GW150914
Detection of Gravitational Waves from a Binary Black Hole

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ON BEHALF OF LIGO-VIRGO COLLABORATIONS

outline

1. The Observation Run O1 and the searches
2. GW150914: detection and significance
3. Source characterictics
4. Multimessenger followups
5. The future: O2 and beyond

Observing Run 01

After a shut-down period for upgrades, the Advanced LIGO interferometers of Handford (H1) and Livingston (L1) (USA) have started a first Observing Run **O1** on **September 15 2015**.

On **September 14 at 9:50:45 UTC** the interferometers have detected a possible Gravitational Waves signal.

The LIGO-Livingston detector entered observation mode roughly 30 minutes prior to GW150914 after completing injection tests in a stable, operational state.
The LIGO-Hanford detector had been in observation mode for over an hour.

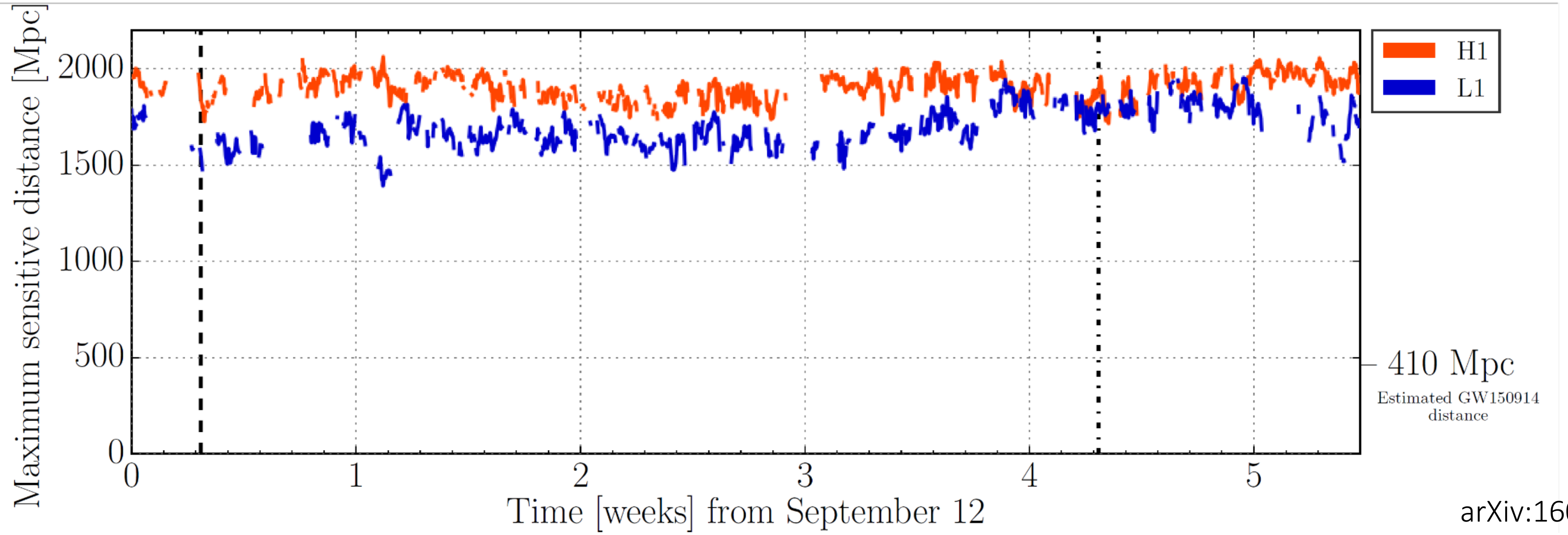
GW150914

The signal was seen first by the analysis pipeline for generic transient search, *Coherent WaveBurst,* running in an *on-line* configuration.

In addition to cWB, the signal has since then been analysed *off-line* by two pipelines, *pyCBC* and *gstlal-SVD*, specifically designed for the search of compact coalescing binaries signals.

The analysed time (September 12 - October 20 2015) until now is of **38 days**, for a period of coincidence between the two interferometers of about **16 days**.

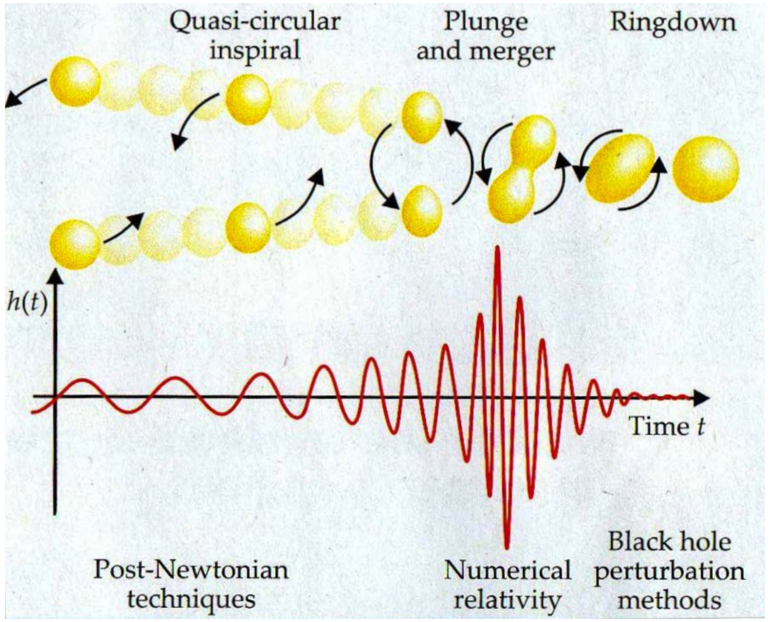
Detector performances during O1

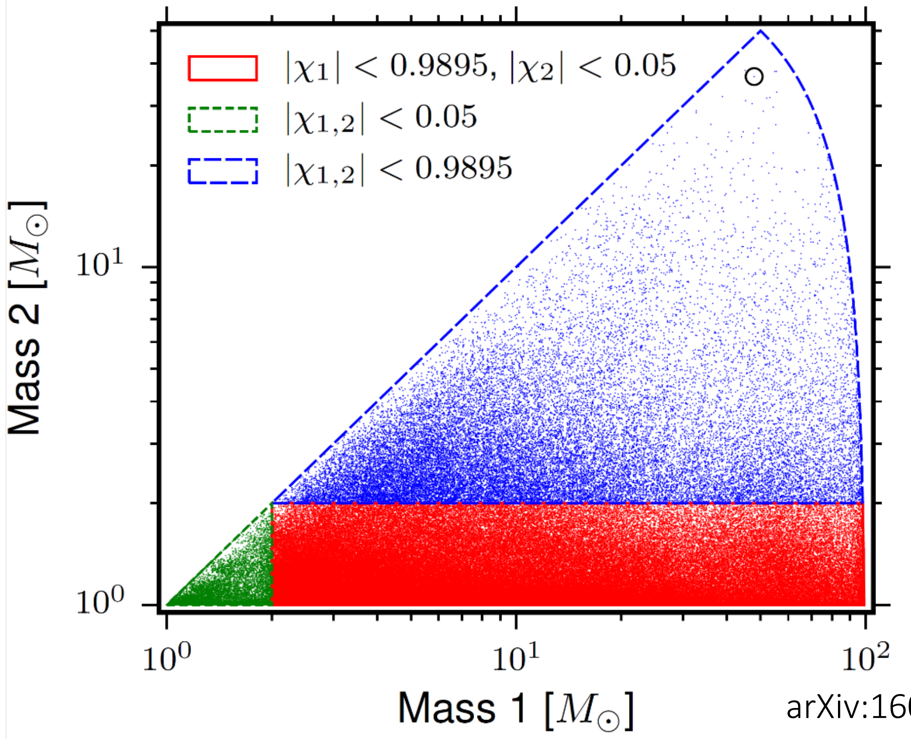


arXiv:1602.03844

The maximum sensitivity during the analyzed period to a binary black hole system with the same observed spin and mass parameters as GW150914 for optimal sky location and source orientation and detected with a Signal-to-Noise Ratio of 8.

