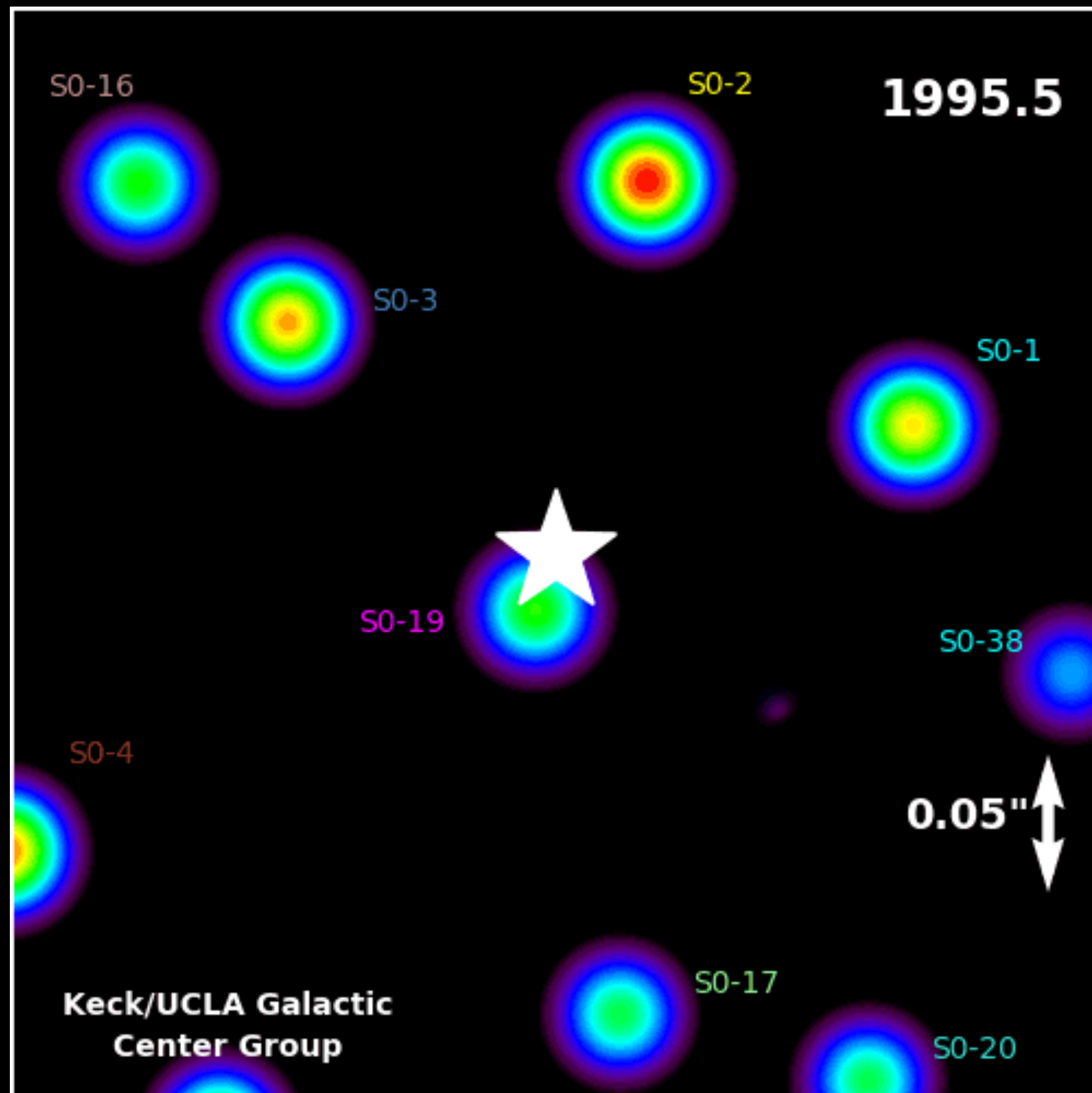
There are super massive black holes at the centers of most massive galaxies

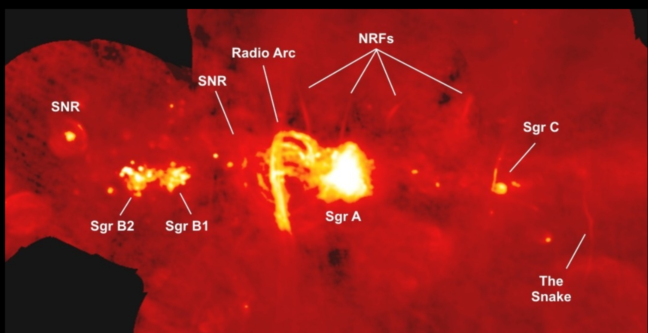
- There is one at the center of our Milky Way!
- ~ 4 million x mass of the sun
- This is one of the EHT targets



There are super massive black holes (SMBHs) at the centers of most massive galaxies

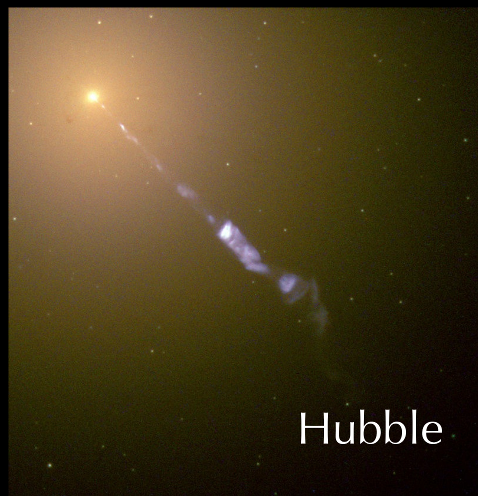
Primary EHT targets

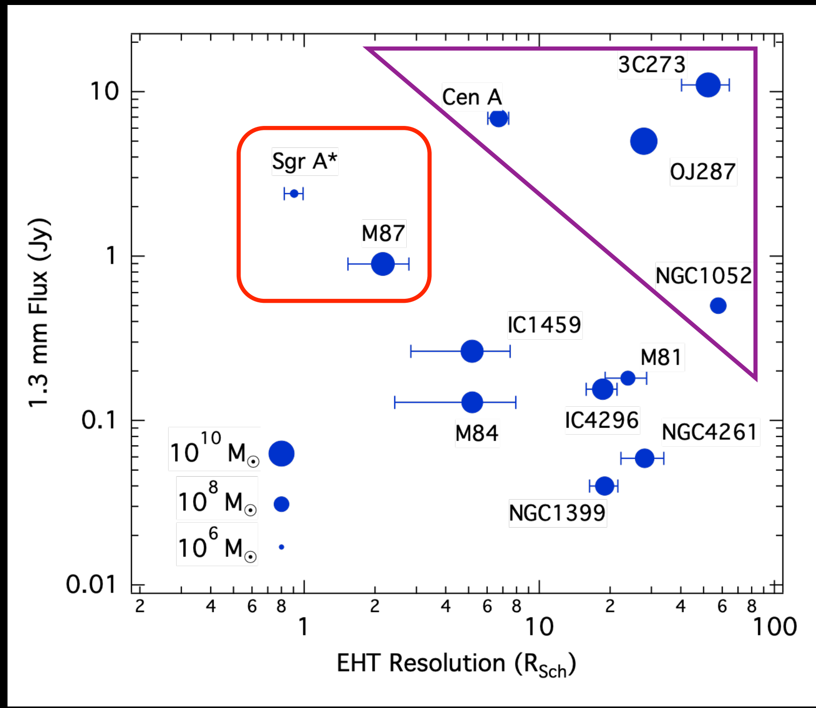
Sgr A*



VLA/GBT
NRAO/AUI/NSF Yusef-Zadeh, et.al.

M87





Psaltis 2018

Mass $\cong 4.3 \times 10^6 M_\odot$
Distance $\cong$ 8.3 kpc
Shadow $\cong 50\mu$arcsec

Mass $\cong 6.5 \times 10^9 M_\odot$
Distance $\cong$ 16.4 Mpc
Shadow $\cong 40\mu$arcsec

There is also a SMBH in the center of M31 (5-23 e7 x mass of the Sun)

