Overview and prospect of the gravitational-wave transient search in LVK's fourth observing run

Leo Tsukada
Pennsylvania State University

CTA-Japan workshop
2024/02/20

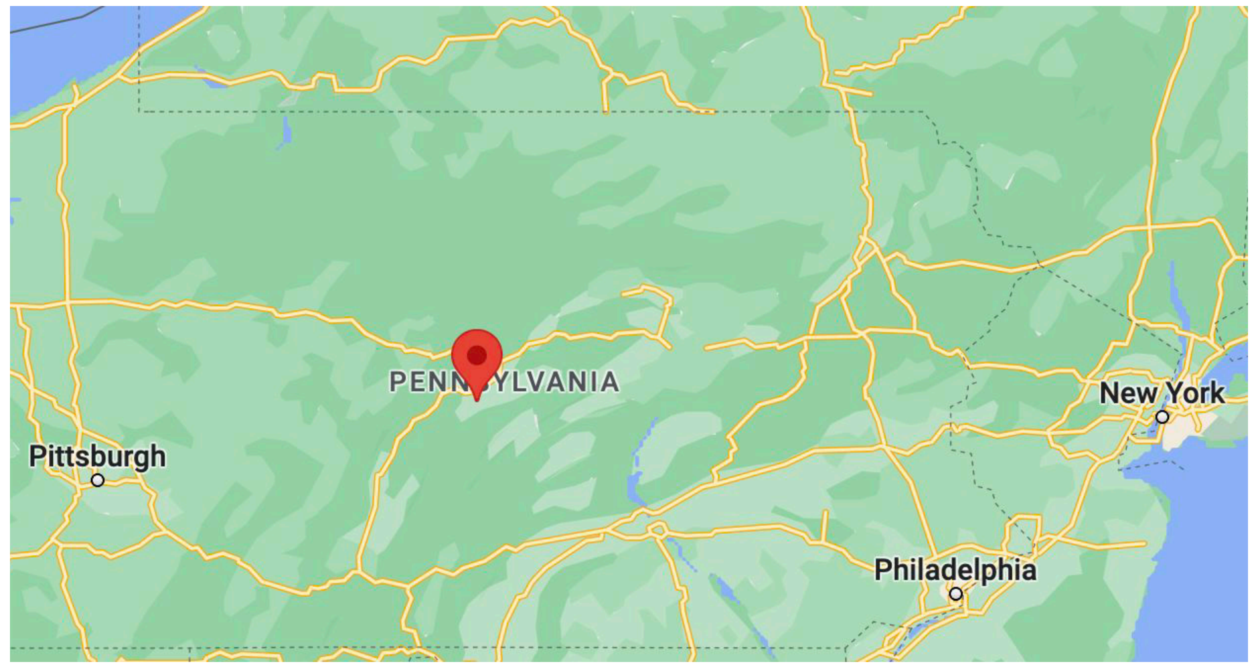
Who Am I?

- Leo Tsukada

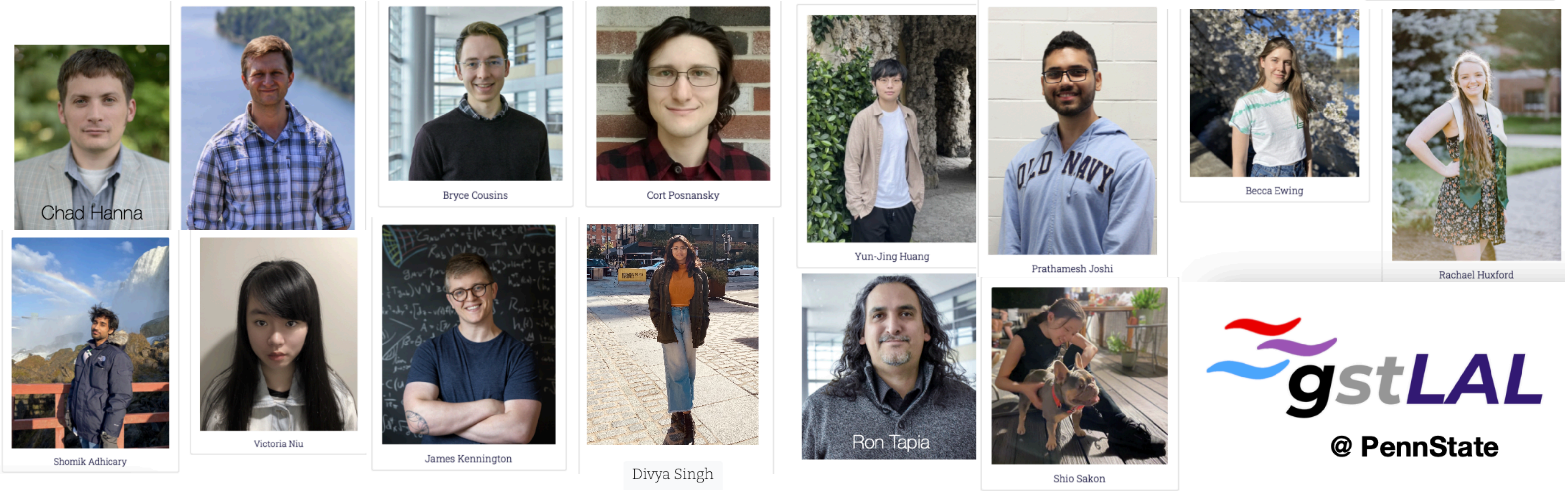
- Research area : Gravitational wave data analysis

  Development of GW detection pipeline
  Search for stochastic GW background
  etc …

- Pennsylvania State University



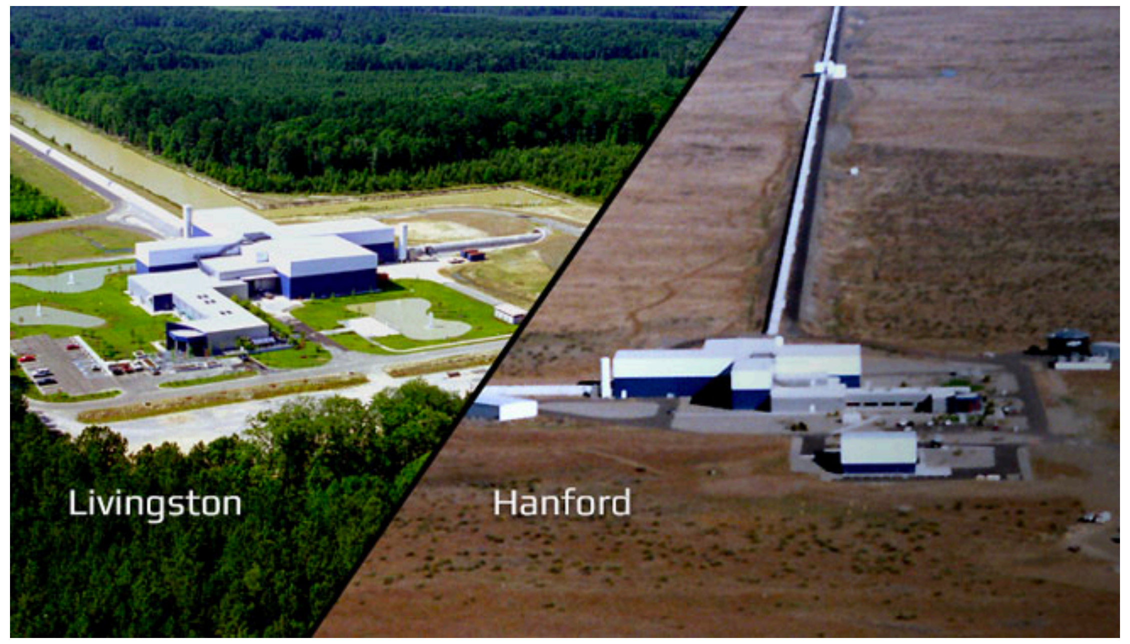
- Penn State LIGO group



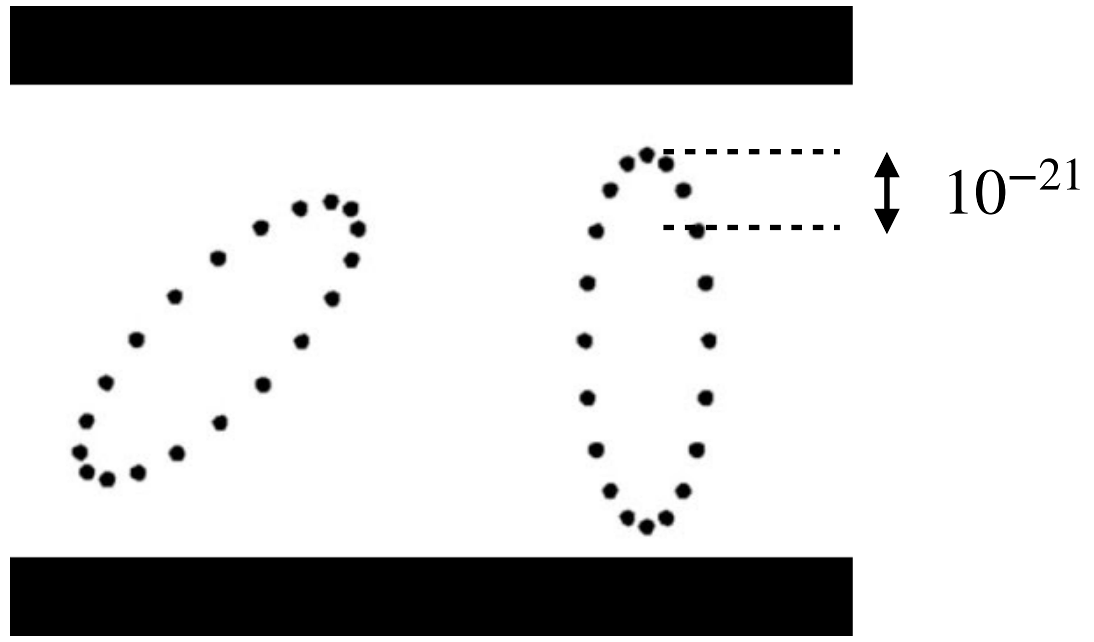
Gravitational-wave astronomy

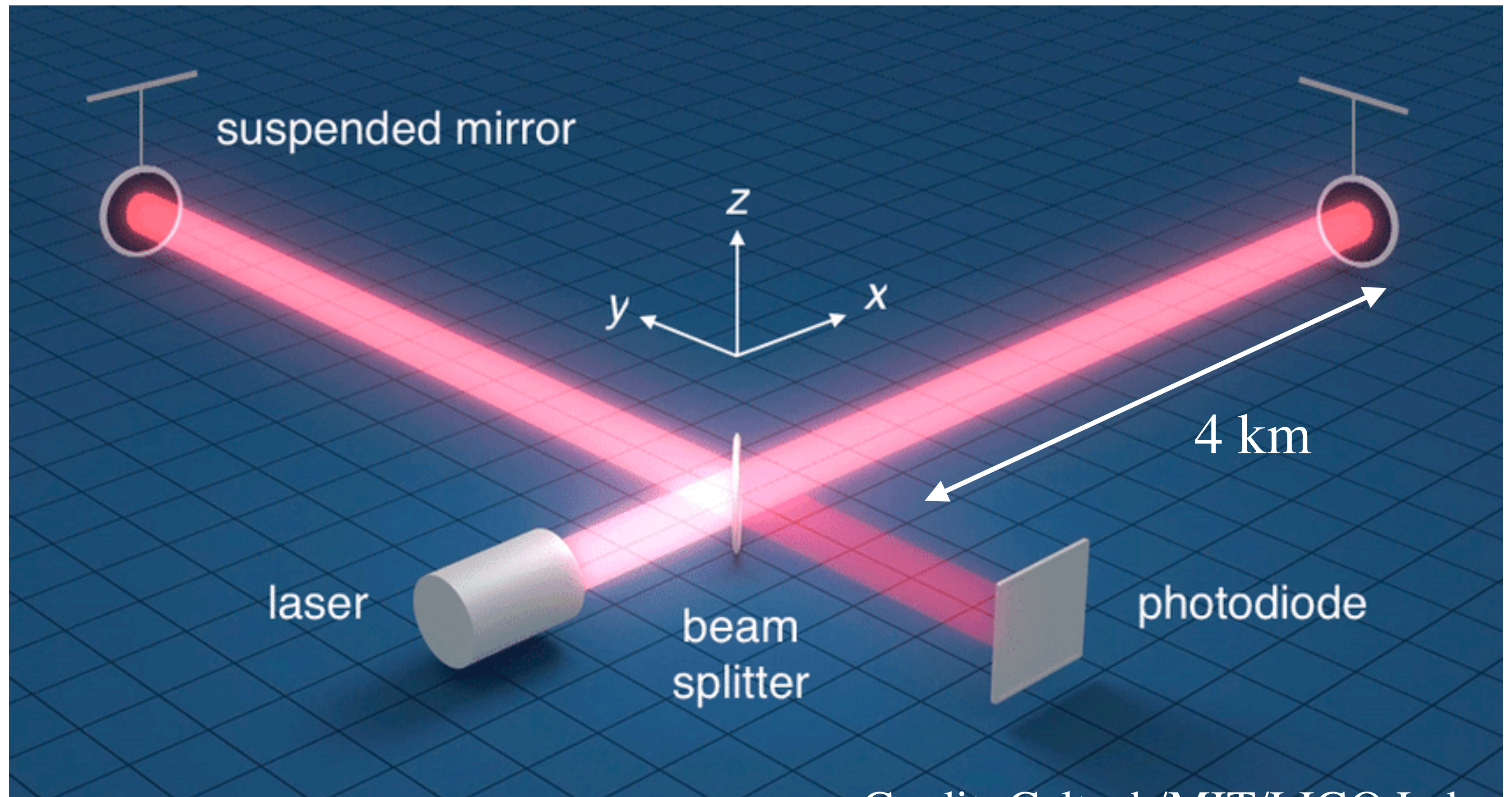
- Gravitational waves
  Oscillation of a spacetime due to gravity

LIGO



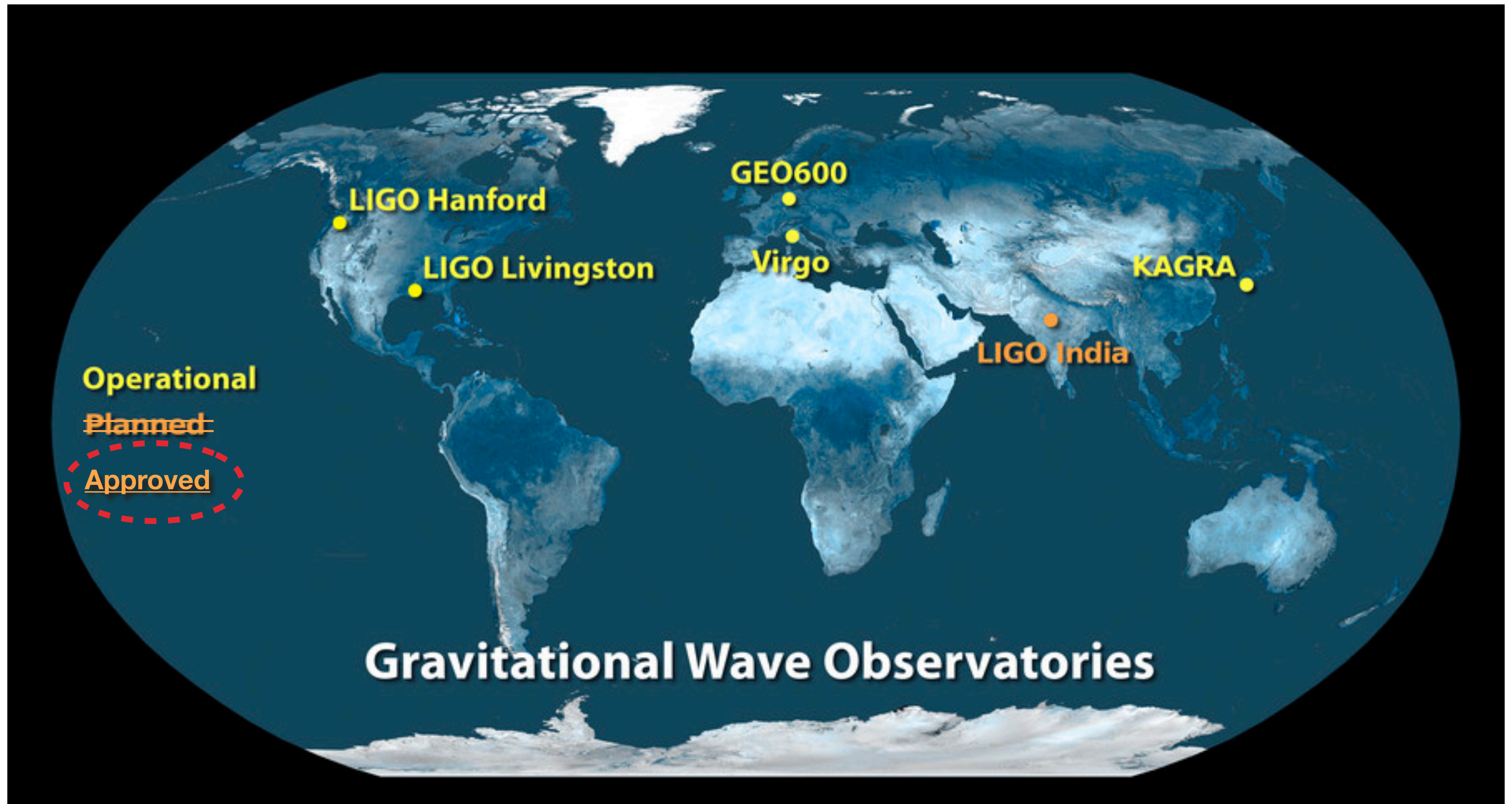
Effect of GWs





Credit: Caltech/MIT/LIGO Lab

- LIGO-Virgo-KAGRA (LVK) detector network



Credit: Caltech/MIT/LIGO Lab

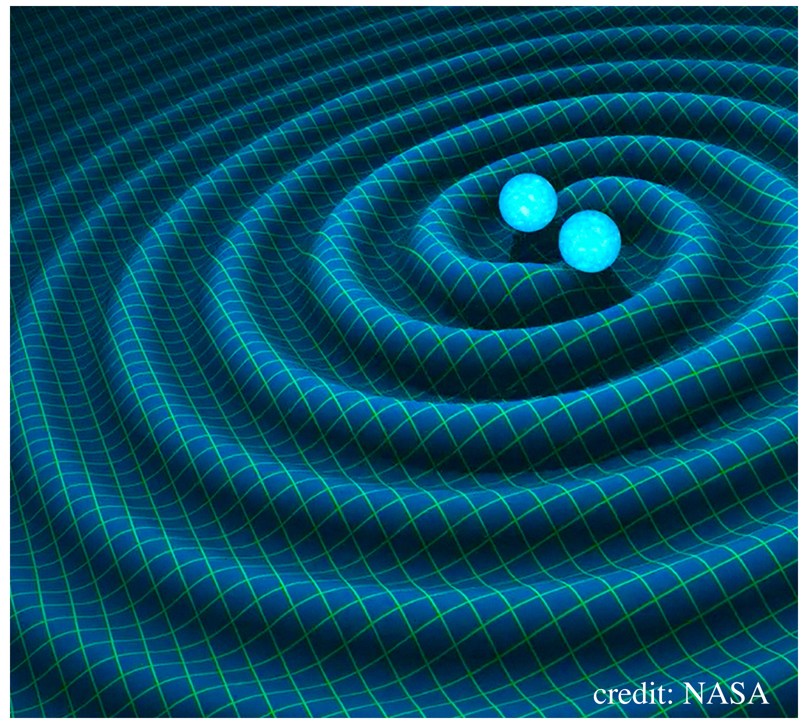
A larger network improves:

- a detection significance
- sky localization of GW sources
- a coverage of the operational period.

