Search for black hole merger families

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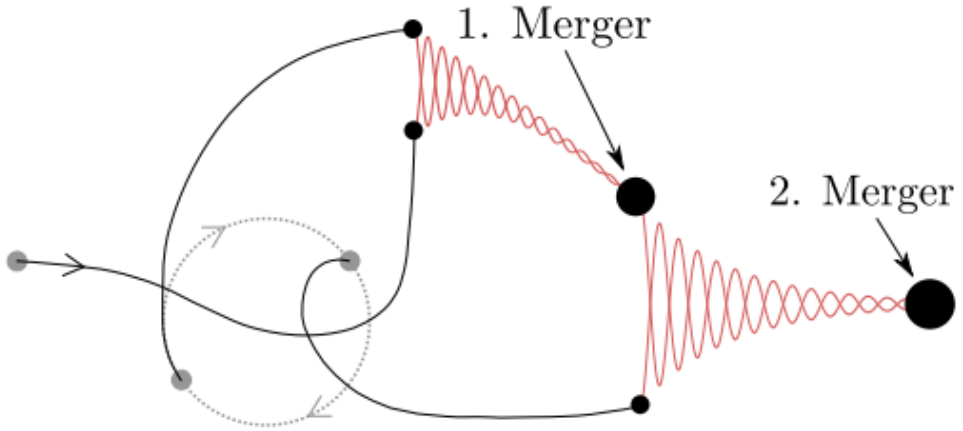
BASED ON VESKE ET AL. (2021) APJL **907** L48 HTTPS://DOI.ORG/10.3847/2041-8213/ABD721

Binary black hole (BBH) mergers

- Three observing runs of advanced LIGO and Virgo detectors
- Catalogs were released by LIGO Scientific and Virgo Collaborations
  - GWTC-1, GWTC-2, GWTC-2.1
- Extra detections from other groups with open data (Nitz et al., Zackay et al., Venumadhav et al.)
- Eccentric search for GW190521 (Gayathri et al. 2020)
- Collection of binary black hole mergers, but formation channels are still not constrained, e.g.
  - Field binaries
  - Chemically homogenous binary evolution
  - Mergers in AGN/GN
  - Dynamical mergers in dense stellar clusters
  - Primordial black holes

Hierarchical triple mergers

- Dynamical formation scenario in dense environments
- 3 BHs bound to each other
- 3rd body facilitates the inspiral of the binary
- Two consecutive BBH mergers
  - Time between mergers can be several years under certain configurations
- Involved BHs are directly related to each other, so this channel can be directly tested



Properties of hierarchical triple mergers

- Final BH of first merger (#1) is one of the components of second merger (#2)
  - Same mass, same spin magnitude
- Two mergers should happen at the same location
- Eccentricity is expected, especially for merger #1

Search inputs

- Statistical search based on likelihood ratio assuming two hypotheses
  - Unrelated mergers
  - Hierarchical triple mergers
- Time order: Merger #1 happens first
- Mass:
  - Mass of the remnant of merger #1 should be consistent with one of the components of merger #2 for hierarchical triple mergers.
  - For unrelated mergers, masses of the components of merger #2 are independently drawn from a 1G BH mass distribution

Search inputs

- Spin: Different distributions of hypotheses $\chi_{\mathrm{eff}} = \frac{\boldsymbol{a}_1 m_1 + \boldsymbol{a}_2 m_2}{m_1 + m_2} \cdot \hat{L}$ for different
  - Actual spins are not used because hard to mimic their uncertainties for background generation
- Localization:
  - 3D localizations of two mergers should agree for hierarchical triple mergers
  - 3D localizations are independent in sky for unrelated mergers
- Eccentricity: Not used, because there is no such estimate
- **Performance:** 90% of hierarchical triple mergers are detected with 3 sigma significance

1G BH mass distribution

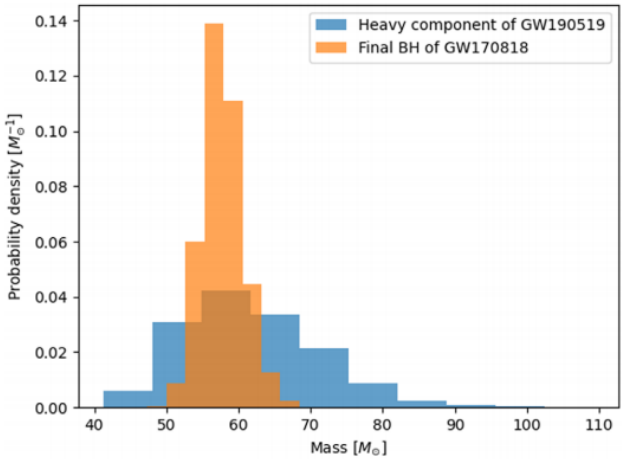
- 1G BH mass distribution is observationally not well constrained
- Theory suggests a mass gap between ~50-135 M
- We use the power-law+peak model with 4 different upper bounds: 50, 60, 70, 100 M

