Que sait on de la matière nucléaire, son impact astrophysique et quels sont les progrès attendus?

Micaela Oertel

micaela.oertel@obspm.fr

Merci à mes collaborateurs: F. Gulminelli, M. Hempel, T. Klähn, M. Mancini, J. Novak, A. Pascal, A. Raduta, S. Typel

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

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Outline

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1. Some general remarks
2. What do we know ?
3. Some open problems
   - Equation of state
   - Reaction rates

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2. What do we know ?

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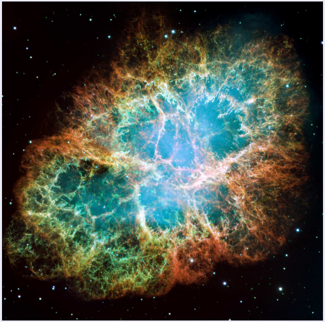
   - Equation of state
   - Reaction rates

4. What can we expect from future work ?

Outline

Why are we interested in hot and dense matter ?

Crab nebula (Hubble telescope)



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

Microphysics point of view :

- Study (strongly interacting) matter under extreme conditions of temperature, density ans asymetry (p/n-ratio) not reachable in terrestrial experiments
- Neutrino interactions (with matter and neutrino oscillations)

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

and matter composition changes dramatically throughout ! [Review MO et al RMP 2017]

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

What do we need as input from microphysics ?

- An equation of state (EoS)
- (Weak) reaction rates

- The EoS thermodynamically relates different quantities to close the system of hydrodynamic equations. The number of parameters depends and equilibrium conditions, e.g.
  - 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 and binary mergers :
    - 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)
- Reaction rates enter if equilibrium is not reached, in particular neutrino-matter interactions coupling hydrodynamic equations with neutrino transport

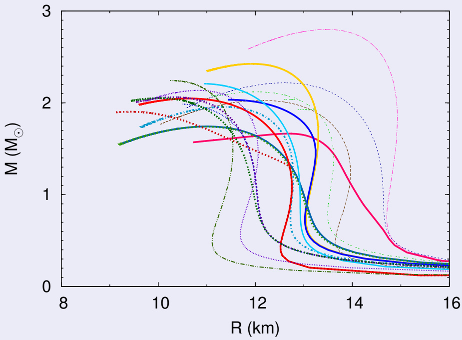
How to constrain the EoS ?

Mass-radius relation of a cold neutron star

- M and R
  - GR, stationarity+spherical symmetry
  - Equation of state (EoS)

  $\rightarrow$ solving TOV-system

Different EoS models (taken from http ://compose.obspm.fr)



- Maximum mass is a GR effect, value specific for each EoS
- Determining mass and radius of one object considered as holy grail

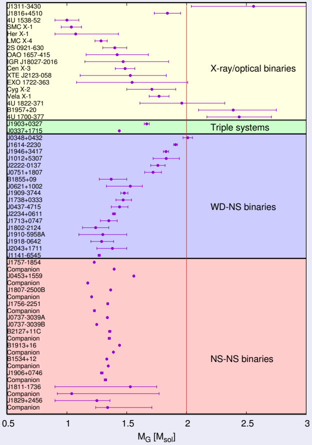
How to constrain the EoS ?

1. Neutron star 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
  - PSR J1614-2230 :
    $M = 1.908 \pm 0.016 M_\odot$ [Arzoumanian et al 2018]
  - PSR J0348+0432 :
    $M = 2.01 \pm 0.04 M_\odot$ [Antoniadis et al 2013]

Given EoS ⇔ maximum mass

Additional particles add d.o.f.
→ softening of the EoS
→ lower maximum mass
→ constraint on core composition



[update from Lattimer & Prakash, 1012.3208]

How to constrain the EoS ?

