Gravitational Wave Astronomy with LIGO and Virgo

Chad Hanna - Penn State

Black Holes and Neutron Stars with Gravitational Waves - October 7, 2019

Charles E. Kaufman Foundation
A SUPPORTING ORGANIZATION OF THE PITTSBURGH FOUNDATION
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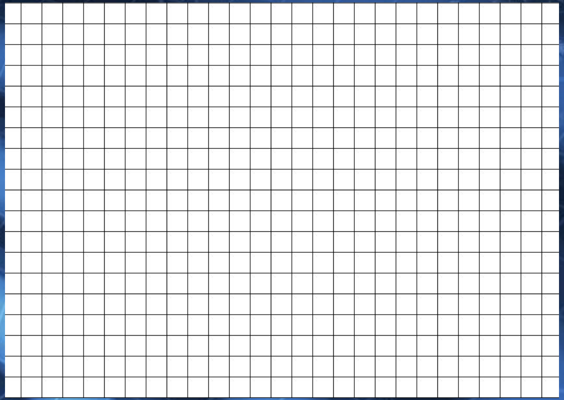
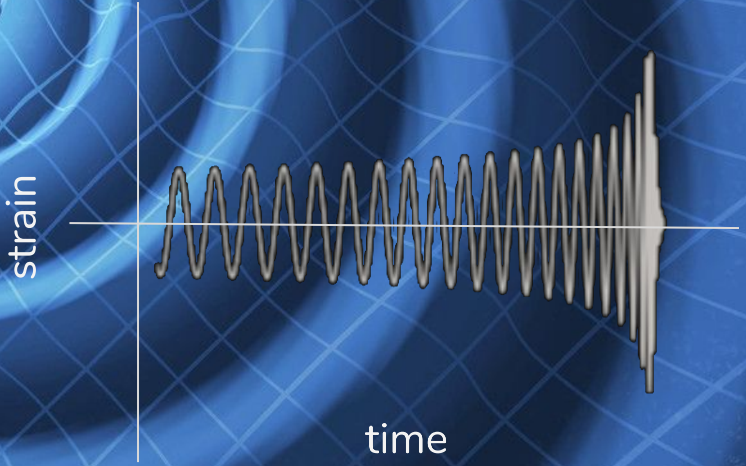
NSF
LSC LIGO Scientific Collaboration

Distant observers see changes in length: strain = ΔL/L

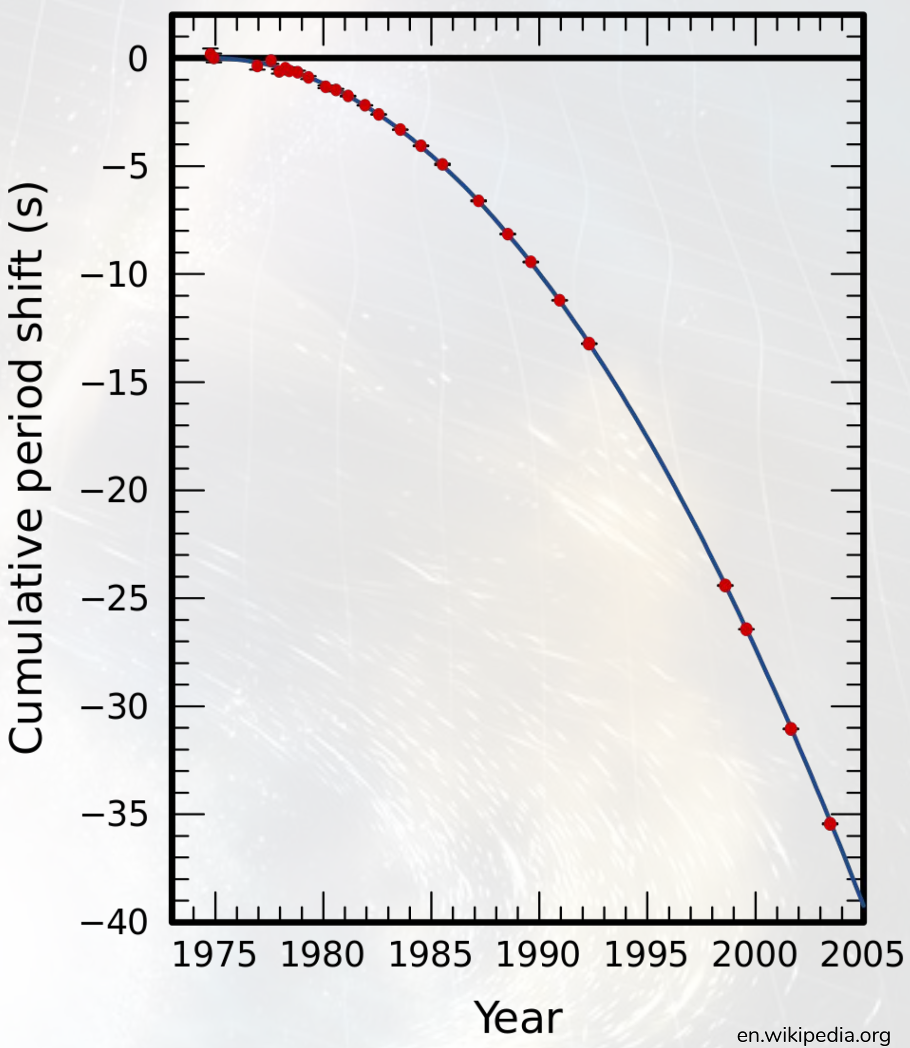


Energy loss drives the binary to merge. Peak strain on Earth: 10^{-21}

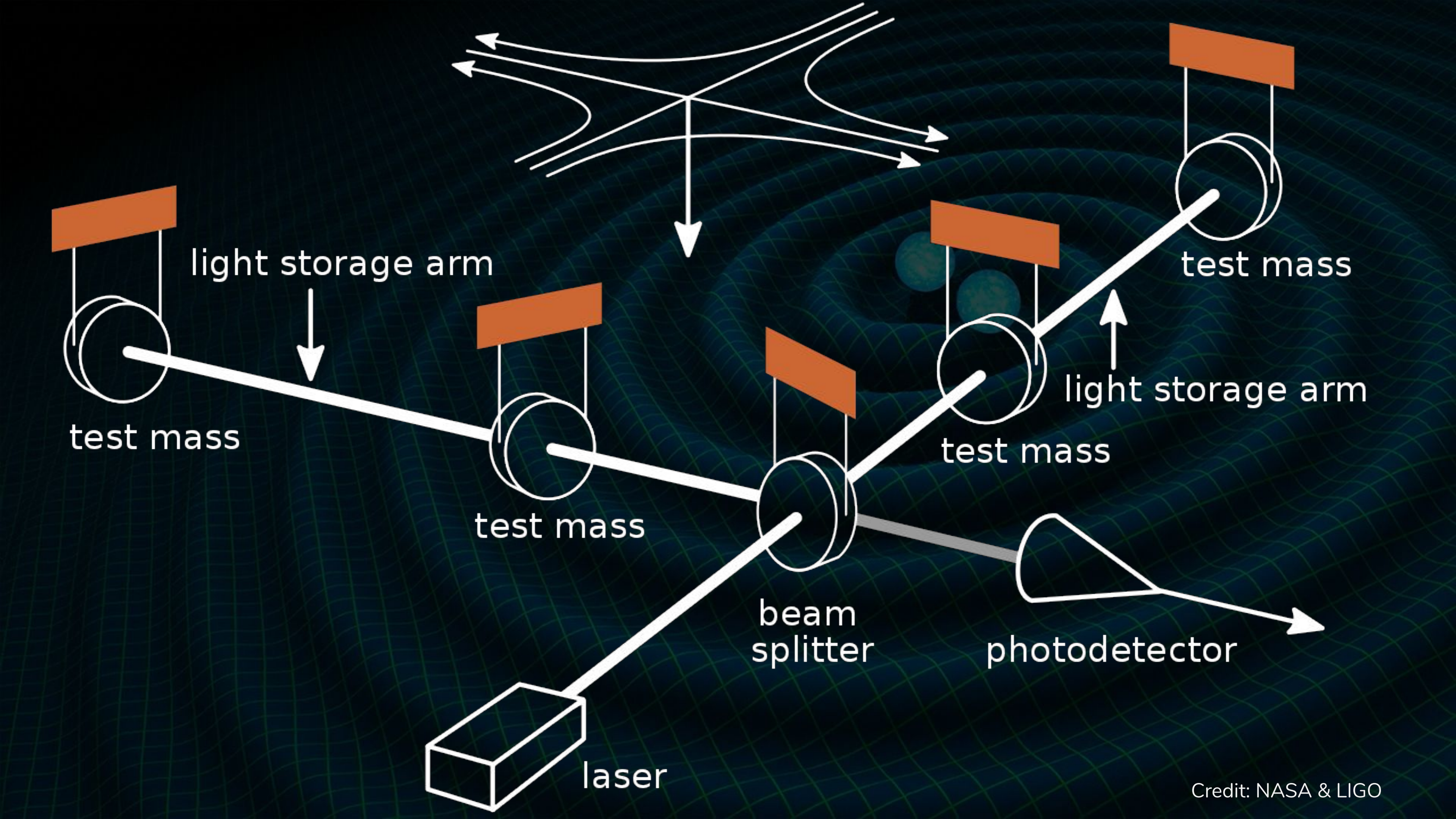
Waveform depends on $M_1, m_2, \mathbf{s}_1 \mathbf{s}_2$, position, orientation,...



