

New results from LIGO's fourth gravitational wave observing run

Daiki Tanabe(Academia Sinica)

2025.11.07

GW-CMB 2025



Me

Daiki Tanabe (postdoc in Academia Sinica in Taiwan)

Until 2021:

- Graduate school of SOKENDAI, in KEK CMB group
- Worked on temperature monitoring system of POLARBEAR-2 telescope

Since April, 2021:

- Joined gravitational waves experiment group
- Worked on coating characterization system for LIGO
- Worked on mirror deformation simulation for LIGO
- Working on CHRONOS detector in NCU

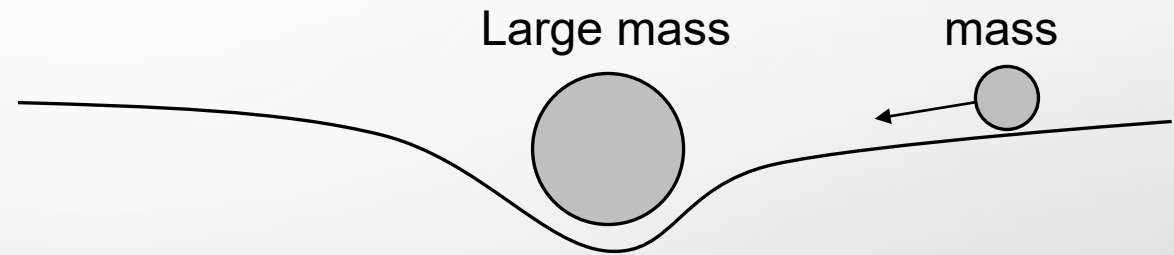


Outline

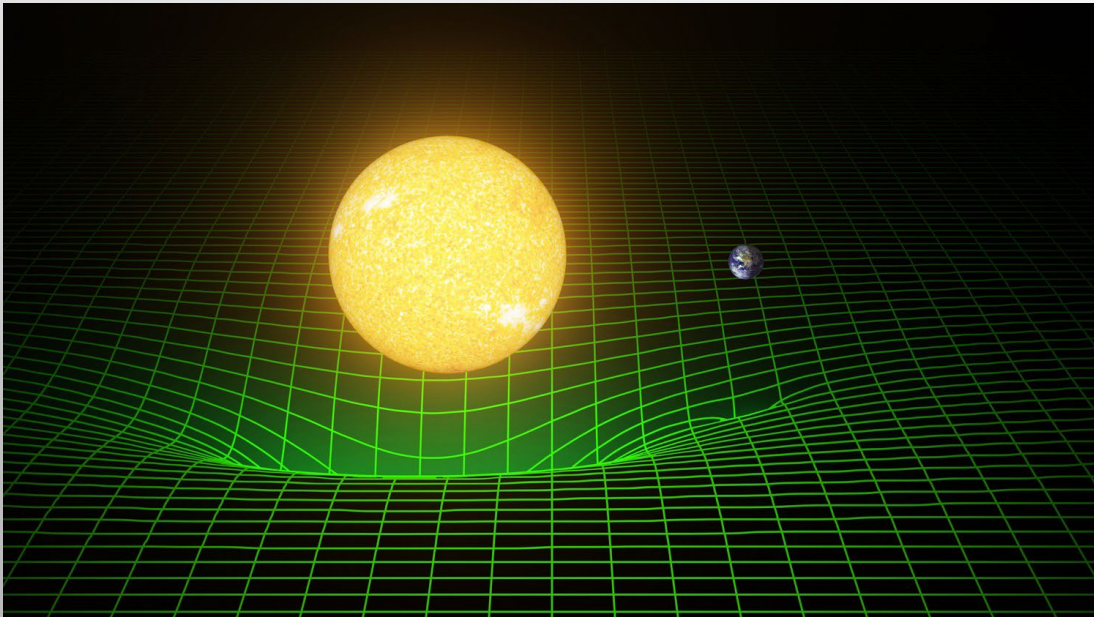
- Gravitational wave science
- Observation principle of LIGO
- Results of LIGO's latest observation run
- Activities in Taiwan
- Summary

Mass and gravity

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



Spacetime distortion -> Gravitational potential



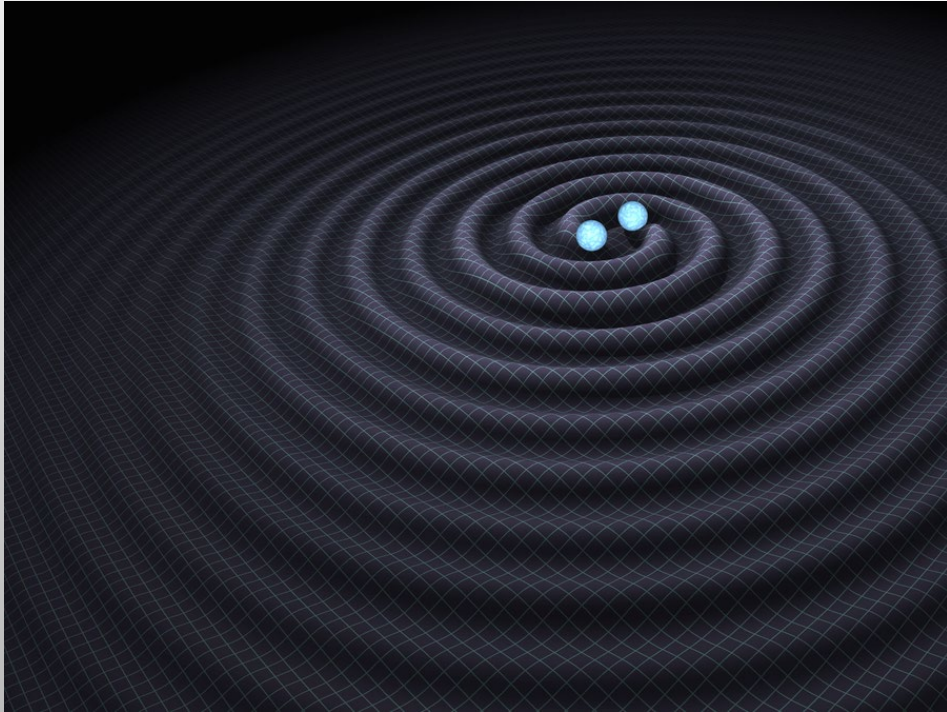
T. Pyle/Caltech/MIT/LIGO Lab

Einstein's equation

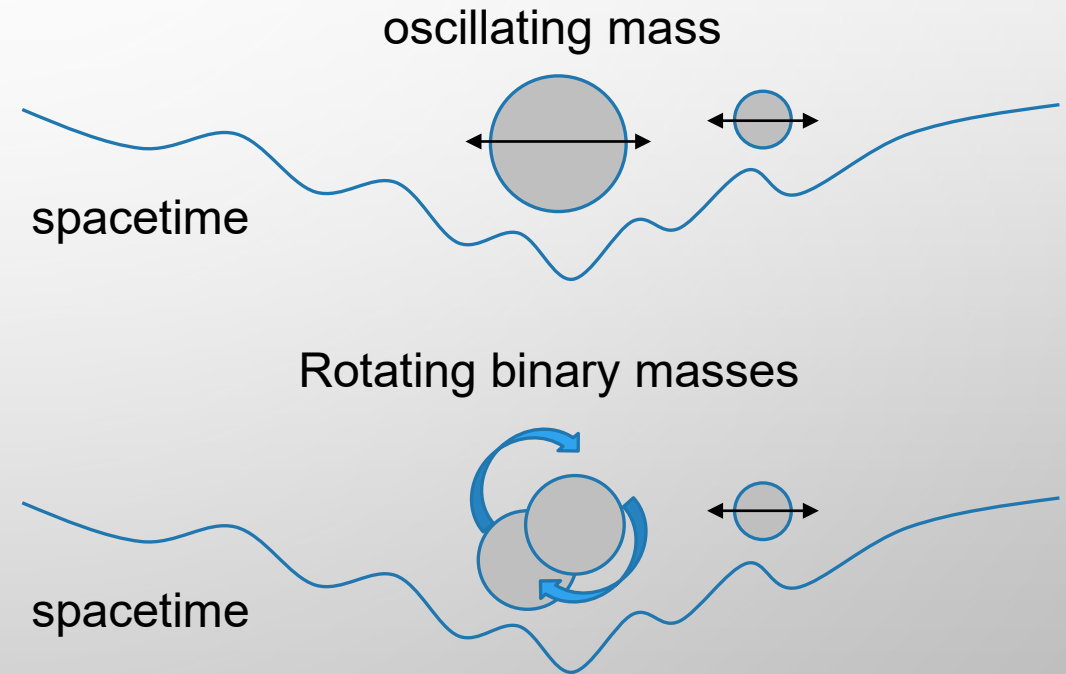
$$\underbrace{G_{\mu\nu}}_{\text{Spacetime curvature}} = \frac{8\pi G}{c^4} \underbrace{T_{\mu\nu}}_{\text{Energy and momentum}}$$

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

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

Spacetime perturbation

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

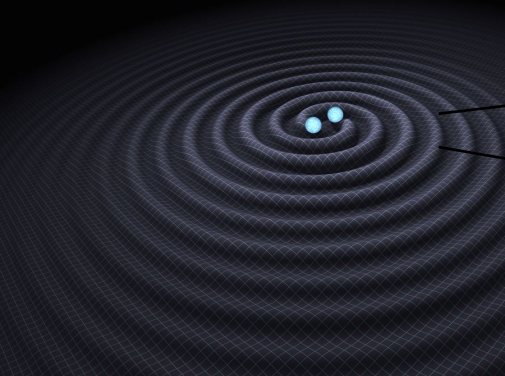
Wave equation

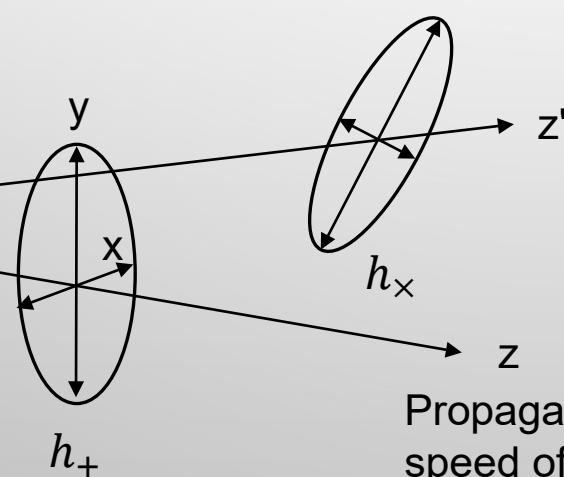
$$\frac{1}{2} \left(\frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \nabla^2 \right) h_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Space components
Quadrupole radiation

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

Lorentz gauge $\nearrow$ Transverse-traceless gauge $\downarrow$





Propagate at speed of light

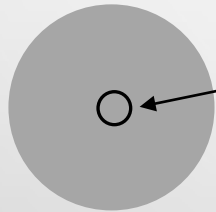
Two polarizations:
Plus-mode and cross-mode

Compact binary

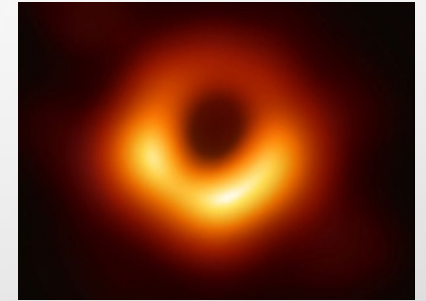
Compact binary = Binary of two point-like objects

Almost the same as “**Neutron star** (NS) pair or **Black hole** (BH) pair”.

Neutron star



Black hole



(<https://spectrum.ieee.org/the-inside-story-of-the-first-picture-of-a-black-hole>)

Remnant after supernova

Mass $< 3 M_{\odot}$

Radius ~ 20 km

Consists of neutrons and
exotic matters

Remnant after supernova

Mass $> 5 M_{\odot}$

Radius > 8 km

Cannot know internal structure

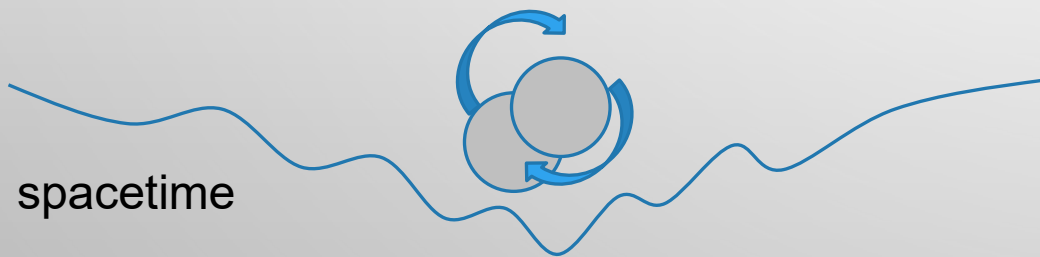
Compact binary

Compact binary = Binary of two point-like objects

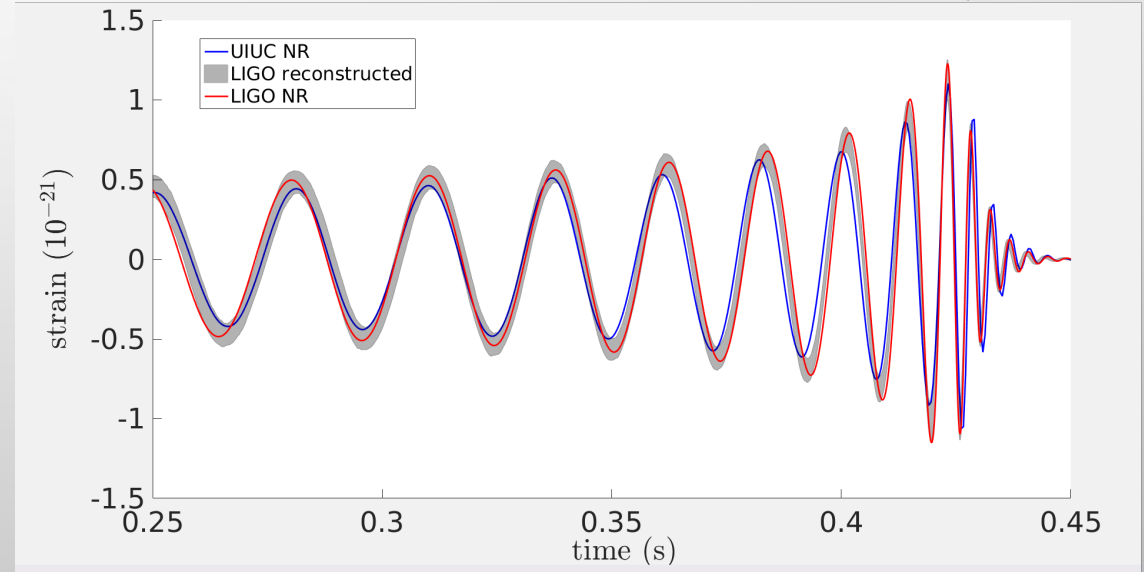
Almost the same as “**Neutron star** (NS) pair or **Black hole** (BH) pair”.

Recently detected GW events are from BH-BH, NS-NS, and BH-NS.

GW from compact binary has an unique waveform.



Reconstructed spacetime strain from the first detected binary black hole merger



Typical waveform of gravitational wave

Waveform has 3 phases.

Inspiral: Rotate around each other.

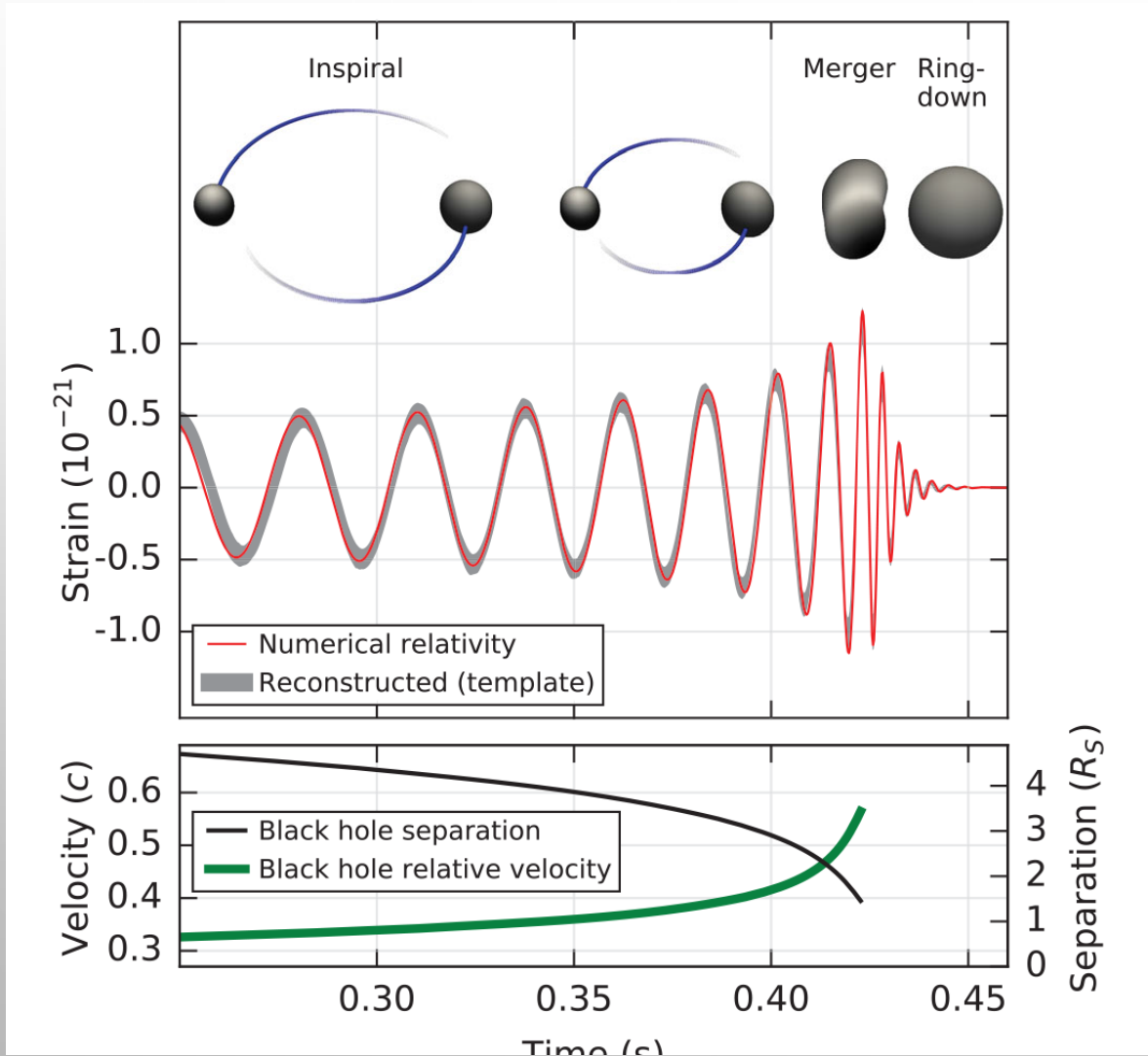
- Mass of sources
- Radius of rotation
- Post-Newtonian terms

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

Briefly saying, each phase tells

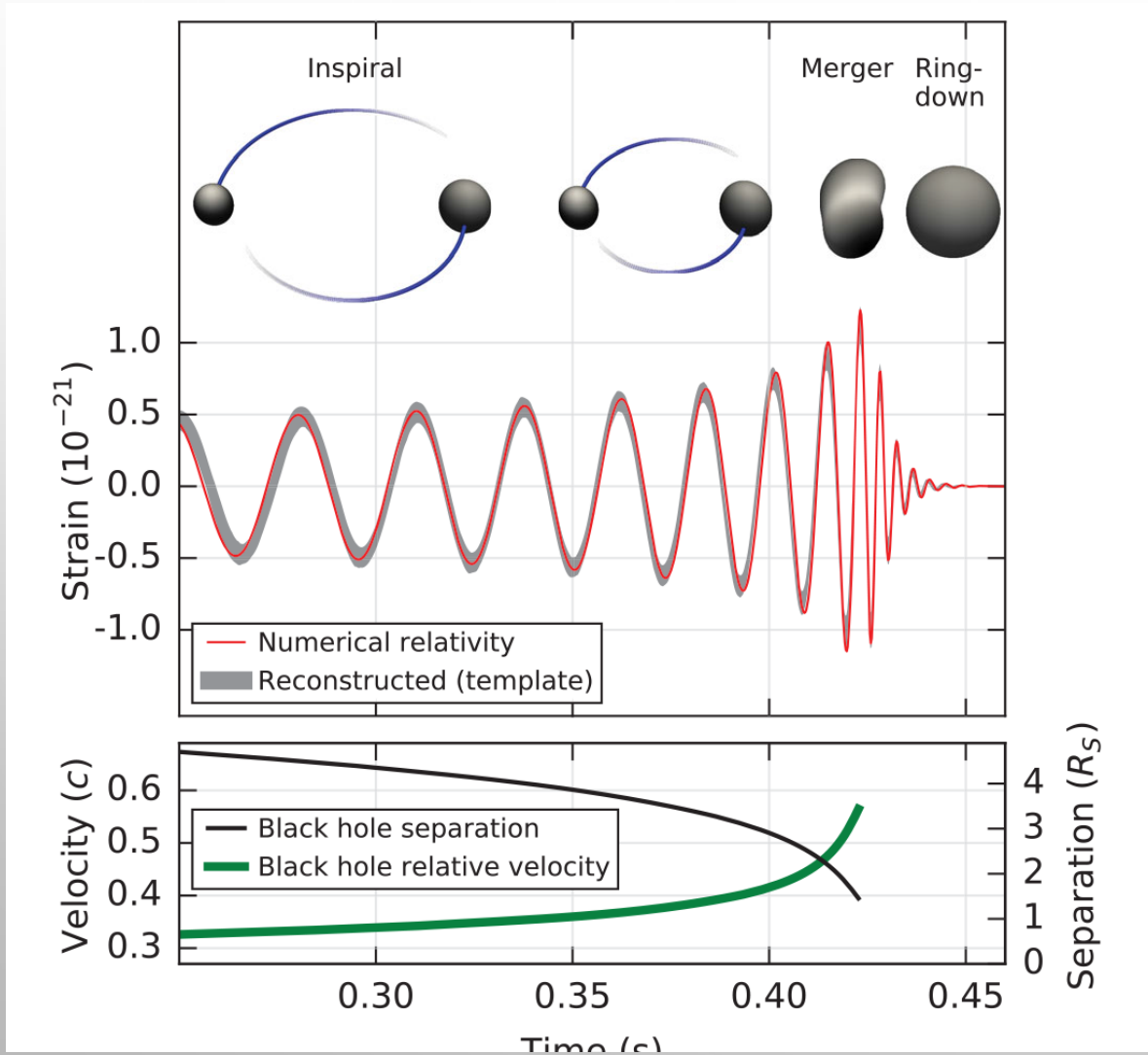
Inspiral: External parameters in weak field.

- Mass, radius, distance...

Merger: Both in strong field.

Ringdown: Internal natures in strong field.

- Deformation, Black hole solutions...



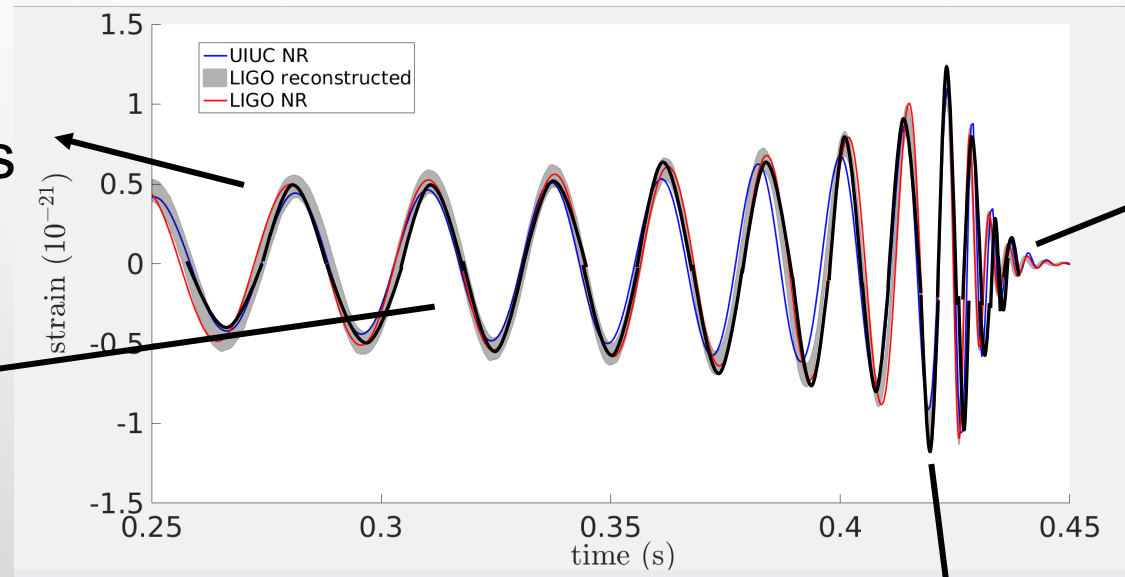
Particle / cosmological physics in gravitational wave

Strong gravity field can cause extremely high energy phenomena.

(Black hole)
Test of gravity theories

Mass, spin

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



(Neutron star)
Exotic particles and
phases

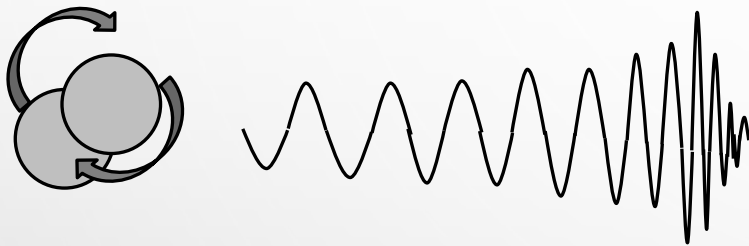
(Black hole)
Test of gravity theories

(Neutron star)
Electromagnetic emission

Hubble constant

Other sources of gravitational waves

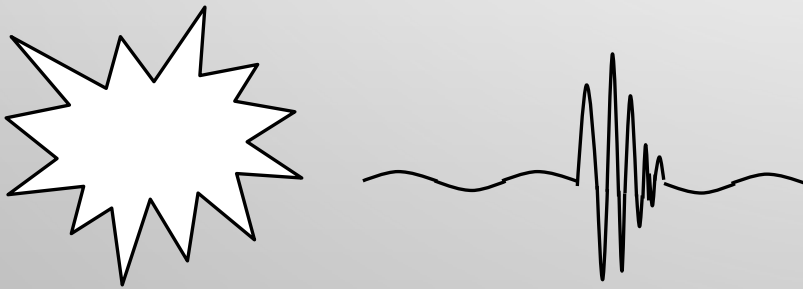
Compact binary mergers



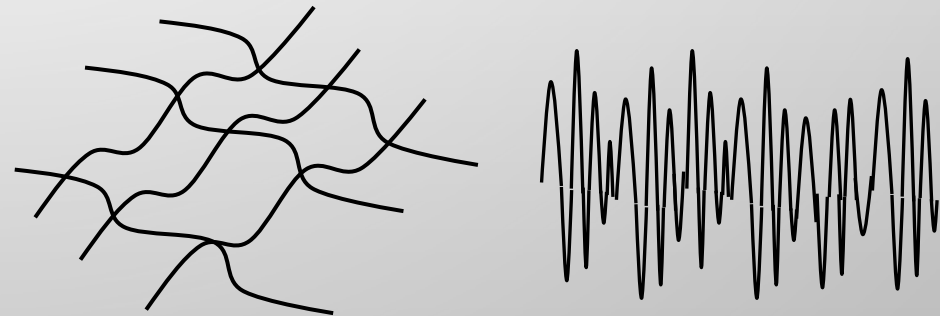
Pulsars



Supernovae



Stochastic background



Detector for tiny fluctuation

However, the spacetime strain of gravitational wave is very small.

