Neutron stars: probing ultra-dense and hot matter

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Séminaire DPhN, 2 février 2018

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Outline

A neutron star : a star made of neutrons....

- 1932, Landau (Phys. Z. Sowjetunion, 1, 285)
  Possibility of stars with a central density comparable to that of nuclei
- 1934, Baade and Zwicky (Phys. Rev. 45, 138)
  Prediction of the existence of neutron stars : *With all reserve we advance the view that supernovae represent the transition from ordinary stars into neutron stars, which in their final stages consist of extremely closed packed neutrons.*
- 1939, Tolman, Oppenheimer, and Volkov
  General relativistic neutron star models :
  $M \approx 1.5 M_\odot$ and $r \sim$ 10 km $\longrightarrow$ density $\sim 0.1\ \mathrm{fm}^{-3}$

Walter Baade

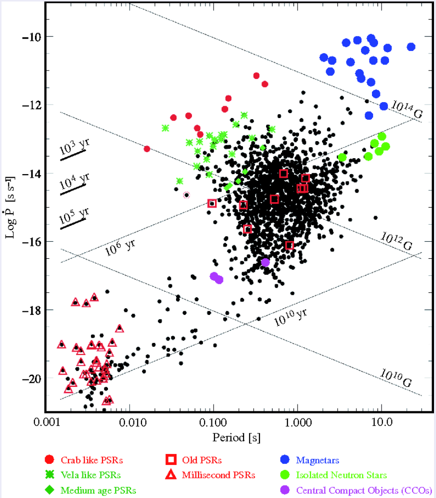
Fritz Zwicky

Signal too weak to be observed $\longrightarrow$ almost forgotten until 1967 : discovery of pulsars by Hewish and Bell

Nowadays

- Almost 3000 neutron stars have been observed as pulsars, among others Crab, Vela, Geminga, Hulse-Taylor, double pulsar, ...
- Pulsars in many different systems
- Estimate of age and surface magnetic field from measured $P, \dot{P}$ (Rotating magnetic dipole model)
- "Magnetars" have extremely high magnetic fields ($\sim 10^{15}$ G at the surface)

P-$\dot{P}$ diagram



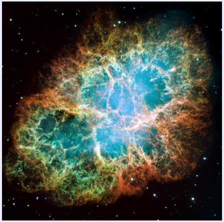
[Becker et al., 1305.4842]

Core-collapse supernovae : birth of a compact object

Supernova explosions observed since almost 2000 years
SN 1006, 1054, 1181, ... : report by arab and/or chinese astronomers
Two different classes

- Thermonuclear explosions
  - Type Ia Supernovae : ignition of runaway nuclear fusion in a white dwarf and subsequent explosion
- Core-collapse supernovae
  - All other types : gravitational collapse and subsequent explosion of a massive ($M \gtrsim$8-10$M_\odot$) star at the end of its life
    $\longrightarrow$ formation of a neutron star or a stellar black hole

Crab nebula (Hubble telescope)



SN1987A

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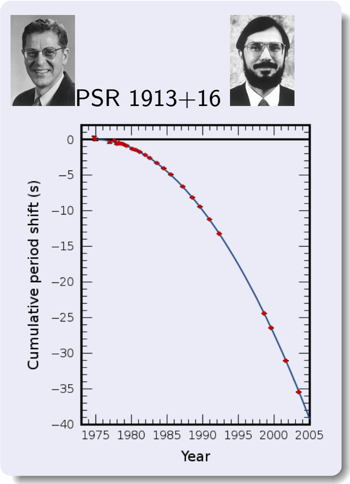
Binary neutron stars



First system observed in 1974 by Hulse and Taylor, nowadays $\sim$ 15 known systems

Extremely relativistic $\longrightarrow$ precise observations allow for testing general relativity and determining neutron star masses

Good source of gravitational waves $\longrightarrow$ change in orbital motion via gravitational wave emission : first (indirect) evidence for gravitational waves (Nobel prize for Hulse and Taylor 1993)

August 17, 2017 : first detection of the coalescence of a binary neutron star (GW + electromagnetic counterpart)

No binary NS-BH system known

Why studying dense and hot matter ?

What do we need as input from microphysics ?

