Seeing the Unseeable

Technology Used for First Image of an Galactic Black Hole

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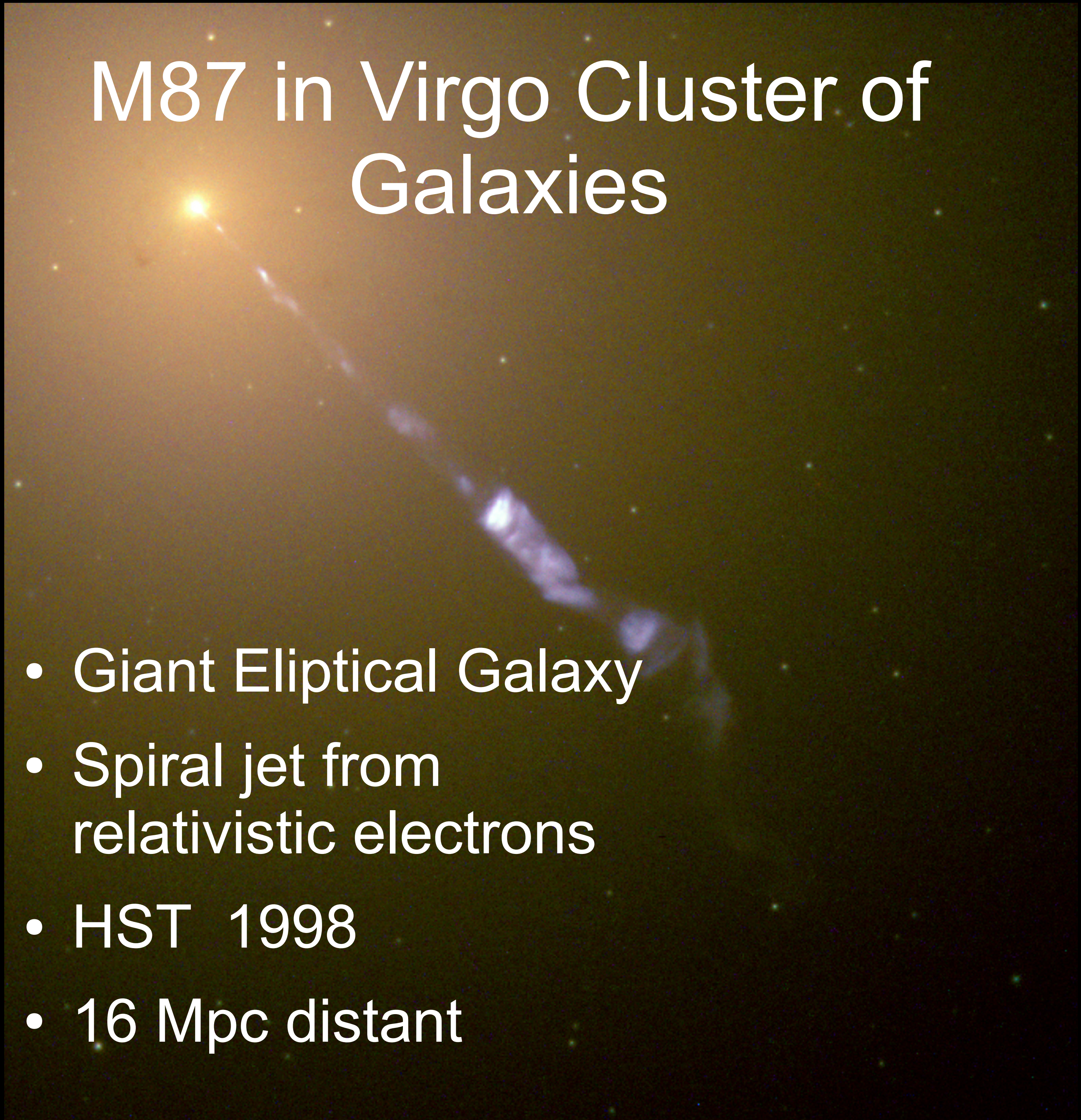
Event Horizon Telescope Collaboration