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

Schwarzschild radius
Source distance

NS-NS ($1.4M_{\odot} - 1.4M_{\odot}$): $r_g \sim 3 \text{ km}$
Distance: 100 Mpc ($\sim 3 \times 10^{24} \text{ m}$) $\longrightarrow h \sim 1 \times 10^{-21}$

Interferometer is the only solution to detect it.

Gravitational wave detectors



Having many detectors can improve sky coverage and source localization.

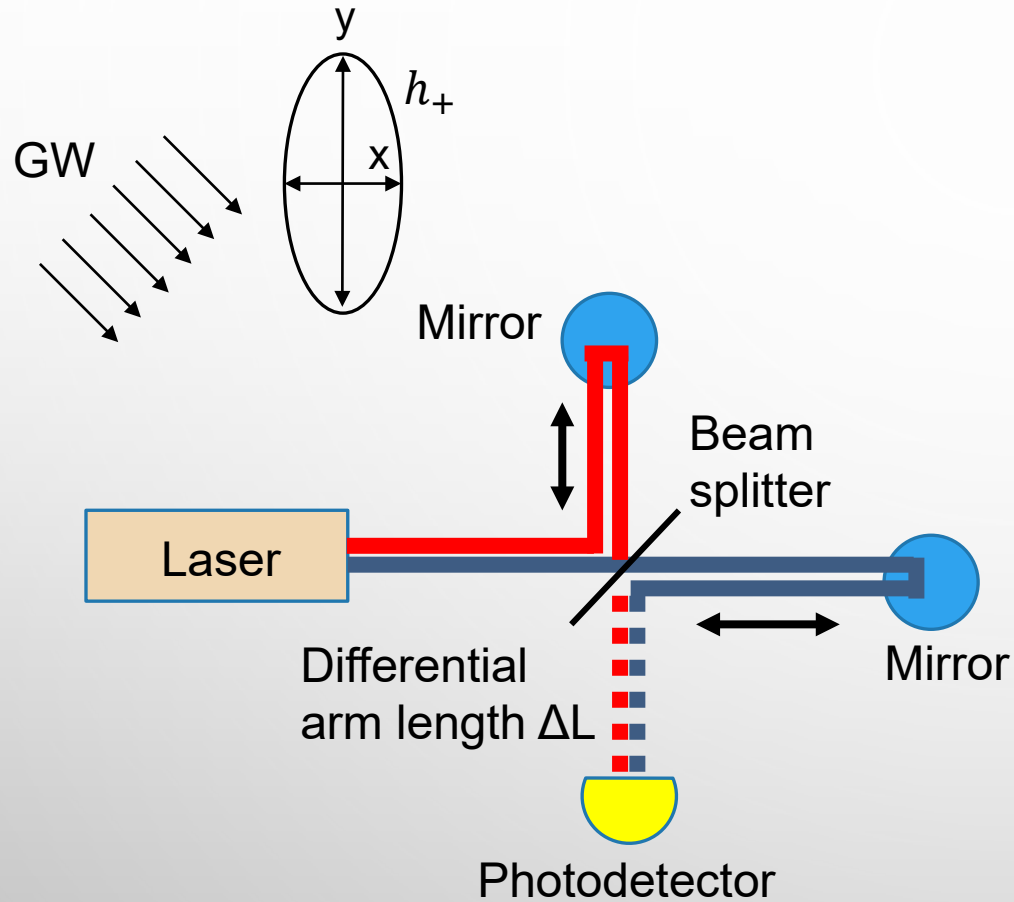
LIGO Scientific Collaboration



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

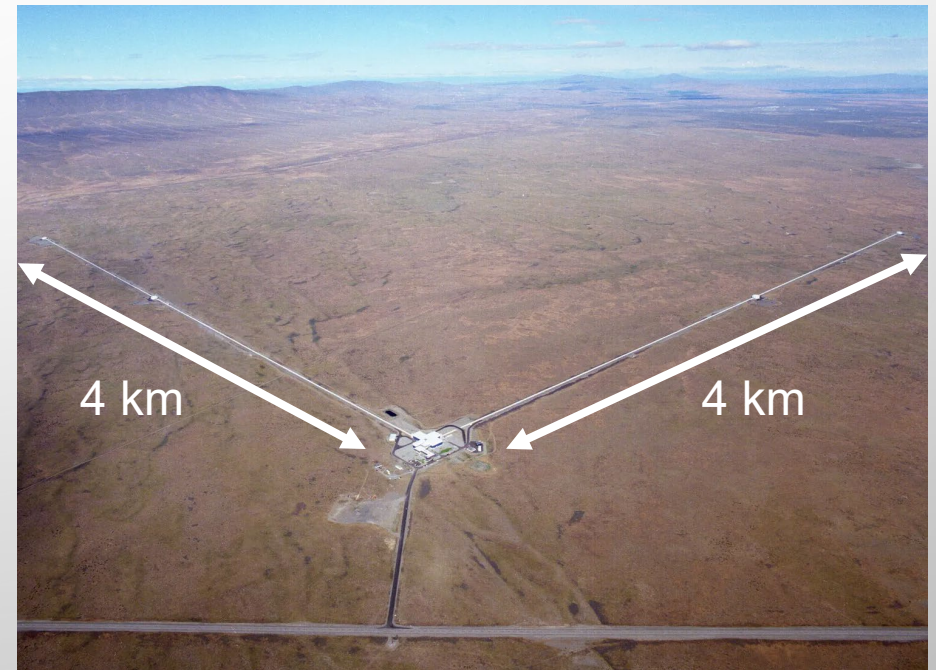
10 collaborators,
2 institutes
from Taiwan.

Michelson interferometer



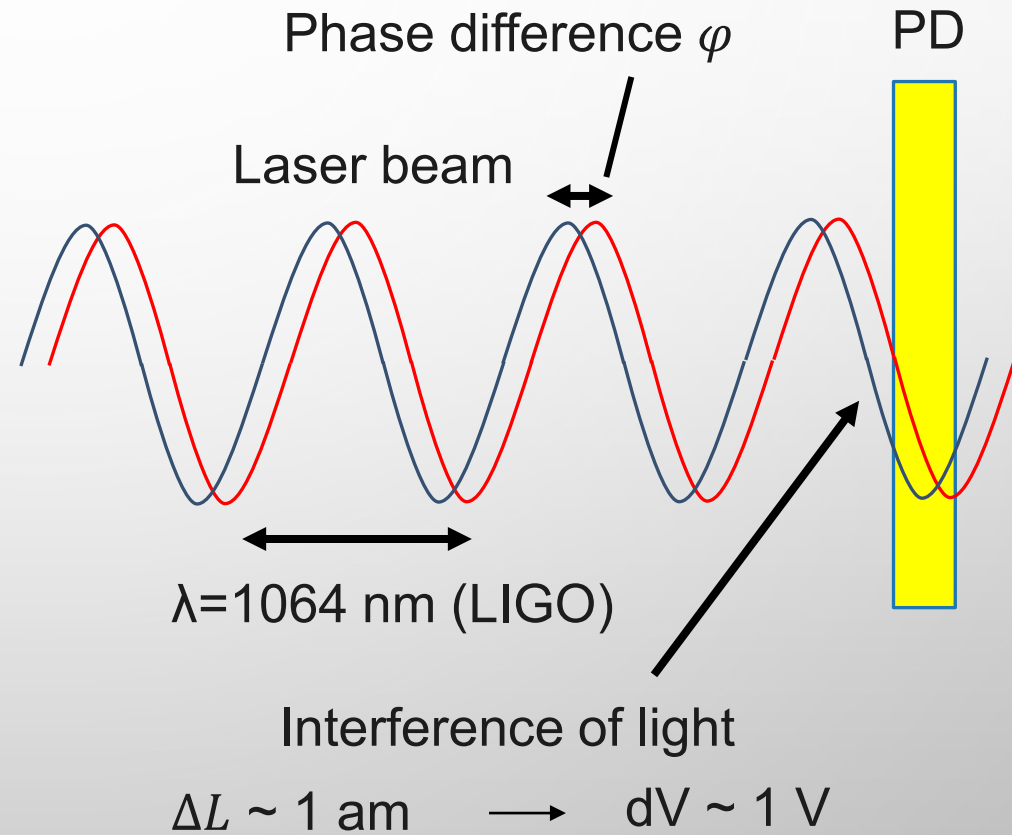
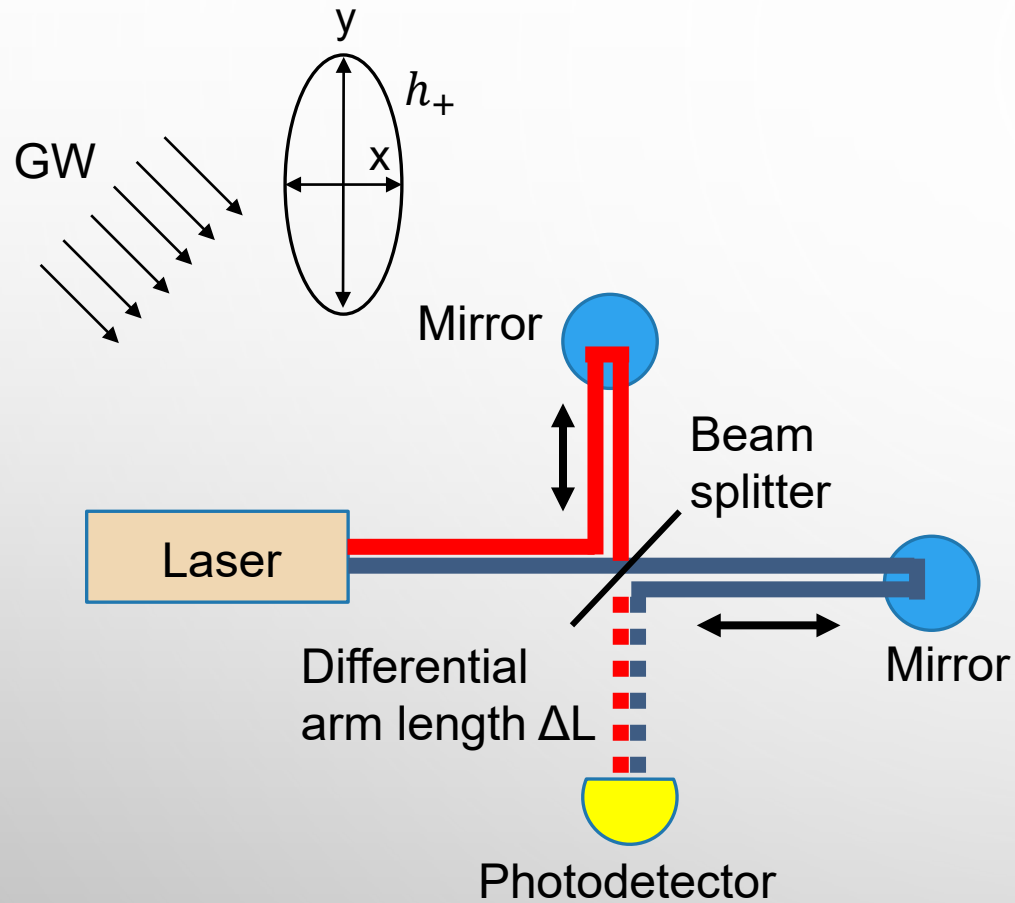
Strain of arm length $\Delta L \sim hL$
(Effective L is extended by multiple reflections)

LIGO Hanford Observatory



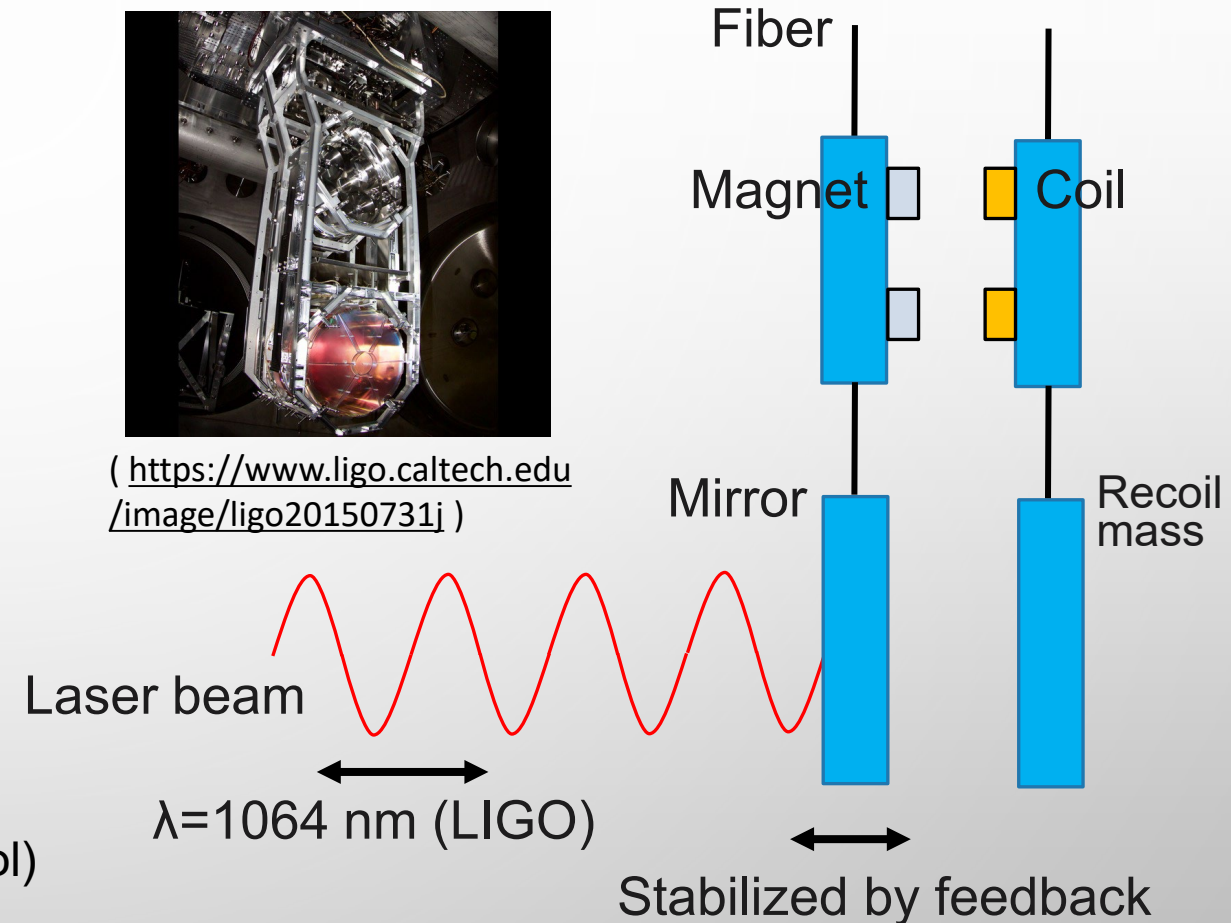
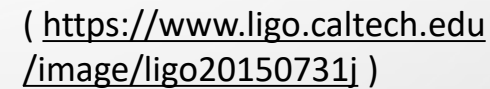
(<https://www.britannica.com/topic/Laser-Interferometer-Gravitational-wave-Observatory#/media/1/1562918/205865>)

Interferometer as sensor



Strain of arm length $\Delta L \sim hL$
(Effective L is extended by multiple reflections)

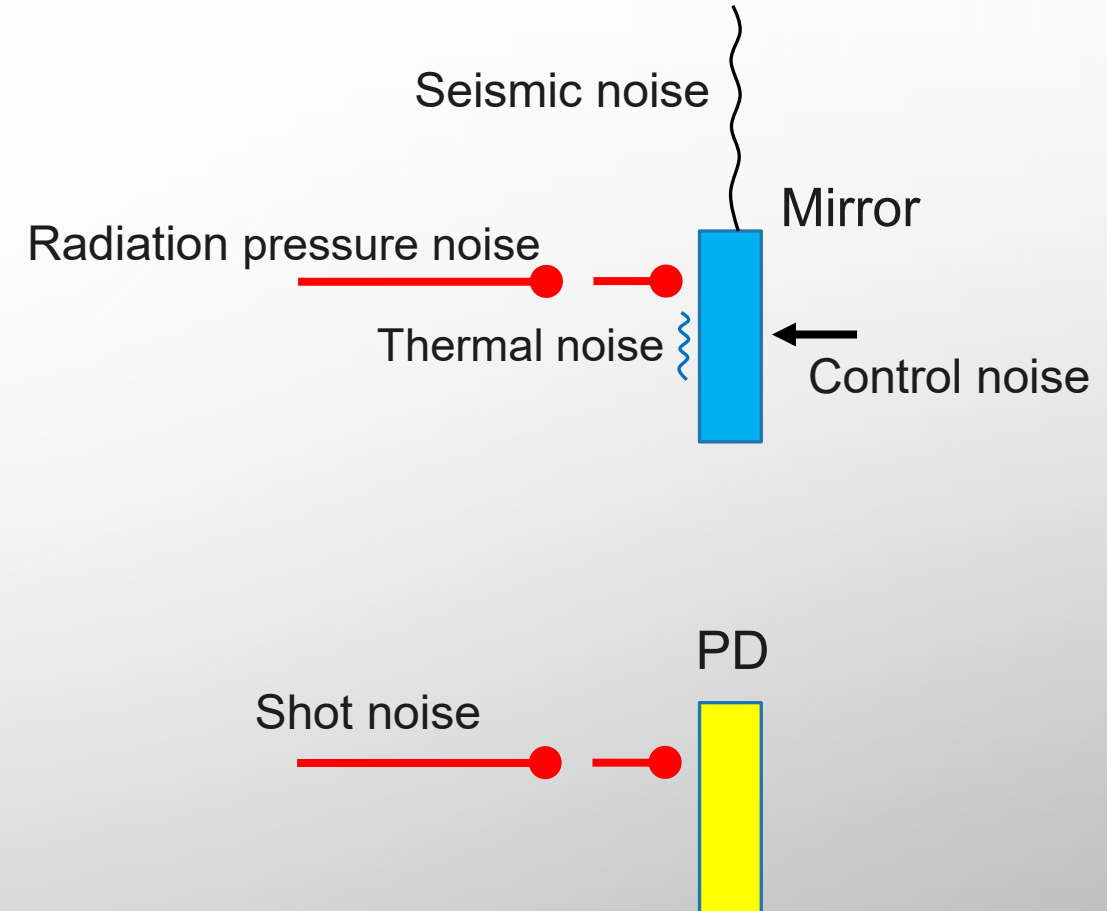
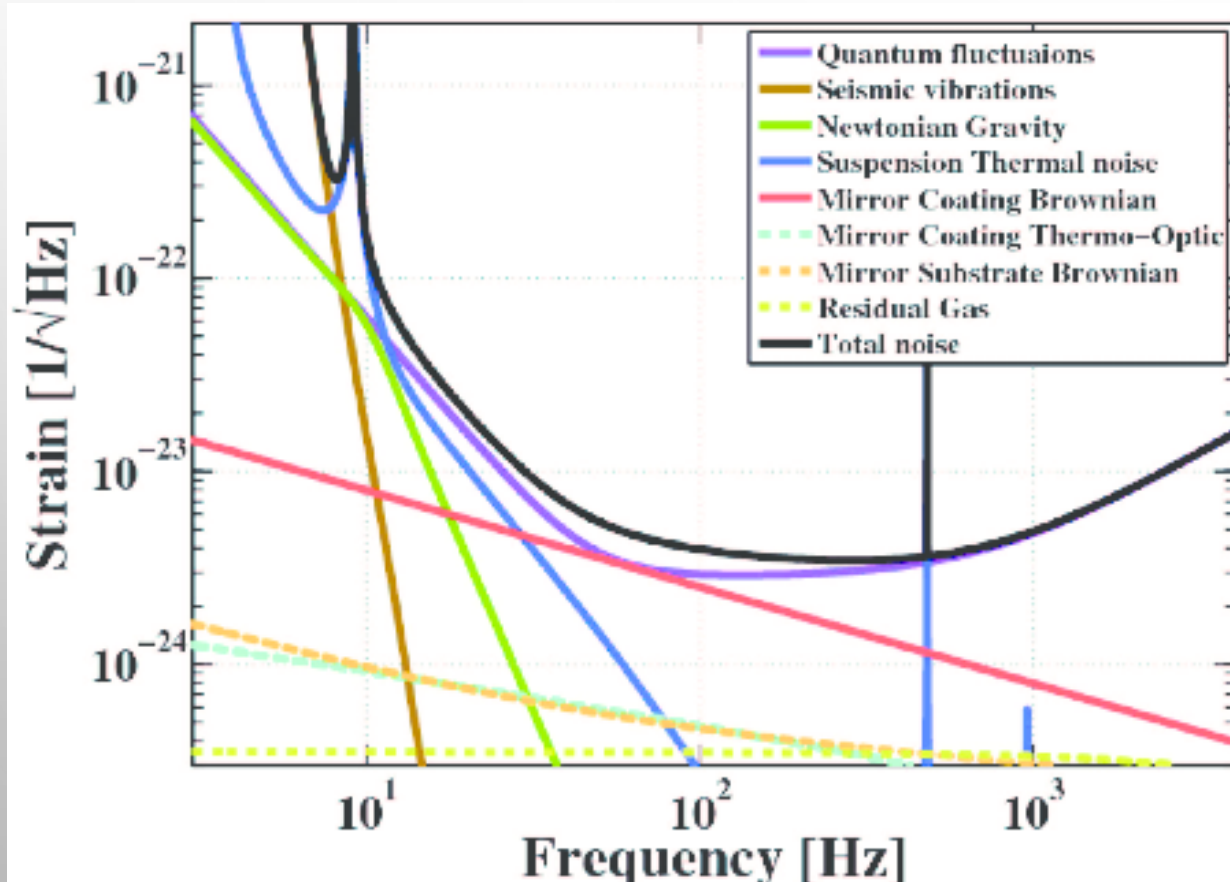
The diagram illustrates the optical layout of a laser interferometer. A laser beam (red line) is emitted from a **Laser** and passes through a **Beam splitter**. The beam is split into two paths: a horizontal path to a **Mirror** and a vertical path to another **Mirror**. The horizontal path is labeled **Differential arm length ΔL** . Both beams reflect back to the beam splitter and recombine. The recombined beam is directed to a **Photodetector** (yellow semi-circle). Two feedback loops are shown: **Feedback (local control)** (green arrows) and **Feedback (DARM control)** (blue arrows). A coordinate system with x and y axes and a vertical arrow labeled h_+ is shown, along with **GW** (gravitational wave) waves represented by parallel lines.



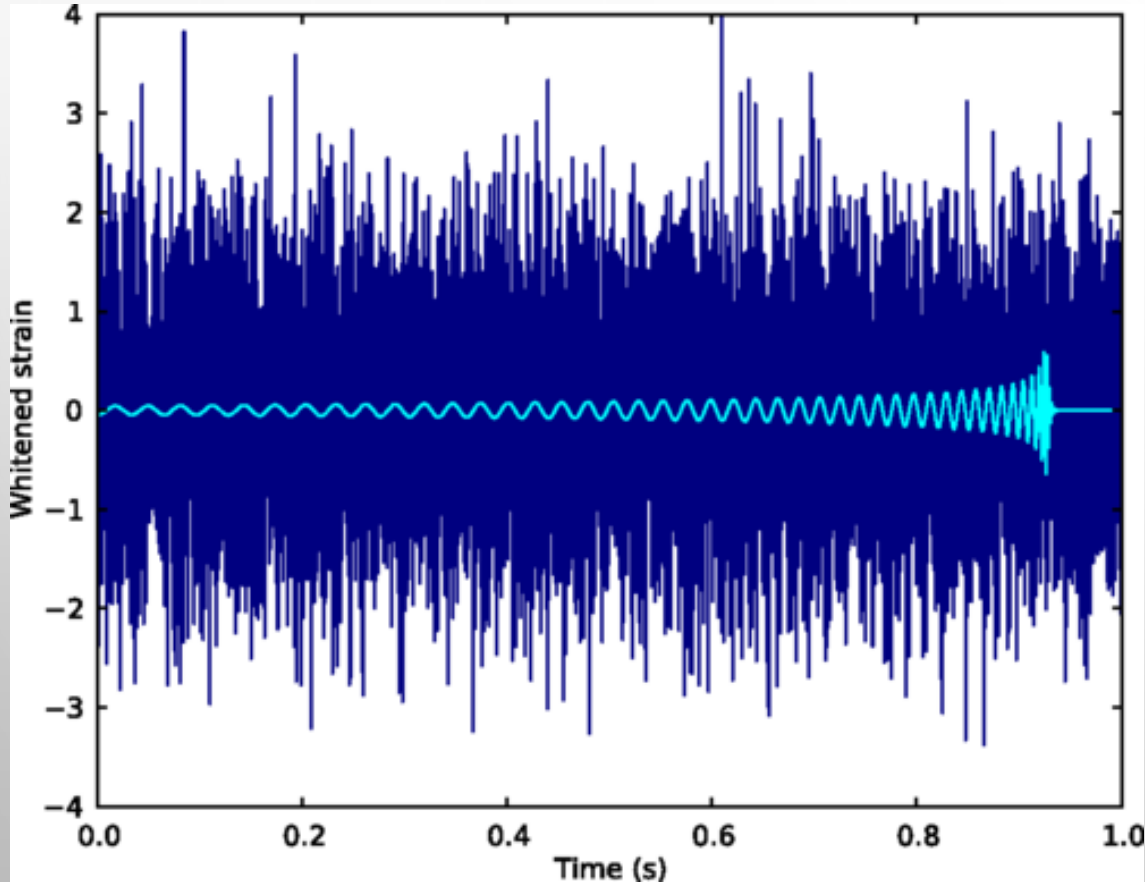
18

Noise sources of detector

Strain sensitivity of LIGO in the third run (simplified)



Event detection



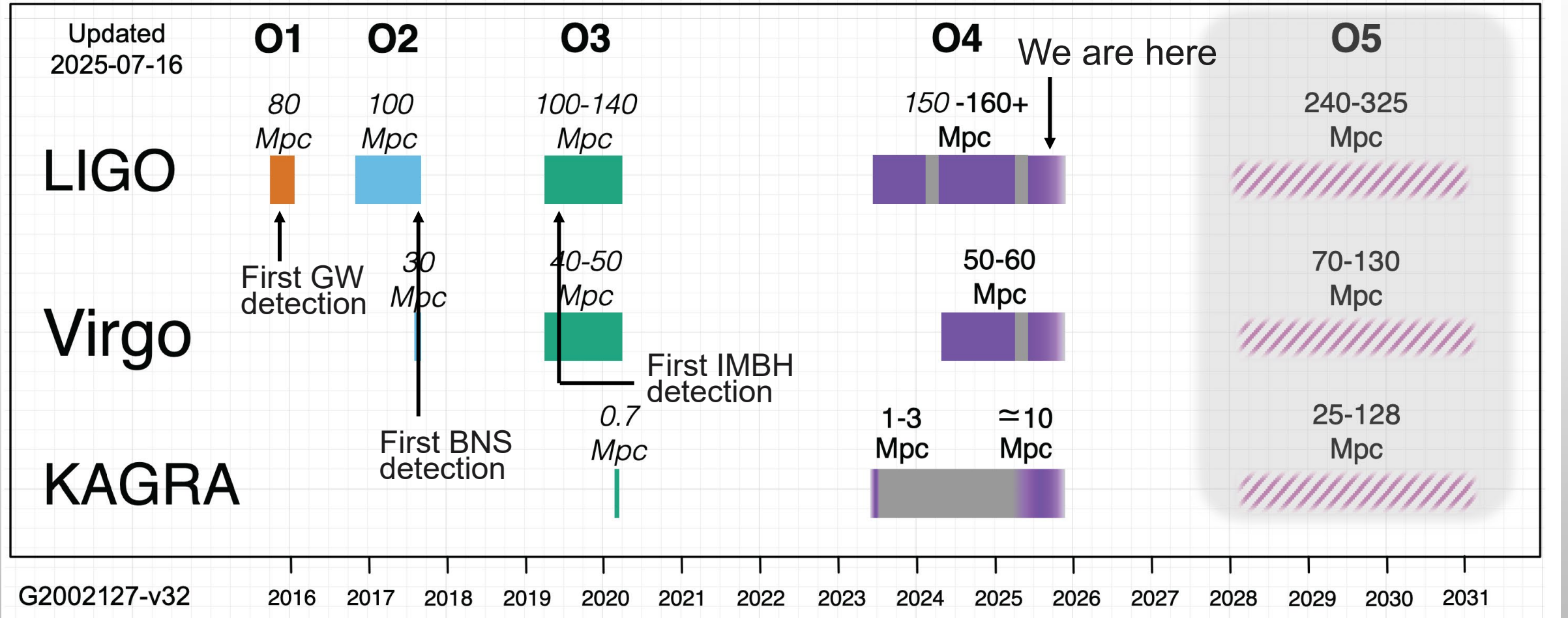
GW signal looks covered by noise.

