Title: Deciphering Gravitational Wave Observations

Speakers: Stephen Fairhurst

Collection/Series: Colloquium

Subject: Other

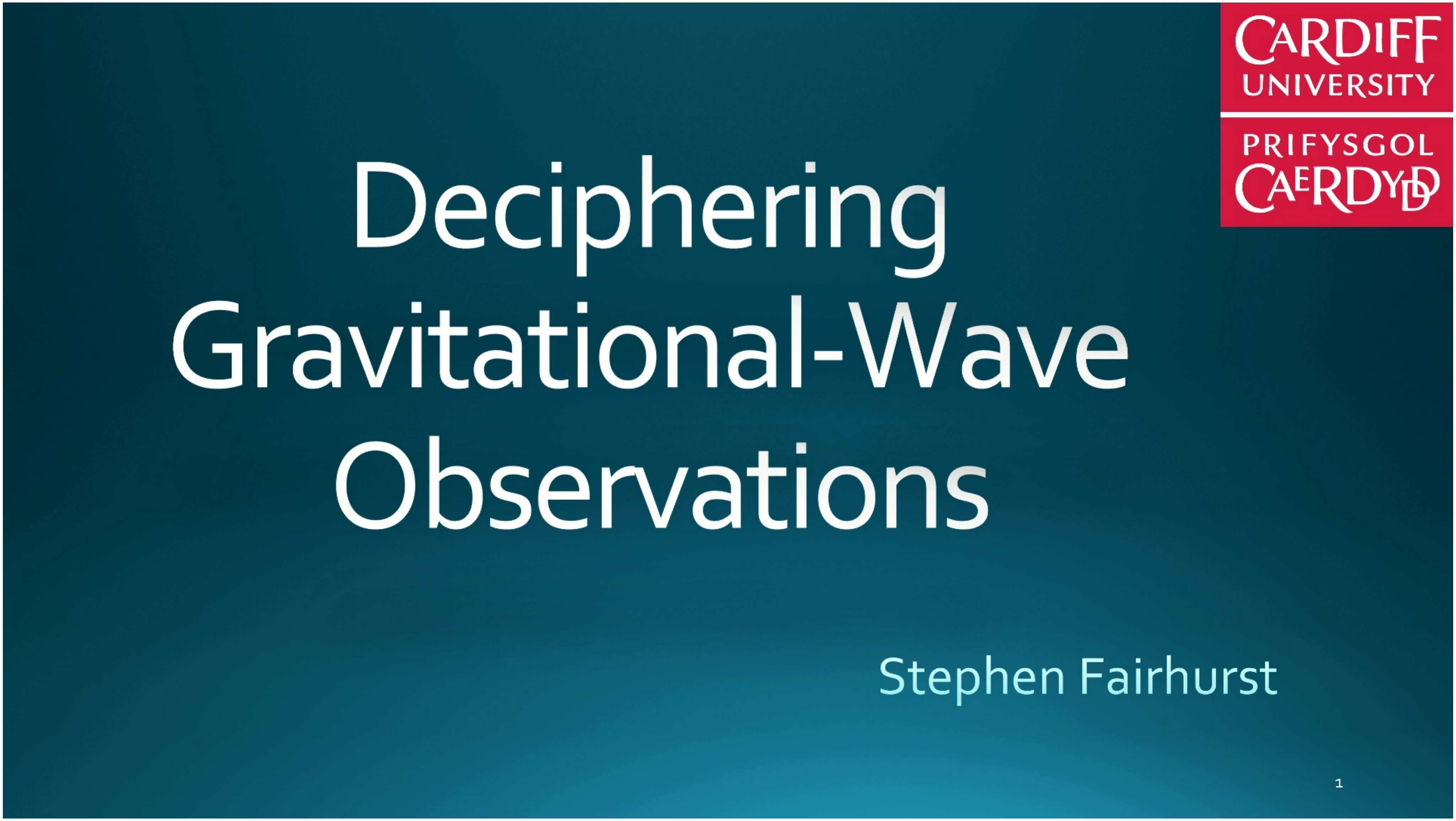
Date: November 06, 2024 - 2:00 PM

URL: https://pirsa.org/24110057

Abstract:

Gravitational Waves emitted by colliding black holes were detected for the first time by LIGO in 2015. The subsequent observation of merging neutron stars in 2017, and its electromagnetic counterpart signal, attracted the attention of the astronomy community worldwide. Over two hundred gravitational wave signals have been observed to date, with several new observations per week.

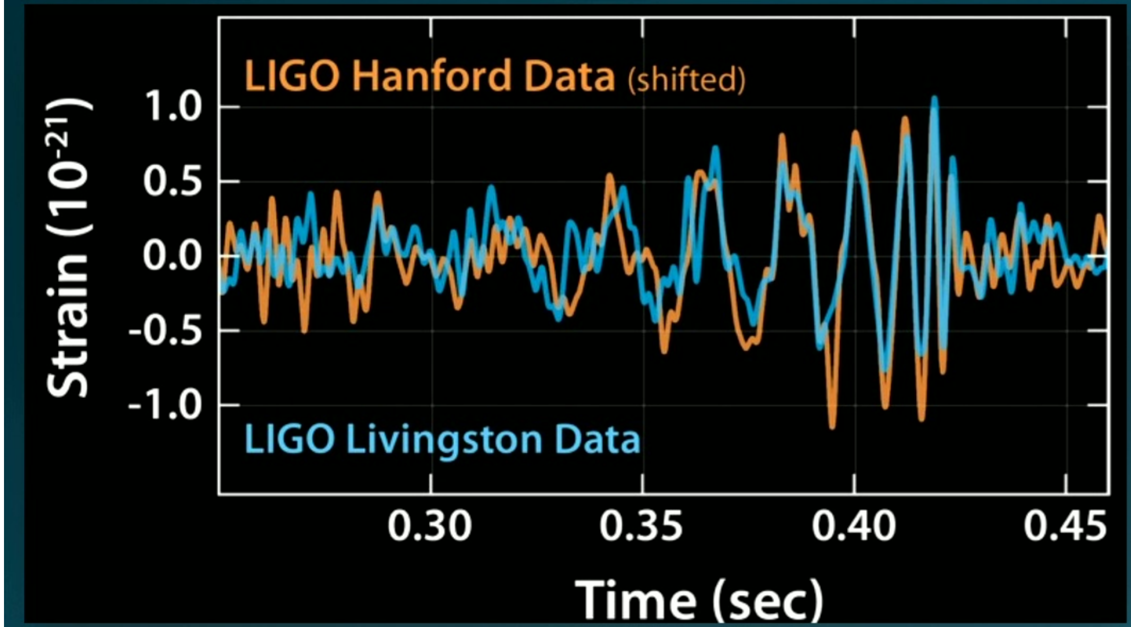
The properties of a binary system, such as the masses and spins of each black hole, the system's orientation and location, are all encoded in different, subtle ways into the emitted gravitational waveform. In this talk, I will present an intuitive explanation of how the observed waveform can be used to extract the physical parameters of the system. I will focus on less commonly observed phenomena, such as higher gravitational wave multipoles, spin-induced orbital precession and binary eccentricity. I will discuss how these features can be observed and the new insights they provide on the properties of the system and the formation and evolution of individual binaries and populations.

