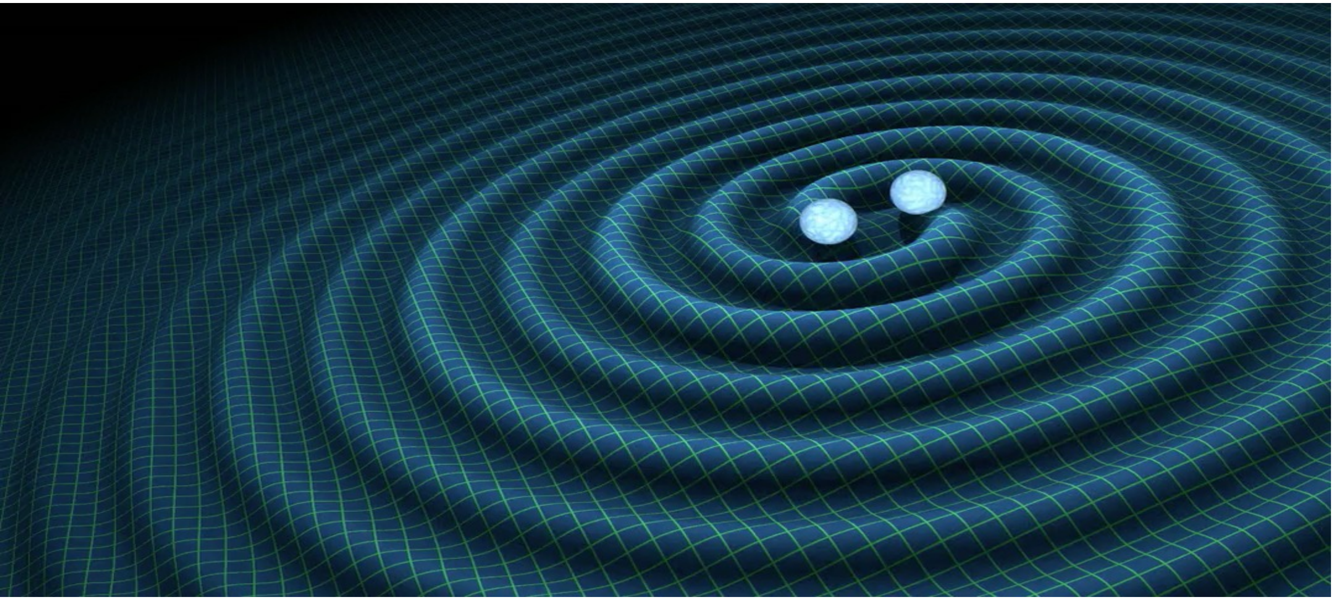
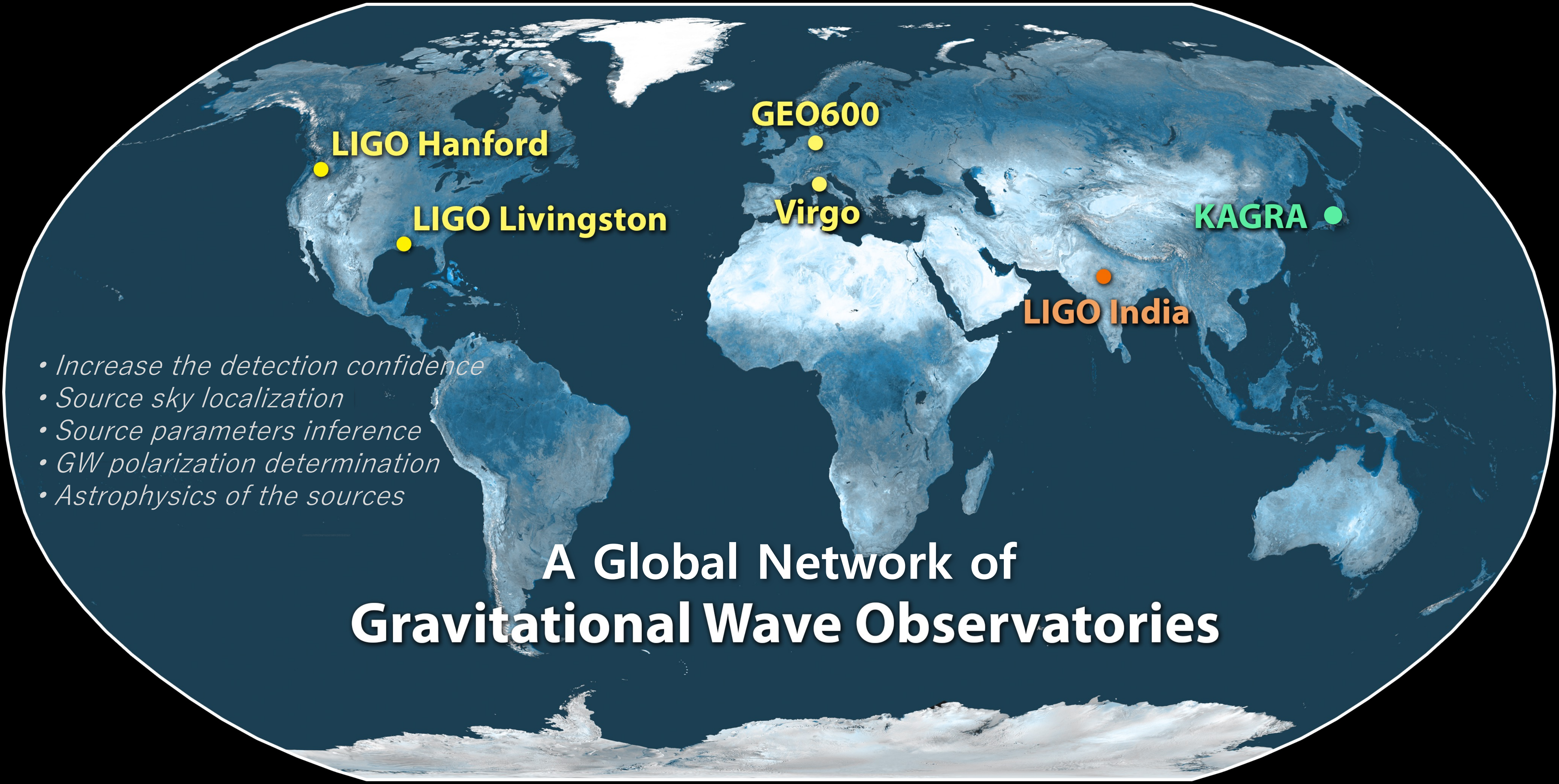


Introduction to the GW Science/Analysis

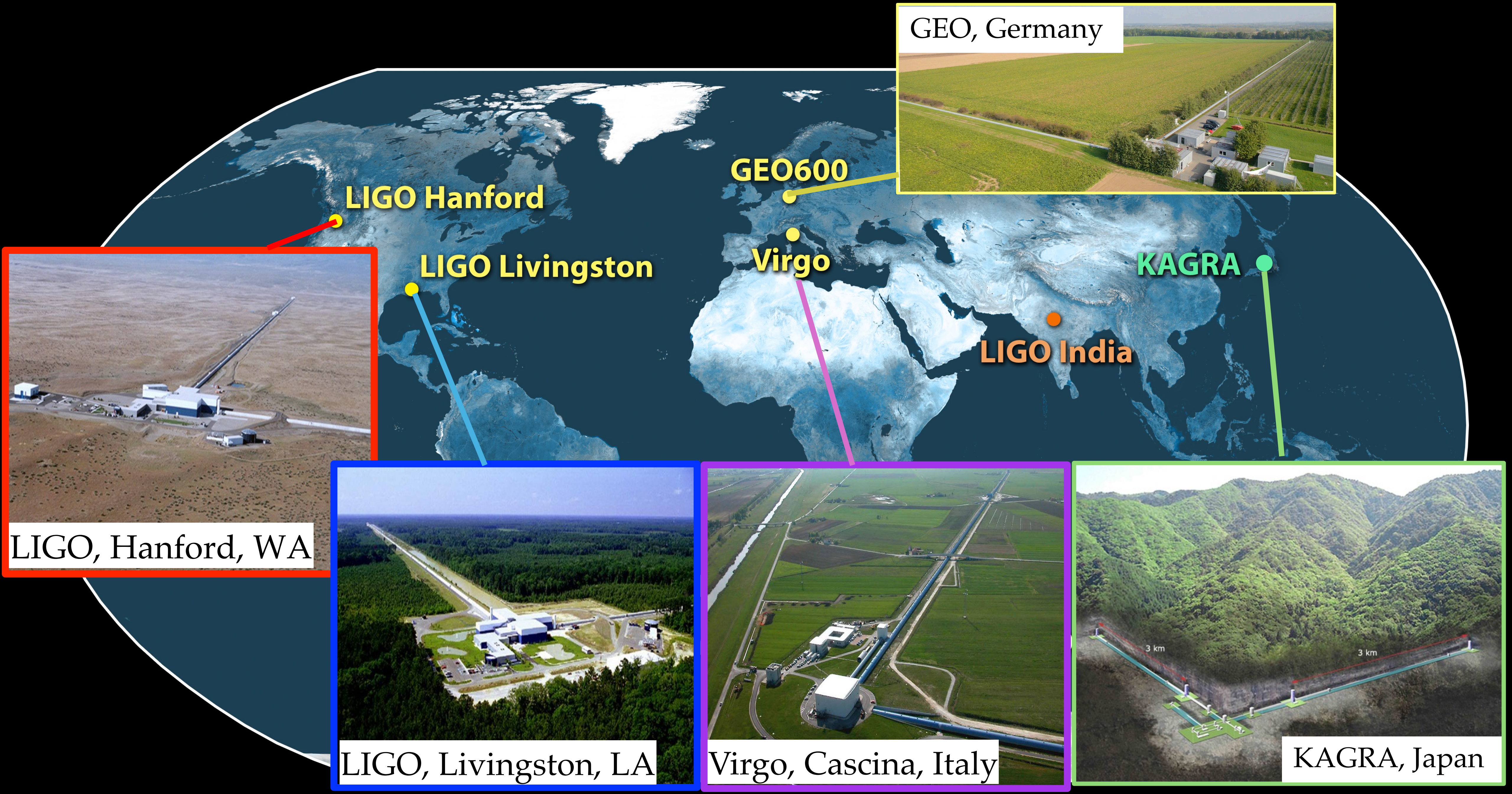
Takahiro Sawada
Institute for Cosmic Ray Research (ICRR), The University of Tokyo

Wave Open Data Workshop #7 (2024)
National Museum of Natural Science, Taichung
April 18, 2024

Many materials were reproduced from VIR-0245A-23, LIGO-G2200820



Credit: Caltech/MIT/LIGO Lab

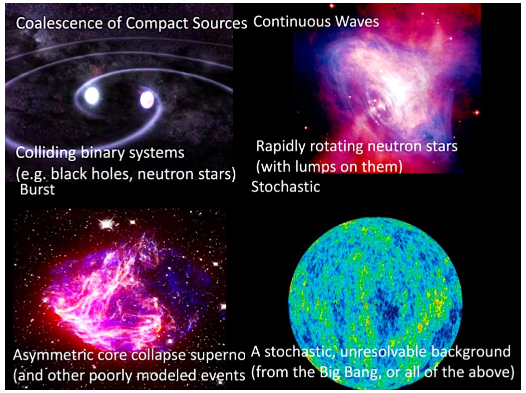


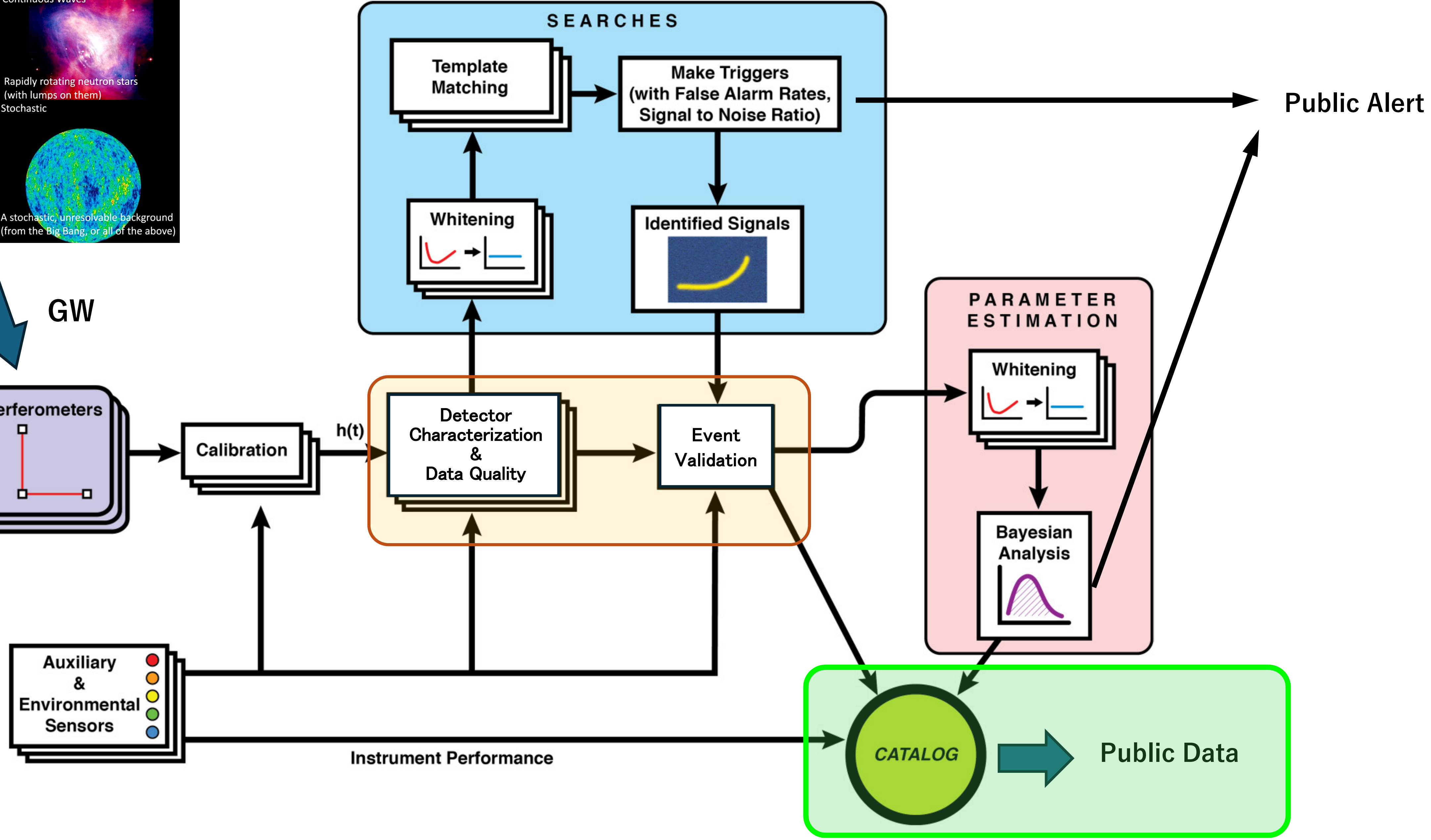
Credit: Caltech/MIT/LIGO Lab

LVK Dataflow (simplified)

[B. P. Abbott et al., 2020 Class. Quantum Grav. 37 055002]

Gravitational-Wave (GW) sources

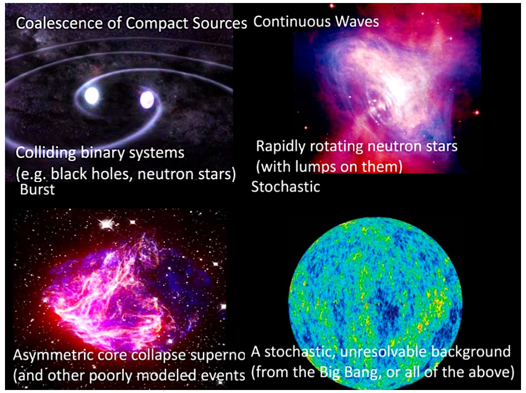


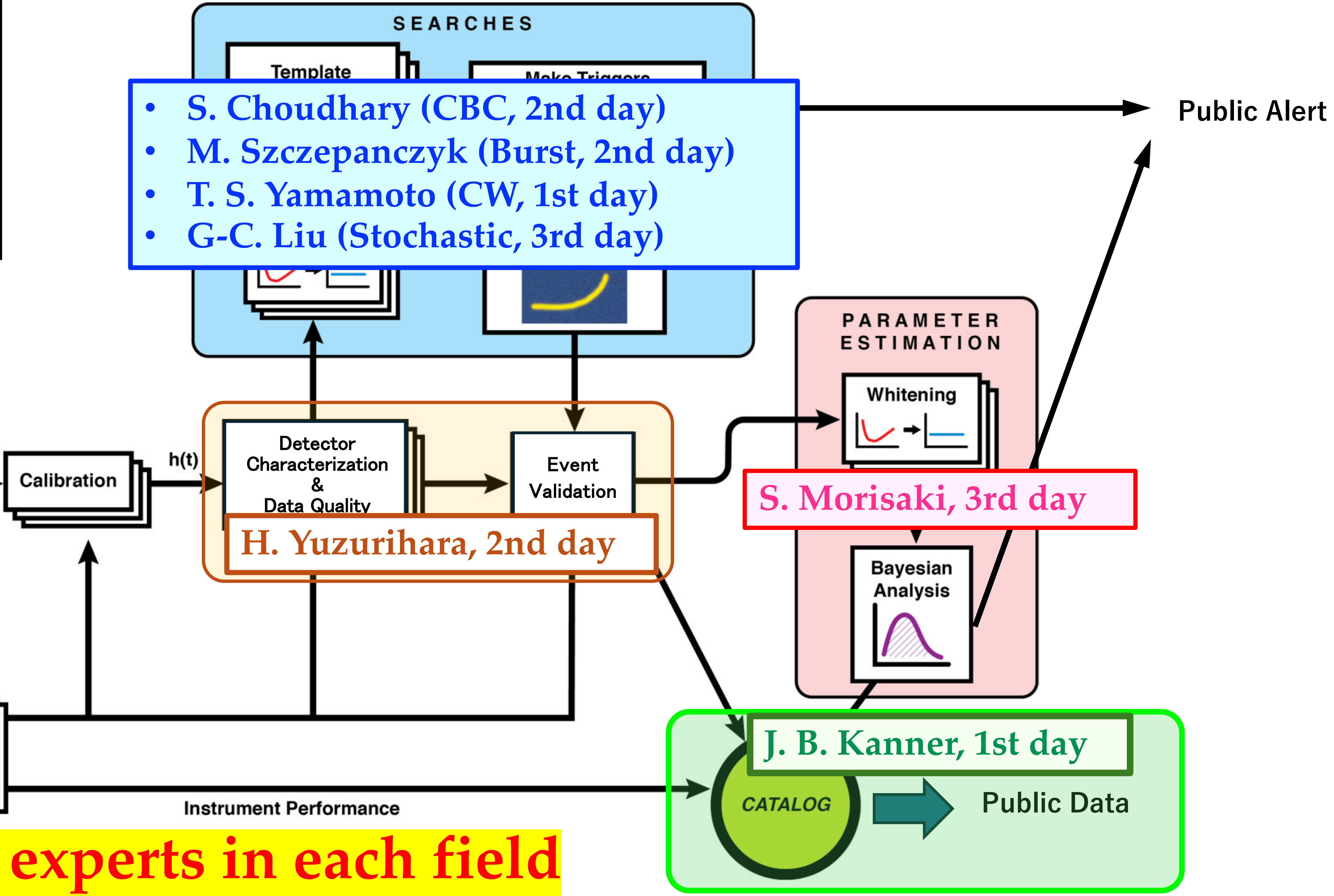


LVK Dataflow (simplified)

