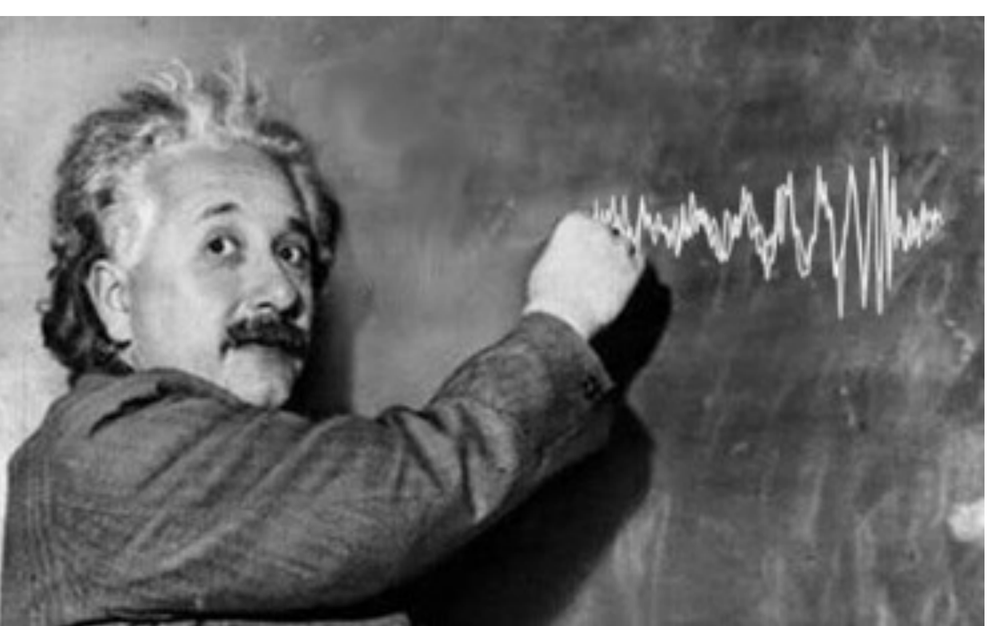
GW150914

Observation of Gravitational Waves
from a
Binary Black Hole Merger

Paul Lasky

for the LIGO Scientific Collaboration



Rumours are ALWAYS wrong

Hi all, the LIGO rumour seems real, and will apparently come out in Nature Feb 11 (no doubt with press release), so keep your eyes out for it.

Spies who have seen the paper say they have seen gravitational waves from a binary black hole merger. they claim that the two detectors detected it consistent with it moving at speed c given the distance between them, and quote an equivalent 5.1 sigma detection. the bh masses were 36 and 29 solar masses initially and 62 at the end. Apparently the signal is spectacular and they even see the ring-down to kerr at the end.

Woohoo! (I hope)

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Physical Review Letters

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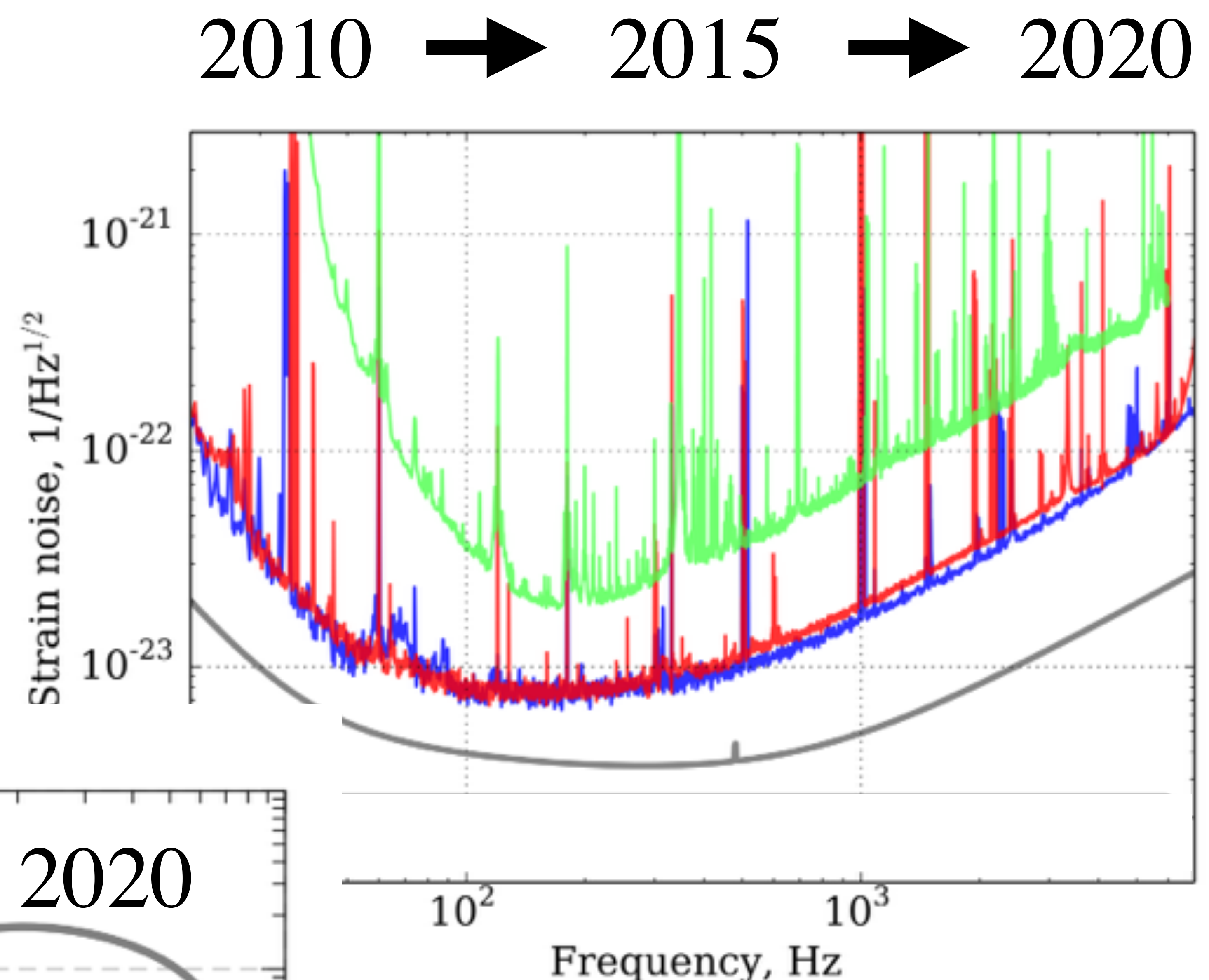
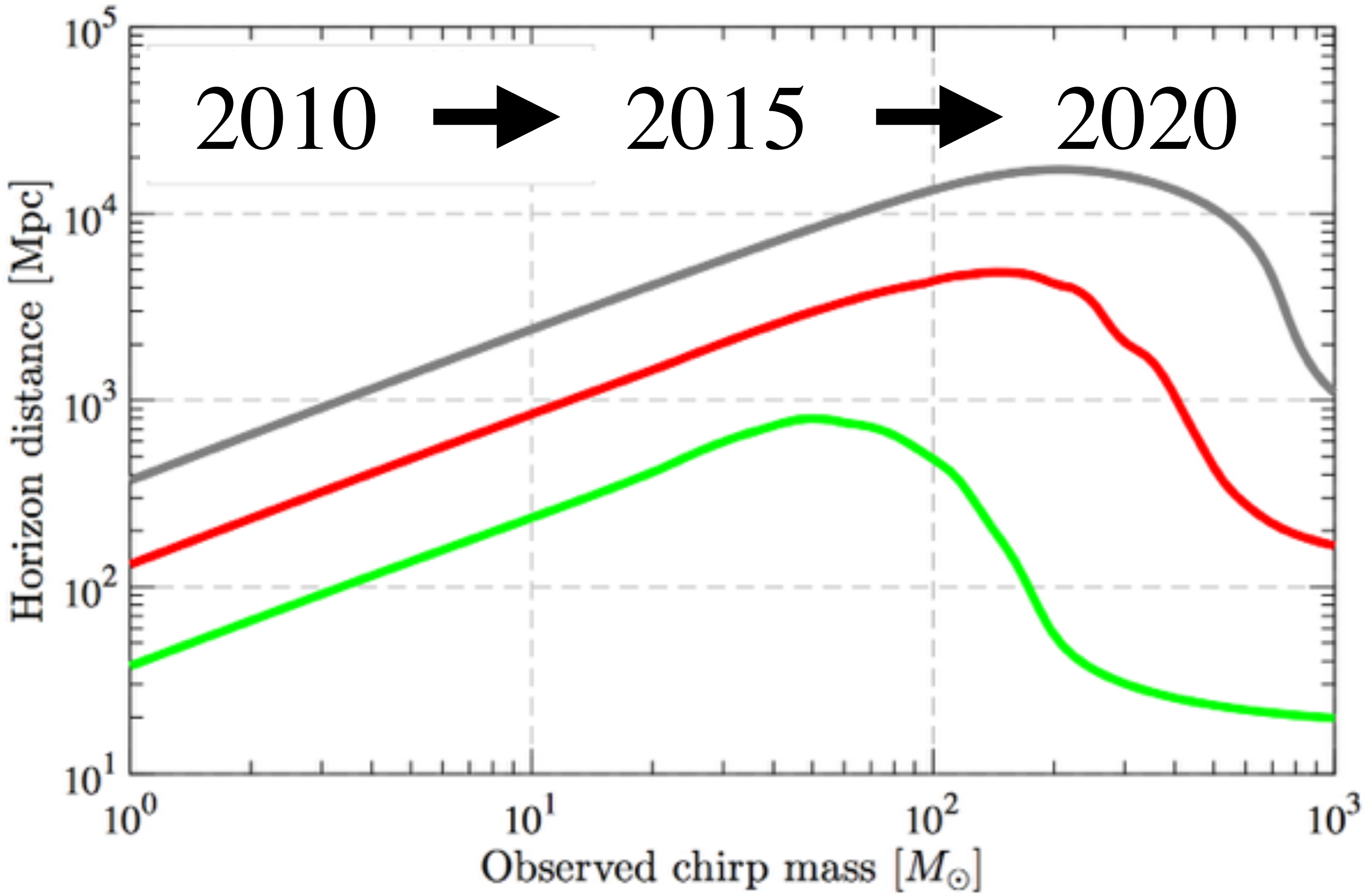
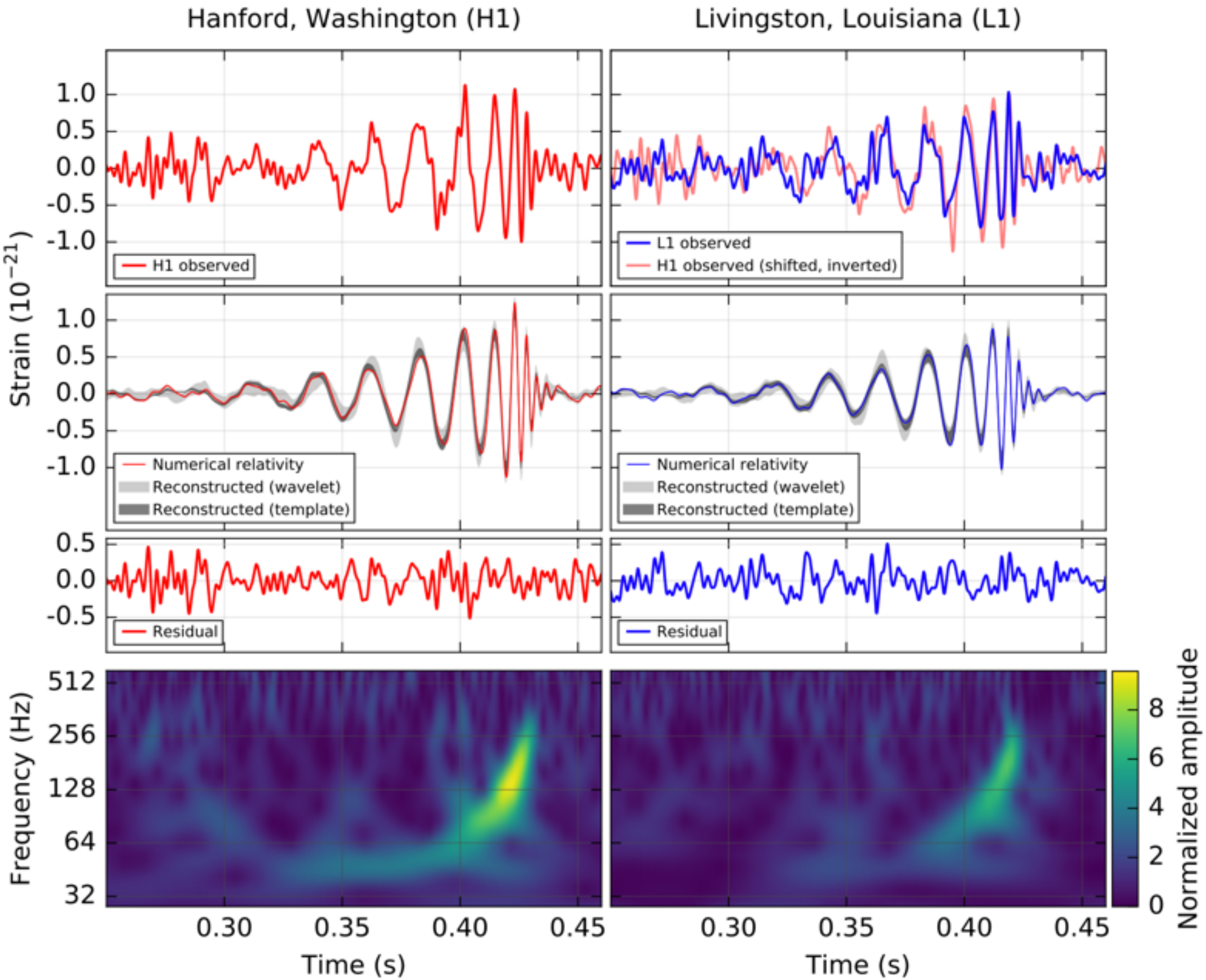
much greater than

