Core Collapse Supernova: Role of Hyperonic Matter

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Plan of the Talk

- Introduction
- Microphysics: Equation of State (EoS)
- Dynamical Core Collapse Simulations with GR1D Code
- Numerical Results
- Summary

Introduction:

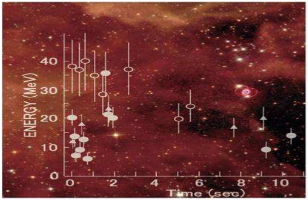
There are mainly two kinds of supernova:

- Type Ia, which are thought to be the thermonuclear explosions of accreting white dwarf stars,
- All the rest (Type II, Ib, Ic etc.) happen when the iron core of a massive star collapses to a neutron star or black hole.

We are interested mainly in core collapse supernova which occur most frequently in nature.

Introduction: Core Collapse Supernova

The core collapse supernova explosion mechanism is being investigated over the last five decades.



- The supernova SN1987A, since its discovery, has become the most studied star remnant in history and has provided great insights into supernovae and their remnants.
- Observation of a burst of neutrino signal for at least 12s after the explosion strongly supports to the scenario that a proto neutron star (PNS) was initially present in the core which cooled via neutrino emission.

From Nuclear Physics to Astrophysics

✗Equation of State (EoS)
✗Neutrino Reactions
✗Nuclear Data

✗Hydrodynamics
✗Neutrino Transfer
✗Stellar Models

✓Numerical simulations of core-collapse supernova
✓Supercomputing technology

Challenges:
✗Properties of dense matter at high density & temperature.
✗Role of neutrinos in supernova core.
✗Composition of matter

Ref: K. Sumiyoshi

Microphysics: Equation of State

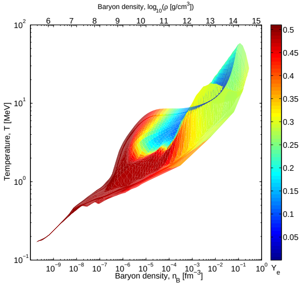
Microphysics inputs such as equation of state (EoS) are important for simulations of stellar collapse for a wide range of density, Temperature and composition.

Typical condition after core-bounce:

- $T \sim 10\text{MeV}$
- $Y_p \leq 0.3$
- $\rho_b \geq \rho_0$

Typical supernova EoS covers

- density $(10^4 - 10^{15}\mathrm{g/cm^3})$,
- temperature $(0 - 100\text{MeV})$,
- composition $(Y_p \sim 0 - 0.6)$.



Phase space of covered in core collapse simulation of a $40M_{solar}$ progenitor with Shen EoS

T. Fischer et al, ApJS 2011

Nuclear Equation of State

Constituents are free nucleons, light nuclei, ideal gas of nuclei and uniform nuclear matter. Single nucleus approximation was employed. Shell effects are neglected.

Lattimer-Swesty(LS)

- Based on Skyrme type interaction with two and many body terms for uniform matter
- compressible liquid drop model for non-uniform matter

Lattimer and Swesty, 1991

Shen et al. Nuclear Physics A, 637 (1998) 435

Shen Nuclear EoS

- Shen nuclear EoS is based on a Relativistic Mean Field model at intermediate and high densities ($\rho > 10^{14.2}$ gm/cc).
- At low temperature ($T < 14$MeV), and ($\rho < 10^{14.2}$ gm/cc), Thomas Fermi approximation is used.

Other EoS...

- Parameterised EoS (Baron-Cooperstein, Takahara-Suko,Bruenn, Swesty... 1980)
- Mixture of nuclei (Hempel & Schanffner-Bielich 2011, Hempel 2012)
- Variational calculation with bare nuclear forces Argonne v18 and UrbanaIX (Togashi et. al., Constantinou et. al. 2014)
- Statistical Model (Mishustin & Botvina 2004, 2010)
- Multifragmentation of nuclei in heavy ion collisions (Buyukcizmeci 2014)

Strangeness in the post-bounce phase of a core-collapse supernova

- Pauli exclusion principle dictates the appearance of strange degrees of freedom in the high density baryonic matter.
  - Hyperons
  - Bose-Einstein condensates of Kaons
  - Quarks
- Recent Observations put limit of $2M_{\odot}$ on neutron star mass.
  D.J. Champion, et al., Science, 320, 1309 (2008).
  P. B. Demorest et. al., Nature **467**, 1081 (2010).

