The Discovery of Black Holes

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Brief Overview of Black Hole

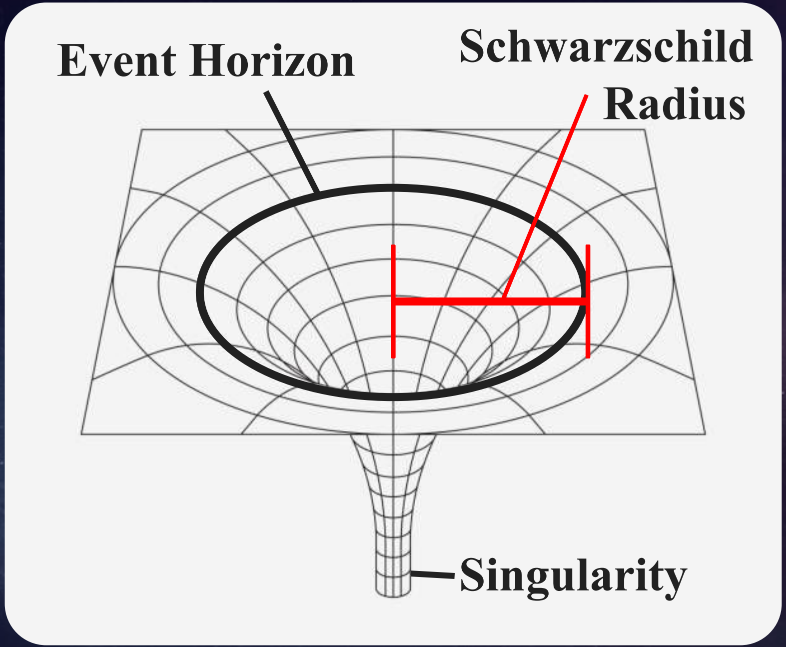

Figure 1: Black Hole Wireframe

01

Early Theorizations of Black Holes

1783~1904

Figure 2: John Michell

Key Concepts

In the 1700s, Newton was one of the leading minds in the field of Physics.

Newton's Corpuscular Theory of Light

- Light is a stream of particles called corpuscles that have some mass and by the Law of Gravitation must be affected by Gravity.

Concept of Escape Velocity

- The minimum speed needed for an object to break free from the gravitational pull of a body. Ve = SQRT(2GM/r)

John Michell

The Origin to the "Invisible" Star

- John Michell was an English astronomer and geologist

- Sent a letter to Henry Cavendish in 1783 describing a calculation about a theoretical star that could have a gravitational pull so strong that light itself wouldn't be able to escape.[3]

- "All light emitted from such a body would be made to return towards it, by its own proper gravity"[1]

Figure 3: John Michell

John Michell

Defining the “Dark” Star

- He named these theoretical objects “Dark Stars”.
- We wouldn’t be able to see them **BUT**
- He predicted we could locate a “Dark Star” by observing a visible star that appears to be orbiting something “invisible”. [1]
- This turned out to be one of the ways we confirmed the existence of Black Holes centuries later.

Pierre-Simon Laplace

An Independent Discovery

• Pierre-Simon Laplace was a french mathematician

• Independently had the same idea as John, proposed the idea in his book "*Exposition du système du monde*". *(1796)*

• Calculated similarly to Michell but his "Dark Star" required a diameter 250x that of the Sun's.[6]

• He **may** have retracted his discussion about "Dark Stars" from later editions of his book in 1799.

Figure 4: Pierre-Simon Laplace

Thomas Young

A Shift in Physics

- Thomas Young was an English scientist
- Best known for his work in Optics, and the Double Slit Experiment
- In his experiment, he cuts two slits in a sheet of metal and shines light through onto a screen.[2]