Measuring the Mass of the SMBH in the center of the Milky Way

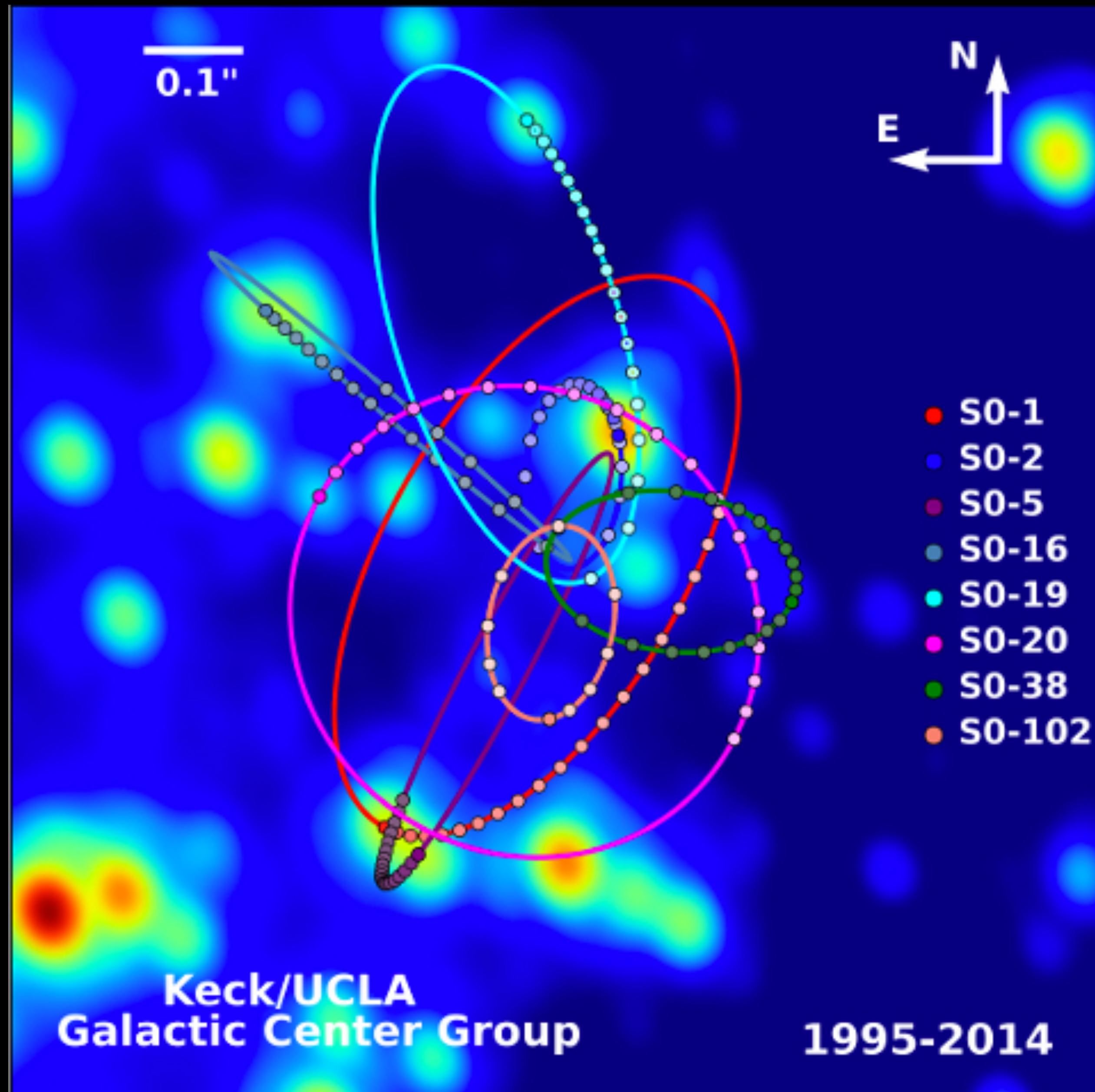
Kepler's 3rd Law

$$M = \frac{4\pi^2 a^3}{GP^2}$$

$a = r_{peri} / (1-e)$

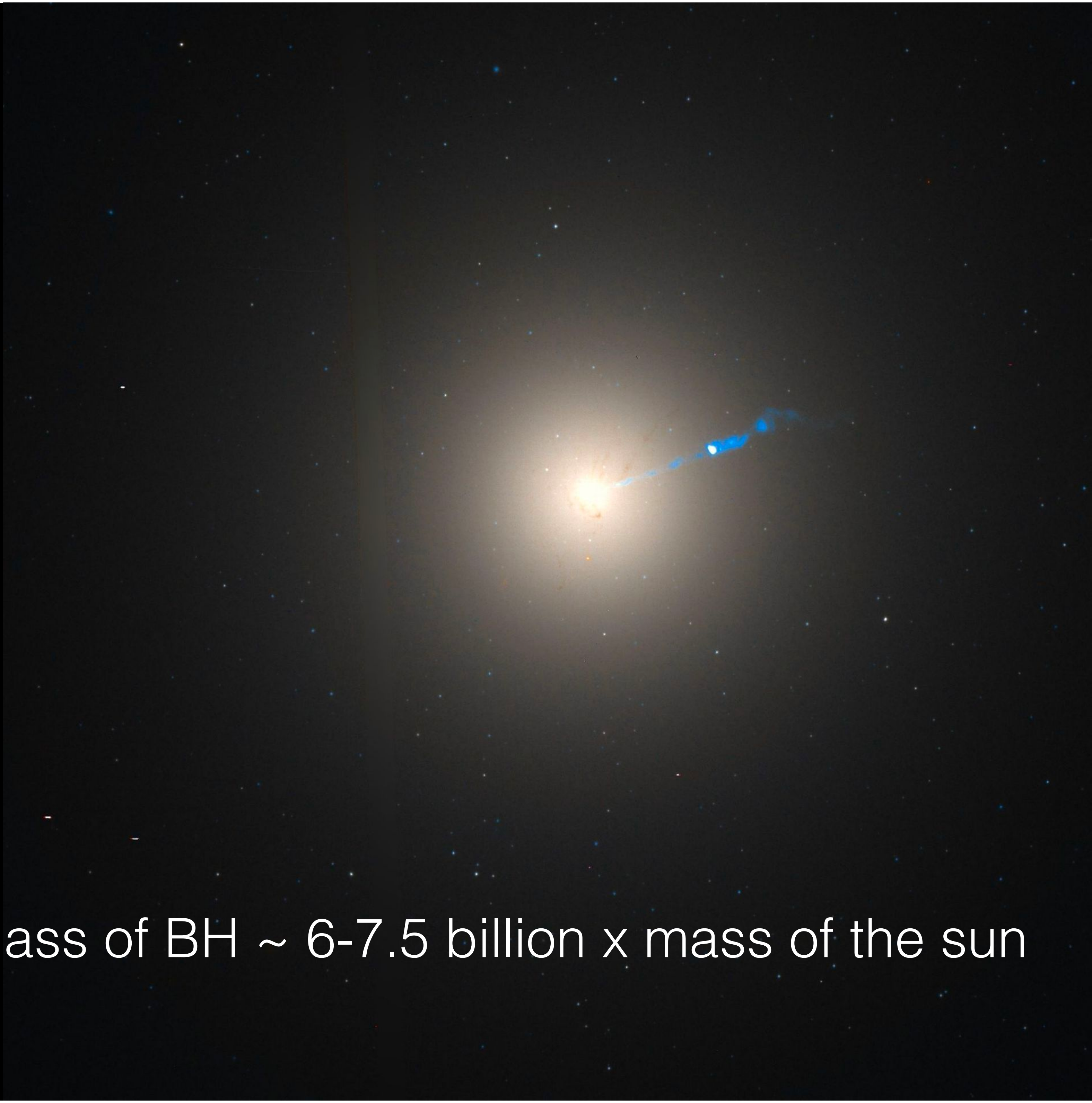
S0-2:
$r_{peri} = 120$ AU
$e = 0.8763$
$P = 15.2$ years

M ~ 4e6 Msun



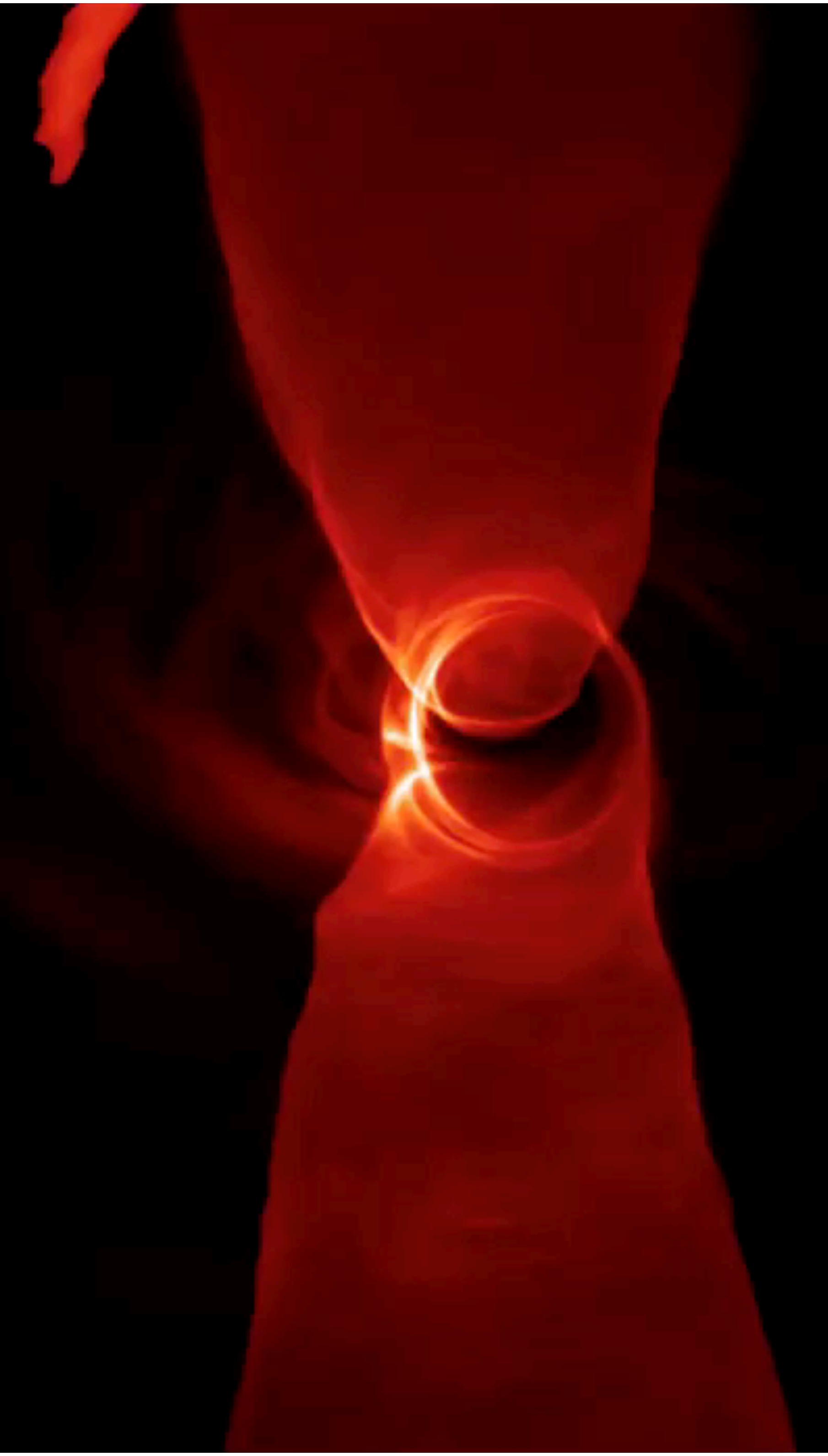
M87

16.4 Mpc away



- Mass of BH ~ 6-7.5 billion x mass of the sun

X-ray and Radio Image of the region surrounding the SMBH

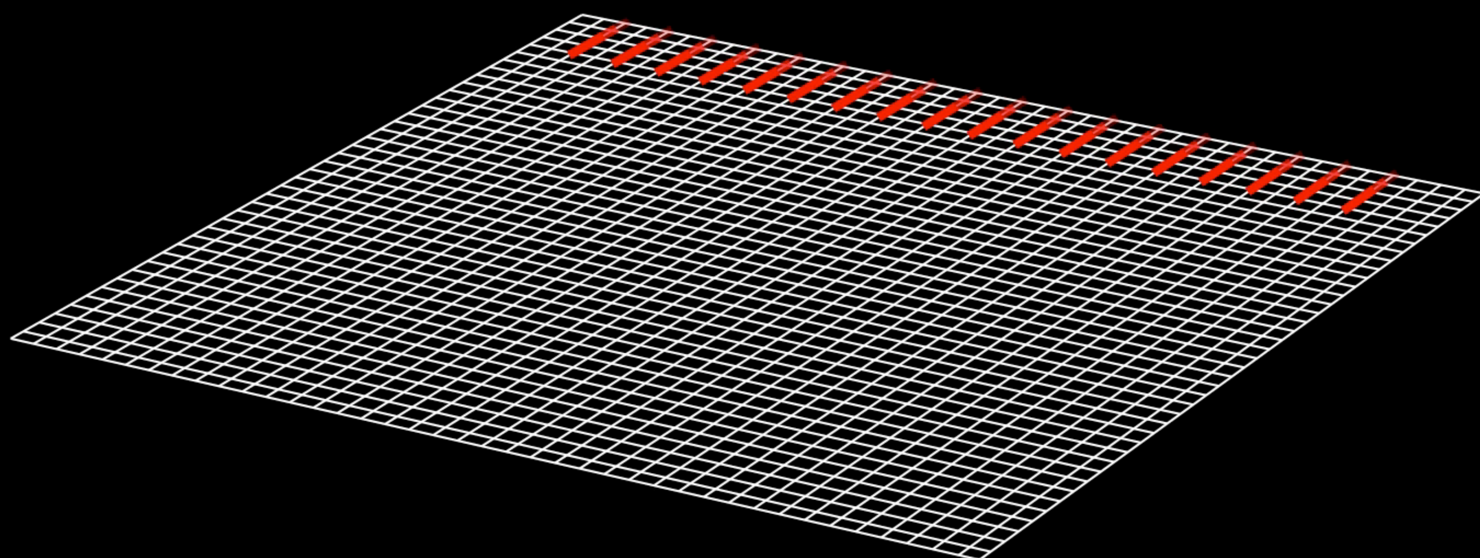


Event Horizon Telescope

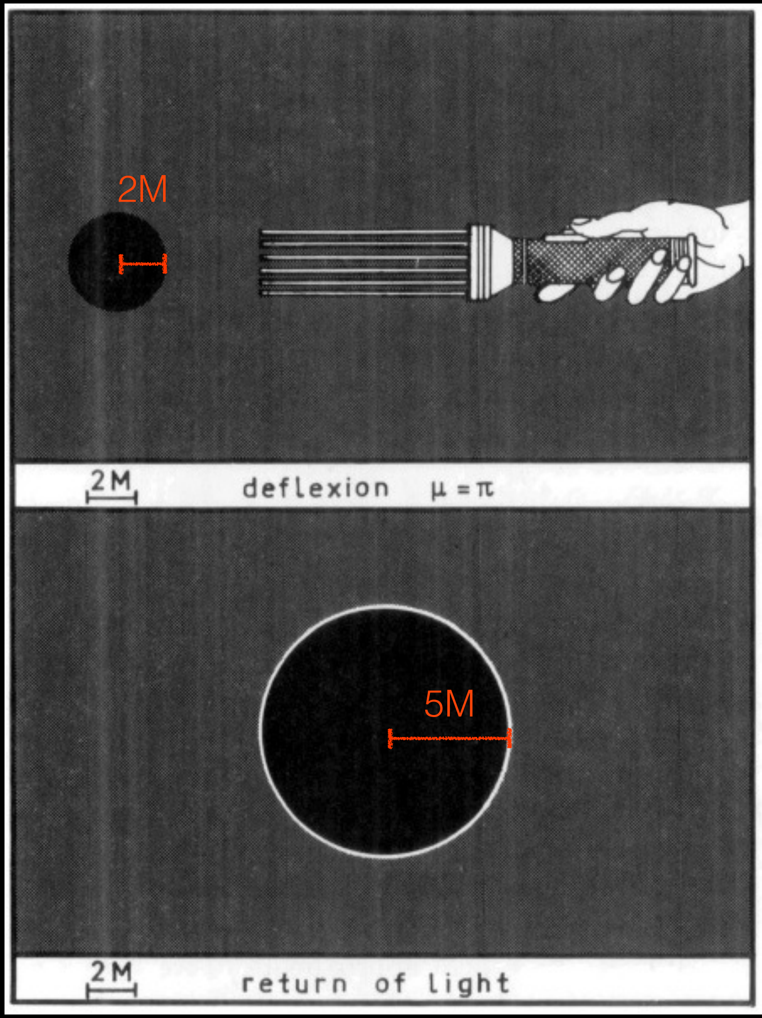
First Results from the Event Horizon Telescope

