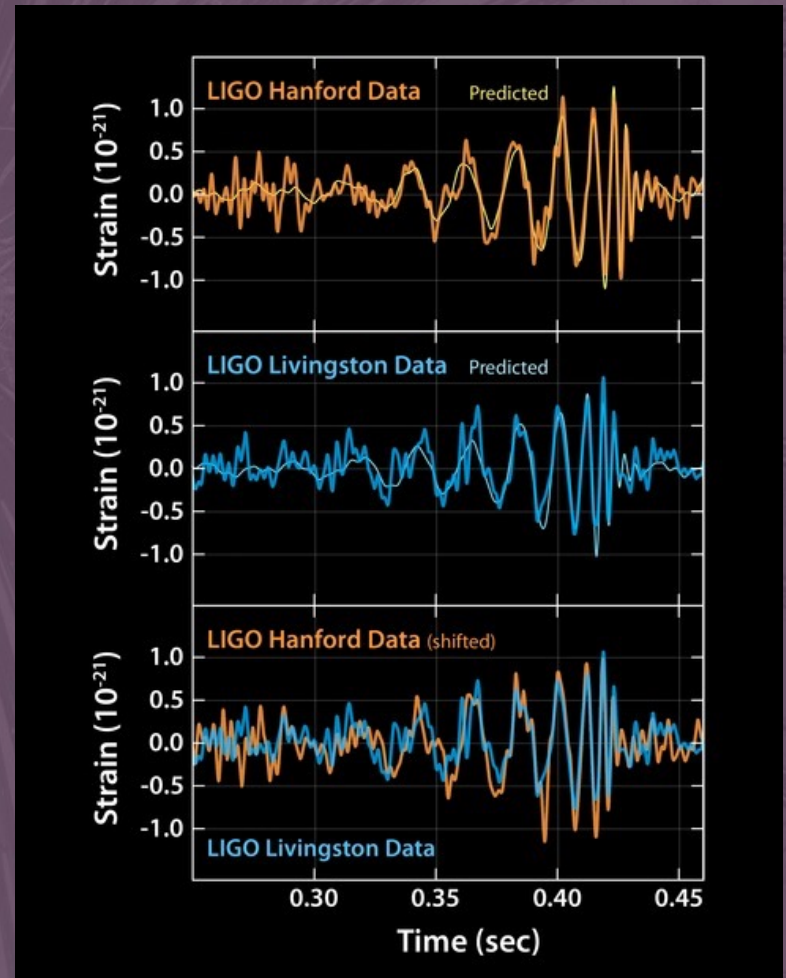
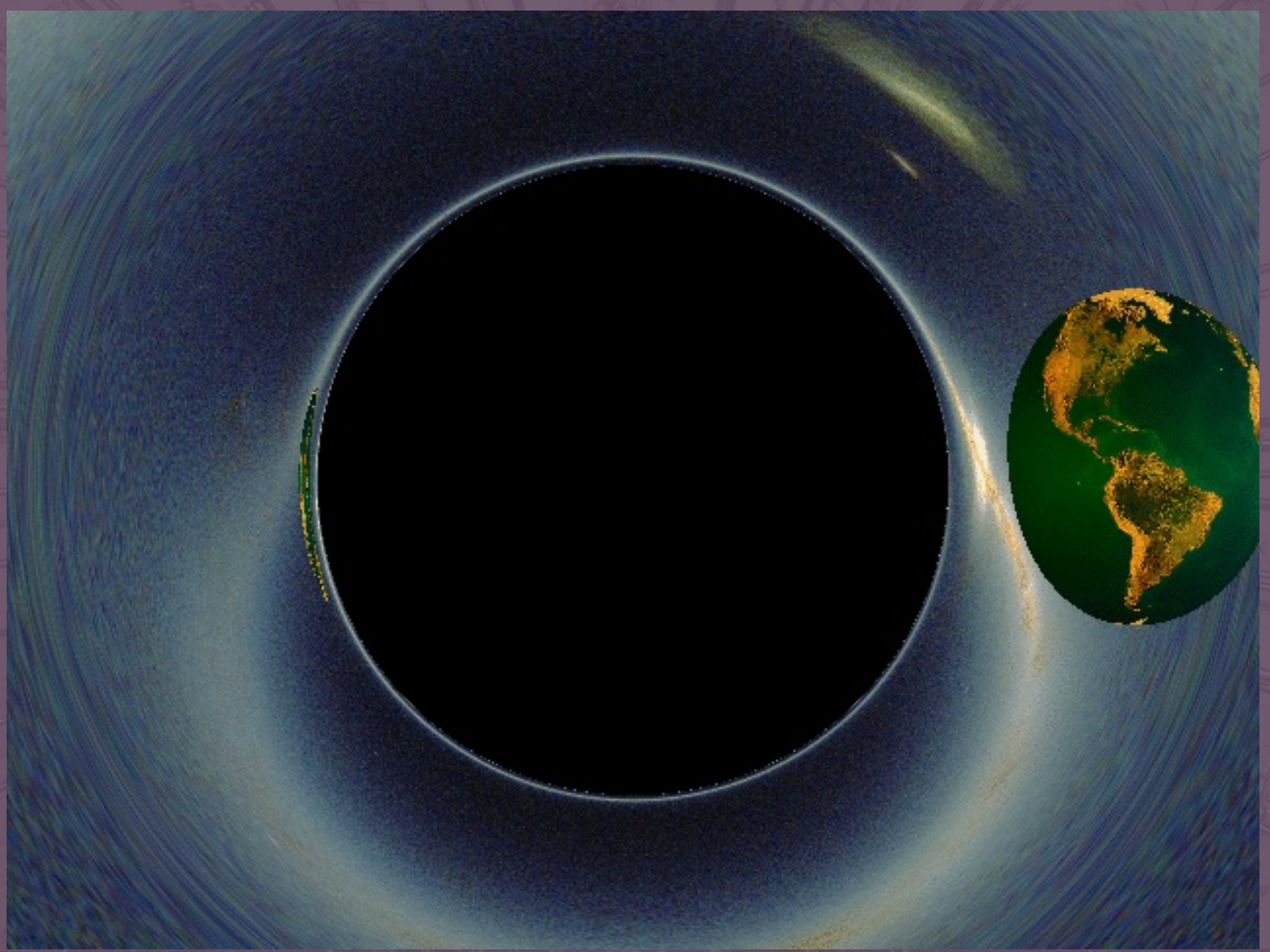