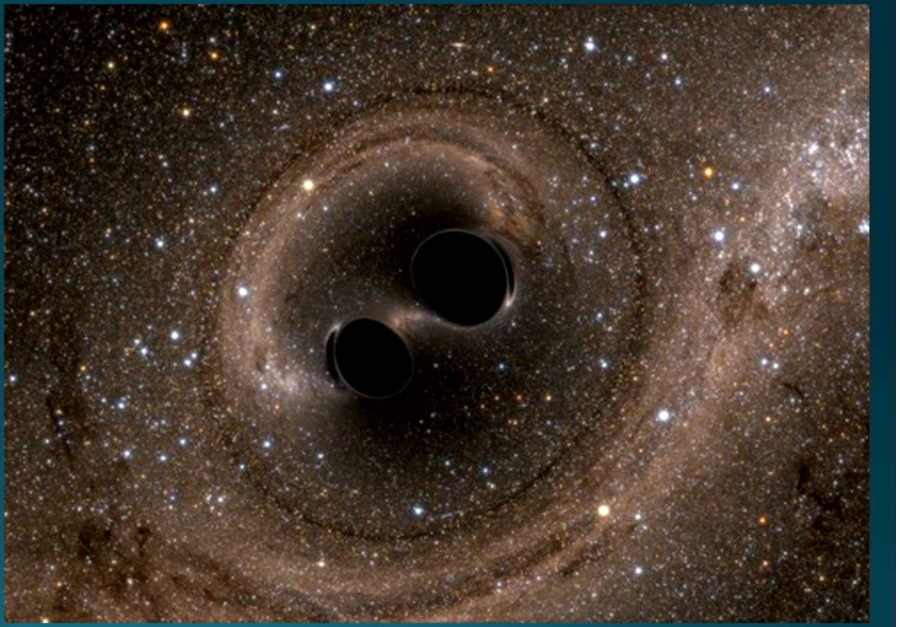


Deciphering Gravitational-Wave Observations

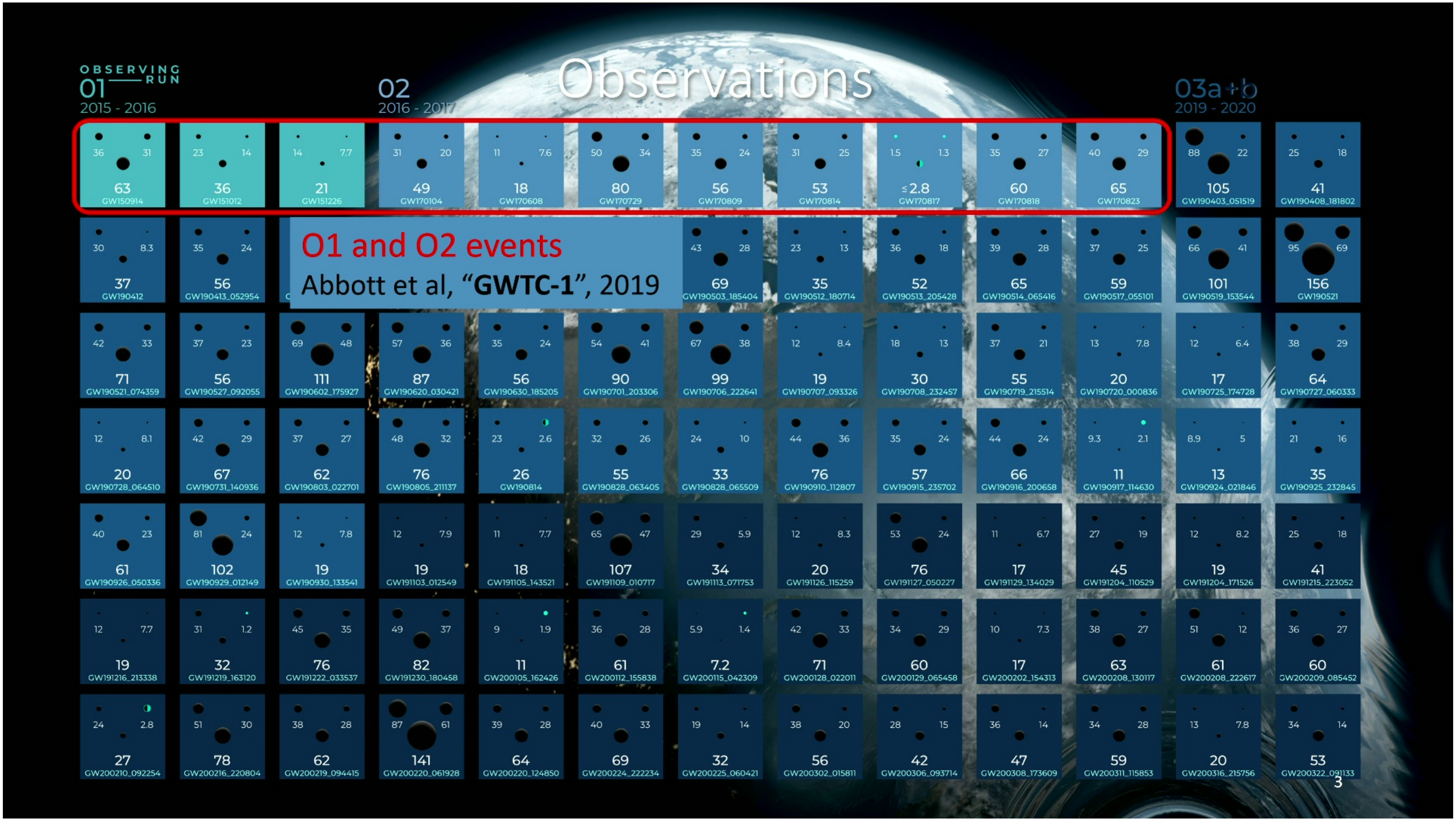
Stephen Fairhurst

2015: First Detection – GW150914





Abbott et al, arXiv: 1602.03837



Observations

OBSERVING RUN
O1
2015 - 2016

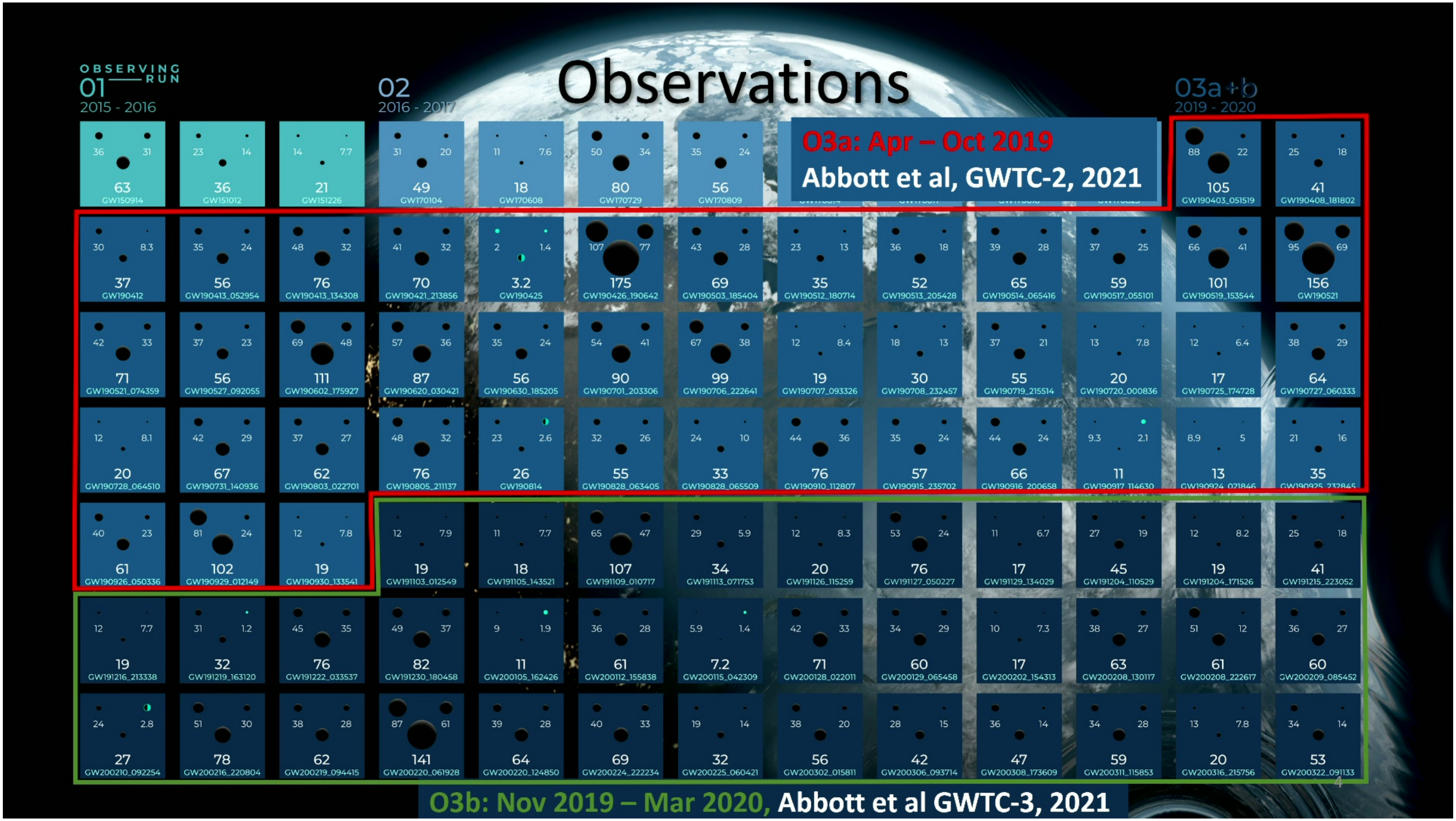
O2
2016 - 2017

O3a+b
2019 - 2020

O1 and O2 events

Abbott et al, “**GWTC-1**”, 2019

36 31 63 GW150914	23 14 36 GW151012	14 7.7 21 GW151226	31 20 49 GW170104	11 7.6 18 GW170608	50 34 80 GW170729	35 24 56 GW170809	31 25 53 GW170814	1.5 1.3 ≤2.8 GW170817	35 27 60 GW170818	40 29 65 GW170823	88 22 105 GW190403_051519	25 18 41 GW190408_181802
30 8.3 37 GW190412	35 24 56 GW190413_052954					43 28 69 GW190503_185404	23 13 35 GW190512_180714	36 18 52 GW190513_205428	39 28 65 GW190514_065416	37 25 59 GW190517_055101	66 41 101 GW190519_153544	95 69 156 GW190521
42 33 71 GW190521_074359	37 23 56 GW190527_092055	69 48 111 GW190602_175927	57 36 87 GW190620_030421	35 24 56 GW190630_185205	54 41 90 GW190701_203306	67 38 99 GW190706_222641	12 8.4 19 GW190707_093326	18 13 30 GW190708_232457	37 21 55 GW190719_215514	13 7.8 20 GW190720_000836	12 6.4 17 GW190725_174728	38 29 64 GW190727_060333
12 8.1 20 GW190728_064510	42 29 67 GW190731_140936	37 27 62 GW190803_022701	48 32 76 GW190805_211137	23 2.6 26 GW190814	32 26 55 GW190828_063405	24 10 33 GW190828_065509	44 36 76 GW190910_112807	35 24 57 GW190915_235702	44 24 66 GW190916_200658	9.3 2.1 11 GW190917_114630	8.9 5 13 GW190924_021846	21 16 35 GW190925_232845
40 23 61 GW190926_050336	81 24 102 GW190929_012149	12 7.8 19 GW190930_133541	12 7.9 19 GW191103_012549	11 7.7 18 GW191105_143521	65 47 107 GW191109_010717	29 5.9 34 GW191113_071753	12 8.3 20 GW191126_115259	53 24 76 GW191127_050227	11 6.7 17 GW191129_134029	27 19 45 GW191204_110529	12 8.2 19 GW191204_171526	25 18 41 GW191215_223052
12 7.7 19 GW191216_213338	31 1.2 32 GW191219_163120	45 35 76 GW191222_033537	49 37 82 GW191230_180458	9 1.9 11 GW200105_162426	36 28 61 GW200112_155838	5.9 1.4 7.2 GW200115_042309	42 33 71 GW200128_022011	34 29 60 GW200129_065458	10 7.3 17 GW200202_154313	38 27 63 GW200208_130117	51 12 61 GW200208_222617	36 27 60 GW200209_085452
24 2.8 27 GW200210_092254	51 30 78 GW200216_220804	38 28 62 GW200219_094415	87 61 141 GW200220_061928	39 28 64 GW200220_124850	40 33 69 GW200224_222234	19 14 32 GW200225_060421	38 20 56 GW200302_015811	28 15 42 GW200306_093714	36 14 47 GW200308_173609	34 28 59 GW200311_115853	13 7.8 20 GW200316_215756	34 14 53 GW200322_091133



Observations

OBSERVING RUN 01
2015 - 2016

02
2016 - 2017

O3a+b
2019 - 2020

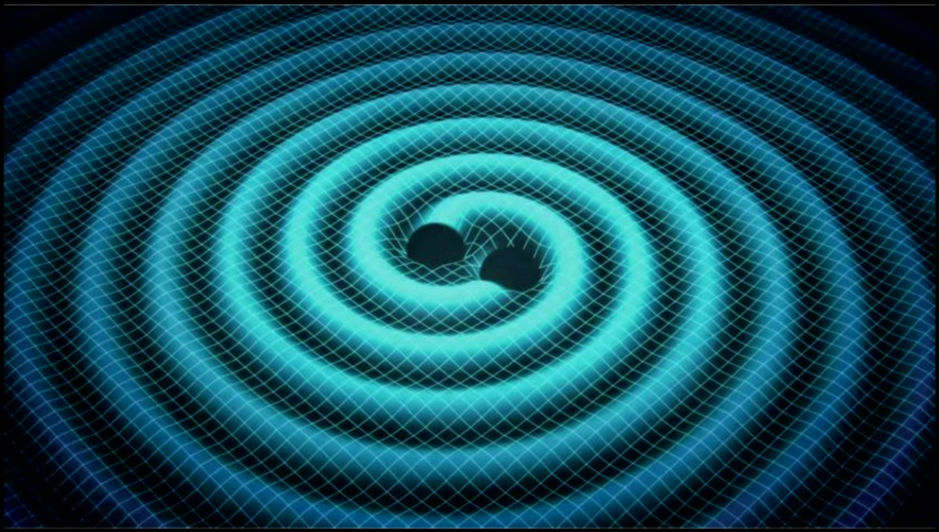
O3a: Apr – Oct 2019
Abbott et al, GWTC-2, 2021

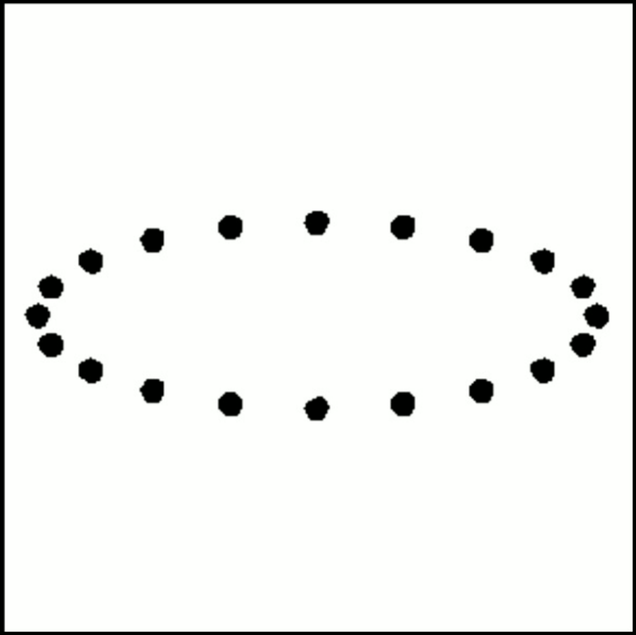
36 31 63 GW150914	23 14 36 GW151012	14 7.7 21 GW151226	31 20 49 GW170104	11 7.6 18 GW170608	50 34 80 GW170729	35 24 56 GW170809					88 22 105 GW190403_051519	25 18 41 GW190408_181802
30 8.3 37 GW190412	35 24 56 GW190413_052954	48 32 76 GW190413_134308	41 32 70 GW190421_213856	2 1.4 3.2 GW190425	107 77 175 GW190426_190642	43 28 69 GW190503_185404	23 13 35 GW190512_180714	36 18 52 GW190513_205428	39 28 65 GW190514_065416	37 25 59 GW190517_055101	66 41 101 GW190519_153544	95 69 156 GW190521
42 33 71 GW190521_074359	37 23 56 GW190527_092055	69 48 111 GW190602_175927	57 36 87 GW190620_030421	35 24 56 GW190630_185205	54 41 90 GW190701_203306	67 38 99 GW190706_222641	12 8.4 19 GW190707_093326	18 13 30 GW190708_232457	37 21 55 GW190719_215514	13 7.8 20 GW190720_000836	12 6.4 17 GW190725_174728	38 29 64 GW190727_060333
12 8.1 20 GW190728_064510	42 29 67 GW190731_140936	37 27 62 GW190803_022701	48 32 76 GW190805_211137	23 2.6 26 GW190814	32 26 55 GW190828_063405	24 10 33 GW190828_065509	44 36 76 GW190910_112807	35 24 57 GW190915_235702	44 24 66 GW190916_200658	9.3 2.1 11 GW190917_114630	8.9 5 13 GW190924_021846	21 16 35 GW190925_232845
40 23 61 GW190926_050336	81 24 102 GW190929_012149	12 7.8 19 GW190930_133541	12 7.9 19 GW191103_012549	11 7.7 18 GW191105_143521	65 47 107 GW191109_010717	29 5.9 34 GW191113_071753	12 8.3 20 GW191126_115259	53 24 76 GW191127_050227	11 6.7 17 GW191129_134029	27 19 45 GW191204_110529	12 8.2 19 GW191204_171526	25 18 41 GW191215_223052
12 7.7 19 GW191216_213338	31 1.2 32 GW191219_163120	45 35 76 GW191222_033537	49 37 82 GW191230_180458	9 1.9 11 GW200105_162426	36 28 61 GW200112_155838	5.9 1.4 7.2 GW200115_042309	42 33 71 GW200128_022011	34 29 60 GW200129_065458	10 7.3 17 GW200202_154313	38 27 63 GW200208_130117	51 12 61 GW200208_222617	36 27 60 GW200209_085452
24 2.8 27 GW200210_092254	51 30 78 GW200216_220804	38 28 62 GW200219_094415	87 61 141 GW200220_061928	39 28 64 GW200220_124850	40 33 69 GW200224_222234	19 14 32 GW200225_060421	38 20 56 GW200302_015811	28 15 42 GW200306_093714	36 14 47 GW200308_173609	34 28 59 GW200311_115853	13 7.8 20 GW200316_215756	34 14 53 GW200322_091133

O3b: Nov 2019 – Mar 2020, Abbott et al GWTC-3, 2021

Gravitational Waves

Originate from accelerating masses



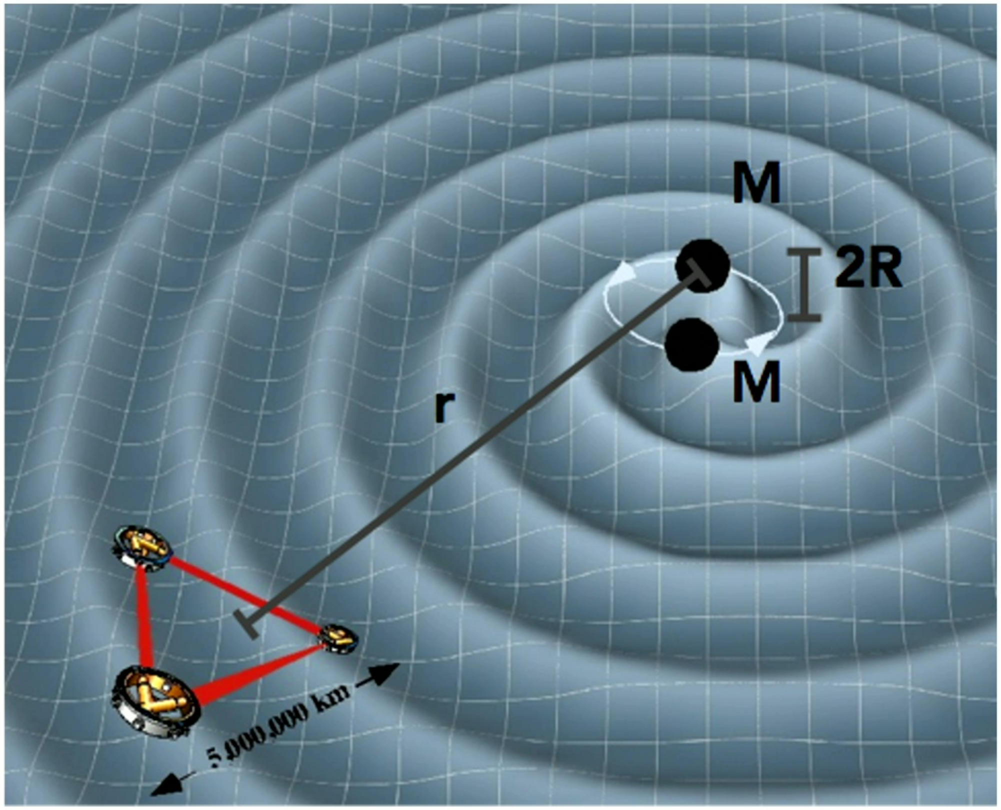


Generating gravitational waves

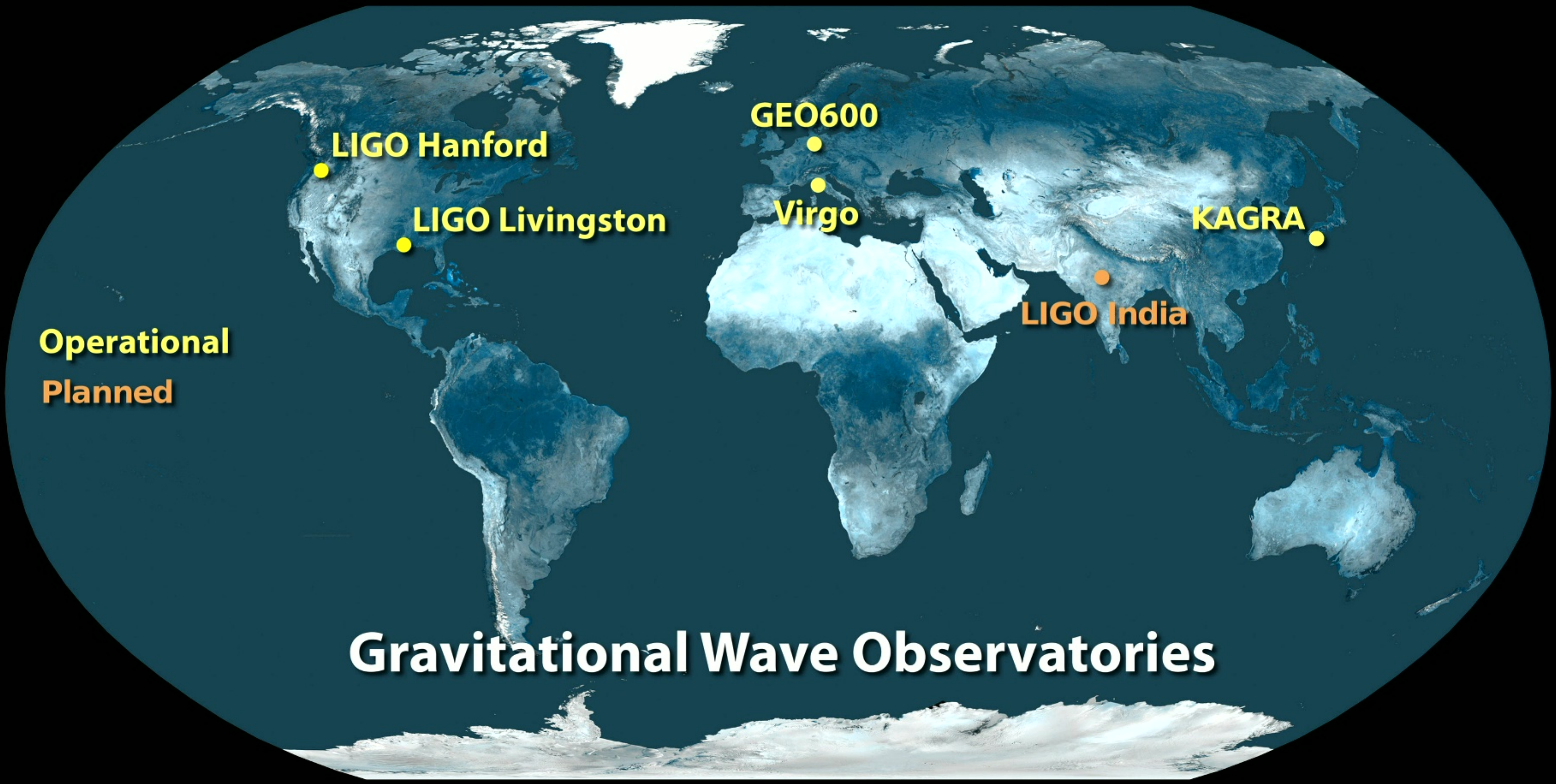
- Time varying mass quadrupole generates gravitational waves
- Binary system is ideal

