The Basics and History of Black Holes:
From Early Predictions to Current Topics

Hailey, Isabell, Sebastien, Maddy
ASTR 312

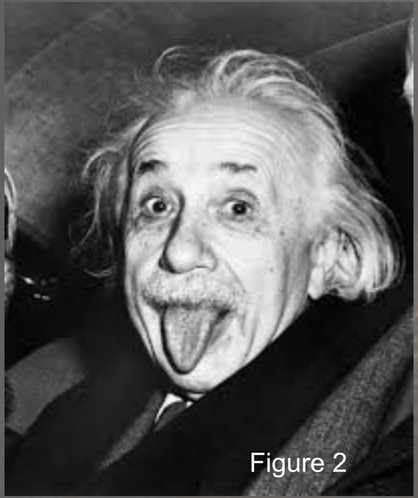
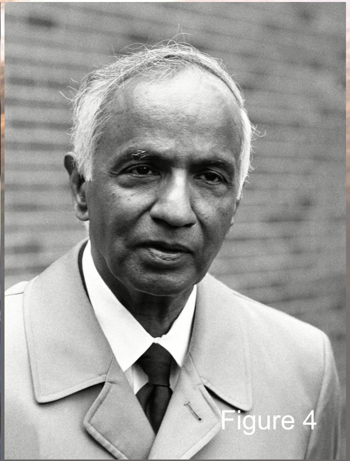


Figure 2


Figure 3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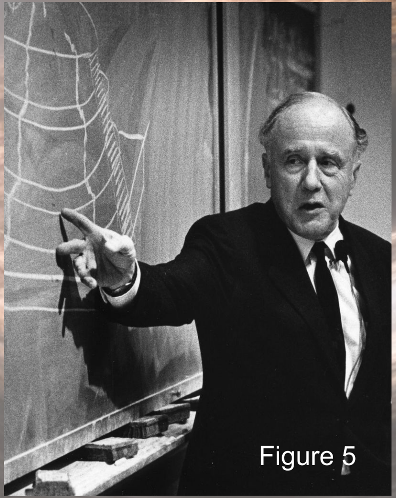
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Figure 1

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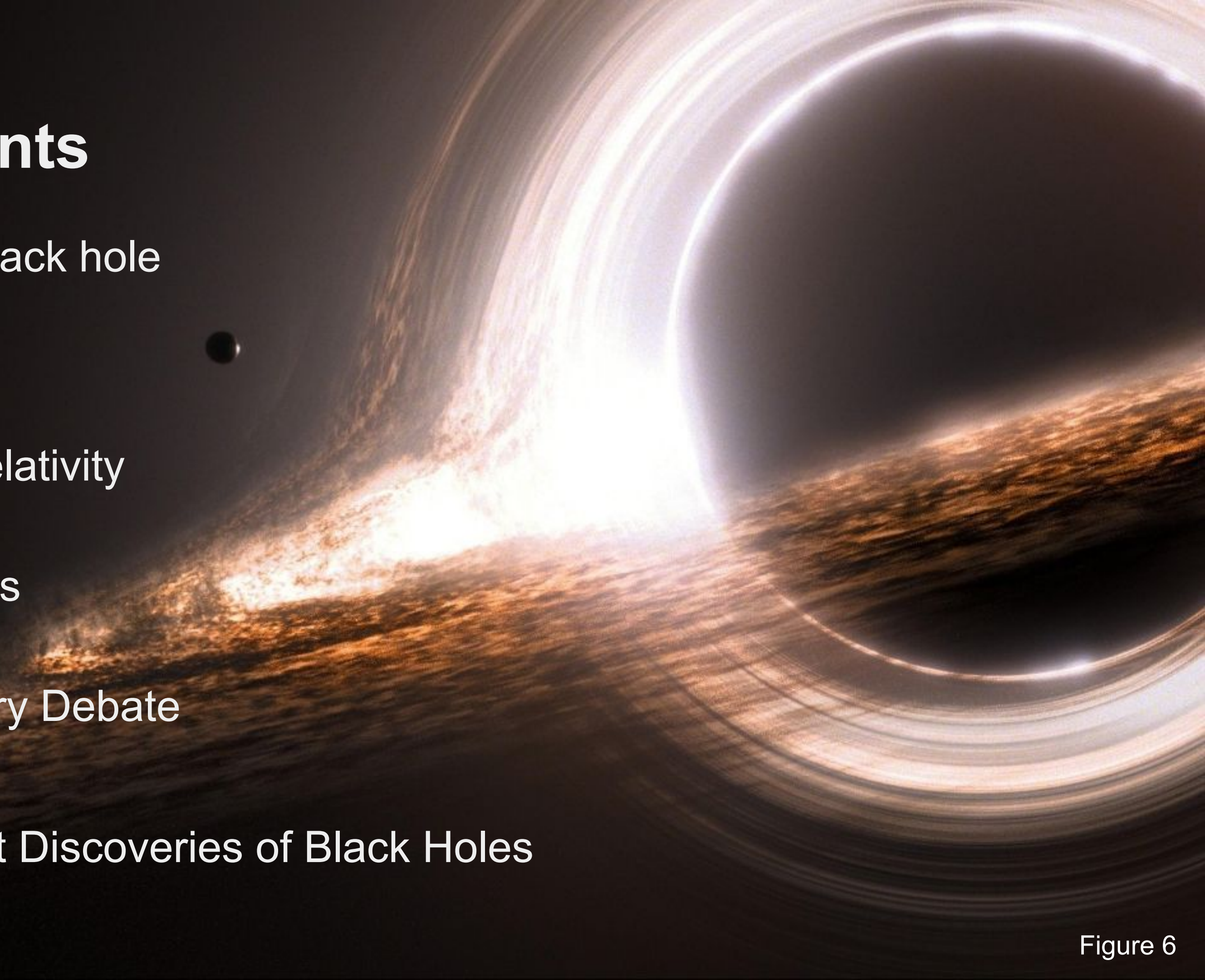


Figure 6

What are Black Holes?