Astronomy 1142: Black Holes

Professor David Weinberg

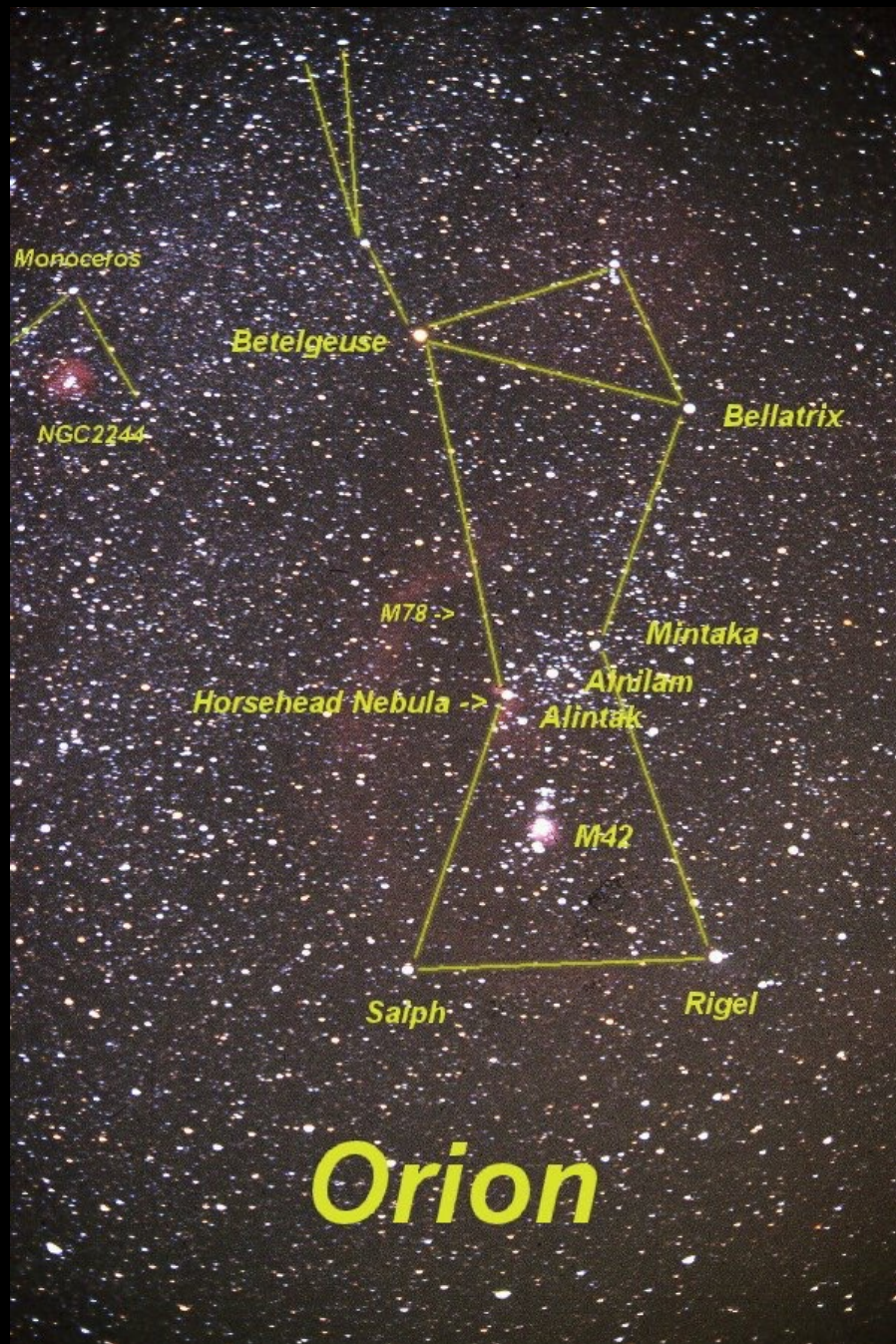
Autumn 2021





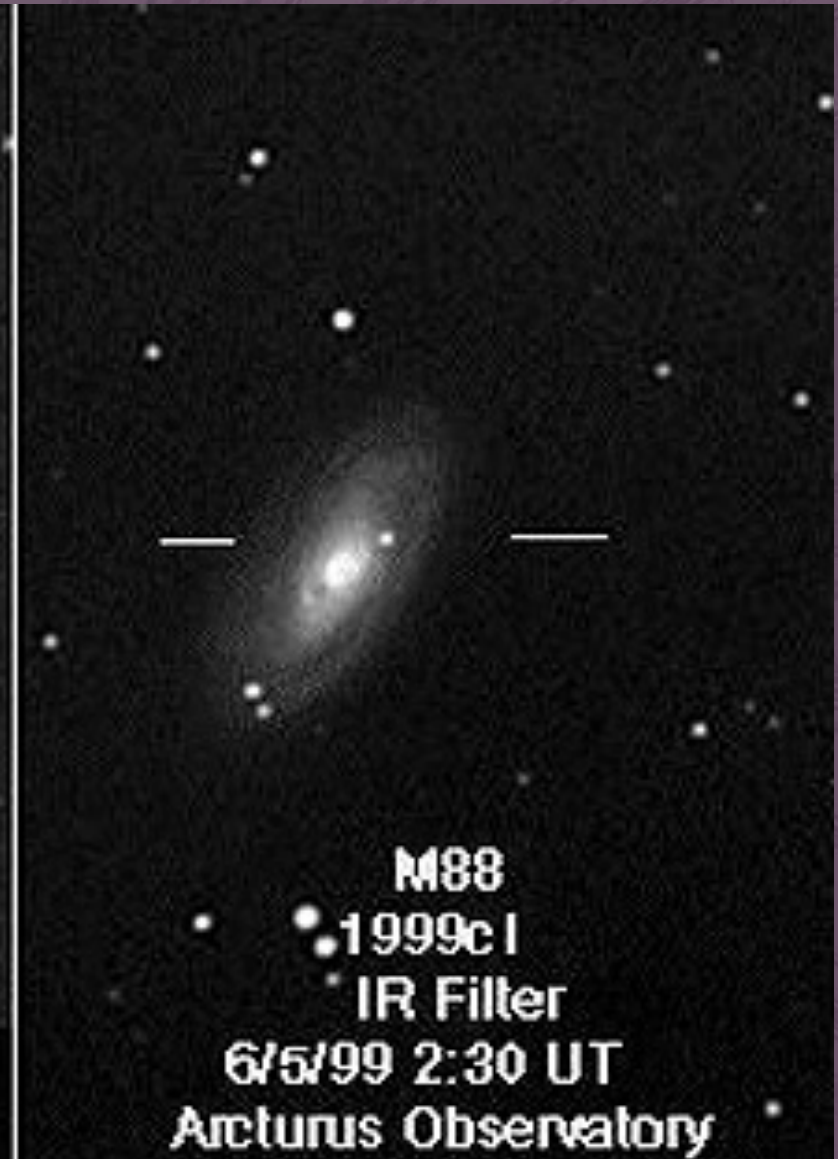
- 
1. Write down two things you know (or think you know) about black holes.
 2. Write down two questions you have about black holes.



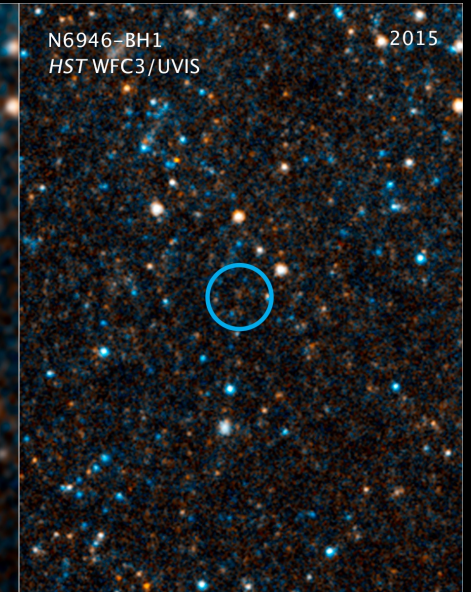
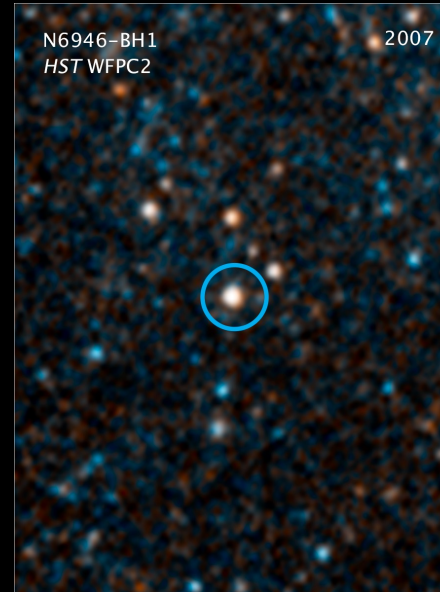




Supernova explosion in a nearby galaxy.