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

Event detection and alarm are automated.

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

Observation history

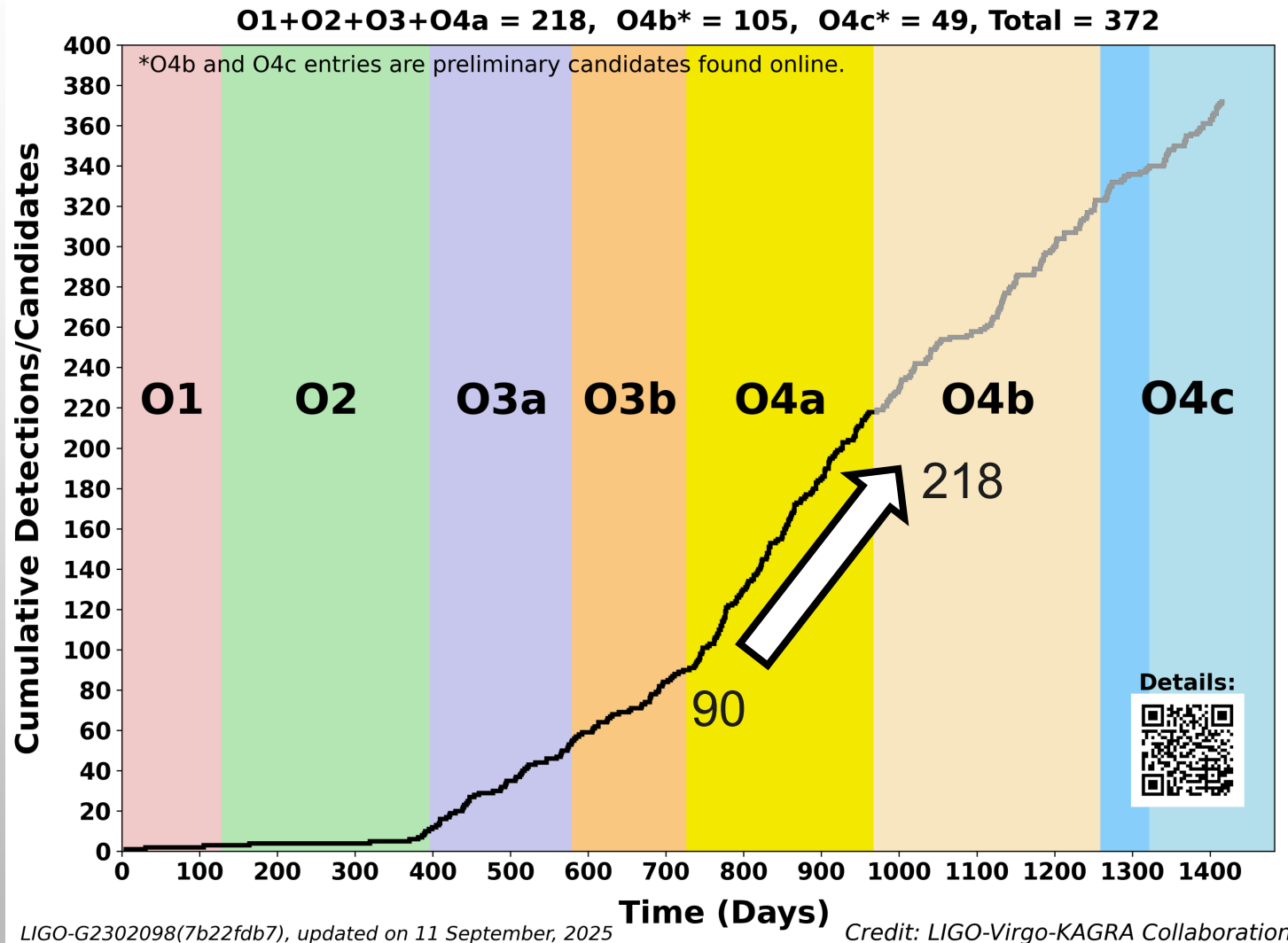


(<https://observing.docs.ligo.org/plan/>)

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

1 pc: ~ 3.3 light years

Fourth observing run



Since 2023 May 24 15:00:00 UTC

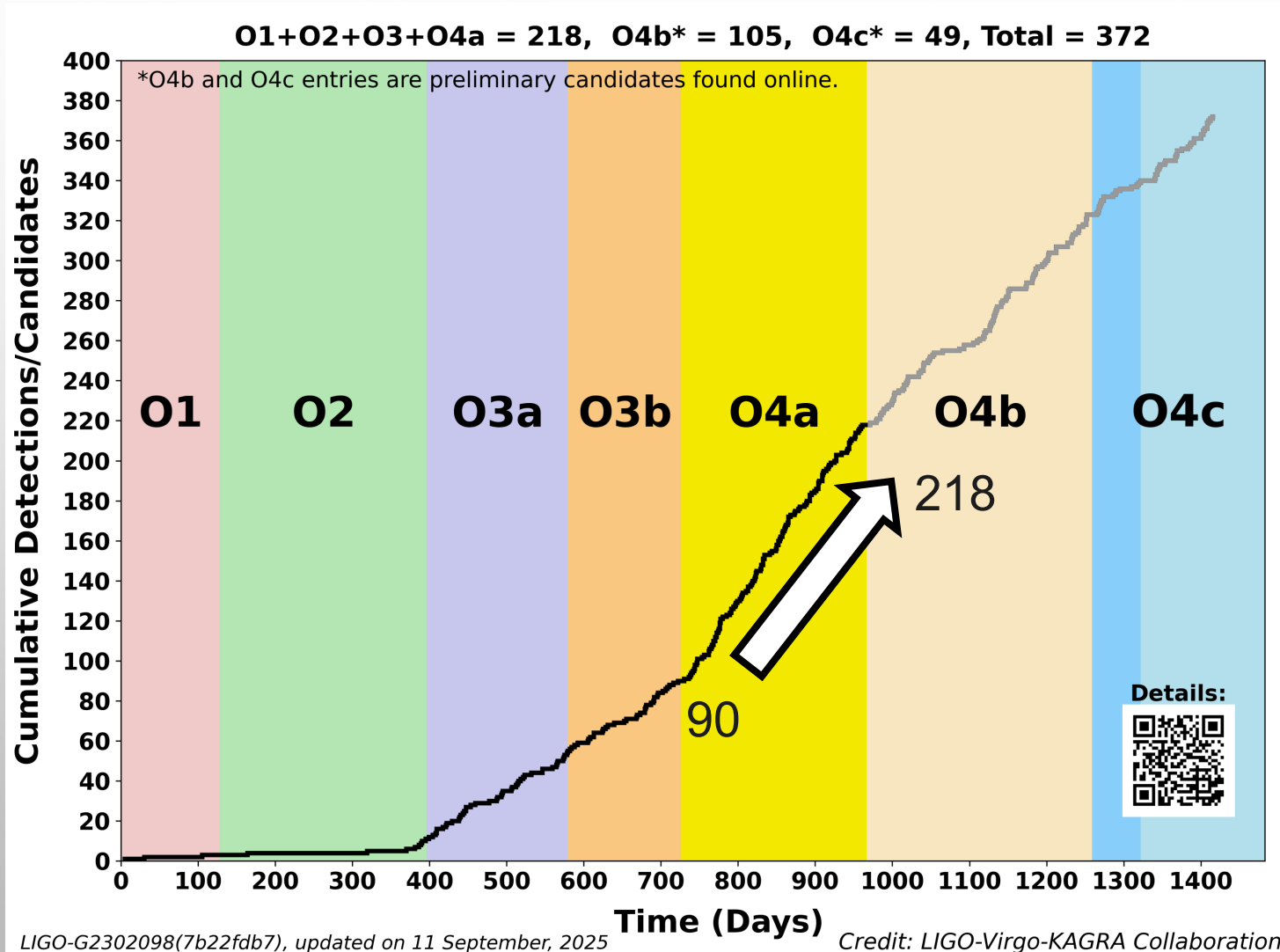
Until 2024 Jan. 16 16:00:00 UTC

Detected 128 candidates of GW events.

Three members from NCU joined operation at the observation site.

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

Fourth observing run



First detection era



Statistical evaluation era

Publications based on O4a data

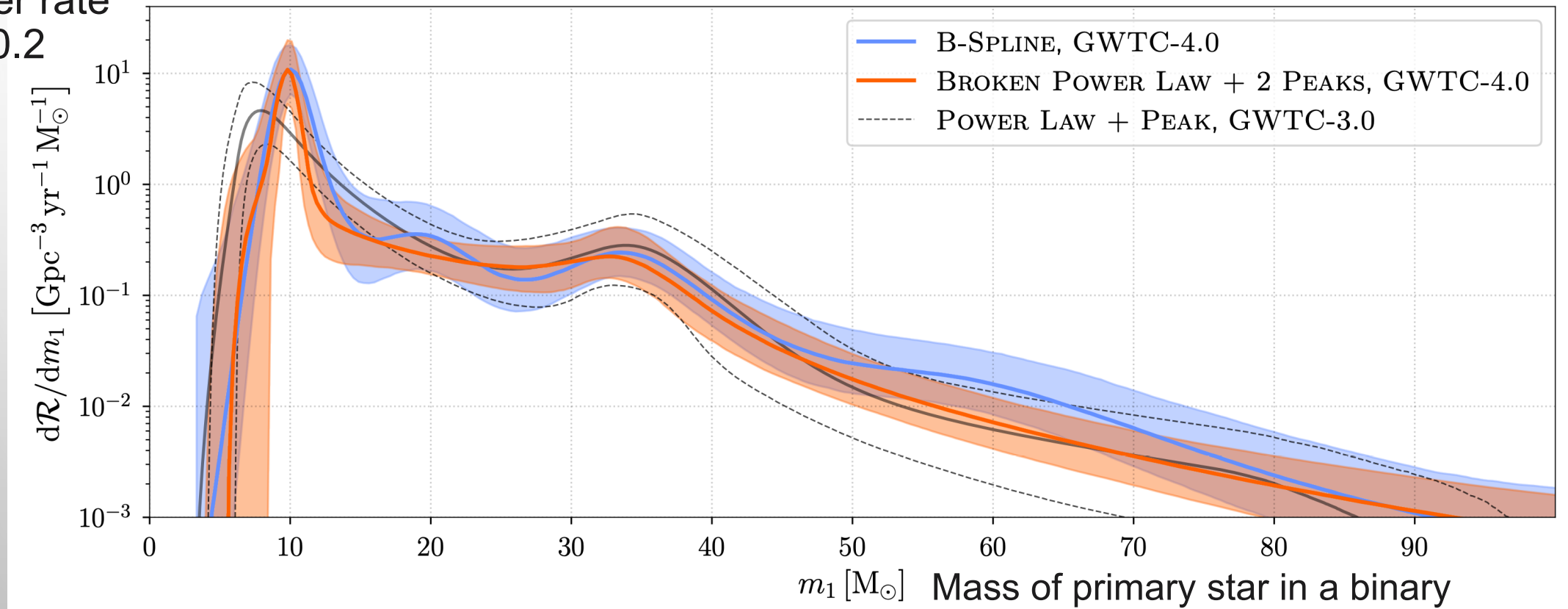
- Observation of Gravitational Waves from the Coalescence of a 2.5-4.5 M_{sun} Compact Object and a Neutron Star, *Astrophys. J. Lett.* 970, L34 (2024), arXiv: 2404.04248
- Swift-BAT GUANO follow-up of gravitational-wave triggers in the third LIGO-Virgo-KAGRA observing run, *Astrophys. J.* 980, 207 (2025), 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 M_{sun} , 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
- Directed searches for gravitational waves from ultralight vector boson clouds around merger remnant and galactic black holes during the first part of the fourth LIGO-Virgo-KAGRA observing run, arXiv: 2509.07352
- 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

Publications based on O4a data

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Population properties of merging compact binaries (1)

Merger rate
at $z=0.2$



(<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.

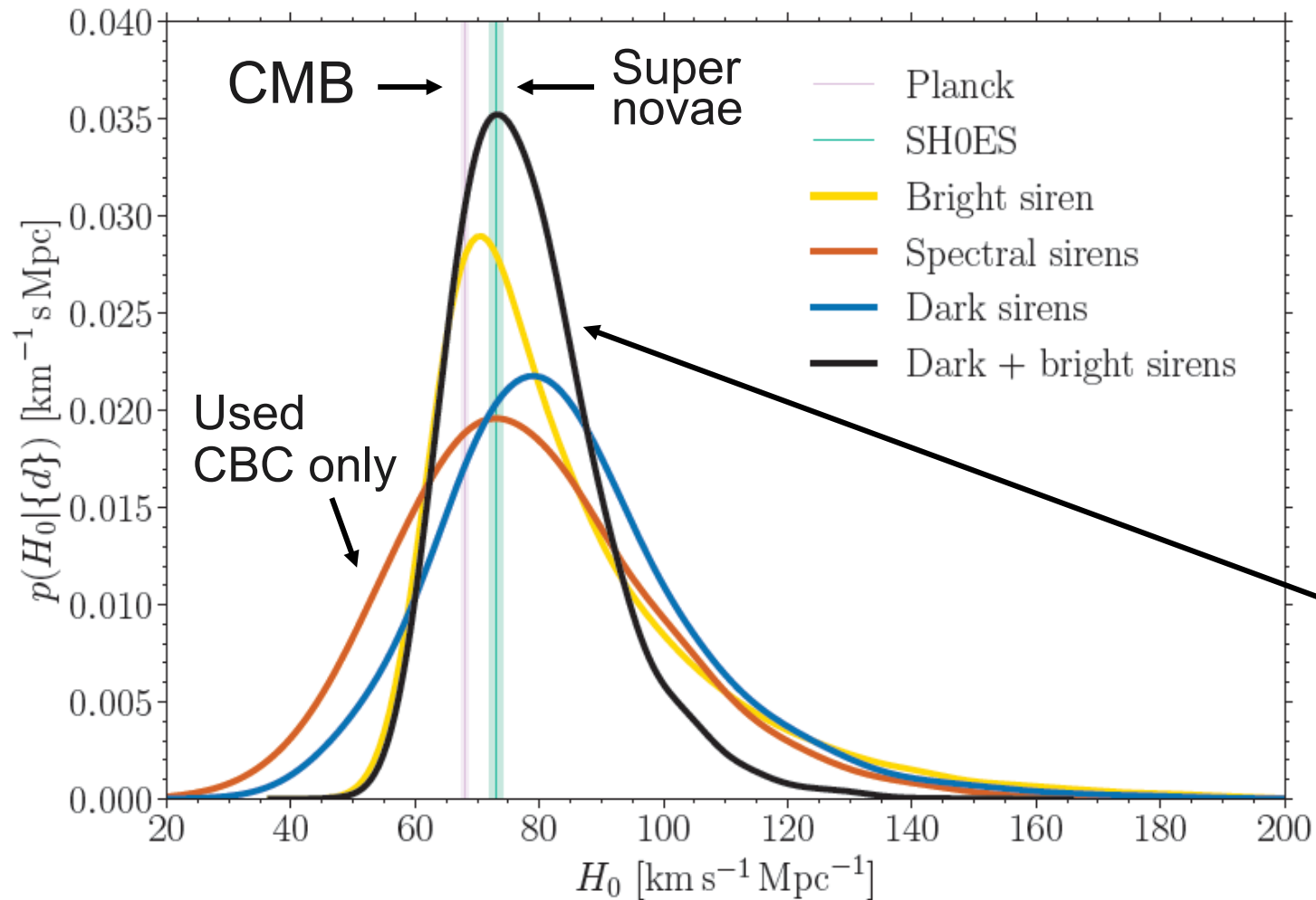
GW provides luminosity distance of the sources.

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)



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

All methods were consistent.

Uncertainties are comparable.

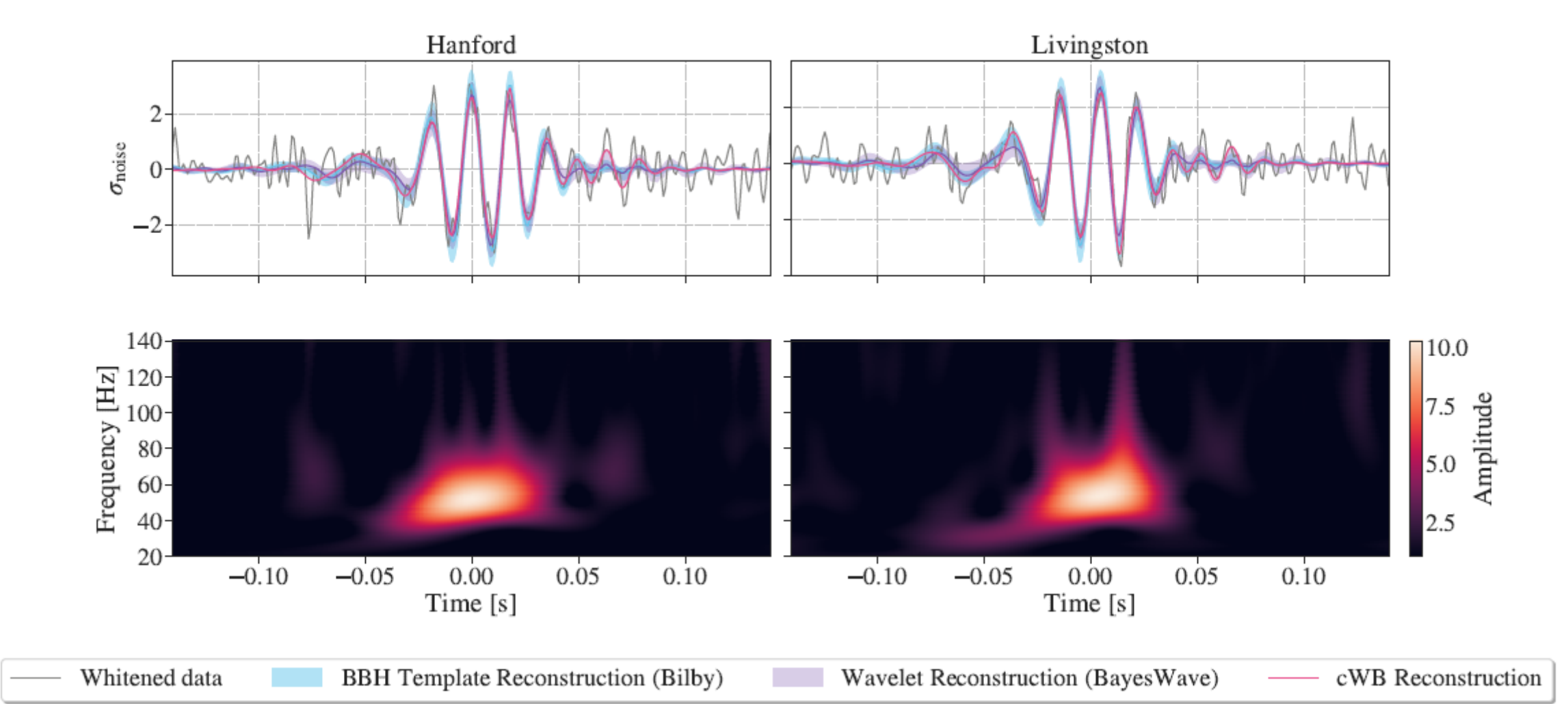
No evidence of modified gravity.

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>)

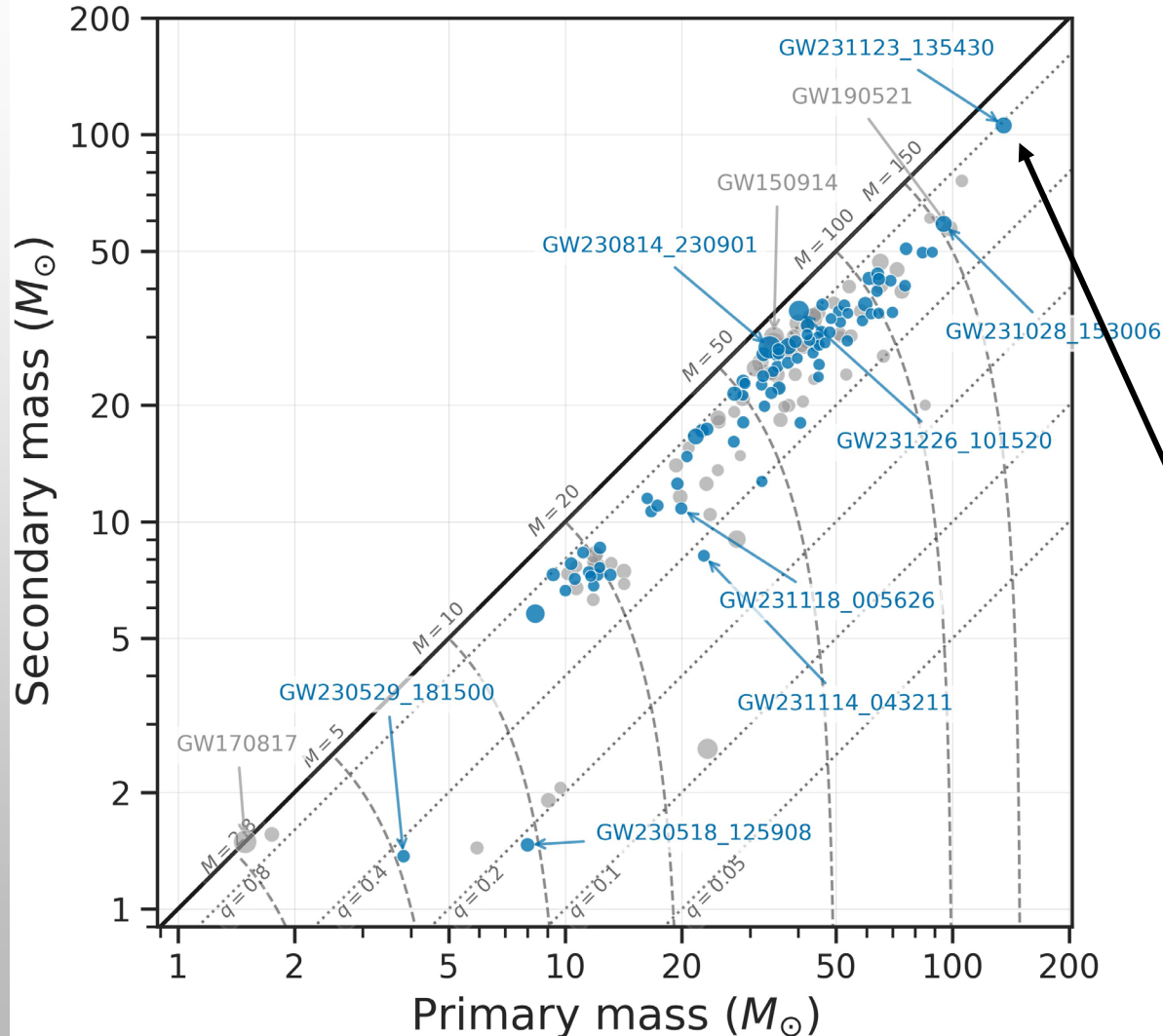
GW231123: a Binary Black Hole Merger with Total Mass 190-265 $M_{\odot}$ (1)



(<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)



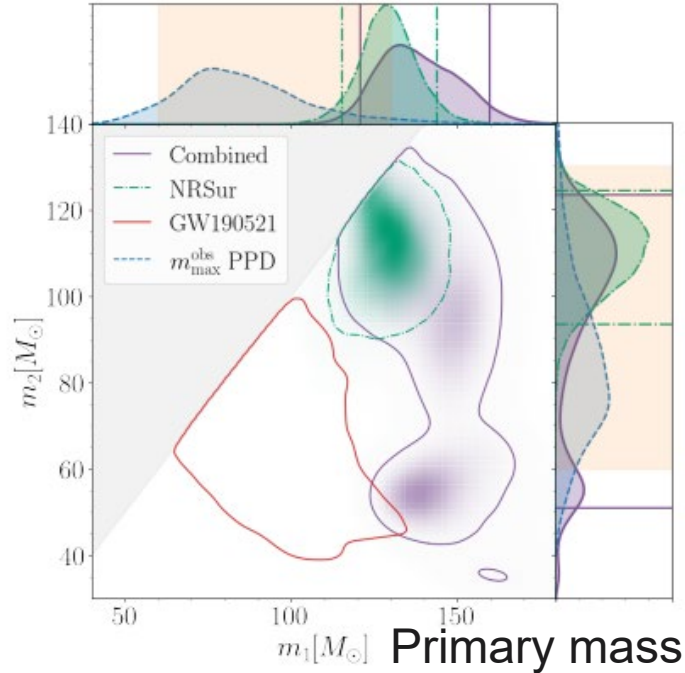
$100M_{\odot} - 100000M_{\odot}$ BH are rarely found.
(Intermediate mass black hole)

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

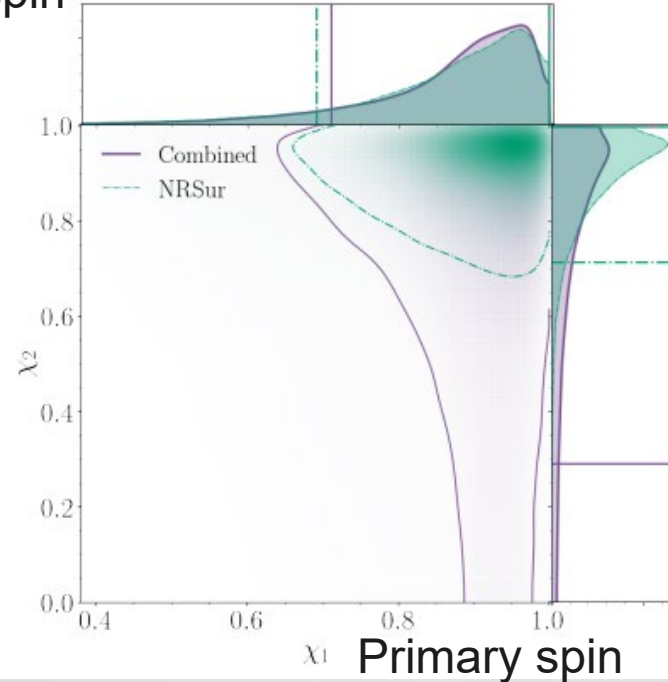
Sources of this event were in this region.