Woohoo! (I hope)

credit: Chris North

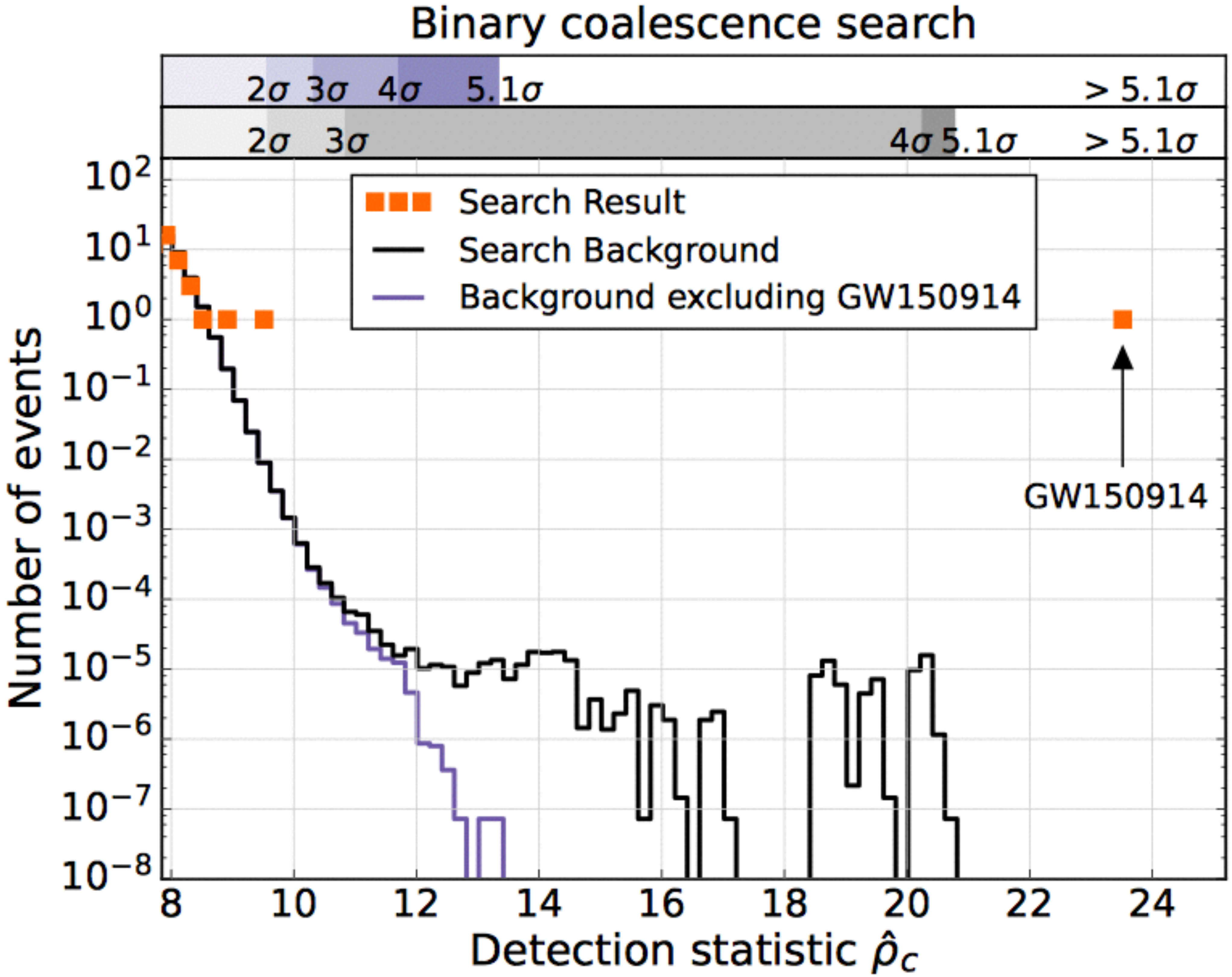

2010 → 2015 → 2020
10^{-21}
10^{-22}
10^{-23}
Strain noise, 1/Hz$^{1/2}$
10^2
10^3
Frequency, Hz