- Weak reaction rates (neutrino-matter interactions)
- An equation of state

We want to understand :

- Neutron stars
  - Several minutes(!) after their birth $T \lesssim 1$ MeV $\rightarrow$ temperature effects on the EoS can in general be neglected
  - Strong, electromagnetic, and weak reactions are in equilibrium (this includes in particular β-equilibrium)
- Core-collapse supernovae and subsequent neutron star/black hole formation
  - 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
- Binary neutron star mergers and neutron star black hole mergers
  - Close to merger matter is heated up
  - Very high densities reached in post-merger supermassive neutron star

What is "hot and dense" ?

Large domains in density, temperature and electron fraction have to be covered

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

and matter composition changes dramatically throughout ! (Review MO et al RMP 2017)

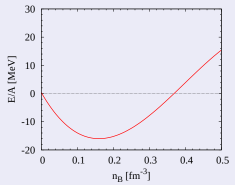
Different regimes :

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

Plan

Constraints from nuclear physics

Energy per baryon of symmetric matter

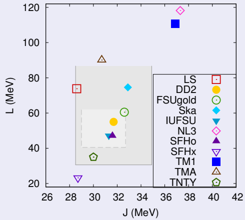


- Nuclear masses (binding energies) for many nuclei close to stability
- Extracting parameters of symmetric nuclear matter around saturation (n_0, E_B, K, J, L)
- Data from heavy ion collisions (flow constraint, meson production, ...)

- 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

Compact star matter not accessible in terrestrial laboratories (density, asymmetry) nor to ab-inito calculations !

Example : symmetry energy and slope (Lattimer & Lim 2013, MO et al 2017)

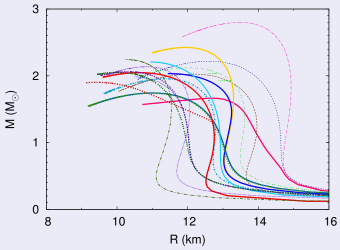


Modelling a neutron star

- Compactness $\Xi = \dfrac{GM}{Rc^2} \sim 0.2 \rightarrow$ GR gravitation (maximum mass !)

- Assumption of perfect fluid :
  $T^{\mu\nu} = (p + \varepsilon)u^\mu u^\nu + p g^{\mu\nu}$
  cold matter + β-equilibrium
  $\rightarrow$ EoS function of one parameter,
  $p(n_B), \varepsilon(n_B)$ (or equivalent)
- Simplest case : static equilibrium, spherical symmetry $\rightarrow$TOV system
  $\rightarrow$ global quantities such as
  gravitational/baryon mass and radius

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



- Maximum mass is a GR effect, value given by the EoS
- Numerical solutions exist for non-spherical cases (rotation, em field, ...)
  Publicly available codes
  - http ://www.lorene.obspm.fr
  - http ://www.gravity.phys.uwm.edu/rns/

Constraints from observations

Observations	Quantities detected	Dense matter properties
Orbital parameters in binary systems	Neutron star masses	Equation of state (EoS), high densities
GW from binary systems	Tidal deformability	Compactness, EoS
Pulsar timing	Glitches	Evidence for superfluid component
X-ray observations	Surface temperature	Heat transport/neutrino emission, superfluidity
	Radii	EoS, also low and intermediate densities (crust)
Pulsar timing	NS rotation frequencies	EoS via mass-shedding limit
GWs	Oscillations	Eigenmodes (EoS, crust properties)
QPO	Radii	EoS
	Asterosismology	Eigenmodes

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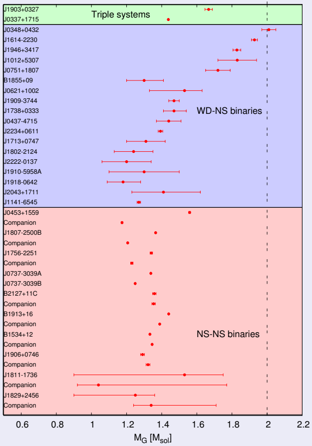
Neutron star observations

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 :
    $M = 1.928 \pm 0.017 M_\odot$ (Fonseca et al 2016)
  - PSR J0348+0432 :
    $M = 2.01 \pm 0.04 M_\odot$ (Antoniadis et al 2013)

Given EoS $\Leftrightarrow$ maximum mass

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



(update from Lattimer & Prakash, 1012.3208)

