Probing ultra-dense matter with gravitational waves

Micaela Oertel

micaela.oertel@astro.unistra.fr

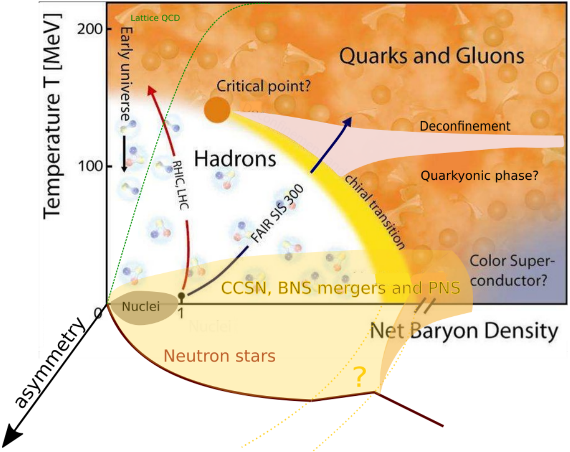
Observatoire astronomique de Strasbourg
CNRS / Université de Strasbourg

Working group meeting, GdR OG- extreme matter, Caen, October 10-11, 2024

Based on work with many collaborators, special thanks to P. Char, A. Fantina, C. Mondal, F. Gulminelli, J. Novak, A.R. Raduta, L. Suleiman

Observatoire astronomique de Strasbourg | ObAS

Strongly interacting matter



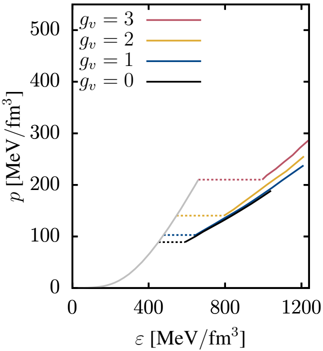
Neutron stars contain matter under extreme conditions difficult to access

Questions : What can we learn from future GW observations on EoS, composition and reaction rates ?

Observatoire astronomique de Strasbourg | ObAS

Composition at high densities/temperatures

- Nwe hadronic degrees of freedom (hyperons, ...) at high density/temperature if energetically favored
  - Hadron-quark phase transition possible in the NS core/PNS/merger remnant
  - Possibly additional superconducting phase transitions in quark matter core
  - Possible quarkyonic phase
  - New degrees of freedom → impact on EoS
  - Cold matter in β-equilibrium : phase transition → jump in (energy) density

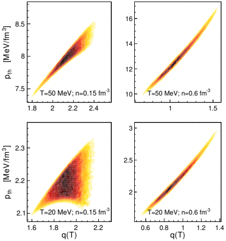


[Otto+2020]

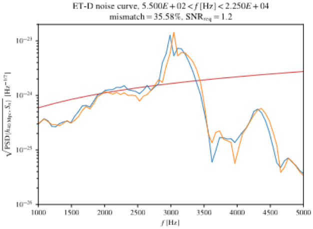
Post-merger phase

Thermal and out of equilibium effects ?

- Thermal effects in the EoS dominated by effective mass [Constantinou+2014,2015,Raduta+2024]
- Impact of effective mass on PNS [Schneider+2019,2020,Yasin+2020] and merger remnant [Fields+2023,Miravet-Tenes+2023]
- In BNS remnant potentially detectable with 3rd generation detectors [Raithel+2024]



[Raduta+2024]



[Hammond+2023]

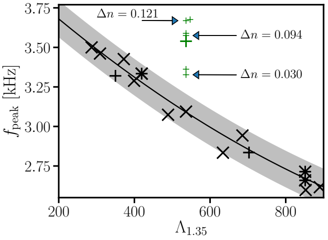
- Shift in peak frequency due to different treatment of weak reactions [Hammond+2023]
- Impact of muons [Gieg+2024,Loffredo+2022] and pions on the dynamics [Vijayan+2023,Pajkos+2024]

Observatoire astronomique de Strasbourg | ObAS

Post-merger phase

Can we detect a phase transition?

- Onset with smooth transition
  - Reduced thermal pressure in presence of additional degrees of freedom
    → shift in postmerger frequencies [Blacker+2023]
- First order phase transition
  - Very strong phase transition with no stable hybrid NS [Most+2018, Ecker+2019, ...]
    → almost immediate collapse to BH at onset of phase transition
    → almost no identifiable signal

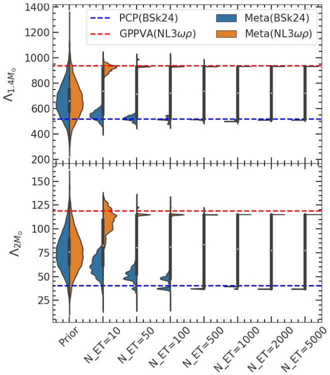


[Bauswein+2019]

- Strong phase transition with stable hybrid NS and considerable quark core in merger remnant [Bauswein+2019,Most+2019,Weih+2020]
  → Oscillations frequencies show imprint
  → Clear signal of phase transition
- Smooth transition leads to softening of EoS, potentially distinguishable
- Presence of hyperons impact thermal effects and peak frequency [Blacker+2024]

NS EoS from inspiral phase ?

