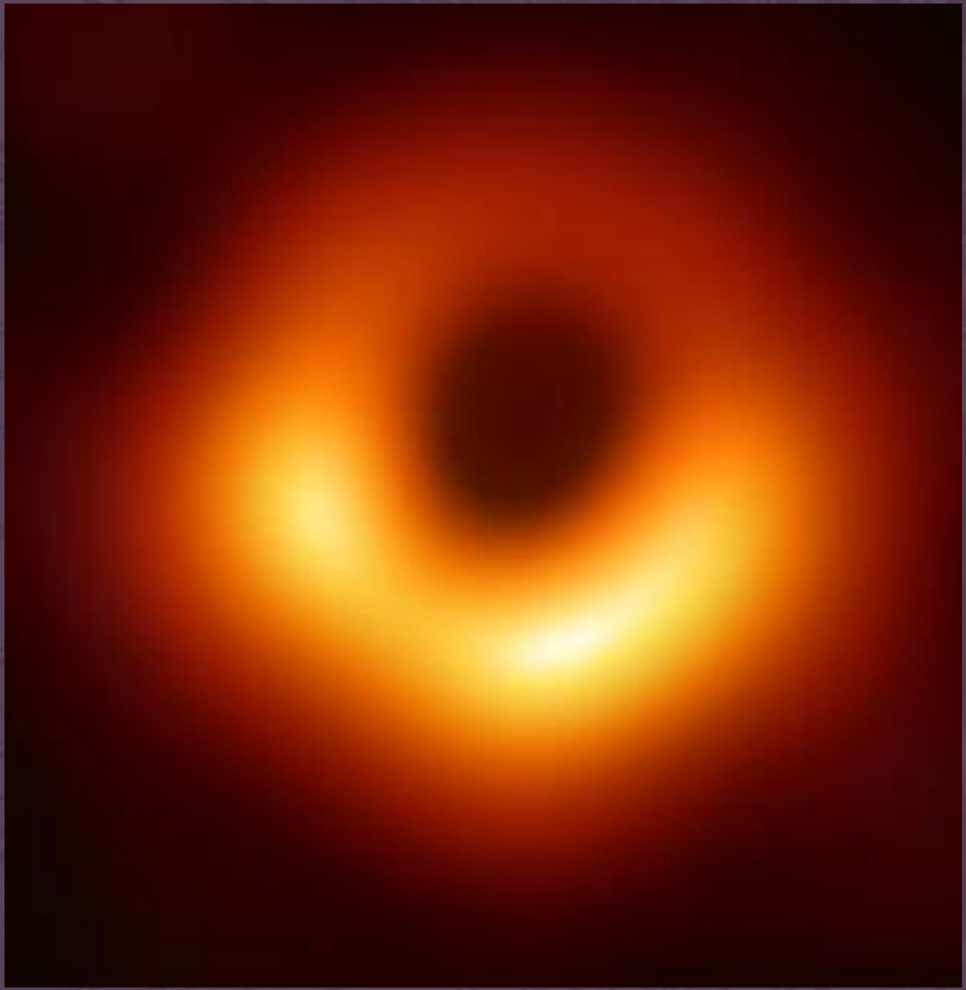
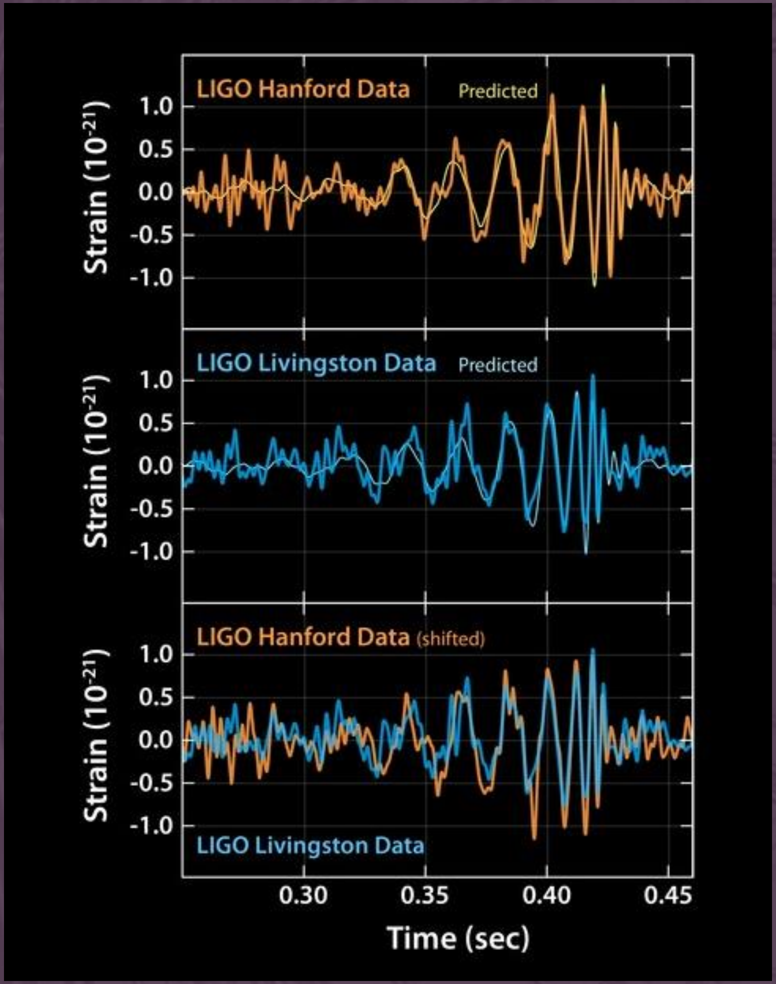
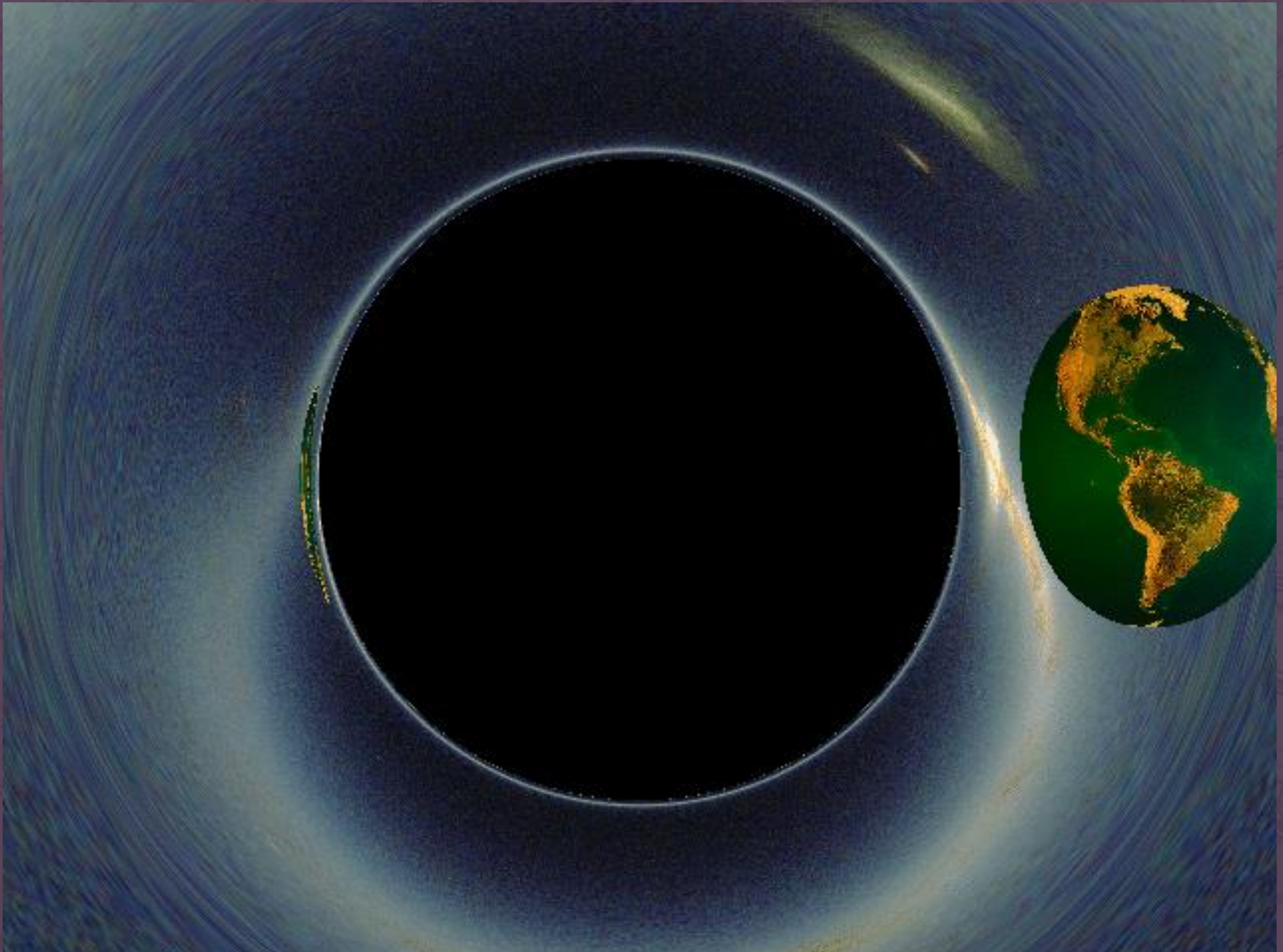
Astronomy 2142: Black Holes

