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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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 *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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- 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:
  - $M_{\text{TOV}} \geq 2.0 M_\odot$
  - $\tilde{\Lambda} < 720$ for GW1701817
    $(q \in [0.73, 1], M_{\text{chirp}} = 1.186 M_\odot)$
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- *Other robust constraints that we can use?*
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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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Straightforward
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Less straightforward (esp. HMNS-hyp)

Straightforward
Methodology

- How to enforce BH-hyp or HMNS-hyp, \textit{without using quasi-universal relations}?
  - Additional input with unknown uncertainties for general EOS
  - Are known to be violated for EOSs with, e.g. 1st-order PTs \cite{Lau2017, Bandyopadhyay2018, Han2019, Bozzola2019}

Sample quasi-universal relation, \cite{Lau2017}
Methodology

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- Possible evolutions of GW170817:
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- Possible evolutions of GW170817:

\begin{itemize}
  \item Non-rotating NS stable \textit{(no BH!)}
  \item Prompt collapse to BH (tension with kilonova) \cite{Bauswein2017}
\end{itemize}
Methodology

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- Possible evolutions of GW170817:

  
  \[
  M_{\text{TOV}} \quad M_{\text{supra}} \quad M_{\text{thresh}}
  \]

  - Non-rotating NS stable (*no BH!*)
  - Remnant supported by *uniform* rotation
  - Supported by *differential* rotation
  - Prompt collapse to BH (tension with kilonova)  
    
    [Bauswein+ Astrophys. J. Lett. 850, (2017)]
Methodology

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Depend on EOS; require *simple hydrostatic/stationary* GR codes

Depend on EOS; requires *expensive merger simulations*
Methodology

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

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

Mass of binary

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

Non-rotating NS stable (no BH!)
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Supported by *differential* rotation

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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);
Ruiz+ Phys. Rev. D 97, (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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- Demand, for $M_{\text{chirp}}$ fixed, there exists a $q \in [0.73, 1]$, such that both:
  1) $M_{B,\text{remn}}(q) \geq M_{B,\text{crit}}$, $M_{B,\text{crit}} \in \{M_{B,\text{TOV}}, M_{B,\text{supra}}\}$
  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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HMNS-hyp effectively $M_{\text{TOV}} = 2.19M_\odot$ cut
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

\[ \text{Without } \tilde{\Lambda} \quad \text{With } \tilde{\Lambda} \]

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

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Conclusions

• New constraints on $M_{\text{TOV}}$ within our ensemble framework:

  \[ \text{BH-hyp} \implies M_{\text{TOV}} \leq 2.53 M_\odot \quad \text{HMNS-hyp} \implies M_{\text{TOV}} \leq 2.19 M_\odot \]

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

• Discussion of GW190814, other future measurements in 2105.05132.

• Most robust regions $[R(2.0 M_\odot) \geq 11 \text{ km and BH-/HMNS-hyp}]:$
Conclusions

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Thank you for your attention!
Details, additional results....
Quick detail of EOS interpolation

- \( \{ \mu_i, (c_s^2)_i \}_{i=1}^N \) random
- Connected piecewise linearly
- Enforce subluminality, 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. $n = \frac{dp}{d\mu}$

\[ (c_s^2)_{\text{CET}} \rightarrow \cdots \rightarrow (c_s^2)_{i} \rightarrow \cdots \rightarrow (c_s^2)_{N-1} \rightarrow (c_s^2)_{\text{PQCD}} \]

CEFT

nuclear: $h/s$

\[ \mu_{\text{nucl}} \rightarrow \mu_1 \rightarrow \cdots \rightarrow \mu_i \rightarrow \cdots \rightarrow \mu_{N-1} \rightarrow \mu_{\text{PQCD}} \]

pQCD: $X \in [1, 4]$
GW190814 compatible with BH-hyp, but not HMNS-hyp...

- Would imply \( \max(c_s^2) \geq 0.51 \ldots \)
- ...but hard to reconcile with multimessenger picture of GW170817
- Compatible with \( R(2.0M_\odot) \geq 11 \text{ km} \)
Radii at different masses:

Weih+ Astrophys. J. 881, 73 (2019)
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Future measurements

Radii at different masses:
Weih+ Astrophys. J. 881, 73 (2019)
### Numerical MR limits with various hypotheses

| Assumptions | $R_{2.0, \text{min}}$ (km) | $R_{1.4}$ (km) | $R_{1.6}$ (km) | $R_{1.8}$ (km) | $R_{2.0}$ (km) | $M_{\text{TOV}}$ ($M_\odot$) |
|-------------|-----------------------------|----------------|----------------|----------------|----------------|-------------------------|
| –           | –                           | 9.6–13.4       | 9.8–13.3       | 9.7–13.5       | 9.3–13.7       | 2.98                    |
| TOV         | –                           | 9.6–13.4       | 9.8–13.2       | 9.7–13.4       | 9.3–13.6       | 2.53                    |
| Supra       | –                           | 9.7–13.4       | 9.8–13.2       | 9.7–13.3       | 9.3–13.3       | 2.19                    |
| TOV         | 10.9                        | 10.6–13.2      | 10.7–13.2      | 10.9–13.4      | 10.9–13.6      | 2.53                    |
| TOV         | 11.1                        | 10.7–13.2      | 10.9–13.2      | 11.0–13.4      | 11.1–13.6      | 2.53                    |
| TOV         | 11.4                        | 10.9–13.2      | 11.1–13.2      | 11.2–13.4      | 11.4–13.6      | 2.53                    |
| TOV         | 12.2                        | 11.5–13.1      | 11.7–13.2      | 12.0–13.4      | 12.2–13.6      | 2.53                    |
| Supra       | 10.9                        | 10.8–13.2      | 10.9–13.2      | 10.9–13.3      | 10.9–13.3      | 2.19                    |
| Supra       | 11.1                        | 10.8–13.2      | 11.0–13.2      | 11.1–13.3      | 11.1–13.3      | 2.19                    |
| Supra       | 11.4                        | 11.2–13.2      | 11.3–13.2      | 11.4–13.3      | 11.4–13.3      | 2.19                    |
| Supra       | 12.2                        | 11.9–13.1      | 12.0–13.2      | 12.1–13.3      | 12.2–13.3      | 2.19                    |