Using Neutron Stars to Understand Fundamental Physics

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Collaboration with: Mark G. Alford, Alexander Haber, and Ingo Tews
arXiv: 2205.10283, 2302.02989, and 2304.07836
Where are we going? Part 1 of 4

1. Compact stars and the **phase diagram** of nature

2. New models for neutron star **phenomenology**

3. Studying the **lightest** observed compact star

4. Some possible directions of **future work**
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Fundamental Forces

Gravity  Electroweak  Strong
Earthly Matter: Water

- Solid
- Liquid
- Gas
- Triple Point
- Critical Point

Diagram showing the changes in state of water under varying pressure and temperature.
$T$

$300 \text{ Kelvin} \sim 10^{-8} \text{ MeV}$

$150 \text{ MeV}$

$1 \text{ GeV}$
Neutron Star Mergers

Neutron Stars

Early Universe

Heavy Ion Colliders

300 Kelvin $\sim 10^{-8}$ MeV

$150$ MeV

$300$ Kelvin

$\mu$

$1$ GeV

$\mu$

$T$
$\mu$

300 Kelvin $\sim 10^{-8}$ MeV

150 MeV

$T$

Universe

Heavy Ion Colliders

Lattice QCD

Perturbative QCD

Neutron Star Mergers

Neutron Stars
Why else are neutron stars interesting?

All fundamental forces are relevant!

<table>
<thead>
<tr>
<th>Strong</th>
<th>Gravity</th>
<th>Electromagnetism</th>
<th>Weak</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stabilizes</strong> star against gravity</td>
<td>Second most <strong>dense</strong> object in the universe (~$10^{15}$ g/cm$^3$)</td>
<td>Strongest <strong>magnetic fields</strong> in the universe</td>
<td>Isospin <strong>equilibration</strong> $\rightarrow$ Bulk viscosity</td>
</tr>
<tr>
<td></td>
<td><strong>Gravitational waves</strong> from merger</td>
<td>Charge <strong>neutrality</strong></td>
<td><strong>Nucleosynthesis</strong></td>
</tr>
</tbody>
</table>

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https://nineplanets.org/questions/how-big-is-the-sun/
$10^{14}$ times smaller than the Sun
Conclusions: Part 1 of 4

- Neutron stars are...
  - extremely compact
  - used as a “laboratory” to explore some region of the phase diagram of matter
  - cool and dense ($\mu / T$ large)

- QCD cannot be solved exactly → phenomenological models needed
Where are we going? Part 2 of 4

1. Compact stars and the **phase diagram** of nature

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Why develop new phenomenological models?

• Neutron star mergers probe regions of neutron-rich matter

• Most equations of state are calibrated to isospin-symmetric matter (50% neutrons) and extrapolated to ~90% neutron matter

• Let’s calibrate models to neutron-rich matter!
Summary: Part 2 of 4

• Want **better** microscopic models of nuclear matter that are constrained by:

  • Properties of **neutron matter** (how?)

  • Saturation properties of **isospin-symmetric** nuclear matter

  • Observations of **neutron star** structure
# Relativistic Mean-Field Theory (RMFT)

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relativistic theory (e.g., $v_{\text{sound}} &lt; c$) ☑</td>
<td>Not a controlled approximation ☹</td>
</tr>
<tr>
<td>Tractable calculations ☑</td>
<td>Reasonable to about 6 times nuclear saturation density ($\sim 1\text{fm}^{-3}$) ☑ ☹</td>
</tr>
<tr>
<td>Finite temperature and out of equilibrium physics included ☑</td>
<td>No phase transition to deconfined quarks ☹</td>
</tr>
<tr>
<td>Microscopic information available ☑</td>
<td>Coupling constants need to be fit to something ☑</td>
</tr>
</tbody>
</table>

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\[ \mathcal{L} = \mathcal{L}_N + \mathcal{L}_M + \mathcal{L}_l \]

\[ \mathcal{L}_N = \bar{\psi} \left[ i \gamma^\mu \partial_\mu - m_N + g_\sigma \langle \sigma \rangle - g_\omega \langle \omega_0 \rangle - \frac{g_\rho}{2} \tau_3 \langle \rho_0 \rangle \right] \psi \]

\[ \mathcal{L}_M = - \frac{1}{2} m_\sigma^2 \langle \sigma \rangle^2 - b \frac{M}{3} (g_\sigma \langle \sigma \rangle)^3 - \frac{c}{4} (g_\sigma \langle \sigma \rangle)^4 + \frac{1}{2} m_\omega^2 \langle \omega_0 \rangle^2 \]
\[ + \frac{1}{2} m_\rho^2 \langle \rho_0 \rangle^2 + \Lambda (g_\rho \langle \omega_0 \rangle \langle \rho_0 \rangle)^2 \]

\[ \mathcal{L}_l = \bar{\psi}_e (i \gamma^\mu \partial_\mu - m_e) \psi_e \]
\[ \mathcal{L} = \mathcal{L}_N + \mathcal{L}_M + \mathcal{L}_l \]

\[ \mathcal{L}_N = \bar{\psi} \left[ i \gamma^\mu \partial_\mu - m_N + g_\sigma \langle \sigma \rangle - g_\omega \langle \omega_0 \rangle - \frac{g_\rho}{2} \tau_3 \langle \rho_{03} \rangle \right] \psi \]

\[ \mathcal{L}_M = -\frac{1}{2} m_\sigma^2 \langle \sigma \rangle^2 - \frac{b}{3} M (g_\sigma \langle \sigma \rangle)^3 - \frac{c}{4} (g_\sigma \langle \sigma \rangle)^4 + \frac{1}{2} m_\omega^2 \langle \omega_0 \rangle^2 \]

\[ + \frac{1}{2} m_\rho^2 \langle \rho_{03} \rangle^2 + \Delta (g_\rho \langle \omega_0 \rangle \langle \rho_{03} \rangle)^2 \]

\[ \mathcal{L}_l = \bar{\psi}_e (i \gamma^\mu \partial_\mu - m_e) \psi_e \]
Nuclear Physics Data to Constrain Our Model

