The Multimessenger Picture of Binary Neutron Star Mergers

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Multimessenger Picture

- Gravitational Waves
  - inspiral signal: chirp
  - postmerger signal

- Electromagnetic Waves
  - short GRB
  - kilo/macronovae
  - radio flares

- Neutrinos
  - high neutrino luminosity
The BNS merger
GW170817

(c) Mark Myers, Swinburne University of Technology
Gravitational Waves
Gravitational Waves

LIGO detected several hundred of orbits for GW170817
Gravitational Waves

- compare signal with a large number of templates
Waveform models

- How do we know what to search for?

Intrinsic parameters for BHs and NSs
- masses
- spins
- eccentricity

Additionally for NSs
- internal composition

Observational parameters:
- inclination
- distance
- polarization
Waveform models

<table>
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<th>Time domain</th>
<th>Frequency domain</th>
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<td><strong>Post-Newtonian models</strong></td>
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<tr>
<td>+ fast to compute</td>
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<td>- inaccurate near merger</td>
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**Effective one body formalism**

+ agree well with most NR data
- slow to compute

→ surrogate model to allow fast evaluation

**NR simulations**

+ solve full Einstein equations
+ addition of microphysics possible
+ predictions for the postmerger
- only the last orbits can be evolved
- SUPER slow

**Phenomenological tides**

+ combination of PN/EOB/NR
+ accurate until merger
- just a fit
Phenomenological Tides

Combination of PN/EOB/NR knowledge

\[ \Psi_{\text{NRtidal}} = -\kappa_{\text{eff}}^{T} \ \bar{c}_{\text{Newt}} \ \frac{x^{5/2}}{X_{A}X_{B}} \times \]

\[ \frac{1 + \hat{n}_{1}x + \hat{n}_{3/2}x^{3/2} + \hat{n}_{2}x^{2} + \hat{n}_{5/2}x^{5/2}}{1 + \hat{d}_{1}x + \hat{d}_{3/2}x^{3/2}} \]

Effective tidal coupling constant:

\[ \kappa_{\text{eff}}^{T} = \frac{2}{13} \left[ \left( 1 + 12 \frac{X_{B}}{X_{A}} \right) \left( \frac{X_{A}}{C_{A}} \right)^{5} k_{2}^{A} + (A \leftrightarrow B) \right] \]
Advances in Numerical Relativity

increasing accuracy of simulations

Phys. Rev. D96 (2017) no.12, 121501
Advances in Numerical Relativity

\[ \partial_t \chi = \frac{2}{3} \chi [\alpha(\hat{K} + 2\Theta) - D_i \beta^i] \]

\[ \partial_t \tilde{\gamma}_{ij} = -2\alpha \tilde{A}_{ij} + \beta^k \tilde{\gamma}_{ij,k} + \tilde{\gamma}_{ik} \beta^k_{,j} - \frac{2}{3} \tilde{\gamma}_{ij} \beta^k_{,k} \]

\[ \partial_t \hat{K} = -D^i D_i \alpha + \alpha [\tilde{A}_{ij} \tilde{A}^{ij} + \frac{1}{3} (\hat{K} + 2\Theta)^2] + 4\pi \alpha [S + \rho_{\text{ADM}}] + \beta^i K_{,i} + \alpha \kappa_1 (1 - \kappa_2) \Theta \]

\[ \partial_t \tilde{A}_{ij} = -\chi [-D_i D_j \alpha + \alpha (R_{ij} - 8\pi S_{ij})] \]

\[ + \alpha [(\hat{K} + 2\Theta) - 2\tilde{A}^k_{,i} \tilde{A}_{kj} + \beta^k \tilde{A}_{ij,k} + \tilde{A}_{ik} \beta^k_{,j} - \frac{2}{3} \tilde{A}_{ij} \beta^k_{,k}] \]

\[ \partial_t \hat{\Gamma}^i = -2\tilde{A}^{ij} \alpha_{,j} + 2\alpha [\hat{\Gamma}_{jk}^{i} \tilde{A}^{jk} - 2\tilde{A}^{ij} \ln(\chi),_{j}] \]

\[ -\frac{2}{3} \tilde{\gamma}^{ij} (\hat{K} + 2\Theta),_{j} - 8\pi \tilde{\gamma}^{ij} S_{ij} + \tilde{\gamma}^{jk} \beta_{j}^{i,k} \]

