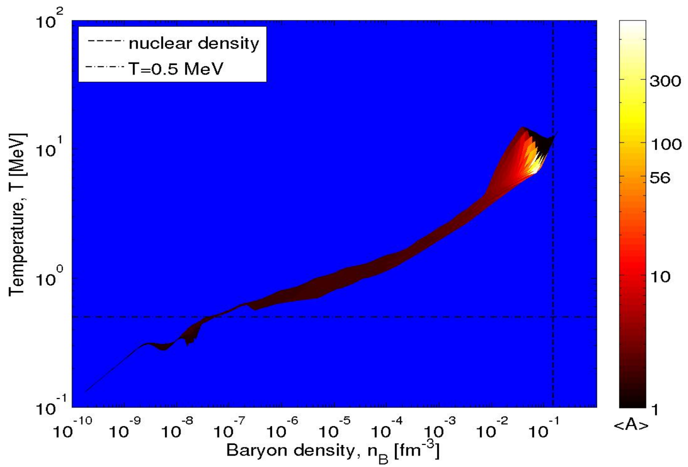
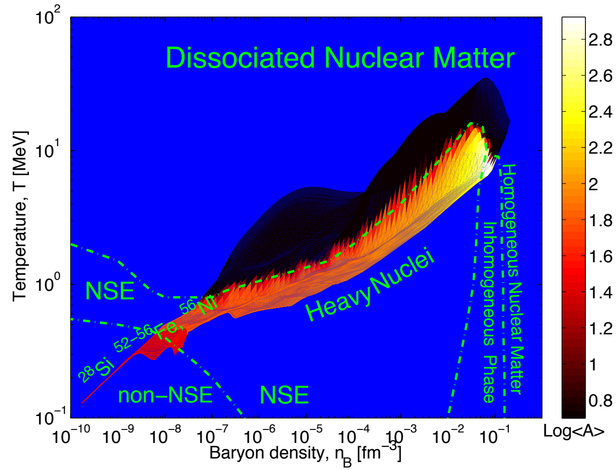
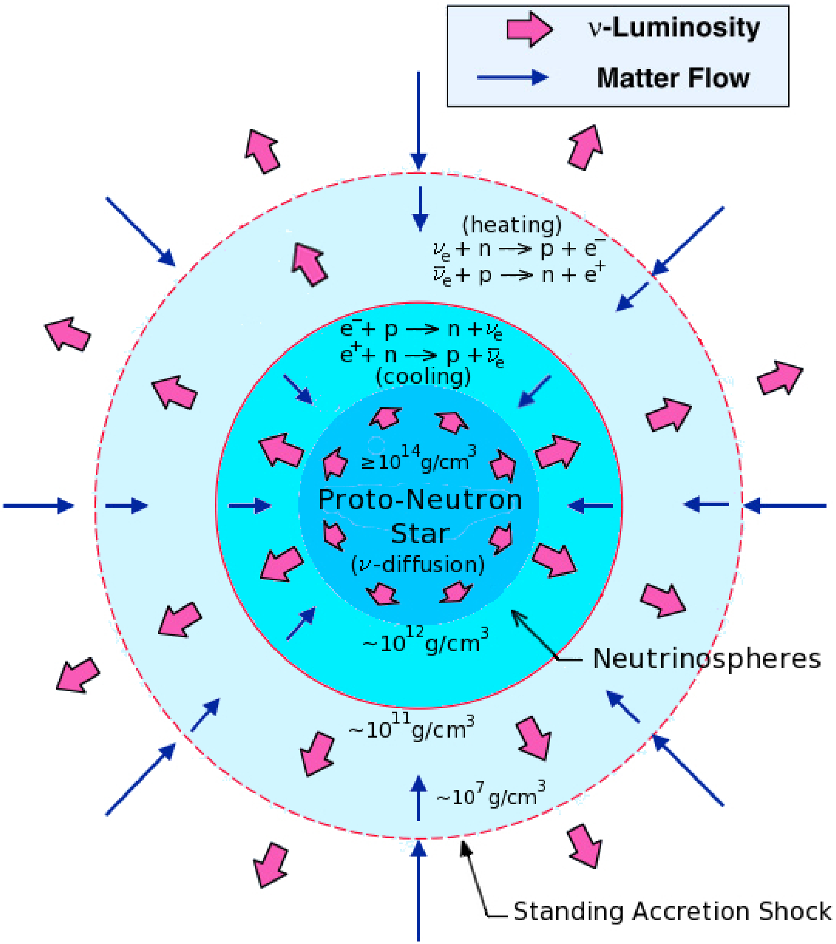




Explosions of Massive Stars

The Concept of Neutrino-Driven Explosions of Massive Stars in Theory



Why neutrinos?