Slides Courtesy of:
Dr. Lia Medeiros
&
Dr. Chi-Kwan Chan

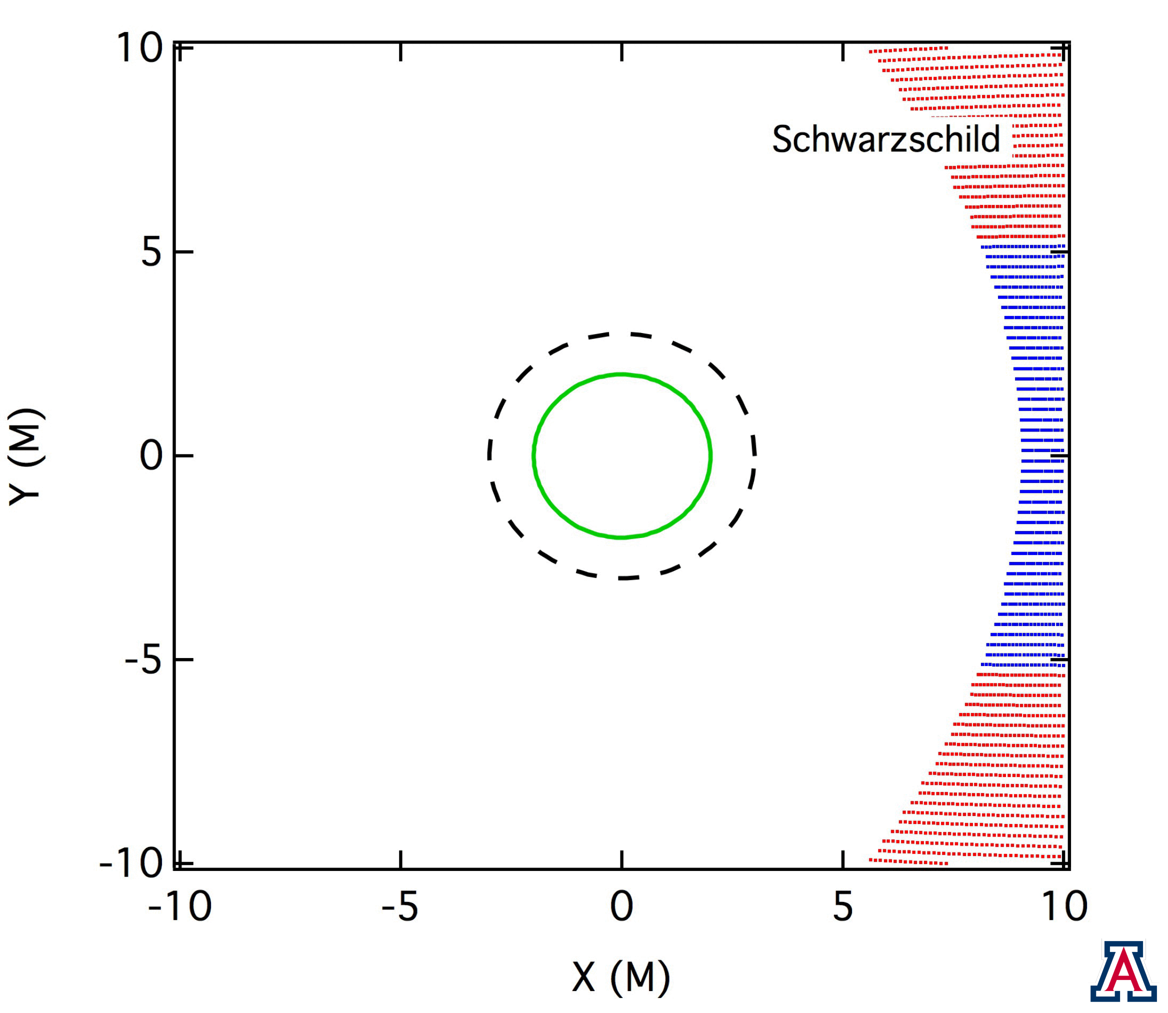
The Movie: Interstellar

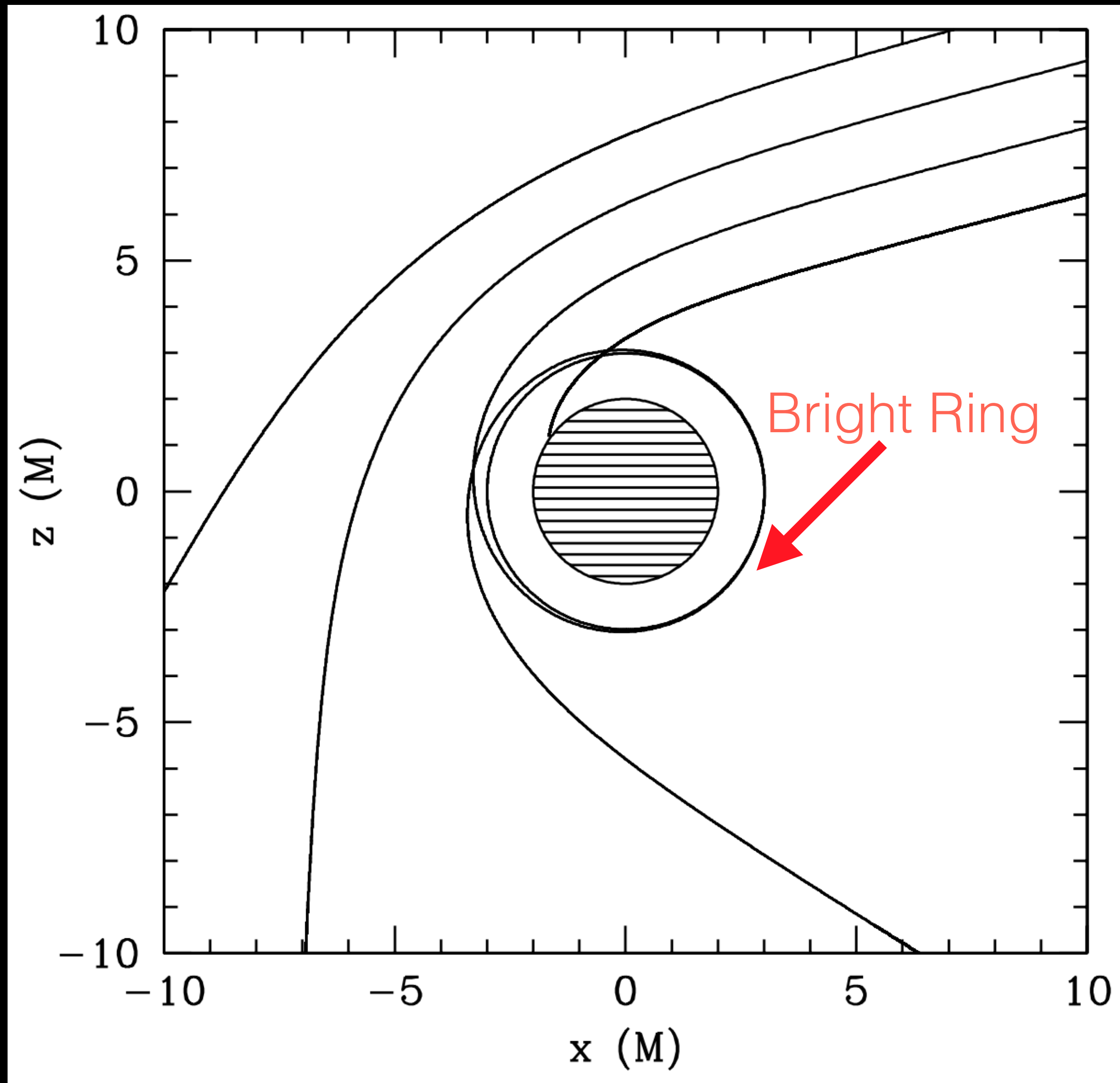


The Black Hole Shadow



Bardeen 1973, Luminet 1979



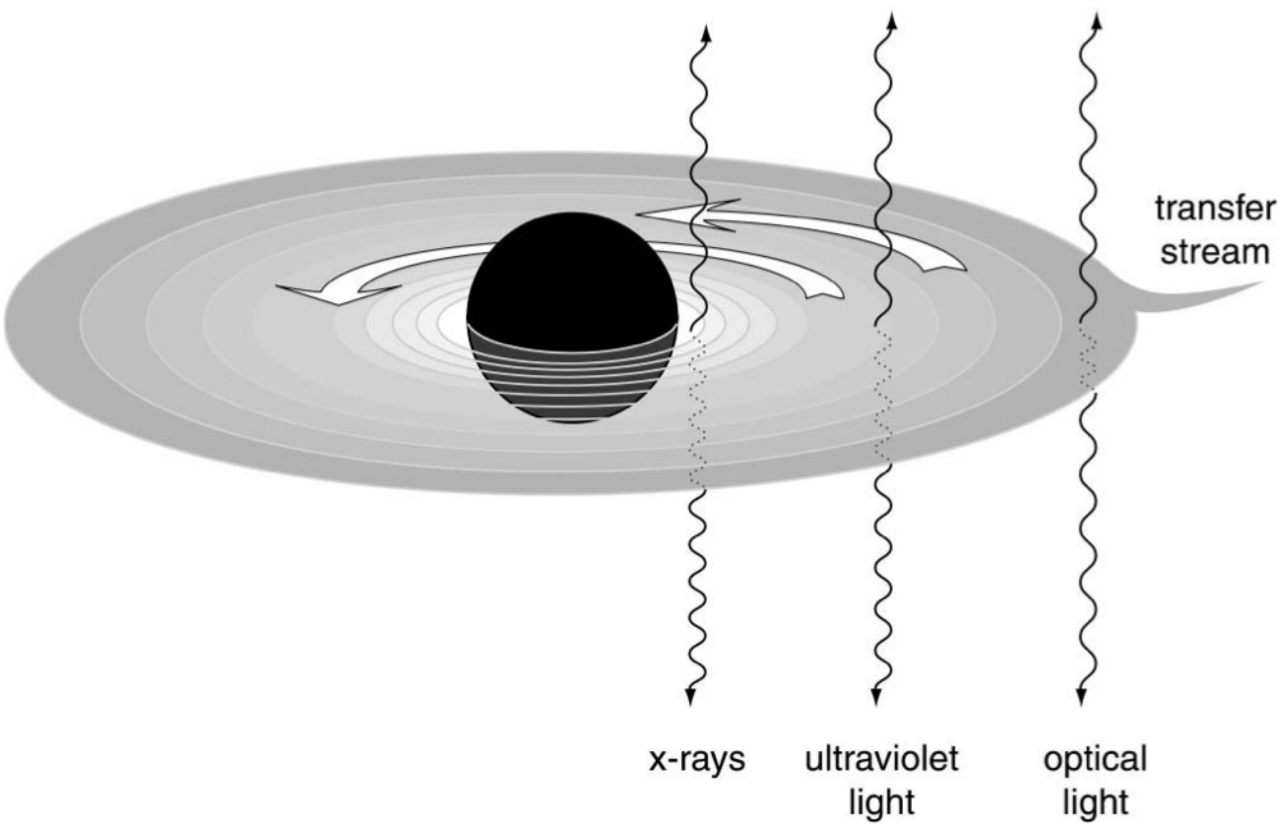


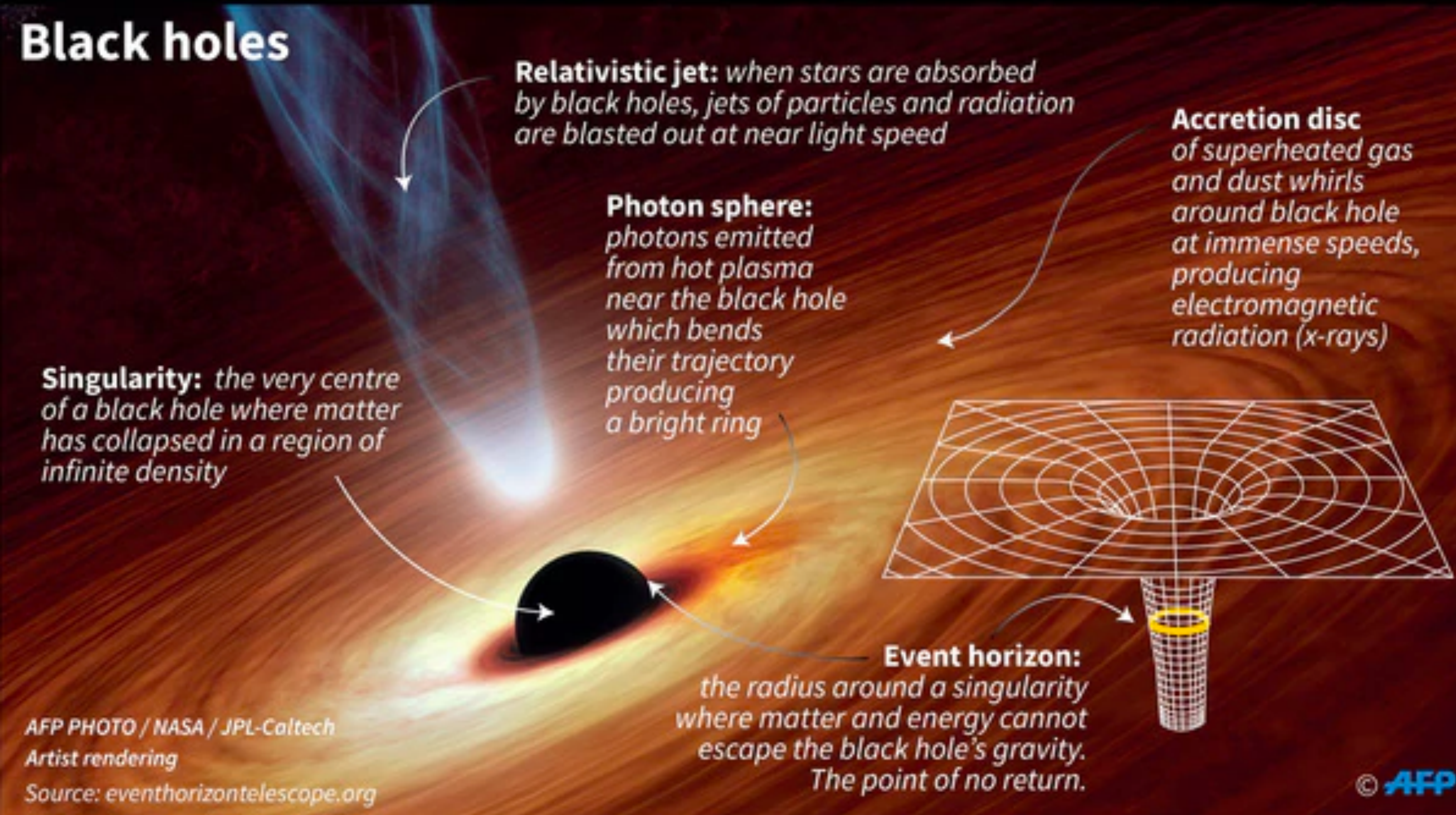
Johannsen & Psaltis 2010

Black Holes and Accretion Disks

Energy Release From Central Engines

Some of it will emerge as a mix of ***thermal emission*** from various parts of the accretion disk; some emerges as a ***non-thermal synchrotron emission*** from particles accelerated by the magnetic fields embedded in the accretion disk or the BH itself




Black holes
Relativistic jet: when stars are absorbed by black holes, jets of particles and radiation are blasted out at near light speed
Accretion disc of superheated gas and dust whirls around black hole at immense speeds, producing electromagnetic radiation (x-rays)
Photon sphere: photons emitted from hot plasma near the black hole which bends their trajectory producing a bright ring
