Multi-Messenger Astronomy

Ray Li (NCKU)

Outline

- Multi-Wavelength Astronomy
- Multi-Messenger Astronomy
- How to detect neutrinos?
- How to detect gravitational waves?
- MMA Examples

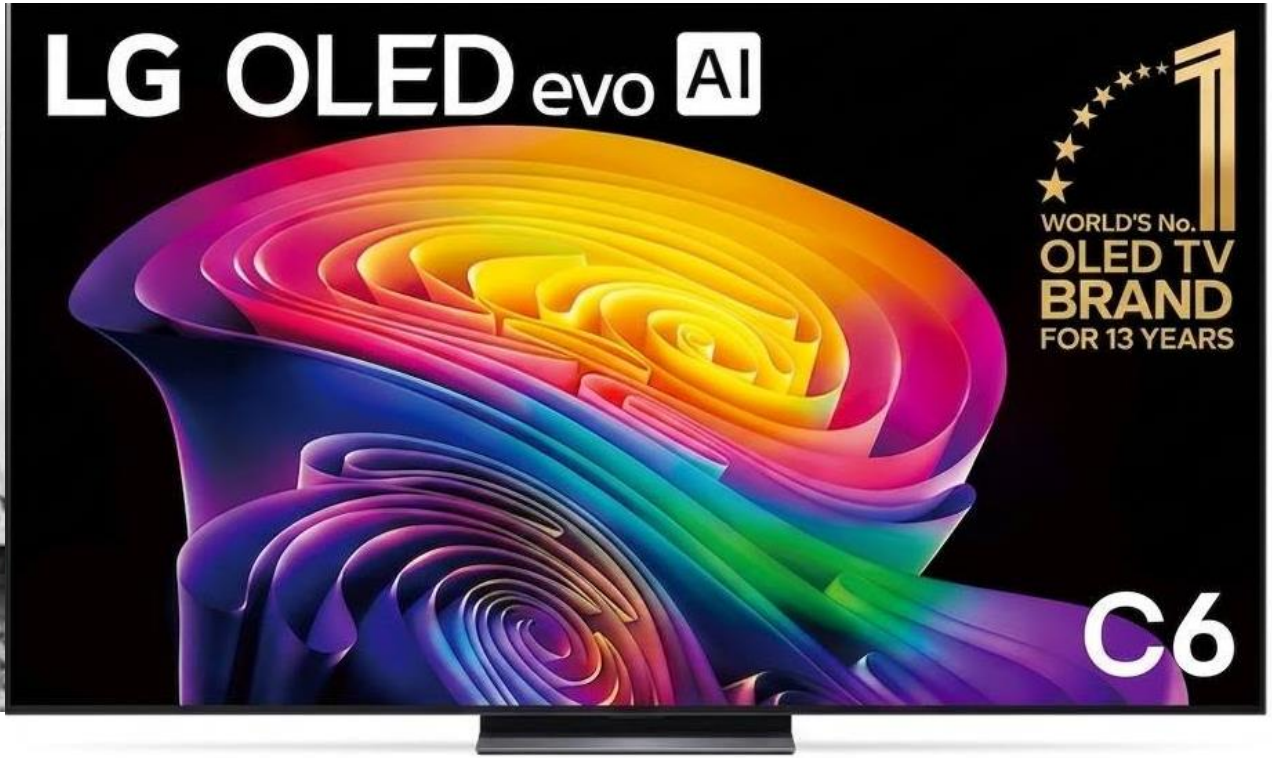
What is Multi-Wavelength Astronomy

- For multi-wavelength, we usually mean the four types: **gamma-ray**, **X-ray**, **UV and optical/infrared (OIR)**, **radio**.

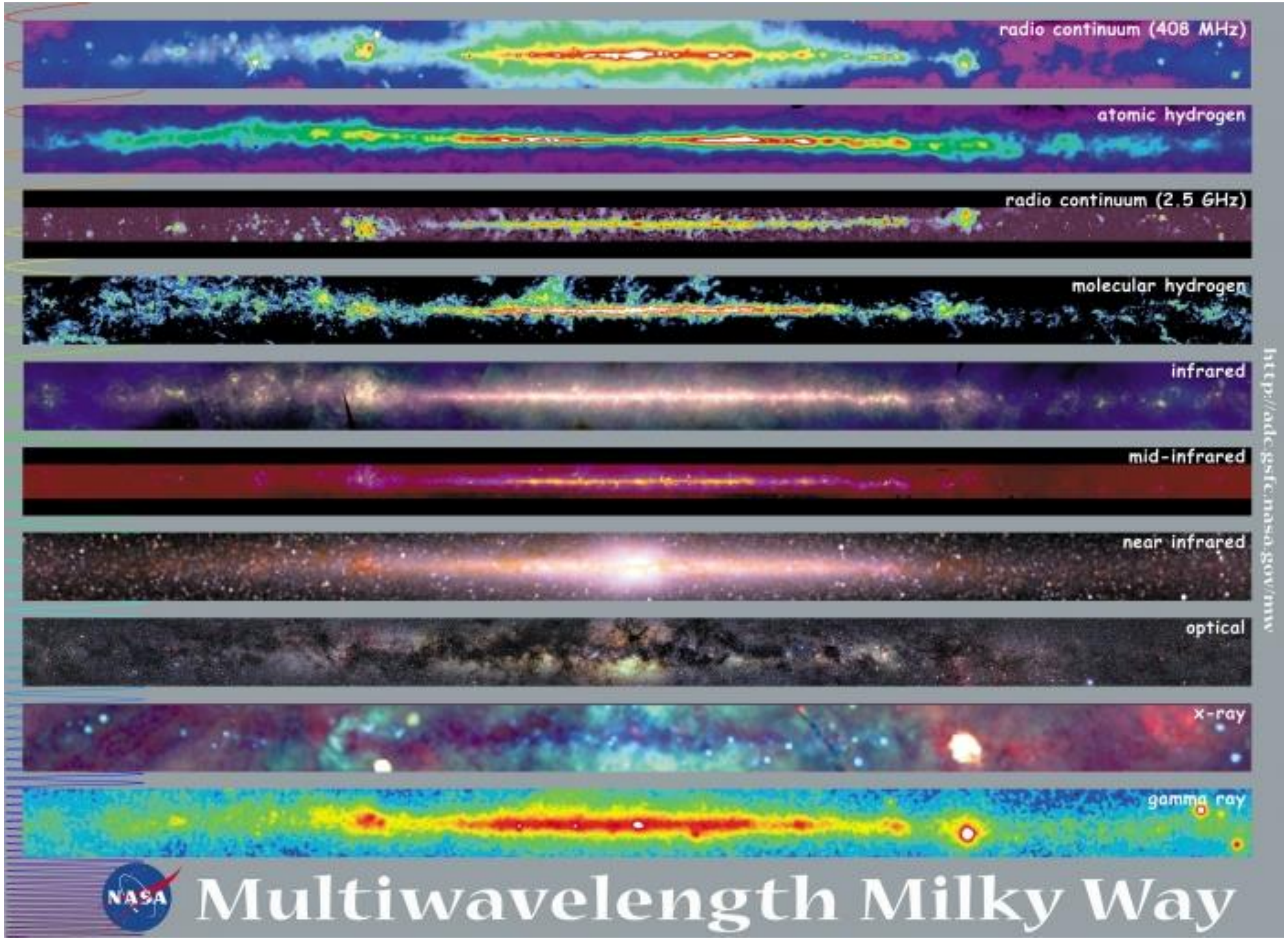
- For most of the astronomical object classes, they often have the "best" wavelength to be observed.

    - UV/OIR observations for studying stars
    - Sub-mm/radio observations for star formation
    - X-ray observations for compact objects

Why Multi-Wavelength Astronomy



Why Multi-Wavelength Astronomy



- Different wavelength gives us very different types of information
- For example, the Milky Way looks differently in the infrared and optical bands. Why is that?


gamma ray
X-ray
ultraviolet
visible
infrared
microwave
radio

Why people did single-wavelength?

