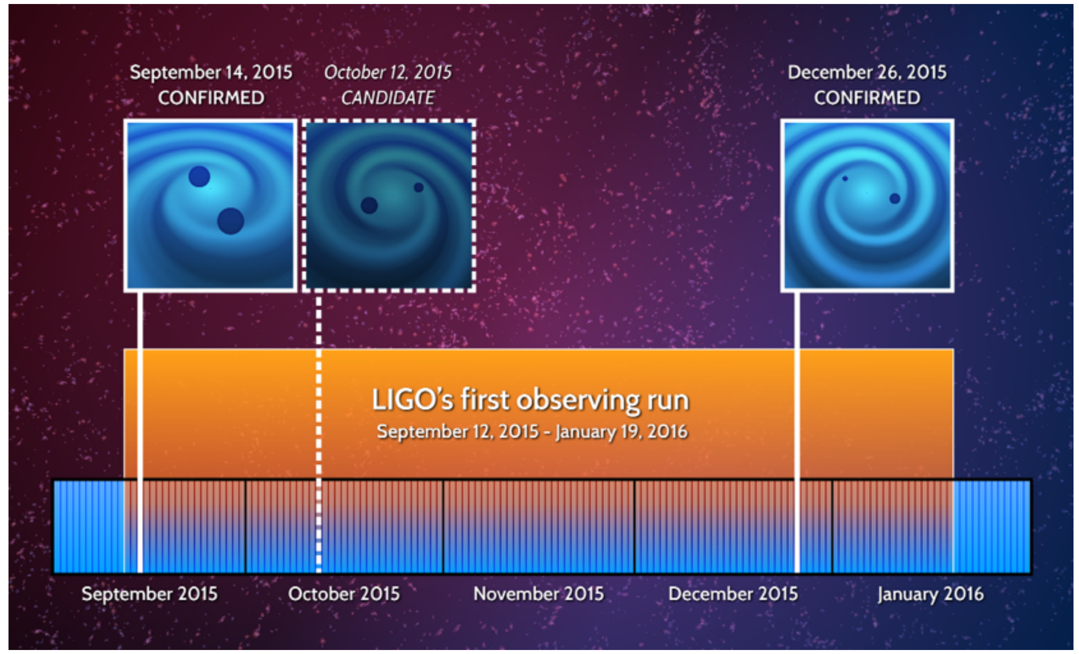
Credit: LIGO/R. Hurt



LIGO-G1601327-v2

PROPERTIES AND IMPLICATIONS OF LIGO'S FIRST CROP OF BINARY BLACK HOLES

N. K. Johnson-McDaniel (for the LIGO Scientific Collaboration and Virgo Collaboration)

ICTS-TIFR seminar

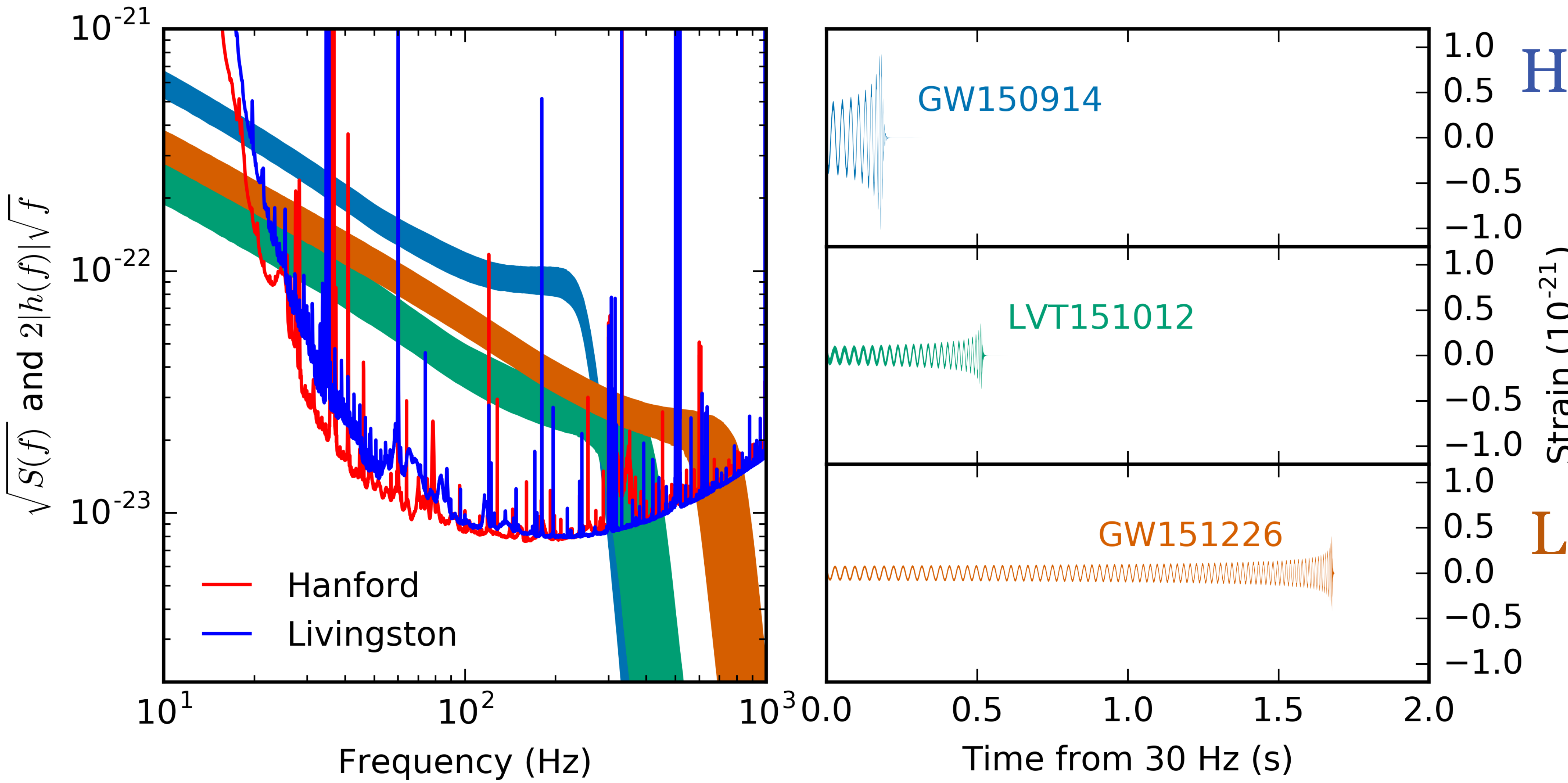
June 17th, 2016

Primarily a summary of:

* Binary Black Hole Mergers in the first Advanced LIGO Observing Run, arXiv:1606.04856 (the "O1 BBH paper")

* GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence, PRL 116, 241103 (2016)

REMINDER OF THE OBSERVED SIGNALS



Higher mass (~ 71 M)

(~ 44 M)

