

# Summary on the GW events observed and their implications

**Workshop for the 10th Anniversary of the Discovery of  
Gravitational Waves and KGWG Assembly Meeting**

Inje University, Hyung Won Lee

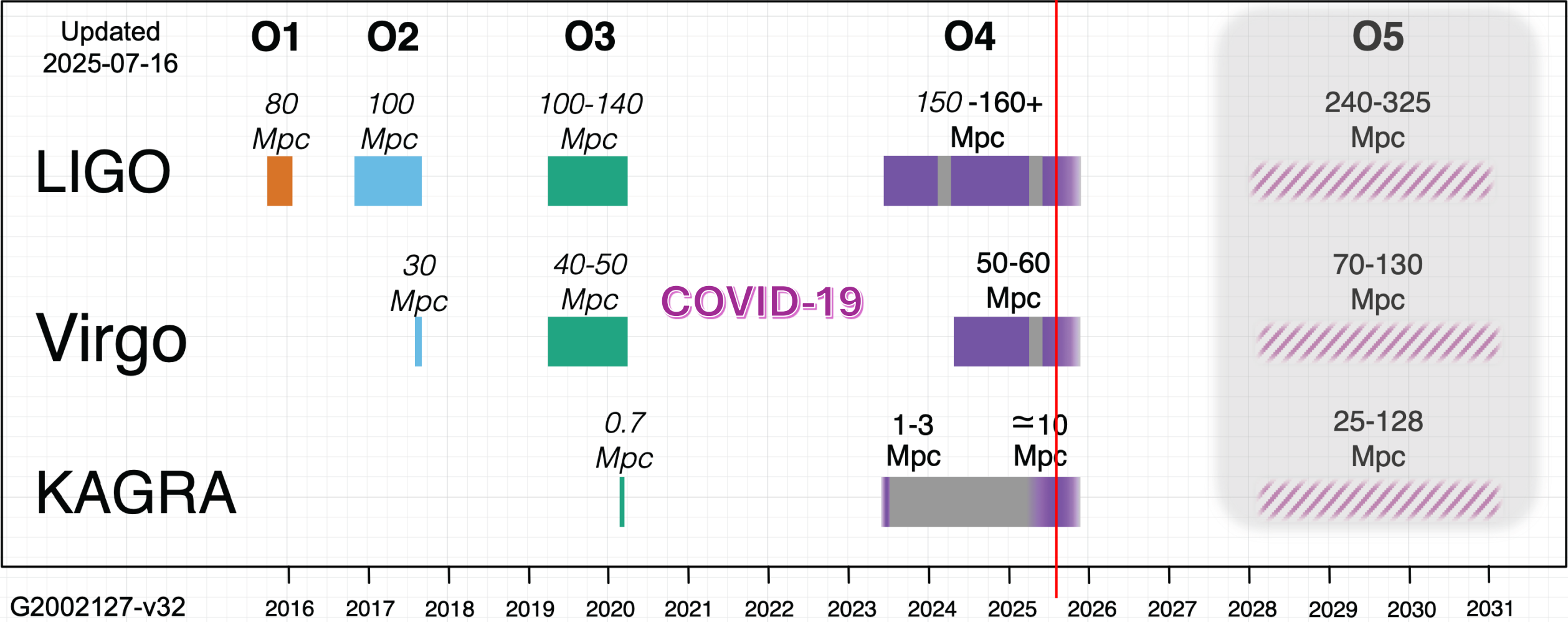
# Contents

- Observing schedule
- Observed events
- New discoveries
- Implications

# Observing Schedules

<https://observing.docs.ligo.org/plan/>

# Observing Schedule ([IGWN](#) | [Observing Plans](#))

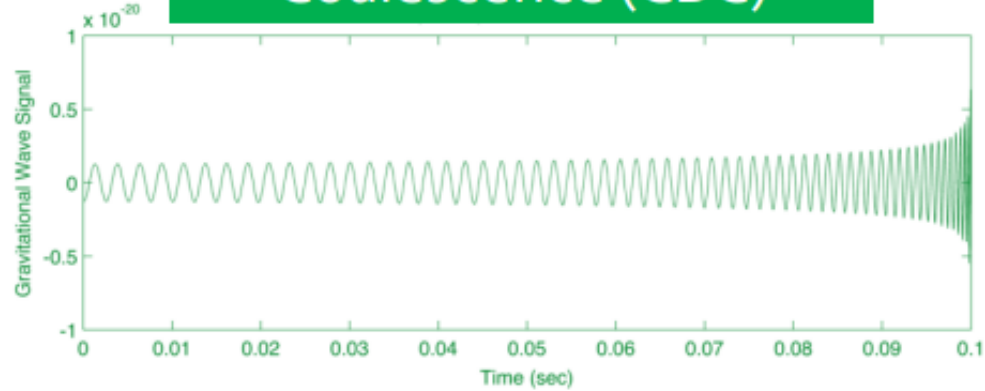


# Observational Periods

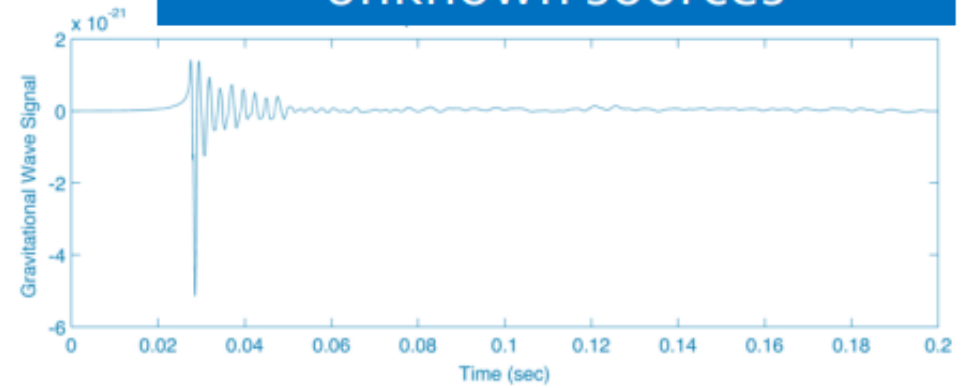
Observing Run	Start Date & Time (UTC)	End Date & Time (UTC)
<b>O1</b>	September 12, 2015 at 15:00 UTC	January 19, 2016 at 16:00 UTC
<b>O2</b>	November 30, 2016 at 16:00 UTC	August 25, 2017 at 22:00 UTC
<b>O3a</b>	April 1, 2019 at 15:00 UTC	October 1, 2019 at 15:00 UTC
<b>O3b</b>	November 1, 2019 at 15:00 UTC	March 27, 2020 at 17:00 UTC
<b>O4a</b>	May 24, 2023 at 14:00 UTC	January 16, 2024 at 15:59 UTC
<b>O4b</b>	April 10, 2024 at 15:00 UTC	January 28, 2025 at 17:00 UTC
<b>O4c</b>	January 28, 2025 at 17:00 UTC	November 18, 2025 at 16:00 UTC

# Potential Sources

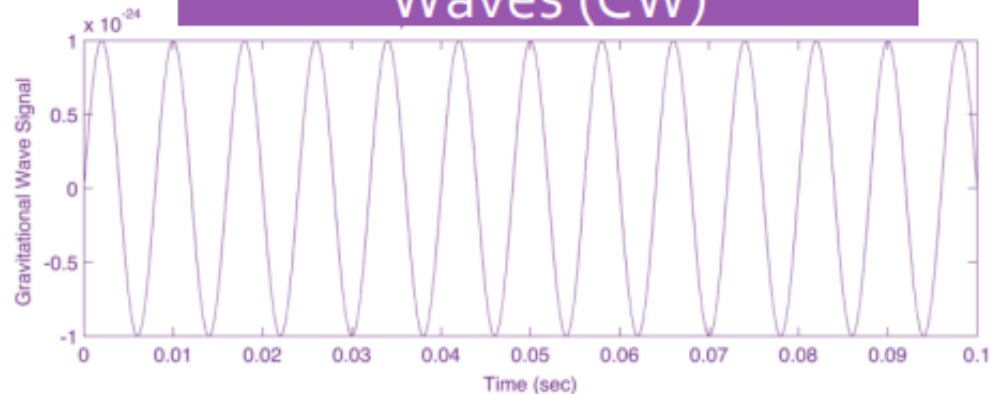
Compact Binary  
Coalescence (CBC)



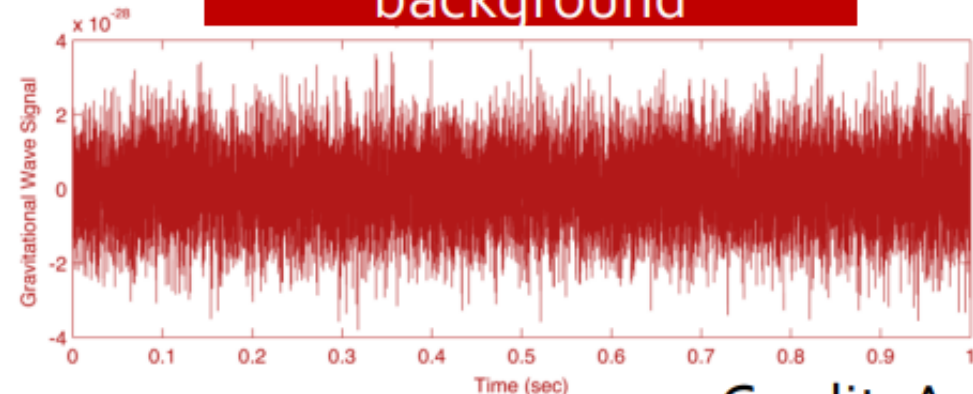
Bursts from short-duration,  
unknown sources



Continuous Gravitational  
Waves (CW)



Stochastic  
background



# O4 schedule

The **O4 run** started on 24 May 2023 and is scheduled to end on 18 November 2025. The O4 data release schedule is:

Data set	Data collection date range	Months of data	h(t) release date
O4a	2023-05-24 to 2024-01-16 16:00:00 UTC	7.7	2025-08-26
O4b	2024-04-10 to 2025-01-28 17:00:00 UTC	9.5	2026-05-26
O4c	2025-01-28 17:00:00 UTC to 2025-11-18 17:00:00 UTC	10	2026-12-16

The public data release schedule is shortened during O4 operations.

# Public Alerts(<https://gracedb.ligo.org>)

GraceDB Public Alerts ▾ Latest Search Documentation Login

Please log in to view full database contents.

## LIGO/Virgo/KAGRA Public Alerts

- More details about public alerts are provided in the [LIGO/Virgo/KAGRA Alerts User Guide](#).
- Retractions are marked in **red**. Retraction means that the candidate was manually vetted and is no longer considered a candidate of interest.
- Less-significant events are marked in **grey**, and are not manually vetted. Consult the [LVK Alerts User Guide](#) for more information on significance in O4.
- Less-significant events are not shown by default. Press "**Show All Public Events**" to show significant and less-significant events.

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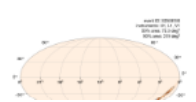
O4 Significant Detection Candidates: **224** (250 Total - 26 Retracted) @25 August 2025

O4 Low Significance Detection Candidates: **4409** (Total)

[Show All Public Events](#)

Page 1 of 17. [next](#) [last](#) »

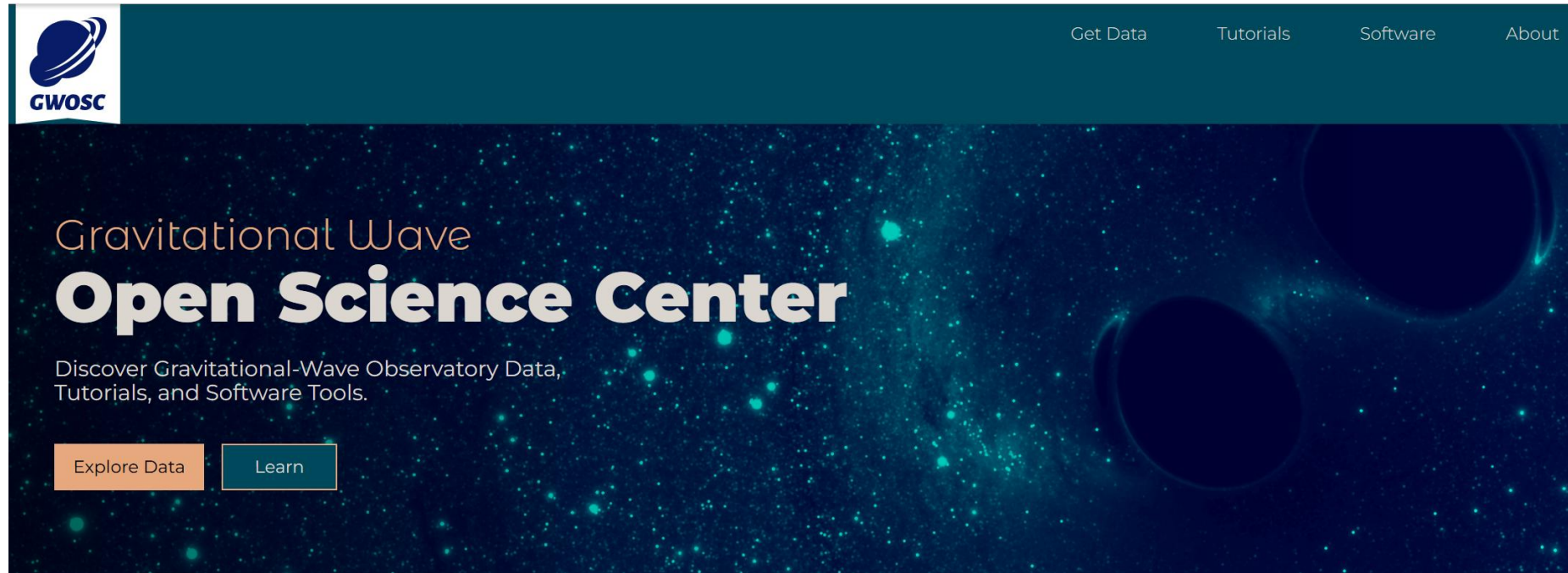
SORT: EVENT ID (A-Z) ▾

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
<a href="#">S250818t</a>	BBH (>99%)	Yes	Aug. 18, 2025 03:08:58 UTC	<a href="#">GCN Circular Query</a> <a href="#">Notify LVK</a>		1 per 1846.6 years	

# Observed Events

<https://gwosc.org>

# Observed Events(<https://gwosc.org>)



## Event Catalog

The Gravitational-wave Transient Catalog (GWTC) is a cumulative set of events detected by LIGO, Virgo, and KAGRA.



## Open Data Workshop

Participants will receive a crash-course in gravitational-wave data analysis that includes lectures, software tutorials, and a data challenge.



## Tutorials

Learn with tutorials that will lead you step-by-step through some common data analysis tasks.

# GWTC(Gravitational-Wave Transient Catalog)



The Gravitational-wave Transient Catalog (GWTC) is a cumulative set of gravitational wave transients maintained by the LIGO/Virgo/KAGRA collaboration. The online GWTC contains confidently-detected events from multiple data releases. For further information, see documentation for individual releases: [GWTC-1](#), [GWTC-2](#), [GWTC-2.1](#), and [GWTC-3](#).

Note, this catalog is only updated periodically, and may not contain recently published events. For the most recent events, you can browse [all available events](#).

Previous versions of this catalog are archived in [zenodo](#).

- Toggle columns on/off with Display button at right.
- Click an event name for all versions and more information.
- Values in the table below are from the **Default SEARCH** and **Default PE** cases found in the individual event's page.
- See [Event Portal Usage Notes](#) for more details.

List contains 93 events.

Upto GWTC-3.0

# GWTC



The Gravitational-wave Transient Catalog (GWTC) is a cumulative set of gravitational wave transients maintained by the LIGO/Virgo/KAGRA collaboration. The online GWTC contains confidently-detected events from multiple data releases. For further information, see documentation for individual releases: [GWTC-1](#), [GWTC-2](#), [GWTC-2.1](#), [GWTC-3](#), and [GWTC-4.0](#).

Note, this catalog is only updated periodically, and may not contain recently published events. For the most recent events, you can browse [all available events](#).

Previous versions of this catalog are archived in [zenodo](#) or are available using the following links:

- [Cumulative GWTC-1.0](#)
- [Cumulative GWTC-2.0](#)
- [Cumulative GWTC-2.1](#)
- [Cumulative GWTC-3.0](#)
- [Cumulative GWTC-4.0](#)

# GWTC

**i** The Gravitational-wave Transient Catalog (GWTC) is a cumulative set of gravitational wave transients maintained by the LIGO/Virgo/KAGRA collaboration. The online GWTC contains confidently-detected events from multiple data releases. For further information, see documentation for individual releases: [GWTC-1](#), [GWTC-2](#), [GWTC-2.1](#), [GWTC-3](#), and [GWTC-4.0](#).

