ASTR 340: Origin of the Universe

Prof. Benedikt Diemer

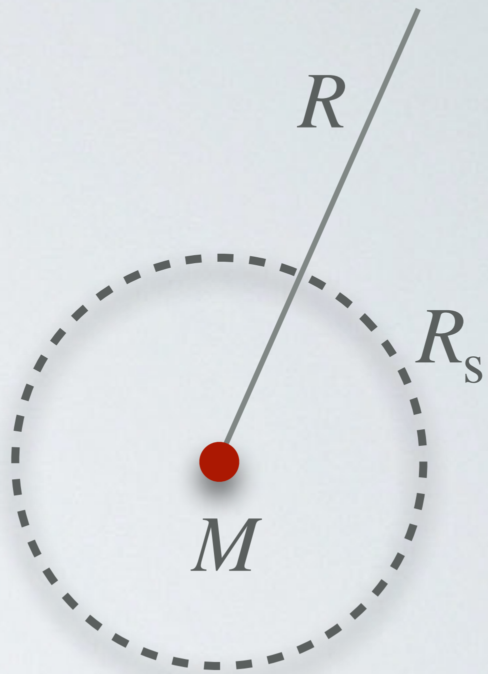
Lecture 24 • Listening to the Universe with gravitational waves

11/30/2021

Recap

Schwarzschild Metric

- First exact solution of the equations of GR (by Karl Schwarzschild in 1916)
- Describes gravitational field in (empty) space around a point mass
- Described by spacetime interval
- Features of Schwarzschild's solution:
  - Radius of the sphere representing the **event horizon** is called the **Schwarzschild radius**
  - Reduces to Newton's law of gravity / flat space at large $R >> R_s$
  - Space-time curvature becomes infinite at center (**R = 0, called a space-time singularity**)
- R_s is same as Newtonian solution, but that is a little coincidental



$$\Delta s^2_{\text{flat}} = (c\Delta t)^2 - \Delta r^2 - \text{angle terms}$$

Schwarzschild metric:

$$\Delta s^2 = \left(1 - \frac{R_s}{R}\right)(c\Delta t)^2 - \frac{\Delta r^2}{\left(1 - \frac{R_s}{R}\right)} - \text{angle terms}$$

Schwarzschild radius:

$$R_s = \frac{2GM}{c^2}$$

Participation: Recap #1

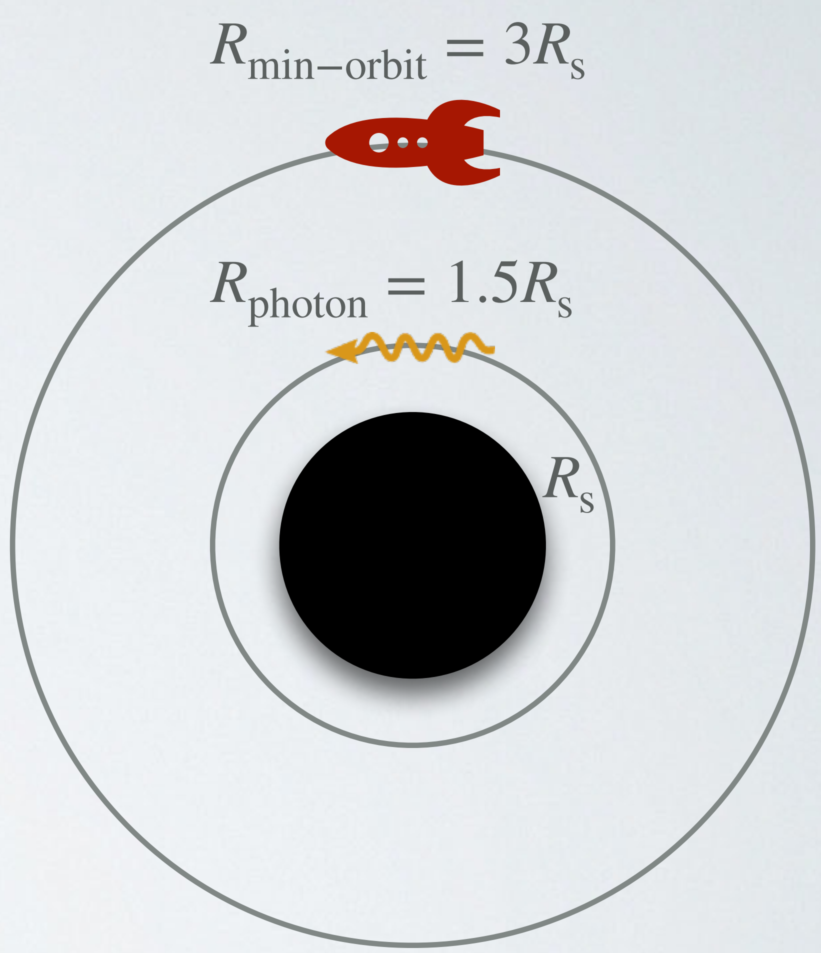
TurningPoint:
How large is the event horizon of a solar-mass black hole?

Session ID: diemer

30 seconds

Event horizon, photon orbit, matter orbit

- **Schwarzschild radii are small**
  - $R_s = 2GM/c^2 = 3\ \text{km}\ (M/M_\odot)$
  - For BH at center of Milky Way, $R_s = 0.08\ \text{AU}$
- Events inside the event horizon are **causally disconnected** from events outside of the event horizon (no information can be sent from inside to outside the horizon)
- Once inside the event horizon, future light cone always points toward singularity (any motion must be inward)
- Any light emitted at R_s is **infinitely redshifted** (and cannot be observerd from outside)
- **Light rays** can orbit at 1.5 R_s (forming a sphere of photons)
- Stable, **circular orbits for matter** are not possible inside 3 R_s



Participation: Recap #2

TurningPoint:
Will the black holes we see in the Universe evaporate due to Hawking radiation?

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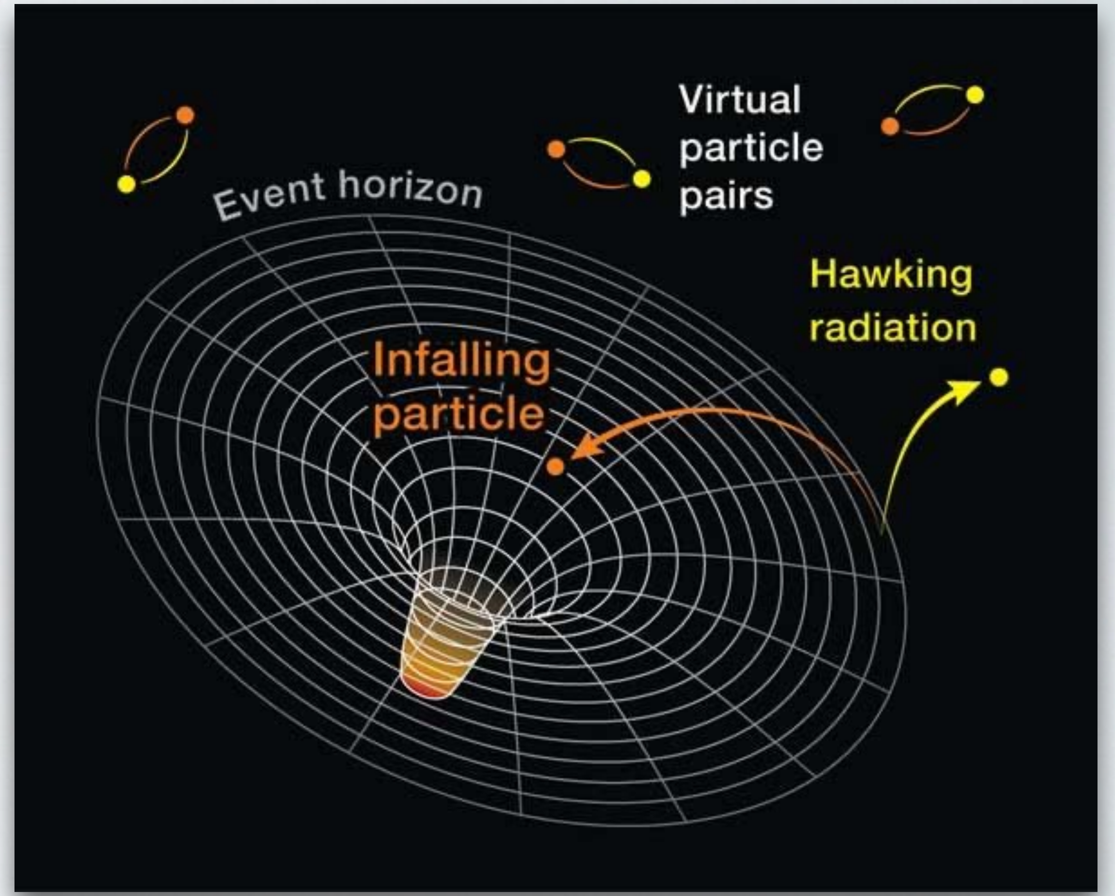
30 seconds

Antimatter and black holes

- No-hair theorem: antimatter black holes are indistinguishable from matter black holes
- In the case of black holes, matter and antimatter would not annihilate; they would merge like normal matter black holes
- However, antimatter BHs cannot explain the matter-antimatter asymmetry because there is no known process that would cause antimatter but not matter to collapse into BHs



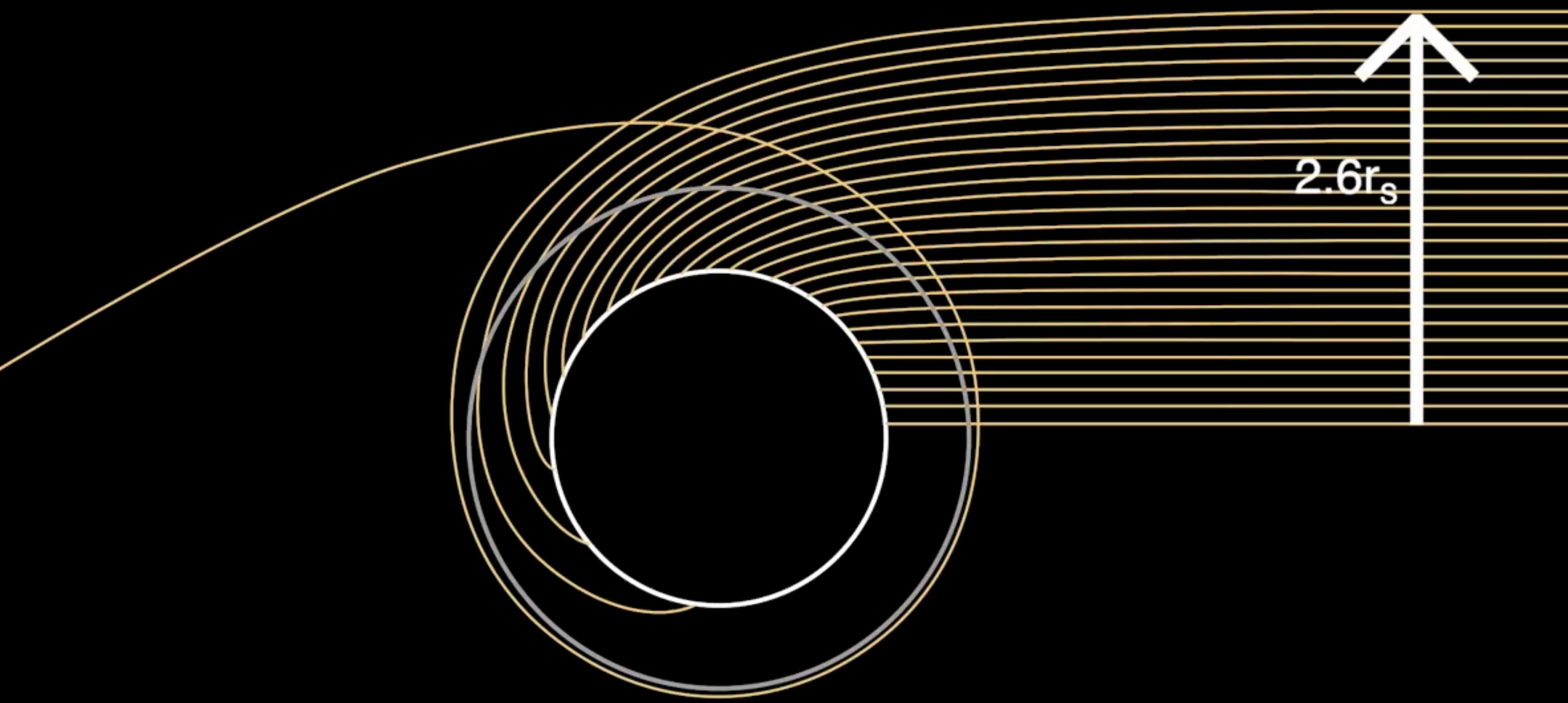
Today

- The Event Horizon Telescope Image
- Compact objects
- Gravitational waves
- Listening to the Universe

