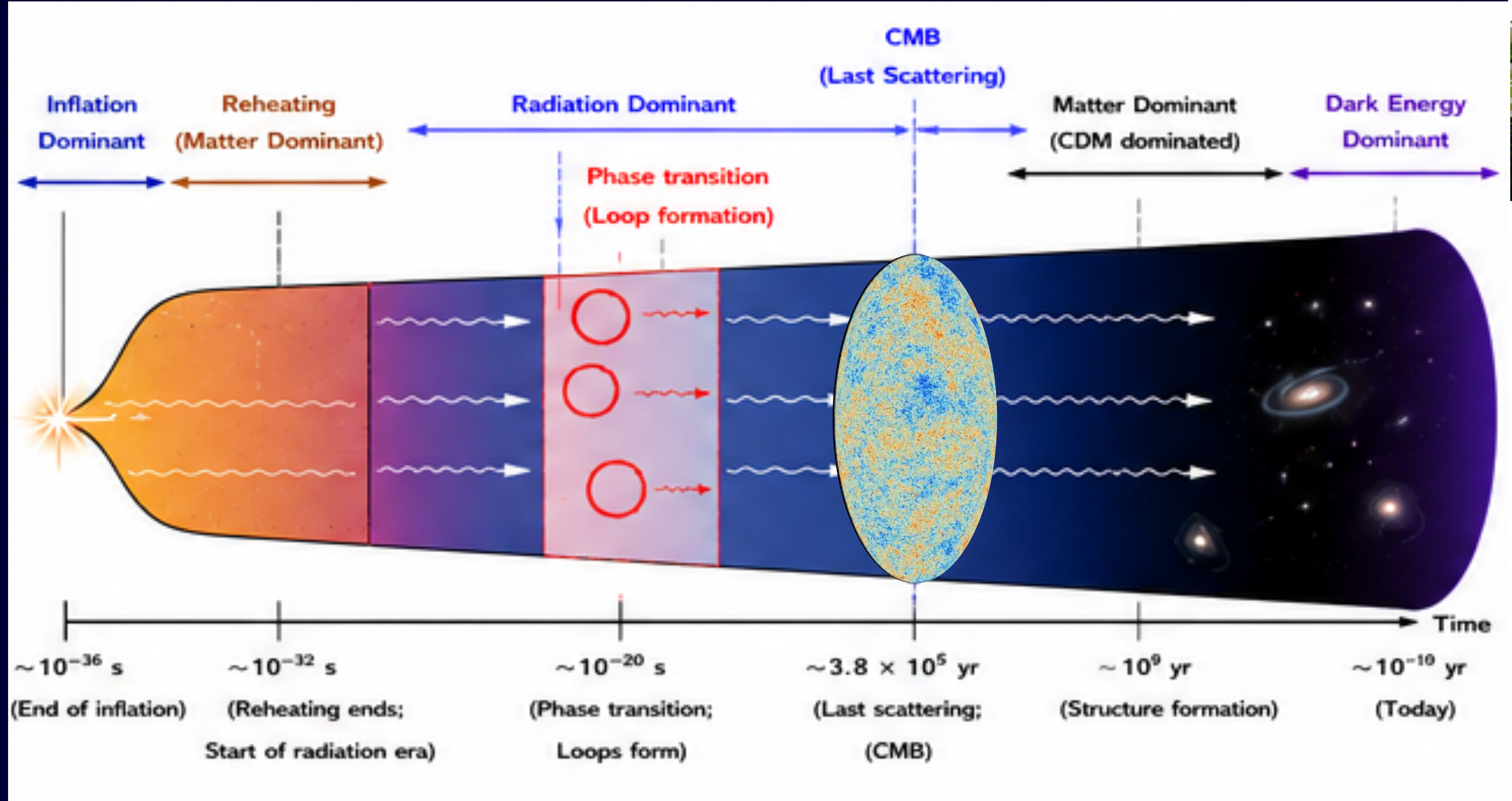
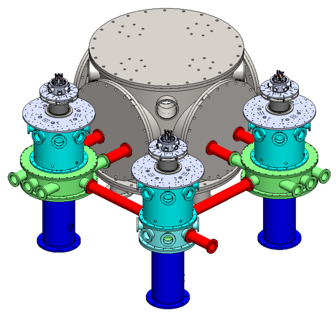
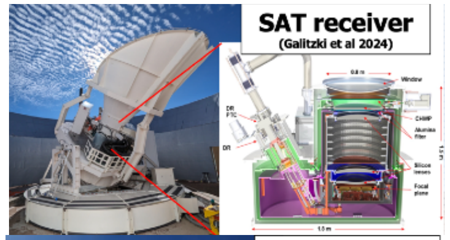
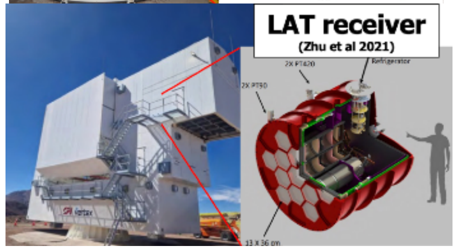








Experimental approach to observe wide-band Stochastic Gravitational Wave Background

Yuki Inoue
National Central University

GW-CMB 2026

CHRONOS

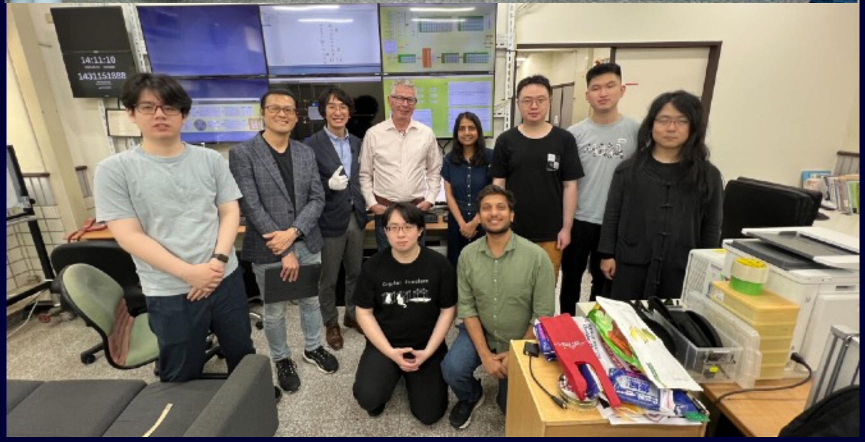
Taiwan-LIGO instrumentation group

National Central University
Yuki Inoue (PI)
Vivek Kumar
Hsiang-Yu Huang
Avani Patel
Ta-Chun Yu
Kun-Yao Chang

Academia Sinica
Tsz-King Wong
Feng-Kai Lin
Daiki Tanabe

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

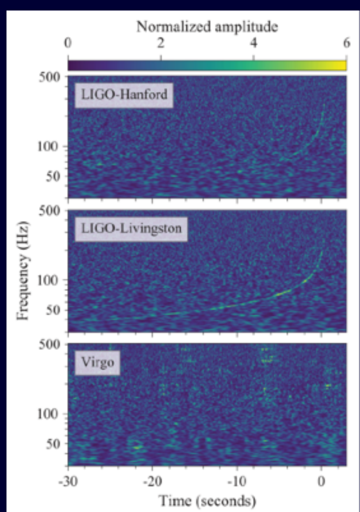
13 staffs and students join our group

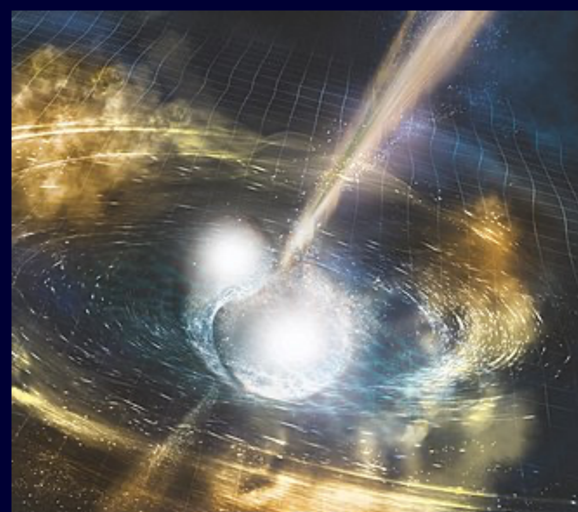
Outline

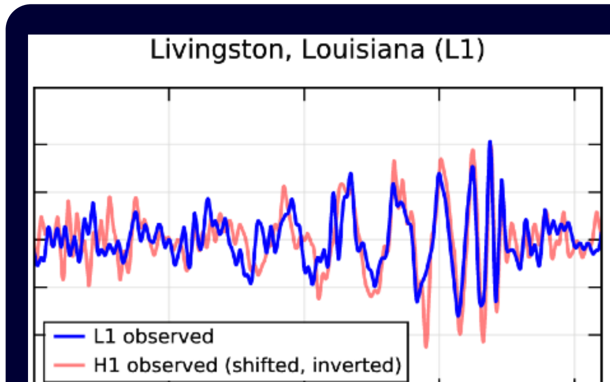
- Introduction
- Science
- Project Overview
- Schedule
- Summary

Introduction

10 years anniversary from the first detection of Gravitational wave





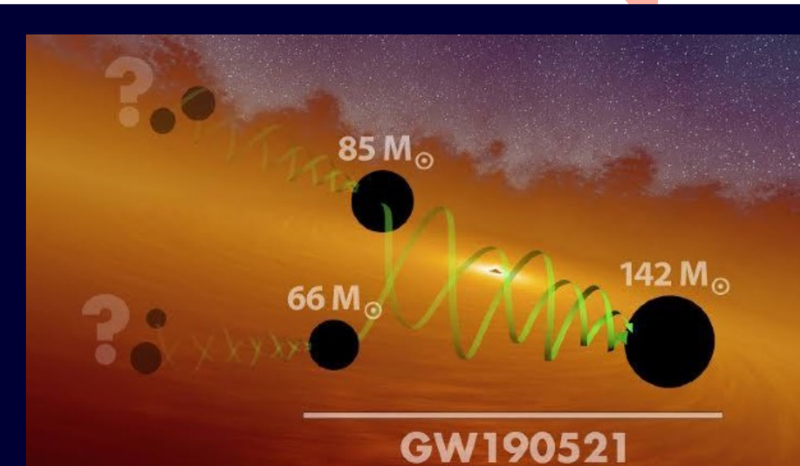


Main topics

2025 Aug. O4-a Data release

2023 May.24 Observation 4 start

2019 May. 21 IMBH

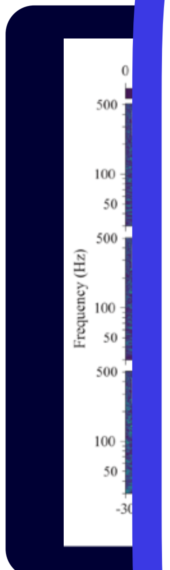


2017 Aug. 17 BNS

2015 Sep.14 The first detection

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!

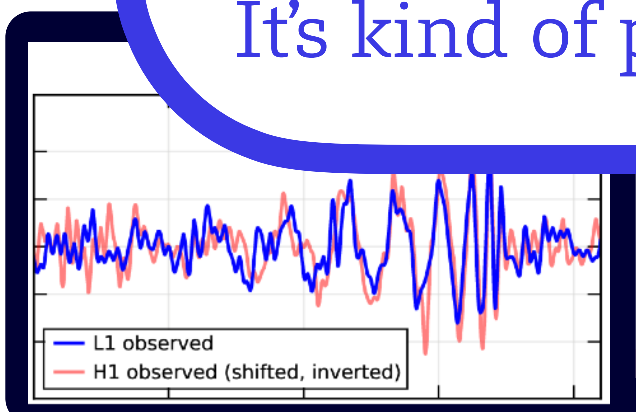
~400 events

This Talk!

O4

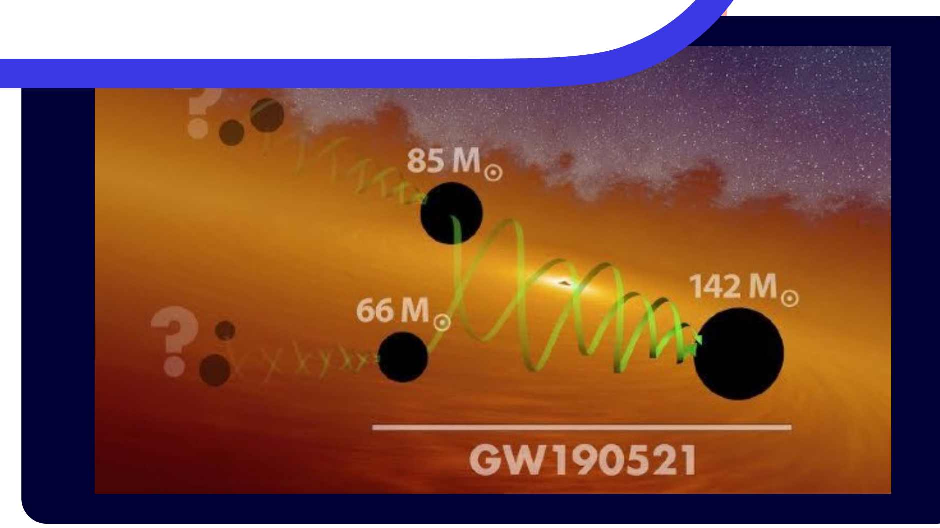
The statistical evaluation era!

