

Different aspects of core collapse supernovae

Outline

- Motivation
- Introduction
- Input Physics
- The Possible fate
- Discussion

Collaborators

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Stuart Whitehouse

Christian Winteler

Motivation

- Star formation
- Stellar evolution
- Stellar death

“We are all made out of stellar dust!”
(chemical evolution of the elements)

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

explosion

bh.-formation

Discussion

Motivation

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

explosion

bh.-formation

Discussion

Thermonuclear SN (SN Ia)



SN Ia SN2001el in NGC 1448



Core collapse SN (SN Ib, Ic, II)



SN 1987A in the large Magelanic Cloud

$M > 8 M_{\odot}$

Motivation

Thermonuclear SN

Core collapse SN

1. neutrino signal
2. gravitational wave
3. $E_{expl} \sim 1 \times 10^{51} \text{ ergs}$
4. nuclear abundance of the ejecta

SN 1987a

Hirata et al. (1987, 1988)

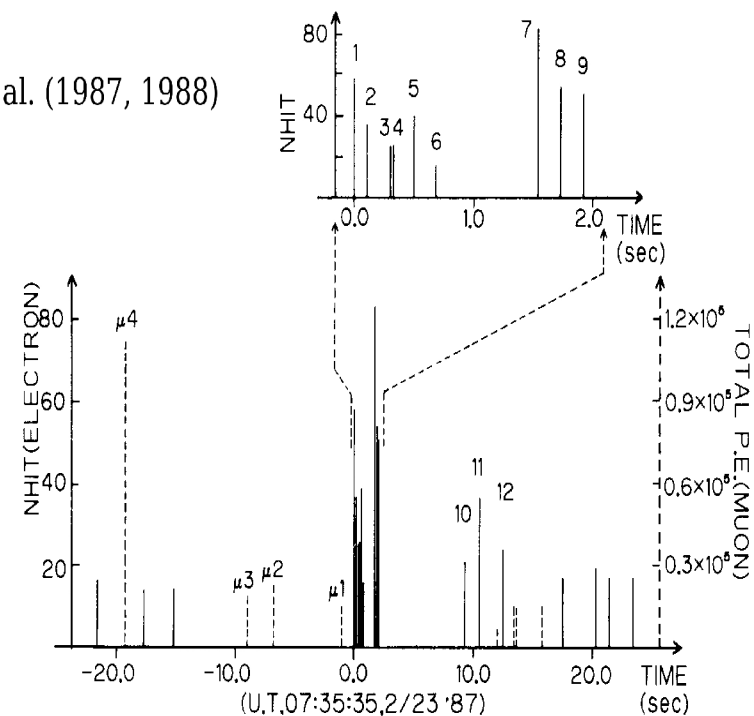


FIG. 2. The time sequence of events in a 45-sec interval centered on 07:35:35 UT, 23 February 1987. The vertical height of each line represents the relative energy of the event. Solid lines represent low-energy electron events in units of the number of hit PMT's, N_{hit} (left-hand scale). Dashed lines represent muon events in units of the number of photoelectrons (right-hand scale). Events $\mu 1$ - $\mu 4$ are muon events which precede the electron burst at time zero. The upper right figure is the 0-2-sec time interval on an expanded scale.

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

explosion

bh.-formation

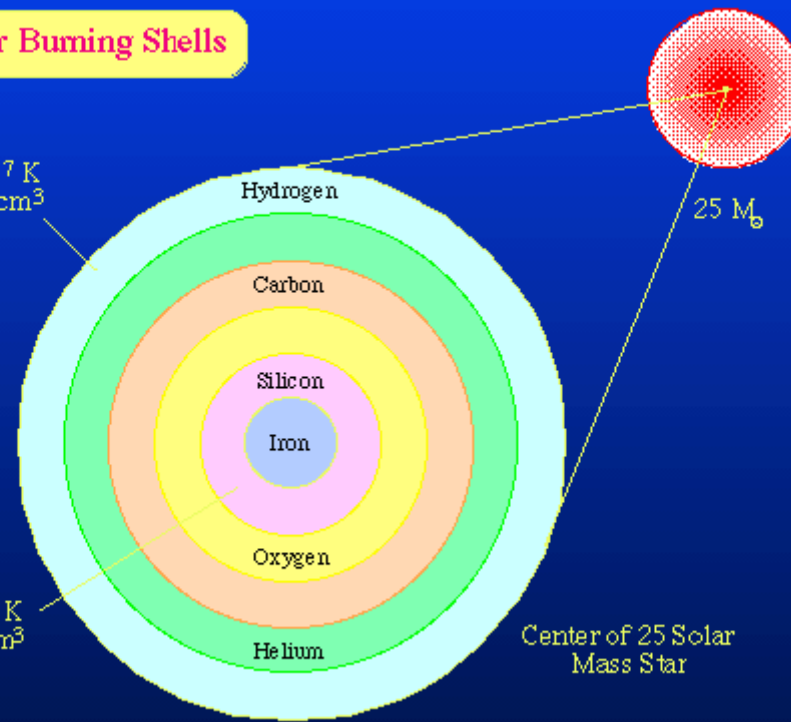
Discussion

Introduction: stellar models

Stellar Burning Shells

$$T = 2 \times 10^7 \text{ K}$$

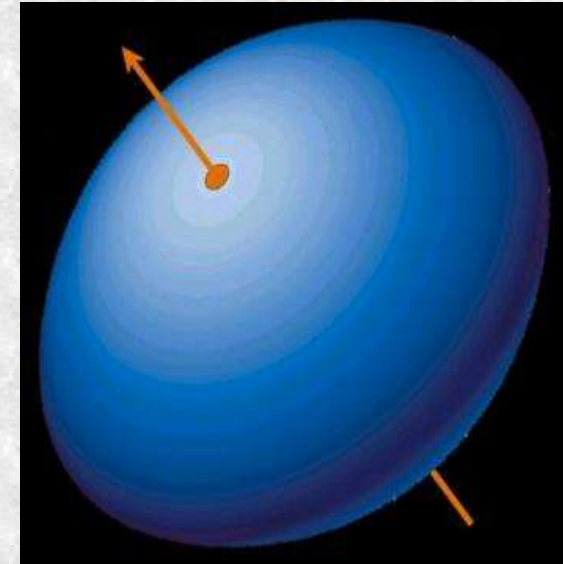
$$\rho = 10^2 \text{ g/cm}^3$$



$$T = 4 \times 10^9 \text{ K}$$

$$\rho = 10^7 \text{ g/cm}^3$$

Center of 25 Solar
Mass Star



Nuclear Fuel	Process	$T_{\text{threshold}}$ 10^6 K	Products	Energy per nucleon (Mev)
H	PP	~4	He	6.55
H	CNO	15	He	6.25
He	3α	100	C, O	0.61
C	C+C	600	O, Ne, Mg, Si	0.54
O	O+O	1000	Mg, S, P, Si	~0.3
Si	Nuc eq.	3000	Co, Fe, Ni	<0.18

- Nuclear burning
- Mass loss
 - winds
 - rotation
- Enclosed central mass ('Fe'-core)
 - Progenitor models?

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

explosion

bh.-formation

Discussion

Introduction: Progenitor models

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

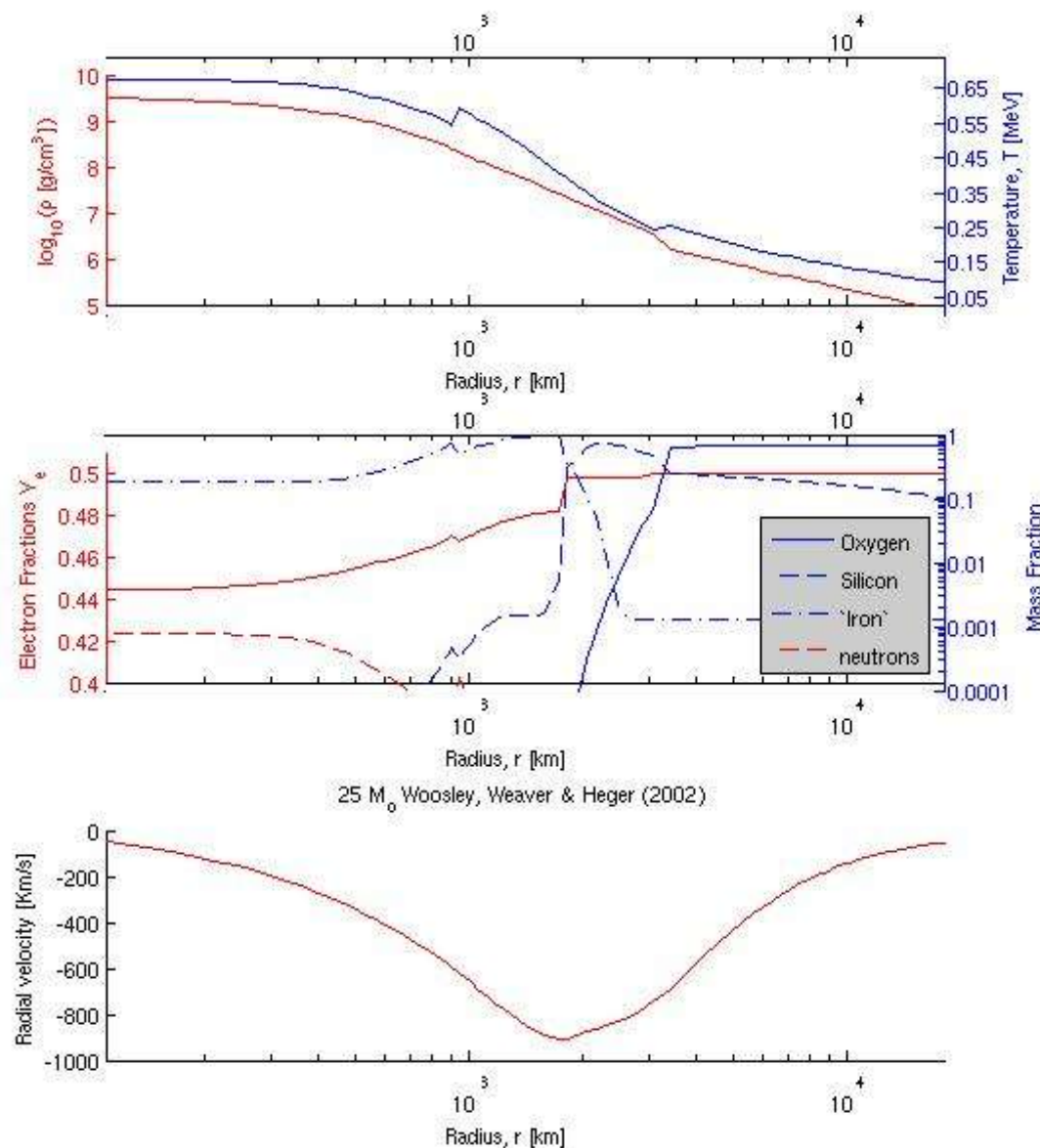
explosion

bh.-formation

Discussion

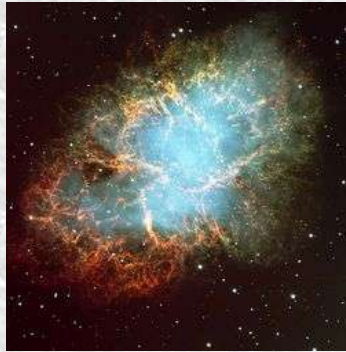
Initial models for
core collapse!