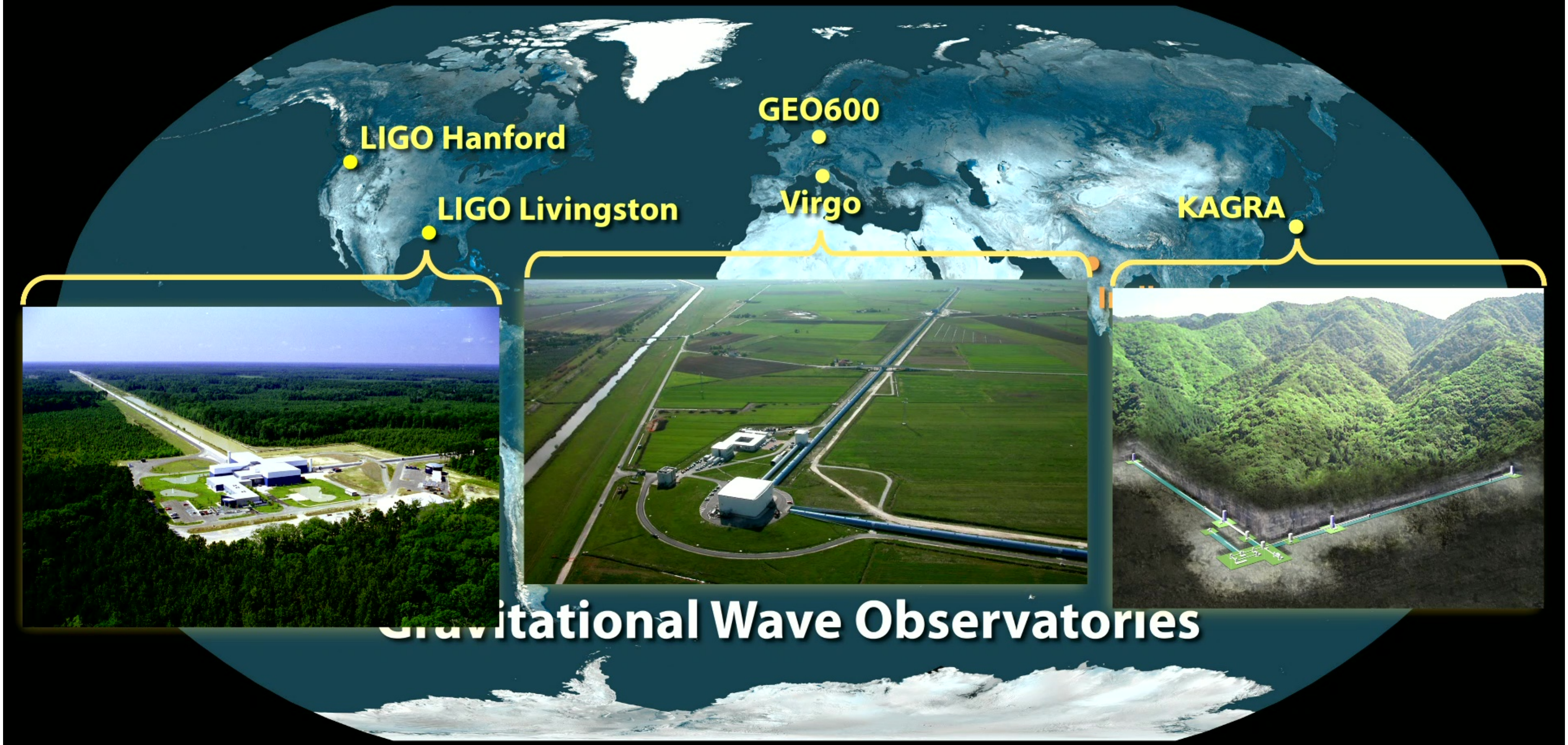
$$h \sim \left(\frac{GM}{c^2 R}\right)\left(\frac{GM}{c^2 r}\right)$$

