Introduction to Gravitational wave experiments: Exploring the Universe from LIGO and CHRONOS

Yuki Inoue

on behalf of CHRONOS collaboration

Department of Physics, National Central University



AGWAM 2026 Jul. 5

Yuki Inoue



Associate professor in National Central University
Adjunct Associate research fellow in Academia Sinica
PI of CHRONOS experiment

- Research history:
  - 2011-2016: POLARBEAR/Simons Array (Cosmic Microwave Background)
    - Alumina Filter, Alumina Optics, Cold Optics design, AR coating
  - 2016-2021: KAGRA (Gravitational Wave experiment in Japan)
    - Calibration and Reconstruction
  - 2021-Now: LIGO (Gravitational Wave experiment in US)
    - Calibration and HR coating
  - 2025-Now: CMB
  - 2026-Now: CHRONOS
- Education
  - CHiP International GW Summer school
  - Design team of Bando Kobe Science Museum







Team CHRONOS

National Central University
Yuki Inoue (PI)
Masashi Hazumi
Daiki Tanabe
Vivek Kumar
Hsiang-Yu Huang
Ta-Chun Yu

Academia Sinica
Tsz-King Wong
Feng-Kai Lin

Senior Member
Chao Shiuh

University of Philippine, Diliman
Mario Organo





NCU-CMB group (from 2025 April)

National Central University
Yuki Inoue
Masashi Hazumi

Calibration Analysis

Data analysis and pipeline development for Ongoing Observation

Core-Optics R&D

R&D for the new technology of GW with Taiwan semiconductor technology

Experimental Cosmology

Landscape of Gravitational wave stochastic background study with GW and CMB data

10 staffs and students join our group

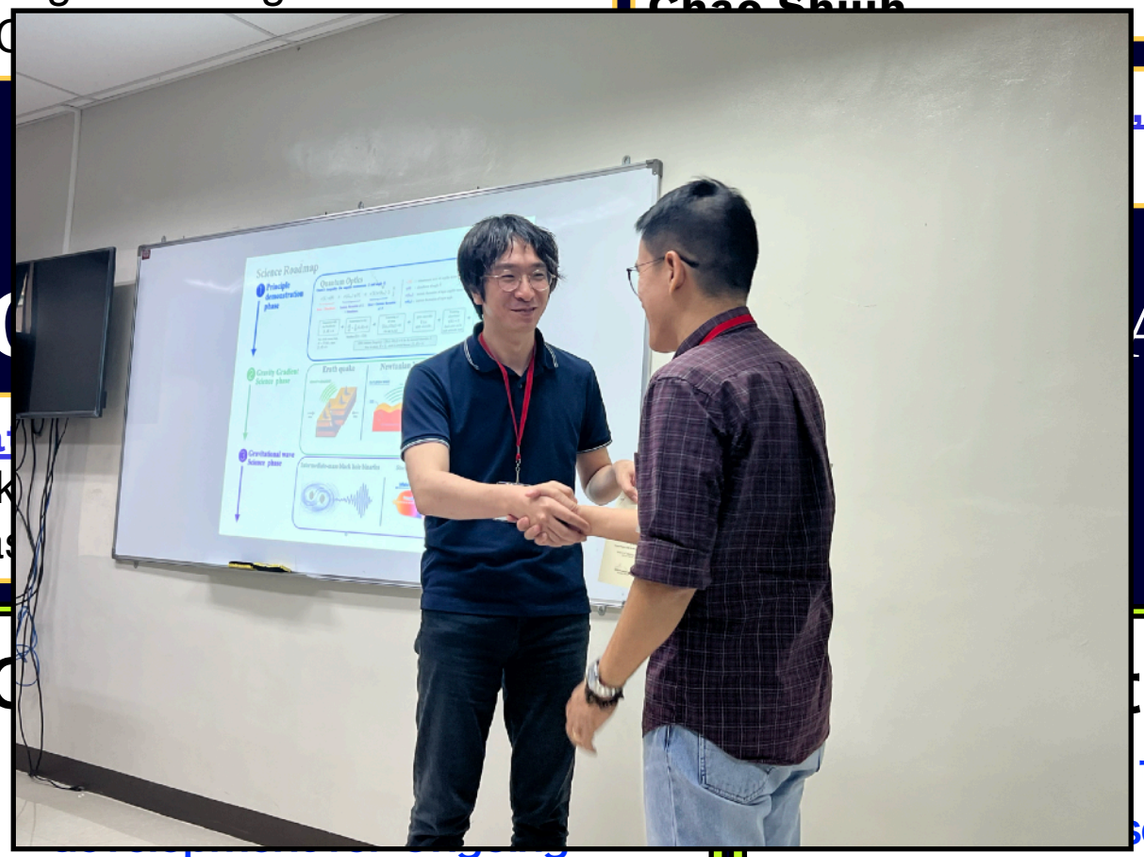
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Yuk
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Observation

technology

GW and CMB data

10 staffs and students join our group

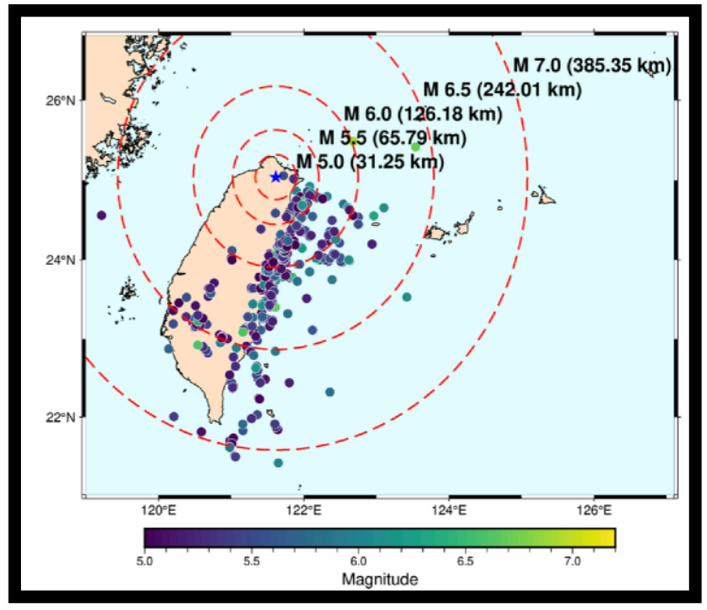
Geophysical Gravity effects

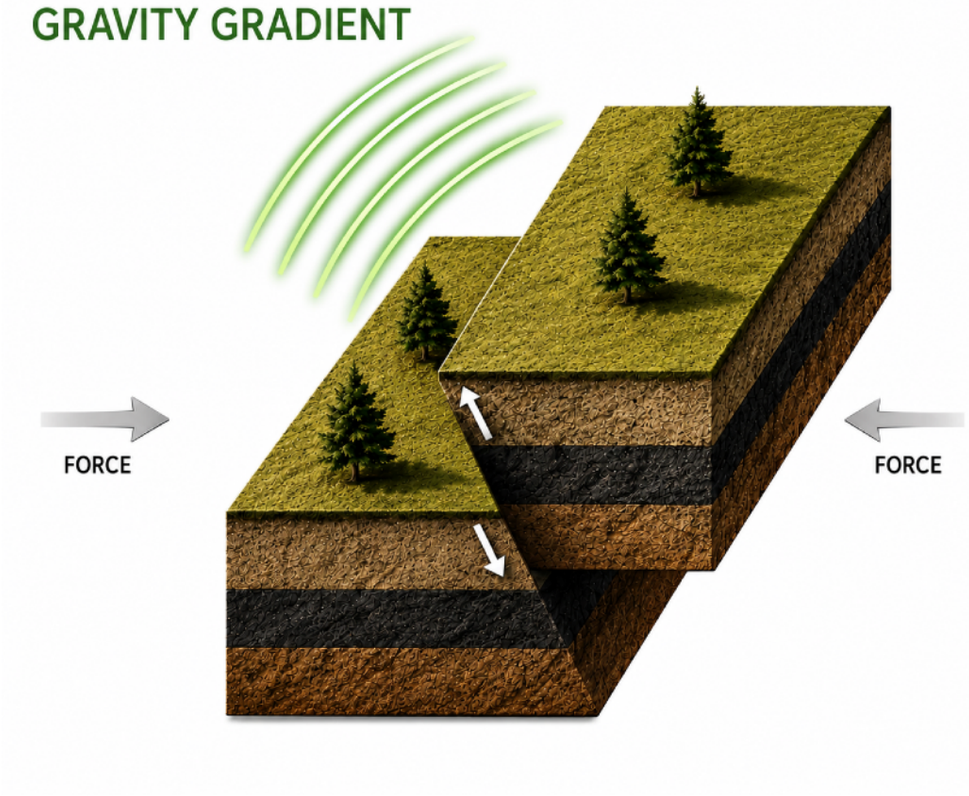
Prospects for Observing Gravity-gradient Noise and Earthquake Gravity Signals with CHRONOS

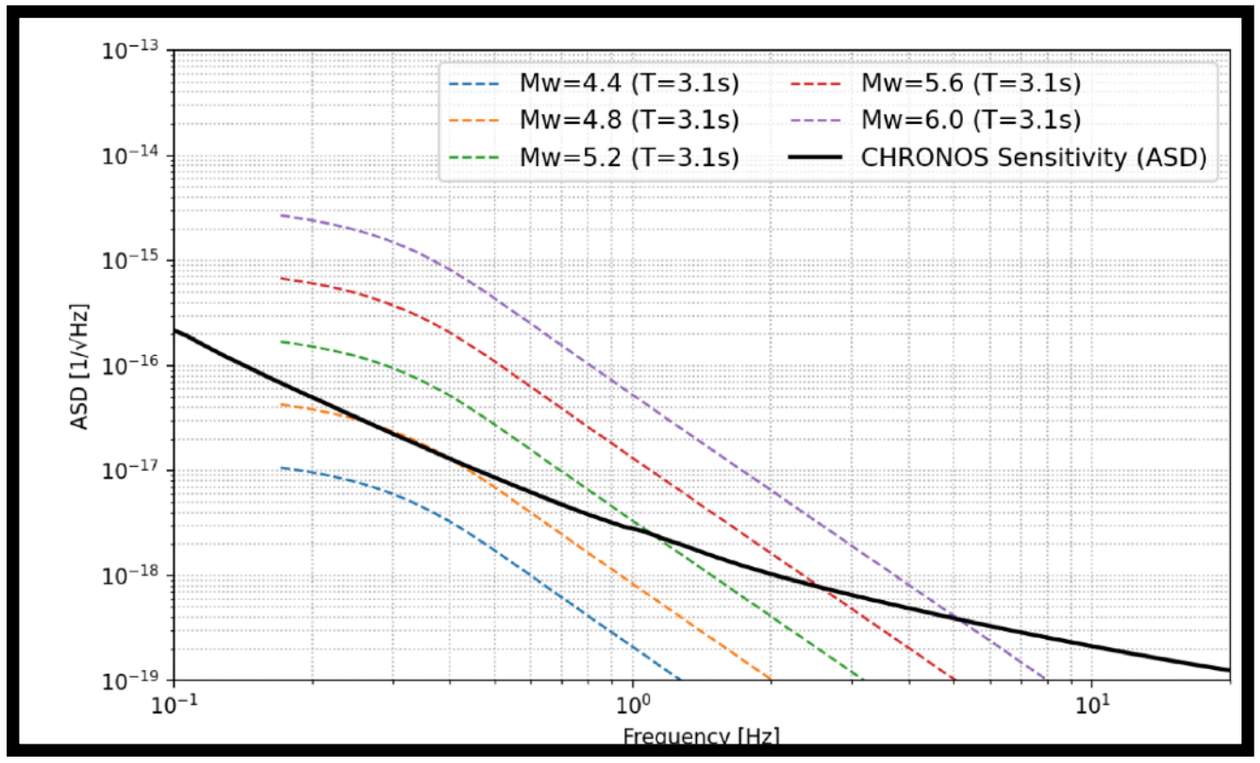
Mario Juvenal S. Onglao III[1,2,*] Yuki Inoue[2,3,4,5,†], and Daiki Tanabe[2,3,4,5]

[1]National Institute of Physics, University of the Philippines - Diliman, Quezon City, Philippines
[2]Center for High Energy and High Field Physics, National Central University, Taoyuan, Taiwan
[3]Department of Physics, National Central University, Taoyuan, Taiwan
[4]Institute of Physics, Academia Sinica, Taiwan
[5]High Energy Accelerator Research Organization (KEK), Japan
†Corresponding author: Yuki Inoue, iyuki@ncu.edu.tw



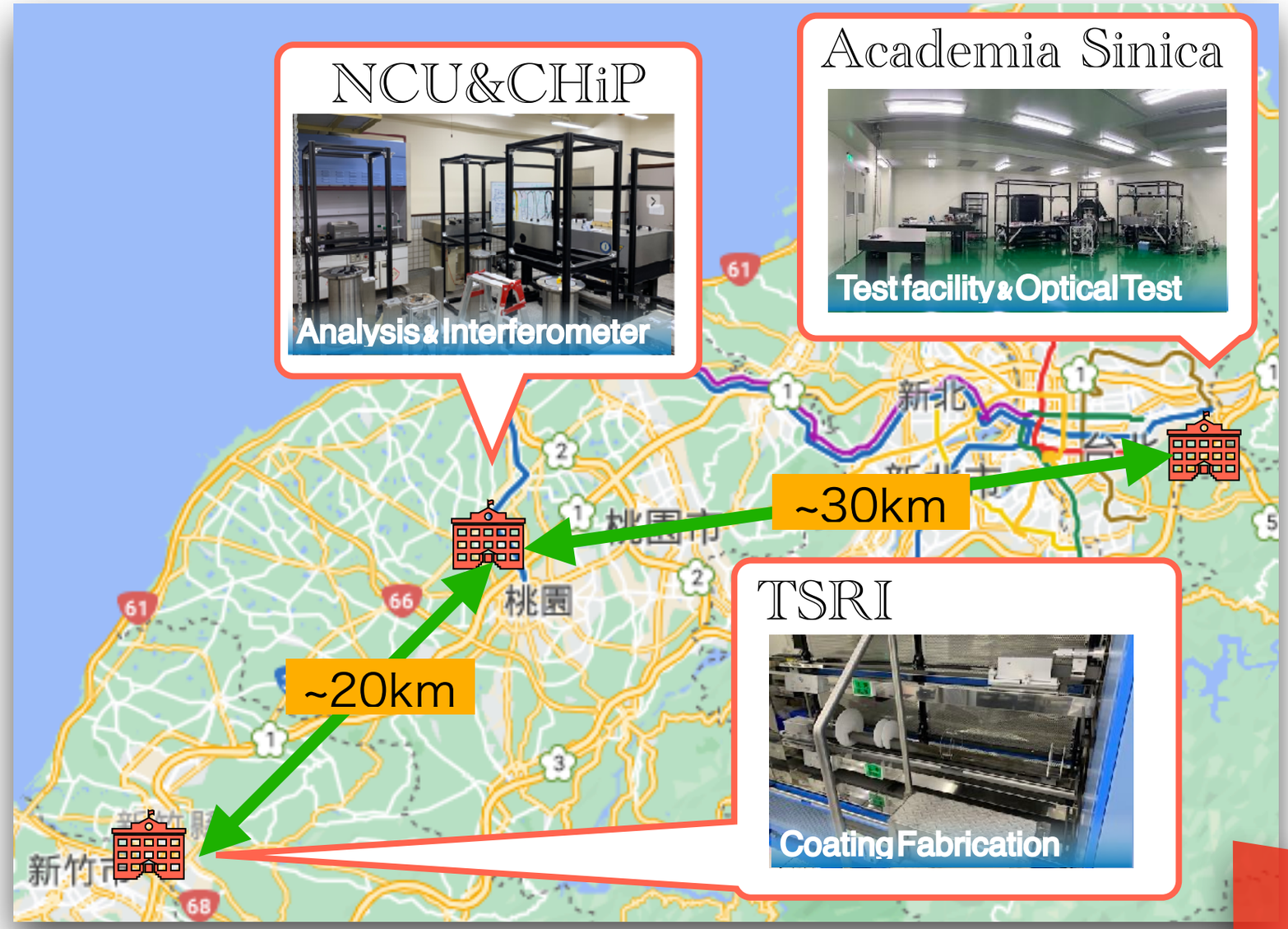






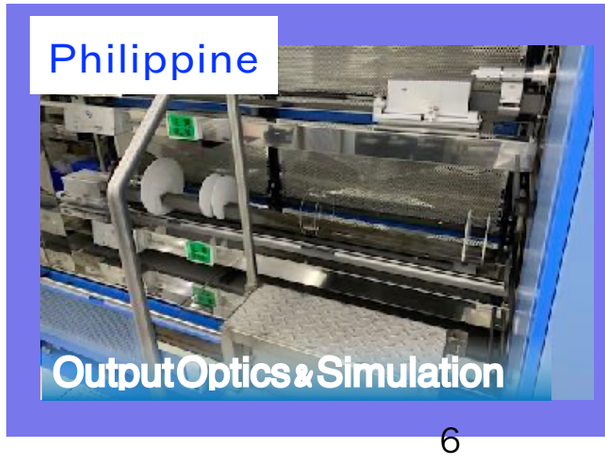
arXiv: 2606.19124

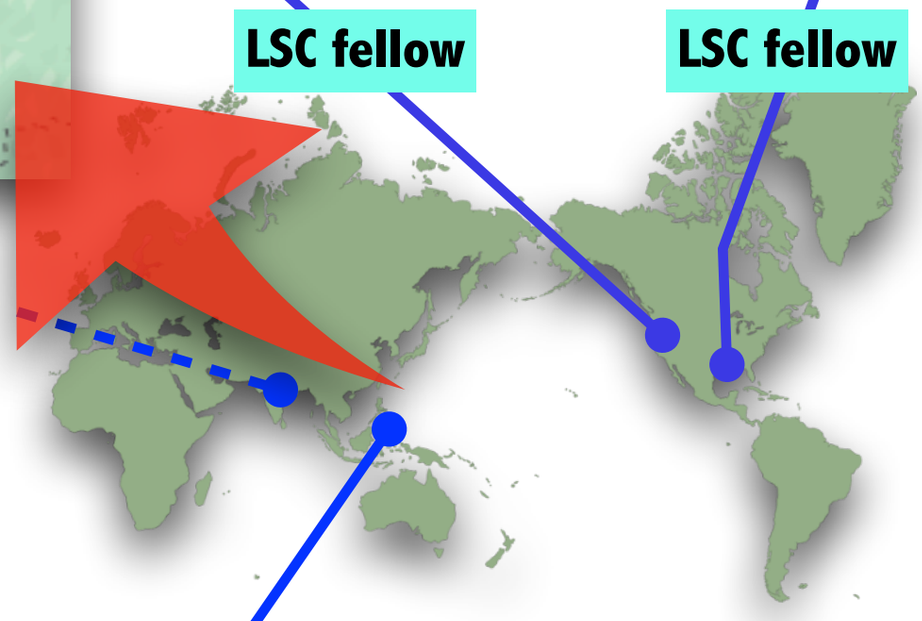
Taiwan-LIGO instrumentation group and World









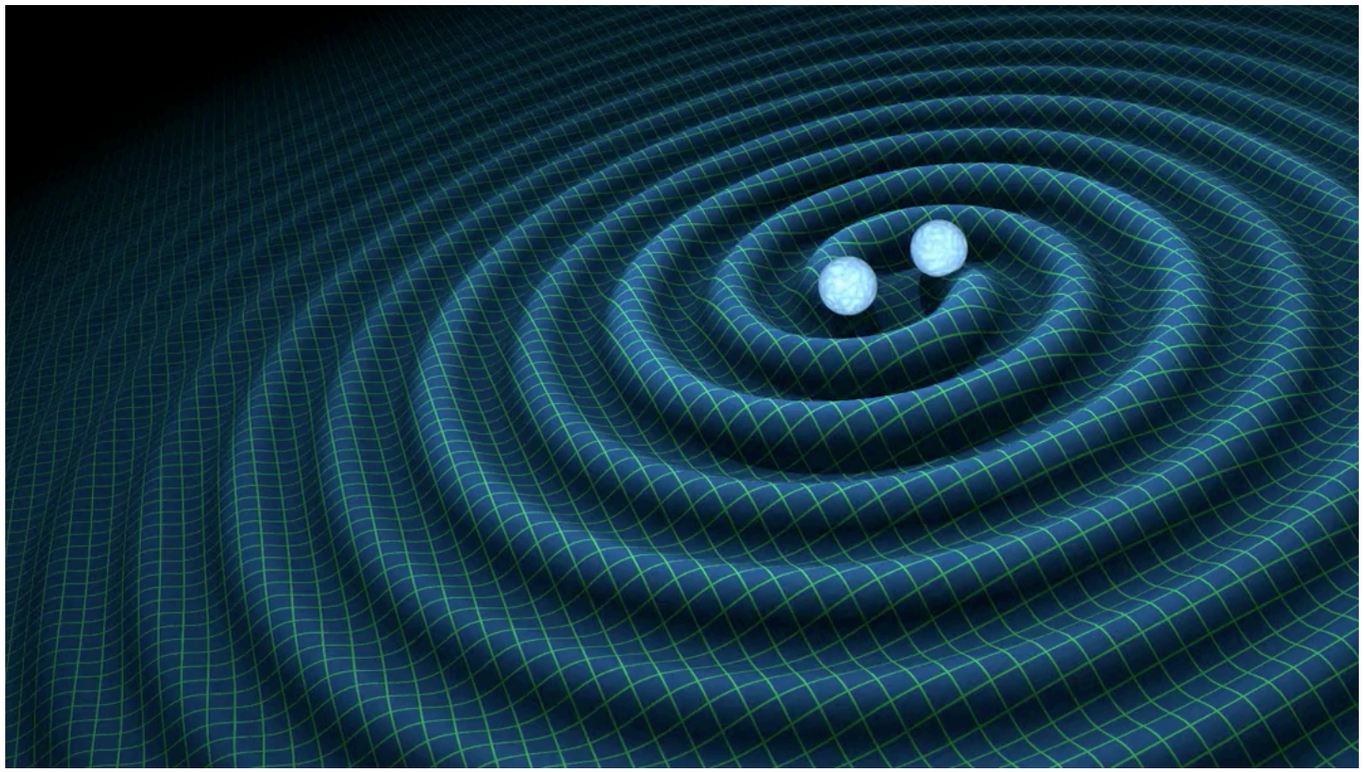


Outline

- Introduction
- Principle demonstration phase
- Gravity gradient phase
- Gravitational Wave phase
- Schedule
- Summary

Introduction





Science target: Gravitational waves and Astrophysics
Project: LIGO Scientific collaboration
Mission: Observation 4 is ongoing
(2023 May-2025 end of Nov.)
Contribution from Our group: Calibration and Coating

Metric

$$ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu$$

Metric

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

Perturbation

$$\left(\frac{\partial^2}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) h = 0$$

$$h_{ij} = A_{ij} \times \exp\left[\mathrm{i}(\omega t - kz)\right]$$

$$A_{ij} \equiv \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$





Typical gravitational wave strain sensitivity

$$h \sim \frac{2G}{c^4 R}\ddot{I} \sim \frac{r_g}{R} = \frac{\text{Schwarzschild radius}}{\text{Distance from the source}}$$

Solar mass NS-NS: r_g~3km

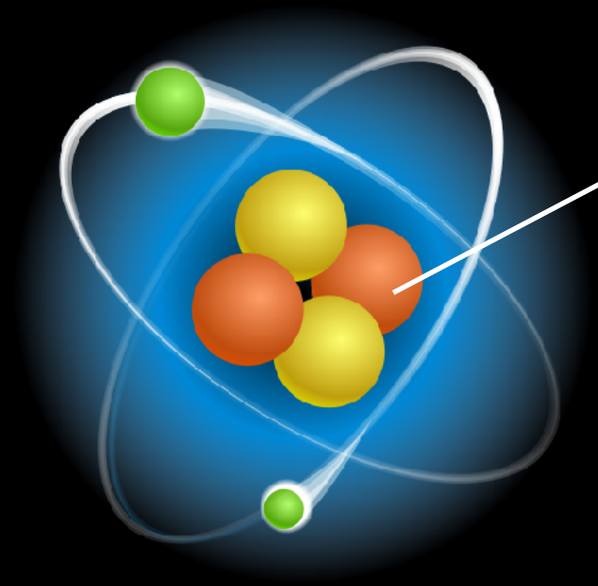
Typical distance: 100Mpc

$h \sim \delta L/L \sim 10^{-21}$

δL~2000km x 10^{-21}

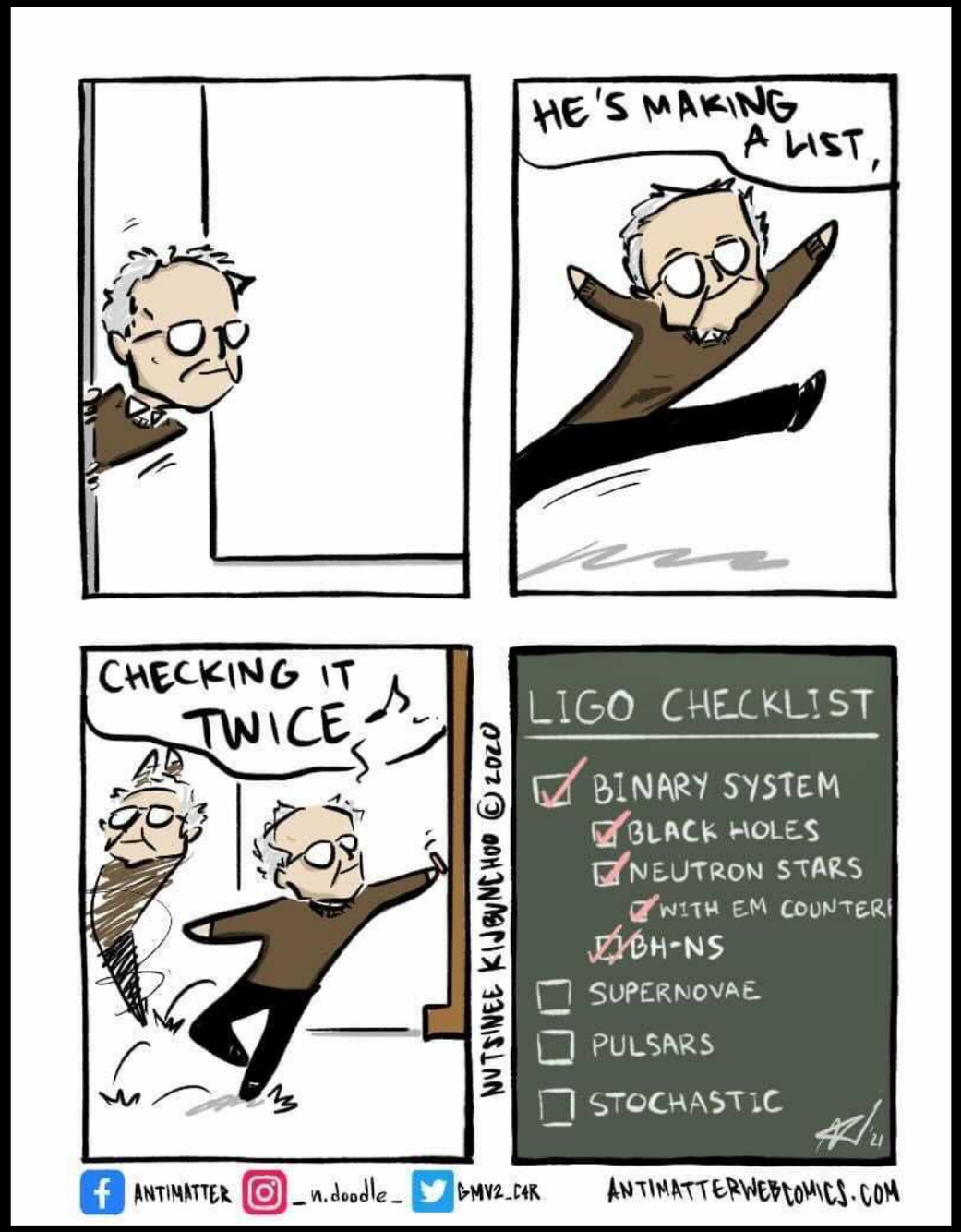
~10^{-15}m~1fm



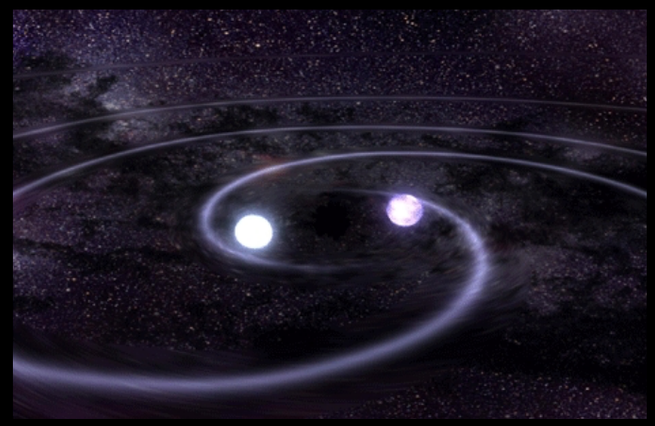


Amplitude of GW is very tiny

Gravitational wave source



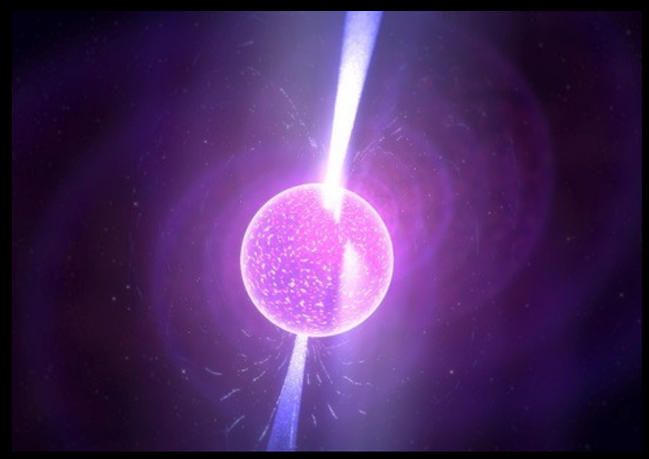
BINARY SYSTEMS



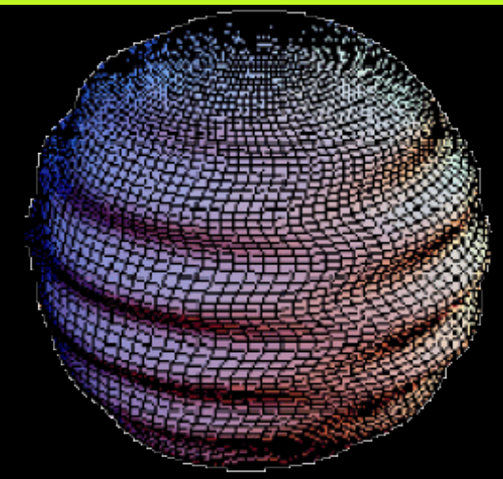
SUPER NOVA



PULSER



STOCHASTIC BACKGROUND



Gravitational wave observation network

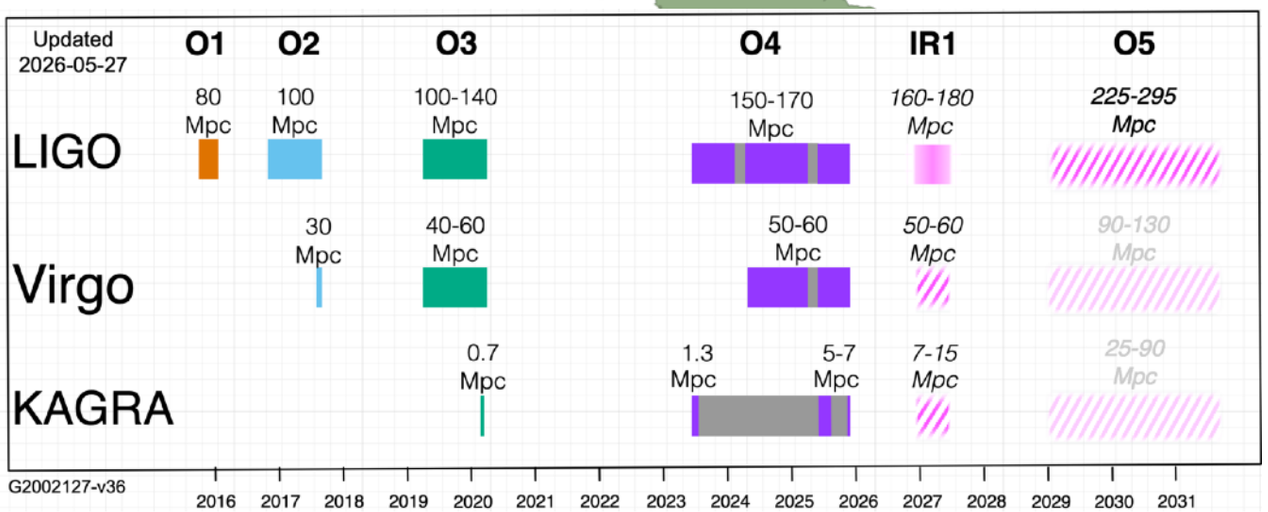

Virgo


KAGRA

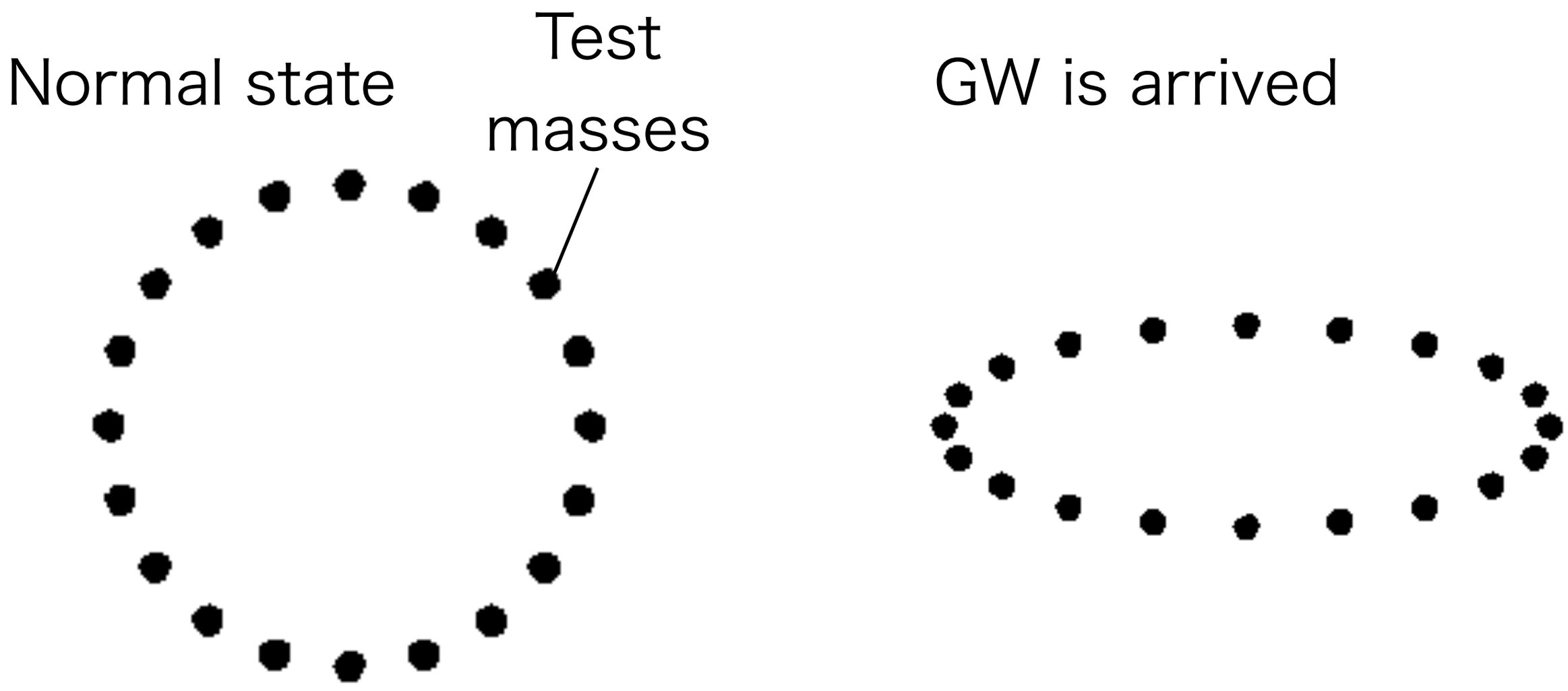

LIGO Hanford


LIGO Livingston


LIGO Aundha (2030)

