Ultra-dense matter in neutron stars

Astrophysical constraints and gravitational waves

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Journée de la Division ≪ Champ et Particules ≫ de la SFP: la Gravitation

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

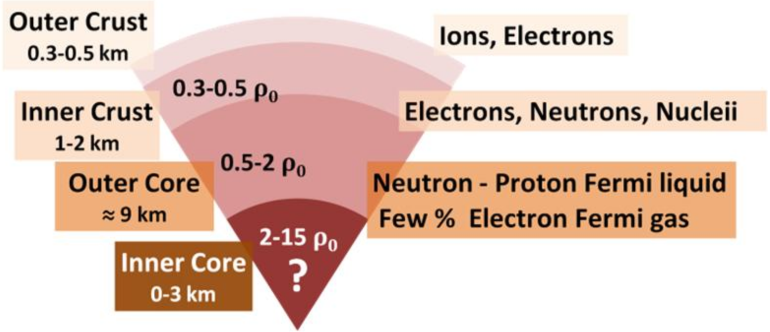
- 1932, Landau (Phys. Z. Sowjetunion, 1, 285)
  Possibility of stars with a central density comparable to that of nuclei
- 1934, Baade and Zwicky (Phys. Rev. 45, 138)
  Prediction of the existence of neutron stars : *With all reserve we advance the view that supernovae represent the transition from ordinary 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 $\rightarrow$ density $\sim 0.1\ \mathrm{fm}^{-3}$

Walter Baade

Fritz Zwicky

It is slightly more complicated

Standard picture of the inner structure



- crust formed of nuclei, neutron gas in inner crust
- transition to the core characterised by transition to homogeneous matter
- composition close to the center almost unknown (hyperons, kaon/pion condensate, quark matter . . . ?)

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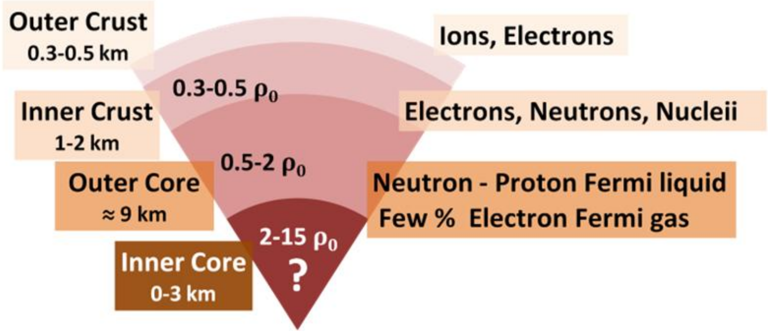

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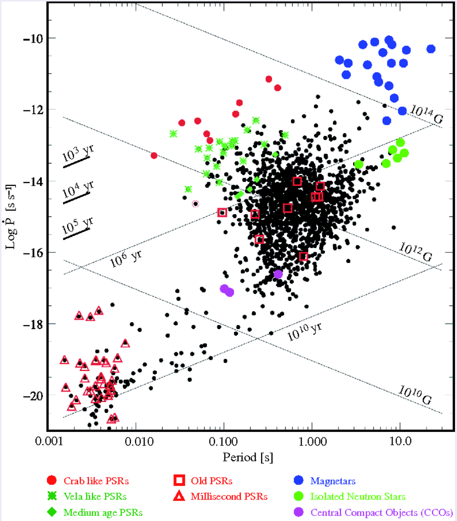
Neutron star matter not accessible in terrestrial laboratories (density, asymmetry) nor to ab-inito calculations

On the observational side

- Almost 3000 neutron stars have been observed as pulsars (G. Theureau's talk), among others Crab, Vela, Geminga, Hulse-Taylor double pulsar, ...
- Several NS-NS binary systems known
- Some NSs observed via surface emission

P-$\dot{P}$ diagram



[Becker et al., 1305.4842]

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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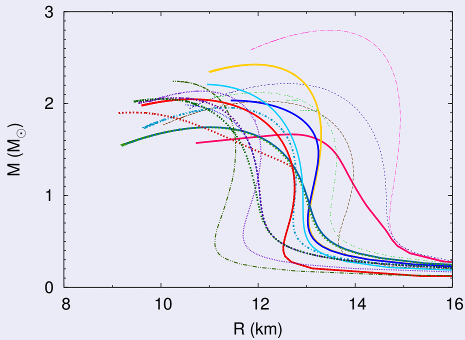
Mass-radius relation

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

  $\rightarrow$ solving TOV-system
- Matter in old NSs can be considered as cold and in weak equilibrium

  $\rightarrow$ EoS : $p(\varepsilon)$

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



- Maximum mass is a GR effect, value given by the EoS
- Determining mass and radius of one object considered as holy grail

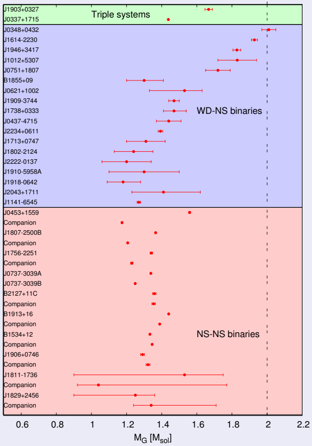
Neutron star observations

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 ⇔ 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]