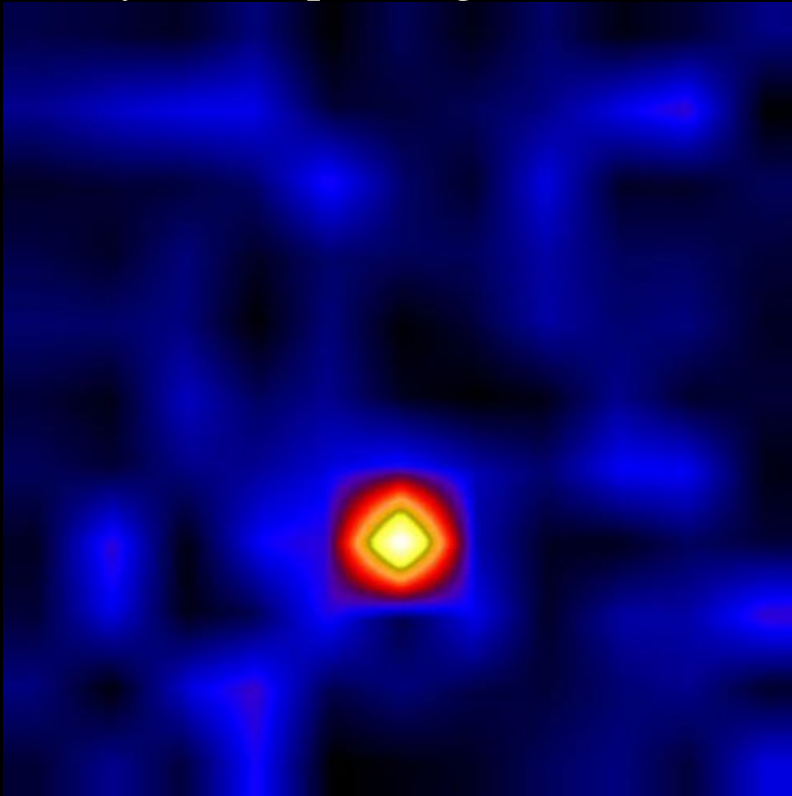
Formation of a “stellar mass” BH ($3 - 100 \times M_{\text{sun}}$)



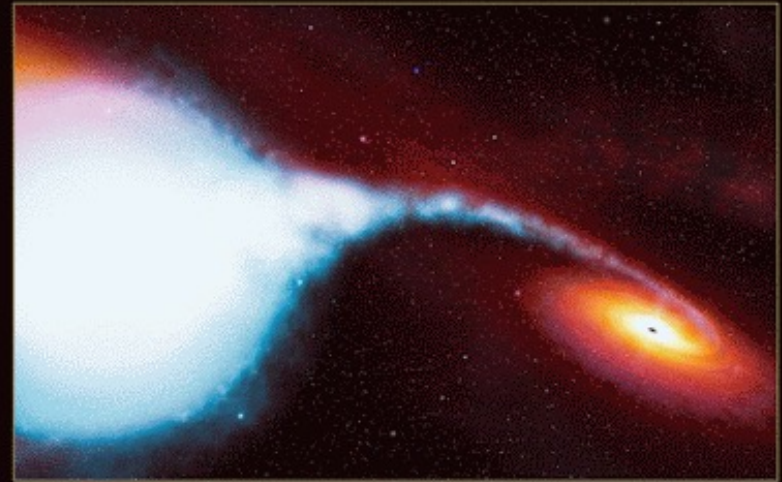
How can we find black holes?

Gas falling towards a BH heats dramatically, glows in X-rays.

X-ray telescope image.



Artist's conception.



CYGNUS-X1 *Black hole*

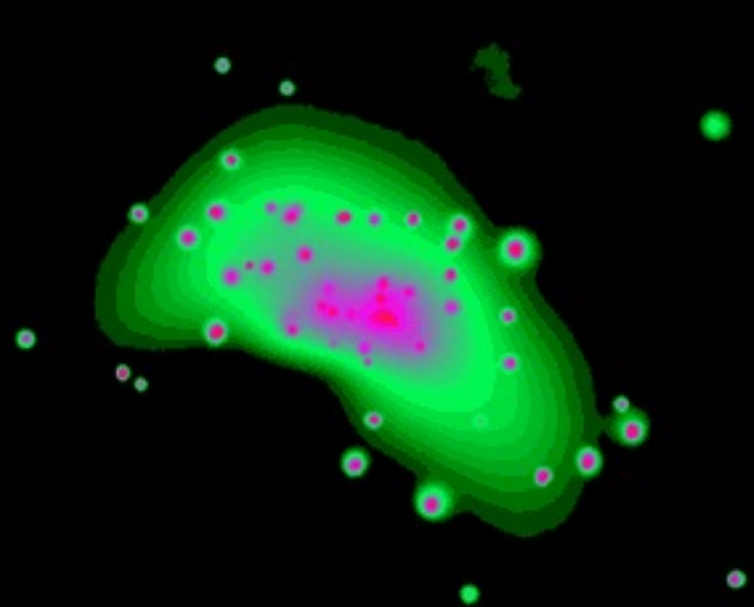
Cygnus X-1, first widely accepted black hole.