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

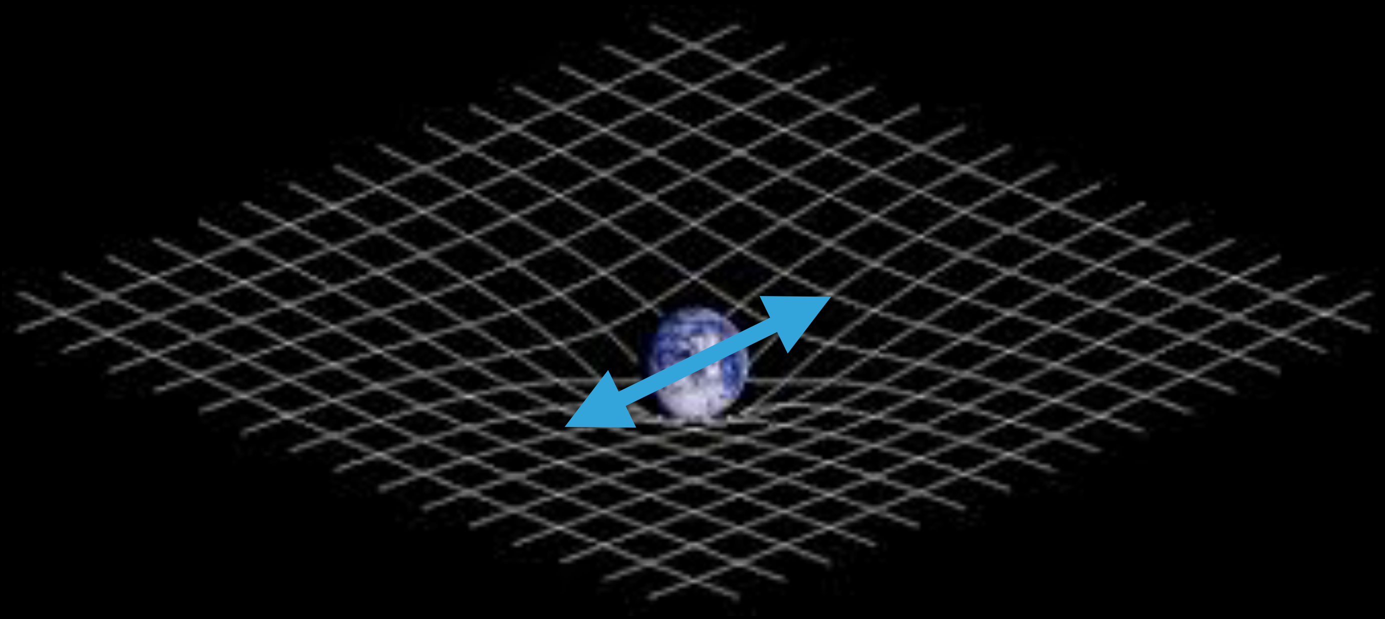


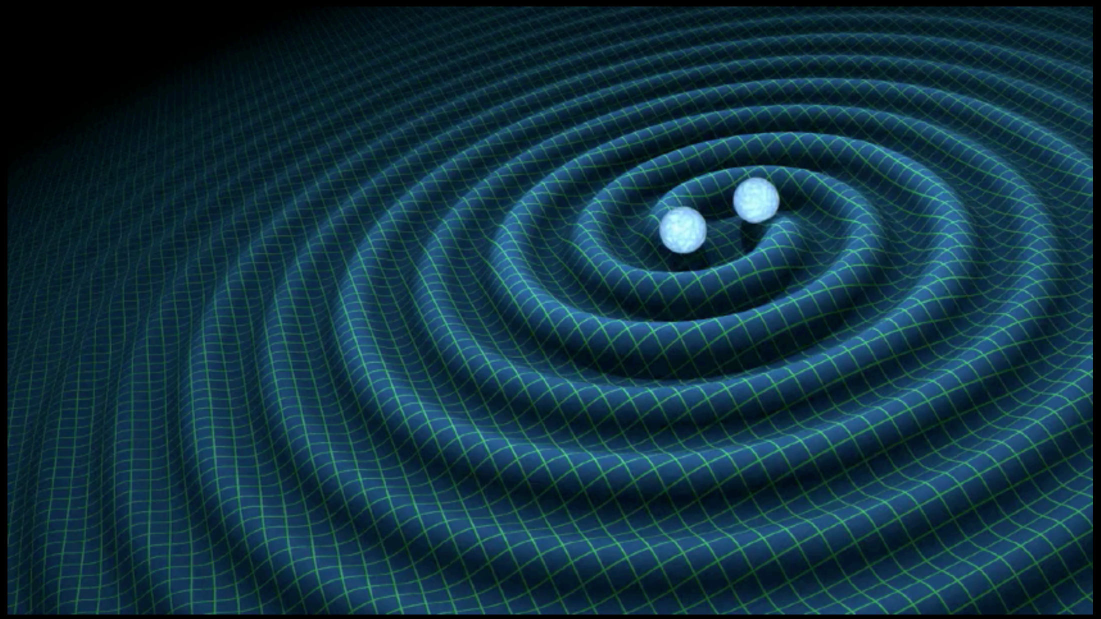
2017 Aug. 17 BNS

2015 Sep.14 The first detection



How to generate Gravitational Waves





- Science target is observation of gravitational waves.
- GW is generated by the oscillation of the massive object.

Metric

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

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

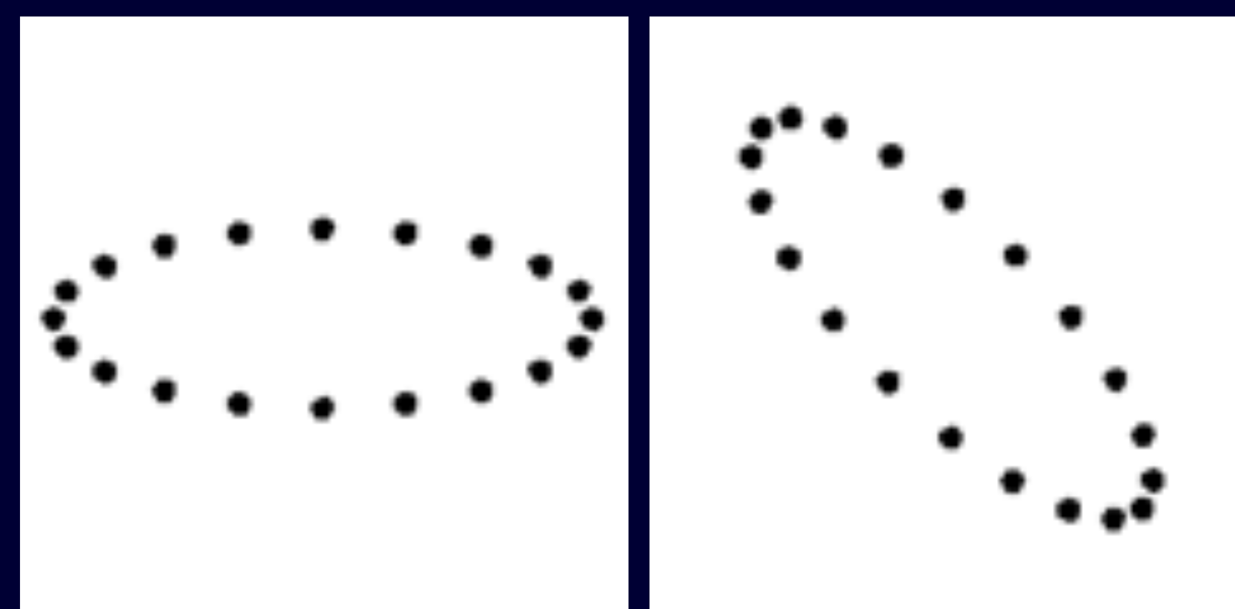
Metric

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

Perturbation

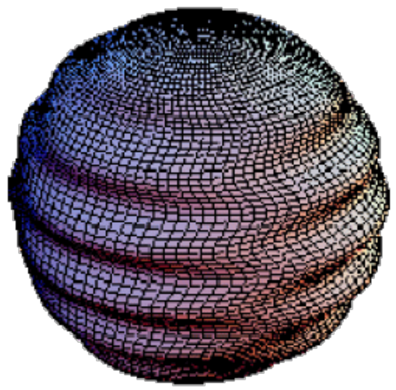
$$A_{ij} = \begin{bmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

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



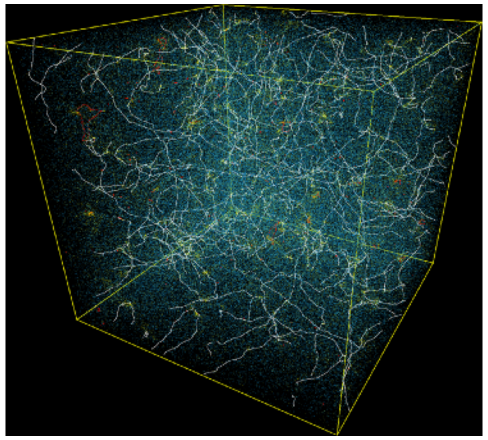
Stochastic background source

Primordial



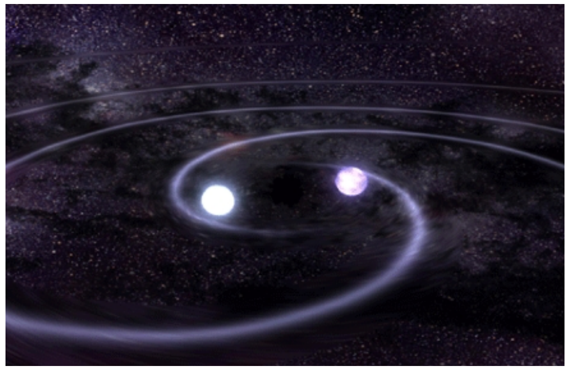
- Initial fluctuation with Inflation

Phase transition

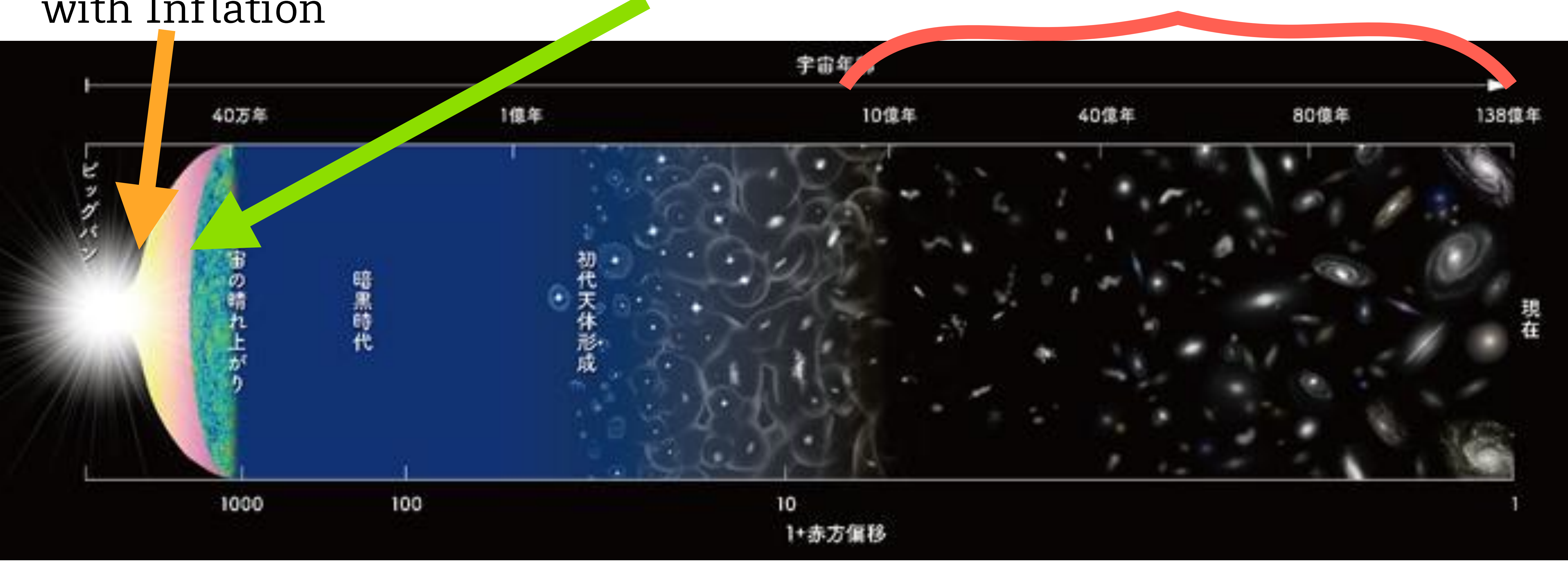


- Cosmic string

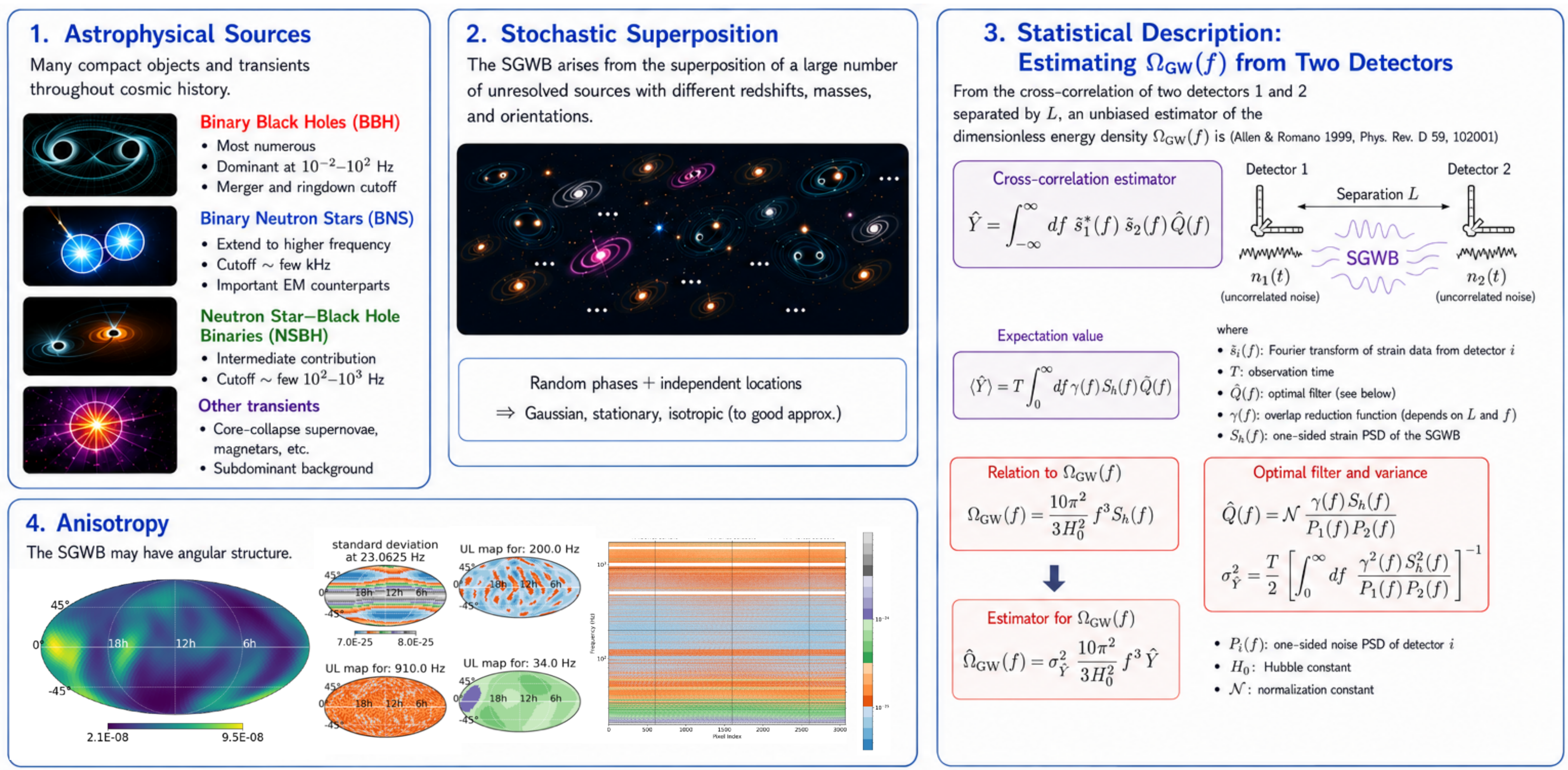
Astronomical



- BBH and BNS



Astronomical Stochastic background



R. Abbott et al. (LVK) Phys.Rev.D 105 (2022)

Cosmic string origin of SGWB

What are cosmic strings?

Topological line defects formed in spontaneous symmetry breaking in the early Universe. Characterized by the tension μ (energy per unit length).