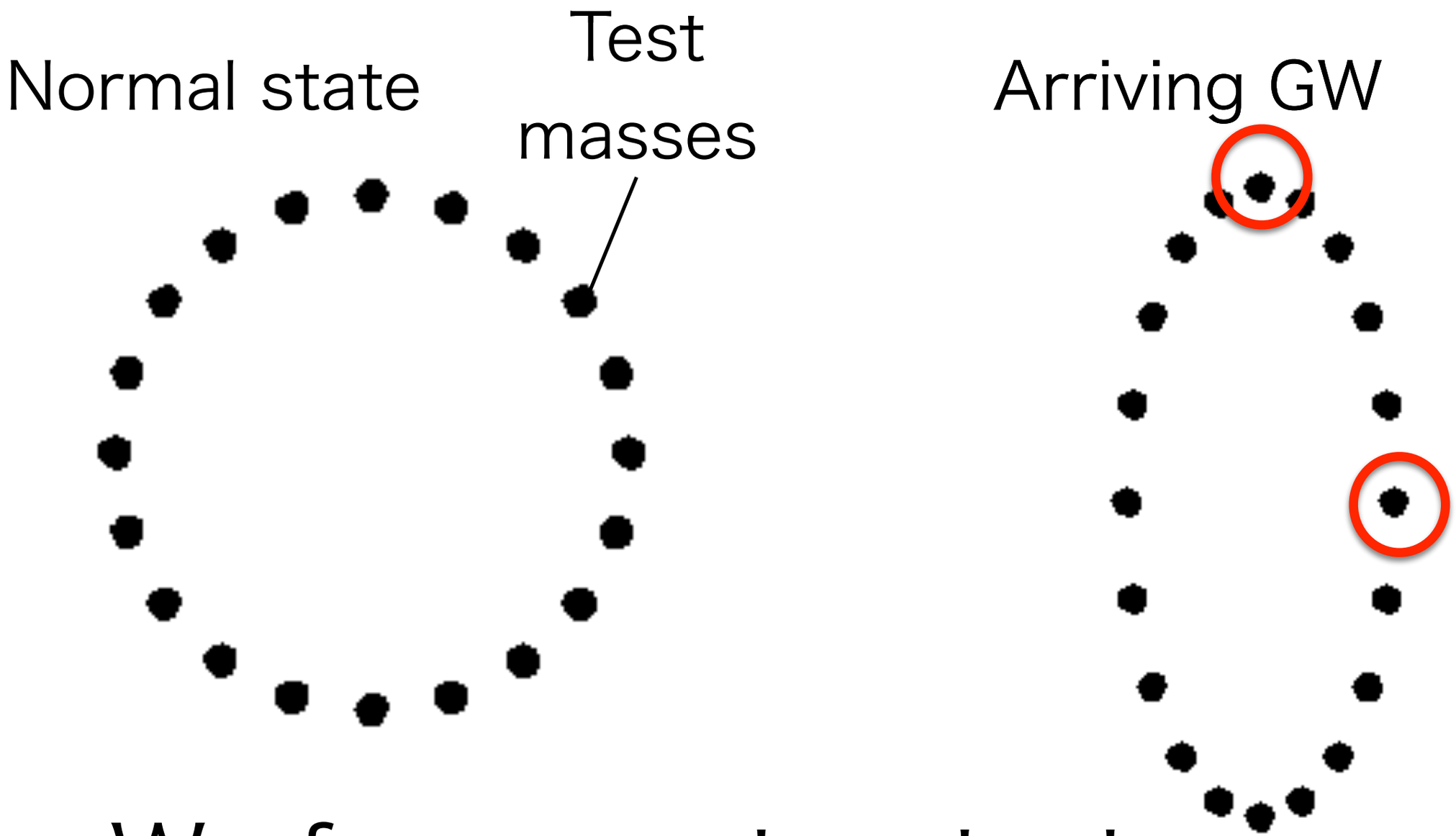


Principle of Observation



Test masses are moved by GWs.

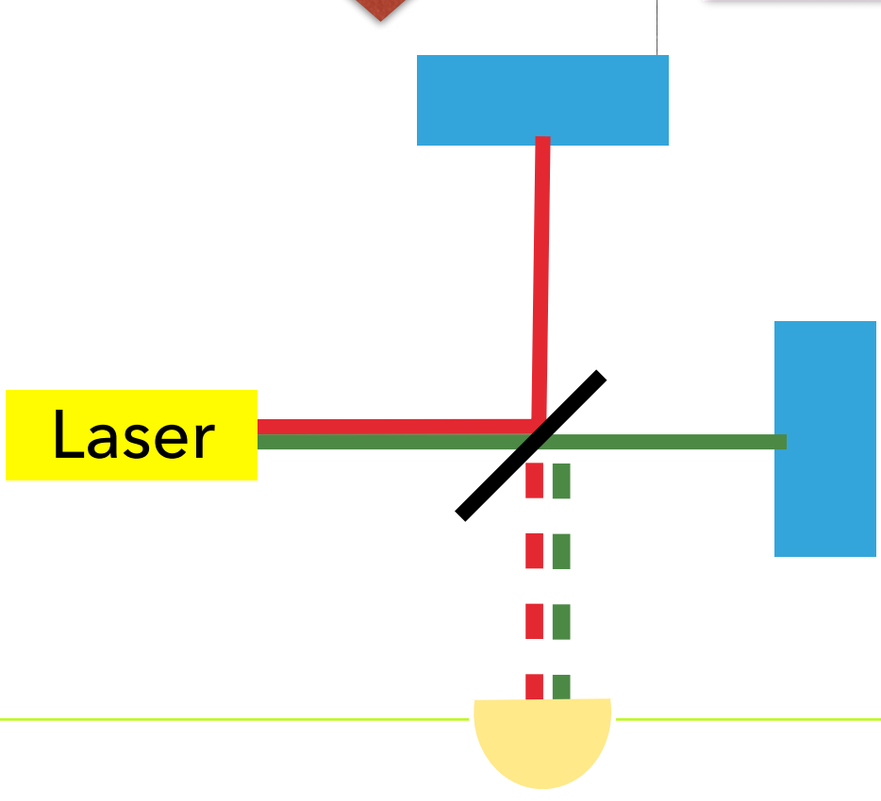
Principle of Observation

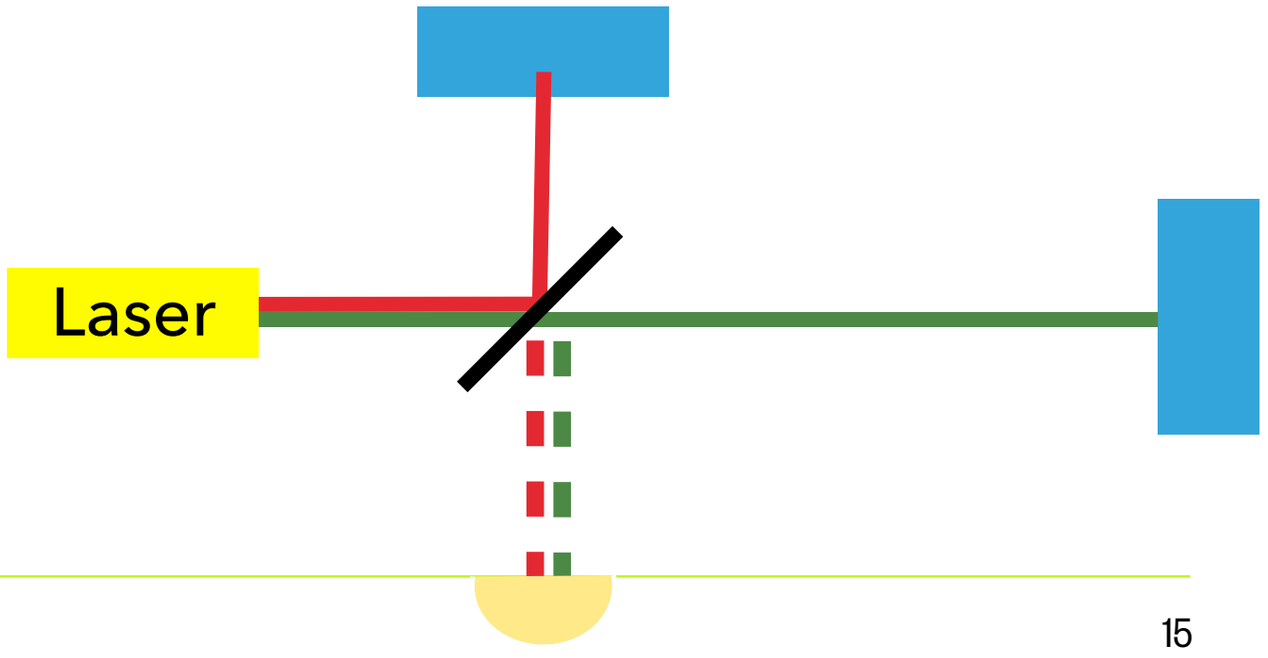


We focus on two test masses.

Principle of Observation(LVK)

We replace the test masses to the mirror.





LIGO

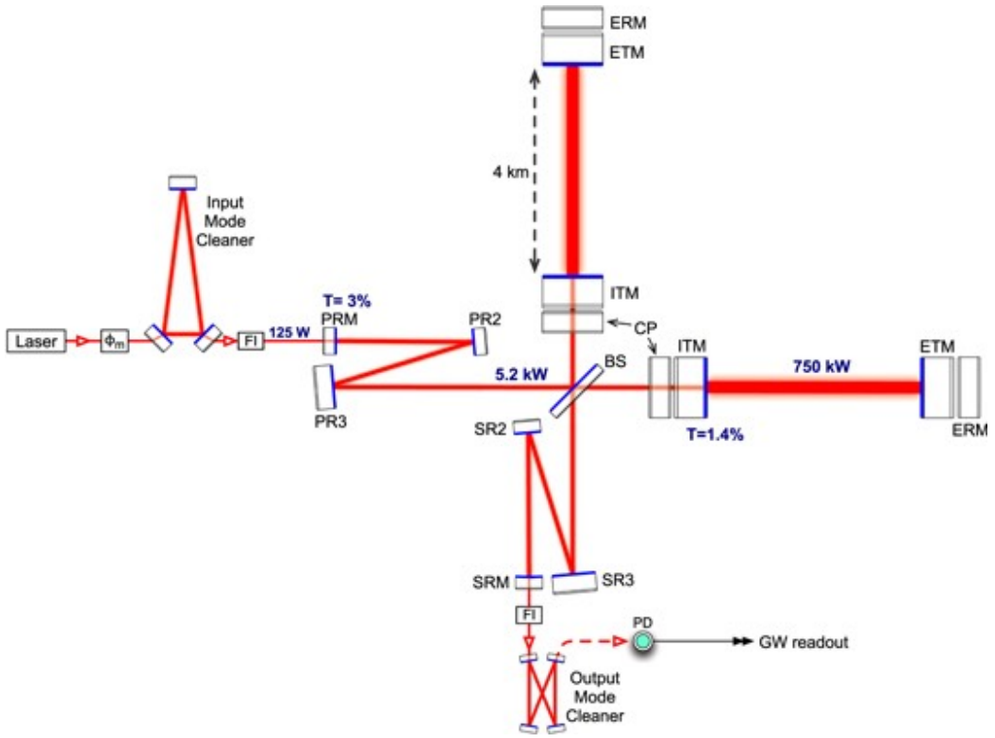


Table 1. Main parameters of the Advanced LIGO interferometers. PRC: power recycling cavity; SRC: signal recycling cavity.

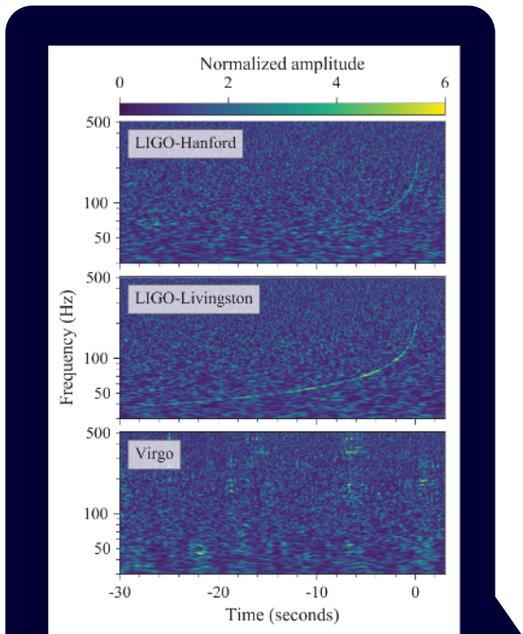
Parameter	Value
Arm cavity length	3994.5 m
Arm cavity finesse	450
Laser type and wavelength	Nd:YAG, $\lambda = 1064$ nm
Input power, at PRM	up to 125 W
Beam polarization	linear, horizontal
Test mass material	Fused silica
Test mass size & mass	34cm diam. x 20cm, 40 kg
Beam radius ($1/e^2$), ITM / ETM	5.3 cm / 6.2 cm
Radius of curvature, ITM / ETM	1934 m / 2245 m
Input mode cleaner length & finesse	32.9 m (round trip), 500
Recycling cavity lengths, PRC / SRC	57.6 m / 56.0 m

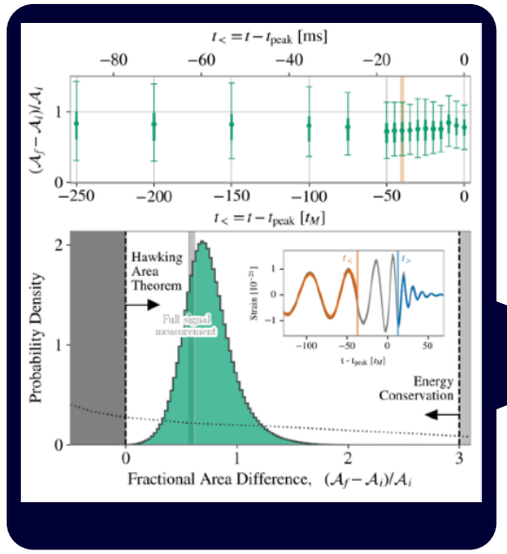
- *Dual recycling Fabry Perot Michelson Interferometer*
- *40kg test mass*
- *125W laser*
- *Frequency dependent squeezing option (LIGO and Virgo)*

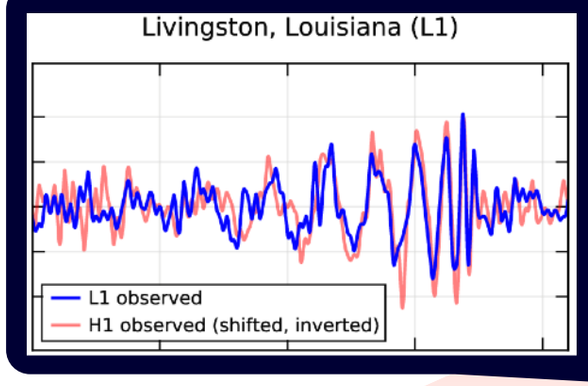
First Invited Patrick Brady
Spokes person of LIGO (2025 May)



10 years anniversary from LIGO discovery



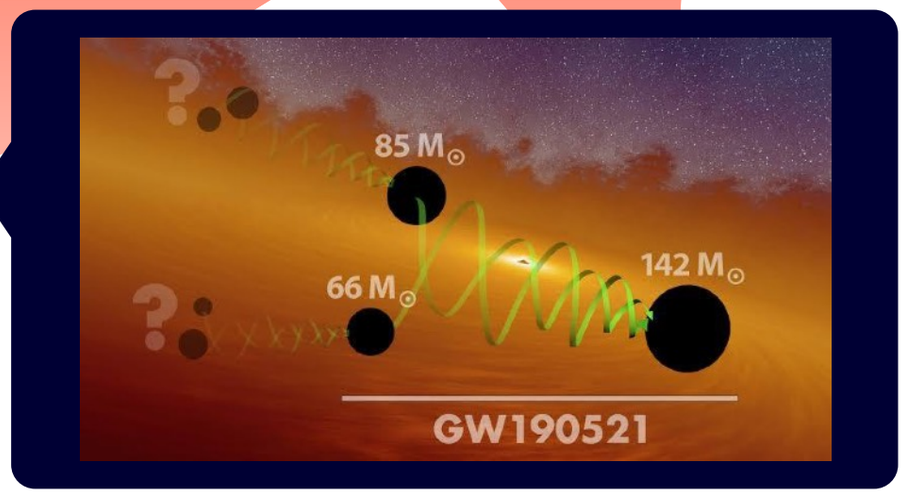




2015 Sep.14 The first detection

2017 Aug. 17 BNS

2019 May. 21 IMBH



2023 Nov.23 The largest Kerr black hole

2025 Jan.14 Hawking's area law

2026 IR1

Introduction

10 years anniversary from the first detection of Gravitational wave

Main message of This talk!

OX = Observation X

Previous works

O1, O2, O3

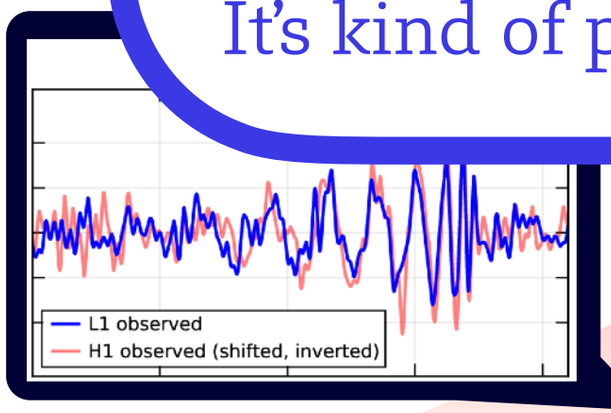
The first detection era!

This Talk!

O4

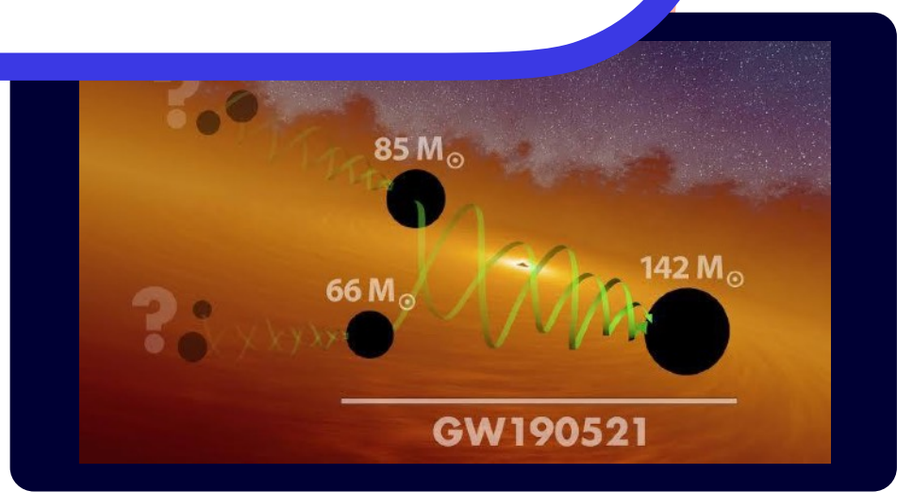
The statistical evaluation era!

It's kind of phase transition to new era of GW observation!



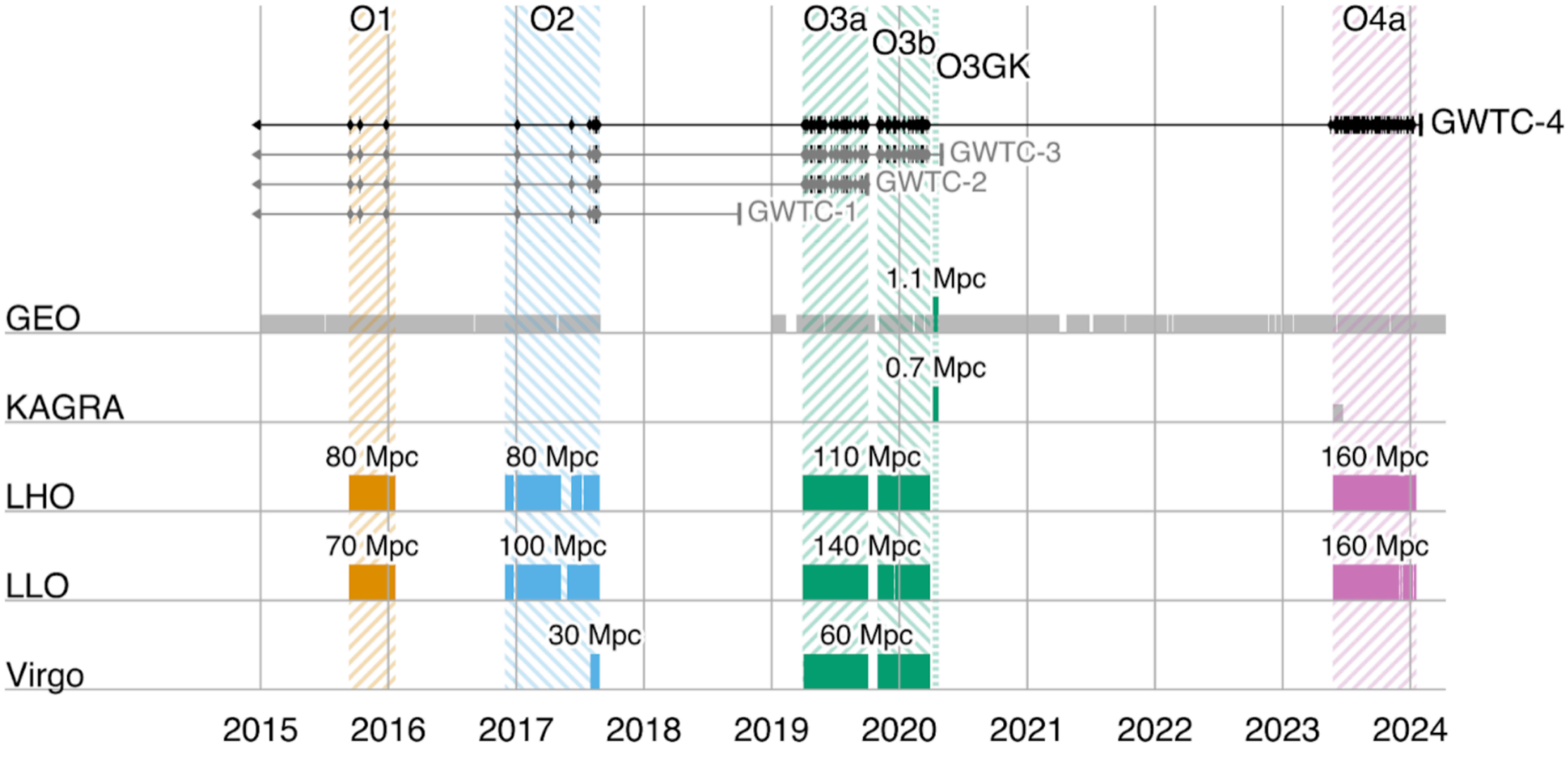
2017 Aug. 17 BNS

2015 Sep.14 The first detection



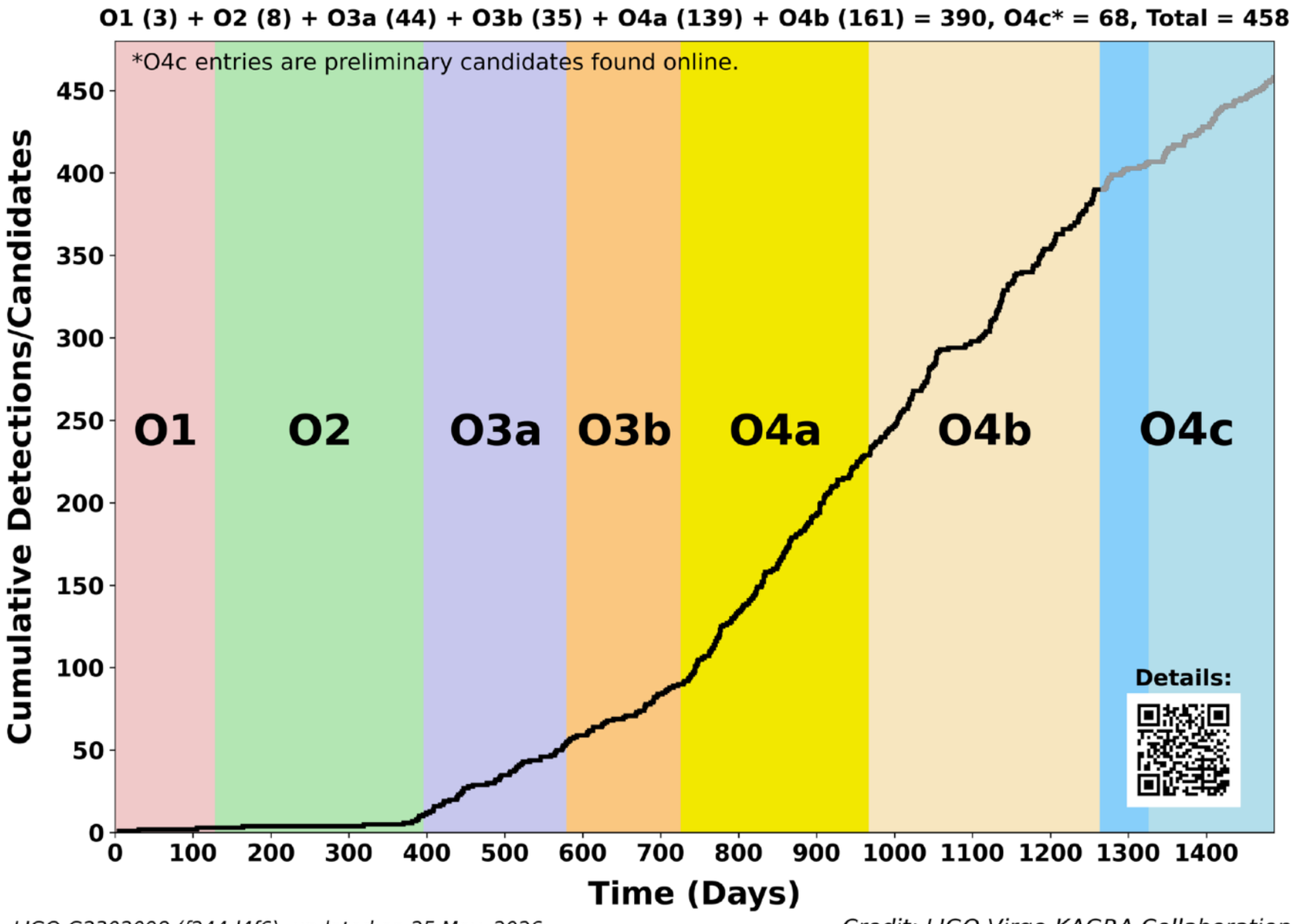
Overview of O4-a

Binary Range（Mpc）=
average distance at which the detector can detect a compact binary coalescence with SNR = 8



This talk focus on the result of O4-a data（GWTC-4）

Number of detections



The era of O(100) events!