Professor David Weinberg

Spring 2025

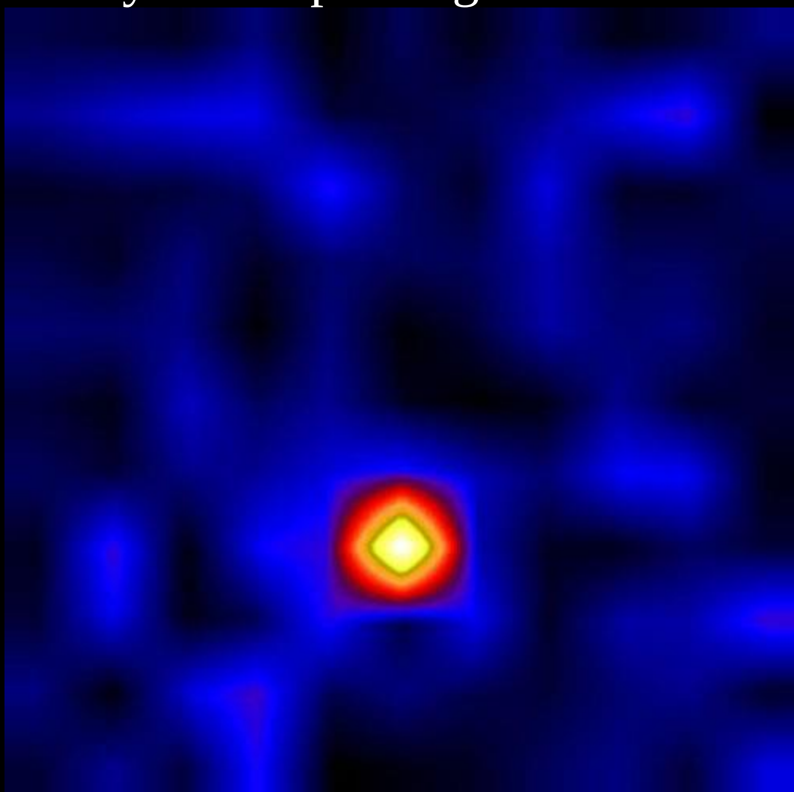




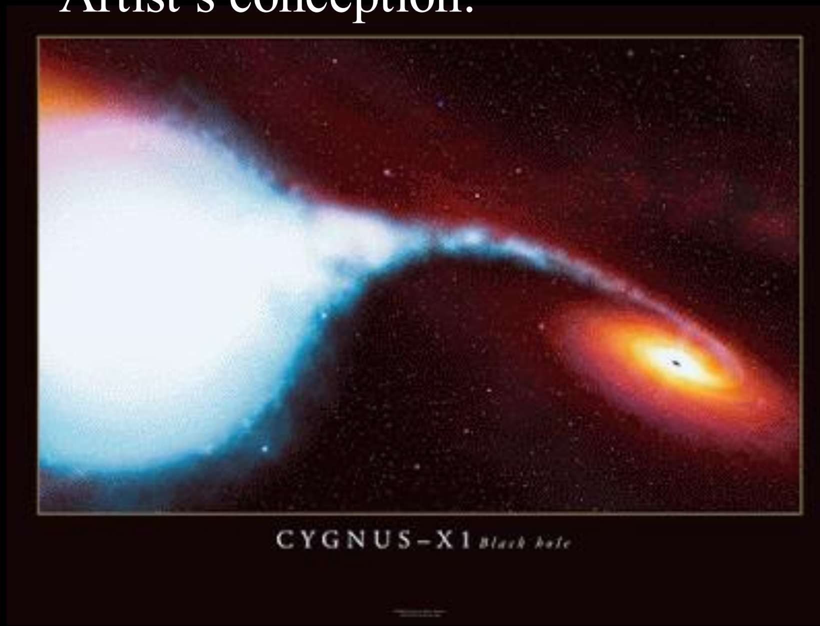


How can we find black holes?
Gas falling towards a BH heats dramatically, glows in X-rays.

X-ray telescope image.



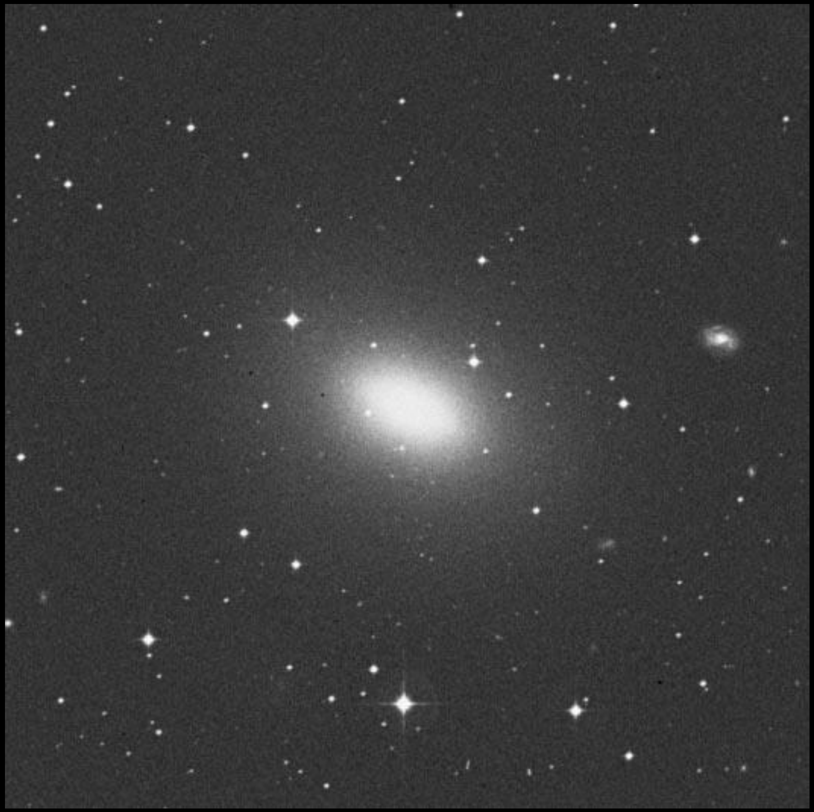
Artist's conception.



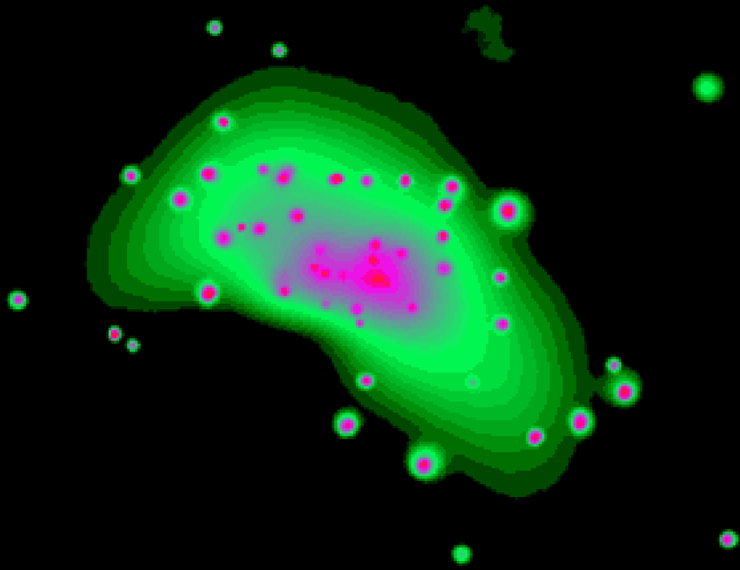
Cygnus X-1, first widely accepted black hole.

