観測天文学特別講義I @ 理1-1043

October 20, 2025

Observational Astronomy Advanced Course I

レーザー干渉計型重力波検出器
Laser interferometric gravitational wave detectors
1. Introduction

Yuta Michimura

RESCEU, University of Tokyo

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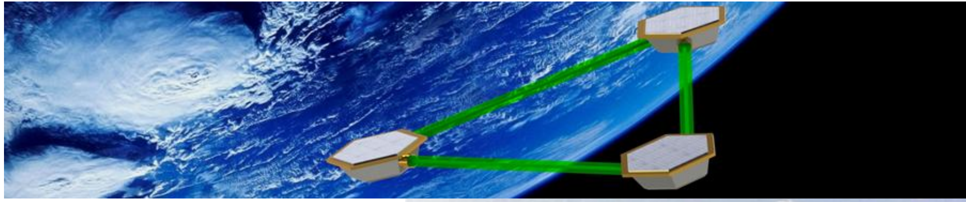
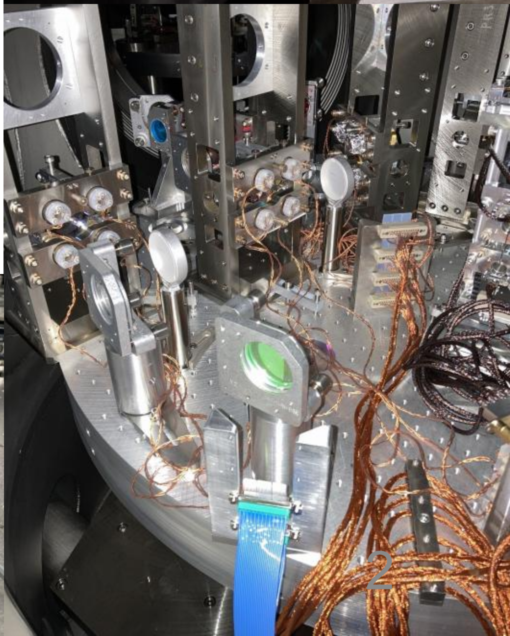
SLIDES

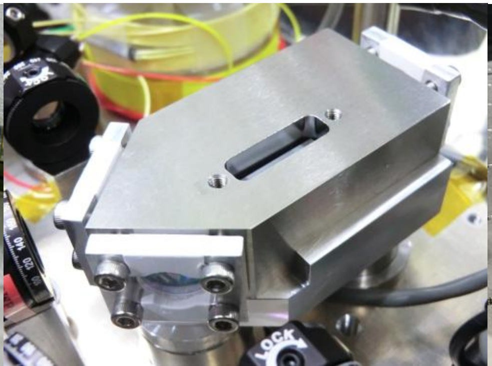


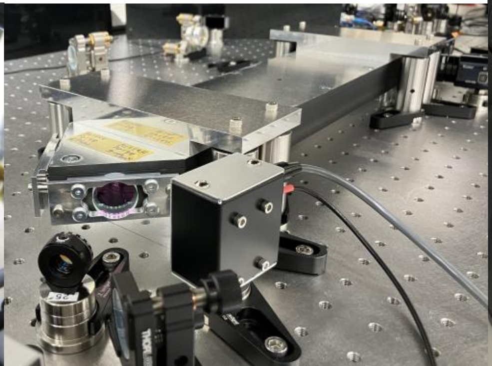
About Me

- Yuta Michimura 道村 唯太
- Born in 1987
- 博士(理学) in 2015
  Kimio Tsubono & Masaki Ando
- 2014-2022 Assistant Professor
  Department of Physics,
  The University of Tokyo
- 2022-2024 Research Scientist
  LIGO Laboratory,
  California Institute of Technology
- 2024- Associate Professor
  Research Center for the Early Universe,
  The University of Tokyo

Interested in
- Gravitational waves
- Dark matter
- Tests of gravity
- Quantum gravity







RESCEU (ビッグバンセンター)

- Founding director: Katsuhiko Sato
- 5 groups from Department of Physics and Department of Astronomy
- 理学部4号館 6階

S. Mukohyama(New)
Gravity theories

J. Yokoyama(Physics)
Cosmology
→Kavli IPMU director

K. Cannon(Physics)
GW data analysis

K. Hotokezaka(Physics)
Compact binaries etc.

T. Shigeyama(Astronomy)
Supernovae etc.
Director

Y. Michimura(Physics)
Experimental gravity

Objectives of This Lecture Series

- レーザー干渉計を用いた重力波検出の原理や感度を上げる方法、重力波観測の現状と将来計画について理解を深めることを目標とする。また、重力波観測技術の応用例についても紹介する。
- The goal of this course is to deepen the understanding of the principles of gravitational wave detection using laser interferometers, methods to improve sensitivity, the current status of gravitational wave observations, and future plans. Additionally, applications of gravitational wave observation technology will be introduced.

Topics Covered

- Current status of gravitational wave observations
- Laser interferometers and optical cavities
- Fundamentals of spectral analysis
- Seismic noise and thermal noise
- Quantum noise
- Applications of gravitational wave techniques to other fields
- Next-generation gravitational wave telescopes and space-based gravitational wave telescopes

- *Open to any suggestions!*

Further Reading

- Eric D. Black, Ryan N. Gutenkunst, *An introduction to signal extraction in interferometric gravitational wave detectors*, Am. J. Phys. 71, 365 (2003)
- Peter R. Saulson, *Fundamentals of Interferometric Gravitational Wave Detectors* (World Scientific, 1994)
- 中村卓史, 三尾典克, 大橋正健 編著『重力波をとらえる』(京都大学学術出版会, 1998)
- 日野幹雄『スペクトル解析』(朝倉書店, 2010)
- 片山徹『フィードバック制御の基礎』(朝倉書店, 2002)
- 東京大学 物理学実験II ブラウン運動 テキスト

Logistics

- In-class small assignment given at the beginning of each lecture
- ~10 min at the end of each lecture will be allocated for answering and answer sheets will be collected
- Schedule:
  Oct 20 (Mon) 2限 10:25-12:10
  Oct 24 (Fri) 3限 13:00-14:45
  Oct 31 (Fri) 3限 13:00-14:45
  Nov 17 (Mon) 2限 10:25-12:10
  Nov 25 (Tue) 2限 10:25-12:10 (Monday classes)
  Nov 28 (Fri) 3限 13:00-14:45
  Dec 5 (Fri) 3限 13:00-14:45
- Slides can be downloaded from the link below:
  https://yutamich.gitlab.io/lectures.html#lectures

Assignment for Oct 20

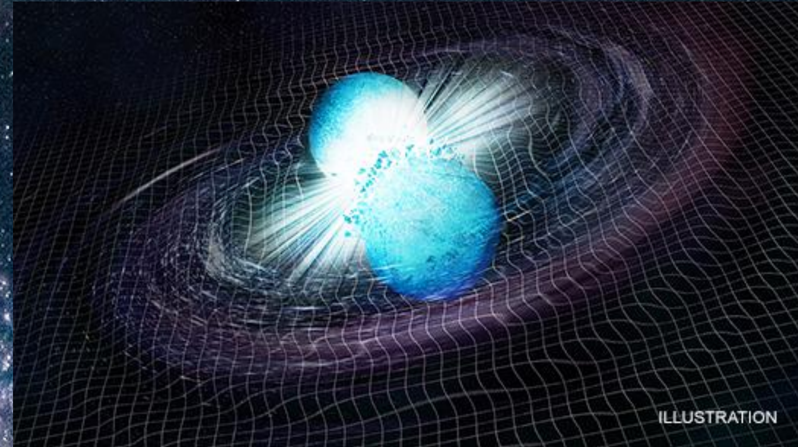
- What would you like to hear or learn about in this lecture series?

- You may also answer from the Google Form below https://forms.gle/6AwJ48XcpWQXqMon9

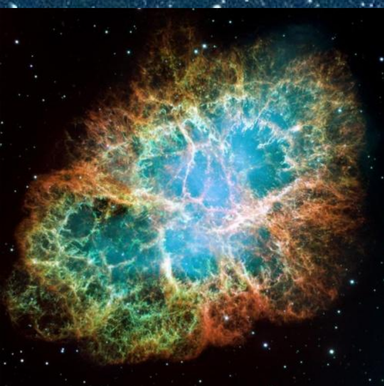
Don't forget to put your name and student#

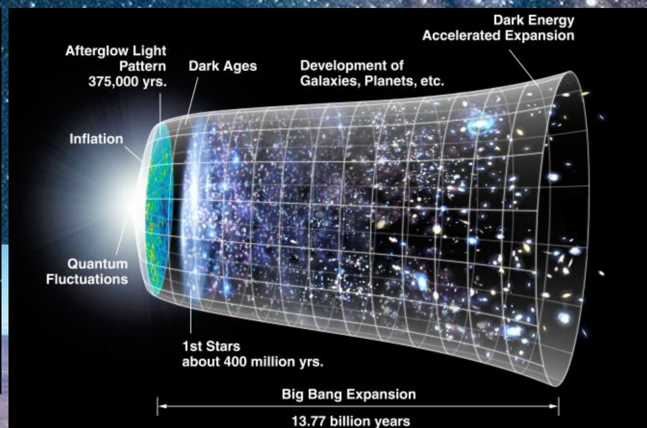
You may answer in any language

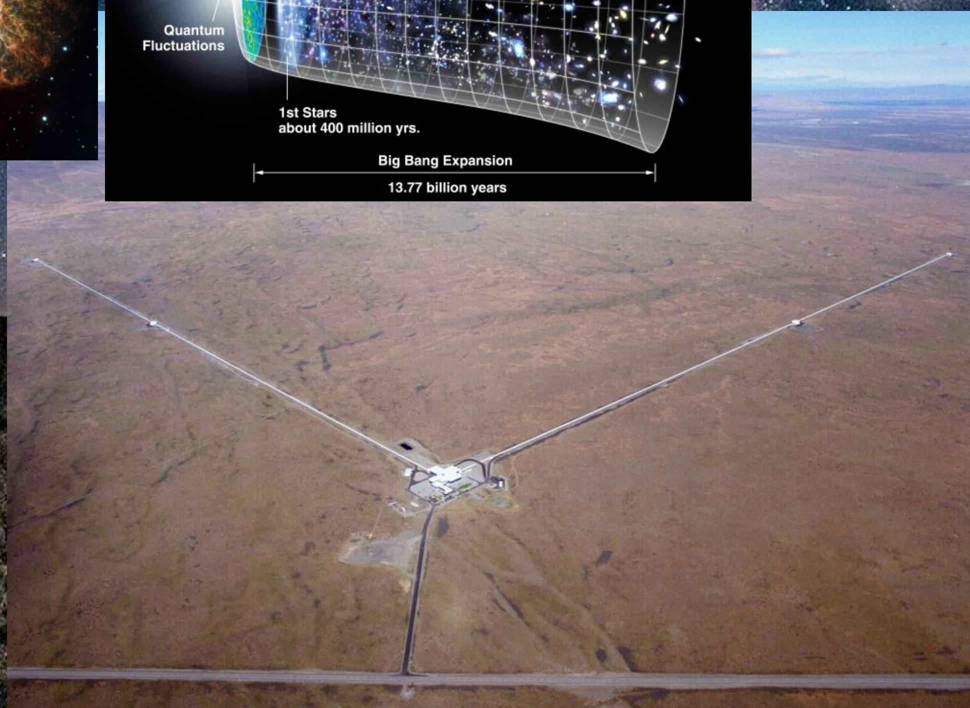

Star
HIP 65426
Exoplanet
HIP 65426 b
JWST
NIRCam
F300M
NIRCam
F444W
MIRI
F1140C
Planet
MIRI
F1550C
Credit:NAOJ



ILLUSTRATION

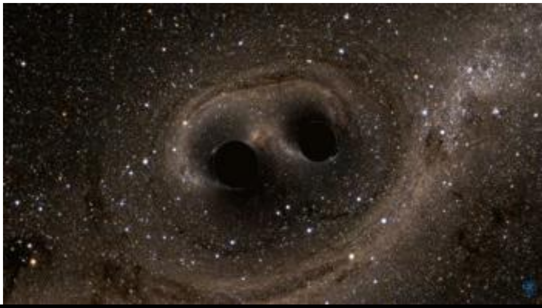


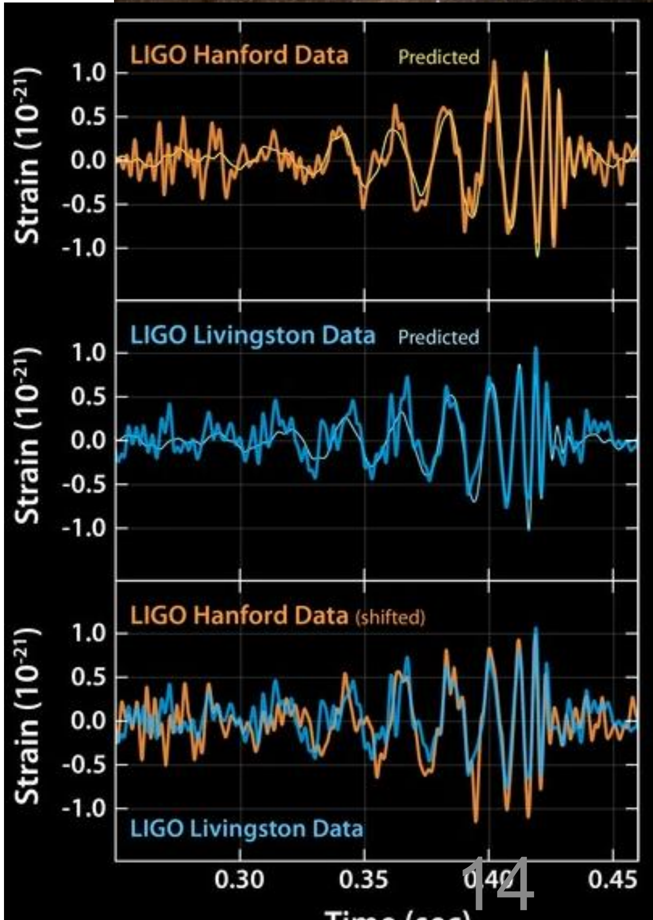

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years



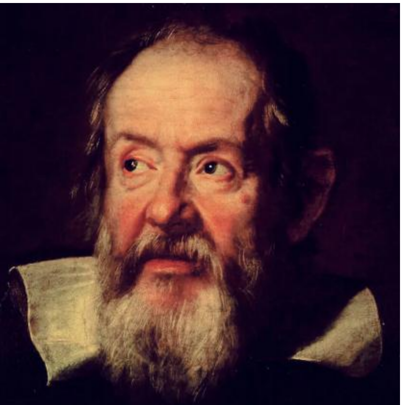
GW150914: First Sound

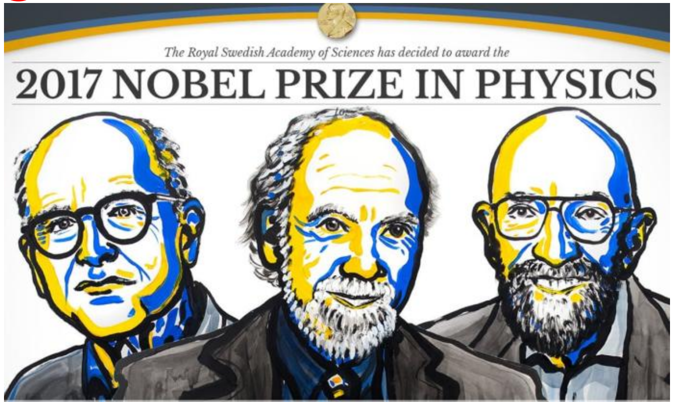
- **September 14, 2015**:
  Two LIGO detectors in the US detected gravitational waves from merging black holes
  → Beginning of astronomy with "sound"
- **1609**: Galileo made telescopes
  → Beginning of astronomy with "light" (electromagnetic waves)





Caltech/MIT/LIGO Lab



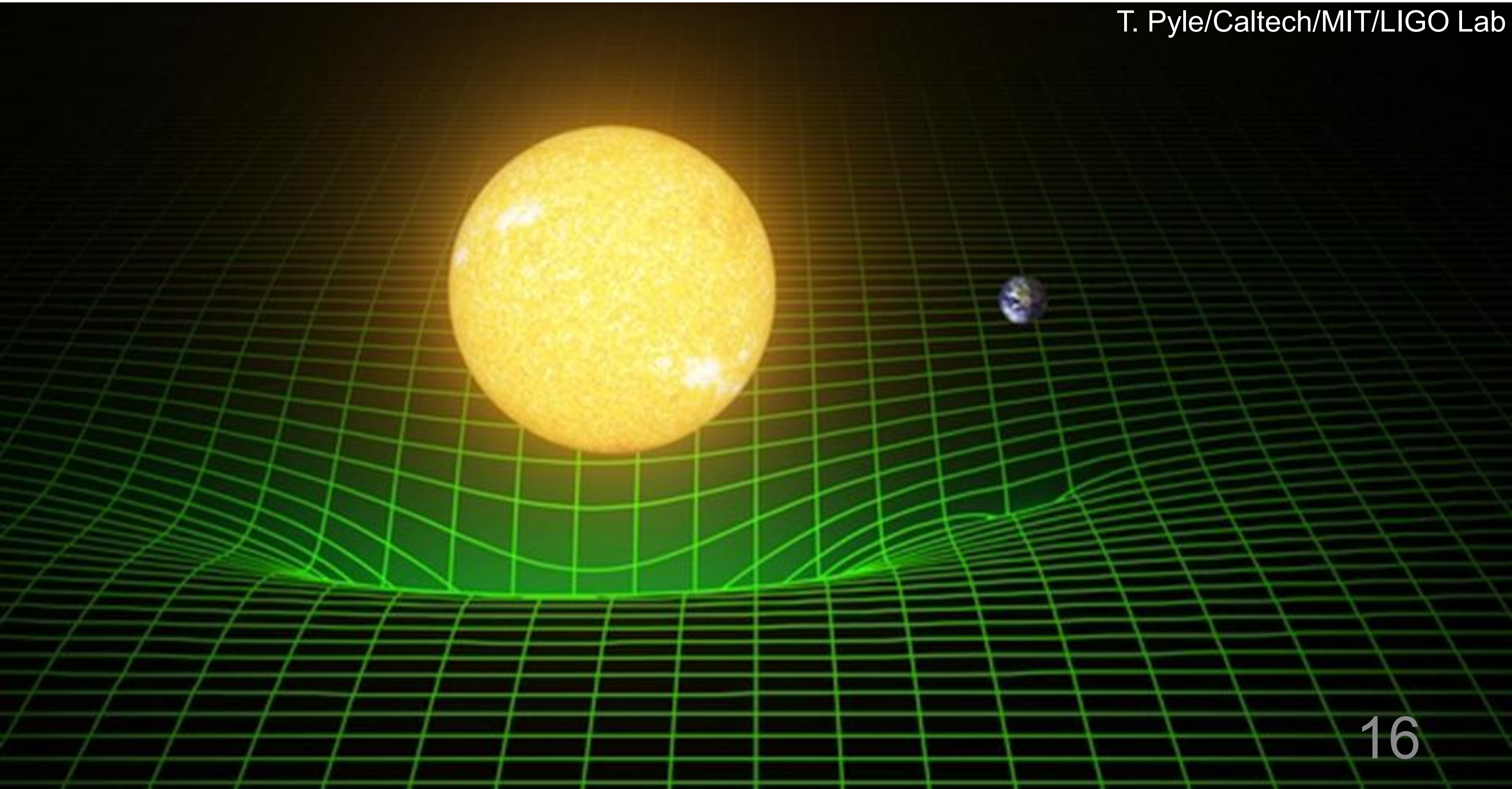


Plan of the Lecture Today

- **What are gravitational waves?**
  - Einstein's general relativity
- **History of gravitational wave observations**
  - It took 100 years to detect them
- **The status of gravitational wave observations**
  - By LIGO-Virgo-KAGRA detectors
- **How do we detect them?**
  - Laser interferometer

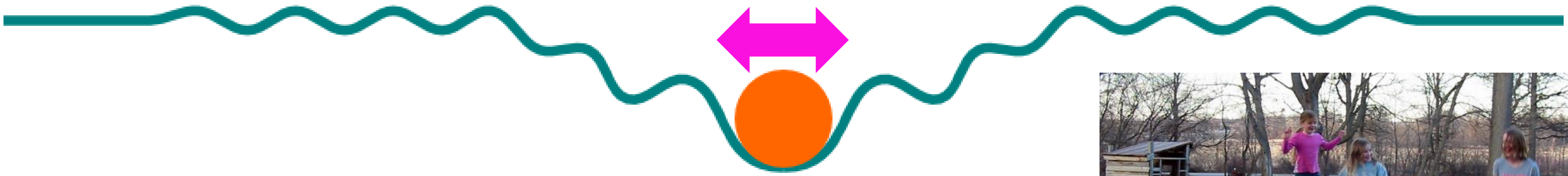
Gravity in General Relativity

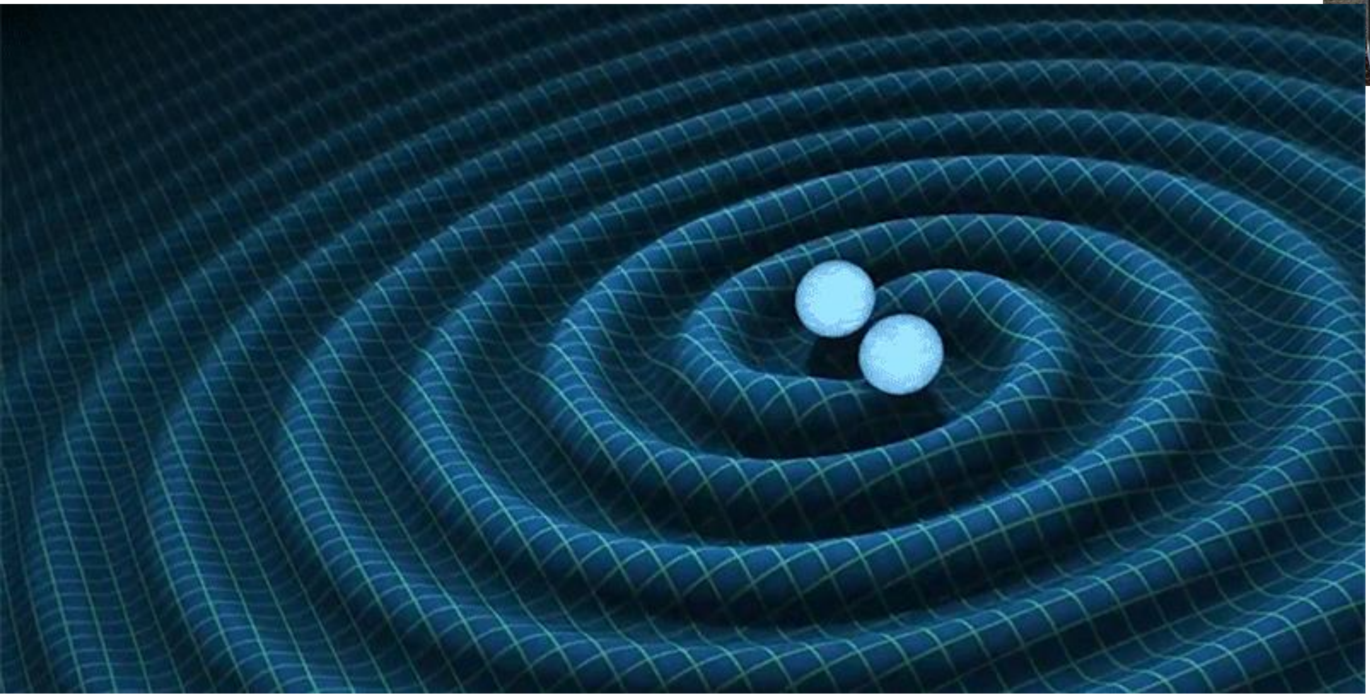
- space-time bends with presence of mass
- bending affects motion of objects → gravity



Gravitational Waves

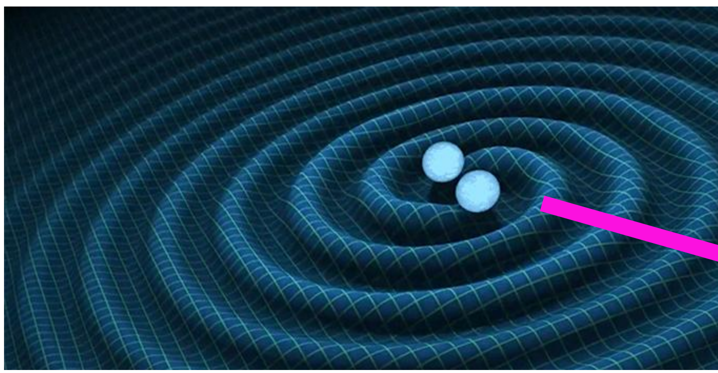
- ripples in space-time created by motion of objects

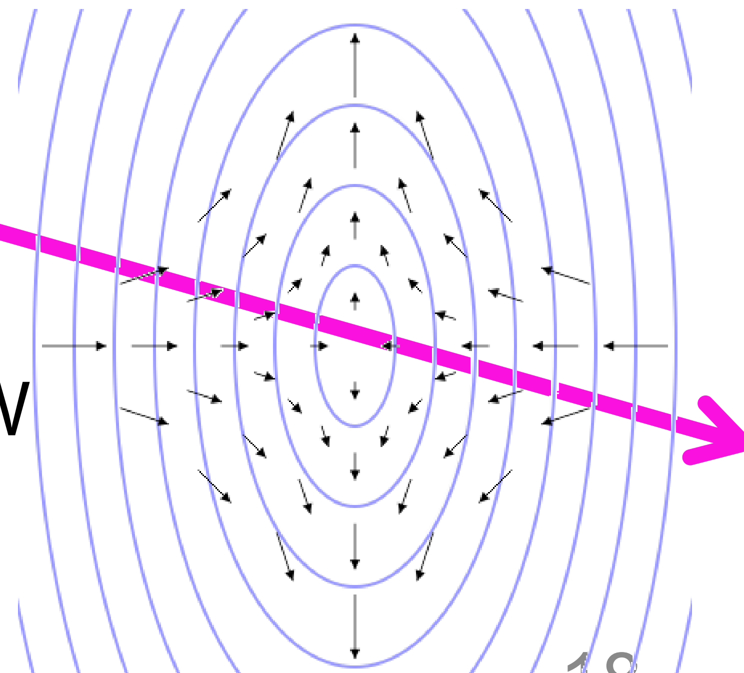




Characteristics of GWs

- propagates at the speed of light
- quadrupole radiation (+ mode and x mode)
- high transmissivity $\leftrightarrow$ very weak interaction





