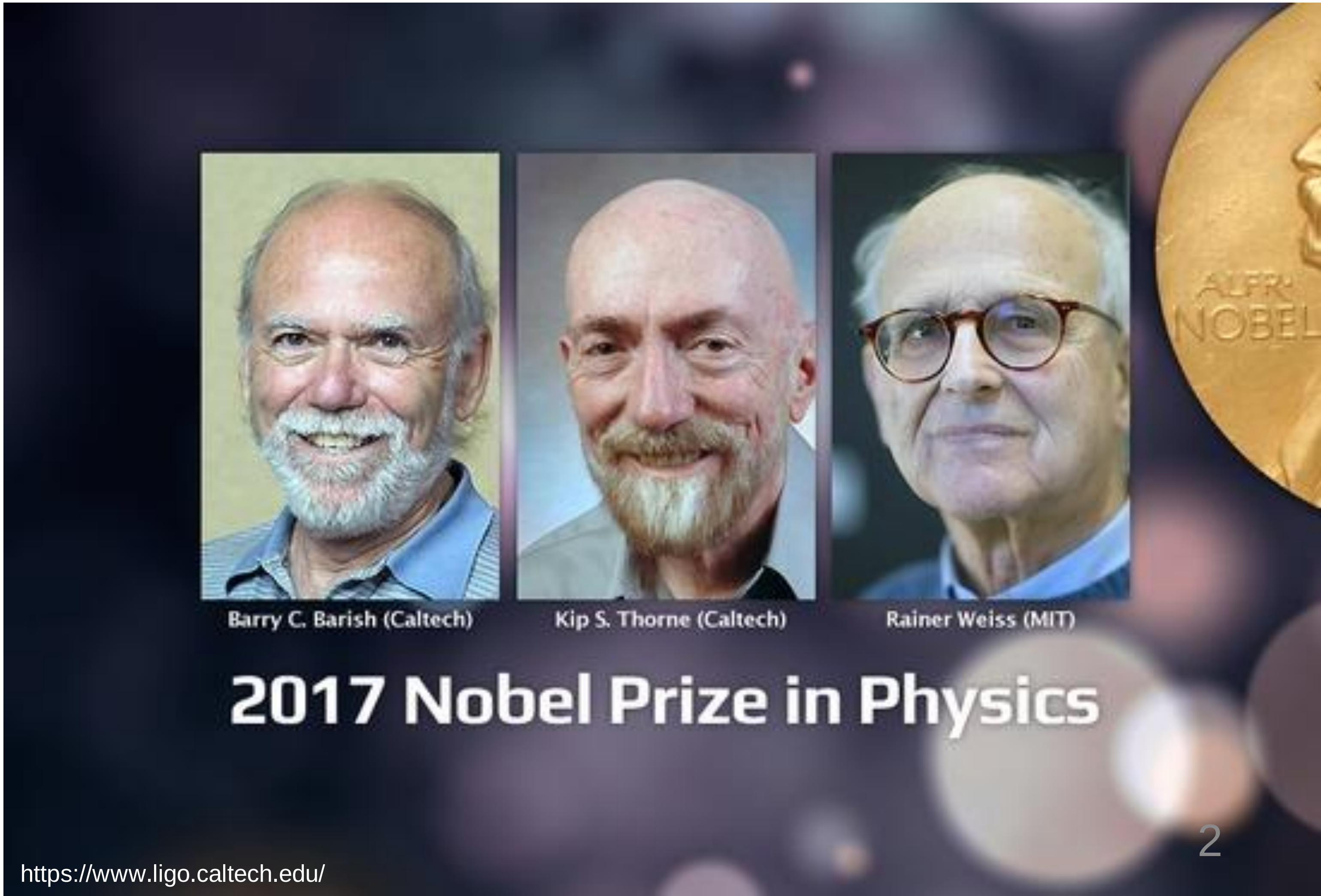
Laser Interferometry for Gravitational Wave Astronomy

Yuta Michimura

Department of Physics, University of Tokyo

Nobel Prize in Physics 2017

- *for decisive contributions to the LIGO detector and the observation of gravitational waves*



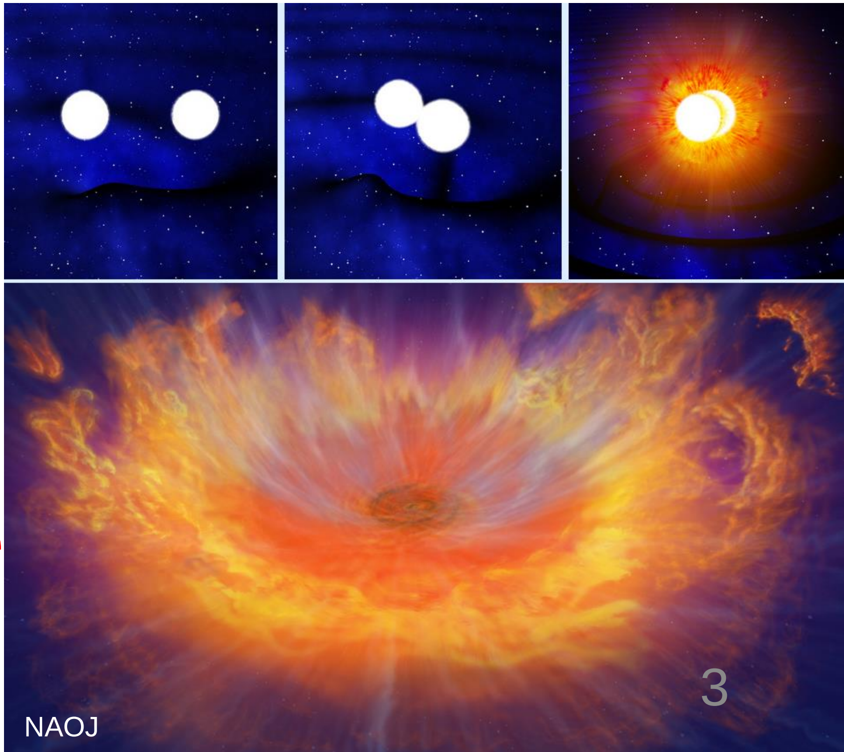
https://www.ligo.caltech.edu/

GWs Announced So Far

- Binary black holes
  GW150914 (first event)
  LVT151012 (candidate)
  GW151226
  GW170104
  GW170814

- Binary neutron stars
  GW170817 (GW and light)

- Dawn of gravitational wave astronomy

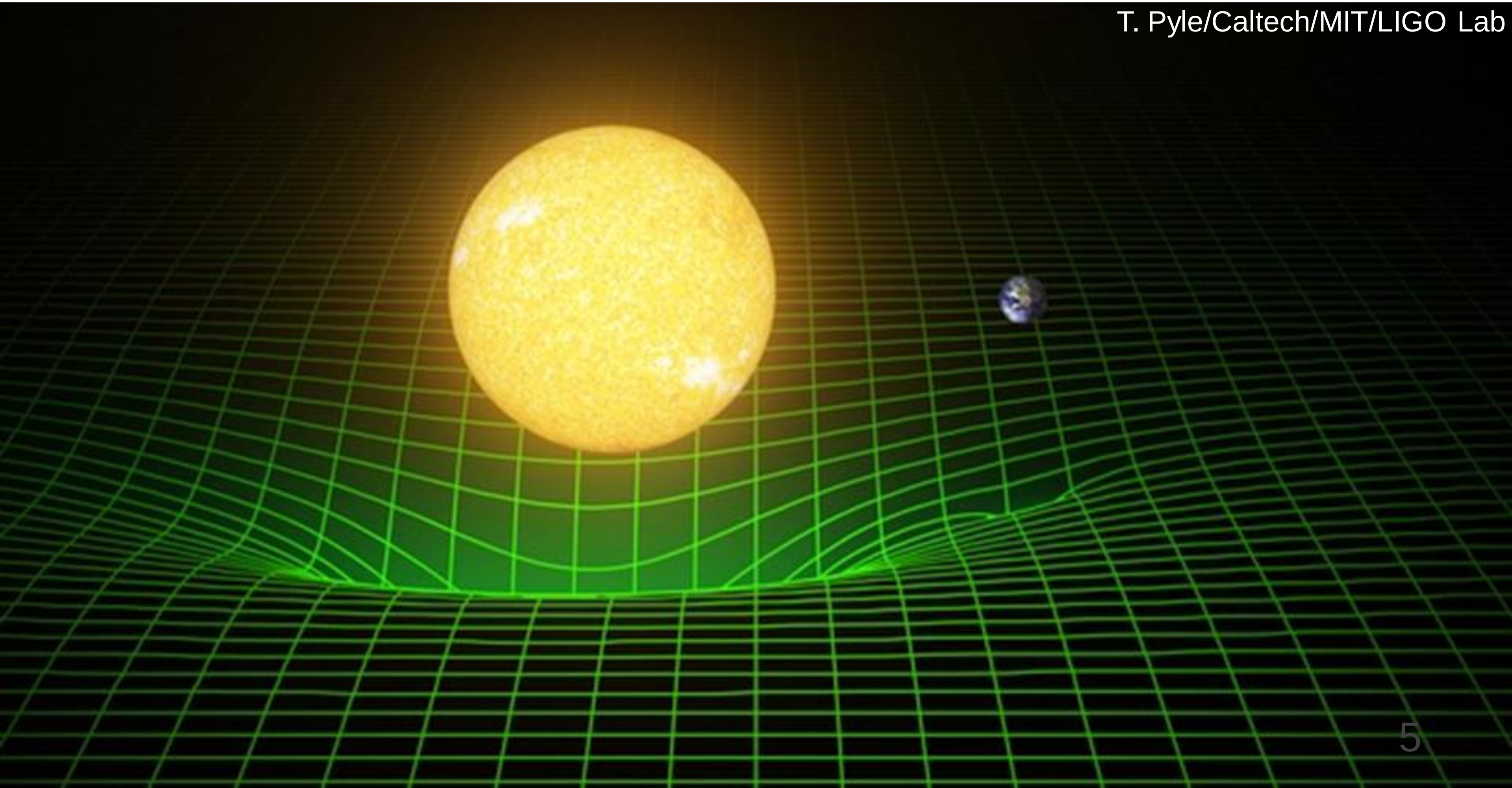


Contents

- Introduction to gravitational waves
  characteristics, sources, detection
- First detections by LIGO and Virgo
  binary black holes
  binary neutron stars
  solved mysteries and new mysteries
  global network of GW observation
- KAGRA at Kamioka, Gifu, Japan
  underground construction
  cryogenic operation
- Future of gravitational wave astronomy
  longer baseline
  space borne observatory

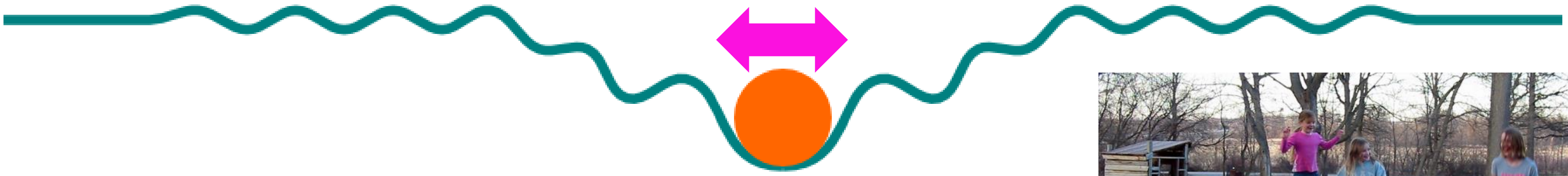
Gravity in General Relativity

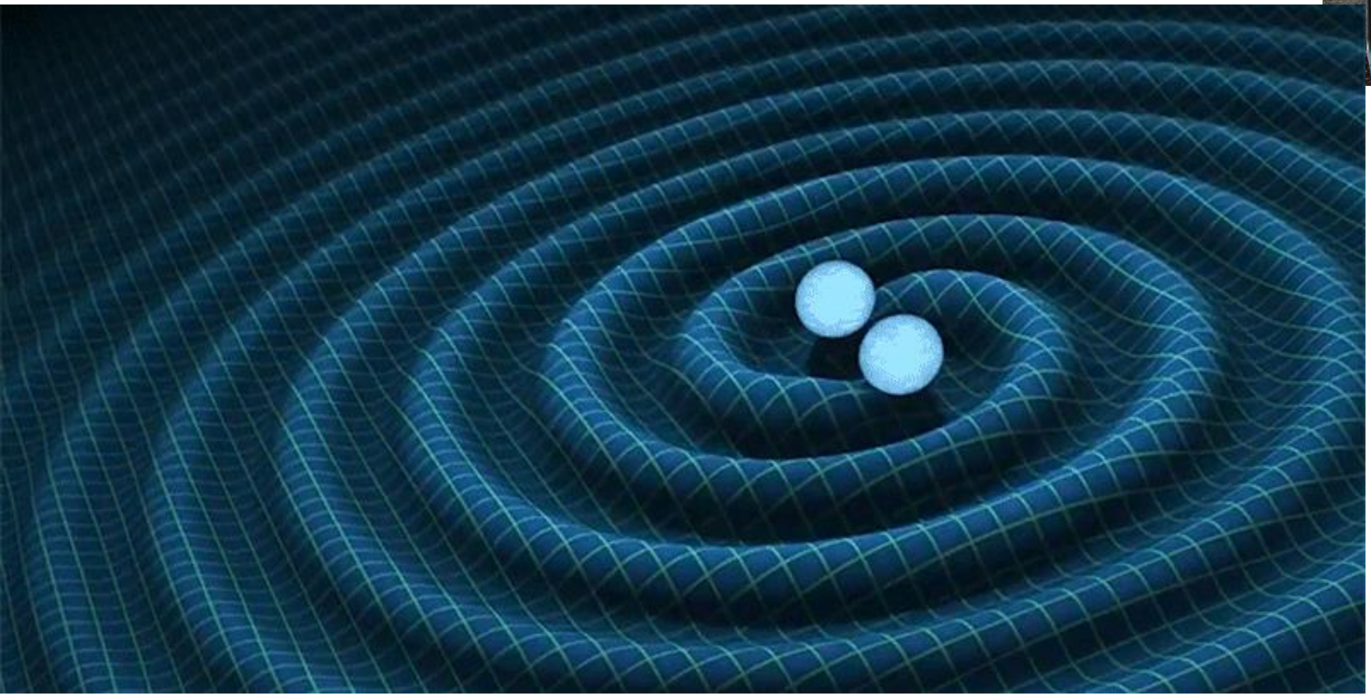
- space-time bends with presence of mass
- bending affects motion of objects → gravity



Gravitational Waves

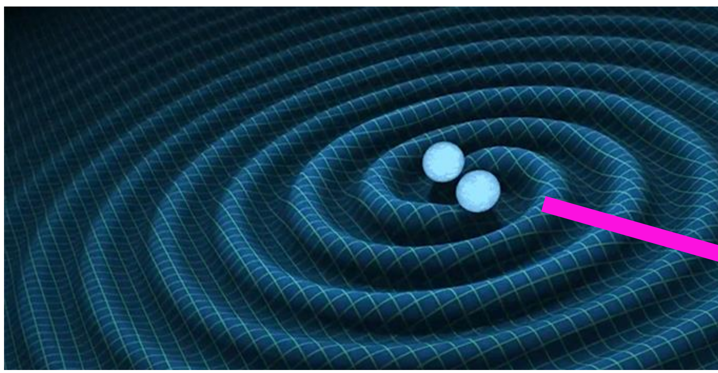
- ripples in space-time created by motion of objects

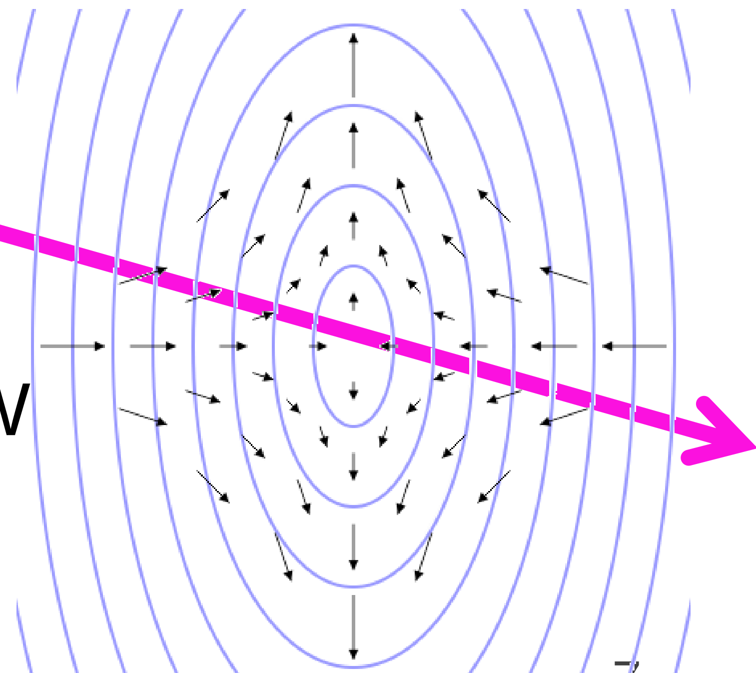




Characteristics of GWs

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

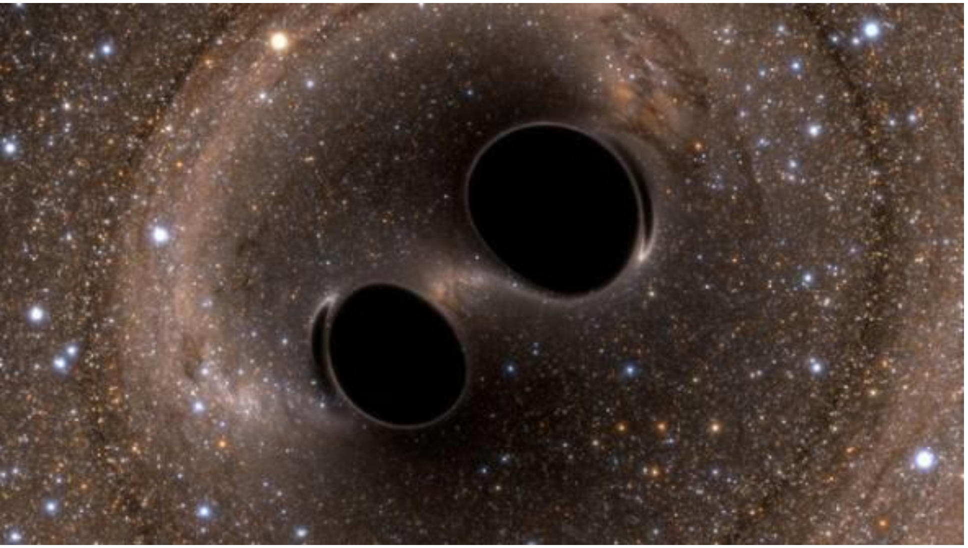




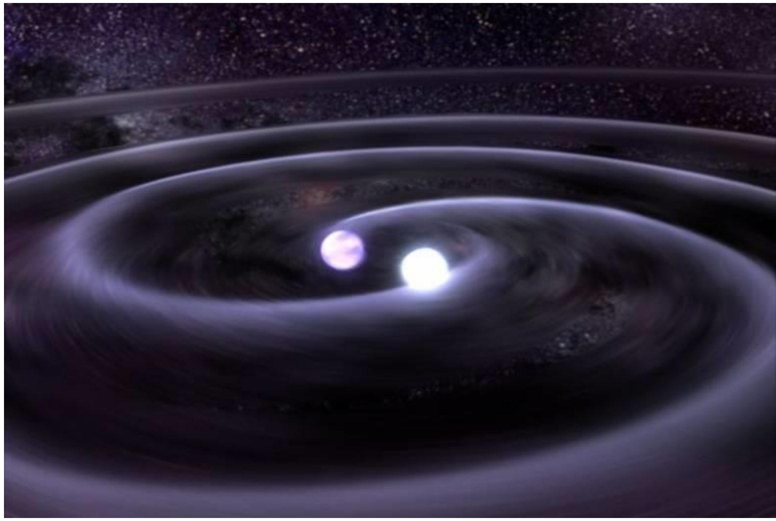
- large mass and large acceleration creates large GW
- amplitude of GW
  fraction of length change

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

Sources of GWs

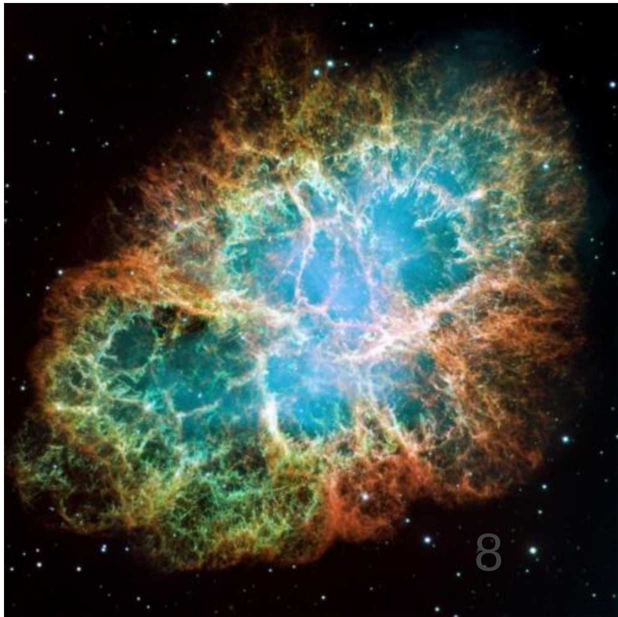


Binary black holes



Binary neutron stars

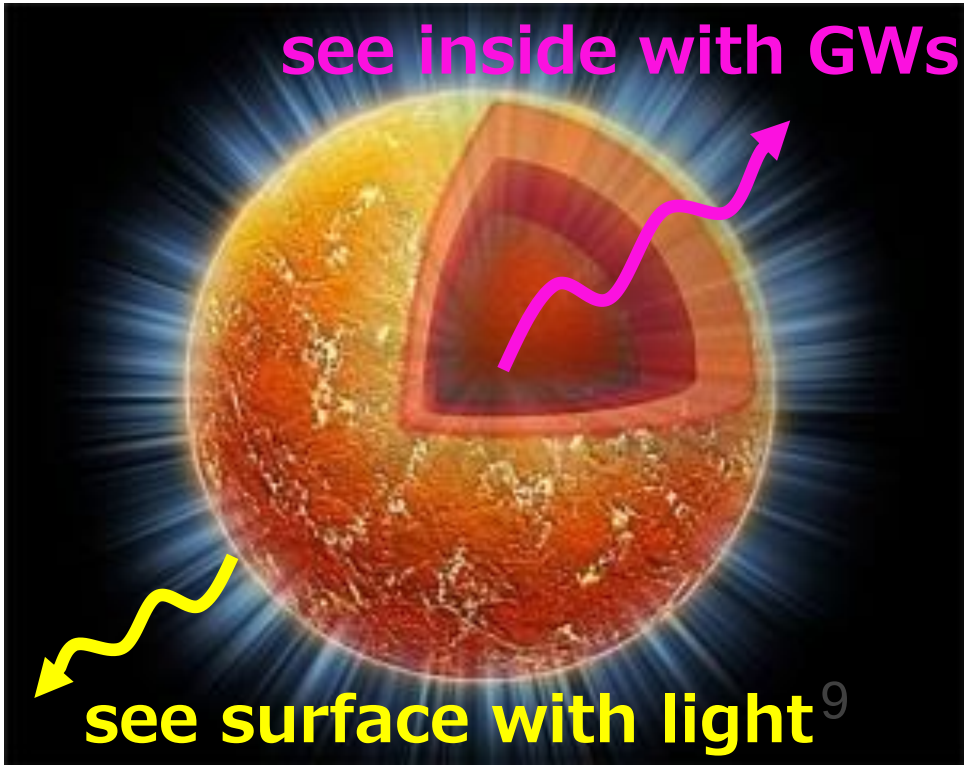
Pulsars



Supernovae

What’s So Great About GWs

- Investigate inside the stars
  - high transmissivity of GW
  - equation of state of neutron stars
- Observe stellar objects cannot be seen with electromagnetic waves
  - black holes,
  - dark matter,
  - unknown unknowns?



