Science result of LIGO in worldwide observation 4

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2026.01.05

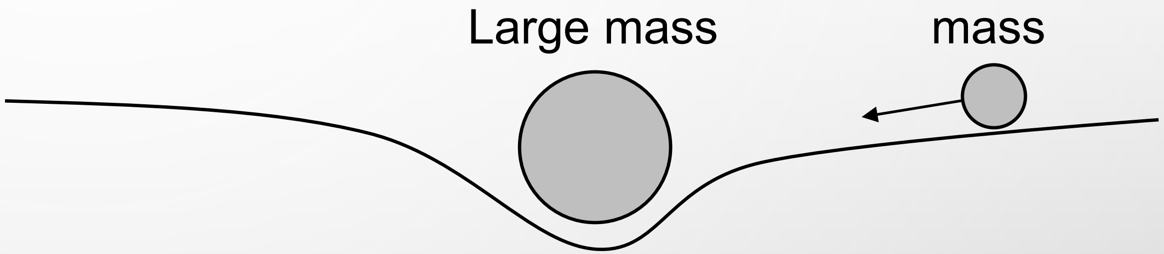
2025 CHiP annual meeting

Outline

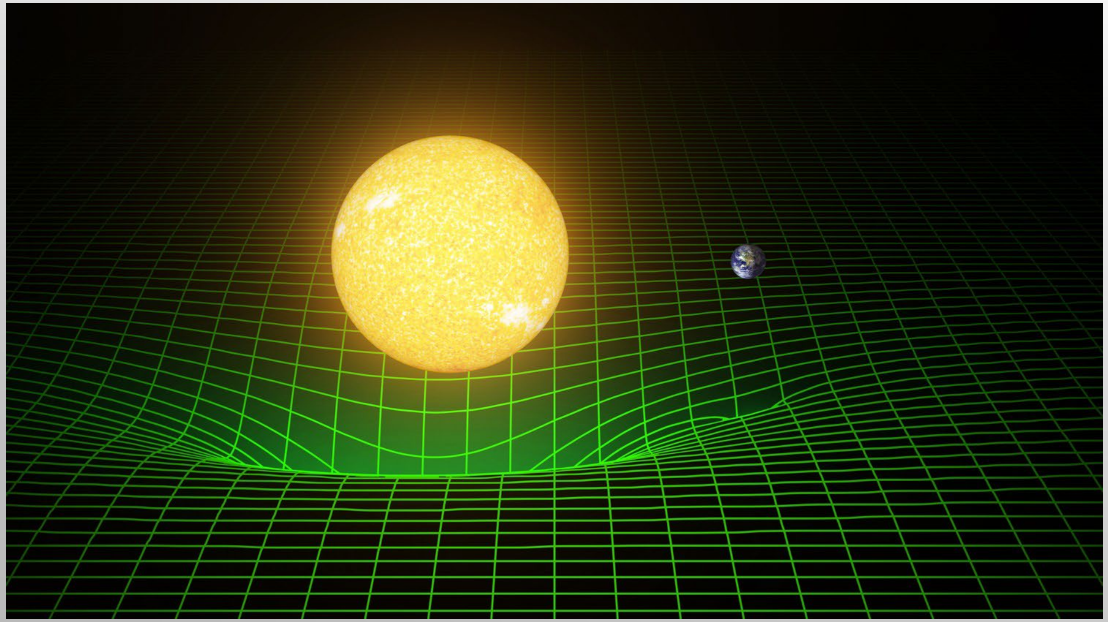
- Gravitational wave science
- Observation principle of LIGO
- Results of LIGO’s latest observation run
- Activities in Taiwan
- Summary

Mass and gravity

According to the general relativity, **mass distorts spacetime.**



Spacetime distortion -> Gravitational potential



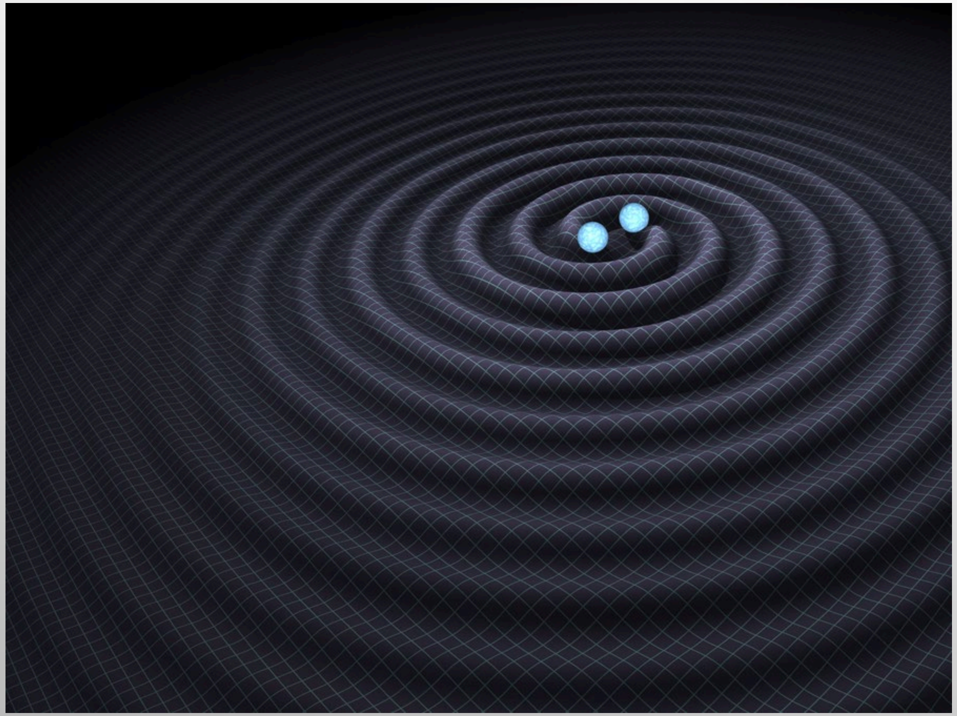
T. Pyle/Caltech/MIT/LIGO Lab

Einstein's equation

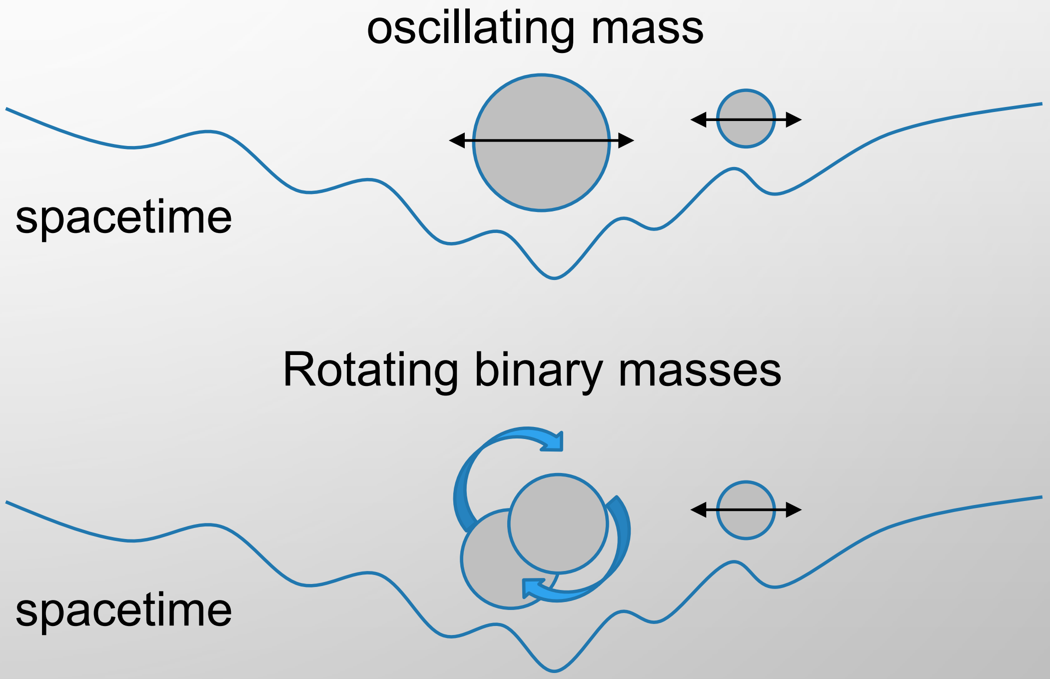
$$\underbrace{G_{\mu\nu}}_{\text{Spacetime curvature}} = \frac{8\pi G}{c^4} \underbrace{T_{\mu\nu}}_{\text{Energy and momentum}}$$

Gravitational wave

When a mass oscillates, distortion of spacetime makes waves.



R. Hurt (Caltech-IPAC)



Shape of spacetime distortion

When a mass oscillates, distortion of spacetime makes waves.

Einstein's equation

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Lorentz gauge →

Wave equation

$$\frac{1}{2}\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2\right) h_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Spacetime perturbation

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

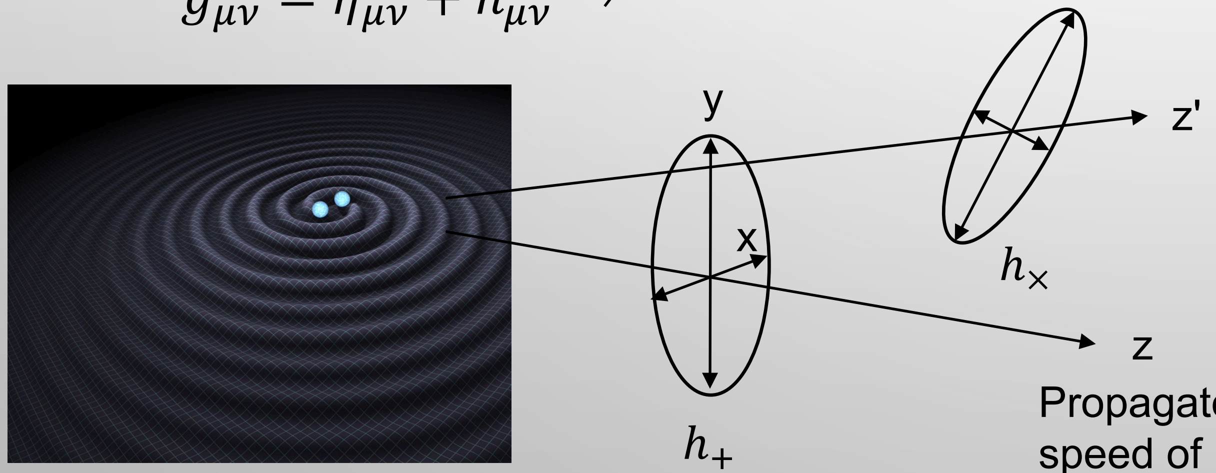
Space components
Quadrupole radiation

$$h_{ij}^{TT} = \frac{1}{r}\frac{2G}{c^4}\frac{\partial^2}{\partial t^2}\int \rho x^i x^j d^3x \cdot \left(t - \frac{r}{c}\right)$$

Transverse-traceless gauge ↓

$$h_{ij}^{TT} = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

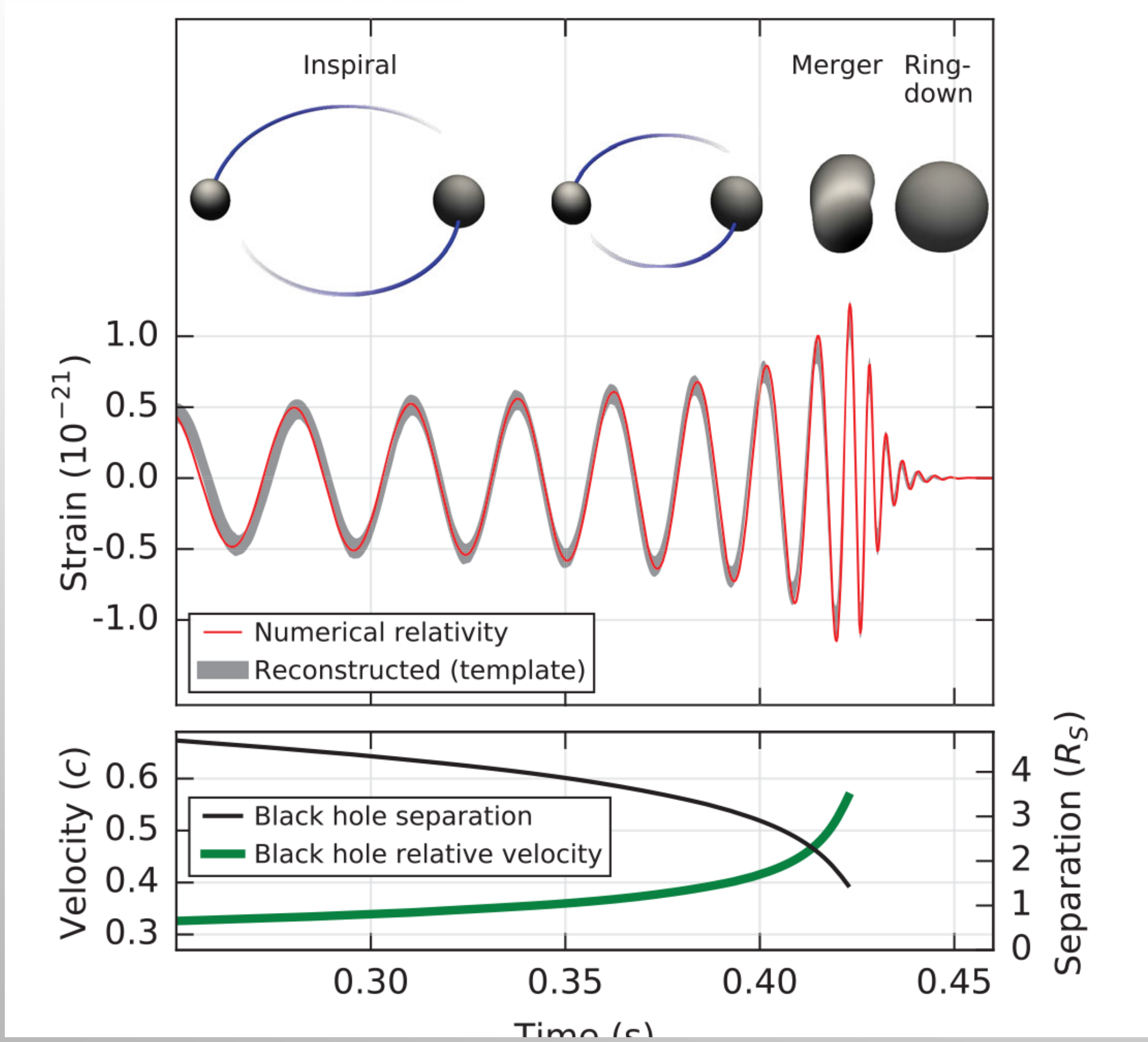
Two polarizations:
Plus-mode and cross-mode



Propagate at speed of light

R. Hurt (Caltech-IPAC)

Typical waveform of gravitational wave



(https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.061102)

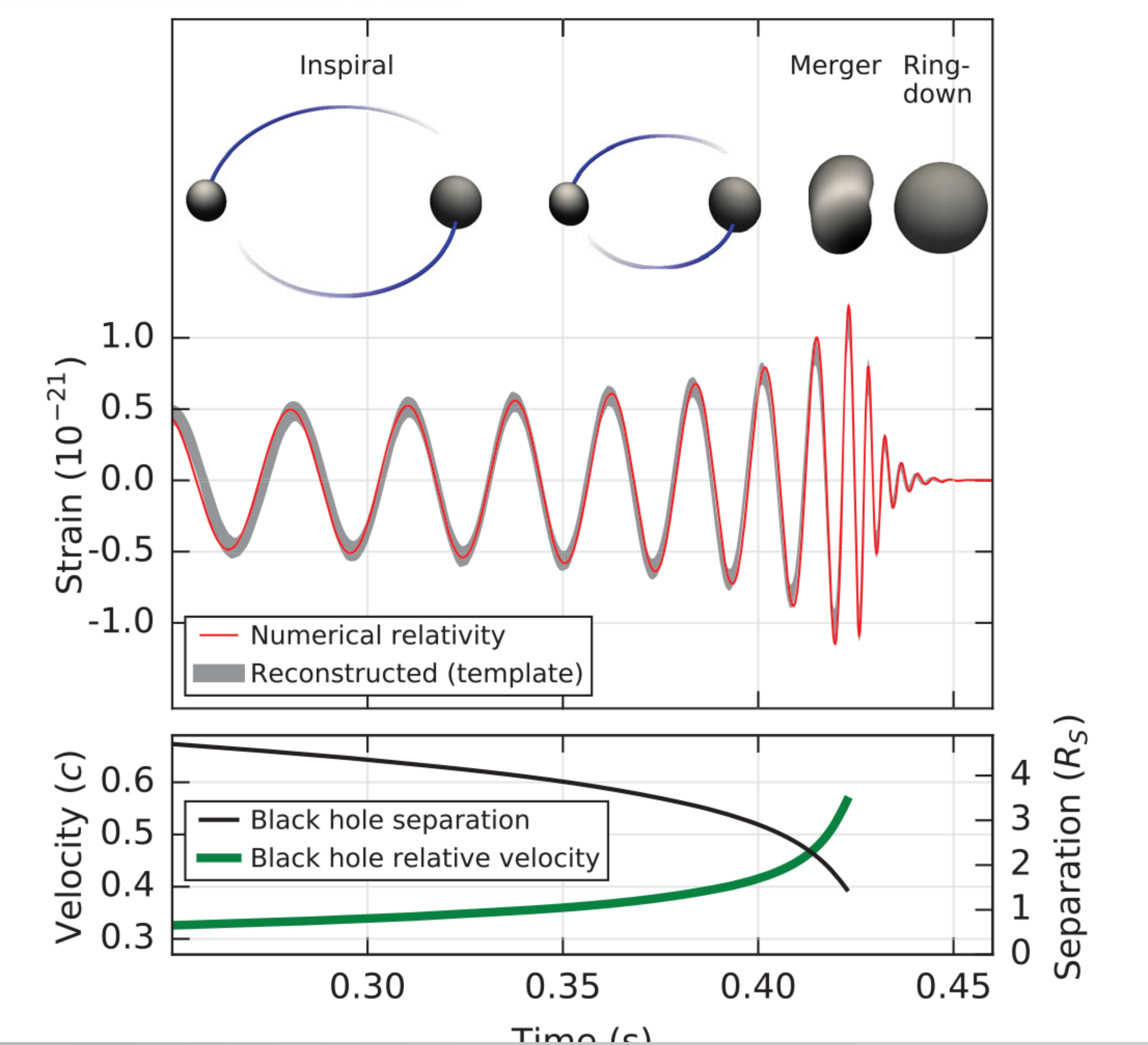
Waveform has 3 phases.

Inspiral: Rotate around each other.
- Mass of sources
- Radius of rotation
- Post-Newtonian terms

Merger: Binary objects merge.
- Minimum radius of rotation
- Size of sources

Ringdown: Oscillation decays.
- Mass of merged object
- Spin of merged object
- Deformation of sources

Typical waveform of gravitational wave



(https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.061102)

Briefly saying, each phase tells

Inspiral: **External parameters in weak field.**

- Mass, radius, distance…

Merger: Both in strong field.