- large mass and large acceleration creates large GW
- GW strain
  = fraction of length change

$$h = \frac{\delta L}{L}$$

Amplitude So Small

10^3 km

1 m

10^{-3} mm

10^{-6} µm

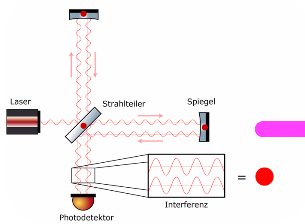
10^{-9} nm

10^{-12} pm

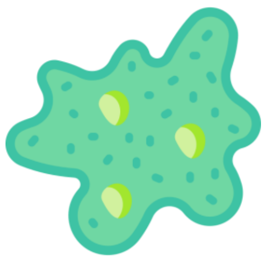
10^{-15} fm

10^{-18} am

10^{-21} zm



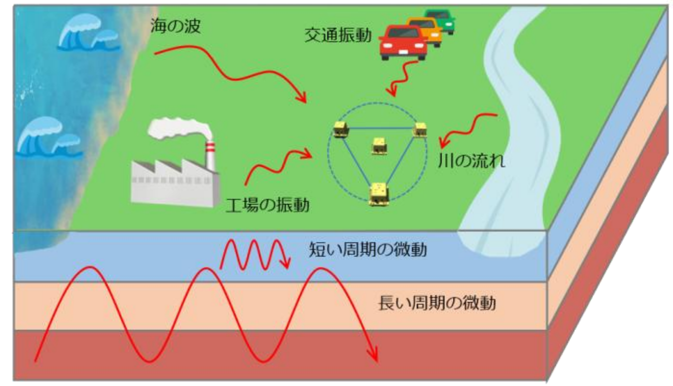
Strain 10^{-21}



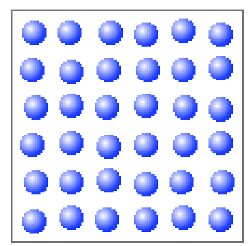
Amoeba ~10^{-4} m

Atom ~10^{-10} m

Proton ~10^{-15} m



Seismic vibrations ~ 10^{-6} m



Thermal vibrations ~ 10^{-15} m

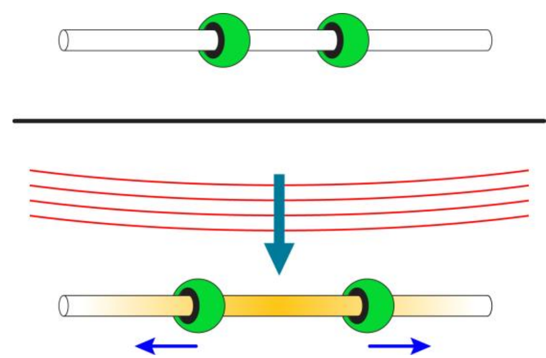
Quantum limit ~ 10^{-20} m

Target sensitivity

Heisenberg's uncertainty principle

History of Gravitational Waves

- 1915 Einstein formulated General Relativity
- 1916 Einstein predicted gravitational waves
- 1936 Einstein submitted a paper saying that GWs do not exist on second thought
  → got criticized and got angry

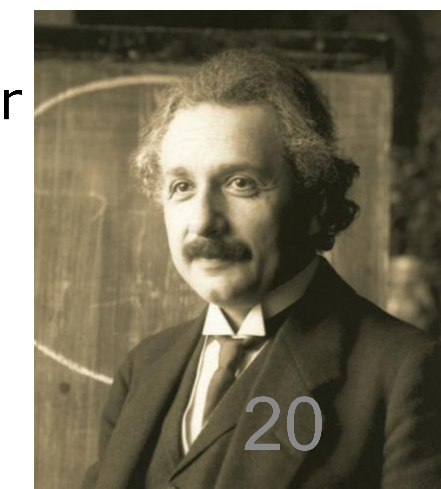


- 1957 Chapel Hill Conference
  Feynman's "sticky bead argument"
  GWs started to theoretically accepted

Howard Robertson

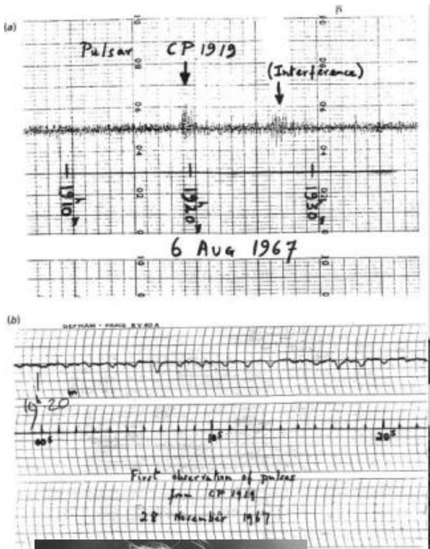
Richard Feynman

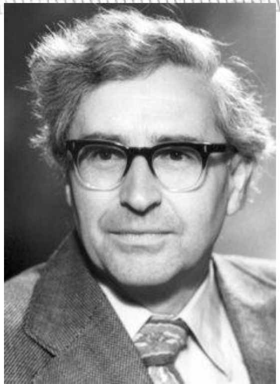
John Wheeler



Pulsars and Indirect Evidence

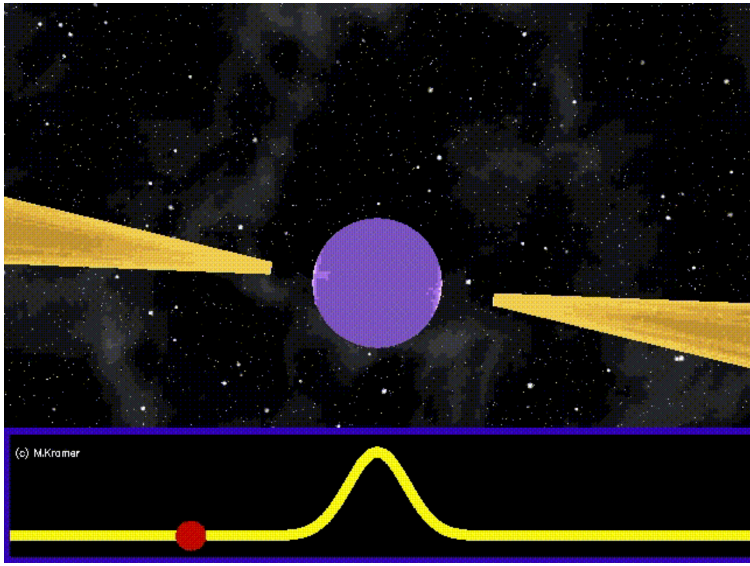
- 1967 Bell and Hewish discovered a radio source which has 0.04 sec pulse with a period of 1.3373011 sec
  →Pulsar (later discovered to be a neutron star)





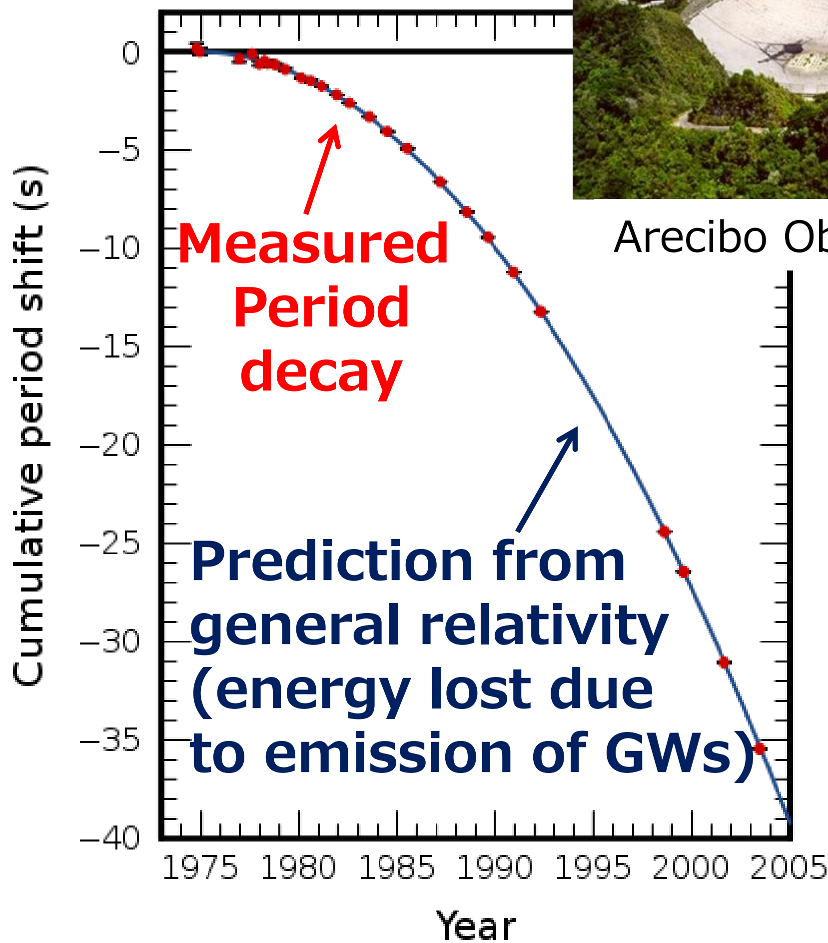
1974

Little green men 1

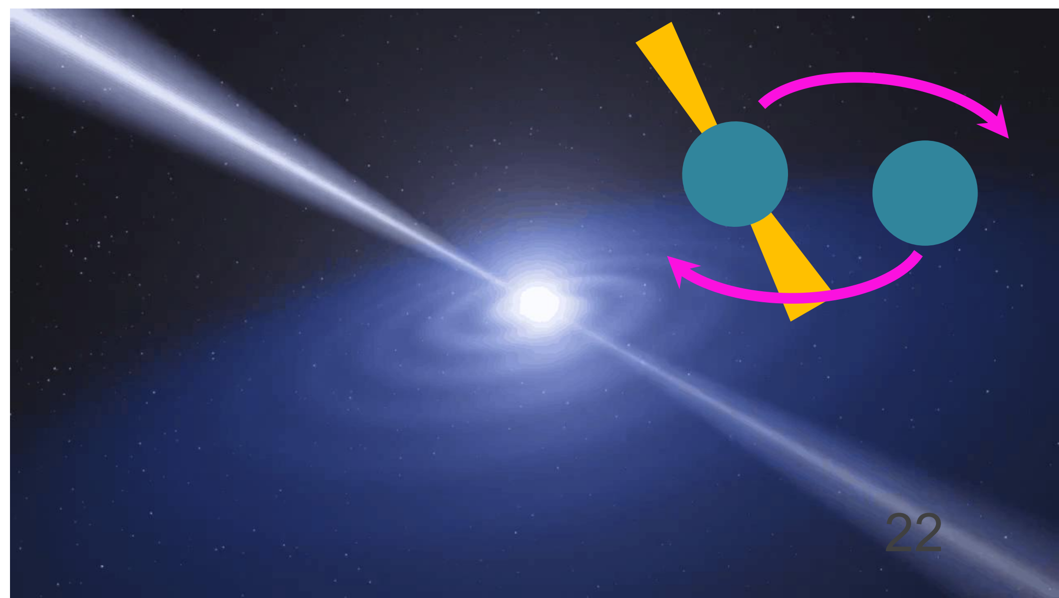


Pulsars and Indirect Evidence

- 1974 Hulse and Taylor discovered a binary pular

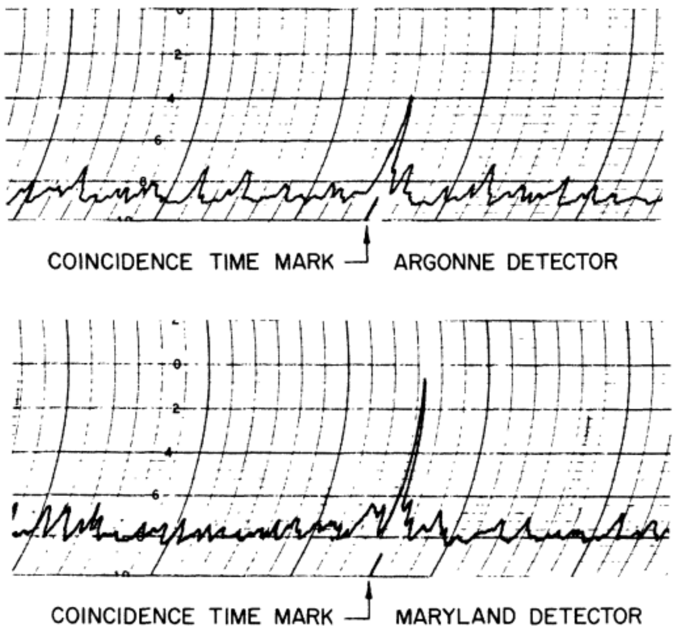


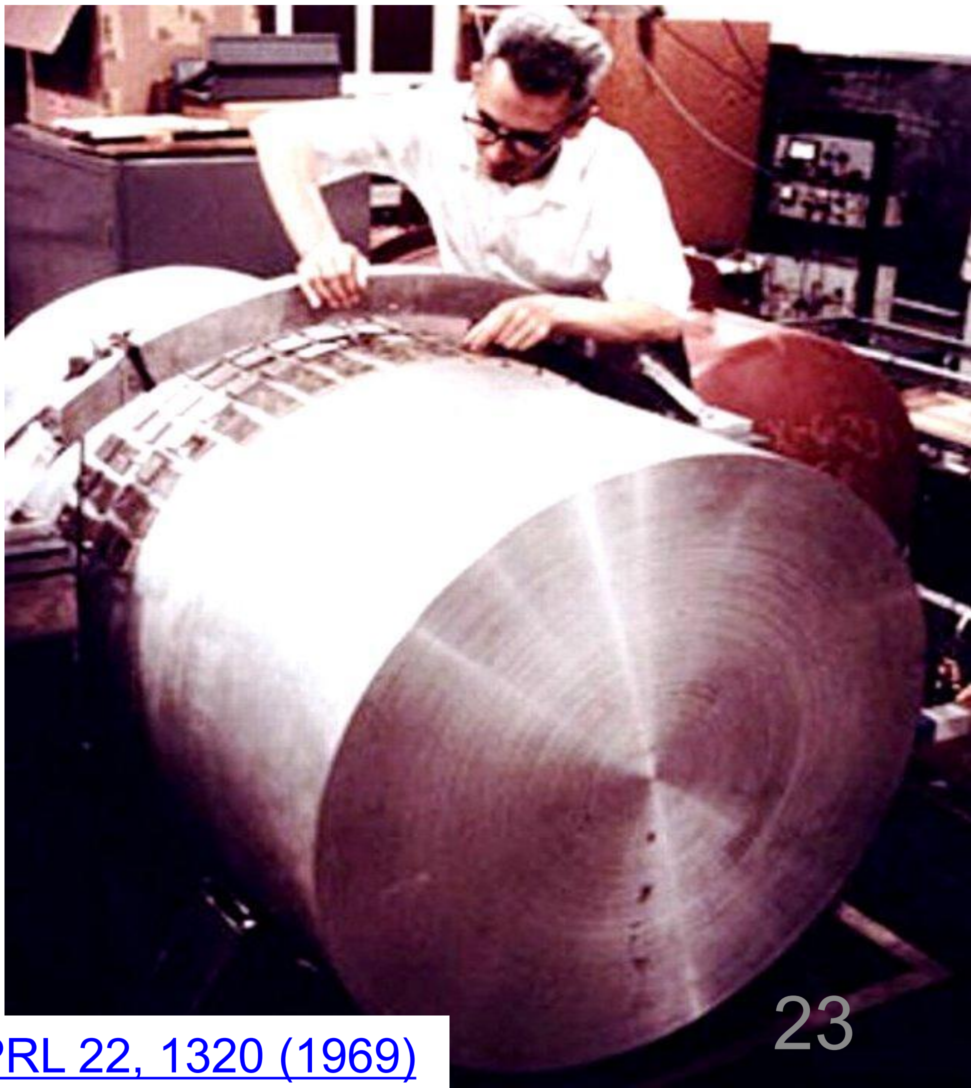
Arecibo Observatory



Weber's "Detection"

- 1969 Joseph Weber claimed a detection of gravitational waves
- Later discovered to be wrong
- But this motivated for direct detection

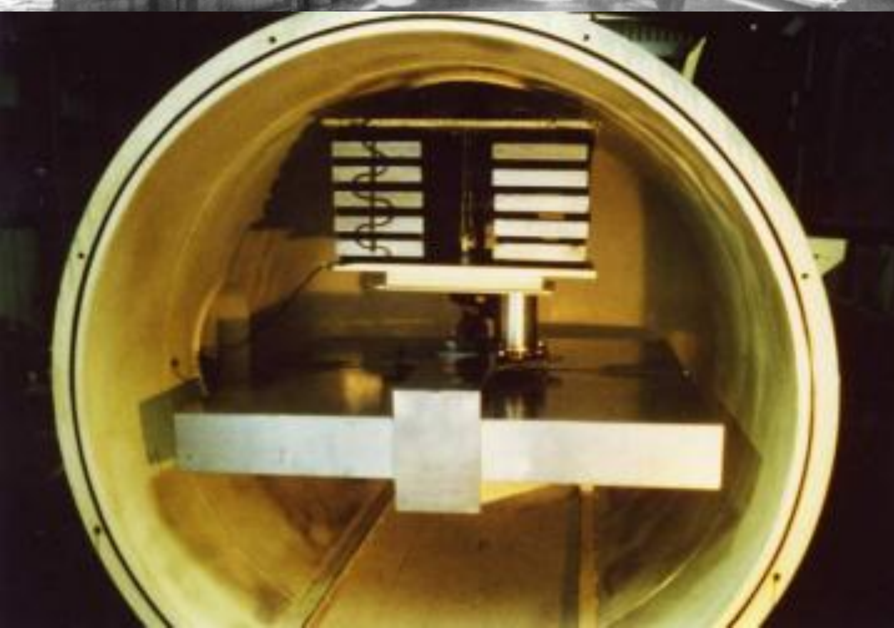




J. Weber, [PRL 22, 1320 (1969)]

Follow-up Experiments in Japan

Hiromasa Hirakawa, 1971



GW experiments in Japan started at Hongo Campus

Kimio Tsubono

Laser Interferometric Detectors

- 1960s Rai Weiss got the idea when he had to teach a graduate course on general relativity at MIT

Internal Report 1972

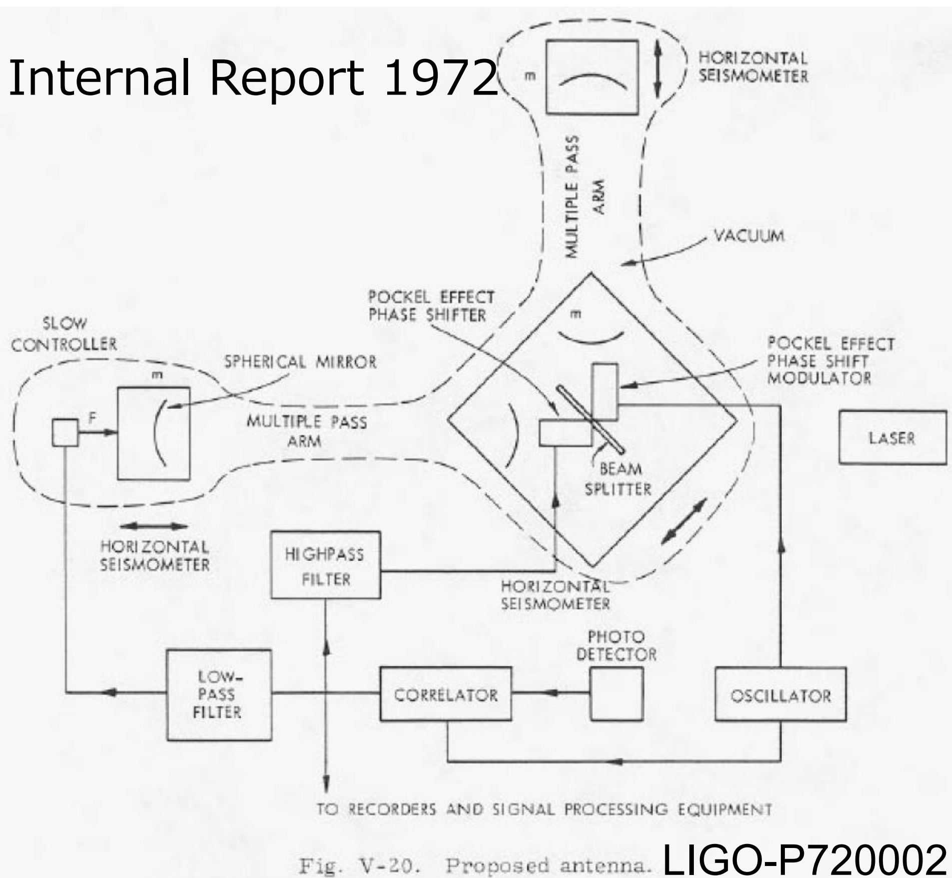
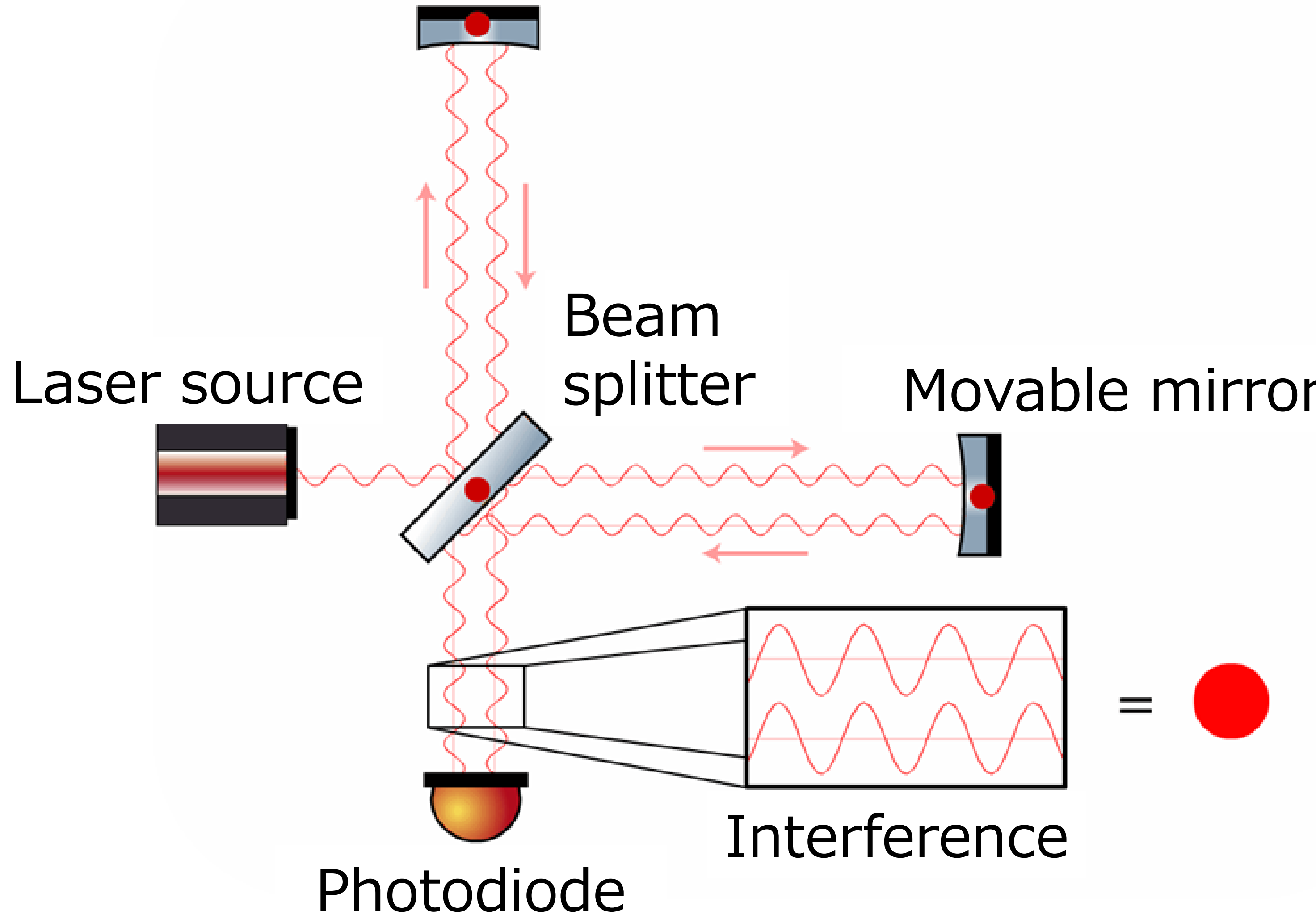


Fig. V-20. Proposed antenna.

