The detection of Gravitational Waves

Piero Rapagnani

INFN Rome
&
University of Roma Sapienza

LIGO & VIRGO

- In 2004 LIGO and Virgo started a first exercise to test the data exchange and compare the software performance developed in the two collaborations.

- In 2007 a formal *Memorandum of Understanding (MoU)* between the two collaborations was signed: “”*We intend to carry out the search for gravitational waves in a spirit of teamwork, not competition. “”*

- *“”The terms governing work on data analysis are exclusive; that is, the parties agree that all of the data analysis work that they do will be carried out under the framework of this agreement… omissis…, all subsequent observational data will be open to both collaborations, to be used in the framework of Joint Data Analysis Groups on all gravitational wave analysis topics. All gravitational wave data analysis will be carried out under the umbrella of this agreement between LIGO and VIRGO; there will be no LSC-only or Virgo-only gravitational wave data analyses while this agreement remains in force. “”*

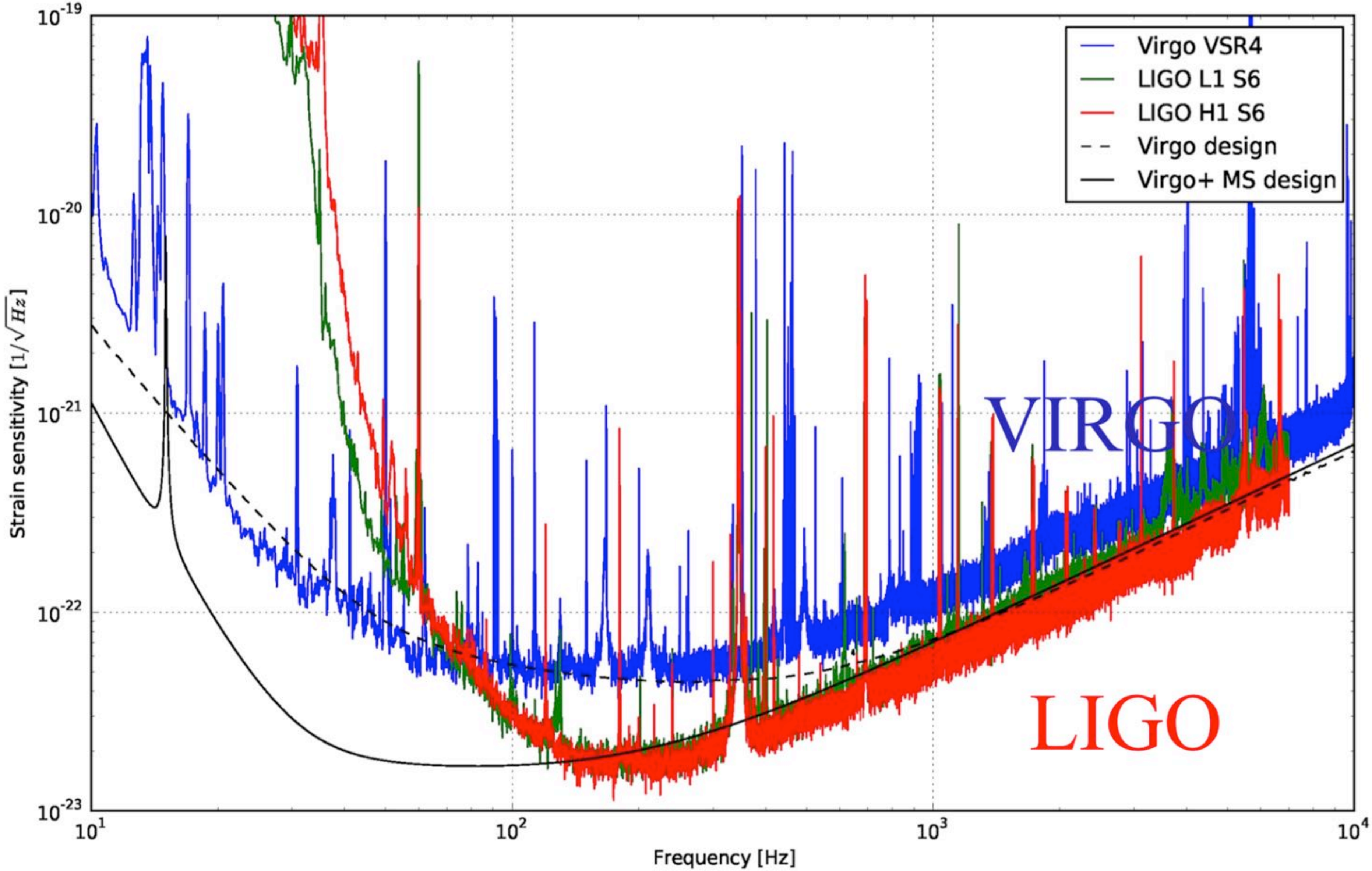
The network since 2007

MOU to be signed between LIGO Scientific Collaboration and Virgo:

– Full exchange of data, joint analysis

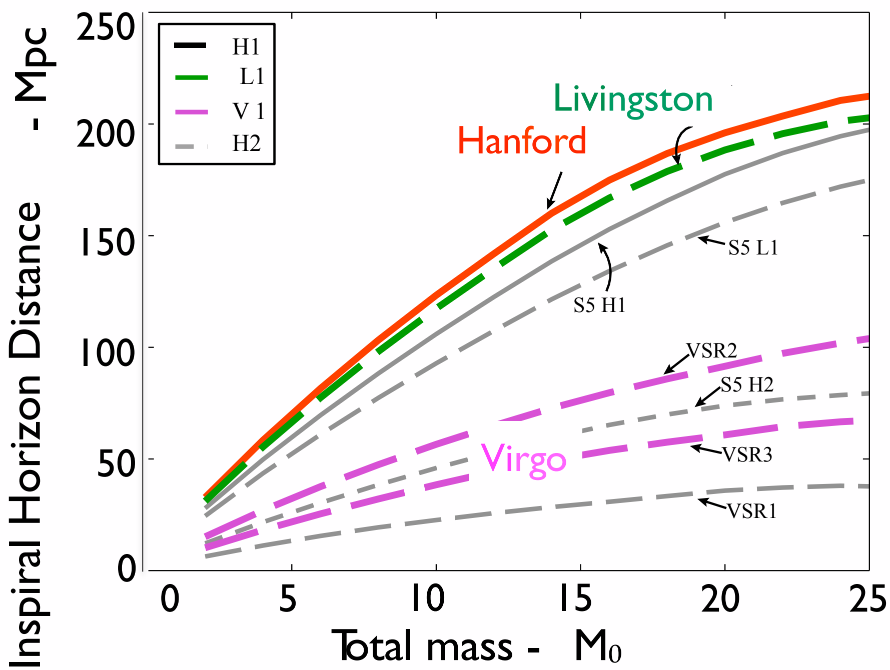
4 detectors to operate as a **SINGLE MACHINE**
Great scientific value added

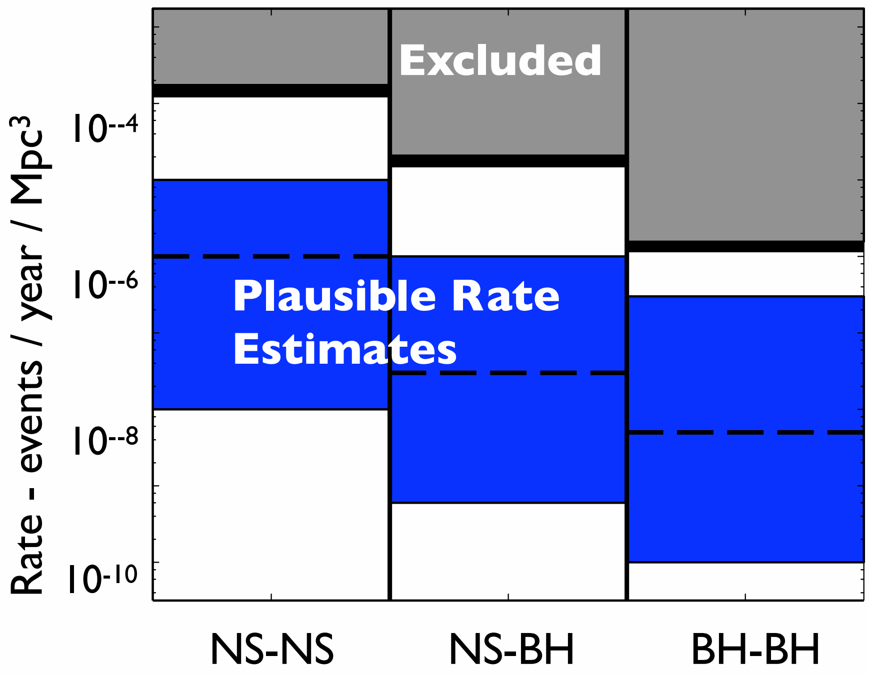
Sensitivity of LIGO-Virgo Runs 2007-2011



GW Science From First Generation(2007-2011)

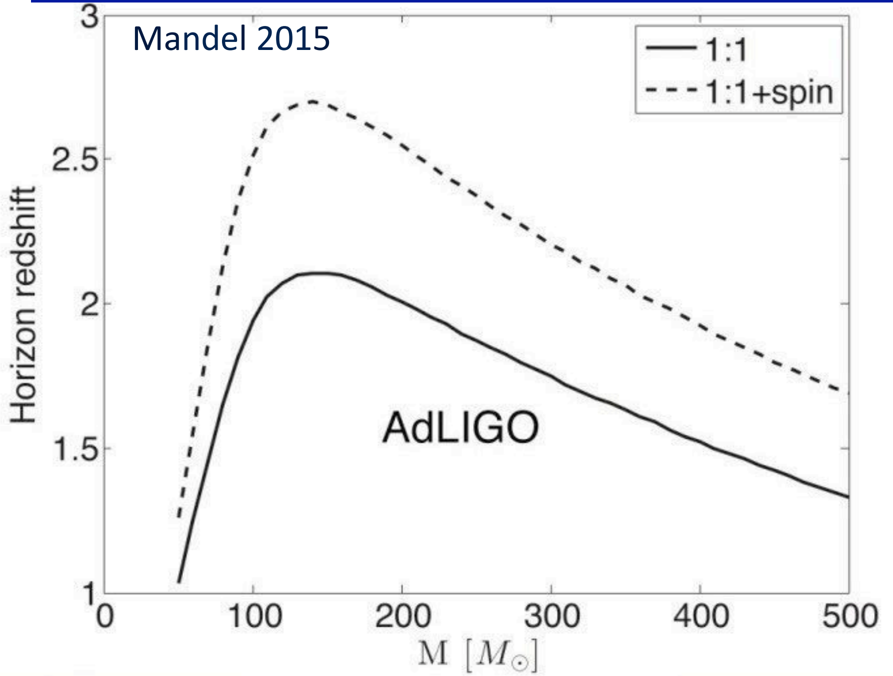
PRD 85 (2012) 08202

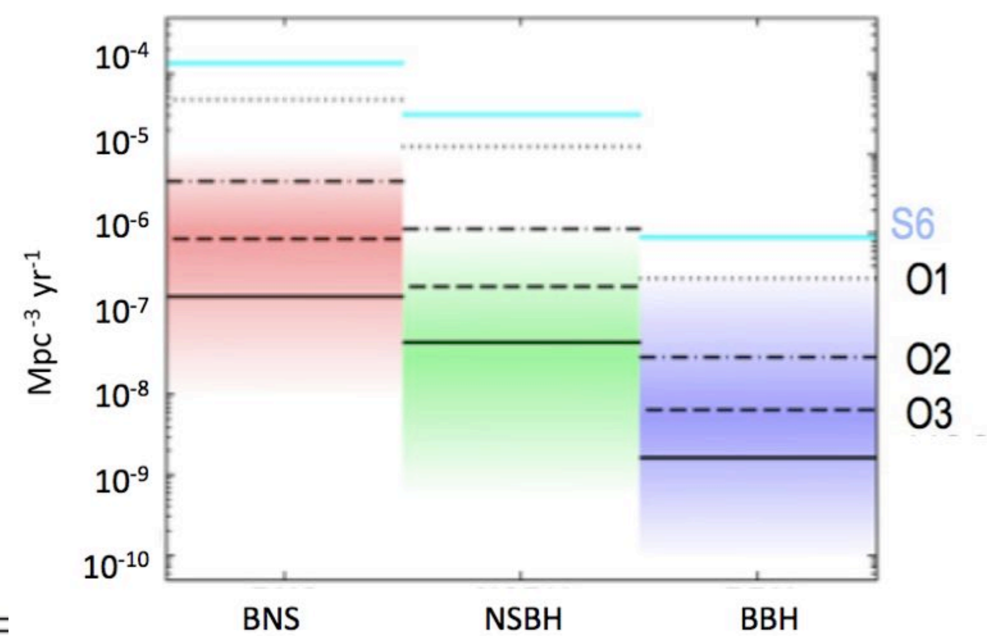




Compact Coalescing Binaries
Detection perspectives with advanced detectors

Phys. Rev D85 (2012) 082002GW





Epoch		2015	2016–2017	2017–2018	2019+	2022+ (India)
Estimated run duration		3 months	6 months	9 months	(per year)	(per year)
BNS range/Mpc	LIGO	40–80	80–120	120–170	200	200
	Virgo	—	20–60	60–85	65–130	130
BNS detections		0.0004–3	0.006–20	0.04–100	0.2–200	0.4–400

