WG1: Matter under extreme conditions

Massimo Mannarelli and Violetta Sagun

Rome, February 12, 2024

QCD matter under extreme conditions

Quantum Chromodynamics is an asymptotically free theory.

At **large** energy scales:

- Quarks and gluons are the correct degrees of freedom
- Hard probes can investigate the hadronic structure
- Perturbative methods can be applied

Issues:

- Such energy scales hardly realized in compact objects

QCD matter under extreme conditions

Quantum Chromodynamics is an asymptotically free theory.

At **large** energy scales:

- Quarks and gluons are the correct degrees of freedom
- Hard probes can investigate the hadronic structure
- Perturbative methods can be applied

Issues:

- Such energy scales hardly realized in compact objects
- Degeneracy between microscopic realizations

QCD matter under extreme conditions

Quantum Chromodynamics is an asymptotically free theory.

At **large** energy scales:

- Quarks and gluons are the correct degrees of freedom
- Hard probes can investigate the hadronic structure
- Perturbative methods can be applied

Issues:

- Such energy scales hardly realized in compact objects
- Degeneracy between microscopic realizations
- Zoo of possible phases

QCD matter under extreme conditions

Quantum Chromodynamics is an asymptotically free theory.

At **large** energy scales:

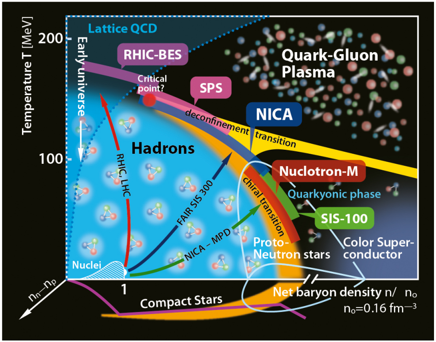
- Quarks and gluons are the correct degrees of freedom
- Hard probes can investigate the hadronic structure
- Perturbative methods can be applied

Issues:

- Such energy scales hardly realized in compact objects
- Degeneracy between microscopic realizations
- Zoo of possible phases
- Numerical methods do not work at large baryonic densities

Phases of strongly interacting matter

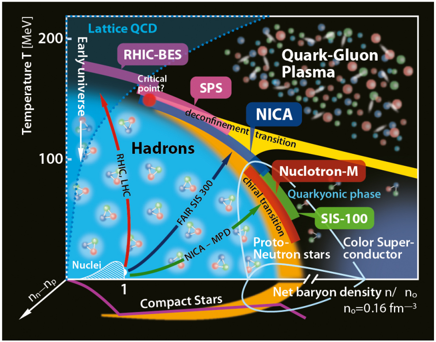
Seeking the Equation of State (EoS) of strongly interacting matter



- What is matter made of?

Phases of strongly interacting matter

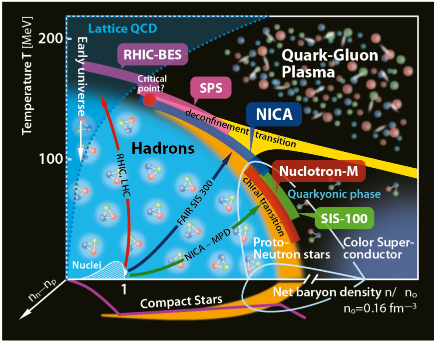
Seeking the Equation of State (EoS) of strongly interacting matter



- What is matter made of?
- How are phases connected?

Phases of strongly interacting matter

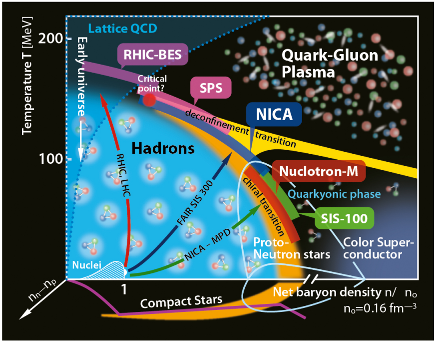
Seeking the Equation of State (EoS) of strongly interacting matter



- What is matter made of?
- How are phases connected?
- How do we probe them?

