A new beginning for transient Gravitational-wave astrophysics

CaJAGWR, Caltech, November 8th, 2016
Gravitational-wave astrophysics

Fundamentally new way to learn about the Universe:

• Is General Relativity in the correct theory of Gravity?

• What happens when matter is compressed to nuclear densities?

• What are the properties of the population(s) of compact objects?

• Is the mechanism that generates gamma-ray bursts a compact binary coalescence?
Quantum fluctuations in the early universe

Binary Supermassive Black Holes in the galactic nuclei

Compact Binary Coalescences

Compact objects captured by Supermassive Black Holes

Rotating Neutron Stars, Supernovae

Cosmic microwave background polarization

Pulsar Timing

Space Interferometers

Ground Interferometers

The Gravitational Wave Spectrum

[Inspired from http://science.gsfc.nasa.gov/663/research/]
100 years ago: General Relativity and Gravitational Waves

• **Before Einstein**: Newtonian gravity
100 years ago:
General Relativity and Gravitational Waves

- 1915: Einstein’s General Relativity, gravitation due to spacetime curvature
100 years ago: General Relativity and Gravitational Waves

- 1916: Albert Einstein predicts the existence of gravitational waves
100 years ago: General Relativity and Gravitational Waves

- The wave travels at the **speed of light**, is transverse, and has **two polarisations**:

  - Weak coupling with matter

- **High-precision** length measurement: **Laser Interferometers**
- **Dense** masses moving **fast**: **merging compact objects**
~30 years ago:
Laser Interferometer Gravitational-wave Observatory

- Two sites **10 light-milliseconds** apart
- Measurement of **space-time** deformations with $\Delta L/L: \sim 10^{-21}$!
Inspiral

-0.76s

GW150914: September 14, 2015 at 09:50:45 UTC

Credit: SXS Collaboration/Canadian Institute for Theoretical Astrophysics/SciNet
Overview (or how can we study transient GWs?)

- Introduction
  - **Compact Binary Coalescence**
  - LIGO
- **Extracting astrophysics**
  - Waveform models
  - Parameter Estimation
- Beyond aLIGO first observing run:
  - **Astrophysics** with **multiple events**
Compact Binary Coalescence

- **Intrinsic** parameters: primary and secondary **masses** and **spins** (and eccentricity)

- **Extrinsic**: time, **sky-position**, distance, **orientation**, reference phase

Credit: LIGO
LIGO measurement technique

- Very complex instrument (control loops)
- Model of the noise

[LIGO-Virgo Collaboration, 2016]
Parameter Inference: **GW150914** observation

- How do we extract the **scientific content**?
Gravitational waveform models

- **2 models** of the **signal** as a proxy for systematic errors:
  - **Double-aligned-spin model** \((\text{SEOBNRv2-ROM, [Taracchini, et al., 2014; Pürrer, 2014]})\)
  - **Single-precessing-spin model** \((\text{IMRPhenomPv2, [Hannam et al. Phys. 2014]})\)
Gravitational waveform models

- **2 models** of the **signal** as a proxy for systematic errors:
  - **Double-precessing-spin model** (*SEOBNRv3, [Pan et al., 2014; Babak et al., 2016]*)
  - **Single-precessing-spin model** (*IMRPhenomPv2, [Hannam et al. Phys. 2014]*)
Masses from the inspiral and ringdown

- Chirp mass: \( \mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \)
- Total mass: \( \text{ringdown} \)
- Mass ratio: \( q = \frac{m_1}{m_2} \)
Effects of spins

- 2 spin vectors
  - **Magnitude**: orbital hang-up
  - **Mis-alignment**: precession and modulations

![Graph showing strain over time with markers for different waveform models.](image)
Effects of spins

- 2 spin vectors
  - Magnitude: orbital hang-up
- Mis-alignment: precession and modulations
Parameter Estimation

- We want the **posterior** probability of parameters $\vec{\lambda}$, given the data $\vec{x}$. With **Bayes'** theorem:

$$p(\vec{\lambda}|\vec{x}, M) = \frac{p(\vec{\lambda}|M) p(\vec{x}|\vec{\lambda}, M)}{p(\vec{x}|M)}$$

- Fit a **model** to the data (**noise** and **signal** models)
- Build a **likelihood** function
- Specify **prior** knowledge
- **Numerically** estimate the resulting **distribution** (**sampling algorithms**)

SPINSpiral [van der Sluys, Raymond, et al. 2008], LALInference [Veitch, Raymond, et al., 2015]
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SPINSpiral [van der Sluys, Raymond, et al. 2008], LALInference [Veitch, Raymond, et al., 2015]
• How close is the remainder to the mean?