The Hulse-Taylor Pulsar PSR B1913+16 provided conclusive evidence that double compact objects would be gravitational wave sources



en.wikipedia.org


light storage arm
test mass
test mass
test mass
light storage arm
test mass
beam
splitter
photodetector
laser
Credit: NASA & LIGO

Initial LIGO operated from 2002 - 2010

Virgo joined in 2007

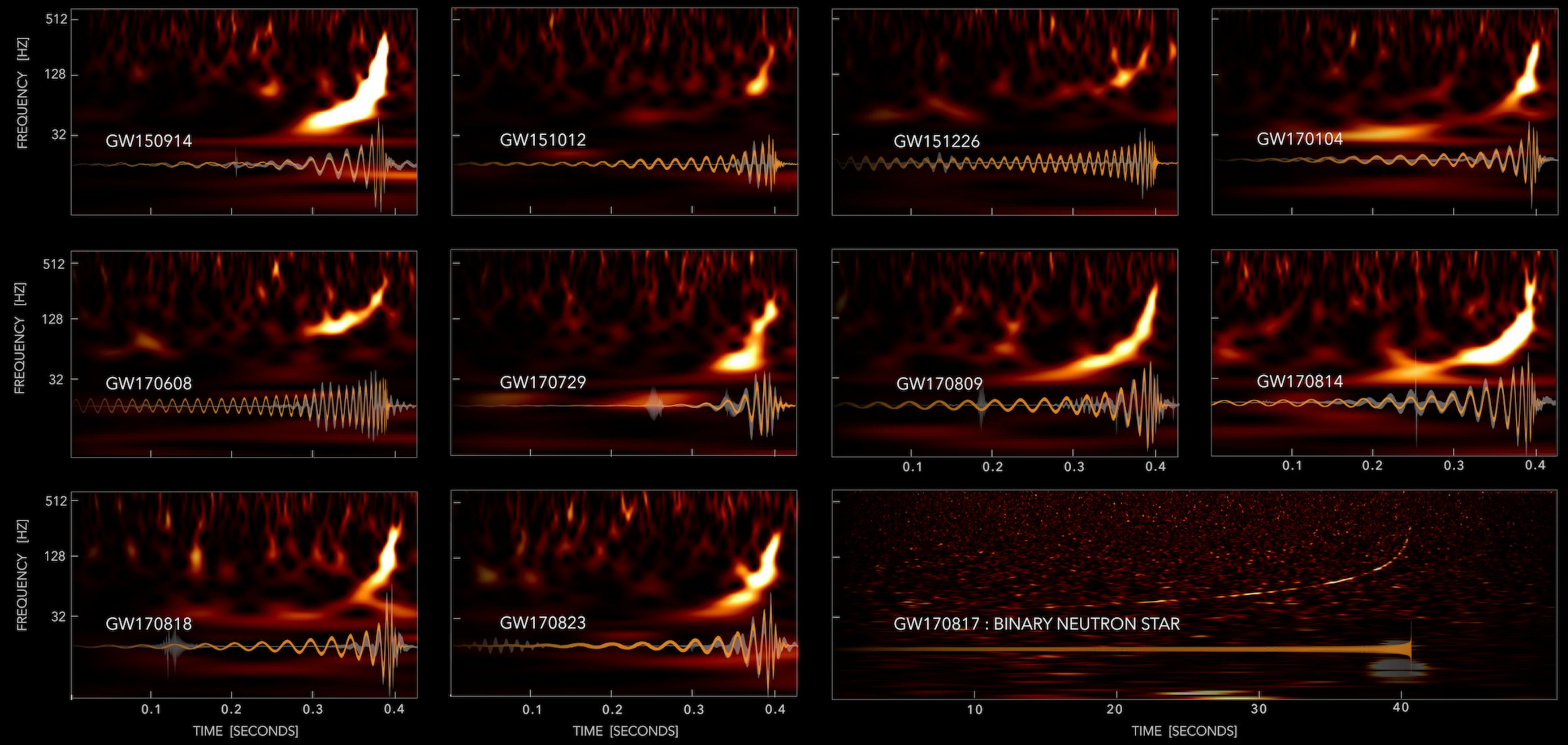
No gravitational waves were discovered

Advanced LIGO was constructed between 2010-2015

Immediately upon turning on, the first binary black hole merger was discovered: GW150914

Credit: LIGO & Virgo, ICRR U Tokyo

GWTC-1 - GWs discovered from September 2015 - August 2017



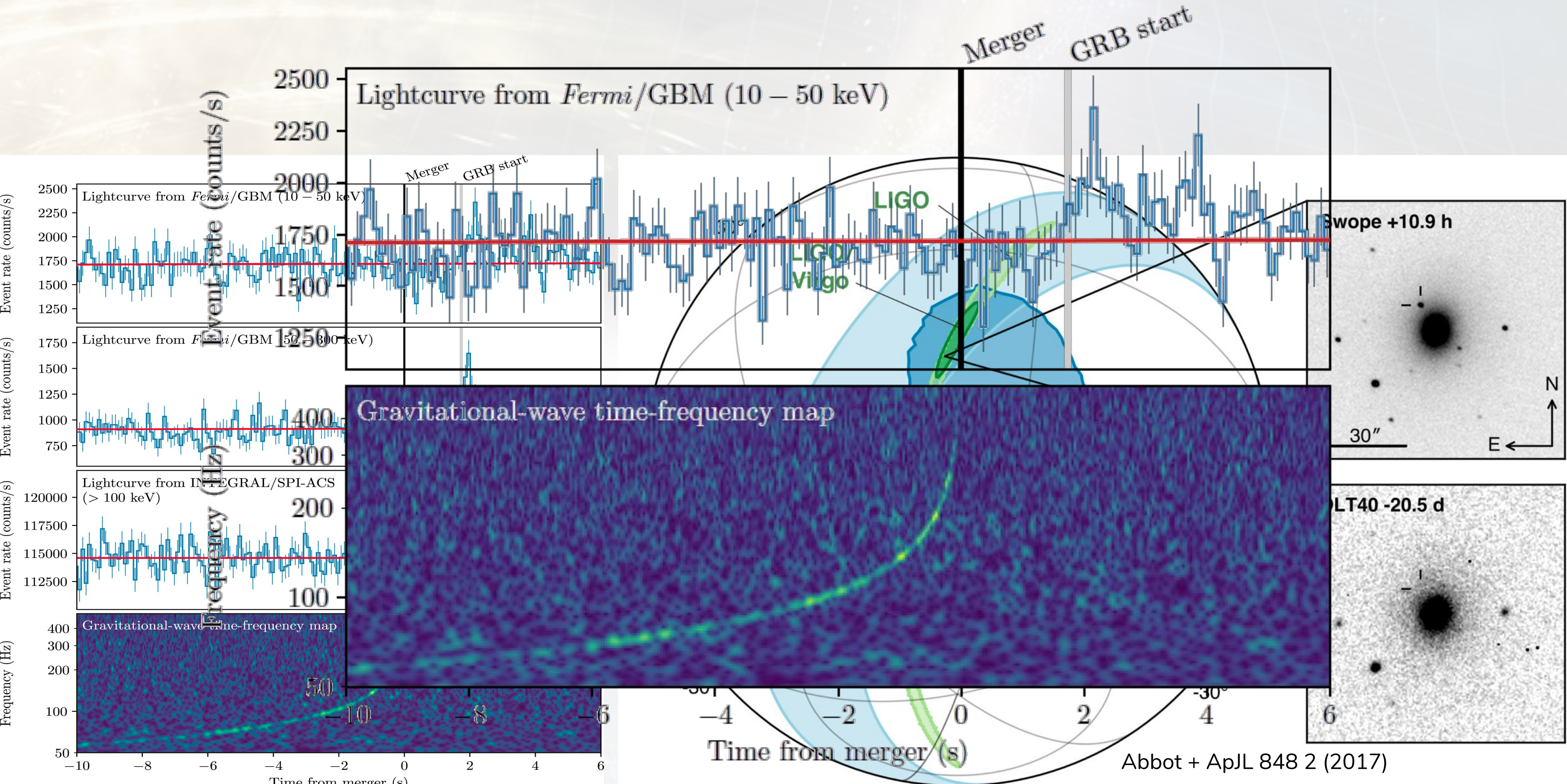
LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23 WAVELET (UNMODELED) EINSTEIN'S THEORY S. GHONGE, K. JANI | GEORGIA TECH

GWTC-1 - GWs discovered from September 2015 - August 2017

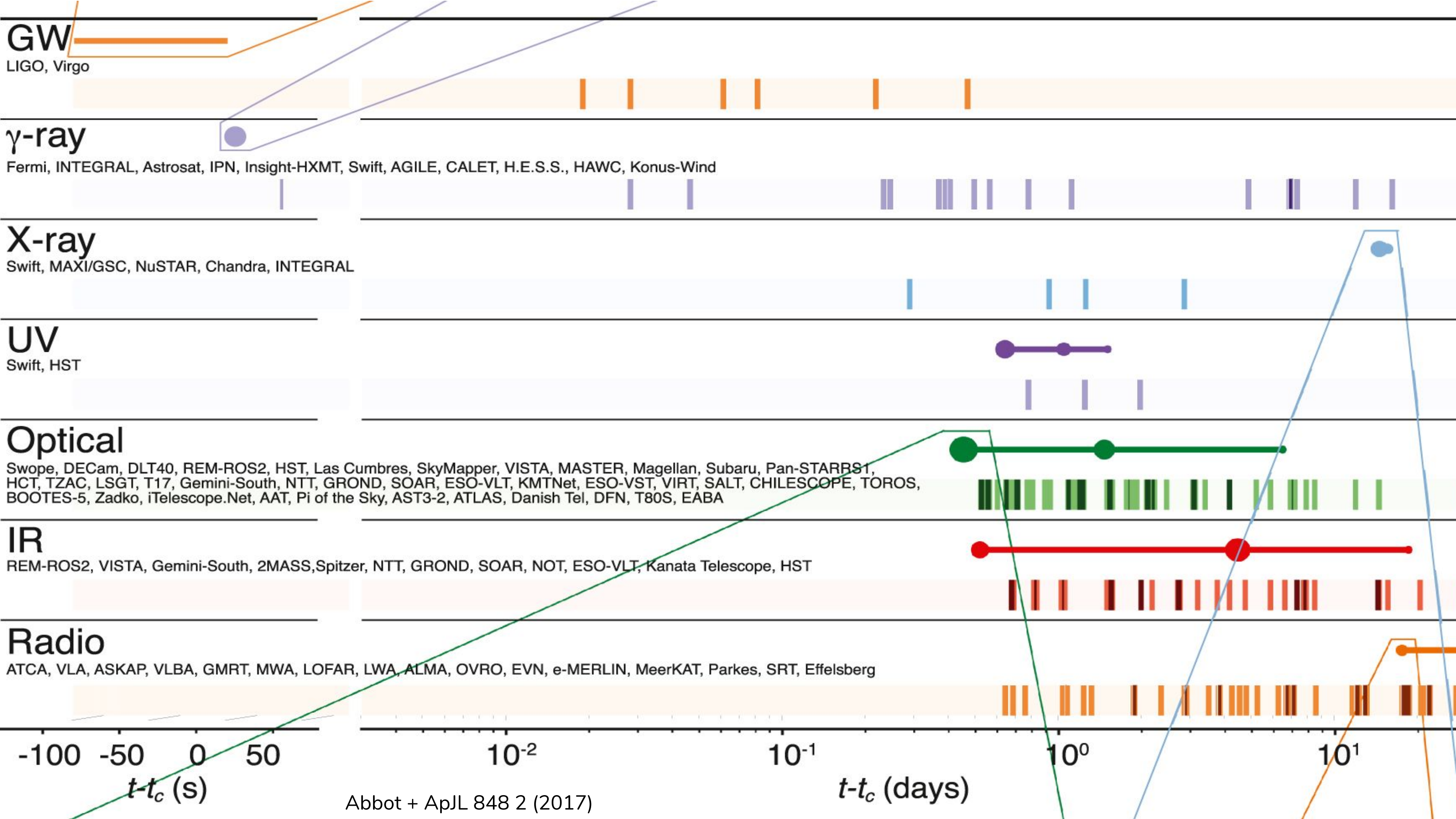
B. P. Abbott et al. 2019

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	χ_{eff}	$M_f/M_\odot$	a_f	$E_{rad}/(M_\odot c^2)$	z	$\Delta\Omega/\mathrm{deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$0.09^{+0.03}_{-0.03}$	180
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.05}_{-0.1}$	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$0.34^{+0.13}_{-0.14}$	1651

