Gravitational-wave Transient Astronomy on the Rise

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DCC: G1800710
2015 — 2016: First Observing Run

GW150914 and the birth of gravitational-wave astronomy
Advanced Interferometer Spectral Sensitivity

**Spectral sensitivity during O1**

- **Low Frequency:** motion of the Earth coupling into motion of the test masses
- **Monochromatic Lines:** calibration lines, 60 Hz power line and harmonics thereof
- **High Frequency:** uncertain photon arrival times at photodetector

**Graphical Elements:**
- Seismic motion
- Power line couplings
- Calibration lines
- Shot noise

**Graph Details:**
- **h(f)** amplitude spectral density [strain/√Hz]
- **Frequency** [Hz]

**Reference:**
PRL 116, 131103 (2016)
“Chirps” in the time domain (monotonically increasing in frequency vs time)
Lower mass $\rightarrow$ Higher frequency content / longer “in band”
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O1 BBH Events

PRX 6, 041015 (2016)
Parameter Degeneracies: Primarily sensitive to the *chirp mass* — leaves large *degeneracies* along contours of chirp mass

\[
M_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}
\]

\[
\chi_{\text{eff}} = \frac{m_1 s_{1,z} + m_2 s_{2,z}}{m_1 + m_2}
\]

Frequency content (and thus “length in band” affected by both *effective spin* and *mass ratio* at same order in expansion of radiation amplitude/phase
After GW170104:

12 - 213 Gpc⁻³yr⁻¹

Power law ($\alpha = -2.35$) only:

40 - 213 Gpc⁻³yr⁻¹

Towards Pop. Distributions:
Constraints on the primary mass distribution from BBH observations — alpha ~ 2.5 ± 1 but new obs. and other features change the distribution

PRX 6, 041015 (2016)
2016 — 2017: Second Observing Run

Binary black hole astrophysics, an international network of interferometers, and huge steps forward in multi-messenger astronomy
GW170104

Remnant mass ~47 M☉

$\Delta L_\odot = 880$ Mpc

$z = 0.18$

PRL 118, 221101 (2017)
Lowest chirp mass $\sim 8 M_\odot$
GW170814
PRL 119, 141101 (2017)
The first three detector network detection
H ~ 7.3 / L ~ 13.7 / V ~ 4.4

Precession:
distribution tilted further towards hints of precession
All mass posteriors in context:

→ Heavier BBH more sensitive to total mass, not chirp mass
→ LVT151012 weakest signal, large ambiguity
→ Volumetric sensitivity increases along the diagonal
All spin posteriors in context:

→ Mass ratio usually means second spin is unconstrained
→ Most distributions have significant weight near zero spin
→ GW searches do not include precession effects (could lead to observational bias)
Assume various simple distributions of spin magnitude. Use these as proxies for low, high, and flat. Using existing observations, infer a virtual “population” giving rise to those distributions in effective spin.

Current detections:
Bayes Factors (evidence for one model versus another) already disfavors high/flat mag. aligned spin.

Fl: Flat mag., isotropic dir.
FA: Flat mag. aligned dir.
HI: High mag, isotropic dir.
HA: High mag, aligned dir.
LI: Low mag, isotropic dir.
LA: Low mag, aligned dir.
Farr, et al. 2017 (Nature)
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Additional detections:
After 10 additional detections from each model

Similar statistical procedure, but use mass distributions to determine how many mass observations are required to confidently discern a given BH natal kick prescription.

**Kick Prescription:**
- Full: \( v_{BH} = v_{NS} \)
- Fallback: \( v_{BH} = (1-f) v_{NS} \)
- Proportional: \( v_{BH} = \frac{M_{NS}}{M_{BH}} v_{NS} \)

**Distinguishability:**
Cluster populations are very similar across prescriptions, so \( \beta \) becomes easier to measure — Kick disruption changes the mass population density and so some prescriptions (proportional) can be distinguished easier than others even with only mass.

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O2 Part 2

GW170817/GRB170817A, astrophysics with neutron stars
GW170817

Metzger 2018, arXiv:1710.05931

https://youtu.be/x_Akn8fUBeQ

NASA Goddard SFC

PRL 119, 161101
Binary dynamics is affected by the EoS through the **tidal deformation** of neutron stars

...but is highly subdominant... enters into the analytical phase expression used by searches and “PE” at $O((v/c)^{10})$

This is subordinate to the masses, mass ratio, spins, spin interactions, ...
**GW170817**

**chirp mass**: measured to within \(~10^{-3}\)

**EoS (through \(\Lambda\))**: disfavor stiff (\(R(M) > 14\) km)

**inclination**: GW alone cannot exclude 0, but host galaxy association can

**spin** \((\chi_i = c|\mathbf{S}_i|/Gm_i^2)\): Cannot place strong constraint

Updated plots in talk by B. Lackey
NSBH remain elusive, but expected to constrain models in the coming observing runs.
2019 and beyond: towards design sensitivity

