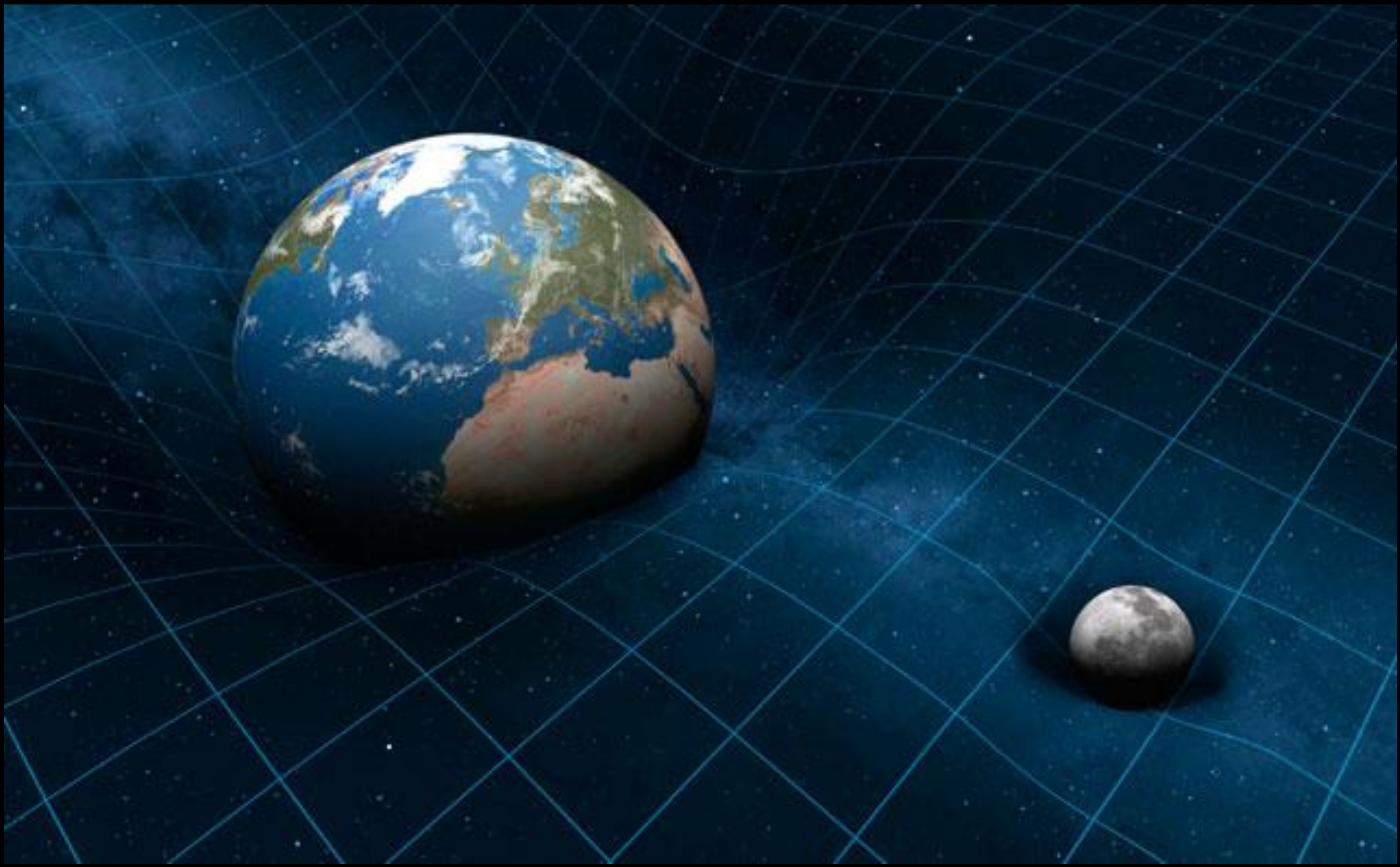
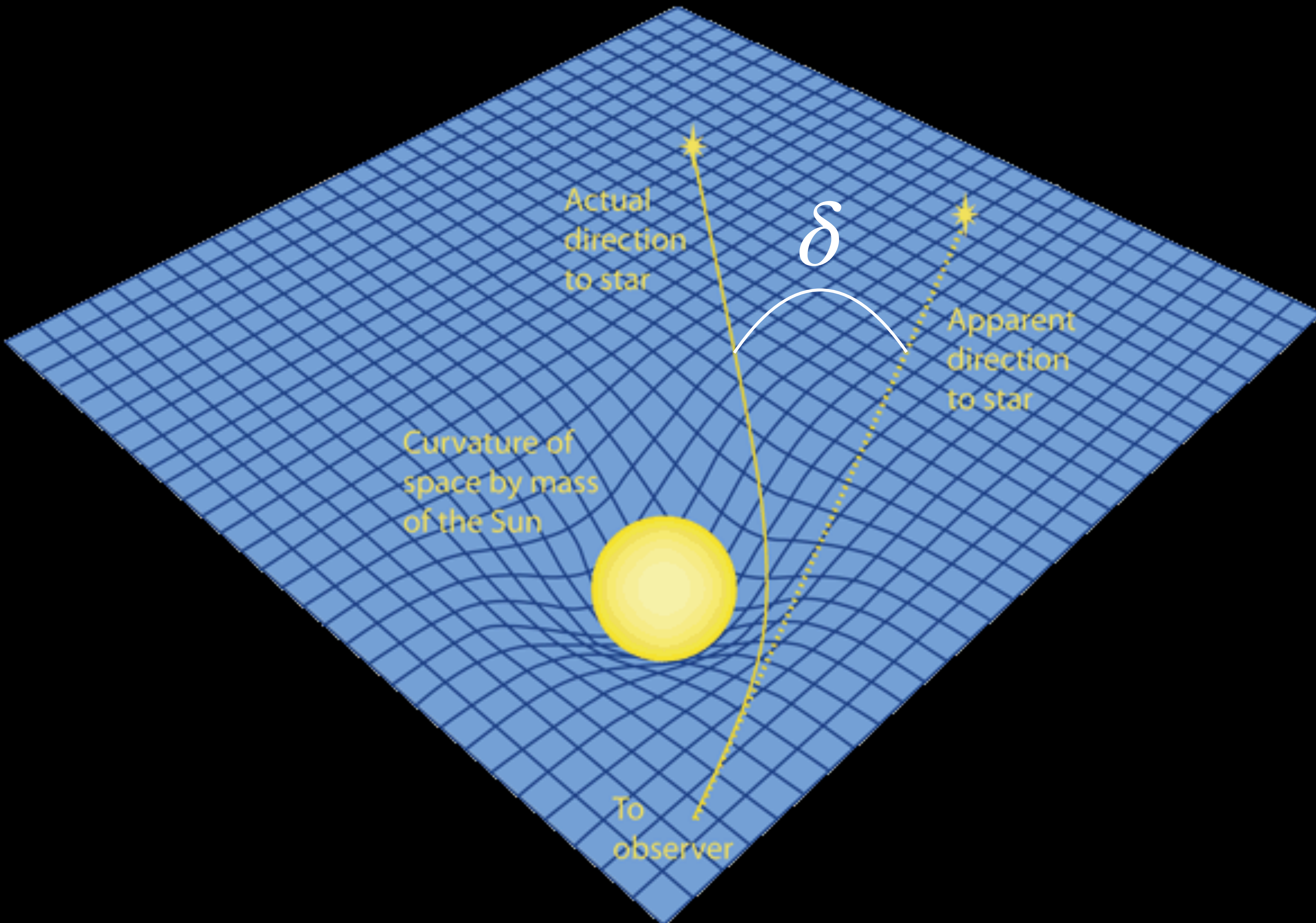
First Sight of a Black Hole

Recent Results from the Event Horizon Telescope





Actual
direction
to star
δ
Apparent
direction
to star
Curvature of
space by mass
of the Sun
To
observer

A Problem

The deflection of starlight is small:

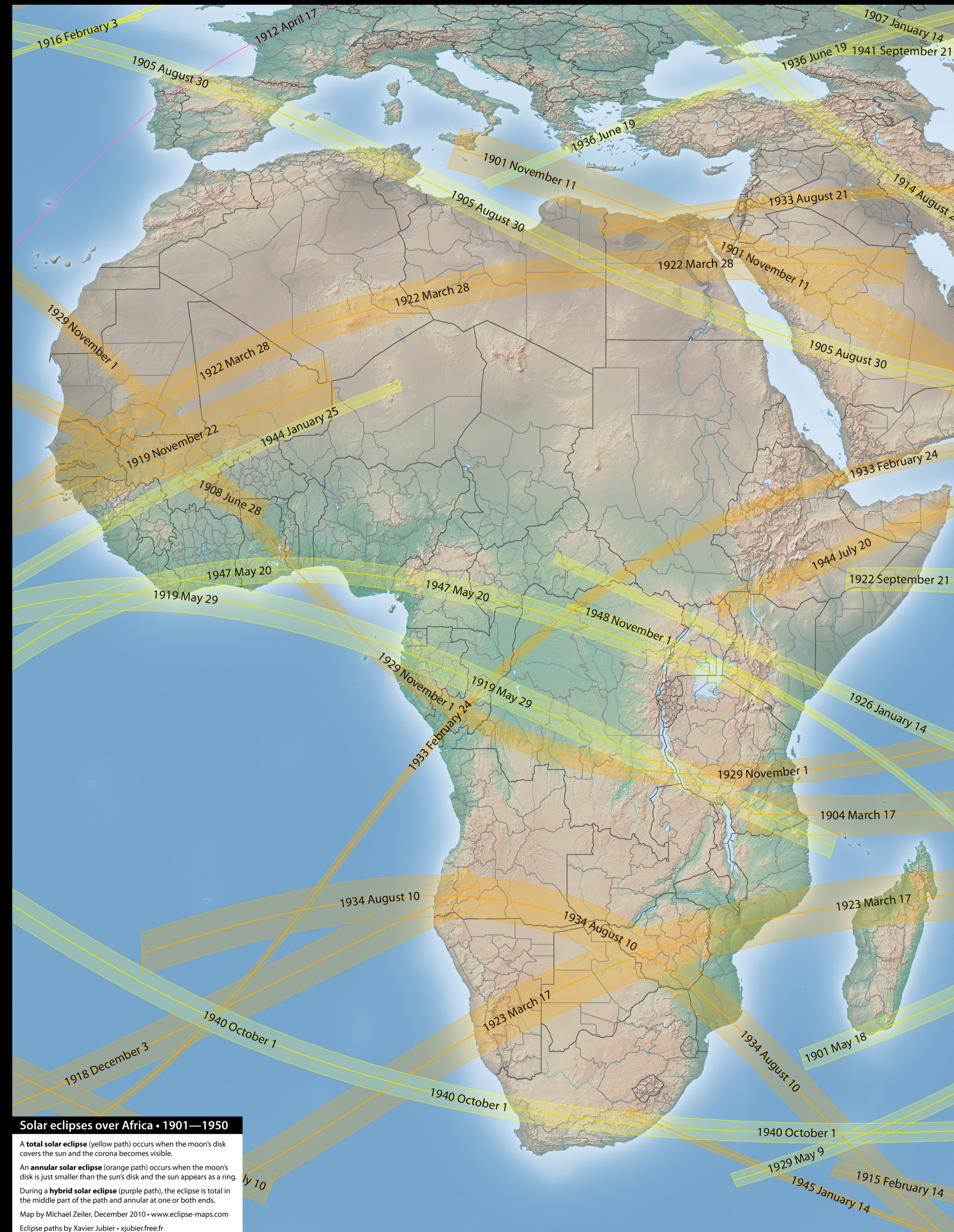
"Newtonian" prediction: $\delta_N = \frac{2GM_{\text{Sun}}}{c^2 R_{\text{Sun}}} = 0.825$ arcsec