$$P \sim \frac{GM^2 v^6}{c^5 R^2}$$

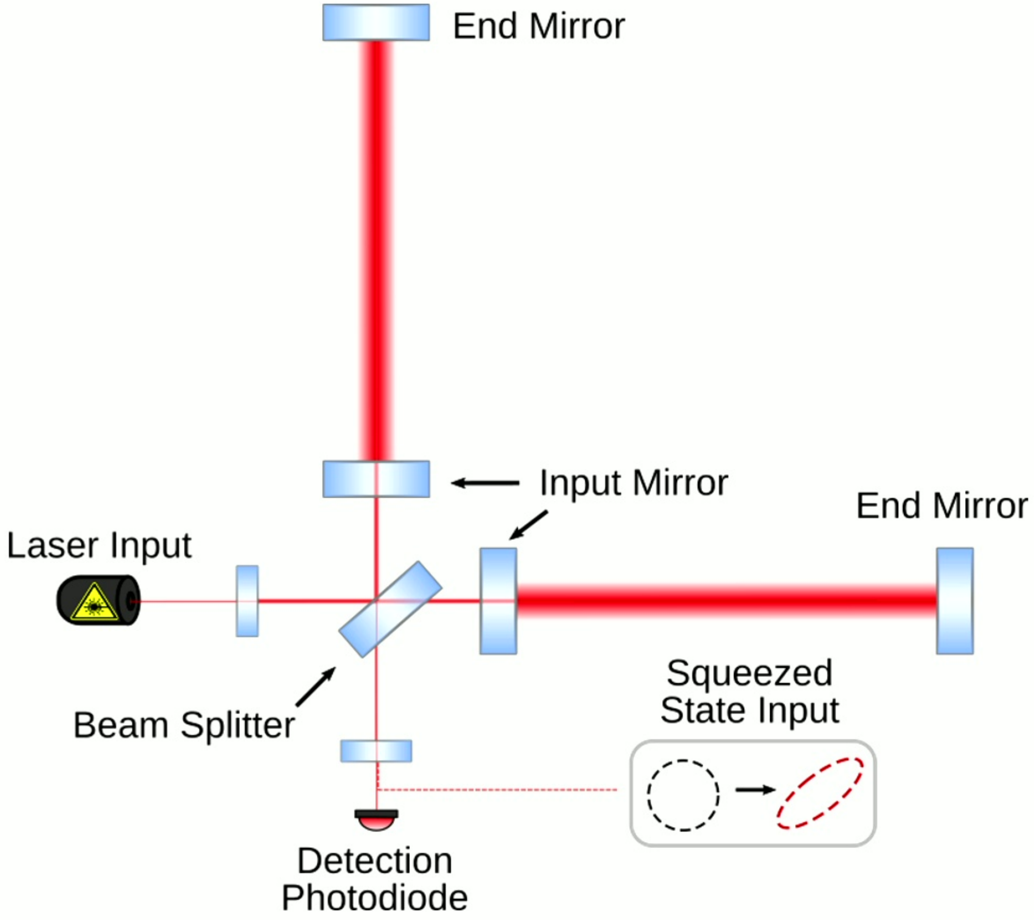


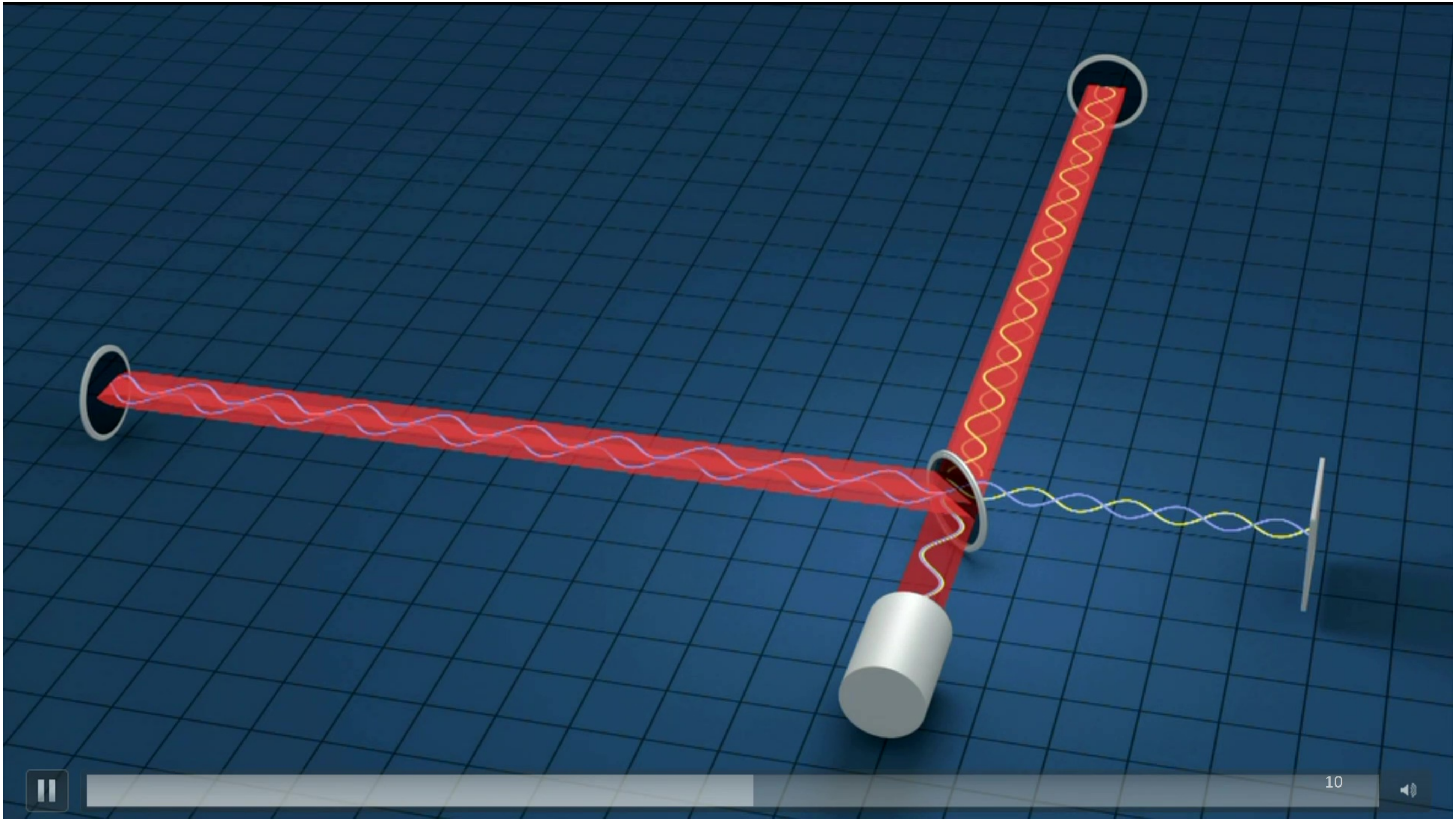
Gravitational Wave Observatories

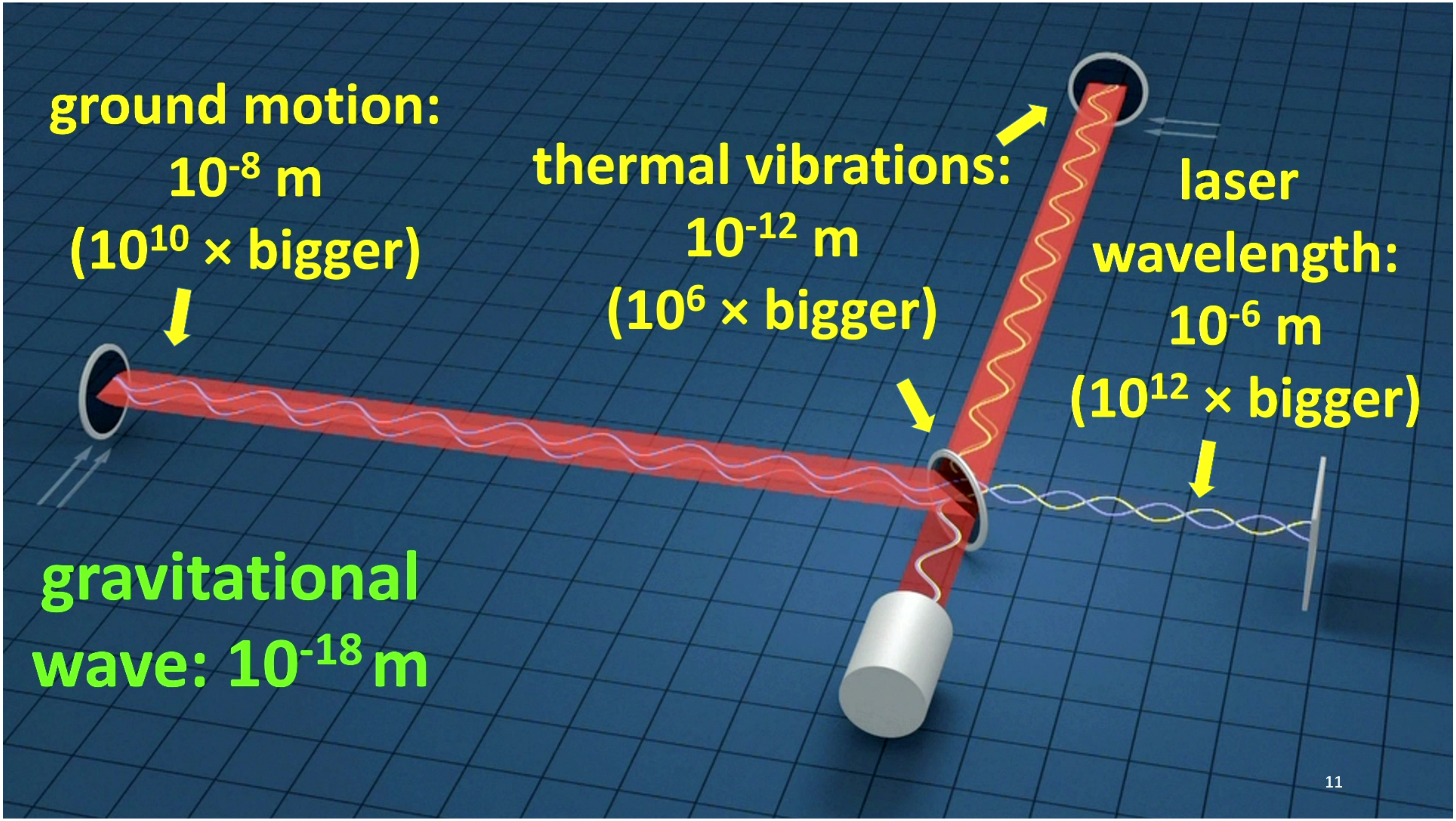



GEO600
LIGO Hanford
LIGO Livingston
Virgo
KAGRA
itational Wave Observatories

Gravitational Wave Detectors




10

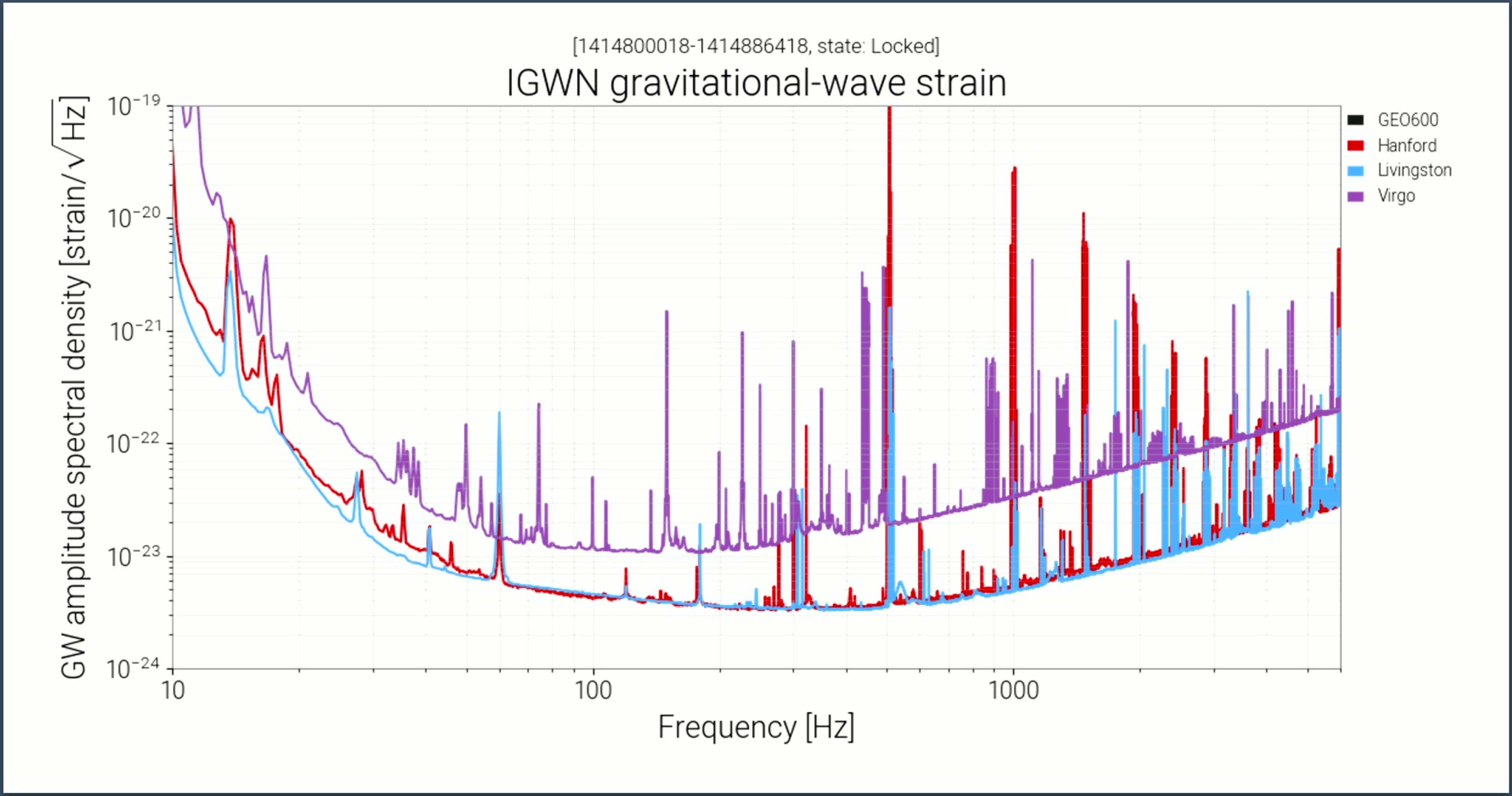


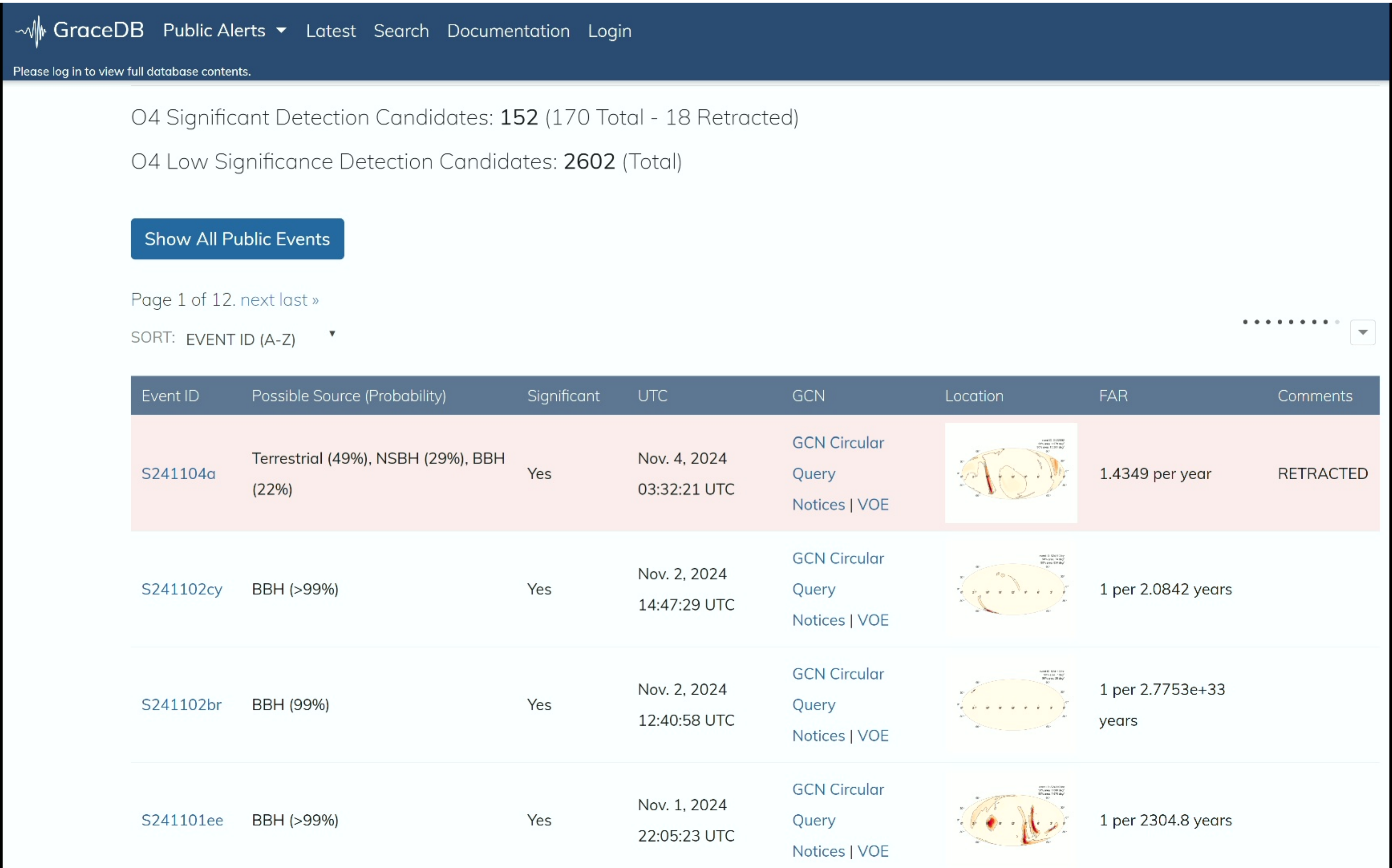
ground motion:
10^{-8} m
(10^{10} × bigger)

thermal vibrations:
10^{-12} m
(10^{6} × bigger)

laser wavelength:
10^{-6} m
(10^{12} × bigger)

gravitational wave: 10^{-18} m


[1414800018-1414886418, state: Locked]
IGWN gravitational-wave strain
GW amplitude spectral density [strain/$\sqrt{\text{Hz}}$]
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10
100
1000
Frequency [Hz]
GEO600
Hanford
Livingston
Virgo



Please log in to view full database contents.

O4 Significant Detection Candidates: **152** (170 Total - 18 Retracted)

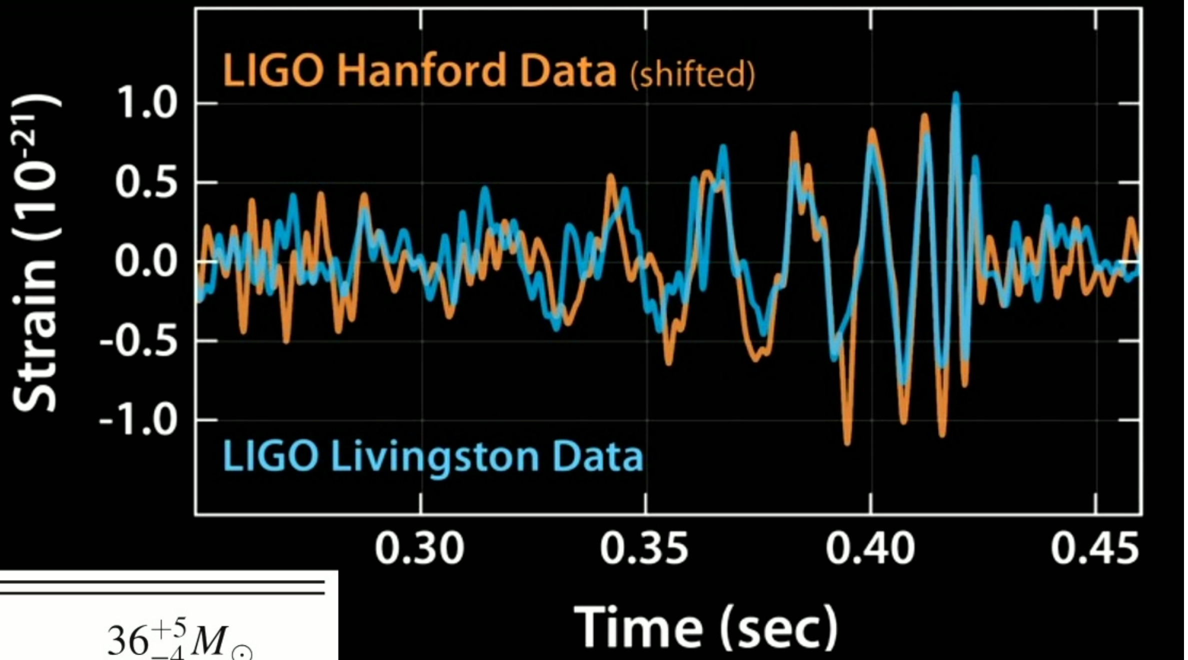
O4 Low Significance Detection Candidates: **2602** (Total)

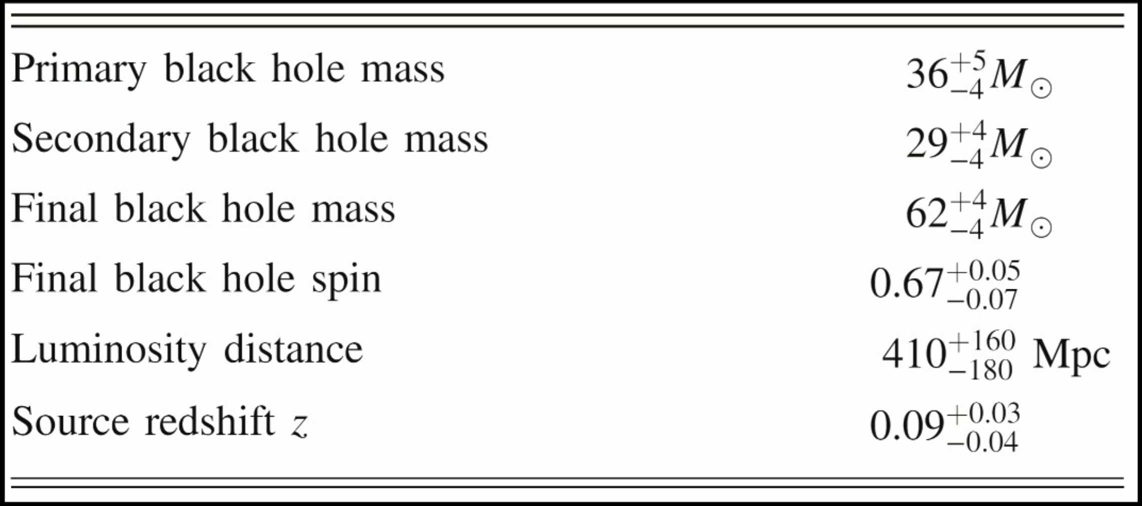
Page 1 of 12. next last »

SORT: EVENT ID (A-Z)

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S241104a	Terrestrial (49%), NSBH (29%), BBH (22%)	Yes	Nov. 4, 2024 03:32:21 UTC	GCN Circular Query Notices | VOE		1.4349 per year	RETRACTED
S241102cy	BBH (>99%)	Yes	Nov. 2, 2024 14:47:29 UTC	GCN Circular Query Notices | VOE		1 per 2.0842 years	
S241102br	BBH (99%)	Yes	Nov. 2, 2024 12:40:58 UTC	GCN Circular Query Notices | VOE		1 per 2.7753e+33 years	
S241101ee	BBH (>99%)	Yes	Nov. 1, 2024 22:05:23 UTC	GCN Circular Query Notices | VOE		1 per 2304.8 years	

How to go from this …





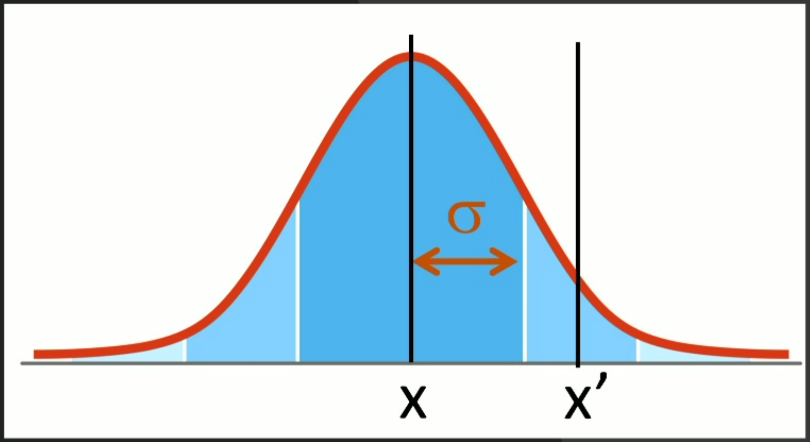
Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

… to this?

Measurement Accuracy

- Can distinguish x and x’ if

$$|x - x'| \geq \text{few } \sigma$$

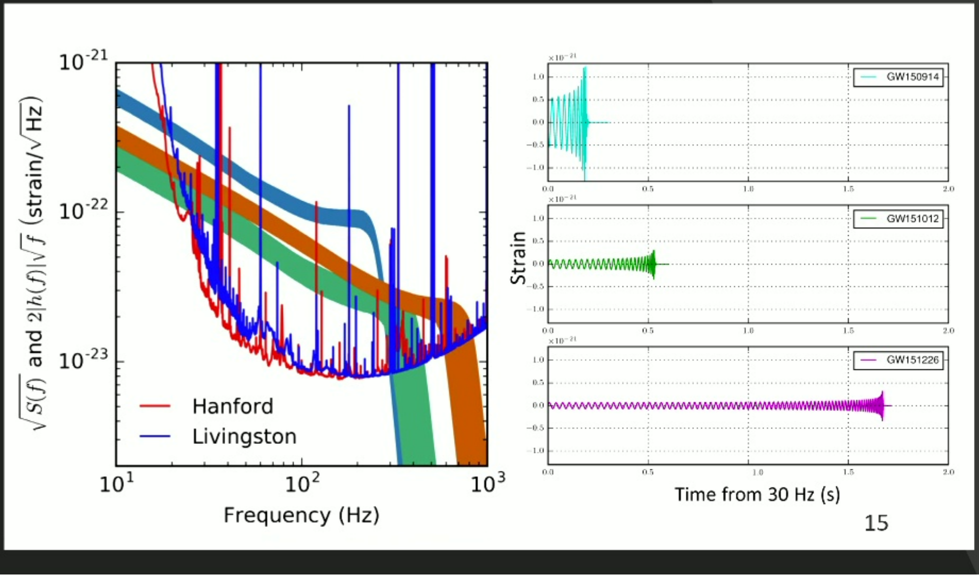


- For gravitational waves, can distinguish waveforms h_1 and h_2 if

$$|h_1 - h_2| \geq \text{few}$$

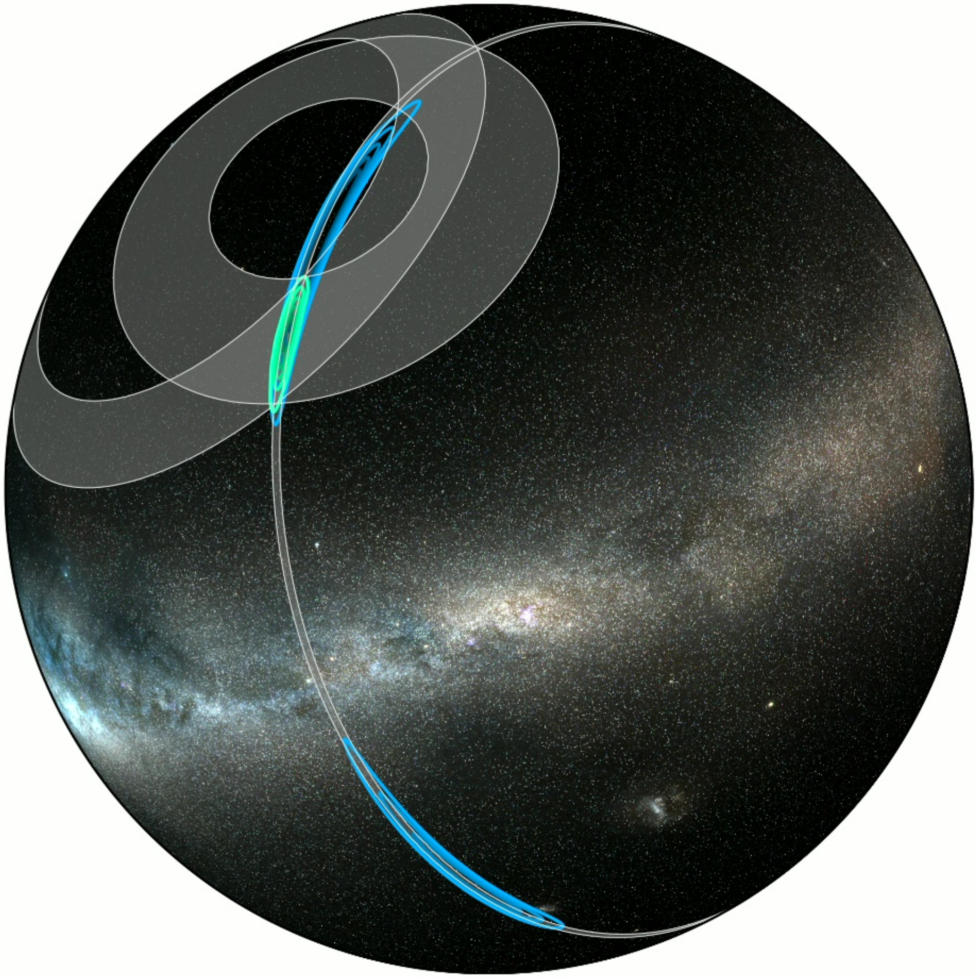
where

$$(h_1, h_2) = 4\,\mathrm{Re}\int_0^\infty \frac{h_1(f)h_2^*(f)}{S(f)}\,df$$



Source localization

- Localization primarily from time delays between detectors
- Using relative amplitude and phase improves accuracy



Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)