Figure 5: Thomas Young

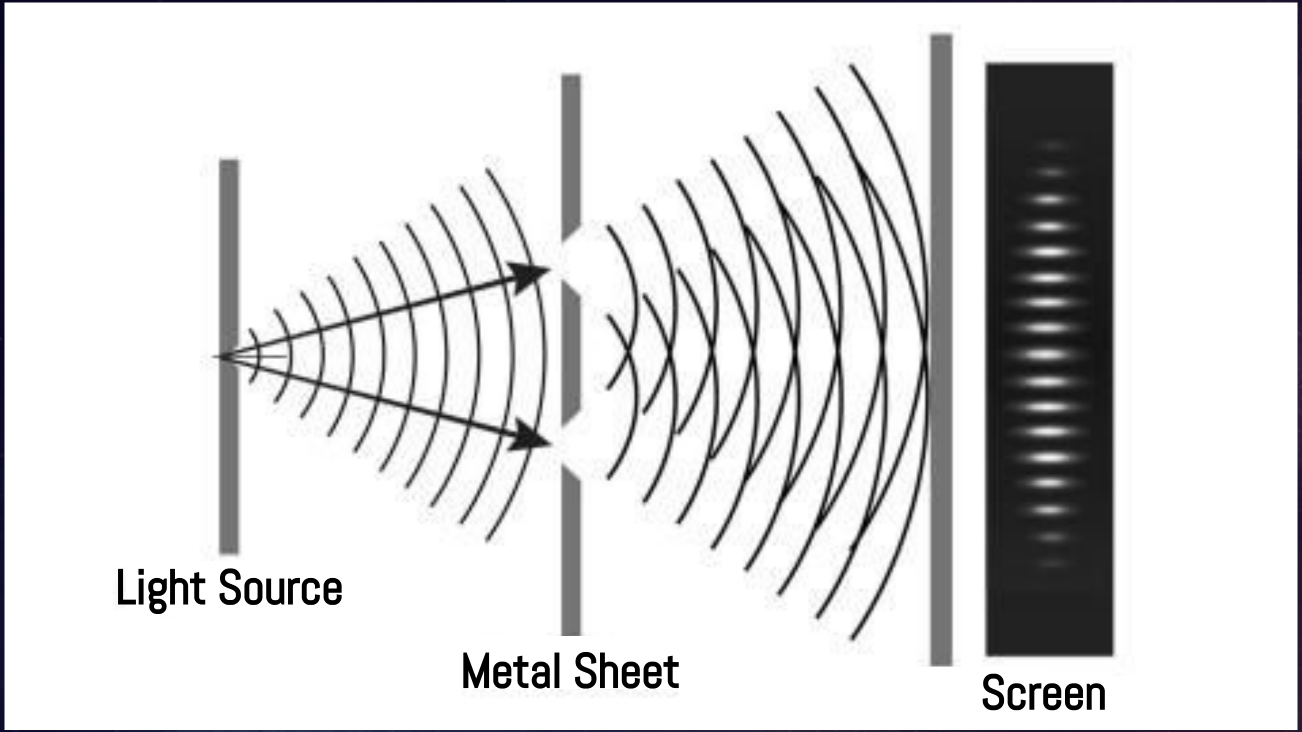

Figure 6. The Double Slit Experiment

The Dismissal of Dark Stars

Why the Theory Was Abandoned

- The theory of the "Dark Star" was somewhat dismissed in the late 1700s - early 1800s partly due to Young's experiment.

- **Why was this experiment such a big deal?**
    - Under Newtonian physics, mass is affected by gravity
    - If light was a wave without mass, gravity would have no effect on it.
    - In terms of the "Dark Stars", they couldn't physically exist because light would just be able to ignore the gravitational pull and escape.

02

Mathematical & Theoretical Development

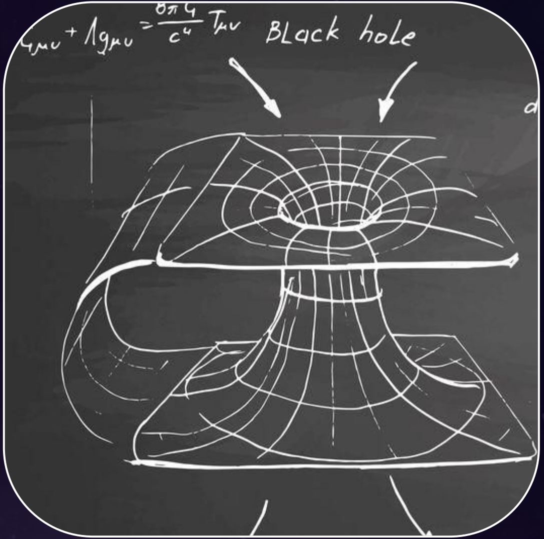

Figure 7: Black Hole.