Galaxy NGC 4697

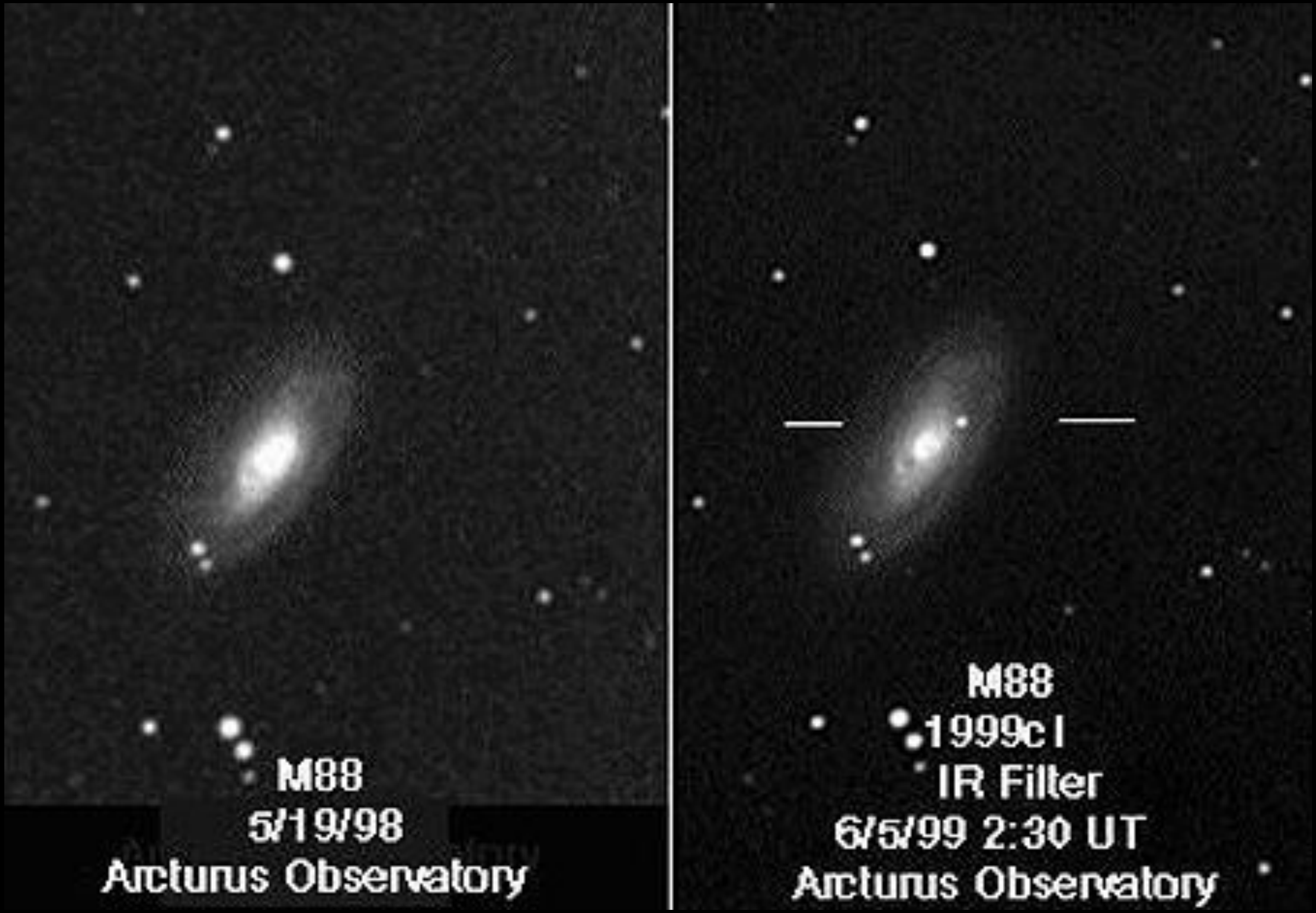
Optical light



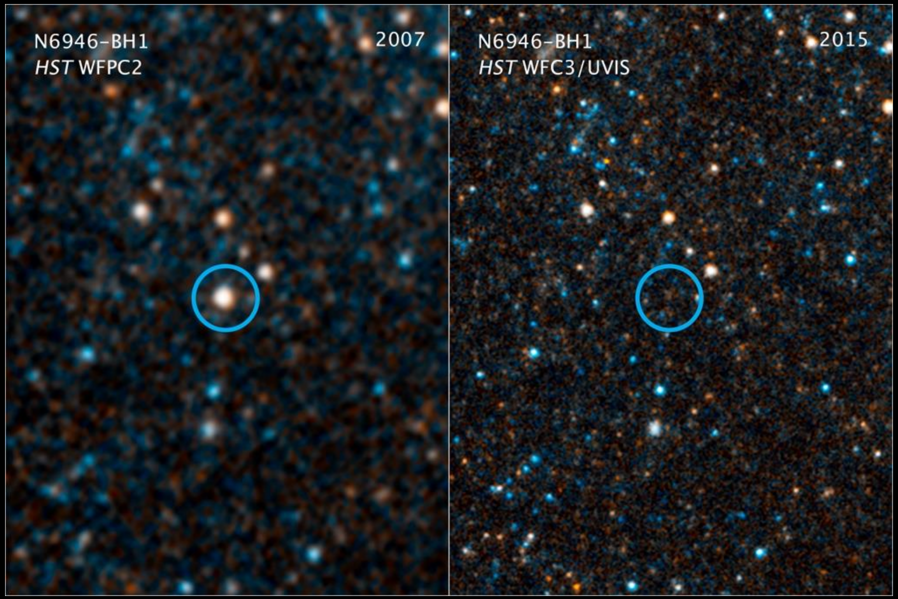
X-rays



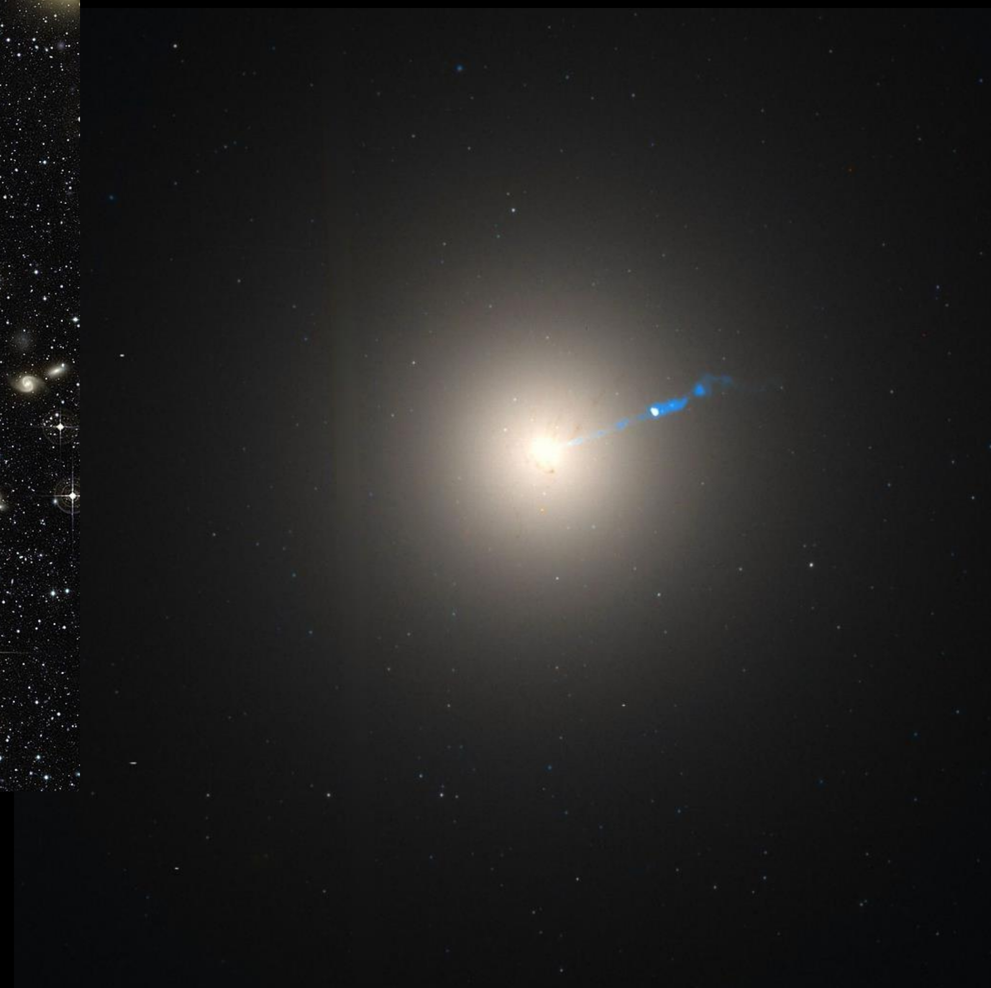
Supernova explosion in a nearby galaxy.



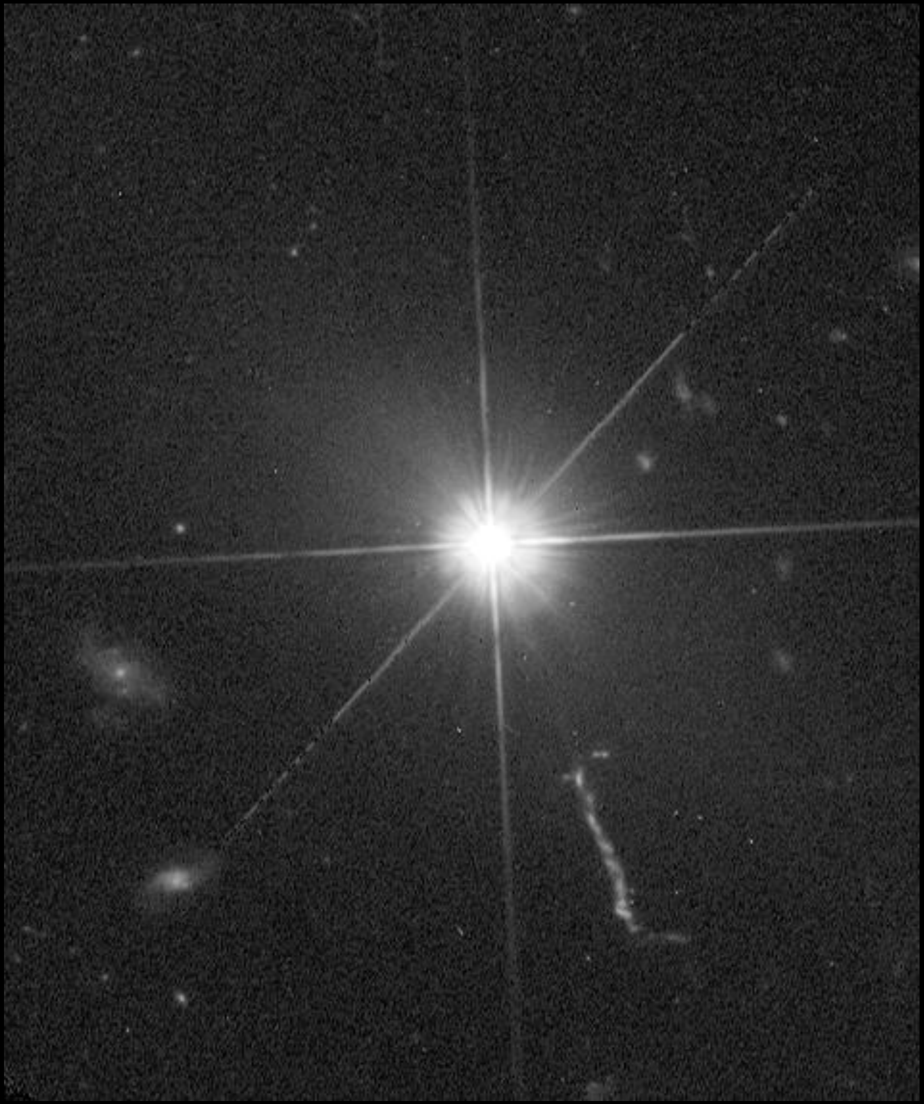
Formation of a "stellar mass" BH (3 – 100 $\times$ M_{sun})