Source localization

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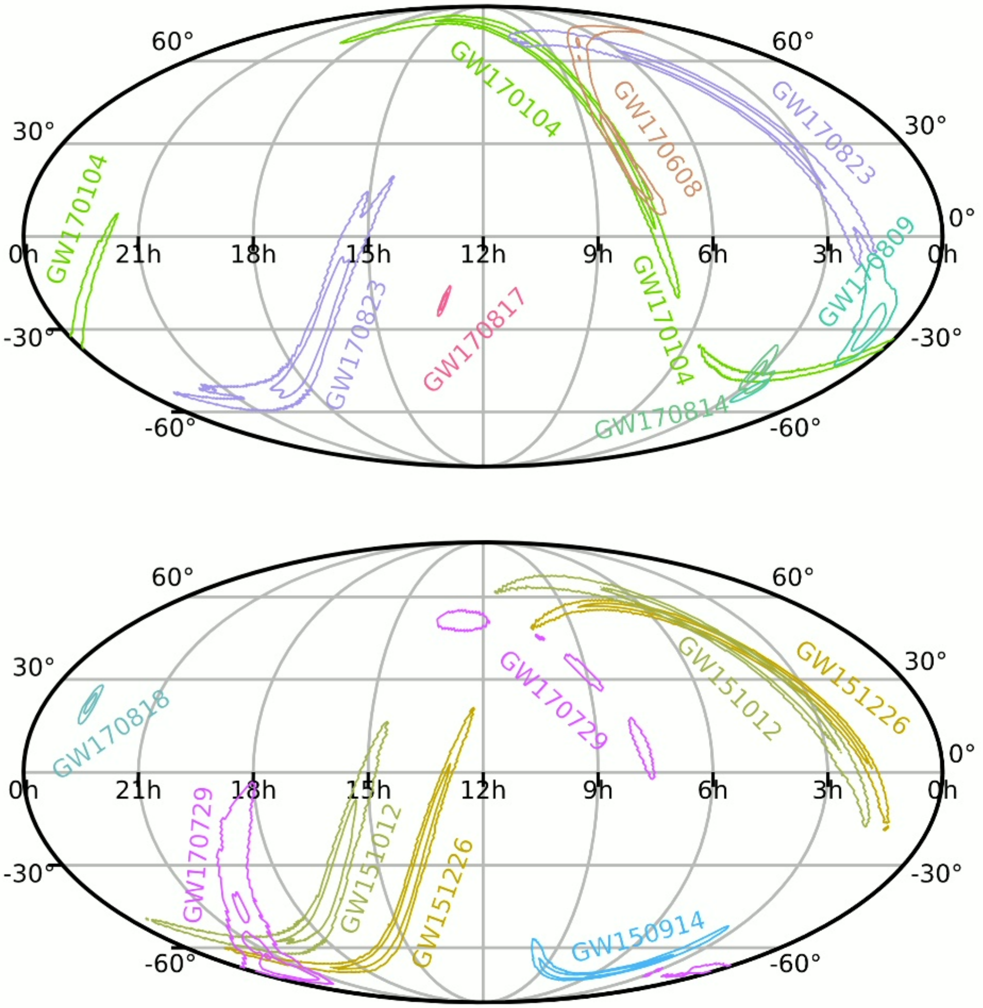
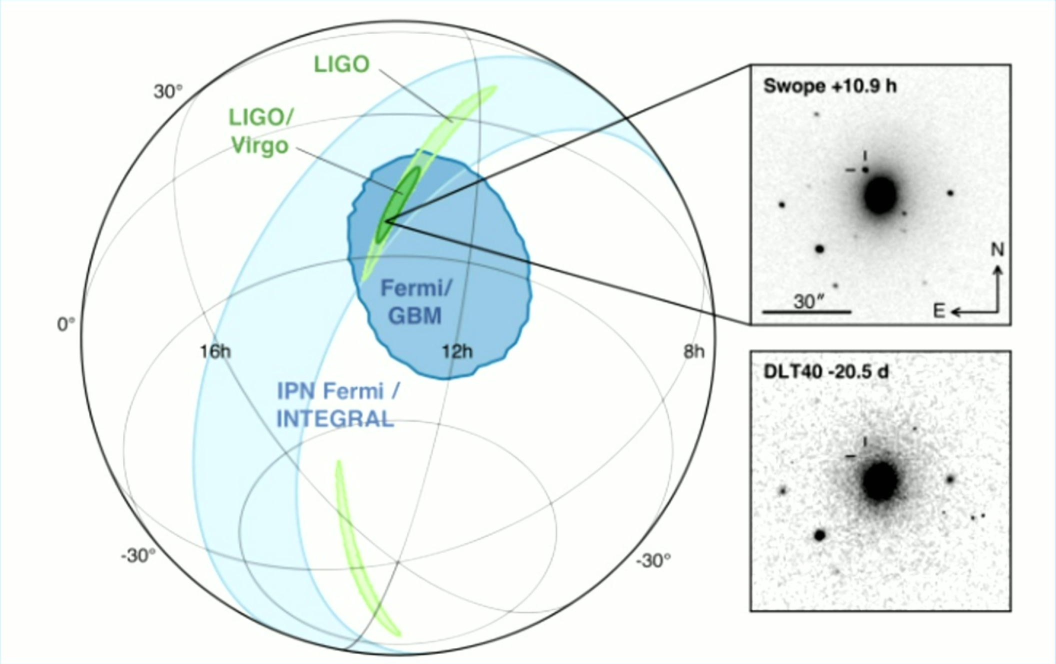


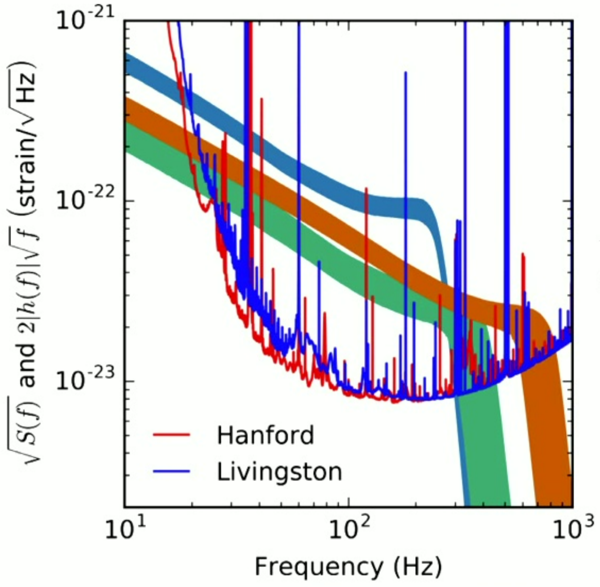
GW170817: Neutron Stars and Multi-messenger Observation

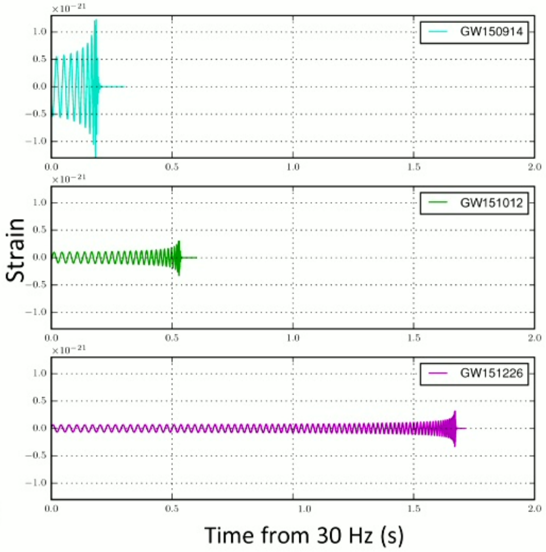


From Abbott et al, “**Multi-Messenger Observations of a Binary Neutron Star Merger** ”, 2017

Masses

- Orbits decay due to emission of gravitational waves
- **Leading order** evolution of waveform determined by “chirp mass”

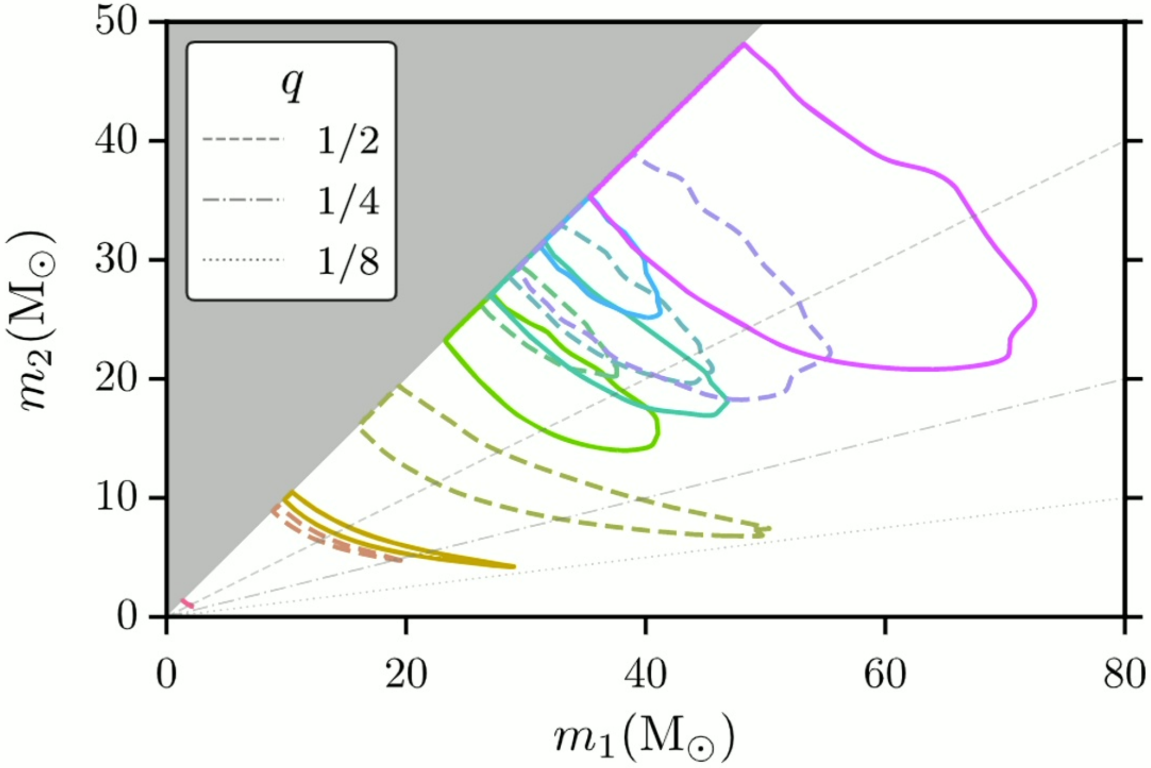




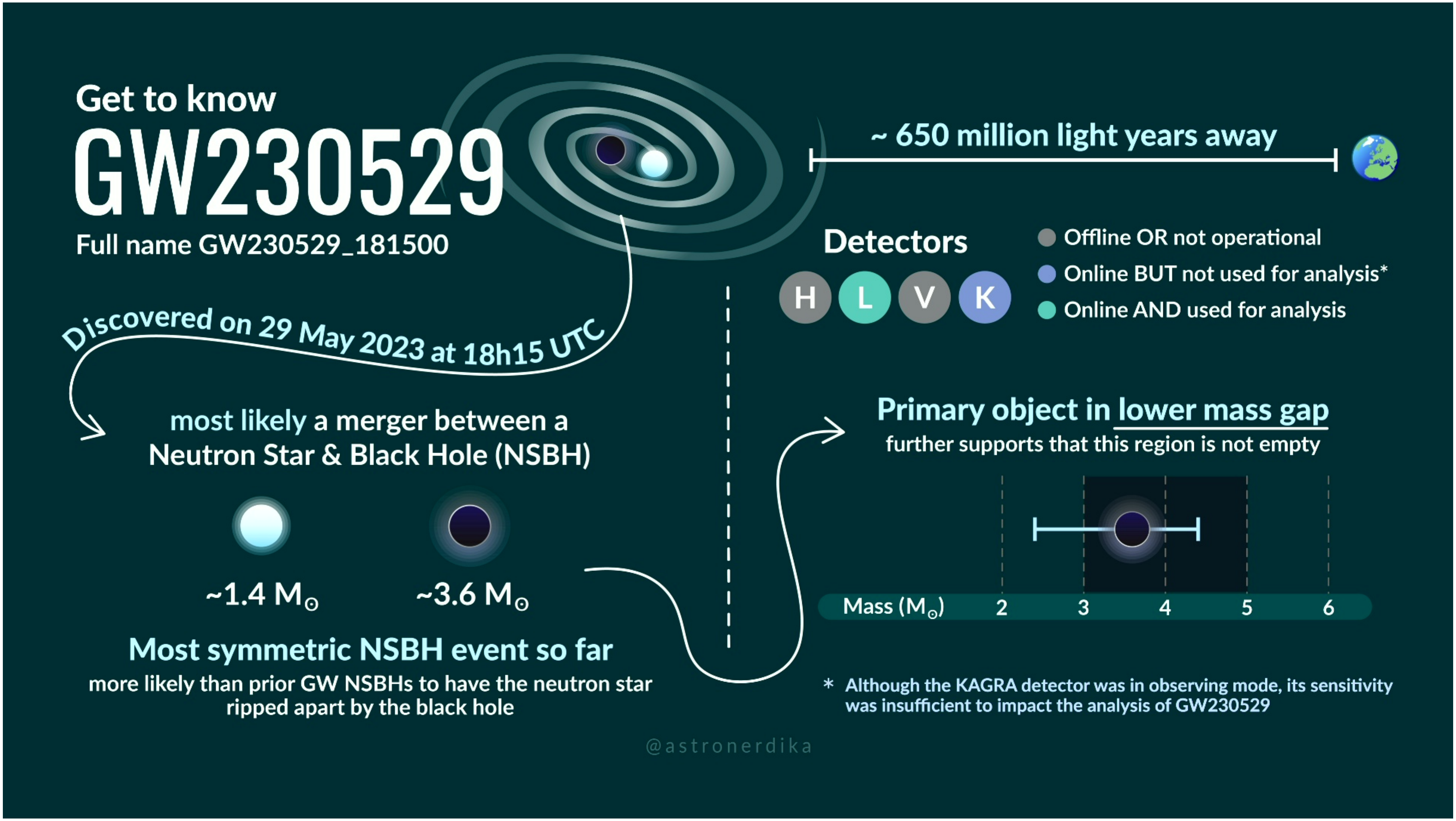
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}} \simeq \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right]^{3/5}$$

Masses

- Orbits decay due to emission of gravitational waves
- **Leading order** evolution of waveform determined by "chirp mass"



$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}} \simeq \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$



Get to know

GW230529

Full name GW230529_181500

Discovered on 29 May 2023 at 18h15 UTC

~ 650 million light years away

Detectors

H L V K

- ● Offline OR not operational
- ● Online BUT not used for analysis*
- ● Online AND used for analysis

most likely a merger between a Neutron Star & Black Hole (NSBH)

~1.4 $M_\odot$

~3.6 $M_\odot$

Most symmetric NSBH event so far

more likely than prior GW NSBHs to have the neutron star ripped apart by the black hole

Primary object in lower mass gap

further supports that this region is not empty

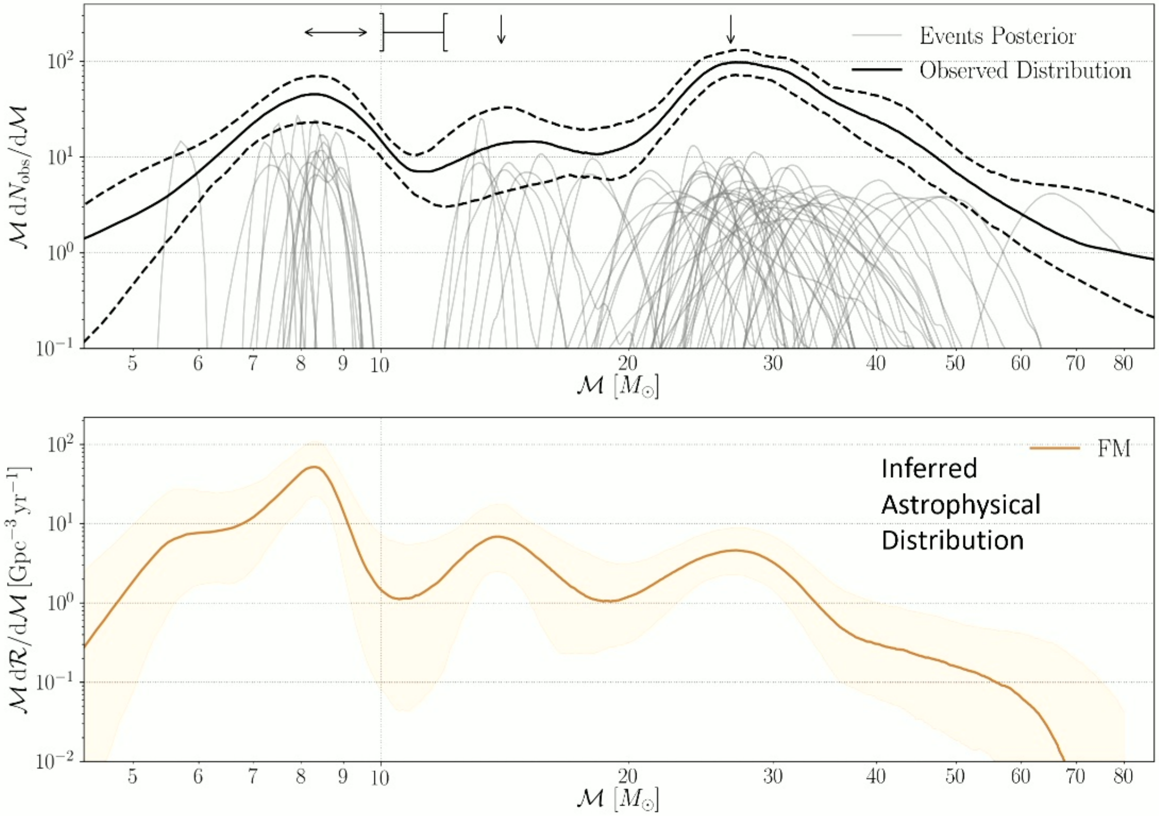
* Although the KAGRA detector was in observing mode, its sensitivity was insufficient to impact the analysis of GW230529