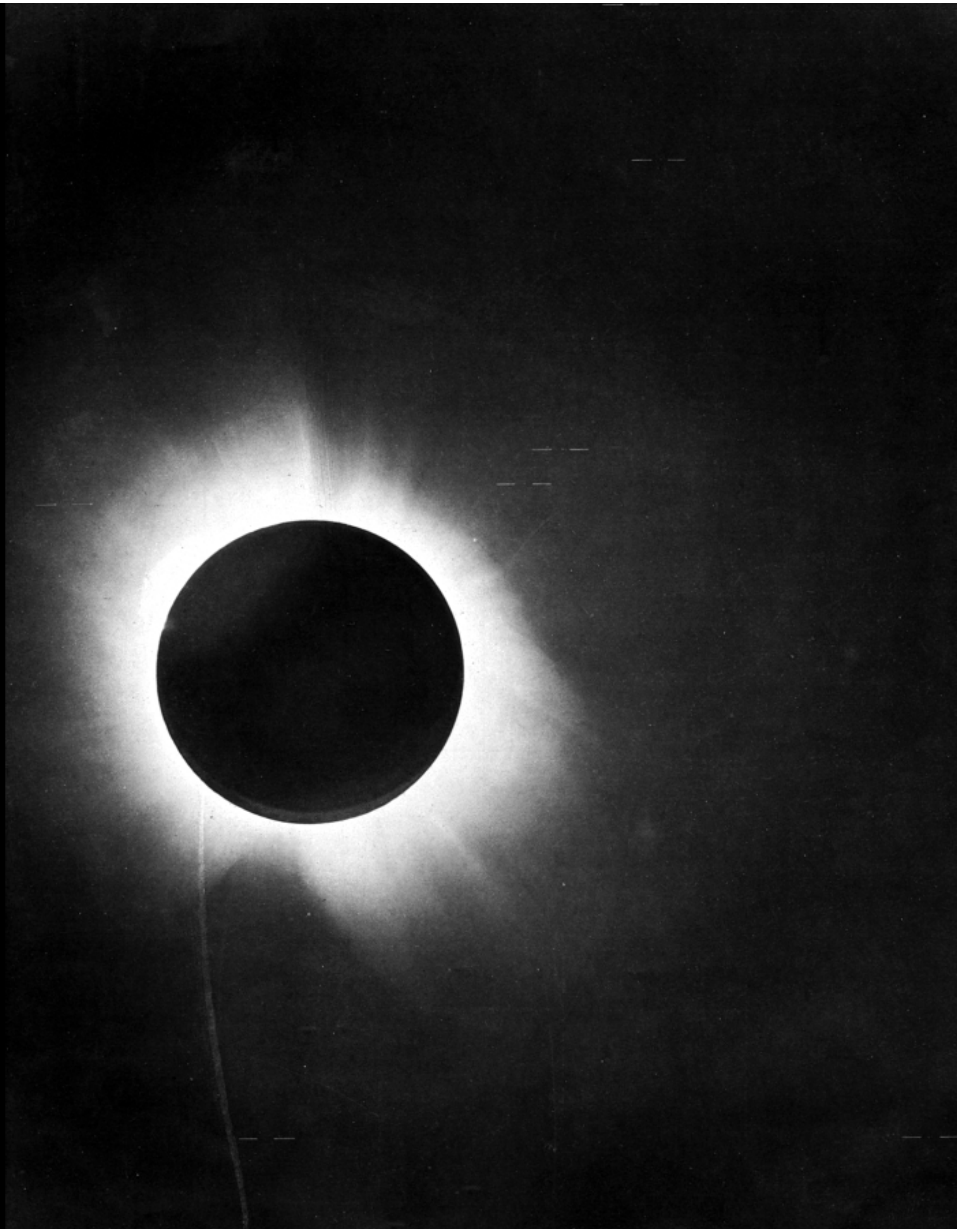
Einstein's prediction: $\delta_E = 2\delta_N = \frac{4GM_{\text{Sun}}}{c^2 R_{\text{Sun}}}$

$= 1.75$ arcsec

Sobral
State of Ceará
Brazil
3.69°S, 40.35°W
Cuba
Dominican Republic
Puerto Rico
Honduras
Caribbean Sea
Nicaragua
Costa Rica
Panama
Venezuela
French Guiana
Guyana
Suriname
Colombia
Sobral
Ecuador
Brazil
Peru
Bolivia
3D
Google
Google Data SIO, NOAA, U.S. Navy, NGA, GEBCO IBCAO INEGI Landsat / Copernicus PGC/NASA U.S. Geological Survey
Camera : 10,675 km 11°06'10"S 36°08'53"W 100%


Príncipe
São Tomé and Príncipe
1.61°N, 7.41°E
Red Sea
Mauritania
Mali
Niger
Chad
Sudan
Eritrea
Senegal
Burkina Faso
Guinea-Bissau
Guinea
Benin
Nigeria
Djibouti
Ethiopia
Sierra Leone
Côte d'Ivoire
Togo
Ghana
Liberia
Central African Republic
South Sudan
Príncipe
Gulf of Guinea
Equatorial Guinea
Gabon
Uganda
Kenya
Rwanda
Burundi
DRC
Tanzania
Angola
Zambia
Malawi
Mozambique
Zimbabwe
3D
Google
Data SIO, NOAA, U.S. Navy, NGA, GEBCO IBCAO Landsat / Copernicus U.S. Geological Survey Camera : 10,020 km 3°14'00"N 38°28'57"E 100%


Solar eclipses over South America • 1901—1950
A total solar eclipse (yellow path) occurs when the moon's disk covers the sun and the corona becomes visible.
An annular solar eclipse (orange path) occurs when the moon's disk is just smaller than the sun's disk and the sun appears as a ring.
During a hybrid solar eclipse (purple path), the eclipse is total in the middle part of the path and annular at one or both ends.
Map by Michael Zeiler, December 2010 • www.eclipse-maps.com
Eclipse paths by Xavier Jubier • xjubier.free.fr
1923 September 10
1919 November 22
1916 February 3
1912 April 17
1940 October 1
1912 October 10
1922 March 28
1919 May 29
1947 November 12
1944 January 25
1937 June 8
1941 March 27
1947 May 20
1907 July 10
1908 December 23
1904 September 9
1918 December 3
1927 January 3
1933 February 24
1914 February 25
1923 March 17
1930 October 21
1921 October 1

Solar eclipses over Africa • 1901—1950
A total solar eclipse (yellow path) occurs when the moon's disk covers the sun and the corona becomes visible.
An annular solar eclipse (orange path) occurs when the moon's disk is just smaller than the sun's disk and the sun appears as a ring.
During a hybrid solar eclipse (purple path), the eclipse is total in the middle part of the path and annular at one or both ends.
Map by Michael Zeiler, December 2010 • www.eclipse-maps.com
Eclipse paths by Xavier Jubier • xjubier.free.fr
1916 February 3
1912 April 17
1905 August 30
1907 January 14
1936 June 19
1941 September 21
1901 November 11
1914 August 21
1933 August 21
1922 March 28
1929 November 1
1944 January 25
1919 November 22
1933 February 24
1908 June 28
1944 July 20
1947 May 20
1922 September 21
1919 May 29
1948 November 1
1926 January 14
1904 March 17
1934 August 10
1923 March 17
1940 October 1
1918 December 3
1901 May 18
1929 May 9
1915 February 14
1945 January 14



Results

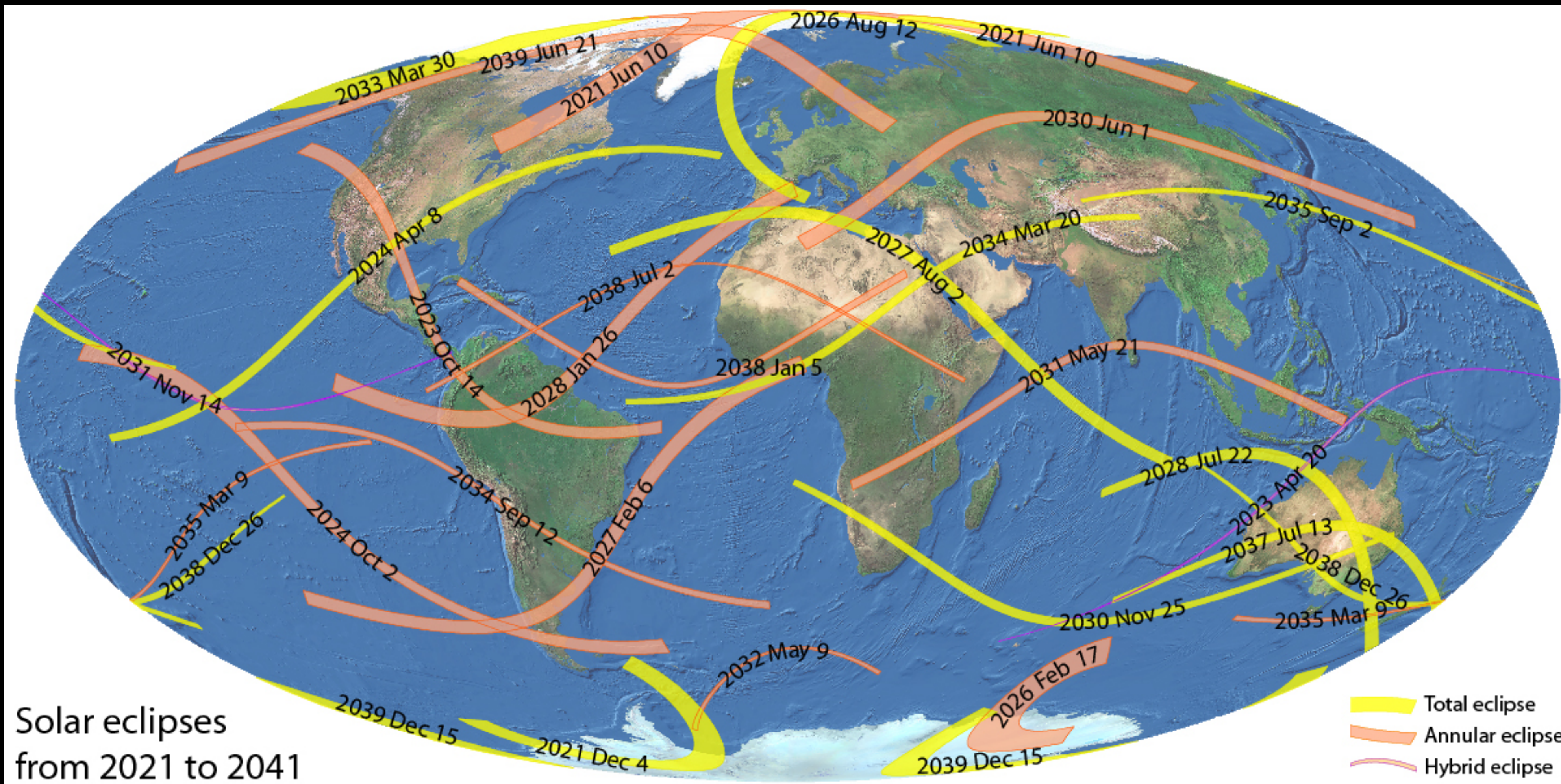
Gravitational displacement at the Sun's limb in seconds of arc

Determination	Displacement
Predicted from Einstein's Theory	1.75
4-inch plates reduced by Dyson *et al*.	1.98 ± 0.18
4-inch plates measured on the Zeiss	1.90 ± 0.11
Astrographic plates reduced by Dyson *et al*.	0.93
Astrographic plates measured on the Zeiss	1.55 ± 0.34

Principe result reduced by Eddington 1.61 ± 0.3


LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse


2026 Aug 12
2021 Jun 10
2039 Jun 21
2033 Mar 30
2021 Jun 10
2030 Jun 1
2035 Sep 2
2024 Apr 8
2034 Mar 20
2027 Aug 2
2038 Jul 2
2023 Oct 14
2028 Jan 26
2038 Jan 5
2031 May 21
2031 Nov 14
2028 Jul 22
2023 Apr 20
2034 Sep 12
2035 Mar 9
2038 Dec 26
2024 Oct 2
2027 Feb 6
2037 Jul 13
2038 Dec 26
2030 Nov 25
2035 Mar 9
2032 May 9
2026 Feb 17
2039 Dec 15
2021 Dec 4
2039 Dec 15
Solar eclipses
from 2021 to 2041
Total eclipse
Annular eclipse
Hybrid eclipse