2010 → 2015 → 2020
10^5
10^4
10^3
10^2
10^1
Horizon distance [Mpc]
10^0
10^1
10^2
10^3
Observed chirp mass [$M_\odot$]

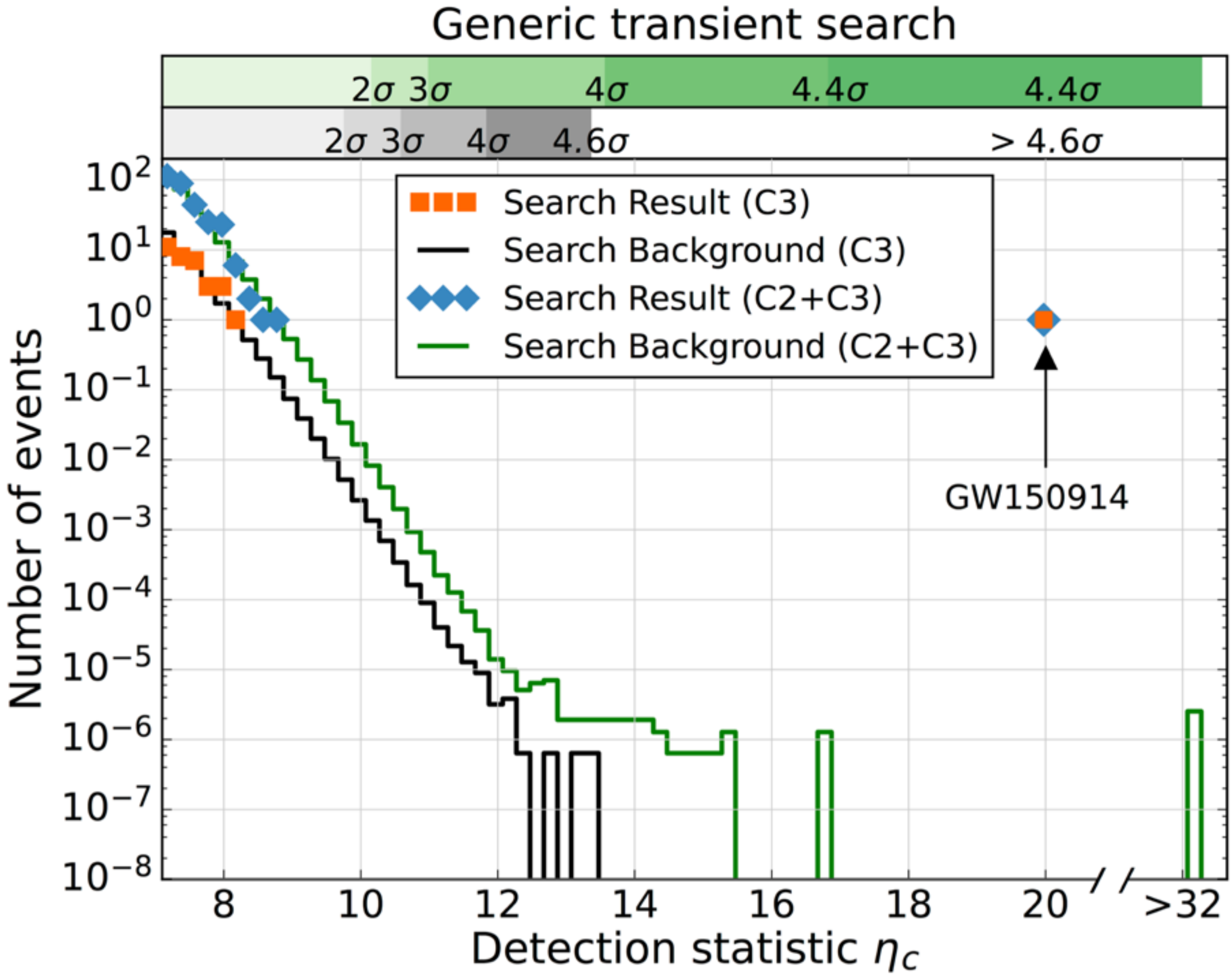


Peak displacement of interferometer arms:

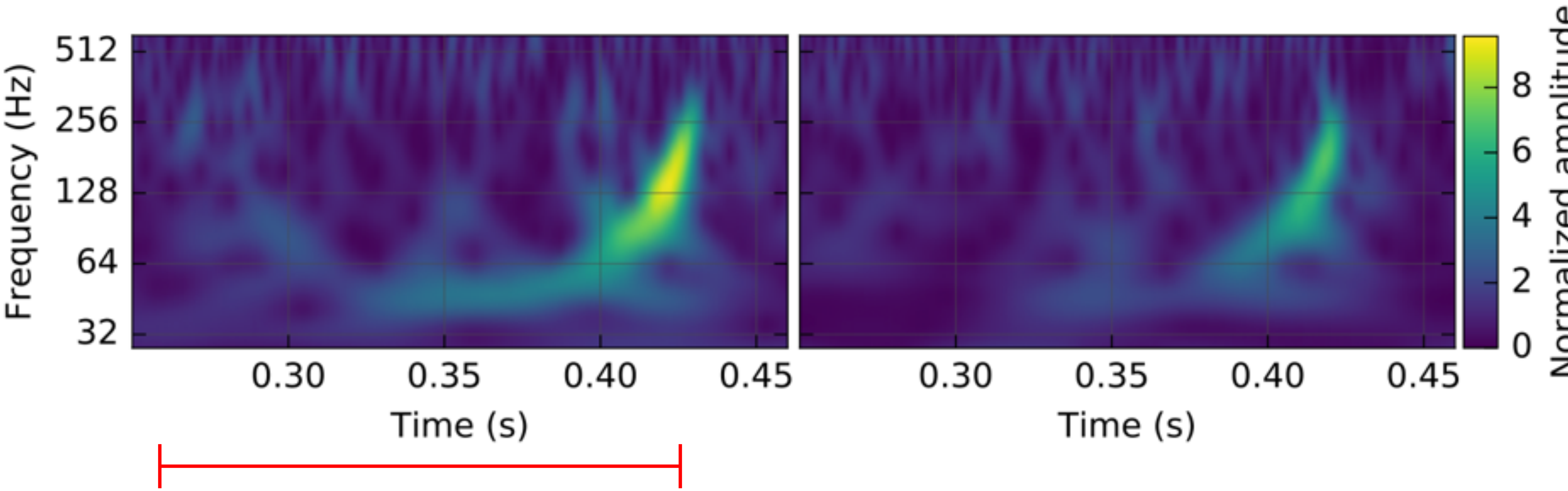
$$0.002\,\text{fm} = 2 \times 10^{-18}\,\text{m}$$



False Alarm Rate << 1 in 203,000 years


Generic transient search
2σ 3σ 4σ 4.4σ 4.4σ
2σ 3σ 4σ 4.6σ > 4.6σ
Search Result (C3)
Search Background (C3)
Search Result (C2+C3)
Search Background (C2+C3)
GW150914
Number of events
Detection statistic η_c
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 >32

Black Holes?



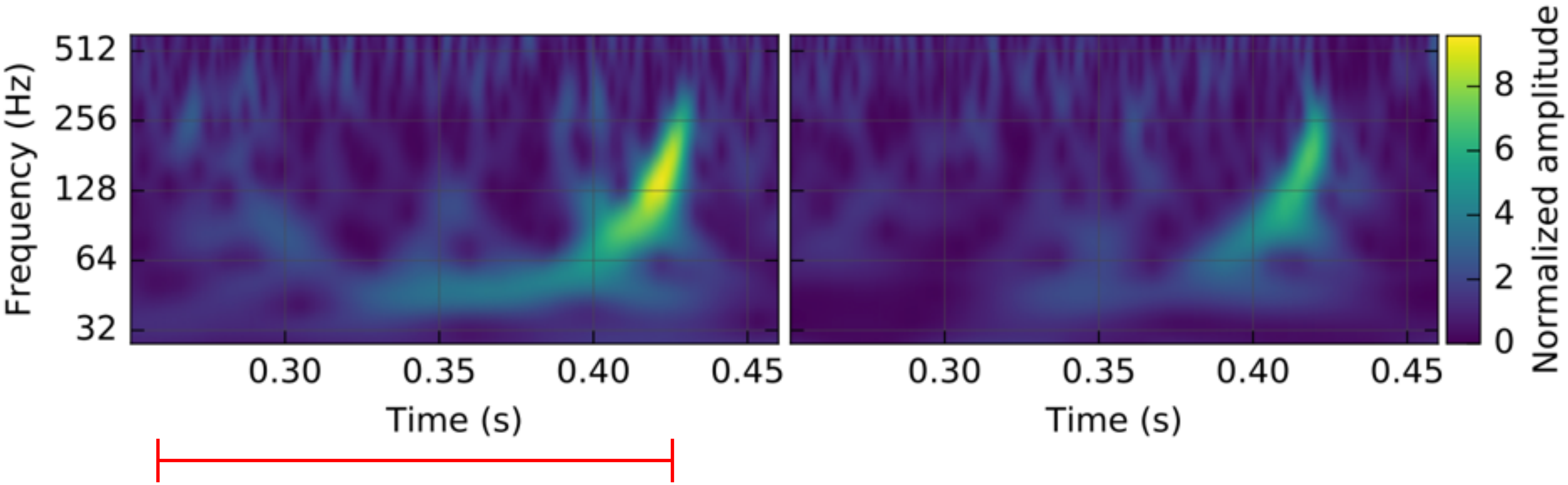
frequency evolution gives

$$\mathcal{M} \equiv \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left(\frac{5}{96}\pi^{-8/3} f^{-11/3} \frac{df}{dt}\right)^{3/5} \approx 30\, M_\odot$$

$$\rightarrow \quad m_1 + m_2 \gtrsim 70\, M_\odot$$

(detector frame)

Black Holes?