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- [Cumulative GWTC-1.0](#)
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- [Cumulative GWTC-2.1](#)
- [Cumulative GWTC-3.0](#)
- [Cumulative GWTC-4.0](#)

- Toggle columns on/off with Display button at right.
- Click an event name for all versions and more information.
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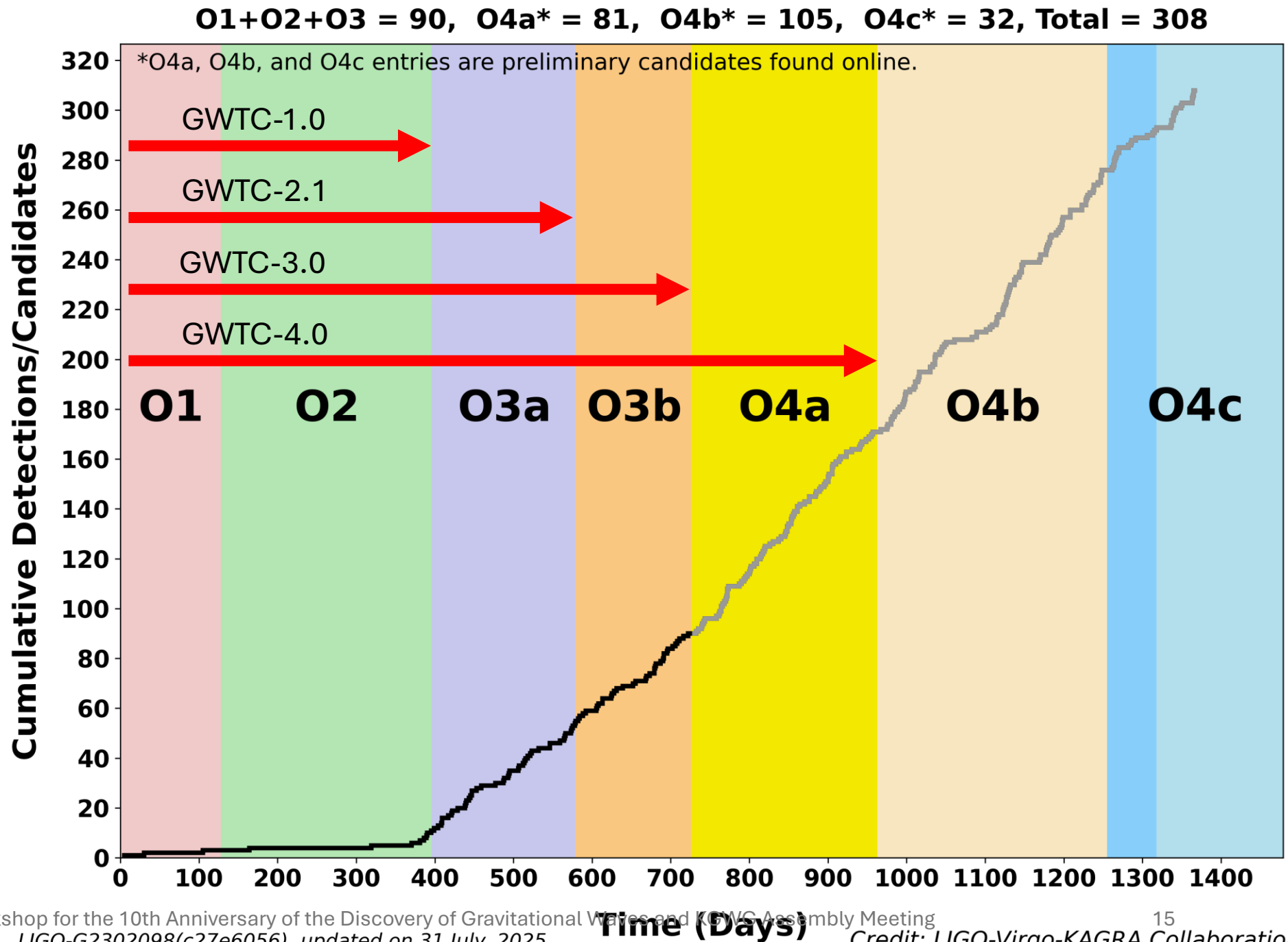
List contains 219 events.

Upto GWTC-4.0

# Observation Events

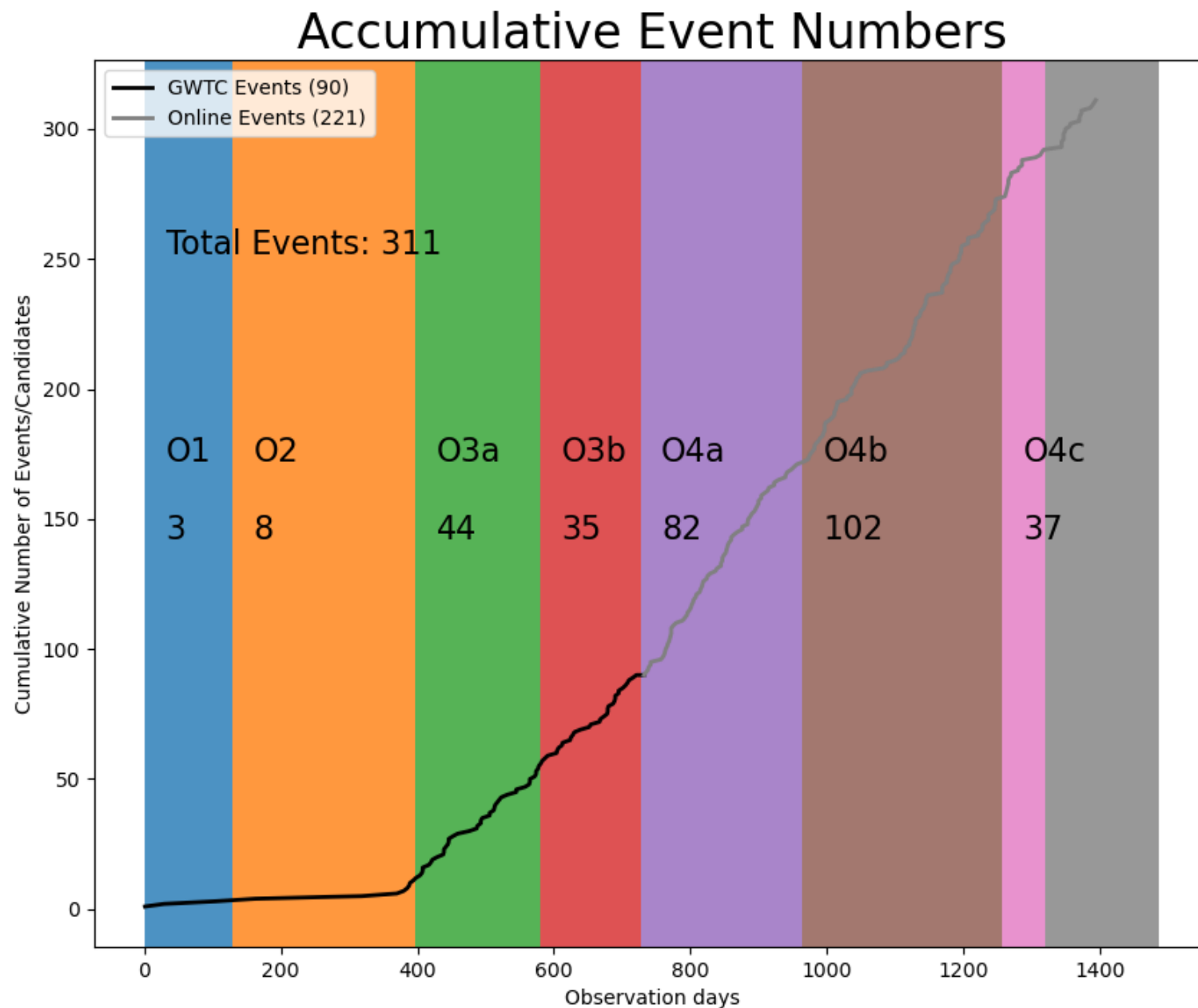
GWTC Version	Data	New Counts(metric)	New PE	Count
GWTC-1.0	O1+O2	+11 (FAR<1/30d & p_astro >= 0.5)	11	11
GWTC-2.0	O1-O3a	+39 (FAR<2/yr)	39	50
GWTC-2.1	O1-O3a	+8, -3 (p_astro > 0.5)	44+11 = 55	55
GWTC-3.0	O1-O3b	+35 (p_astro > 0.5)	35	90
GWTC-4.0	O1-O4a	+128 (p_astro > 0.5)	86	218

# Cumulative Detections



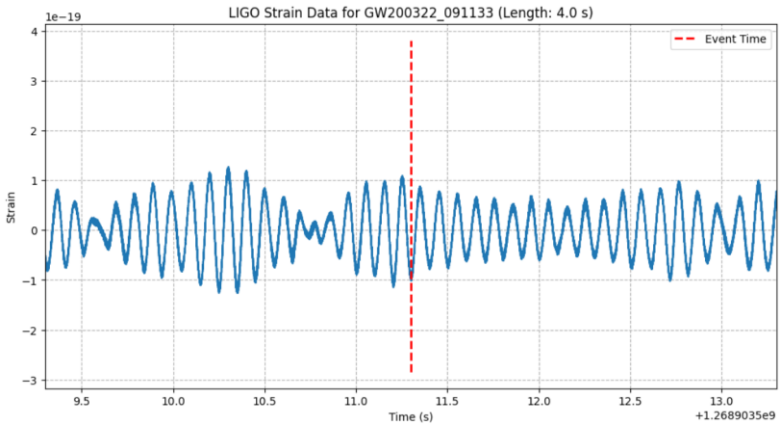
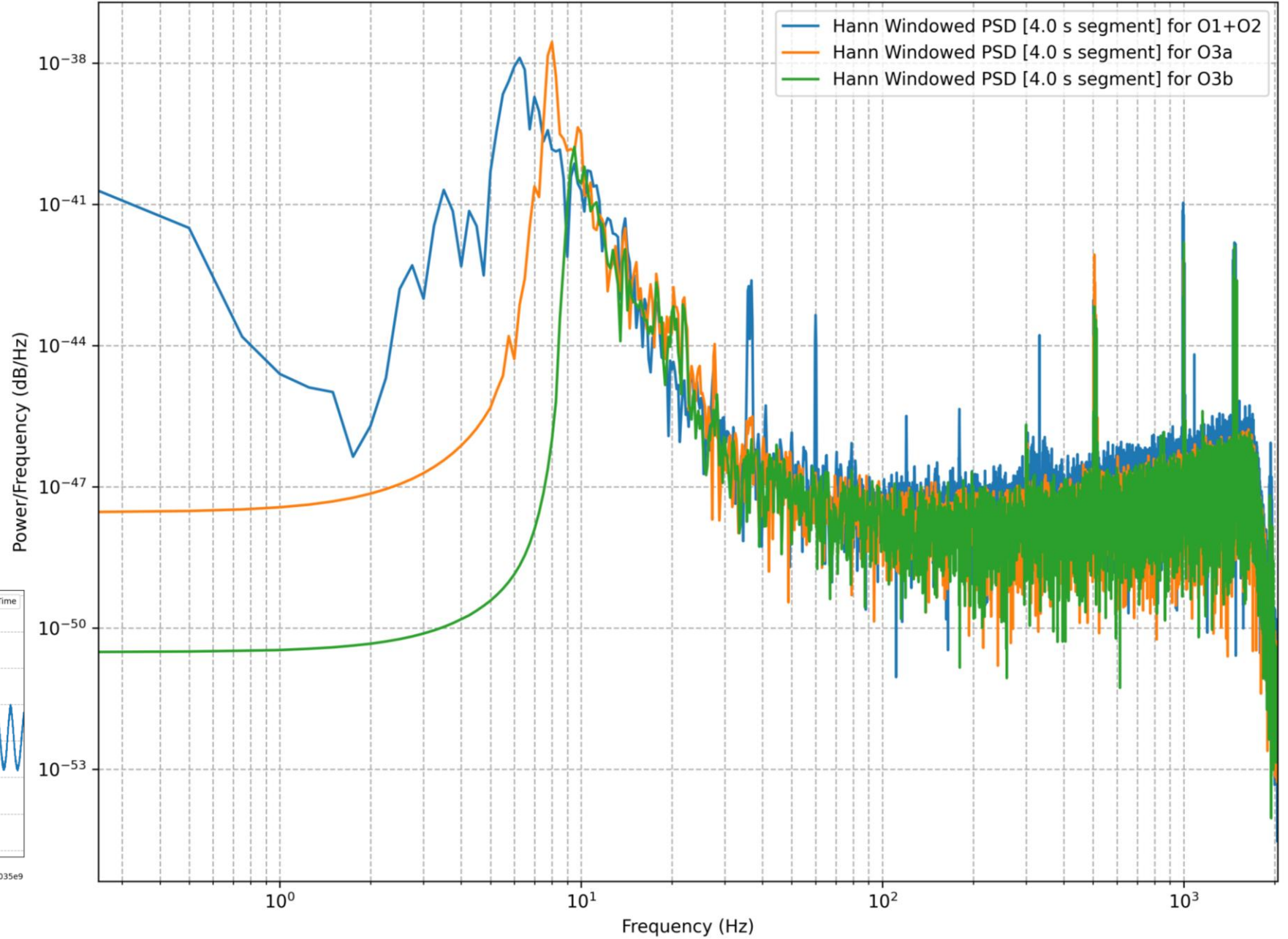
# Cumulative Detections

By August 24, 2025 (not official)