[B. P. Abbott et al., 2020 Class. Quantum Grav. 37 055002]

Gravitational-Wave (GW) sources





- S. Choudhary (CBC, 2nd day)
- M. Szczepanczyk (Burst, 2nd day)
- T. S. Yamamoto (CW, 1st day)
- G-C. Liu (Stochastic, 3rd day)

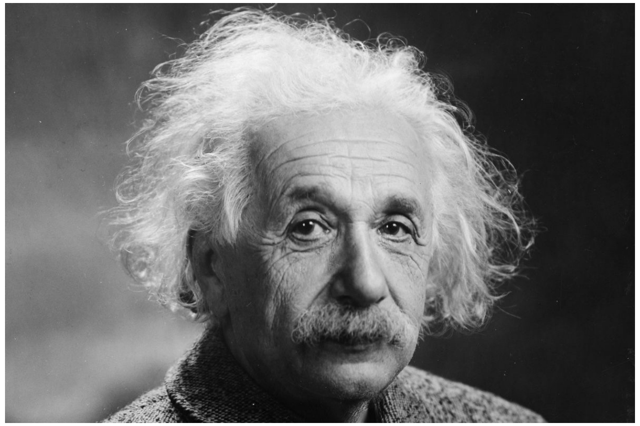
H. Yuzurihara, 2nd day

S. Morisaki, 3rd day

J. B. Kanner, 1st day

Lectures by experts in each field

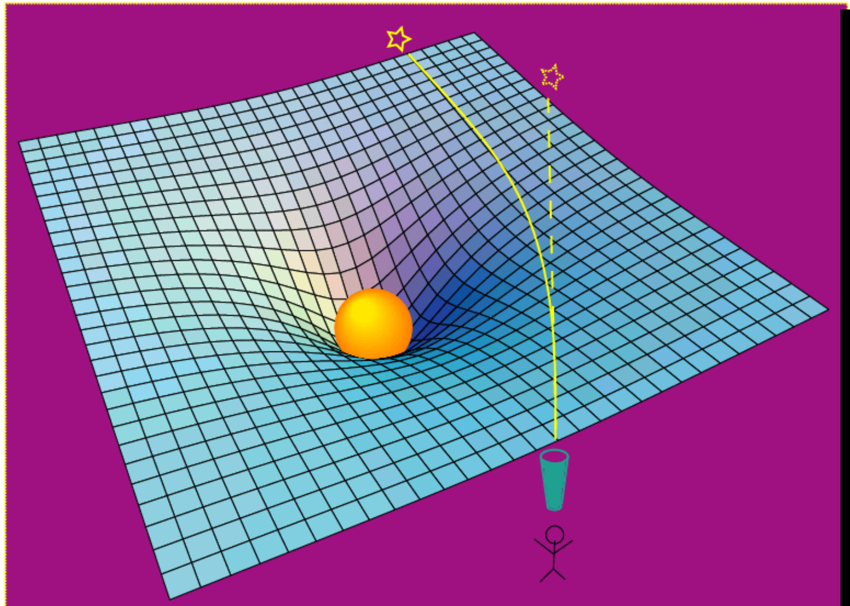
What are Gravitational Waves (GW) ?



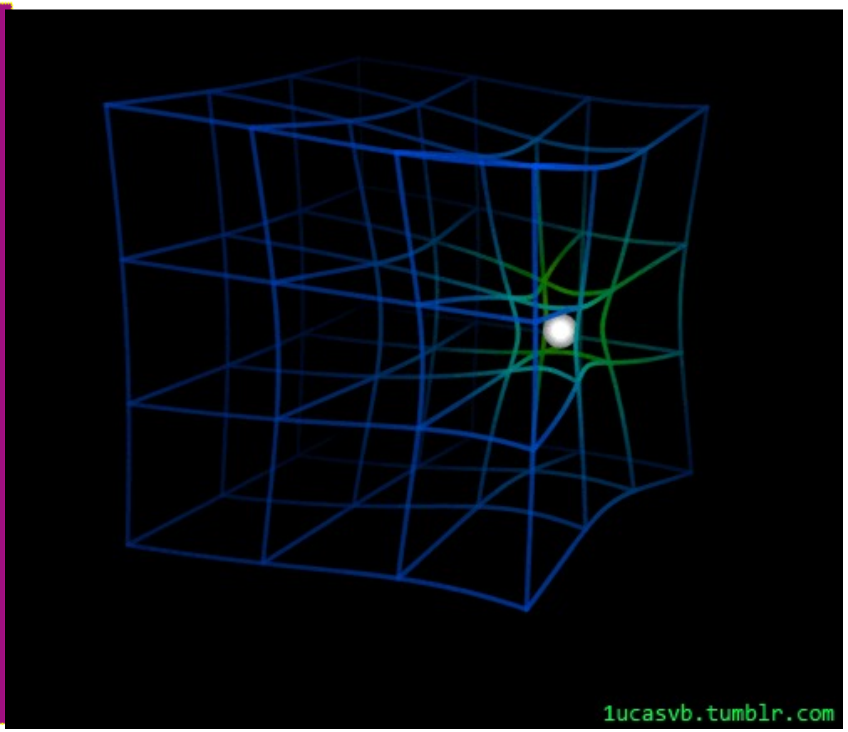
Albert Einstein

"Mass tells spacetime how to curve,
spacetime tells mass how to move"
---J. Wheeler

Prediction from General Relativity

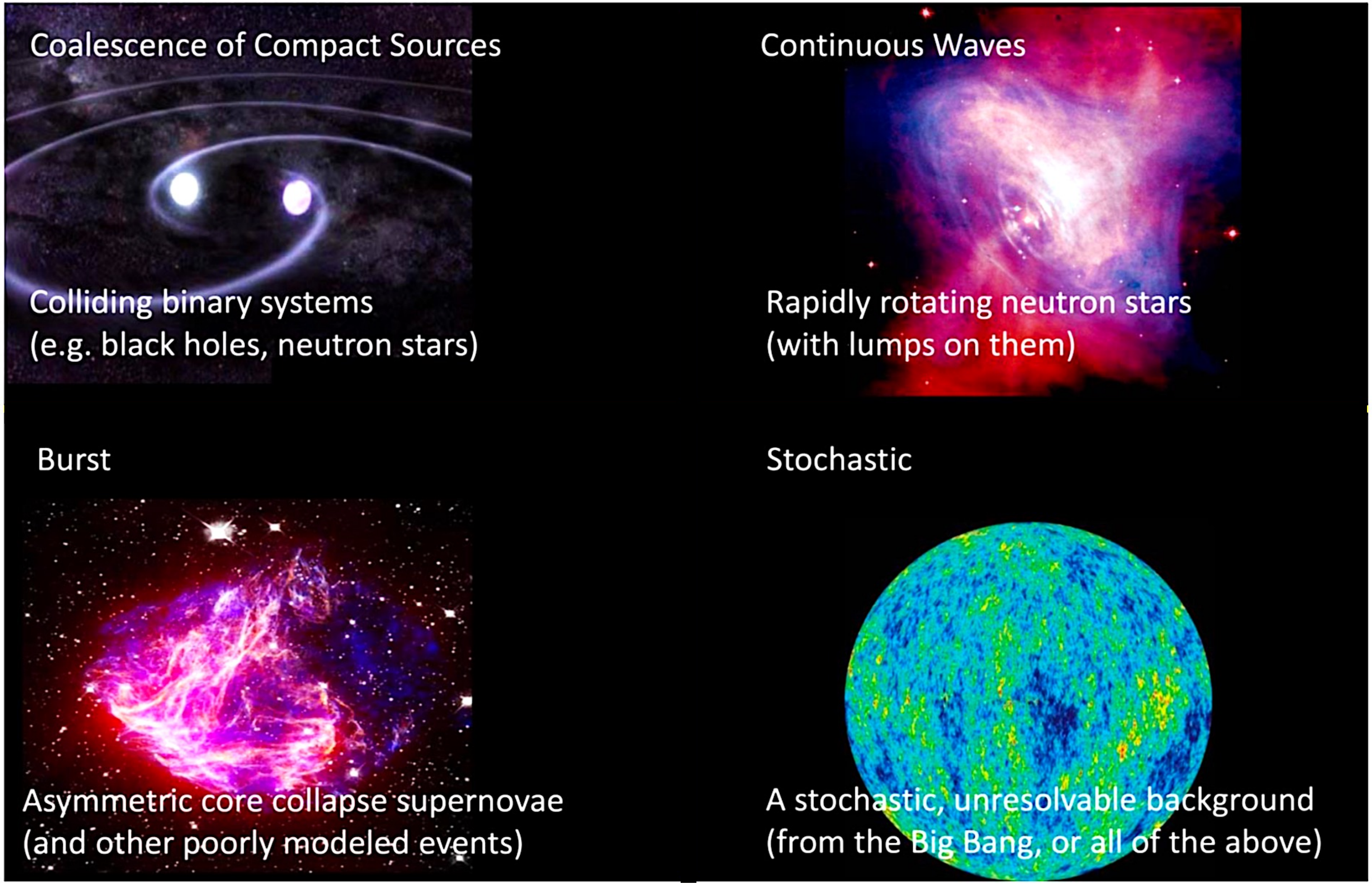


A massive object shifts apparent position of a star



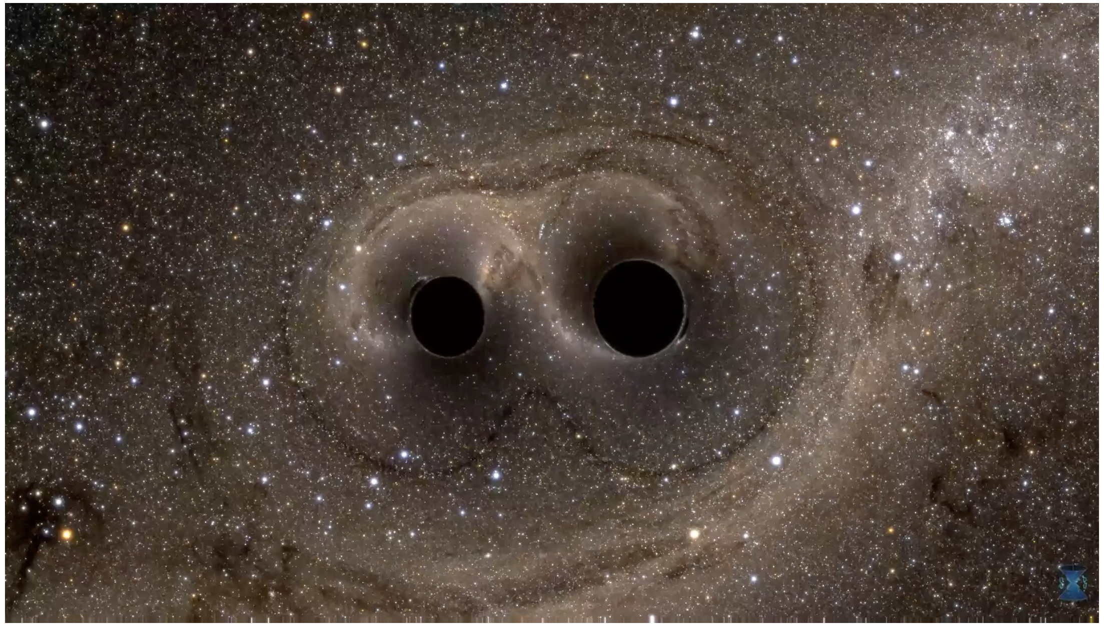
- GWs are ripples of space-time produced by rapidly accelerating mass distributions.
- Provide info on mass displacement
- Weakly coupled
- Propagate at speed of light
- Two polarizations "+" and "x"
- Emission is quadrupolar at lowest order

Gravitational Wave Sources

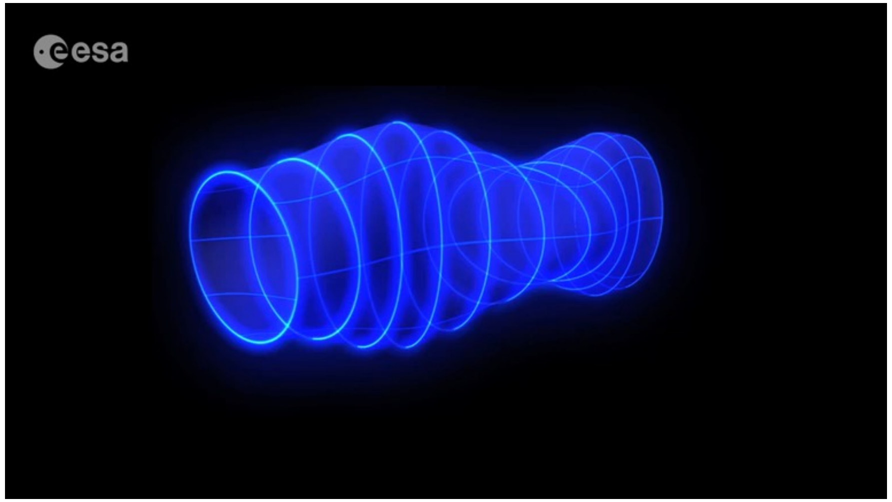


Gravitational Waves Affect Spacetime

Black holes inspiralling around each other



Spacetime stretches and squeezes
as gravitational waves pass



We measures the
distortions of
spacetime
by our detectors.

1916- : A century of progress

Theoretical developments

- 1916: GW prediction (Einstein)

1957: Chapel Hill Conference (Bondi, Feynman, Pirani, etc.)

- 1963: rotating BH solution (Kerr)
- 1990's: CBC PN expansion (Blanchet, Damour, Deruelle, Iyer, Will, Wiseman, etc.)
- 2000: BBH effective one-body approach (Buonanno, Damour)
- 2006: BBH merger simulation (Baker, Lousto, Pretorius, etc.)

Experiments

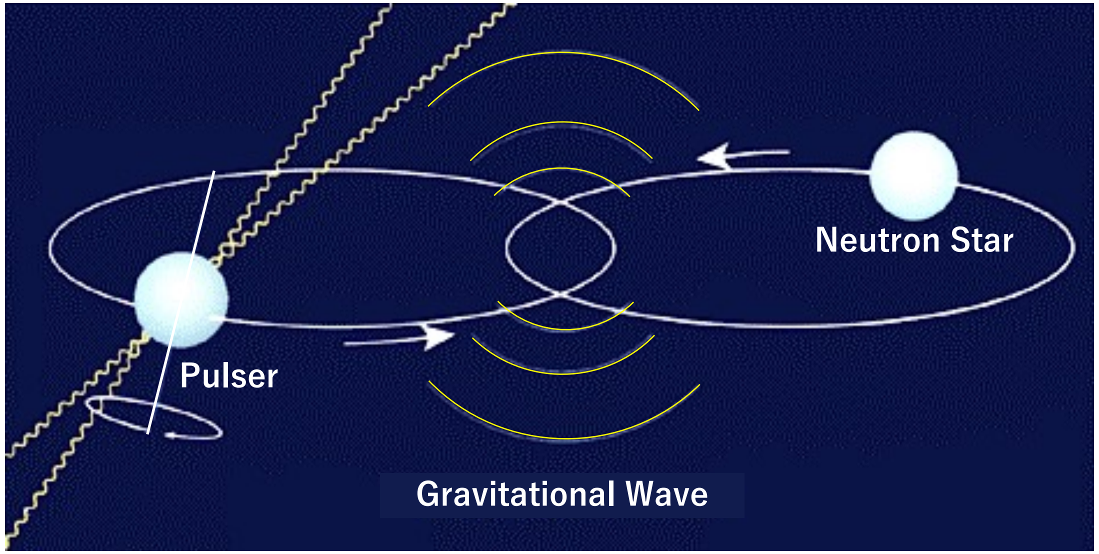
- 1960's: first Weber bars
- 1970: first IFO prototype (Forward)
- 1972: IFO design studies (Weiss)
- 1974: PSRB 1913+16 (Hulse & Taylor)
- 1980's: IFO prototypes (10m-long) (Caltech, Garching, Glasgow, Orsay)
  → End of 1980's: Virgo (Brillet, Giazotto) and LIGO proposals (Drever, Thorne, Weiss)
- 1990's: LIGO and Virgo funded
- 2005-2011: initial IFO « science » » runs
- 2007: LIGO-Virgo MoU
- First half of the 2010's: Upgrades
- First GW detections (2015 BBH, 2017 BNS, 2020 NSBH)

→ More and more signals since then!

