Nuclear equation of state in explosive astrophysical systems

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Institute for Theoretical Physics, Goethe University, Frankfurt, Germany

International Symposium on Nuclear Symmetry Energy (NuSYM10)
RIKEN Nishina Center, Wako, Japan
28. July, 2010

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Outline

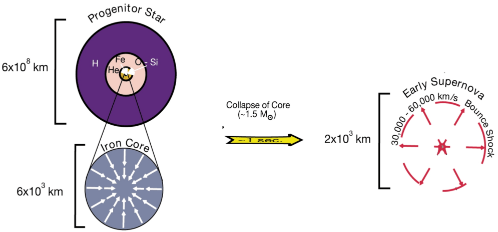
- Introduction to Core Collapse Supernovae
  - Mechanism and Matter Conditions
  - Problems and Solutions
  - Input Physics
- Nuclear Matter Equation of State in Supernovae
  - Hadronic Equations of State
  - Influence and role in Core Collapse supernova
  - Exotic Matter in Core Collapse Supernovae

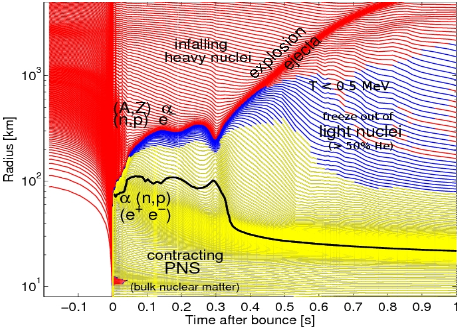
With

- T. Fischer
- M. Hempel
- M. Liebendoerfer
- A. Mezzacappa
- G. Pagliara
- J. Schaffner-Bielich
- F.-K. Thielemann

Supernova explosion

- Gravitational collapse of a massive star with $M > 8M_{\odot}$ at the end of its life
- Core collapse to nuclear density
- Repulsive nucleon interaction halt the collapse
- Inner core rebounds $\longrightarrow$ formation of a shock wave
- When shock wave passes the neutrinospheres $\longrightarrow$ burst of neutrinos
- Formation of a hot and dense proto neutron star at the center





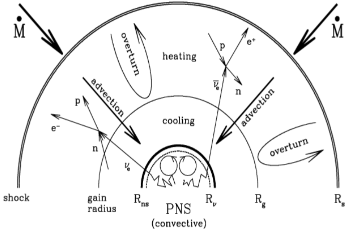
Figures: top: A. Burrows, Nature 403; bottom: T. Fischer, talk at CSQCD II, May 2009

To revive a shock wave

Problem: shock looses too much energy due to disintegration of nuclei and emission of neutrino burst, stalls as accretion shock at $r \sim 100$km

Neutrino driven (H.A.Bethe, J.R.Wilson, 1985):

- Neutrinos revive stalled shock by energy deposition, standing accretion shock instabilities

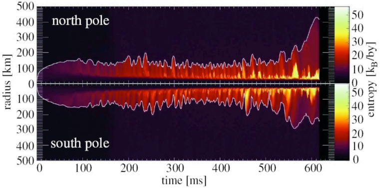


Acoustic mechanism (A.Burrows et al., 2006):

- G-modes of the core: sound waves steepen into shock waves

By magnetohydrodynamics (G.S.Bisnovatyi-Kogan, 1971):

- Transfer of angular momentum via a strong magnetic field



Phase transition (I.A.Gentile et al., 1993):

- Collapse of proto neutron star to a more compact hybrid star configuration

Figures: top: H-Th. Janka, AA 368 (2001); bottom: A.Marek and H.-Th. Janka, ApJ 694 (2009)

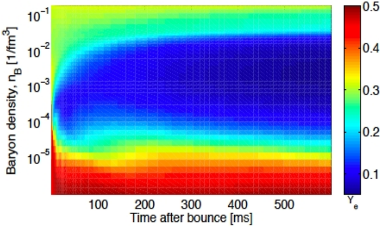
Supernova simulations

- General relativistic hydrodynamics in multi-D
- Neutrino transport
- Weak interaction reaction rates (for electron and neutrino capture)
- Nuclear matter equations of state

  covering:
  - T : 0 MeV$-\geq$ 100 MeV
  - Yp : 0.01$-\geq$ 0.6
  - n_b : 10^5 g/cm$^3-\geq 10^{15}$ g/cm^3

