SUPERMASSIVE BLACK HOLES: EVIDENCE AND IMAGES

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TWO SUPERMASSIVE BLACK HOLES

- Astronomers now think that all quasars (active galactic nuclei) and almost all large galaxies contain supermassive black holes (>10^5 M_{Sun}) at their centers.
- Today we will examine the black hole at the center of our spiral Milky Way Galaxy and the black hole at the center of the giant elliptical galaxy M87 in the Virgo galaxy cluster. The shadow of each of these black holes has been imaged by the Event Horizon Telescope (EHT).
- We will not spend more than about 90 seconds on the Supermassive Black Hole song by Muse (2006).

CENTER OF MILKY WAY

Located above the person's head in this ESO photo, in a dusty and dark region of Sagittarius, lies the center of our Galaxy, Sgr A*.

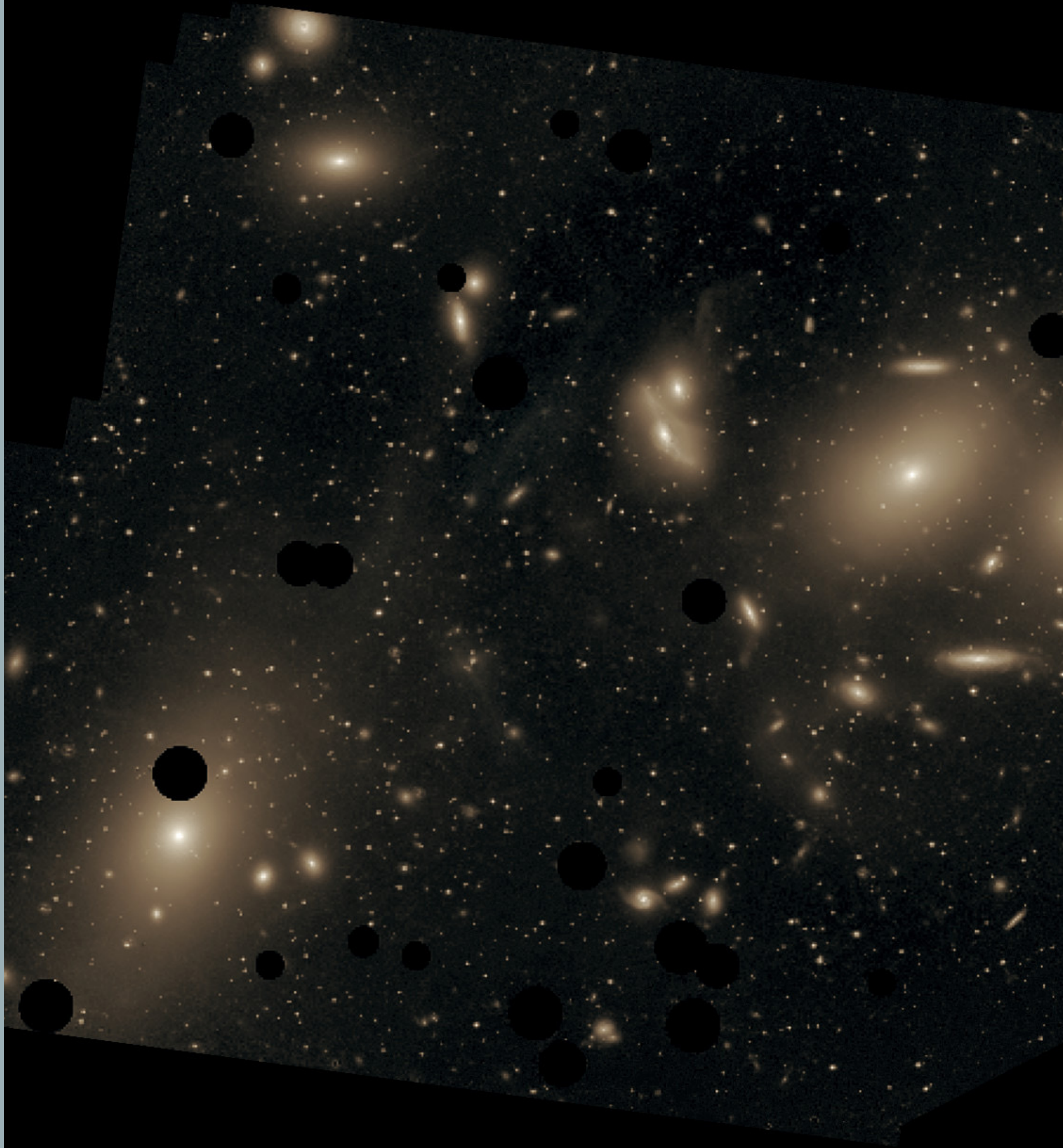
The photo, taken on the Chajnantor Plateau in Chile, also contains bright Saturn and Mars, as well as a greenish comet and red Antares to the right of Mars.