Gravitational-wave zoology

Transient

- Compact binaries
  - Black hole (BH)
  - Neutron star (NS)
  - ➡ Already detected



credit: NASA

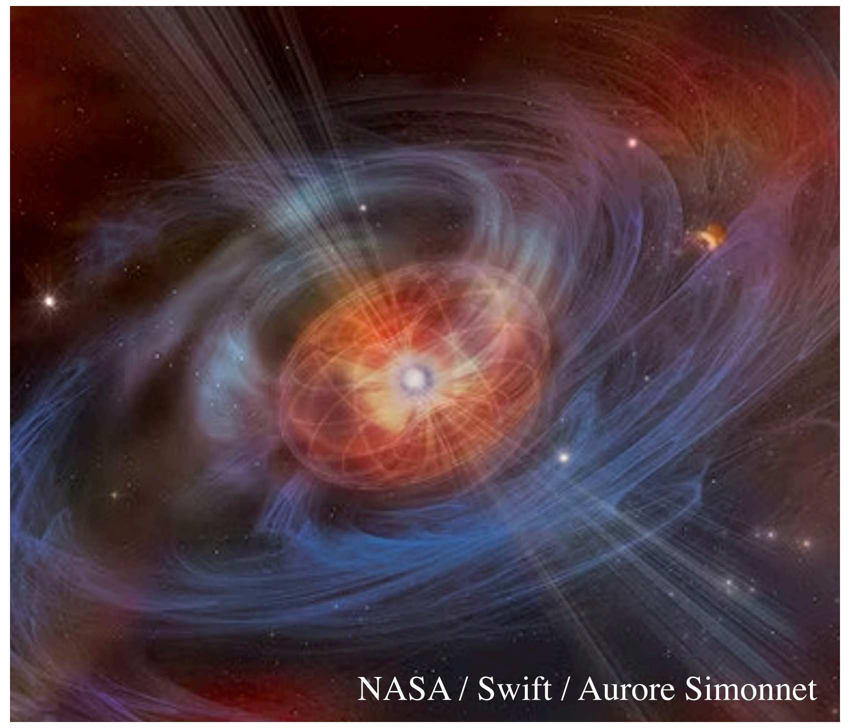
Soubrette/Istock/Getty Images Plus

- Bursts
  - Core-collapse supernova
  - Cosmic strings

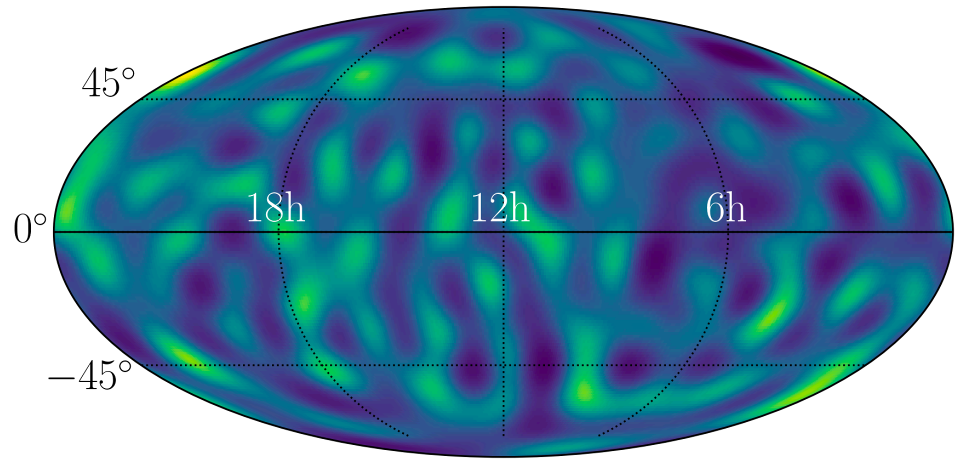
Modeled

Unmodeled

- Continuous waves
  - Pulsars
  - Boson cloud around a BH



NASA / Swift / Aurore Simonnet



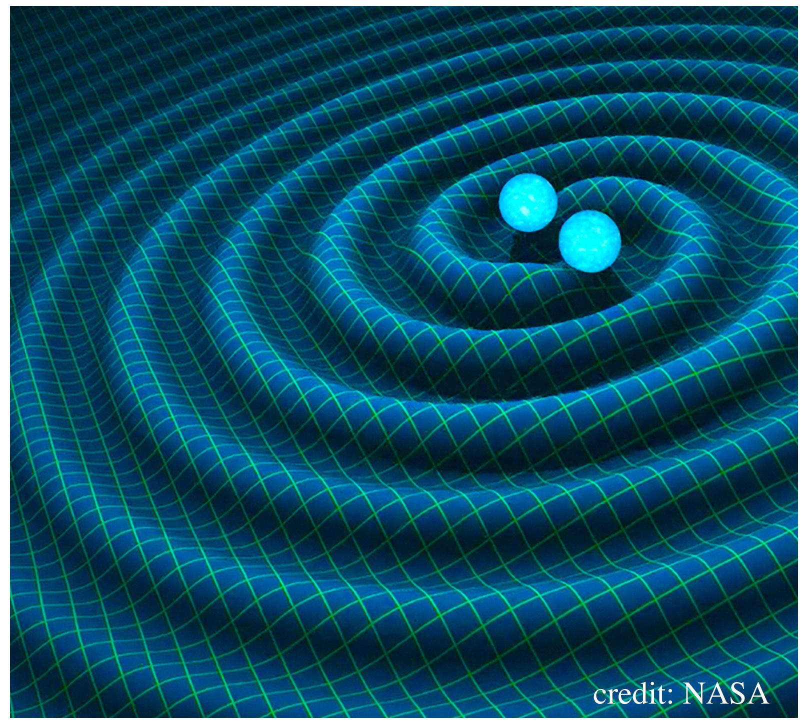
- Stochastic backgrounds
  - A population of compact binaries pulsars / supernovae
  - Inflation

Persistent

Gravitational-wave zoology

Transient

- Compact binaries
  - Black hole (BH)
  - Neutron star (NS)
  - ➡ Already detected

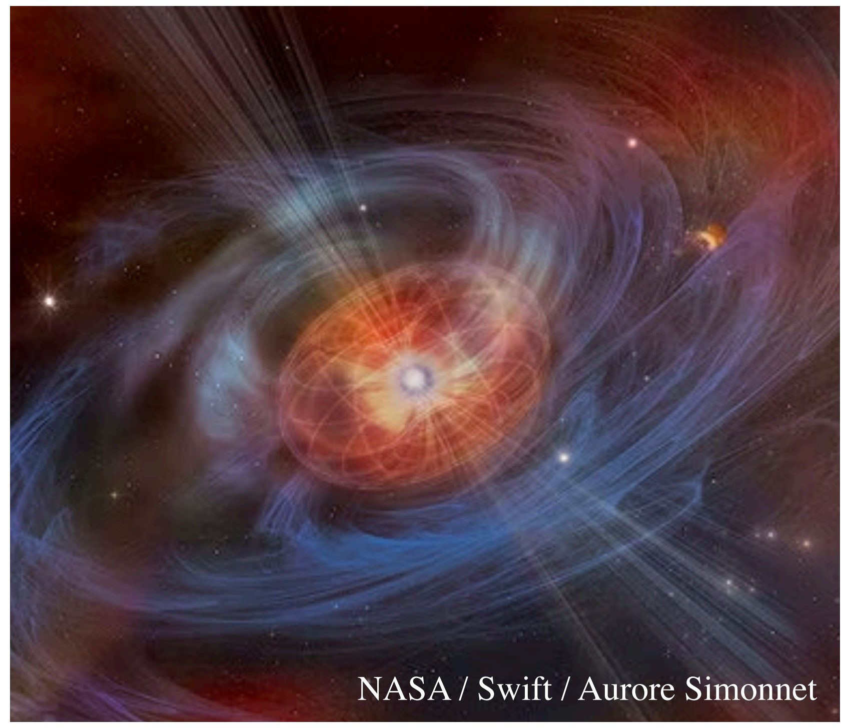

credit: NASA

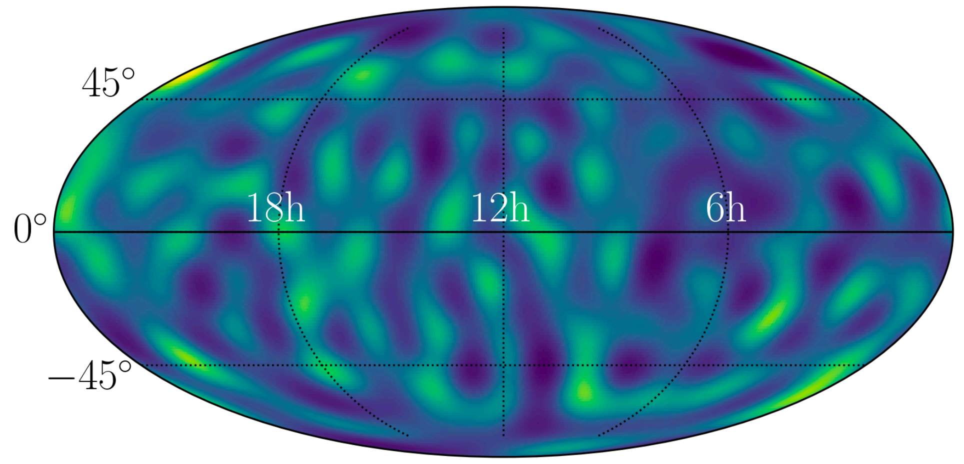

Soubrette/Istock/Getty Images Plus

- Bursts
  - Core-collapse supernova
  - Cosmic strings

Modeled ↔ Unmodeled

- Continuous waves
  - Pulsars
  - Boson cloud around a BH


NASA / Swift / Aurore Simonnet

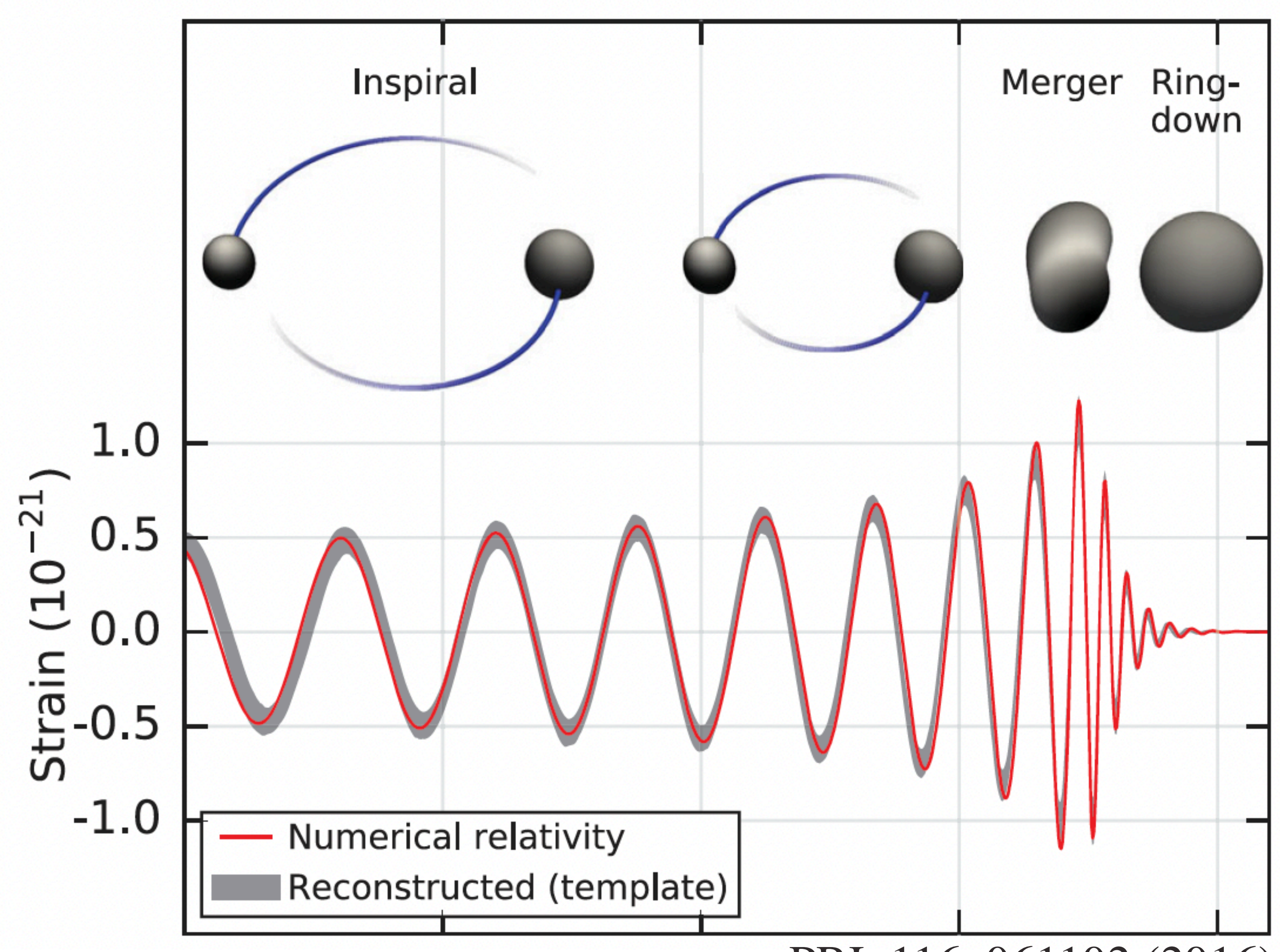


- Stochastic backgrounds
  - A population of compact binaries pulsars / supernovae
  - Inflation

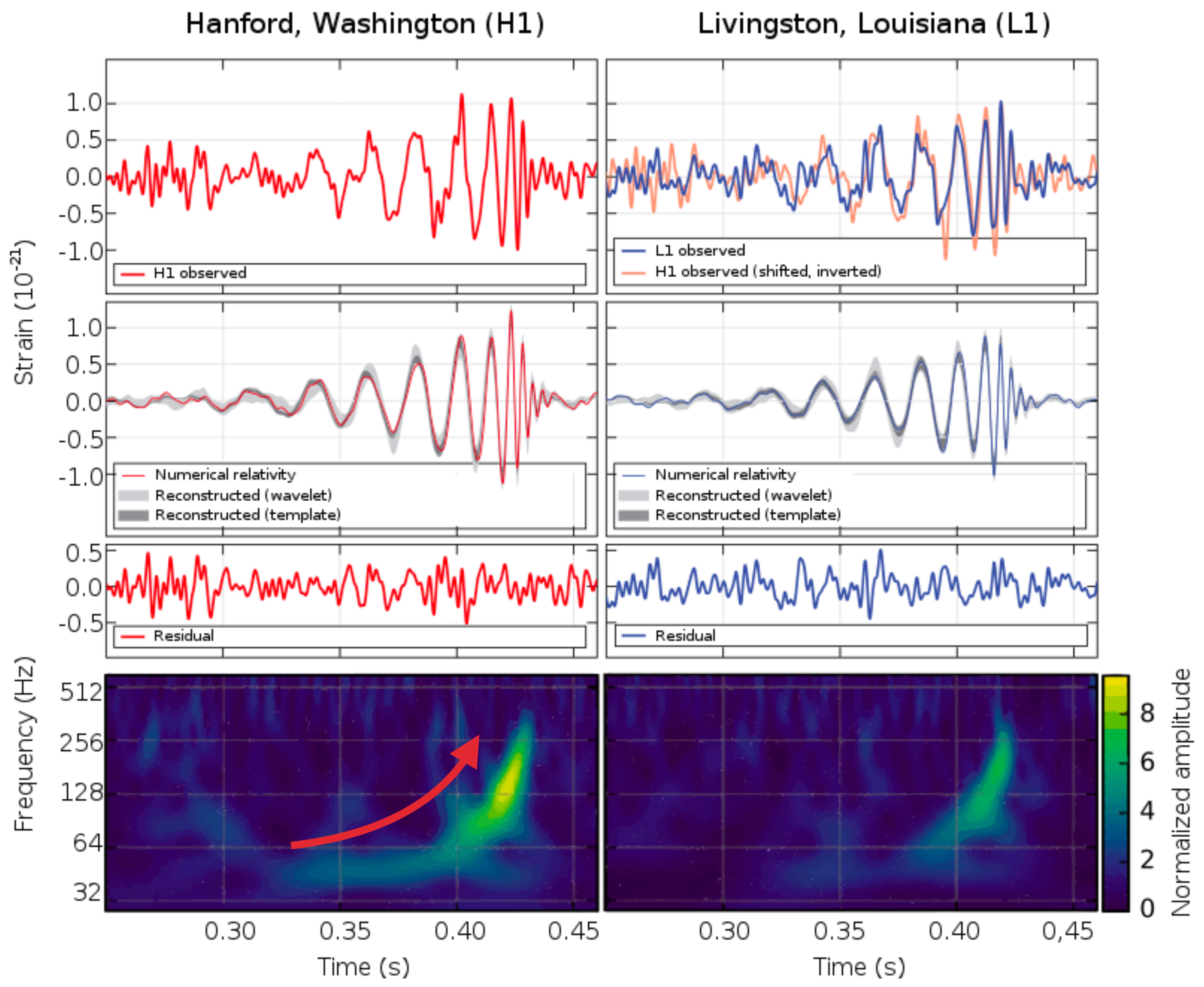
Persistent

First detection

- GW150914
  The first GW signal from a binary black hole (BBH)



PRL 116, 061102 (2016)

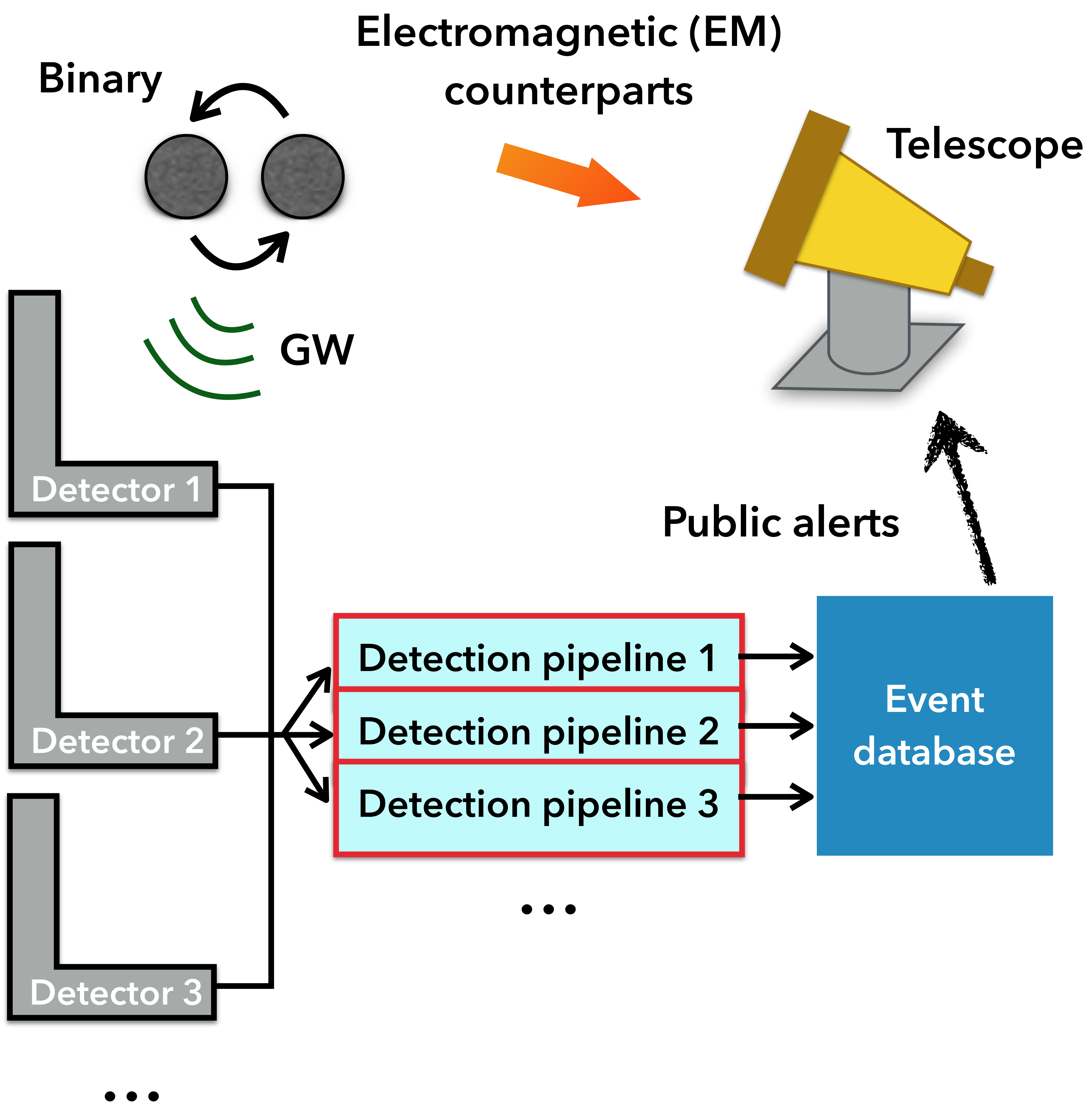


WE HAVE DETECTED GRAVITATIONAL WAVES!

