



General Relativity

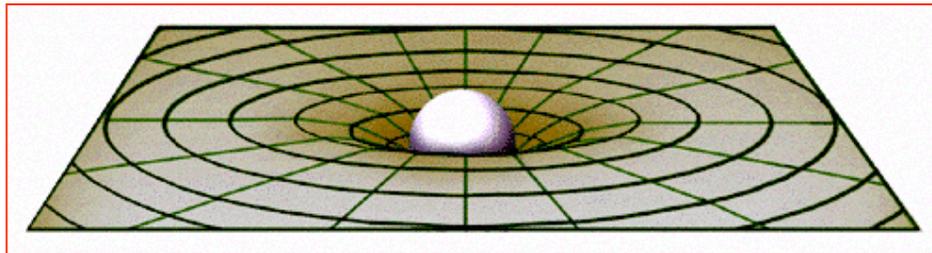
- Einstein's theory of General Relativity is a theory of gravity
- The basic idea is to drop Newton's idea of a mysterious force between masses and replace it with the 4-dimensional

SpaceTime Continuum



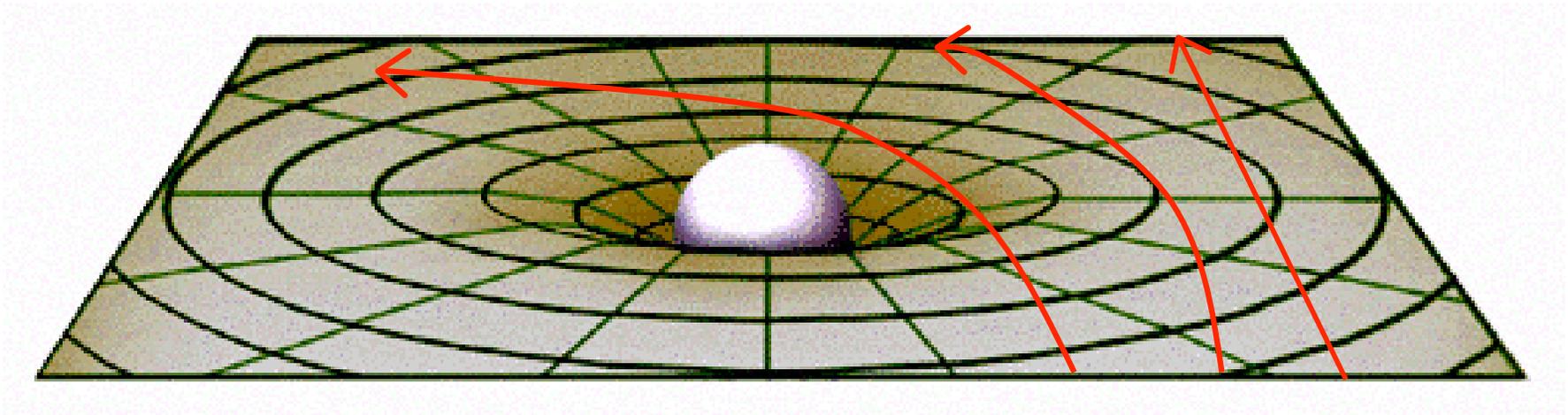
General Relativity

- In GR, mass (or energy) warps the spacetime fabric of space.

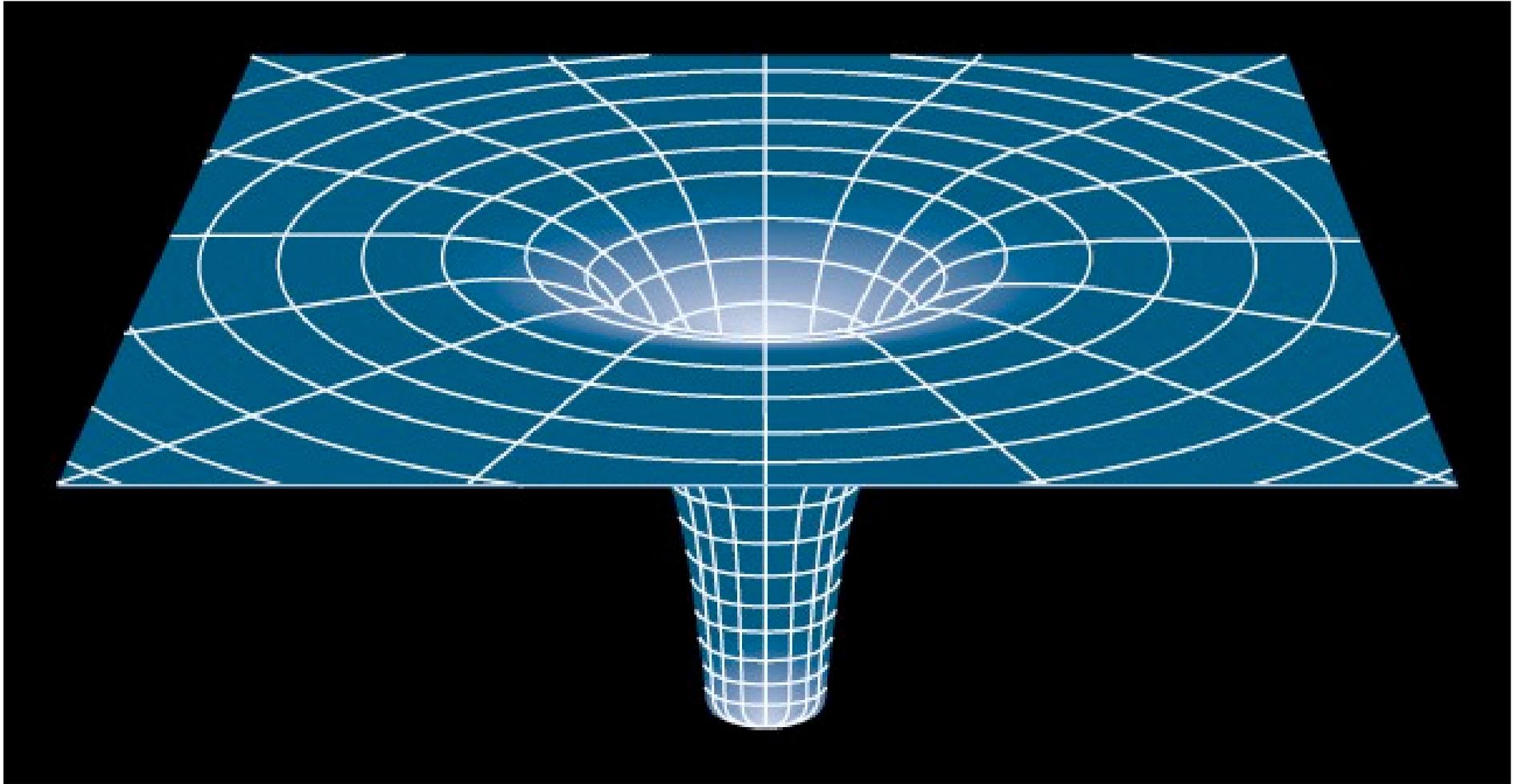


- Orbits of planets around stars are not due to a central force, but rather the planets are traveling in straight lines through curved space

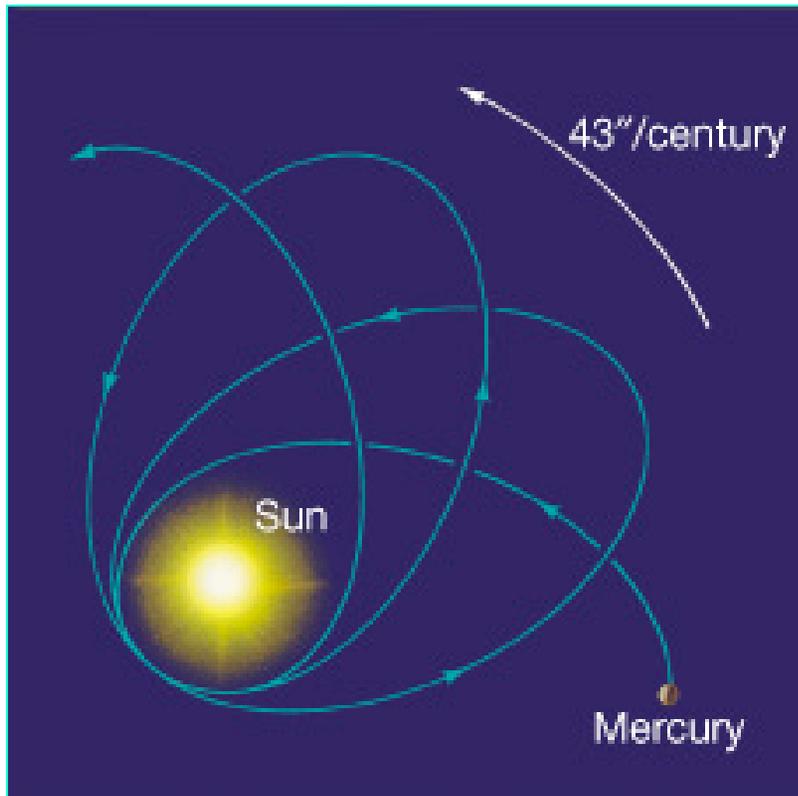
Imagine tossing a shotput onto your bed and rolling marbles at different speeds and distances from the shotput. (also imagine that you have a frictionless blanket on the bed).



The marbles that are moving slowly or close will fall down toward the shotput. If you look from above, it will appear as if the marbles were attracted to the shotput.