Data release plan

2027

O4c->GWTC-6

Compact binary coalescence

Binary Neutron Star

Binary Blackhole

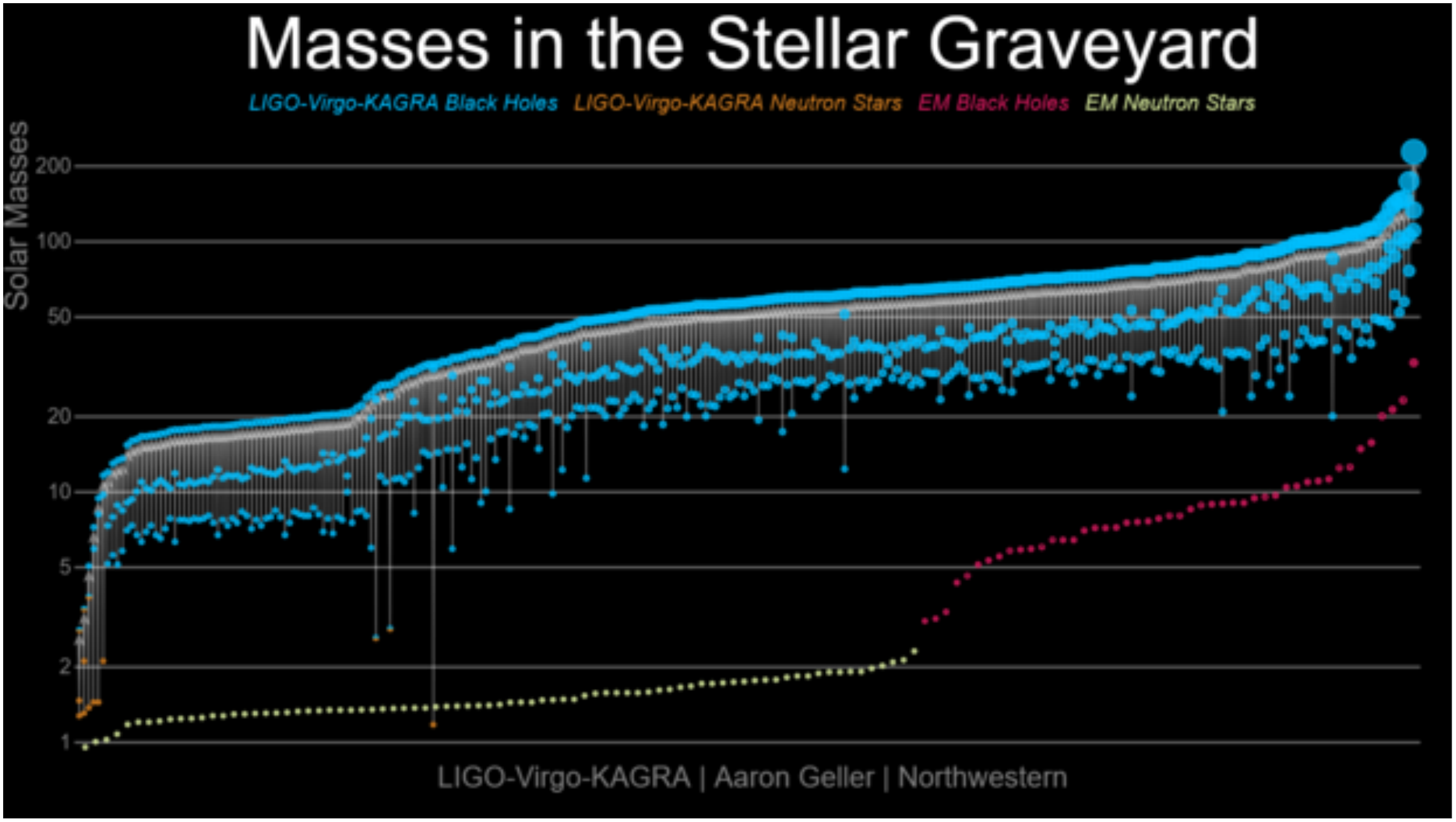
Neutron star- Black hole binary

Events

Total number of events ~ 458

Every 2.8 days we detect new events

O4-b result


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Hubble constant

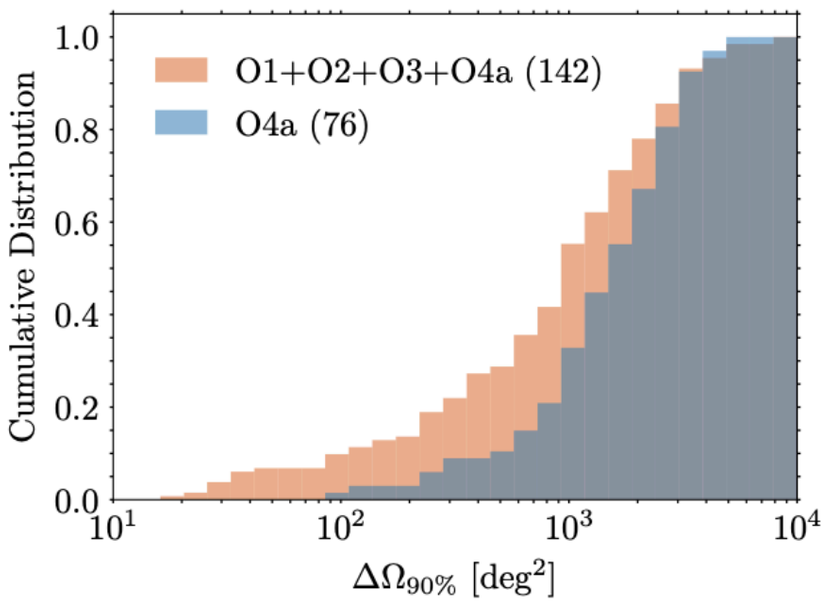


Figure 2. Cumulative distribution of the size of the 90% CR of the sky localization of CBC candidates observed during O1+O2+O3+O4a in orange (142 total events including GW170817) and O4a-only in blue (76 events). It can be seen that the typical sky localization of O4a events was larger than that of O1–O3 events.

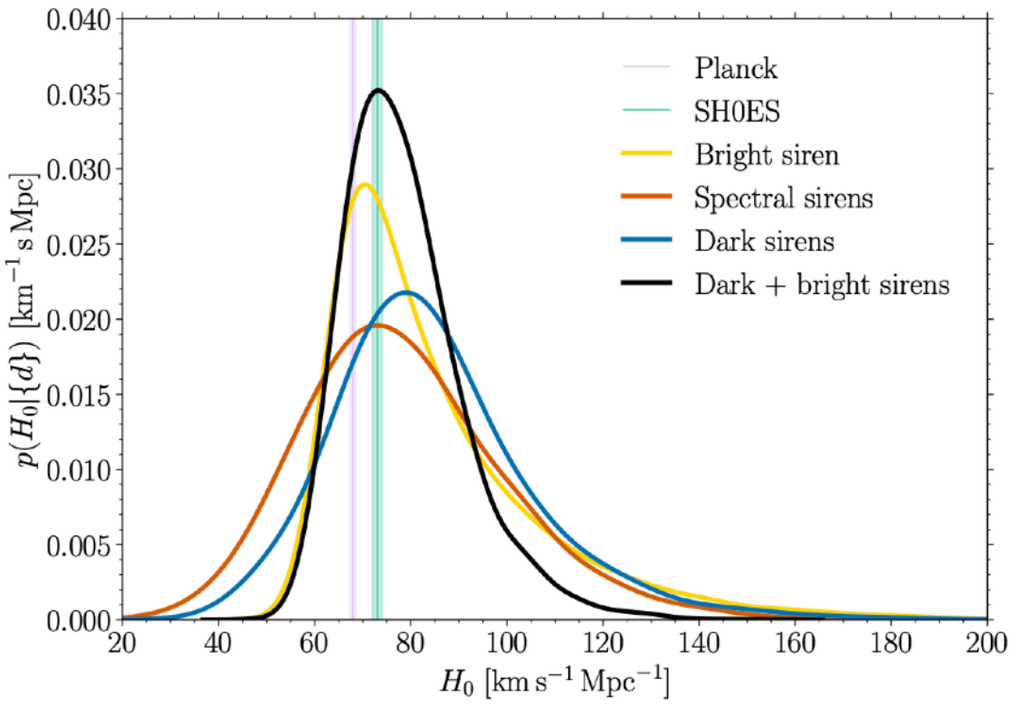


Figure 4. Hubble constant posterior for different cases. Yellow curve: posterior obtained from the bright siren GW170817 and its EM counterpart. Orange curve: posterior obtained with the spectral siren method and the FULLPOP-4.0 mass model. Blue curve: posterior obtained using all dark sirens with GLADE+ K-band in the luminosity-weighting case ($\epsilon = 1$) and the FULLPOP-4.0 mass model. Black curve: posterior after combining the dark and bright siren results. The pink and green shaded areas identify the 68% CI constraints on H_0 inferred from CMB anisotropies (Ade et al. 2016) and in the local Universe from SH0ES (Riess et al. 2022), respectively.

Bright siren: BNS with optical counter part

Dark siren: BBH with estimated host galaxy

Spectral siren: Use mass distribution $M_{det} = (1+z)M$

Catalog	Period	Number of Events	Purpose / Significance
GWTC-1 (O1–O2)	2015–2017	~10 events	Proof of concept
GWTC-2 (O3a)	2019	~39 events	Early population analysis
GWTC-3 (O3b)	2019–2020	~90 events	First full-scale spectral-siren trial
GWTC-4 (early O4)	2023–2024	>200 events	Toward 10 % precision on H_0

https://arxiv.org/pdf/2509.04348

$$H_0 = 76.6^{+13.0}_{-9.5}\,(76.6^{+25.2}_{-14.0})\,\mathrm{km\,s^{-1}\,Mpc^{-1}}.$$

Principle of spectral strain method

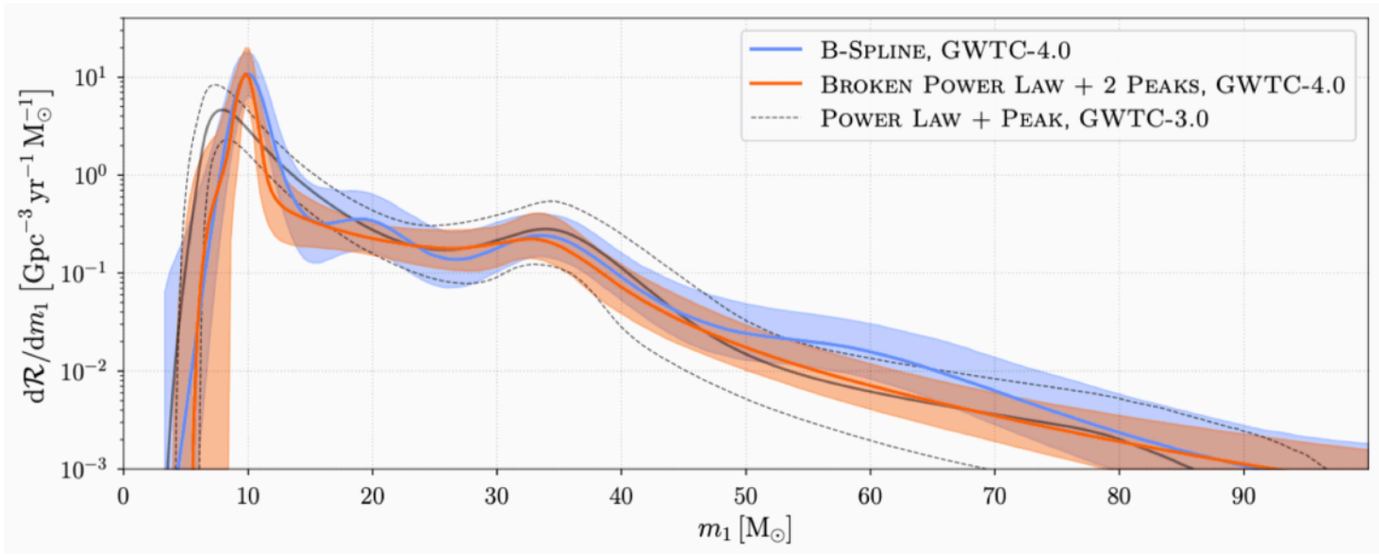


Figure 2: Primary black hole mass spectrum, i.e. the distribution of masses of the larger-mass black hole (the 'primary') in our detected binary systems. GWTC-4.0 (blue/orange) refines the earlier GWTC-3.0 Power Law + Peak (black dashed), with clearer support for structure around ~10 $M_\odot$ and ~35 $M_\odot$.

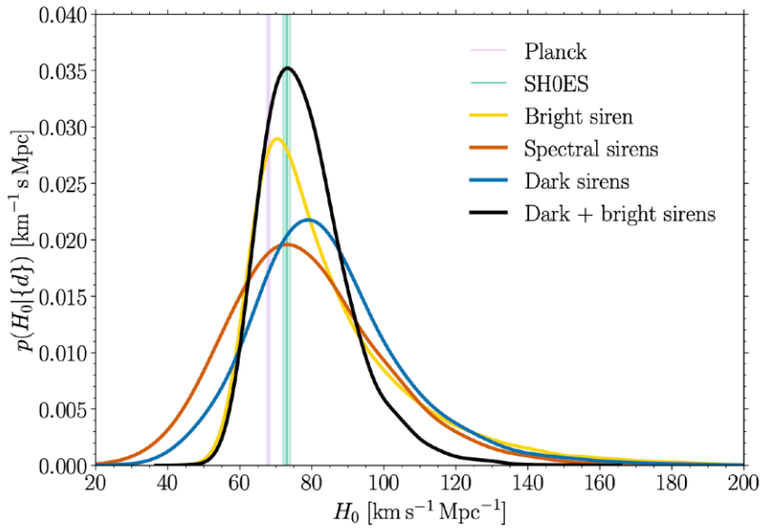


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Universe expands → redshift z stretches GW waveform $m_{\rm det} = (1+z)\, m_{\rm src}$

$$p(z \mid m_{\rm det}) \propto p\left(m_{\rm src} = \frac{m_{\rm det}}{1+z} \mid \lambda\right)\, p(z \mid H_0)$$

If $p(z \mid m_{\rm det})$ has strong features (peaks/cutoffs), their redshifted positions constrain the cosmic expansion.

Hubble constant is consistent with other method.

High SNR event

PHYSICAL REVIEW LETTERS **135,** 111403 (2025)

Editors' Suggestion | Featured in Physics

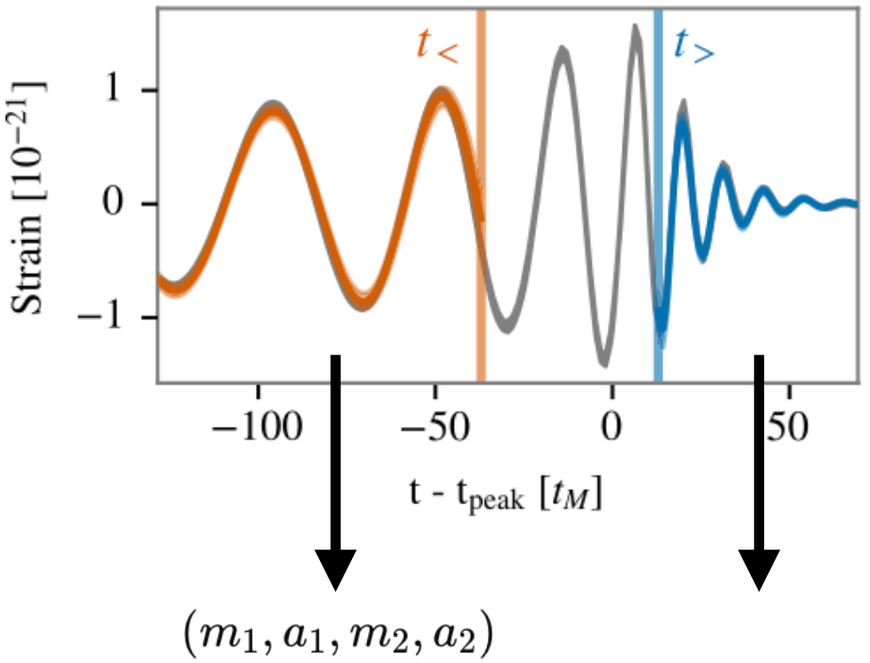
GW250114: Testing Hawking's Area Law and the Kerr Nature of Black Holes

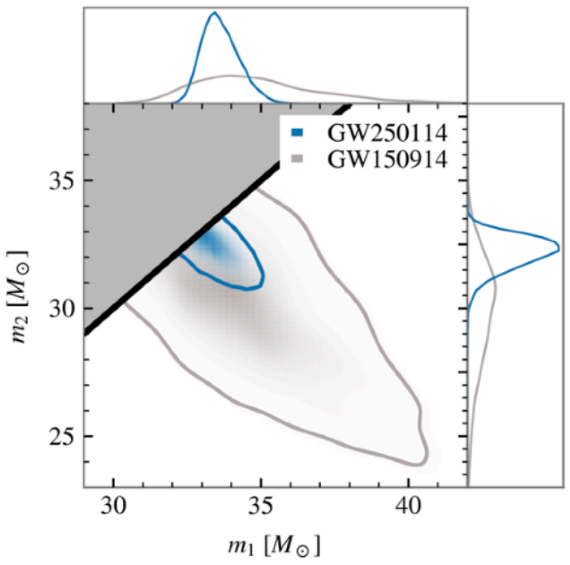
A. G. Abac *et al.*[*]
(LIGO Scientific, Virgo, and KAGRA Collaborations)

(Received 13 August 2025; revised 25 August 2025; accepted 26 August 2025; published 10 September 2025)

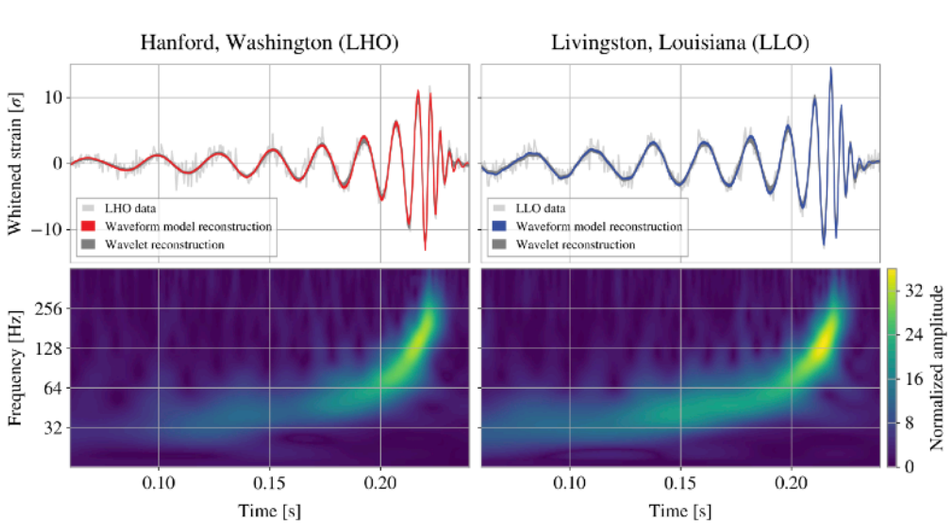
The gravitational-wave signal GW250114 was observed by the two LIGO detectors with a network matched-filter signal-to-noise ratio of 80. The signal was emitted by the coalescence of two black holes with near-equal masses $m_1 = 33.6^{+1.2}_{-0.8} M_\odot$ and $m_2 = 32.2^{-0.8}_{-1.3} M_\odot$, and small spins $\chi_{1,2} \leq 0.26$ (90% credibility) and negligible eccentricity $e \leq 0.03$. Postmerger data excluding the peak region are consistent with the dominant quadrupolar ($\ell = |m| = 2$) mode of a Kerr black hole and its first overtone. We constrain the modes' frequencies to ±30% of the Kerr spectrum, providing a test of the remnant's Kerr nature. We also examine Hawking's area law, also known as the second law of black hole mechanics, which states that the total area of the black hole event horizons cannot decrease with time. A range of analyses that exclude up to five of the strongest merger cycles confirm that the remnant area is larger than the sum of the initial areas to high credibility.

DOI: 10.1103/kw5g-d732





Prediction vs. Direct estimation



SNR~80!

Tests of

1. Hawking's area law

2. No-Hair theory (Kerr Nature of BH)

Hawking's area law

Goal: Experimental verification of **Hawking's area theorem**

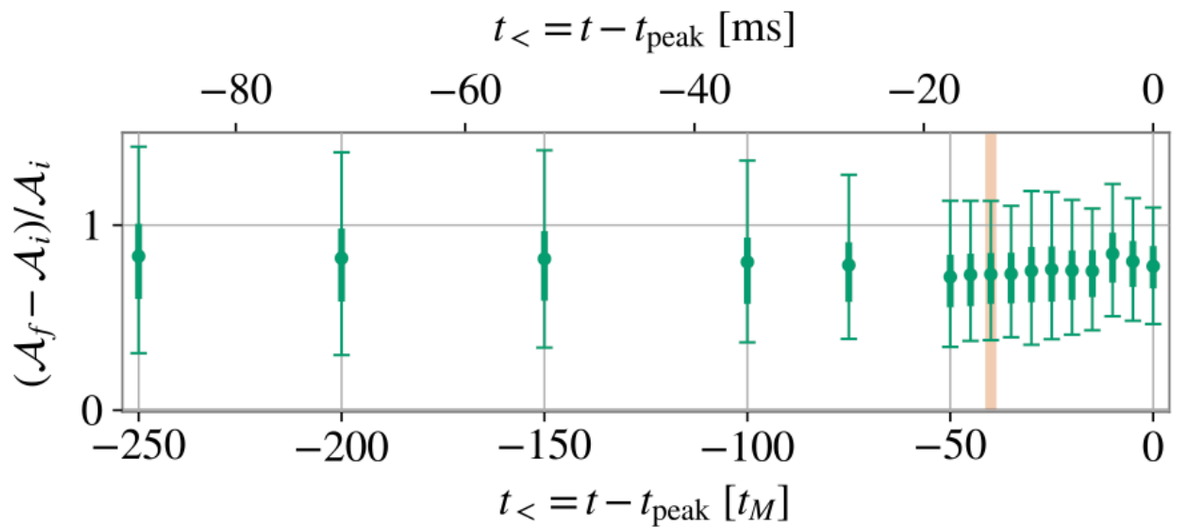
$$A_f \geq A_1 + A_2$$

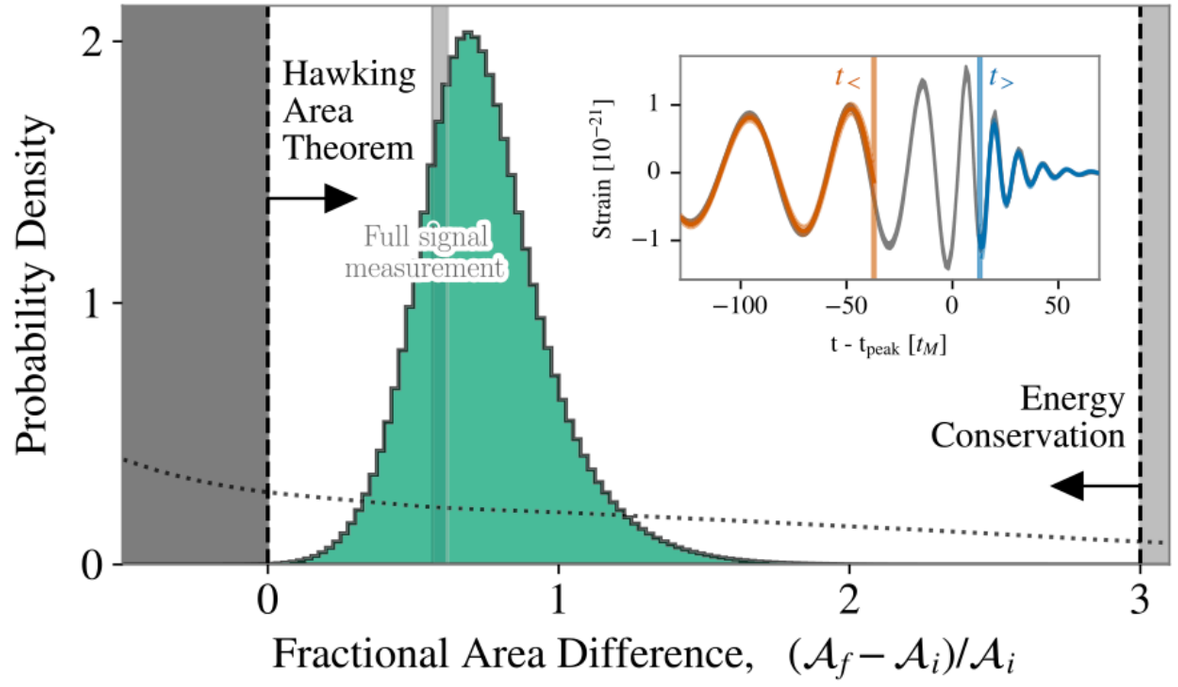
- Calibrated strain $h(t)$ from LIGO/Virgo.
- Split into two statistically independent segments:
  - **Inspiral:** pre-merger portion.
  - **Post-merger:** $t > t_{\rm peak} + 5t_M$.
- Waveform model — NRSur7dq4 / IMRPhenomXPHM.
- Bayesian parameter estimation for each segment.

$$A_i = A_1 + A_2, \qquad A_f = 8\pi M_f \left(M_f + \sqrt{M_f^2 - a_f^2} \right).$$

Evaluate: $\Delta_A = \dfrac{A_f - A_i}{A_i}$.

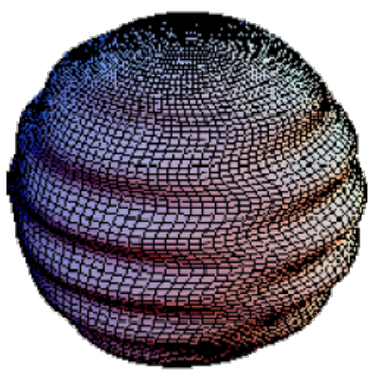
- $P(\Delta_A > 0) \approx 97\%$ → 3–5 σ support.
- $M_f \simeq 68\, M_\odot,\ a_f \simeq 0.69.$
- No evidence for area decrease.





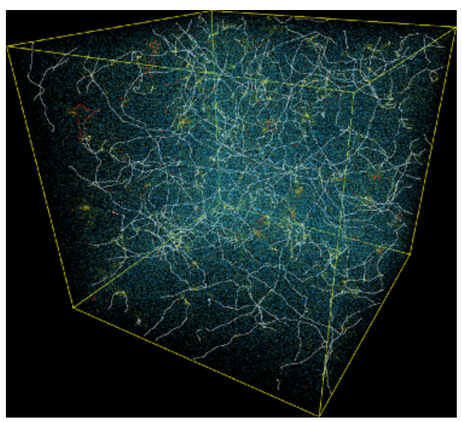
Stochastic background source

Primordial



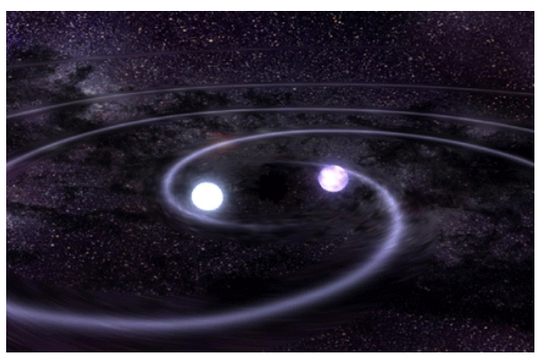
- Initial fluctuation with Inflation

Phase transition



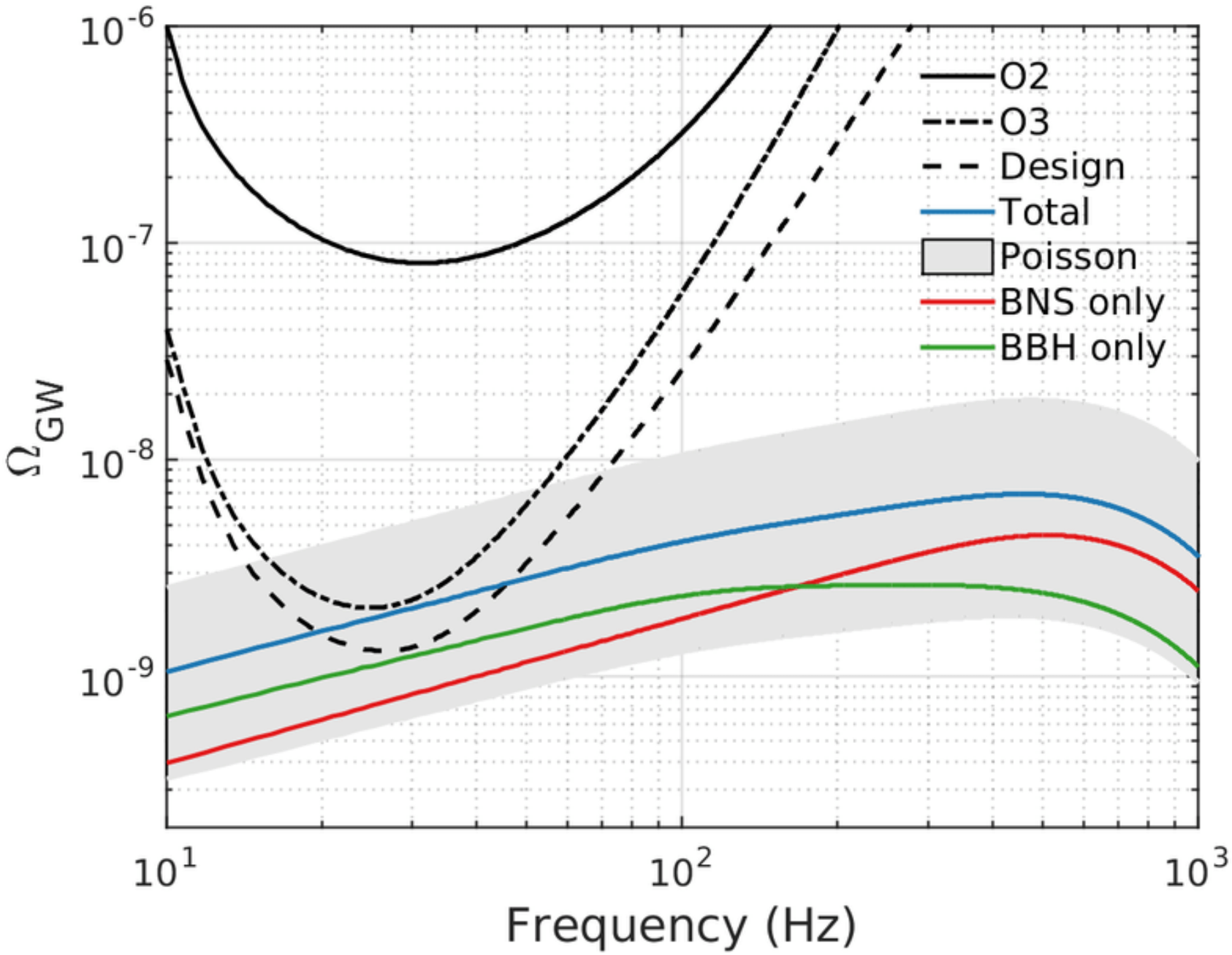
- Cosmic string

Astronomical

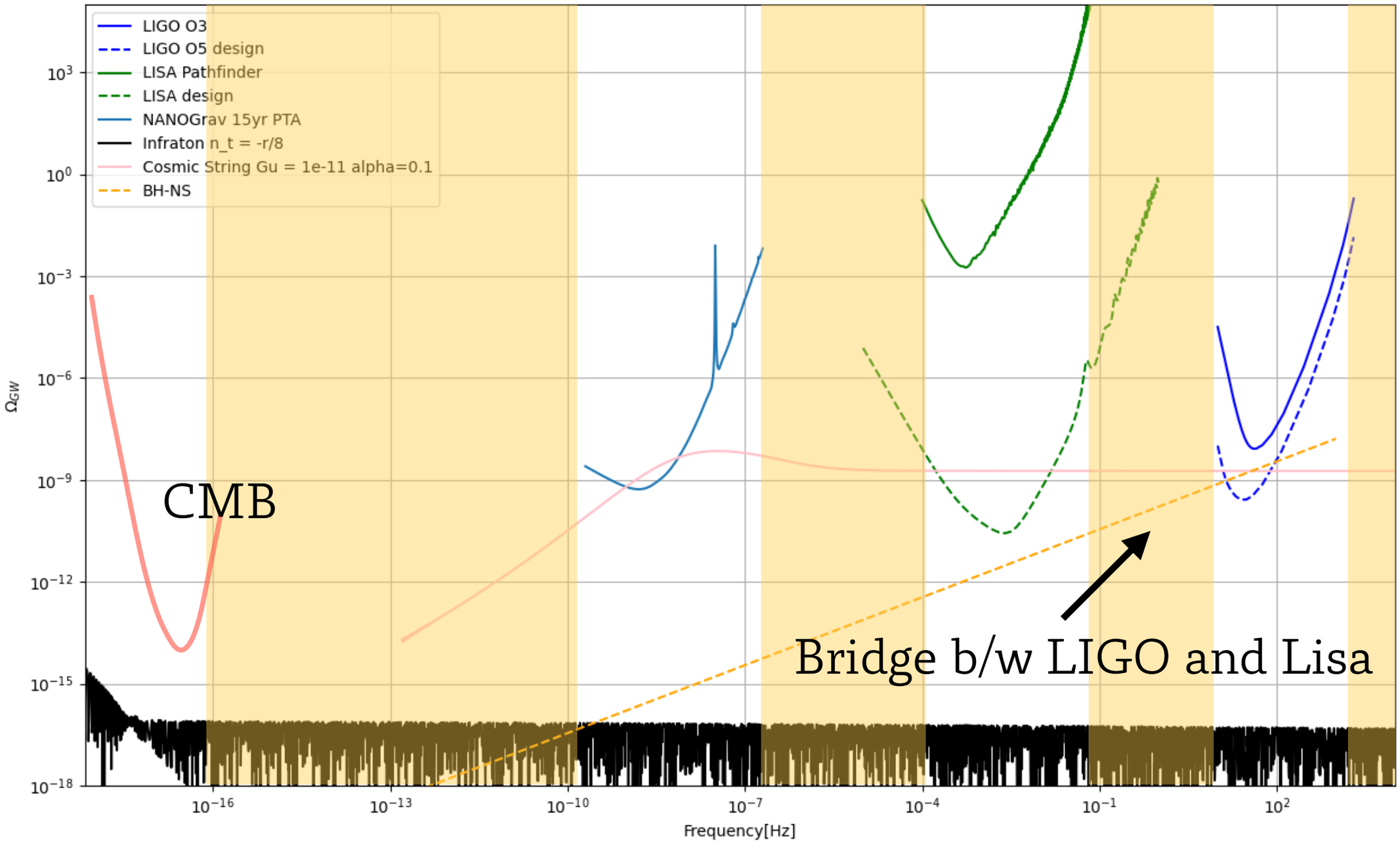


- BBH and BNS

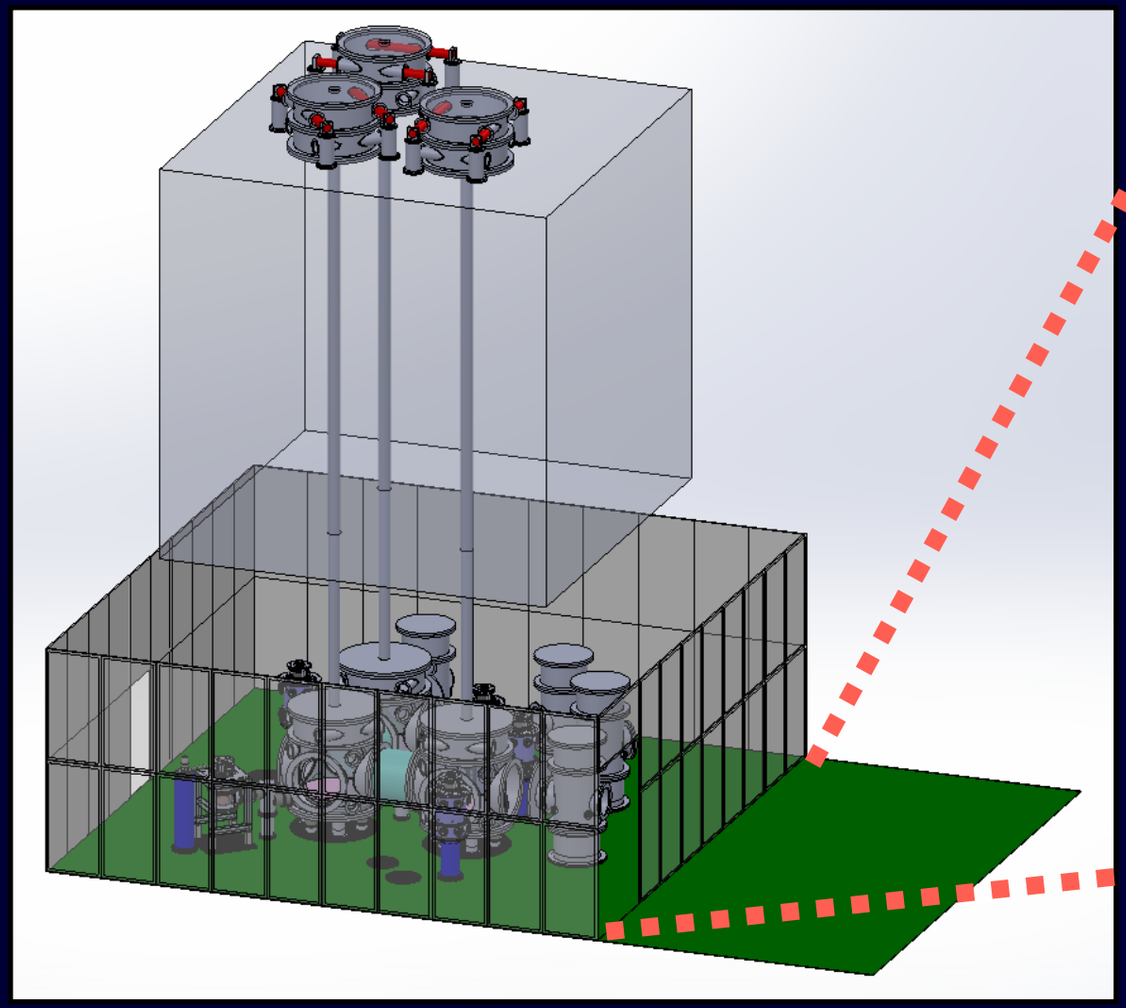
Next expected discovery: Astronomical Stochastic Background