Compact Binary Coalescences searches





arXiv:1602.03839

- Searches use waveform predictions to perform **matched filtering.**
- Waveform parameters (masses and spins) are distributed to cover the target search space so that the matched-filter Signal-to-Noise Ratio loss is never greater than 3%.

How to discriminate between signals and noise: the χ^2 veto

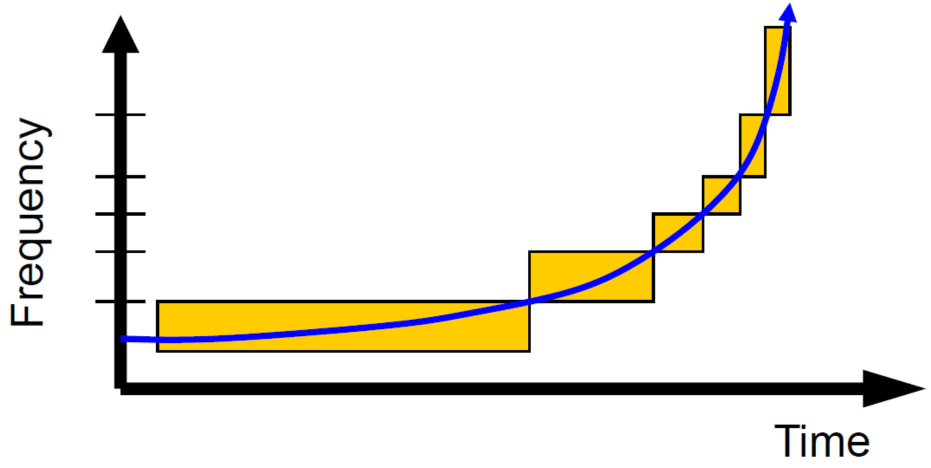
- We check the consistency of the SNR with an inspiral signal by splitting the template into *p* bins of equal power and constructing a matched filter ρ^l for each of these bins:

$$\chi^2 = p \sum_{l=1}^{p} \left[\left(\frac{\rho_c}{p} - \rho_c^l \right)^2 + \left(\frac{\rho_s}{p} - \rho_s^l \right)^2 \right]$$

or checking the consistency between the SNR time series and the waveform autocorrelation time-development.

- We expect that real GW signals return a low number for the χ^2 test, while noise transients will return a high number.
- We use the SNR and the χ^2 to construct our detection statistics:

$$\hat{\rho} = \begin{cases} \rho \Big/ \left[(1 + (\chi_r^2)^3)/2\right]^{\frac{1}{6}}, & \text{if } \chi_r^2 > 1, \\ \rho, & \text{if } \chi_r^2 \leq 1. \end{cases}$$



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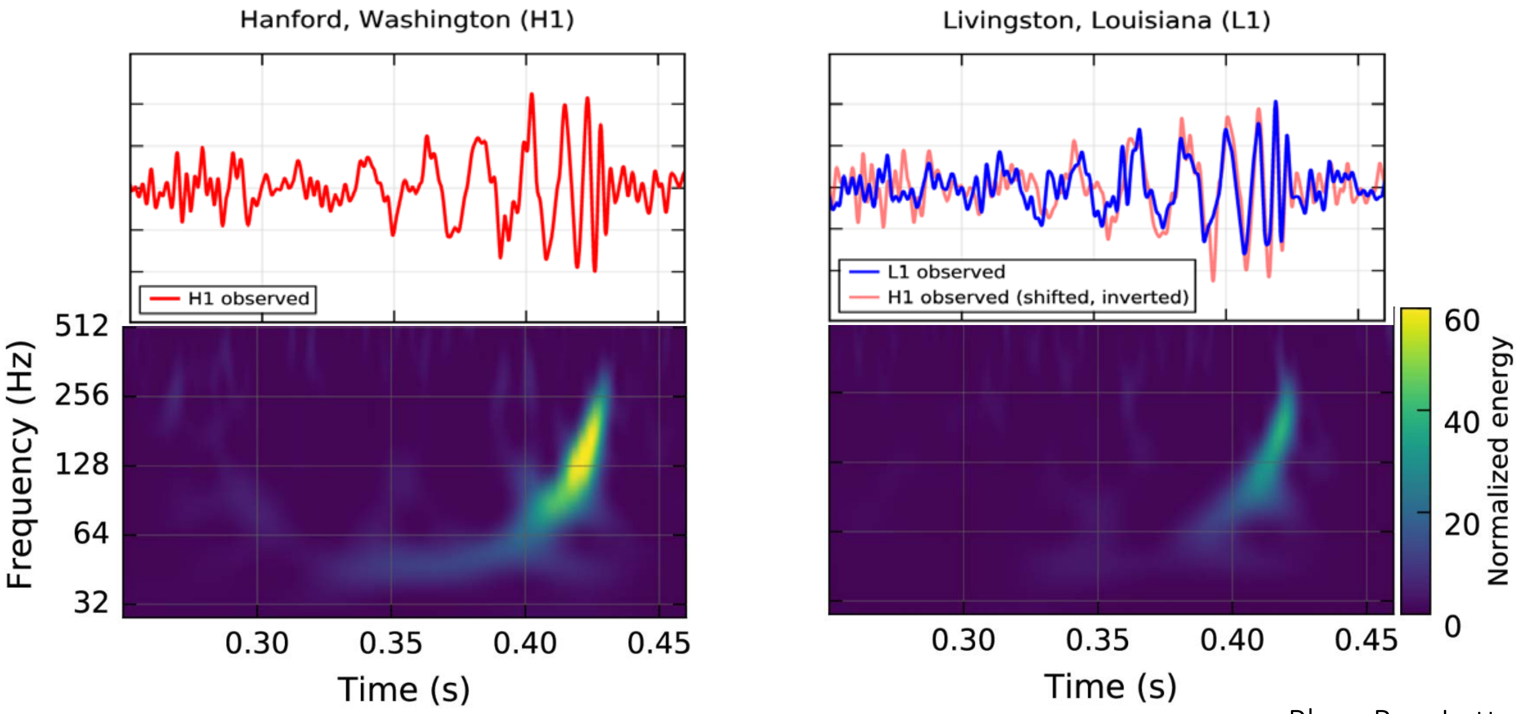
The detection of GW150914



Phys. Rev. Lett. 116, 061102 (2016)

- The time series are filtered with a 35-350 Hz band-pass filter.
- The signal arrived first at L1 and 6.9 ms later at H1.
- Over 0.2 s, the signal increases in frequency and amplitude in about 8 cycles from 35 to 150 Hz where the amplitude reaches a maximum.