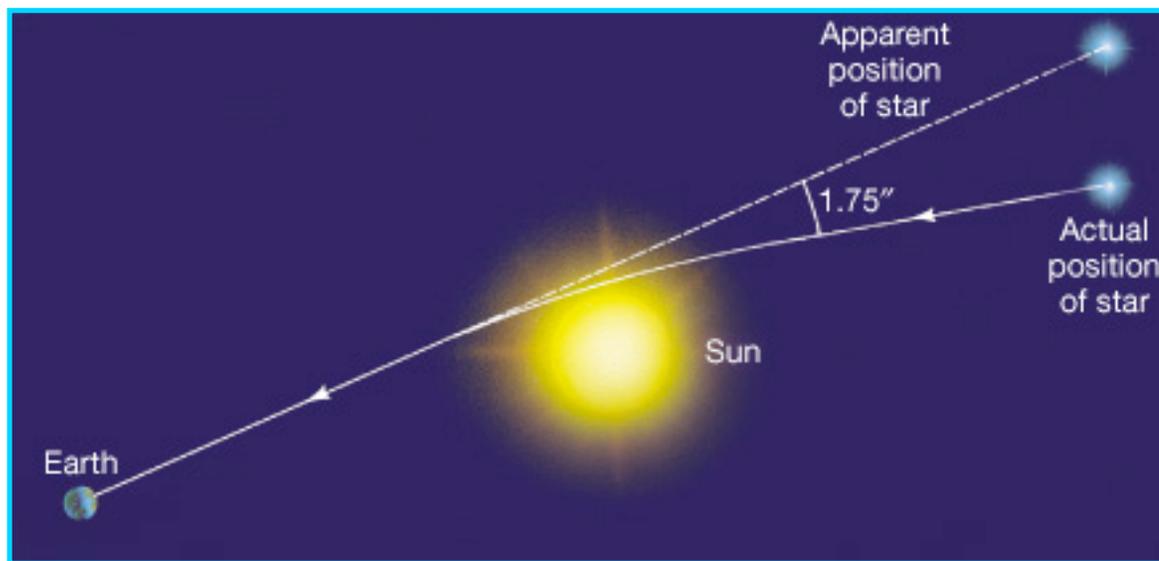
Fabric of Space



- This is a **RADICALLY** different view of the Universe and gravity
- In regions where space is not strongly curved, GR reduces to Newton's law of gravity
- Einstein pointed out his new theory would explain the **Precession of the Perihelion of Mercury**

The Deflection of Starlight

- There were several other predictions of GR, one important one was that light rays would also follow straight lines through curved space.



Tests of GR

- In 1919, during a total eclipse of the Sun, the predicted deflection of starlight for stars near to the limb of the Sun was measured and Einstein became a household name.
- GR also predicted that time would slow in strongly curved space. This was verified experimentally in 1958.

Tests of GR

- There is another long list of predictions made by GR -- in every case to date, they have verified the theory perfectly.
- One of the more useful predictions was for gravitational lenses.



On to Black Holes

- One important difference between Newtonian gravity and General Relativity is that photons are affected by 'gravity' in GR.
- This is what leads to the idea of Black Holes. It starts with the concept of escape velocity.

Escape Velocity

- Imagine feebly tossing a rocketship up in the air. It falls back to Earth because its kinetic energy was less than its gravitational potential energy.
- However, toss it with a larger and larger velocity and it will go higher and higher before falling back to Earth.
- There is a velocity above which it will not return to Earth -- this is the escape velocity.

Escape Velocity

- To determine the escape velocity from Earth you set the gravitational potential energy equal to kinetic energy and solve for velocity

$$V_{escape} = \sqrt{\frac{2 \times G \times M}{R}}$$

Mass of the object from which you want to escape

Radius from which you want to escape

Escape Velocity

- Note that the escape velocity doesn't depend on the mass of the escaping body.
- For the Earth, put in the mass and radius of the Earth (for escape from the surface of the Earth) and you get:

$$V_{\text{esc}} = 11 \text{ km/sec} = 25,000 \text{ miles/hr}$$

Escape Velocity

- Now suppose you shrink the Earth to 1/100 of its current radius (at constant mass).
What happens to V_{esc} ?

$$V_{esc} = \sqrt{\frac{2GM}{R}}$$
$$V_{esc} \propto \sqrt{\frac{1}{R}}$$

As R goes up, V_{esc} goes down

As R goes down, V_{esc} goes up

Don't forget the square root

For this case, V_{esc} increases by 10x

Escape Velocity

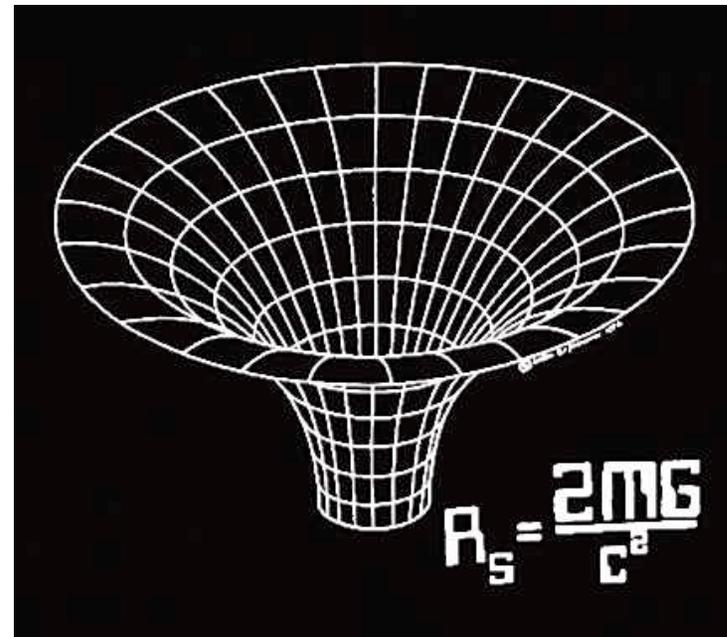
- Reduce the radius of the Earth to 1cm and

$$V_{\text{esc}} = c \text{ (speed of light)}$$

- In this new theory of Gravity, where photons are affected by gravity, if the escape velocity equals or exceeds the speed of light, that object can no longer be observed. This is a Black Hole

Black Holes

- The critical radius for which an object of a particular mass has an escape velocity of 'c' is called the Schwarzschild Radius.
- This is also called
- the 'Event Horizon'.



Schwarzschild Radius

- You can easily calculate the Schwarzschild radius for any mass by setting $V_{esc}=c$

$$V_{esc} = c = \sqrt{\frac{2MG}{R_s}}$$
$$c^2 = \frac{2MG}{R_s} \Rightarrow R_s = \frac{2MG}{c^2}$$

- Every object has a radius at which it becomes a Black Hole

Black Holes

- But, it is VERY, VERY difficult to compress an object to its Schwarzschild radius.
- For the Sun, you would have to somehow overcome thermal pressure, then e-degeneracy, then neutron degeneracy. We know of no 'cosmic vice' that can do that.

Black Holes

- But, go back to a neutron star and we are building a pretty big vice. Thermal pressure has already been overcome as has e-degeneracy pressure.
- There is a limit to the pressure that can be generated by neutron degeneracy. Its hard to calculate, but is probably between $2M_{\odot}$ and $3M_{\odot}$

Black Holes

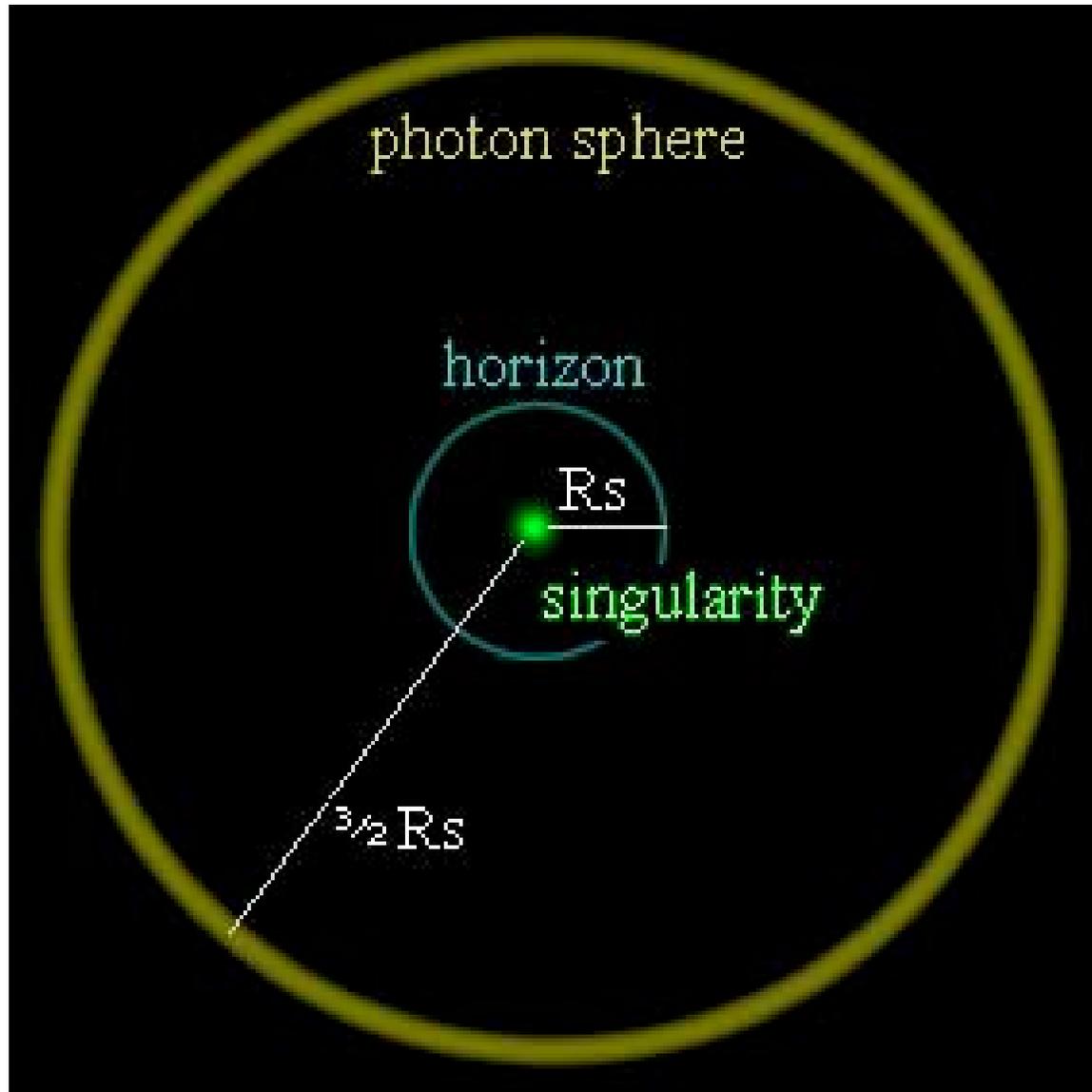
- Think about the n-star core of a SNII explosion. If say $1.6M_{\odot}$ of material falls back, the core will exceed the neutron degeneracy limit and undergo collapse to zero volume (what?) zero volume.