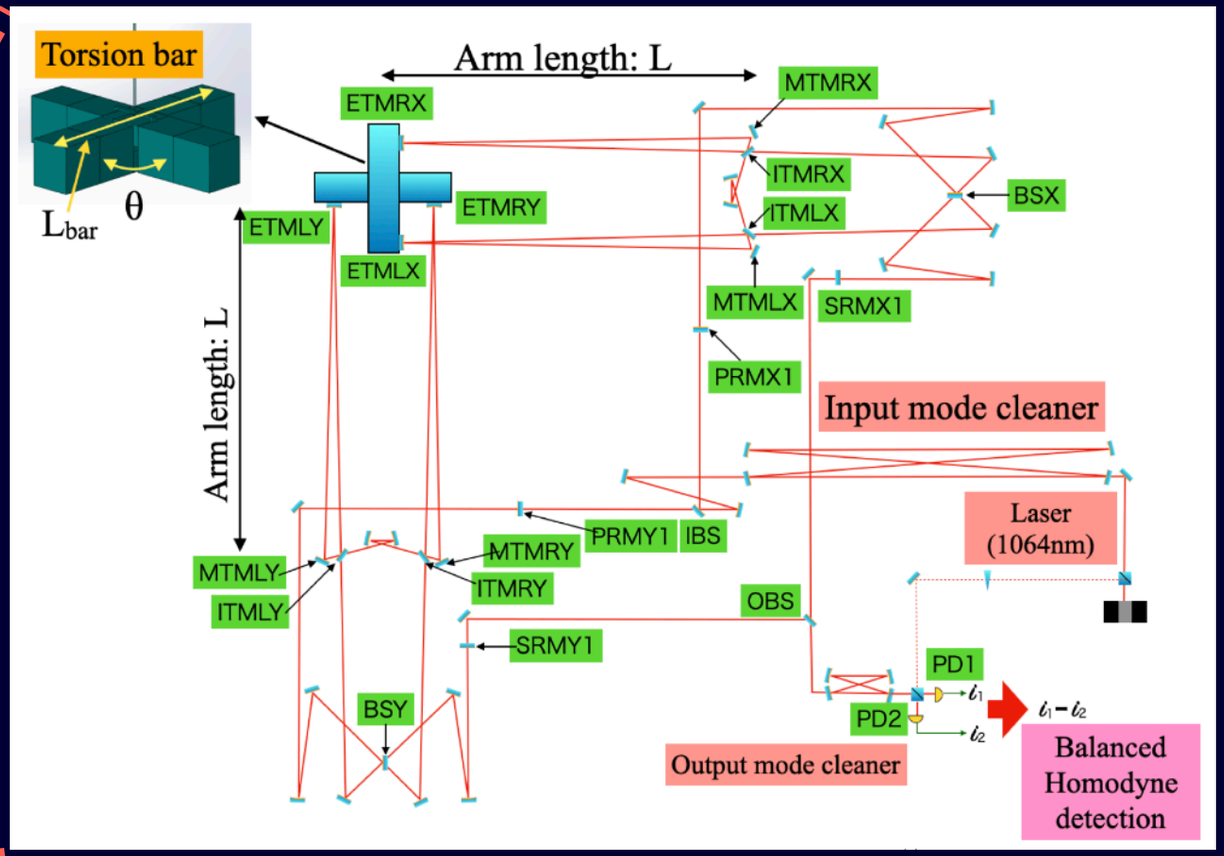


The new window of GW observation?



CHRONOS Overview

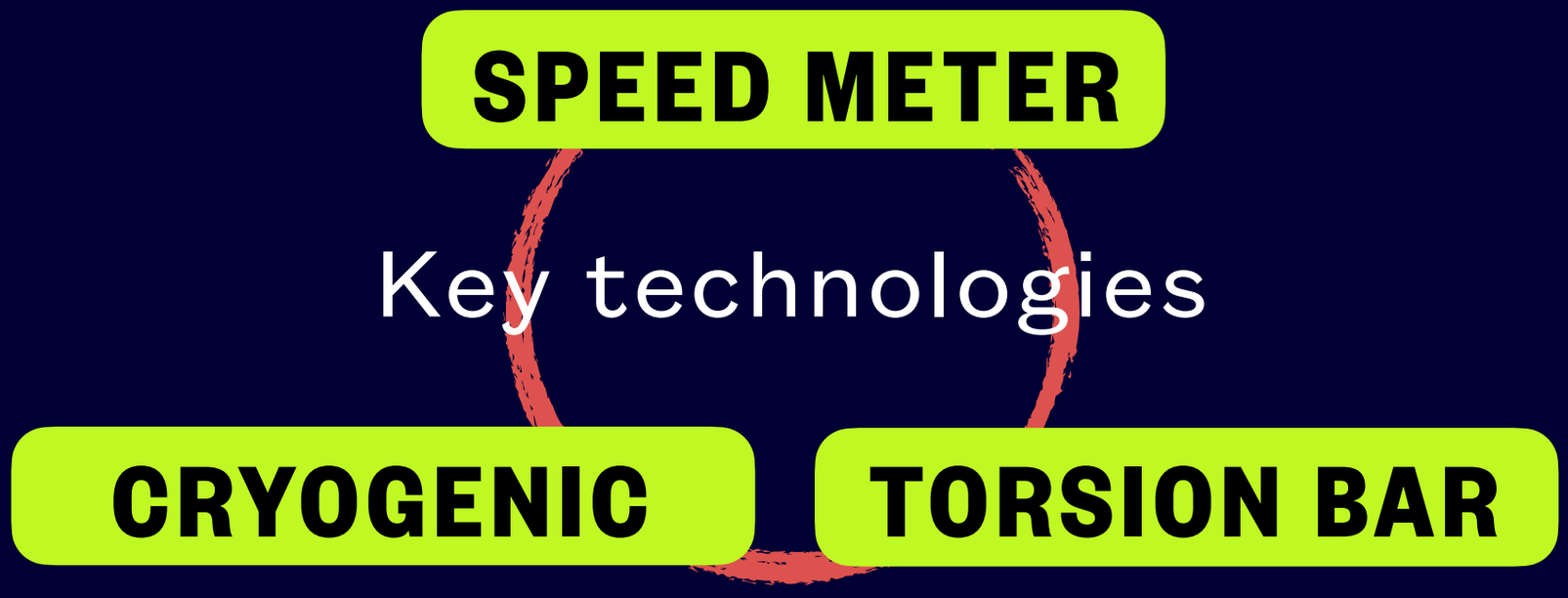




Cryogenic sub-**H**z c**RO**ss torsion bar detector with quantum **NO**n-demolition **S**peed meter

CHRONOS Overview

- Mission: Search for Intermediate black hole on Sub-Hz range
- Method: Interferometorical Speed meter
- Full success: First detection of Intermediate Black hole merger on O($10^4 M_\odot$) range
- Unique point: 10m x 10m Observatory



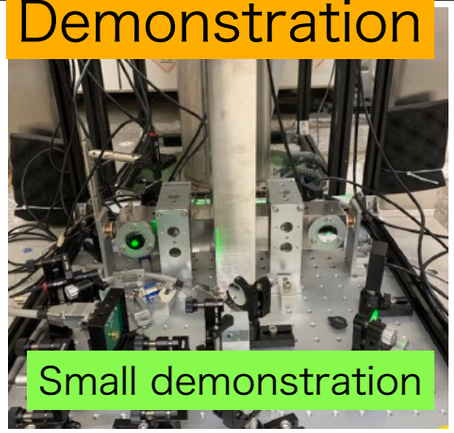
CHRONOS Overview

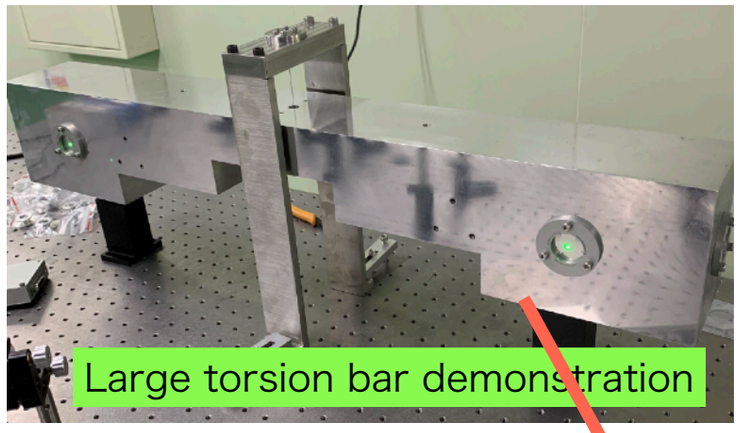
- Location: Underground site in Taiwan
- R&D is ongoing
  - Phase 1: R&D for Key technologies (2020-2025)
  - Phase 2: Integration test (2025-2033)
  - Phase 3: Construction of CHRONOS in Underground lab (2030-2035)

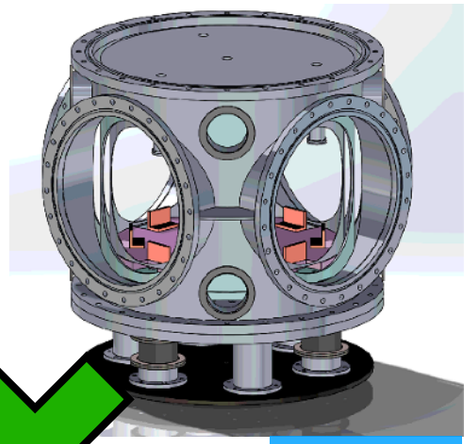
CHRONOS's target observation year = 2035

Summary of CHRONOS interferometer

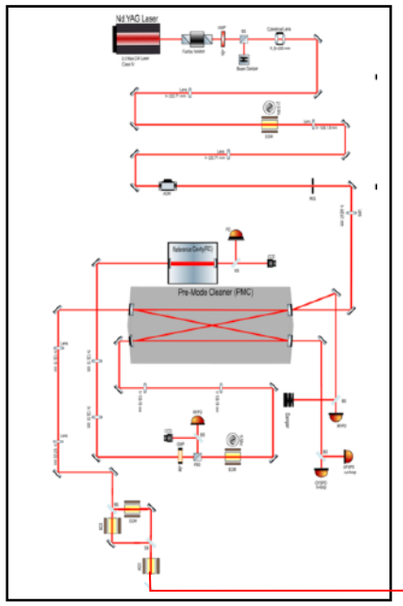
Demonstration

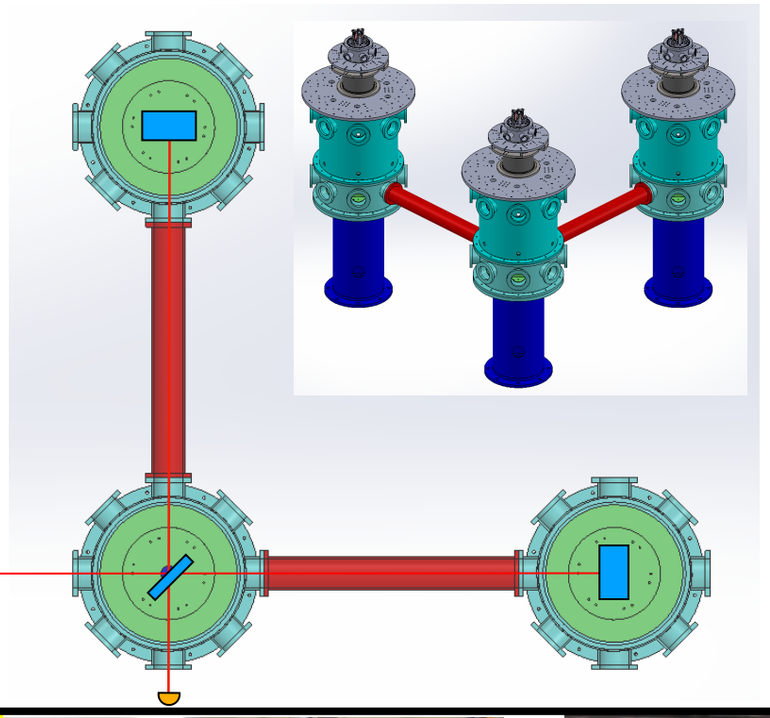

Small demonstration


Large torsion bar demonstration

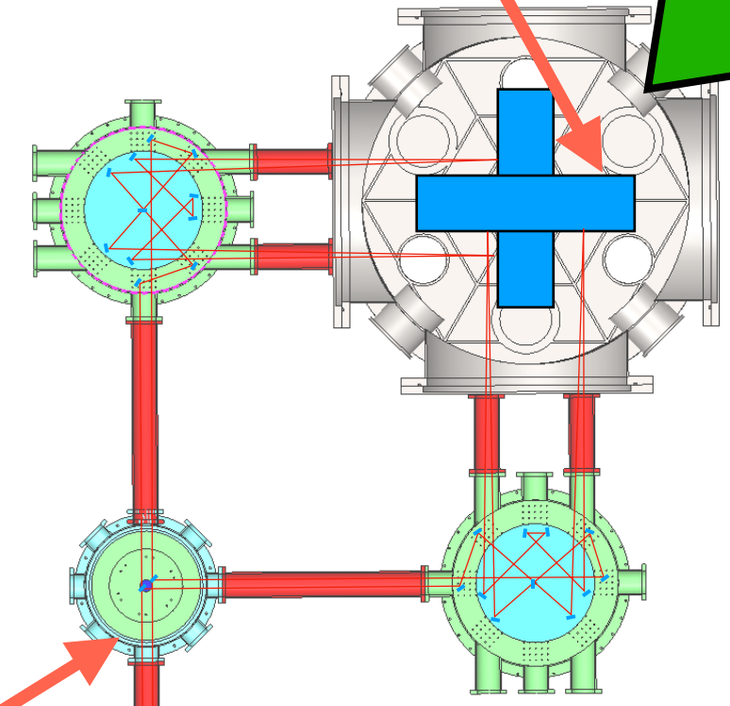

Reuse

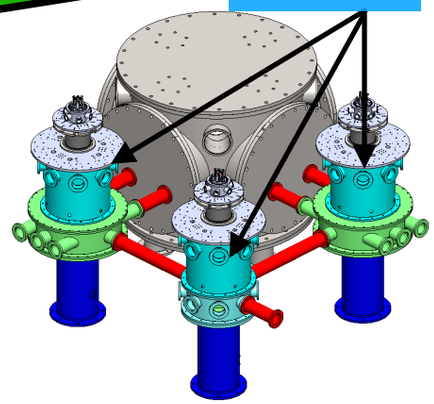
Current system

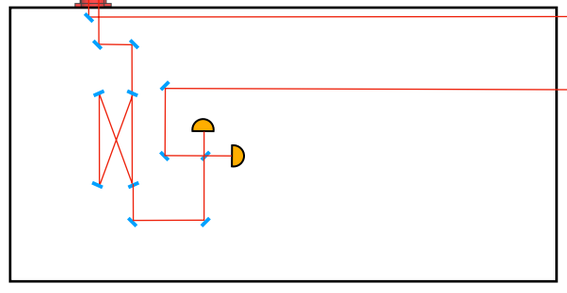


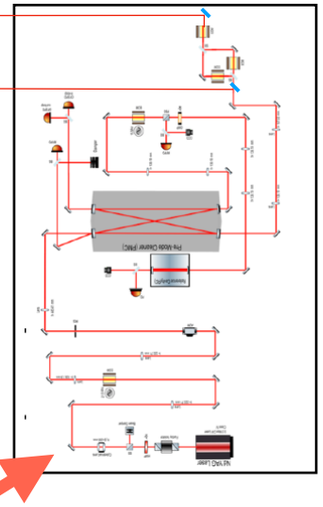


Upgrade

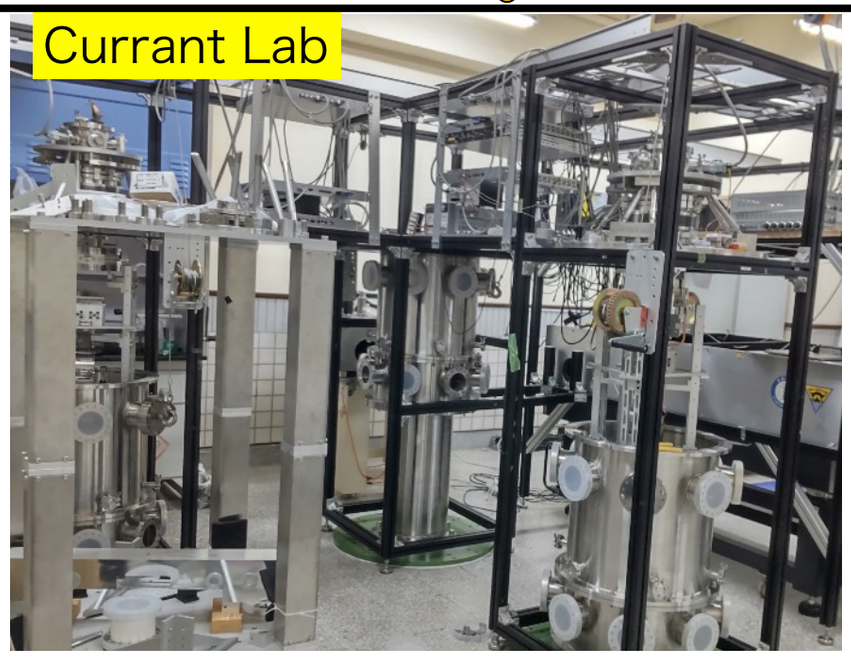




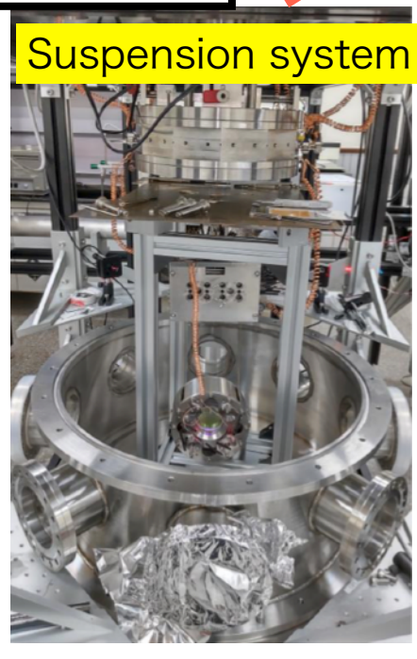


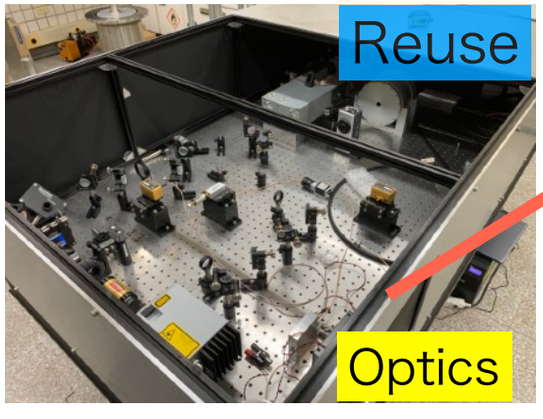


Currant Lab



Suspension system

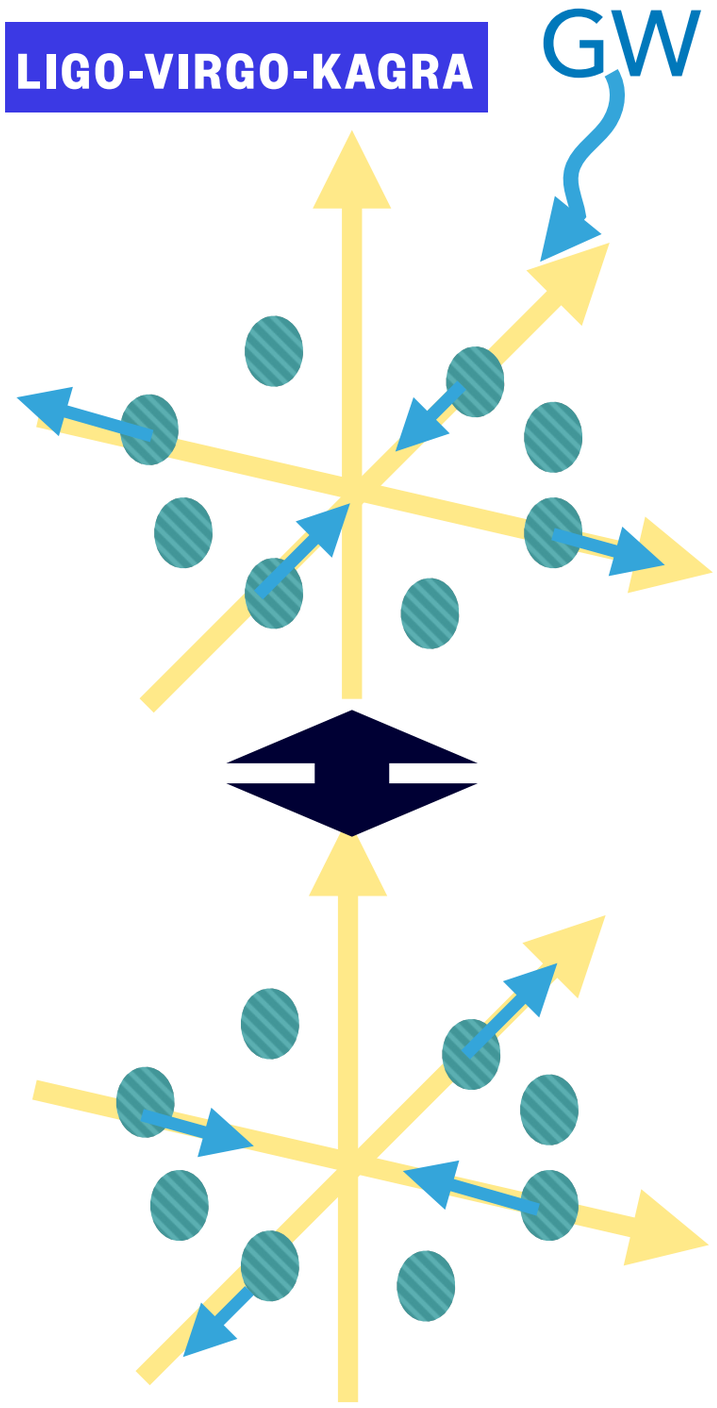



Reuse

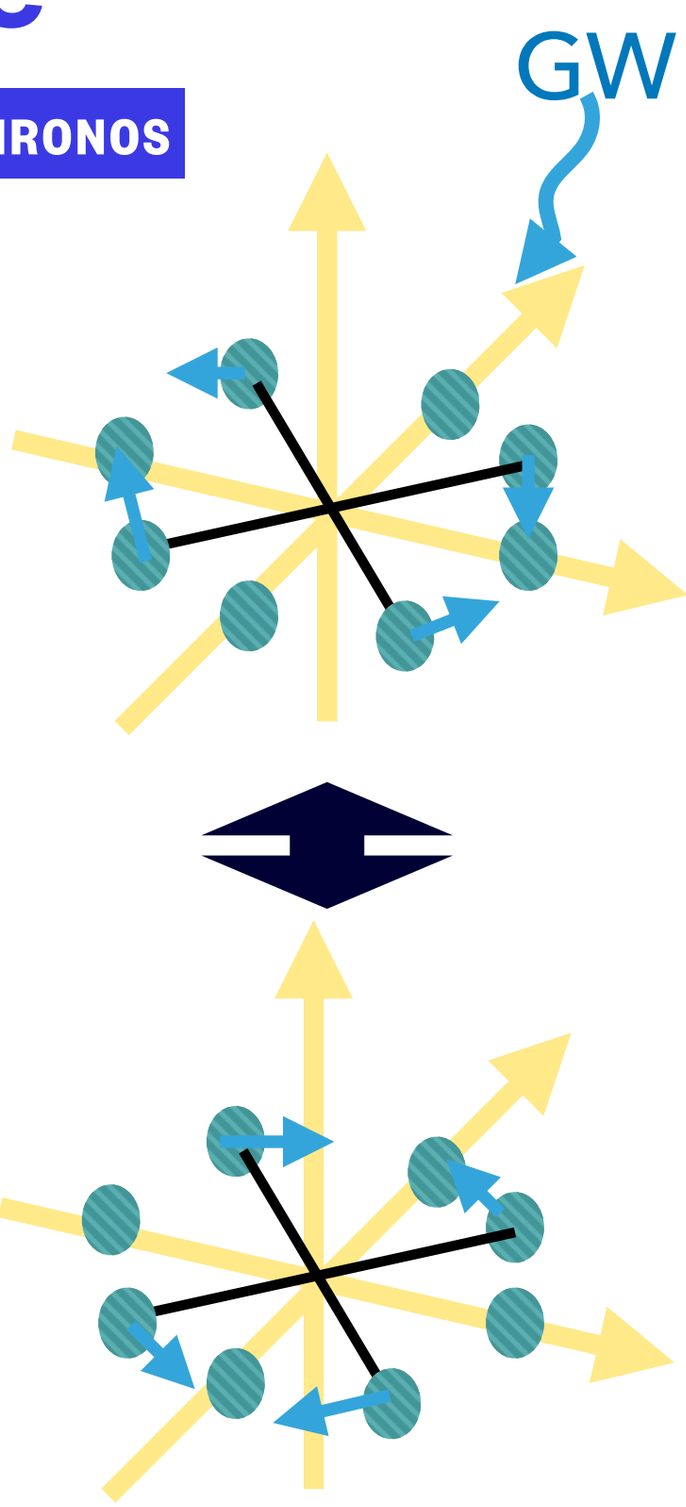
Optics

Comparison of principle

LIGO-VIRGO-KAGRA

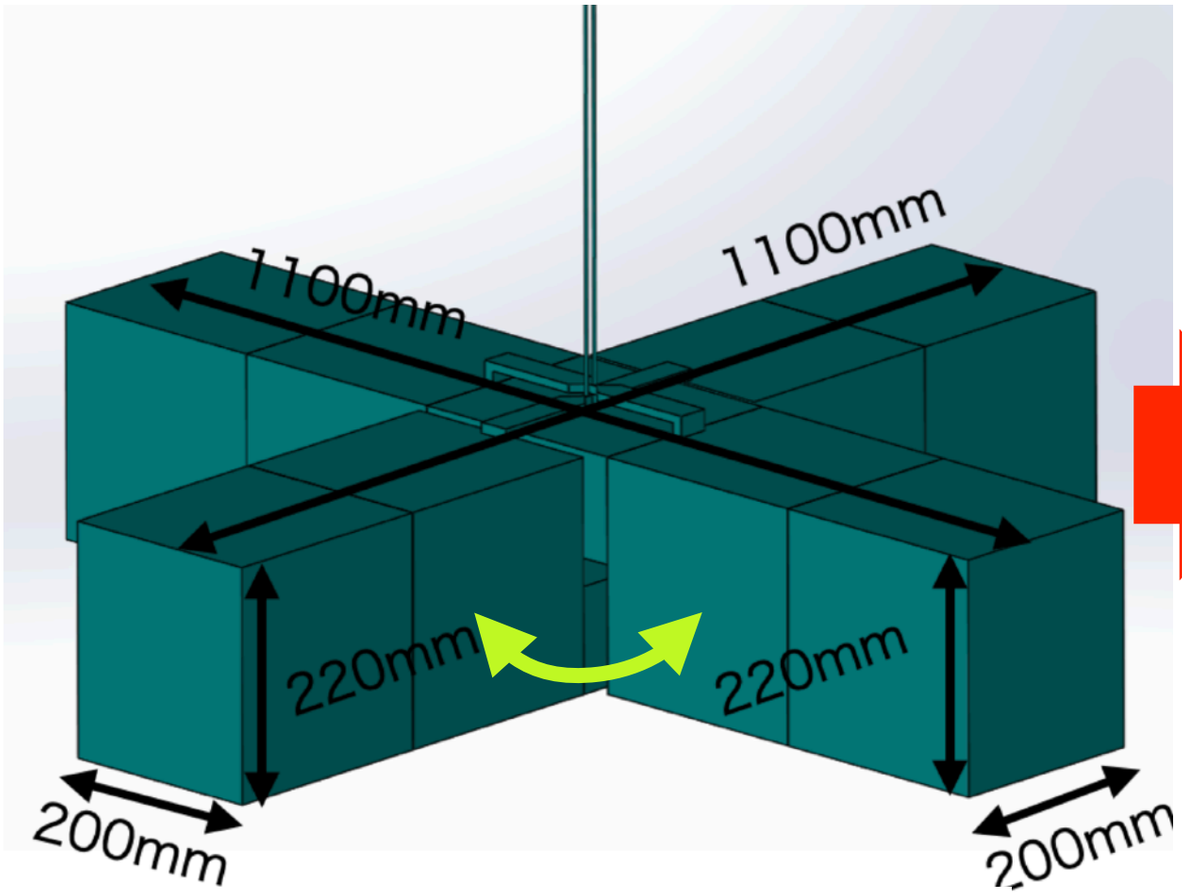


CHRONOS



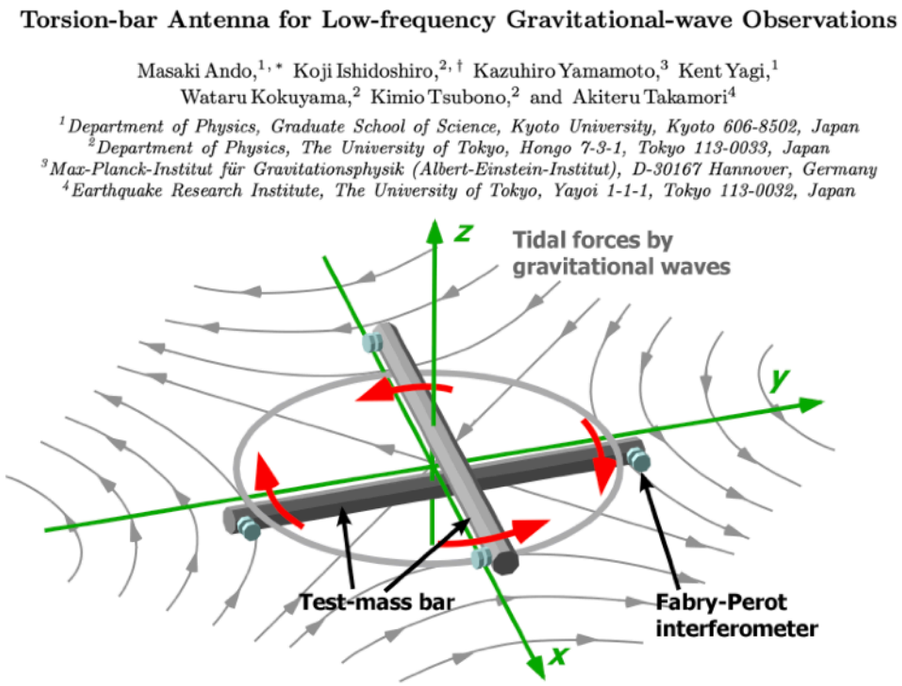
LIGO and CHRONOS have Independent detection method

CHRONOS test mass



We need to monitor the angle by laser interferometer method.