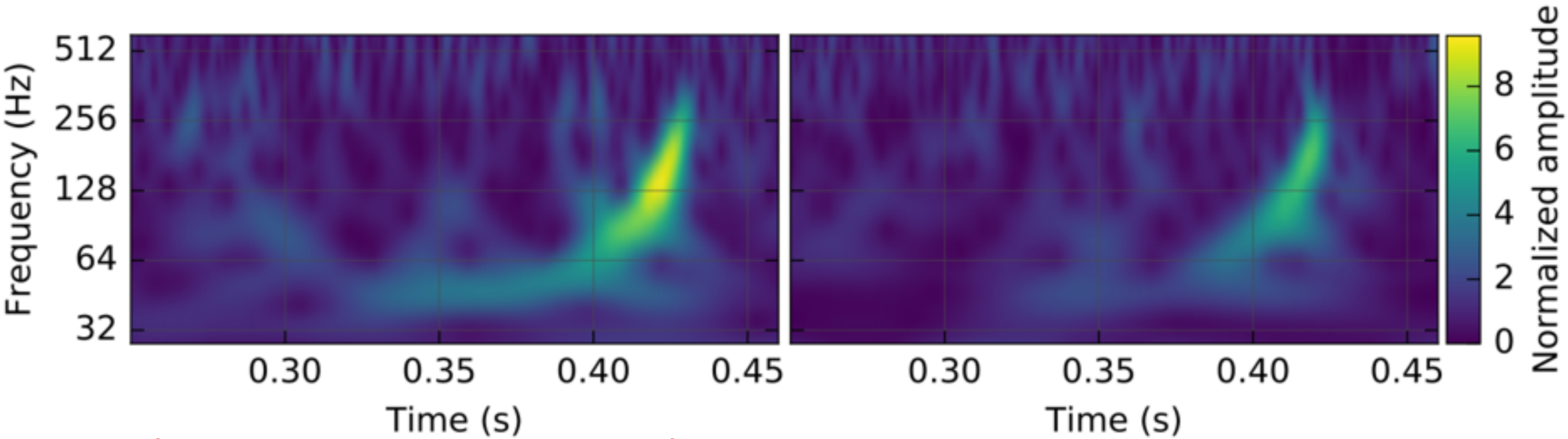
$$\mathcal{M} \approx 30 M_\odot$$

$$m_1 + m_2 \gtrsim 70\, M_\odot$$

$\mathrm{f_{GW}} \approx 150\,\mathrm{Hz}$ ➡ $\mathrm{f_{orbital}} \approx 75\,\mathrm{Hz}$

➡ $\mathrm{separation} \approx 350\,\mathrm{km}$

Black Holes?



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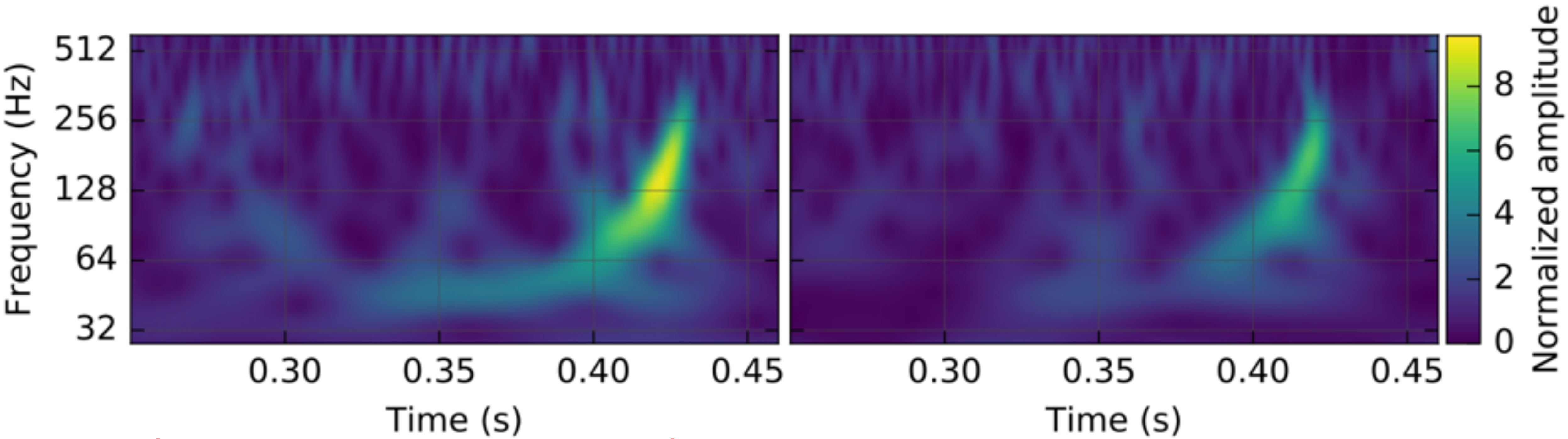
NS/NS?

$$m_1 + m_2 \ll 10\, M_\odot$$

Black Holes?



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NS/NS?

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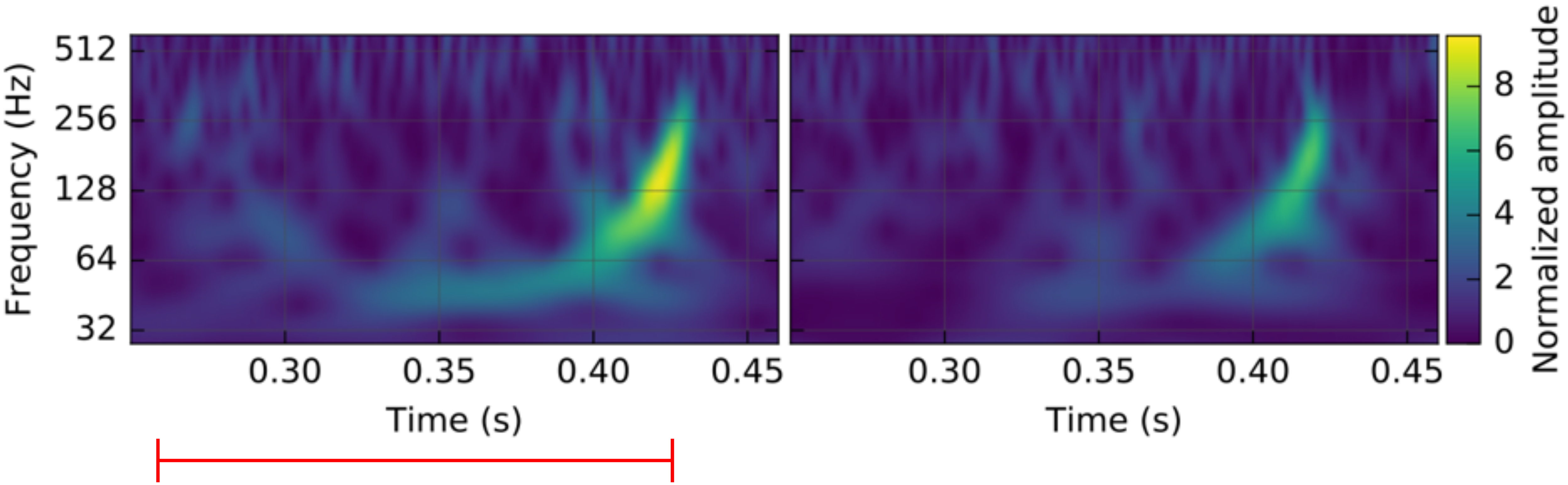
NS/BH? $m_2 \approx 2\, M_\odot$ & $\mathcal{M} \approx 30 M_\odot$

→ $m_1 \approx 1,700\, M_\odot$

→ $\mathrm{r}_1 \approx 5,000\,\text{km}$

Black Holes?