Probe beyond local universe

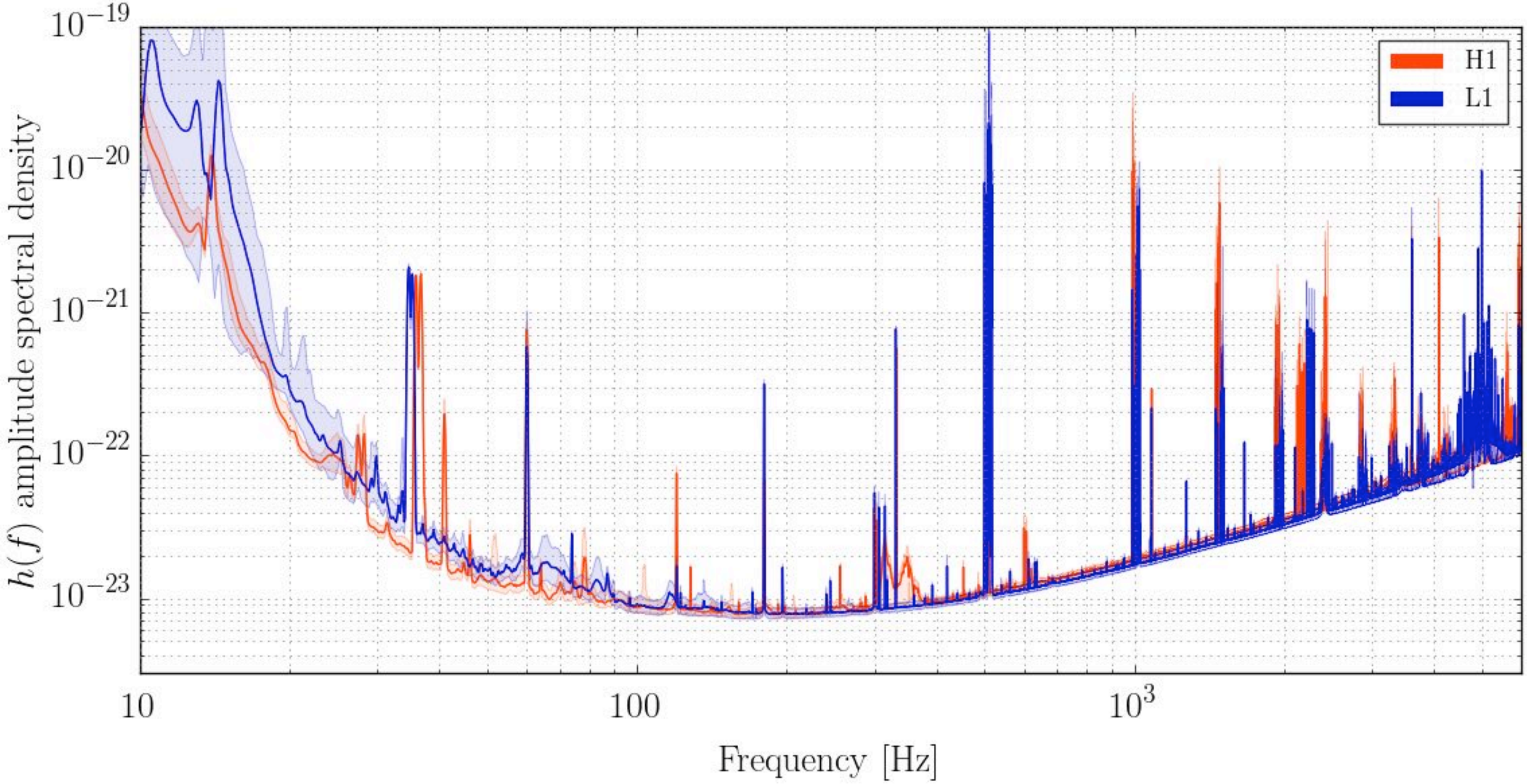
$100\ M_\odot + 100\ M_\odot$ BBH visible out to ~16 Gpc at design sensitivity (~5 Gpc in O1), even further if the source is spinning

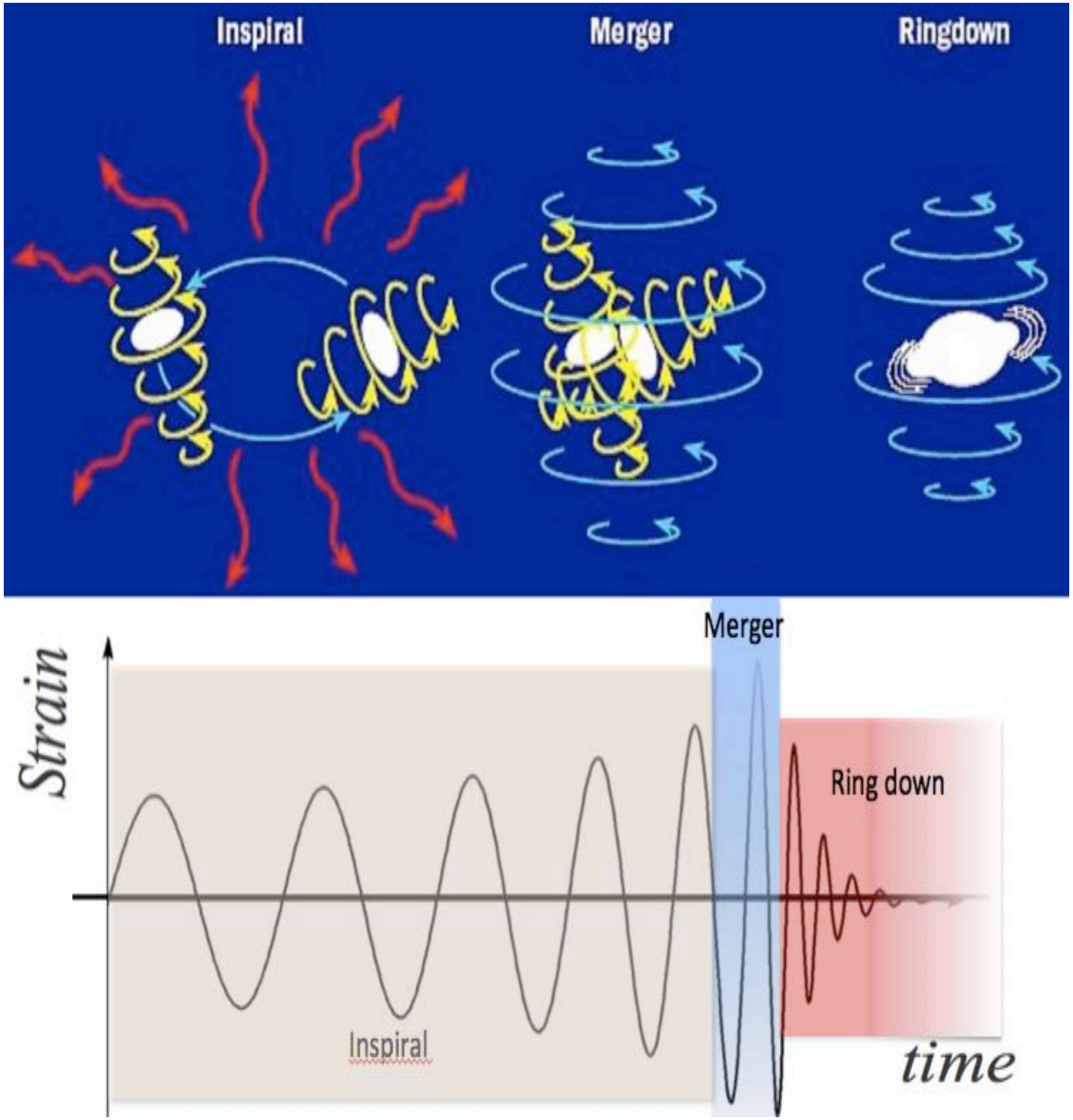
The first observing run of LIGO in the advanced configuration took place from September 12, 2015 to January 19, 2016