1905–1970

Albert Einstein (1879–1955)

The Development of General Relativity

The Need for Innovation

- Newtonian physics was incapable of explaining various phenomena, and thus was incomplete.[7]

Special & General Relativity (1905–1915)

- Originally 'Relativity', Einstein built upon his theory to develop the theory of General Relativity.[7]
- Empirical validation: The explanation of Mercury's anomalous perihelion precession.[7,8]

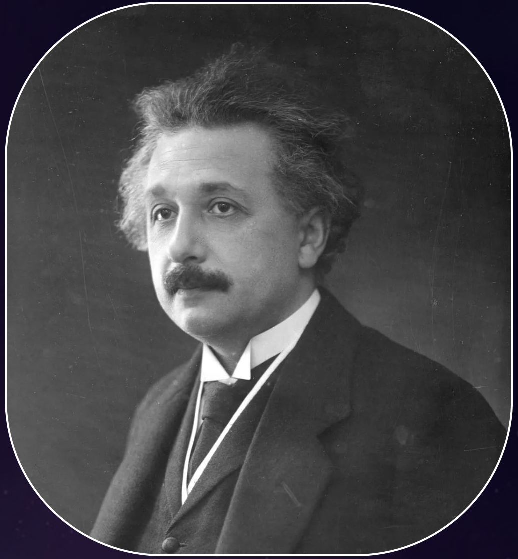

Figure 8: Albert Einstein.

Mercury’s Perihelion Precession

- **Perihelion Precession** – Shifting of planetary orbits over time
- Observed precession exceeds Newtonian gravity by 43” (arcsec) per century.
- General Relativity accurately calculated the observed precession of Mercury. [7,8]

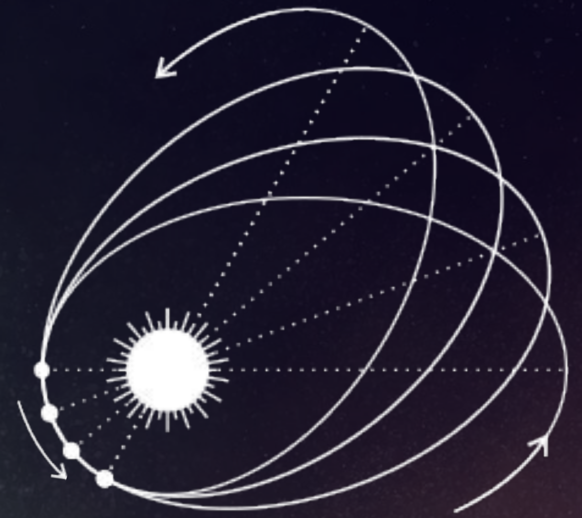

Figure 9: Change in Orbit over time.

Karl Schwarzschild (1873–1916)

Mathematical Application of General Relativity

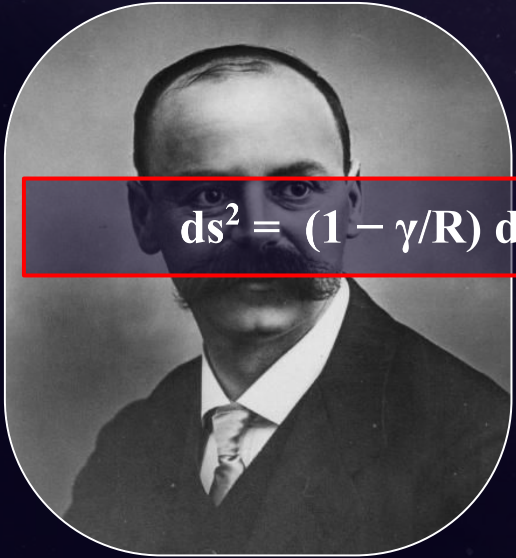

Figure 10: Karl Schwarzschild

Schwarzschild Metric (1915)

$$r_s = 2GM/c^2$$

- Early derivation of Einstein's field equations into an applicable equation for measuring spacetime.[9]

$$ds^2 = (1 - \gamma/R)\, dt^2 - (dR^2/(1 - \gamma/R)) - R^2\, (d\theta^2 + \sin^2\theta\, d\varphi^2)$$

'Coordinate Artifacts' of GR (1915)

- Through his solution, he discovered the <u>Schwarzschild Radius</u>, now known to be related with event horizons. Unbeknownst to him, this 'quirk' would be the first *clue* for the existence of black holes.[8,9]

J. R. Oppenheimer (1904–1967) & H. Snyder (1913–1962)

Theoretical Formation of Black Holes

Size Limit of Large Stars (1939)

- *Tolman-Oppenheimer-Volkoff* (TOV) *Mass limit* of neutron stars [Originally ~0.7 $M_\odot$].[10]

Black Hole Formation Process (1939)

- Stars surpassing the TOV limit that have exhausted thermonuclear fusion, and lack internal pressure, would collapse towards its schwarzschild radius.[11]

Figure 11: J. Robert Oppenheimer

Figure 12: Hartland Snyder.