Part 1: The Event Horizon Telescope Image

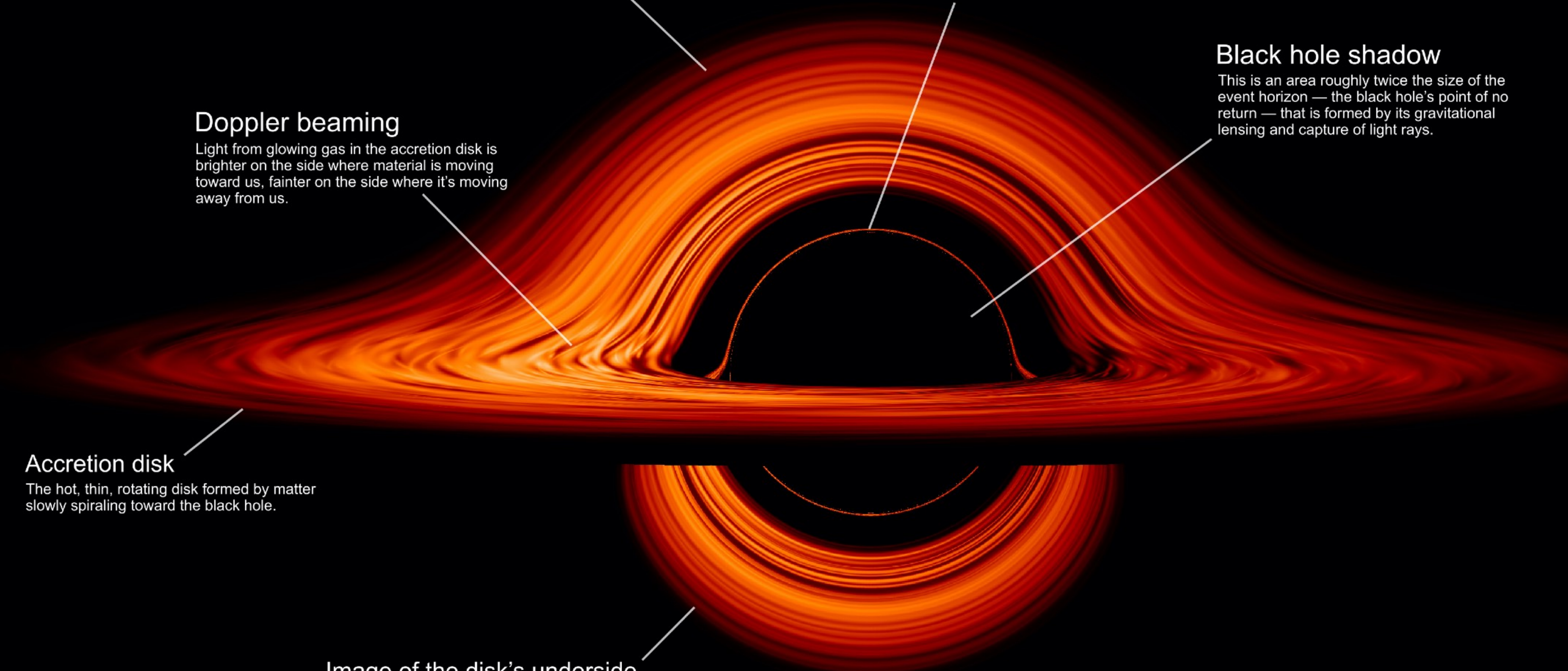

$M_{\mathrm{BH}} \approx 10^8 M_\odot$
Interstellar

What does the event horizon look like?



Video: Derek Muller / Veritasium

How do we see an accretion disk?



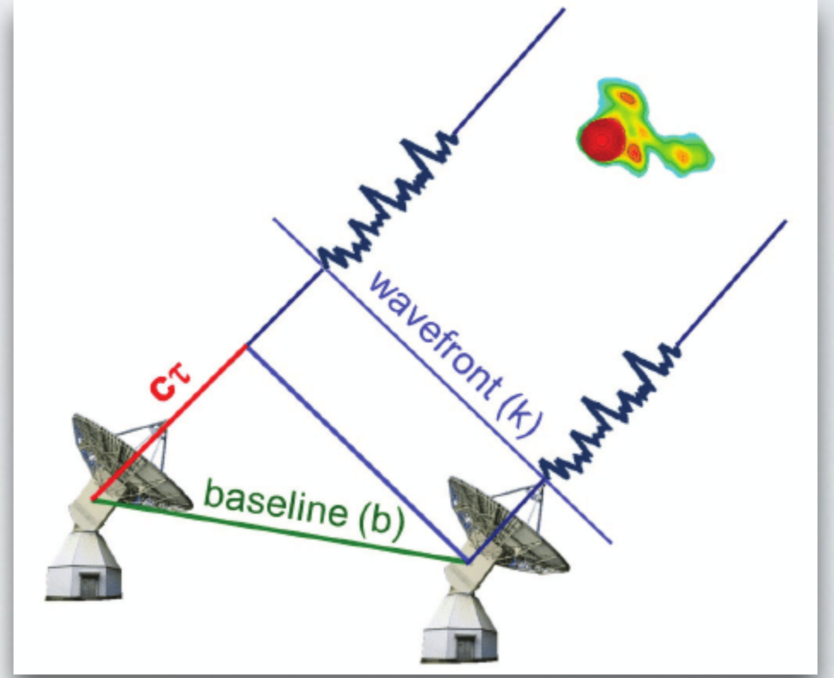
NASA's Goddard / J. Schnittman

How do we see an accretion disk?

Ryan James Smith

Observing black holes with interferometry

- Quick calculation of **angular size of M87 black hole** event horizon
  - Distance to M87: 16.4 Mpc
  - $R_s = 3 \text{ km} \times 6 \times 10^9 = 1.8 \times 10^{15} \text{ cm} = 120 \text{ AU} = 6 \times 10^{-4} \text{ pc}$
  - $\alpha = 6 \times 10^{-4}/16.4 \times 10^6 \times 180/\pi \approx 2 \times 10^{-9}$ degrees
  - For comparison, resolution of Hubble Space Telescope is 10^{-5} degrees
- One technique to go to higher resolution is **interferometry**, where we measure the time difference between the arrival of a wavefront at different points
- The resolution is inversely proportional to the baseline
- In Very Long Baseline Interferometry (VLBI), we use **multiple telescopes** that are combined to form a single observatory



Event Horizon Telescope (EHT)

