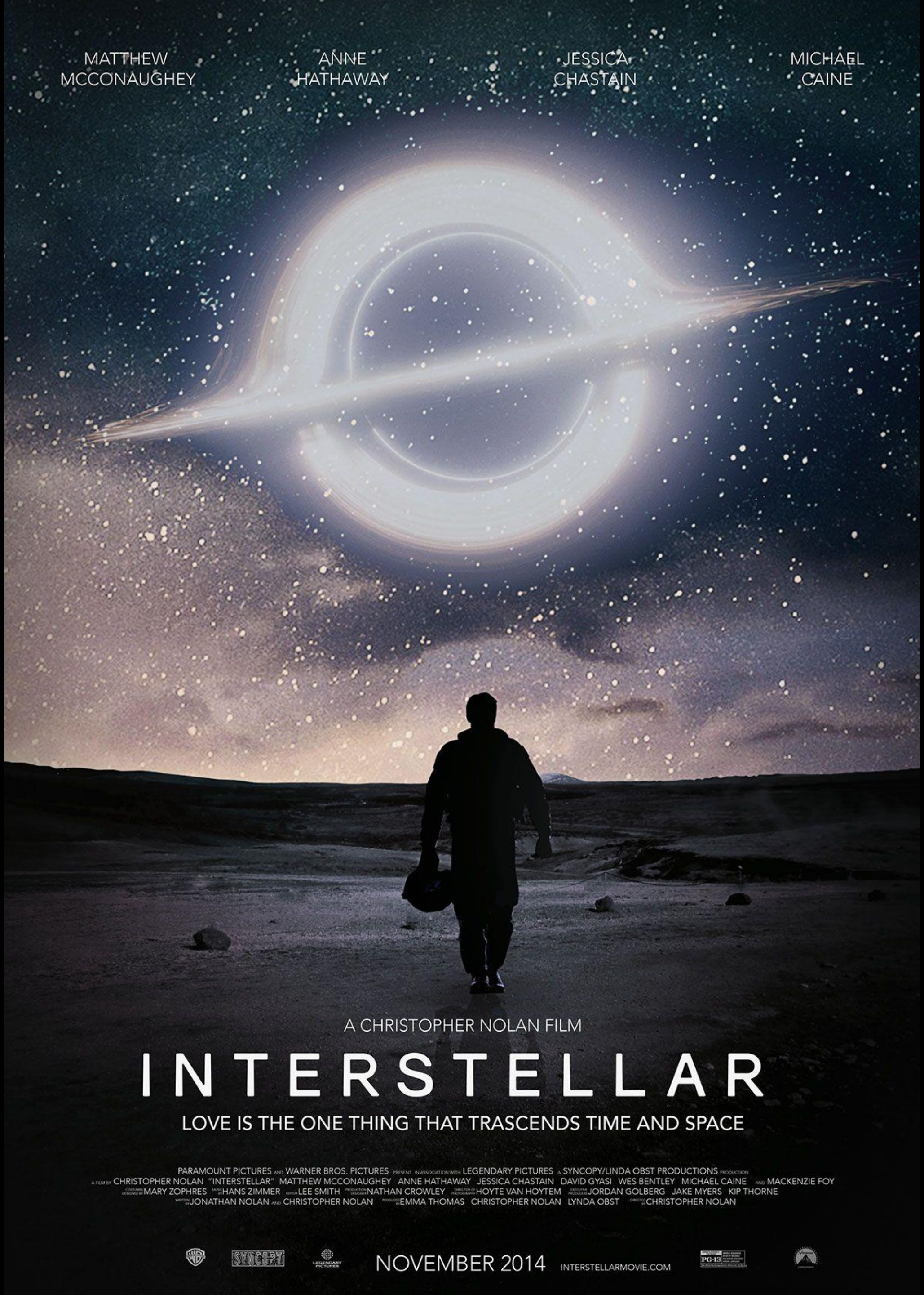

MATTHEW MCCONAUGHEY
ANNE HATHAWAY
JESSICA CHASTAIN
MICHAEL CAINE
A CHRISTOPHER NOLAN FILM
INTERSTELLAR
LOVE IS THE ONE THING THAT TRASCENDS TIME AND SPACE
PARAMOUNT PICTURES AND WARNER BROS. PICTURES PRESENT IN ASSOCIATION WITH