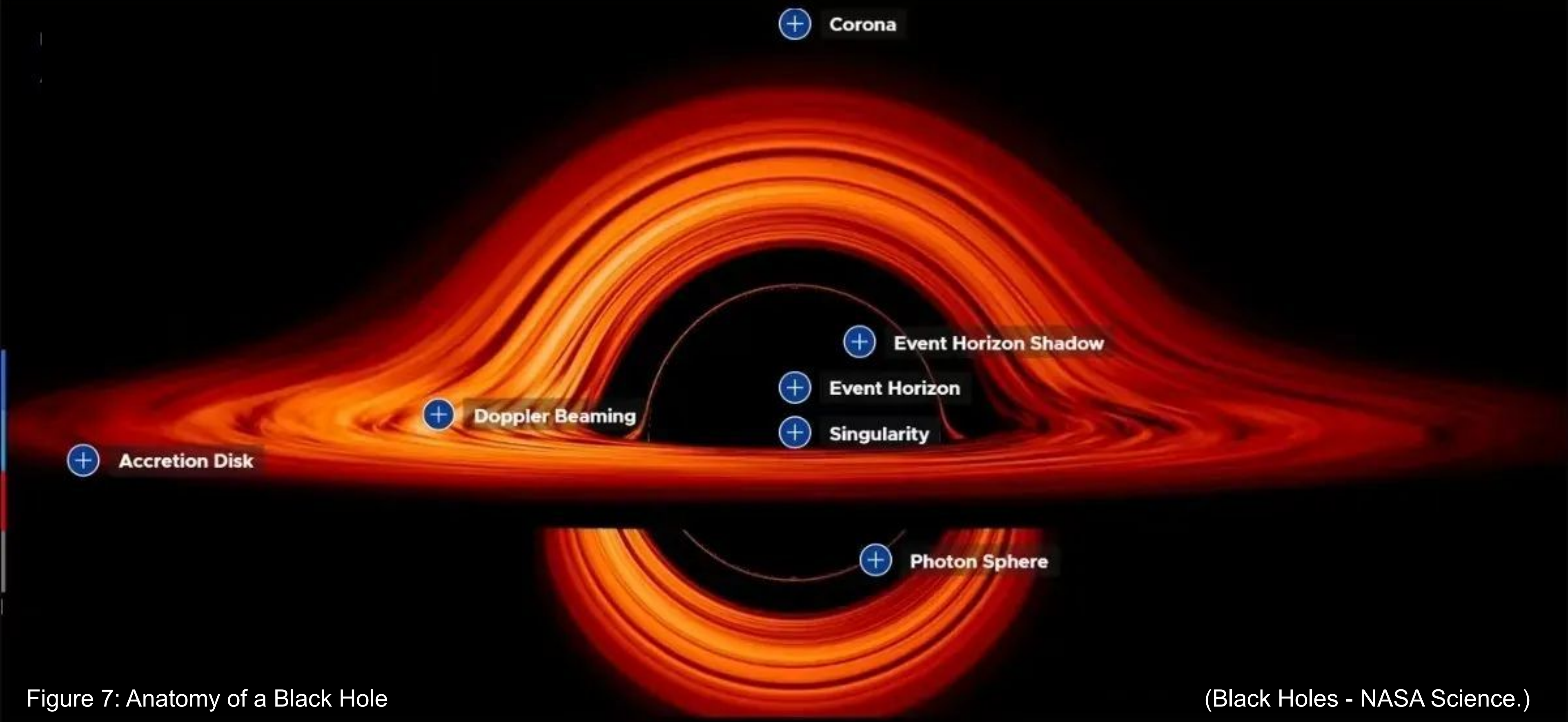
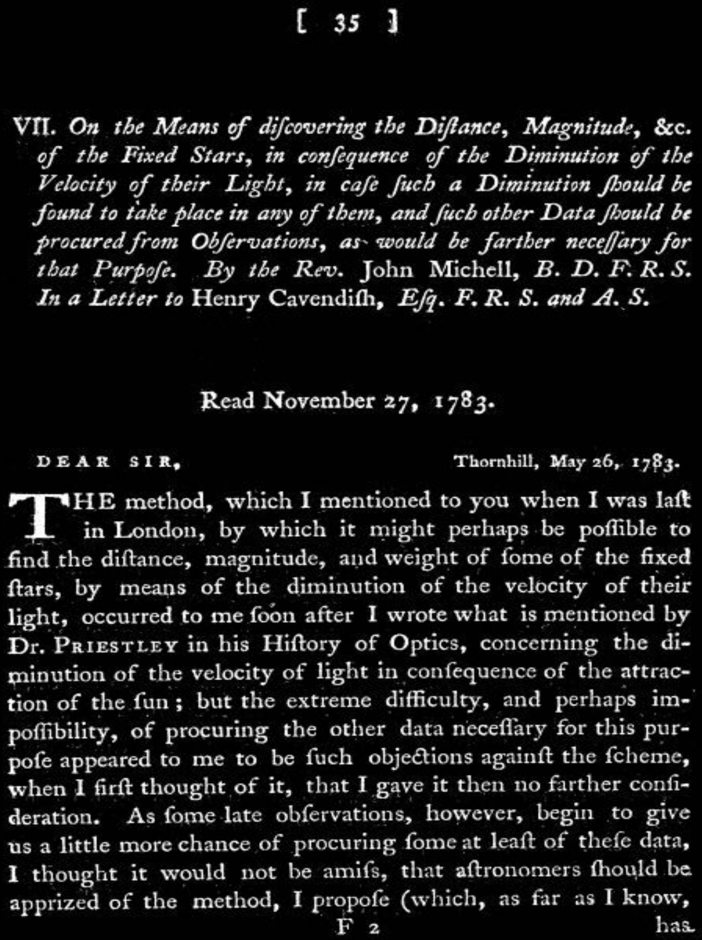


Figure 7: Anatomy of a Black Hole

(Black Holes - NASA Science.)


Figure 8

Early Ideas (1700s–1800s)


[35]

VII. *On the Means of diſcovering the Diſtance, Magnitude, &c. of the Fixed Stars, in conſequence of the Diminution of the Velocity of their Light, in caſe ſuch a Diminution ſhould be found to take place in any of them, and ſuch other Data ſhould be procured from Obſervations, as would be farther neceſſary for that Purpoſe. By the Rev.* John Michell, *B. D. F. R. S. In a Letter to* Henry Cavendiſh, *Eſq. F. R. S. and A. S.*

Read November 27, 1783.

DEAR SIR, Thornhill, May 26, 1783.

THE method, which I mentioned to you when I was laſt in London, by which it might perhaps be poſſible to find the diſtance, magnitude, and weight of ſome of the fixed ſtars, by means of the diminution of the velocity of their light, occurred to me ſoon after I wrote what is mentioned by Dr. PRIESTLEY in his Hiſtory of Optics, concerning the diminution of the velocity of light in conſequence of the attraction of the ſun; but the extreme difficulty, and perhaps impoſſibility, of procuring the other data neceſſary for this purpoſe appeared to me to be ſuch objections againſt the ſcheme, when I firſt thought of it, that I gave it then no farther conſideration. As ſome late obſervations, however, begin to give us a little more chance of procuring ſome at leaſt of theſe data, I thought it would not be amiſs, that aſtronomers ſhould be apprized of the method, I propoſe (which, as far as I know,

F 2 has

Figure 9

English Reverend, John Michell

1749 - 1827

- Hypothesized the existence of a dark star in 1783.

- He thought if a star was massive enough, its gravity would trap light.

- Earliest known idea relating to black holes

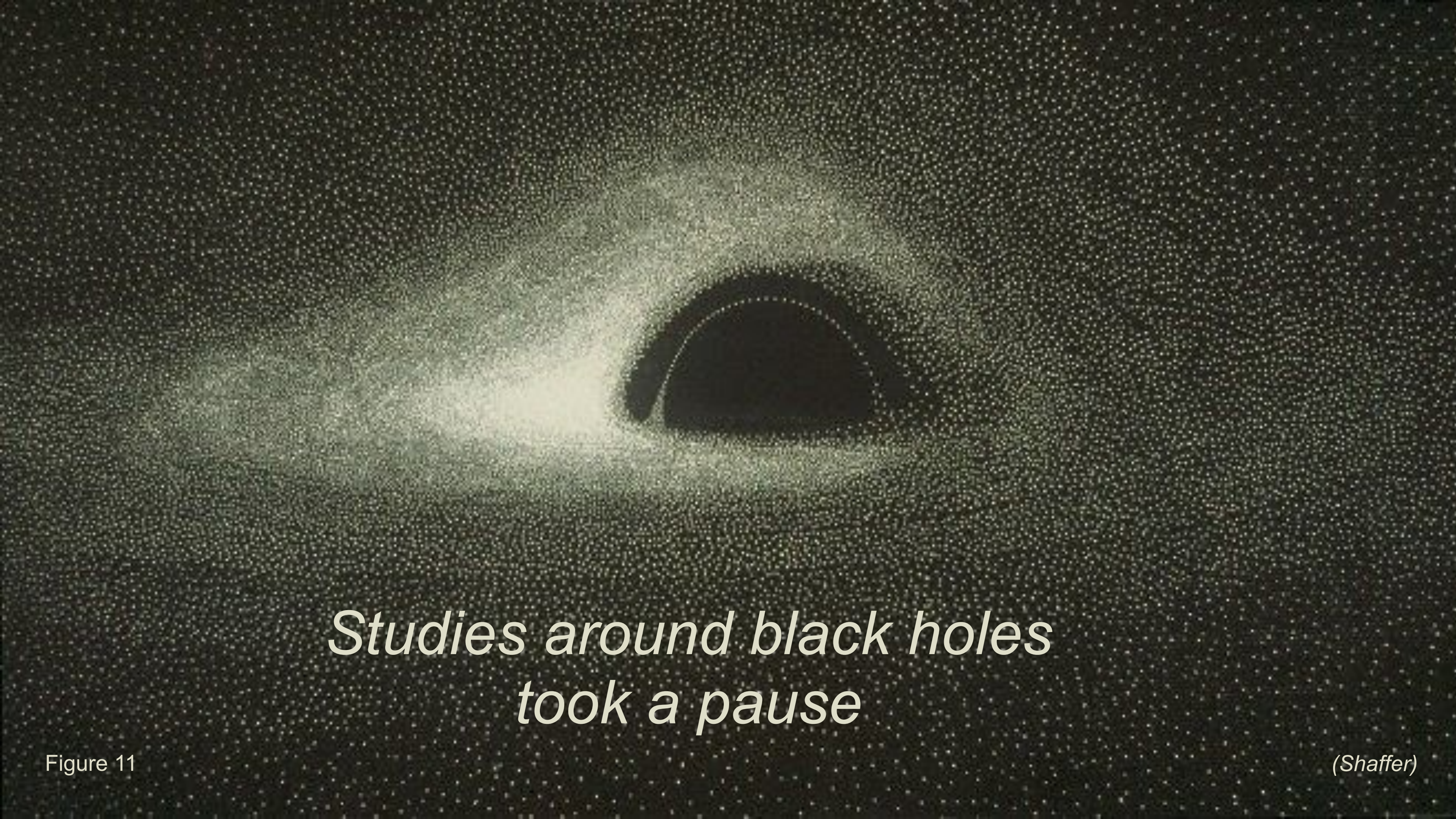
(N. C. Robertson)