A Global Network of Radio Telescopes

2018 Observatories

ALMA — Atacama Large Millimeter/submillimeter Array
CHAJNANTOR PLATEAU, CHILE

APEX — Atacama Pathfinder EXperiment
CHAJNANTOR PLATEAU, CHILE

30-M — IRAM 30-M Telescope
PICO VELETA, SPAIN

JCMT — James Clerk Maxwell Telescope
MAUNAKEA, HAWAII

LMT — Large Millimeter Telescope
SIERRA NEGRA, MEXICO

SMA — Submillimeter Array
MAUNAKEA, HAWAII

SMT — Submillimeter Telescope
MOUNT GRAHAM, ARIZONA

SPT — South Pole Telescope
SOUTH POLE STATION

GLT — The Greenland Telescope
THULE AIR BASE, GREENLAND, DENMARK

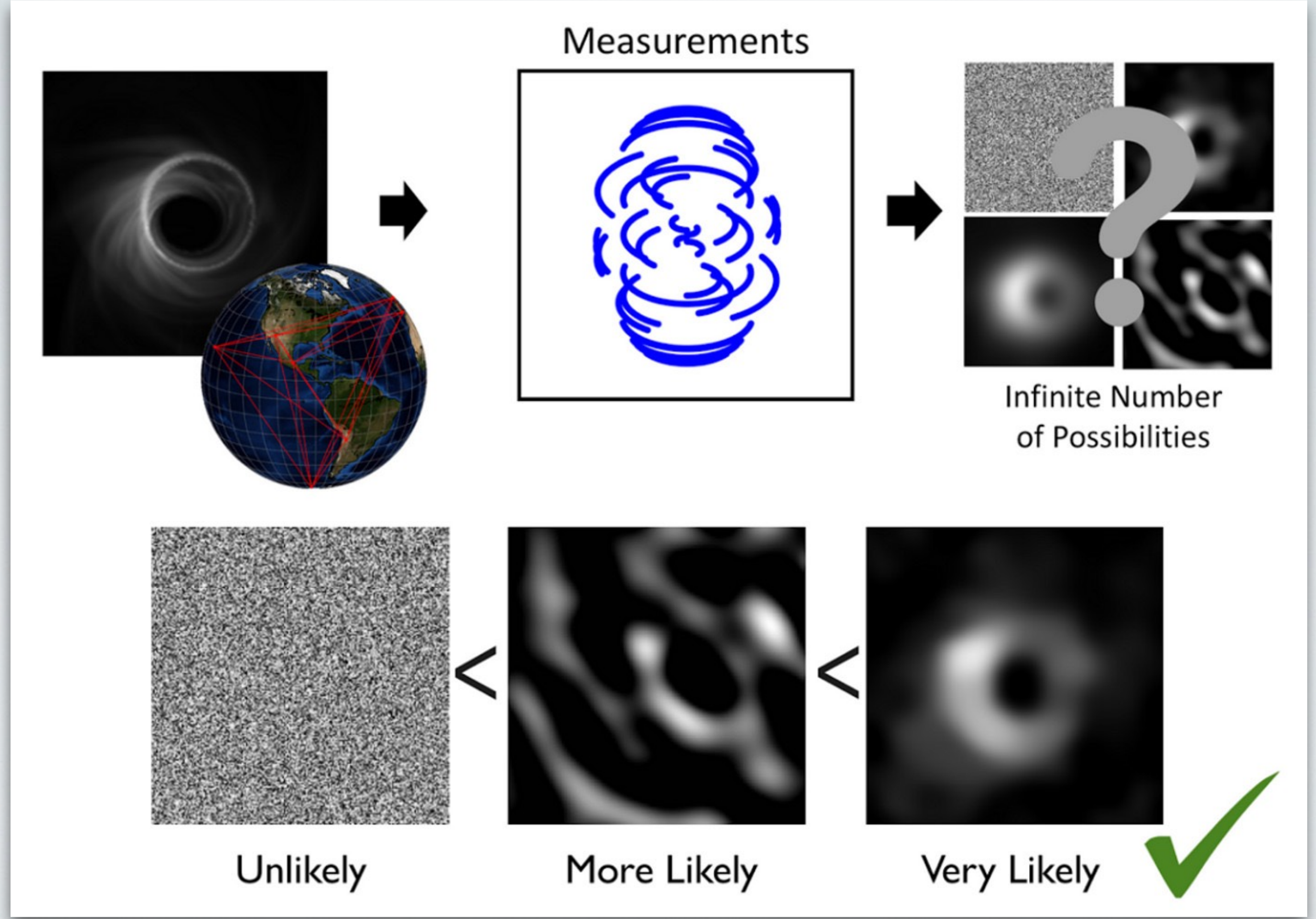
Observing in 2020

Kitt Peak — Kitt Peak 12-meter Telescope
KITT PEAK, ARIZONA, USA

NOEMA — NOEMA Observatory
PLATEAU DE BURE, FRANCE

NSF AUI NRAO

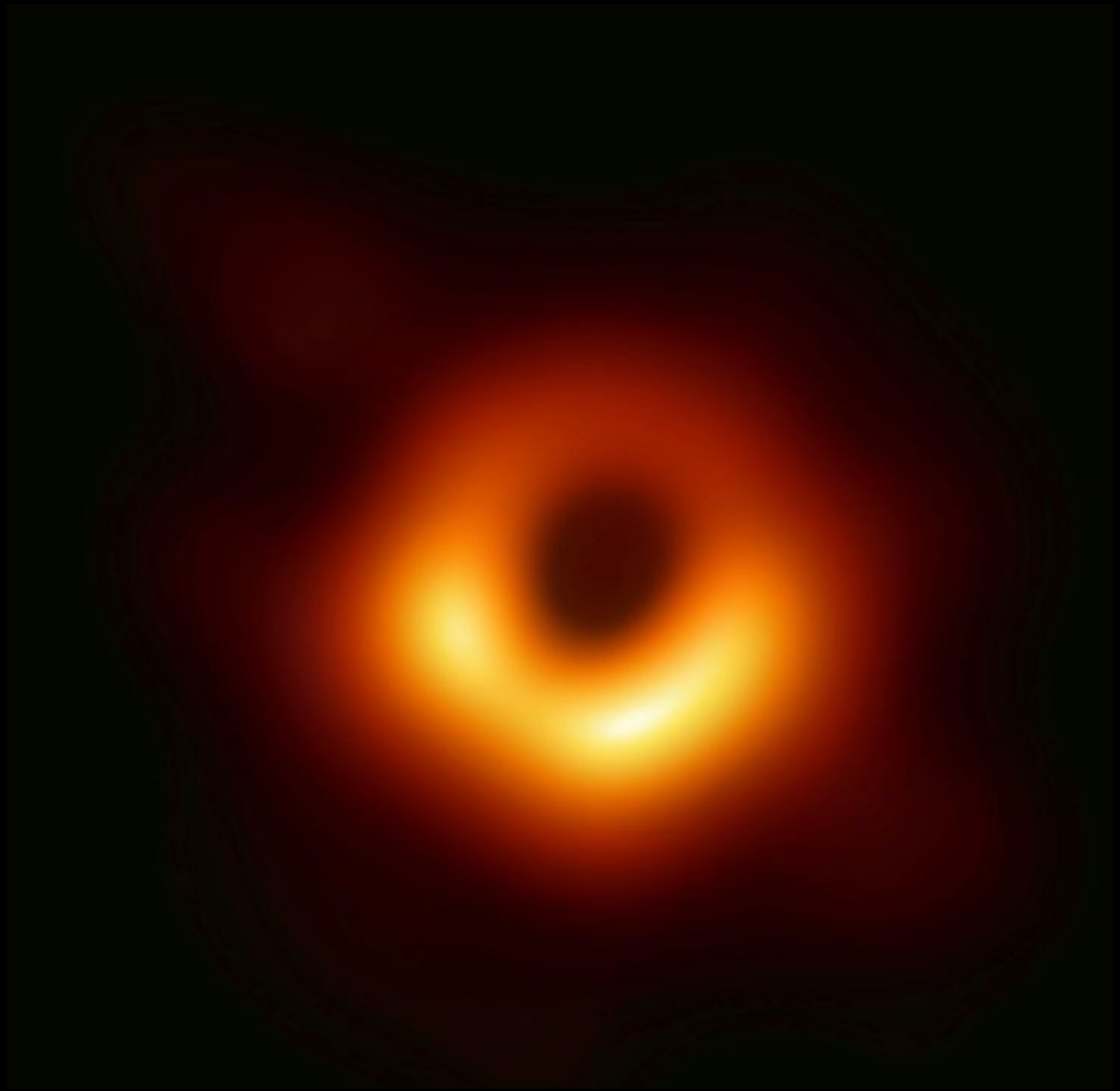
Observing M87 black hole



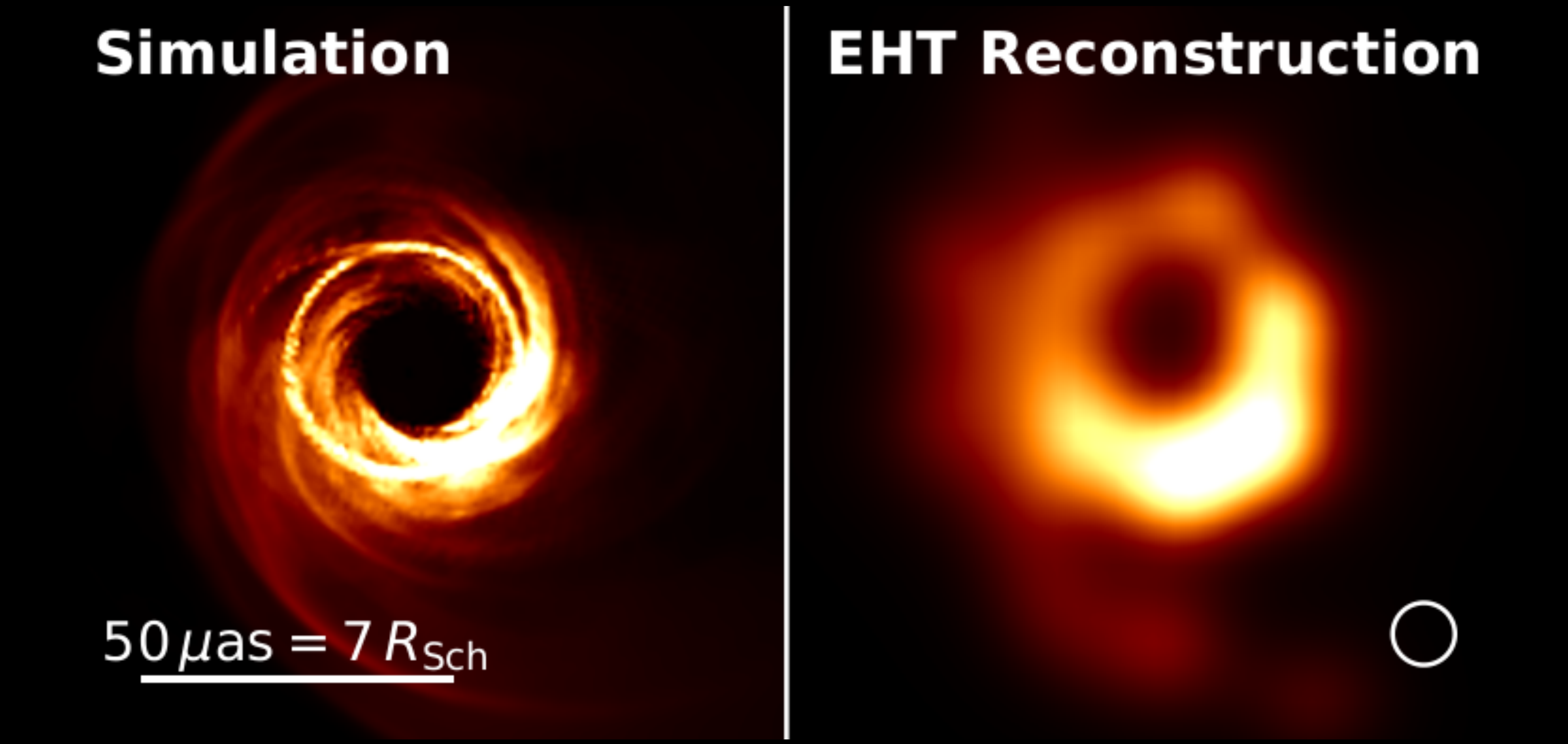
EHT Collaboration

EHT Image

- Image is nearly **edge-on** to the accretion disk, but light paths make it look like a face-on disk **Asymmetric** because of beaming (accretion disk is coming towards us on one side)
- **Shadow corresponds to about 2.6 R_s** because light rays nearby still get sucked into BH
- This means we are also "seeing" the **back side** of the black hole (or rather its shadow)