1. Photodisintegration
2. Density increase
3. Weak interactions

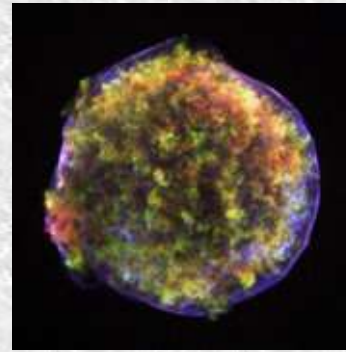


Introduction:

core collapse phenomenology

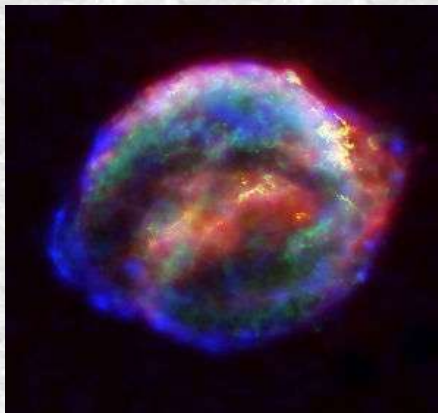


SN1054, Crab-pulsar/nebula



SN1572, Tycho'SN

(NASA/CXC/Rutgers/J.Warren &
J.Hughes et al.)



SN1604, Kepler's SN (Chandra
X-ray Observatory)

$$\left(g_{\mu\nu}, T^{\mu\nu} \right) \rightarrow \begin{aligned} G^{\mu\nu} &= 8\pi T^{\mu\nu} && \text{(Einstein equation)} \\ \nabla_\nu T^{\mu\nu} &= \partial_\nu T^{\mu\nu} + \Gamma_{\mu\delta}^\nu T^{\delta\mu} + \Gamma_{\mu\delta}^\mu T^{\nu\delta} = 0 && \text{(conservation equations)} \end{aligned}$$

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

explosion

bh.-formation

Discussion

Introduction:

core collapse phenomenology

$$\left(g_{\mu\nu}, T^{\mu\nu} \right) \rightarrow \nabla_{\nu} T^{\mu\nu} = \partial_{\nu} T^{\mu\nu} + \Gamma_{\mu\delta}^{\nu} T^{\delta\mu} + \Gamma_{\mu\delta}^{\mu} T^{\nu\delta} = 0$$



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

$$\left(\Gamma = \sqrt{1 + u^2 - \frac{2m}{r}} \right)$$

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

$$T^{aa} = p + \rho K$$

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

$$T^{\theta\theta} = T^{\phi\phi} = p + \frac{1}{2} \rho (J - K)$$

Liebendörfer et al.(2004)

$$T_{;\nu}^{t\nu} = \frac{\partial}{\alpha \partial t} (e + J) + (p + \rho K) \frac{\partial}{\alpha \partial t} \left(\frac{1}{\rho} \right) + \frac{1}{\alpha} \frac{\partial}{\partial a} (4\pi r^2 \alpha \rho H) + \frac{\alpha u}{r} (J - 3K)$$

$$T_{;\nu}^{a\nu} = \frac{\partial}{\partial t} \left(\frac{1}{(4\pi r^2 \rho)} H \right) + (1 + e + J) \frac{\partial \alpha}{\partial a} + \frac{1}{\rho} \frac{\partial}{\partial a} (\alpha (p + \rho K)) + \frac{\alpha}{3VD} (J - 3K)$$

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

explosion

bh.-formation

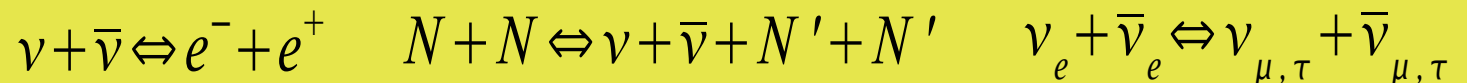
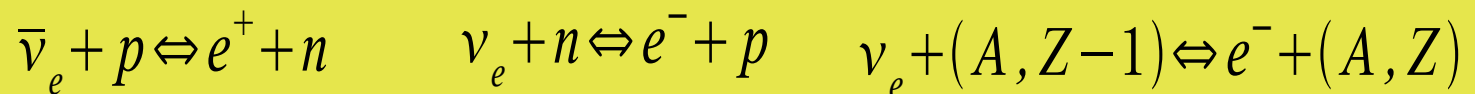
Discussion

Introduction:

core collapse phenomenology

$$\left(g_{\mu\nu}, T^{\mu\nu} \right) \rightarrow \nabla_{\nu} T^{\mu\nu} = \partial_{\nu} T^{\mu\nu} + \Gamma_{\mu\delta}^{\nu} T^{\delta\mu} + \Gamma_{\mu\delta}^{\mu} T^{\nu\delta} = 0$$

$$\left(n, p, \alpha, C^{12}, \dots, O^{16}, \dots, Si^{28}, \dots, Fe^{56}, \dots, Zn^{60}, e \right)$$



Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

explosion

bh.-formation

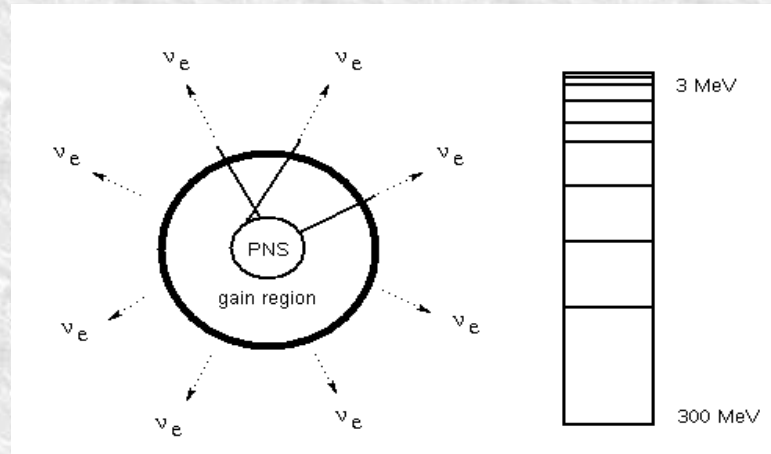
Discussion

Introduction:

core collapse phenomenology

$$\left(g_{\mu\nu}, T^{\mu\nu}\right) \rightarrow \nabla_{\nu} T^{\mu\nu} = \partial_{\nu} T^{\mu\nu} + \Gamma_{\mu\delta}^{\nu} T^{\delta\mu} + \Gamma_{\mu\delta}^{\mu} T^{\nu\delta} = 0$$

$$f(t, \vec{x}, \vec{u}) \rightarrow u^{\mu} \left(\frac{\partial f}{\partial x^{\mu}} + \frac{\partial f}{\partial u^{\delta}} \Gamma_{\mu\nu}^{\delta} u^{\nu} \right) = \Omega(f) \quad (\text{Transport equation})$$



$$f(t, r, E, \mu \equiv \cos\theta)$$

$$J = \int_0^{\infty} \int_{-1}^{+1} d\mu E^2 dE f(t, r, E, \mu)$$

$$H = \int_0^{\infty} \int_{-1}^{+1} \mu d\mu E^2 dE f(t, r, E, \mu)$$

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

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

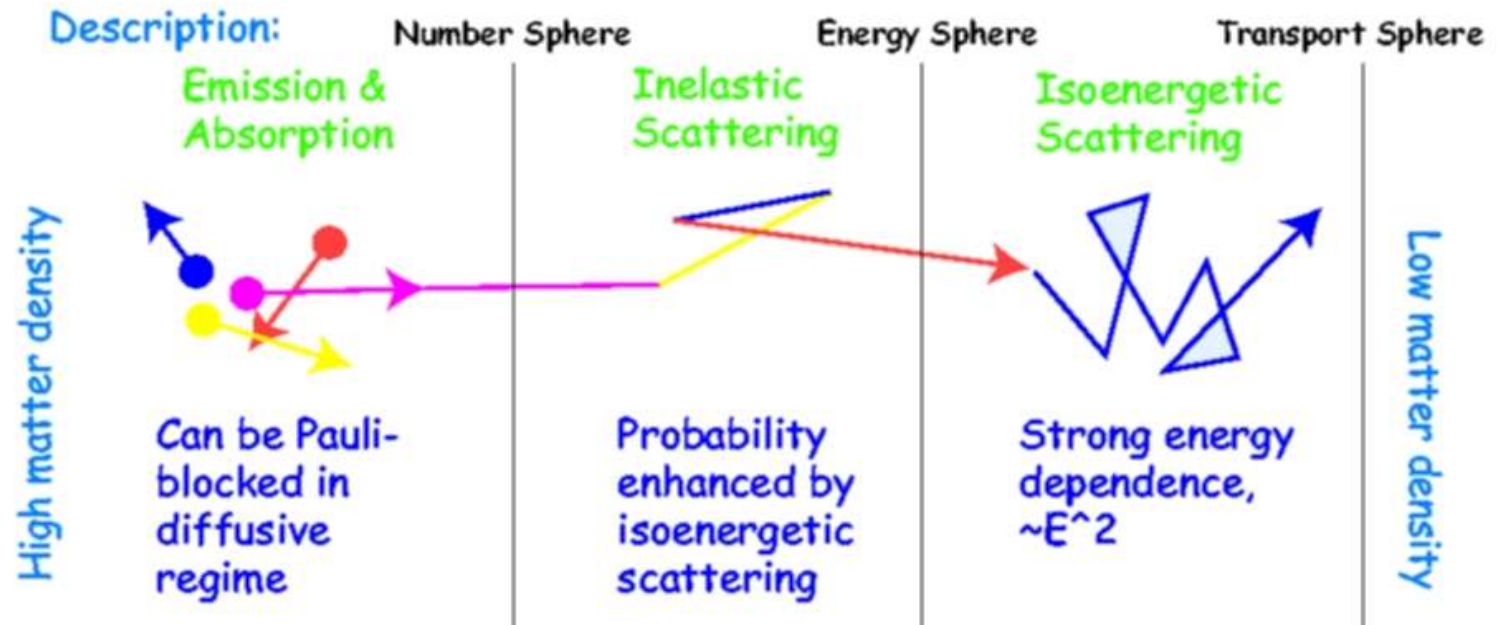
explosion

bh.-formation

Discussion

Input physics: neutrinos

Bruenn (1985), Horowitz et al. (2003)