Neutron star observations

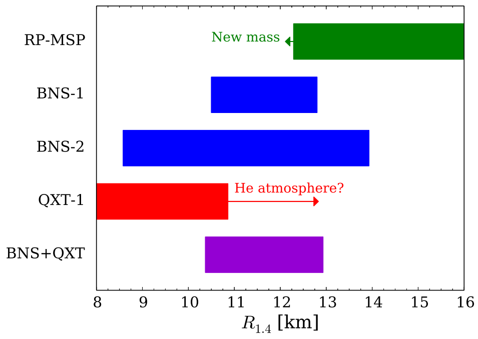
2. Radius estimates from X-ray observations

- Radii from different types of objects, but model dependent :
  - Atmosphere modelling (much recent progress)
  - 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 $M = 1.4 M_\odot$



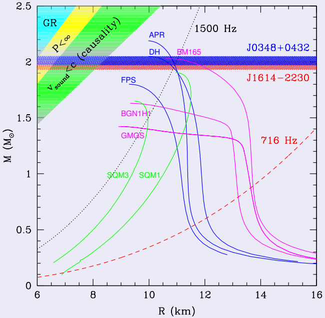
(courtesy M. Fortin, CAMK)

See also new determination by J. Nättilä et al $R(1.9 M_\odot) = 12.4 \pm 0.4$km

Neutron star observations

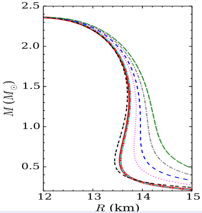
3. Pulsar timing

- Measurements of rotational frequency
  - $f = 716$ Hz (PSR J1748-2446ad) (Hessels et al, Science 2006)
- Theory : Kepler frequency (Haensel et al. A&A 2009)
  $f_K = 1008\,\mathrm{Hz}\,(M/M_\odot)^{1/2}\,(R/10\mathrm{km})^{-3/2}$



(Courtesy M. Fortin, CAMK)

NS radii, dependence on crust-core transition



(Fortin et al. 2016)

→ A measured frequency of 1.4 kHz would constrain $R_{1.4} < 9.5$ km !

Remark of caution

Radii are sensitive to rotation and to treatment of crust-core transition !

GW from binary NS mergers

- GW170817 : first detection of a NS-NS merger with LIGO/Virgo detectors
- Information on EoS from different phases
  - Inspiral → masses of objects
  - Late inspiral → tidal deformability $\tilde{\Lambda}$ depends on matter properties

    (Read et al, Faber & Rasio, Hinderer et al ...)

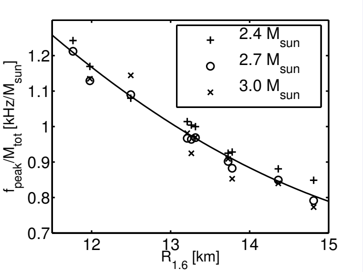
GW170817

$\tilde{\Lambda} < 800$ (90% confidence level)

(low spin prior) (Abbott et al 2017)

  - Post merger oscillations → peak frequency strongly correlated with NS radius

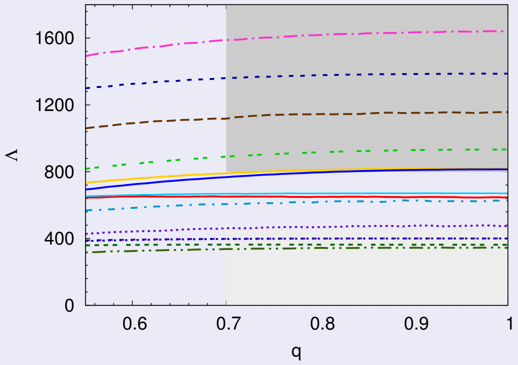
    (Bauswein et al, Sekiguchi et al, ...)



(Bauswein et al 2016)

- Tidal deformability $\tilde{\Lambda}$ depends on matter properties
- $\tilde{\Lambda}(M_{chirp}, q, \mathrm{EoS})$
- $\sim 5\%$ uncertainty from crust treatment preliminary !
- $\lesssim 10\%$ uncertainty from thermal effects preliminary !