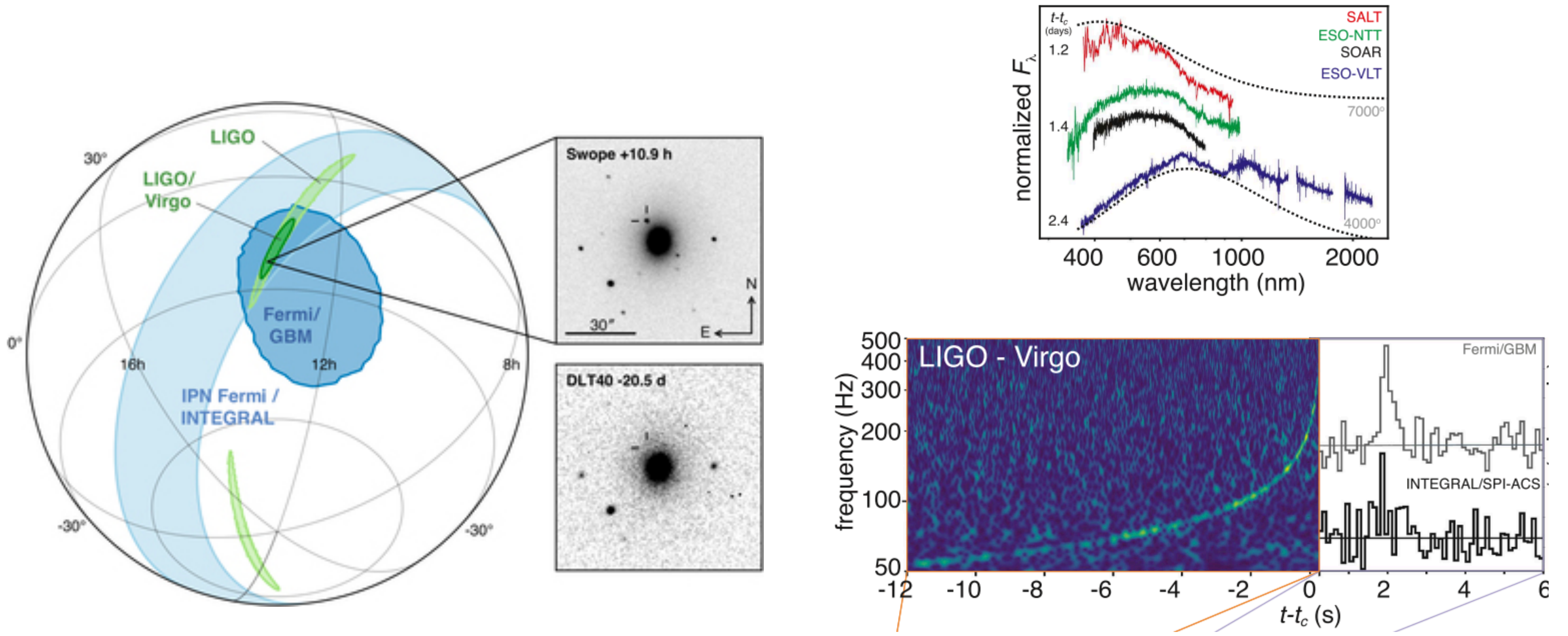
– DAVE REITZE, DIRECTOR OF LIGO

- GWs are consistent with the general relativity.
- A BBH does exist and merge.
- The discovery of “heavy” BHs (~ 30 $M_{\odot}$)

Multi-messenger astronomy



- Joint detection of GW170817



Astrophys. J. Lett. 848, no.2, L12 (2017).

- Equations of state for nuclear matter
- Emission mechanism of GRB
- Independent constraints on H_0

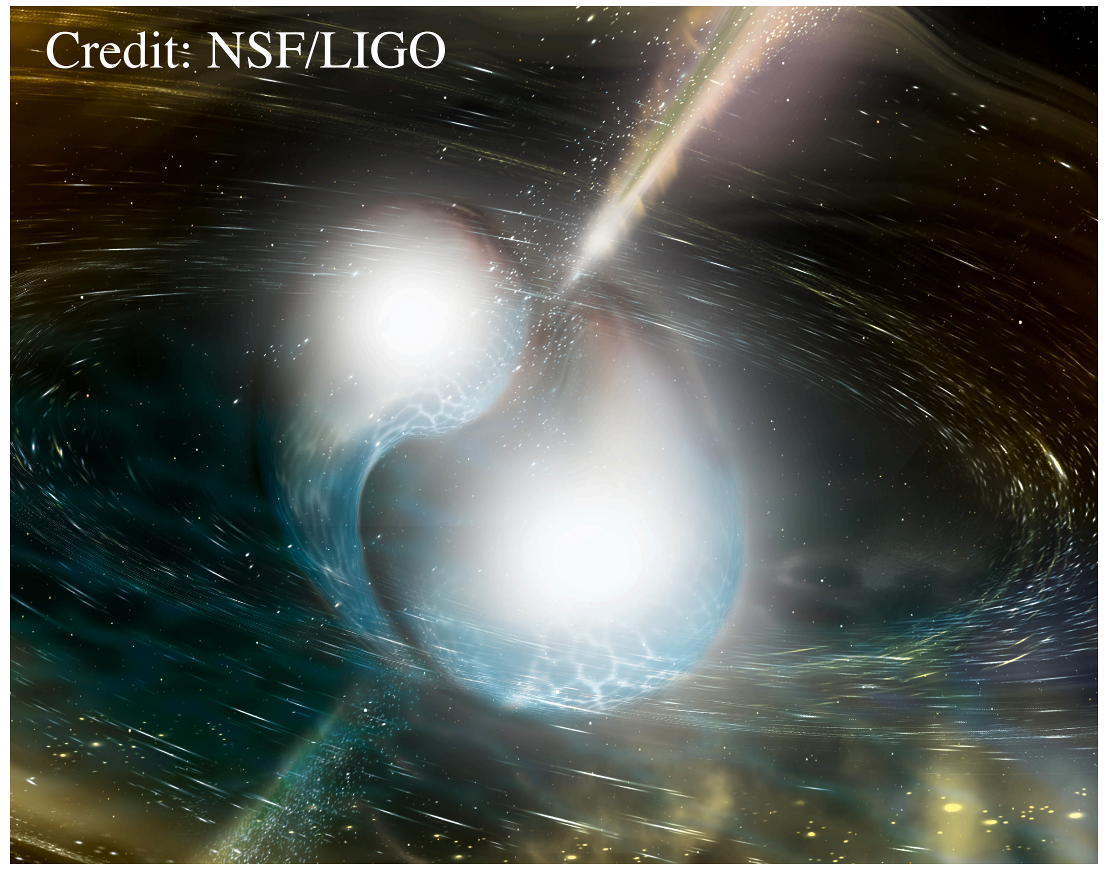
etc…

Gamma-ray counterparts

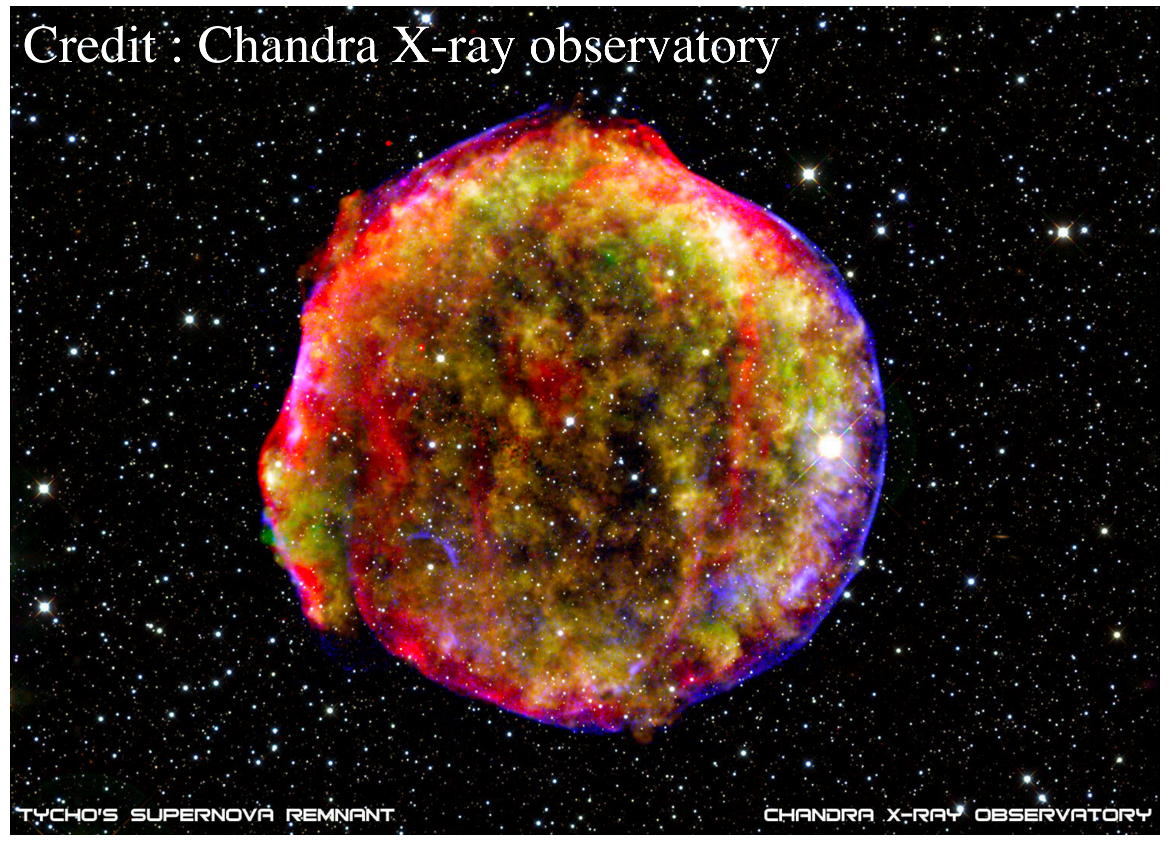
- keV - MeV Gamma-ray
- GeV - TeV Gamma-ray

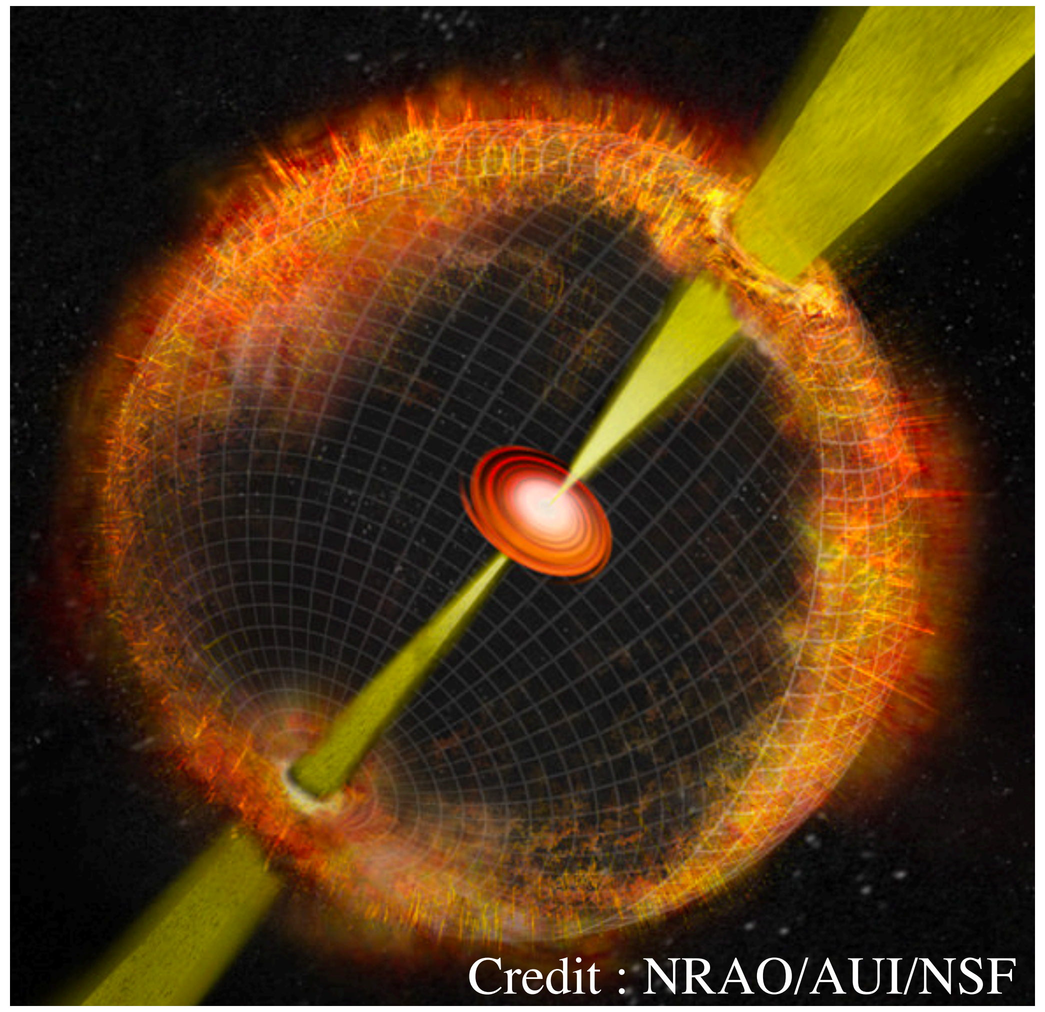
Compact binary merger

Short GRB (?)