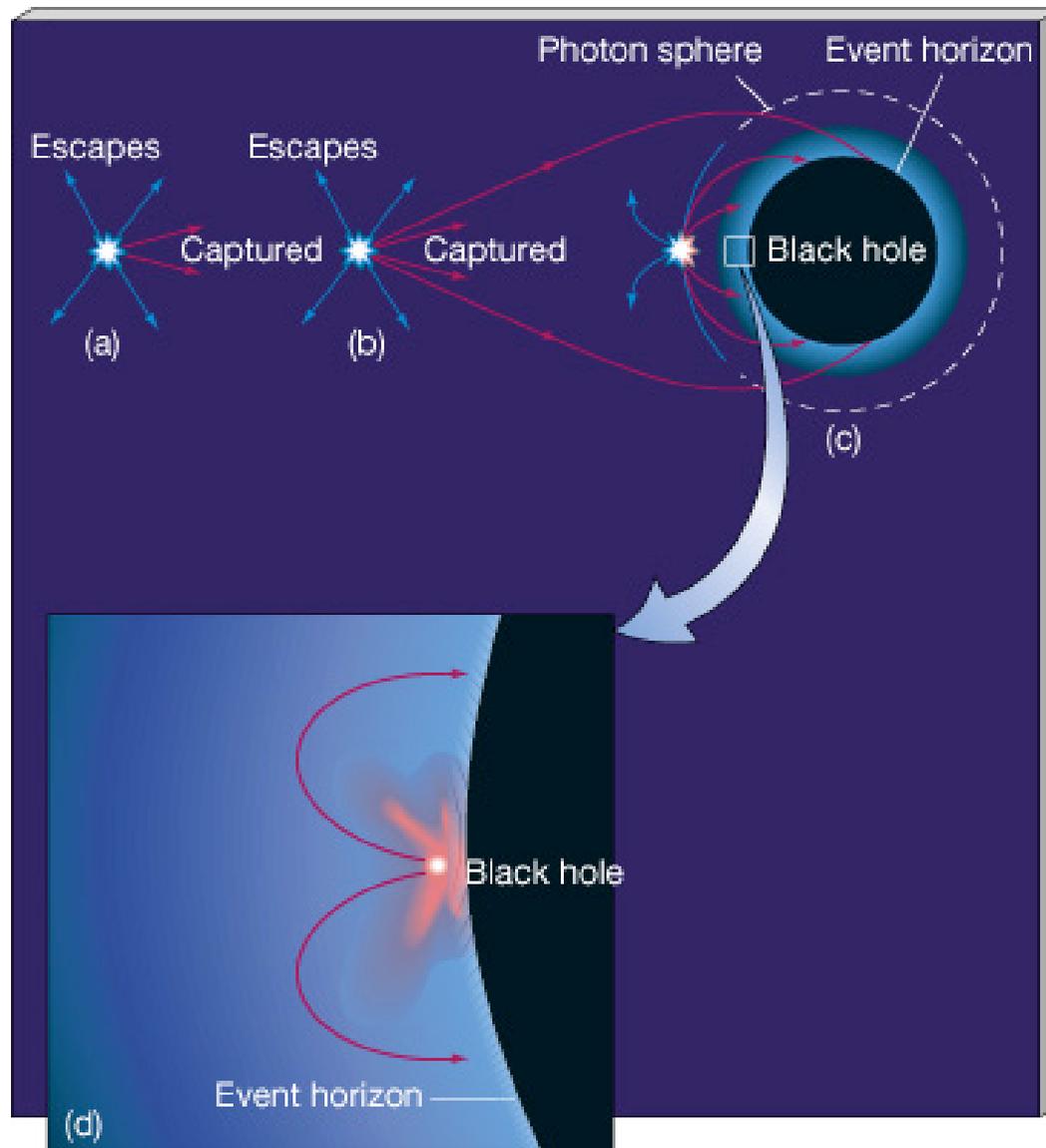


Black Holes

- What is left behind?
- The gravitationally force (i.e. a warp in spacetime) including a `singularity' at the center of the warp
- An Event Horizon with radius given by

$$R_{\text{Sch}}=8.9\text{km}$$





Black Hole FAQs

- What would happen if the Sun collapsed into a Black Hole, would the Earth be dragged in?
- No, the gravitational force at the distance of the Earth would not change.

- Is the Event Horizon a physical boundary?

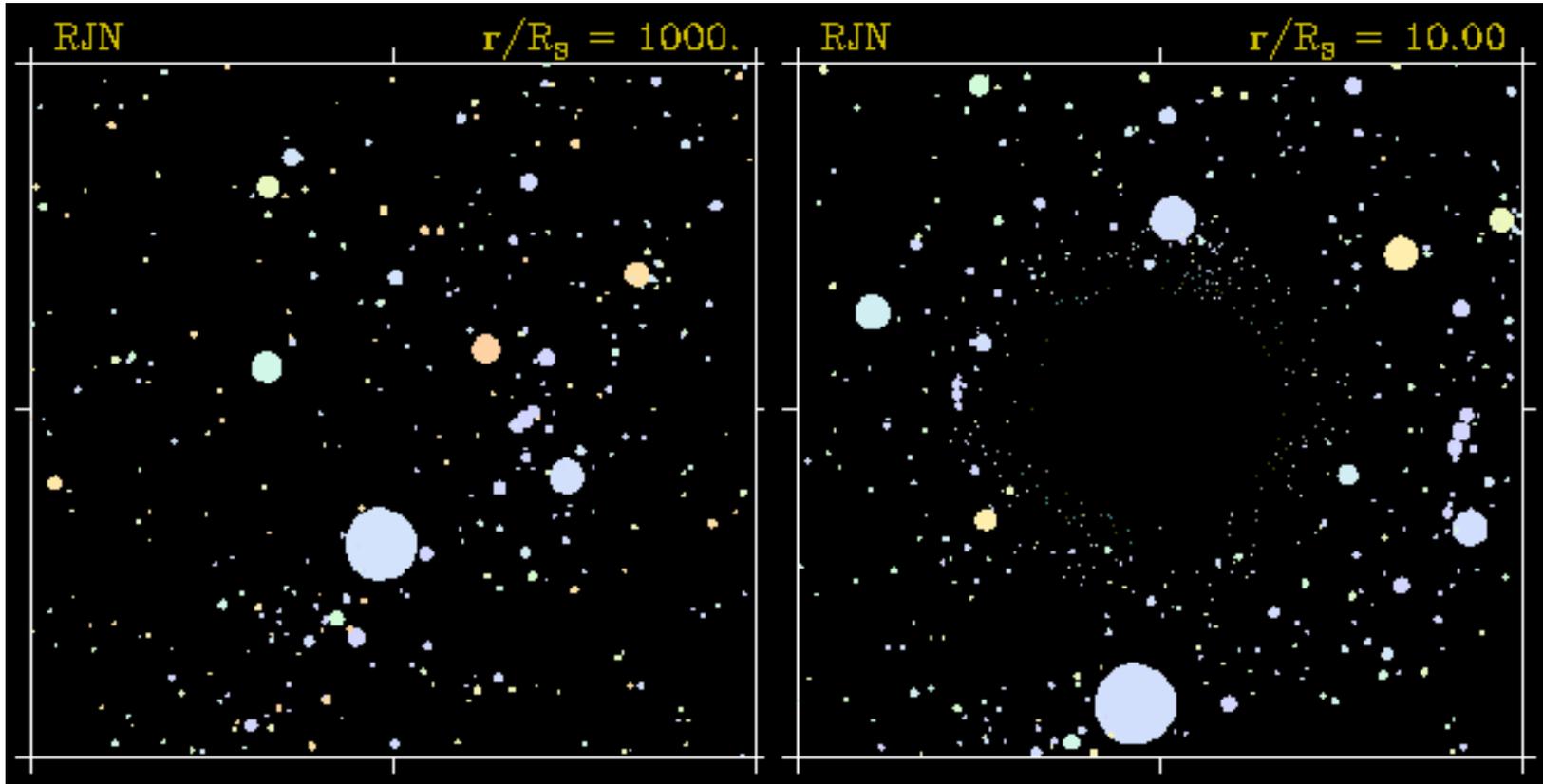
No, it is simply the distance from the center where the escape velocity of c .