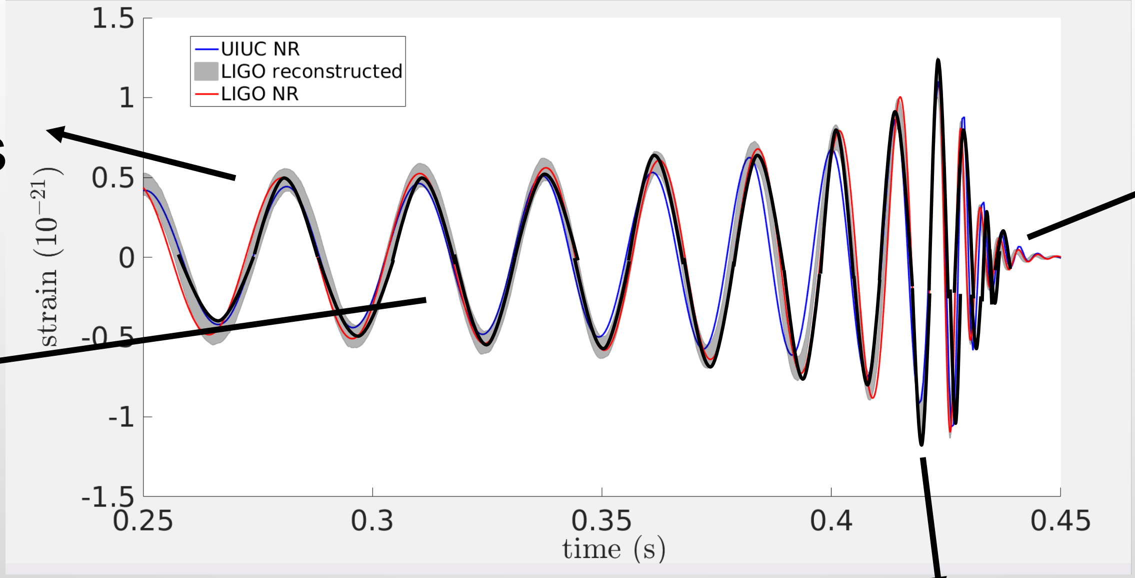
Ringdown: **Internal natures in strong field.**

- Deformation, Black hole solutions…

Particle / cosmological physics in gravitational wave

Strong gravity field can cause extremely high energy phenomena.

(Black hole)
Test of gravity theories



(Neutron star)
Exotic particles and phases
(Black hole)
Test of gravity theories

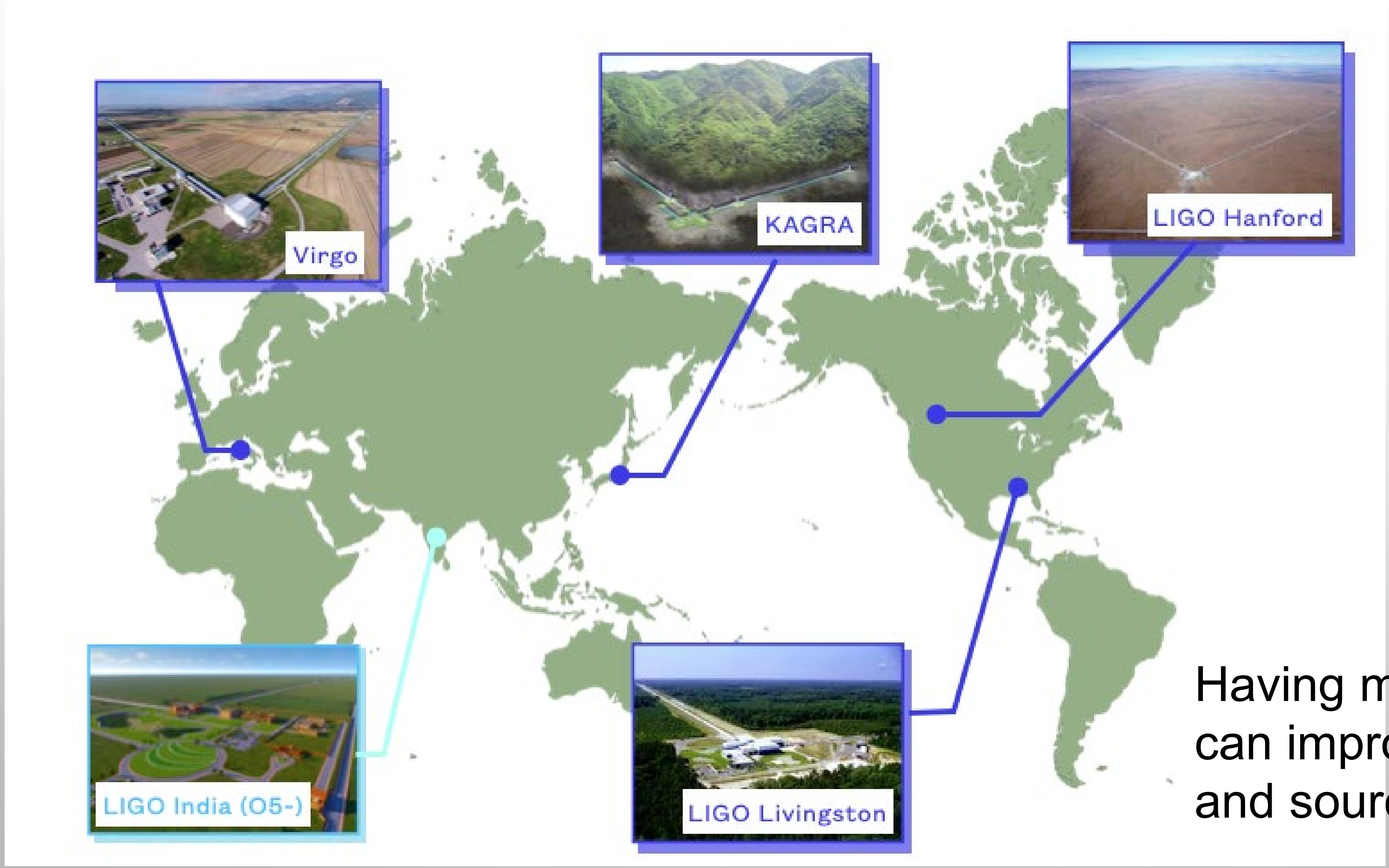
Mass, spin

Origin of massive black holes
Search of intermediate mass black holes (IMBHs)

(Neutron star)
Electromagnetic emission

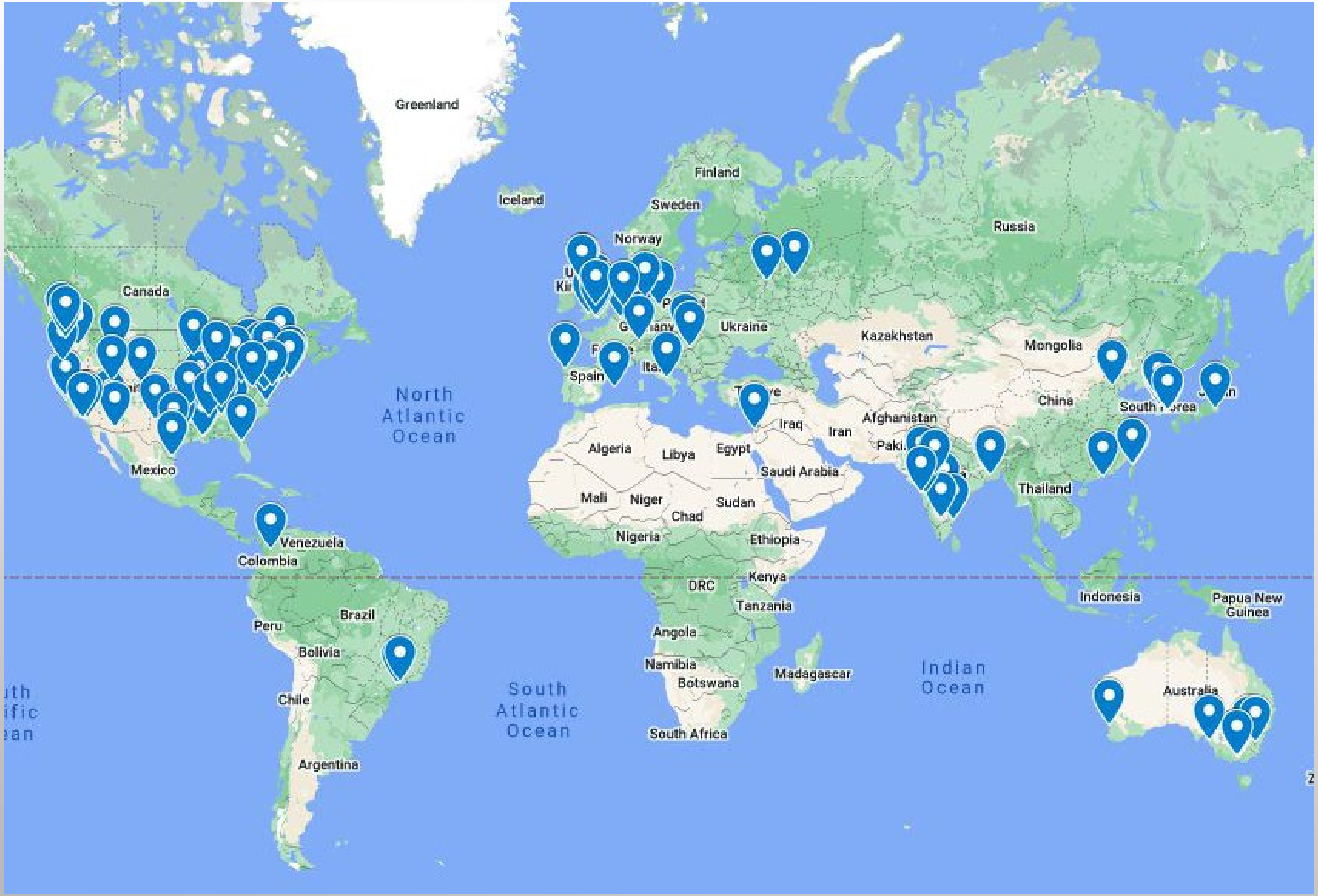
Hubble constant

Gravitational wave detectors



Having many detectors can improve sky coverage and source localization.

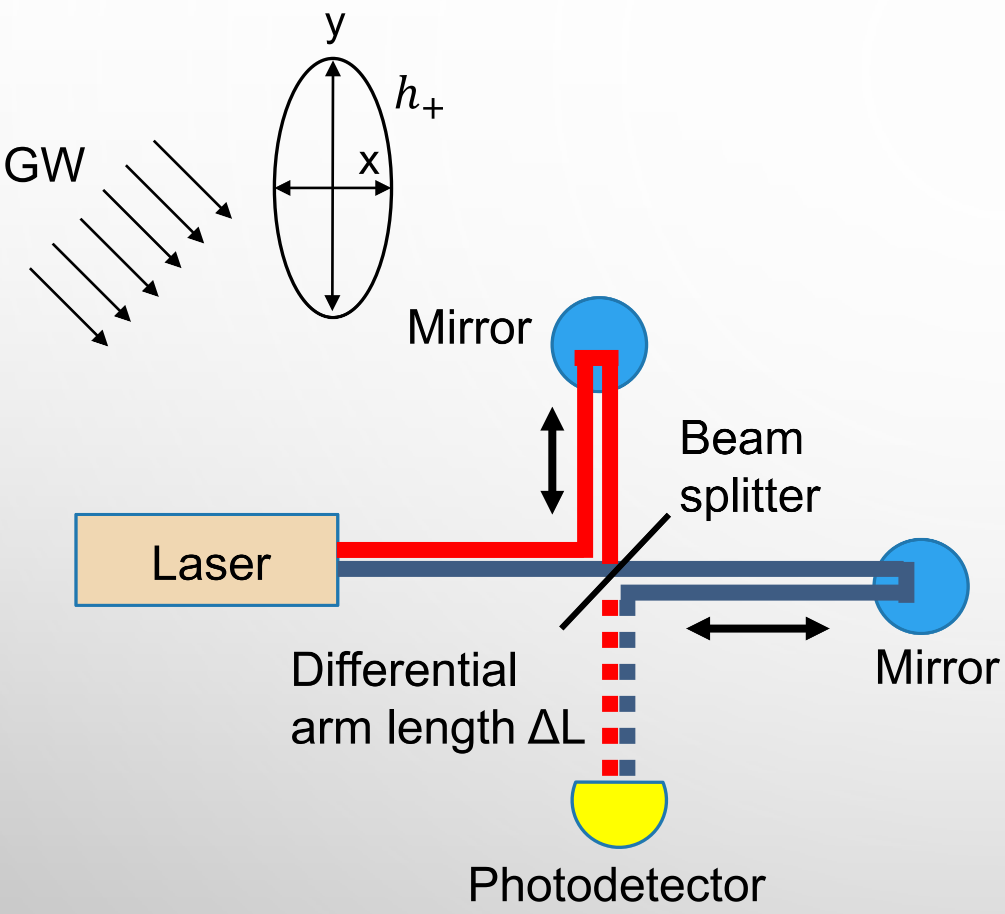
LIGO Scientific Collaboration



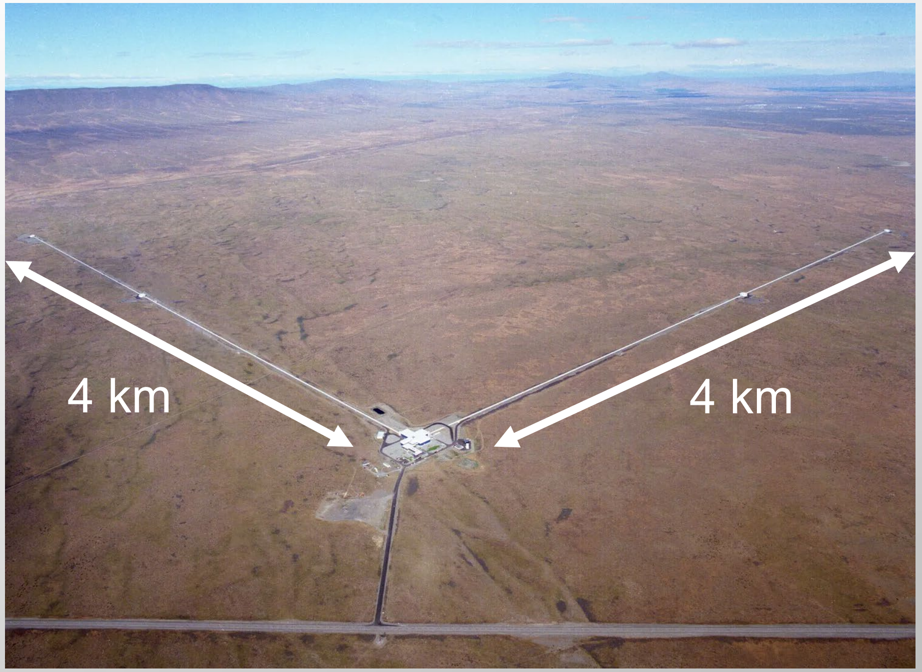
1654 collaborators,
93 groups,
145 institutes
in the world.

NCU, AS, NTHU
join from Taiwan.

Michelson interferometer



LIGO Hanford Observatory



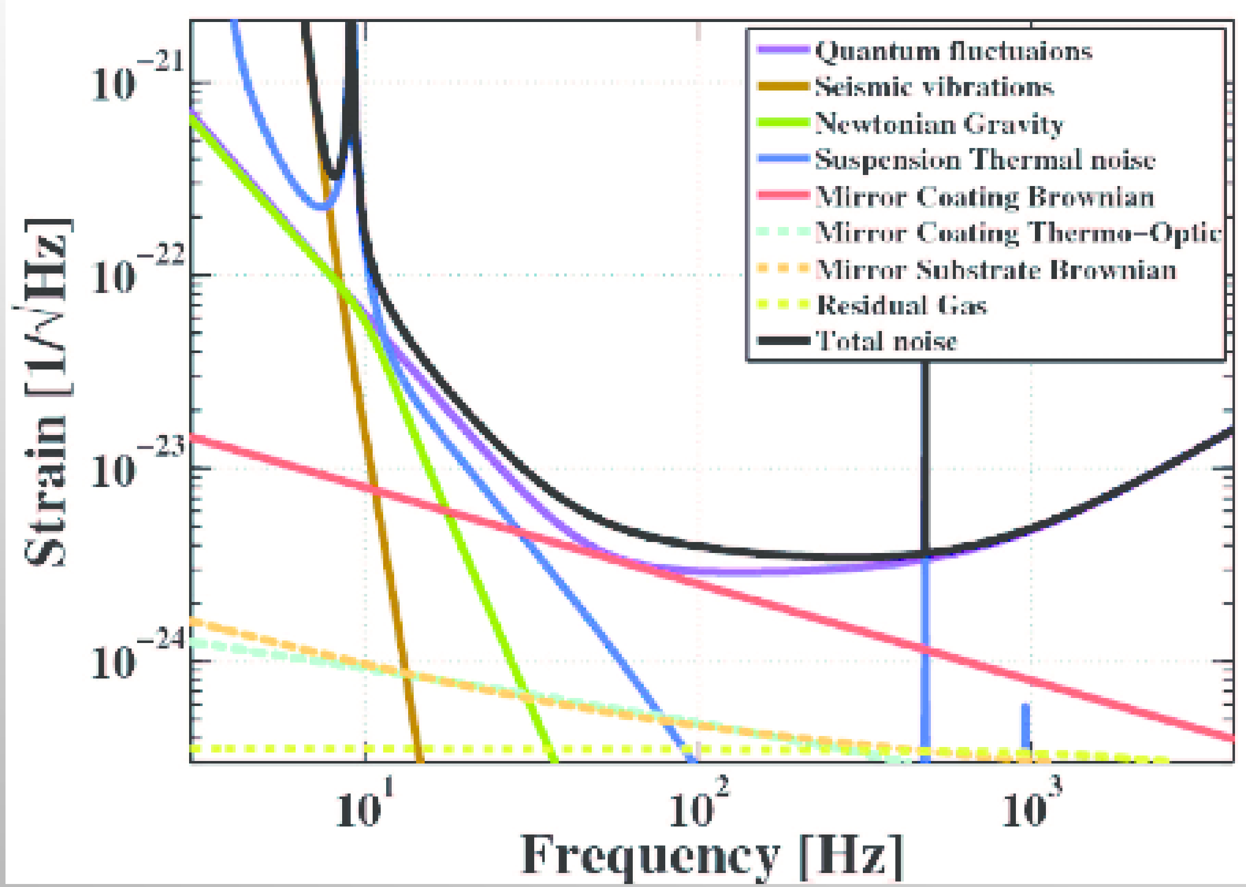
(https://www.britannica.com/topic/Laser-Interferometer-Gravitational-wave-Observatory#/media/1/1562918/205865)