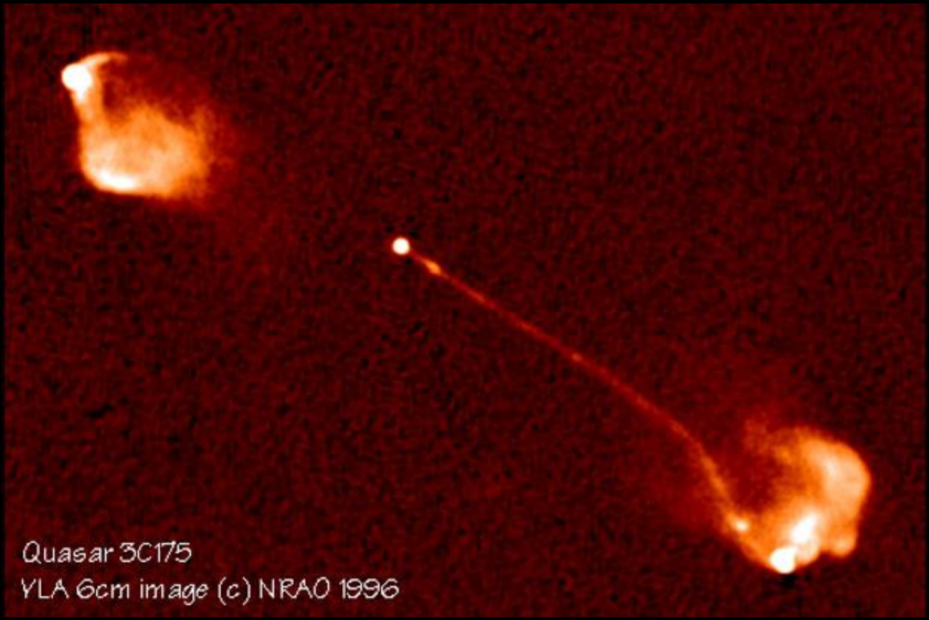
“Supermassive” black holes at galaxy centers ($10^6 - 10^{10} \times M_{sun}$)

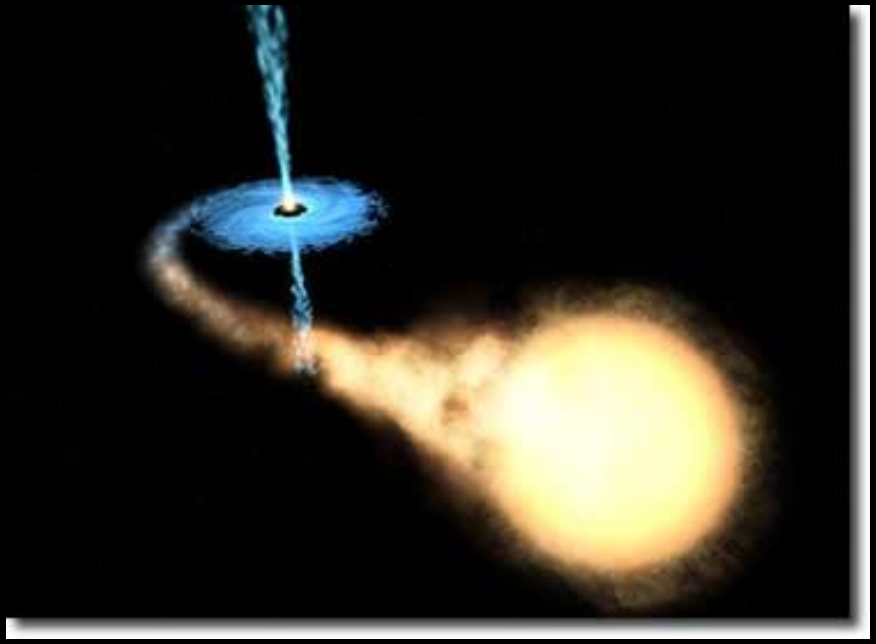


3C 273, optical light (HST)

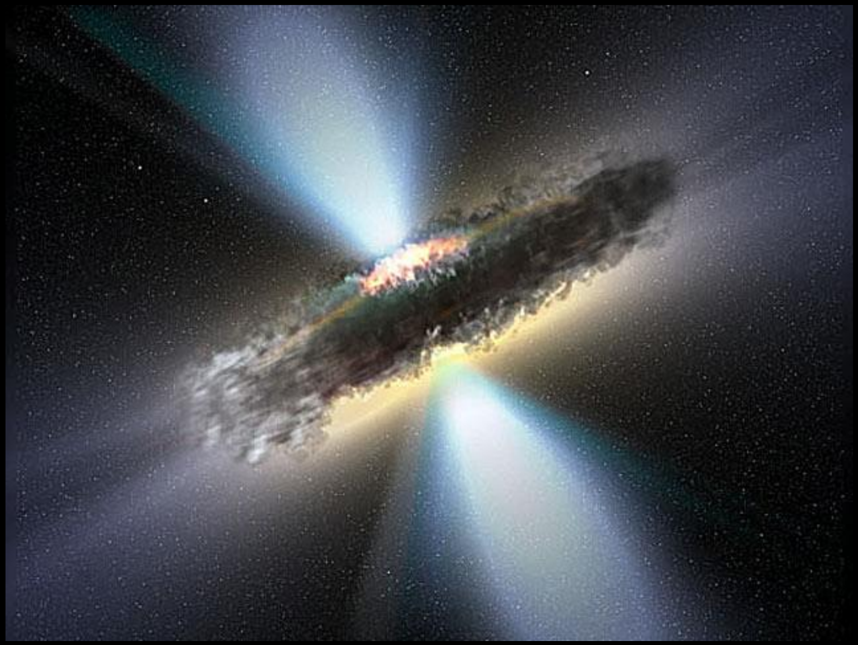


3C 175, radio waves





Artist’s conception.



