Nuclear equations of state for (CC)-supernovae

Micaela Oertel

micaela.oertel@obspm.fr

Laboratoire Univers et Théories (LUTH)
CNRS / Observatoire de Paris/ Université Paris Diderot

Russbach school on nuclear astrophysics, Russbach, March 10-16, 2013

OUTLINE

1. INTRODUCTION

OUTLINE

1. INTRODUCTION
2. STANDARD SUPERNOVA EQUATIONS OF STATE

OUTLINE

1. INTRODUCTION

2. STANDARD SUPERNOVA EQUATIONS OF STATE

3. DEVELOPMENTS IN THE SUB-SATURATION REGIME

OUTLINE

OUTLINE

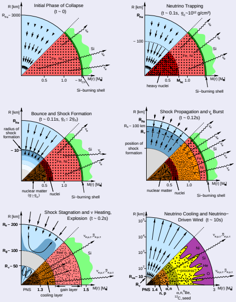
1. INTRODUCTION
2. STANDARD SUPERNOVA EQUATIONS OF STATE
3. DEVELOPMENTS IN THE SUB-SATURATION REGIME
4. DEVELOPMENTS IN THE SUPRA-SATURATION REGIME
5. SUMMARY AND OUTLOOK

MATTER COMPOSITION AND EQUATION OF STATE

Matter composition changes dramatically through the core collapse

- Starting point : onion like structure with iron/nickel core+ degenerate electrons
- Upon compression (+deleptonisation) : heavier and more neutron rich nuclei
- For $n_B \gtrsim n_0/2$: nuclei disappear in favor of free nucleons
- Composition of matter above n_0 and at $T \gtrsim 10$ MeV relatively unknown

DIFFERENT STAGES OF A SUPERNOVA



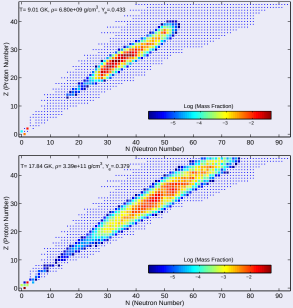
(Janka et al. '07)

Matter composition and equation of state

Matter composition changes dramatically through the core collapse

- Starting point : onion like structure with iron/nickel core+ degenerate electrons
- Upon compression (+deleptonisation) : heavier and more neutron rich nuclei
- For $n_B \gtrsim n_0/2$: nuclei disappear in favor of free nucleons
- Composition of matter above n_0 and at $T \gtrsim 10$ MeV relatively unknown

Nuclear abundancies at different stages



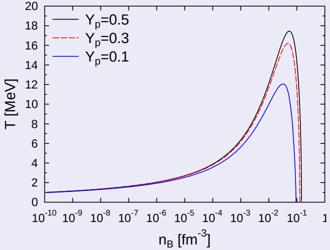
(Janka et al. '07)

MATTER COMPOSITION AND THE EQUATION OF STATE

Matter composition changes dramatically through the core collapse

- Starting point : onion like structure with iron/nickel core+ degenerate electrons
- Upon compression (+deleptonisation) : heavier and more neutron rich nuclei
- For $n_B \gtrsim n_0/2$: nuclei disappear in favor of free nucleons
- Composition of matter above n_0 and at $T \gtrsim 10$ MeV relatively unknown

PHASE DIAGRAM OF BULK NUCLEAR MATTER (RMF/TMA)



(Hempel & Schaffner-Bielich '09)

CONSTRUCTION OF AN EQUATION OF STATE

The equation of state (EOS) thermodynamically relates different quantities to close the system of hydrodynamic equations.