GW170817: First multi-messenger source of GWs



Abbot + ApJL 848 2 (2017)



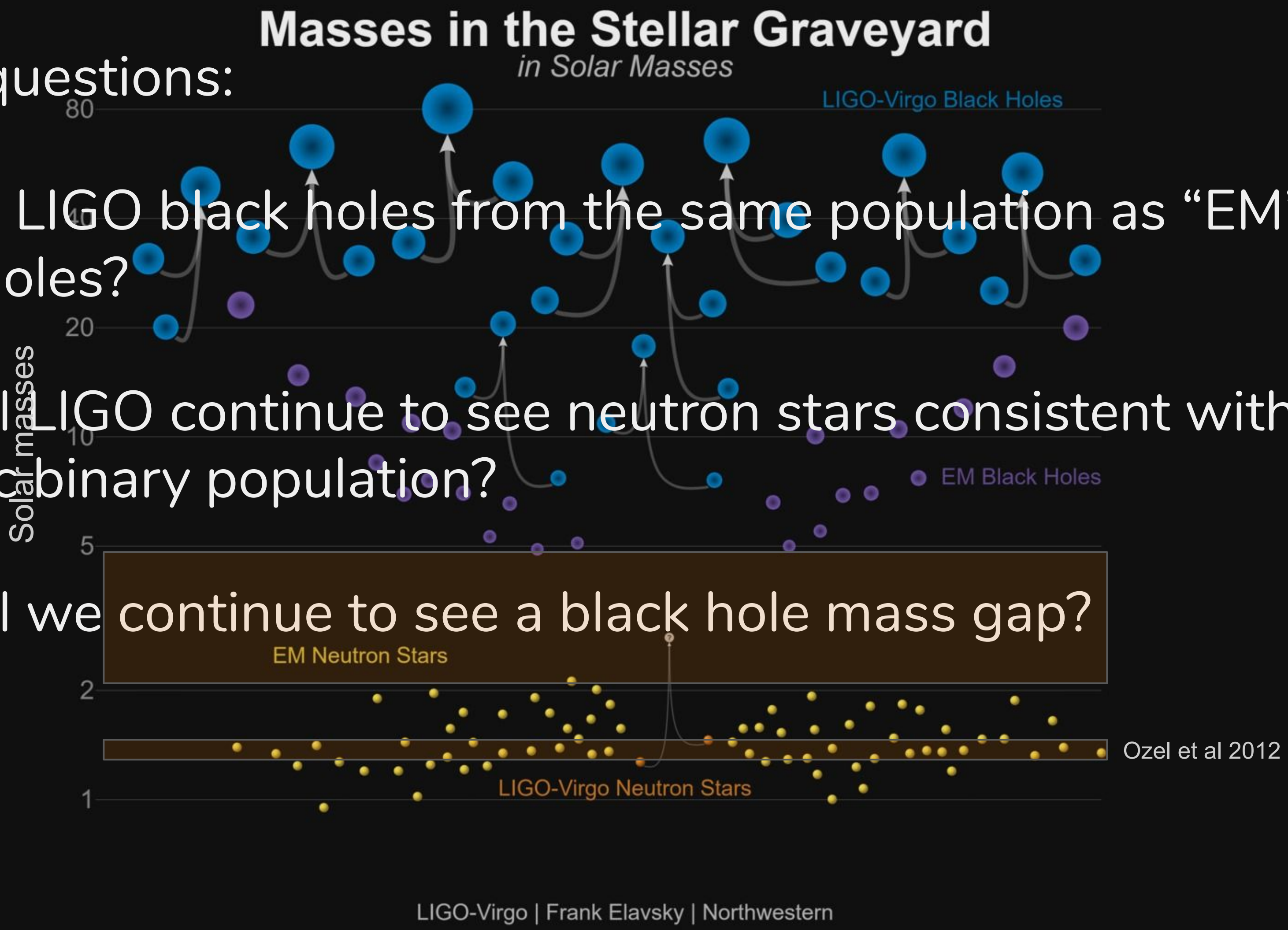
Abbot + ApJL 848 2 (2017)

Open questions:

Are LIGO black holes from the same population as “EM” black holes?

Will LIGO continue to see neutron stars consistent with galactic binary population?

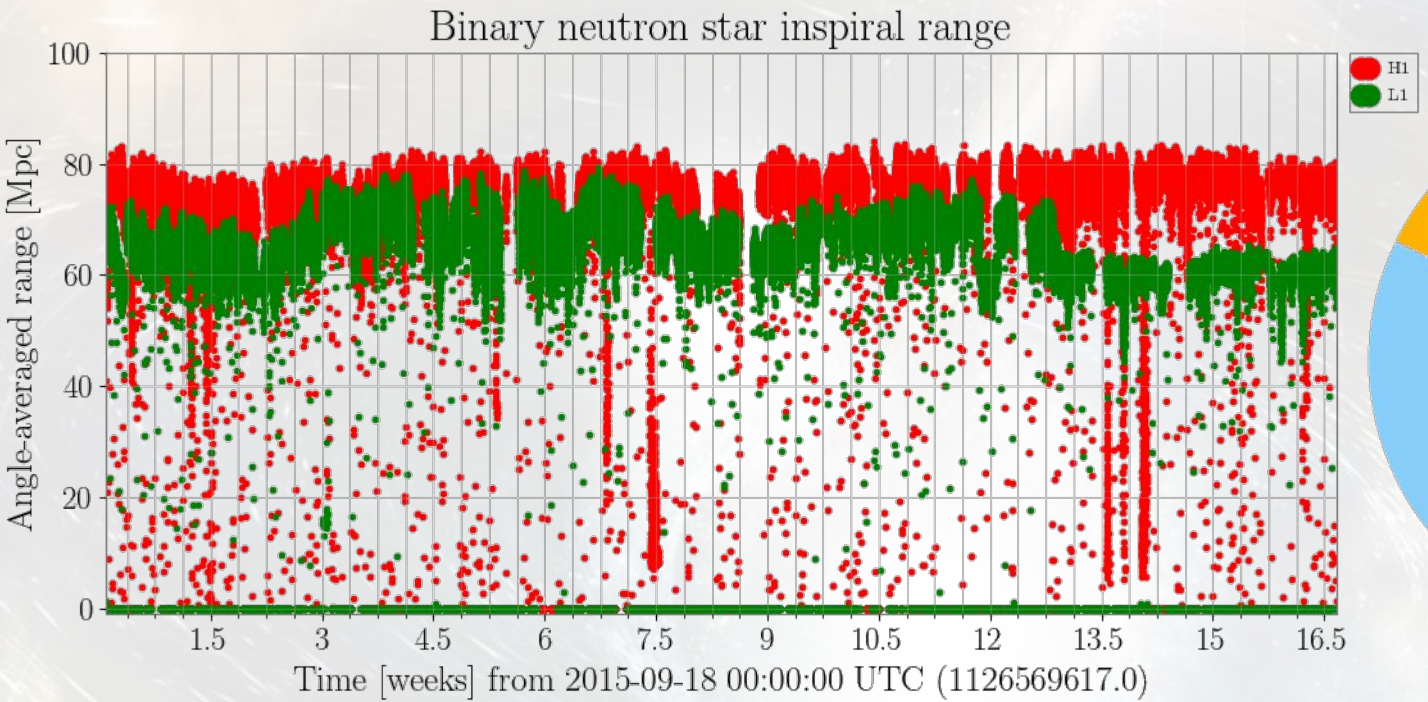
Will we continue to see a black hole mass gap?