- What happens if a Black Hole absorbs some mass?

As M increases, the Schwarzschild radius also increases.

- Is there any reason to believe that Black Holes exist?

You Bet!



Black Hole Evidence

- The best stellar-mass cases are binary x-ray sources.



Cygnus X-1 is a good example.

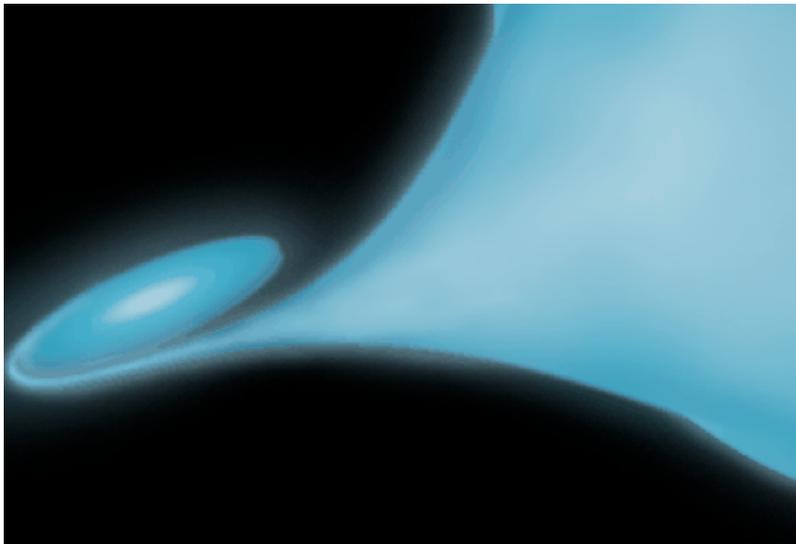
Black Hole Evidence

- Cyg X-1 is a bright x-ray source. Look there in the visual part of the spectrum, we see a $30M_{\odot}$ blue main-sequence star which is a spectroscopic binary with a period of 5.6 days.
- The companion has a mass of between 5 and $10M_{\odot}$. What is it?

Cygnus X-1

- There is no sign of the companion at any wavelength (but, remember the x-rays) so what is it?
 - 1) A red giant would be easily seen
 - 2) A main-sequence star would be seen with a little effort
 - 3) Can't be a WD because $M > 1.4M_{\odot}$
 - 4) Can't be a n-star because $M > 3M_{\odot}$

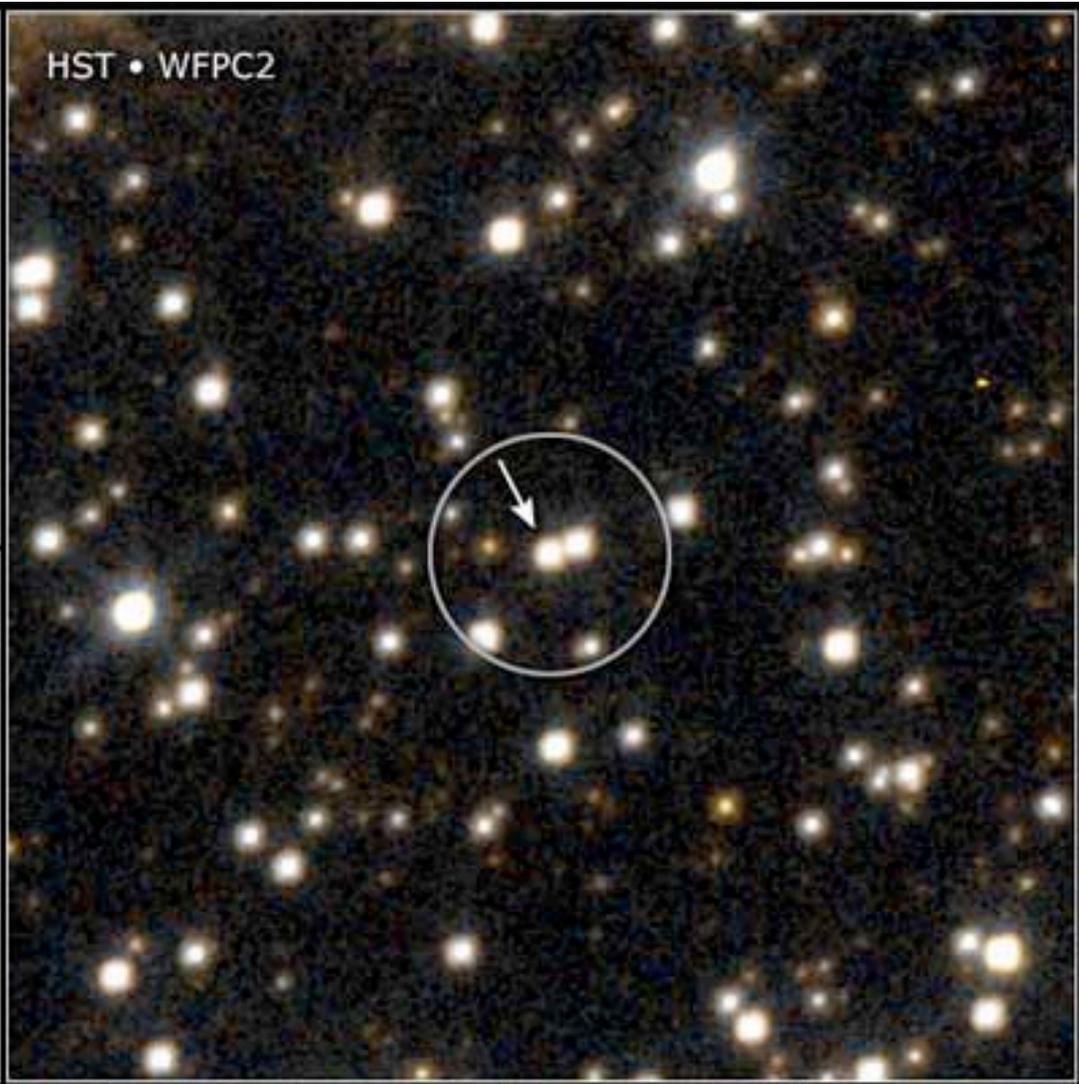
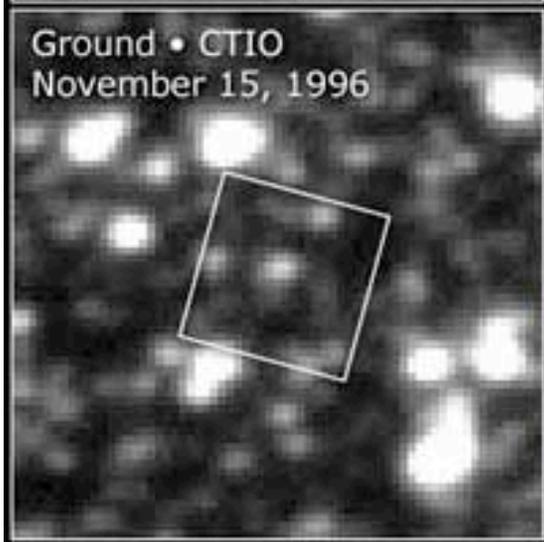
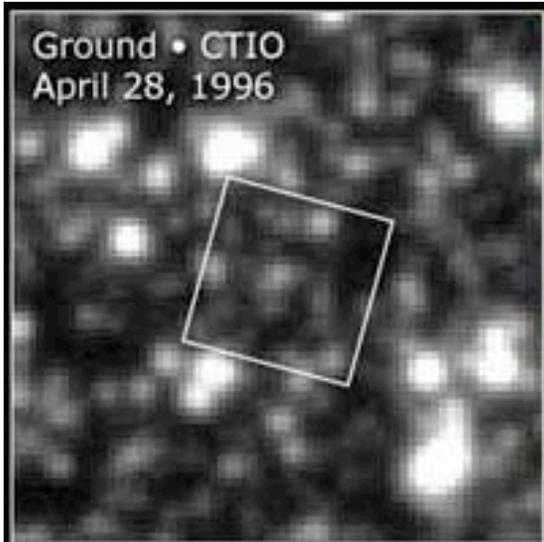
Cygnus X-1



- By elimination, we are left with a black hole
- The x-rays back this up. In an accreting WD we see UV radiation, in an n-star we see `soft' x-rays, in Cyg X-1 we see `hard' x-rays because the accreting material falls into a deeper potential well.

Stellar-mass Black Holes

- We now have a few dozen excellent stellar-mass black hole candidates and few people doubt that such objects exist.
- There was a `microlensing' event in 1996 that was ascribed to a blackhole gravitationally lensing a background star.
- There are various claims that x-ray transients are black holes accreting little bits of stuff.