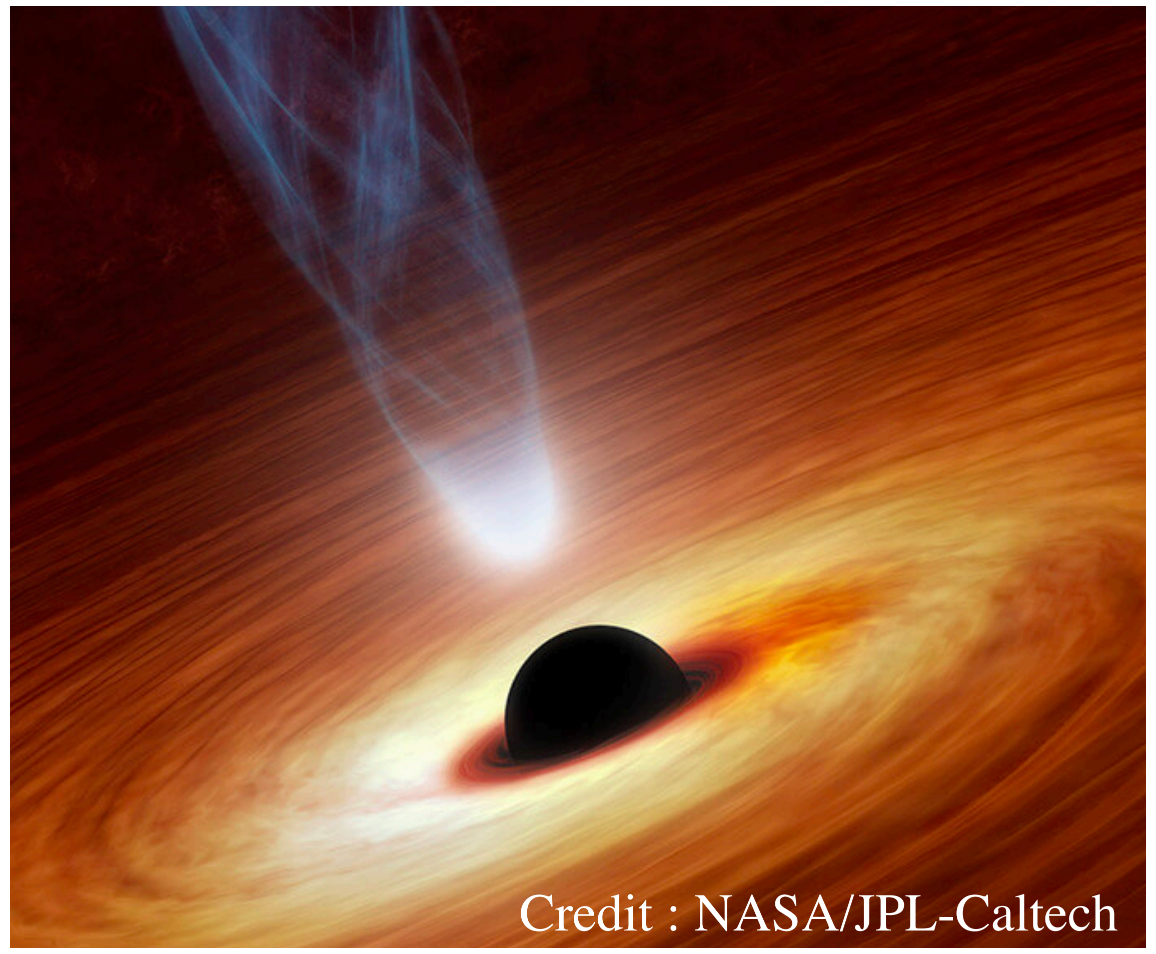
Supernova remnant





Core-collapse Supernova

Long GRB



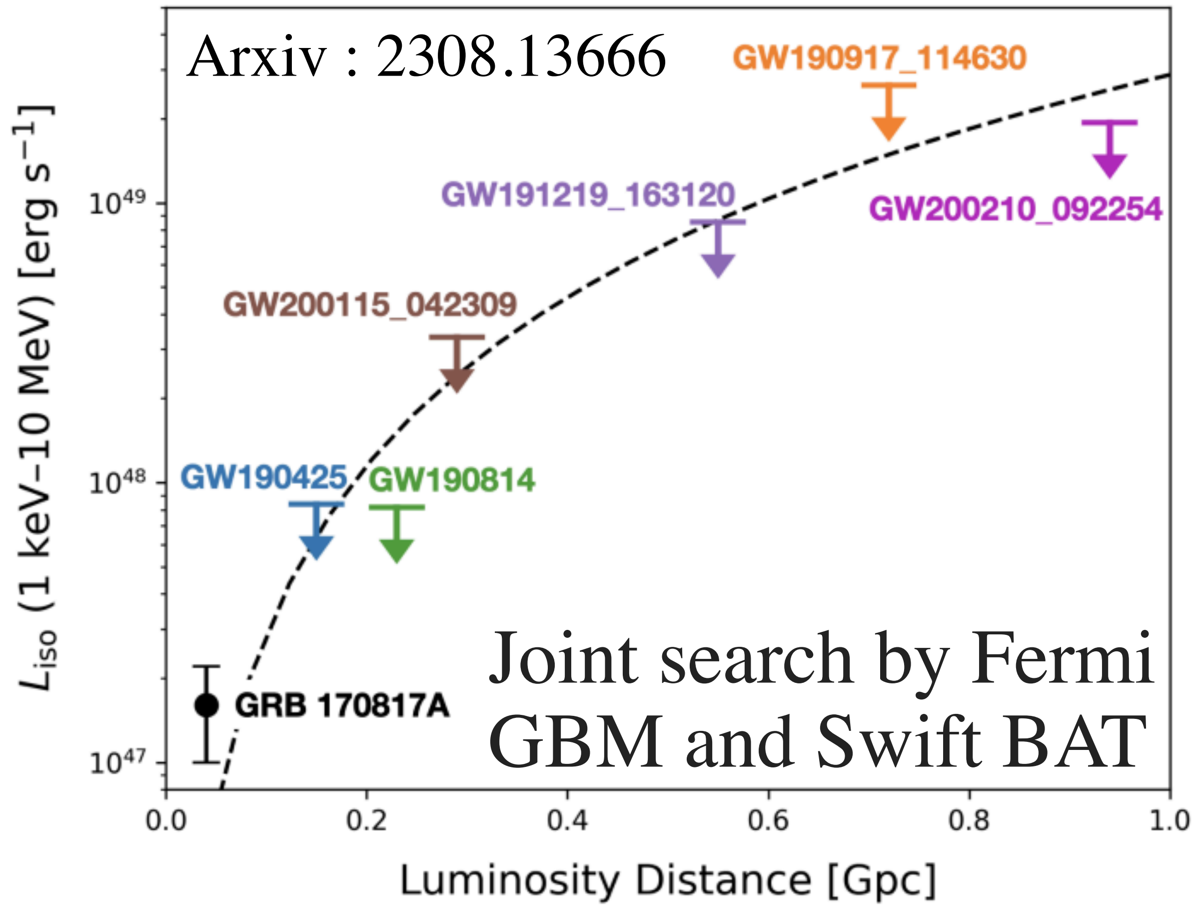
Active Galactic Nuclei

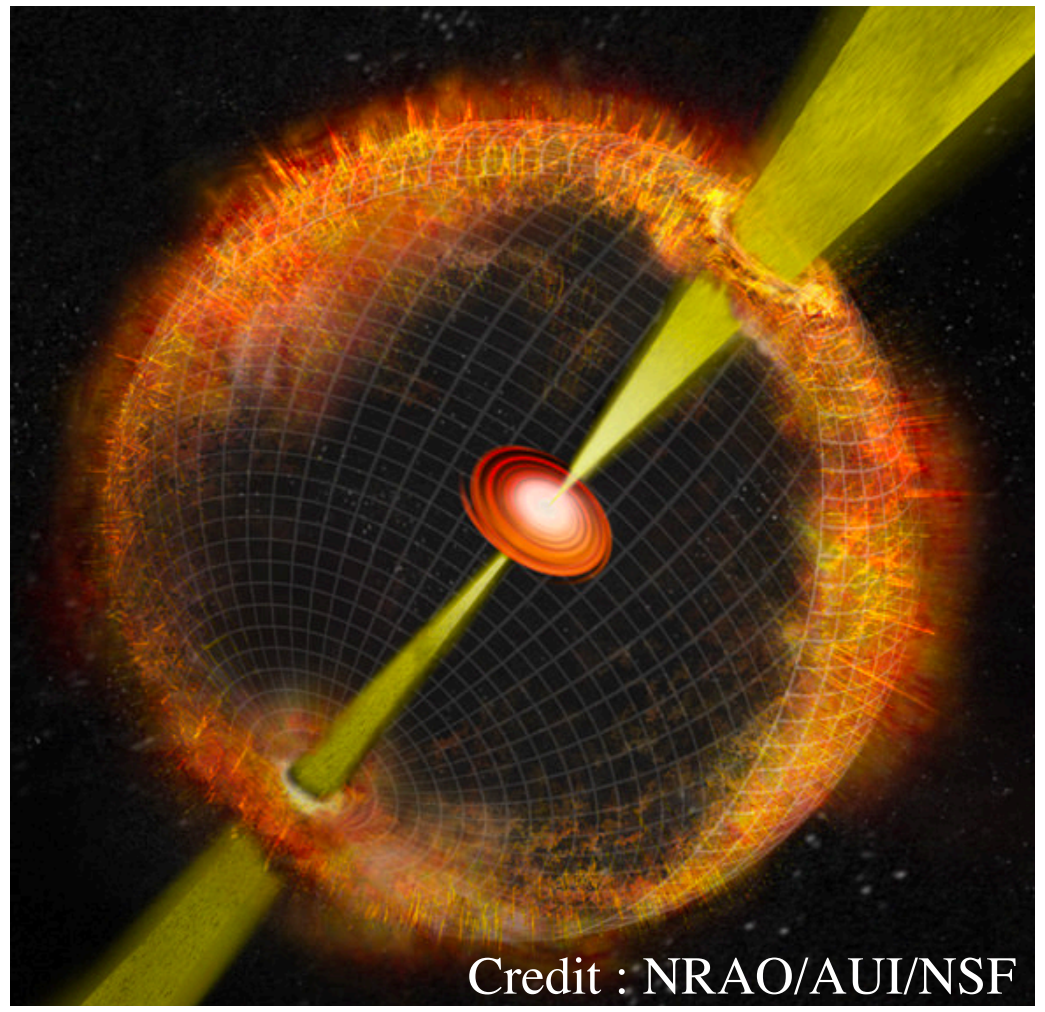
Gamma-ray counterparts

- keV - MeV Gamma-ray

Compact binary merger

Short GRB (?)



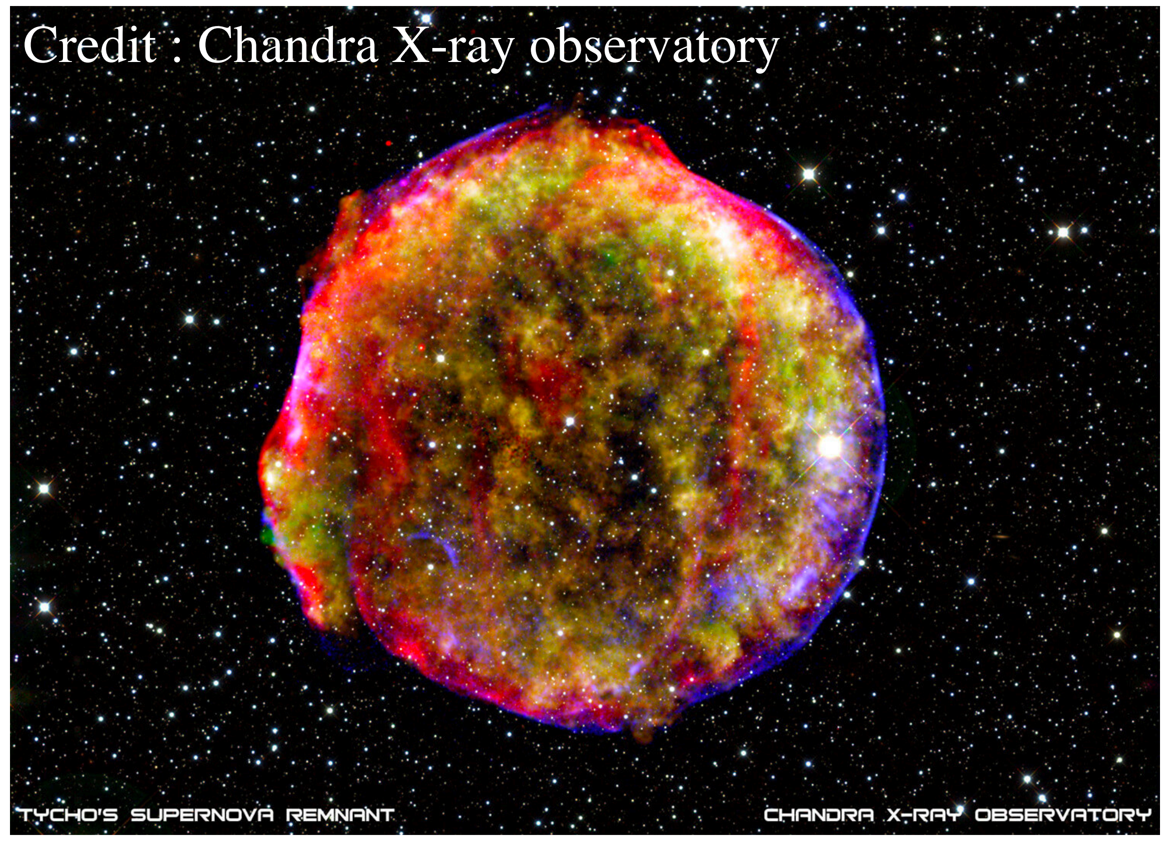

Credit : NRAO/AUI/NSF

Core-collapse Supernova

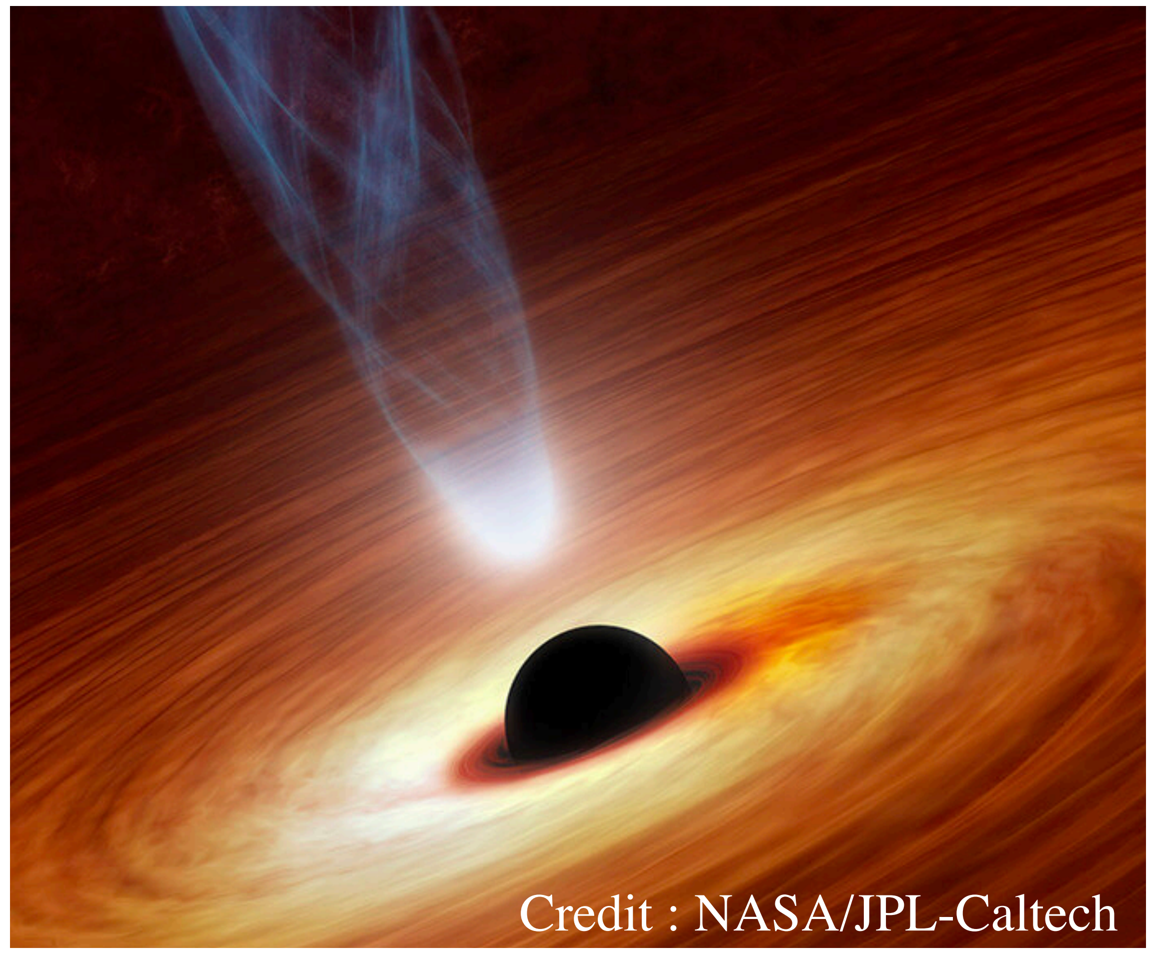
Long GRB

- GeV - TeV Gamma-ray

Supernova remnant



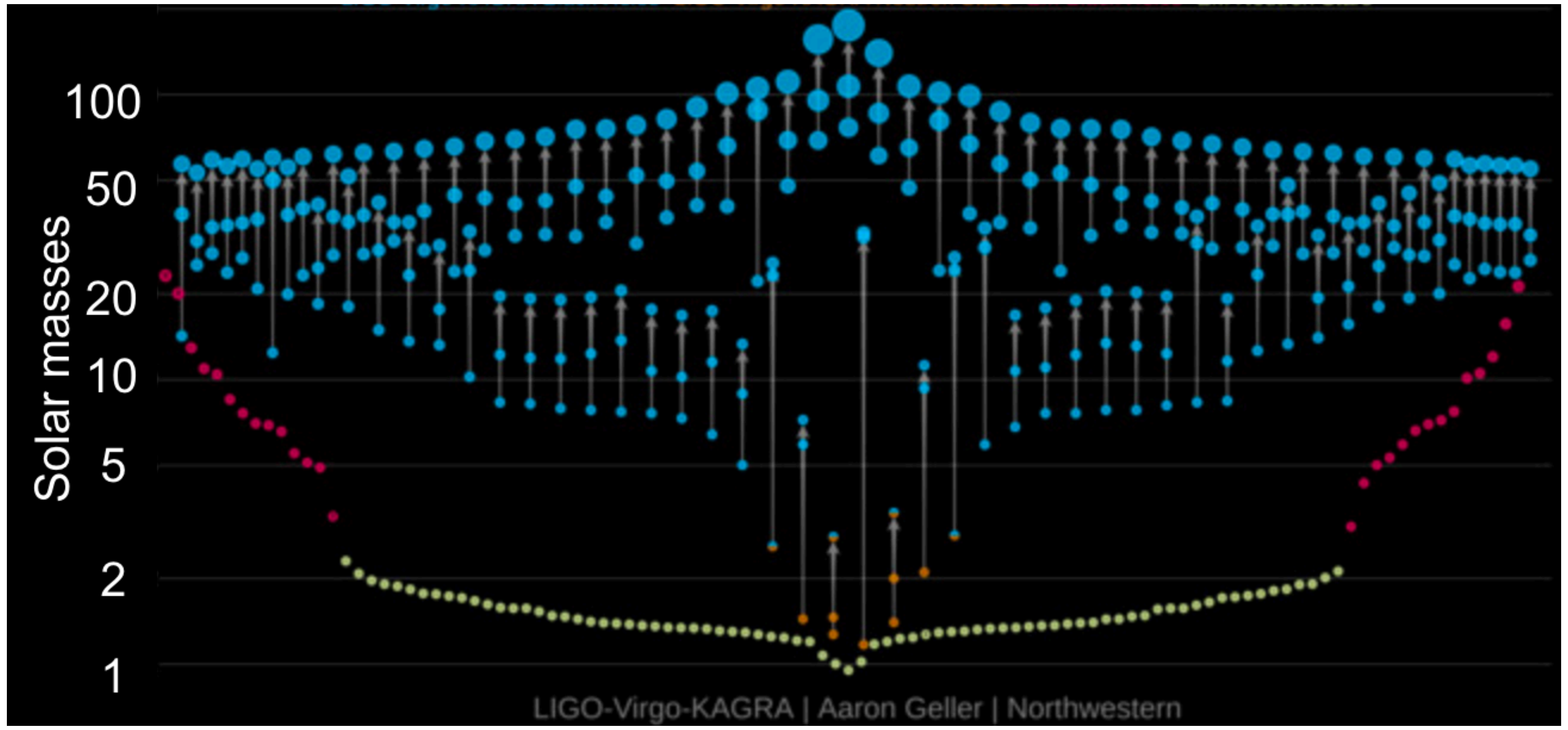
Credit : Chandra X-ray observatory


Credit : NASA/JPL-Caltech

Active Galactic Nuclei

Gravitational-wave catalog

- Gravitational Wave Transient Catalog (GWTC)

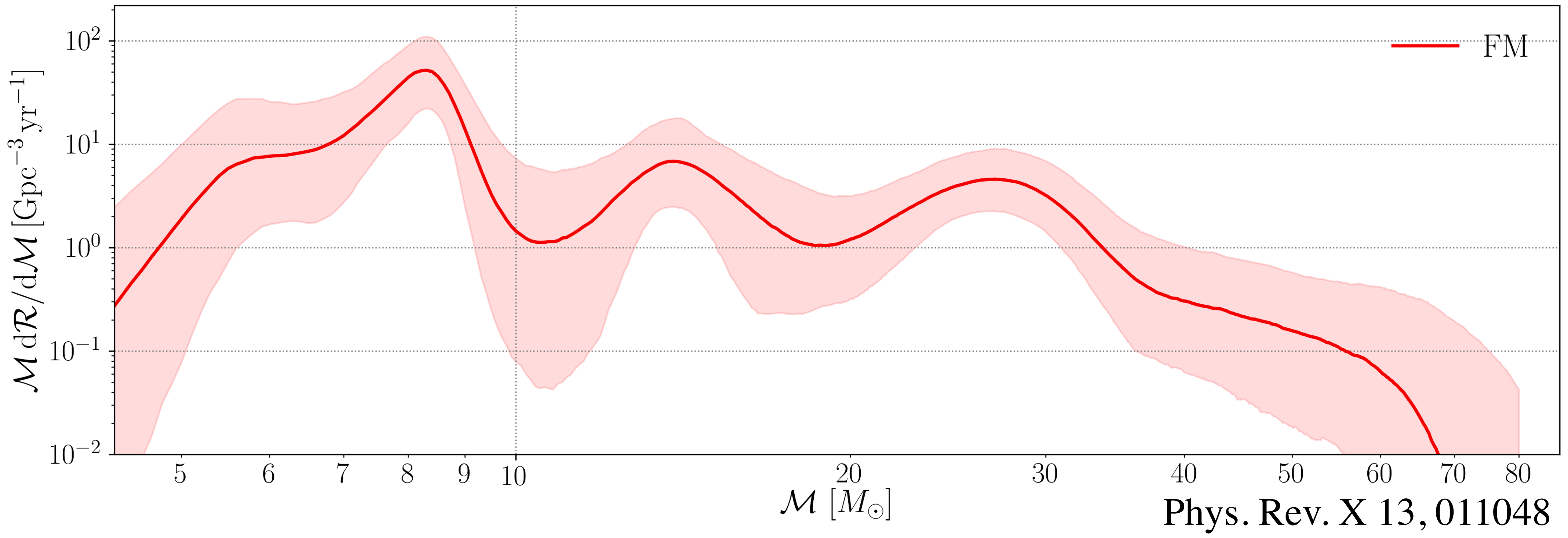


: EM observation (X-ray binaries, pulsars)

: GW observation (90 CBC signals by 2020)