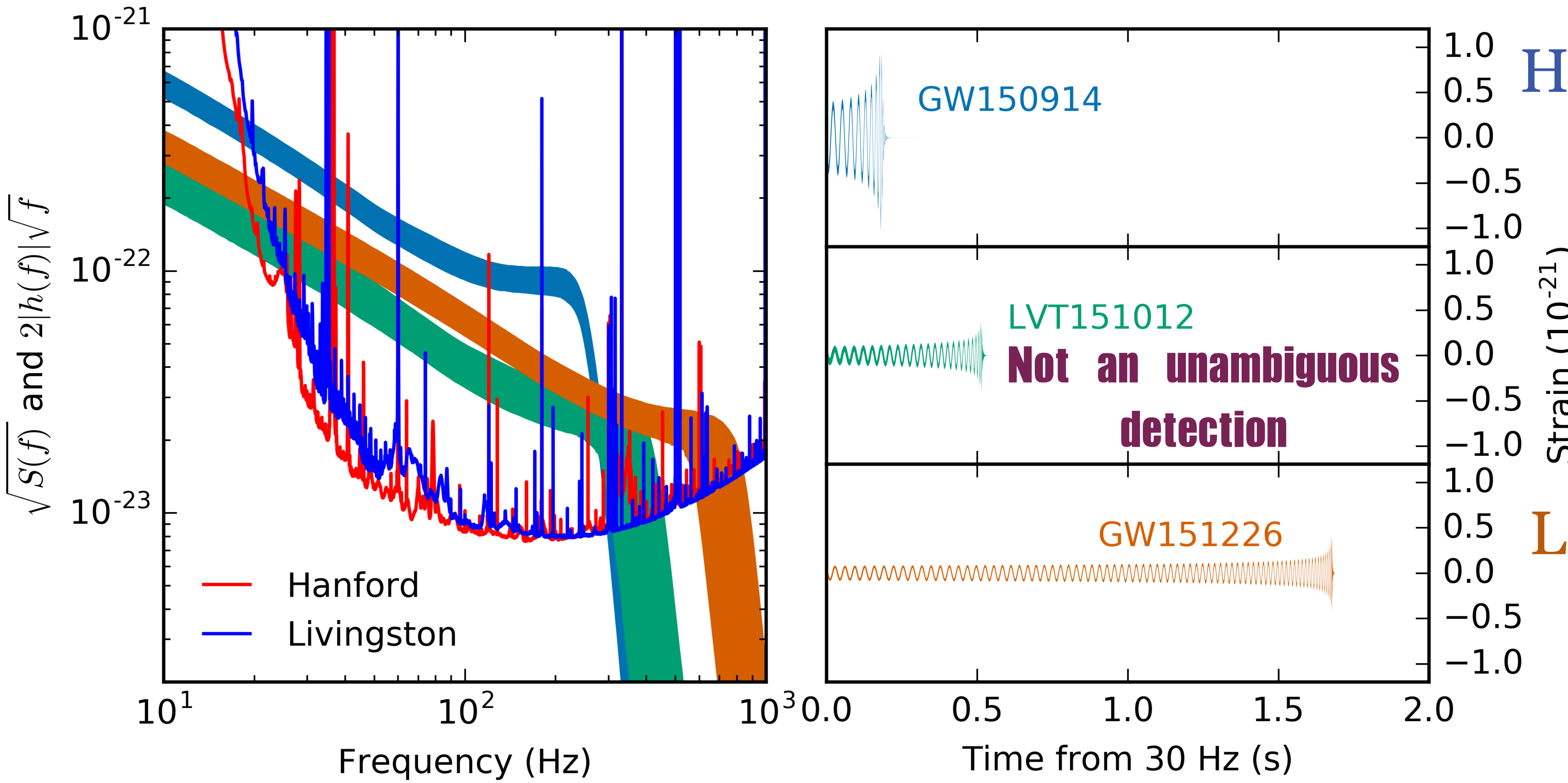
Lower mass (~ 24 M)

[Redshifted masses; ~10-20% effect]

[Figure from O1 BBH paper]

N.B.: These curves look so nice because they're reconstructed based on the templates used in parameter estimation

REMINDER OF THE OBSERVED SIGNALS



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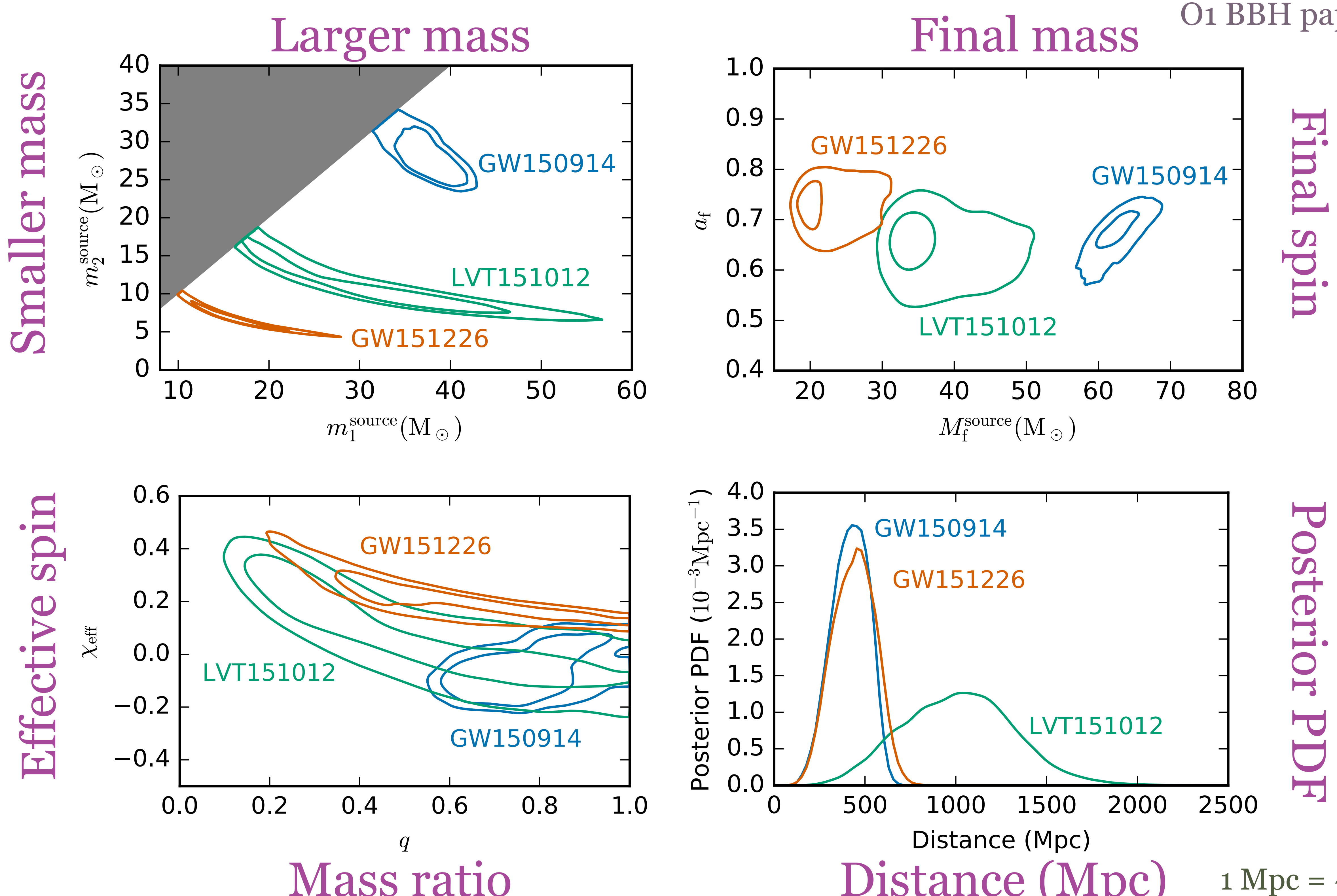
OUR FIRST GLIMPSE OF THE DIVERSITY OF THE BINARY BLACK HOLE POPULATION

