Lower Bound on the Tidal Deformability of Neutron Stars

Sophia Han

University of Tennessee, Knoxville

INT Workshop INT-18-71W
Apr. 19th, 2018 @Seattle
**Dense matter in neutron stars**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Observables</th>
</tr>
</thead>
<tbody>
<tr>
<td>equations of state</td>
<td>mass, radius, tidal deformation, Mol…</td>
</tr>
<tr>
<td>thermal &amp; transport properties, vortex pinning</td>
<td>cooling, spin-down, glitches, neutrinos, GW…</td>
</tr>
</tbody>
</table>

- Massive pulsars observed ~2 solar masses
- Pre-merger GW signals detected limit tidal deformability
- Tidal Love numbers 0.05~0.15
- Speed of sound monotonically increasing with pressure from zero

Postnikov, Prakash & Lattimer, arXiv:1004.5098
EoSs with discontinuity

- Technical problem: matching boundary conditions properly
- First studied in the incompressible limit:
  energy density is constant everywhere inside the star, but
  jump to zero at the surface

\[
C_0^{\text{sing}} = - \frac{4\pi Gr^2}{m(r) + 4\pi Gr^3 p} \frac{d\varepsilon}{dr}
\]

\[
d\varepsilon \frac{dr}{dr} = -\varepsilon_0 \delta(r - R)
\]

\[\ell = 2, 3, 4\]

delta-function singular term proportional to $3/R$

- Applicable to any sharp interface with abrupt density change

Damour & Nagar, arXiv:0906.0096
Generalize to PTs in hybrid stars

- Model-independent parametrization of high-density matter

\[
\left( \frac{p_{\text{trans}}}{\varepsilon_{\text{trans}}}, \Delta \varepsilon / \varepsilon_{\text{trans}}, c_{\text{QM}}^2 \right)
\]

Zdunik & Haensel, arXiv:1211.1231
Alford, SH & Prakash, arXiv:1302.4732

\[\epsilon_0, QM - \Delta \varepsilon = \Delta \varepsilon / \epsilon_{\text{trans}} c_{\text{QM}}^2\]

Hadronic EoSs

Zdunik & Haensel, arXiv:1211.1231
Alford, SH & Prakash, arXiv:1302.4732
- Model-independent parametrization on high-density matter
- Sizable decrease in both $k_2$ and $R$

Generalize to PTs in hybrid stars
Generalize to PTs in hybrid stars

- Model-independent parametrization on high-density matter
- Sizable decrease in both $k_2$ and $R$

DBHF + CSS ($c_{QM}^2=1$)
-No singularity (good for simulations!), but rapidly changing behavior

\[ \varepsilon(p) = \frac{1}{2} \left( 1 - \tanh \left( \frac{p - p_{\text{trans}}}{\delta p} \right) \right) \varepsilon_{\text{NM}}(p) + \frac{1}{2} \left( 1 + \tanh \left( \frac{p - p_{\text{trans}}}{\delta p} \right) \right) \varepsilon_{\text{QM}}(p) \]

Alford, Harris & Sachdeva, arXiv:1705.09880
- No singularity (good for simulations!), but rapidly changing behavior

$$\varepsilon(p) = \frac{1}{2} \left( 1 - \tanh \left( \frac{p - p_{\text{trans}}}{\delta p} \right) \right) \varepsilon_{\text{NM}}(p) + \frac{1}{2} \left( 1 + \tanh \left( \frac{p - p_{\text{trans}}}{\delta p} \right) \right) \varepsilon_{\text{QM}}(p)$$

Alford, Harris & Sachdeva, arXiv:1705.09880
- $\Lambda$ values slightly lower compared to sharp 1st-order transition
- Agrees with the discontinuous limit as $\delta p \rightarrow 0$

$SFHo + CSS \ (c_{QM}^2=1)$

SH & Steiner, in prep.
Mimic quark models with PTs

Dexheimer, Negreiros & Schramm, arXiv:1411.4623
Constraints on PT-like EoSs

Better knowledge of nuclear matter helps

- Massive pulsars observed ~2 solar masses
- Pre-merger GW signals detected limit tidal deformability

![Diagram showing constraints on EoSs with regions labeled D, B, and C.](attachment:image.png)
Combined tidal deformability

- Strikingly insensitive to the mass ratio $q = m_2/m_1$ for nuclear matter
- Chirp mass measured to high precision $\Rightarrow$ estimate range of $\tilde{\Lambda}$

Soft/Stiff Hadronic EoS

$\tilde{\Lambda}$

$q = m_2/m_1 = 0.4 - 1.0$

$0.9\, M_\odot \leq m_1, m_2 \leq M_{\text{max}}$
Theoretical lower bound

Soft nuclear matter + strong phase transition immediately above saturation -> lowest
Soft nuclear matter + strong phase transition immediately above saturation

-NSs obey the same EoS (!)

Is stiffer EoS like DBHF completely ruled out?

Phys. Rev. Lett. 119, 161101
Theoretical lower bound

Soft nuclear matter + strong phase transition immediately above saturation

-NSs obey the same EoS (!)
Is stiffer EoS like DBHF completely ruled out?

DBHF + CSS ($c_{QM}^2=1$)

$\gamma = m_2/m_1 = 0.7 \sim 1.0$
$2.73 M_\odot \leq m_{\text{tot}} \leq 2.78 M_\odot$

Chirp Mass ($M_\odot$)
Soft nuclear matter + strong phase transition immediately above saturation

-NSs obey the same EoS (!) Is stiffer EoS like DBHF completely ruled out? Not necessarily
Theoretical lower bound

Soft nuclear matter + strong phase transition immediately above saturation

-NSs obey the same EoS (!)
Is stiffer EoS like DBHF completely ruled out?
Not necessarily
Soft nuclear matter + strong phase transition immediately above saturation

-NSs obey the same EoS (!)
Is stiffer EoS like DBHF ruled out?

-Could we identify phase transition through future detections?
Soft nuclear matter + strong phase transition immediately above saturation

-NSs obey the same EoS (!)
  Is stiffer EoS like DBHF ruled out?

-Could we identify phase transition through future detections?

-Is it possible to distinguish NS-NS, HS-HS and NS-HS mergers?
Summary

- Dense matter EoSs categorized in terms of $c_s^2 = \frac{dp}{d\varepsilon}$
  a) monotonically increasing and smooth
  b) abrupt discontinuity
  c) smooth but varies rapidly in short range of pressures
  (novel feature to emerge in simulations?)
- Theoretical lowest value of NS tidal deformability is determined by phase transition from soft NM to stiffest QM
- Better constraints to expect
  a) narrow down uncertainties in NM: theory & experiment
  b) multiple detections to map $\tilde{\Lambda}(M_{\text{chirp}})$
- Future work
  role of PTs in properties other than EoS
THANK YOU!

Q & A