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

Secondary mass



Secondary spin



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

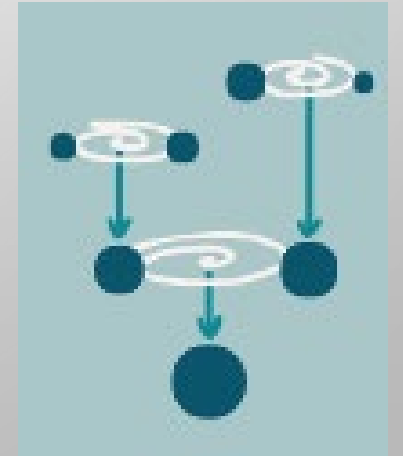
Luminosity distance: 0.7 – 4.1 Gpc

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

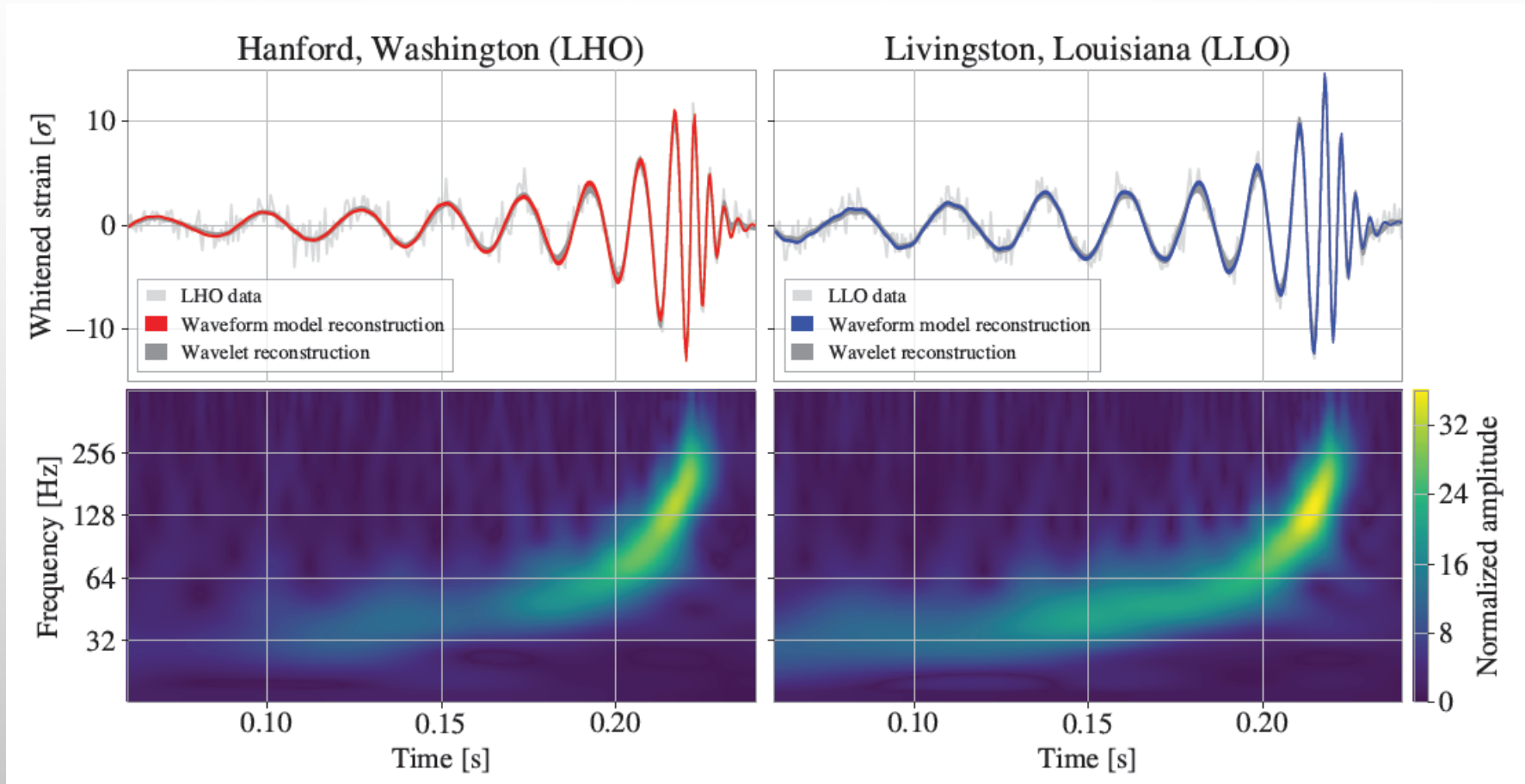
Network SNR: 22.5

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

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)



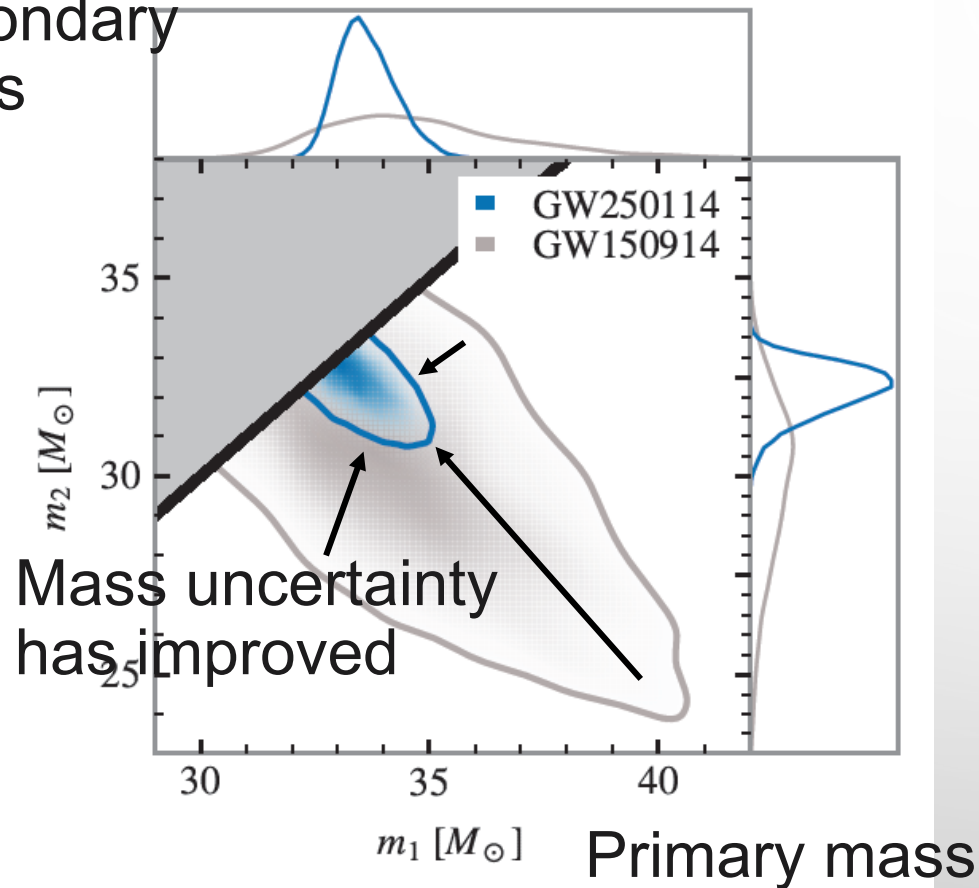
(<https://arxiv.org/abs/2509.08054>)

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)

Secondary
mass



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 magnitude is similar to the first detection, but the precision has improved.

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

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)



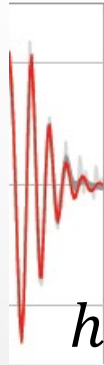
GW detector is insensitive to charge

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)



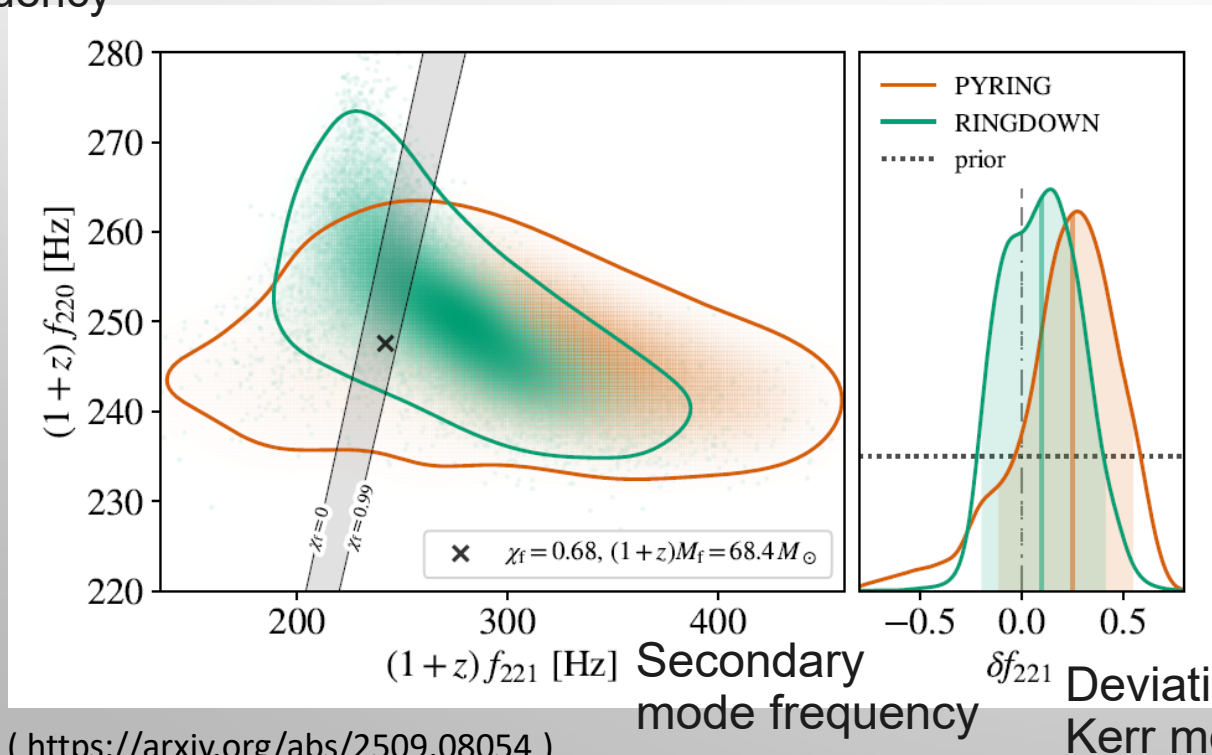
Ringdown modes:

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

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

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

Primary mode frequency



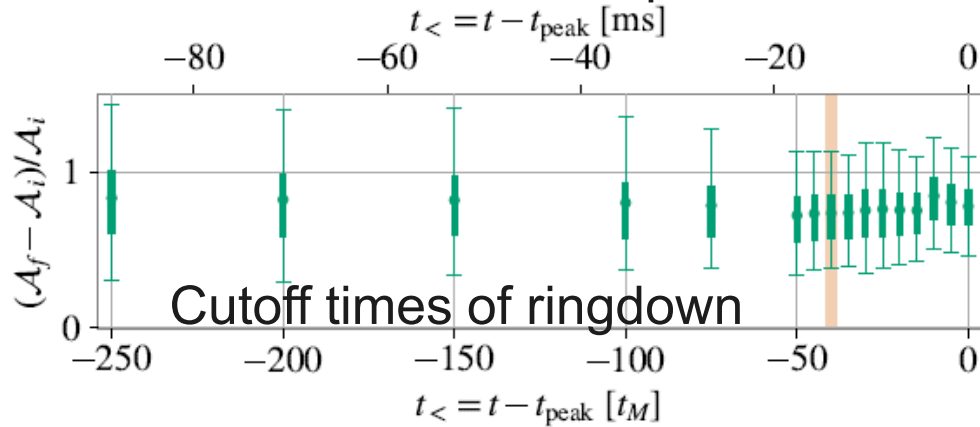
Quasi-normal modes were consistent with Kerr solution.



Valid to test Hawking's area law.

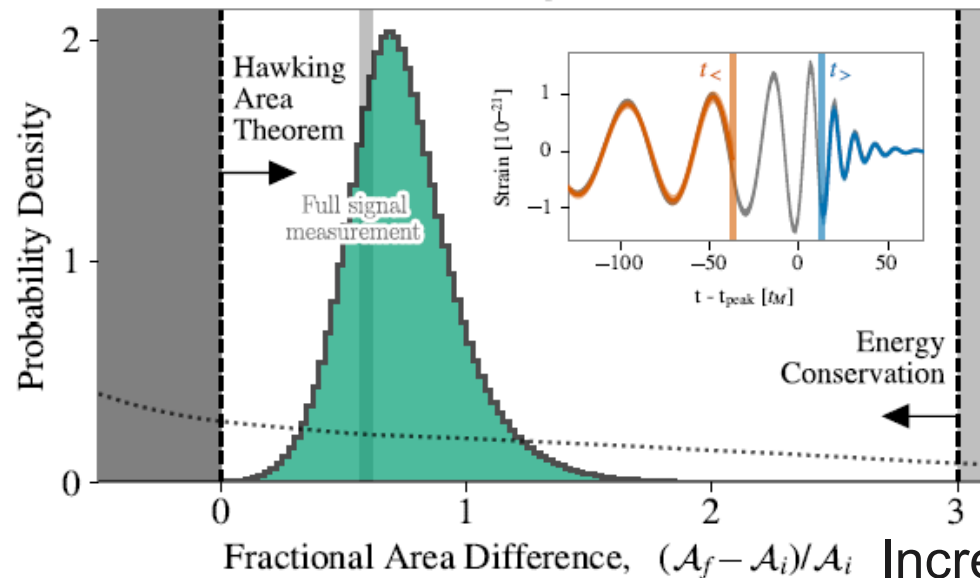
GW250114: Testing Hawking's area law and the Kerr nature of black holes (5)

Cutoff times of in-spiral



Calculated area with assumptions of
(1) general relativity at in-spiral and ringdown,
(2) Kerr black holes.

Results favored increase of area at $>3.3\sigma$
regardless of cutoff time of each phase.
-> Consistent with Hawking's area law.



Increase of area

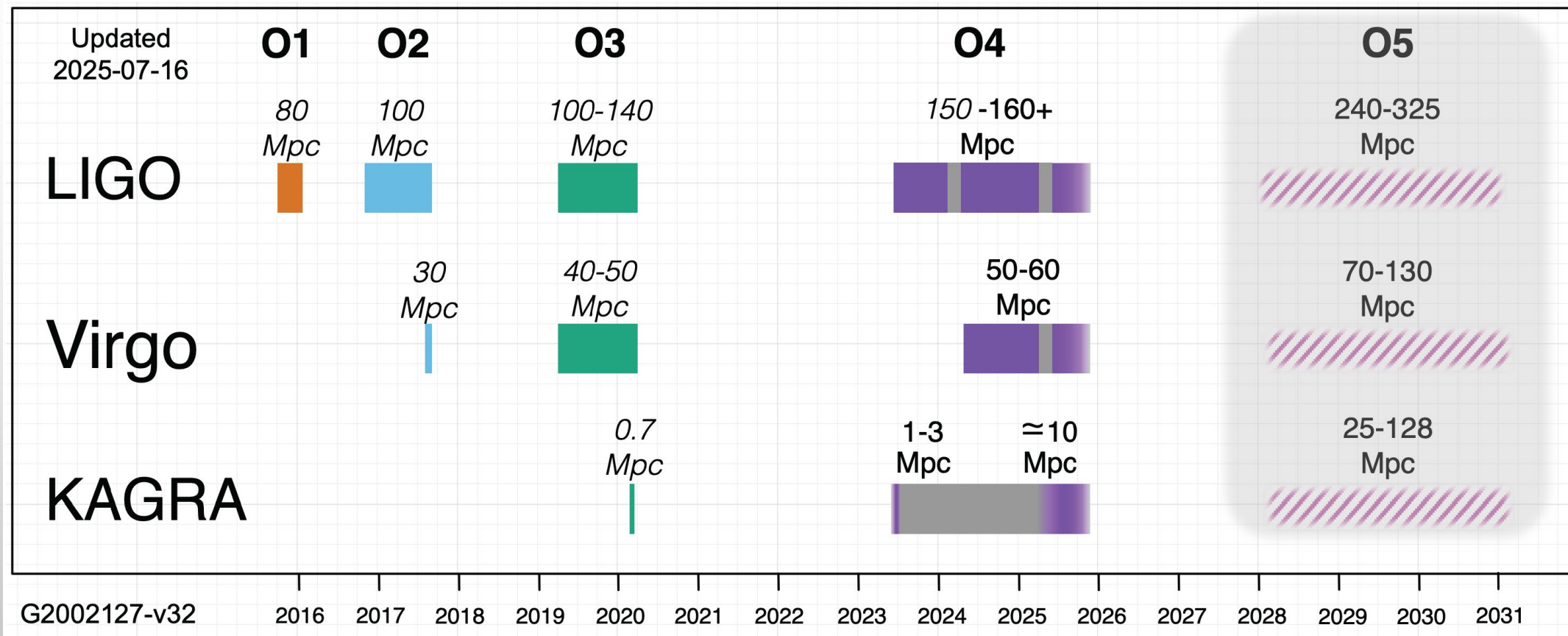
Summary of science

- **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.

Analysis pipeline contributed by NCU was used in the observation.

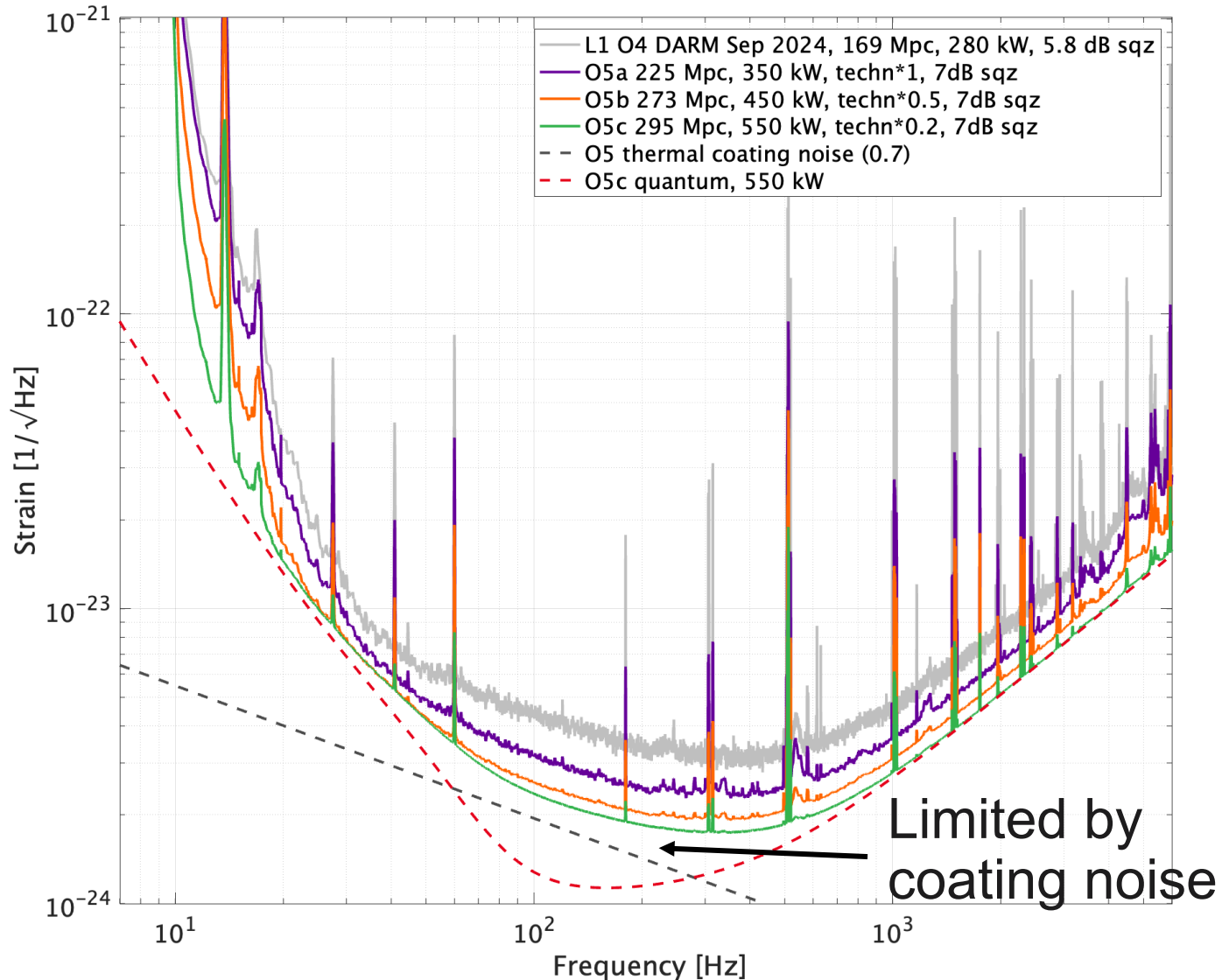
NCU members joined on-site operation.

Future plan



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

O5 sensitivity



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 by three phases.

Activity in Taiwan 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

Coating:

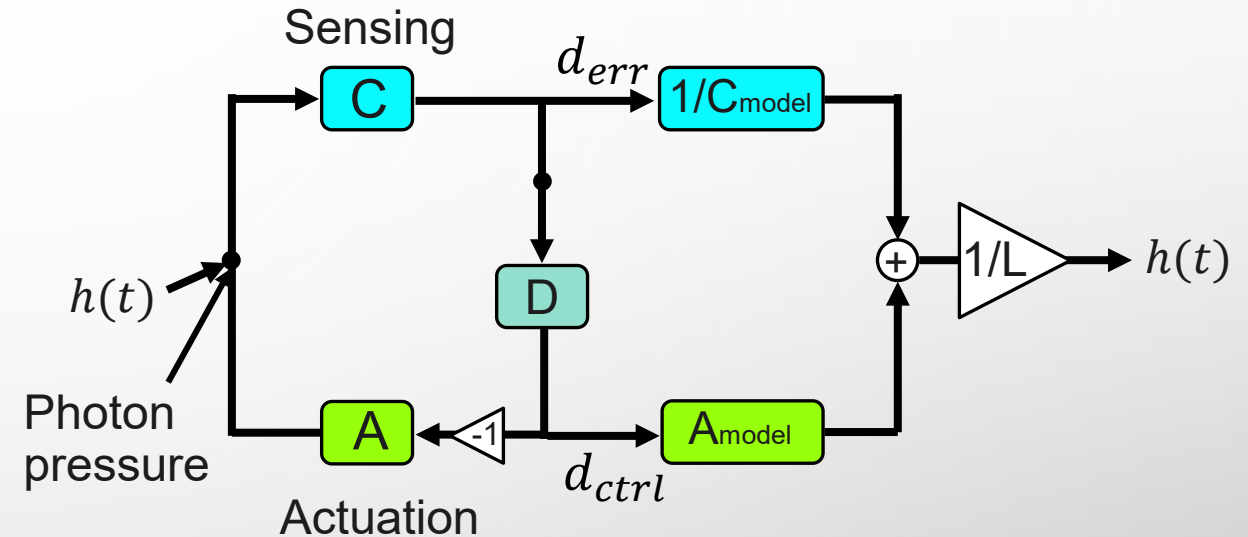
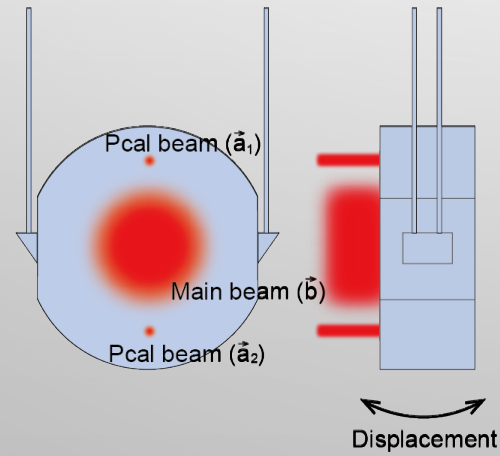
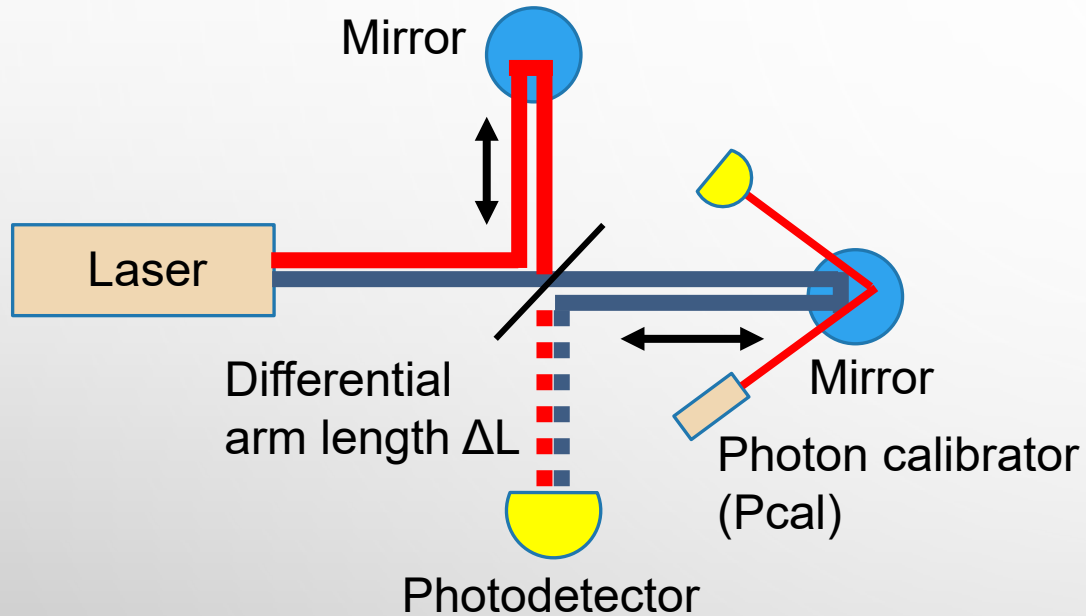
- Fabrication of highly reflective layers
- Characterization of coating loss

SGWB:

- Collaboration with CMB experiment

Calibration of GW detector

$h(t)$ is not linear to the detector signal because of feedback.