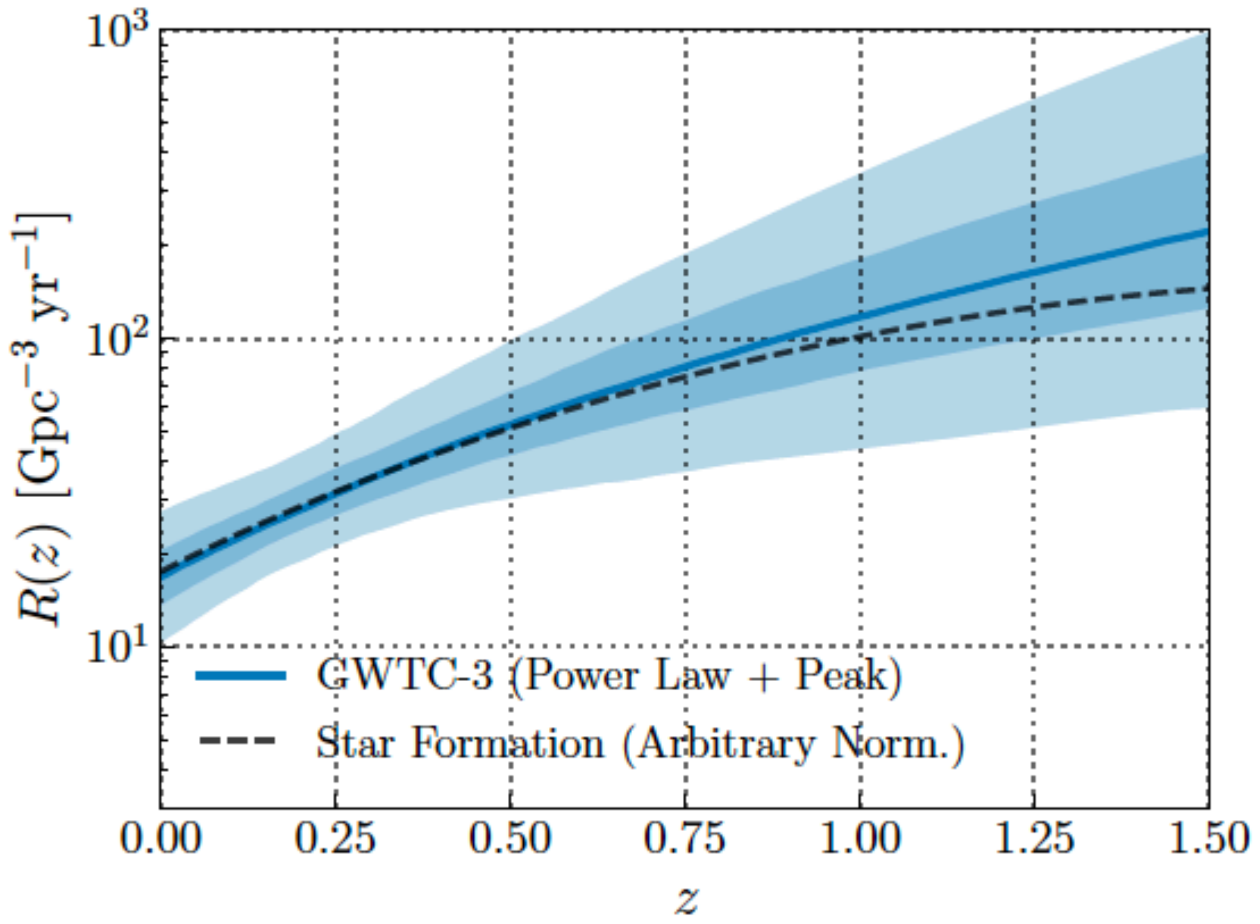
86 BBH
2 NSBH
2 BNS

- Inferred mass distribution



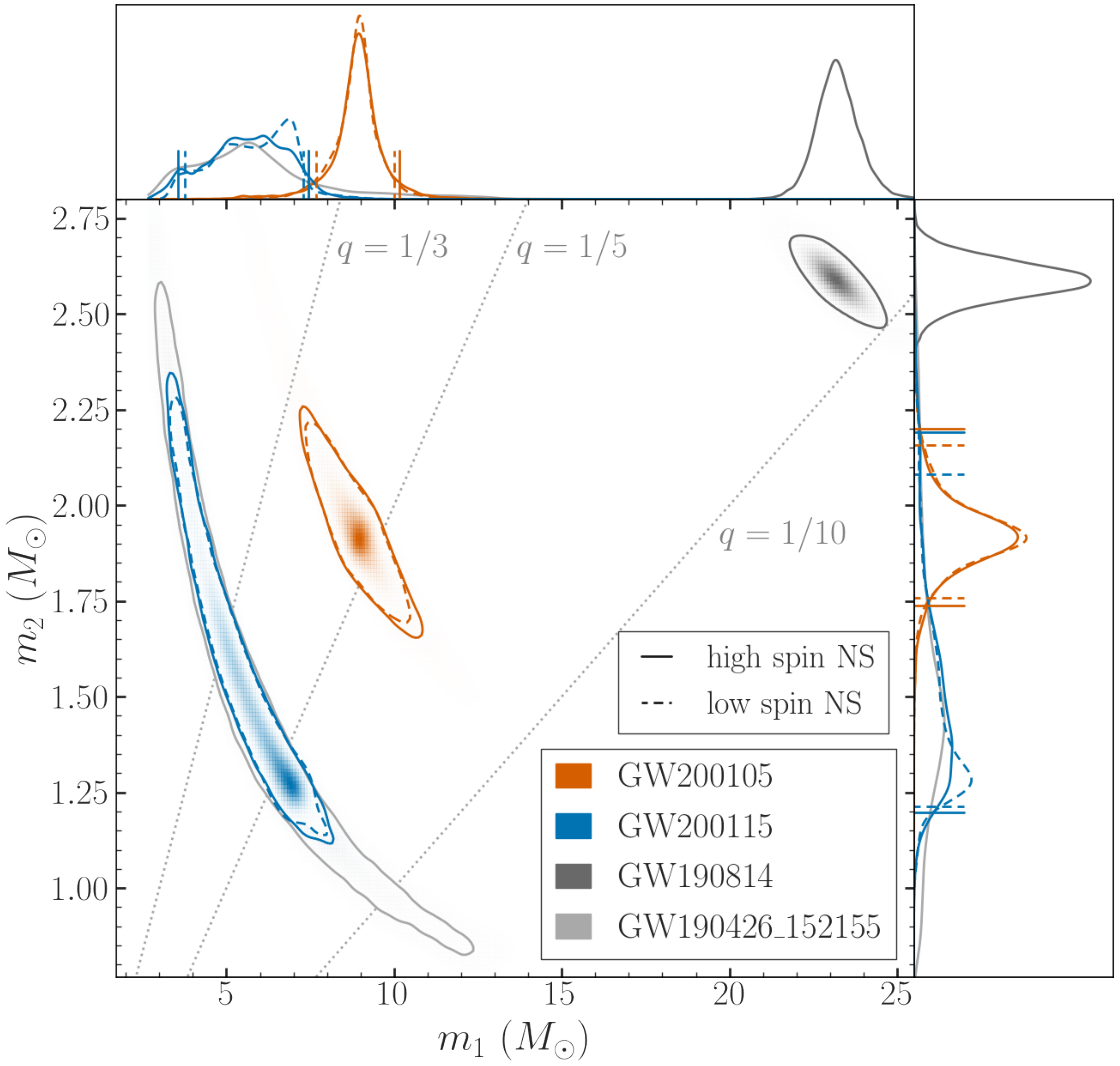
Phys. Rev. X 13, 011048

- Merger rate evolution



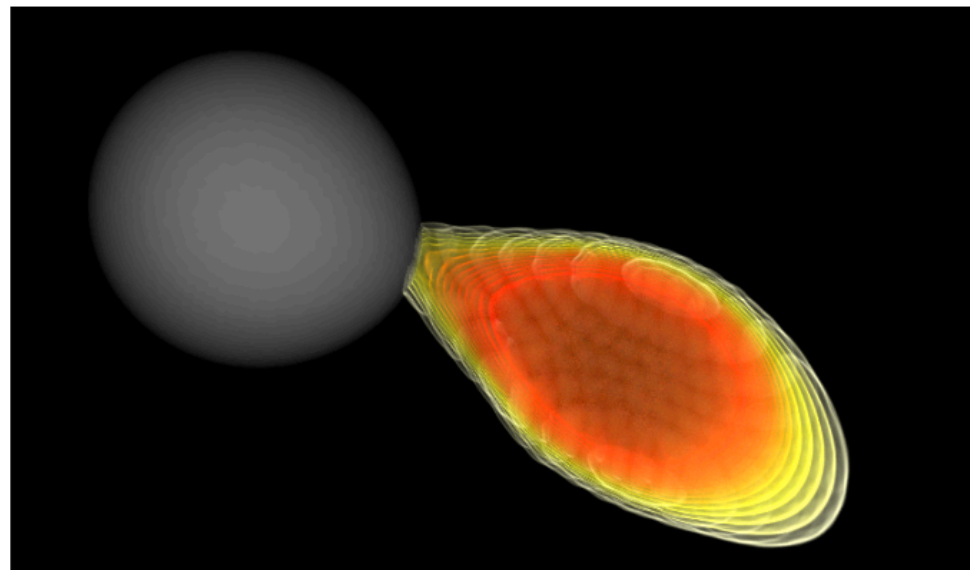
GW200105 & 200115 : first NSBHs

Inferred component masses



ApJL 915 L5 (2021)

	m_1	m_2
GW200105	$8.9^{+1.2}_{-1.5} M_\odot$	$1.9^{+0.3}_{-0.2} M_\odot$
GW200115	$5.7^{+1.8}_{-2.1} M_\odot$	$1.5^{+0.7}_{-0.3} M_\odot$



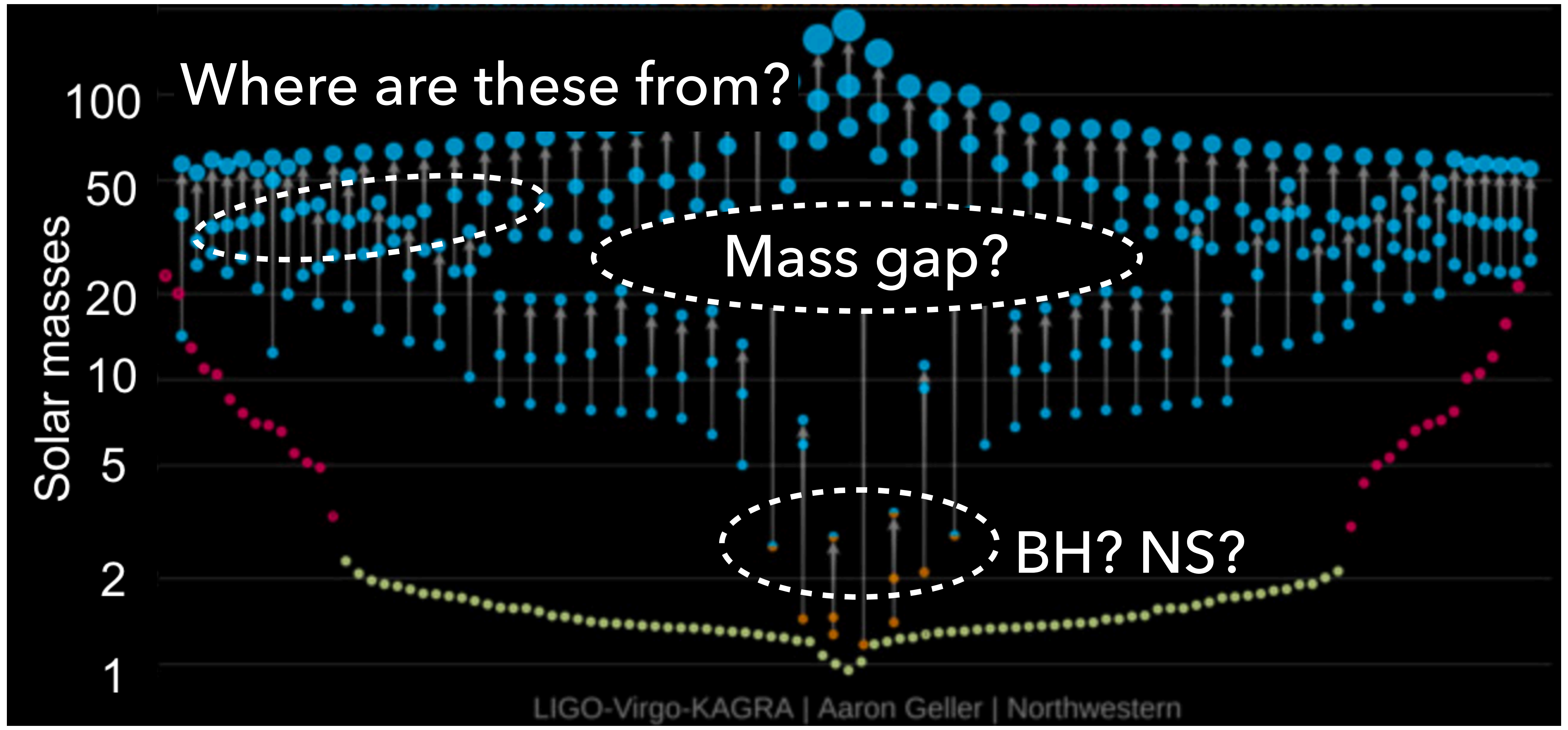
Credit : S.V.Chaurasia, T.

- No evidence of tidal effects
- No EM counterparts

NS plunged into a BH?

Open Questions

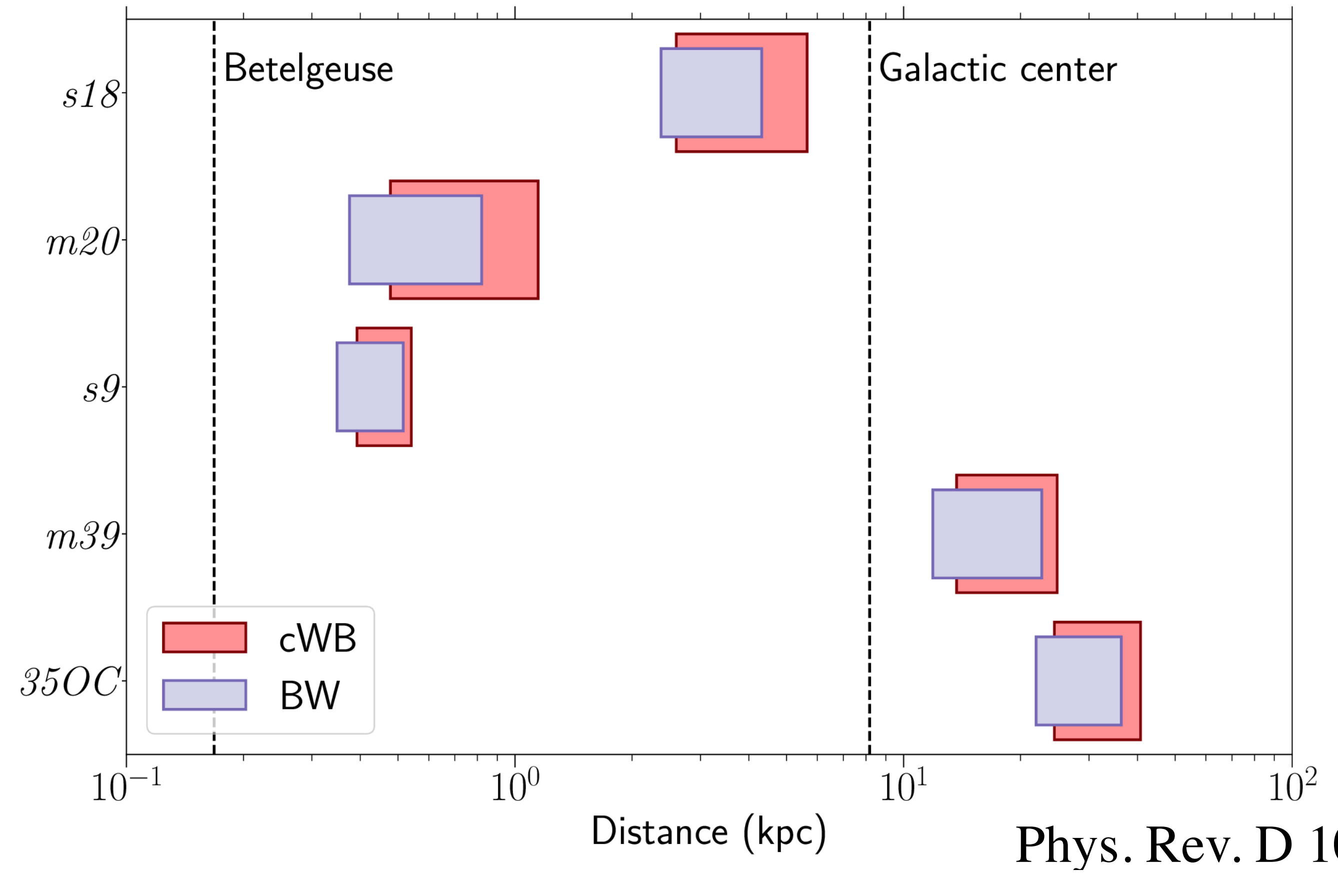
- Gravitational Wave Transient Catalog (GWTC)



  - What happens after the merger?
  - What about the spin distribution?
    ➡ Non-zero spin? precession?
  - More multi-messenger observations?

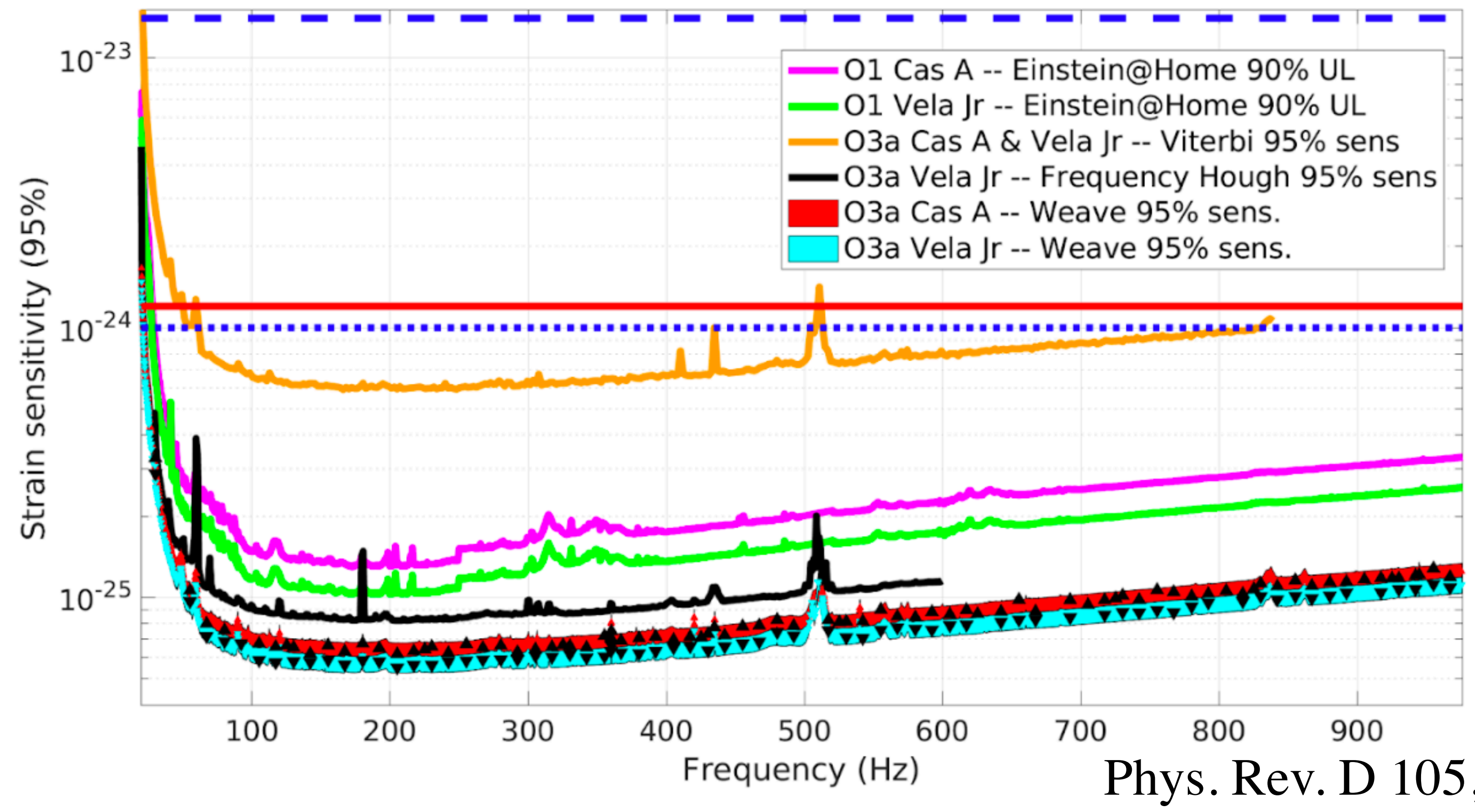
- How about other GW sources?