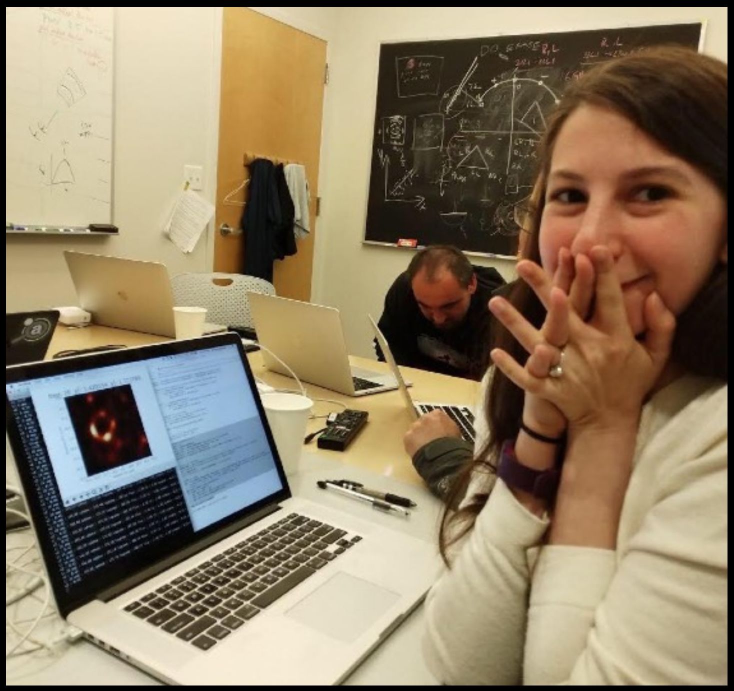


Observing M87 black hole

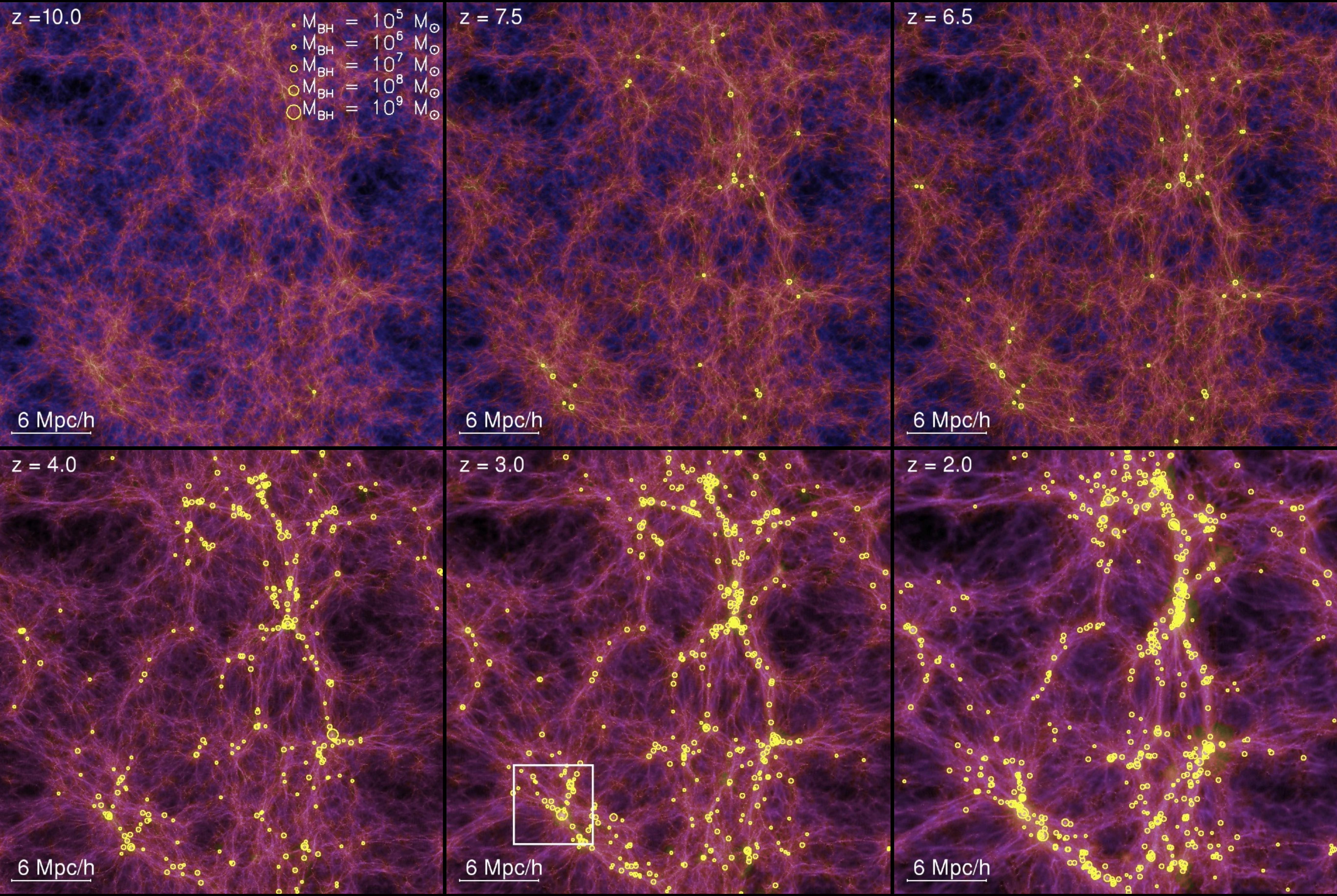


EHT Collaboration / Andrew Chael

EHT Collaboration

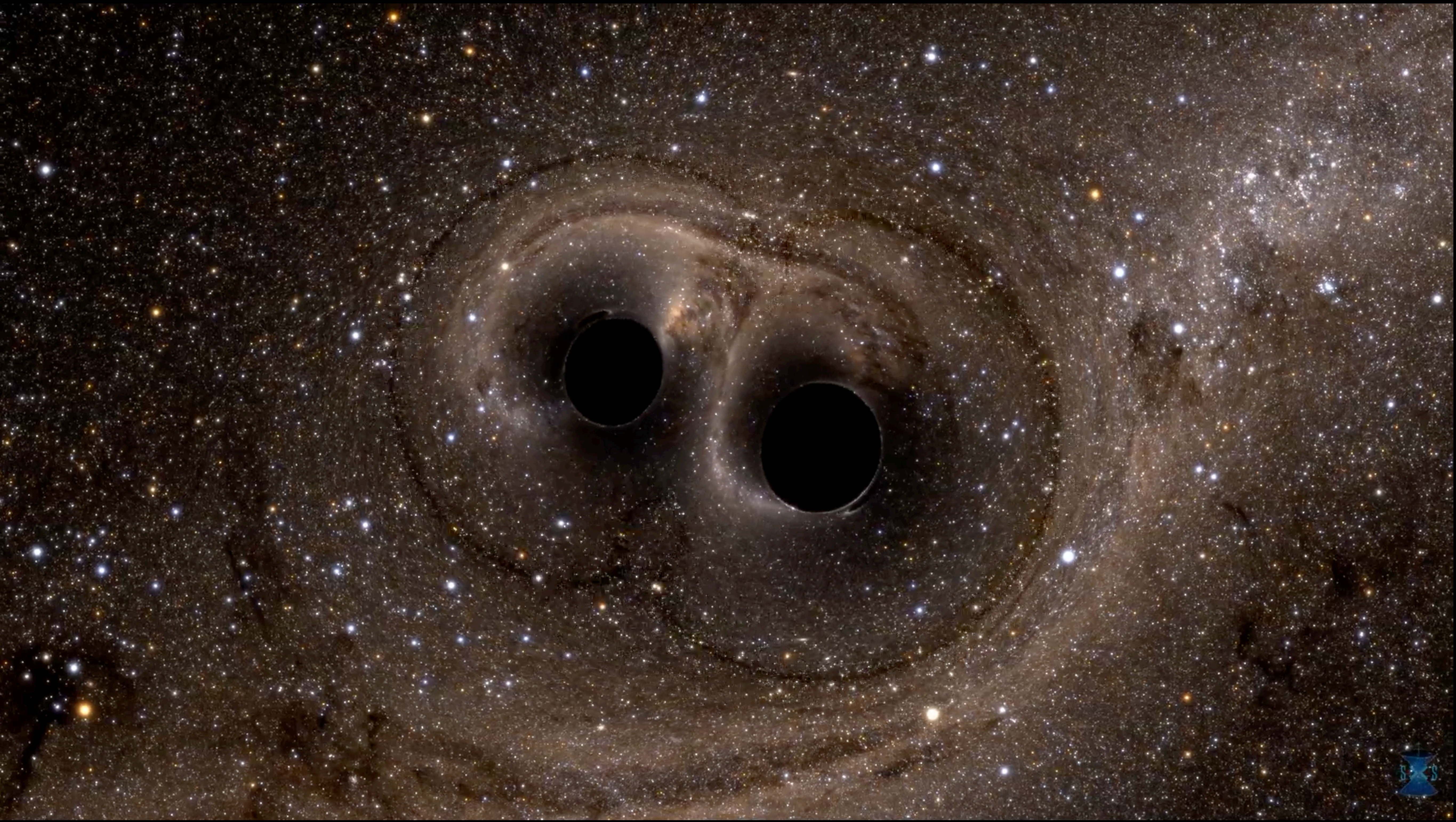


Part 2: Compact objects

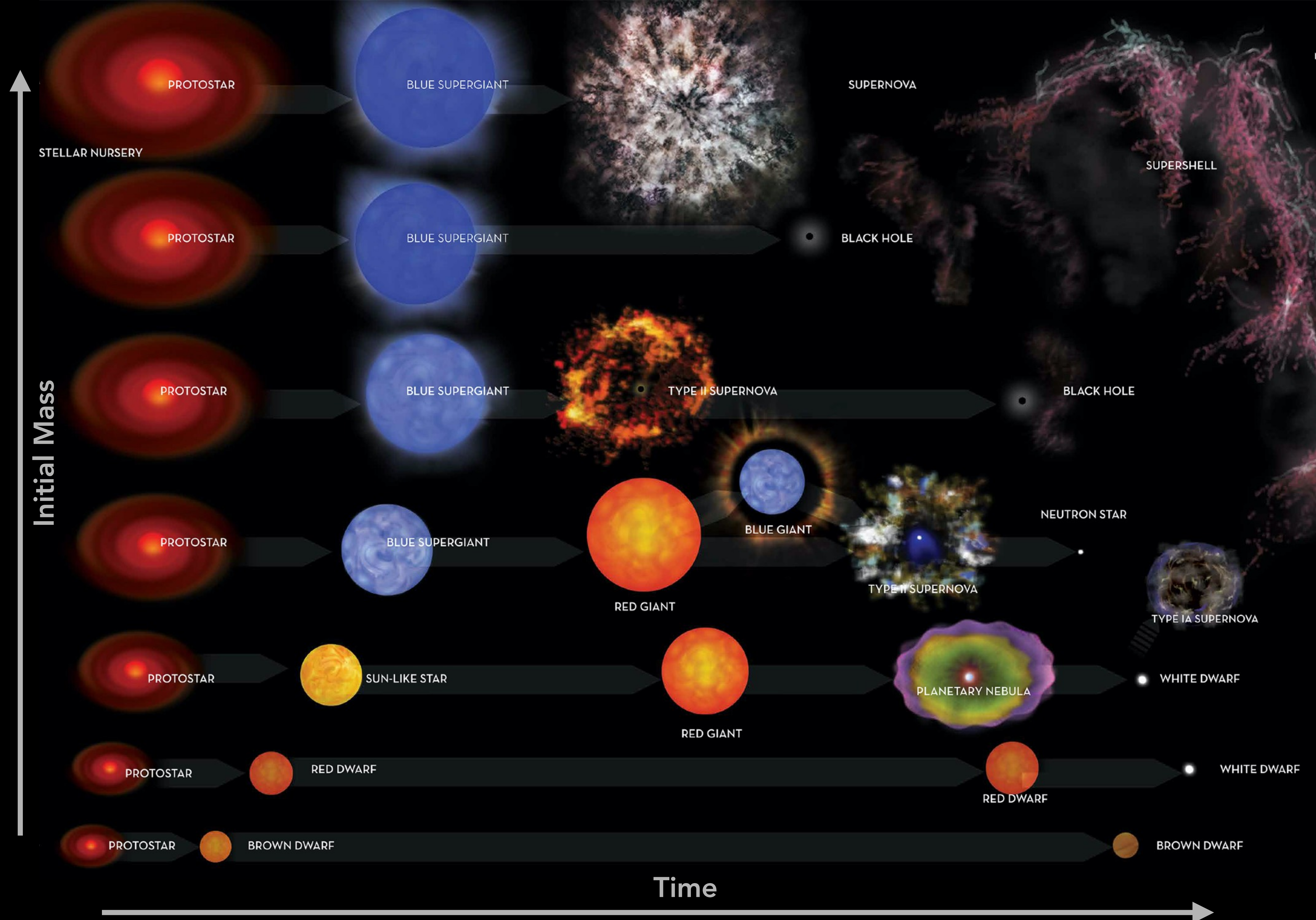


Simulation & Visualization: Tiziana di Matteo

Black hole merger (simulation)



Caltech-Cornell SXS group



Summary of stellar evolution

NASA

Participation: Compact objects

TurningPoint:

Out of a white dwarf, neutron star, and black hole with 1.2 solar masses each, which is largest?

Session ID: diemer

30 seconds

Compact objects

- **White dwarf**
  - Made of C / O / Ne / Mg nuclei + electrons
  - Mass about 0.15 - 1.4 $M_\odot$
  - Radius about 7000 km (one Earth radius)
  - Average density about 10^6 g/cm^3

- **Neutron star**
  - Made of neutrons
  - Mass about 1.1 to 2.1 $M_\odot$
  - Radius about 10 - 20 km
  - Average density about 10^{14} g/cm^3

- **Black hole**
  - Made of ???
  - Any mass theoretically, 5 - 10^{10} $M_\odot$ in our Universe
  - Schwarzschild radius R_s depends on mass
  - Average density inside R_s depends on mass

Part 3: Gravitational waves

Participation: Transverse vs. longitudinal

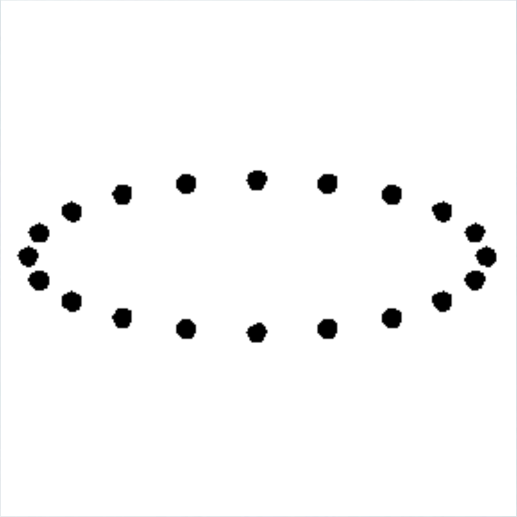
TurningPoint:
Are light and sound waves transverse or longitudinal?

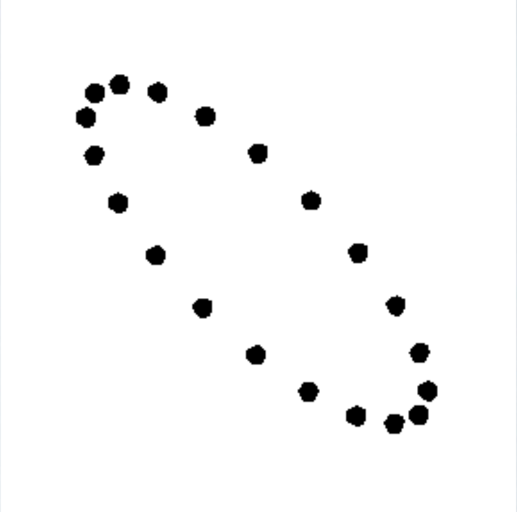
Session ID: diemer

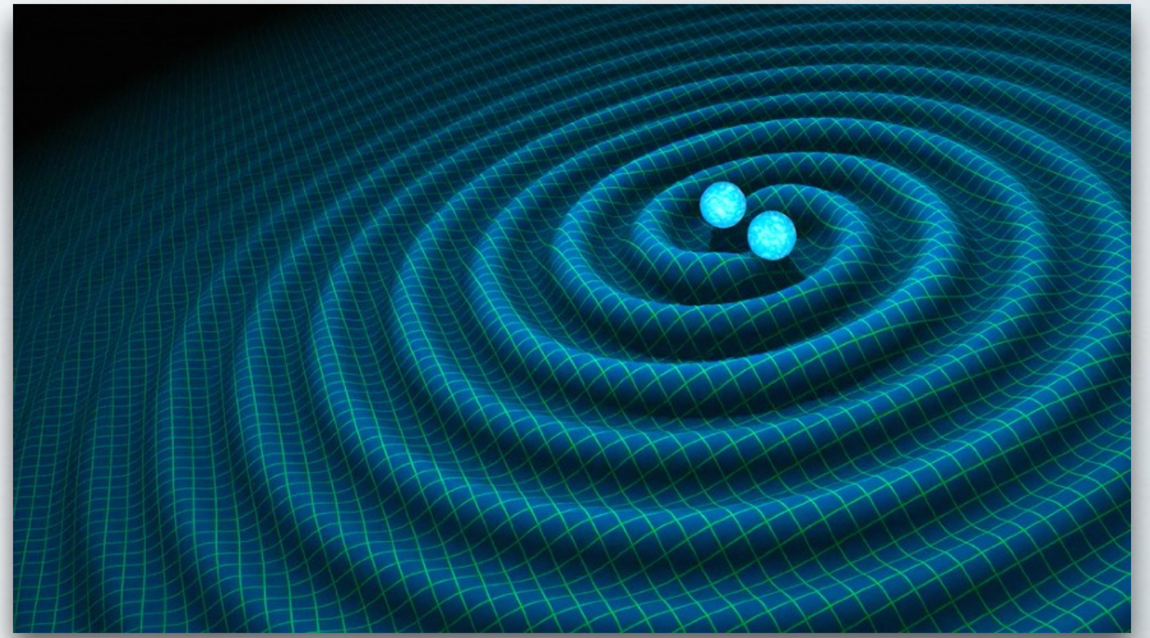
30 seconds

What are gravitational waves?

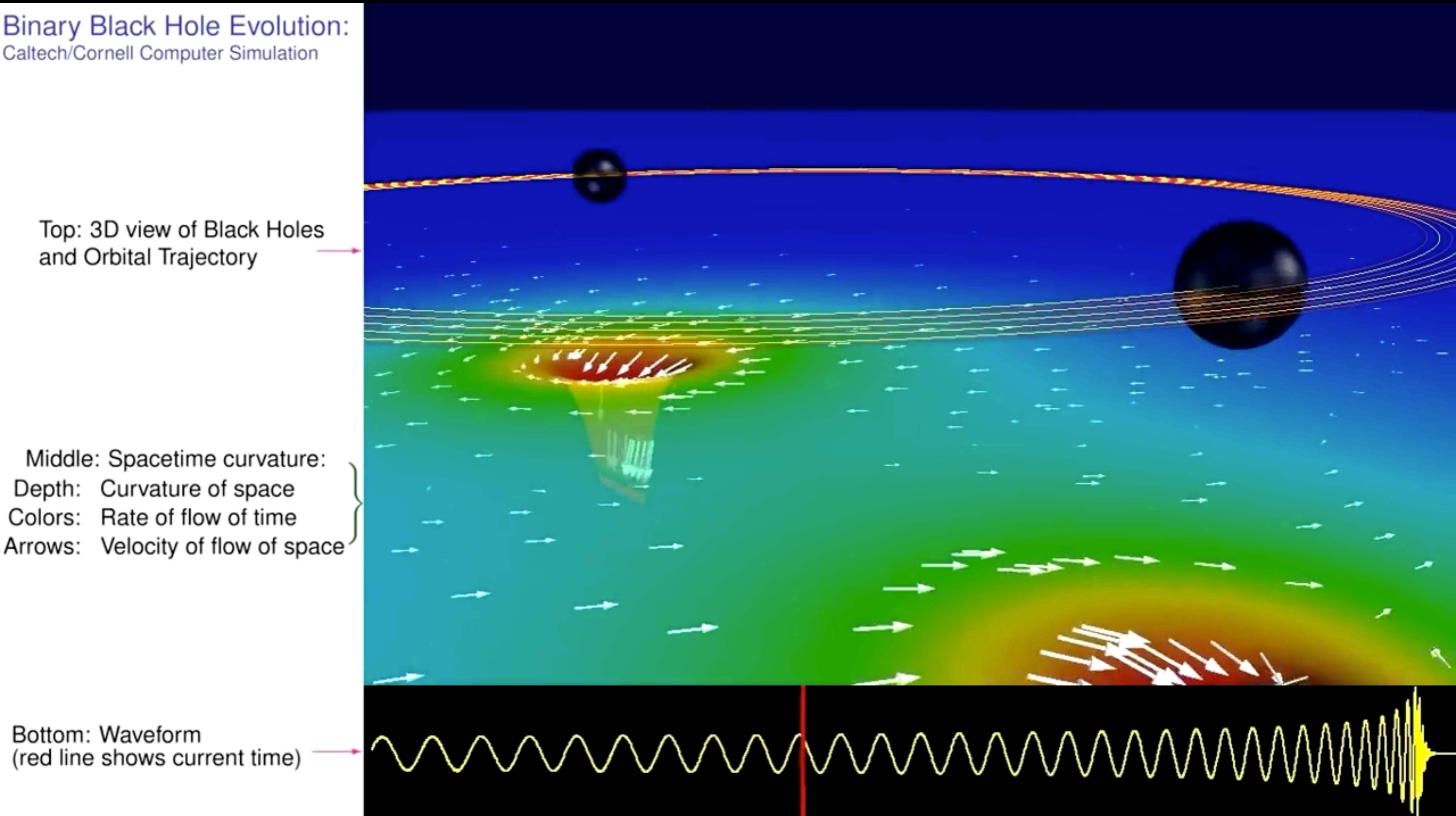
- **Accelerating masses** produce changes in spacetime geometry (if not spherically/rotationally symmetric)
- Periodically moving bodies (e.g. orbiting stars) create periodic ripples in spacetime curvature
- Ripples travel at **speed of light** through space
- These gravitational waves manifest as a **contraction and expansion of spactime** (“strain”) with a certain frequency
- Strain is measured in **dimensionless units** of length/length
- The effect is **very weak**, 10^{-20} or less!
- GWs **do “feel” the effect of mass/energy**: they lose energy by accelerating masses. However, this **effect is tiny** and does not significantly diminish the GWs.