M87 IN THE VIRGO CLUSTER

In this ESO photo by Chris Mihos, dark circles indicate where images of foreground stars have been removed. The long exposure shows the faint glow of gas and stars between the galaxies.

North is up and east to the left.

M87 is the large galaxy at the lower left of the image. The jet from the center is faintly visible.



ALMA

The Atacama Large Millimeter/Submillimeter Array (ALMA) on the Chajnantor Plateau at altitude 5000 m in Chile. Signals for the array telescopes can be combined as if they were part of one detector. ALMA is one of the telescopes spread around the world that comprise the EHT.

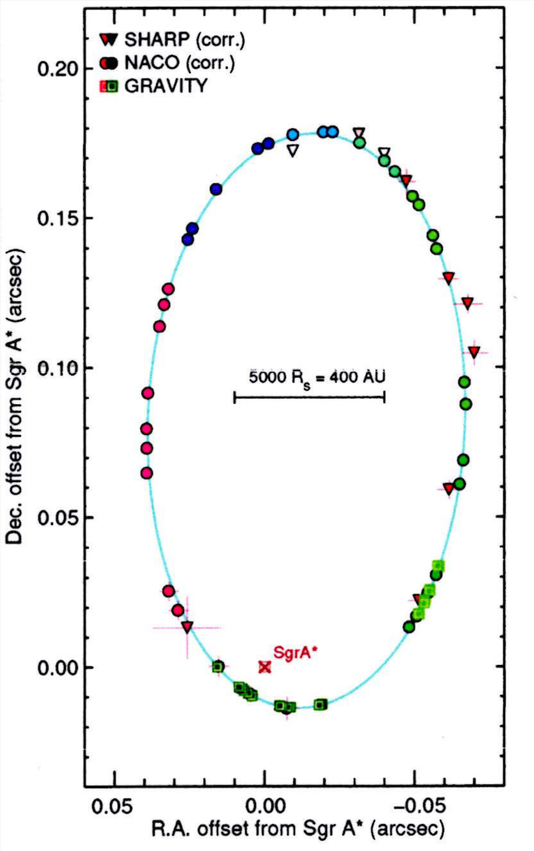
YOUR TURN – PAGE 1

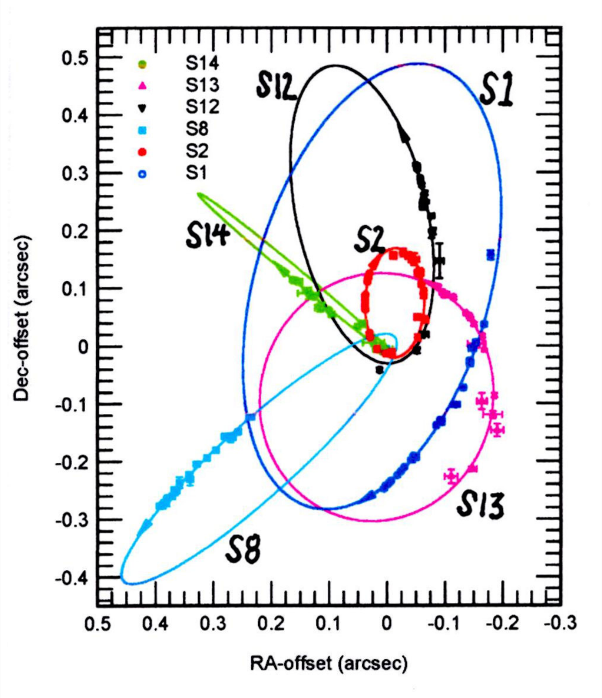
- Now it is your turn to gain some practical understanding of angular sizes from one degree to one arcsecond.
- Work with a partner to take the measurements and do the calculations on the front side (page 1) of the "How Big is a Supermassive Black Hole" worksheet.