Detection of GWs

- Most common detector: laser interferometer
- Rai Weiss (MIT) proposed in 1960s

Internal report (1972)

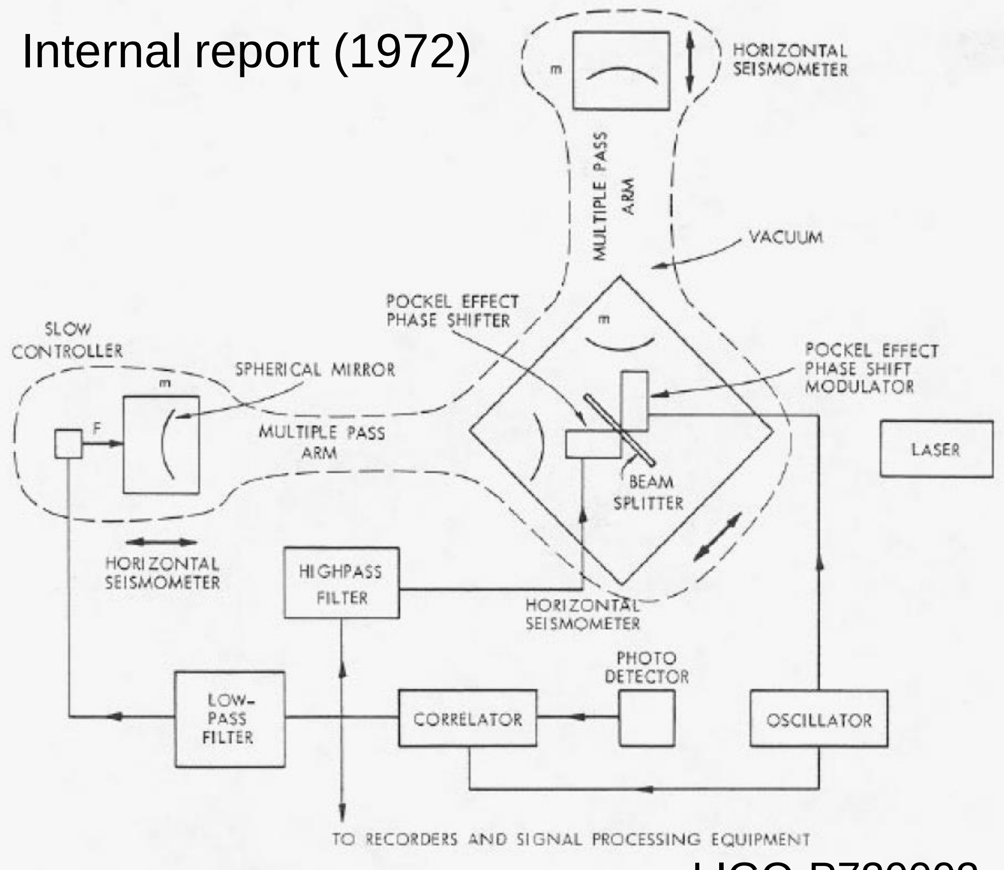
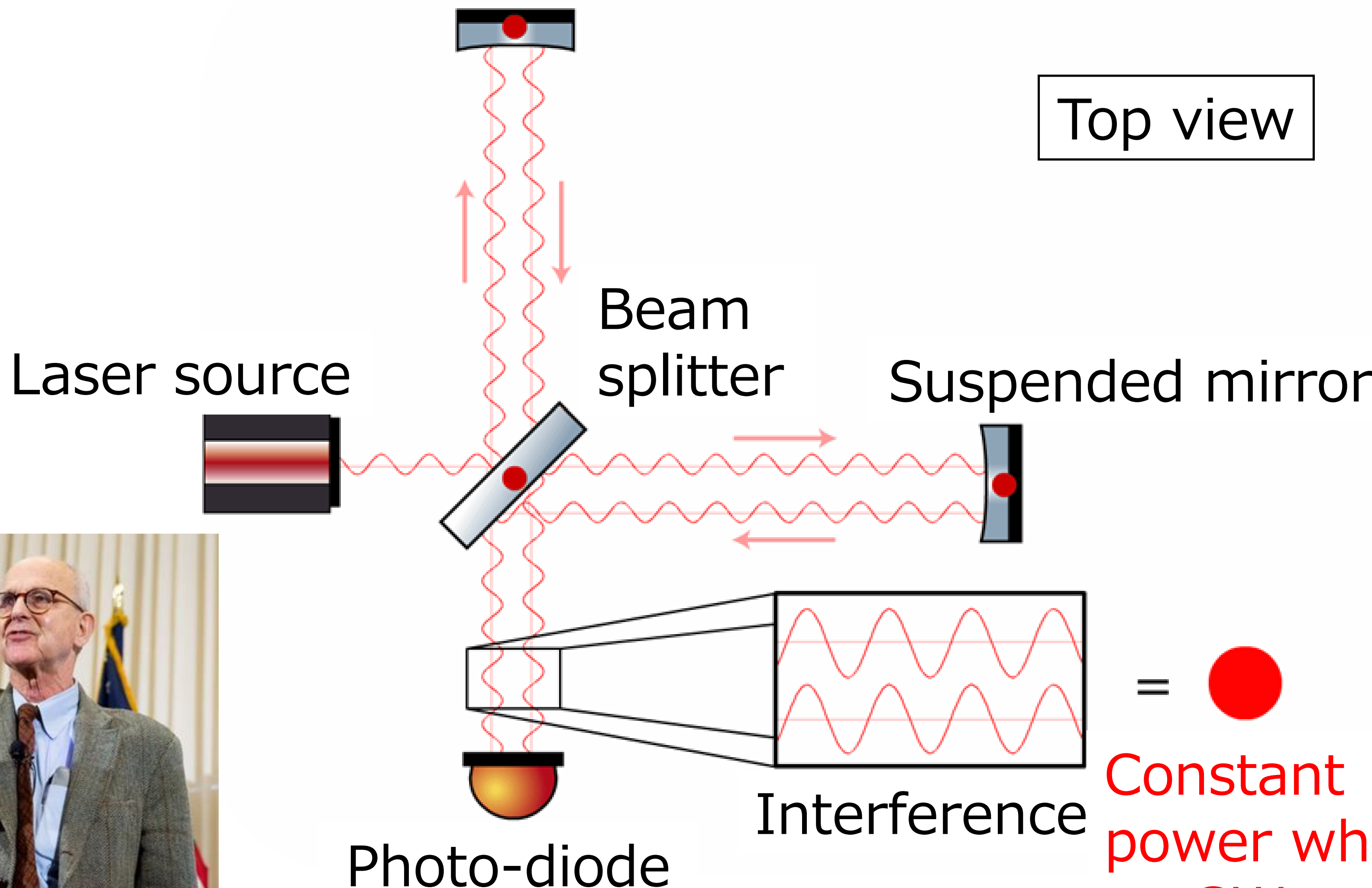


Fig. V-20. Proposed antenna.

LIGO-P720002

Laser Interferometric GW Detector

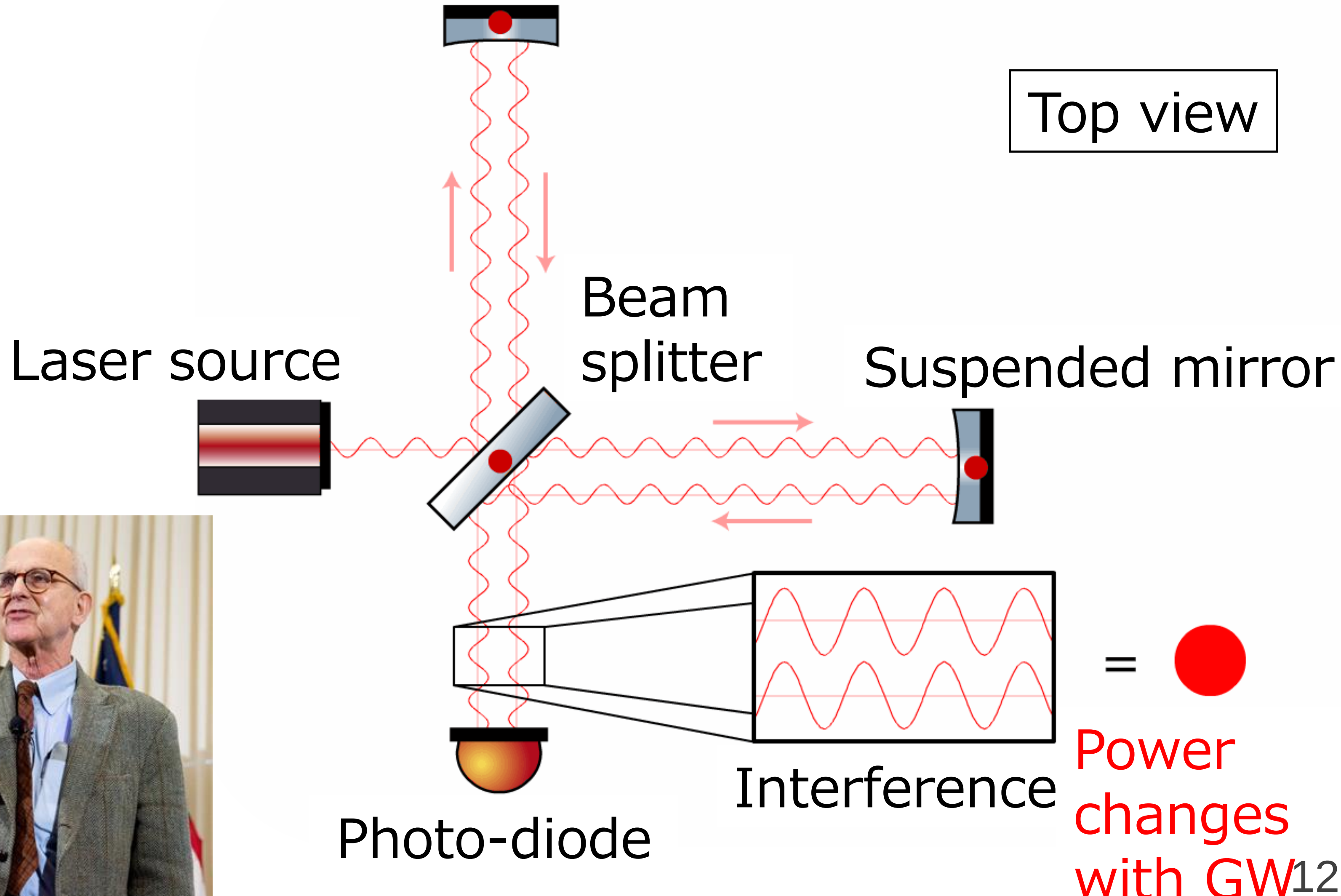
- measure differential arm length change



Constant power when no GW

Laser Interferometric GW Detector

- measure differential arm length change

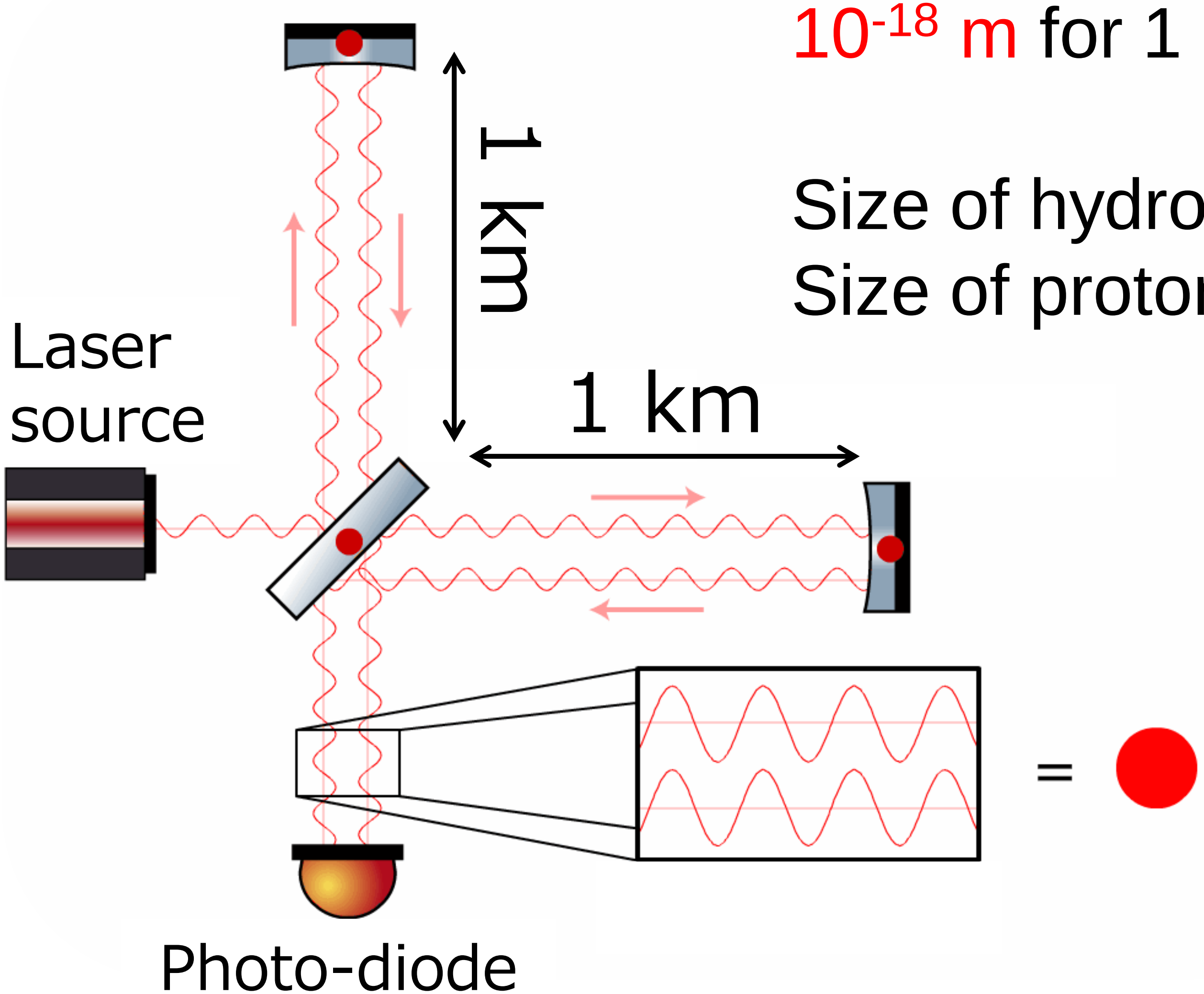


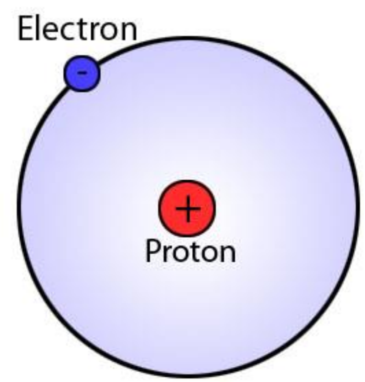
Amplitude of GWs

- for example, h ~ 10^{-21}

10^{-18} m for 1 km arm

Size of hydrogen atom: 10^{-11} m
Size of proton: 10^{-15} m





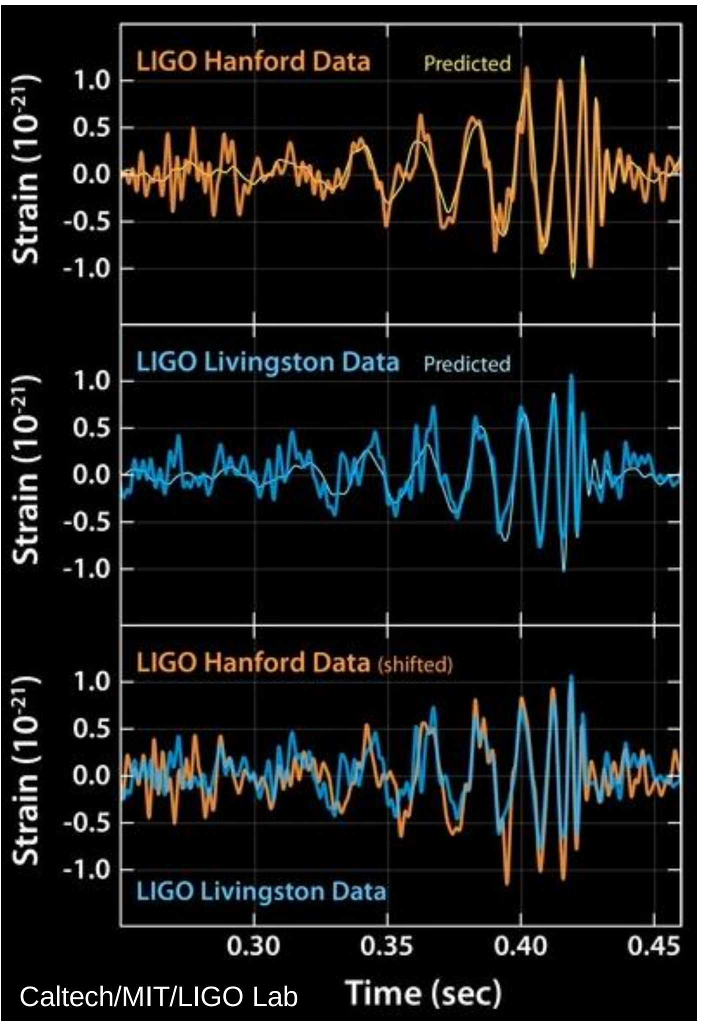
History of GW Detection

- 1916 Einstein predicted GW
- 1960s Weiss proposed interferometric detection
- 2000s Started first searches for GW
  LIGO (USA 4 km), TAMA300 (Japan 300m),
  GEO600 (Germany 600m), Virgo (Italy 3km)
  → No detection
- 2011 LIGO started upgrade
- 2015 Advanced LIGO started operation
- 2016 First detection announced

David Reitze "We did it"