ORIGINAL PAPER


Torsion-bar Antenna for Low-frequency Gravitational-wave Observations

Masaki Ando,[1,*] Koji Ishidoshiro,[2,†] Kazuhiro Yamamoto,[3] Kent Yagi,[1]
Wataru Kokuyama,[2] Kimio Tsubono,[2] and Akiteru Takamori[4]

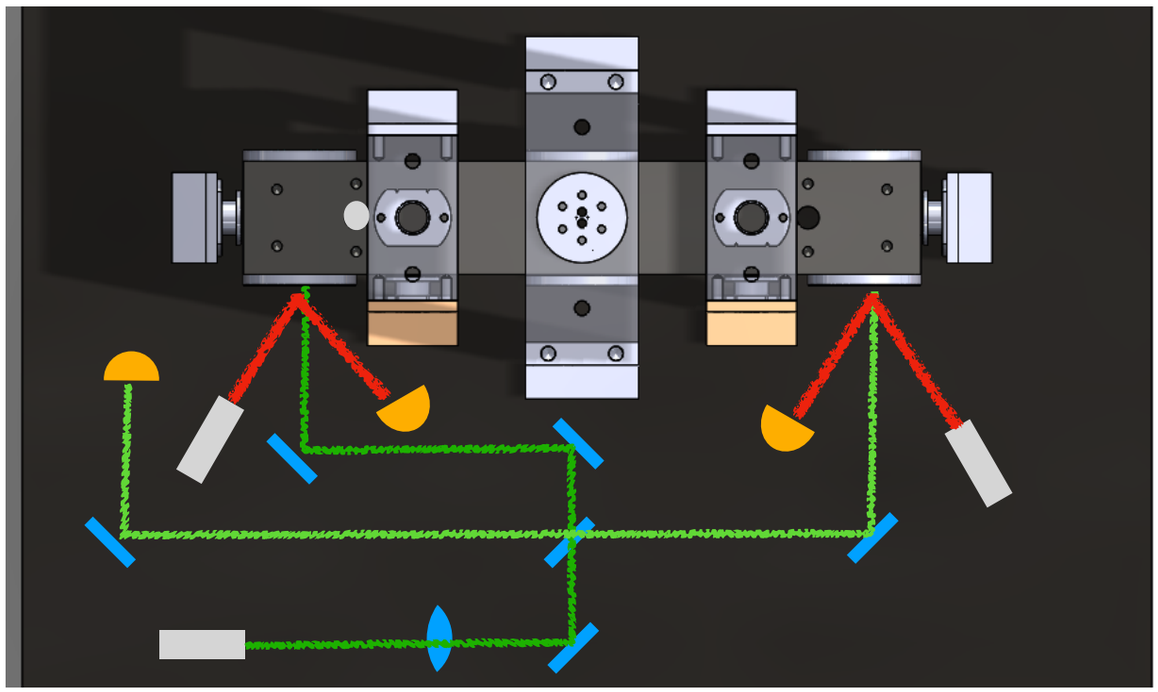
[1] *Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan*
[2] *Department of Physics, The University of Tokyo, Hongo 7-3-1, Tokyo 113-0033, Japan*
[3] *Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), D-30167 Hannover, Germany*
[4] *Earthquake Research Institute, The University of Tokyo, Yayoi 1-1-1, Tokyo 113-0032, Japan*

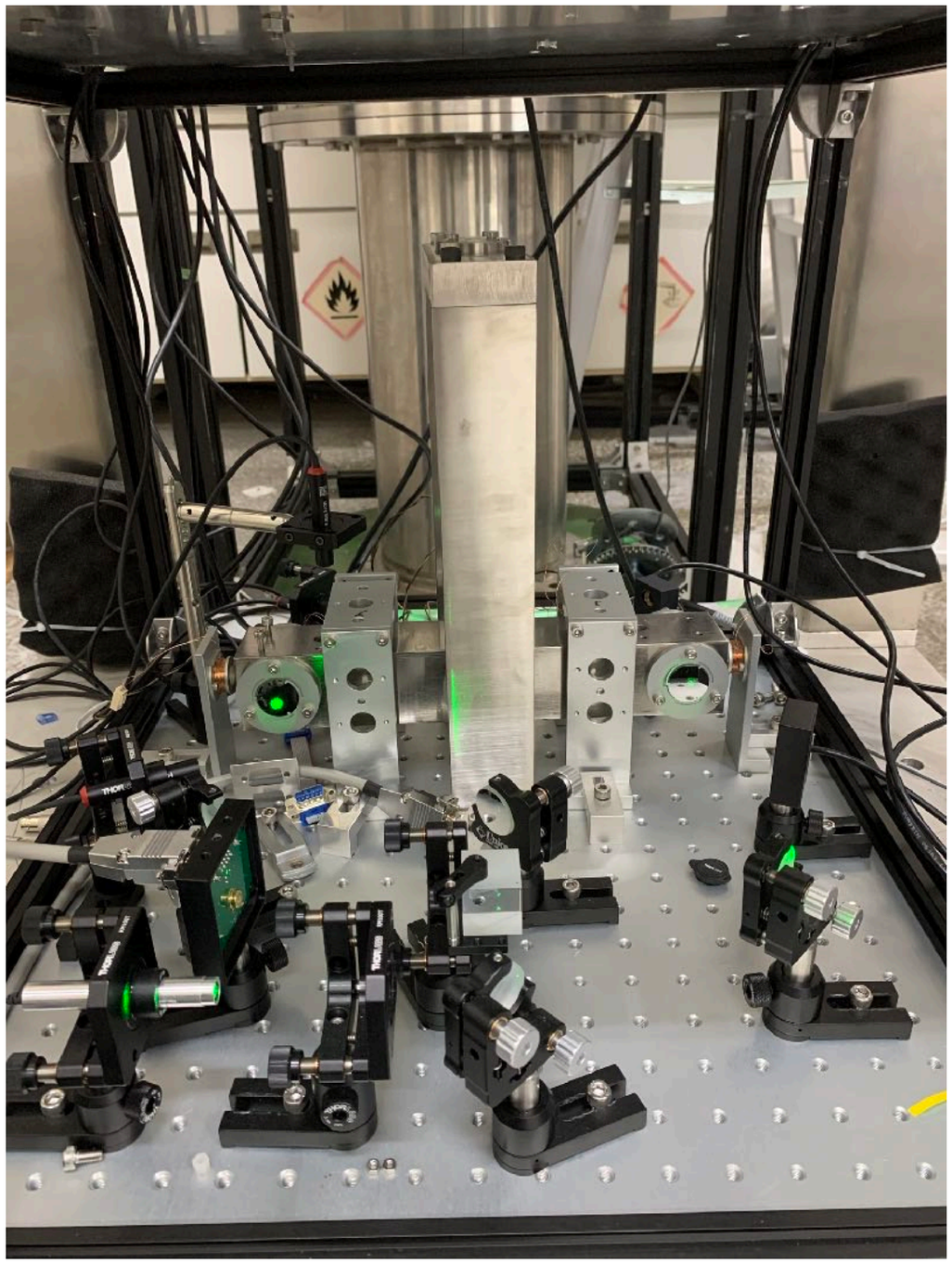
$$\theta(\Omega) \simeq \frac{I_{\rm eff}}{2I}\left(h_+ F_+ + h_\times F_\times\right).$$

TOBA and TorPeDOR already demonstrate the principle of torsion bar detector.

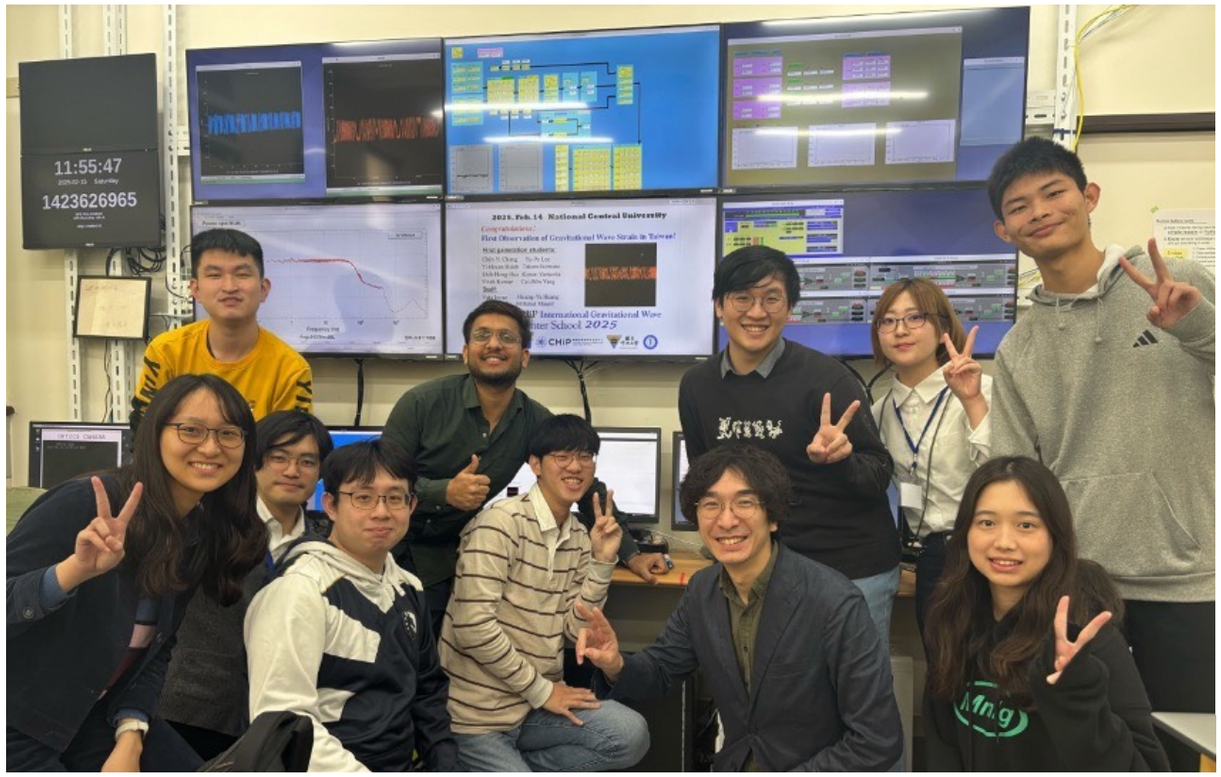
Demonstration with mini-CHRONOS

- 300mm torsion bar
- First Demonstration of technology
- Educational system
- Text book and lecture
- 10days program

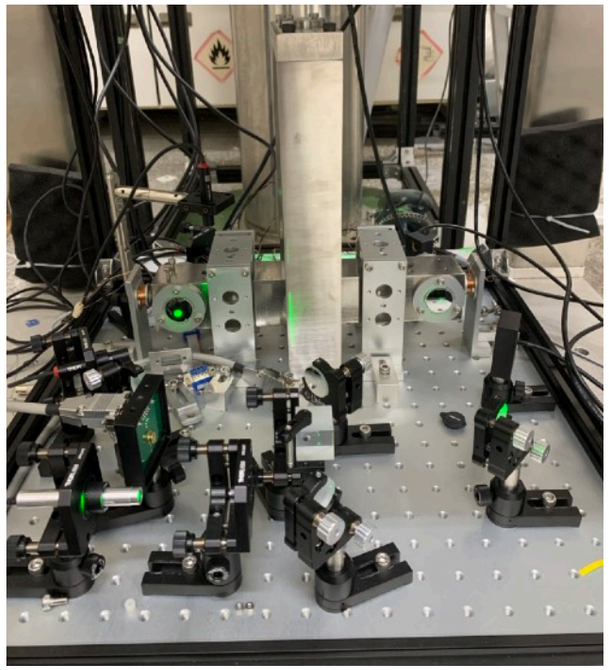


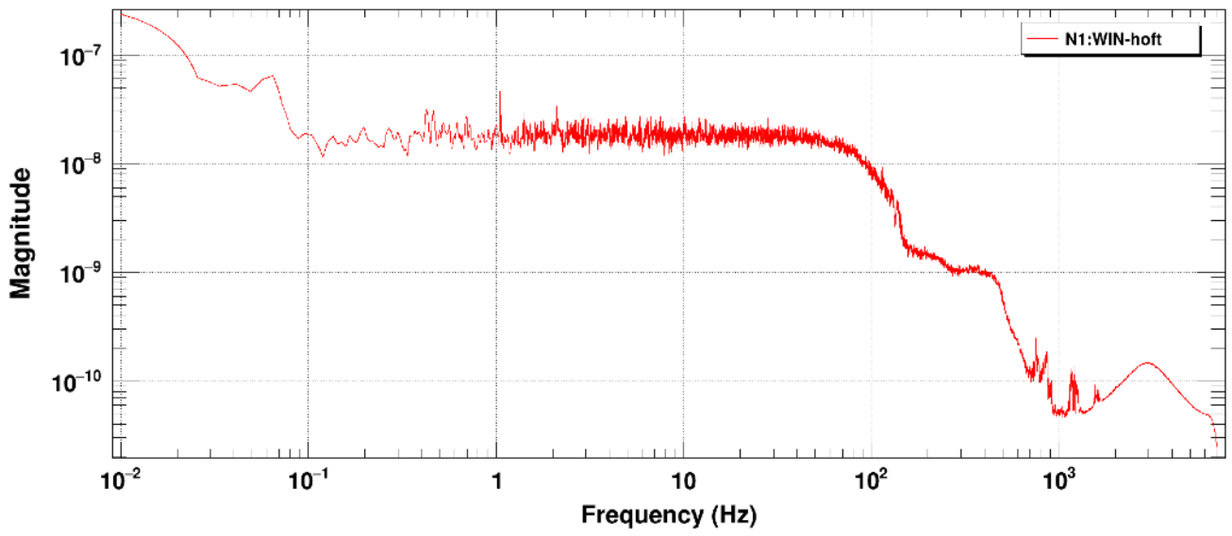


Winter school and Summer school





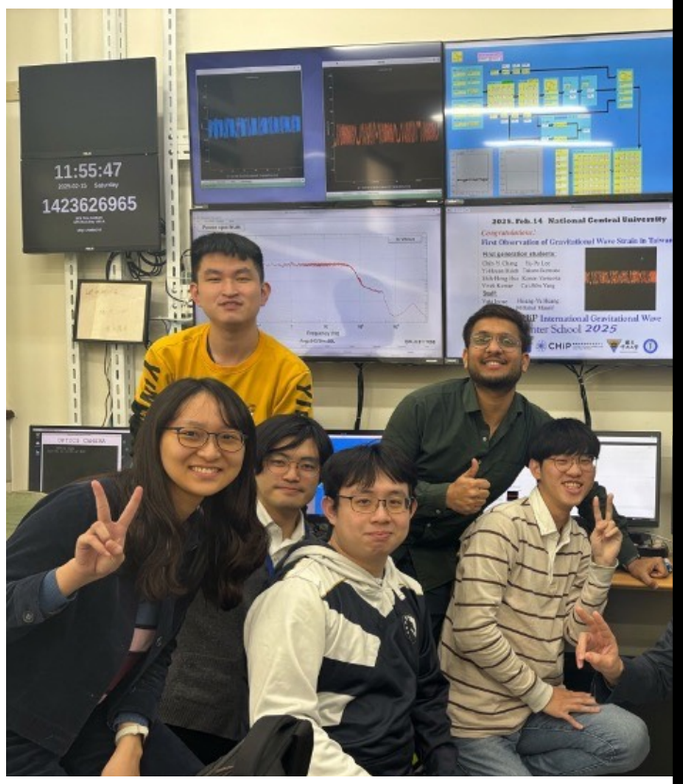




We organized CHiP International GW summer/winter school!

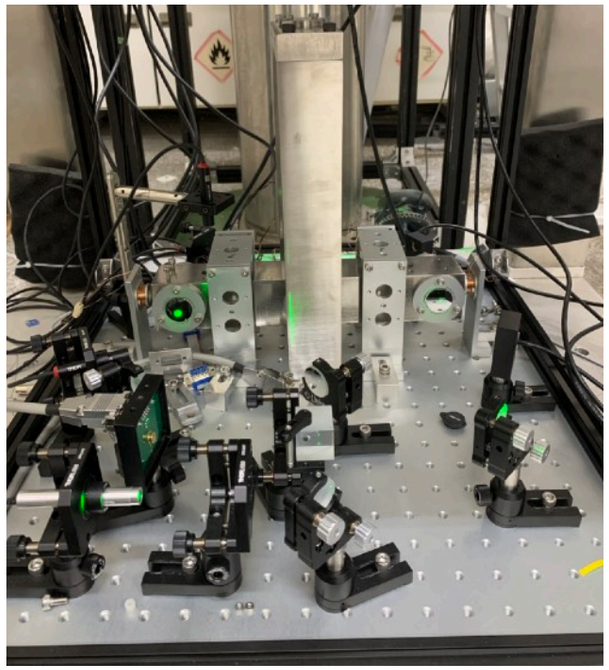
In the school, we tried to reconstruct h(t) signal from interferometer response.

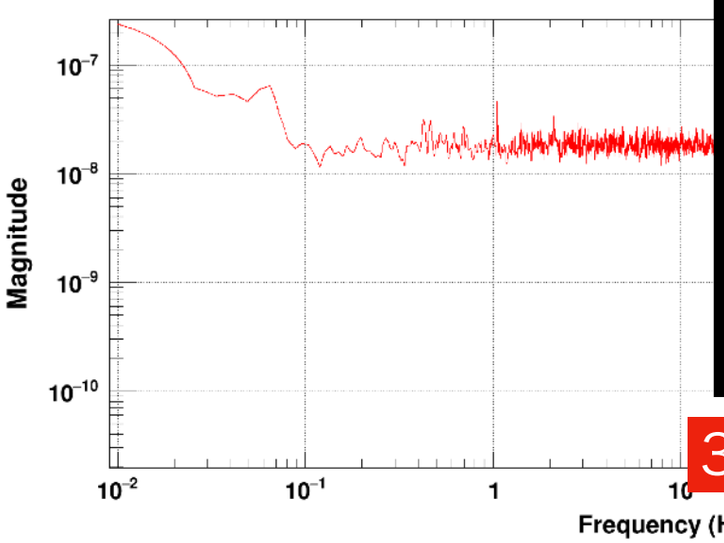
Winter sc mer school











ized CHiP International

ner/winter school!

ool, we tried to

ct h(t) signal from

interferometer response.

3 participants are still acceptable!

Quantum Non-demolition

Quantum Nondemolition Measurements

VLADIMIR B. BRAGINSKY, YURI I. VORONTSOV, AND KIP S. THORNE Authors Info & Affiliations

SCIENCE · 1 Aug 1980 · Vol 209, Issue 4456 · pp. 547-557 · DOI: 10.1126/science.209.4456.547

C.M. Caves, K.S. Thorne, R.W.P. Drever, V.D. Sandberg, M. Zimmermann, Rev. Mod. Phys. 52, 341 (1980)

GW detector can improve the sensitivity more than standard quantum limit.

One of the historically important questions for the quantum measurement.

1927 Heisenberg Uncertainty principle

$$\epsilon(x)\eta(p) \geq \frac{\hbar}{2}$$

→ ?

Challenge to Heisenberg Uncertainty principle!



Non-demolition system?

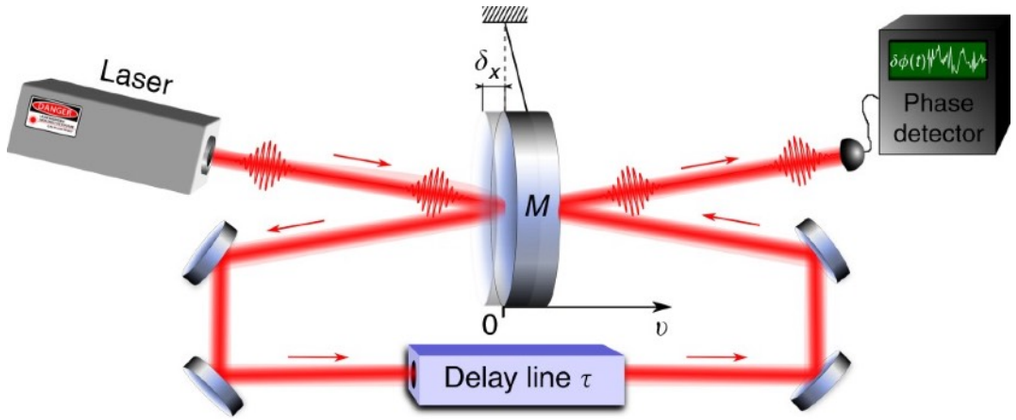
Ozawa's inequality (for angular momentum L and angle θ)

$$\underbrace{\epsilon(L)\,\eta(\theta)}_{\text{Error}\times\text{Disturbance}} + \underbrace{\sigma(L_{in})\,\eta(\theta)}_{\text{Intrinsic fluctuation of } L \times \text{Disturbance}} + \underbrace{\epsilon(L)\,\sigma(\theta_{in})}_{\text{Error}\times\text{Intrinsic fluctuation of } \theta} \geq \frac{\hbar}{2}$$

- $\epsilon(L)$: measurement error of angular momentum $\hat{L}$
- $\eta(\theta)$: disturbance of angle $\hat{\theta}$
- $\sigma(L_{in})$: intrinsic fluctuation of input angular momentum
- $\sigma(\theta_{in})$: intrinsic fluctuation of input angle

M. Ozawa, Phys. Rev. Lett. 60, 385 (1988), J. Maddox, Nature 331, 559 (1988)

J. Erhart et al. Nature Physics (2012) doi:10.1038/nphys2194.



Speed meter!

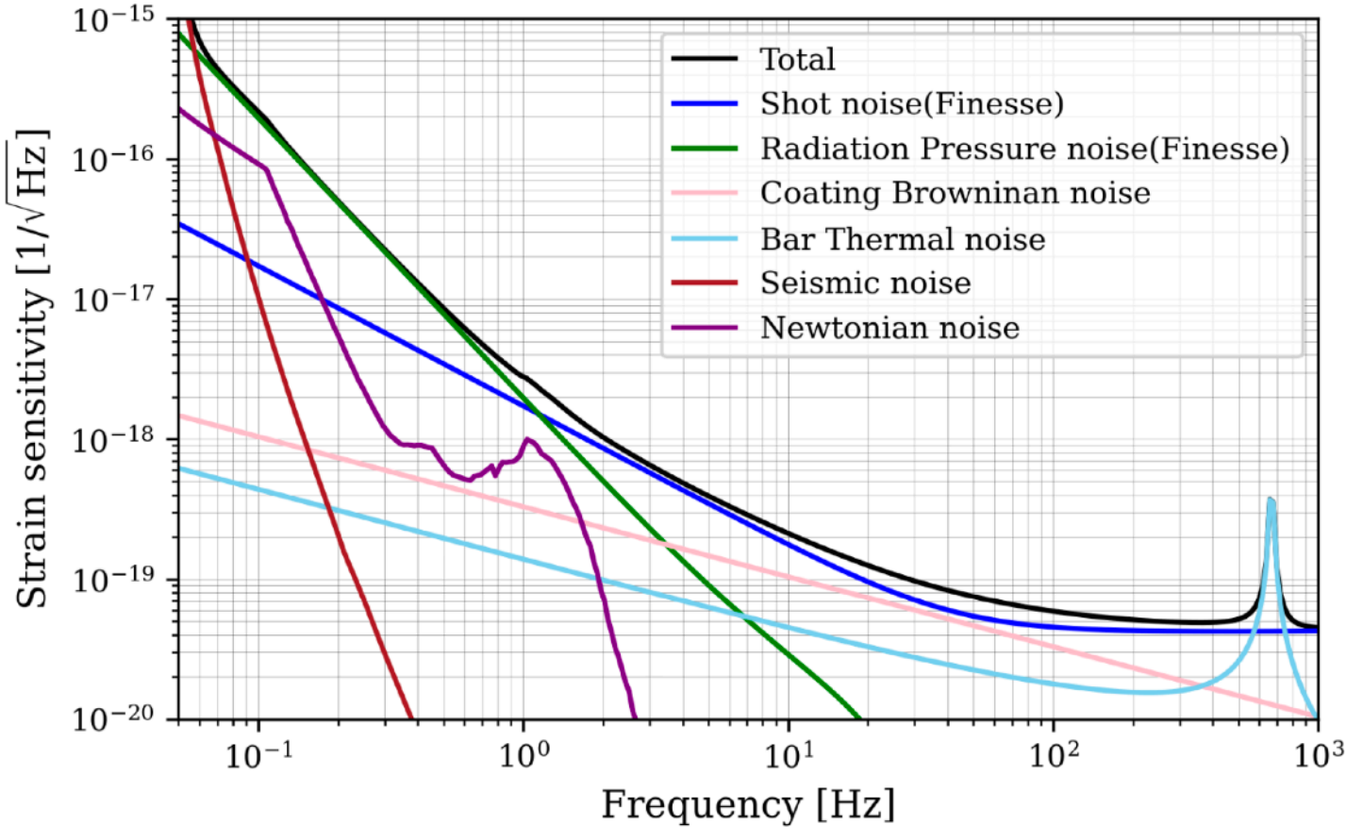
Photo detector = $\delta\,\theta\,(t+\tau)-\delta\,\theta\,(t) = \Omega\,\tau$ measurement,

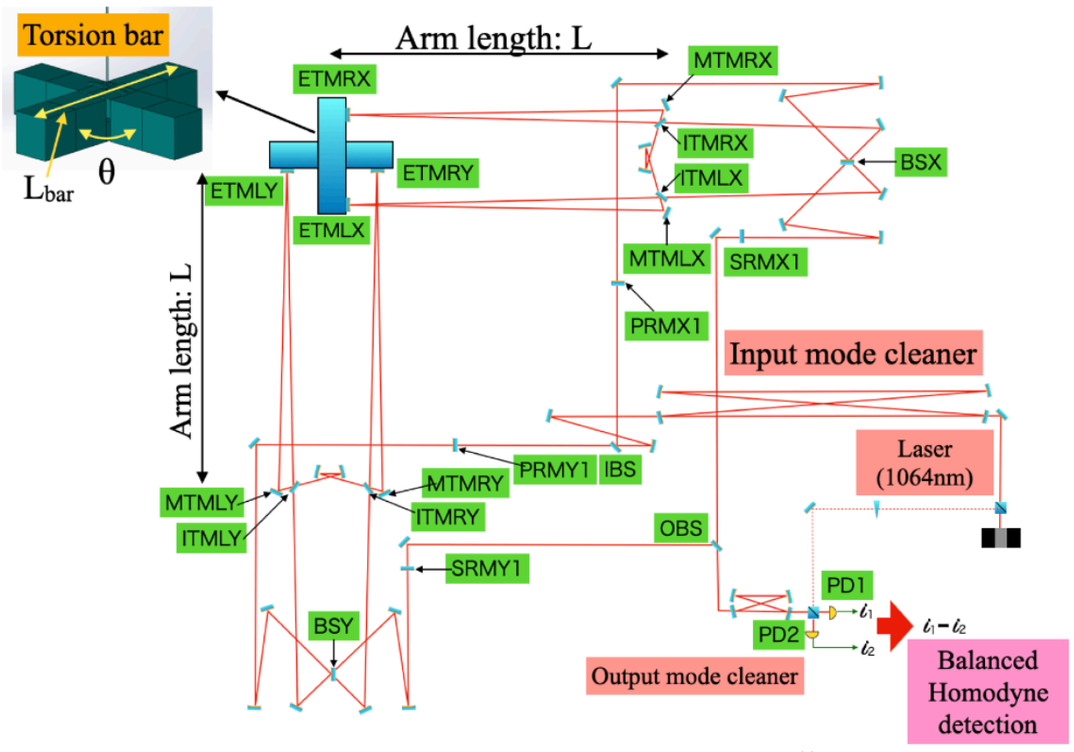
where τ is constant.

Probe is proportional to anglar momentum!

$$\dot{L} = [\hat{H}, \hat{L}] = 0 \quad \Rightarrow \text{non-demolition!}$$

Expected sensitivity





Instruments detail will be explained in Next Talk!

Publications

Main project paper

Optical design and sensitivity optimization of Cryogenic sub-Hz cROss torsion bar detector with quantum NOn-demolition Speed meter (CHRONOS)

Yuki Inoue,[1,2,3,4,*] Daiki Tanabe,[3,2,4] M.Afif Ismail,[1,2,3] Vivek Kumar,[3,5] Mario Juvenal S Onglao III,[5,2] and Ta-Chun Yu[1,2]

Y.Inoue and D.Tanabe et. al. arXiv: 2510.24780
under reviewing in C.Q.G

Upgrade paper

CHRONOS: Cryogenic sub-Hz cROss torsion bar detector with quantum NOn-demolition Speed meter

Yuki Inoue,[1,2,3,4,*] Hsiang-Chieh Hsu,[3] Hsiang-Yu Huang,[1,2] M.Afif Ismail,[1,2,3] Vvek Kumar,[3,5] Miftahul Ma'arif,[1,2] Avani Patel,[1,2] Daiki Tanabe,[3,2,4] Henry Tsz-King Wong,[3,2] and Ta-Chun Yu[1,2]

Y.Inoue et. al. arXiv: 2509.23172

Intensity noise paper Published!

Torque cancellation effect of Intensity noise for Cryogenic sub-Hz cROss torsion bar detector with quantum NOn-demolition Speed meter (CHRONOS)

Daiki Tanabe[a,b,d†], Yuki Inoue[c,d,a,b‡], Vivek Kumar[c,a], Miftahul Ma'arif[c,d], Ta-Chun Yu[c,d]

Daiki Tanabe *et al*. *Class. Quantum Grav.* **43** 125017(2026)

Calibration paper Accepted!

Improving calibration accuracy with torque coupled gravity field calibrator for sub-Hz gravitational wave observation in CHRONOS

Yuki Inoue,[1,2,3,4,*] Daiki Tanabe,[2,3,4] and Vivek Kumar[1,2]

[1]*Department of Physics,National Central University, Taoyuan, Taiwan*
[2]*Center for High Energy and High Field (CHiP), National Central University, Taoyuan, Taiwan*
[3]*Institute of Physics, Academia Sinica, Taipei, Taiwan*
[4]*Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Tsukuba, Japan*
(Dated: February 24, 2026)

Y.Inoue et. al. Accepted by PTEP

Yukawa Gravity paper

Probing Yukawa Gravity with Modulated Newtonian Cancellation in the Torsion bar type detector

Yuki Inoue,[1,2,3,4,*] Hsiang-Yu Huang,[1,2] Vivek Kumar,[1,2] and Daiki Tanabe[2,3]

Y.Inoue et. al. arXiv: 2604.11167
under reviewing in PRD

Last week!

Gravity gradient paper

Prospects for Observing Gravity-gradient Noise and Earthquake Gravity Signals with CHRONOS

Mario Juvenal S. Onglao III,[1,2,*] Yuki Inoue,[2,3,4,5] and Daiki Tanabe[2,3,4,5]

M.Onglao et. al. arXiv: 2606.19124

Science paper Published!

Science of Cryogenic sub-Hz cROss torsion bar detector with quantum NOn-demolition Speed meter (CHRONOS)

Yuki Inoue,[1,2,3,4,*] Hsiang-Yu Huang,[1,2] Vivek Kumar,[1,2] Mario Juvenal S. Onglao II,[5,2] Daiki Tanabe,[3,2,4] and Ta-Chun Yu[1,2]

Y.Inoue et. al. arXiv: 2604.0626

Sensitivity paper Published!

Noise budget of Cryogenic sub-Hz cROss torsion-bar detector with quantum NOn-demolition Speed meter (CHRONOS)

Mario Juvenal S. Onglao III,[1,2,*] Hsiang-Yu Huang,[3,2] Yuki Inoue,[3,2,4,5] Vivek Kumar,[3,2] and Daiki Tanabe[4,2,5]

M.Onglao et. al. arXiv: 2604.05840

Instruments paper Published!