Total coincident time: 51.5 days

The data quality checks reduce the hunting time to: 48.6 days

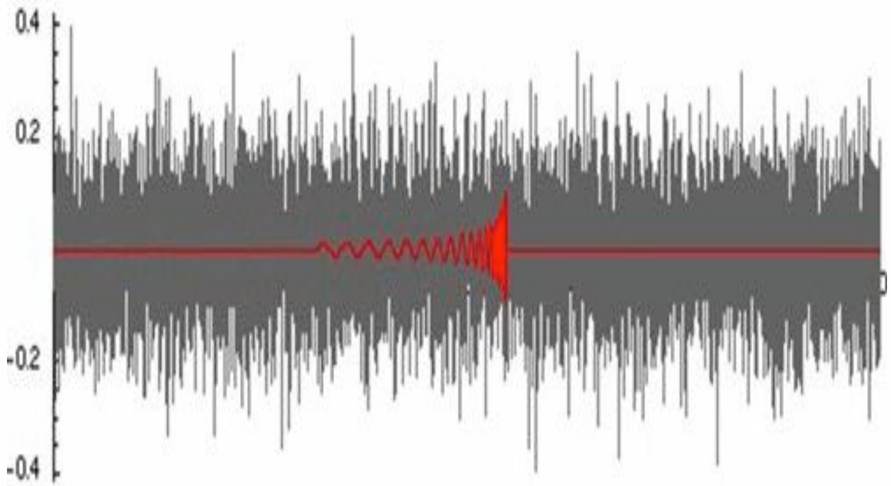
LIGO Sensitivity in O1



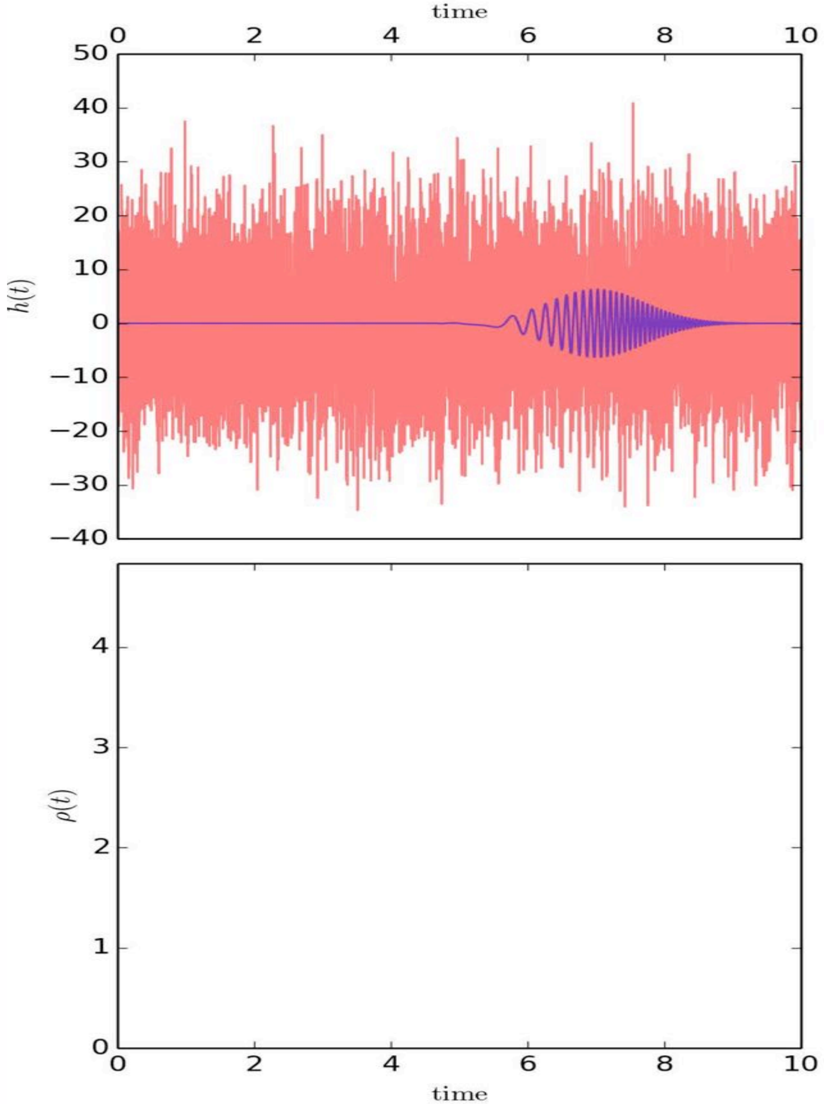


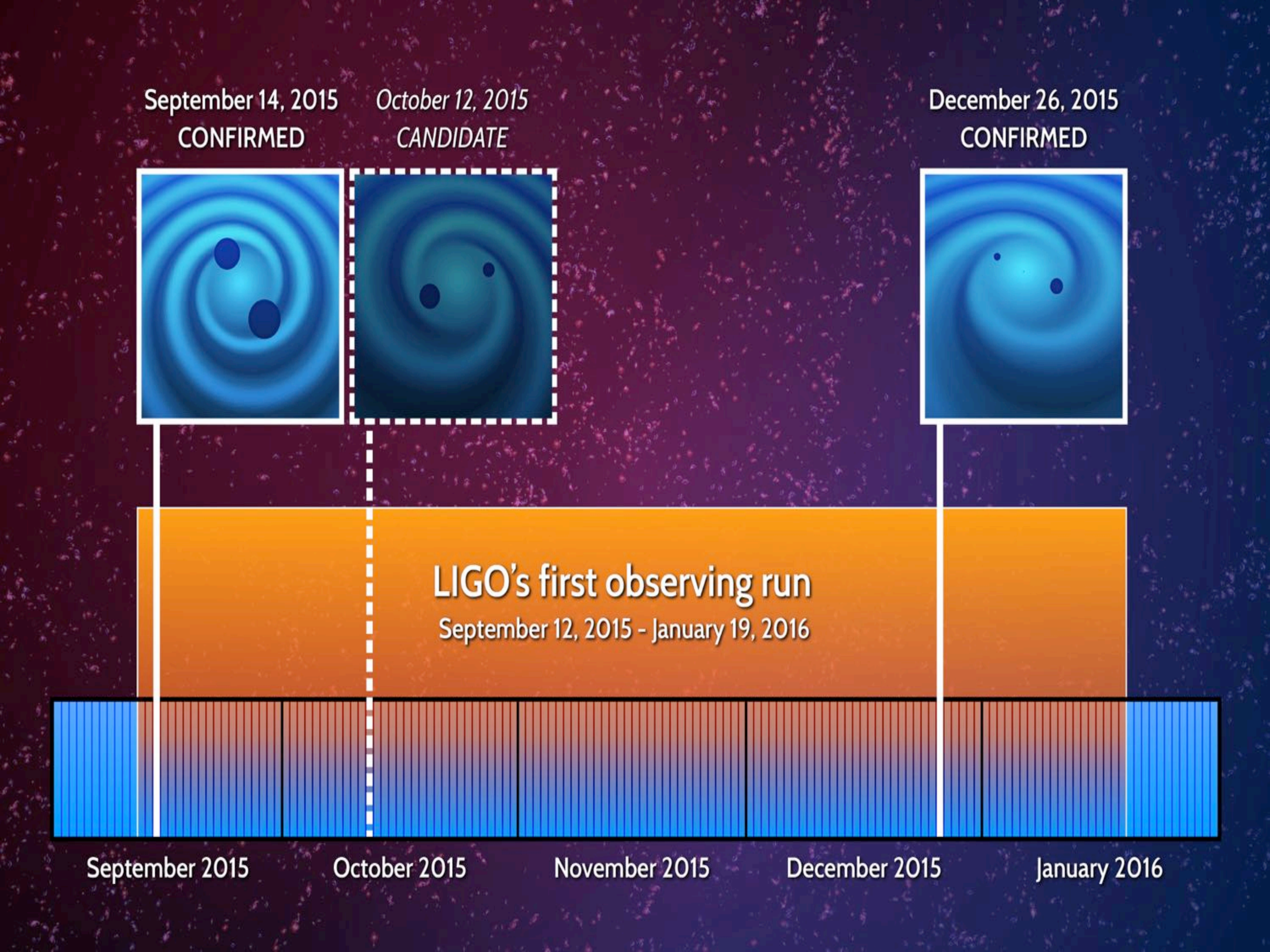
The search for black hole signals is performed over a range of frequencies from 30 Hz to several kHz.

These are the typical frequencies of the gravitational waves emitted during the late inspiral, merger and ringdown of stellar mass black hole binaries.



The *matched filter*, is obtained by correlating the hypothetical signal with the interferometer output signal to infer the presence of the gravitational wave signal hidden in the data.




September 14, 2015
CONFIRMED
October 12, 2015
CANDIDATE
December 26, 2015
CONFIRMED
LIGO's first observing run
September 12, 2015 - January 19, 2016
September 2015
October 2015
November 2015
December 2015
January 2016

The search identified two black hole mergers:

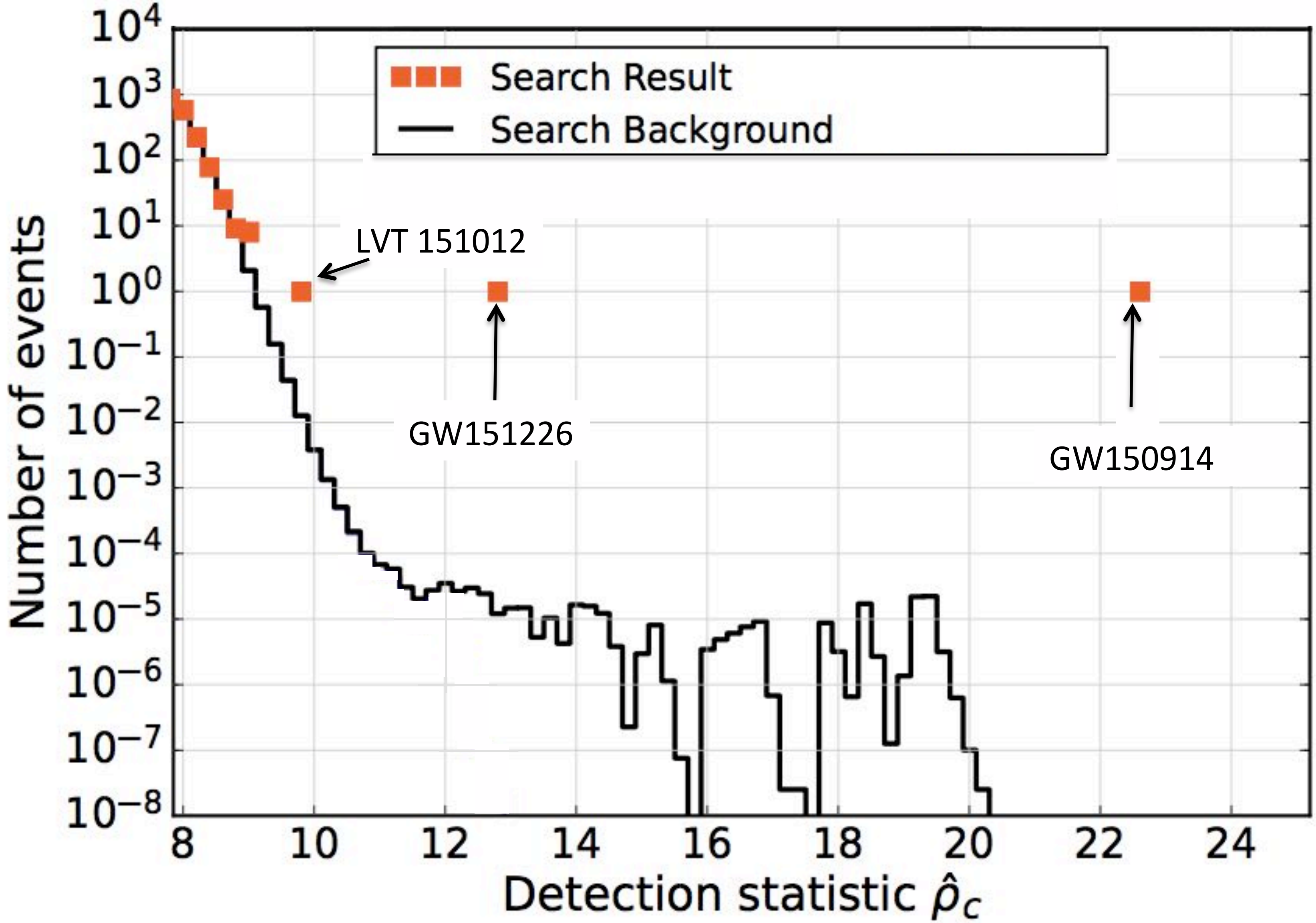
GW150914 → Signal/Noise =24

GW151226 → Signal/Noise = 13

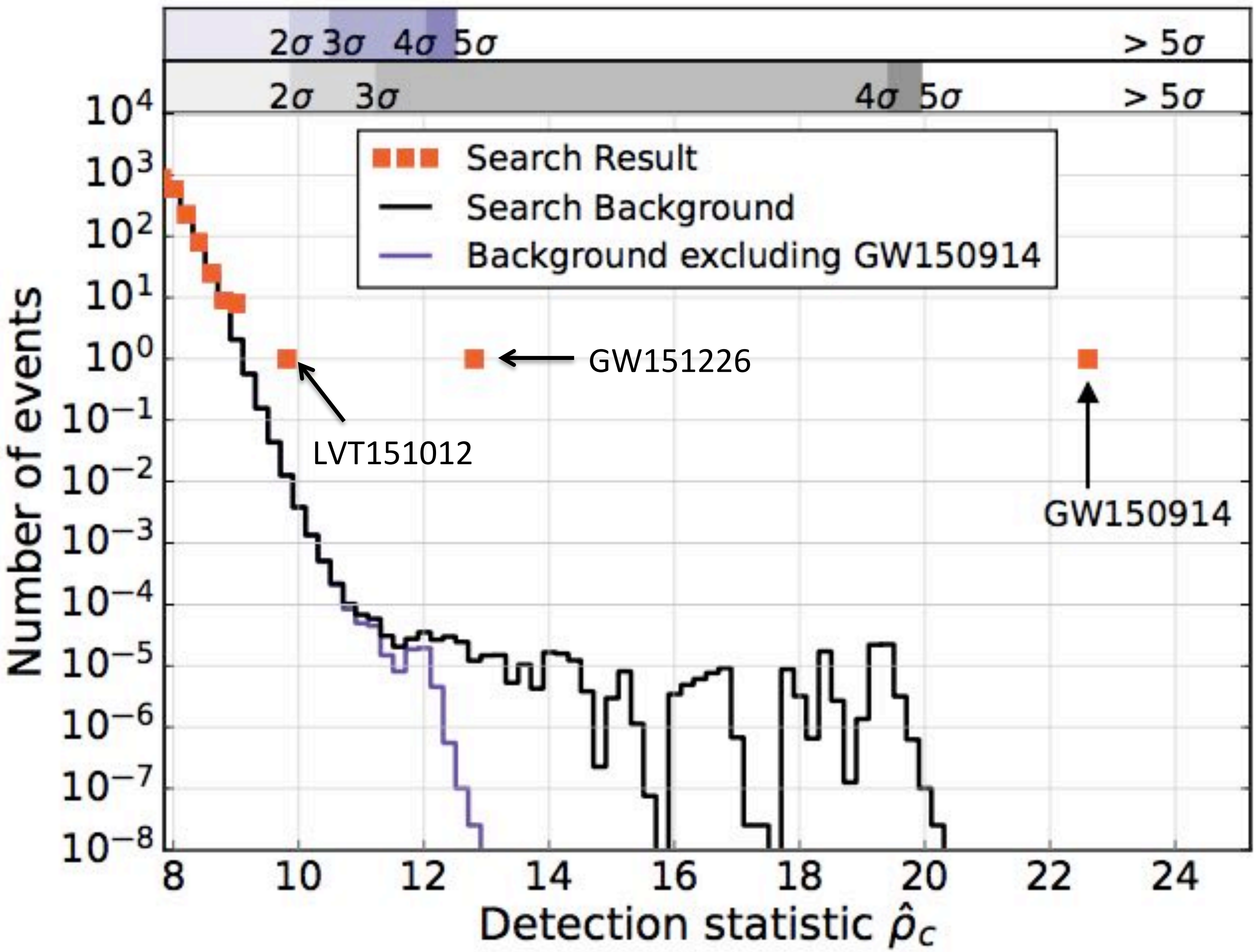
+

LVT151012 → Signal/Noise *=9.7*

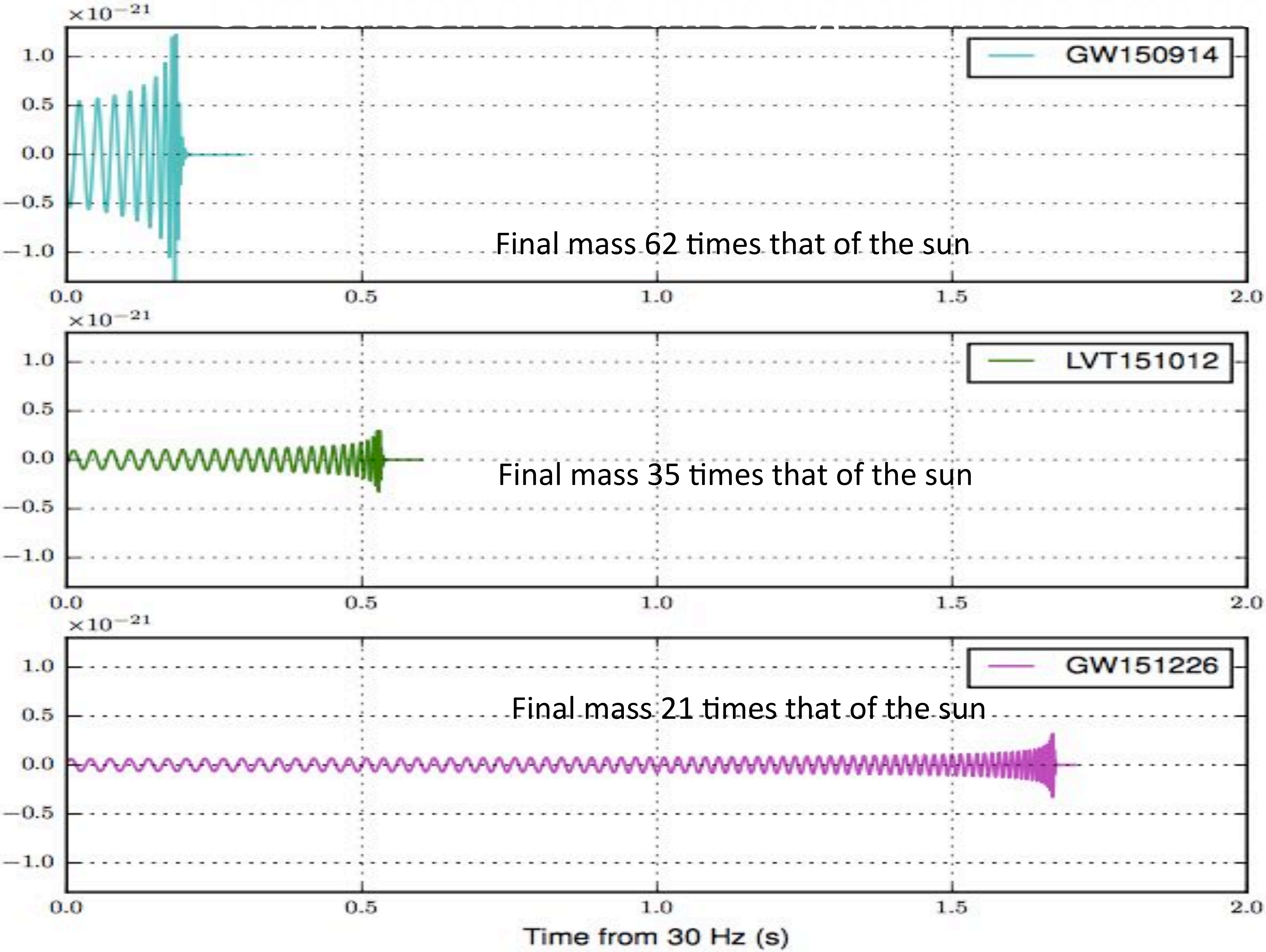
While we are not so confident to tag this as a detection, it is more likely to be a gravitational wave signal than not



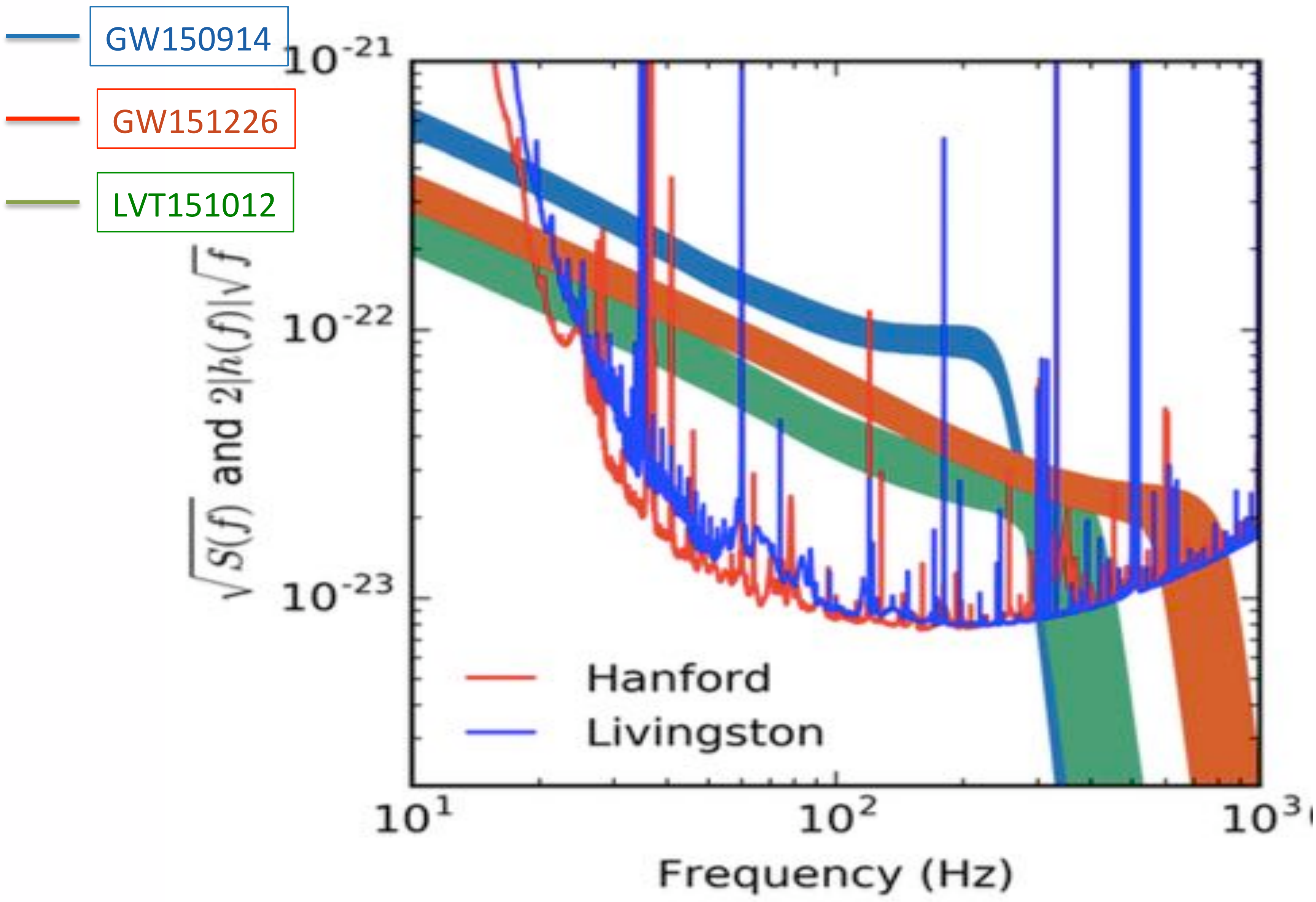
Search Result
Search Background
LVT 151012
GW151226
GW150914
Number of events
Detection statistic $\hat{\rho}_c$
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
8 10 12 14 16 18 20 22 24



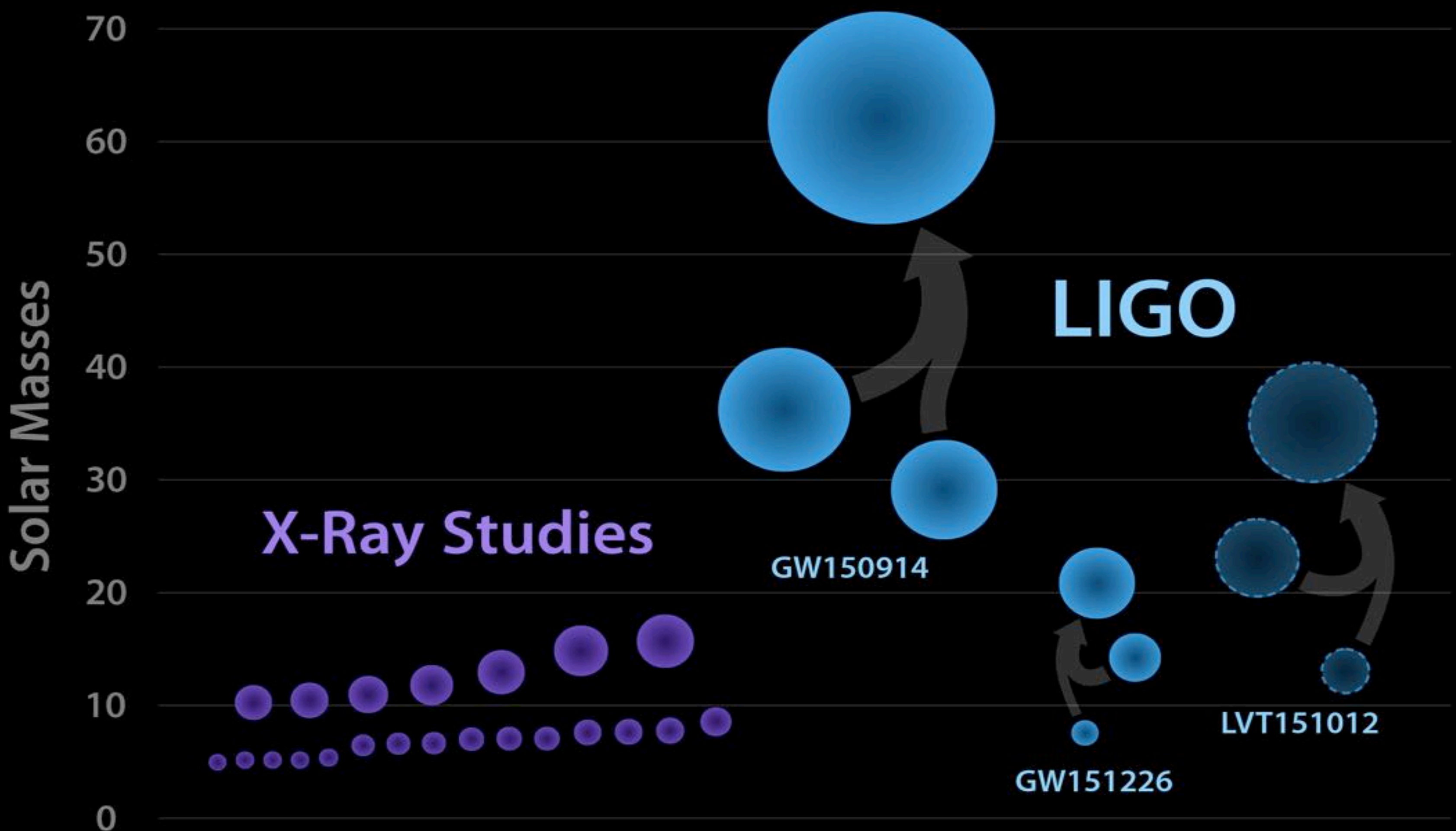
2σ 3σ 4σ 5σ > 5σ
2σ 3σ 4σ 5σ > 5σ
Search Result
Search Background
Background excluding GW150914
GW151226
LVT151012
GW150914
Number of events
Detection statistic $\hat{\rho}_c$


