Multimessenger constraints for ultra-dense matter

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NSs as multi-messenger laboratories for dense matter (online), 2021-06-16

Work in Collaboration with:
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V. Paschalidis, A. Vuorinen

arXiv: 2105.05132
Approach and motivation

- Extend NS EOS beyond controlled nuclear regime; use knowledge that QCD EOS goes to pQCD at high densities.
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- Use \textit{parametrized-EOS ensemble approach} to determine all allowed behaviors of the EOS between low and high density constraints. Want to be as conservative as possible!
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- Extend NS EOS beyond controlled nuclear regime; use knowledge that QCD EOS goes to pQCD at high densities.

- Use *parametrized-EOS ensemble approach* to determine all allowed behaviors of the EOS between low and high density constraints. Want to be as conservative as possible!

- Has provided evidence for *quark matter cores* in massive NSs, identifying transition with softening of the EOS. Generic for EOSs with $\max(c_s^2) \leq 0.5$. *Annala et al. Nature Phys. 2020*
Motivation

- So far, have only used *most robust* constraints:
  - $M_{\text{TOV}} \geq 2.0M_\odot$
  - $\tilde{\Lambda} < 720$ for GW1701817
    ($q \in [0.73, 1]$, $M_{\text{chirp}} = 1.186M_\odot$)
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  - In 2105.05132, add the following two results:
    - BH formed in GW170817 (**BH-hyp**) [possibly with HMNS first (**HMNS-hyp**)]
    - $R(2.0M_\odot) \geq 11$ km, from measurement of PSR J0740+6620 by NICER+XMM

**Also look at:**
- GW190814
- future measurements
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  ![Graph showing pressure vs. energy density](image)

Less straightforward (esp. HMNS-hyp)

Straightforward
Methodology

- How to enforce BH-hyp or HMNS-hyp, without using quasi-universal relations?
  - Additional input with unknown uncertainties for general EOS
  - Are known to be violated for EOSs with, e.g. 1\textsuperscript{st}-order PTs: 

Methodology

- How to enforce BH-hyp or HMNS-hyp, \textit{without} using quasi-universal relations?
- Possible evolutions of GW170817:

![Diagram showing mass ranges of binary system with labels: $M_{\text{TTOV}}$, $M_{\text{supra}}$, $M_{\text{thresh}}$]
Methodology

• How to enforce BH-hyp or HMNS-hyp, \textit{without using quasi-universal relations}?

• Possible evolutions of GW170817:

\begin{itemize}
  \item Non-rotating NS stable \textit{(no BH!)}
  \item Prompt collapse to BH (tension with kilonova) \textit{[Bauswein+ Astrophys. J. Lett. 850, (2017)]}
\end{itemize}
Methodology

• How to enforce BH-hyp or HMNS-hyp, *without using quasi-universal relations?*

• Possible evolutions of GW170817:

![Mass of binary diagram]

- $M_{\text{TOV}}$
- $M_{\text{supra}}$
- $M_{\text{thresh}}$

Non-rotating NS stable *(no BH!)*

Remnant supported by *uniform* rotation

Supported by *differential* rotation

Prompt collapse to BH (tension with kilonova)

Methodology

• How to enforce BH-hyp or HMNS-hyp, \textit{without using quasi-universal relations}?

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- Non-rotating NS stable (\textit{no BH!})
- Remnant supported by \textit{uniform} rotation
- Supported by \textit{differential} rotation
- Prompt collapse to BH (tension with kilonova)

\[\text{Depend on EOS; require simple hydrostatic/stationary GR codes}\]
\[\text{Depend on EOS; requires expensive merger simulations}\]

\[\begin{align*}
M_{\text{TOV}} & \quad M_{\text{supra}} & \quad M_{\text{thresh}} \\
\text{Mass of binary} & \\
\end{align*}\]
Methodology

**BH-hyp requires:** $M_{\text{remn}} \geq M_{\text{TOV}}$

**HMNS-hyp requires:** $M_{\text{remn}} \geq M_{\text{supra}}$

Mass of binary

$M_{\text{TOV}}$  $M_{\text{supra}}$  $M_{\text{thresh}}$

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**Mass of binary**

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- $M_{\text{TOV}}$
- $M_{\text{supra}}$
- $M_{\text{thresh}}$

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*kilonova and GRB suggest BH formed near $M_{\text{supra}}$