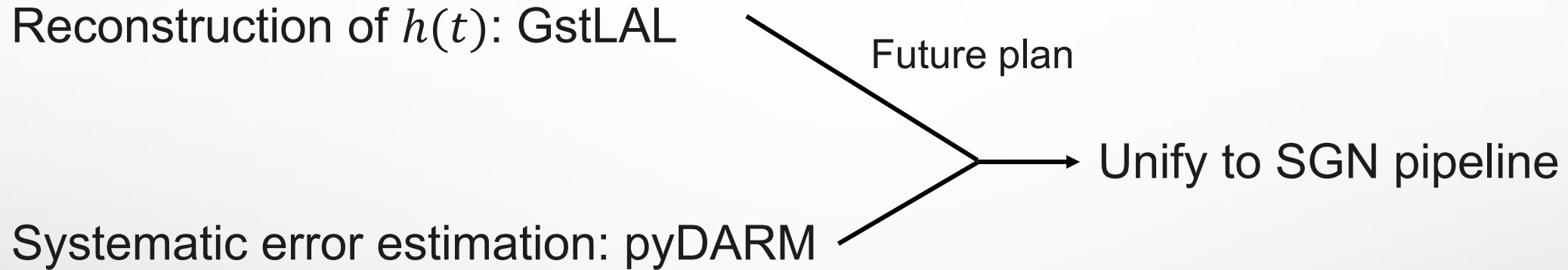


Push the mirror with a known laser power to measure detector response.

-> Reconstruct $h(t)$ with frequency filters.

When noise is reduced, systematic error becomes more serious.

Calibration software

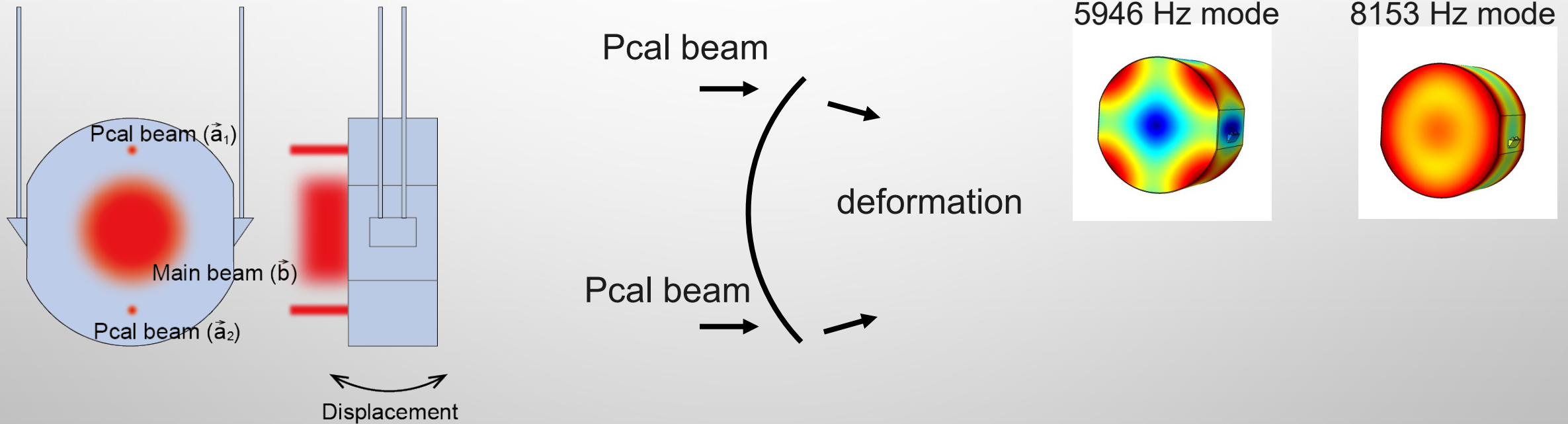


- NCU improved the model and high frequency accuracy in GstLAL.
- NCU contributed to the update release of pyDARM.
- NCU member is testing the SGN pipeline at LLO.
- We are discussing to build LIGO's remote control room in NCU.

Works of Avani Patel (postdoc), Miftahul Ma'arif (student),
Hsiang-Yu Huang (student), You-Ru Lee (student)

Calibration device

We use “Photon Calibrator (Pcal)” to know displacement-signal relationship.
When we inject laser to the mirror, it deforms a bit.



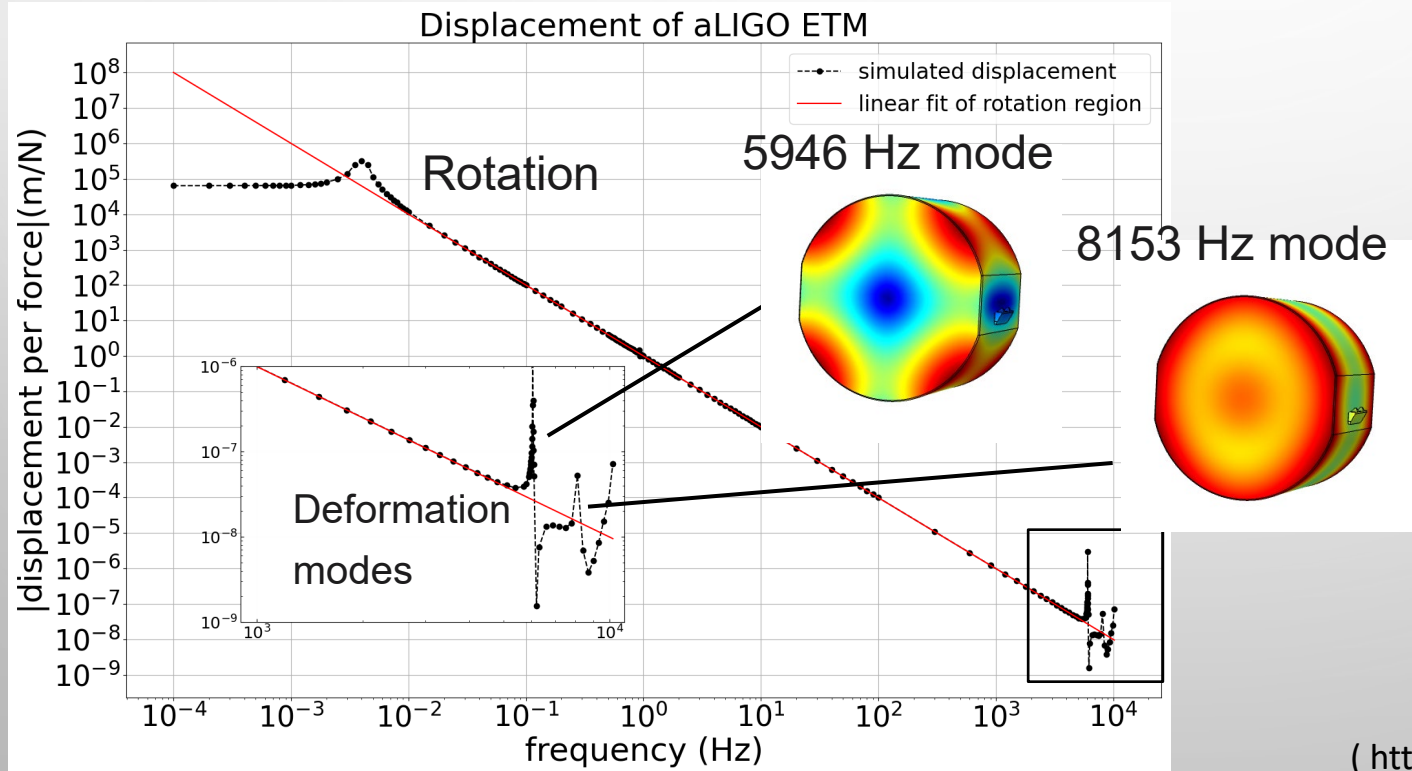
I evaluated the impact of deformation for mirrors of LIGO, Virgo, KAGRA, and LIGO's future upgrade plan.

Mirror deformation and NS equation of state

Pcal excites deformation modes of mirror in kHz region.

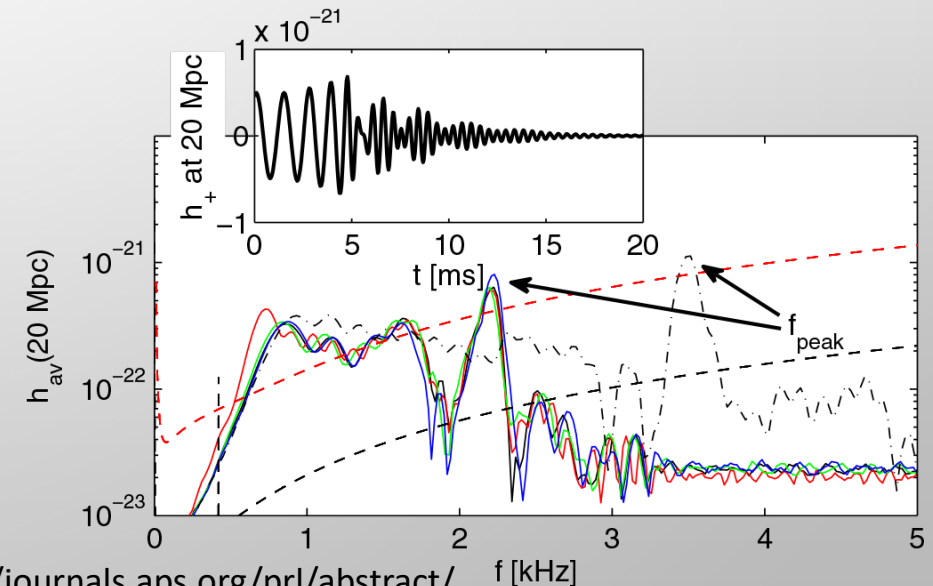
It becomes a dominant systematic error in NS equation of state.

I evaluated it and am designing a new Pcal to suppress excitation.



Simulated ringdown spectrum of BNS.

Peak frequency is sensitive to EoS model.



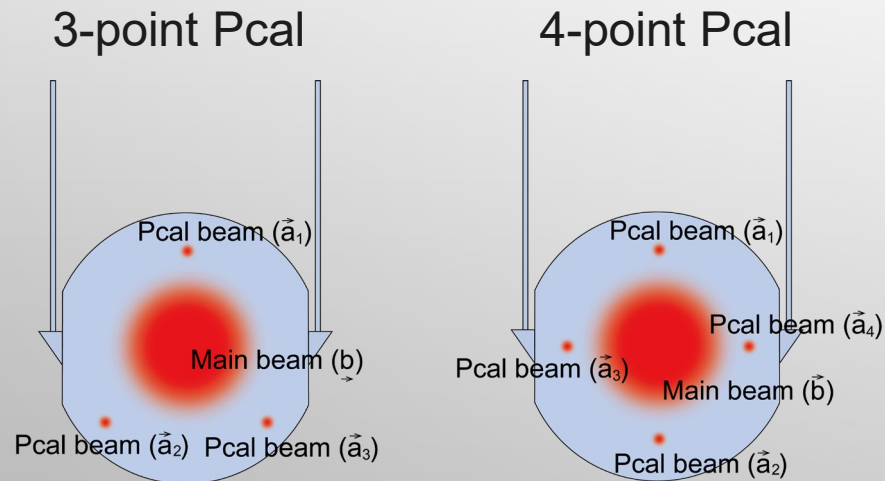
(<https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.108.011101>)

Next generation Pcal

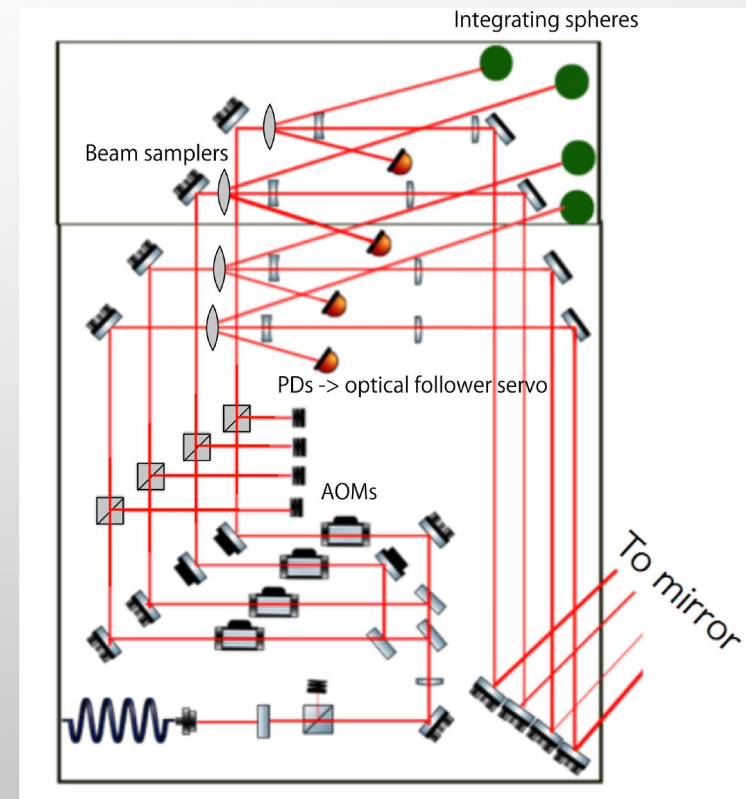
I am designing a next-generation Pcal to suppress excitation of the deformation modes.

Injecting 3 or 4 beams may suppress two fundamental modes.

Proof-of-principle simulation is ongoing.



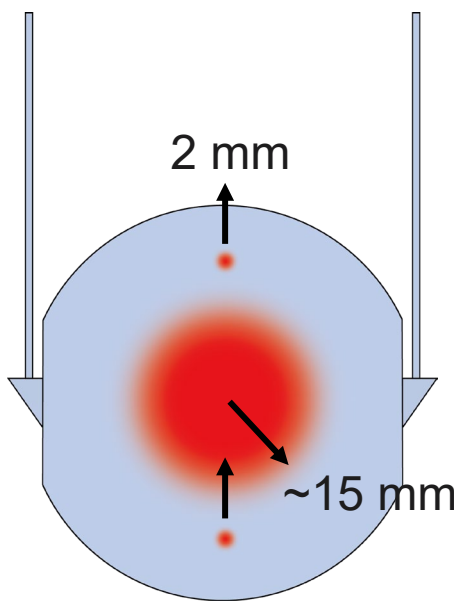
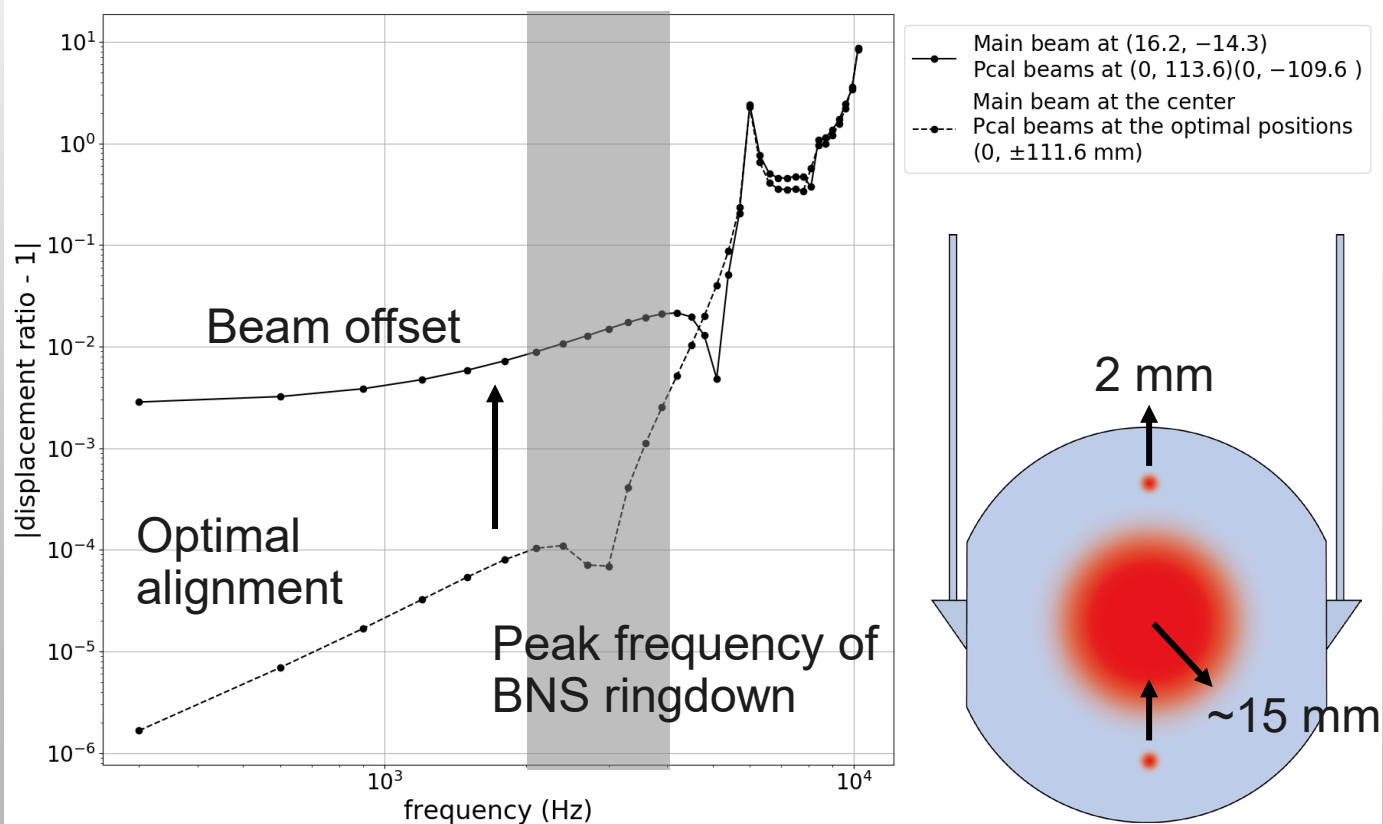
Optical layout of 4-point Pcal



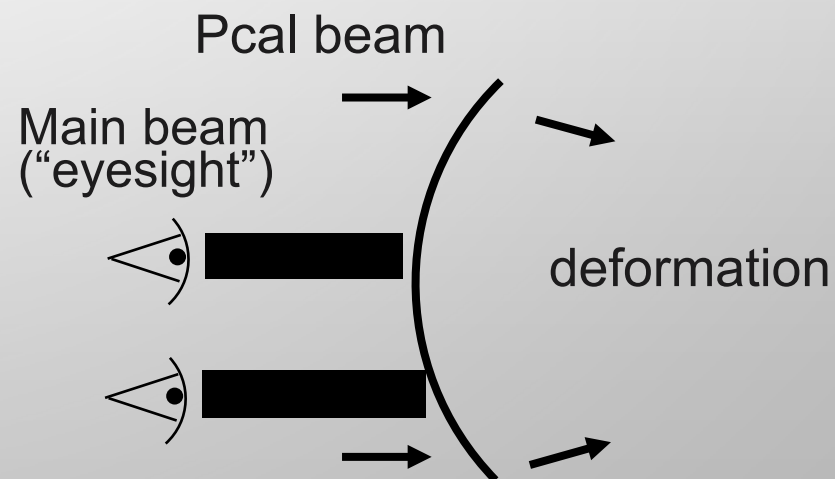
Calibration device

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

cement ratio of aLIGO ETM by Worst case estimation based on LHOX measurement
Main beam at (16.2, -14.3), Pcal beams at (0, 113.6)(0, -109.6)



It rises to $>1\%$ error with the actual aLIGO's alignment precision. We have to consider it in calibration for accuracy in high frequency.



Stochastic background

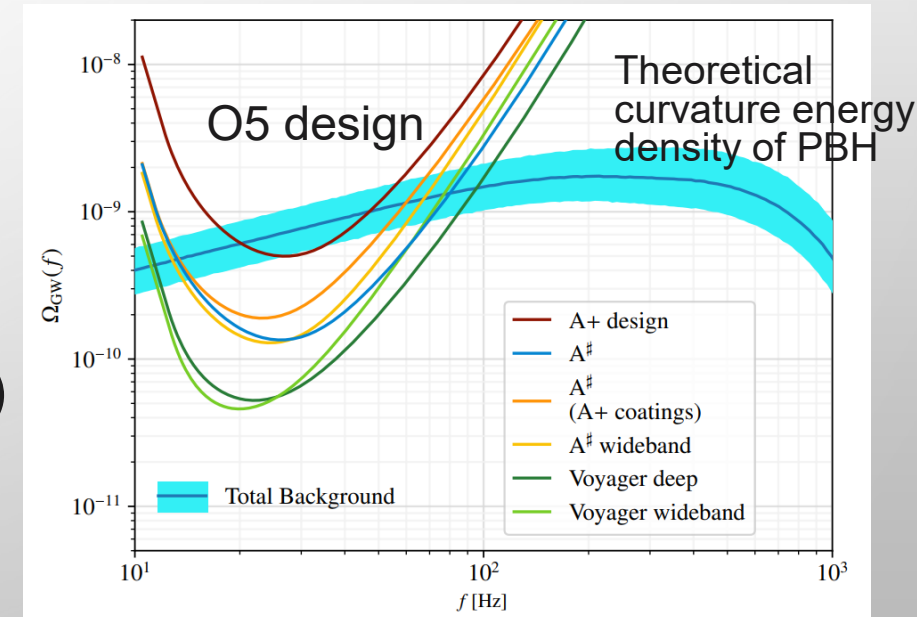
Stochastic background is a GW background from

- Unidentified compact binary mergers
- **Primordial black holes generated in the early universe**
- Primordial gravitational wave generated in inflation
- Cosmic strings

Primordial BH is sensitive to scalar spectral index n_s .
(One of Λ CDM cosmological parameters,
scale invariance of scalar curvature perturbation)

Sensitivity of LIGO O5 could test it.

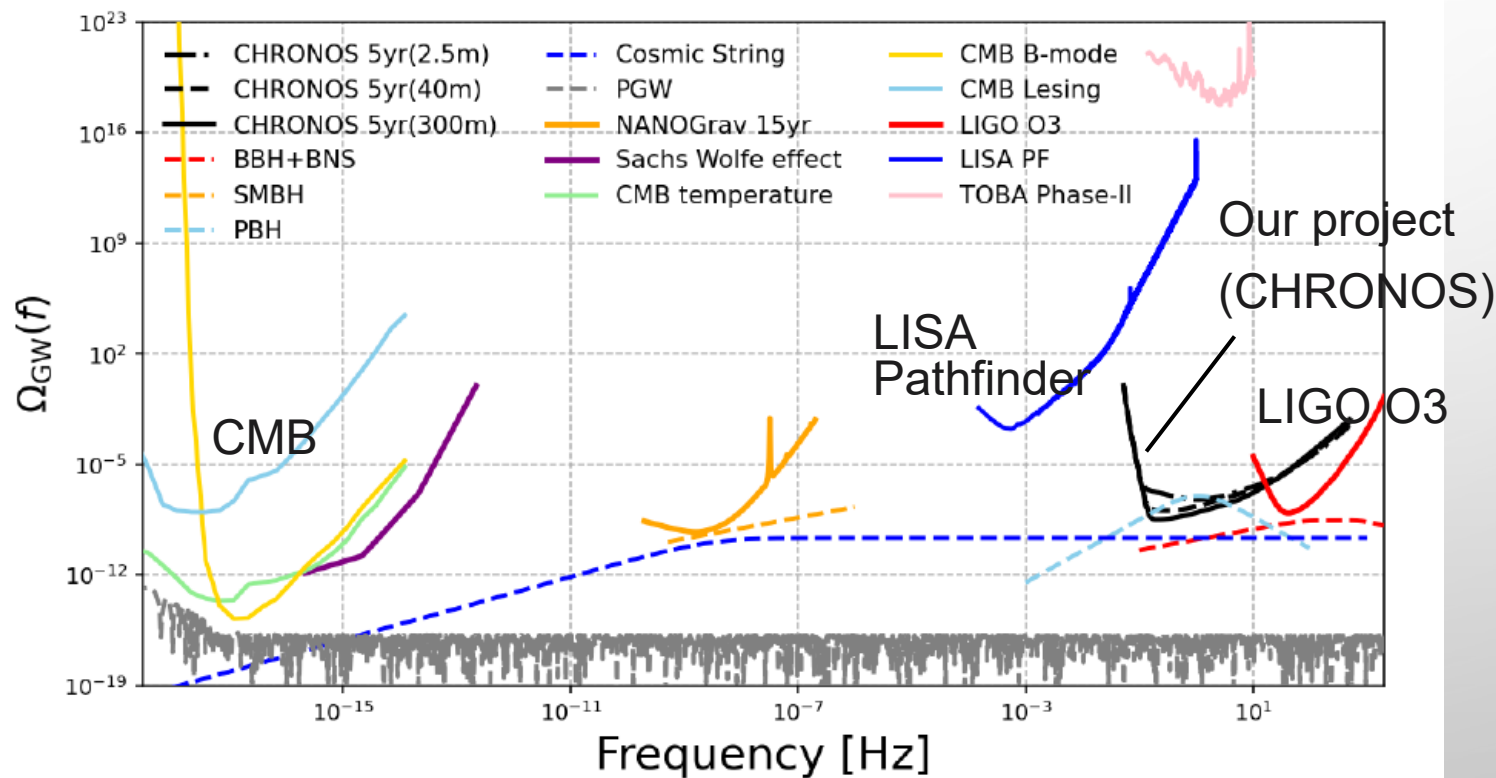
An NCU member (Hsiang-Yu Huang) studies with LIGO's stochastic background study team.



(<https://dcc.ligo.org/LIGO-T2200287/public>)

Stochastic background landscape with CMB

We explore wide frequency range of GW background by collaboration of GW and CMB experiment (Simons Observatory) with Prof. Masashi Hazumi.



Simons Observatory



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

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.