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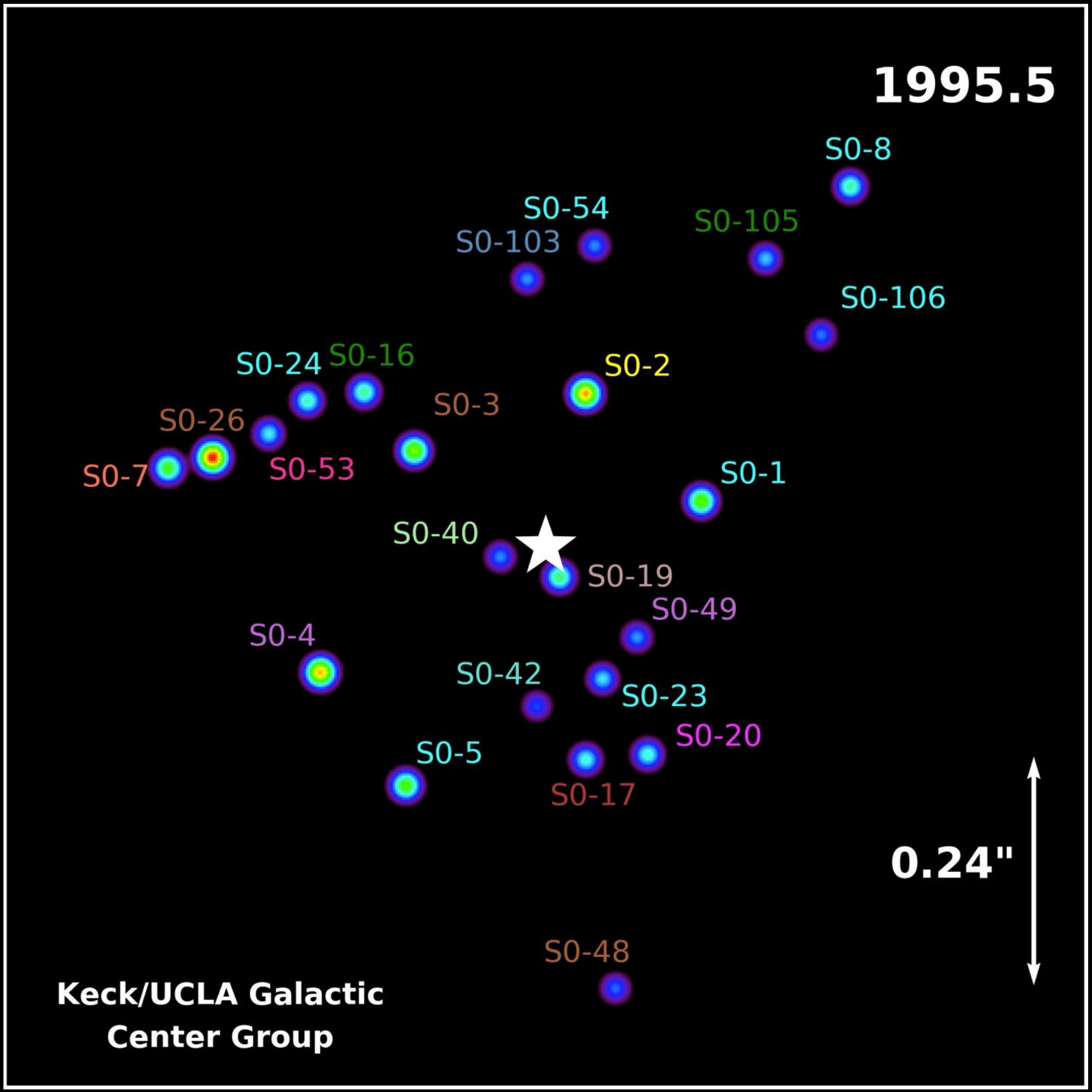
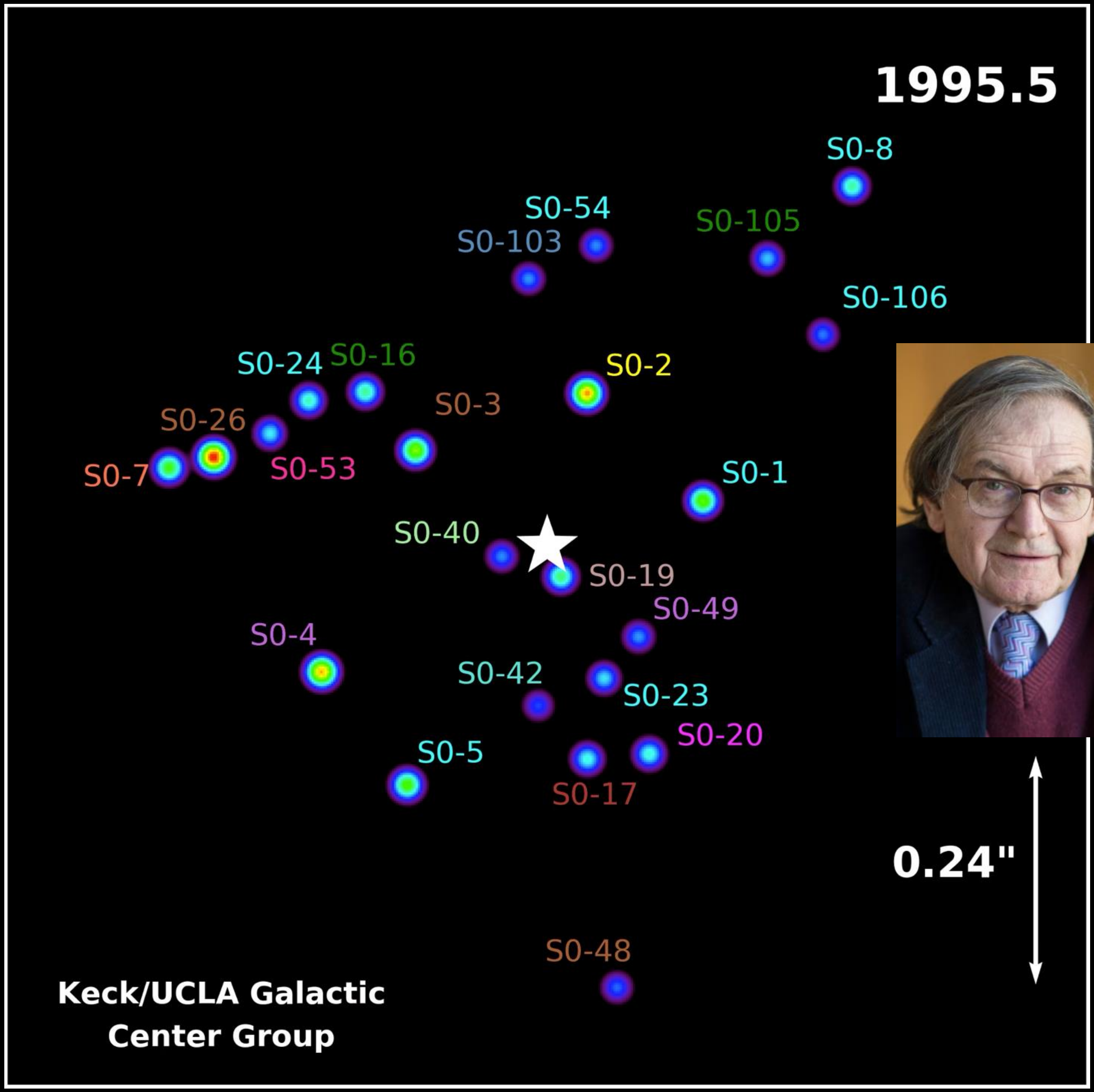


Motion of stars near the center of the Milky Way Galaxy, over 14 years. Data and visualization by Andrea Ghez and collaborators, UCLA.

Central black hole is four million times the mass of our Sun.

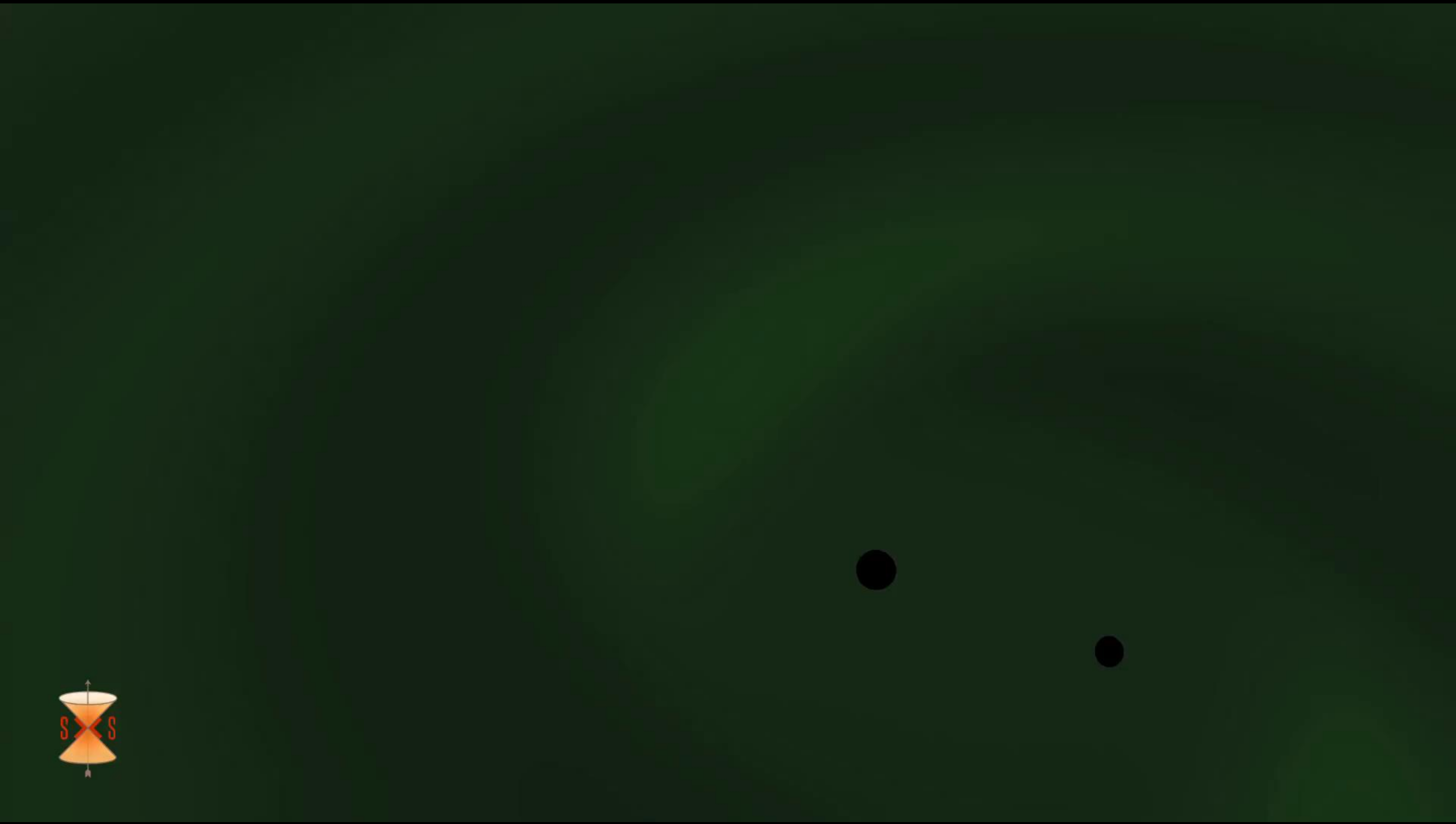


Motion of stars near the center of the Milky Way Galaxy, over 14 years. Data and visualization by Andrea Ghez and collaborators, UCLA.