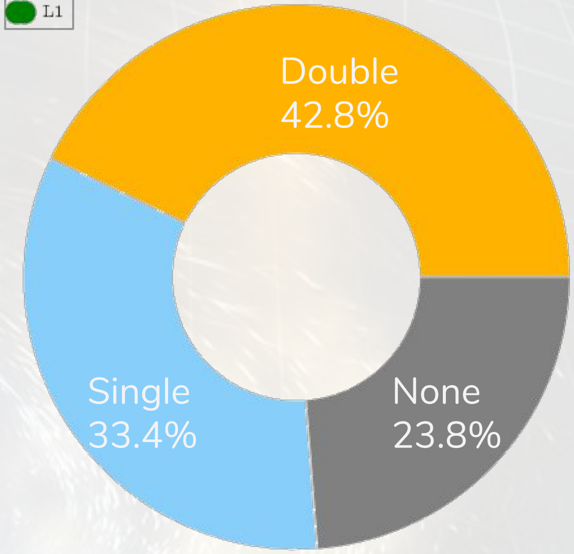


Timeline

O1

Sept '15 -- Jan '16





Timeline

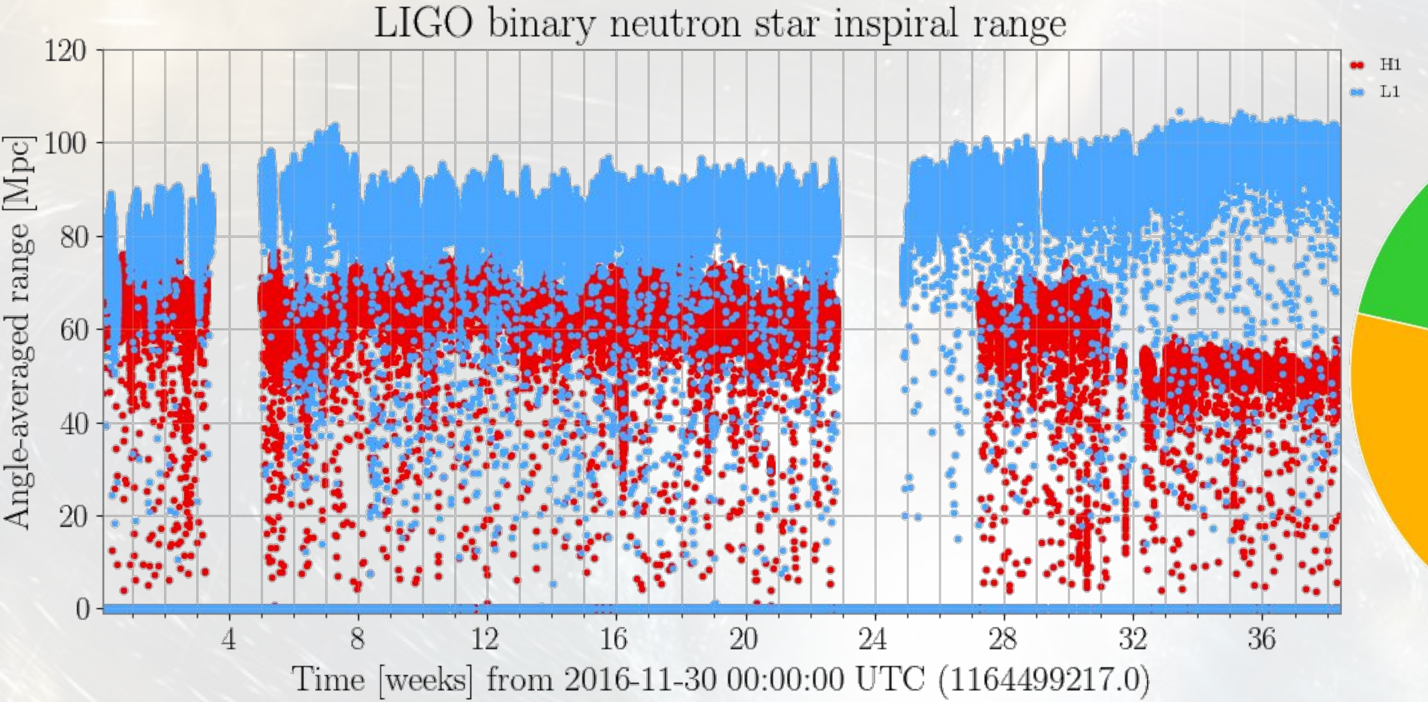
O1

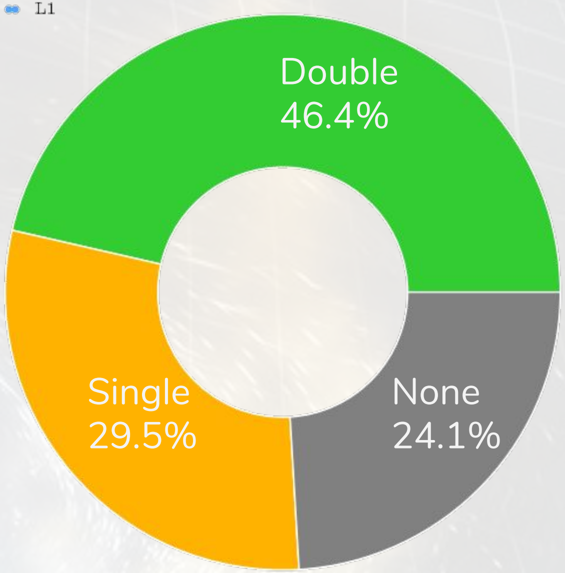
Commissioning -
No data

O2

Sept ‘15 -- Jan ‘16

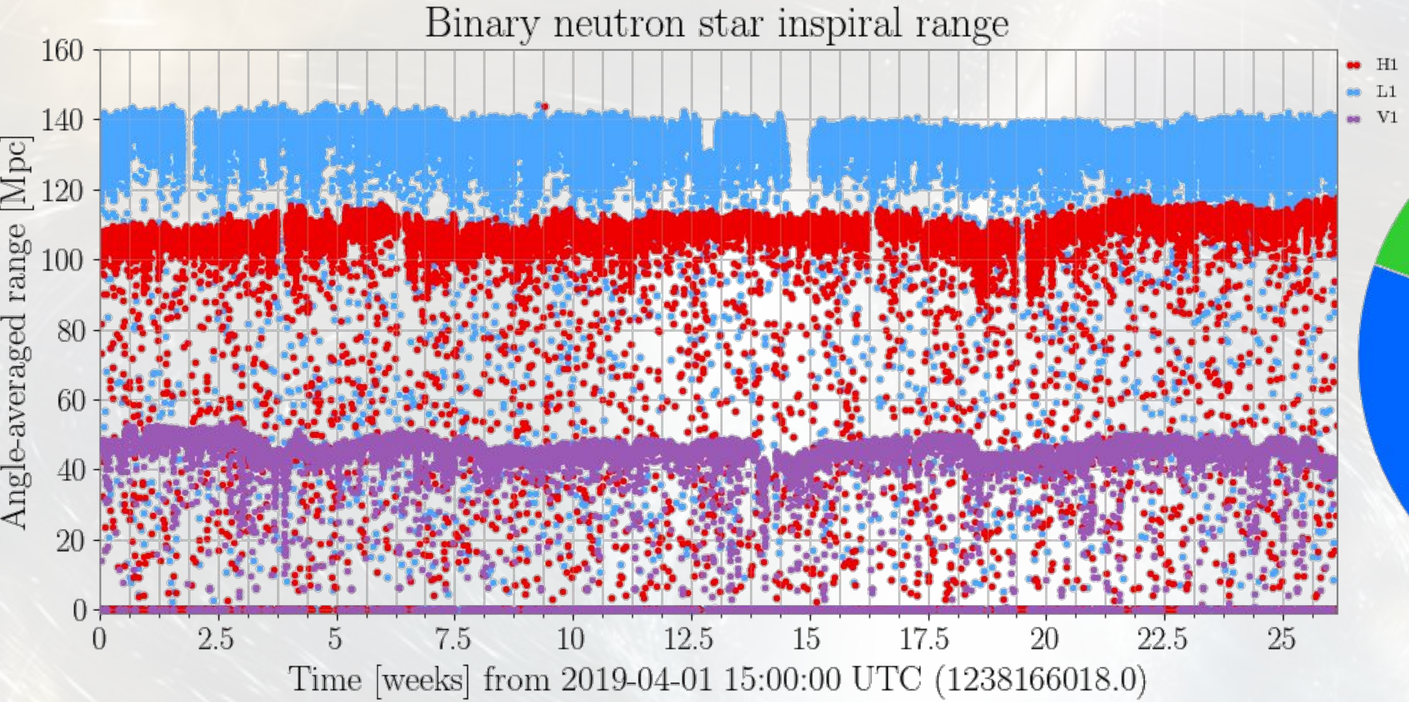
Nov ‘16 -- Aug ‘17

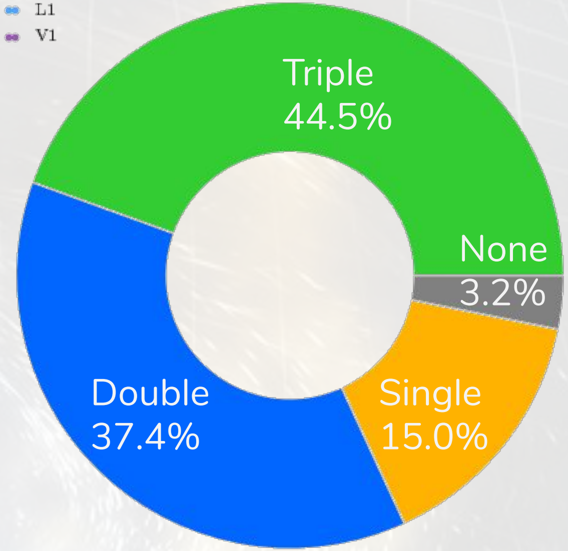


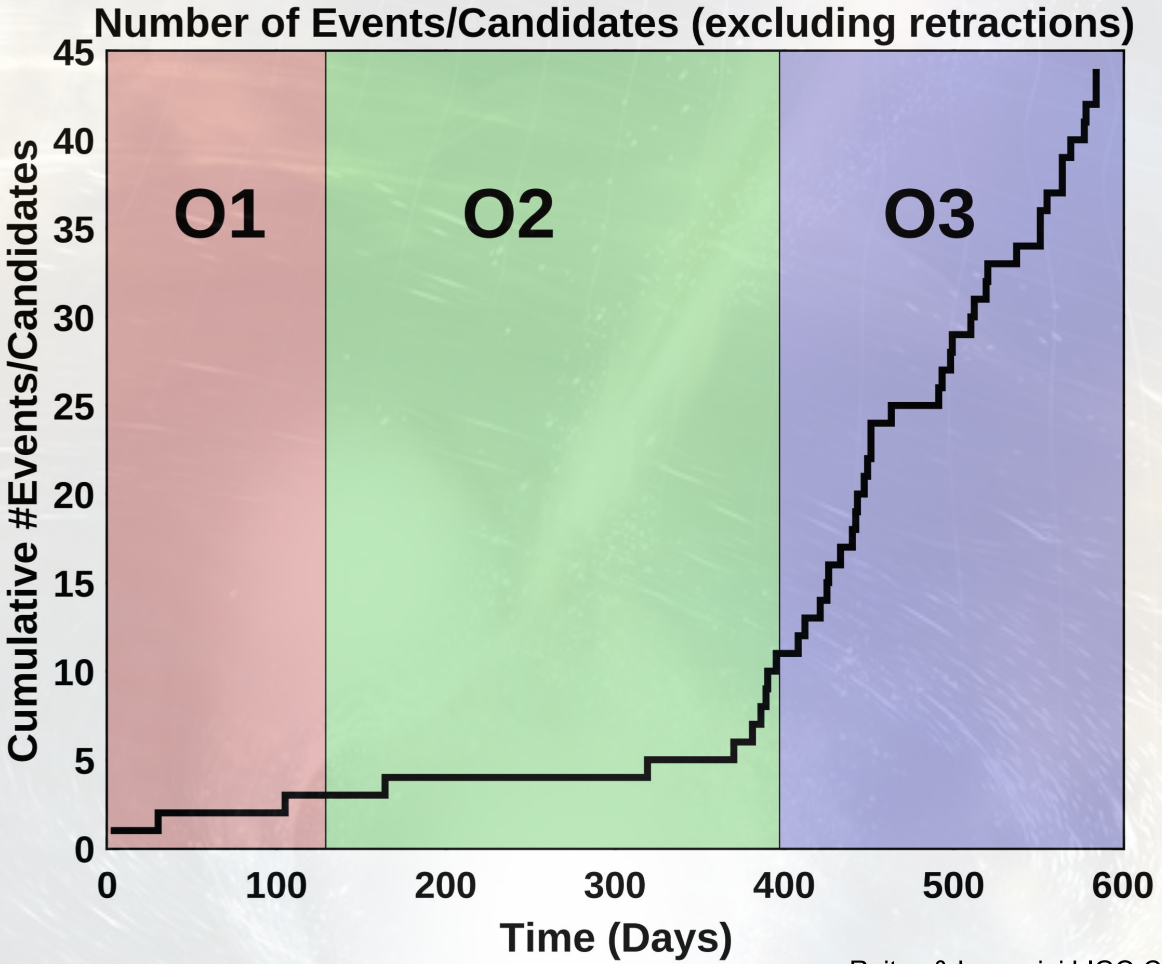


Timeline

O1	Commissioning - No data	O2	Commissioning- No data	O3a
Sept '15 -- Jan '16		Nov '16 -- Aug '17		Apr '19 -- Sep '19