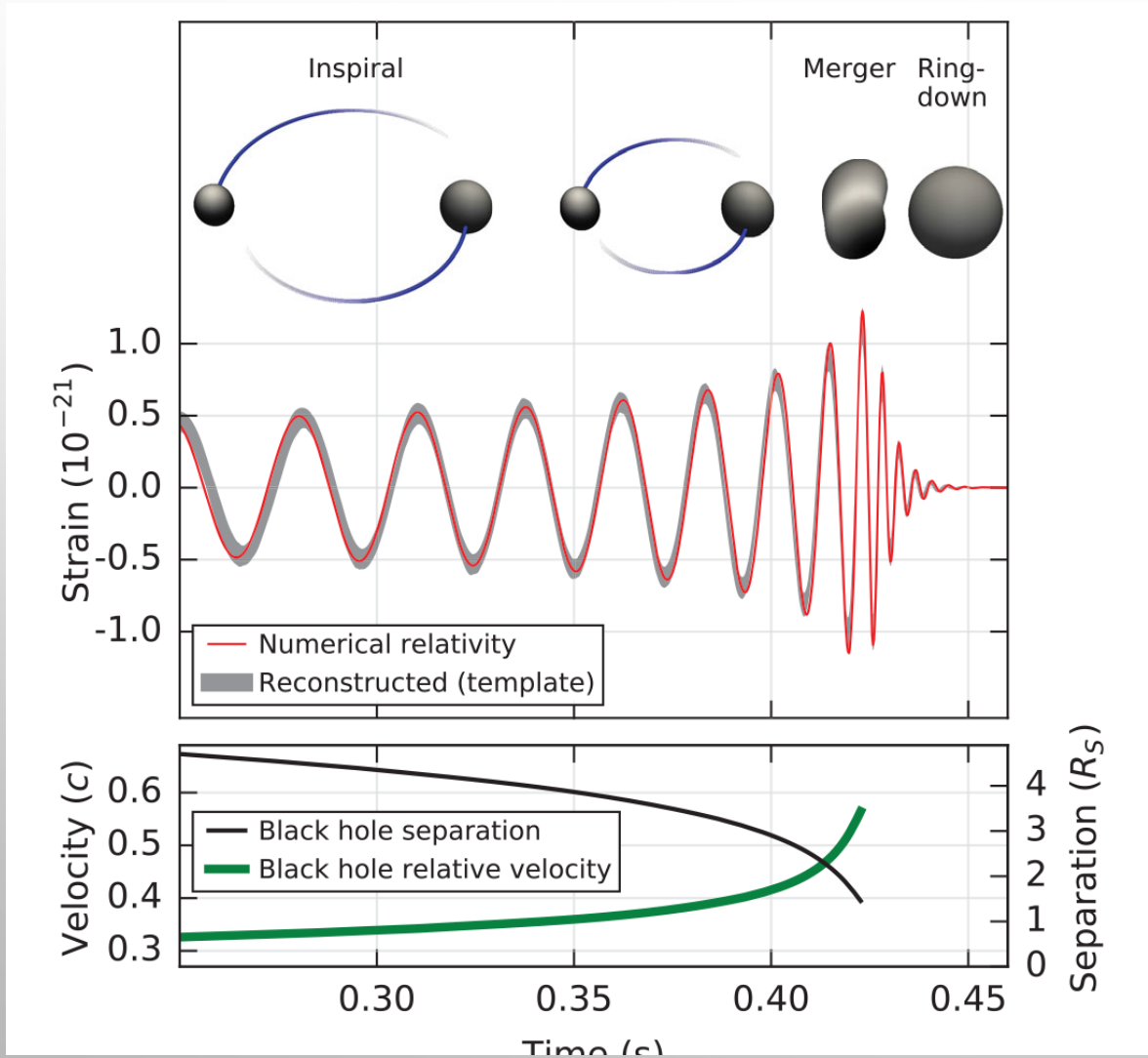
Merger: Numerical general relativity.

Weak field approximation is no longer valid.

Ringdown: Perturbation on BH solution.

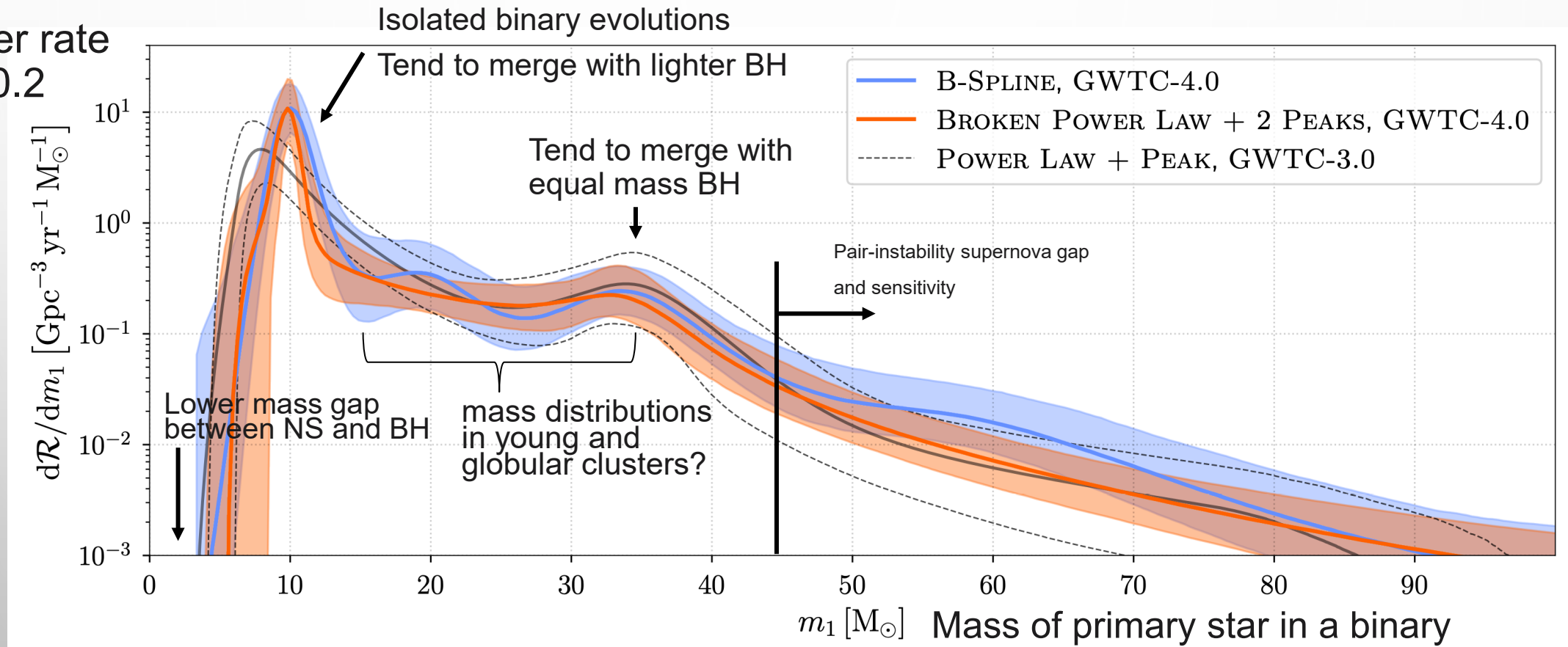
$$h(t) \simeq e^{-\frac{\omega_R(t-t_0)}{2Q}} \cos(\omega_R(t-t_0))$$

For NS, extra “fluid mode” exists.



Population properties of merging compact binaries (2)

Merger rate
at $z=0.2$



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

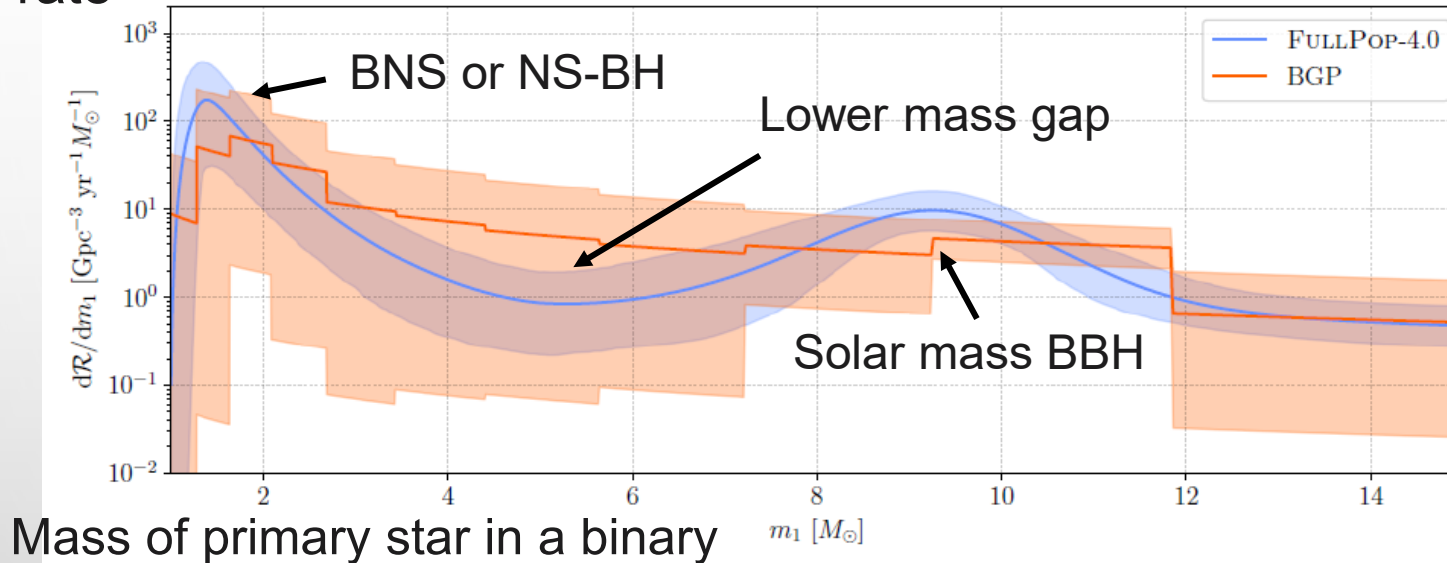
Measured relationship between merger rate and mass ratio favors:

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

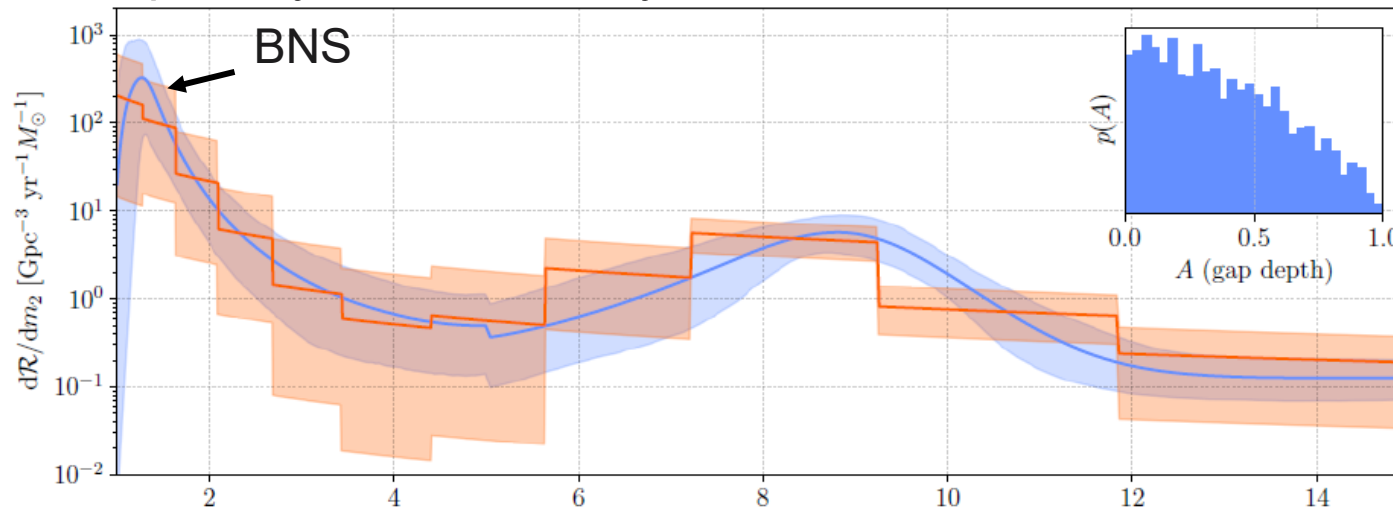
$\gtrsim 10M_\odot$: Formation by stable mass transfer

Population properties of merging compact binaries (3)

Merger rate
at $z=0$



Mass of primary star in a binary

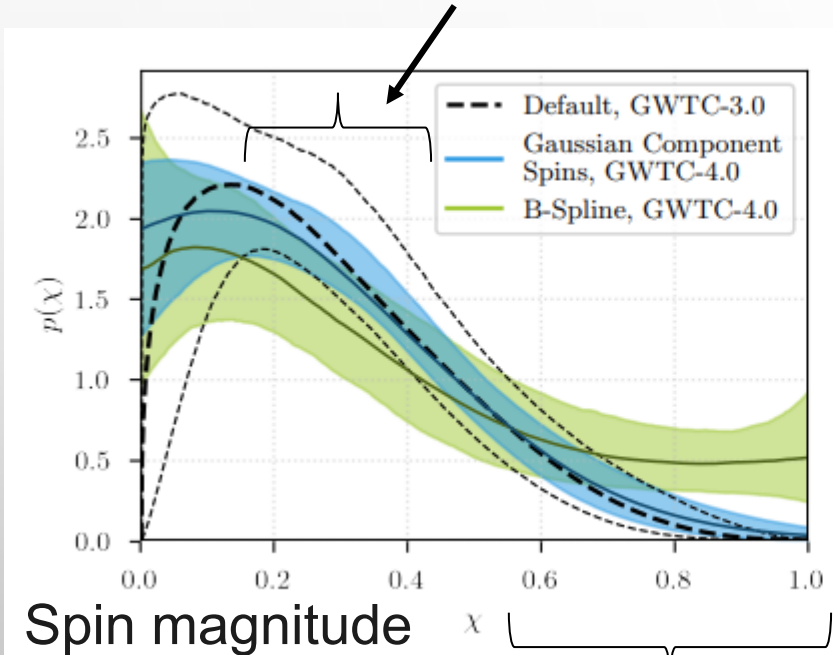


Mass of secondary star in a binary

$A=1.0$ is perfect
lower mass gap
(disfavored)

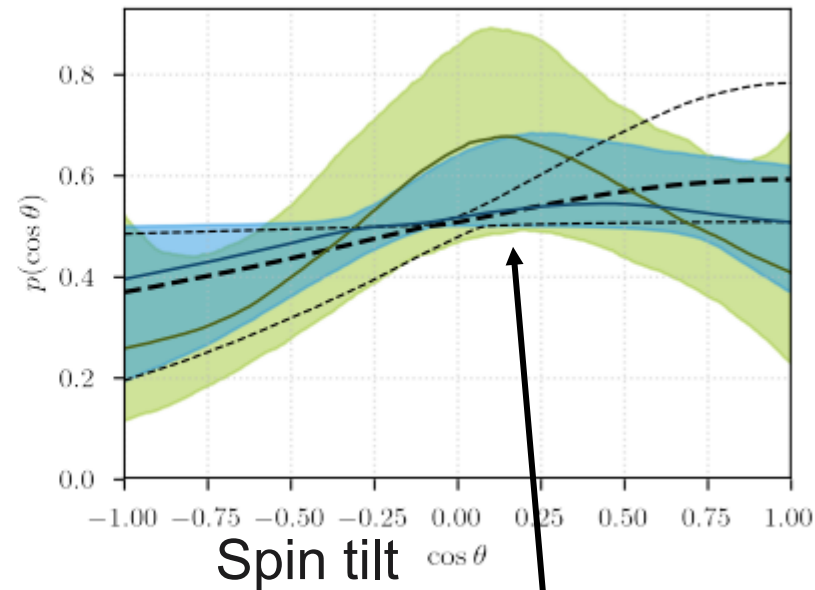
Population properties of merging compact binaries (4)

Second star is spinned
up by tidal force



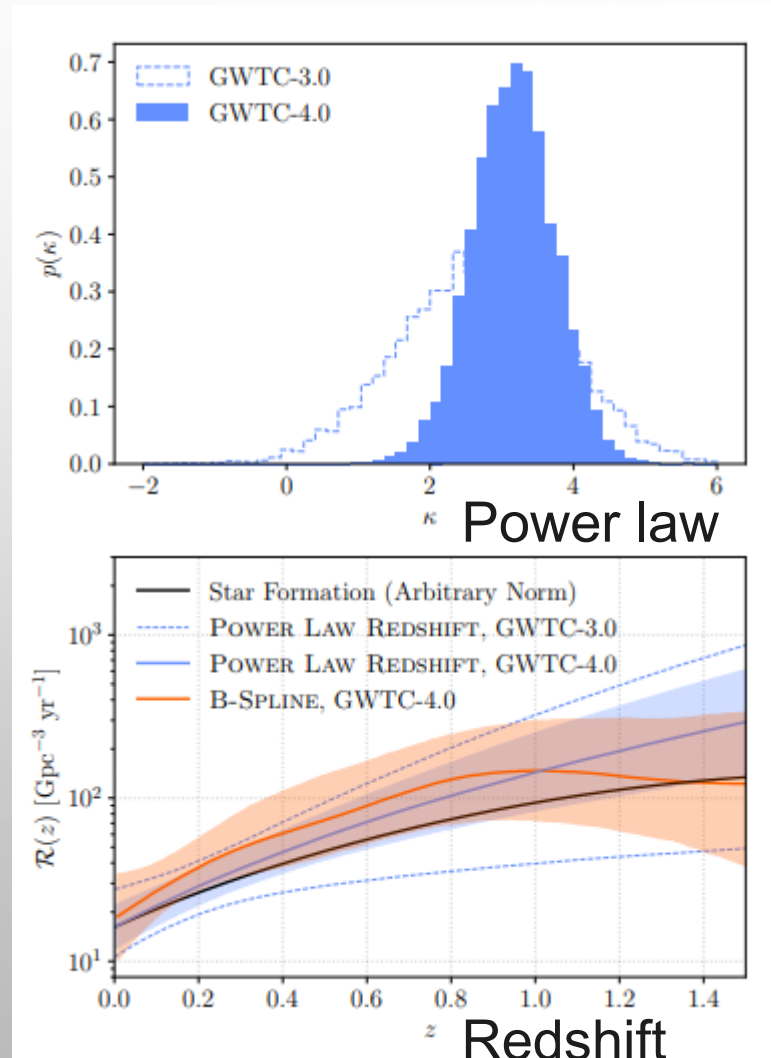
(<https://arxiv.org/abs/2508.18083>)

Chemically homogeneous evolution
Hierarchical mergers

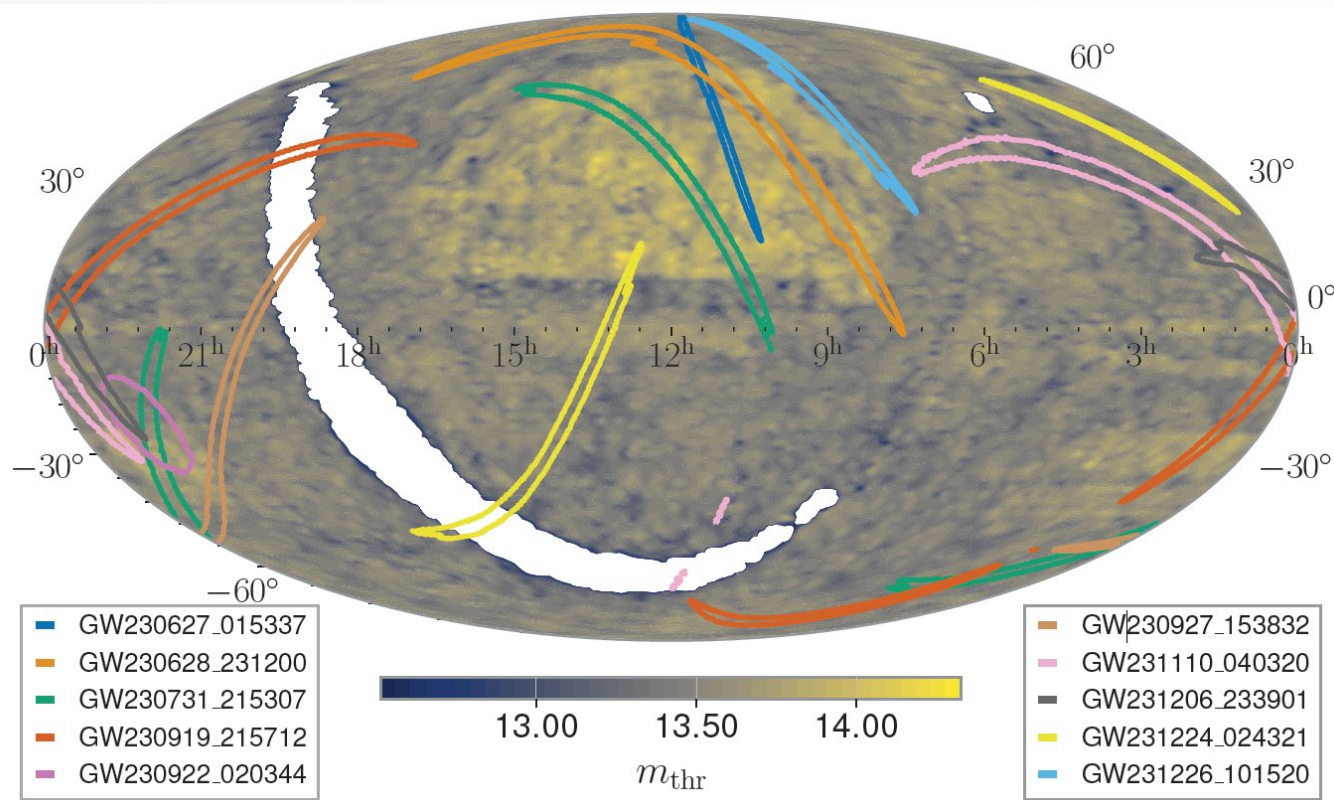


Non-zero spin tilt does not exclude
neither isolated evolution nor
dynamic formation

Population properties of merging compact binaries (5)



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

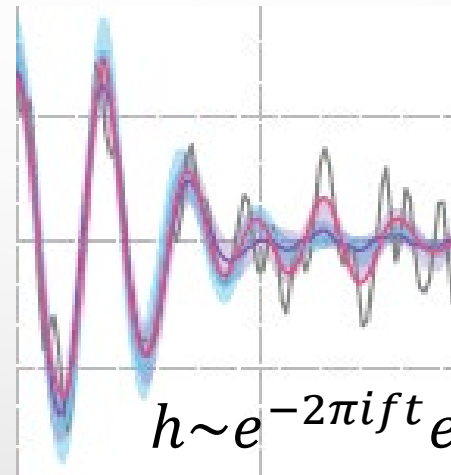


The sky localization was not good enough due to absence of Virgo.

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

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

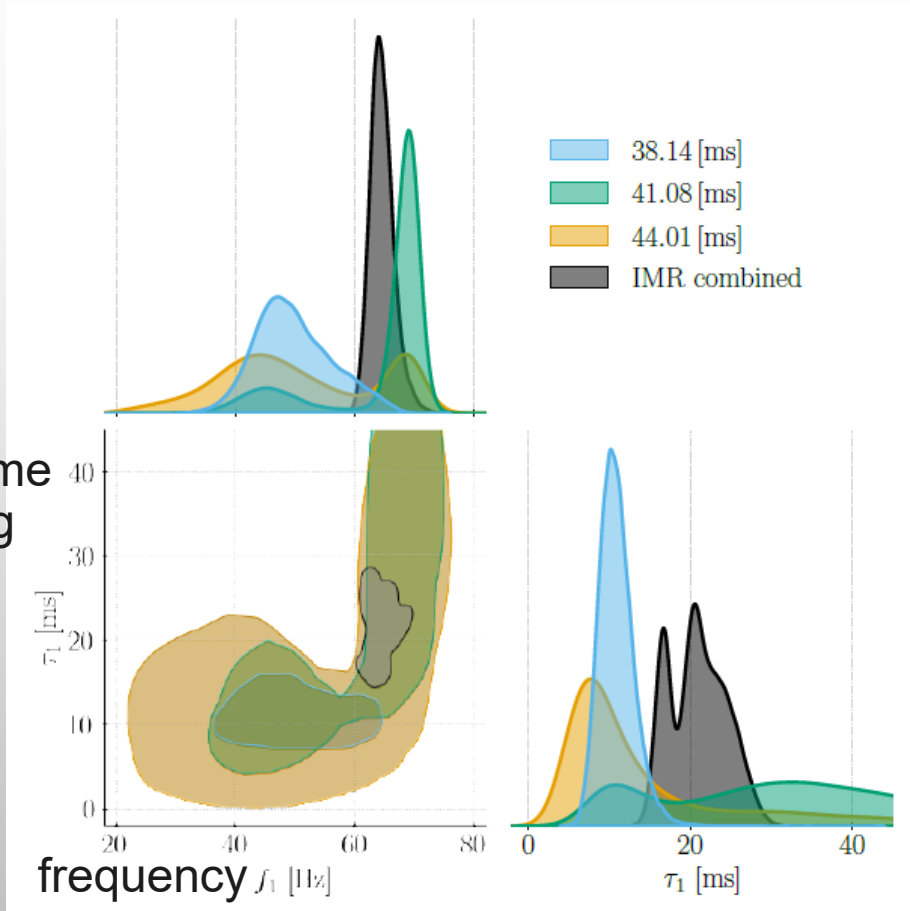
Large signal at merger & ringdown phases enables **black hole spectroscopy**.



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

-> Probe of internal structures.

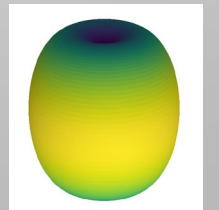
Consistent with $(l, m, n) = (2, 2, 0)$ and several additional modes, but theoretical modeling is not enough to determine the property of merged BH.



Start time of fitting

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

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



Coating activities in Taiwan

Major update from O4 to O5 is replacement of mirror coating.
We fabricate multi-stack layers of SiN, SiON, and a-Si with TSRI.

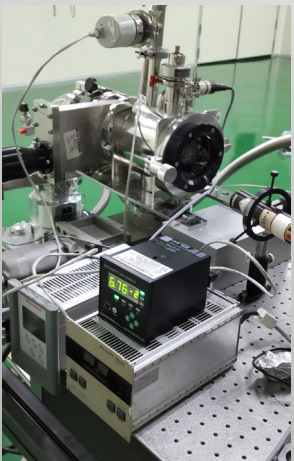


We are also developing coating loss characterization systems in AS.