French Mathematician Pierre-Simon Laplace

1749 - 1827

- Gifted mathematician
- Independently he made the same prediction as Michell around a similar time.
- Big star invisible due to great density where no light would escape its surface
- He did not believe in the existence of black holes

(Robertson, Montgomery, Schaffer)



Studies around black holes took a pause

Figure 11

(Shaffer)

Einstein and Relativity (1915-1916)

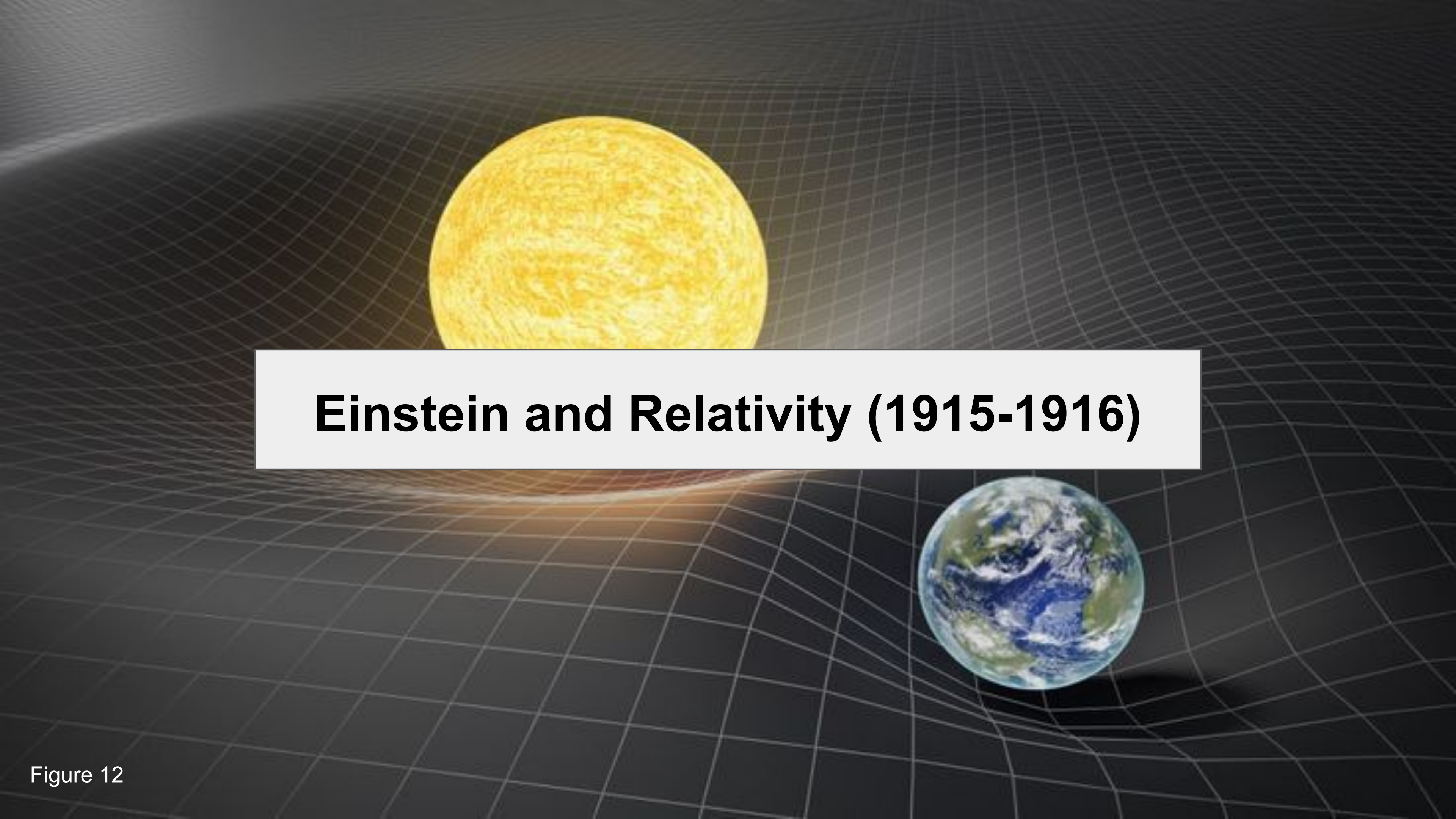


Figure 12

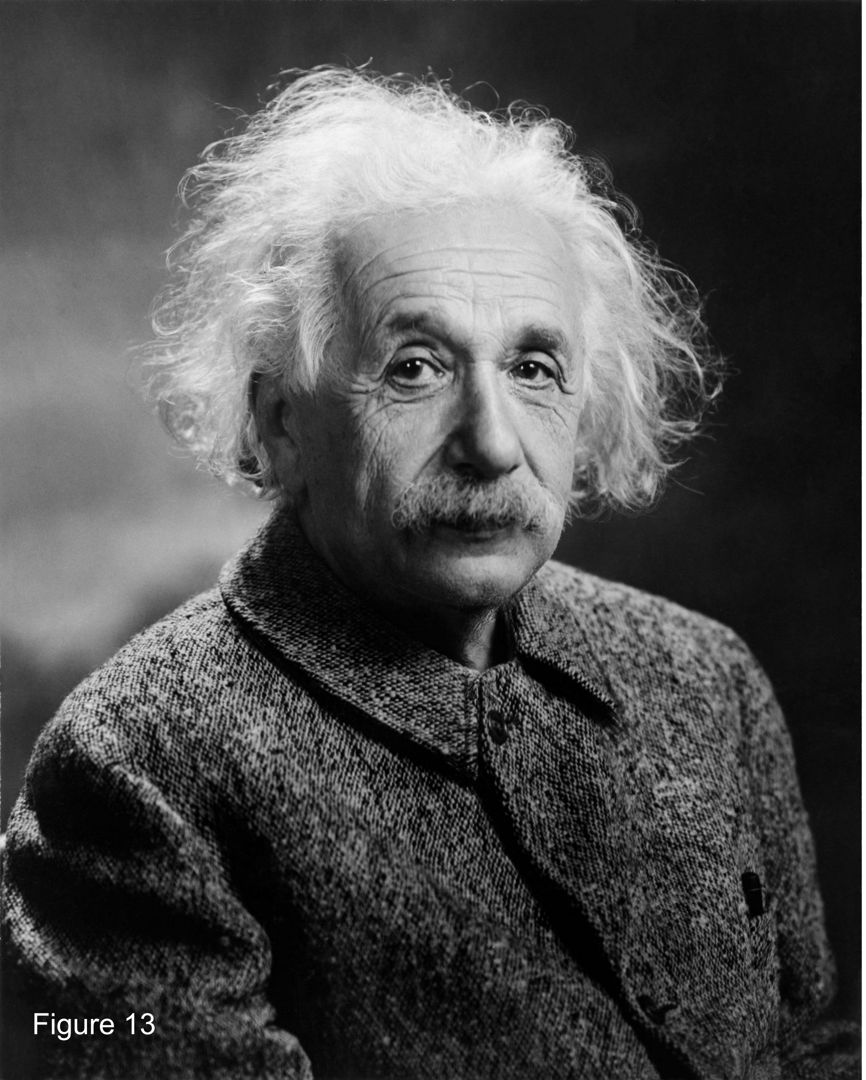


Figure 13

German Theoretical Physicist
Albert Einstein

1879 - 1955

- Published theory of General Relativity in 1915

- Proposing that "concentrations of mass and energy curve the structure of spacetime, affecting the motion of anything passing near — including light"

- Offered a new perspective on the mechanism of gravity

(Einstein's Theory of Gravitation.)