Strain of arm length $\Delta L \sim hL$

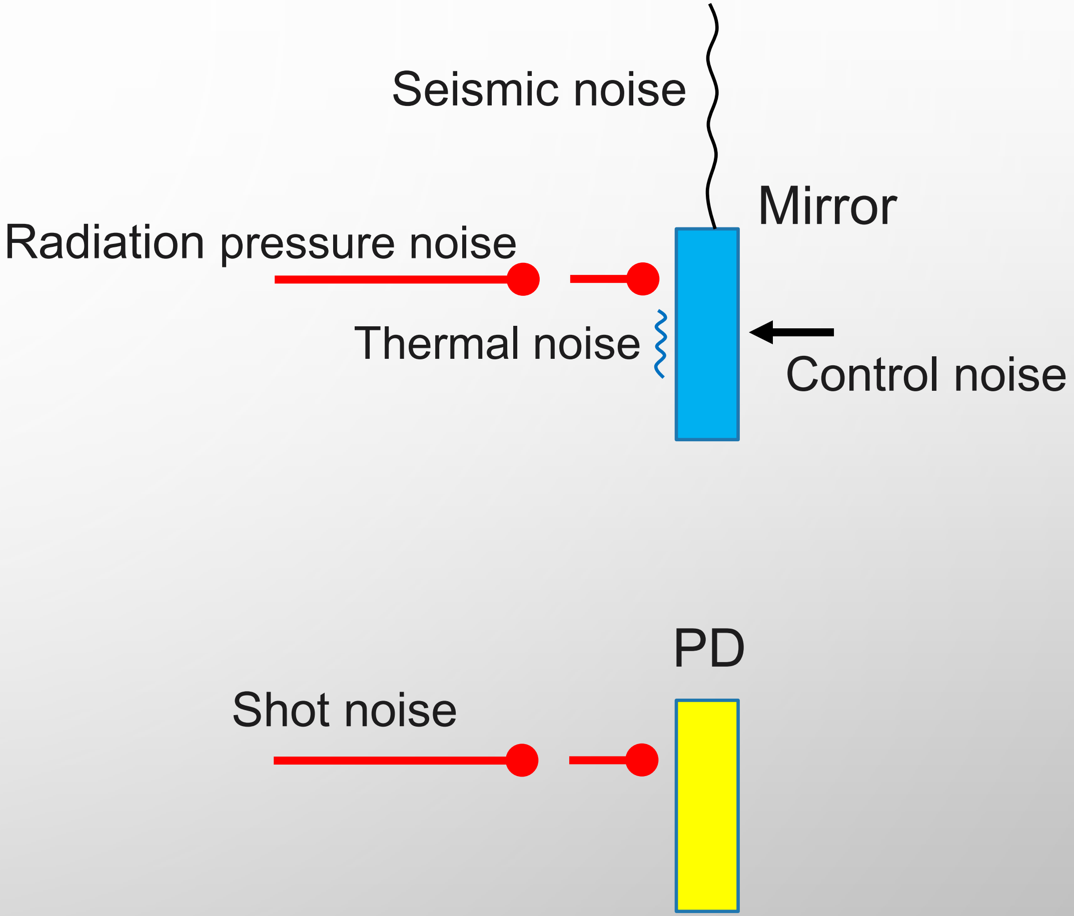
(Effective L is extended by multiple reflections)

Noise sources of detector

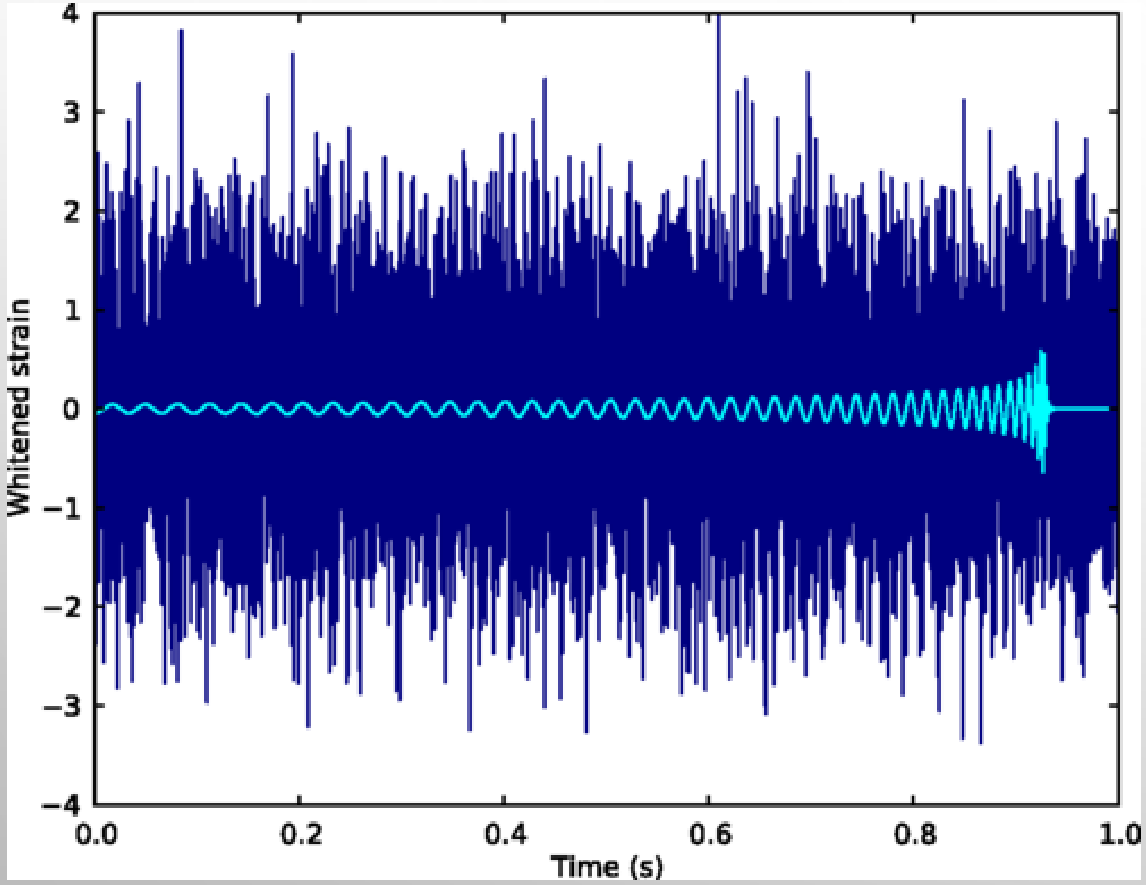
Strain sensitivity of LIGO in the third run (simplified)



(https://astrobites.org/2022/01/05/detecting-gravitational-waves-with-asteroids/)



Event detection



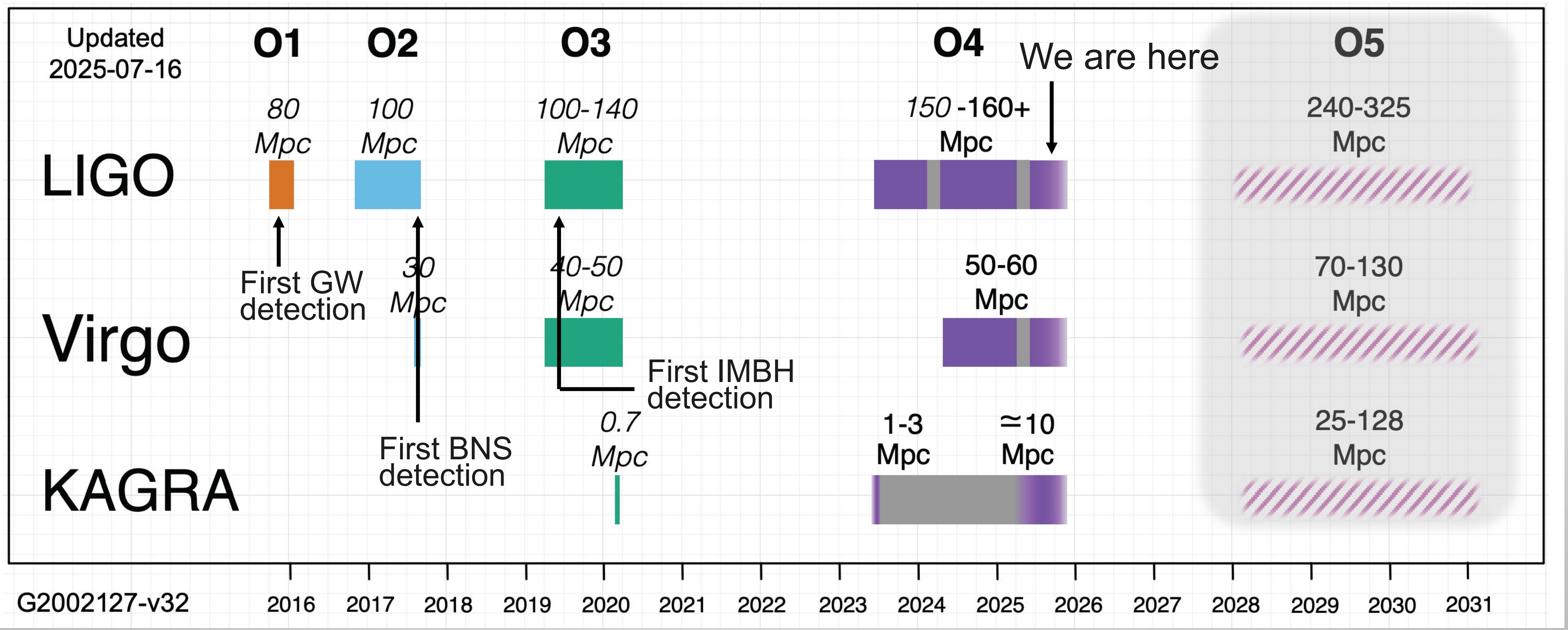
(https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.120.141103)

GW signal looks covered by noise.

Signal of compact binary merger is searched by pattern matching (matched filtering) based on theoretically simulated waveforms.

Event detection and alarm are automated.

Observation history

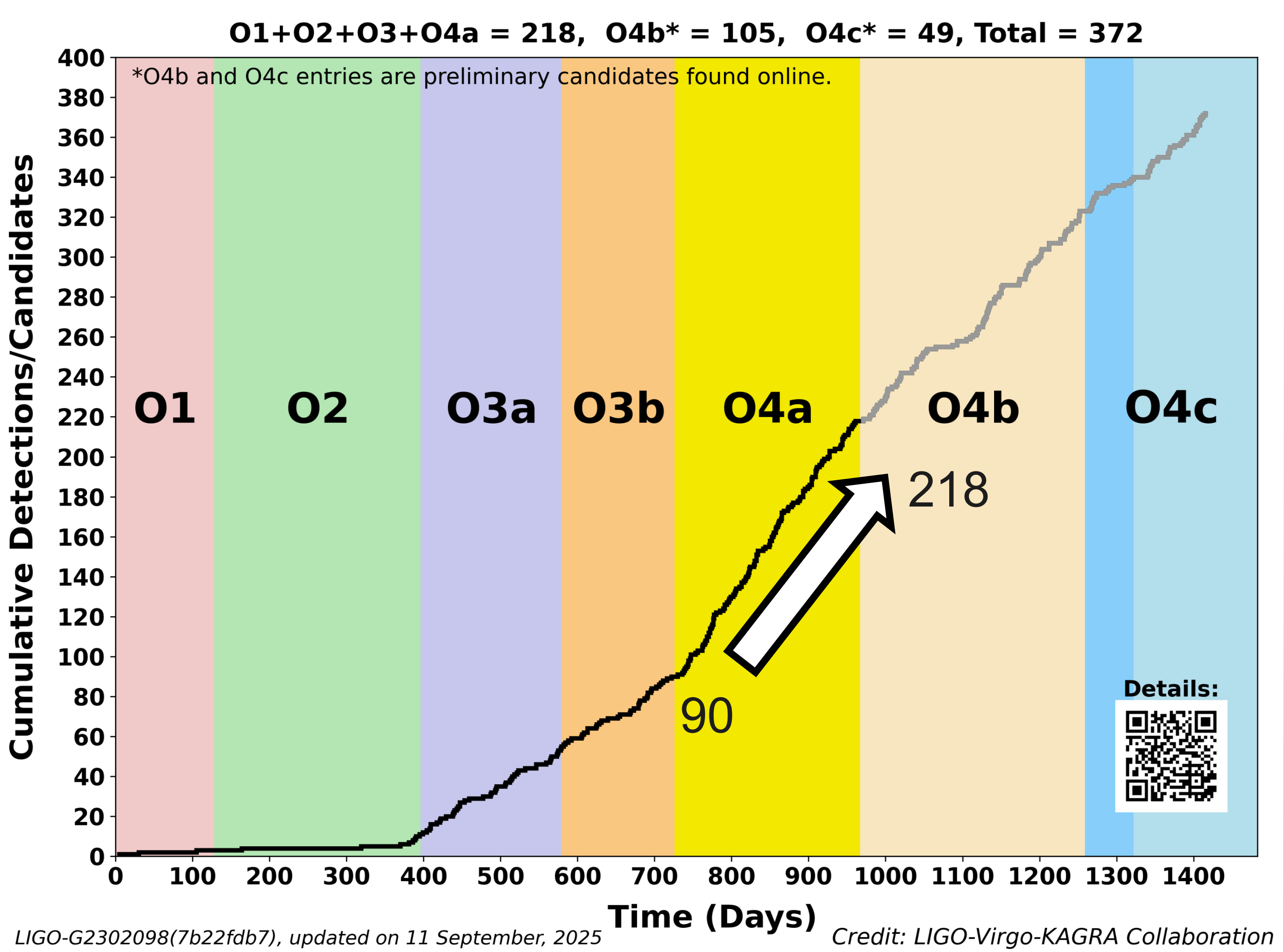


(https://observing.docs.ligo.org/plan/)

Unit is a detectable distance of $1.4 M_\odot$ - $1.4 M_\odot$ binary neutron star.

1 pc: ~3.3 light years

Fourth observing run



(https://dcc.ligo.org/LIGO-G2502029)

Since 2023 May 24 15:00:00 UTC

|

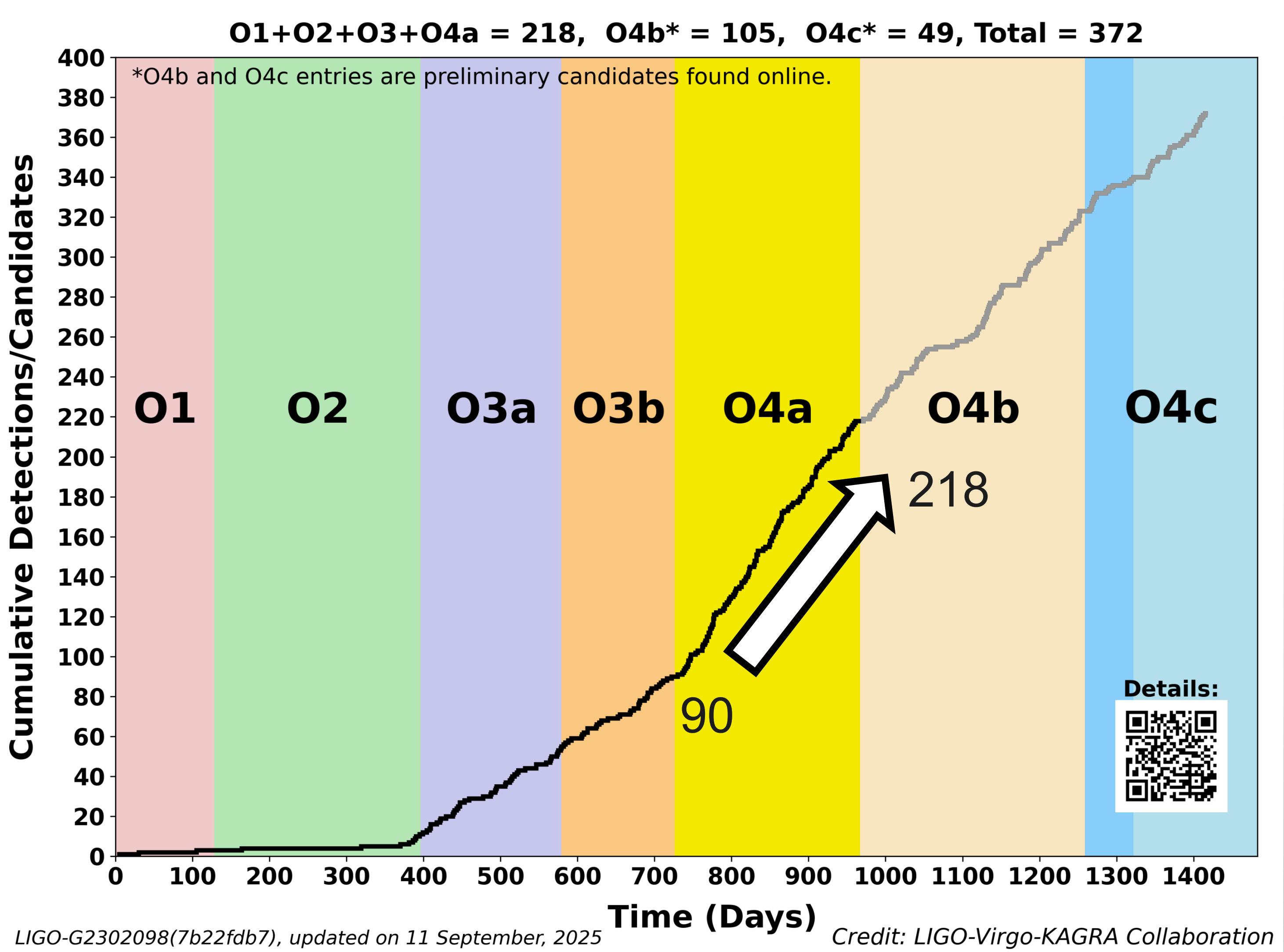
Until 2024 Jan. 16 16:00:00 UTC

Detected 128 candidates of GW events.

Three members from NCU joined operation at the observation site.

NCU made fundamental contributions in the error estimation pipeline and on-site operation.

