Modeling compact objects in the multi-messenger era

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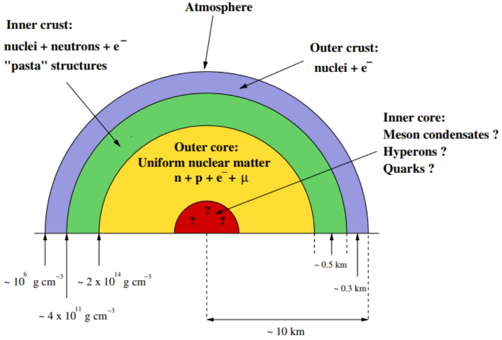
Introduction

Neutron stars

- End-products of stellar evolution during core-collapse supernova events
- Complex structure, with density around nuclear saturation density $\rho_0 \simeq 2.7 \times 10^{14}$ g cm^{-3}



[Image : Isaac Vidaña]

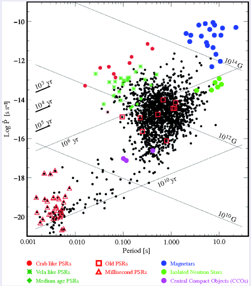
- Macroscopic objects with extreme density $\longrightarrow$ probe strongly interacting matter under extreme conditions
  Interactions ? Composition of dense matter ? Are there phase transitions ?

On the observational side

Neutron stars

- Almost 3000 neutron stars have been observed as pulsars, among others Crab, Vela, Geminga, Hulse-Taylor double pulsar
- Several NS-NS binary systems known
- Accreting neutron stars in binary systems
- Precise masses and spin periods
- Information on magnetic field, radius, surface temperature more difficult since in general model-dependent

P-$\dot{P}$ diagram



[Becker et al., 1305.4842]

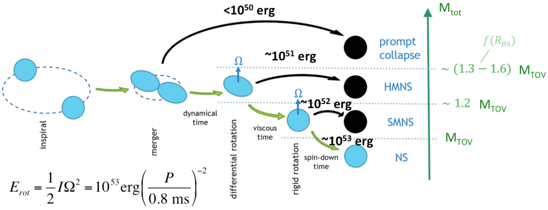
- Some recent advances : high mass pulsars with $M \gtrsim 2M_\odot$ (PSR J1614-2230,...), NICER radius measurements

On the observational side

Binary neutron star mergers

- GW170817 : first detection of a NS-NS merger with LIGO/Virgo detectors

- Information from different phases
  - Inspiral → masses of objects
  - Late inspiral → tidal deformability $\tilde{\Lambda}$



[Metzger 2019]

  - Post merger GW emission not yet detected but in reach for 3rd generation detectors ; peak frequency of remnant oscillations strongly correlated with EoS and NS radius

    [Bauswein+, Sekiguchi+, Rezzolla+...]

  - Electromagnetic counterpart with information about ejecta properties, kilonova, ...

- GW200105 and GW200115 : first detection of two BH-NS merger events with LIGO/Virgo detectors

Future

- Many other experimental/observational projects underway or planned :
  - Pulsar observations (SKA and precursors) with precise NS mass determinations, moment of inertia, ...
  - NS radius determinations from x-ray and GW (tidal deformability) detections with high precision from Advanced and 3rd generation detectors
  - GW from BNS post-merger phase in reach for 3rd generation detectors
  - Neutrinos from next galactic supernova with efficient detectors (Super/Hyper-Kamiokande, ...)

$\rightarrow$ need precise modelisation including numerical simulations and microphysics input (EoS and neutrino interaction rates) !

- Matter properties covering large domains in density, temperature and electron fraction

	Cold NS	CCSN	BNS merger
Temperature (MeV)	$\lesssim 0.1$	0-100	0-100
Density (fm^{-3})	10^{-14}-1	10^{-14}-5	10^{-14}-5
Electron fraction	β-eq.	~ 0.01-0.6	~ 0.01-0.5

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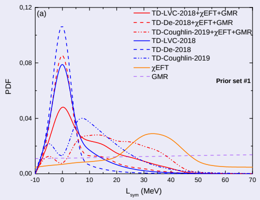
Binary neutron star mergers

Inspiral

- Tidal deformability depends on matter properties [Read+, Faber & Rasio, Hinderer+,...]
  $\longrightarrow$ NS radius and cold EoS

- Much effort to develop (semi-)agnostic EoS [Margueron+2018,Carreau+2020,Essick+2021,Capano+2019,...]
- Can be combined with constraints from
  - NS masses ($M_{\rm NS} > 1.97 M_\odot$)
  - Nuclear masses, experiments for nuclear matter parameters, neutron matter calculations, ...
  - NS radii (NICER results)