Einstein's Field Equation

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Figure 14

Gravitational Time Dilation:

- More massive objects produce stronger gravitational fields

- If strong enough, these can warp spacetime so severely that time itself slows down near them

- Mathematically predicted by general relativity

Figure 15

German Physicist and Astronomer Karl Schwarzschild

1873 - 1916

- German physicist and astronomer (Born in Frankfurt in 1873)
- First person to formulate solutions to Einstein's equations of general relativity
- Produced critical work on the mathematical underpinnings of black holes

(*Maguire, David W*)

Schwarzschild's Solution to Einstein's Equations

Time Dilation

Radial Length Contraction

$$ds^2 = -\left(1 - \frac{R_S}{r}\right)c^2 dt^2 + \frac{1}{\left(1 - \frac{R_S}{r}\right)} dr^2 + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)$$

Invariant Line Element

Schwarzschild Radius

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

Figure 16

The Schwarzschild solution: predicts that if a massive star collapses under its own gravity, it can create a region where space time curvature becomes so extreme, no matter can escape (including light)

- laid the foundation for our understanding of black holes
- The implications of his work were not widely recognized until decades later

The Schwarzschild Radius

- Defines the margins of this region, also known as the event horizon
- Within the event horizon lies a point of infinite density - the singularity
- Schwarzschild solution was not interpreted as a real physical object, but rather a hypothetical product of mathematics

Schwarzschild Radius

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

Figure 17

$$\mathit{Density} = \frac{\mathit{Mass}}{\mathit{Volume}}$$

Figure 18

Chandrasekhar vs. Eddington - A fundamental Debate (1930s)

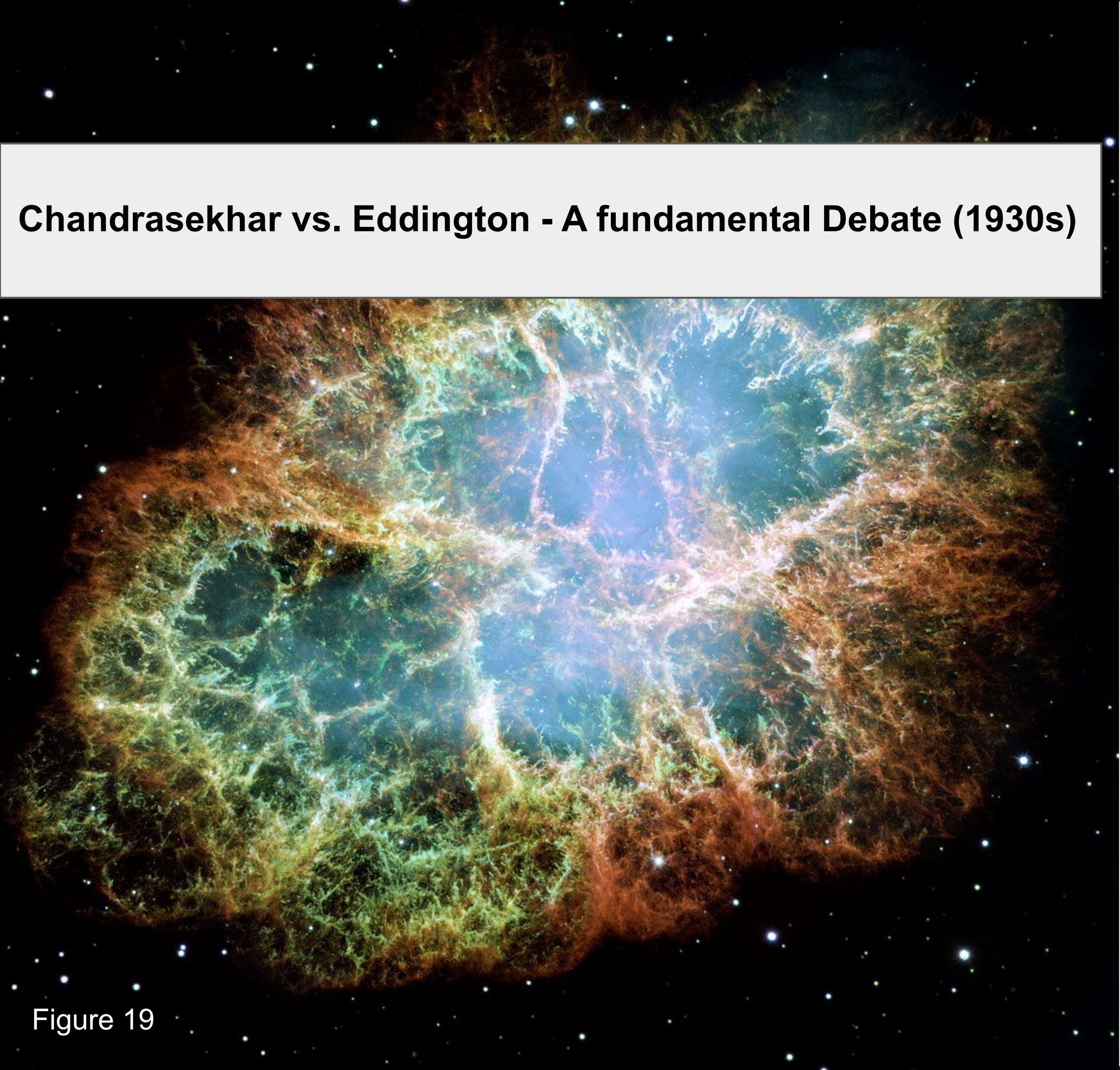


Figure 19

Chandrasekhar vs. Eddington—an unanticipated confrontation

For many years astronomers did not accept the validity of a young scientist's application of the new physics because it was ridiculed by a preeminent astronomer.

Kameshwar C. Wali

The subject is a fair field for the struggle to gain knowledge by scientific reasoning; and, win or lose, we find the joy of contest.

—Sir Arthur Stanley Eddington, *The Internal Constitution of the Stars* (1926).

Stellar evolution has for many years been one of the most exciting fields of research in astronomy and astrophysics. In the early 1930s, a young astrophysicist named Subrahmanyan Chandrasekhar certainly felt this excitement when in his theoretical work he found a fundamental parameter that determines the destiny of stars. By appling both relativity and the new quantum mechanics, Chandrasekhar found a critical mass, below which stars end up as white dwarfs, and above which, as later work would show, they end up as neutron stars or black holes.

Although we now recognize the "Chandrasekhar limit" as a major discovery, its validity and importance remained in doubt among astronomers in large part because a single individual felt that all stars should become white dwarfs in their terminal stages. A dramatic and unanticipated confrontation took place at the January 1935 meeting of the Royal Astronomical Society of England. As we will see, the brilliant but young Chandrasekhar, armed with a fairly simple derivation based on special relativity and the Fermi–Dirac quantum-statistical distribution laws, was no match for the ridicule by Arthur Stanley Eddington, a renowned scientist with tremendous international stature, authority and influence. And because physicists failed to counter Eddington publicly in their own area of expertise, astronomers remained confused about stellar evolution until the 1950s.

Chandrasekhar has given[1] a partial account of the controversy. But a fuller account of the 1935 meeting and the circumstances leading to it demonstrates how discovery in science is often beset by obstacles that do not arise logically or objectively. Human factors, such as personal biases, prestige, and authority play just as important a role in science as in art or literature.

A glance at our current view of stellar evolution will help us appreciate the importance of the issue at the center of the controversy.

Our present understanding

A star is born, or so observational evidence tells us, in the middle of a condensing cloud of interstellar gas and dust, composed mainly of hydrogen. All-pervading gravitational forces, which are primarily responsible for the condensation, compress the stellar material. In time, the interior becomes hot enough to initiate a nuclear reaction in which the hydrogen nuclei fuse to form helium. The star turns on.

This steady transformation of hydrogen into helium releases enormous amounts of energy, creating enough internal pressure to balance the crushing forces of gravity. The star reaches equilibrium. During this "adult stage," the star is situated on the so-called "main sequence" of the Hertzsprung–Russell diagram—a plot of a star's spectral type, or surface temperature, against its absolute luminosity, or total energy output. Eventually, all of the central hydrogen is converted into helium. The star leaves the main sequence as gravitational forces take over and compress the central helium core. As the temperature of the interior rises, the outer layers, where some hydrogen may still be burning, expand; the diameter of the star increases to ten or a hundred times its main-sequence value. At this stage, we call the star a red giant.

Complex processes subsequently occur. In stars somewhat more massive than the Sun, core temperatures rise enough to burn the helium and to create carbon and oxygen. This process generates energy and pressure once again, and the star reaches another equilibrium stage, which last until all the central helium is burnt and an oxygen and carbon core remains. Then, gravitational contraction begins again. When the temperatures are high enough to initiate carbon–oxygen reactions, elements like neon, magnesium and silicon are created. Thus, in its struggle for survival against the forces of gravity, a star may synthesize more and more complex elements in its interior nuclear furnace. During any of the stages, instabilities may develop, producing nova or supernova explosions that eject large fragments of the star into outer space.

The question arises: What happens after a star finally exhausts all its nuclear fuel and can no longer produce the necessary energy and pressure to withstand gravity? Current thought is that the final mass of the star, or of the stellar remnant of a nova or supernova, determines the nature of its terminal stage: a white dwarf, a neutron star or a black hole. Only stars of fairly low final mass become white dwarfs or neutron stars. For a star to become a white dwarf, its mass must not exceed the critical value of 1.44 solar masses. Neutron stars are remnants with masses three or four times that of the Sun. More massive stars do not become white dwarfs or neutron stars unless they lose substantial amounts of their mass. They cannot win against gravity; their ultimate fate is surrender—they become black holes.