Order of the tension μ

String width	➡	Energy density inside string	➡	String tension (energy per unit length)
$\delta \sim m^{-1}$ (m: mass scale)		$\sim \lambda v^4$ (λ: coupling)		$\mu \sim (\lambda v^4) \times (m^{-1})^2 \sim v^2$

Key parameter: $G\mu$ (dimensionless)

$$G\mu = 10^{-6}\left(\frac{v}{10^{16}\,\mathrm{GeV}}\right)^2$$

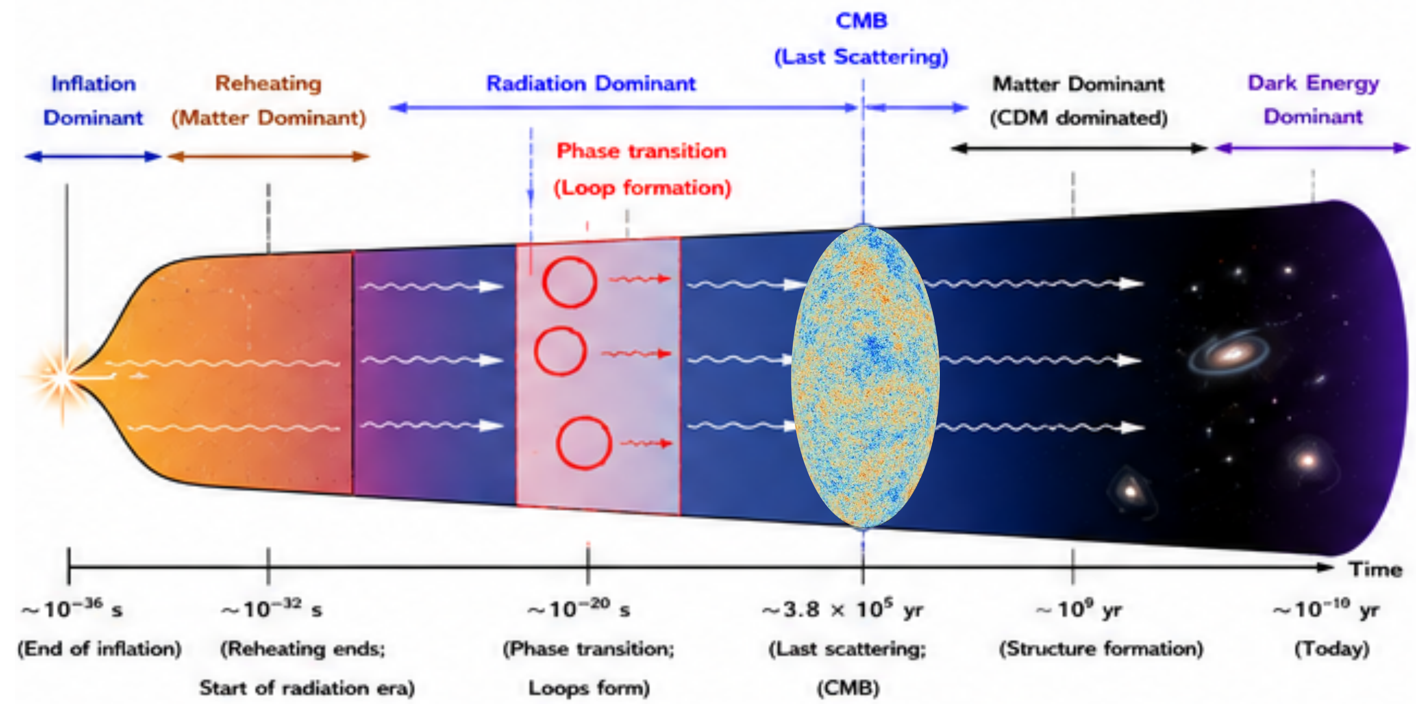
G : Newton's constant

v : symmetry breaking scale

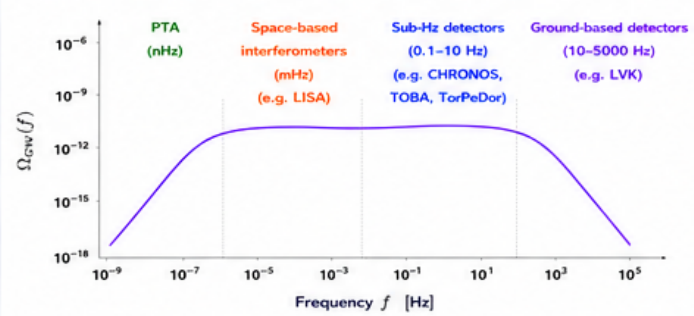
Measuring $G\mu$ directly probes the energy scale of symmetry breaking!

Cosmic strings exist only for a short period in the early Universe.

They form loops at a phase transition and then decay, emitting gravitational waves.



The SGWB from cosmic strings has a broad and characteristic spectrum.

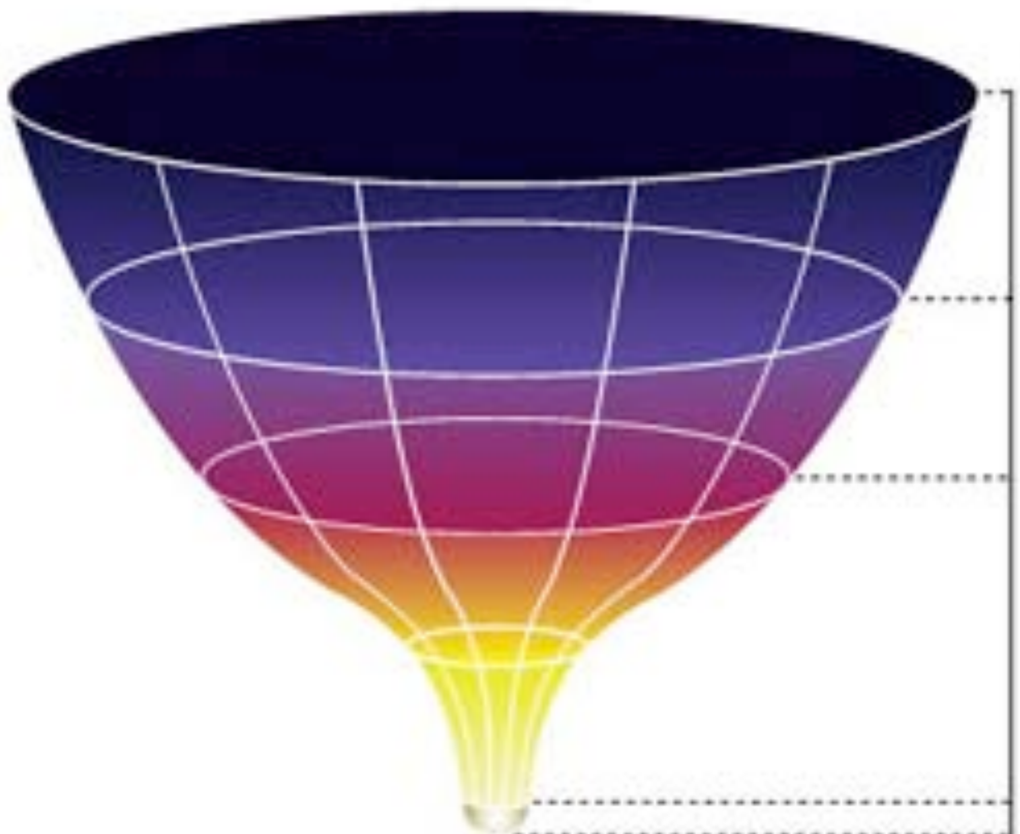


Spectral features
- Low frequency: large loops and cusps
- Mid frequency: loop oscillations and kinks
- High frequency: small loops and high harmonics
- Overall: broadband power-law-like spectrum (broken power law)

Parameter	Meaning / Role	Impact on observations
$G\mu$	String tension (strength of gravity)	Sets overall amplitude of SGWB: $\Omega_{GW}(f) \propto (G\mu)^2$ Main target of observations
α	Loop size parameter (correlation length)	Affects energy density $\rho_s \,/\, \rho_{tot} \sim \alpha G\mu$
Loop size distribution	Initial loop size and production efficiency	Affects spectral shape and peak frequency
Emission mechanisms (spectrum)	Loop oscillation modes, cusps, kinks	Determine spectral slope and features
Loop reconnection probability p	Reconnection probability of string intersections	Affects loop production rate (and thus amplitude)

Primordial Gravitational wave

Primordial GW come back to observable universe

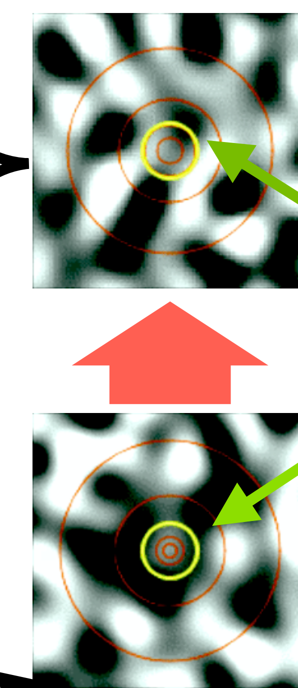


Now

Last Scattering Surface

Big Bang era

Inflation era



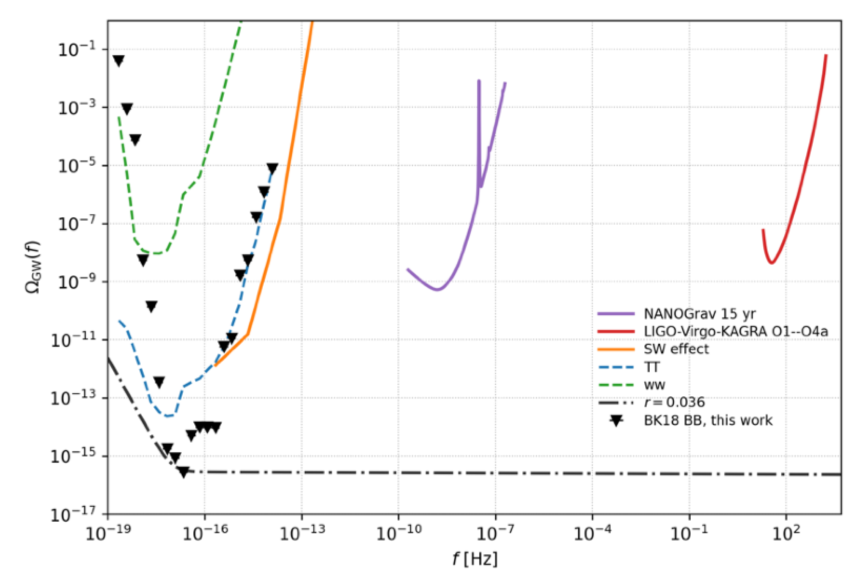
HORIZON

Frozen out

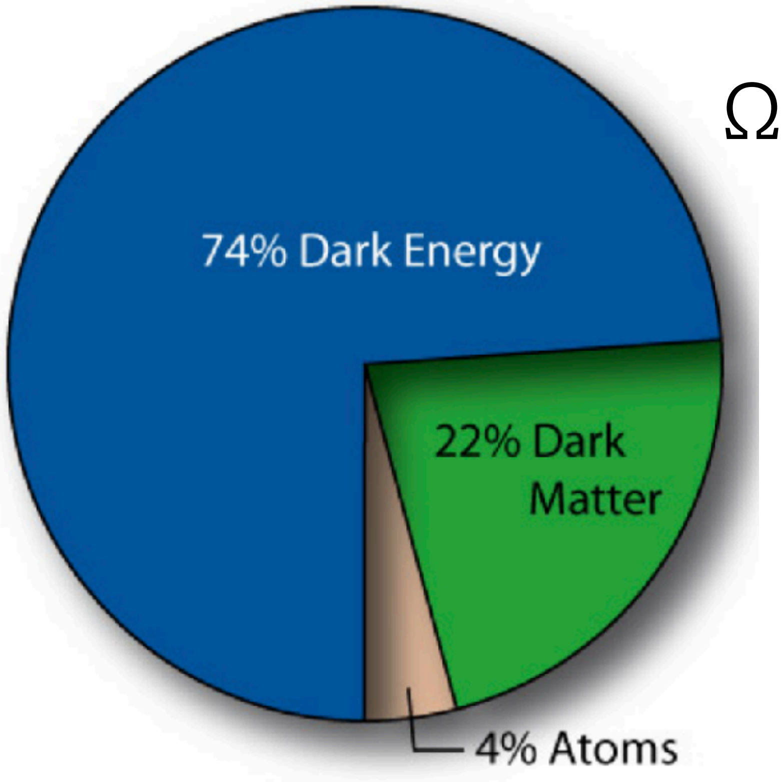
$$\Omega_{GW}(k,\tau_0) = \frac{\mathcal{P}_T(k)}{12H_0^2}k^2 \cdot \begin{cases} \frac{\tau_*^2}{\tau_0^2}\left[A(k)j_2(k\tau_0) + B(k)y_2(k\tau_0)\right]^2, & \text{if } k > k_*, \\ \left[\frac{3j_2(k\tau_0)}{k\tau_0}\right]^2, & \text{if } k < k_*, \end{cases}$$