Tidal deformability for different EoS, $q = M_1/M_2$



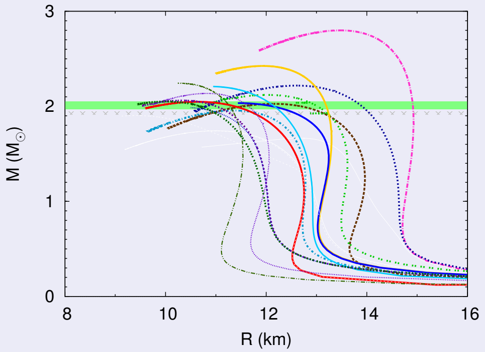
Tidal deformability

Mass-radius relations

- Some EoS (giving less compact NSs) excluded by limit on $\tilde{\Lambda}$

- Additional (model dependent) constraints from relation with EM observations
  - M_{tot} + no prompt BH collapse (Bauswein et al 2017)
  - M_{tot} + estimate of energy loss to ejecta (Margalit& Metzger 2017)
  - Ejecta masses + composition (Shibata et al 2017)
  - $\tilde{\Lambda} \gtrsim 450$ from ejecta masses (Radice et al 2017)

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



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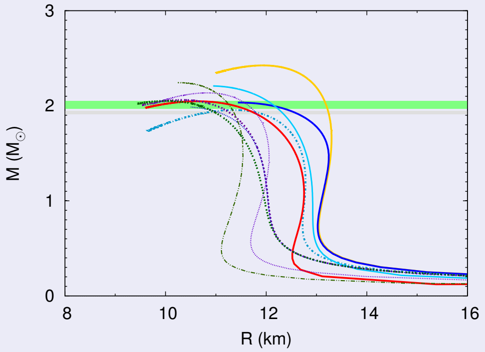

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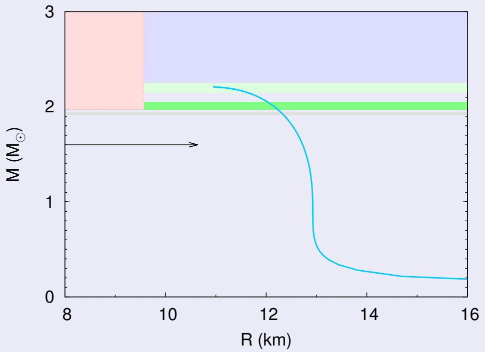
Different EoS models compatible with M_{max}, $\tilde{\Lambda}$ and EM constraints



Plan

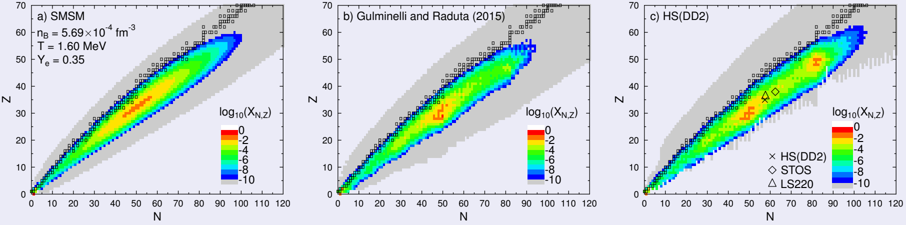
Clustered matter

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) (Mo et al 2017)

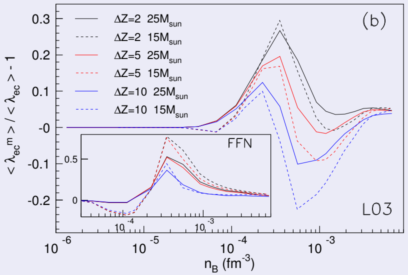


Reaction rates

- Overall reaction rates : matter composition + individual rates
  - Homogeneous matter : calculate individual rates in hot and dense medium
    → 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 $N = 82$
    → up to 30% change in overall EC rate

Nuclear masses and EC rates



(Raduta et al 2016)

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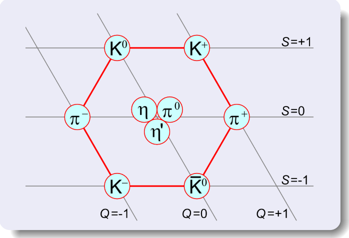
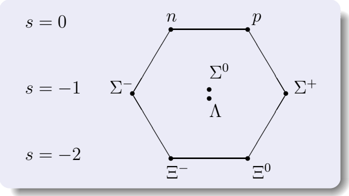
Particle content : there is nothing exotic !