\[ + \frac{1}{3} \tilde{\gamma}^{ij} \beta_{kj}^{i} + \beta_{j}^{i} \tilde{\Gamma}_{,j} - \tilde{\Gamma}_{d}^{j} \beta_{j}^{i} + \frac{2}{3} \tilde{\Gamma}_{d}^{i} \beta_{j}^{j} \]

\[ \partial_t \Theta = \alpha \frac{1}{2} H + \partial_k Z^k - (2 + \kappa_2) \kappa_1 \Theta + \beta^i \Theta,_{i} \]
Advances in Numerical Relativity

Coverage of large region of BNS parameter space

- spinning systems
- high mass ratio systems
- precessing systems
- eccentric systems

Inclusion of microphysics

- neutrino schemes
- magnetic fields (ideal/resistive MHD)
- viscous hydrodynamics
Advances in Numerical Relativity


• Precessing and Spinning configurations
  – spin effects even in late inspiral as important as tidal effects
  – spin effects effect the postmerger evolution
Advances in Numerical Relativity

- Eccentric systems
  - f-mode induces oscillations due to close encounters
Advances in Numerical Relativity

- Eccentric systems
  - f-mode induces oscillations due to close encounters
Advances in Numerical Relativity

- Predictions about ejecta mass and compositions
  - dynamical ejecta:
    - tidal tail
    - shock heating
  - disk winds
    - neutrino driven winds
    - magnetic winds
    - secular

Class. Quant. Grav. 34 (2017) no.10, 105014
Advances in Numerical Relativity

Predicting merger outcome
Testing Waveform models

Combination of semi-analytical tidal effective-one-body and numerical relativity
Testing Waveform models

LIGO most sensitive to phase evolution – early alignment

Graph showing phase evolution for different models: SLY, H4, MS1b, PhenomPv2, PhenomPv2 NRTidal, TaylorF2, TaylorF2 Tides.
Testing Waveform models

LIGO most sensitive to phase evolution – alignment in late inspiral
Gravitational Waves

- Chirp signal during the inspiral

Determine the mass

Sky localization

28 sq-deg

Normalized amplitude

Frequency (Hz)

Time (seconds)

Determine the EOS

Gravitational Waves: Parameter Estimation

- Mass Constraints


LIGO-Virgo/Frank Elavsky
Gravitational Waves: Parameter Estimation

- Sky localization
Gravitational Waves: Parameter Estimation

- Sky localization
Gravitational Waves: Parameter Estimation

- Determine the Equation of State

GW observations favor Nss with smaller radii
Gravitational Waves: Postmerger

- postmerger signal at higher frequencies with low chances of detection
Gravitational Waves: Postmerger

- postmerger signal at higher frequencies with low chances of detection

no postmerger signal for GW170817 detected
Neutrinos
Neutrinos

- heating during the NS merger virial temperature

\[ T_{\text{vir}} \sim 25 \text{ MeV} \left( M / 2.5 \, M_\odot \right) \left( 100 \, \text{km}/R \right) \]

Electron-positron production

\[ n + e^+ \rightarrow p + \bar{\nu}_e \]

- Also production of heavy leptons etc.

Lehner et al., arXiv:1603.00501
Neutrinos

- Detection of neutrinos very unlikely

Lehner et al, arXiv:1603.00501

GW170817 @ 40Mpc
< 0.0003 neutrinos

Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817
with ANTARES, IceCube, and the Pierre Auger Observatory

ANTARES Collaboration, IceCube Collaboration, The Pierre Auger Collaboration,
and LIGO Scientific Collaboration and Virgo Collaboration
(See the end matter for the full list of authors.)