LIGO-P720002

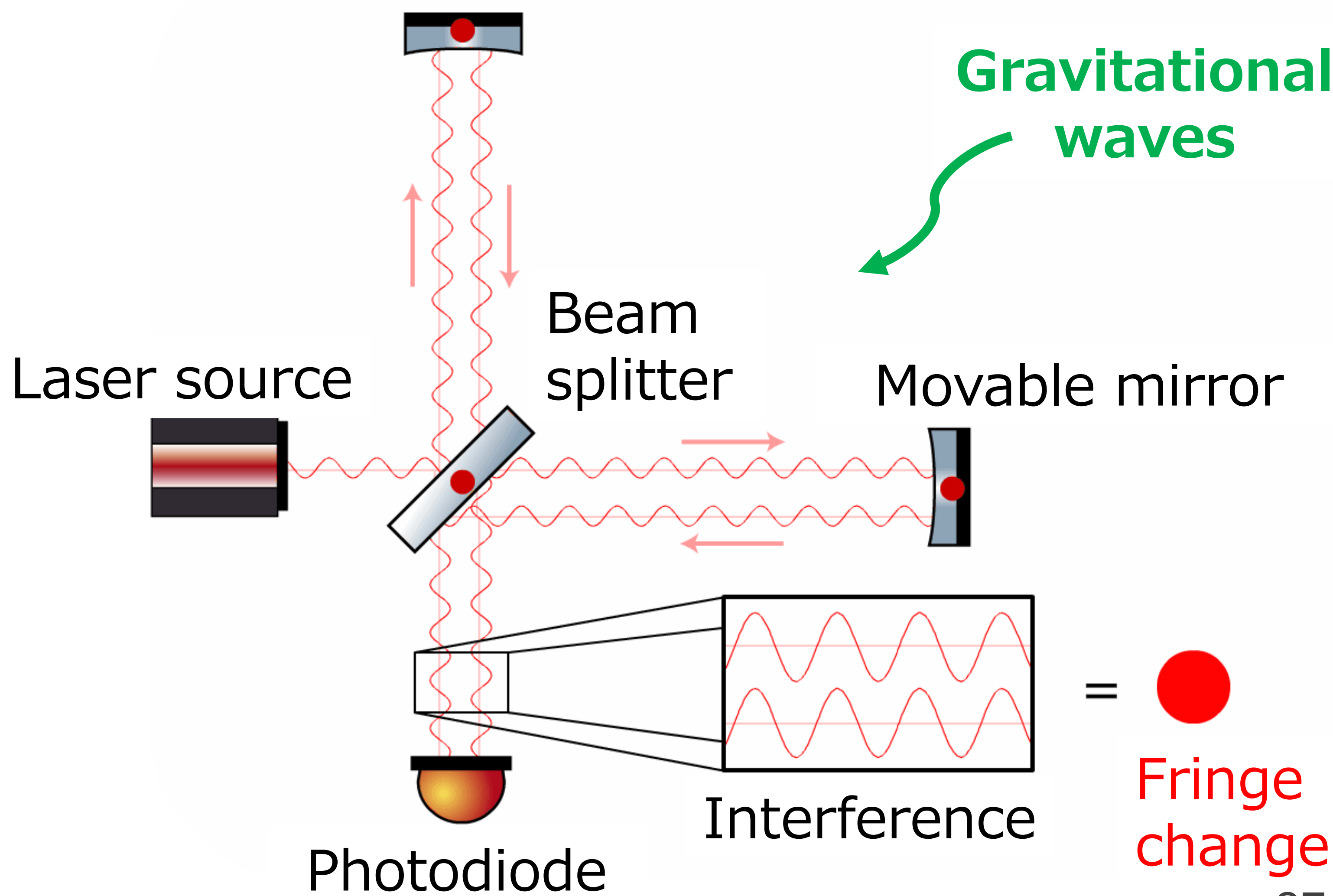
Laser Interferometric GW Detectors

- Measures differential arm length change



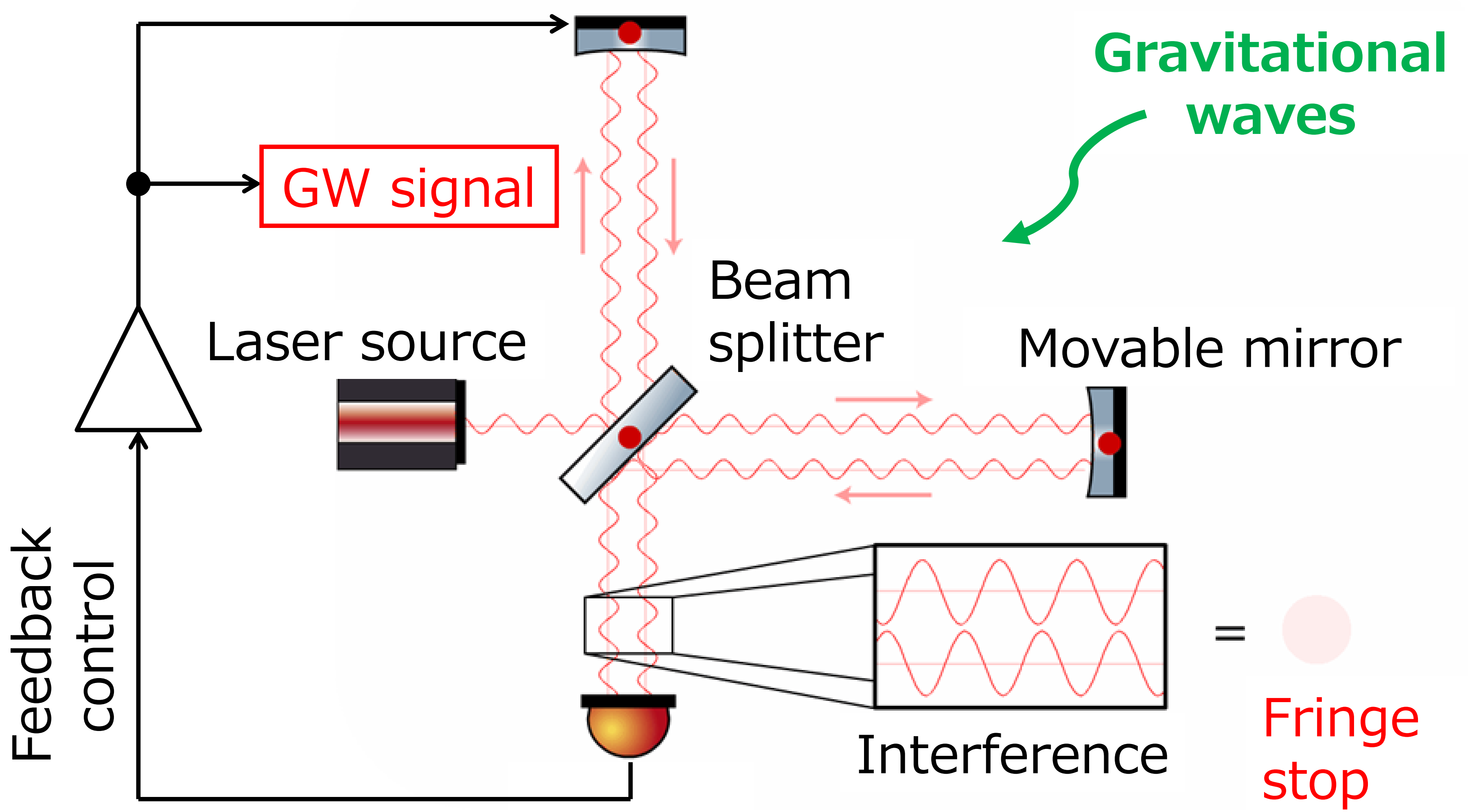
Laser Interferometric GW Detectors

- Measures differential arm length change



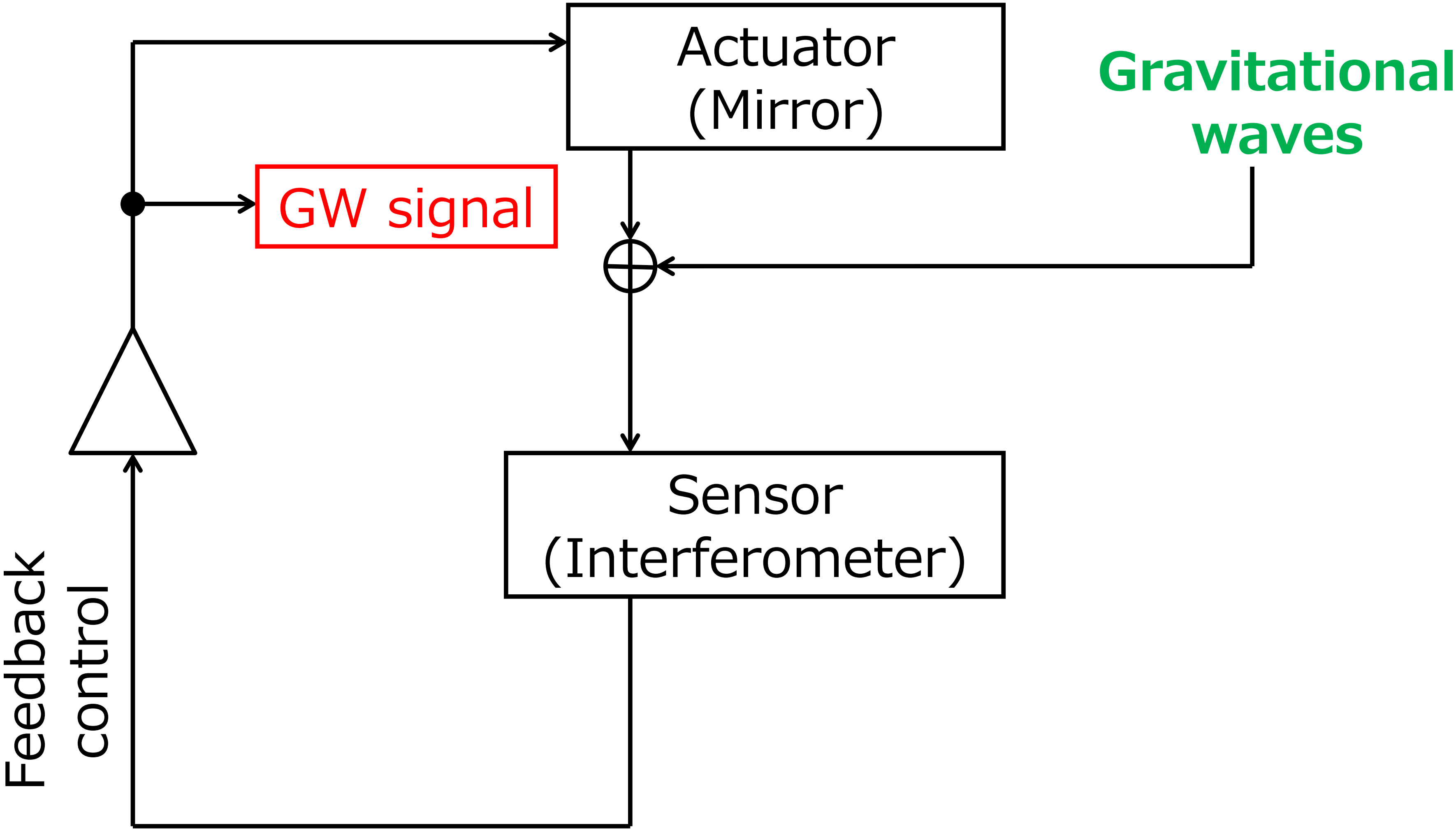
Interferometer Control

- Control mirror positions to “lock” the fringe



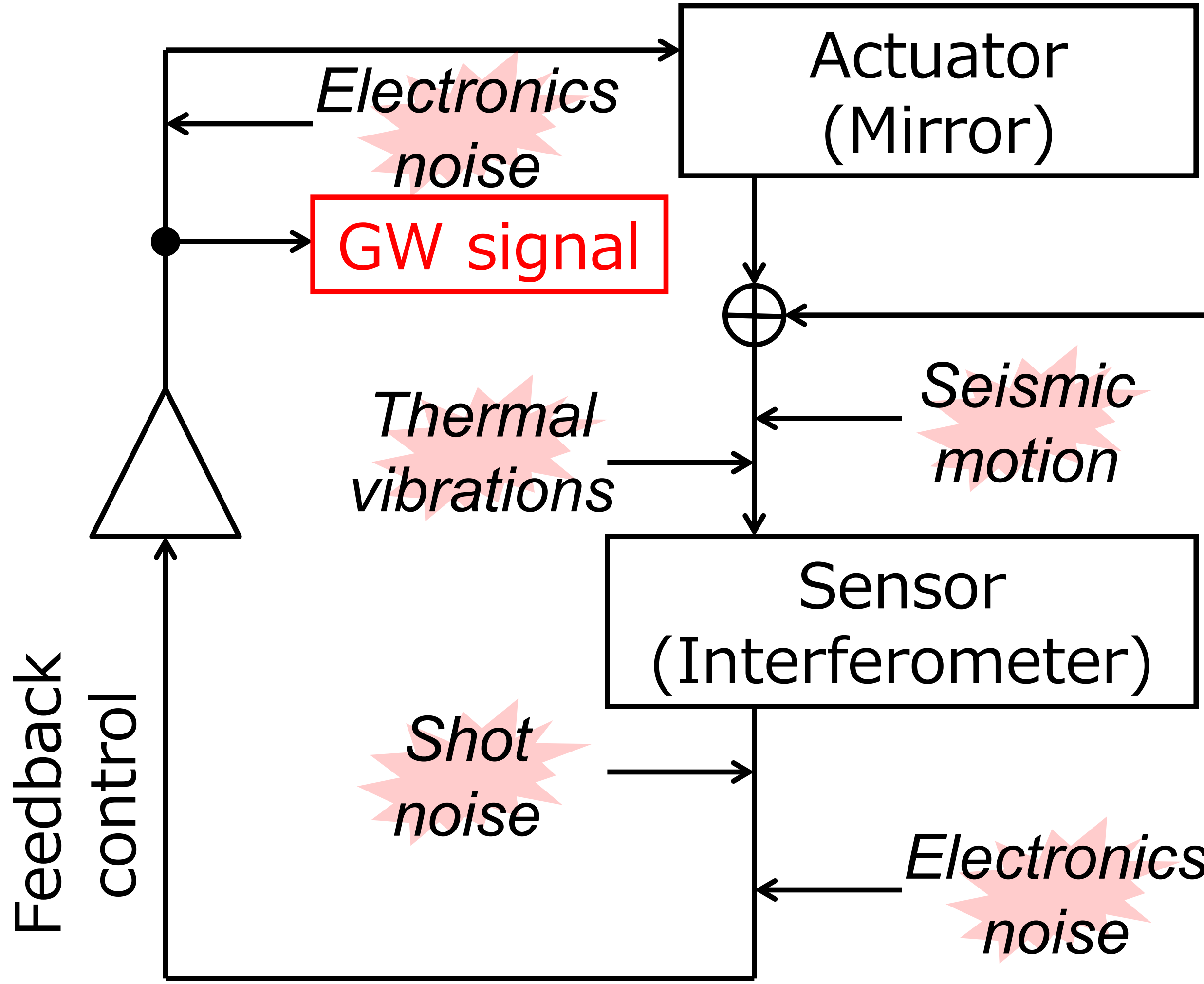
Linear System

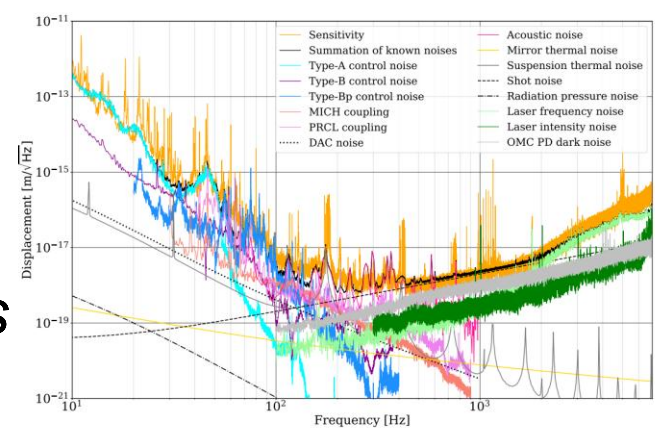
- Control makes the system linear



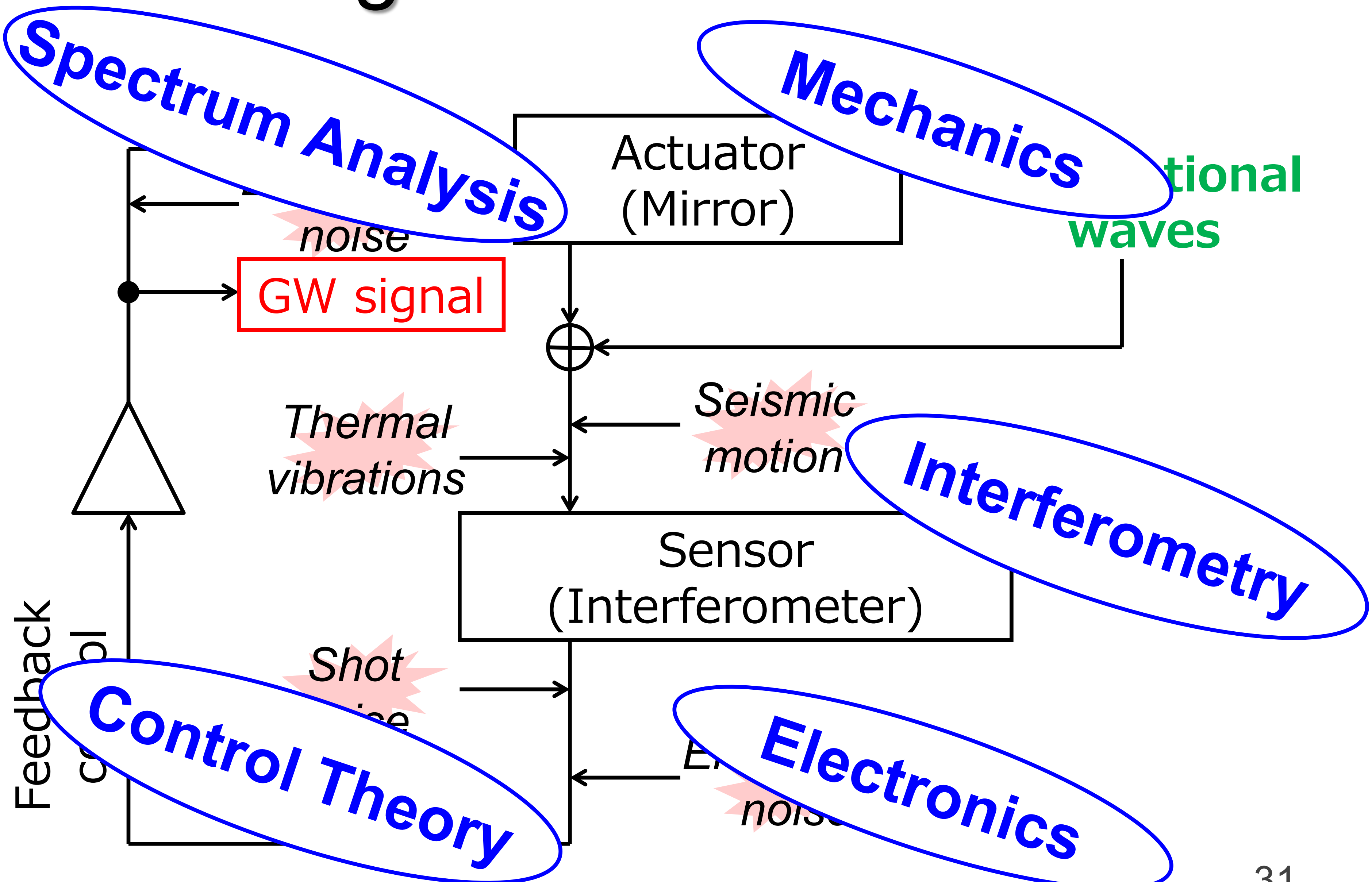
Noises and Sensitivity

- Noises in the loop limits the sensitivity



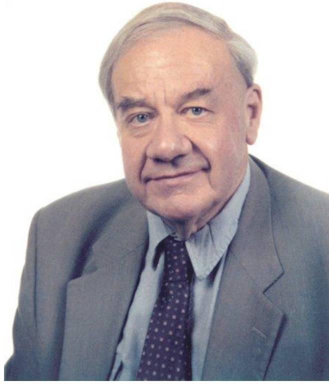


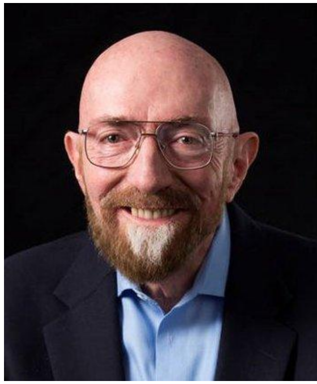
Things You Need to Know



History of Laser Interferometers

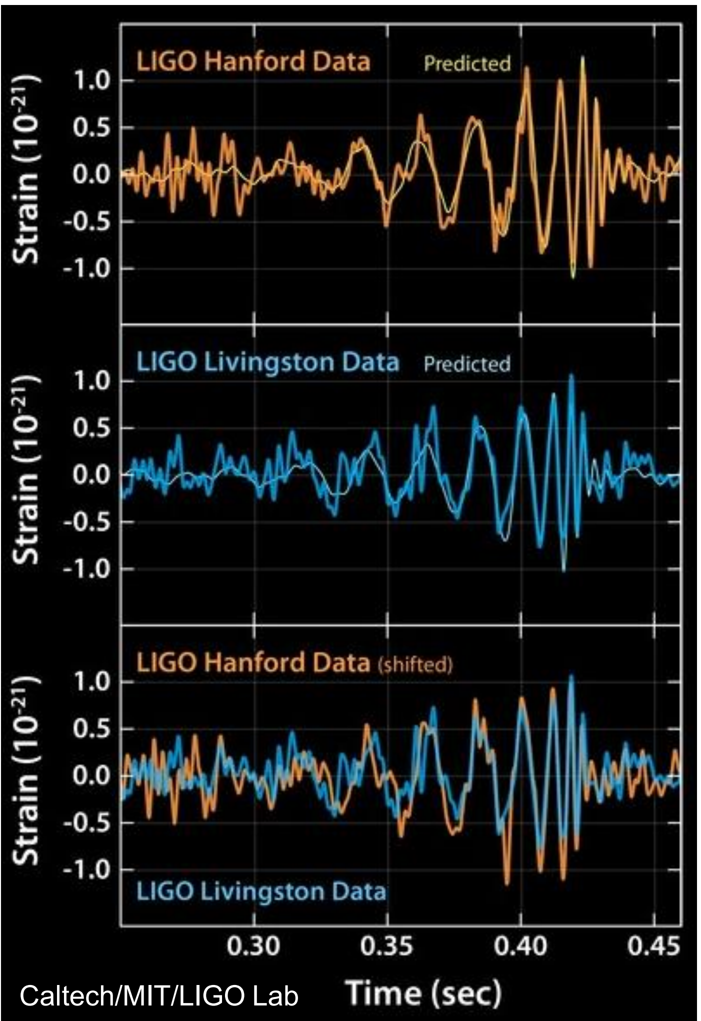
- 1970s-1980s Prototypes at MIT (1.5 m→5 m) / Garching, Germany (3 m→30 m) / Glasgow, Scotland / Caltech (40 m) / ISAS TENKO (10 m→100 m) / UTokyo (3 m)
- 1984 LIGO project started by Drever, Weiss, and Thorne
- 1995 TAMA300 started construction in Mitaka
- 2000 TAMA300 recorded the best sensitivity
- 2000s Initial detectors started operation (1G)
  LIGO (US, 4 km) / TAMA300 (Japan, 300 m)
  GEO600 (Germany, 600 m) / Virgo (Italy, 3 km)
- 2011 LIGO started upgrade
- 2015 Advanced LIGO started observing run, and first detection

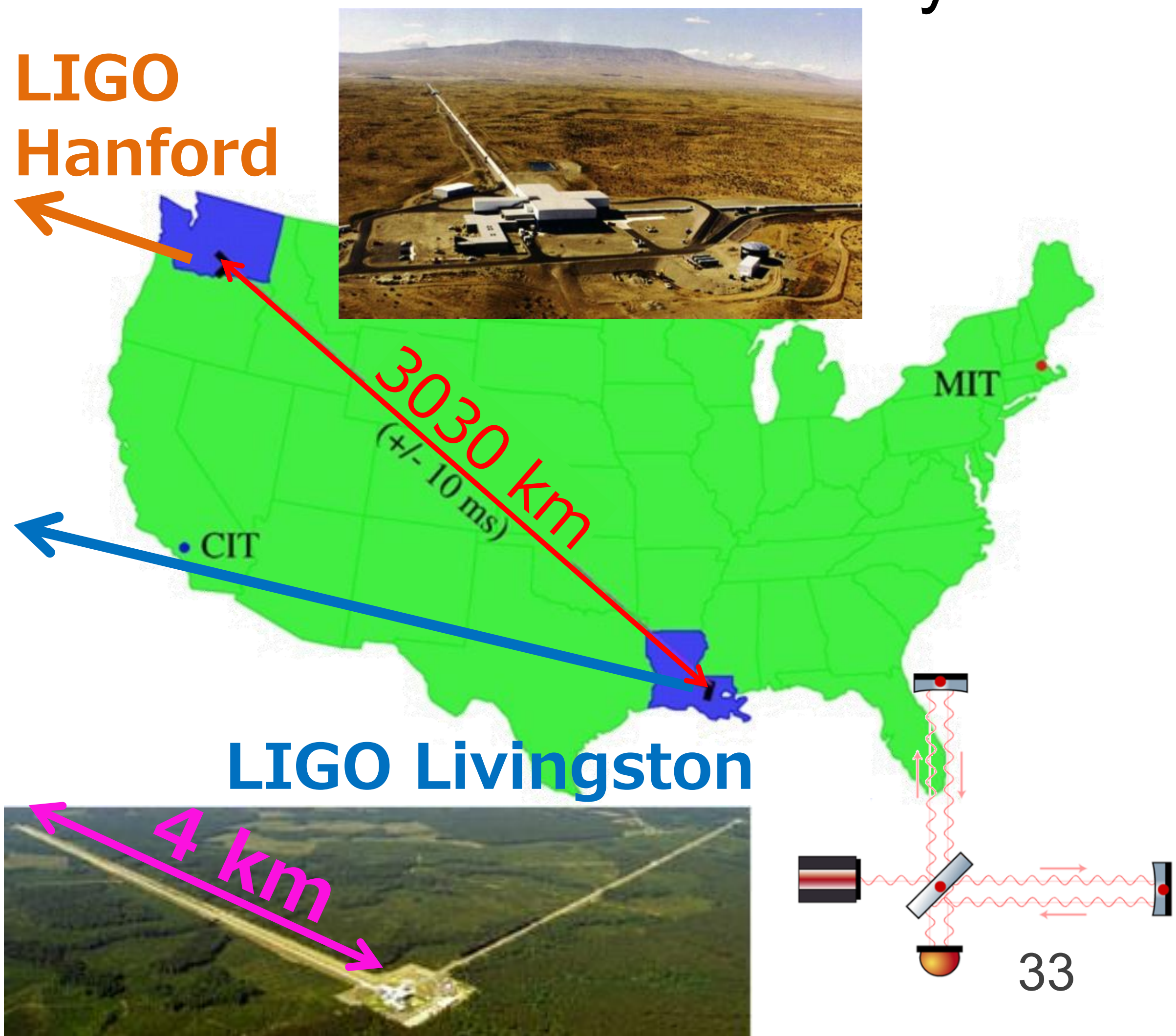




First Detection by LIGO Detectors

- On September 15, 2015, two detectors separated by ~3000 km detected almost simultaneously