2020 Nobel Prize in Physics
Andrea Ghez
Reinhard Genzel
Roger Penrose

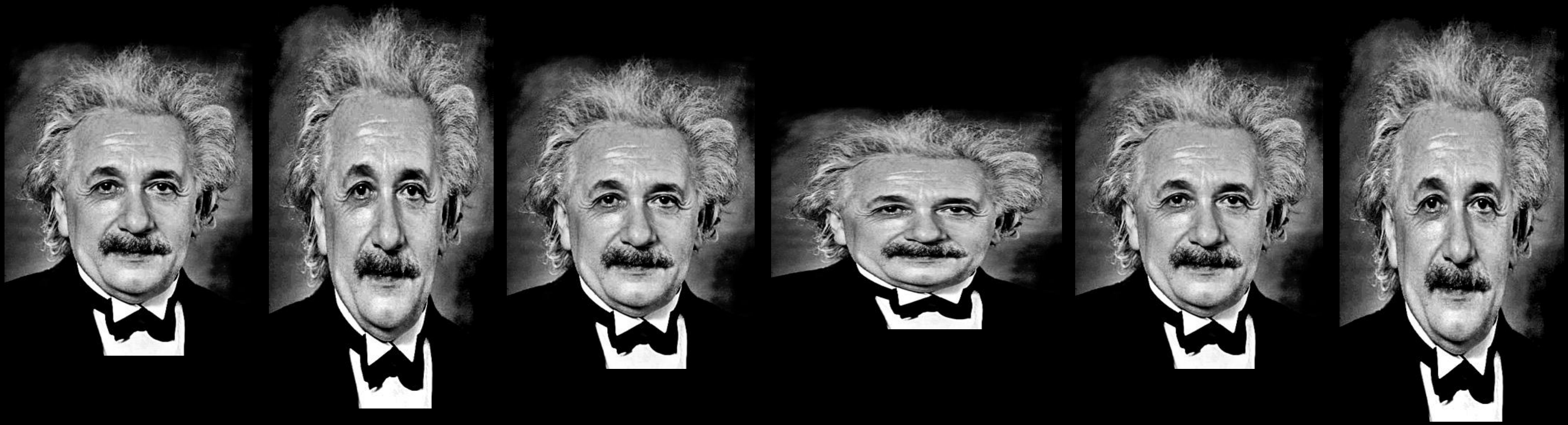
Inspiral of merging black holes

Videos available at ligo.caltech.edu

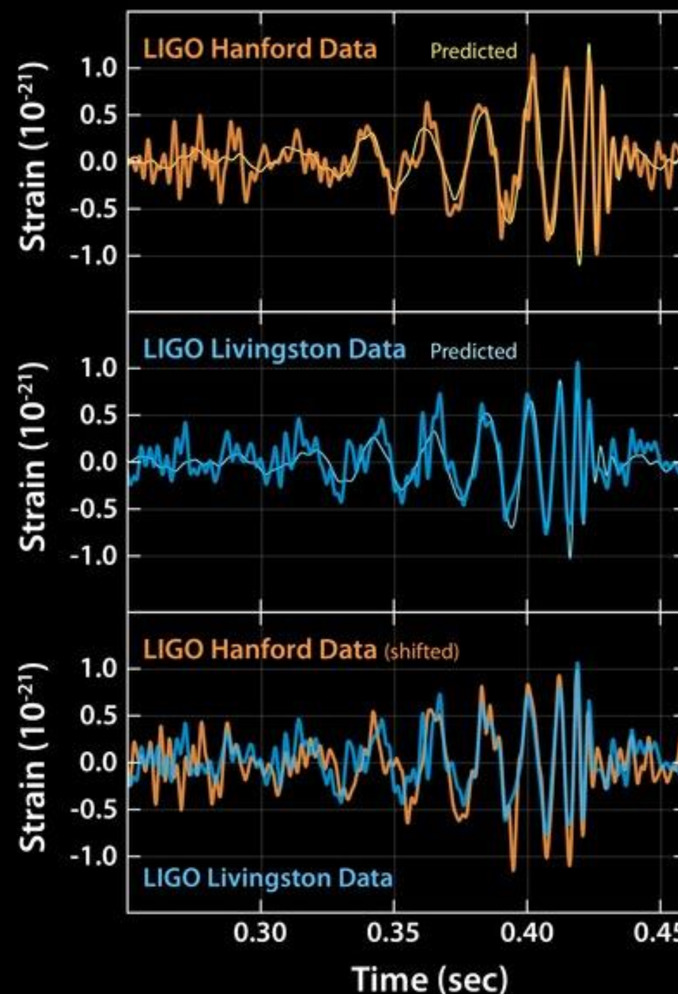


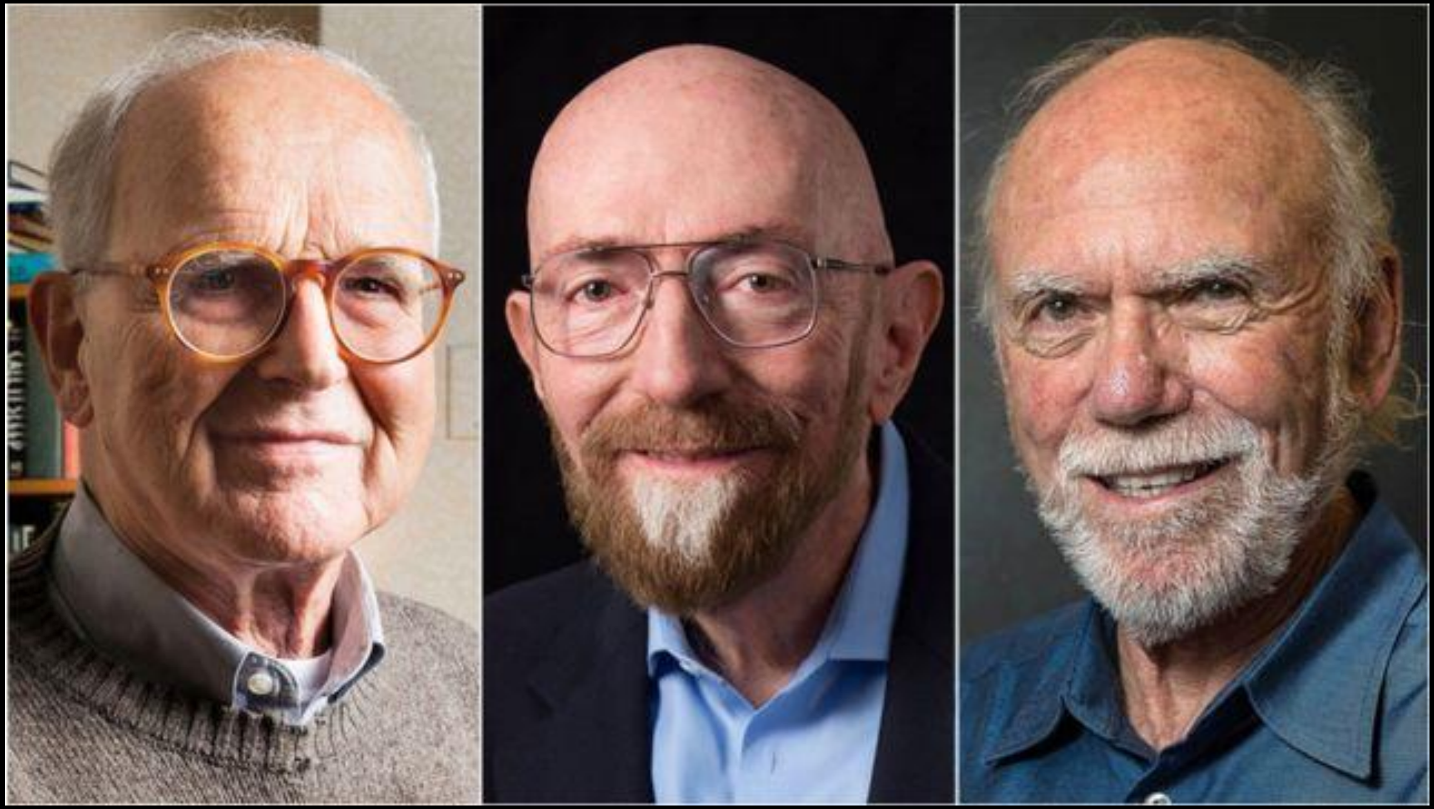
Gravitational Waves

Created by accelerating masses, e.g., orbiting stars or black holes.



Stretch and squeeze distances in an oscillating pattern as they pass.


LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)



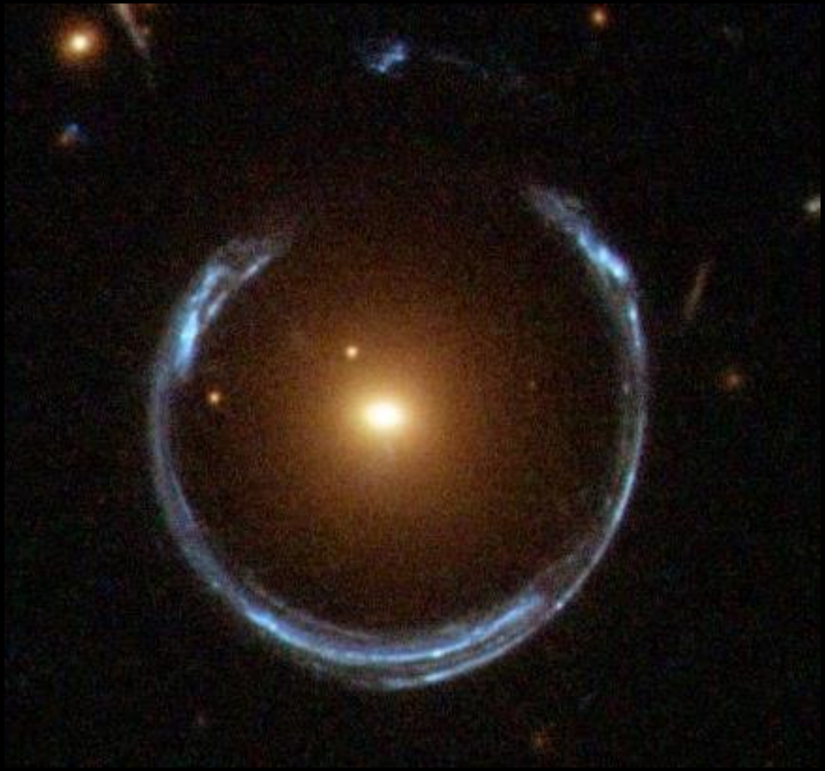
2017 Nobel Prize in Physics
Rai Weiss, Kip Thorne, Barry Barish

Subramanyan Chandrasekhar

Gabriela Gonzales

Nergis Mavalvala

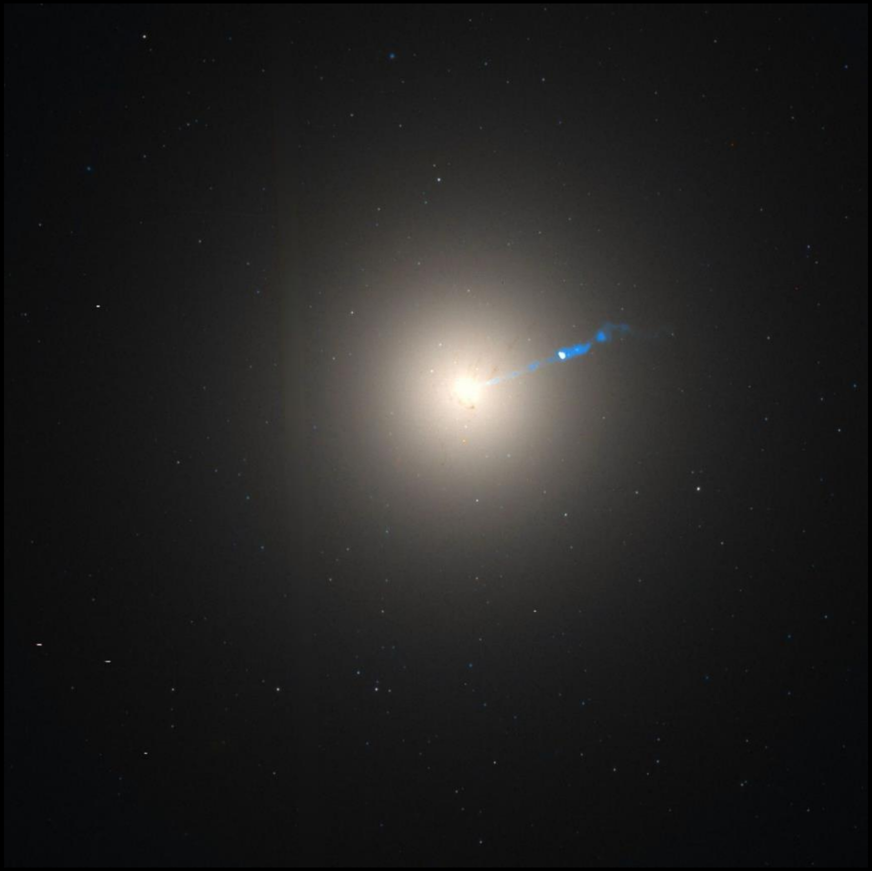
Vicky Kalogera



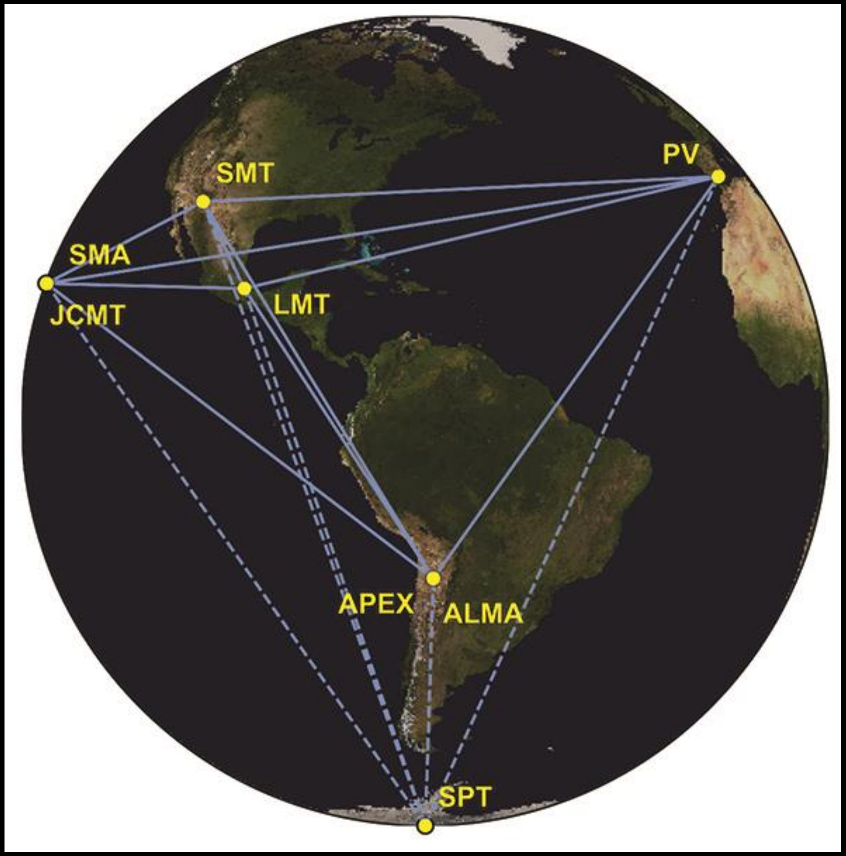
Real telescope image of a galaxy gravitationally lensing a background galaxy.

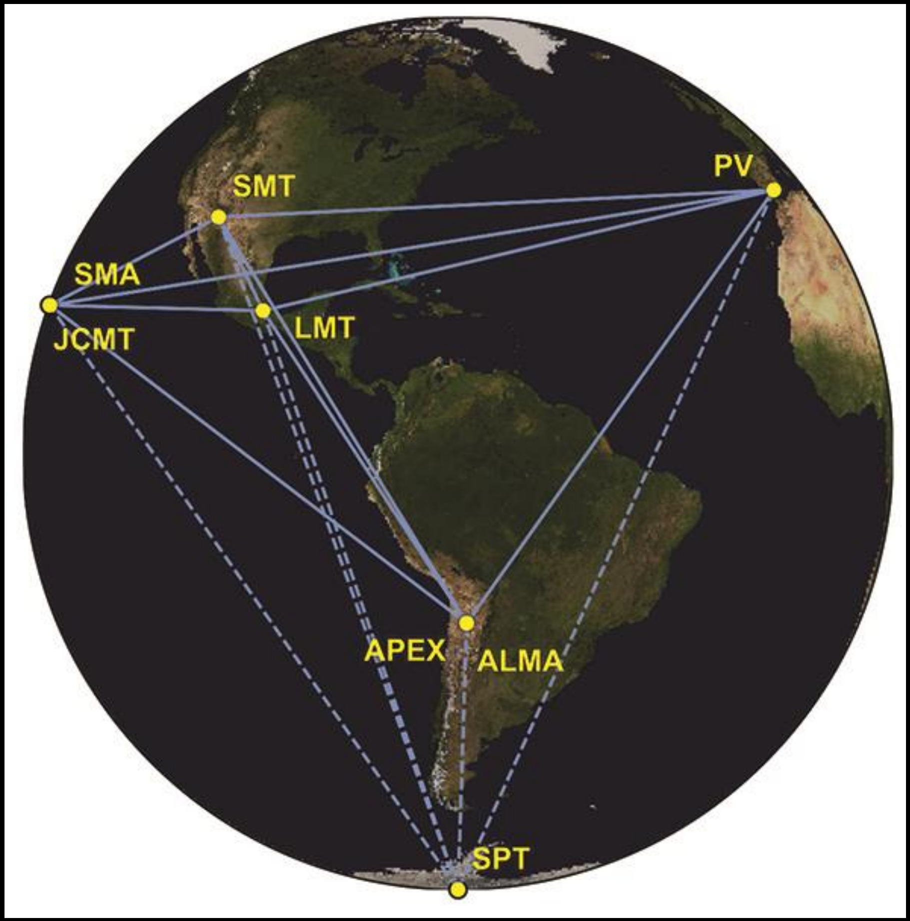
Artist’s conception of shadowing and gravitational lensing by a black hole.

