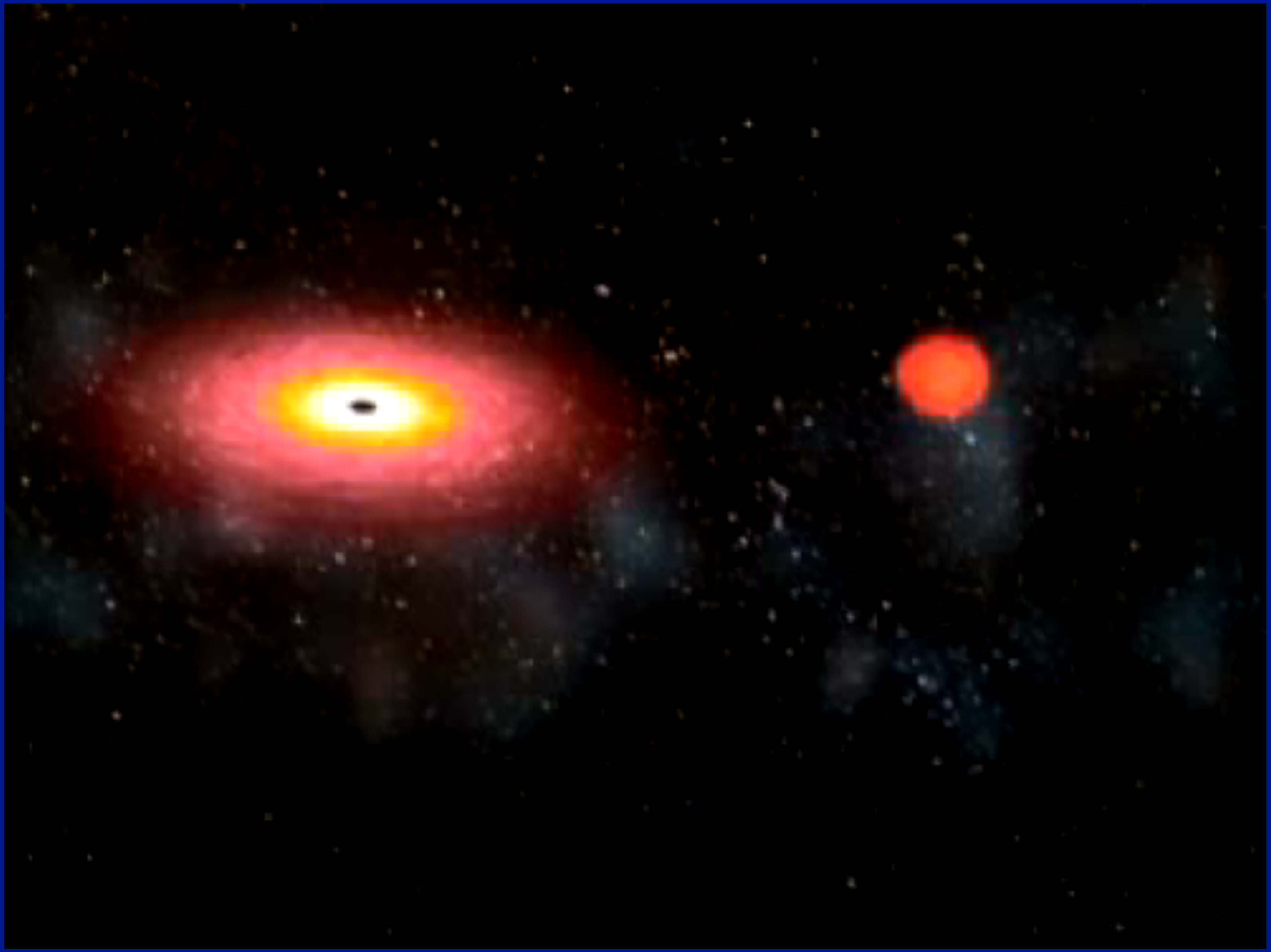
Announcements

- Test #3 Next Tuesday, Nov. 8
- Bring your UNM ID!
- Bring two number 2 pencils
- Review for test on Monday, Nov 7 at 3:25pm

Neutron Star - Black Hole merger



Review for Test #3 Nov 8

Topics:

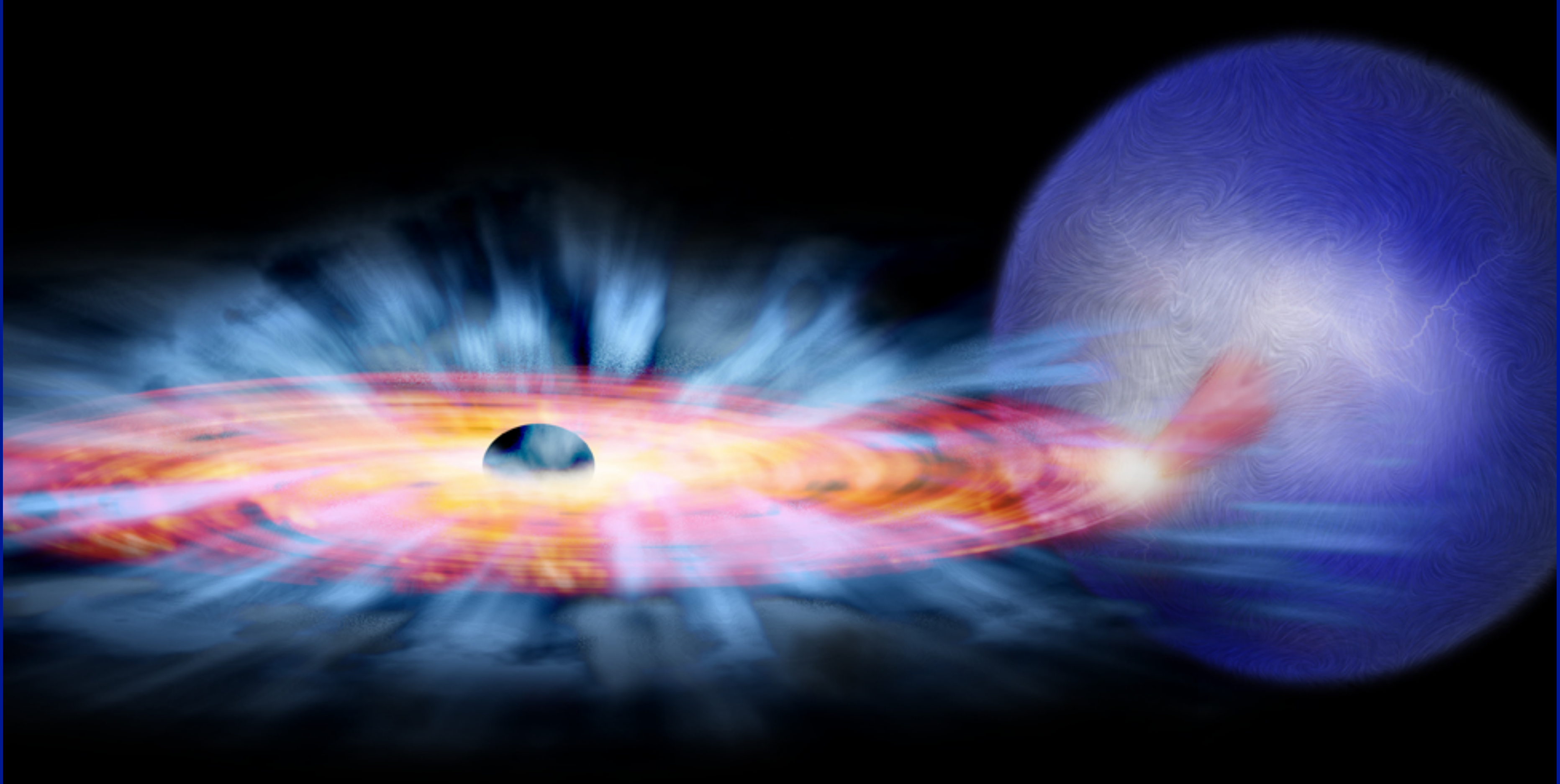
- Stars (including our Sun)
- The Interstellar medium
- Stellar Evolution and Stellar Death
- Gamma Ray Bursts
- Neutron stars, pulsars and magnetars
- Black Holes and General Relativity

Methods

- Conceptual Review and Practice Problems Chapters 9 - 13
- Review lectures (on-line) and know answers to clicker questions
- Try practice quizzes on-line
- Bring:
- Two Number 2 pencils
- Simple calculator (no electronic notes)

Reminder: There are NO make-up tests for this class

Black Holes



A stellar mass black hole accreting material from a companion star

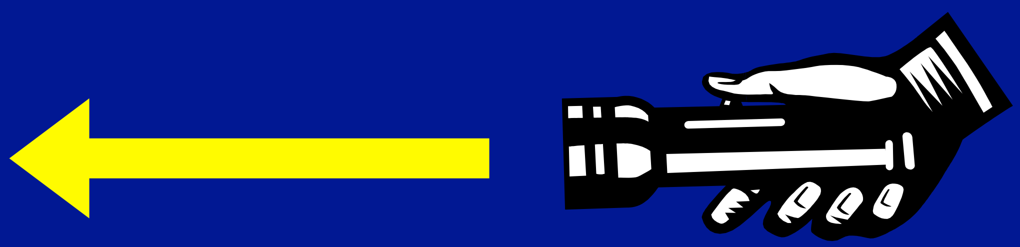
Black Holes and General Relativity

General Relativity: Einstein's description of gravity (extension of Newton's). Published in 1915. It begins with:

The Equivalence Principle

Let's go through the following series of thought experiments and arguments:

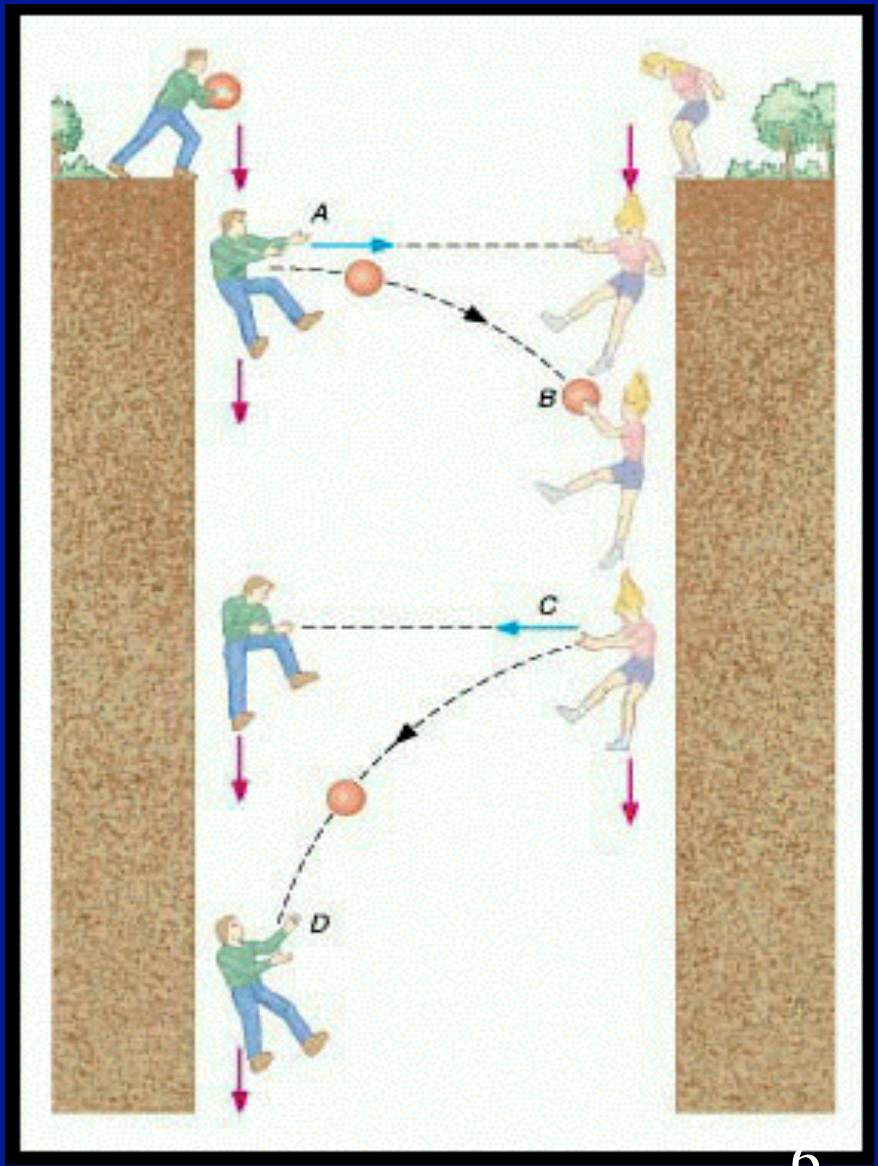
1) Imagine you are far from any source of gravity, in free space, weightless. If you shine a light or throw a ball, it will move in a straight line.