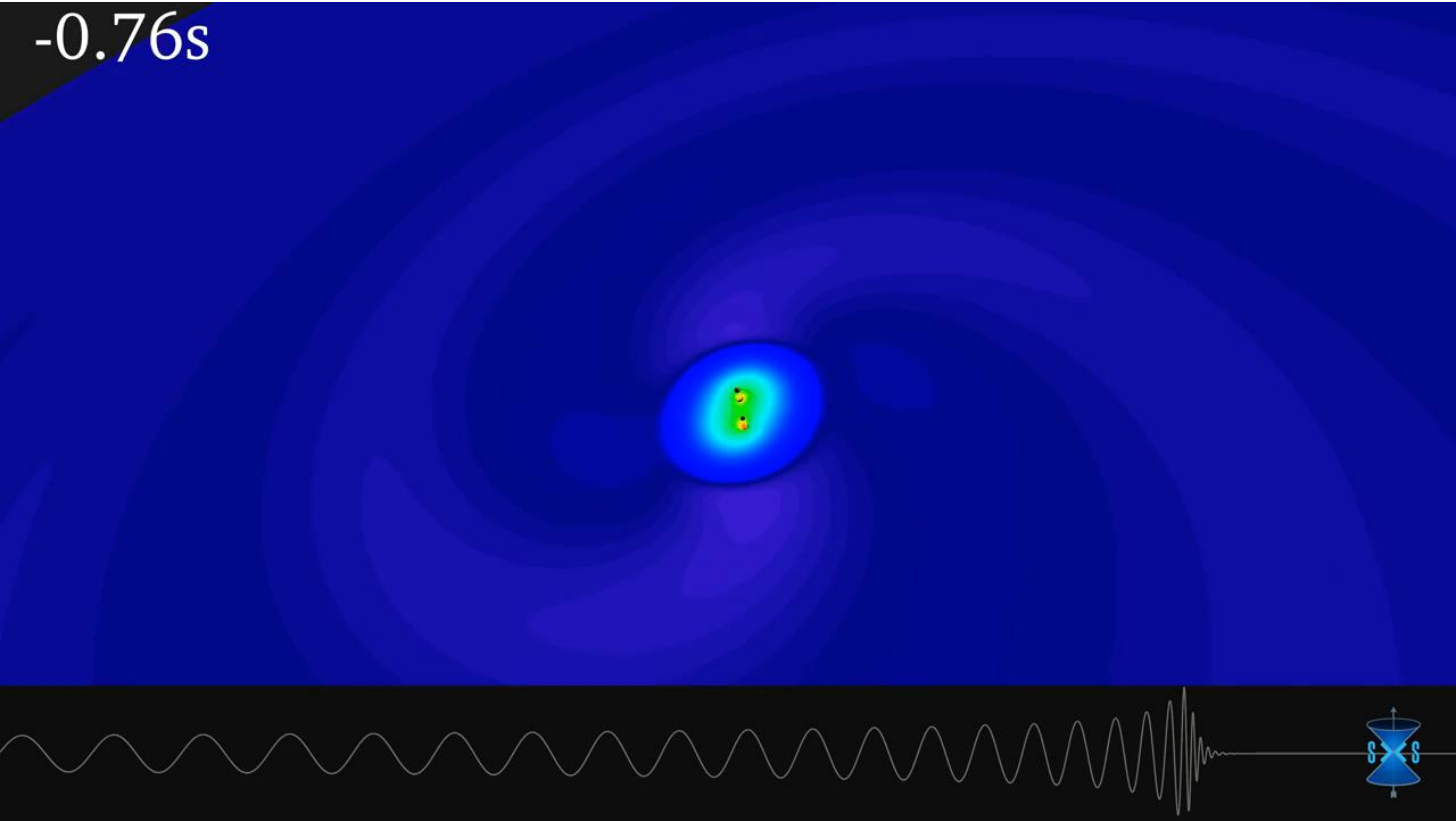




Binary Black Hole Merger

- Two black holes merging into one

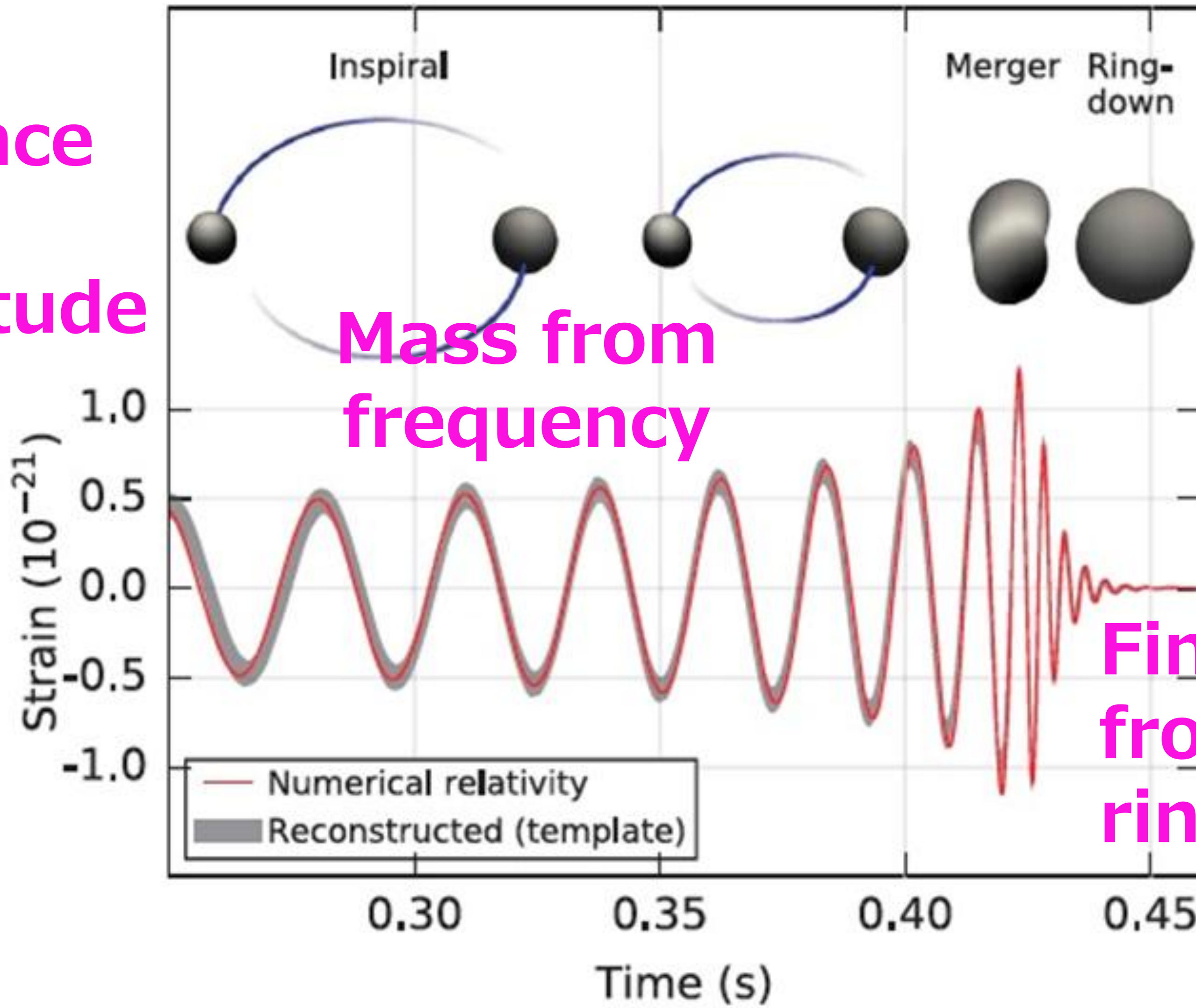
https://youtu.be/c-2XIuNFgD0



Distance and Mass from Waveform

- 36 M_sun +29 M_sun → 62 M_sun

Distance from amplitude

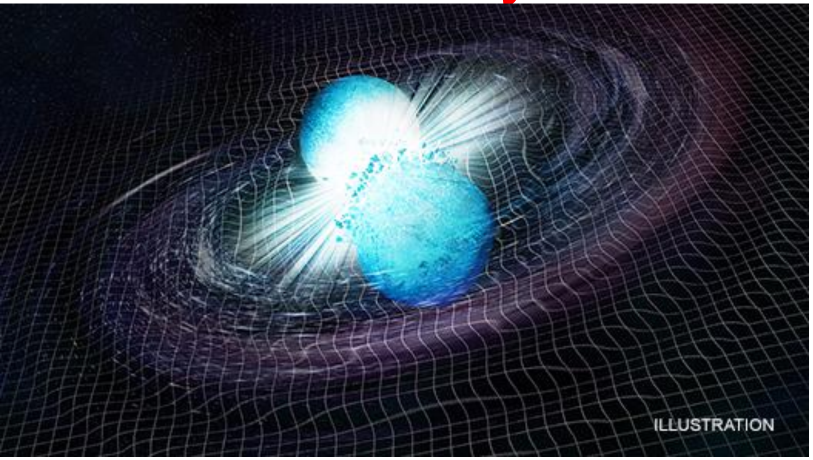


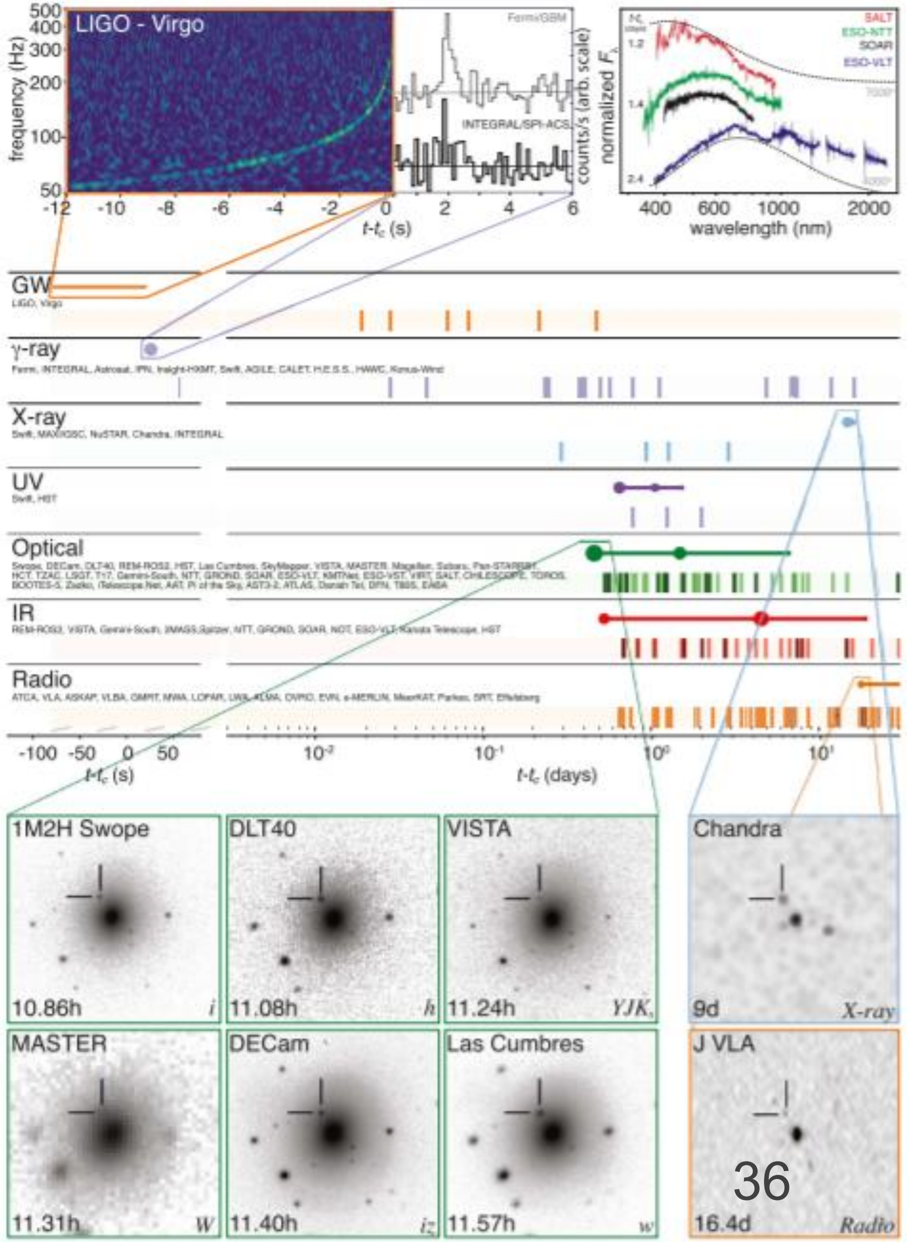
Mass from frequency

Final mass from ringdown

Binary Neutron Star Merger

- GW170817
- Coincident detection of gamma ray burst
  later with other electromagnetic observations
- Multimessenger astronomy



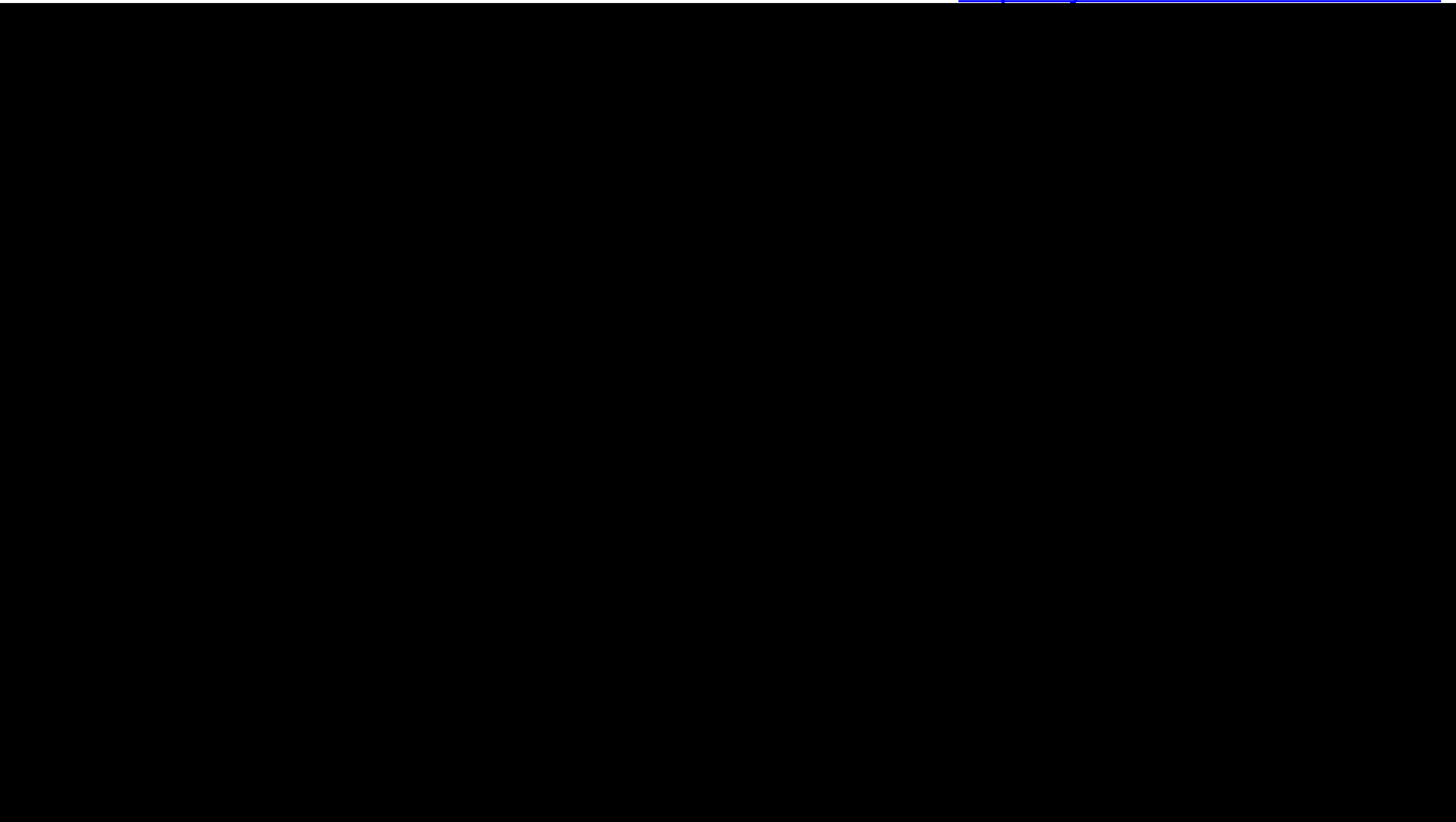


ApJL, 848:L12, (2017)

Binary Neutron Star Merger

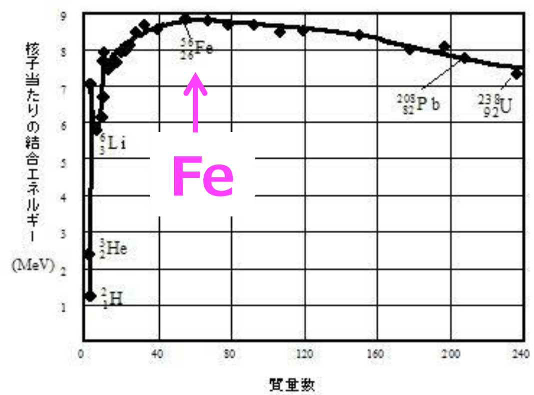
- Short gamma ray burst after gravitational waves

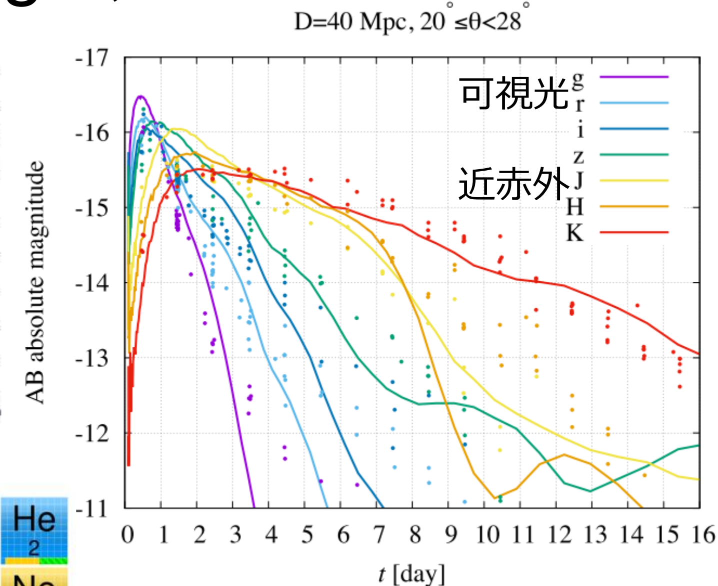
https://youtu.be/e7LcmWiclOs



Origin of Heavy Elements

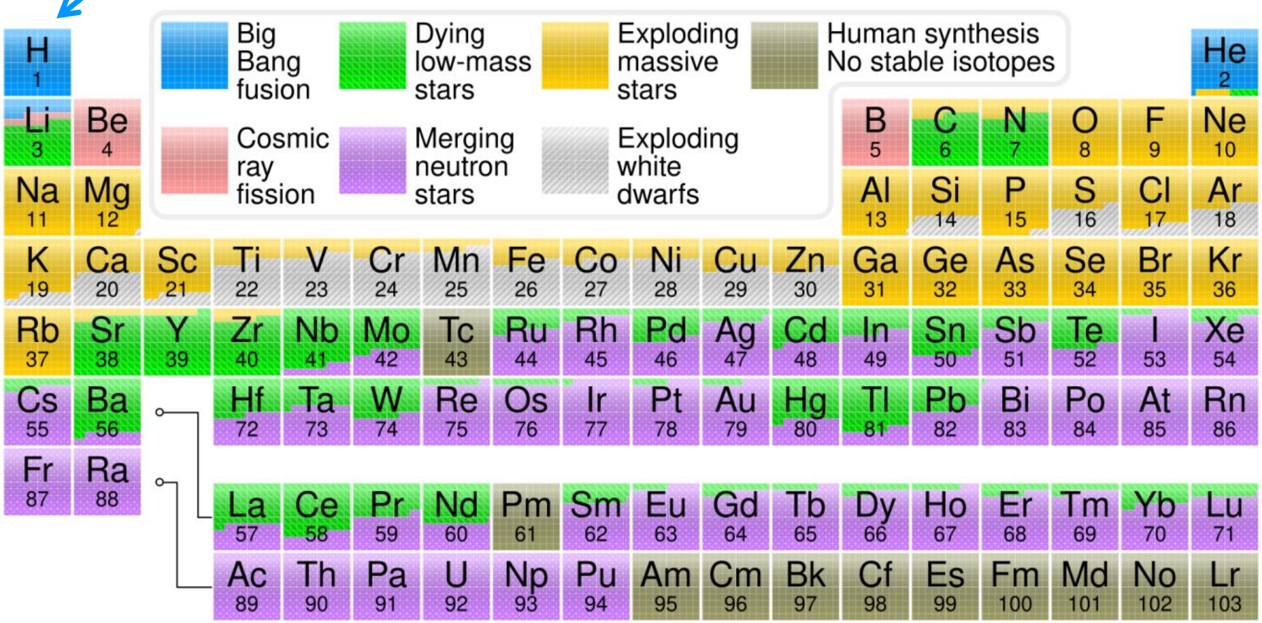
- From light curves after the merger, evidence for r-process elements was found (kilonova)





K. Kawaguchi+, [ApJL **865**, L21 (2018)]

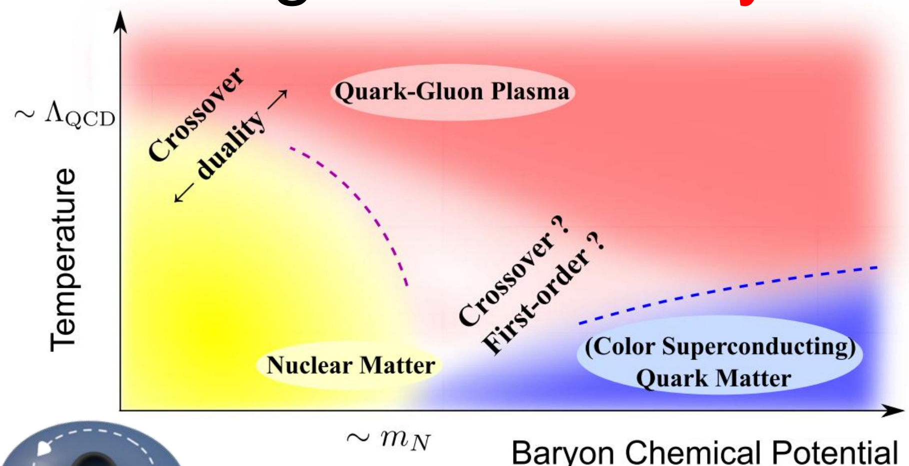
From big bang



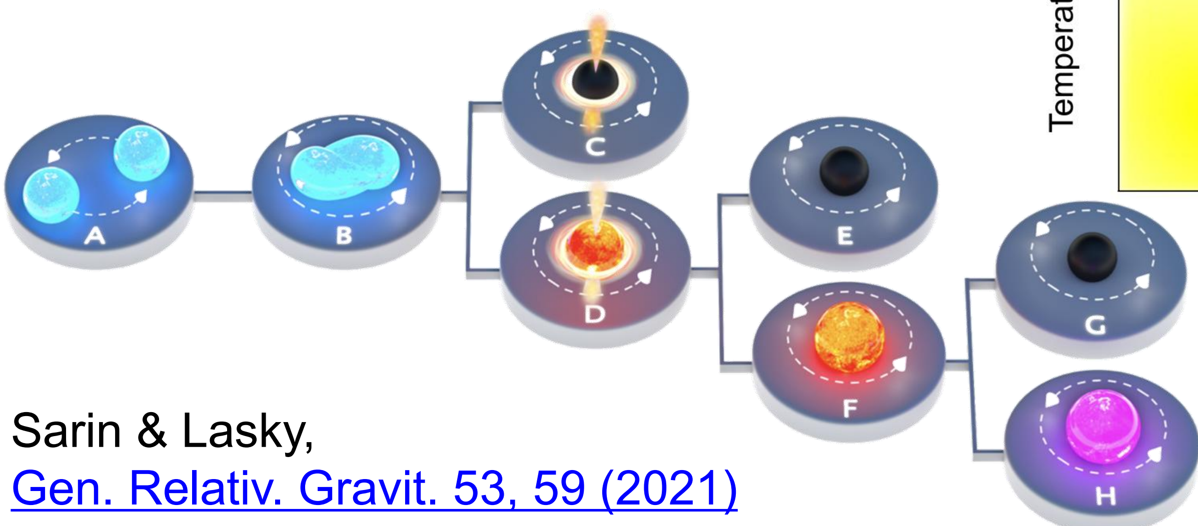
From merging neutron stars

Neutron Star Open Questions

- What happened after the merger?
- What are the progenitors of GRBs and kilonovae?
  - Short/long GRBs explained by BNS?
  - Diversity of kilonovae? c.f. GRB211211A, GRB230307A
- Can BNS mergers explain the origin of all heavy elements?
- QCD phase transition?



Fujimoto+,
[PRL 130, 091404 (2023)]()

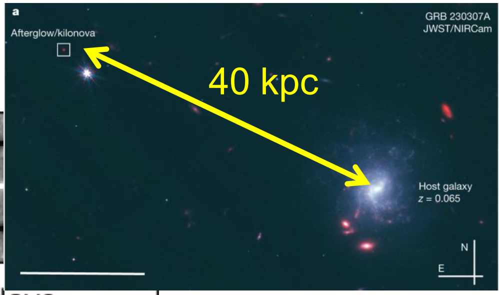


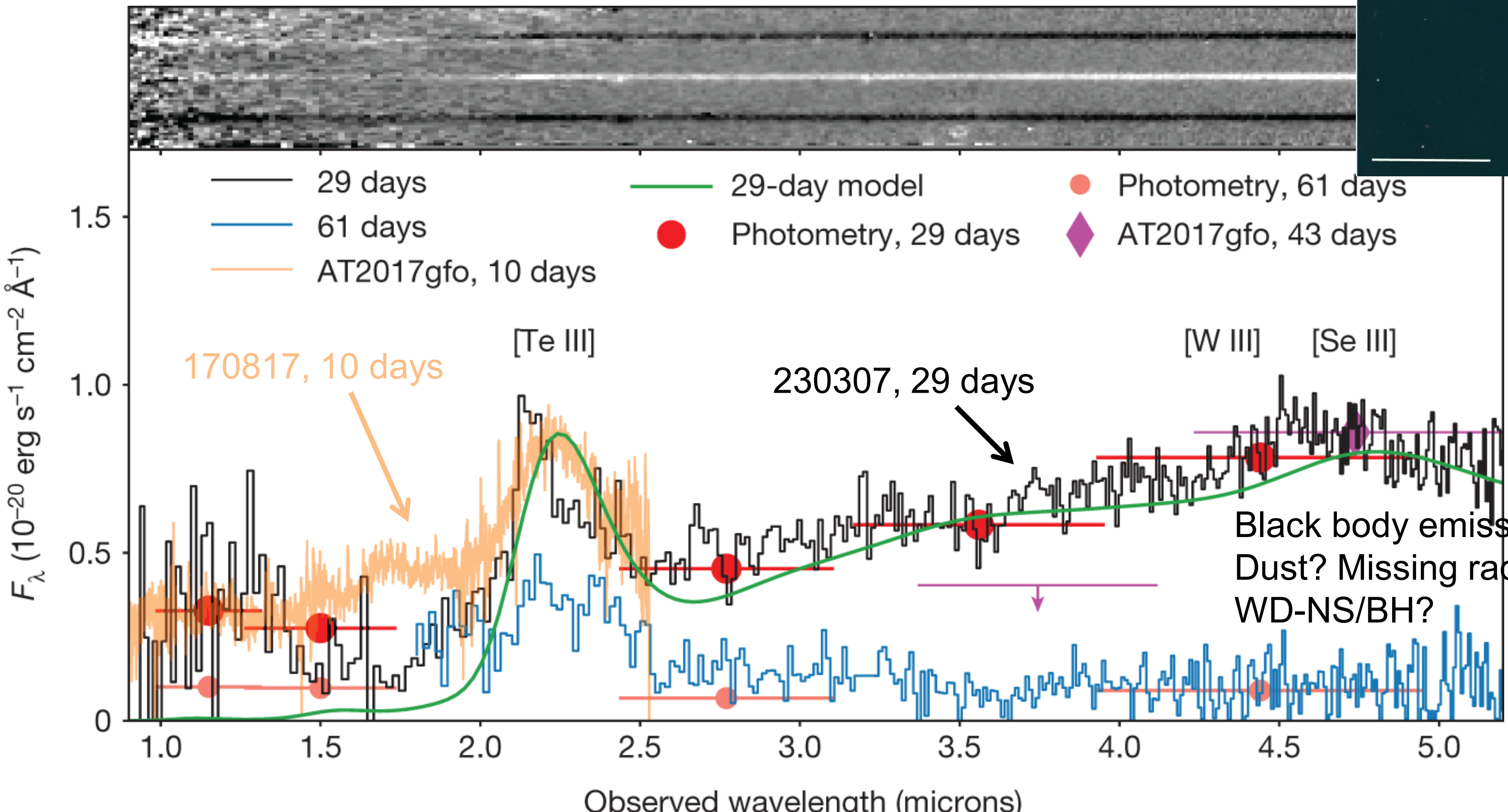
Sarin & Lasky,
[Gen. Relativ. Gravit. 53, 59 (2021)]()

GRB230307A Excess

- Not collapsar due to large offset (~40 kpc) from host galaxy
- Likely BNS merger but long GRB (~ 35 sec)
- Similar kilonova to 170817 but extremely red