Gravitational Waves
hard to find, but known to exist

Binary pulsar and Tests of General Relativity – Hulse & Taylor (1974)

PSR 1913+16



Credit: Nobelprize.org

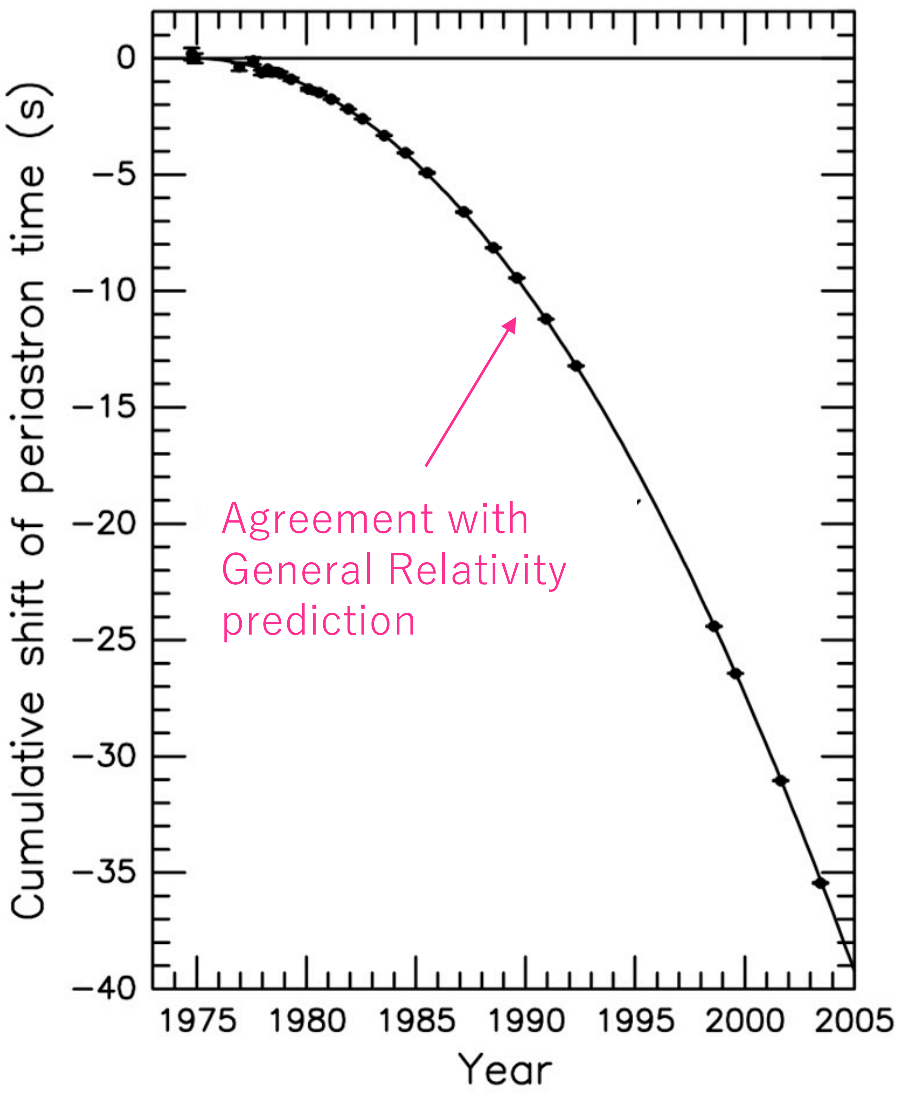
Binary Neutron Star system

- separated by 10^6 miles
- $m_1 = 1.4\ M_\odot$(Solar Mass); $m_2 = 1.36\ M_\odot$; $\varepsilon = 0.617$

Prediction from general relativity

- spiral in by 3 mm/orbit
- rate of change orbital period

Emission of gravitational waves



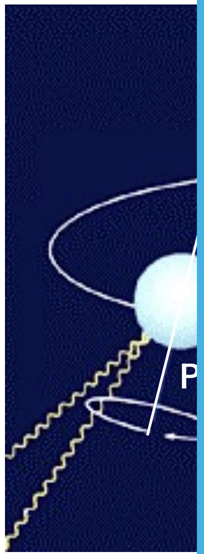
Gravitational Waves

hard to find, but known to exist

Binary pulsar and Tests of General Relativity

– Hulse

PSR 19



Binary Neu

- se
- m

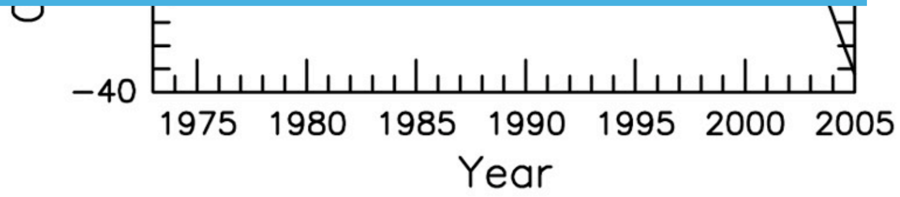
1993 Nobel Prize in Physics:
"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation."

R. Hulse and J. Taylor, orbital decay measurements with J. Weisberg

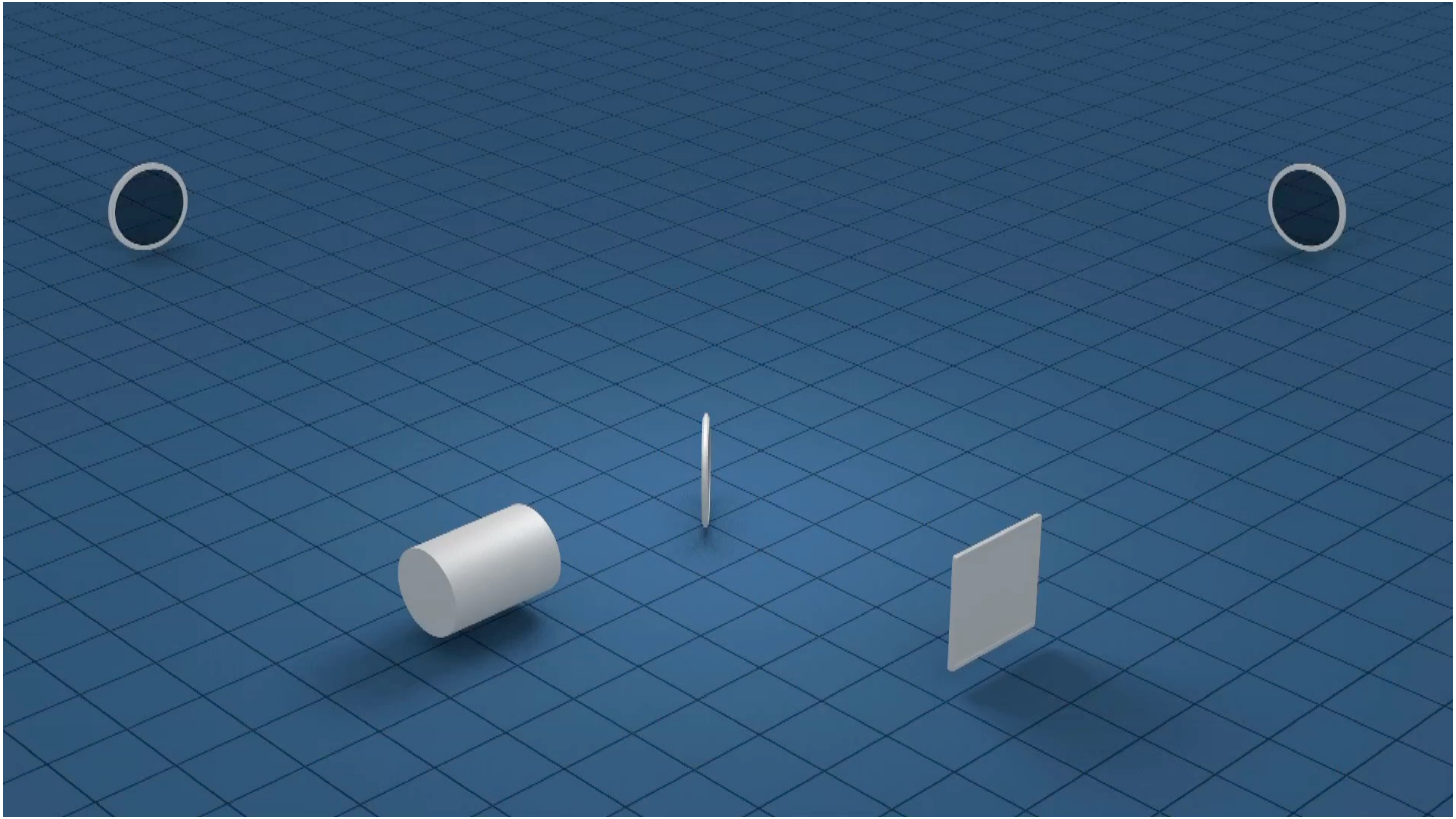
Prediction from general relativity

- spiral in by 3 mm/orbit
- rate of change orbital period

Emission of gravitational waves

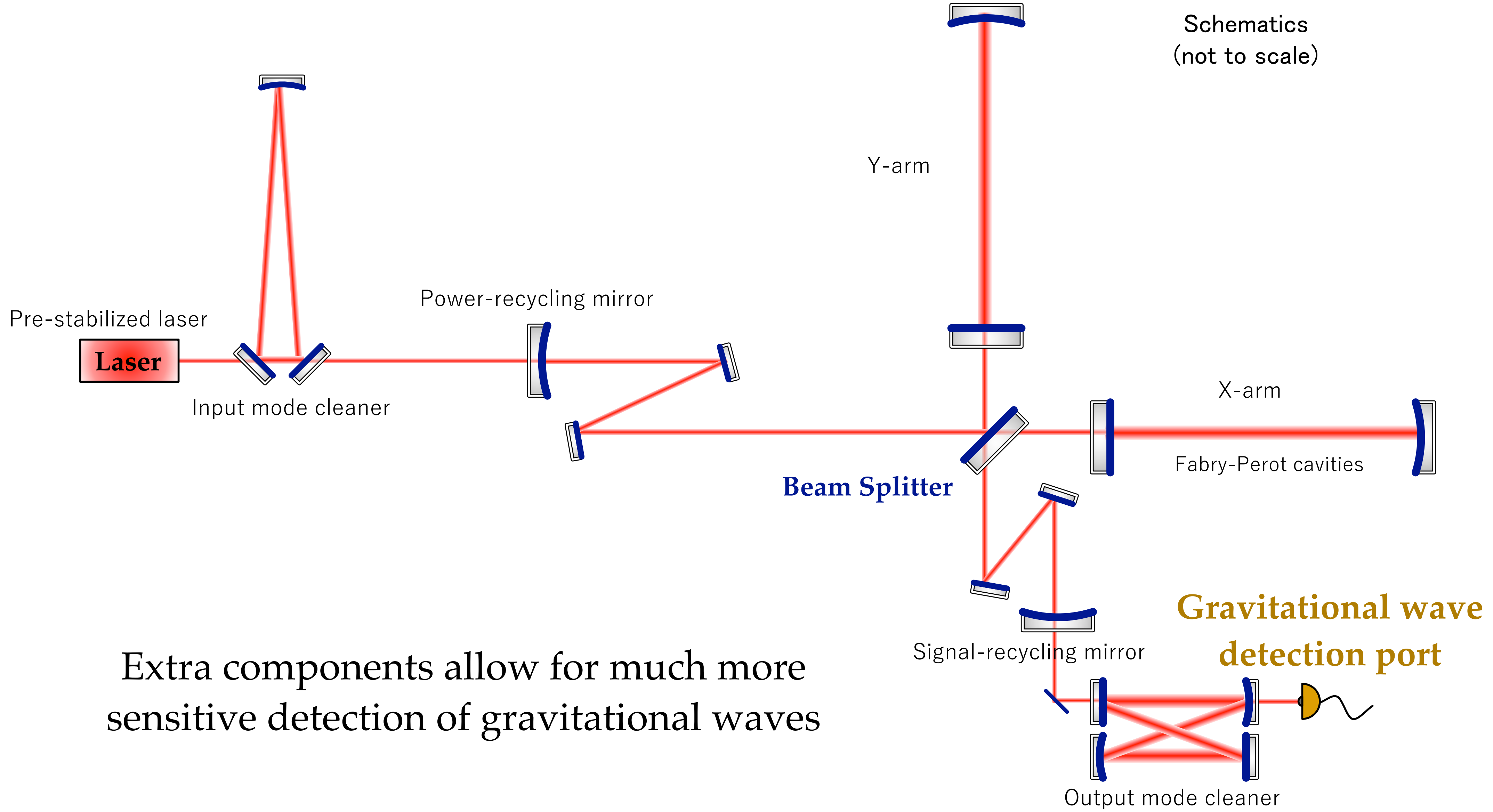


Michelson Interferometers



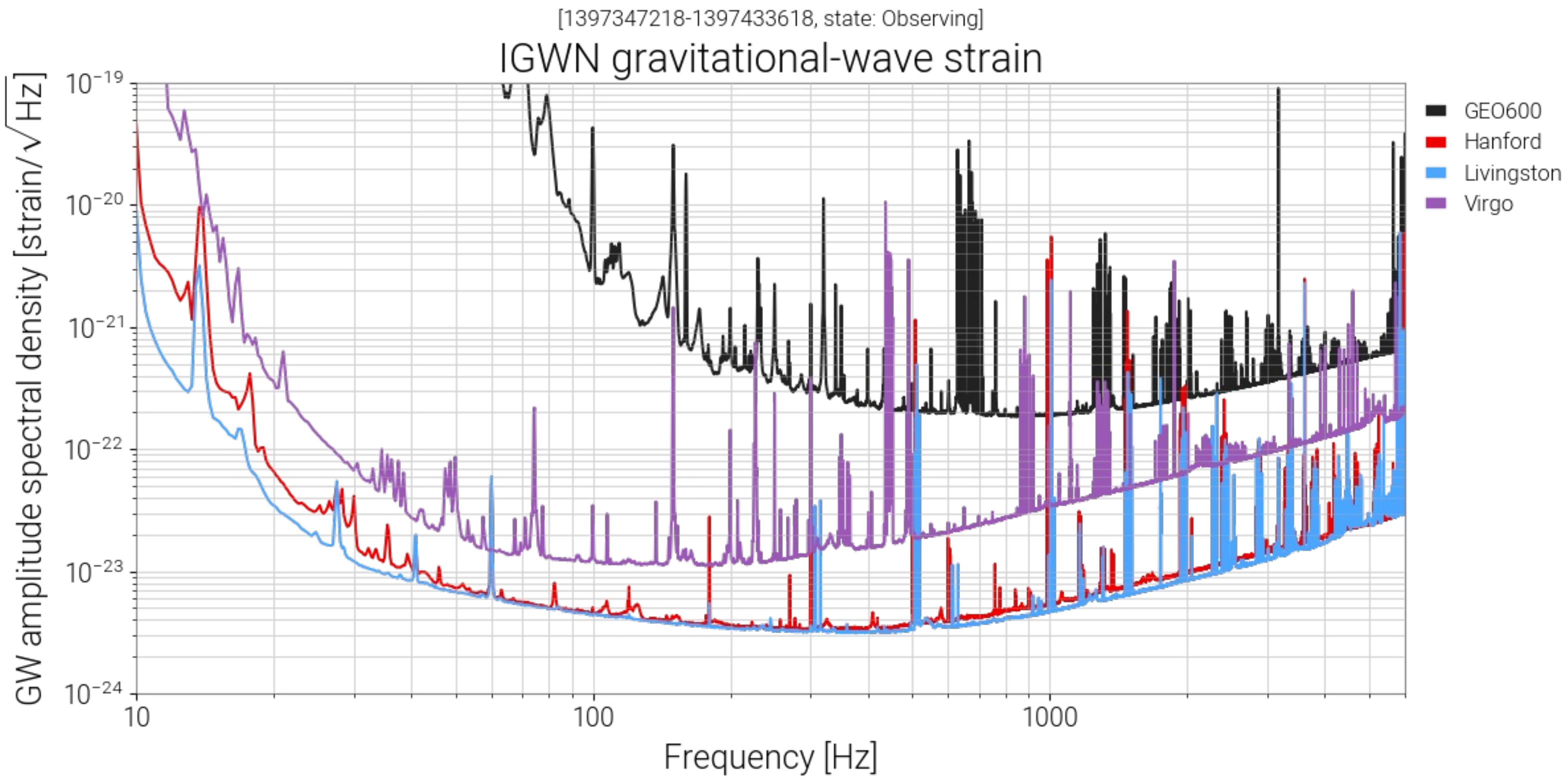
T. Pyle, Caltech/MIT/LIGO Lab

Layout of “*advanced generation*” GW interferometer



Extra components allow for much more sensitive detection of gravitational waves

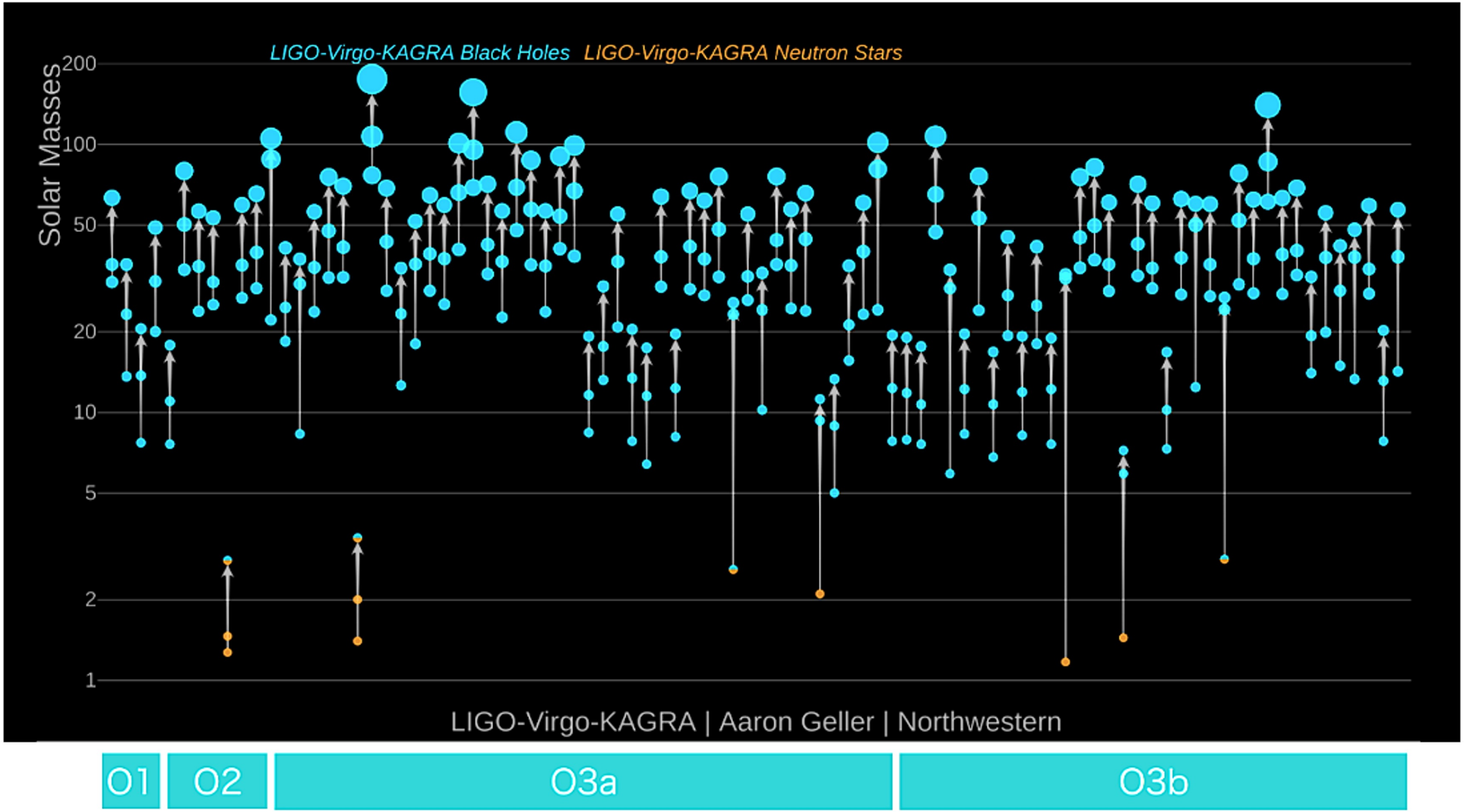
Noise & Sensitivity



https://gwosc.org/detector_status/day/20240417/

- Noise: any kind of disturbance which pollutes the output signal
- Detecting a GW of frequency *f* if amplitude *h* "larger" than noise at that frequency
- Interferometers are wide-band detectors
  - GW can span a wide frequency range
  - Frequency evolution with time is a key feature of some GW signals → Compact binary coalescences
- Numerous sources of noise
  - Fundamental
    → Cannot be avoided; optimize design to minimize these contributions
  - Technical
    → Should not be there, but dominant more often than not!; Continuous struggle
  - Environmental
    → Isolate the instrument as much as possible; monitor external noises
- IFO sensitivity characterized by its amplitude spectrum density (ASD, unit: 1/√Hz)