×10^−21
GW150914
Final mass 62 times that of the sun
LVT151012
Final mass 35 times that of the sun
GW151226
Final mass 21 times that of the sun
Time from 30 Hz (s)

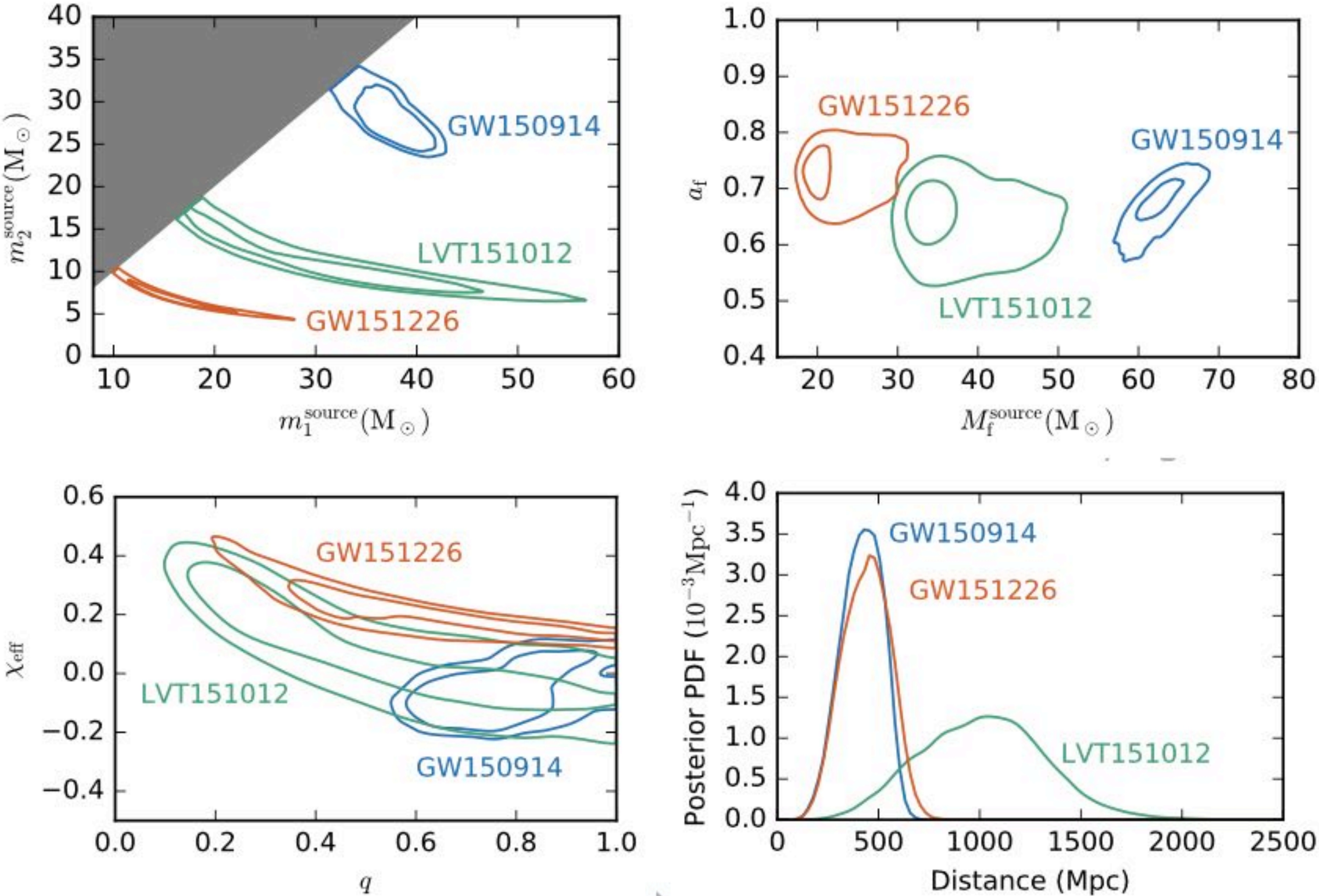
Spectral components of the triggers



Black Holes of Known Mass

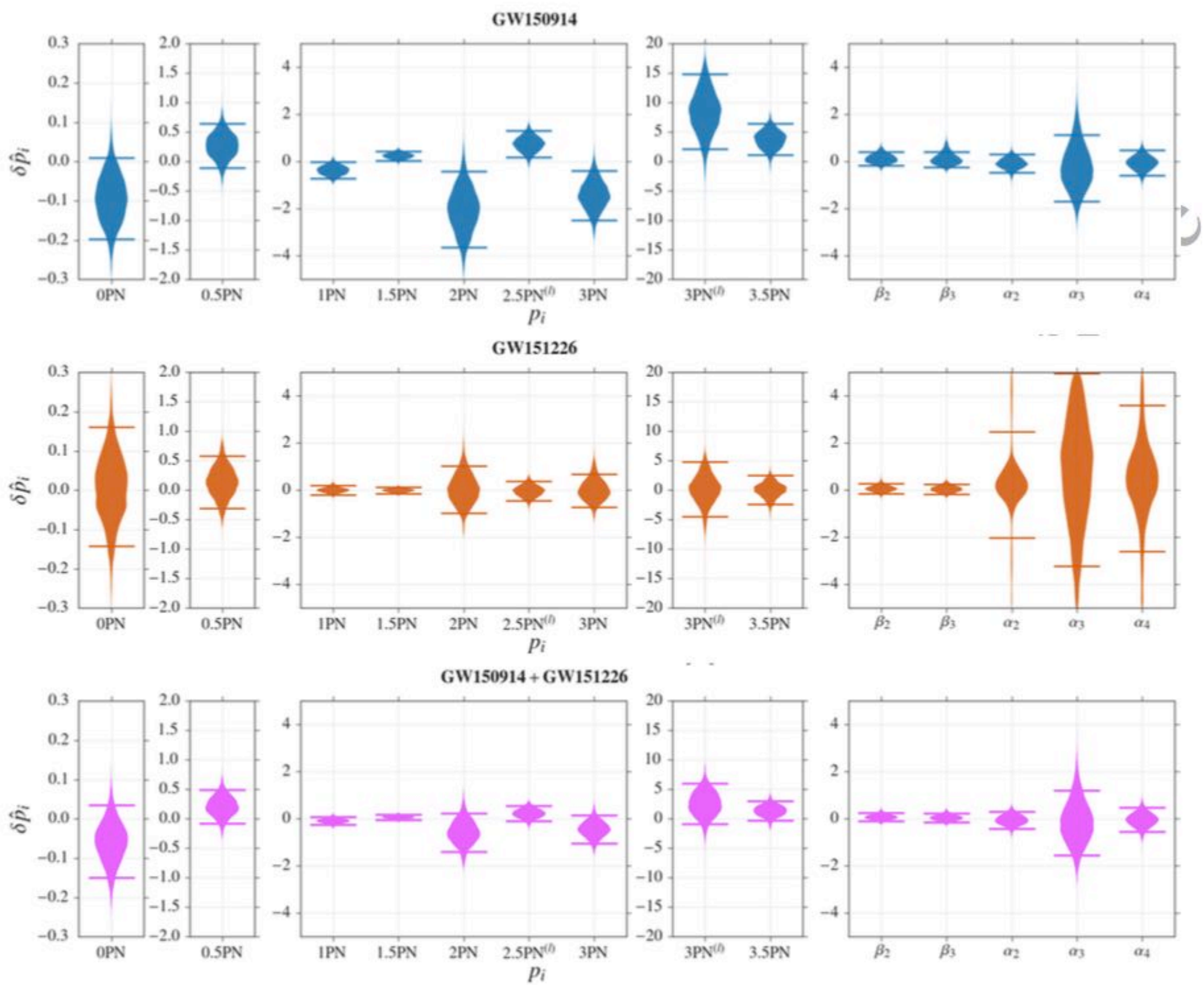


90% contour plots of the BBH perameters

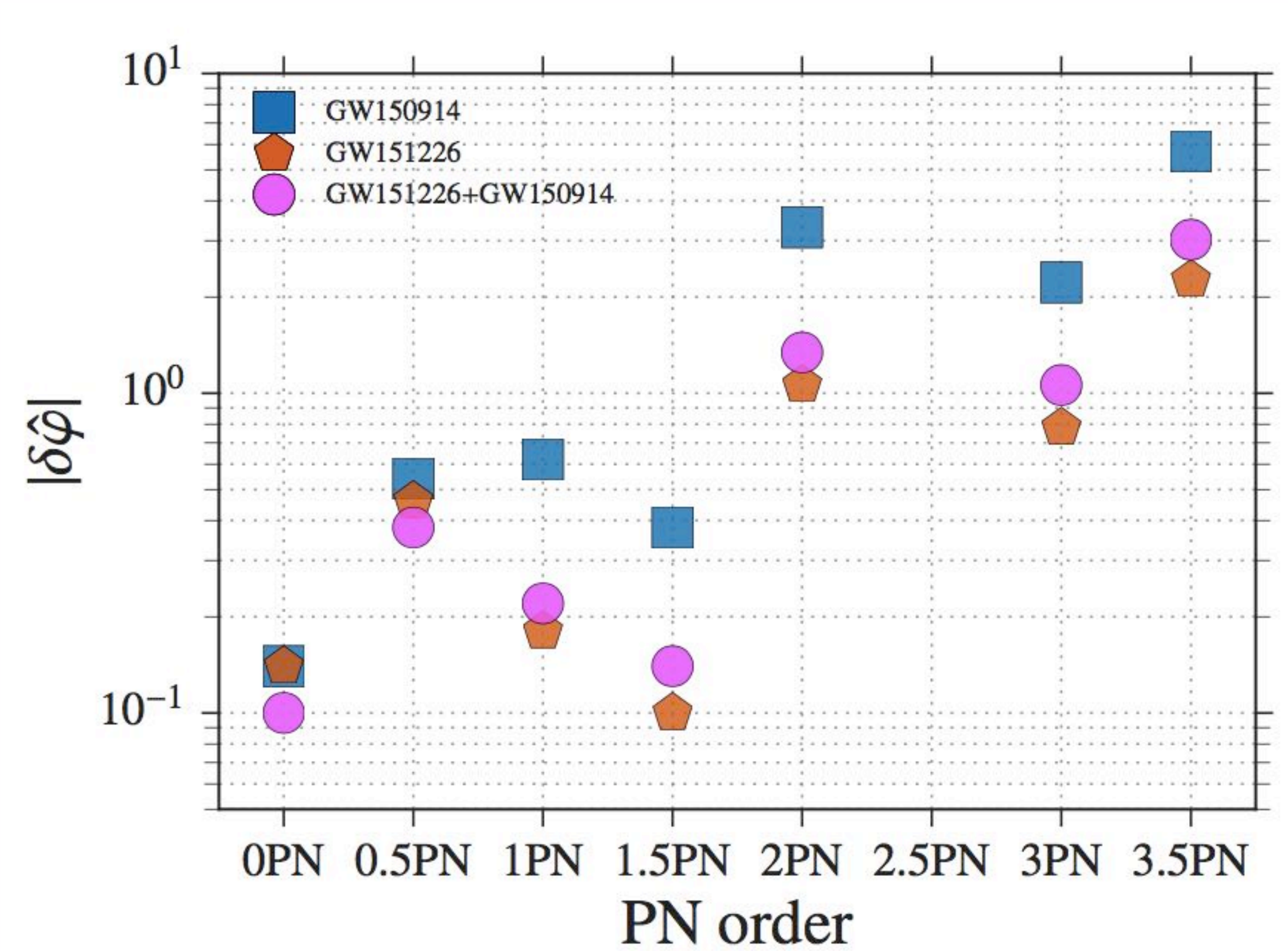


Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate $\mathrm{FAR}/\mathrm{yr}^{-1}$	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