Singularity: the very centre of a black hole where matter has collapsed in a region of infinite density
Event horizon: the radius around a singularity where matter and energy cannot escape the black hole's gravity. The point of no return.
AFP PHOTO / NASA / JPL-Caltech
Artist rendering
Source: eventhorizontelescope.org
© AFP

Relevant Sizes

Event Horizon (Schwarzchild Radius):

Escape Speed = Speed of Light

0.5V^2 = GM/R

R = Event Horizon = 2G M/c^2

$$Rsch = \frac{2GM_{BH}}{c^2}$$

Photon Radius (or Sphere):

Radius where photons orbit the Black Hole, at the speed of light.

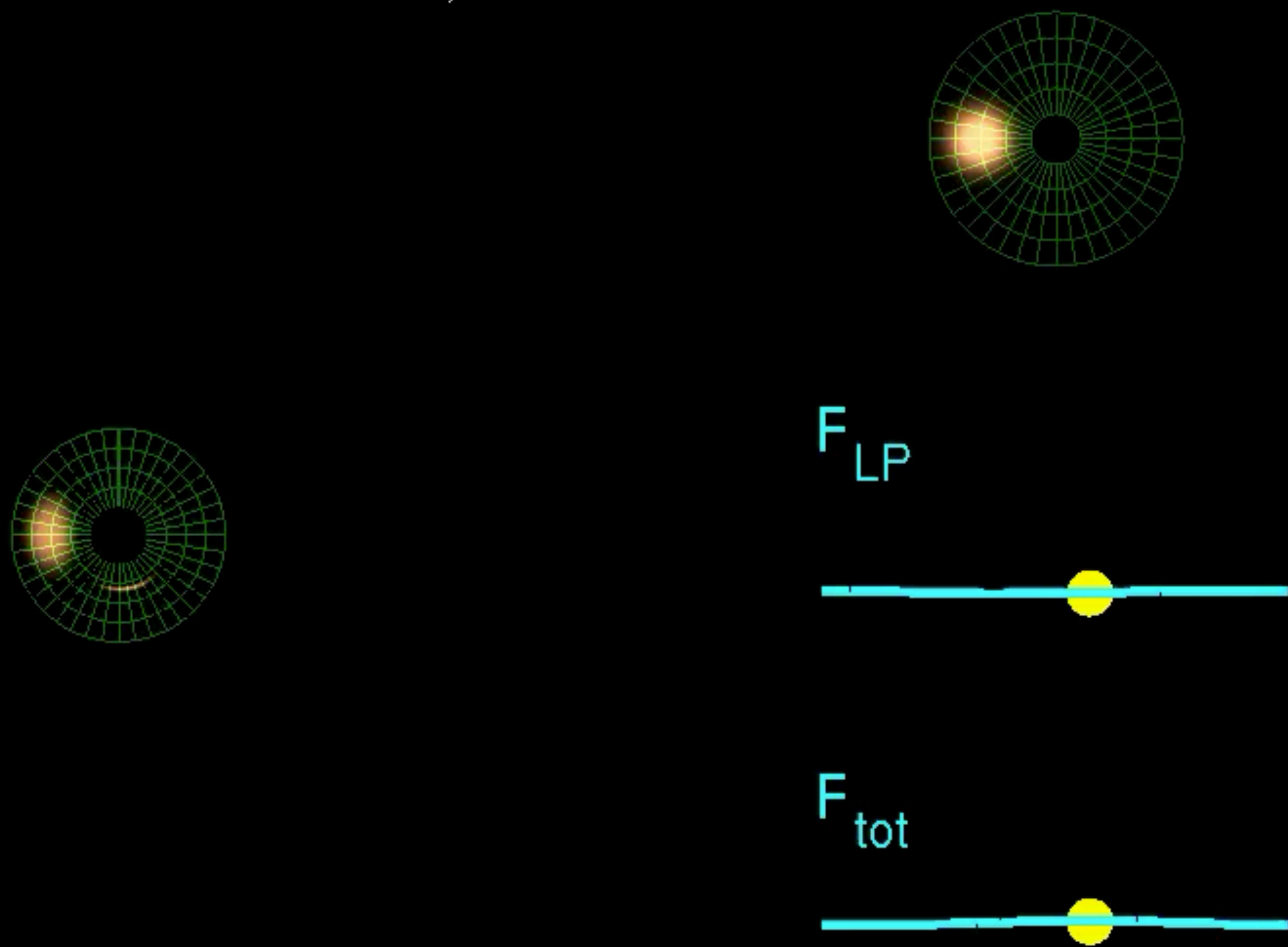
Photon Radius = 1.5 *Event Horizon

Bright Ring in EHT image = 2.6* Event Horizon

—> lensed Photon Radius.

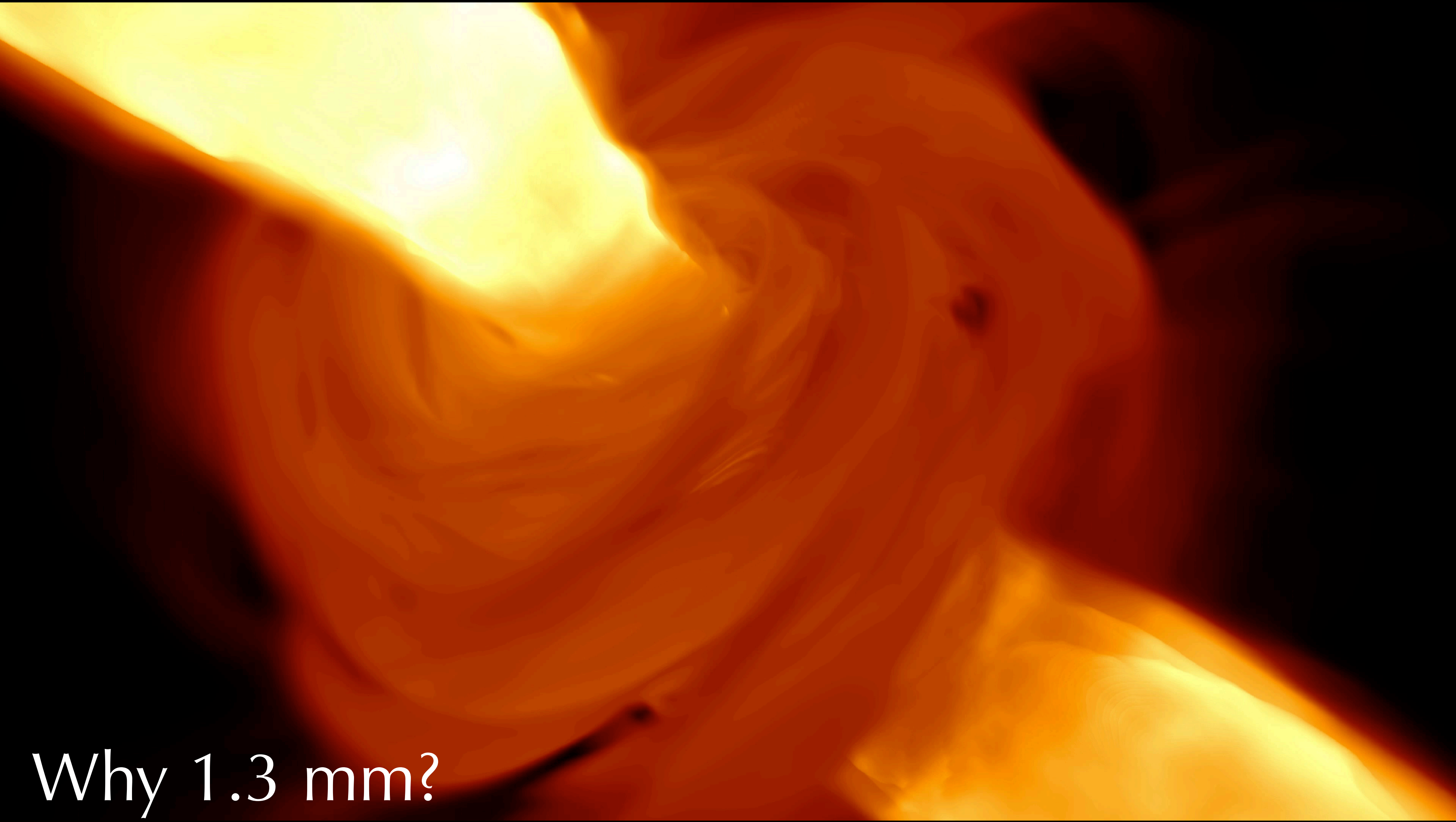
So if you measure the size of the Imaged Ring, you can get out the Mass of the Black Hole predicted by GR - which we can compare against other measurements of the same Black Hole.

a=0, r=6M



Broderick & Loeb, 2006, MNRAS, 367, 905


The Movie: Interstellar



Why 1.3 mm?