2. GW from binary NS mergers

- GW170817 : first detection of a NS-NS merger with LIGO/Virgo detectors
- Late inspiral → tidal deformability $\tilde{\Lambda}$ depends on matter properties

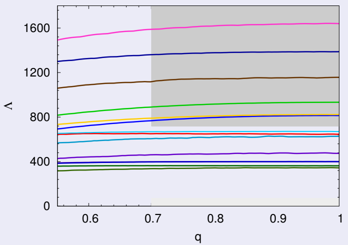
GW170817

$70 < \tilde{\Lambda} < 720$ (90% confidence level)

(low spin prior) [Abbott et al 2018]

- $\tilde{\Lambda}(M_{chirp}, q, \mathrm{EoS})$
- $\sim 5\%$ uncertainty from crust treatment
- $\lesssim 10\%$ uncertainty from thermal effects

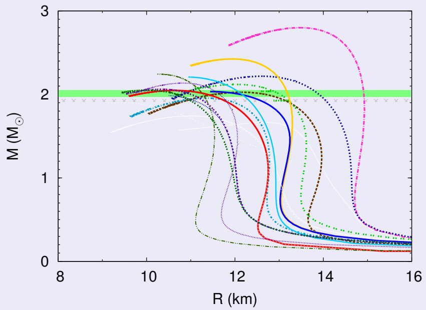
$\tilde{\Lambda}$ for different EoS models, q is mass ratio



What do we know about the EoS ?

- NS masses and $\tilde{\Lambda}$ constraints compatible with nuclear physics results :
  - Ab-initio neutron matter calculations
  - Nuclear masses, experiments for nuclear matter parameters, ...
- Non-nucleonic degrees of freedom (hyperons, mesons, quarks) might exist in the central part

Different EoS models compatible with $M_{max} > 1.97 M_{\odot}$



- Remark : Constraints essentially on homogeneous matter at relatively low densities (except for NS masses) and vanishing temperature

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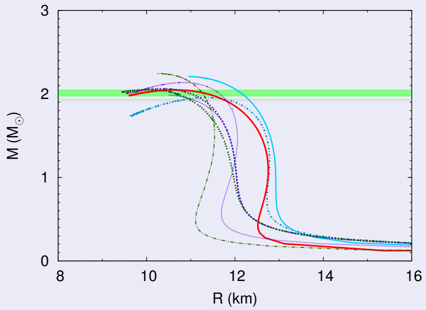

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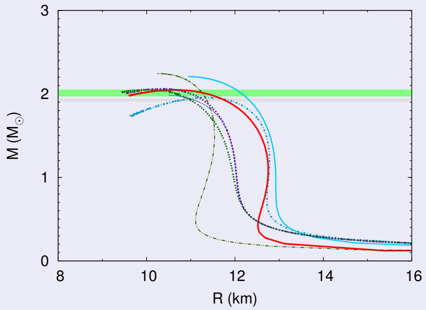
EoS compatible with $M_{max} > 1.97 M_\odot$, $\tilde{\Lambda}$ and nuclear physics



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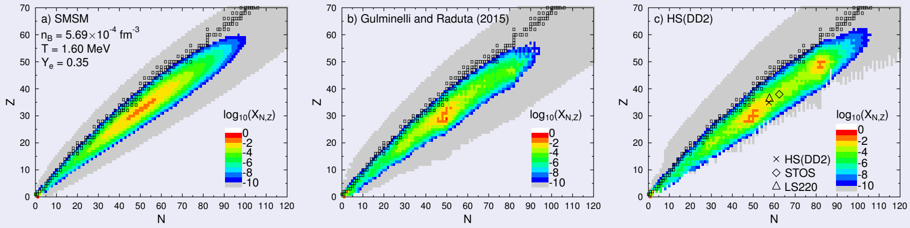
Some open problems

Equation of state

- Clusterised matter :
  - Theoretical description of inhomogeneous system (interplay of Coulomb and strong interaction, surface effects, thermal effects ...)
  - Masses of (neutron rich) nuclei
  - Transition to homogeneous matter (stellar matter is electrically neutral !)

Nuclear abundances within different models (same thermodynamic conditions during CCSN collapse phase)



- Homogeneous matter : interactions and particle content at high densities and temperatures, is there a (first order) phase transition ?

