GT4 : Nuclear astrophysics

Many different stars

In our Galaxy (Milky Way), there are ∼ 200 billion stars

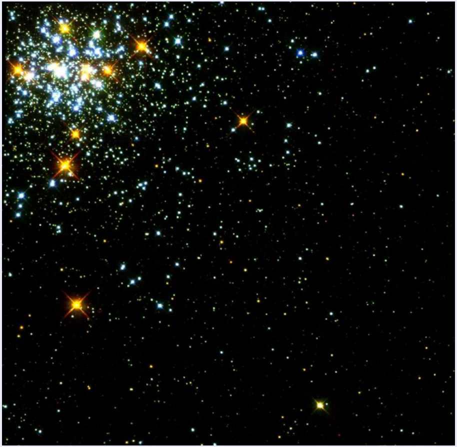
Stellar masses :
$0.2 M_\odot < M < 100 M_\odot$
(solar mass : $M_\odot = 2 \times 10^{30}$kg)

Stellar (effective temperatures) :
$3 \times 10^3 \lesssim T_{eff} \lesssim 4 \times 10^4$K

Energy produced by nuclear burning [Bethe, Weizsäcker & Critchfield]

Stellar graveyard (compact objects) : when does gravity ultimately win ?

Open cluster NGC 1818 in the Large Magellanic Cloud



GT4 : Nuclear astrophysics

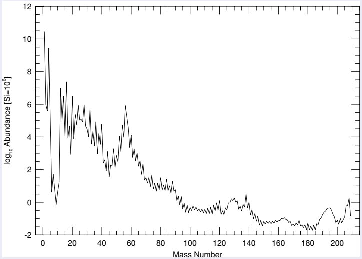
Big questions

We want to understand

1. What are the nuclear processes which drive the evolution of stars, galaxies and the Universe ?
2. Where do the different elements come from forming the building blocks for life ?

- H ($\approx$ 75%) and ^{4}He ($\approx$ 25 %) by far the most abundant baryons known in the Universe
- Different groups of nuclei
  - Light elements up to B (rare)
  - C,N,O, Ne, Mg, Si, iron peak nuclei (much more abundant)
  - Heavy nuclei
- Different sites for the production of these elements (nucleosynthesis)

Solar system abundances [Hix & Thielemann 1999]



1. What is the nature of matter under extreme conditions not reachable in present laboratories ?

French community

Naturally interdisciplinary nuclear physics, astrophysics and theoretical physics → IN2P3, INP, INSU

Nucleosynthesis

- Experiments for key reactions : CSNSM, IPNO, GANIL, CENBG, IPHC ?
- Stellar abundance observations : GEPI, CENBG
- Modelling : IAP, LUPM

Compact objects

- Dense matter modelling : LPC, IPNL, GANIL, IPNO, LUTH
- Experiments (heavy-ion collisions) : GANIL, Subatech, LPC
- Observations : Nançay, IRAP, IPAG, CENBG, Obs. Strasbourg, AIM
- Modelling : LUTH, AIM, IPNL, IAP

Strong connection with gravitational waves (GdR OG), detection of binary neutron star mergers by Virgo/LIGO

Around 50 participants at the first group meeting (september 2018, Observatoire de Paris)

Dense matter and compact objects

Some open questions

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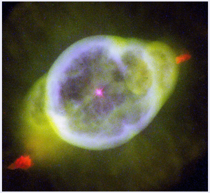
Assemblée Générale GdR RESANET 2018

And if no more nuclear fuel is available ?