The detection waveform

- The CBC pipelines report the same matched-filter SNR for the individual detector triggers in the Hanford detector H1 and the Livingston detector L1:

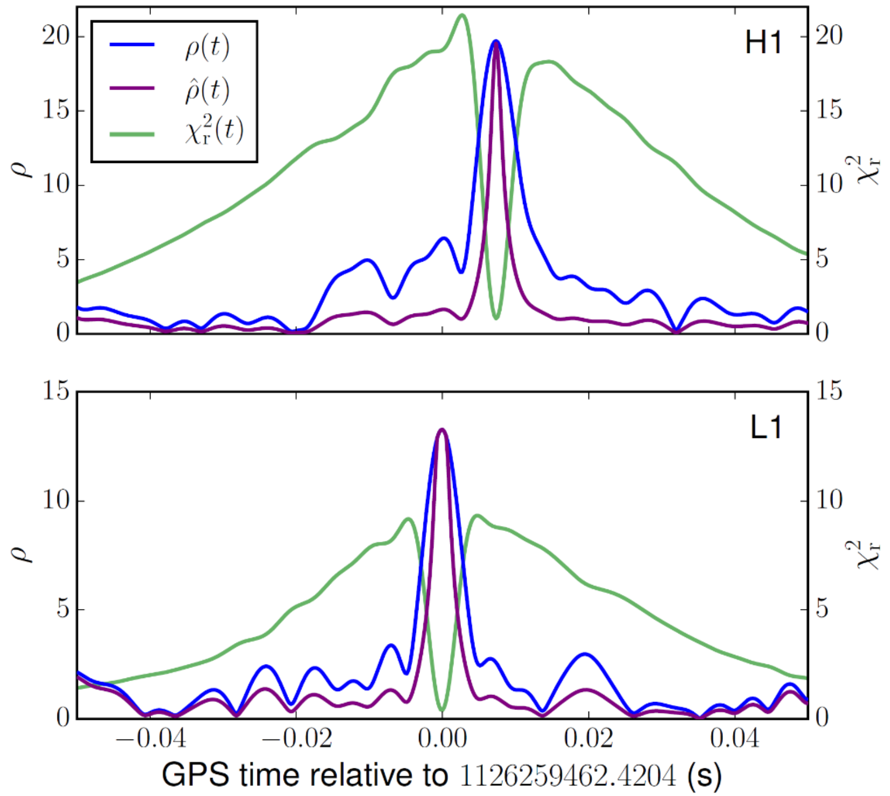
H1: SNR = 20 L1: SNR = 13

GW150914 was found with the same template in both analyses with component masses which are consistent with detailed parameter estimation of GW150914.

- The matched-filter SNR peaks in both detectors at the time of the event and the value of the reduced chi-squared statistic is:

H1: $\chi_r^2 = 1$ L1: $\chi_r^2 = 0.7$

indicating an excellent match between the waveform and the data.



arXiv:1602.03839

Significance of the detection

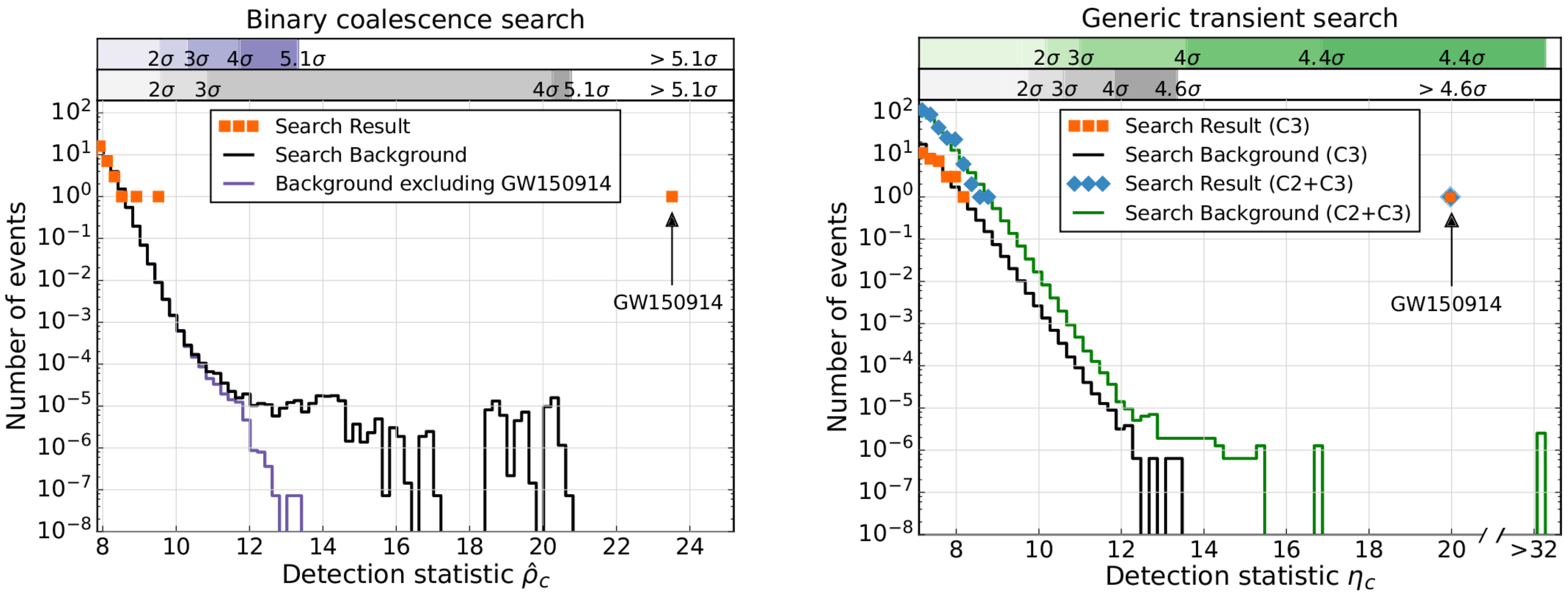
- To determine the statistical significance of GW150914, we estimate the ***search background***, i.e. the rate at which the detector produces noise events with a detection statistic value equal to or higher than the detection candidate GW150914. This rate can be quantified in the ***False-Alarm Rate*** and in the *False-Alarm Probability*.

- We use different methods for this estimation, one being a ***time-shift technique*** where the time-stamps of one detector's data are artificially shifted by an offset that is larger than the H1-L1 propagation time. Then the data set is analysed in the same way of the search foreground and new events are produced.

- GW150914 have detection statistics that are larger than any background event: we can only place an upper bound on its FAR and FAP:

$$FAR < \frac{1}{203000} yrs^{-1} \qquad FAP < 2 \times 10^{-7}$$, i.e a ***significance*** $> 5.1\,\sigma$

Search results for CBC and generic transient searches



Phys. Rev. Lett. 116, 061102 (2016)

Property of the source and inferred parameters

- The Parameter estimation analysis is based on a complete analysis of the data surrounding an event.

It takes as input only the time of arrival of the signal.