Outline

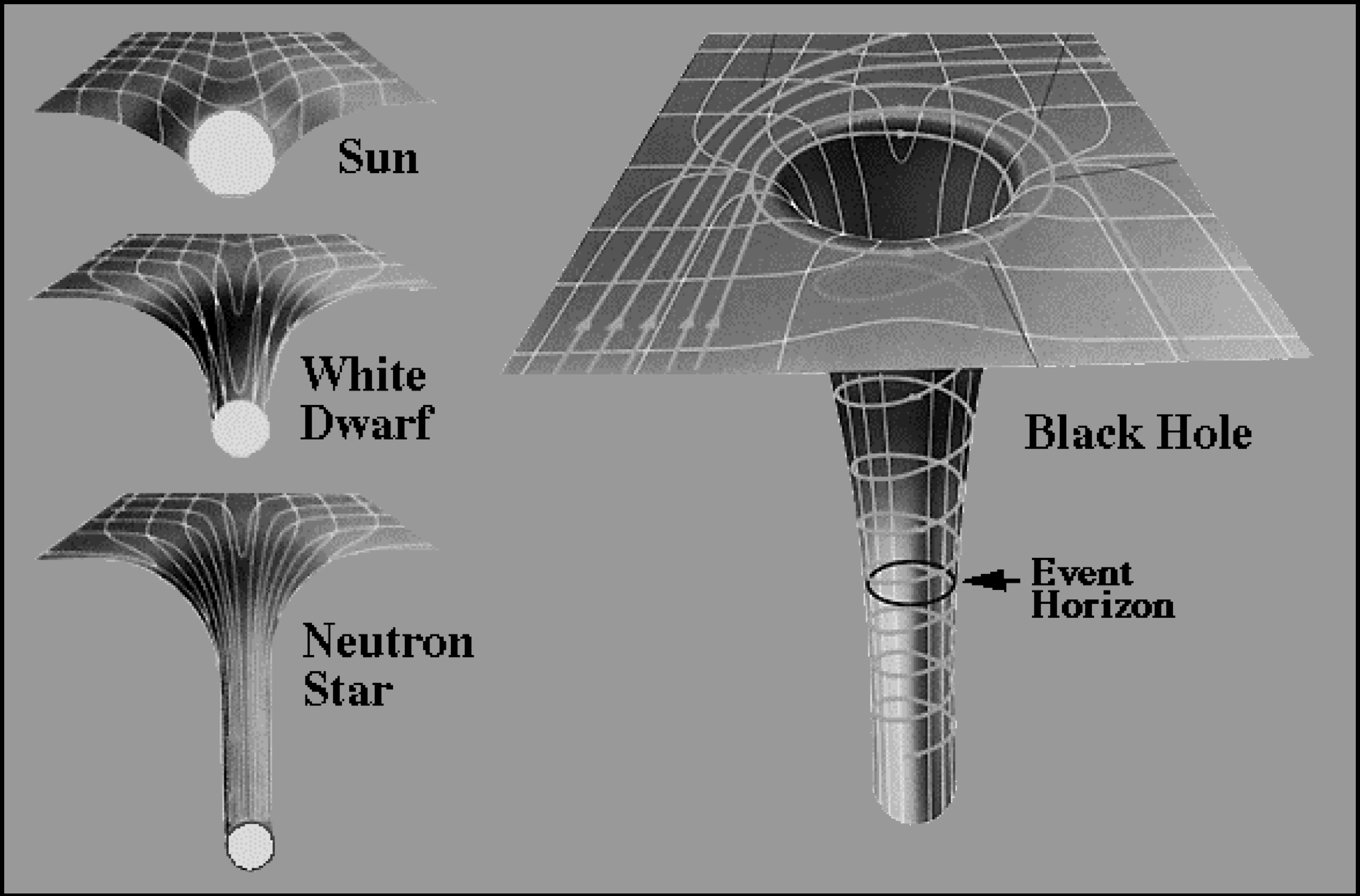
I. Black Holes

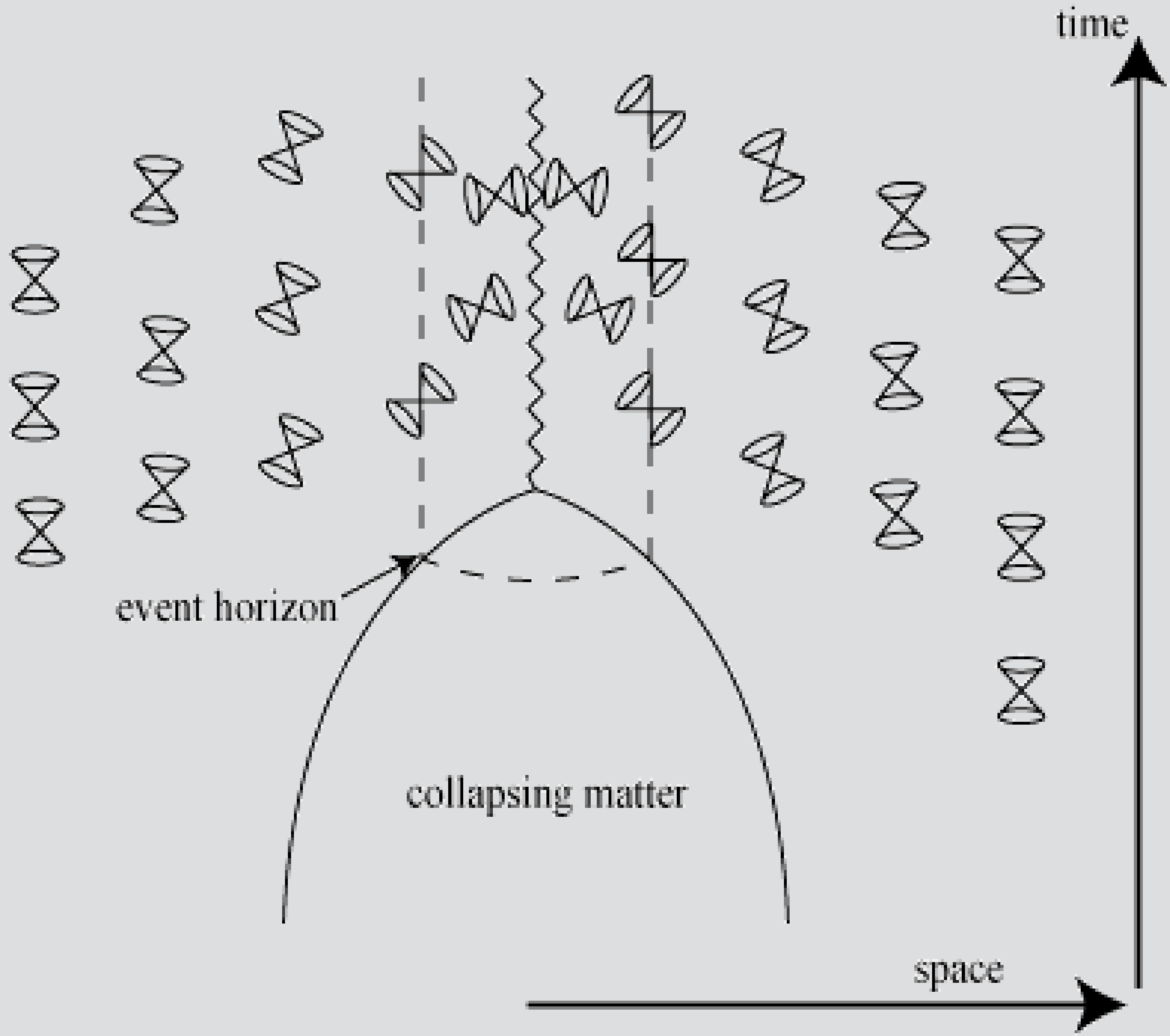
II. Event Horizon Telescope

III. The Image

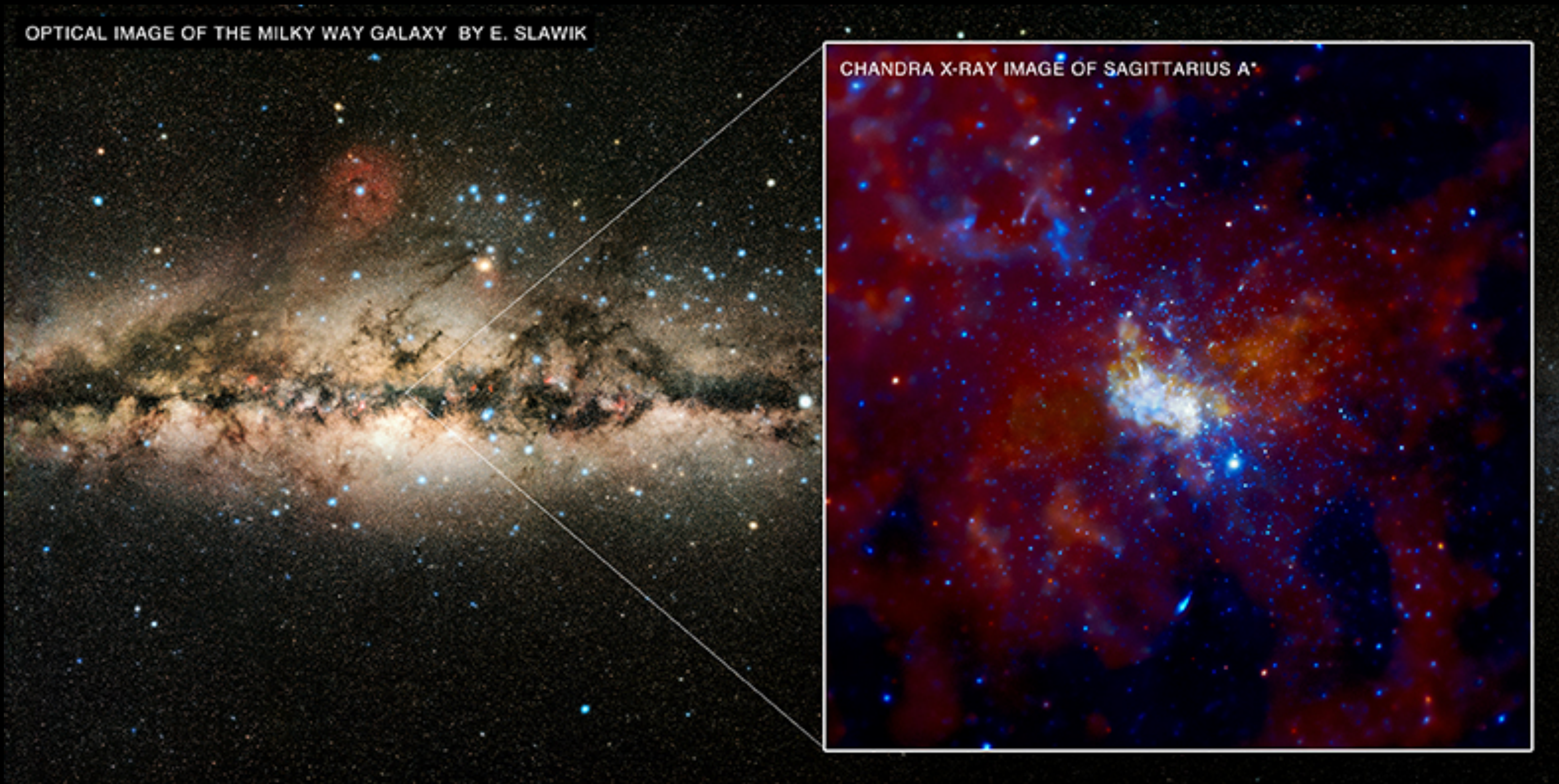
IV. The Future of Black Holes

Black Holes



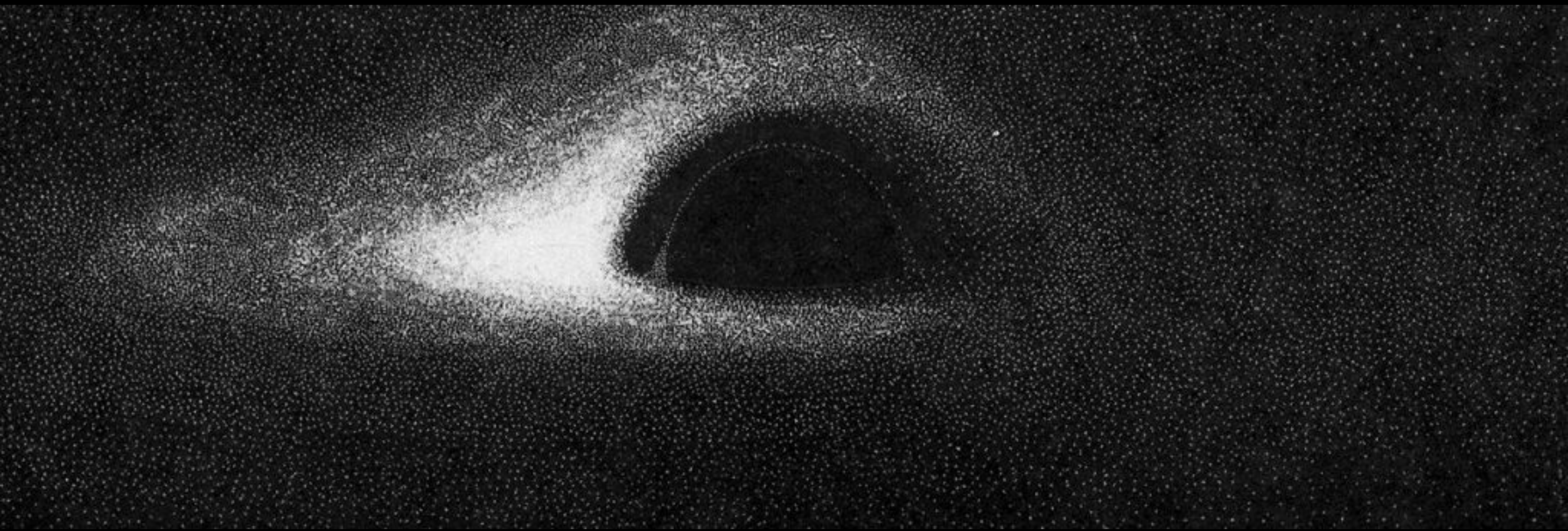


The event horizon is "a perfect unidirectional membrane: causal influences can cross it in only one direction”. —D. Finkelstein 1958



OPTICAL IMAGE OF THE MILKY WAY GALAXY BY E. SLAWIK
CHANDRA X-RAY IMAGE OF SAGITTARIUS A*

In the 1970’s Jim Bardeen, Jean-Pierre Luminet and others make first theoretical images of a Black Hole