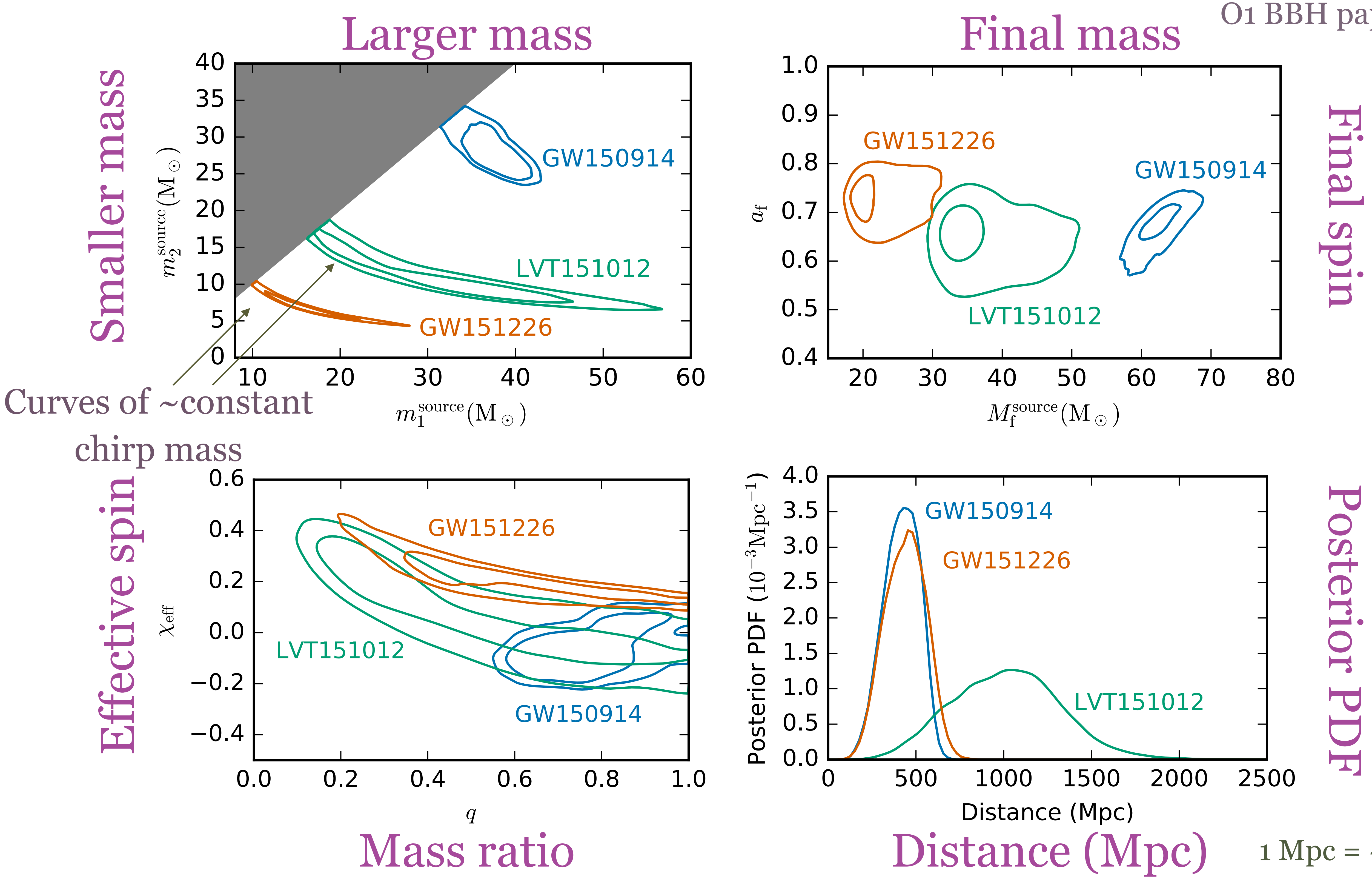
[Figure from O1 BBH paper]



1 Mpc = ~3 Mly

OUR FIRST GLIMPSE OF THE DIVERSITY OF THE BINARY BLACK HOLE POPULATION

[Figure from O1 BBH paper]



1 Mpc = ~3 Mly

OUR FIRST GLIMPSE OF THE DIVERSITY OF THE BINARY BLACK HOLE POPULATION

- The primary difference in the three binaries is their total mass: In the source frame (i.e., without redshifts), these are $65.3^{+4.1}_{-3.4}$, 37^{+13}_{-4}, $21.8^{+5.9}_{-1.7}$ $M_\odot$.

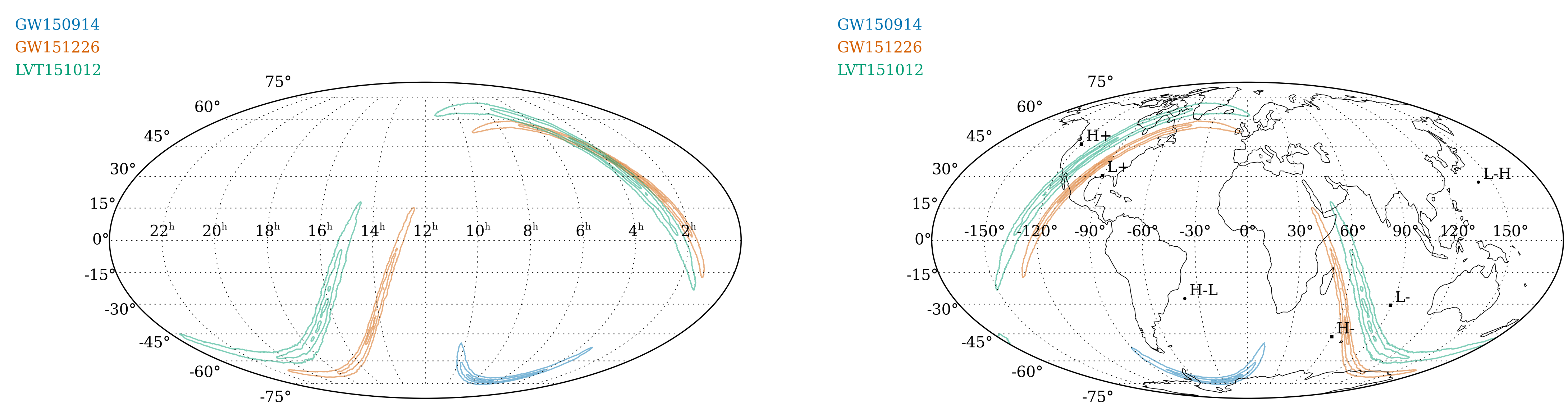
GW150914 LVT151012 GW151226

- This difference in total mass translates directly into a difference in the radiated energy: $3.0^{+0.5}_{-0.4}$, $1.5^{+0.3}_{-0.4}$, $1.0^{+0.1}_{-0.2}$ $M_\odot c^2$.

- However, the peak gravitational wave luminosity is independent of the mass and is roughly the same (and impressively large) for all three events: ~200 $M_\odot c^2$/s.

- These binaries were not very well localised on the sky (90% credible regions from 230 to 1600 square degrees), though we do know that GW150914 came from a completely different portion of the sky than the other two events.

OUR FIRST GLIMPSE OF THE DIVERSITY OF THE BINARY BLACK HOLE POPULATION



[Figure from O1 BBH paper]

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A FEW SPECIAL PROPERTIES OF GW151226

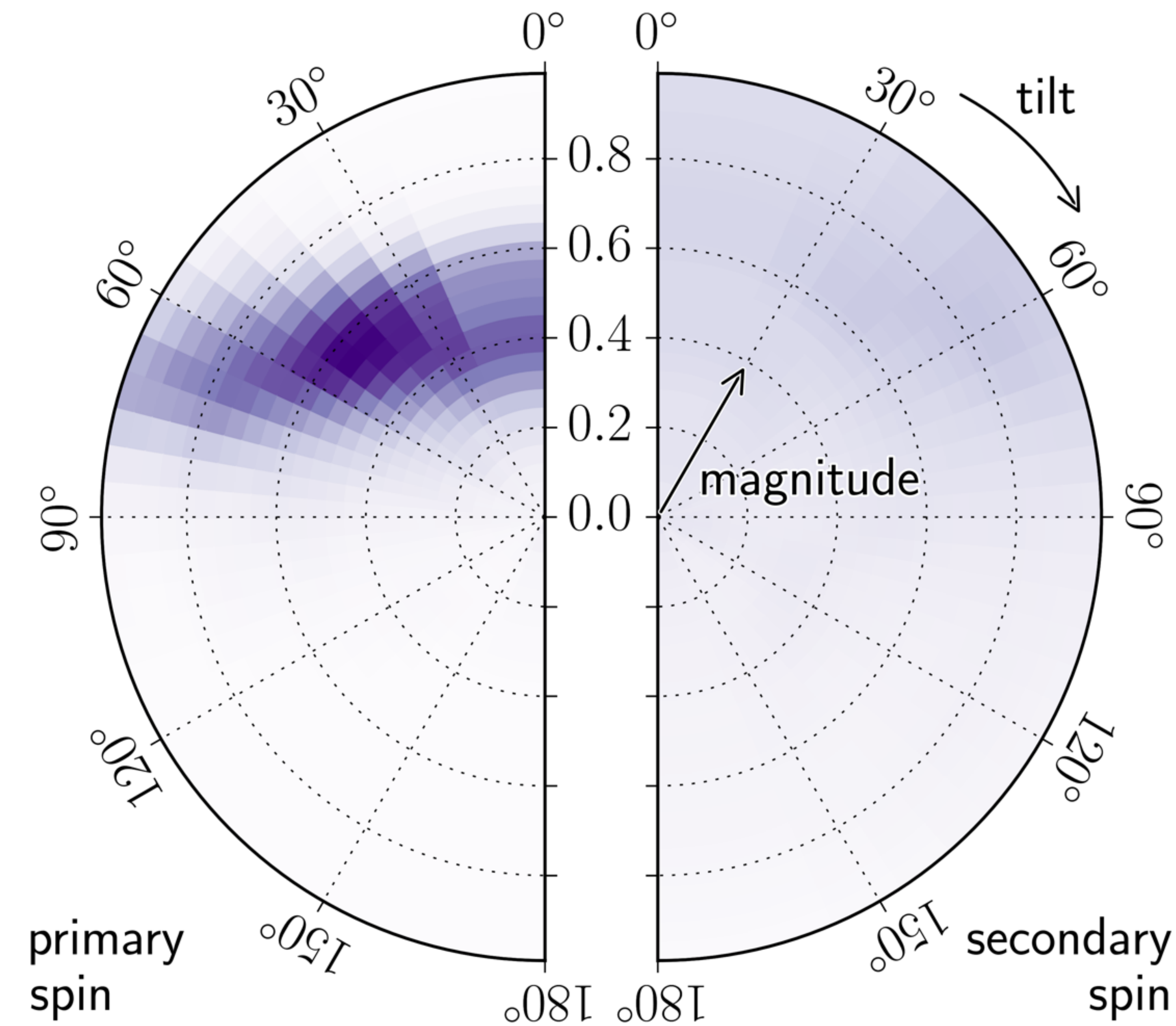
- In addition to being the lowest-mass binary detected so far, GW151226 has some other notable features.

