The Event Horizon Telescope

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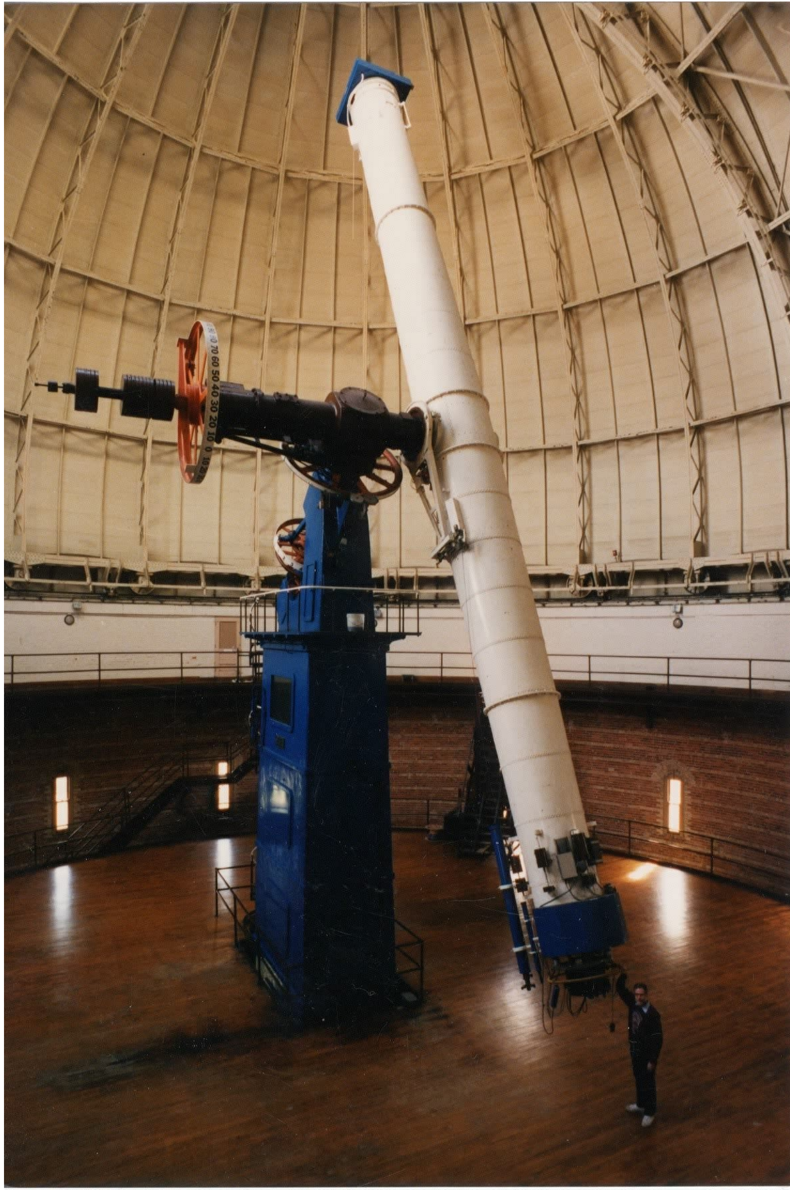
What is the Event Horizon Telescope



What is the Event Horizon Telescope

The Event Horizon Telescope

Operates at Radio wavelengths and utilizes multiple radio telescopes

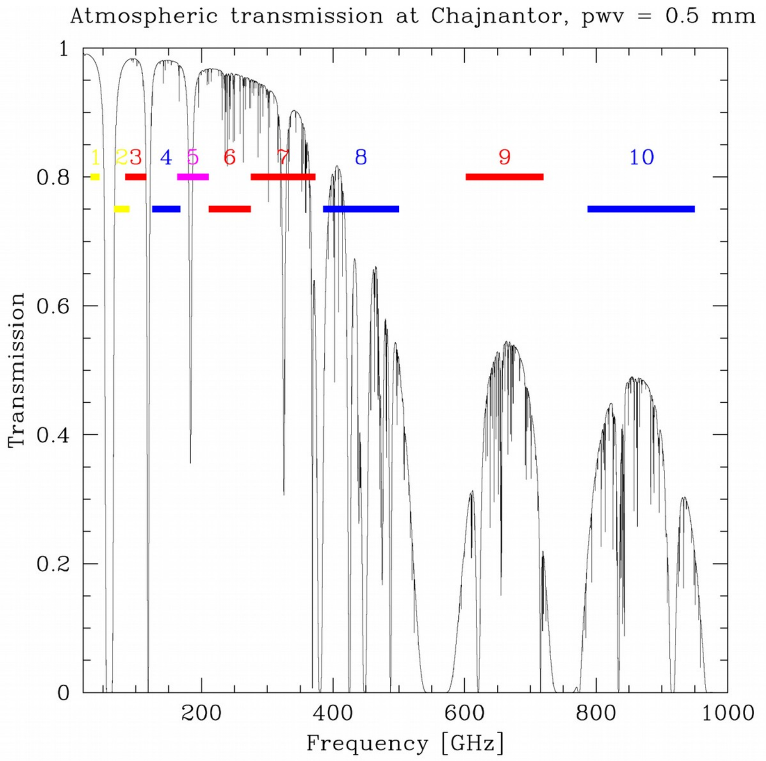
The Event Horizon Telescope

The Event Horizon Telescope

It combines the observations from single dish and telescope arrays to make a single image

Observations

- The Event Horizon Telescope observes at 1.3 mm or 230.6 GHz
- This is in a high transmission region



The Event Horizon Telescope

A radio interferometer is an array of radio antennas that simultaneously observe a target. This acts as a single telescope with a very large but incompletely-filled aperture of the spacing between telescopes. The aperture is only sampled at the locations at which there is a telescope but the size of the baseline sets the resolution of the array. The larger the baseline the smaller the resolution.

