

ASTROPHYSICS OF COMPACT OBJECTS

PART IV: OUTLOOK: COMPACT OBJECTS AS PROBE OF FUNDAMENTAL PHYSICS

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Lecture LAPTH, Annecy, November 20-25, 2025

OUTLINE

① STRONGLY INTERACTING MATTER

② THEORY OF GRAVITY

③ BSM PHYSICS

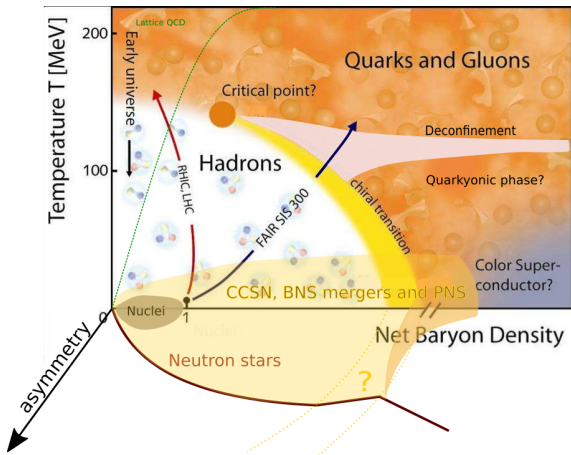
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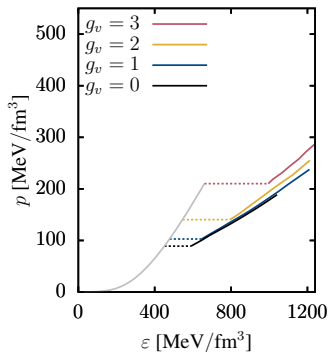
COMPACT STARS IN THE QCD PHASE DIAGRAMM



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

COMPOSITION AT HIGH DENSITIES/TEMPERATURES

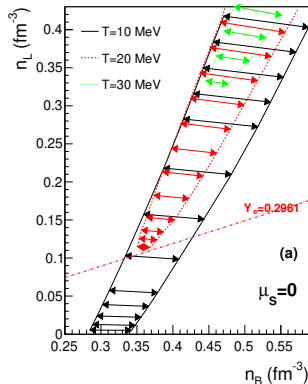
- New degrees of freedom \rightarrow impact on EoS
 - ▶ Hadrons : hyperons, mesons
 - ▶ Hadron-quark phase transition possible in the NS core/PNS/BNS merger remnant
 - ▶ Possibly additional superconducting phase transitions in quark matter core
 - ▶ Possible quarkyonic phase
- Cold matter in β -equilibrium : first order phase transition \rightarrow jump in (energy) density



[Otto+2020]

COMPOSITION AT HIGH DENSITIES/TEMPERATURES

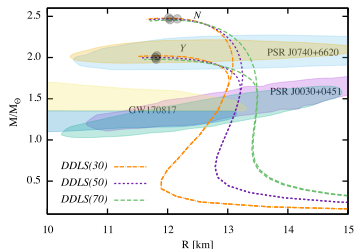
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- Hot matter with different Y_e : thermodynamic instability region as function of relevant densities



[Gulminelli+2013]

SIGNATURES OF A PHASE TRANSITION ?

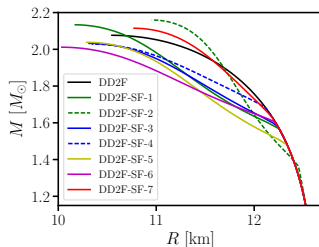
- Heavy-ion collision experiments study transition from hadronic matter to quark-gluon plasma at low density and high temperatures
- QCD lattice simulations study similar domain
- Global NS properties (M , R , Λ) based on the EoS show imprint of onset
- Transport properties very sensitive to matter constituents and phases (thermal evolution), but many different possibilities ...
- Oscillations (e.g. r -mode instabilities)



[Tsiopelas+2024]

