EoS for neutron stars and core-collapse supernovae

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Outline

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

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2. Brief summary of experimental, theoretical, and observational constraints

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4. Homogeneous matter

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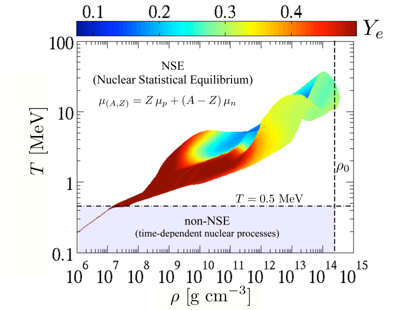
Matter composition and equation of state

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



[Courtesy T. Fischer]

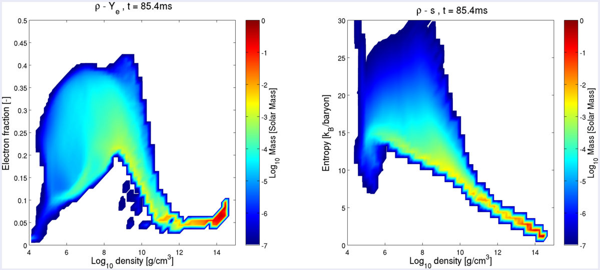
Matter composition and equation of state

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



[Courtesy A. Perego]

Matter composition and equation of state

We want to describe all : CCSN, binary mergers and neutron stars $\longrightarrow$ Domains in density, temperature and asymetry :

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

Different regimes :

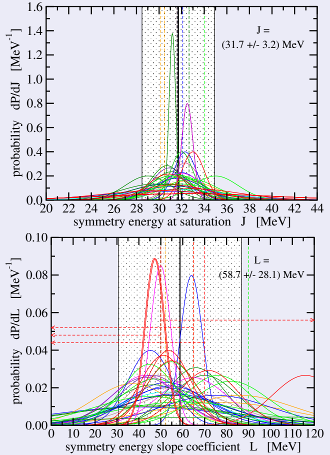
- Very low densities and temperatures :
  - dilute gas of non-interacting nuclei $\longrightarrow$ nuclear statistical equilibrium (NSE)
- Intermediate densities and low temperatures :
  - gas (crystal) of interacting nuclei surrounded by free nucleons $\longrightarrow$ beyond NSE
- High densities and temperatures :
  - nuclei dissolve
    $\longrightarrow$ strongly interacting (homogeneous) hadronic matter
  - potentially transition to the quark gluon plasma
- The equation of state (EoS) thermodynamically relates different quantities to close the system of hydrodynamic equations. The number of parameters depends and equilibrium conditions, most general one $P(n_B, T, Y_i)$

Constraints on the EoS

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)
- Low density neutron matter : Monte-Carlo simulations and EFT approaches

Distribution of values for J and L



[MO, M. Hempel, T. Klähn, S. Typel 2017]

Constraints on the EoS from observations

1. NS masses

- Observed masses in binary systems (NS-NS, NS-WD, X-ray binaries) with most precise measurements from double neutron star systems.
- 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]

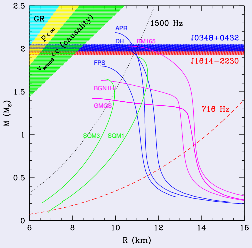
2. NS radii

- Radius determinations so far model dependent (atmosphere model, distance, ...), new projects underway (NICER, SKA, ...)

3. Rotation frequency

- Measurements of rotational frequency very precise
  - $f = 716$ Hz (PSR J1748-2446ad) [Hessels et al, 2006]

but for the moment well below Kepler frequency

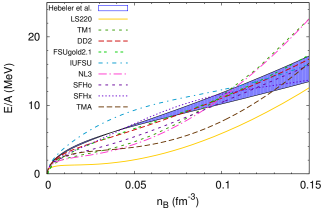


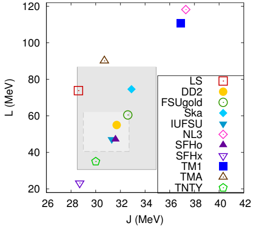
(Courtesy of M. Fortin, CAMK)

Compatibility with the constraints

- Many (most) general purpose EoS not compatible with constraints on the EoS !

1. Ab-initio neutron matter calculations
   - Ab-initio calculations in good agreement below roughly saturation
   - Most EoS show deviations, only DD2, IUFSU, and SFHo in reasonable agreement





2. Symmetry energy and slope
   - Quantities strongly correlated with NS properties (radius !)
   - Limits extracted from variety of experiments

[Lattimer & Lim 2013, MO et al 2017]

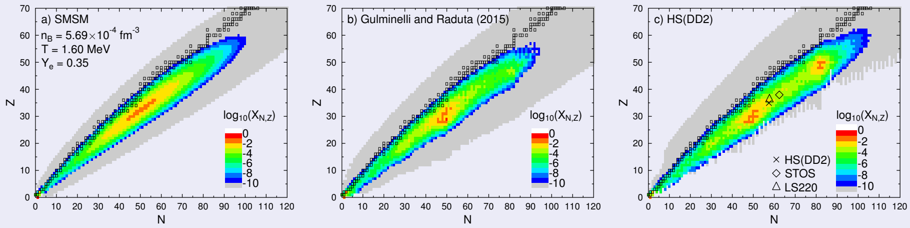
Remark : Constraints essentially on homogeneous matter at relatively low densities

Statistical models for inhomogeneous matter

- Much recent progress in description of inhomogeneous system using extended NSE approaches
- Main differences between models arising from
  - Binding energies of (neutron rich) nuclei
  - Treatment of excited states
  - Modelling of transition to homogeneous matter (stellar matter is electrically neutral !)