Fourth observing run



(https://dcc.ligo.org/LIGO-G2502029)

First detection era

⇩

Statistical evaluation era

Publications based on O4a data

- Observation of Gravitational Waves from the Coalescence of a 2.5-4.5 M_sun Compact Object and a Neutron Star, Astrophys. J. Lett. 970, L34 (2024), arXiv: 2404.04248
- Swift-BAT GUANO follow-up of gravitational-wave triggers in the third LIGO-Virgo-KAGRA observing run, Astrophys. J. 980, 207 (2025), arXiv: 2407.12867
- A Search Using GEO600 for Gravitational Waves Coincident with Fast Radio Bursts from SGR 1935+2154, Astrophys. J. 977, 255 (2024), arXiv: 2410.09151
- Search for gravitational waves emitted from SN 2023ixf, Astrophys. J. 985, 183 (2025), arXiv: 2410.16565
- Search for continuous gravitational waves from known pulsars in the first part of the fourth LIGO-Virgo-KAGRA observing run, Astrophys. J. 983, 99 (2025), arXiv: 2501.01495
- GW231123: a Binary Black Hole Merger with Total Mass 190-265 Msun, arXiv: 2507.08219
- All-sky search for short gravitational-wave bursts in the first part of the fourth LIGO-Virgo-KAGRA observing run, arXiv: 2507.12374
- All-sky search for long-duration gravitational-wave transients in the first part of the fourth LIGO-Virgo-KAGRA Observing run, arXiv: 2507.12282
- GWTC-4.0: Population Properties of Merging Compact Binaries, arXiv: 2508.18083
- GWTC-4.0: Updating the Gravitational-Wave Transient Catalog with Observations from the First Part of the Fourth LIGO-Virgo-KAGRA Observing Run, arXiv: 2508.18082
- GWTC-4.0: Methods for identifying and characterizing gravitational-wave transients, arXiv: 2508.18081
- GWTC-4.0: An Introduction to Version 4.0 of the Gravitational-Wave Transient Catalog, arXiv: 2508.18080
- Open Data from LIGO, Virgo, and KAGRA through the first part of the fourth observing run, arXiv: 2508.18079
- Upper Limits on the Isotropic Gravitational-Wave Background from the first part of LIGO, Virgo and KAGRA's fourth Observing Run, arXiv: 2508.20721
- GWTC-4.0: constraints on the cosmic expansion rate and modified gravitational-wave propagation, arXiv: 2509.04348
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- GW230814: investigation of a loud gravitational-wave signal observed with a single detector, arXiv, 2509.07348
- Black Hole Spectroscopy and Tests of General Relativity with GW250114, arXiv: 2509.08099
- GW250114: Testing Hawking's area law and the Kerr nature of black holes, Phys. Rev. Lett. 135, 111405 (2025), arXiv: 2509.08054
- Directional Search for Persistent Gravitational Waves: Results from the First Part of LIGO-Virgo-KAGRA's Fourth Observing Run, arXiv: 2510.17487

(https://pnp.ligo.org/ppcomm/Papers.html)

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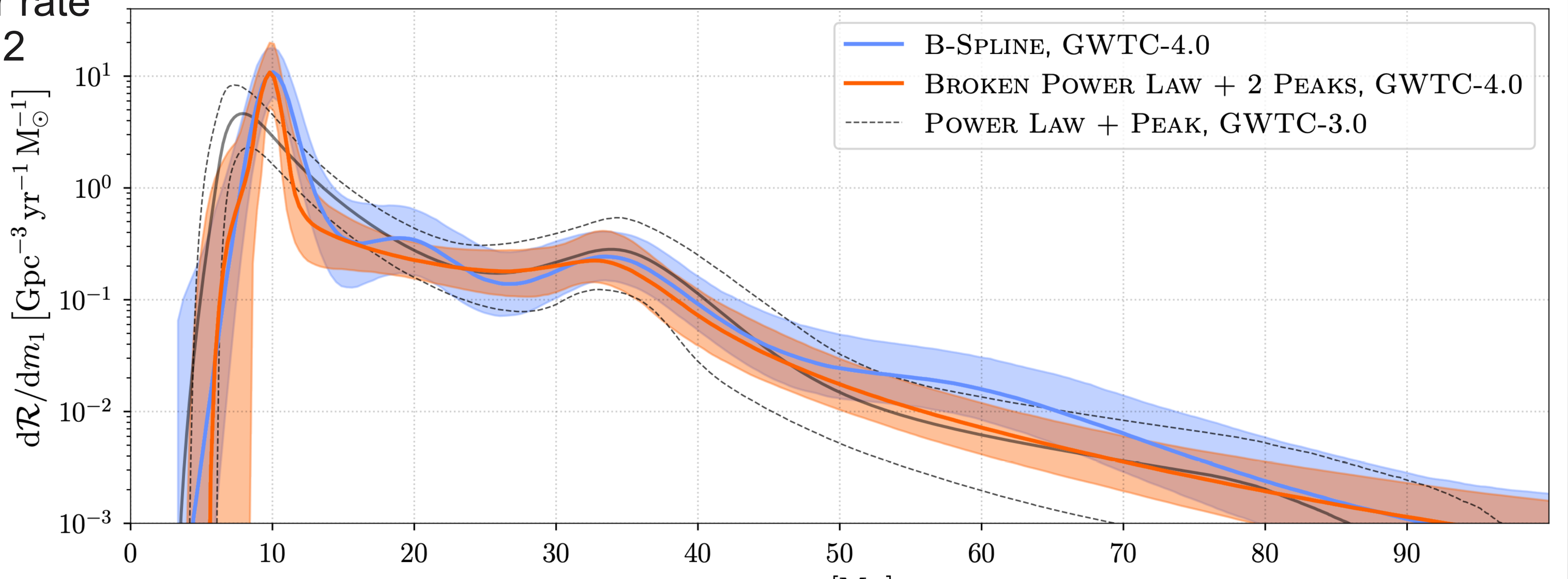
Population properties of merging compact binaries (1)

Merger rate
at z=0.2



Mass of primary star in a binary

(https://arxiv.org/abs/2508.18083)

Now we have enough events for statistical study of compact binaries.

GWTC-4.0: constraints on the cosmic expansion rate and modified gravitational-wave propagation (1)

Hubble constant (H_0) is an expansion rate of the universe today.

Measurement with supernovae and cosmic microwave background are not consistent.

GW can be another probe.

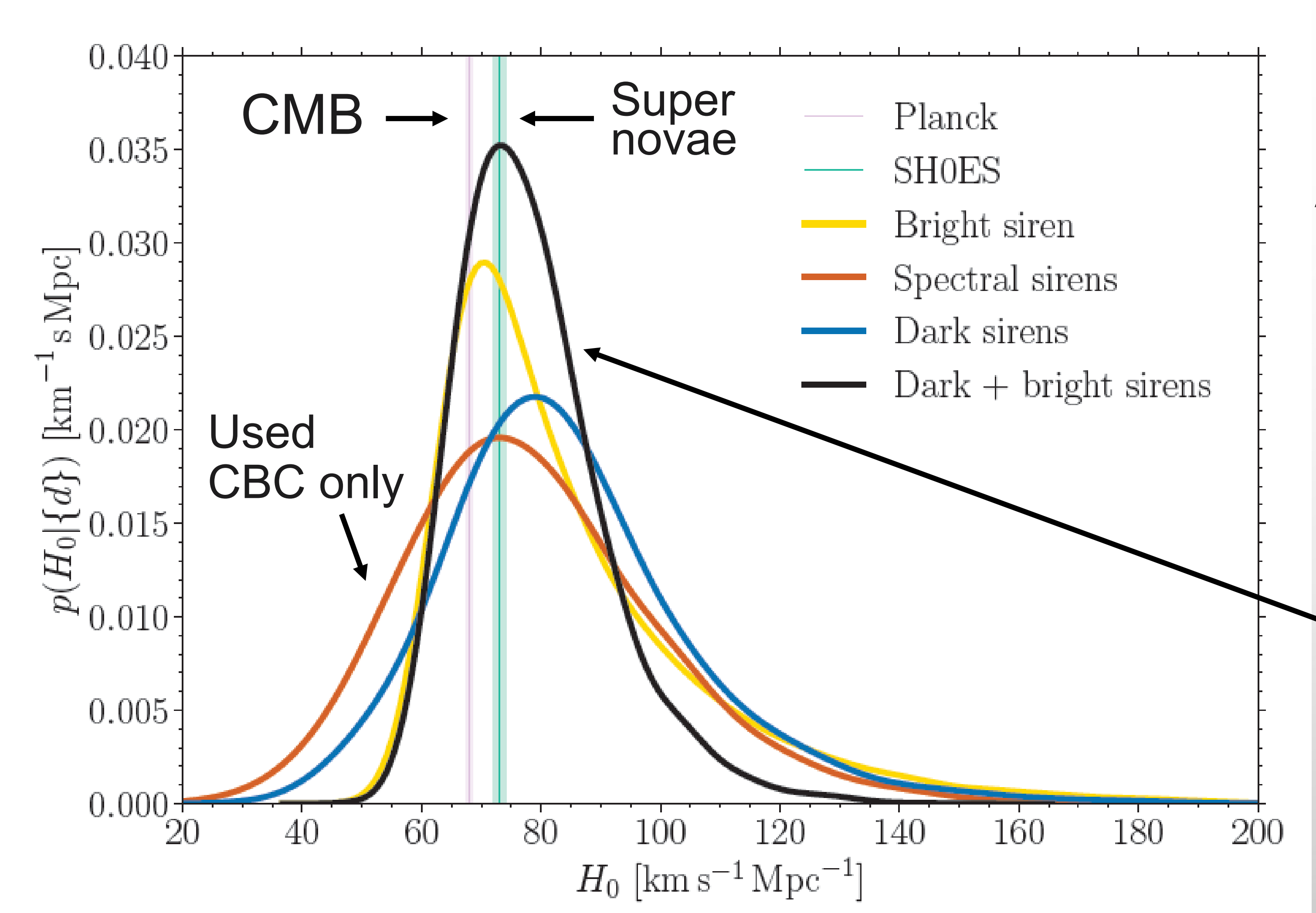
GW provides luminosity distance of the sources.

Combining it with another measurement of redshift, it gives Hubble constant.

- Redshift of the host galaxy of BNS (“bright siren”, most precise)
- Theoretical model of mass-redshift relationship (“spectral siren”)
- Redshift of each BBH event estimated by a galaxy survey (“dark siren”)

Compared these methods with the new dataset with sophisticated analysis.

GWTC-4.0: constraints on the cosmic expansion rate and modified gravitational-wave propagation (2)



$$H_0 = 76.6^{+13.0}_{-9.5}\left(^{+25.4}_{-14.0}\right)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}.$$

All methods were consistent.

Uncertainties are comparable.

No evidence of modified gravity.

Sky localization will improve when Virgo joins.

141 GW events &

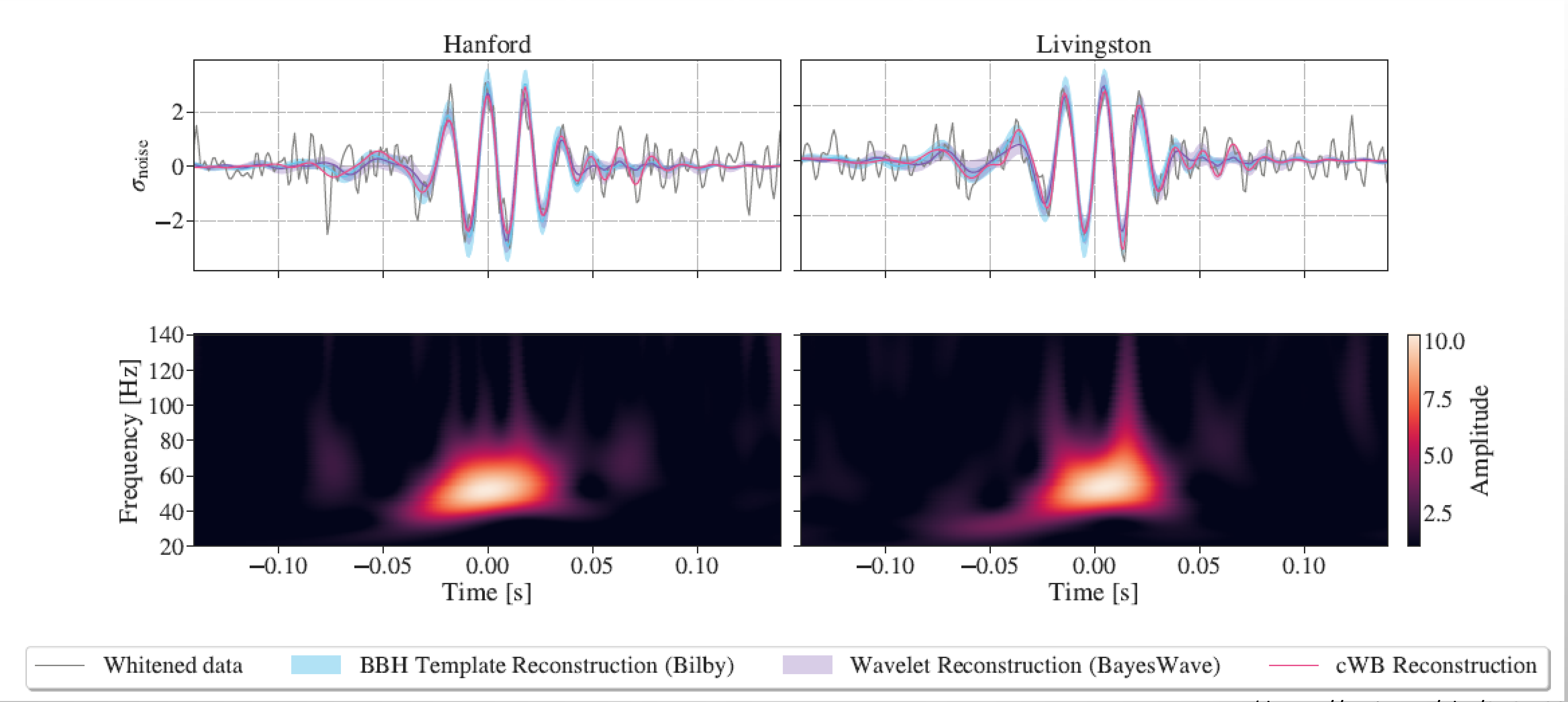
1 optical observation of BNS &

FULLPOP-4.0 merger rate model &

GLADE+ galaxy catalog

(https://arxiv.org/abs/2509.04348)

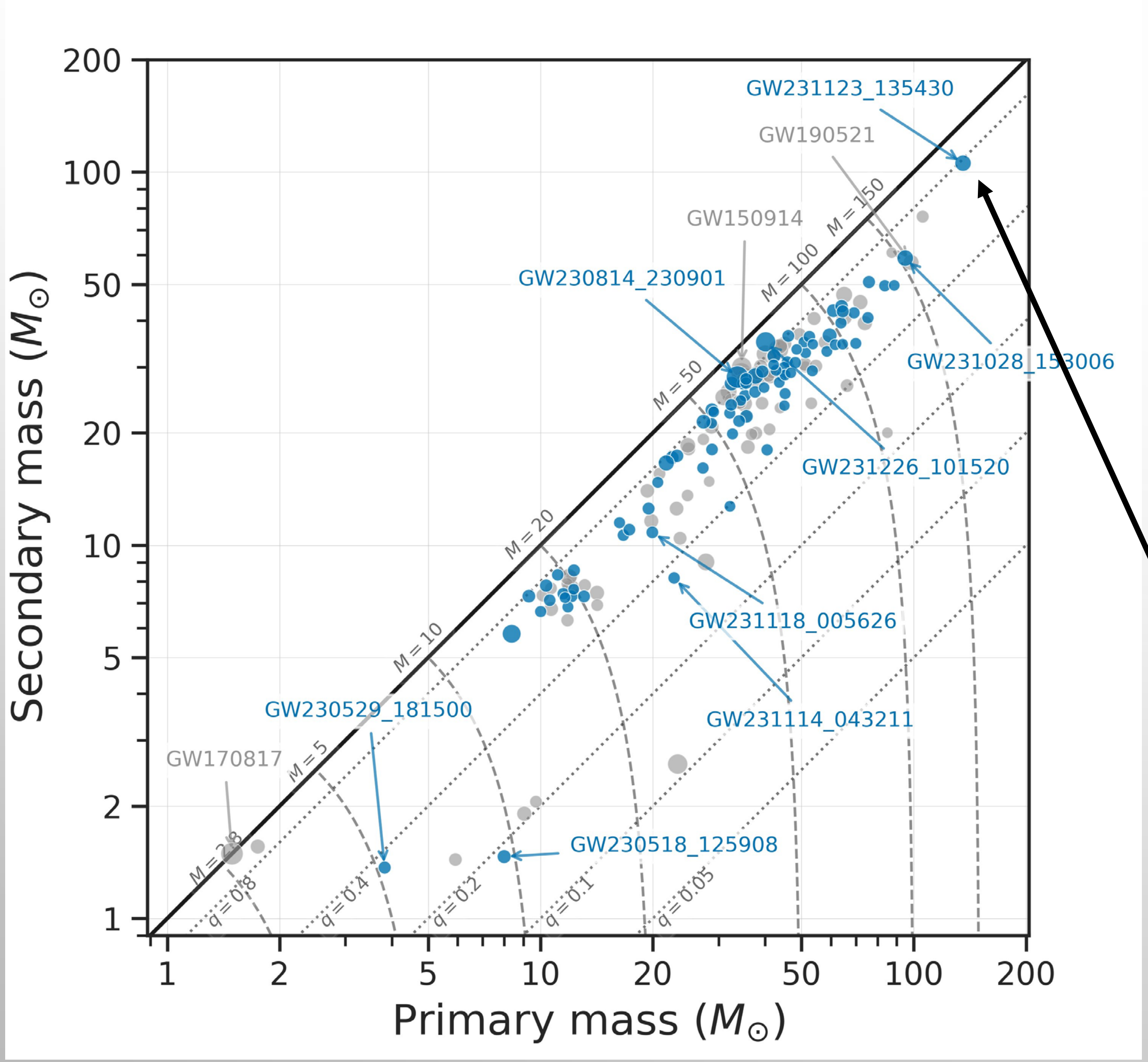
GW231123: a Binary Black Hole Merger with Total Mass 190-265 $M_\odot$ (1)



(https://arxiv.org/abs/2507.08219)

Heaviest BBH ever found, suggesting hierarchical BH merger.

GW231123: a Binary Black Hole Merger with Total Mass 190-265 $M_\odot$ (2)



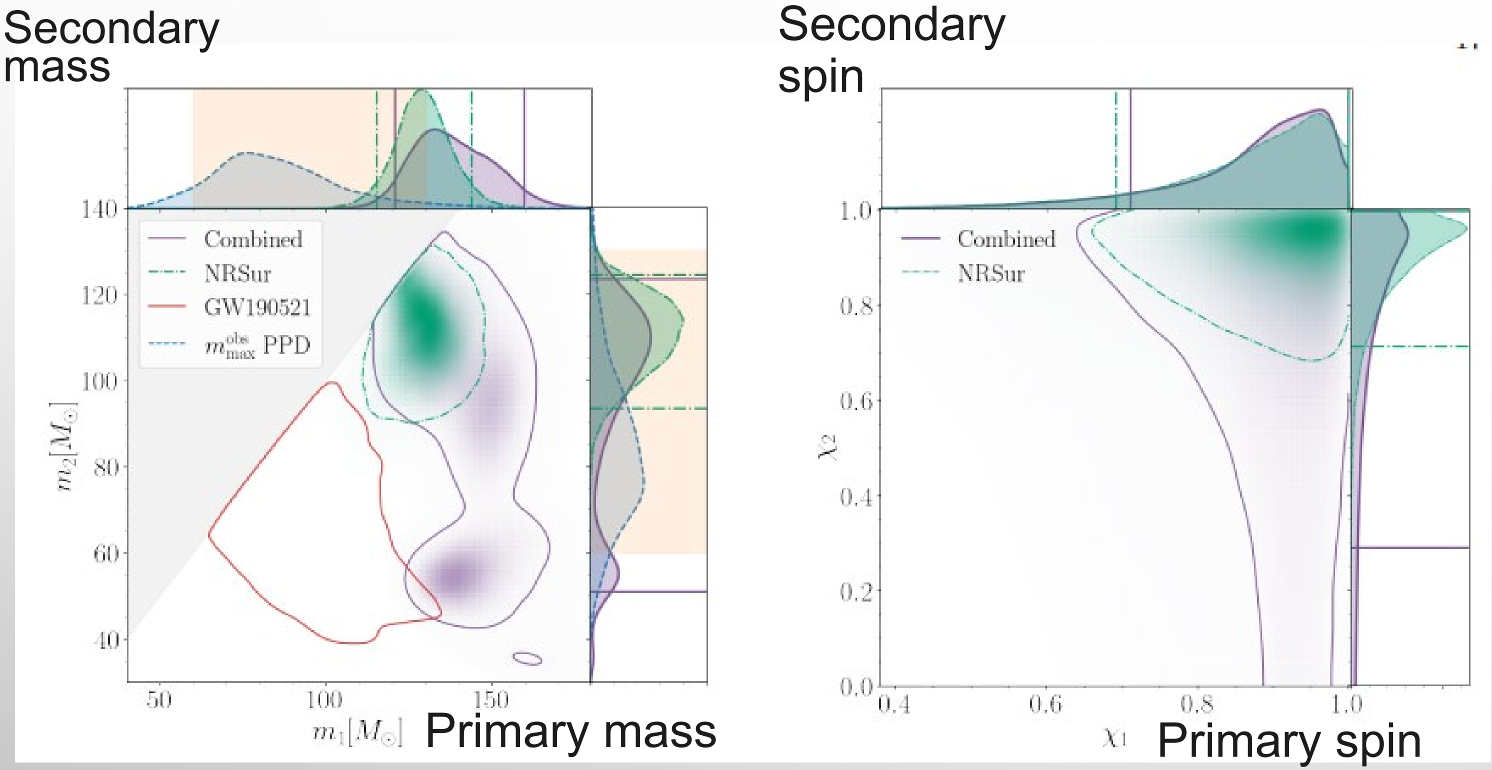
$100M_\odot - 100000M_\odot$ BH are rarely found. (Intermediate mass black hole)

The $60M_\odot - 130M_\odot$ BH cannot be generated by supernovae due to electron-positron pair-instability.