Phases of strongly interacting matter

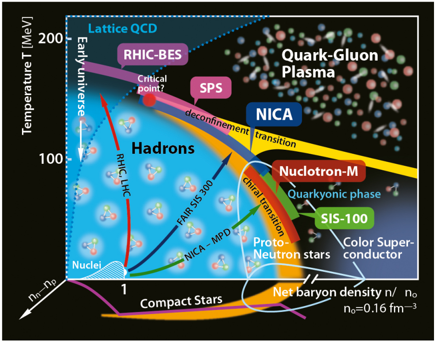
Seeking the Equation of State (EoS) of strongly interacting matter



- What is matter made of?
- How are phases connected?
- How do we probe them?
- How do HICs contribute?

Phases of strongly interacting matter

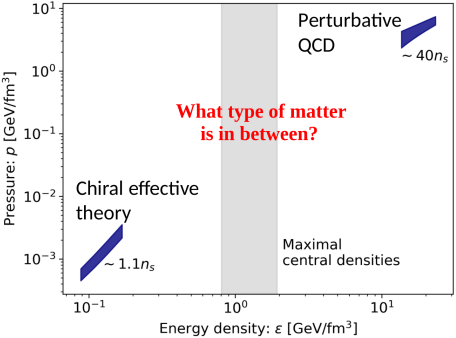
Seeking the Equation of State (EoS) of strongly interacting matter



- What is matter made of?
- How are phases connected?
- How do we probe them?
- How do HICs contribute?
- How do Astro+GW contribute?

Constraints on the EOS from pQCD and χPT

- **Chiral perturbation theory** works up to $\sim n_0$
- **Perturbative QCD** works above $\sim 40 n_0$

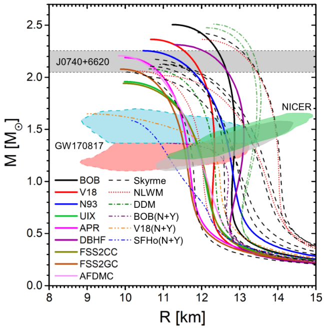


Connecting χ**PT** with **pQCD** imposing causality and stability constrains the EoS

Komoltsev & Kurkela PRL128 (2022)

Do we need deconfined quark matter?

Several purely nucleonic EoSs compatible with all multi-messenger constraints

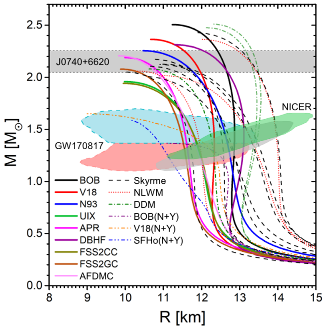


Burgio et al., Prog. Part. Nucl. Phys. 120, 103879 (2021)

- Masses and radii measurements poorly restrict the possible EoSs

Do we need deconfined quark matter?

Several purely nucleonic EoSs compatible with all multi-messenger constraints

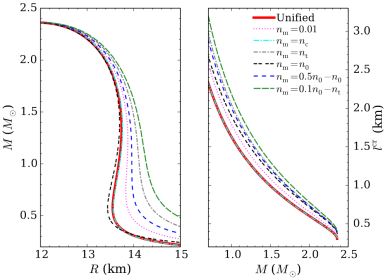


Burgio et al., Prog. Part. Nucl. Phys. 120, 103879 (2021)

- Masses and radii measurements poorly restrict the possible EoSs
- Need of precise and reliable simultaneous mass and radius measurements

Is the purely nucleonic description consistent?

