Hot and dense matter in neutron stars and core-collapse supernovae

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Les grandes questions en physique nucléaire fondamentale, June 21 - 22, 2016

Outline

1. Some general remarks

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2. What do we know ?
3. Open problems
   - Clusterised matter
   - Homogeneous matter
   - What about "exotic" matter ?

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4. Summary

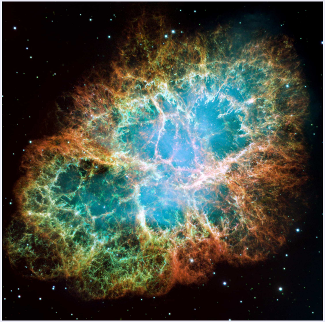
Why are we interested in hot and dense matter ?

Astrophysical point of view :

- Supernovae/hypernovae (stellar evolution, explosion mechanism, formation of compact objects,...)
- Compact object mergers (gravitational waves, γ-ray bursts, ...)
- Site for production of heavy elements and chemical evolution of the universe

$\rightarrow$ see talks this afternoon

Crab nebula (Hubble telescope)



Microphysics point of view :

- Neutrino interactions (with matter and neutrino oscillations)
- Study (strongly interacting) matter under extreme conditions of temperature and density not reachable in terrestrial experiments

What is "hot and dense" ?

We want to describe :

- Core-collapse supernovae and subsequent neutron star/black hole formation
- Binary neutron star mergers and neutron star black hole mergers
- Neutron stars

→ Large domains in density, temperature and asymetry have to be covered

temperature	$0\ \mathrm{MeV} \leq T < 150\ \mathrm{MeV}$
baryon number density	$10^{-11}\ \mathrm{fm}^{-3} < n_B < 10\ \mathrm{fm}^{-3}$
electron fraction	$0 < Y_e < 0.6$

and matter composition changes dramatically throughout !

Different regimes :

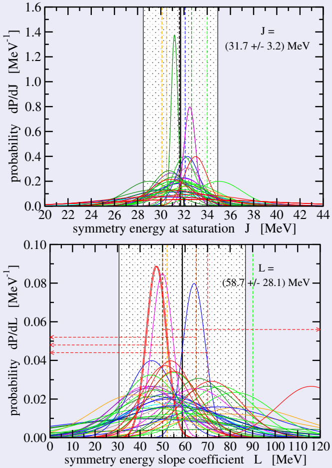
- Very low densities and temperatures :
  - dilute gas of non-interacting nuclei → nuclear statistical equilibrium (NSE)
- Intermediate densities and low temperatures :
  - gas of interacting nuclei surrounded by free nucleons → beyond NSE
- High densities and temperatures :
  - nuclei dissolve
    → strongly interacting (homogeneous) hadronic matter
  - potentially transition to the quark gluon plasma

Constraints on the EoS

1. Constraints related to nuclear experiments and theoretical developments

- Extracting parameters of symmetric nuclear matter around saturation (n_0, E_B, K, J, L)
- Data from heavy ion collisions (flow constraint, meson production, ...)
- Data on nucleon-nucleon interaction fixing startpoint of many-body calculations (data on hyperonic interactions scarce $\rightarrow$ talk by E. Khan)
- Low density neutron matter : Monte-Carlo simulations and EFT approaches

Distribution of values for J and L

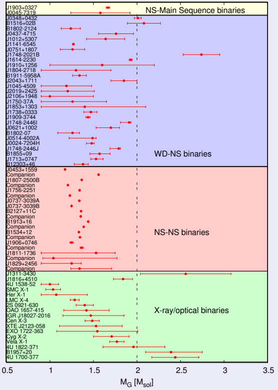


[MO, M. Hempel, T. Klähn, S. Typel 2016]

Constraints on the EoS

2. Constraints from astrophysical observations

- 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
  - $M = 1.928 \pm 0.017 M_\odot$ (PSR J1614-2230)
    [Demorest et al 2010, Fonesca et al 2016]
  - $M = 2.01 \pm 0.04 M_\odot$ (PSR J0348+0432)
    [Antoniadis et al 2013]



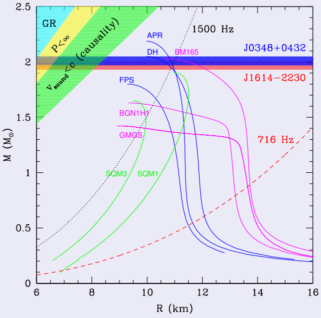
[Update from Lattimer & Prakash, 1012.3208]

- 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

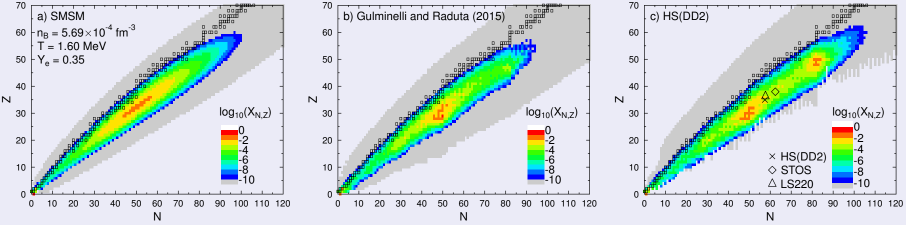
Clustered matter

Nuclear abundances important for composition of (proto-)neutron star crust, nucleosynthesis and CCSN matter

Modelling does not only depend on the interaction chosen :

- Theoretical description of inhomogeneous system (interplay of Coulomb and strong interaction, surface effects, ...)
- Binding energies of (neutron rich) nuclei
- Treatment of excited states
- Transition to homogeneous matter (stellar matter is electrically neutral !)