- Matter not considerably heated up before merger
  $\rightarrow$ NS radius and cold β-equilibrated EoS
- Meta-modelling approach to nuclear matter incorporating information from nuclear physics DinhThi+2021,Davis+2024] + simulated events with ET
- NS EoS can be determined very precisely with 3rd generation detectors

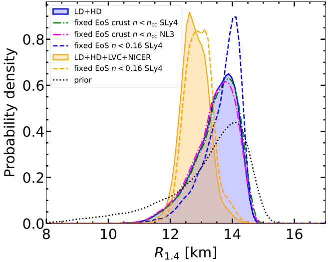


[Iacovelli+2023]

- CUTER tool for crust reconstruction available : https://zenodo.org/doi/10.5281/zenodo.10781538
- Uncertainties from waveform modelling and degeneracies with modified gravity/BSM

NS EoS from inspiral phase ?

- Matter not considerably heated up before merger
  $\rightarrow$ NS radius and cold β-equilibrated EoS
- Meta-modelling approach to nuclear matter incorporating information from nuclear physics DinhThi+2021,Davis+2024] + simulated events with ET
- NS EoS can be determined very precisely with 3rd generation detectors
- Unique vs unified crust uncertainties of same order [Gamba+202,Davis+2024]



[Davis+2024]

- CUTER tool for crust reconstruction available : https://zenodo.org/doi/10.5281/zenodo.10781538
- Uncertainties from waveform modelling and degeneracies with modified gravity/BSM

Observatoire astronomique de Strasbourg | ObAS

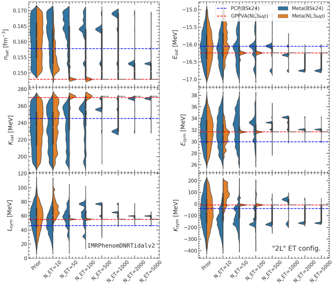
Nuclear properties and matter composition ?

- But : no information a priori about composition in absence of a phase transition

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

  Reason is that only β-equilibrated EoS determined

  Additional information on symmetric matter needed



[Iacovelli+2023]

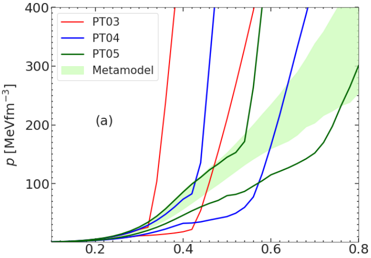
- Can we detect a phase transition with 3rd generation detectors ? Depends on onset density, masses, distance, . . .

  [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]

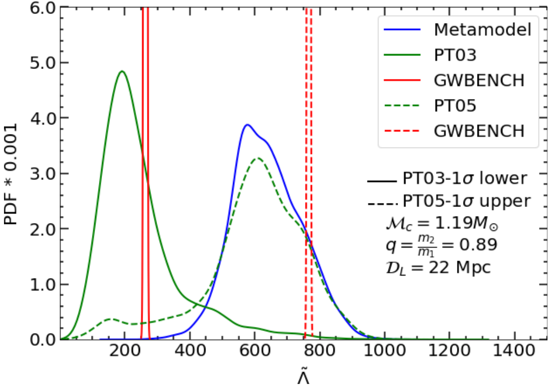
- Simulate observations with 3rd generation detector network (ET +2CE)
  - Detector response estimated using Fisher matrix formalism within GWBENCH [Borhanian2021]
  - Fixing spins and inclination, varying distance and two component masses
  - $\tilde{\Lambda}$ computed from injected EoS and m_i

Observatoire astronomique de Strasbourg | ObAS

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 high-density PT difficult to distinguish



[Mondal+2023]

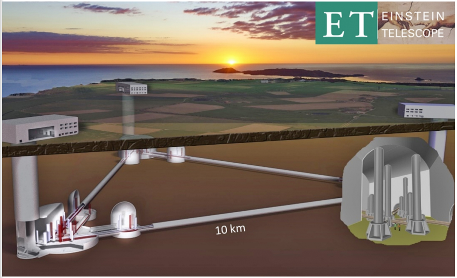
- Possible to identify a strong PT with an early (low density) onset, high density onset masked [see also Tan+2022,Mroczek+2023]
- Analysis with cumulation of events to be done

Observatoire astronomique de Strasbourg | ObAS

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, but β-equilbrated EoS alone not sufficient to pin down composition and nuclear model



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

Summary and outlook

(Hot) matter with different compositions

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

$\rightarrow$ need to combine all this information to understand the phase diagram of strongly interacting matter