- For example, for a cold neutron star in β-equilibrium :
  - equations depend on baryon number density and pressure $\rightarrow$ EOS is $P(n_B)$ (or equivalent)
- For core collapse :
  - equations depend on baryon number density, lepton number density (no β-equilibrium), temperature, and pressure $\rightarrow$ EOS is $P(n_B, T, Y_L)$ (or equivalent)
- Use thermodynamic principles to obtain thermodynamically consistent EOS (e.g. $s = -\partial f / \partial T|_{n_i}$)
- EOS is called many times during a simulation and evaluation is expensive $\rightarrow$ use EOS in tabulated form with interpolation

THE "STANDARD" EOS

- Two EOS mainly used in simulations :
  - Lattimer-Swesty (NPA 1991) :
    Non-relativistic nuclear liquid drop model including surface effects and Coulomb effects
    Thermodynamically consistent (minimisation of the free energy)
  - H. Shen et al. (NPA 1998) :
    Relativistic mean field model with TM1 parameter set
    Finite size effects via Thomas-Fermi approximation
- Same limiting assumptions for particle content : free nucleons, α particles + one (average) heavy nucleus, electrons/positrons, photons
- Lattimer-Swesty and Shen et al. EOS publicly available in tabulated form
- Some simulations employ the Hillebrandt & Wolff EOS (A & A 1984) :
  - Nuclear statistical equilibrium (NSE) model at low densities
    Hartree-Fock single nucleus approximation for the intermediate density region
    Homogeneous matter treated by Skyrme non-relativistic model

IS THE CLASSICAL PICTURE ADEQUATE ?

I. Can we neglect the effects of having many different nuclei at subsaturation density ?

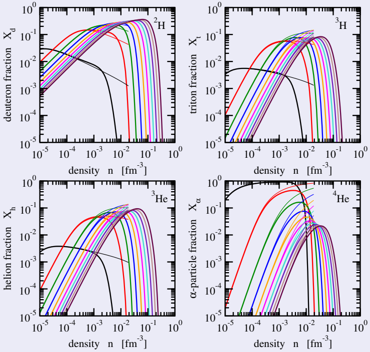
- Lattimer & Burrows (ApJ 1984) : Single nucleus approximation reasonable for thermodynamic quantities (pressure, entropy,...)
- Potentially important for deleptonisation and neutrino-matter interaction rates
- Model construction underway focussing on different aspects :
  - Light clusters
  - Heavy clusters
  - Transition from inhomogeneous to homogeneous nuclear matter
- At low densities NSE description good (ideal gas of nuclei)
- At higher densities, close to saturation, medium effects become important → interaction of clusters and with the surrounding nucleons cannot be neglected
- Different approaches beyond NSE
  - Quantum statistical
  - Virial expansion at low densities
  - Phenomenological excluded volume correction
  - . . .

LIGHT CLUSTERS

(Typel et al. PRC 2010, S. Heckel et al. PRC 2009, Sumiyoshi & Röpke PRC 2008, Röpke PRC 2009, Horowitz & Schwenk NPA 2006, ...)

- Conclusions :
  - Light clusters other than α-particles, in particular deutons, are abundant
  - Only small differences in global thermodynamic quantities except in some small density/temperature regions
- Electron antineutrino spectra from supernovae modified due to differences in the free proton fraction (Arcones et al. PRC 2008)

ABUNDANCIES IN GENERALIZED RMF MODEL BY TYPEL ET AL. (PRC 2010)

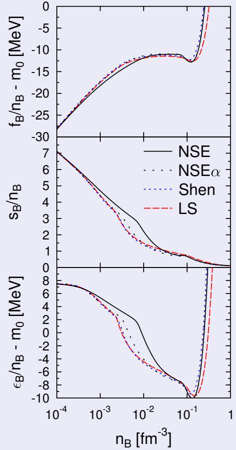


LIGHT CLUSTERS

(Typel et al. PRC 2010, S. Heckel et al. PRC 2009, Sumiyoshi & Röpke PRC 2008, Röpke PRC 2009, Horowitz & Schwenk NPA 2006, ...)