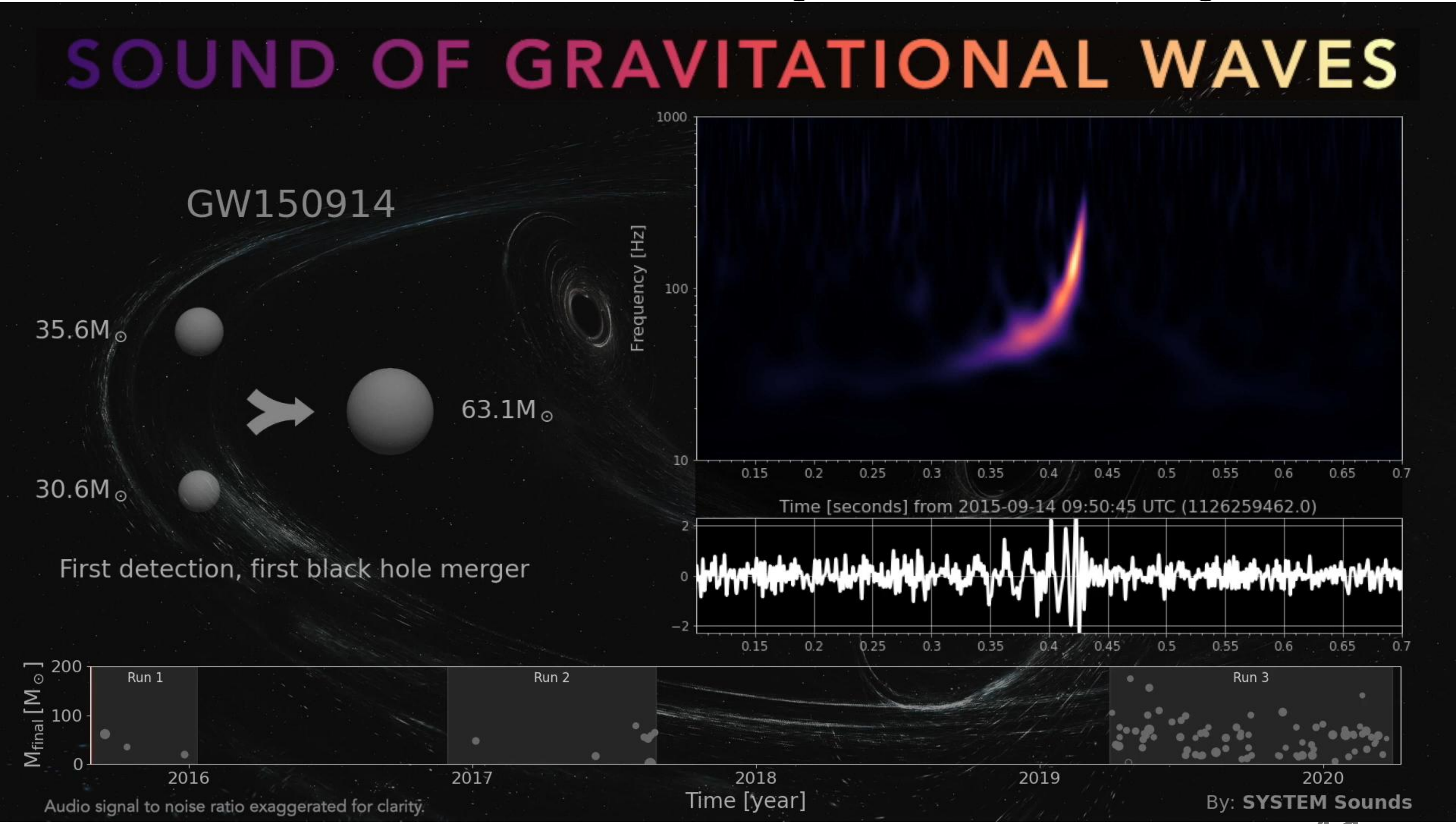
A. J. Levan+, Nature **626**, 737 (2024)





Sound from Binary Coalescences

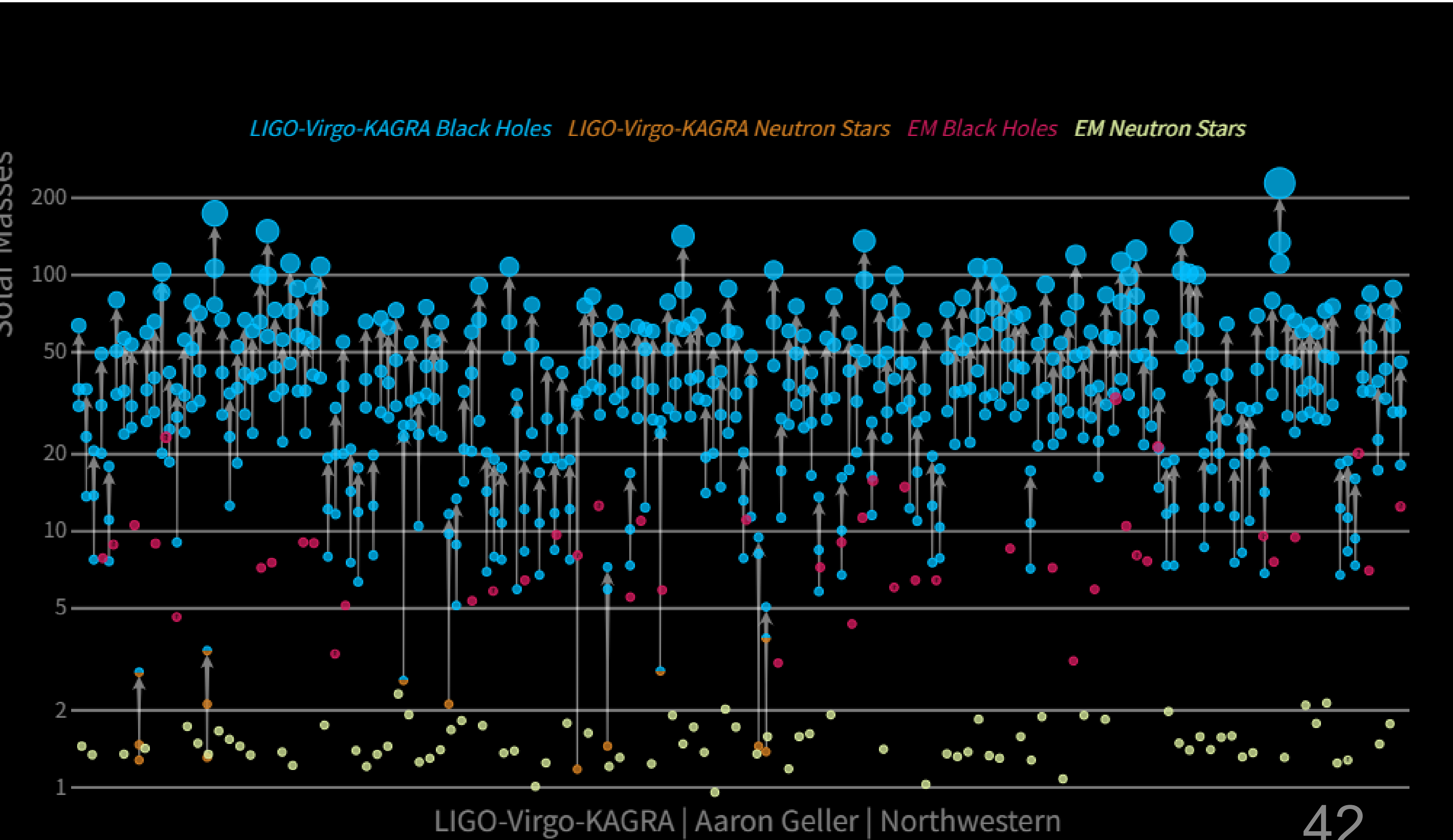
- Louder if closer, tone is higher if mass is lighter



https://youtu.be/gT1VwCTe_90

Mass of Events Detected So Far

Latest list including O4a results released on Aug 25, 2025



Super-Massive Black Holes

Center of galaxies

Intermediate-Mass Black Holes

of unknown origin (>~100 $M_\odot$)

Pair-instability mass gap (65-130 $M_\odot$)

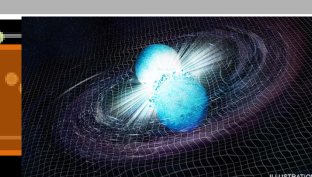
Stellar-Mass Black Holes

from gravitational collapse of stars

(~5-65 $M_\odot$)

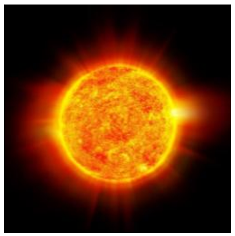
Lower mass gap (3-5 $M_\odot$)

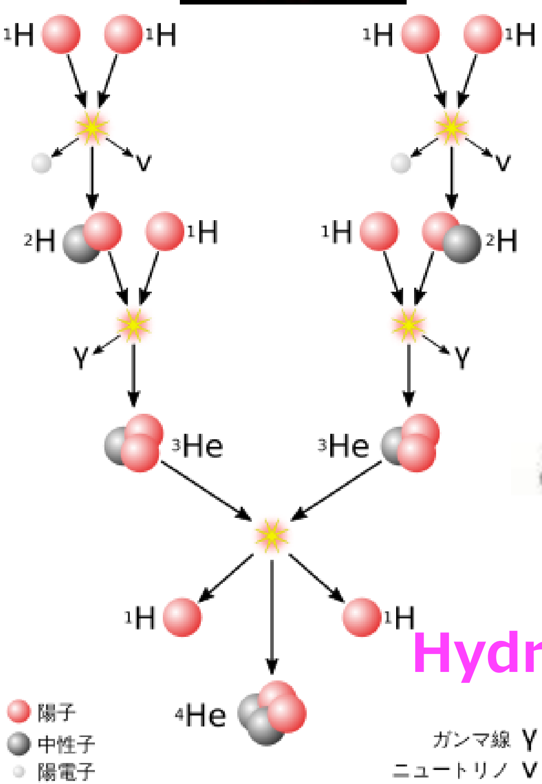
Neutron stars (< ~2 $M_\odot$)



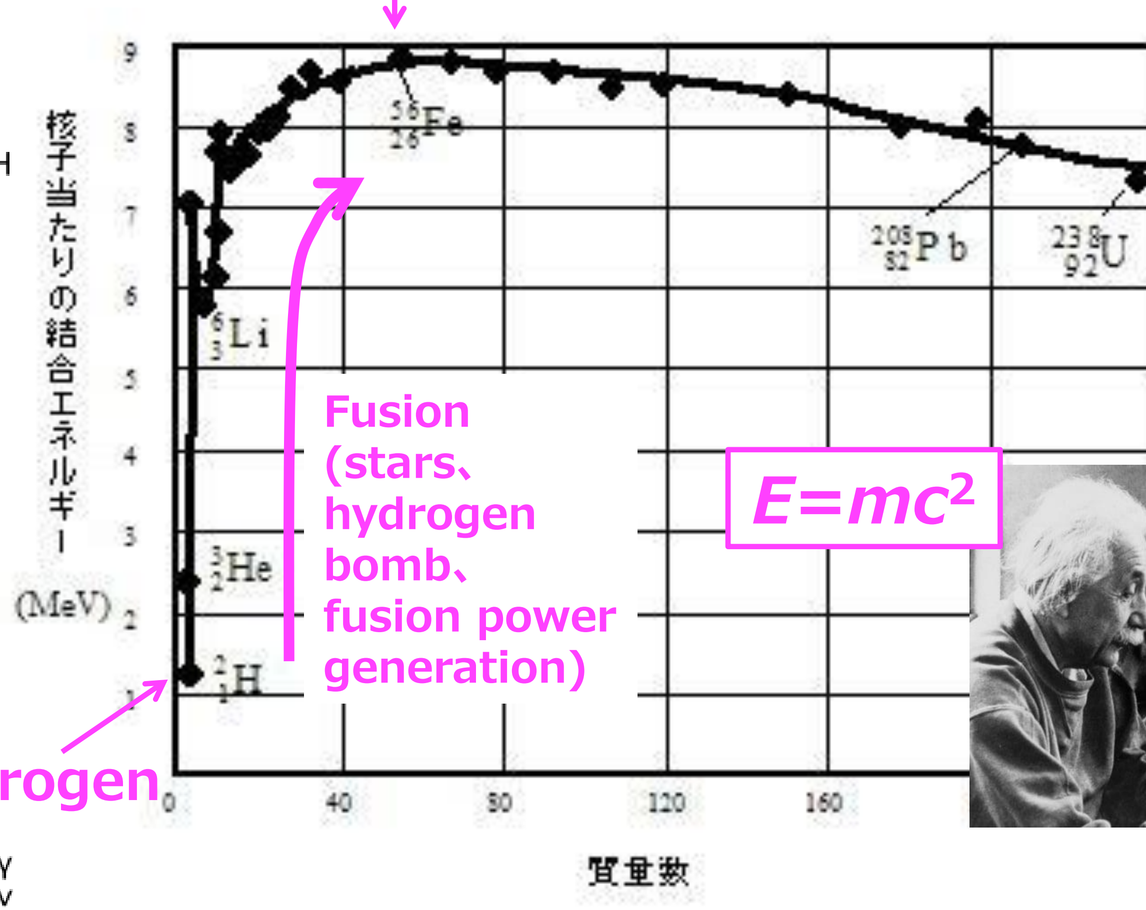
How do stars shine?

- Stars support its gravity with nuclear fusion
- Stars will gravitationally collapse in the end





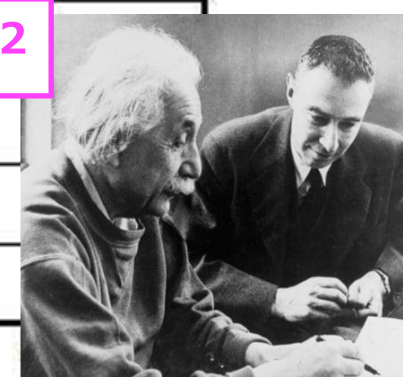
Iron is the most stable



Hydrogen

Fusion (stars、hydrogen bomb、fusion power generation)

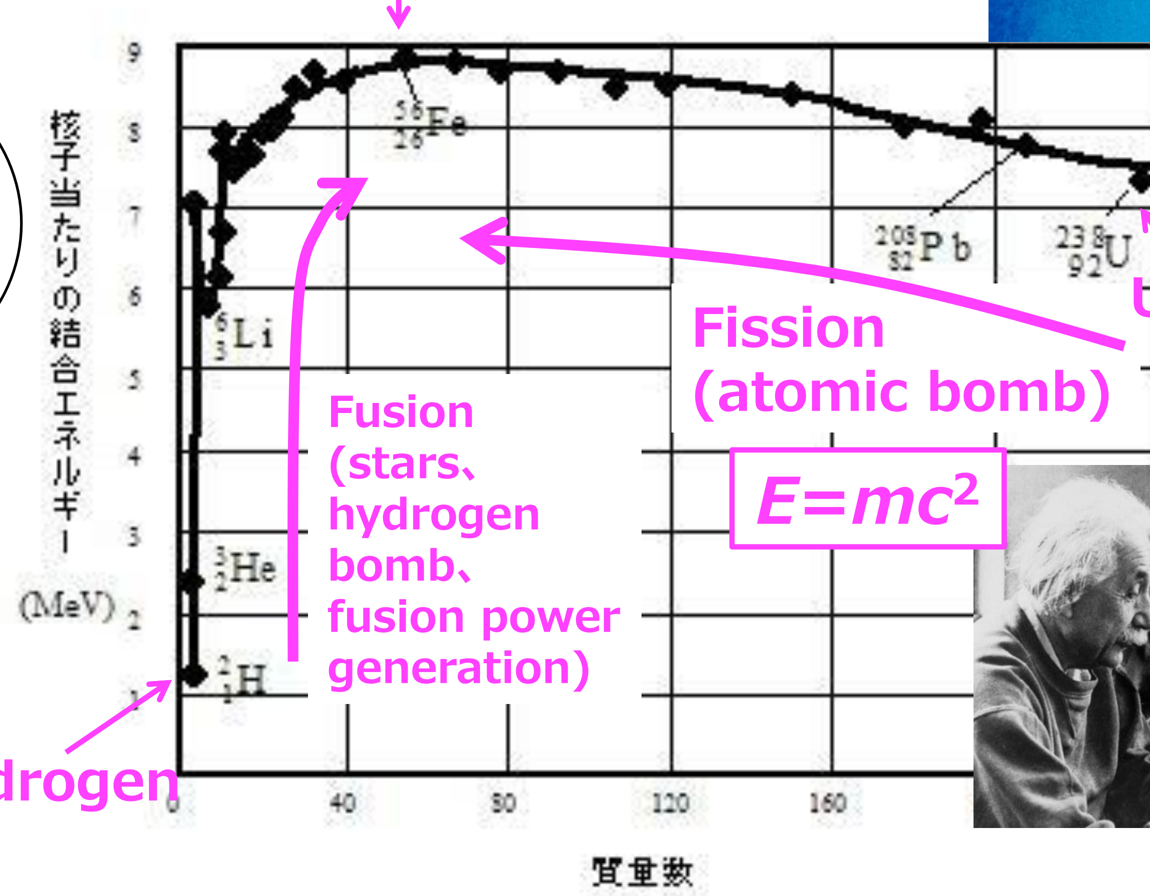
$\boxed{E=mc^2}$



Nuclear Fusion and Fission

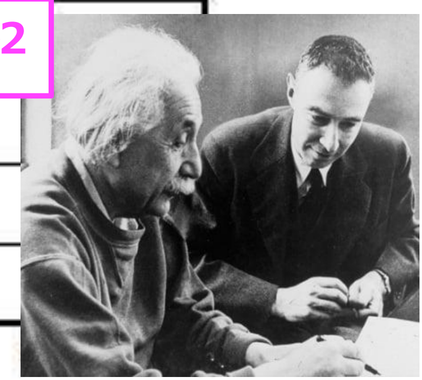
- Gravitational collapse creates heavy elements
- Nuclear fission creates energy
  →Atomic bomb

Iron is the most stable



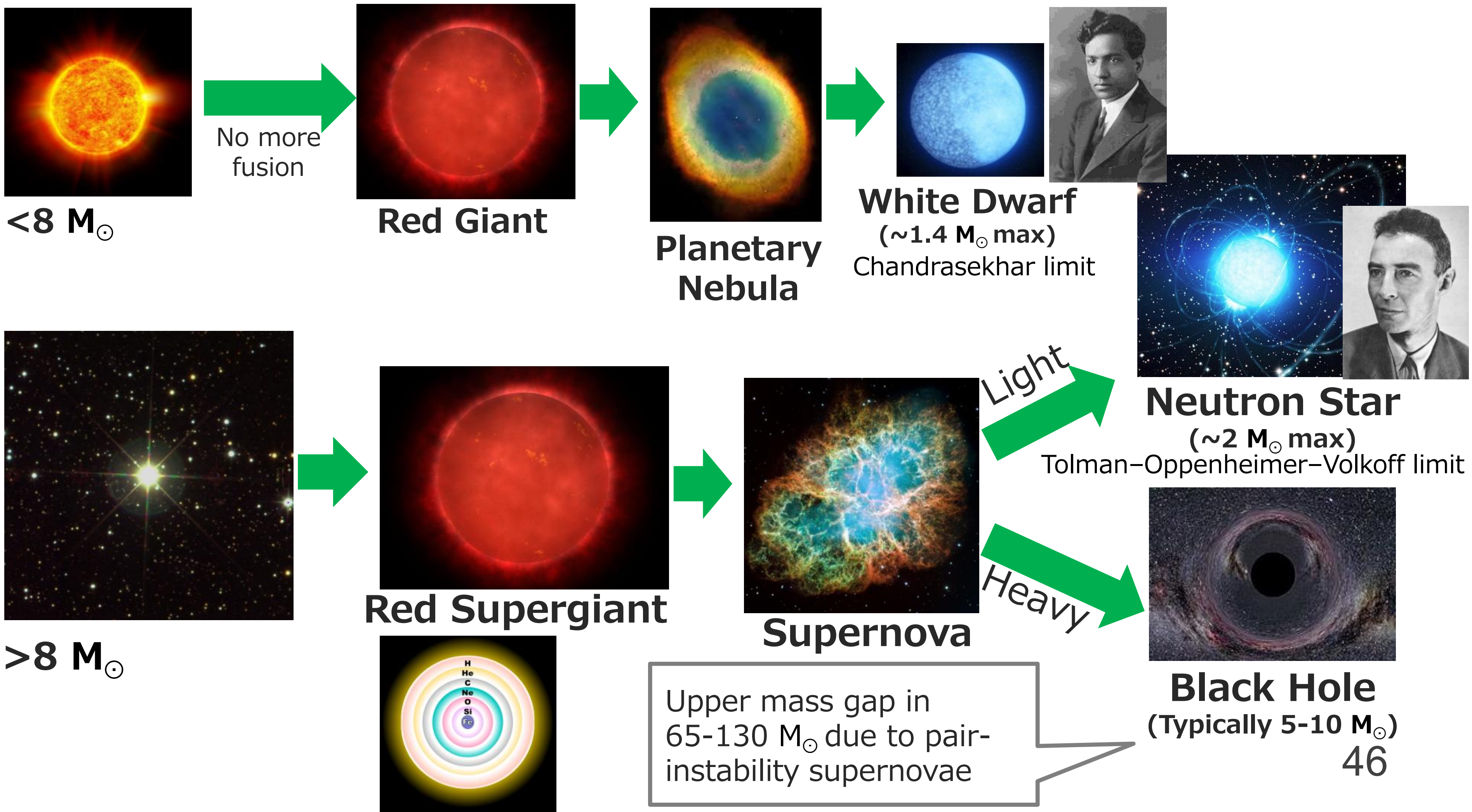
$\boxed{E=mc^2}$

I am become Death, the destroyer of worlds



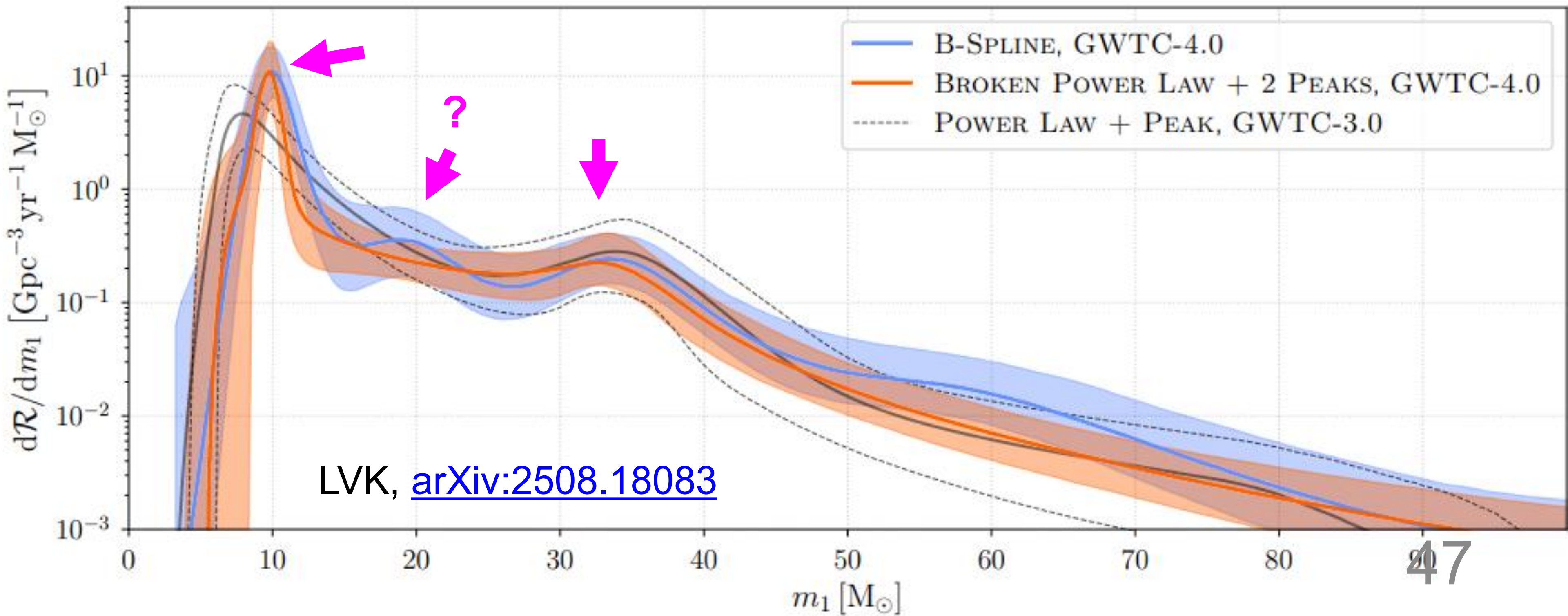
Fate of Heavy Stars

- Mass gap between neutron stars and black holes, upper mass gap due to pair-instability supernovae



Population Studies

- Peaks at ~10 $M_\odot$ and ~35 $M_\odot$, origin uncertain
- Studies on spin to find out if binaries are formed in isolation or dynamically



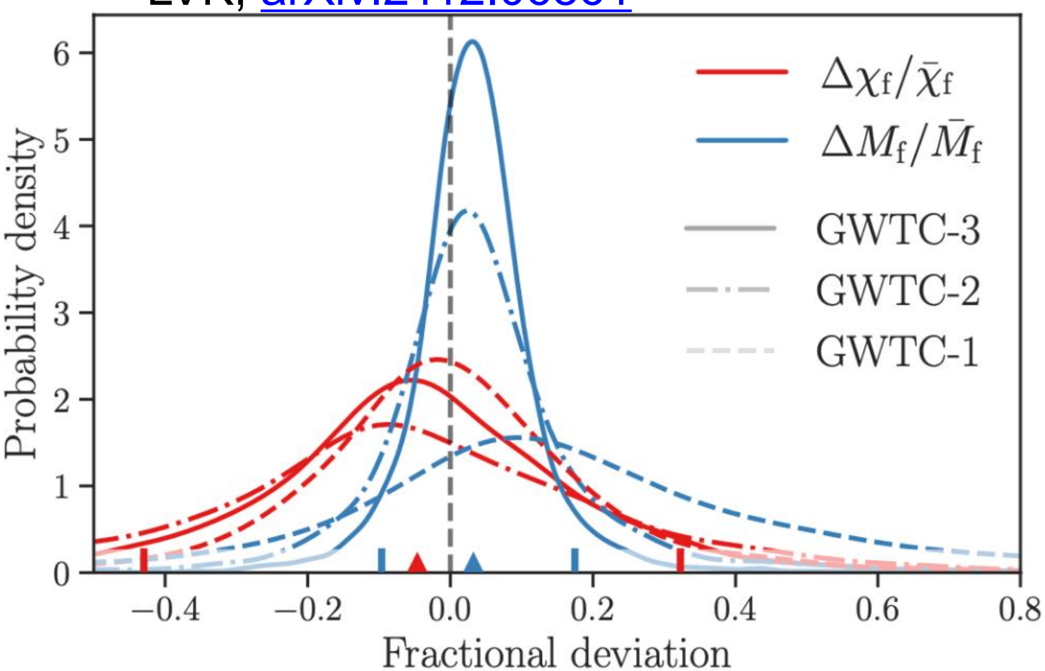
Tests of General Relativity

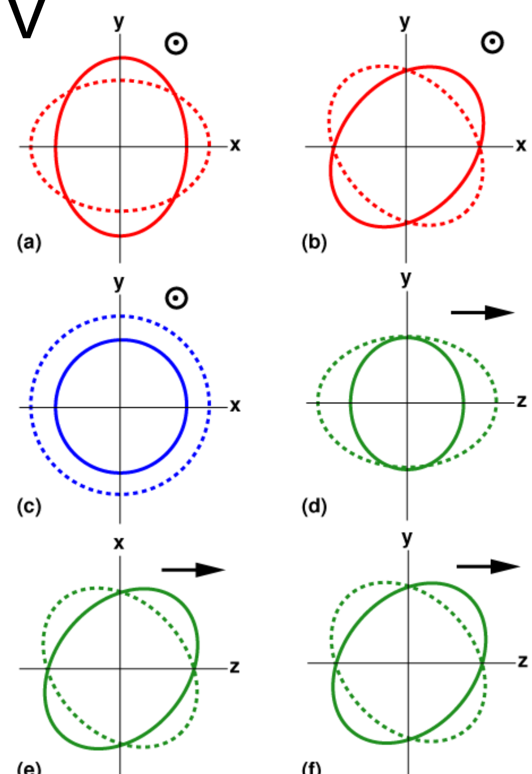
- Novel tests in strong-field regime
- Inspiral and post-inspiral signals are consistent
- No evidence for beyond-GR polarizations
  - Need for 4+ detectors to distinguish 4+ polarizations