White dwarf

[NGC 3242, Hubble]

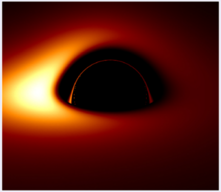


Neutron star

[Crab nebula, Chandra]

Black hole

[GYOTO, Vincent et al 2011]



- Low and intermediate mass stars : He burning core becomes degenerate, temperature not high enough to ignite Carbon burning $\rightarrow$ expulsion of the envelope, core contracts until forming a white dwarf (electron degeneracy pressure stabilizes the star)
- Stars with $M \gtrsim 8 - 10 M_\odot$ at ZAMS continue nuclear burning until reaching iron (lowest energy per nucleon)
  $\rightarrow$ core-collapse supernova explosion
  $\rightarrow$formation of a neutron star (stabilised by nuclear forces)
  or a black hole at the center

Supernovae

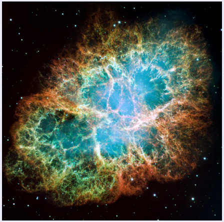
Supernova explosions observed since almost 2000 years

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

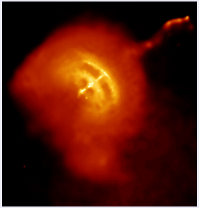
Neutron stars

- Almost 3000 neutron stars have been observed as pulsars, among others Crab, Vela, Geminga, Hulse-Taylor double pulsar, ...

Crab pulsar

Hubble (blue, optic), Chandra (red, X)

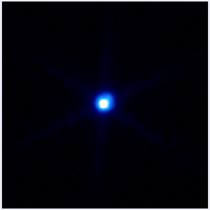
Vela pulsar



Chandra (X)

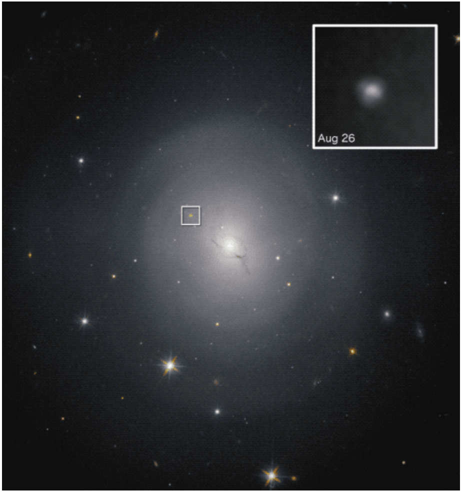
- Some ("the magnificant seven") have been observed only by their thermal emission
- "Magnetars" have extremely high magnetic fields ($\sim 10^{15}$ G at the surface)
- About 15 binary neutron star systems known
- No binary NS-BH system known

RX J 1856-37



GW170817 and electromagnetic counterparts

A transient source in NGC4993



August 17, 2017 : first detection of the coalescence of a binary neutron star (GW) by Virgo/LIGO

Observation (electromagnetic) of this source by several telescopes in different wave lengths (γ, X-rays, UV, visible, infrared and radio)

The radiation has becomes less intense and less energetic with time

So-called Kilonova interpreted as radiation from the produced r-process elements

What do we know about the EoS ?

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

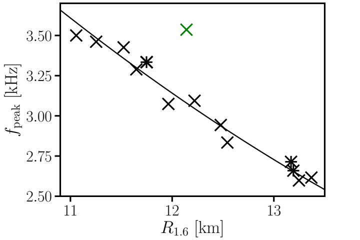
    [Read et al, Faber & Rasio, . . .]

    Attention : extraction of radii is not model-independent [Sieniawska et al 2018]

GW170817

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

(low spin prior) [Abbott et al 2017/2018]



[Bauswein et al 2018]

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

    [Bauswein et al, Sekiguchi et al, . . .]

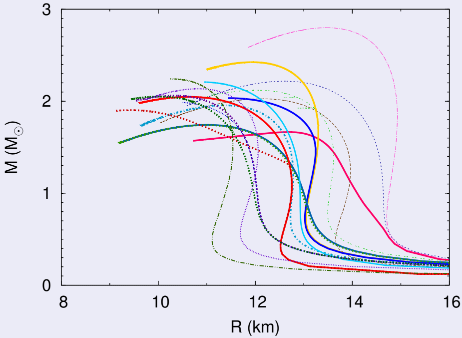
Mass-radius relation

- 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

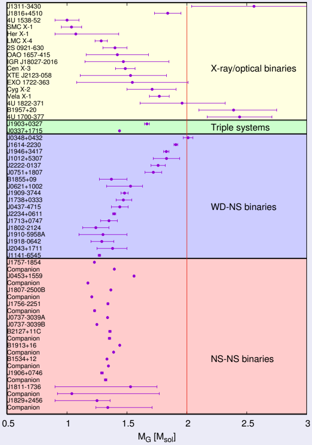
What do we know about the EoS ?

