What can we learn from gravitational waves emitted by heavy neutron stars mergers?

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[in collaboration with Hun Tan, Travis Dore, Jaki Noronha-Hostler and Veronica Dexheimer]

DNP Workshop before April APS ‘21
April 14th, 2021
What is it that you do?

Experimental Relativity

Gravity Theory

Gravitational Wave Astrophysics
What is it that you do?

What can we learn about nuclear physics from the inspiral of heavy neutron stars?
A zoo of sources
A zoo of sources

Time: -0.63 seconds

[Credit: Teresita Ramirez / Geoffrey Lovelace / SXS Collaboration / LIGO Virgo Collaboration]
Masses in the Stellar Graveyard

in Solar Masses

LIGO-Virgo Black Holes

EM Black Holes

EM Neutron Stars

LIGO-Virgo Neutron Stars

GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern
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GW190814

GW190425

GW170817

GWTC-2 plot v1.0

LIGO-Virgo I Frank Elavsky, Aaron Geller I Northwestern
How do you extract information from gravitational
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**Modelling**  1. Create template “filters”
How do you extract information from gravitational

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**Data Analysis**
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**Modelling** 1. Create template “filters”

**Data Analysis** 2. Cross-correlate filters & data
How do you extract information from gravitational

**Modelling**  1. Create template “filters”

**Data**       2. Cross-correlate filters & data

**Analysis**

\[
\mathcal{L} = e^{-\frac{1}{2}(s-h \mid s-h)} = e^{4\Re \int \left[\tilde{s}^*(f) - \tilde{h}^*(f, \lambda^\mu)\right]\left[\tilde{s}(f) - \tilde{h}(f, \lambda^\mu)\right] \frac{df}{S_n(r)}}
\]
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The Likelihood function is given by:

\[ \mathcal{L} = e^{-\frac{1}{2}(s-h \mid s-h)} = e^{\mathcal{R} \int \left[ \tilde{s}^\ast(f) - \tilde{h}^\ast(f, \lambda^\mu) \right] \left[ \tilde{s}(f) - \tilde{h}(f, \lambda^\mu) \right] \frac{df}{S_n(r)}} \]
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Likelihood

$$\mathcal{L} = e^{-\frac{1}{2}(s-h \mid s-h)} = e^{4\Re \int [\tilde{s}^*(f) - \tilde{h}^*(f, \lambda^\mu)] [\tilde{s}(f) - \tilde{h}(f, \lambda^\mu)] \frac{df}{S_n(r)}}$$

Fourier transform

inner product
How do you extract information from gravitational

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detector noise (spectral noise density)
How do you extract information from gravitational

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\[ \mathcal{L} = e^{-\frac{1}{2} \left( s h | s h \right)} = e^{4 \Re \int \left[ \tilde{s}^*(f) - \tilde{h}^*(f, \lambda^\mu) \right] \left[ \tilde{s}(f) - \tilde{h}(f, \lambda^\mu) \right] \frac{df}{S_n(r)}} \]

- Likelihood function
- Fourier transform
- Inner product
- Template (projection of GW metric perturbation)
- Detector noise (spectral noise density)
How do you extract information from gravitational

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- inner product
- template (projection of GW metric perturbation)
- detector noise (spectral noise density)
- Fourier transform
- template param that characterize system
How do you extract information from gravitational

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  3. Find filter that maximizes the likelihood function.

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- **inner product**
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How do you extract information from gravitational

**Modelling**
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**Data Analysis**
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The waveform model is key to extract physics information from GW data through matched filtering.

$$\mathcal{L} = e^{-\frac{1}{2} \langle s - h | s - h \rangle} = e^{4R \int \left[ \tilde{s}^*(f) - \tilde{h}^*(f, \lambda^\mu) \right] \left[ \tilde{s}(f) - \tilde{h}(f, \lambda^\mu) \right] \frac{df}{S_n(r)}}$$

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How do you model the GWs emitted in the inspiral

[see e.g. Blanchet, Liv. Rev. in Rel., [Flanagan & Hinderer, PRD77 ('08)]
How do you model the GWs emitted in the inspiral?