Margalit and Metzger, Astrophys. J. Lett. 850, (2017);
Rezzolla+ Astrophys. J. Lett. 852, (2018);
Methodology

- Technical point: \( M \) not conserved, \( M_B = \bar{m} \cdot N_B \) is!

\[
M_{B,\text{remn}} = M_{B,1} + M_{B,2} - M_{B,\text{ejecta}}
\]
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*Ignore; most conservative
Methodology

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\[ M_{B,\text{remn}} = M_{B,1} + M_{B,2} - M_{B,\text{ejecta}} \]

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- Demand, for $M_{\text{chirp}}$ fixed, there exists a $q \in [0.73, 1]$, such that both:
  1) $M_{B,\text{remn}}(q) \geq M_{B,\text{crit}}$, \hspace{1cm} $M_{B,\text{crit}} \in \{M_{B,\text{Tov}}, M_{B,\text{supra}}\}$
  2) $\tilde{\lambda}(q) < 720$ (low-spin priors)
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  2) $\tilde{\lambda}(q) < 720$ (low-spin priors) *also look at high-spin priors

*additionally, implement $R(2M_\odot)$ lower bounds
Results
Results: BH-hyp + PSR J0740+6620 – most conservative
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BH-hyp effectively $M_{\text{TOV}} = 2.53M_\odot$ cut
Results: BH-hyp + PSR J0740+6620 – most conservative

Main result
Results: HMNS-hyp + PSR J0740+6620 – more consistent with kilonova, GRB
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Most robust result consistent with kilonovae, GRB
Results: HMNS-hyp + PSR J0740+6620 – more consistent with kilonova, GRB

Even most restrictive consistent with with large QM cores!

(max(\(c_s^2\)) \(\lesssim\) 0.5 \(\implies\) large QM cores)
Results: different implementations of GW170817

\[ \begin{align*}
\text{Without } \tilde{\Lambda} & \quad \text{With } \tilde{\Lambda} \\
\end{align*} \]

* approximately cuts on \( M_{\text{Tov}} \), even in full analysis

Results: different implementations of GW170817

Without $\tilde{\Lambda}$

With $\tilde{\Lambda}$

* approximately cuts on $M_{TOV}$, even in full analysis

Conclusions

- New constraints on $M_{\text{TOV}}$ within our ensemble framework:
  \[ \text{BH-hyp} \implies M_{\text{TOV}} \leq 2.53M_\odot \quad \text{HMNS-hyp} \implies M_{\text{TOV}} \leq 2.19M_\odot \]

- BH-hyp, HMNS-hyp, and $R(2.0M_\odot) \geq 11.0, 11.4, 12.2$ km all compatible with QM cores in massive NSs

- Discussion of GW190814, other future measurements in 2105.05132.

- Most robust regions [$R(2.0M_\odot) \geq 11$ km and BH-/HMNS-hyp]:
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Thank you for your attention!
Details, additional results....
Quick detail of EOS interpolation

- \{\mu_i; (c_s^2)_i\}_{i=1}^N \text{ random}
- Connected piecewise linearly
- Enforce subluminalty, thermodynamic consistency:
  \[\forall i : 0 < (c_s^2)_i < 1\]
- No explicit phase trans., but don’t restrict softness of EOS
  (tantamount to 1st order PT)
Quick detail of EOS interpolation

- Integrate twice to get other thermodynamic variables:
  1. \( c_s^2(\mu) = \frac{n}{\mu} \left( \frac{dn}{d\mu} \right)^{-1} \)
  2. \( n = \frac{dp}{d\mu} \)
GW190814 compatible with BH-hyp, but not HMNS-hyp...

- Would imply $\text{max}(c_s^2) \geq 0.51$...
- ...but hard to reconcile with multimessenger picture of GW170817
- Compatible with $R(2.0M_\odot) \geq 11$ km
Future measurements

Radii at different masses:
Future measurements

Radii at different masses:
Radii at different masses:
<table>
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<tr>
<th>Assumptions</th>
<th>$R_{2.0,\text{min}}$ (km)</th>
<th>$R_{1.4}$ (km)</th>
<th>$R_{1.6}$ (km)</th>
<th>$R_{1.8}$ (km)</th>
<th>$R_{2.0}$ (km)</th>
<th>$M_{\text{TOV}}$ ($M_\odot$)</th>
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<td>9.6–13.4</td>
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