

Seeing the Unseeable

Technology Used for First Image of an
Galactic Black Hole




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First Image of a Shadow of a Galactic Black Hole

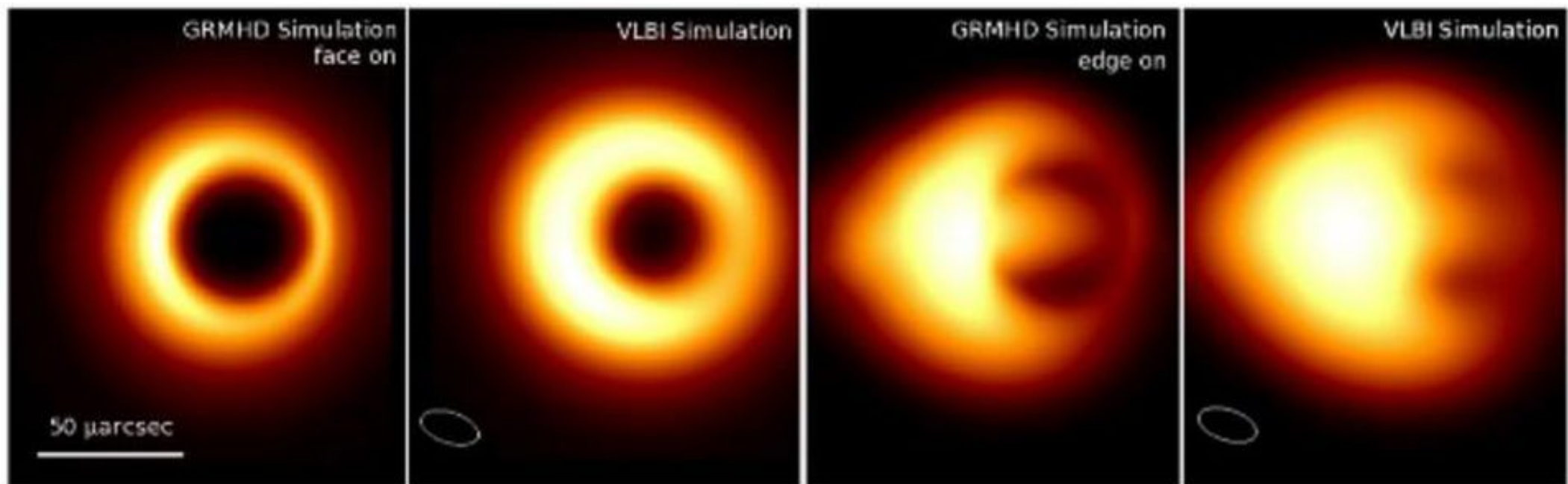
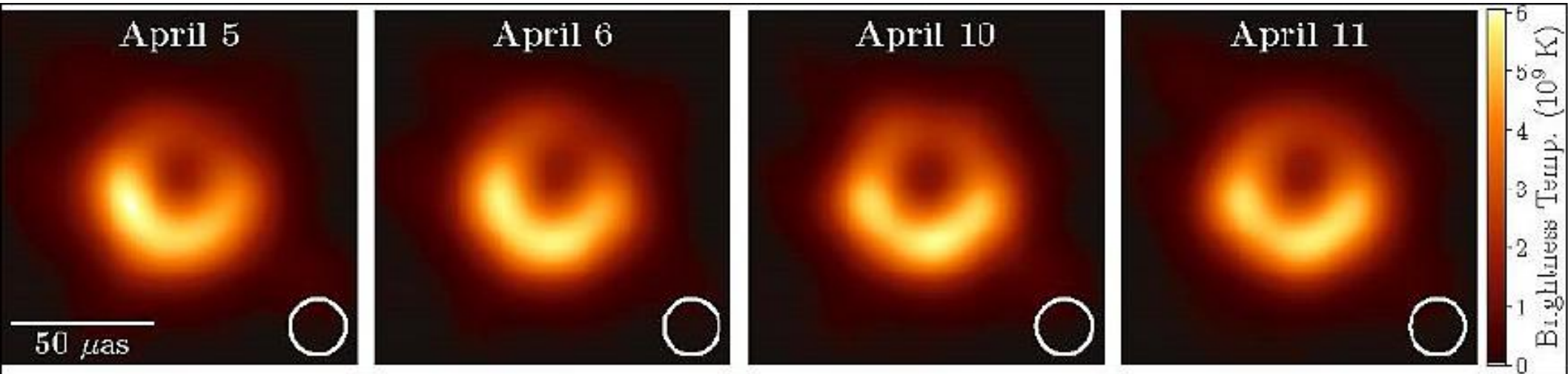
- M87* Images and group of 6 papers released in April 2019
- Image provide by Event Horizon Telescope
 - VLBI Very Long Baseline Interferometry
- Consistent with a $6.5 \pm 0.7 \times 10^9 M_{\odot}$
 - Kerr (rotating) Black Hole
- Bright lower portion of image is dopler-shifted moving towards us darker portion moving away