Fit relativistic mean-field theory to **symmetric** and **neutron** matter

- **Isospin-Symmetric Matter**
  - Binding energy
  - Pressure
  - Incompressibility

- **Neutron Matter**
  → Chiral Effective Field Theory
Chiral Effective Field Theory (ChiEFT)

- Based on the symmetries of QCD with nucleon and pion degrees of freedom
- Controlled approximation to QCD valid at low densities
- Theory fitted to data from scattering experiments

Commonly used relativistic mean-field theories are inconsistent with ChiEFT for neutron matter
Uncertainty in Chiral Effective Field Theory

ChiEFT data from Tews et al. (arXiv:1801.01923)
Uncertainty in Chiral Effective Field Theory

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Simultaneous Nuclear Physics Constraints

Binding Energy [MeV] vs Baryon Density [$n_0$]

- ChiEFT Upper
- RMF fit
- ChiEFT Lower
Simultaneous Nuclear Physics Constraints

Binding Energy [MeV] vs Baryon Density [$n_0$]

ChiEFT Upper
ChiEFT Lower
RMF fit
Symmetric Nuclear Matter

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How can neutron stars constrain our model?

Relativistic Mean-Field Theory \rightarrow \text{Equation of State} \rightarrow \text{TOV} \rightarrow \text{Mass-Radius Curve}

Measurements of Neutron Star Mass and Radius
Equation of State

Observations

\( \frac{p(\varepsilon)}{\varepsilon_s} \)

maximum mass

small range of radii

\( M(R) \)
Developed QMC-RMF1,2,3,4: models of nuclear matter that are constrained by isospin-symmetric and neutron matter and by observations of neutron star structure

Ready for use in neutron star merger simulations: compose.obspm.fr/eos/297

• Tabulated over a range of temperatures, densities, and proton fractions

• Provides an equation of state \((p,\varepsilon,s,\mu,\ldots)\)

• Provides particle dispersion relations and effective masses
Where are we going? Part 3 of 4

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A strangely light neutron star within a supernova remnant

\[ M = 0.77^{+0.20}_{-0.17} \, M_\odot \]

\[ R = 10.4^{+0.86}_{-0.78} \, \text{km} \]
Studying the Lightest Compact Star

\[ M = 0.77^{+0.20}_{-0.17} \, M_\odot \quad R = 10.4^{+0.86}_{-0.78} \, \text{km} \]

• Caution: Parameter estimation & formation mechanism

• What is the composition of this star?
  • Quark star
  • Neutron star
  • Hybrid star
  • Etc...

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Nuclear models only reach $2\sigma$ consistency with the HESS J1731-347 measurement

- Possibly because:
  - Measurement uncertainties underestimated
  - **Additional** nuclear physics not included in the family of RMFs used
  - Nucleons are not the only relevant degree of freedom
The graphs depict the binding energy per nucleon ($E_{\text{bind}}$) as a function of baryon density ($n_0$) for different forms of matter. The graph on the left shows the binding energy for pure neutron matter and symmetric nuclear matter, with the QMC-SOFT line highlighted. The graph on the right demonstrates the relationship between mass and radius for different compact objects, including PSR J0740+6620 and J1731-347, with the QMC-SOFT line superimposed.
Hybrid Equation of State

Alford, Han, Prakash 1302.4732

Energy Density

$\varepsilon_{0,\text{QM}}$  $\varepsilon_{\text{trans}}$  $\Delta \varepsilon$

Quark Matter

Slope = $c_{\text{QM}}^{-2}$

Nuclear Matter

Pressure $p_{\text{trans}}$
\[ c_{QM}^2 = 0.48 \]

\[ n_{tr} \in \{2n_0, 2.4n_0\} \]

\[ \frac{\Delta \epsilon}{\epsilon} \in \{0.004, 0.151\} \]
Conclusions: Part 3 of 4

**If HESS J1731-347 measurement is credible**

• **Most** compact stars could be **hybrid stars** with a nuclear matter “mantle” and a quark matter “core”

• Nuclear models **do not** have to be as “stiff”

• Future observations could help **constrain** low-energy nuclear theory
Parts 1-3 Conclusions

• Neutron stars can be used as a “laboratory” to explore part of the phase diagram of matter

• Developed new models for neutron stars constrained by nuclear physics and astrophysics

• Most compact stars could be hybrid stars with a nuclear matter “mantle” and a quark matter “core”
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Future work

• Weak interaction transport properties
  • Urca processes with arbitrary neutrino distribution
  • Strangeness equilibration in quark matter at merger temperatures

• Interested in the rest of the phase diagram of matter
  • Is there is a critical endpoint?
  • Is chiral symmetry restored at deconfinement?
  • Other phases of matter?