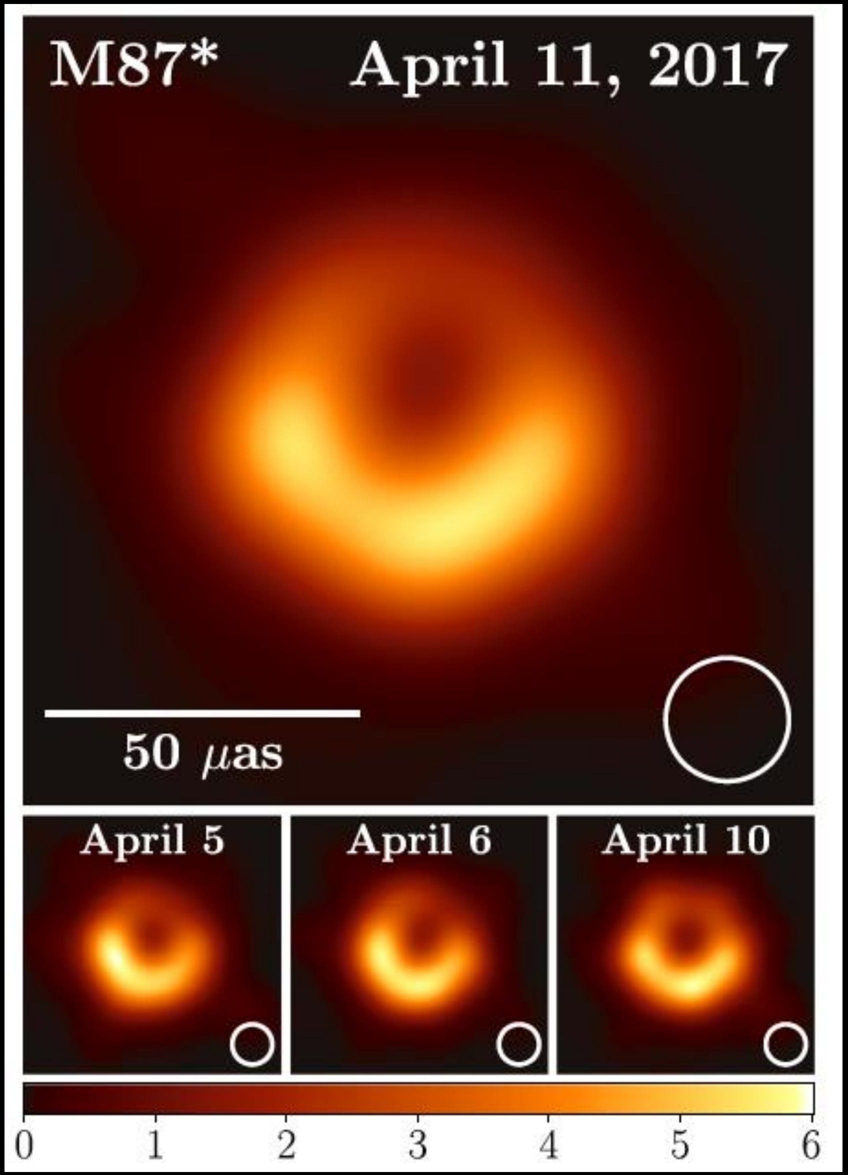
M87, optical image with jet



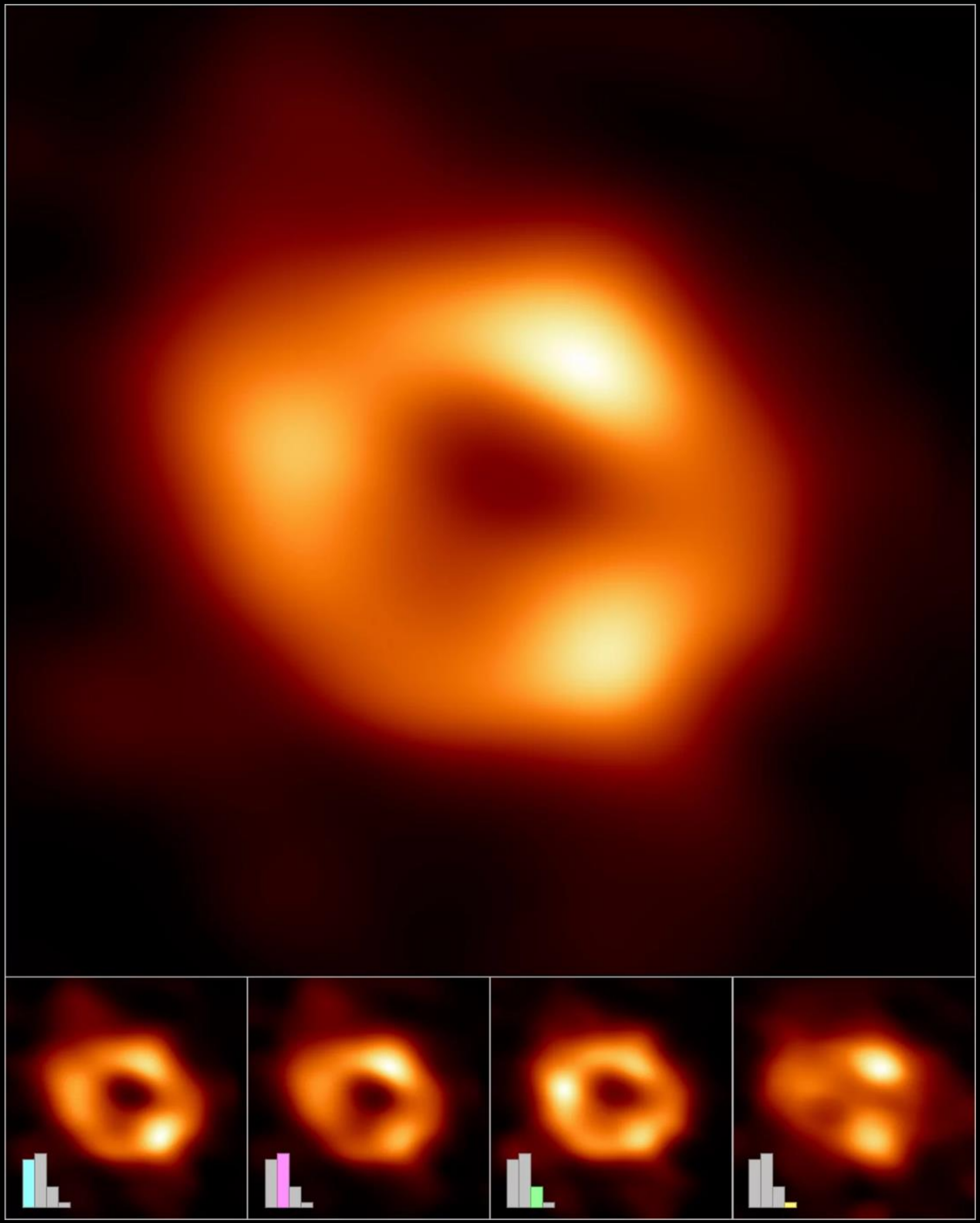
Event Horizon Telescope network







EHT image of BH at center of M87



EHT image of BH at center of Milky Way galaxy

A brief history of an idea

- 1686: Newton’s theory of gravity
- 1783: Michell proposes idea of “dark stars”
- 1796: Laplace popularizes this idea
- 1800: light consists of waves, not particles
- 1907-1916: Einstein’s theory of gravity (General Relativity)
- 1916: Schwarzschild solution to Einstein’s equations, describing black holes
- 1925-1930: Existence of white dwarfs
- 1930: Maximum mass of white dwarfs; collapse of massive stars could produce black holes
- 1930s-1950s: Theory of supernovae and neutron stars. Neutron stars also have a maximum mass.
- 1960s: Theory of BHs developed further.

- 1963: First discovery of quasars.
- 1970: First X-ray satellite. Many bright X-ray sources, some too massive to be neutron stars.
- 1970s-1990s: Case for stellar mass BHs and supermassive BHs gets stronger, alternatives eliminated.
- Late 1990s-2000s: Demonstration that most nearby galaxies have central supermassive black holes.
- 2000s: Increasing evidence that supermassive BHs help govern the formation of their host galaxies.
- 2015: First direct detection of gravitational waves from merging BHs, in a galaxy 1 billion light years away.
- 2019: First direct image of the shadow cast by a BH event horizon, in the galaxy M87.
- Today: ~ 100 gravitational wave events, Milky Way BH event horizon has also been imaged.