First Image of a Shadow of a Galactic Black Hole

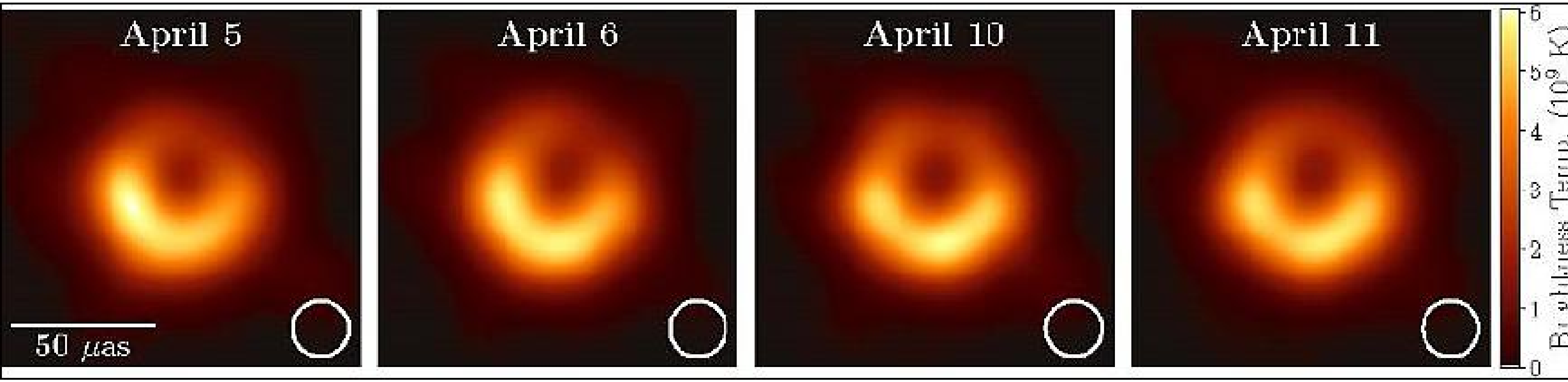
- M87* Images and group of 6 papers released in April 2019
- Image provide by Event Horizon Telescope
  - VLBI Very Long Baseline Interferometry
- Consistent with a 6.5 +/- 0.7 x 10^9 $M_\odot$
  - Kerr (rotating) Black Hole
- Bright lower portion of image is dopler-shifted moving towards us darker portion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

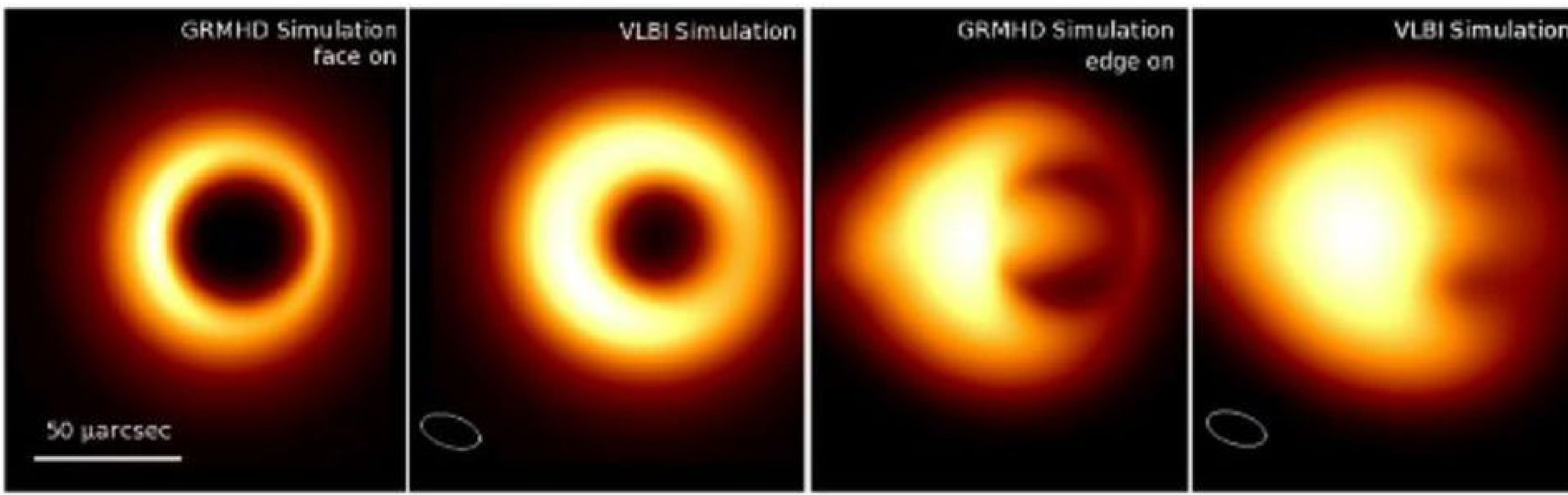
M87 in Virgo Cluster of Galaxies



- Giant Eliptical 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 than 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
    - $10^{-8} – 10^5$ $M_{\odot}$