Matching problem



Fortin et al. Phys.Rev.C 94, 3, 035804 (2016)

Ferreira & Providencia, Universe 6(11), 220 (2020)

- Only a few EoSs have a unified crust-core description
- Matching procedure results in uncertain radii

Is the purely nucleonic description consistent?

Geometrical problem

Are neutrons and protons the correct degrees of freedom in the NS core?

The central number densities obtained with nuclear EoSs exceed $2n_0$.

Is the purely nucleonic description consistent?

Geometrical problem

Are neutrons and protons the correct degrees of freedom in the NS core?

The central number densities obtained with nuclear EoSs exceed $2n_0$.

In nuclear matter, nucleons are treated as pointlike objects.
The nucleon radius is $r_0 \simeq 0.8$ fm. Specific volume $\simeq 0.4$ fm^{-3}.

- At $n \gtrsim 2n_0$ can we treat nucleons as poinlike?

Is the purely nucleonic description consistent?

Geometrical problem

Are neutrons and protons the correct degrees of freedom in the NS core?

The central number densities obtained with nuclear EoSs exceed $2n_0$.

In nuclear matter, nucleons are treated as pointlike objects.
The nucleon radius is $r_0 \simeq 0.8$ fm. Specific volume $\simeq 0.4$ fm^{-3}.

- At $n \gtrsim 2n_0$ can we treat nucleons as poinlike?
- Meson exchange models assume distances $\ell > 1$ fm

Is the purely nucleonic description consistent?

Geometrical problem

Are neutrons and protons the correct degrees of freedom in the NS core?

The central number densities obtained with nuclear EoSs exceed $2n_0$.

In nuclear matter, nucleons are treated as pointlike objects.
The nucleon radius is $r_0 \simeq 0.8$ fm. Specific volume $\simeq 0.4$ fm^{-3}.

- At $n \gtrsim 2n_0$ can we treat nucleons as poinlike?
- Meson exchange models assume distances $\ell > 1$ fm
- At $n \gtrsim 2n_0$ is single nucleon description valid? Short distances imply large momentum scattering

Is the purely nucleonic description consistent?

Softening problem

Neutron star masses $\gtrsim 2M_\odot$ require stiff EoSs.

Hyperon puzzle: With increasing baryonic density Σ baryons (as well as other fermionic states) decays are Pauli blocked.

Is the purely nucleonic description consistent?

Softening problem

Neutron star masses $\gtrsim 2M_\odot$ require stiff EoSs.

Hyperon puzzle: With increasing baryonic density Σ baryons (as well as other fermionic states) decays are Pauli blocked.

Populating such states may increases the compressibility.
The stellar center tends to become unstable

Is the purely nucleonic description consistent?

Softening problem

Neutron star masses $\gtrsim 2M_\odot$ require stiff EoSs.

Hyperon puzzle: With increasing baryonic density Σ baryons (as well as other fermionic states) decays are Pauli blocked.

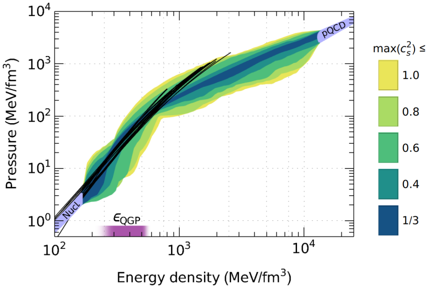
Populating such states may increases the compressibility.
The stellar center tends to become unstable

Possible ways out:

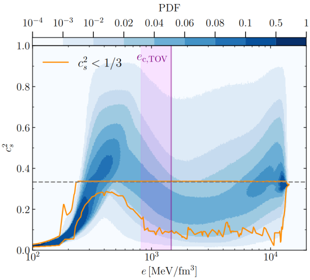
- Strong hyperon interactions
- Liberation of quark degrees of freedom

NS matter EoS

- The QCD input suggests the EoS **softens** at high baryonic densities
- **Peak in the speed of sound**? Does this peak correspond to the hadronic or quark phase?
- How the results would be modified with a 1^{st}-order phase transition?