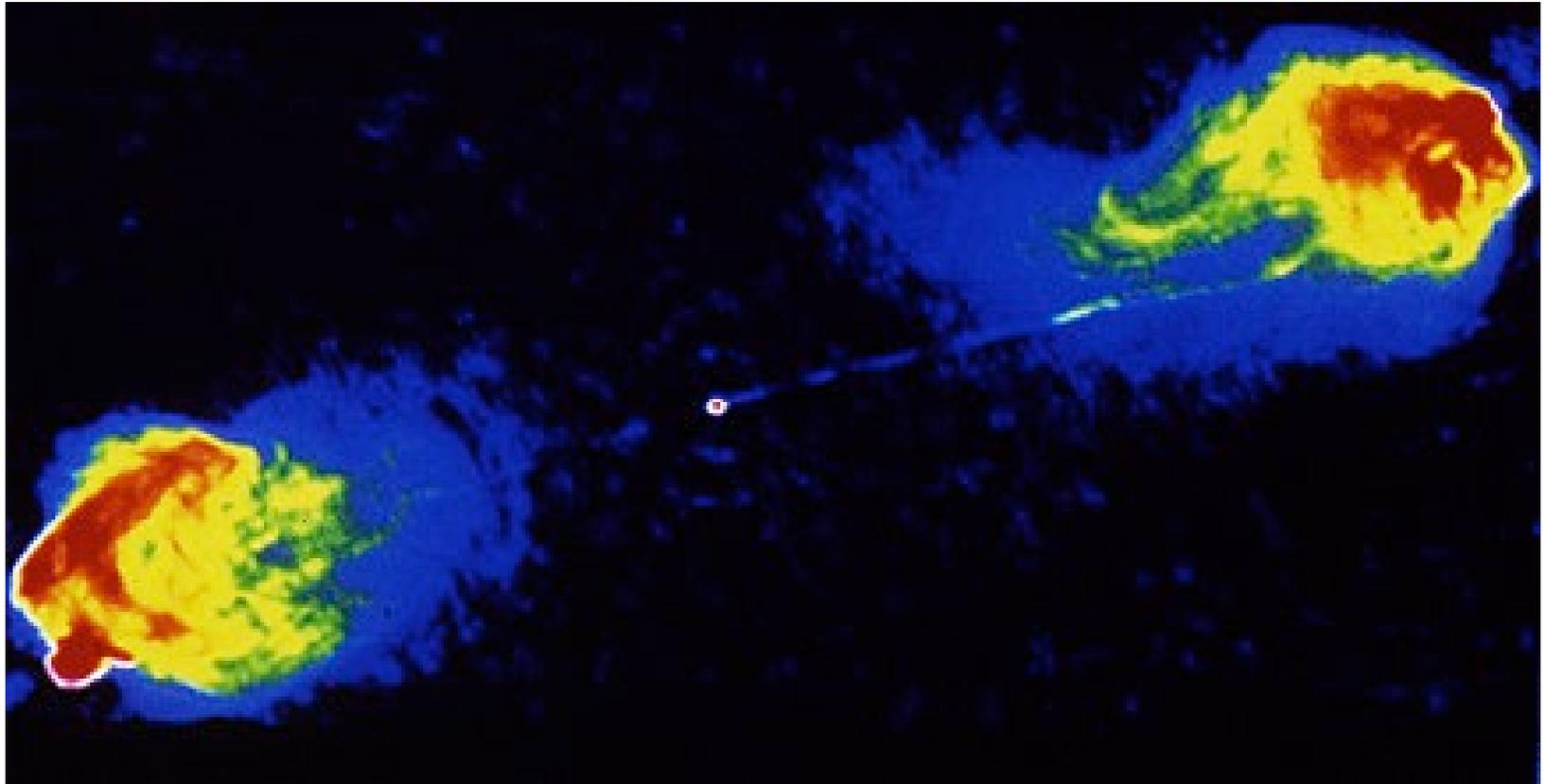
Supermassive Black Holes

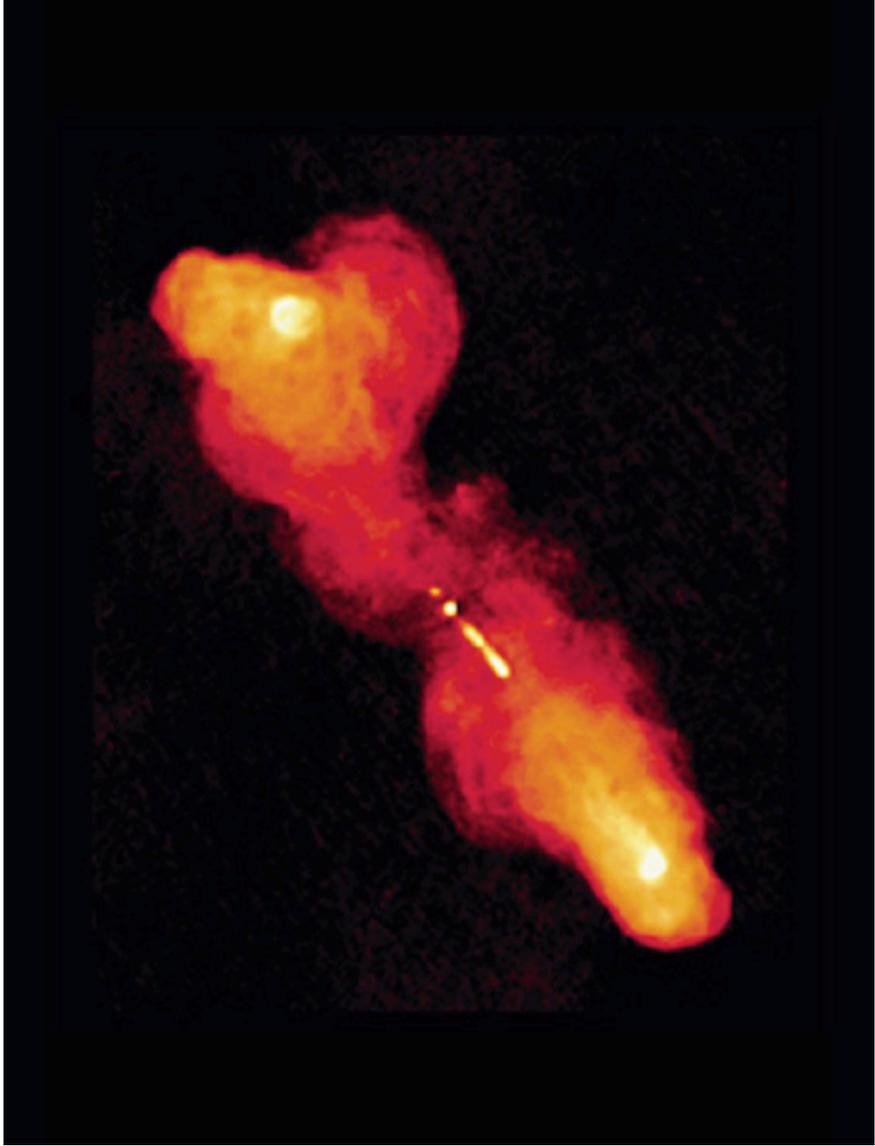
- Since the early 1960s extraordinarily energetic objects called `qso's or `quasars' have been identified a large distances and lookback times.
- The only explanation astronomers could come up with for their energy source was accreting mass onto a large ($>10^5 M_{\odot}$) black hole.

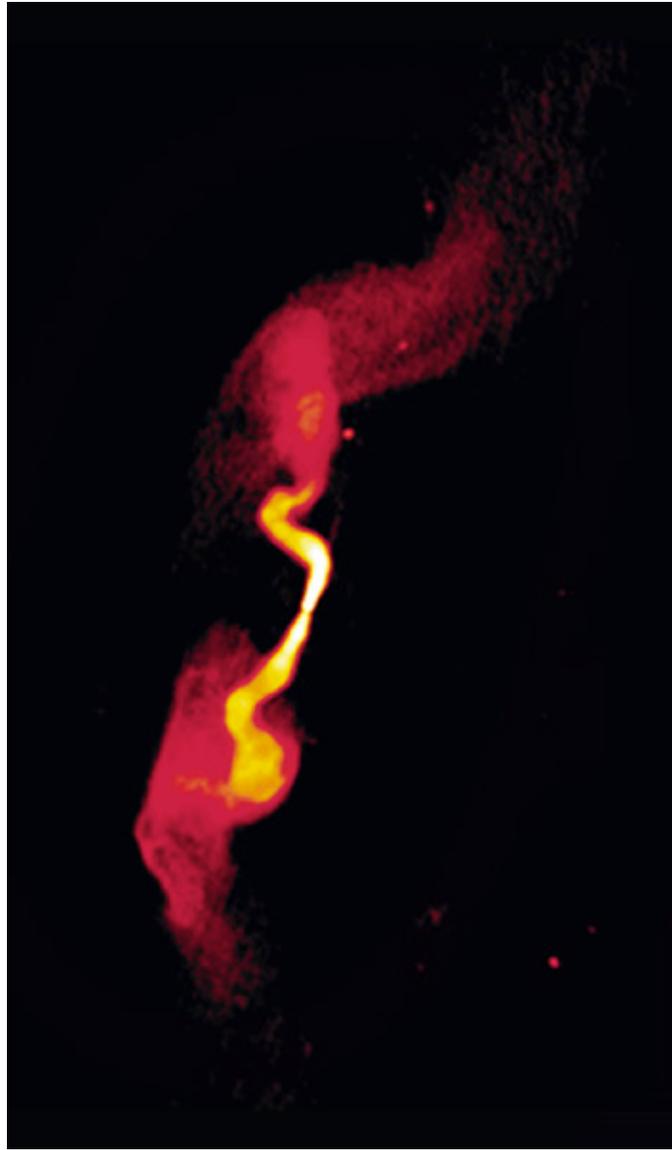
Supermassive Black Holes



- QSOs had large radio jets emitted at enormous velocities.
- Eventually it became clear that QSOs were all located in the cores of galaxies and nearby counterparts were identified.