LEGENDARY PICTURES A SYNCOPY/LINDA OBST PRODUCTIONS PRODUCTION
A FILM BY CHRISTOPHER NOLAN "INTERSTELLAR" MATTHEW MCCONAUGHEY ANNE HATHAWAY JESSICA CHASTAIN DAVID GYASI WES BENTLEY MICHAEL CAINE AND MACKENZIE FOY
COSTUMES DESIGNED BY MARY ZOPHRES MUSIC BY HANS ZIMMER EDITOR LEE SMITH PRODUCTION DESIGNER NATHAN CROWLEY DIRECTOR OF PHOTOGRAPHY HOYTE VAN HOYTEM EXECUTIVE PRODUCERS JORDAN GOLBERG JAKE MYERS KIP THORNE
WRITTEN BY JONATHAN NOLAN AND CHRISTOPHER NOLAN PRODUCED BY EMMA THOMAS CHRISTOPHER NOLAN LYNDA OBST DIRECTED BY CHRISTOPHER NOLAN
NOVEMBER 2014
INTERSTELLARMOVIE.COM
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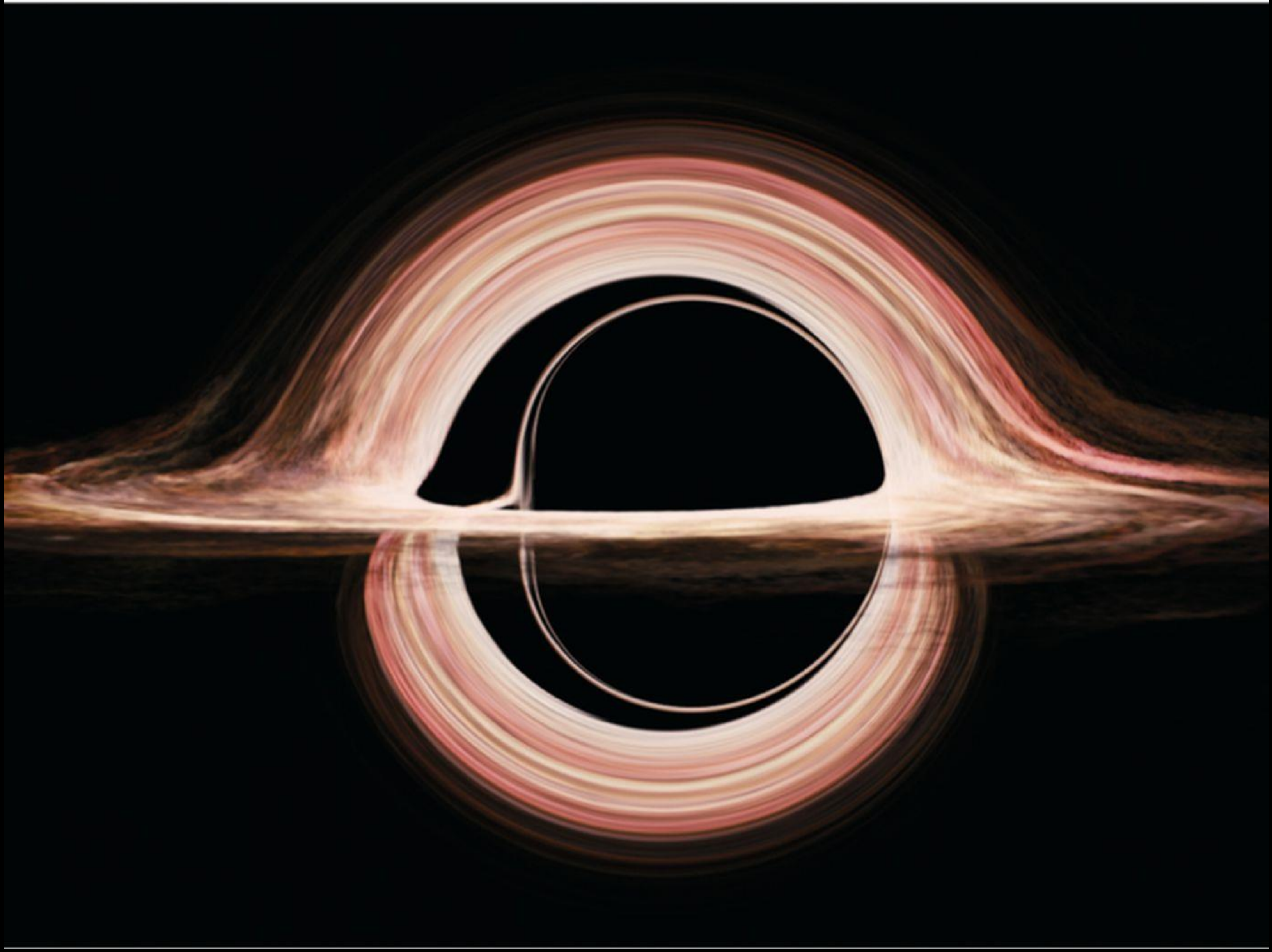
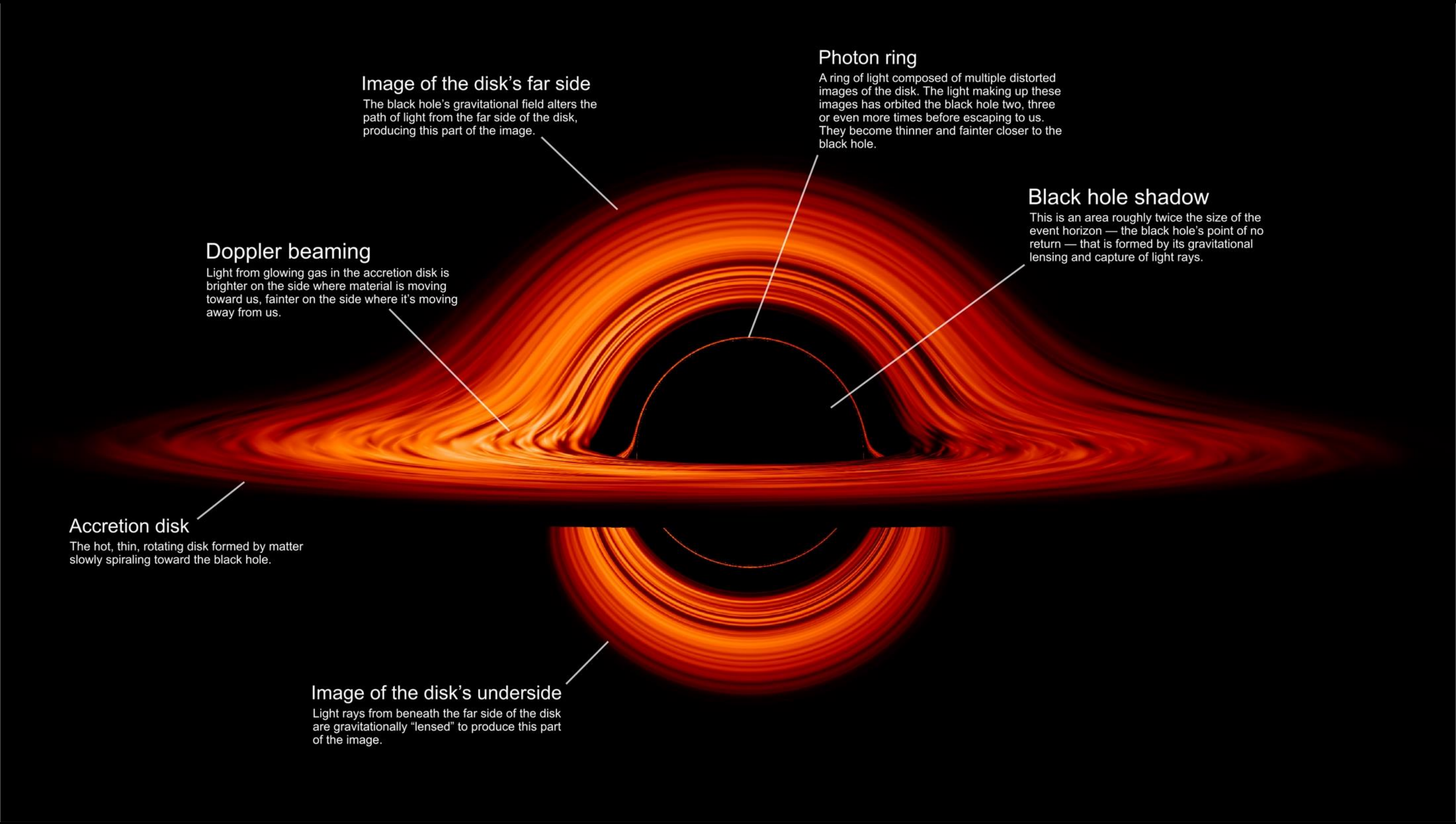
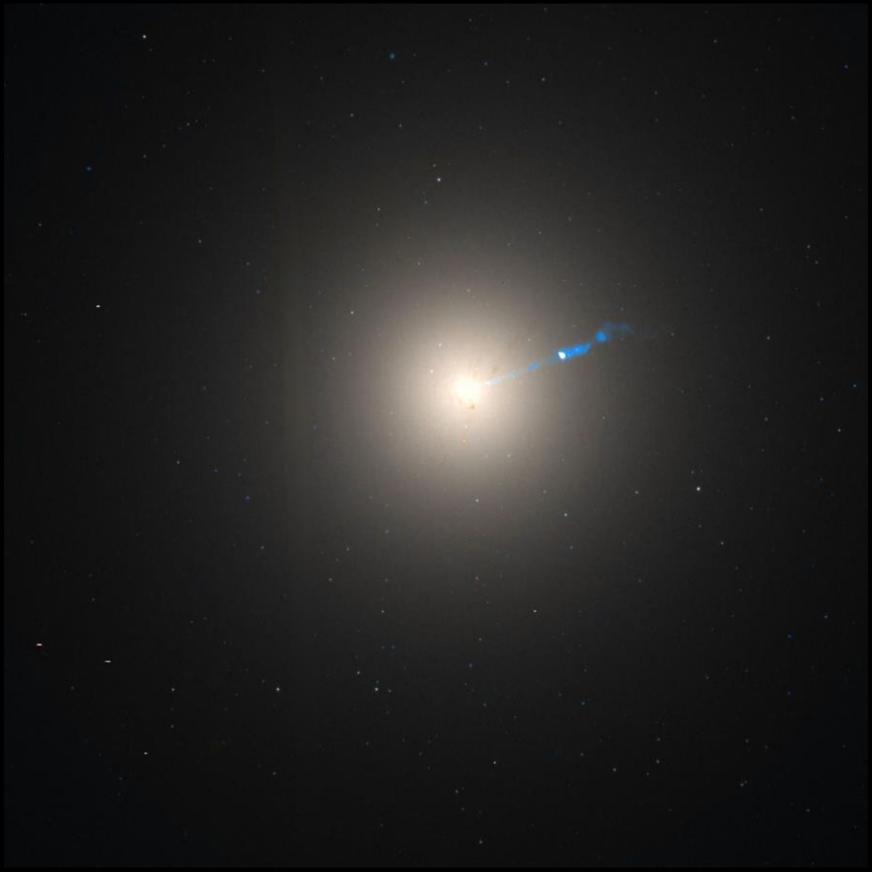
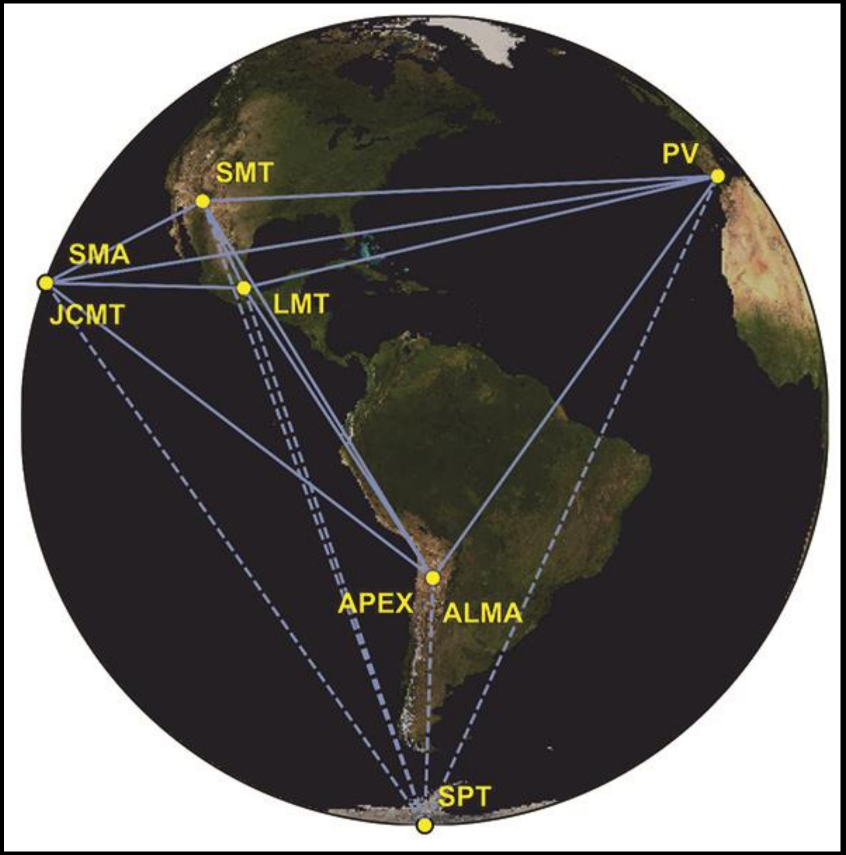