M87 in Virgo Cluster of Galaxies

The image shows the galaxy M87, also known as Bode's Galaxy, in the Virgo Cluster. It is a large, elliptical galaxy with a bright central core. A prominent, multi-colored jet of relativistic electrons extends from the core, appearing as a bright blue and purple streak against the dark background of space. The jet has a complex, filamentary structure. The background is filled with numerous other stars and galaxies, typical of a galaxy cluster.

- Giant Elliptical Galaxy
- Spiral jet from relativistic electrons
- HST 1998
- 16 Mpc distant

Four Dates Were Recorded of M87*



Galactic Black Holes

- Black Holes are compact objects that occur when neutron degeneracy fails to support the object & collapses to a point
- Three+ types are recognized in the Universe Zoo
 - Stellar BH from collapsed stars during supernovae
 - 3-100 M_{\odot}
 - Intermediate BH from stellar BH mergers (GWs detected by LIGO)
 - 100-10,000 M_{\odot}
 - **Super Massive (Galactic) BH at the center of galaxies**
 - $> 10^5 M_{\odot}$
 - Most galaxies have SMBH and likely come from GBH mergers
 - Primordial BH - Theoretical
 - $10^{-8} - 10^5 M_{\odot}$

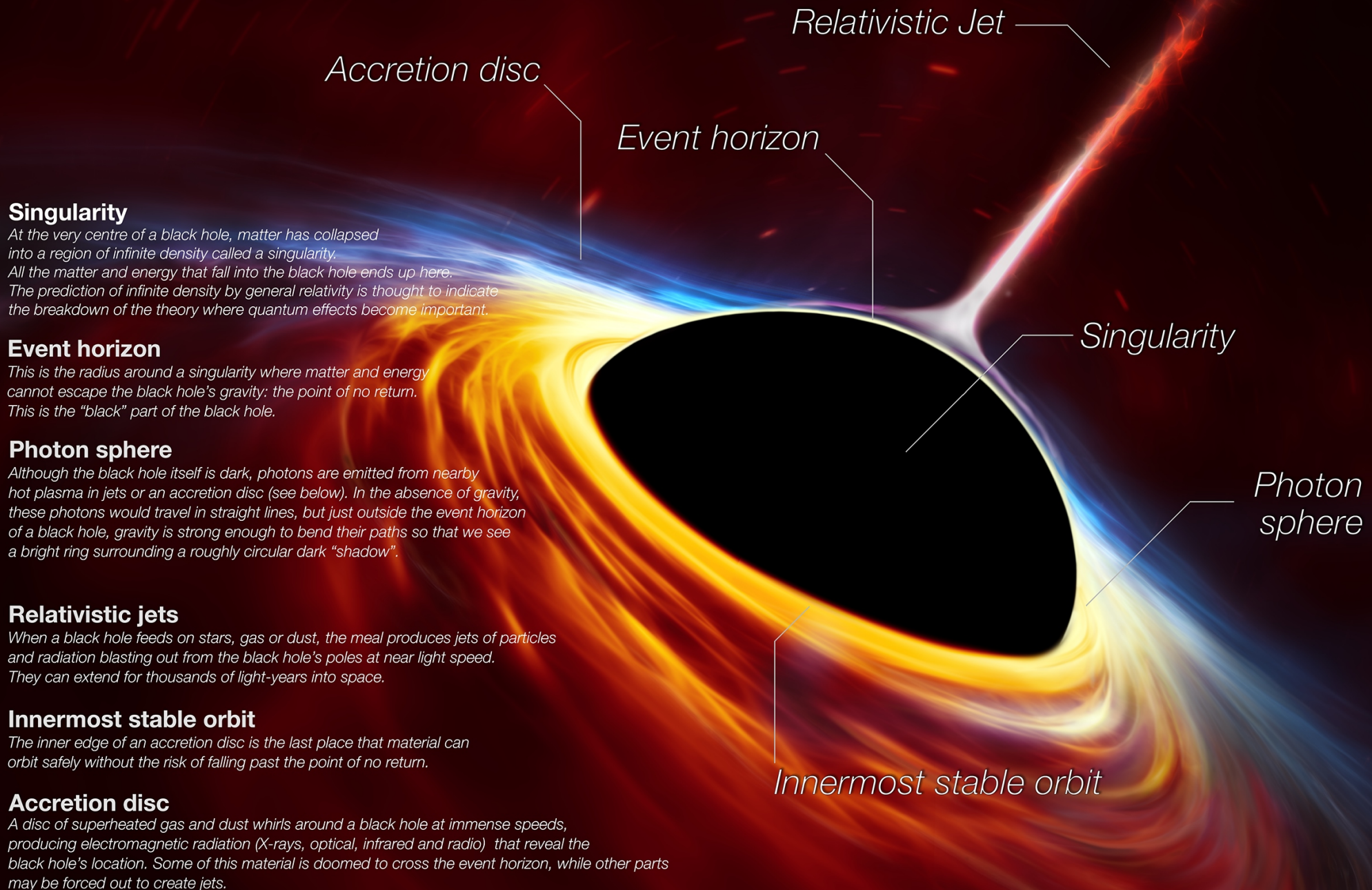
When Was the Black Hole Concept First Described?

- Multiple Choice – pick a century
 - A) 17th
 - B) 18th
 - C) 19th
 - D) 20th
 - E) 21st

So Who Thought of a BH first?

- Rev John Michell (1724-1793) (No image available)
 - Queen's College, Oxford (1748)
 - Mathematics (4th Wrangler)
 - Polymath - Most famous for contributions to Geology
 - Michell's Paper 1783 in Philosophical Transactions of the Royal Society of London (title too long to print)
 - No light would escape if $> 500 \times M_{\odot}$
 - Based on Herchel (1782) and Newton's 39th proposition in "Principia"
 - Problems: light *corpuscles* attracted by gravity & Density of object same as our Sun
 - Laplace provided a more mathematical proof in 1799

Schematic of a Black Hole



Singularity

At the very centre of a black hole, matter has collapsed into a region of infinite density called a singularity.

All the matter and energy that fall into the black hole ends up here.

The prediction of infinite density by general relativity is thought to indicate the breakdown of the theory where quantum effects become important.

Event horizon

This is the radius around a singularity where matter and energy cannot escape the black hole's gravity: the point of no return.

This is the "black" part of the black hole.

Photon sphere

Although the black hole itself is dark, photons are emitted from nearby hot plasma in jets or an accretion disc (see below). In the absence of gravity, these photons would travel in straight lines, but just outside the event horizon of a black hole, gravity is strong enough to bend their paths so that we see a bright ring surrounding a roughly circular dark "shadow".