Sources of gravitational waves



Caltech-Cornell SXS group

Gravitational wave spectrum

- What produces gravitational waves?
  - Many events, e.g., the solar system! But much too weak to detect
  - **Spinning neutron stars** (due to non-spherical imperfections)
  - **Compact object mergers** (two neutron stars, two black holes, or NS-BH)
  - **Inflation** (not symmetric because of quantum fluctuations in the early Universe)
- Gravitational waves **carry energy away** from their source
  - For example, cause compact objects to spiral toward each other

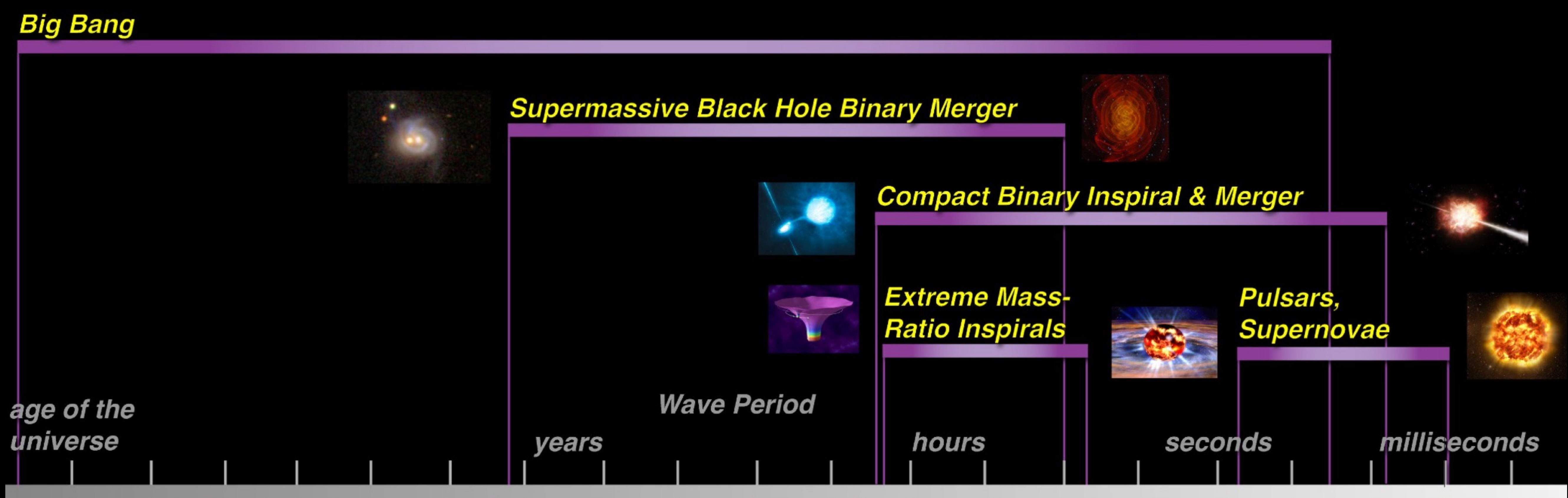
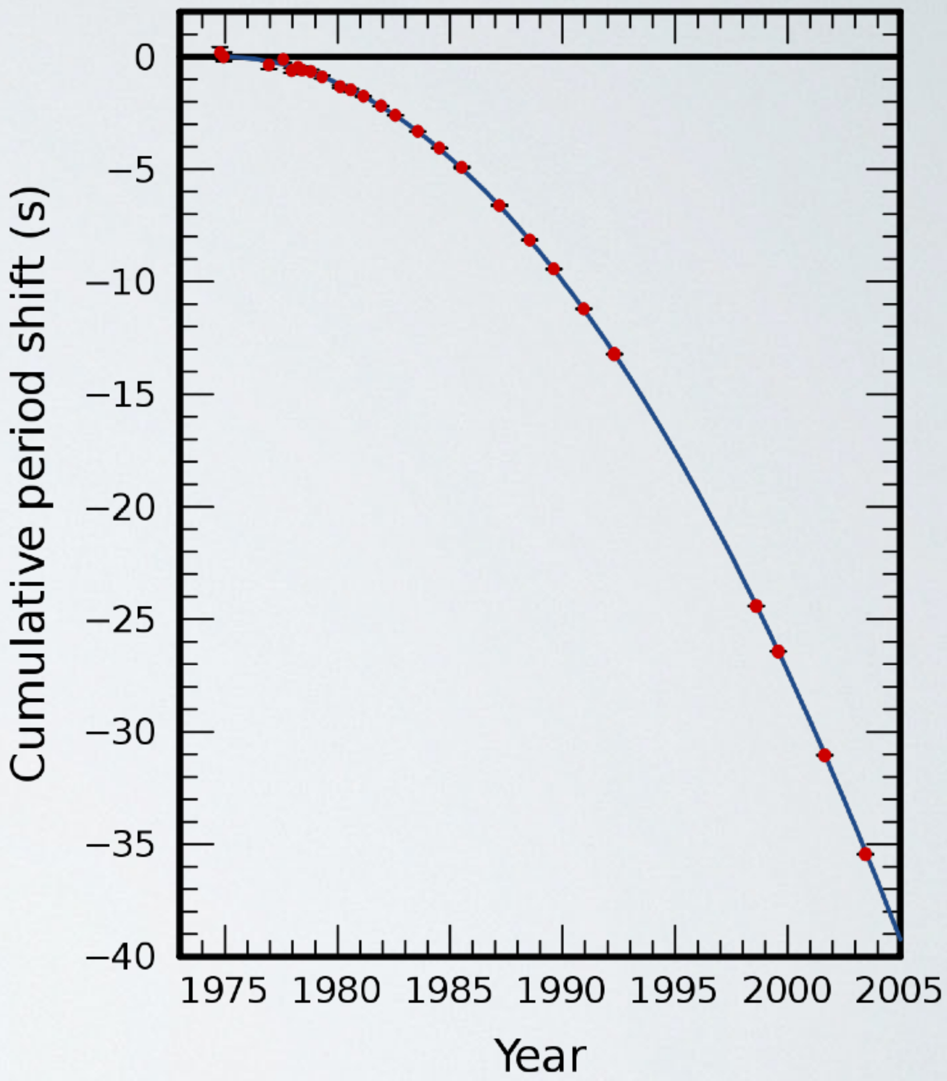


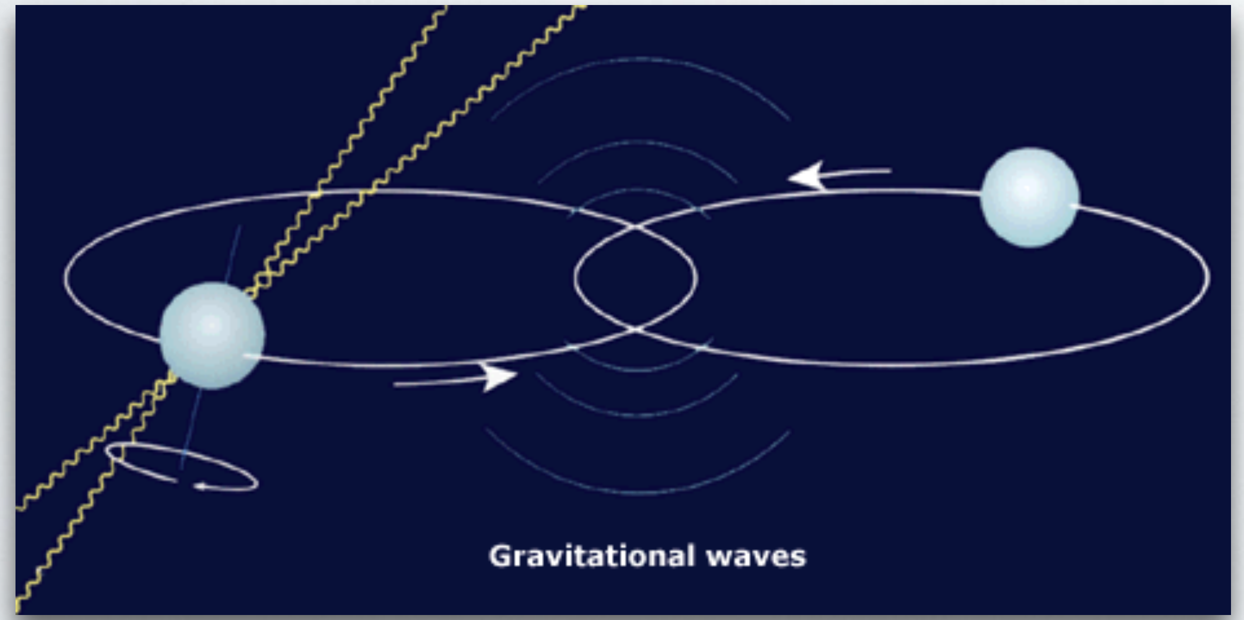
Image: Karan Jani

Part 4: Listening to the Universe

Hulse-Taylor pulsar

- Binary neutron star system where one NS is a pulsar
- Pulsar is spinning on its axis (period of 59ms)
- Emits pulse of radio waves towards Earth with each revolution — a very accurate **clock**!
- Orbit is **shrinking due to gravitational waves** at exactly the rate predicted by General Relativity

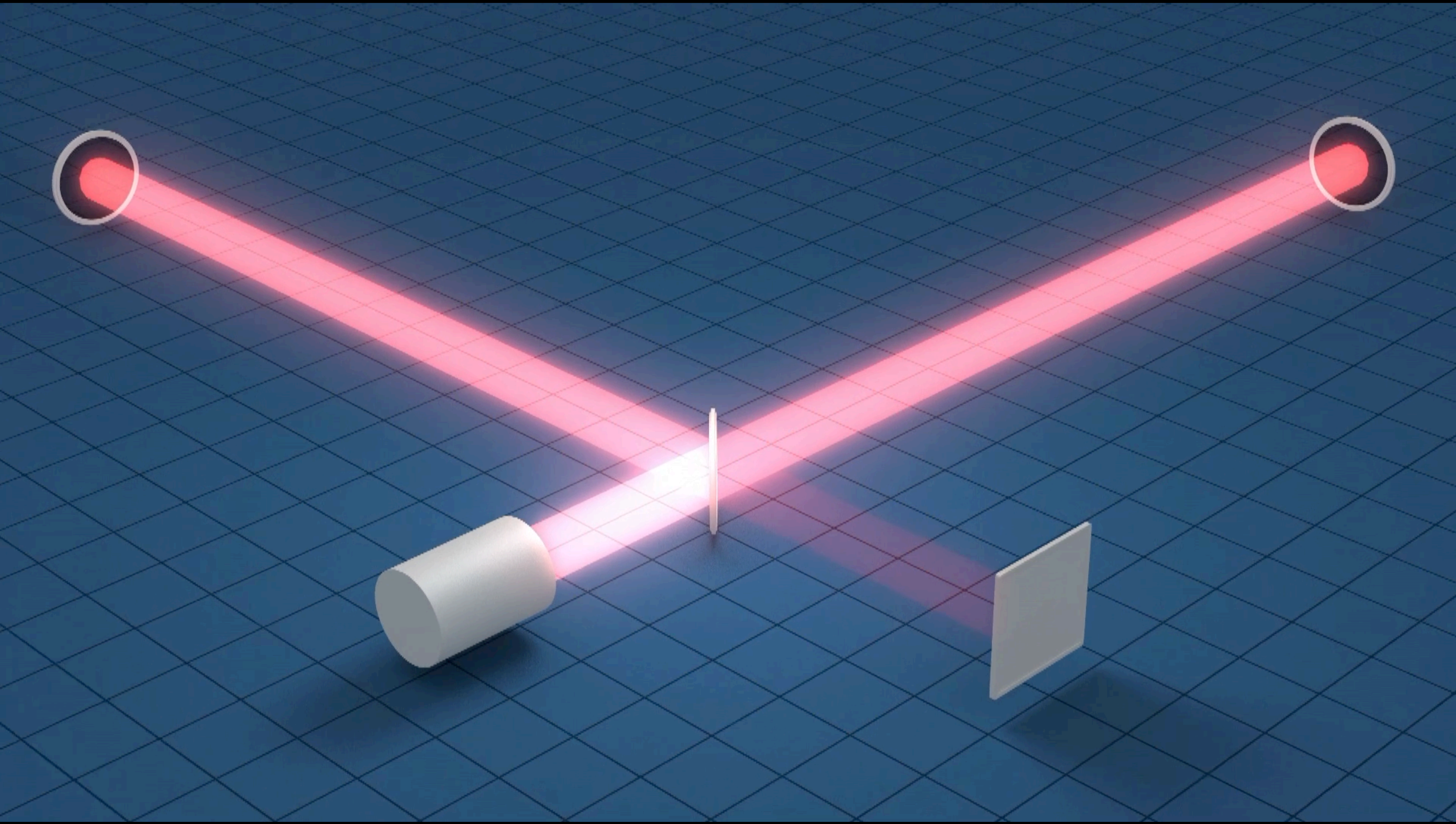




Weber Experiment

- How do you search for gravitational waves? Look for tidal forces as gravitational wave passes: local compression or expansion of space
- Pioneered by Joseph Weber (UMD Professor)
- Looked for “ringing” in a metal bar caused by passage of gravitational waves
- Insufficient technology in the 1970’s for detection
- “Weber memorial garden” at the entrance of the PSC