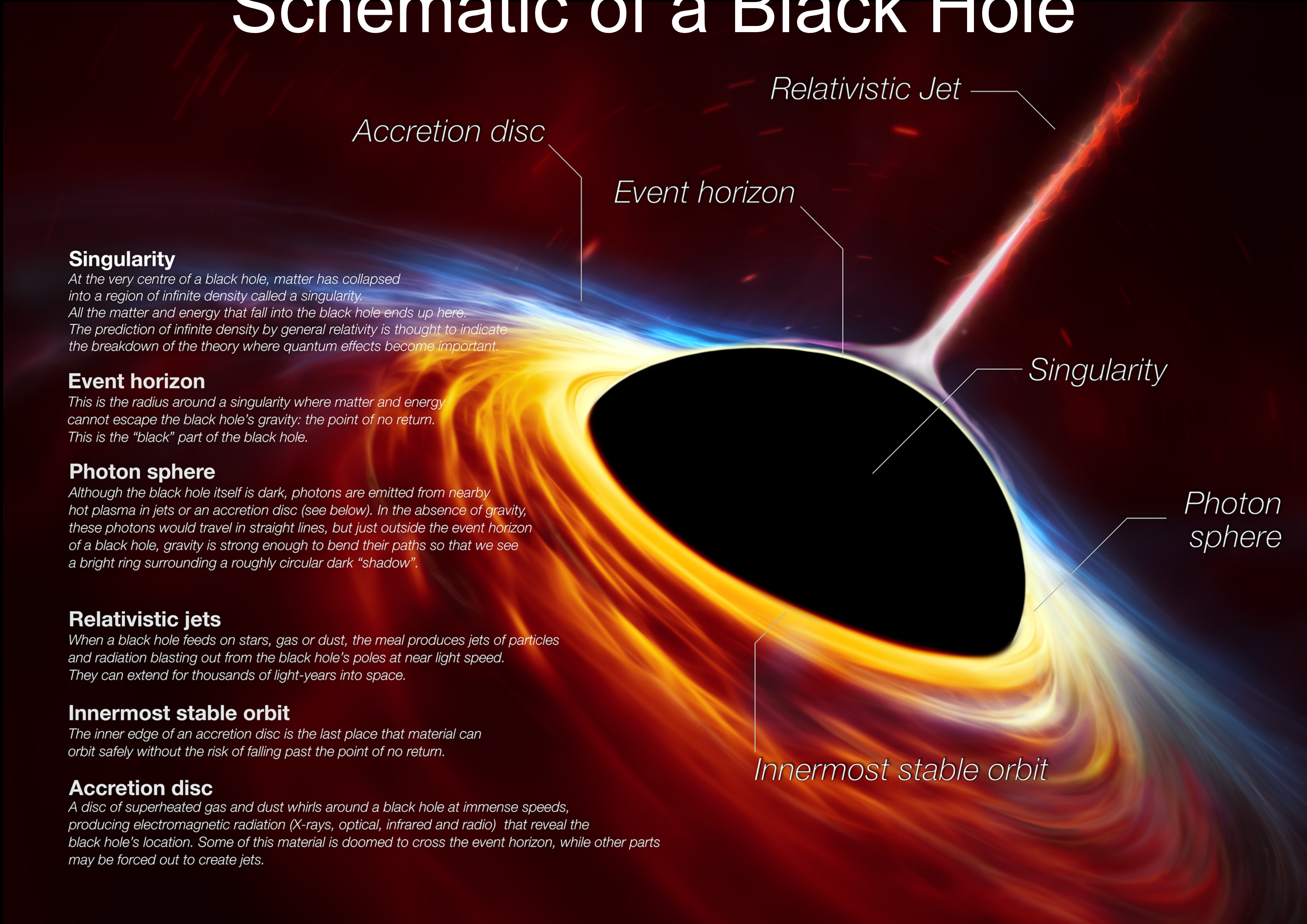
When Was the Black Hole Concept First Described?