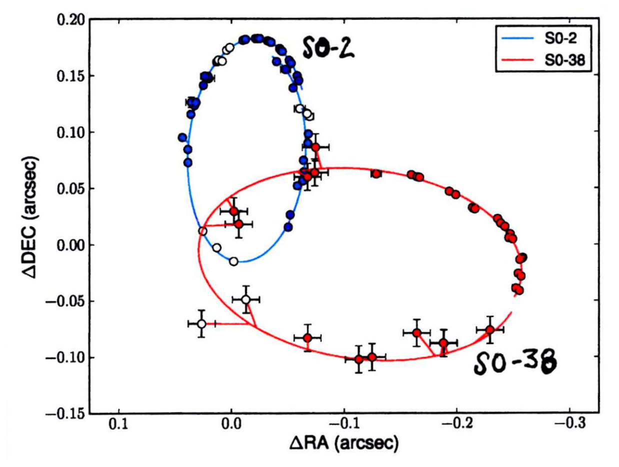
STARS ORBITING SGR A*

- In the early days of radio astronomy, the brightest radio source in the constellation Sagittarius was named Sgr A. When the source was later determined to be nearly a point source and its location more precisely determined, it became Sgr A* and recognized as the center of our Milky Way.
- Located in a dusty region that absorbs visible light, the stars in the vicinity of Sgr A* are visible in infrared light. Beginning in the 1990s Reinhard Genzel at ESO in Chile and Andrea Ghez at the Keck Observatory in Hawaii employed adaptive optics and infrared detectors to image stars in the region. As stars moved over the years, they could plot their orbits.
- Hubble Telescope zoom-in to Galactic center Sgr A*.
- Twenty years of time-lapse images of stars around Sgr A* from ESO.
- Physics of a two-body orbit: $(m_1 + m_2) = \left(\frac{4\pi^2}{G}\right)\left(\frac{a^3}{T^2}\right)$, where a = semi-major axis of relative orbit, T = orbit period, and m = mass

STAR ORBITS AND SGR A* MASS
GHEZ (RIGHT)
GENZEL (CENTER AND LEFT)
[STAR S2 (SO-2) IS IN ALL THREE PLOTS]