In spite of their work, Oppenheimer & Snyder's research wasn't *fully* recognized.

Q: Why Was This the Case?

- WWII began less than 2 months after its publication
- Singularities (**Infinite** density) were considered impossible
- Required extremely specific, idealistic conditions
  (Spherical distribution, nonrotating, adiabatic, pressureless)

Roger Penrose (1931–)

Mathematical Proof of Singularities

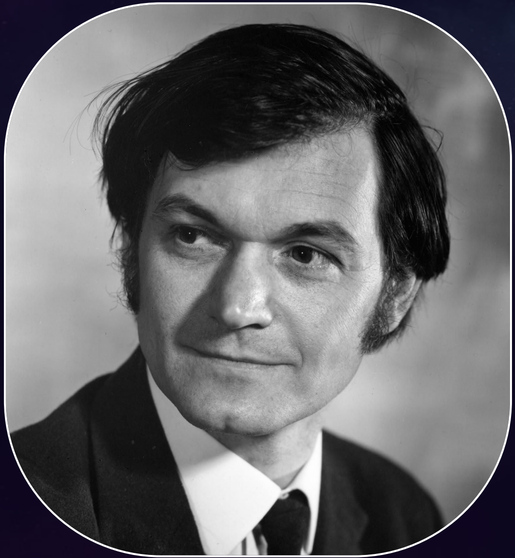

Figure 13: Roger Penrose.

Inevitability of Singularities (1965)

- Removed (former) idealistic conditions
- Introduced concept of ***trapped surfaces*** [12]
- Demonstrated definitively that black holes aren't a quirk of idealistic GR, but instead a direct consequence.

Assumptions for Singularity Dismissal [12]

- Negative Energy
- Spacetime manifold is incomplete
- General Relativity Breaks Down

03

Discovery Of "Black Holes"

Figure 14: The Cygnus X-1 System

1971 - 2000

If we can’t observe a black hole directly, what signs in space would make you suspect one is there?

Warped Or Bent Light

Black holes can be surrounded by rings of gas and dust, called accretion disks, that emit light across many wavelengths, including X-rays.[13]

Stars Orbiting “Nothing”

A black hole's intense gravity can cause stars to orbit around it in a particular way. Astronomers tracked the orbits of several stars near the center of the Milky Way.[13]

Gravitational Waves

Scientists can detect some gravitational waves by the ripples' effect on detectors.[13]

Paul Murdin (1942-) & Louise Webster (1941-1990)

First Observational Evidence For a Black Hole

The Discovery of Cygnus X-1

- X-ray Sources From Constellation Cygnus
- Observation: *Lone* Blue Supergiant in Orbit
- Theorized an Invisible Companion Star.[14]
- Invisible Star estimated ~20 Solar Masses, (TOV Limit: 2.8)
- Ended Up On The Conclusion It Must Be A Black Hole.[14]
- Conducted Their Work ~1972.[15]