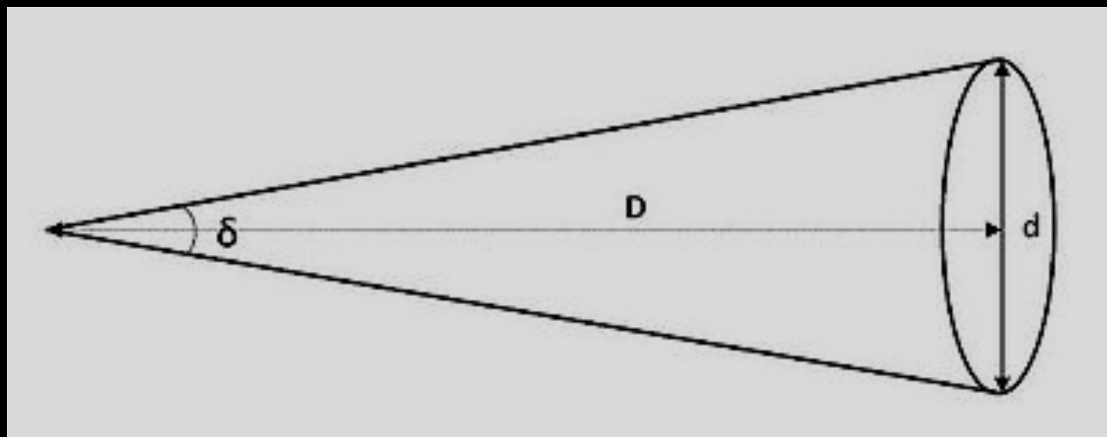
Imaging Black Holes:
a Much Worse Problem

We characterize the size of a black hole with the radius of its event horizon, known as the Schwarzschild radius:

$$R_S = \frac{2GM}{c^2}$$

BH Sun	$R_S = 3$ km
Sag A*	$R_S = 12 \times 10^6$ km
M87*	$R_S = 19.5 \times 10^9$ km

Imaging Black Holes:
a Much Worse Problem



Sun	$\delta = 0.53^{\circ} = 1913$ asecs
BH Sun	$\delta = 8251\ \mu$asecs
Sag A*	$\delta = 20\ \mu$asecs
M87*	$\delta = 16\ \mu$asecs

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Event Horizon Telescope (EHT)

A Global Network of Radio Telescopes

2018 Observatories

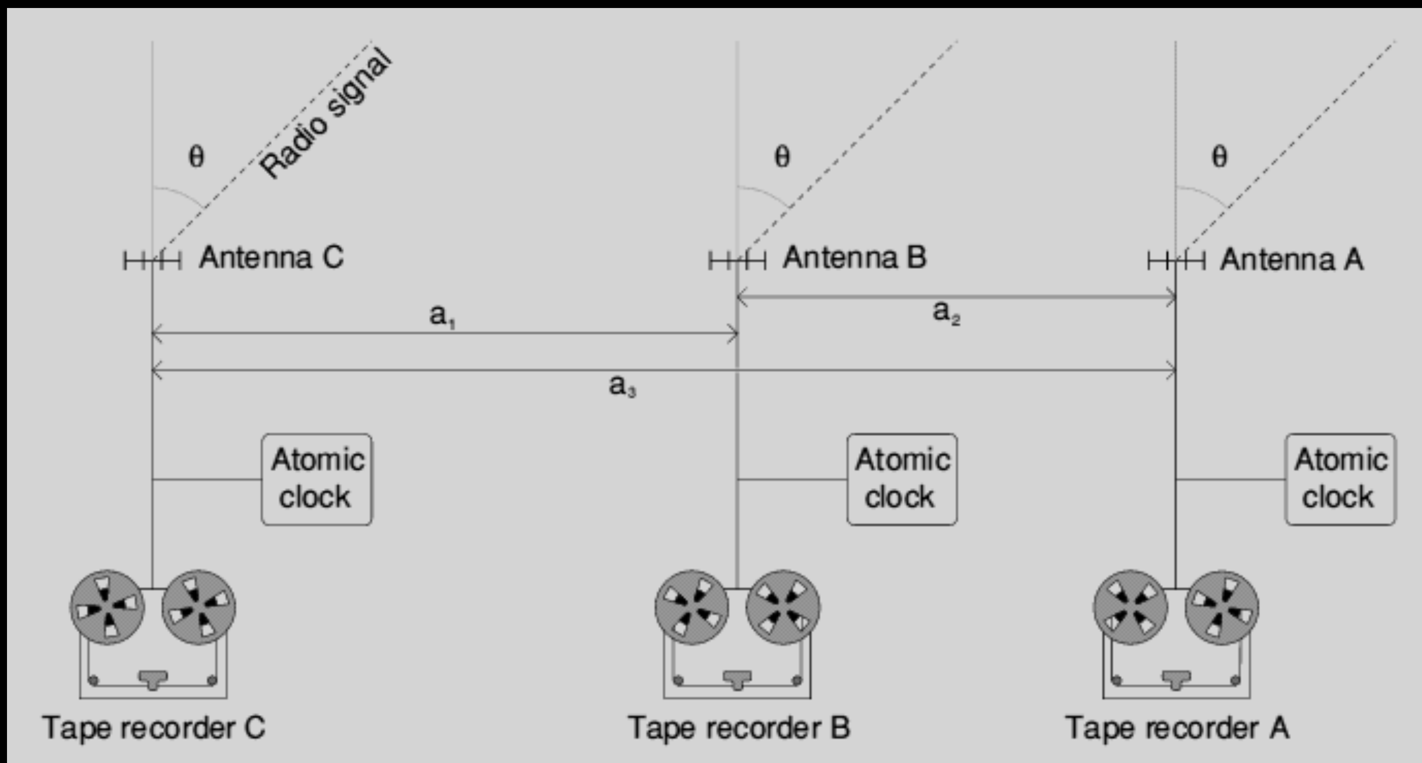
- **ALMA** — Atacama Large Millimeter/ submillimeter Array
  CHAJNANTOR PLATEAU, CHILE
- **APEX** — Atacama Pathfinder EXperiment
  CHAJNANTOR PLATEAU, CHILE
- **30-M** — IRAM 30-M Telescope
  PICO VELETA, SPAIN
- **JCMT** — James Clerk Maxwell Telescope
  MAUNAKEA, HAWAII
- **LMT** — Large Millimeter 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

Observing in 2020

- **Kitt Peak** — Kitt Peak 12-meter Telescope
  KITT PEAK, ARIZONA, USA
- **NOEMA** — NOEMA Observatory
  PLATEAU DE BURE, FRANCE

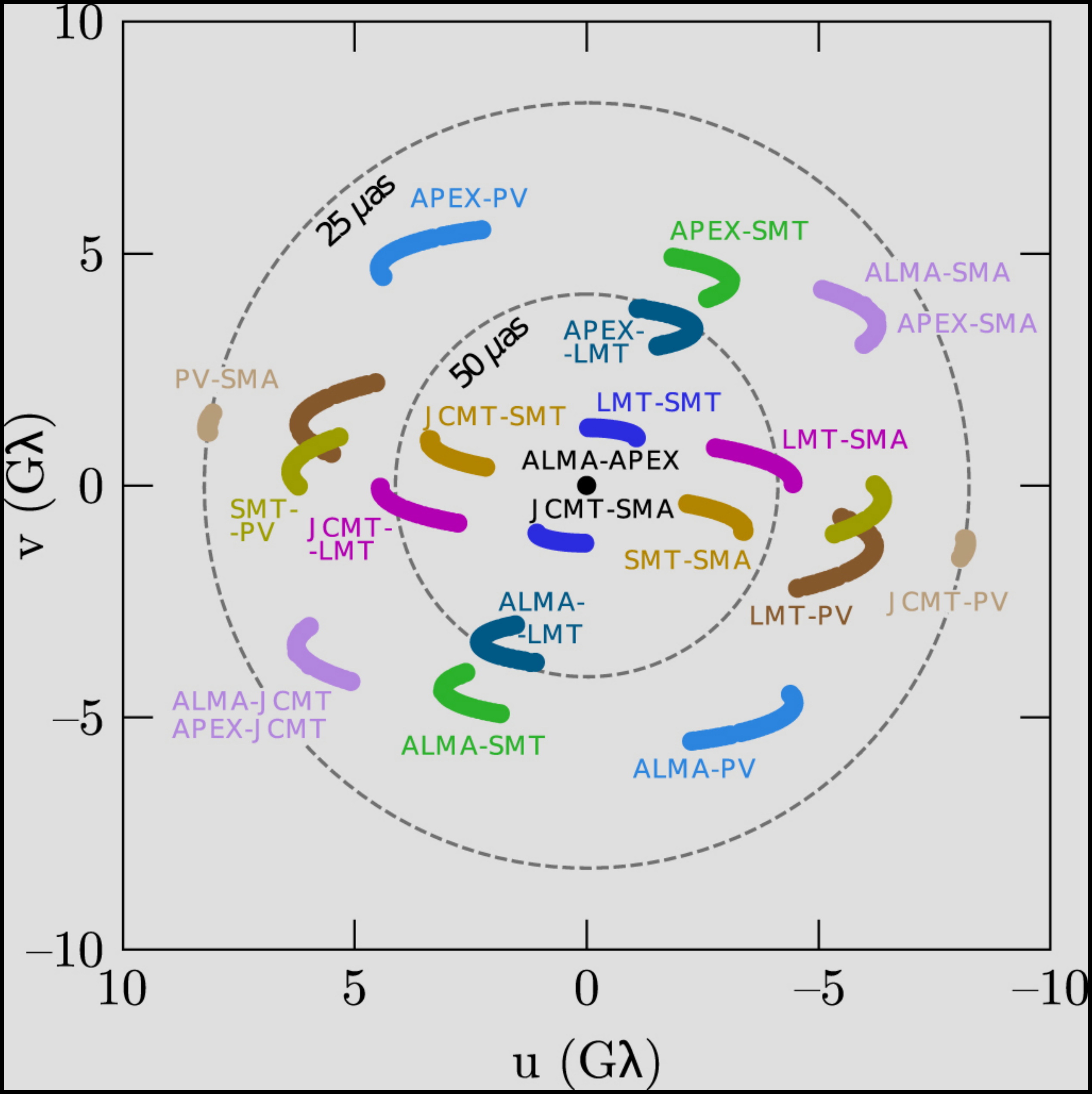
NRAO

Signals from the telescopes are recorded locally and time stamped using extremely precise and stable atomic clocks

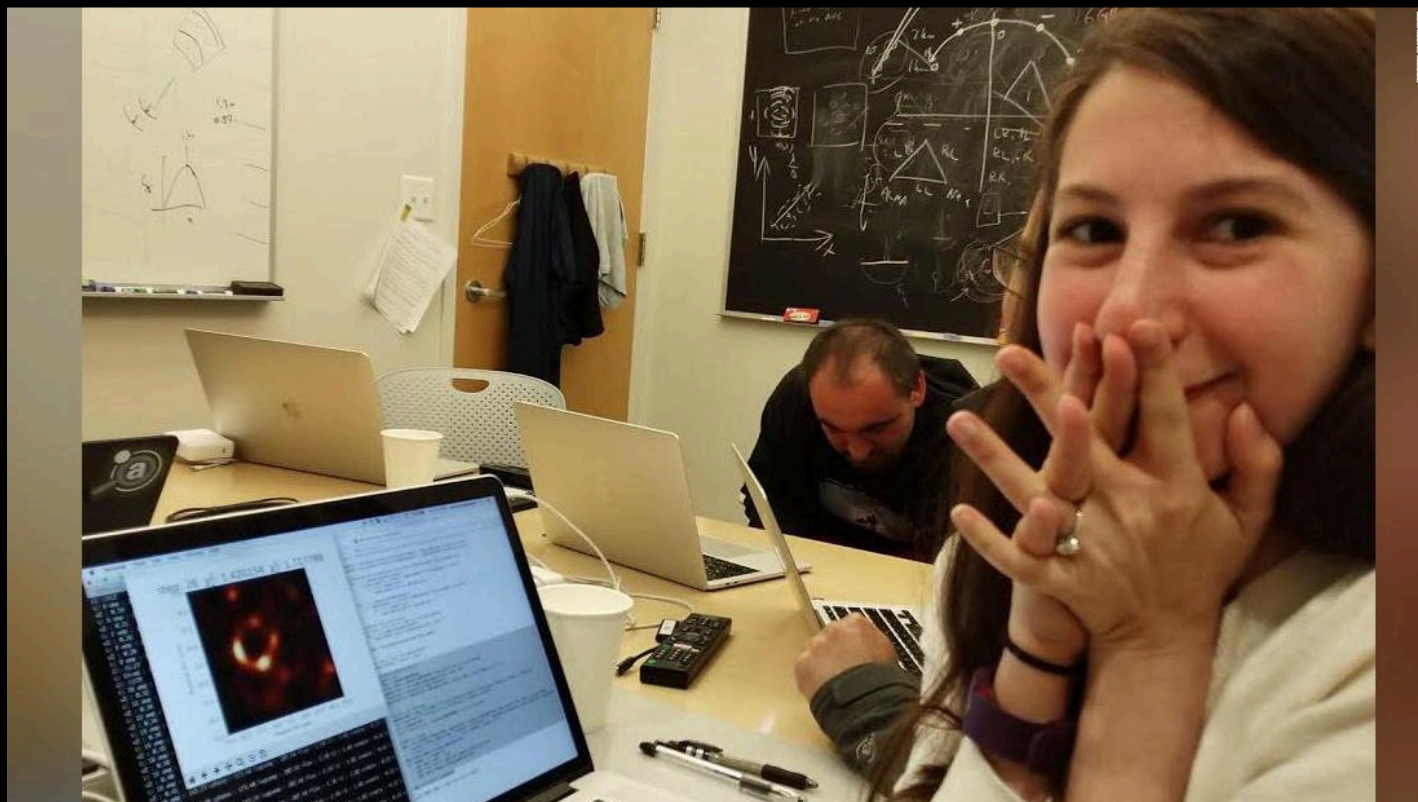


The data are collected and compared carefully; they use both time stamp and predicted time delays to align the signals