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

$$\nu + e^\pm \Leftrightarrow \nu + e^\pm$$

$$\nu + (A, Z) \Leftrightarrow \nu + (A, Z)$$

$$\nu_e + (A, Z-1) \Leftrightarrow e^- + (A, Z) \quad \nu + \bar{\nu} \Leftrightarrow e^- + e^+$$

$$\nu + N \Leftrightarrow \nu + N$$

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

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

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

$$N + N \Leftrightarrow \nu + \bar{\nu} + N' + N' \quad \text{Thompson et al. (2002)}$$

$$\nu_e + \bar{\nu}_e \Leftrightarrow \nu_{\mu, \tau} + \bar{\nu}_{\mu, \tau} \quad \text{Buras et al. (2003)}$$

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

explosion

bh.-formation

Discussion

Input physics: neutrinos

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

explosion

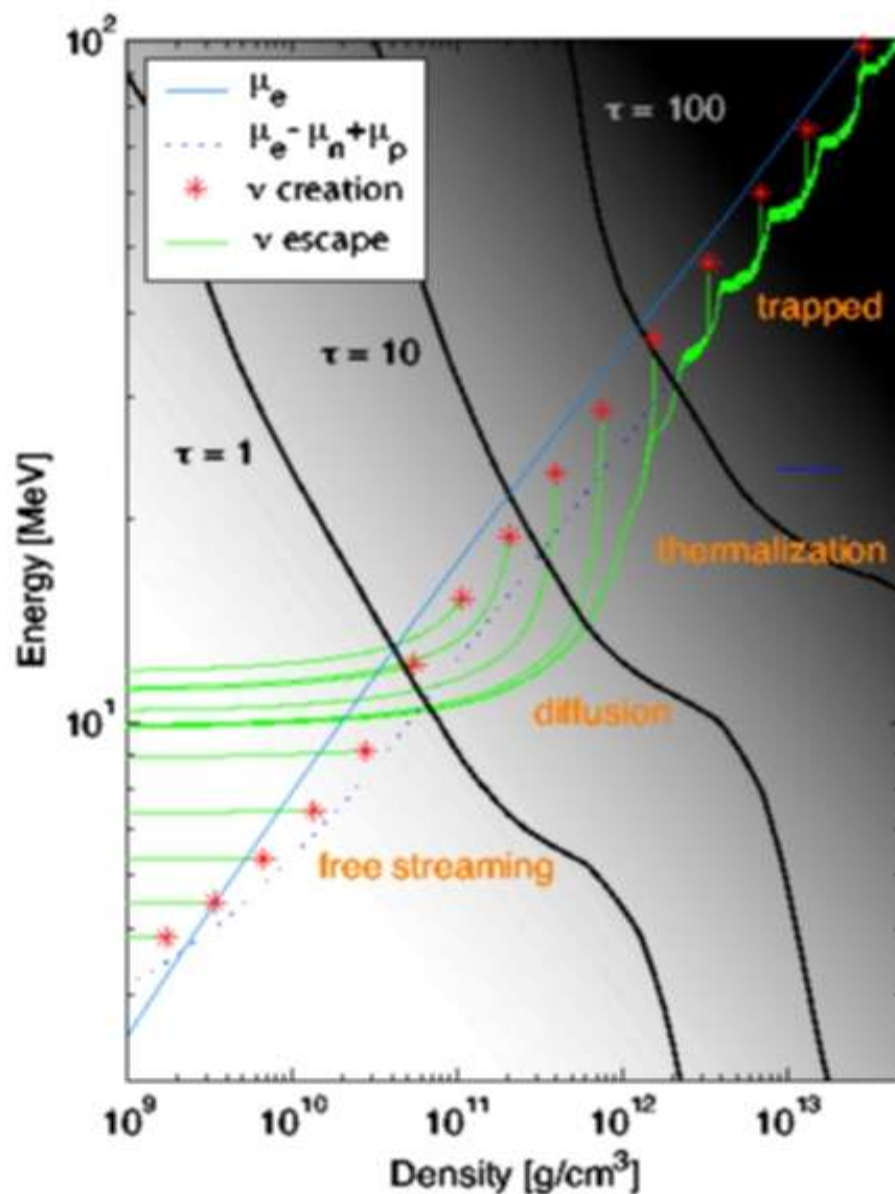
bh.-formation

Discussion

grs15e

Input physics: neutrinos

Matrinez-Pinedao, Liebendörfer & Frekers (2002)



λ (mean-free-path)

$$\tau = \int dr \frac{1}{\lambda}$$

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

explosion

bh.-formation

Discussion

Input physics: neutrinos

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

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

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

$$\nu + e^\pm \Leftrightarrow \nu + e^\pm$$

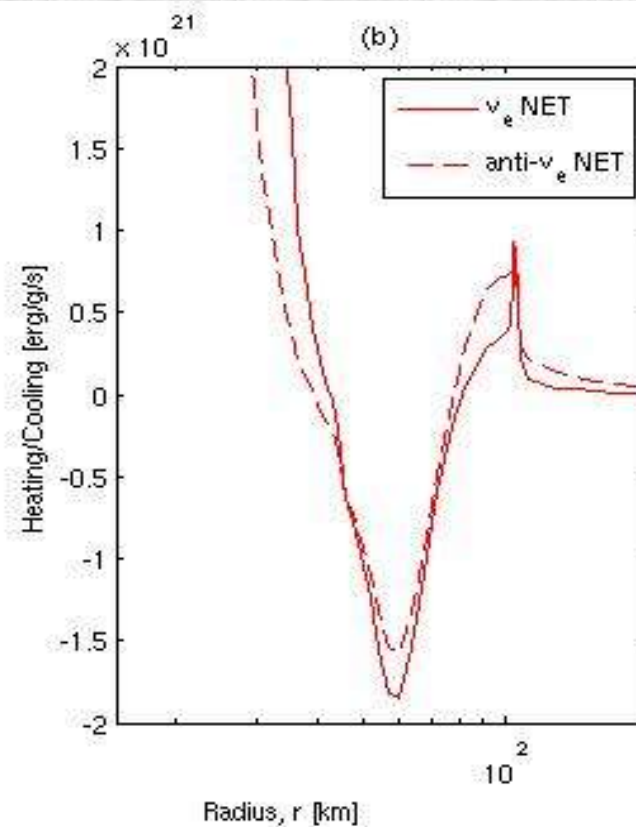
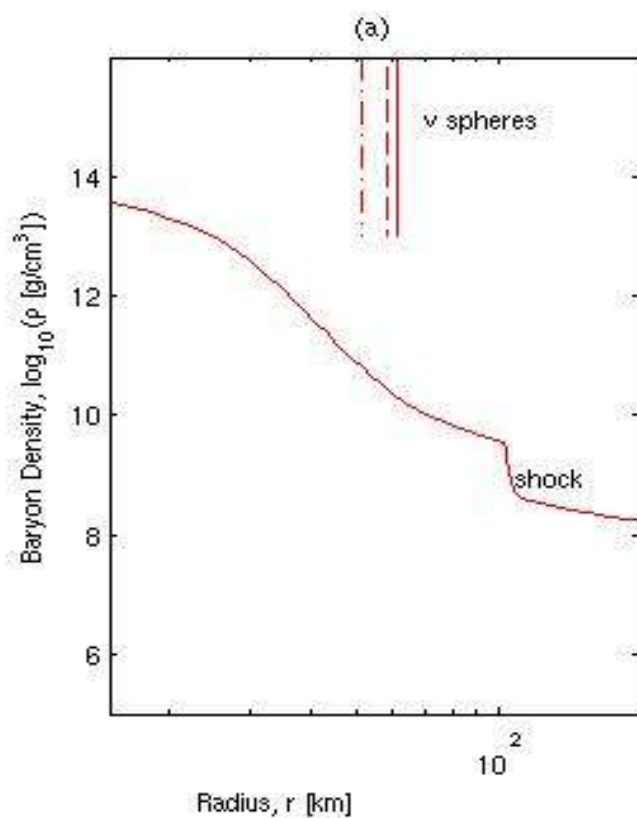
$$\nu + N \Leftrightarrow \nu + N$$

$$\nu + (A, Z) \Leftrightarrow \nu + (A, Z)$$

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

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

$$\nu_e + \bar{\nu}_e \Leftrightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$$



Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

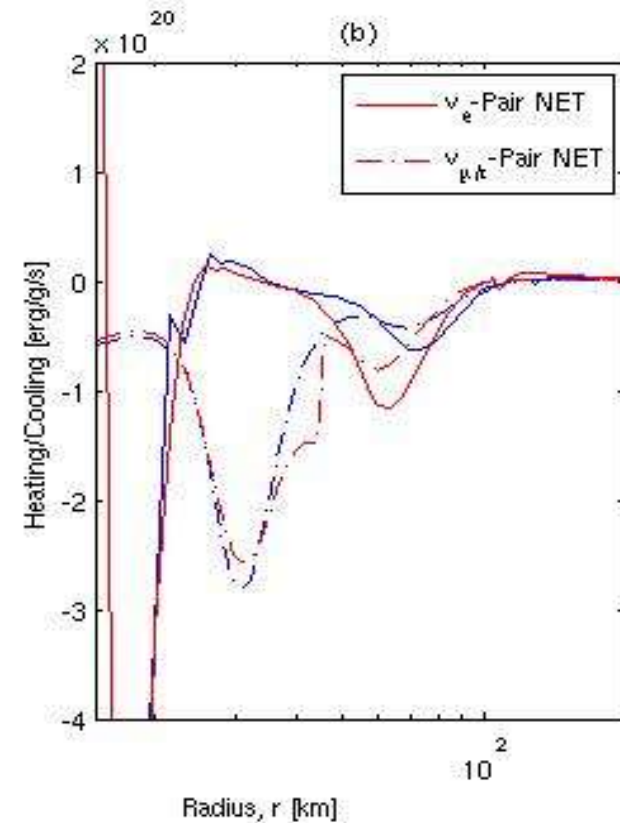
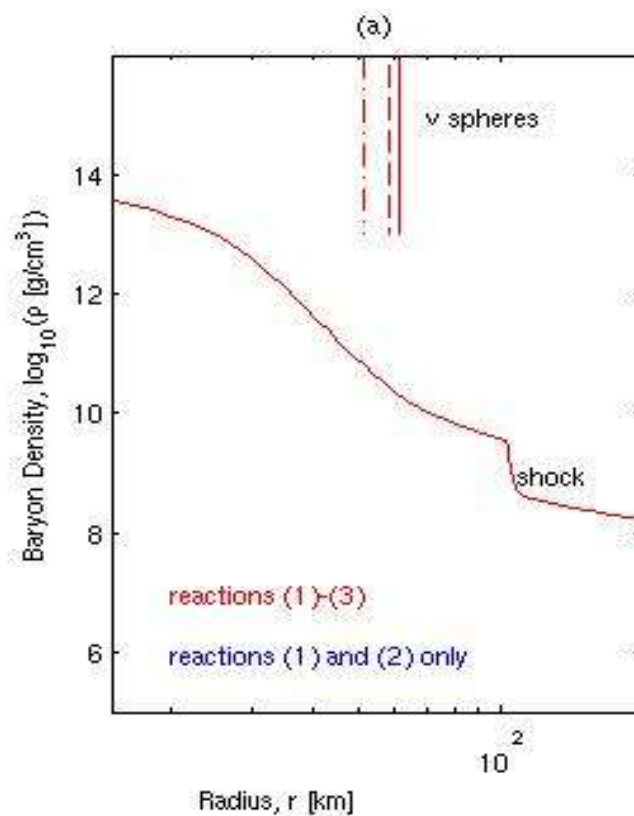
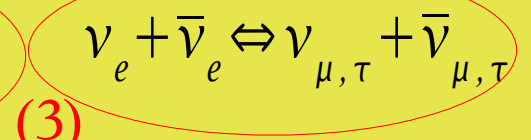
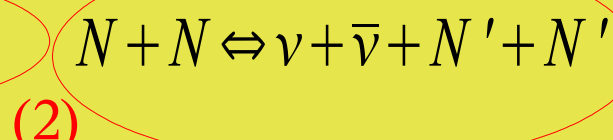
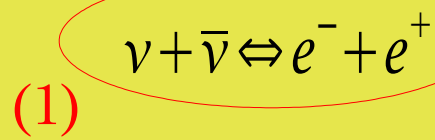
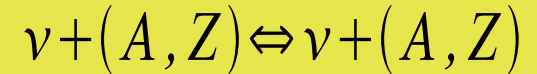
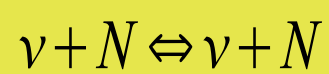
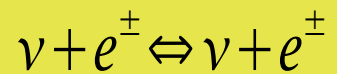
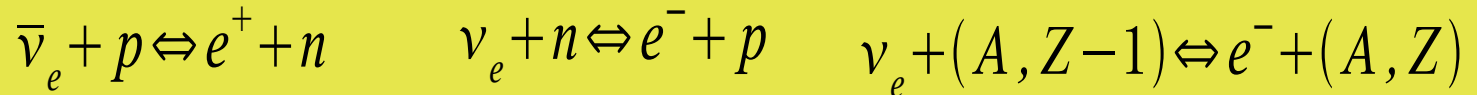
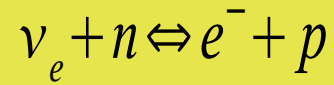
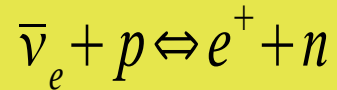
Possible fate