- Conclusions :
  - Light clusters other than α-particles, in particular deutons, are abundant
  - Only small differences in global thermodynamic quantities except in some small density/temperature regions
- Electron antineutrino spectra from supernovae modified due to differences in the free proton fraction (Arcones et al. PRC 2008)

BARYONIC THERMODYNAMIC PROPERTIES AT $T = 5$ MEV, $Y_p = 0.3$, MODEL BY HEMPEL & SCHAFFNER-BIELICH (NPA 2010)

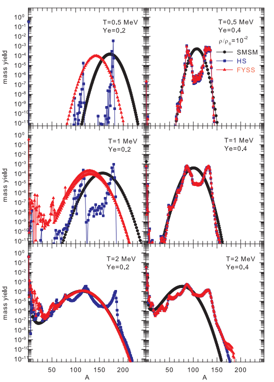


HEAVY CLUSTERS

(Hempel & Schaffner-Bielich NPA 2010, Raduta & Gulminelli PRC 2010, PRC 2012, Typel et al. NPA 2013, G. Shen et al. PRC 2011, Meixner et al. arxiv 1303.0064, Blinnikov et al. A&A 2011, Botvina & Mishustin NPA 2010, Furusawa et al. ApJ 2011, ...)

- Conclusions :
  - Distribution very different from SNA, in particular gap filled between “heavy” and “light” clusters
  - Only small differences in global thermodynamic quantities except in some small density/temperature regions
- Effect on the simulations comparable to using different nuclear interaction models (Hempel et al. ApJ 2012, Steiner et al. 1207.2184)

MASS DISTRIBUTION IN DIFFERENT NSE MODELS (BUYUKCIZMECI ET AL. ARXIV 1211.5990)

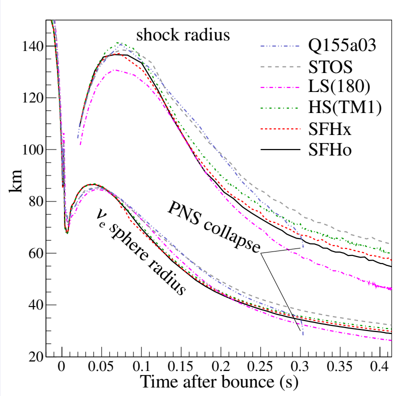


HEAVY CLUSTERS

(Hempel & Schaffner-Bielich NPA 2010, Raduta & Gulminelli PRC 2010, PRC 2012, Typel et al. NPA 2013, G. Shen et al. PRC 2011, Meixner et al. arxiv 1303.0064, Blinnikov et al. A&A 2011, Botvina & Mishustin NPA 2010, Furusawa et al. ApJ 2011, ...)

- Conclusions :
  - Distribution very different from SNA, in particular gap filled between “heavy” and “light” clusters
  - Only small differences in global thermodynamic quantities except in some small density/temperature regions
- Effect on the simulations comparable to using different nuclear interaction models (Hempel et al. ApJ 2012, Steiner et al. 1207.2184)

SHOCK RADIUS AND NEUTRINOSPHERE, $15 M_\odot$ PROGENITOR, 1D(STEINER ET AL. ARXIV 1207.2184)

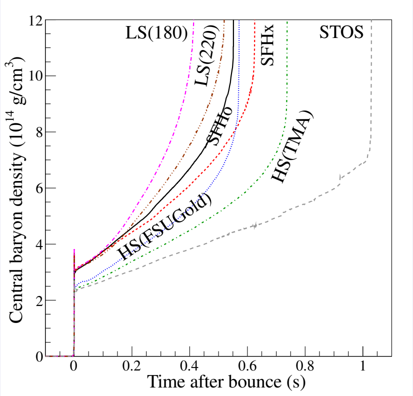


HEAVY CLUSTERS

(Hempel & Schaffner-Bielich NPA 2010, Raduta & Gulminelli PRC 2010, PRC 2012, Typel et al. NPA 2013, G. Shen et al. PRC 2011, Meixner et al. arxiv 1303.0064, Blinnikov et al. A&A 2011, Botvina & Mishustin NPA 2010, Furusawa et al. ApJ 2011, ...)