  J. Antoniadis et. al., Science **340**, 6131 (2013).
- Presence of strange hadrons results in a softer EoS which lowers maximum mass of the neutron star.
- These observations put stringent constraints on the model of neutron star and abandons most of the soft EoS models.

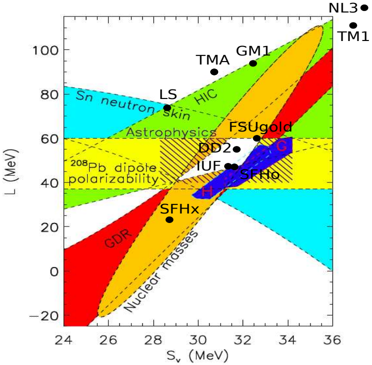
Hyperon Matter and EoS

- Λ hyperons, being the lightest hyperons with an attractive potential of ~ -30 MeV in nuclear matter, are believed to populate the dense matter first among all strange baryons.
- Threshold Condition for Λ hyperons $\mu_n = \mu_\Lambda$
- Other hyperons, Ξ & Σ are excluded due to their relatively higher threshold and lack of experimental data.
- Recently Shen et. al extended their nuclear EoS to include Λ hyperons [Ref:Shen et al. ApJ197 (2011)]
- Michaela Oertel and collaborators also constructed hyperon EoS [Ref: M. Oertel et al. PRC85 (2012)]

  Those hyperon EoS are not compatible with a $2M_\odot$ neutron star

New Hyperon EoS

- The hyperon EoS should be compatible with a $2M_{\odot}$ neutron star
- The EoS should satisfy the experimental constraint on the value of parameter (L) corresponding to the density dependence of the symmetry energy.



J. M. Lattimer and Y. Lim, ApJ 771, 51 (2013)

Pic. Ref. : Matthias Hempel

Hyperon EoS within observational mass limit

- We construct the hyperon EoS tables for densities ($10^3 - 10^{15}\mathrm{g/cm}^3$), temperatures ($0.1 - 158$MeV) and proton fractions ($0.01 - 0.6$).
- We adopt a Density Dependent Relativistic Mean Field (RMF) Model to describe uniform matter including hyperons.
- At low temperature and sub-saturation density, matter is mainly composed of light and heavy nuclei coexisting with unbound nucleons. This is treated in the Nuclear Statistical Equilibrium model (Saha Equation) (Hempel and Schaffner, Nucl. Phys. A837, 210 (2010)).
- We treat electrons and positrons as a uniform background and add their contribution as a non-interacting ideal Fermi-Dirac in the EoS table.
- Similarly, the black-body contribution of photons is also included in the EoS table.

Density Dependent Relativistic Model:

- The interaction between baryons is mediated by the exchange of scalar (σ) and vector (ω, ϕ, ρ) mesons.
- The Lagrangian density for baryons is given by

$$
\begin{aligned}
\mathcal{L}_B &= \sum_{B=N,\Lambda} \bar{\Psi}_B \left(i\gamma_\mu \partial^\mu - m_B^* - g_{\omega B}\gamma_\mu \omega^\mu - g_{\phi B}\gamma_\mu \phi^\mu \right. \\
&\left. - g_{\rho B}\gamma_\mu \boldsymbol{\tau}_B \cdot \boldsymbol{\rho}^\mu \right) \Psi_B \\
&+ \frac{1}{2}\left(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2 \right) \\
&- \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2 \omega_\mu \omega^\mu - \frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} + \frac{1}{2}m_\phi^2 \phi_\mu \phi^\mu \\
&- \frac{1}{4}\boldsymbol{\rho}_{\mu\nu} \cdot \boldsymbol{\rho}^{\mu\nu} + \frac{1}{2}m_\rho^2 \boldsymbol{\rho}_\mu \cdot \boldsymbol{\rho}^\mu \ .
\end{aligned}
$$