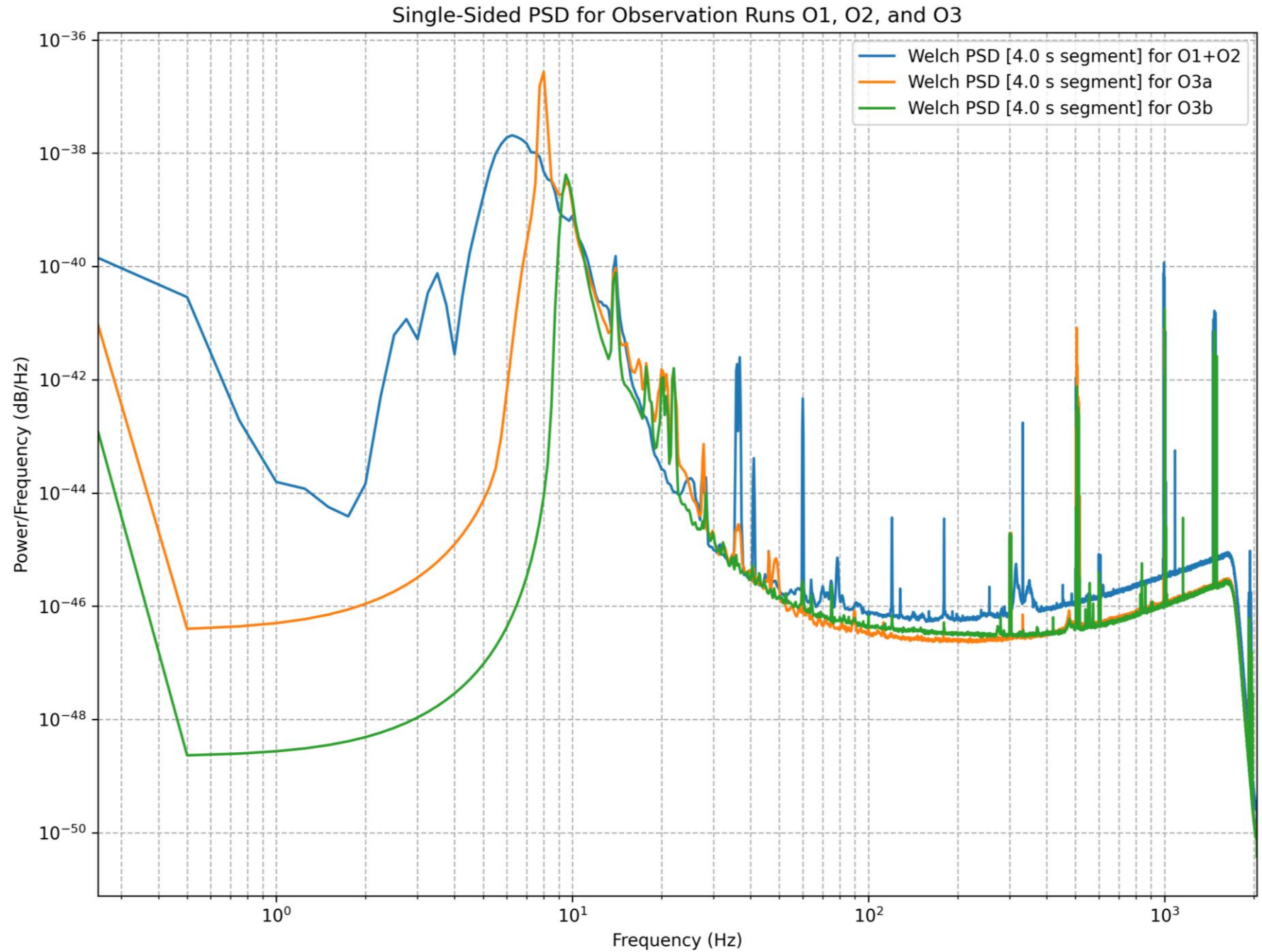


# PSD Evolution

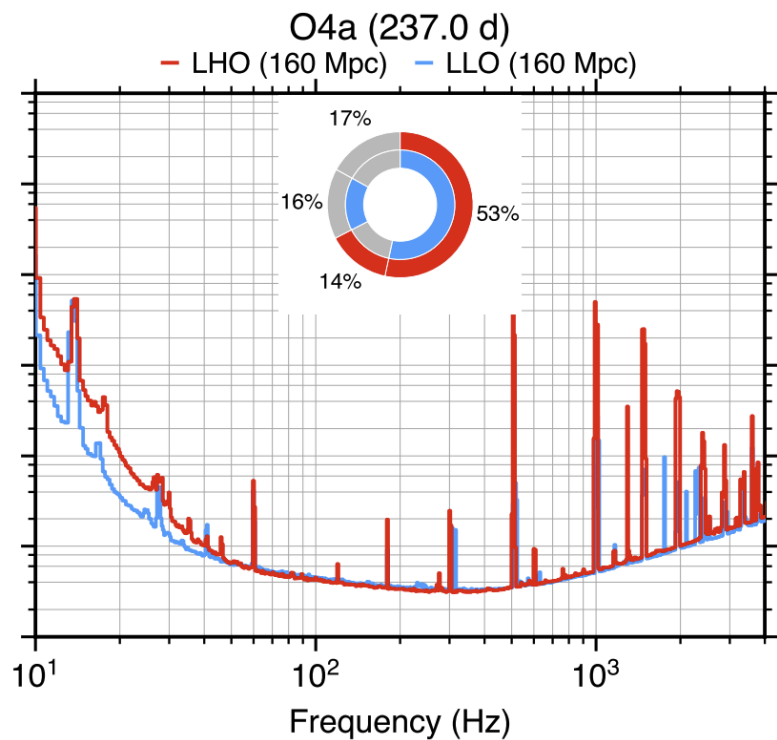
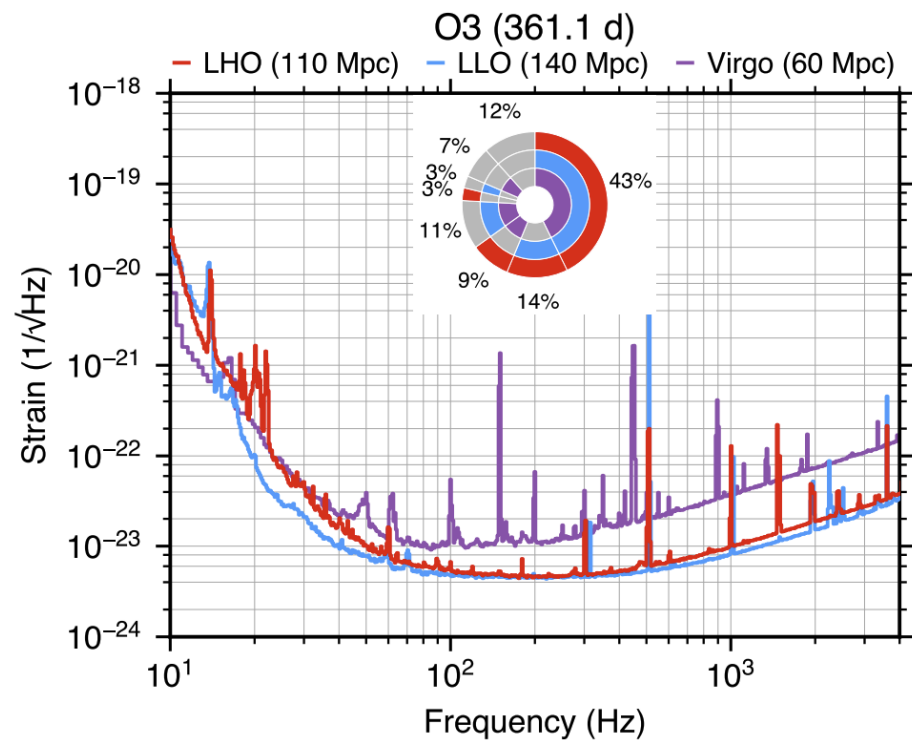
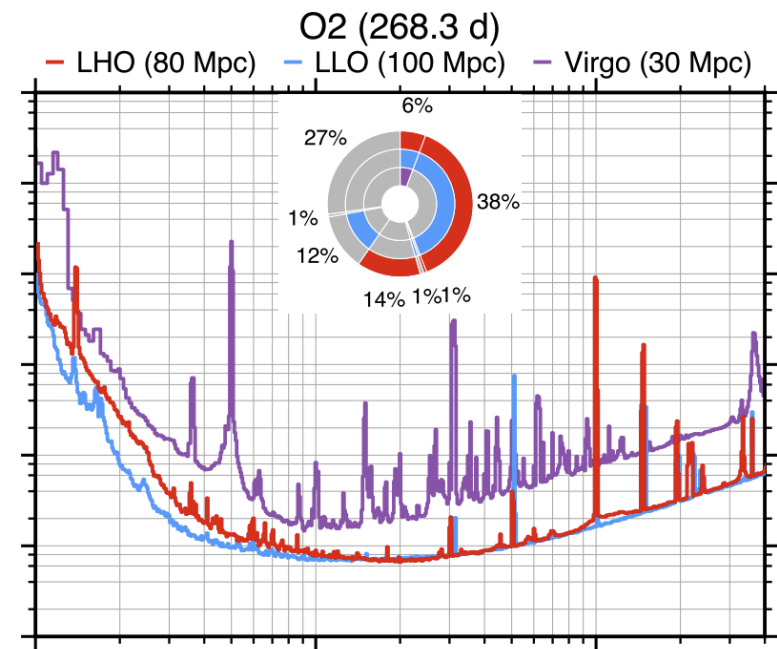
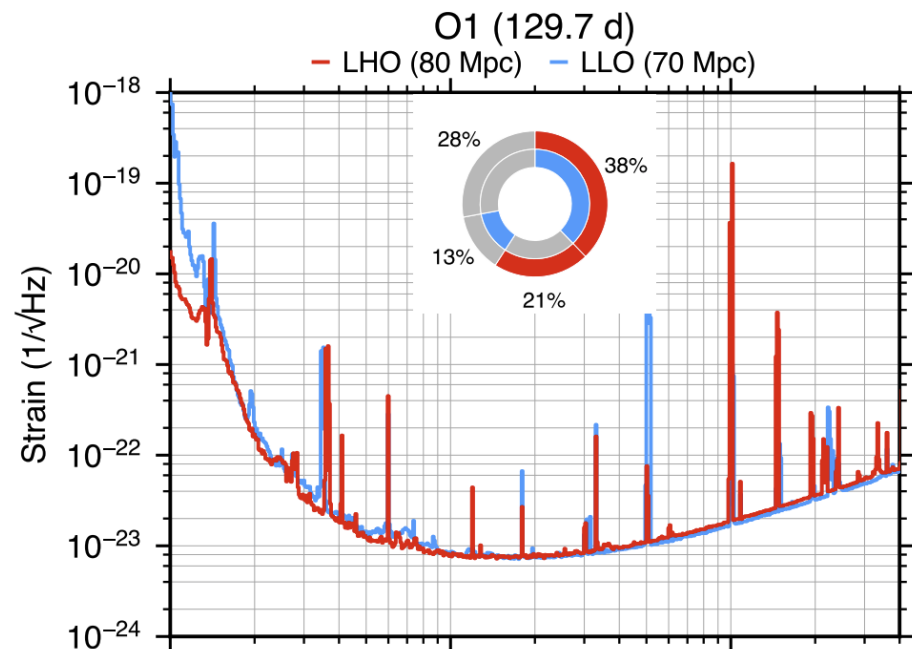
Single-Sided PSD for Observation Runs O1, O2, and O3



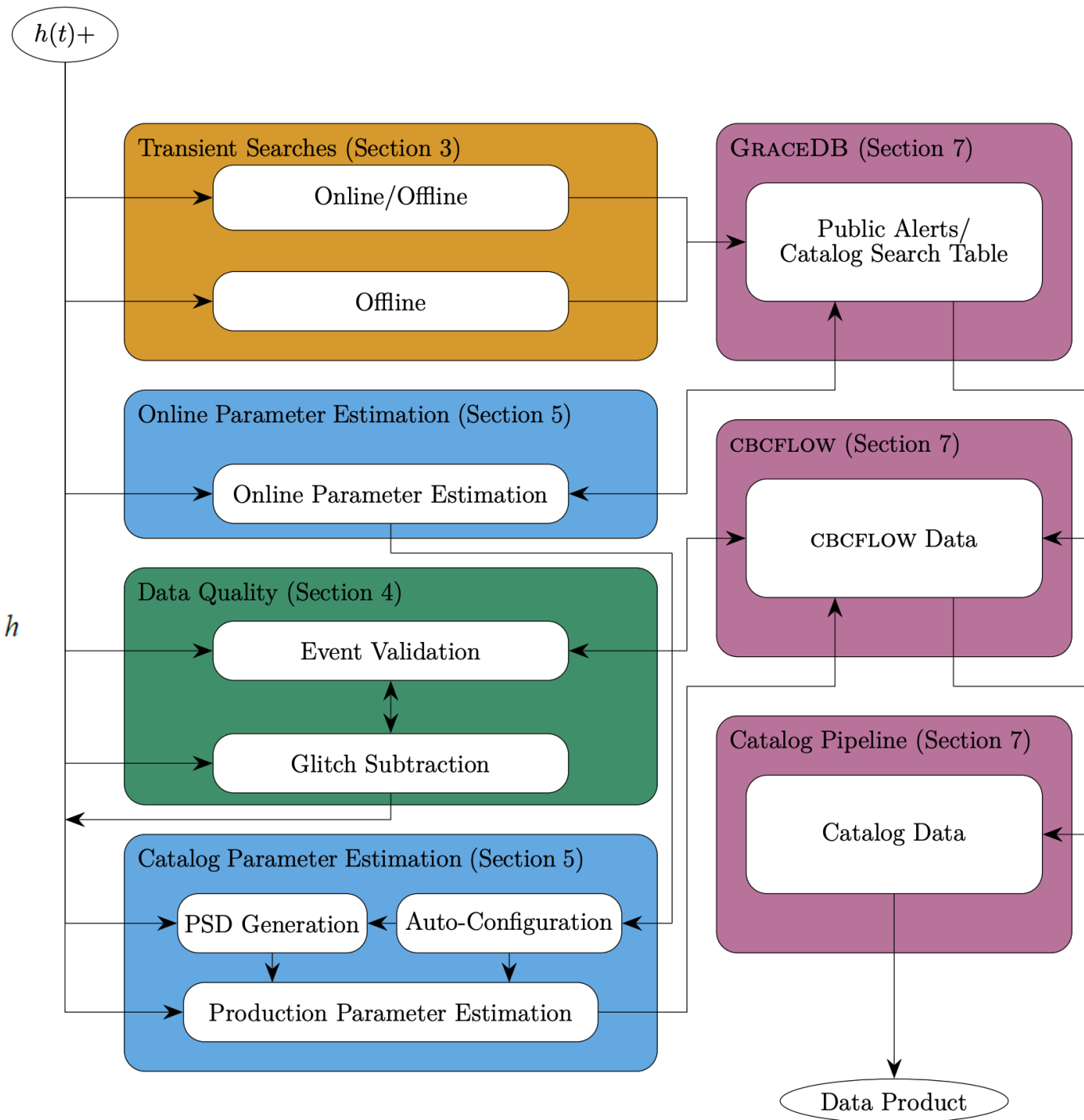
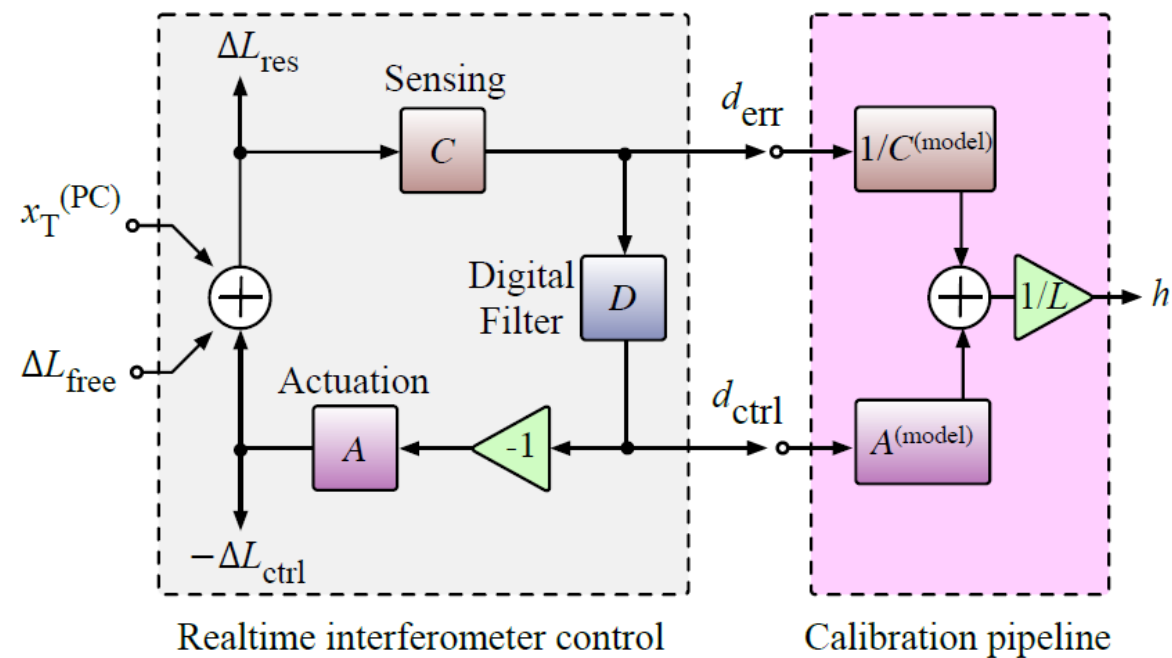
# PSD Evolution



# PSDs for Observational Runs

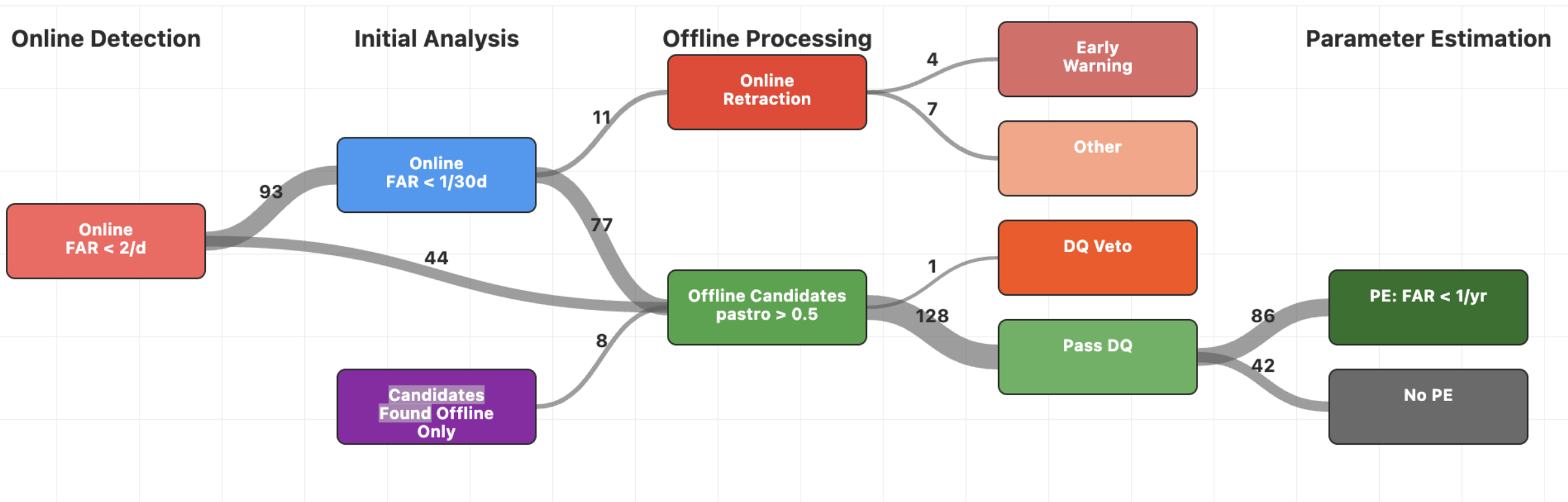


# O4a Data Flow

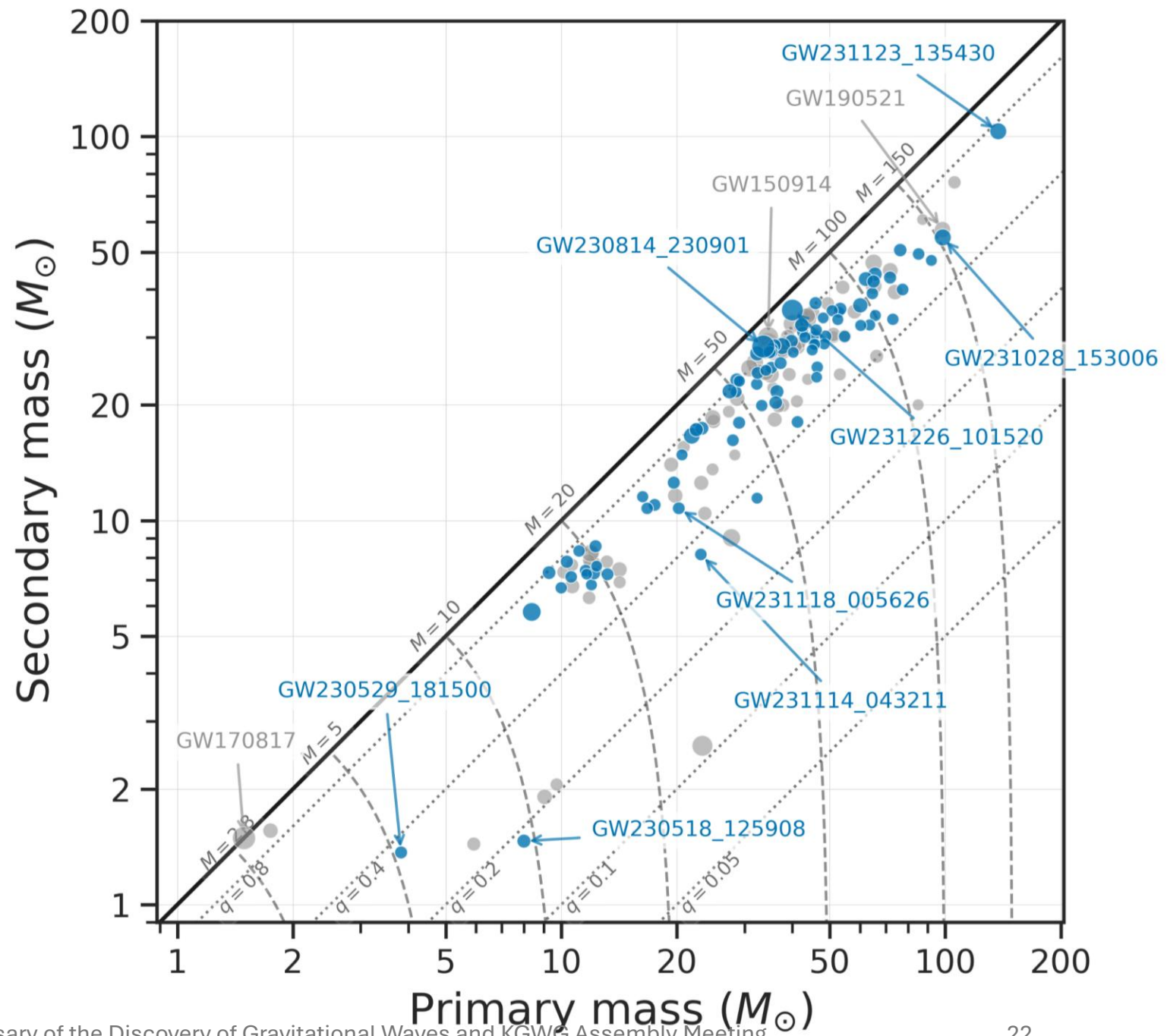


# Event Selection Processes

- Five pipelines ran online: cWB-BBH, GstLAL, MBTA, PyCBC, and SPIIR



# Mass-mass Plot



# GWTC-4.0 at a Glance

*129*

New candidates

*219*

Total number of candidates in the  
cumulative catalogue(O1-O4a)

*86*

New candidates with full parameter  
estimation results

# **GWTC-4.0 Released**

# GWTC-4.0 Papers

- Catalog - Introduction: <https://arxiv.org/abs/2508.18080>
- Catalog - Methods: <https://arxiv.org/abs/2508.18081>
- Catalog - Results: <https://arxiv.org/abs/2508.18082>
- Populations: <https://arxiv.org/abs/2508.18083>
- Open data: <https://arxiv.org/abs/2508.18079>

# GWTC-4.0: Introduction

DRAFT VERSION AUGUST 26, 2025

Typeset using L<sup>A</sup>T<sub>E</sub>X twocolumn style in AAS<sub>T</sub>E<sub>X</sub>631

## **GWTC-4.0: An Introduction to Version 4.0 of the Gravitational-Wave Transient Catalog**

THE LIGO SCIENTIFIC COLLABORATION, THE VIRGO COLLABORATION, AND THE KAGRA COLLABORATION  
(SEE THE END MATTER FOR THE FULL LIST OF AUTHORS)

### ABSTRACT

The Gravitational-Wave Transient Catalog (GWTC) is a collection of short-duration (transient) gravitational-wave signals identified by the LIGO–Virgo–KAGRA Collaboration in gravitational-wave data produced by the eponymous detectors. The catalog provides information about the identified candidates, such as the arrival time and amplitude of the signal and properties of the signal’s source as inferred from the observational data. GWTC is the data release of this dataset and version 4.0 extends the catalog to include observations made during the first part of the fourth LIGO–Virgo–KAGRA observing run up until 2024 January 31. This paper marks an introduction to a collection of articles related to this version of the catalog, GWTC-4.0. The collection of articles accompanying the catalog provides documentation of the methods used to analyze the data, summaries of the catalog of events, observational measurements drawn from the population, and detailed discussions of selected candidates.