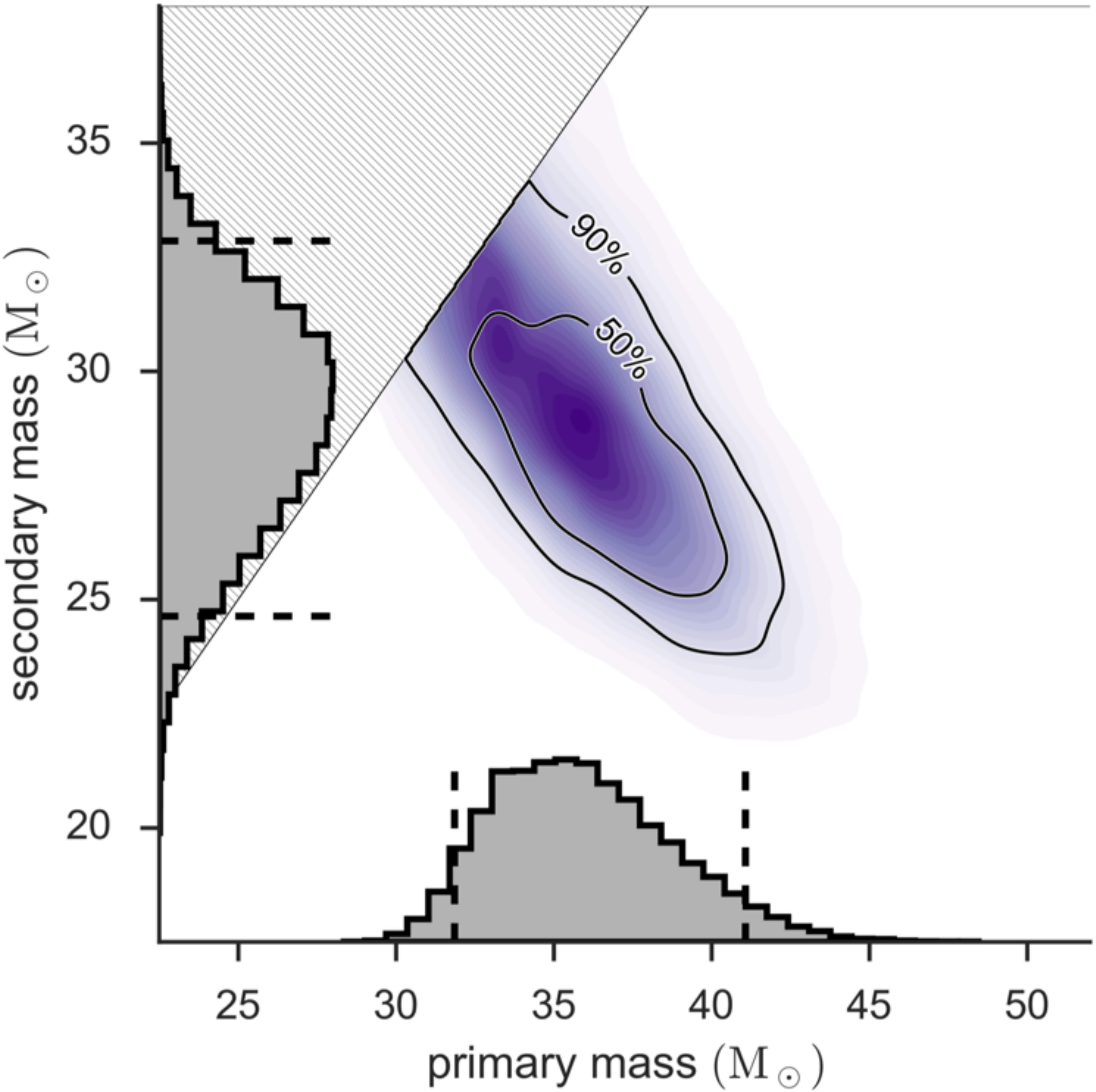
$$\mathcal{M} \approx 30 M_\odot$$

$$m_1 + m_2 \gtrsim 70\, M_\odot$$

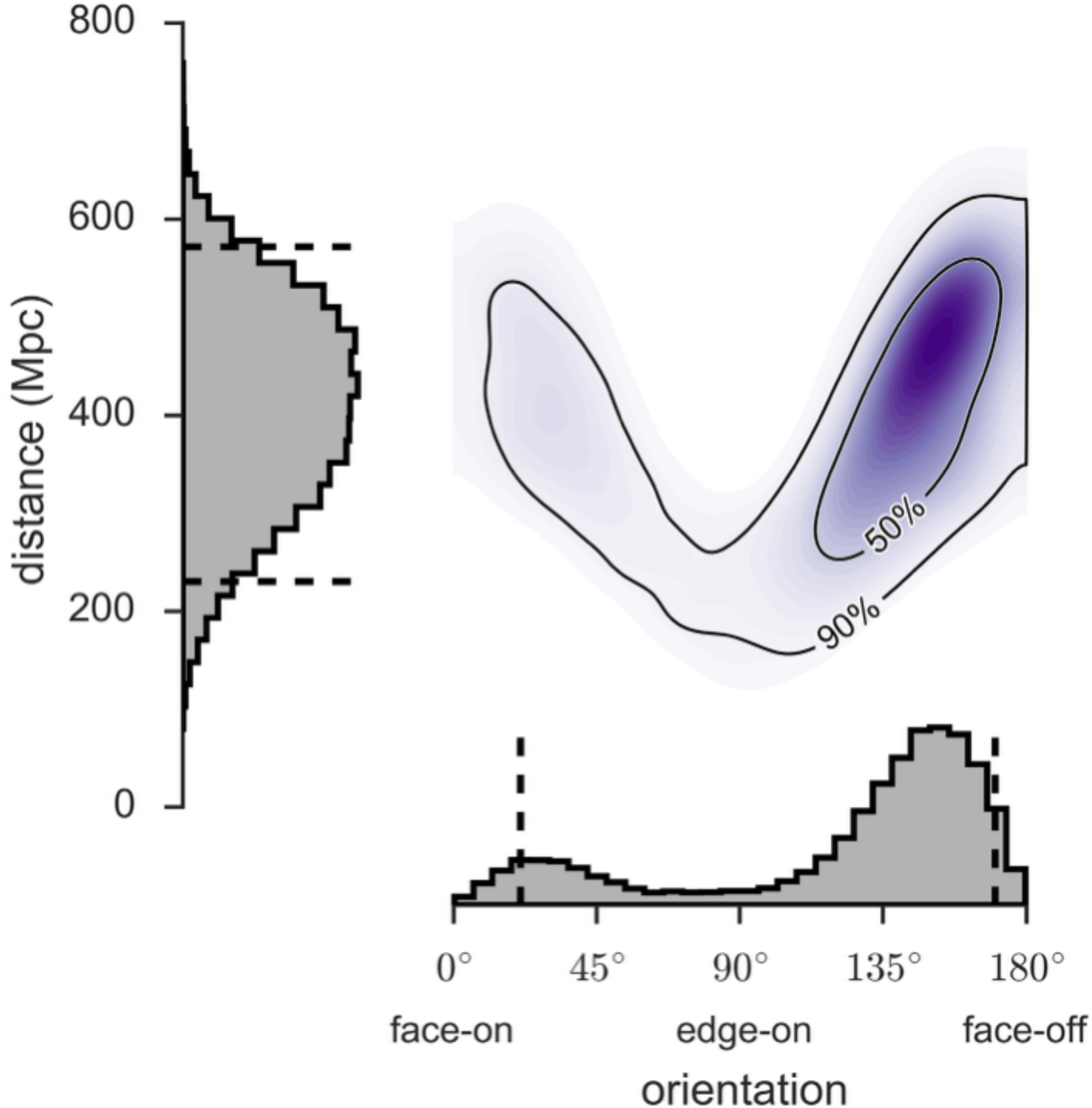
$$\text{separation} \approx 350\,\text{km}$$