$\sim 10^{53}$ erg (energy of the neutrino radiation field)

$\sim 10^{51}$ erg (explosion energy, observations)

Alternative scenarios:

(a) Magneto-rotational [a] [b] [c] (10^{14-16} G, rotation rates)

(b) Acoustic mechanism[d] (controversal)

[a] LeBlank and Wilson (1970)
[b] Bisnovatyi-Kogan et al. (2008)
[c] Takiwaki et al. (2010)
[d] Burrows et al. (1995, 2006)

Charged current reactions: heating/cooling

$$\begin{aligned} e^- + p &\rightleftharpoons n + \nu_e, \\ (e^- + \langle A, Z\rangle &\rightleftharpoons \langle A, Z-1\rangle + \nu_e), \\ e^+ + n &\rightleftharpoons p + \bar{\nu}_e, \end{aligned}$$

Neutral current reactions: thermalization

$$\text{scattering} \begin{cases} \nu + N \rightleftharpoons \nu + N \quad (N = n, p)\,, \\ (\nu + \langle A, Z\rangle \rightleftharpoons \nu + \langle A, Z\rangle), \\ \nu + e^{\pm} \rightleftharpoons \nu + e^{\pm}, \end{cases}$$

$$\text{pair reactions} \begin{cases} e^- + e^+ \rightleftharpoons \nu + \bar{\nu}, \\ N + N \rightleftharpoons N + N + \nu + \bar{\nu} \;\; (N = n, p,)\,, \\ \nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau}, \end{cases}$$

Neutrino-Driven Explosions in Simulations

Spherical symmetry

1. 8.8 $M_\odot$ O-Ne-Mg-core [a] [b] [c]
   - Steep density profile
   - 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 !

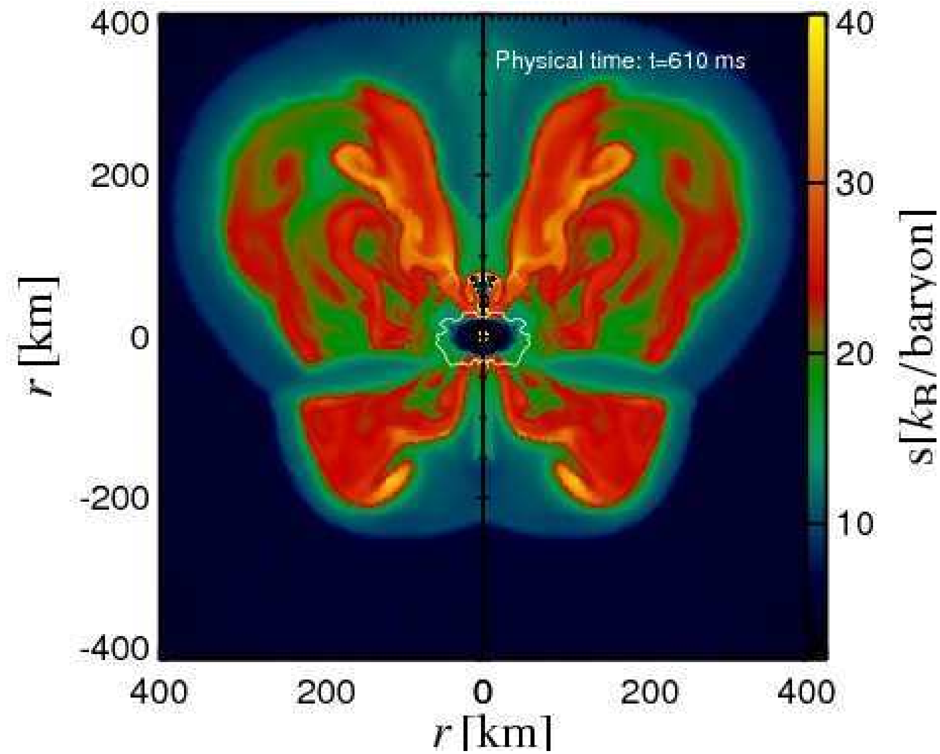
[a] Kitaura et al. (2006)
[b] Fischer et al. (2009)
[c] Nomoto (1983,1984,1987)

Multi-dimensional models

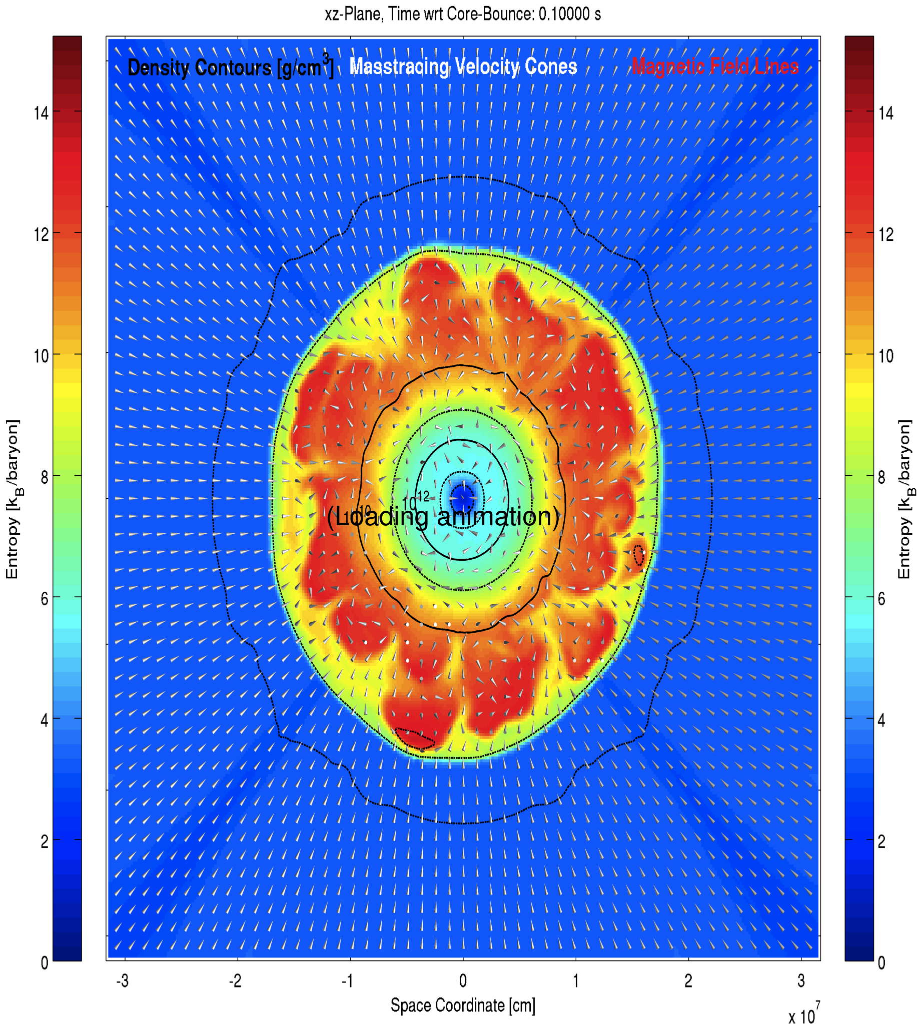
1. Rotation,convection,fluid instabilities
2. More efficient ν-heating
3. Low $E_{\text{explosion}} \simeq 0.5 \times 10^{51}$ erg
4. ν-transport approximations[a]
5. Axial symmetry only