# GWTC-4.0: Methods

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## **GWTC-4.0: Methods for Identifying and Characterizing Gravitational-wave Transients**

THE LIGO SCIENTIFIC COLLABORATION, THE VIRGO COLLABORATION, AND THE KAGRA COLLABORATION  
(SEE THE END MATTER FOR THE FULL LIST OF AUTHORS)

### ABSTRACT

The Gravitational-Wave Transient Catalog (GWTC) is a collection of candidate gravitational-wave transient signals identified and characterized by the LIGO–Virgo–KAGRA Collaboration. Producing the contents of the GWTC from detector data requires complex analysis methods. These comprise techniques to model the signal; identify the transients in the data; evaluate the quality of the data and mitigate possible instrumental issues; infer the parameters of each transient; compare the data with the waveform models for compact binary coalescences; and handle the large amount of results associated with all these different analyses. In this paper, we describe the methods employed to produce the catalog’s fourth release, GWTC-4.0, focusing on the analysis of the first part of the fourth observing run of Advanced LIGO, Advanced Virgo and KAGRA.

# GWTC-4.0: Results

## GWTC-4.0: Updating the Gravitational-Wave Transient Catalog with Observations from the First Part of the Fourth LIGO-Virgo-KAGRA Observing Run

THE LIGO SCIENTIFIC COLLABORATION, THE VIRGO COLLABORATION, AND THE KAGRA COLLABORATION

(Compiled: August 26, 2025)

### ABSTRACT

Version 4.0 of the Gravitational-Wave Transient Catalog (GWTC-4.0) adds new candidates detected by the LIGO, Virgo, and KAGRA observatories through the first part of the fourth observing run (O4a: 2023 May 24 15:00:00 to 2024 January 16 16:00:00 UTC) and a preceding engineering run. In these new data, we find 128 compact binary coalescence candidates that are identified by at least one of our search algorithms with a probability of astrophysical origin  $p_{\text{astro}} \geq 0.5$  and that are not vetoed during event validation. We also provide detailed source property measurements for 86 of these that have a false alarm rate  $< 1 \text{ yr}^{-1}$ . Based on the inferred component masses, these candidates are consistent with signals from binary black holes and neutron star–black hole binaries (GW230518\_125908 and GW230529\_181500). Median inferred component masses of binary black holes in the catalog now range from  $5.79 M_{\odot}$  (GW230627\_015337) to  $137 M_{\odot}$  (GW231123\_135430), while GW231123\_135430 was probably produced by the most massive binary observed in the catalog. For the first time we have discovered binary black hole signals with network signal-to-noise ratio exceeding 30, GW230814\_230901 and GW231226\_101520, enabling high-fidelity studies of the waveforms and astrophysical properties of these systems. Combined with the 90 candidates included in GWTC-3.0, the catalog now contains 218 candidates with  $p_{\text{astro}} \geq 0.5$  and not otherwise vetoed, more than doubling the size of the catalog and further opening our view of the gravitational-wave Universe.

# GWTC-4.0: Populations

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## GWTC-4.0: Population Properties of Merging Compact Binaries

THE LIGO SCIENTIFIC COLLABORATION, THE VIRGO COLLABORATION, AND THE KAGRA COLLABORATION

(Compiled: 26 August 2025)

### ABSTRACT

We detail the population properties of merging compact objects using 158 mergers from the cumulative Gravitational-Wave Transient Catalog 4.0, which includes three types of binary mergers: binary neutron star, neutron star–black hole binary, and binary black hole mergers. We resolve multiple over- and under-densities in the black hole mass distribution: features persist at primary masses of  $10 M_{\odot}$  and  $35 M_{\odot}$  with a possible third feature at  $\sim 20 M_{\odot}$ . These are departures from an otherwise power-law-like continuum that steepens above  $35 M_{\odot}$ . Binary black holes with primary masses near  $10 M_{\odot}$  are more likely to have less massive secondaries, with a mass ratio distribution peaking at  $q = 0.74^{+0.13}_{-0.13}$ , potentially a signature of stable mass transfer during binary evolution. Black hole spins are inferred to be non-extremal, with 90% of black holes having  $\chi < 0.57$ , and preferentially aligned with binary orbits, implying many merging binaries form in isolation. However, we find a significant fraction, 0.24–0.42, of binaries have negative effective inspiral spins, suggesting many could be formed dynamically in gas-free environments. We find evidence for correlation between effective inspiral spin and mass ratio, though it is unclear if this is driven by variation in the mode of the distribution or the width. The binary black hole merger rate increases with redshift as  $(1+z)^{\kappa}$  with  $\kappa = 3.2^{+0.94}_{-1.00}$ , consistent with the cosmic star formation density. While there is no evidence of the mass spectrum evolving with redshift, the distribution of effective inspiral spin is found to broaden as redshift increases out to  $z \approx 1$ . We infer the local merger rates (i.e., at redshift  $z = 0$ ) to be  $7.6\text{--}250 \text{ Gpc}^{-3} \text{ yr}^{-1}$  for binary neutron stars,  $9.1\text{--}84 \text{ Gpc}^{-3} \text{ yr}^{-1}$  for neutron star–black hole binaries, and  $14\text{--}26 \text{ Gpc}^{-3} \text{ yr}^{-1}$  for binary black holes; all values reflect central 90% credible intervals.

# Open Data

DRAFT VERSION AUGUST 26, 2025

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## **Open Data from LIGO, Virgo, and KAGRA through the First Part of the Fourth Observing Run**

THE LIGO SCIENTIFIC COLLABORATION, THE VIRGO COLLABORATION, AND THE KAGRA COLLABORATION

### ABSTRACT

LIGO, Virgo, and KAGRA form a network of gravitational-wave observatories. Data and analysis results from this network are made publicly available through the Gravitational Wave Open Science Center. This paper describes open data from this network, including the addition of data from the first part of the fourth observing run (O4a) and selected periods from the preceding engineering run, collected from May 2023 to January 2024. The public data set includes calibrated strain time series for each instrument, data from additional channels used for noise subtraction and detector characterization, and analysis data products from version 4.0 of the Gravitational-Wave Transient Catalog.

# New Discoveries

# GW150914

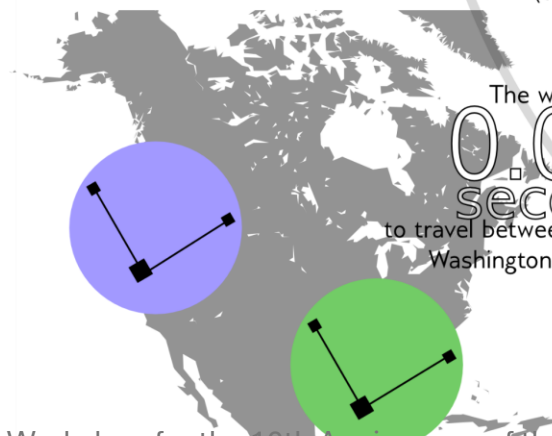
## The first direct detection of gravitational waves

An 'interesting' signal is detected at both LIGO sites

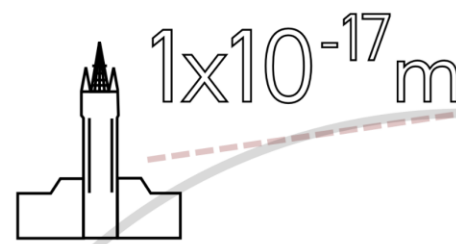
14 Sept 2015

Rapid analysis suggested the signal was from two black holes crashing into each other.

Detailed analysis was performed over the following months...



The wave took **0.007 seconds** to travel between the detectors in Washington and Louisiana



$1 \times 10^{-17}$  m

The distance from Glasgow to Edinburgh changed by one-tenth the radius of a Hydrogen nucleus as the wave passed through Scotland.



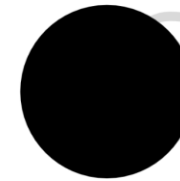
**180,000 km/s**

The speed of the black holes when they collided (0.6 times the speed of light)



The black holes merged more than **1 billion years ago**

(That's before multicellular life evolved on Earth)



The final merger of the black holes was

**500 billion**

times brighter in gravitational waves than our entire Galaxy is in electromagnetic radiation.

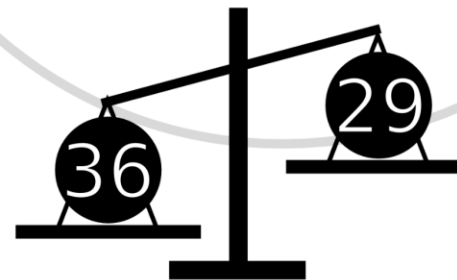
In 0.2 seconds three times the mass of the sun was turned into gravitational wave energy.



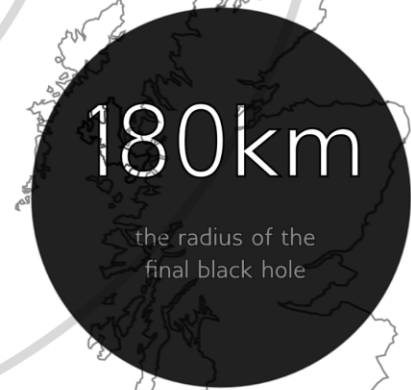
It would take

**5000 years**

to run the analysis on a desktop computer. 10 supercomputers were used to perform the calculations.



The two black holes had the mass of 36 and 29 Suns



**180km**

the radius of the final black hole

# GW151226 The Boxing Day Event

Type  
Black hole merger

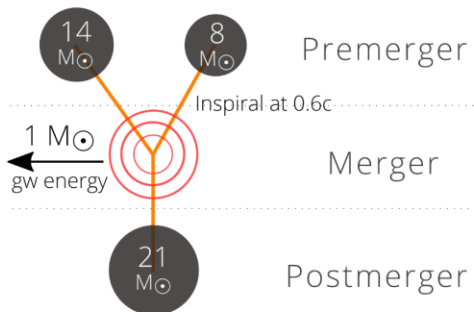
Discovered  
26 December 2015

Distance  
1.3 Billion light years

The final black hole is  
**120 km**  
wide



## Family Tree

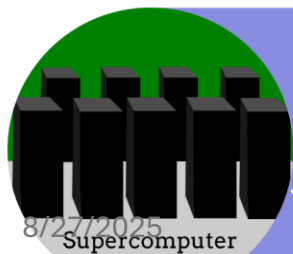


1  $M_{\odot}$  = Mass of the Sun

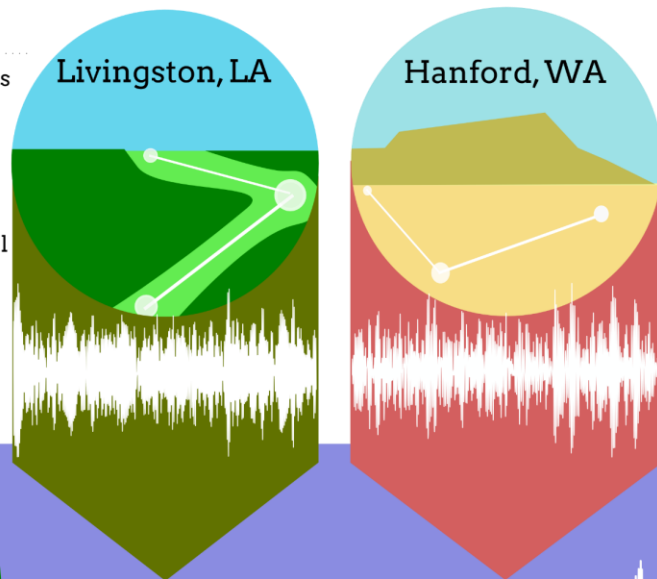
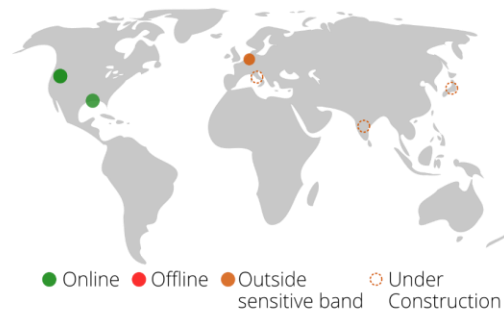
Data was collected at the LIGO sites in Washington and Hanford, and compared with supercomputer simulations in a process called matched filtering.

This was done to identify the signal amongst background noise.

A gravitational wave can be detected when it closely matches one of the simulations.



## Network Status

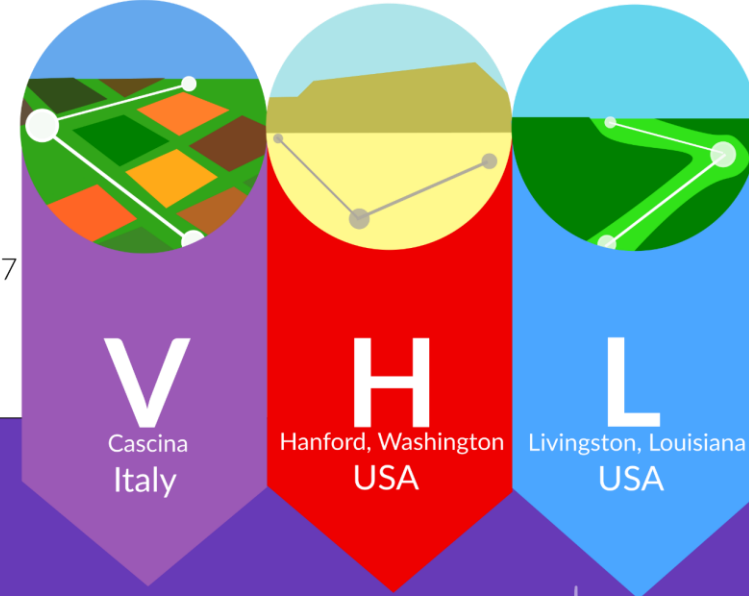


Workshop for the 10th Anniversary of the Discovery

Ruler by Stéphanie Walter from the Noun Project

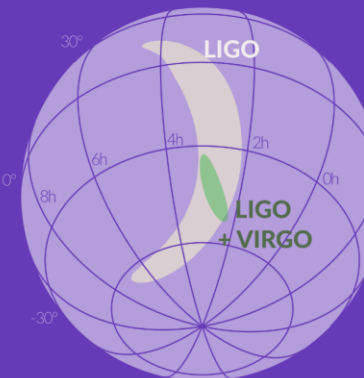
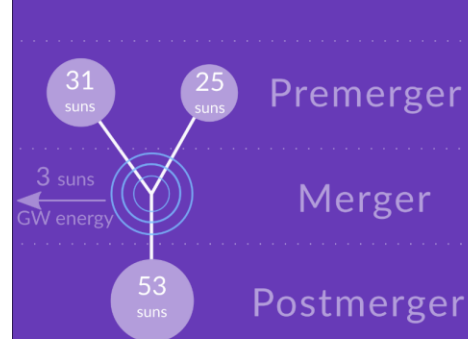
Discovered  
14 August 2017

Distance  
1.8 Billion light years



BBH  
Binary Black Hole Merger

GW170814 is the first Gravitational Wave event which was detected by three interferometers: the Advanced LIGO detectors in the USA, and Advanced Virgo in Italy.



A third detector allows us to be about 10 times more precise about where the event originated in the sky.

# GW170814

# GW170104

Remnant BH  
**49**  
Solar Masses

Binary Black Hole Merger

## SIZE

The final black hole which was created by the merger of the two black holes is

**270 KM**

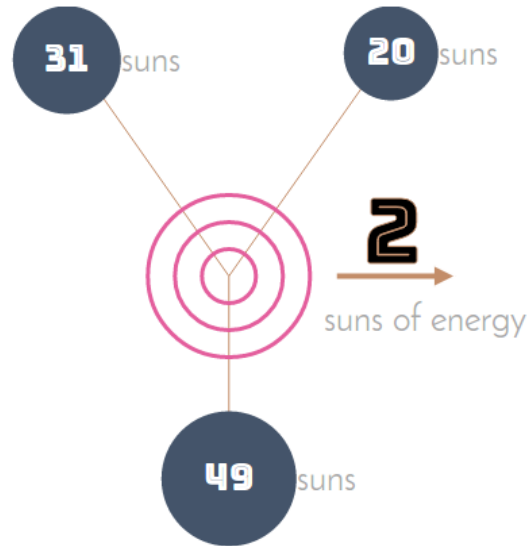
wide.