Instrumental development for Cryogenic sub-Hz cROss torsion bar detector with quantum NOn-demolition Speed meter (CHRONOS)

Daiki Tanabe,[1,2,3,4,*] Hsiang-Yu Huang,[3,2] Yuki Inoue,[3,2,1,4] Mario Juvenal S. Onglao III,[5,3,2] and Ta-Chun Yu[3,2]

D.Tanabe et. al. arXiv: 2604.05801

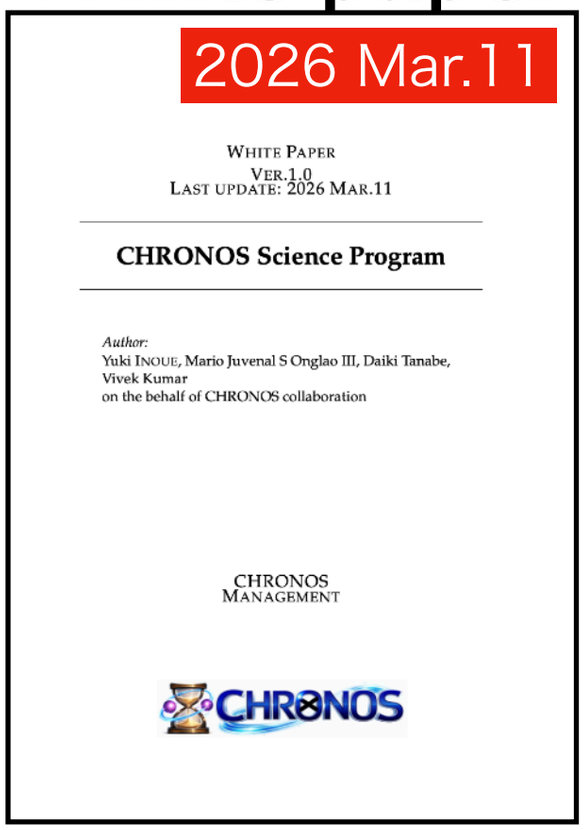
In preparation (Release soon)

Elastic deformation paper (Tanabe et al.)
Stochastic background paper (Inoue et al.)
Photon pressure actuator paper (Tanabe et al.)
Mirror coating paper (Kumar et al.)
Dark matter paper (Inoue et al.)

Collaboration is very welcome!!

White paper

2026 Mar.11



WHITE PAPER
VER.1.0
LAST UPDATE: 2026 MAR.11

CHRONOS Science Program

Author:
Yuki INOUE, Mario Juvenal S Onglao III, Daiki Tanabe, Vivek Kumar
on the behalf of CHRONOS collaboration

CHRONOS MANAGEMENT

arXiv: 2603.10070

Science Roadmap

1 Principle demonstration phase

Quantum Optics

Ozawa's inequality (for angular momentum L and angle θ)

$$\underbrace{\epsilon(L)\,\eta(\theta)}_{\text{Error} \times \text{Disturbance}} + \underbrace{\sigma(L_{in})\,\eta(\theta)}_{\text{Intrinsic fluctuation of } L \times \text{Disturbance}} + \underbrace{\epsilon(L)\,\sigma(\theta_{in})}_{\text{Error} \times \text{Intrinsic fluctuation of } \theta} \geq \frac{\hbar}{2}$$

- $\epsilon(L)$: measurement error of angular momentum $\hat{L}$
- $\eta(\theta)$: disturbance of angle $\hat{\theta}$
- $\sigma(L_{in})$: intrinsic fluctuation of input angular momentum
- $\sigma(\theta_{in})$: intrinsic fluctuation of input angle

$[\hat{L}, \hat{\theta}] \simeq i\hbar$ (small-angle approximation)

Commutation with the Hamiltonian $[\hat{L}, \hat{H}] = 0$ → Conservation in time $\frac{d\hat{L}}{dt} = \frac{1}{i\hbar}[\hat{L}, \hat{H}] = 0$ → Commuting at all times $[\hat{L}(t_1), \hat{L}(t_2)] = 0$ (for any t_1, t_2) → QND observable $\hat{L}$ is a QND observable. → Vanishing disturbance $\eta(L) \to 0$ (back-action can be made arbitrarily small) → **CHRONOS** Experimental demonstration of QND measurement of angular momentum.

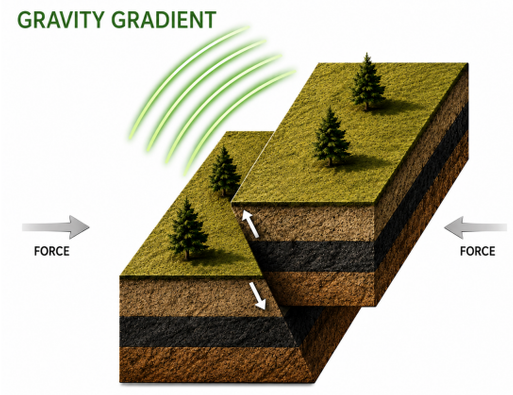
For a freely rotating body, $\hat{H} = \hat{L}^2/(2I)$, hence $[\hat{L}, \hat{H}] = 0$.

Therefore $\hat{L}(t) = \hat{L}(0)$.

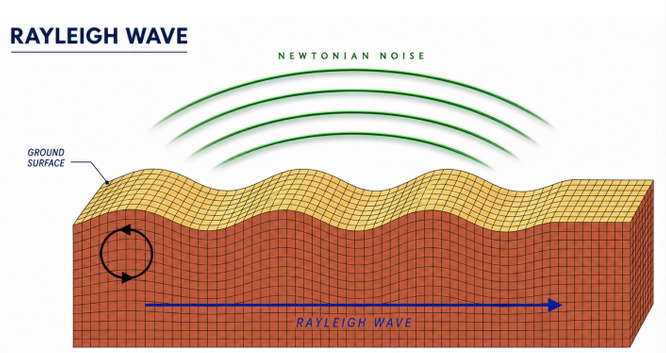
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Here we choose $\hat{A} = \hat{L}$, which is satisfied because $[\hat{L}, \hat{H}] = 0$.

2 Gravity Gradient Science phase

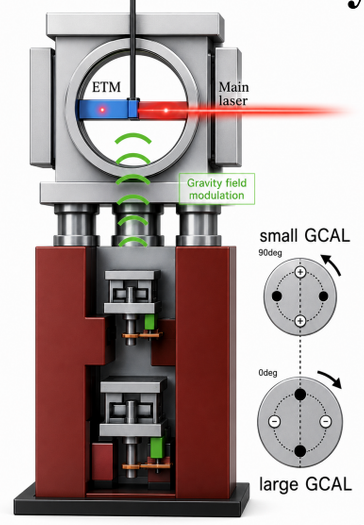
Erath quake



Newtonian Noise

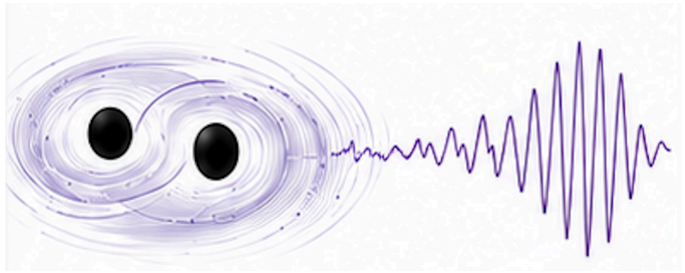


Yukawa Gravity

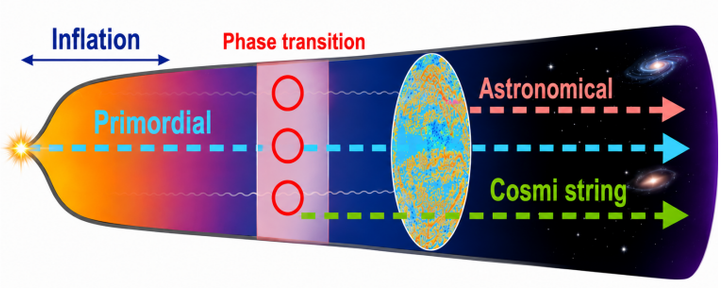


3 Gravitational wave Science phase

Intermediate-mass black hole binaries



Stochastic Gravitational Wave Background

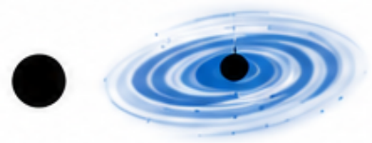


Intermediate mass black hole

1 MASS HIERARCHY

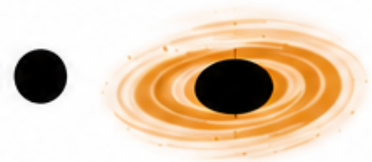
Stellar-mass Black Holes

$10 - 100\ M_\odot$



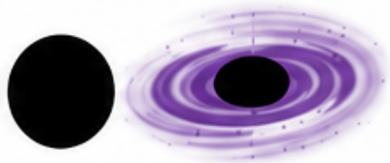
Intermediate-mass Black Holes (IMBHs)

$10^2 - 10^5\ M_\odot$



Supermassive Black Holes (SMBHs)

$10^6 - 10^{10}\ M_\odot$



IMBHs are the missing link in the mass spectrum.

2 FORMATION CHANNELS

(A) Hierarchical Mergers



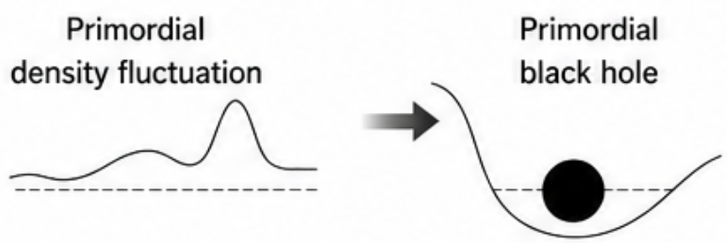
Growth through repeated mergers in dense stellar environments.

(B) Direct Collapse



Rapid collapse of massive gas in the early Universe.

(C) Primordial Origin



Collapse of primordial overdensities in the early Universe.

3 SPIN AS A PROBE OF FORMATION

The dimensionless spin parameter

$$a_* = \frac{cJ}{GM^2}$$

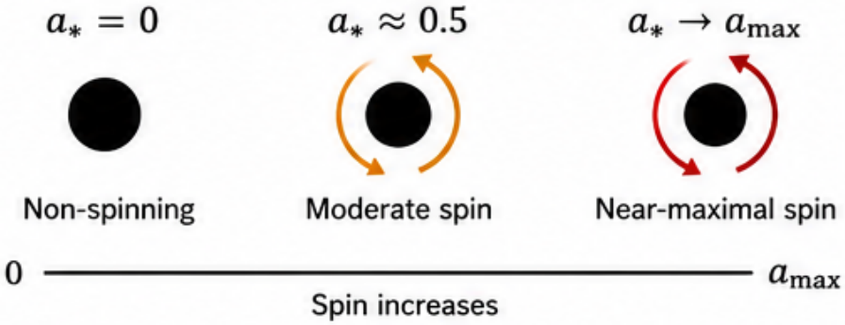
measures the black hole spin.

Relativistic effects require $0 \leq a_* < a_{\max}$.

Maximum spin: $a_{\max} = 1 - \varepsilon$

(Thorne limit from relativistic effects)

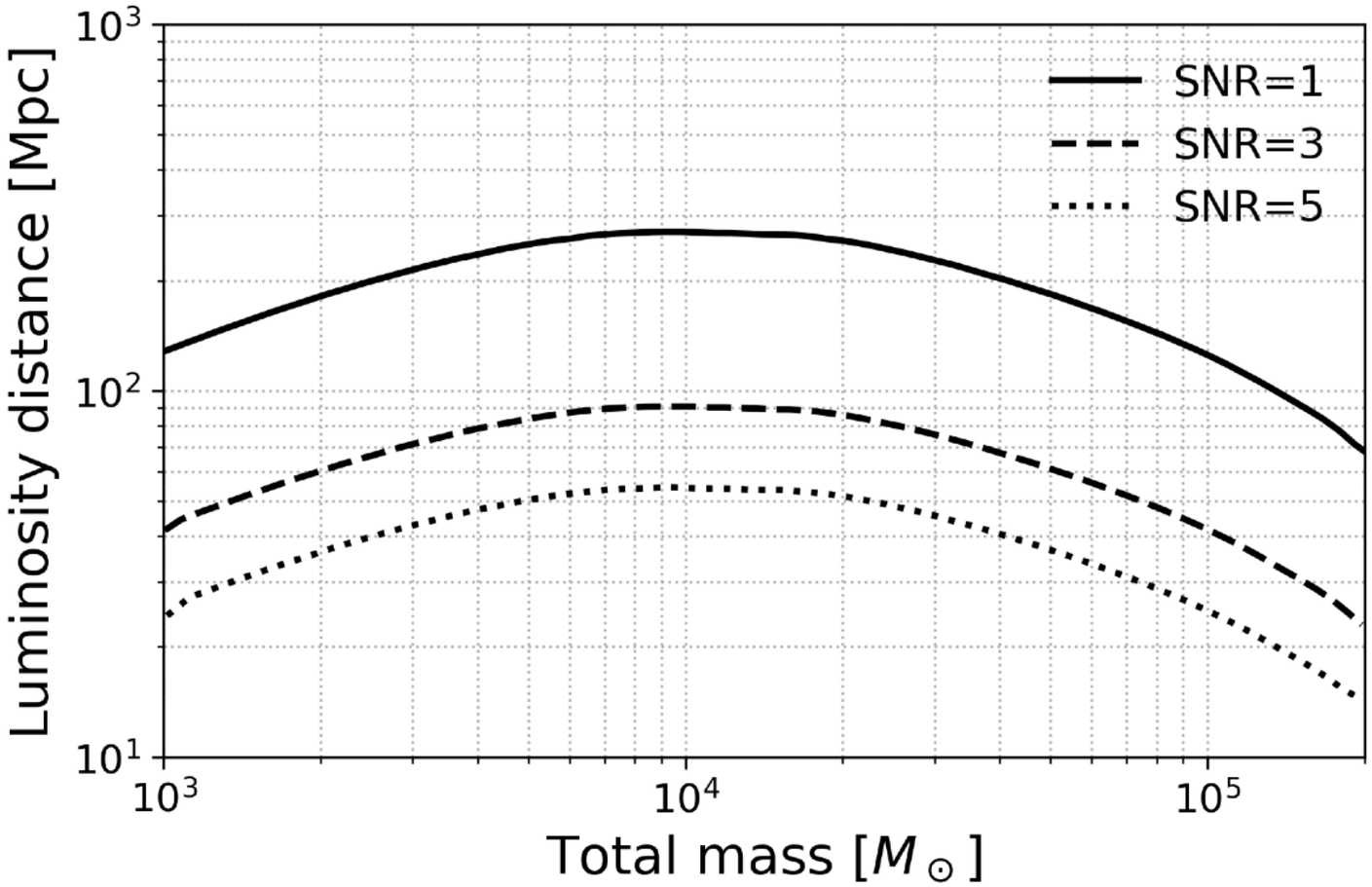
$\varepsilon \simeq 4.3 \times 10^{-4} \rightarrow a_{\max} \simeq 0.99957$

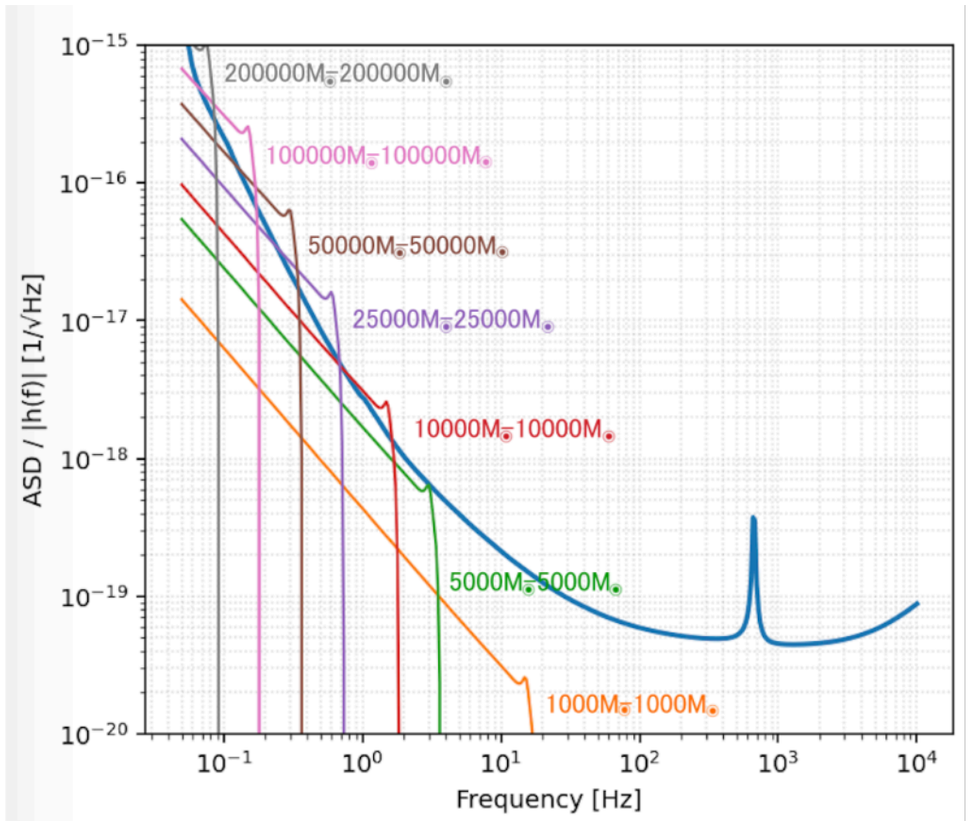


Formation scenario	Expected spin characteristics (qualitative)
Hierarchical mergers	Typically moderate spins ($a_* \sim 0.1 - 0.7$)
Prolonged (coherent) accretion	Tends to produce high spins ($a_* \rightarrow a_{\max}$)
Chaotic / random accretion	Broad, often low-to-moderate spins
Primordial formation	Broad distribution (model-dependent)

Measuring spins of IMBHs helps discriminate formation scenarios.

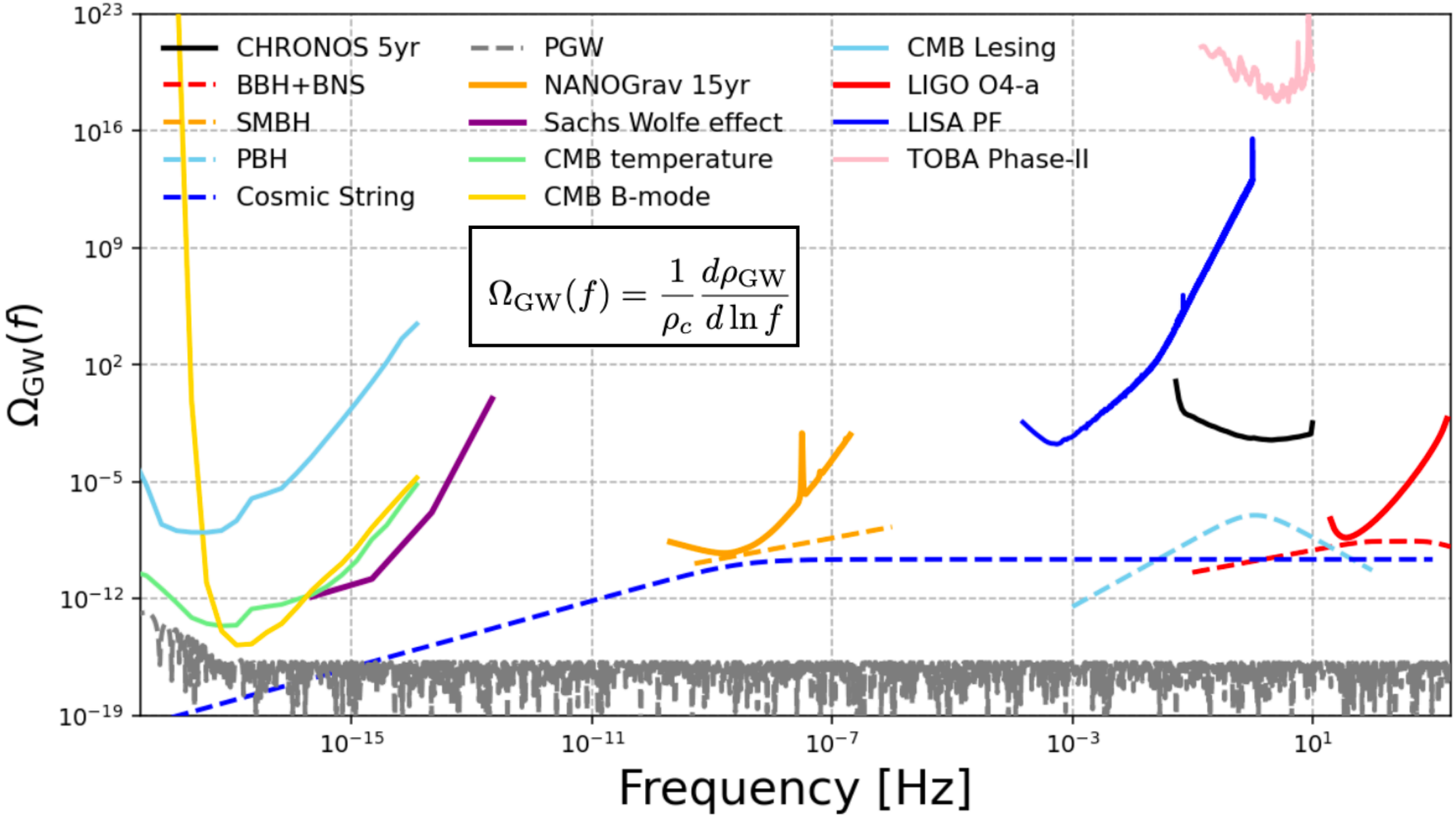
Intermediate mass black hole



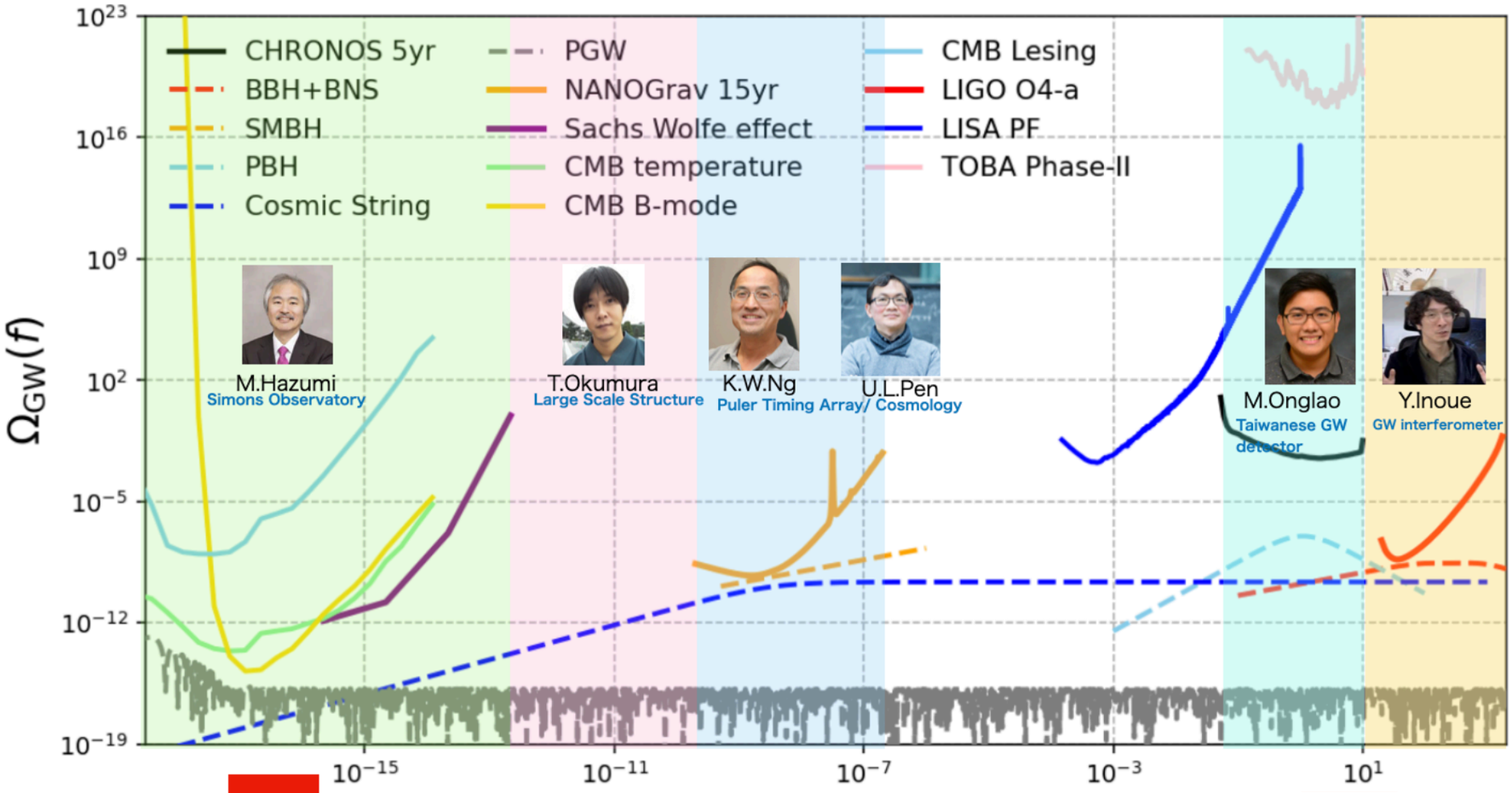


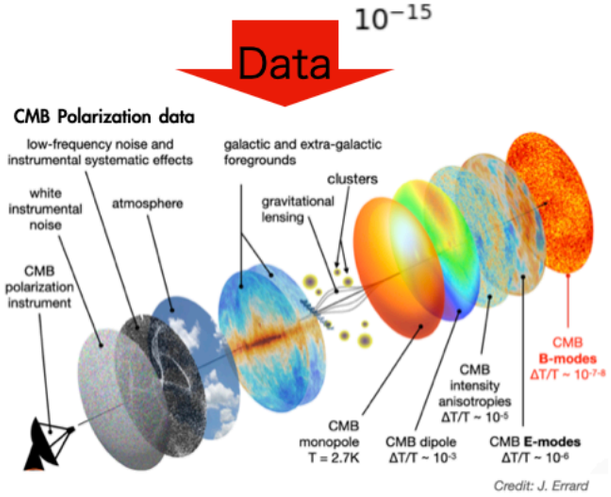
CHRONOS is sensitive to Inter mediate Black Hole

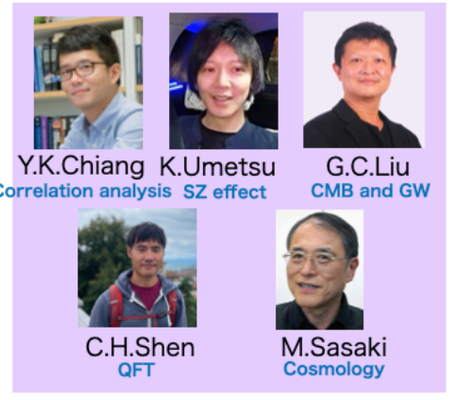
Stochastic Background

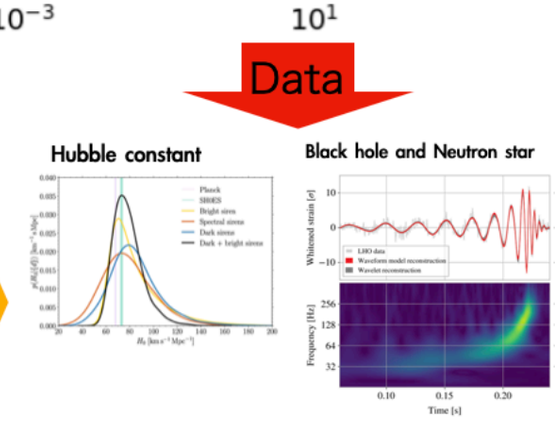


Team Taiwan


CHRONOS 5yr
BBH+BNS
SMBH
PBH
Cosmic String
PGW
NANOGrav 15yr
Sachs Wolfe effect
CMB temperature
CMB B-mode
CMB Lesing
LIGO O4-a
LISA PF
TOBA Phase-II
$\Omega_{GW}(f)$
10^{23}
10^{16}
10^{9}
10^{2}
10^{-5}
10^{-12}
10^{-19}
10^{-15}
10^{-11}
10^{-7}
10^{-3}
10^{1}
Frequency [Hz]
M.Hazumi
Simons Observatory
T.Okumura
Large Scale Structure
K.W.Ng
Puler Timing Array
U.L.Pen
Cosmology
M.Onglao
Taiwanese GW detector
Y.Inoue
GW interferometer


Data
CMB Polarization data
low-frequency noise and instrumental systematic effects
galactic and extra-galactic foregrounds
white instrumental noise
atmosphere
gravitational lensing
clusters
CMB polarization instrument
CMB monopole T = 2.7K
CMB dipole ΔT/T ~ 10⁻³
CMB intensity anisotropies ΔT/T ~ 10⁻⁵
CMB E-modes ΔT/T ~ 10⁻⁶
CMB B-modes ΔT/T ~ 10⁻⁷⁻⁸
Credit: J. Errard


Y.K.Chiang
Correlation analysis
K.Umetsu
SZ effect
G.C.Liu
CMB and GW
C.H.Shen
QFT
M.Sasaki
Cosmology


Data
Hubble constant
Black hole and Neutron star
Time [s]

Science Roadmap

1 Principle demonstration phase

2026-2030

Quantum Optics

Ozawa's inequality (for angular momentum L and angle θ)

$$\underbrace{\epsilon(L)\,\eta(\theta)}_{\text{Error} \times \text{Disturbance}} + \underbrace{\sigma(L_{in})\,\eta(\theta)}_{\text{Intrinsic fluctuation of } L \times \text{Disturbance}} + \underbrace{\epsilon(L)\,\sigma(\theta_{in})}_{\text{Error} \times \text{Intrinsic fluctuation of } \theta} \geq \frac{\hbar}{2}$$

- $\epsilon(L)$: measurement error of angular momentum $\hat{L}$
- $\eta(\theta)$: disturbance of angle $\hat{\theta}$
- $\sigma(L_{in})$: intrinsic fluctuation of input angular momentum
- $\sigma(\theta_{in})$: intrinsic fluctuation of input angle

$[\hat{L}, \hat{\theta}] \simeq i\hbar$ (small-angle approximation)

Commutation with the Hamiltonian $[\hat{L}, \hat{H}] = 0$ → Conservation in time $\frac{d\hat{L}}{dt} = \frac{1}{i\hbar}[\hat{L}, \hat{H}] = 0$ → Commuting at all times $[\hat{L}(t_1), \hat{L}(t_2)] = 0$ (for any t_1, t_2) → QND observable $\hat{L}$ is a QND observable. → Vanishing disturbance $\eta(L) \to 0$ (back-action can be made arbitrarily small) → **CHRONOS** Experimental demonstration of QND measurement of angular momentum.