Relativistic jets

When a black hole feeds on stars, gas or dust, the meal produces jets of particles and radiation blasting out from the black hole's poles at near light speed.

They can extend for thousands of light-years into space.

Innermost stable orbit

The inner edge of an accretion disc is the last place that material can orbit safely without the risk of falling past the point of no return.

Accretion disc

A disc of superheated gas and dust whirls around a black hole at immense speeds, producing electromagnetic radiation (X-rays, optical, infrared and radio) that reveal the black hole's location. Some of this material is doomed to cross the event horizon, while other parts may be forced out to create jets.

The Ultimate Escape Velocity

The Schwartzchild Radius

- We learned in Ch. 2 that the escape velocity of any mass is:

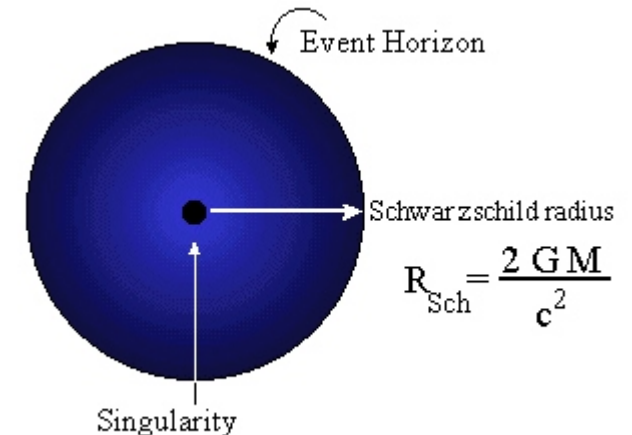
$$v = \sqrt{(2GM/r)}$$
$$r = 2GM/v^2$$

(notice that the radius is directly proportional to mass)

- Substituting the mass of the Sun and speed of light

$$r = \sqrt{((2(6.67 \times 10^{-11} \text{ N m}^2/\text{kg}^2)(2 \times 10^{30} \text{ kg}))/((3 \times 10^8 \text{ m/s})^2))}$$
$$r = 2964 \text{ m}$$
$$r = 3 \text{ km}$$

- The Event Horizon is just a mathematical boundary where nothing (even light) can escape



Simple Schematic of a Vacuum Black Hole

M87* Event Horizon

- Radius using solar masses for M87* we get:

$$M_{M87*} = 6.5 \times 10^9 M_{\odot}$$

$$R_{M87*} = 3 \text{ km} \times M_{M87*} = (3 \text{ km}) 6.5 \times 10^9 M_{\odot}$$

$$R_{M87*} = 19.5 \times 10^9 \text{ km}$$

- Converting to Astronomical Units

$$R_{M87*} = 19.5 \times 10^9 \text{ km} / 1.5 \times 10^8 \text{ km/AU}$$

$$R_{M87*} = 130 \text{ AU}$$

- Comparable to size of Solar System

Challenges

- Angular Resolution
 - 10 μ asec
- Weather
- Atmospheric Absorption and Extinction
- Extremely high frequencies 230 GHz to 345 GHz
- Timing for correlation
- Massive Quantities of Data ~5000 TB

Angular Resolution

- Angle of Schwarzschild radius for Sgr A* is 10 microarcseconds
 - M87* is slightly smaller
- However shadow of M87* is ~40 μas
- EHT Approximate Angular Resolution 10.7 μas baseline at 230 GHz

$$\theta = \frac{\lambda}{\Delta} = \frac{1.3 \text{ mm}}{10,700 \text{ km}} = (1.21 \times 10^{-10} \text{ rad})(2.06 \times 10^{11} \mu\text{asec}/\text{rad}) = 25 \mu\text{asec}$$

- Image processing reduces this to about 10 μasec

Event Horizon Telescope (EHT)