- Conclusions :
  - Distribution very different from SNA, in particular gap filled between “heavy” and “light” clusters
  - Only small differences in global thermodynamic quantities except in some small density/temperature regions
- Effect on the simulations comparable to using different nuclear interaction models (Hempel et al. ApJ 2012, Steiner et al. 1207.2184)

CENTRAL DENSITY EVOLUTION(STEINER ET AL. 1207.2184)



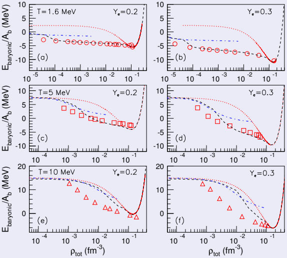
TRANSITION FROM INHOMOGENEOUS TO HOMOGENEOUS NUCLEAR MATTER

Transition from inhomogeneous to homogeneous nuclear matter in most EOS described by first order liquid gas phase transition

- Gibbs condition for phase transition : $P_I = P_{II}, \quad \mu^i_I = \mu^i_{II}$
- Many approaches use $P_I = P_{II}, \quad \mu^B_I = \mu^B_{II}, \quad Y^I_p = Y^{II}_p$
  $\rightarrow \mu^C_I \neq \mu^C_{II}$ $\rightarrow$ not in phase equilibrium !

- Gas-cluster mixture versus phase coexistence + ensemble non-equivalence $\longrightarrow$ continuous (not first order) transition (Raduta & Gulminelli PRC 2010, PRC 2012)
- With electrons : Coulomb quenching favors additionally continuous transition
- Effect on cluster distribution and thermodynamic quantities in transition region

BARYONIC ENERGY PER BARYON AS FUNCTION OF BARYON DENSITY, MODEL BY RADUTA & GULMINELLI (PRC 2010)



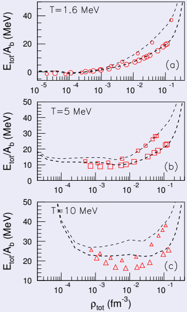
TRANSITION FROM INHOMOGENEOUS TO HOMOGENEOUS NUCLEAR MATTER

Transition from inhomogeneous to homogeneous nuclear matter in most EOS described by first order liquid gas phase transition

- Gibbs condition for phase transition : $P_I = P_{II}, \quad \mu_I^i = \mu_{II}^i$
- Many approaches use $P_I = P_{II}, \quad \mu_I^B = \mu_{II}^B, \quad Y_p^I = Y_p^{II}$
  $\rightarrow \mu_I^C \neq \mu_{II}^C$ $\rightarrow$ not in phase equilibrium !

- Gas-cluster mixture versus phase coexistence + ensemble non-equivalence → continuous (not first order) transition (Raduta & Gulminelli PRC 2010, PRC 2012)
- With electrons : Coulomb quenching favors additionally continuous transition
- Effect on cluster distribution and thermodynamic quantities in transition region

TOTAL ENERGY PER BARYON AS FUNCTION OF BARYON DENSITY, MODEL BY RADUTA & GULMINELLI (PRC 2010)



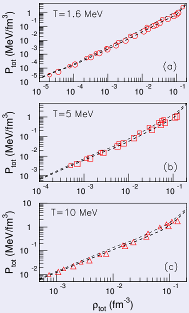
Transition from inhomogeneous to homogeneous nuclear matter

Transition from inhomogeneous to homogeneous nuclear matter in most EOS described by first order liquid gas phase transition

- Gibbs condition for phase transition : $P_I = P_{II}, \quad \mu_I^i = \mu_{II}^i$
- Many approaches use $P_I = P_{II}, \quad \mu_I^B = \mu_{II}^B, \quad Y_p^I = Y_p^{II}$
  $\rightarrow \mu_I^C \neq \mu_{II}^C$ → not in phase equilibrium !

- Gas-cluster mixture versus phase coexistence + ensemble non-equivalence → continuous (not first order) transition (Raduta & Gulminelli PRC 2010, PRC 2012)
- With electrons : Coulomb quenching favors additionally continuous transition
- Effect on cluster distribution and thermodynamic quantities in transition region

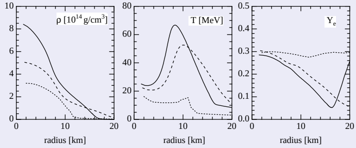
Total pressure as function of baryon density, model by Raduta & Gulminelli (PRC 2010)



Is the classical picture adequate ?