Matter dominant $\propto f^0$

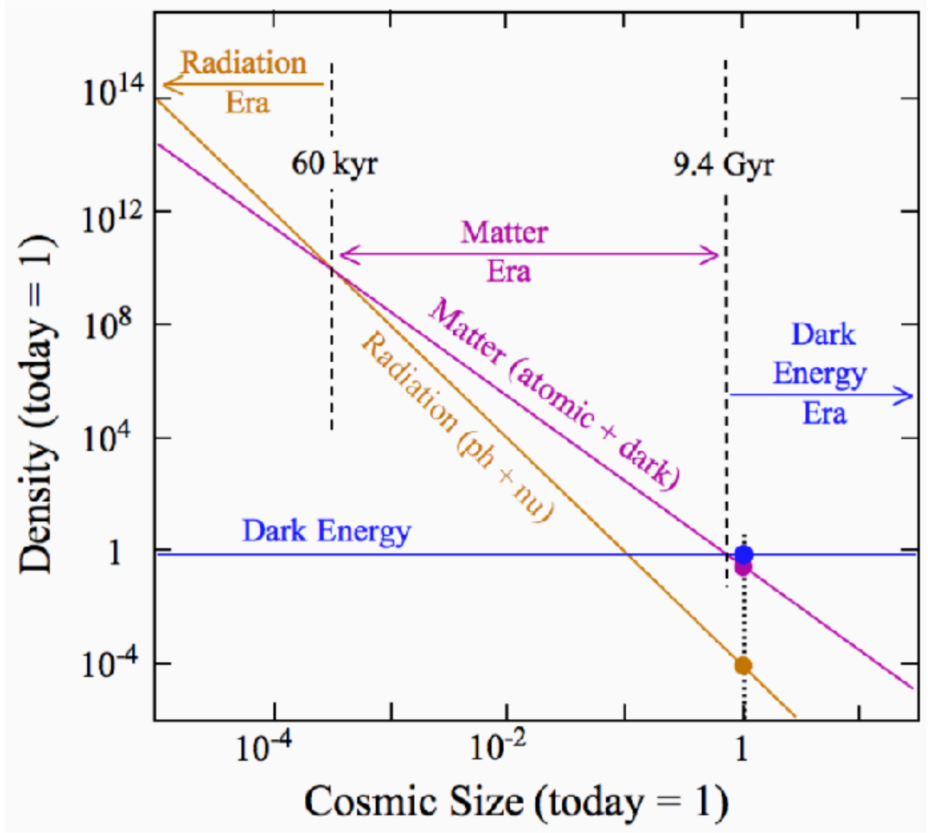
Radiation dominant $\propto f^{-2}$



Density parameter



$\Omega i = \rho_{\,i} / \rho_{\,cr}$

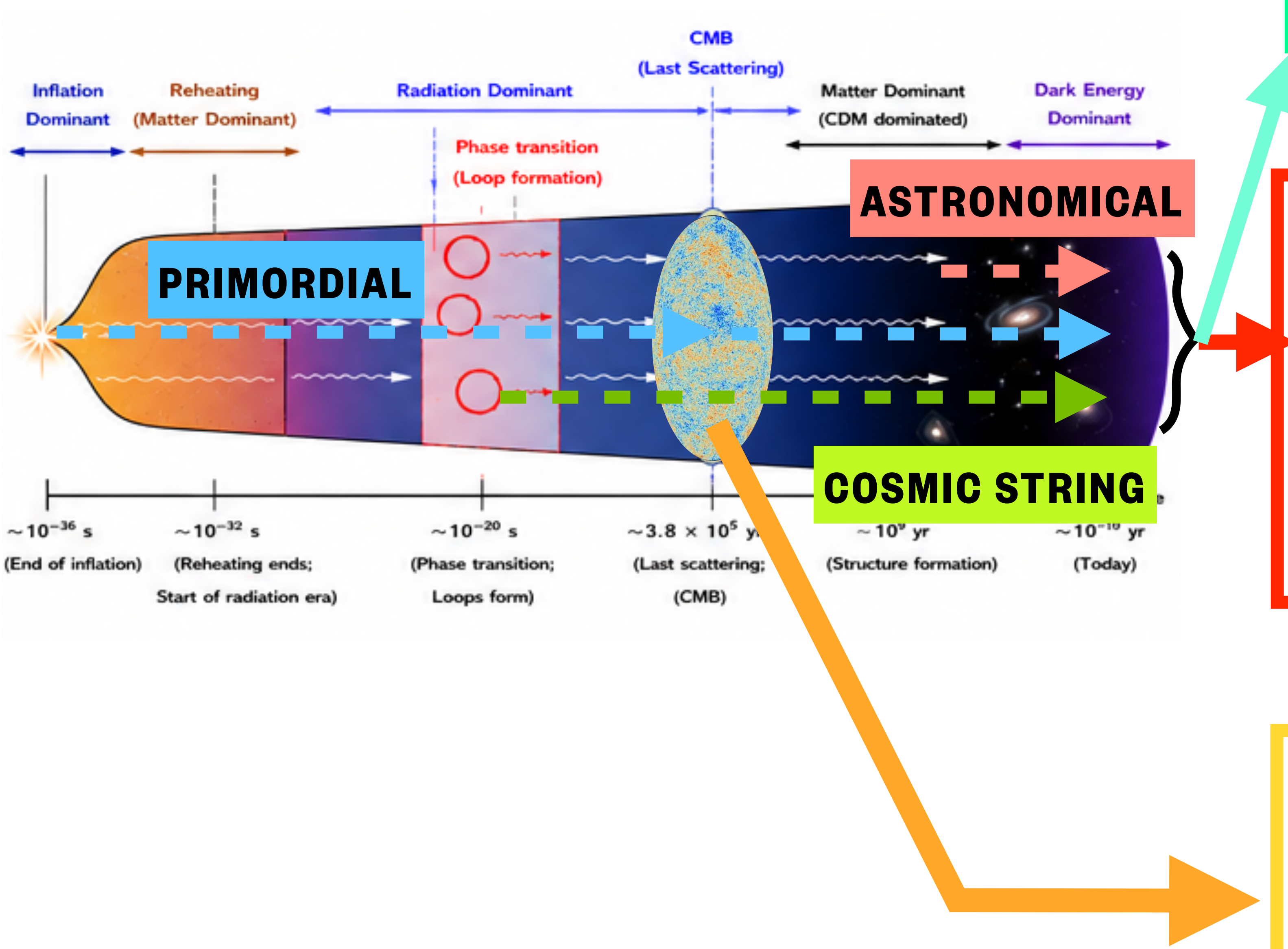


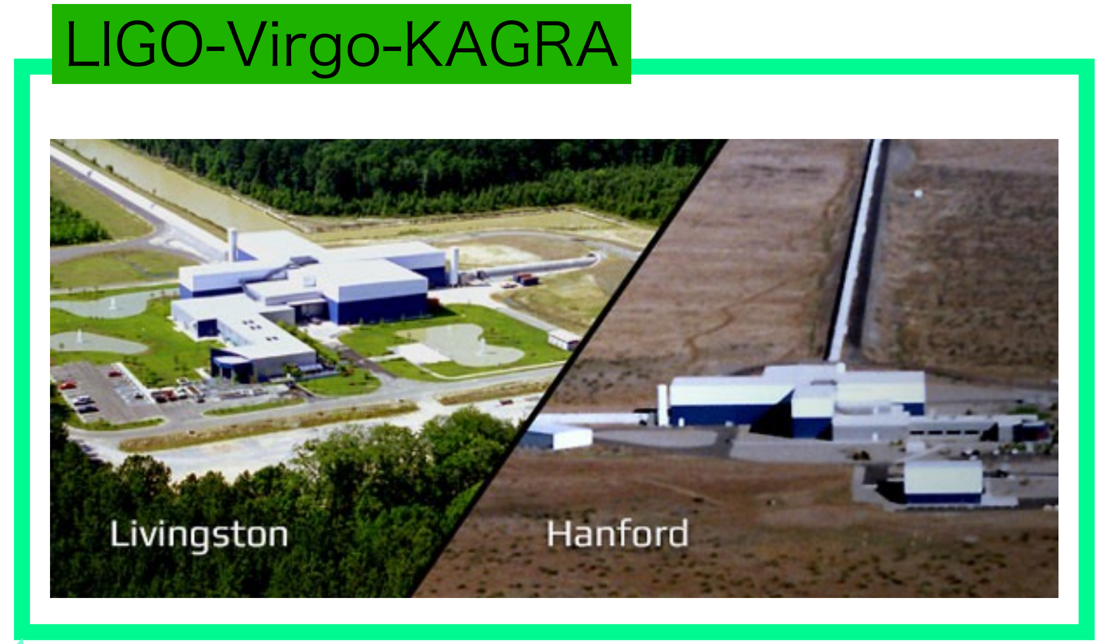
Friedmann equation: $H^2(t) = H_0^2\left[\Omega_{\gamma,0}a^{-4} + \Omega_{m,0}a^{-3} + \Omega_{\kappa}a^{-2} + \Omega_{\Lambda}\right]$

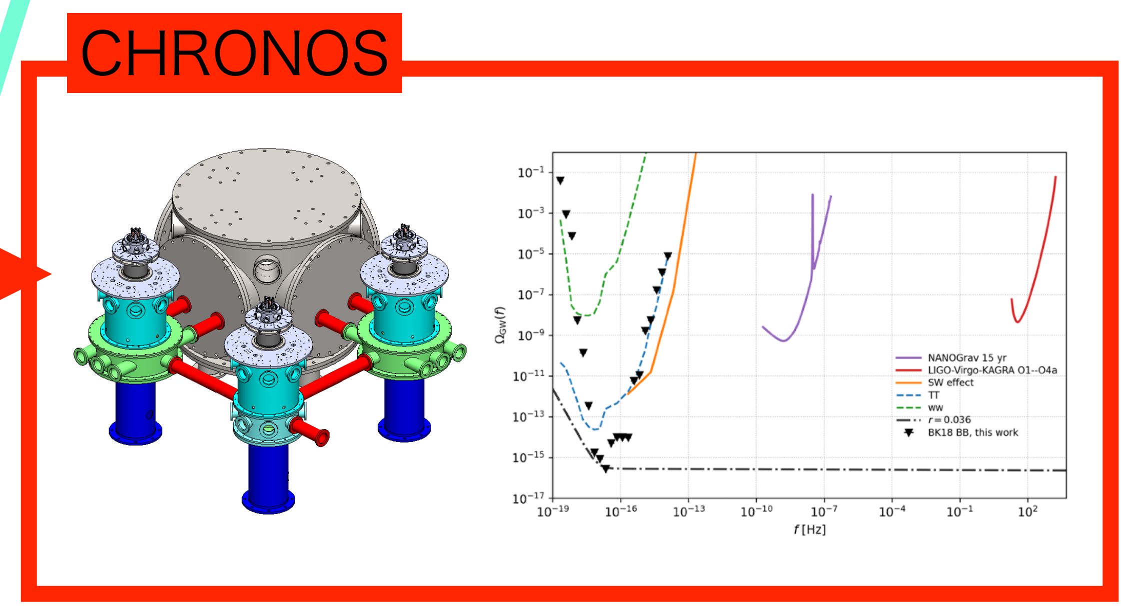
radiation matter curvature dark energy

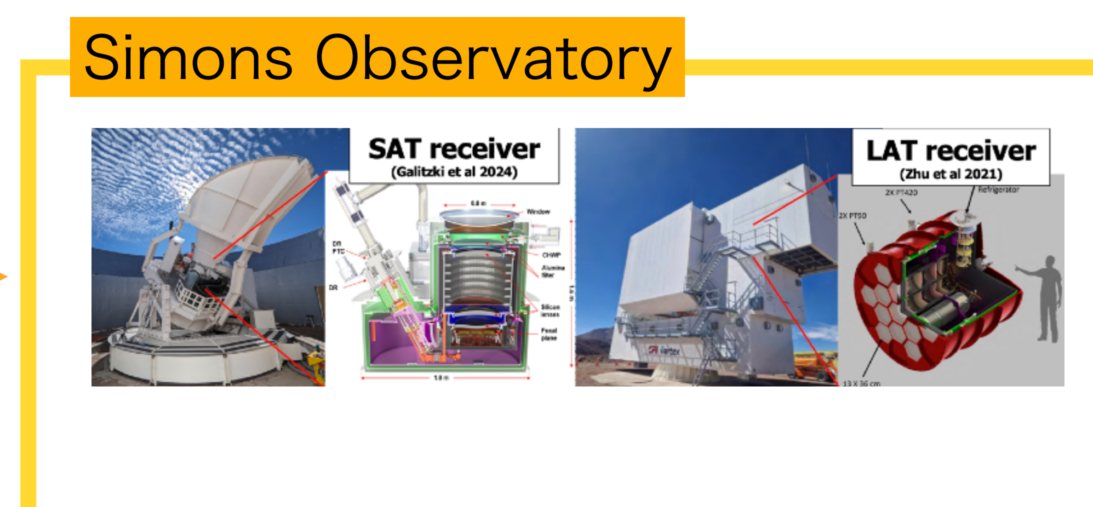
Fundamental questions: What's the energy density of GW, Ω_{GW}?

Experiment and GW source









LIGO

- The world largest GW detector in US.
- The most sensitive probe for SGWB.

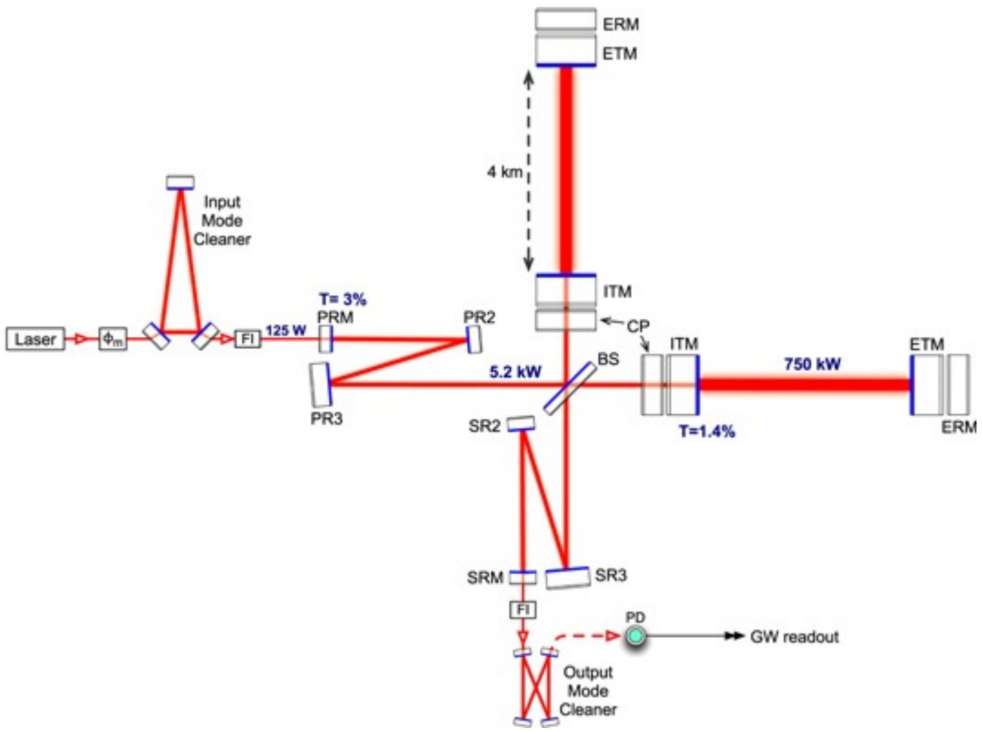
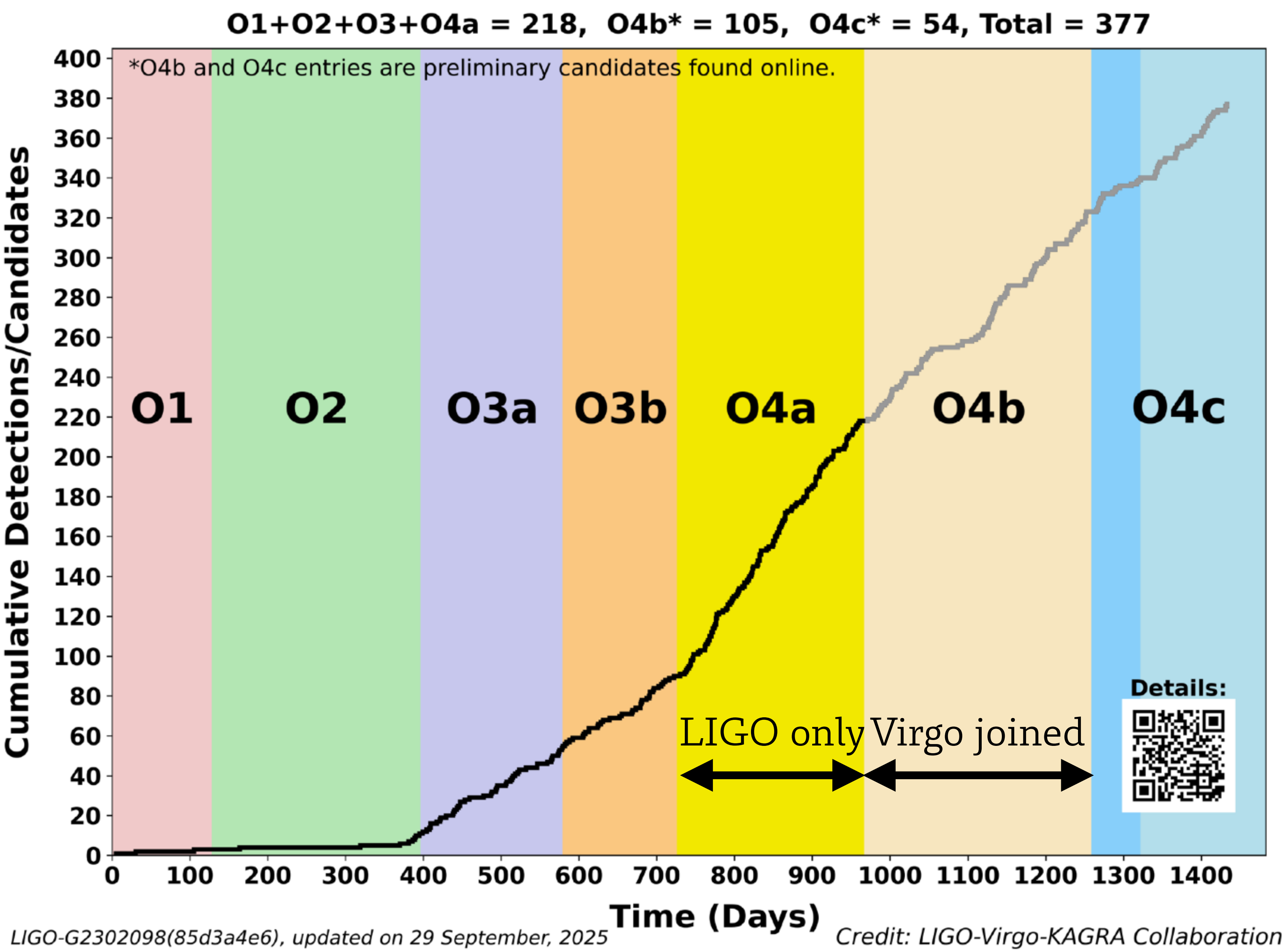


Table 1. Main parameters of the Advanced LIGO interferometers. PRC: power recycling cavity; SRC: signal recycling cavity.

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

Number of detections



The era of O(100) events!