The Event Horizon Telescope

The Hubble Space Telescope has a resolution of 0.04”. For millimeter wavelength observations one would need a 5km diameter telescope to achieve this resolution.

Angular resolution ~ 0.11” (λ/550nm) (1/B_{max}), where B_{max} is the longest baseline
The maximum angular scale the source is resolved if $\theta > \lambda/B_{min}$, where B_{min} is the minimum separation between apertures.

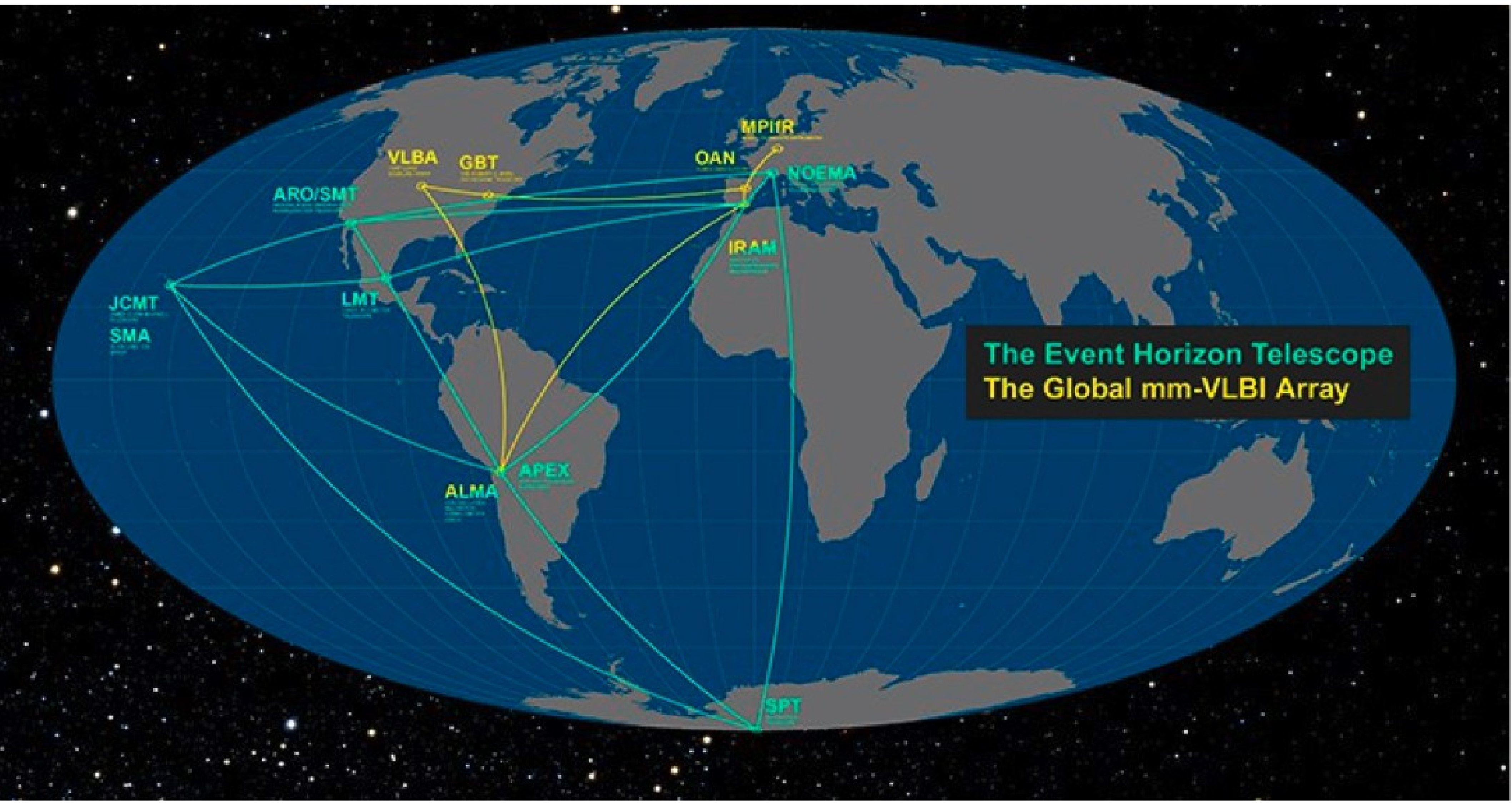
An interferometer is sensitive to a range of angular sizes $\lambda/B_{max} < \theta < \lambda/B_{min}$

The nearest massive black hole, Sgr A*, is in the center of our galaxy, about 26,000 light-years away. The size of Sgr A* is about 53 micro-arcseconds.

Farther away is the supermassive black hole at the center of galaxy M87. This black hole is about 1500 times more massive and 2000 times farther away than Sgr A*. So M87 is about 22 micro-arcseconds compared to the 53 micro-arcseconds of Sgr A*.