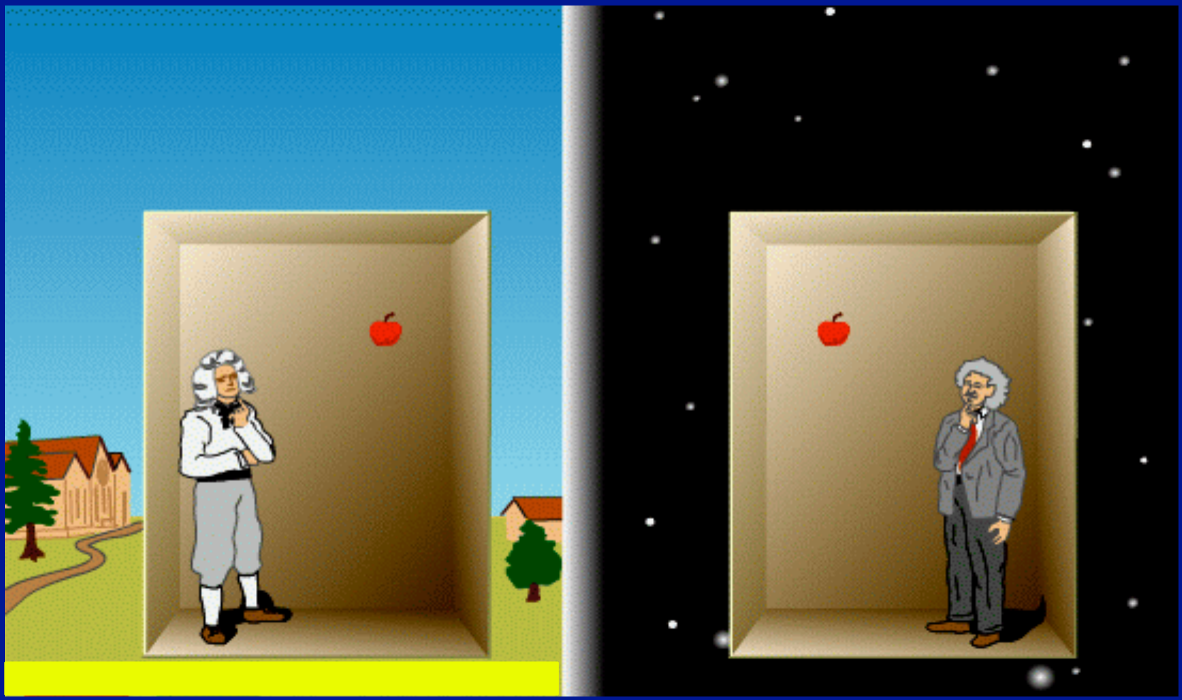


2. If you are in <u>freefall</u>, you are also weightless. Einstein says these are equivalent. So in freefall, the light and the ball also travel in straight lines.

3. Now imagine two people in freefall on Earth, passing a ball back and forth. From their perspective, they pass the ball in a <u>straight line</u>. From a stationary perspective, the ball follows a <u>curved</u> path. <u>So will a flashlight beam</u>, but curvature of light path is small because light is fast (but not infinitely so).

The different perspectives are called <u>frames of reference</u>.