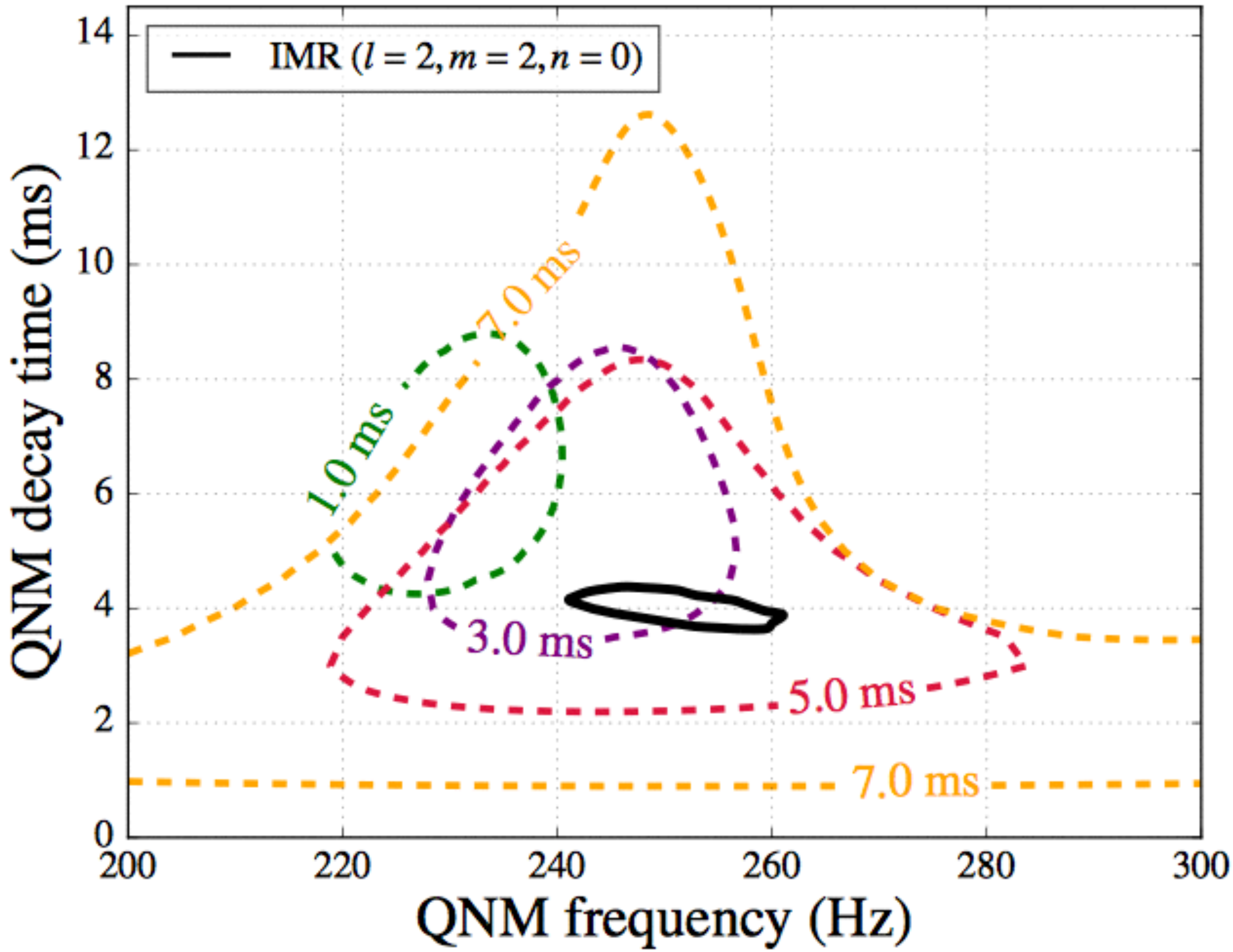
BH/BH:

only known objects compact enough to reach an orbital frequency of 75 Hz without merging



90%
50%
35
30
25
20
secondary mass $(M_\odot)$
25
30
35
40
45
50
primary mass $(M_\odot)$


800
600
400
200
0
distance (Mpc)
50%
90%
0°
45°
90°
135°
180°
face-on
edge-on
face-off
orientation



Posteriors assume different start times after merger

GW150914:FACTSHEET

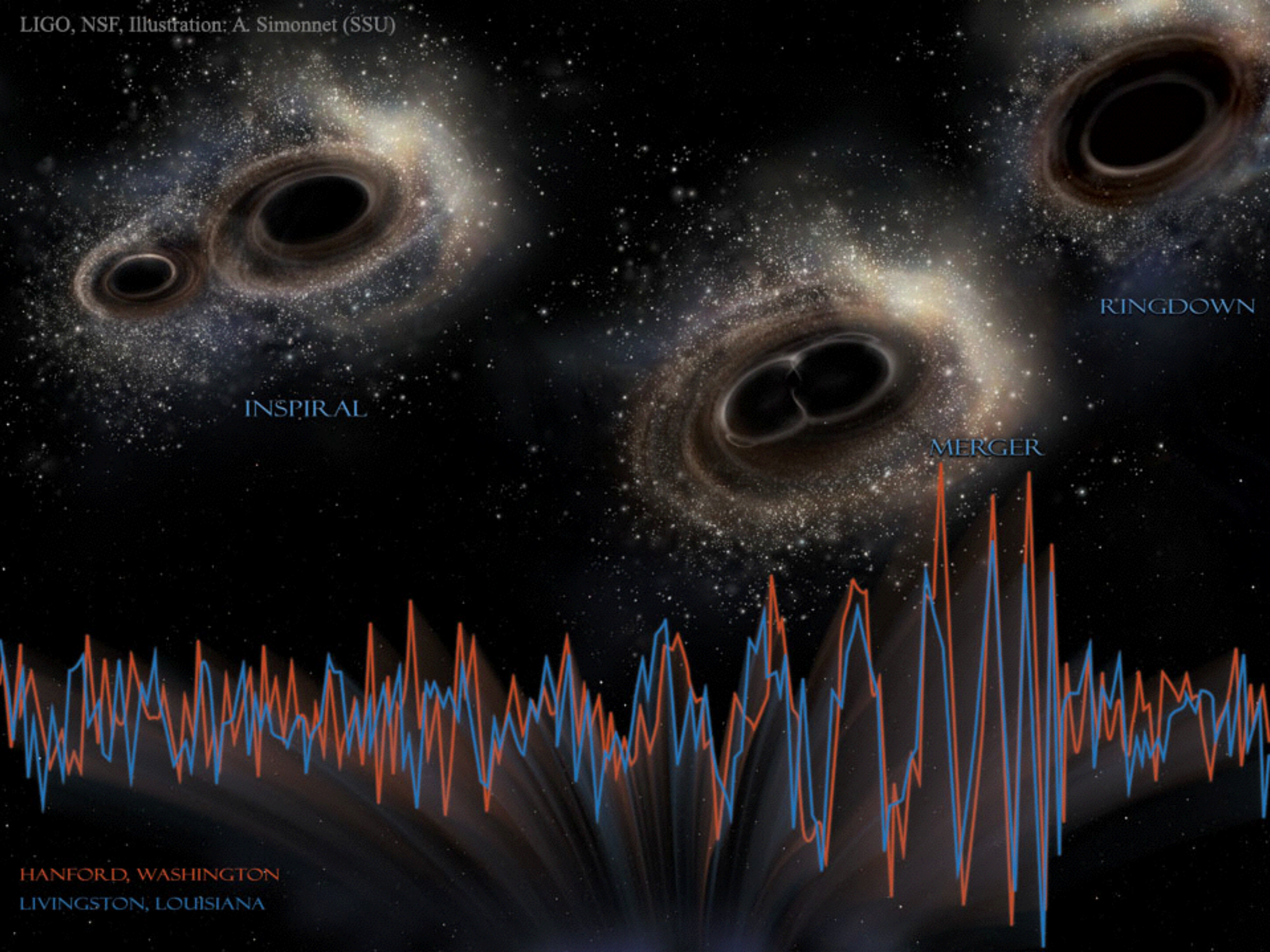
BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 190 to 590 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	**M⊙**
total mass	60-70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58-67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