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]

WHAT DO WE KNOW ABOUT THE EOS ?

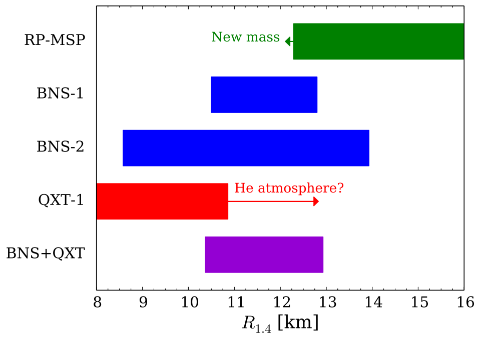
RADIUS ESTIMATES FROM X-RAY OBSERVATIONS

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

2σ ERROR BARS, RADII AT $M = 1.4M_\odot$



[courtesy M. Fortin, CAMK]

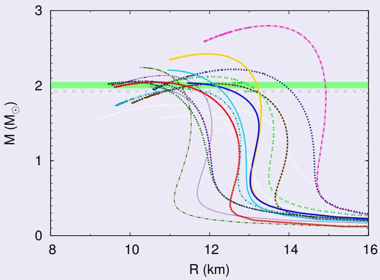
Results from NICER expected soon (february 2019 ?) with radius determination to 5%

What do we know about the EoS ?

- Reliable constraints from
  - NS masses ($M_{\rm NS} > 1.97 M_\odot$)
  - GW170817 tidal deformability $\tilde{\Lambda}$
- Constraints compatible with nuclear physics results :
  - Ab-initio neutron matter calculations
  - Nuclear masses, experiments for nuclear matter parameters, ...

[see e.g. Margueron et al 2018]

Different EoS models compatible with $M_{max} > 1.97 M_\odot$ [https://compose.obspm.fr]



- Non-nucleonic degrees of freedom (hyperons, mesons, quarks) might still exist in the central part
- Remark : Constraints essentially on homogeneous matter at relatively low densities (except for NS masses) and vanishing temperature

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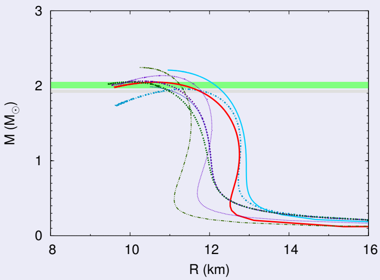
Different EoS models compatible with $M_{\rm NS}$, $\tilde{\Lambda}$ [https://compose.obspm.fr]



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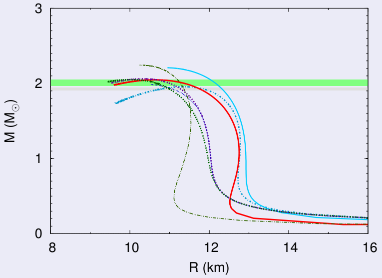
EOS MODELS COMPATIBLE WITH $M_{\rm NS}$, $\tilde\Lambda$ AND NUCLEAR PHYSICS [HTTPS://COMPOSE.OBSPM.FR]



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Dense matter in neutron stars

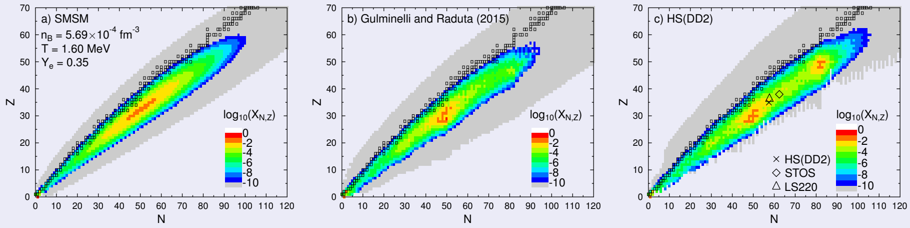
Observations	Quantities detected	Dense matter properties
Orbital parameters in binary systems	Neutron star masses	Equation of state (EoS), high densities
GW from binary systems	Tidal deformability	Compactness, EoS
Pulsar timing	Glitches	Evidence for superfluid component
X-ray observations	Surface temperature	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

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, (neutron) shell closures
  - Transition to homogeneous matter (stellar matter is electrically neutral !)