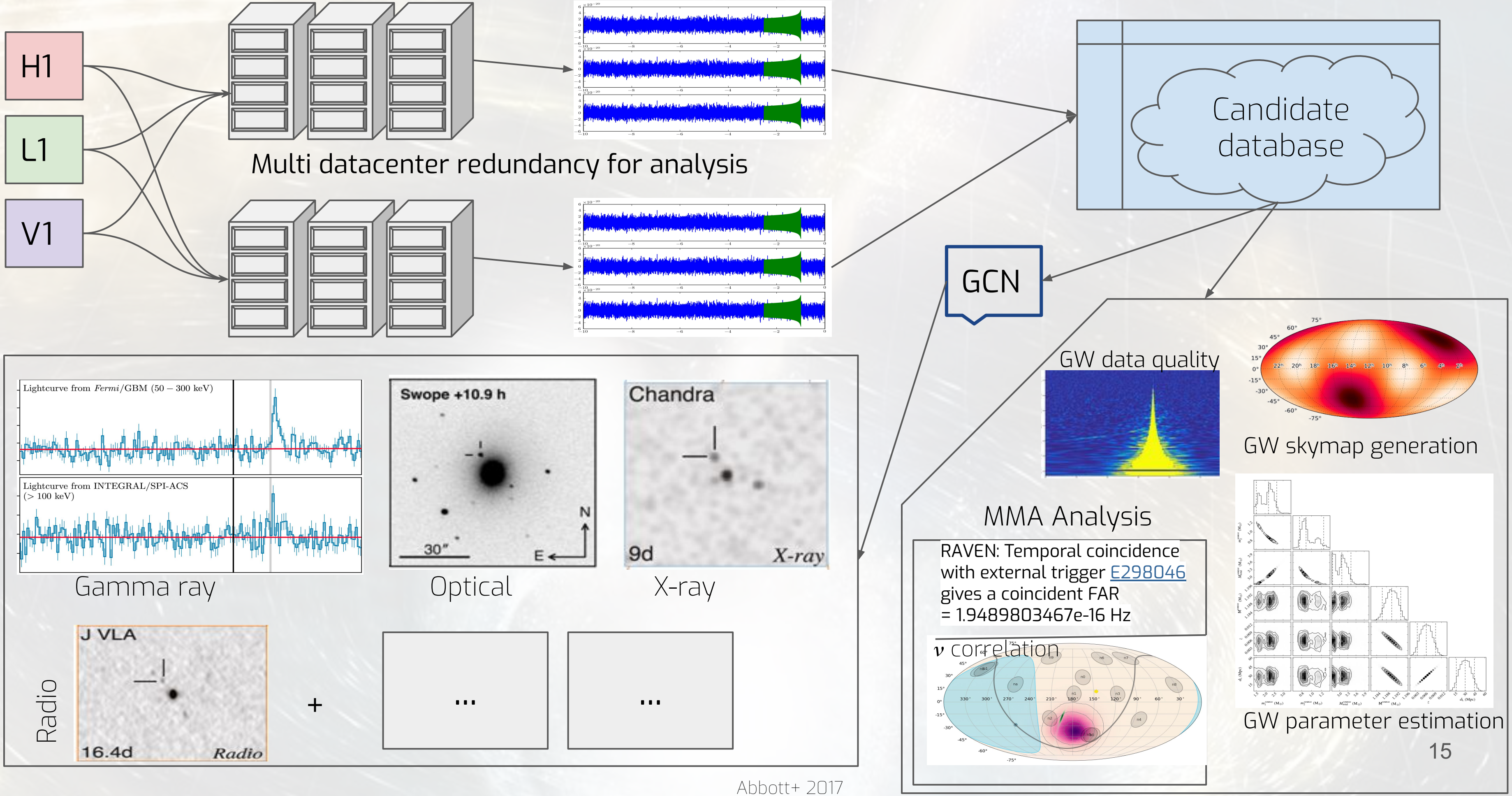






Reitze & Lazzarini LIGO Caltech

Real-time GW data processing (this is not a complete diagram)



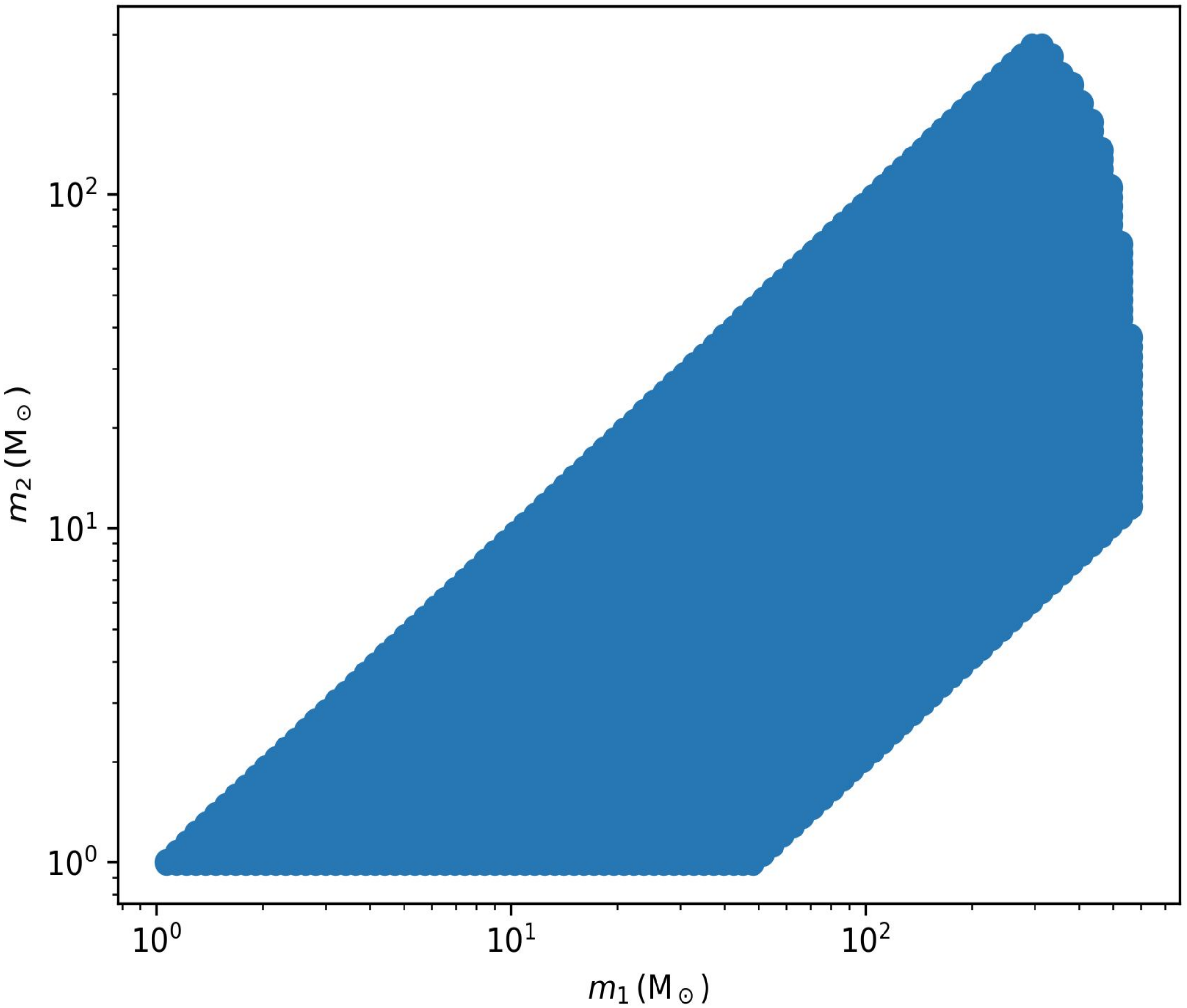
Abbott+ 2017

Real-time analysis covers:

- Component: 1 - 600 $M_\odot$
- Total < 600 $M_\odot$
- NS spin < 0.05
- BH spin < 1
- Q < 50

Millions of templates are searched in parallel

Candidates are uploaded to GW database within 20 seconds of data acquisition.

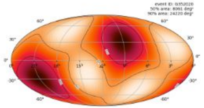
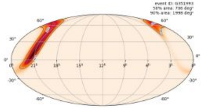