Combined coverage over the 4 nights of observing



The collaboration split into 4 teams that each independently reconstructed images from the interferometry data



www.ted.com/talks/katie_bouman_what_does_a_black_hole_look_like?language=en

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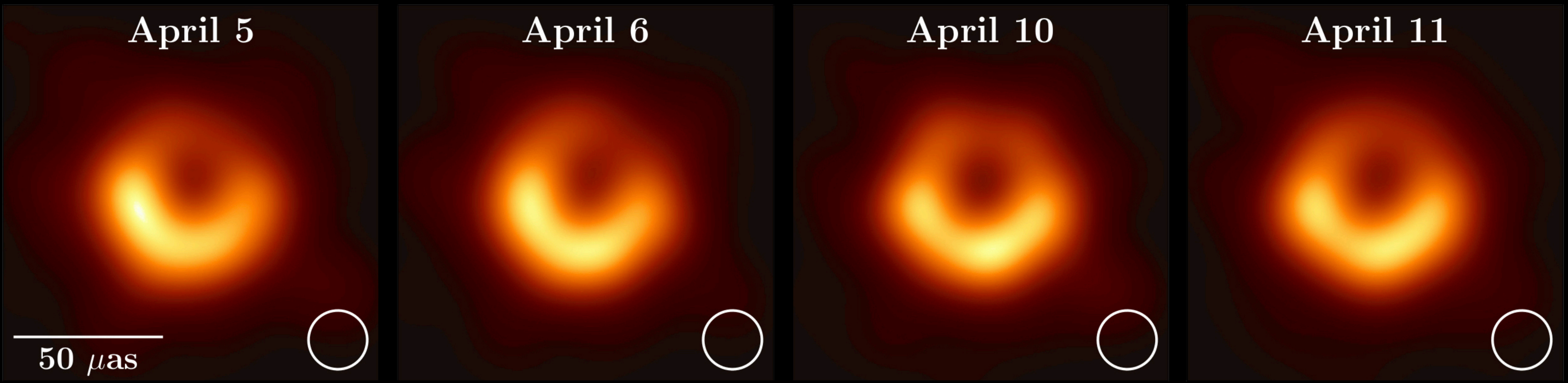
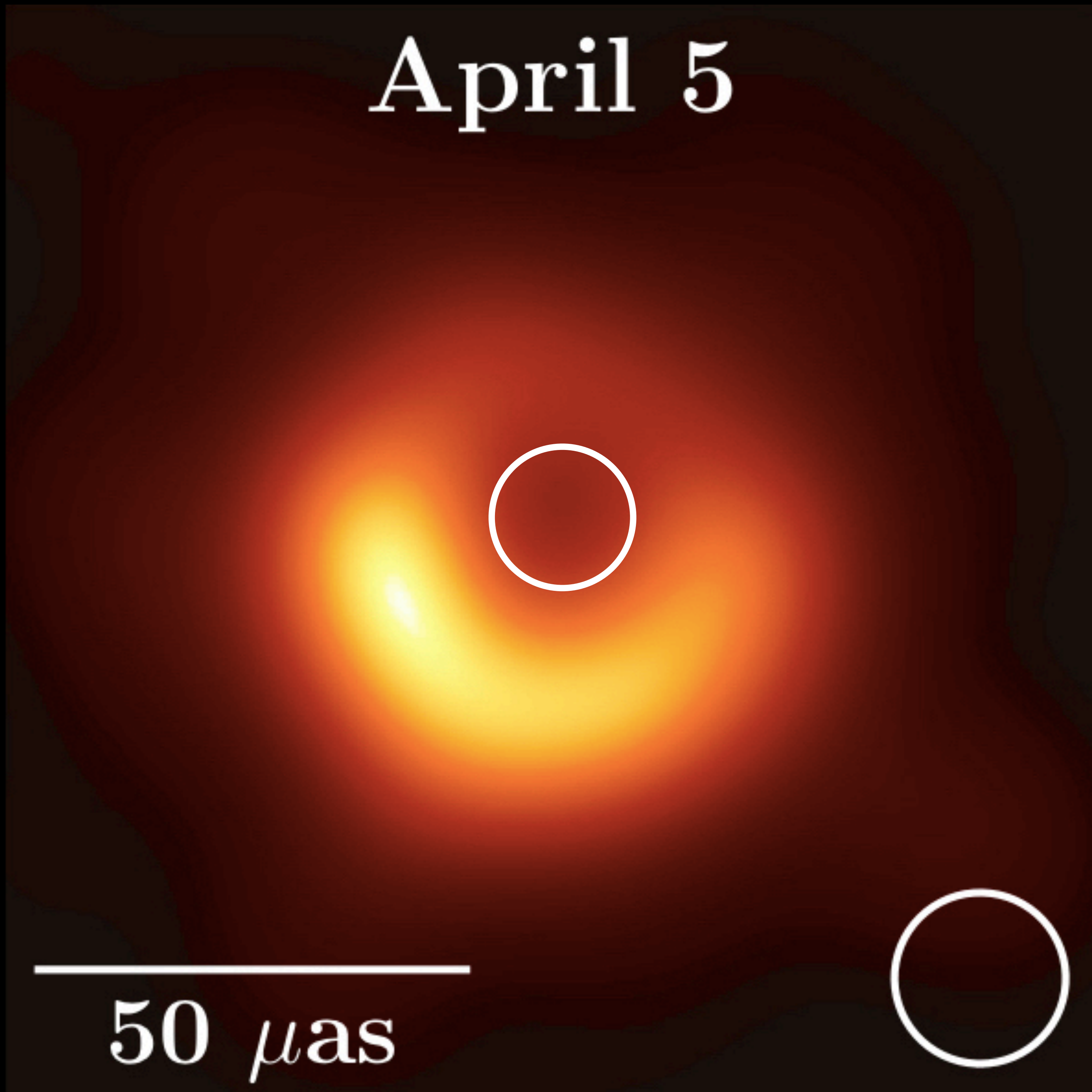
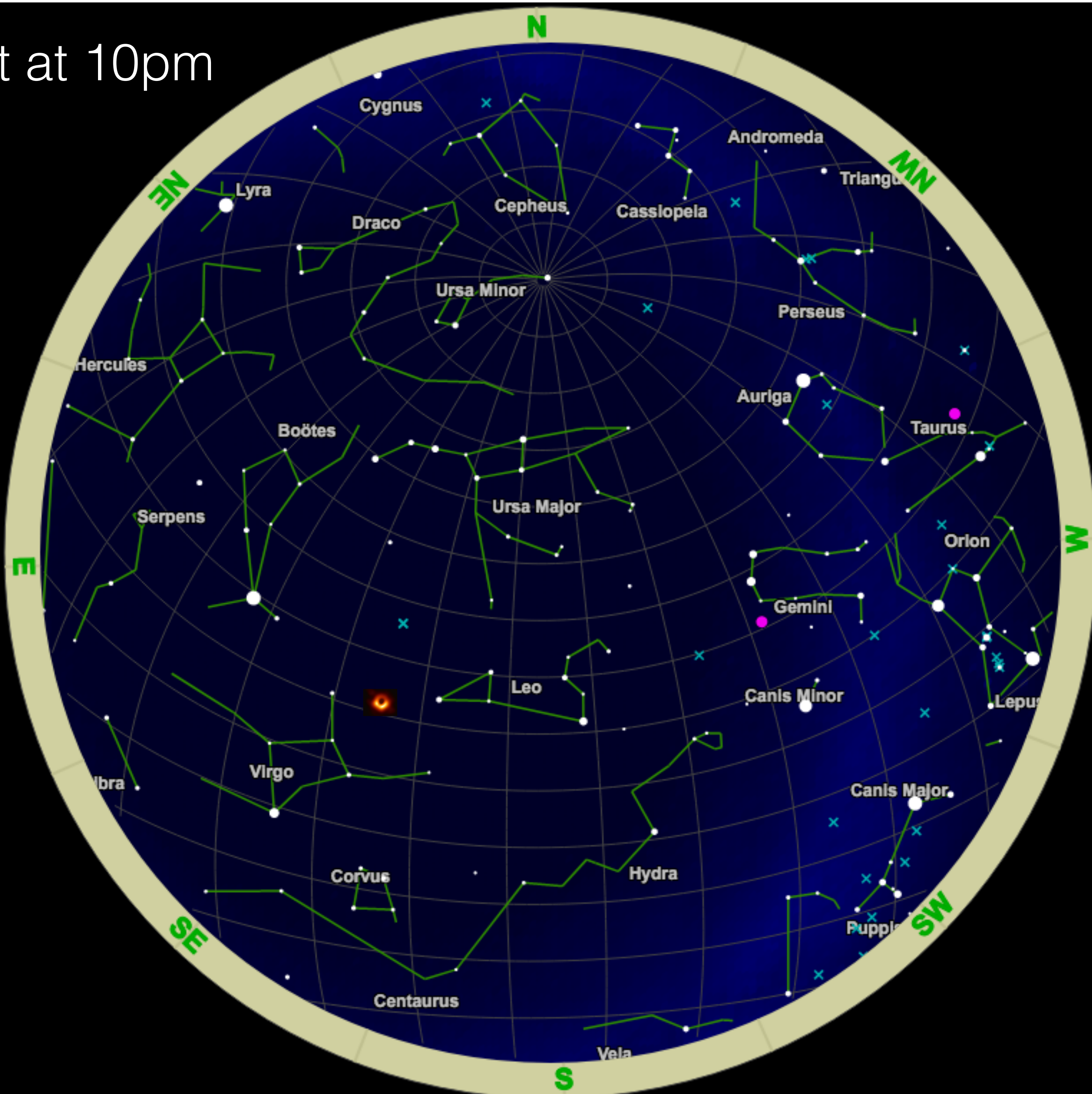