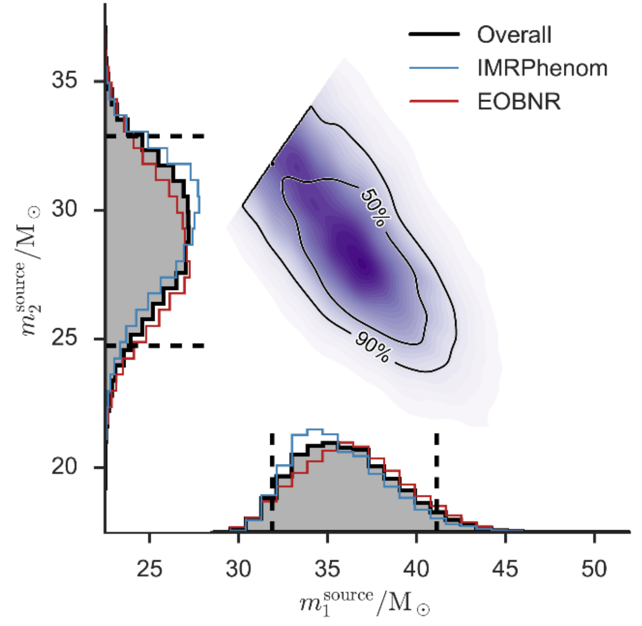
- It differs from the search as:
  - It examines coherently H1 and L1 data
  - It uses waveform models that include the full richness of the physics introduced by the BH spins
    - *EOBNR* with spins aligned to *L* and *IMRPhenom* - an effective-precessing-spin model
  - It covers the full multidimensional parameter space of the models with a fine sampling
  - It accounts for uncertainty ih the calibration of the measured strain

- The property of the source is provided by the Probability Density Function $p\left(\vec{\theta}|\vec{d}\right)$ of the unknown

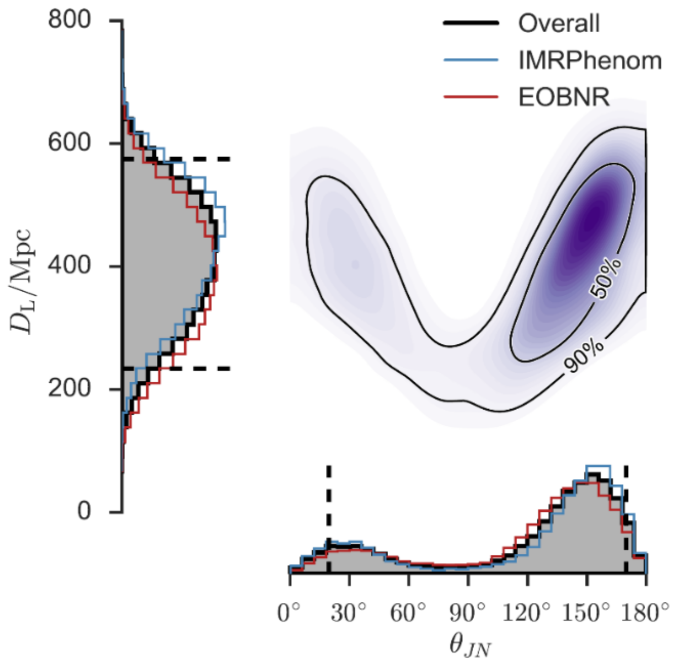
parameters $\vec{\theta}$ given the data streams from the instruments $\vec{d}$:

$$p\left(\vec{\theta}|\vec{d}\right) \propto L\left(\vec{d}|\vec{\theta}\right) p\left(\vec{\theta}\right)$$

Credible intervals:
masses and distance/orbital plane orientation



The masses of the two compact objects are nearly equal and an order of magnitude larger than the conservative upper limit for the mass of a stable NS: these imply that they are stellar mass Black Holes.

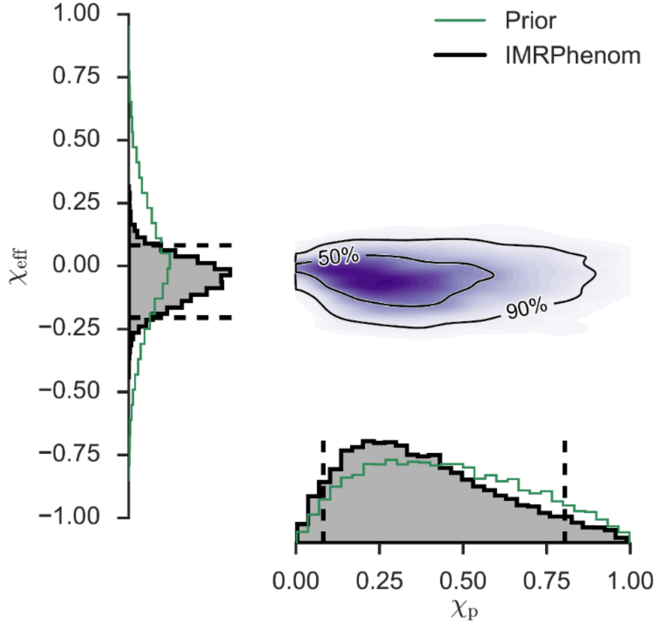


The luminosity distance is strongly correlated to the inclination of the orbital plane with respect the line of sight

θ_{JN} is the angle between the total angular momentun and the line of sight.

arXiv:1602.03840

Credible intervals: spin of the BHs



Spins enter the precessing model through two effective parameters:

$$\chi_{\rm eff} = \frac{c}{GM}\left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right)\cdot\frac{\boldsymbol{L}}{|\boldsymbol{L}|}$$

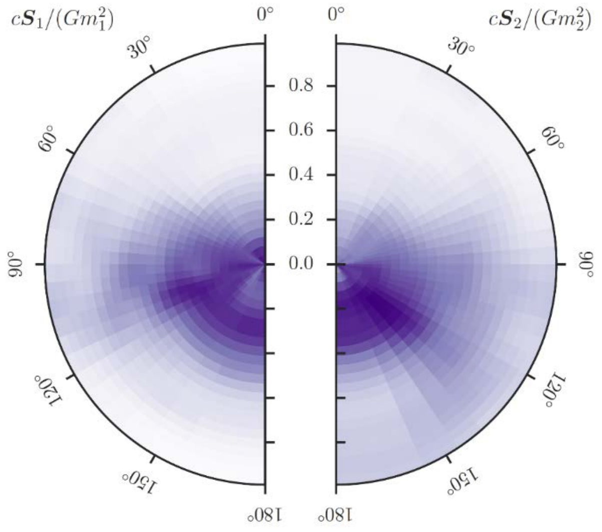
affects the inspiral rate

$$\chi_{\rm p} = \frac{c}{B_1 G m_1^2}\max(B_1 S_{1\perp}, B_2 S_{2\perp})$$

affects the precession of the orbital plane

We can constrain $\chi_{\rm eff} = -0.07^{+0.16}_{-0.17}$ but for $\chi_{\rm p}$ the data are uninformative

arXiv:1602.03840



We can however constrain the dimensionless spin of the primary BH $a_1 = cS_1/(Gm_1^2)$ to less than 0.7 and thus disfavour it being maximally spinning.