- Peak of mm-IR emission for Sgr A*
- Atmosphere is transparent
- ISM effects are minimal
- Accretion flow becomes optically thin

Ozel, Psaltis, & Narayan 2000; Chan et al. 2015

A special purpose supercomputer: computer gaming on steroids

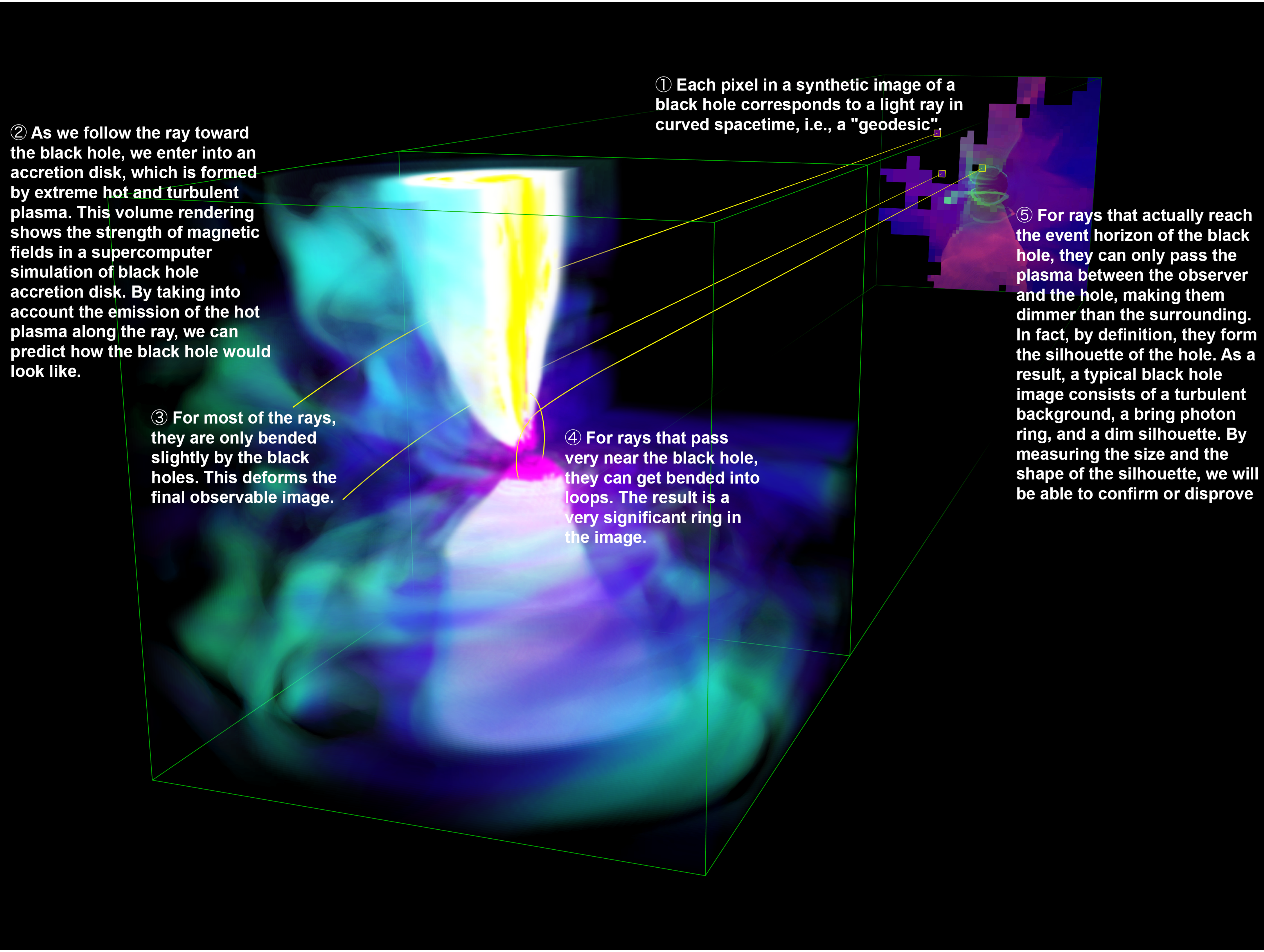
67x2 NVIDIA GPUs

$1.8M (NSF MRI grant)

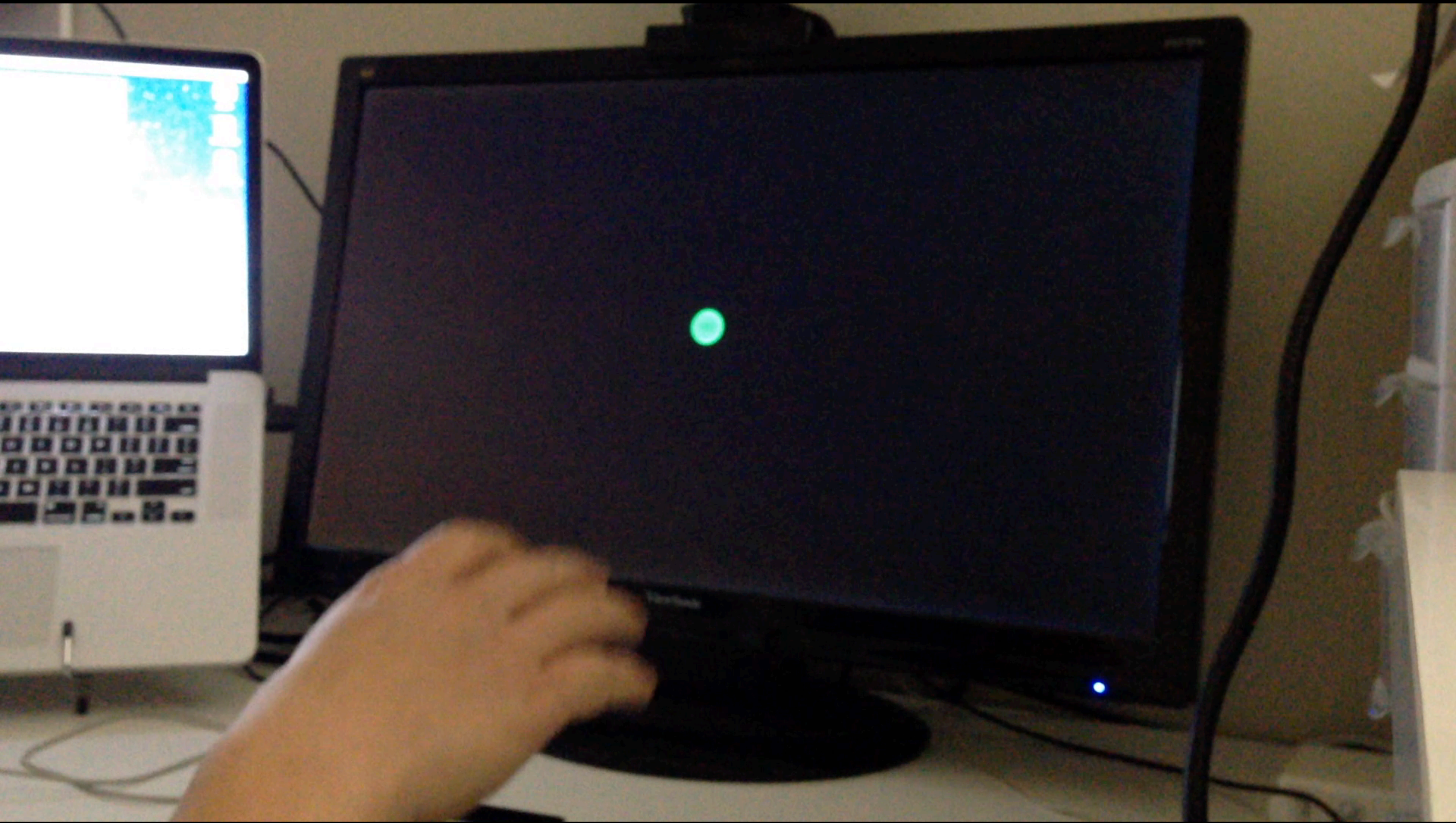
The Green500 List

Listed below are the November 2013 The Green500's energy-efficient supercomputers ranked from 1 to 10.

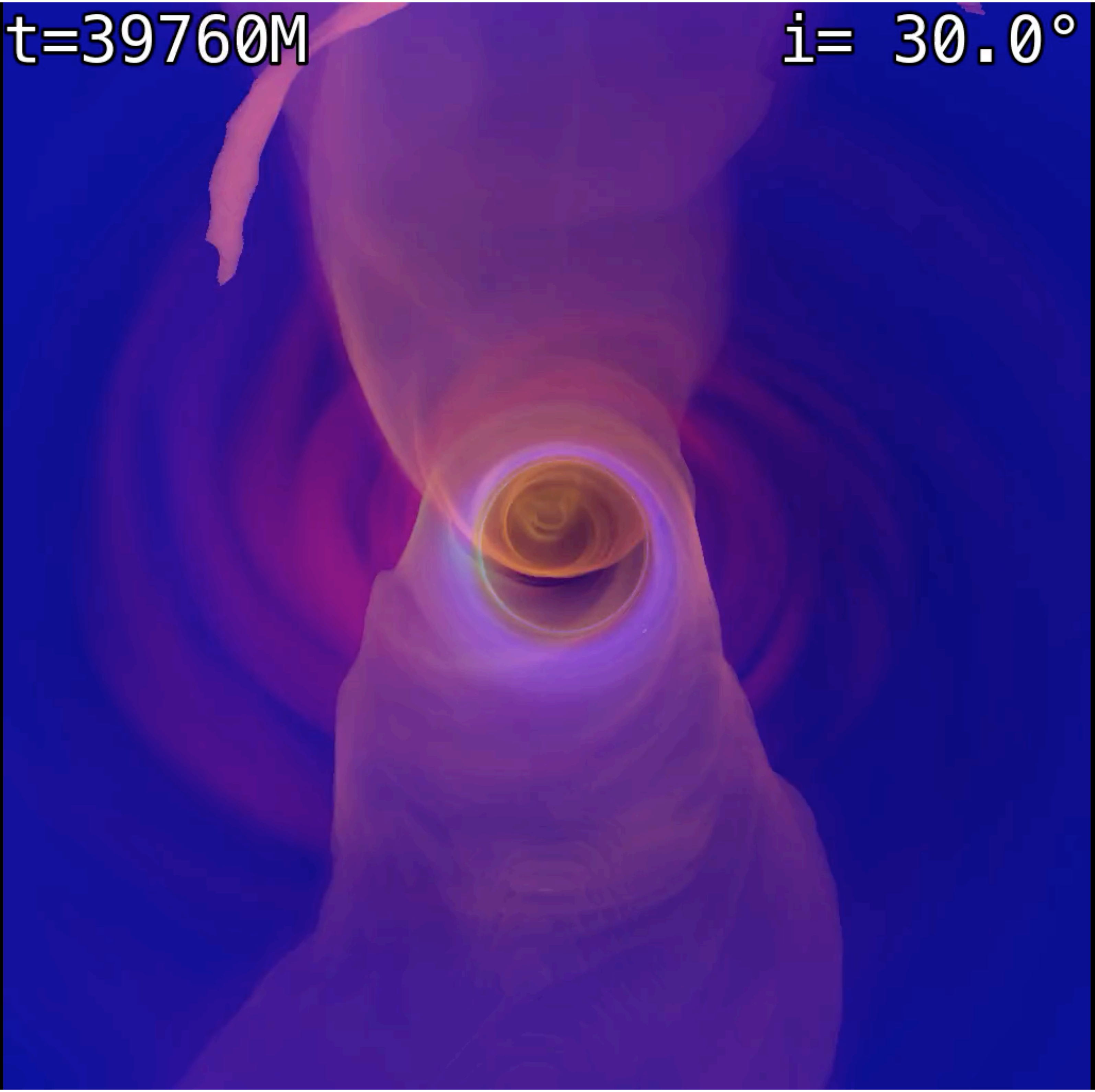
Green500 Rank	MFLOPS/W	Site*	Computer*	Total Power (kW)
1	4,503.17	GSIC Center, Tokyo Institute of Technology	TSUBAME-KFC - LX 1U-4GPU/104Re-1G Cluster, Intel Xeon E5-2620v2 6C 2.100GHz, Infiniband FDR, NVIDIA K20x	27.78
2	3,631.86	Cambridge University	Wilkes - Dell T620 Cluster, Intel Xeon E5-2630v2 6C 2.600GHz, Infiniband FDR, NVIDIA K20	52.62
3	3,517.84	Center for Computational Sciences, University of Tsukuba	HA-PACS TCA - Cray 3623G4-SM Cluster, Intel Xeon E5-2680v2 10C 2.800GHz, Infiniband QDR, NVIDIA K20x	78.77
4	3,185.91	Swiss National Supercomputing Centre (CSCS)	Piz Daint - Cray XC30, Xeon E5-2670 8C 2.600GHz, Aries interconnect , NVIDIA K20x Level 3 measurement data available	1,753.66
5	3,130.95	ROMEO HPC Center - Champagne-Ardenne	romeo - Bull R421-E3 Cluster, Intel Xeon E5-2650v2 8C 2.600GHz, Infiniband FDR, NVIDIA K20x	81.41
6	3,068.71	GSIC Center, Tokyo Institute of Technology	TSUBAME 2.5 - Cluster Platform SL390s G7, Xeon X5670 6C 2.930GHz, Infiniband QDR, NVIDIA K20x	922.54
7	2,702.16	University of Arizona	iDataPlex DX360M4, Intel Xeon E5-2650v2 8C 2.600GHz, Infiniband FDR14, NVIDIA K20x	53.62
8	2,629.10	Max-Planck-Gesellschaft MPI/IPP	iDataPlex DX360M4, Intel Xeon E5-2680v2 10C 2.800GHz, Infiniband, NVIDIA K20x	269.94
9	2,629.10	Financial Institution	iDataPlex DX360M4, Intel Xeon E5-2680v2 10C 2.800GHz, Infiniband, NVIDIA K20x	55.62
10	2,358.69	CSIRO	CSIRO GPU Cluster - Nitro G16 3GPU, Xeon E5-2650 8C 2.000GHz, Infiniband FDR, Nvidia K20m	71.01