Takeda+, PRD 98, 022008 (2018)

- Graviton mass < 1.3×10^{-23} eV

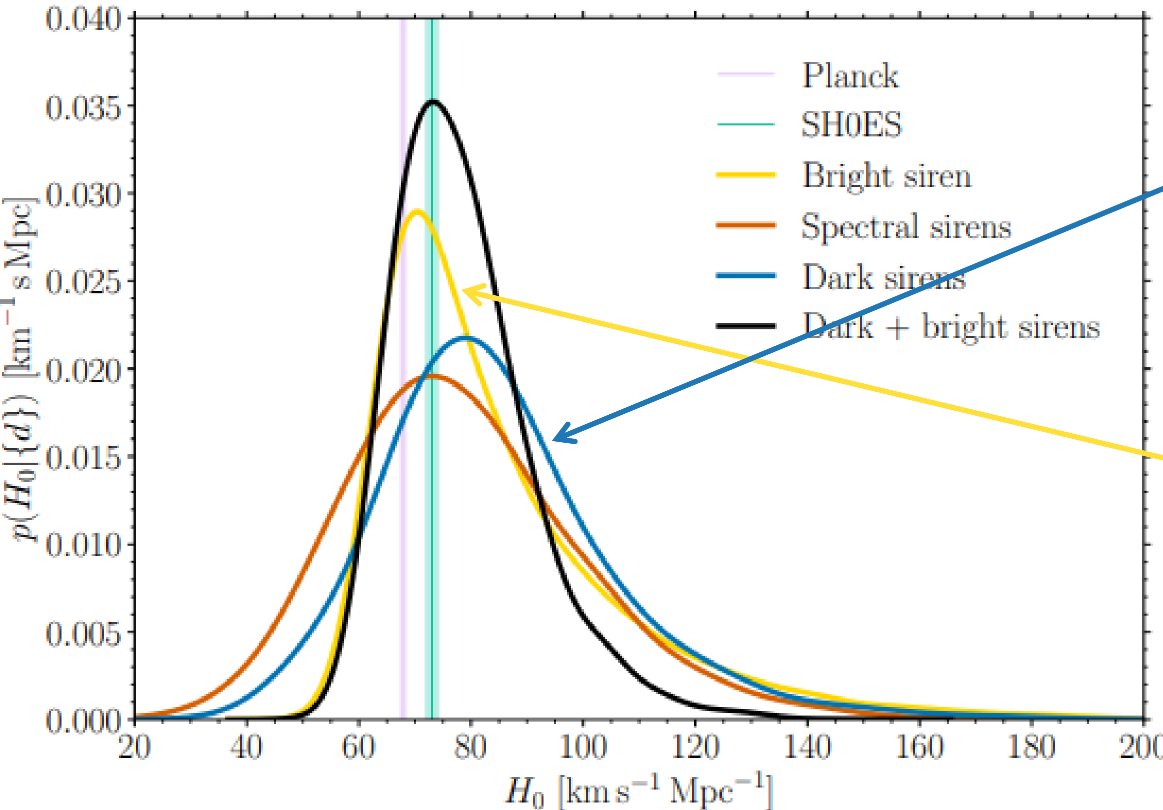
LVK, arXiv:2112.06861





Cosmic Expansion Measurements

- Using luminosity distance measured by GW
- Dark siren also possible by using a galaxy catalog
- Independent test of DESI BAO dynamical dark energy results should be possible in the future e.g. arXiv:2504.04646



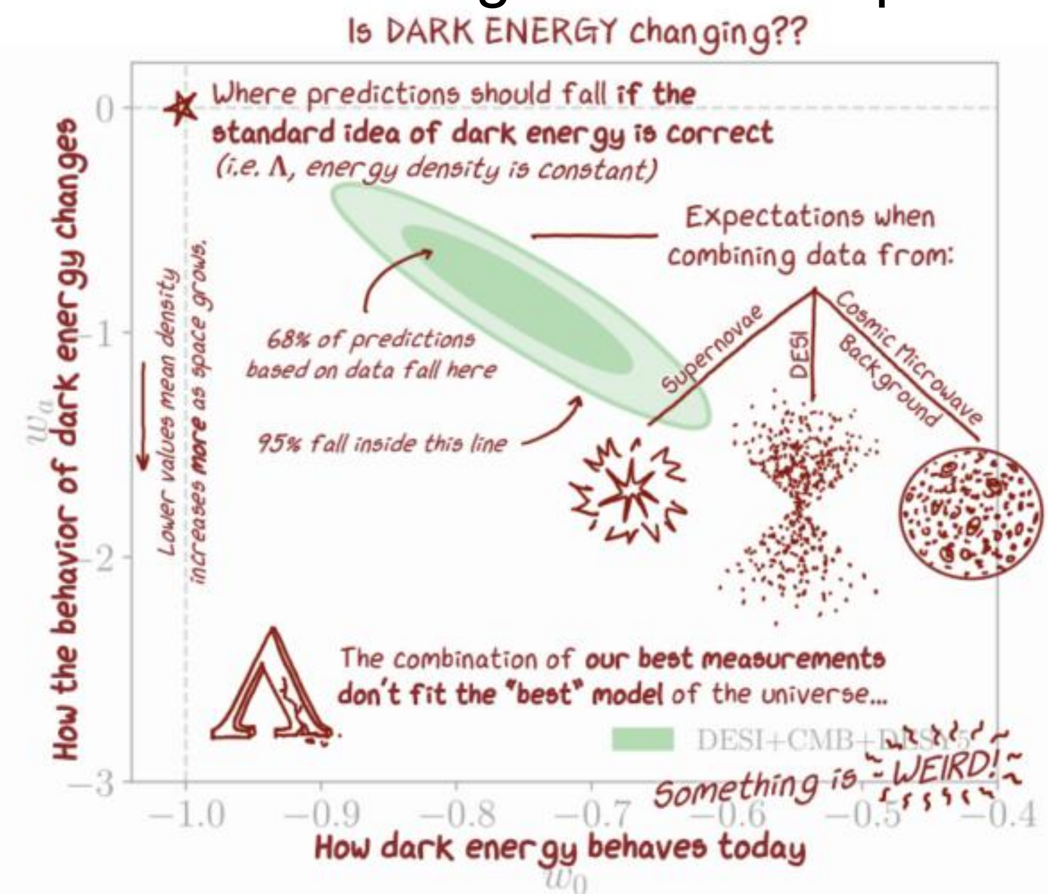
With BBH x galaxy catalog
(dependent on assumptions on BBH source mass distribution)

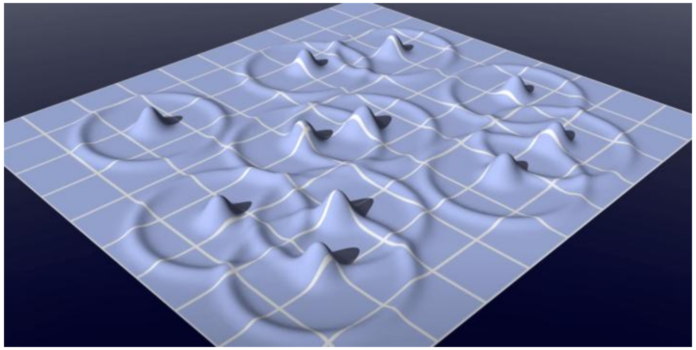
GW170817 only

LVK, arXiv:2509.04348

DESI Results for Cosmic Expansion

- Dark Energy Spectroscopic Instrument Data Release 2
  - 4 m optical telescope in Arizona DESI, [arXiv:2503.14738](https://arxiv.org/abs/2503.14738)
- Baryon acoustic oscillation measurements from more than 14 million galaxies and quasars





$$w(z) = w_0 + w_a \frac{z}{1+z}$$

-1 is ΛDCM

0

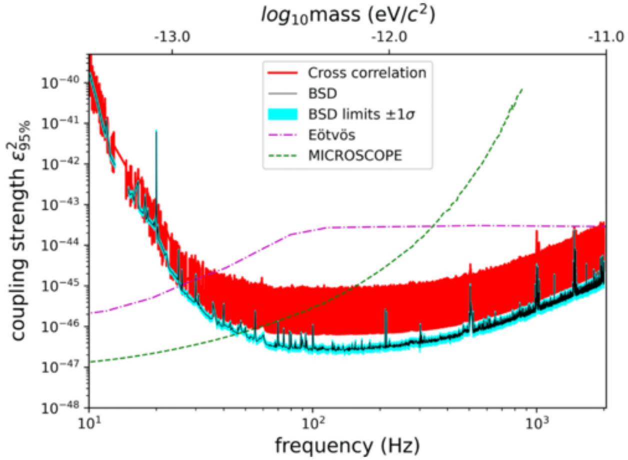
2.8-4.2σ tension

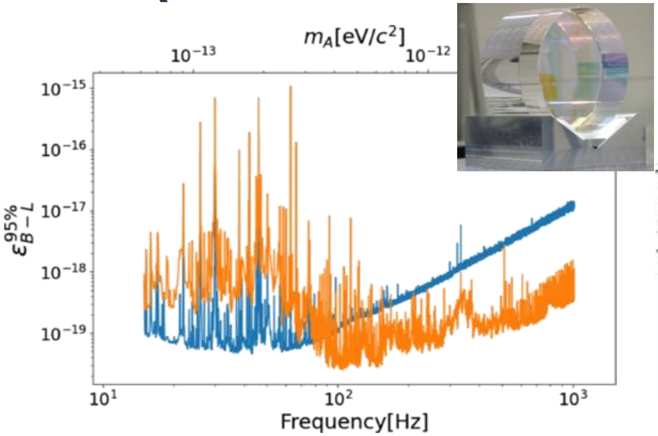
Cosmological constant is not constant?
Violation of ΛCDM?

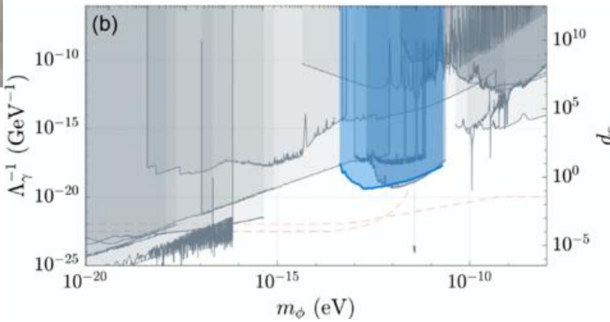
Searches for New Physics

Personal Picks!

Ultralight dark matter (10^{-13}~10^{-11} eV range)





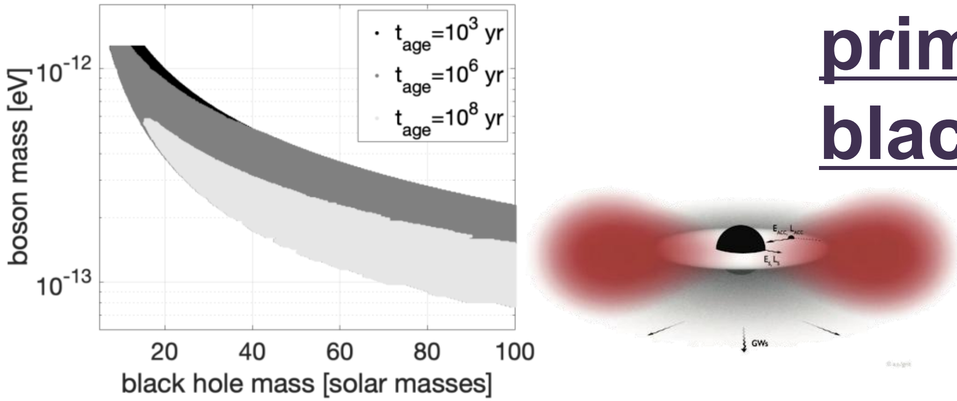


Vector DM from LV
LVK, PRD 105, 063030 (2022)

Vector DM from KAGRA
LVK, PRD 110, 042001 (2024)

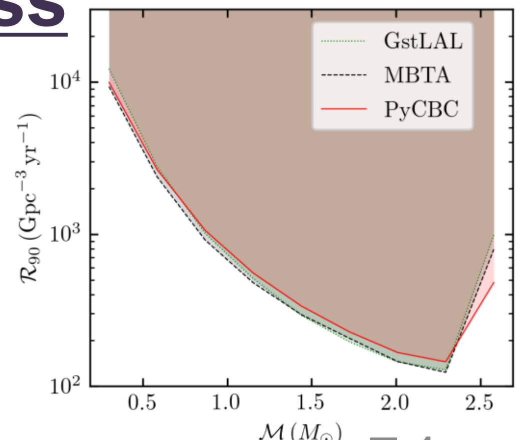
Scalar DM from LIGO/GEO
Göttel+, PRL 133, 101001 (2024)

Boson clouds



LVK, PRD 105, 102001 (2022)

Sub-solar-mass primordial black holes

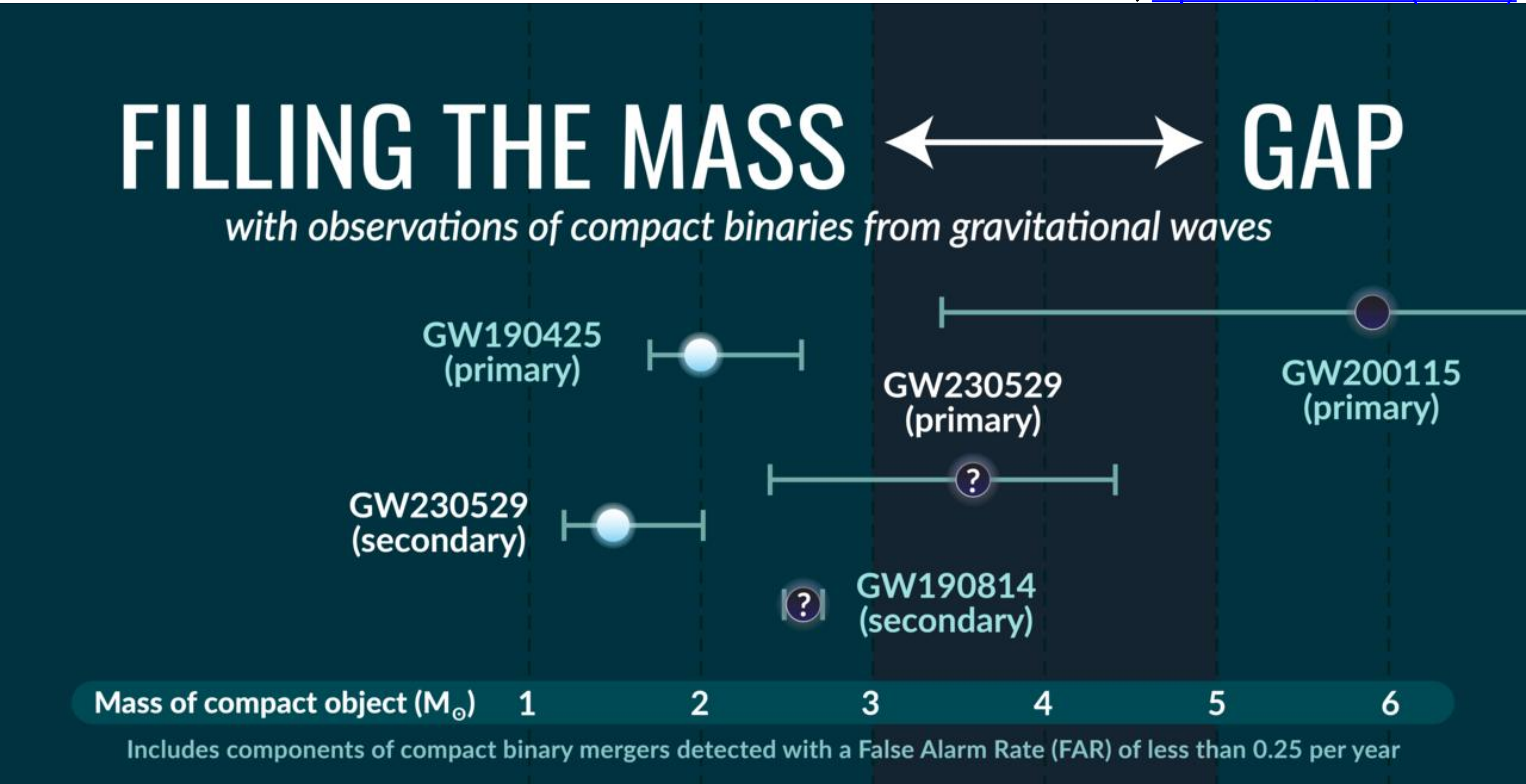


LVK, MNRAS 524, 5984 (2023)

GW230529: Lightest NS-BH?

- Single detector event, no EM counterparts

LVK, [ApJL 970, L34 (2024)]

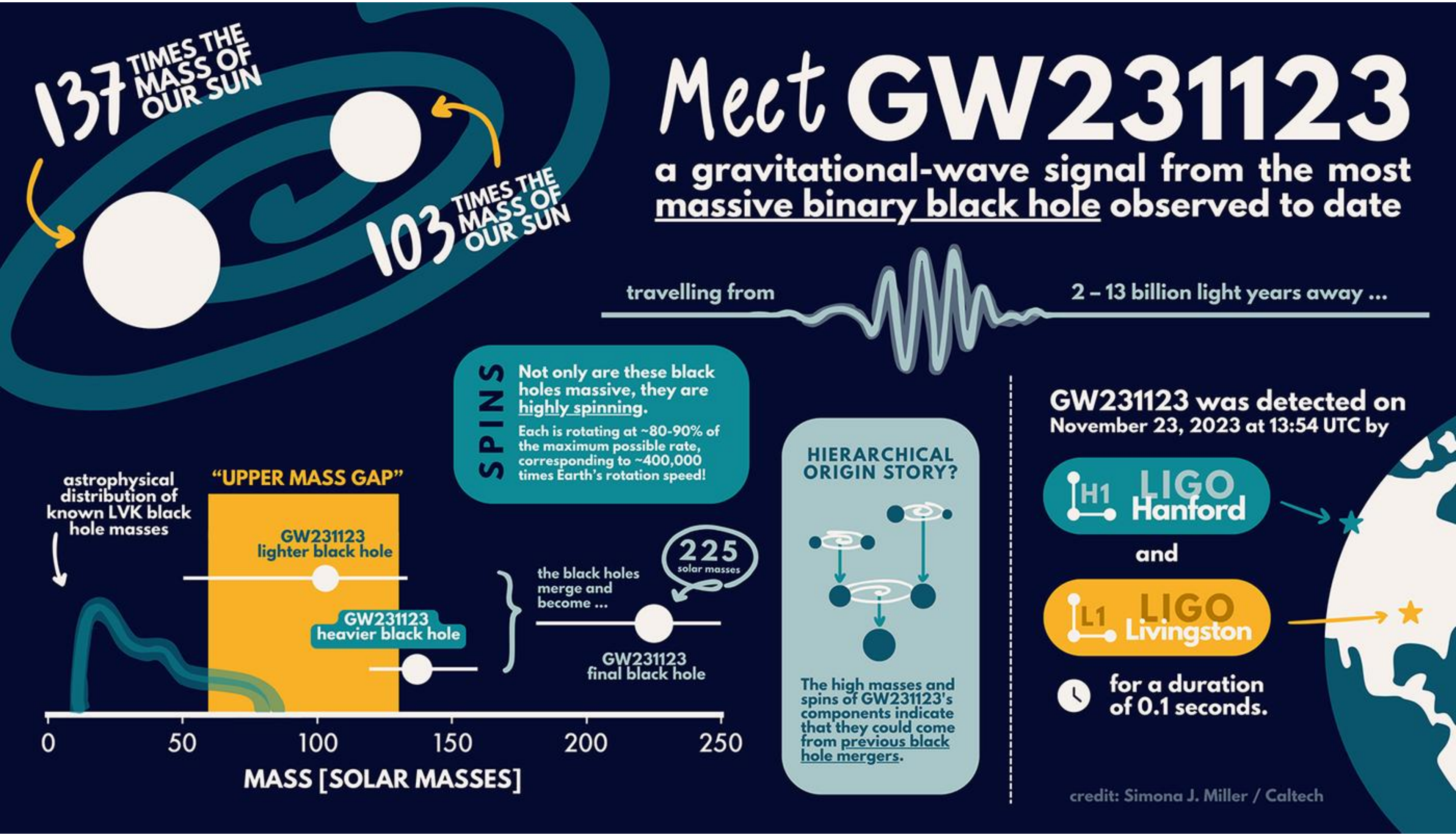


Credit: S. Galaudage, Observatoire de la Côte d'Azur.

GW231123: Heaviest BBH

- Released on July 10, 2025

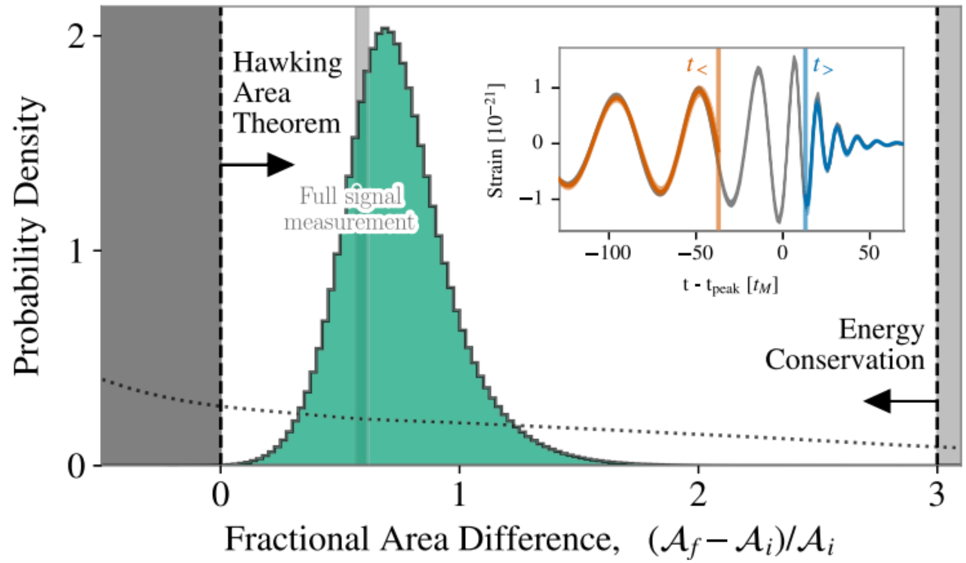
LVK, [arXiv:2507.08219](https://arxiv.org/abs/2507.08219)

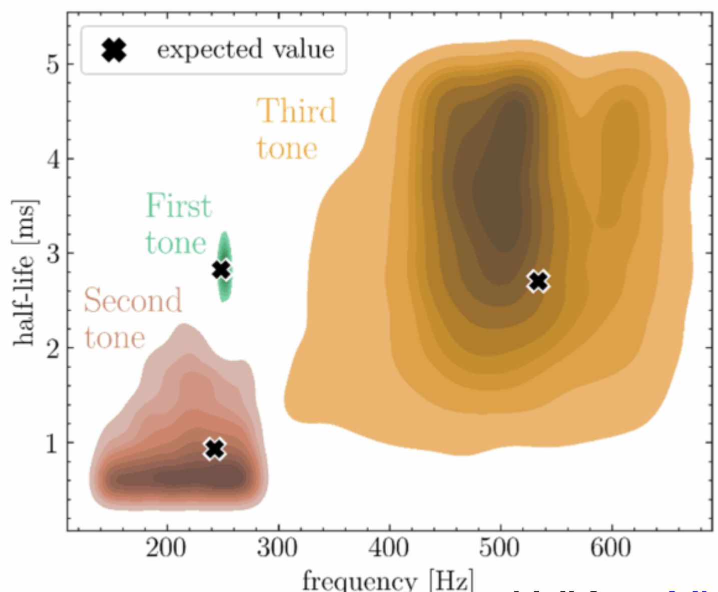


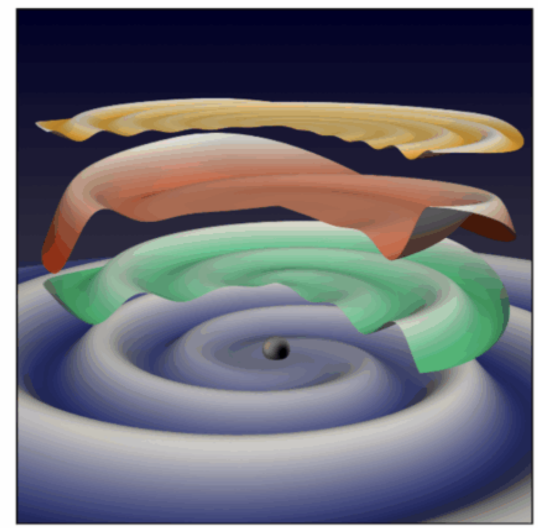
GW250114: Loudest BBH

LVK, [PRL 135, 111403 (2025)]

- Released on September 9, 2025
- Network SNR of 80 (Hanford + Livingston)
- Confirmation of overtones
- Hawking's area law (BH entropy increases)

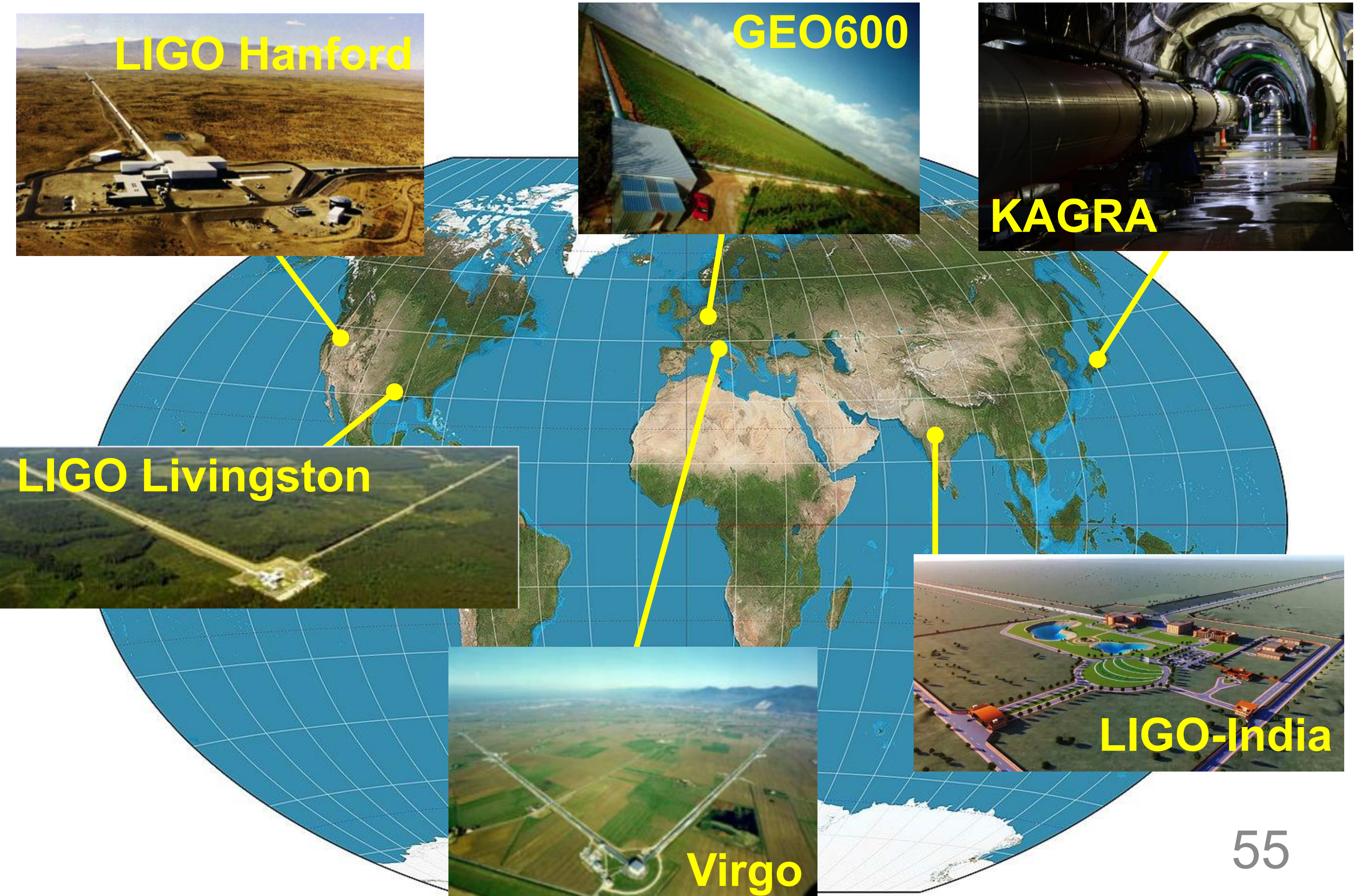






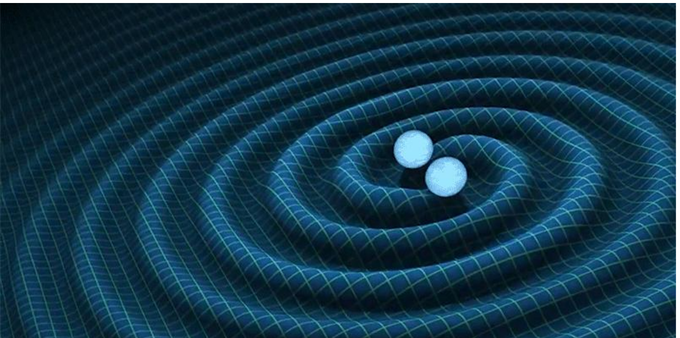
LVK, [arXiv:2509.08054]