explosion

bh.-formation

Discussion

Input physics: neutrinos



Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

explosion

bh.-formation

Discussion

Input physics: neutrinos

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

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

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

$$\nu + e^\pm \Leftrightarrow \nu + e^\pm$$

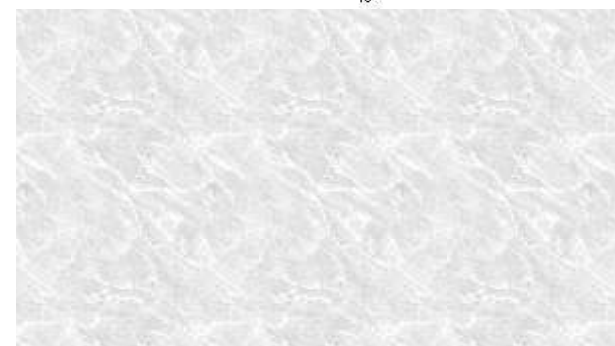
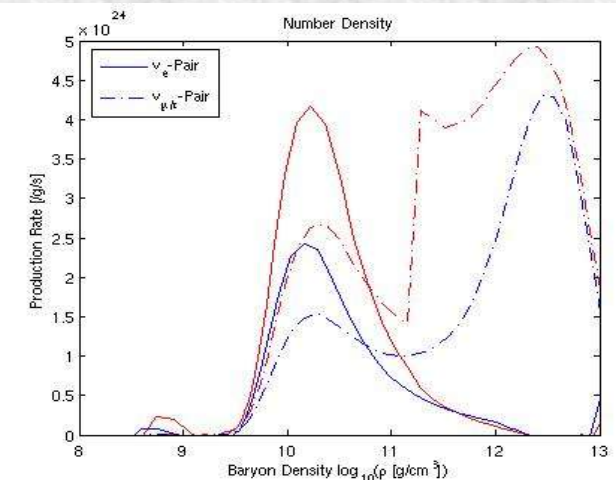
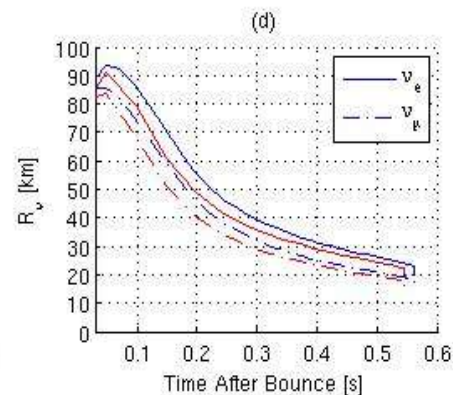
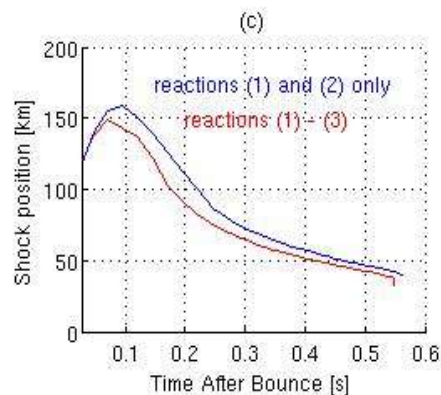
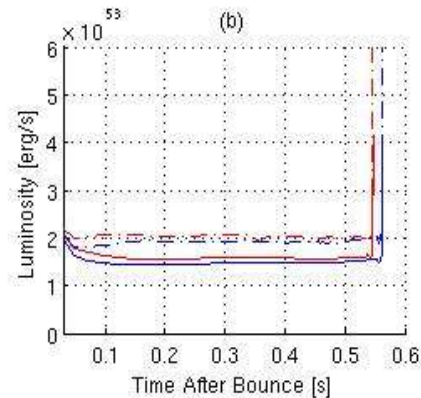
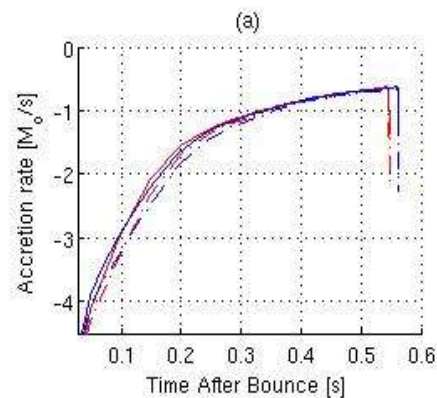
$$\nu + N \Leftrightarrow \nu + N$$

$$\nu + (A, Z) \Leftrightarrow \nu + (A, Z)$$

$$(1) \quad \nu + \bar{\nu} \Leftrightarrow e^- + e^+$$

$$(2) \quad N + N \Leftrightarrow \nu + \bar{\nu} + N' + N'$$

$$(3) \quad \nu_e + \bar{\nu}_e \Leftrightarrow \nu_{\mu, \tau} + \bar{\nu}_{\mu, \tau}$$



Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

explosion

bh.-formation

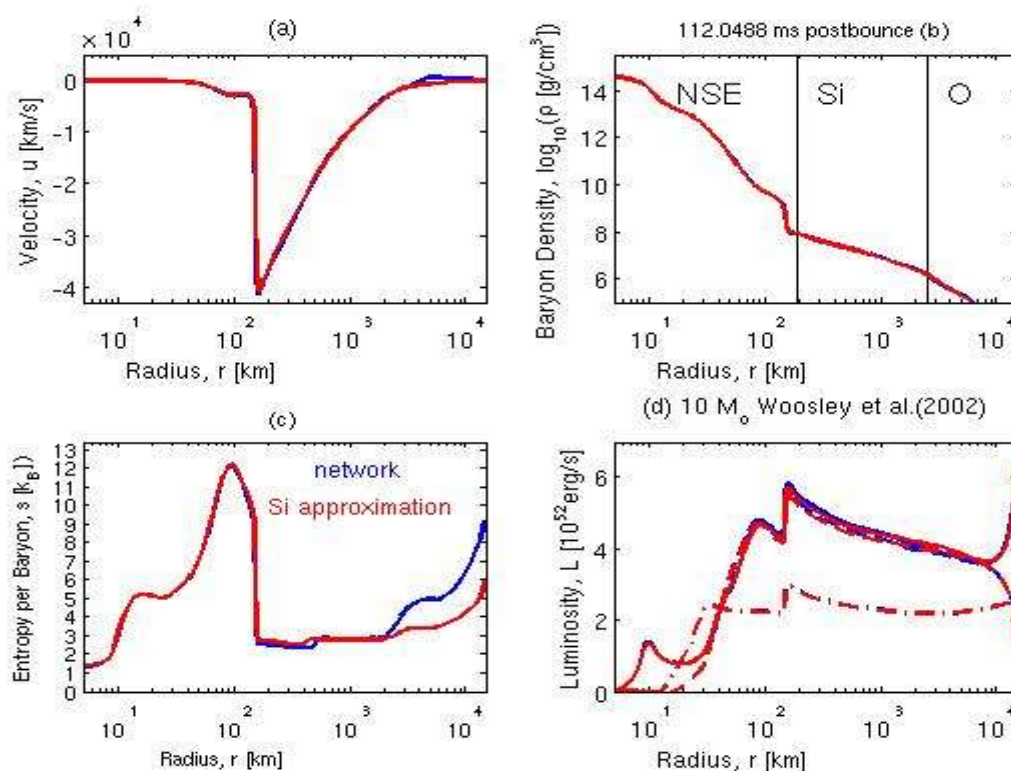
Discussion

Input physics: nuclear reactions

F-K. Thielemann, lecture notes

$$n_i = \rho N_A Y_i$$

$$\dot{Y}_i = \sum_j N_j^i \lambda_j Y_j + \sum_{i,j} \frac{N_{j,k}^i}{1 + \delta_{ik}} \rho N_A \langle \sigma v \rangle_{j,k} Y_j Y_k$$



NSE approximation

$$T > 0.45 \text{ MeV}$$

$$Y(A, Z) \sim (\rho N_A)^{A-1} \frac{A^{3/2}}{2^A} \left(\frac{2\pi \hbar^2}{m_u kT} \right)^{\frac{3}{2}(A-1)} e^{\frac{\mu}{kT}} Y_n Y_p \quad \begin{matrix} A_i Y_i = \sum_i X_i = 1 \\ Z_i Y_i = Y_e \end{matrix}$$