① Each pixel in a synthetic image of a black hole corresponds to a light ray in curved spacetime, i.e., a "geodesic".
② As we follow the ray toward the black hole, we enter into an accretion disk, which is formed by extreme hot and turbulent plasma. This volume rendering shows the strength of magnetic fields in a supercomputer simulation of black hole accretion disk. By taking into account the emission of the hot plasma along the ray, we can predict how the black hole would look like.
③ For most of the rays, they are only bended slightly by the black holes. This deforms the final observable image.
④ For rays that pass very near the black hole, they can get bended into loops. The result is a very significant ring in the image.
⑤ For rays that actually reach the event horizon of the black hole, they can only pass the plasma between the observer and the hole, making them dimmer than the surrounding. In fact, by definition, they form the silhouette of the hole. As a result, a typical black hole image consists of a turbulent background, a bring photon ring, and a dim silhouette. By measuring the size and the shape of the silhouette, we will be able to confirm or disprove

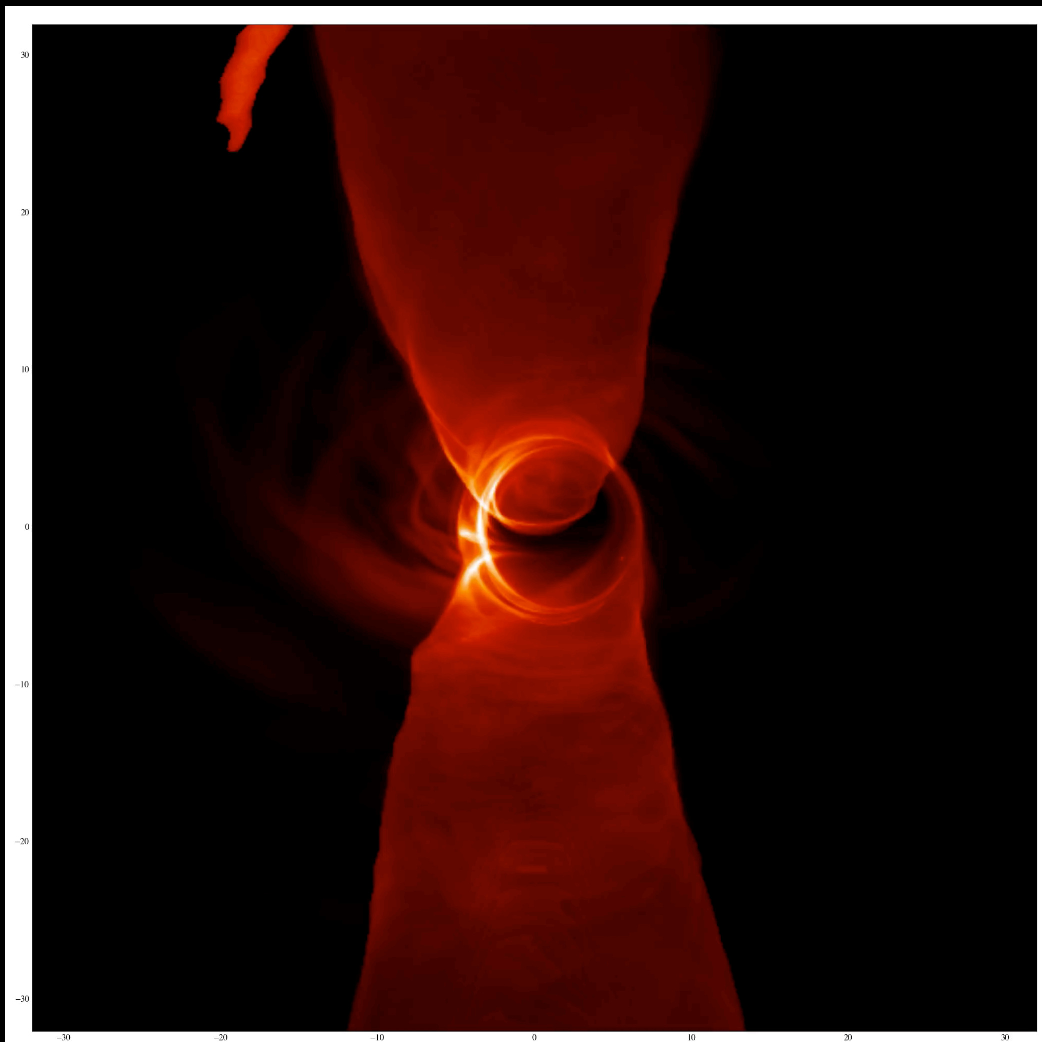
General Relativistic Ray Tracing with GPUs: A Game Changer

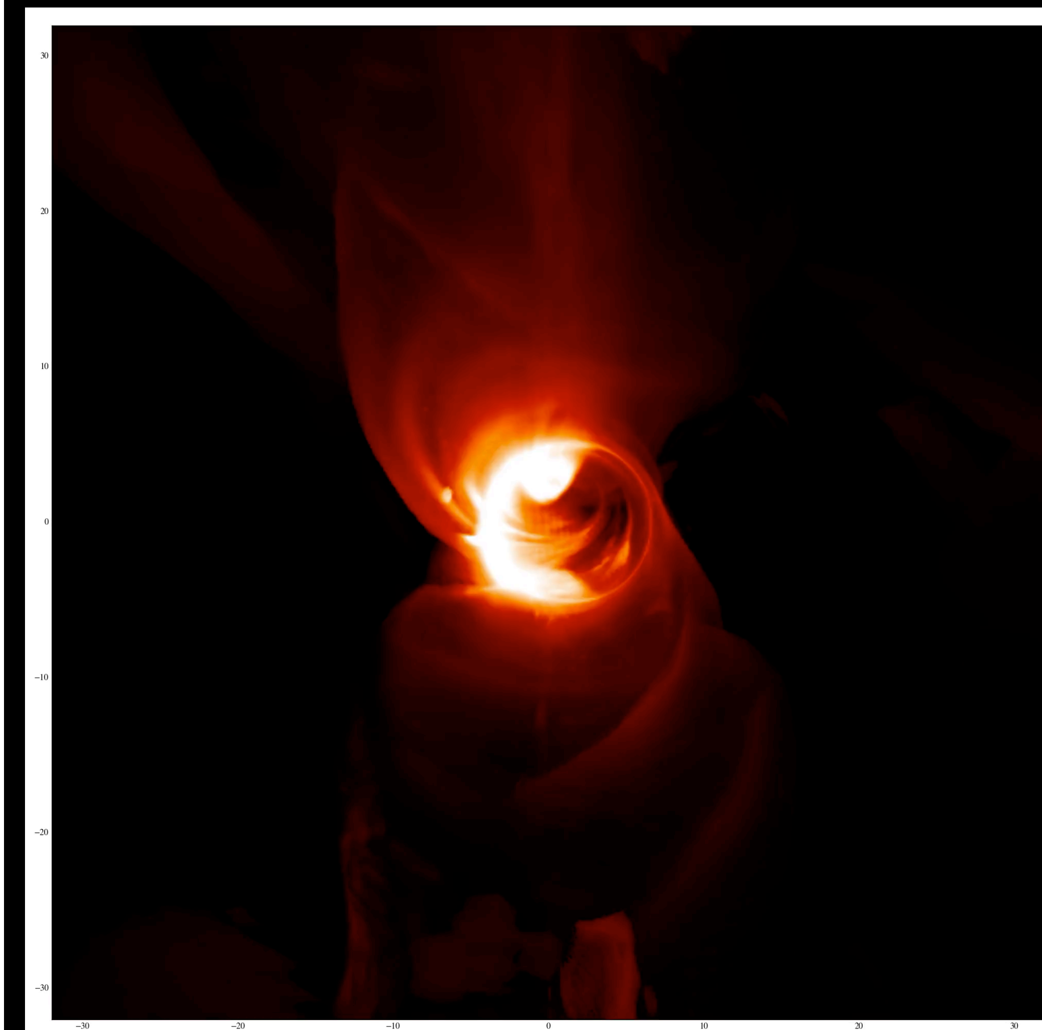


Video: Chi-Kwan Chan/Arizona

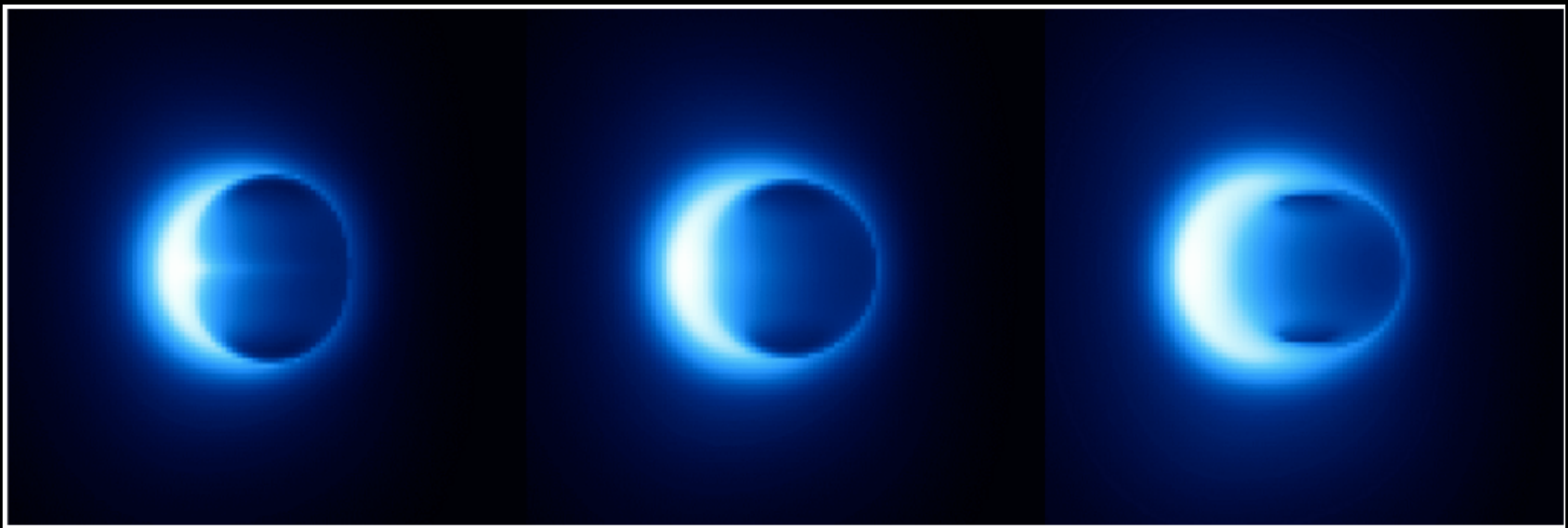

t=39760M
i= 30.0°

Lia Medeiros, Feryal Ozel:
Image depends on Black hole spin, Bfield, Plasma Physics