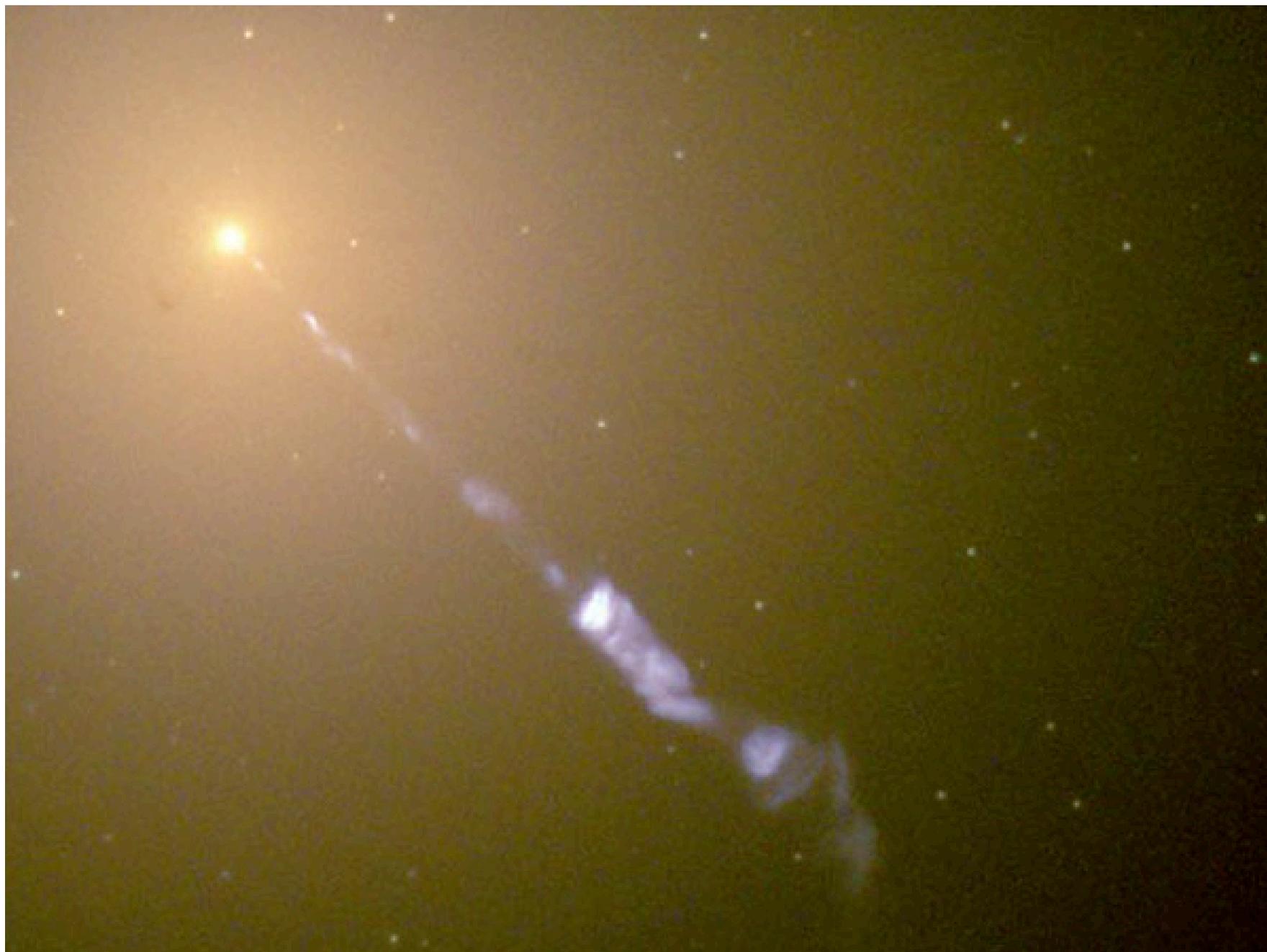


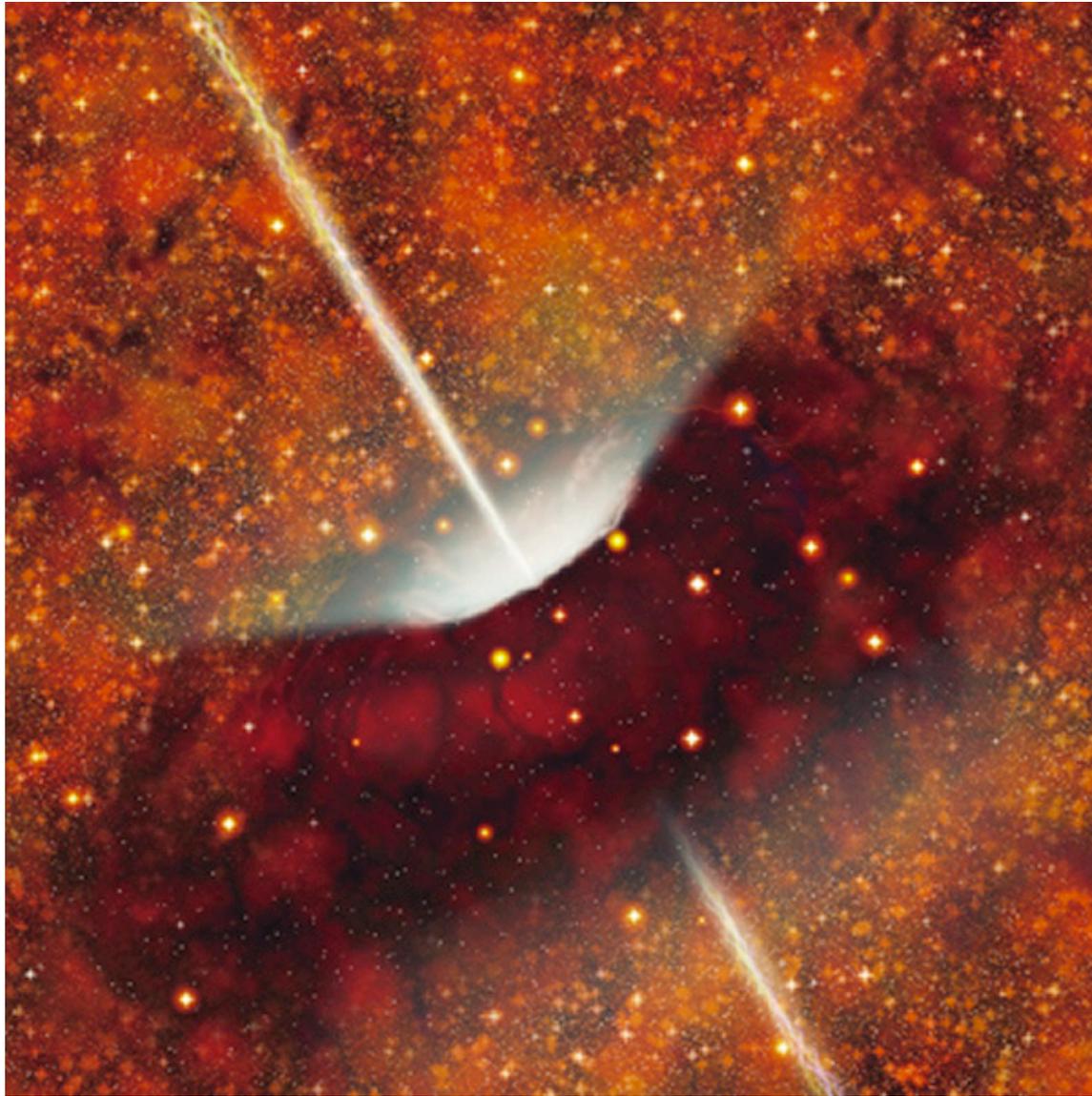






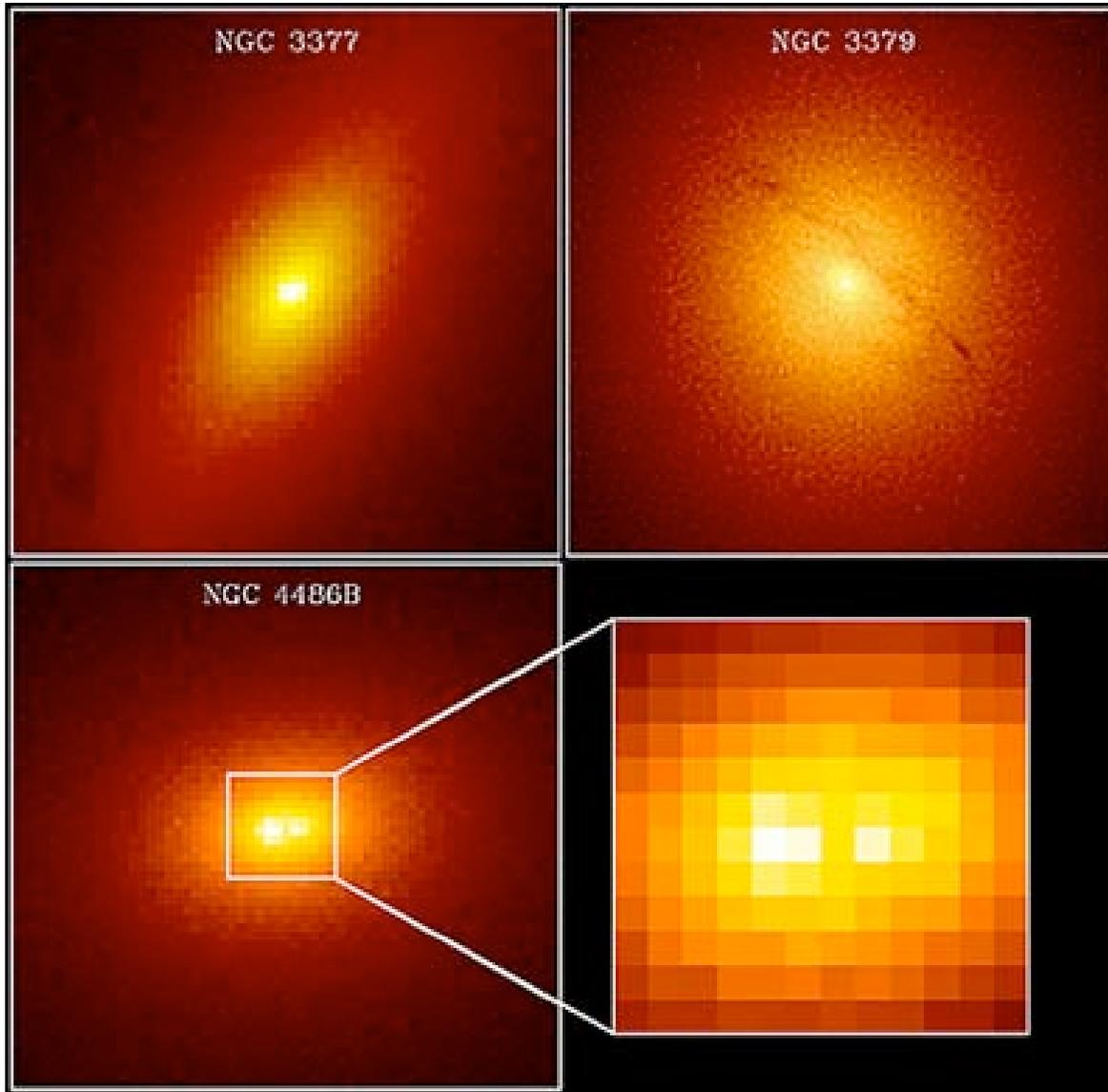
AAT 60



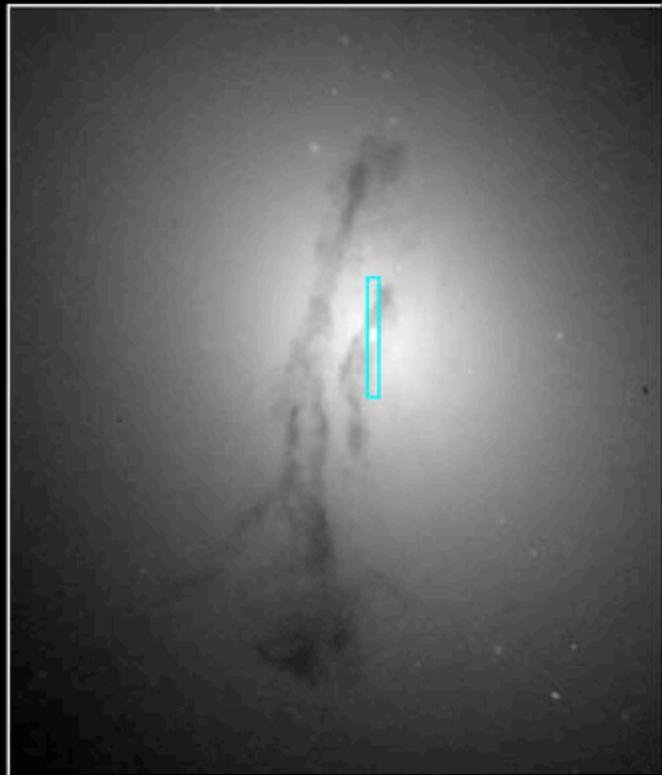




- Cen A radio jets
- The nearby systems allowed observations much closer to the central engine and over time the evidence for the black holes has become more direct