Galaxy NGC 4697

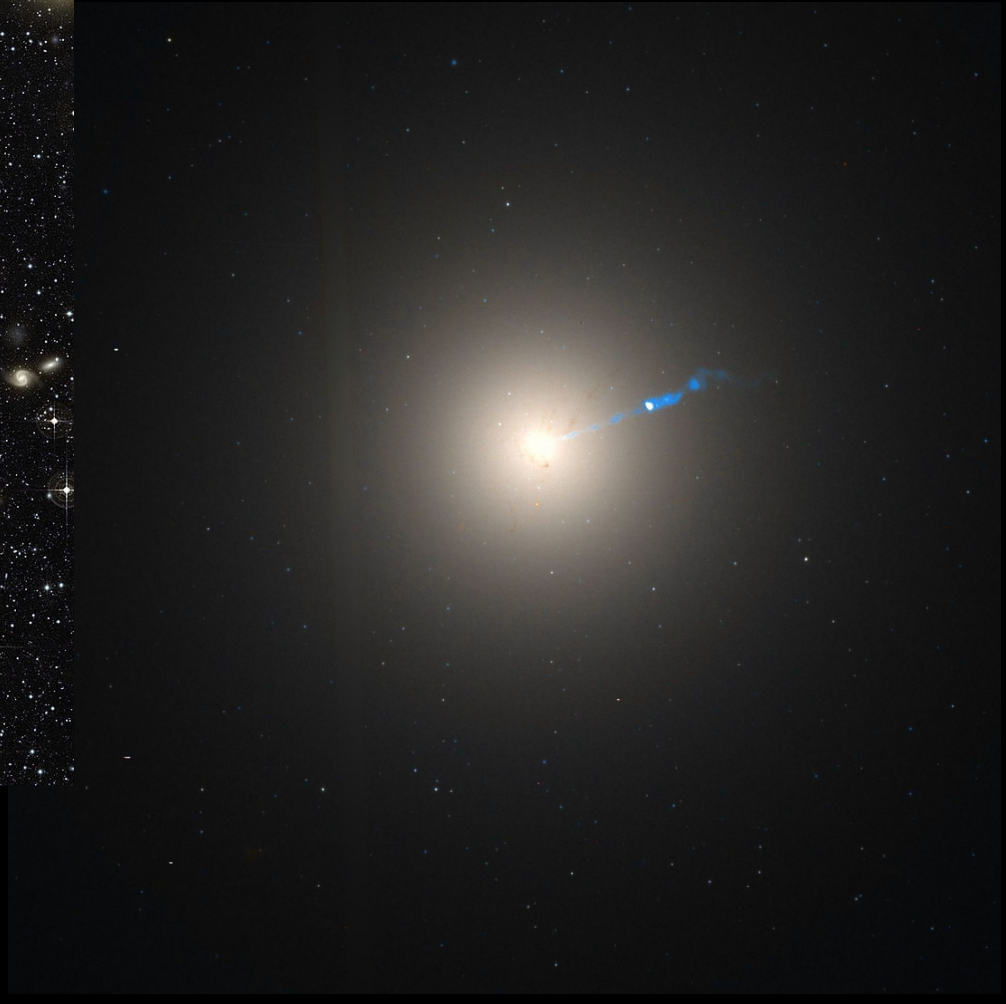
Optical light



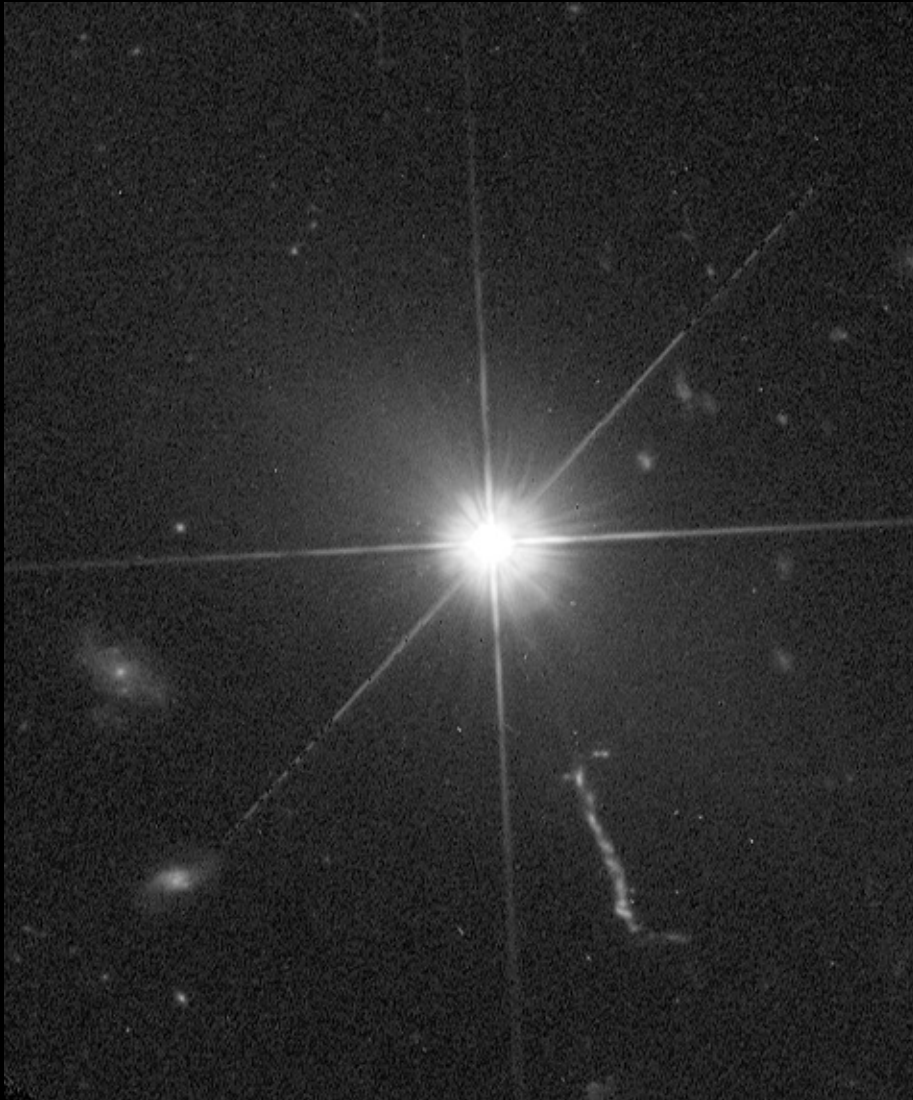
X-rays



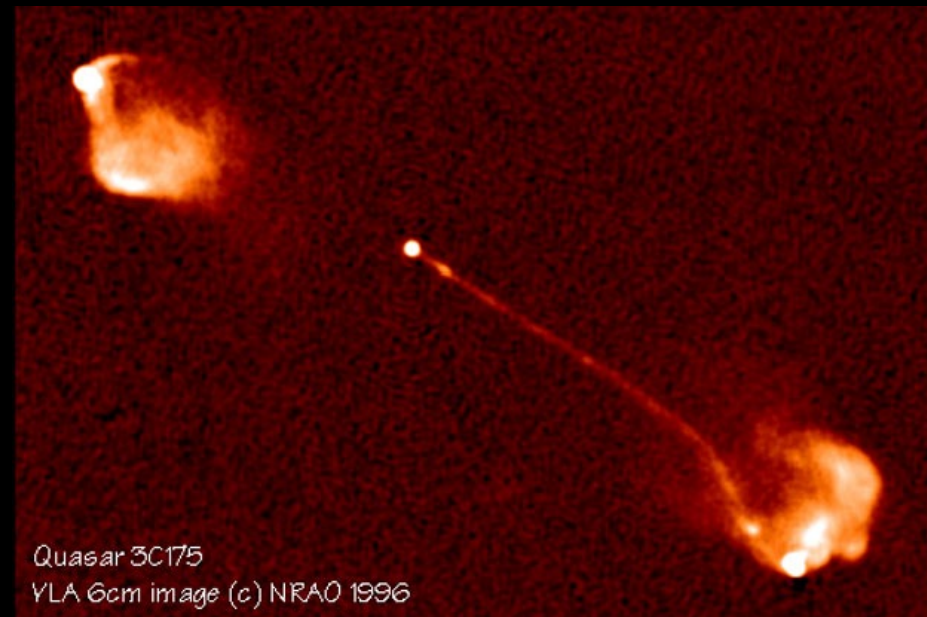
“Supermassive” black holes at galaxy centers ($10^6 - 10^{10} \times M_{\text{sun}}$)