This is how big it would look if it was drawn on a map of Italy.



## EVOLUTION

The gravitational waves observed from GW170104 were created when two black holes collided, and merged to form a larger black hole.



## AGE

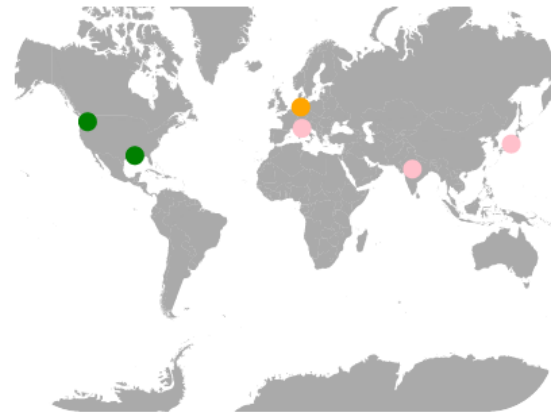
While the gravitational waves from the event were detected on 4 January 2017, they started their journey around

**2 BILLION**

years ago; around the time multicellular life had started to evolve on Earth.

## DETECTION


Detecting gravitational waves requires special, sensitive instruments. GW170104 was discovered by the Advanced LIGO detectors in the USA.

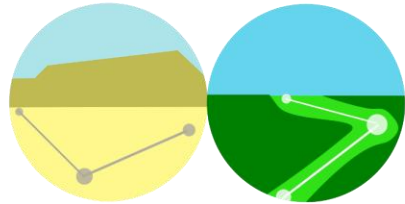


Key: online offline insufficient sensitivity under construction

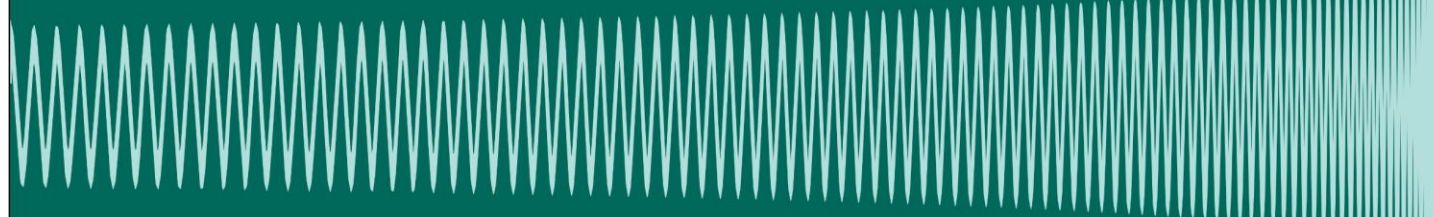
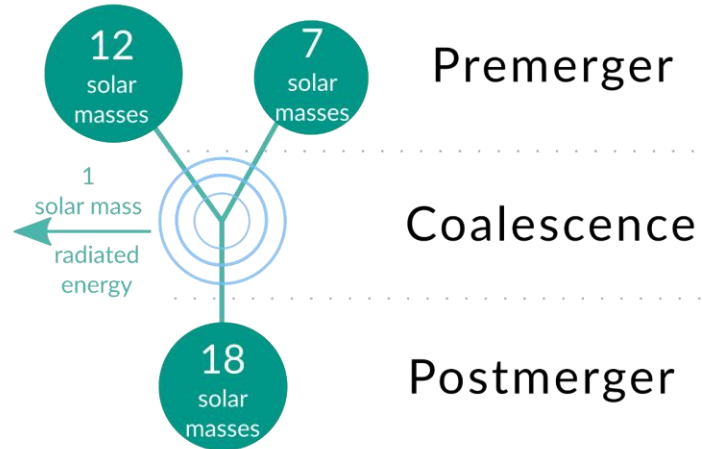
More detectors are being built around the world to help us to make better observations.

 Discovered  
8 June 2017

 Distance  
1.1 billion  
light years

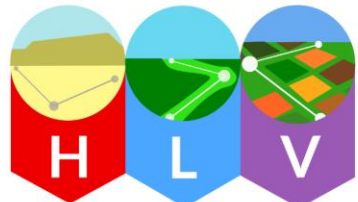


Observed by  
LIGO Livingston Observatory  
and  
LIGO Hanford Observatory



# GW170817

**Binary neutron star merger**  
 A LIGO / Virgo gravitational wave detection with associated electromagnetic events observed by over 70 observatories.



**Distance**  
130 million light years

**Discovered**  
17 August 2017

**Type**  
Neutron star merger

**12:41:04 UTC**  
 A gravitational wave from a binary neutron star merger is detected.

**gravitational wave signal**  
 Two neutron stars, each the size of a city but with at least the mass of the sun, collided with each other.

**gamma ray burst**  
 A short gamma ray burst is an intense beam of gamma ray radiation which is produced just after the merger.

**+ 2 seconds**  
 A gamma ray burst is detected.

**kilonova**  
 Decaying neutron-rich material creates a glowing kilonova, producing heavy metals like gold and platinum.

**+10 hours 52 minutes**  
 A new bright source of optical light is detected in a galaxy called NGC 4993, in the constellation of Hydra.

**radio remnant**  
 As material moves away from the merger it produces a shockwave in the interstellar medium - the tenuous material between stars. This produces emission which can last for years.

**+11 hours 36 minutes**  
 Infrared emission observed.

**+15 hours**  
 Bright ultraviolet emission detected.

**+9 days**  
 X-ray emission detected.

**+16 days**  
 Radio emission detected.

GW170817 allows us to measure the expansion rate of the universe directly using gravitational waves for the first time.

Detecting gravitational waves from a neutron star merger allows us to find out more about the structure of these unusual objects.

This multimessenger event provides confirmation that neutron star mergers can produce short gamma ray bursts.

**Au**  
 The observation of a kilonova allowed us to show that neutron star mergers could be responsible for the production of most of the heavy elements, like gold, in the universe.

Observing both electromagnetic and gravitational waves from the event provides compelling evidence that gravitational waves travel at the same speed as light.

Workshop for the 10th Anniversary of the D

# GW190521

The most massive black hole collision observed so far

**Discovery**  
21 May 2019

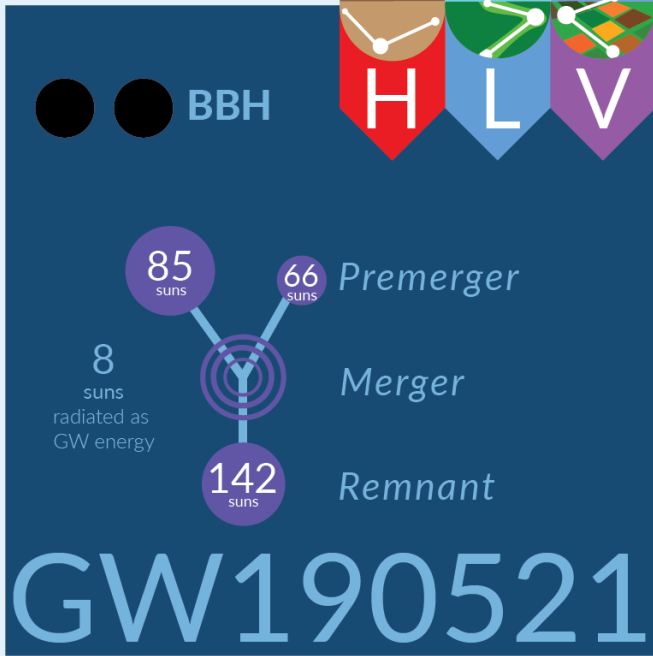
**Distance**  
17 billion light years away

**3 Detectors**  
 Three detectors made the observation: the two LIGO detectors in the USA and Virgo in Italy.

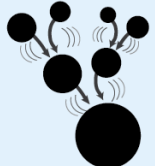


**Binary Black Hole Merger**

**High Masses**  
 This is the heaviest pair of black holes which have ever been observed colliding.

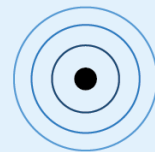


**Origin Story**  
 The black holes which collided to make GW190521 are so massive that we're not sure how they were formed. One possibility is that they are both the result of previous black hole collisions.



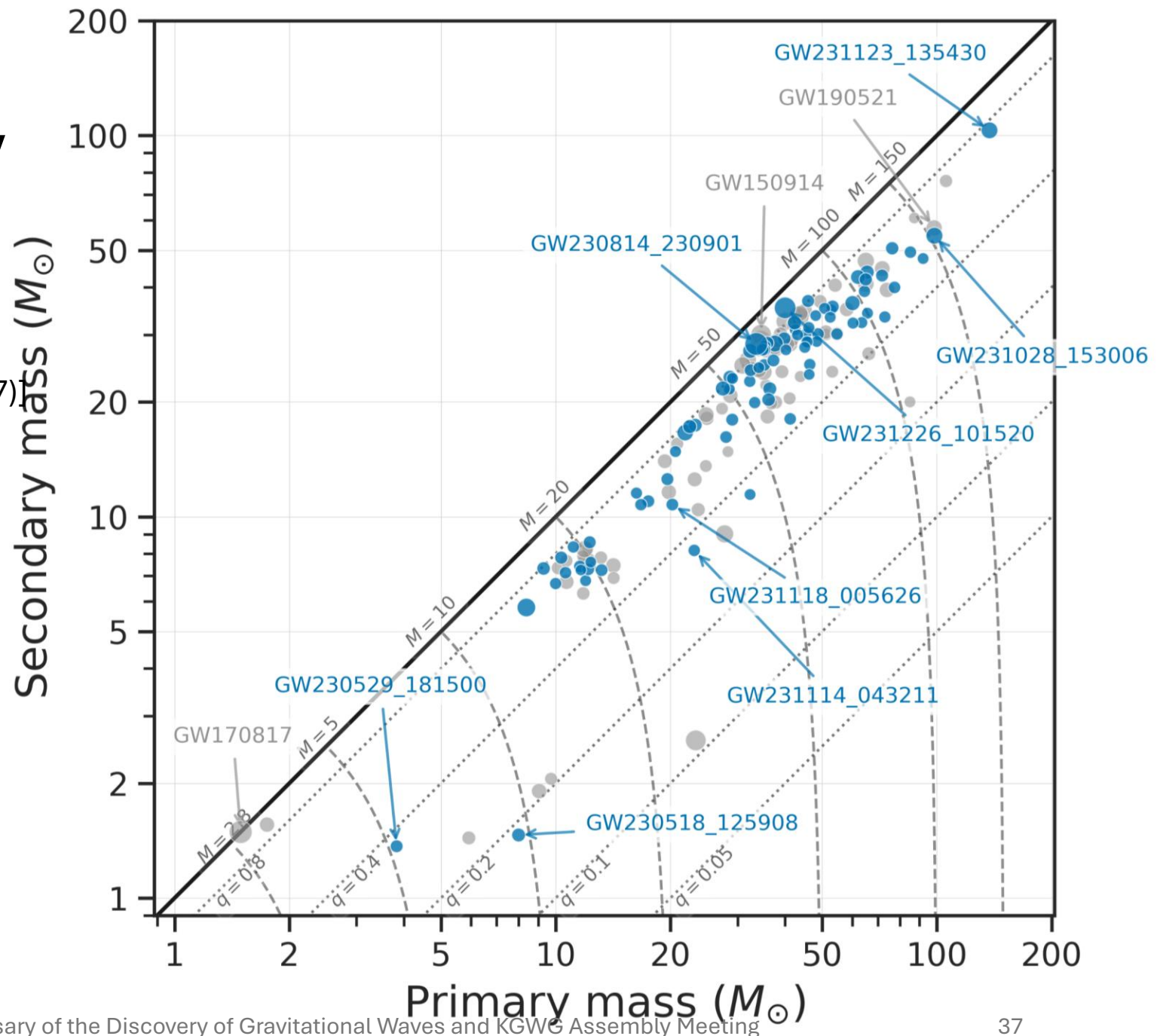
**Ringdown**  
 The black hole formed in the collision continues to vibrate after the merger, and "rings" like a bell for a while. This lets us test our theories.

Once again Einstein's *General Relativity* passed this test.



# O1~O3 summary

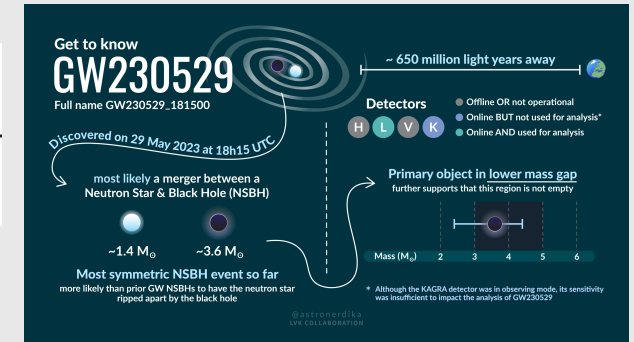
- Two BNS
  - GW170817 [LVC, PRL119.161101 (2017)]
  - GW190425 [LVC, ApJL892.L3 (2020)]
- Two NSBH
  - GW200105 [LVC, ApJL915.L1]
  - GW200115 [LVC, ApJL915.L1]
- Unusual mass events
  - GW231123, etc.



# New Discoveries

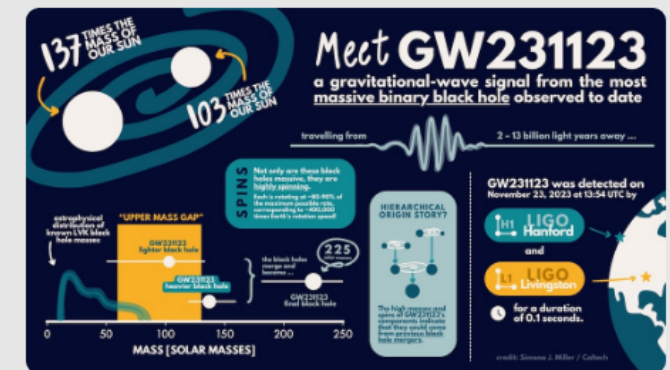
Download Analysis Ready Data Products [GW230529\\_181500](#)

- This version of the data release includes subtraction of noise contributions from non-linear couplings.
- At the time of GW230529\_181500 only the L1 detector was observing.



## GW231123 Data Released

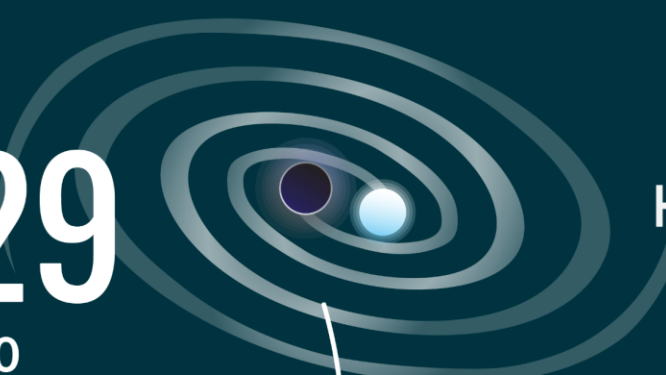
[Read the notes](#) for the release of [the GW231123\\_135430 event!](#) GW231123 is the merger of the most massive black holes ever observed with gravitational waves. The merger produced a final black hole more than 225 times the mass of our Sun. The signal was observed during the fourth observing run (O4) of the LVK network on November 23, 2023.



Get to know

# GW230529

Full name GW230529\_181500



~ 650 million light years away



Discovered on 29 May 2023 at 18h15 UTC

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

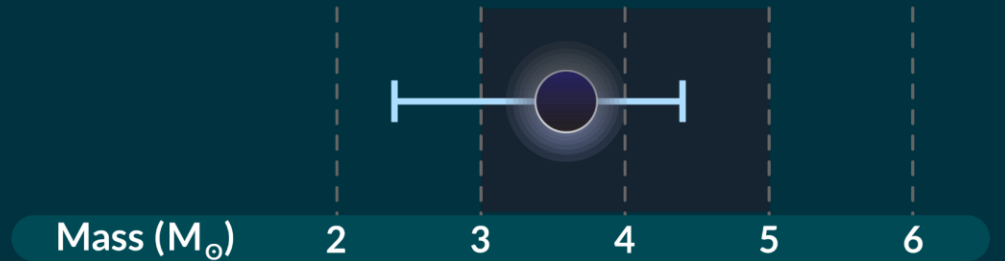
more likely than prior GW NSBHs to have the neutron star ripped apart by the black hole

## Detectors



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

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

137 TIMES THE MASS OF OUR SUN

103 TIMES THE MASS OF OUR SUN

# Meet GW231123

a gravitational-wave signal from the most massive binary black hole observed to date

travelling from

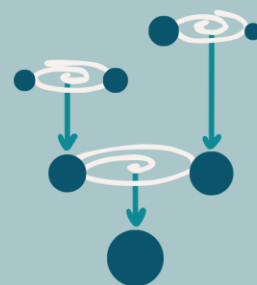
2 – 13 billion light years away ...

## SPINS

Not only are these black holes massive, they are highly spinning.

Each is rotating at ~80-90% of the maximum possible rate, corresponding to ~400,000 times Earth's rotation speed!

## HIERARCHICAL ORIGIN STORY?



The high masses and spins of GW231123's components indicate that they could come from previous black hole mergers.