[a] Burrows (1995, 2006) (acoustic mechanism), Blondin & Mezzacappa (2003) (MGFL, SASI), Bruenn et al. (2009) (MGFL, nucl. reaction network), Kotake et al. (2005) (SASI, GW), Foglizo et al. (2007) (SASI)

Figure: 15 $M_\odot$, Marek & Janka (2009) (ray-by-ray)



First (Preliminary) Results from 3D MHD Simulations (ν-transport approximation IDSA)



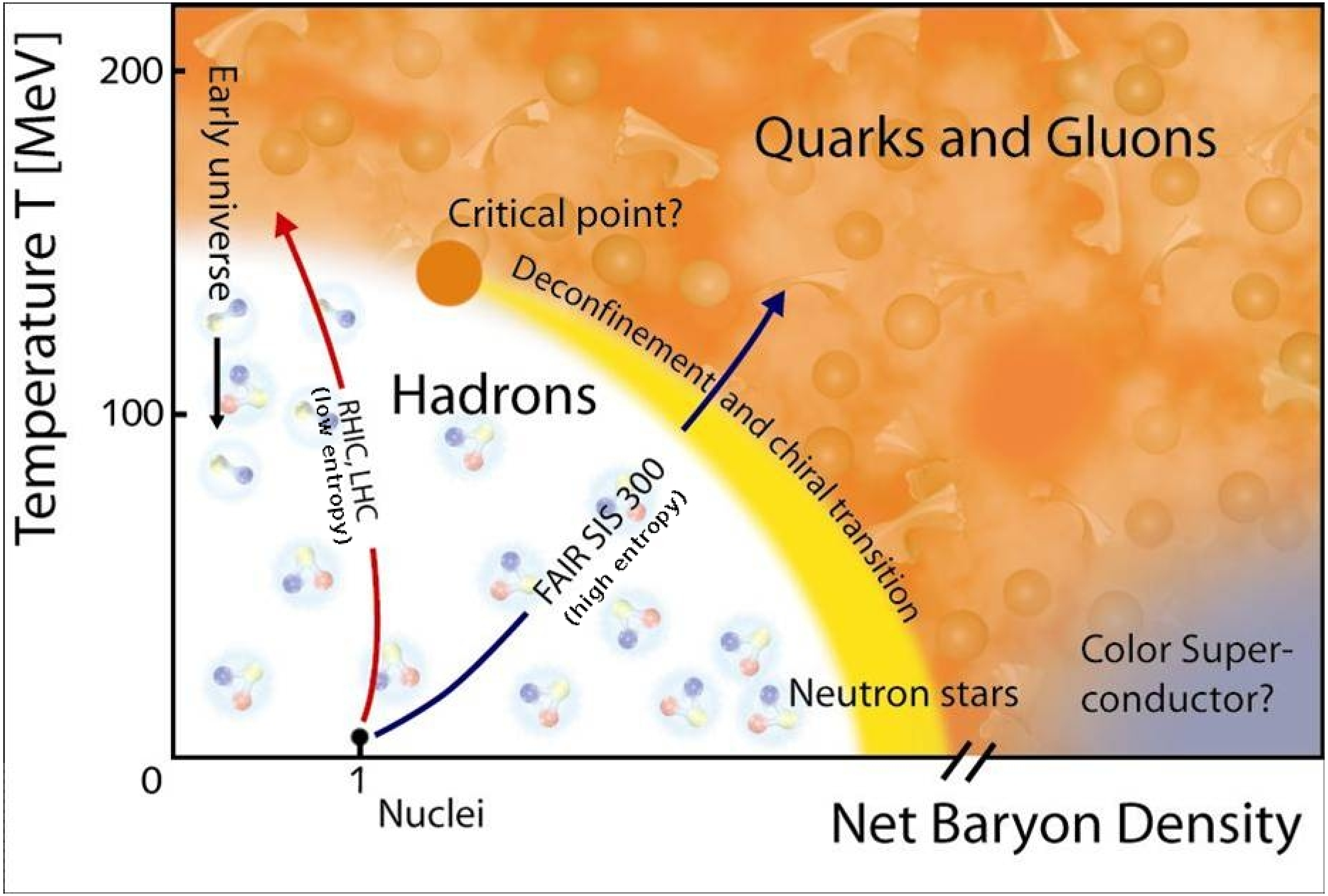
Liebendörfer et al. (2010) in preparation