Neutron star observations

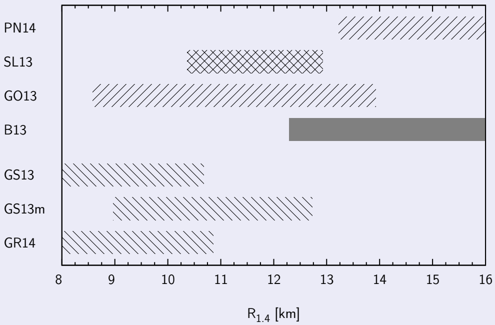
2. Radius estimates from X-ray observations

- 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 $M = 1.4M_\odot$ star 10-15 km

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



[courtesy M. Fortin, CAMK]

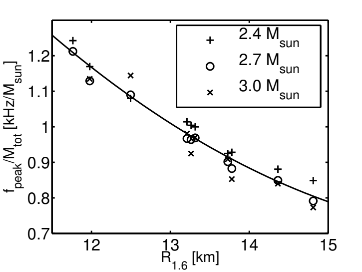
GW FROM BINARY NS MERGERS

- GW170817 : first detection of a NS-NS merger with LIGO/Virgo detectors
- Information on EoS from different phases
  - Inspiral $\rightarrow$ masses of objects
  - Late inspiral $\rightarrow$ tidal deformability $\tilde{\Lambda}$ depends on matter properties
    [Read et al, Faber & Rasio, ...]

GW170817

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

(low spin prior) [Abbott et al 2017]



[Bauswein et al 2016]

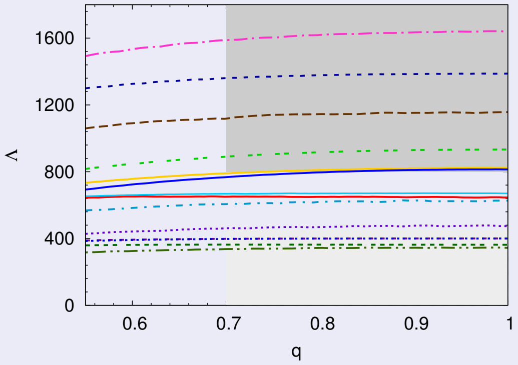
  - Post merger oscillations $\rightarrow$ peak frequency strongly correlated with NS radius
    [Bauswein et al, Sekiguchi et al, ...]

Tidal deformability

Constraints on the EoS

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

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



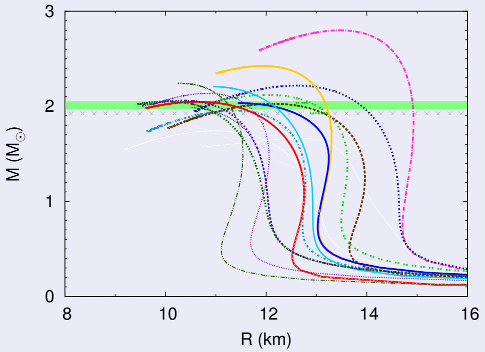
Tidal deformability

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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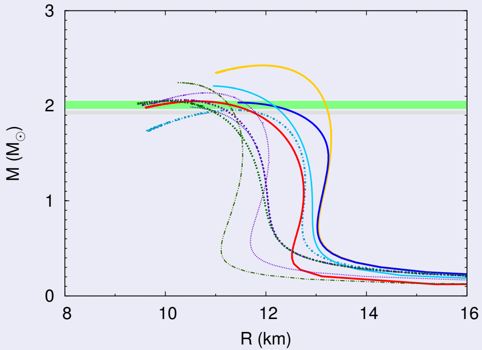

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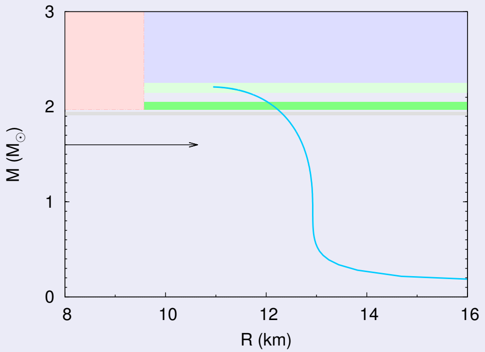
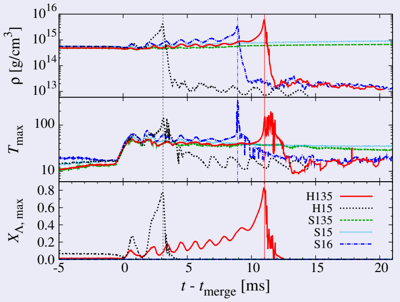


Summary and outlook

Neutron star matter not accessible in terrestrial laboratories

- Two robust observations, M_{max} and $\tilde{\Lambda}$, allow to strongly constrain many EoS
- Same EoS disfavored by a variety of nuclear physics experiments [MO et al 2017]

Temperature and density for a NS merger simulation



[Shibata et al. 2011]

Future

Observational prospects

- New pulsars with precise mass determinations (SKA, . . .)
- Radii (NICER, SKA, . . .)
- New binary merger events

Modelling of post-merger phase

- Matter is strongly heated up ! Need EoS with thermal effects (hyperons . . .) [Marques et al 2017]
- Neutrino treatment for matter composition (kilonova)
- . . .