Listening to Black Holes with Gravitational Waves

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KICP 20th Anniversary
June 8 2024
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Gravitational-wave observatories

- LIGO Livingston
- LIGO Hanford
- KAGRA
- Virgo
- LIGO India (coming ~2030)
$O1 + O2 + O3 = 90, \ O4a^* = 81, \ O4b^* = 24, \ Total = 195$

* $O4a$ and $O4b$ entries are preliminary candidates found online.

Cumulative Detections/Candidates

Time (Days)

O1  O2  O3a  O3b  O4a  O4b
I join KICP

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I graduate, move to CIERA, move to CITA
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Observing Binary Black Holes

How big is each black hole?

$m_1$  $m_2$

How fast are they spinning?
Where are the spin axes pointing?

$\chi_1$  $\chi_2$

How far away and long ago did they merge?

$D_L(z)$
From Single Events to a Population: Hierarchical Bayesian Inference

- Introduce a population model that describes the distributions of masses, spins, redshifts across multiple events.
- Example: Fit a power law to black hole masses.
- Take into account measurement uncertainty and selection effects.
- Don’t just fit the “detected distribution!” (Essick & MF 2024)
Cosmology with binary black hole (and neutron star) mergers

- Standard siren cosmography
- Evolution of stars and their environments across cosmic time
- Chemical enrichment history
Probing cosmic history with gravitational waves

Merger rate density

$R(z) \left[ \text{Gpc}^{-3} \text{yr}^{-1} \right]

\begin{align*}
10^1 & \quad 10^2 \\
0.00 & \quad 0.25 \quad 0.50 \quad 0.75 \quad 1.00 \\
\text{GWTC-3 (Power Law + Peak)} & \\
\text{Star Formation (Arbitrary Norm.)} &
\end{align*}

Redshift

LVK PRX 13 011048 (2023)
Method based on MF, Farr & Holz 2018 ApJL 863 L41
Merger rate follows progenitor formation rate with a delay time.
LIGO-Virgo-KAGRA’s Oldest Black Holes

We have probably observed black holes that formed in the Universe’s first billion years (Even though they all merged within the last 8 billion years)

MF & van Son, ApJL 957 L31 (2023)
If we know the progenitor formation rate, we can measure delay time distribution

Blue: Inference of the black hole merger rate as a function of cosmic time

Solid lines: Predicted merger rate evolution from different delay time distributions

GWTC-2
Madau-Fragos SFR
$\tau_{\text{min}} = 10$ Myr
$\tau_{\text{min}} = 100$ Myr
$\tau_{\text{min}} = 1$ Gyr
$\tau_{\text{min}} = 3$ Gyr

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MF & Kalogera 2021, ApJL 914 L30
Delay time distribution informs the population of mergers’ host galaxies

Vijaykumar, MF, Adhikari & Holz arXiv:2312.03316
See also Adhikari, MF, Holz, Wechsler & Fang 2020
Compare against theoretical predictions for delay time distribution

$\Delta N_{BBH} / \Delta t_{\text{delay}}$ [Gyr$^{-1} \times 10^{6} M_\odot^{-1}$]

- $t_{\text{min}} = 10$ Myr
- $\propto t_{\text{delay}}^{-1}$
- $\propto t_{\text{delay}}^{-0.35}$

- All BBHs
- Common envelope channel
- Stable channel

MF & van Son (2023)
Alternatively, if we know the delay time distribution, we can infer the **progenitor formation rate**

![Graph showing the progenitor formation rate as a function of formation redshift](image)

- **Rate** \( [\text{Gpc}^{-3} \text{yr}^{-1}] \)
- **Formation redshift** \( z_{\text{form}} \)

- Prior
- Posterior, \( \alpha_T = -1 \)
- \( 10^{-6} M_\odot^{-1} \times \) UV SFR (KYZ21)
- \( 10^{-6} M_\odot^{-1} \times \) UV+IR SFR (KYZ21)

MF & van Son (2023)
Progenitor formation rate divided by star formation rate:

**Efficiency**

![Graph showing the efficiency of progenitor formation rate divided by star formation rate over formation redshift. The graph includes lines for different values of $\alpha_{\tau}$, with $\alpha_{\tau} = -1$, $\alpha_{\tau} = -0.7$, and $\alpha_{\tau} = -0.35$. The y-axis represents the differential number of BBHs per unit mass of star formation, and the x-axis represents the formation redshift $z_{\text{form}}$. The graph shows a trend where the efficiency increases with increasing redshift, particularly for higher values of $\alpha_{\tau}$.](image)

MF & van Son (2023)
Efficiency depends on metallicity

\[ dN_{\text{BBH}}/dM_{\text{SF}}(Z) [M_{\odot}^{-1}] \]

\[ y \ln(w - \log_{10} Z/Z_\odot) \]

MF & van Son (2023)
Infer chemical enrichment history

$\alpha = -1$

$\alpha = -0.35$

Average metallicity

$\langle \log_{10}(Z/Z_\odot) \rangle$

Formation redshift $z_{\text{form}}$

MF & van Son (2023)
Do black holes grow via repeated mergers?
Using spin to distinguish hierarchical mergers

- 2g black holes tend to spin at dimensionless spin magnitude ~0.7 (e.g., MF, Farr & Holz 2017)
- Hierarchical mergers are dynamically assembled, so spin tilts are randomly oriented
- Fixed fraction of hierarchical mergers will have large, misaligned spins
Hierarchical mergers may account for all black holes above $\sim 60 M_\odot$, but are a very small contribution at lower masses.

Fraction of binaries with (moderately) large, misaligned spins

Fraction of hierarchical mergers
Connection to supermassive black holes?

As a first step, how much mass is available?

- **Blue**: Extrapolate mass in stellar-mass binary black hole mergers to the early Universe according to star formation rate and delay time model.
- **Green**: Mass in supermassive black holes (empirical model TRINITY).

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Cosmic Explorer and Einstein Telescope would map the black hole merger rate across all of cosmic time, from the very first black holes.

Also map the redshift evolution of the mass distribution (e.g. MF+ 2021) and spin distribution (e.g. Bavera, MF+ 2022)
Gravitational-wave probes of the high-redshift Universe

- Gravitational waves probe the metallicity-specific star-formation history:
  - Delay times between progenitor formation and black hole merger imply that we are already probing star formation up to $z \sim 6$
  - Evolution of the binary black hole merger rate with redshift implies a preference for low-metallicity progenitors
- Do stellar-mass black hole mergers inform the supermassive black hole population?
  - Mergers can produce black holes heavier than 100 solar masses
  - No clear signatures of hierarchical black hole mergers in the LVK band (yet)
Learning from gravitational-wave populations
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• How are black holes and neutron stars made?
  • Where is the **pair-instability mass gap**?
  • Is there a **mass gap between neutron stars and black holes**?
  • What are the **natal spins** of neutron stars and black holes?
  • How do neutron stars and black holes find **merger partners**?
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  • Does their progenitor rate follow the (low-metallicity?) (globular cluster?) **star formation rate**?
  • What are the **host galaxies** of gravitational-wave sources?
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- What are the cosmological implications of gravitational-wave sources?
  - Standard sirens may help arbitrate the **Hubble constant tension**
  - Probe **dark energy** via background expansion and **modified gravitational-wave propagation**
  - Learn about **large scale structure**, gravitational-wave **lensing**