- Spherical Fe-core collapse
- Spherical core bounce
- Asphericities shortly after bounce
- Convection
- Increased ν-heating efficiency
- Hydrodynamic instabilities

  (e.g. SASI, advective acoustic cycle)

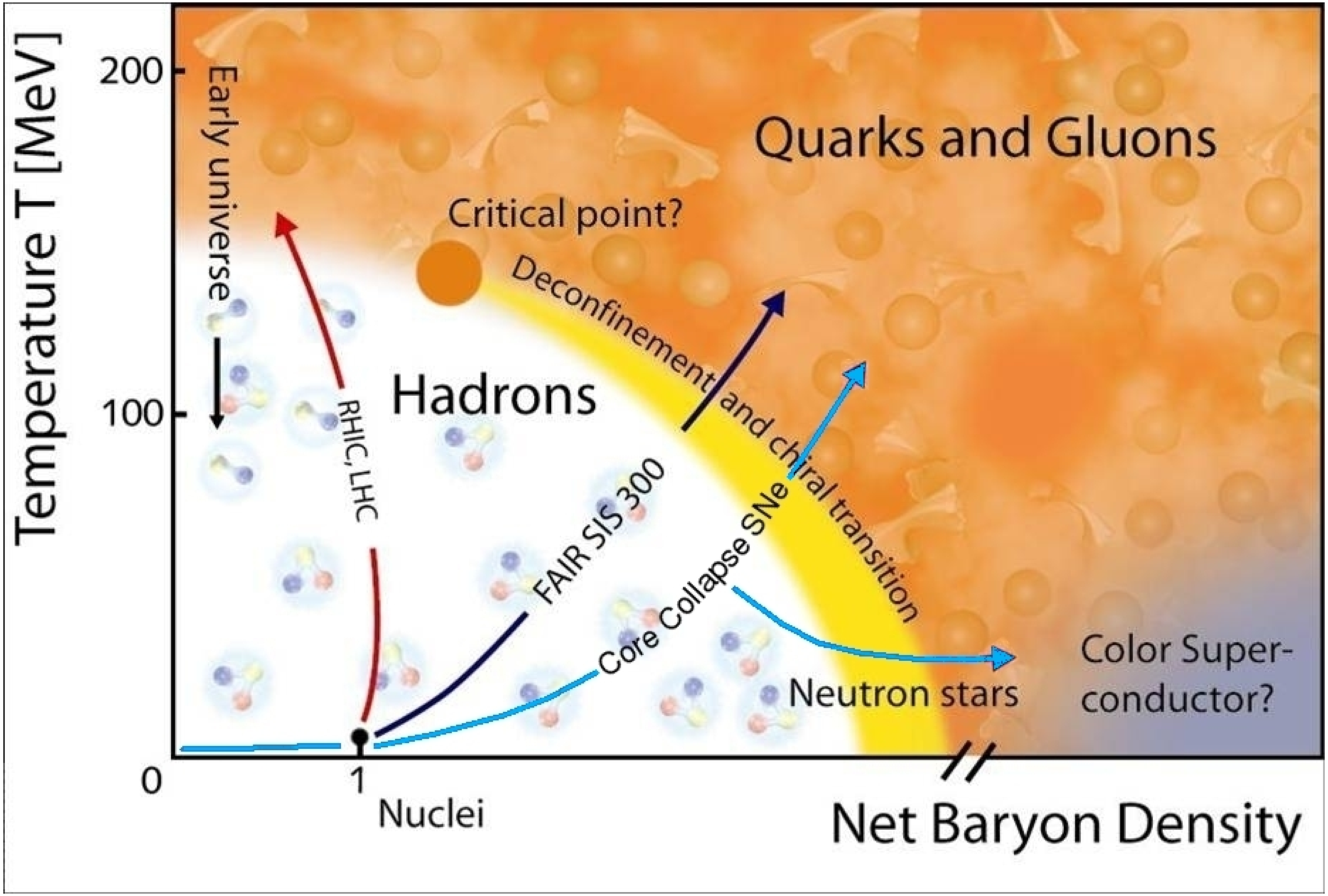
Quark Matter in Proto-Neutron Stars

The QCD Phase Diagram [1]