$\rightarrow$ modelling does not only depend on the interaction chosen, knowing $K, L, \cdots$ is not sufficient !

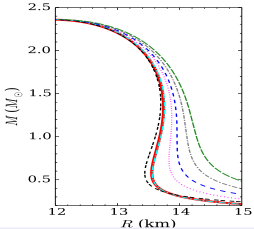
Nuclear abundances within different models (same thermodynamic conditions, gas density negligible)



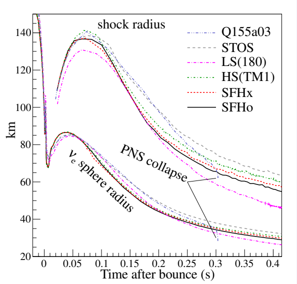
Some implications for compact objects

- Importance of unified NS models
  [Fortin et al PRC 2016, Brussels group, ...]
- Only small differences in global quantities (pressure, ...), but comparable to differences in nuclear interaction models
- Important for weak interaction rates

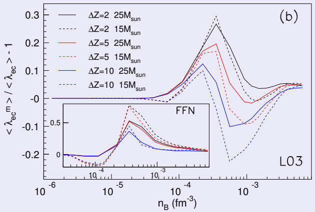
NS radii, dependence on crust-core transition
[Fortin et al. PRC 2016]



CCSN, shock radius and neutrinosphere
[Steiner et al. ApJ 2013]



Nuclear masses and EC rates
[Raduta et al 2016]



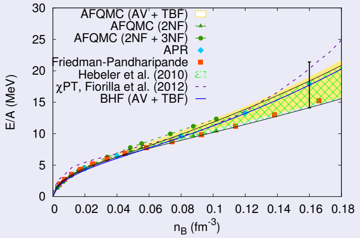
Models for homogeneous matter

- Two types of models :

  1. "ab initio" microscopic calculations starting from the basic few-body interaction
     - ⋆ (Dirac)-Brueckner-Hartree-Fock
     - ⋆ Self-consistent Green's function
     - ⋆ Monte Carlo techniques
     - ⋆ RG evolved forces
     - ⋆ ...

     → much progress in particular for (dilute) neutron matter !

Different ab initio neutron matter calculations



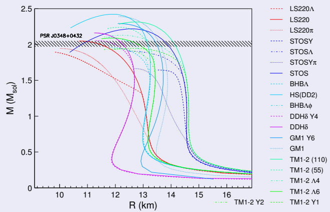
  2. phenomenological models with effective interactions
     - ⋆ liquid drop
     - ⋆ mean field (Skyrme, Gogny, RMF, ...)

     → many variants, up to now unified/general purpose models only for effective interactions

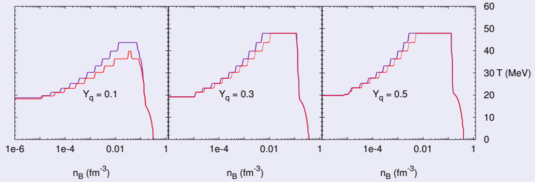
Particle content of dense matter ?

- In NSs : most classical models predict hyperons at $n_B \gtrsim 2 - 3n_0$ but give maximum neutron star masses of $\sim 1.4 M_\odot$
- Modify the interaction adding high density repulsion [Bednarek et al. '12, Bonanno & Sedrakian '12,Weissenborn et al. '12, MO et al. '12,. . .]

Different hyperonic interactions [MO et al 2015]



Regions with hyperon content $Y_S > 10^{-4}$ [Marques et al 2017]



- Thermal effects favor appearance of hyperons : region with hyperons almost independent of interaction

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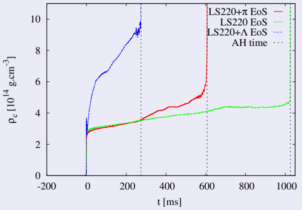
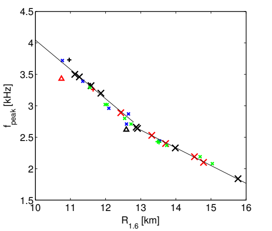
And in simulations . . .

- Strong reduction of time until black-hole collapse by including Λ-hyperons in the EoS (Nakazato et al. ApJ 2012, Sumiyoshi et al. ApJL 2009, Peres et al. PRD 2013, Banik et al. 1404.6173)

Central density as a function of postbounce time, progenitor with solar metallicity, $40 M_\odot$ progenitor [Peres et al. 2013]



GW peak frequency of merger against radius of a $1.6 M_\odot$ NS (Bauswein et al. 2012)



- Strong dependence on EoS in NS mergers →neutrino and GW signal ? [Sekiguchi et al 2011, Bauswein et al 2012, . . .]

Summary and outlook

1. Summary
   - Much progress in recent years on general purpose EoS
     - Inhomogeneous matter : statistical models with entire nuclear distribution
     - Homogeneous matter : non-nucleonic degrees of freedom included consistent with contraints
   - Not only nuclear matter parameters are important ! Modelling of inhomogeneous matter influences CCSN (weak reactions, ...) and NS (radii, ...)
2. Outlook
   - Most general purpose models not compatible with constraints ! Improve reliability (modern interactions compatible with constraints, coupling with ab initio methods, nuclear data for neutron rich nuclei, ...)
   - EoS and reaction rates should be treated consistently