Figures: T. Fischer, talk at CSQCD II, May 2009

Figure: 10 $M_\odot$



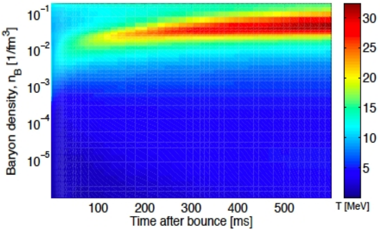


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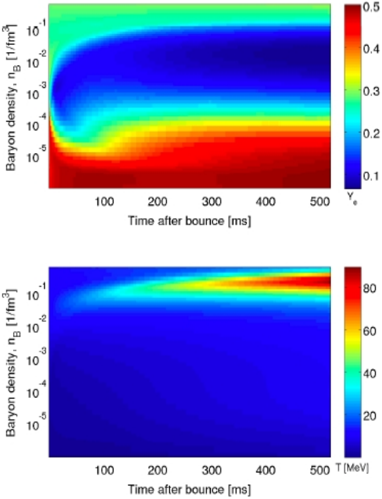
Figure: 40 $M_\odot$



Hadronic equations of state for supernova simulations

Lattimer-Swesty equation of state:

- Based on Skyrme type interaction with two and multibody term
- $S_0 = 29.3\text{MeV}$, $K_0 = 180, 220, 375\text{MeV}$, $n_0 = 0.155\text{fm}^{-3}$
- Components: Neutrons, protons, α particles, and representative heavy nucleus
- Compressible liquid drop model
- Simplified treatment of pasta phases between $1/10 n_0$ - $1/2 n_0$

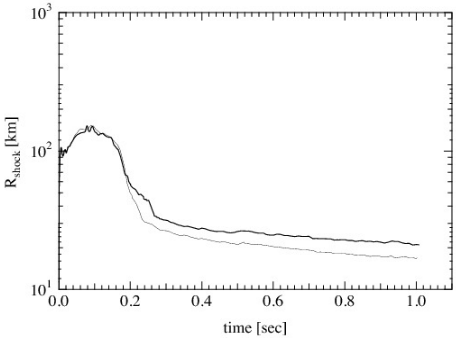
Shen et al. equation of state:

- Relativistic mean field, TM1 (fitted to Relativistic Brueckner Hartree Fock and properties of neutron rich nuclei)
- $S_0 = 36.9\text{MeV}$, $K_0 = 281\text{MeV}$, $n_0 = 0.145\text{fm}^{-3}$
- Components: Neutrons, protons, α particles, representative heavy nucleus
- Thomas-Fermi calculations
- No pasta phases, nuclei are spherical, no shell effects

Lattimer-Swesty and Shen EoS in Supernova Simulations - 1D

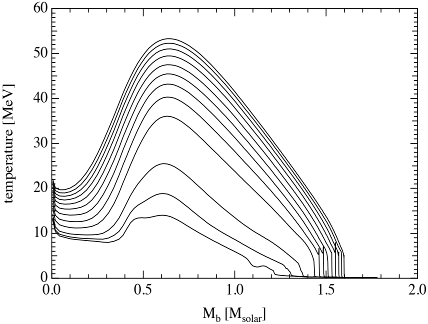
Sumiyoshi et al., ApJ 629, 922-932, 2005
Collapse of a $15M_\odot$ star up to 1s after core bounce with Shen et al. and Lattimer-Swesty EoS

- Higher symmetry energy of Shen et al. EoS $\longrightarrow$ smaller free proton fraction and less neutron rich nuclei
- Larger lepton fraction for Shen et al. $\longrightarrow$ larger inner core (in radius and enclosed mass) than for Lattimer-Swesty EoS
- Evolution of shock wave similar for Shen et al. and Lattimer-Swesty for the first 200ms
- Shock front at $t_{pb} \gtrsim$ 200ms: depends on contraction and thermal evolution (neutrino heating) of proto neutron star