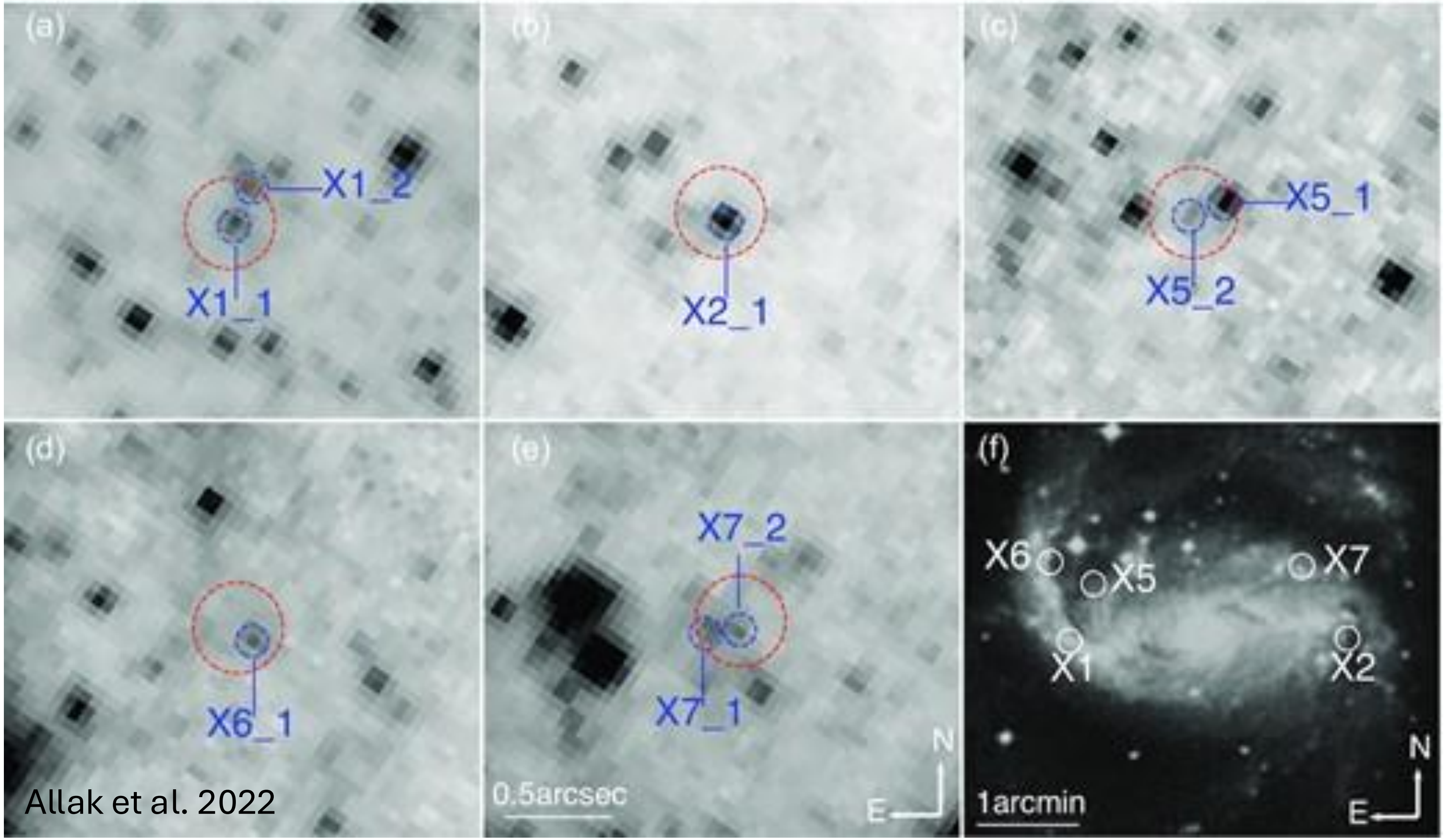
- Difficult Telescope Time

- Skill Differences in Data Analysis

- Not every objects can be easily observed in multi-wavelength

- **Link between the multi-wavelength data**
  - **Position and Time**

Example: ULXs in NGC 1672



Allak et al. 2022

What is Multi-Messenger Astronomy

- We study the universe mainly (only) by electromagnetic (EM) wave observations, i.e., we see and study the light.

- Recently, we can understand the universe in other ways – other than EM wave.

    - Gravitational-waves
    - Neutrinos

When did Multi-Messenger Astronomy start?

GW170817: the dawn of multi-messenger astronomy inlcuding gravitational waves

Marica Branchesi (Unlisted)
2020

10 pages
Part of Proceedings, 200th Course of Enrico Fermi School of Physics: Gravitational Waves and Cosmology (GW-COSM)
Published in: *Proc.Int.Sch.Phys.Fermi* 200 (2020) 123-132
Contribution to: GW-COSM, 123-132
DOI: 10.3254/ENFI200006

Abstract: (IOS Press)
On 2017 August 17 the Advanced LIGO and Advanced Virgo detectors detected for the first time the signal, GW170817, from the coalescence of a binary system of neutron stars (Abbott B.P. et al., Phys. Rev. Lett., 119 (2017) 161101). Exactly 1.7 s after the merger time (12:41:04 UTC) the Fermi Gamma-ray Burst Monitor independently detected a gamma-ray burst, GRB170817A (Abbott B.P. et al., Astrophys. J. Lett., 848 (2017) L13; L14). An extensive observing campaign involving more than 70 world-wide ground and space observatories was performed leading to the discovery of the counterpart signals across all the electromagnetic spectrum (Abbott B.P. et al., Astrophys. J. Lett., 848 (2017) L12). This observational campaign marks the birth of multi-messenger astronomy, which uses gravitational waves and electromagnetic emission. The collected multi-messenger data confirmed ten-year-old theoretical models. And at the same time, the richness of details of the taken data will require to develop new theory and to make other observations in the coming years to be interpreted

When did Multi-Messenger Astronomy start?

- SN 1987A in LMC (50 kpc)

- We will talk about it later.

Neutrino Detection

Neutrino

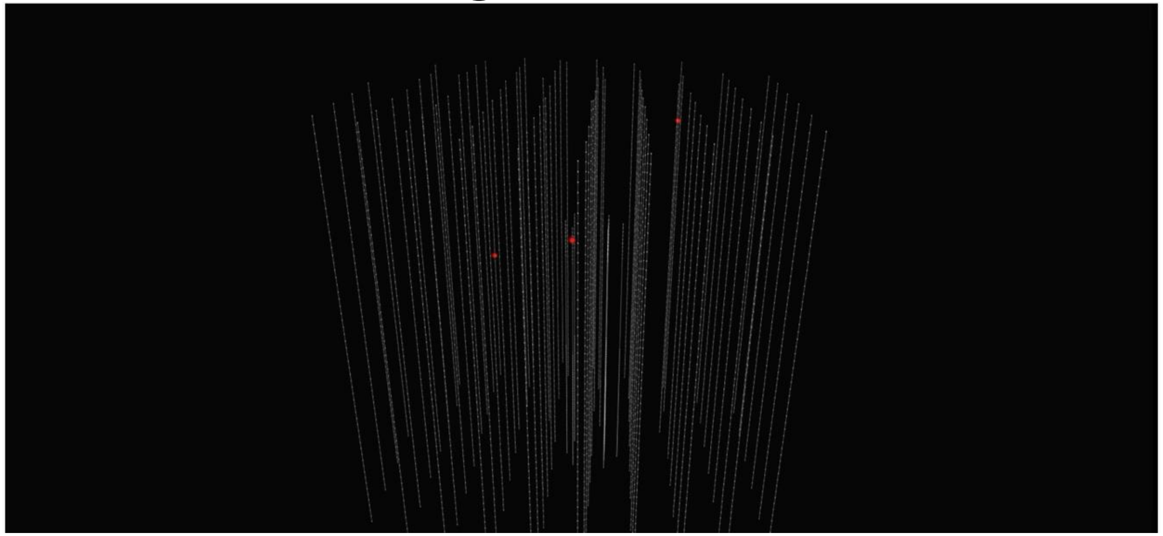
- Neutrinos are ghost particles
  - They do not like to interact with others
  - But they are literally everywhere on Earth

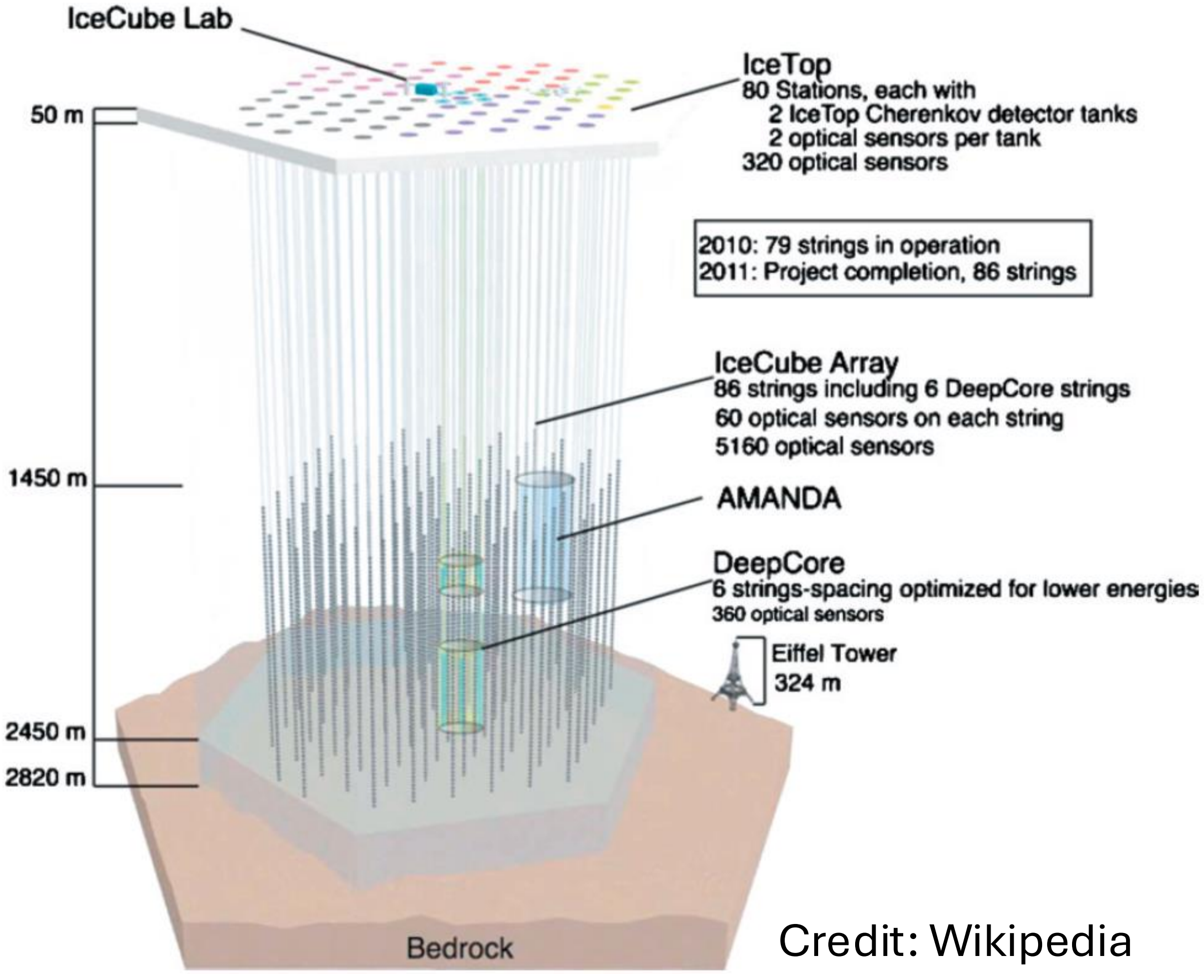
- Sun is a huge source of neutrinos
  - On average, the flux $>10^{10}$ solar neutrinos/cm^2/s!

- Other sources: supernovae, supermassive black hole (e.g., TDEs and AGN flares)

Ice Cube

- Located in Antarctica (South pole)
- Interact with water/ice (hydrogen) to emit high-speed charged particles (still rare).
    - Cherenkov light
    - when a charger particle travel faster than “the speed of light” in the media, it emits weak blue light.