Nuclear abundances within different models (same thermodynamic conditions, gas density negligible)

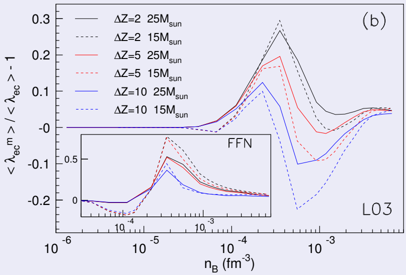


Reaction rates

- Overall reaction rates : matter composition + individual rates
  - Homogeneous matter : calculate individual rates in hot and dense medium $\rightarrow$ collective response
  - Clustered matter : rates on nuclei far from stability (up to now essentially shell model)

- Different (weak) interaction rates are extremely important ! Neutrino emission, electron capture, . . .
- And very sensitive to the different ingredients
  - Example : influence of nuclear masses for nuclei with neutron numbers between $N = 50$ and $N = 82$ $\rightarrow$ up to 30% change in overall EC rate

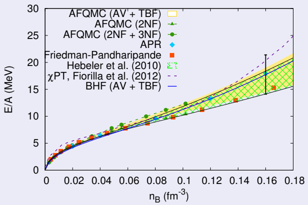
Nuclear masses and EC rates



[Raduta et al 2016]

NEUTRON MATTER AND M-R RELATION

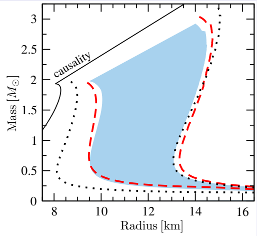
COMPARISON OF DIFFERENT NM CALCULATIONS



- Pure neutron matter well suited for ab-initio calculations
- For $n_B \lesssim 0.16$ fm^{-3}, all ab-initio calculations in reasonable agreement
- Uncertainties mainly due to 3N forces

- Constraints on NS M-R relation from BPS crust $(n_B < n_0/2)$ + NM + polytropes
- But at low M radii very sensitive to crust-core matching and treatment of the crust [M. Fortin et al. 2016]
- Development of 'generic' parameterised EoS

COMBINATION OF NM RESULTS + $M_{max} = 1.97 M_\odot$



[Hebeler et al., 2013]

The hyperon puzzle

1. The problem

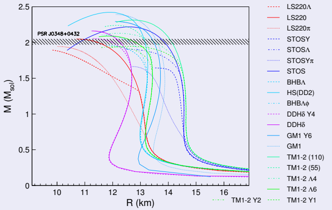
- Most models predict hyperons at $n_B \gtrsim 2 - 3n_0$ but give maximum neutron star masses of $\sim 1.4 M_\odot$ $\rightarrow$ need short-range repulsion to stiffen the EoS

2. Different solutions

- Let quark matter appear early (very early !) enough :
  Phenomenological quark models can be supplemented with the necessary repulsion [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

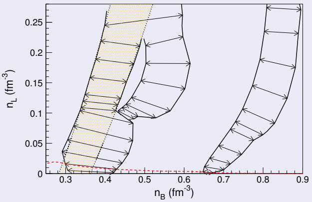


[MO, C. Providencia, F. Gulminelli, A. Raduta 2015]

- Large variety in different radii and strangeness contents

More remarks on 'exotics'

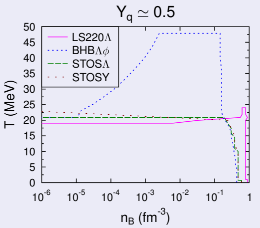
Phase diagram of baryonic matter with strangeness



[MO, F. Gulminelli, C. Providencia, A. Raduta, 2016]

- Is the onset of hyperonic degrees of freedom accompanied by a phase transition ?
- If yes, many interesting effects : neutrino mean free path ...
- Model and interaction dependent

Strangeness fraction $> 10^{-4}$



[MO, M. Hempel, T. Klähn. S. Typel, 2016]

- Temperature effects in favor of non-nucleonic degrees of freedom
- What about nuclear resonances, mesons, muons ?
- Is there a transition to the QGP ?

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Conclusion

We need to know matter properties (EoS and reaction rates) in regions not accesible to experiments !

1. Many open questions :

1. How and under which conditions do non-nucleonic degrees of freedom appear ?
2. When does nuclear matter deconfine ?
3. Can we develop a QCD based framework that covers the relevant range of variables ?
4. How to better treat spatially inhomogeneous matter and cluster formation ?
5. How to describe phase transitions consistently ?

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.