The Event Horizon Telescope has a resolution of approximately 35 micro-arcseconds

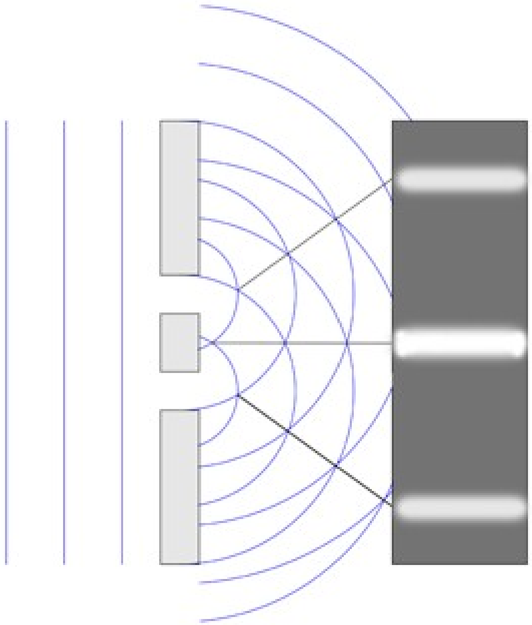
1 arcsecond is 1/3600th of a degree, roughly a dime held up at 2 miles


The Event Horizon Telescope
The Global mm-VLBI Array
MPIfR
VLBA
GBT
OAN
NOEMA
ARO/SMT
IRAM
JCMT
LMT
SMA
APEX
ALMA
SPT

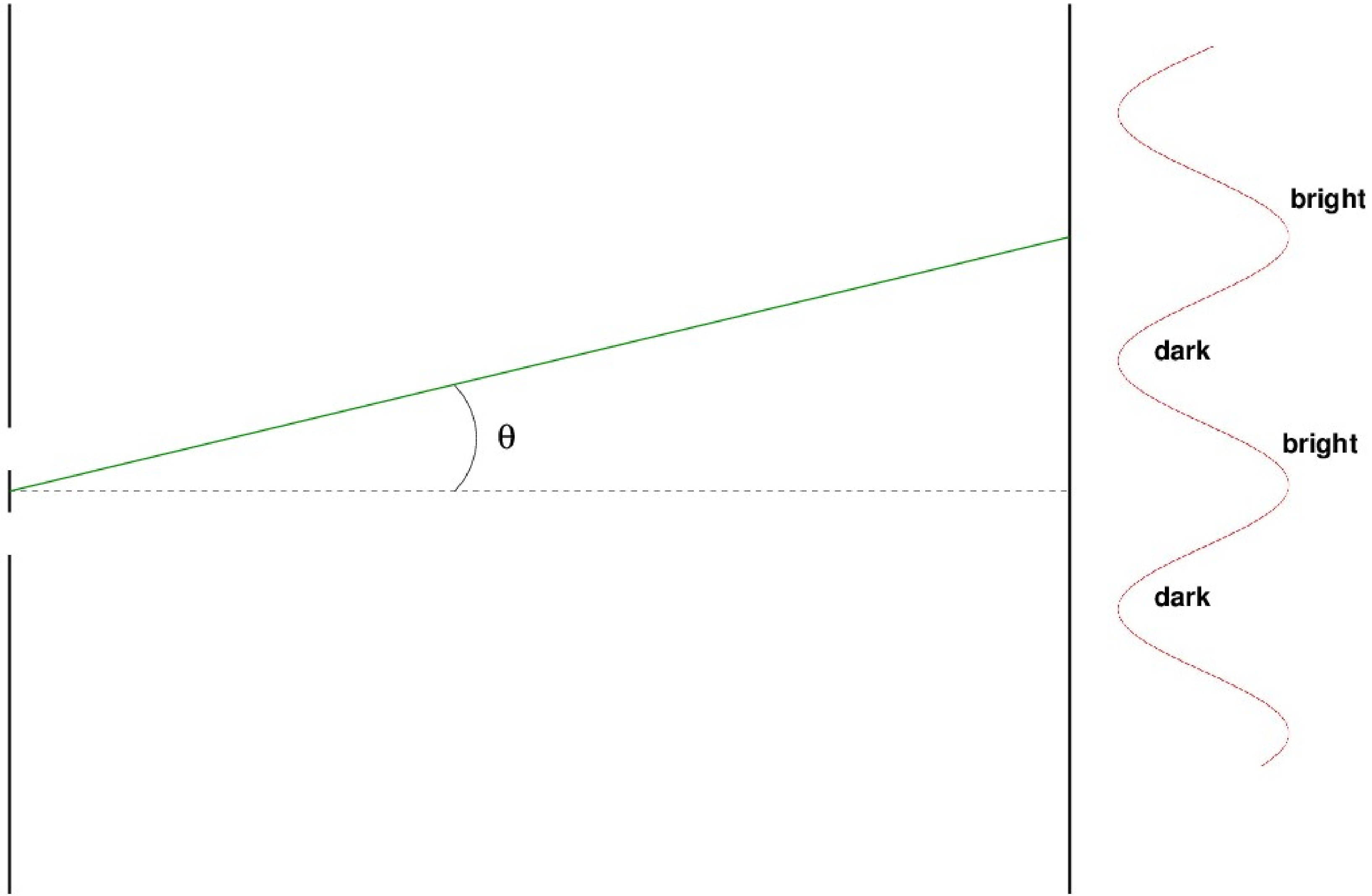
What is an interferometer? The signals arrive at the antennas at slightly different times, depending on the antenna’s location in the array. The signal from each antenna is combined with that from every other antenna in the correlator, and this delay is compensated for in software.