Ref: S. Banik, M. Hempel, D. Bandyopadhyay , ApJS 214 (2014) 22,

P. Char, S. Banik, PRC 90, 015801 (2014)

Density-Dependent Couplings

- The $g_{\alpha B}(\hat{n})$'s, where $\alpha = \sigma,\ \omega$ and ρ specify the coupling strength of the mesons with baryons and are vector density-dependent.
- The density operator $\hat{n}$ has the form, $\hat{n}=\sqrt{\hat{j}_\mu \hat{j}^\mu}$, where $\hat{j}_\mu = \bar{\psi}\gamma_\mu\psi$.
- The meson-baryon couplings become function of total baryon density n i.e. $< g_{\alpha B}(\hat{n}) >= g_{\alpha B}(< \hat{n} >) = g_{\alpha B}(n)$

[Ref: P. Char, S.Banik, PRC 90, 015801 (2014), S. Typel, Phys. Rev. C **71** 064301 (2005), S. Typel, G. Röpke, T. Klähn, D. Blaschke and H.H. Wolter, Phys. Rev.**C 81** 015803,(2010).]

- Interaction among hyperons can be represented by the Lagrangian density

$$\mathcal{L}_{YY} = \sum_B \bar{\psi}_B \left(g_{\sigma^* B}\sigma^* - g_{\phi B}\gamma_\mu \phi^\mu\right)\psi_B + \frac{1}{2}\left(\partial_\mu \sigma^* \partial^\mu \sigma^* m_{\sigma^*}^2 \sigma^{*2}\right) - \frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} + \frac{1}{2}m_\phi^2 \phi_\mu \phi^\mu \ .$$

The thermodynamic potential per unit volume for nucleons is given by

$$\frac{\Omega_B}{V} = \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{2}m_\omega^2\omega_0^2 - \frac{1}{2}m_\phi^2\phi_0^2 - \frac{1}{2}m_\rho^2\rho_{03}^2 - \Sigma^r \sum_{i=n,p,\Lambda} n_i$$
$$-2T\sum_B \int \frac{d^3k}{(2\pi)^3}[ln(1+e^{-\beta(E^*-\nu_B)}) + ln(1+e^{-\beta(E^*+\nu_B)})] \; .$$

Here, $\beta = 1/T$, $E^* = \sqrt{(k^2 + m_B^{*2})}$ and Σ^r is the rearrangement term.

$$P_B = -\Omega_B/V.$$

The energy density is given by,

$$\epsilon_B = \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{1}{2}m_\phi^2\phi_0^2 + \frac{1}{2}m_\rho^2\rho_{03}^2$$
$$+2\sum_B \int \frac{d^3k}{(2\pi)^3} E^* \left(\frac{1}{e^{\beta(E^*-\nu_B)}+1} + \frac{1}{e^{\beta(E^*+\nu_B)}+1} \right) \; .$$

Parameters of the Model

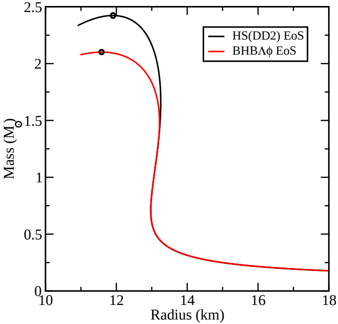
- The density dependent couplings $g_{\sigma N}$ and $g_{\omega N}$ are given by

$$g_{\alpha N} = g_{\alpha N}(n_0) f_\alpha(x)$$
$$f_\alpha(n_b/n_0) = a_\alpha \frac{1 + b_\alpha (x + d_\alpha)^2}{1 + c_\alpha (x + d_\alpha)^2}$$

  Here n_0 is the saturation density, $\alpha = \sigma, \omega$ and $x = n_b/n_0$.
- For ρ mesons, $g_{\rho N} = g_{\rho N}(n_0) exp[-a_\rho(x-1)]$. S. Typel et. al. Phys. Rev.**C 81** 015803,(2010).
- The scaling factors for vector and isovector mesons from the SU(6) symmetry relations of the quark model
  $\frac{1}{2} g_{\omega\Lambda} = \frac{1}{3} g_{\omega N}$; $g_{\rho\Lambda} = 0$; $2 g_{\phi\Lambda} = -\frac{2\sqrt{2}}{3} g_{\omega N}$

Mass-Radius Relation of Neutron Stars

Hyperon EoS is compatible with a 2 $M_\odot$ Neutron Star.