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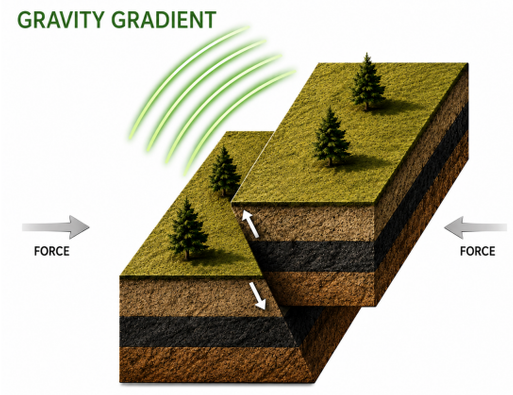
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QND condition (Braginsky): $[\hat{A}(t_1), \hat{A}(t_2)] = 0$ for the measured observable $\hat{A}$.
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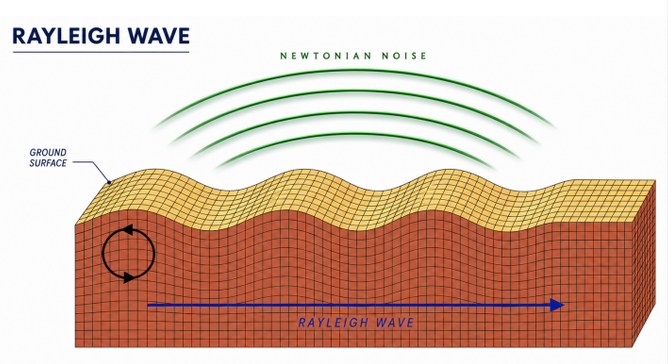
2 Gravity Gradient Science phase

2030-2035

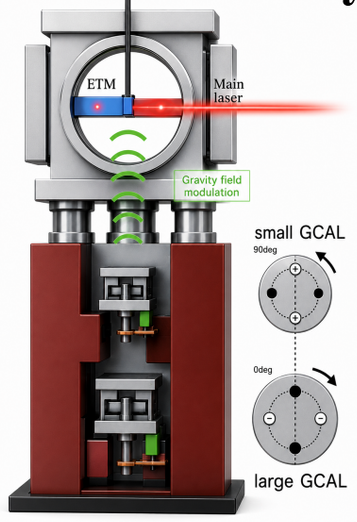
Erath quake



Newtonian Noise



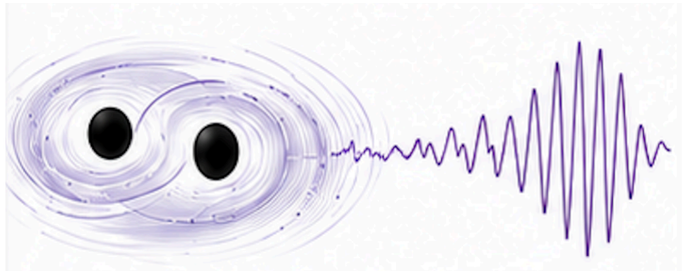
Yukawa Gravity



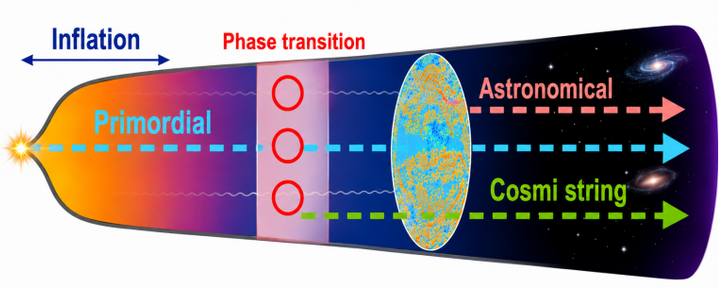
3 Gravitational wave Science phase

2035~

Intermediate-mass black hole binaries



Stochastic Gravitational Wave Background



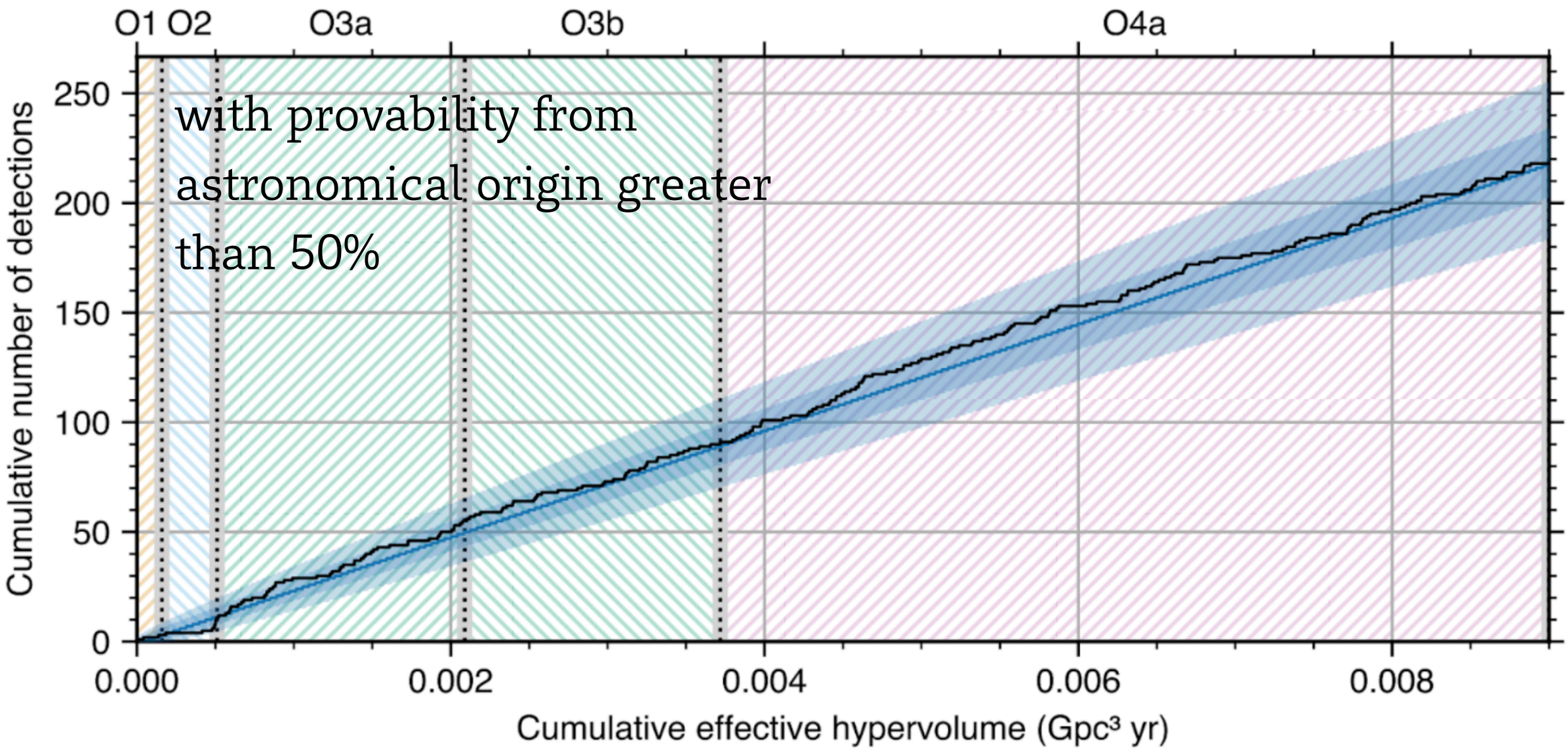
Summary

- LIGO is the world largest GW experiment for GW detection.
- LIGO observed 458 events and released the data from O1 to O4-b.
- CHRONOS is an idea of Taiwanese Sub-Hz GW experiment.
- By using Speed meter, Cryogenic, and Torsion bar system, we will improve the low frequency noise for Sub-Hz region.
- CHRONOS science program has 3 science stages. (i)Quantum (ii) Gravity Gradient (iii) Gravitational Wave
- **Collaboration and Invited talks in next semester are very welcome!!**



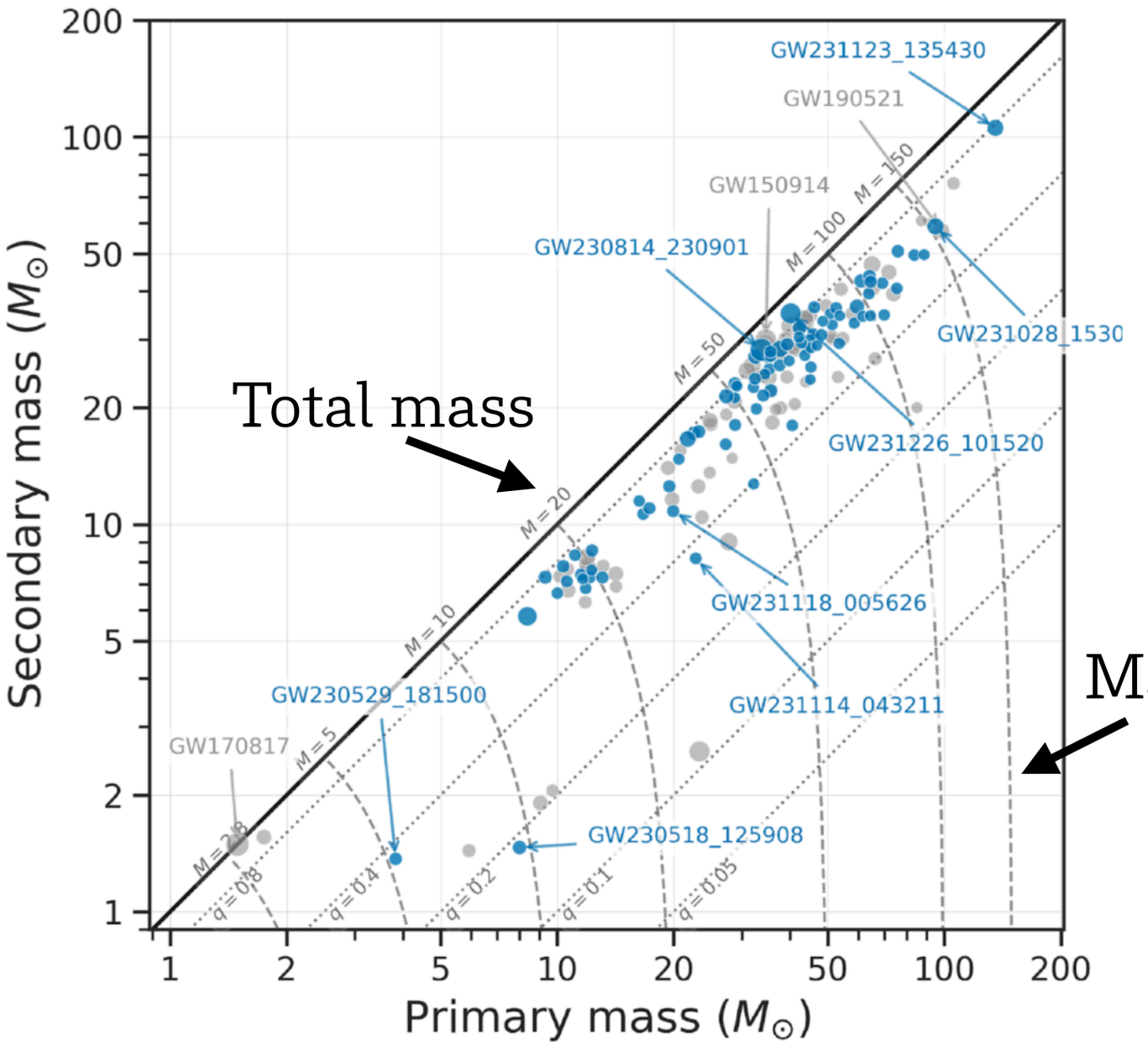
Backup

The cumulative number of detections



Observed Volume × Accumulation time

Mass of events



- No BNS events in O4a
- Observed some BH-NS binary
- IMBH binary (GW231123_124430)

Distribution peaks

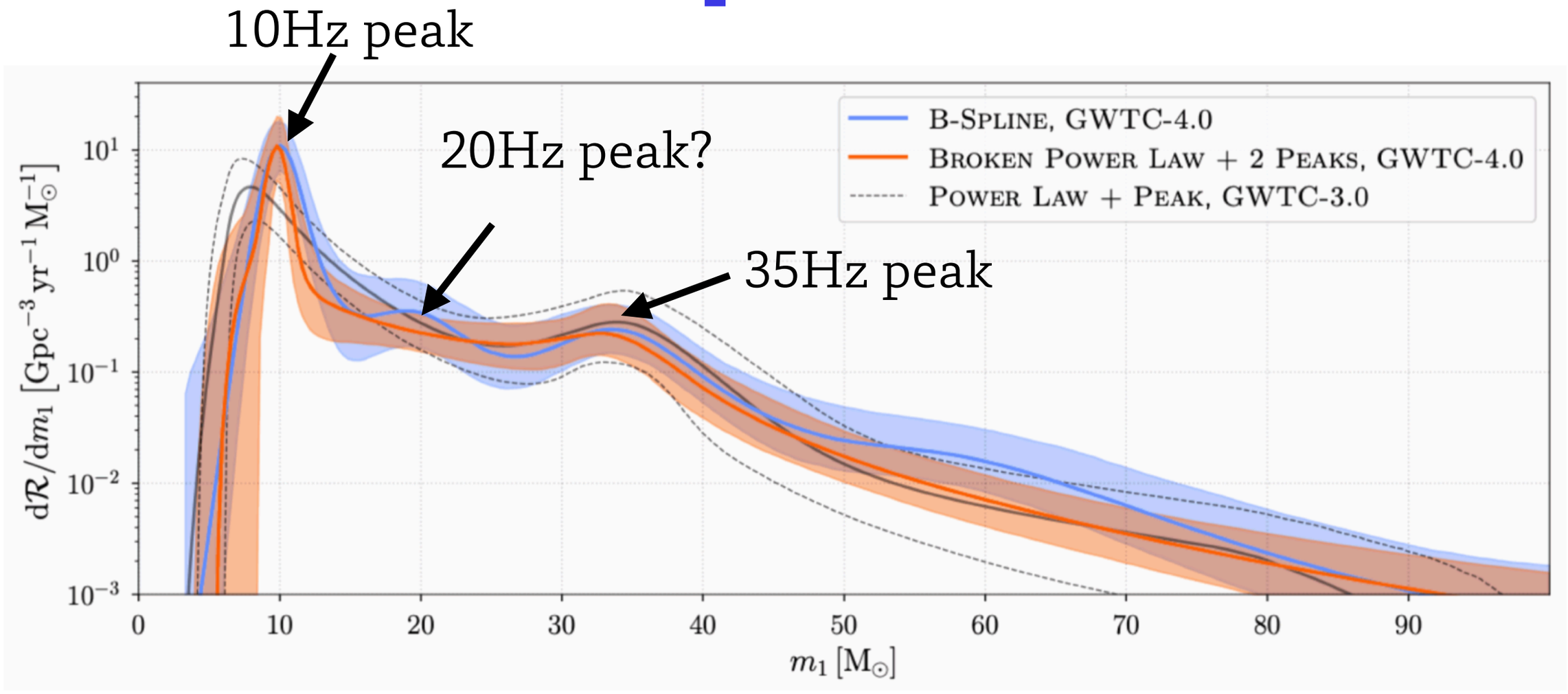
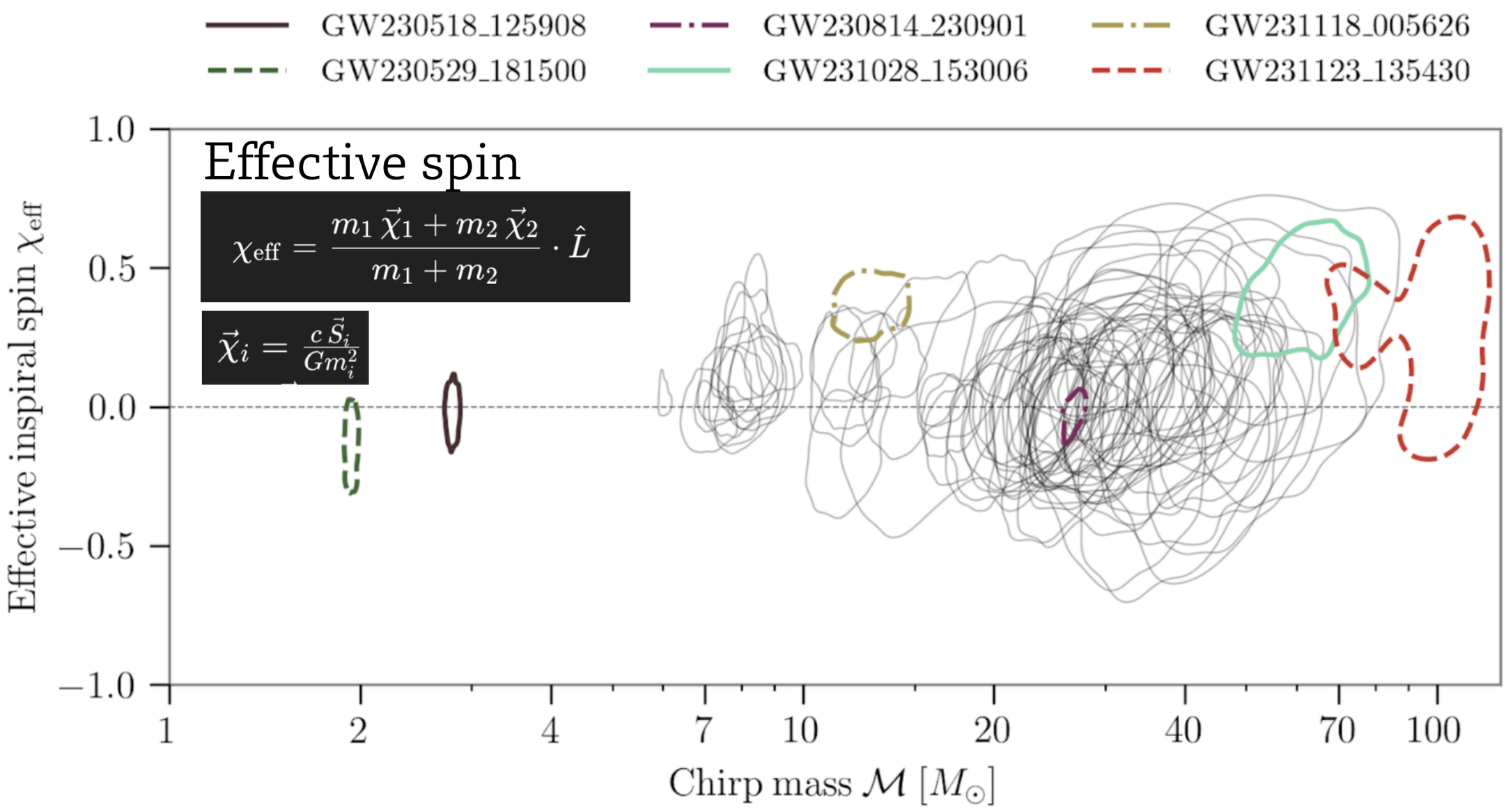


Figure 2: Primary black hole mass spectrum, i.e. the distribution of masses of the larger-mass black hole (the 'primary') in our detected binary systems. GWTC-4.0 (blue/orange) refines the earlier GWTC-3.0 Power Law + Peak (black dashed), with clearer support for structure around ~10 $M_\odot$ and ~35 $M_\odot$.

Spin of events



Hubble constant

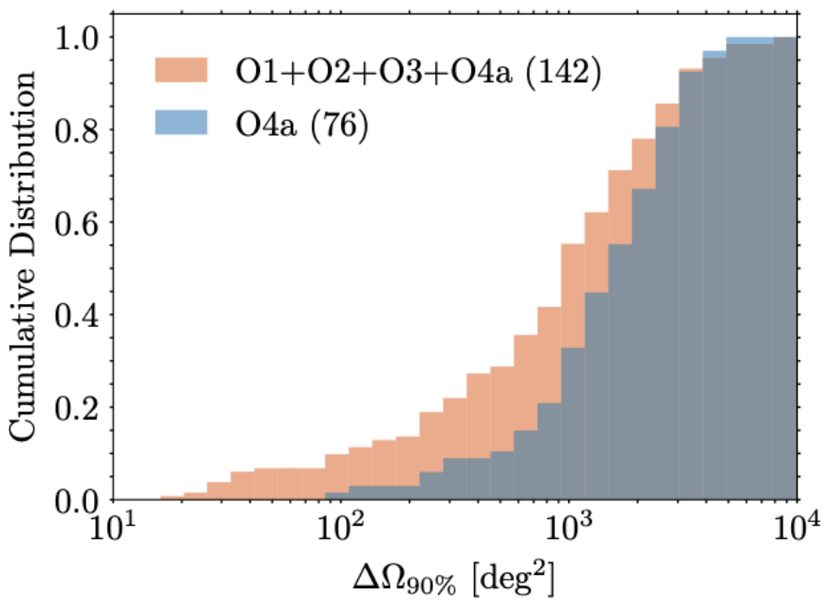


Figure 2. Cumulative distribution of the size of the 90% CR of the sky localization of CBC candidates observed during O1+O2+O3+O4a in orange (142 total events including GW170817) and O4a-only in blue (76 events). It can be seen that the typical sky localization of O4a events was larger than that of O1–O3 events.

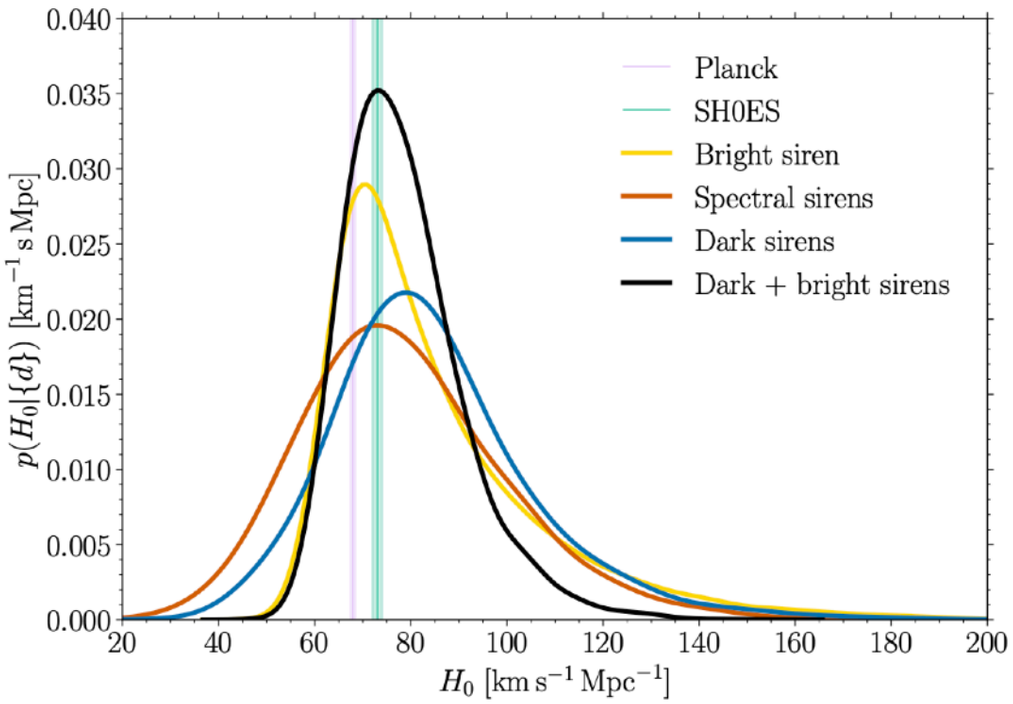


Figure 4. Hubble constant posterior for different cases. Yellow curve: posterior obtained from the bright siren GW170817 and its EM counterpart. Orange curve: posterior obtained with the spectral siren method and the FULLPOP-4.0 mass model. Blue curve: posterior obtained using all dark sirens with GLADE+ K-band in the luminosity-weighting case ($\epsilon = 1$) and the FULLPOP-4.0 mass model. Black curve: posterior after combining the dark and bright siren results. The pink and green shaded areas identify the 68% CI constraints on H_0 inferred from CMB anisotropies (Ade et al. 2016) and in the local Universe from SH0ES (Riess et al. 2022), respectively.

Bright siren: BNS with optical counter part

Dark siren: BBH with estimated host galaxy

Spectral siren: Use mass distribution $M_{det} = (1+z)M$

Catalog	Period	Number of Events	Purpose / Significance
GWTC-1 (O1–O2)	2015–2017	~10 events	Proof of concept
GWTC-2 (O3a)	2019	~39 events	Early population analysis
GWTC-3 (O3b)	2019–2020	~90 events	First full-scale spectral-siren trial
GWTC-4 (early O4)	2023–2024	>200 events	Toward 10 % precision on H_0

https://arxiv.org/pdf/2509.04348

$$H_0 = 76.6^{+13.0}_{-9.5}\,(76.6^{+25.2}_{-14.0})\,\mathrm{km\,s^{-1}\,Mpc^{-1}}.$$

Principle of spectral strain method

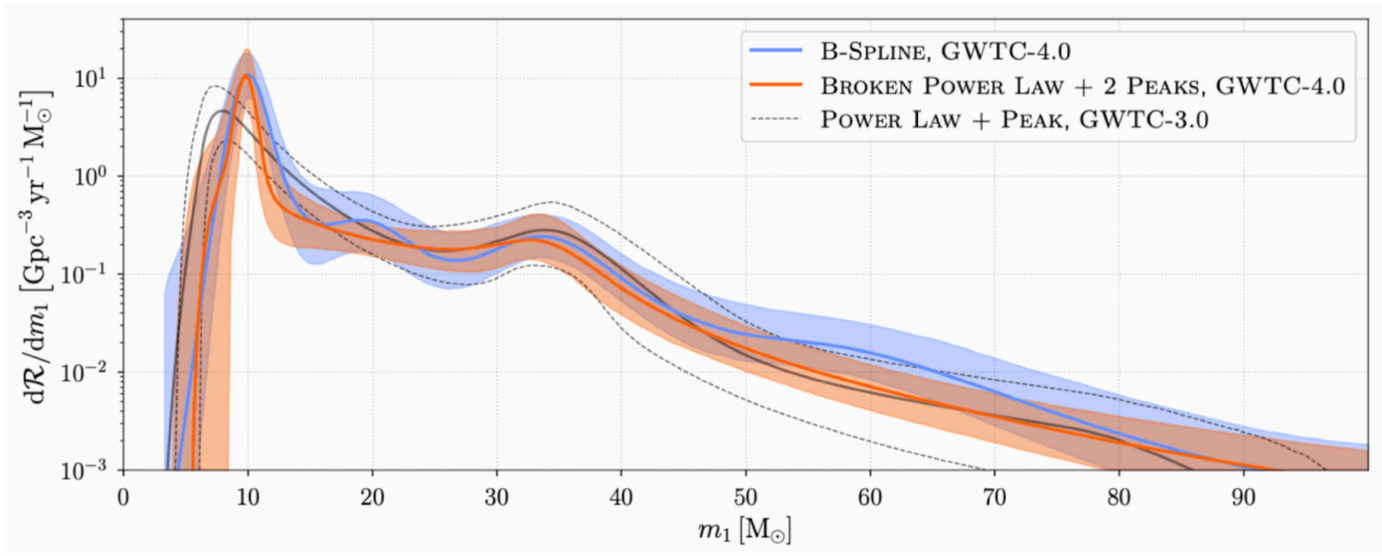


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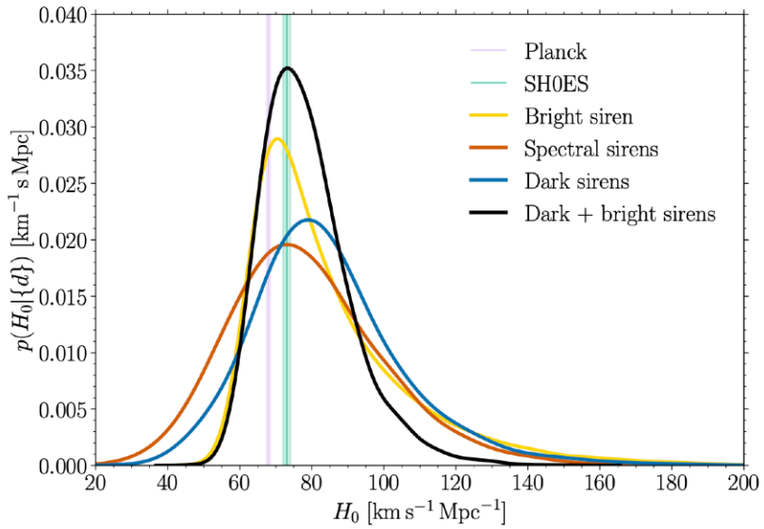


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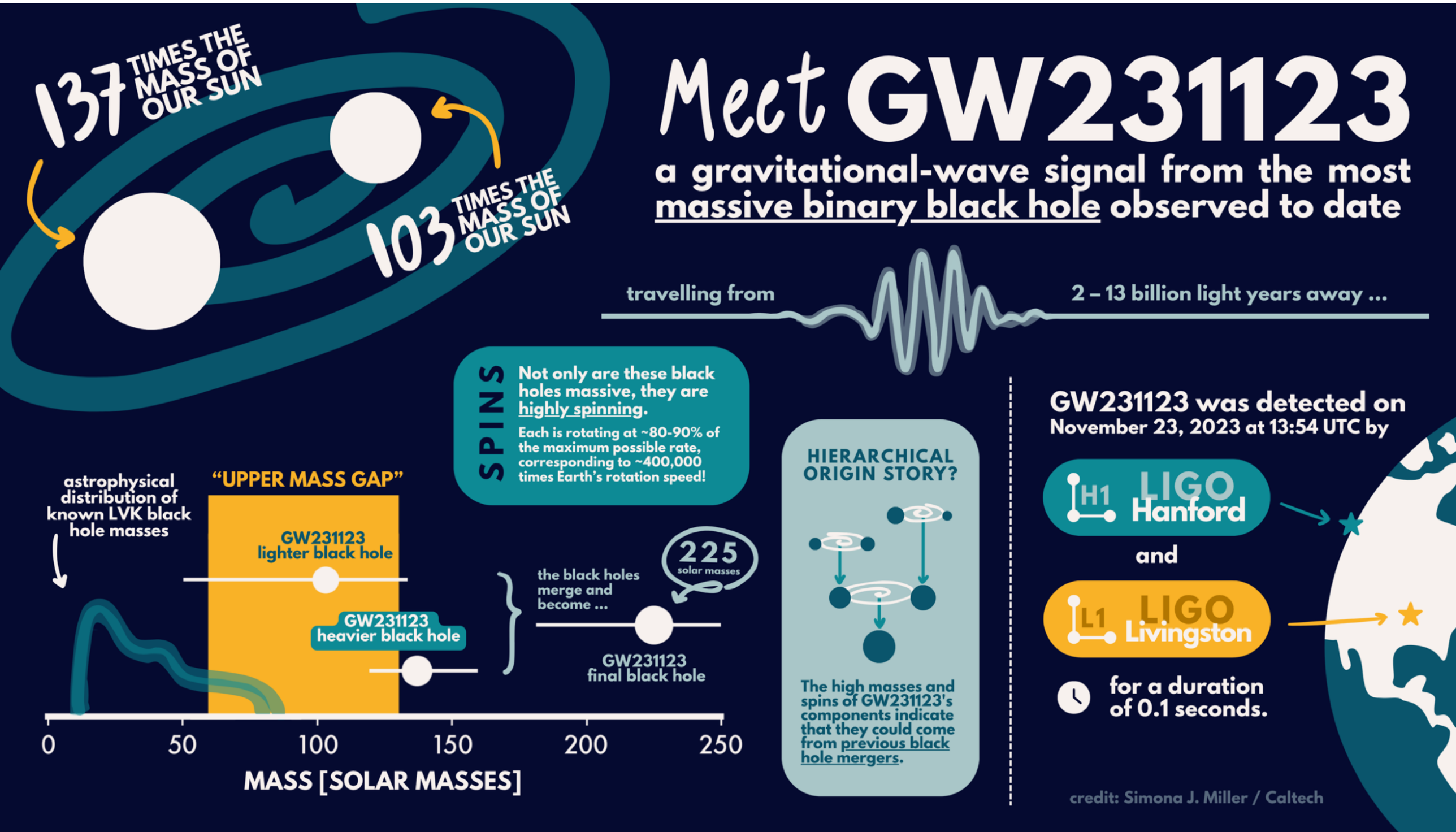
Universe expands → redshift z stretches GW waveform $m_{\rm det} = (1+z)\, m_{\rm src}$

$$p(z \mid m_{\rm det}) \propto p\left(m_{\rm src} = \frac{m_{\rm det}}{1+z} \mid \lambda\right)\, p(z \mid H_0)$$

If $p(z \mid m_{\rm det})$ has strong features (peaks/cutoffs), their redshifted positions constrain the cosmic expansion.

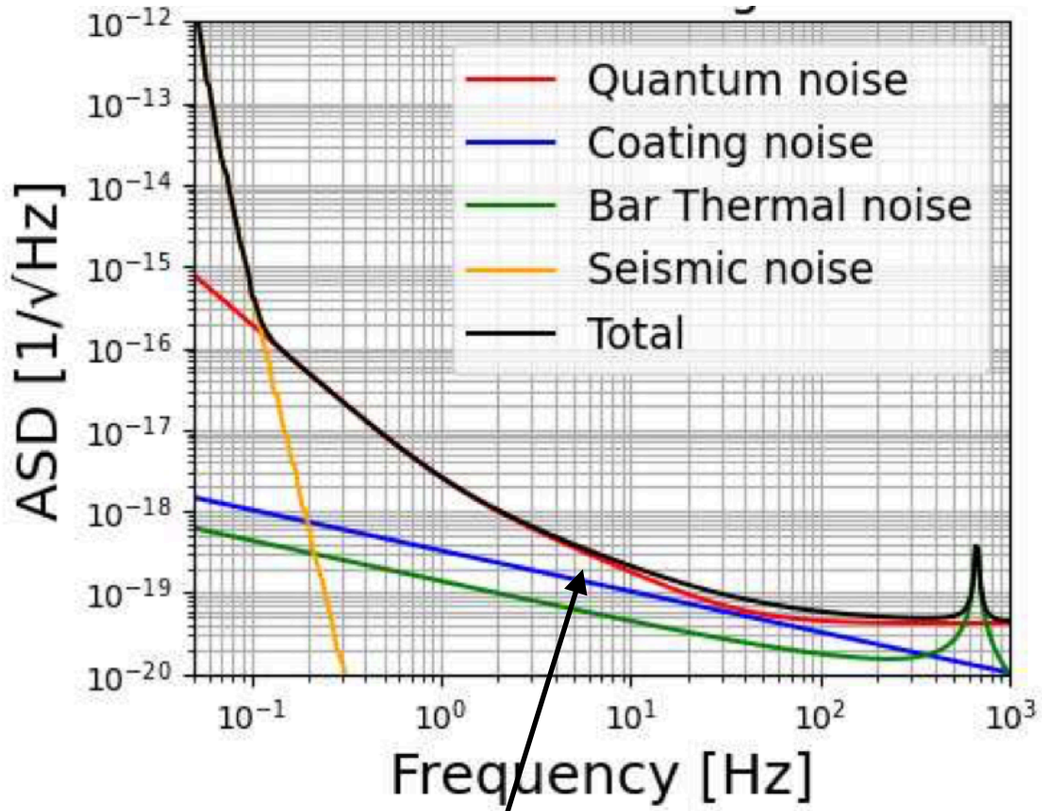
Hubble constant is consistent with other method.