Final Black Hole parameters

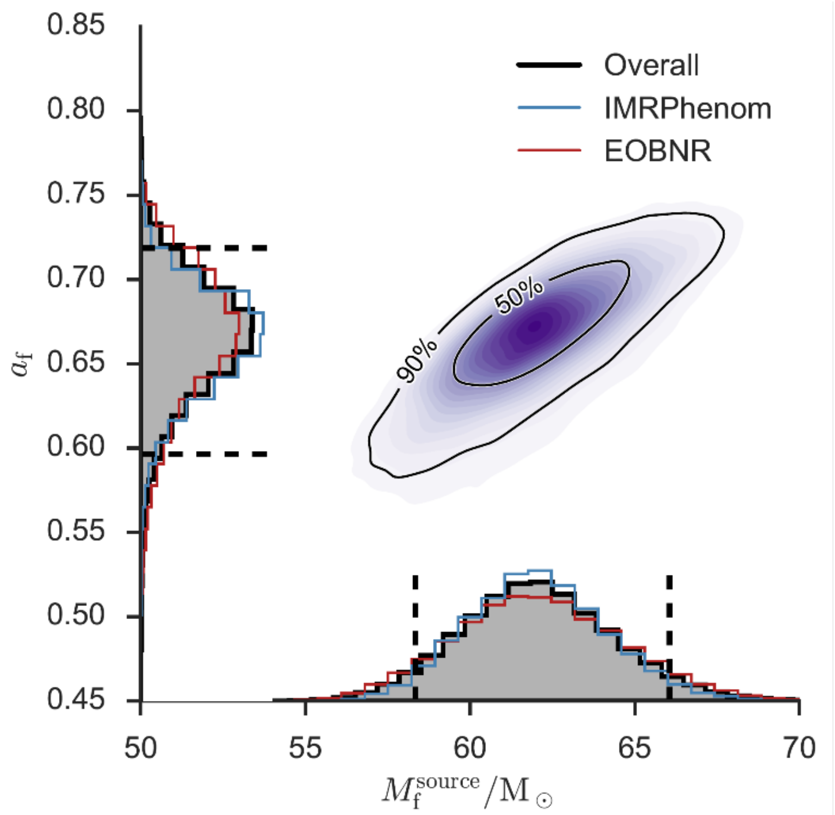
- The two BHs merge into a Kerr BH

- The total energy radiated in GWs can be estimated From the mass of the final BH:

$$E_{\mathrm{rad}} = 3.0^{+0.5}_{-0.4}\,\mathrm{M}_{\odot}$$

- The maximum istantaneous GW luminosity:

$$L = 3.5^{+0.5}_{-0.4} \times 10^{56} \mathrm{erg\,s}^{-1}$$



arXiv:1602.03840

Summary of the estimated parameters

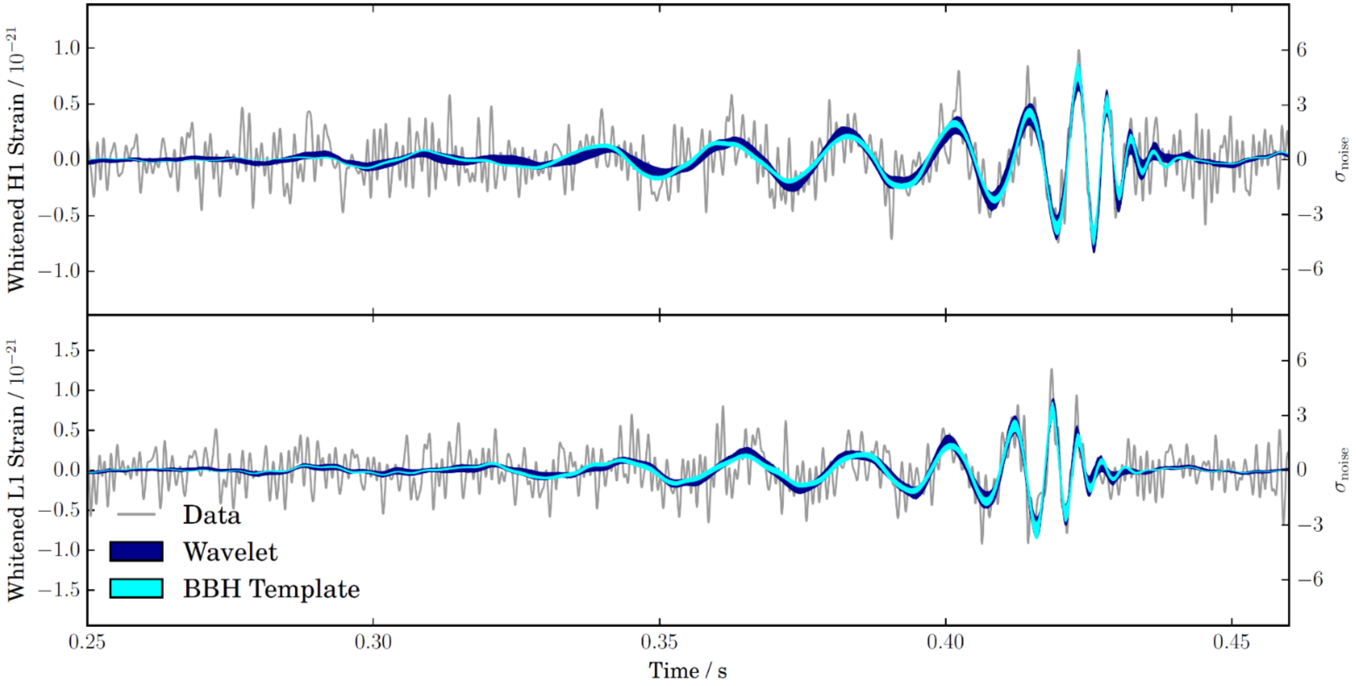
Estimated source parameters

Quantity	Value	Upper/Lower error estimate	Unit
Primary black hole mass	**36**	+5 -4	M sun
Secondary black hole mass	**29**	+4 -4	M sun
Final black hole mass	**62**	+4 -4	M sun
Final black hole spin	**0.67**	+0.05 -0.07	
Luminosity distance	**410**	+160 -180	Mpc
Source redshift, *z*	**0.09**	+0.03 -0.04	
Energy radiated	**3**	+0.5 -0.5	M sun

- The evidence for a coherent signal hypothesis divided by that for Gaussian noise strongly favors the presence of the signal:

$$\ln \mathcal{B}_{s/n} \sim 290$$

A minimal assumption analysis

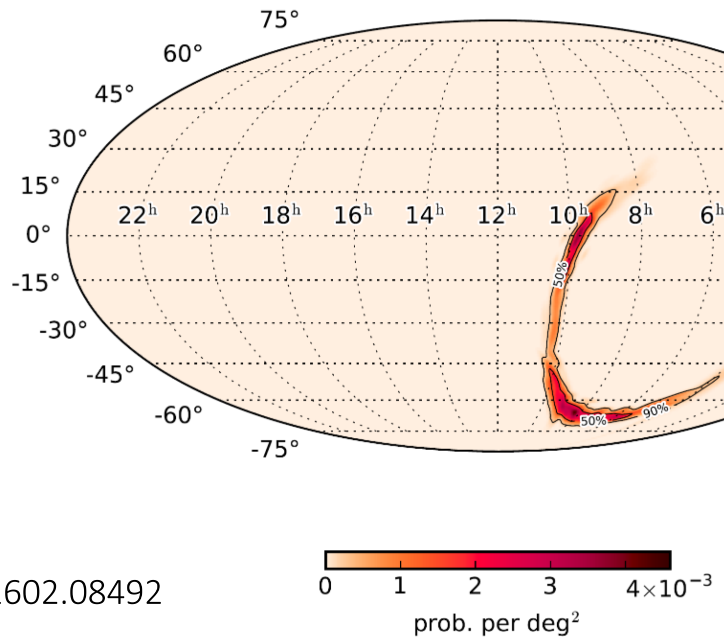


arXiv:1602.03840

- We can infer the PDF of the GW strain through a linear combination of elliptically polarized sine-Gaussian wavelets.
- The actual data and the reconstructed waveform under the two model assumptions show a remarkable agreement.