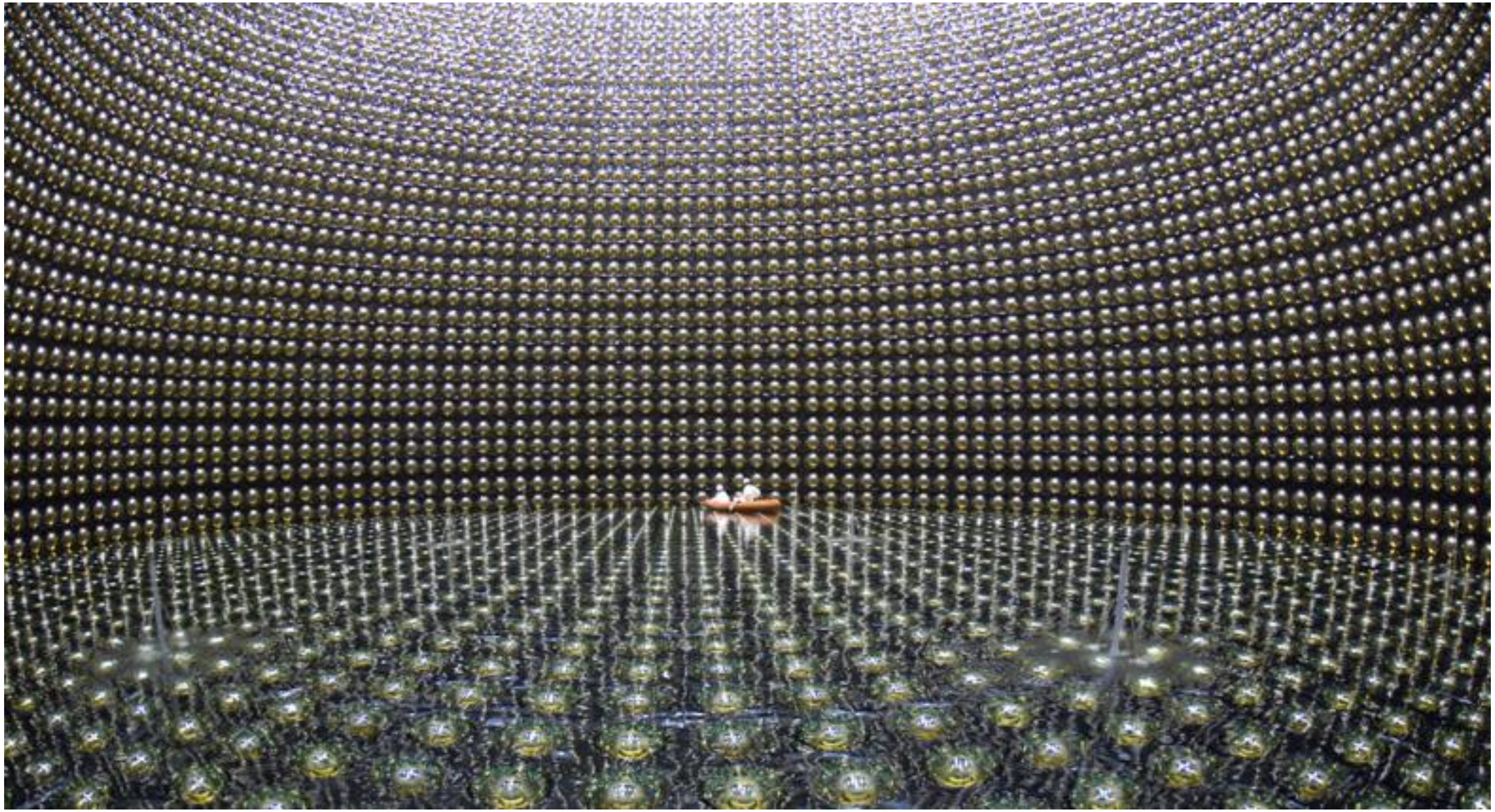




Credit: Wikipedia

Water: Super Kamiokande (Japan)