- 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 x $M_\odot$
  - 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

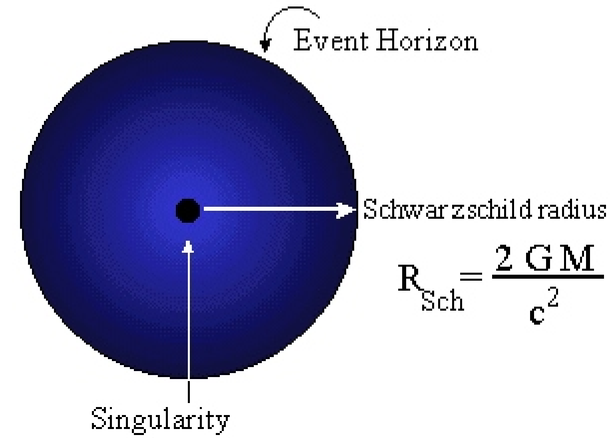


The Ultimate Escape Velocity The Schwartzchild Radius

- 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)



Simple Schematic of a Vacuum Black Hole

- Substituting the mass of the Sun and speed of light

$$r = \sqrt{((2(6.67x10^{-11}\,N\,m^2/kg^2)(2x10^{30}\,kg))/(3x10^8\,m/s)^2)}$$
$$r = 2964\,m$$
$$r \;\; = 3\,km$$

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

M87* Event Horizon

- Radius using solar masses for M87* we get:

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

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

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

- Converting to Astronomical Units

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

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

- Comparable to size of Solar System

Challenges

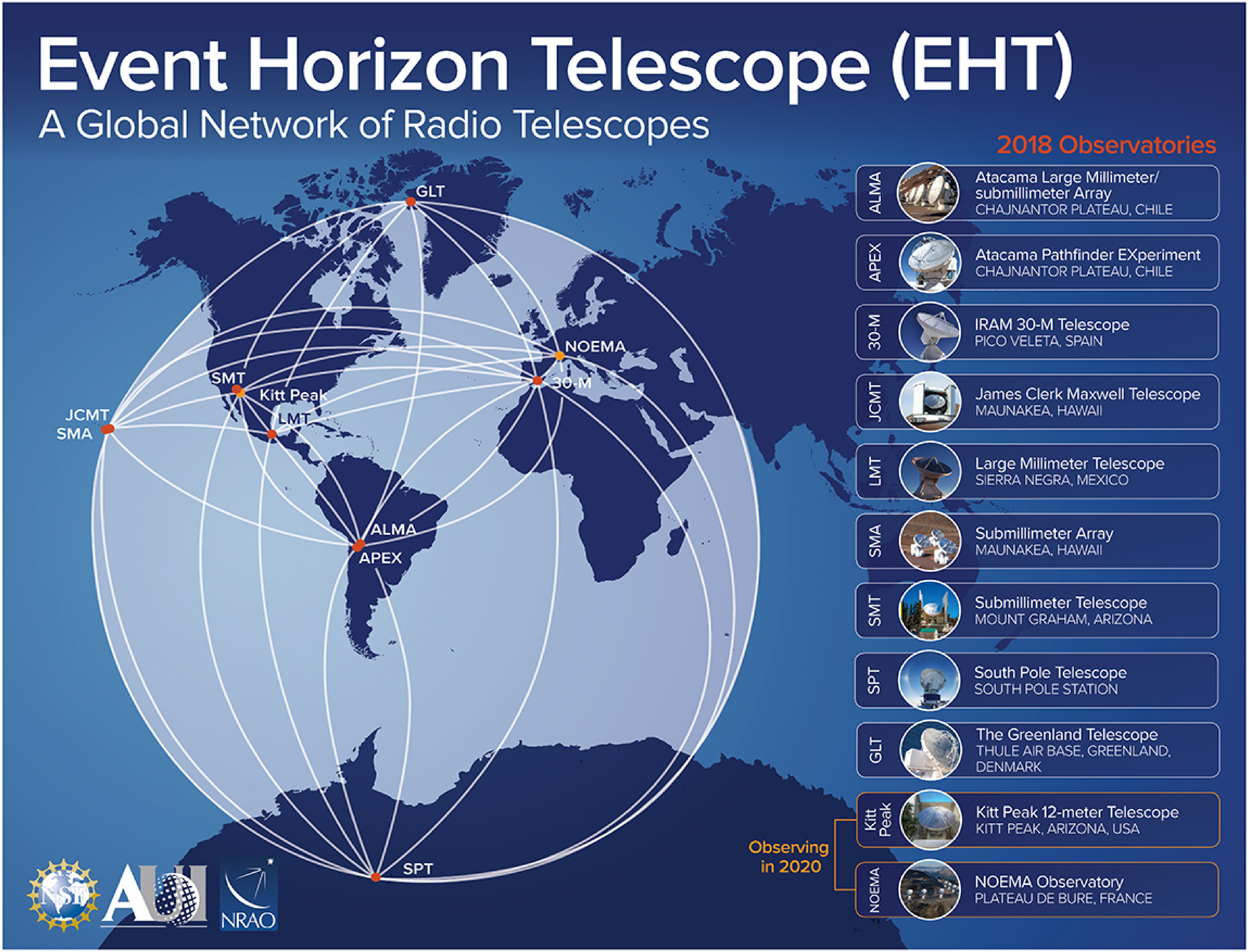
- Angular Resolution
  - 10 μasec
- Weather
- Atmospheric Absorption and Extinction
- Extremely high frequencies 230 GHz to 345 GHz
- Timing for correlation
- Massive Quantities of Data ~5000 TB