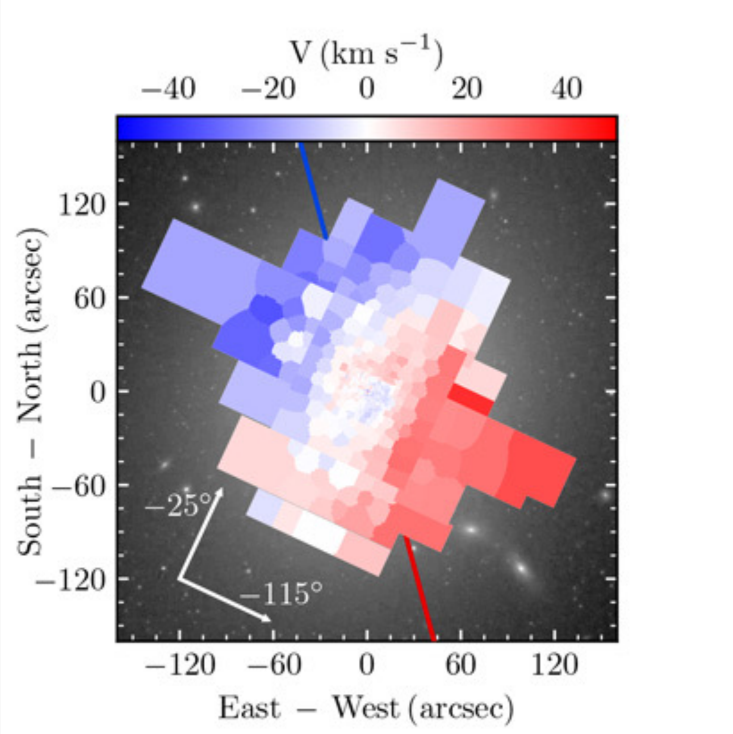






STAR MOTION AROUND M87*

- **Using the Keck telescope, Berkeley astronomers mapped the velocity of stars around the center of M87 to determine the 3D structure of the galaxy. Blue squares are regions of stars moving toward Earth; red are regions of stars moving away from us. The red-blue line is the rotation axis of the galaxy, displaced by 40 degrees from the major and minor axes of the galaxy as determined from optical images taken by the Hubble Space Telescope. (Image by Emily Liepold, Chung-Pei Ma and Jonelle Walsh) 2023**
  This information allows more precise determination of the central black hole mass.