Test-particles

$T \sim 10^6 \text{ K} \sim 10^{-5} \text{ MeV}$
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- Test-particles: $T \sim 10^6 \text{ K} \sim 10^{-5} \text{ MeV}$
- Tidal deformations: $T \sim 10^8 \text{ K} \sim 10^{-3} \text{ MeV}$
- Merger: $T \sim 10^{12} \text{ K} \sim 10^2 \text{ MeV}$

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\tilde{h}(f) = A(f)e^{i\psi_{pp}(f)} + i\psi_{tidal}(f)
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\[ \psi_{\text{tidal}} = f(m_1, m_2) v(f)^5 \Lambda \]

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Gravitational waves encode the tidal deformabilities

\[ \tilde{h}(f) = \mathcal{A}(f) e^{i\psi_{\text{pp}}(f)} + i\psi_{\text{tidal}}(f) \]

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[see e.g. Blanchet, Liv. Rev. in Rel., [Flanagan & Hinderer, PRD77 ('08)]
What’s Love got to do with it*?

[see e.g. Yagi & Yunes, Phys. Repts 681 (2017)]

* “it” being nuclear physics.
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What’s Love got to do with it*?

If you measure Love, you can
(i) infer the radius, and
(ii) you can let the data select between EoS models.

[see e.g. Yagi & Yunes, Phys. Repts 681 (2017)]

* “it” being nuclear physics.
First GW measurements of Love (and Radius)

[LIGO, PRL 121 ('18)]
The GW170817 observation allowed for the first GW constraints on the Love number (and thus the radius) [LIGO, PRL 121 ('18)]
What else can we learn about nuclear physics? Consider $c_s^2$...

Recent studies indicate a steep rise or bump

Bedaque & Steiner, PRL 114, '15; Alford et al, PRD92, '15;
What else can we learn about nuclear physics? Consider $c_s^2$...

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Quarkyonic Matter

One physical mechanism:

See e.g. Zhao & Lattimer, 2004.08293.
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Other studies indicate sharp kinks

Chiral mean field model (hyperons and quarks)

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What else can we learn about nuclear physics? Consider $c_s^2$…

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Other studies indicate sharp kinks

A kinky or bumpy speed of sound seems to be somewhat general in several nuclear physics models with quarks d.o.f.


Chiral mean field model (hyperons and quarks)


QHC19 (crossover to quarks)


See e.g. Zhao & Lattimer, 2004.08293.
Kinky and bumpy neutron stars

[Tan, Noronha-Hostler, Yunes, PRL 125, ’20; + in prep with Dexheimer, Dore]
Holding the location of the bump constant, \( \uparrow \text{width} \) \( \uparrow M_\odot \)
Kinky and bumpy neutron stars

Holding the location of the bump constant, ↑ width ↑ $M_\odot$

$\uparrow n_B/n_{\text{sat}}$ for the rise, ↑ the radius (and max central density)

[Tan, Noronha-Hostler, Yunes, PRL 125, ’20; + in prep with Dexheimer, Dore]
If GW190814 is a NS-BH merger, what does this say about $c_s^2$?

Large enough $M_\odot$ and match of R constraints requires step rise in $c_s^2$ between $n_B/n_{sat} \sim 2 - 3$
Isn’t this in conflict with LIGO’s observations?

The spectral representation cannot capture bumps/kinks/jumps in the EOS, can push the M-R curve out-of-bounds!

[Ref. Tan, Noronha-Hostler, Yunes, PRL 125, ’20; + in prep with Dexheimer, Dore]
How can we be sure that it’s a neutron star and not a black hole?