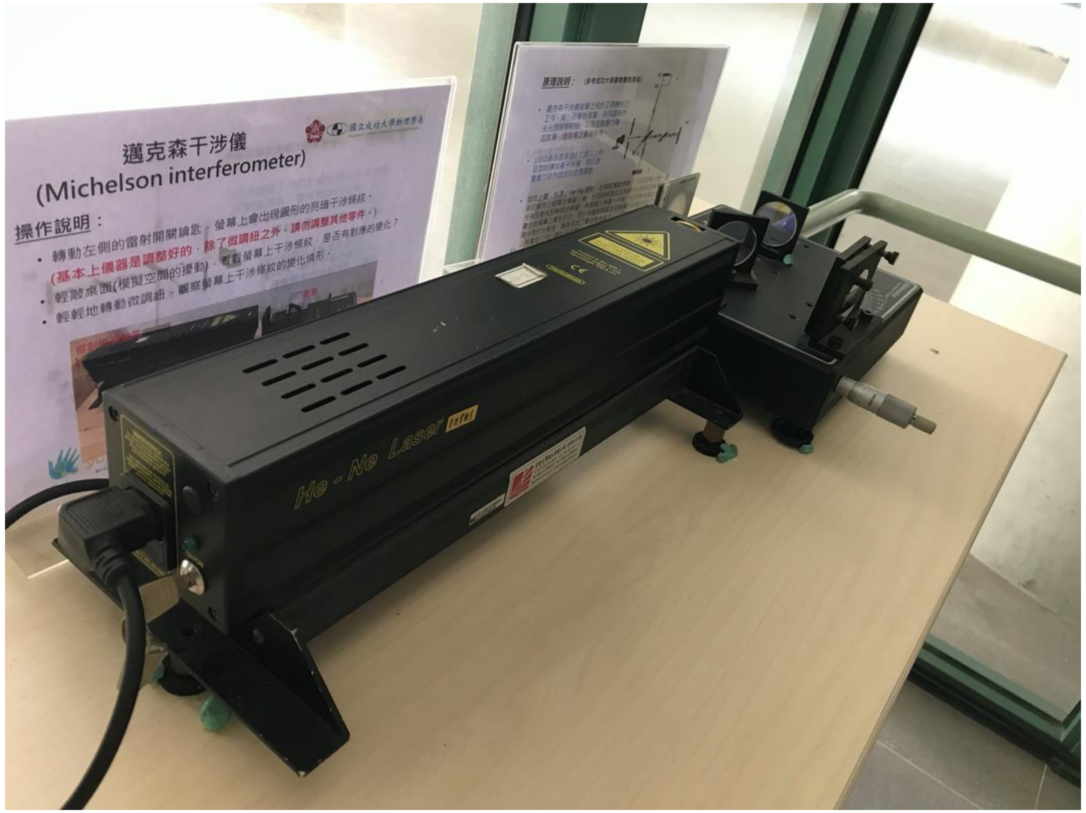
Credit: phys.org

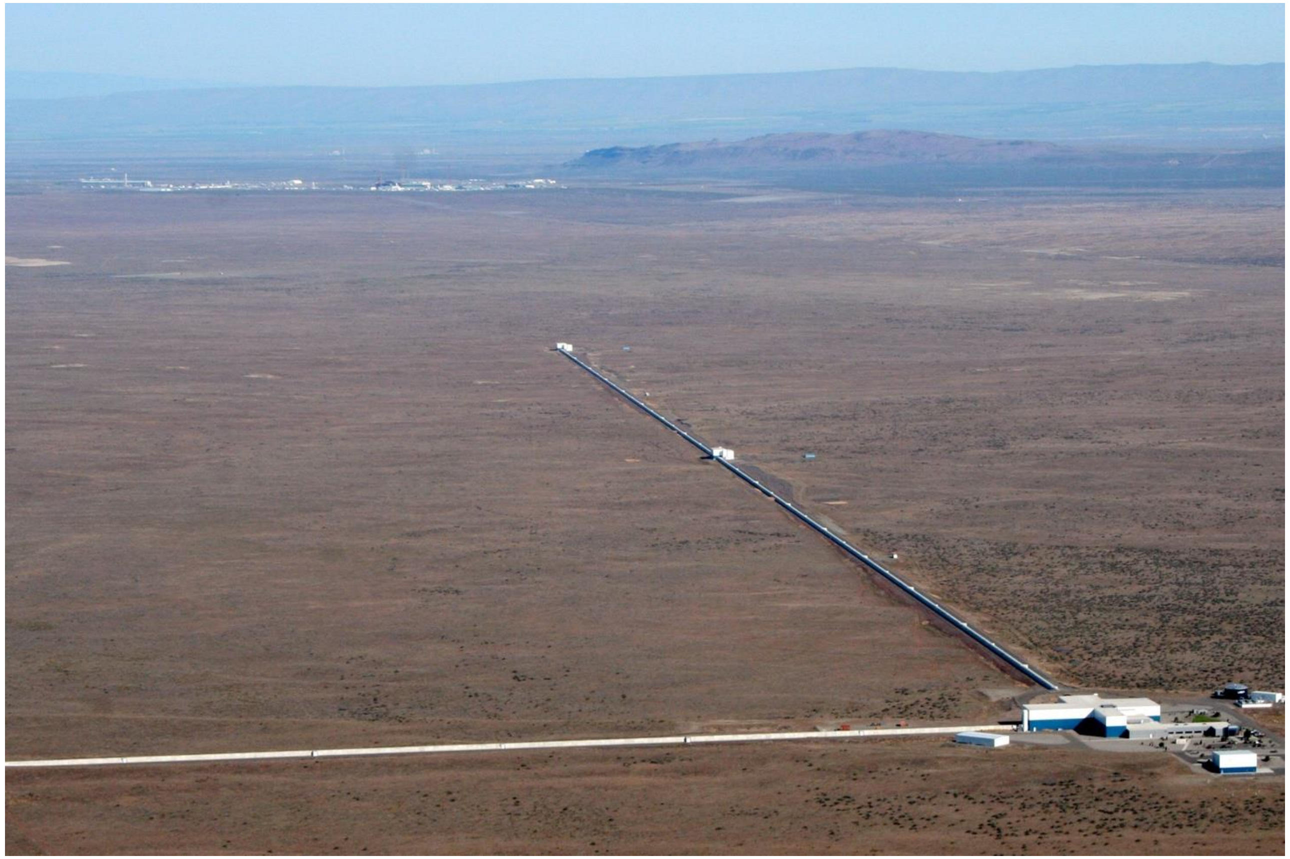


Gravitational-Wave Detection

Gravitational wave

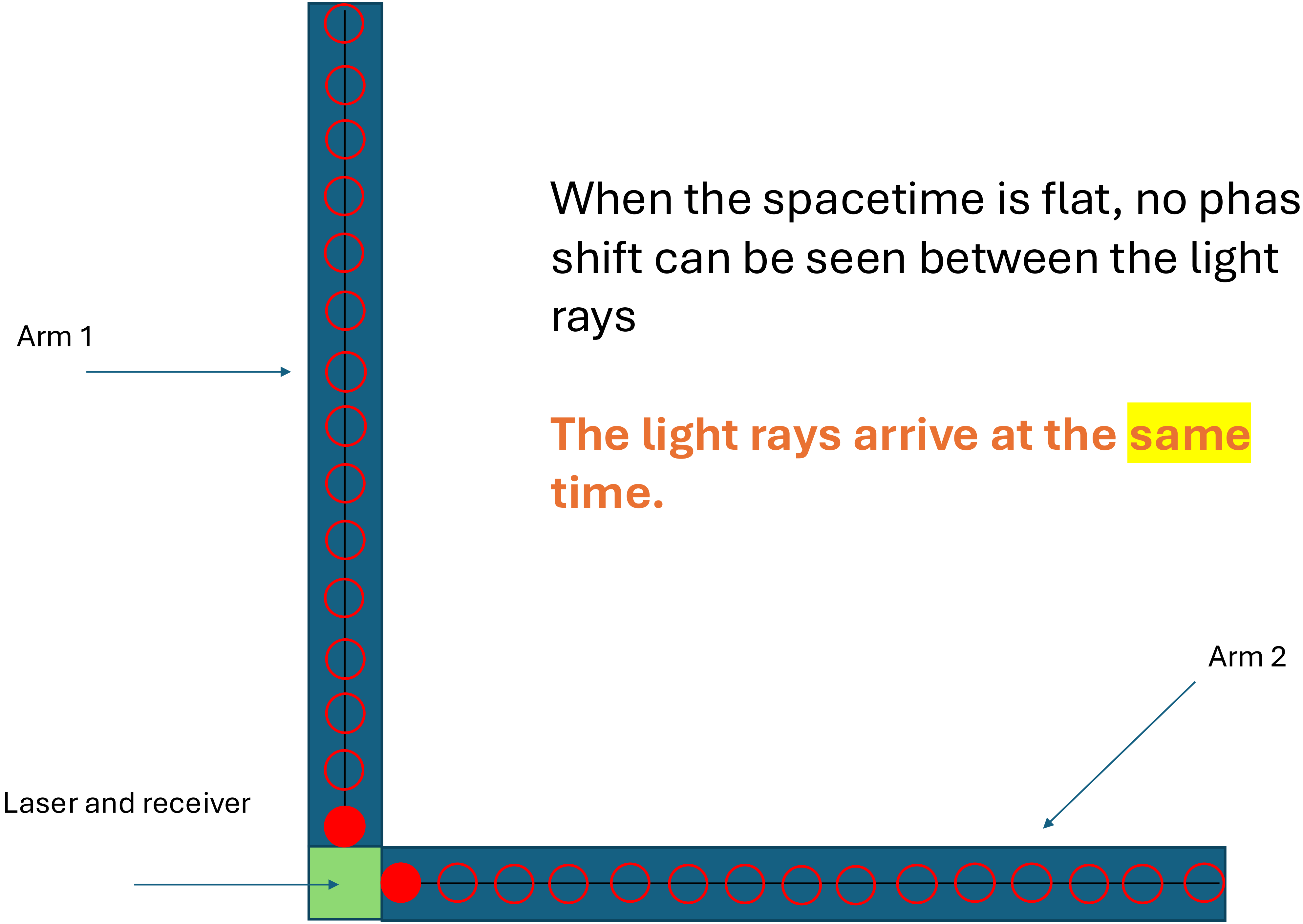
- Basically, a Michelson Interferometer.

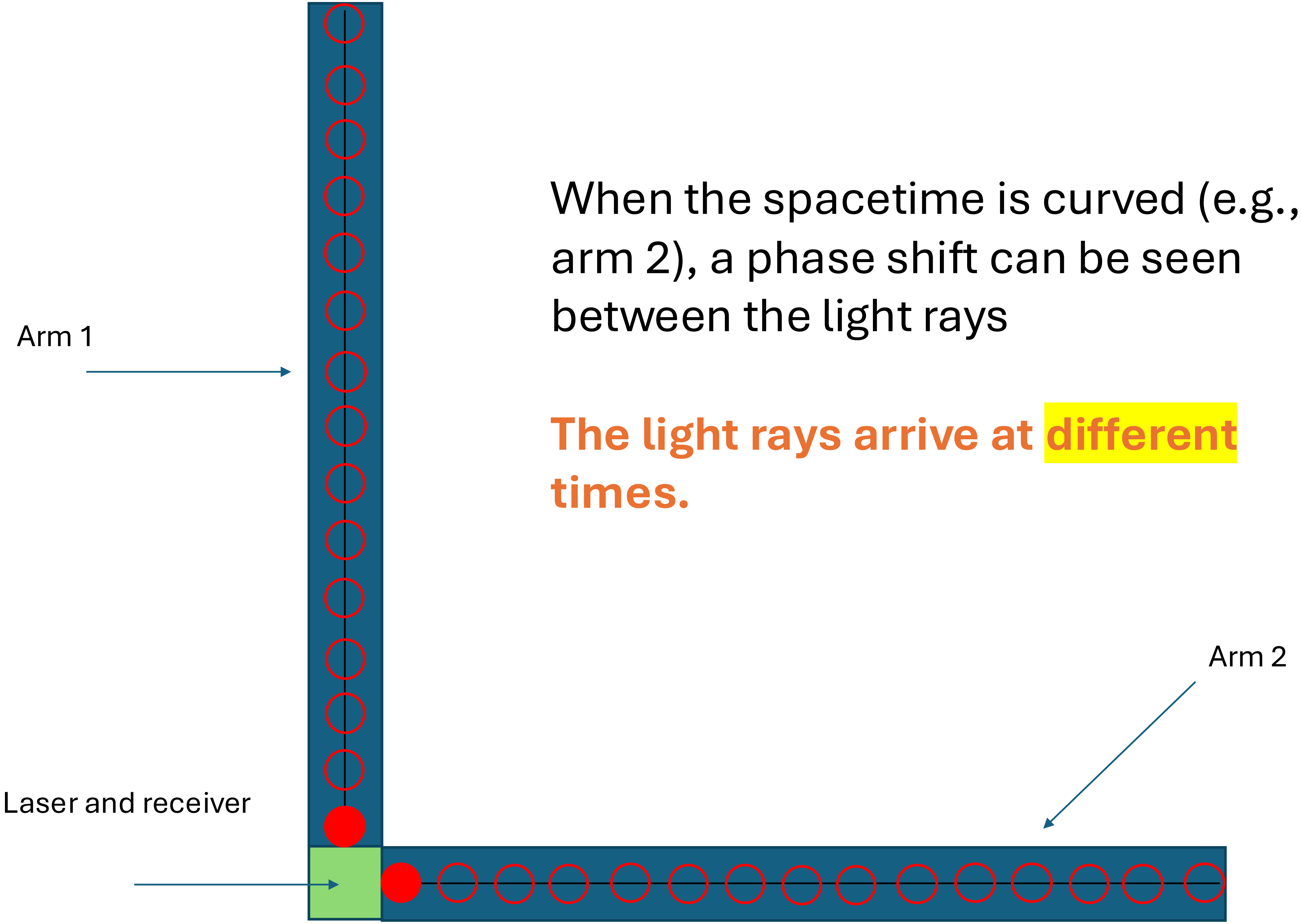




When the spacetime is flat, no phase shift can be seen between the light rays

The light rays arrive at the same time.





When the spacetime is curved (e.g., arm 2), a phase shift can be seen between the light rays

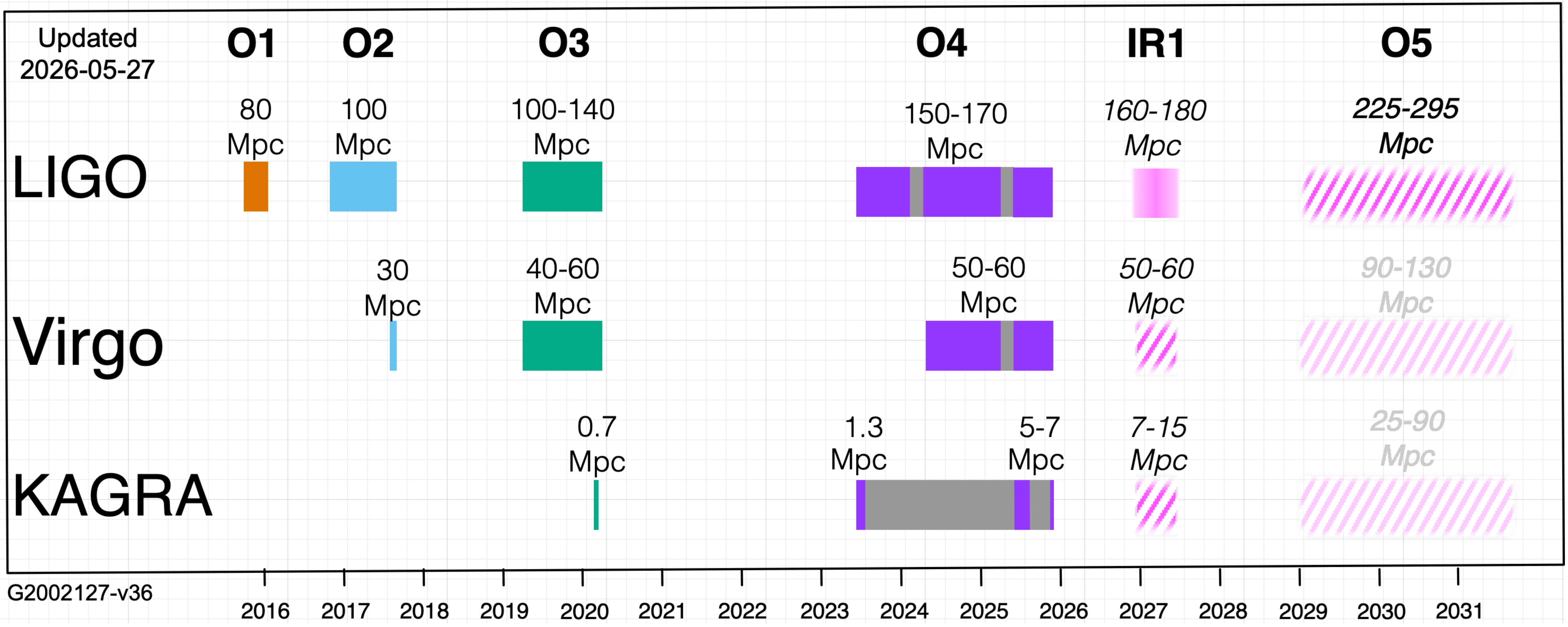
The light rays arrive at different times.