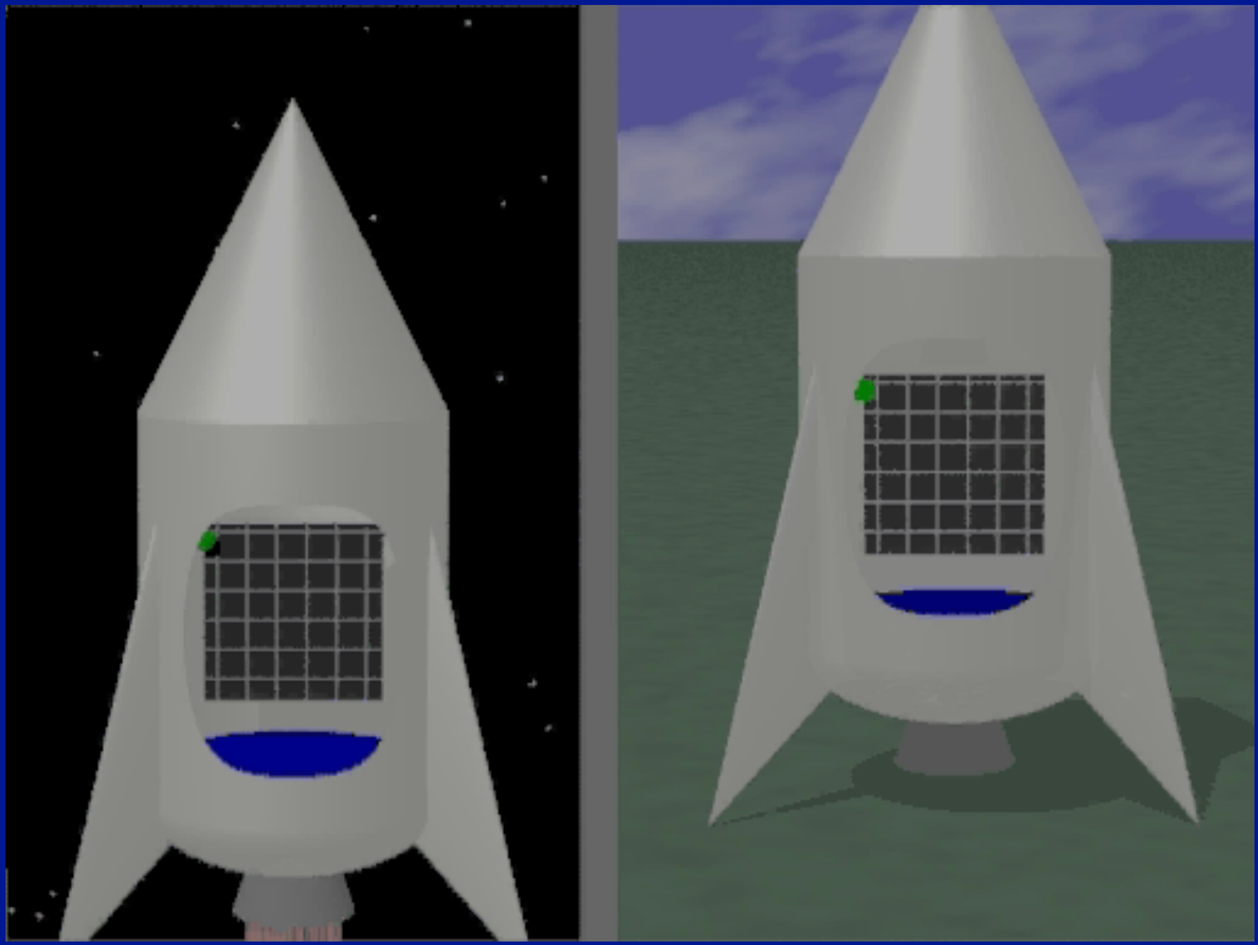


4. Gravity and acceleration are equivalent. An apple falling in Earth's gravity is the same as one falling in an elevator accelerating upwards, in free space.

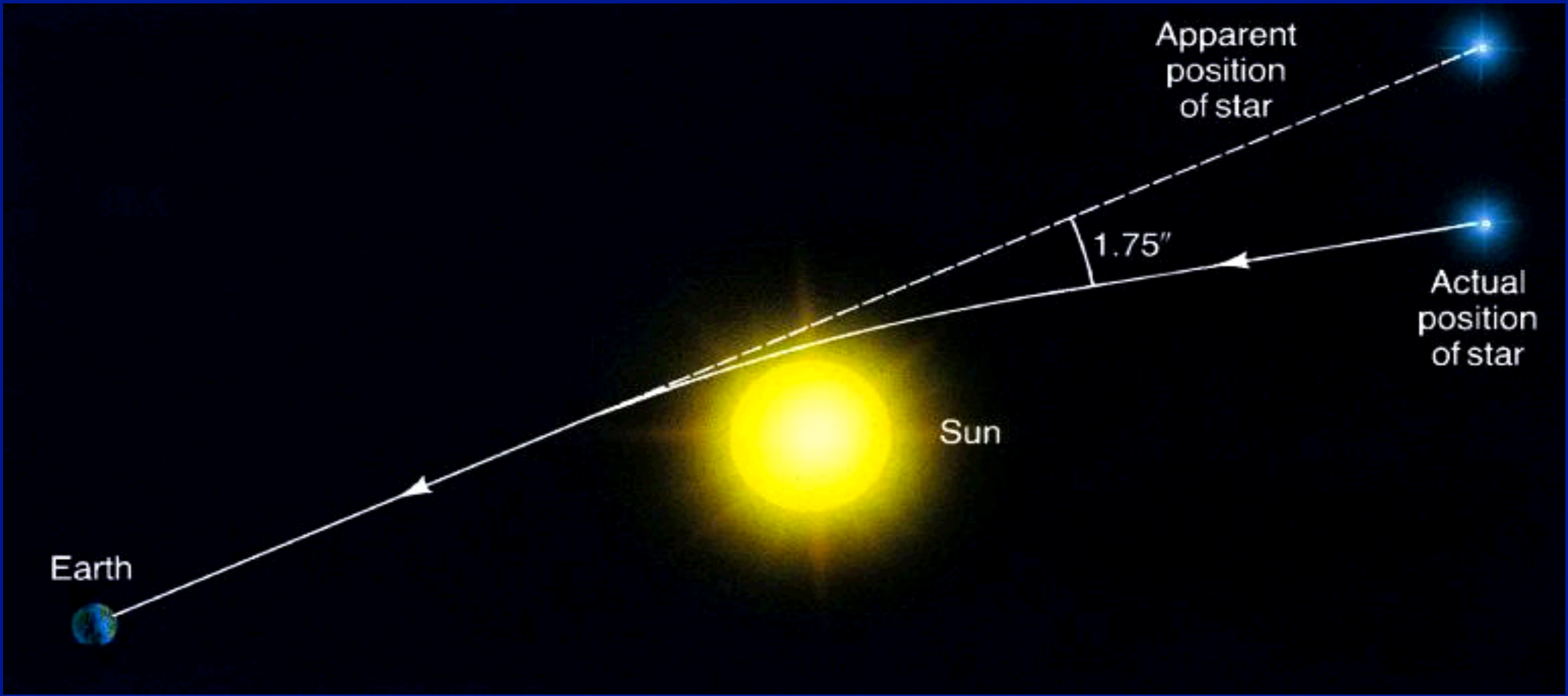
5. All effects you would observe by being in an accelerated frame of reference you would also observe when under the influence of gravity.