[1] The GSI homepage, www.gsi.de

The QCD Phase Diagram



Construction of the Quark Hadron Phase Diagram

Figure: The MIT bag model[a], $Y_p \simeq 0.3$

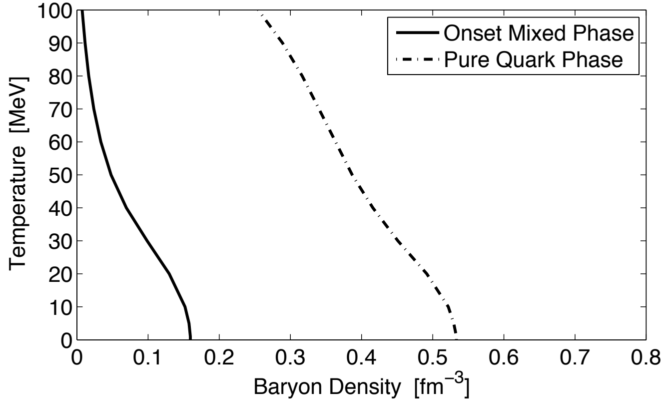
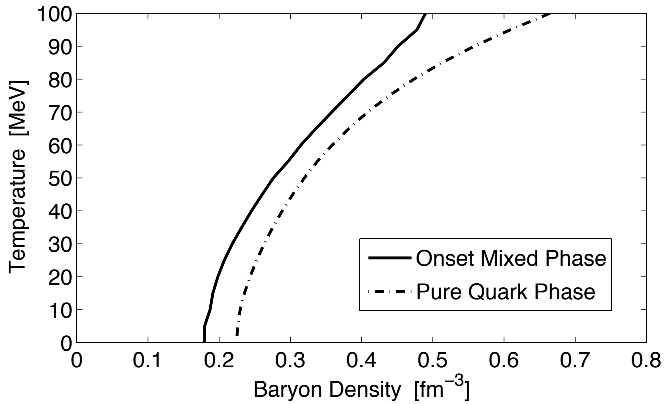


Figure: The PNJL model[b], $Y_p \simeq 0.3$



[a] Sagert et al. (2009)
[b] Sandin and Blaschke (2008)

Quark matter descriptions and the mixed phase

1. The MIT bag model

   (Fermi-gas, the bag pressure B defines confinement)

   $$B^{1/4} = 145, \ \ldots, 200 \text{ MeV}$$

2. The PNJL model

   (Based on the QCD Lagrangian)

   - Similar critical densities:

     $n_c(T \simeq 0) \simeq 0.17 \text{ fm}^{-3}$ (MIT bag)

     $n_c(T \simeq 0) \simeq 0.18 \text{ fm}^{-3}$ (PNJL)

   - Different behavior of the critical density for finite T

     $n_c(T)$ reduces for increasing T (MIT bag)

     $n_c(T)$ increases for increasing T (PNJL)

3. The problem: the transition from quarks confined in hadrons to the quark-gluon plasma at finite T and n_B

$\longrightarrow$ Construction of the coexistence region/mixed phase

(Maxwell construction, Gibbs conditions)

$\longrightarrow$ Thermodynamics

(required for use in astrophysical applications)

Evolution of the Central Mass Elements in the QCD Phasediagram (PNJL)

Figure: 20 $M_\odot$, non-exploding model

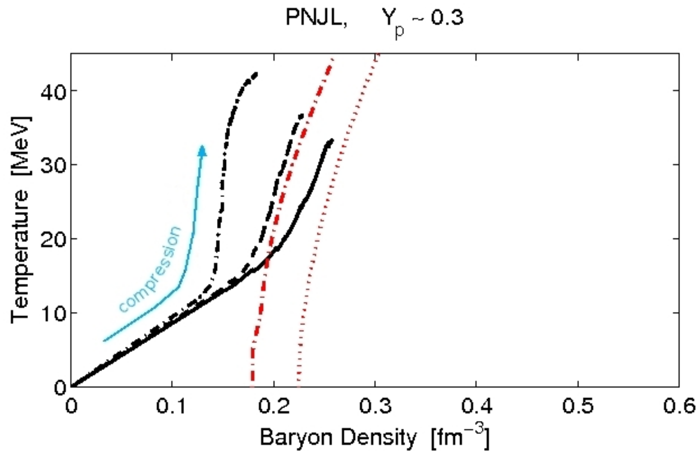
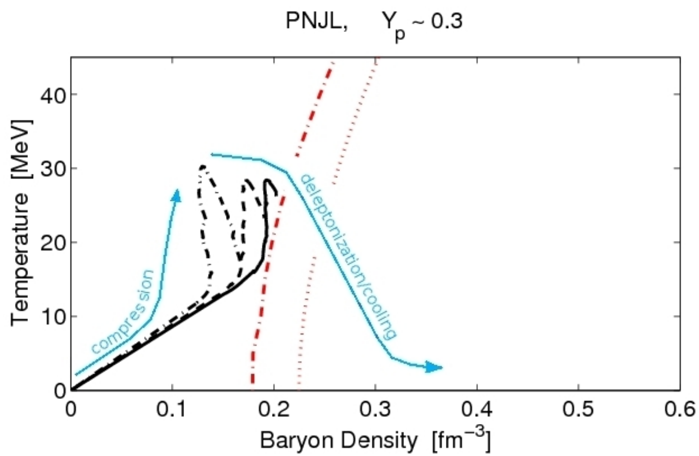
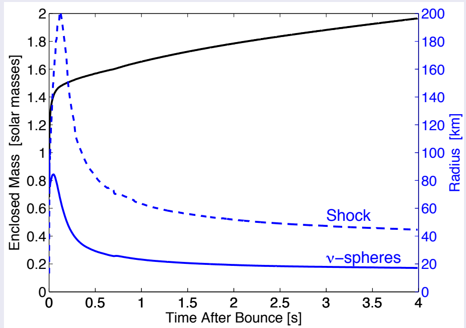