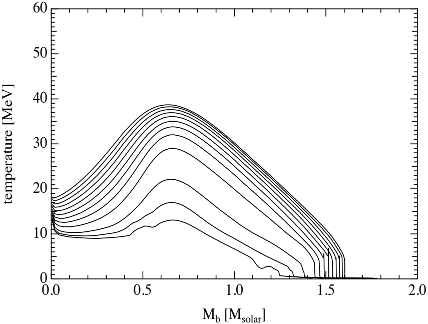


Lattimer-Swesty and Shen EoS in Supernova Simulations - 1D

Lattimer-Swesty

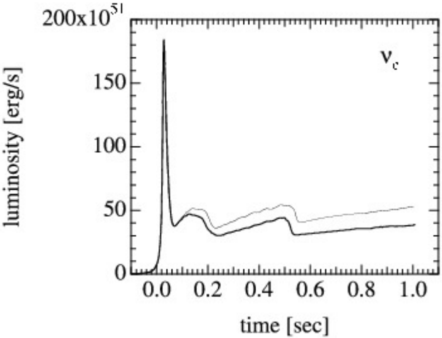


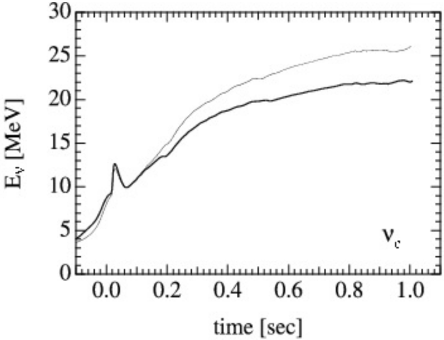
Shen et al.



- Due to stiffer EoS $\longrightarrow$ the contraction of the core for Shen et al. is smaller than for Lattimer-Swesty
- Different temperature distributions and locations of neutrino spheres affect neutrino luminosities and energies

Lattimer-Swesty and Shen EoS in Supernova Simulations - 1D





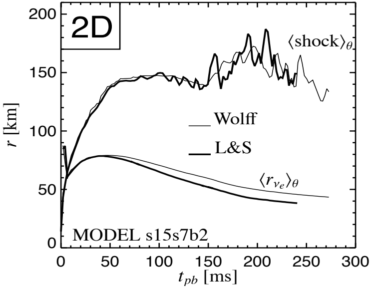
Similar results for

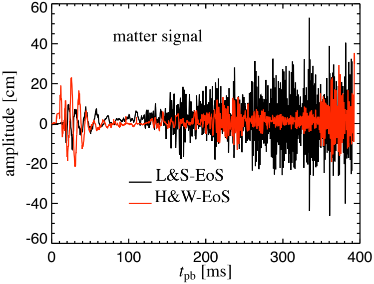
- Sumiyoshi et al. 1995 (A& A, 303, 475) $\longrightarrow$ evolution of proto neutron stars with TM1 and TMS (different symmetry energies)
- Janka et al., Phys. Rep. 442 (2007) $\longrightarrow$ collapse and postbounce evolution for $t_{pb} = 300$ms

Instabilities and grav. waves - 2D

Marek et al., A& A 496 (2009)

- Lattimer-Swesty EoS: $K_0 = 180$MeV, $S_0 = 29.3$MeV
- Wolff-Hillebrandt: based on Skyrme Hartree-Fock, $K_0 = 263$MeV, $S_0 = 32.9$MeV
- Negative gradients in entropy and lepton fraction $\rightarrow$ convection
- Different compactness of proto neutron star influences convective overturn
- Grav. wave caluclation by Scheidegger et al. (A & A, 514, 2010) of prompt convection in 3D: Lattimer-Swesty for $K_0 = 180, 220, 370$MeV are very similar, but difference between Lattimer-Swesty and Shen et al. EoS is seen