A Global Network of Radio Telescopes

2018 Observatories



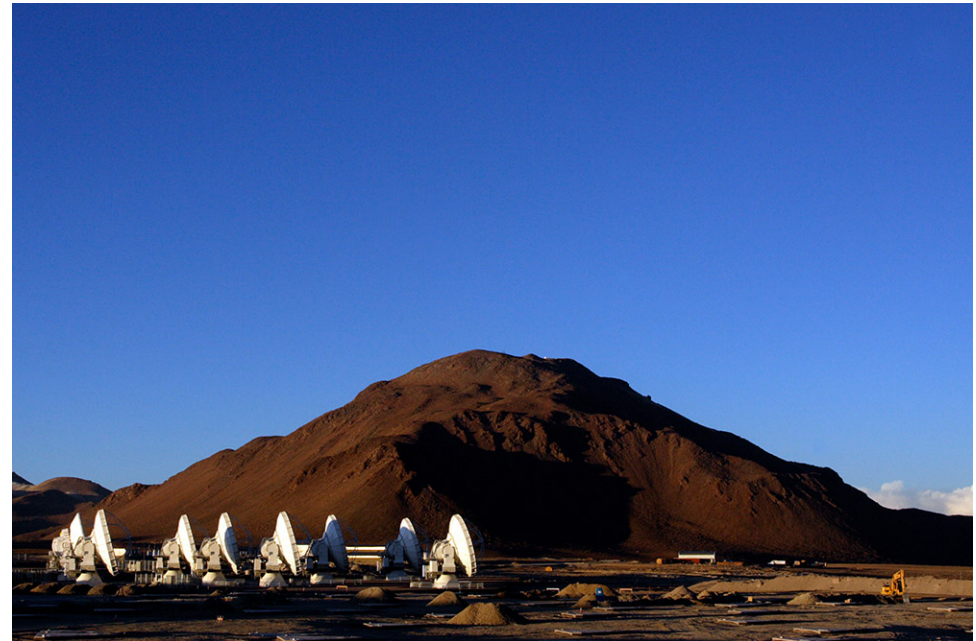
- ALMA**  Atacama Large Millimeter/submillimeter Array
CHAJNANTOR PLATEAU, CHILE
- APEX**  Atacama Pathfinder EXperiment
CHAJNANTOR PLATEAU, CHILE
- 30-M**  IRAM 30-M Telescope
PICO VELETA, SPAIN
- JCMT**  James Clerk Maxwell Telescope
MAUNAKEA, HAWAII
- LMT**  Large Millimeter Telescope
SIERRA NEGRA, 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
- Kitt Peak**  Kitt Peak 12-meter Telescope
KITT PEAK, ARIZONA, USA
- NOEMA**  NOEMA Observatory
PLATEAU DE BURE, FRANCE

