Binary neutron stars: from gravitational to particle physics

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Plan of the talk

- The richness of merging binary neutron stars
- GW spectroscopy: EOS from frequencies
- GW170817: a game changer:
  - maximum mass
  - threshold mass
  - radii and deformabilities
- Signatures of quark-hadron phase transitions
- Accretion disks from BH-NS simulations
- Fast ejecta in BH-NS simulations
- GW190425
The two-body problem in GR

• For black holes the process is very simple:

\[
\text{BH} + \text{BH} \rightarrow \text{BH} + \text{GWs}
\]

• For NSs the question is more subtle: the merger leads to a hyper-massive neutron star (HMNS), ie

\[
\text{NS} + \text{NS} \rightarrow \text{HMNS} + \ldots \ ? \rightarrow \text{BH} + \text{torus} + \ldots
\]

• HMNS phase can provide clear information on EOS

GW170817

\[\text{GW150914}\]

\[\text{Abbott+ 2016}\]

\[\text{Hanford, Washington (H1)}\]

\[\text{Livingston, Louisiana (L1)}\]

\[\text{Strain (×10^{-22})}\]

\[\text{Frequency (Hz)}\]

\[\text{Normalized amplitude}\]

\[\text{Wex 2016}\]
The two-body problem in GR

• For black holes the process is very **simple**:  

  \[ \text{BH} + \text{BH} \rightarrow \text{BH} + \text{GWs} \]

• For NSs the question is more **subtle**: the merger leads to an hyper-massive neutron star (HMNS), i.e., a metastable equilibrium:  

  \[ \text{NS} + \text{NS} \rightarrow \text{HMNS}+\ldots? \rightarrow \text{BH}+\text{torus}+\ldots? \rightarrow \text{BH} + \text{GWs} \]

• **Ejected matter** undergoes nucleosynthesis of heavy elements.
Broadbrush picture

$M/M_{\text{max}}, q \sim 1$

- Binary ($\leq 1\text{kHz}$)
- HMNS ($2 - 4\text{kHz}$)
- Black hole + torus ($5 - 6\text{kHz}$)
- Black hole ($6 - 7\text{kHz}$)

Time scales:
- $[10^6 - 10^7 \text{ yr}]$
- $[1\text{ ms} - 1\text{ s}]$
- $[1 - 100\text{ s}]$
Quantitatively, differences are produced by:

- total mass (prompt vs delayed collapse)
- mass asymmetries (HMNS and torus)
- soft/stiff EOS (inspiral and post-merger)
- magnetic fields (equil. and EM emission)
- radiative losses (equil. and nucleosynthesis)

Qualitatively, this is what normally happens:
merger $\rightarrow$ HMNS $\rightarrow$ BH + torus
GW spectroscopy and how to constrain the EOS

In frequency space

- Initial LIGO
- Advanced LIGO
- Einstein Telescope
- NS-NS merger
- BH-BH merger
- tidal effects

Graph showing the square root of the signal-to-noise ratio $S_n(f)$ and $2(f |h(f)|)^{1/2}$ as a function of frequency $f$ (Hz) with a focus on the effects of EOS as neutron stars merge.
A spectroscopic approach to the EOS

A spectroscopic approach to the EOS


This is GW spectroscopy

Universal relations can be found between frequencies and stellar properties
Quasi-universal behaviour of GW frequency at amplitude peak 
(Read+2013, Bernuzzi+ 2014, Takami+ 2015, LR+2016, …)

Quasi-universality implies that once \( f_{\text{max}} \) is measured, so is the tidal deformability, hence \( I, Q, M/R \)

Similar quasi-universal relations also for \( f_1, f_2, f_3 \)

These relations can be used for a spectroscopic approach to the EOS
A spectroscopic approach to the EOS

- **Universal behaviour** and **analytic modelling** of post-merger relates position of these peaks with the EOS.
- **Question:** how well can we constrain the EOS (radius) given \(N\) detections?