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

explosion

bh.-formation

Discussion

Input physics: the EoS

$$G^{\mu\nu} = 8\pi T^{\mu\nu}$$

$$\nabla_\nu T^{\mu\nu} = 0 \quad u^\mu \left(\frac{\partial f}{\partial x^\mu} + \frac{\partial f}{\partial u^\delta} \Gamma_{\mu\nu}^\delta u^\nu \right) = \Omega(f)$$

1. Hot and dense nuclear matter

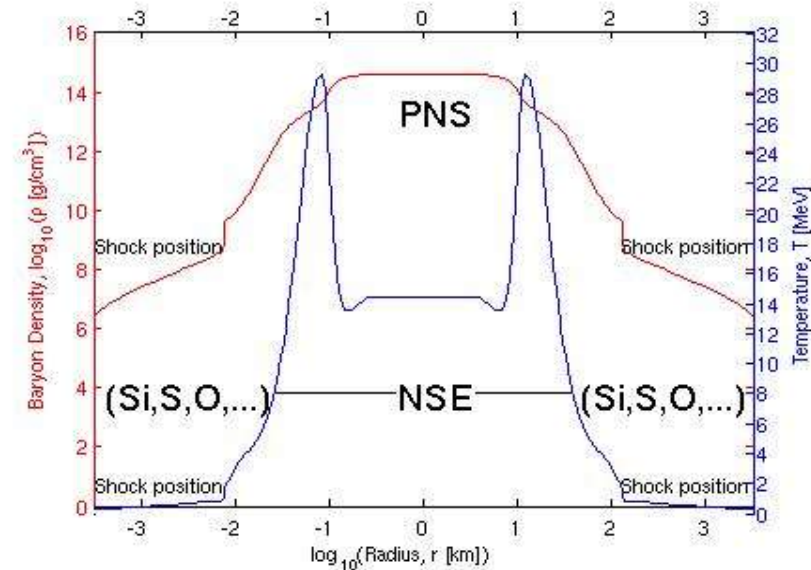
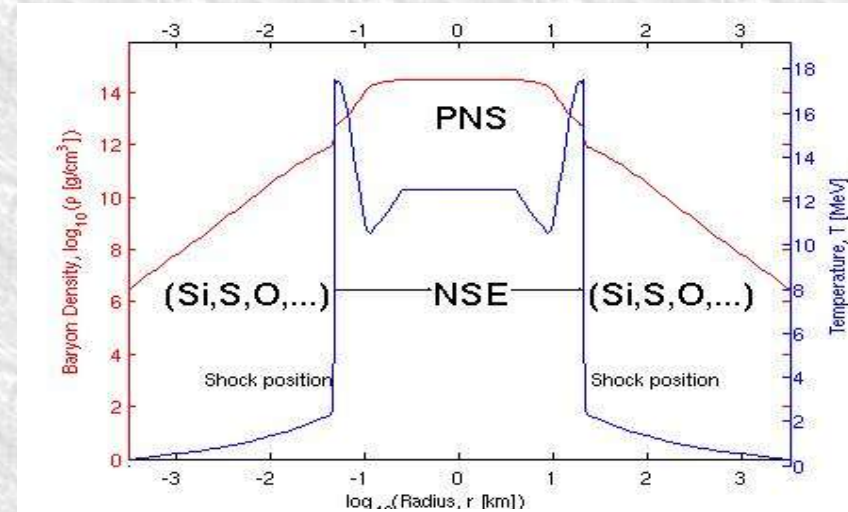
$$T \in [0.01, 200] \text{ MeV}$$

$$\rho \in [10^4, 10^{16}] \text{ g/cm}^3$$

$$y_e \in [0.01, 0.65]$$

$$\left\{ e, p, s, \mu_n, \mu_p, \mu_e, x_n, x_p, x_\alpha, x_A \right\}$$

(2 (3) different regimes)



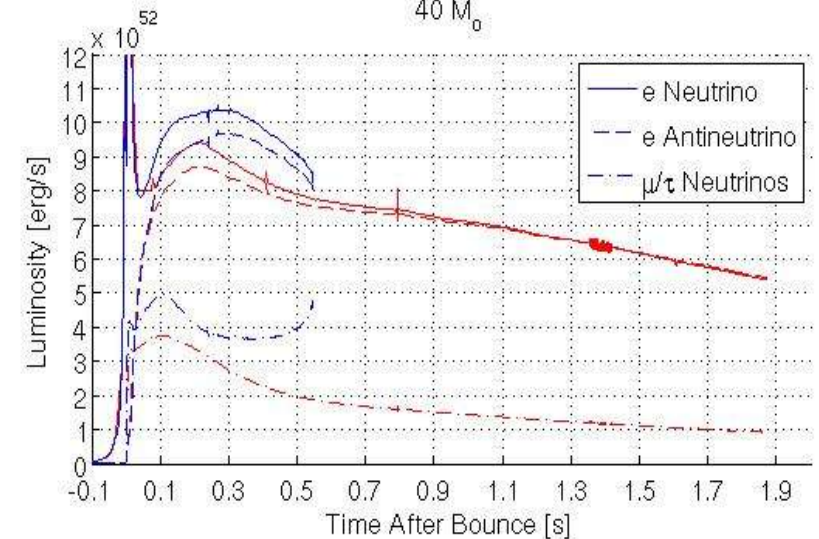
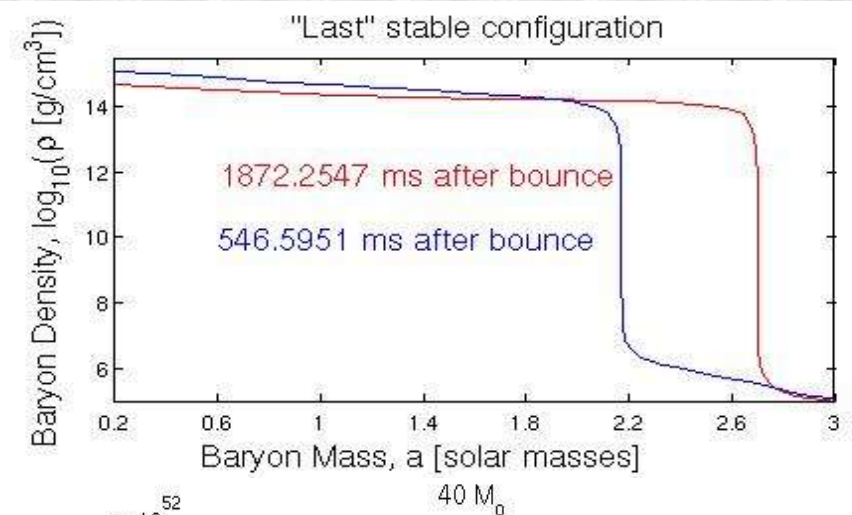
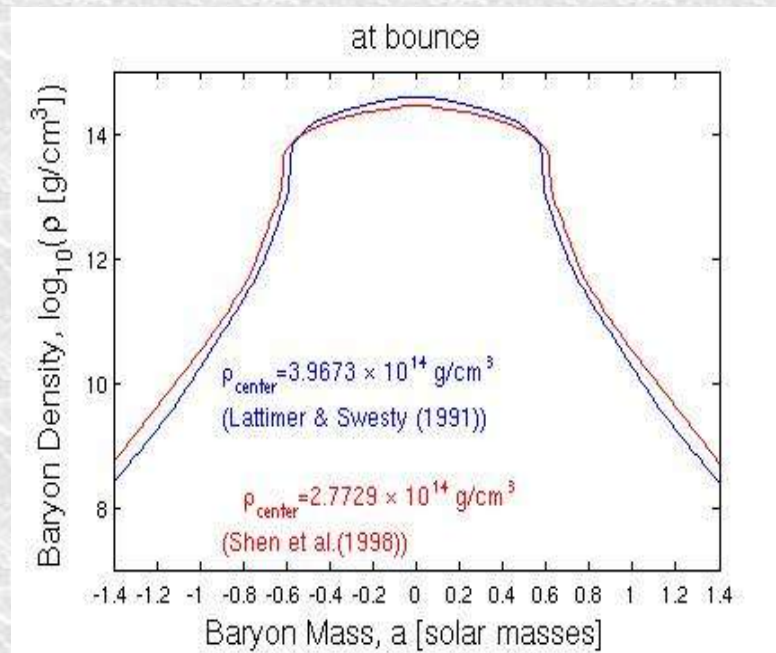
- Motivation
- Introduction
- stellar models
- progenitor models
- core collapse phenomenology
- Input physics
- neutrino physics
- nuclear reactions
- The EoS
- Possible fate
- explosion
- bh.-formation
- Discussion

Input physics: the EoS

$$G^{\mu\nu} = 8\pi T^{\mu\nu} \quad u^\mu \left(\frac{\partial f}{\partial x^\mu} + \frac{\partial f}{\partial u^\delta} \Gamma_{\mu\nu}^\delta u^\nu \right) = \Omega(f)$$

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

1. Hot and dense nuclear matter
2. Different eos (stiffness)



Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

explosion

bh.-formation

Discussion

The possible fate

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

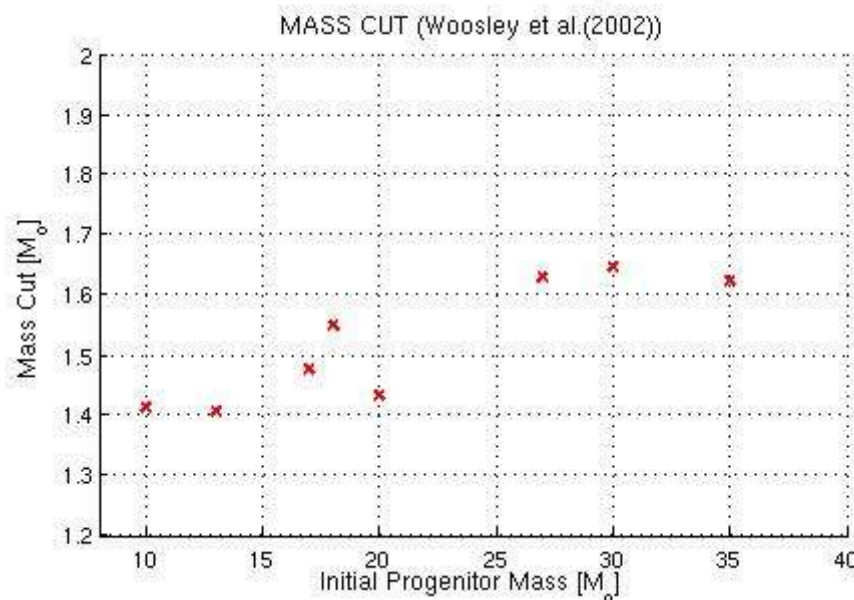
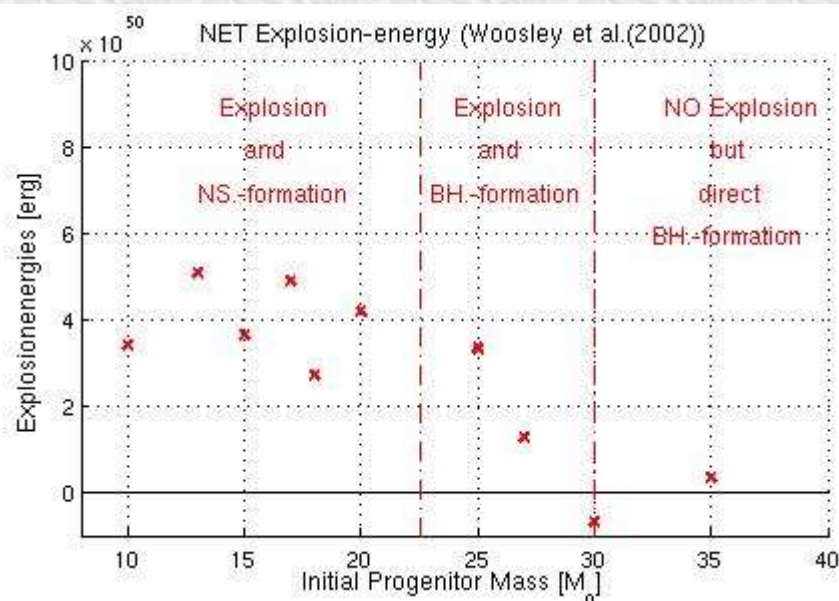
The EoS