LIGO and Virgo

- Location: Hanford/Livingston (LIGO) and Italy (Virgo)
  - 3 detectors
- Arm length: 4km (LIGO) and 3km (Virgo)
- The laser power is extremely high. Not only to travel a long long distance, but also to have a high S/N ratio.
- The laser doesn’t not just travel from end to end; It goes back and forth, e.g., 150 times for LIGO.
- Sensitivity: 1/10000 the width of a proton!

KAGRA

- Location: Japan
- Arm length: 3km
- Two special features:
  - Cryogenic mirror (20K)
  - Built underground (about 200m)
- Taiwan is also one of the important partners of the project.


Updated 2026-05-27
O1
O2
O3
O4
IR1
O5
80 Mpc
100 Mpc
100-140 Mpc
150-170 Mpc
160-180 Mpc
225-295 Mpc
LIGO
30 Mpc
40-60 Mpc
50-60 Mpc
50-60 Mpc
90-130 Mpc
Virgo
0.7 Mpc
1.3 Mpc
5-7 Mpc
7-15 Mpc
25-90 Mpc
KAGRA
G2002127-v36
2016
2017
2018
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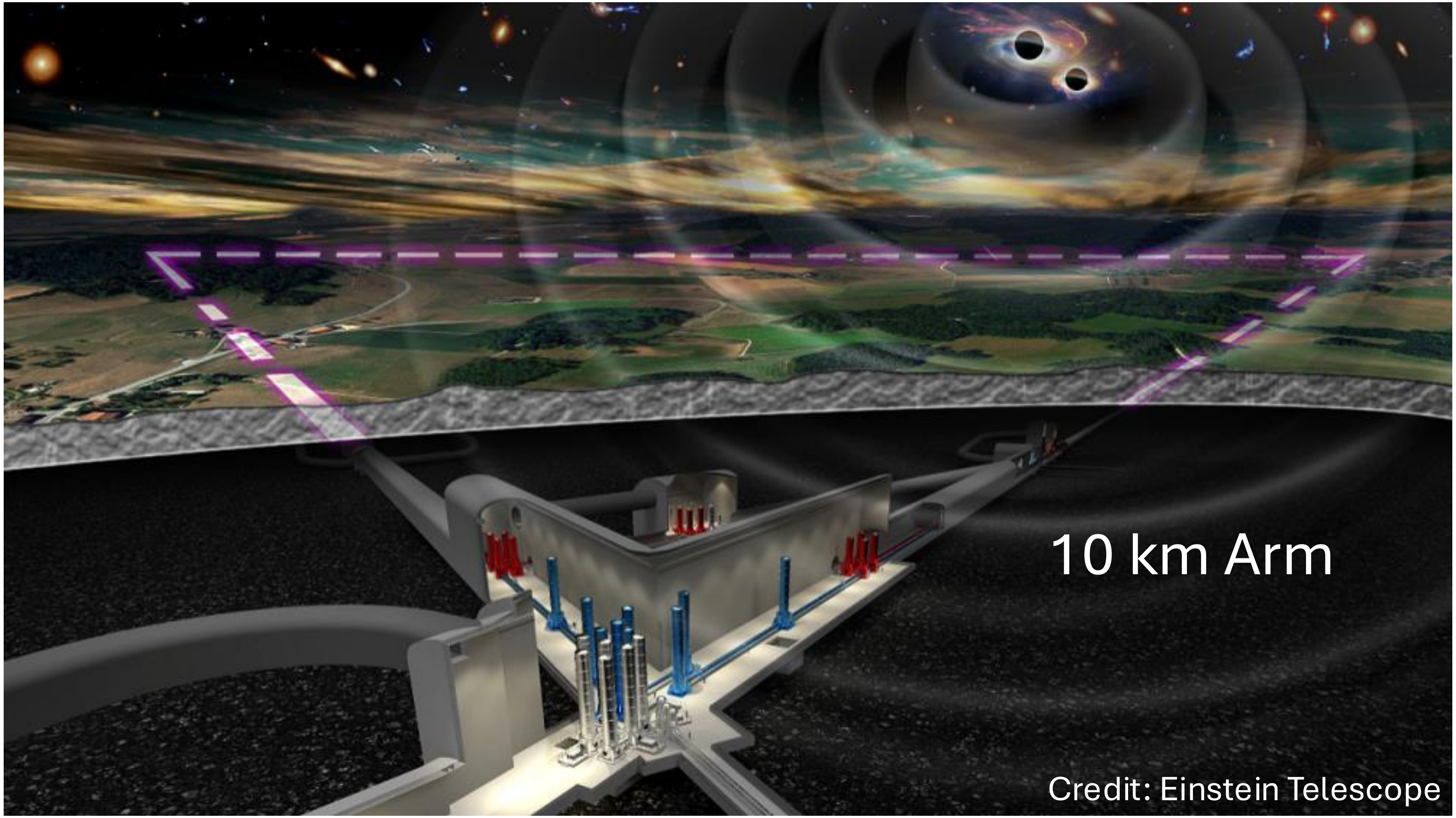
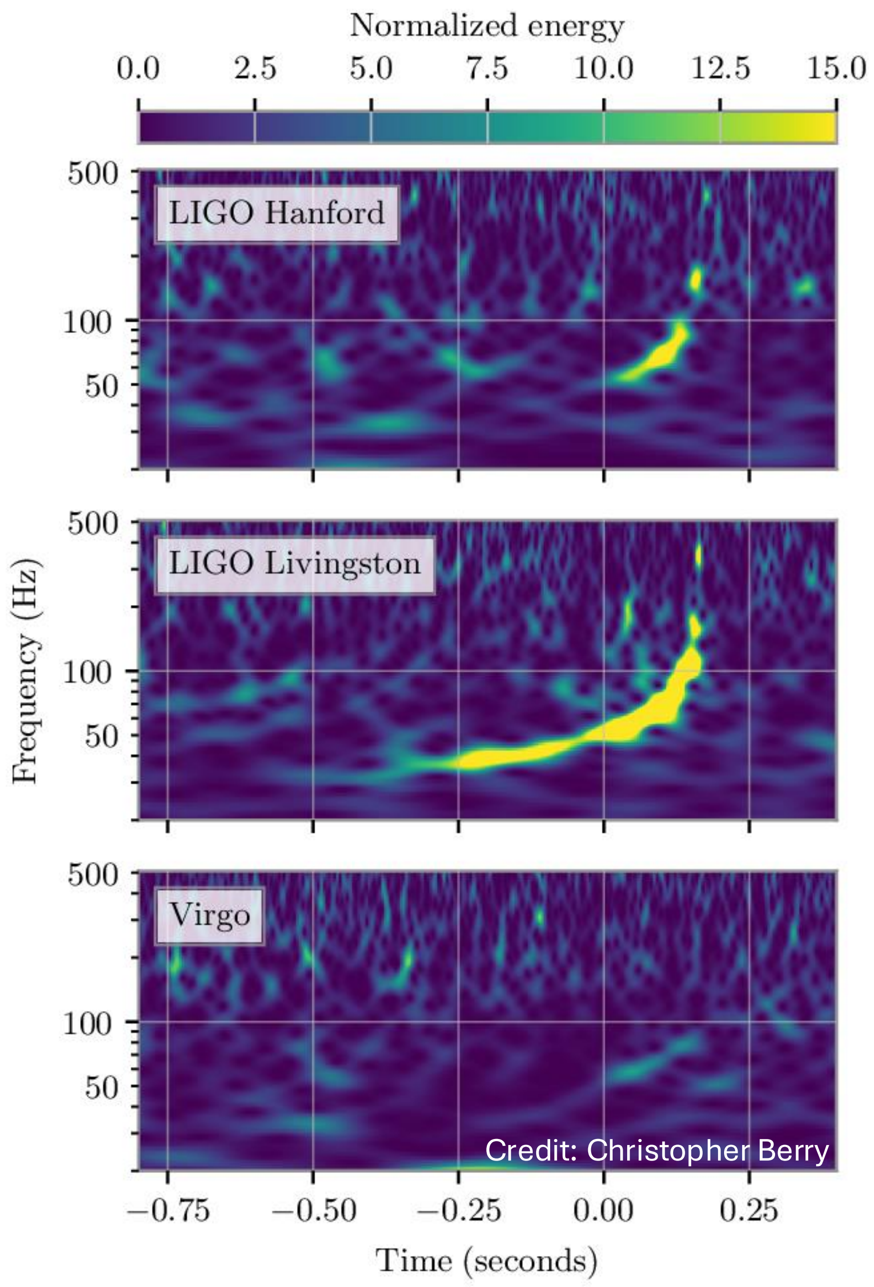
3rd generation: Einstein Telescope (ET)