Testing GR with the EHT



Prolate

Circular:
standard GR

oblate

The Event Horizon Telescope

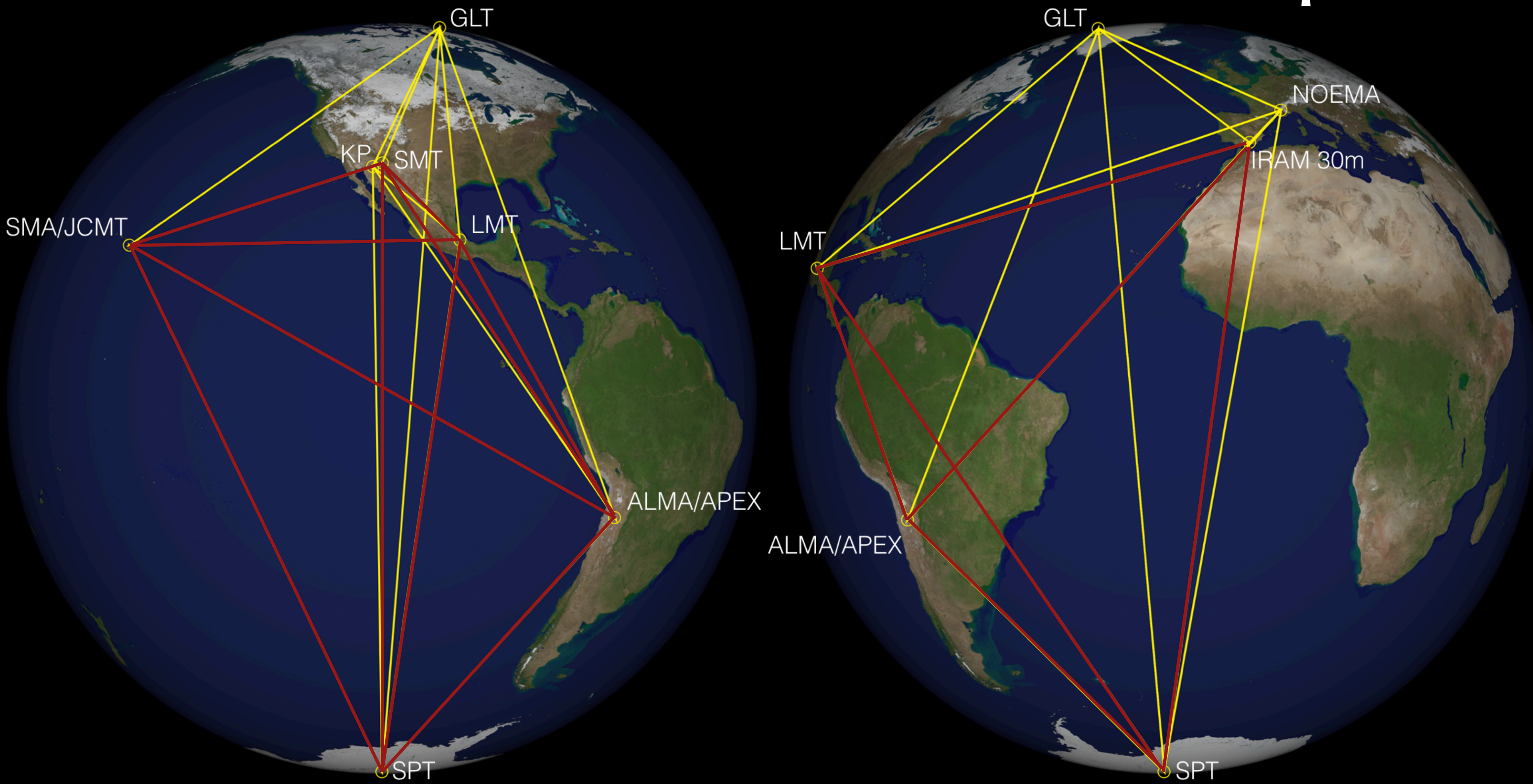


Image credit: Dan Marrone

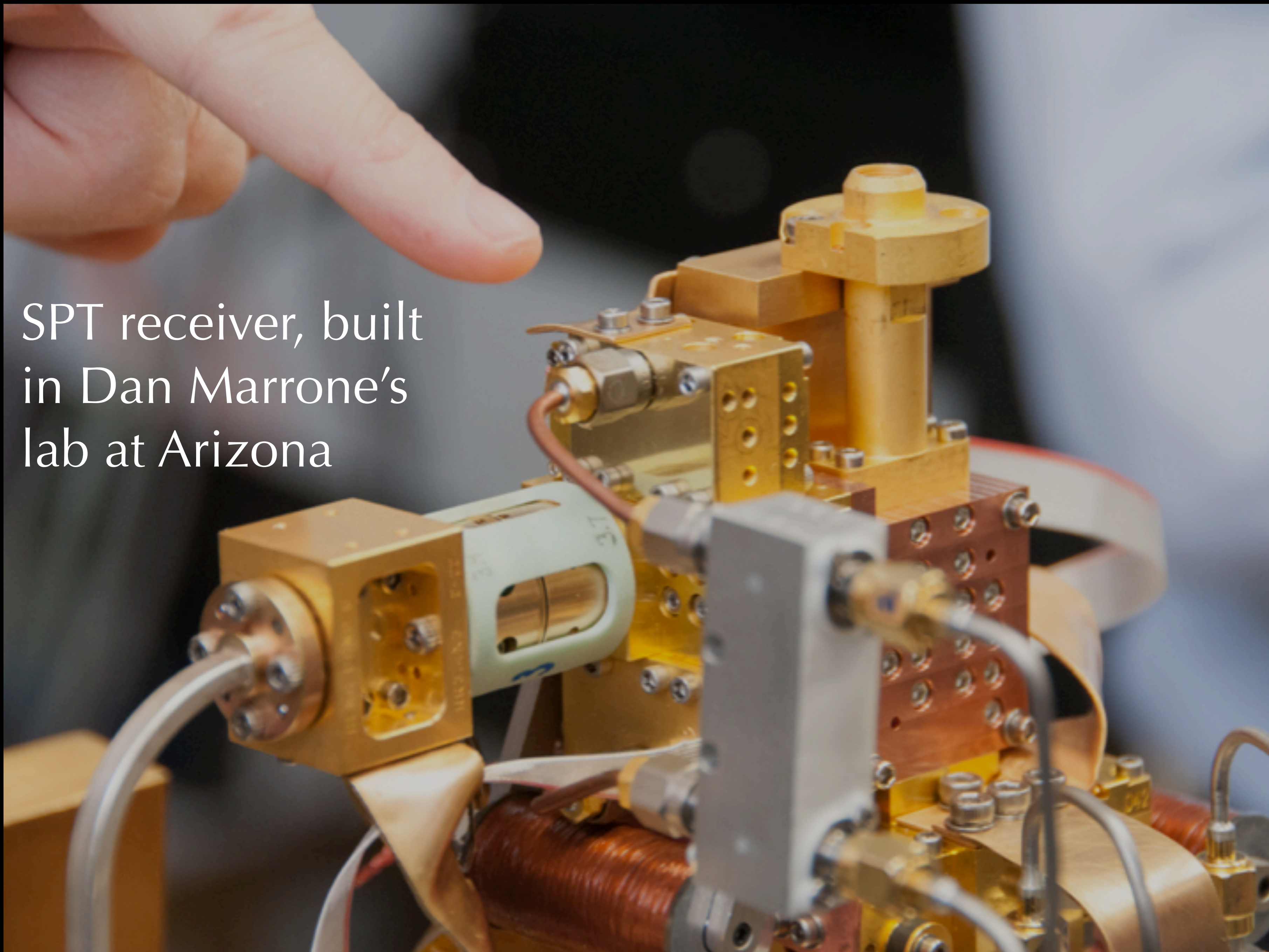
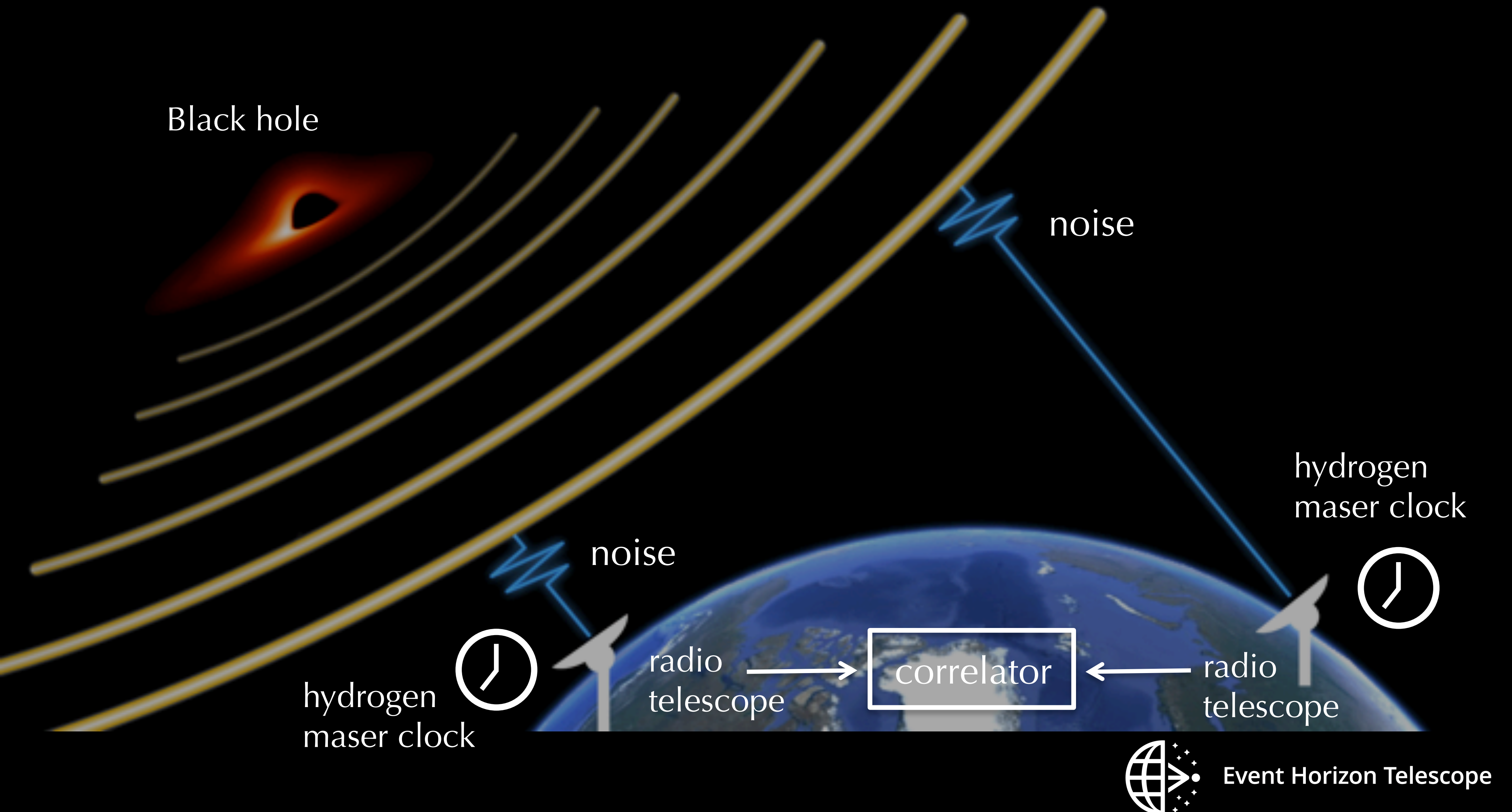