Most massive Binary Black hole



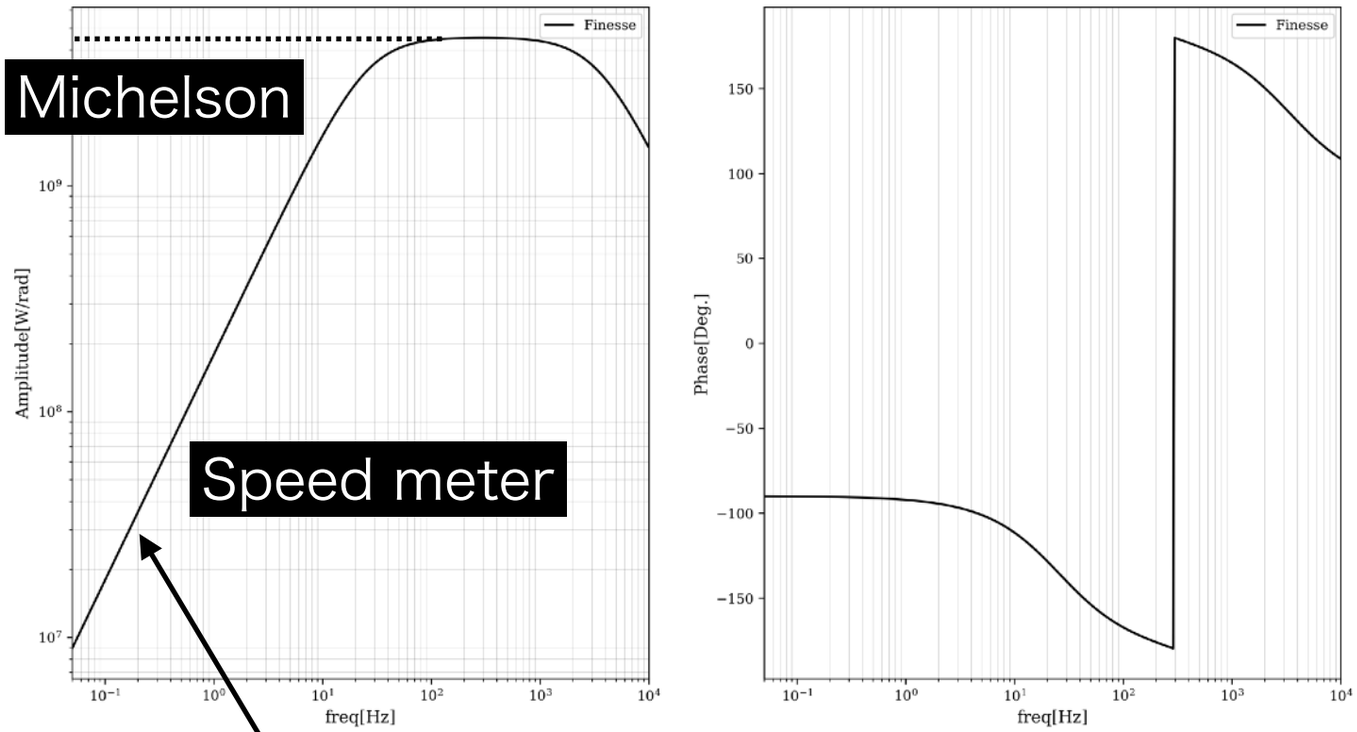
How to demonstrate QND speed meter?

(i) Noise spectrum



1/f structure!

(ii) Transfer function



1/f Tail of Sensing function!

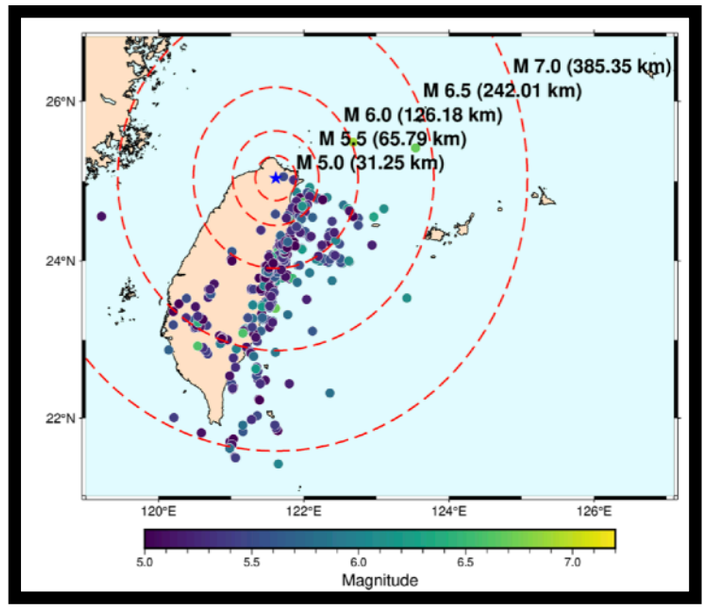
Geophysical Gravity effects

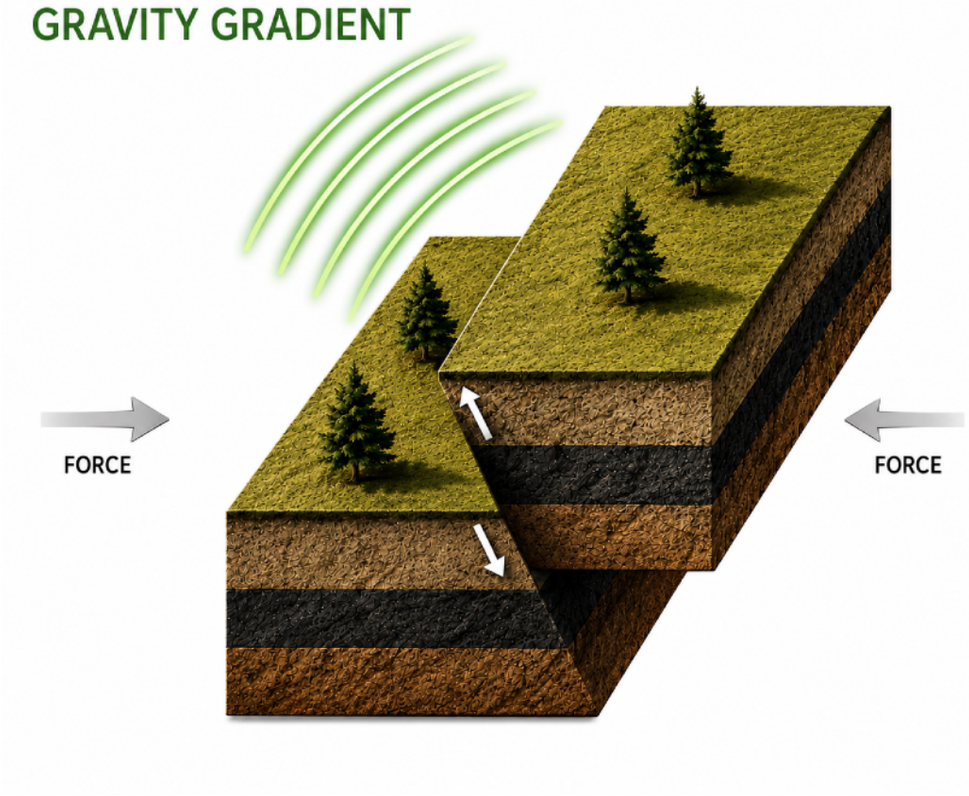
Prospects for Observing Gravity-gradient Noise and Earthquake Gravity Signals with CHRONOS

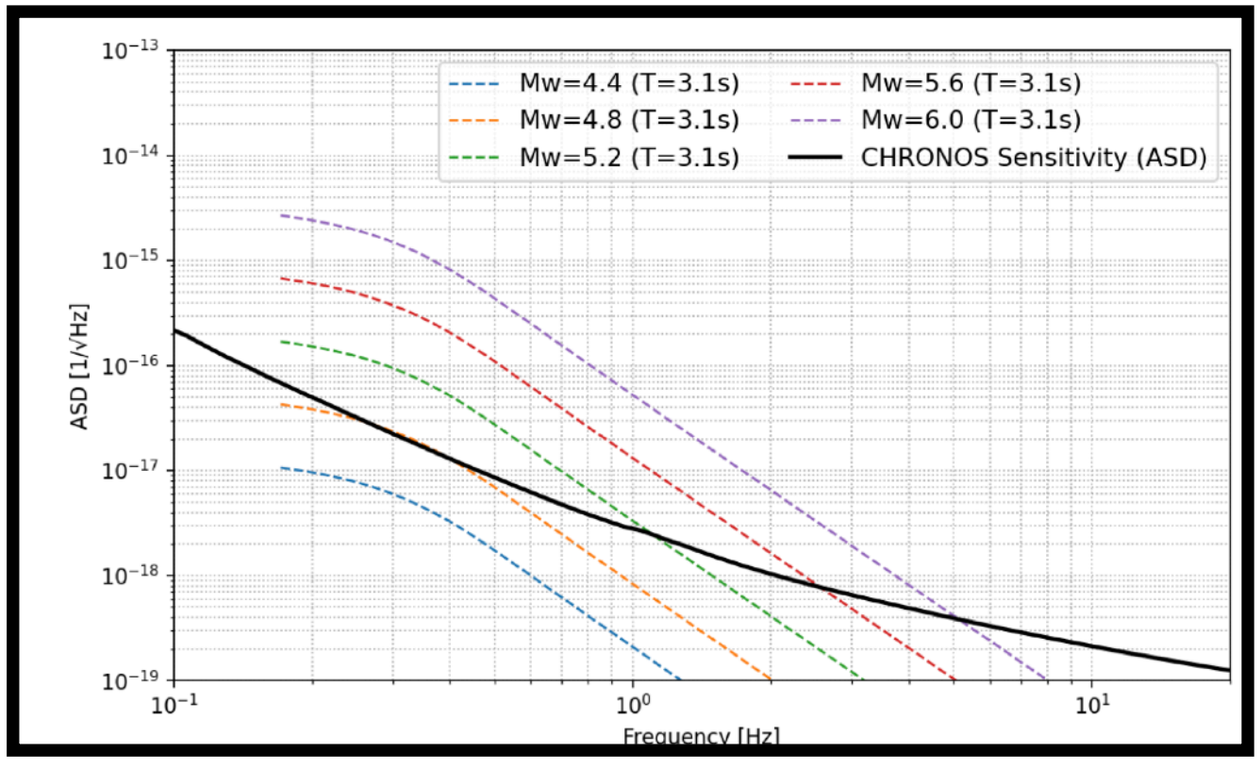
Mario Juvenal S. Onglao III[1,2,*] Yuki Inoue[2,3,4,5,†], and Daiki Tanabe[2,3,4,5]

[1]National Institute of Physics, University of the Philippines - Diliman, Quezon City, Philippines
[2]Center for High Energy and High Field Physics, National Central University, Taoyuan, Taiwan
[3]Department of Physics, National Central University, Taoyuan, Taiwan
[4]Institute of Physics, Academia Sinica, Taiwan
[5]High Energy Accelerator Research Organization (KEK), Japan
†Corresponding author: Yuki Inoue, iyuki@ncu.edu.tw









arXiv: 2606.19124

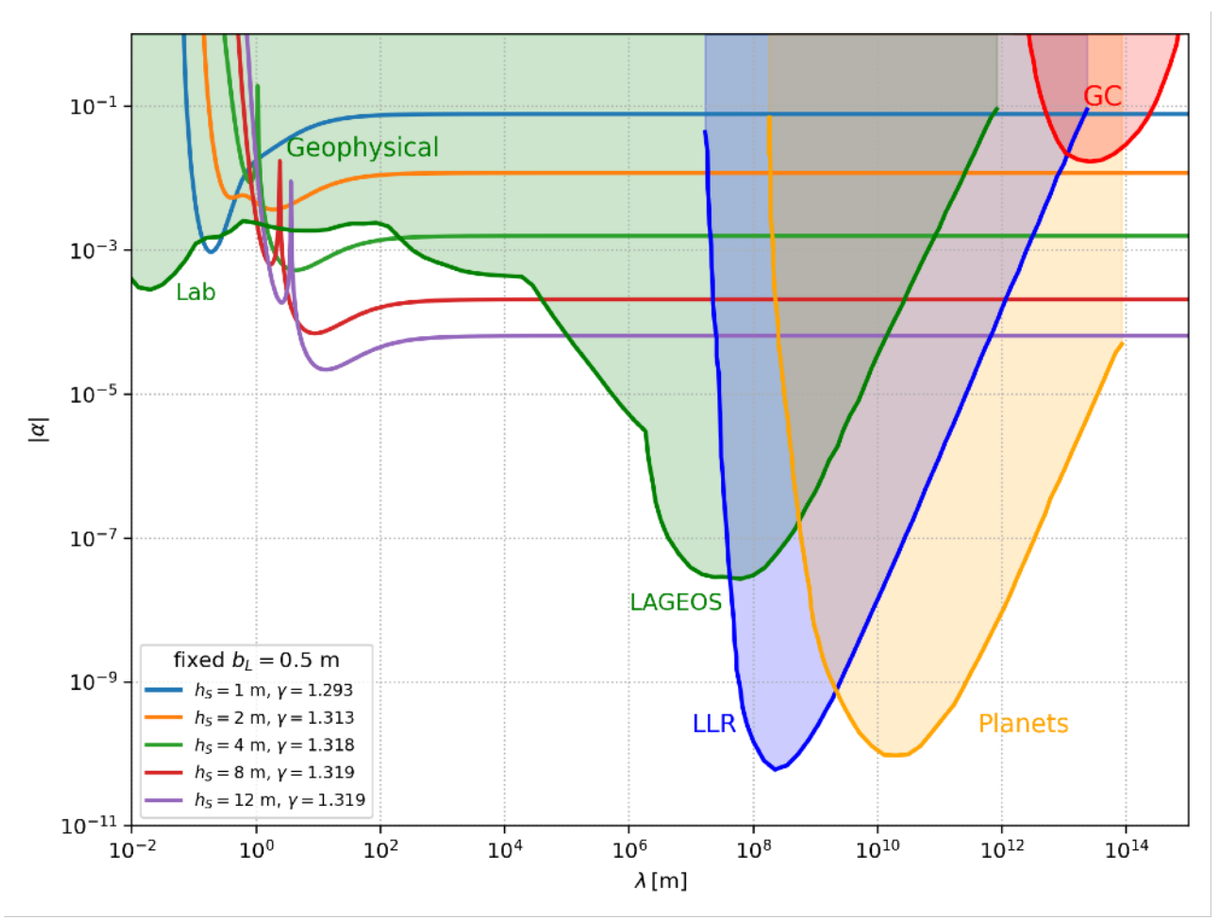
Probing Yukawa Gravity with Modulated Newtonian Cancellation in the Torsion bar type detector

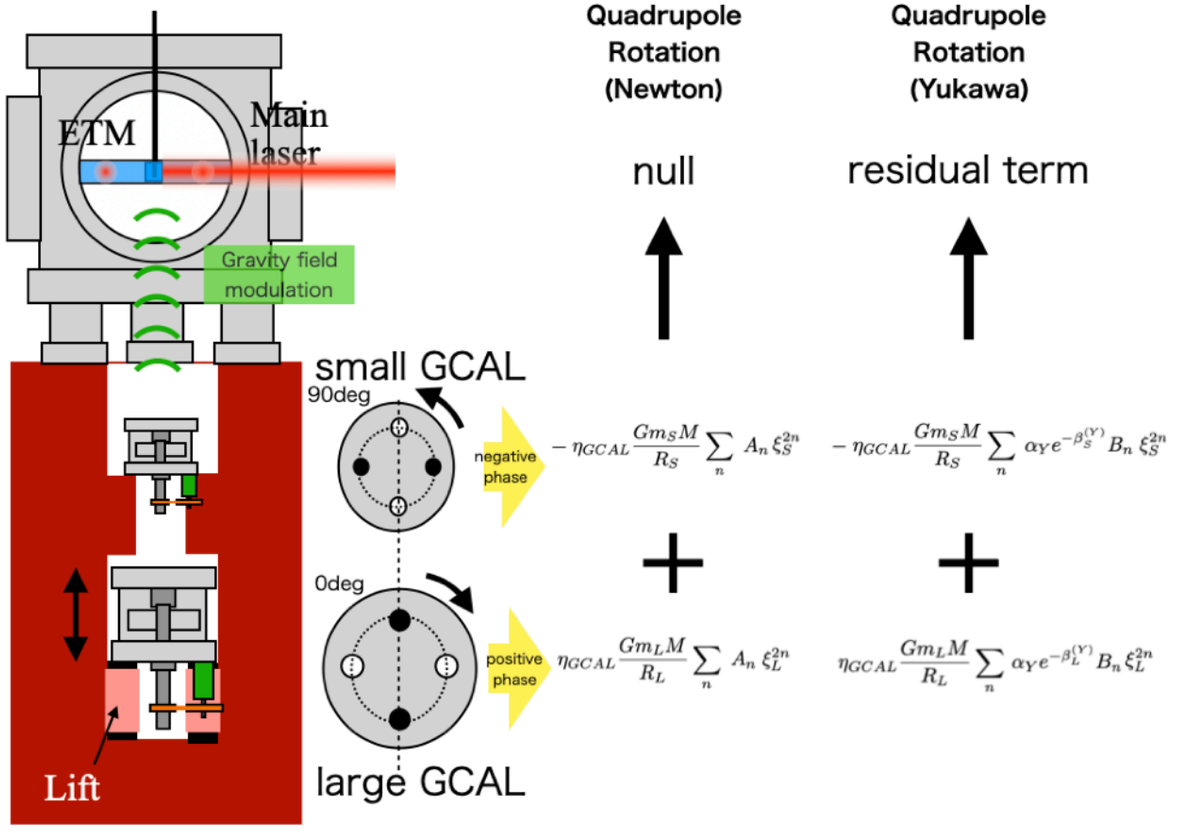
Yuki Inoue,[1,2,3,4,*] Hsiang-Yu Huang,[1,2] Vivek Kumar,[1,2] and Daiki Tanabe[2,3]

[1] *Department of Physics,National Central University, Taoyuan, Taiwan*
[2] *Center for High Energy and High Field (CHiP), National Central University, Taoyuan, Taiwan*
[3] *Institute of Physics, Academia Sinica, Taipei, Taiwan*
[4] *Institute of Particle and Nuclear Studies, High Energy Acceleration Research Organization (KEK), Tsukuba, Japan*

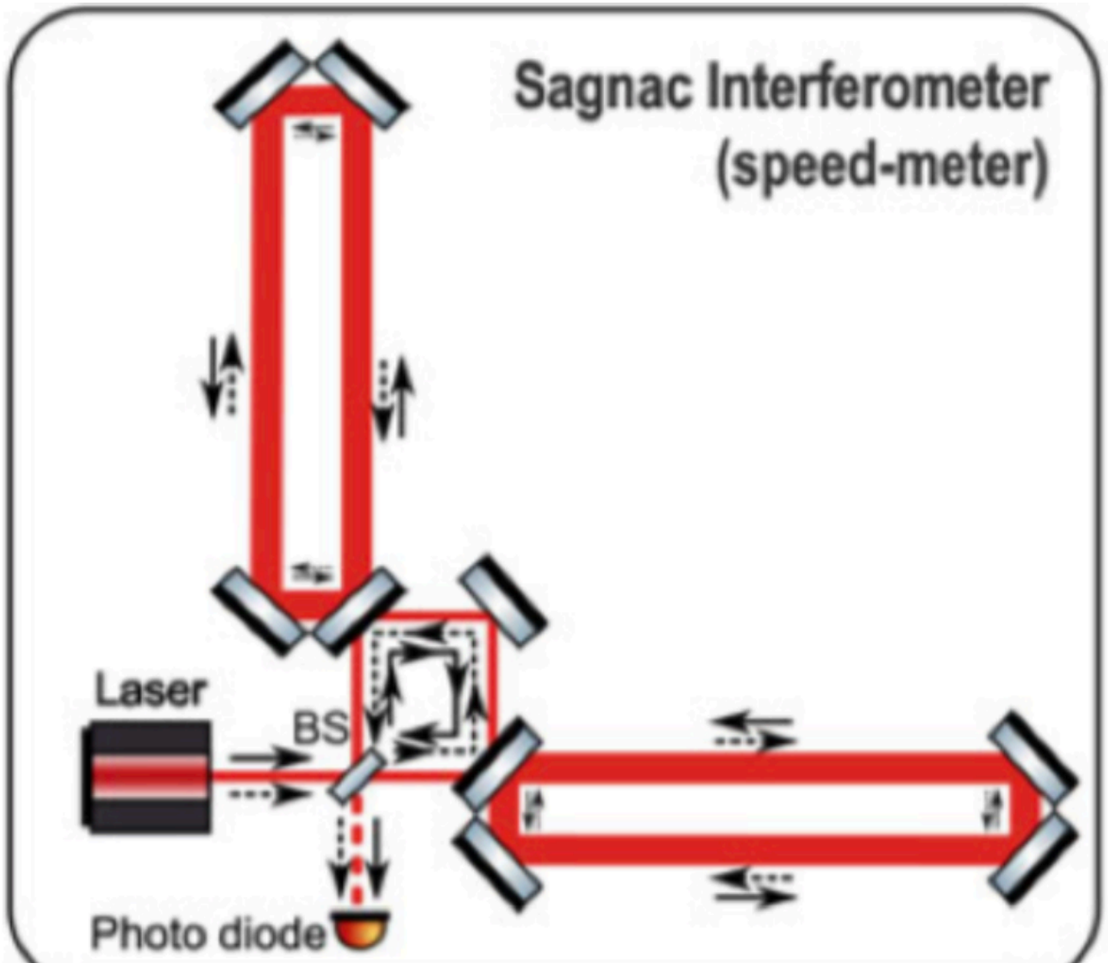
Newtonian + Yukawa Potential

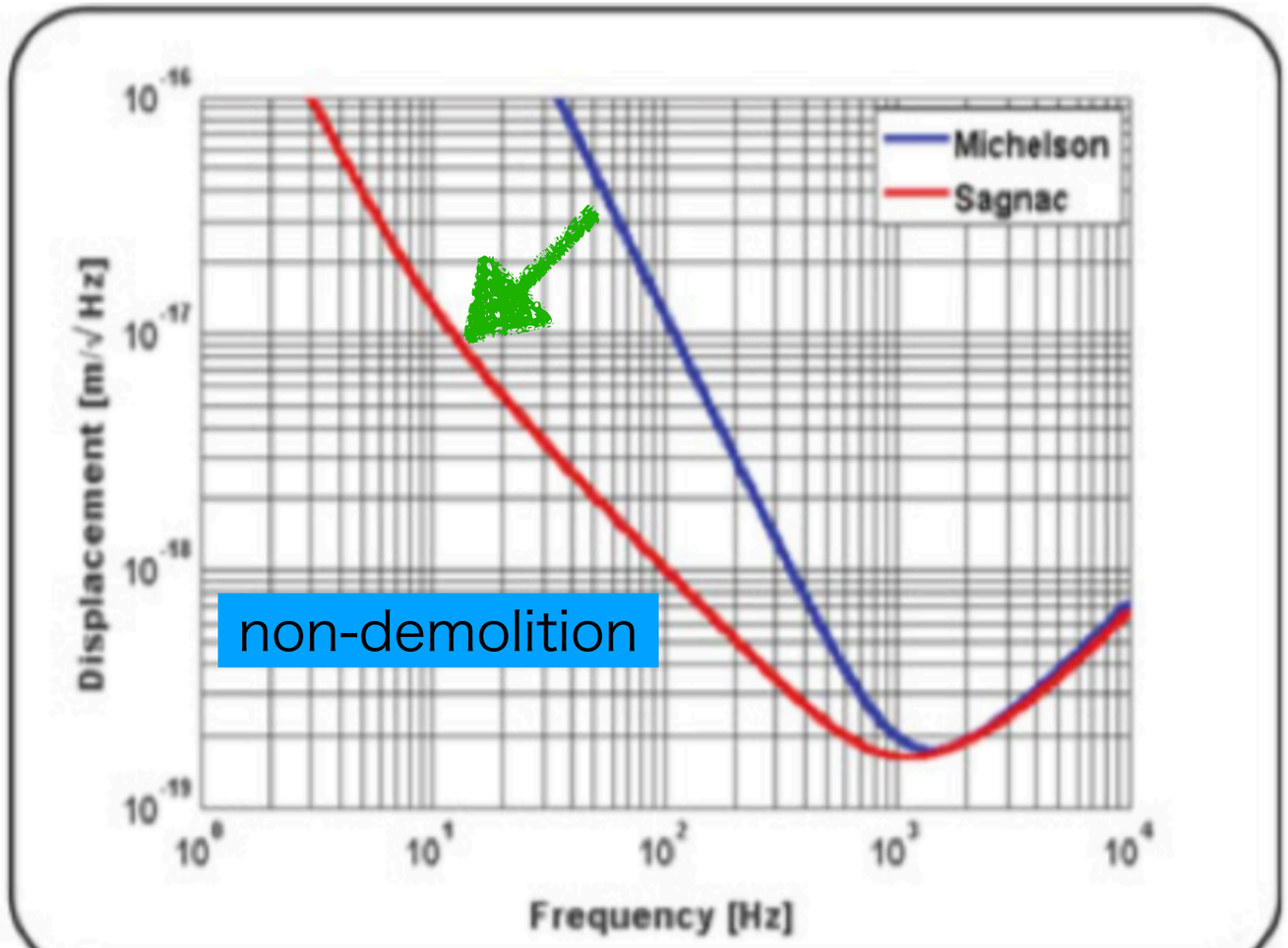
$$V(r) = -\frac{GmM}{r}\left(1 + \alpha_Y e^{-r/\lambda}\right),$$





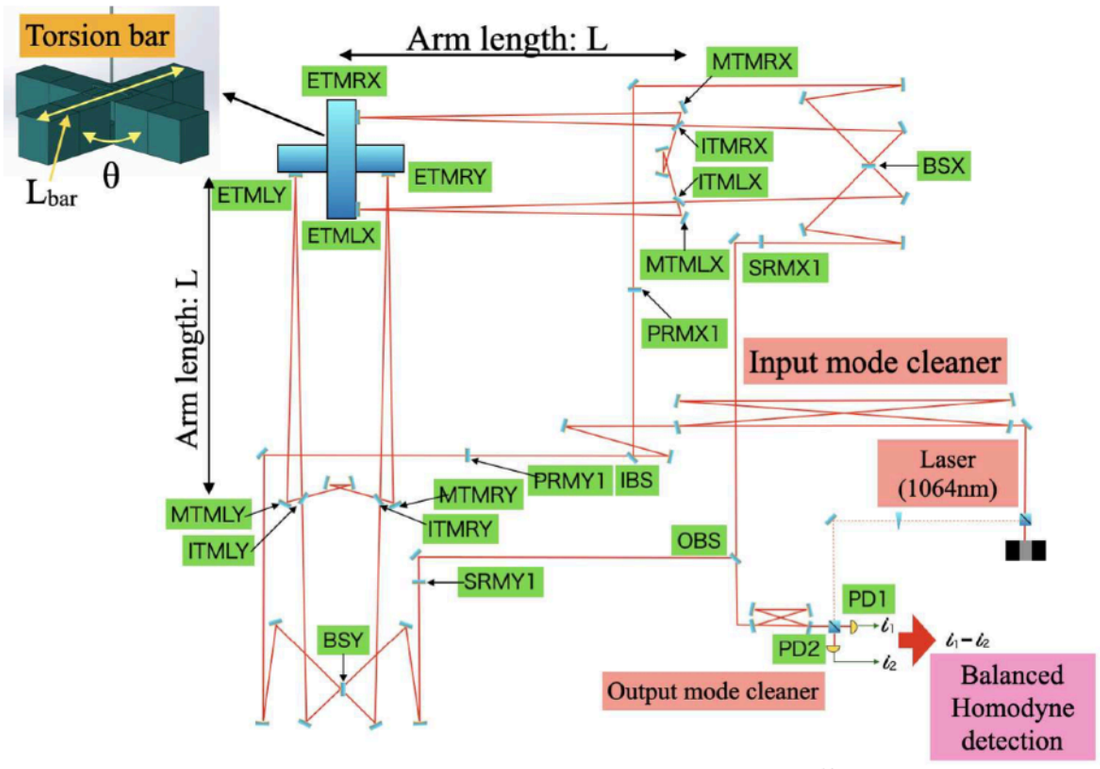
Fabry–Pérot Michelson vs. Sagnac Speed meter

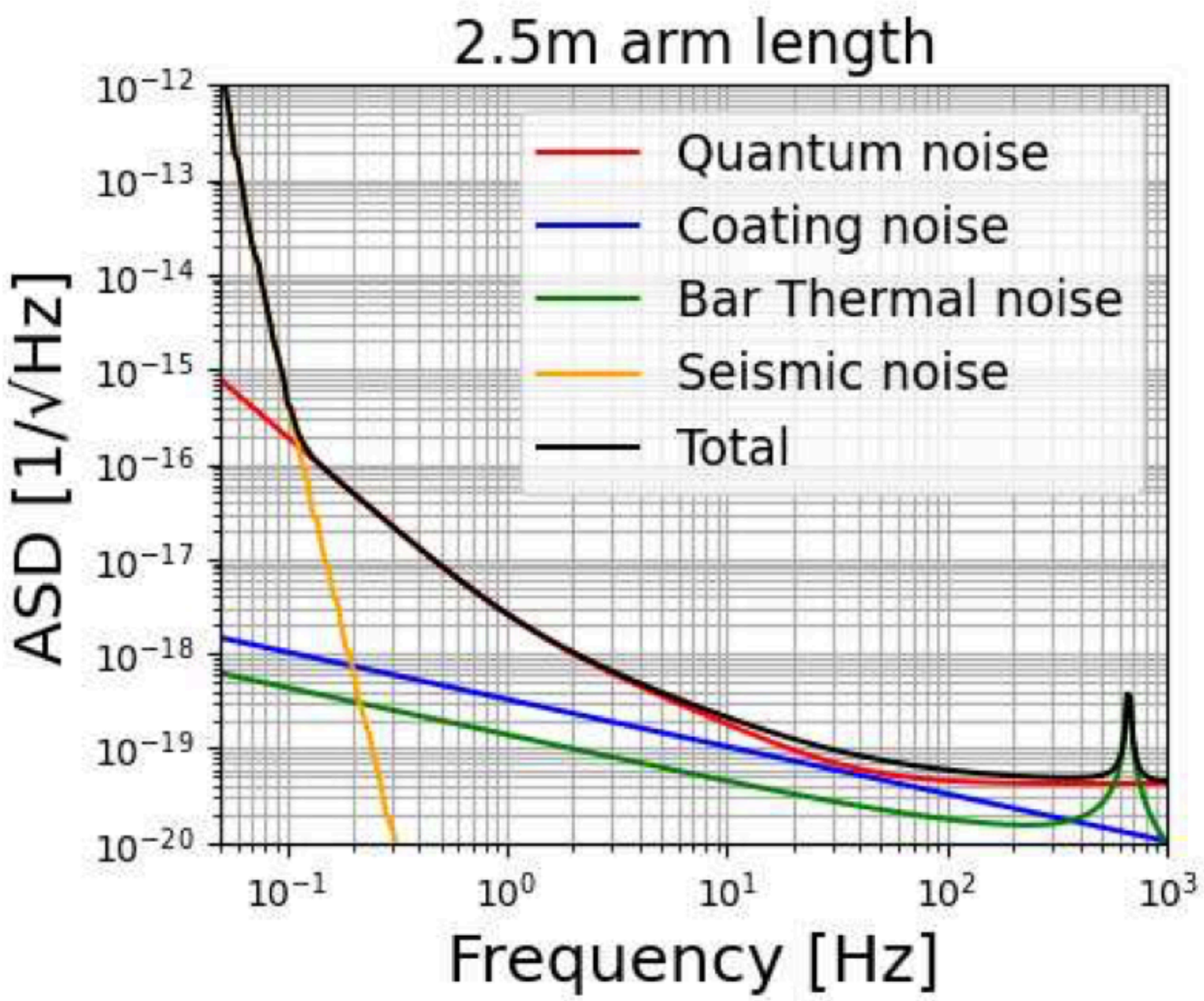




	Fabry–Pérot Michelson	Sagnac speed meter
Input	$ma=F=A\exp(i\omega t)$	$ma=F=A\exp(i\omega t)$
Output	$\|x\|=A/(m\omega^2)\exp(i\omega t)=F/(m\omega^2)$	$\|v\|=A/(m\omega)\exp(i\omega t)=F/(m\omega)$

Sensitivity:





We calculate the realistic interferometer configuration for future testing. This is the first trial of combination idea with Torsion bar and Speed meter. We will submit two new paper in this week.