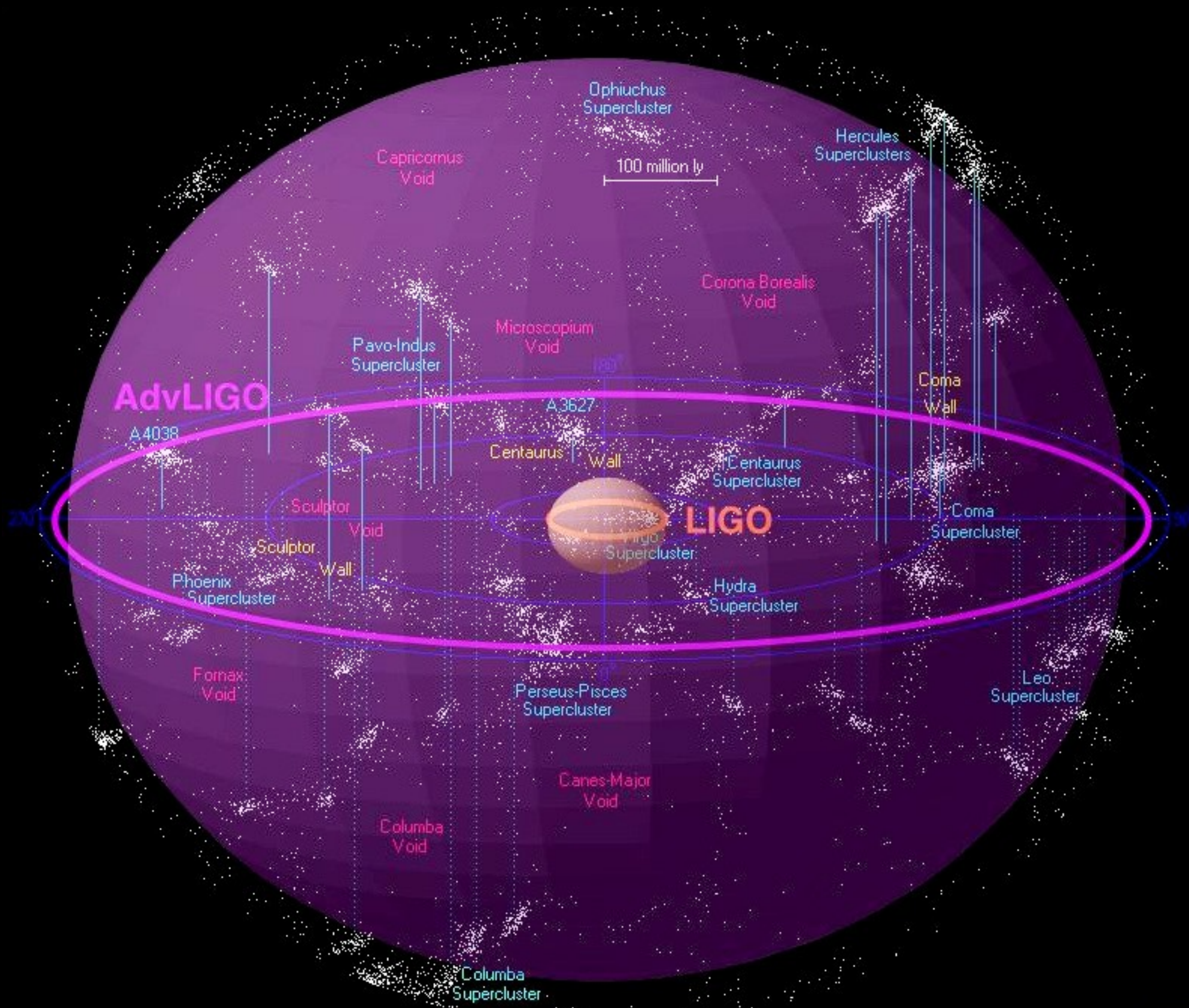
The LIGO experiment



LIGO Collaboration

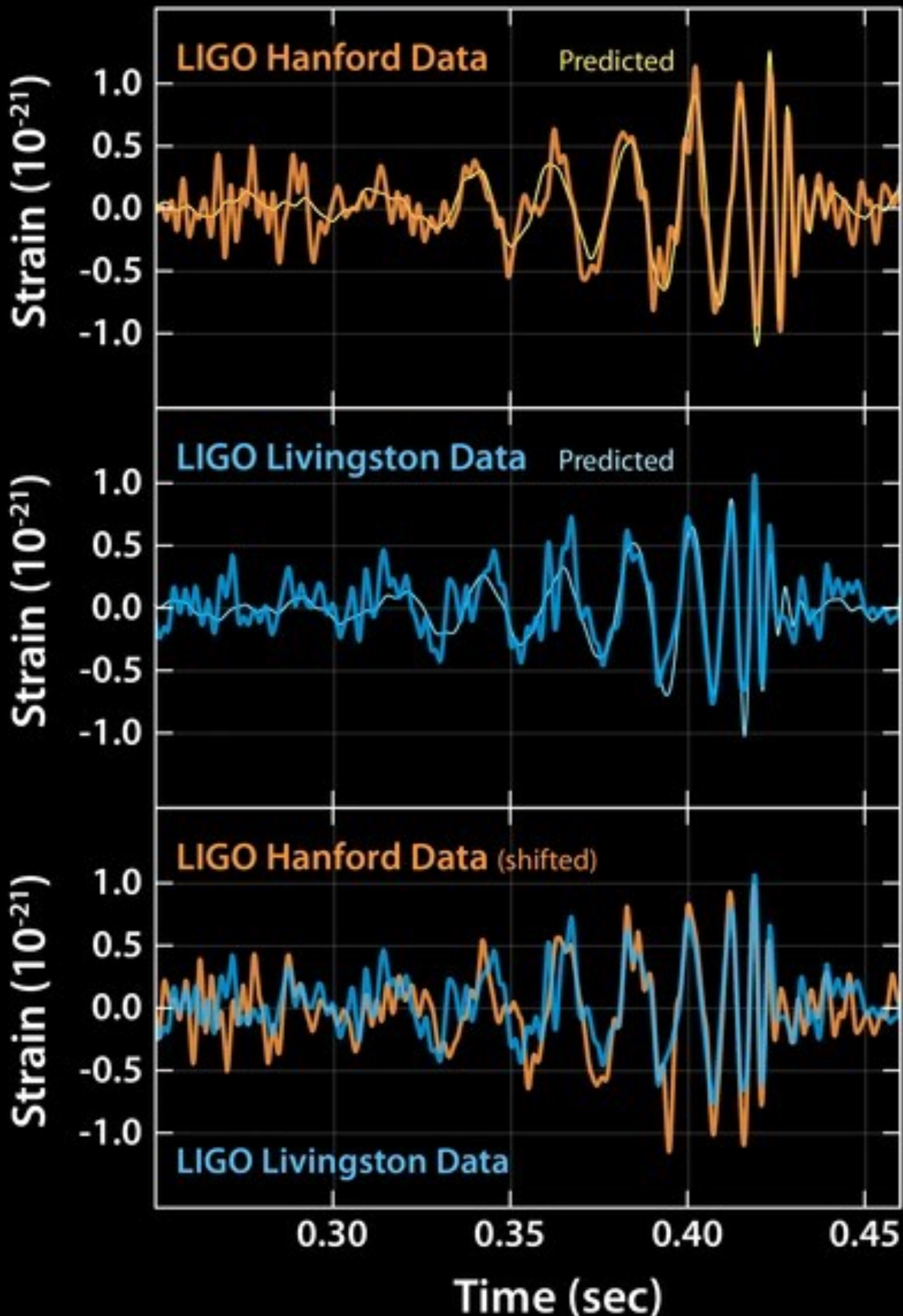
The LIGO experiment

- Laser Interferometer Gravitational Wave Observatory
- Two L-shaped 4km at each of two sites in Hanford WA and Livingston LA
- Can detect gravitational waves frequencies of about 10-1000 Hz
- Very sensitive, so need to worry about:
    - Seismic noise: earthquakes, wind, ocean waves, traffic
    - Thermal noise, quantum noise etc.
- What does it detect?
    - Stellar-mass black holes and/or neutron star mergers



LIGO Collaboration

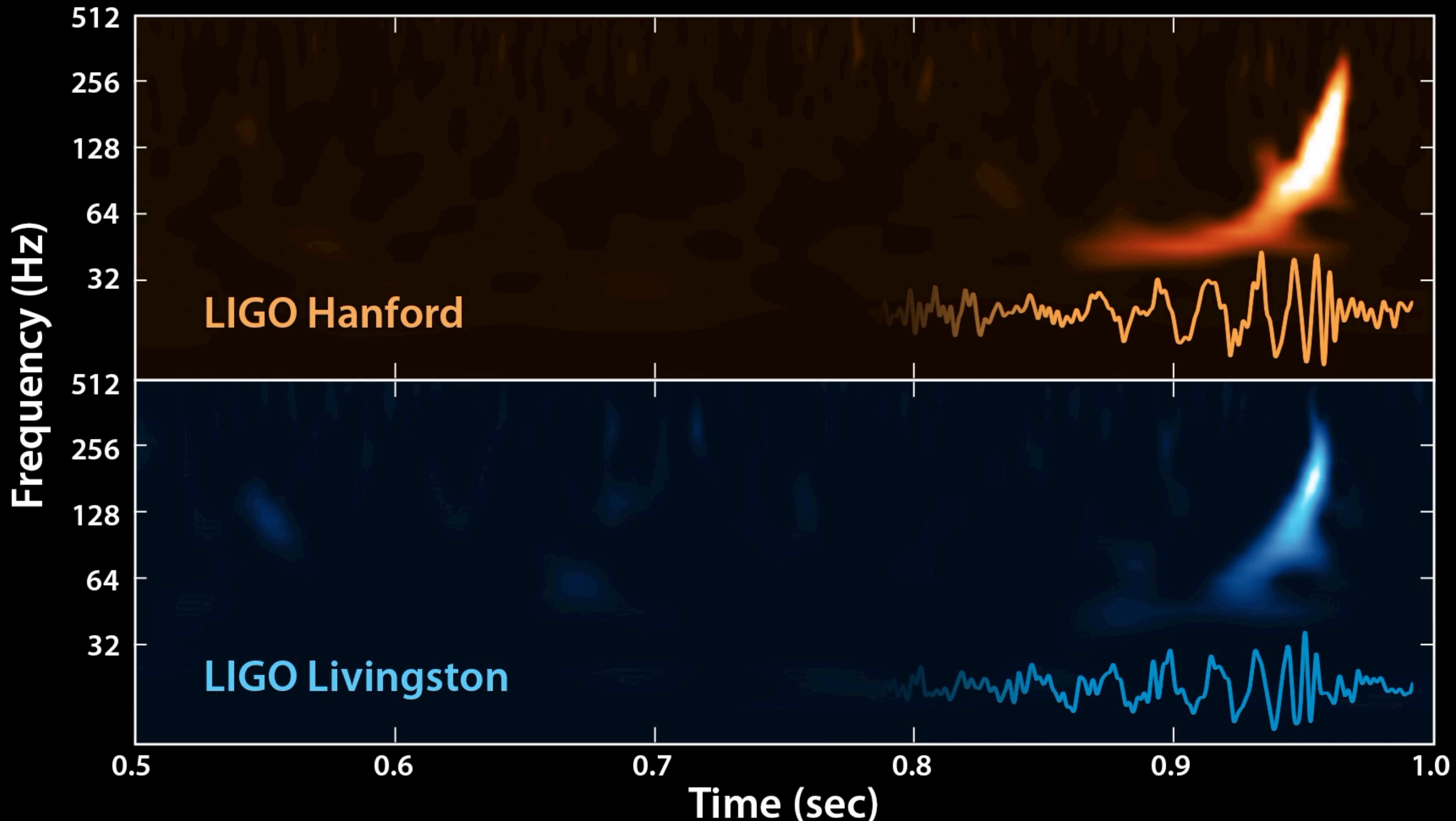
First LIGO detection



- GW150914 (observed on 09/14/2015)
- **Signal in both detectors** means it cannot be from local noise source
- **Time shift** of about 7 ms due to geographical distance between detectors
- Shape of best-fitting waveform tells us **mass and spin of black holes** (or some combination)
- **BH-BH merger** with about 30 + 35 $M_\odot$
- Total energy released was 5×10^{54} erg (equivalent to $3\ M_\odot c^2$)