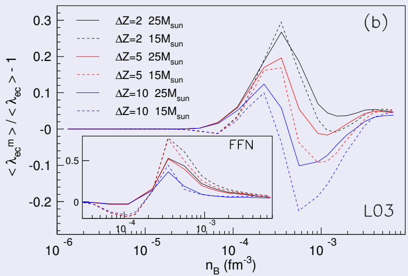
Some open problems

Reaction rates

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

- Different (weak) interaction rates are extremely important ! Neutrino emission for (P)NS cooling, CCSN neutrino signal, BNS merger ejecta composition, ...
- Very sensitive to the different ingredients
  - Example : influence of nuclear masses
    $\rightarrow$ up to 30% change in overall EC rate

Nuclear masses and EC rates



[Raduta et al 2016]

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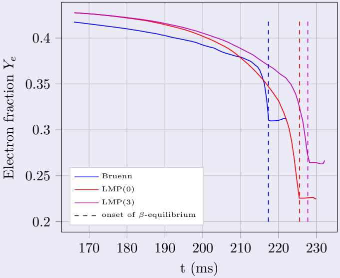
Y_e during collapse with different rates



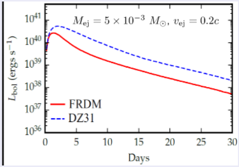
[Pascal et al, in preparation]

What can we expect from future work ?

Multi-messenger observations

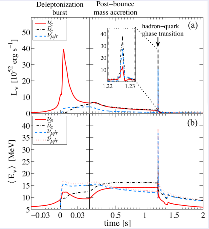
- EM observations of BNS mergers
  - Abundances of produced elements sensitive to Y_e of ejecta (EoS, merger dynamics) and nuclear masses far from stability
  - Abundances determine energy released by radioactive decays $\rightarrow$ impact on final lightcurve (with M_{ej}, v_{ej})

Bolometric kilonova lightcurves over 30 days



[Barnes et al 2016]

CCSN neutrino signal



[Fischer et al 2017]

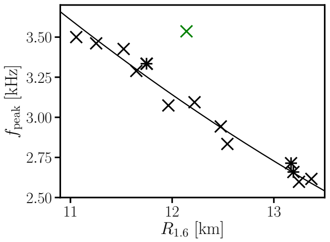
- Neutrino signal of a galactic CCSN detectable
  - Sensitive to neutrino-matter interactions (couplings, particle content, ...)
  - Sensitive to neutrino oscillations
  - Sensitive to the underlying EoS (phase transition ...)

What can we expect from future work ?

Gravitational waves

- Information on EoS from different phases of BNS mergers (or NS-BH mergers)
  - Inspiral → masses of objects
  - Late inspiral → tidal deformability, additional $\tilde{\Lambda}$ values from LIGO/Virgo runs
  - Post merger oscillations very sensitive to matter EoS → peak frequency strongly correlated with NS radius

    [Bauswein et al, Sekiguchi et al, . . .]
  - Post-merger phase accessible to future detections ?



[Bauswein et al 2018]

- GW detections from core-collapse and early proto-neutron star phase ?
- GW detections from neutron stars (oscillations) ?

Again high sensitivity to matter properties but theoretical work needed to relate unambigously signal to matter properties

What can we expect from future work ?

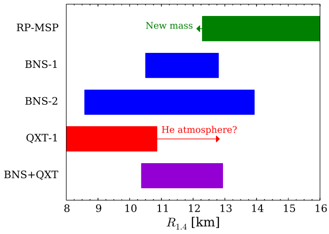
Electromagnetic NS observations

- X-ray observations of NS radii from different types of objects, but very model dependent :
  - Atmosphere modelling
  - Interstellar absorption (X-ray observations !)
  - Distance, magnetic fields, rotation, ...

Many discussions

Consensus : radius of a fiducial $M = 1.4 M_\odot$ star 10-15 km

2σ error bars, radii at $M = 1.4 M_\odot$



[courtesy M. Fortin, CAMK]

- NICER (launched June 2017) should considerably improve the situation
- Radiotelescope SKA : many new precisely determined masses, radius via moment of inertia ?
- Precise astrometry of X-ray binaries $\longrightarrow$ new massive NSs ?

l'Observatoire de Paris — LUTH
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Summary

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

1. Constraints on the EoS for the moment almost exclusively on cold matter, much progress recently, two reliable ones from massive NSs and GW170817 tidal deformability $\longrightarrow$ some models no longer viable
2. But EoS of cold matter alone is not sufficient, e.g.
    1. Thermal effects and matter composition e.g. for neutrino-matter interactions and elemental abundances ((P)NS cooling, CCSN explosion mechanism and neutrino signal, heavy element nucleosynthesis, ...)
    2. Superfluidity in NSs, magnetic field effects ($\longrightarrow$ talk by J. Novak)

Many open questions and much work needed, for the theorists from nuclear physics modellisation, simulations of compact objects to multi-messenger data analysis