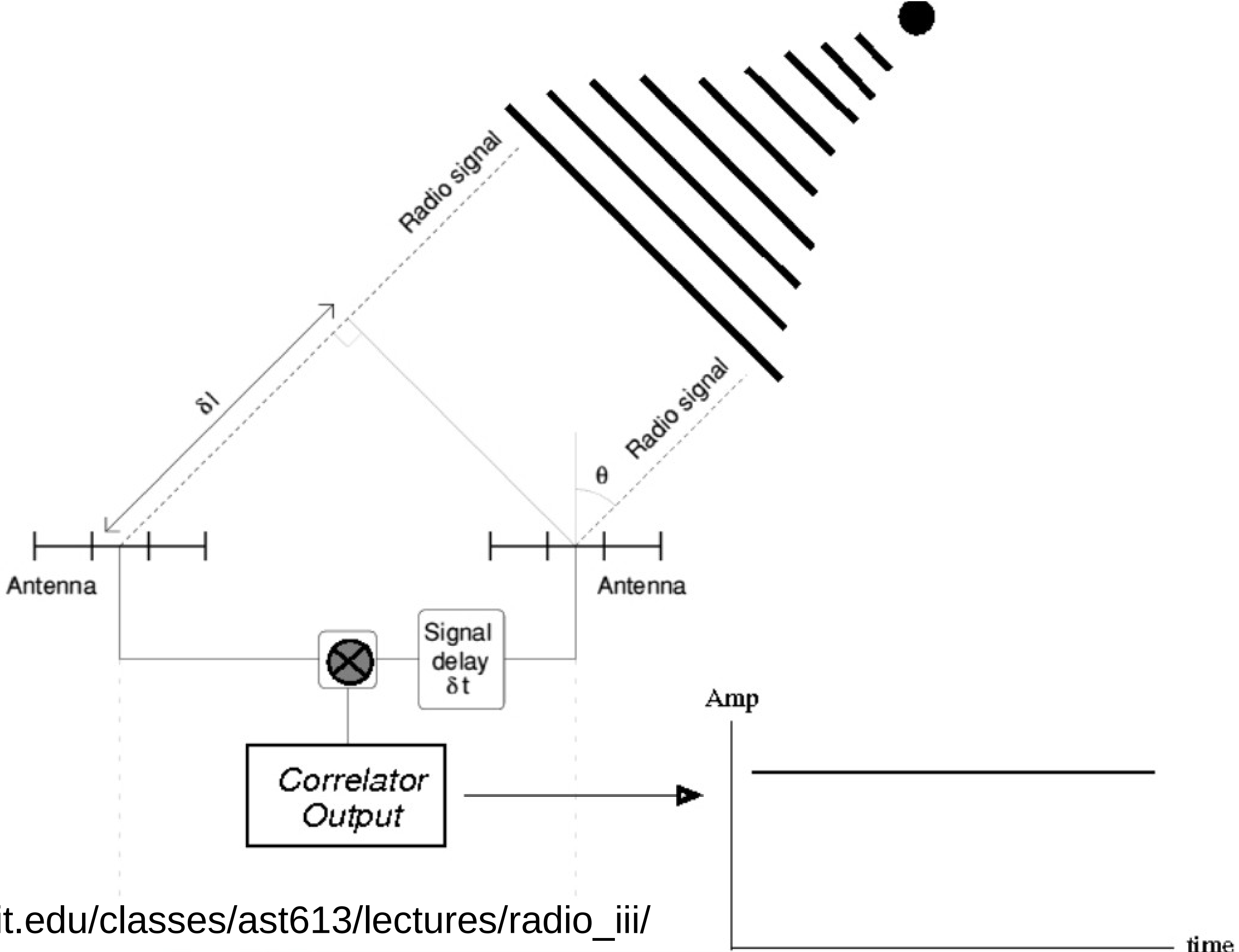
The signals from different points in the sky arrive at slightly different times at each antenna. This is the signal we are looking for.

An interferometer measures the interference pattern produced by multiple apertures, like a 2-slit experiment.



https://plus.maths.org/content/physics-minute-double-slit-experiment-0


θ
bright
dark
bright
dark



http://spiff.rit.edu/classes/ast613/lectures/radio_iii/

Each pair of antennas will generate a visibility - amplitude and phase.

More baselines means better amplitude and phase coverage, better image fidelity.

The goal of calibration is to correct these amplitudes and phases for atmospheric and instrumental effects

- The Amplitude calibrator sets absolute flux of all other sources in observation. The Phase calibrator corrects amplitude and phase vs. time.

- Choose a quasar that is:

  •Bright enough to get reasonable signal to noise in a few minutes

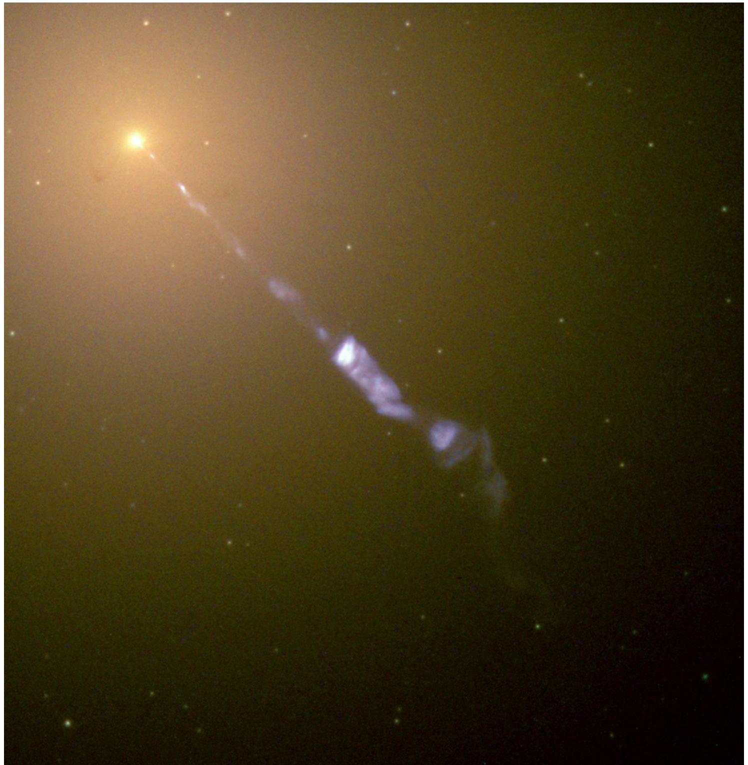
  •As close as possible to science target