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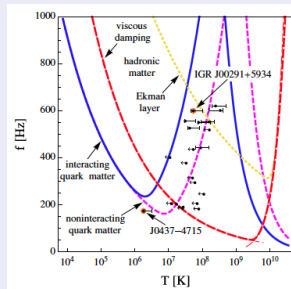


[Bauswein+ 2019]

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r -MODE INSTABILITY REGIONS



[Alford & Schwenzer]



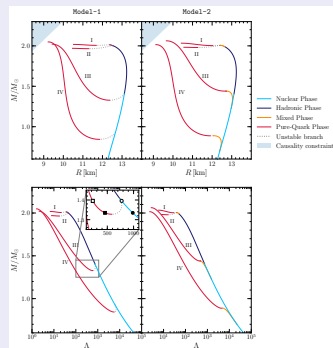
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CAN WE DETECT A PHASE TRANSITION IN BINARY MERGERS ?

INSPIRAL - TIDAL DEFORMABILITY

- Same as mass-radius, the relation $\Lambda(M)$ deviates if new degrees of freedom appear
- Strong first order phase transition with unstable branch
→ discontinuity
- Relation Λ - R not obvious to extract (twin branch with two R for same M)
- Imprint on GW signal depends on mass for onset of phase transition

Λ VS GRAVITATIONAL MASS WITH PHASE TRANSITION

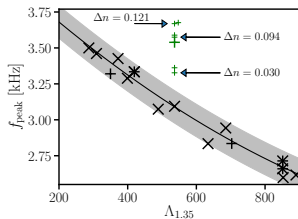


[Montana 2018]

CAN WE DETECT A PHASE TRANSITION IN BINARY MERGERS ?

POST MERGER SIGNAL

- Even if NS prior to merger do not contain PT, the dense merger remnant might
- Different cases
 - ▶ Very strong first order PT with no stable hybrid NS
 - almost immediate collapse to BH at onset of phase transition
 - almost no identifiable signal



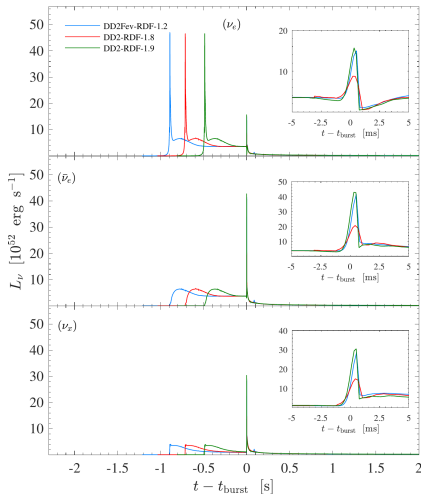
[Bauswein+ 2019]

- ▶ Strong phase transition with stable hybrid NS and considerable quark core in merger remnant
 - Oscillation frequencies show imprint of matter properties
 - Clear signal of phase transition
- ▶ Smooth transition leads to softening of EoS (impact thermal effects) and therefore peak frequency, potentially distinguishable

CORE-COLLAPSE SUPERNOVAE

NEUTRINO SIGNAL

- First order PT during core-collapse can lead to formation of second shock wave
 - aid the explosion
 - second neutrino burst (potentially observable)



[Khosravi Largani+ 2024]



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TEST OF THEORY OF GRAVITY

Many possibilities, a few ideas for reading :

- Tests of GR with pulsar timing (post-Keplerian parameters), see <https://arxiv.org/pdf/2112.06795>
- Tests of the strong equivalence principle with a triple system, <https://arxiv.org/pdf/2005.01388>
- Relativistic stars in alternative theories, e.g. <https://arxiv.org/pdf/1606.06627>
- GW170817 and modified theories of gravity, e.g. <https://arxiv.org/pdf/1711.07403>
- Dynamical scalarisation in neutrons stars (<https://doi.org/10.1103/PhysRevLett.70.2220>) and BNS mergers <https://arxiv.org/pdf/2302.11596>

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Please join this afternoon's discussion
led by Francesca Calore