Figure: 20 $M_\odot$, ν-driven explosion

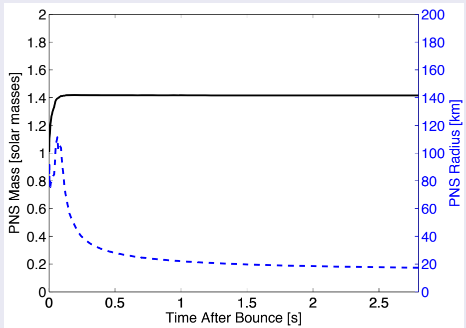


The appearance of quark matter in PNSs

1. Non-exploding models
   - Central n_B and T increase on timescale $\sim$ 1 second
   - Continued rise of the enclosed mass



2. Explosion models



Evolution of the Central Mass Elements in the QCD Phasediagram (MIT bag)

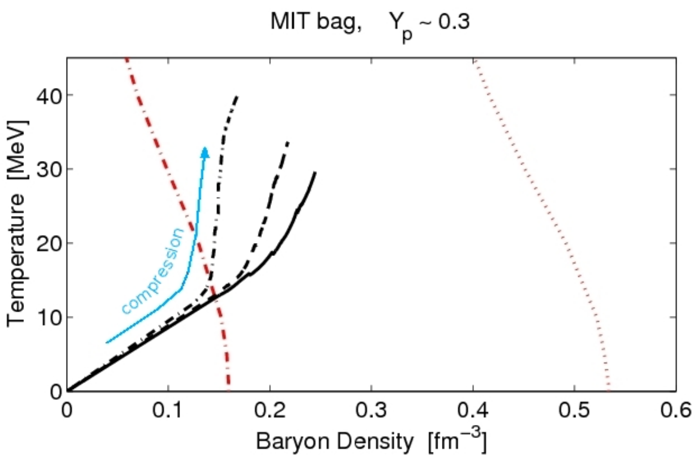


Figure: 20 $M_\odot$, non-exploding model

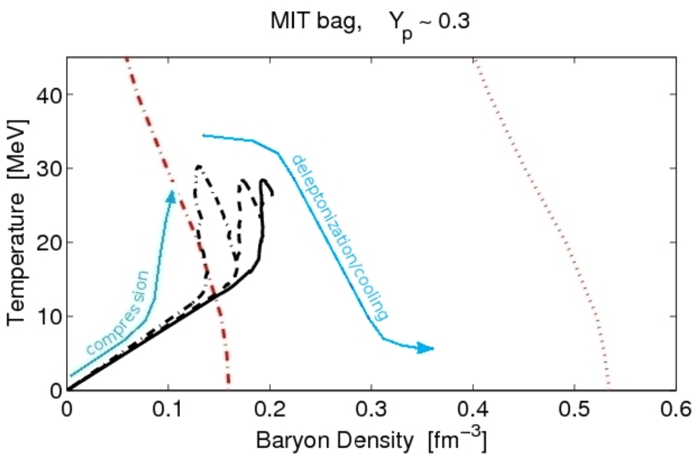


Figure: 20 $M_\odot$, ν-driven explosion

Phase Diagram for 3-flavor Quark Matter Based on MIT Bag

Figure: (MIT bag) $Y_p \simeq 0.1$, $Y_p \simeq 0.3$, $Y_p \simeq 0.5$

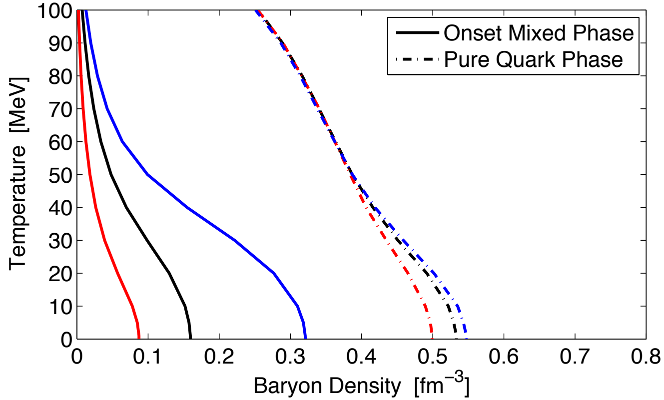
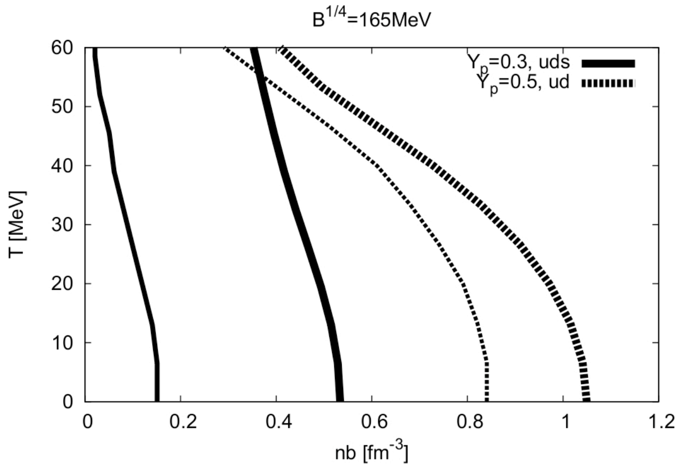