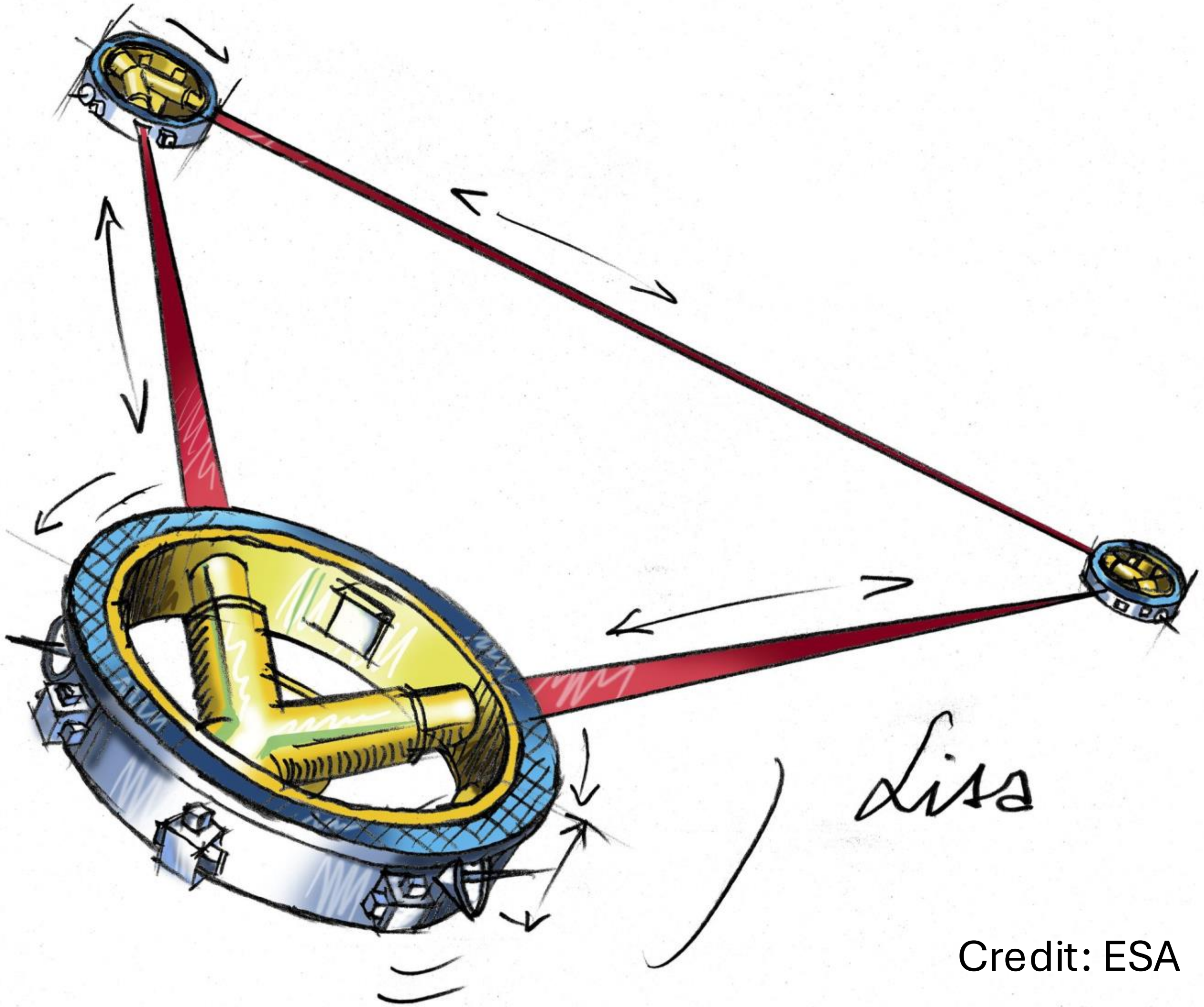
Do we need longer arms?

- For LIGO, the arm length is 4km, but the effective is about 1200km since the laser will go back and forth about 300 times between the mirrors as mentioned.
- So, the optimized wavelength for LIGO is $\frac{\lambda}{2} \approx 1200$ km. As GW travels at the speed of light, the optimized frequency is around 100 Hz.



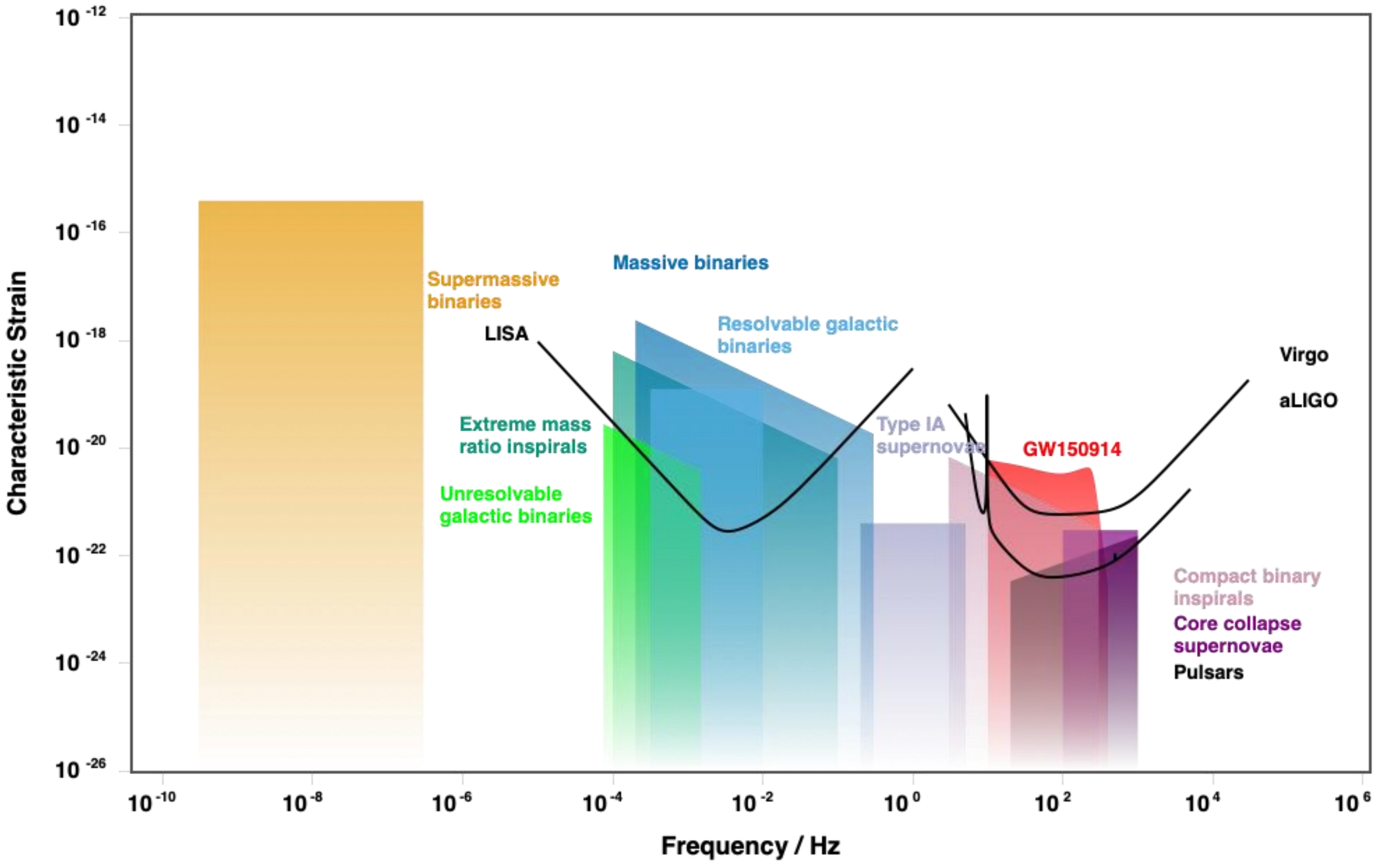
Laser Interferometer Space Antenna (LISA)

- NASA and ESA mission
- Arm length: 2.5 million km!
- Advantage: Low (no?) seismic noise
- Disadvantage: The arc cannot be locked
- LISA Pathfinder
  - tested the idea in 2015
- Planned to be launched in 2034