Such is our present understanding of the life cycle of stars. Let us now go back a half century and follow the scientific developments that led to Chandrasekhar's discovery of the criti-

Kameshwar C. Wali is an elementary-particle theorist at Syracuse University, in New York. He is writing a biography of Subrahmanyan Chandrasekhar.

Figure 20

0031-9228 / 82 / 1000 33–08 / $01.00

The Fate of Massive Stars - Chandrasekhar's Position

Chandrasekhar limit: Proposed maximum mass possible for a white dwarf star to maintain stability

- When stars exceed this limit electrons and protons combine → form neutron star

Neutron star: an incredibly dense stellar remnant made up up tightly packed neutrons

If the collapsing core is massive enough, the star continues collapsing into **a black hole (**The White Dwarf Affair, 2024**)**

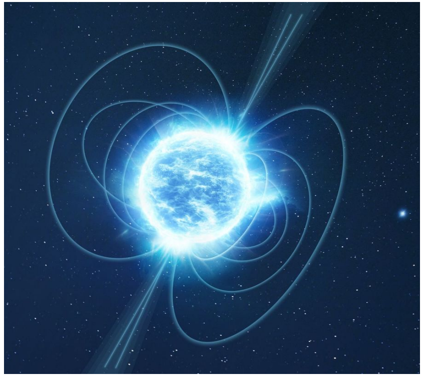


Figure 21:Neutron star

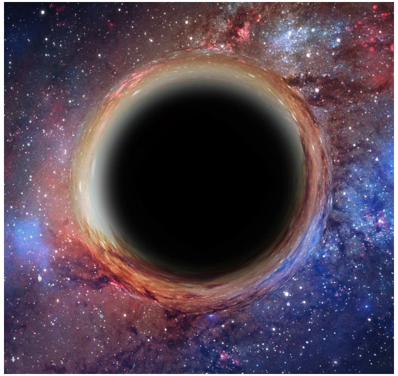


Figure 22: Black hole

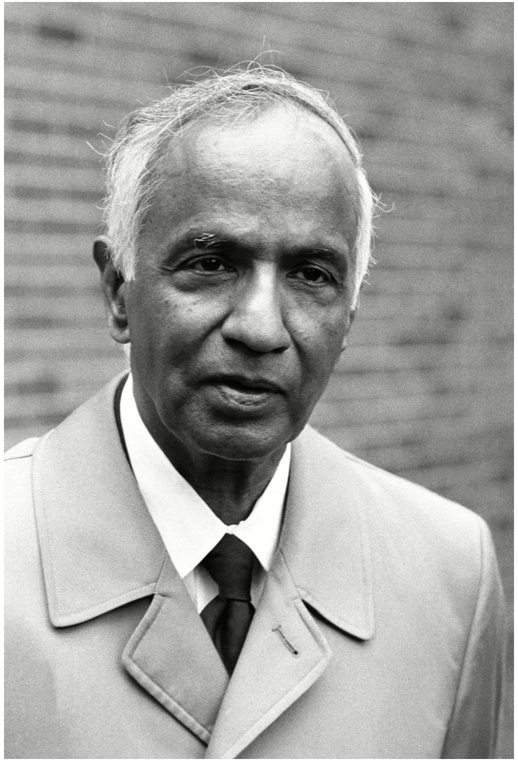


Figure 23: Subrahmanyan Chandrasekhar, 1983

The Fate of Massive Stars - Eddington's Position

Stellar Stability: Rejected Chandrasekhar's limit, he instead proposed inherent stability by an unknown physical mechanism

Public influence:

- Highly respected astrophysicist
- Public dismissal severely hindered early acceptance of Chandrasekhar's revolutionary ideology

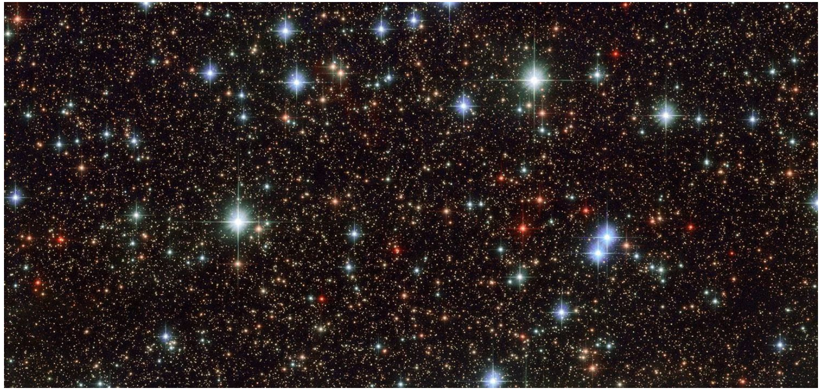


Figure 24

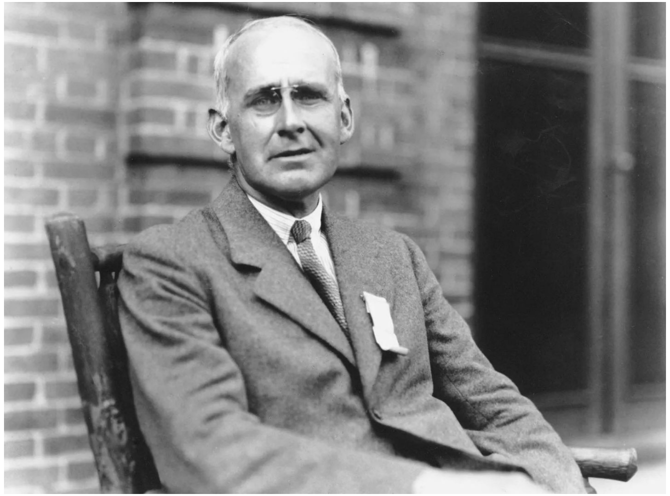
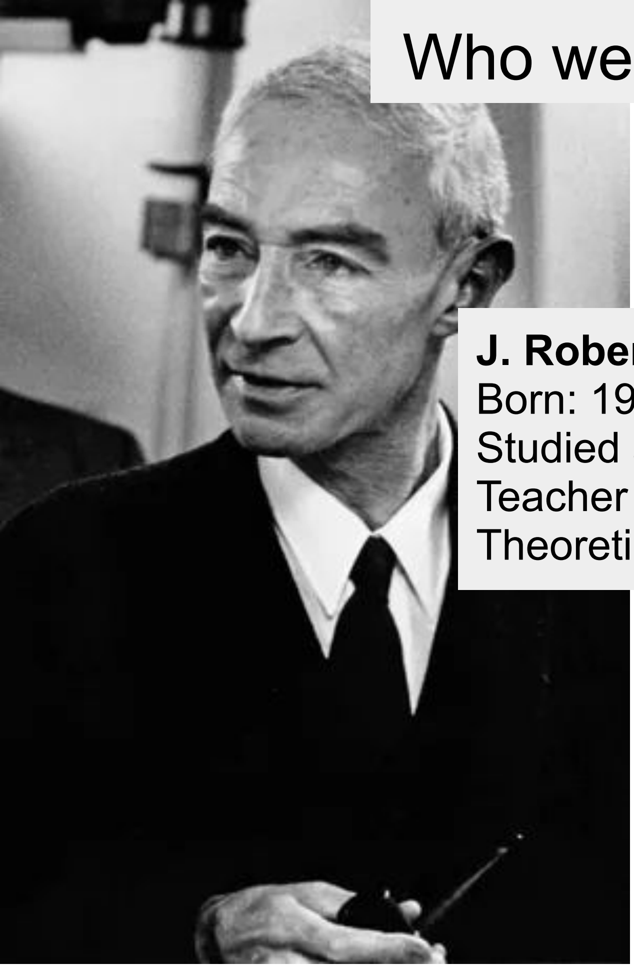


Figure 25: S. Eddington

"I think there should be a law of Nature to prevent a star from behaving in this absurd way!" — Arthur S. Eddington

Who were Oppenheimer and Snyder?



J. Robert Oppenheimer
Born: 1904, New York, New York, USA
Studied at Harvard.
Teacher at Berkeley
Theoretical Physicist

Hartland Snyder
Student of Oppenheimer
Born: 1913, Salt Lake City, Utah, USA
Physicist at Berkeley

Figure 26: Oppenheimer

Figure 27: Snyder

What did They Discover?