- It is the only binary of the three that we are able to say has a spinning component:

  At least one of its black holes must have been spinning with at least 20% of the maximum spin (or a horizon equatorial velocity of at least ~0.1c) at the *99%* credible level.

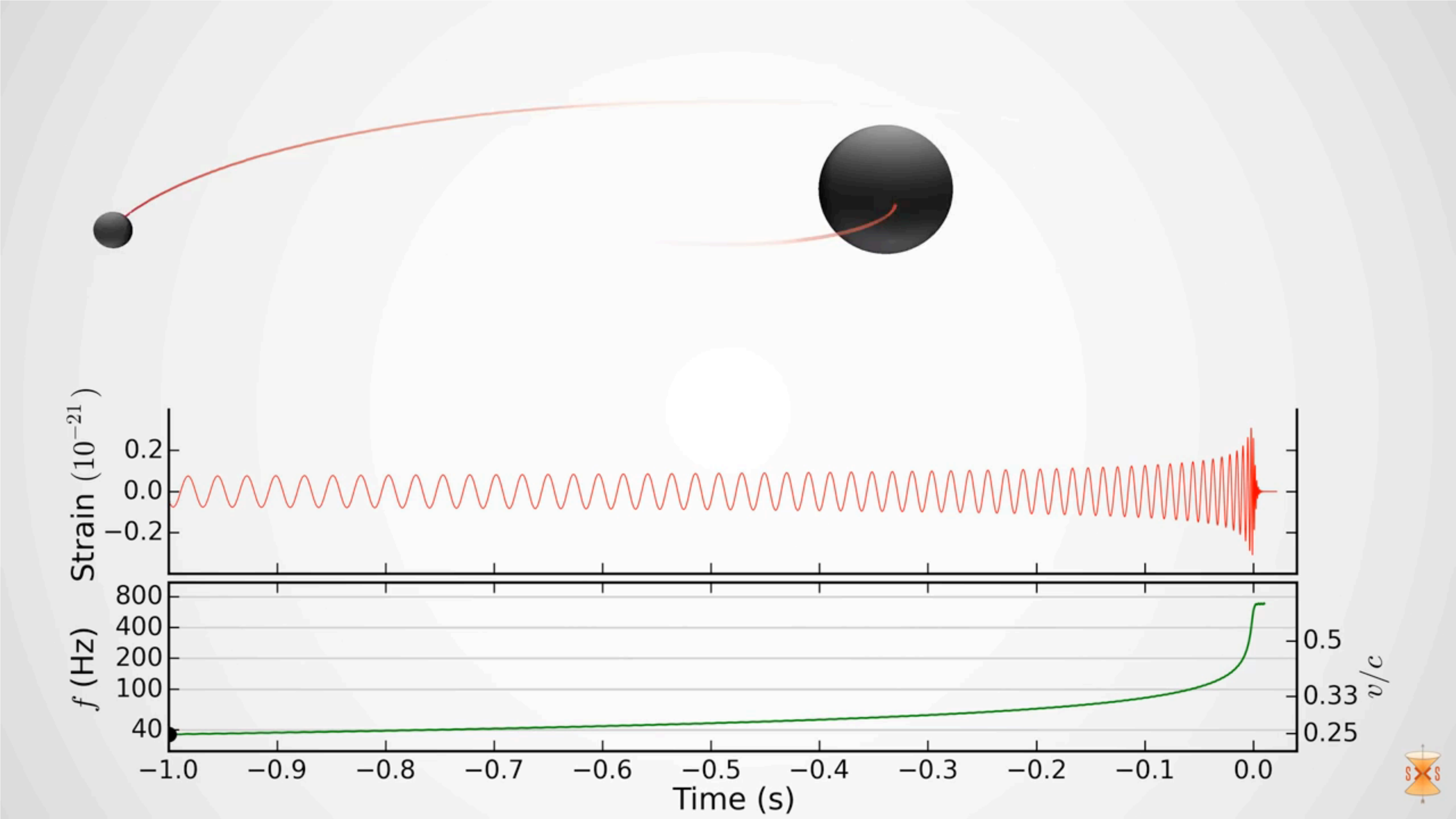
- It also has the largest median final spin, 74% of maximum, compared to 66% or 68% of maximum for the other two.

A FEW SPECIAL PROPERTIES OF GW151226



Posteriors on the magnitude and direction of the spins, from the GW151226 paper [annotations from the science summary]

A VISUALIZATION OF A SYSTEM CONSISTENT WITH GW151226

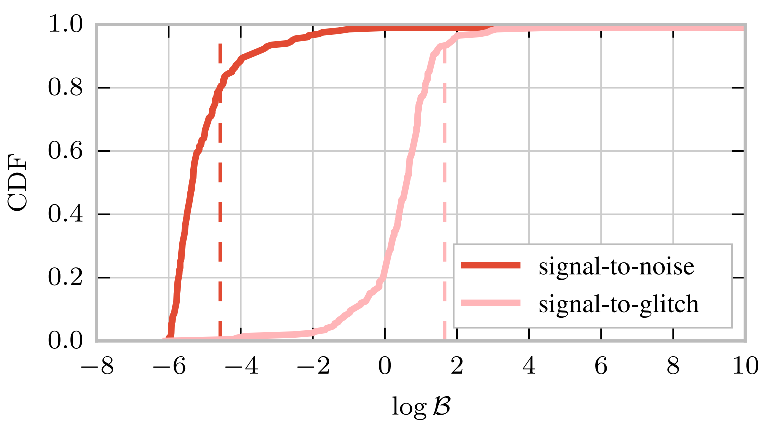


Nonprecessing binary with mass ratio ~3.3 and spins of ~0.5 and ~0.4 (one aligned and one antialigned); YouTube link

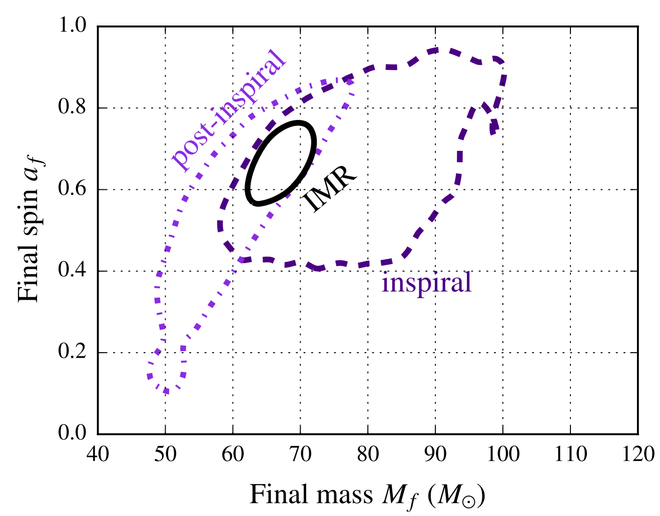
Credit: SXS Collaboration/www.black-holes.org

TESTS OF GENERAL RELATIVITY WITH THE O1 BBH RESULTS: A REMINDER OF THE TESTS MADE WITH GW150914

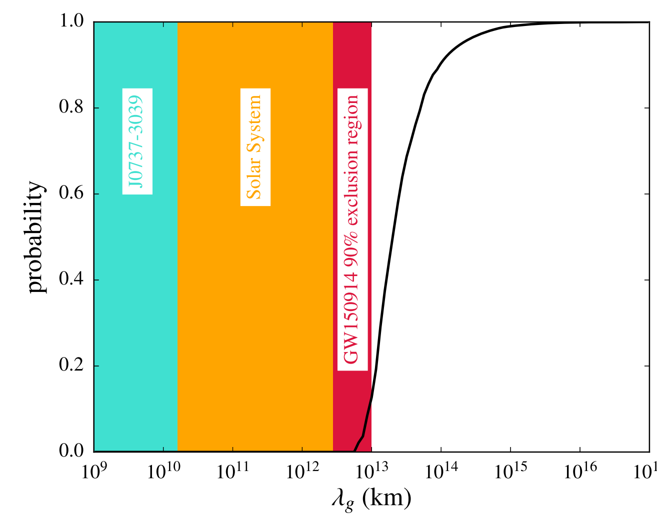
- The relatively high SNR and high mass of GW150914 made it possible to apply a whole suite of tests to the signal, described in PRL 116, 221101 (2016).