Nuclear abundances within different models (same thermodynamic conditions during CCSN collapse phase) [Mo et al 2017]



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

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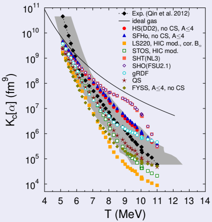
  - Masses of (neutron rich) nuclei, (neutron) shell closures
  - Transition to homogeneous matter (stellar matter is electrically neutral !)
  - Cluster abundances in Fermi energy HICs (several tens of MeV/nucleon) sensitive to in-medium cluster properties
  - Need more data (N/Z-ratio, equilibrium and relation to T, n_B, . . .)

Equilibrium constant of α-particles [Hempel et al 2015]



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

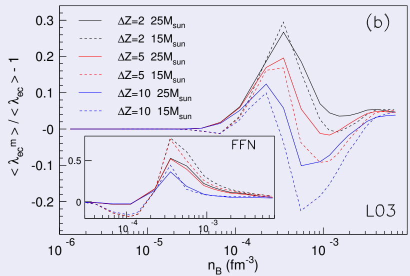
Some open problems

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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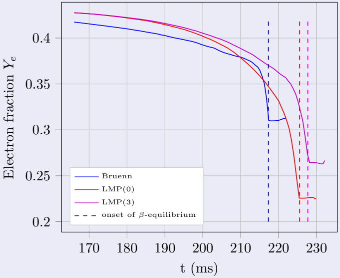
Y_e during collapse with different rates



[Pascal et al, in preparation]

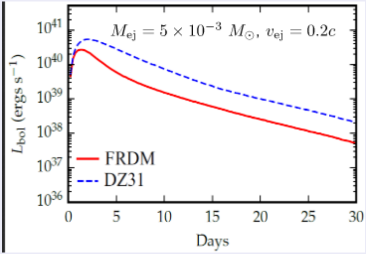
Some open questions

r-process nucleosynthesis

Long standing debate on astrophysical site for r-process
Strong evidence for main r-process in BNS mergers after GW170817

- Future kilonova observations
  - Abundances of produced elements sensitive to Y_e of ejecta (EoS, merger dynamics), nuclear masses far from stability, fission rates of superheavy nuclei, β-decay
  - Abundances determine energy released by radioactive decays and thermalization $\rightarrow$ impact on final lightcurve

Bolometric kilonova lightcurves over 30 days



[Barnes et al 2016]

- Detailed modelling required as combination of nuclear physics input and dynamical models
  - M_{ej}, v_{ej}, probably different ejecta with different characteristics
  - Progenitor properties (masses, rotation, magnetic fields, ...)
  - Detailed neutrino treatment, impact of physical viscosities

Summary

Equation of state

- Much recent progress with NS masses, GW170817, flexible parameterisations, new data expected from Virgo/LIGO, NICER, SKA, ATHENA, ...
- Importance of measuring nuclear matter properties (K,L,...) at $n_B > n_0$ to improve parameterisations
- Better understanding of clustering effects for NS crust and core collapse
- Determine composition and interactions at high densities/temperatures

EoS is not all !

- Neutrino reaction rates consistent with matter composition (CCSN, NS cooling, BNS ejecta composition)
- Nuclear superfluidty (Glitches, NS oscillations)
- Transport properties (NS cooling, oscillations, magnetic field structure)

Many open questions and much work needed, theory, experiment, observations and simulations

Active french community, reinforcement strongly needed for binary dynamics