Probing ultra-dense matter with gravitational waves

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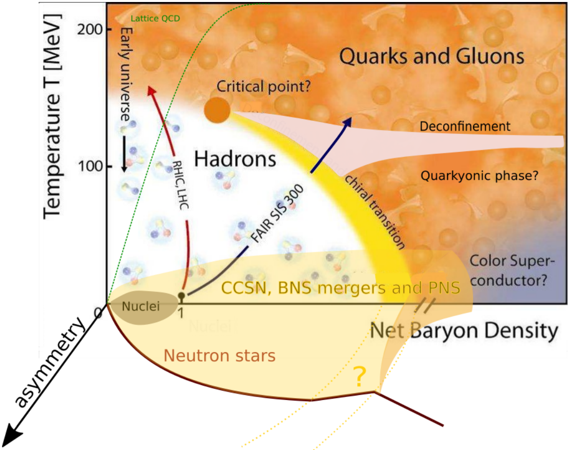
Strongly interacting matter



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

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Matter composition and equation of state

CCSN, binary mergers and neutron stars

$\rightarrow$ Domains in density, temperature and asymetry :

temperature	0 MeV $\leq T < 150$ MeV
baryon number density	10^{-11} fm^{-3} $< n_B < 10$ fm^{-3}
electron fraction	$0 < Y_e < 0.6$

Different regimes (strongly interacting !) :

- Very low densities and temperatures :
  - dilute gas of non-interacting nuclei $\rightarrow$ nuclear statistical equilibrium (NSE)
- Intermediate densities and low temperatures :
  - gas (crystal) of interacting nuclei surrounded by free nucleons $\rightarrow$ beyond NSE
- High densities and temperatures :
  - nuclei dissolve
    $\rightarrow$ strongly interacting (homogeneous) hadronic matter
  - potentially transition to a quark gluon plasma
- Matter not necessarily in chemical equilibrium (nuclei/neutrinos)

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Equation of state

Different philosophy

Microscopic modelling

- Phenomenological or ab intio modelling
- Direct connection with nuclear physics information
- Predicts EoS and composition, access to reaction rates
- Many sources of (systematic) uncertainties
- Meta-modelling approaches allow for larger flexibility/incorporation of constraints

(Non-)parametric EoS

- Piecwise polytropes, sound speed representation, Gaussian processes etc
- Large flexibility, fast evaluation and easy to handle
- No ad hoc assumptions on any underlying physics
- No access to composition
- No relation to non-equilibrium processes

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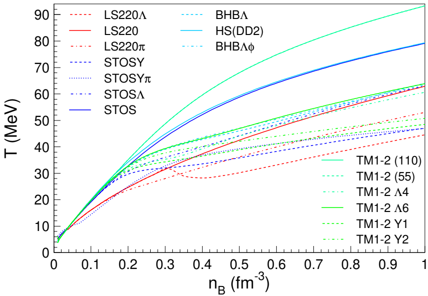
Composition at high densities/temperatures

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

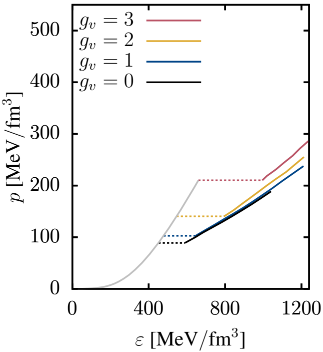


[MO+2016]

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
- Possible quarkyonic phase
- New degrees of freedom → impact on EoS
- Cold matter in β-equilibrium : phase transition → jump in (energy) density



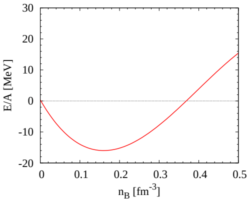
[Otto+2020]

Constraints from nuclear physics

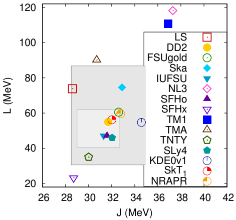
Experiments

- Symmetric nuclear matter (i.e. $n_n = n_p$) : minimum at saturation density
  $\longrightarrow$Taylor expansion

$$E(n_B, \beta) = E_b + \frac{1}{18} K x^2 + \frac{1}{162} K' x^3$$
$$+ \beta^2 \left(J + \frac{1}{3} L x + \frac{1}{18} K_{sym} x^2\right)$$



- Coefficients extracted from nuclear experiments



(Lattimer & Lim 2013, MO+ 2017, . . .)