Figures:Janka et al., Phys. Rep. 442 (2007), Marek et al., A& A 496 (2009)

Nuclei are important

Single nucleus approximation should be replaced by an ensemble of nuclei

- During core collapse: electron capture on free protons and nuclei $\longrightarrow$ determines lepton fraction at bounce and size of the core
- Neutrino spectra are formed at the neutrionsphereas where $\rho \sim 10^{11}\text{g}/\text{cm}^3$
- Shock stalls at densities of $\rho \sim 10^{9}\text{g}/\text{cm}^3$
- Additional neutrino heating behind the stalled shock front due to neutrino nucleus interaction convection,

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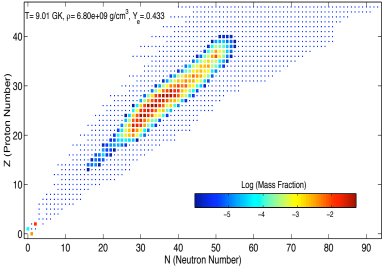
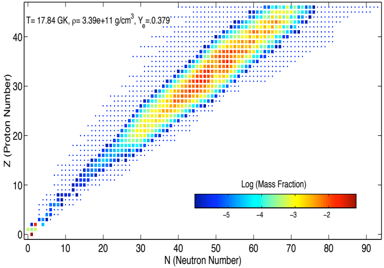
Figures taken from Janka et al., Phys. Rep. 442 (2007), correspond to presupernova stage (top) and neutrino trapping phase (bottom)



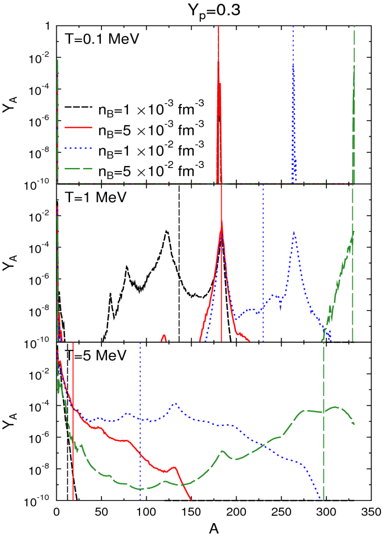


A statistical model for a complete supernova

EoS

M. Hempel and J.Schaffner-Bielich, Nuclear Physics A, Volume 837, Issue 3-4, p. 210-254.

- Thermodynamic consistent nuclear statistical equilibrium model
- Relativistic mean-field model for nucleons, excluded volume effects for nuclei
- Detailed phenomenological model for the liquid-gas phase transition of nuclear matter
- New aspects: shell effects, distribution of nuclei, all light clusters



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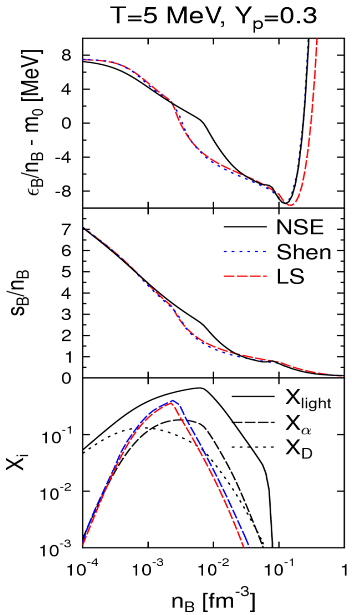


Further Models

Nuclear Statistical Equilibrium:

- C. Ishizuka, A. Ohnishi, and K. Sumiyoshi, Nucl. Phys. A 723, 517 (2003)
- A. S. Botvina and I. N. Mishustin, arXiv:0811.2593
- S. I. Blinnikov, I. V. Panov, M. A. Rudzsky, and K. Sumiyoshi, arXiv:0904.3849

Other Approaches:

