Exotic Matter Produced in Neutron-Star Mergers

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ArXiv 2004.03039
Neutron-Star Core Modelling

- Landau predicted giant nuclei formed when normal nuclei come in close contact at great density and “laws of ordinary quantum mechanics break down” in 1931

- Chadwick discovered neutron in 1932

- Baade and Zwicky proposed that heavy stars explode as supernovae and give birth to neutron stars in 1939

- Oppenheimer and Volkoff modeled neutron stars as cold, degenerate Fermi gas in 1939
Neutron-Star Core Modelling

- Attractive and repulsive aspects of nuclear force introduced in relativistic model by Walecka in 1974
- Higher-order interactions added to better reproduce nuclear saturation properties by Boguta and Bodmer in 1977
- Hyperons included in modeling by Glendenning in 1979
- Negative parity baryons studied in stars by VD in 2008
Neutron-Star Core Modelling

- Hybrid stars with a “quarkian” core suggested by Ivanenko and Kurdgelaidze in 1969
- Pure quark stars proposed by Itoh in 1970
- Presence of a mixed phase (with hadrons and deconfined quarks) inside neutron stars that conserves global charge proposed by Glendenning in 1991
- Presence of a mixed phase inside proto-neutron stars that conserve global charge and global lepton fraction investigated by Roark and VD in 2018
Neutron-Star Structure

- Nuclear density $\rho_0 \sim 10^{15} \text{ g/cm}^3$
CMF (Chiral Mean Field) Model

- Non-linear realization of the linear sigma model
- Includes baryons (+ leptons) and quarks
- Fitted to reproduce nuclear, astrophysical, lattice QCD
- Baryon and quark effective masses

\[
M_B^* = g_B \sigma \sigma + g_B \delta \tau_3 \delta + g_B \zeta \zeta + M_{0B} + g_B \Phi \Phi^2 \\
M_q^* = g_q \sigma \sigma + g_q \delta \tau_3 \delta + g_q \zeta \zeta + M_{0q} + g_q \Phi (1 - \Phi)
\]

- 1\textsuperscript{st} order phase transitions or crossovers
- Potential for \( \Phi \) deconfinement order parameter

\[
U = (a_0 T^4 + a_1 \mu_B^4 + a_2 T^2 \mu_B^2) \Phi^2 \\
+ a_3 T_o^4 \ln (1 - 6 \Phi^2 + 8 \Phi^3 - 3 \Phi^4)
\]
QCD Phase Diagram for High Energy

- Results from the CMF model
Local vs Global Charge Neutrality

- Absence / presence of mixture of phases: surface tension ???
- “Mixed” quantities like baryon number density
Particle Population from Model

- Hadronic phase: hadrons (neutrons, protons, and Λ hyperons) plus electrons and muons
- Quark phase: quarks (up, down, and strange) plus electrons

with mixture of phases
Stellar Central Density

- Modified General Relativity equations for deformed stars predict lower central stellar density for larger rotational frequencies (at fixed baryon number)

- As massive stars grow old new degrees of freedom appear

- Larger central densities present in mixed phase
Stellar Central Density

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- As massive stars grow old new degrees of freedom appear.

- Larger central densities present in mixed phase.

\[ \rho_c = \text{central density (fm}^{-3} \text{)} \]

\[ n \text{ (Hz)} \]

NOT ACCESSIBLE 😞

shearing frequency

\[
\begin{align*}
\text{Frequency (Hz)} & = 0 & 200 & 400 & 600 & 800 & 1000 & 1200 & 1400 & 1600 \\
\text{Central Density (fm}^{-3} \text{)} & = & & & & & & & & 
\end{align*}
\]
But How Can We Probe the Interiors of Neutron Stars?
Neutron Star Merger 170817

- Observed by LIGO/VIRGO in 17 August 2017
- From galaxy NGC 4993 140 million light-years away
- Observed electromagnetically by 70 observatories on 7 continents and in space
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postmerger not yet observed!
Hadronic Merger Simulations

What we can do nowadays

average stellar mass
Merger Simulation with Deconf.

- 3D \((T, \rho_B, Y_c)\) CMF EoS with/without quarks
- Solve coupled Einstein-hydrodynamics system using Frankfurt/IllinoisGRMHD code (FIL)
- Interesting results for final masses of 2.8 and 2.9 \(M_{\odot}\)

- Effects from quarks (h, f, phase) only after the merger
Inside the Neutron-Star Merger

- As neutron stars merge, a hot ring with some quarks forms around the center.
- Then a very hot region forms in the center with lots of quarks.
Merger in the QCD Phase Diagram

- Background: 2D \((T,n_B)\) CMF EoS with 1\(^{\text{st}}\) order phase transition for \(Y_Q=Q/B=0.05\)
Merger in the QCD Phase Diagram

- 3D \((T, n_B, Y_Q)\) CMF EoS with 1\textsuperscript{st} order phase transition for binaries with final mass of \(2.9 \, M_{\odot}\) after deconfinement (\(~5 \, \text{ms}\)) but before collapse to black hole.
Merger in the QCD phase Diagram

- Tracking maximum temperature $T_{\text{max}}$ and density $n_{\text{max}}$ in merger
QCD Phase Diagram for High Energy

- Results from the CMF model
More Phase Diagrams

- Tracking maximum temperature ● and density ◆

- Increase in abs. value of charged chemical potential until phase transition, when it drops

- Decrease in charge fraction of core when quarks appear (not reaching heavy-ion/supernovae conditions)
Simulation

- Our simulation on Youtube
Inside Hypermassive Neutron Star

- At 5 ms after merger
  - Increase of temperature, entropy per baryon, and s-quark fraction at phase transition
  - Total strangeness (hyperons \(\rightarrow\) s-quarks) remains \(~\) same
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Tidal Deformability

- Normalized stellar quadripole deformation by companion
- Calculated from finite-size effects in end of inspiral: $76 \rightarrow 1045$ with 90% confidence (De et al. 2018)
- Related to NS radius of $M=1.4 \, M_{\odot}$ (Raithel et al. 2018)
- Universal relation?
Exploring Isovector Coupling

- Using 3 relativistic EoS’s that fulfil standard nuclear and astrophysical constraints: NL3, MBF, and CMF
- New vector-isovector channel $L_{\omega\rho} = g_{\omega\rho}g_{\omega}^{\mu}g_{\rho}^{\mu}\omega_\mu\omega^\mu \rho_\mu\rho^\mu$
suggested by Horowitz and Piekarewicz

- Non-trivial relation between $\Lambda$ and $R_{1.4M_{\text{Sun}}}$
Exploring Isovector Coupling

- New vector-isovector channel also in much better agreement with Effective Field Theory calculations from Hebeler et. al (2013) available for low densities
Conclusions and Outlook

- Astrophysics provides an ideal testing ground for nuclear physics
- Unique conditions created in neutron-star mergers
- Now, in addition to observe light, we can also understand the universe through gravitational waves
- More realistic models with temperature/exotic degrees of freedom needed to study
  - relation between tidal deformability and nuclear physics
  - realistic neutron-star merger simulations
- More merger data coming ... so, maybe, there will be a clear first signature for quark deconfinement phase transition will from astrophysics!