Examples:

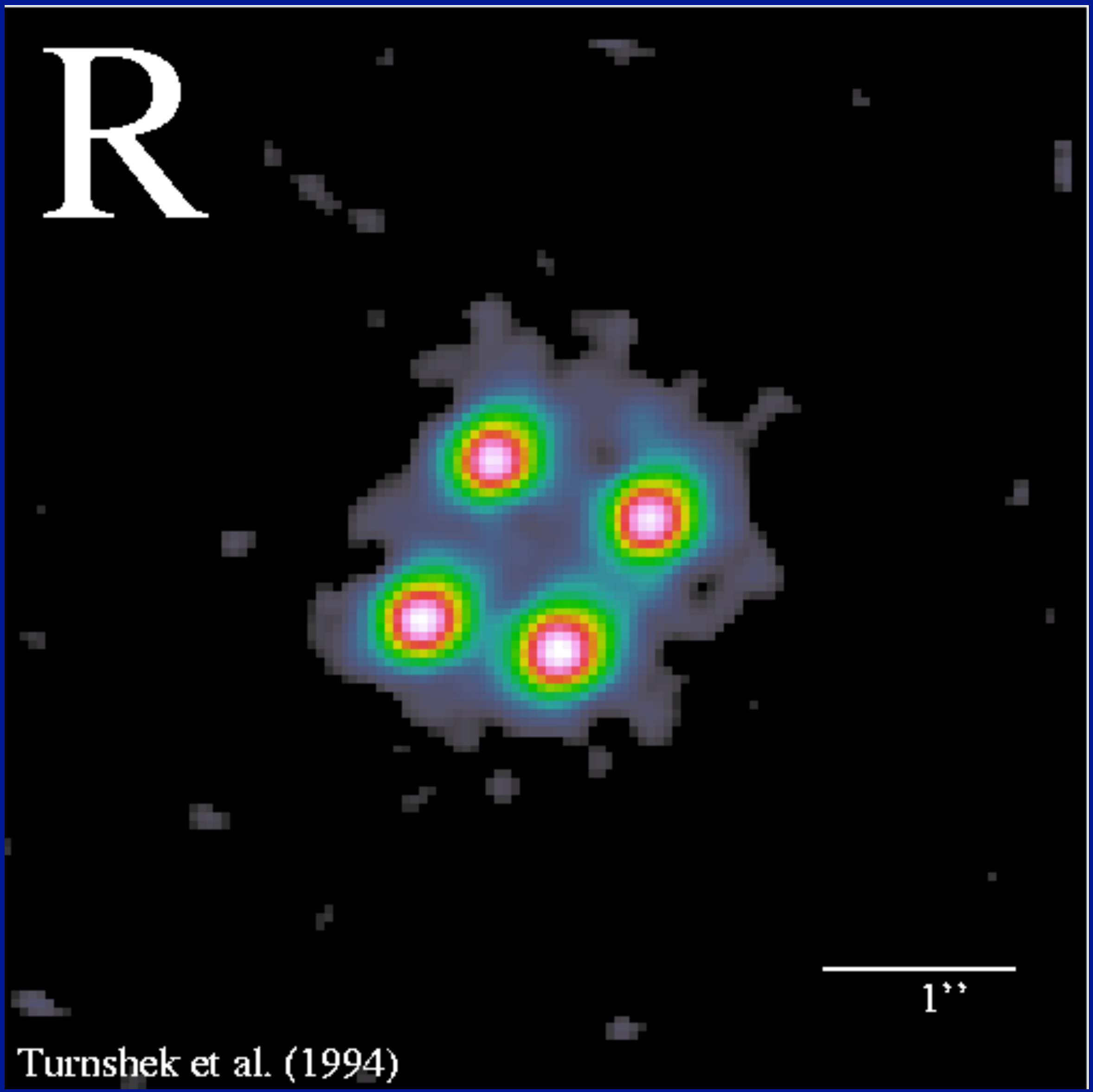
1) Bending of light. If light travels in straight lines in free space, then gravity causes light to follow curved paths.