- Typel, S. Röpke, G. Klähn, T. Blaschke, D. Wolter, H. H.P hysical Review C, vol. 81, Issue 1, id. 015803
- W. G. Newton and J. R. Stone, Phys. Rev. C 79, 055801 (2009), 3D mean field Hartree-Fock calculation
- Shen, G.; Horowitz, C. J.; Teige, S., Physical Review C, vol. 82, Issue 1, Equation of state of dense matter from a density dependent relativistic mean field model
- A.Fantina et al.Physics Letters B, Volume 676, Issue 4-5, temperature dependence of nuclear symmetry energy in Lattimer-Swesty equation of state
- M. Oertel and A.Fantina, extending the Lattimer-Swesty equation of state implementing hyperons and pions

Hyperons in supernovae

Ishizuka et al. (JPG. 35,2008):

- Shen et al. equation of state with hyperons
- Simulation of an adiabatic collapse of an iron core
- Hyperon fraction very small (10^{-3}), no effect on the dynamics
- No neutrino transport
- Keil and Janka, A& A, 296, 1995, Baumgarte et al. ApJ. 468, 1996, Pons et al., ApJ., 513, 1999, show no significant influence on the dynamics and neutrino signal from the appearance of hyperons in the early evolution of proto neutron stars

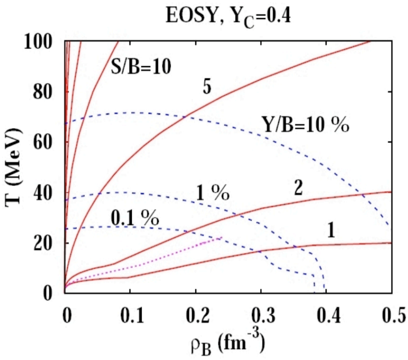
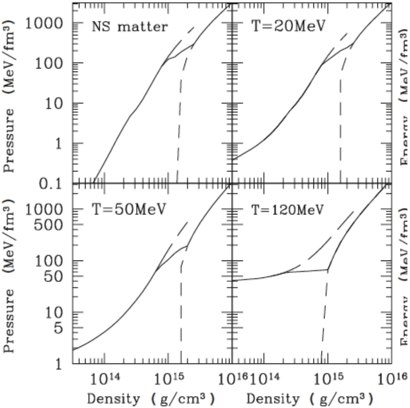


Figure 6. Hyperon fraction contours and adiabatic paths in supernova matter at $Y_C = 0.4$ from the hyperonic EOS table without pions (EOSY). The contours of the fixed number fraction of hyperons (sum of strange baryons) are shown by dashed lines. The solid lines denote the contour of fixed entropy per baryon (isentropy). The dotted line shows the trajectory of the dense matter at center during core collapse and bounce.

Quark Matter in Supernovae

Nakazato et al. (Phys.Rev.D, 77, 2008):

- EoS by Shen with phase transition to quark matter
- Core collapse SN of a 100 $M_\odot$ progenitor with Boltzmann neutrino transport
- High critical densities ($> 5n_0$) $\longrightarrow$ phase transition shortens time until black hole formation



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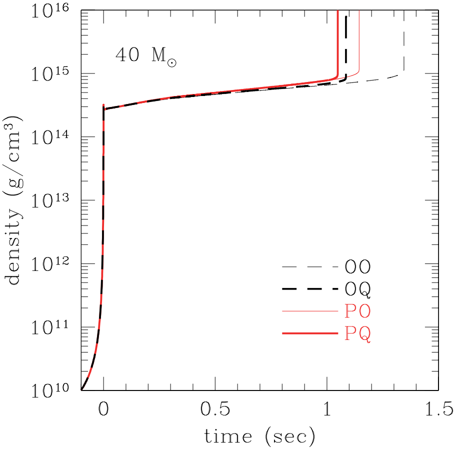
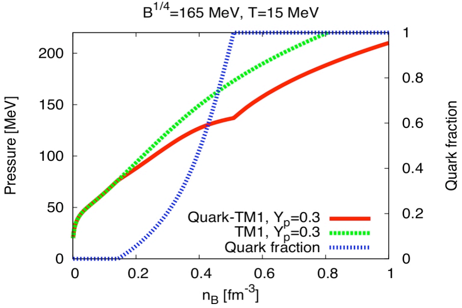