Multimessenger analysis of GW150914: EM followup observations

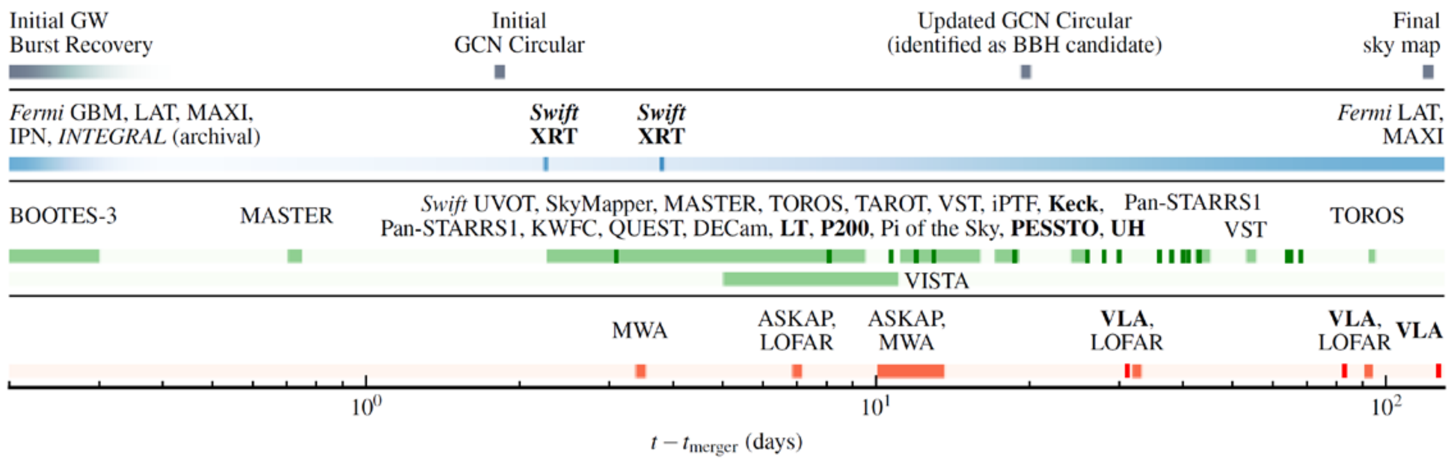
GW150914 detection triggered the EM followup observation program: skymaps of the event were passed to the astronomical patners.

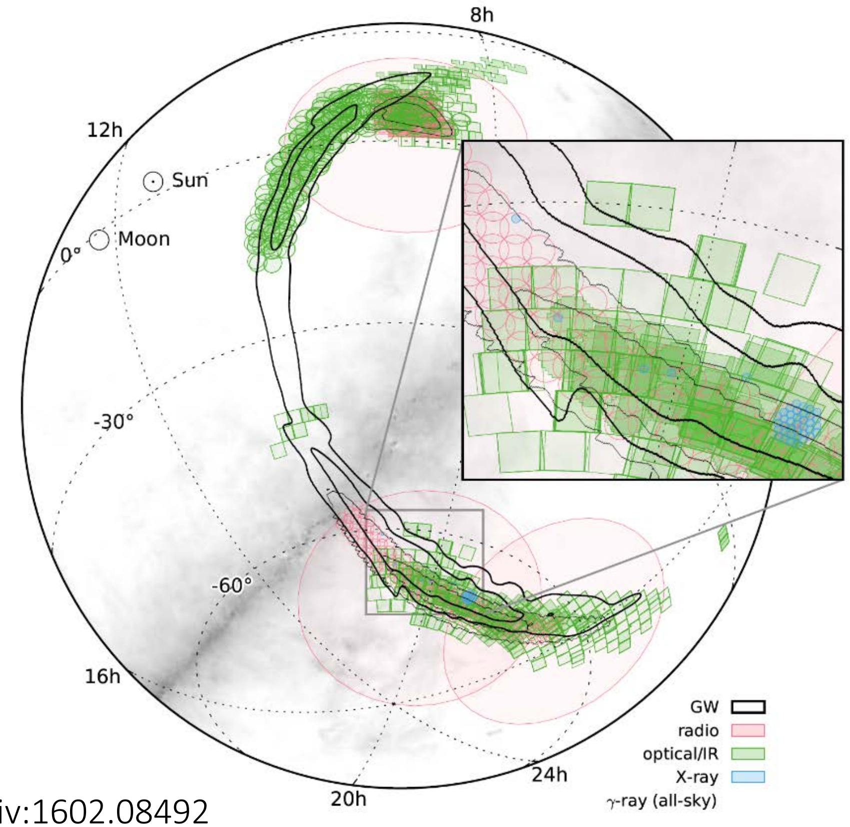


arXiv:1602.08492

- 90% probability → 610 deg^2
- 50% probablity → 150 deg^2
- 90% 3-dimensional volume probability → 10^{-2} Gpc^3

EM followup observations





arXiv:1602.08492

- Fermi GBM reported an EM potential counterpart of GW150914.

Not confirmed by INTEGRAL. Discussions and verifications still on going. (arXiv:1602.03920, arXiv:1602.04180).

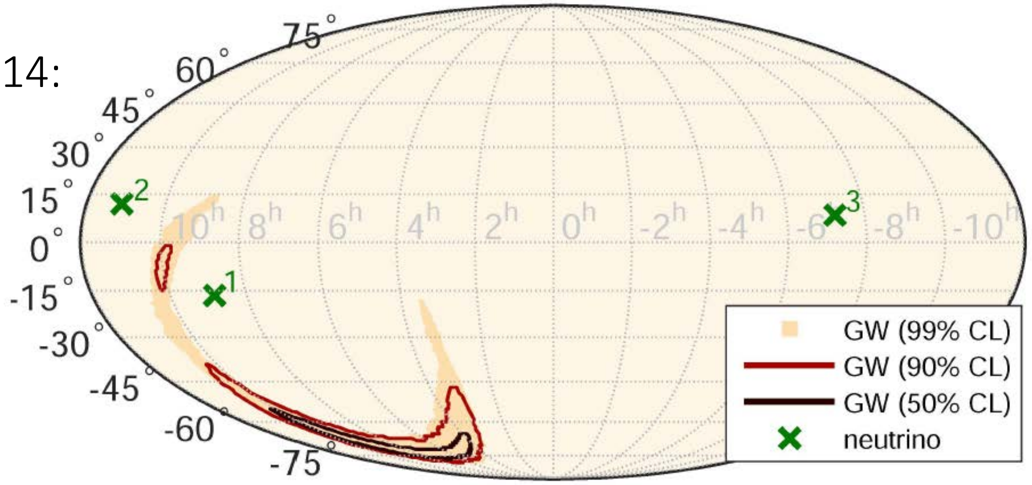
Multimessenger analysis of GW150914: High-energy neutrino followup

- IceCube and Antares neutrino detectors performed a followup search of GW150914

- Within ±500 s of the gravitational wave event, the number of neutrino candidates detected by IceCube and Antares were three and zero, respectively.
This is consistent with the expected atmospheric background, and none of the neutrino candidates were directionally coincident with GW150914