Data release plan

2026

O4b->GWTC-5

2027

O4c->GWTC-6

Compact binary coalescence

Binary Neutron Star

Binary Blackhole

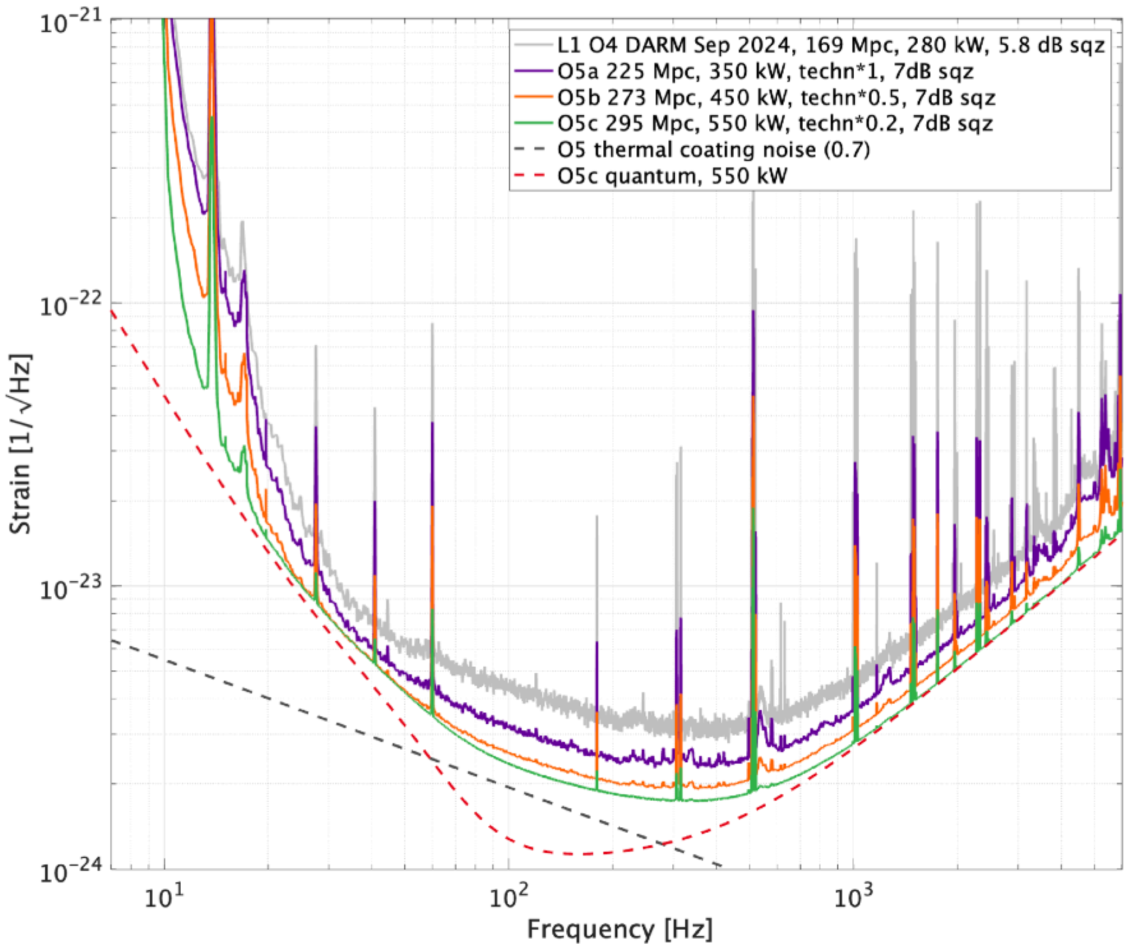
Neutron star- Black hole binary

Events

Total number of events ~ 377

Every 2.8 days we detect new events

Sensitivity

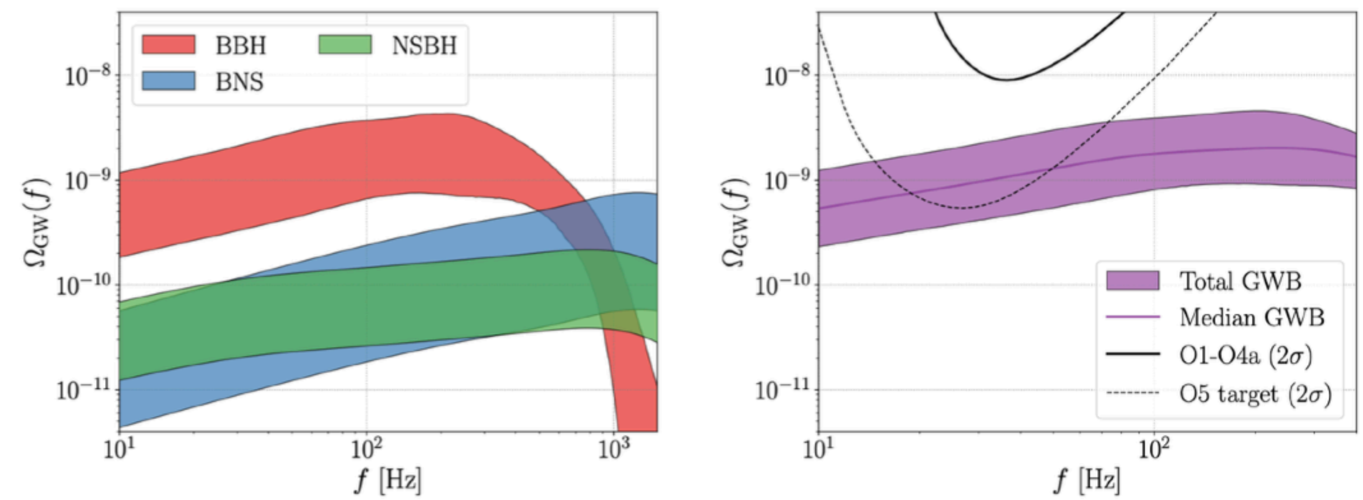


O5 epoch	BNS range	Arm Power	Tech. noise @100 Hz	Squeezing @1 kHz
O5a	225 Mpc	350 kW	$2 \times 10^{-24}/\sqrt{\text{Hz}}$	7 dB
O5b	273 Mpc	450 kW	$1 \times 10^{-24}/\sqrt{\text{Hz}}$	7 dB
O5c	295 Mpc	550 kW	$4 \times 10^{-25}/\sqrt{\text{Hz}}$	7 dB

Upper Limits on the Isotropic Gravitational-Wave Background from the first part of LIGO, Virgo, and KAGRA's fourth Observing Run

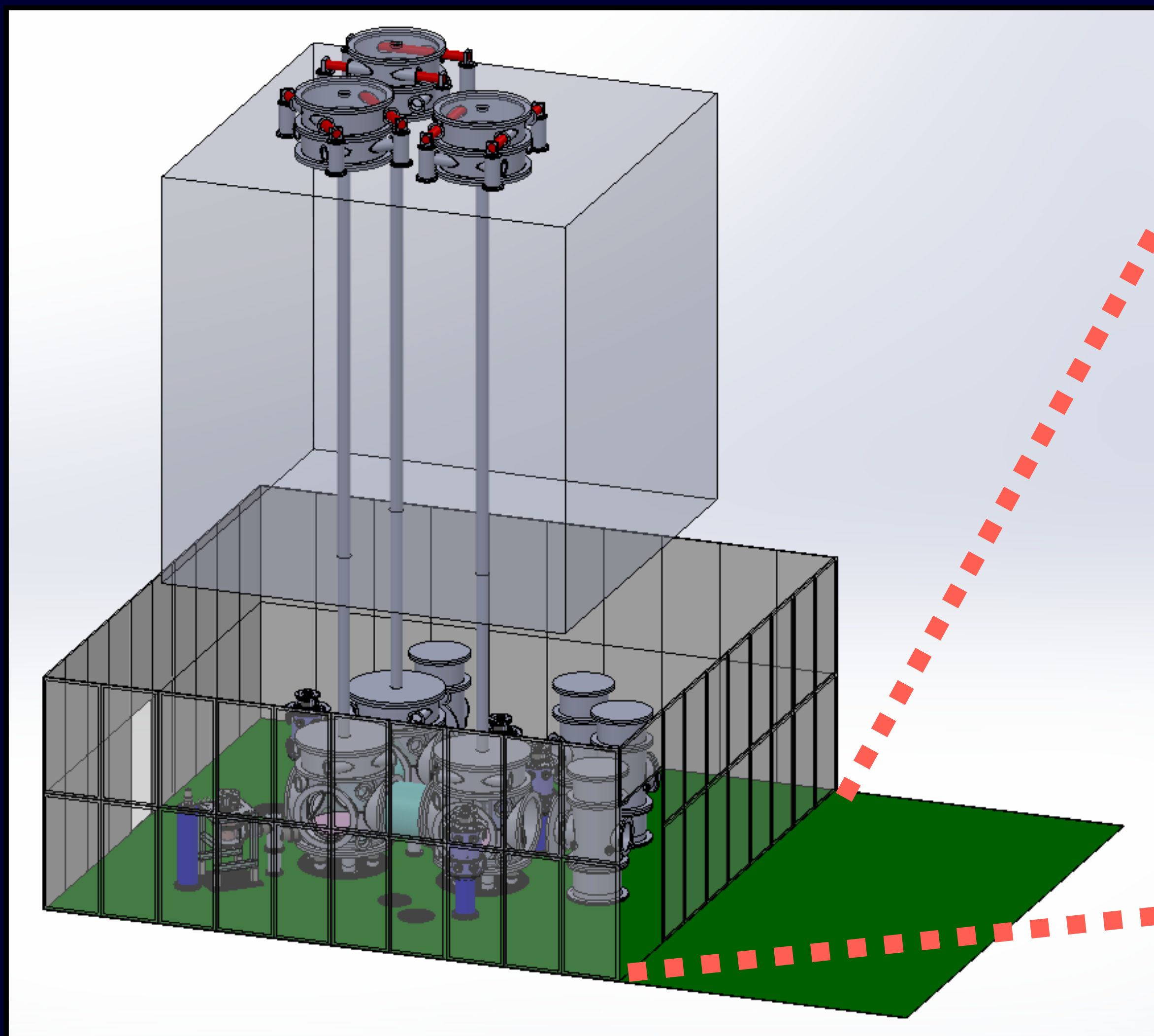
Phys. Rev. D - **Accepted**1 December, 2025

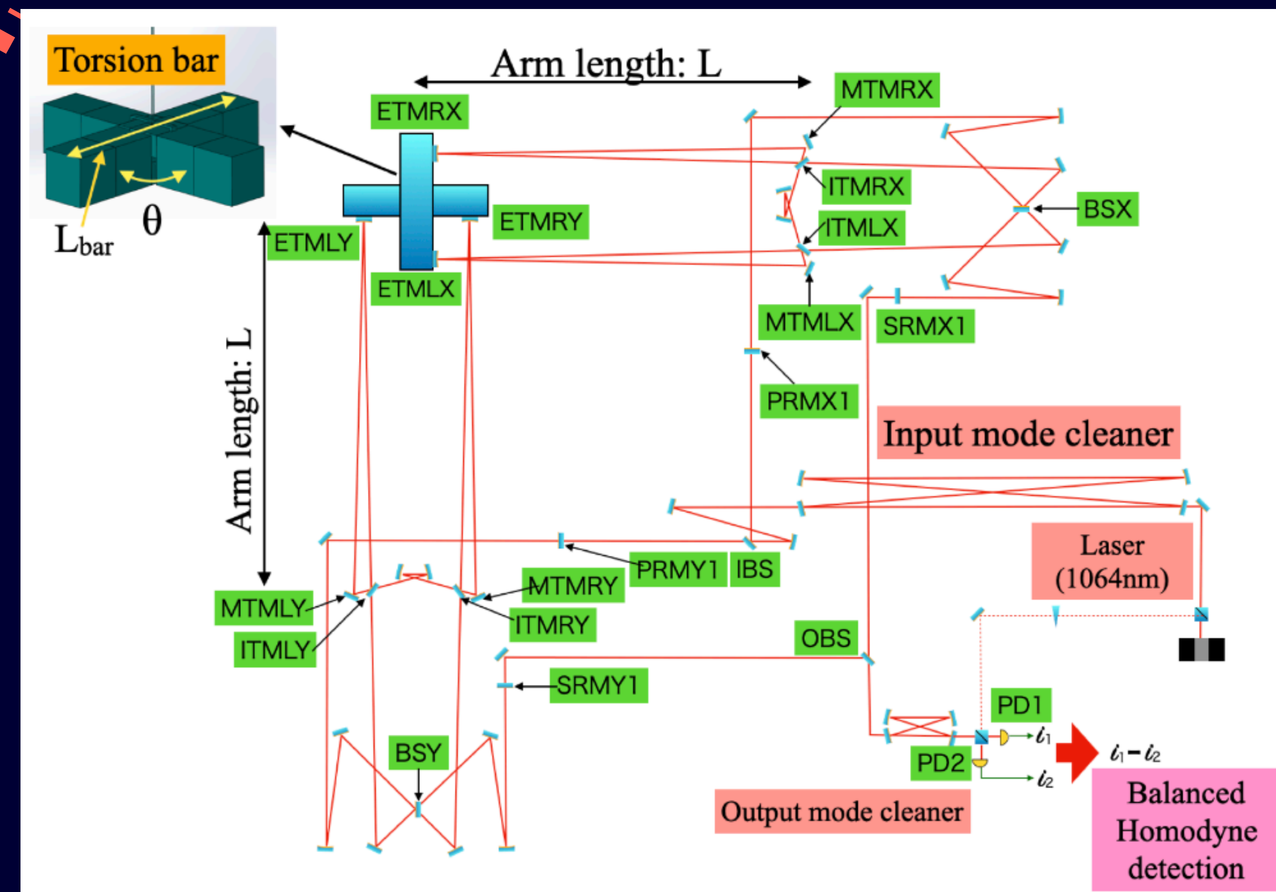
DOI: https://doi.org/10.1103/wq57-sjt2



- The expected sensitivity of O5 will be reach the signal of the astronomical stochastic background.

CHRONOS Overview





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

CHRONOS Overview

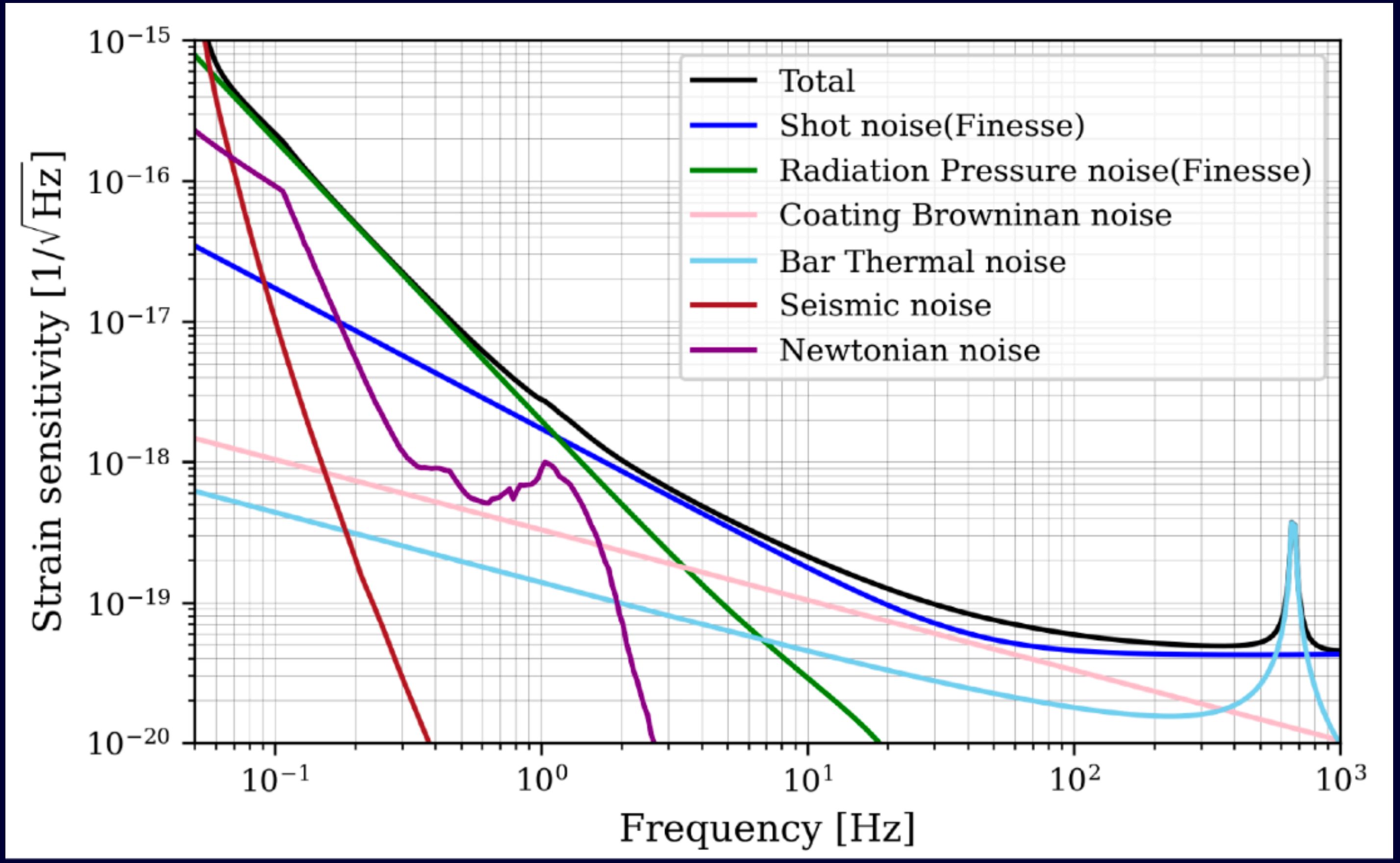
- Mission: Search for Intermediate black hole on Sub-Hz range
- Method: Interferometorical Speed meter
- Unique point: 10m x 10m Observatory
- Location: Underground site in Taiwan