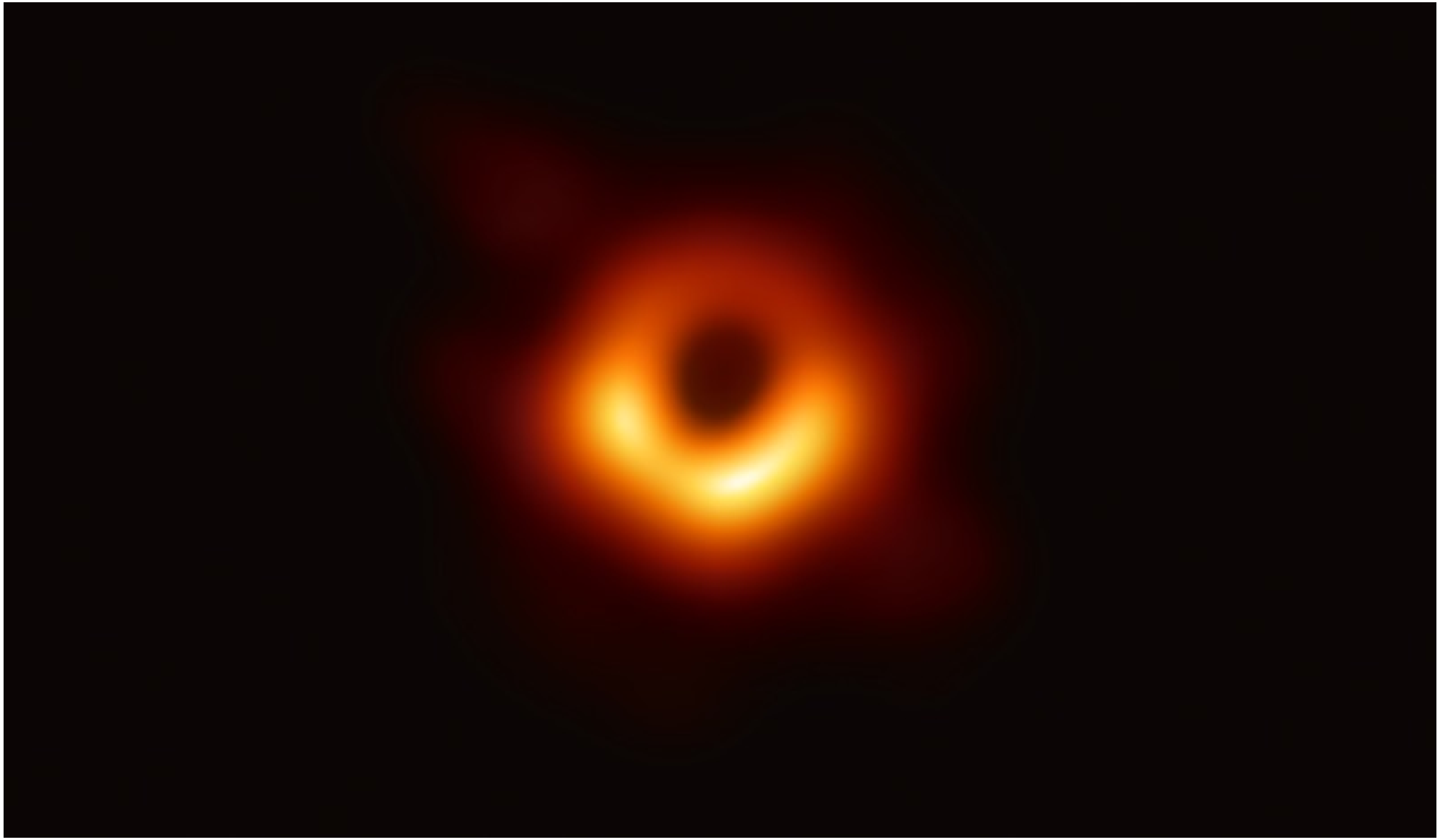
Stability: Since there are no connections between the radio dishes, the recordings made at each site have to be stable enough so that they can be compared later. If the signals cannot be precisely compared in time the phase measurements won’t be possible. The EHT uses atomic clocks to time-stamp the recorded data to enable these phase measurements.

Synchronization: To ensure recordings are made simultaneously the EHT requires synchronization at the level of a millionth of a second. This is achieved through use of Global Positioning Service (GPS) receivers located at each telescope.