Possible fate

explosion

bh.-formation

Discussion

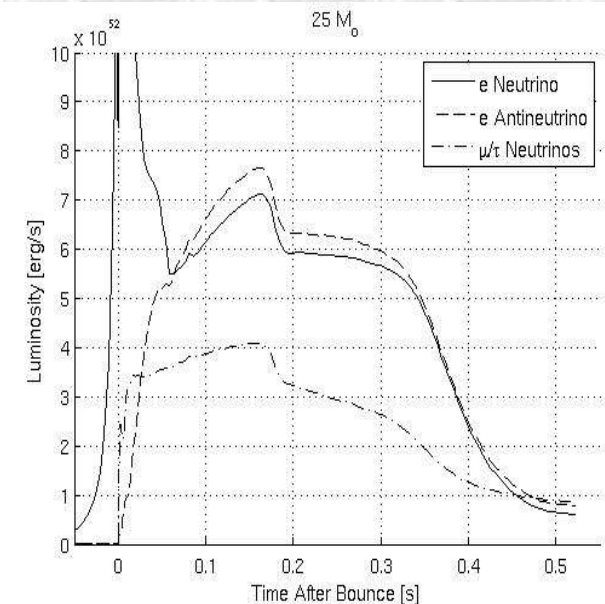
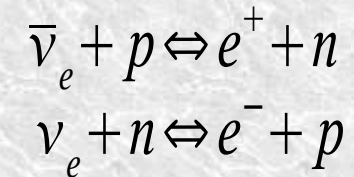
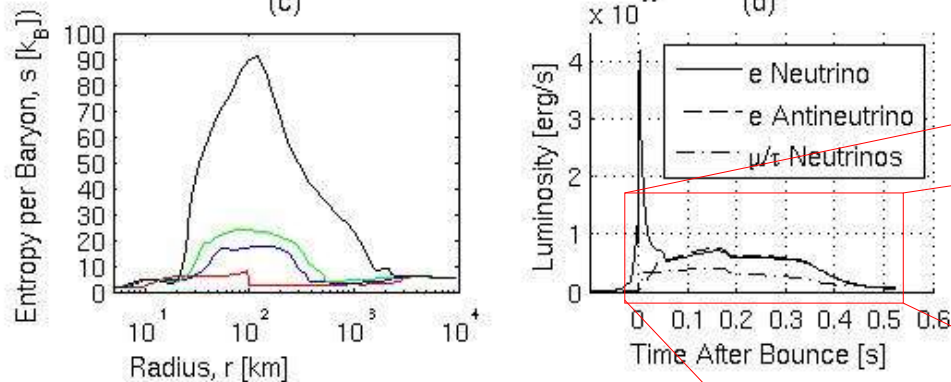
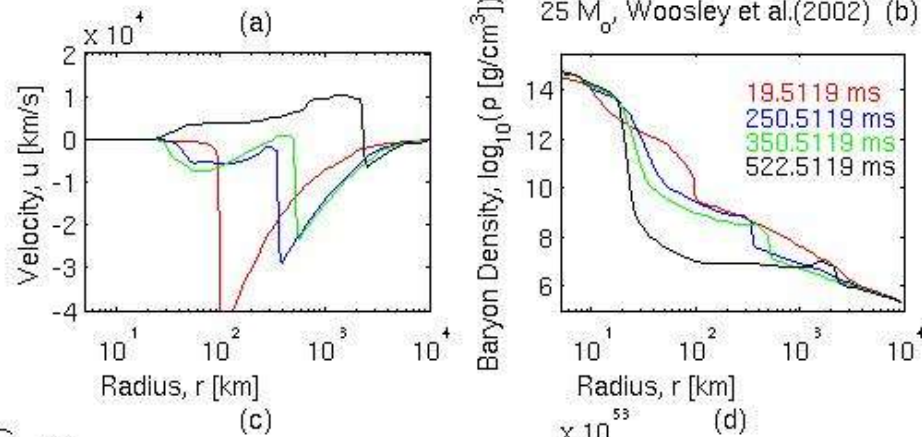


$$E = \int_R^r \left(e + \frac{u^2}{2} - \frac{m}{r} \right) 4\pi r^2 \rho dr$$

$$(E_{expl}, r_{cut}) = \max(E(r))$$

The possible fate: Explosions

1. Explosion mechanism: artificially enhanced heating and cooling rates



Motivation

Introduction

stellar models

progenitor models

core collapse phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

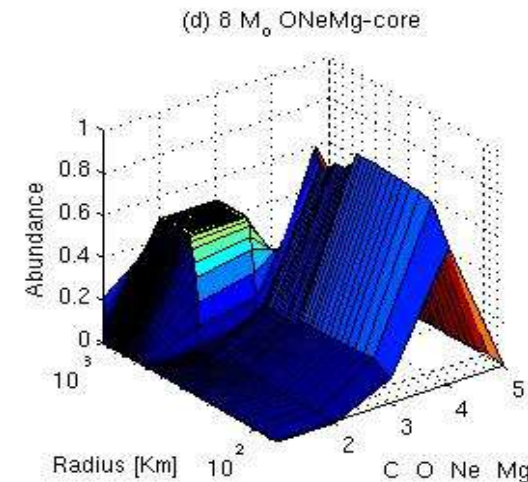
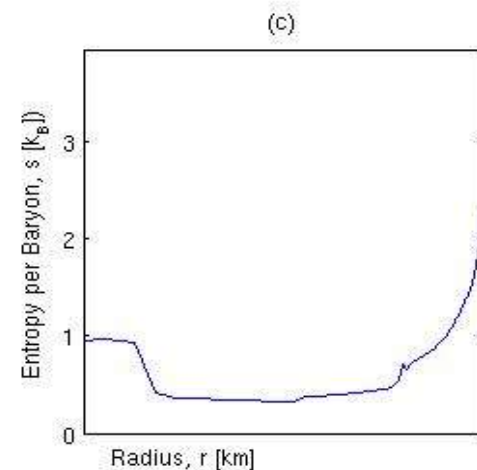
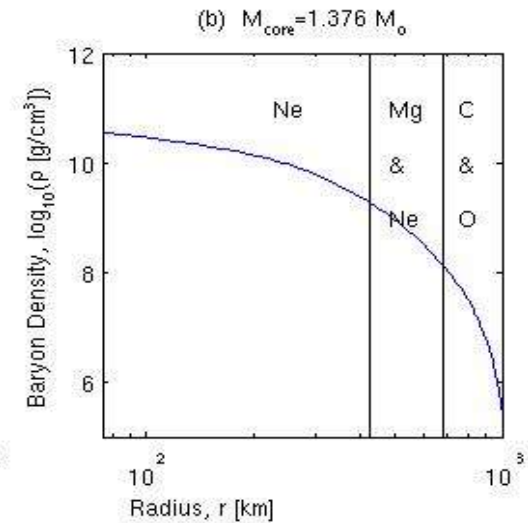
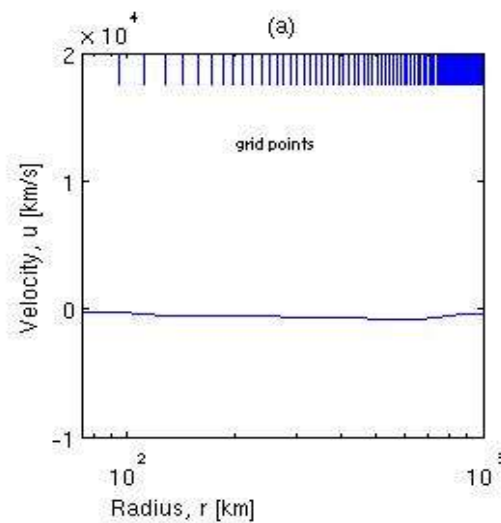
explosion