LVK transient GW detections O1~O3 arXiv:2111.03606 [gr-qc]



Only found coalescing binaries so far

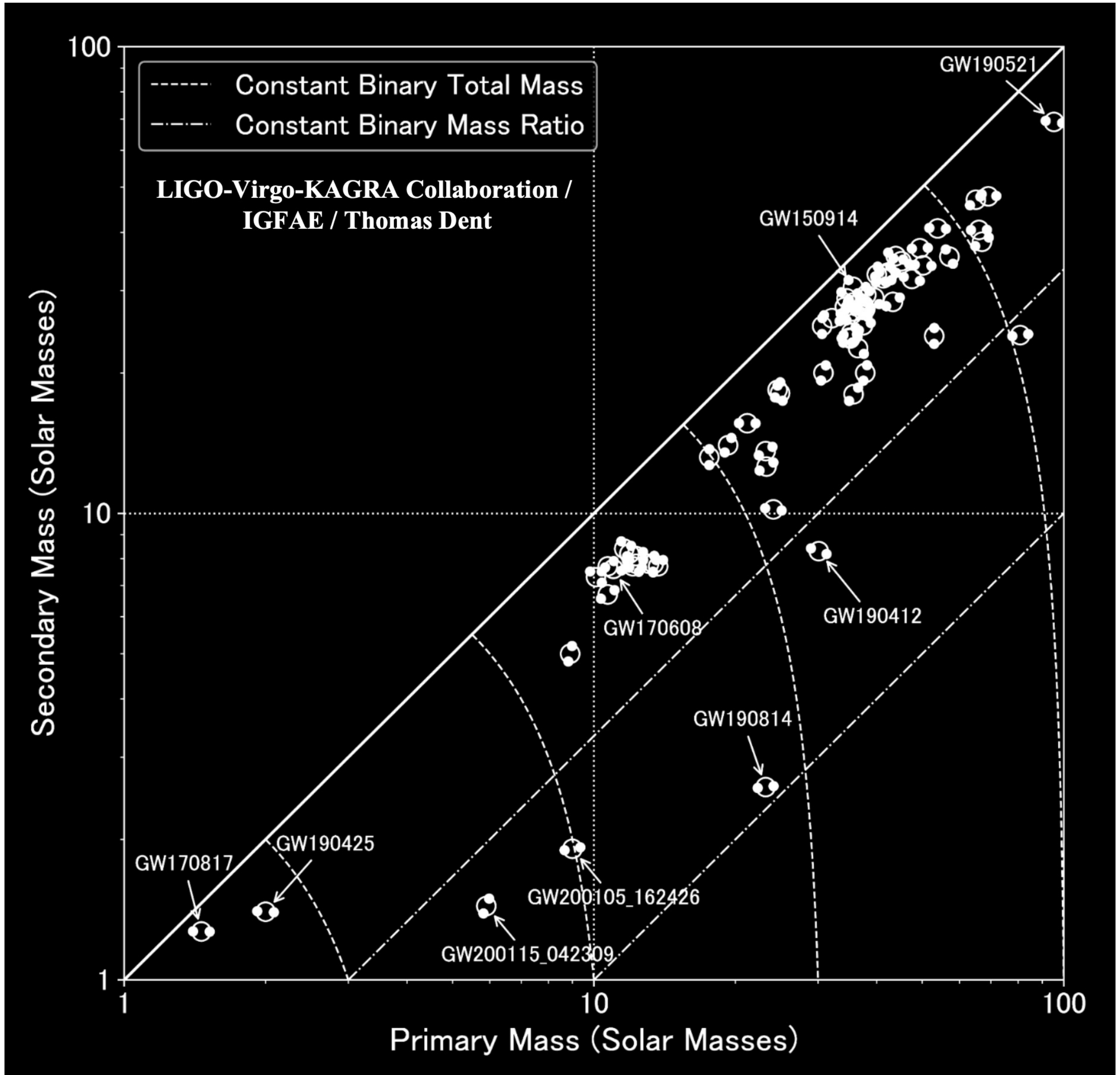
LVK transient GW detections

All compact binary merger

- The three expected types have been detected
  - **BBH:** Binary black hole
  - **BNS:** Binary neutron star
  - **NSBH:** Neutron star – Black hole

Classified by the masses of the compact objects which have merged

- **x-axis**: primary mass
  → Heavier object
- **y-axis**: secondary mass
  → Lighter object



LVK transient GW detections

All compact binary merger

- The three expected types have been detected
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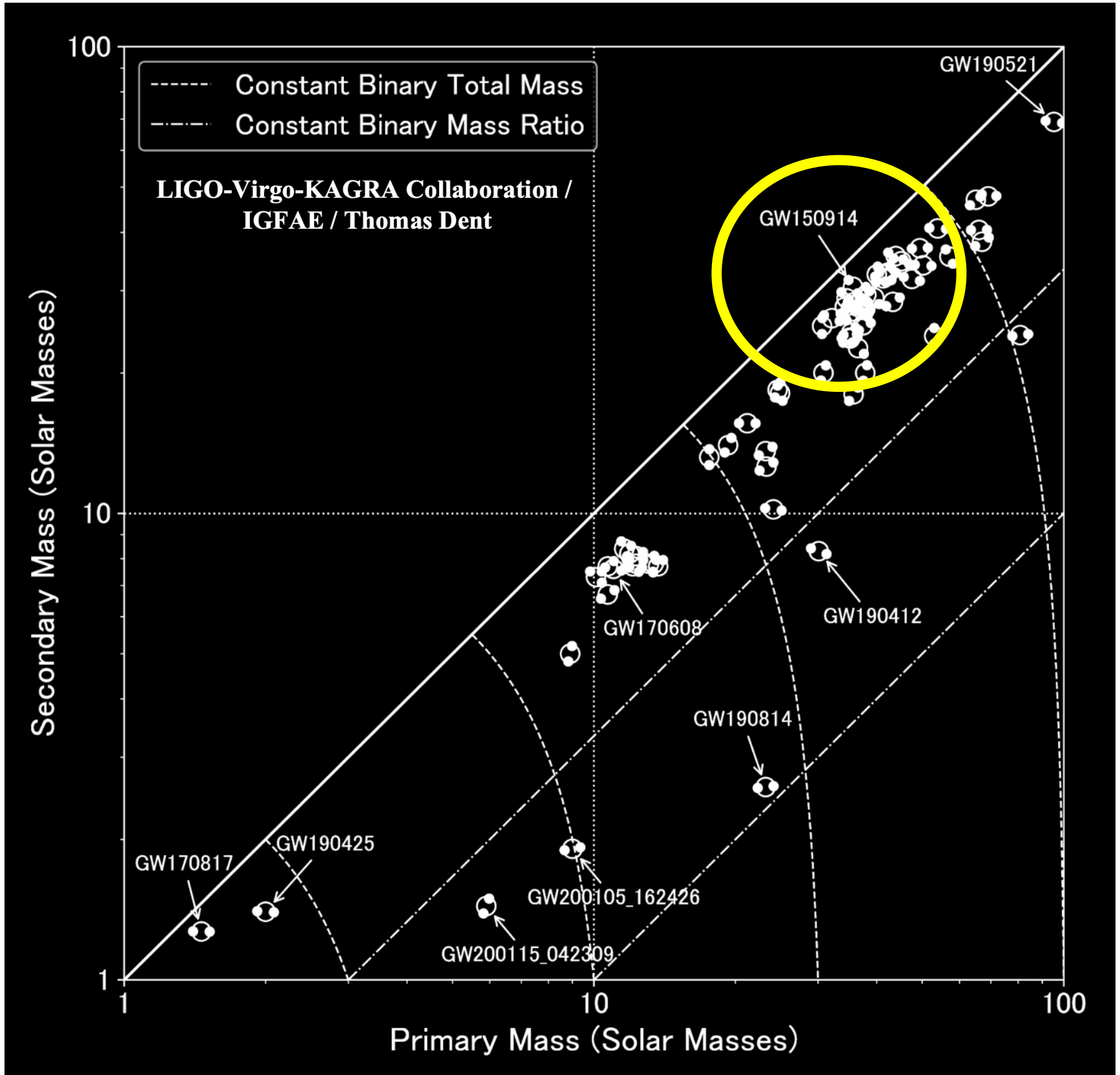
  - **BNS:** Binary neutron star
  - **NSBH:** Neutron star – Black hole

GW150914

- First direct GW detection
- (B)BHs exist

→ Now in the bulk of the detected sources

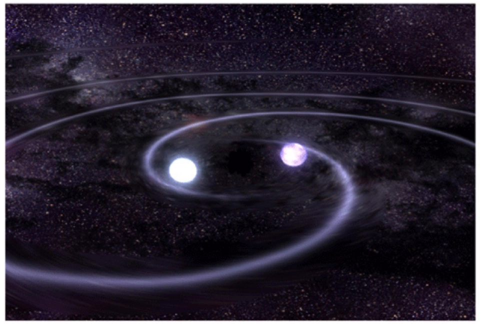


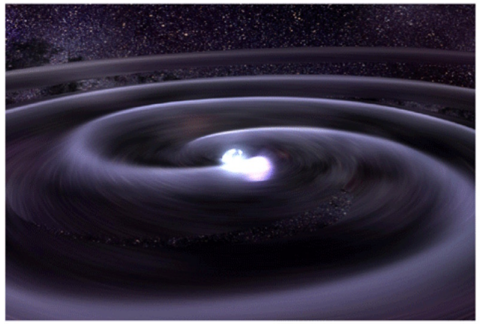
The dawn of gravitational wave astrophysics

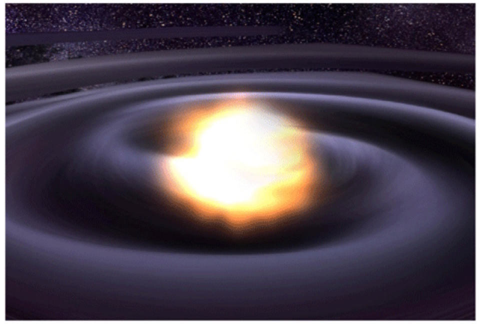
GW150914: First Detection

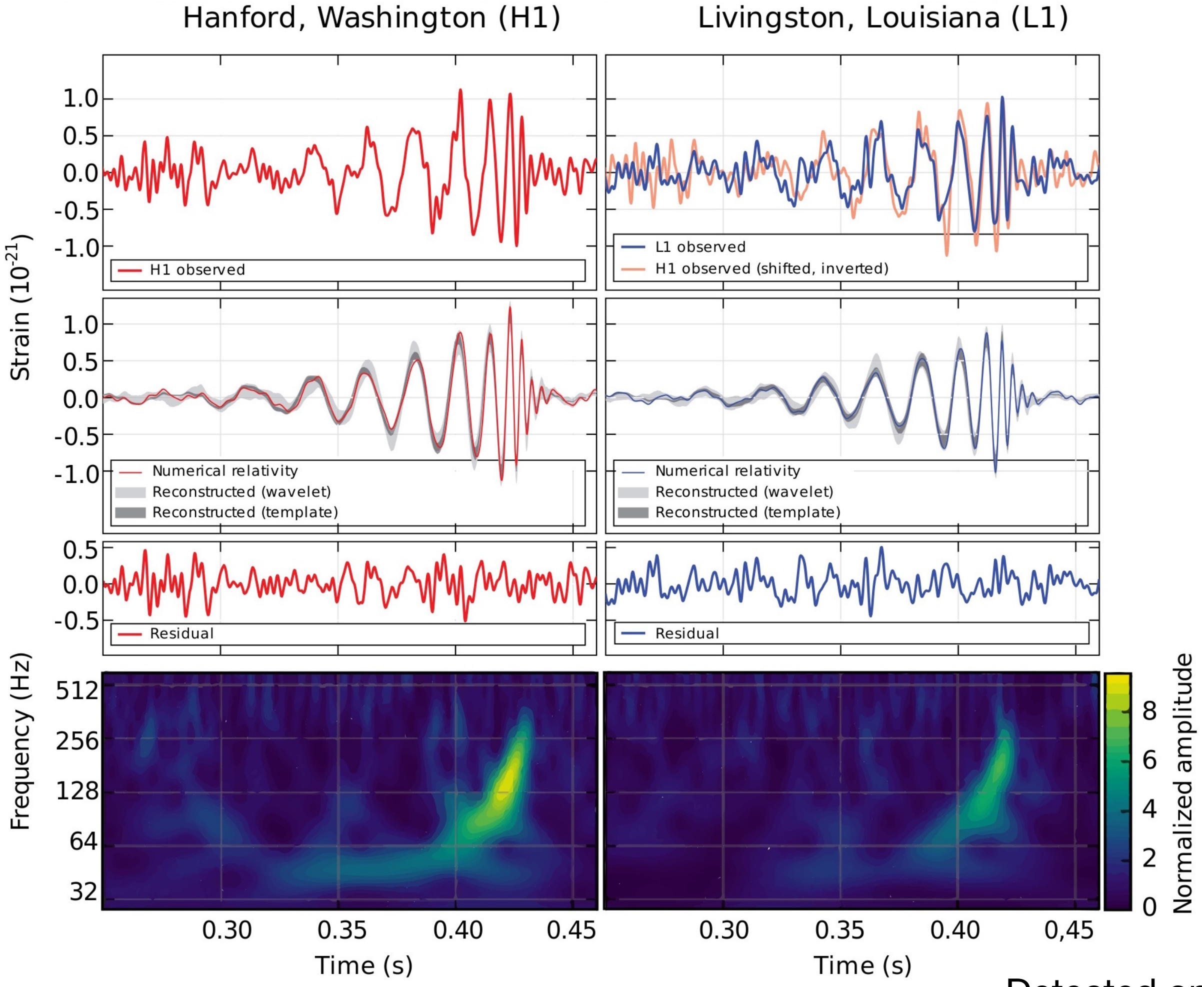
M ≈ 29 & 36 M⊙
D ≈ 1.3 billion l.y. (410 Mpc)
ΔE ≈ 3 M⊙