First Detection of GW by aLIGO

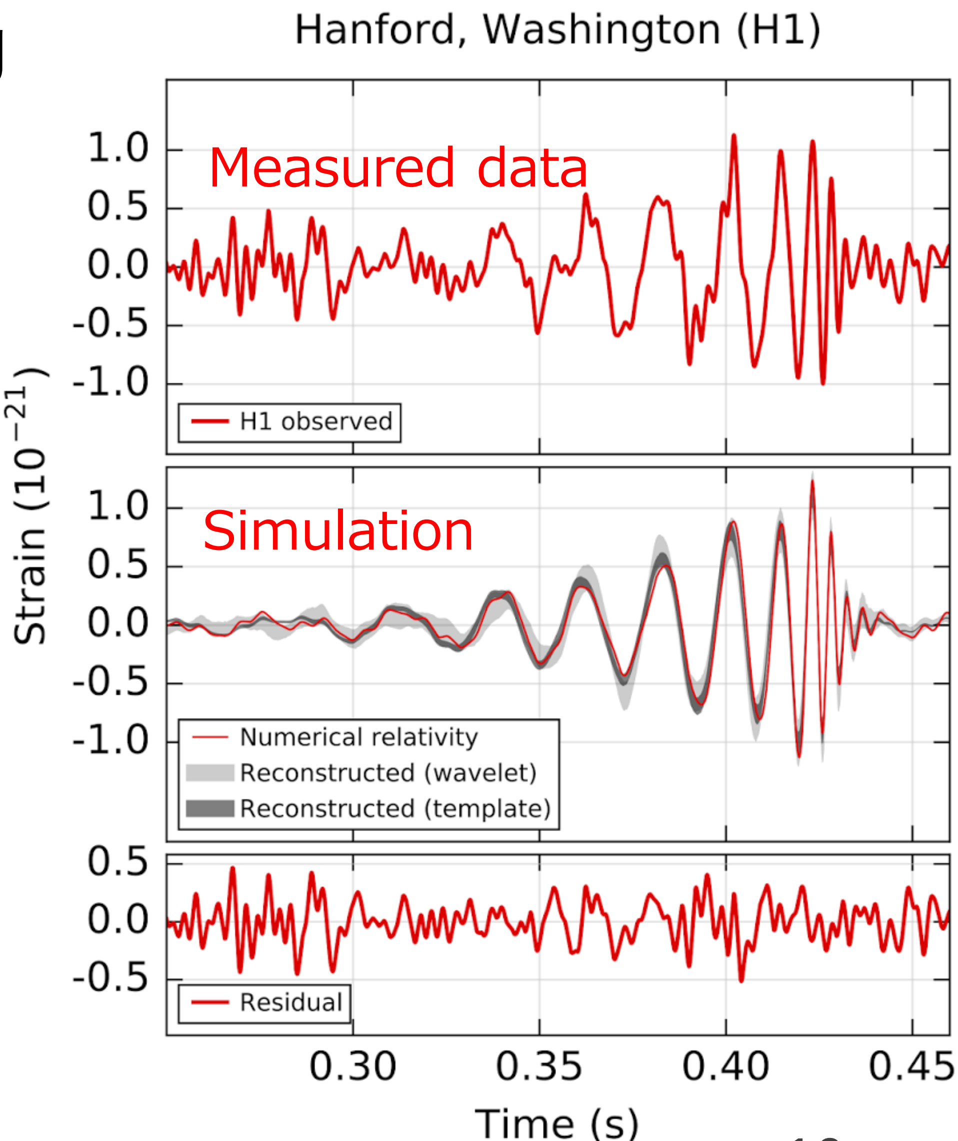
- by two detectors 3030 km away, at almost the same time (7 msec)



Waveform of GW

- can be calculated using numerical relativity
- perfectly matched with calculation

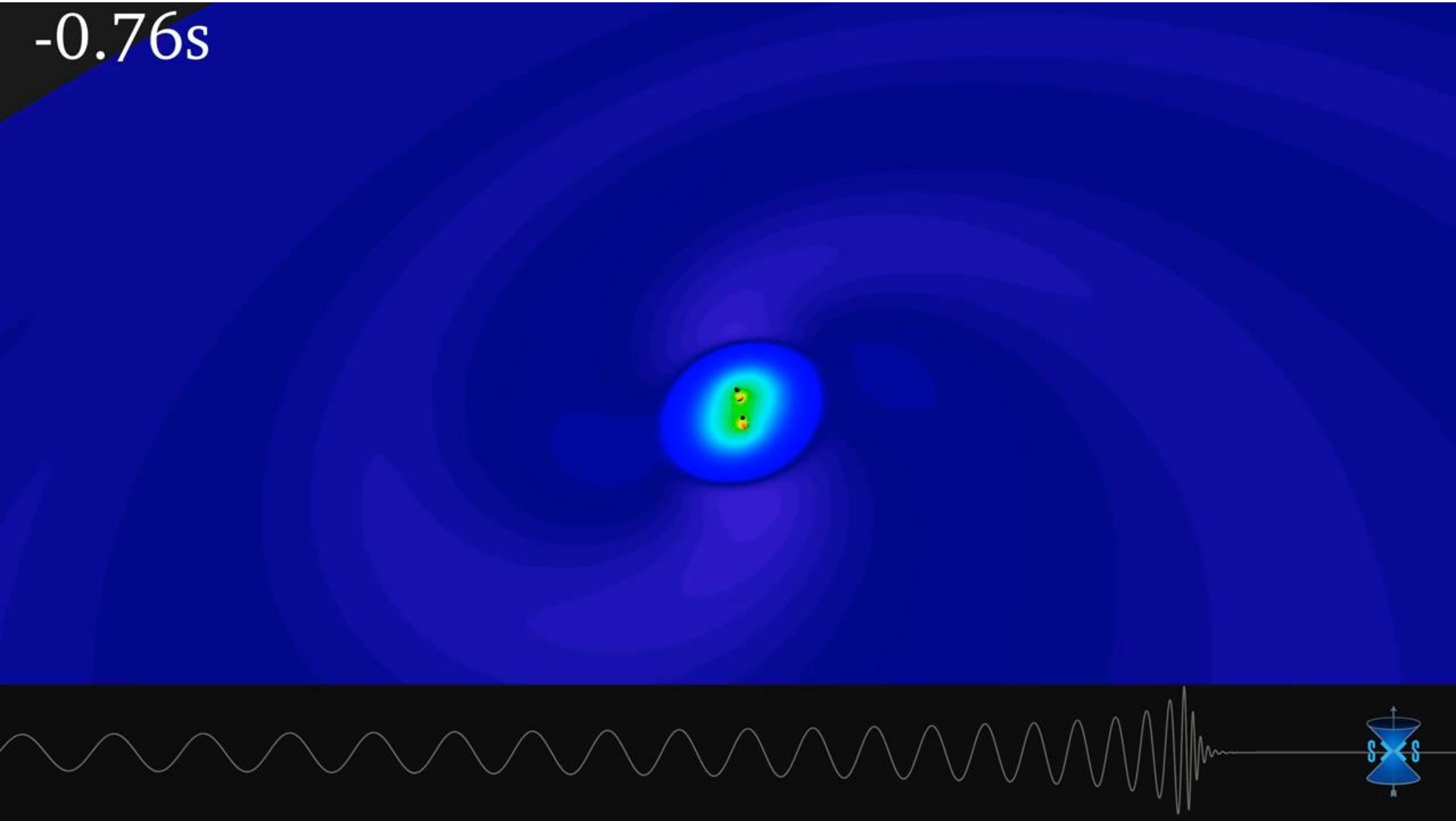
- test of general relativity in strong-field regime



Simulation of Binary BH merger

- two inspiring BHs → single BH

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



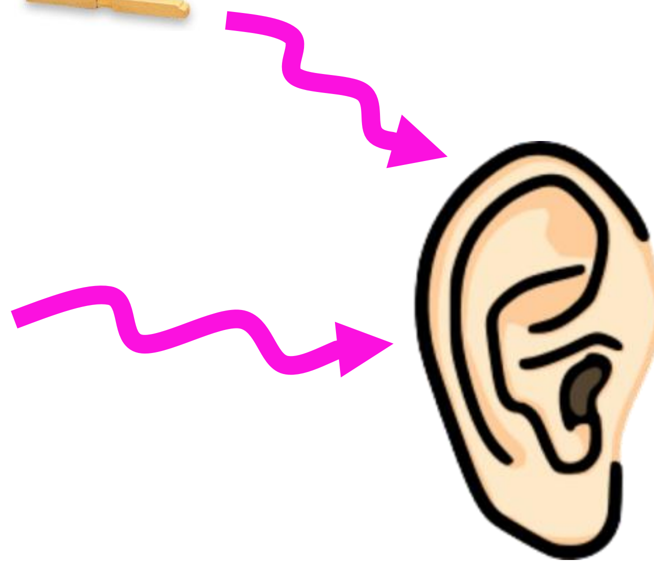
Information from GW

- mass from pitch (frequency)
- distance from loudness

quiet when far

high-pitched for small drum

low-pitched for large drum



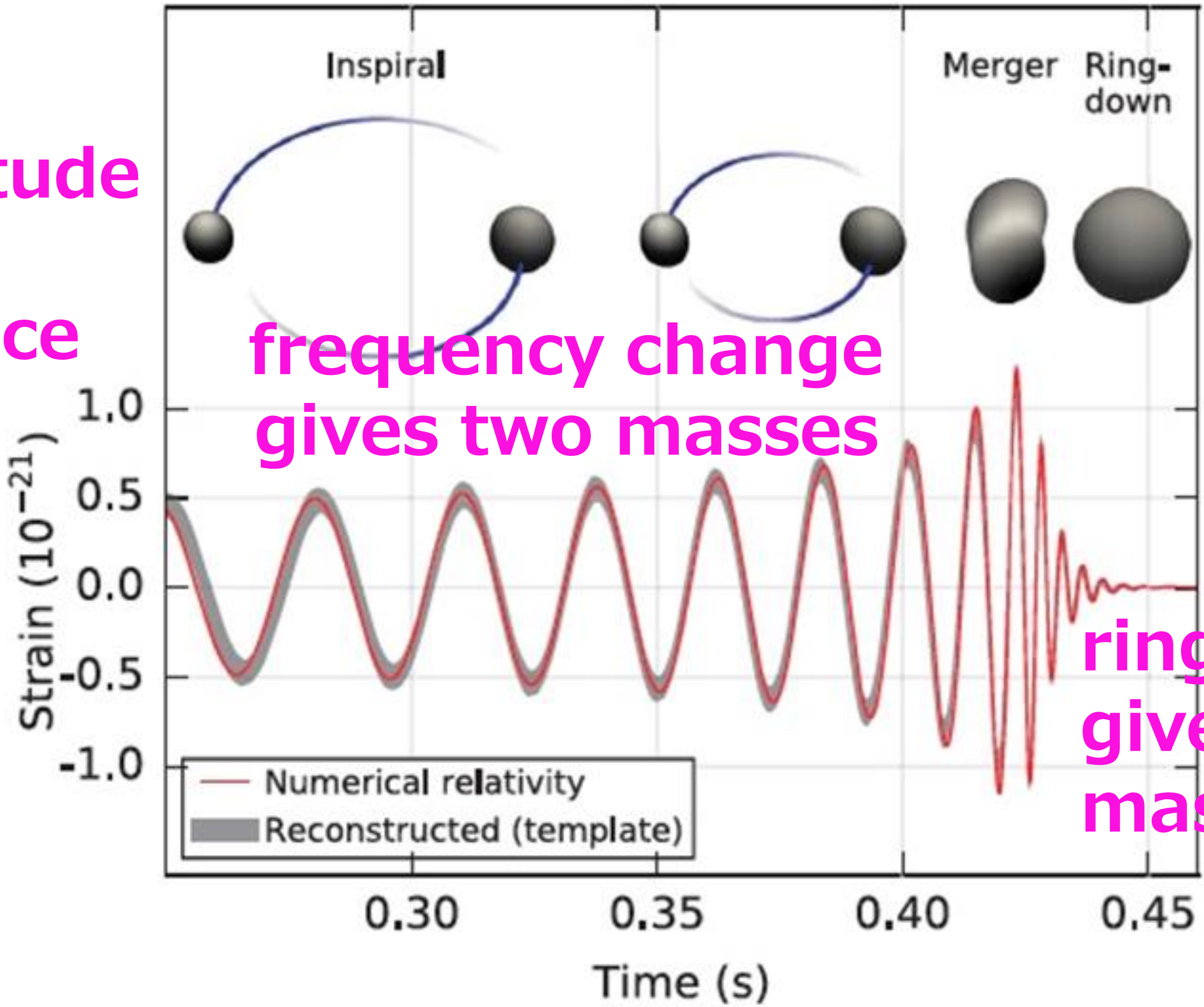
Information from GW

- mass and distance of the source

amplitude gives distance

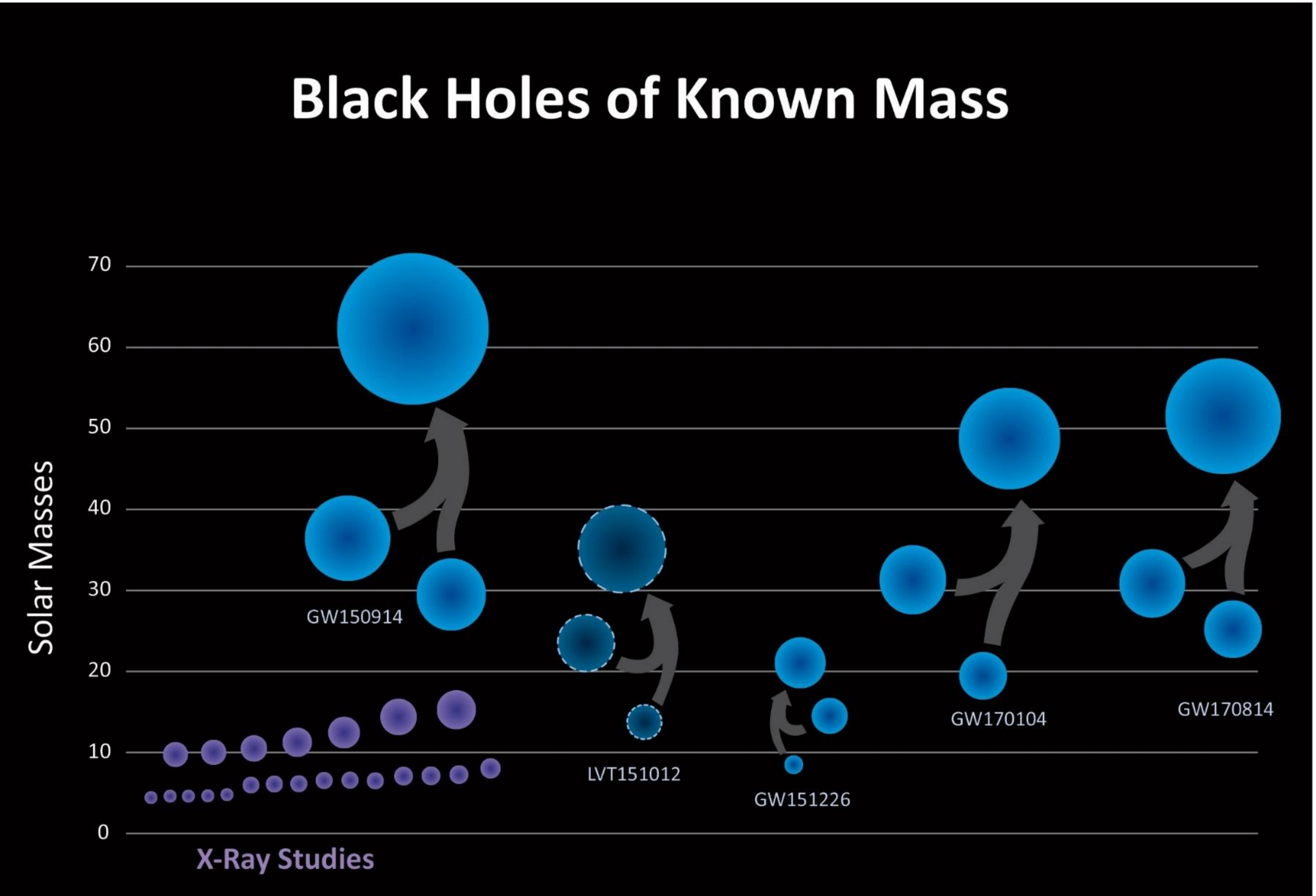
frequency change gives two masses

ringdown gives final mass



Masses of Black Holes

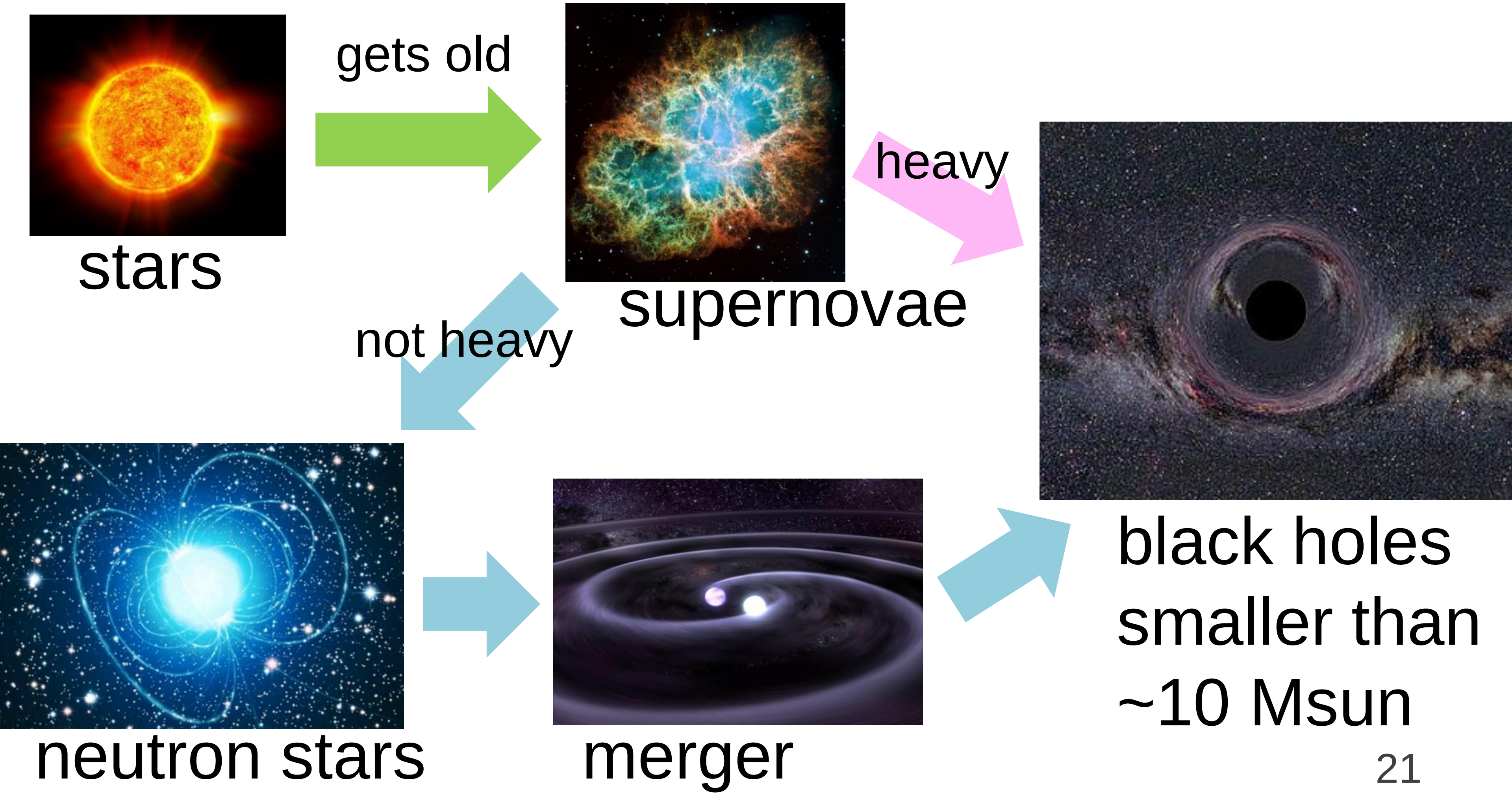
- much heavier than known stellar-mass BHs



http://www.virgo-gw.eu/docs/GW170814/

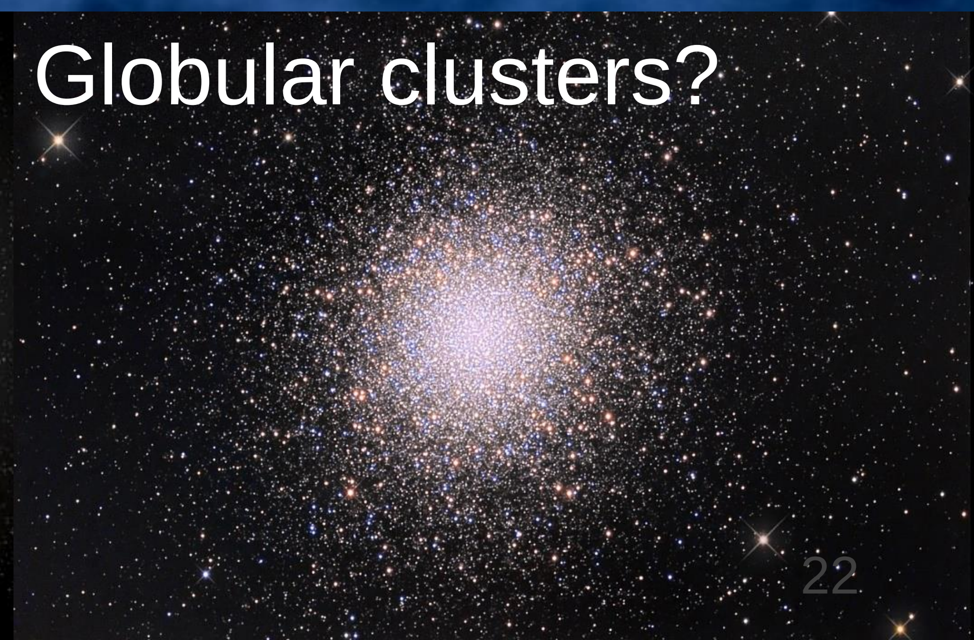
New Mystery: Origin of Heavy BHs

- supernovae and neutron star mergers only generate BHs smaller than ~10 solar mass