Core collapse supernova observable distance



Phys. Rev. D 104, 122004

Strain upper limit on Cas A, Vela nebulae



Phys. Rev. D 105, 082005

Observing runs

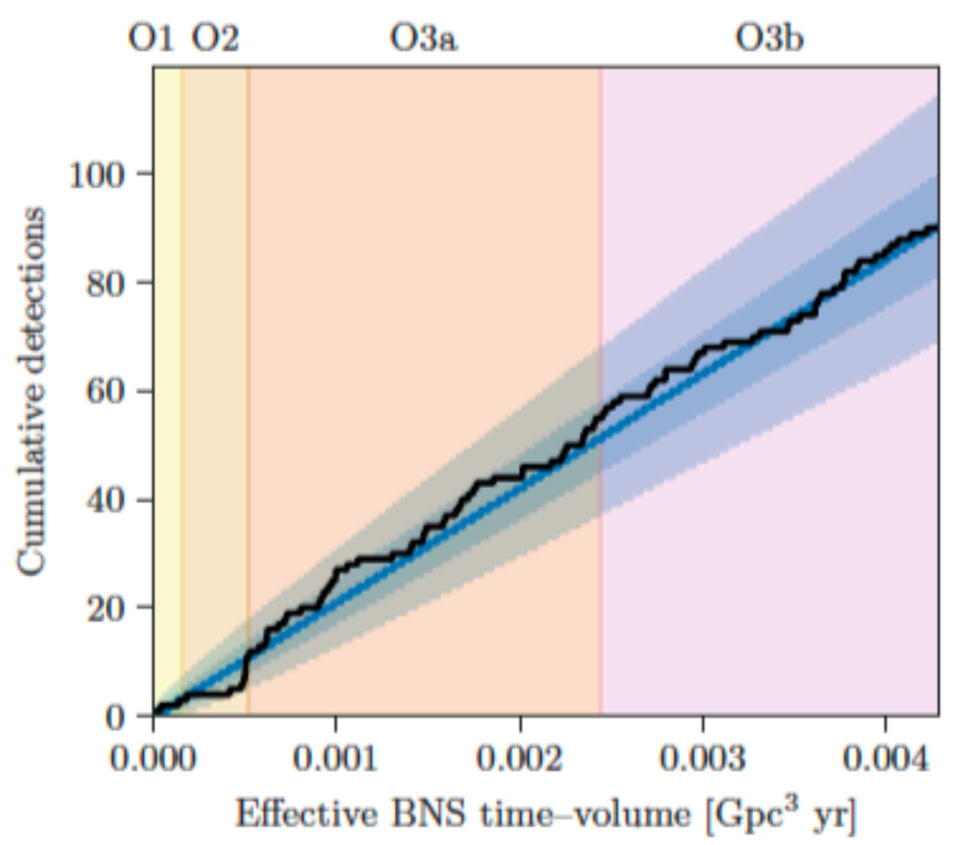
- Three observing runs in the past (O1 - O3)
  - Detected CBC events

    O1 : 3 → O2 : 11 → O3 : 90

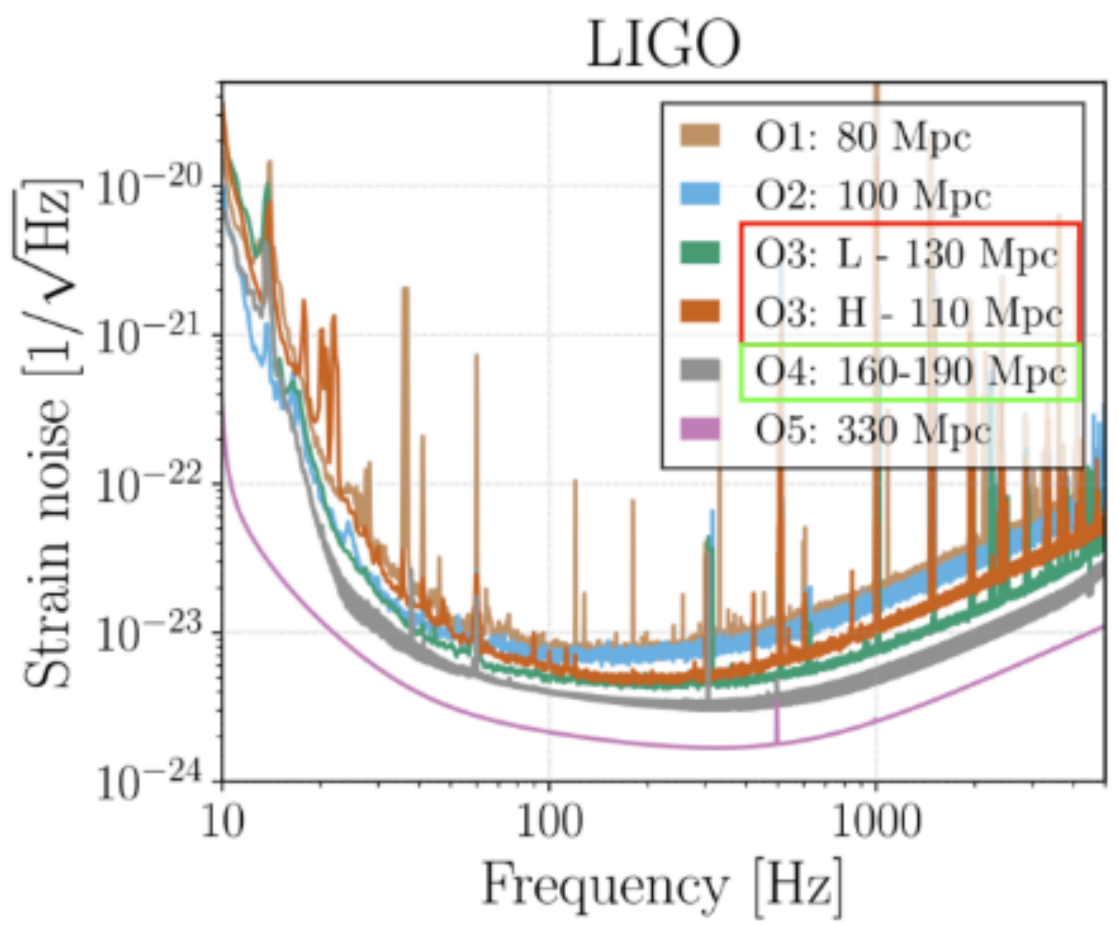
    +8 +79
  - Sensitivity improvement (BNS range)

    80 Mpc → 130 Mpc

    (cf. GW170817 : ~ 40 Mpc)



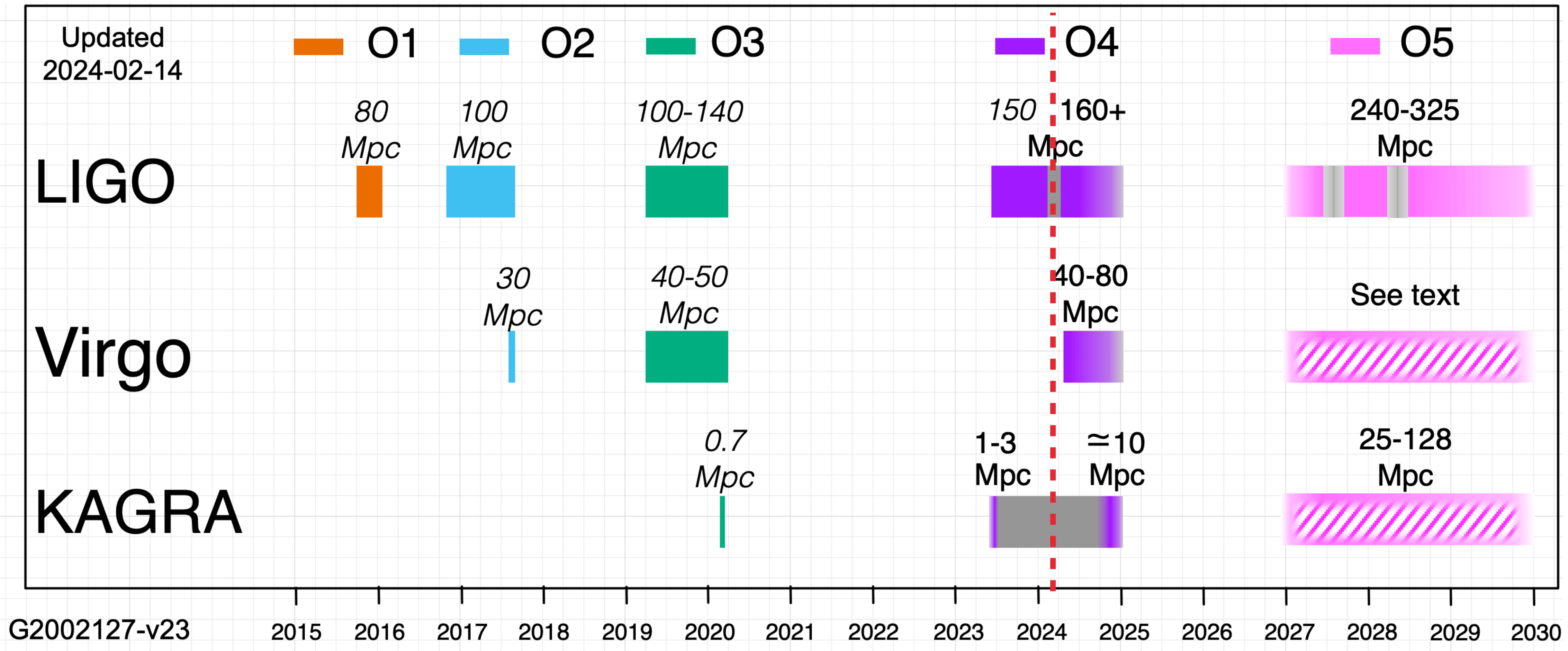
R. Abbott *et al.*



- Fourth observing run (O4)
  - May 2023 - Jan. 2024 : O4a

    Only two LIGOs operating
  - April 2024 - Jan. 2025 : O4b

    Virgo and KAGRA (?) are joining

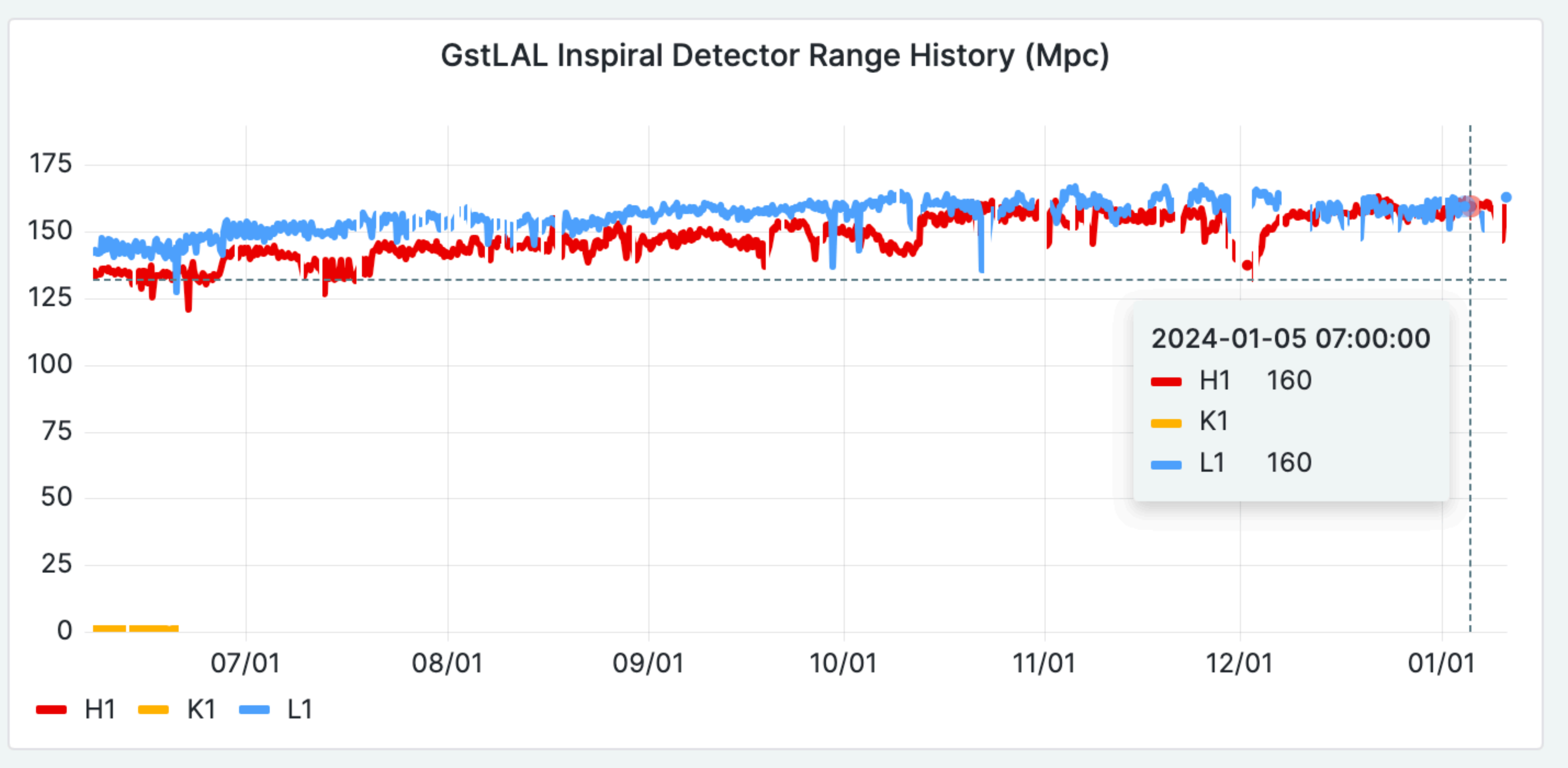


Here we are

https://www.ligo.org/scientists/GWEMalerts.php

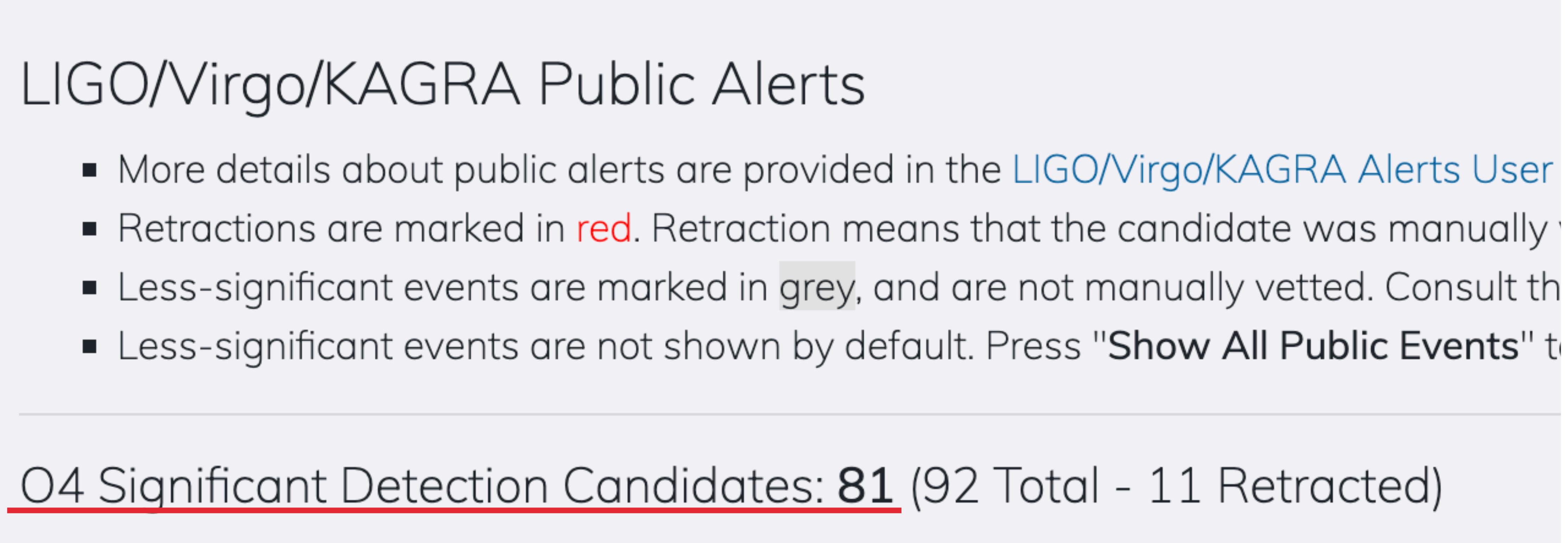
Fourth observing run

- Sensitivity evolution during O4a



online.ligo.org

- Significant detections in O4a



LIGO/Virgo/KAGRA Public Alerts

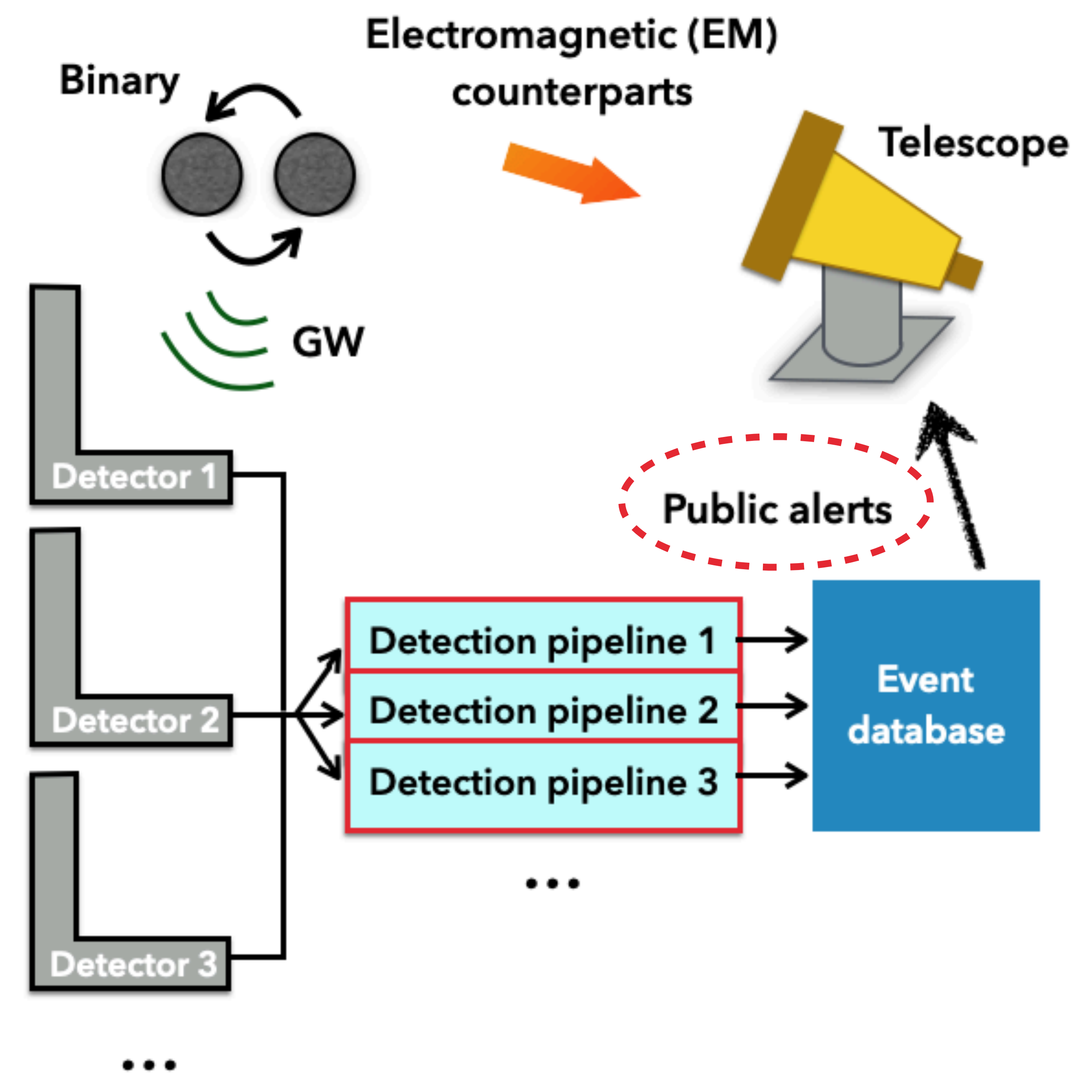
- More details about public alerts are provided in the LIGO/Virgo/KAGRA Alerts User
- Retractions are marked in red. Retraction means that the candidate was manually
- Less-significant events are marked in grey, and are not manually vetted. Consult th
- Less-significant events are not shown by default. Press "**Show All Public Events**" t

O4 Significant Detection Candidates: **81** (92 Total - 11 Retracted)

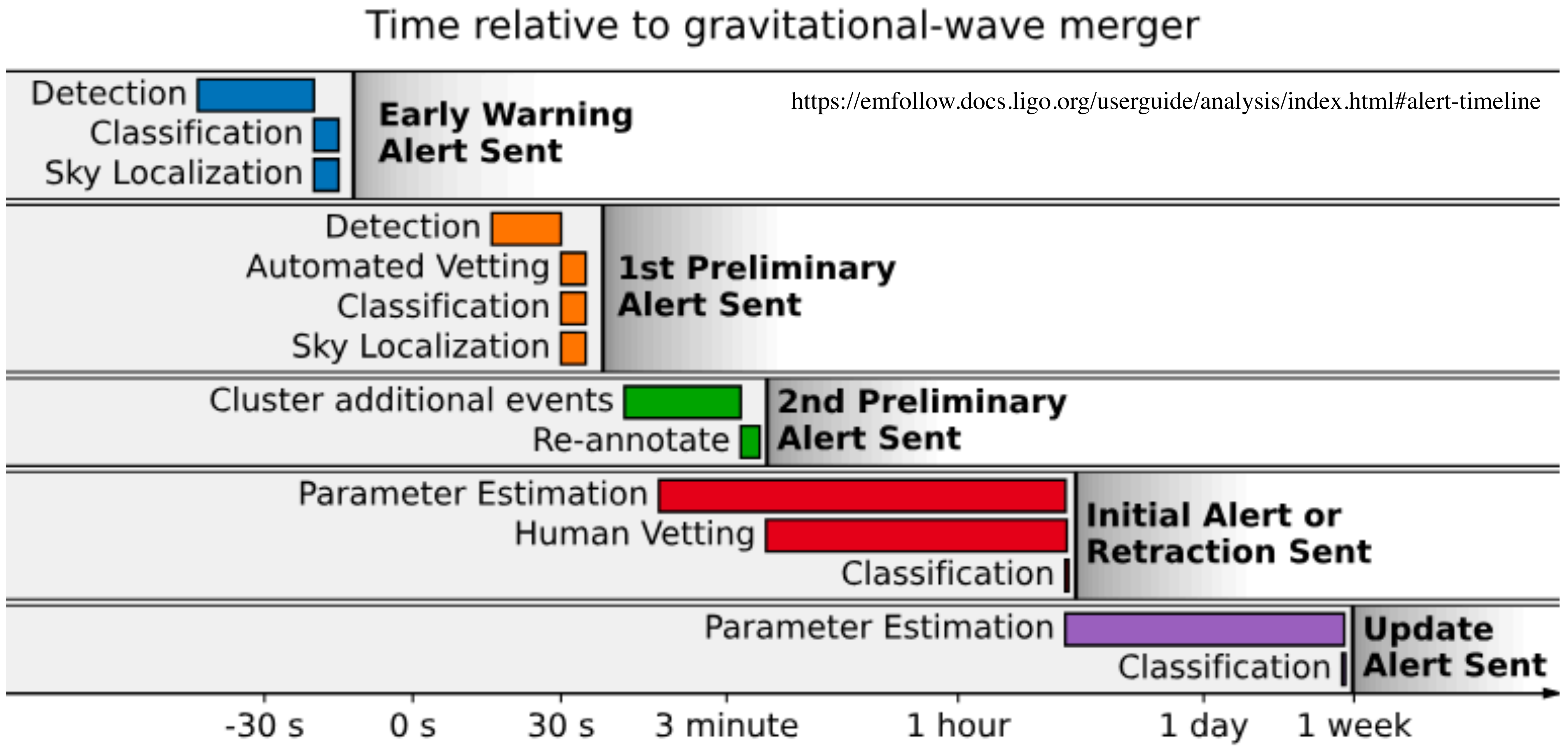
https://gracedb.ligo.org/superevents/public/O4/

- Significant detection
  = False alarm rate < 1 / month (CBC)
- Already as many as the previous runs combined
- No burst event was detected.
- Some retractions due to data quality issues.