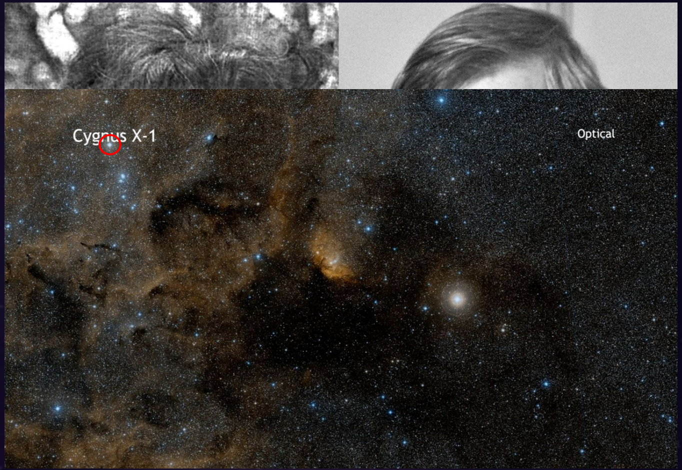

Figure 15: Paul Murdin and Louise Webster
Figure 16: Cygnus X-1

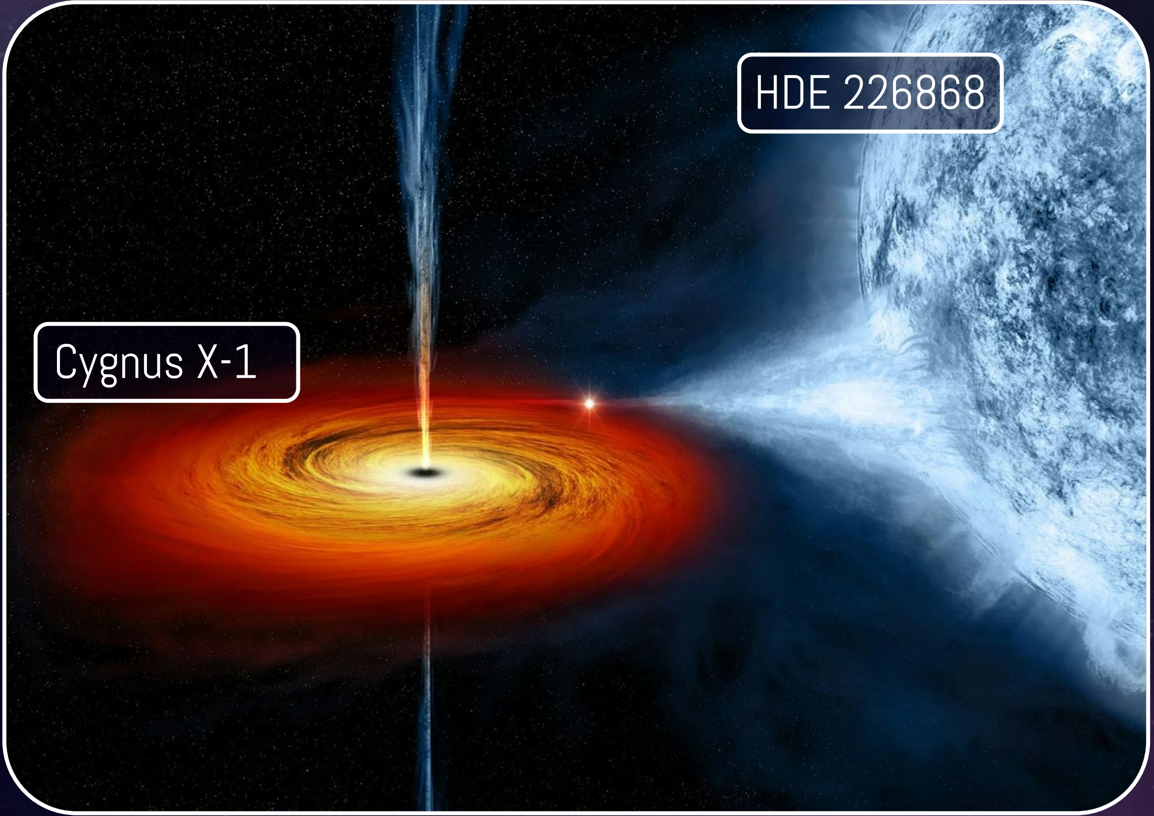

Figure 17: The mystery of black holes

Charles Thomas Bolton (1943-)

Also The "First To Discover a Black Hole"

Figure 18: Charles Thomas Bolton

- Worked at David Dunlap Observatory, Toronto Canada
- Also used high Precision Spectroscopy Plus the satellite UHURU to detect X-ray[16]
- Independently Confirmed The Same Theory As Webster & Murdin
- Conducted His Work ~1972 The Same Year As Webster & Murdin

04

Black Holes in the "Modern" age

Figure 19: Quasar

1973 – 2025+

Stephen Hawking (1942 - 2018)

Revolutionizing black hole physics

Hawking radiation:
• Predicted that black holes emit tiny amounts of thermal radiation

Area Theorem:
• The total surface area of a black holes event horizon can never decrease

Quantum and Gravity Breakthrough:
• His work linked quantum field theory, thermodynamics, and general relativity

Figure 20: Stephen Hawking

Modern Times

What Are We Currently Doing?