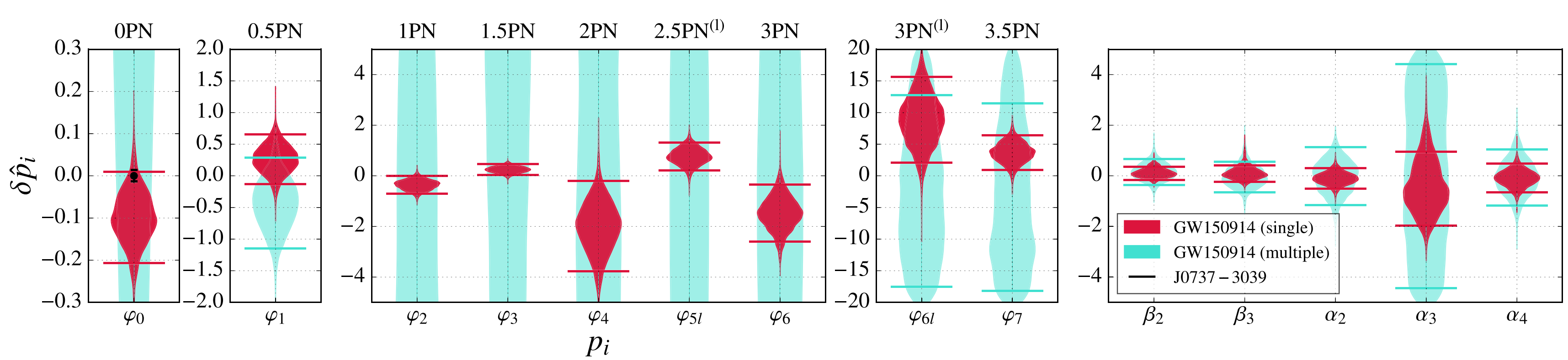
Consistency of residuals with noise after subtracting the most-probable template



Consistency of low- and high-frequency parts of the signal



Constraints on GW dispersion



Constraints on parameterized deviations from GR

TESTS OF GENERAL RELATIVITY WITH THE O1 BBH RESULTS: COMBINING TOGETHER PARAMETER CONSTRAINTS FROM GW150914 AND GW151226

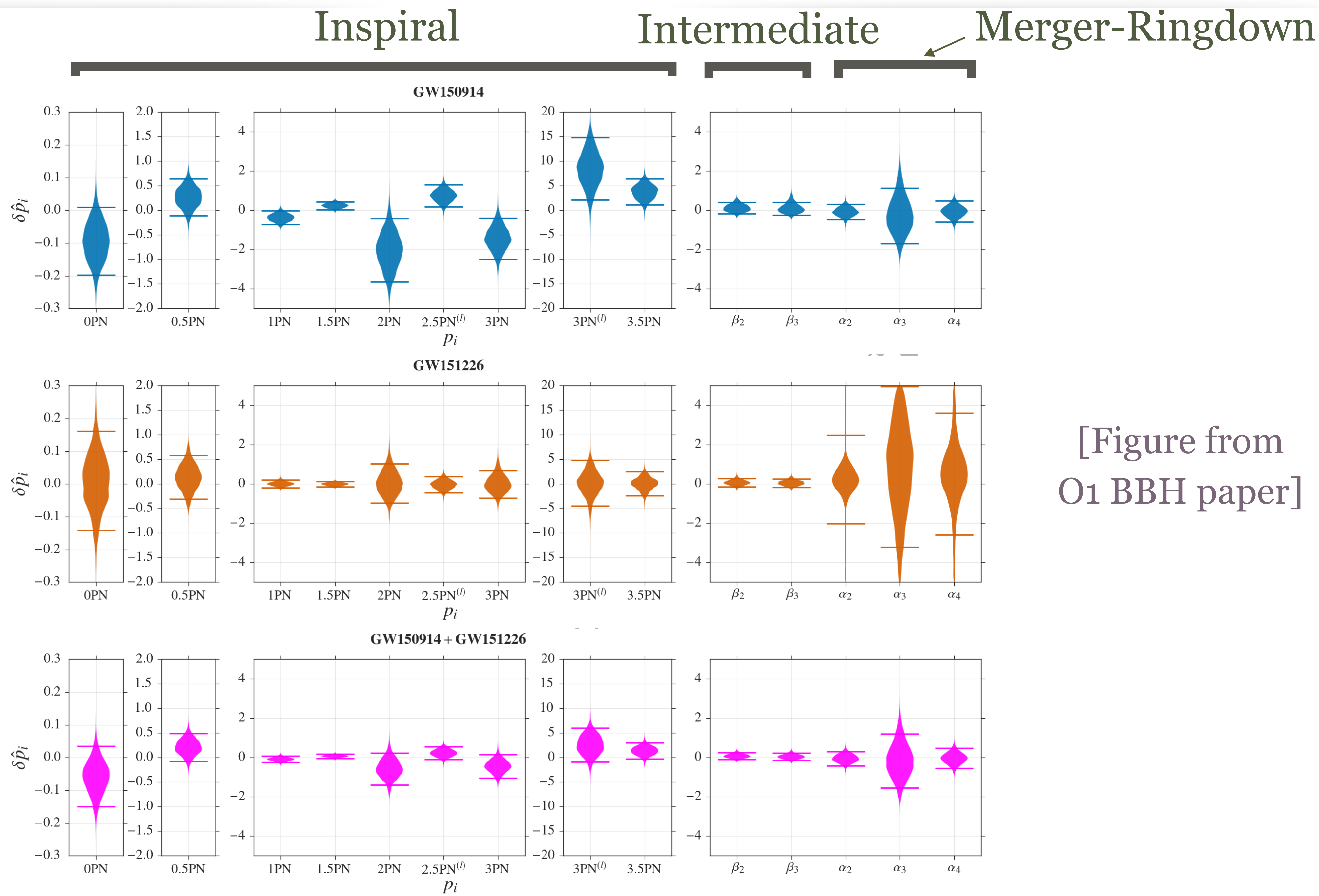
- The only test that receives an update with GW151226 is the parameterized test:

  The overall SNR is not high enough to perform the residual test and the SNR in the ringdown is not high enough for the IMR consistency test.

  One *can* perform the dispersion/massive graviton test, but does not find an improvement in the bounds.

  (LVT151012 is not a strong enough signal to be of significant use to tests of GR.)