April 5
April 6
April 10
April 11
50 μas

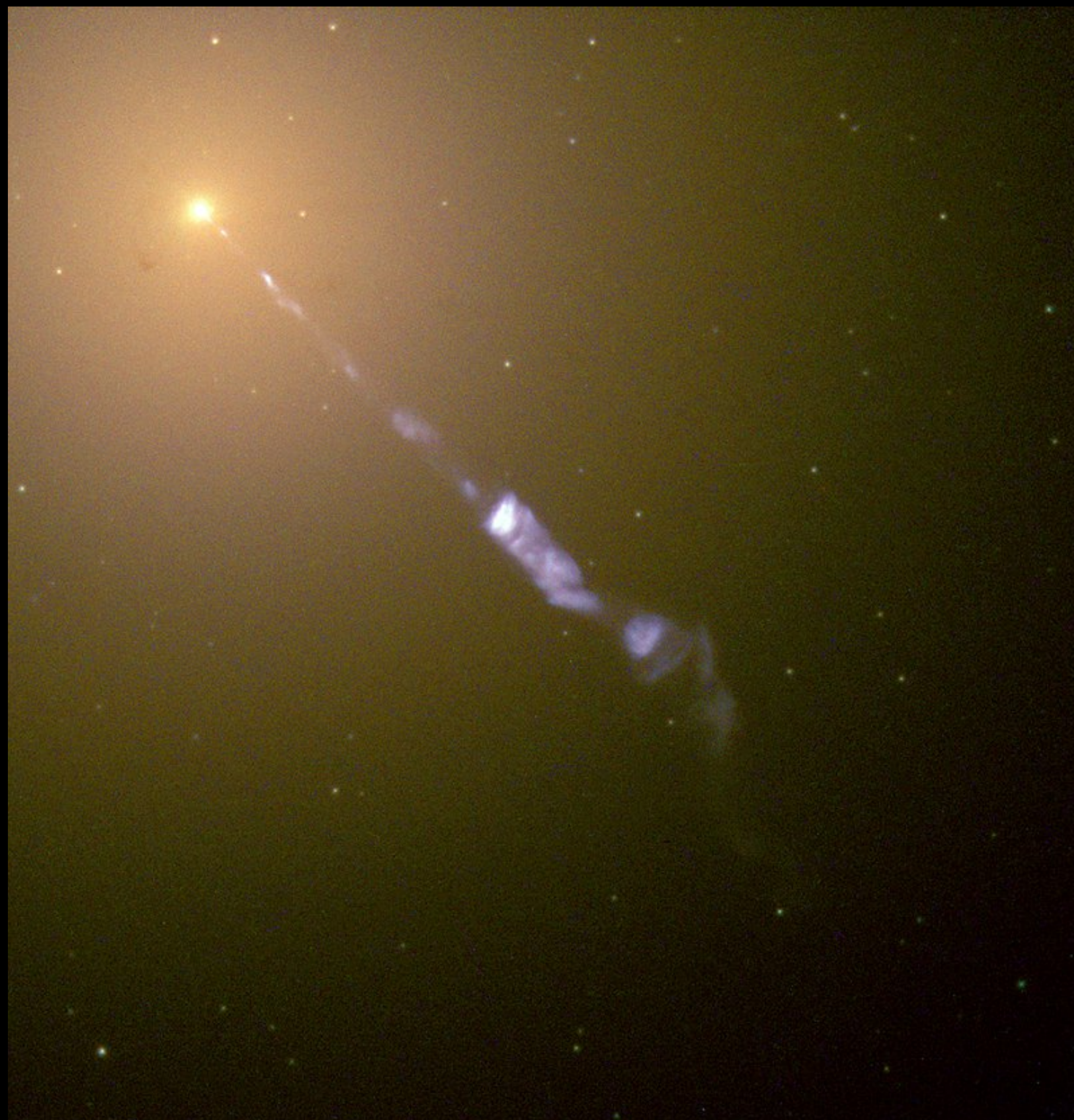

April 5
50 μas

Tonight at 10pm

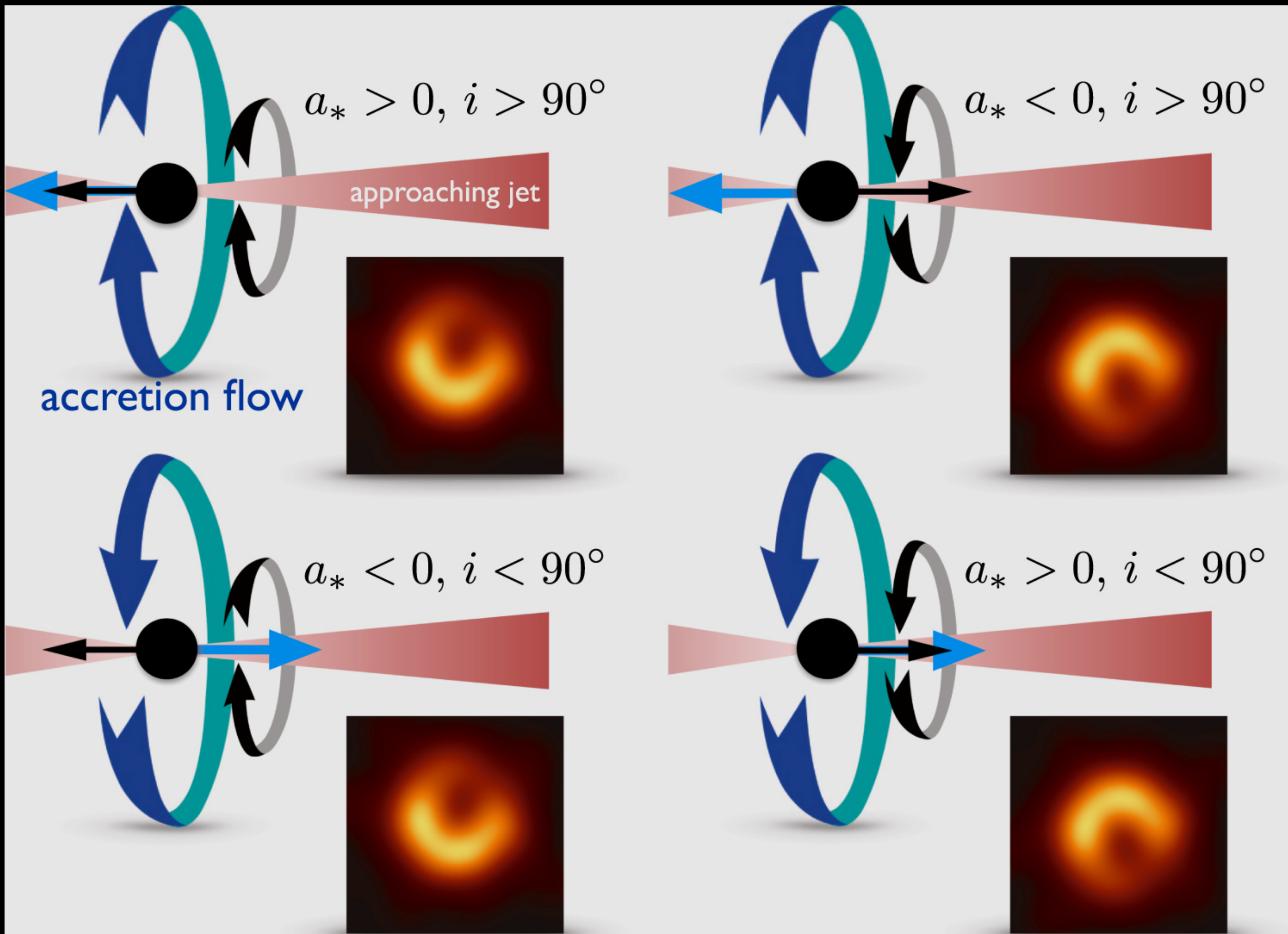


https://in-the-sky.org

The image is consistent with a spinning black hole



These images are consistent with a spinning black hole.
How is it spinning?



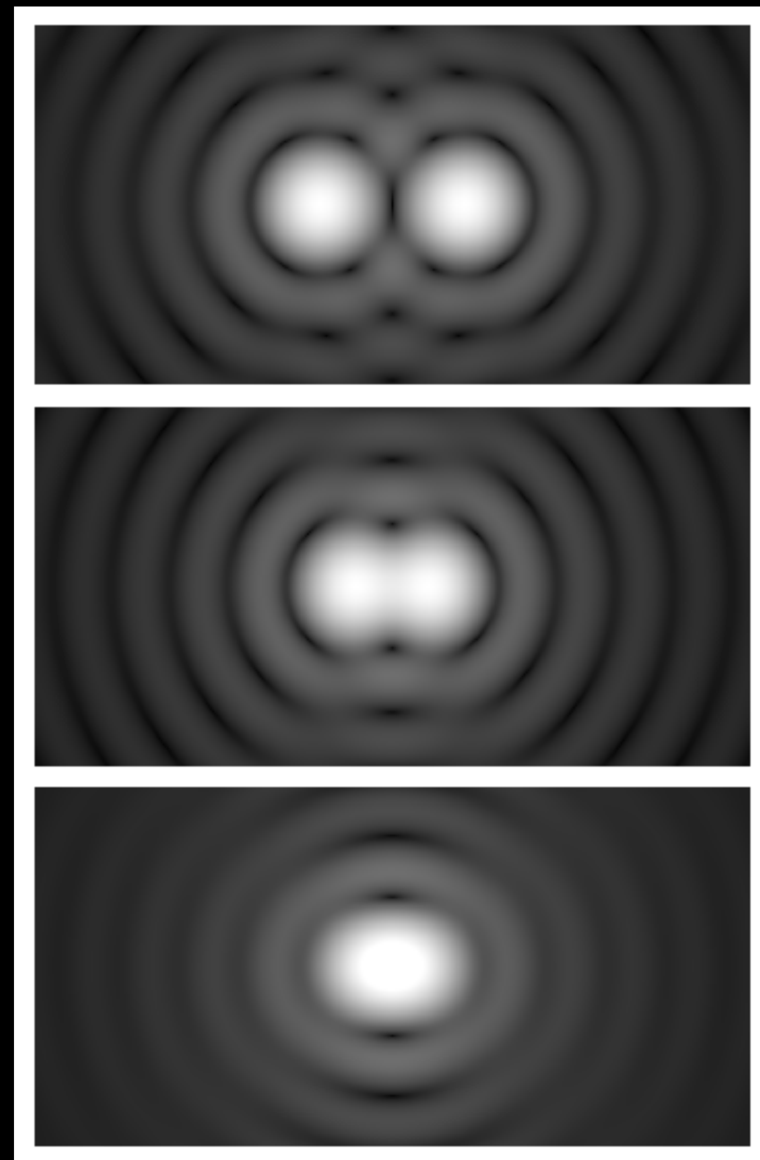
Why is the image blurry?