Observing
in 2020



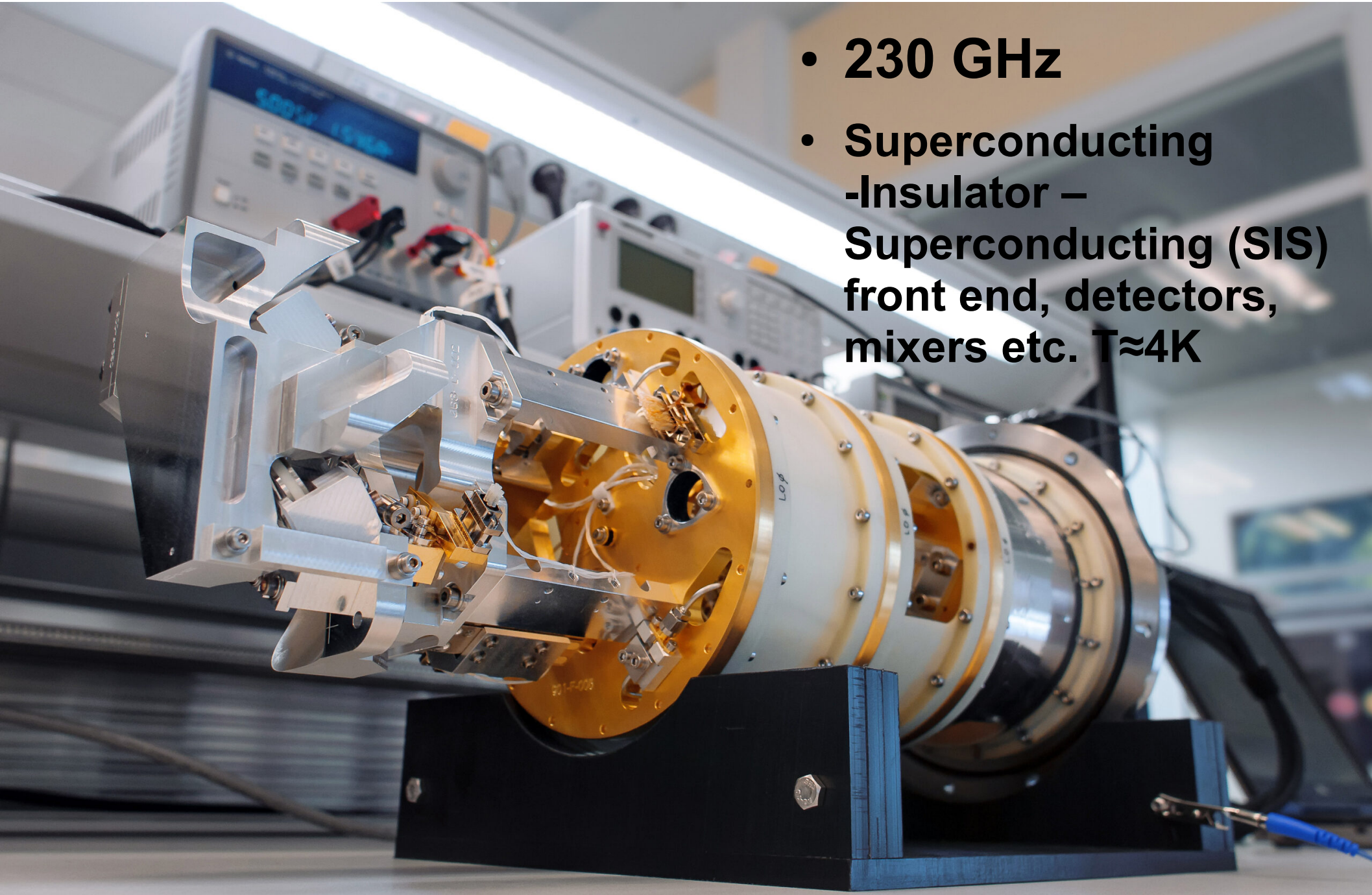
ALMA Site

- Atacama Large Millimeter/Submillimeter Array
 - 5000 m altitude
 - Chile
 - 66 Antennas
 - 8.6 to 0.32 millimeters (31 to 1000 GHz)
 - \$1.5 Billion
- Largest by far of the EHT observatories
- Superconductor – insulator – Superconductor technology in receivers



ALMA Receiver Front End

- 230 GHz
- Superconducting
-Insulator –
Superconducting (SIS)
front end, detectors,
mixers etc. $T \approx 4\text{K}$



Data Correlator

- “ROACH2 DBE” converts baseband data at 16 Gs/s
 - Expand to $4 \times 6 = 64$ Gs/s
- Recorded and distributed to 32 Hard disks
 - ~5000 TB of data
- Disks transported for correlation to
 - Max Planck Institute in Bonn, Germany
 - Haystack Observatory in Westford, Massachusetts



- Time stamped data
 - Hydrogen Masers for short scale stability
 - GPS disciplined for long term stability

South Pole Antenna



New Observations of “Our” BH

- Sgr A* SMBH at Milky Way Center
- Observations at 86 GHz