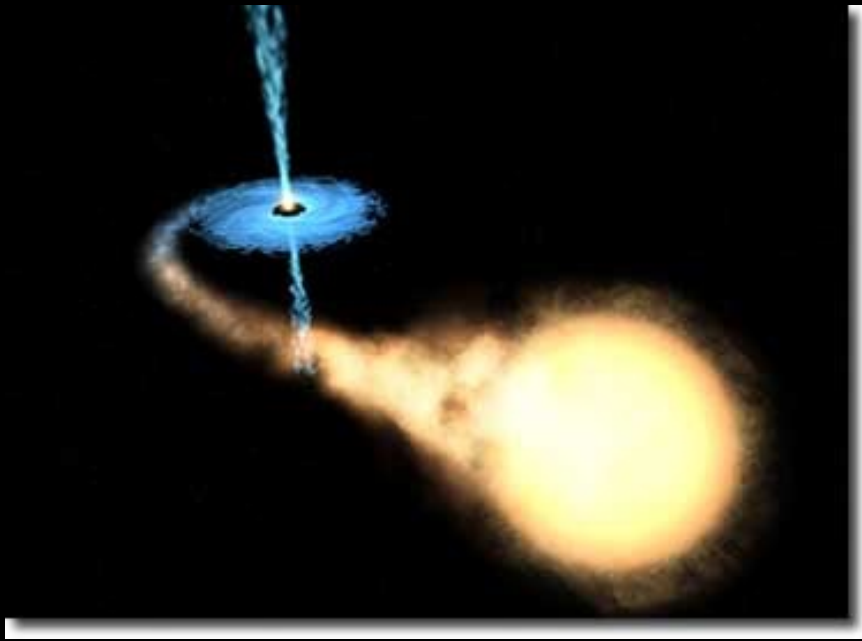


3C 273, optical light (HST)

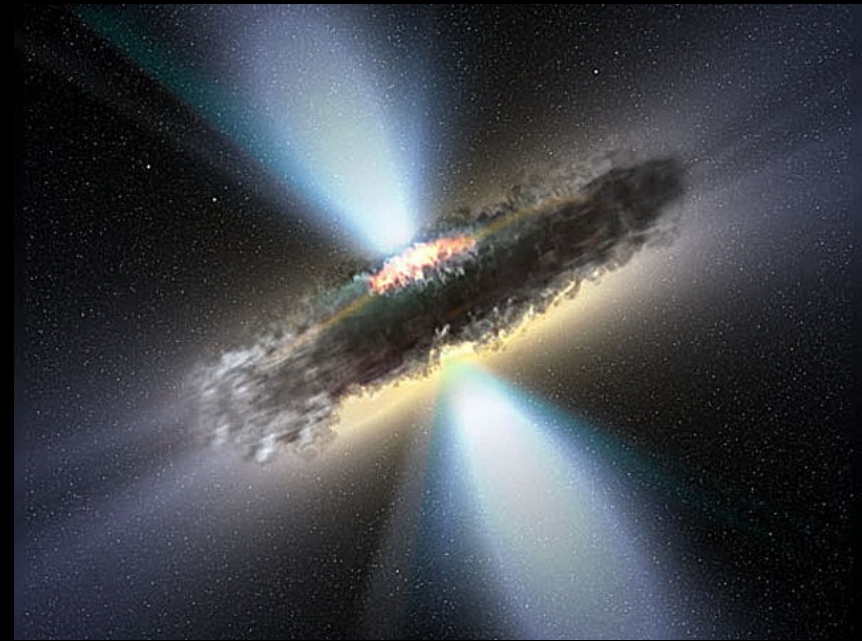


3C 175, radio waves

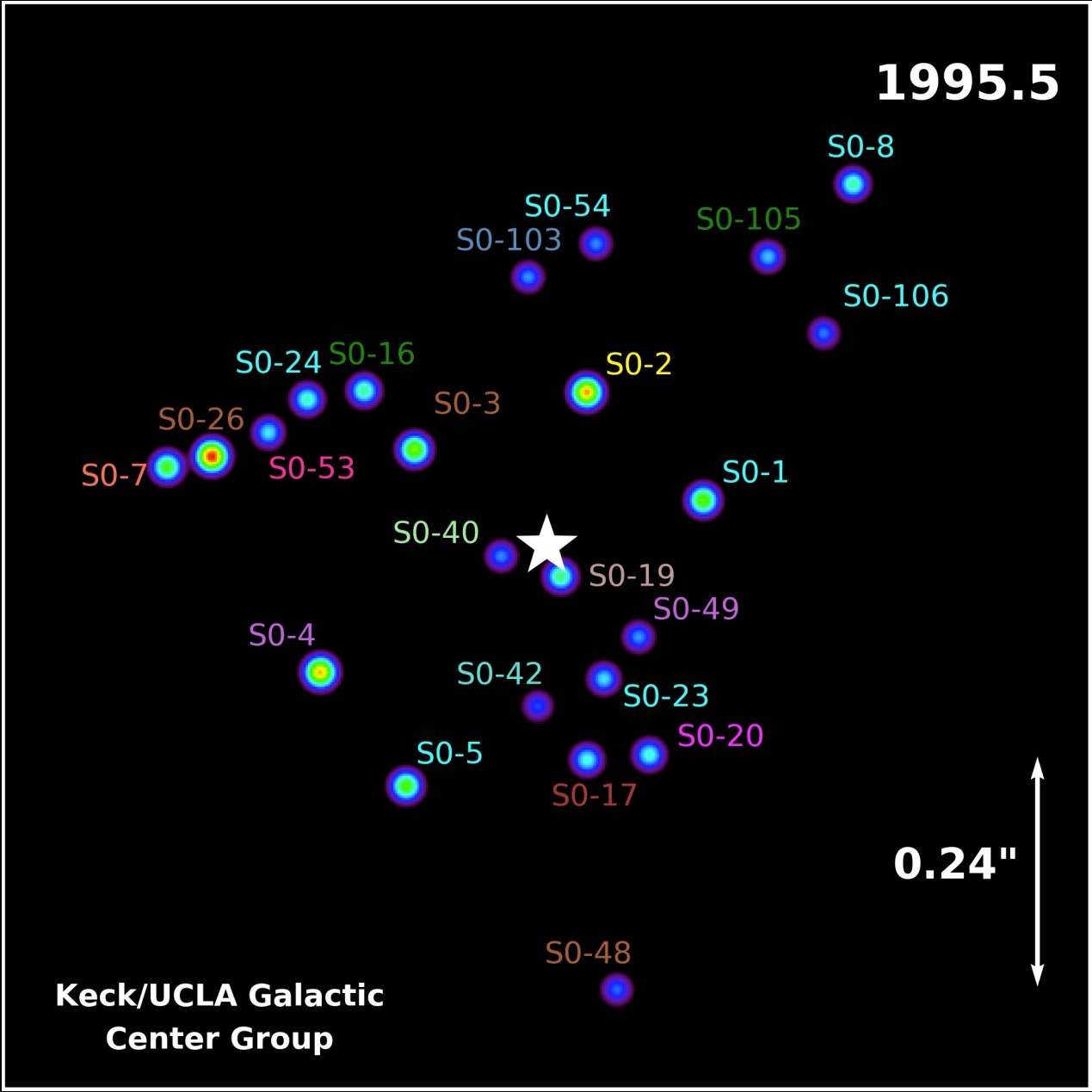




Artist's conception.



Artist's conception.