- Nuclear masses (binding energies) for many nuclei close to stability
- Data from heavy ion collisions (flow constraint, meson production, . . .)
- Data on nucleon-nucleon interaction fixing startpoint of many-body calculations

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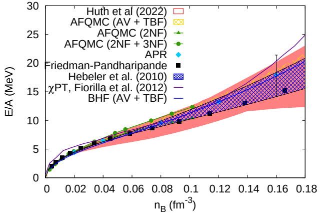
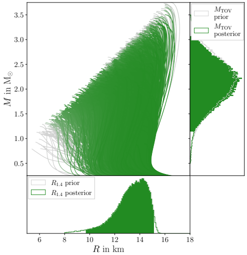
Constraints from nuclear physics

Theory

- Low density neutron matter : different ab initio approaches (Monte-Carlo simulations, EFT approaches) the different results agree fairly well
- Uncertainty quantification within χEFT approaches [Hebeler+2010, Drischler+2016,Huth+2021,. . .]



Update from [MO+2017]



[Koehn+2024]

- Symmetric nuclear matter : difficult for ab initio calculations and large uncertainties
- A few ab initio calculations at finite temperature
- Perturbative QCD at ultra-high densities

[Komoltsev+2021]

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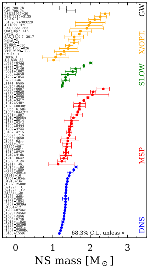
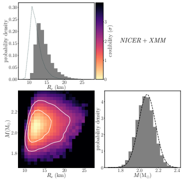
On the astrophysical side

Pulsar observations

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



[CompOSE, courtesy L. Suleiman]



[Miller+ 2021]

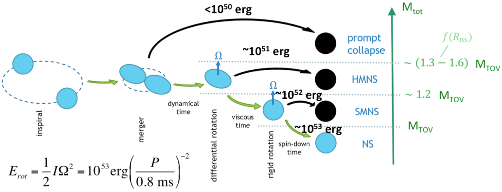
- Radius estimates from x-ray observations
  - Radii from different types of objects, consensus on radius of a fiducial $M = 1.4M_\odot$ star 10-15 km
  - NICER results gave for the first time mass and radius of the same star

On the astrophysical side

Gravitational waves

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

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



[Metzger 2019]

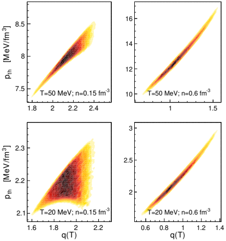
  - Post merger GW emission not yet detected but in reach for 3rd generation detectors
  - Electromagnetic counterpart with information about ejecta properties, kilonova, . . .

- What can we learn from future observations ?

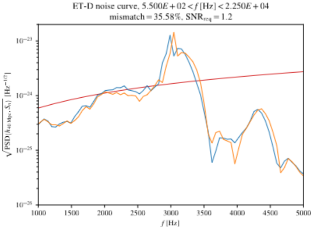
Post-merger phase

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]

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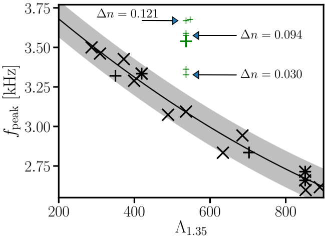
Post-merger phase

Can we detect a phase transition ?