• **discriminating stiff/soft EOSs possible even with moderate \(N \sim 10\)**
  - **stiff EOSs:** \(|\Delta R/\langle R\rangle| < 10\%\) for \(N \sim 20\)
  - **soft EOSs:** \(|\Delta R/\langle R\rangle| \sim 10\%\) for \(N \sim 50\)
• **golden binary:** \(\text{SNR} \sim 6\) at 30 Mpc
  - \(|\Delta R/\langle R\rangle| \sim 2\%\) at 90\% confidence

GW170817: a game changer

Tootle, Papenfort, Most, LR ApJL (2021)
Limits on the maximum mass

• The remnant of GW170817 was 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: $M_{\text{TOV}}$
Limits on the maximum mass

- The remnant of GW170817 was 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: \( M_{\text{max}} \)

- \( M_{\text{max}} \) simple and quasi-universal function of \( M_{\text{TOV}} \)
  (Breu & LR 2016)

\[
M_{\text{max}} = 1.20^{+0.02}_{-0.05} \, M_\odot
\]
Limits on the maximum mass

- The remnant of GW170817 was 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.

- **Stability line** is simply extended in larger space (Weih+18)
GW170817 produced object "X"; GRB implies a BH has been formed: "X" followed two possible tracks: 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 much more likely because of large ejected mass (long lived).
- Final mass is near $M_{\text{max}}$ and we know this is universal!
let’s recap…

• Consider **evolution track (2)**

• Use measured **gravitational mass** of GW170817

• Remove **rest-mass** deduced from kilonova emission (need conversion baryon/gravitational)

• Use **universal relations**, account for errors to obtain

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

GW170817; similar estimates by other groups (Margalit+ 2018, Shibata+ 2018, Ruiz+ 2018)
Tension on the maximum mass

The recent detection of GW190814 has created a significant tension on the maximum mass

\[ M_1 = 22.2 - 24.3 \, M_\odot \]
\[ M_2 = 2.50 - 2.67 \, M_\odot \]  

smallest BH or heaviest NS!

If secondary in GW190814 was a NS, all previous results on the maximum mass are incorrect.

No EM counterpart was observed with GW190814 and no estimates possible for ejected matter or timescale for survival.

How do we solve this tension?
Tension on the maximum mass

- We can nevertheless explore impact of larger maximum mass, i.e., what changes in the previous picture if

\[ \frac{M_{\text{TOV}}}{M_\odot} \gtrsim 2.5 \, ? \]

- In essence, this is a multi-dimensional parametric problem satisfying conservation of rest-mass and gravitational mass.

- Observations provide limits on gravitational and ejected mass.

- Numerical relativity simulations provide limits on emitted GWs.

- All the rest is contained in 10 parameters that need to be varied within suitable ranges.
Genetic algorithm

• A genetic algorithm is used to sample through the parameter space of the 10 free parameters.

• The algorithm reflects genetic adaptation: given a mutation (i.e. change of parameters) it will be adopted if it provides a better fit to data.

• Consider first previous estimate:

\[ \frac{M_{\text{TOV}}}{M_{\odot}} \lesssim 2.3 \]
First hypothesis: $M_{\text{TOV}} / M_\odot \lesssim 2.3$

- Total mass emitted in GWs is in perfect **agreement** with predictions from numerical relativity

- Total mass ejected is in perfect **agreement** with predictions from kilonova signal
Second hypothesis: $M_{\text{TOV}} / M_\odot \gtrsim 2.5$

- Total mass emitted in GWs is much larger than predicted from simulations;
- Mismatch becomes worse with larger masses

- Total mass ejected is in perfect much smaller than observed from kilonova signal.
Tension on the maximum mass

Nathanail, Most, LR (2020)

• The recent detection of GW190814 has created a significant tension on the maximum mass

\[ M_1 = 22.2 - 24.3 \, M_\odot \]
\[ M_2 = 2.50 - 2.67 \, M_\odot \quad \text{smallest BH or heaviest NS!} \]

• If secondary in GW190814 was a NS, all previous considerations are incorrect.

• No EM counterpart was observed with GW190814 and no estimates possible on ejected matter or timescale for survival.

• **How do we solve this tension?**

• Solution: secondary in GW190814 was a **BH at merger** but could have been a NS before
Threshold Mass to prompt collapse
Another universal behaviour

- Interestingly, a **universal behaviour** can be found also when computing the **threshold mass** to prompt collapse.