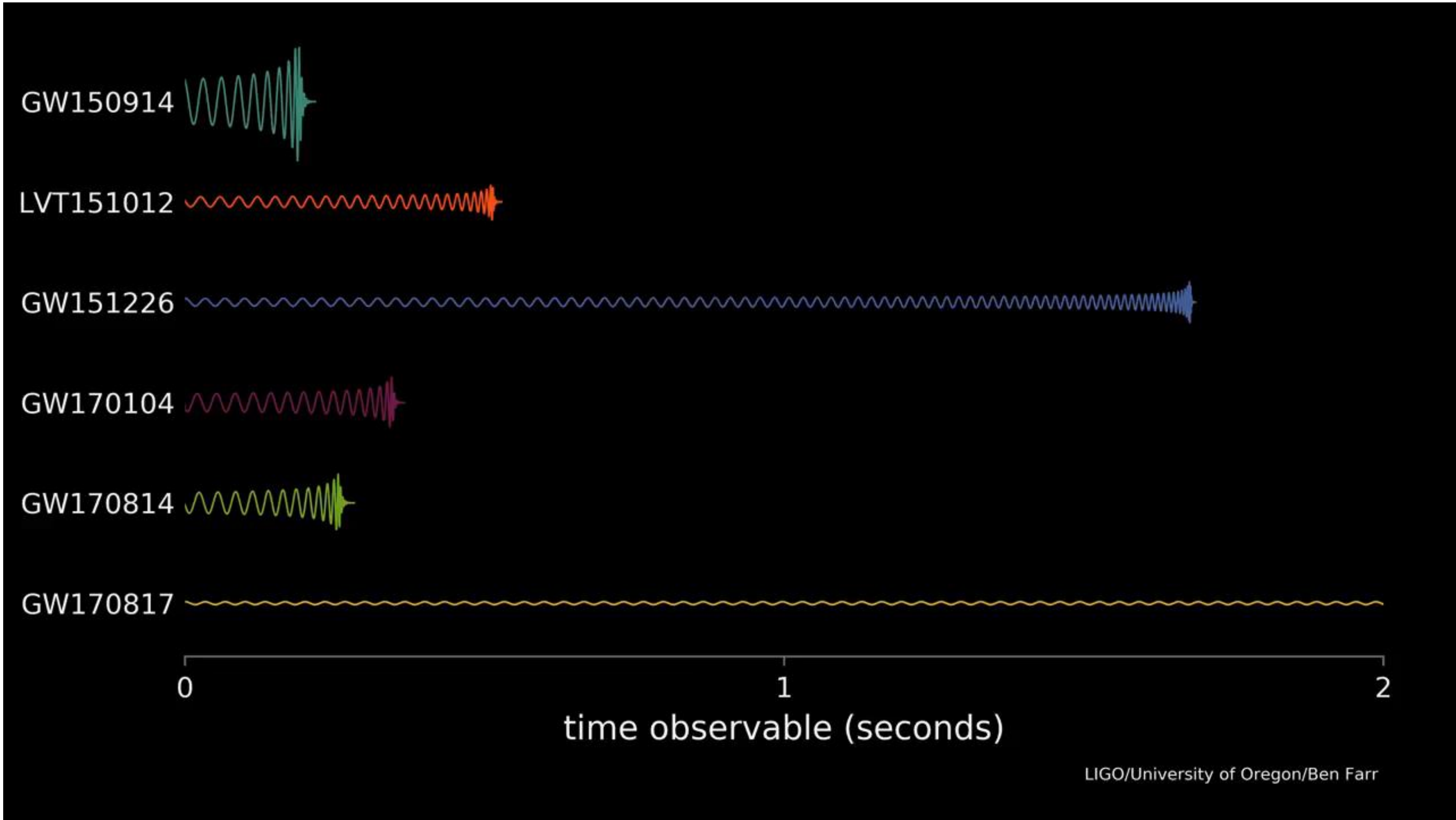
New Mystery: Origin of Heavy BHs

- many ideas
- more events with more precise parameter estimation necessary



First Detection of Binary NS

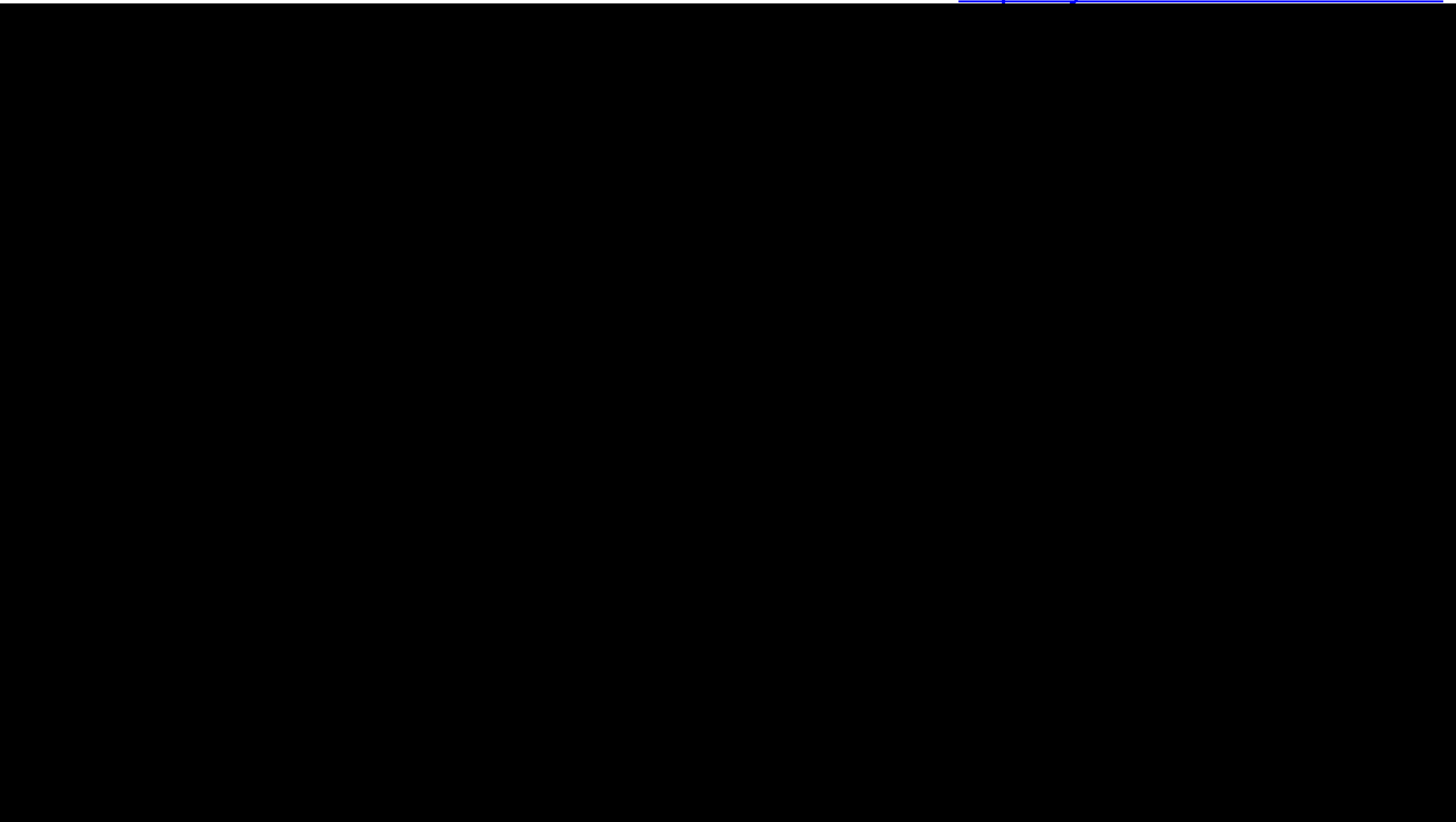
- Jointly by Advanced LIGO and Advanced Virgo
- longer, upto higher frequency https://youtu.be/RyXD_cSIaPc



Binary Neutron Star Merger

- GW → short gamma-ray burst → kilonova

https://youtu.be/e7LcmWiclOs



Binary Neutron Star Merger

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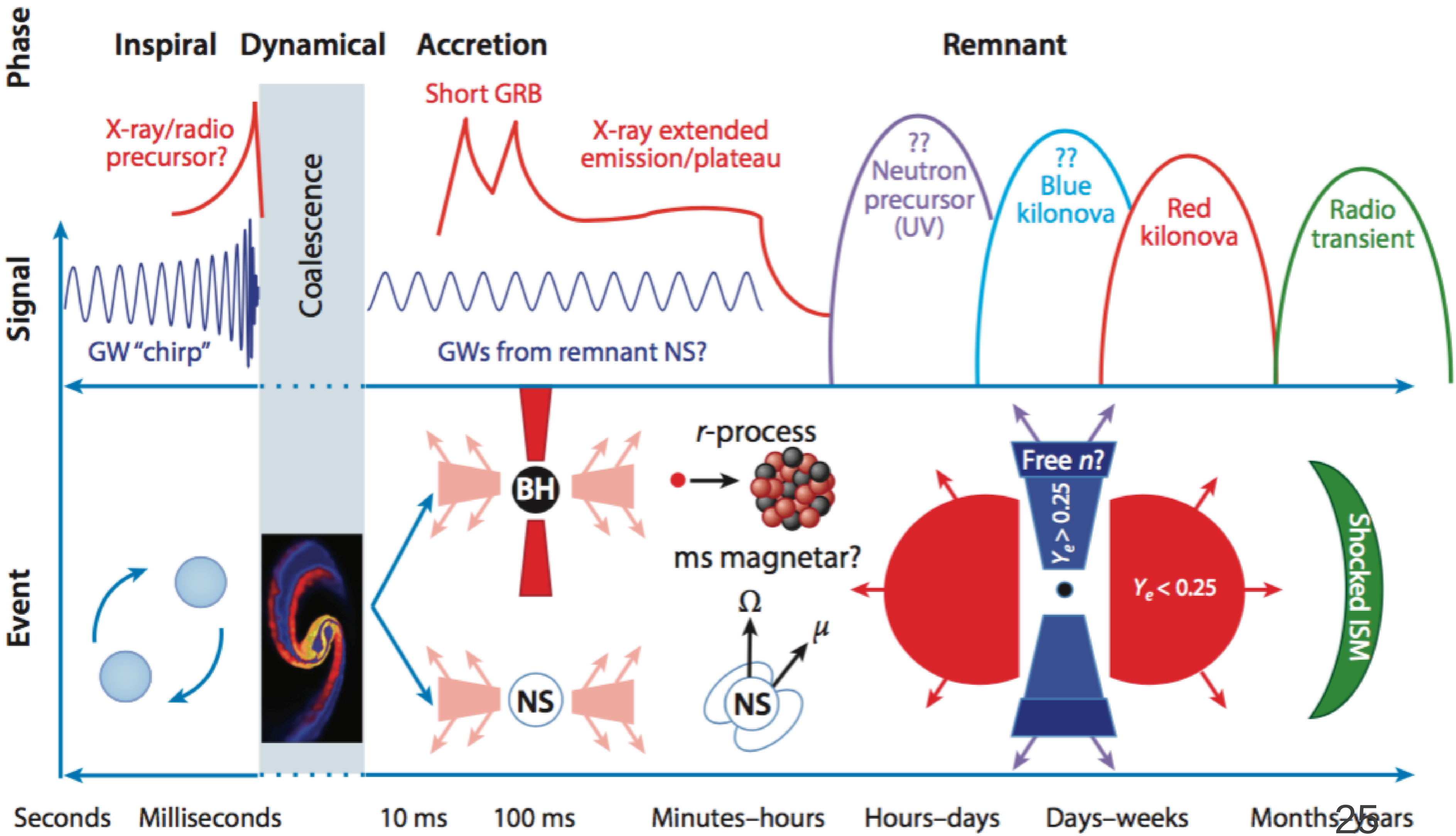
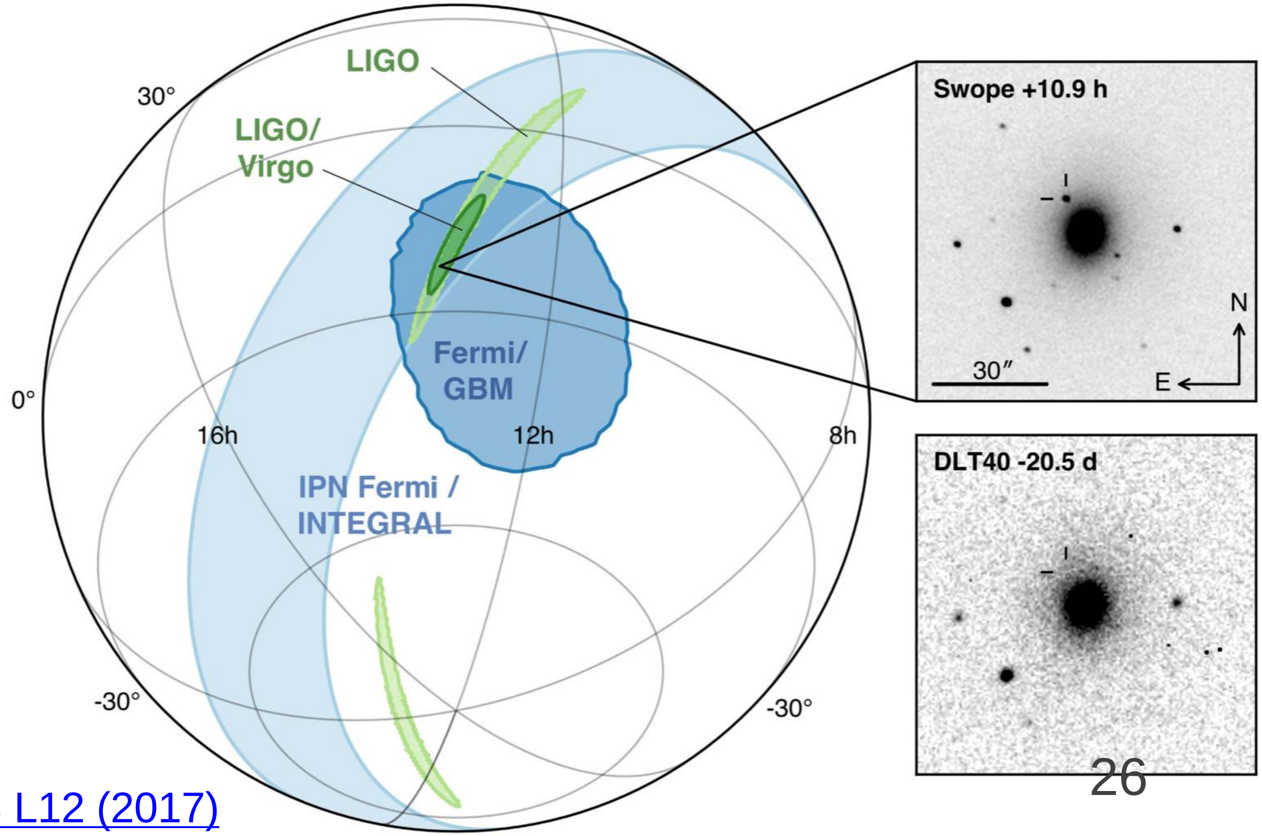


R. Fernández and B. D. Metzger, Annu. Rev. Nucl. Part. Sci. 2016. 66, 23 (2016)

First Detection of Binary NS

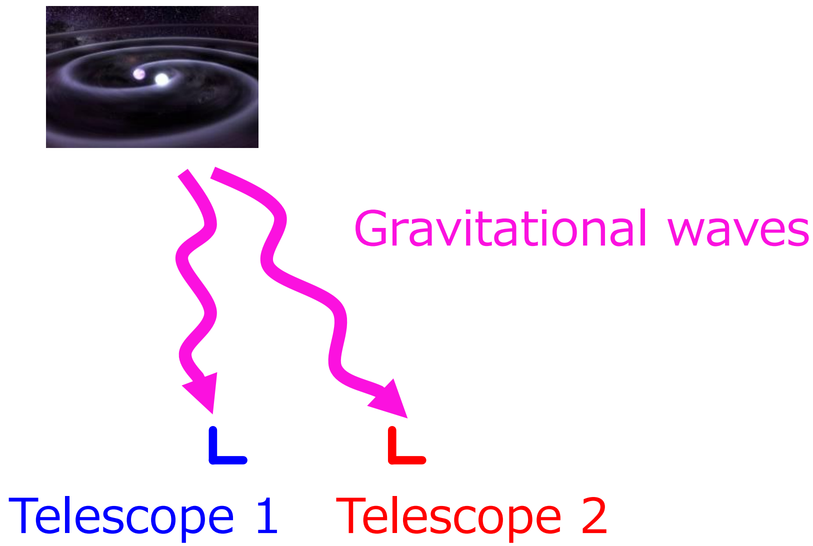
- Jointly by Advanced LIGO and Advanced Virgo
  sky localization improved
  from 190 deg^2 to 30 deg^2 with Virgo
- Follow-up observations by many telescopes
  gamma-ray,
  X-ray, UV,
  optical, IR,
  radio
  (& neutrino)



ApJL 848 L12 (2017)

Sky Localization

- done with timing difference

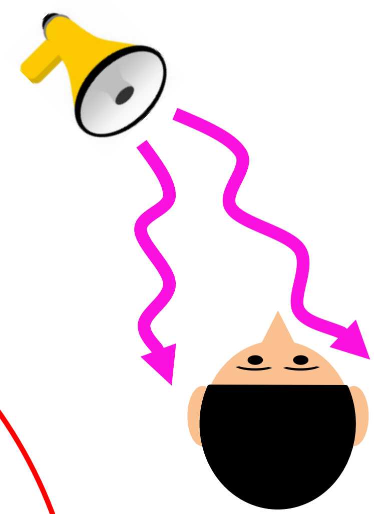


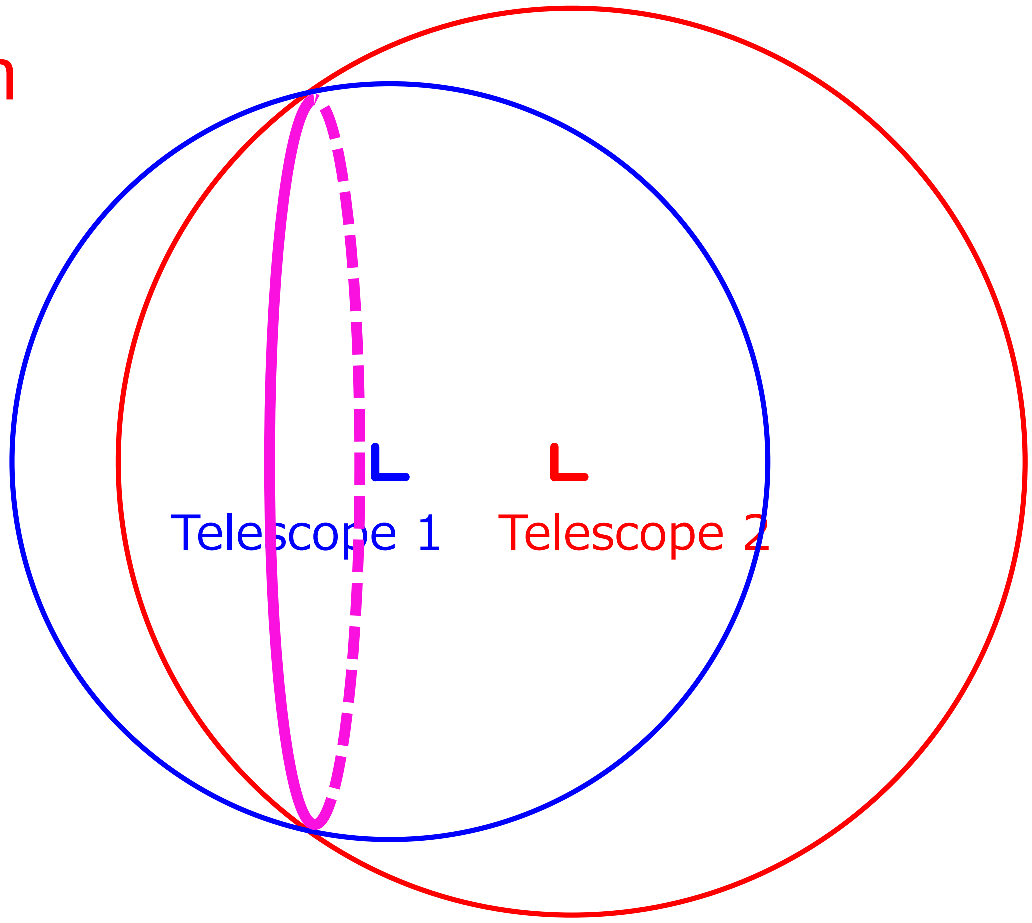
different location gives slightly different arrival time