Observed! In 1919 eclipse by Eddington



Gravitational lensing of a single background quasar into 4 objects



1413+117 the
"cloverleaf" quasar
A 'quad' lens

Gravitational lensing. The gravity of a foreground cluster of galaxies distorts the images of background galaxies into arc shapes.

Saturn-mass black hole

Clicker Question:

Eddington and his team were able to see a star appear from behind the sun sooner than expected during the 1919 solar eclipse due to:

A: bending of the light by heat waves from the sun

B: bending of the light due to the mass of the sun

C: acceleration of the light to higher speeds by the sun

D: bending of the light by strong magnetic fields

Clicker Question:

Einstein's equivalence principle states that:

A: Mass and Energy are related

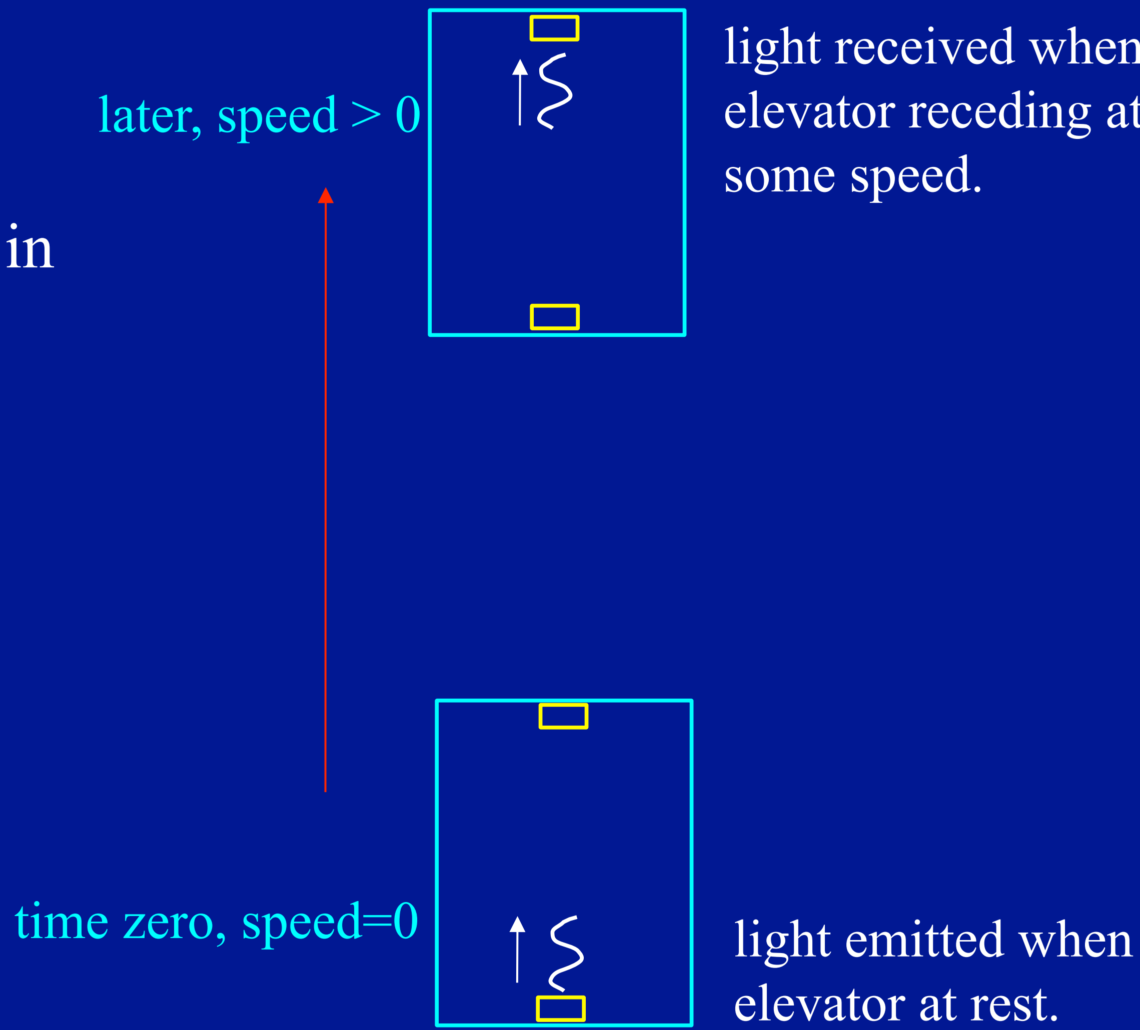
B: All clocks appear to record time at the same rate regardless of how fast they move.