M87 Black Hole

- $M=(6.5\pm0.7)\times10^9\ M_{solar}$ Black Hole
- Has a jet

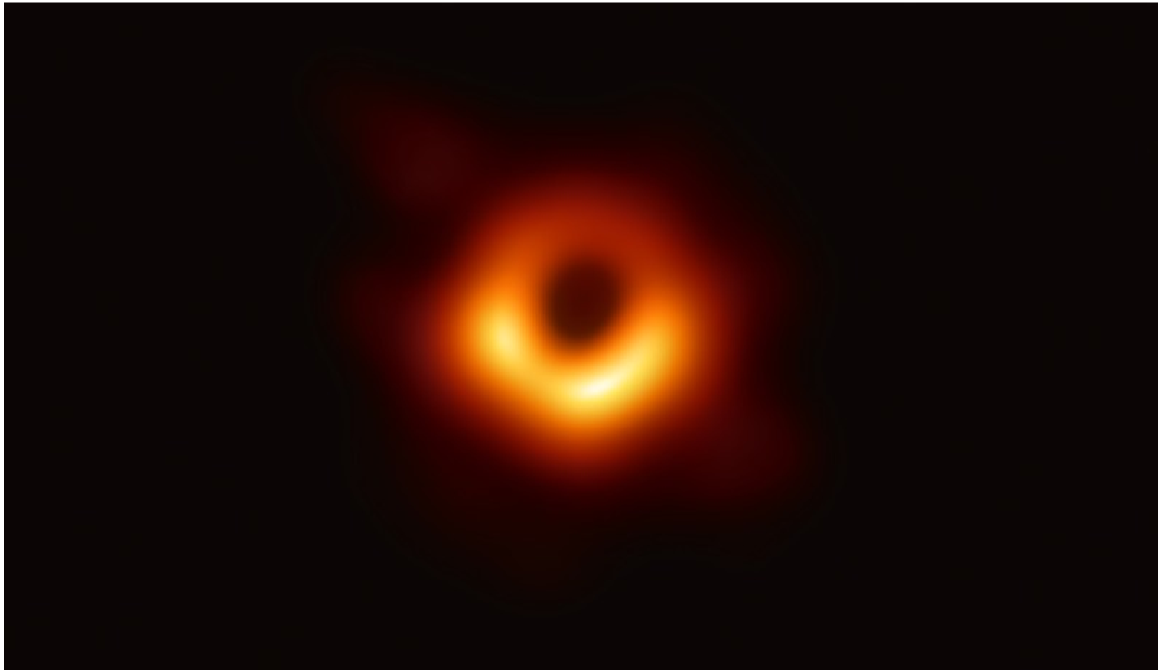




EHT image of center of M87

So What are We Seeing?

- We are looking at material being accreted by the Black Hole, plus the shadow of the Black Hole.



The Event Horizon

- So what is the Event Horizon?

  It is the boundary between the Black Hole and the rest of the universe where the escape velocity is just equal to the speed of light.

  For a non-rotating Black Hole this is the Schwarzschild radius

Schwarzschild Metric

- $ds^2 = -(1 - 2GM/c^2r)\,dt^2 + (1 - 2GM/c^2r)^{-1}\,dr^2 + r^2 d\Omega^2$

Space-time distance

Angular dependance

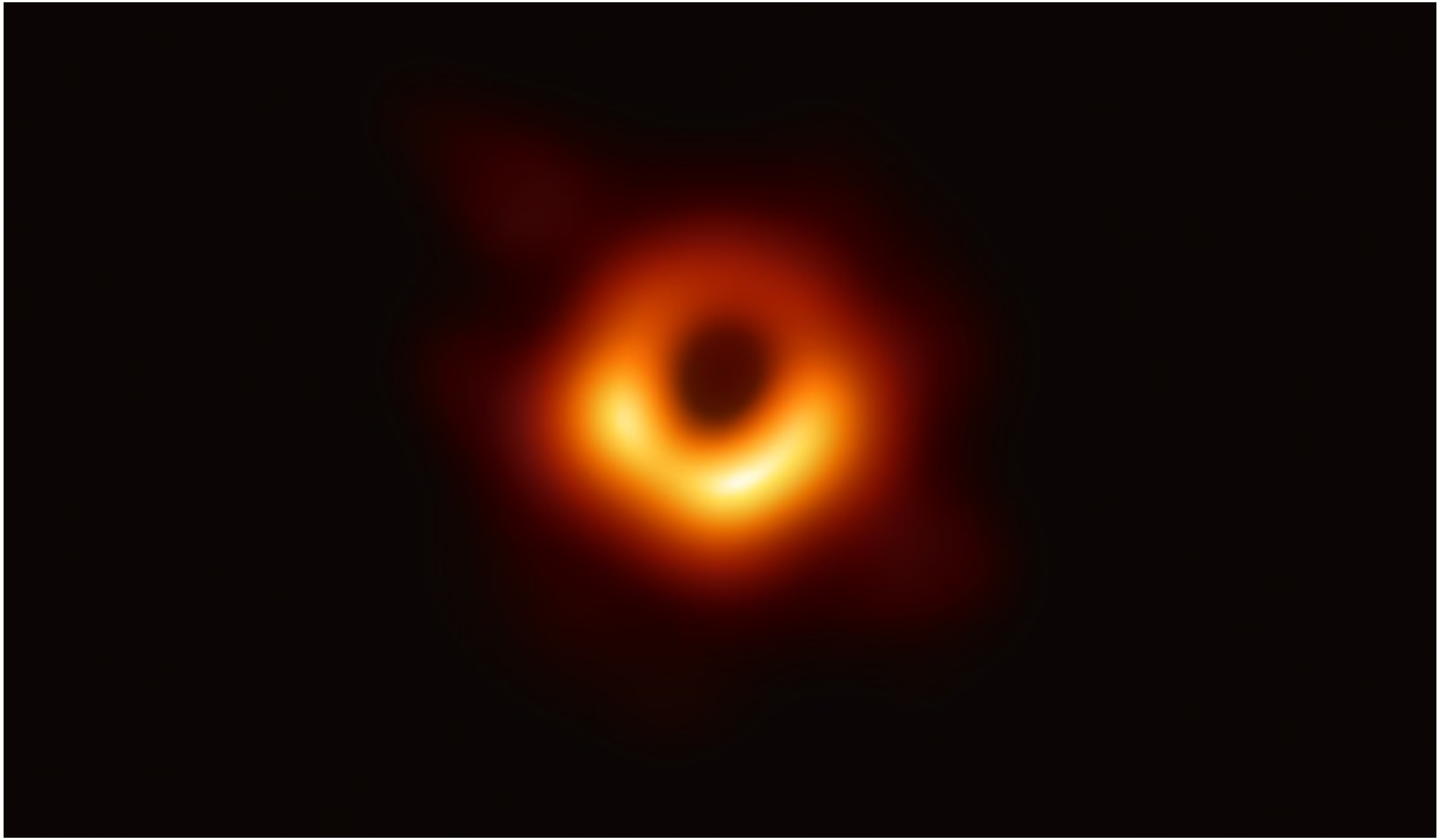
Goes to infinity at r=0,
this is the singularity

