Neutron stars: probing ultra-dense matter

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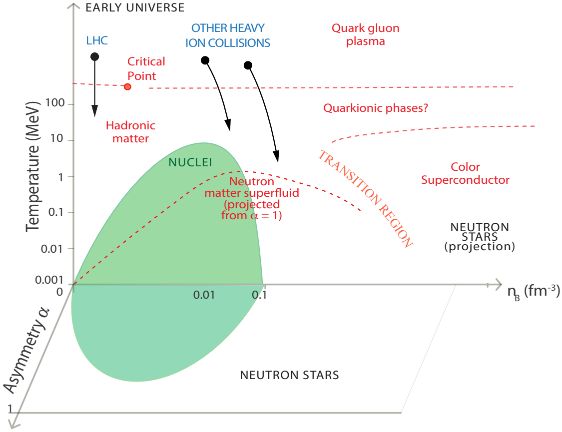
Based mainly on C. Mondal, M. Antonelli, F. Gulminelli, M. Mancini, J. Novak, MO, MNRAS 524, (2023) 3464

Strongly interacting matter

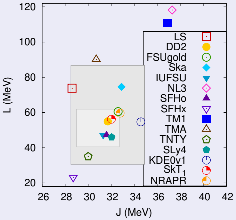


[Watts+2015]

Neutron star matter is strongly interacting matter under extreme conditions not accessible in terrestrial laboratories (density, asymmetry) and non-perturbative many-body problem from the theory side

Constraints from nuclear physics

Example : symmetry energy and slope (Lattimer & Lim 2013, MO+ 2017, ...)

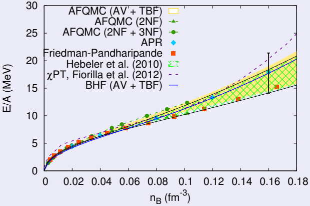


- Nuclear masses (binding energies) for many nuclei close to stability
- Extracting parameters of symmetric nuclear matter around saturation (n_0, E_B, K, J, L)
- Data from heavy ion collisions (flow constraint, meson production, ...)

[See e.g. many talks at this meeting]

- Data on nucleon-nucleon interaction fixing startpoint of many-body calculations
- Low density neutron matter : Monte-Carlo simulations and EFT approaches
  [See e.g. talk by Kai Hebeler]

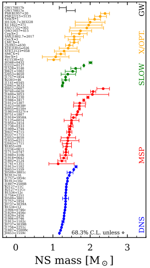
Different ab initio neutron matter calculations [MO+2017]



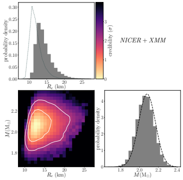
On the astrophysical side

Pulsar observations

- Observed masses in binary systems (NS-NS, NS-WD, x-ray binaries)
  - Most precise ones from NS-NS binaries
  - Massive ones $\longrightarrow$ constraints on core composition/EoS
- Prospects for asteroseismology, moment of interia, rotation frequencies, cooling, …



[CompOSE, courtesy L. Suleiman]



[Miller+ 2021]

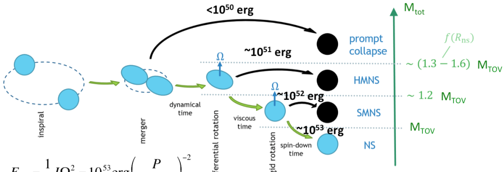
- Radius estimates from x-ray observations
  - Radii from different types of objects, consensus on radius of a fiducial $M = 1.4 M_\odot$ star 10-15 km
  - NICER results gave for the first time mass and radius of the same star [see talk by S. Guillot]

On the astrophysical side

Gravitational waves

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

- Information from different phases [see e.g. talk by J. Read]
  - Inspiral → masses of objects
  - Late inspiral → tidal deformability $\tilde{\Lambda}$



$$E_{rot} = \frac{1}{2} I\Omega^2 = 10^{53}\,\text{erg}\left(\frac{P}{0.8\,\text{ms}}\right)^{-2}$$

[Metzger 2019]

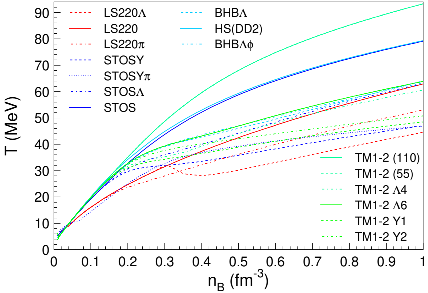
  - Post merger GW emission not yet detected but in reach for 3rd generation detectors
  - Electromagnetic counterpart with information about ejecta properties, kilonova, . . .

- Many observables sensitive to EoS properties, what about the composition ?

Composition at high densities/temperatures

Hadronic degrees of freedom

- Example : Hyperons can appear if the chemical potential is high enough to make conversion $N \to Y$ energetically favorable
- At onset density : smooth transition or first order phase transition
- Enhanced production at finite temperature in merger remnant/CCSN
- There can be others : Δ-resonances, pion/kaon condensates [see talks by A. Sedrakian, D. Bandyopadhyay]

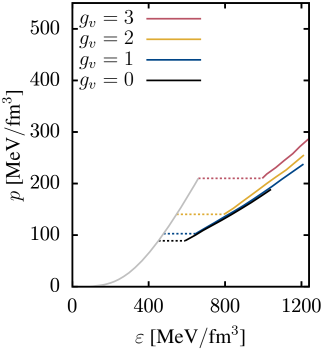


[MO+2016]

Composition at high densities/temperatures

Quark matter

- Hadron-quark phase transition possible in the NS core/PNS/merger remnant
- Possibly additional superconducting phase transitions in quark matter core
- New degrees of freedom → impact on EoS
- Cold matter in β-equilibrium : phase transition → jump in (energy) density

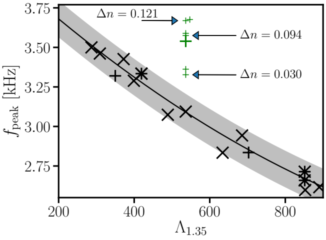


[Otto+2020]

Matter composition from binary mergers ?