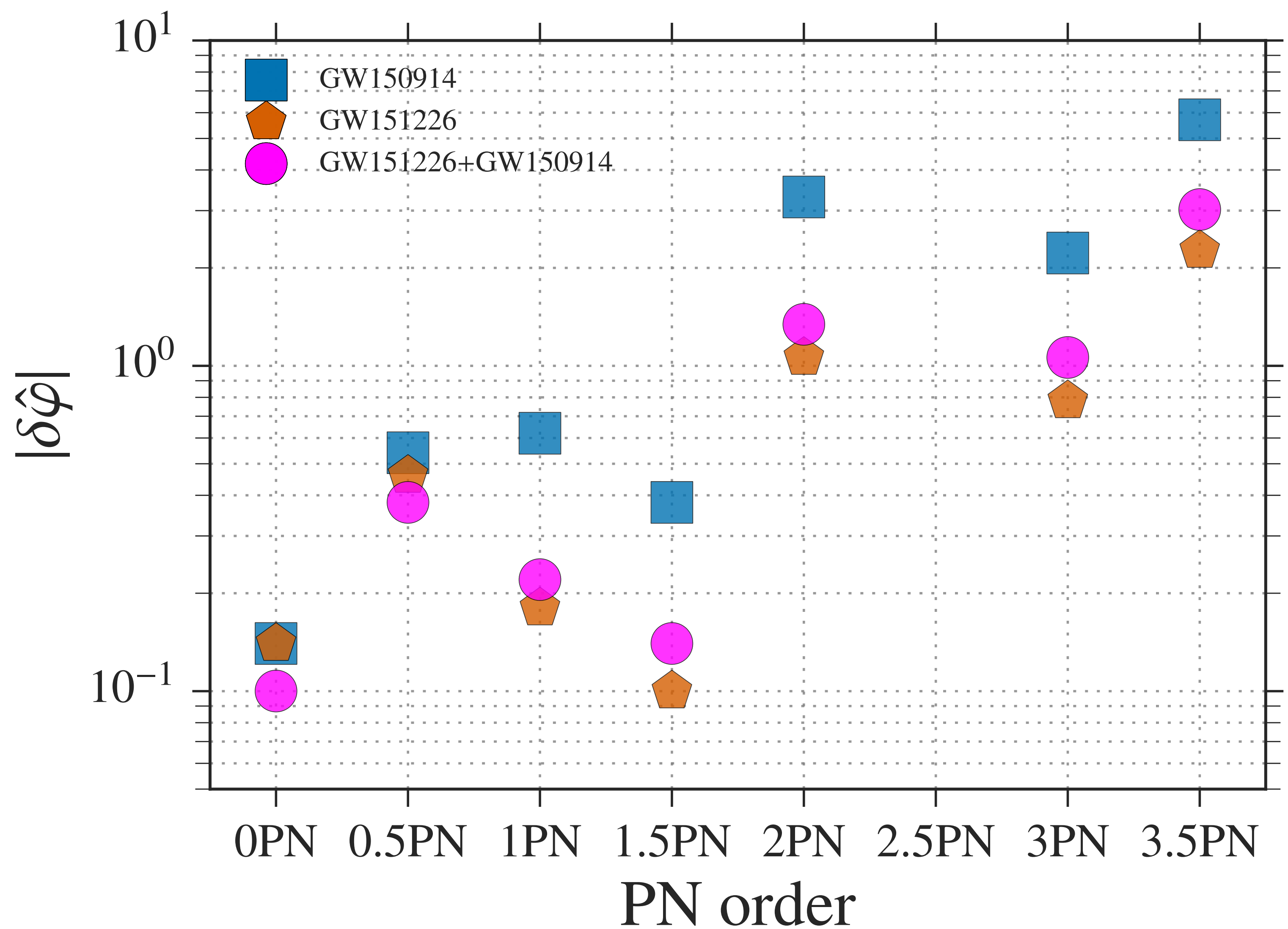
TESTS OF GENERAL RELATIVITY WITH THE O1 BBH RESULTS: COMBINING TOGETHER PARAMETER CONSTRAINTS FROM GW150914 AND GW151226



[Figure from O1 BBH paper]

The tight constraints on the 1.5PN term are particularly interesting, as this contains the leading-order backscattering and spin-orbit coupling.

TESTS OF GENERAL RELATIVITY WITH THE O1 BBH RESULTS: COMBINING TOGETHER PARAMETER CONSTRAINTS FROM GW150914 AND GW151226



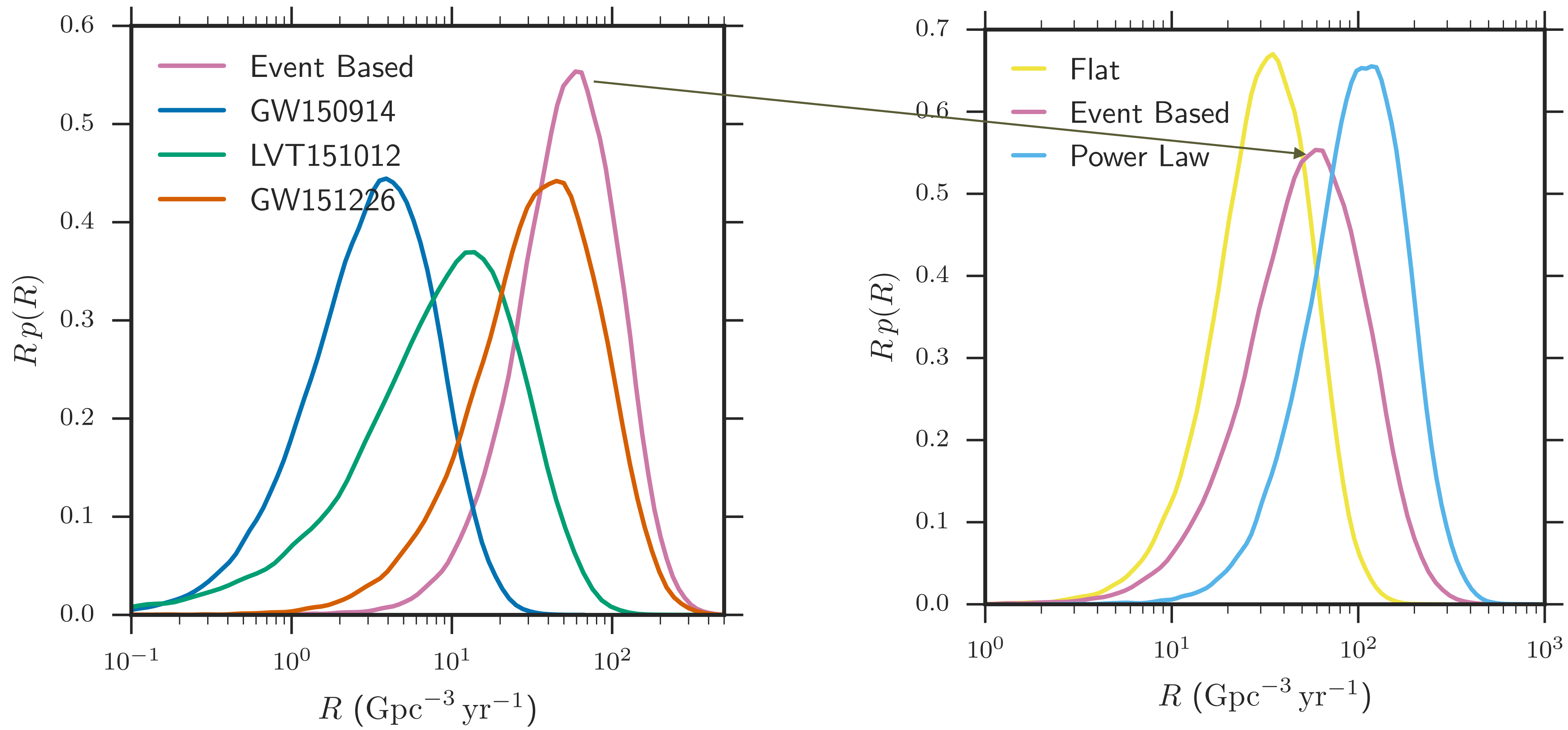
[Figure from O1 BBH paper]

Comparison of upper bounds on deviations of post-Newtonian coefficients.

UPDATES OF BINARY BLACK HOLE RATE ESTIMATES USING ALL OF O1

N.B.: The rates analysis assigns an 87% probability to LVT151012 being of astrophysical origin.

[Figures from O1 BBH paper]