Sky Localization

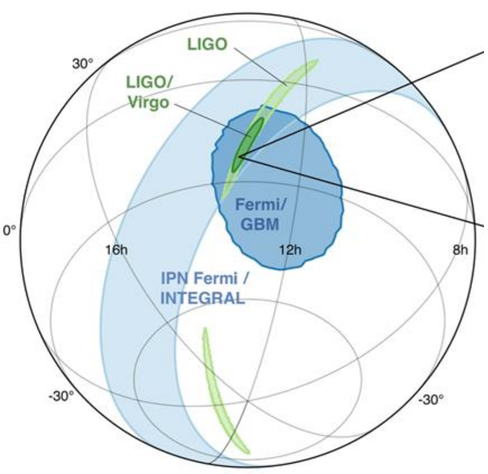
- done with timing difference

with 2 telescopes,
we get the
circular region





same as
our ears

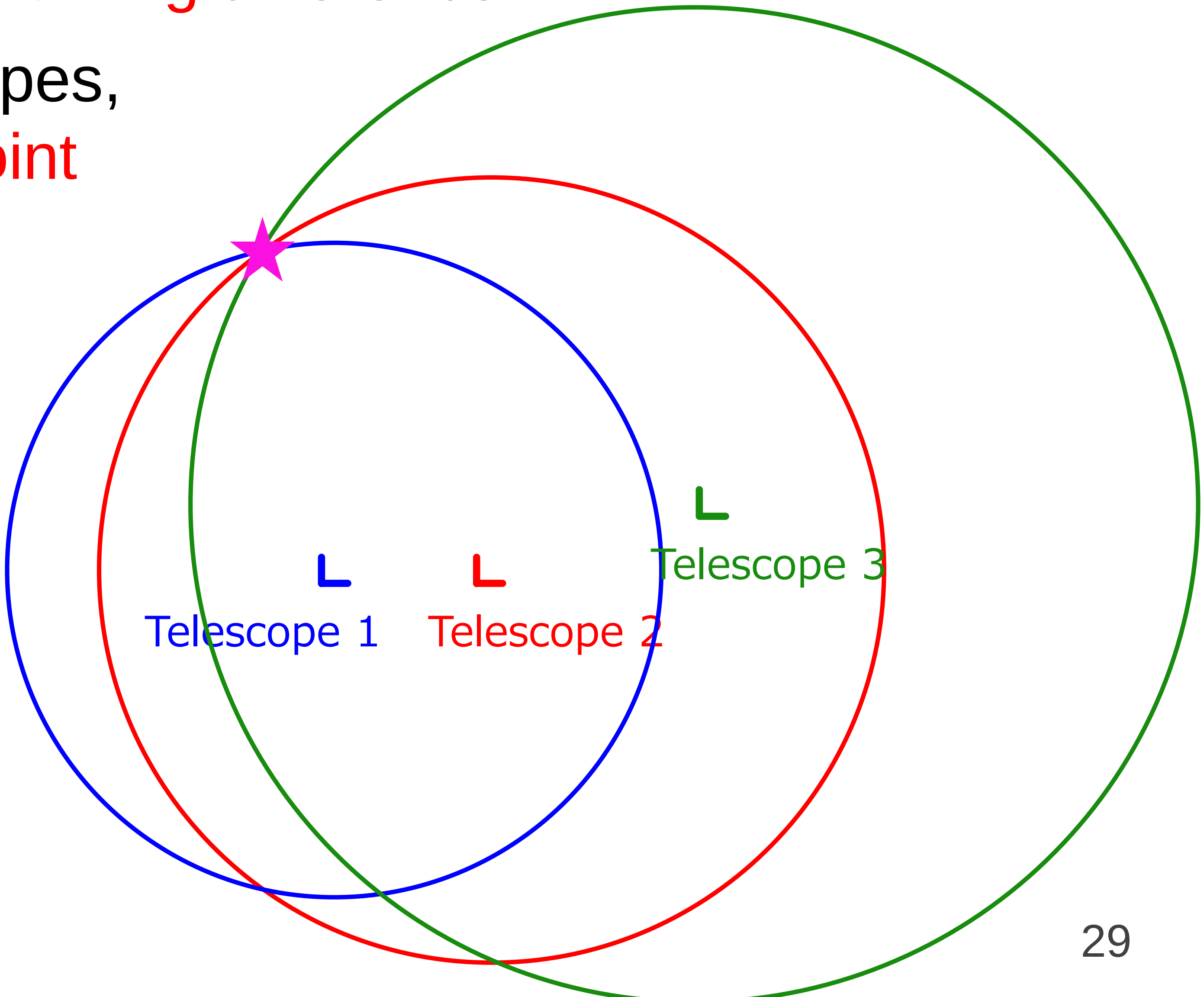


Sky Localization

- done with timing difference

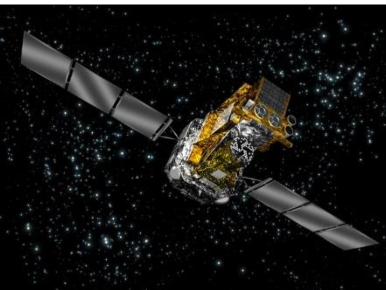
with 3 telescopes,
we can pin-point
the location

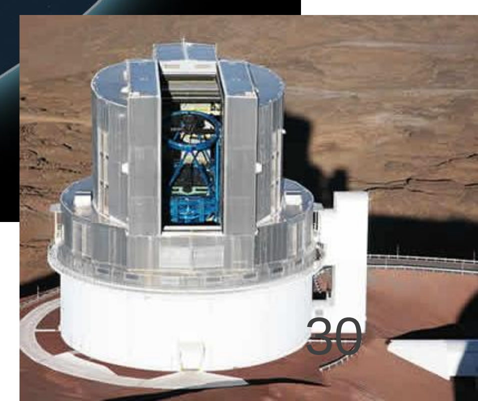
essential
for follow-up
observations



Electromagnetic Follow-up

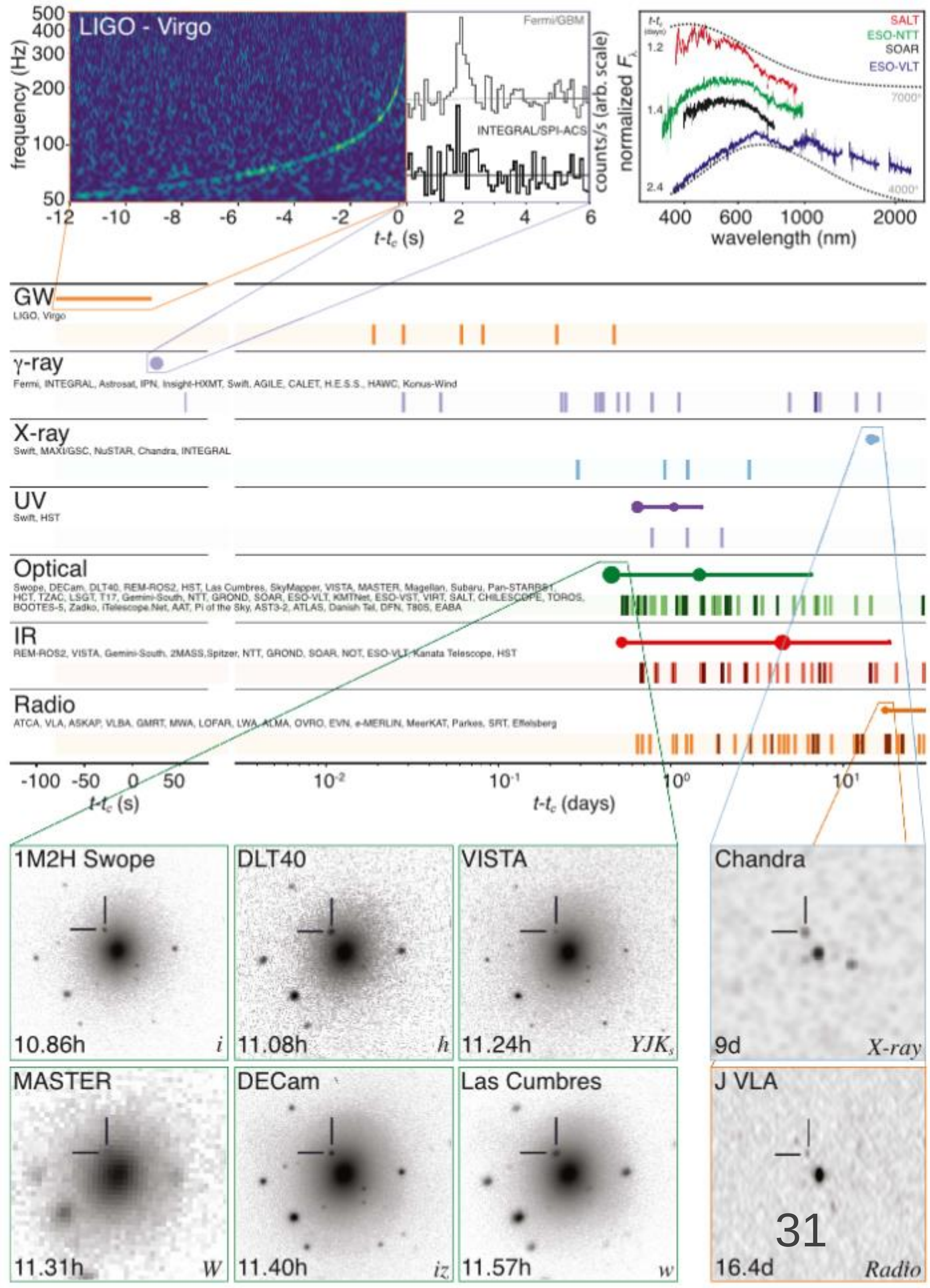
- many telescopes pointed the GW170814





Electromagnetic Follow-up

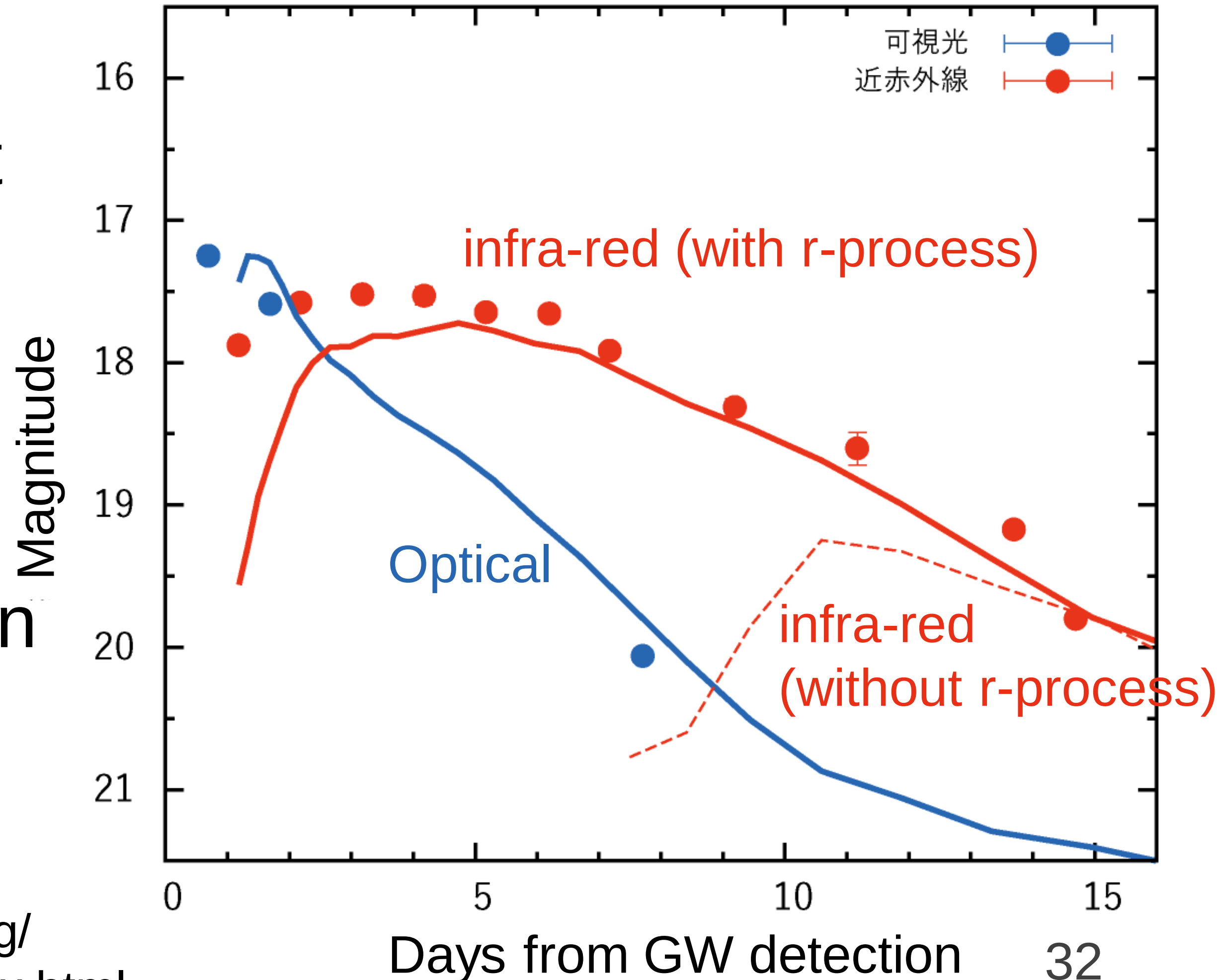
- in the following hours, days and weeks
- at various wavelengths
- consistent with merger
  → short gamma-ray burst
  → kilonova



[ApJL 848 L12 (2017)](#)

Light Curves by J-GEM

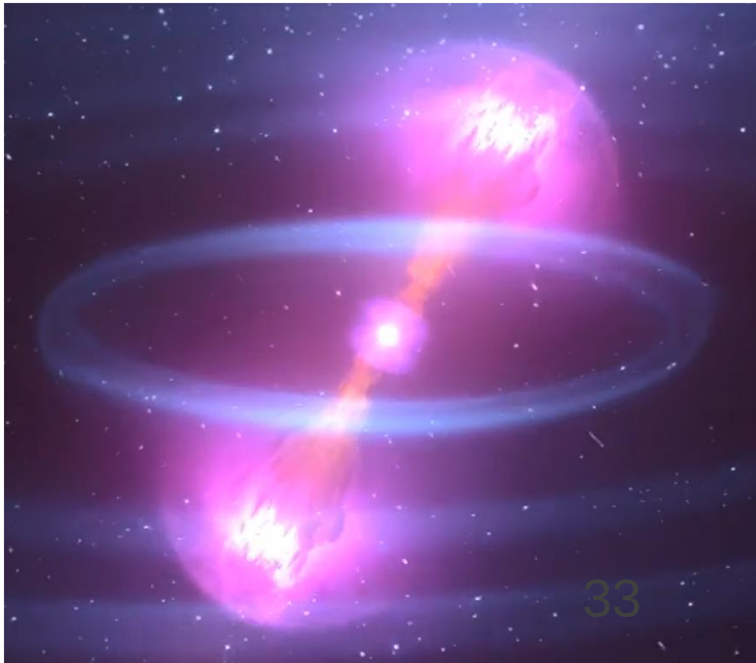
- Japanese collaboration of Gravitational wave Electro-Magnetic follow-up
- Consistent light curves with heavy element creation by r-process
- but brighter than expected



https://www.subarutelescope.org/Pressrelease/2017/10/16/j_index.html

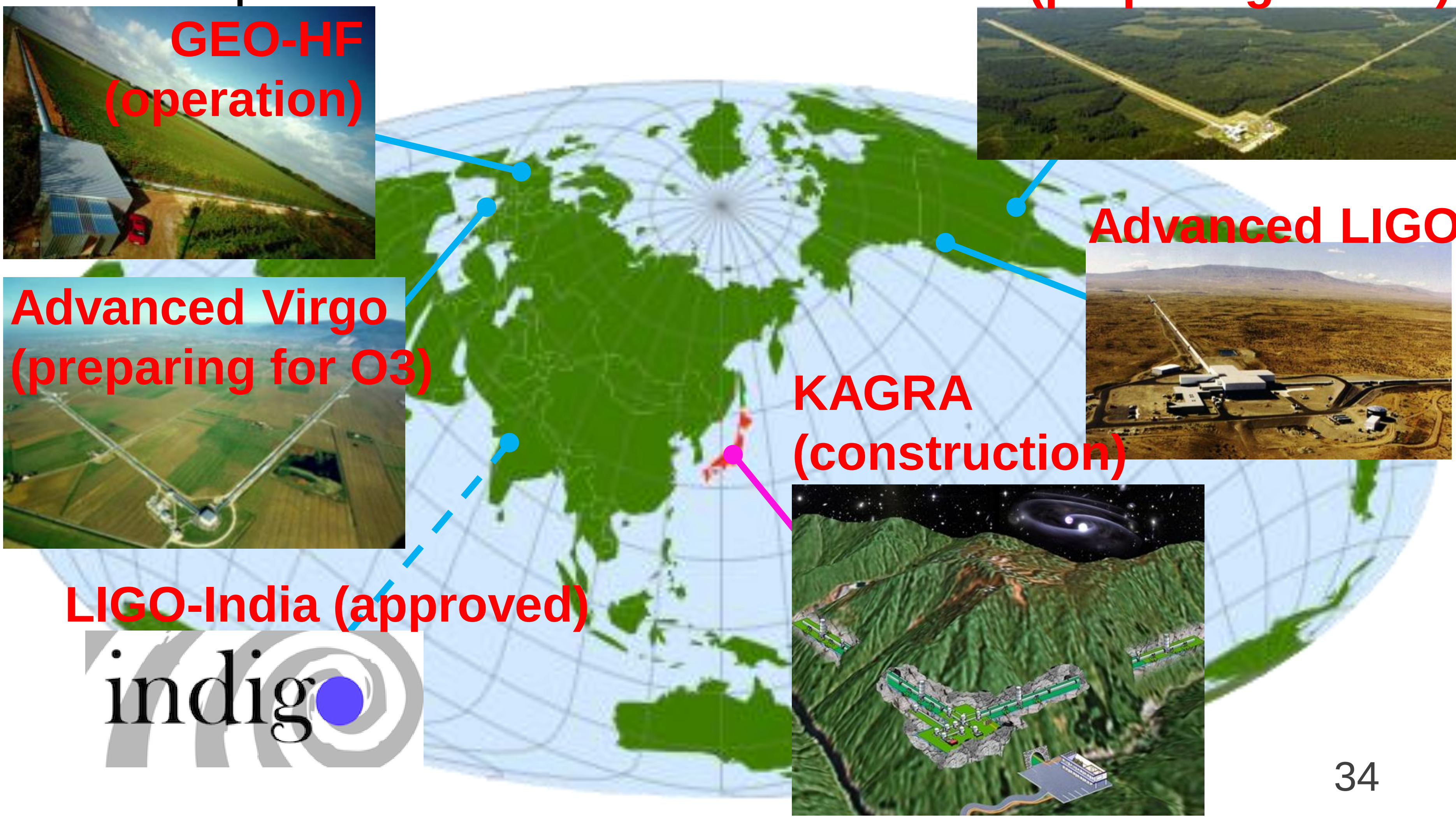
Solved and Unsolved Mysteries

- Origin of short gamma-ray bursts
  - coincidence with NS merger, as expected
  - but too faint: why?
- Origin of heavy elements
  - consistent light curve with calculations
  - but do all heavy elements come from BNS mergers?
- Remnant of NS merger
  - BH or NS or ??
  - equation of state
- More event and more precise parameter estimation necessary



Global Network of GW Telescopes

- For more event, better localization and parameter estimation



KAGRA Under Construction

- at underground site of Kamioka mine, Gifu, Japan
- 3-km cryogenic gravitational-wave telescope
- more than 60 institutes,
  more than 200 collaborators around the world

etc...