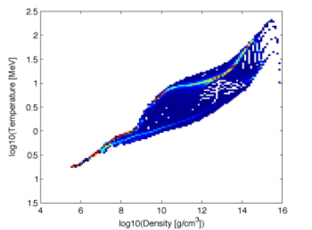
II. Can we trust the existing EOS in the high density/high temperature region ?

Example : profiles for a $40 M_\odot$ progenitor at $0, 500, 680$ ms after bounce



(Sumiyoshi et al. '09)

Example : density and temperature range for a $40 M_\odot$ progenitor



(T. Fischer, Ladek Zdroj '09)

Extreme conditions :

$$\rho = 10^6 \mathrm{g/cm}^3 \cdots 10^{15} \mathrm{g/cm}^3$$
$$T = 0.2 \mathrm{MeV} \cdots 150 \text{ MeV}$$
$$Y_e = 0.05 \cdots 0.5$$

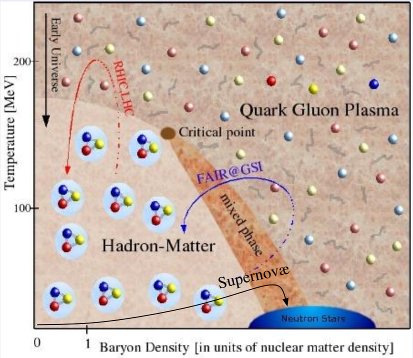
The temperatures and densities reached suggest that additional particles (hyperons, mesons, quarks, . . .) should be added (as conjectured for neutron stars and measured in heavy ion collisions) !

QUARK MATTER IN SUPERNOVAE ?

(Sagert et al. PRL 2009, Meixner et al, arXiv 1303.0064, . . .)

- Lattice QCD : T_c of roughly 150-200 MeV at vanishing baryon number density
  Quantitative location of the other borders not very well known
- Discussed as possibly occuring in the center of neutron stars (for many years !)
- Could lead to a second shock wave in supernova events (Sagert et al. PRL '09, Fischer et al. 2011) helping to produce a succesful explosion

PHASE TRANSITION BETWEEN HADRONIC MATTER AND THE QGP

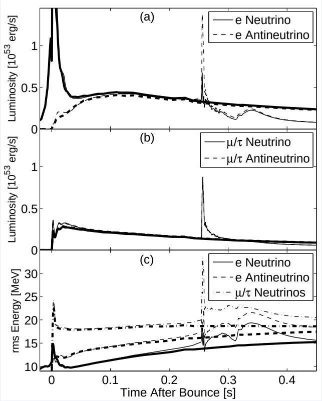


Quark matter in supernovae ?

(Sagert et al. PRL 2009, Meixner et al, arXiv 1303.0064, ...)

- Lattice QCD : T_c of roughly 150-200 MeV at vanishing baryon number density
  Quantitative location of the other borders not very well known
- Discussed as possibly occuring in the center of neutron stars (for many years !)
- Could lead to a second shock wave in supernova events (Sagert et al. PRL 2009, Fischer et al. 2011) helping to produce a succesful explosion

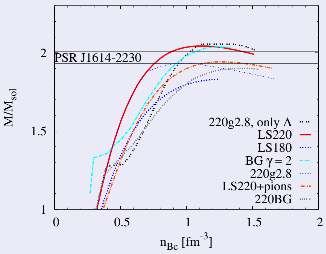
Imprint of the second shock wave on neutrino spectra from Sagert et al. (PRL 2009)



And in the intermediate density region ?