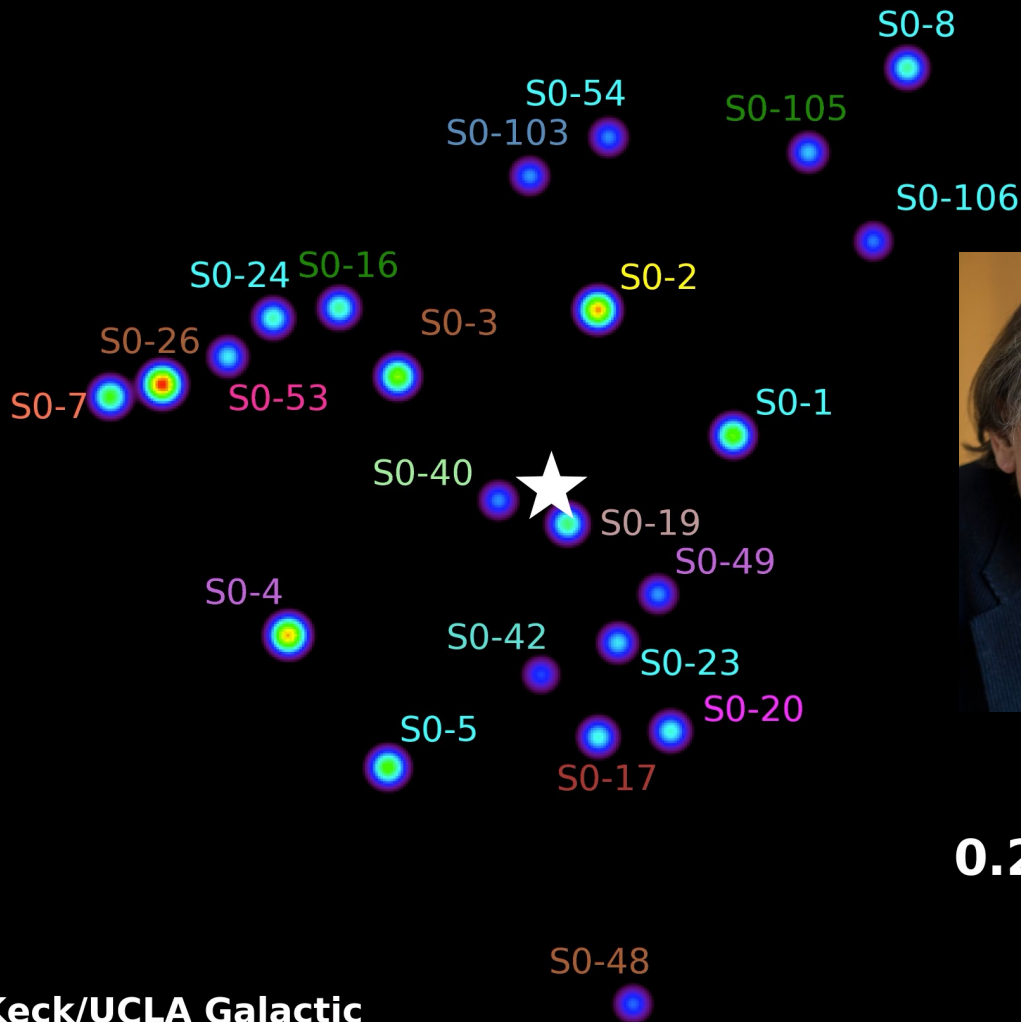


Motion of stars near the center of the Milky Way Galaxy, over 14 years. Data and visualization by Andrea Ghez and collaborators, UCLA.

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.

1995.5



0.24"

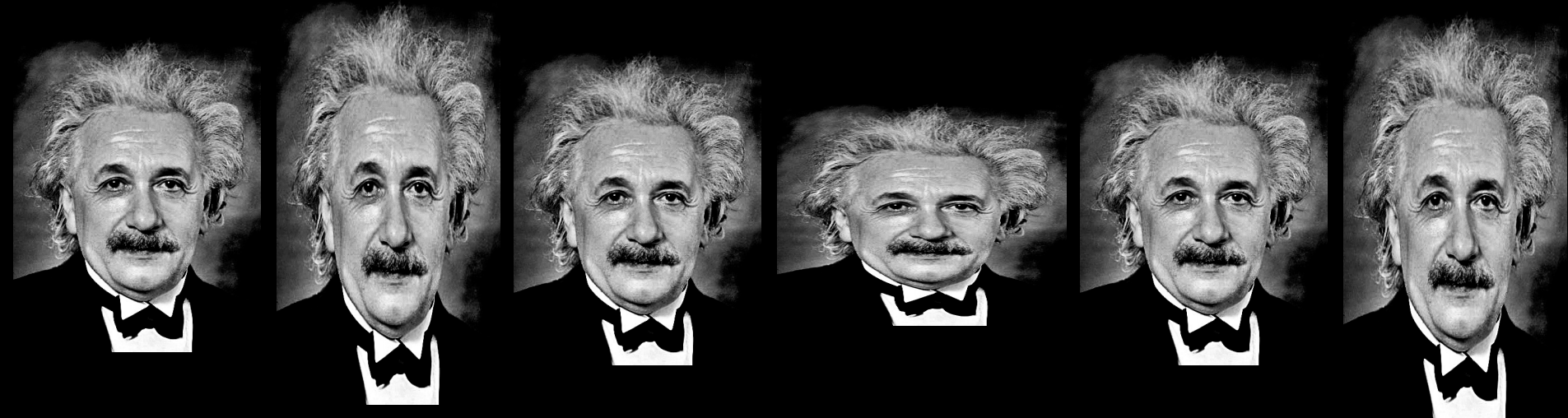
2020 Nobel Prize in Physics
Andrea Ghez
Reinhard Genzel
Roger Penrose

Inspiral of merging black holes
Videos available at ligo.caltech.edu

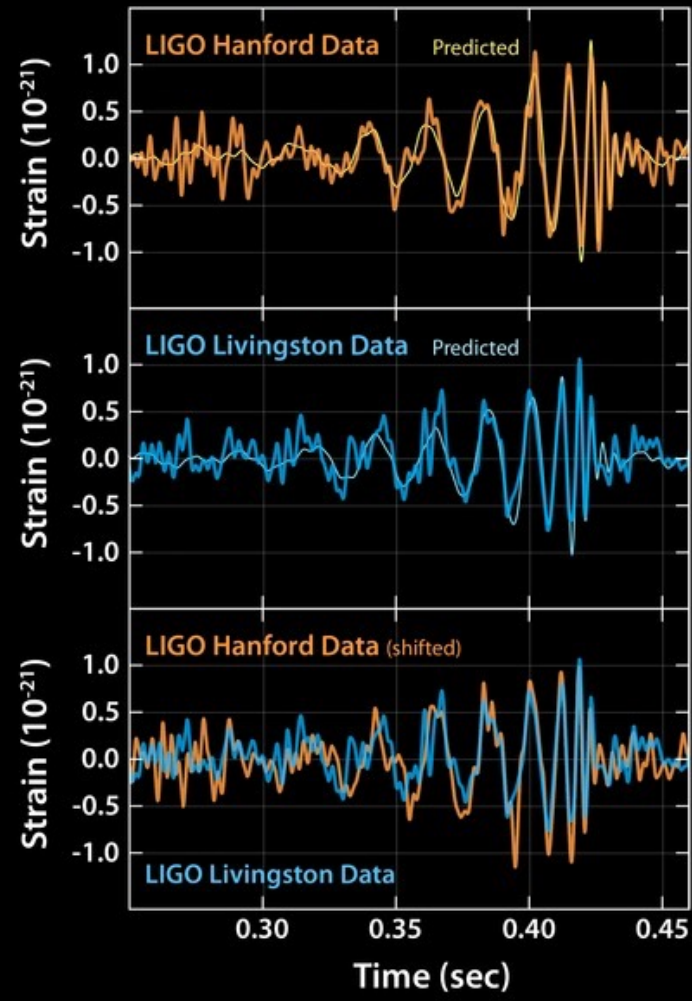
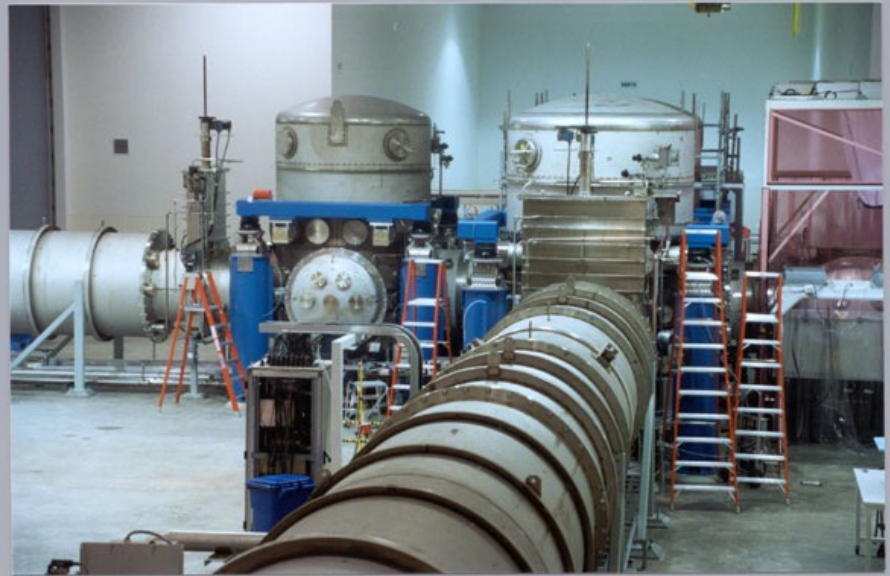