image credit: CK Chan, Dan Marrone's lab, UA


Photo credit: Daniel Michalik/SPT

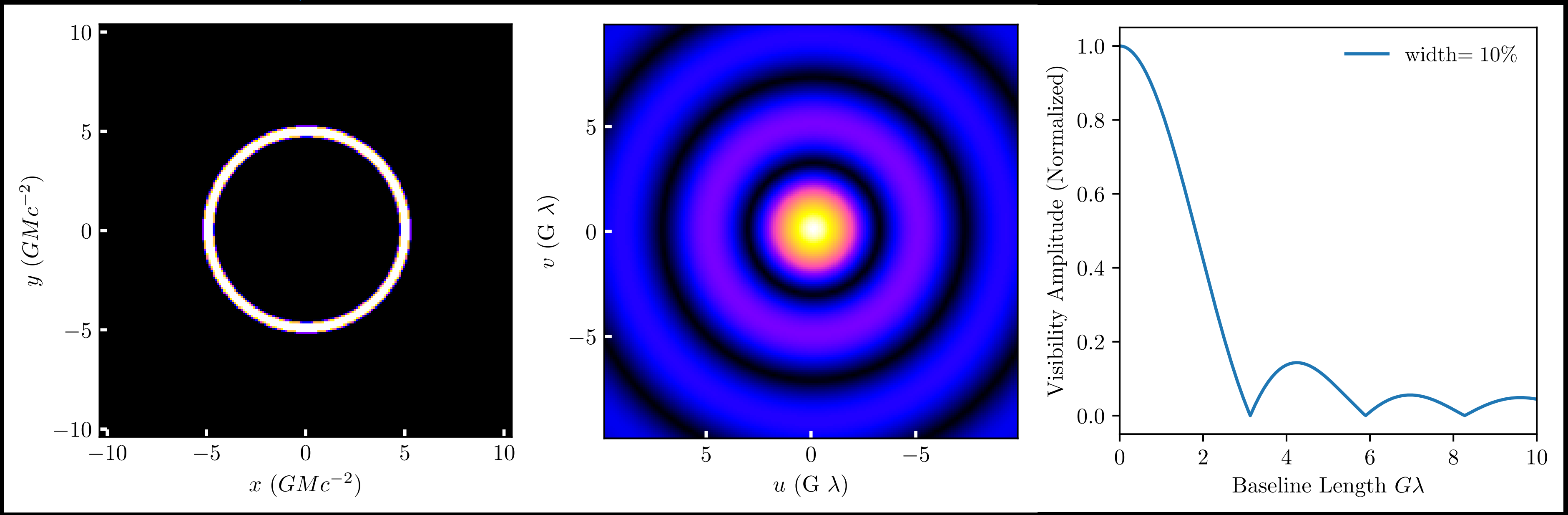
Very Long Baseline Interferometry



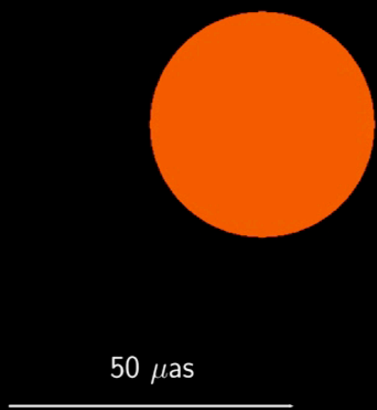
simple black hole image

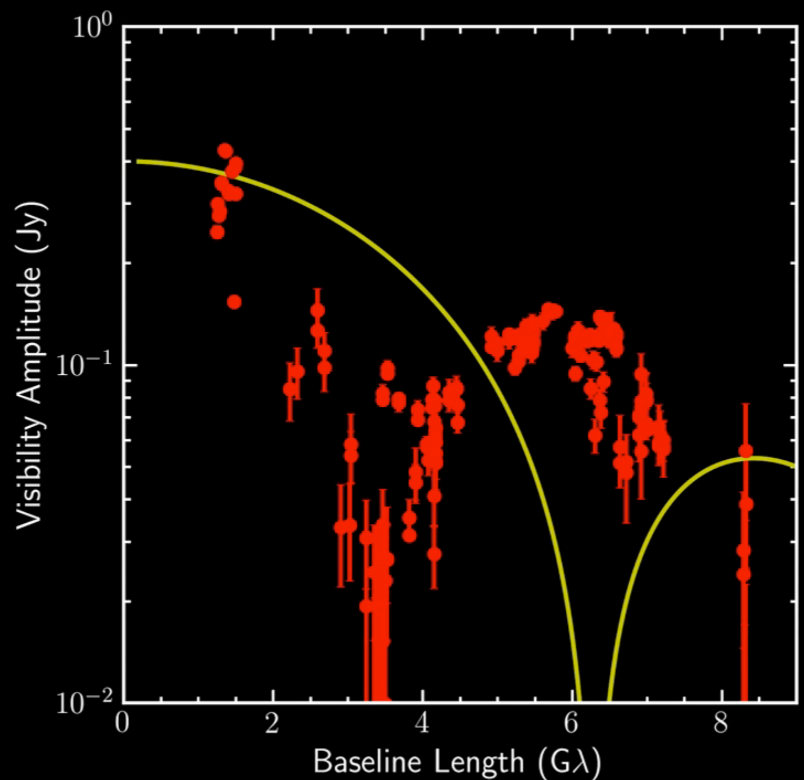
amplitude of the Fourier transform of the image, or visibility amplitude

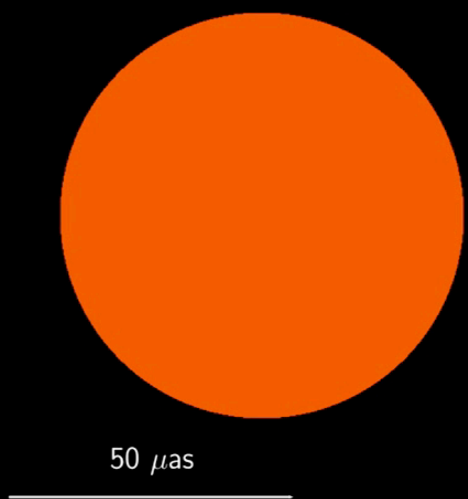
cross-sections of visibility amplitude

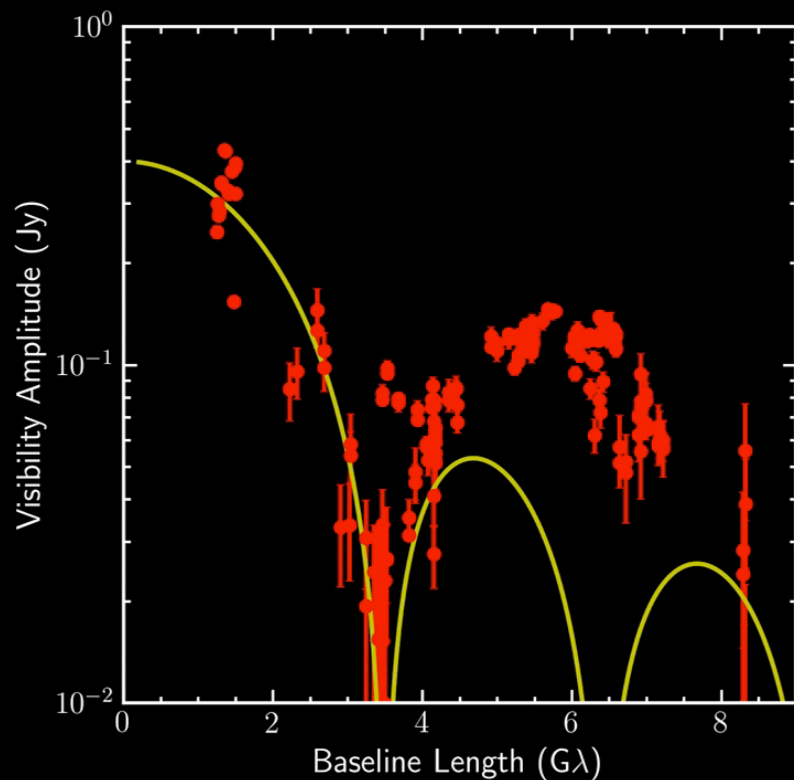


The amplitude of the Fourier transform of a ring is a Bessel function

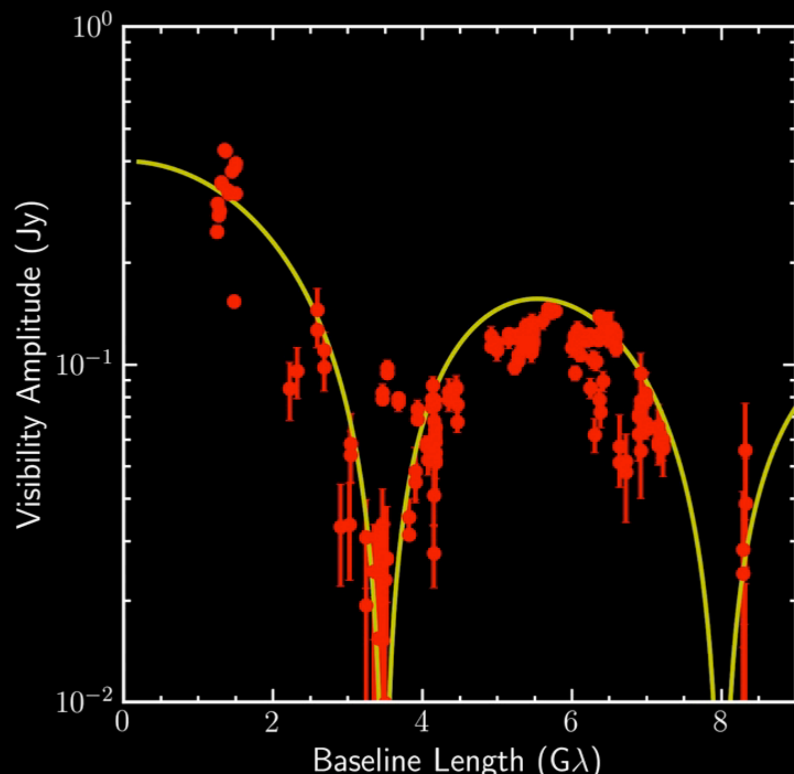

50 μas


10^0
10^{-1}
10^{-2}
0
2
4
6
8
Visibility Amplitude (Jy)
Baseline Length (Gλ)

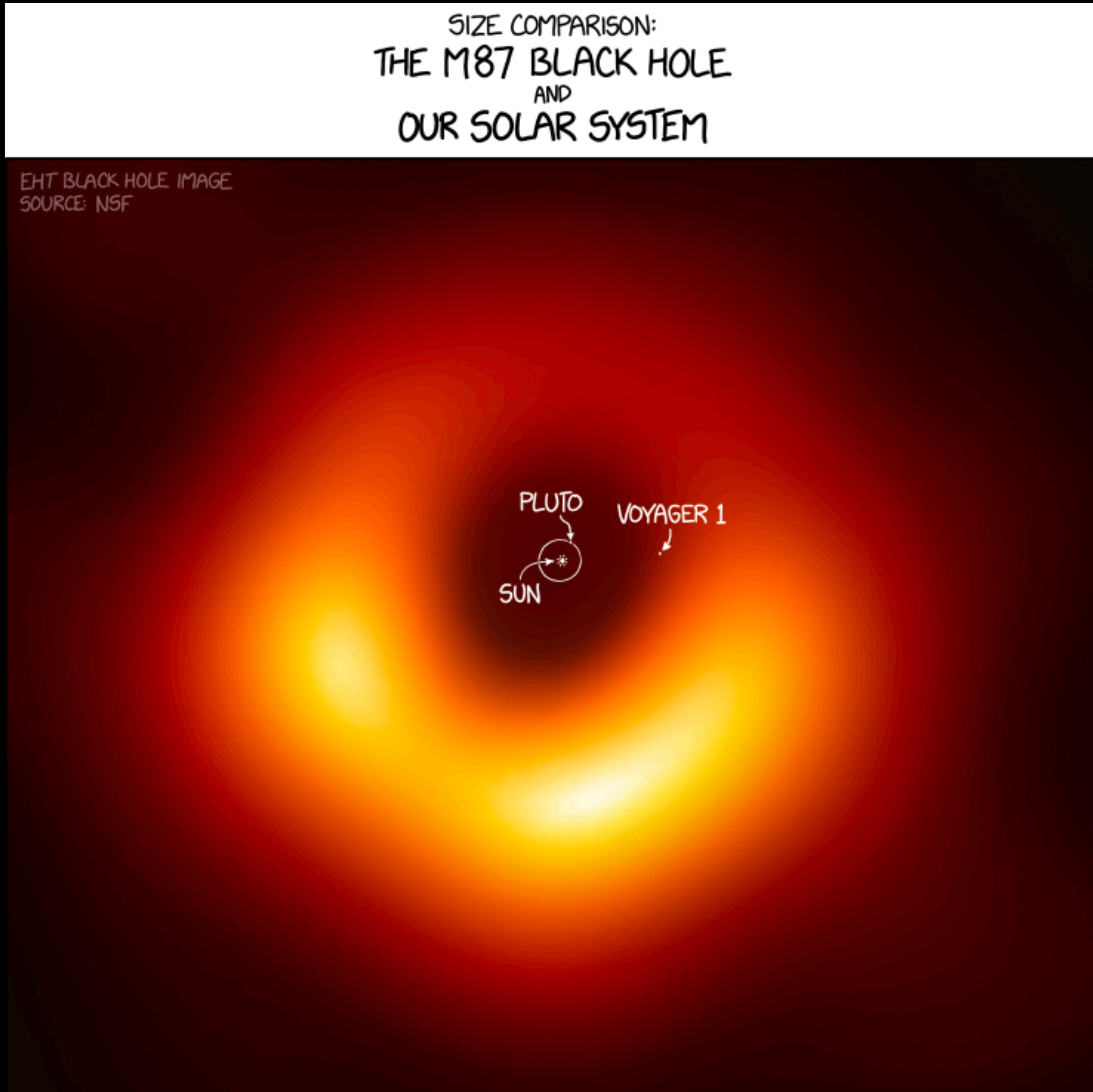

50 μas


10^0
10^{-1}
10^{-2}
0
2
4
6
8
Visibility Amplitude (Jy)
Baseline Length (Gλ)


50 μas


Visibility Amplitude (Jy)
Baseline Length (Gλ)
10^0
10^−1
10^−2
0
2
4
6
8

ARIZONA



SIZE COMPARISON:
THE M87 BLACK HOLE
AND
OUR SOLAR SYSTEM
EHT BLACK HOLE IMAGE
SOURCE: NSF
PLUTO
VOYAGER 1
SUN

XKCD