1.3 Billion Years Ago, 2 black holes merged into 1.



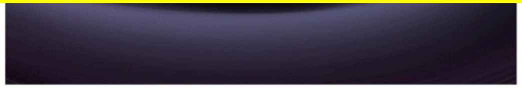




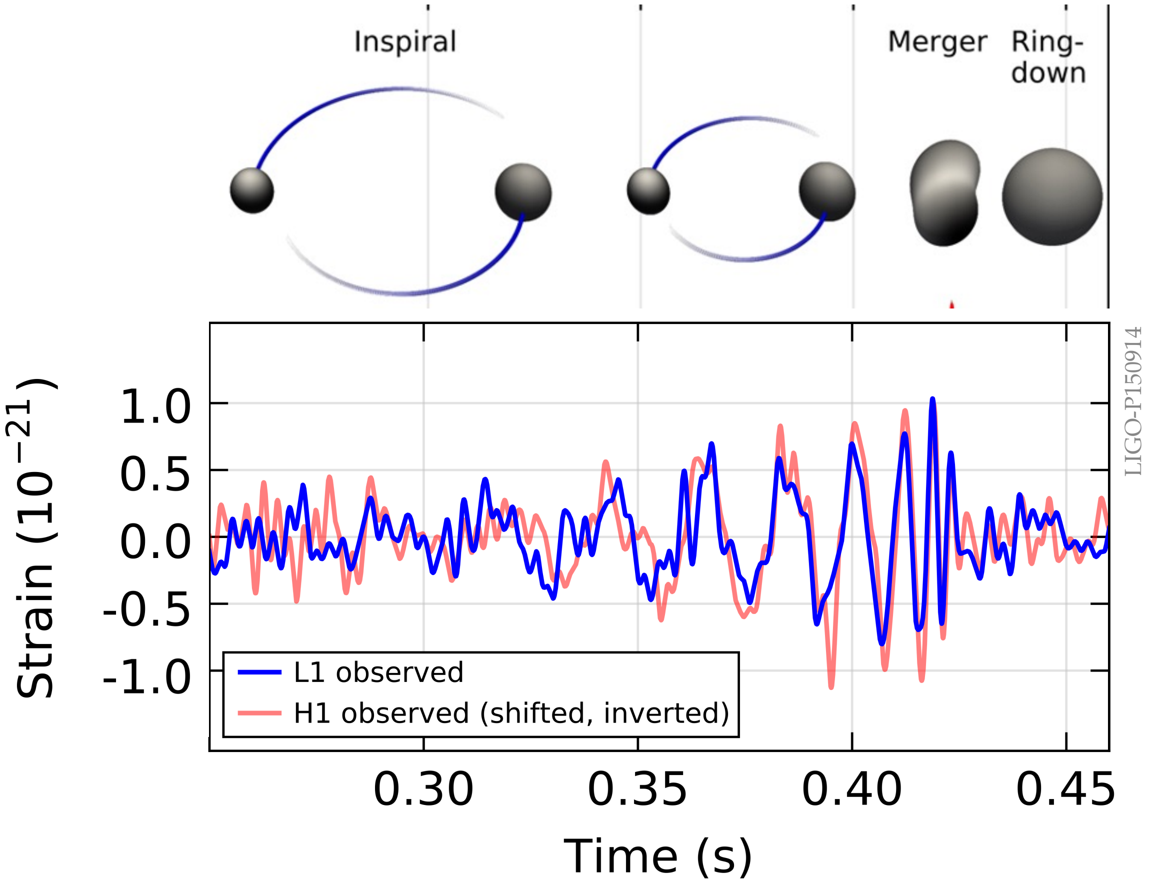


Detected on September 14, 2015

The dawn of gravitational wave astrophysics



Astrophysics from Data

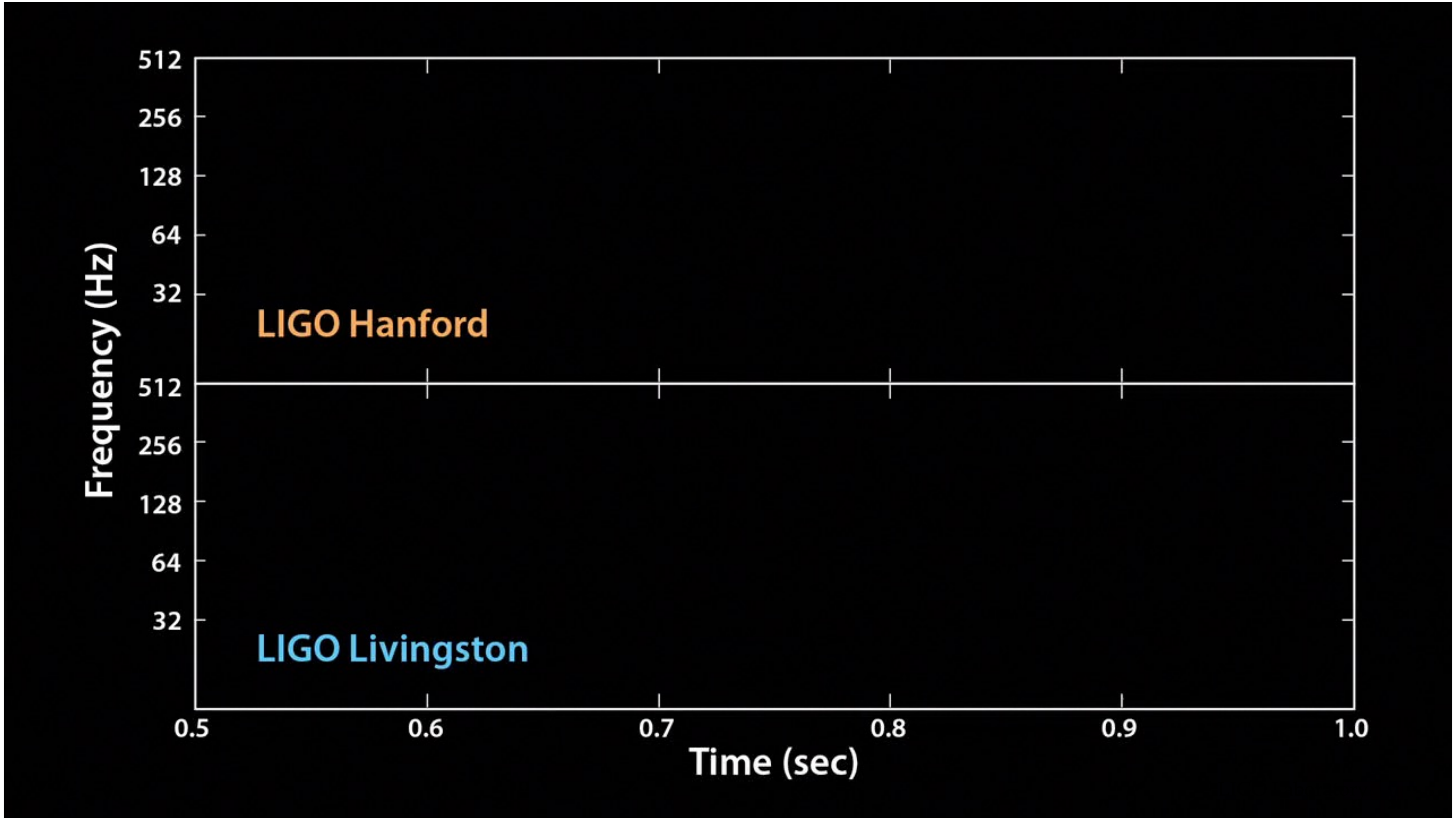


- How massive were the 2 black holes?
- How much were they spinning?
- How far apart were they before they touched?
- How massive is the final black hole?
- How much mass turned into energy?
- How far away was the system?
- How long ago did the merger happen?

⋮

Hear Black Holes Collide!

1.4 billion light years away



LVK transient GW detections

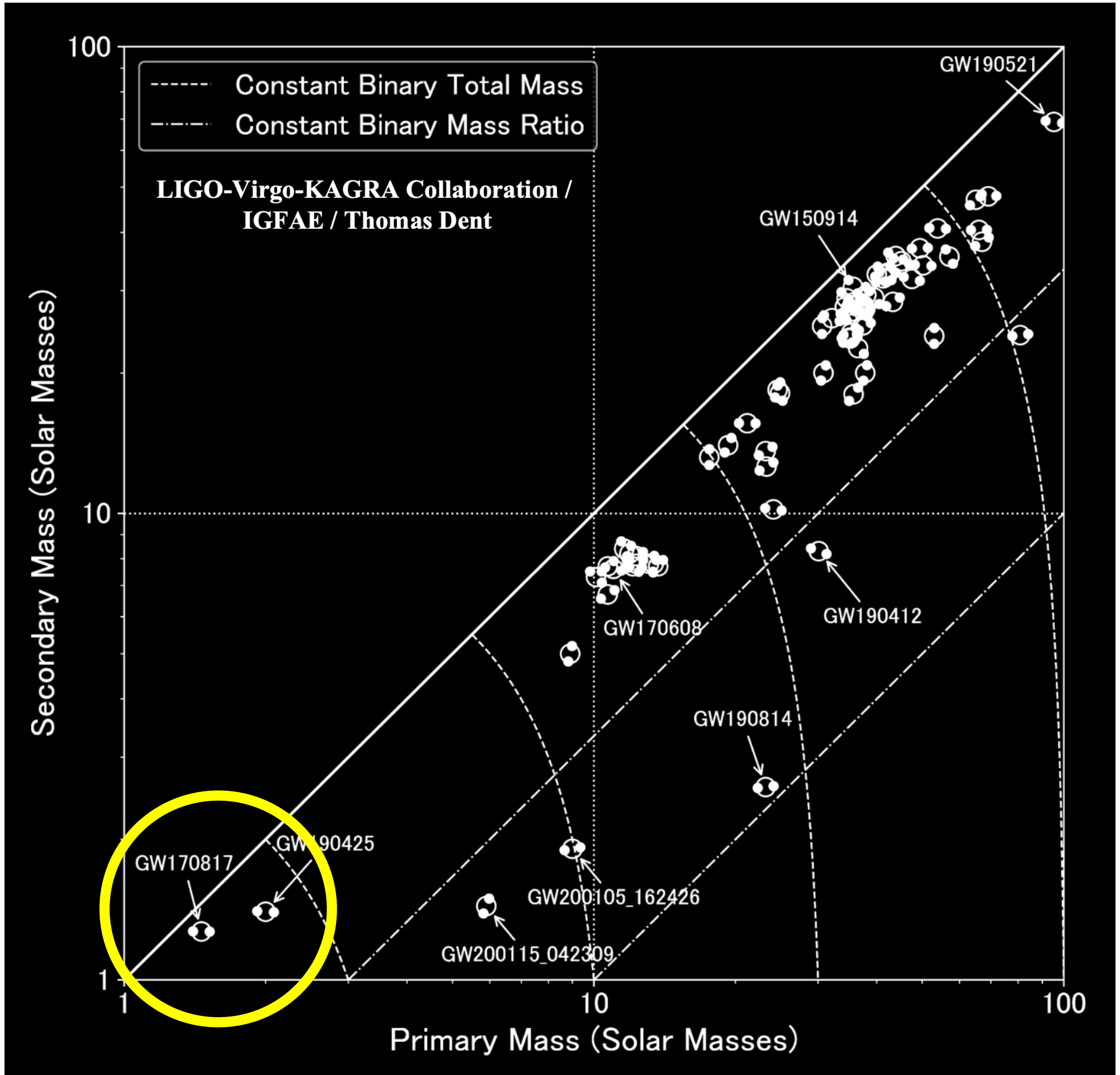
All compact binary merger

- The three expected types have been detected
  - **BBH**:
    Binary black hole
  - **BNS**:
    Binary neutron star
  - **NSBH**:
    Neutron star – black hole

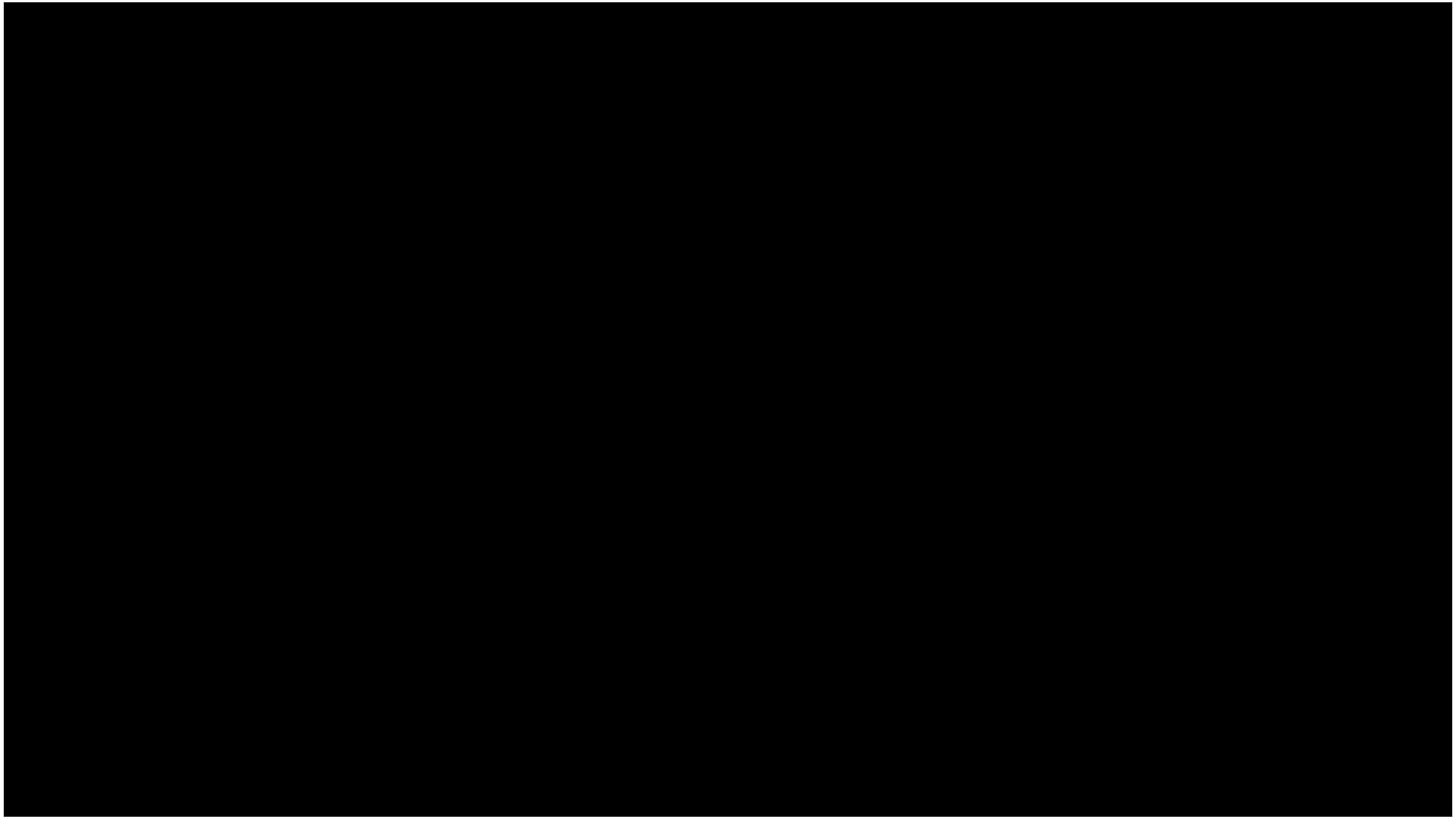
GW170817

- First BNS merger ever
- 3-detector event
- 3 days after GW170814
- BNS are gamma-ray burst progenitors

→ Birth of multi-messenger astronomy *with* GWs

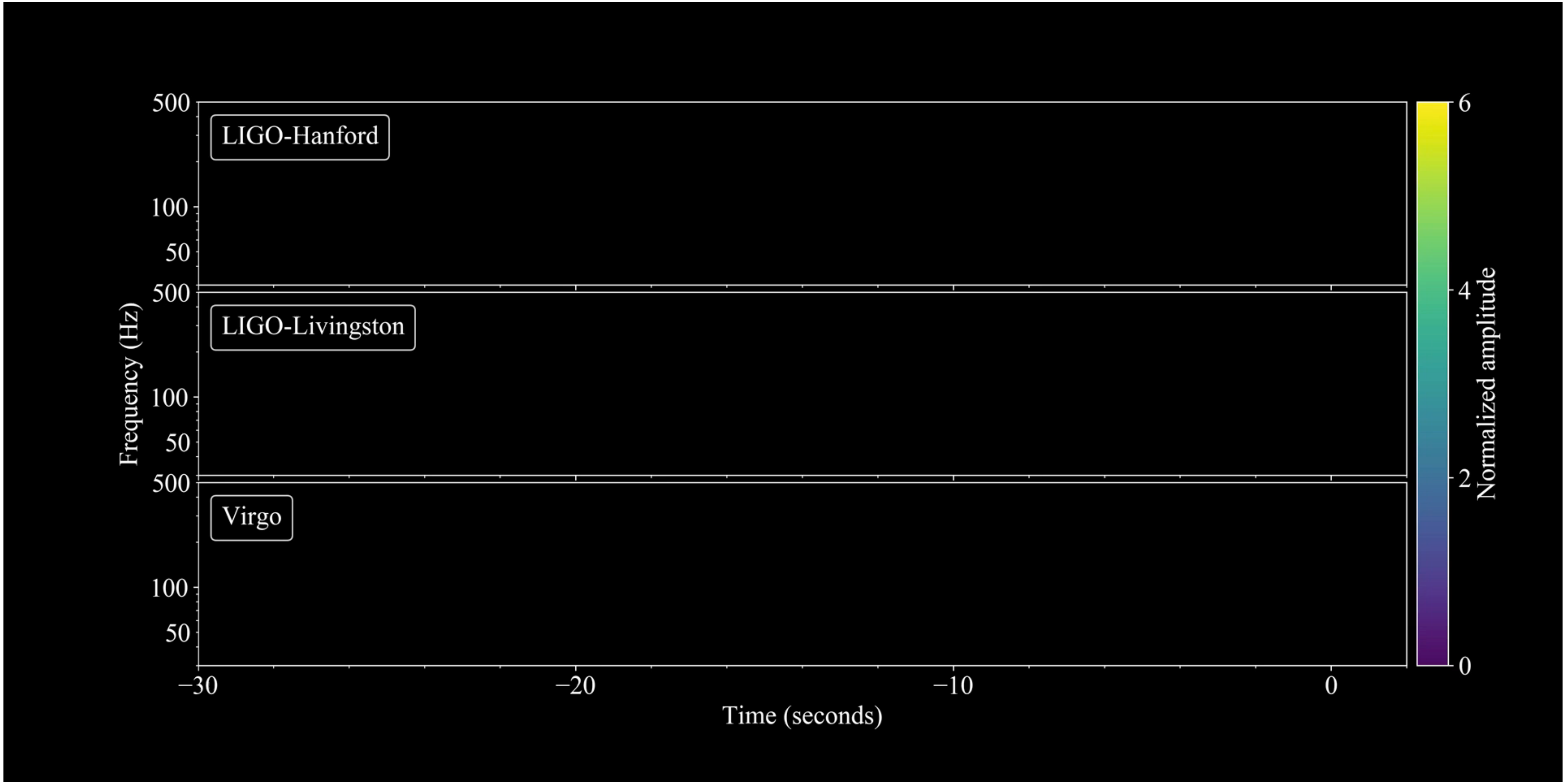


Matter is Ejected by BNS



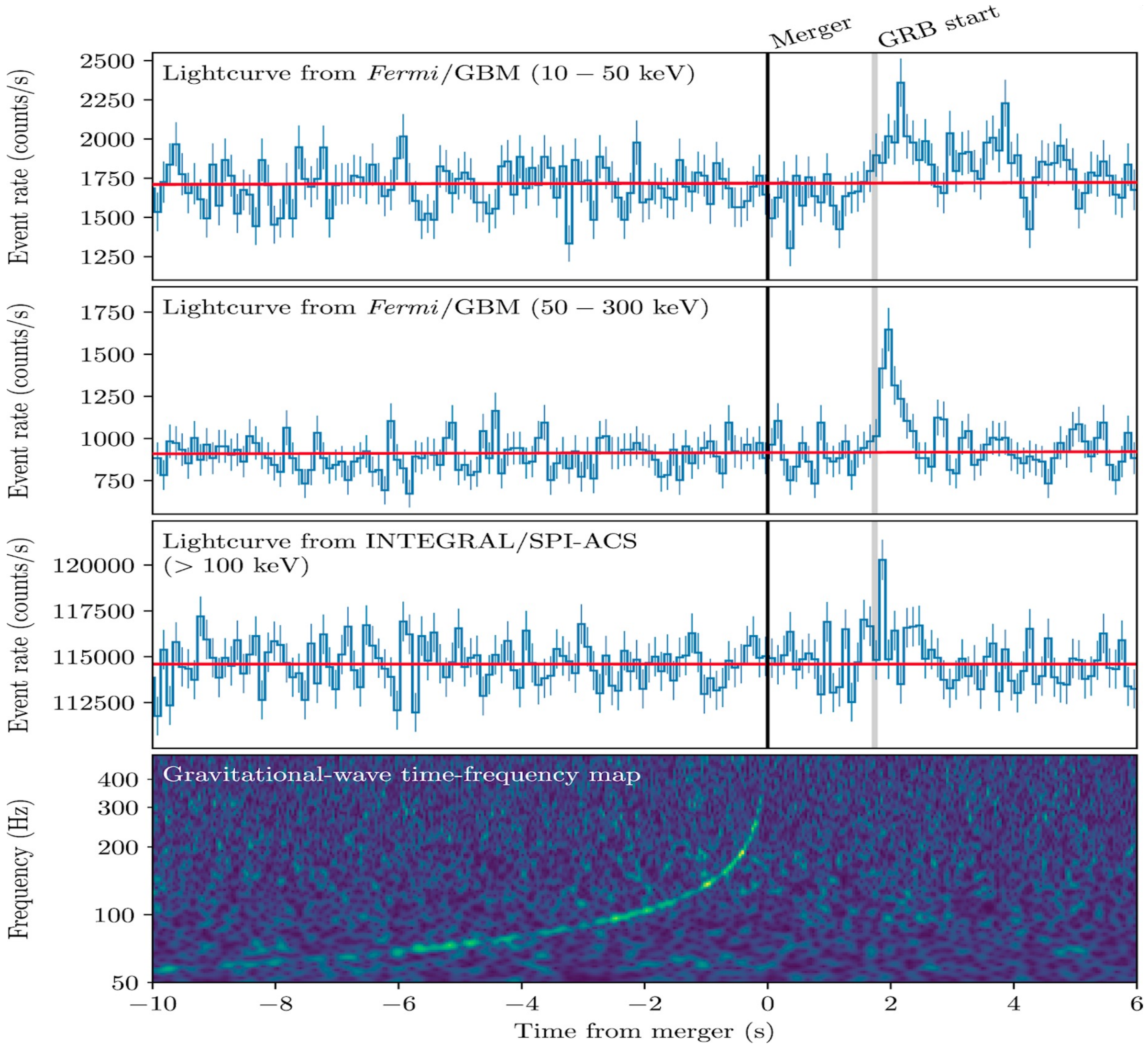
Hear Neutron Stars Collide!