- Very massive stars collapse indefinitely under their own gravity
- Light cannot escape the collapsing region
- Observer sees the surface appear to “freeze” in time (“frozen star”)
- First realistic physical model of a black hole

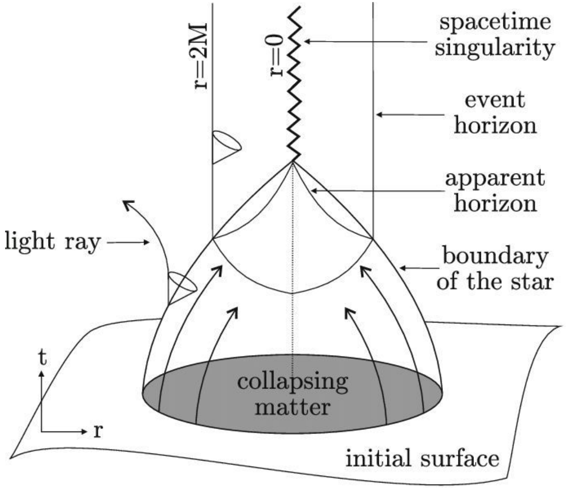


Figure 29:Model

Their paper “On Continued Gravitational Contraction” explained the Oppenheimer- Snyder Model. This model theorized the formation of what we now call black holes.

$$ds^2 = -d\tau^2 + A^2(\eta)\left(\frac{dR^2}{1-2M\frac{R_-^2}{R_b^2}\frac{1}{R_+}} + R^2 d\Omega^2\right)$$

Delayed Recognition

- Published in 1939 → overshadowed by WWII
- Black holes seemed too extreme, “unphysical”
- Limited technology to detect them
- Ideas ahead of their time
- The extent of their work not coming into light

  until 1960s.

Figure 30/31: Oppenheimer/ Groves:At Trinity test site in Alamogordo, New Mexico.

The Debate in the Mid-20th Century (1950s–60s)

Why did scientists reject black holes?

- Seen as mathematical oddities not physical objects
- Lacked evidence or observational support
- Idea of infinite collapse seemed unrealistic
- Influential skeptics shaped opinion

Figure 32

John Wheeler's Role

- Physicist responsible for bringing revived interest to black hole theories after WW2.
- Popularized the term "black hole" (1967)
- Helped shift the conversation and made the concept more understandable.
- Encouraged viewing them as physical objects.

Born: 1911, Jacksonville, Florida, U.S.
Professor of Physics at Princeton University
Physicist

Figure 33: John Wheeler

How the Controversy Ended

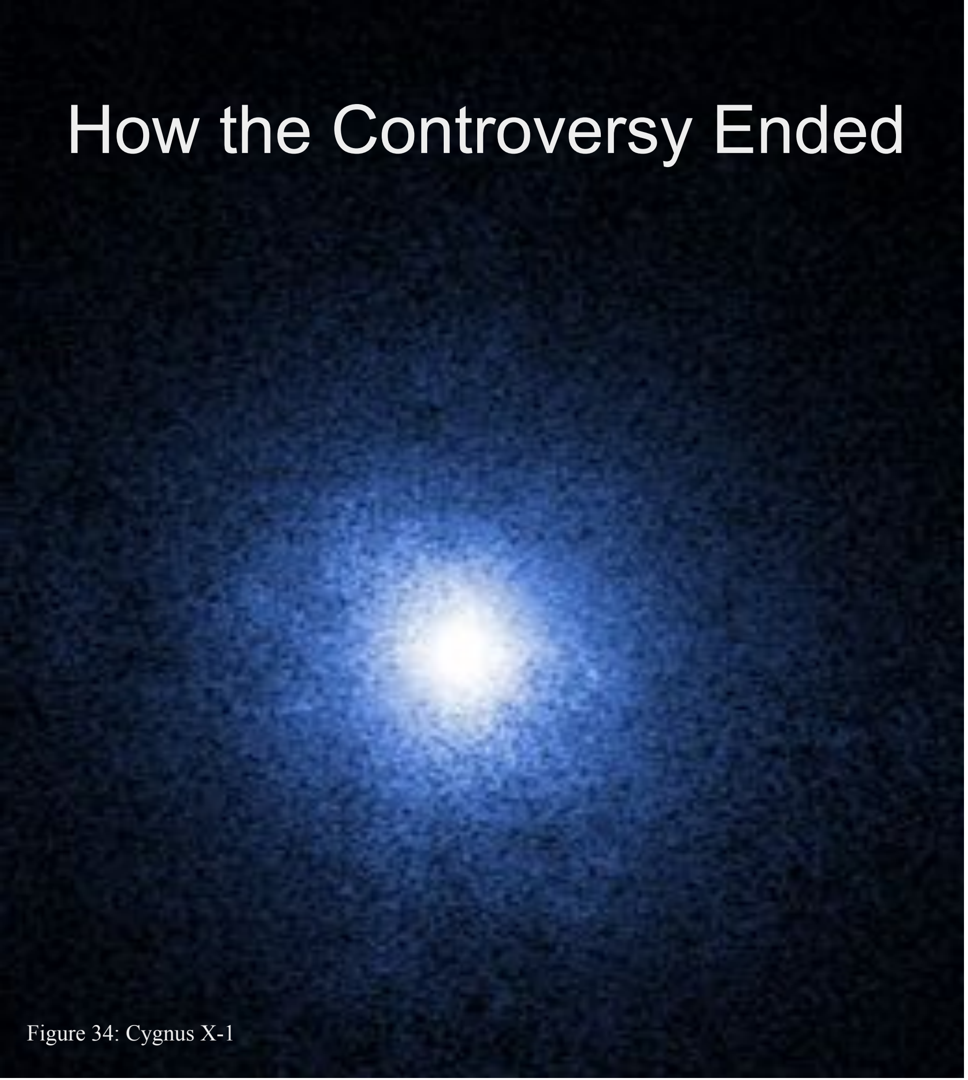


Figure 34: Cygnus X-1

X-ray discoveries: Cygnus X-1

Unseen massive objects observed

Evidence matched collapse predictions

Black holes accepted as real by late 1960s–70s.

What would happen if the Sun was replaced by a Black hole?

A) The entire solar system would be sucked into the black hole and turned into spaghetti

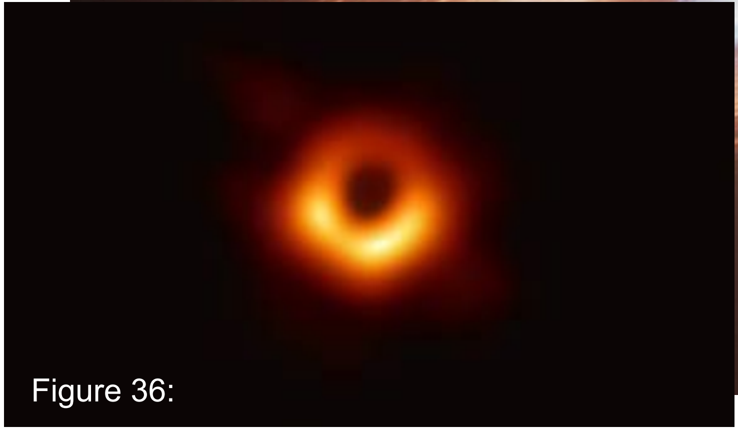
B) Gravity would become stronger on Earth

C) Earth would be freezing cold

(Black Holes - NASA Science.)

Figure 35

Recent & Latest Discoveries of Black Holes



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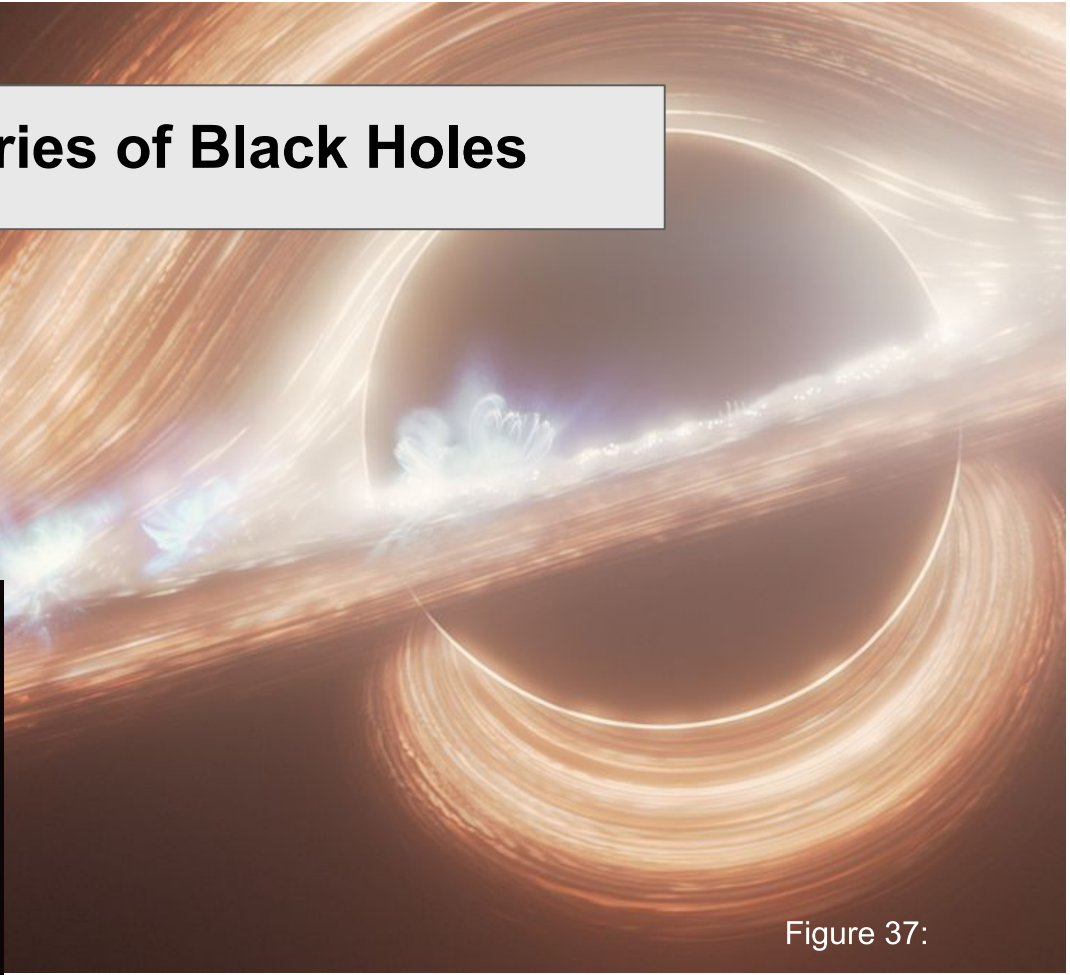