Location of KAGRA

2.5 hours from Tokyo by Hokuriku-Shinkansen

★ **OIST**

1 hour drive from Toyama

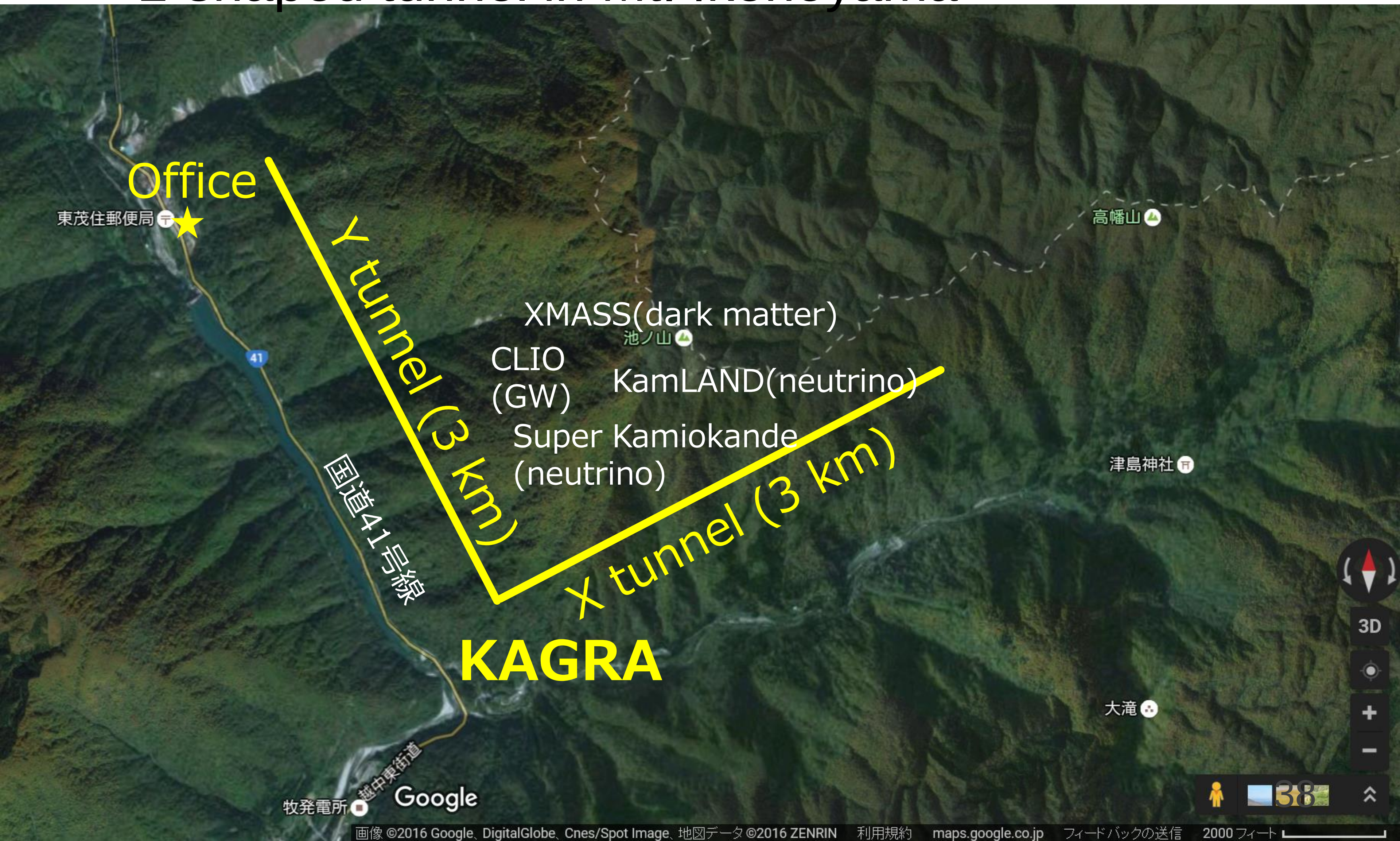
Kamioka

June 2015

Feb 2016

Kamioka Underground Observatory

- L-shaped tunnel in Mt. Ikenoyama



KAGRA Tunnel

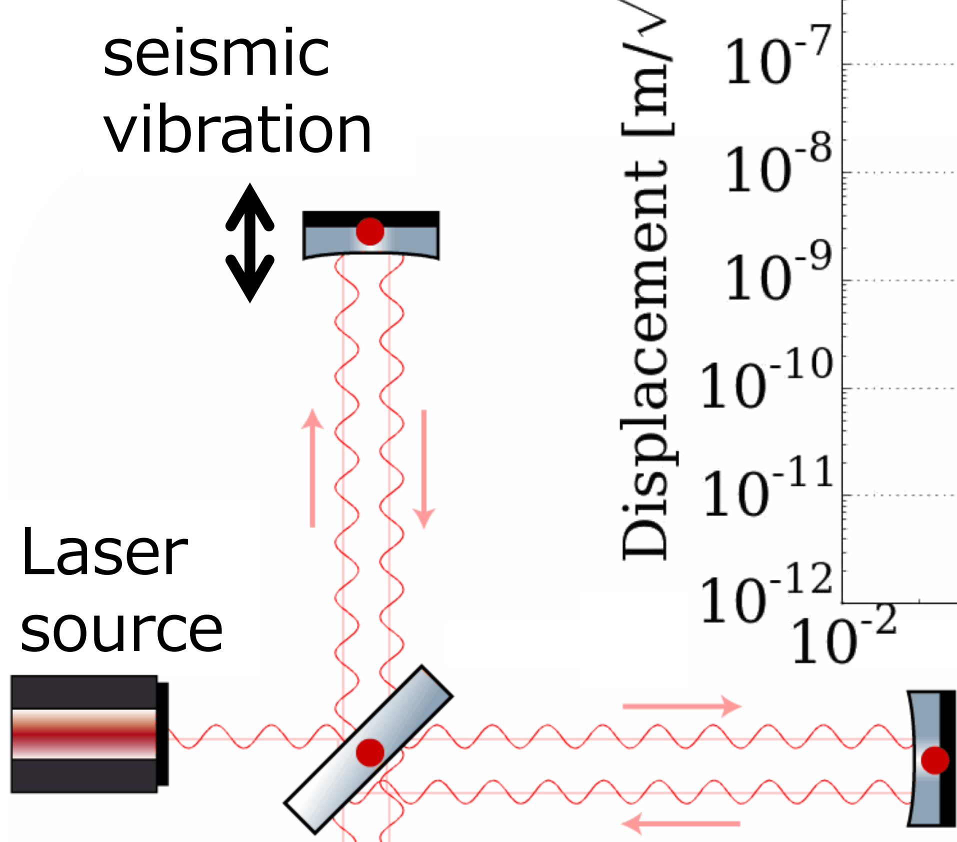
- two 3-km long vacuum pipes for laser beams to go back and forth

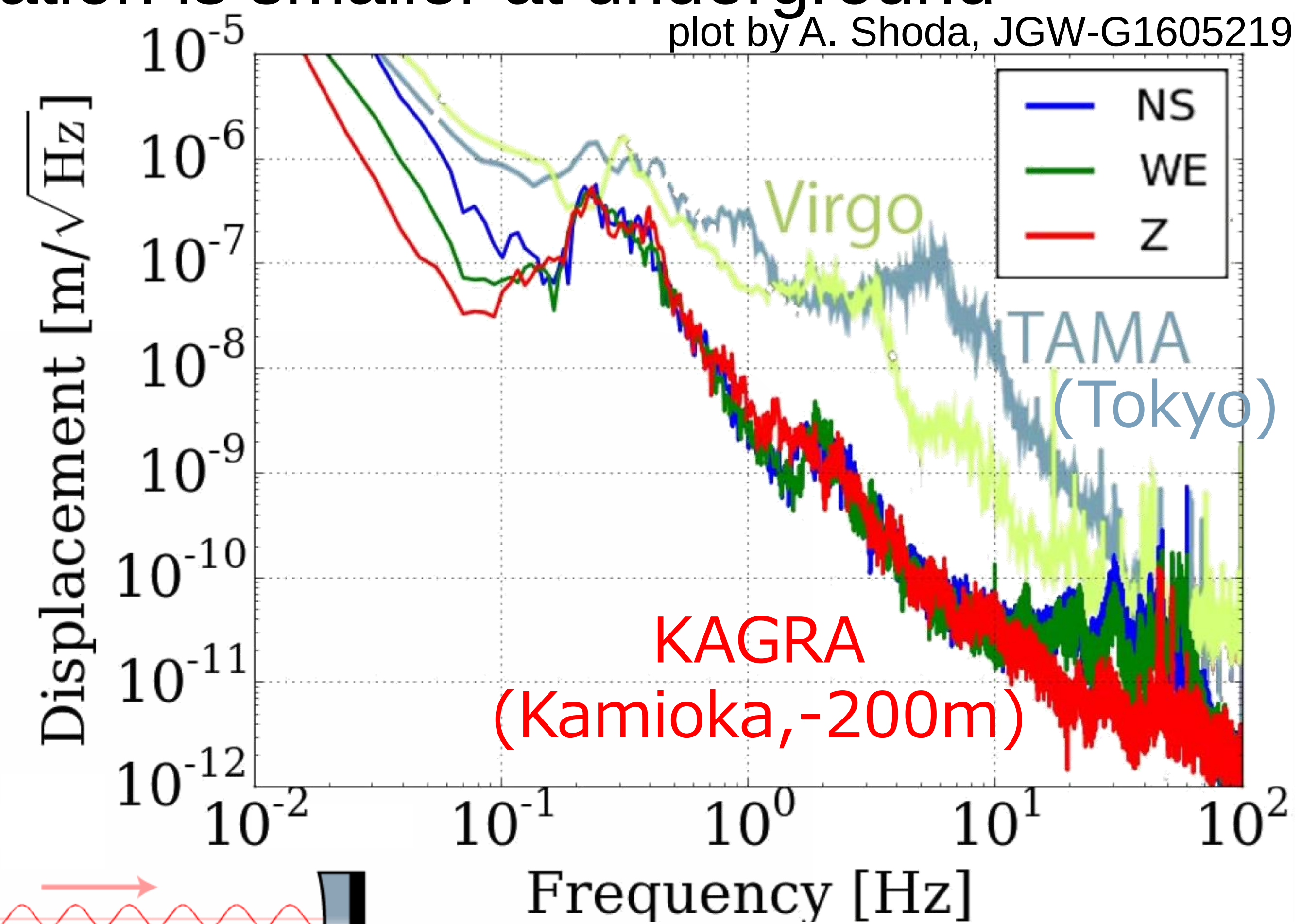
Working Style at Underground

- helmet, safety vest, boots, oximeter
- electric bicycle

Why Underground?

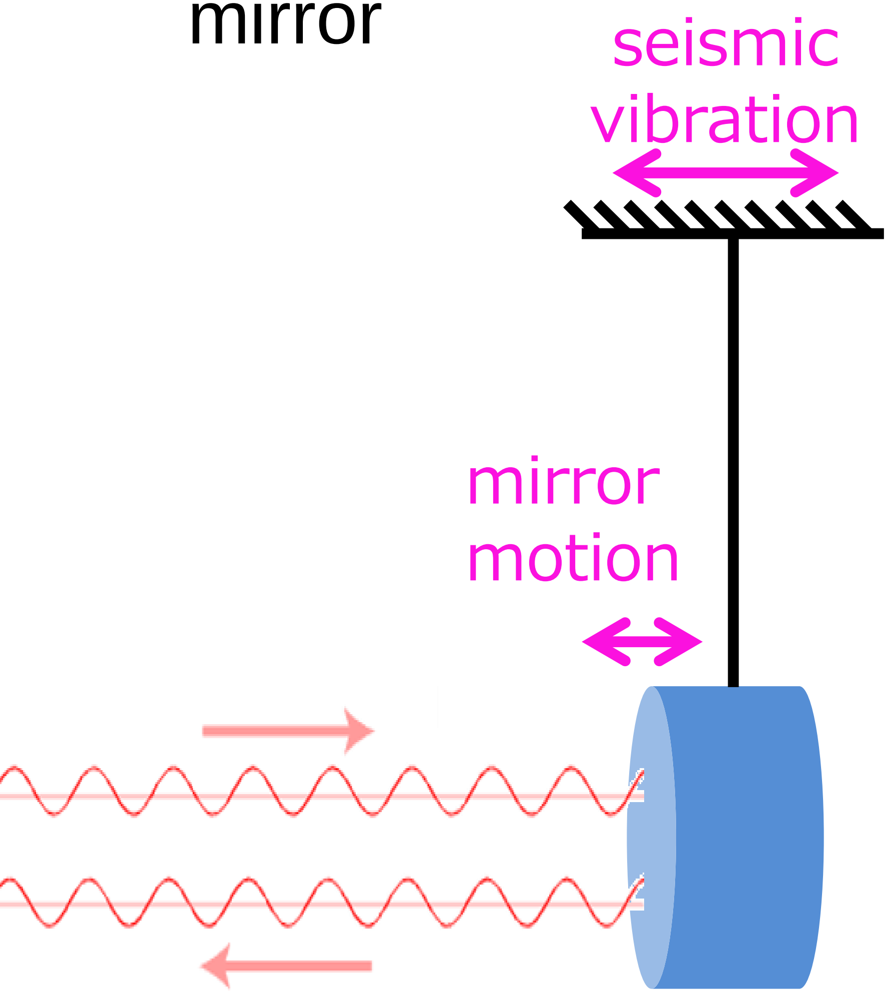
- vibration of mirror fakes GW signal
- seismic vibration is smaller at underground





Suspension for Vibration Isolation

- seismic vibration is attenuated by suspending a mirror



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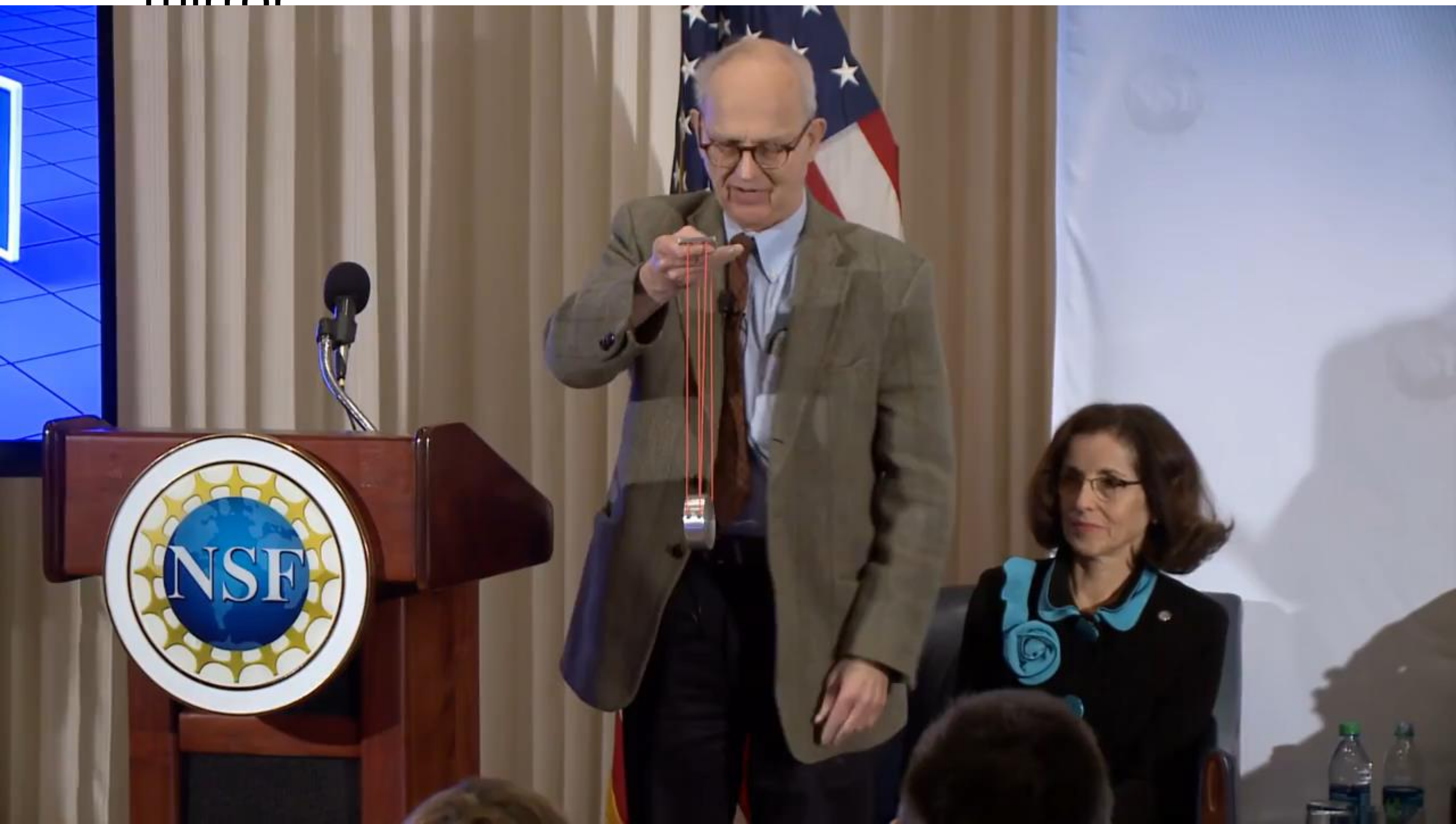
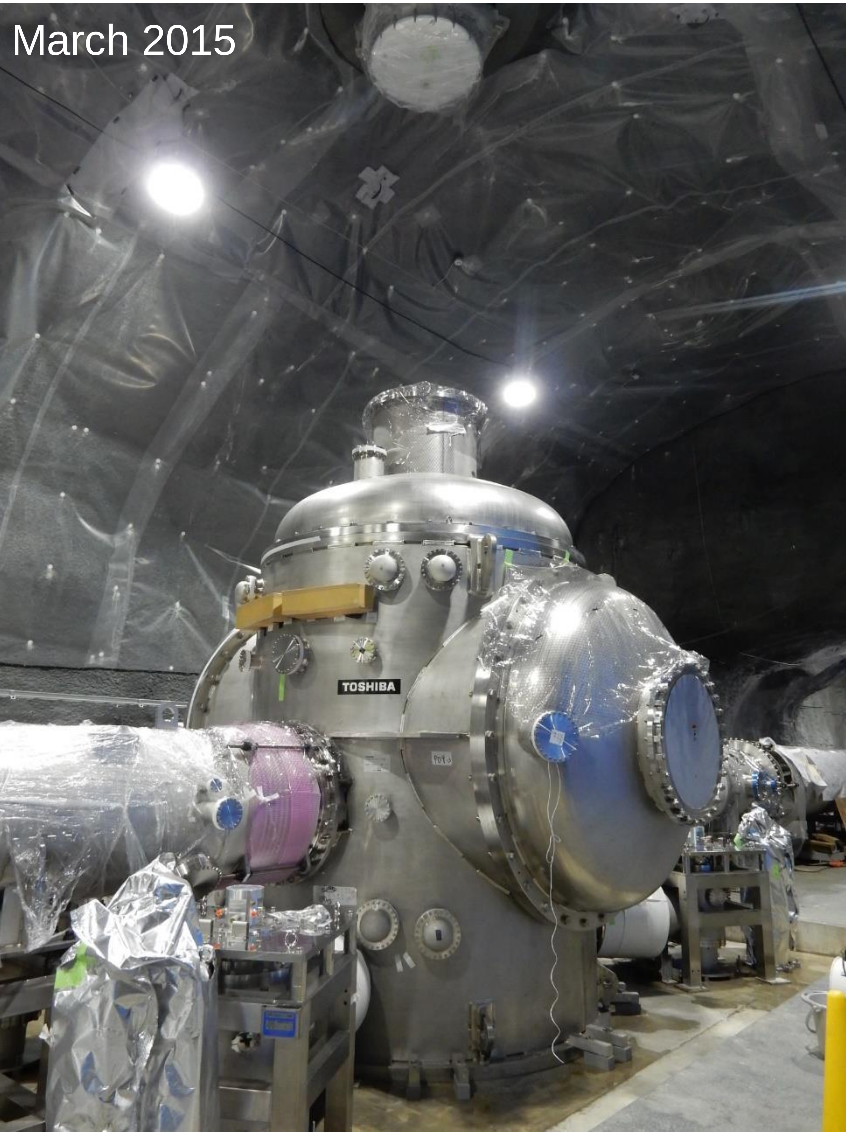
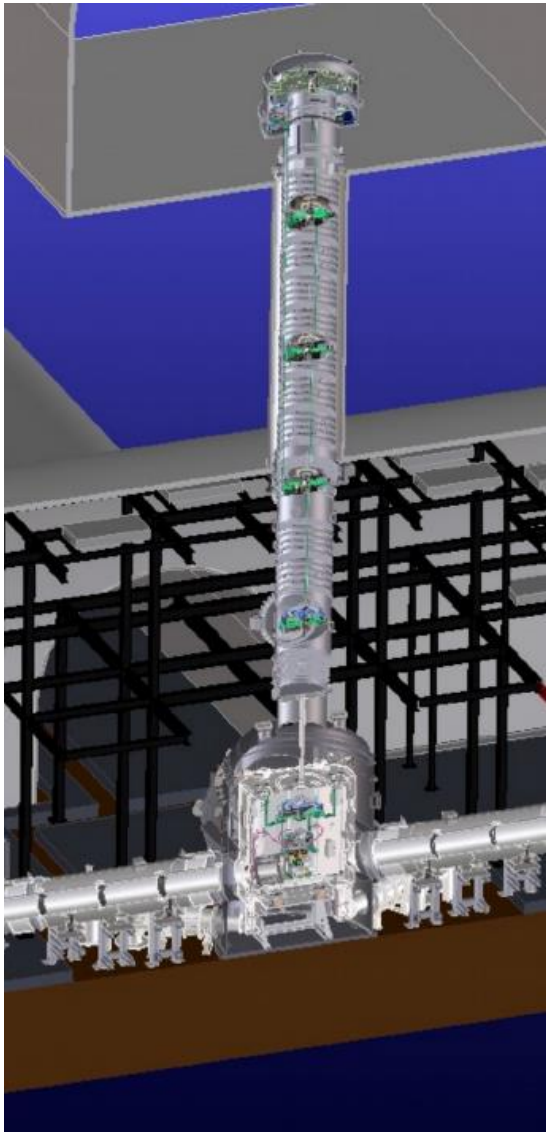
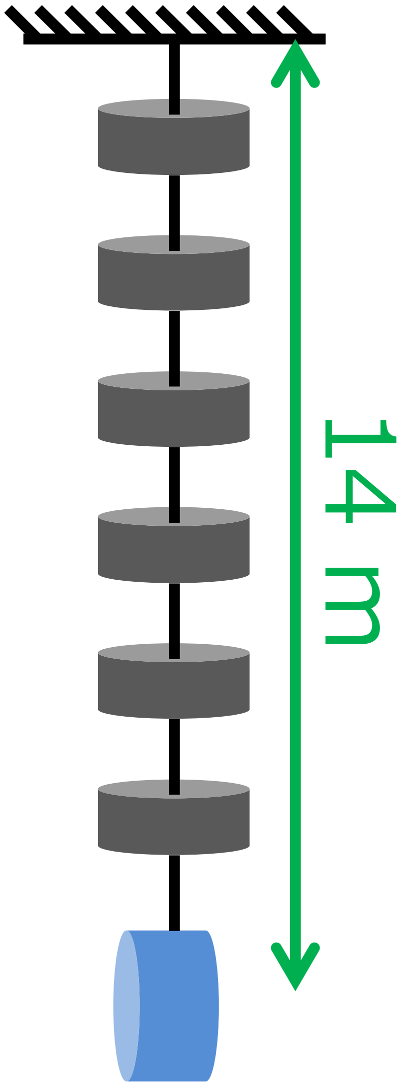