Ongoing research

- Detecting gravitational waves from black hole mergers. LIGO detectors
- Simulating black hole behaviour with computers
- Studying the center of most galaxies

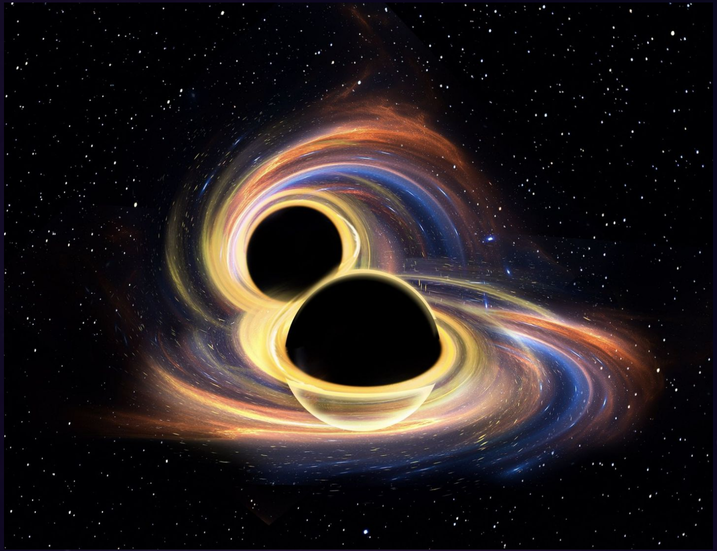

Figure 21: LIGO Detects Massive Black Hole

What Do We Know?

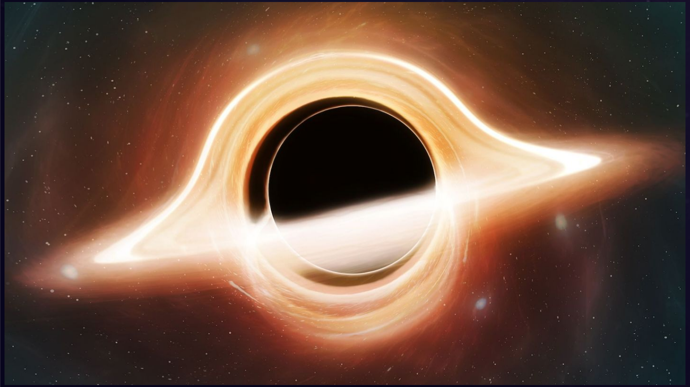

Figure 22: Black Hole

How Far Have We Come?

- Black holes warp space time
- They form from collapsing stars
- Can merge, producing detectable gravitational waves
- Black holes can power quasars and active galactic nuclei

What Don’t We Know

Where Do We Have Yet To Go?

Mysteries

- What happens inside the event horizon
- How to solve the information paradox
- How quantum gravity works near black holes
- The extreme environment outside event horizon