Annala et al. Nature Physics 16, 9 (2020)
Fujimoto et al., PRL 129, 25, 252702 (2022)
Kojo PRD 104, 7, 074005 (2021)



Altiparmak et al., APJL 939, 2, L34 (2022)
Gorda et al., APJ 950, 2, 107 (2023)
Annala et al. PRX 12 (2022)
Han et al., Sci.Bull. 68, 913 (2023)
Marczenko et al., PRC 107, 2, 025802 (2023)

Phase transitions

At **high temperature and low baryonic densitiy** HIC and LQCD agree: there is a crossover.

At **high baryonic density**

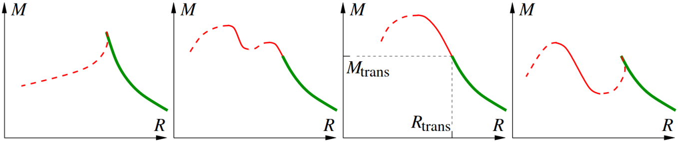
- Should we expect a phase transition?
- What is the onset density?
- Is the superconducting phase realized?
- Are other exotic phases possible?
- How many quark flavors are relevant for NSs?

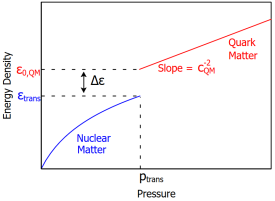
How can we give robust answers to these questions?

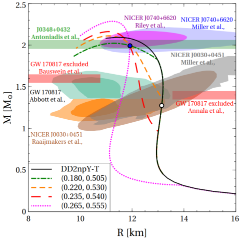
M-R diagram for hybrid stars

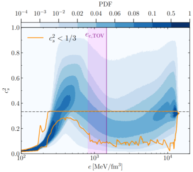
The transition pressure, energy density discontinuity, and the quark matter speed of sound define the shape of the M-R diagram for hybrid stars

Different topologies of the M-R diagram of hybrid stars







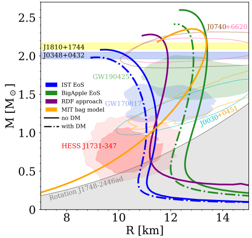


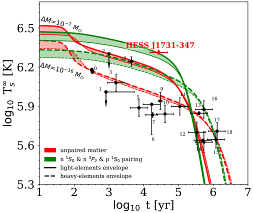
Alford et al. PRD 88 (2013) 8, 083013

Ivanytskyi & Blaschke PRD 105 (2022) 11,

How could we probe the interior composition of compacts stars

- Pulsar mass measurements
  PSR J0348+0432, PSR J1810+1744,
  PSR J0952-0607, PSR J0740+6620
- X-ray measurements with NICER and HESS
  PSR J0740+6620, PSR J0030+0451,
  HESS J1731-347
- NS cooling
- Star's oscillations
- NS glitches
- Gravitational-wave inference of GW170817 and GW190425
- Inference of AT2017gfo
- Multi-messenger analysis





Sagun et al. APJ 958, 1, 49 (2023)

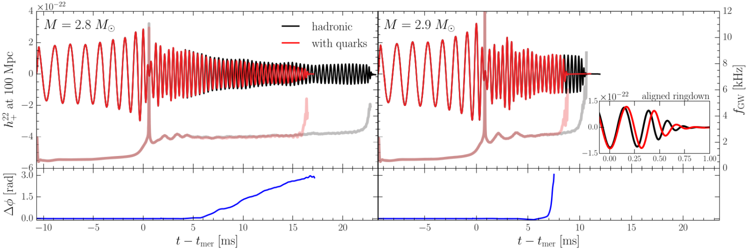
Probing a deconfinement phase transition in NS mergers