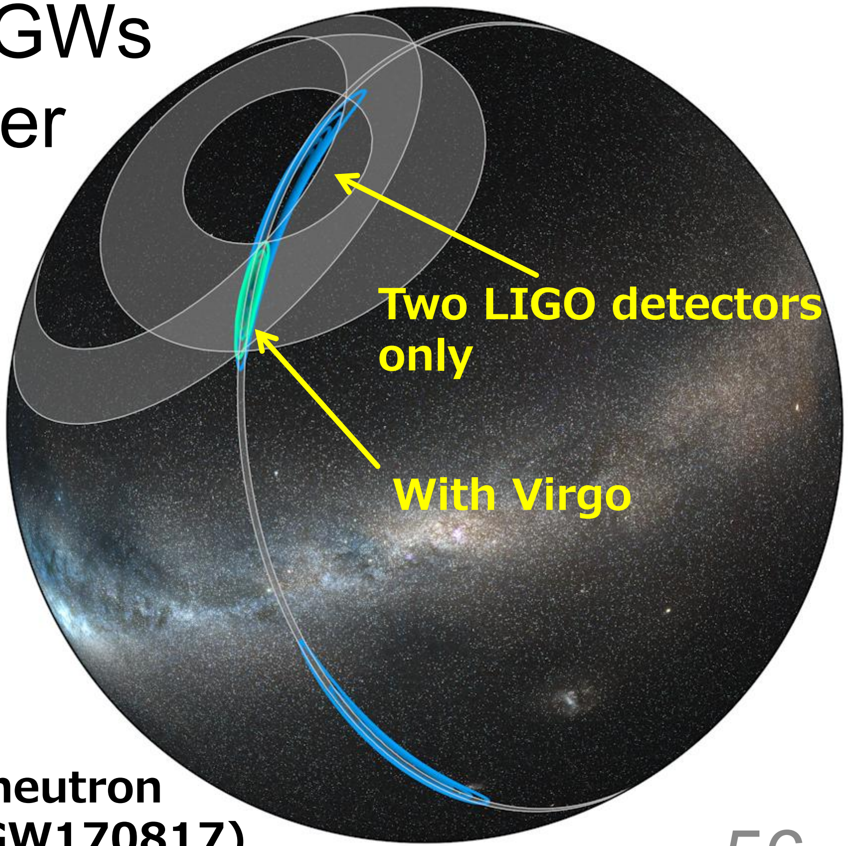
Global Network of GW Detectors



Why Multiple Detectors?

- Triangulation for sky localization
  → allows to look for electro-magnetic counterparts (hear and see the event)
- Measure polarization of GWs to estimate distance better
  → Hubble constant
- Look for non-standard GW polarizations to test general relativity



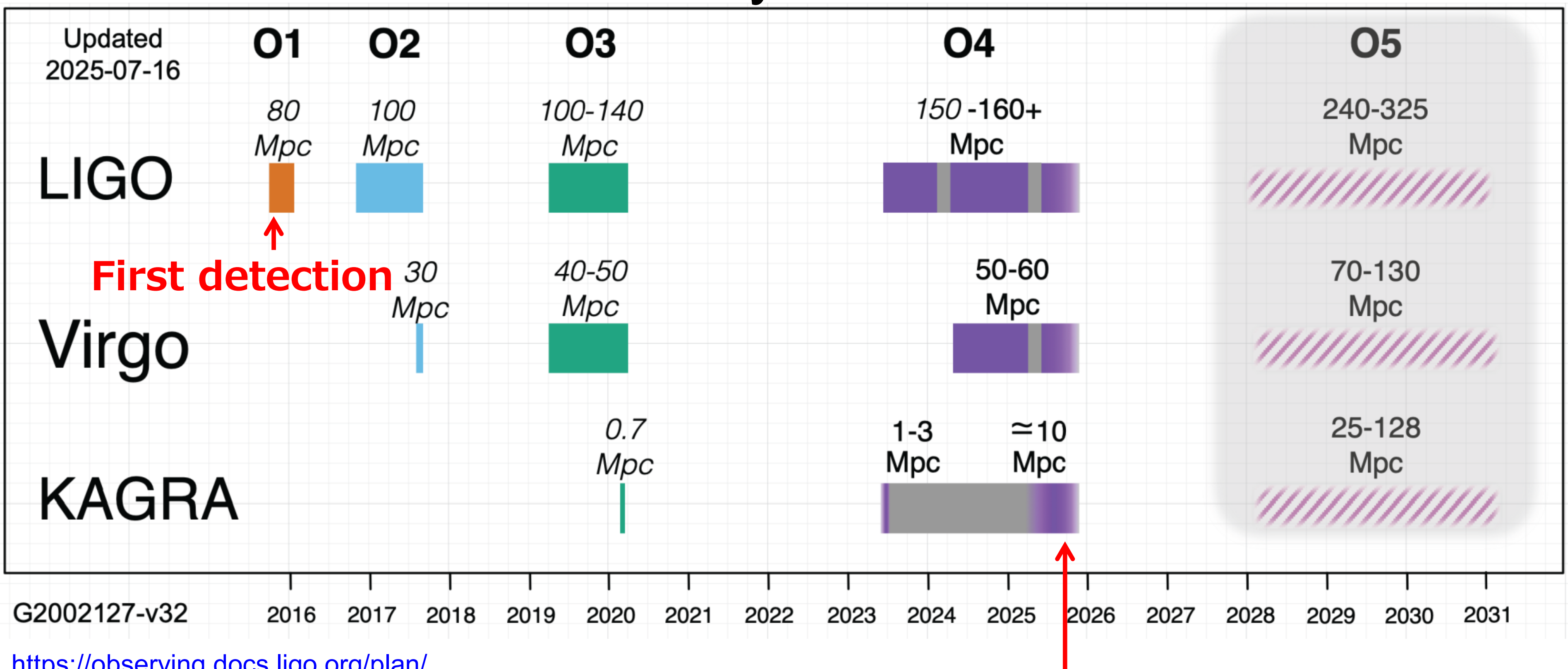


First binary neutron star event (GW170817)

Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)

LIGO-Virgo-KAGRA Observations

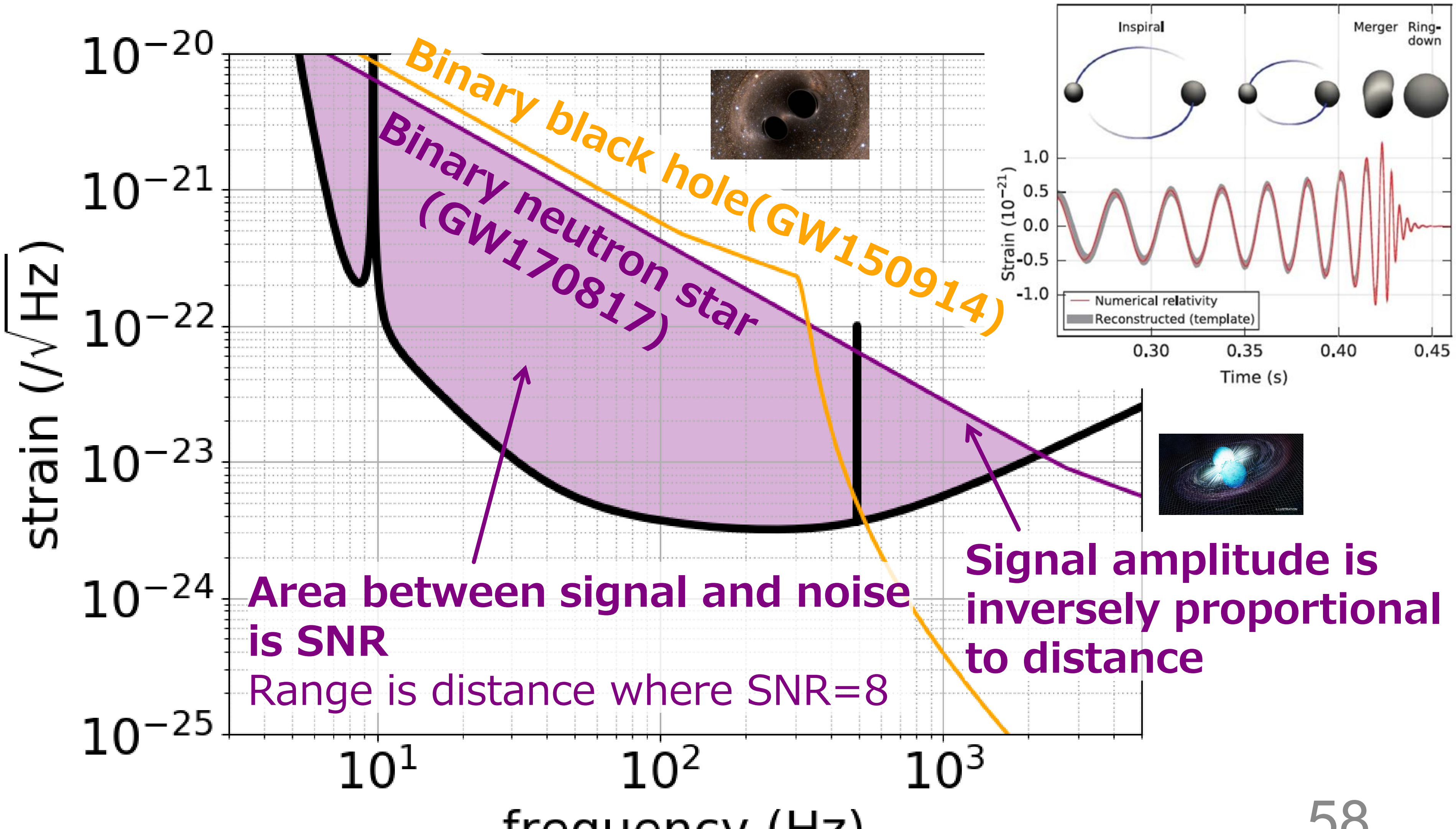
- Coordinated runs to detect GW signals by multiple detectors for better sky localization etc.



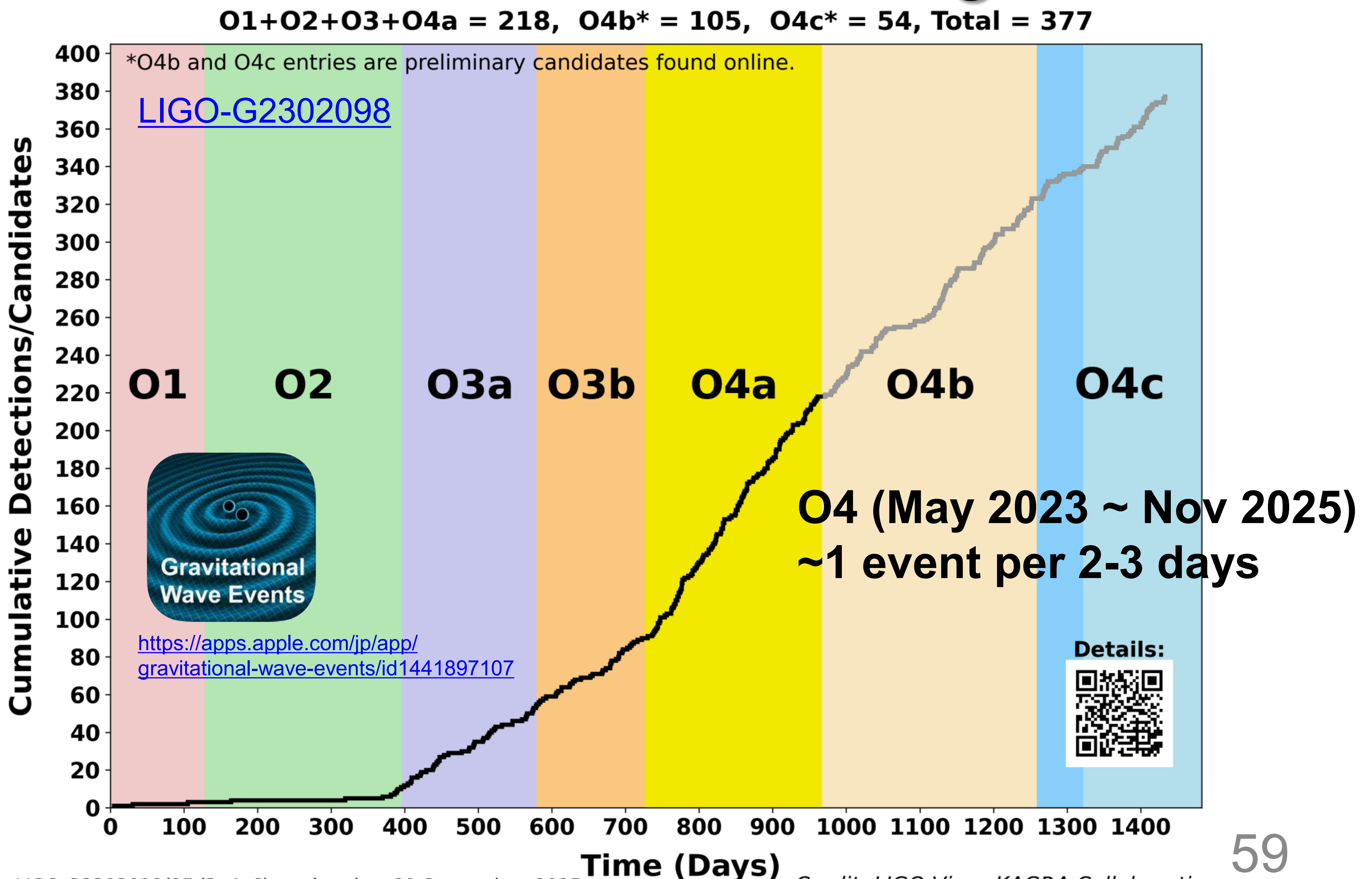
https://observing.docs.ligo.org/plan/

Inspiral Range

- x2 the sensitivity, x8 the detection rate



Now in O4 Observing Run

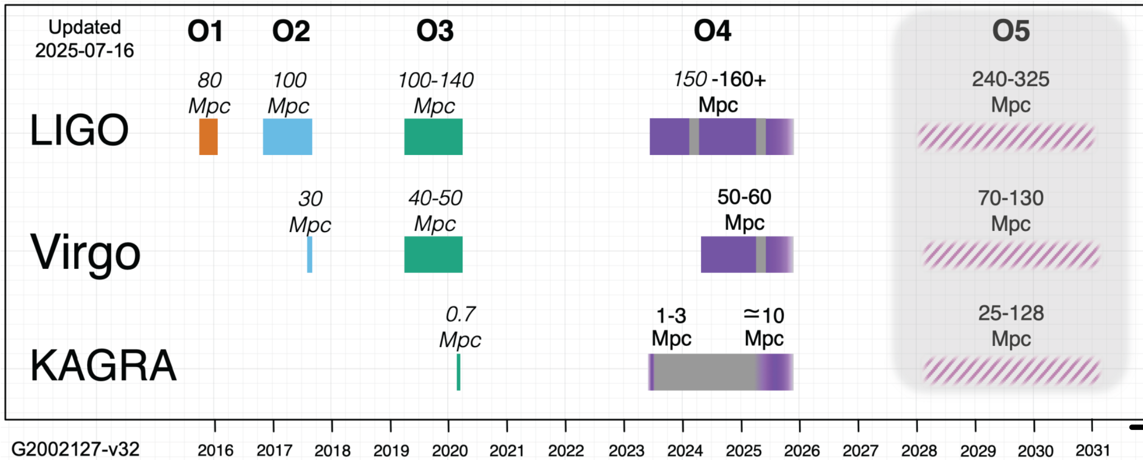


LIGO-G2302098(85d3a4e6), updated on 29 September, 2025

Credit: LIGO-Virgo-KAGRA Collaboration

Next Generation Detectors

- Next generation detectors coming in late 2030s, with space-based detectors (multi-band!)



O6

LIGO A#

Virgo_nEXT

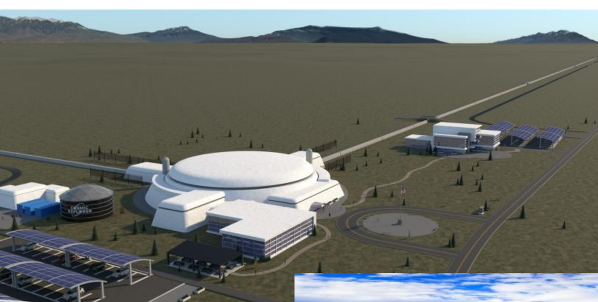
KAGRA HF ?

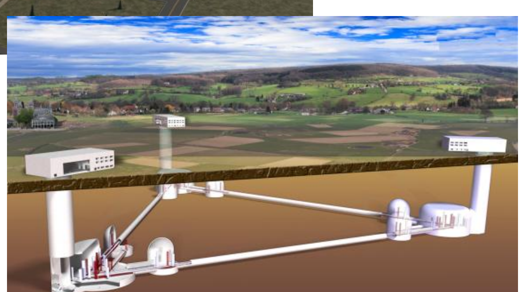
2030s **2040s**

LIGO India

Cosmic Explorer

Einstein Telescope

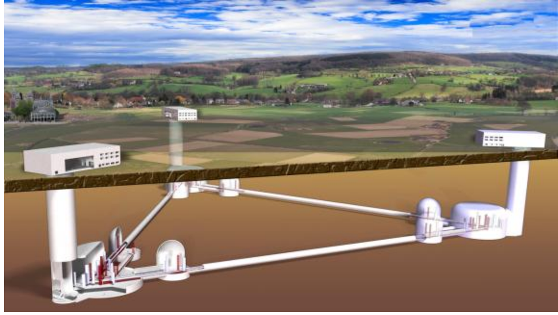




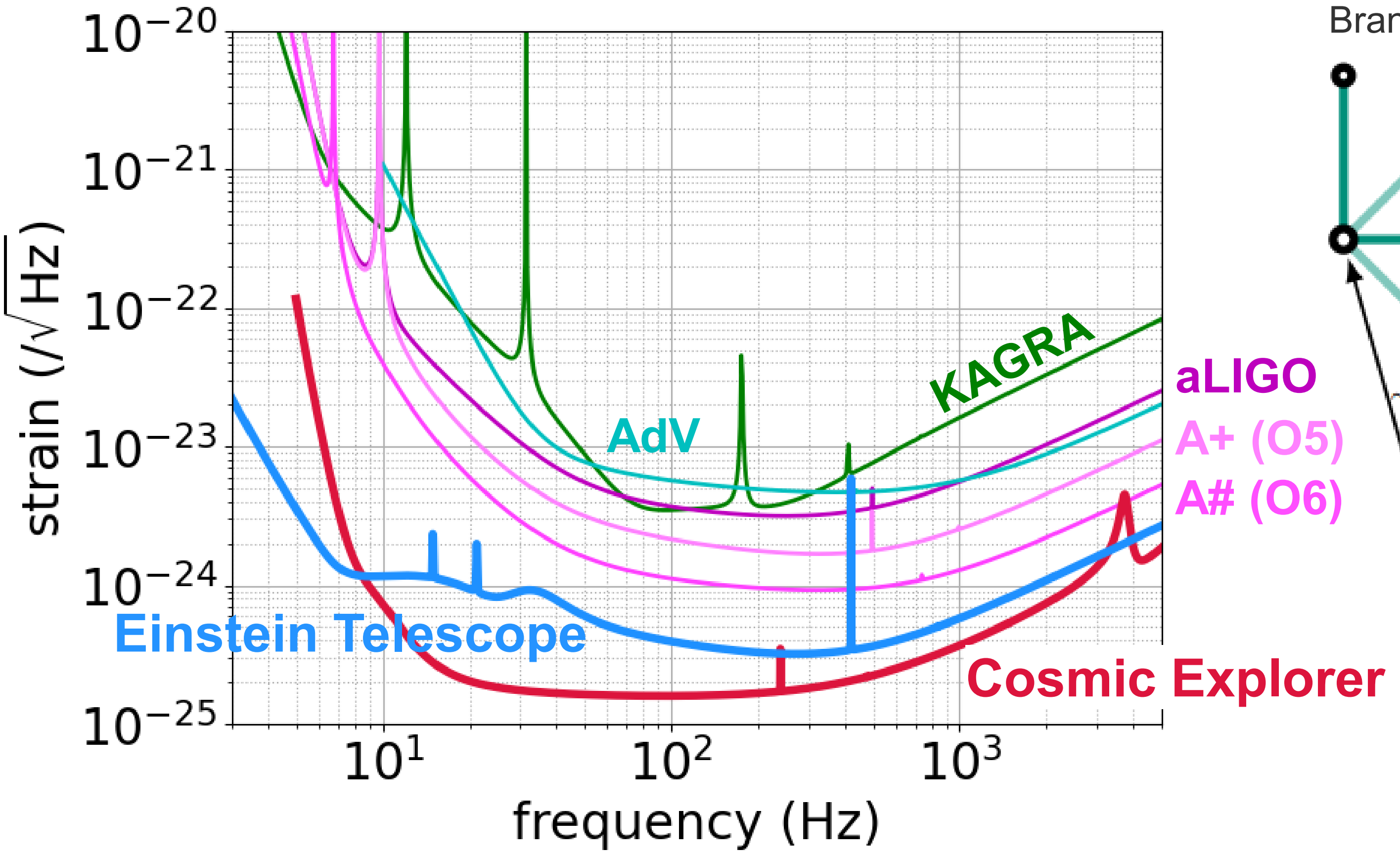
B-DECIGO

LISA

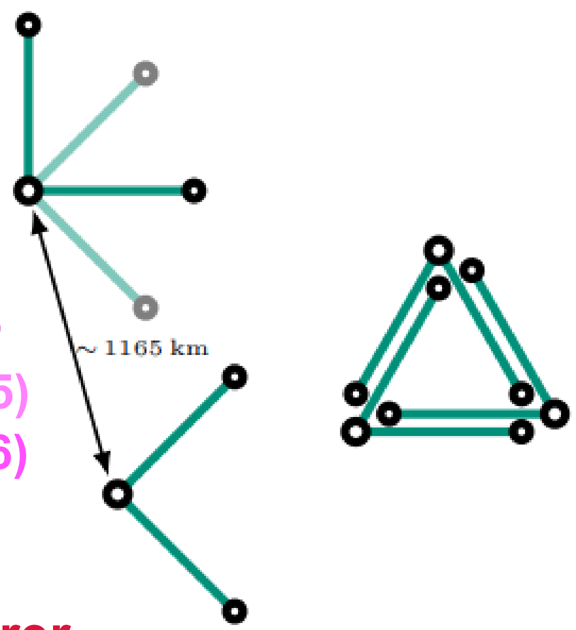
Einstein Telescope



- Xylophone configuration
  - 10 K silicon interferometer for low frequency
  - Room temp. fused silica interferometer for high frequency
- 10 km △ or two 15 km L, underground

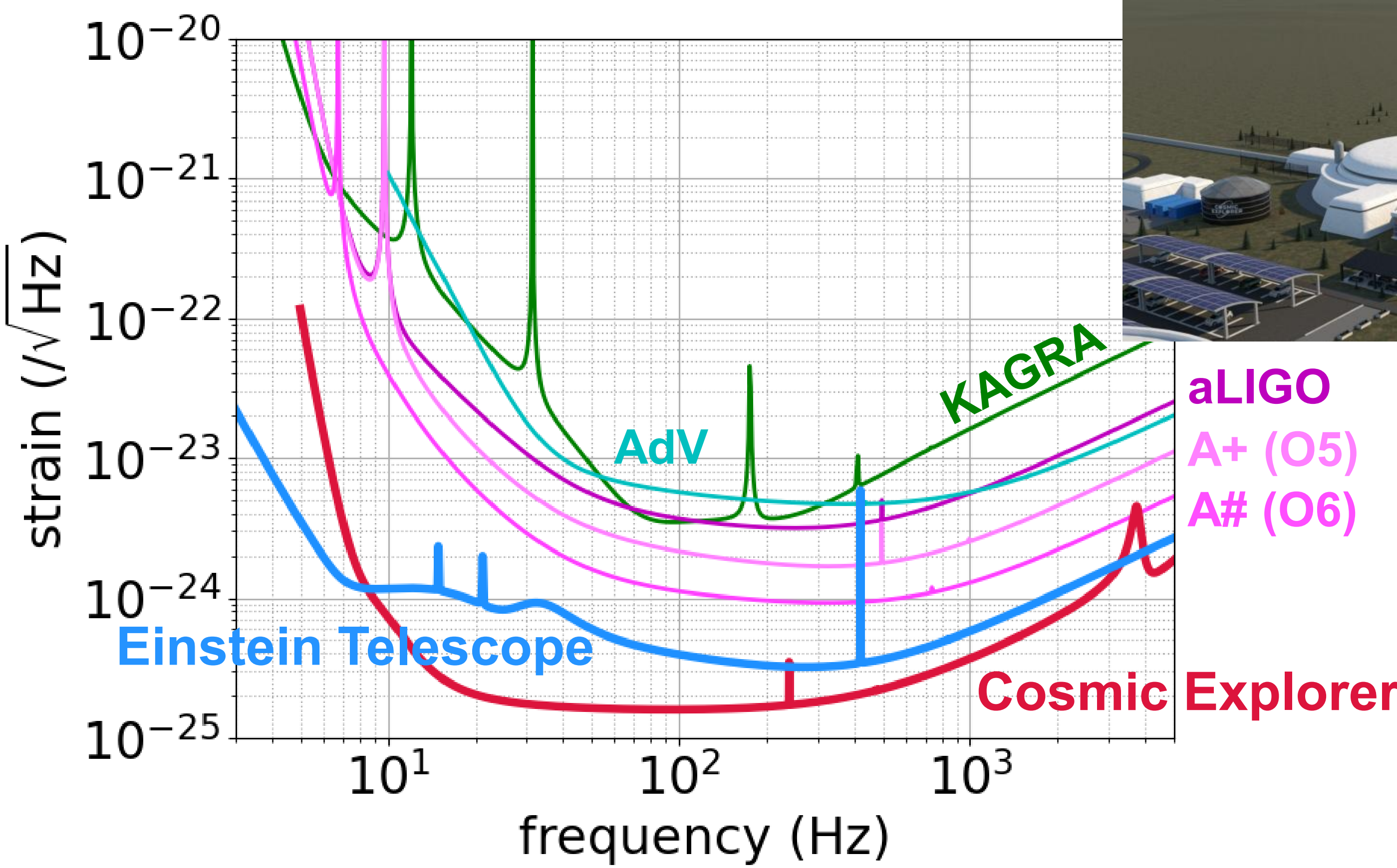


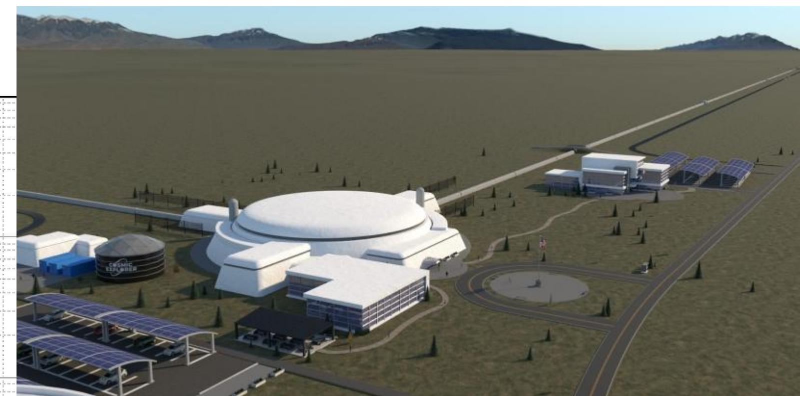
Branchesi+, JCAP 07, 068 (2023)