Post-merger phase

- Onset with smooth transition
  - Reduced thermal pressure in presence of additional degrees of freedom
    $\rightarrow$ shift in postmerger frequencies [Blacker+2023]
- First order phase transition
  - 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,Most+2019,Weih+2020]
  $\rightarrow$ Oscillations frequencies show imprint of matter properties
  $\rightarrow$ Clear signal of phase transition
- Smooth transition leads to softening of EoS, potentially distinguishable

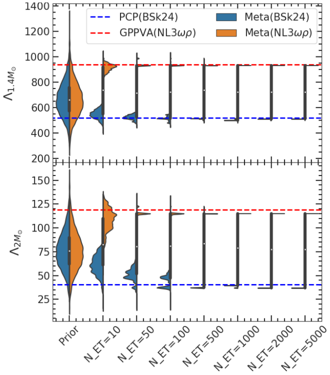
Matter composition from binary mergers ?

Inspiral

- Matter not considerably heated up before merger
  → NS radius and cold β-equilibrated EoS
- NS EoS can be determined very precisely with 3rd generation detectors
- But : no information a priori about composition in absence of a phase transition

  [Mondal& Gulminelli 2021, Iacovelli+2023, Imam+2023]

  Additional information on symmetric matter needed



[Iacovelli+2023]

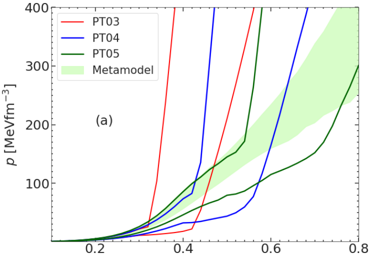
- Can we detect a phase transition with 3rd generation detectors ?
  Depends on onset density, masses, distance, . . .

  [Sieniawska+2018, Tews+2018, Montana+2018, Han+2018, Christian+2018. . .]

Detectability of a PT during BNS inspiral

Setup of the study

- Metamodel approach to nuclear matter (function of NMPs+ consistent CLDM crust) [Dinh Thi+2021] and quark matter (constant sound speed) [Mondal+2023]
- Injected EoS chosen within the ranges covered
- Three possible PT onset densities



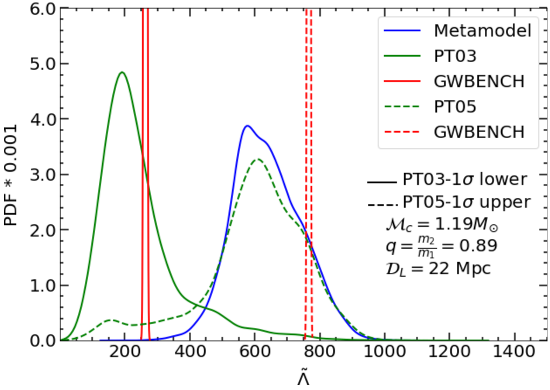
[Mondal+2023]

- Simulate observations with 3rd generation detector network (ET +2CE)
  - Detector response estimated using Fisher matrix formalism within GWBENCH [Borhanian2021]
  - Fixing spins and inclination, varying distance and two component masses
  - $\tilde{\Lambda}$ computed from injected EoS and m_i

Detectability during BNS inspiral

Bayesian analysis with one loud event

- 450 simulated events (distance, component masses, injected EoS)
  - Mass ratio has little effect
  - Higher chirp mass can make it easier to distinguish
  - The smaller the distance the easier
  - A late PT is difficult to distinguish



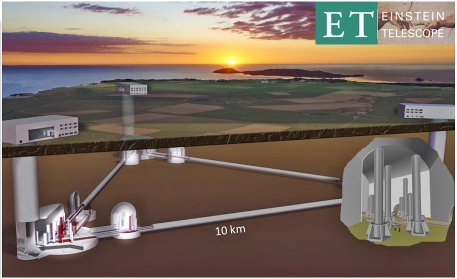
[Mondal+2023]

- Possible to identify a strong PT with an early (low density) onset, high density onset masked [see also Tan+2022,Mroczek+2023]
- Analysis with cumulation of events to be done

Summary and outlook

Cold and β-equilibrated matter

- Advanced and 3rd generation GW decetors together with other observational projects underway or planned (NICER, SKA and precursors, ...) will pin down precisely the NS EoS
- Low density PT probably identifiable



[European project for a ground-based 3rd generation GW detector]

(Hot) matter with different compositions

- GW from BNS post-merger phase in reach for 3rd generation detectors
- Neutrinos from next galactic supernova with efficient detectors (Super/Hyper-Kamiokande, ...)
- Nuclear physics experiments (HIC, ...) for more symmetric matter

→ how to combine all this information to understand the phase diagram of strongly interacting matter ?