@astronerdika

Mass Population

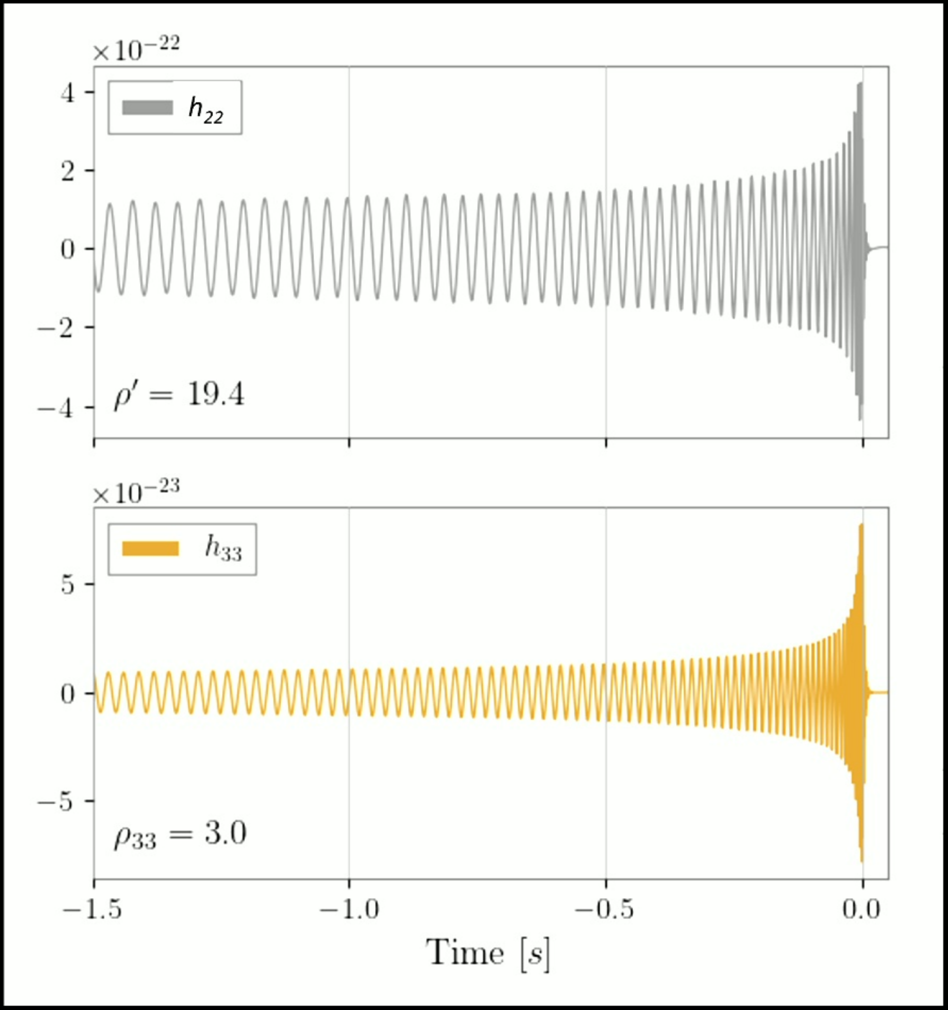
Over-density between $8M_\odot$ and $10M_\odot$ and around $26M_\odot$.

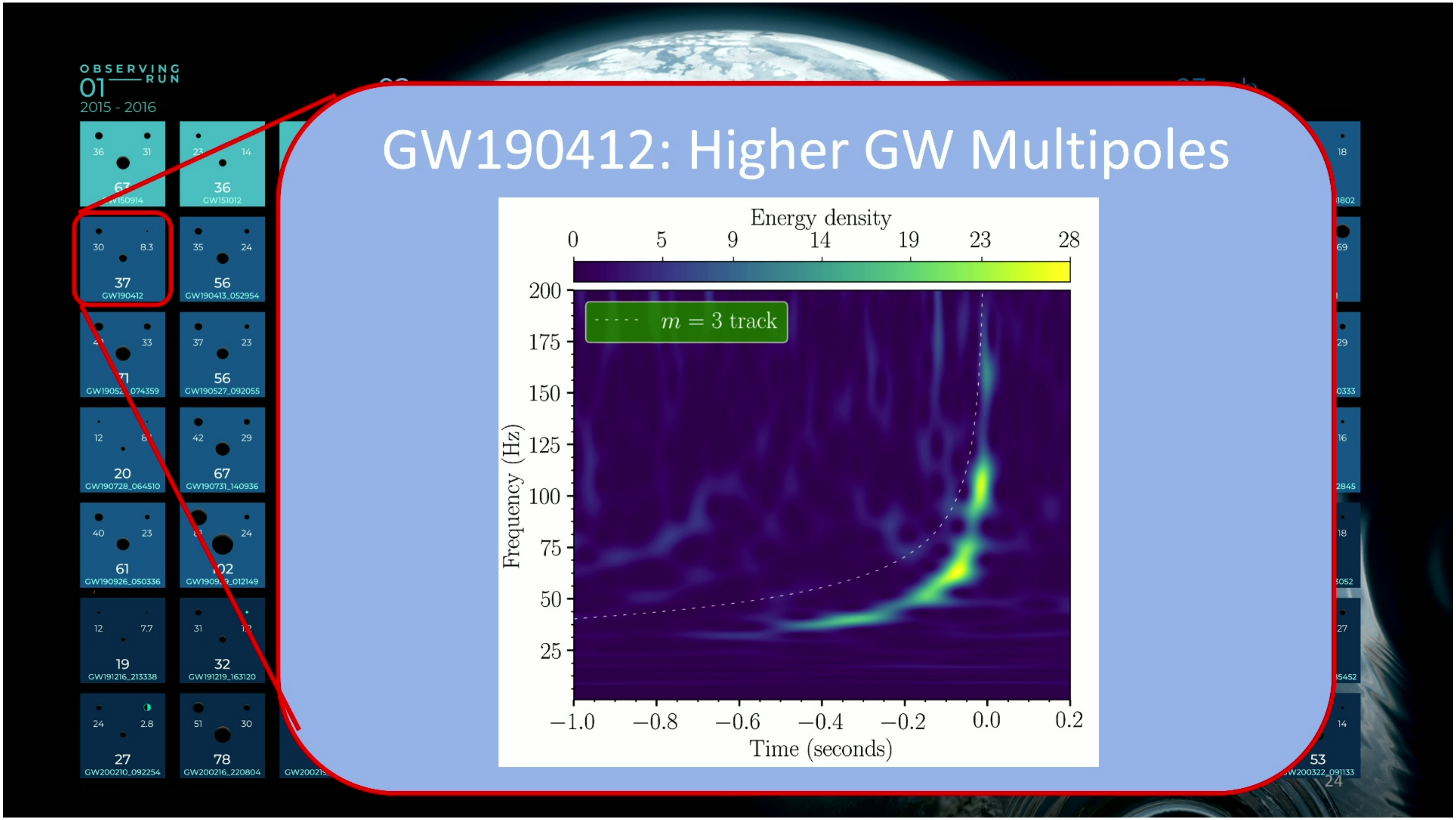
- A **weaker feature** at around $14M_\odot$
- **Absence** of mergers between $10M_\odot$ and $12M_\odot$.



Higher Multipoles

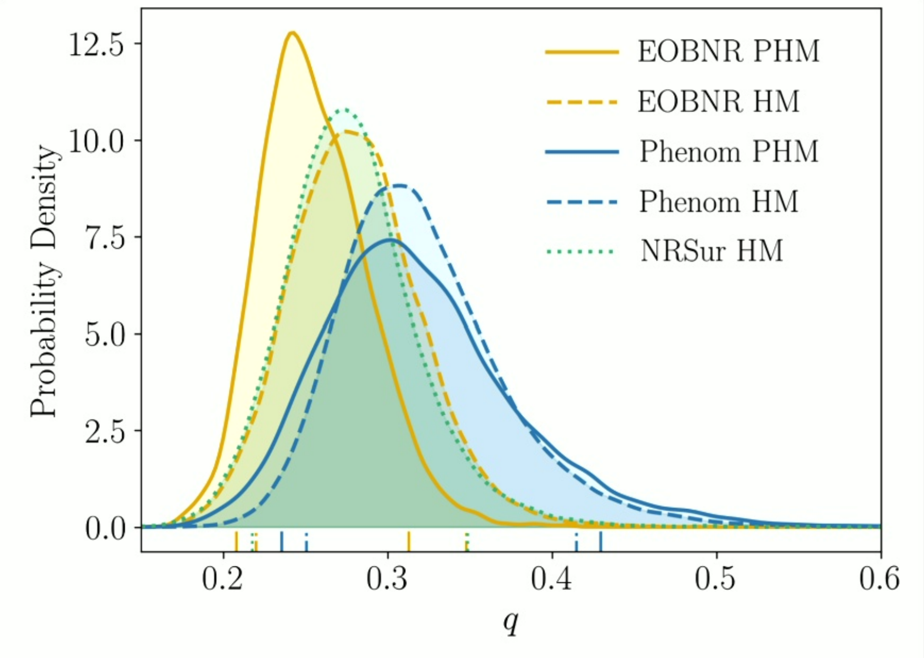
- Gravitational wave can be decomposed as infinite sum of spherical harmonics
- (*l*, m) = (2, 2) is dominant
- Other harmonics contribute, particularly (3, 3) and (4, 4)
- Many modes vanish for equal mass and/or face-on systems



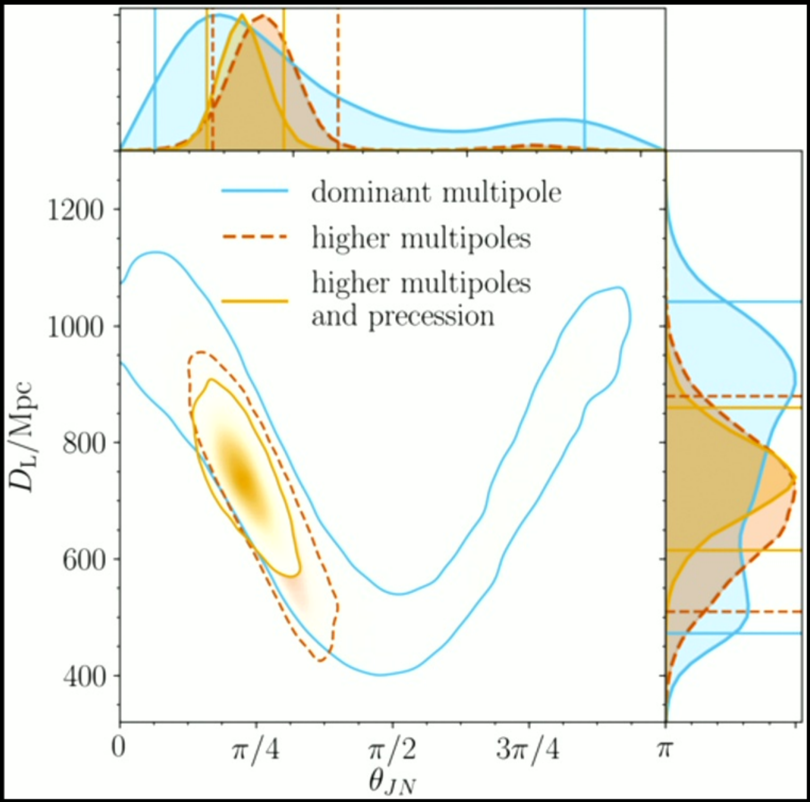


GW190412: Higher GW Multipoles

GW 190412: Unequal mass and higher harmonics



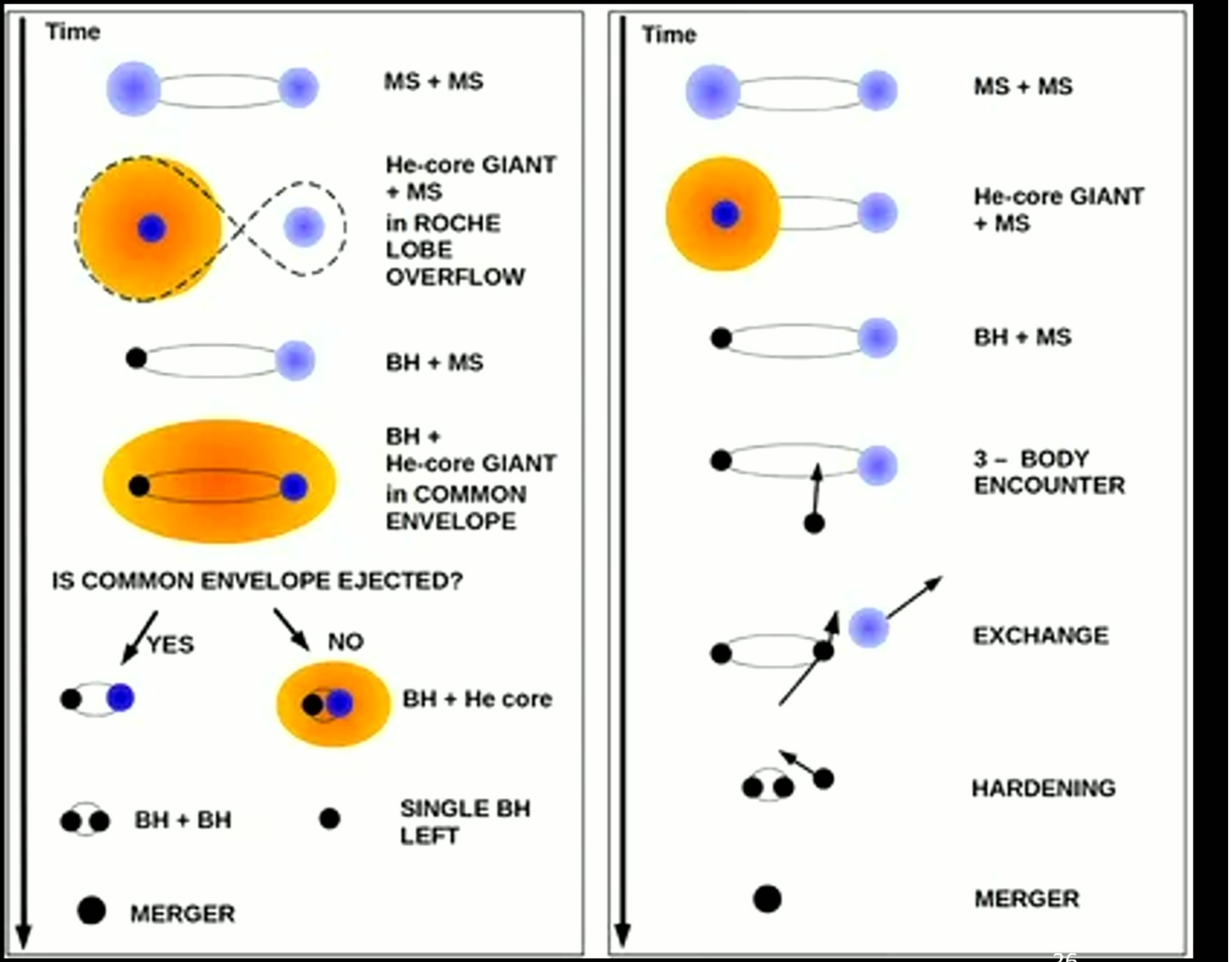
Mass ratio, m_2/m_1



Spins

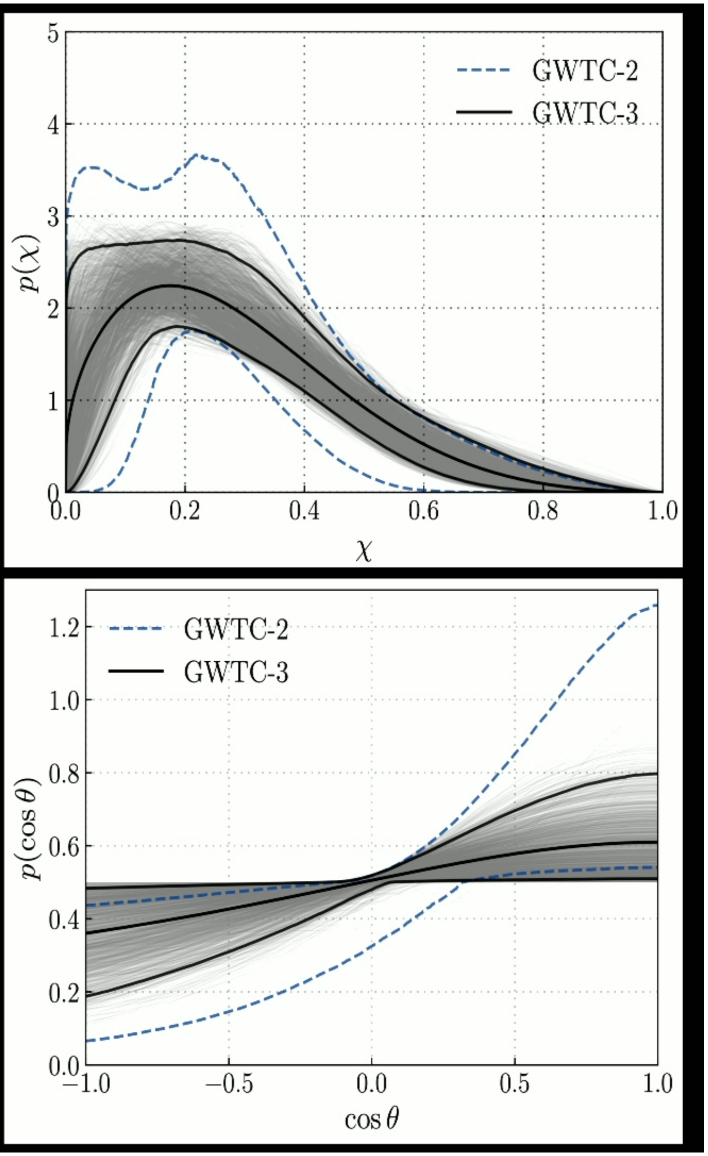
Spins can teach us about binary formation scenarios

