EoS at High-Baryon Density and Compact Stellar Objects

Veronica Dexheimer
Summary

- Introduction to compact stars
- Neutron-star equation of state (EoS)
- Ingredients for the EoS
- Modern sources for EoS’s
- EoS constraints
- Recent conclusions
- Deconfinement in supernova simulations
- Deconfinement in merger simulations
- Comparison of mergers and heavy-ion collisions
- Conclusions
Introduction to compact stars

- White dwarfs: lattice of e.g. carbon, oxygen + degenerate electron gas
- Neutron stars: lattice of iron + degenerate gas of neutrons and electrons + core
- Black holes: ?
Strange Quark Star

- Surface
  - Degenerate electron layer

Core
- Electrons
- u,d,s quarks (color-superconducting)

Neutron Star

Surface
- Hydrogen/Helium plasma
- Iron nuclei

Outer Crust
- Ions
- Electron gas

Inner Crust
- Heavy ions
- Relativistic electron gas
- Superfluid neutrons

Outer Core
- Neutrons, protons
- Electrons, muons

Inner Core
- Neutrons
- Superconducting protons
- Electrons, muons
- Hyperons (Σ, Λ, Ξ)
- Deltas (Δ)
- Boson (π, K) condensates
- Deconfined (u,d,s) quarks/color-superconducting quark matter

_mod_phys Lett. A 29 (2014) 1430022

E-Print: 1408.0079
Strange Quark Star

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Mod.Phys.Lett.A 29 (2014) 1430022
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Neutron-star equation of state (EoS)

- Official meaning: a thermodynamic equation relating state variables (usually including the pressure)
- In astrophysics we (when available) also provide:
  - full thermodynamic list of variables
  - particle composition
  - microscopic information (pairing gaps, ...)
  - stellar properties ...
- 1D or 2D (usually for neutron stars or isospin symmetric)
- 3D (usually $n_B$, $T$, $Y_Q$) ...

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Ingredients for the EoS

- Crust EoS with nuclei (pasta?)
- Outer core EoS with interacting (pairing?) nucleons and leptons
- Inner core EoS with interacting (pairing?) nucleons, hyperons, $\Delta$’s, mesons, (transition to?) quarks
- Within description appropriate for high density and finite temperature (quantum relativistic description?)
- Reproduce chiral symmetry restoration (parity doubling?)
- Reproduce lattice QCD results at finite temperature?
- In agreement with heavy-ion collision physics at finite temperature?
- Reproduce perturbative QCD results in the relevant regime
Modern sources for EoS’s

* **CompOSE**

  CompStar Online Supernovae Equations of State
  [https://compose.obspm.fr](https://compose.obspm.fr)
  (Stefan Typel, Micaela Oertel, Thomas Klaehn)

* Online service provides 1D, 2D, 3D EoS tables for astrophysical applications

* Additional software to combine or interpolate data, calculate additional quantities, and graph EoS dependencies

* Instruction manual with summarized **providers quick guide** and **users quick guide**

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\[ \rho_{\text{ratio}} = \frac{p_{\text{th}}(\rho, T)}{p_0} \]

\[ p_{\text{th}}(\rho, T) \equiv p(\rho, x_T, T) - p(\rho, x_0, 0) \]

\[ M_{\text{ratio}} = \frac{M_{\text{max}}^\text{hot} - M_{\text{max}}^\text{cold}}{M_{\text{max}}^\text{cold}} \]

\[ 2.1 < \frac{M_{\text{max}}}{M_\odot} < 2.4 \]
Modern sources for EoS’s

- **muses**
  Modular Unified solver of the Equation of state
  https://muses.physics.illinois.edu/

- Modular: while at low $\mu_B$ the EoS is known from 1st principles, at high $\mu_B$ there will be different models for the user to choose

- Unified: different modules will be merged together to ensure maximal coverage of the phase diagram

- Developers: physicists + computer scientists will work together to develop the software that generates EoS’s over large ranges of temperature and chemical potentials to cover the whole phase diagram

- Users: interested scientists from different communities, who provide input to the future open-source cyberinfrastructure
PI and co-PIs

1. Nicolas Yunes; University of Illinois at Urbana-Champaign; PI
2. Jacquelyn Noronha-Hostler; University of Illinois at Urbana-Champaign; co-PI
3. Jorge Noronha; University of Illinois at Urbana-Champaign; co-PI
4. Claudia Ratti; University of Houston; co-PI and spokesperson
5. Veronica Dexheimer; Kent State University; co-PI

External collaborators

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6. Gordon Baym; University of Illinois at Urbana-Champaign
7. Mark Alford; Washington University in Saint Louis
8. Elias Most; Princeton University
EoS constraints

- Experimental nuclear physics data
  - saturation properties: $n_0$, $B/A$, $K$, $M_N^*/M_N$, $U_\Lambda$, ...
  - symmetry energy and derivative at saturation
  - LG critical point

- Observational data
  - stellar max. masses
  - stellar masses, some with corresponding radii
  - stellar mass with tidal deformability and radius
  - possible very large masses
  - cooling data

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EoS constraints

- 1\textsuperscript{st}-principle theory
  - ChEFT: low T and n_B
    \(\rightarrow\) guides the nuclear EoS
  - lattice QCD: EoS, susceptibilities, partial pressures, (smooth) phase transition line, critical point exclusion \(\rightarrow\) allows calibration of EoS at large T
  - perturbative QCD: extremely large T and \(\mu_B\)
    \(\rightarrow\) guides quark matter EoS
Recent Conclusions

“If the bound on the speed of sound is actually violated – as it is strongly suggested by our results– the speed of sound, as a function of the energy density, has a peculiar shape.