Bayesian analysis with semi-agnostic EoS [Güven+2020]

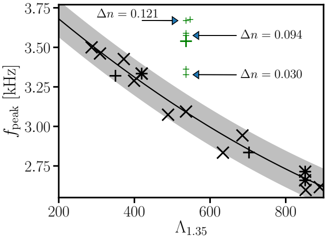


- High precision expected for 3rd generation GW detectors $\longrightarrow$ NS radius to 100m ?
- Importance of unified treatment (homogeneous $\leftrightarrow$ clusterised) matter for interpretation in terms of EoS
- Still many uncertainties for central part : non-nucleonic degrees of freedom (hyperons, mesons, quarks) might exist

Detect a phase transition in binary mergers ?

Post-merger phase

- Even if NS prior to merger do not contain quark core, the dense merger remnant might [Bauswein+2019, Most+2018, Ecker+2019...]
- Different cases for post-merger :
  - Very strong phase transition with no stable hybrid NS [Most+2018, Ecker+2019, ...]
    $\rightarrow$ almost immediate collapse to BH at onset of phase transition
    $\rightarrow$ almost no identifiable signal



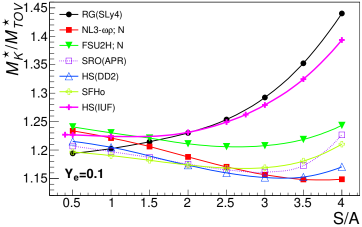
[Bauswein+2019]

  - Strong phase transition with stable hybrid NS and considerable quark core in merger remnant [Bauswein+2019]
    $\rightarrow$ Oscillations frequencies show imprint of matter properties
    $\rightarrow$ Clear signal of phase transition
  - Smooth transition leads to softening of EoS, but not distinguishable from EoS dependence of signal

Constraints on TOV mass from GW170817

Finite temperature effects on the EoS

- Idea to extract limits on $M^\star_{\rm TOV}$ from GW170817 : [Rezzolla+2018,Shibata+2019, ...]
  - No prompt collapse for GW170817, but formation of a differentially rotating HMNS
  - Internal viscosities lead to rigid rotation, the star collapses upon crossing the stability line for rigid rotation



- Then apply universal relation between $M^\star_K$ and $M^\star_{\rm TOV}$
- But the merger remnant might still be hot and (partly) out of β-equilibrium upon collapse and universality is lost ! $\rightarrow$ considerably relaxed limits

New limits for TOV mass [Khadkikar+2021]

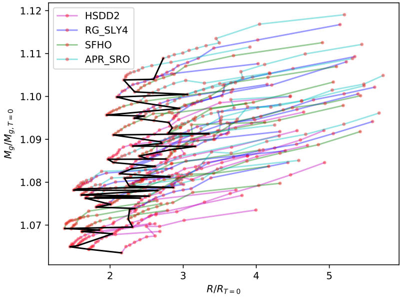
$$2.15^{+0.10}_{-0.07} M_\odot < M^\star_{\rm TOV} < 2.24^{+0.12}_{-0.10} M_\odot$$

Proto-neutron star mass and radius

Finite temperature effects on the EoS

- CCSN simulations indicate that M_{PNS} and R_{PNS} can be measured with GW
  [Torres-Forne+2019]
- Questions :[Préau+2021]
  - What can be learned about the cold β-equilibrated EoS ?
  - Can we constrain the hot EoS ?

- After 1s, R_{PNS} still very different from NS radius
- Difficult to disentangle various EoS
- Uncertainty on entropy profiles dominates



[Préau+2021]

Summary and outlook

Summary

- Understanding the structure of compact stars and dense matter properties needs interplay of modeling and experiments/observations
- Some examples
  - Combination of constrains on the cold NS EoS
  - Possibility of detecting a phase transition from post-merger oscillations
  - Thermal effects in the EoS are important for the interpretation of (GW) data from CCSN/PNS and BNS merger remnants

Outlook

- Very bright future for understanding the structure of compact stars with present and upcoming observations needs precise modeling
- Some examples
  - Interpretation of tidal deformability needs precise crust modeling
  - Neutrino-nucleon interactions and neutrino treatment to determine ejecta composition in CCSN and BNS mergers $\rightarrow$ conditions for nucleosynthesis
  - Better model thermal effects in the EoS
  - Relate HMNS and PNS oscillations to microphysics