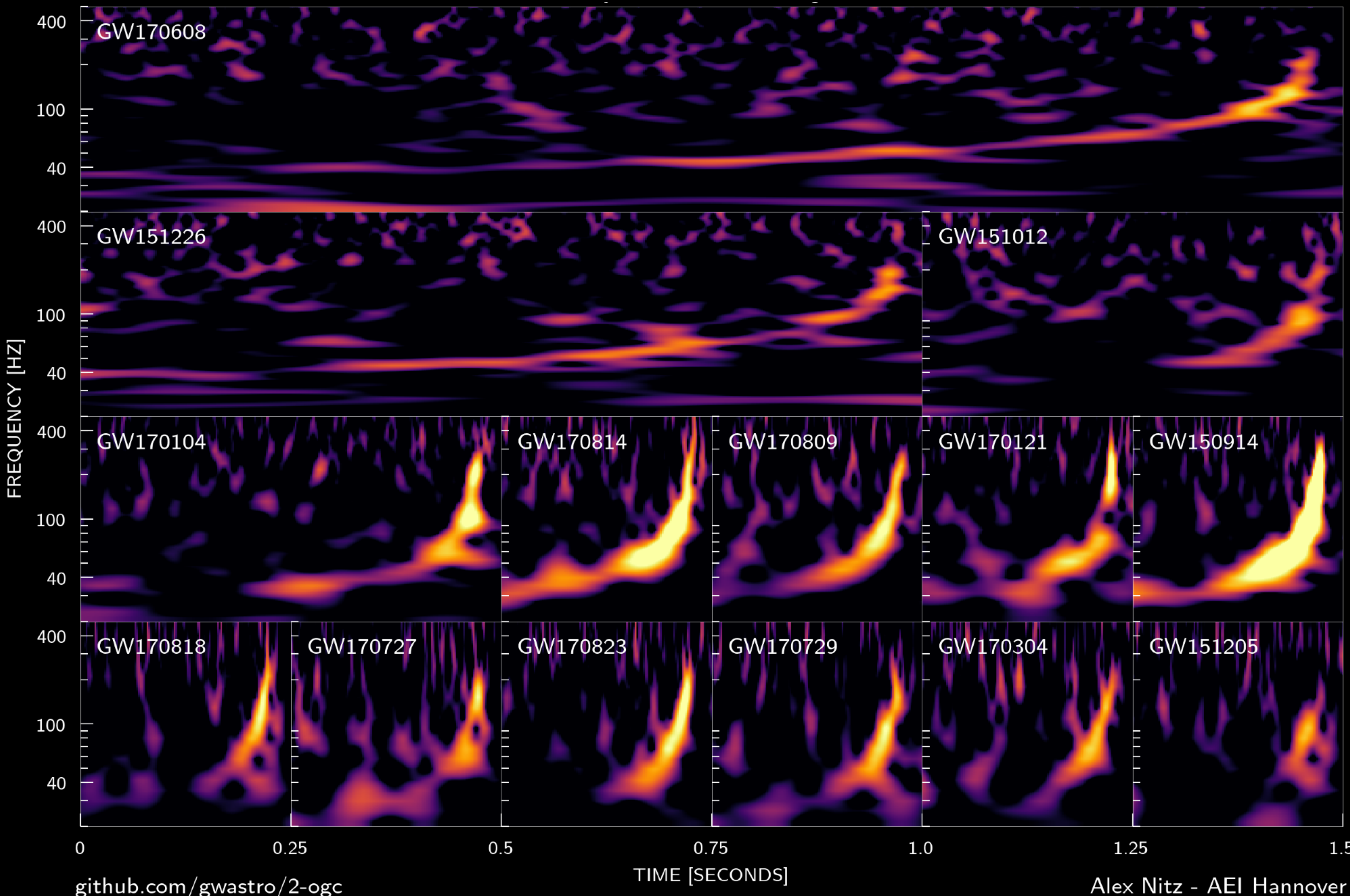
LIGO Collaboration

The "sound" of merging black holes



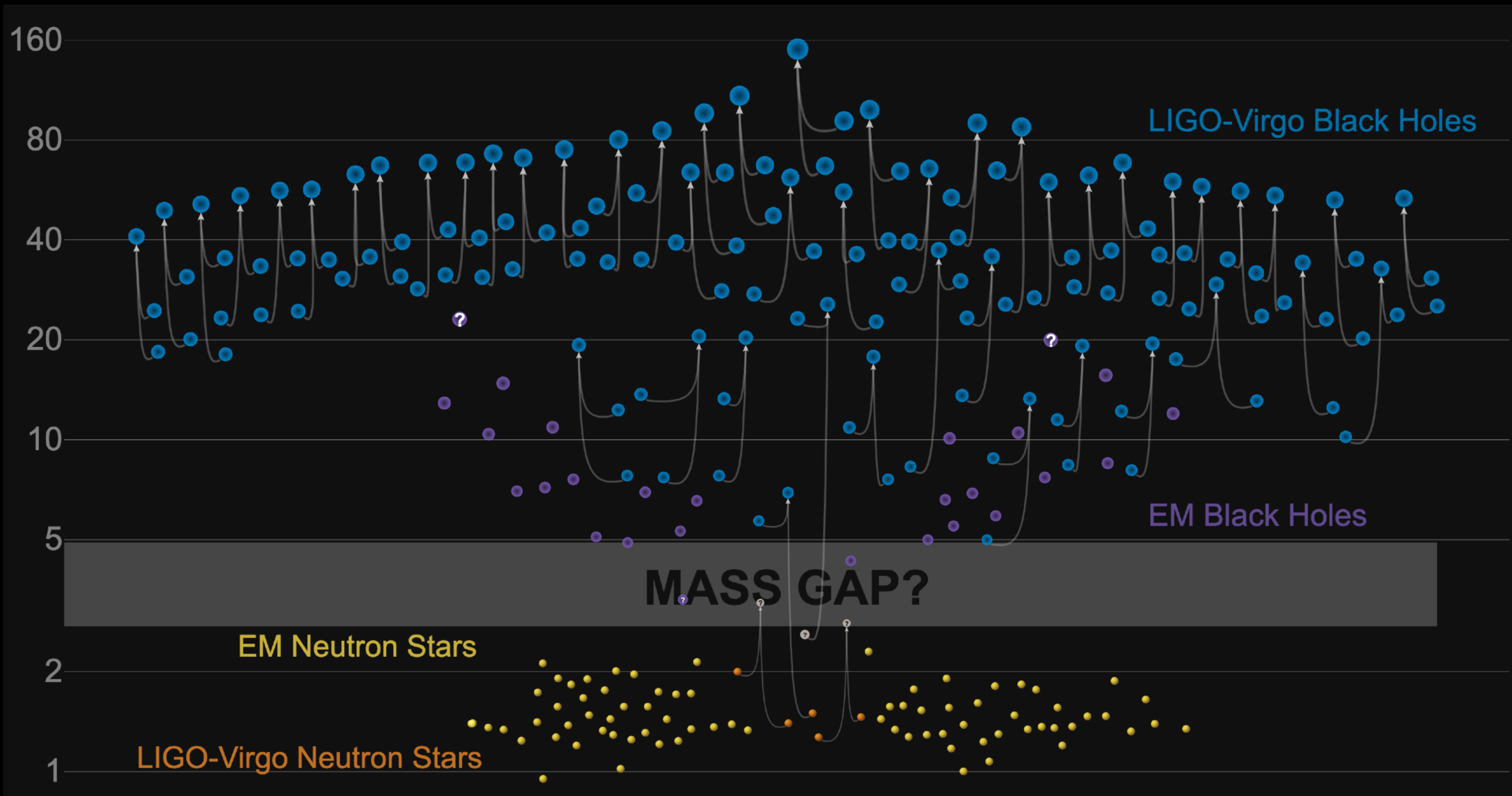
LIGO Collaboration

BH-BH mergers



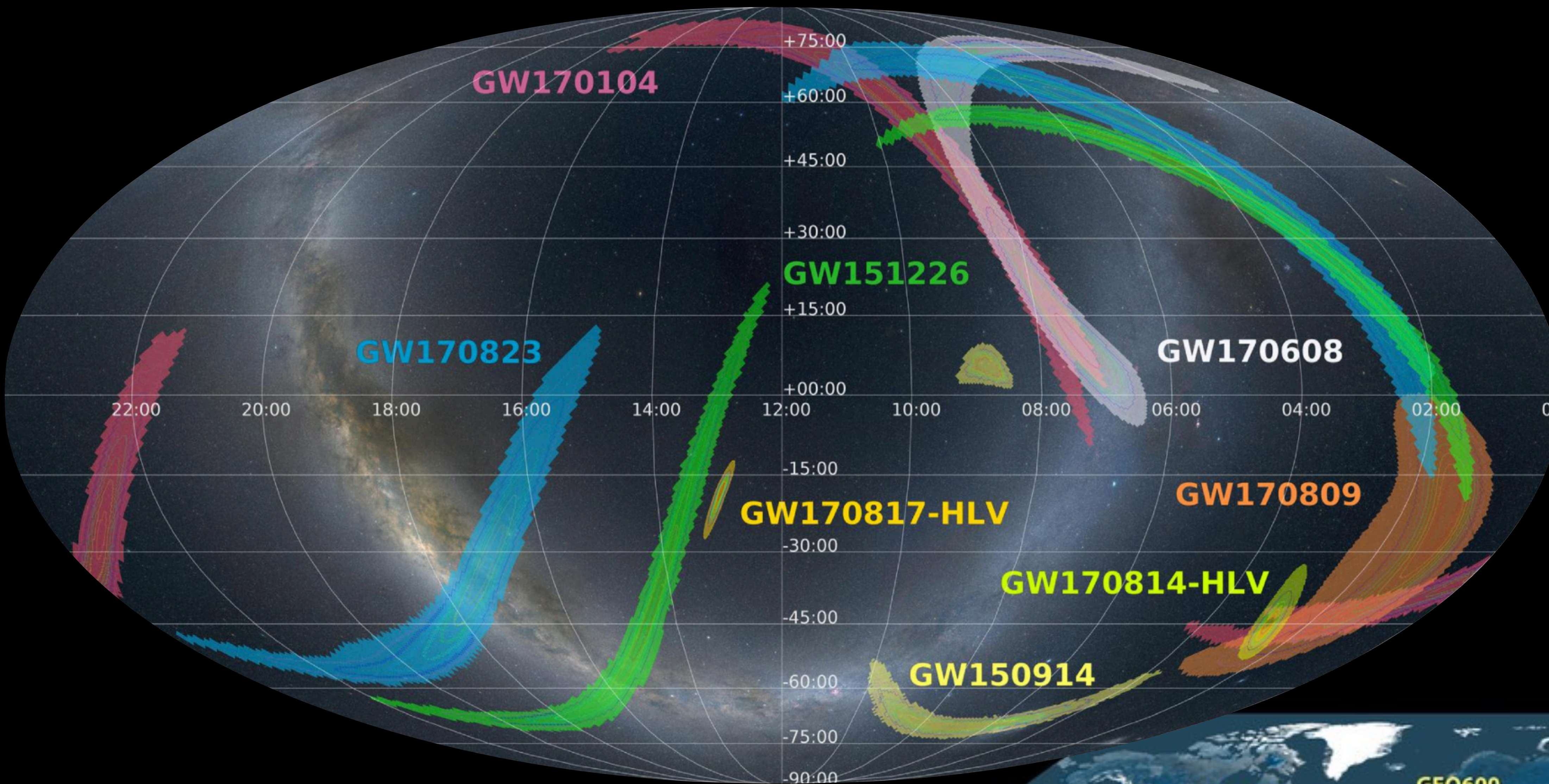
LIGO Collaboration / A. Nitz et al.