130 million light years away



First BNS-GRB association

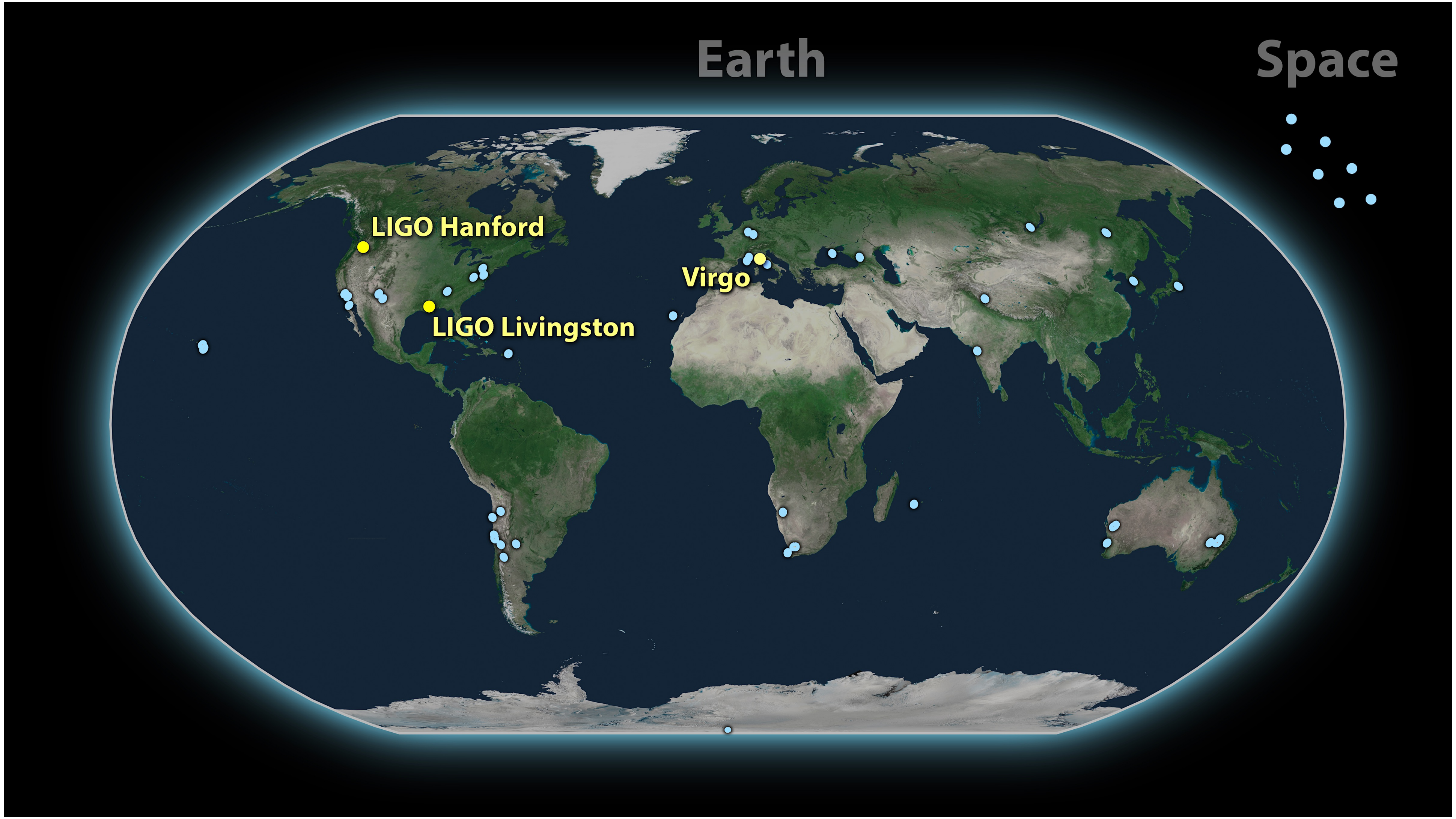
B. P. Abbott et al 2017 ApJL 848 L13



- GW170817 & GRB 170817A
  - Fractional difference in speed of gravity and the speed of light is between -3 x 10^{-15} and 7 x 10^{-16}
- GW170817 & AT 2017gfo
  - Binary neutron star mergers produce kilonova explosions that generate heavy elements

Follow-up Observations

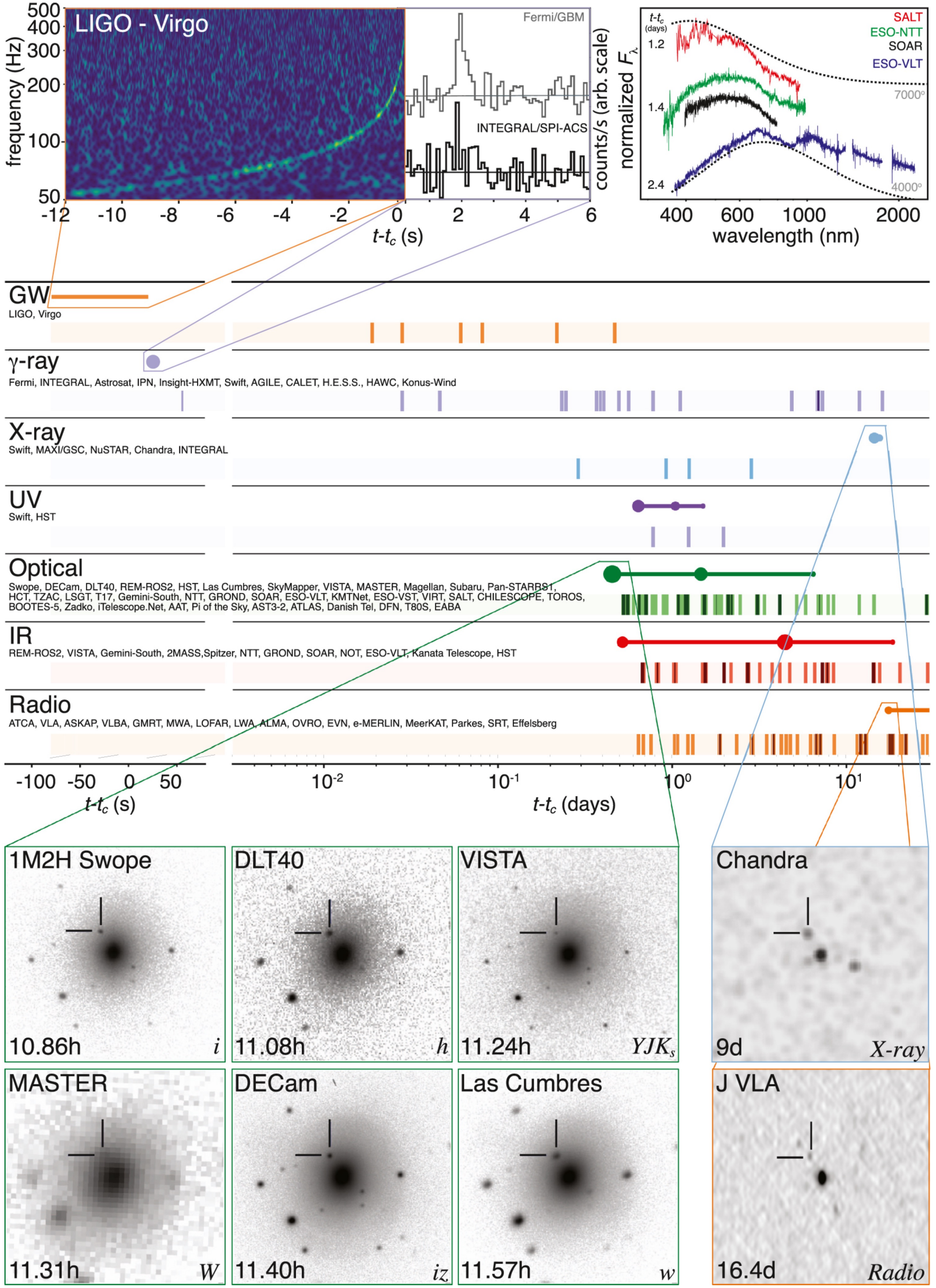
More than 70 groups using 100 instruments looked at the remnant from the merger



This represents about ¼ of the world's astronomers!

Light and Gravitational Waves

- Seeing gamma rays and gravitational waves confirms that gravitational waves travel at the speed of light
- Confirms that neutron star collisions can make gamma ray bursts
- Localizing these events, so many astronomers can observe them with different telescopes
- See signatures of heavy elements, like gold and platinum



Exploiting Multi-Messenger Information

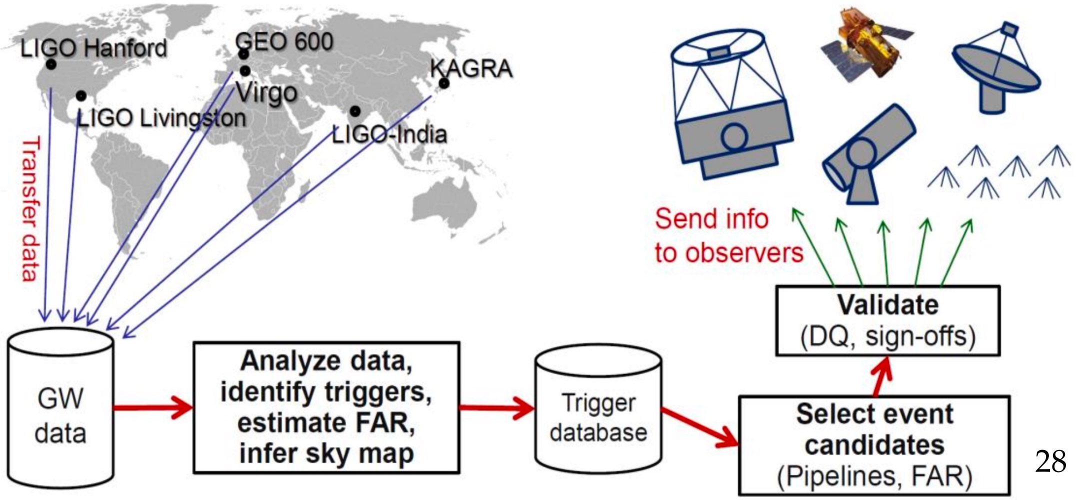
GW detections: the released energy is not always fully converted into GWs
→ Other types of radiation emitted: possibly electromagnetic waves, neutrinos, etc.

- Astrophysical alerts → tailored GW searches
  - Time and source location known; possibly the waveform

} Examples: γ-ray burst, type-II supernova

- And vice-versa: the LVK network is also releasing its most significant alerts
  - Real-time searches of compact binary coalescences and burst signals

→ O2: Agreements signed with ~75 groups – 150 instruments, 10 space observatories
→ O3: Public alerts on Gamma-ray Coordinates Network (GCN)
https://gracedb.ligo.org
→ O4 changes:
see later slides



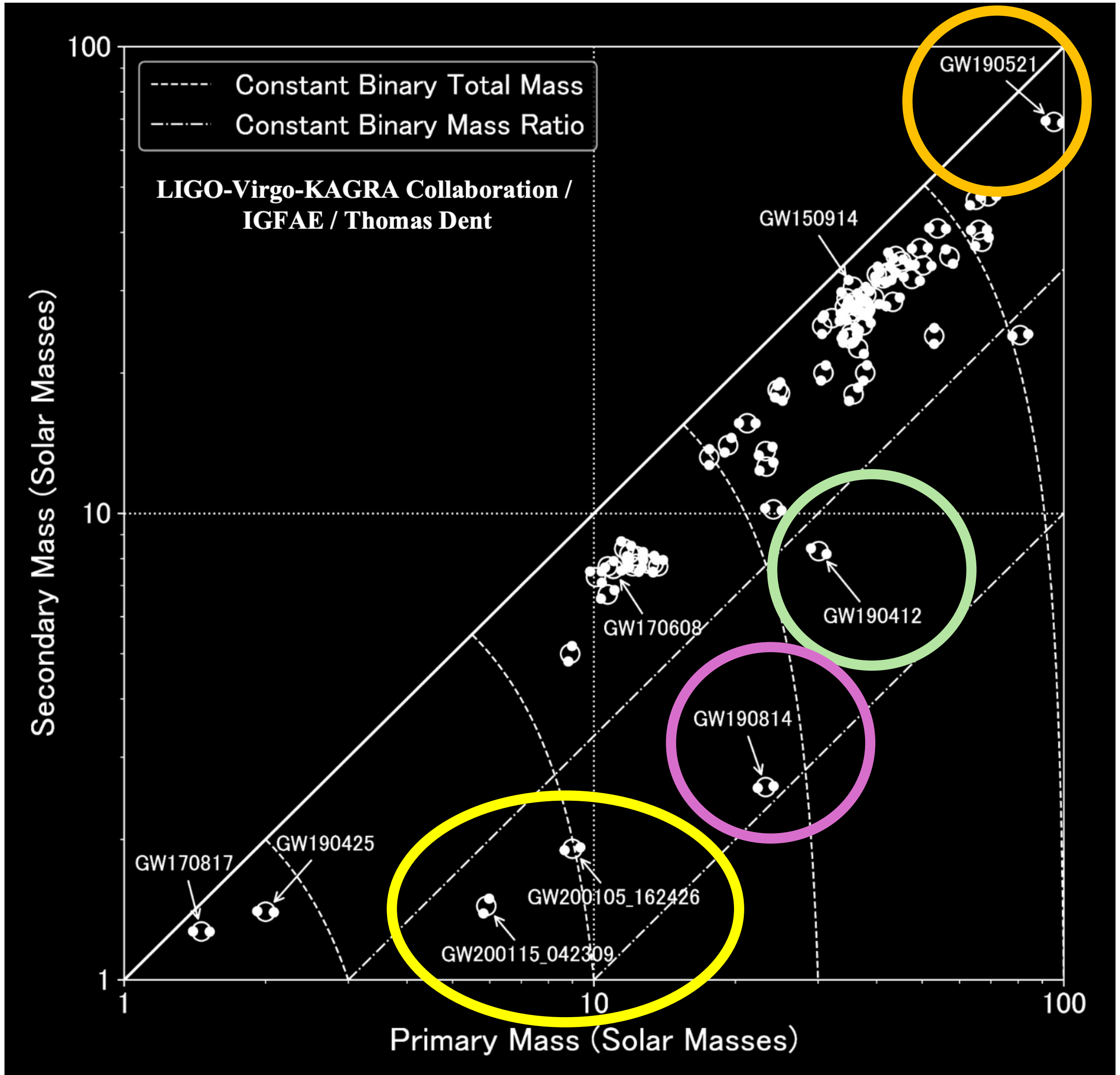
LVK transient GW detections

GW190521
- BHs exist in pair instability mass gap
- → Heaviest source detected to date

GW190814
- Compact objects heavier than NS and lighter than BH do exist

GW190412
- Binary system with large mass ratio

GW200105_162426
GW200115_042309
- First NSBH mergers
- detected in January 2020

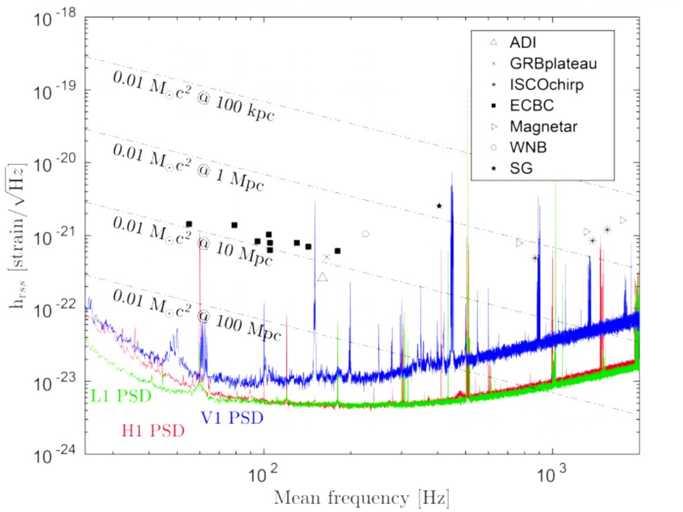


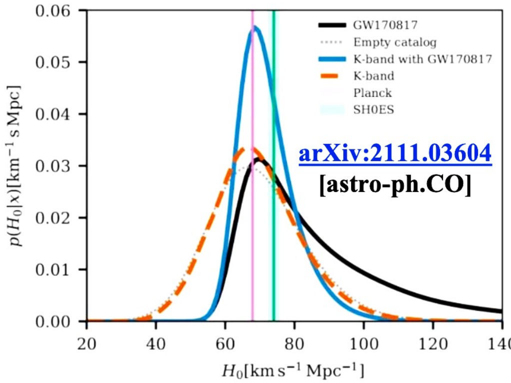
A variety of other results

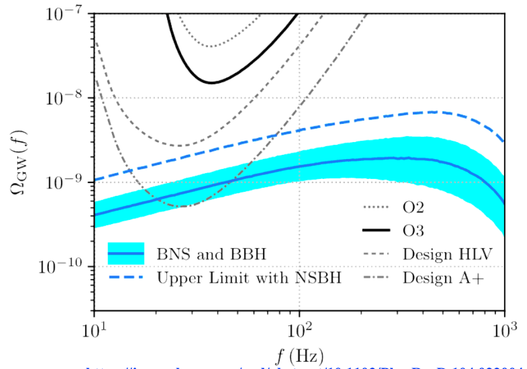
Documented in companion papers of the catalog releases:
(Current issue: GWTC-3 – arXiv:2111.03606 [gr-qc])

