Probing subatomic physics with gravitational waves from neutron star binary inspirals

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Overview

- Gravitational waves (GWs) now available for probing fundamental physics in unexplored regimes

- Interpretation of GW signals from binaries relies on theoretical models

- Required: detailed understanding of GW signatures of matter
  - Focus in this talk on the inspiral: clean, cumulative, currently accessible regime

- What have we learned so far?

- Outlook to future prospects
Neutron stars (NSs)

- Gravity compresses matter to up to several times nuclear density

- Thousands observed to date, some masses $> 2$ Msun

- Quantum pressure (neutron degeneracy) can only support up to $\sim 0.7$ Msun

- Unique window onto strongly-interacting subatomic matter
Conjectured NS structure

- **crust** ~ km
  - Lattice of neutron rich nuclei
  - $10^{10}$ times stronger than steel
  - Free neutrons

- **outer core**
  - Uniform liquid (neutron superfluid, superconducting protons, electrons, muons)

- **deep core**
  - $\approx 2x$ nuclear density, nucleons overlap - new degrees of freedom relevant
  - Condensates? Deconfined quarks?

- [Density of iron ~ 10 g/cm$^3$]
  - $\sim 10^6$ g/cm$^3$ inverse $\beta$-decay
  - $\sim 10^{11}$ g/cm$^3$ neutron drip
  - $\sim$ few $x$ $10^{14}$ g/cm$^3$
Neutron stars as QCD labs

- Characterize phases of QCD, probe deconfinement
- Deeper understanding of strong interactions, their unusual properties, e.g.
  - **asymptotic freedom** (weaker force at shorter distances)
  - **Vacuum** (condensate) has important effects, e.g. mass

  - proton mass: ~ 938 MeV
  - only ~ 1% due to Higgs
NSs as labs for emergent structural complexity

- Collective phenomena, multi-body interactions
- Effects of the excess of neutrons over protons (isospin asymmetry)?
- How do nucleons and their quarks and gluons assemble and interact to create the structure of matter?
Gravitational waves (GWs) from binary systems

Details of the waveform encode fundamental source properties

- Measurements: data cross-correlated with theoretical waveform models

- **Details of the waveform encode fundamental source properties**

  - Mass ratio 1:10
  - Misaligned spins
GW signatures of matter

BH-BH (low mass)  BH-NS

merger

ringdown, disruption, postmerger, ...

Spin-induced multipoles

Absorption

**tidal effects:**
excitation of characteristic quasi-normal modes

- resonant +
- non-resonant

GW spectroscopy of NS interiors

Generic phenomena (any objects that are not classical GR black holes in 4d), associated characteristic parameters encode object’s internal structure
In a binary: tidal field $\mathcal{E}$ due to curvature from companion

When variations in tidal field are much faster than NS’s internal timescales (adiabatic limit):

Induced deformation:

$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

tidal deformability parameter

=0 for a BH

[Kol, Smolkin ‘11, Chia ‘20, Casals, LeTiec ‘20,…]

computed from Einstein’s equations for linearized perturbations to equilibrium

[TH 2008]
Properties of NS matter reflected in global observables

NS matter models (equations of state)

Mass vs. radius

Tidal deformability $\lambda$ vs. mass

log [pressure] vs. log [density above nuclear]

mass (Msun) vs. radius (km)

mass (Msun) vs. tidal parameter $\lambda$ ($10^{36}$g cm$^{-2}$ s$^{-2}$)

NICER

GWs
Influence on GWs

- **Energy** goes into deforming the NS
  \[ E \sim E_{\text{orbit}} + \frac{1}{4} Q \, \varepsilon \]

- moving multipoles contribute to gravitational radiation
  \[ \dot{E}_{\text{GW}} \sim \left[ \frac{d^3}{dt^3} (Q_{\text{orbit}} + Q) \right]^2 \]

- approx. GW phase:
  \[ \frac{d\phi_{\text{GW}}}{dt} = 2\omega \quad \frac{d\omega}{dt} = \frac{\dot{E}_{\text{GW}}}{dE/d\omega} \]

\[ \Delta \phi_{\text{GW}}^{\text{tidal}} \sim \lambda \frac{(M\omega)^{10/3}}{M^5} \]

- for two NSs: most sensitive to:
  \[ \dot{\Lambda} = \frac{13}{16 M^5} \left[ \left( 1 + 12 \frac{m_2}{m_1} \right) \lambda_1 + \left( 1 + 12 \frac{m_1}{m_2} \right) \lambda_2 \right] \]

Example: nonspinning inspirals starting from 30 Hz

GW frequency \( \sim 30 \text{Hz} \)

\( \sim 350 \text{Hz} \)

\( \geq 750 \text{Hz} \)

[from Guerra, TH 2019]
More general tidal coupling of NS matter to dynamics for slowly rotating NSs

spacetime near the NS viewed on the orbital scale:

worldline + multipoles

\( m, S^i, Q^{ij}, Q^{ij}_B, \ldots \)

tidally induced mass & current multipoles (* matter contributions to them)