Credit: ESA

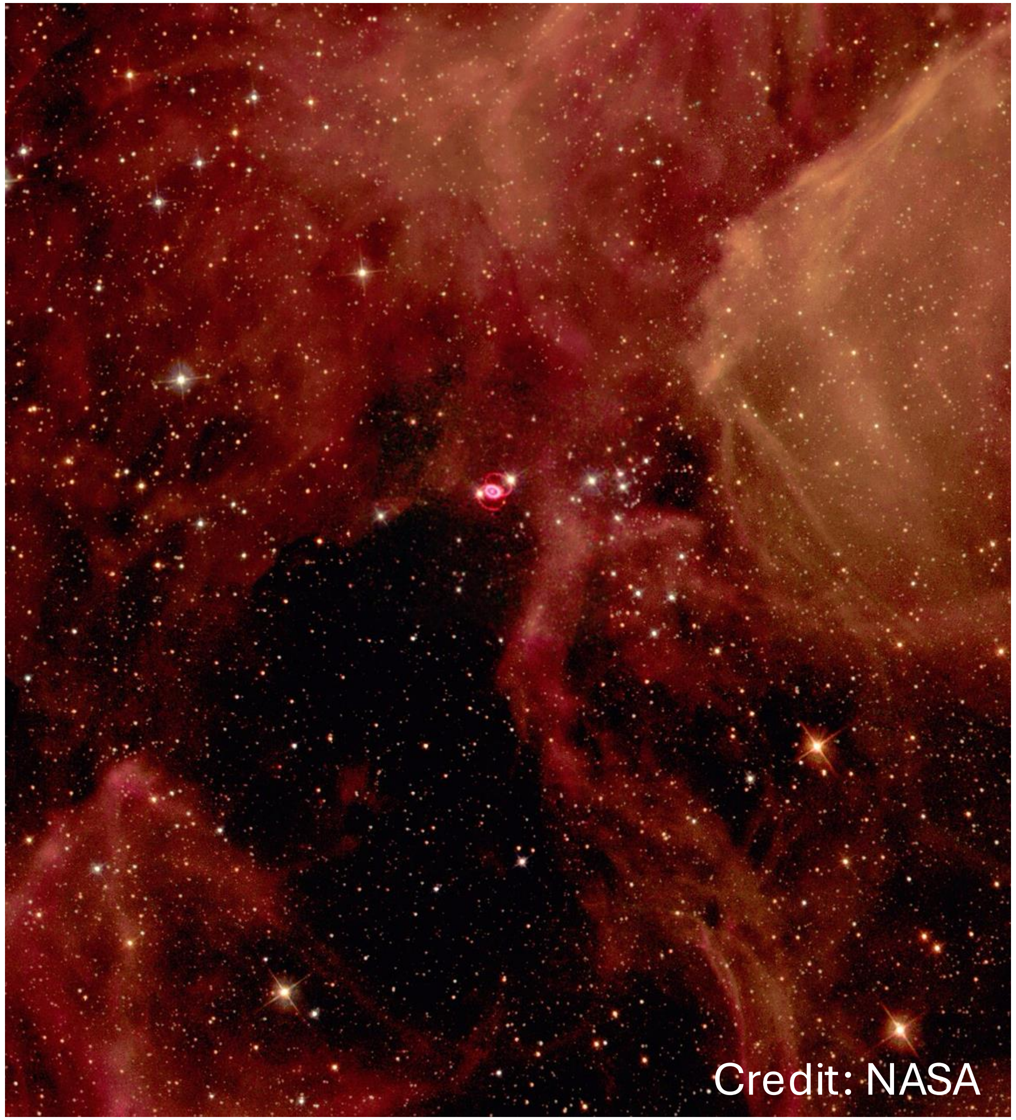
Sensitivity of the GW Telescopes



A Few MMA Examples

SN 1987A

- Discovered on February 24, 1987. It was the closest supernova since 1604.
- **Location:** Large Magellanic Cloud (LMC)
- **Distance:** about **50 kpc**
- **Type:** Core-Collapse Supernova (Type II)



The First Messenger: Neutrinos

(Forget Sun for the moment)

- Neutrinos were detected **3 hours before** the optical light reached Earth.
  - This confirmed that neutrinos escape the collapsing core almost instantly, while photons are delayed by the shockwave moving through the star's envelope.
- **Energy Release:** $\sim 3 \times 10^{53}$ ergs.
  - Over 99% of the supernova's total energy was emitted as neutrinos.

The 24 Detections

- **Kamiokande II**
  - Detected 12 neutrinos. Located in Japan..
- **IMB Experiment**
  - Detected 8 neutrinos. Located in a salt mine near Lake Erie, Ohio.
- **Baksan**
  - Detected 5 neutrinos. Located in Russia. Together, these verified the core-collapse model.

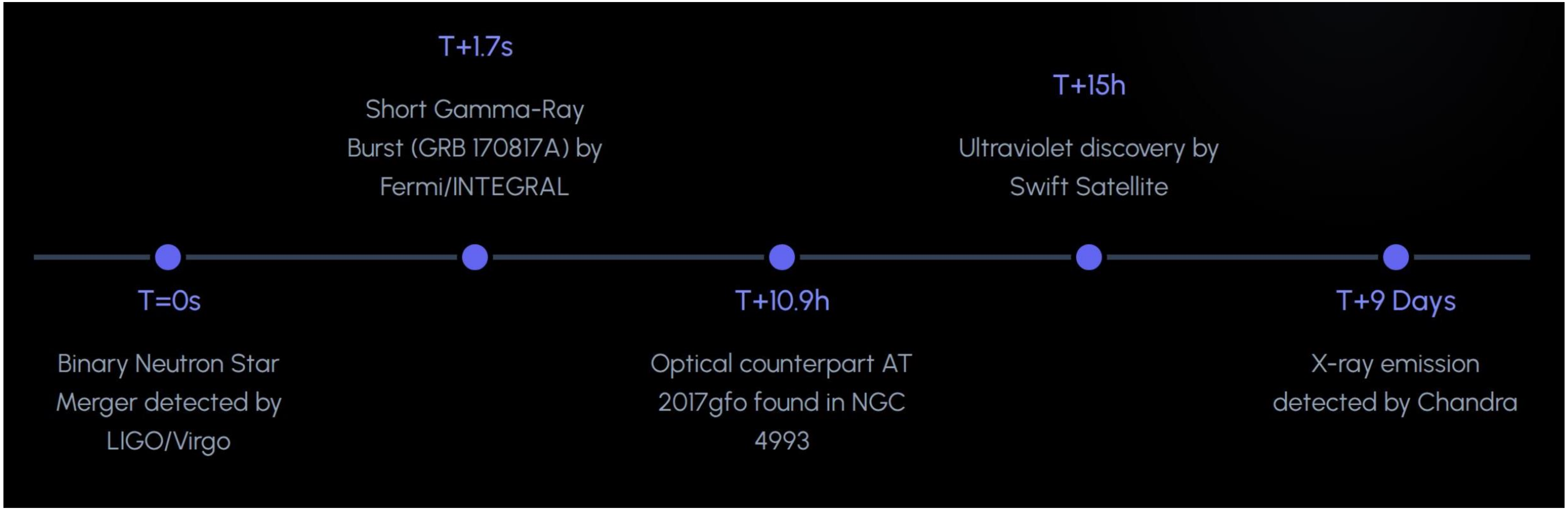
Other Neutrino Astronomical Events—

supermassive black holes

- **TXS 0506+056**
  - Located 1.35 Gpc away, this Blazar—a galaxy with a supermassive black hole jet pointing at Earth.
  - IC170922A (about 300 TeV) with 3.5 sigma
- **NGC 1068**
  - A steady emitter of high-energy neutrinos after 10+ years of data integration.
  - 4.2 sigma
- **AT2019dsg**
  - Tidal Disruption Event
  - 3.0 sigma (200 TeV)