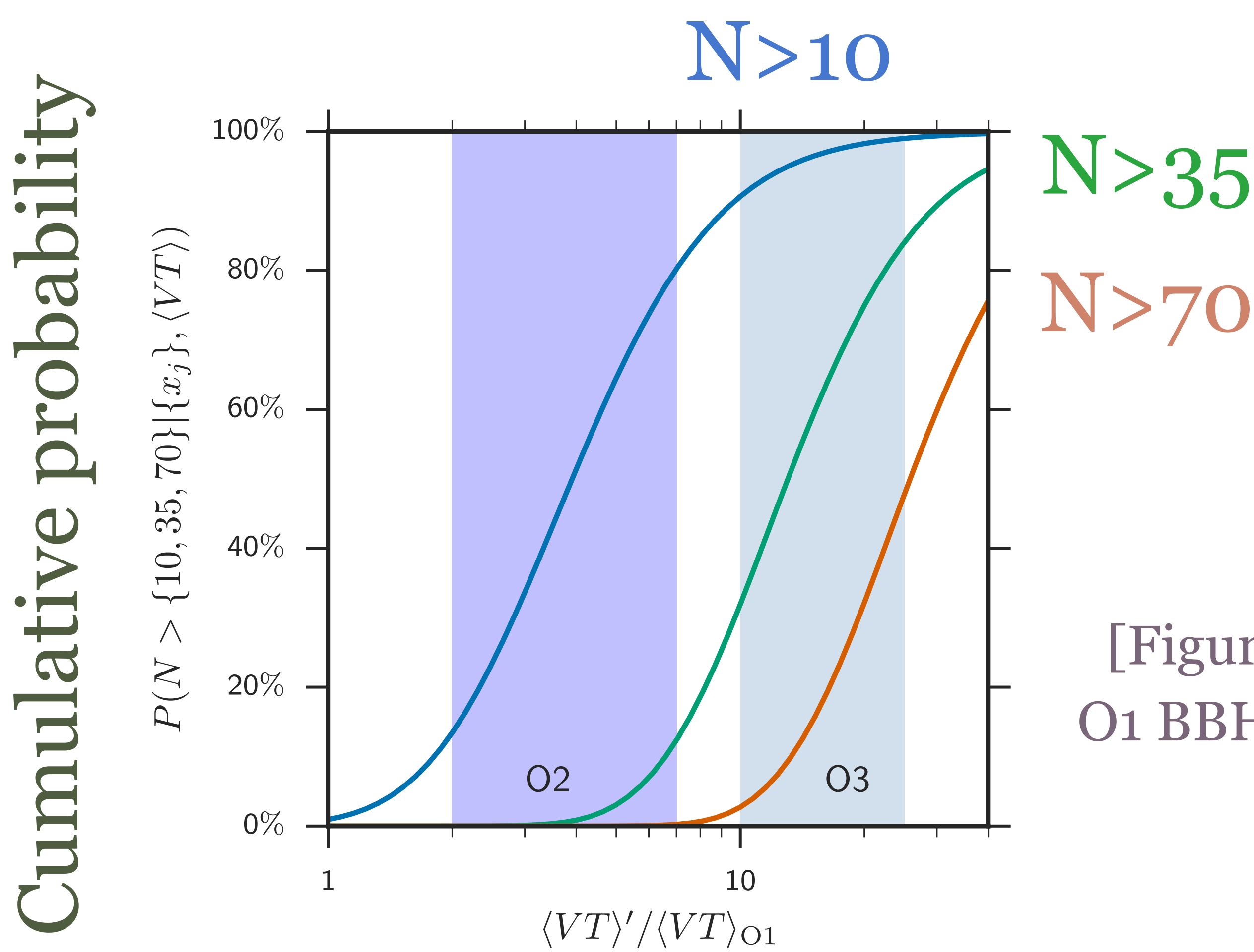


Two ways of performing rate estimates:

1. Take all binaries in the universe to be like one of the three O1 binaries. Here GW151226 dominates the rate estimate, as the lowest-mass system (so it could only be detected relatively nearby).

2. Use a fiducial mass distribution. Here two choices are made to bracket the expected mass distribution.

UPDATES OF BINARY BLACK HOLE RATE ESTIMATES USING ALL OF O1



Volume surveyed (relative to O1)

[Figure from O1 BBH paper]

With 3 times as much coincident data, and one more clear detection, the rate estimate gets a bit sharper, going from the initial 2-600 $Gpc^{-3}\ yr^{-1}$ to 9-240 $Gpc^{-3}\ yr^{-1}$.

One can convert this rate estimate into an estimate of the number of confident binary black hole detections we can expect in future LIGO runs, notably O2 (6 months, starting later this year) and O3 (9 months, starting in 2017).

We expect binary black hole detections to become routine in the next few years.

ASTROPHYSICAL IMPLICATIONS

- GW150914 is consistent with a wide variety of binary black hole formation channels, including isolated binary evolution (either via the standard common envelope phase or via chemically homogeneous evolution in a tidally locked binary) and dynamical formation.

  Its high masses imply formation in an environment with at most half solar metallicity (fraction of elements heavier than Hydrogen).

- GW151226 and LVT151012 (if an astrophysical signal) are also compatible with both isolated and dynamical formation, though the low masses of GW151226 ($14.2^{+8.3}_{-3.7}$ and $7.5^{+2.3}_{-2.3}$ $M_\odot$) are likely inconsistent with chemically homogeneous evolution, which is thought to require higher masses. There is a 4% probability that the secondary of GW151226 lies in the putative 3-5 $M_\odot$ gap between neutron stars and black holes.

  Both of these binaries could have been formed from higher mass progenitors at solar metallicity, or by lower-mass progenitors at lower metallicities. They have masses in line with those inferred from X-ray observations of black holes in binaries (with non-black hole companions).

ASTROPHYSICAL IMPLICATIONS

- If one assumes that a single formation channel is operating, the inferred lower limit on the rate of binary black hole coalescences disfavours certain scenarios (e.g., low-mass globular clusters in the dynamical formation case, or very high natal kicks of several 100 km/s for black holes in the isolated binary channel). However, multiple channels are likely in operation.

- The revised rate still leads to a stochastic gravitational wave signal of unresolved merging black hole binaries that is potentially measurable with several years of observation at design sensitivity.

- With the expected wealth of binary black hole detections in the coming years, population models will start to become highly constrained, by estimates of the mass and spin distributions of stellar mass binary black holes in our universe.

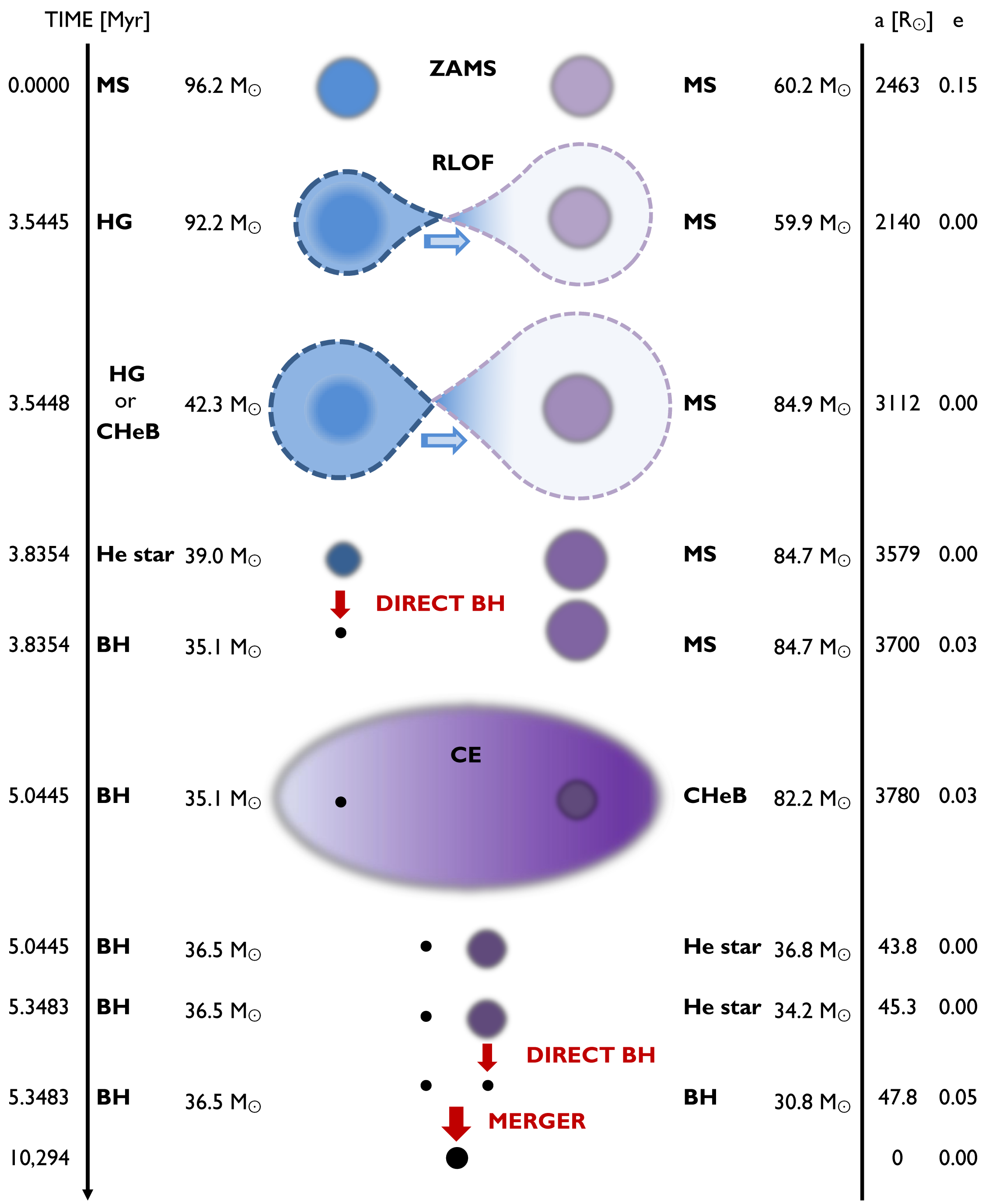
  For a first taste, the LSC obtained constraints on the power law index of the binary black hole component mass distribution assuming (for simplicity, but not very realistically) a single power law from 5 to 100 $M_\odot$; the index is then $\alpha = 2.5^{+1.5}_{-1.6}$.