*Talk from Oleg Komoltsev*

Astrophys.J. 860 (2018) 2, 149 e ePrint: 1801.01923

Astrophys.J. 885 (2019) 4 e-Print: 1903.08963

Nucl.Phys.A 843 (2010) 37-58 e-Print: 0912.3800

Phys.Rev.Lett. 114 (2015) 3, 031103 e-Print: 1408.5116
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Not necessarily related to deconfinement?

Talk by Michael Marczenko, poster by Jorge Noronha,

Phys. Rev. D 103 (2021) 7, L071504 e-Print: 2101.05813

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Recent Conclusions

✶ “Bumps” in effective models

✶ Stellar masses and radii: information about “bump”

Phys.Rev.D 105 (2022) 2, 023018 e-Print: 2106.03890

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Deconfinement in supernova simulations

- Second burst of neutrinos after bounce when 3D hybrid EoS Shen-MIT bag model with mixed phase (thin lines) is used

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Deconfinement in merger simulations

- 3D CMF EoS with/without quarks into hydrodynamics system using full GR Frankfurt/Illinois GRMHD code: effects from quarks (h, f, phase) only after the merger

- 3D DD2-SF (RDF) hybrid EoS with mixed phase (+ hadronic ones) into GR SPH code: different postmerger dominant frequencies for hybrid EoS

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> What if the transition is smooth?

Talk by Kenji Fukushima

- 3D DD2-SF (RDF) hybrid EoS with mixed phase (+ hadronic ones) into GR SPH code: different postmerger dominant frequencies for hybrid EoS

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Comparisons with heavy-ion collisions

- CMF with excluded volume that reproduces crossover
  \cite{AstronAstrophys608.2017.A110.ePrint:1706.09191}

- Relativistic hydrodynamics simulations using: full GR Frankfurt/Illinois GRMHD code and Frankfurt SHASTA code

- Final merger mass of 2.9 M\textsubscript{Sun} and low-energy collision with E\textsubscript{lab} = 450 MeV
  e-Print: 2201.13150

- Similar geometry across 18 orders of magnitude
Comparisons with heavy-ion collisions

- Time evolution of systems with averaged equatorial and averaged transverse plane

- Present similar temperatures/entropies per baryon with different distributions
Comparisons with heavy-ion collisions

- Similar trajectories in phase diagram (other than stellar cold center dominated by gravity) allow connection of merger mass with lab energy.
Conclusions

* New tight constraints from experiment, observation, and theory are slowly determining dense matter and neutron-star core properties
* EoS repositories help speeding up understanding of dense matter
* Neutron-star mergers create unique ideal conditions to create and detect deconfinement to quark matter in astrophysics
* LIGO, Virgo, and KAGRA are closely coordinating to start O4 Observing run together in mid-December 2022 (March 2022 update; next update May 2022)
Hadronic Merger Simulations

What we can do nowadays
Takami, Rezzolla, Baiotti (2014, 2015), Rezzolla+ (2016)

average stellar mass
Neutron-Star Merger Simulation

- 3D \((T, n_B, Y_Q)\) CMF tables with 1\textsuperscript{st} order phase transition
- Coupled Einstein-hydrodynamics system \((Frankfurt/IllinoisGRMHD\ code)\)
- Hot ring forms first, then very hot region in the center with quarks

\textit{PRL} 122 (2019) 6, 061101 e-Print: \texttt{1807.03684}
Simulation

🌟 Our simulation (Youtube)  

*PRL* 122 (2019) 6, 061101 e-Print: [1807.03684](https://arxiv.org/abs/1807.03684)
Merger in the QCD Phase Diagram

- 3D CMF EoS with 1\textsuperscript{st} order phase transition
- Hypermassive star with final mass of 2.9 M_{Sun} at \sim 5 ms (after deconfinement but before collapse to black hole)

\textit{Eur.Phys.J.A} 56 (2020) 2, 59
e-Print: \textcolor{blue}{1910.13893}
Inside Hypermassive Neutron Star

- At 5 ms after merger

- Increase of temperature, entropy per baryon, and s-quark fraction at phase transition

- Reaching heavy-ion entropies but with lots of net strangeness

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Deconfinement in the Tidal Deformability

- $1^{\text{st}}$-order phase transitions tilt the mass-radius diagram

- Can create structure in the binary Love relations: slope, hill, drop, and swoosh

- Evident swoosh for twin stars

e-Print: 2111.10260
The Mass Distribution of Neutron Stars in Gravitational-Wave Binaries

Philippe Landry$^1$ and Jocelyn S. Read$^1$

Figure 1. Measured masses and inferred mass distribution for NSs in GW binaries. Top: Marginal one-dimensional mass likelihoods $P(d|m)$ for the NSs in the BNS mergers GW170817 and GW190425, the NSBH mergers GW200105 and GW200115, and the candidate NSBH merger GW190814. Bottom: Median and symmetric 90%
3D QCD Phase Diagrams

* Example: temperature vs. free energy vs. charge fraction

\[ Y_Q = \frac{Q_B}{B} \]

\[ \tilde{\mu} = \mu_B + Y_Q \mu_Q + Y_S \mu_S \]

\[ Y_Q = Y_I + \frac{1}{2} - \frac{1}{2} Y_S \]

* Other possibilities: strangeness, magnetic field, ...