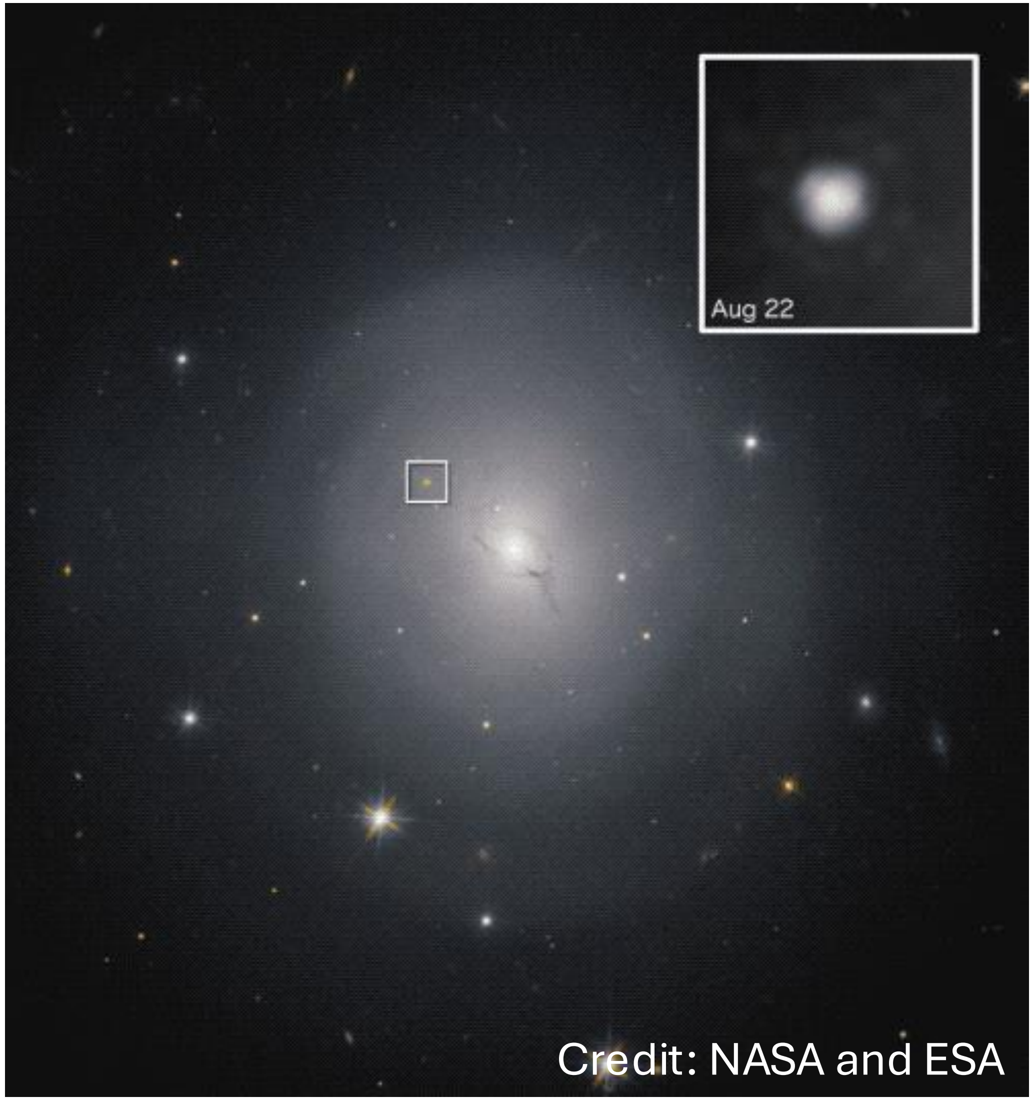
GW170817

- The first joint detection of Gravitational Waves and Light
  - August 17, 2017



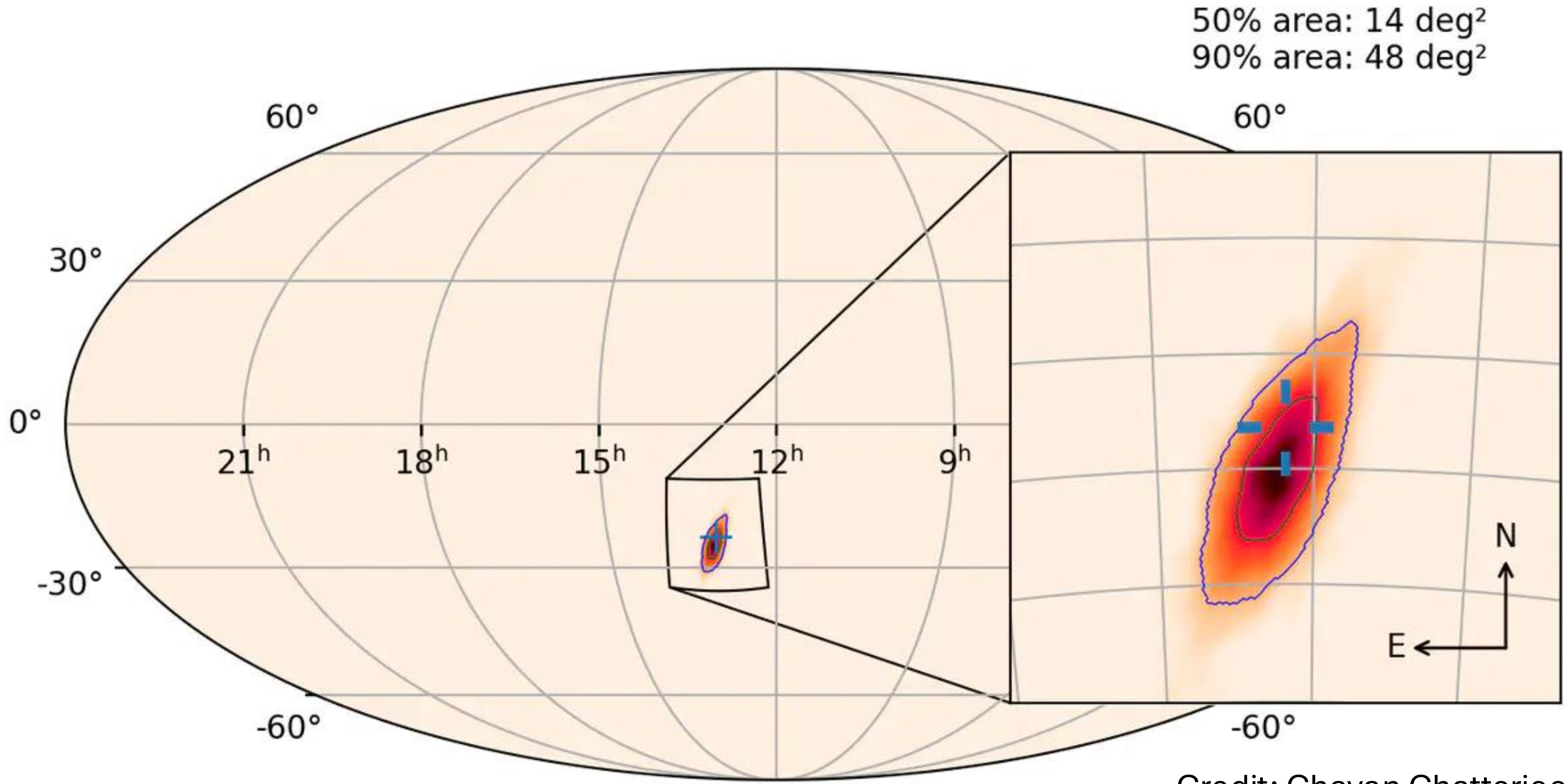
AT 2017gfo/GRB 170817A in NGC 4993

- Progenitor: Binary Neutron Star (BNS) merger
- Location: 40 Mpc away
- The closest known short GRB (born to be special!)



Credit: NASA and ESA

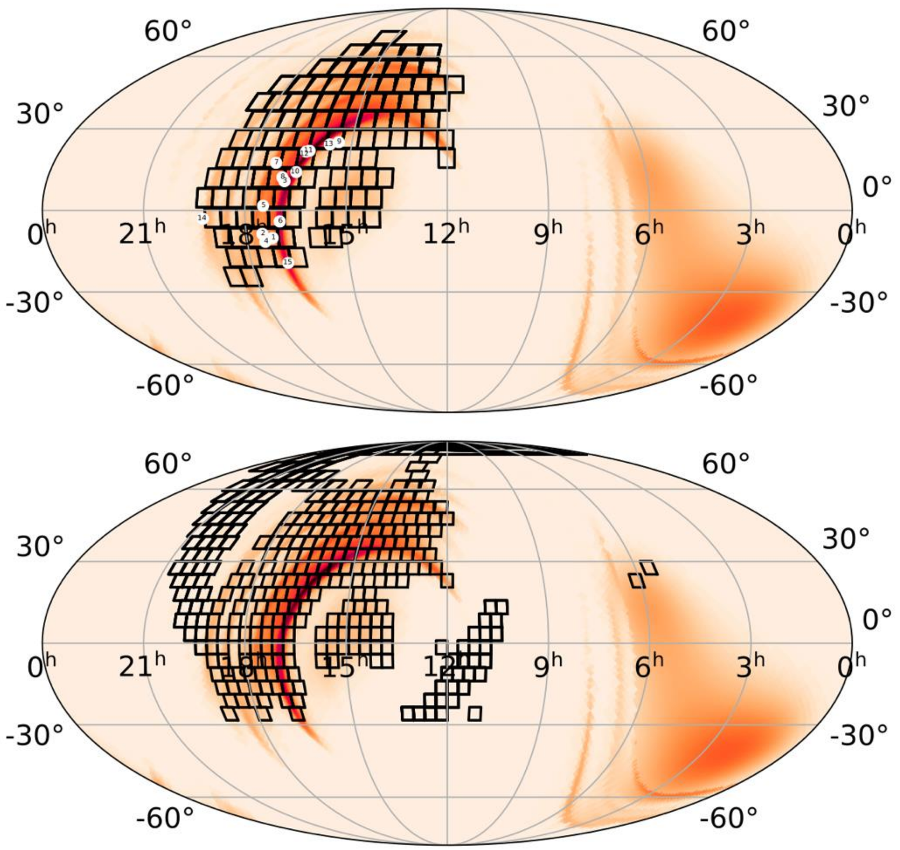
Localization of GW170817



Credit: Chayan Chatterjee

Other GW events with known EM counterparts?

No, but we tried very hard to find (e.g., S190521g)



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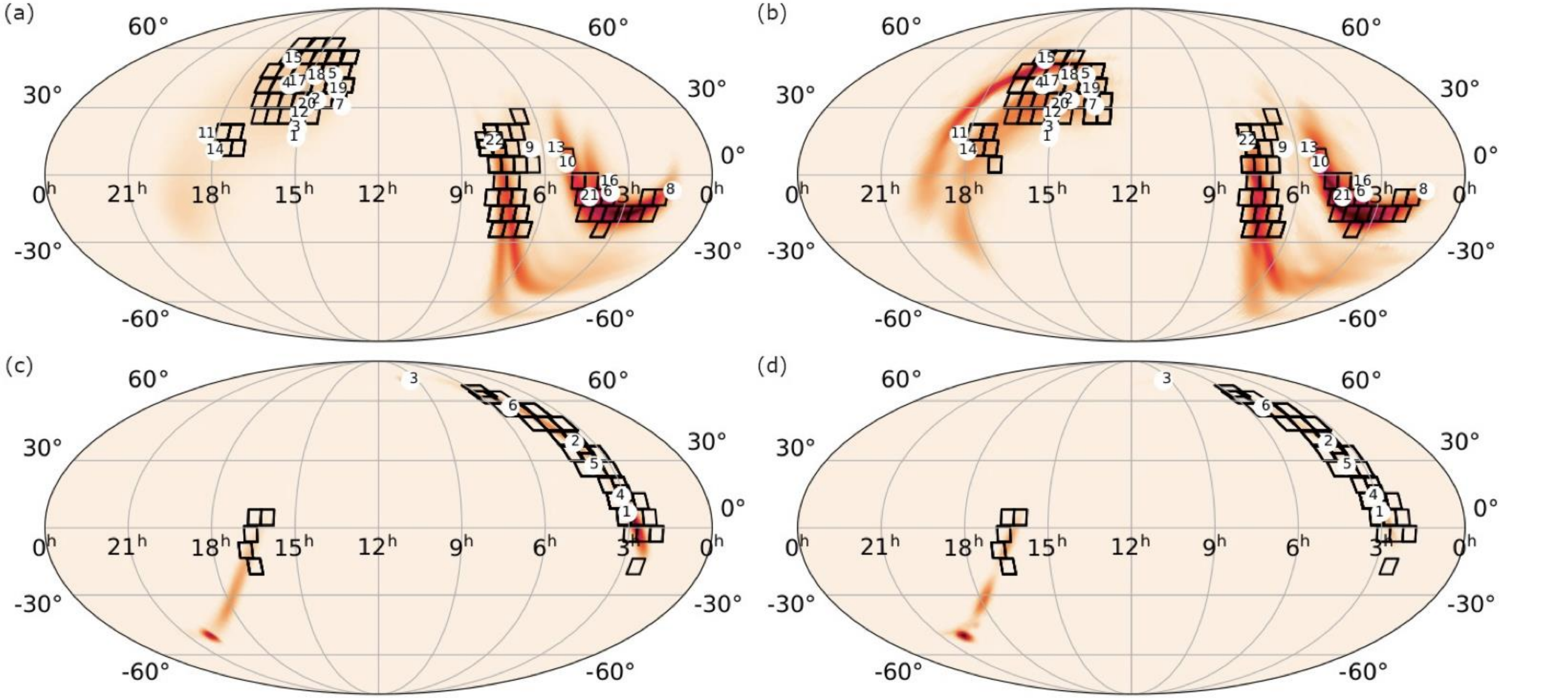

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Take home messages

- What is Multi-Wavelength Astronomy?
- What is Multi-Messenger Astronomy?
  - In both cases, positional accuracy is a key factor.

- For GWs, we carry out study-hub for Taiwan students to learn how to analyse GW data every year. Come and join us if you are interested.