General Relativity tests in the strong interaction regime -I

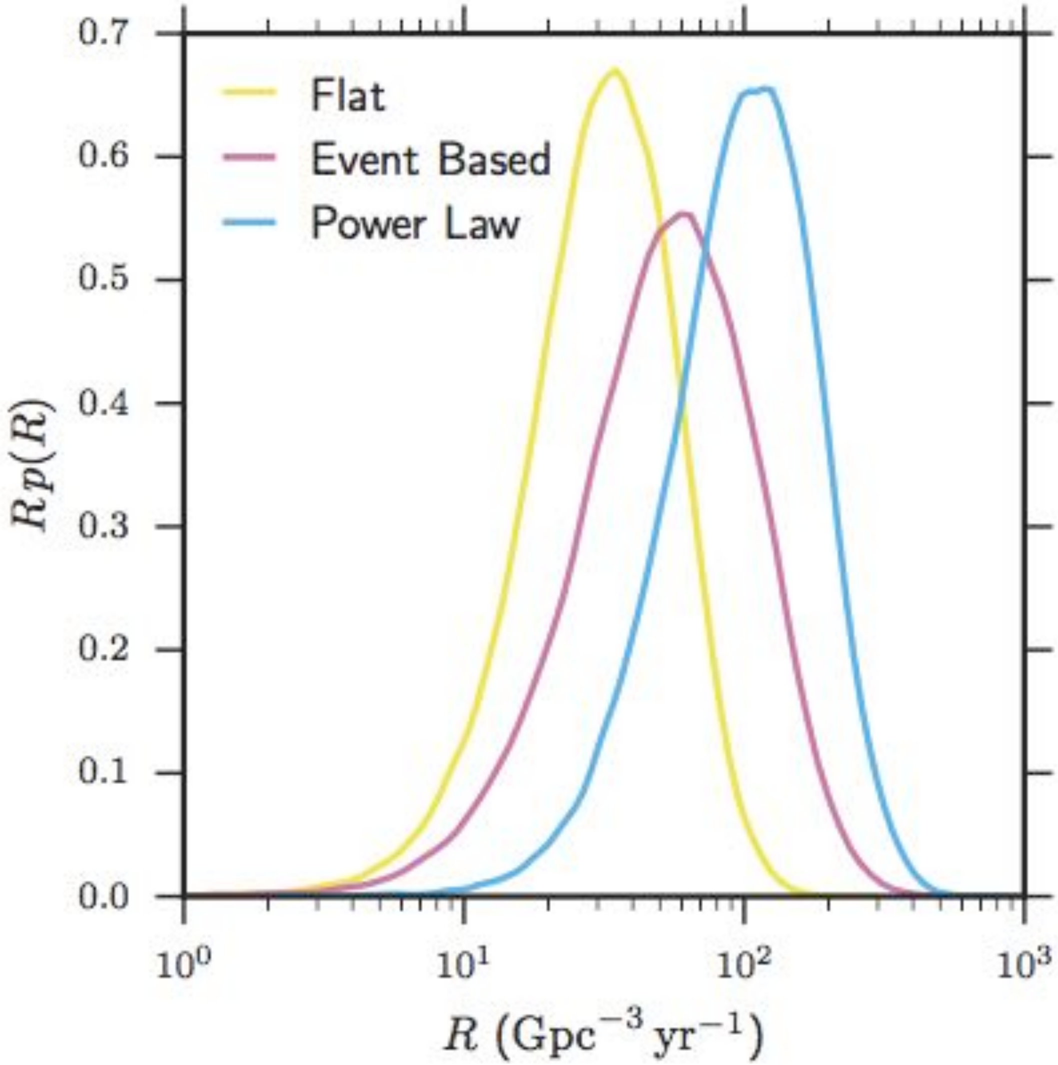


General Relativity tests in the strong interaction regime – II



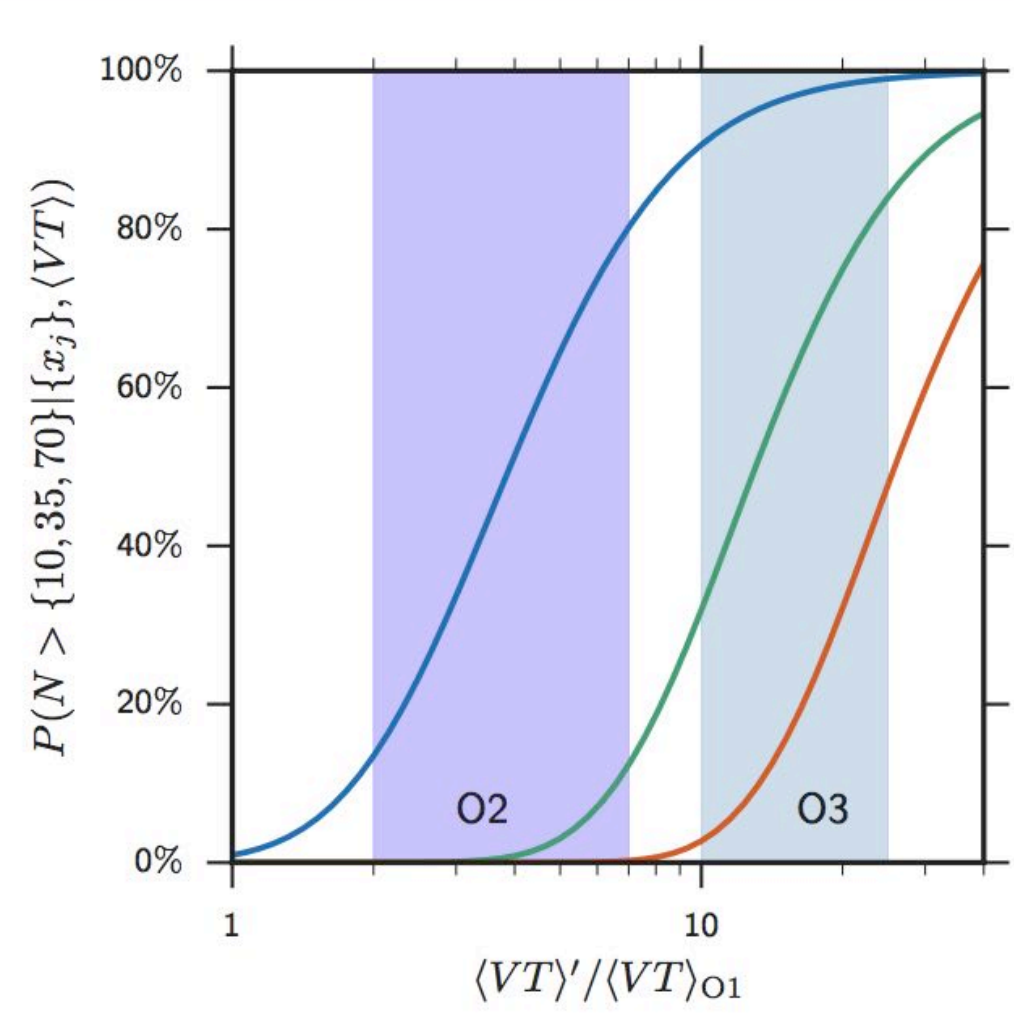
Estimated Event Rate of BBH

It depends the assumption done on the mass distribution



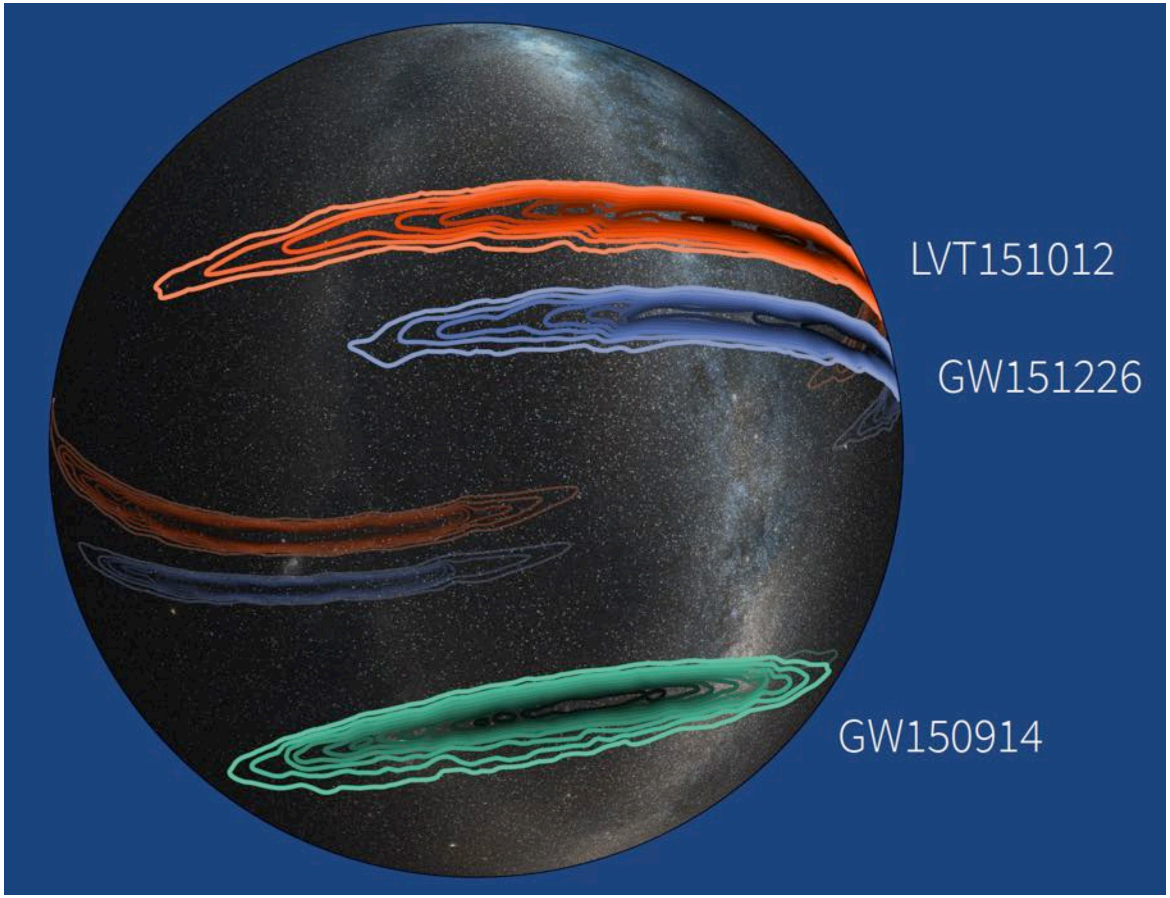
Rate Range
9 - 240 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