- Aligned spins in isolated binary
- Arbitrary orientation in dynamical binary
- Larger spins in hierarchical mergers



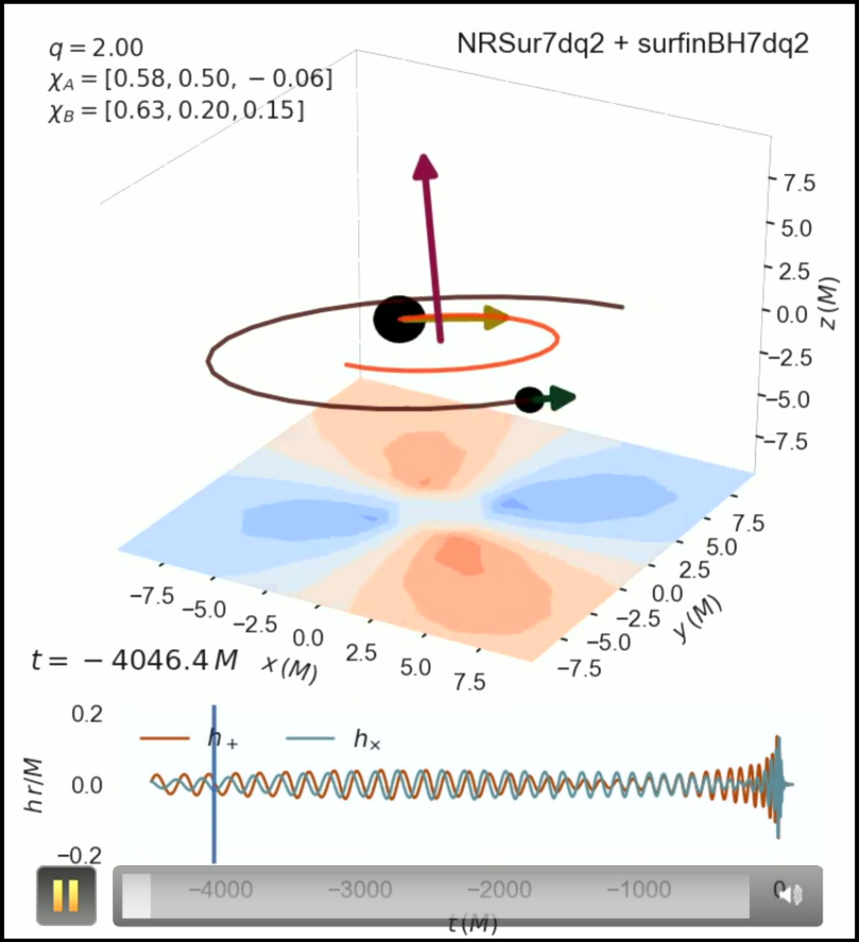
Spin Population

- Spin **magnitudes** generally small but non-vanishing.
- Significant **spin-orbit misalignment**
- Despite misalignment, spin orientations are **not isotropic**; challenge to purely-dynamical origin

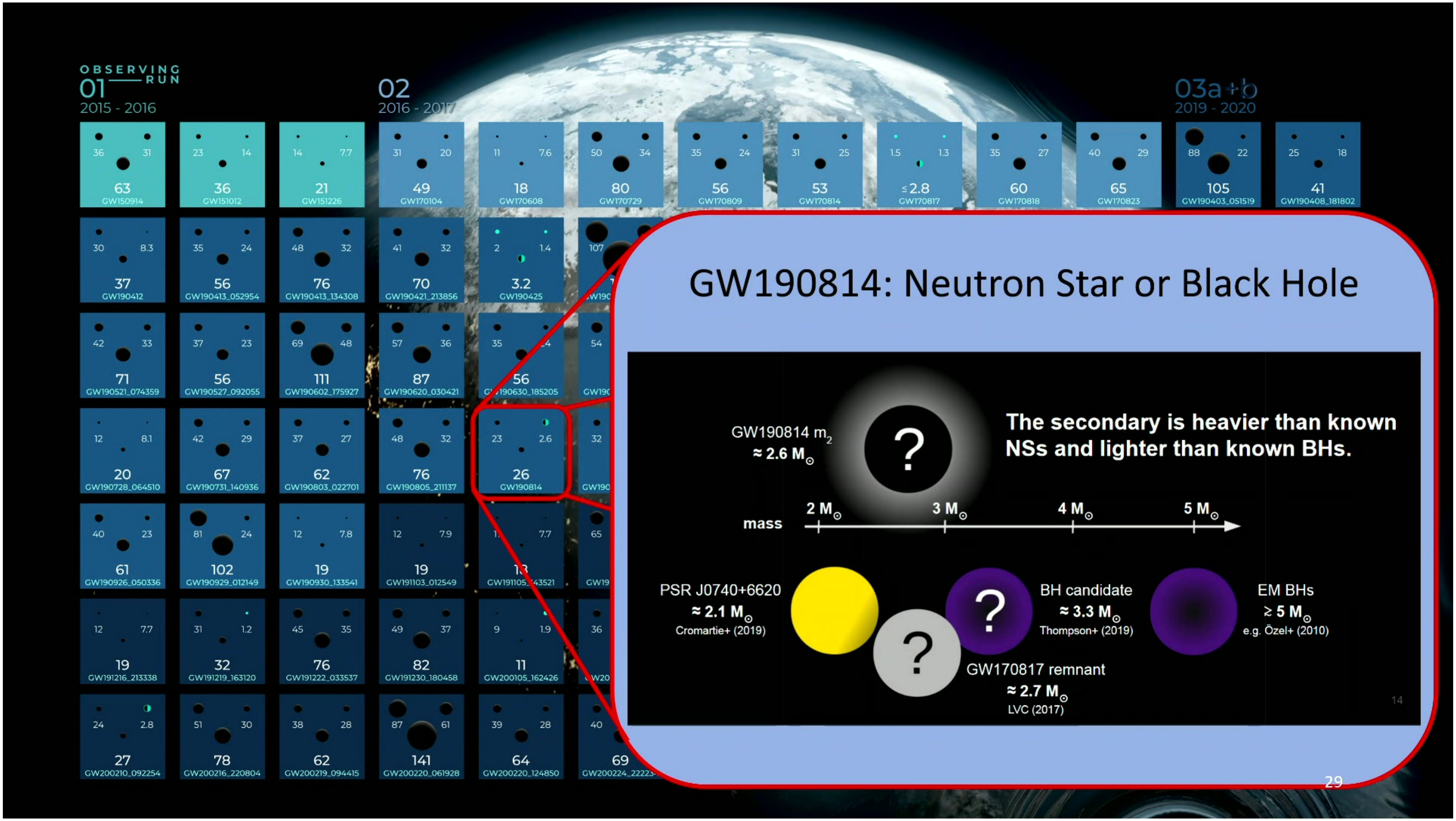


Precession

- If spins are mis-aligned with orbital angular momentum, then orbital plane changes over time
- Direction of angular momentum remains (approximately) constant
- Leads to modulations of the waveform. Can be interpreted as "beating" of different harmonics with similar frequency



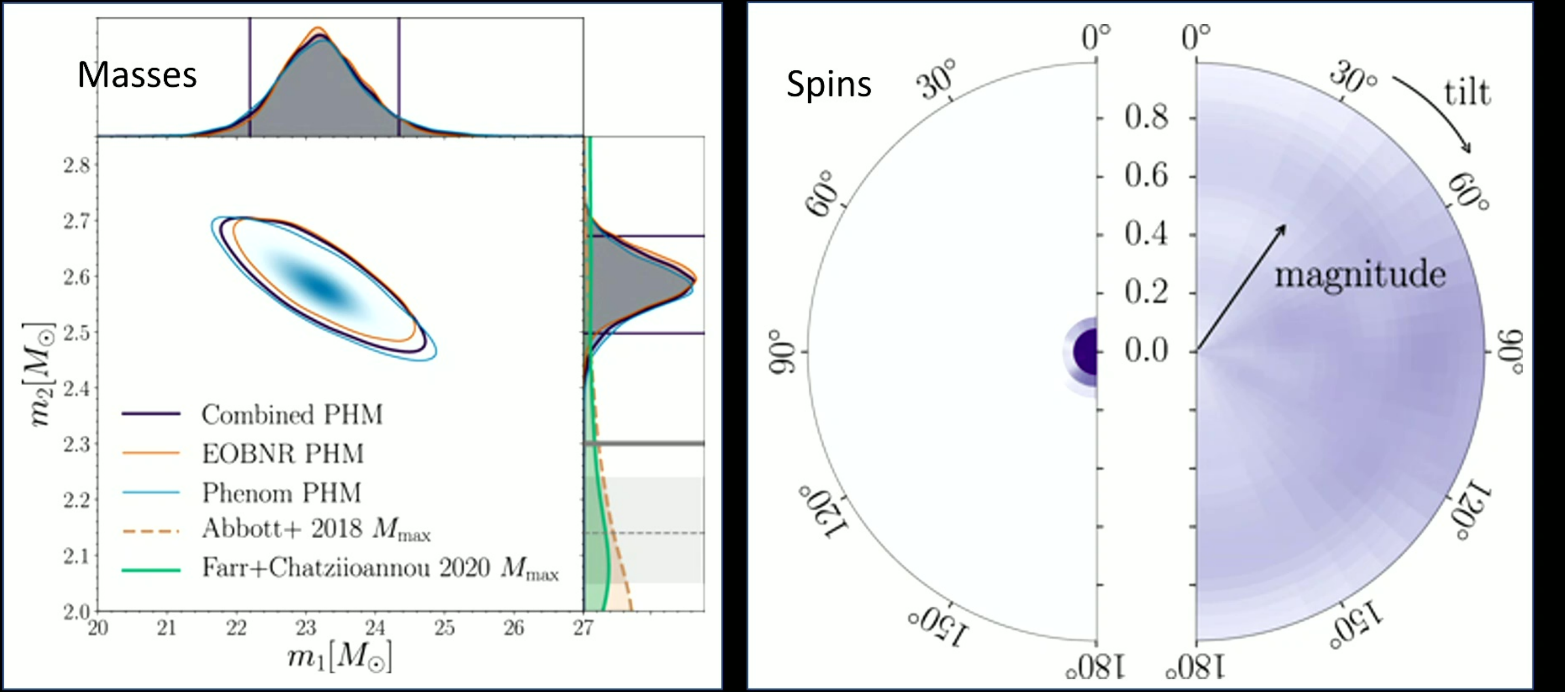
From: https://vijayvarma392.github.io/binaryBHexp



GW190814: Neutron Star or Black Hole

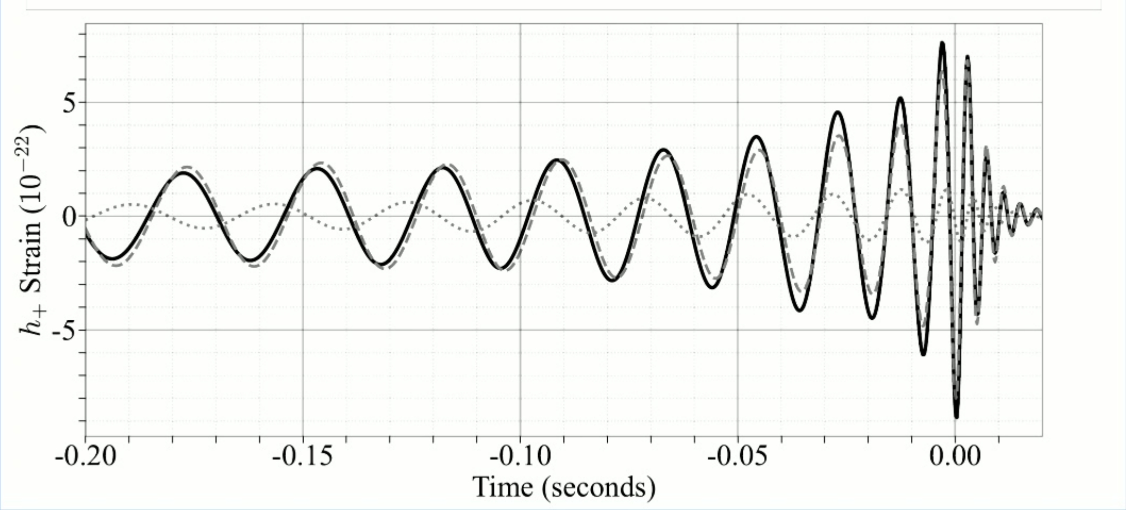
The secondary is heavier than known NSs and lighter than known BHs.

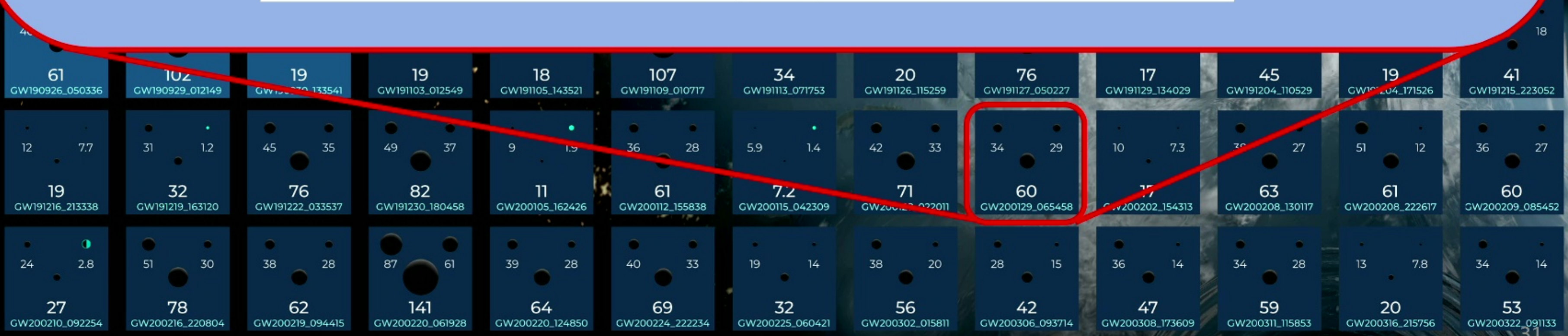
GW190814: A 2.6 $M_\odot$ compact object



From Abbott et al, “GW190814: Gravitational Waves from the Coalescence of a 23 $M_\odot$ Black Hole with a 2.6 $M_\odot$ Compact Object”, 2020

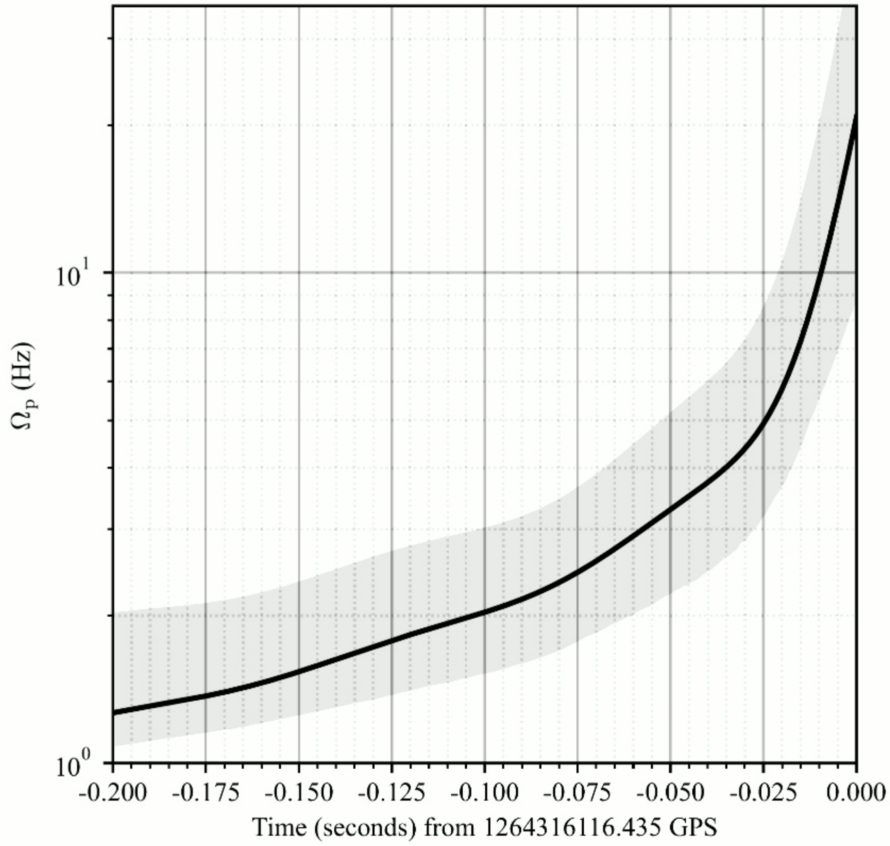
GW200129: Strong Evidence for Precession



