Hyperons in neutron stars and supernova cores

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Outline

1. Some general remarks on the EoS of hot and dense matter

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2. Constraints on the EoS

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2. Constraints on the EoS
3. Why wondering about "exotic" matter ?
4. The hyperon puzzle in neutron stars
5. Hyperons in hot and dense matter

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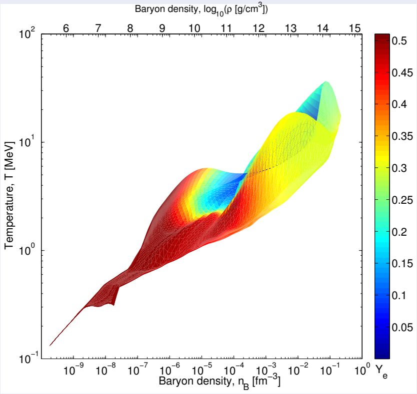
Outline

Matter composition and equation of state

Large domains in density, temperature and asymetry have to be covered and matter composition changes dramatically throughout !

1. Core-collapse supernovae
   - 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

Typical ranges in a core-collapse SN



(Fischer et al. '11)

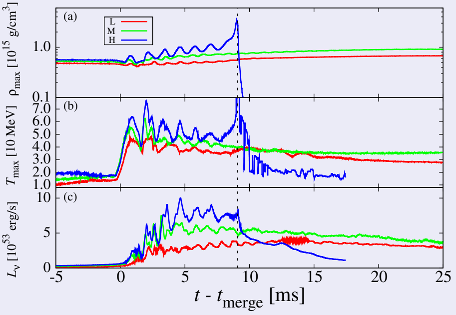
Matter composition and equation of state

Large domains in density, temperature and asymetry have to be covered and matter composition changes dramatically throughout !

2. Neutron star mergers

- Starting point : two (intermediate mass) neutron stars with core + crust
- Close to merger matter is heated up
- Very high densities reached in post-merger supermassive neutron star

Typical ranges in a NS merger



(Sekiguchi et al. '11)

- Probable site for r-process nucleosynthesis in the ejecta

Some general remarks on the EoS

The equation of state (EoS) thermodynamically relates different quantities to close the system of hydrodynamic equations. The number of parameters depends on equilibrium conditions :

- For a cold neutron star in β-equilibrium :
  - EoS is $P(n_B)$ (or equivalent)
- For core collapse and NS mergers (β-equilibrium not always acheived) :
  - EoS is $P(n_B, T, Y_L)$ (or equivalent)

Status some years ago :

NS EoS

- Many models
  - different nuclear interactions
  - different approaches (many-body, phenomenological,...)
  - different compositions (+ mesons, hyperons, quarks)

Core collapse EoS

- Few models (Hillebrandt&Wolff A&A 1984, Lattimer & Swesty NPA 1991, H. Shen et al. NPA 1998)
  - single nucleus approximation
  - only nucleons ($+ e^{\pm}, \gamma$) at high densities/temperatures
  - only three different phenomenological models

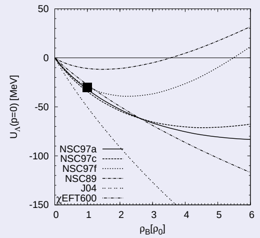
Constraints on the EoS

Basic assumption : the same (effective) interaction can be used in the whole (T, n_B, Y_L) range (e.g. Fedoseew, Lenske '15)

1. Constraints related to nuclear experiments and theoretical developments

- Extracting parameters of symmetric nuclear matter around saturation (n_0, E_B, K, S, L)
- Data from heavy ion collisions (flow constraint, meson production, ...)
- Data on nucleon-nucleon interaction fixing startpoint of many-body calculations
- Experimental data on hyperonic interactions scarce
- Low density neutron matter : Monte-Carlo simulations and EFT approaches
- Lattice QCD simulations (but not possible for high densities)

Λ single partical potential

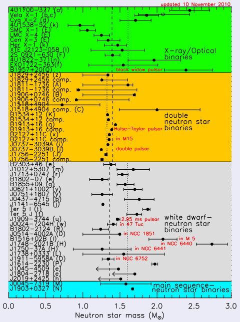


(Djapo, Schaefer, Wambach PRC '08)

Constraints on the EoS

2. Main present constraint on supra-saturation density : neutron star masses

- Observed masses in binary systems (NS-NS, NS-WD, X-ray binaries) with most precise measurements from double neutron star systems.
- Many NS-NS systems give masses close to $1.4 M_\odot$
- Two precise mass measurements in NS-WD binaries
  - $M = 1.97 \pm 0.04 M_\odot$ (PSR J1614-2230)
    (Demorest et al, Nature 2010)
  - $M = 2.01 \pm 0.04 M_\odot$ (PSR J0348+0432)
    (Antoniadis et al, Science 2013)