From “Gravitational lensing by spinning black holes in astrophysics, and in the movie *Interstellar*”, by James, von Tunzelmann, Franklin, & Thorne, *Classical and Quantum Gravity*, 2015.



https://www.nasa.gov/universe/nasa-visualization-shows-a-black-holes-warped-world/

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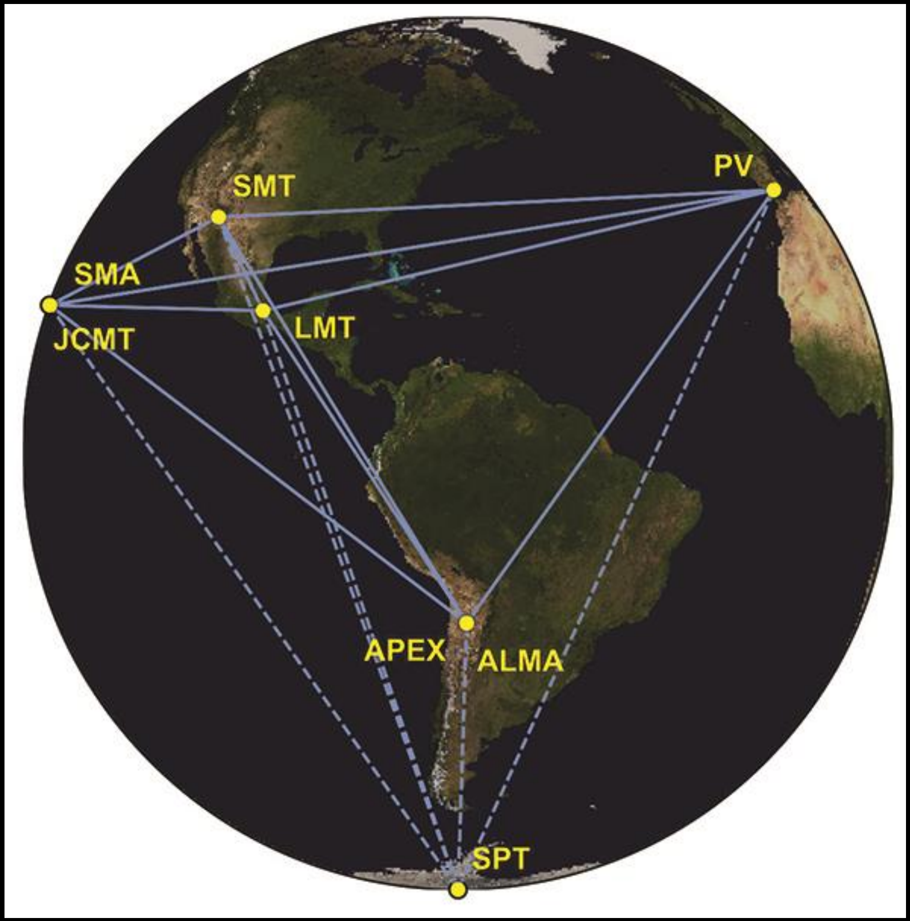
First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole

The Event Horizon Telescope Collaboration
(See the end matter for the full list of authors.)
Received 2019 March 1; revised 2019 March 12; accepted 2019 March 12; published 2019 April 10

Abstract

When surrounded by a transparent emission region, black holes are expected to reveal a dark shadow caused by gravitational light bending and photon capture at the event horizon. To image and study this phenomenon, we have assembled the Event Horizon Telescope, a global very long baseline interferometry array observing at a wavelength of 1.3 mm. This allows us to reconstruct event-horizon-scale images of the supermassive black hole candidate in the center of the giant elliptical galaxy M87. We have resolved the central compact radio source as an asymmetric bright emission ring with a diameter of $42 \pm 3\ \mu$as, which is circular and encompasses a central depression in brightness with a flux ratio $\gtrsim$10:1. The emission ring is recovered using different calibration and imaging schemes, with its diameter and width remaining stable over four different observations carried out in different days. Overall, the observed image is consistent with expectations for the shadow of a Kerr black hole as predicted by general relativity. The asymmetry in brightness in the ring can be explained in terms of relativistic beaming of the emission from a plasma rotating close to the speed of light around a black hole. We compare our images to an extensive library of ray-traced general-relativistic magnetohydrodynamic simulations of black holes and derive a central mass of $M = (6.5 \pm 0.7) \times 10^9 M_{\odot}$. Our radio-wave observations thus provide powerful evidence for the presence of supermassive black holes in centers of galaxies and as the central engines of active galactic nuclei. They also present a new tool to explore gravity in its most extreme limit and on a mass scale that was so far not accessible.