GW231123 was detected on November 23, 2023 at 13:54 UTC by

H1 LIGO Hanford

and

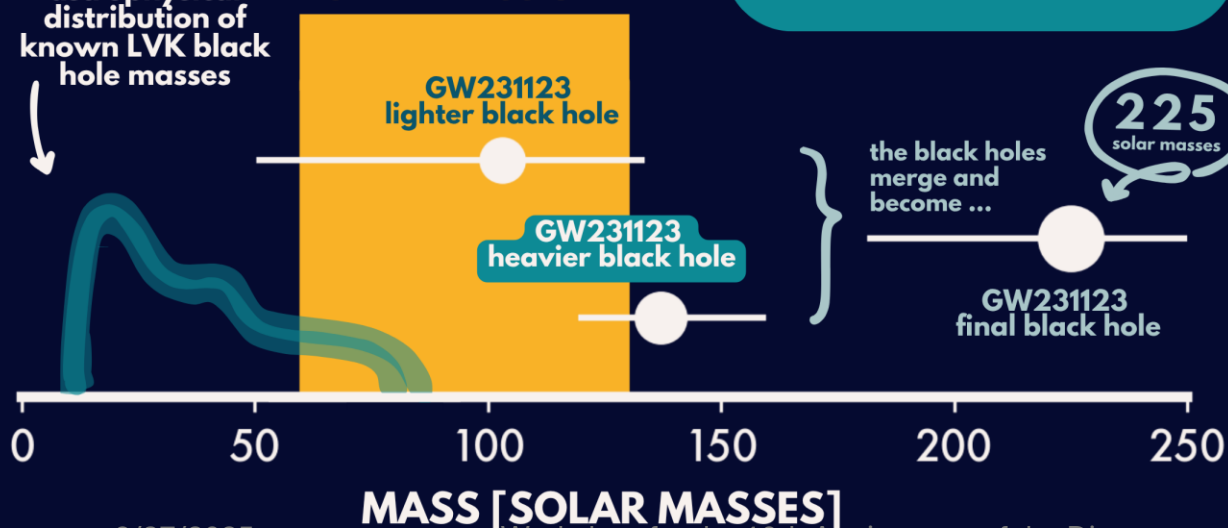
L1 LIGO Livingston



for a duration of 0.1 seconds.

astrophysical distribution of known LVK black hole masses

## "UPPER MASS GAP"



태양 질량의  
**137 배**

태양 질량의  
**103 배**

# GW231123 의 모든 것

관측 사상 가장 무거운 블랙홀 쌍성의 중력파 신호

20-130억 광년

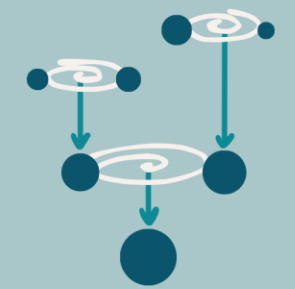
떨어진 곳으로부터 날아온 ...

## 자전

이러한 블랙홀들은 무거울뿐만 아니라 매우 빠르게 자전하고 있다. 각각은 지구 자전속도의 ~40만배에 해당하는 가능한 최대 한계치의 ~80-90%로 회전하고 있다.



## 기원에 대한 다중병합 시나리오?



GW231123의 높은 질량과 자전값이 시사하는 바는 이것들이 이전의 블랙홀 병합으로부터 형성되었을 수 있다는 것이다.

GW231123은 2023년 11월 23일 13:54(세계 표준시)에 아래 관측소에서 검출되었다:

**H1** 라이고  
헨포드

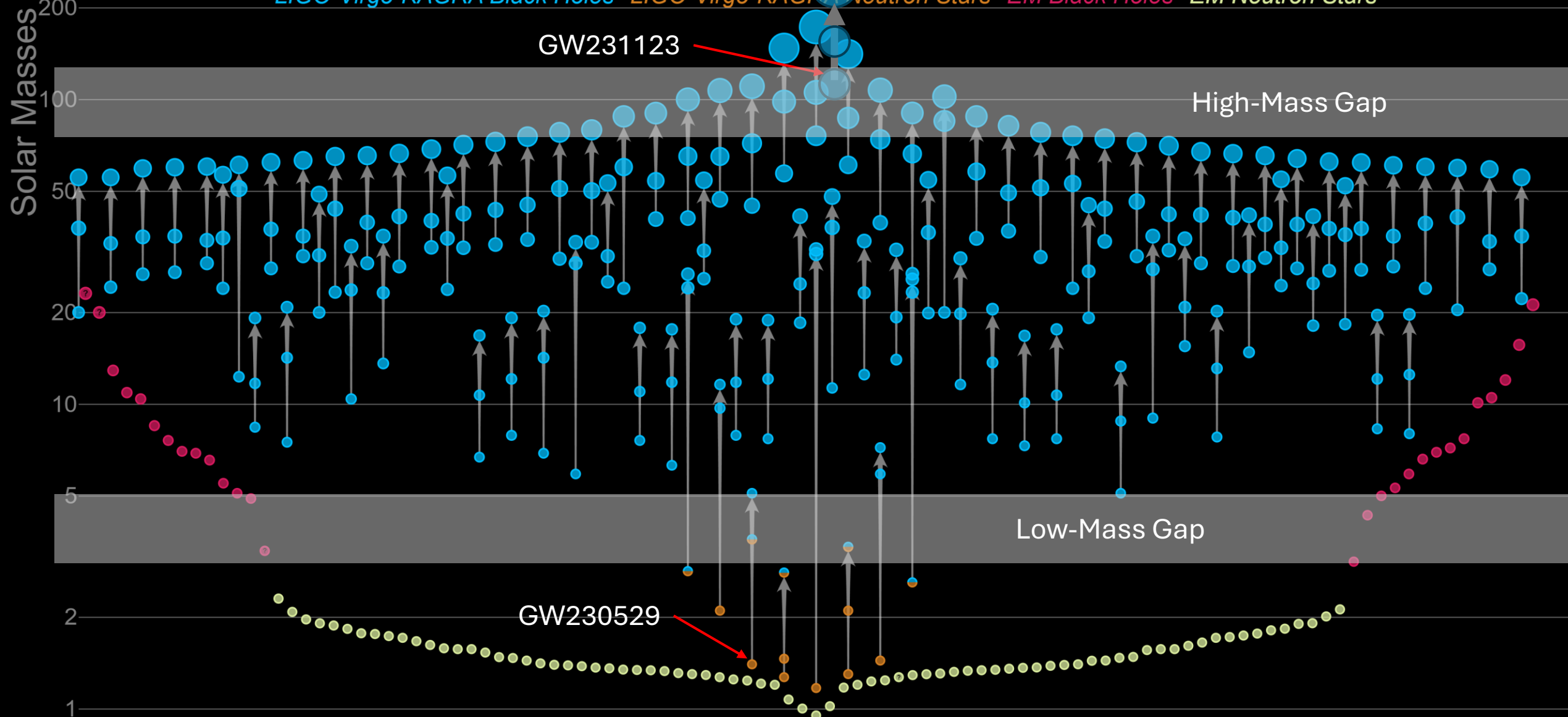
와

**L1** 라이고  
리빙스톤

지속 시간 **0.1 초**

# Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars EM Black Holes EM Neutron Stars

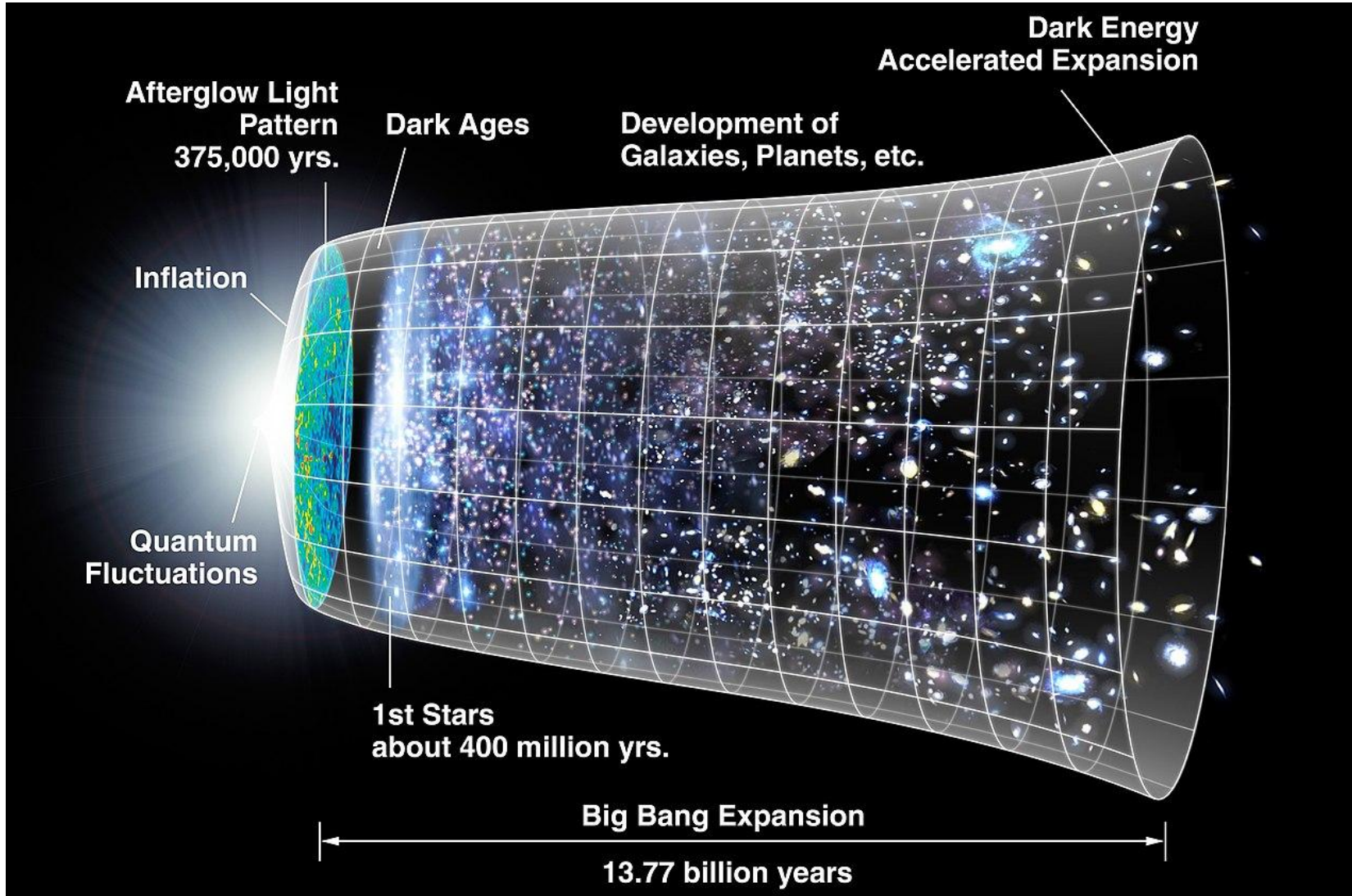


# Implications

# Implications

- New Astronomical Tools
- Testing General Relativity
- Exploring Cosmic Phenomena
- The Rise of Multi-Messenger Astronomy

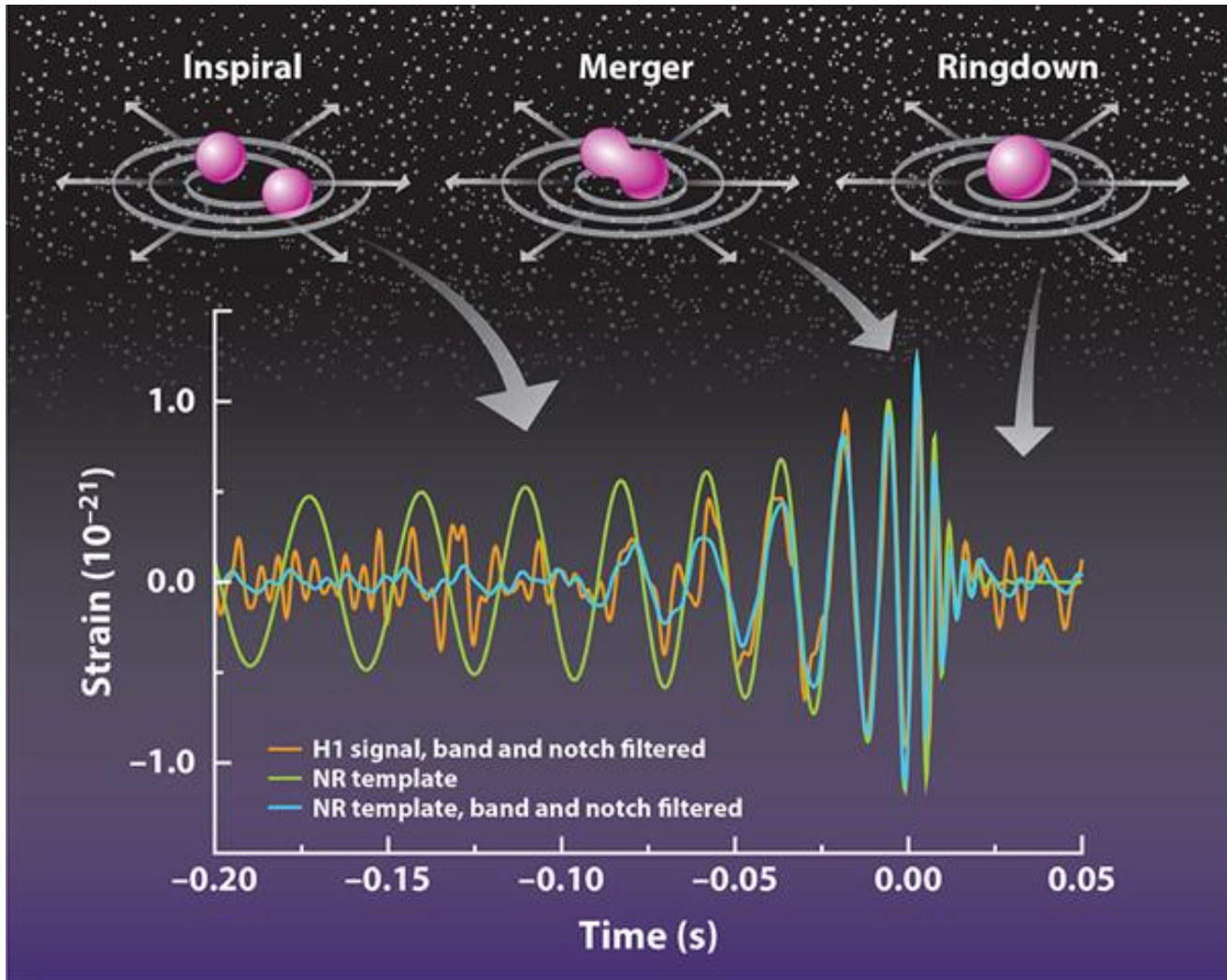
# New astronomical tools



Signal before CMB  
Blackhole generated signal

Credit: NASA

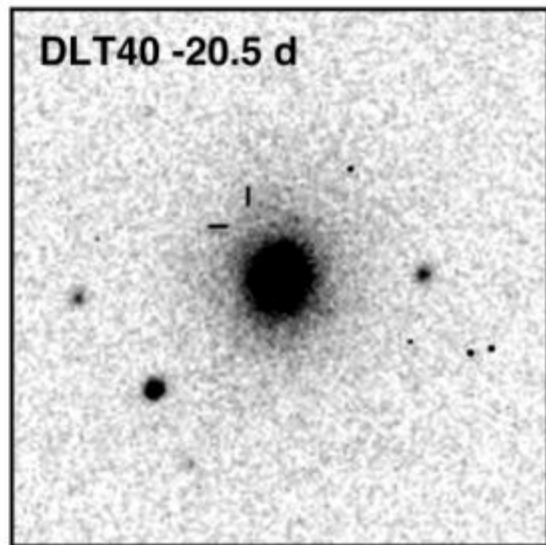
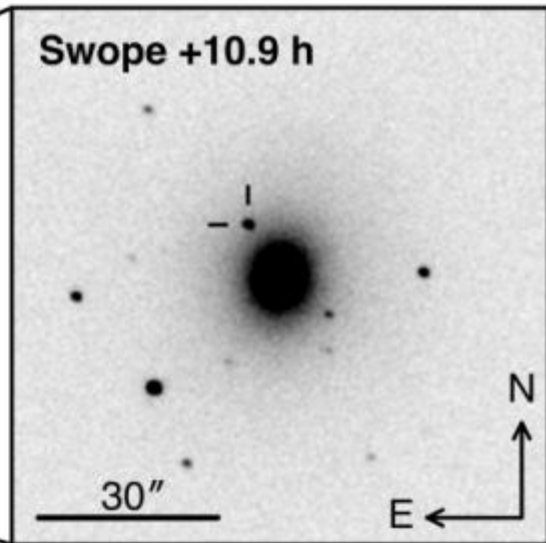
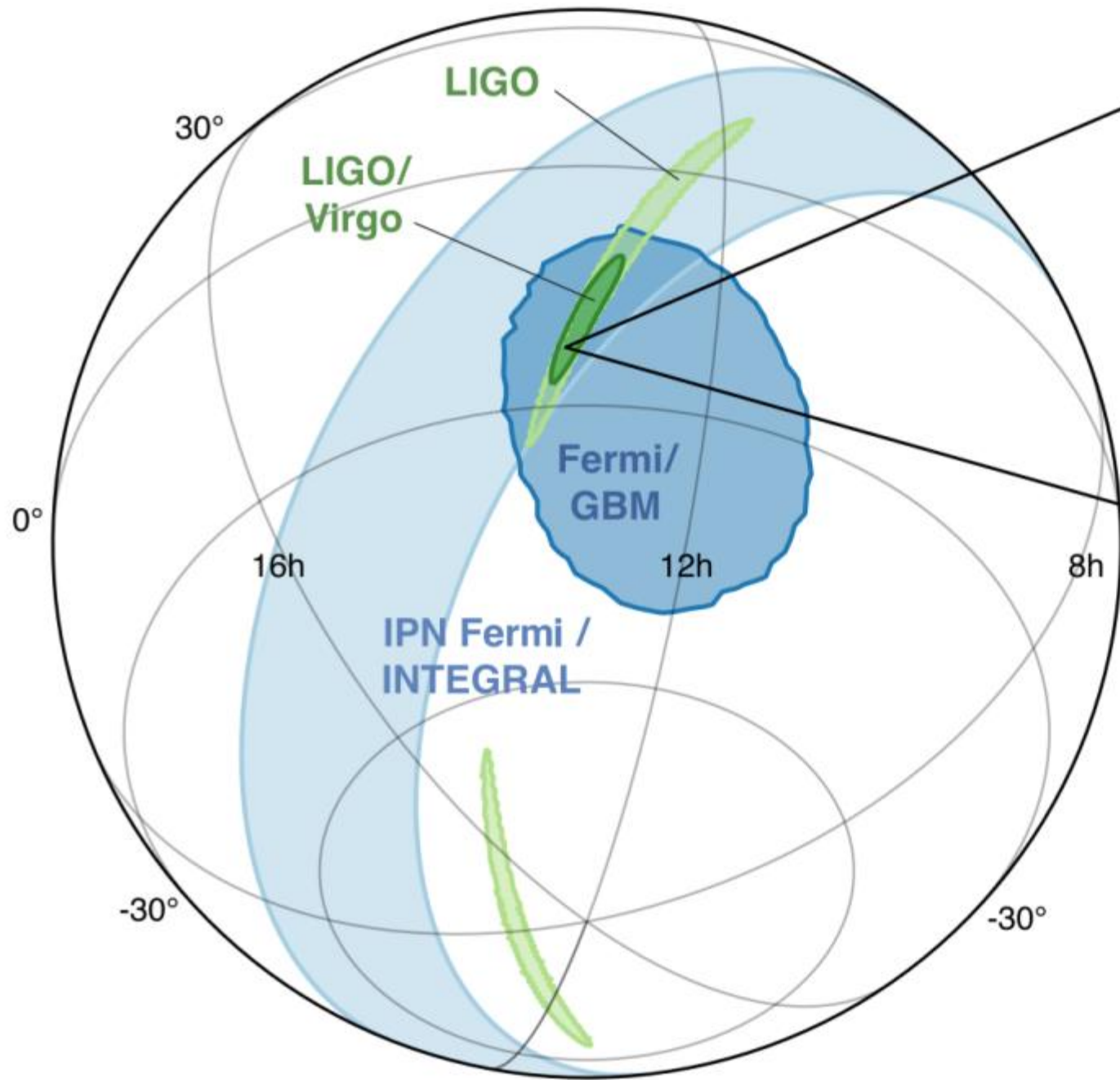
# Testing General Relativity