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Abstract

The Advanced LIGO and Advanced Virgo observatories recently discovered gravitational waves from a binary neutron star inspiral. A short gamma-ray burst (GRB) that followed the merger of this binary was also recorded by the Fermi Gamma-ray Burst Monitor (Fermi-GBM), and the Anti-Coincidence Shield for the Spectrometer for the International Gamma-Ray Astrophysics Laboratory (INTEGRAL), indicating particle acceleration by the source. The precise location of the event was determined by optical detections of emission following the merger. We searched for high-energy neutrinos from the merger in the GeV–EeV energy range using the ANTARES, IceCube, and Pierre Auger Observatories. No neutrinos directionally coincident with the source were detected within ±500 s around the merger time. Additionally, no MeV neutrino burst signal was detected coincident with the merger. We further carried out an extended search in the direction of the source for high-energy neutrinos within the 14 day period following the merger but found no evidence of emission. We used these results to probe dissipation
EM signals

GW170817
DECam observation
(0.5–1.5 days post merger)

GW170817
DECam observation
(>14 days post merger)
EM Signals

Timeline
EM Signals – sGRBs

GRB170817A

– GRB detection 1.7s after the merger
  → constrain speed of gravity
    \[-3 \times 10^{-15} \leq \frac{\Delta v}{v_{EM}} \leq +7 \times 10^{-16}\]
  → test equivalence principle
  → Lorentz invariants violation test
– time coincidence (4.4 sigma)
– spatial coincidence (5.2 sigma)
– two components:
  – main emission: peak
  – tail emission consistent with blackbody radiation

APJL, 848:L13
EM Signals – sGRBs

- low luminosity
- different possible scenarios


**EM Signals - sGRBs**

*Emerging EM Signals from sGRBs: A Concordant Picture of Photons from a Neutron Star Merger*

Kasliwal et al., *Science* 16 Oct 2017

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Figure 2: The evolution of EM170817 derived from the observed spectral energy distribution. (A) Bolometric luminosity, (B) Blackbody temperature, (C) Photospheric radius, (D) Inferred expansion velocity. Individual points represent blackbody fits performed at discrete epochs to which the observed photometry has been interpolated using low-order polynomial fits. Dashed lines represent an independent Markov-Chain Monte Carlo fit without directly interpolating between data points (see (10) for methodology and best-fit parameter values). The solid red lines (in A and B) represent the results of a hydrodynamical simulation of the cocoon model where the UVOIR emission is composed of (in A) cocoon cooling (yellow dashed line labeled 1), fast macronova (>0.4c; green dashed line labeled 2), and slow macronova (<0.4c; blue dashed line labeled 3).
EM Signals – sGRBs

- BH + disk system
  - Neutrino & anti-neutrino annihilation
  - Magnetic field amplification and jet formation

Ruiz et al., APJ. 824 (2016), L6
Kuichi et al., PRD92, 124034
EM Signals – Kilonova

- pseudo-black body radiation from r-process elements
- formation of heavy elements

Metzger, arxiv:1710.05931
EM Signals – Kilonova

- possible models:

  two component model
EM Signals – Kilonova

• possible models:

AT2017gfo: an anisotropic and three-component kilonova counterpart of GW170817

- three components evolved by semi-analytical model

Perego et al, APJ 850 (2017) L37
EM Signals – radio signals

ongoing radio observations support cocoon model

also: Sub-relativistic outflows with peak times of a few months up to years

\[ t_{\text{peak}}^{\text{rad}} = 1392 \text{ days} \times \left( \frac{T_{\text{ej}}}{10^{49} \text{ erg}} \right)^{\frac{1}{3}} \left( \frac{n_0}{\text{cm}^{-3}} \right)^{-\frac{1}{3}} \left( \frac{v_{\text{ej}}}{0.1} \right)^{-\frac{5}{3}} \]
EM Signals – Applications

- Maximum mass of NSs
  - Ma et al., arXiv:1711.05565
    \[ M_{\text{max}} < (2.19, 2.32)M_\odot \]
  - Rezzolla et al., arXiv: 1711.00314
    \[ 2.01 \pm 0.04 \leq M_{\text{TOV}}/M_\odot \leq 2.16 \pm 0.03 \]
  - Ruiz et al., arxiv:1711.00473
    \[ M_{\text{max}}^{\text{sph}} \lesssim 2.16M_\odot \]
  - Shibata et al., arxiv:1710.07579
    \[ 2.15–2.25M_\odot \]
EM Signals – Applications

• Constraining the EOS:

Radice et al., arxiv:1711.03647
Summary

- Neutron star mergers are central engines for sGRBs and kilo/macronovae
- Neutron star mergers produce heavy elements
- MMA allows EOS and maximum mass constraints
- MMA constraints speed of gravity, Lorentz variation, equivalence principle