Probability to detect BBH events



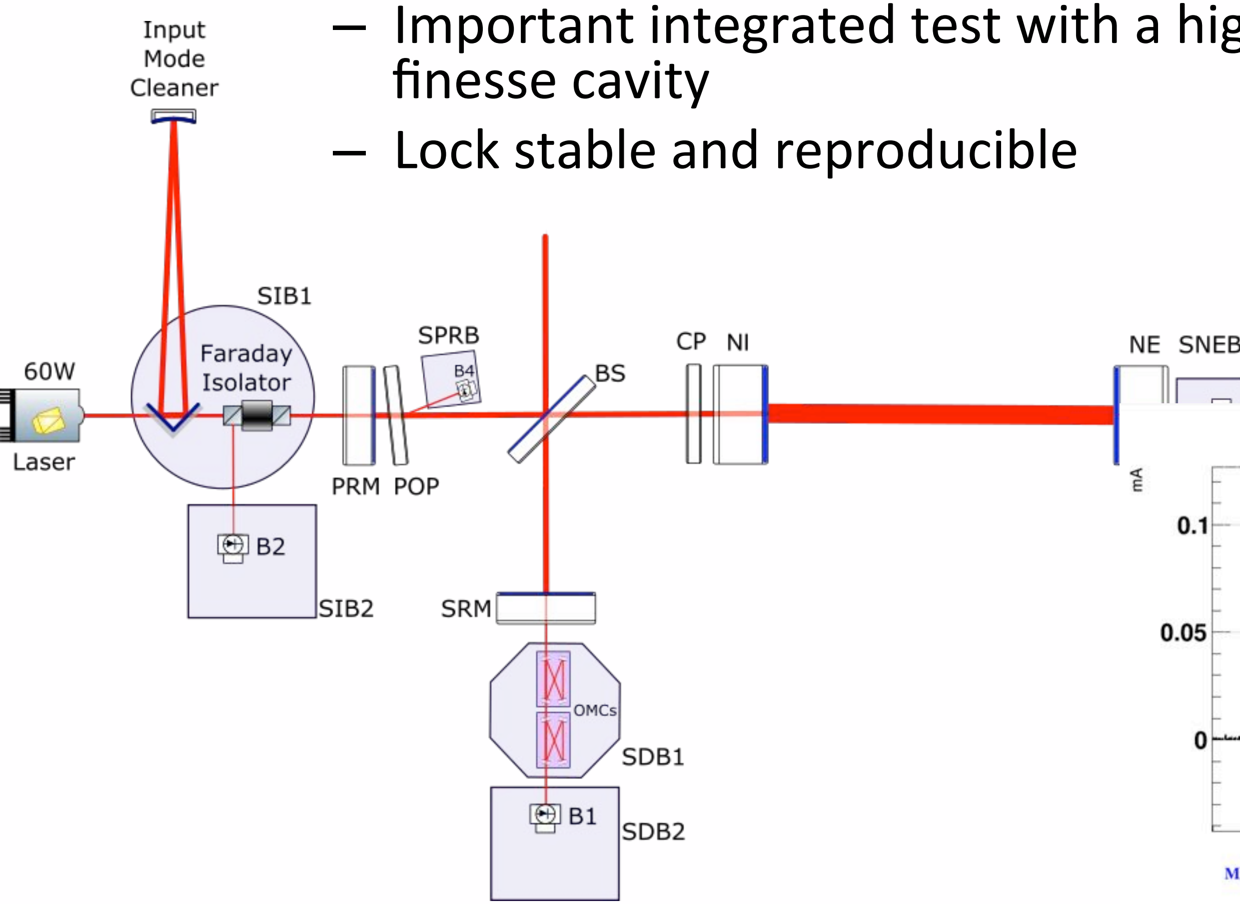
The probability of observing $N > 10$, $N > 35$, and $N > 70$ highly significant events, as a function of surveyed time-volume.

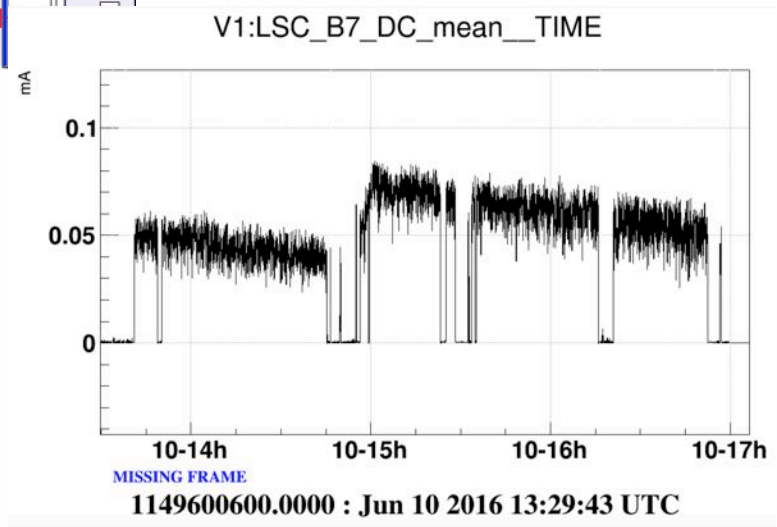
Sky Locations of Gravitational-wave Events GW150914, GW151226 and Candidate LVT151012



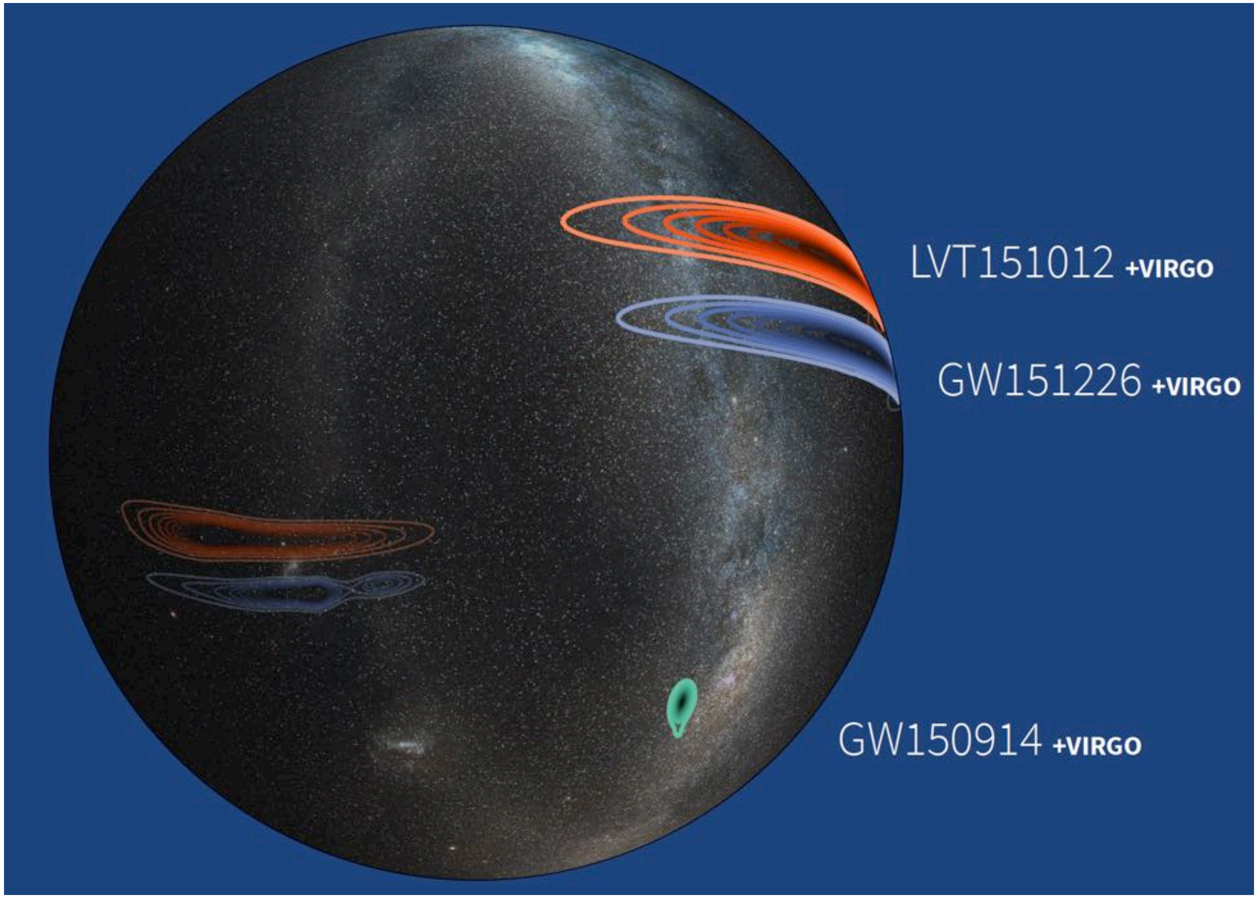
Advanced Virgo is progressing to join aLIGO in O_2

- 3km FP cavity locked
  - Important integrated test with a high finesse cavity
  - Lock stable and reproducible

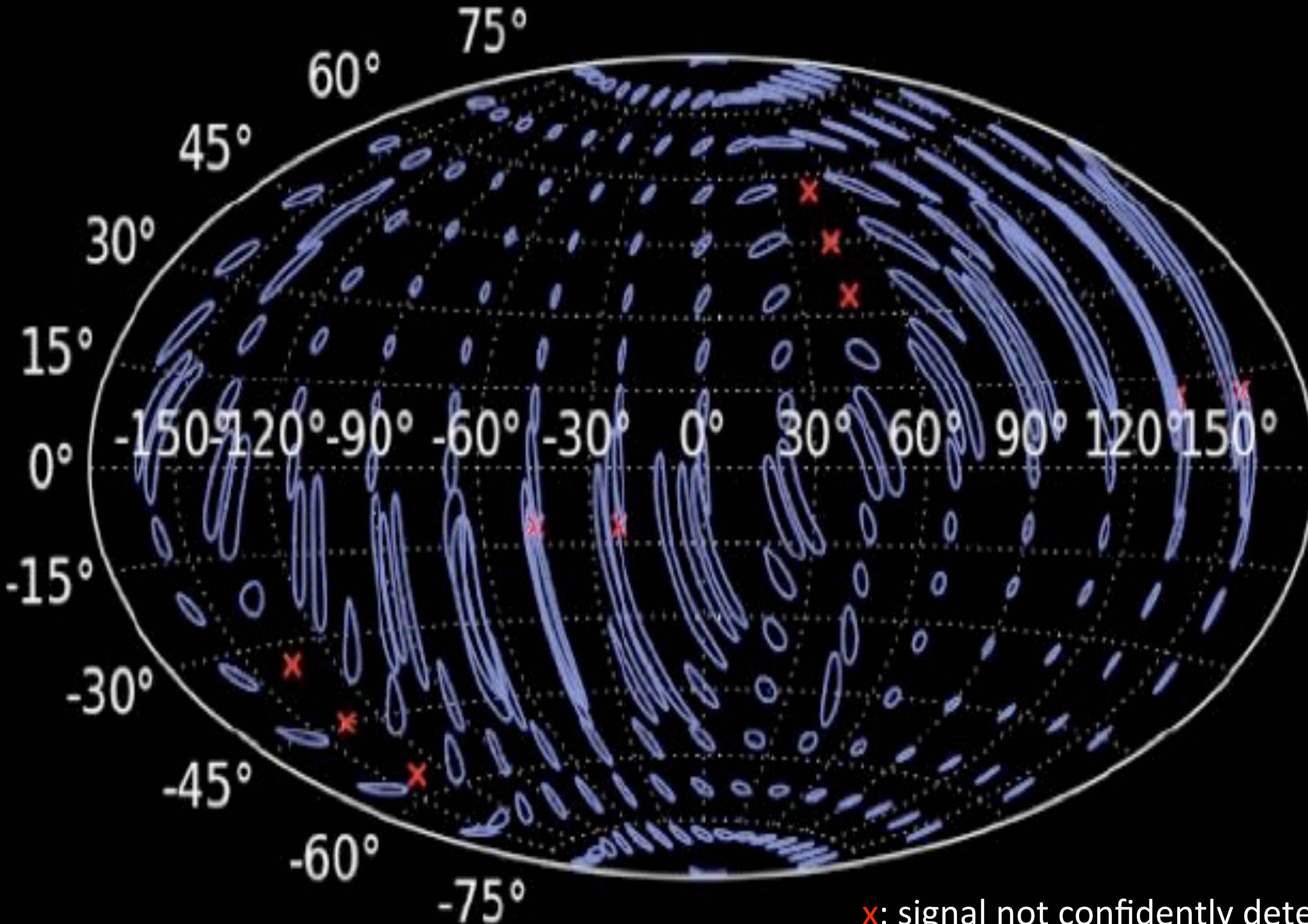




Simulated Sky Locations of O1 Events and Candidate Including the Virgo Interferometer