Figure 37:

Stephen Hawking (1942-2018)

Hawkings Radiation (Hawking, Stephen W.).

- Black holes emit energy in the form of particle radiation
- They can “evaporate” overtime. What happens?

Information Paradox

- Clash between Quantum Physics and General relativity

Black hole Entropy & Thermodynamics (Bardeen, James M., Brandon Carter, and Stephen W. Hawking)

- Temperature
- Entropy
- Energy conservation
- Predictable

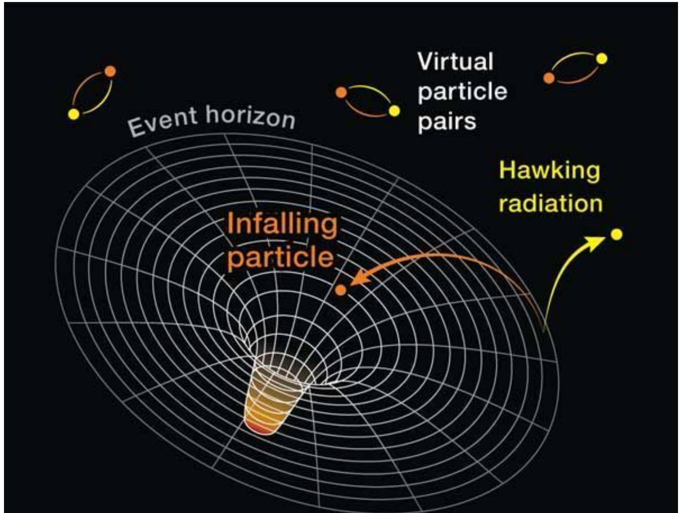


Figure 38:

Figure 39:

“Hawking applied quantum mechanics to make black holes more complex” - *Xavier Calmet in*

First Imagery of a Black Hole

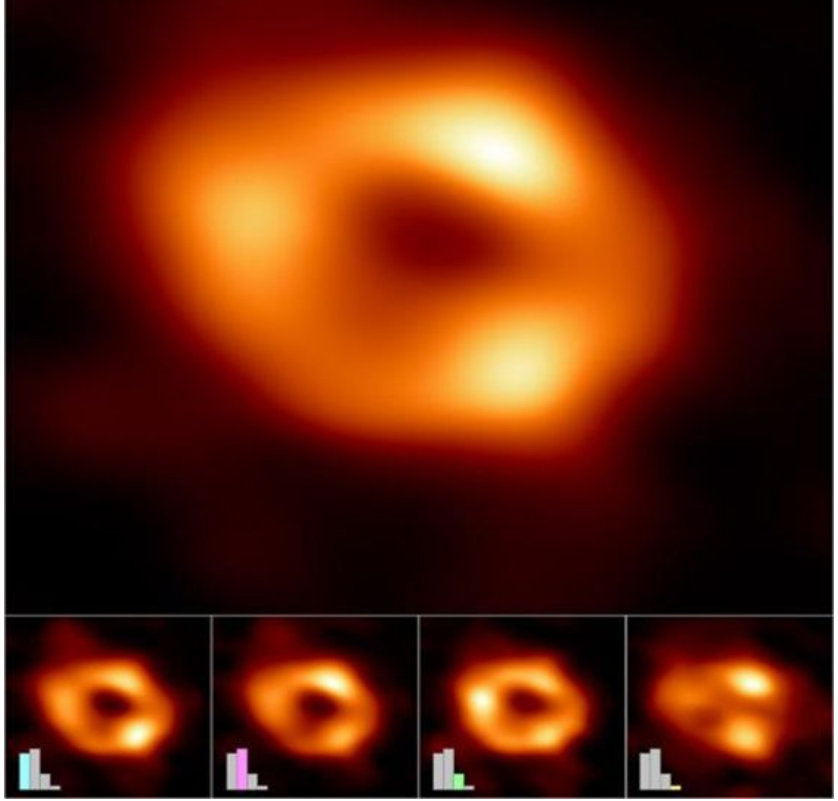
2019 first real imagery released

Through combined data, they were able to comprise an image of Sagittarius A, which is the black hole center of our galaxy and exists 27,000 light years away.

Provided valuable insight to previously theorized interpretation of black holes

(Center for Astrophysics | Harvard & Smithsonian)

Figure 40: EHT imagery of Sagittarius A at Center of our galaxy



“We were stunned by how well the size of the ring agreed with predictions from Einstein’s Theory of General Relativity" -EHT Project Scientist Geoffrey Bower from the Institute of Astronomy and Astrophysics

Black Hole with Tremendous Growth

September 2025 NASA's Chandra X-ray Observatory made the discovery

This black hole weighs about a billion times the mass of the sun and is located about 12.8 billion light years away from Earth.

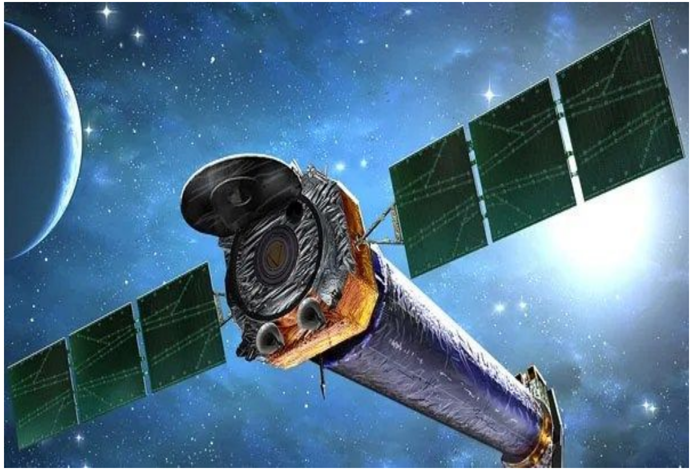


Figure 41: NASA's Chandra X-ray Observatory station

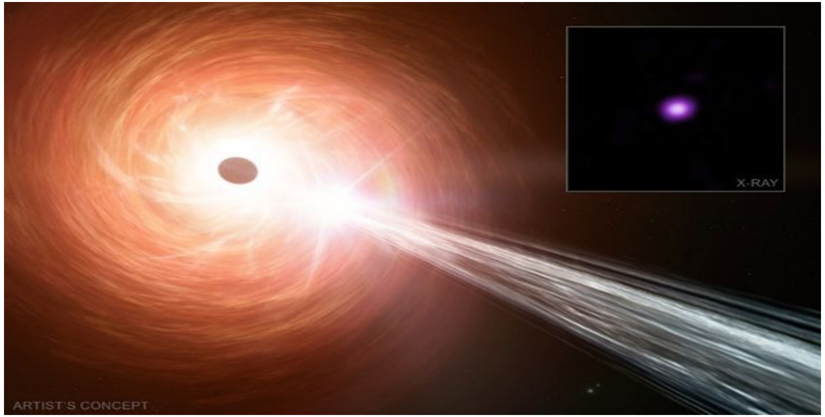


Figure 42: Concept of supermassive blackhole

Highest energy readings of any black discovered in history

Astronomers call it a "Quasar"

(Mohon, L)