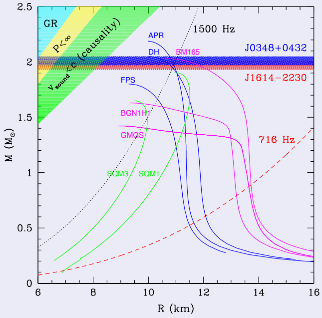
(Lattimer & Prakash, 1012.3208)

- $2\ M_\odot$ perhaps not the end of the story (e.g. indications for a $2.4\ M_\odot$ NS in B1957+20 (van Kerkwijk et al., ApJ 2011))

Constraints on the EoS

3. Other NS observations

- Measurements of rotational frequency
  - $f = 716$ Hz (PSR J1748-2446ad)
    (Hessels et al, Science 2006)
  - $f = 1122$ Hz not confirmed ! (XTE J1739-285) (Kaaret et al. ApJ 2007)
- Theory : Kepler frequency $f_K = 1008\,\mathrm{Hz}\,(M/M_\odot)^{1/2}\,(R/10\mathrm{km})^{-3/2}$
  (Haensel et al. A&A 2009)
  $\rightarrow$ A measured frequency of 1.4 kHz would constrain $R_{1.4} < 9.5$ km !



(Courtesy of M. Fortin, CAMK)

- Radius determinations so far model dependent (atmosphere model, distance, ...)
- Moment of inertia, asteroseismology, ...model dependent, too $\rightarrow$ no stringent constraint so far

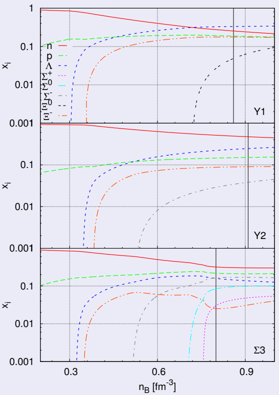
Why wondering about "exotics" ?

There is nothing "exotic", particles are known for a long time from experiments !

- Classical example : hyperons can appear in cold dense matter if μ_Y becomes large enough to make the conversion of N into Y energetically favorable.

- In compact stars strangeness changing weak equilibrium assumed $\rightarrow \mu_S = 0$ (e.g. $\mu_\Lambda = \mu_n$)
- The order in which the different hyperons appear depends on the interaction
- Most models predict that they appear at $n_B \sim 2 - 3n_0$
  Similar result for different types of models
  - Phenomenological mean field models (Glendenning ApJ '85, Balberg & Gal NPA '98, ...)
  - Microscopic many body calculations (Baldo et al. PRC '98, Vidaña et al. PRC '00, Djapo et al. PRC '08 ...)
- Similar arguments for other particles, much dependent on interaction

Particle abundances in β-equilibrated cold NS matter



(M.O., C. Providencia, F. Gulminelli, A. Raduta, '15)

The hyperon puzzle

1. The problem

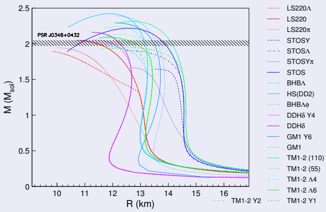
- Most models predict hyperons at $n_B \gtrsim 2 - 3n_0$ but give maximum neutron star masses of $\sim 1.4M_\odot$ $\rightarrow$ need short-range repulsion to stiffen the EoS

2. Different solutions

- Let quark matter appear early (very early !) enough :
  Phenomenological quark models can be supplemented with the necessary repulsion (Armen's talk, Weissenborn et al., '11, Alford et al. '07,...)

- Modify the interaction
  - In microscopic models (BHF) this seems to be a problem (Vidaña et al., '11, Schulze & Rijken '11)
  - In phenomenological models not difficult (Bednarek et al. '12, Bonanno & Sedrakian '12,Weissenborn et al. '12, MO et al. '12,...), high density repulsion mainly via YY interaction

Different hyperonic interactions



(MO, C. Providencia, F. Gulminelli, A. Raduta, JPG 2015)

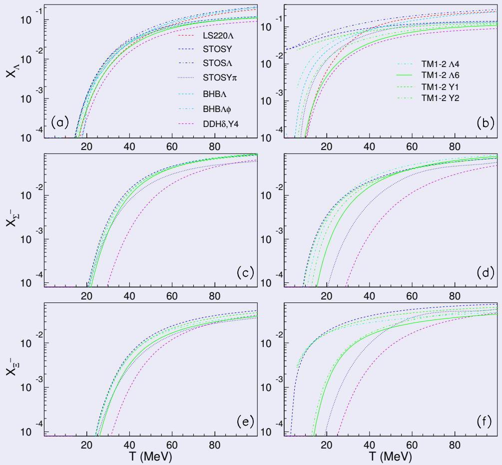
- Large variety in different radii and strangeness contents
  $R < 10$ km would be difficult !