Open public GW alerts: https://gracedb.ligo.org/superevents/public/O3/

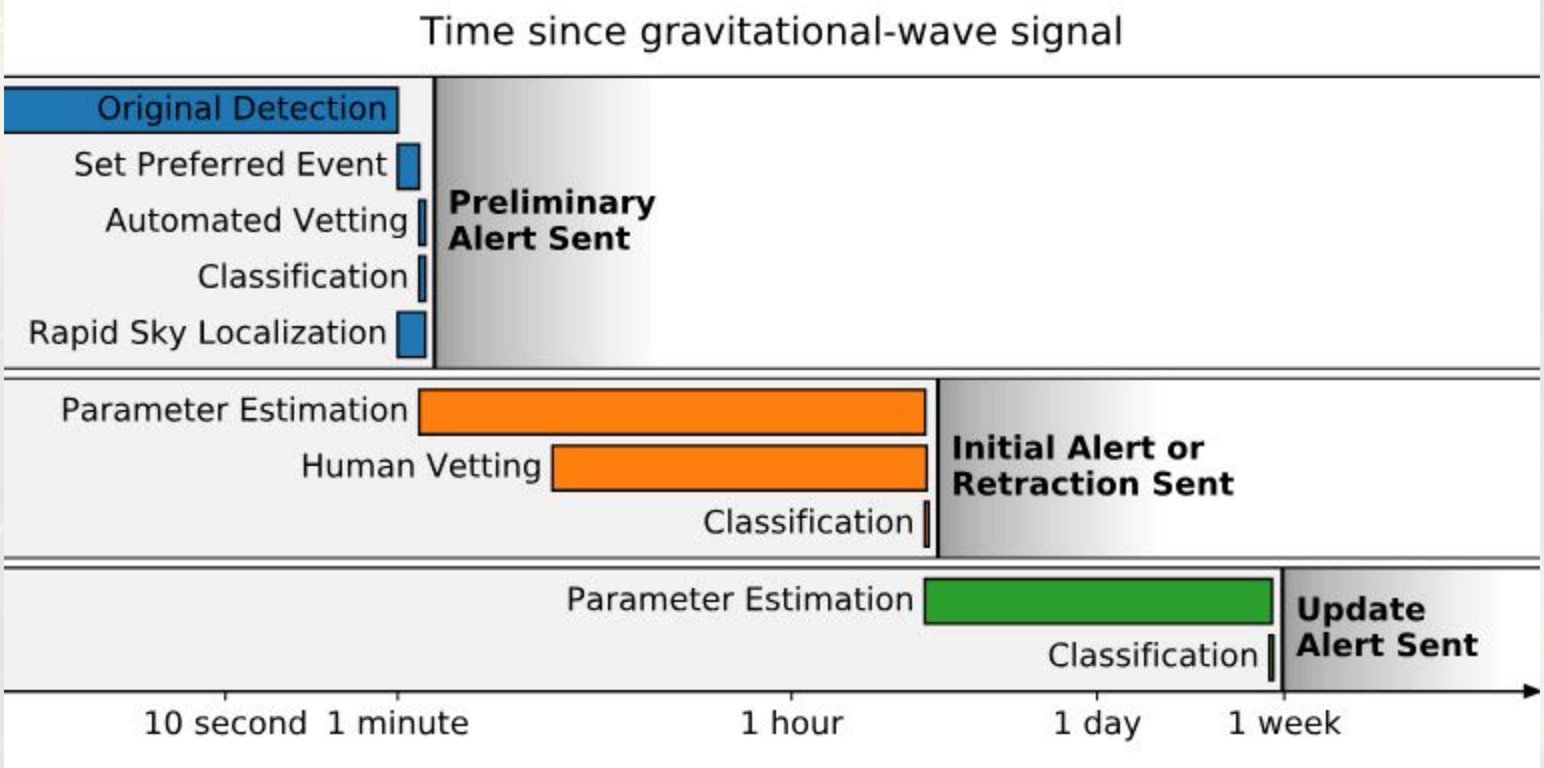
LIGO/Virgo O3 Public Alerts

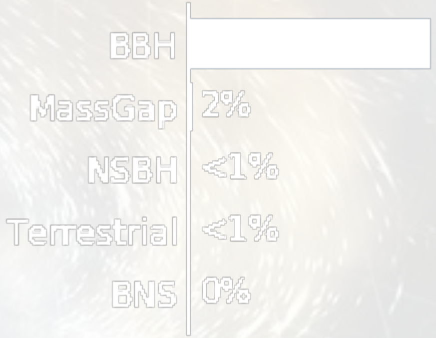
Detection candidates: 33

SORT: EVENT ID (A-Z)

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR
S190930t	NSBH (74%), Terrestrial (26%)	Sept. 30, 2019 14:34:07 UTC	GCN Circulars Notices | VOE		1 per 2.0536 years
S190930s	MassGap (95%), Terrestrial (5%)	Sept. 30, 2019 13:35:41 UTC	GCN Circulars Notices | VOE		1 per 10.534 years

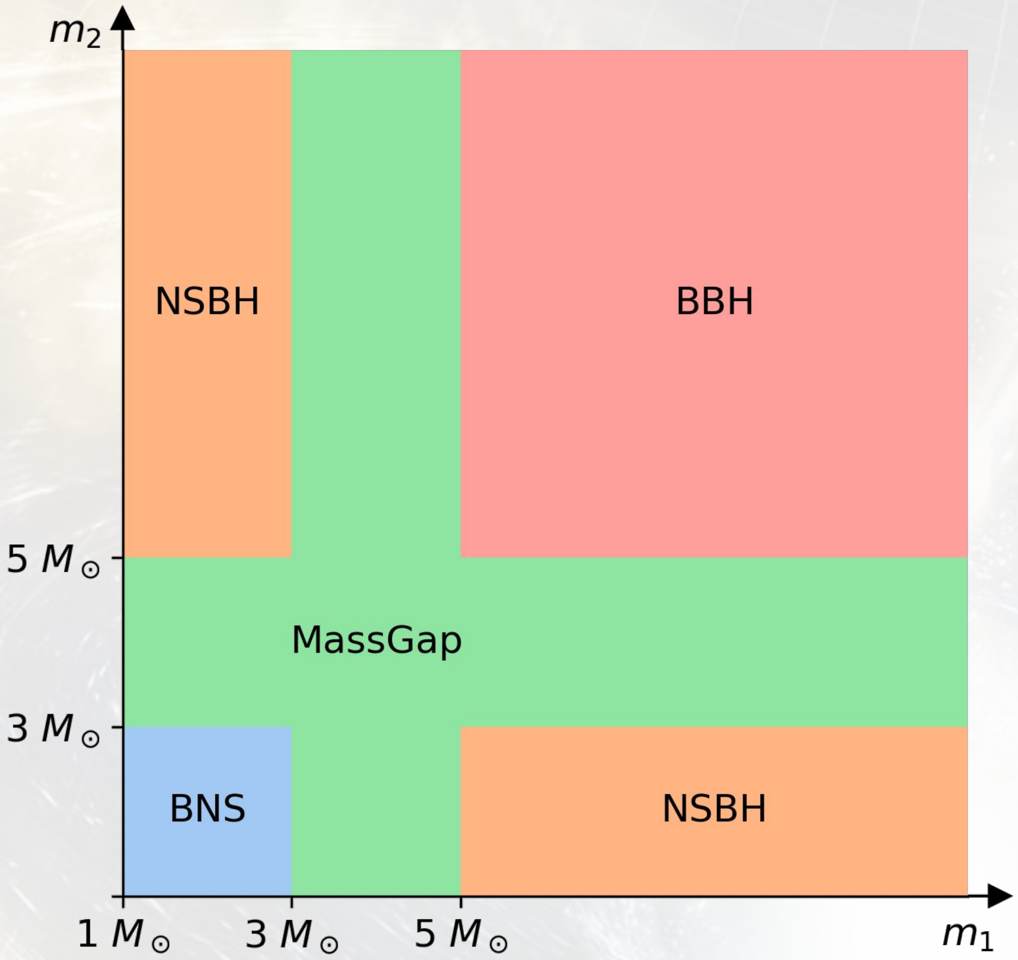
Open public GW alerts: https://emfollow.docs.ligo.org/userguide





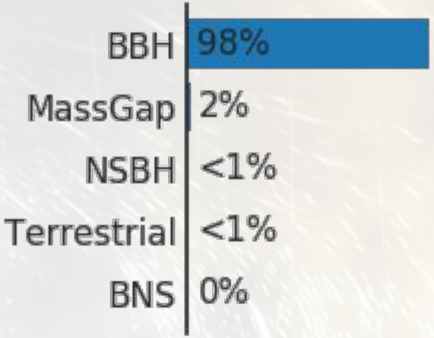
PROB_NS: 0.00 [range is 0.0-1.0]
PROB_REMNANT: 0.00 [range is 0.0-1.0]
FAR (yr^{-1}) 1 per 13.354 years

https://gracedb.ligo.org Foucart, F., Hinderer, T. & Nissanke (2018)



We provide "p-astro" classification based on the mass definitions to the left.

```
PROB_NS:       0.00 [range is 0.0-1.0]
PROB_REMNANT:  0.00 [range is 0.0-1.0]
```



https://emfollow.docs.ligo.org/userguide/

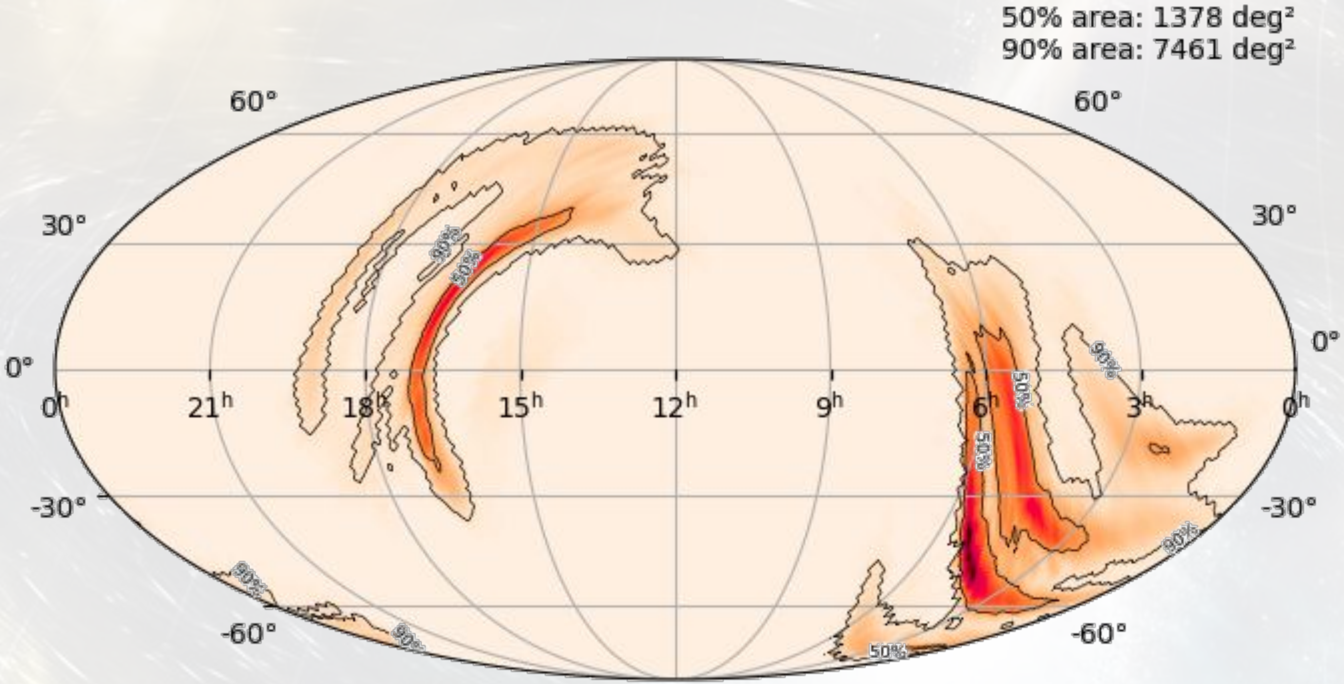
Number classified as BBH/Mass Gap: 23
Number classified as BNS: 4 (1 definite **, 1 reclassified as NSBH if real)
Number classified as NSBH: 4 (1 definite **)
Number classified as terrestrial: 2

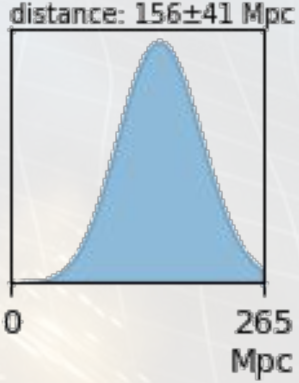
There have been >1000 GCNs associated with follow-up

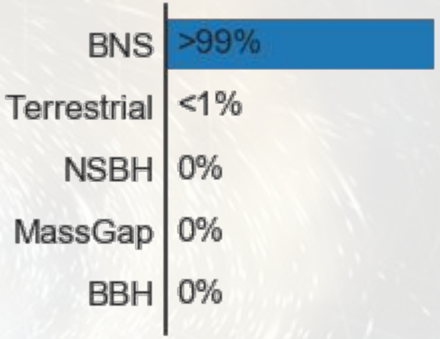
**based on mass alone - we do not know that there was an NS

BNS : S190425z (Definite GW)

Originally discovered as L only (V contributed very low SNR)