Sources of this event were in this region.

(https://x.com/LIGO/status/1960395507001438268)

GW231123: a Binary Black Hole Merger with Total Mass 190-265 $M_\odot$ (3)



(https://arxiv.org/abs/2507.08219)

Initial mass: $137^{+22}_{-17}\ M_\odot$ and $103^{+20}_{-52}\ M_\odot$

Initial spin: $0.90^{+0.10}_{-0.19}$ and $0.80^{+0.20}_{-0.51}$

Final mass: $225^{+26}_{-43}\ M_\odot$

Final spin: $0.84^{+0.10}_{-0.16}$

Luminosity distance: $0.7 - 4.1$ Gpc

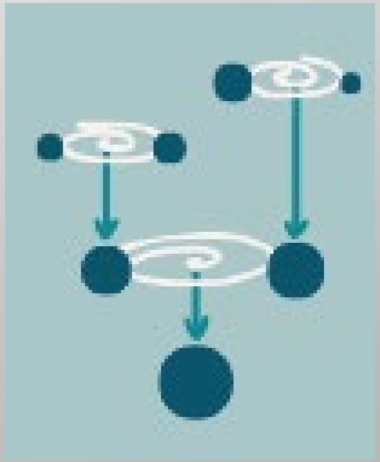
Redshift: $0.39^{+0.27}_{-0.24}$

Network SNR: 22.5

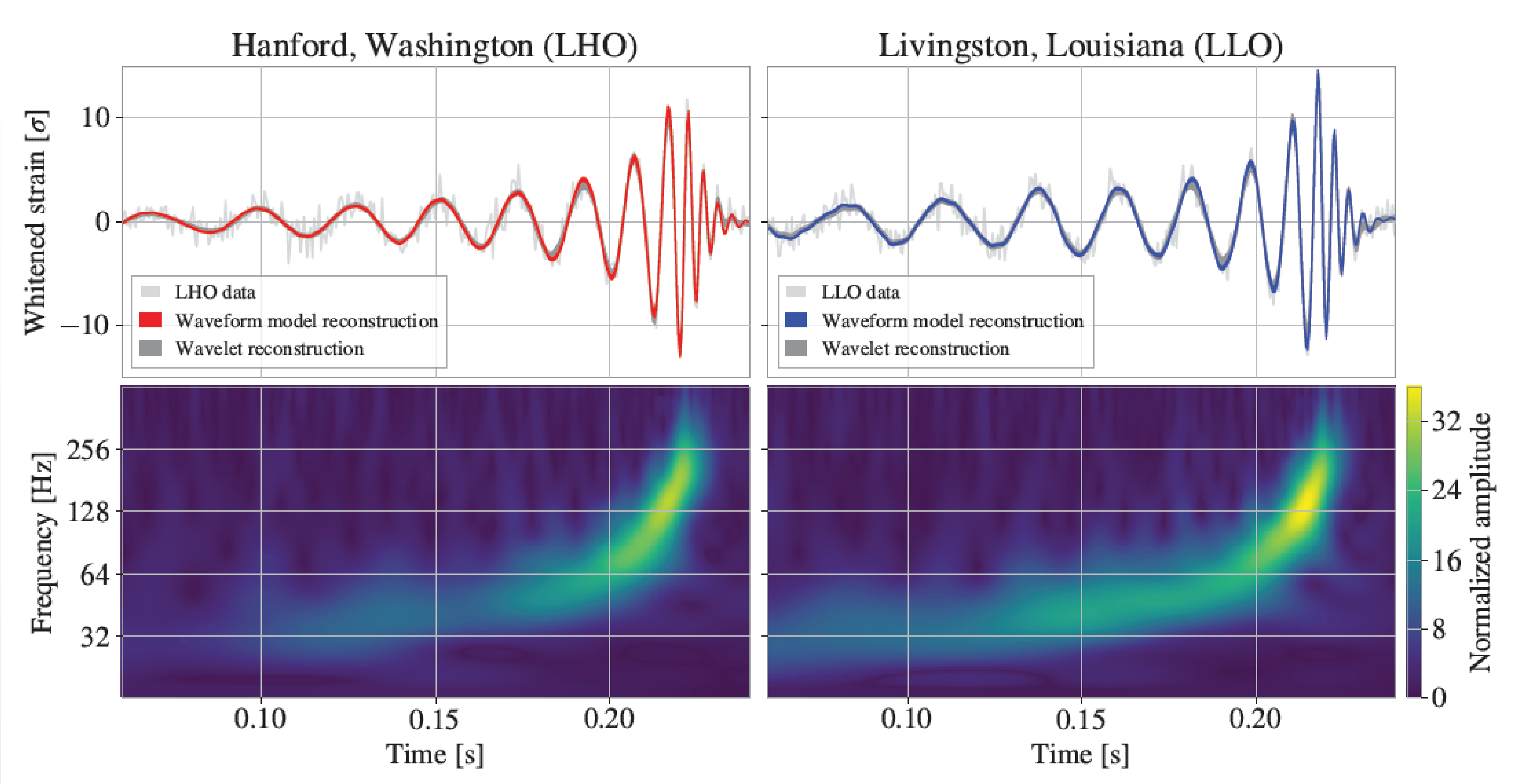
Initial masses are in the range of $60M_\odot - 130M_\odot$ with high spin

-> **Each of them were made by binary black hole merger.**

Scenario of intermediate mass black hole?



GW250114: Testing Hawking's area law and the Kerr nature of black holes (1)

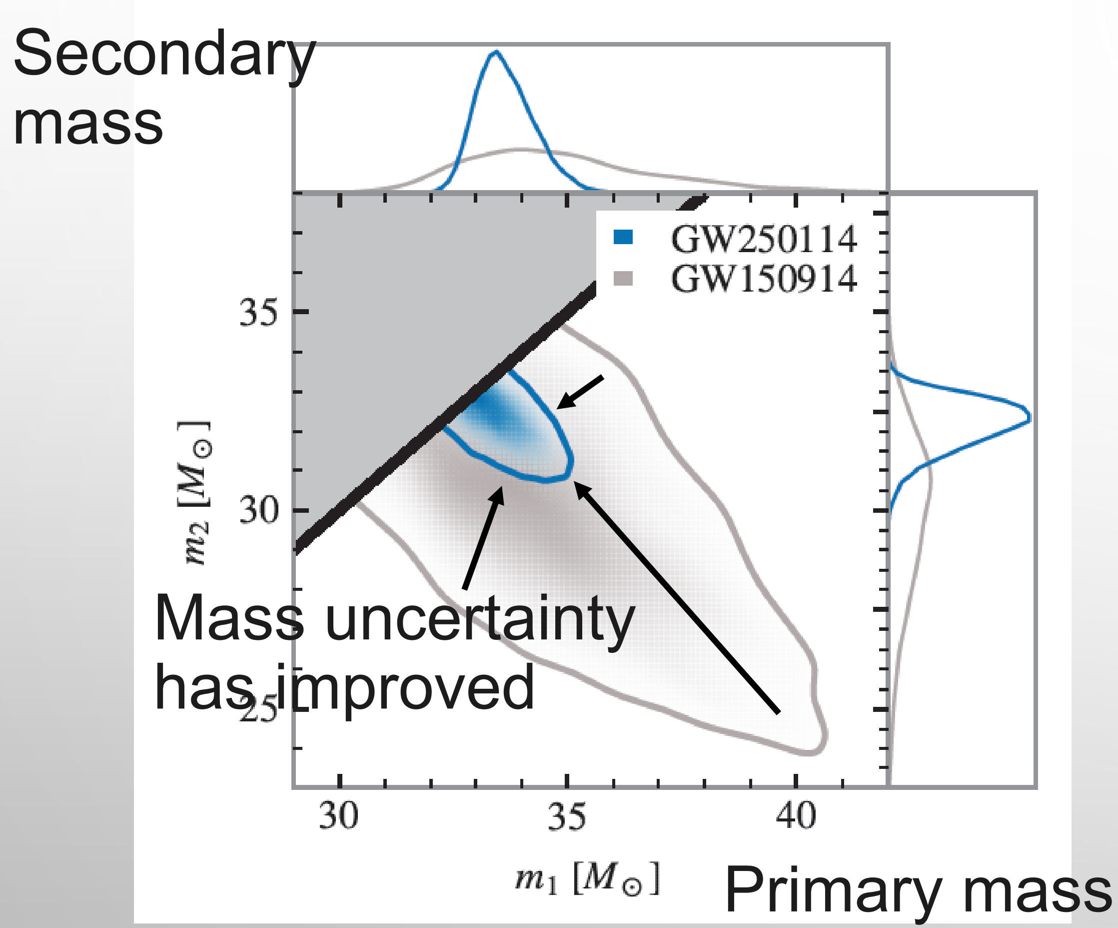


(https://arxiv.org/abs/2509.08054)

The highest SNR event to date. (~80)

Tested Hawking's area law and Kerr nature with this event.

GW250114: Testing Hawking's area law and the Kerr nature of black holes (2)



(https://arxiv.org/abs/2509.08054)

Initial mass: $33.6^{+1.2}_{-0.8}\ M_\odot$ and $32.2^{+0.8}_{-1.3}\ M_\odot$

Initial spin: ≤ 0.24 and ≤ 0.26

Final mass: $62.7^{+1.0}_{-1.1}\ M_\odot$

Final spin: $0.68^{+0.01}_{-0.01}$

Network SNR: 77-80

GW profiles were similar to the first detection, but the precision has improved.

GW250114: Testing Hawking's area law and the Kerr nature of black holes (3)

- Black hole is characterized by only mass, spin, and charge. (No-hair theorem)
- Area of event horizon behaves as entropy due to its simplicity.
- Area does not decrease during overall merger process. (Hawking's area law)
  - $A_f \geq A_i \equiv A_1 + A_2$
  - No Hawking radiation, no naked singularity, no alternative gravity theory

Fit ringdown spectrum of BBH GW by functions of mass and spin. (Kerr nature)

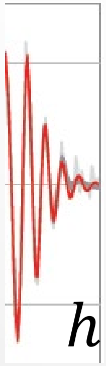
↓

Compare the dominant modes with a model of Kerr BH.

↓

Calculate area of the event horizons at initial and final states.

GW250114: Testing Hawking's area law and the Kerr nature of black holes (4)



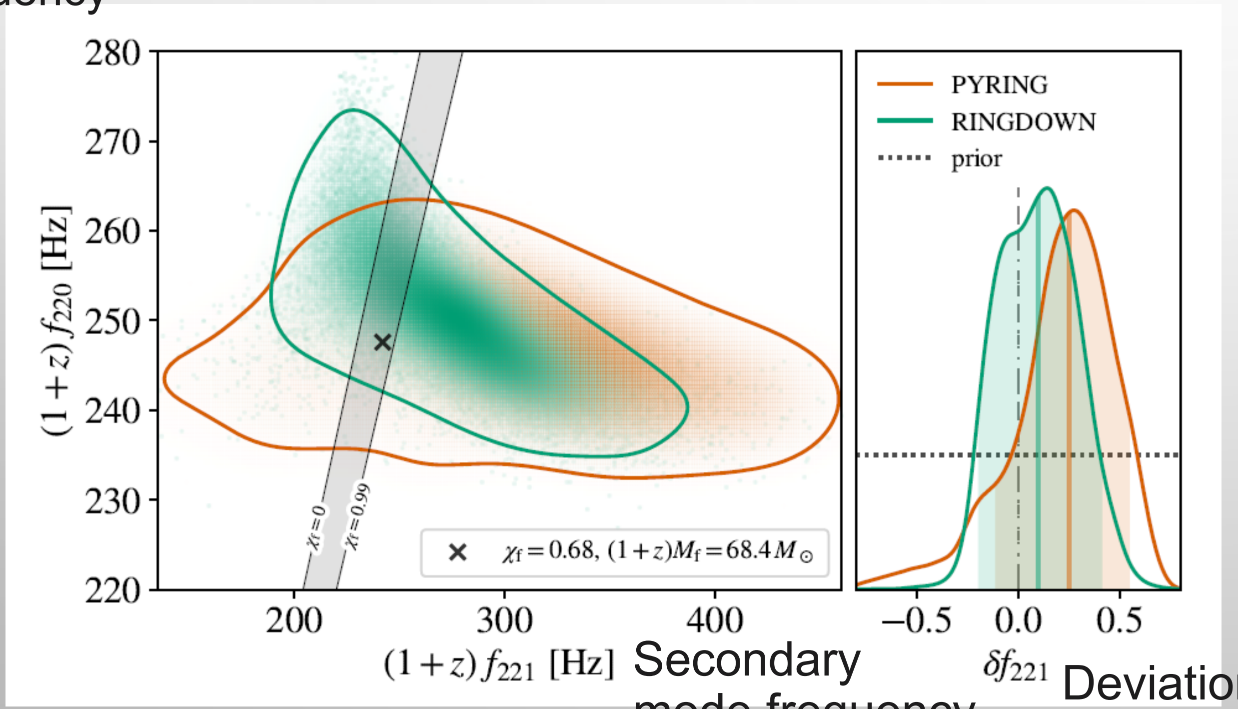
Ringdown modes:

$t > 3.54$ ms: $f_{220} = 247^{+6}_{-6}$ Hz, $\gamma_{220} = 221^{+39}_{-32}$ Hz

$t > 2.02$ ms: f_{220} with $f_{221} = 249^{+8}_{-9}$ Hz, $\gamma_{221} = 708^{+116}_{-107}$ Hz

$h \sim e^{-2\pi i f t} e^{-\gamma t}$

Primary mode frequency



Secondary mode frequency

Deviation from Kerr model

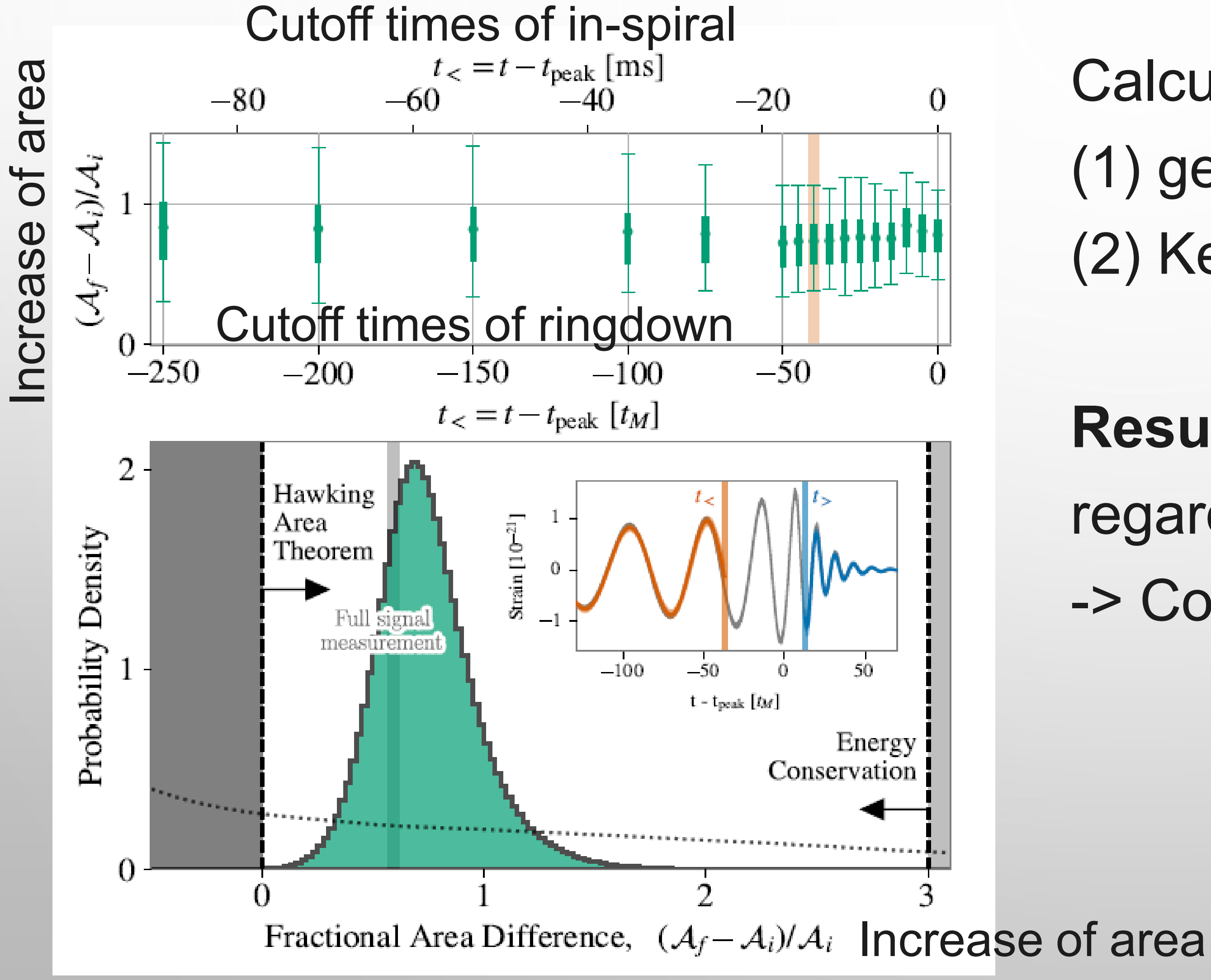
Quasi-normal modes were consistent with Kerr solution.

↓

Valid to test Hawking's area law.

(https://arxiv.org/abs/2509.08054)

GW250114: Testing Hawking's area law and the Kerr nature of black holes (5)



Calculated area with assumptions of

(1) general relativity at in-spiral and ringdown,

(2) Kerr black holes.

Results favored increase of area at >3.3σ

regardless of cutoff time of each phase.