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 km baseline at 230 GHz

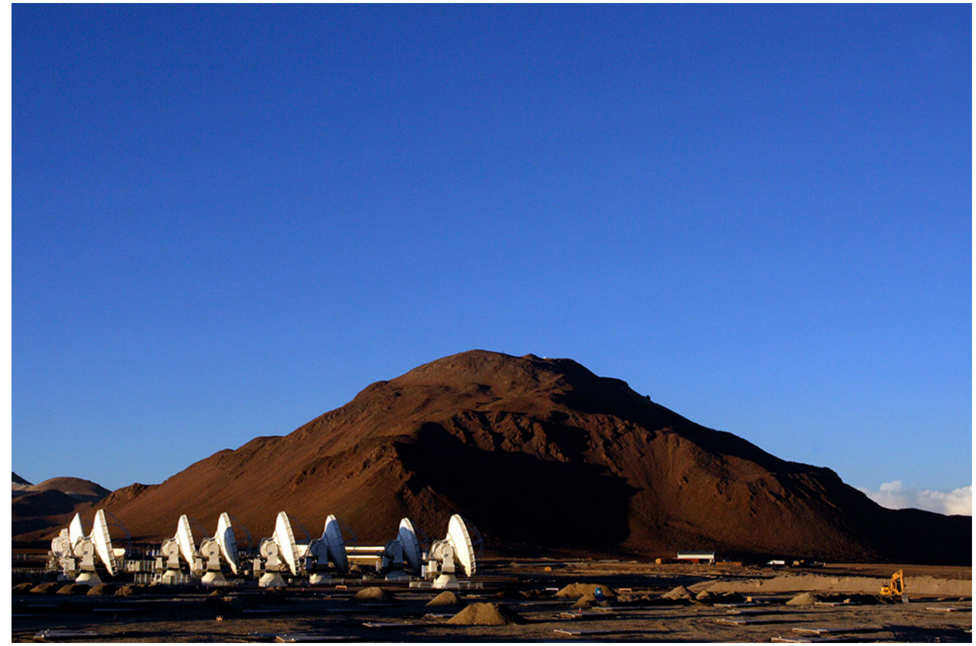
$$\theta = \frac{\lambda}{\Delta} = \frac{1.3\,\mathrm{mm}}{10,700\,\mathrm{km}} = (1.21\times 10^{-10}\,\mathrm{rad})(2.06\times 10^{11}\,{}^{\mu\mathrm{asec}}\!/\!_{\mathrm{rad}}) = 25\mu\mathrm{asec}$$