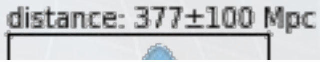






BNS -> NSBH : S190426c (Marginal)

Initially Classified as a BNS but very, very marginal



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TITLE: GCN CIRCULAR
NUMBER: 24411
SUBJECT: LIGO/Virgo S190426c: Update on Source Classification
DATE: 19/05/06 16:21:43 GMT
FROM: Deep Chatterjee at University of Wisconsin, Milwaukee <deep@uwm.edu>

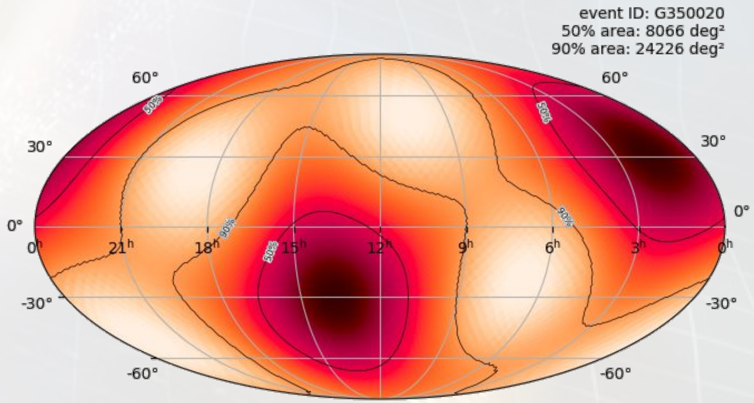
LIGO/Virgo S190426c: Update on Source Classification

The LIGO Scientific Collaboration and Virgo Collaboration report:

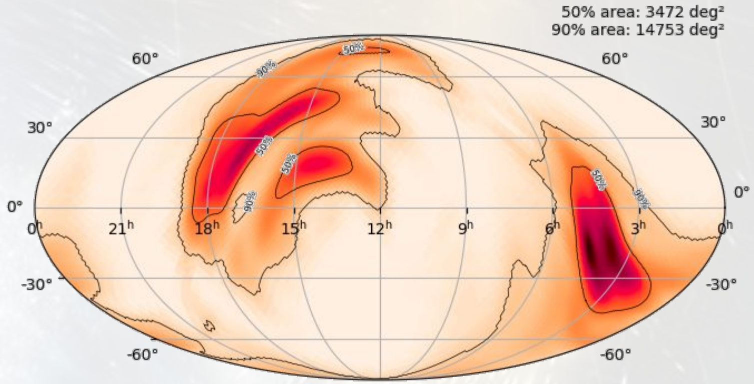
Based on posterior support from preliminary parameter estimation [1,2], under the assumption that the candidate S190426c is astrophysical in origin, the relative probabilities amongst the signal categories NSBH : MassGap : BNS : BBH are revised to be approximately 12 : 5 : 3 : 0.

Other marginal BNS : S190901ap, S190910h

S190910h: BNS (61%), Terrestrial (39%)
L1

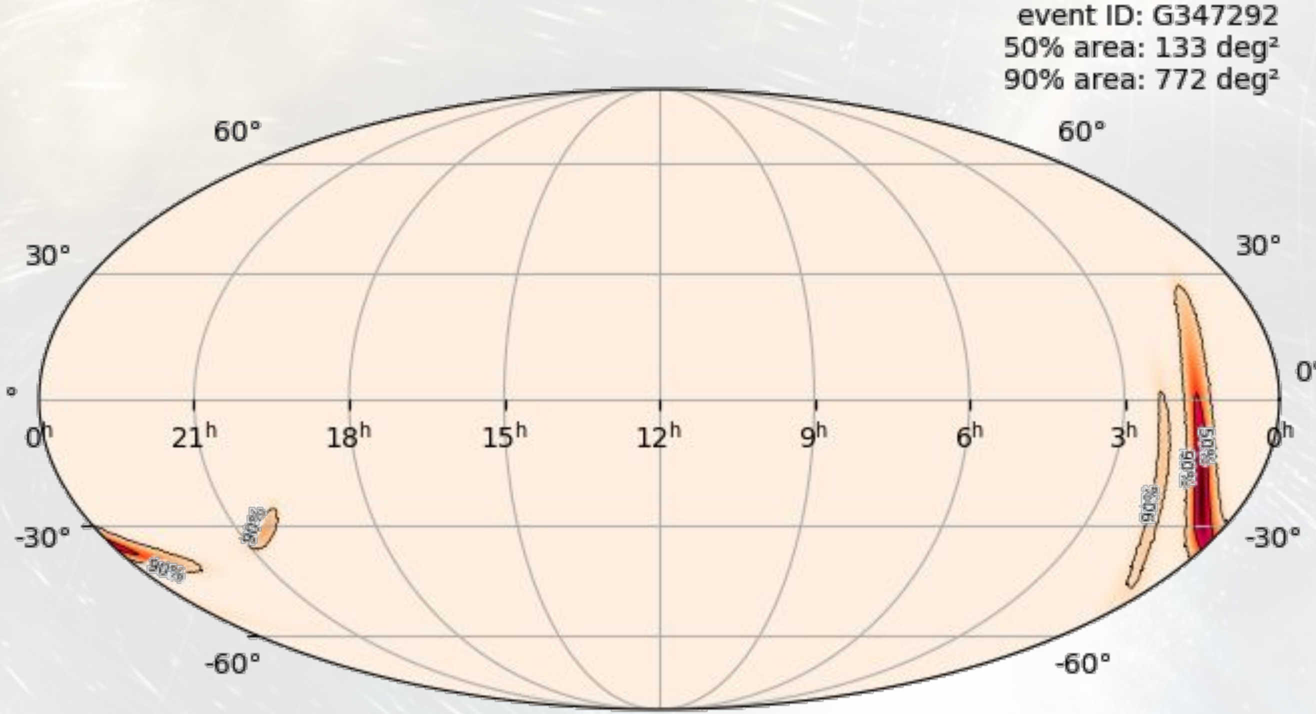


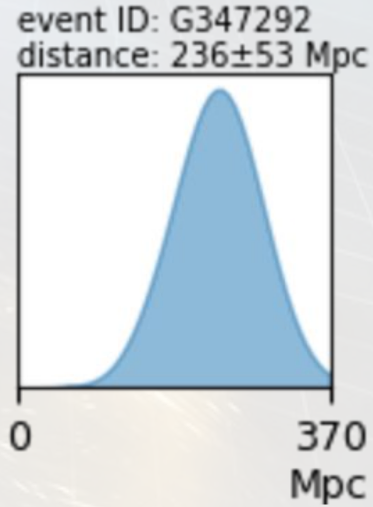
S190901ap: BNS (86%), Terrestrial (14%)
L1, V1

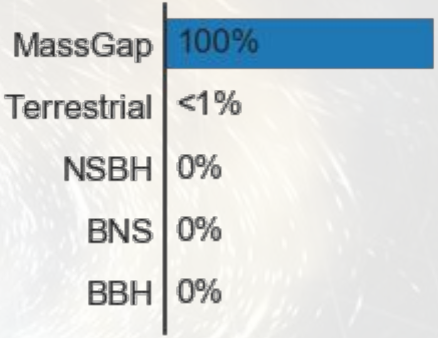


S190814bv (Definite GW)

Originally discovered as L,V only

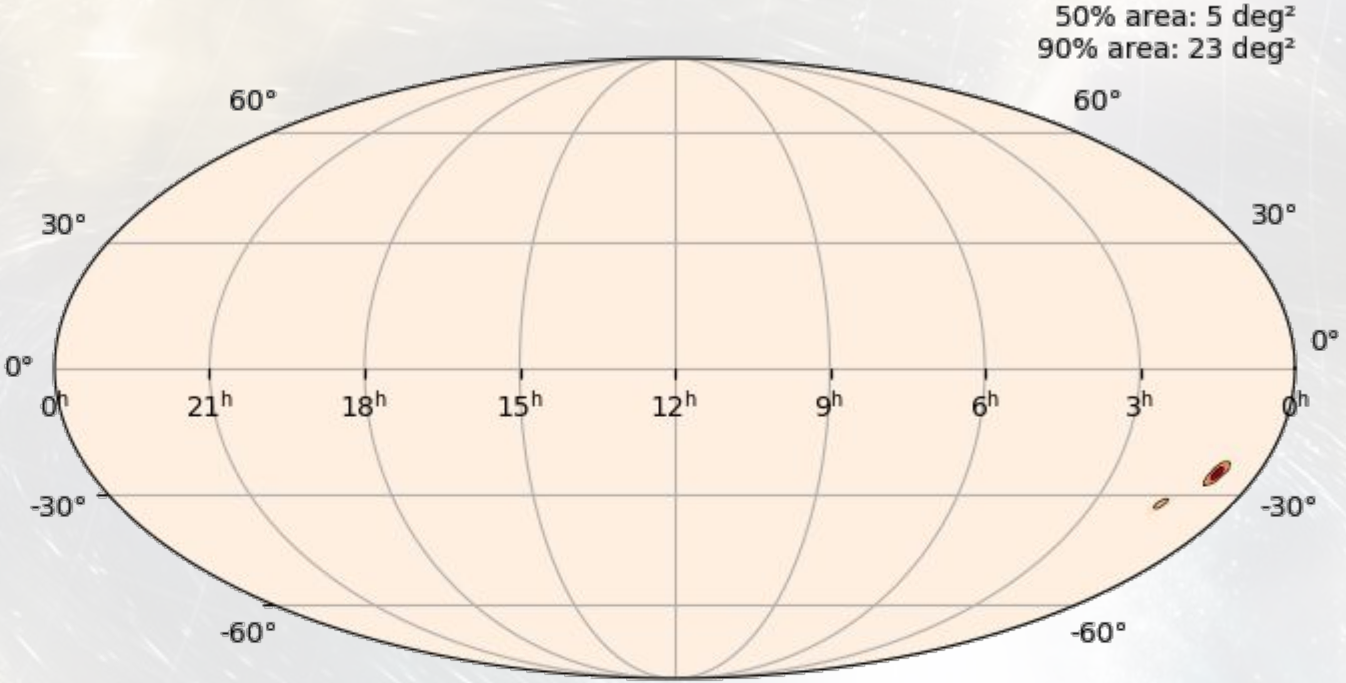


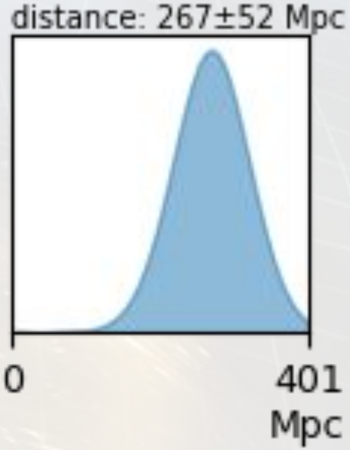


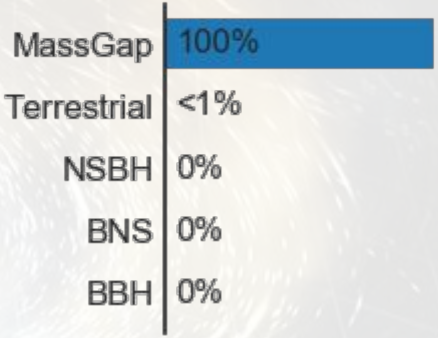


S190814bv (Definite GW)