- Hyperons and mesons (pions and kaons) have been for a long time discussed to appear in the core of neutron stars (Glendenning ApJ 1985, ...)
- They can appear there if their chemical potential becomes large enough to make the conversion of N into Y energetically favorable.
  - Details strongly dependent on the interaction
  - Constraints on the interaction from hypernuclear data scarce
  - Many phenomenological models with hyperons in agreement with a two solar mass neutrons star (Bednarek et al. A& A 2012, Bonanno & SedrakianA& A 2012,Weissenborn et al. PRC 2012, NPA 2012, M.O. et al. PRC 2012, ...) by adding short-range repulsion for hyperons

Mass-central density relation for a cold neutron stars and different EOS



- Temperature effects in favor of appereance of these additional particles

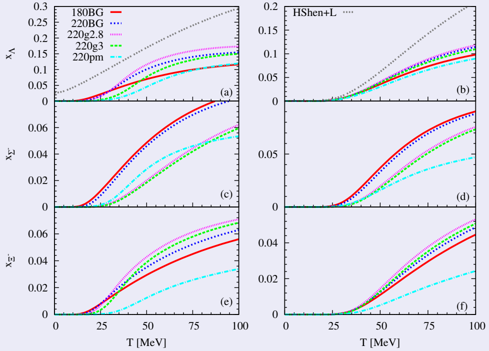
HYPERONS IN SUPERNOVA EOS

(Nakazato et al. ApJ 2012, Sumiyoshi et al. ApJL 2009, Ishizuka et al. J. Phys. G 2008, H. Shen et al. ApJ 2011, M.O. et al. PRC 2012, F. Gulminelli et al. arXiv 1301.0390, . . .)

- Extended H. Shen type RMF models with hyperons for the moment not compatible with two solar mass neutron star

- Here : local potential model by Balberg and Gal (Balberg & Gal '97) similar to LS EOS for nuclear part (LS+ EOS)
- Choose values of the parameters compatible with hyperonic data and PSR J 1614-2230
- Thermal effects increase hyperon fractions
- Effect on thermodynamic quantities not negligeable

DIFFERENT HYPERON FRACTIONS AS FUNCTION OF T FOR $n_B = 0.3$ AND 0.15 FM^{-3}, $Y_e = 0.1$ (M.O. ET AL. PRC 2012)



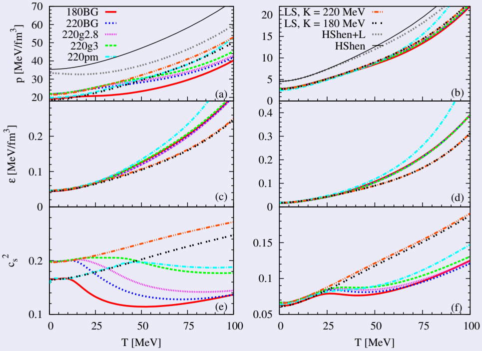
Hyperons in supernova EOS

(Nakazato et al. ApJ 2012, Sumiyoshi et al. ApJL 2009, Ishizuka et al. J. Phys. G 2008, H. Shen et al. ApJ 2011, M.O. et al. PRC 2012, F. Gulminelli et al. arXiv 1301.0390, . . .)

- Extended H. Shen type RMF models with hyperons for the moment not compatible with two solar mass neutron star

- Here : local potential model by Balberg and Gal (Balberg & Gal '97) similar to LS EOS for nuclear part (LS+ EOS)
- Choose values of the parameters compatible with hyperonic data and PSR J 1614-2230
- Thermal effects increase hyperon fractions
- Effect on thermodynamic quantities not negligeable

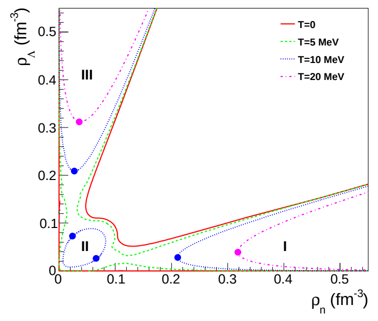
Thermodynamic quantities as function of T for $n_B = 0.3$ and 0.15 fm^{-3}, $Y_e = 0.1$ (M.O. et al. PRC 2012)



STRANGENESS DRIVEN PHASE TRANSITION IN STAR MATTER ?