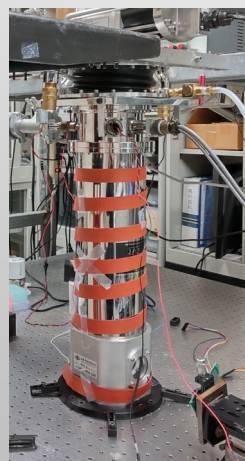
SiN+a-Si coating
on 6-inches wafer



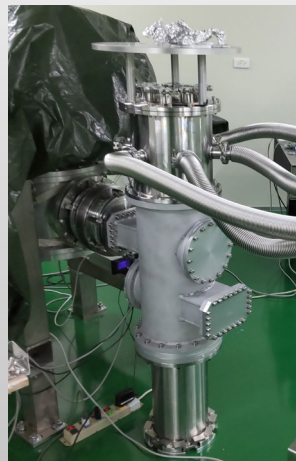
300 K
mechanical loss



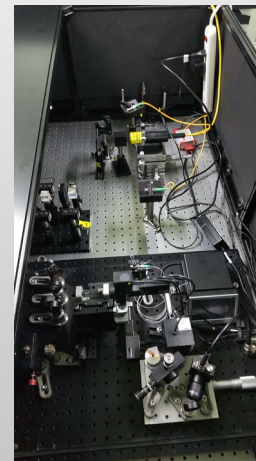
Cryo
mechanical loss



Cryo mechanical loss
(Disk)



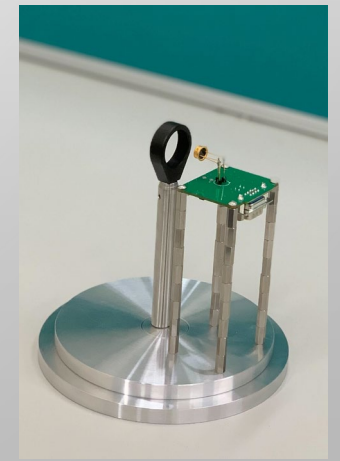
300 K
absorption



Cryo
absorption



300 K
scattering



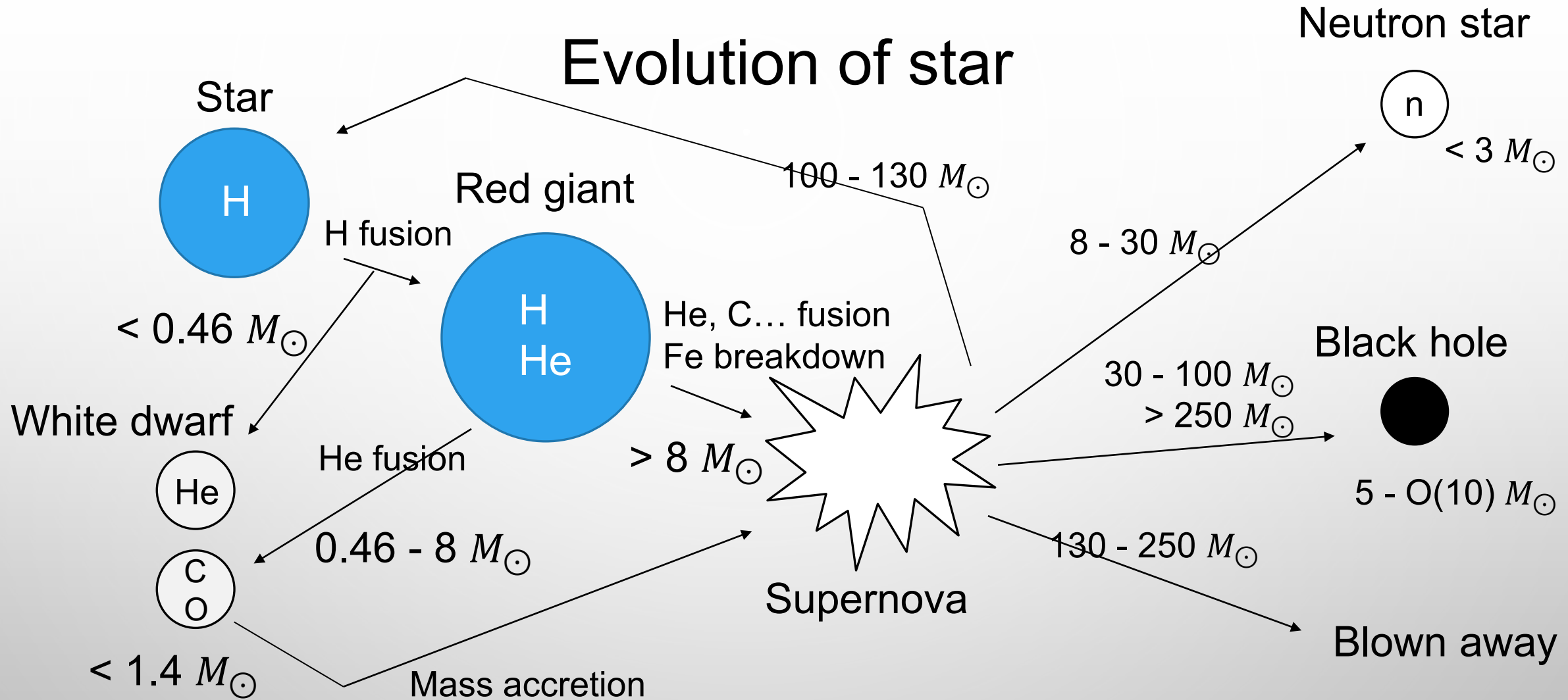
Masses of compact stellar bodies

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.

Evolution of star



Mass of NS and BH is limited by mass of the star.

Origin of Supermassive black holes

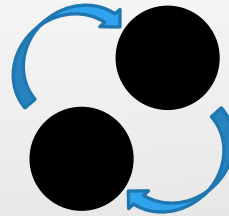
Black holes of $> O(100000) M_{\odot}$ are observed by X-ray,
but **how they were grown up is unknown.**

Supermassive star?



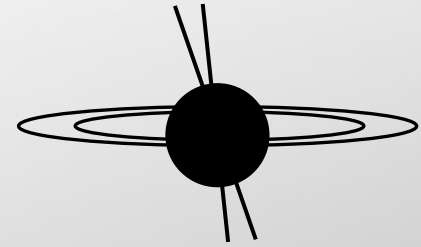
$> O(100) M_{\odot}$ stars are
not found.

BH merger?



Event is too rare.
Intermediate mass
BHs are not found
a lot.

Gas accretion?



Accretion rate should have
Eddington limit.
Mechanism to exceed it is
unknown.

Origin of Intermediate mass black holes

Black holes of $O(100-10000) M_{\odot}$ are rarely observed.

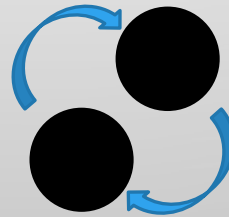
We have only 3 candidate GW events. ($\sim 100 M_{\odot}$)

GW from heavier black holes is in low frequency,
which is hard to detect due to seismic noise of a detector.

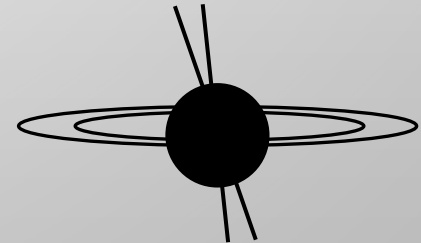
Supermassive star?



BH merger?



Gas accretion?

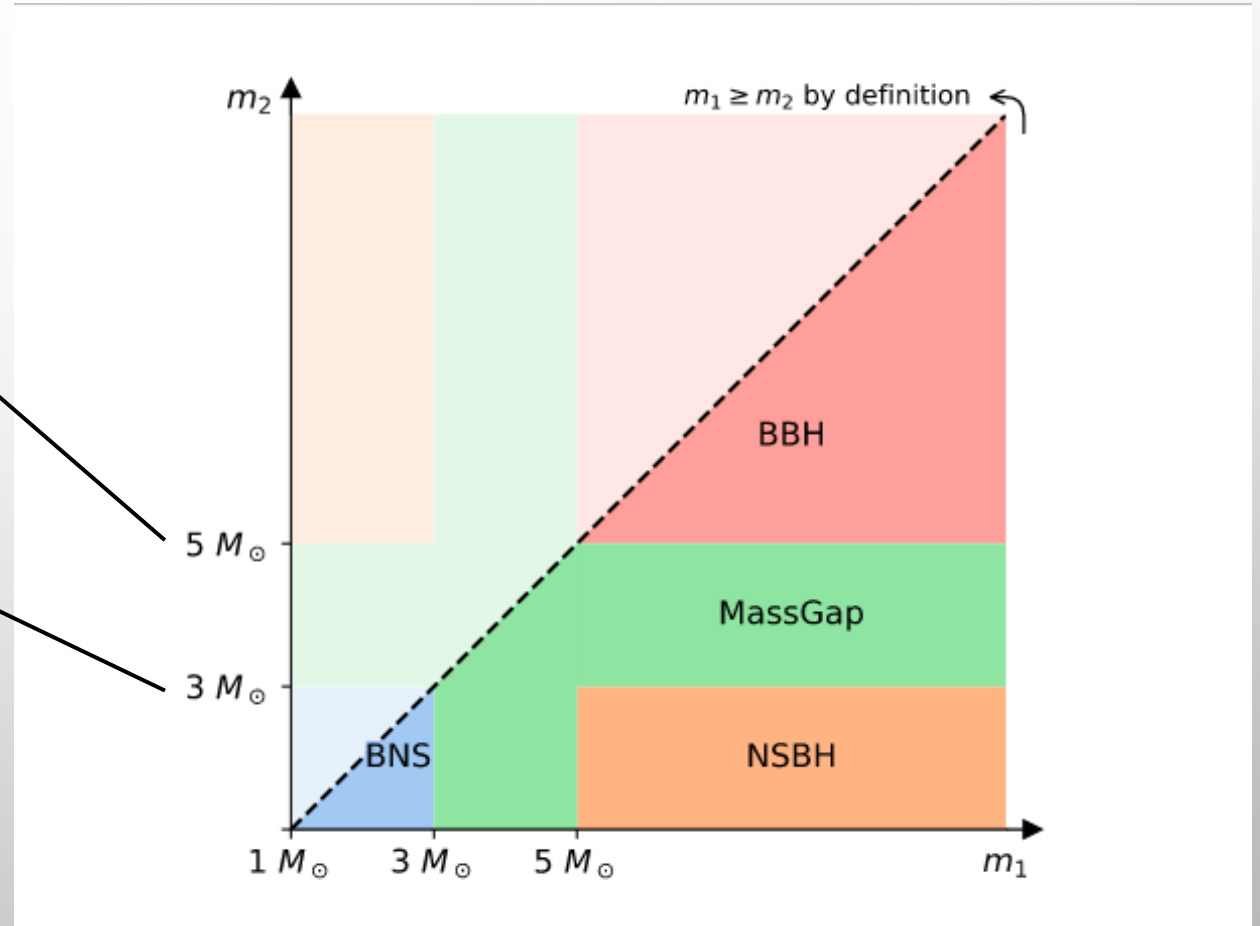


Mass gap: Absence of lighter black hole

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

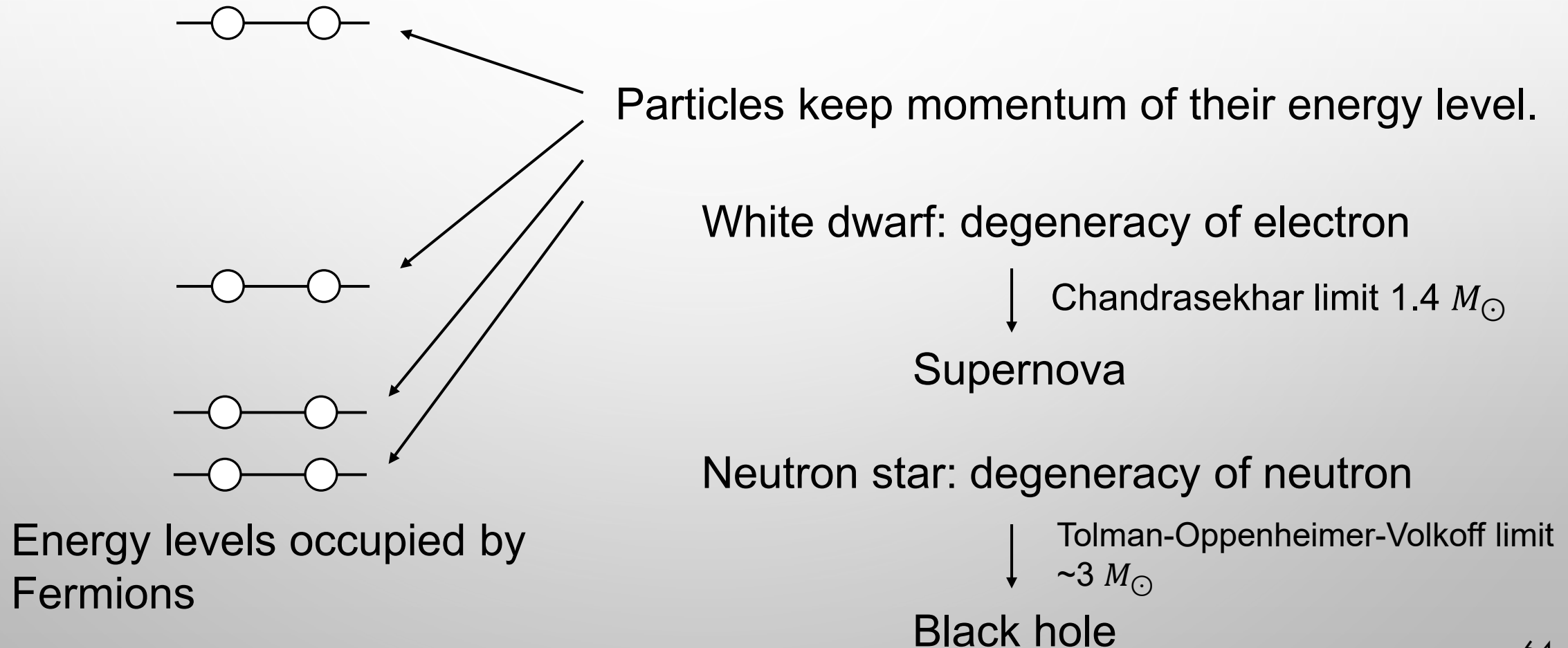
BH lighter than $5 M_{\odot}$ is not found.

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



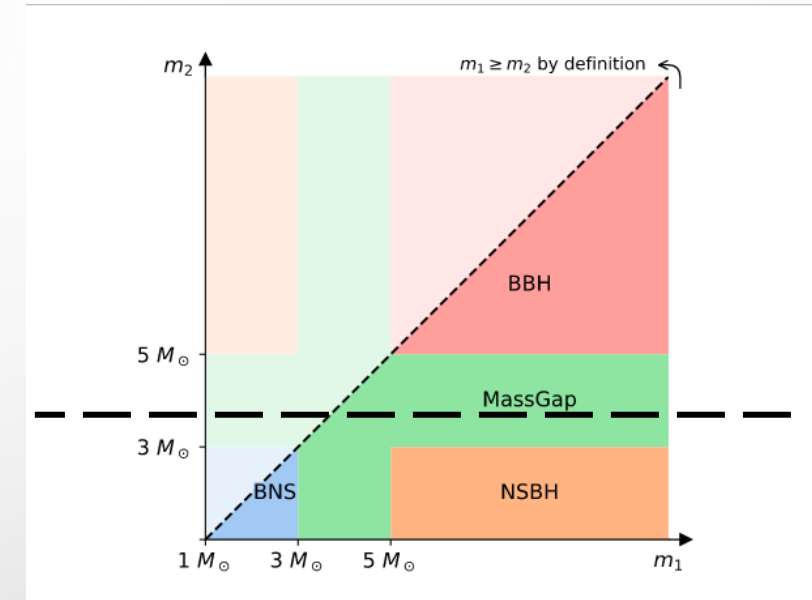
Degeneracy pressure

Pauli exclusion principle keeps force against gravity.



What determines the upper mass of neutron star?

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



Nuclear physics

Revealing exotic
phenomena in NS

Astrophysics

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

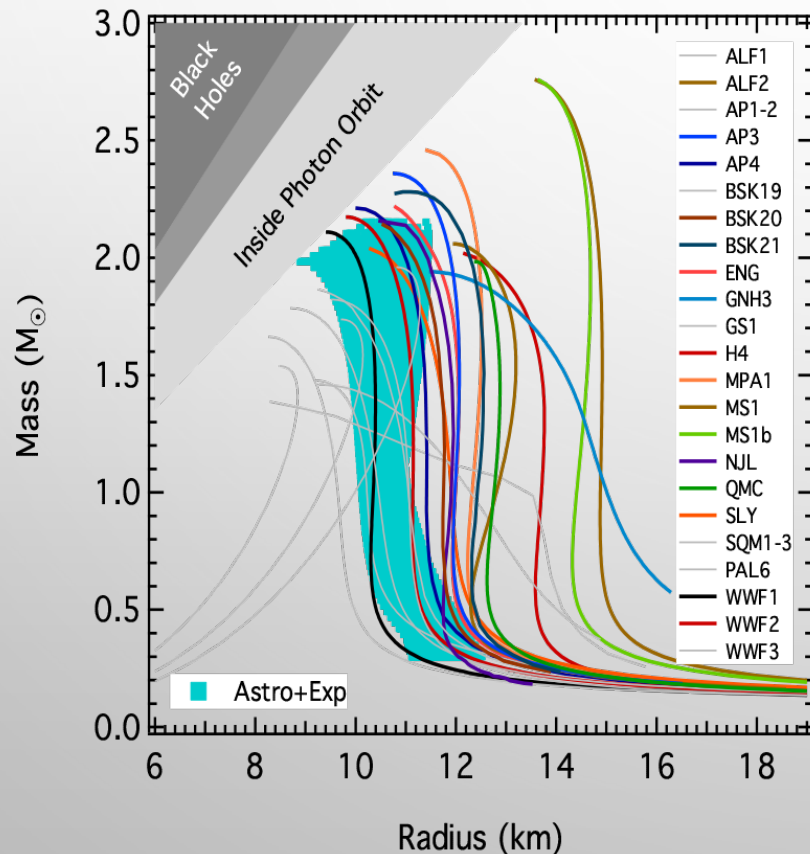
EoS and M-R measurement

Many EoSs have been proposed.

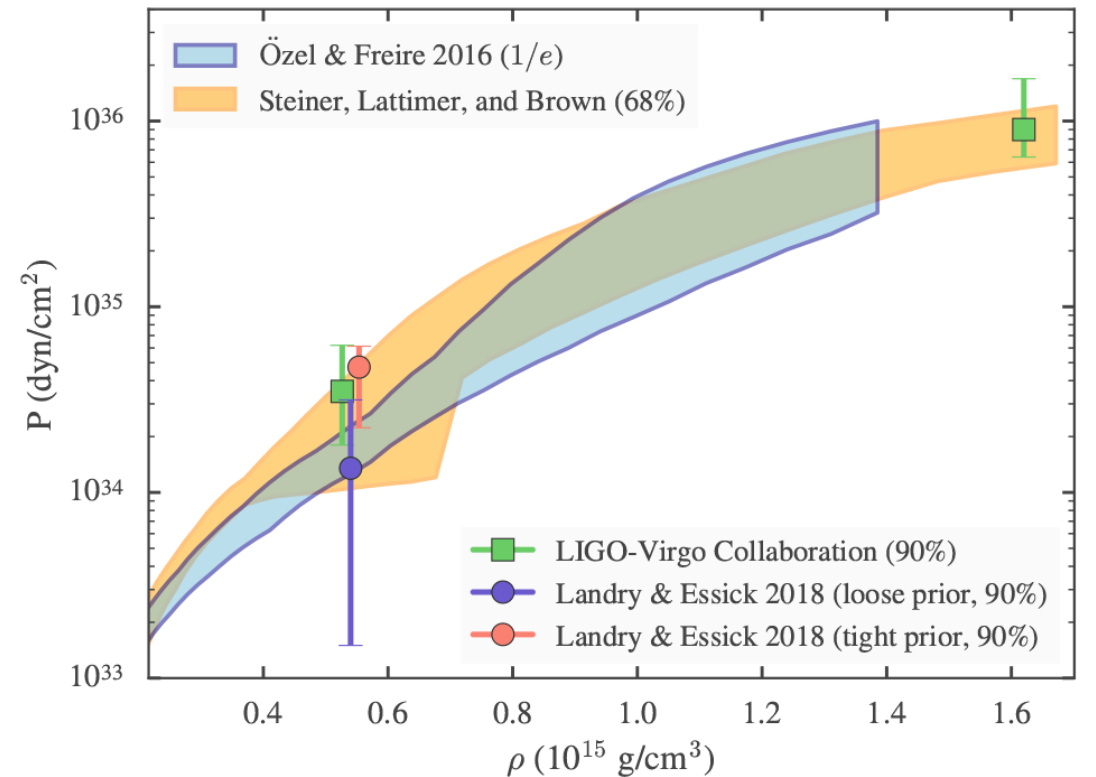
They favor $\sim 2 M_{\odot}$ at the typical NS radius.

Blue band is favored by optical observation.

GW170817 event is consistent with previous models.



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

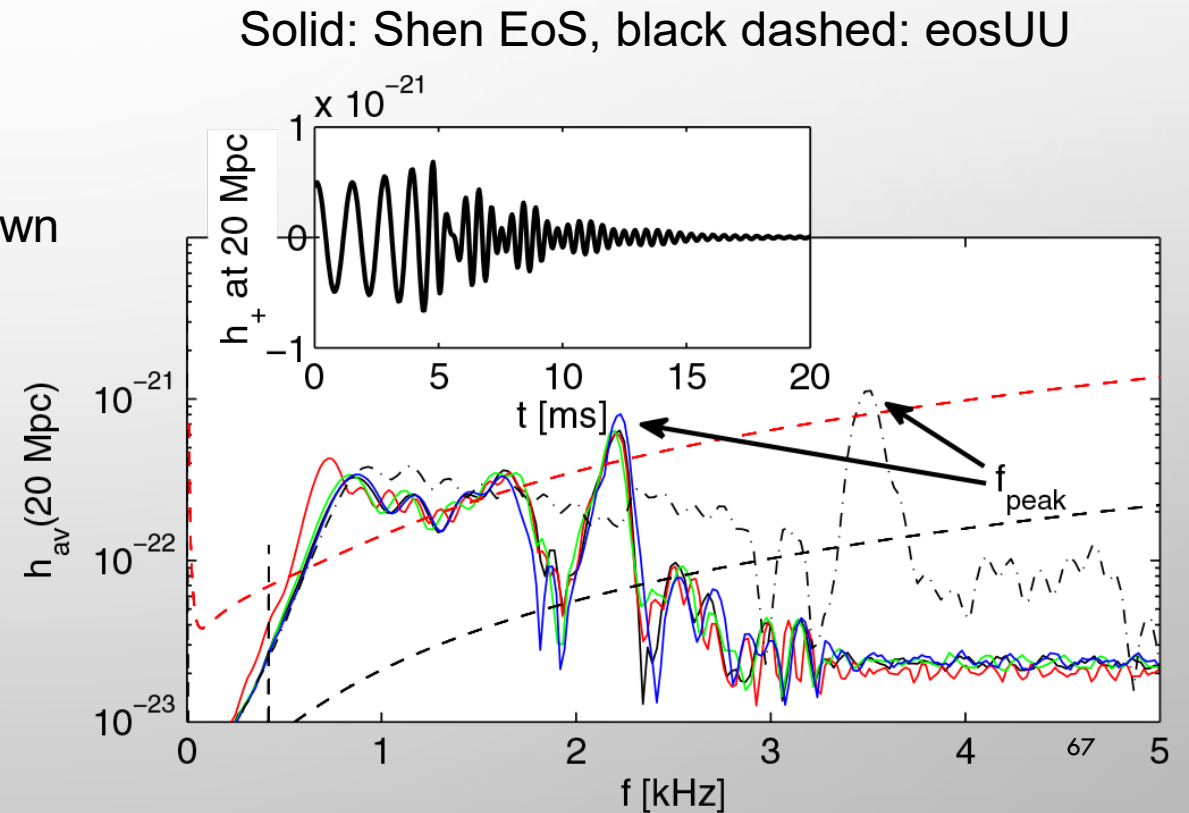
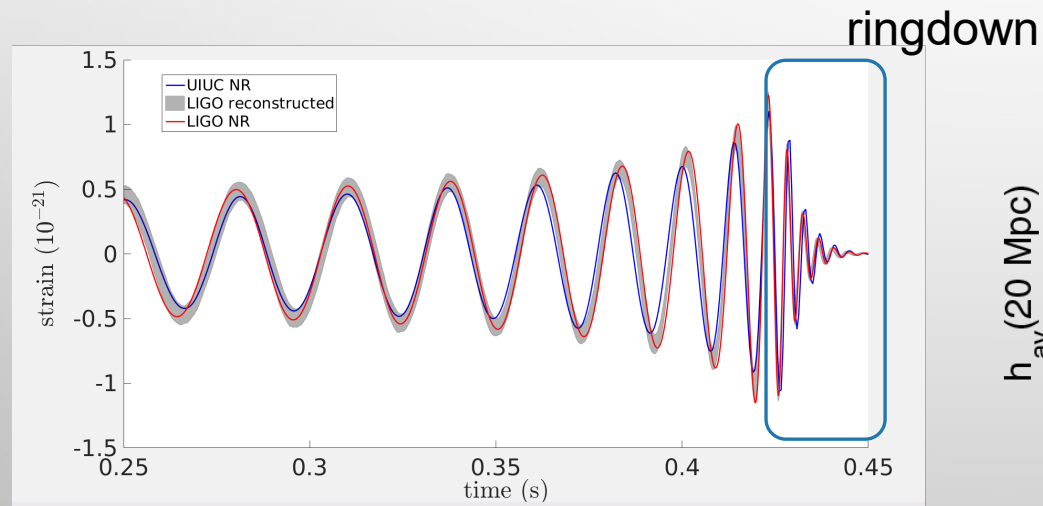


(<https://arxiv.org/abs/1904.10002>)

EoS and ringdown peak

Second harmonics of GW ringdown signal reflects the internal structure.

It appears in 2-4 kHz region.