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Needs measurements of $\Lambda \sim 3-20$, current detectors can measure $\Lambda \sim 100 - 400$

[Tan, Noronha-Hostler, Yunes, PRL 125, ’20; + in prep with Dexheimer, Dore]
Summary and Outlook
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• Future upgrades crucial to a further understanding Quantum Chromodynamics
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“Assumptions are made and most assumptions are wrong.”
Thank You
Why start with speed of sound: $c_s^2$?

Connection to the susceptibilities

$$
\chi_2 = \frac{d^2 P}{d\mu_B^2} \text{ at } T=0:
$$

$$
c_s^2 = \frac{n_B}{\mu_B \chi_2}
$$

Fermi

LIGO

Gamma rays, 50 to 300 keV

GRB 170817A

Counts per second

Gravitational-wave strain

GW170817

Frequency (Hz)

Time from merger (seconds)
\[ \tilde{h}(f) = A(f) e^{i\psi_{pp}(f)} + i\psi_{tidal}(f) \]

\[ \psi_{tidal} = f(m_1, m_2) v(f)^5 \Lambda \]

\[ \Lambda = g(m_1, m_2) \lambda_1 + h(m_1, m_2) \lambda_2 \]
Use binary Love relations to write $\lambda_1=\lambda_1(\lambda_2)$ and then a GW measurement of $\Lambda$ gives you $\lambda_1$, and the relations give you $\lambda_2$!
\[ \tilde{h}(f) = A(f) e^{i\psi_{pp}(f)} + i\psi_{\text{tidal}}(f) \]

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Use binary Love relations to write \( \lambda_1 = \lambda_1(\lambda_2) \) and then a GW measurement of \( \Lambda \) gives you \( \lambda_1 \), and the relations give you \( \lambda_2 \)!

If you have measured \((m_1, \lambda_1)\) and \((m_2, \lambda_2)\), then \( \lambda_1 = \lambda_1(C_1) \) and \( \lambda_2 = \lambda_2(C_2) \) relations give you \((m_1, R_1)\) and \((m_2, R_2)\)!
The baldness of compact objects
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\[ \bar{I} = \frac{\lambda}{M^5} \]

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I-Love-Q relations

[Yagi & Yunes, Science 341 ('13), Yagi & Yunes, PRD 88 ('13)]
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I-Love-Q relations

[Yagi & Yunes, Science 341 (’13), Yagi & Yunes, PRD 88 (’13)]
The moment of inertia, quadrupole moment and Love number satisfy (approx Universal), EoS-insensitive relations!
Binary Love relations

\[ \bar{\lambda}_{s,a} = \frac{1}{2} (\bar{\lambda}_1 \pm \bar{\lambda}_2) \]

[Yagi & Yunes, CQG Letters 33 ('16)]
\[ \bar{\lambda}_{s,a} = \frac{1}{2} (\bar{\lambda}_1 \pm \bar{\lambda}_2) \]

The tidal Love numbers satisfy (approx Universal), EoS-insensitive relations (that only depend on the mass ratio)!

[Yagi & Yunes, CQG Letters 33 ('16)]
Improvements in extraction of EoS
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Via stacking
(with aLIGO at design sensitivity, 2021-2023)
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[Agathos et al, PRD 92 ('05)]
Improvements in extraction of EoS

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Single and future observations with 3G detectors
($\lambda_0$=150, GW170817)

[Agathos et al, PRD 92 ('05)]

[Carson, et al, arXiv ('19)]
Beyond 2G detectors

2021  2025  2029  2033  2036

aLIGO    A+    LIGO-India    Voyager
aVirgo   KAGRA

- improved quantum noise
- improved thermal coating
- increased range to 140% wrt aLIGO

- silicon mirrors and suspensions
- low temperature (120K)
- increased range to 200% wrt aLIGO

Moderate Improvements
Beyond 2G detectors

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- 2033: Cosmic Explorer

- 2036: Einstein Telescope, LISA, DECIGO

Moderate Improvements
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Moderate Improvements

New physics
3G ground-based detectors
3G ground-based detectors