S. Banik, M. Hempel, D. Bandyopadhyay, ApJS 214 (2014) 22,

P. Char, S. Banik, PRC 90, 015801 (2014)

Dynamical Core Collapse of a Massive Star

- We interpolate the original EoS table, to generate more data.
- Check for the thermodynamical consistency
- For various progenitor models of Woosley et al. we performed the simulations using a spherically symmetric GR hydrodynamics code called $GR1D$ for the EoS.
- GR1D studies systematics stellar collapse to neutron stars and black hole formation. [C. D. Ott and E. O'Connor, Class. Quant. Grav. 27, 114103, 2010]

GR1D Code

The line element of a Spherically Symmetric General Relativistic Model is given by,

$$ds^2 = -\alpha(r,t)^2 dt^2 + X(r,t)^2 dr^2 + r^2 d\Omega^2 \ ,$$

where $\alpha(r,t) = exp^{(\Phi(r,t))}$ & $X(r,t) = [1 - 2m(r)/r]^{-1/2}$.

In ideal hydrodynamics, the Fluid stress-energy tensor & matter current density are

$$\begin{aligned} T^{\mu\nu} &= \rho h u^{\mu} u^{\nu} + g^{\mu\nu} P \\ J^{\mu} &= \rho u^{\mu} \end{aligned}$$

where ρ is the matter density, P is the Fluid pressure, $h = 1 + \epsilon + P/\rho$ is the specific enthalpy, ϵ the internal energy, u^{μ} is the 4-velocity of the Fluid.

Fluid evolution equations are derived from local conservation laws

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

[C. D. Ott and E. O'Connor, Class. Quant. Grav. 27, 114103, 2010]

Neutrino Mechanism

Neutrino effects are very crucial in supernova simulations.

- ν-emission/absorption : cooling/heating

$$e^- + p \longleftrightarrow \nu_e + n$$
$$e^+ + n \longleftrightarrow \bar{\nu}_e + p$$

- Scattering

$$\nu_i + N \longleftrightarrow \nu_i + N$$
$$\nu_i + e \longleftrightarrow \nu_i + e$$

- Pair creation/annihilation

$$e^- + e^+ \longleftrightarrow \nu_i + \bar{\nu}_i$$
$$N + N \longleftrightarrow N + N + \nu_i + \bar{\nu}_i$$
$$\gamma^* \longleftrightarrow \nu_i + \bar{\nu}_i$$

- It might be included via Boltzmann transport treatment.

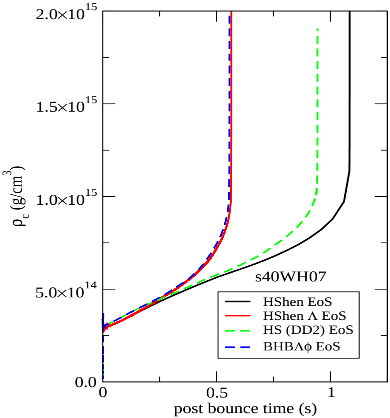
Neutrino scheme in GR1D

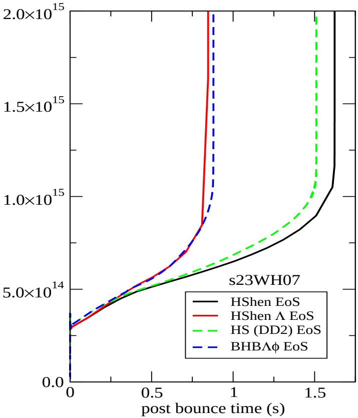
- Neutrino emission takes place after electron-capture by free or bound protons leading to fall of Y_e at the core.
- Prebounce: effective $Y_e(\rho)$ approximation. [Liebendörfer, ApJ 633, 1042 (2005)].
- Postbounce: 3-flavor, energy-averaged neutrino leakage scheme, which captures the effects of cooling.
- The leakage scheme provides approximate energy and number emission rates.
- Neutrino heating is included via a parameterized charged-current heating scheme. [H. T. Janka, A & A, **368**, 527 (2001)]