Hybrid EoS with Gibbs construction

PRL 102, 081101 (2009)
I. S., T. Fischer, M. Hempel, G. Pagliara, J. Schaffner-Bielich, A. Mezzacappa, F.-K. Thielemann, M. Liebendoerfer

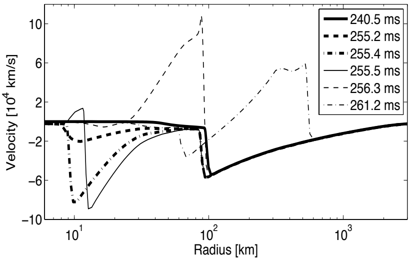
- EoS by Shen with phase transition to quark matter
- Quark EoS: Bag model
- Chosen parameters for low critical density:
  $B^{1/4} = 162$ MeV and 165MeV
  $m_s = 100$MeV, $m_u = m_d = 0$
- For $Y_p = 0.3$ and beginning of mixed phase: EoS relatively stiff and similar to hadronic EoS

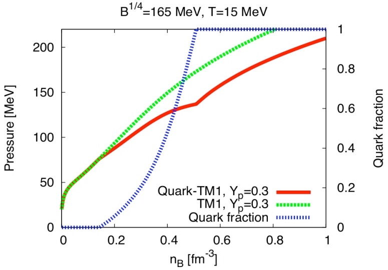


Quark Matter in Core Collapse

Supernovae

- Progenitors: 10 $M_\odot$ and 15 $M_\odot$ (Woosley et al. 2002)
- GR hydrodynamics and Boltzmann neutrino transport in spherical symmetry (Liebendoerfer et al. 2004)
- Mixed phase of quarks and hadrons appears at core bounce in the center of the PNS
- Softening of the EoS in mixed phase for higher quark fractions $\longrightarrow$ contraction of the PNS till pure quark matter is reached
- Formation of second shock front which turns into shock wave
- Second shock wave accelerates and leads to the explosion of the star





Comparison of different Bag constants

- Shock heating of deleptonized hadronic matter leads to second neutrino burst, dominated by anti-neutrinos
- For $B^{1/4}$=165MeV second neutrino burst is ∼200 ms later than for $B^{1/4}$=162MeV

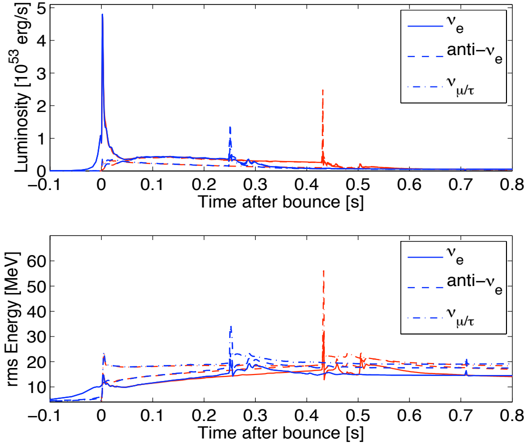


Fig: T.Fischer, Neutrino luminosities and rms neutrino energies, at 500km radius for different Bag constants, $10M_\odot$ progenitor

Summary

- Robust explosion mechanism/trigger for explosion is still missing
- Many open issues (Multi-D Simulations, neutrino transport, nuclear equation of state, ...)
- Up to now - only two mainly used nucelar equations of state
- Only one representative nucleus
- No systematic study on the influence of the symmetry energy
- Sensitivity of neutrino signal and gravitational wave signal to nuclear symmetry energy
- Future studies: Influence of the symmetry energy on supernova dynamics, inclusion of an ensemble of nuclei and corresponding weak interaction rates
- ...
- Up to now: Inclusion of hyperons at high densities shows no significant influence on supernova/proto neutron star dynamics
- Quark matter phase transition in the early post-bounce phase of core-collapse supernova can trigger the explosion
- $\longrightarrow$ has to be tested on compatibility with neutron star cooling data and mass-radius observations