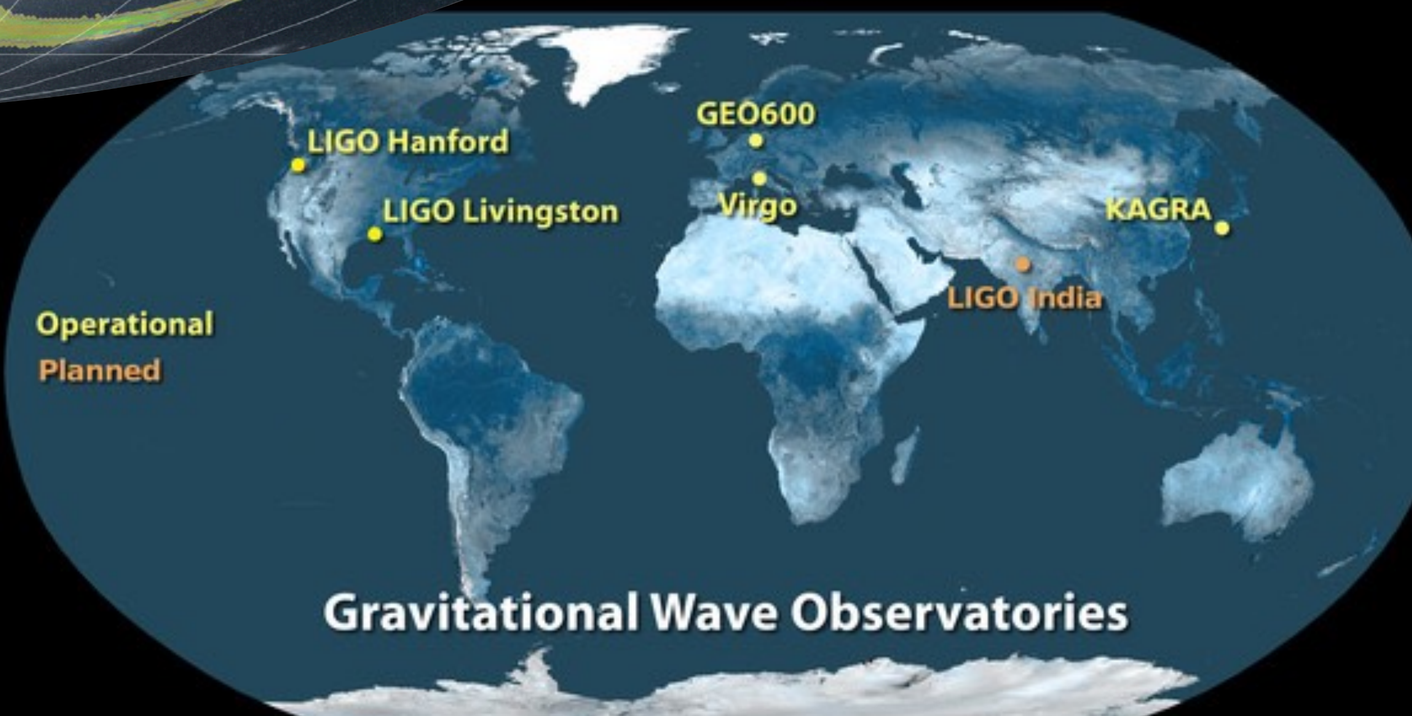
Summary of LIGO mergers detected



LIGO Collaboration • F. Elavsky, A. Geller

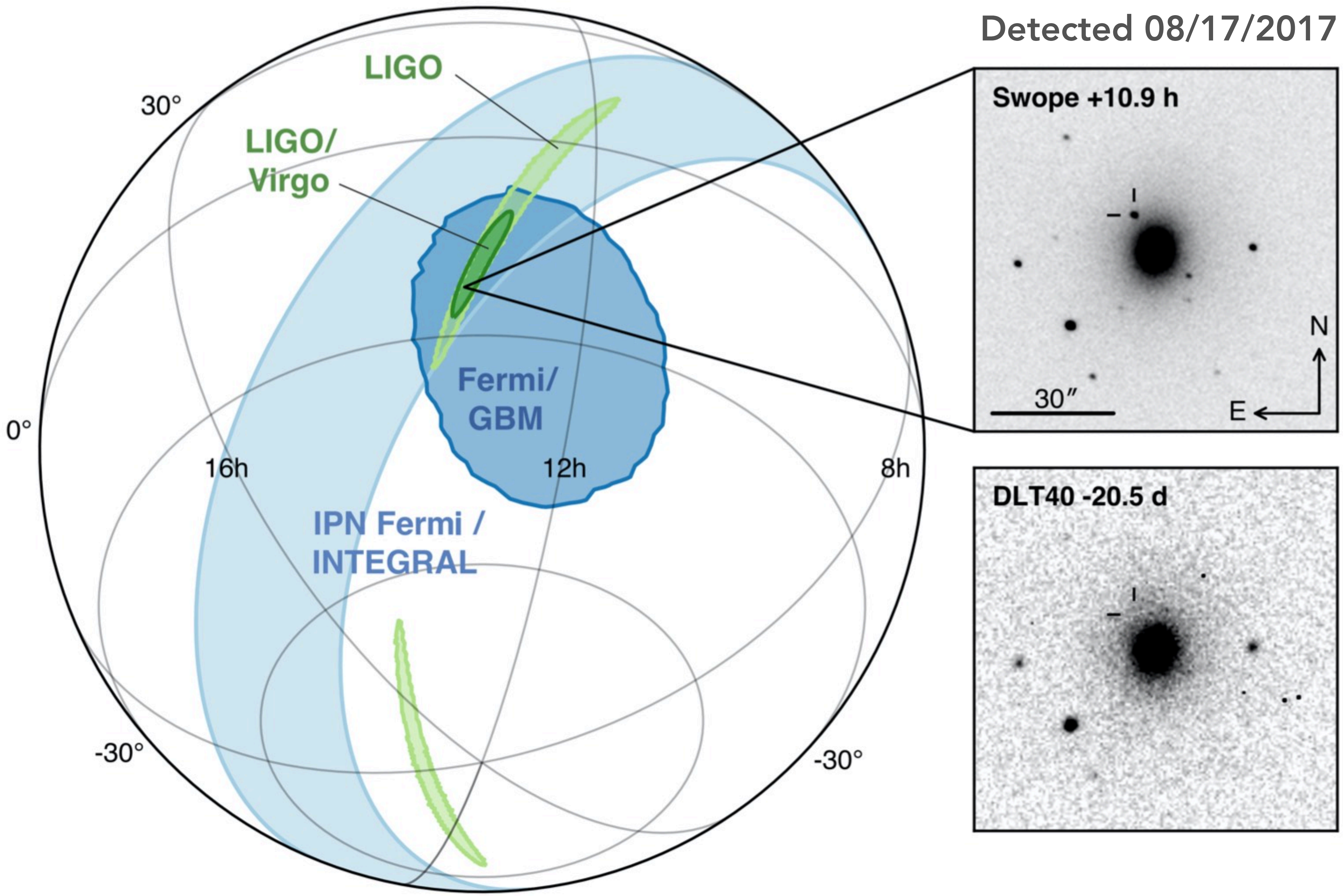
Localization of sources





LIGO Collaboration

Optical detection of NS-NS merger



LIGO Collaboration

What's the big deal with GWs?

- What physical messengers do we receive from the Universe?
  - Electromagnetic radiation (from radio to optical to gamma rays)
  - Energetic particles (cosmic rays)
  - Gravitational waves!
- GWs open up an era of **multi-messenger astronomy**

Nobel Prize 2017

- Development for LIGO started in the 1960s!
- Very risky research at the time because not clear that the concept would work

Gravitational wave spectrum

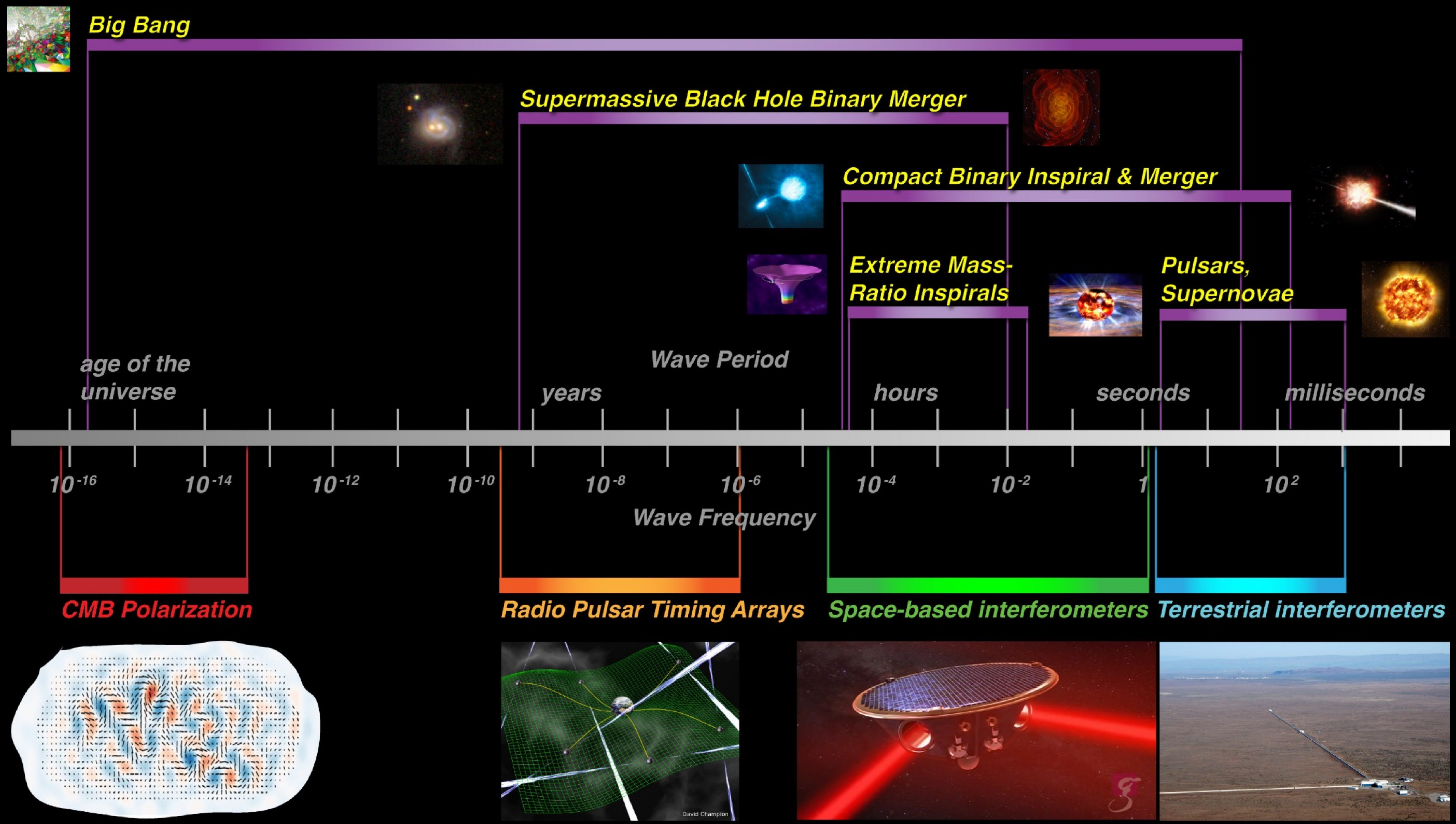
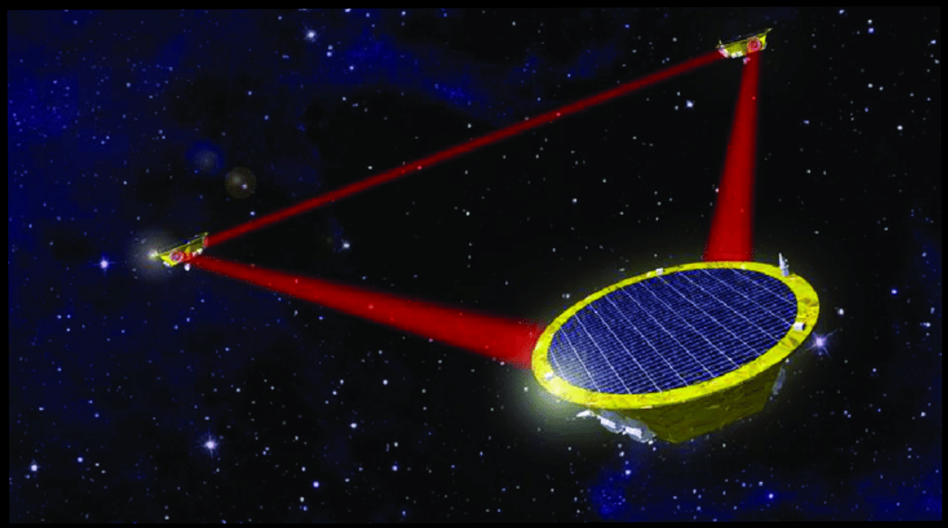
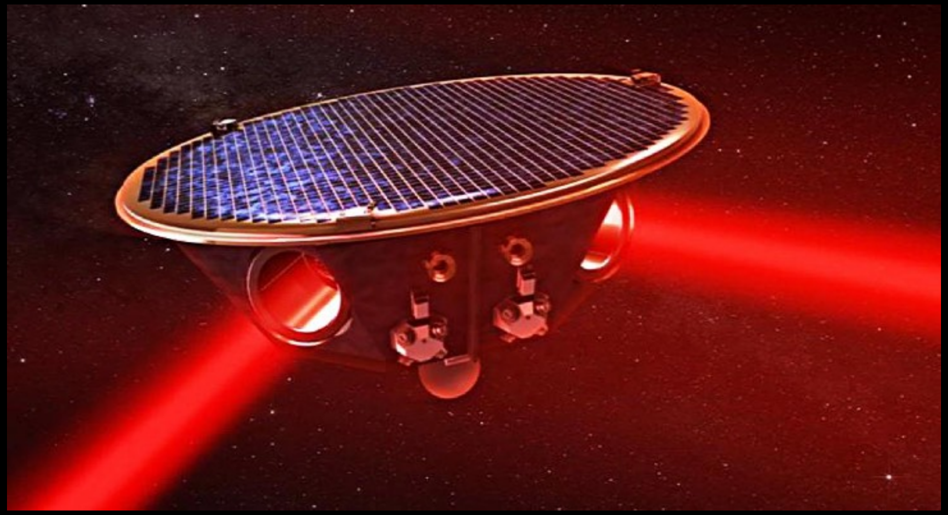
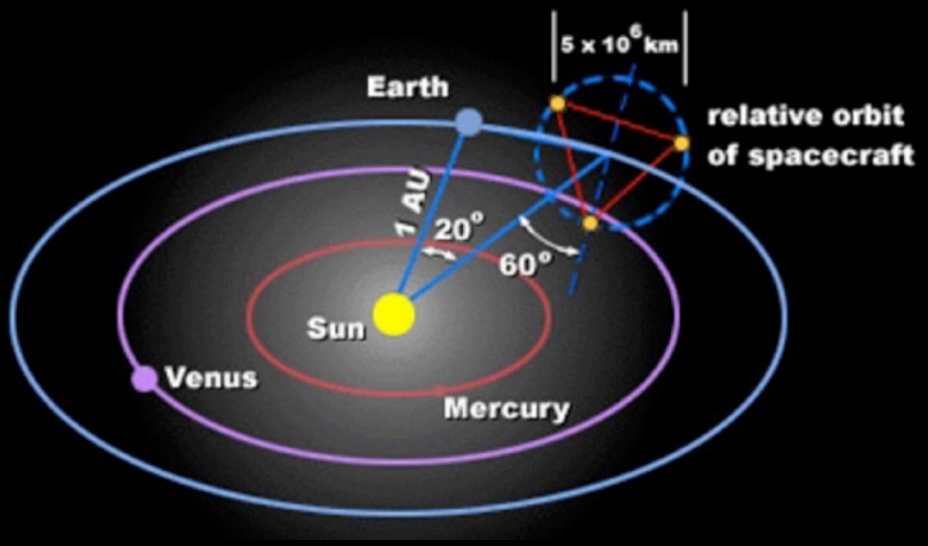


Image: Karan Jani

Future instruments: GWs in space







- Laser Interferometer Space Antenna (LISA)
- Space-based version of LIGO
- Sensitive to lower frequencies (0.0001 – 0.1Hz)
- Will be able to see
  - Normal binary stars in the Milky Way
  - Stars spiraling into large black holes in the nearby Universe
  - Massive black holes spiraling together anywhere in the universe!
- Has been planned for a long time, unclear when it will happen

Take-aways

- **Compact objects** include white dwarfs, neutron stars, and black holes
- **Orbiting bodies** radiate gravitational waves, shrink their orbit, and eventually **merge**
- **Gravitational waves** manifest themselves as extremely small contractions and expansions of spacetime
- Gravitational waves are rapidly becoming a major new way to observe the Universe

Next time…

We'll talk about:

- Inflation and multiverses

Assignments

- Post-lecture quiz (by tomorrow night)
- Homework #5 (by Thursday night)

Reading:

- H&H Chapter 16