[C. D. Ott and E. O'Connor, ApJ 730, 70 (2011)]

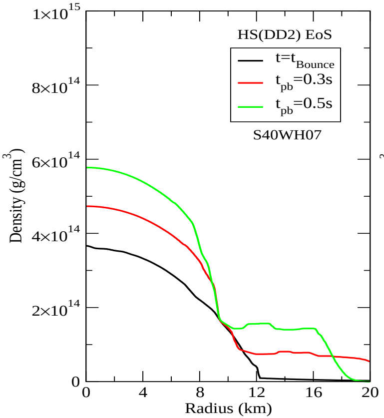
Supernova Simulations with HShen and BHB EoSes

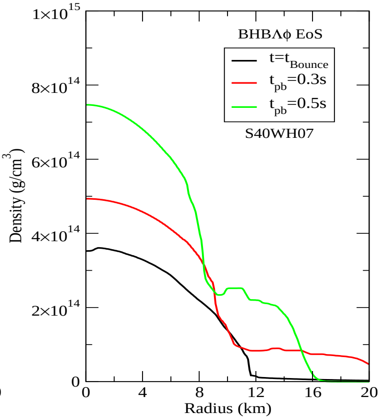
P. Char, S. Banik, D. Bandyopadhyay, Astrophys. J. 809(2), 116 (2015)