• Assumptions: gaussianity and stationarity
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SPINSpiral [van der Sluys, Raymond, et al. 2008], LALInference [Veitch, Raymond, et al., 2015]
Parameter Estimation

- We want the **posterior** probability of parameters \( \tilde{\lambda} \), given the data \( \tilde{x} \). With **Bayes' theorem**:

\[
p(\tilde{\lambda}|\tilde{x}, M) = \frac{p(\tilde{\lambda}|M)p(\tilde{x}|\tilde{\lambda}, M)}{p(\tilde{x}|M)}
\]

- Fit a **model** to the data (**noise** and **signal** models)
- Build a **likelihood** function
- Specify **prior** knowledge
- **Numerically** estimate the resulting **distribution** (efficient **sampling** algorithms) [Raymond, et al. 2010]

SPINSpiral [van der Sluys, Raymond, et al. 2008], LALInference [Veitch, Raymond, et al., 2015]
Markov-Chain Monte Carlo

- **High dimensional** parameter space
- **Slow** waveform computation

**Efficient** sampling critical (especially with **precession**)

[Raymond, et al. 2010]
Gravitational-wave observations in the first observing run (O1)

$\mathcal{L}$IGO-Virgo Collaboration, 2016
GW150914: masses

- 2 models as a proxy for systematic errors:
  - **Double-precessing-spin** model (*SEOBNRv3*)
  - **Single-precessing-spin** model (*IMRPhenomP*)

\[
\begin{align*}
m_1 &= 35.4^{+5.0}_{-3.4} \, M_\odot \\
m_2 &= 28.9^{+3.3}_{-4.3} \, M_\odot
\end{align*}
\]

[LIGO-Virgo Collaboration, 2016]
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- Errors:

  - Signal strength
  - Model inaccuracies

[LIGO-Virgo Collaboration, 2016]
2.3 GW150914: remnant black hole

- Final values fitted from Numerical Relativity simulations
  - Final mass:
    \[ M_f = 62.2^{+3.7}_{-3.4} M_\odot \]
  - Final (dimensionless) spin:
    \[ a_f = 0.68^{+0.05}_{-0.06} \]
  - \(~3\) solar mass radiated!

[LIGO-Virgo Collaboration, 2016]
GW150914: location

[LIGO-Virgo Collaboration, 2016]
GW150914: location

- **CBC** LIGO sky maps
- **Electromagnetic counterpart**
  - Bayestar $O(\text{minutes})$
  - LALInference-lite $O(\text{hours})$
    - Includes spin effects
    - Sub-threshold triggers in part of a network
  - Full LALInference $O(\text{days-weeks})$
- **Sky localisation** degeneracies with only 2 detectors
  [Raymond, et al., 2009]

[LIGO-Virgo Collaboration, 2016]
GW150914: location

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[LIGO-Virgo Collaboration, et al. 2016]
GW150914: distance - inclination

[LIGO-Virgo Collaboration, 2016]
GW150914: distance - inclination

- **Degeneracies** in extrinsic parameters, strain $h$:

\[
h = -\frac{1 + \cos^2(\iota)}{2 D_L} F_j^+ (\text{R.A., dec, } \psi) H_+ \\
+ \frac{\cos \iota}{D_L} F_j^\times (\text{R.A., dec, } \psi) H_\times
\]

3 angles for the orientation: 
(\text{R.A., dec, } \psi)

Intrinsic waveform: 
\[H_{+\times}(m_1, m_2, \vec{S}_1, \vec{S}_2)\]

- **Sampling** in LALInference 
  [Raymond, Farr, 2014]

[LIGO-Virgo Collaboration, 2016]
GW150914: spins

- Weak constraints on spin magnitude
- Very weak constraints on spin orientation
- Due to Almost equal-mass, face-off binary
  [Raymond, 2012]
  [LIGO-Virgo Collaboration, 2013]
Were the black-holes spinning?

[LIGO-Virgo Collaboration, 2016]
Were the black-holes spinning?