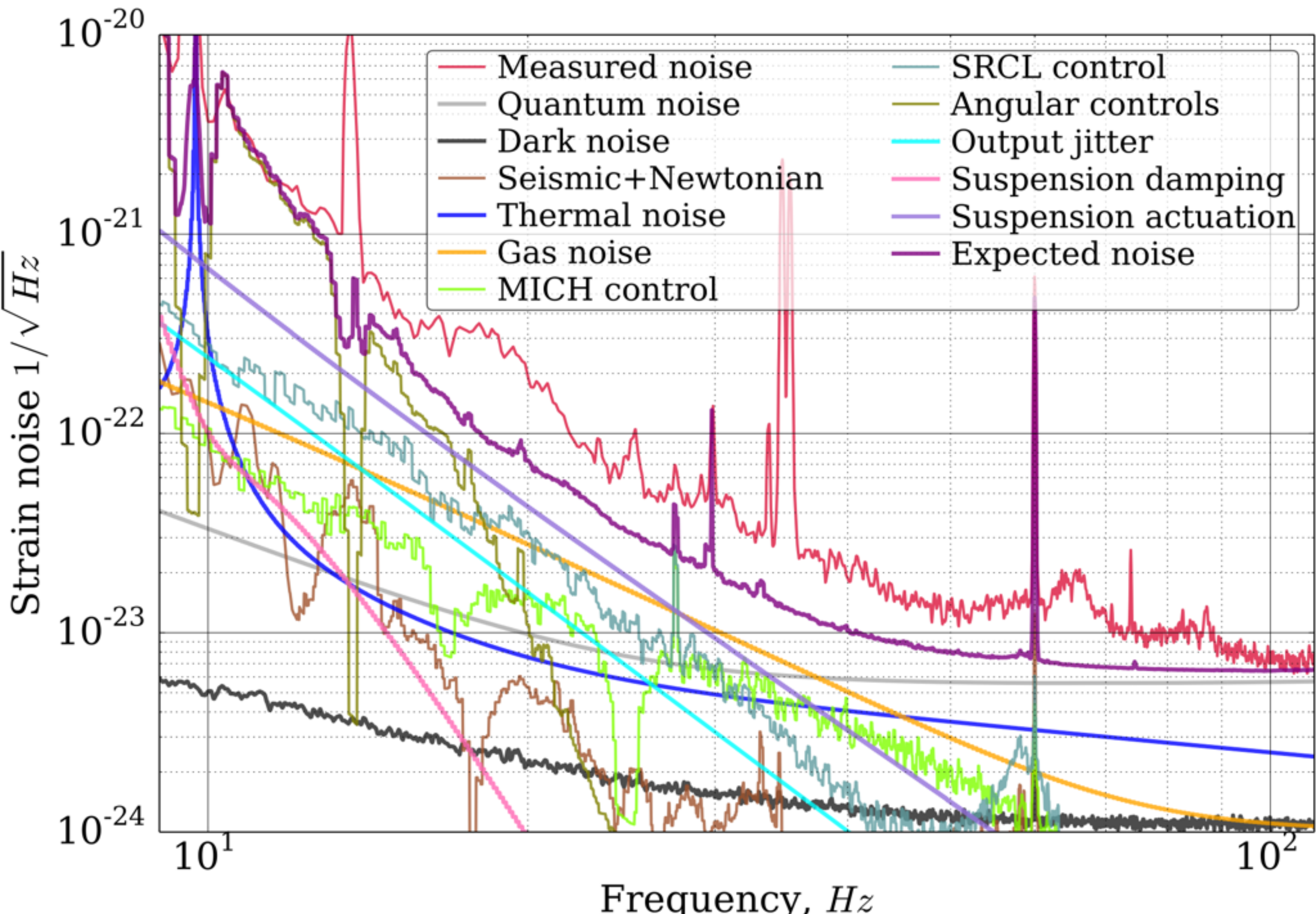
Detector noise introduces errors in measurement. Parameter ranges correspond to 90% credible bounds.
Acronyms: L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear=9.46 x 10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^3 Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2 x 10^{30} kg

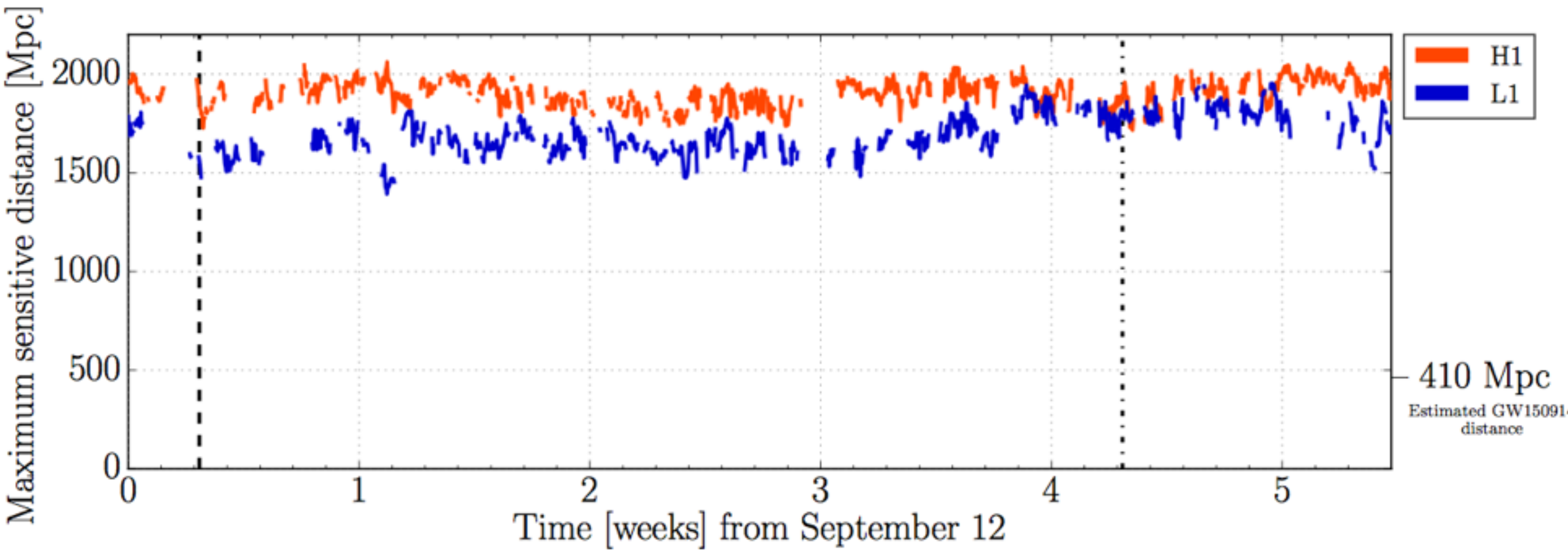

LIGO, NSF, Illustration: A. Simonnet (SSU)
INSPIRAL
MERGER
RINGDOWN
HANFORD, WASHINGTON
LIVINGSTON, LOUISIANA