- The BG-model presents a (first order) phase transition from nuclear to hypernuclear matter. For star matter ($\mu_S = 0$) this transition is strangeness drive, i.e. the order parameter is given essentially by n_S.
- The existence of a such a phase transition depends stronlgy on the (not well known) YY- and NY-interaction. It has been seen e.g. in the RMF model by Schaffner-Bielich et al. (Schaffner-Bielich et al. PRL 2002, Gal & Schafnner-Bielich PRC 2000)

PHASE DIAGRAM OF THE $n\Lambda$-SYSTEM IN THE BG MODEL



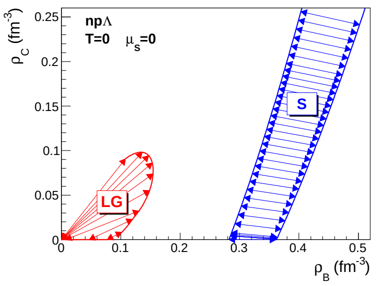
(F.Gulminelli, A. Raduta, M.O., PRC 2012)

The $np\Lambda$-system

- Three density variables : n_n, n_p, n_Λ or equivalently n_B, n_C, n_s related to conserved charges (baryon number, charge and strangeness)$\longrightarrow$ coexistence borders become surfaces in 3D space

- At $\mu_s = 0$ two phase transitions
  - For $n_s = 0$ at subsaturation ($n_B \lesssim n_0 = 0.16\text{fm}^{-3}$) the nuclear liquid-gas transition is recovered
  - For supra-saturation density ($n_B \gtrsim 2n_0$) the strangeness-driven phase transition of the $n\Lambda$-system is recovered

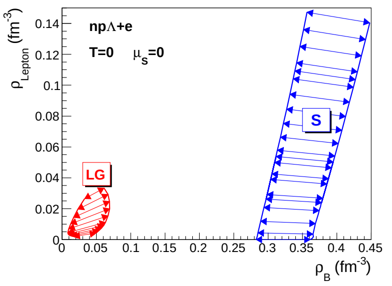
Projection of the coexistence domains in the n_B, n_C-plane for $\mu_s = 0$ (star matter) (F.Gulminelli et al. 1301.0390)



THE $np\Lambda$-SYSTEM WITH ELECTRONS

- Adding electrons means that total charge neutrality has to be fulfilled $n_p = n_e \rightarrow$ charge density no longer good degree of freedom
- Study the system as function of n_B, n_S, n_L
- The LG phase transition triggered by $n_B = n_n + n_p$ $\rightarrow n_p$ fixed by charge neutrality and huge electron incompressibility $\rightarrow$ strong quenching of the phase transition

PROJECTION OF THE COEXISTENCE DOMAINS IN THE n_B, n_L-PLANE FOR $\mu_S = 0$ (STAR MATTER) (F.GULMINELLI ET AL. 1301.0390)



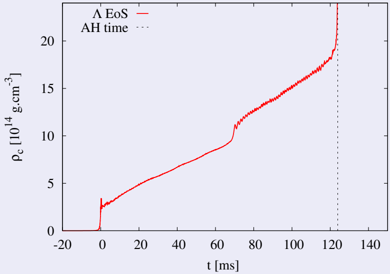
- At suprasaturation density phase transition triggered by n_s
  $\rightarrow$ only loose correlation with n_C
  $\rightarrow$ almost no quenching

AND IN A SIMULATION...

Simulations are 1D GR (COCONUT-CODE) with a neutrino leakage scheme (B. Peres et al. PRD 2013), progenitors have $40M_\odot$ ZAMS (Woosley, Heger, Weaver Rev. Mod. Phys. 2002, Woosley & Weaver ApJ 1995)

- Phase transition density only reached for progenitor with high mass accretion rate (low metallicity)
- Phase transition induces a "mini-collapse" followed by pronounced oscillations ($\sim$ 700 Hz)
- No second shock wave as in simulations with phase transition to QGP (Sagert et al. PRL 2009)

CENTRAL DENSITY AS A FUNCTION OF POSTBOUNCE TIME, PROGENITOR WITH LOW METALLICITY (B. PERES ET AL. PRD 2013)

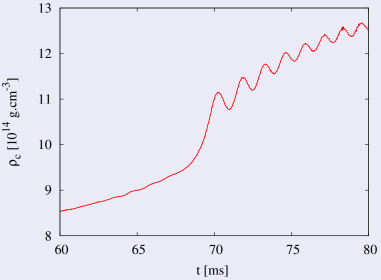


AND IN A SIMULATION...