- UL on the total energy radiated in neutrinos from GW150914:

$$E^{ul}_{\nu,tot} \sim 10^{52}\text{–}10^{54} \left(\frac{D_{gw}}{410\,\mathrm{Mpc}}\right)^2 \mathrm{erg}$$



arXiv:1602.05411

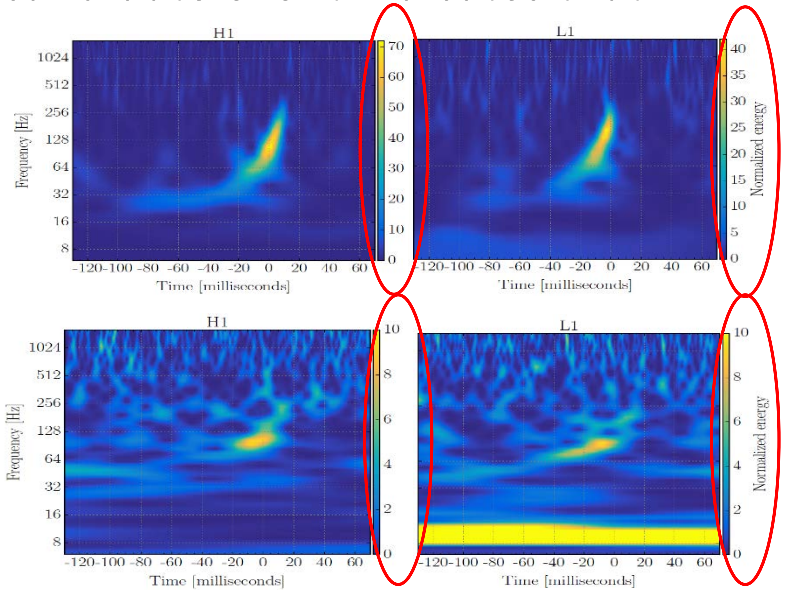
LVT151012 event

- LVT151012 is the second most significant event in the analysed time (September 12 - October 20 2015) but its false alarm probability is not sufficiently low to confidently claim this candidate event as a signal.

- If it is of astrophysical origin, detailed waveform analysis of this candidate event indicates that it is also a binary black hole merger.

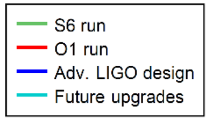
Event	Time (UTC)	FAR (yr^{-1})	$\mathscr{F}$	$\mathscr{M}$ ($M_\odot$)	m_1 ($M_\odot$)	m_2 ($M_\odot$)	χ_{eff}	D_L (Mpc)
GW150914	14 September 2015 09:50:45	$< 5 \times 10^{-6}$	$< 2 \times 10^{-7}$ ($> 5.1\,\sigma$)	28^{+2}_{-2}	36^{+5}_{-4}	29^{+4}_{-4}	$-0.06^{+0.17}_{-0.18}$	410^{+160}_{-180}
LVT151012	12 October 2015 09:54:43	0.44	0.02 ($2.1\,\sigma$)	15^{+1}_{-1}	23^{+18}_{-5}	13^{+4}_{-5}	$0.0^{+0.3}_{-0.2}$	1100^{+500}_{-500}