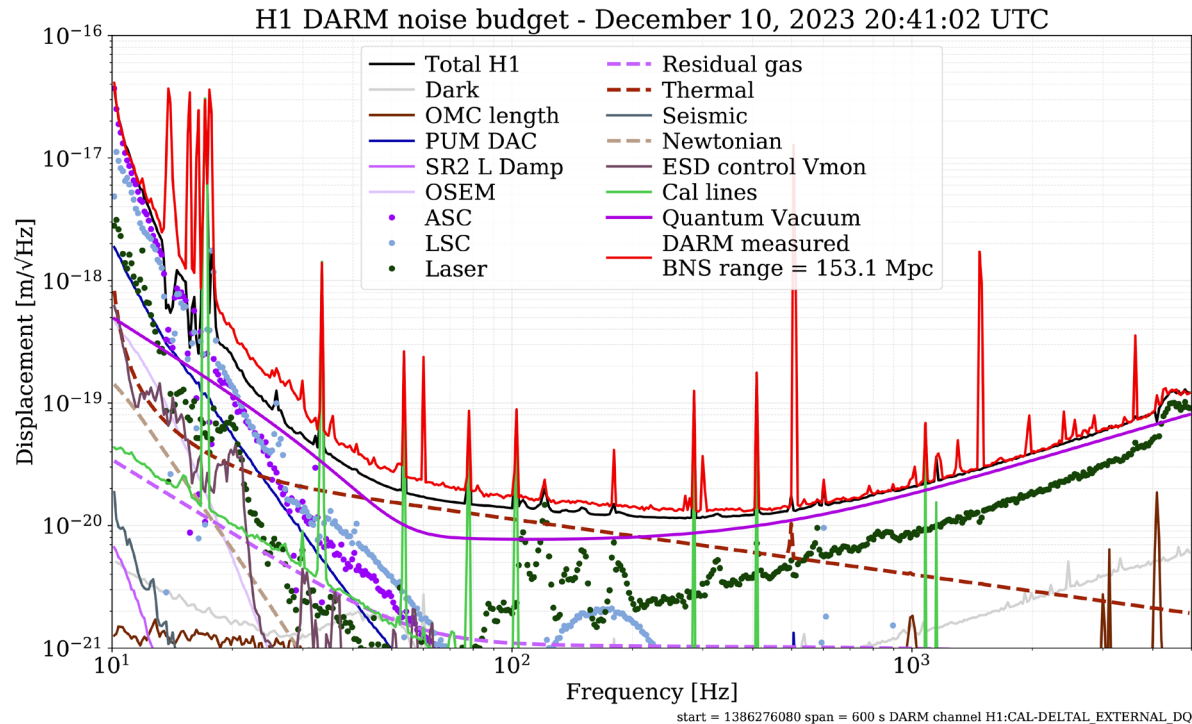


Measurement of high frequency GW

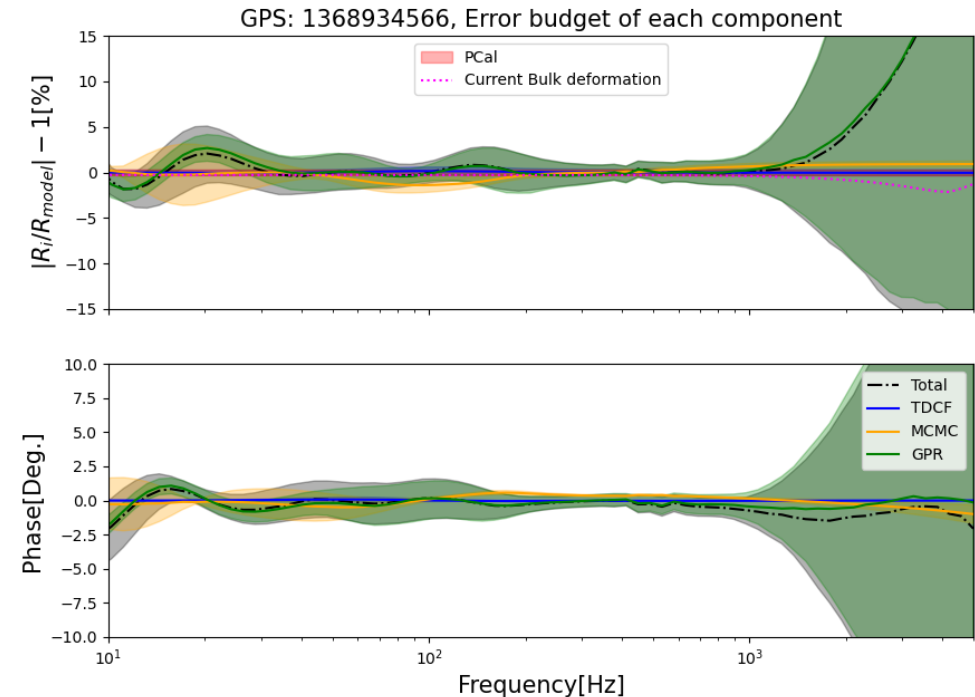
Noise and systematic error have different frequency dependencies.

The kHz region is dominated by bulk deformation.

Sensitivity (noise budget)



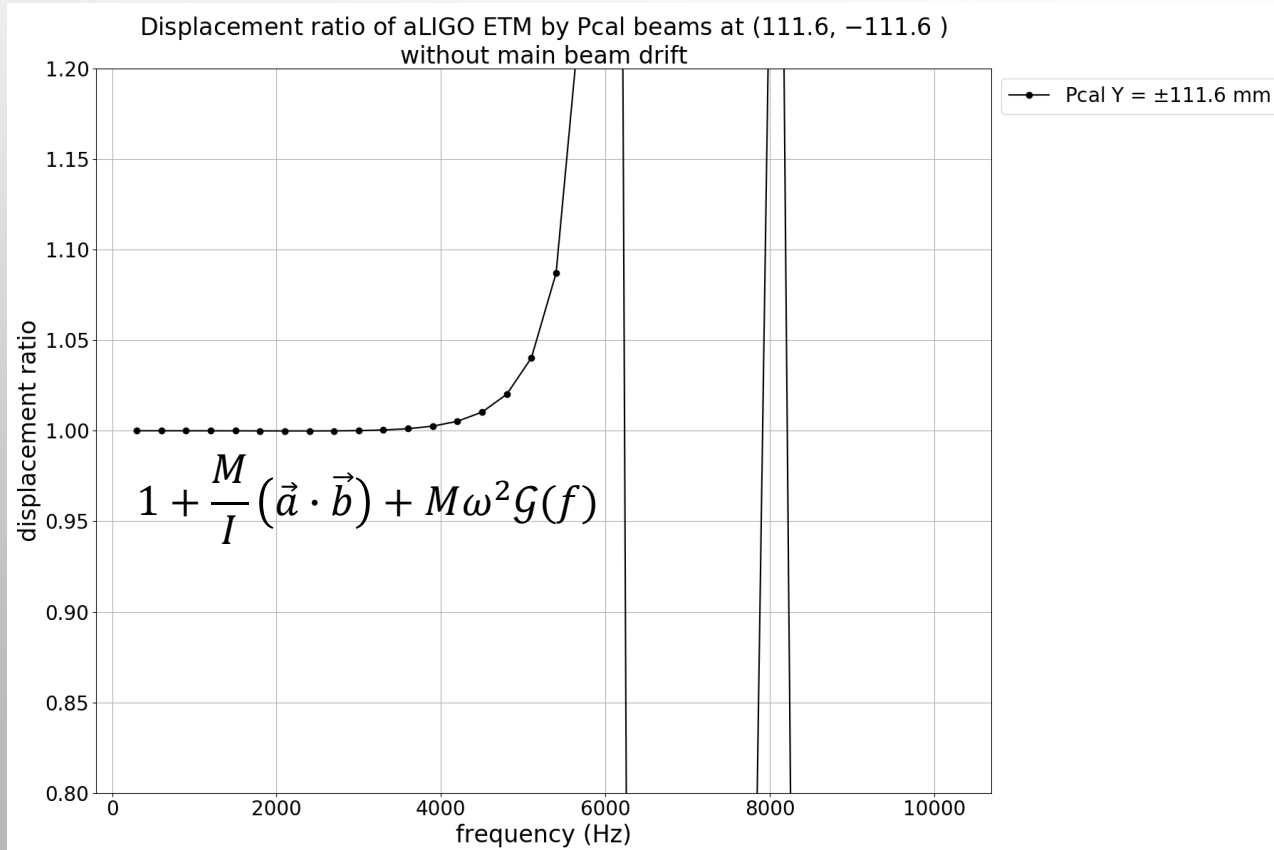
Systematic error estimation



Difference from rigid mass motion

Calibration assumes the rigid-mass pendulum motion ($1/M\omega^2$).

Deformation is evaluated as an excess from the rigid-mass motion.



$$\frac{\vec{x}}{c} = - \frac{2P \cos \theta}{c} \frac{1}{M\omega^2} \left\{ \underbrace{1}_{\text{Power-to-force const.}} + \underbrace{\frac{M}{I}(\vec{a} \cdot \vec{b})}_{\text{Translation}} + \underbrace{M\omega^2 \mathcal{G}(f)}_{\text{Rotation}} \right\} + \underbrace{\text{Deformation}}$$

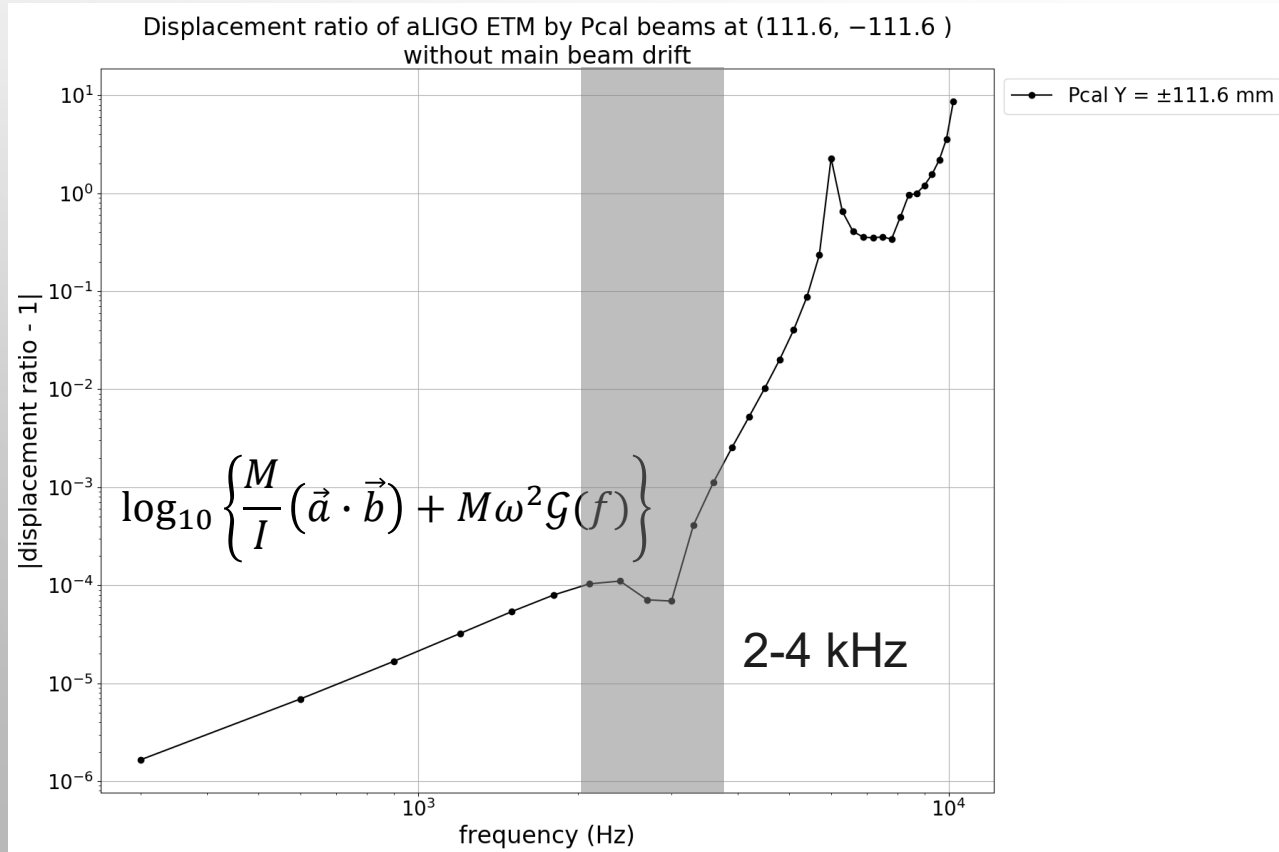
Mirror displacement

Transfer function of suspension

Impact to the NS ringdown frequency

Resonant modes have a tail in the lower frequency region.

It affects to 2-4 kHz range for 0.1% level, but...



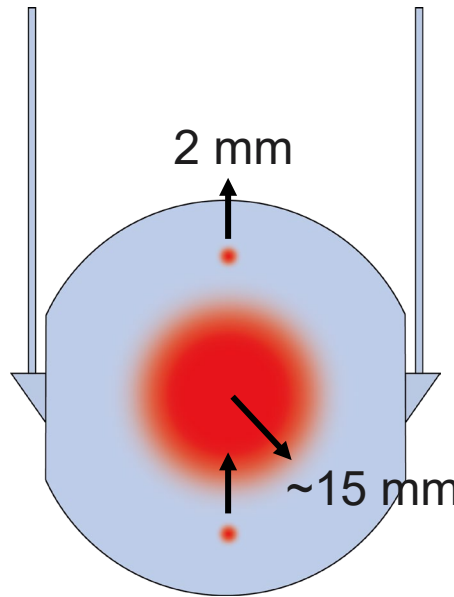
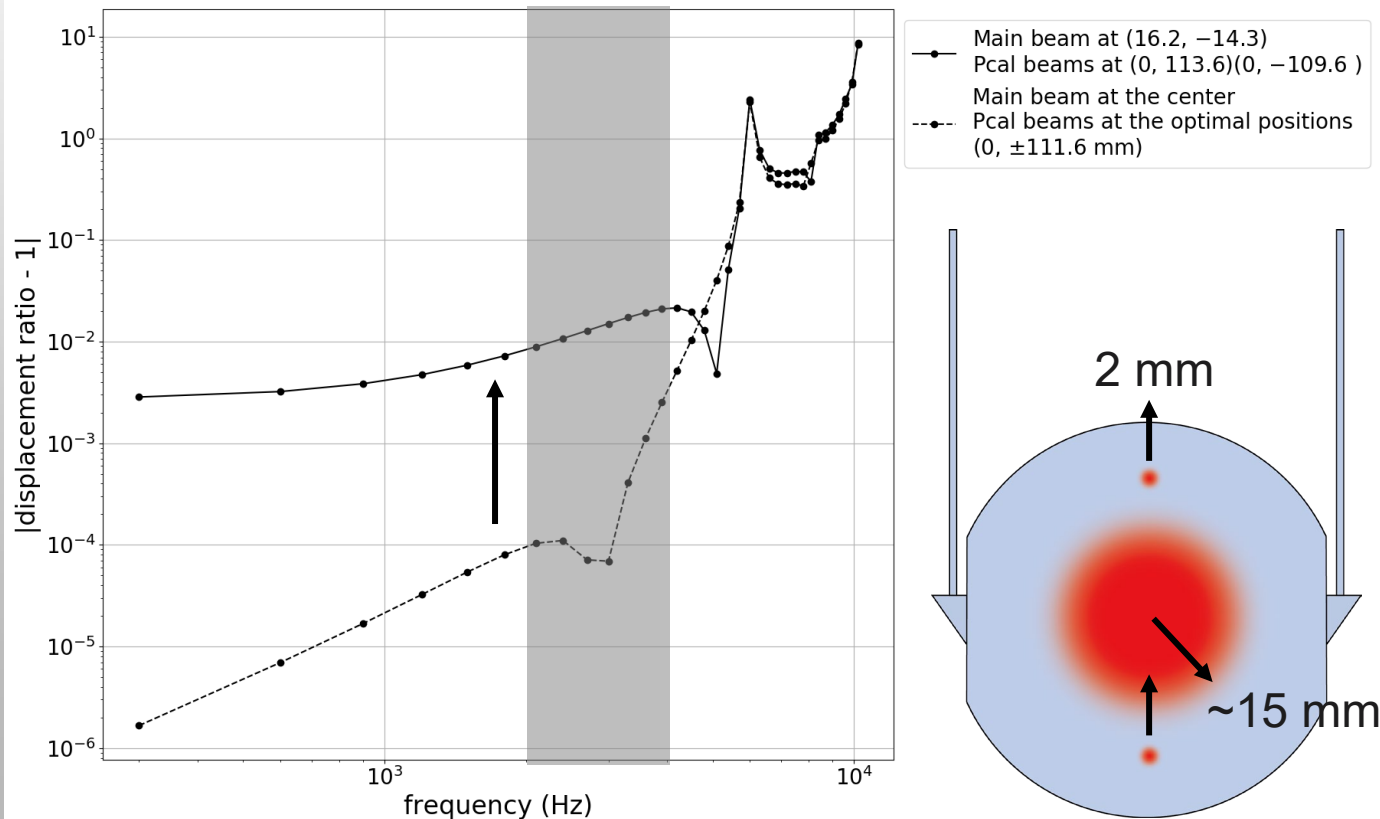
$$\vec{x} = - \frac{2P \cos \theta}{c} \frac{1}{M\omega^2} \left\{ 1 + \frac{M}{I} (\vec{a} \cdot \vec{b}) + M\omega^2 \mathcal{G}(f) \right\}$$

$\vec{x}$: Mirror displacement
 $\frac{2P \cos \theta}{c}$: Power-to-force const.
 $\frac{1}{M\omega^2}$: Transfer function of suspension
 1 : Translation
 $\frac{M}{I} (\vec{a} \cdot \vec{b})$: Rotation
 $M\omega^2 \mathcal{G}(f)$: Deformation

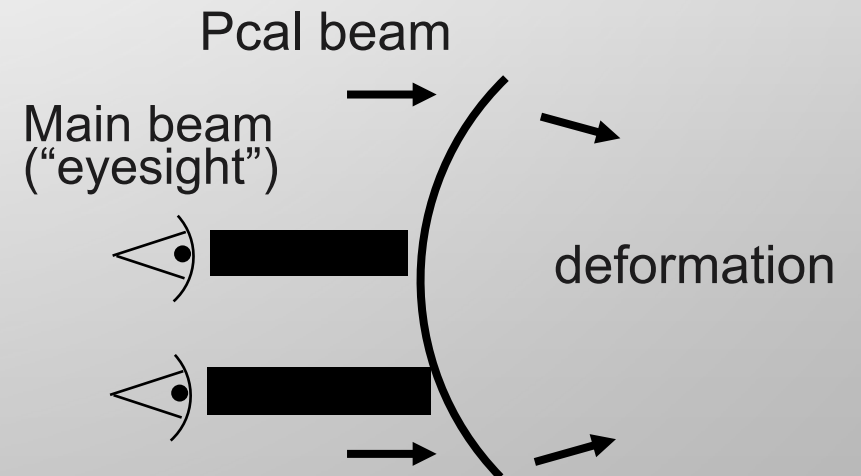
Sensed deformation by misaligned beams

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

cement ratio of aLIGO ETM by Worst case estimation based on LHOX measurement
Main beam at (16.2, -14.3), Pcal beams at (0, 113.6)(0, -109.6)



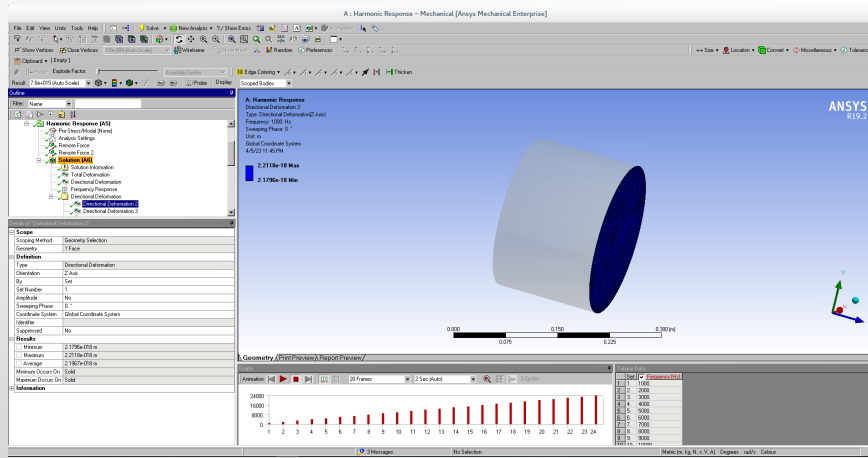
It rises to $>1\%$ error with the actual aLIGO's alignment precision.
We have to consider it in calibration for accuracy in high frequency.



Tools to simulate deformation: FEA software

Finite-element analysis (FEA) software can simulate response of each position of a body.

ANSYS



Modal analysis

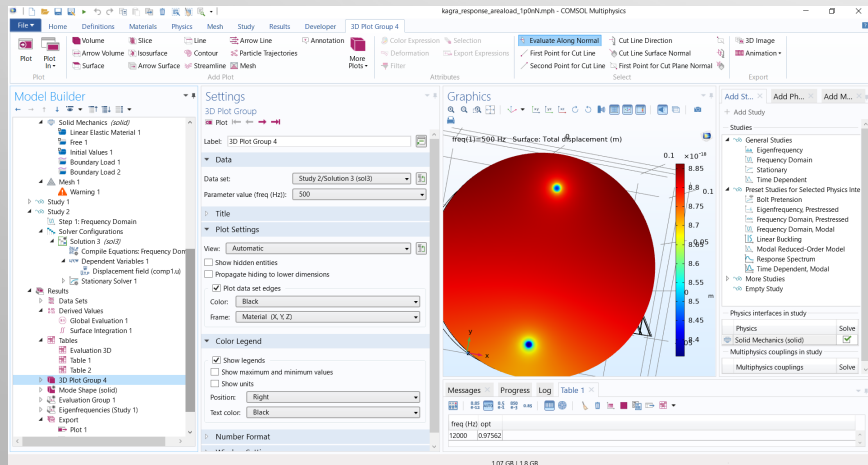
- Calculate resonant frequencies and deformation modes
- Determine the optimal Pcal beam positions



Harmonic response analysis

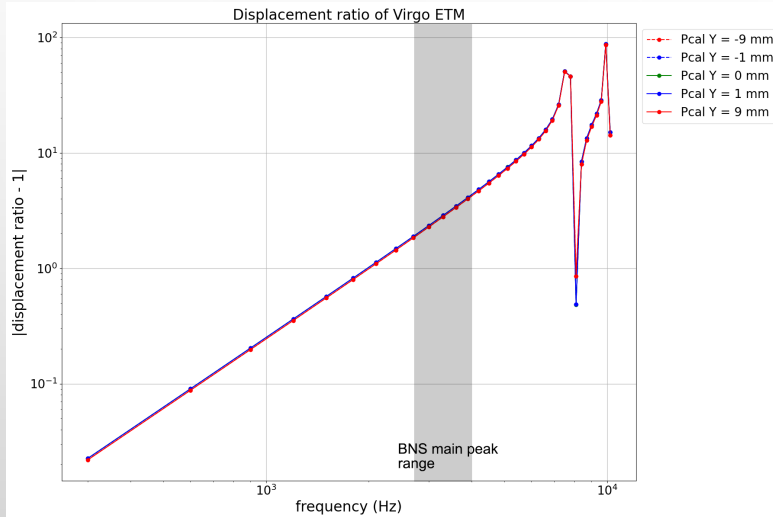
- Calculate deformation against force
- Move beam positions

COMSOL



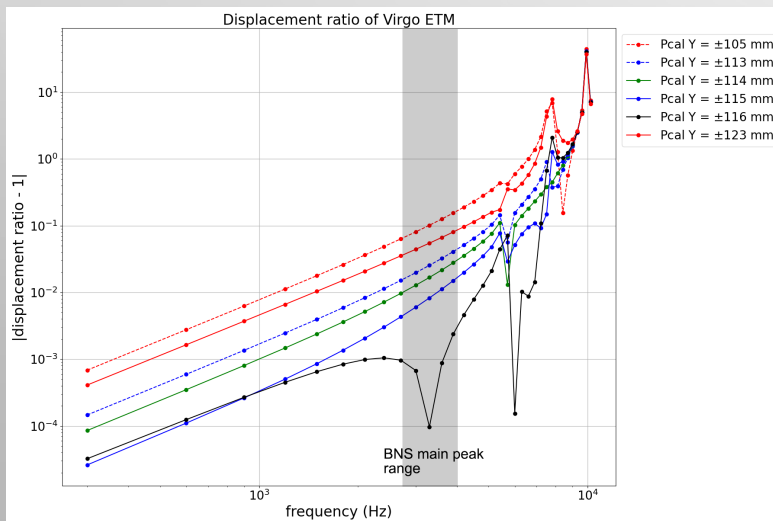
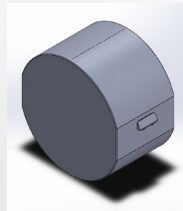
All LVK deformation studies

I have evaluated deformation of all LVK mirrors with their Pcal configuration.



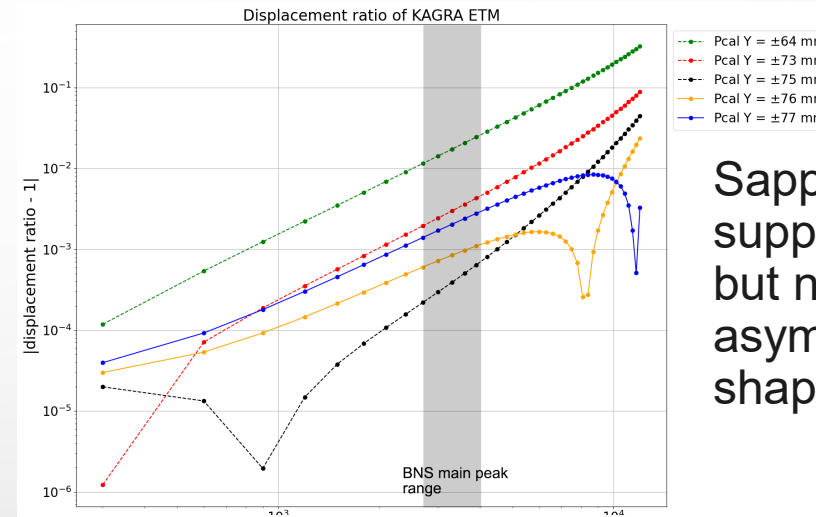
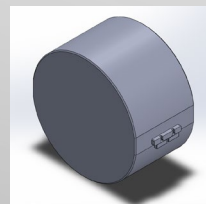
Virgo 1-beam

Effect of drumhead mode is dominant.



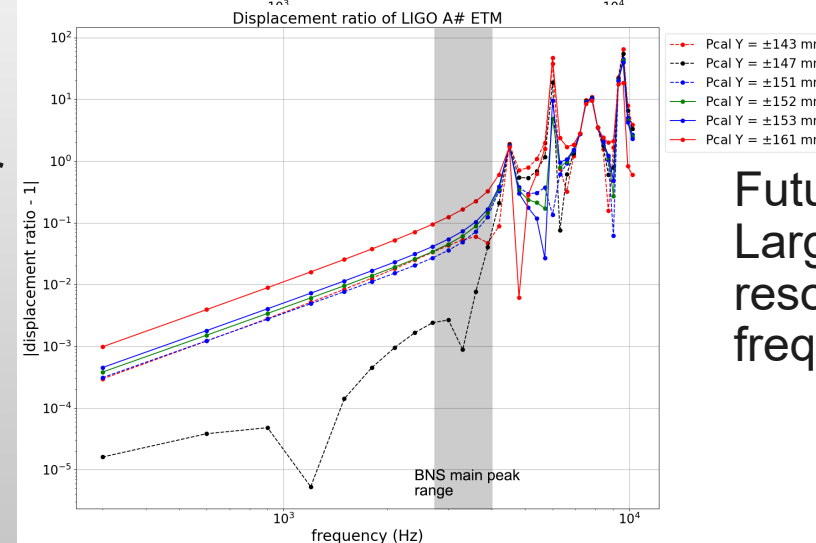
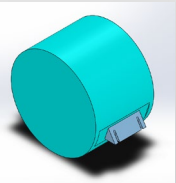
Virgo 2-beams

Situation is similar as aLIGO.



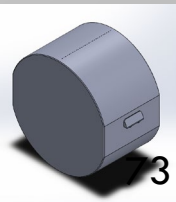
KAGRA

Sapphire is efficient to suppress deformation, but needs to consider asymmetric mirror shape.



LIGO A#

Future project.
Larger mirror moves resonance to lower frequency.



ETM PARAMETERS

	aLIGO	Virgo	KAGRA	LIGO A#
Diameter (mm)	340	350	220	462.930
Thickness (mm)	200	200	150	272.312
Weight (kg)	39.618	42.37	22.994	100
Materials	Fused silica	Fused silica	Sapphire	Fused silica
Density (kg/m ³)	2203	2200	4000	2203
Poisson's ratio	0.1631	0.17	0.3	0.1631
Young's modulus(GPa)	72.6	70	400	72.6
Main beam radius(mm)	62	58	35.3	62

Assumed LIGO A# ETM as a simplified scale-up of aLIGO ETM to be 100 kg.

With suspension