$$\theta \sim \frac{\lambda}{D}$$

$\lambda = 1.3$ mm

$D = 2R_{\mathrm{E}} = 12741$ km

$\implies \theta = 21\ \mu$asecs



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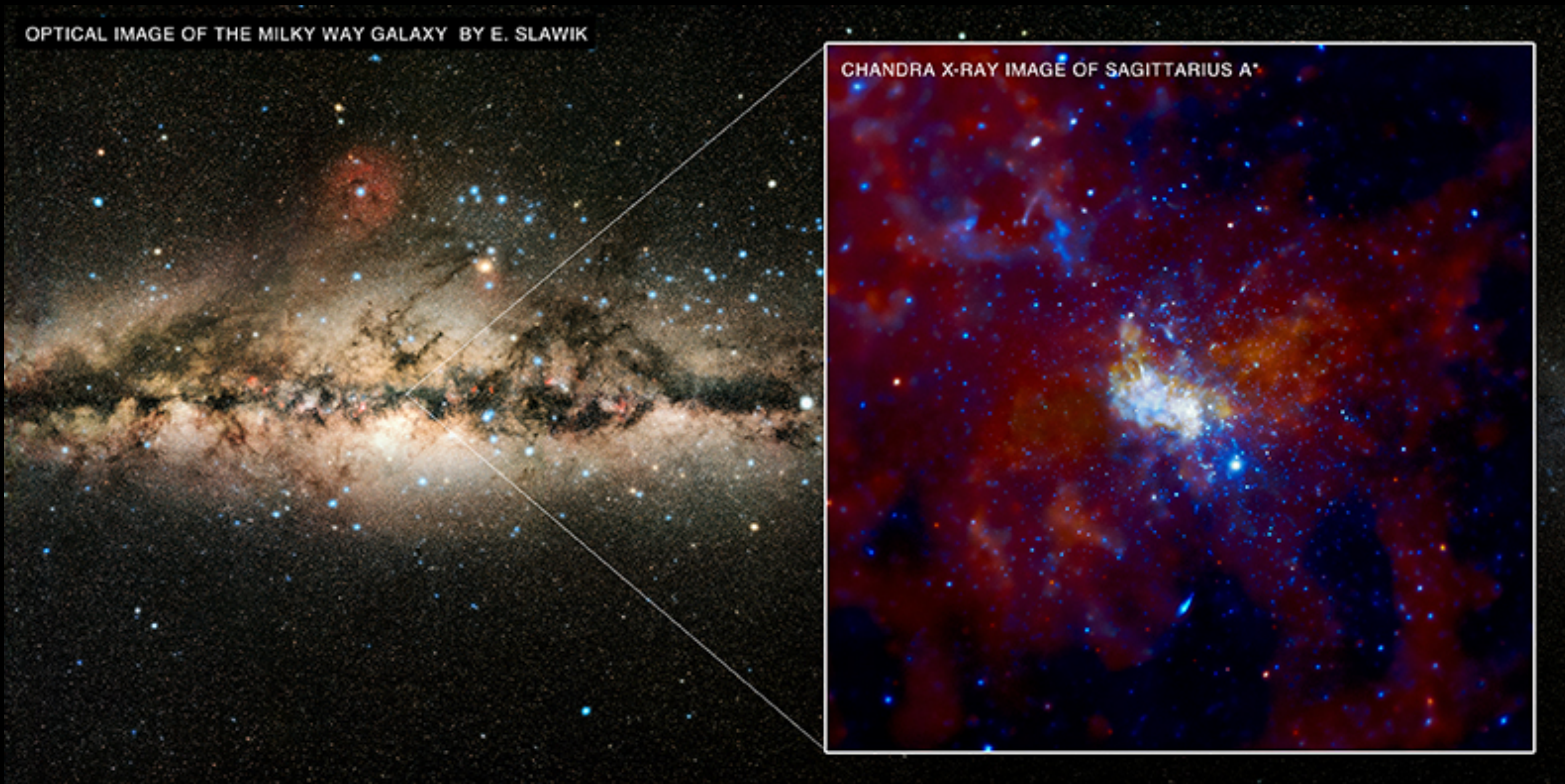
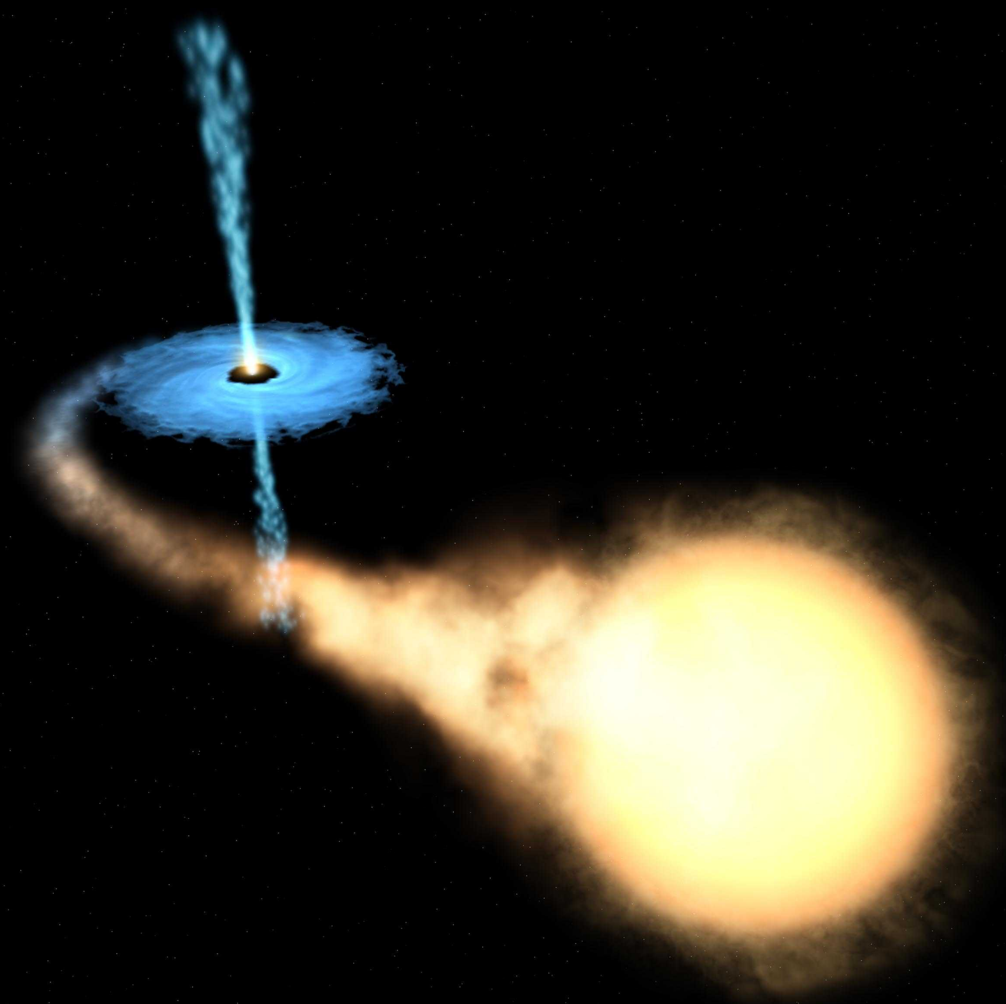
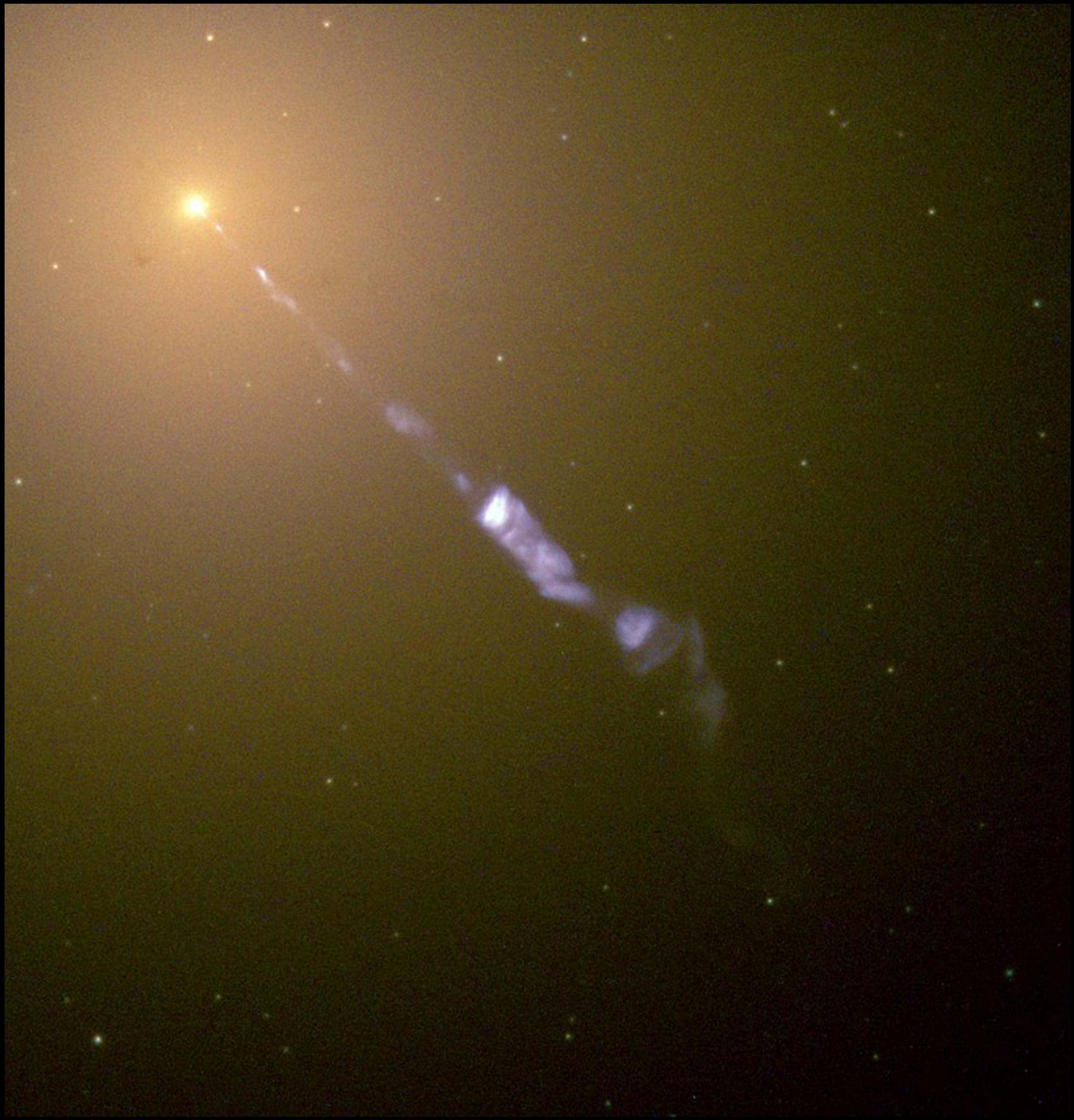
We are waiting for images of our own black hole Sag A*



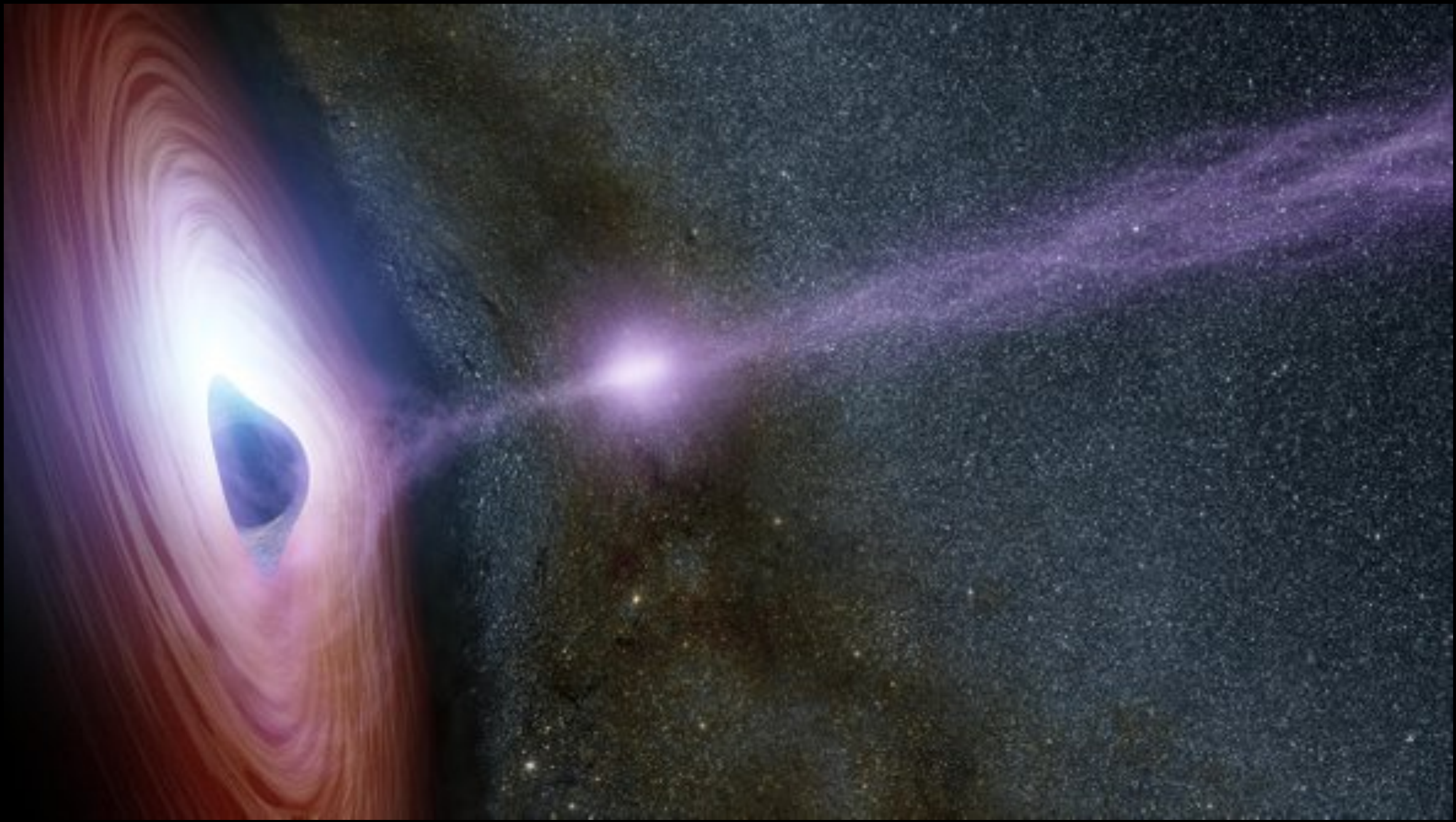
We want to see a movie of black holes eating



We want to know how supermassive black holes drive jets?



Are there quantum effects near the event horizon?