Vibration Isolation System

- 7-stage pendulum over two stories







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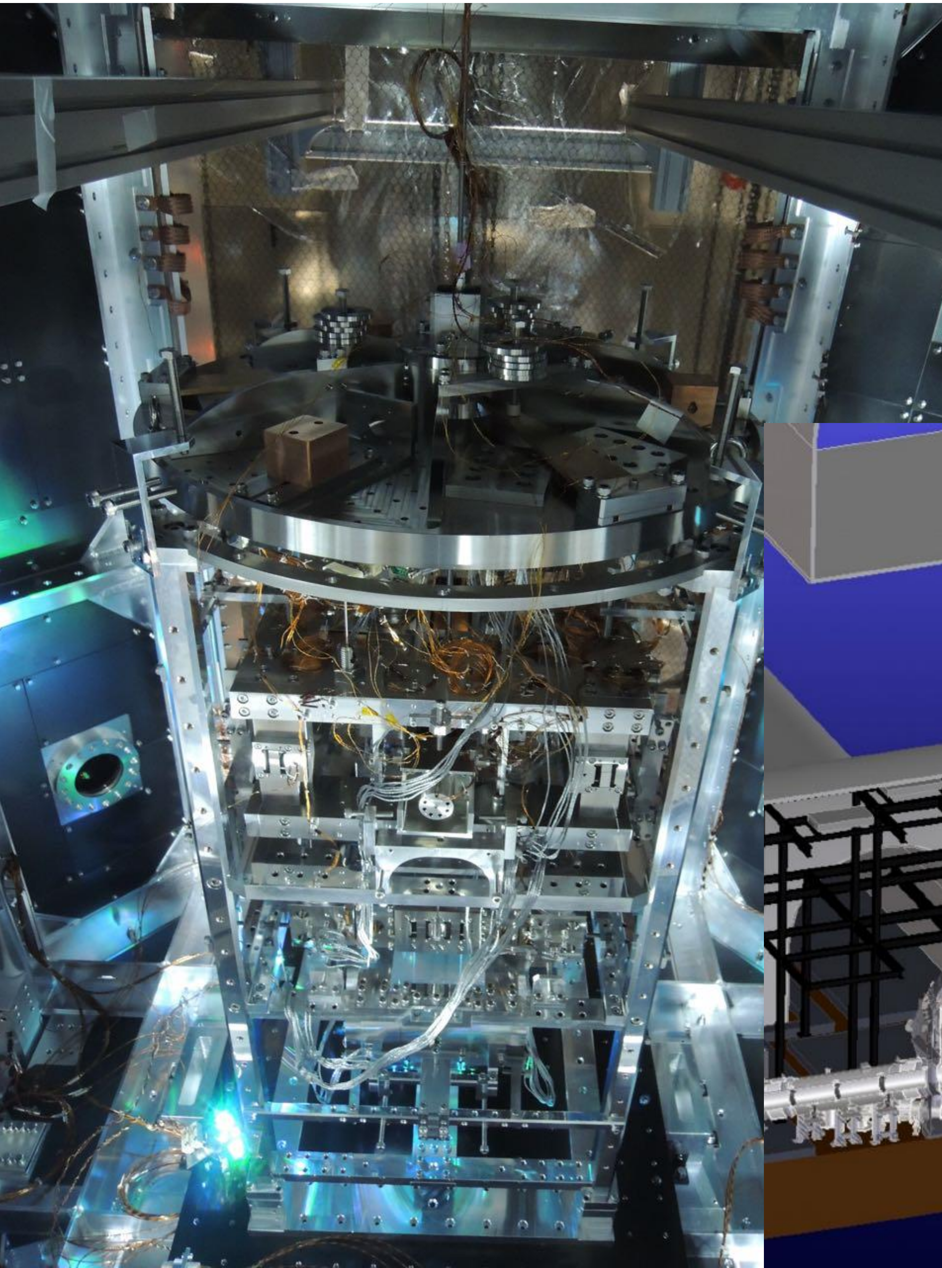
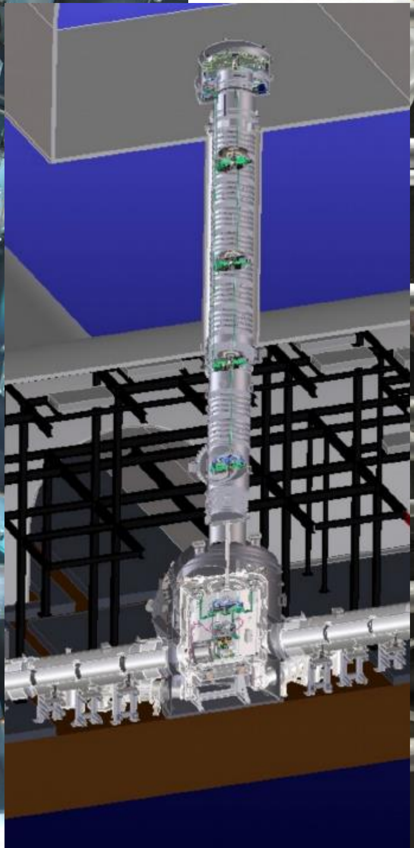
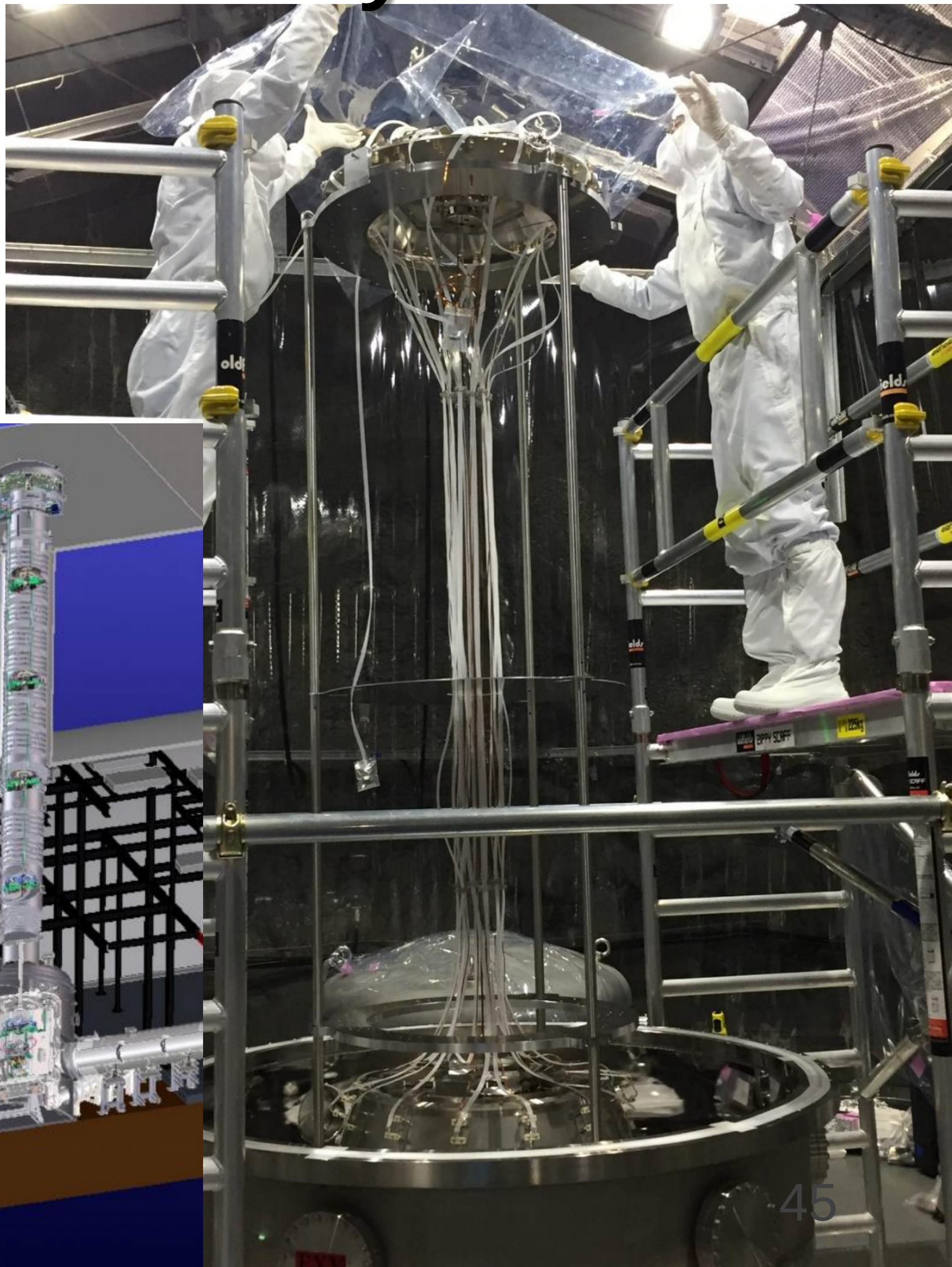
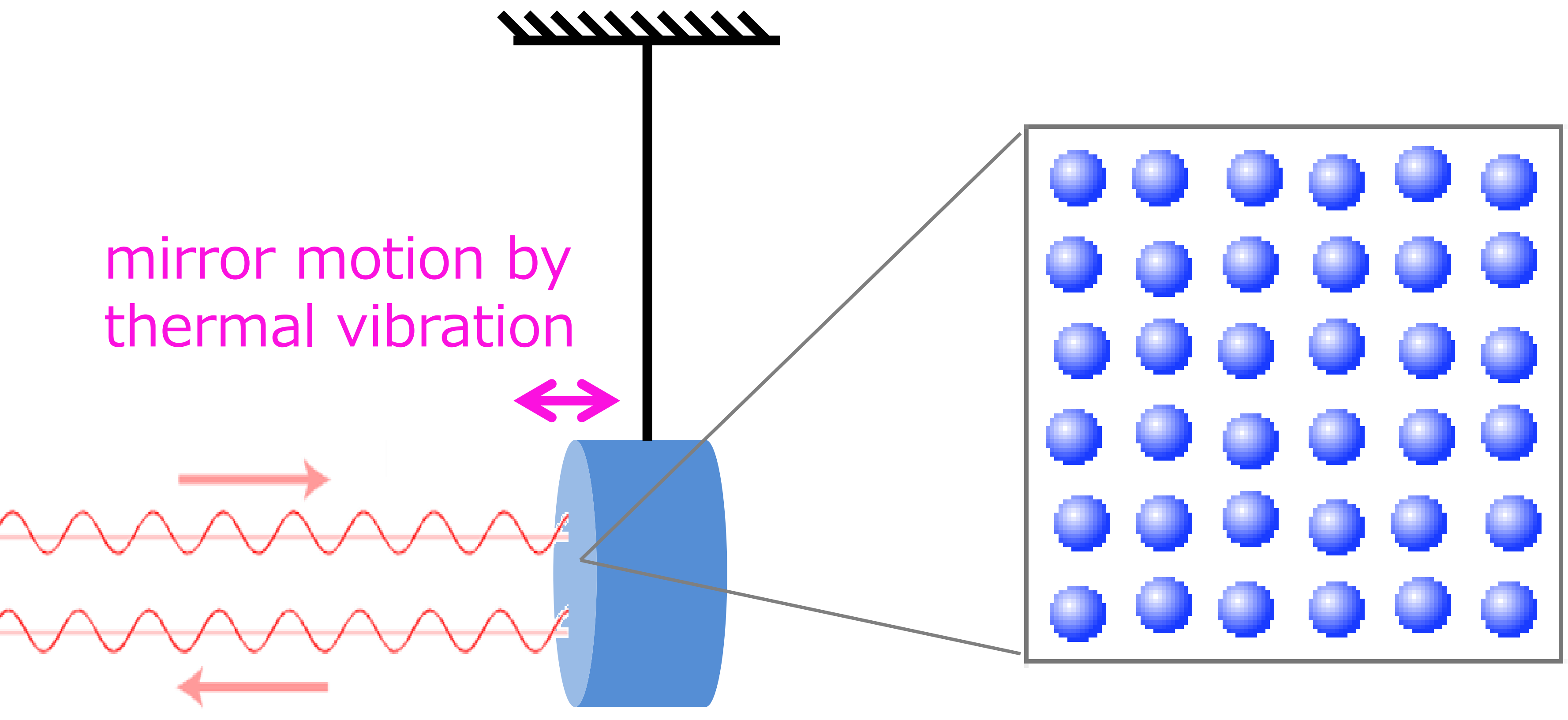






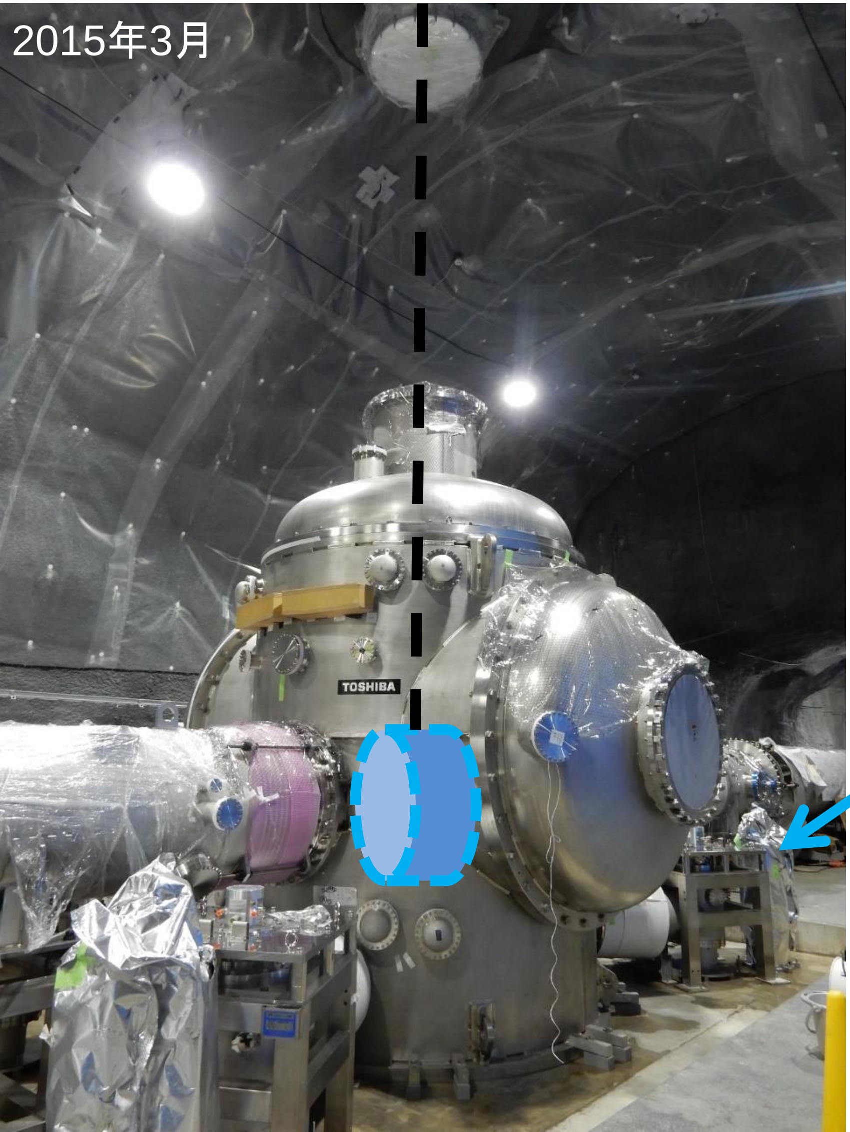
Cooling to Reduce Thermal Noise

- thermal vibration of mirror surface will be noise
- cryogenic cooling to 20 K to reduce thermal noise