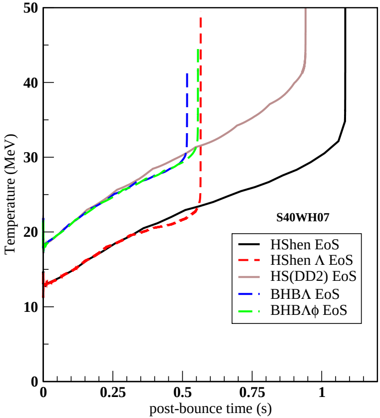


Density Profiles of the PNS

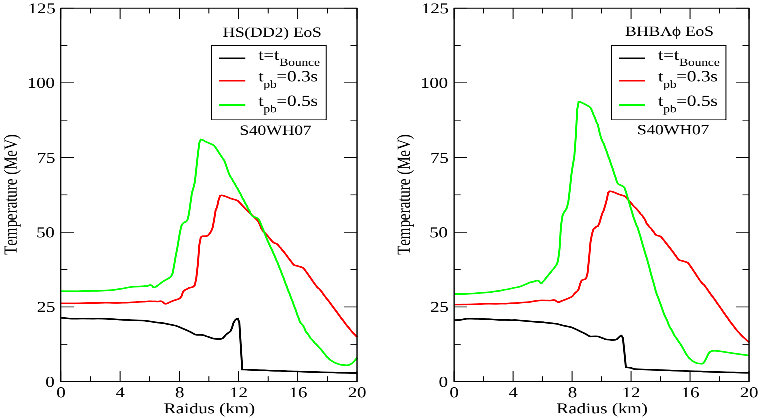




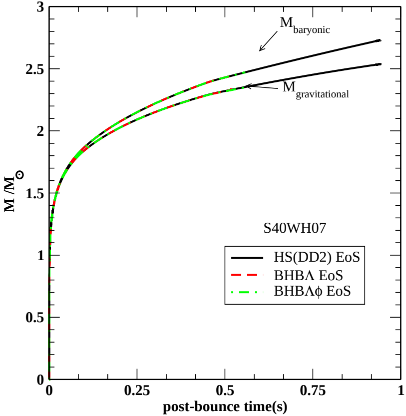
Evolution of Temperature



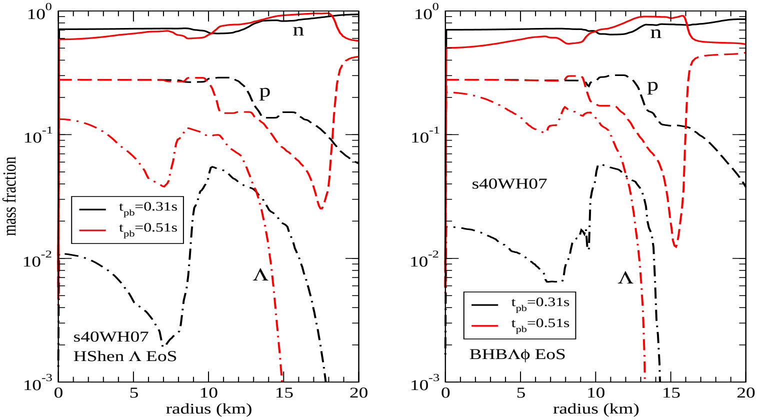
Temperature Profiles of the PNS



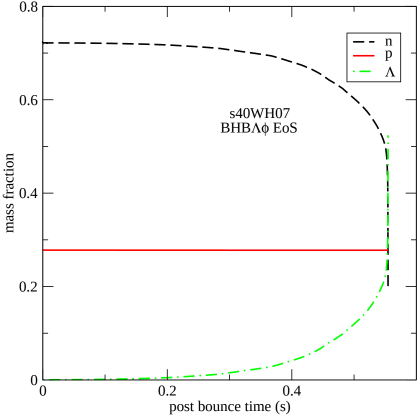
Temporal Evolution of Baryonic and Gravitational Mass



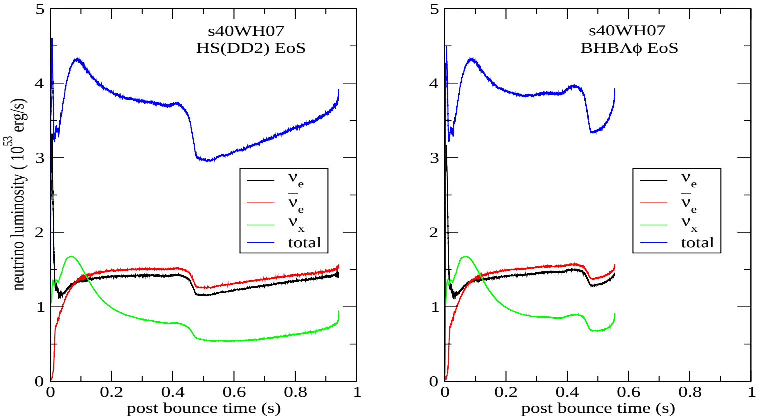
Mass Fraction Profiles of the PNS



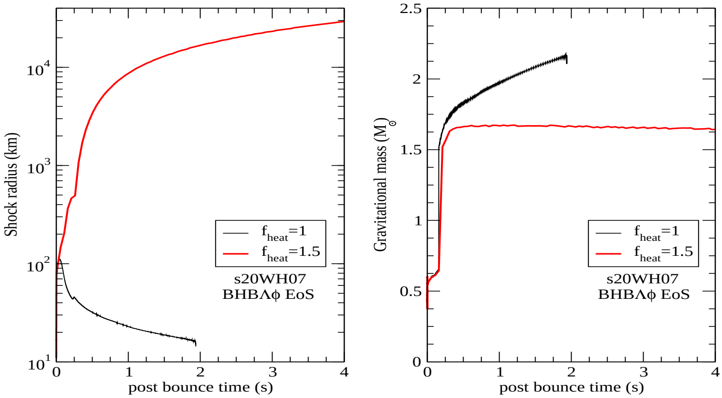
Mass fraction of the constituents with BHB$\Lambda\phi$ EoS



Neutrino Luminosity



Temporal Evolution of Shock Radius and Gravitational Mass of a $20M_\odot$ Progenitor



Summary and Outlook

- Hyperons appear just after bounce. It appears off center at first and prevails at center later.
- We have performed CCSN simulations using the BHB$\Lambda\phi$ EoS which is compatible with a 2 $M_\odot$ neutron stars.
- The appearance of Λ hyperons are studied in great details.
- No second neutrino burst is observed as in quark-hadron phase transition.
- Our aim is to explore the possibility that a hadron-antikaon phase transition during the early post bounce evolution may result in an explosion and its observational consequence in the form of neutrino signatures.

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Thank You