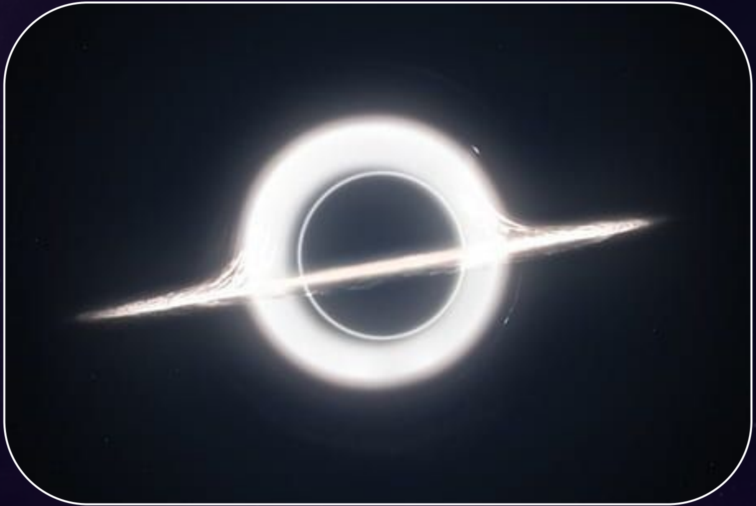

Figure 23: Interstellar black hole

Simulation vs Reality

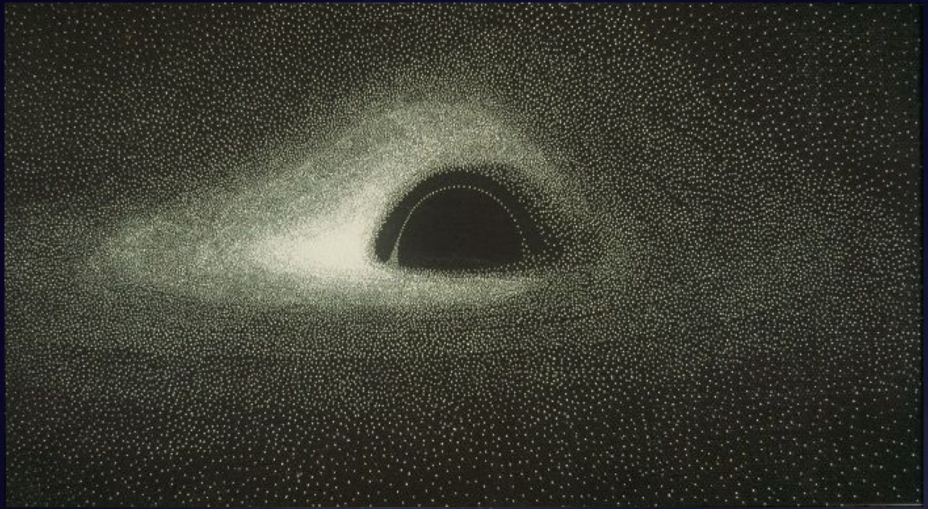

Figure 24: The simulation of a black hole published in 1979 by Jean-Pierre Luminet

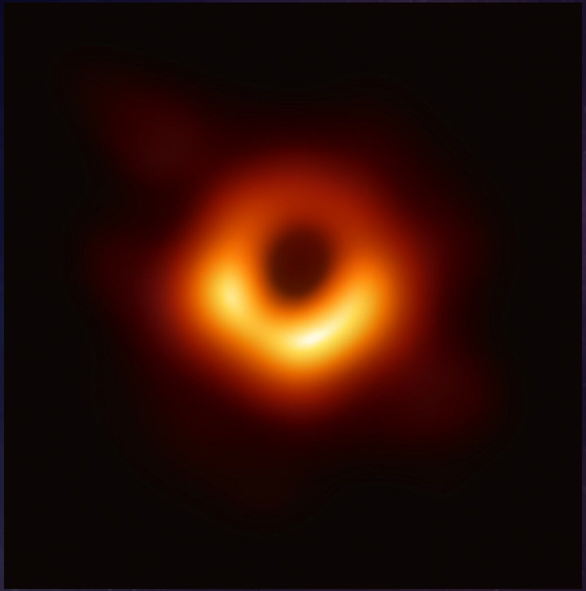

Figure 25: First image of a black hole

The First Picture Of A Black Hole

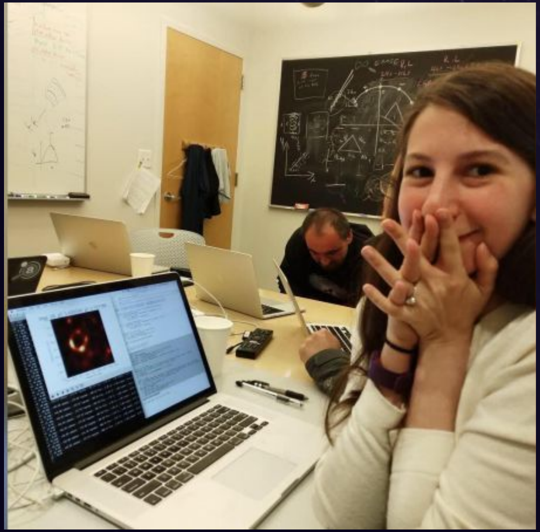

Figure 26: Katie Bouman

How Did It Happen?

- Used international event horizon telescope, a global network of radio telescopes
- Linking the telescopes via very long baseline interferometry(VLBI)
- Over 200 researchers collaborated across multiple continents
- Data processed using complex algorithms, including one lead by Katie Bouman

Thanks!

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