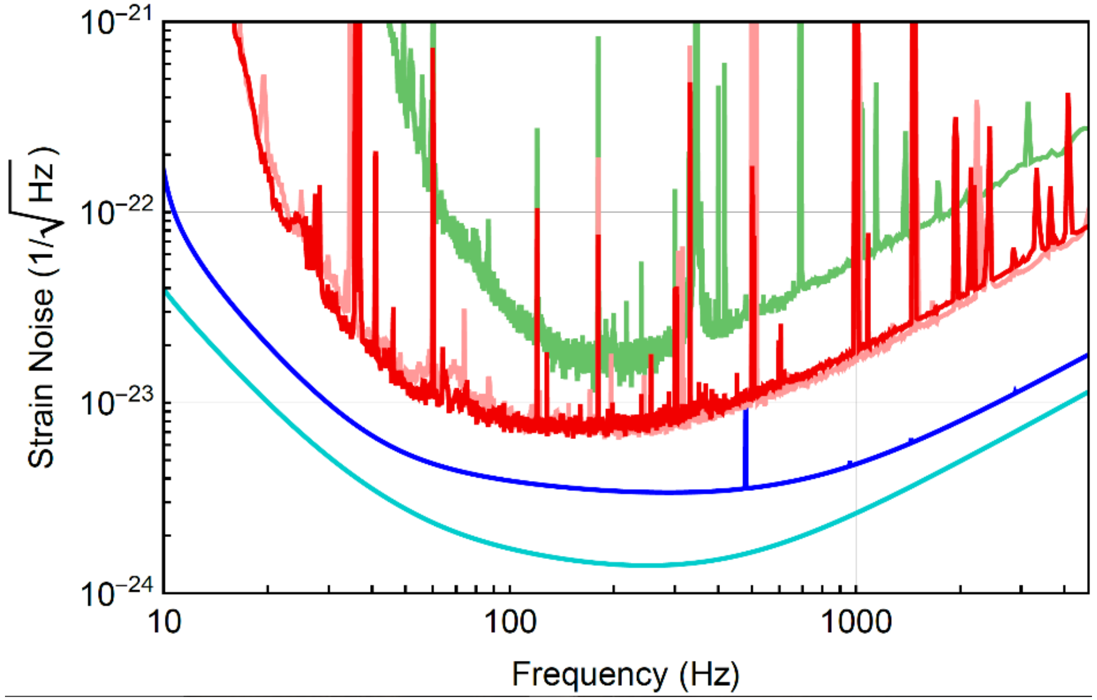
arXiv:1602.03839

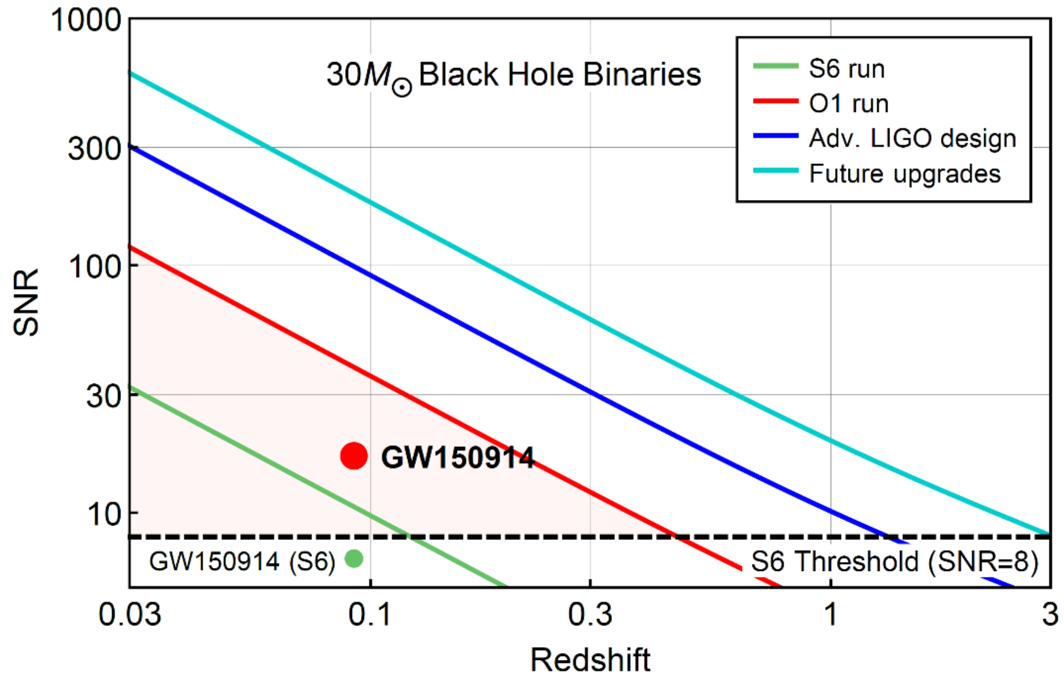


arXiv:1602.03844

GW150914 in the future runs





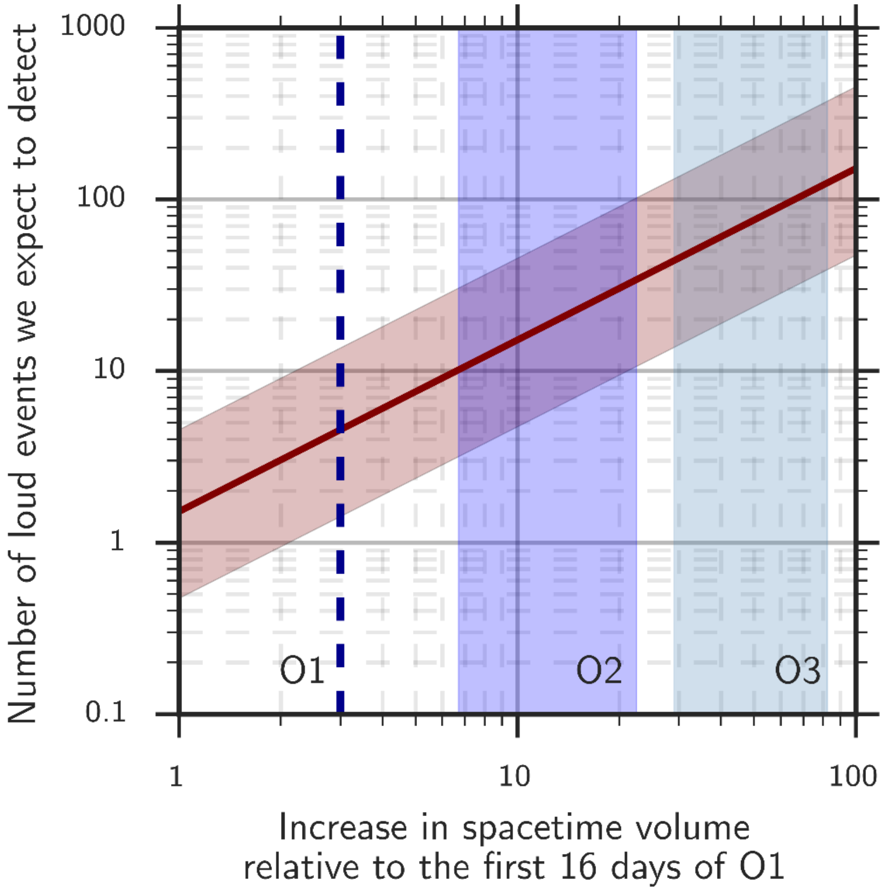


Phy. Rev. Lett. 116, 131103 (2016)

BBH merger and detection rates

- We can infer a conservative 90% credible range on the rate of BBH coalescences of **2-400 Gpc^{-3} yr^{-1}**

- The number of highly significant events ($FAR < 0.01\ yr^{-1}$) is **3-100** for the next run **O2**.

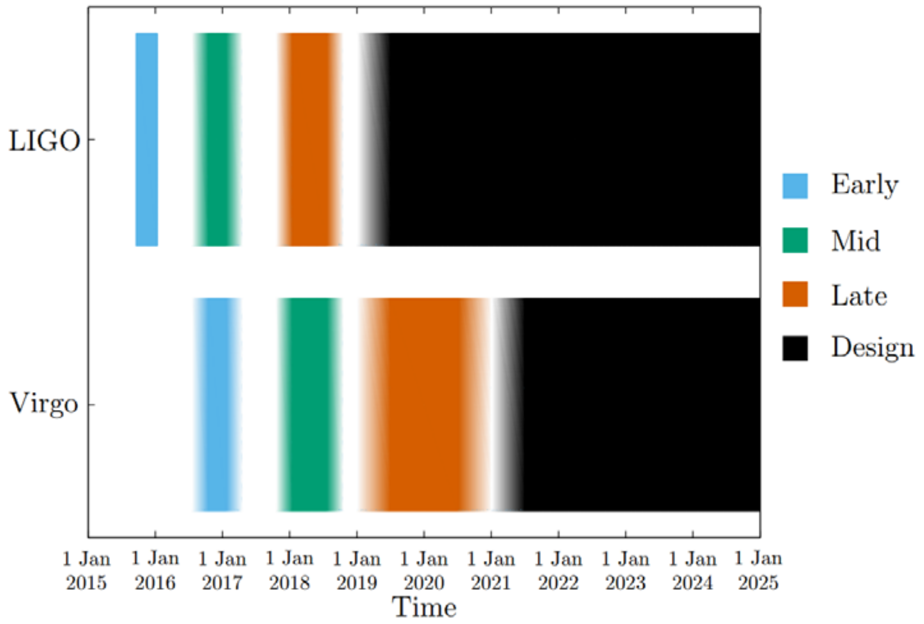


ApJL, 818, L22, 2016

O2 and beyond

- O1 ended on January 2016. The analysis of the full run is still on-going.

- The second observing run O2 will most probably starts this summer 2016. Later in the year the interferometer Virgo will join the run



Early (2015 – 16, 40 – 80 Mpc)
Mid (2016 – 17, 80 – 120 Mpc)
Late (2017 – 18, 120 – 170 Mpc)
Design (2019, 200 Mpc)
BNS-optimized (215 Mpc)

orientation-averaged distance
for BNS detection with SNR = 8

Early (2016–17, 20 – 60 Mpc)
Mid (2017–18, 60 – 85 Mpc)
Late (2018–20, 65 – 115 Mpc)
Design (2021, 130 Mpc)
BNS-optimized (145 Mpc)

Living Reviews in Relativity 19, 1 (2016)

Conclusions

- GW150914 is the *first direct detection* of GW

- GW150914 provides the first observational evidence for the *existence of BBH* which merge within the age of the Universe

- GW150914 provides the most robust evidence for the *existence of heavy* ($\geq 25\ \mathrm{M}_{\odot}$) *stellar-mass BHs*.
    - The final BH more massive than any other found

- GW150914 provides the opportunity to study the two-body motion and to *test General Relativity* in the large velocity, highly nonlinear regime

- ***The detection and analysis of GW150914 open a new era for the physics and astrophysics and mark the birth of Gravitational Astronomy***

References

Phys. Rev. Lett. 116, 061102 (2016)	Observation of Gravitational Waves from a Binary Black Hole Merger
Phy. Rev. Lett. 116, 131103 (2016)	GW150914: The Advanced LIGO Detectors in the Era of First Discoveries
arXiv:1602.03839	GW150914: First results from the search for binary black hole coalescence with Advanced LIGO
arXiv:1602.03840	Properties of the binary black hole merger GW150914
arXiv:1602.03841	Tests of general relativity with GW150914
arXiv:1602.03842	The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914
arXiv:1602.03843	Observing gravitational-wave transient GW150914 with minimal assumptions
arXiv:1602.03844	Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914
arXiv:1602.03845	Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914
ApJL, 818, L22, 2016	Astrophysical Implications of the Binary Black-Hole Merger GW150914
Phys. Rev. Lett.116, 131102 (2015)	GW150914: Implications for the stochastic gravitational-wave background from binary black holes
arXiv:1602.05411	High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and ANTARES