CONCLUSIONS

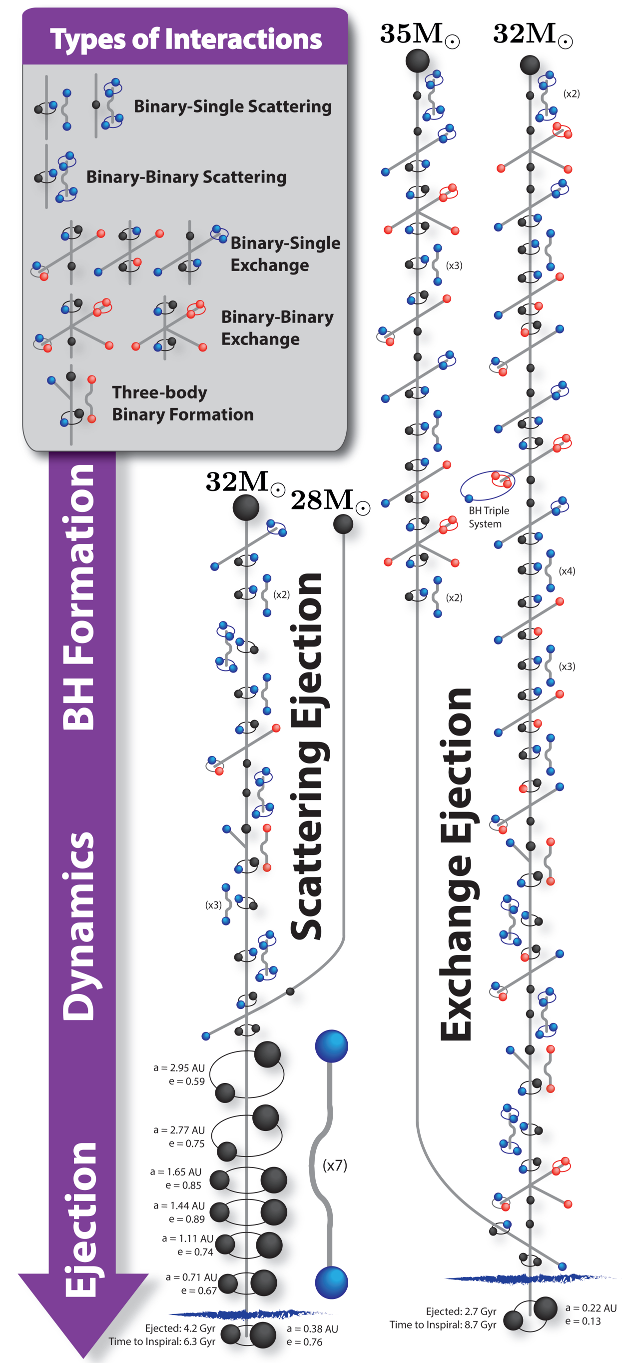
- Advanced LIGO's first observing run gave us the first taste of the fruits of gravitational wave astronomy, with two firm binary black hole coalescences, the famous GW150914 and the later GW151226, and one possible binary black hole, LVT151012.
- These binaries have total masses from ~20 to ~60 $M_{\odot}$, and poorly constrained spins, though we know that at least one component of GW151226 was spinning, with a spin of at least 20% of the maximum.
- We can perform various tests of general relativity, finding no evidence for deviations. The lower-mass GW151226 helps to constrain the inspiral portion of the signal, while GW150914 is more constraining for the merger-ringdown portion.
- We can also constrain the rate of binary black hole coalescences in the universe, and from this expect to see many more mergers in upcoming observing runs (O2 is starting later this year!).
- All these signals are consistent with a wide variety of astrophysical models for their formation, but such models will become increasingly constrained with the expected tens to hundreds of detections in the coming years.

EXTRA SLIDES

EXAMPLE FORMATION CHANNELS FOR GW150914



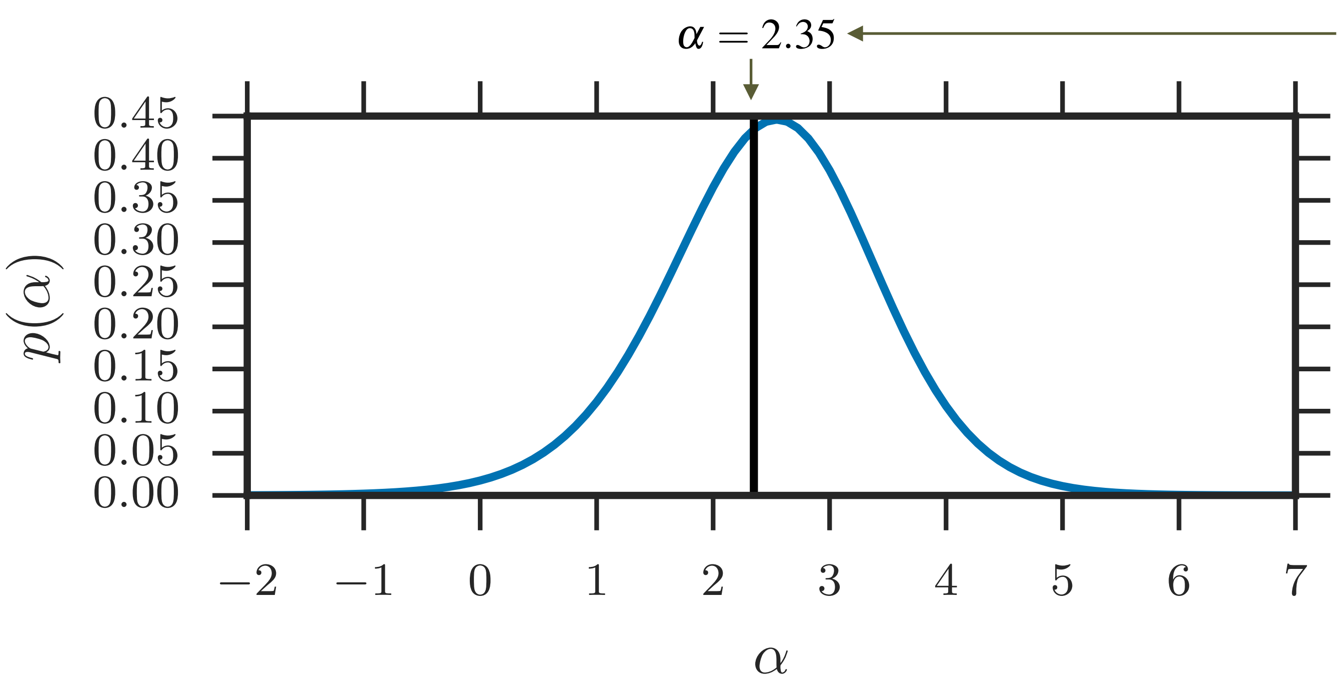
Isolated binary
(Belczynski+, arXiv:1602.04531)



Dynamical formation
(Rodriguez+, ApJL 824, L8, 2016)

ASTROPHYSICAL IMPLICATIONS

$p(m_1) \propto m_1^{-\alpha}$,
m_2 uniform between 5 $M_\odot$ and m_1



"Power Law" distribution used in rate estimation

[Figure from O1 BBH paper]

The median (with 90% credible interval) of $\alpha = 2.5^{+1.5}_{-1.6}$ is not unexpected, as the sensitive time-volume scales like $M^{2.5}$. This is also consistent with the range of ~1.8 to ~5.0 for α obtained from dynamical mass measurements with X-rays (with no accounting for selection effects).

For a first taste, the LSC obtained constraints on the power law index of the binary black hole component mass distribution assuming (for simplicity, but not very realistically) a single power law from 5 to 100 $M_\odot$; the index is then $\alpha = 2.5^{+1.5}_{-1.6}$.