Cosmic Explorer

- 40 km and 20 km L-shaped
  - 40 km only if ET in Europe
- Room temp. fused silica (technical overlap with A#)

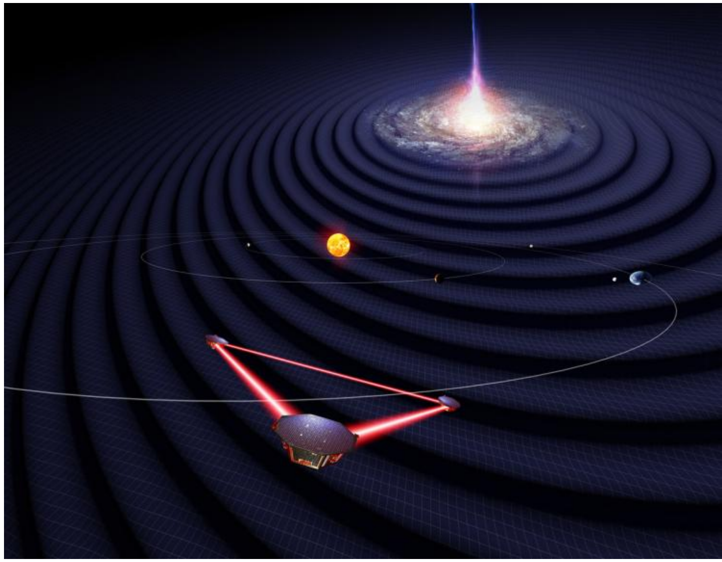




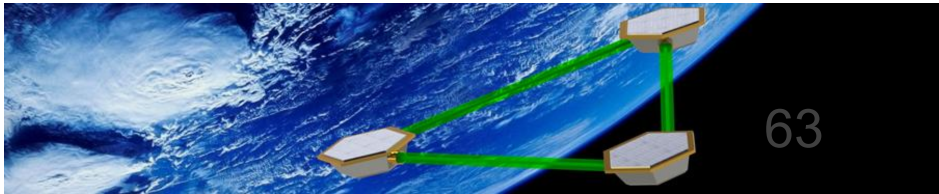
Space-Based Detectors in 2030s

- Arm length of O(10) km is a limit for ground-based
- Also, seismic isolation below 10 Hz is tough

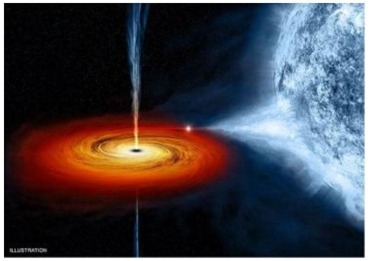
→ Space-based detectors



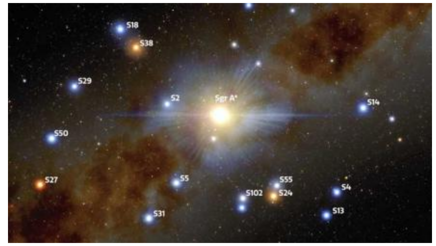
- LISA(りさ): 1-10 mHz region
  - ESA-lead
  - To be launched 2035
  - LISA Pathfinder succeeded in 2016
  - Similar Chinese projects: TianQin (天琴), Taiji (太極)
- DECIGO(でさいご): 0.1-10 Hz region
  - Japan, 2030s



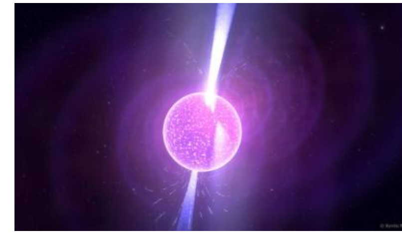
Electromagnetic Wave Spectrum



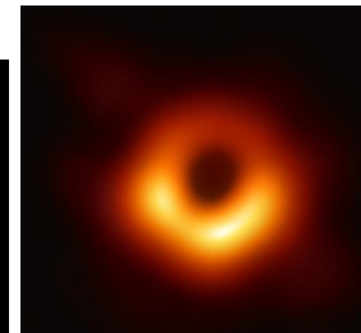
Discovery of Black Holes



Discovery of Super-Massive Black Holes

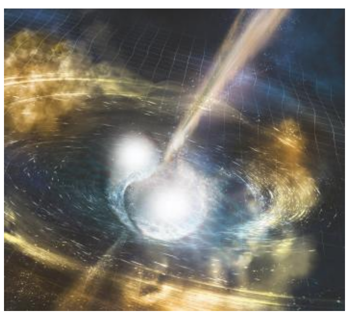


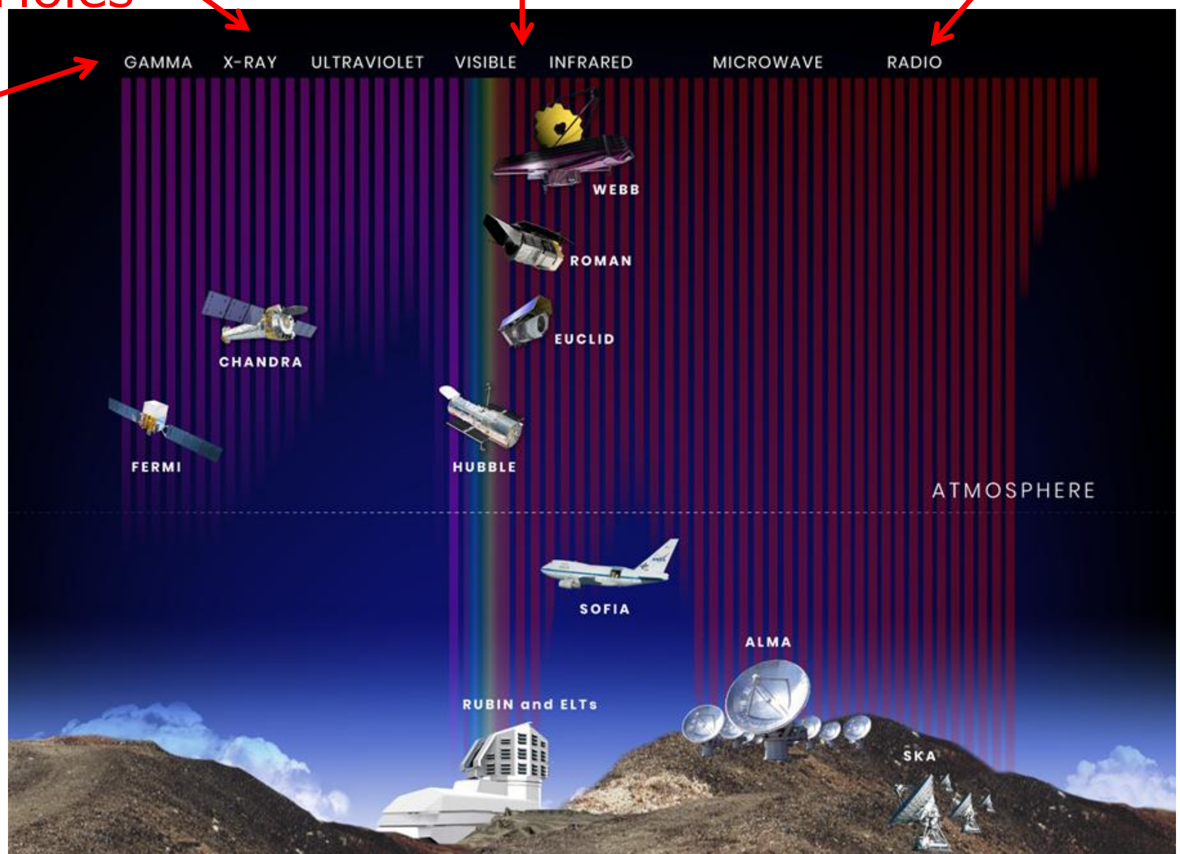
Discovery of Pulsars



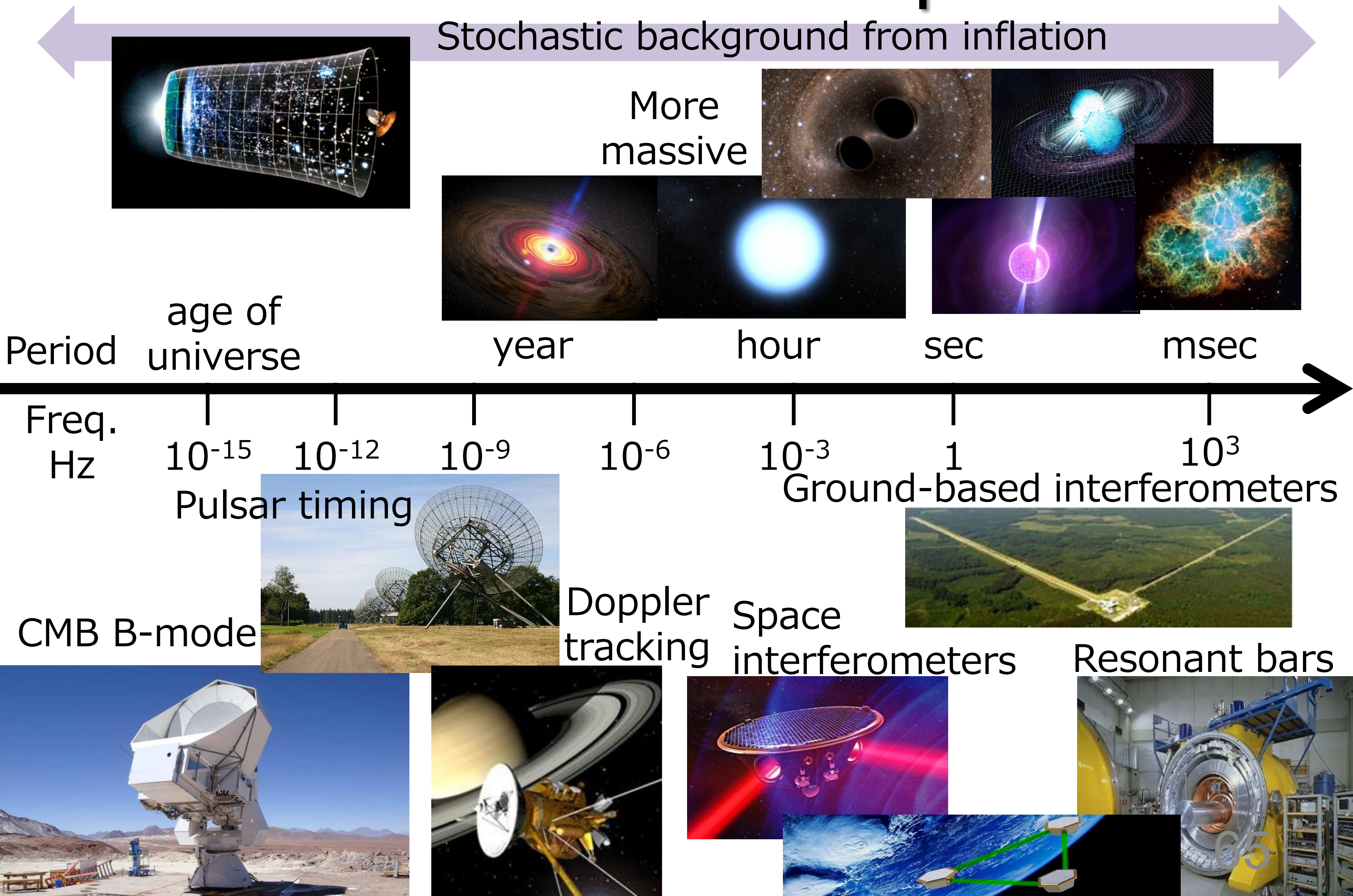
Black Hole Shadow

Gamma-ray Bursts

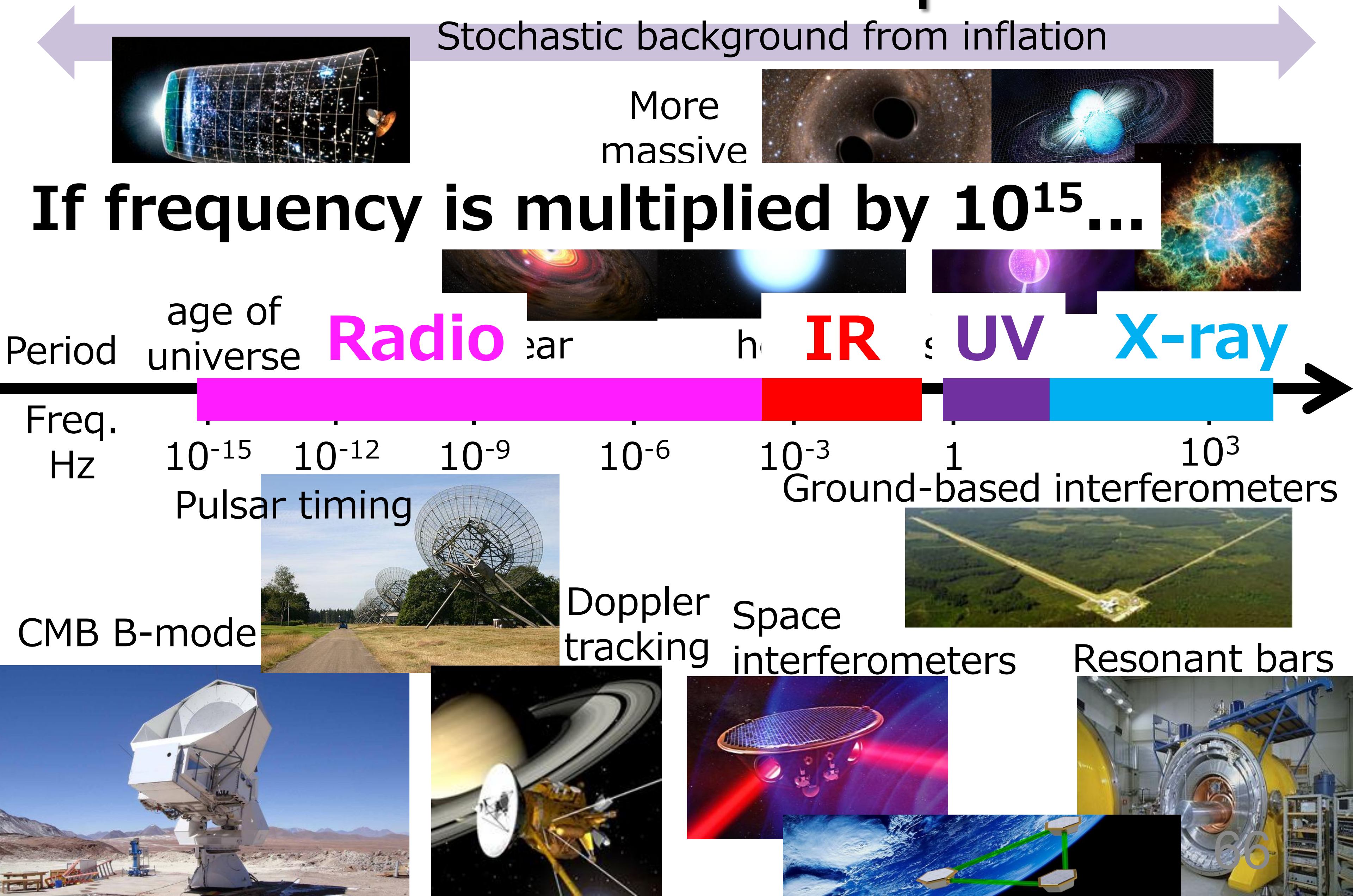




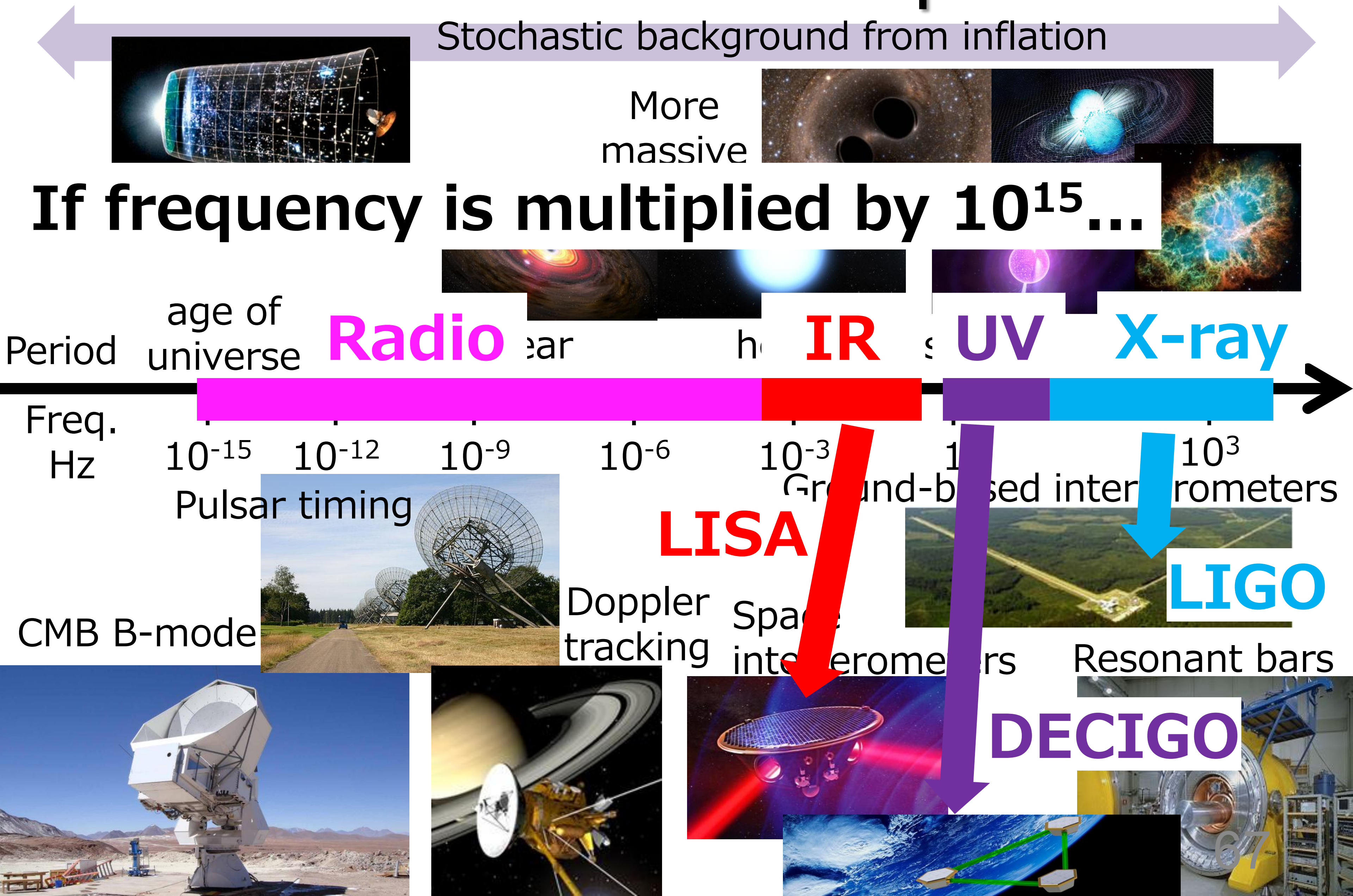
Gravitational Wave Spectrum



Gravitational Wave Spectrum



Gravitational Wave Spectrum

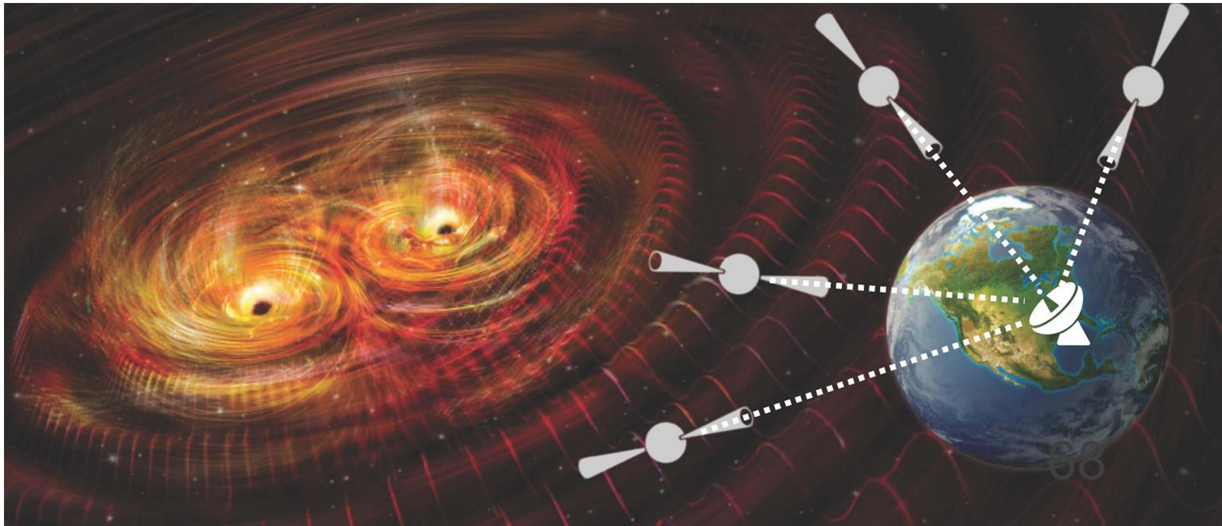


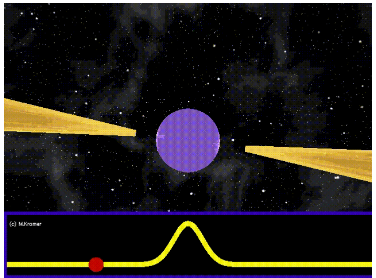
Pulsar Timing Array

- Measures arrival times of pulses for years
- June 2023: Evidence for GW background
  - NANOGrav: North America (15 years of data)
  - EPTA: Europe
  - PPTA: Australia
  - InPTA: India
  - CPTA: China

Celebration
@Caltech

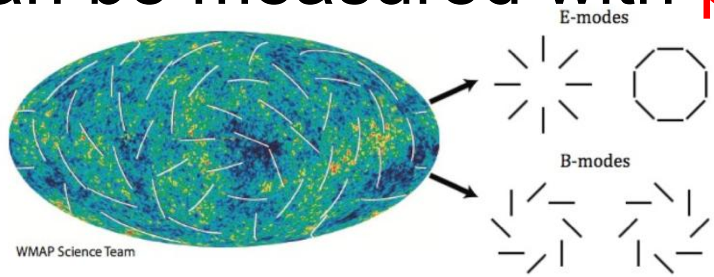
- Superposition of GWs from many super-massive BHs?



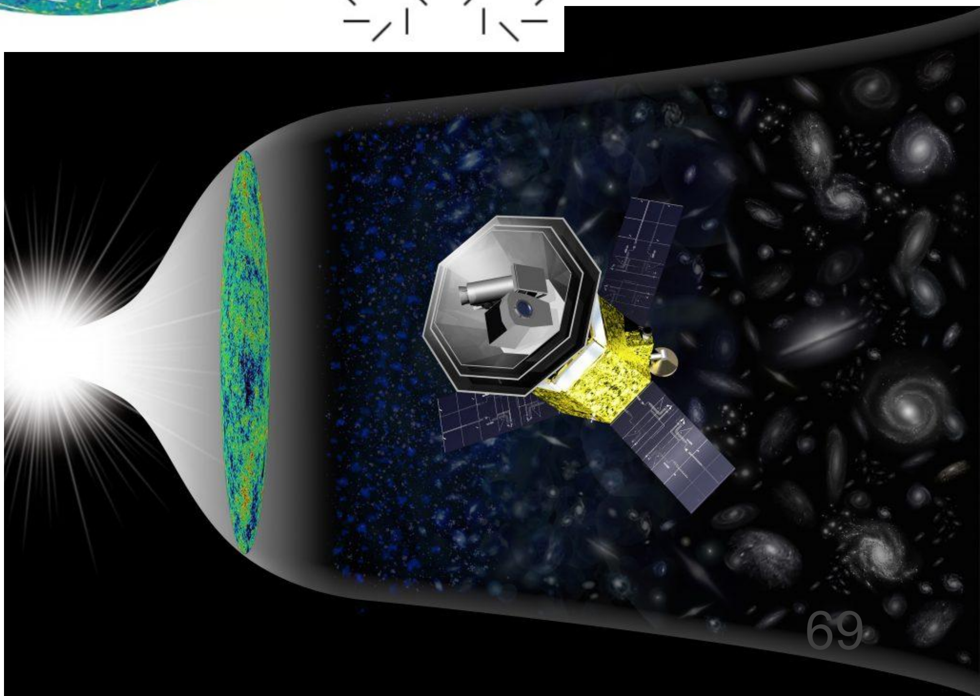


Cosmic Microwave Background

- CMB: Nearly isotropic 2.725 K black body radiation from the universe
- Primordial GWs can be measured with polarization measurements



- LiteBIRD
  Aiming for 2032 launch
- Simons Observatory
  Observation started 2024



Summary

- Gravitational wave astronomy has just started
- First event on September 15, 2015
- We now have more than 300 events
- Detector improvements are necessary for better understanding of the universe
  - Neutron star physics
  - Origin of heavy elements
  - Origin of black holes
  - Cosmic expansion
  - Tests of gravity   etc…
- Developments in other frequency bands are also underway

Assignment for Oct 20

- What would you like to hear or learn about in this lecture series?

- You may also answer from the Google Form below
  https://forms.gle/6AwJ48XcpWQXqMon9

Don't forget to put your name and student#

You may answer in any language