- On the hadronic side, non-nucleonic degrees of freedom such as hyperons and mesons are well known and studied experimentally



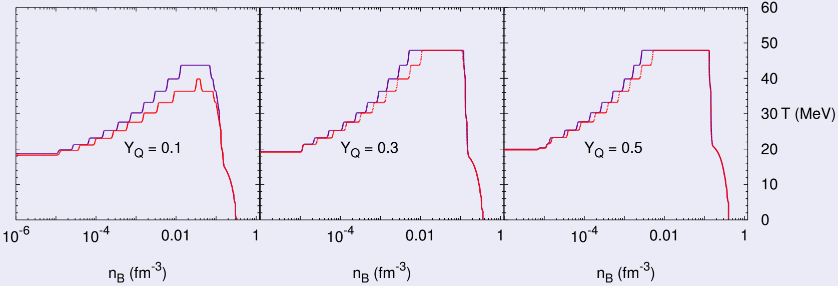
- Pions
  - discovered in 1947 in cosmic rays
  - by far lightest hadrons ($m_\pi \sim 140$ MeV)
  - prominent member of the nuclear interaction
- Kaons, strange cousins of the pions ($m_K \sim 500$ MeV)
- Hyperons
  - first hypernuclei by Daniesz and Pniewski in 1952
  - studied in scattering experiments
- Nuclear resonances ($\Delta, \ldots$)



- Charged leptons other than $e^\pm$: muons ($m_\mu = 105$ MeV) and tauons ($m_\tau = 1.8$ GeV)

Where do hyperons appear?

regions with an overall hyperon fraction $> 10^{-4}$ (Marques et al 2017)

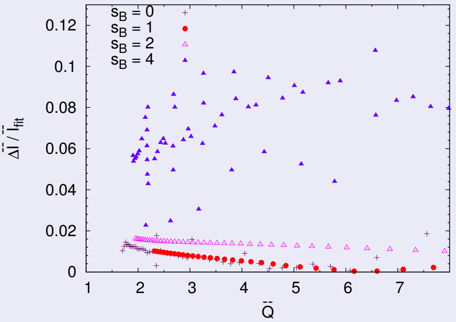


- Low charge fraction favors hyperons
- Hyperons change matter properties at high densities and temperatures (PNS, NS, merger remnant)
- Not only EoS is important, but transport properties, too (e.g. hyperonic DURCA for NS cooling (Fortin et al 2016, Raduta et al 2017))

I-Q relation with hyperons

- I-Love-Q relations : universal (independent of the EoS) relations between moment of inertia, quadrupole moment and deformability for cold slowly rotating NSs (Yagi & Yunes 2013)

- Rotation frequency dependent
- EoS independent if hyperons are included, too
- Relations become temperature dependent as far as thermal effects start to modify the EoS, i.e. for early PNSs and merger remnants (Marques et al 2017)



What about thermal effects for deformability in late inspiral of a BNS merger ?

Plan

Summary

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

- 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, ...)
- Detailed matter composition important for dynamical evolution (transport coefficients, ...), too

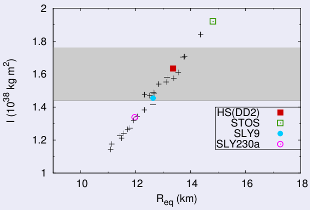
CompOSE data base (T. Klähn, M. Mancini, MO, S. Typel)

- Many EoS models available in tabular form from `https://compose.obspm.fr`
- Compose software for interpolation, calculation of thermodynamic quantities (sound speed, adiabtic index, ...) and extracting compositional information
- Coupled to Lorene for cold neutron stars (J. Novak)

Outlook

1. GW detectors
   - new NS mergers events $\longrightarrow$ deformability
   - post-merger phase probably out of range for present detectors
   - kilonova and r-process nucleosynthesis needs detailed matter composition

Moment of inertia (Livre blanc SKA France)



2. Radiotelescope SKA
   - Many new pulsars with precise mass determinations
   - Radius via moment of inertia ?
   - Fast rotating objects, constraint via Kepler frequency ?
3. NICER, ...
   - Soft X-ray timing and spectroscopy
   - Main goal : radii to $< 5\%$ precision

And...

- 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