Goes to infinity at $r=2GM/c^2$,
This is the Schwarzschild radius

- The Schwarzschild metric describes the solution for a spherically symmetric object. It is bounded by the event horizon or Schwarzschild radius at $r=2GM/c^2$ where the solution goes to infinity. At this radius the escape velocity equals the speed of light, and it is not a solid surface but it is a mathematical surface

Accretion Disk

- When people think of a black hole they think of a giant vacuum cleaner that sucks up all nearby matter. While black holes do grow by swallowing matter it's difficult for it to fall into a black hole. Matter orbits the black hole and can orbit it indefinitely unless something else intervenes. This material forms a disk, and in that disk friction heats the disk and causes material to flow into the black hole. It is this friction which heats the disk and makes it emit light.
- Because black holes are so massive, but at the same time so compact, matter needs to give up a lot of energy to fall all the way in. As a result, some accretion disks around supermassive black holes are incredibly bright, and can outshine all the billions of stars in their host galaxy put together.



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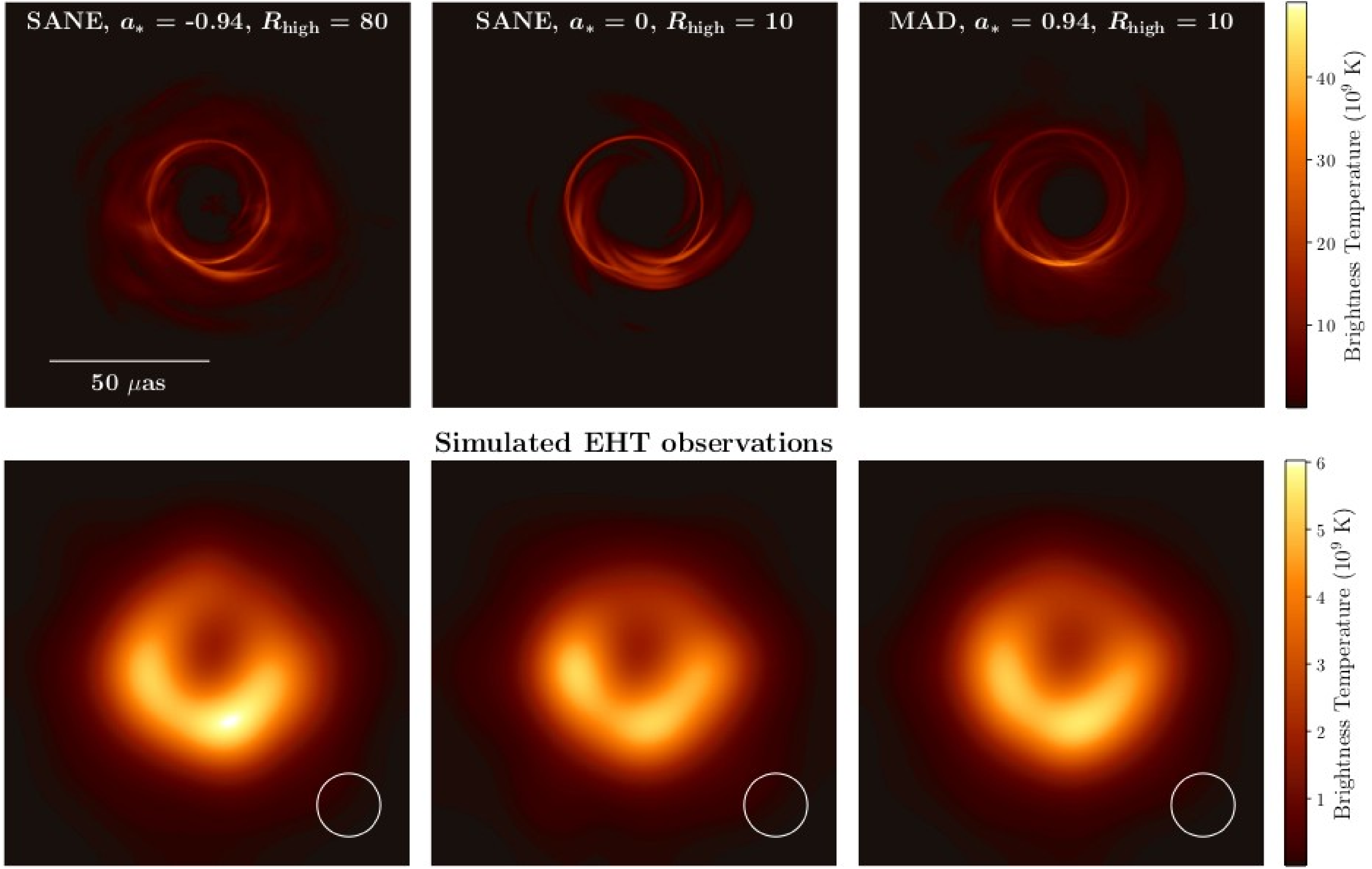