Key technologies

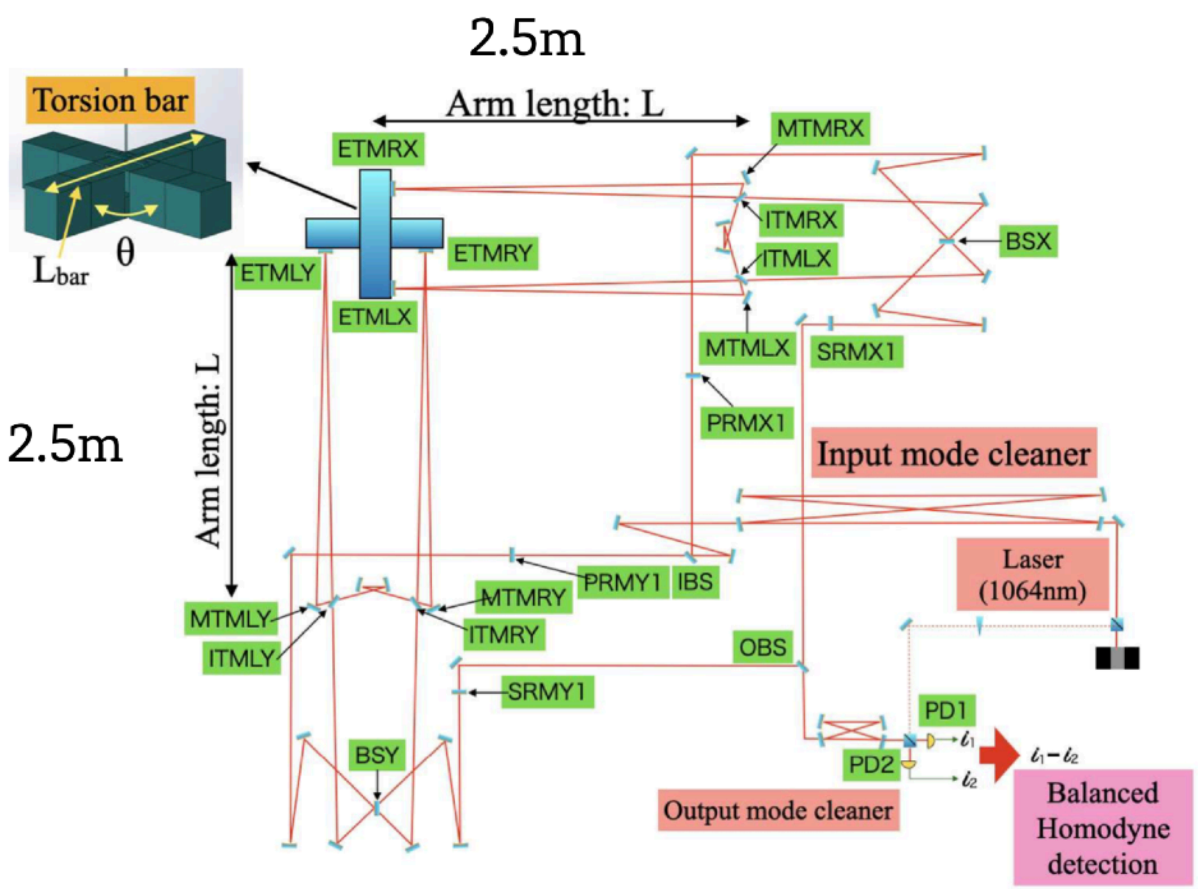
SPEED METER

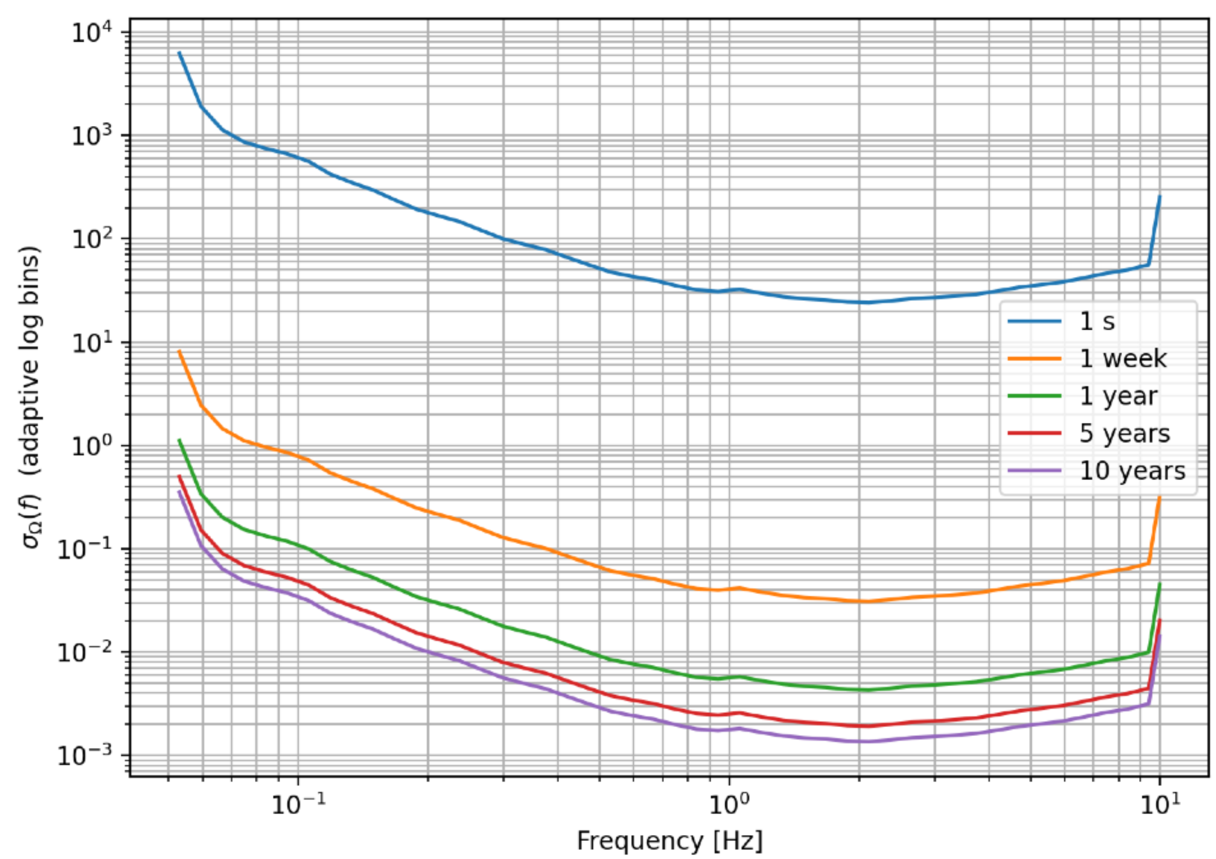
TORSION BAR

CRYOGENIC



Experimental setup and sensitivity





CHRONOS detector is sensitive to the window between LISA and LIGO observation band.

Publications

Main project 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

Optical feasibility 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,[6,2] and Ta-Chun Yu[1,2]

Y.Inoue and D.Tanabe et. al. arXiv: 2510.24780

Intensity noise paper

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]

D.Tanabe and Y.Inoue et. al. C.Q.G accepted

Calibration paper

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 Acceleration Research Organization (KEK), Tsukuba, Japan*
(Dated: February 24, 2026)

Y.Inoue et. al. arXiv: 2602.19436

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

Science paper

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

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

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

White paper

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

In preparation (Release on May)

Elastic deformation paper (Tanabe et al.)
Stochastic background paper (Inoue et al.)
Photon pressure actuator paper (Tanabe et al.)
Gravity gradient paper (Onglao et al.)

Collaboration is very welcome!!

CHRONOS Science stage

- Phase 1: R&D stage(2020-2025)
- Phase 2: Integration test (2026-2033)
- Phase 3: CHRONOS in Underground lab (2030-2035)

SCIENCE STAGE IN PHASE2-3

CHRONOS's target observation year = 2035

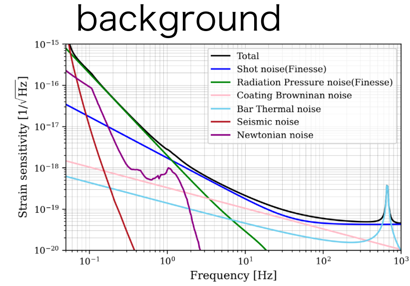
Quantum science

Quantum science for uncertainty principle

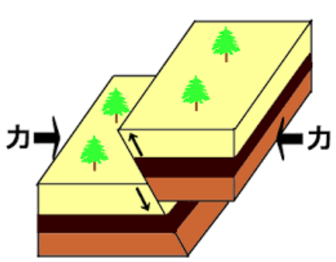
$$\epsilon(A)\eta(B) + \sigma(A_{in})\eta(B) + \epsilon(A)\sigma(B_{in}) \geq \frac{1}{2}|\langle\psi|[\hat{A}_{in}, \hat{B}_{in}]|\psi\rangle|$$