Hyperons in hot and dense matter

(Nakazato et al. '12, Sumiyoshi et al. '09, Ishizuka et al. '08, H. Shen et al. '11, M.O. et al. '12, F. Gulminelli et al. '13, ...)

- For the moment no complete models containing the full baryonic octet and compatible with a 2 $M_\odot$ NS *work in progress*
- Here : comparison of different models
- Thermal effects increase hyperon fractions
- Hyperons are more abundant in models with hard symmetry energy
- Hyperons fractions increase with decreasing Y_q

Different hyperon fractions as function of T for $n_B = 0.3$ and 0.15 fm^{-3}, $Y_e = 0.1$



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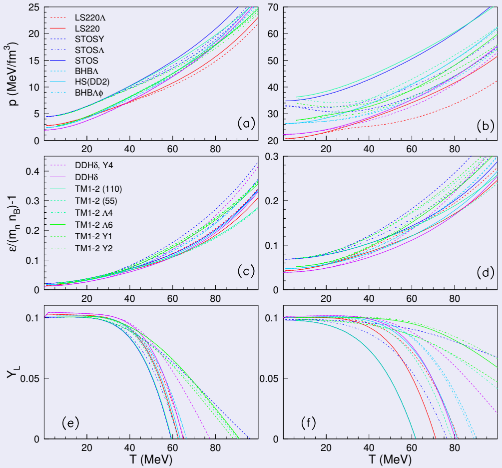
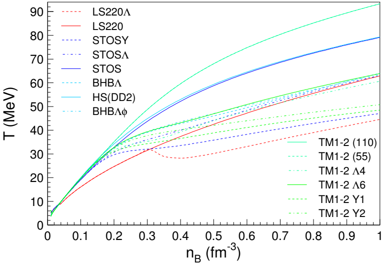
Thermodynamic quantities as function of T for $n_B = 0.3$ and 0.15 fm^{-3}, $Y_e = 0.1$

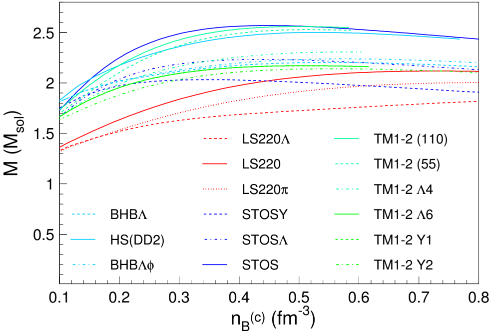


Effect of hyperons on the EoS

1. Temperature for given entropy

- More degrees of freedom $\rightarrow$ entropy distributed in more channels $\rightarrow$ lower temperature





2. Maximum mass at $s_B = 4k_B$

- Correlation proposed between time to BH formation and maximum mass of $s_B = 4k_B$ star (Hempel et al. '11, Steiner et al. '12)
- Strong dependence on EoS $\rightarrow$ good test of thermal effects on the EoS ?

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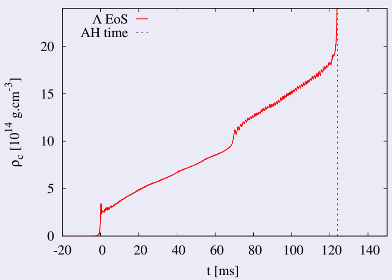
And in a simulation...

Simulations are 1D GR (CoCoNuT-code) with a neutrino leakage scheme (Peres et al. '13), progenitors have $40 M_\odot$ ZAMS (Woosley, Heger, Weaver '02, Woosley & Weaver '95), EoS is LS220Λ

- Phase transition present in the LS220Λ EoS 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. '09)
- Strong reduction of time until BH formation by including Λ-hyperons in the EOS
- Qualitatively similar results with Shen+ hyperons (Nakazato et al. '12, Sumiyoshi et al. '09) and BHB$\Lambda(\Phi)$ (Char et al. '15)

Central density as a function of postbounce time, progenitor with low metallicity (Peres et al. '13)



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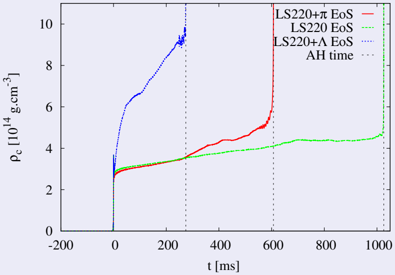


Summary and Outlook

1. Cold β-equilbrated matter in neutron stars

    - Intensive discussion on composition of matter in the central part triggered by high mass NS observations : different solutions proposed without any definite conclusion

2. Hot and dense matter not necessarily in β-equilibrium

    - Is the particle content sufficient at high density and temperature ?
        - Thermal effects are in favor of additional particles (hyperons, ...), EoS are developped compatible with a two solar mass neutron star
        - Visible effect on the simulations for black hole formation and NS mergers due to softening of the EoS, e.g. collapse time to a black hole, GW emission from mergers

Important point : need more information to constrain the intreractions of those particles !