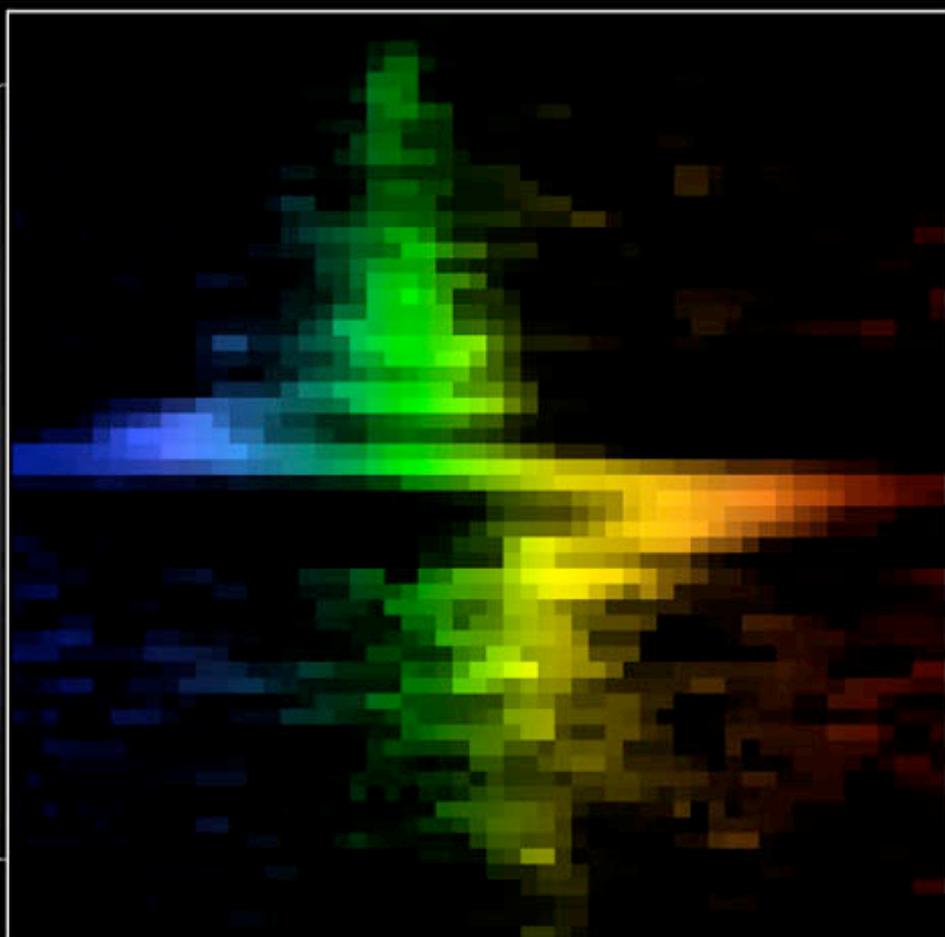


Galaxy M84 Nucleus



WFPC2

Hubble Space Telescope

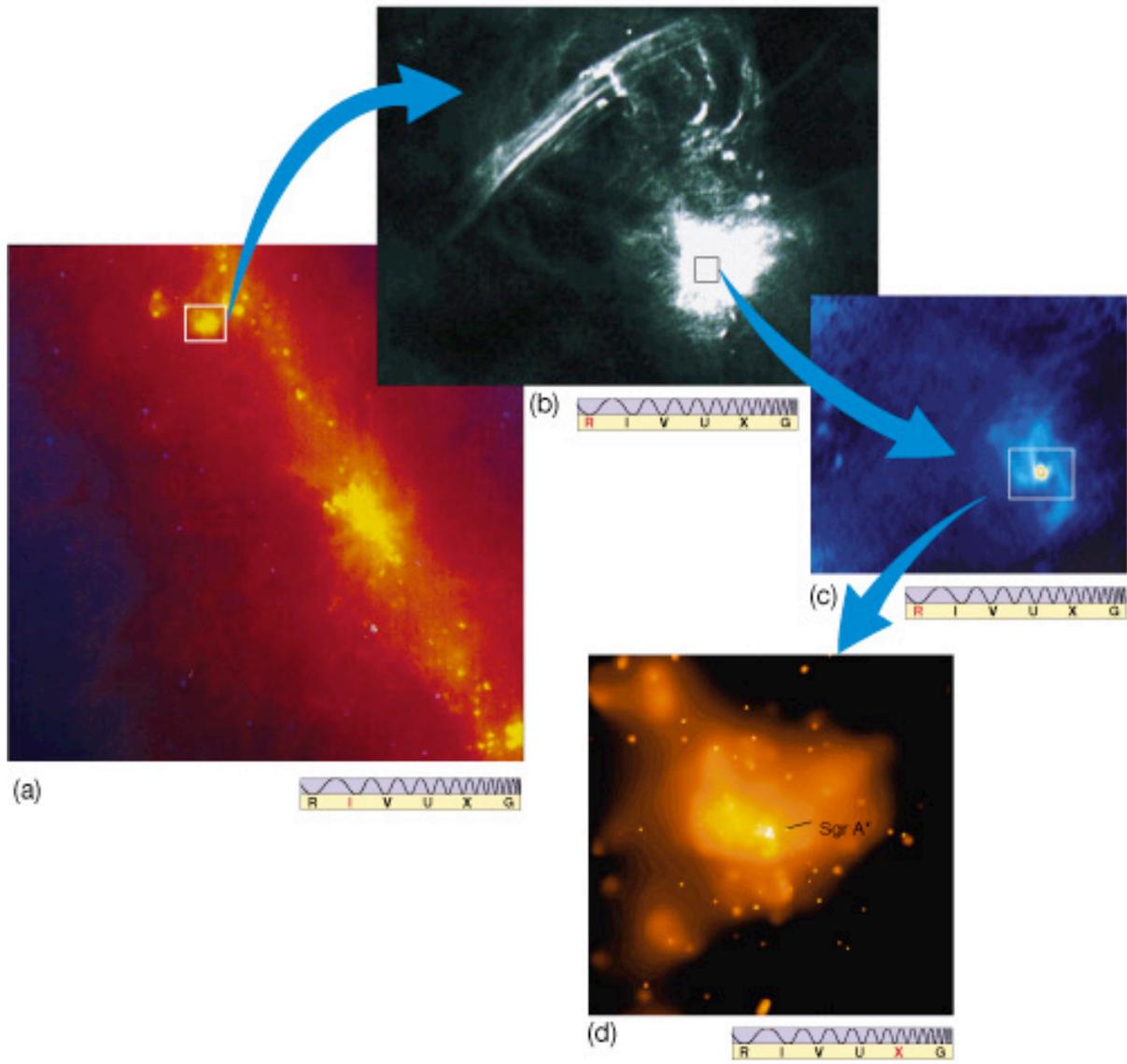


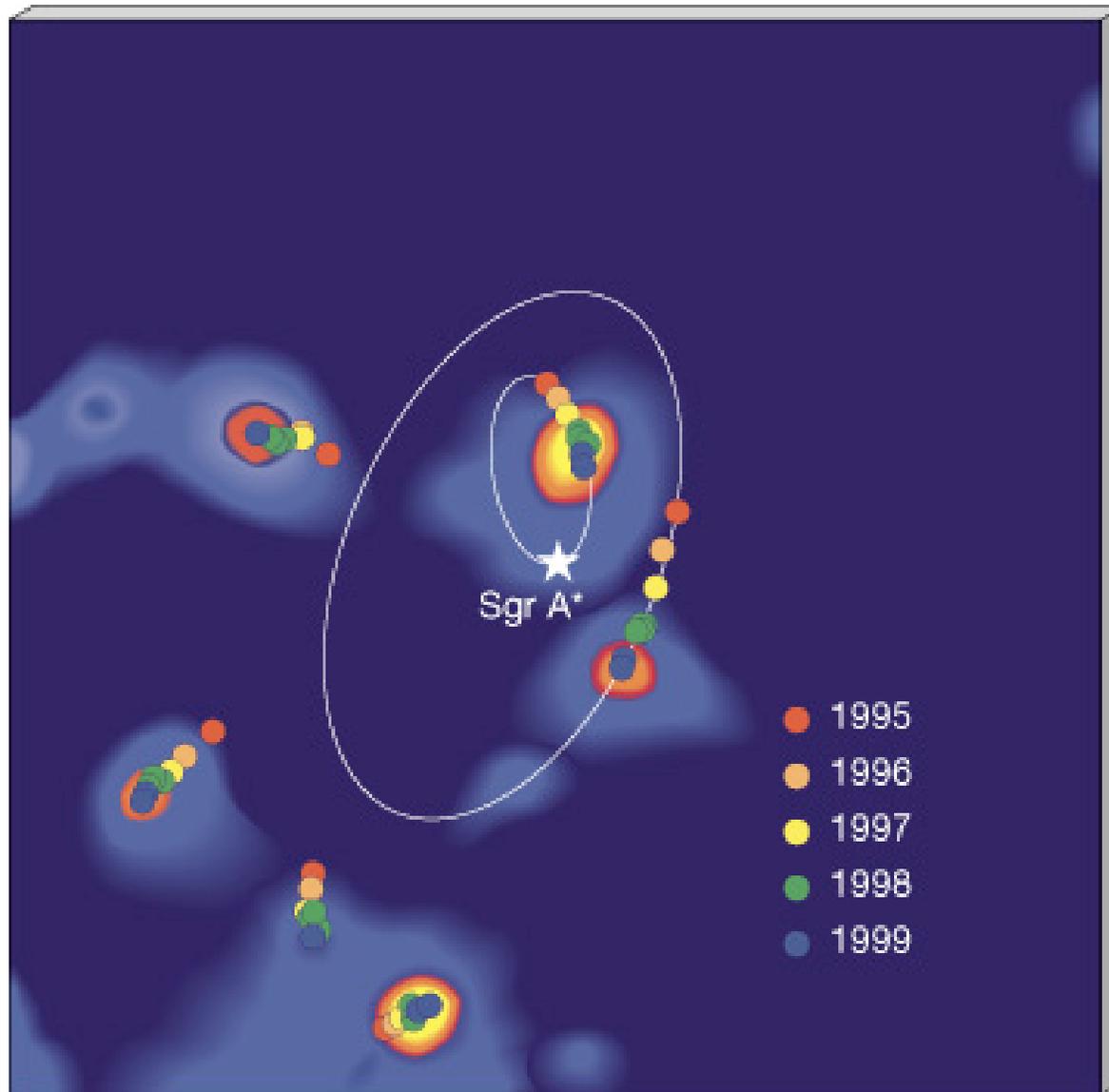
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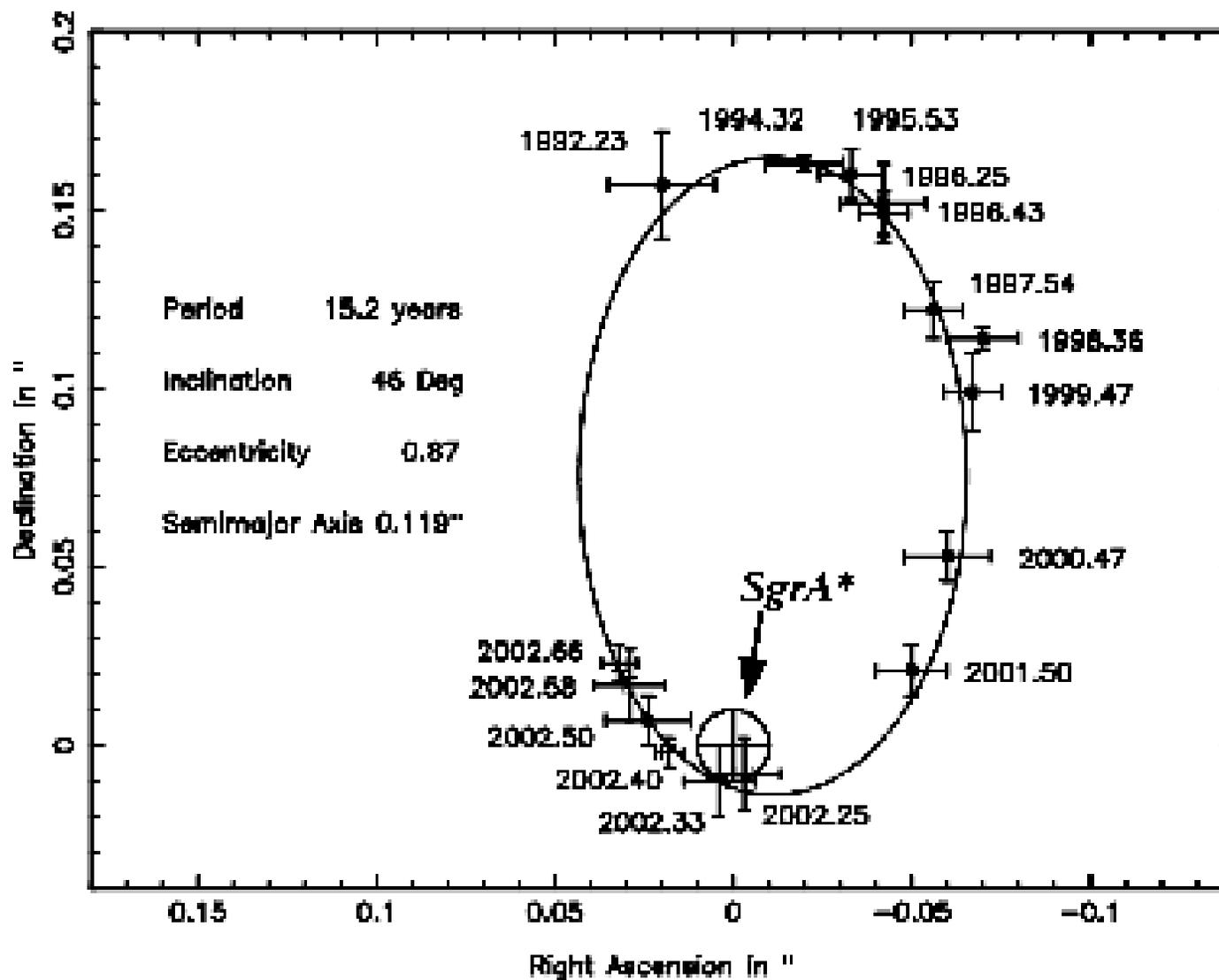
PRC97-12 • ST Sci OPO • May 12, 1997 • B. Woodgate (GSFC), G. Bower (NOAO) and NASA

The Galactic Center

- After years of speculation about a possible supermassive black hole in the center of the Milky Way, work at Keck by Andrea Ghez at UCLA demonstrated convincingly in 1999 that we have a 2 million solar mass black hole at the center of the Galaxy.







Supermassive Black Hole in the Galaxy

- [2002](#) observations pretty much cinch the case for a 2.6 million solar mass black hole in the center of the galaxy.
- See the movie!