-> Consistent with Hawking’s area law.

(https://arxiv.org/abs/2509.08054)

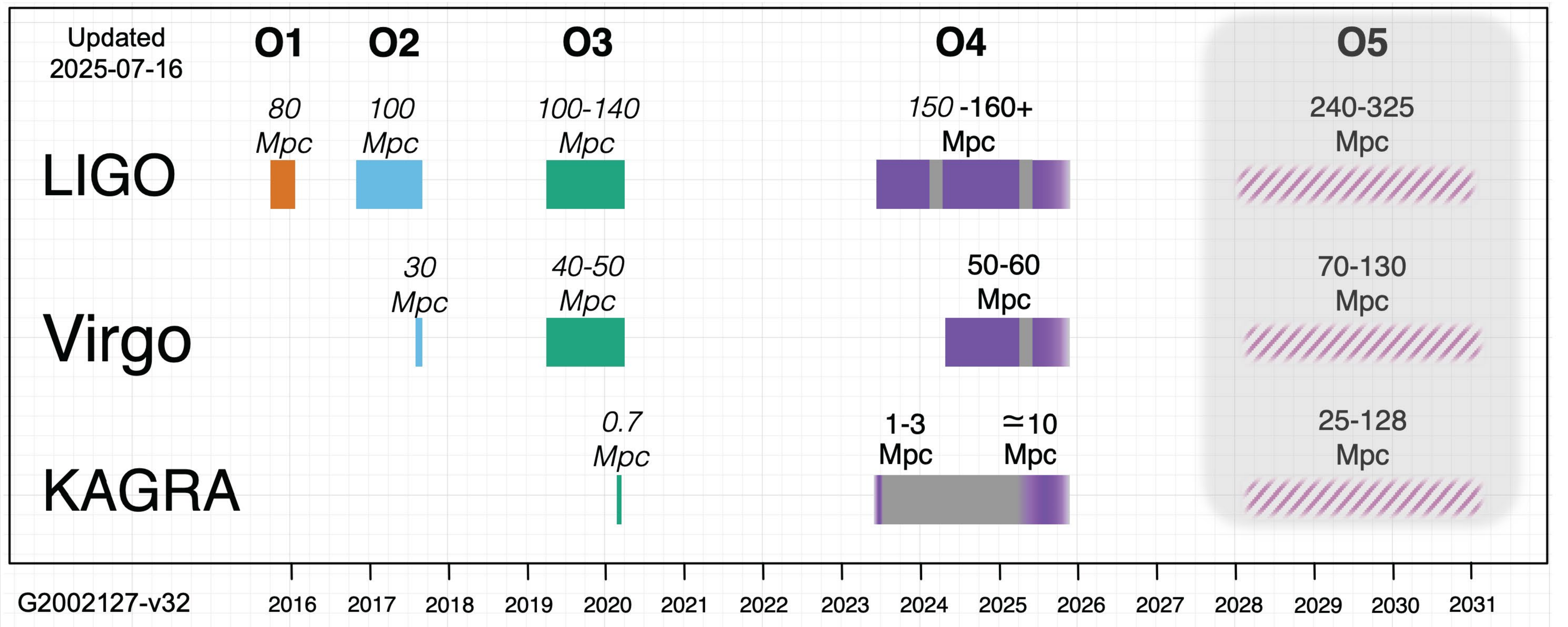
Summary of science

- **A large number (218) of events enabled us statistical studies using GW.**
- Mass population was shown.
- Hubble constant derived by 3 methods showed consistent mean values and comparable uncertainties.
- The heaviest intermediate-mass BH event indicated preceding mergers.
- The highest SNR event tested Kerr nature and Hawking’s area law.

Error estimation pipeline contributed by NCU was used in the observation.

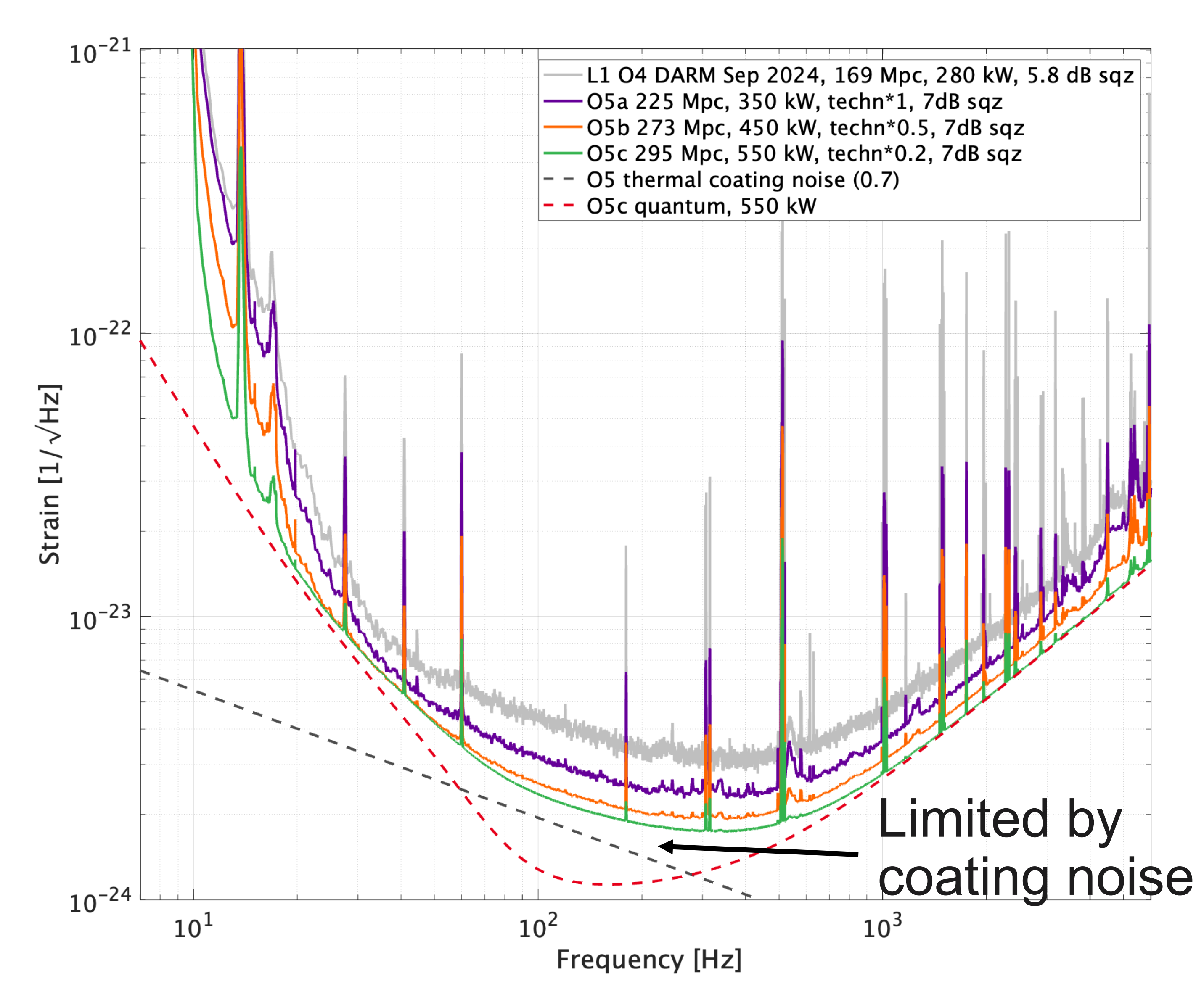
NCU members joined on-site operation.

Future plan



- O4 ends in Nov. 2025.
- O5 comes in 2027 with twice higher sensitivity.
- LISA will be launched in 2030's.

O5 sensitivity



(https://dcc.ligo.org/LIGO-T2500310/public)

Planned upgrade is

- Laser power
  - From 280 kW to 350 kW and more
- Coating thermal noise
  - 30% noise reduction by replacing mirror coating
- Quantum noise
  - 6.8-7.3 dB (~50%) noise reduction by squeezing

It gradually increases the sensitivity to 225, 273, and 295 Mpc in three phases.

Activity in NCU&AS toward O5 and post-O5

We contribute to **Calibration**, **Mirror coating**, and **Stochastic background study** for LIGO.

With Dr. Patrick Brady, an ex-spokesperson of LIGO

Calibration:

- Development of analysis pipeline
- Study of mirror deformation caused by calibrator (speaker's work)

Coating:

- Fabrication of highly reflective layers
- Characterization of coating loss (speaker's work)

SGWB:

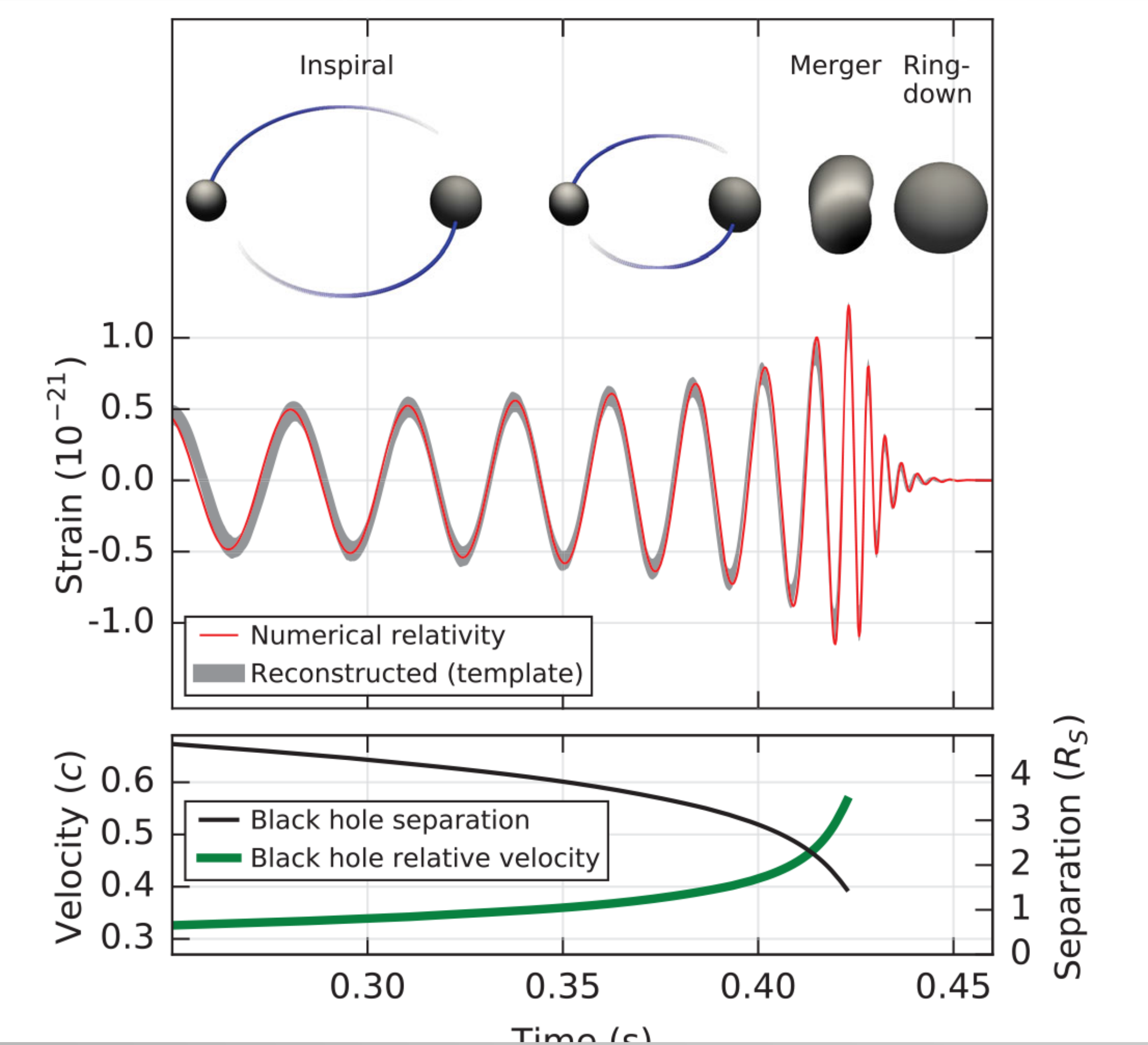
- Error estimation

Summary

- LIGO, Virgo, KAGRA collaboration released results of 1st part of O4 run.
- A large number (218) of events enabled us statistical studies using GW.
- Mass population was shown.
- Hubble constant derived by 3 methods showed consistent mean values and comparable uncertainties.
- The heaviest intermediate-mass BH event indicated preceding mergers.
- The highest SNR event tested Kerr nature and Hawking's area law.
- Taiwan team including NCU contributed to this observation in calibration.

Appendix

TYPICAL WAVEFORM OF GRAVITATIONAL WAVE



(https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.061102)

Waveforms are modeled by

Inspiral: Post-Newtonian perturbation.

$$h(t) \simeq \frac{GM_c}{c^2 D\omega^{1/4}} \cos(-2\omega^{5/8})$$

$$\omega = \frac{c^3(t_c - t)}{5G} \frac{(m_1 + m_2)^{1/5}}{(m_1 m_2)^{3/5}}$$

Frequency gets faster depending on masses.

Merger: Numerical general relativity.

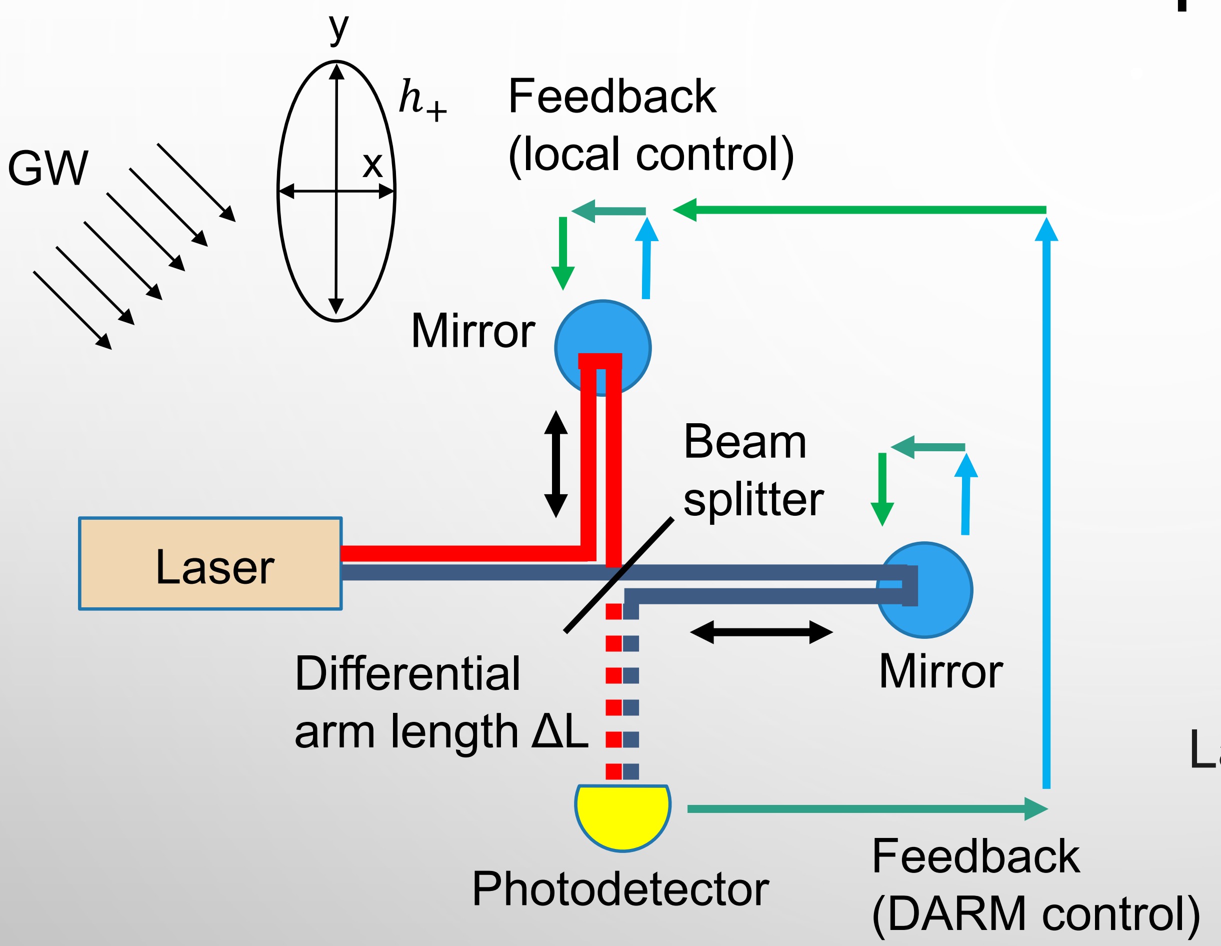
Weak field approximation is no longer valid.

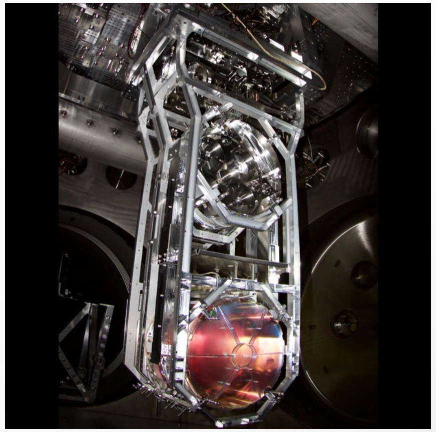
Ringdown: Perturbation on BH solution.

$$h(t) \simeq e^{-\frac{\omega_R(t-t_0)}{2Q}} \cos(\omega_R(t-t_0))$$

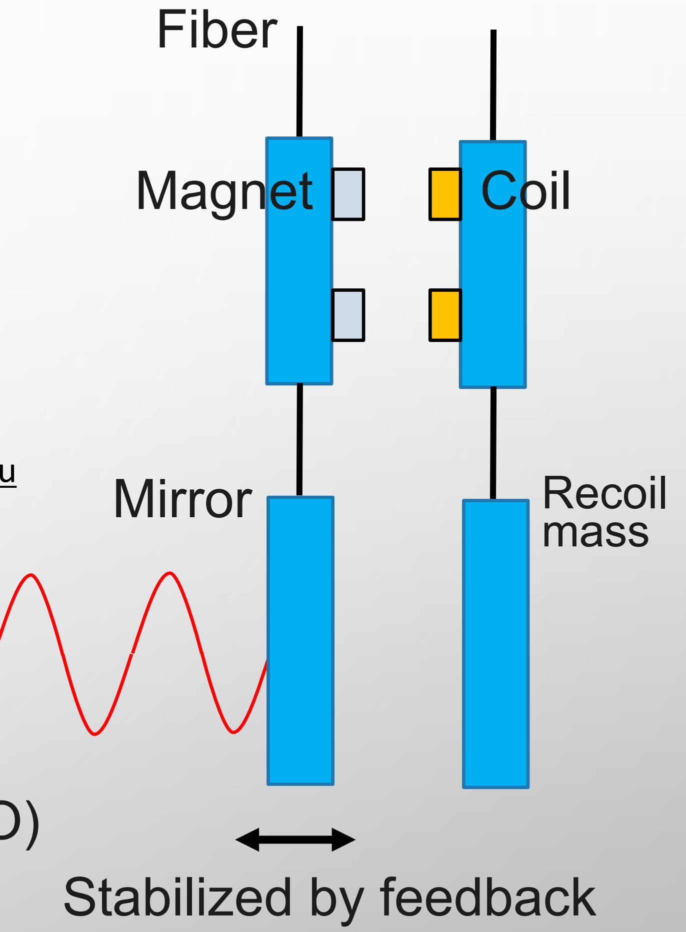
For NS, extra “fluid mode” exists.