Effective action describing the binary dynamics:

\[
S \approx S_{pp} + \int d\tau \left[ -\frac{z}{2} Q_{ij} \mathcal{E}_{ij} - \frac{z}{2} \dot{Q}^{ij}_B B_{ij} + L^{\text{Coriolis}} + L^{\text{FD}} + L^{\text{osc}} + \ldots \right]
\]

- point-particle part
- multipoles interact with companion’s spacetime curvature
- Effects of NS’s spin on its tidal response
- frame-dragging: Q’s angular momentum interacts with orbital angular mom. & companion’s spin

[Steinhoff, TH +2016, 2020, 2021]
More general tidal coupling of NS matter to dynamics for slowly rotating NSs

Multipoles (due to quasi-normal modes) behave as harmonic oscillators, e.g. one mode each:

\[ L^{osc} \approx \frac{z}{4\lambda z^2 \omega_f^2} \frac{dQ_{ij}}{d\tau} \frac{dQ_{ij}}{d\tau} - \frac{z}{4\lambda} Q_{ij} Q_{ij} + \ldots \] dominated by fundamental (f-)modes

\[ + \frac{3z}{32(\sigma_{stat} - \sigma_{irrot})} \frac{d\dot{Q}_{ij}^B}{d\tau} \frac{d\dot{Q}_{ij}^B}{d\tau} + \frac{2z\sigma_{stat}}{3} B_{ij} B_{ij} + \ldots \] subdominant, but mode frequencies \( \propto \) NS's spin

two different magnetic tidal deformabilities [Landry, Poisson, Pani+, Damour, Nagar, ...]

\[ S \approx S_{pp} + \int d\tau \left[ -\frac{z}{2} Q_{ij} \mathcal{E}_{ij} - \frac{z}{2} \dot{Q}_{ij}^B B_{ij} + L^{Coriolis} + L^{FD} + L^{osc} + \ldots \right] \]

point-particle part  
multipoles interact with companion’s spacetime curvature  
Effects of NS’s spin on its tidal response  
frame-dragging: Q’s angular momentum interacts with orbital angular mom. & companion’s spin

[Steinhoff, TH +2016, 2020, 2021]
Impact of finite $f$-mode frequency during inspiral

Scalings:

- **$f$-mode frequency:** $\omega_f \sim \sqrt{\frac{m}{R^3}}$ (internal structure - dependent)
- **tidal forcing** frequency: $\sim 2\omega \sim 2\sqrt{\frac{M}{r^3}}$

Enhanced tidal effects even if the resonance is not fully excited

Example tidal response during a quasi-circular inspiral

$f$-modes effects included in the effective one body model SEOBNRv4T

[TH + 2016, Steinhoff, TH,+ 2017, Steinhoff, TH + 2021]
Results from NS binary GW events (low spin priors)

GW170817

GW190425 (?)

90% credible interval
(different state-of-the-art
waveform models)

GW170817

GW190425

90% upper limit

Total mass $\sim 2.8 \text{ Msun}$

Total mass $\sim 3.4 \text{ Msun}$

$$\tilde{\Lambda} = \frac{13}{16} M^5 \left[ \left(1 + 12 \frac{m_2}{m_1} \right) \lambda_1 + \left(1 + 12 \frac{m_1}{m_2} \right) \lambda_2 \right]$$
Joint EoS constraints: $2.14 \ M_\odot$ pulsar, GWs, NICER

+ subatomic physics inputs:
  - **Low density**: Fermi liquid theory, chiral effective theory
  - **High density**: speed of sound conformal limit $c_s^2 \rightarrow \frac{1}{3}$

GW constraints on $f$-mode frequency

- Measuring both $\lambda$ and $\omega_f$ (@ quadrupole & octupole for each NS - 8 matter parameters total)
- using an approximate efficient frequency-domain model  
  [Schmidt, TH 2019]

Results for GW170817

$\chi_{\text{SS}}$ and $\chi_{\text{BP}}$

$f$-mode frequency

Dimensionless tidal deformability

Pratten, Schmidt, TH 2020

Pratten, Schmidt, TH 2020
Planned detector developments

Next observing run O4 to start ~ mid-2022
(Near/reaching design sensitivity)

Further upgrades in mid-2020s

2030s (?): 3G detectors (*Einstein Telescope, Cosmic Explorers*):
10x better sensitivity, wider bandwidth

More accurate measurements of nearby sources,
greater number & diversity of events

- map out tidal deformability vs mass
- look for subdominant effects
  - GW spectroscopy of NSs during inspiral
- tidal disruption/merger/postmerger
Conclusions

Neutron stars are unique testbeds for important questions in subatomic physics

- Progress and prospects for exploring them with GWs
- Significant further effort on accurate theoretical modeling required
- Important interdisciplinary connections, e.g. with
  - astronomy (NICER, radio, EM counterparts …)
  - experiments (neutron rich nuclei, heavy ion collisions, …)
  - theoretical advances (nuclear, QCD, …)