Extra Slides

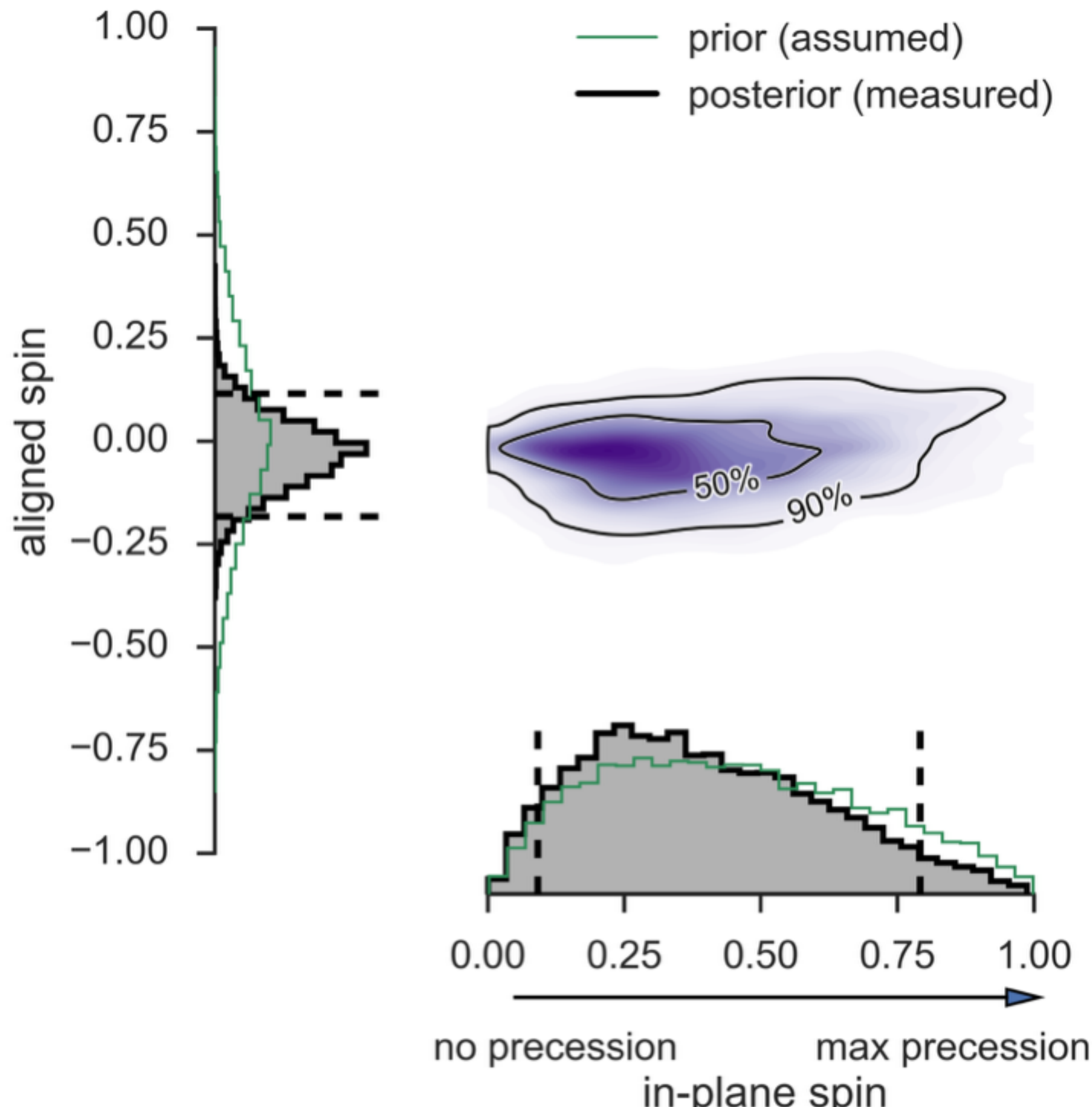
paper and companion papers

https://dcc.ligo.org/LIGO-P150914/public

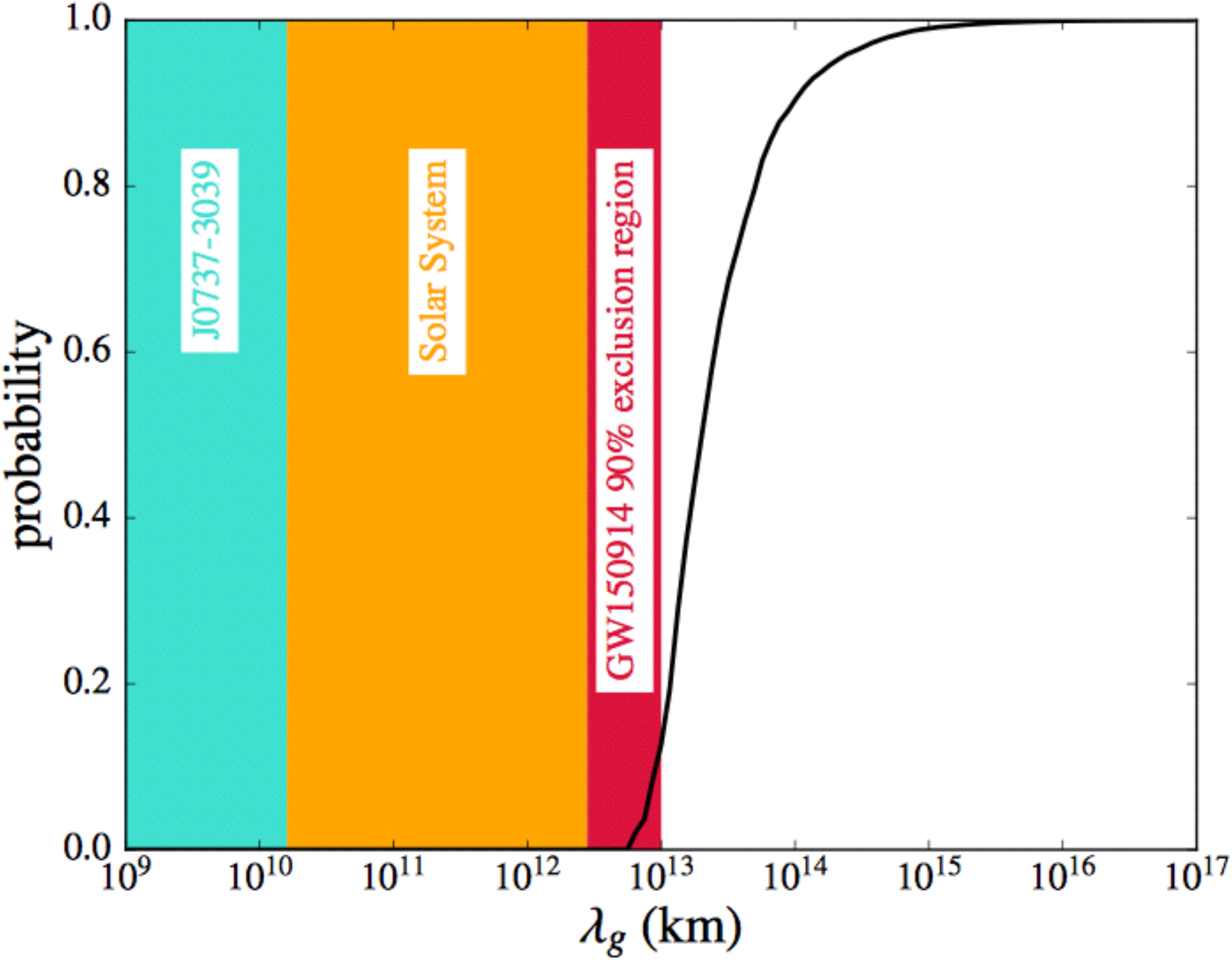

Measured noise
Quantum noise
Dark noise
Seismic+Newtonian
Thermal noise
Gas noise
MICH control
SRCL control
Angular controls
Output jitter
Suspension damping
Suspension actuation
Expected noise
Strain noise $1/\sqrt{Hz}$
Frequency, Hz
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}

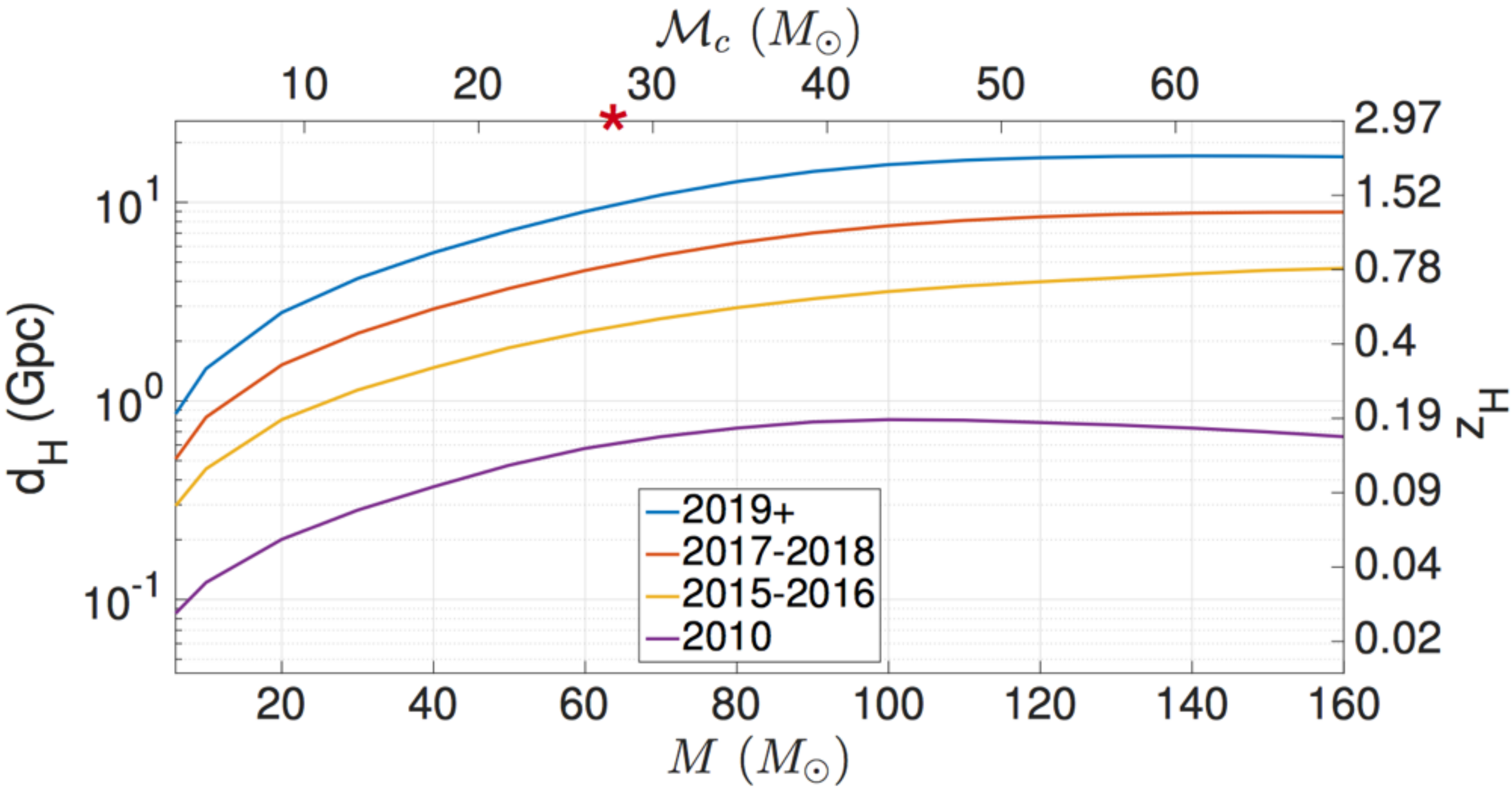


Maximum sensitive distance [Mpc]
2000
1500
1000
500
0
0
1
2
3
4
5
Time [weeks] from September 12
H1
L1
410 Mpc
Estimated GW150914 distance



prior (assumed)
posterior (measured)
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
aligned spin
50%
90%
0.00
0.25
0.50
0.75
1.00
no precession
max precession
in-plane spin


J0737-3039
Solar System
GW150914 90% exclusion region
probability
1.0
0.8
0.6
0.4
0.2
0.0
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
λ_g (km)



$\mathcal{M}_c$ $(M_\odot)$
10
20
30
40
50
60
2.97
1.52
0.78
0.4
0.19
0.09
0.04
0.02
z_H
10^1
10^0
10^{-1}
d_H (Gpc)
2019+
2017-2018
2015-2016
2010
20
40
60
80
100
120
140
160
M $(M_\odot)$


ASIA
AFRICA
Atlantic
Ocean
Pacific
Ocean
Indian
Ocean