Key words: accretion, accretion disks – black hole physics – galaxies: active – galaxies: individual (M87) – galaxies: jets – gravitation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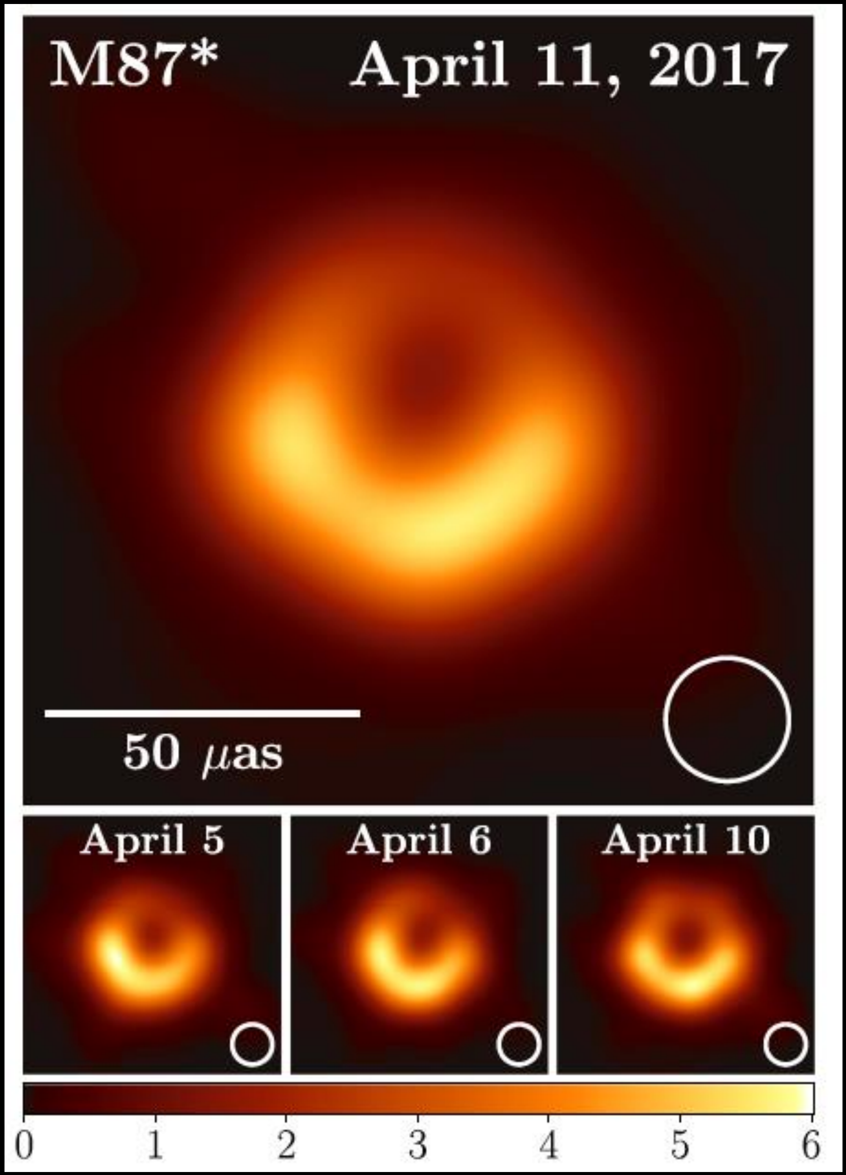
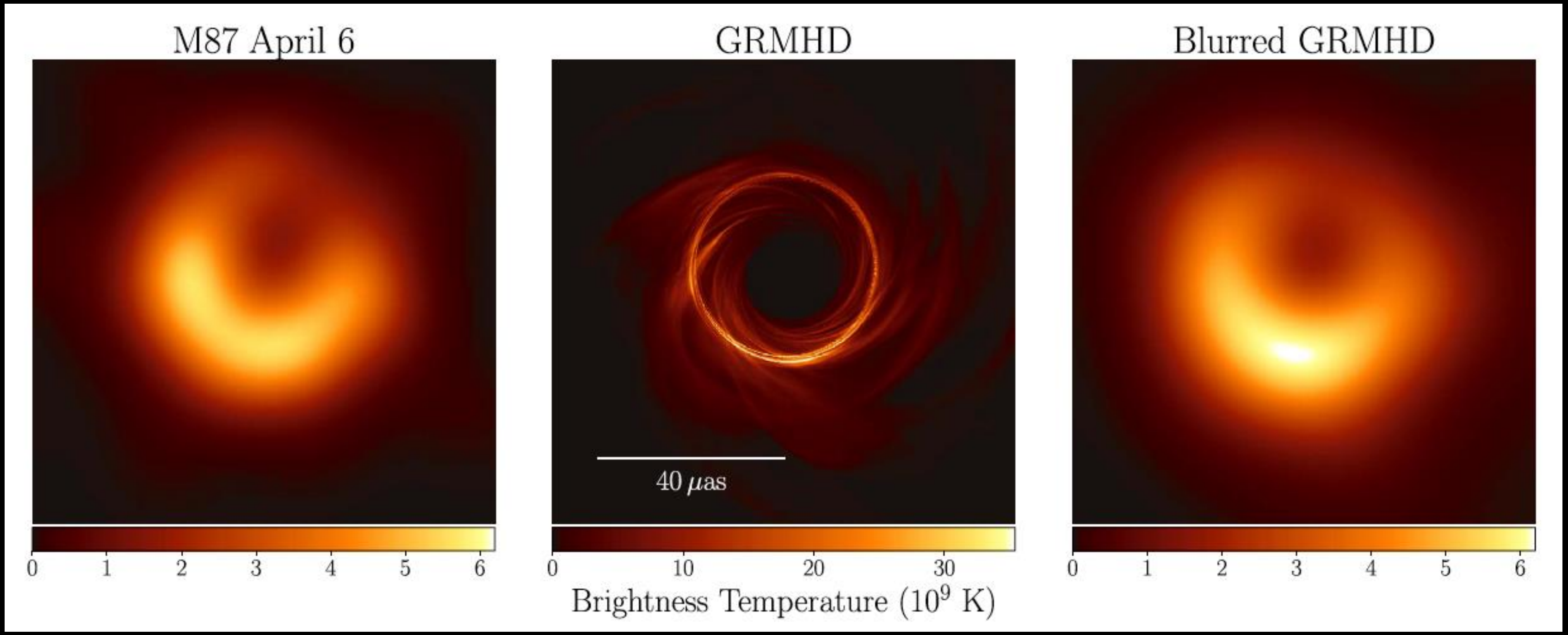

M87*
April 11, 2017
50 μas
April 5
April 6
April 10
0
1
2
3
4
5
6

Observed image

Theoretically predicted image, perfect resolution

Theoretical image blurred to EHT resolution



Bright ring is the "photon ring" arising because light rays go many times around the black hole.