Gravitational Waves

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



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





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



Subramanyan Chandrasekhar



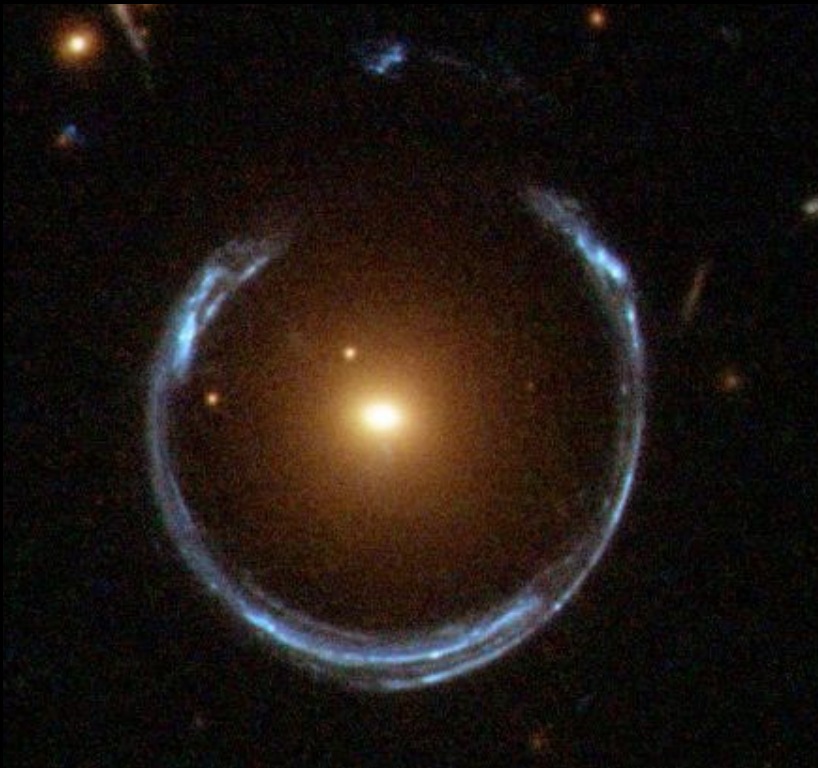
Gabriela Gonzales



Nergis Mavalvala



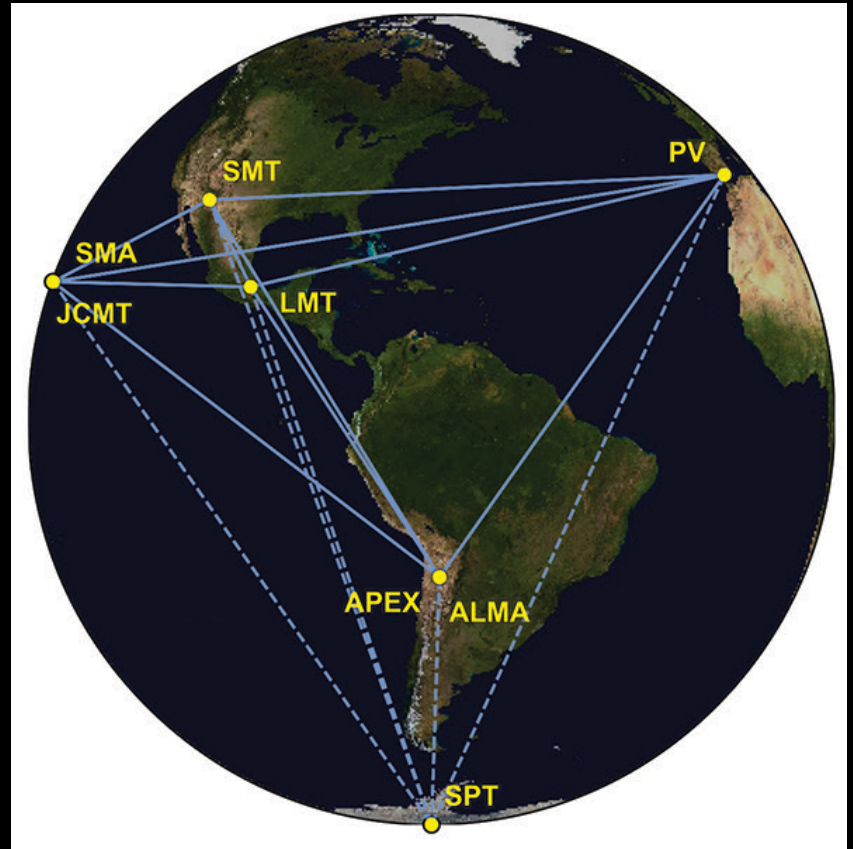
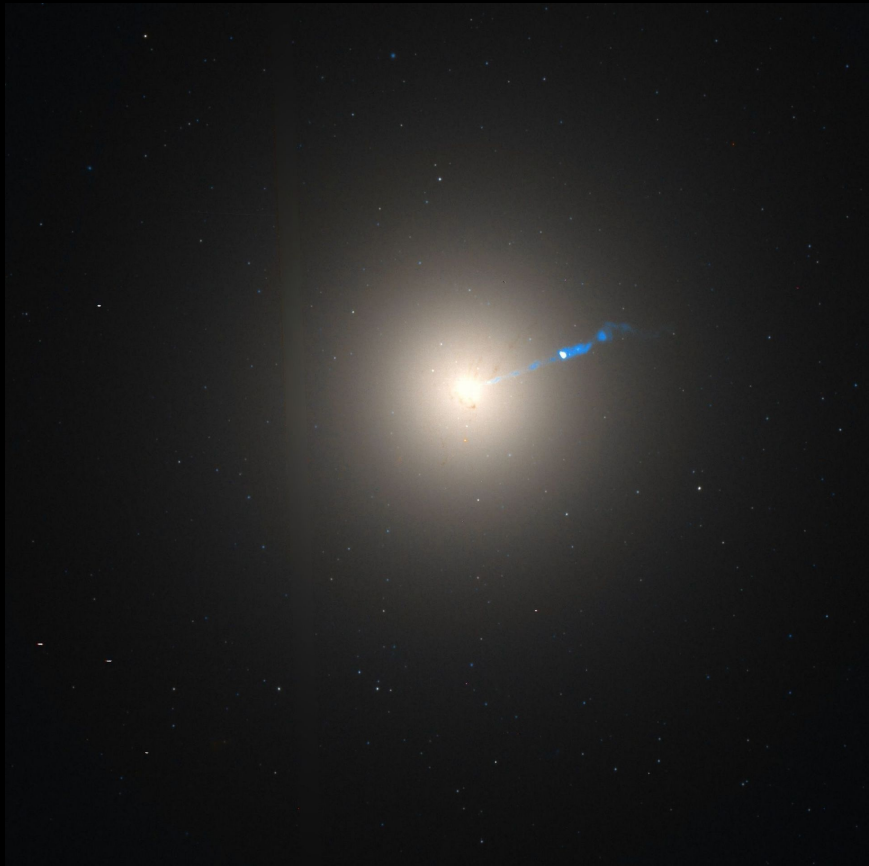
Vicky Kalogera