Figure: The MIT bag model

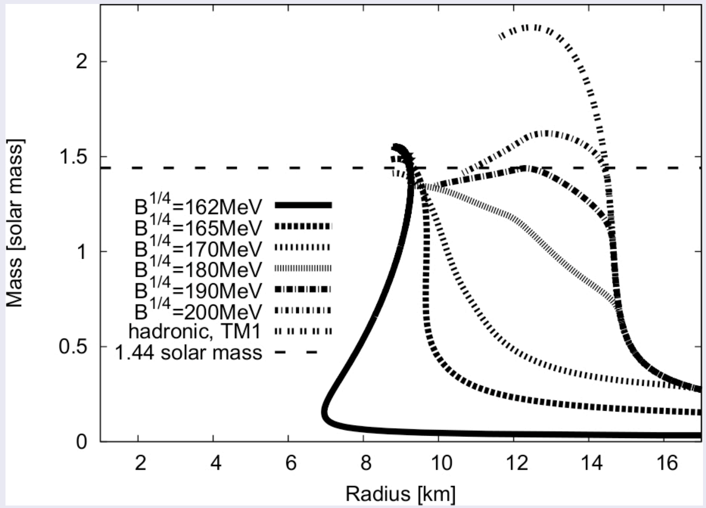


Requirements of the model and dependencies

1. Isospin asymmetry

$$n_c = n_c(T, Y_p)$$

2. Maximum Mass (Mass-Radius relation)



3. Consistent with data from heavy-ion collisions

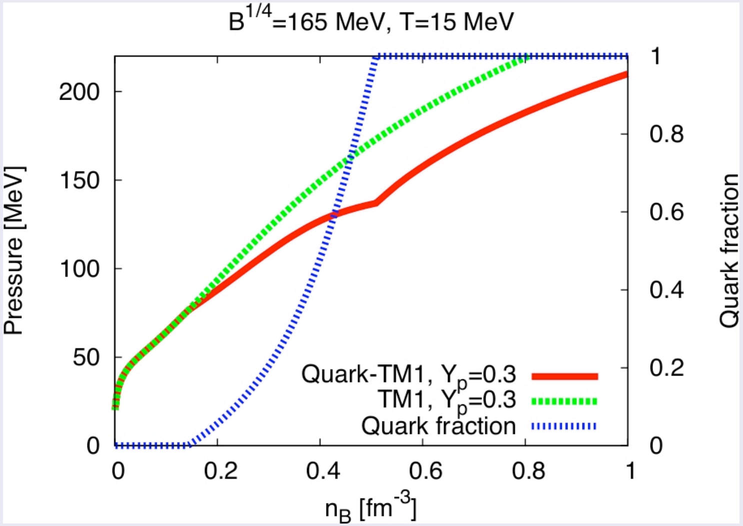
4. Timescales to establish equilibrium
(production of strangeness)

$$u + d \leftrightarrow u + s$$

$m_u \simeq m_d \simeq 0$, $m_s \simeq 100$ MeV

Proto-Neutron Star Collapse due to the Quark Hadron Phasetransition

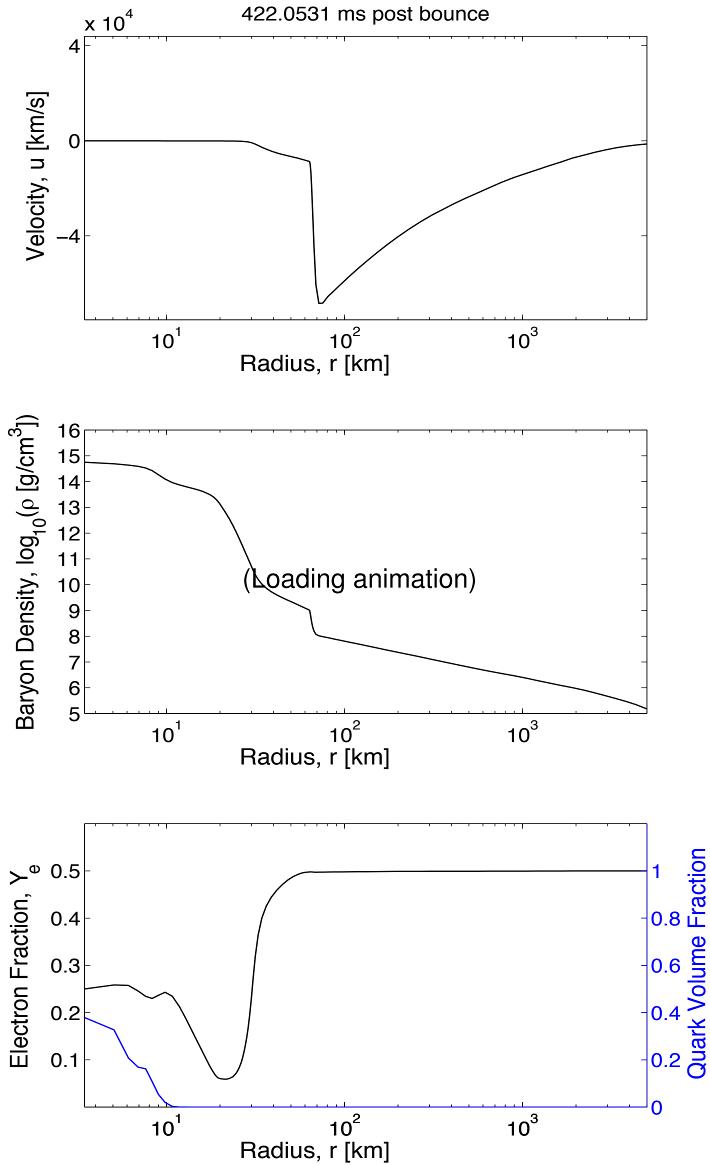
Construction of the quark matter EoS



- 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 ⟶ Explosions !
     (even in spherical symmetry)