- **Compact object populations and merger rates**
  → From one to many detections
- **Tests of General Relativity**
  → Using BBH mergers
- **Cosmology: Hubble constant**
  → Independent measurement
  - GW170817-like events
    or statistical approach
- **Upper limits** for burst, continuous waves and stochastic background signals

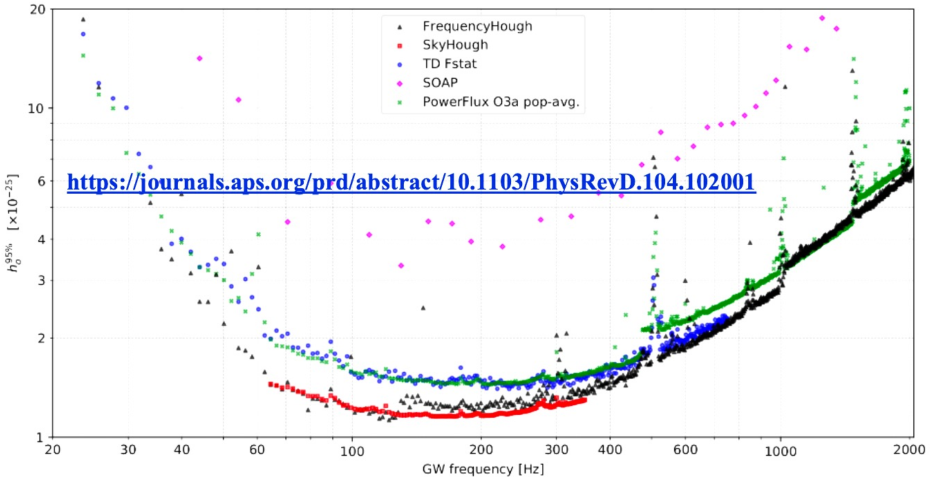
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.104.102001





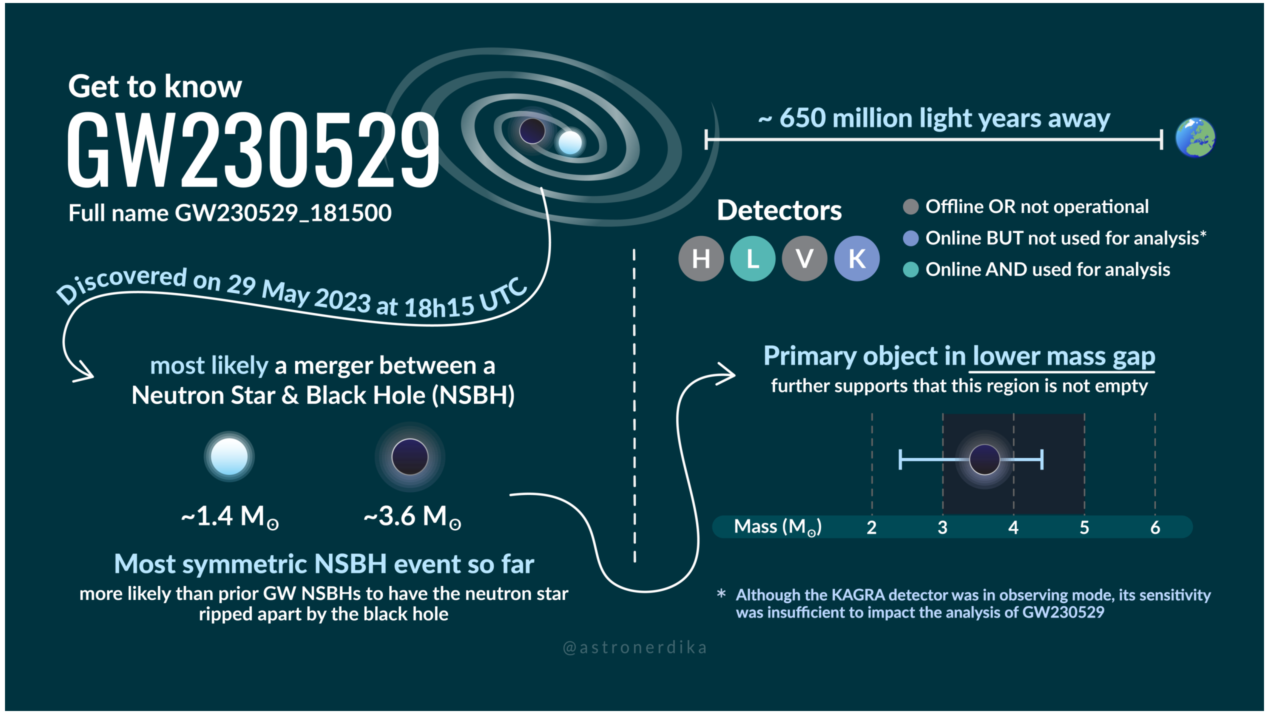


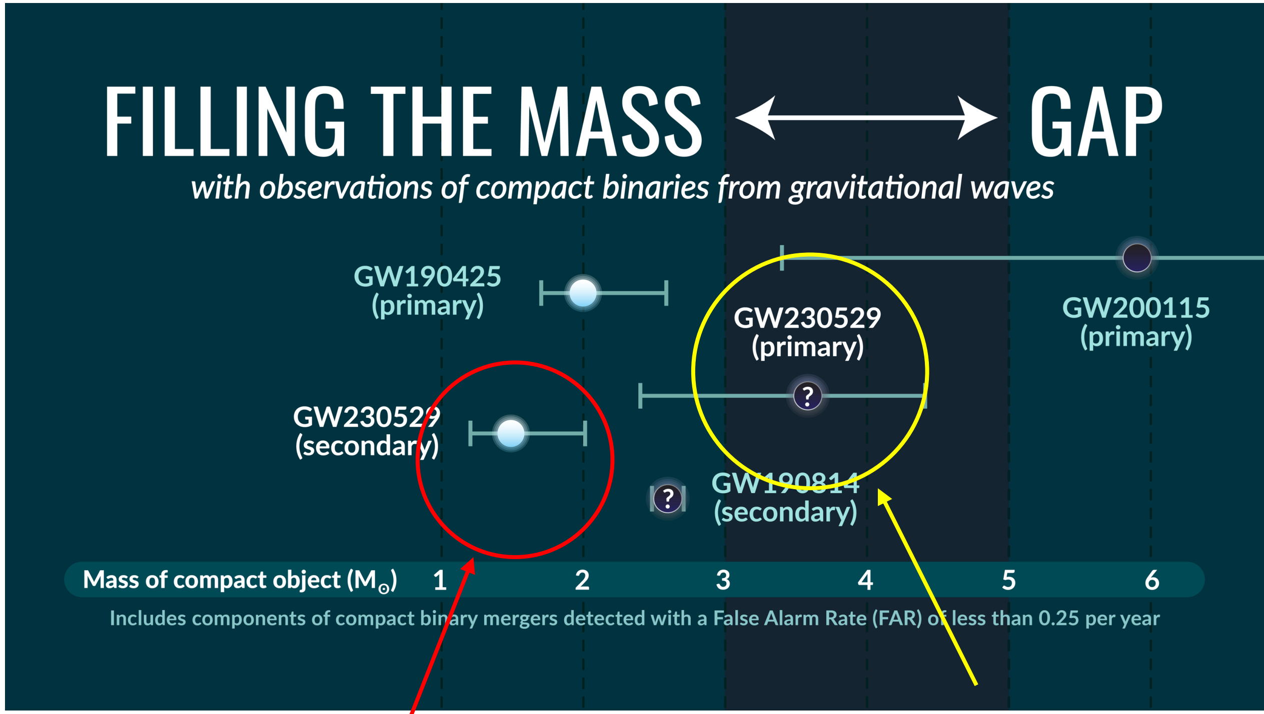
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.104.022004



A New Result: We are starting to show the interesting results of our O4 observations

April 5, 2024, the LIGO-Virgo-KAGRA Collaboration announced the discovery of GW230529 from O4a data



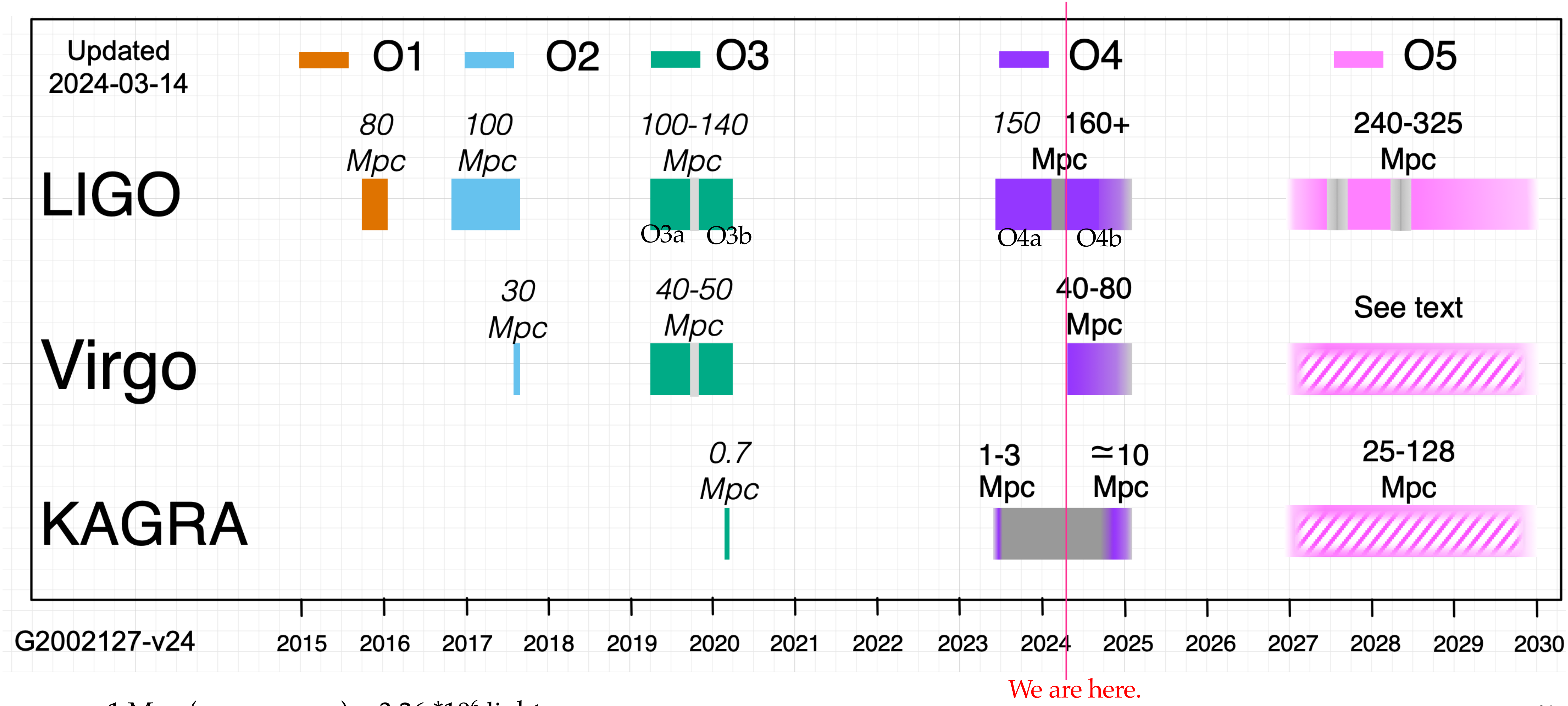


almost certainly a neutron star

larger than the expected range for neutron stars and smaller than the expected range for black holes

Observing Run O4b started April 10th, 2024

Announcement page: https://observing.docs.ligo.org/plan/

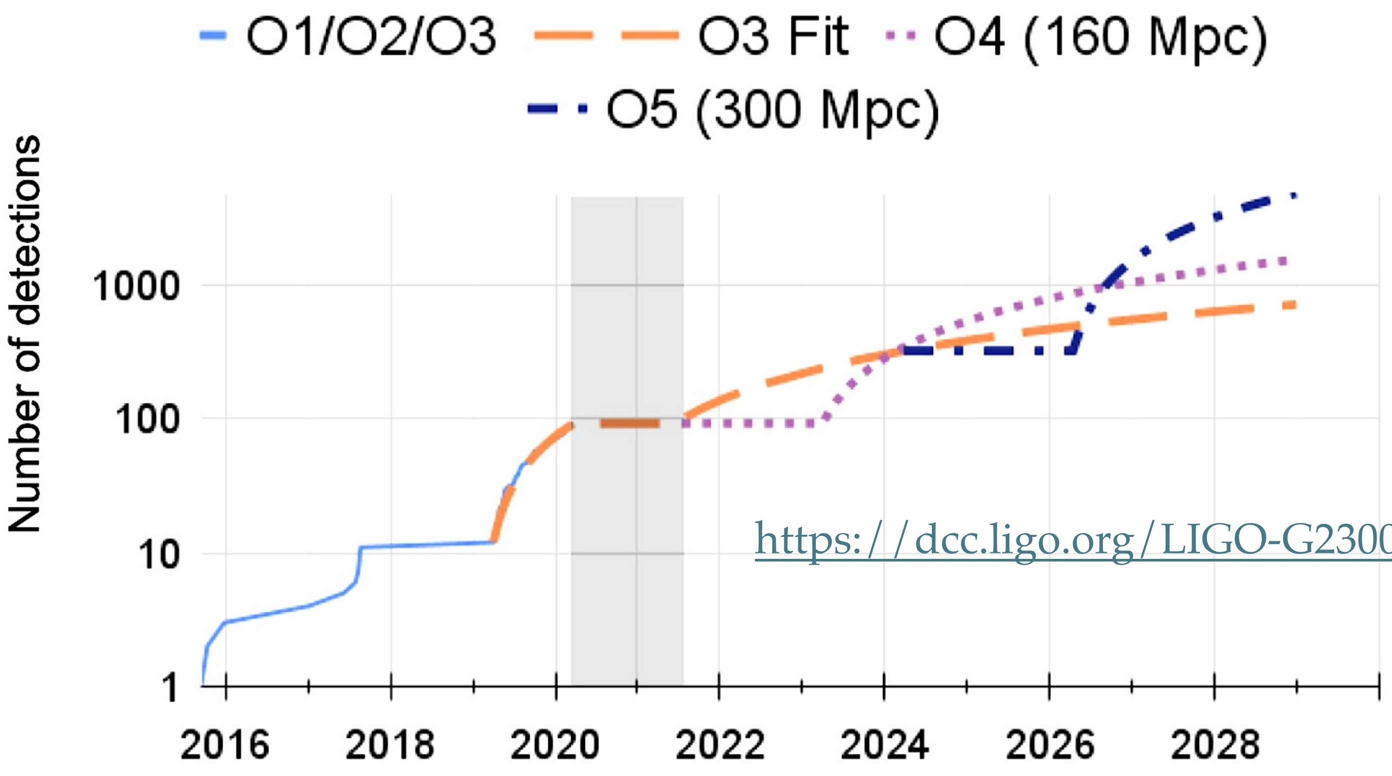


- 1 Mpc (megaparsec) = 3.26 *10^6 light-year

Why alternating data taking and upgrade periods??

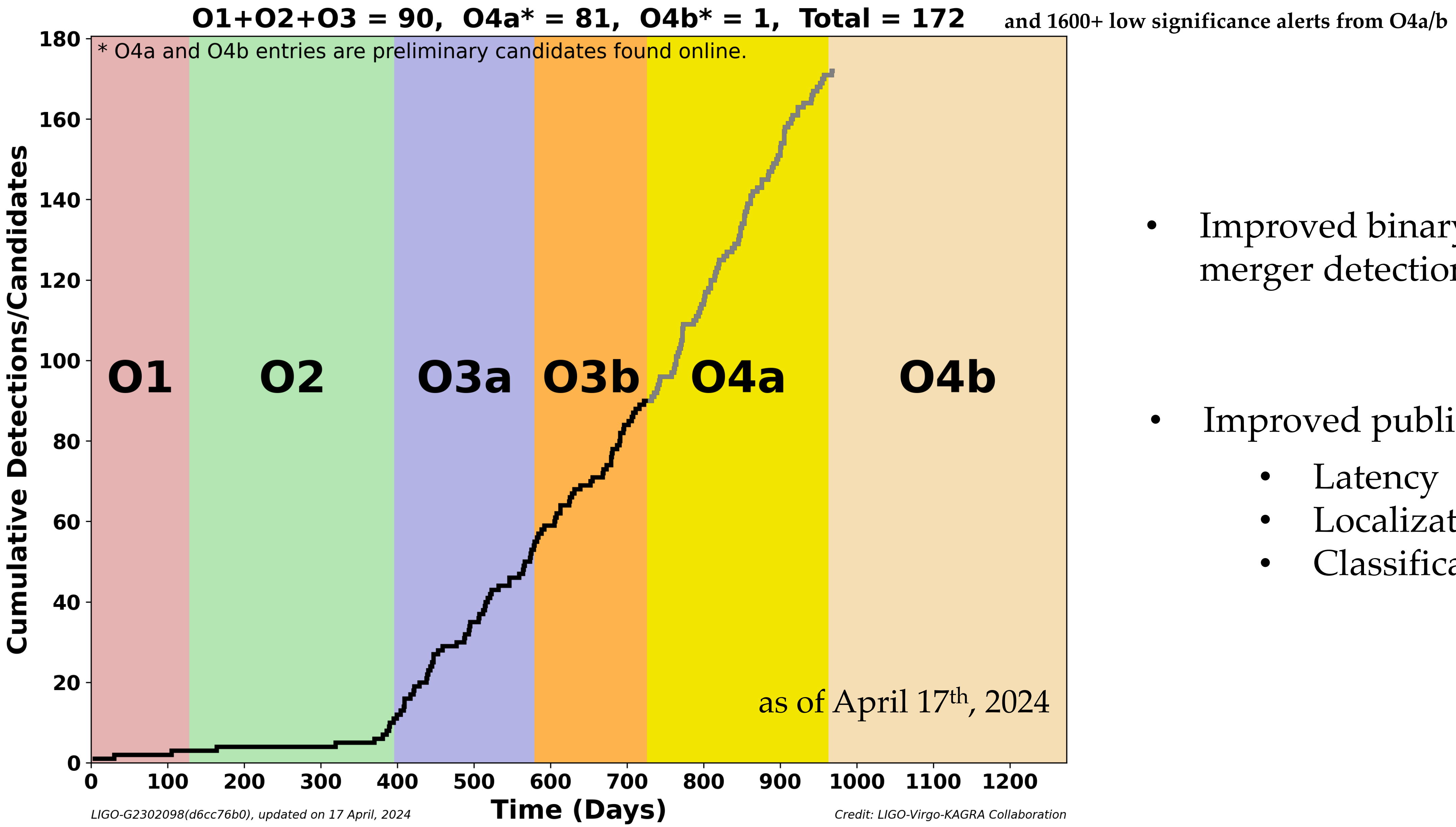
Trading Sensitivity and Observing Time

- Crude extrapolation to O4 and O5 assuming BNS range of second most sensitive detector and similar duty cycle and performance to O3.
- Other science
  - Improved SNR
  - New sources?