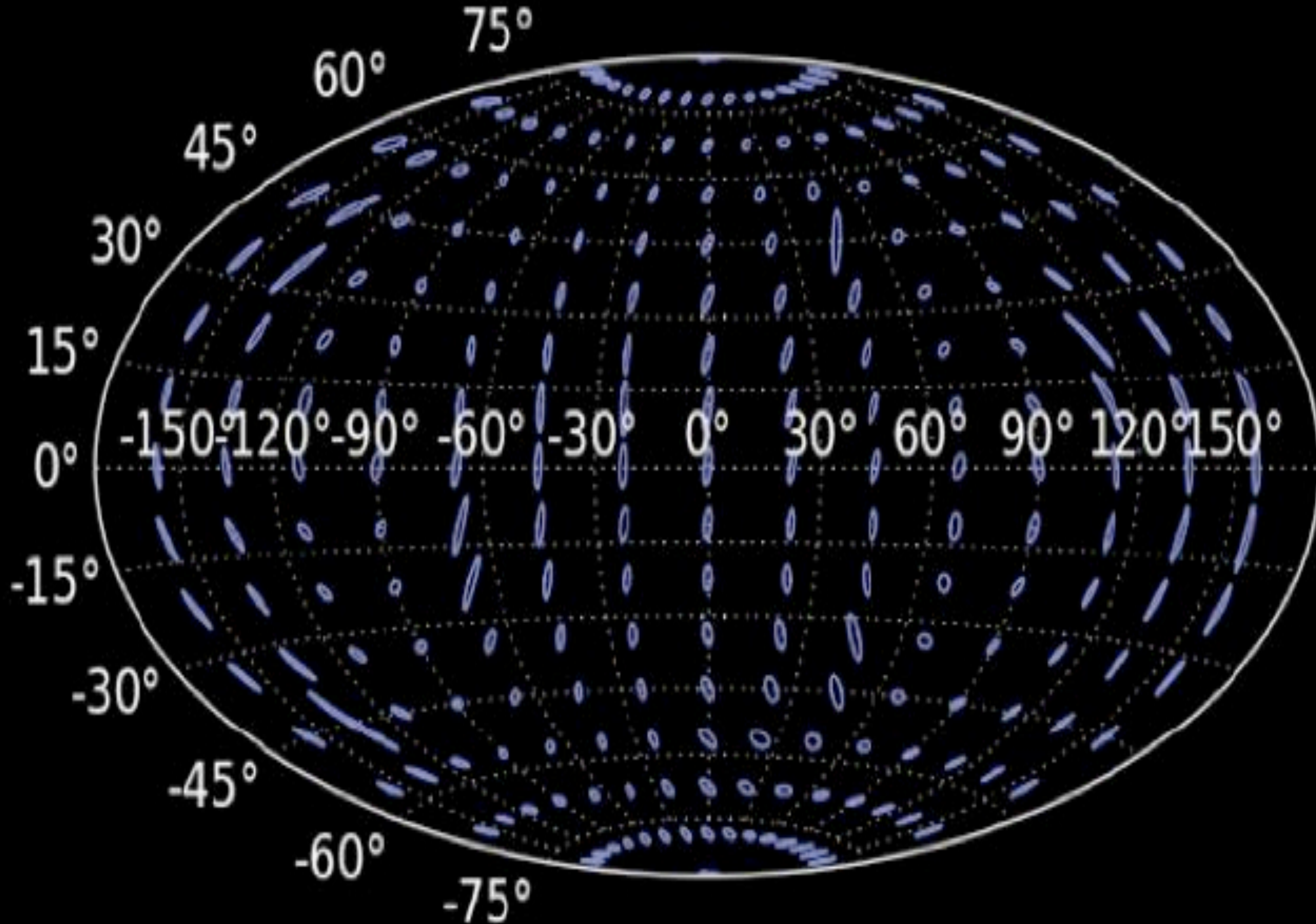


Simulation of Localization of a Gravitational Wave Event by the US LIGO and European Virgo Detectors

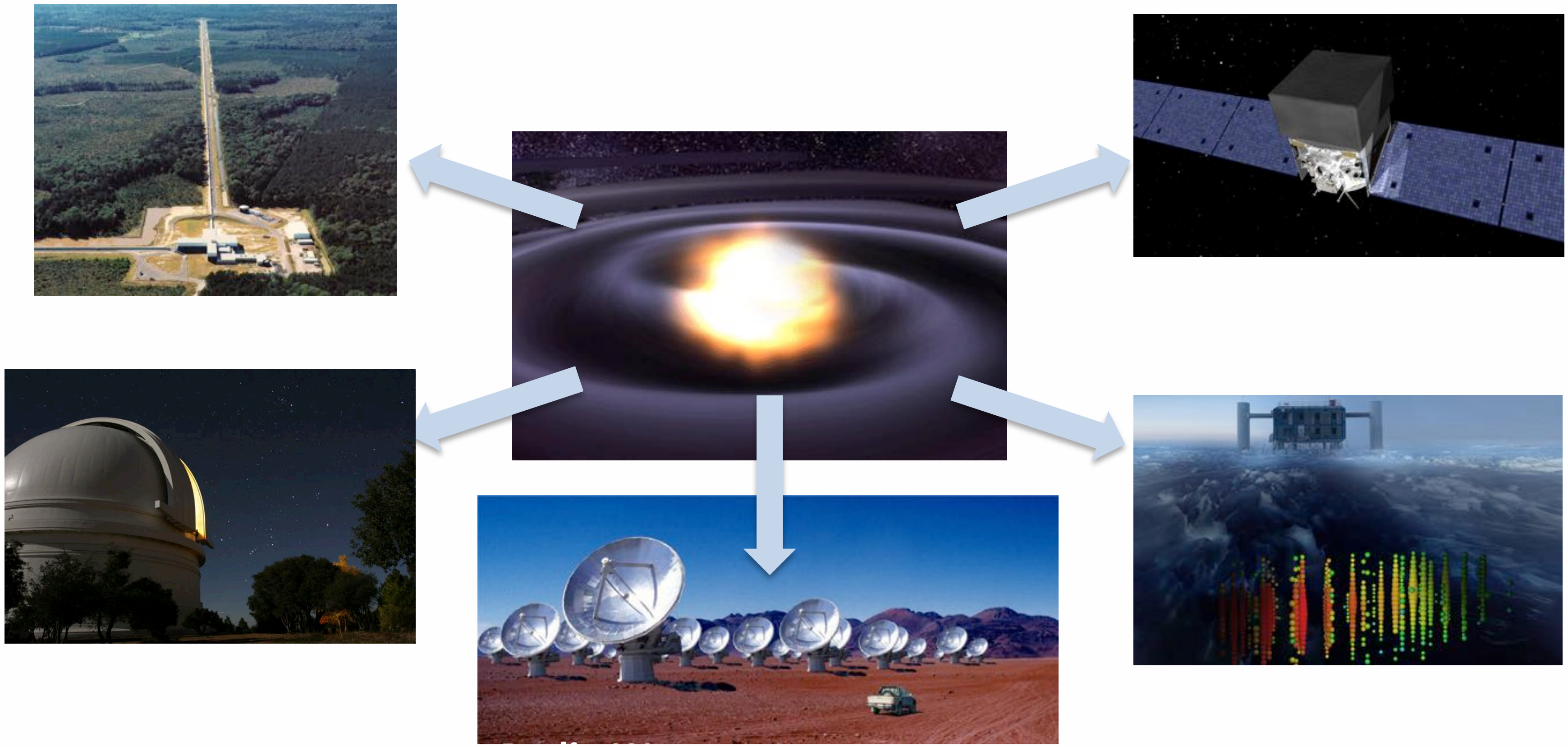


x: signal not confidently detected

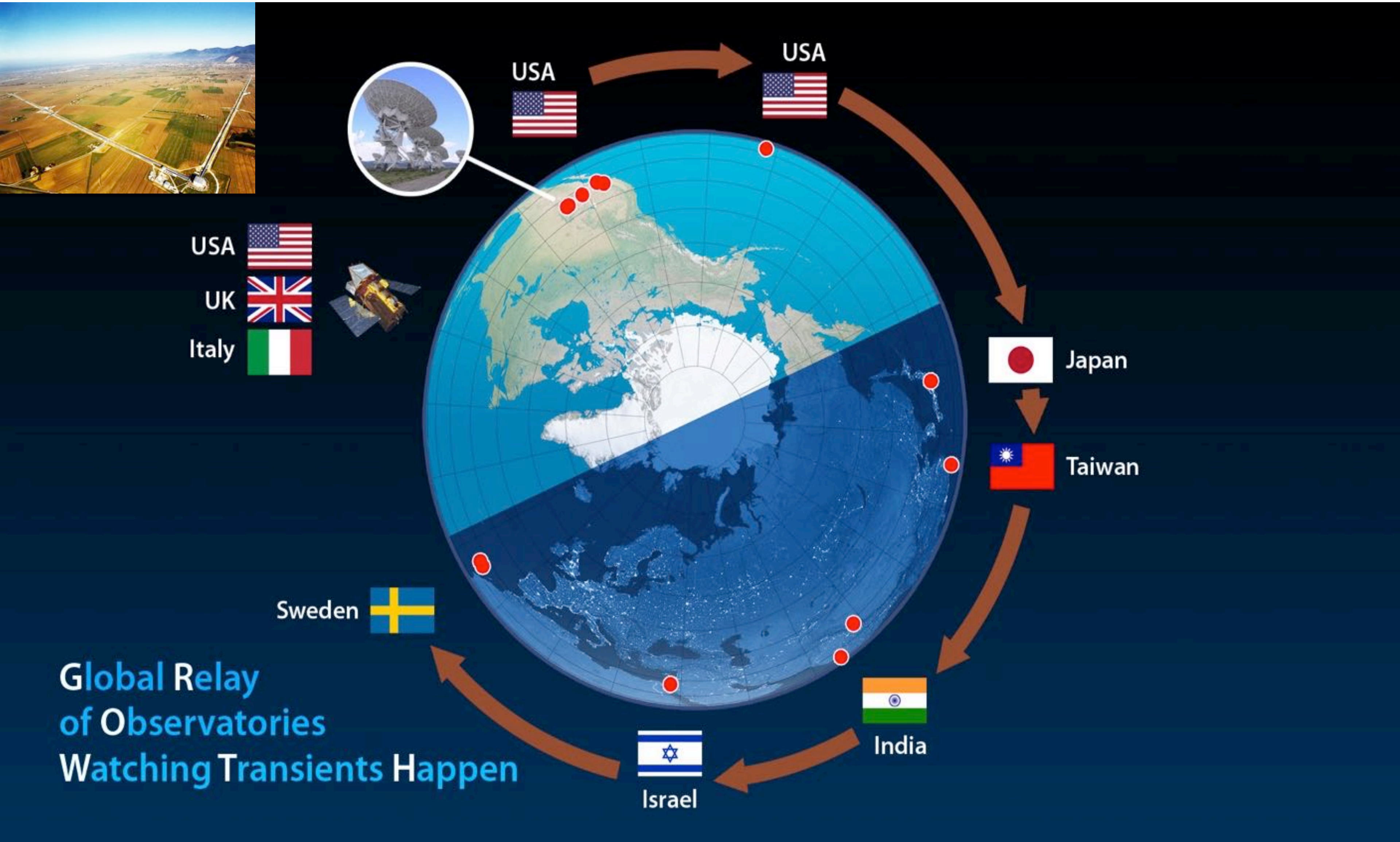
Simulation of Localization of a Gravitational Wave Event by the US LIGO, European Virgo, and LIGO-India Detectors



Multi-Messenger Astronomy:
Gravitational Wave + Electromagnetic +Neutrinos



Multi-Messenger Astronomy: Gravitational Wave + Electromagnetic +Neutrinos



Conclusion

- During its first observing run we have observed gravitational waves from the coalescence of two stellar-mass BBHs:
  - GW150914
  - GW151226

  and the third candidate
  - LVT151012 also likely to be a BBH system

- The inferred rate of BBH mergers based on our observations is 9–240 Gpc^{-3} yr^{-1}

- We are confident that in the future observing runs will observe many more BBHs.