GW151226  

LVT151012

[LIGO-Virgo Collaboration, 2016]
Some results of the first observing run (O1)

- Observational medium delivers heavy stellar mass black-holes
- Merging binary black holes exist in a broad mass range
- New access to black holes spins (GW151226 at least one black-hole spinning)
- Measured masses and spins consistent with both:
  - Isolated binary evolution (more aligned spins)
  - Dynamical formation (more misaligned spins)
- Statistical errors dominate waveform systematical errors
Ongoing work in Gravitational-wave astrophysics

- Joint analysis of **electromagnetic** and **gravitational-wave** data
- Understanding of **extreme** astrophysical phenomena
- Higher **probability of astronomical** origin, better **estimations**
- Testing **General Relativity** (with black-hole **ringdowns**)

- Waveform modelling:
  - **Reduced Order Modelling** [Canizares, Field, Gair, Raymond, et al., 2015]
  - **Calibration** of waveform **models** against **Numerical Relativity** [Bohé, Shao, Taracchini, Buonanno, Babak, Harry, Hinder, Ossokine, Pürrer, Raymond, et al., 2016]
  - Towards **automated interferometers** control [Driggers, Raymond, et. al., 2014]
  - **Combining** observations [Raymond, Price, 2015; Raymond, Price, Gendler, in prep]
Towards Automated Control

- Improving gravitational-wave observatories:
  - More **sensitive** detector
  - Higher **duty cycle**
  - Inform design of **future instruments**
  - Optimize for specific **astrophysical sources**
Towards Automated Control

- **Trial in** offline data of the Caltech 40m interferometer
- **Loop:** initial lock acquisition for length control

### Graph

- **Axes:**
  - Cavity Length
  - Frequency [Hz]

- **Legend:**
  - Free running noise (estimated)
  - Original suppressed noise
  - New suppressed noise (estimated)
  - Free running RMS
  - Original suppressed RMS
  - New suppressed RMS

- **Note:** Noise reduced!
Beyond the first observing run (O1)

- **More** Binary Black Holes
- Better spin constraints (magnitude AND orientation)
- **Neutron stars** in binaries
- New tests of **General Relativity**
- Neutron stars equation of state
- Population of **compact objects**

[Increase in spacetime volume relative to O1]

[LIGO-Virgo Collaboration, 2016]
Combining detections

• New **tests** of **General Relativity**

• Neutron stars **equation of state**

• **Mass gap**

• **Field** and **cluster** populations

• **Star formation** parameters

• ….
For instance:

- Neutron-star mass distribution:
  - Iron-core collapse supernovae
    \[ \approx 1.35 \, M_\odot \]
  - Electron-capture supernovae
    \[ \approx 1.25 \, M_\odot \]

[Knigge, et al., 2011, Schwab, et al., 2010]
Parametrisation of a population

- Neutron-star mass distribution:

**Parameters:**

\[
\begin{align*}
\mu_1 &= 1.246 \\
\sigma_1 &= 0.008 \\
\mu_2 &= 1.345 \\
\sigma_2 &= 0.025 \\
h_{12} &= 0.293
\end{align*}
\]

Model inspired by [Schwab, et al., 2010]

*Typical Neutron Star mass estimation from 1 observation*  
[Rodriguez, Farr, Raymond, et al., 2014]
Framework to combine observations

- There is a dense literature on how to use gravitational waves from compact binary coalescence to:
  - distinguish source populations [Stevenson, et al. 2015; Littenberg, et al. 2015, Mandel et al. 2015]
  - mitigate detection and observation bias [Gair, Moore, 2015; Messenger, Veitch, 2012]
  - measure source distribution meta-parameters, [Lackey, Wade 2014]

All of the above in a common treatment [Raymond, Price, 2015; Raymond, Price, Gendler, in prep]

- example with N~1000 (optimistic end of O3), we could resolve the distribution
Future outlook:

• What are the properties of gravitational waves? Is General Relativity still valid under strong-gravity conditions?

• How does matter behave under extremes of density and pressure?

• How abundant are stellar-mass binary black holes? And what are the mass distributions of coalescing compact objects?

• How are compact binaries that coalesce formed, what is their accretion history and what has been their effect on star formation rates?

• Is the mechanism that generates gamma-ray bursts a compact binary coalescence?

• Where and when do massive black holes form, and what role do they play in the formation and evolution of galaxies?

• And the unexpected!