Gravity gradient science

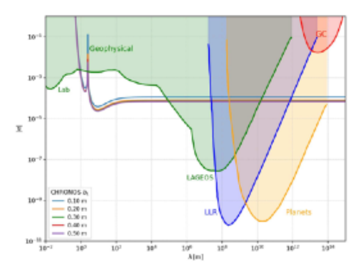
Newtonian gravity background



Earthquake

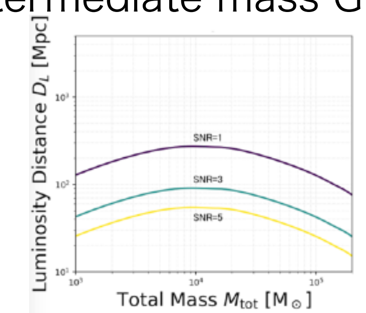


Yukawa Gravity

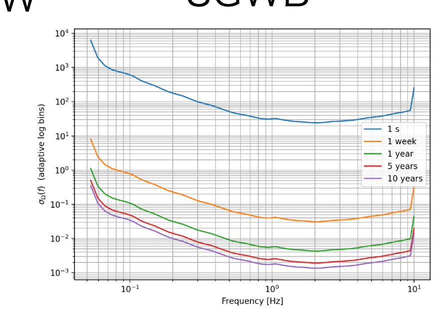


Gravitational wave science

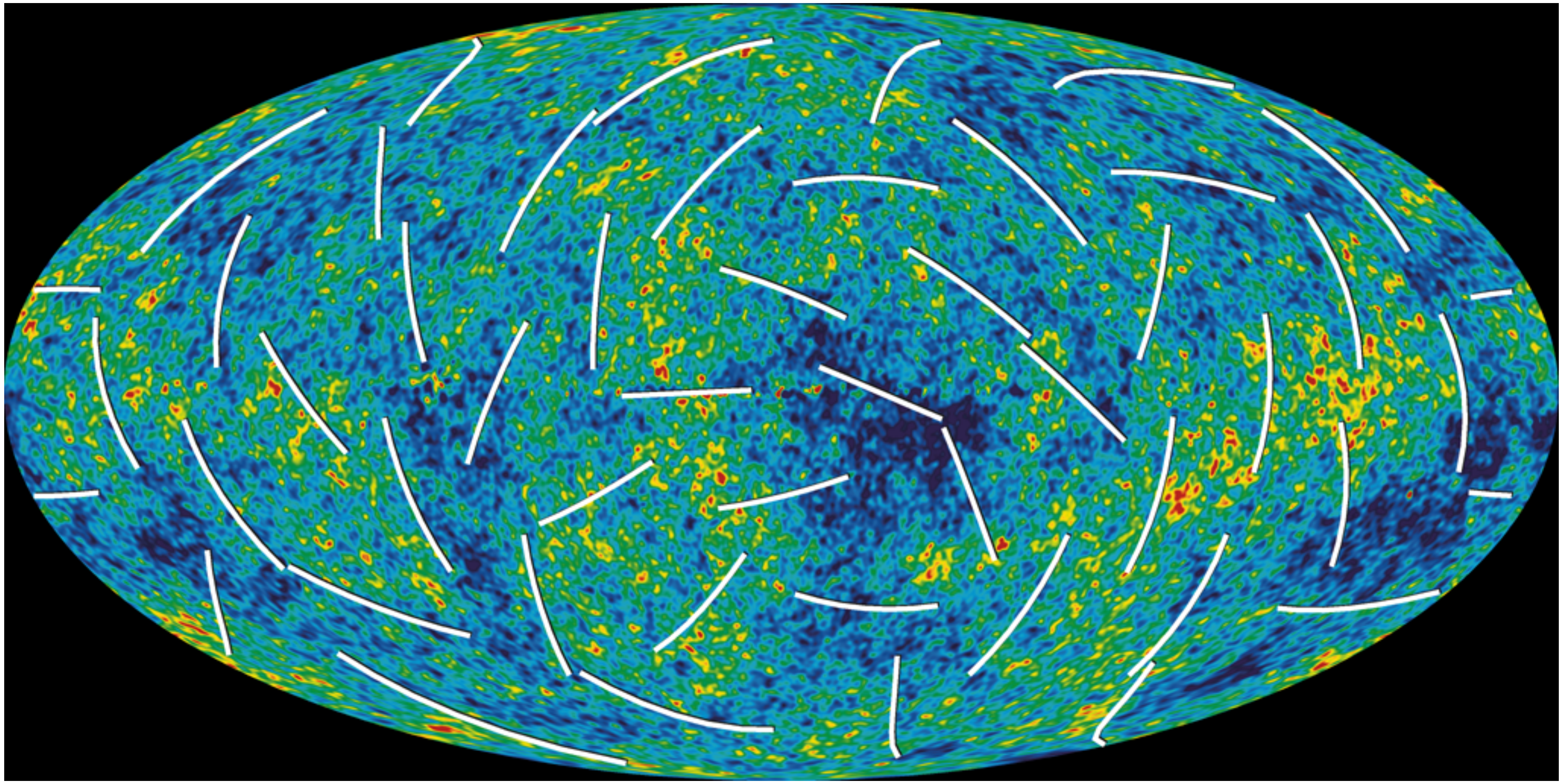
Intermediate mass GW



SGWB

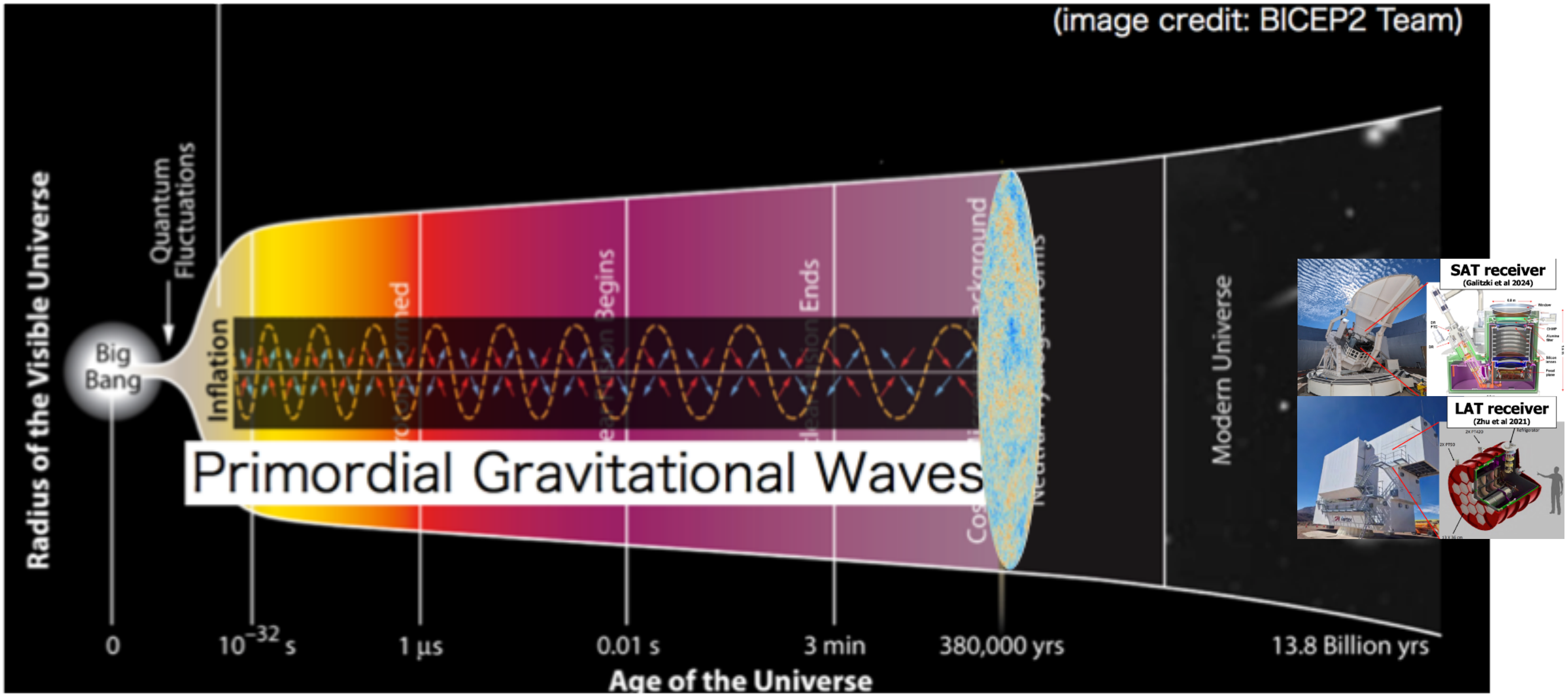


Cosmic microwave background



- Oldest observable photons from the early universe at the age of 380,000 years.
- Polarization pattern

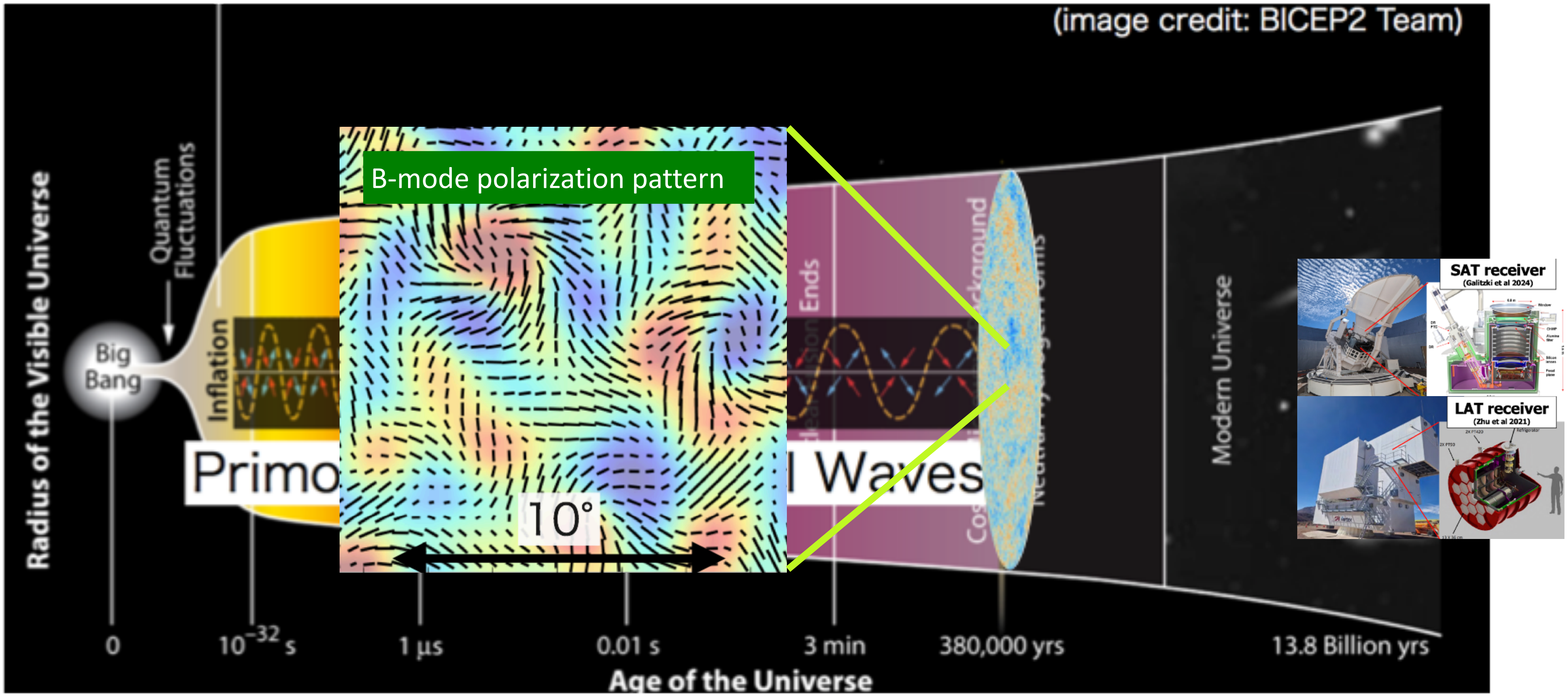
CMB inflationary B-mode polarization



predicted to be imprinted as degree-scale

rot-like polarization pattern (B-mode)

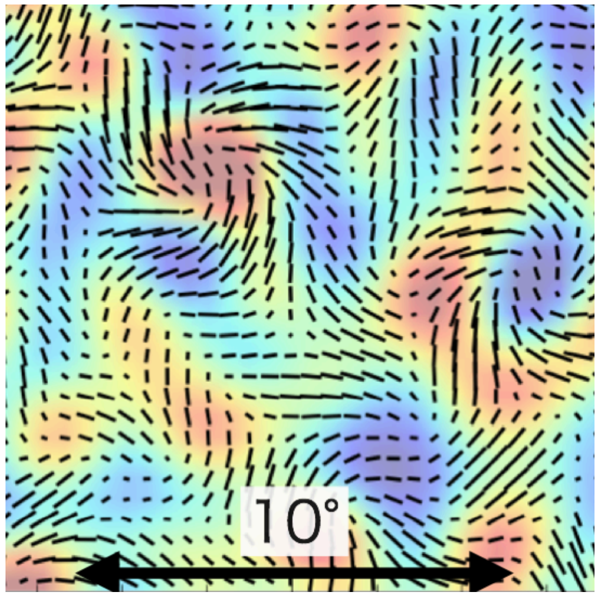
CMB inflationary B-mode polarization

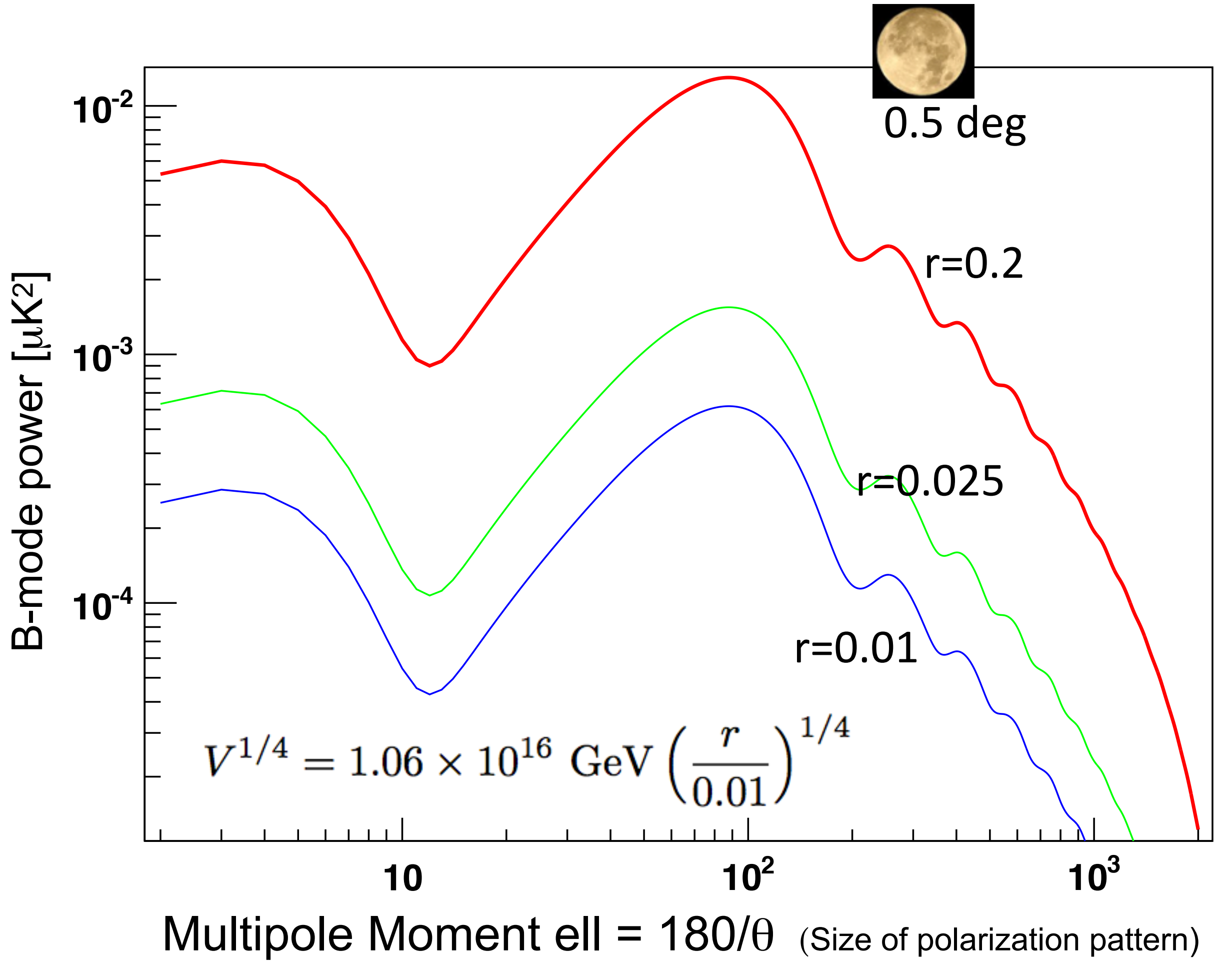


predicted to be imprinted as degree-scale

rot-like polarization pattern (B-mode)

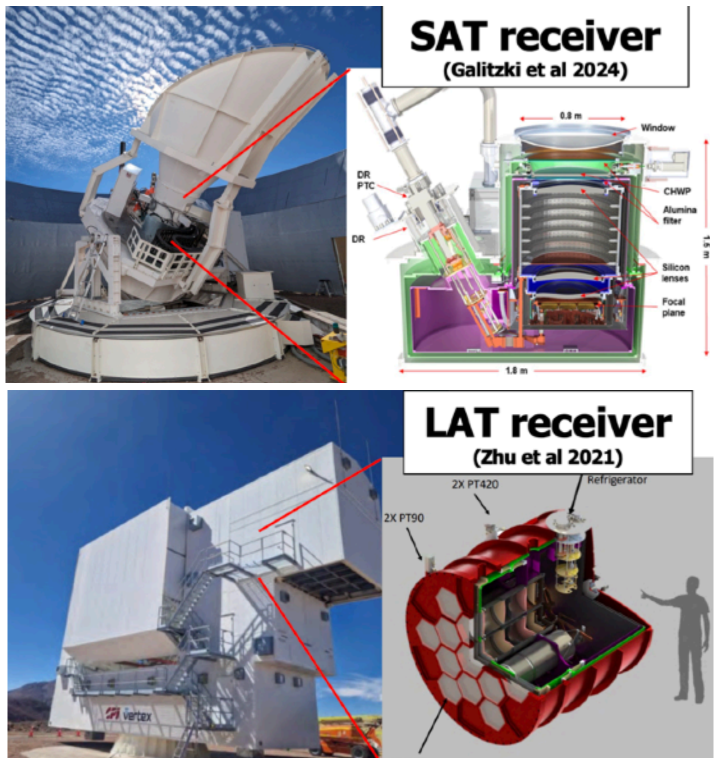
CMB inflationary B-mode

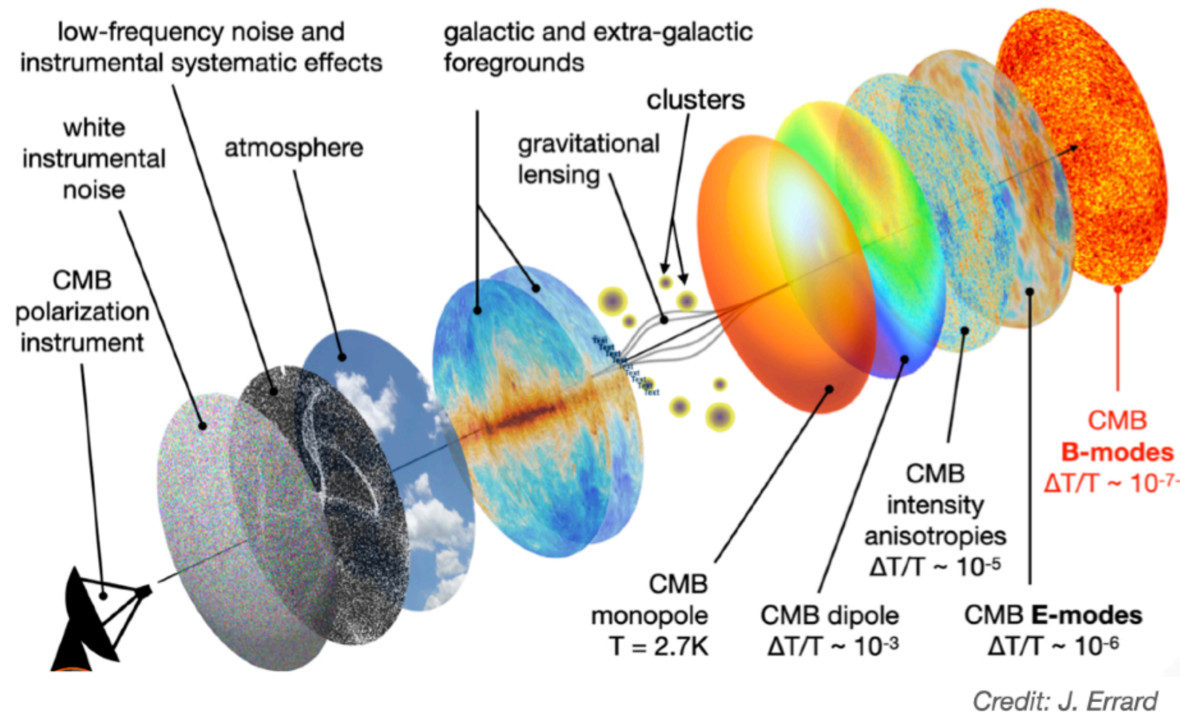




CMB B-mode can be a probe of physics of ultra high energy scale (~GUT scale)!