Asymmetry arises from "Doppler boosting" which makes emission from material moving towards us appear brighter. Requires gas moving close to the speed of light; approaching gas on the bottom of the ring.

Central black region is the shadow cast by the event horizon.

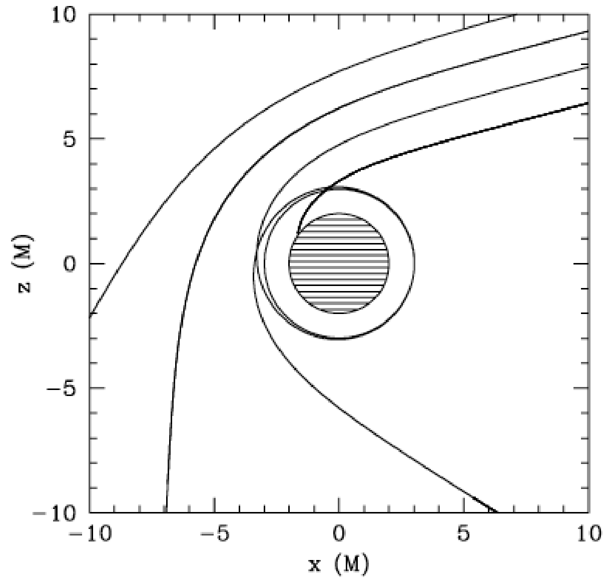


Figure 4. Light rays around a Schwarzschild black hole illustrating the emergence of the bright emission ring. Several light rays approach the black hole from the top right corner. If a ray reaches the photon ring with a 3-momentum that is nearly tangential to the photon orbit, it orbits around the black hole several times, while all other rays are either immediately scattered or captured by the black hole. The footpoints of the orbiting light rays on the image plane will be brighter than those of the nearby rays. The shaded region marks the event horizon.

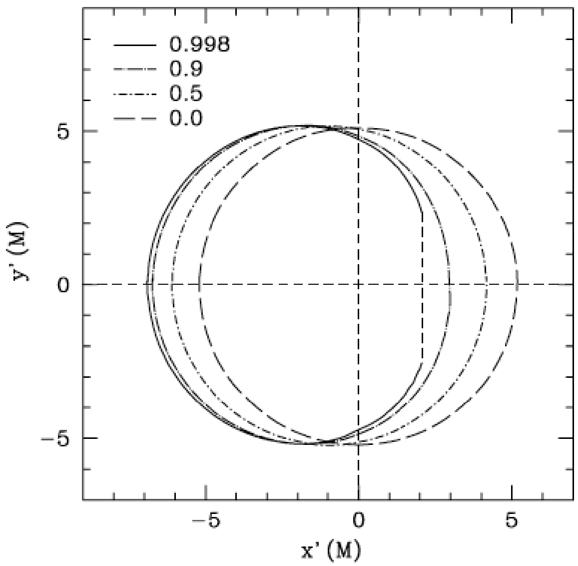


Figure 5. Dependence of the bright photon ring seen by a distant observer on the spin of a Kerr black hole. Increasing the spin leads to a displacement of the photon ring with minimal deformation of its shape. In all cases, the inclination of the observer corresponds to $\cos i = 0.25$.

Johannsen & Psaltis 2010

The Astrophysical Journal Letters, 930:L12 (21pp), 2022 May 10 https://doi.org/10.3847/2041-8213/ac6674

First Sagittarius A* Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole in the Center of the Milky Way

The Event Horizon Telescope Collaboration
(See the end matter for the full list of authors.)
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Abstract

We present the first Event Horizon Telescope (EHT) observations of Sagittarius A* (Sgr A*), the Galactic center source associated with a supermassive black hole. These observations were conducted in 2017 using a global interferometric array of eight telescopes operating at a wavelength of $\lambda = 1.3$ mm. The EHT data resolve a compact emission region with intrahour variability. A variety of imaging and modeling analyses all support an image that is dominated by a bright, thick ring with a diameter of 51.8 ± 2.3 μas (68% credible interval). The ring has modest azimuthal brightness asymmetry and a comparatively dim interior. Using a large suite of numerical simulations, we demonstrate that the EHT images of Sgr A* are consistent with the expected appearance of a Kerr black hole with mass $\sim 4 \times 10^6 M_\odot$, which is inferred to exist at this location based on previous infrared observations of individual stellar orbits, as well as maser proper-motion studies. Our model comparisons disfavor scenarios where the black hole is viewed at high inclination ($i > 50°$), as well as nonspinning black holes and those with retrograde accretion disks. Our results provide direct evidence for the presence of a supermassive black hole at the center of the Milky Way, and for the first time we connect the predictions from dynamical measurements of stellar orbits on scales of 10^3–10^5 gravitational radii to event-horizon-scale images and variability. Furthermore, a comparison with the EHT results for the supermassive black hole M87* shows consistency with the predictions of general relativity spanning over three orders of magnitude in central mass.