Public alerts



- Public alerts
  - Notices : machine-readable, Circular : human-readable
- Timeline

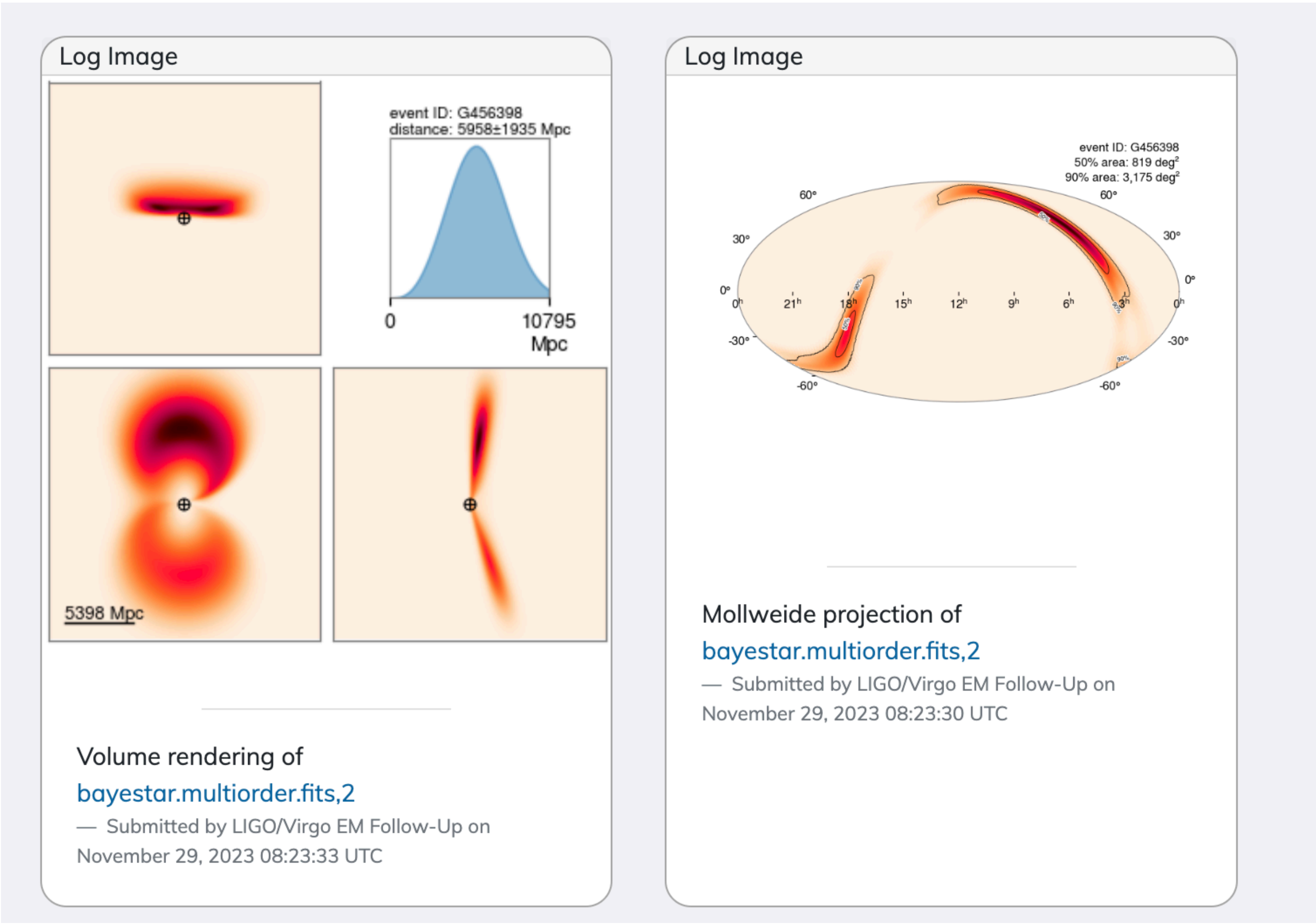


Automated Human-intervened

Alert contents

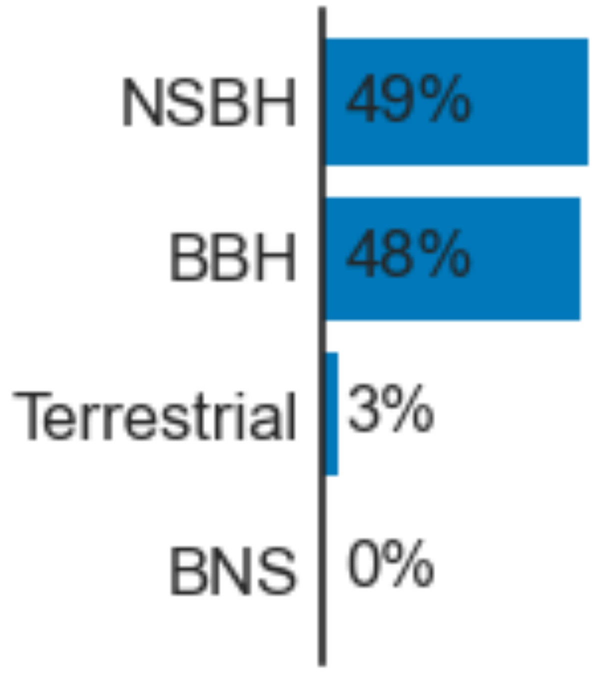
- Localization

3D volume estimate   Skymap



https://gracedb.ligo.org/superevents/S231129ac/view/

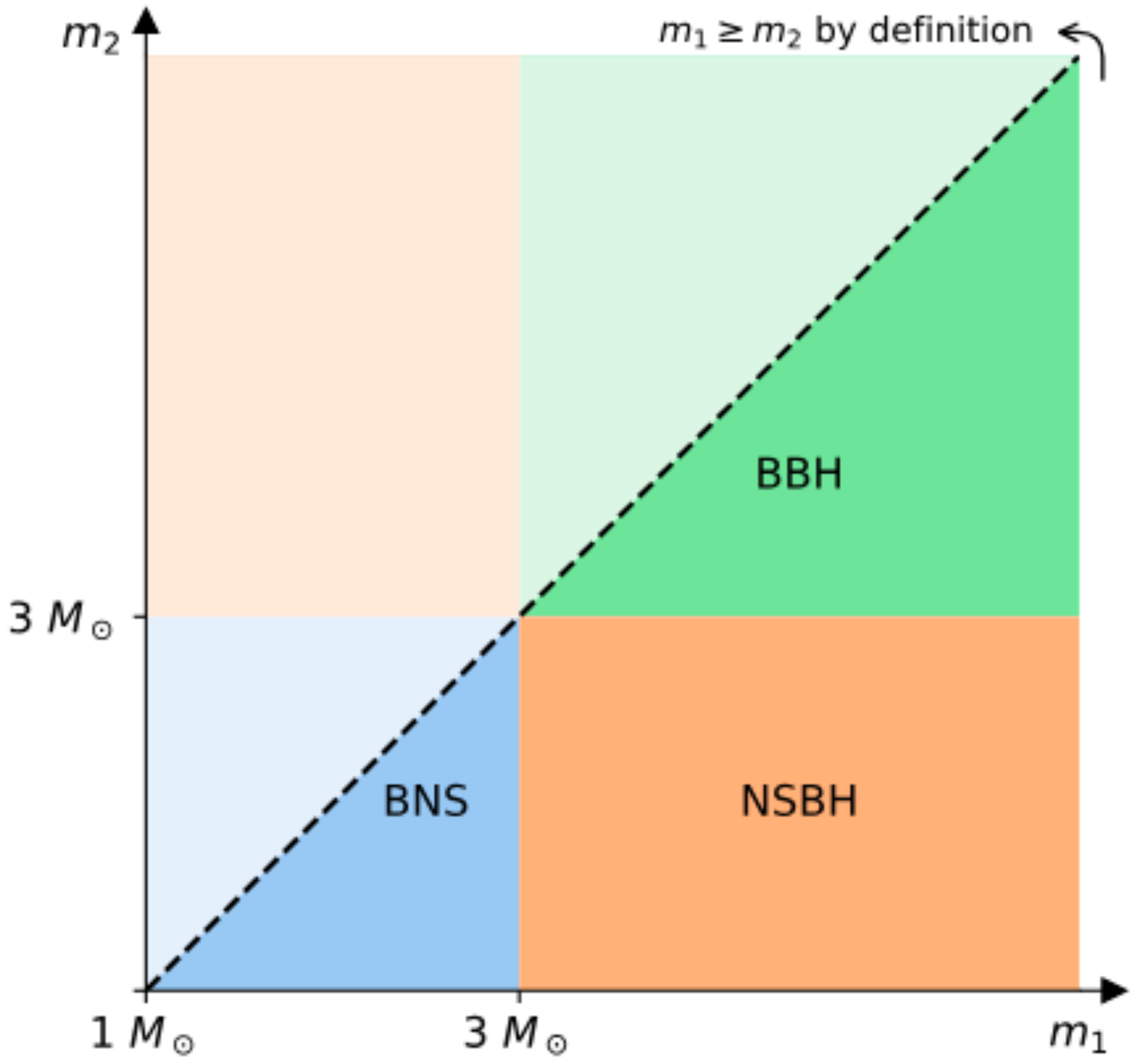
- Source classification



The probability accounts for ;

- statistical significance
- event rate of each category
- uncertainty in the mass measurement

Mass boundaries



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

Sky localization

- Only two LIGOs operating

  Localization : ~ O(1000) deg²

  9 single-detector events

- S230627c

  Found by the two LIGO detectors.

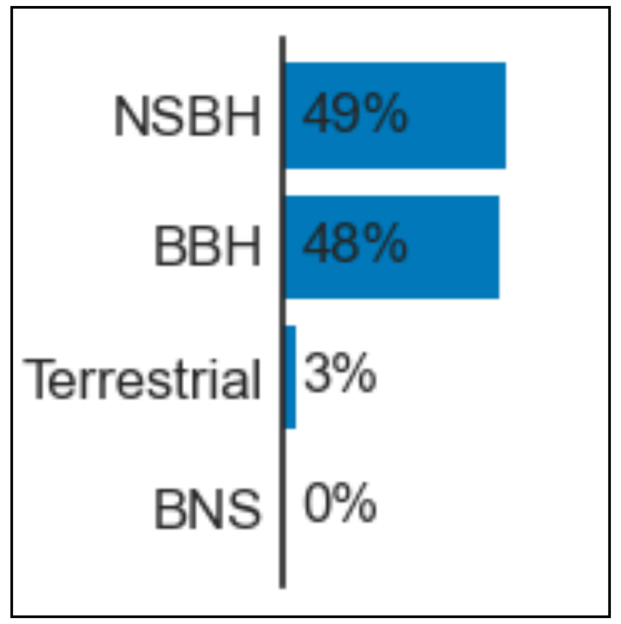
  Luminosity distance : 291 Mpc

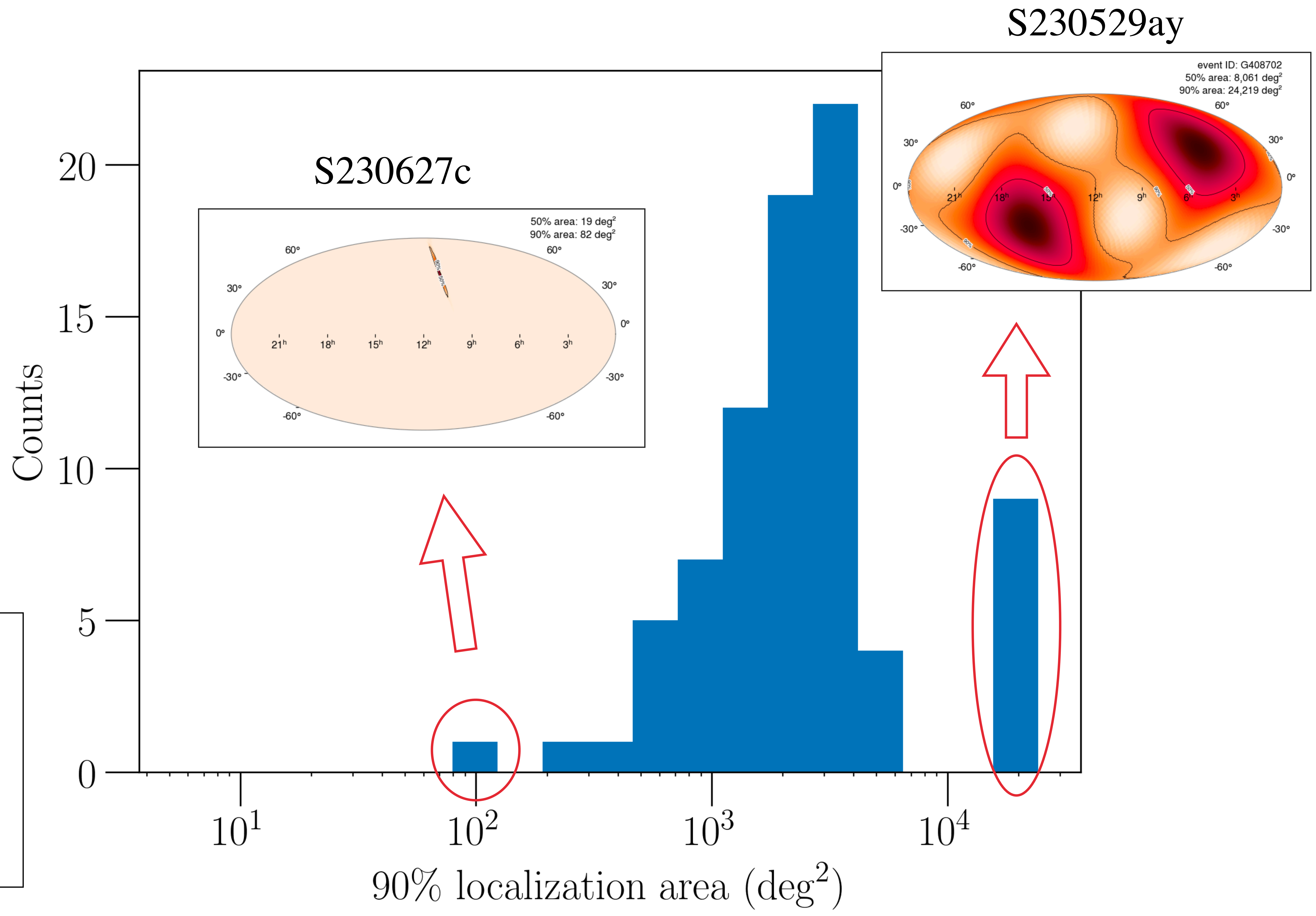
  90% region : 82 deg²

  (cf. GW170817 : 28 deg²)

  NSBH 49%, BBH 48%

  No EM counterparts





S230529ay : potential NSBH?

- S230627c

Found by the one LIGO detector.