- 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

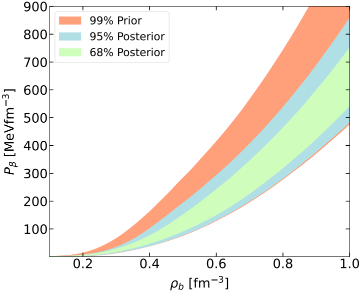


[Bauswein+2019]

- 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
  $\rightarrow$ 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]

Nuclear meta-modelling appoach

- Idea :
  use a flexible parameterisation which allows to incorporate nuclear and astrophysics information
- Original version based on Taylor expansion of symmetric NM Margueron+2018] varying NMPs
- Consistent crust-core matching DinhThi+2021,Davis+2024]



[Char+2023]

- Filters from χEFT, nuclear masses, M_{max}, GW170817
- Many versions developed, similar predictions [Chatterjee+,Beznogov& Raduta,Char+2023,Scurto+2024,Somasundaram+ ...]

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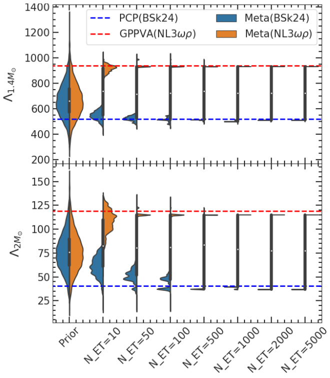
NS EoS from inspiral phase ?

- Matter not considerably heated up before merger
  $\rightarrow$ NS radius and cold β-equilibrated EoS
- Meta-modelling approach to nuclear matter + simulated events with ET
- NS EoS can be determined very precisely with 3rd generation detectors
- Combined MM analysis frameworks constructed [Breschi+2024,Pang+2022]



[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

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NS EoS from inspiral phase?

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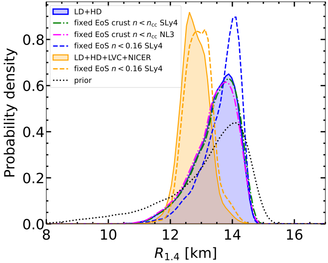
  $\longrightarrow$ NS radius and cold β-equilibrated EoS
- NS EoS can be determined very precisely with 3rd generation detectors
- Unique vs unified crust uncertainties of same order [Gamba+202,Davis+2024]
- Combined MM analysis frameworks constructed [Breschi+2024,Pang+2022]



[Davis+2024]

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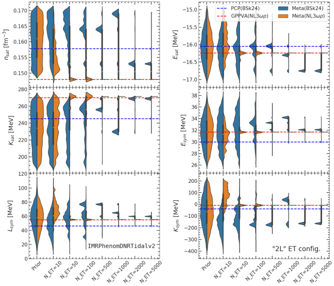
Nuclear properties and matter composition ?

- <u>But</u> : 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. . .]

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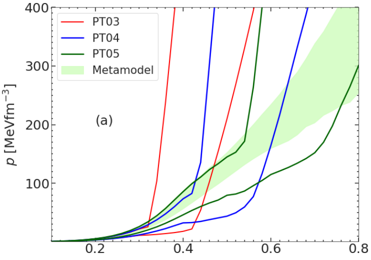
Detectability of a PT during BNS inspiral

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

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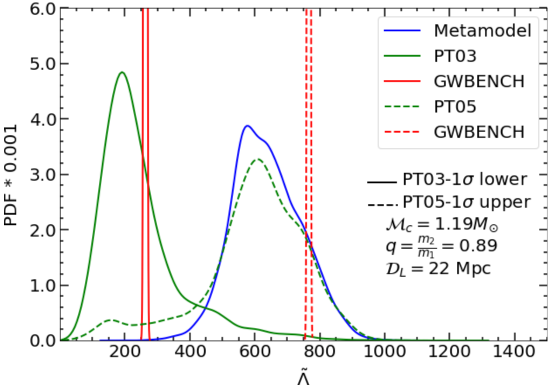
Detectability during BNS inspiral

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

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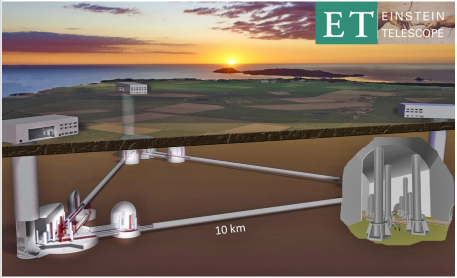
Summary and outlook

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]

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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

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