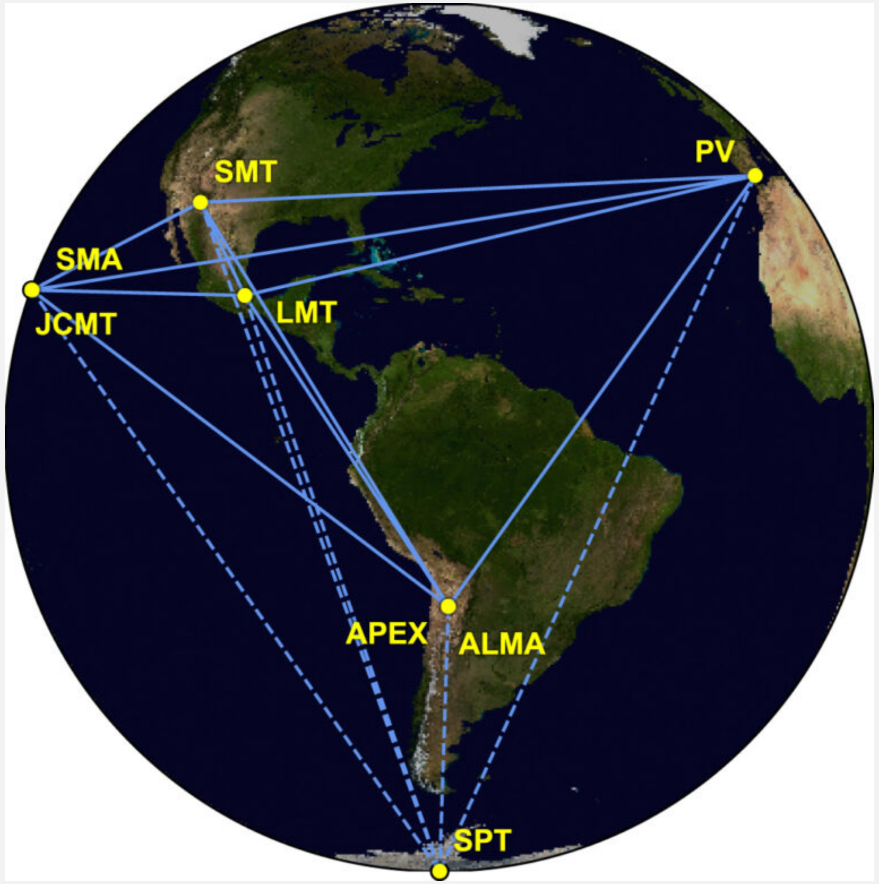
YOUR TURN - PAGE 2

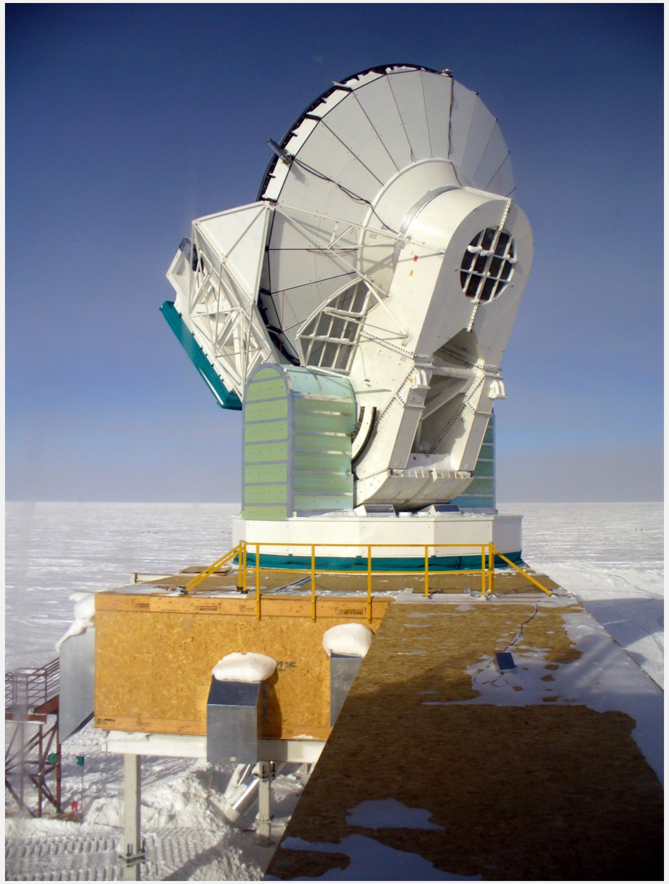
- Now it is your turn to work out the apparent angular size of the supermassive black holes Sgr A* and M87* as seen from Earth.
- Work with a partner to do the calculations on the back side (page 2) of the "How Big is a Supermassive Black Hole" worksheet.

WHY NOT IMAGE BLACK HOLE SHADOWS IN INFRARED OR VISIBLE LIGHT?

- For λ = 1.3 mm radio waves, we need an instrument with effective diameter about D = 13 x 10^3 km.
- Angular resolution is proportional to λ/D.
- To produce an image in 10^{-3} mm near infrared light would require an instrument with effective diameter 10 km. This is not yet feasible.
- Infrared interferometry has been done for D = 10s of meters at the VLT tlelscopes on Cerro Paranal in Chile (photo on right).
- Also, as observed the Sgr A* time-lapse images, the visible and near infrared light is absorbed by the dust surrounding the black holes.