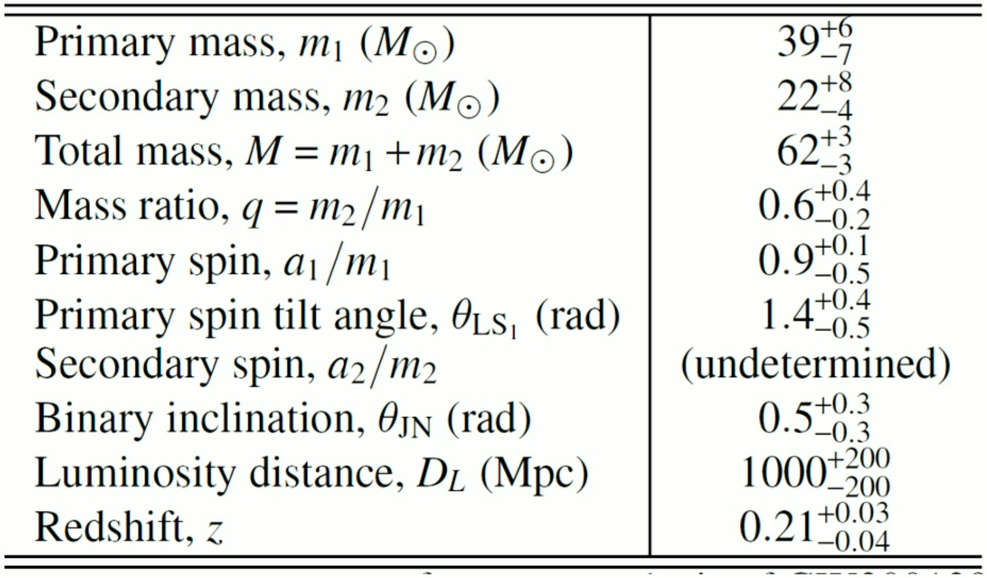


Measurement of precession

- Previously observed in binary pulsars
  - deSitter precession: precession of pulsar spin
  - Frequency ~10^{-10} Hz
- GW200129
  - Strong field precession
  - Both component spins and orbit precess, total angular momentum approximately constant
  - Frequency > 1 Hz
  - About 1 precession cycle in observable waveform



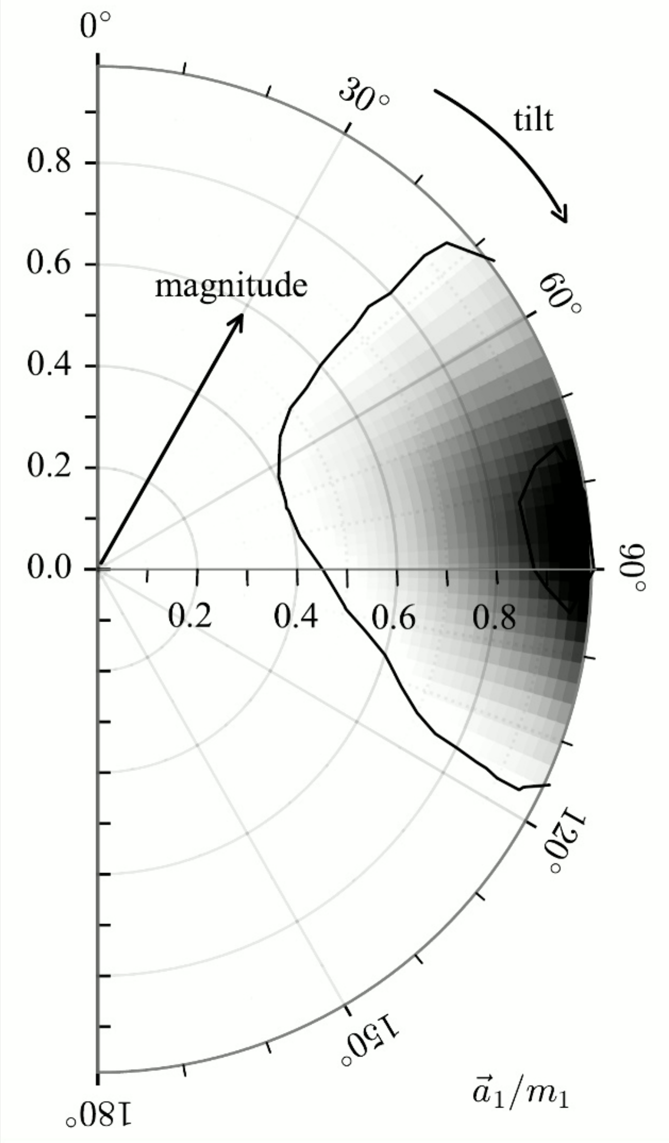
GW200129 Parameters



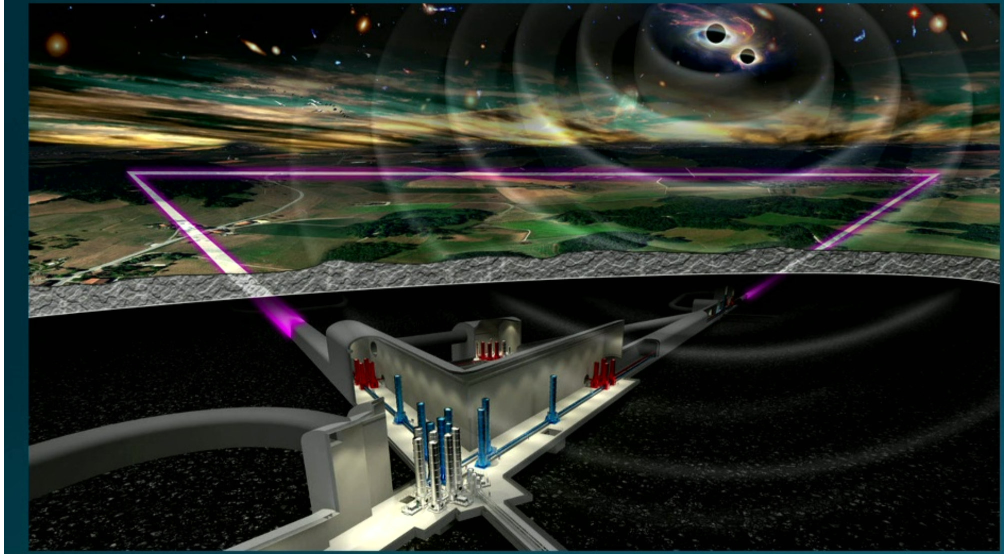
Primary mass, m_1 ($M_\odot$)	39^{+6}_{-7}
Secondary mass, m_2 ($M_\odot$)	22^{+8}_{-4}
Total mass, $M = m_1 + m_2$ ($M_\odot$)	62^{+3}_{-3}
Mass ratio, $q = m_2/m_1$	$0.6^{+0.4}_{-0.2}$
Primary spin, a_1/m_1	$0.9^{+0.1}_{-0.5}$
Primary spin tilt angle, θ_{LS_1} (rad)	$1.4^{+0.4}_{-0.5}$
Secondary spin, a_2/m_2	(undetermined)
Binary inclination, θ_{JN} (rad)	$0.5^{+0.3}_{-0.3}$
Luminosity distance, D_L (Mpc)	1000^{+200}_{-200}
Redshift, z	$0.21^{+0.03}_{-0.04}$

Signal to noise ratio: 26.5

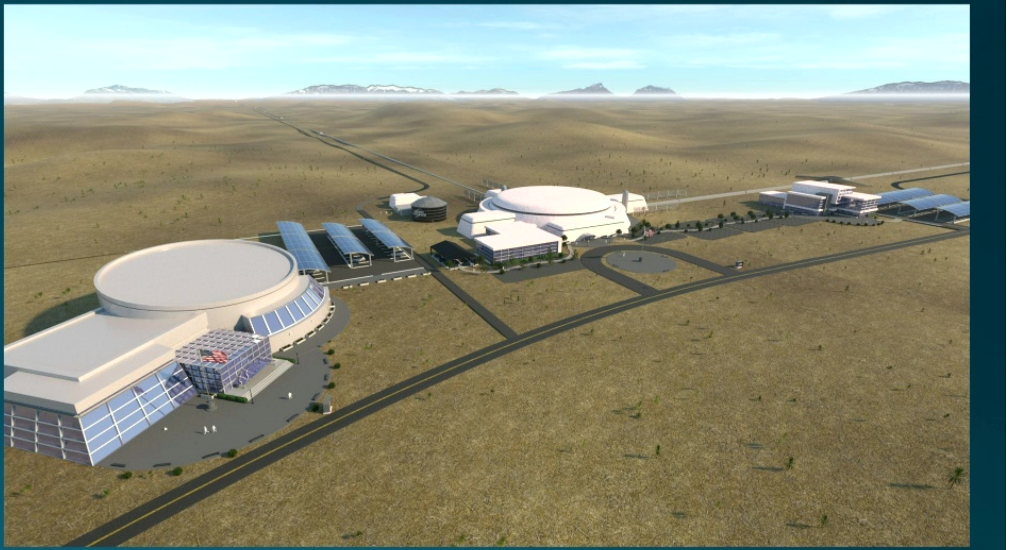
From Hannam et al, “Measurement of general-relativistic precession in a black-hole binary”, arXiv:2112.11300



Einstein Telescope and Cosmic Explorer



Maggiore et al. https://arxiv.org/abs/1912.02622



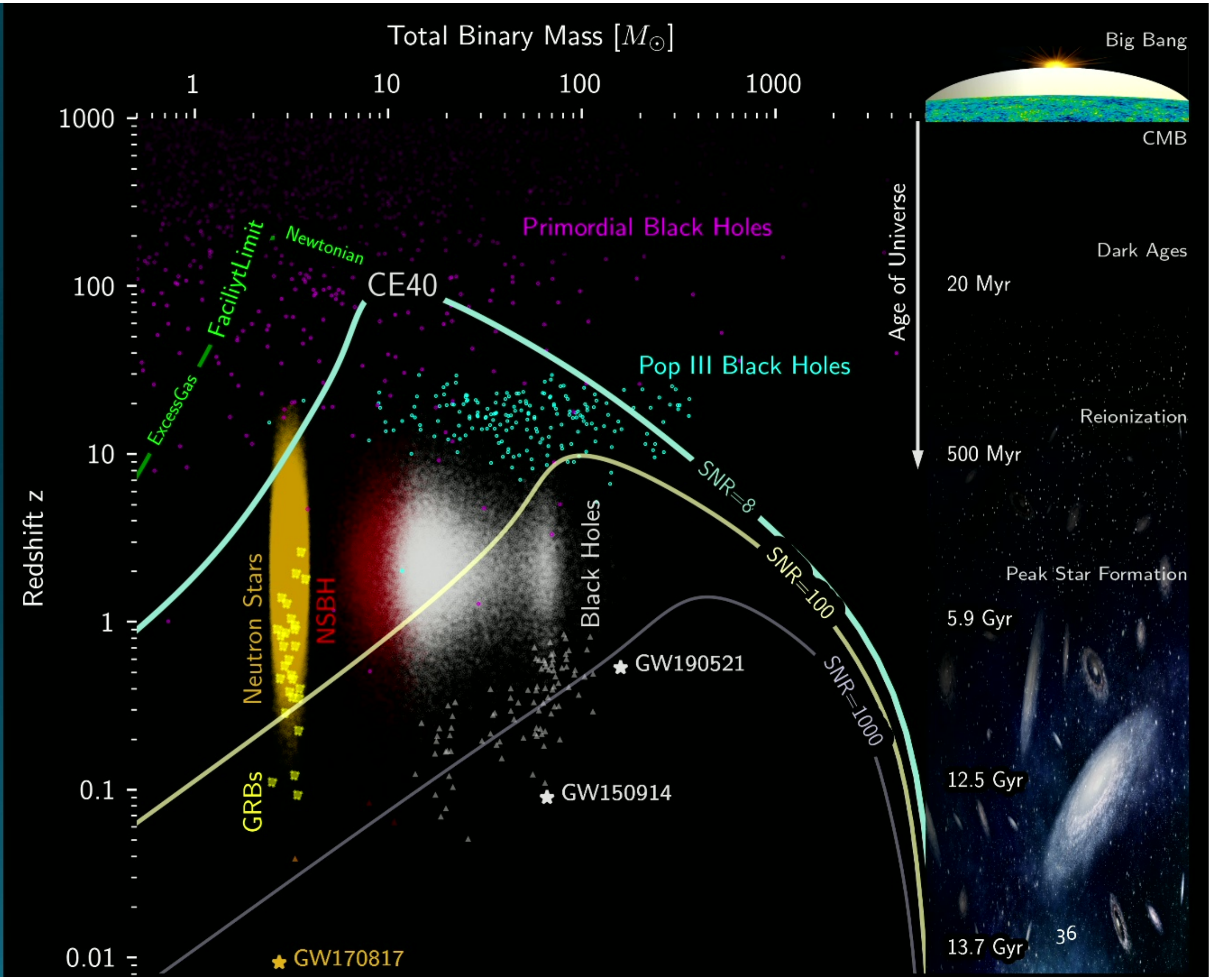
Evans et al. https://arxiv.org/abs/2109.09882

Next Generation GW Observatory Science Book
https://gwic.ligo.org/3Gsubcomm/documents.html

Science Reach

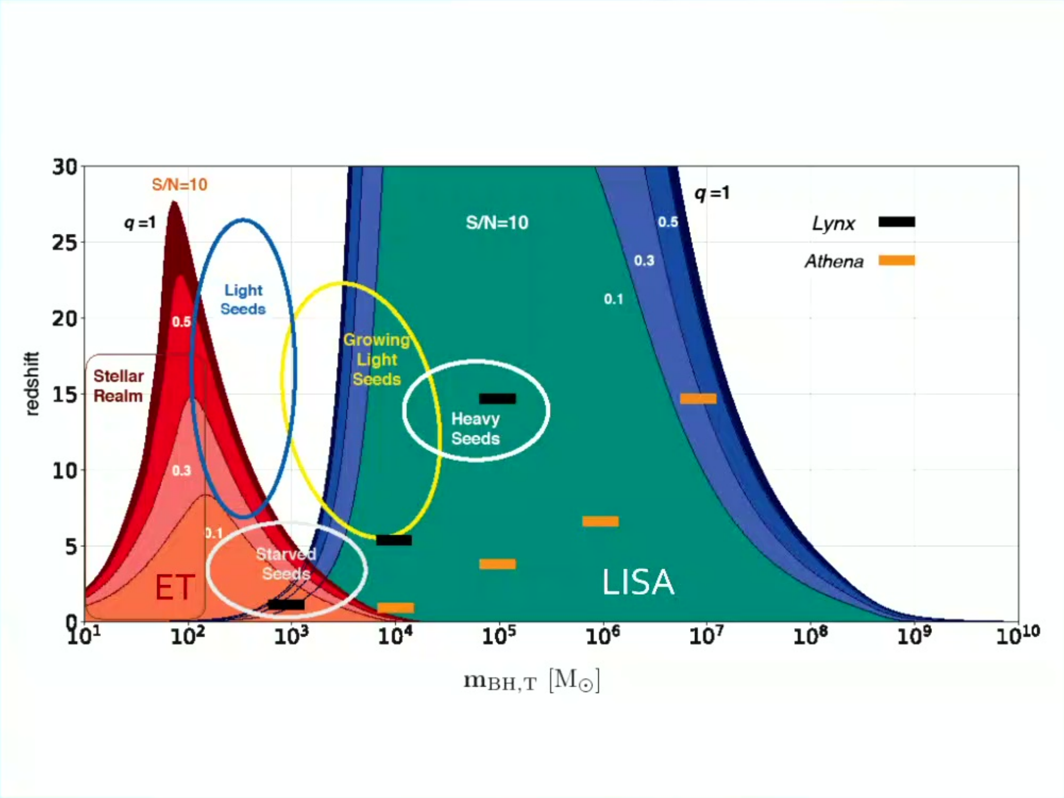
Sensitivity to Black Hole and Neutron Star mergers

From Cosmic Explorer white paper: Evans et al, arXiv:2306.13745



Seed black holes

- Quasars observed at redshift z > 7 are powered by black holes with mass > 10^9 $M_\odot$
- Likely population of seed black holes at high redshifts that grow through accretion and mergers to form supermassive black holes
- Light seeds will be observable to next-generation GW observatory



From Valiante et al https://arxiv.org/abs/2010.15096

Conclusions

We are firmly in the era of routine Gravitational-Wave observations

Individual events and populations are informing our understanding of the formation and evolution of massive binaries

Additional features in the gravitational wave signal enable more accurate measurements

- Have identified higher GW and precession in a subset of events.
- Some evidence for orbital eccentricity

Next generation GW observatory will enable observation of binary mergers in the visible universe

- Prospect of observing the seeds of supermassive black holes