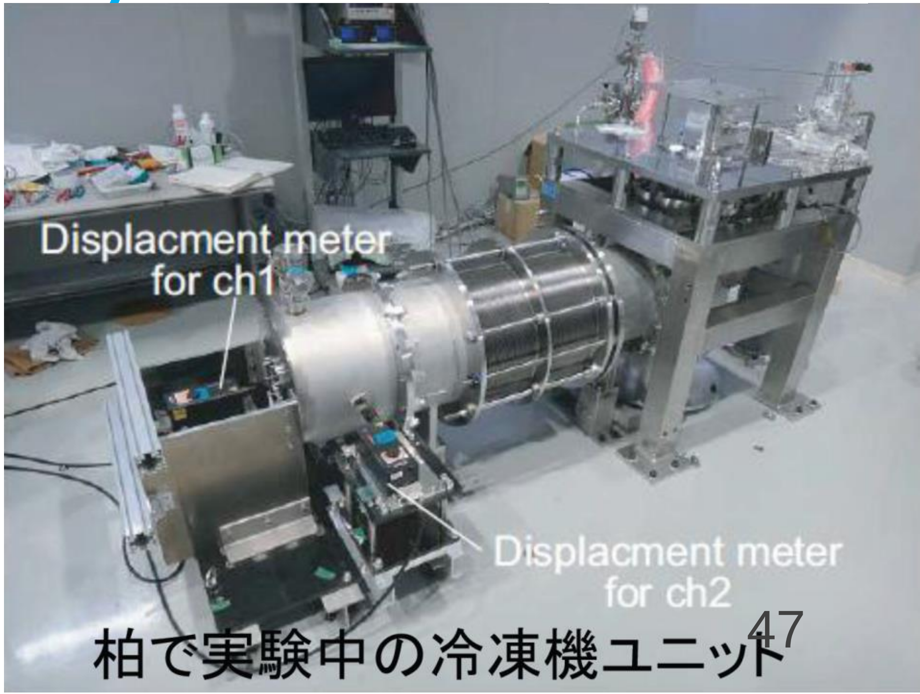


Cryogenics

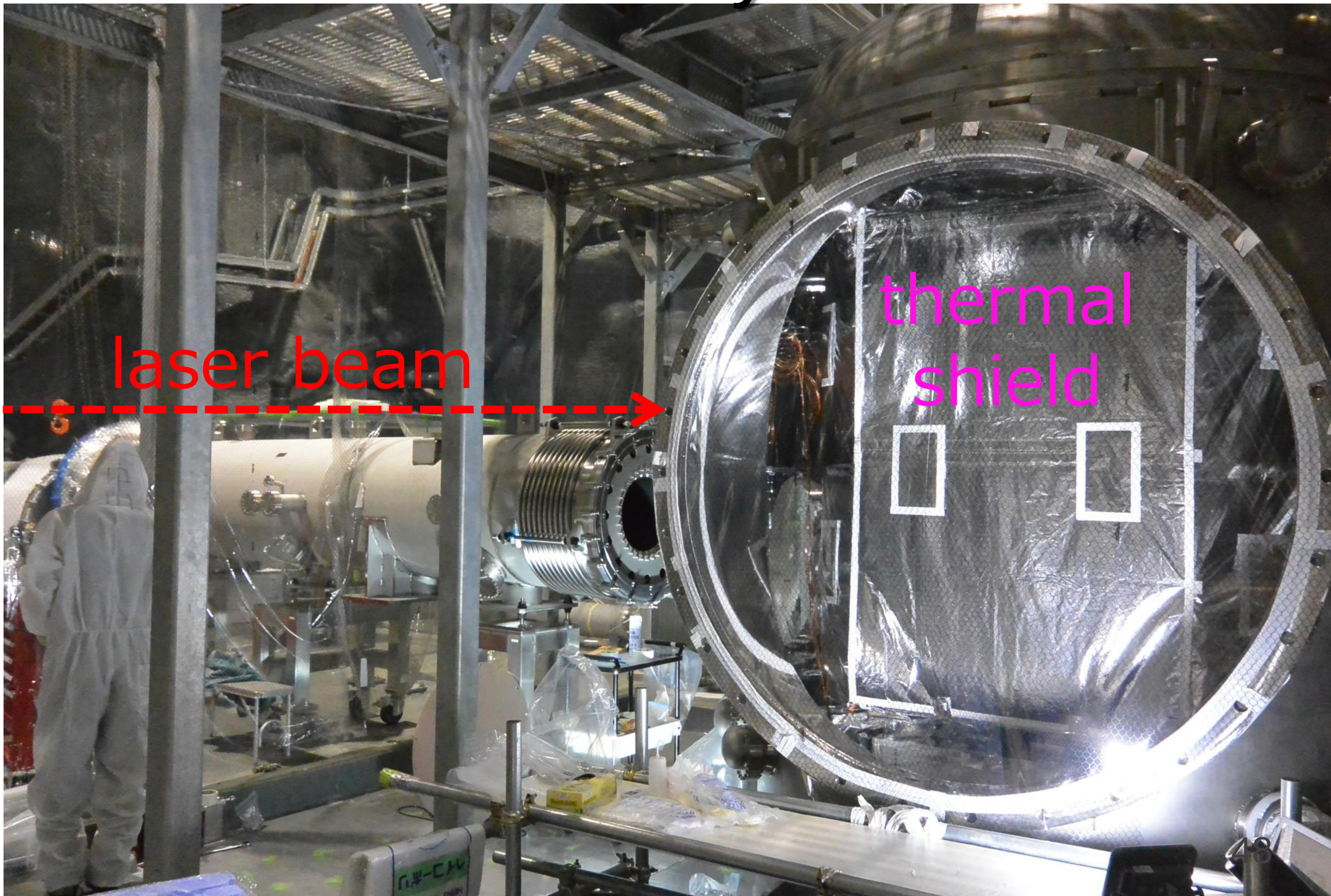
- lowest vibration cryocoolers



cryocooler

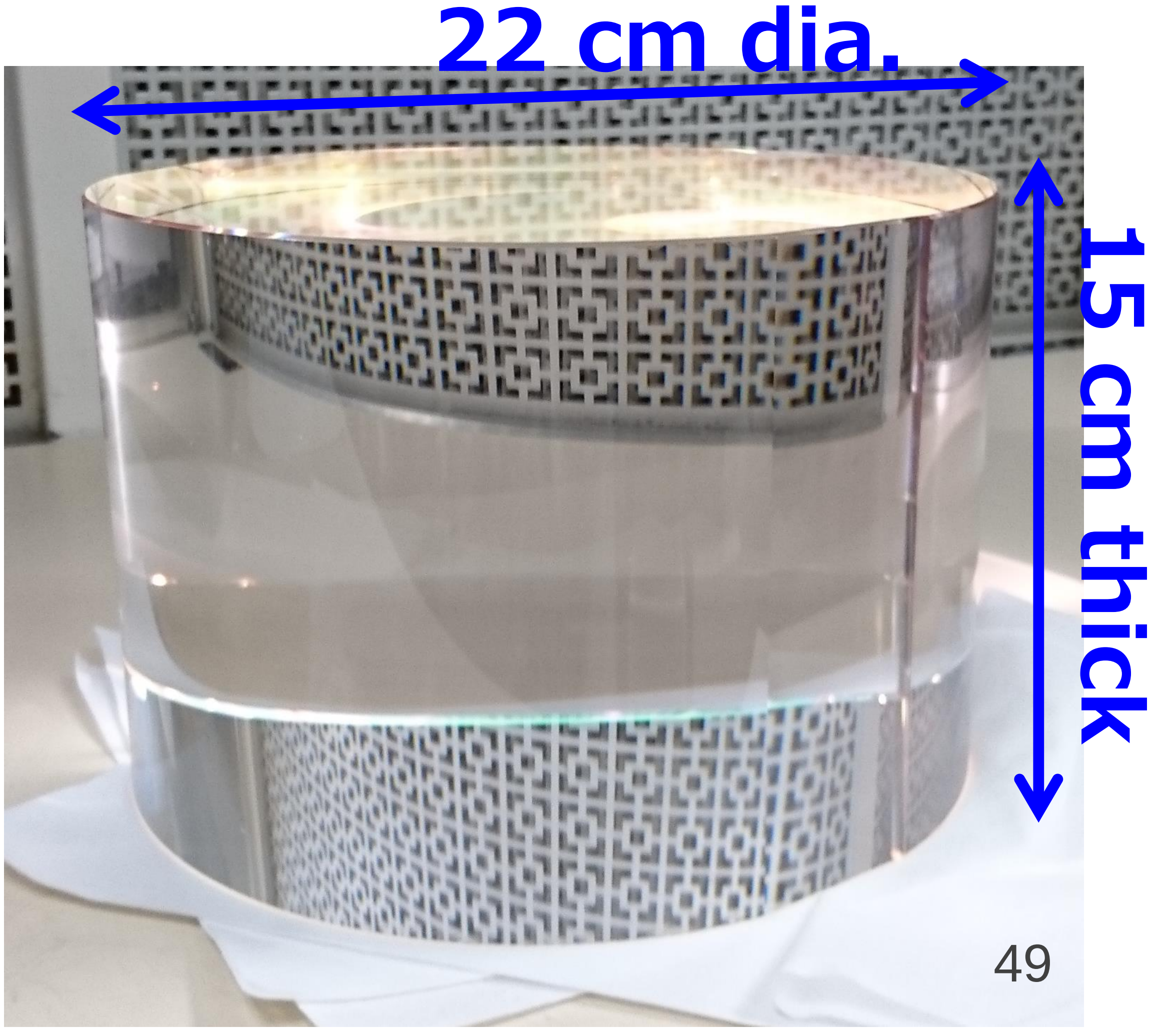


Inside Cryostat



Sapphire Mirror

- artificial sapphire
- low mechanical loss at cryogenic temperatures
- high reflectivity
- low loss
- high quality polish



KAGRA Timeline

2014 — Tunnel excavation finished

2015

2016 — First test operation at room temperature

2017

2018 — First cryogenic test operation

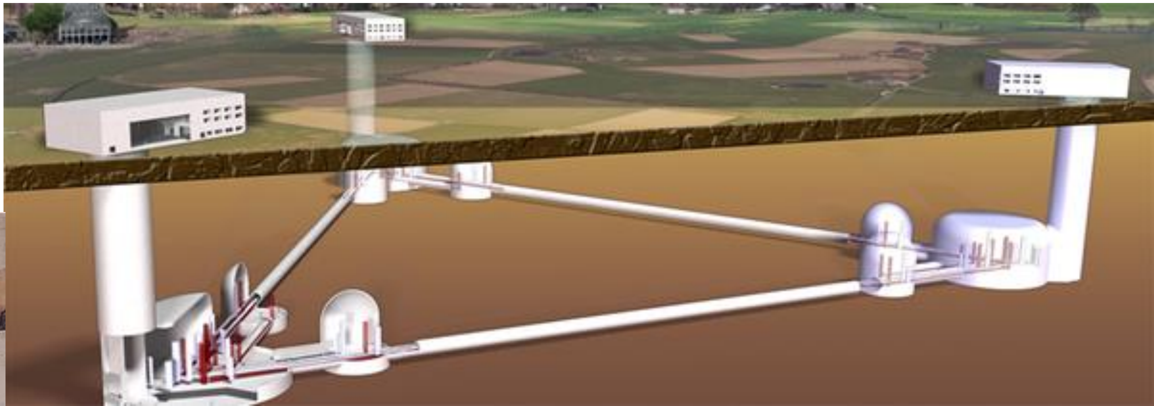
2019 — First operation with full configuration

2020 — Observing runs

http://kyodonews.net/news/2016/03/25/54510

Future Prospects

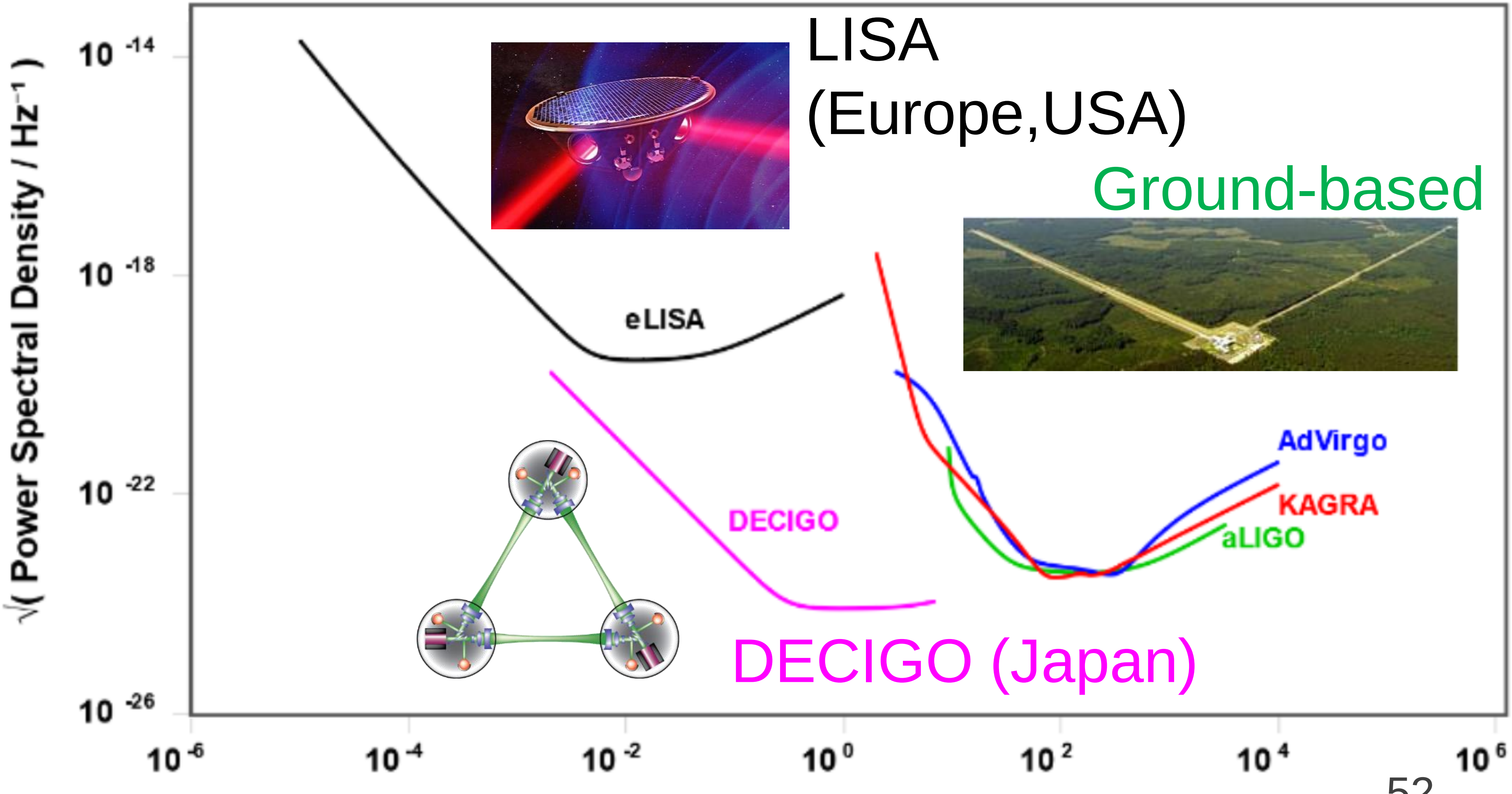
- LIGO (USA)
  quantum optical technique (squeezing)
  cryogenic silicon mirror at 120 K
  → x3 sensitivity
- Next generation detectors
  Einstein Telescope (Europe)
    10 km cryogenic interferometer at underground
  Cosmic Explorer (USA)
    40 km interferometer, 123 K silicon



ET EINSTEIN TELESCOPE

Space Borne GW Telescopes

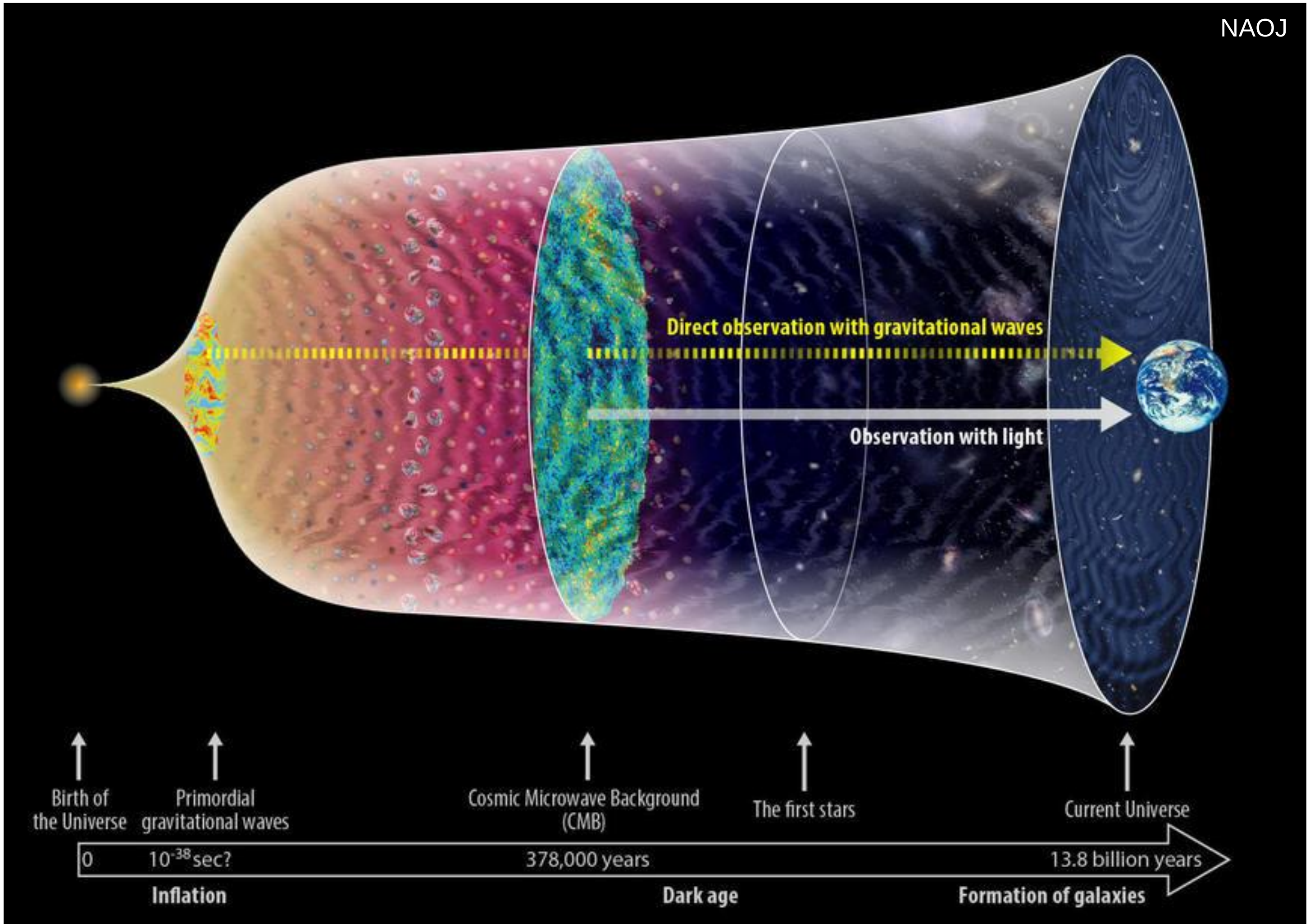
- no seismic vibration, very long arms
  → low frequencies: primordial GWs, massive BHs



http://rhcole.com/apps/GWplotter/

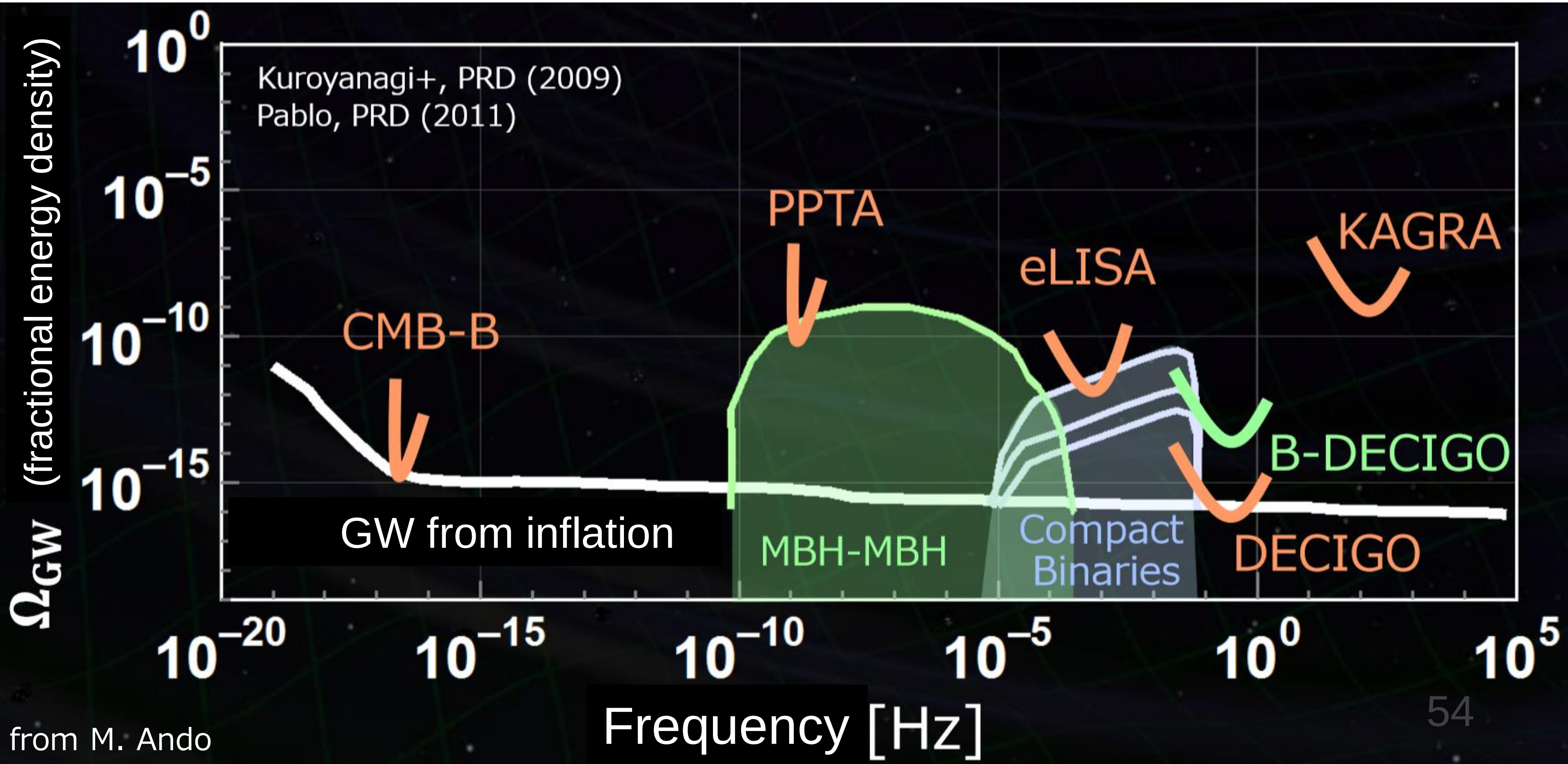
Primordial GWs

- GW from early universe (inflation)
  look into the very beginning of the universe



DECIGO

- DECIGO band is suitable for primordial GW
- for better understanding of history of the universe



Summary

- Whole new frontier of astronomy opened
  - gravitational wave astronomy
  - multi-messenger astronomy
- A lot of mysteries to be solved
  - origin of heavy stellar-mass black holes
  - neutron star equation of state
  - short gamma-ray burst, kilonova, ……
- KAGRA under construction
  - unique techniques: underground and cryogenics
  - observing runs in early 2020s
- Future prospects
  - longer arms, cryogenics, underground
  - space projects (LISA, DECIGO, …)

Additional Slides

Comparison of GW Detectors

	KAGRA	AdVirgo	aLIGO	A+	Voyager
Arm length [km]	3	3	4	4	4
Mirror mass [kg]	23	42	40	80	200
Mirror material	Sapphire	Silica	Silica	Silica	Silicon
Mirror temp [K]	22	295	295	295	123
Sus fiber	35cm Sap.	70cm SiO_2	60cm SiO_2	60cm SiO_2	60cm Si
Fiber type	Fiber	Fiber	Fiber	Fiber	Ribbon
Input power [W]	78	125	125	125	140
Arm power [kW]	340	700	710	1150	3000
Wavelength [nm]	1064	1064	1064	1064	2000
Beam size [cm]	3.5 / 3.5	4.9 / 5.8	5.5 / 6.2	5.5 / 6.2	5.8 / 6.2
SQZ factor	0	0	0	6	8
F. C. length [m]	none	none	none	16	300

LIGO parameters from LIGO-T1600119, AdVirgo parameters from JPCS 610, 01201 (2015)

Multi-Frequency GW Astronomy