Mirror suspension



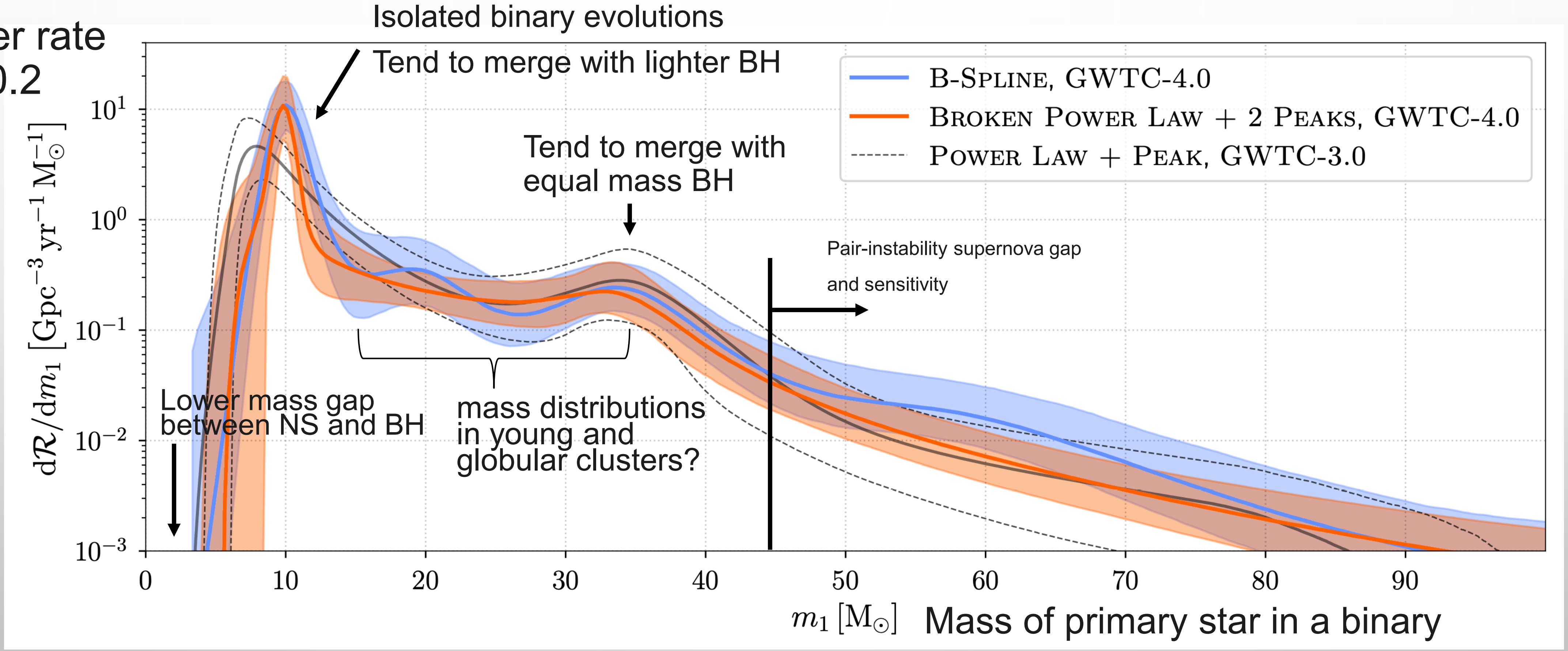


(https://www.ligo.caltech.edu /image/ligo20150731j)



Mirrors are suspended and stabilized by feedback control for reducing vibration and keeping interference.

Population properties of merging compact binaries (2)



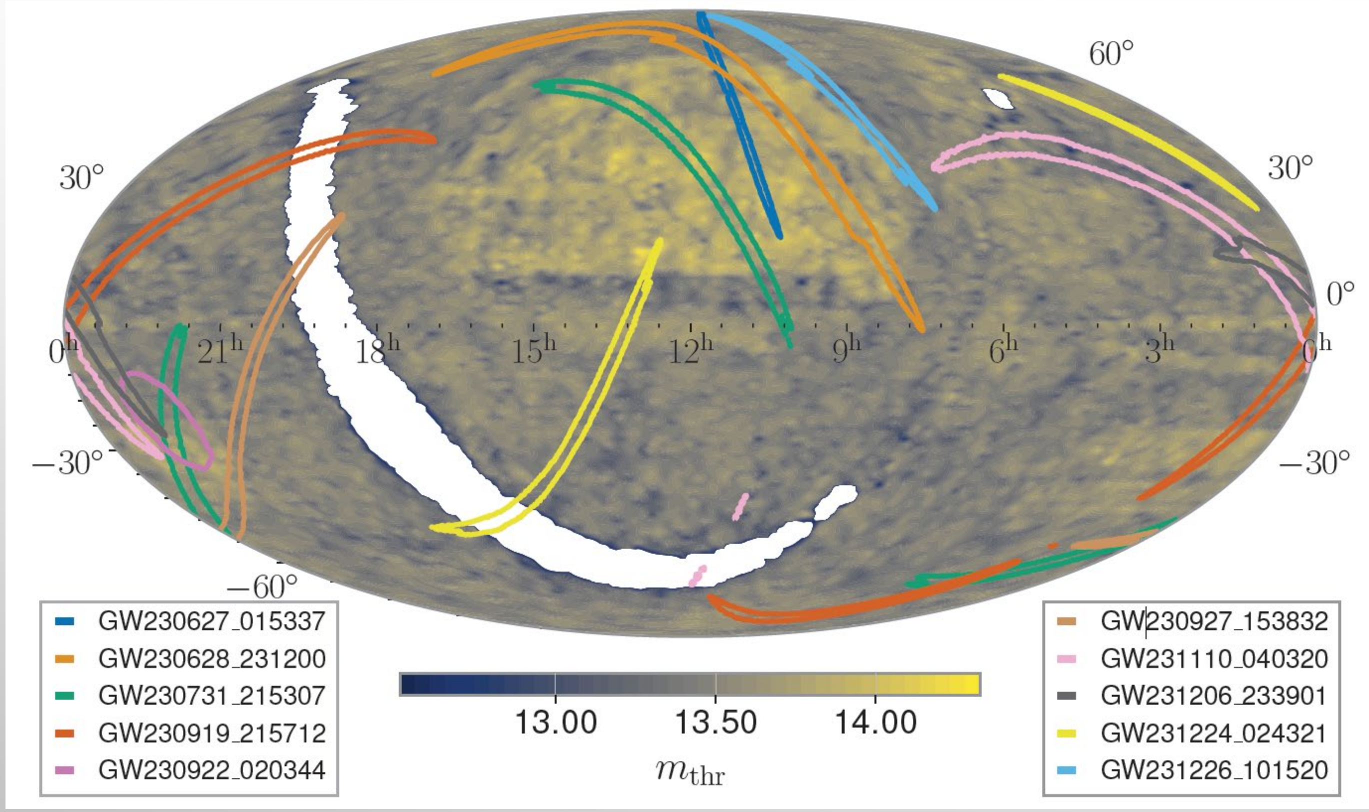
(https://arxiv.org/abs/2508.18083)

Measured relationship between merger rate and mass ratio favors:

$\lesssim 10 M_\odot$: Formation by chemically homogeneous evolution

$\gtrsim 10 M_\odot$: Formation by stable mass transfer

GWTC-4.0: constraints on the cosmic expansion rate and modified gravitational-wave propagation (3)

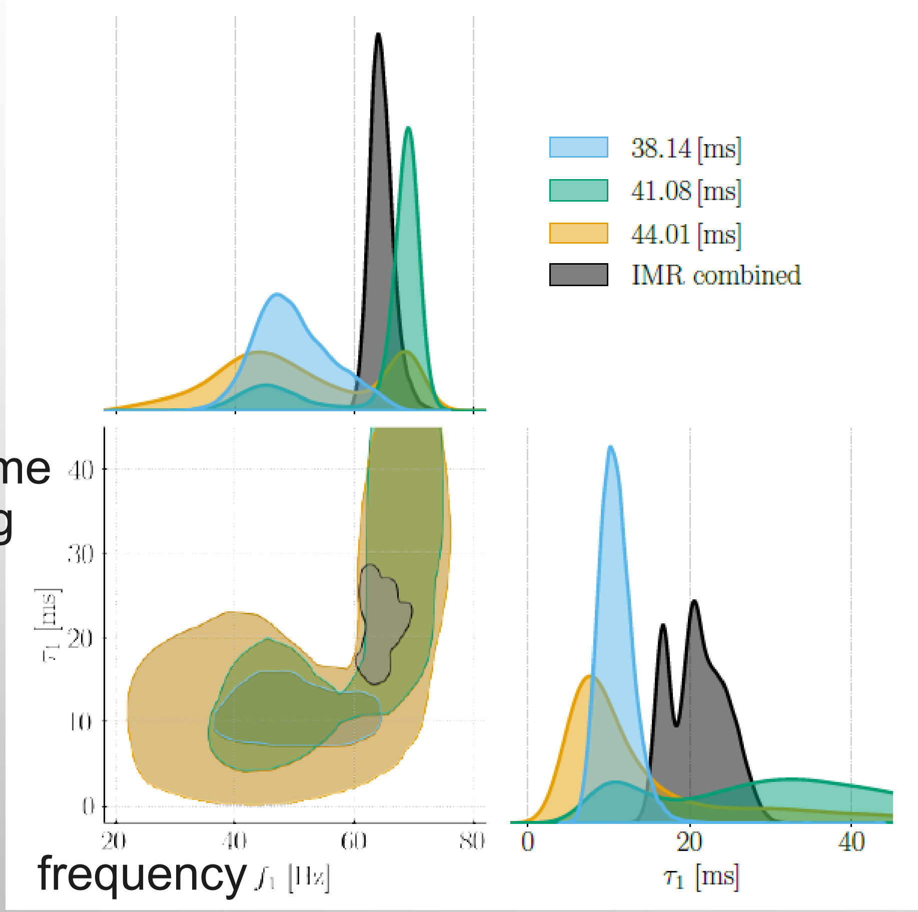


(https://arxiv.org/abs/2509.04348)

The sky localization was not good enough due to absence of Virgo.

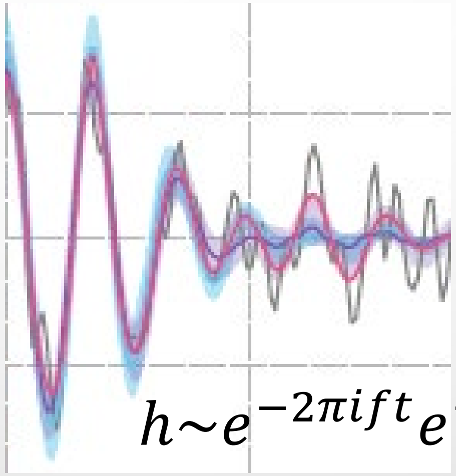
GW231123: a Binary Black Hole Merger with Total Mass 190-265 $M_{\odot}$ (4)

Start time of fitting



(https://arxiv.org/abs/2507.08219)

Large signal at merger & ringdown phases enables **black hole spectroscopy**.



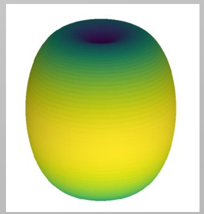
$$h \sim e^{-2\pi i f t} e^{-\gamma t}$$

Fit the ringdown waveform by decaying sine waves or theoretical deformation modes (quasi-normal modes).

-> Probe of internal structures.

Consistent with $(l, m, n) = (2,2,0)$ and several additional modes, but theoretical modeling is not enough to determine the property of merged BH.

Analogy: spherical harmonics function (l,m)=(2,2) mode



Masses of compact stellar bodies

Some mass regions are detected; some are not many.

- Supermassive BH   > O(100000) $M_{\odot}$: Optically observed
- Intermediate mass BH   O(100-10000) $M_{\odot}$: A few GW events
- Stellar mass BH   5 - O(10) $M_{\odot}$: Tens of GW events
- Neutron star   1 - 3 $M_{\odot}$: A few GW events

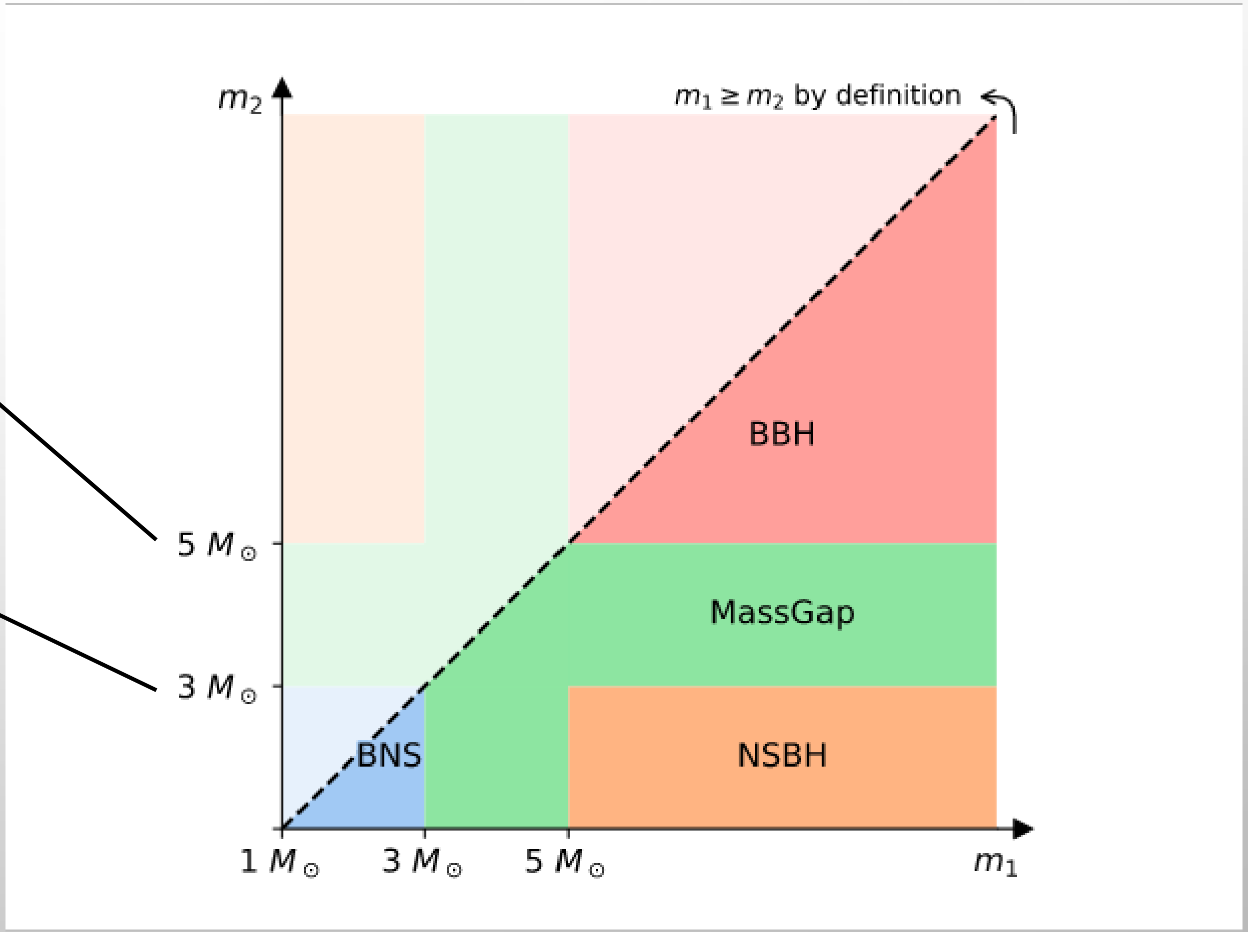
Each mass class has mysteries in its origin.

Mass gap: Absence of lighter black hole

There is a mass gap between the heaviest NS and the lightest BH.

BH lighter than 5 $M_{\odot}$ is not found.

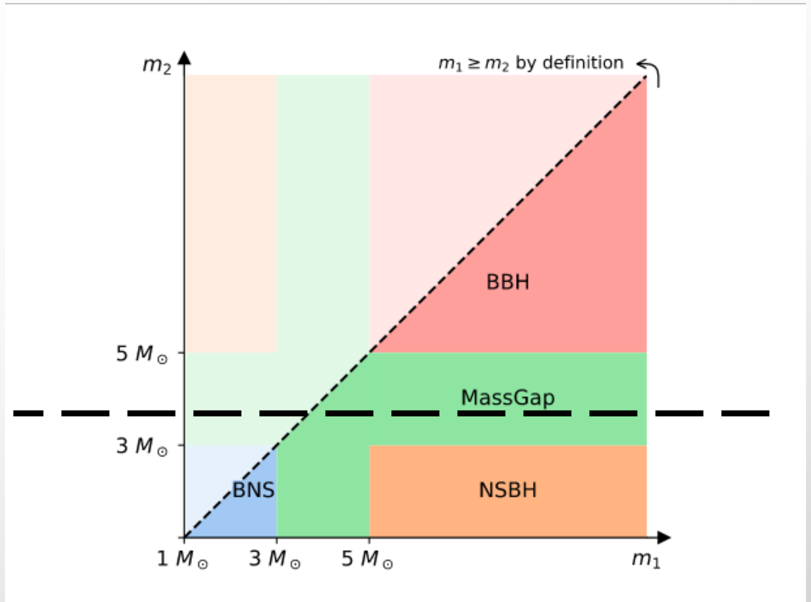
NS heavier than 2.6 $M_{\odot}$ is not found.
It is also constrained by degeneracy pressure, but its mechanism is unknown.



(https://researchmap.jp/denden/misc/39582675/attachment_file.pdf)
(https://emfollow.docs.ligo.org/userguide/content.html#classification-diagram)

What determines the upper mass of neutron star?