Future of gravitational-wave binary astrophysics
The Next ~5 Years

O1, H1/L1 (2015): 60-80 Mpc
The Next ~5 Years

O2, H1/L1 (2016-2017): 60-100 Mpc (middle green)
O2 (2017): ~30 Mpc (top of cyan)
O3+, H1/L1/V1 (2019): H1/L1 120 Mpc (proj.) V1 60 Mpc (proj.)
Detection Potential

**Graph:**
- Blue dashed line: bbh astrophysical aligned
- Green line: bns MW like
- Red line: bns broad
- Purple line: nsbh broad aligned
- Yellow line: nsbh broad isotropic

**Table:**

<table>
<thead>
<tr>
<th>Source Category</th>
<th>Full Year VT</th>
<th>( N_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>BBH / bbh_astrophysical_aligned</td>
<td>( 6.8 \times 10^8 ) Mpc(^3) yr</td>
<td>( 35^{+78}_{-26} )</td>
</tr>
<tr>
<td>BNS / bns_mw_like</td>
<td>( 3.2 \times 10^6 ) Mpc(^3) yr</td>
<td>( 4^{+9}_{-4} )</td>
</tr>
<tr>
<td>BNS / bns_broad</td>
<td>( 7.3 \times 10^6 ) Mpc(^3) yr</td>
<td>( 9^{+19}_{-7} )</td>
</tr>
<tr>
<td>NSBH / nsbh_broad_aligned</td>
<td>( 4.9 \times 10^7 ) Mpc(^3) yr</td>
<td>( 1^{+24}_{-1} )</td>
</tr>
<tr>
<td>NSBH / nsbh_broad_isotropic</td>
<td>( 5.7 \times 10^7 ) Mpc(^3) yr</td>
<td>( 1^{+28}_{-1} )</td>
</tr>
</tbody>
</table>
The Next ~5 Years

→ 4 and 5 detector networks by mid 2020s
→ 202X LIGO to meet design sensitivity (blue curve)
→ Kagra online before 2020
→ LIGO India tentatively for 2024
Extra Slides
Putative strain is embedded in detector noise — cross correlate the model with the data to extract a signal-to-noise ratio (SNR, $\rho$) statistic — this maximizes the likelihood (probability of signal vs probability of noise).

\[
d(t) = h(t) + n(t)
\]

\[
\rho = \int \frac{\tilde{h}_{\text{ref}}(f)\tilde{d}(f)}{S(f)} df
\]

Searches maximize likelihood analytically for speed and over masses/spins by brute force (template banks).

arxiv:1606.04856
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arxiv:1606.04856
**Basic Terminology**

**Observations:** Putative strain from **gravitational wave** is embedded in **detector noise**

\[ d(t) = n(t) + h(t) \]

\[ S(|f|) = 2\delta(f - f')\langle \tilde{n}(f)\tilde{n}(f') \rangle \]

**Noise power spectrum:** Autocorrelation of the noise in the frequency domain — “limiting factor” of the sensitivity of the instrument

**Noise weighted inner product:** frequency-domain cross-correlation between two quantities

\[ (a|b) = 2 \int_{-\infty}^{\infty} \frac{\tilde{a}^*(f)\tilde{b}(f)}{S(f)} \]

**Null Hypothesis \((H_0)\):** Data samples are uncorrelated Gaussian noise with variance proportional to \(S(f)\)

\[ p(H_0) \propto \exp\left(-\frac{(d|d)}{2}\right) \]

**Alternative Hypothesis \((H_1)\):** Data are distributed as in null, *after* subtraction of the signal model \(h\)

\[ p(H_1) \propto \exp\left(-\frac{(d - h|d - h)}{2}\right) \]
Inferred Rates / Probability of Astrophysical Origin

\[ \mathcal{L} = \left\{ \prod_{i} \Lambda_{b g} p_{b g}(x_i) + \Lambda_{f g} p_{f g}(x_i) \right\} \exp(-\Lambda_{b g} - \Lambda_{f g}) \]

Likelihood of obtaining ensemble of ranking statistics \(x_i\) with two categories of events: background (terrestrial) and foreground (astrophysical)
\(\Lambda_{f g, b g}\sim\) expected counts from each category
\(p_{f g}, p_{b g}\) - modeled or measured, for astrophysical distribution of binaries \(p_{f g}\sim\rho^{-4}\)

arxiv:1302.5341
Inferred Rates / Probability of Astrophysical Origin

Obtain probability of astrophysical origin by marginalizing against the counts

\[ p_{\text{astro}}(x|x_i) = \int d\Lambda \frac{\Lambda_{fg} p_{fg}(x)}{\Lambda_{fg} + \Lambda_{bg} p_{bg}(x)} p(\Lambda_{fg}, \Lambda_{bg}|x_i) \]

- GW150914 suppressed since > 99% probable and far to the right
- LVT151012 ~ 87% probable foreground

Model 2 ranking stat.

Model 1 ranking stat.