Simulations are 1D GR (CoCoNuT-code) with a neutrino leakage scheme (B. Peres et al. PRD 2013), progenitors have $40 M_\odot$ ZAMS (Woosley, Heger, Weaver Rev. Mod. Phys. 2002, Woosley & Weaver ApJ 1995)

- Phase transition density only reached for progenitor with high mass accretion rate (low metallicity)
- Phase transition induces a "mini-collapse" followed by pronounced oscillations ($\sim$ 700 Hz)
- No second shock wave as in simulations with phase transition to QGP (Sagert et al. PRL 2009)

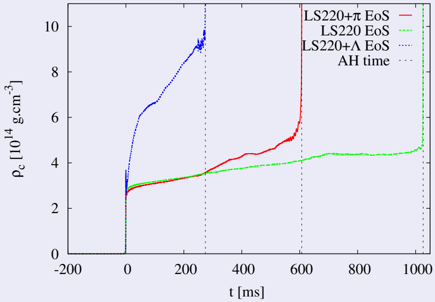
CENTRAL DENSITY AS A FUNCTION OF POSTBOUNCE TIME, PROGENITOR WITH LOW METALLICITY (B. PERES ET AL. PRD 2013)



COMPARISON BETWEEN LS AND LS+ EOS

- Strong reduction of time until black-hole collapse by including Λ-hyperons in the EOS for both progenitor models
- Confirms qualitatively Shen+ hyperons results (Nakazato et al. ApJ 2012, Sumiyoshi et al. ApJL 2009), but much stronger effect (softer nuclear part of LS)

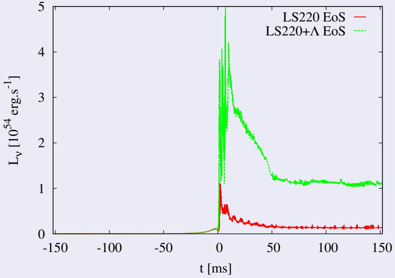
CENTRAL DENSITY AS A FUNCTION OF POSTBOUNCE TIME, PROGENITOR WITH SOLAR METALLICITY (B. PERES ET AL. PRD 2013)



COMPARISON BETWEEN LS AND LS+ EOS

- Total luminosity (leakage is a grey scheme !) very different for LS+Λ : rapid contraction of the PNS after bounce induces a sustained neutrino emission
- In the model with phase transition, oscillations of the PNS are translated to the neutrino luminosity
- Results have to be confirmed by better neutrino transport

INTEGRATED NEUTRINO LUMINOSITY, PROGENITOR WITH SOLAR METALLICITY (B. PERES ET AL. PRD 2013)



Summary and Outlook

- Uncertainties on the nuclear interaction → many different models desireable
  Has improved a lot recently
- Is it necessary to consider the whole distribution of nuclei in the sub-saturation regime ?
  - Big effect on mass distribution
  - Thermodynamic quantities not strongly modified → for the moment no strong influence on simulations can be seen

    But : Coherent treatment of neutrino effects has still to be tested

    But : Effect of thermodynamics in the transition region from inhomogeneous to homogeneous matter has still to be tested
- Is the particle content sufficient at high density and temperature ?
  - EOS available with additional particles (hyperons, . . .) compatible with a two solar mass neutron star
  - Strong effect on the simulations due to strong softening of the EOS in the PNS, e.g. collapse time to a black hole
  - Effect of possible phase transition :
    - Second shock wave induced by transition to QGP
    - Possible transition to hyperonic matter less strong→ no second shock wave, but oscillations of PNS
    - Mean free path for neutrinos strongly reduced in the vicinity of critical point associated to hyperonic transition : effect on neutrino transport has to be explored