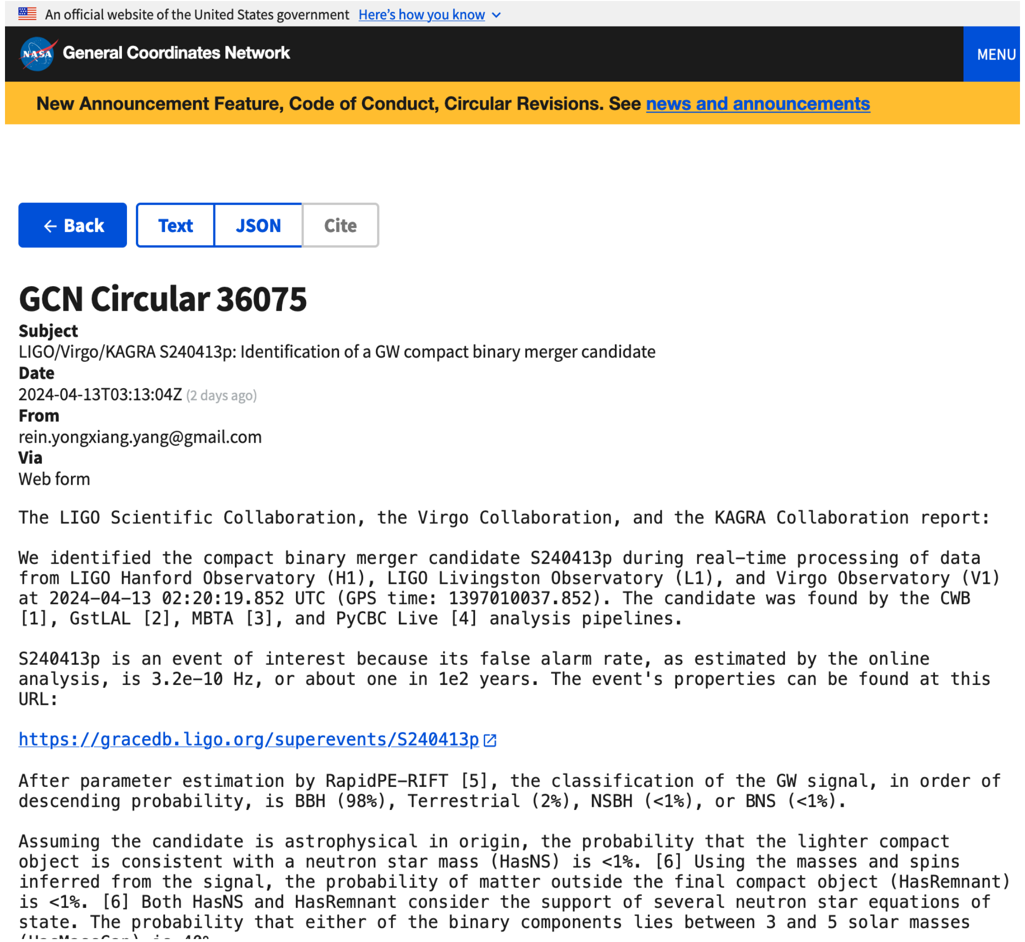
https://dcc.ligo.org/LIGO-G2300154/public

Alternating data taking and upgrade periods should lead to more events in the end.



- Improved binary merger detection rate
- Improved public alerts
    - Latency
    - Localization
    - Classification

Public alert for the 1st significant detection candidate from O4b (April 13, 2024)



An official website of the United States government Here's how you know

General Coordinates Network MENU

New Announcement Feature, Code of Conduct, Circular Revisions. See news and announcements

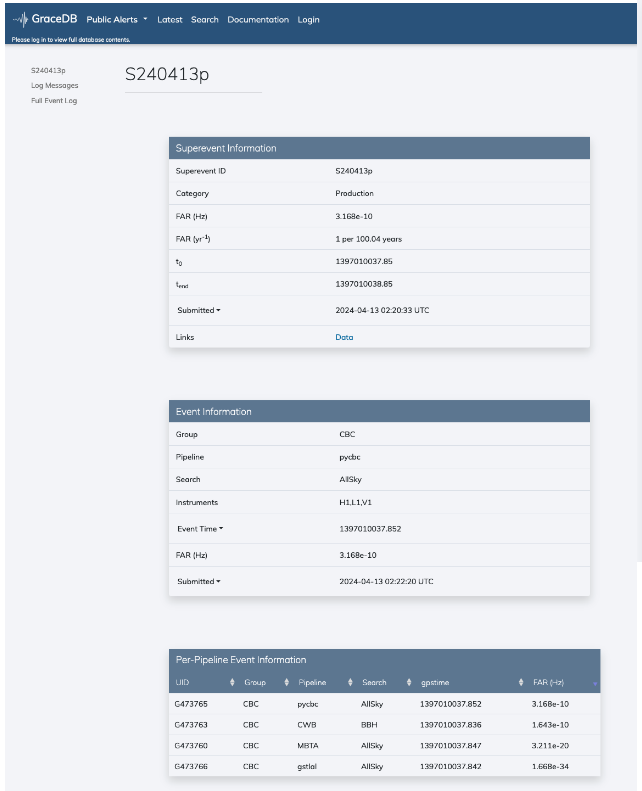
Back | Text | JSON | Cite

GCN Circular 36075

Subject
LIGO/Virgo/KAGRA S240413p: Identification of a GW compact binary merger candidate
Date
2024-04-13T03:13:04Z (2 days ago)
From
rein.yongxiang.yang@gmail.com
Via
Web form

```
The LIGO Scientific Collaboration, the Virgo Collaboration, and the KAGRA Collaboration report:

We identified the compact binary merger candidate S240413p during real-time processing of data
from LIGO Hanford Observatory (H1), LIGO Livingston Observatory (L1), and Virgo Observatory (V1)
at 2024-04-13 02:20:19.852 UTC (GPS time: 1397010037.852). The candidate was found by the CWB
[1], GstLAL [2], MBTA [3], and PyCBC Live [4] analysis pipelines.

S240413p is an event of interest because its false alarm rate, as estimated by the online
analysis, is 3.2e-10 Hz, or about one in 1e2 years. The event's properties can be found at this
URL:

https://gracedb.ligo.org/superevents/S240413p

After parameter estimation by RapidPE-RIFT [5], the classification of the GW signal, in order of
descending probability, is BBH (98%), Terrestrial (2%), NSBH (<1%), or BNS (<1%).

Assuming the candidate is astrophysical in origin, the probability that the lighter compact
object is consistent with a neutron star mass (HasNS) is <1%. [6] Using the masses and spins
inferred from the signal, the probability of matter outside the final compact object (HasRemnant)
is <1%. [6] Both HasNS and HasRemnant consider the support of several neutron star equations of
state. The probability that either of the binary components lies between 3 and 5 solar masses
```

https://gcn.nasa.gov/circulars/36075



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S240413p
Log Messages
Full Event Log

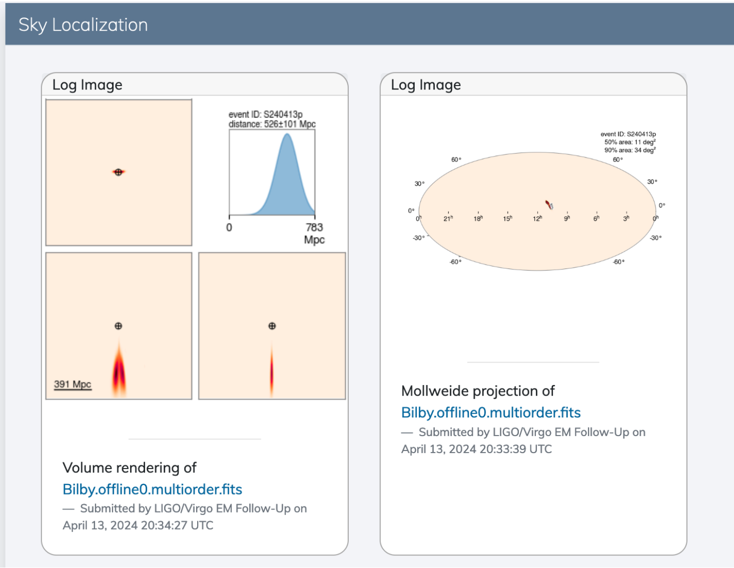
S240413p

Superevent Information	
Superevent ID	S240413p
Category	Production
FAR (Hz)	3.168e-10
FAR (yr^{-1})	1 per 100.04 years
t_0	1397010037.85
t_{end}	1397010038.85
Submitted	2024-04-13 02:20:33 UTC
Links	Data

Event Information	
Group	CBC
Pipeline	pycbc
Search	AllSky
Instruments	H1,L1,V1
Event Time	1397010037.852
FAR (Hz)	3.168e-10
Submitted	2024-04-13 02:22:20 UTC

Per-Pipeline Event Information

UID	Group	Pipeline	Search	gpstime	FAR (Hz)
G473765	CBC	pycbc	AllSky	1397010037.852	3.168e-10
G473763	CBC	CWB	BBH	1397010037.836	1.643e-10
G473760	CBC	MBTA	AllSky	1397010037.847	3.211e-20
G473766	CBC	gstlal	AllSky	1397010037.842	1.668e-34



https://gracedb.ligo.org/superevents/S240413p/view/

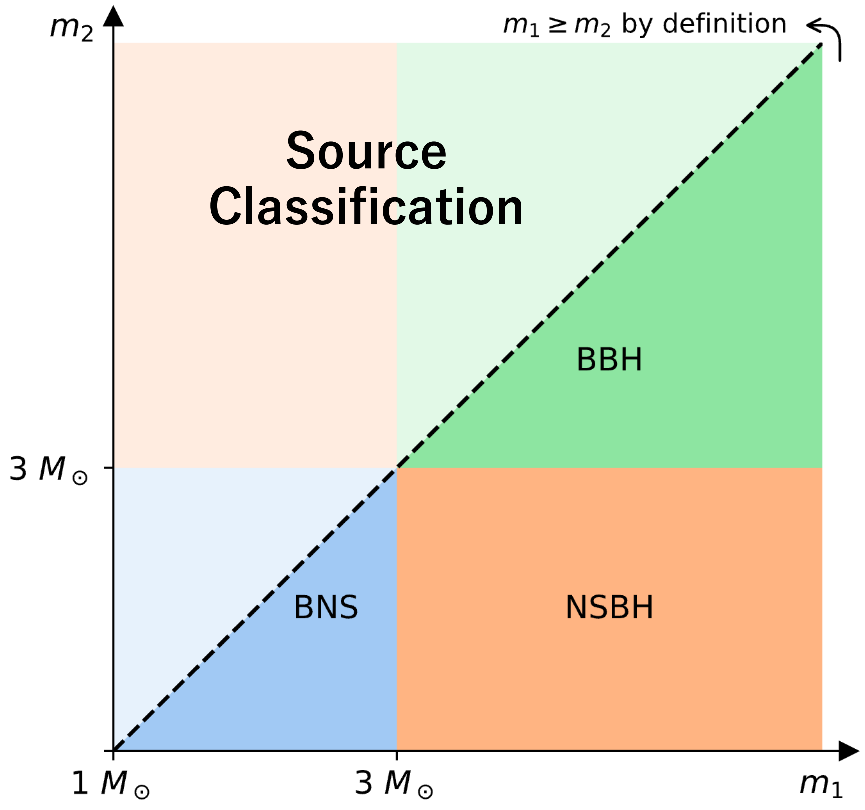
We have started to detect the gravitational wave candidates from O4b!
All are released publicly a short time after our instruments detect them.

Public alerts in O4

See the details: https://emfollow.docs.ligo.org/userguide

Two types of public alerts based on False Alarm Rate (FAR)

- **Significant alerts**
  - Compact binary mergers: FAR < 1/month
  - Bursts: FAR < 1/year
  - Passing automated and human-vetted data quality checks
- **Low significance alerts**
  - FAR up to 2/day
  - Only automated data quality checks



New early warning alert stream

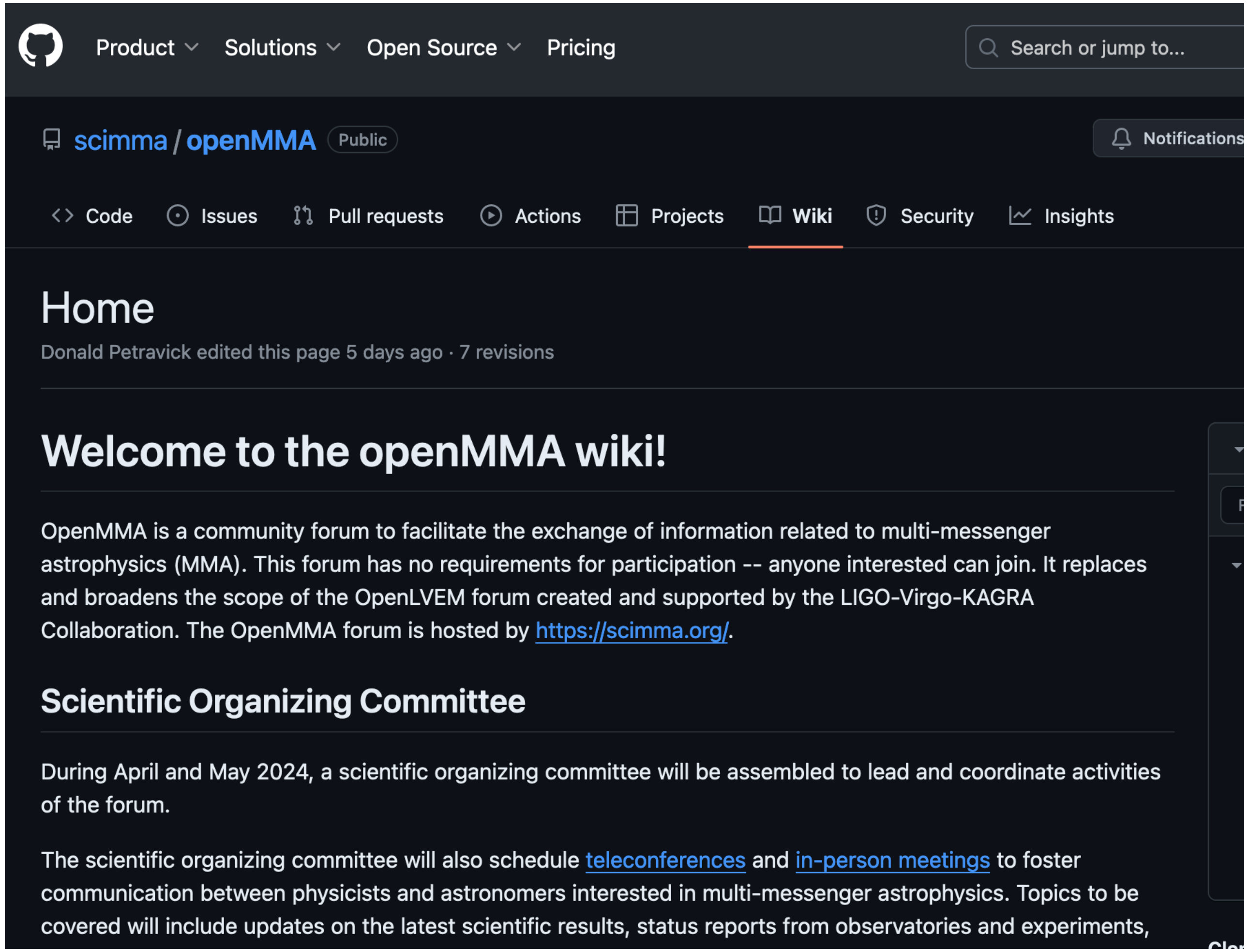
- Goal: send alert *before* merger time
  → "Negative" latency: up to tens of seconds

Public alert sequence

- **Preliminary alerts**
  - First fully automated with a latency < 30 s (typically ~20s)
  - Updates as needed, final one < 5 minutes after online search completed
- **Significant triggers**: rapid response team involved
  - Initial circular or retraction
  - Updates as needed – in particular improved parameter estimation

Welcome to the openMMA forum!

https://github.com/scimma/openMMA/wiki



openMMA is a community forum to facilitate the exchange of information related to multi-messenger astrophysics (MMA).

- Links to various useful LVK documentation and resources:
  - Observing Run Plans
  - Public Alert User Guide
  - Observatory Status
- Telecons
- Apps

Etc.

Summary

- 90 confirmed detections have been made from O1, O2, and O3 observation runs.
  - A harvest of scientific results:
    - Individual events: GW150914, GW170817, etc.
    - Transient catalog: GWTC-3
  - KAGRA joined the network late O3.
- O4a result started to be shown
- The new O4b observing run has just started.
  - 3 detectors at beginning

  → Crossing fingers to see many more interesting events to be discovered!
- 3G already in discussion