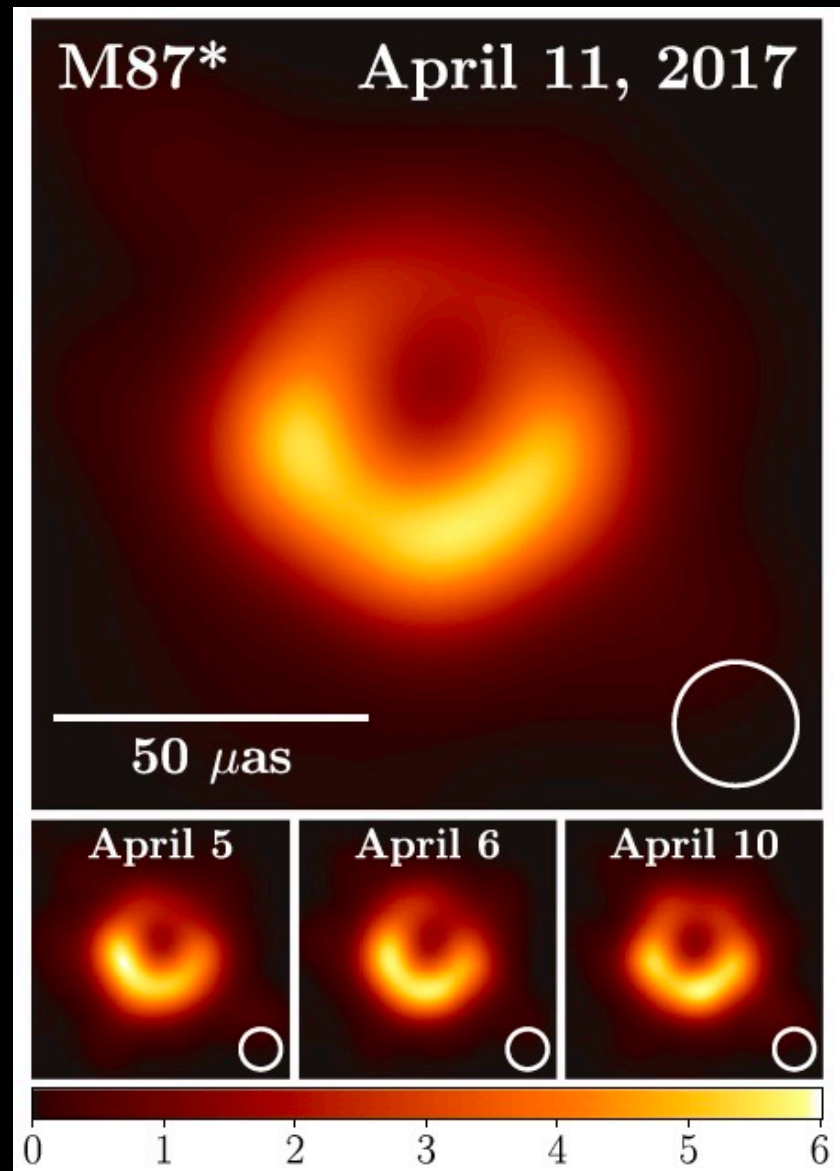
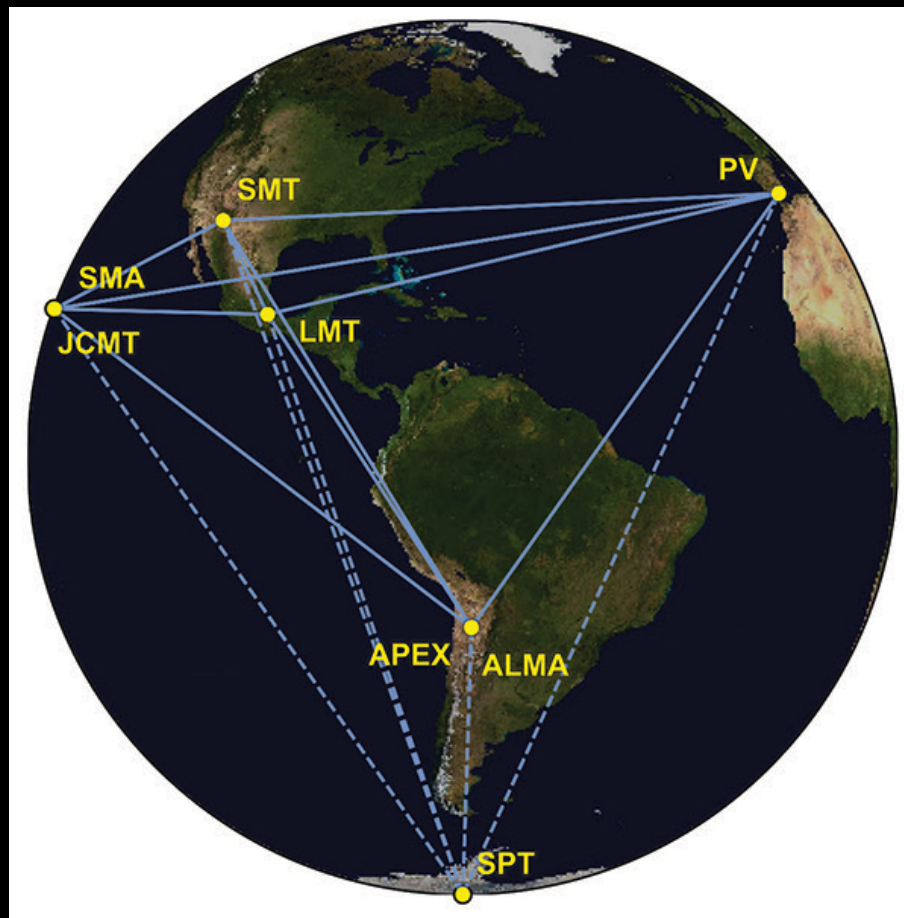


Real telescope image of a galaxy gravitationally lensing a background galaxy.



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





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.

A brief history of an idea

- 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.