bh.-formation

Discussion

The possible fate: Explosions

1. Explosion mechanism
2. ONeMg-core



K. Nomoto (1996)

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

explosion

bh.-formation

Discussion

The possible fate: Black hole formation

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

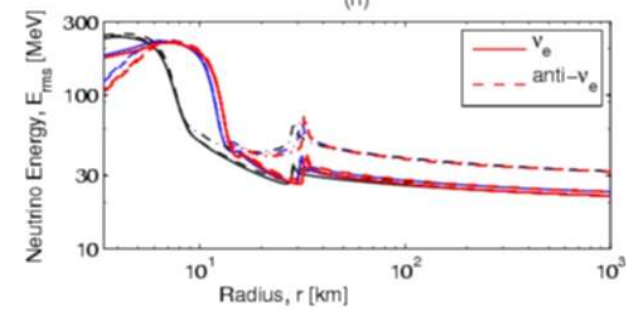
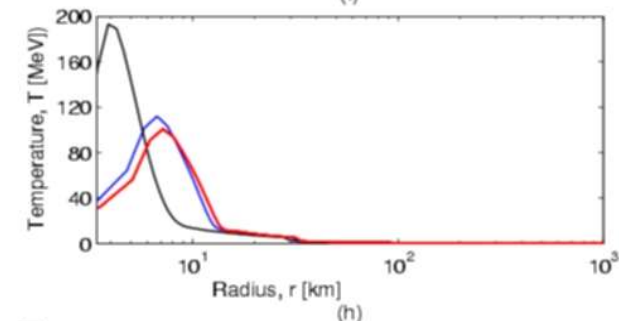
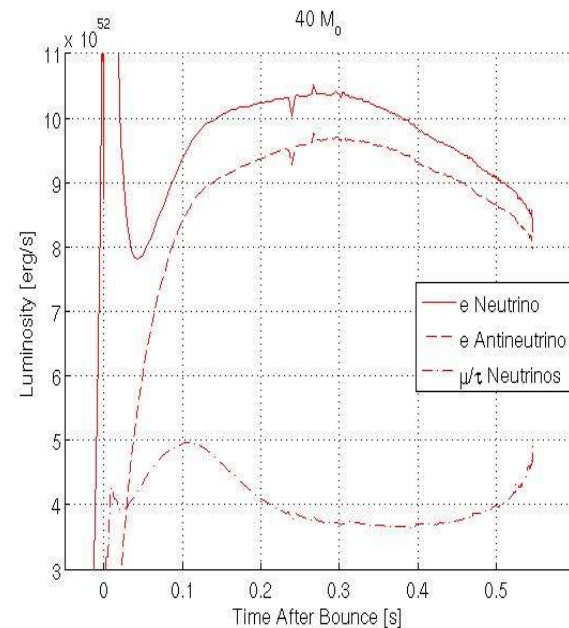
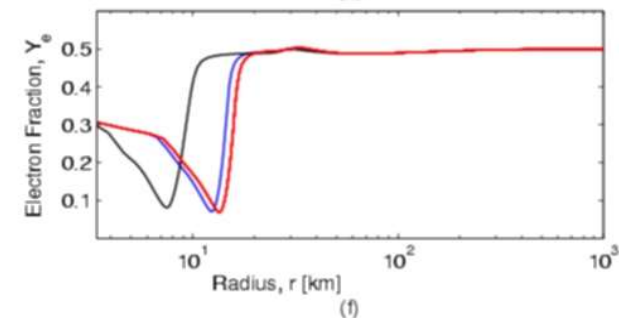
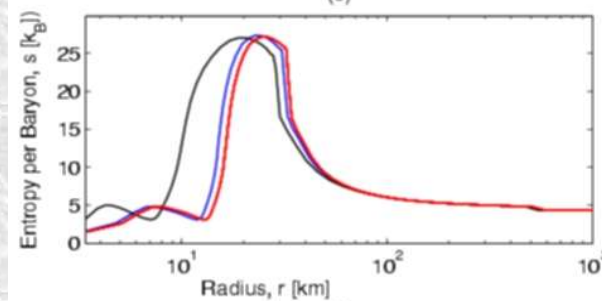
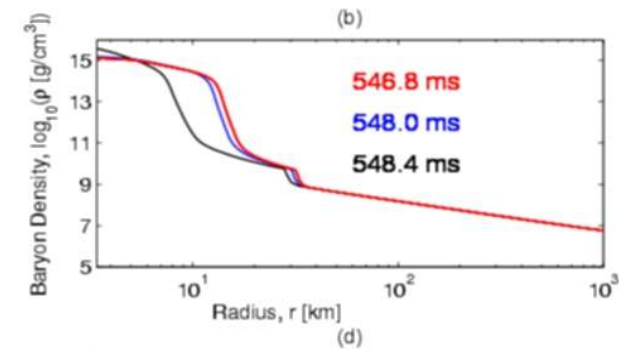
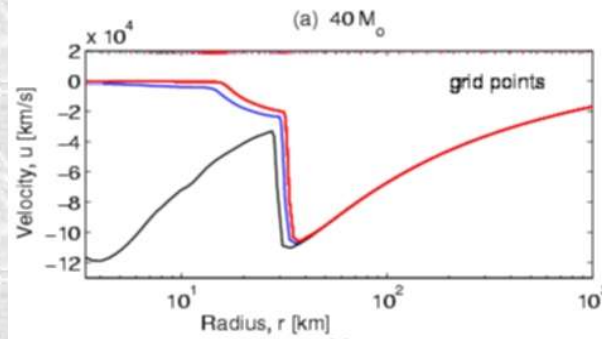
The EoS