H had “low noise” data that was reanalyzed

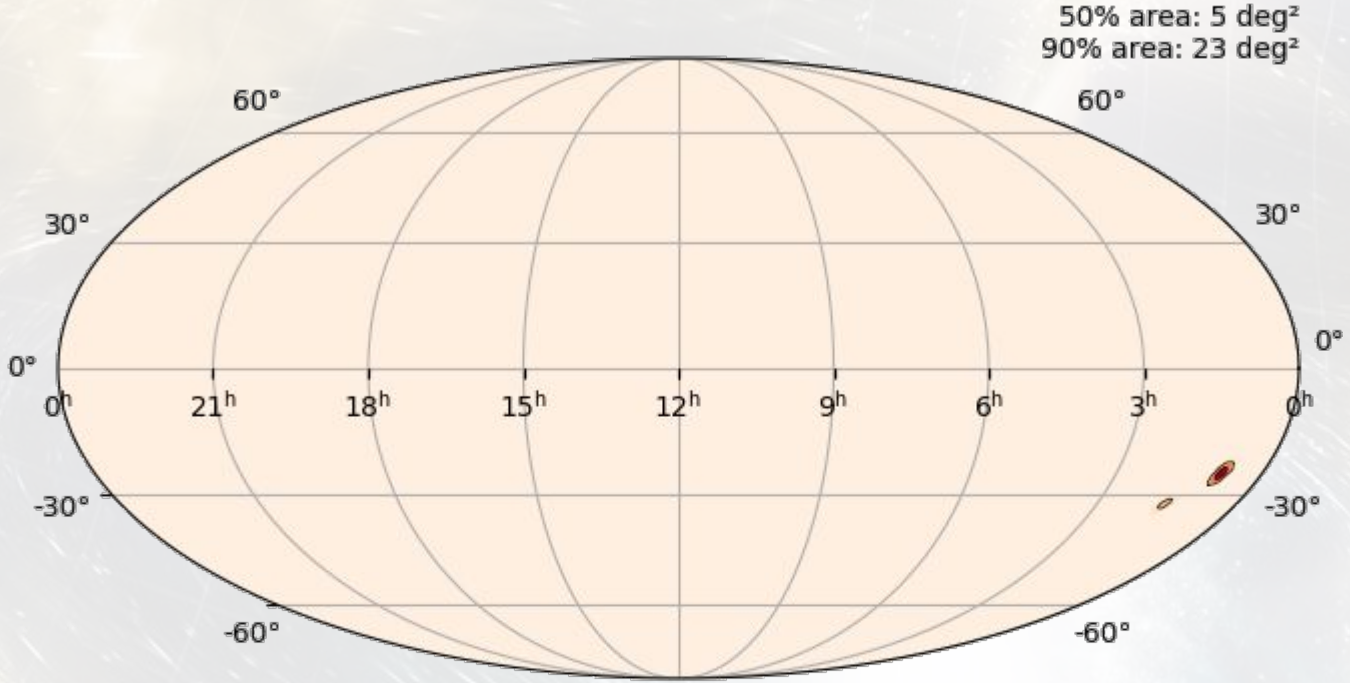


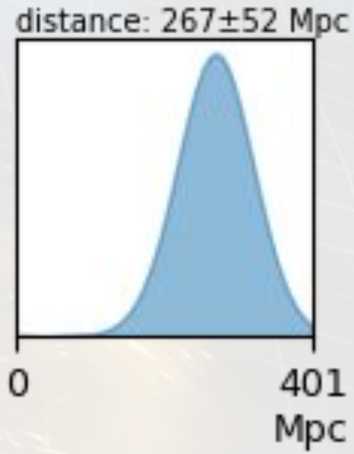


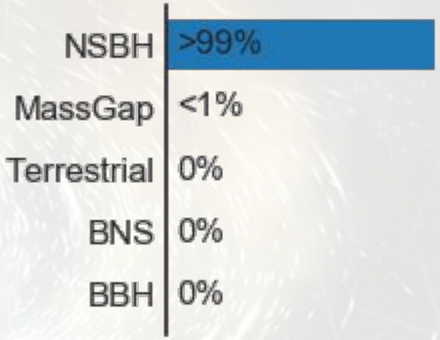


S190814bv (Definite GW)

After follow-up, was reclassified as NSBH

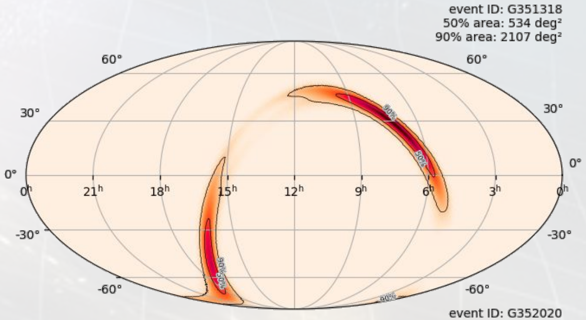




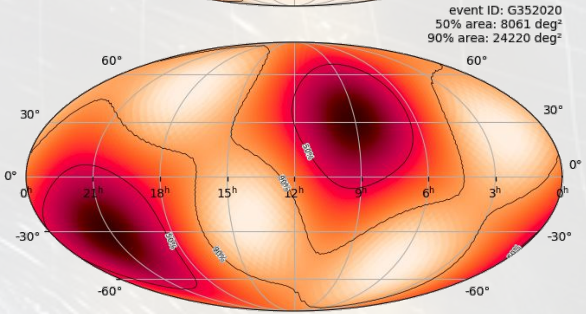


Other marginal NSBH : S190923y, S190930t, S190910d

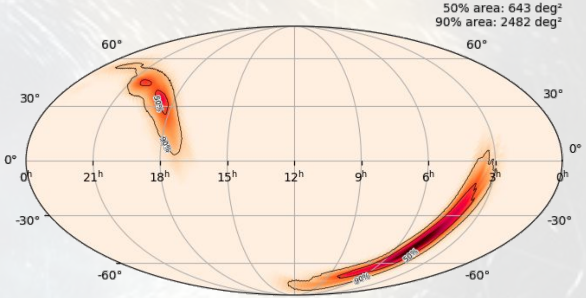
S190923y NSBH (68%), Terrestrial (32%)



S190930t NSBH (74%), Terrestrial (26%)



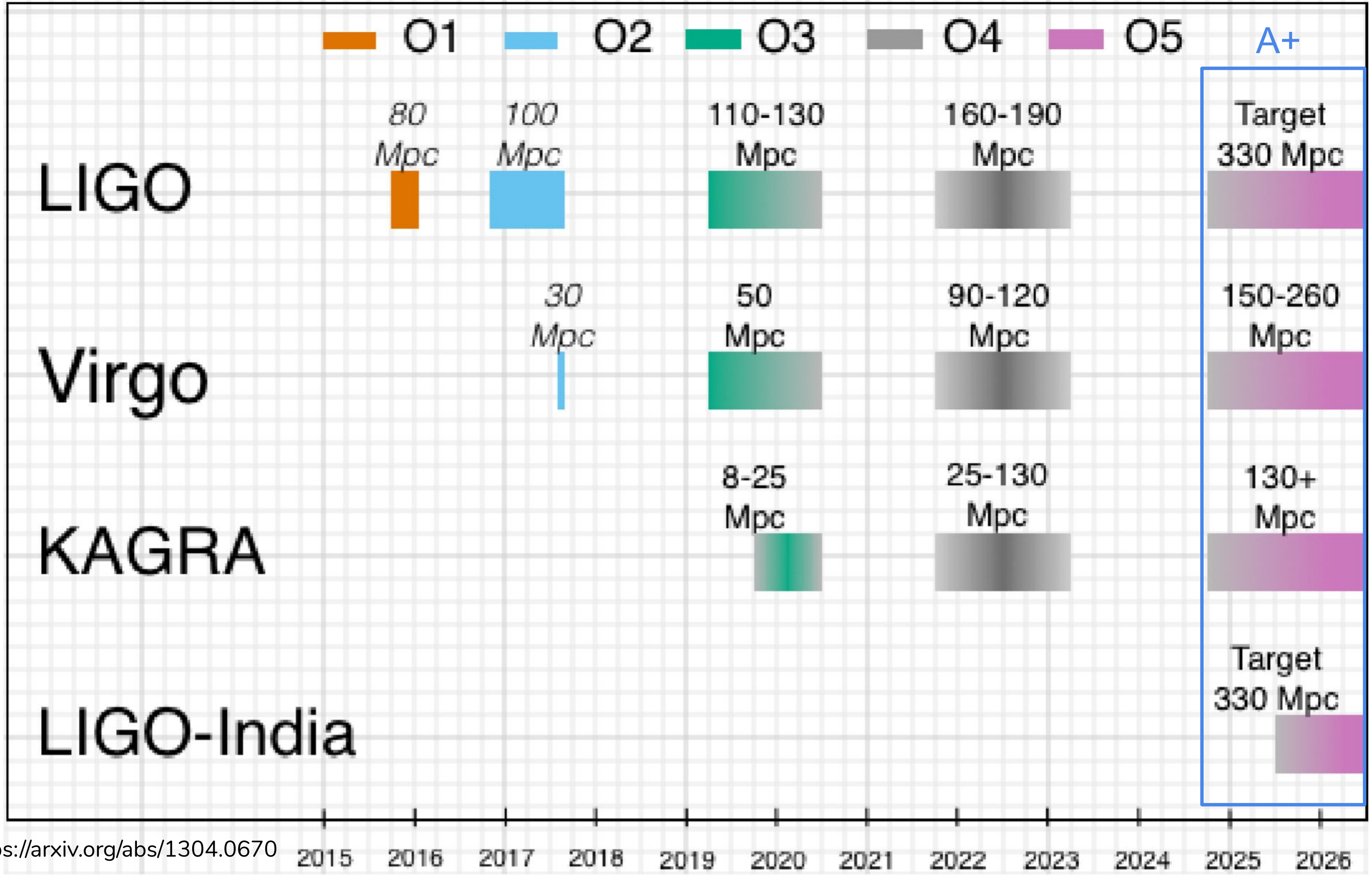
S190910d NSBH (98%), Terrestrial (2%)



Going forward

O3b will begin on November 1, 2019 and run until April 30, 2020.

We are on track for > 50 confident GW detections by the end of the run.



https://arxiv.org/abs/1304.0670

Thanks