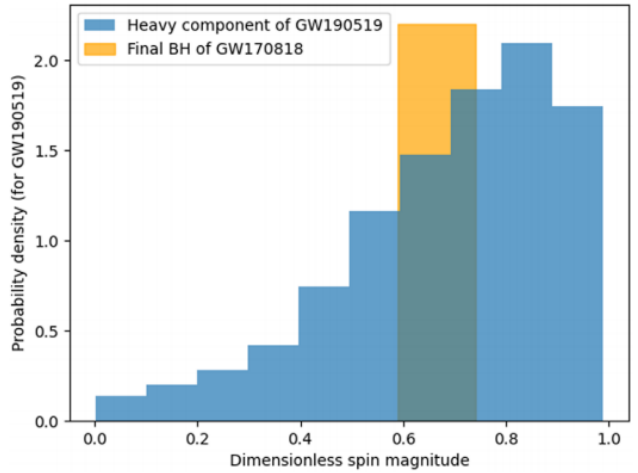
Results (Upper bound=50 M)

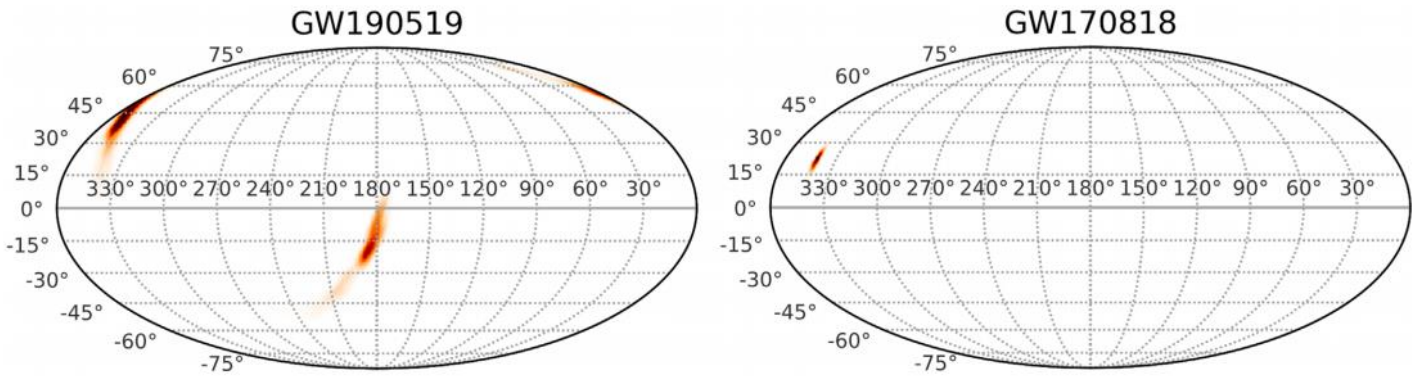
- Previous mergers paired with GW190521 are infinitely significant due to heavier component of GW190521 is certainly >50M
- Partial search without mass (only time order and volume localization)
  - GW190514-GW190521: p=0.14 (0.14 for eccentric GW190521)
  - GW170729-GW190521: p=0.45 (0.24 for eccentric GW190521)
  - GW170823-GW190521: p=0.32 (0.31 for eccentric GW190521)
- Final mass of both GW190514 and GW170729 agree with the heavier mass of GW190521
  - Final mass of GW170823 doesn't agree with BH masses in GW190521
- GW190514's 90% sky localization includes the AGN from which a candidate optical counterpart for GW190521 was observed at ZTF. Distance reconstructions of GW190514 and GW190521 along AGN's direction are nearly identical

Results (Upper bound=60, 70, 100 M)

- GW170818-GW190519 is the most significant pair at ~3 sigma *individual significance* (before trials factor)
- GW190708-GW190915, GW190512-GW190910 are the next significant ones with *p*<1% *individual significance*







Final remarks

- For 60, 70, 100M upper bounds, GW190521 doesn't fit well to the hierarchical triple merger scenario due to heavy secondary mass
- For GW190514-GW190521 pair, eccentricity of GW190521 supports hierarchical triple merger scenario since there is only 1 week between mergers (not enough time for circularization).
  - Further eccentricity analysis of GW190514 will be insightful
- Total of 1431 merger pairs are analyzed. After multiple hypothesis correction (trials factor) no significant pairs with an overall low false alarm rate.
  - Only individually interesting pairs for further investigation, e.g. search for an AGN at the common localization of GW190519 and GW170818.