OJ287 binary black holes 2022

Orbit of two black holes around each other

Observations in the 1800s, 1980 & 2022

Twisted particle jet

(Valtonen et, al.) & (University of Turko)

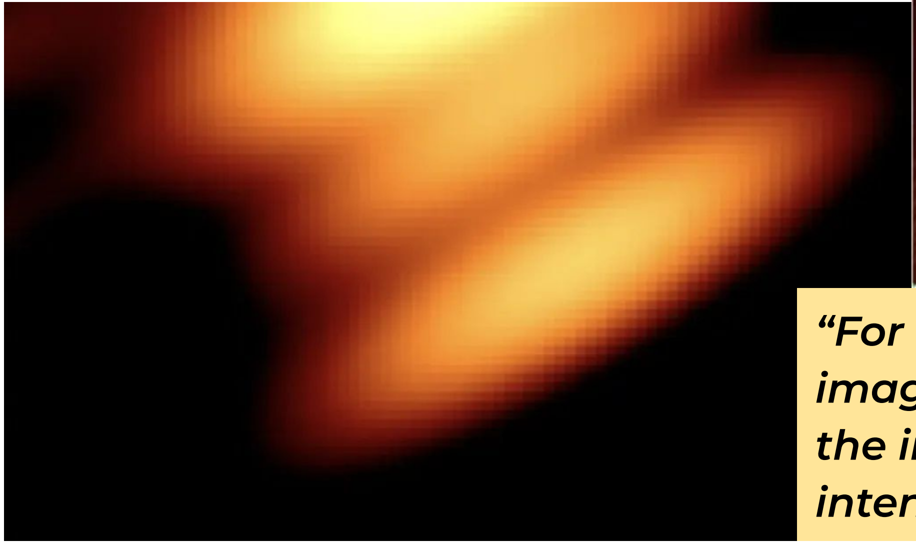


Figure 43: Radio Imagery of Binary Black holes

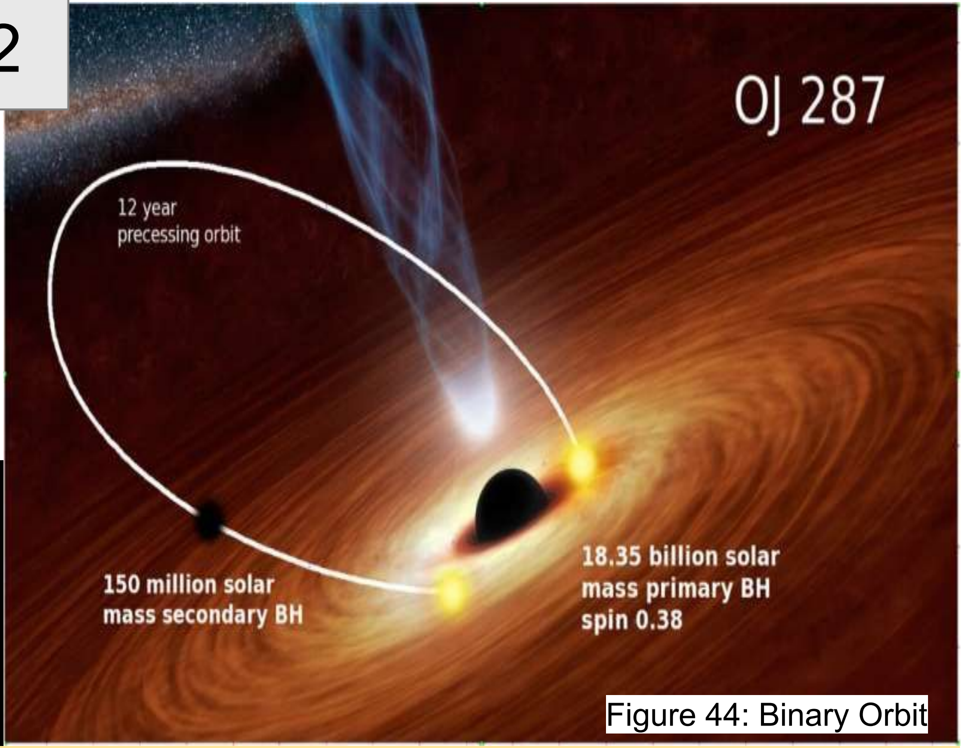


Figure 44: Binary Orbit

"For the first time, we managed to get an image of two black holes circling each other. In the image, the black holes are identified by the intense particle jets they emit" -Mauri Valtonen

What are Black Holes?

A) **Black holes are cosmic vacuum cleaners that actively suck in everything in the universe from any distance**

B) **Black holes are automatic portals that send anything falling in straight into a different dimension**

C) **A black hole is a region where gravity becomes so strong that nothing, not even light, can escape from within**

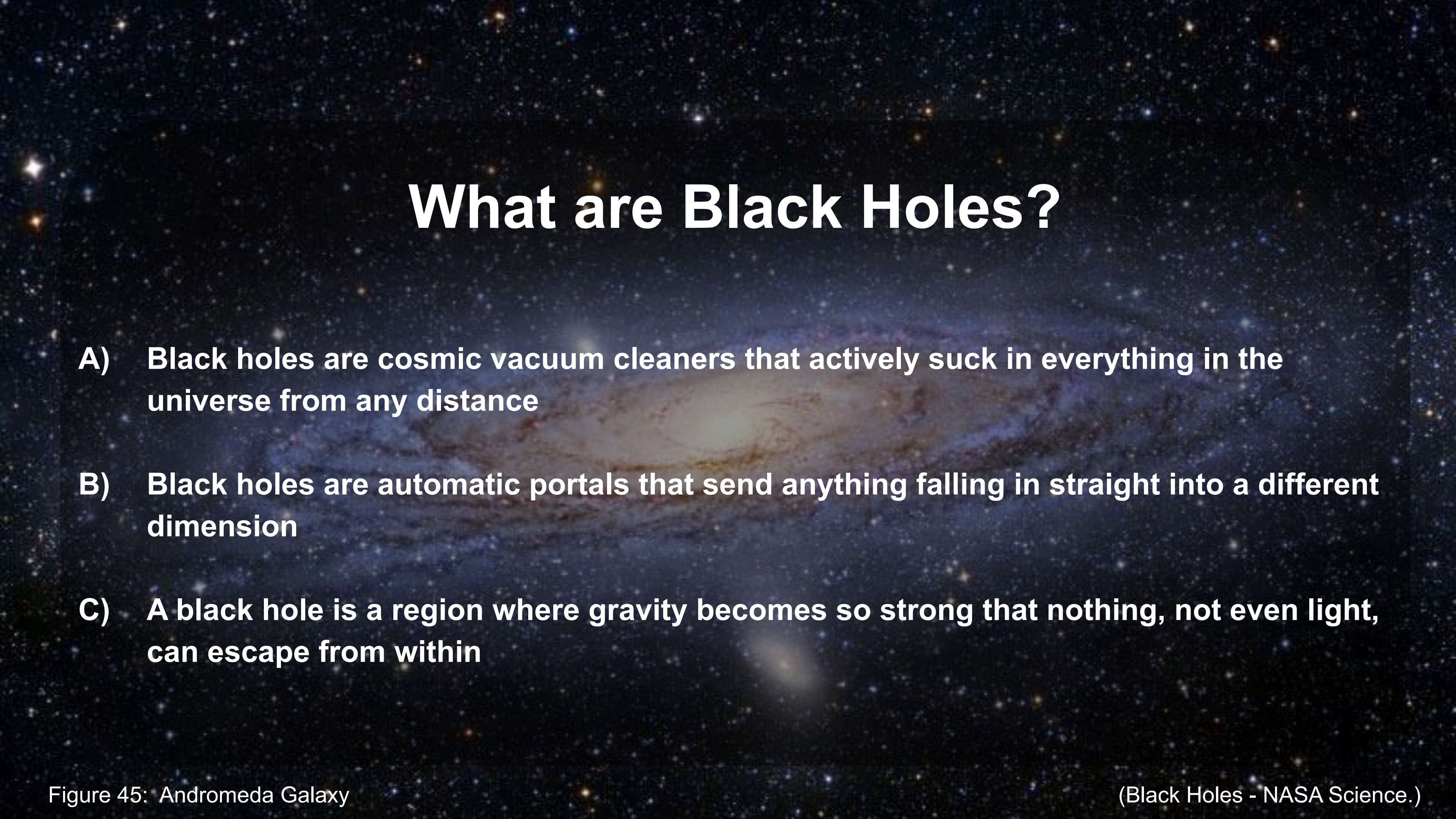


Figure 45: Andromeda Galaxy

(Black Holes - NASA Science.)

Figure 46: Hubble Sees a Horsehead of a Different Colour