Possible fate

explosion

bh.-formation

Discussion



Discussion

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

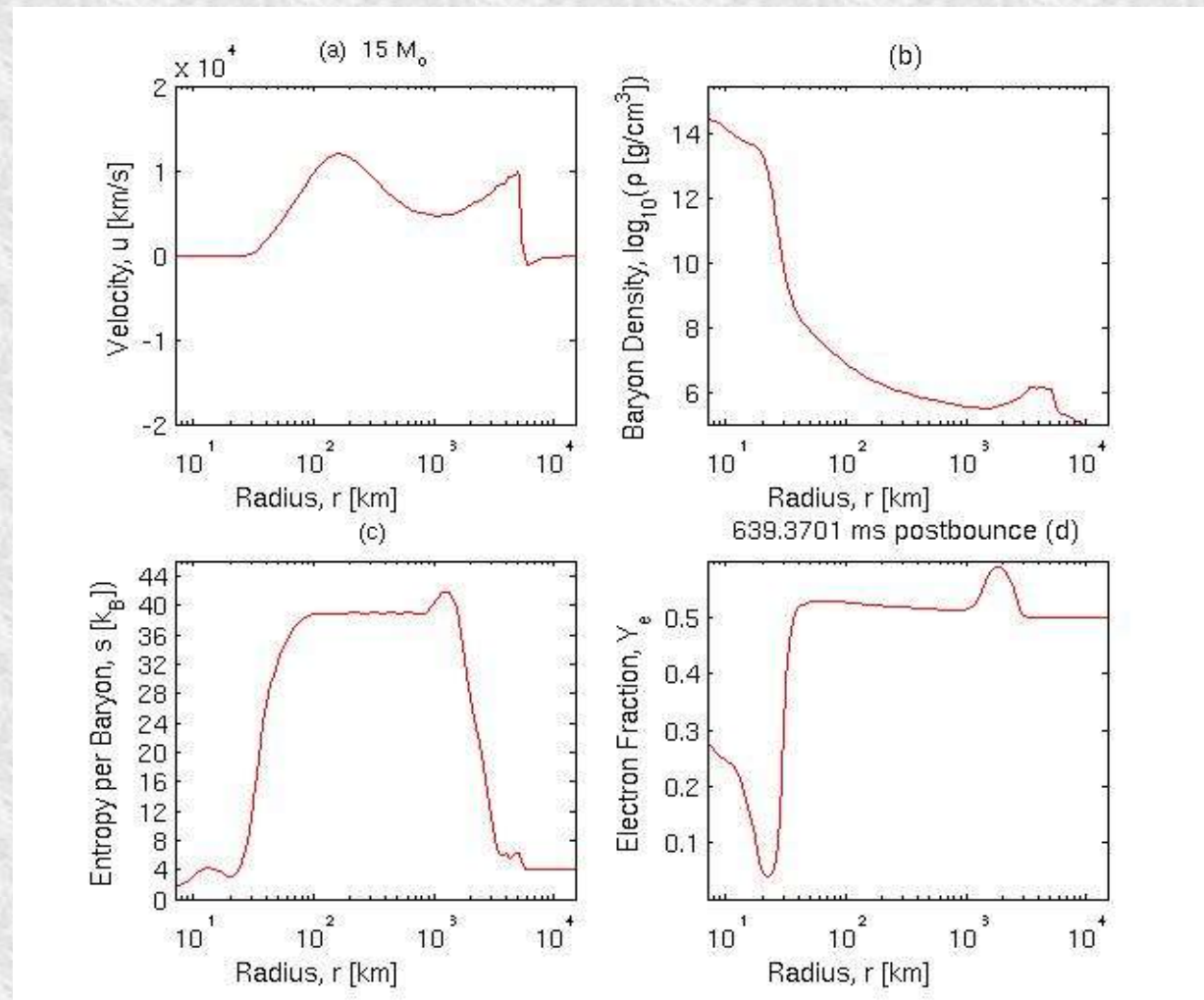
Possible fate

explosion

bh.-formation

Discussion

1. Neutrino Wind



Discussion

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

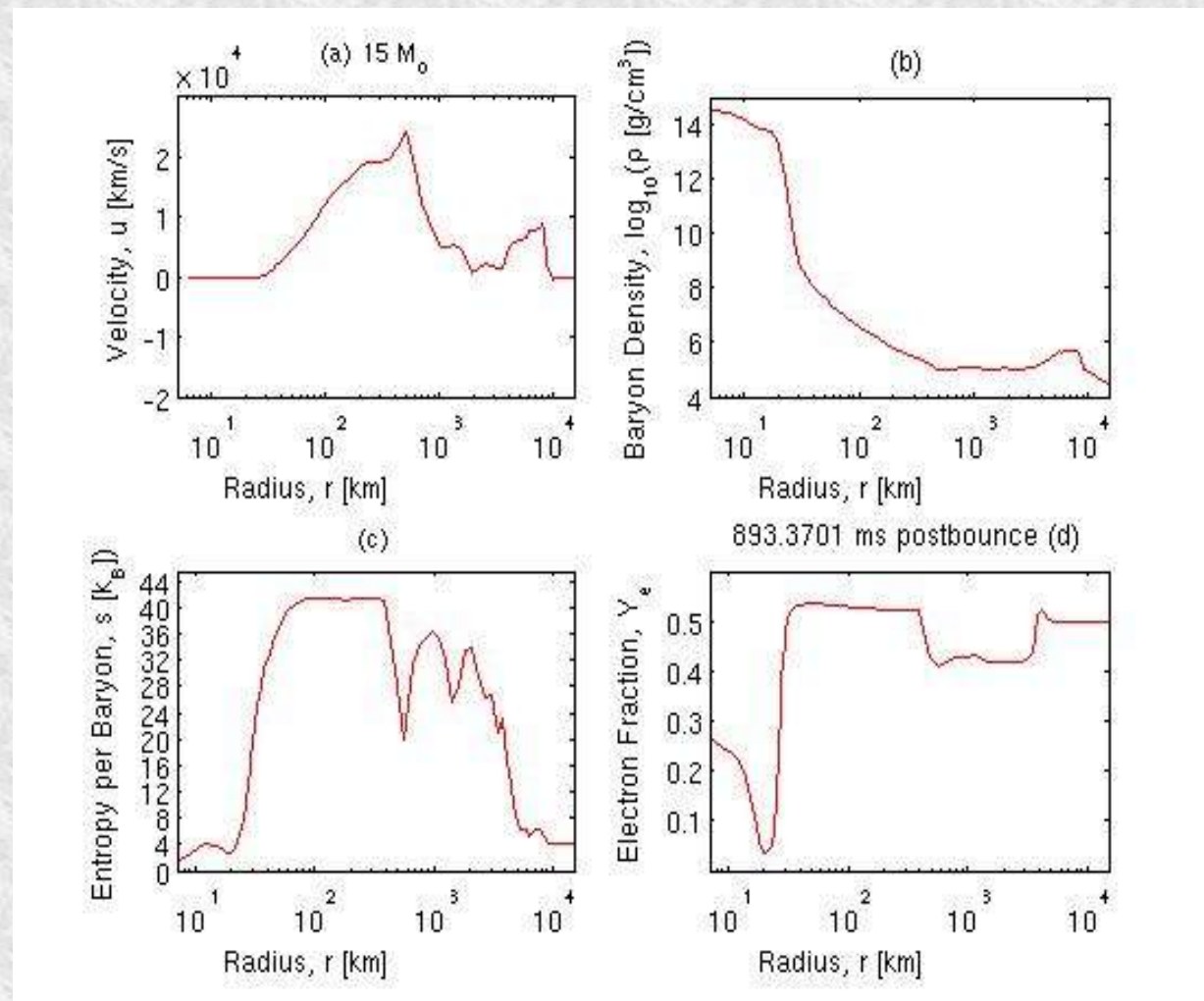
Possible fate

explosion

bh.-formation

Discussion

1. Neutrino Wind



Discussion

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

explosion

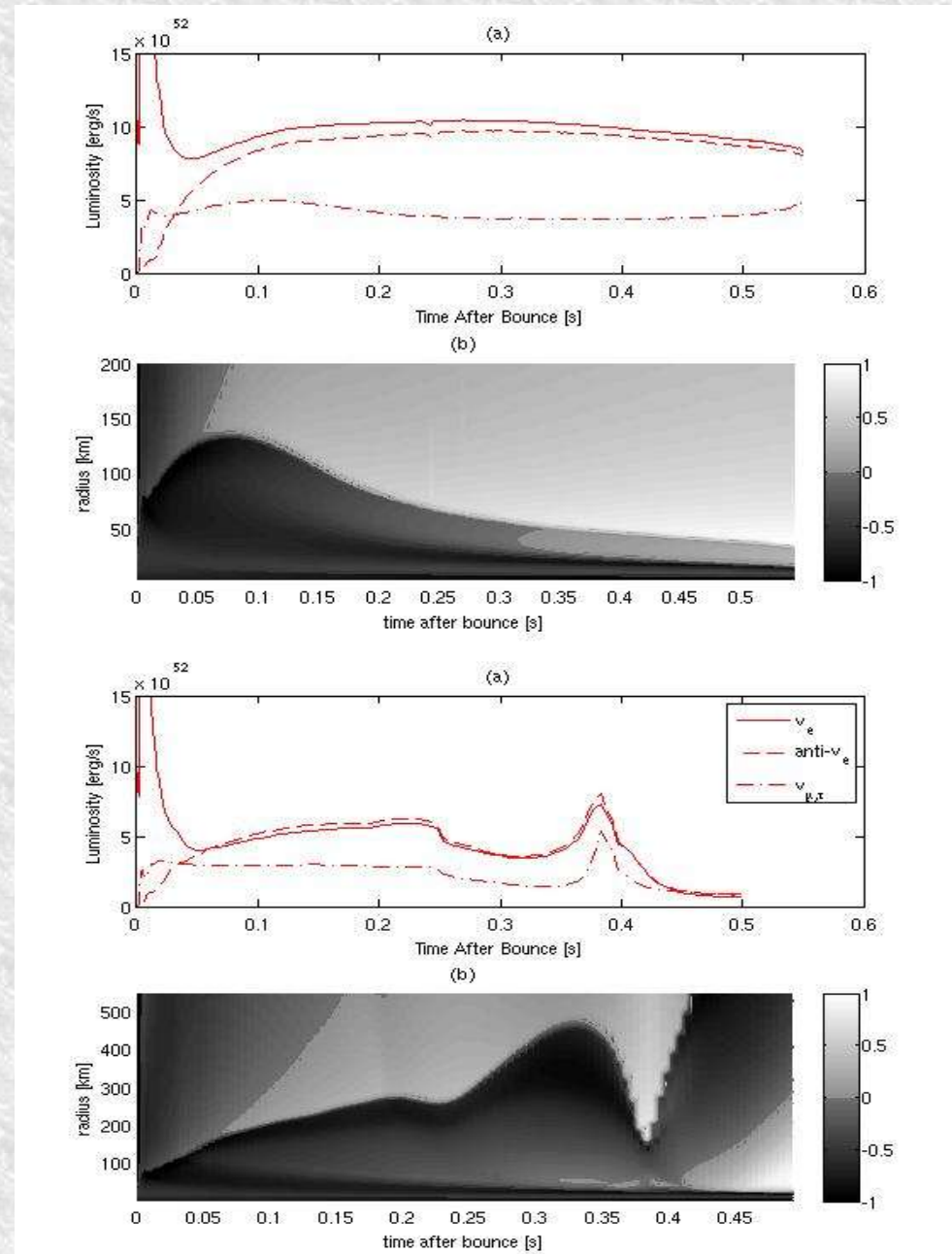
bh.-formation

Discussion

1. Neutrino Wind

2. Neutrino oscillations

$$\frac{y_\nu}{y_\rho} = \frac{y_{\nu_e} + y_{\bar{\nu}_e} + y_{\nu_\mu} + y_{\bar{\nu}_\mu}}{y_\rho}$$



Discussion

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

explosion

bh.-formation

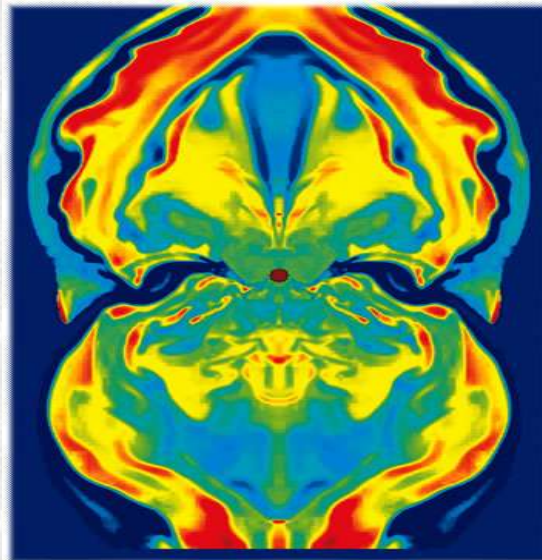
Discussion

1. Neutrino wind
2. Neutrino oscillations
3. Multi-dimensional simulations

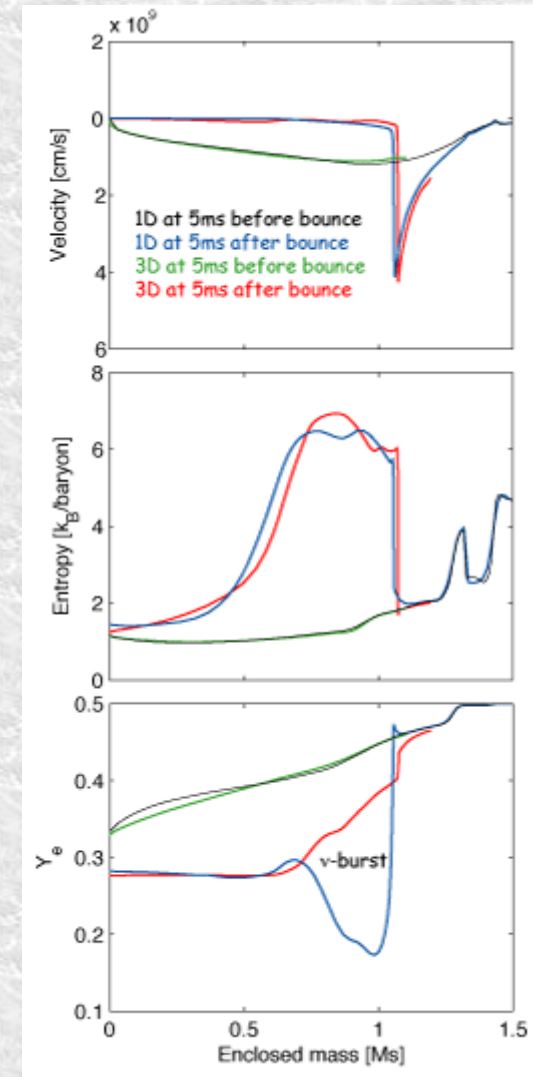
deleptonization

convection and asymmetric neutrino heating/cooling

SASI (standing accretion shock instability)



Liebendörfer (2005)



Review VOL.37 No. 2, onl.

Discussion

Motivation

Introduction

stellar models

progenitor models

core collapse
phenomenology

Input physics

neutrino physics

nuclear reactions

The EoS

Possible fate

explosion

bh.-formation

Discussion

1. Neutrino wind
2. Neutrino oscillations
3. Muldi-dimensional simulations
4. Remnant properties/comparison with observations: **Neutron star kicks**

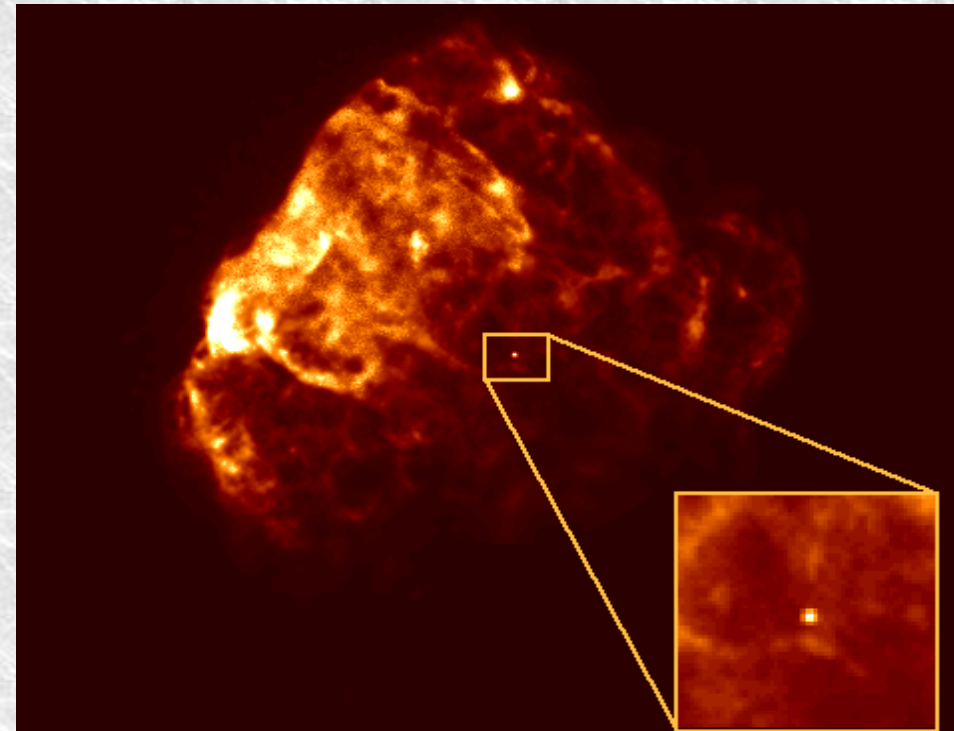
hydrodynamically driven

magnetic fields

asymmetric neutrino transport

$$u \sim 1000 \text{ km/s}$$

Crab-nebula, X-ray



Thank you very much
for your attention