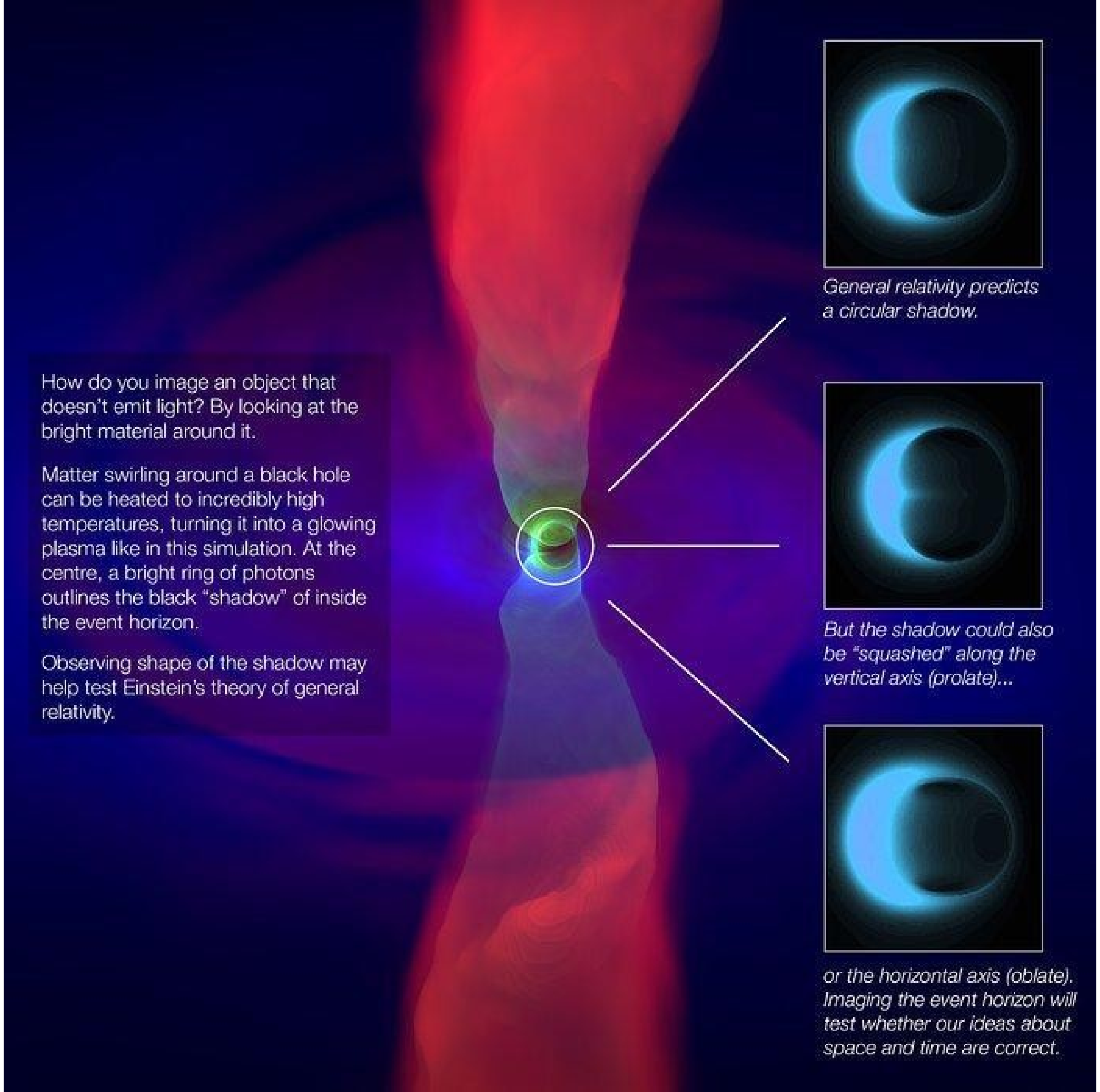
SANE, $a_* = -0.94$, $R_{\rm high} = 80$
SANE, $a_* = 0$, $R_{\rm high} = 10$
MAD, $a_* = 0.94$, $R_{\rm high} = 10$
50 μas
Brightness Temperature (10^9 K)
10
20
30
40
Simulated EHT observations
Brightness Temperature (10^9 K)
1
2
3
4
5
6

Shadow and Ring

- The shadow and ring are caused by a combination of light bending and photon capture at the event horizon.
- Corresponds to 40 micro-arcseconds for M87
- The size scale of the emission ring is set by the photon capture radius R_c. For a non-rotating Schwarzschild black hole, $R_c = 2.5\ R_{Schwarzschild}$. The factor of ~ 2.5 comes from gravitational lensing, which increases the radius of the photon ring with respect to the Schwarzschild radius

Modeling

- The appearance of M87*has been modeled successfully using GRMHD simulations, which describe a turbulent, hot, magnetized disk orbiting a Kerr black hole. They naturally produce a powerful jet and can explain the broadband spectral energy distribution observed in LLAGNs. At a wavelength of 1.3 mm, and as observed here, the simulations also predict a shadow and anasymmetric emission ring.


How do you image an object that doesn't emit light? By looking at the bright material around it.
Matter swirling around a black hole can be heated to incredibly high temperatures, turning it into a glowing plasma like in this simulation. At the centre, a bright ring of photons outlines the black "shadow" of inside the event horizon.
Observing shape of the shadow may help test Einstein's theory of general relativity.
General relativity predicts a circular shadow.
But the shadow could also be "squashed" along the vertical axis (prolate)...
or the horizontal axis (oblate). Imaging the event horizon will test whether our ideas about space and time are correct.

What’s Next

- Observations of Sgr A* the Black Hole in the center of our galaxy will be analyzed
- The Next Generation Event Horizon Telescope will be constructed utilizing new dish designs and locations to double the number of sites around the world