Unified Astronomy Thesaurus concepts: Black holes (162); Kerr black holes (886); Rotating black holes (1406); Heterodyne interferometry (726); Galactic center (565)

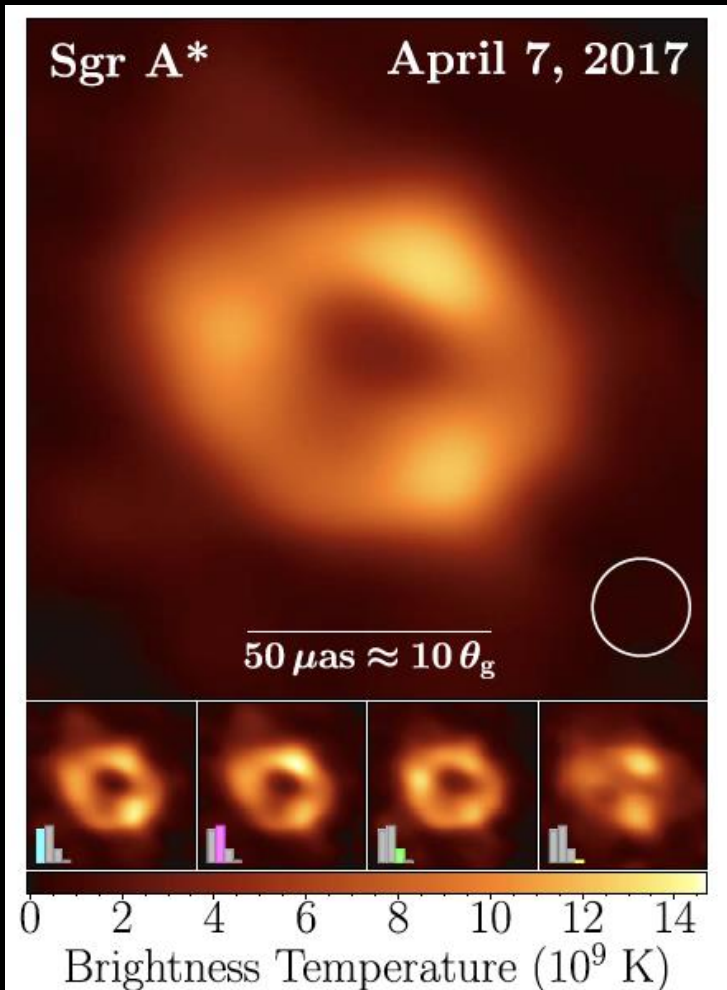

Image of the accretion flow around the Milky Way's central black hole.

Simulated images

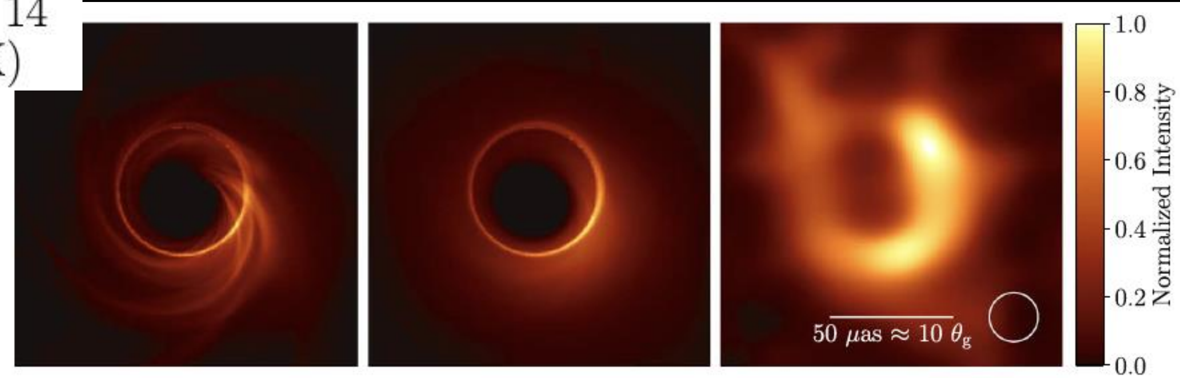

Figure 5. Simulated images of Sgr A*. Left: a single snapshot image of a numerical simulation of Sgr A* that passes 10 out of the 11 observational criteria described in Paper V. Middle: the average of this simulation with time sampling that matches the EHT observational cadence on April 7. Right: representative image reconstruction using synthetic visibilities generated from the simulation in the adjacent panels (see Appendix H in Paper III). This image has been averaged across methodologies and reconstructed morphologies, as in Figure 3. Each panel is shown on a linear brightness scale that is normalized to its peak.