- Phase transition affects tidal deformability, merger dynamics, and postmerger remnant
- Postmerger phase GW frequency peaks show to be dependent on the EoS
- Cross-over looks very similar to the 1st-order phase transition

Next generation of GW telescopes: Einstein Telescope and Cosmic Explorer

Main observational breakthroughs:

- Increased sensitivity $\rightarrow \sim 1000$ sources per year
- Postmerger phase and the frequency of the f_{max} peak
- Octopolar dynamical tides



Most et al., PRL 122, 6, 061101 (2019)

Sources of uncertainties

- Finite temperature effects

Sources of uncertainties

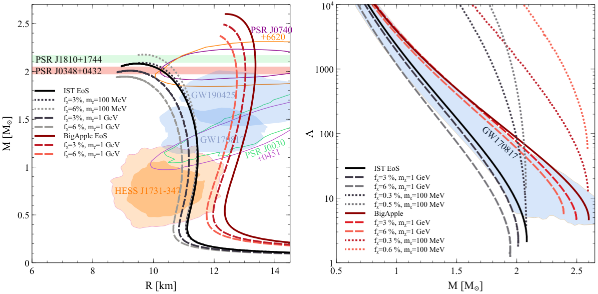
- Finite temperature effects
- Magnetic field

Sources of uncertainties

- Finite temperature effects
- Magnetic field
- Dissipative effects: viscosity

Sources of uncertainties

- Finite temperature effects
- Magnetic field
- Dissipative effects: viscosity
- Accumulated dark matter



Giangrandi et al., APJ. 953, 1, 115 (2023)

Accumulated DM could mimic a stiffening of strongly interacting matter EoS and constraints we impose on it at high densities.

Outlook and conclusions

- The present data indicate a soft EoS at 1.4 $M_\odot$ with a stiffening at higher densities to reach 2.0 $M_\odot$ at radii of around 12 km.

Outlook and conclusions

- The present data indicate a soft EoS at 1.4 $M_\odot$ with a stiffening at higher densities to reach 2.0 $M_\odot$ at radii of around 12 km.
- HIC data suggest softening of the EoS at 2-3n_0.

Outlook and conclusions

- The present data indicate a soft EoS at 1.4 $M_\odot$ with a stiffening at higher densities to reach 2.0 $M_\odot$ at radii of around 12 km.
- HIC data suggest softening of the EoS at 2-3n_0.
- Pure nucleonic EoS has some consistency problem

Outlook and conclusions

- The present data indicate a soft EoS at 1.4 $M_\odot$ with a stiffening at higher densities to reach 2.0 $M_\odot$ at radii of around 12 km.
- HIC data suggest softening of the EoS at 2-3n_0.
- Pure nucleonic EoS has some consistency problem
- The nature of matter above n_0 is still unclear

Outlook and conclusions

- The present data indicate a soft EoS at 1.4 $M_\odot$ with a stiffening at higher densities to reach 2.0 $M_\odot$ at radii of around 12 km.
- HIC data suggest softening of the EoS at 2-3n_0.
- Pure nucleonic EoS has some consistency problem
- The nature of matter above n_0 is still unclear

Outlook and conclusions

- The present data indicate a soft EoS at 1.4 $M_\odot$ with a stiffening at higher densities to reach 2.0 $M_\odot$ at radii of around 12 km.
- HIC data suggest softening of the EoS at 2-3n_0.
- Pure nucleonic EoS has some consistency problem
- The nature of matter above n_0 is still unclear

Open questions:

- Does softening of the EoS occur due to a deconfinement phase transition or in hadronic matter?

Outlook and conclusions

- The present data indicate a soft EoS at 1.4 $M_\odot$ with a stiffening at higher densities to reach 2.0 $M_\odot$ at radii of around 12 km.
- HIC data suggest softening of the EoS at 2-3n_0.
- Pure nucleonic EoS has some consistency problem
- The nature of matter above n_0 is still unclear

Open questions:

- Does softening of the EoS occur due to a deconfinement phase transition or in hadronic matter?
- Does it imply an early strong deconfinement PT to quark matter that stiffens with increasing density?