But what is the **threshold mass**?

finite-temperature effects.
Another universal behaviour

• Interestingly, a **universal behaviour** can be found also when computing the **threshold mass** to prompt collapse.

2. Determine rigorous definition of "**prompt**" collapse and produce dimensionless quantity

\[ t_{\text{coll}} := t_{\text{BH}} - t_{\text{merg}} \]

\[ t_{\text{merg}} : \quad \min(\alpha) = \alpha_{\text{merg}} := 0.35, \]

\[ t_{\text{BH}} : \quad \min(\alpha) = \alpha_{\text{BH}} := 0.2. \]

extremely robust and EOS independent

\[ \tau_{\text{ff}}(M, R) := \frac{\pi}{2} \sqrt{\frac{R^3}{2M}}. \]

free-fall timescale in Oppenheimer-Snyder collapse
Another universal behaviour

• Interestingly, a **universal behaviour** can be found also when computing the **threshold mass** to prompt collapse.

3. Express measured values in terms of dimensionless collapse time.
Another universal behaviour

- Interestingly, a **universal behaviour** can be found also when computing the **threshold mass** to prompt collapse.

4. Seek universal behaviour via **maximum compactness**.  
   \[ C_{\text{TOV}} := \left( \frac{M}{R} \right)_{\text{TOV}} \]  
   A **linear** fit is possible but not satisfactory. A **nonlinear** fit obtained by requiring that

\[
\frac{M_{\text{th}}}{M_{\text{TOV}}} \to 0 \\
\text{for} \\
C_{\text{TOV}} \to 1/2
\]

\[
\frac{M_{\text{th}}}{M_{\text{TOV}}} = a - \frac{b}{1 - cC_{\text{TOV}}}
\]
Another universal behaviour

- Interestingly, a **universal behaviour** can be found also when computing the **threshold mass** to prompt collapse.

5. The detection of a merger not leading to prompt collapse **constraints the radius from below**

\[ M_{\text{tot}} = 2.74^{+0.04}_{-0.01} \, M_{\odot} \]

so that

\[ R_{\text{TOV}} \geq 9.74^{+0.14}_{-0.04} \, \text{km} \]
Another universal behaviour

- Interestingly, a **universal behaviour** can be found also when computing the **threshold mass** to prompt collapse.

5. The detection of a merger not leading to prompt collapse **constraints the radius from below**

\[ R_x = -0.88 \, M^2 + 2.66 \, M + 8.91 \]
A more general behaviour

- All results so far true for **irrotational equal-mass** binaries
- $M_{\text{th}}$ will depend also on **mass ratio** and **spin**
- Intuitively, $M_{\text{th}}$ increases with **positive spin** and **mass ratio**
- We have considered **40 configurations**, **360 simulations**

Clearly, $M_{\text{th}} = M_{\text{th}}(\text{EOS}, q, \chi)$
A more general behaviour

Is this behaviour universal?

Assume separable ansatz

\[ M_{th} = M_{th}(EOS, q, \chi) = \kappa(EOS) f(q, \chi) \]

where \( \kappa(EOS) \) comes from \( q = 1, \chi = 0 \) (Köppel+ 2019)

\[ \kappa(EOS) := \left( a - \frac{b}{1 - cC_{TOV}} \right) M_{TOV} \]

and \( f(q, \chi) \) is a quadratic function of \( q \) and \( \chi \)

\[ f(q, \chi) := a_1 + a_2(1 - q) + a_3\chi + a_4(1 - q)\chi + a_5(1 - q)^2 + a_6\chi^2 \]
Does this work?