- Image processing reduces this to about 10 μasec

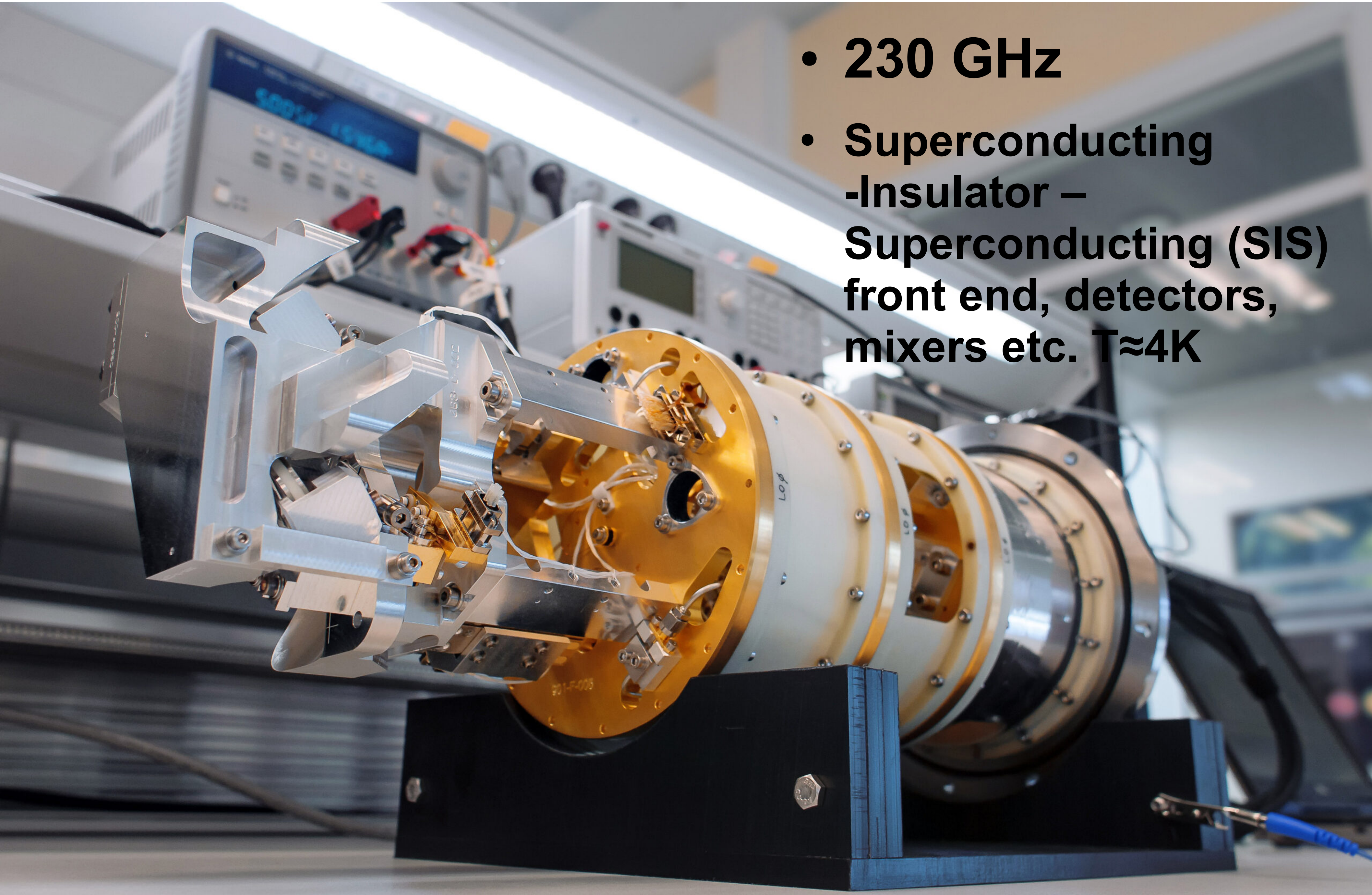

Event Horizon Telescope (EHT)
A Global Network of Radio Telescopes
GLT
NOEMA
30-M
SMT
Kitt Peak
LMT
JCMT
SMA
ALMA
APEX
SPT
NRAO
2018 Observatories
ALMA
Atacama Large Millimeter/ submillimeter Array
CHAJNANTOR PLATEAU, CHILE
APEX
Atacama Pathfinder EXperiment
CHAJNANTOR PLATEAU, CHILE
30-M
IRAM 30-M Telescope
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

ALMA Site

- Atacama Large Millimeter/Submillimeter Array
  - 5000 m altitiude
  - 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≈4K**

Data Correlator

- “ROACH2 DBE” converts baseband data at 16 Gs/s
  - Expand to 4 x 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