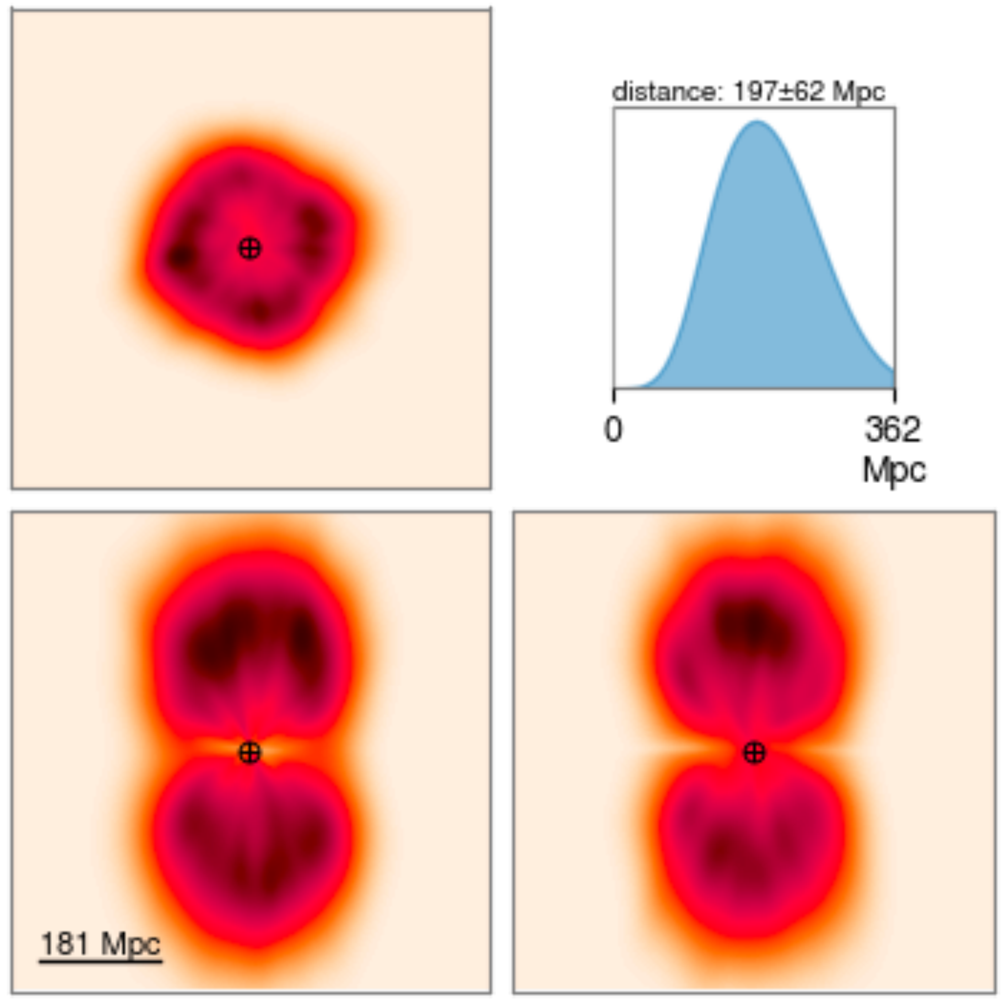
Luminosity distance : 197 Mpc

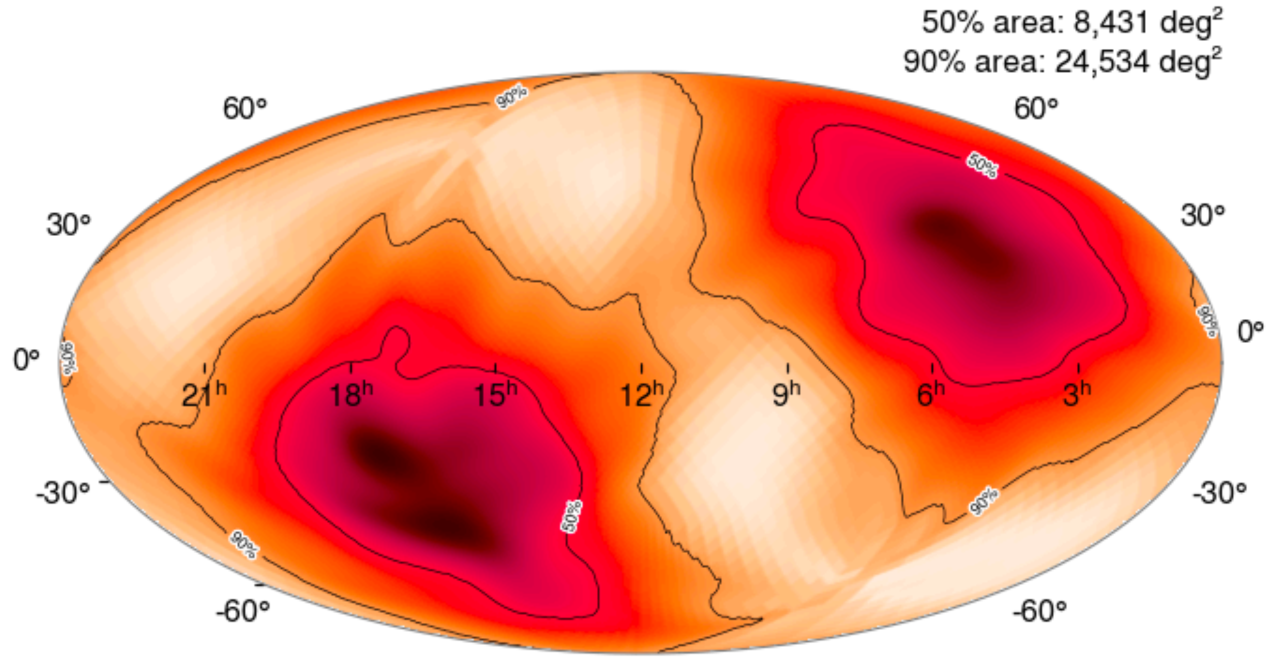
<u>NSBH 62%</u>, BBH 31%

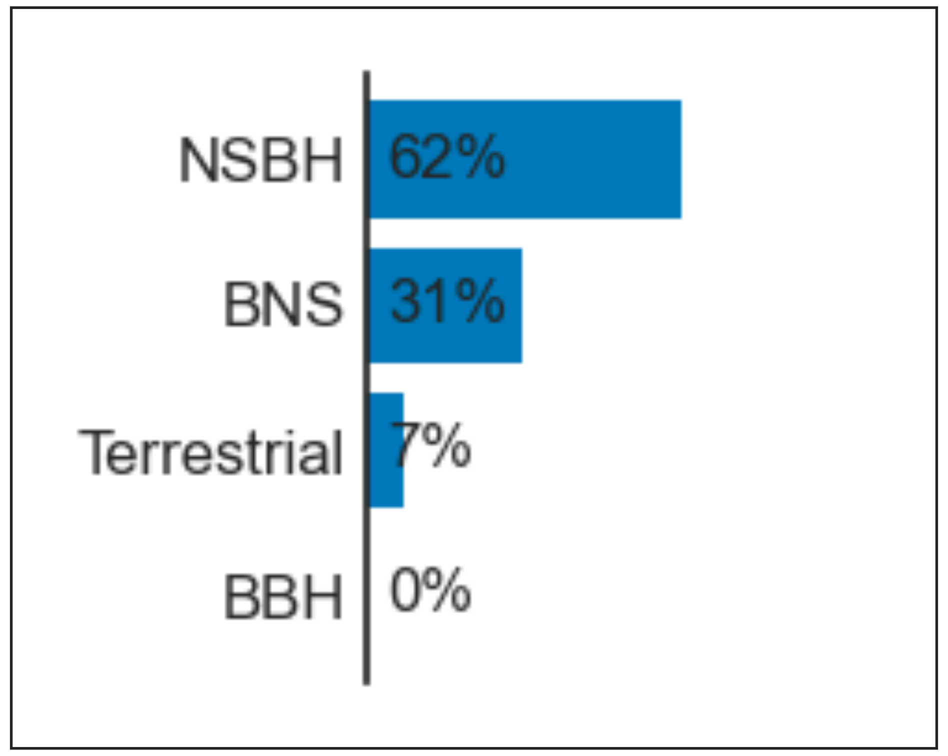
HasMassGap : $3M_\odot < m < 5M_\odot$

HasNS : at least one component is a NS

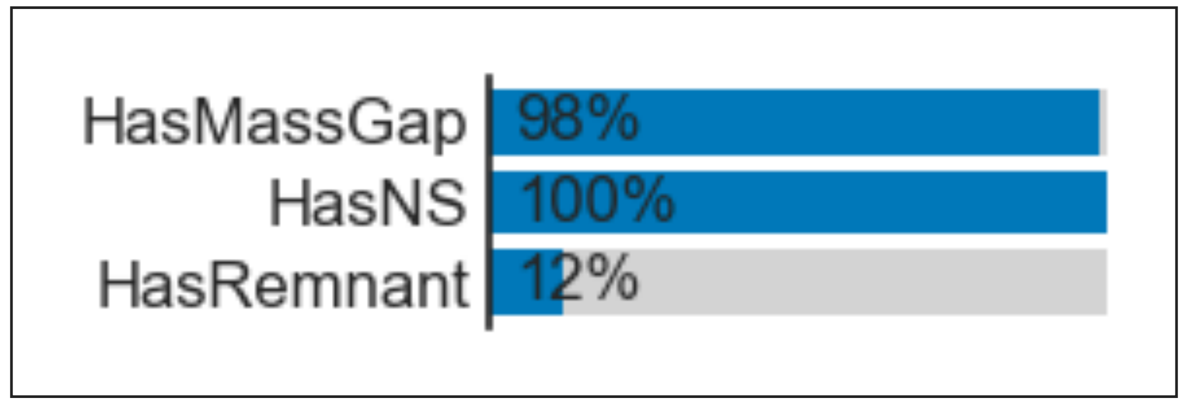
But… no EM counterparts reported.







Other properties



https://gracedb.ligo.org/superevents/S230529ay/view/

Virgo's participation in O4b

LIGO, VIRGO AND KAGRA OBSERVING RUN PLANS

(15 February 2024 update; next update 15 March 2024 or sooner)

The recent commissioning activities have allowed the Virgo detector to routinely achieve a BNS range greater than 45 Mpc. The plan for the forthcoming weeks aims at mitigating known noise sources to further enhance sensitivity, and at addressing excess broadband noise in the most sensitive part of the frequency range (80-200 Hz) to reduce, at least in part, the residual gap with design sensitivity. A growing focus will also be given to improving stability to optimize detector operation for science in view of the start of ER16 and of O4b. At the moment, Virgo is reconsidering its plans for O5 and both the date on which we will be able to enter O5 and the target sensitivity are currently unclear. We expect to be able to define our plans for O5 around mid-2024.

ER16: The engineering run (ER16) will start on 20 March 2024 at 15:00 UTC and last for 2 weeks. Most of these 2 weeks will be focused on gathering multiple-interferometer observation time, so that analysis pipelines can confirm their workflows and determine background rates. However, there will also be time for detector characterization, commissioning, and calibration work.

O4b start: The LIGO Hanford (LHO), LIGO Livingston (LLO), and Virgo detectors plan to commence observing run O4b at 15:00 UTC on 3 April 2024.

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

KAGRA's delay

Regarding the damage situation of KAGRA due to the Noto Peninsula Earthquake on January 1, 2024

Topics 2024.02.05

The large-scale cryogenic gravitational wave telescope KAGRA will participate in the fourth observation operation (O4) of LIGO-Virgo-KAGRA in May 2023, and after one month of observation operation as planned, the observation operation will be completed and the sensitivity will be increased. Although improvement work was being carried out, part of the suspension system that hangs the mirror was damaged by the Noto Peninsula earthquake that occurred on January 1, 2024.

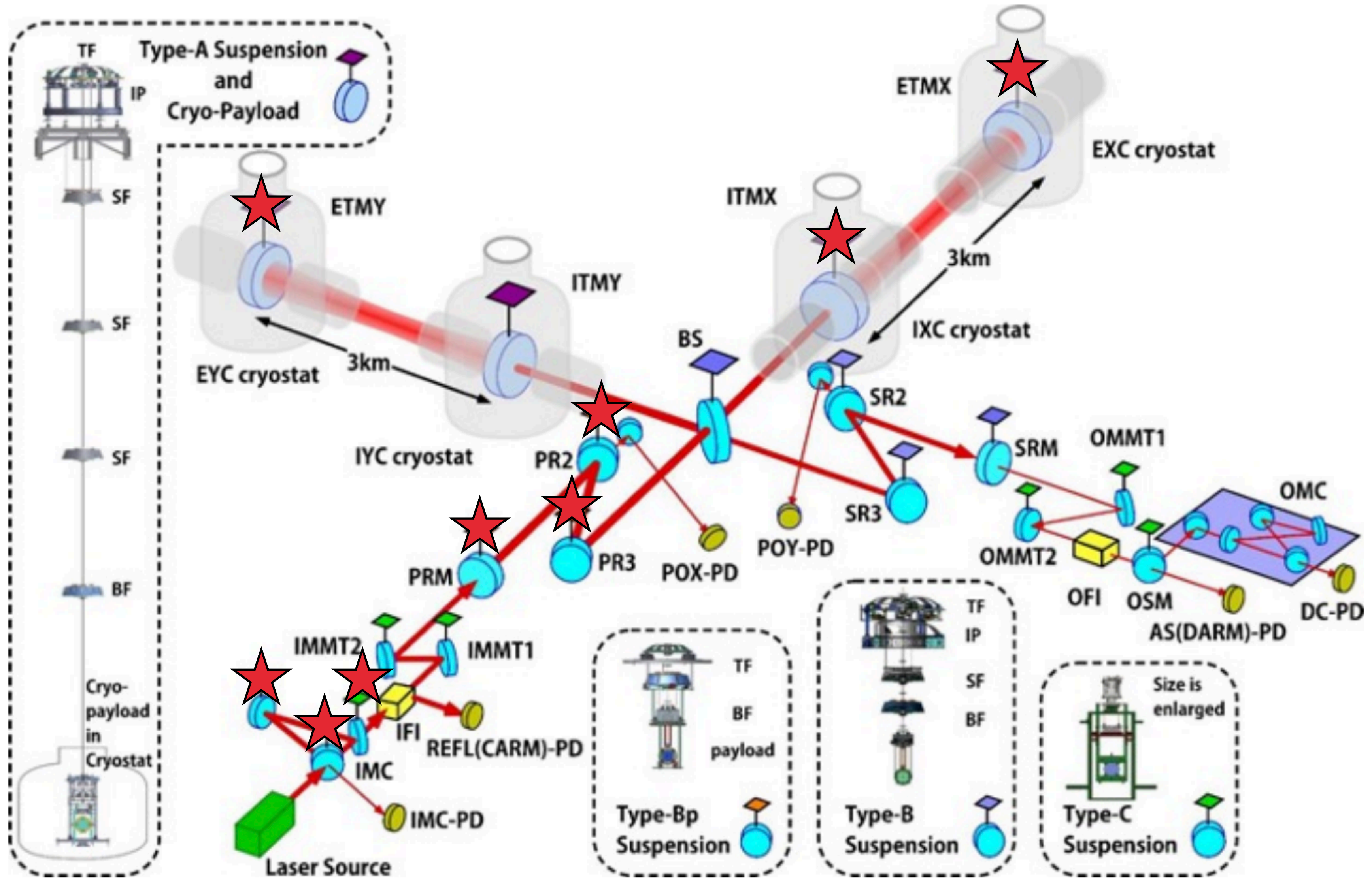
The Institute for Cosmic Ray Research, the University of Tokyo, further investigated the damage situation at KAGRA, and found that the extent of the damage was further expanded.

Specifically, KAGRA has four main types of anti-vibration suspension systems for hanging 20 mirrors, but at least nine of them have defects that require manual adjustment or some parts. was confirmed to have fallen off.

As a result of the above, it is certain that LIGO-Virgo-KAGRA's participation in the second half of the fourth observation operation (O4b) scheduled for March of this year will be delayed. It is not yet clear how long it will take to participate in the observation operation, but we hope to participate by January 2025, when O4b ends.

https://www.icrr.u-tokyo.ac.jp/news/14710/

★ : Suspension systems to be repaired



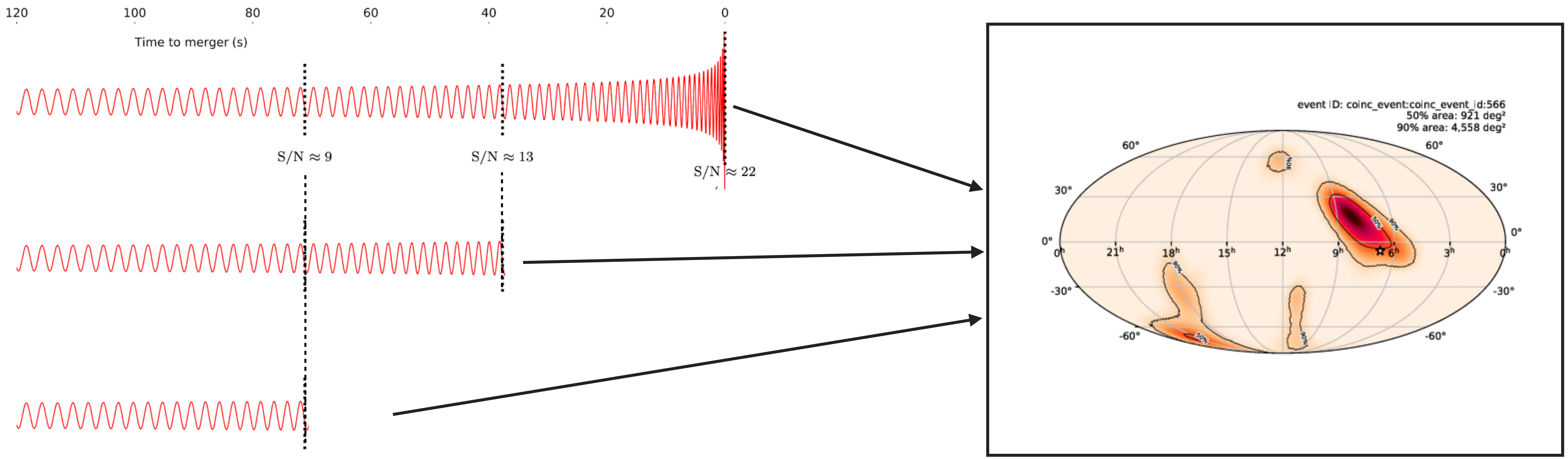
https://www.icrr.u-tokyo.ac.jp/prwps/wp-content/uploads/20240205_ICRR_press_2.pdf

Toward multi-messenger detections

- Early warning (= “negative” latency)

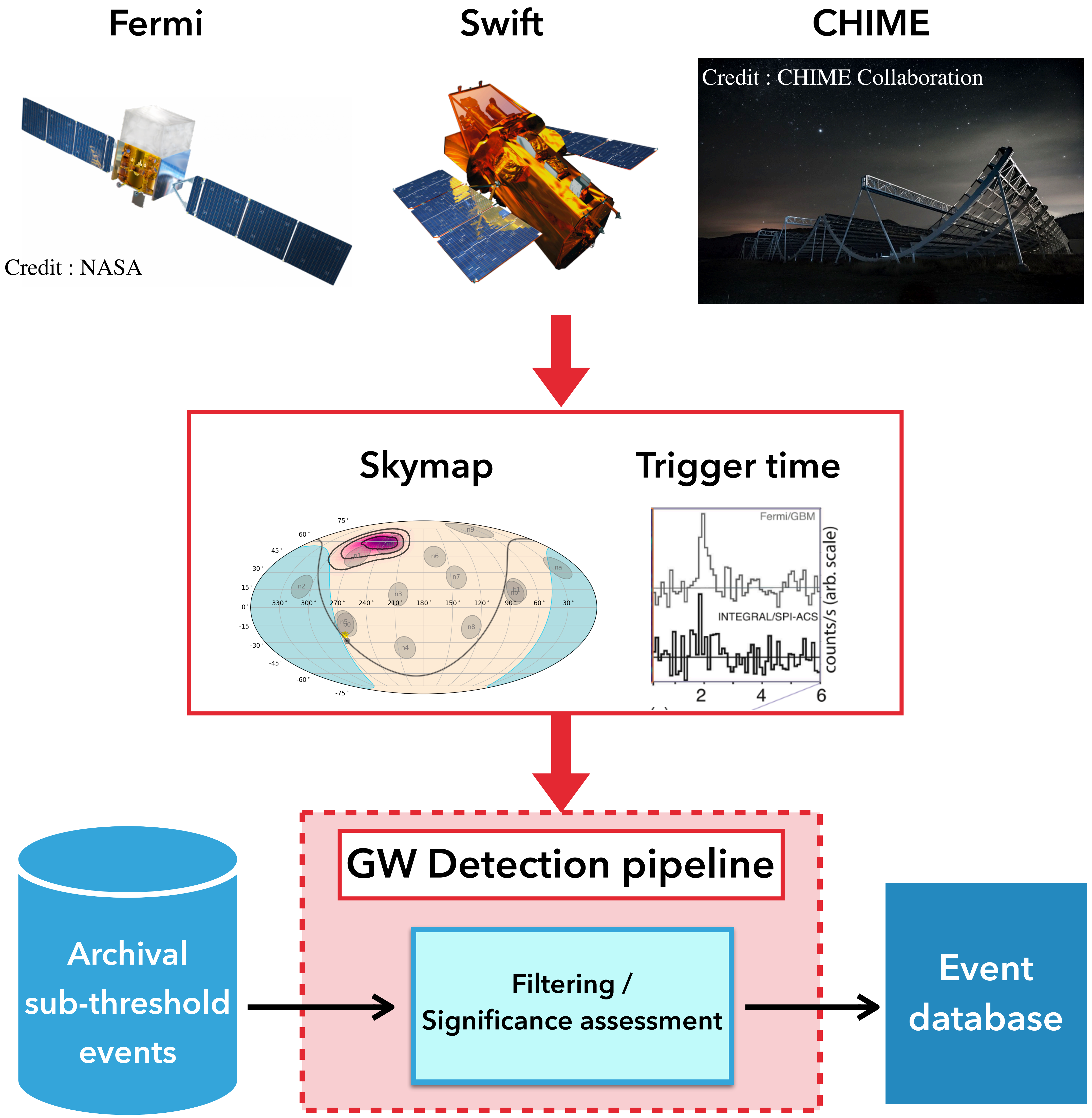
Send a detection alert *before* the merger

latency reduction ⟷ better localization



Toward multi-messenger detections

- EM-triggered search as a GW follow-up
  - Triggered by GRB, FRB detections from e.g. Fermi, Swift and CHIME telescopes.
  - Optimize GW detection pipelines with a EM skymap and trigger time.
  - Dig up weak GW signals we might have missed (potentially in low latency).



Summary

- The fourth observing run by the LVK collaboration has started.
  - 81 GW signals from compact binaries (mostly BBHs) have been detected so far.
  - No multi-messenger or burst detection has been reported.
- The run will be resumed after April 2024 with the Virgo detector.
  - Sky localization will be drastically improved.
  - The operational period will be better covered.
- Several methods have been developed to enhance the multi-messenger discovery.
  - Early warning, coincident searches for EM signals and high energy neutrinos

Stay tuned!!