In the last few years the door has opened to study black holes throughout the skies and at a variety of length scales

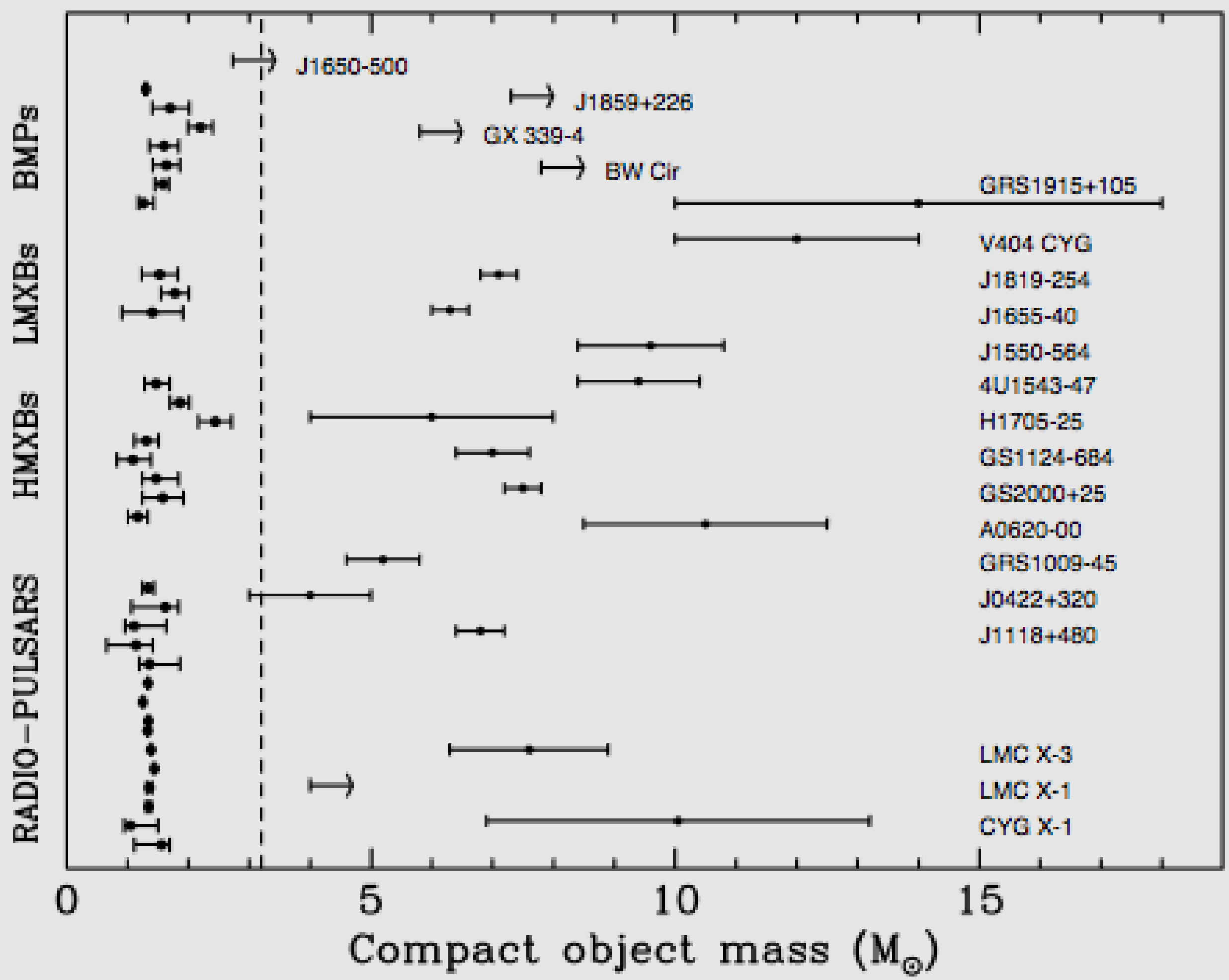


Figure 6. Mass distribution of compact objects in X-ray binaries. Arrows indicate lower limits to BH masses. Figure reproduced from Casares (2007).

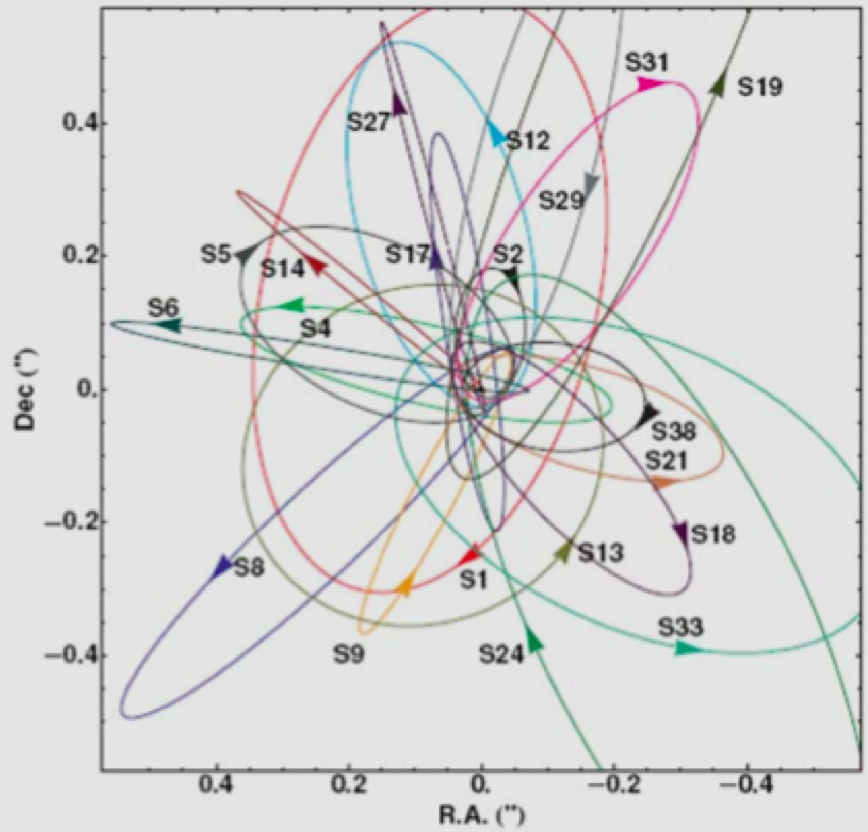
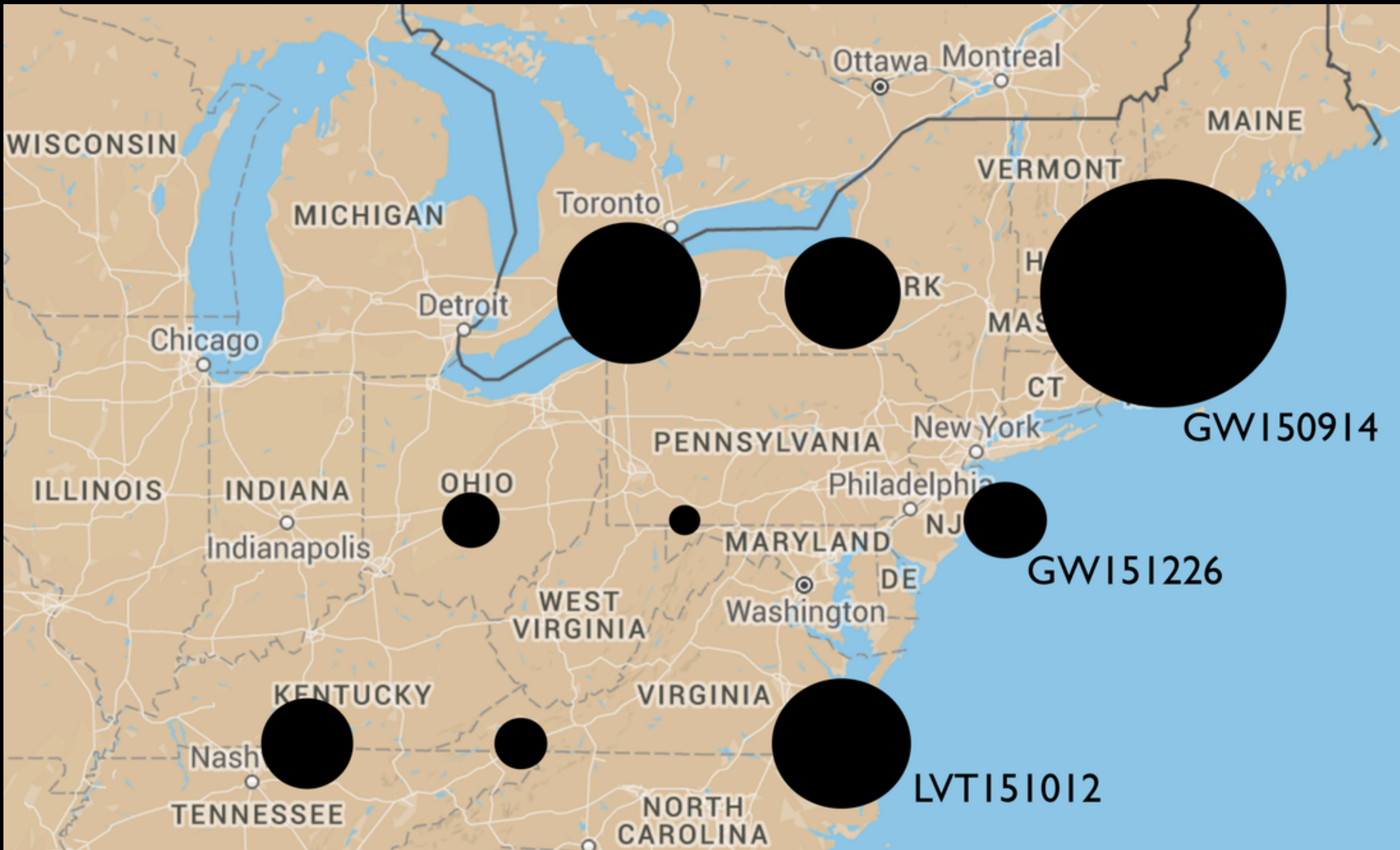
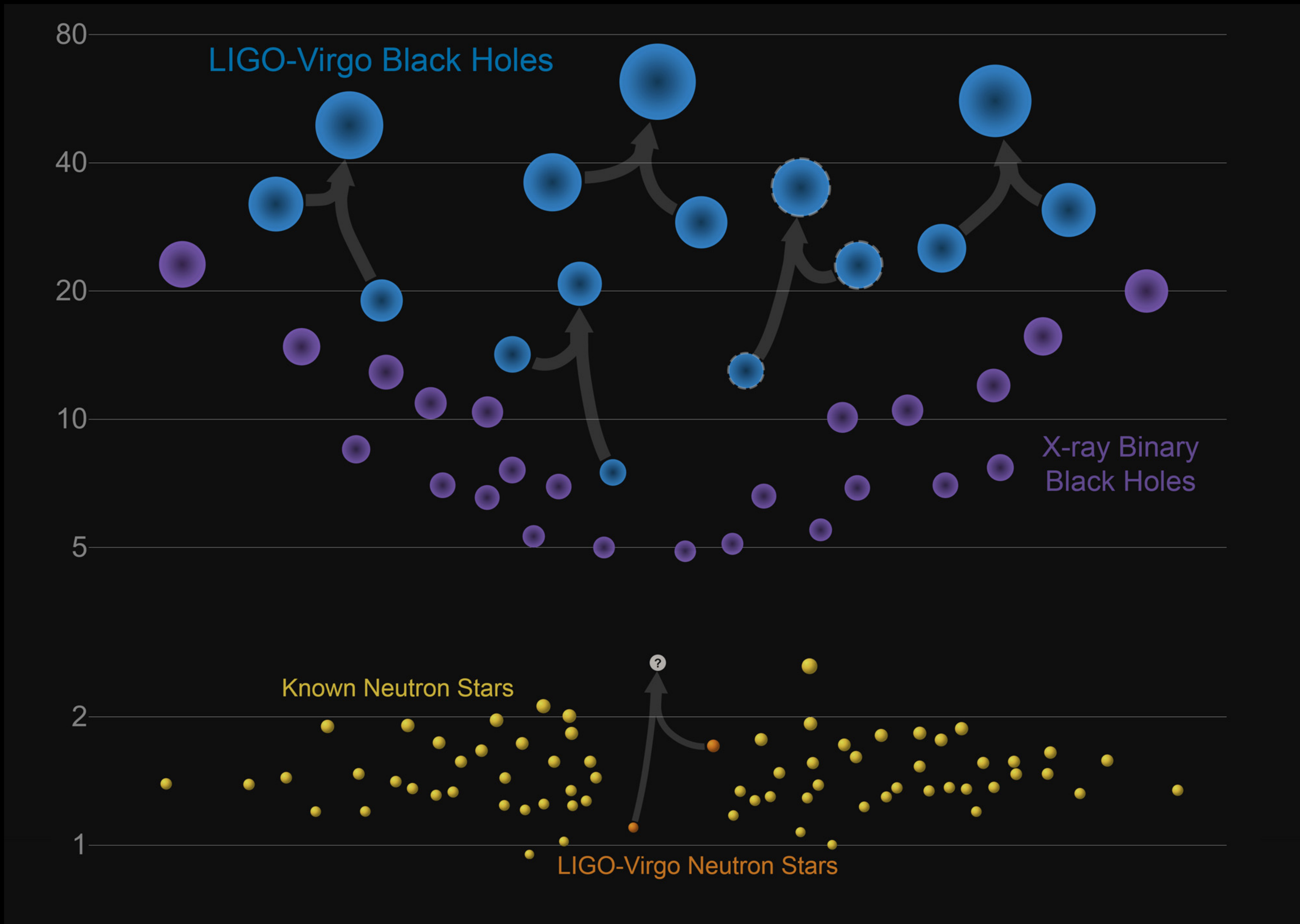


Figure 4.3.2. A summary of 20 of the ~ 30 S-star orbits delineated by the most recent orbital analysis of Gillessen et al. (2009b) [5].

Tracking orbiting stars at the center of the Milky Way accurately established the mass of Sag A* at $4.3 \times 10^6 M_\odot$.


Ottawa
Montreal
MAINE
WISCONSIN
VERMONT
MICHIGAN
Toronto
Detroit
Chicago
CT
New York
PENNSYLVANIA
ILLINOIS
INDIANA
OHIO
Philadelphia
NJ
Indianapolis
MARYLAND
DE
WEST VIRGINIA
Washington
KENTUCKY
VIRGINIA
TENNESSEE
NORTH CAROLINA
GW150914
GW151226
LVT151012

In solar masses



They offer a remarkable laboratory for thermal physics, strong gravity and one day, I hope, for quantum gravity

The End