Outlook and conclusions

- The present data indicate a soft EoS at 1.4 $M_\odot$ with a stiffening at higher densities to reach 2.0 $M_\odot$ at radii of around 12 km.
- HIC data suggest softening of the EoS at 2-3n_0.
- Pure nucleonic EoS has some consistency problem
- The nature of matter above n_0 is still unclear

Open questions:

- Does softening of the EoS occur due to a deconfinement phase transition or in hadronic matter?
- Does it imply an early strong deconfinement PT to quark matter that stiffens with increasing density?
- How to identify the order of the phase transition?

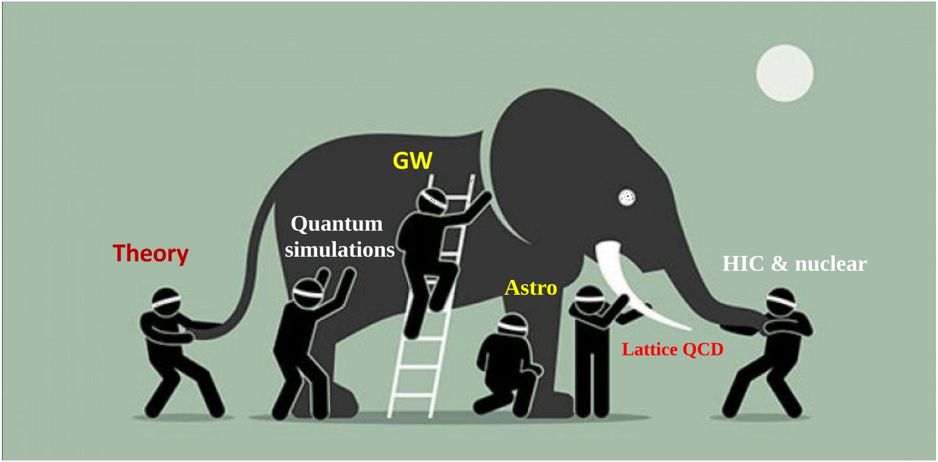
Outlook and conclusions

- The present data indicate a soft EoS at 1.4 $M_\odot$ with a stiffening at higher densities to reach 2.0 $M_\odot$ at radii of around 12 km.
- HIC data suggest softening of the EoS at 2-3n_0.
- Pure nucleonic EoS has some consistency problem
- The nature of matter above n_0 is still unclear

Open questions:

- Does softening of the EoS occur due to a deconfinement phase transition or in hadronic matter?
- Does it imply an early strong deconfinement PT to quark matter that stiffens with increasing density?
- How to identify the order of the phase transition?
- Does dark matter play a role in NS interior?

Much tighter communication between different communities is needed!



List of talks of the session

Properties of quark matter in extreme conditions	*Massimo Mannarelli*
Physics Department - Aula Amaldi (Marconi Building), Sapienza University of Rome	16:15 - 16:40
Constraints on Phase Transition in Neutron Stars in a Generalized Setup	*Jan-Erik Christian*
Physics Department - Aula Amaldi (Marconi Building), Sapienza University of Rome	16:40 - 17:05
Turbulent magnetic field amplification in binary neutron star mergers	*Ricard Aguilera Miret*
Physics Department - Aula Amaldi (Marconi Building), Sapienza University of Rome	17:05 - 17:30
A degeneracy between the effect of dark matter and strongly interacting matter at high densities	*Violetta Sagun*
Physics Department - Aula Amaldi (Marconi Building), Sapienza University of Rome	17:30 - 17:55
Studying strong-interaction matter under extreme conditions with high-energy heavy-ion experiments	*Joachim Stroth*
Physics Department - Aula Amaldi (Marconi Building), Sapienza University of Rome	17:55 - 18:15