- Degeneracy pressure of neutron
- **Nuclear force of neutron and others…?**



Astrophysics

Nuclear physics

Revealing exotic phenomena in NS

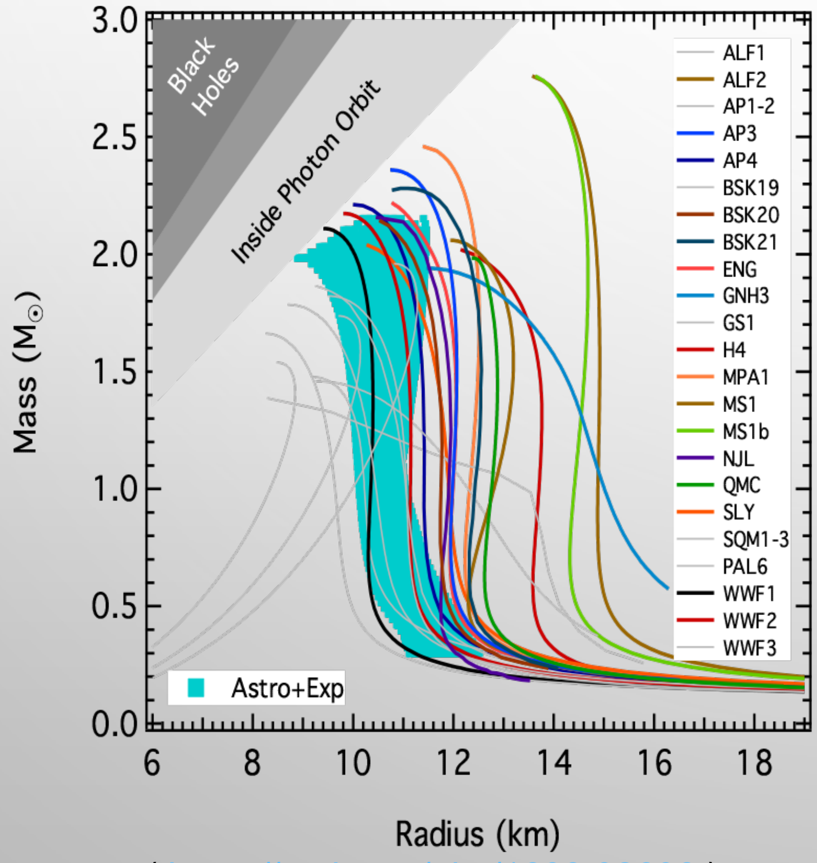
Revealing boundary between NS and BH
Measurement of GW from binary NS

EoS and M-R measurement

Many EoSs have been proposed.

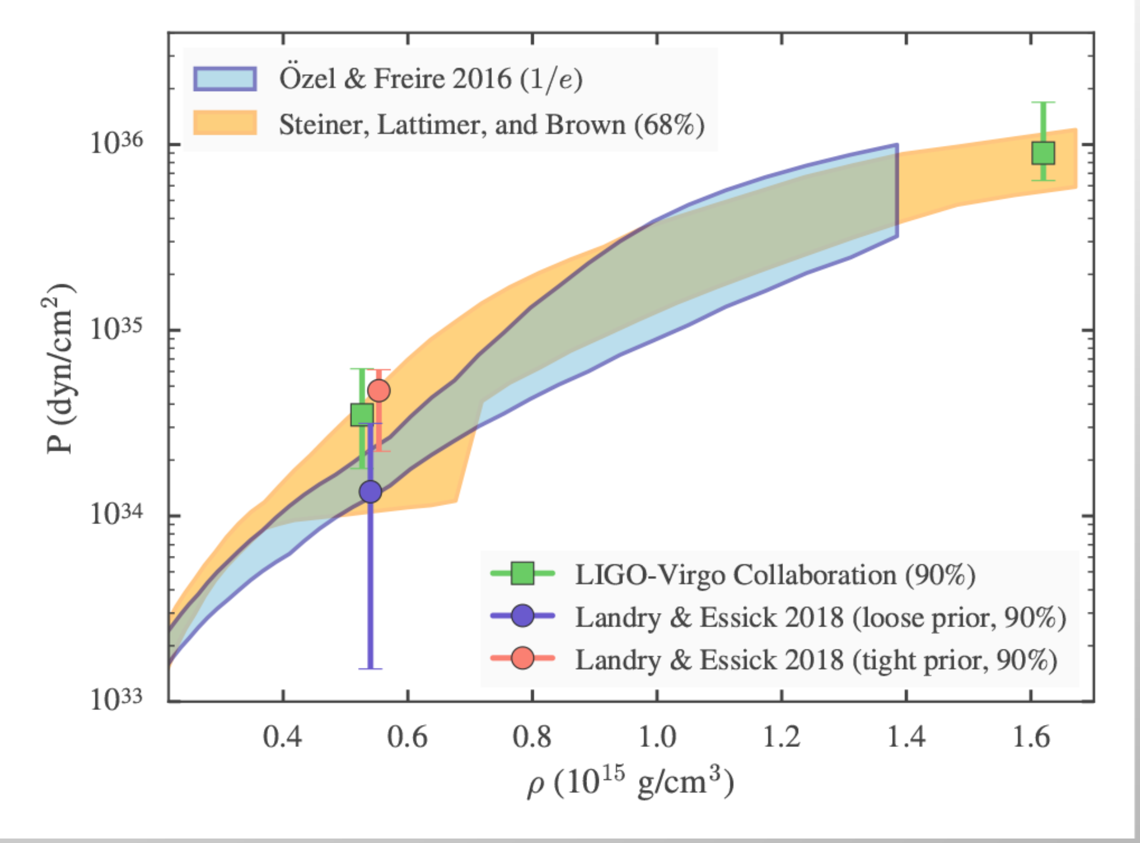
They favor ~2 $M_\odot$ at the typical NS radius.

Blue band is favored by optical observation.



(https://arxiv.org/abs/1603.02698)

GW170817 event is consistent with previous models.



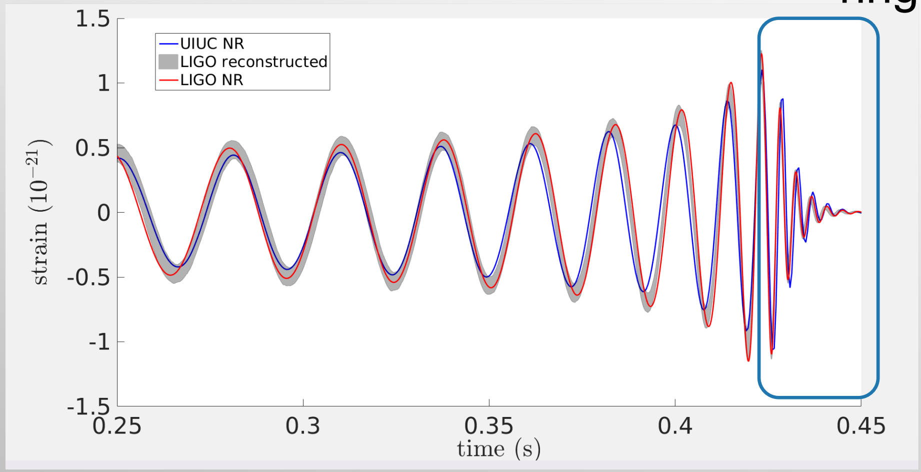
(https://arxiv.org/abs/1904.10002)

EoS and ringdown peak

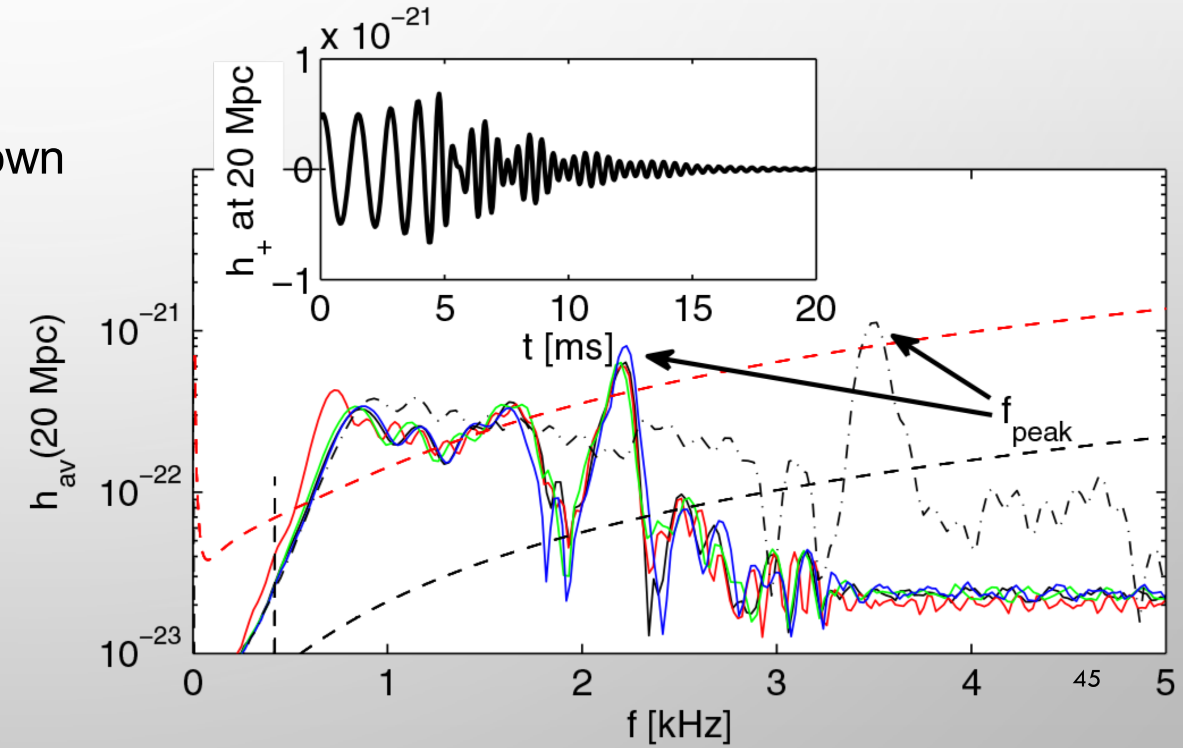
Second harmonics of GW ringdown signal reflects the internal structure.

It appears in 2-4 kHz region.

ringdown



Solid: Shen EoS, black dashed: eosUU



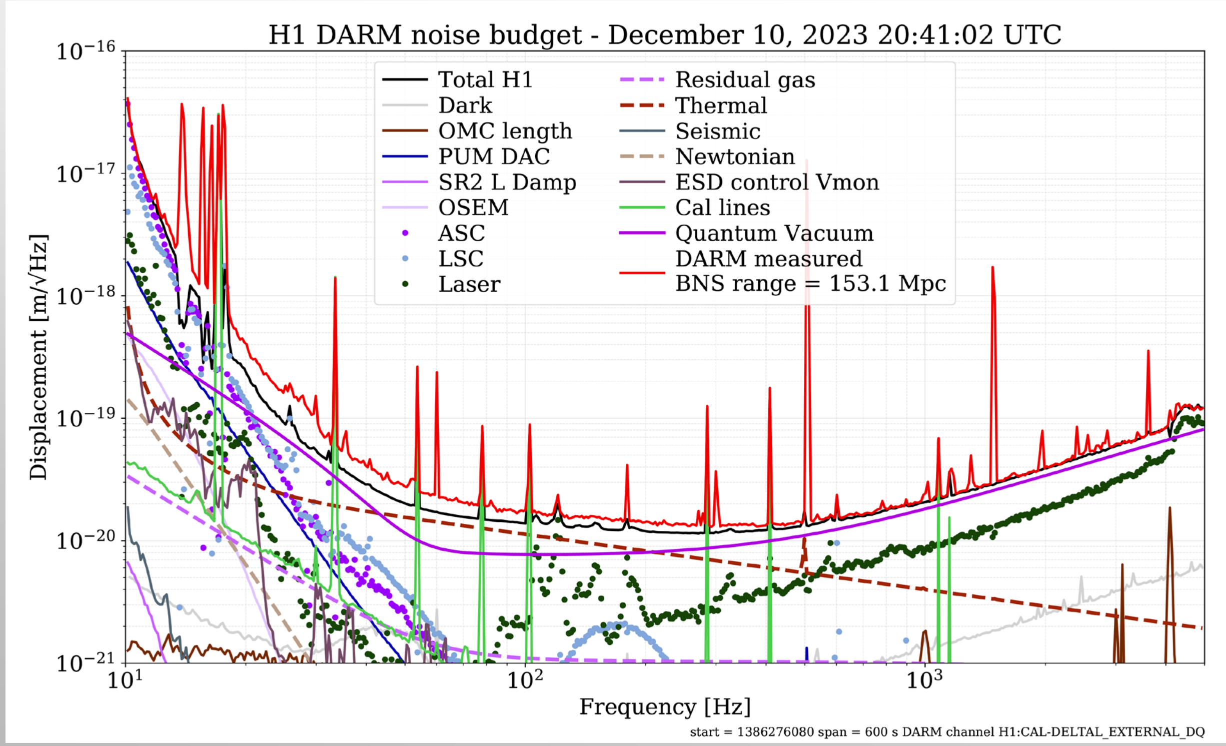
(https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.108.011101)

Measurement of high frequency GW

Noise and systematic error have different frequency dependencies.

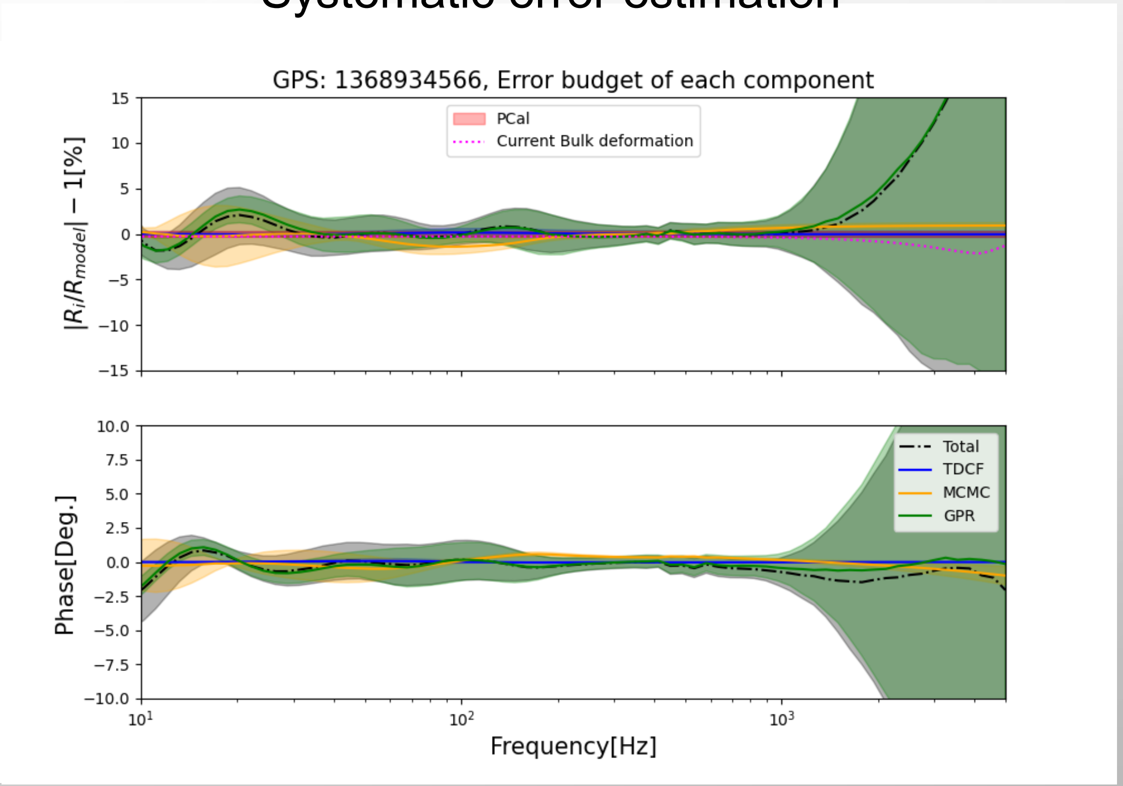
The kHz region is dominated by bulk deformation.

Sensitivity (noise budget)



(https://noisebudget.docs.ligo.org/aligoNB/)

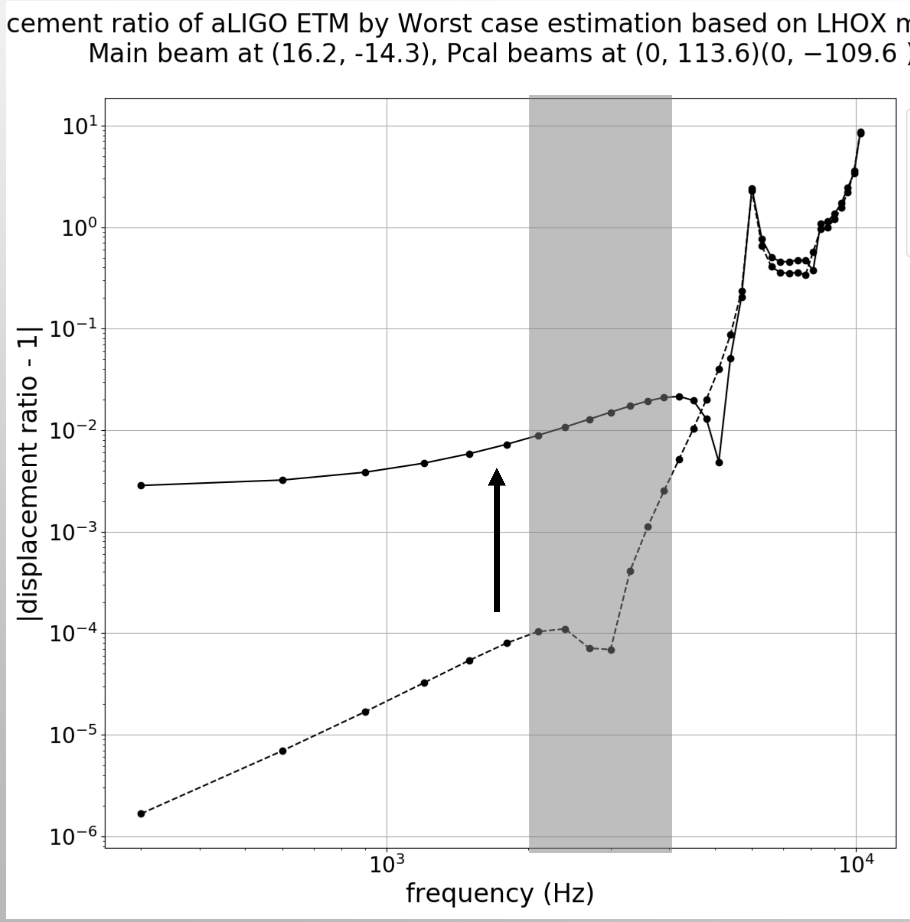
Systematic error estimation

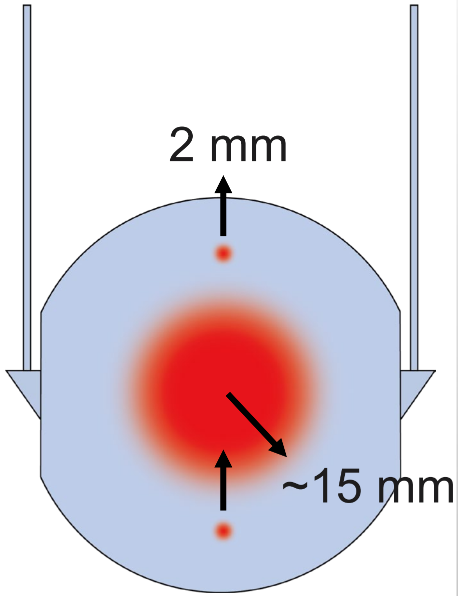


(On the courtesy of Hsiang-Yu Huang)

Sensed deformation by misaligned beams

When the beams are not in the optimized positions, deformation appears as a larger error.





It rises to >1% error with the actual aLIGO's alignment precision.

We have to consider it in calibration for accuracy in high frequency.