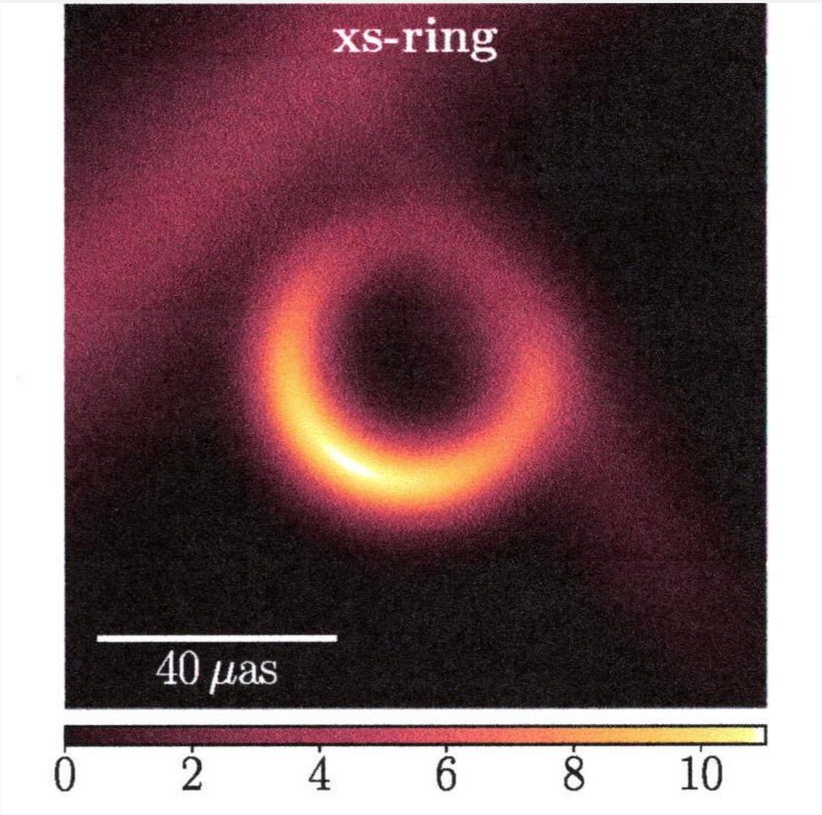
EHT TELESCOPES AND LOCATIONS



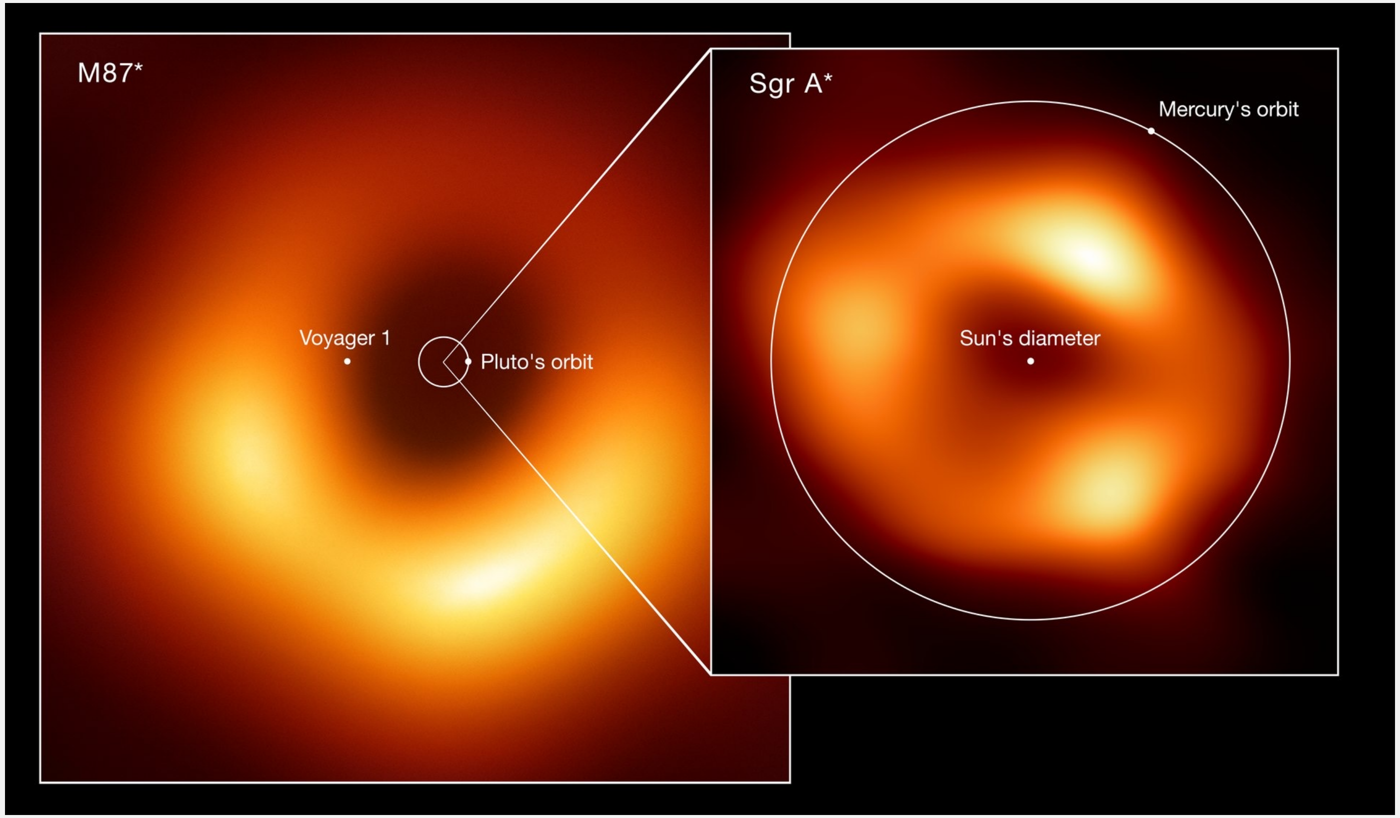


EHT BLACK HOLE SHADOW IMAGES

M87* (2019)



M87* (2019) AND SGR A* (2022)



WHAT ARE WE SEEING?

- Chandra video of M87 observations from radio to γ-ray at many wavelengths and distance scales. Note the importance of the jet from the central black hole in many of the images.
- Veritasium explains what the images show and how Very Long Baseline Interferometry (VLBI) can be used to obtain the images.

TECHNICAL NOTES ON VLBI

- The EHT images depend on correlating independent data streams producing petabytes (2^{50} or about 10^{15} bytes) of data from radio telescopes operating at 1.3 mm (230 GHz or $T = 4.3 \times 10^{-12}$ s). The time delay of greatest correlation between telescope signals indicates the comparative times at which the signal from the source reached the detectors and the corresponding interference bands on the sky at which the source could be located. The high frequency of the signal requires the data streams to be time-stamped with clock signals at the observatories that are synchronized between observatories and accurate to 10^{-14} seconds.
- The hard drives containing the data for an EHT observing run weigh 7 tons and are flown to the two computing centers at MIT's Haystack Radio Observatory in Westford, Massachusetts, and the Max Planck Institute in Bonn, Germany, for correlation.
