Constraints on neutron star properties from GW170817

Elias Roland Most

Institute for Theoretical Physics, Frankfurt

Collaborators: Lukas Weih

Supervisors: Luciano Rezzolla, Jürgen Schaffner-Bielich

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

Institute for Theoretical Physics
Can we translate GW170817 to constraints on the EOS?
Ingredients to constrain EOS

**Numerical relativity**

**Physics modelling**

---

**EOS CONSTRAINTS**

---

Observation

GW170817

Abbott + 2017

Metzger 2017
Maximum mass constraints from GW170817
The outcome of GW170817

- The product of GW170817 was likely a hypermassive star, i.e. a differentially rotating object with initial **gravitational** mass

\[ M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot \]

- Sequences of equilibrium models of **nonrotating** stars will have a maximum mass: \( M_{\text{TOV}} \)
The outcome of GW170817

• The product of GW170817 was likely a hypermassive star, i.e. a differentially rotating object with initial gravitational mass

\[ M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot \]

• Sequences of equilibrium models of nonrotating stars will have a maximum mass: \( M_{\text{TOV}} \)

• This is true also for uniformly rotating stars at mass shedding limit: \( M_{\text{max}} \)

• \( M_{\text{max}} \) is simple and quasi-universal function of \( M_{\text{TOV}} \)

(Breu & Rezzolla 2016)

\[ M_{\text{max}} = (1.20^{+0.02}_{-0.05}) M_{\text{TOV}} \]
The outcome of GW170817

• The product of GW170817 was likely a hypermassive star, i.e. a differentially rotating object with initial gravitational mass

\[ M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot \]

• **Green** region is for uniformly rotating equilibrium models.

• **Salmon** region is for differentially rotating equilibrium models.
The outcome of GW170817

- The product of GW170817 was likely a hypermassive star, i.e. a differentially rotating object with initial gravitational mass

\[ M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot \]

- **Green** region is for uniformly rotating equilibrium models.
- **Salmon** region is for differentially rotating equilibrium models.
- **Supramassive** stars have

\[ M > M_{\text{TOV}} \]

- **Hypermassive** stars have

\[ M > M_{\text{max}} \]
The outcome of GW170817

- Merger product in GW170817 could have followed two possible tracks in diagram: **fast (2)** and **slow (1)**

- It rapidly produced a BH when still **differentially** rotating (2)

- It lost differential rotation leading to a **uniformly** rotating core (1).

- (1) is more likely because of large ejected mass (long lived).

- Final mass is near $M_{\text{max}}$ and we know this is universal!
Maximum mass constraint

- The merger product of GW170817 was initially differentially rotating but collapsed as uniformly rotating object.

- HMNS core has about 95% gravitational mass of
  \[ M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot \]

- Ejected rest mass deduced from kilonova emission
  \[ M_{e j}^{\text{blue}} = 0.014^{+0.010}_{-0.010} M_\odot \]

- Use universal relations and account errors to obtain
  \[ 2.01^{+0.04}_{-0.04} \leq \frac{M_{\text{TOV}}}{M_\odot} \lesssim 2.16^{+0.17}_{-0.15} \]


universal relations and GW170817; similar estimates by other groups
Radius constraints from GW170817: A Frankfurt perspective
GW170817: What do we know?

\[ M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot \]

\[ M_1 = 1.36 - 1.60 M_\odot \]

\[ M_2 = 1.17 - 1.36 M_\odot \]

\[ \tilde{\Lambda}_{1.4} < 800 \]
Kilonova constraints on the tidal deformability

- Consistency with kilonova modelling (mass ejection) requires lower limit on tidal deformability

\[ \tilde{\Lambda} = \frac{16}{13} \left[ \frac{(M_A + 12M_B)M_A^4\Lambda_2^{(A)}}{(M_A + M_B)^5} + (A \leftrightarrow B) \right], \]

Errors unclear
Might be as low as \( \sim 200 \) (Coughlin+ 2018)

Radice et al 2018
Limits on radii and deformabilities

- Constraining NS radii of neutron stars is an effort with thousands of papers published over the last 40 years.
- Question is deeply related with EOS of nuclear matter.
- Can new constraints be set by GW170817?
- Ignorance can be parameterised and EOSs can be built arbitrarily as long as they satisfy specific constraints on low and high densities.
Mass-radius relations

- We have produced $10^6$ EOSs with about $10^9$ stellar models.

- Can impose differential constraints from the maximum mass and from the tidal deformability from GW170817

ERM+(PRL 2018)
one-dimensional cuts

• Closer look at a mass of $M = 1.40 \, M_\odot$

• Can play with different constraints on maximum mass and tidal deformability.

• Overall distribution is very robust

$12.00 < R_{1.4}/\text{km} < 13.45$

$R_{1.4} = 12.45 \, \text{km}$

ERM+ (PRL 2018)
Constraining tidal deformability

- Can explore statistics of all properties of our $10^9$ models.
- In particular can study PDF of tidal deformability: $\tilde{\Lambda}$

- LIGO has already set upper limit:
  
  $$\tilde{\Lambda}_{1.4} \lesssim 800$$

- Our sample naturally sets a lower limit:
  
  $$\tilde{\Lambda}_{1.4} > 375$$
Mass-radius relations

• Presence of a phase transition leads to second stable branch and “twin-star” models.
Constraining tidal deformability: PTs

- Can repeat considerations with EOSs having PTs
- Lower limit much weaker: $\tilde{\Lambda}_{1.4} \gtrsim 35$
- Large masses have sharp cut-off on upper limit:
  \[ \tilde{\Lambda}_{1.7} \lesssim 460 \]

GW detection with $\tilde{\Lambda}_{1.7} \sim 700$ would **rule out** twin stars!
Conclusions

\*GW170817* provides new limits on maximum mass and radii:

\[
2.01^{+0.04}_{-0.04} \leq \frac{M_{\text{TOV}}}{M_\odot} \lesssim 2.16^{+0.17}_{-0.15}
\]

- \(12.00 < R_{1.4}/\text{km} < 13.45\) \(\bar{R}_{1.4} = 12.45\) km
- \(8.53 < R_{1.4}/\text{km} < 13.74\) \(\bar{R}_{1.4} = 13.06\) km

\(\tilde{\Lambda}_{1.7} \lesssim 460\)

hadronic EOS phase transitions

Upper limit on deformability can rule out twin stars
What do we now know about the EOS?

- All constraints applied.
- Outer core determines radius.