IDEA OF THE COMPOSE PROJECT WITHIN NEWCOMPSTAR

Provide data tables for different EoS ready for further use in astrophysics of compact objects and nuclear physics (core team : S. Typel, T. Klähn, MO) :

http ://compose.obspm.fr

- CompOSE is a repository of EoS tables in a common format for direct usage with information on a large number of thermodynamic properties, on the chemical composition of dense matter and, if available, on microphysical quantities of the constituents.
- CompOSE allows to interpolate the provided tables using different schemes to obtain the relevant quantities, selected by the user, for grids that are tailored to specific applications.
- CompOSE can provide information on additional thermodynamic quantities, which are not stored in the original data tables, and on further quantities, which characterize an EoS such as nuclear matter parameters and compact star properties.

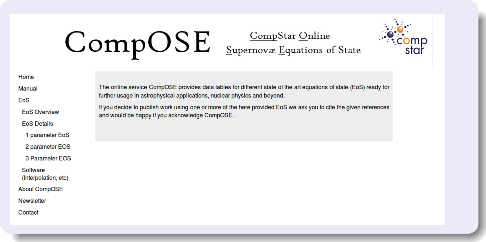
Current status of the Compose project

1. What has been done

1. CompOSE is completely open access (Jean-Yves Giot, Thomas Klähn)
2. Many new data, in particular full 3D models, but including 1D cold NS ones, too
3. 1D NS EoS can be used directly within Lorene to obtain rotating/magnetised NS models (Jérôme Novak)

2. Ongoing work

1. Include polynomial fits in addition to tabulated EoS (F. Burgio, J. Margueron, D. Davesne, A. Pastore)
2. Allow for a more flexible format to include for instance two-fluid EoS, magnetic field dependence, . . . (S. Typel)



CompOSE

CompStar Online Supernovæ Equations of State

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EoS Details
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2 parameter EOS
3 Parameter EOS
Software (Interpolation, etc)
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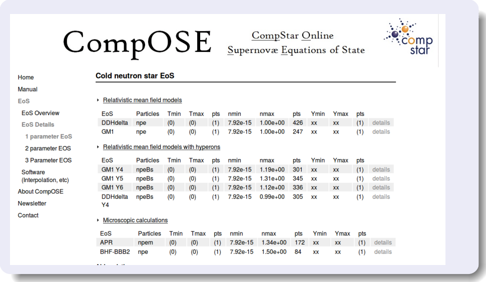
The online service CompOSE provides data tables for different state of the art equations of state (EoS) ready for further usage in astrophysical applications, nuclear physics and beyond.

If you decide to publish work using one or more of the here provided EoS we ask you to cite the given references and would be happy if you acknowledge CompOSE.



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Cold neutron star EoS

Relativistic mean field models

EoS	Particles	Tmin	Tmax	pts	nmin	nmax	pts	Ymin	Ymax	pts	
DDHdelta	npe	(0)	(0)	(1)	7.92e-15	1.00e+00	426	xx	xx	(1)	details
GM1	npe	(0)	(0)	(1)	7.92e-15	1.00e+00	247	xx	xx	(1)	details

Relativistic mean field models with hyperons

EoS	Particles	Tmin	Tmax	pts	nmin	nmax	pts	Ymin	Ymax	pts	
GM1 Y4	npeBs	(0)	(0)	(1)	7.92e-15	1.19e+00	301	xx	xx	(1)	details
GM1 Y5	npeBs	(0)	(0)	(1)	7.92e-15	1.31e+00	345	xx	xx	(1)	details
GM1 Y6	npeBs	(0)	(0)	(1)	7.92e-15	1.12e+00	336	xx	xx	(1)	details
DDHdelta Y4	npeBs	(0)	(0)	(1)	7.92e-15	0.99e+00	305	xx	xx	(1)	details

Microscopic calculations

EoS	Particles	Tmin	Tmax	pts	nmin	nmax	pts	Ymin	Ymax	pts	
APR	npem	(0)	(0)	(1)	7.92e-15	1.34e+00	172	xx	xx	(1)	details
BHF-BBB2	npe	(0)	(0)	(1)	7.92e-15	1.50e+00	84	xx	xx	(1)	details

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And thanks to you for your attention !