- The process involves computing a correlation coefficient for each time offset, for example a Pearson Product Moment Correlation for each pair (*x*,*y*) of data streams:

$$r = \frac{(\Sigma xy) - (\Sigma x)(\Sigma y)}{\sqrt{[n\Sigma x^2 - (\Sigma x)^2][n\Sigma y^2 - (\Sigma y)^2 - (\Sigma y)^2]}}$$

NOBEL PRIZES – A PATTERN(?)

- 2017 – Rainer Weiss, Kip Thorne, and Barry Barish
  for LIGO discoveries of colliding black holes
- 2020 – Andrea Ghez and Reinhard Genzel
  for observations of stars orbiting Sgr A*,
  Roger Penrose
  for mathematical insights related to black holes

NOBEL PRIZES – A PATTERN(?) AND PREDICTION

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  for LIGO discoveries of colliding black holes
- 2020 – Andrea Ghez and Reinhard Genzel
  for observations of stars orbiting Sgr A*,
  Roger Penrose
  for mathematical insights related to black holes
- 2023 – Sheperd Doeleman and ???
  for EHT images of black hole shadows

RESOURCES

- Supermassive Black Hole music video by Muse: https://www.youtube.com/watch?v=Xsp3_a-PMTw
- Hubble zoom to Sgr A*: https://www.youtube.com/watch?v=ygevBQWt_LE
- ESO 20 years of stars orbiting Sgr A*: https://en.wikipedia.org/wiki/Sagittarius_A*#/media/File:SgrA2018.gif
- Chandra video of M87 data from radio to γ-ray: https://chandra.harvard.edu/photo/2021/m87/m87_BU.mp4
- Veritasium video: https://www.youtube.com/watch?v=Q1bSDnuIPbo