Quasi Normal Mode analysis  
Modified Gravity theory test  
Area Law test

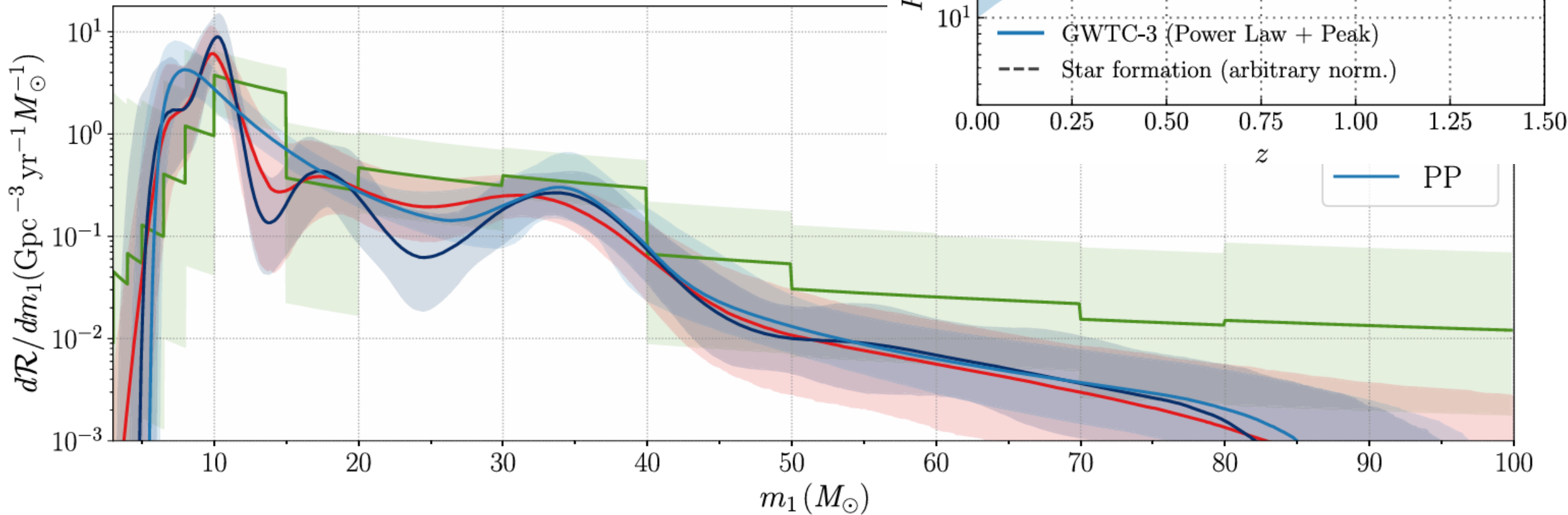
[Physics - Relativity Gets Thorough Vetting from LIGO](#)

# Multi-messenger Astronomy



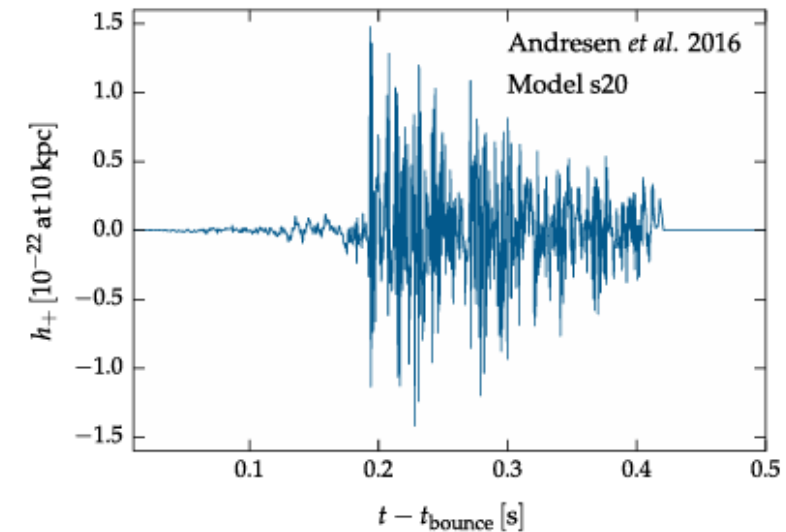
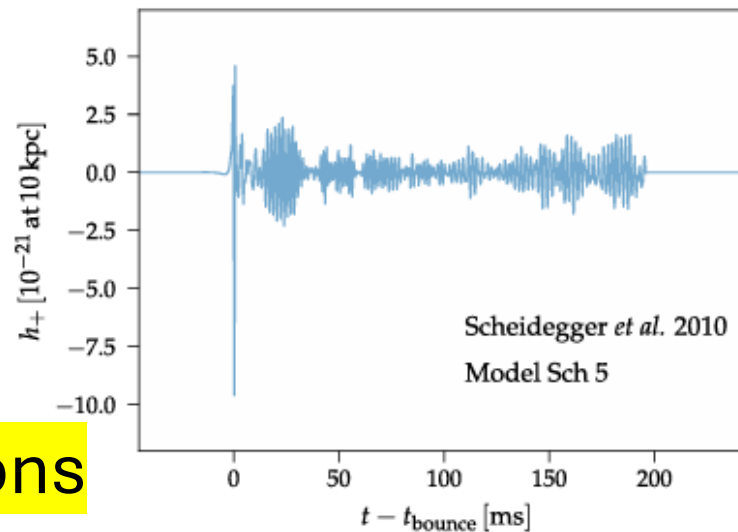
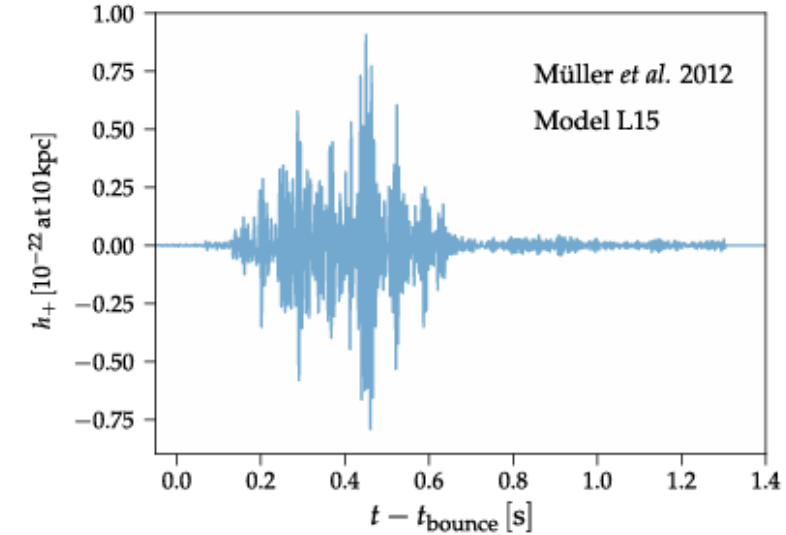
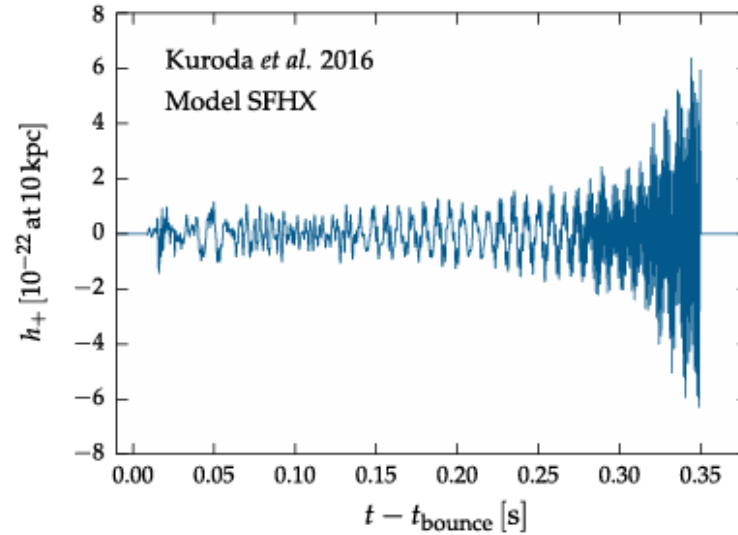
# Astrophysics with CBCs

- Infer population properties [LVK PRX13,011048 (2023)]



# Transient bursts of GWs

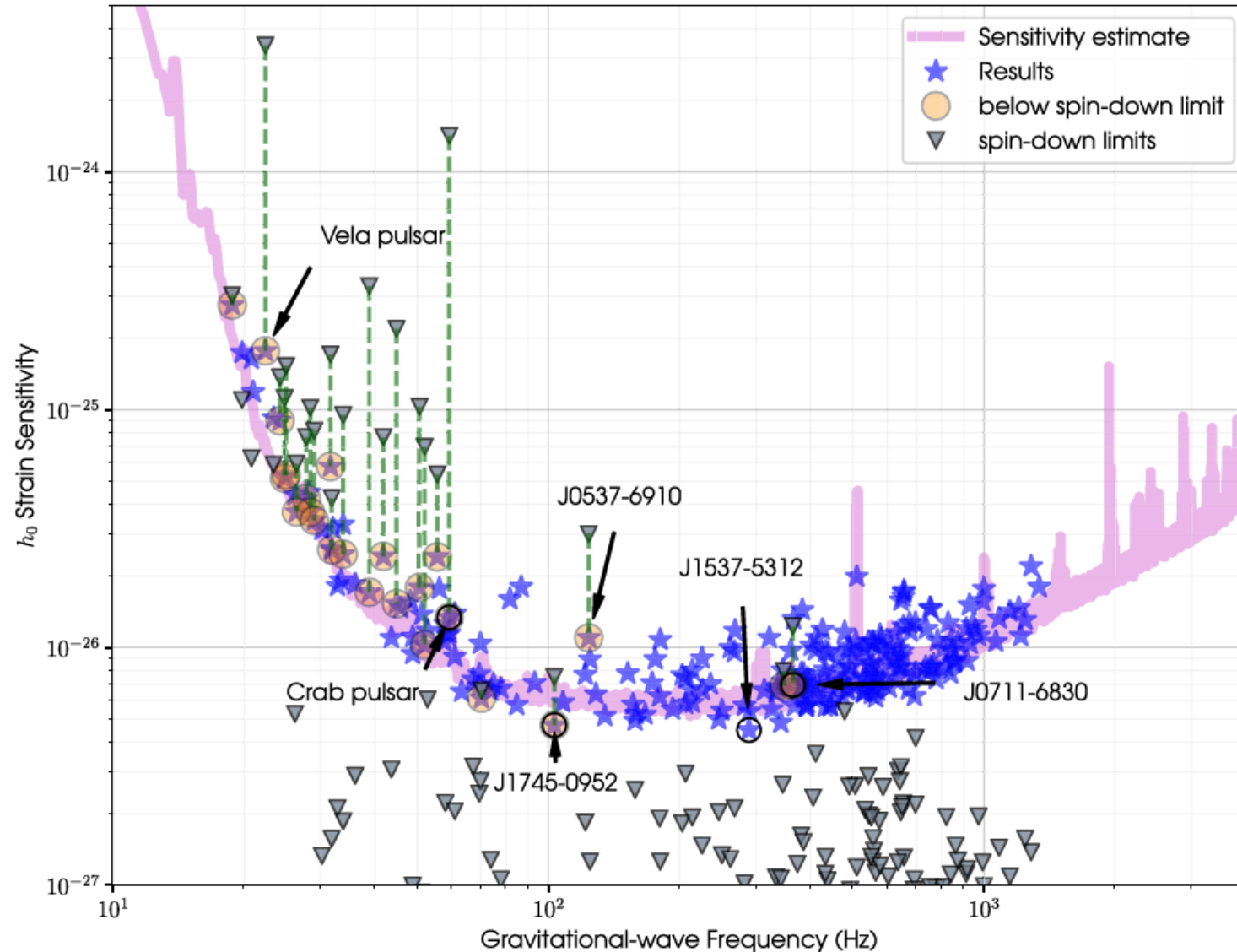
- No non-BBH detection  
PRD104,122004 (2021), PRD104.102001 (2021)



CCSN simulations

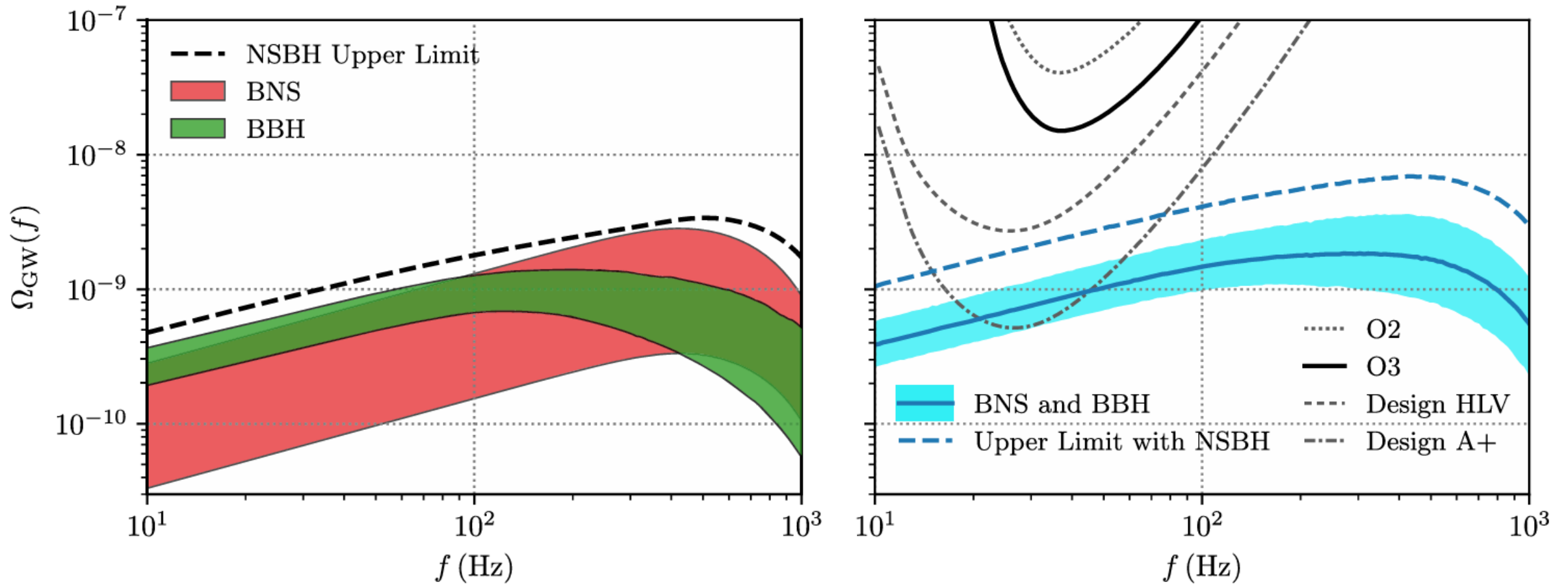
# Continuous gravitational waves(CWs)

- Signals lasting more than  $\approx 30$  minutes subject to Doppler shifts and amplitude modulation
- Amplitude is at least 5 orders of magnitude smaller than CBCs, but longer signal duration may enable detection
- No detection O1-O3
- ApJ 935:1 (2022)