Science of Simons Observatory

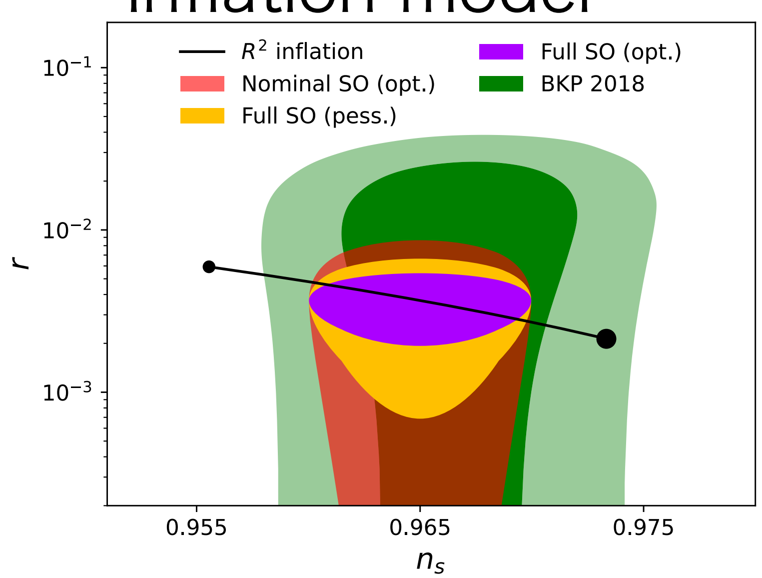




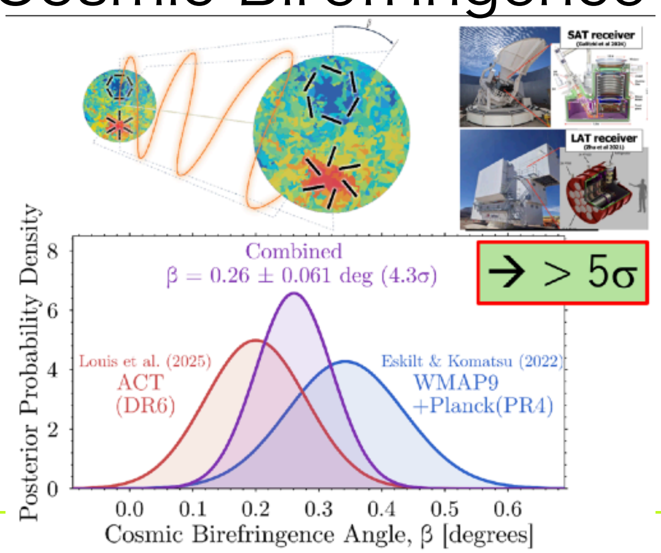
B-mode analysis

Test of standard model with CMB, GW, LSS data

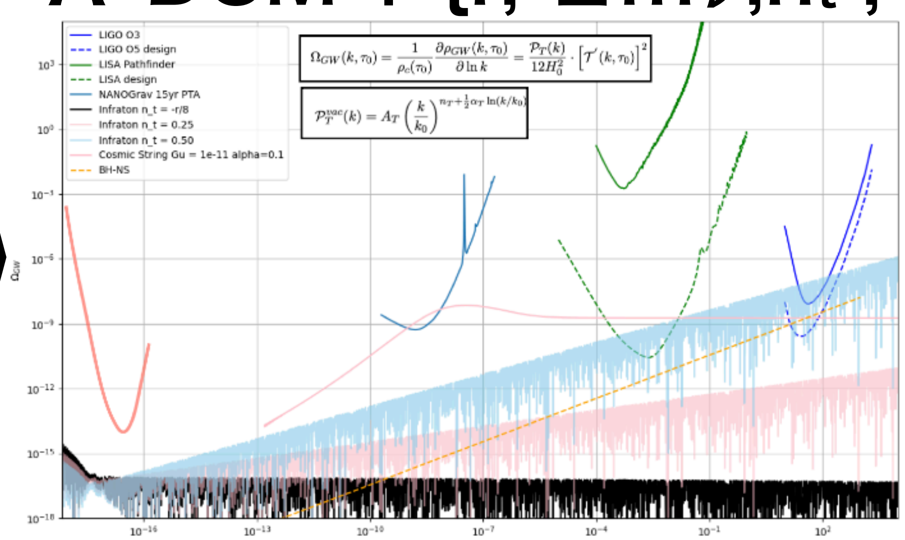
Inflation model



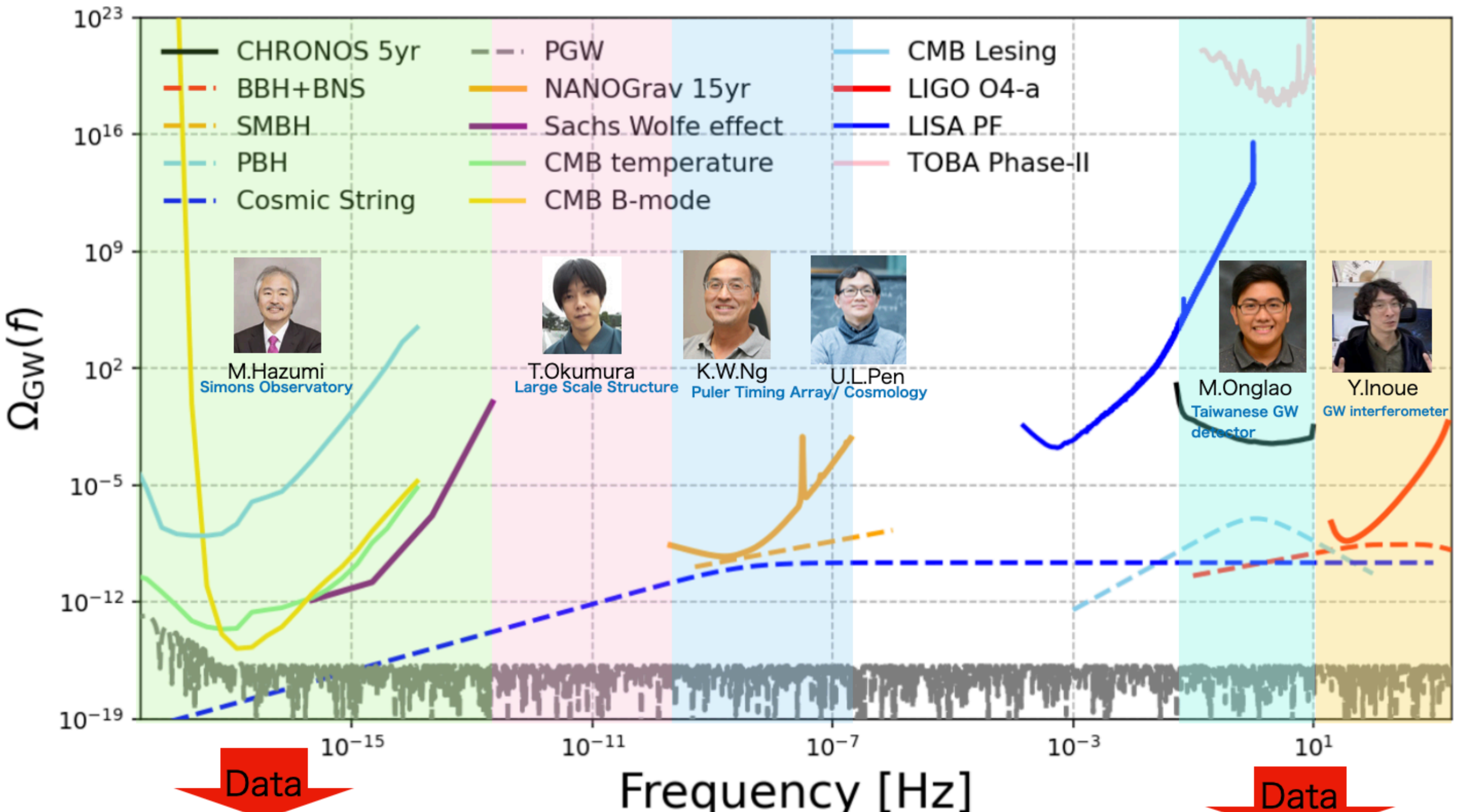
Cosmic Birefringence



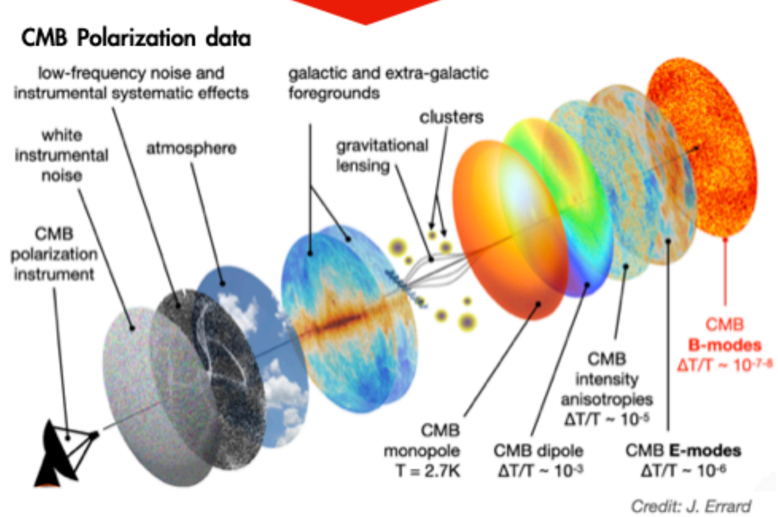
Λ-DCM + {r, Σm_ν, n_t ,…}



Team Taiwan

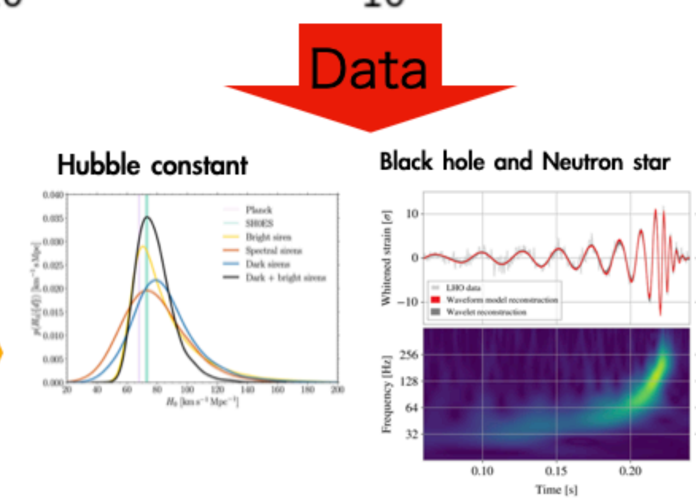


10^{23}
10^{16}
10^{9}
10^{2}
10^{-5}
10^{-12}
10^{-19}
$\Omega_{GW}(f)$
CHRONOS 5yr
BBH+BNS
SMBH
PBH
Cosmic String
PGW
NANOGrav 15yr
Sachs Wolfe effect
CMB temperature
CMB B-mode
CMB Lesing
LIGO O4-a
LISA PF
TOBA Phase-II
M.Hazumi
Simons Observatory
T.Okumura
Large Scale Structure
K.W.Ng
U.L.Pen
Puler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



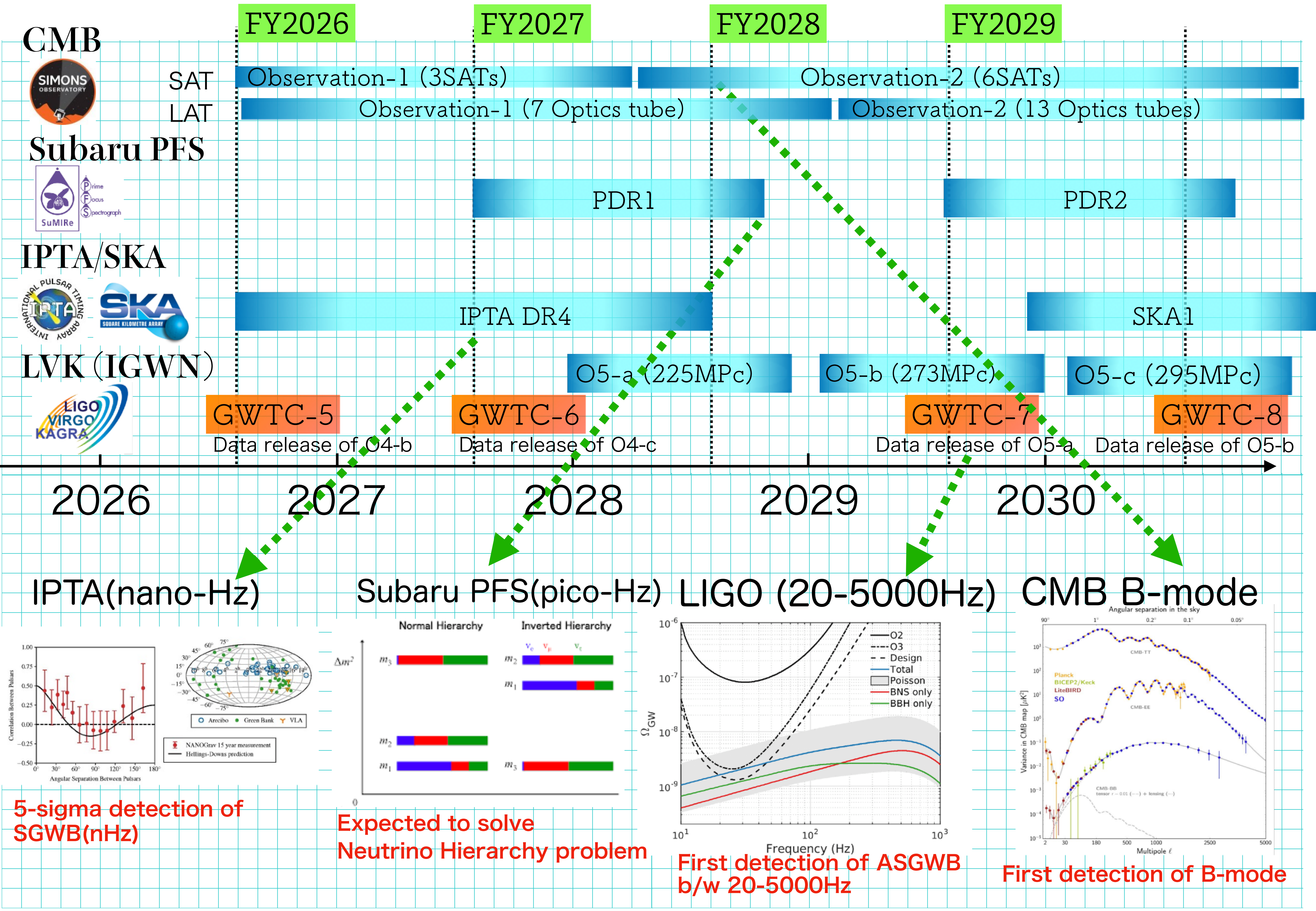
CMB Polarization data
low-frequency noise and instrumental systematic effects
galactic and extra-galactic foregrounds
clusters
white instrumental noise
atmosphere
gravitational lensing
CMB polarization instrument
CMB B-modes ΔT/T ~ 10-7-8
CMB intensity anisotropies ΔT/T ~ 10-5
CMB monopole T = 2.7K
CMB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



Hubble constant
Black hole and Neutron star

The golden age of Observational Cosmology -Expected high impact sciences-



Summary

- National Central University promotes multi-band SGWB observations using CMB experiments, CHRONOS, and LIGO Gravitational wave detector.
- These experiments probe different GW frequency bands and different epochs of the Universe.
- CHRONOS fills the frequency gap between space observations and ground-based interferometers.
- Combined observations enable broadband studies of $\Omega_{GW}(f)$

from primordial to astrophysical origins.

- Multi-band GW cosmology provides a new probe of inflation, cosmic history, and fundamental physics.