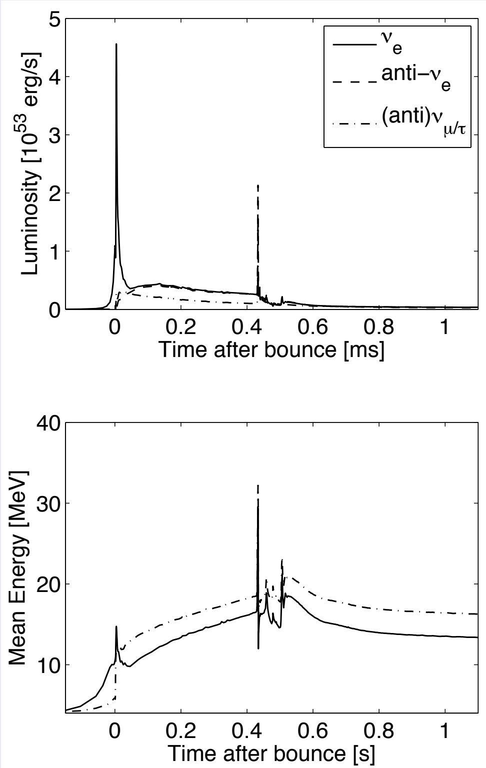


Additional Neutrino Burst from the Quark Hadron Phasetransition

The neutrino observables

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

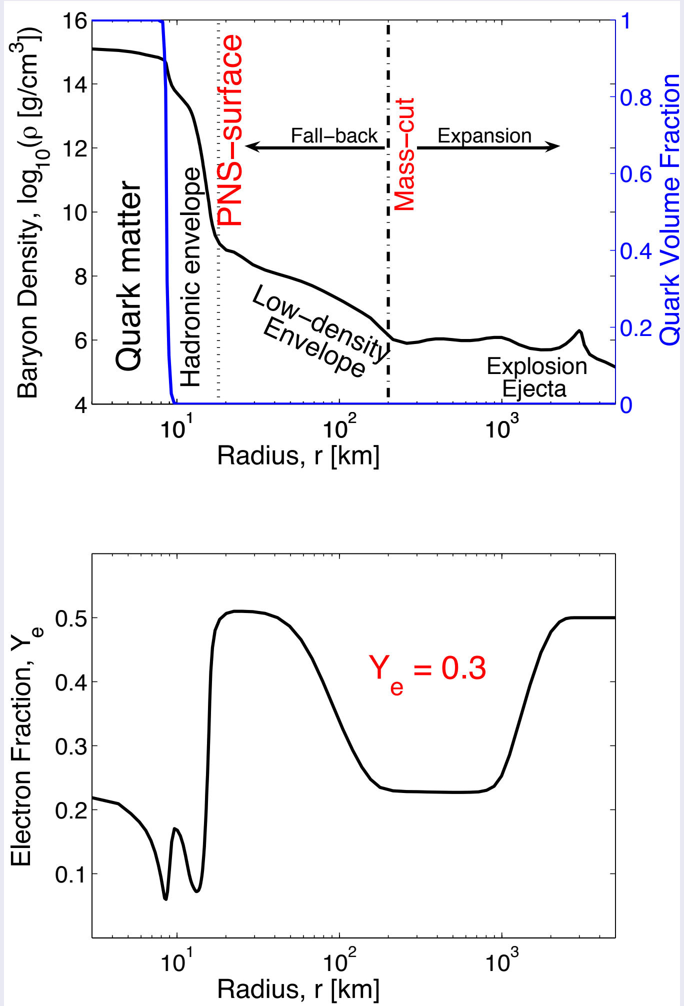
→ Neutrino burst dominated by $\bar{\nu}_e$



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

[a] Dasgupta et al. (2010)

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



Summary

Summary

1. The standard scenario of core collapse supernovae assumes pure hadronic matter only
2. The phase space occupied in core collapse supernovae:

$$\begin{aligned} T &\simeq 10, \ldots, 100 \text{ MeV} \\ n_B &\simeq 0.1, \ldots, 0.5 \text{ fm}^{-3} \\ Y_p &\simeq 0.05, \ldots, 0.3 \end{aligned}$$

$\longrightarrow$ Conditions may favor quark matter over hadronic matter

3. Quark-hadron (hybrid) EoS, $n_c(T, Y_p)$: (Non)Explosion models
4. Construction of a co-existence region (mixed phase): reduced adiabatic index
5. hydrodynamical contraction (collapse) and formation of a strong hydrodynamic shock front

$\longrightarrow$ Explosions (even in spherical symmetry)

6. The remnant: neutron star with quark matter at the interior (hybrid star)
7. Observations?
   - Release of an additional outburst of neutrinos! (dominated by $\bar{\nu}_e$ and $\nu_{\nu/\tau}$)
   - Gravitational waves ?
   - Nucleosynthesis (r-rpocess) ?