# The stochastic GW background

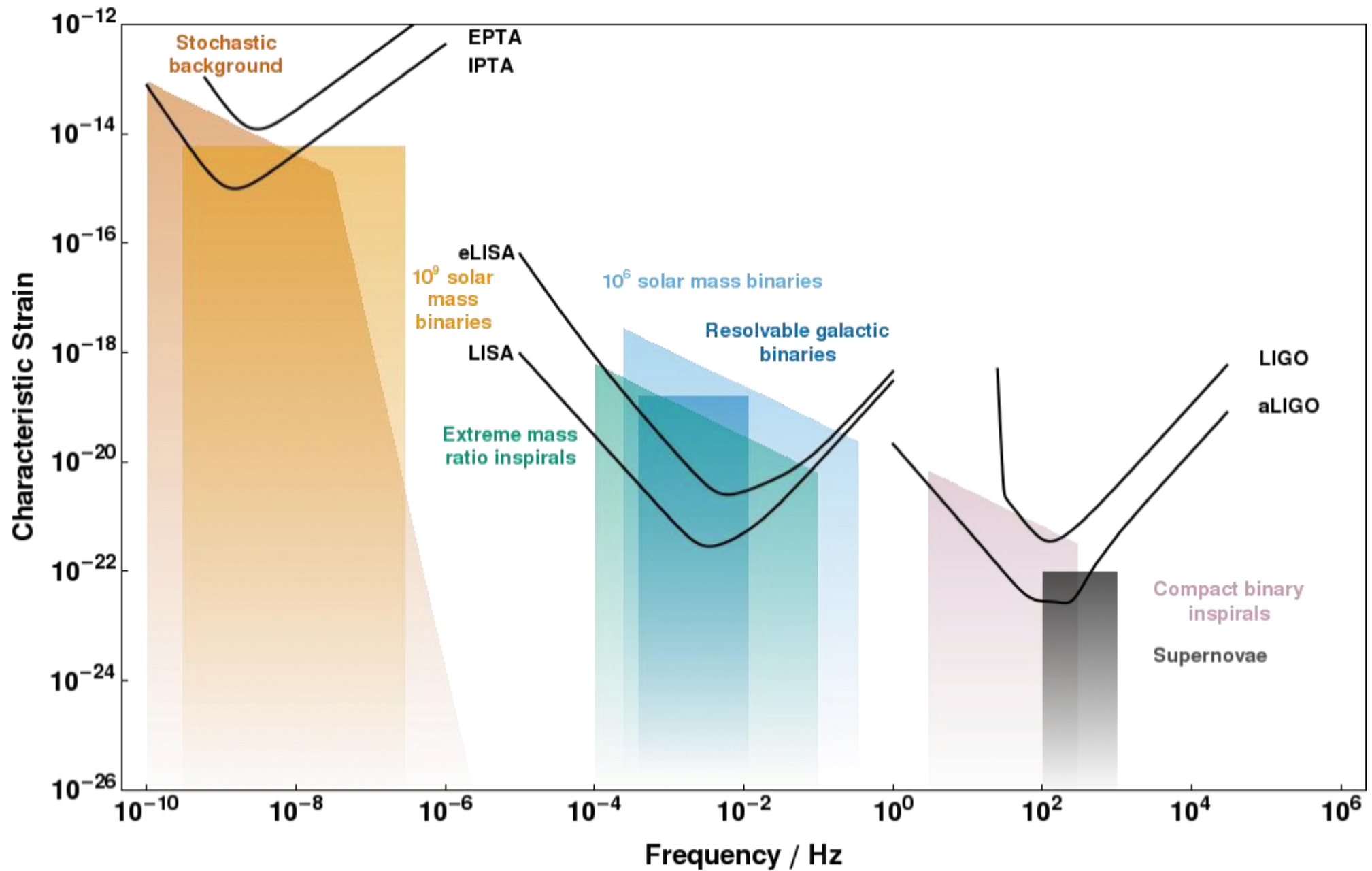
- No detections O1-O3 [PRD104.022004 (2021)]



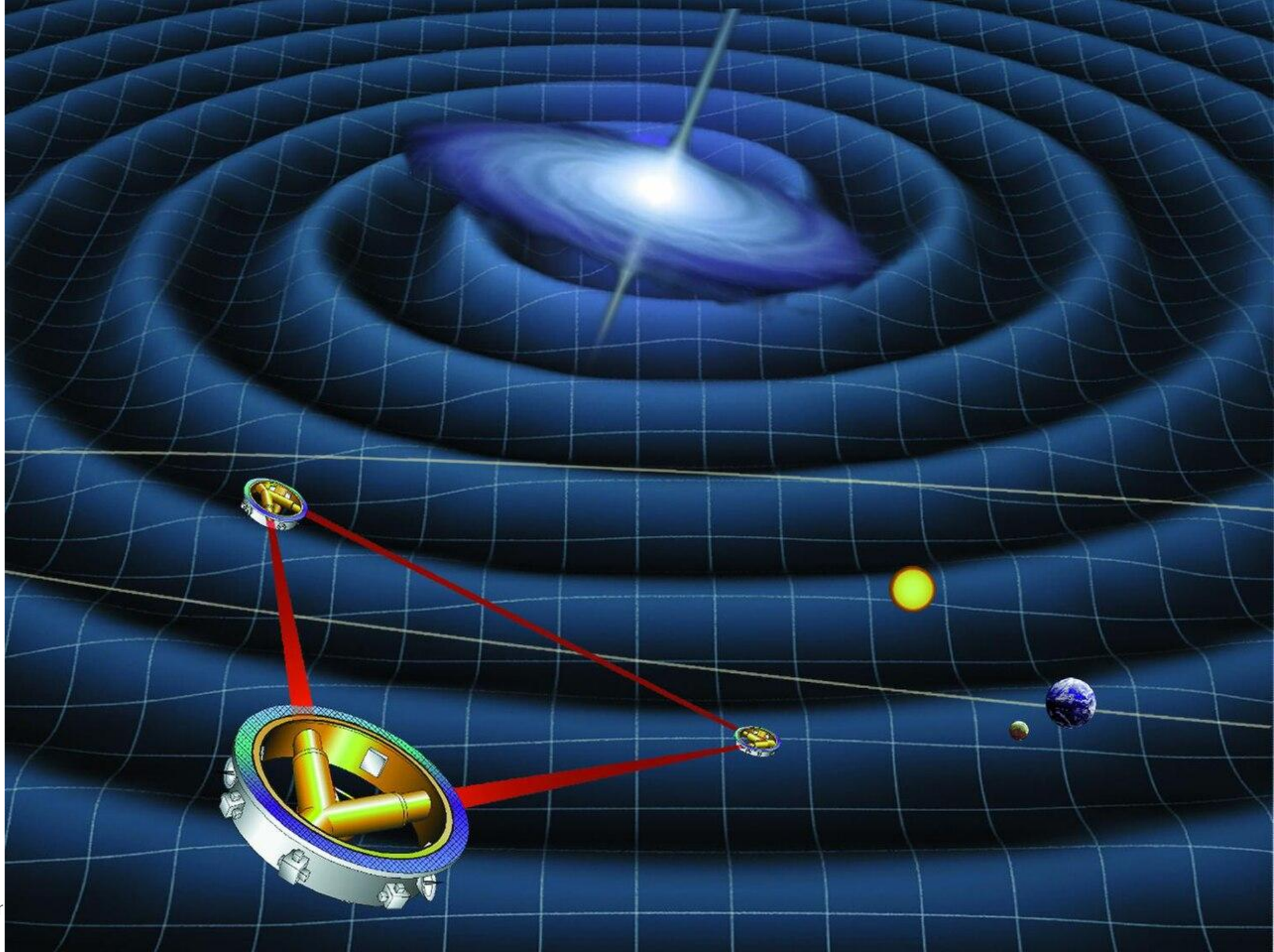
# Technical Advancements

- Seismic and Vibration Isolation
- Laser and Optical Technology
- Vacuum Technology
- Coating Materials
- Data Analysis and Computational Physics

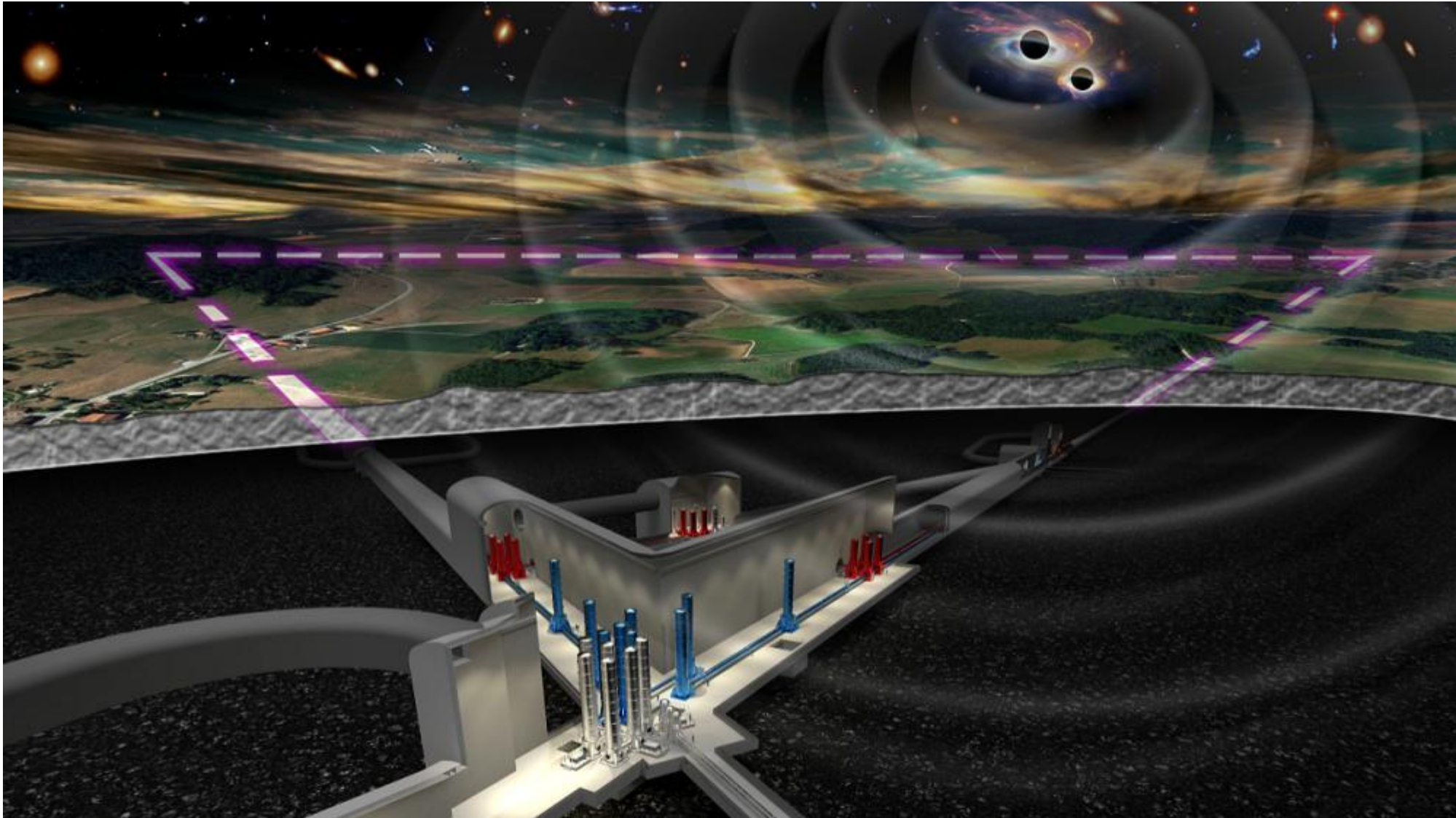
# Future



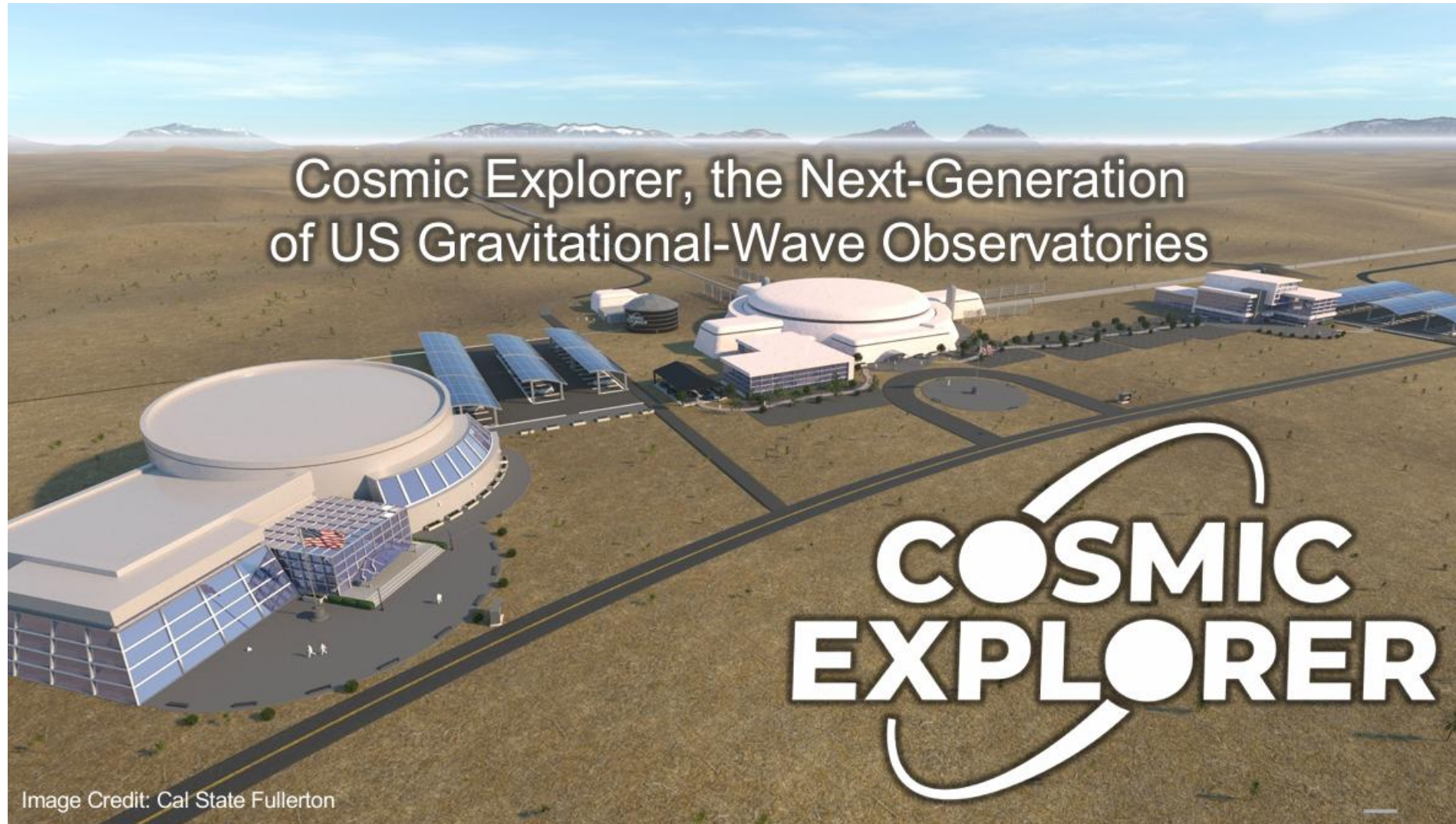
# LISA



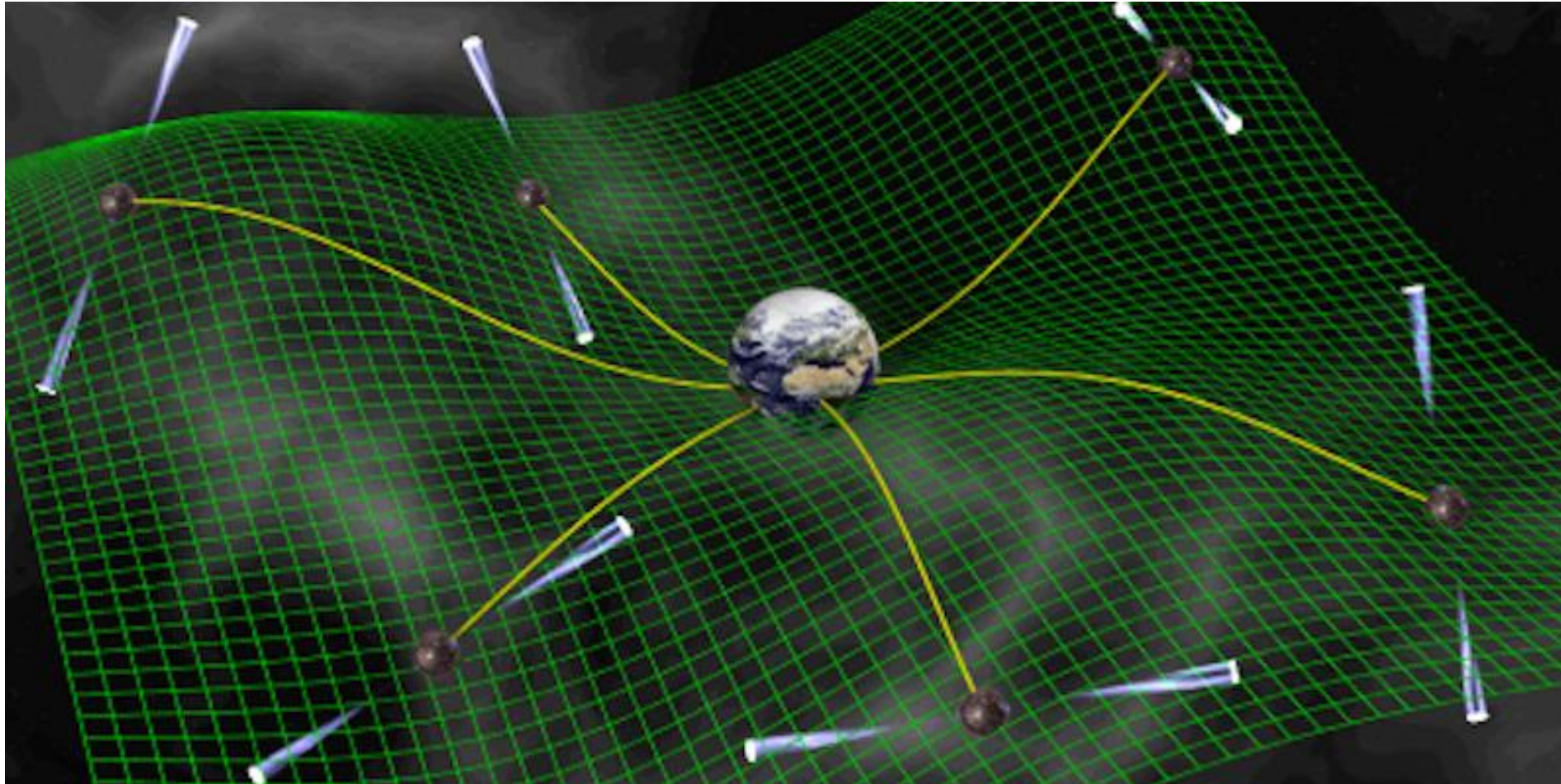
# Einstein Telescope



# Cosmic Exploler



# Pulsar Timing Array(PTA)



# Acknowledgements

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**Thanks!**