Indeed a **universal relation** exists and yields:

- **average deviation** from fit of $\sim 2\%$, and **largest deviation** below $\sim 6\%$.
- $M_{\text{th}}$ **increases** by $\sim 10\%$ for **aligned spins**
- $M_{\text{th}}$ **decreases** by $\sim 5\%$ for **antialigned spins**

Note: dependence on $q$ **not monotonic**: balance between larger “discs” for small $q$ and increased stability for large $q$ yields **local maximum**
Possible to extend logic for lower limit on radius:

\[ R_x(M, q, \chi) = \frac{R_x(M)}{f(q, \chi)} \]

where \( R_x(M) \) is from Köppel+ 2019 and \( f(q, \chi) \) is the same as for \( M_{th} \)

Antialigned binaries provide significantly tighter constraints:

\( R_{TOV} \geq 10.24 \text{ km} \) for \( \chi = -0.3 \) vs \( R_{TOV} \geq 9.44 \text{ km} \) for \( \chi = 0.3 \)
Limits on radii and deformabilities
Limits on radii and deformabilities

• Can new constraints be set on typical radius and tidal deformability by using GW170817?

• **Ignorance** can be parameterised and EOSs can be built arbitrarily as long as they satisfy specific **constraints** on low and high densities.
parametrising our ignorance

- Construct most generic family of NS-matter EOSs

\begin{align*}
\text{from } \mu_b &= 2.6 \text{ GeV} \\
\text{NNLO pQCD} &\text{ Kurkela+ (2014)} \\
\text{Fraga+ (2014)}
\end{align*}

- interpolation by matching 4 polytropes

BPS

polytropic fit of Drischler+ (2016) (large impact on results)
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.
one-dimensional cuts

• Closer look at a mass of $M = 1.40 \, M_\odot$
• Play with different constraints on $M_{\text{TOV}}$ and tidal deformability
• Overall distribution is very robust
Constraining tidal deformability

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

- LIGO has already set upper limit:
  $70 < \tilde{\Lambda}_{1.4} < 720$
- Our sample sets a lower limit:
  $\tilde{\Lambda}_{1.4} > 375$
the largest so far.
Phase transitions and their signatures

Most, Papenfort, Dexheimer, Hanauske, Schramm, Stoecker, LR (2019)
Weih, Hanauske, LR (2020)
• **Isolated** neutron stars probe a small fraction of phase diagram.

• Neutron-star **binary** mergers reach temperatures up to **80 MeV** and probe regions complementary to experiments.

![Graph showing phase diagram](image)

• Considered EOS based on Chiral Mean Field (CMF) model, based on a nonlinear SU(3) sigma model.

• Appearance of quarks can be introduced naturally.
Animations: Weih, Most, LR
Quarks appear at sufficiently large temperatures and densities.

When this happens the EOS is considerably softened and a BH produced.
Gravitational-wave emission

- After ~ 5 ms, quark fraction is large enough to change quadrupole moment and yield differences in the waveforms.
- Sudden softening of the phase transition leads to collapse and large difference in phase evolution.

Observing mismatch between inspiral (fully hadronic) and post-merger (phase transition): clear signature of a PT.
Animations: Weih, Most, LR
A more comprehensive picture

We have recently added another possible scenario for a post-merger PT, which completes the picture of possible scenarios (Weih, Hanauske, LR 2020).
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Different signatures are also quite transparent when shown in terms of the gravitational waves and their spectrograms.

Importance of **DPT** is that it leads to **two** different “stable” $f_2$ frequencies that are easily distinguishable in the PSD.
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A more comprehensive picture

Another signatures is appearance of an $\ell = 2, m = 1$ mode

The mode is triggered by the PT and the non-axisymmetric deformations it produces.
Conclusions

🌟 Spectra of post-merger shows peaks, some ”quasi-universal”.

🌟 When used together with tens of observations, they will set tight constraints on EOS: radius known with $\sim 1$ km precision.

🌟 Threshold mass has universal behaviour with spin and mass ratio.

🌟 GW170817 has already provided new limits on

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

maximum mass

$$12.00 < \frac{R_{1.4}}{\text{km}} < 13.45 \quad \tilde{\Lambda}_{1.4} > 375$$

radius, tidal deformability

$$M_{\text{th}}/M_{\text{TOV}} \approx 1.41 \quad R_{\text{TOV}} \geq 9.74^{+0.14}_{-0.04} \text{ km}$$

threshold mass

🌟 A phase transition after a BNS merger leaves GW signatures and opens a gate to access quark matter beyond accelerators.