C: Time and Money are related

D: An observer cannot distinguish between an accelerating frame due to motion or due to gravity.

2. Gravitational Redshift

Consider accelerating elevator in free space (no gravity).



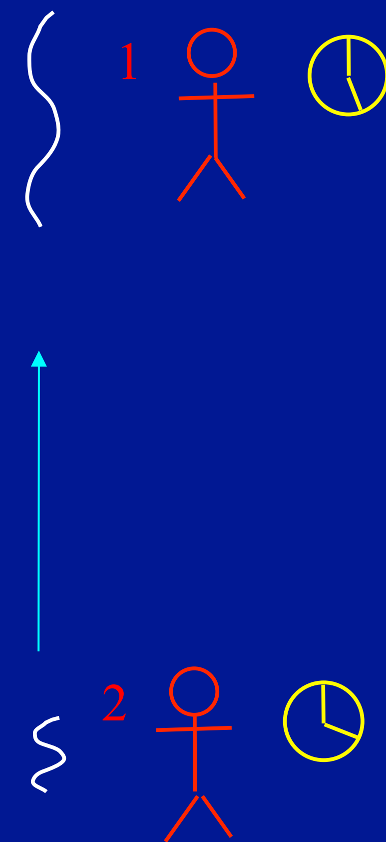
Received light has longer wavelength (or shorter frequency) because of Doppler Shift ("redshift"). Gravity must have same effect! Verified in Pound-Rebka experiment.

3. Gravitational Time Dilation

A photon moving upwards in gravity is redshifted. Since

$$\nu = \frac{1}{T}$$

the photon's period gets longer. Observer 1 will measure a longer period than Observer 2. So they disagree on time intervals. Observer 1 would say that Observer 2's clock runs slow!



All these effects are unnoticeable in our daily experience! They are tiny in Earth's gravity, but large in a black hole's.

Escape Velocity

Velocity needed to escape the gravitational pull of an object.

$$v_{esc} = \sqrt{\frac{2GM}{R}}$$

Escape velocity from Earth's surface is 11 km/sec.

If Earth were crushed down to 1 cm size, escape velocity would be speed of light. Then nothing, including light, could escape Earth.

This special radius, for a particular object, is called the Schwarzschild Radius, R_S. $R_S \propto M$.

Black Holes

If core with about 3 M_{Sun} or more collapses, not even neutron pressure can stop it (total mass of star about 25 M_{Sun}).

Core collapses to a point, a "singularity".

Gravity is so strong that nothing can escape, not even light => black hole.

Schwarzschild radius for Earth is 1 cm. For a 3 M_{Sun} object, it's 9 km.

Clicker Question:

X-rays coming from the surface of a neutron star observed at Earth are shifted to:

A: lower energies.

B: higher energies.

C: the energy doesn't change.

D: lower speeds.

Clicker Question:

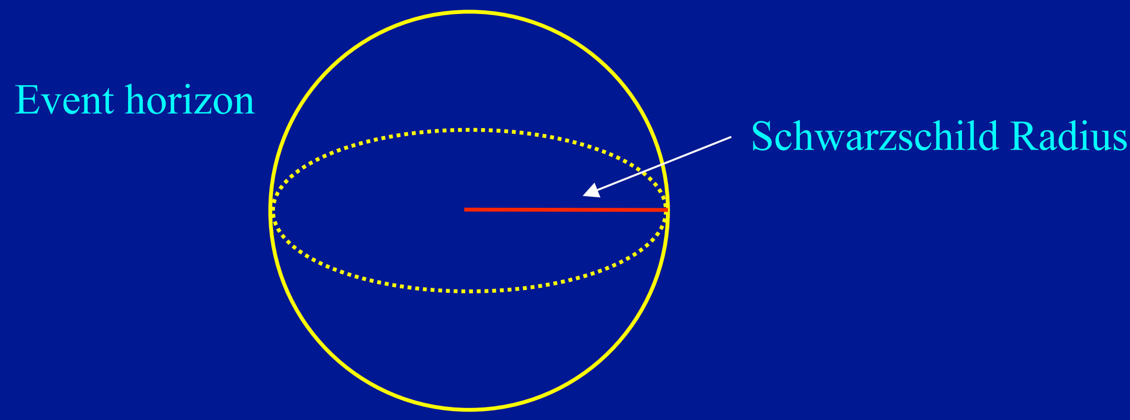
Suppose we start with two atomic clocks and take one up a high mountain for a week. Which is true?

A: The two clocks will show the same amount of time has passed.

B: The mountain clock will be slightly ahead (fast)

C: The mountain clock will be slightly behind (slow)

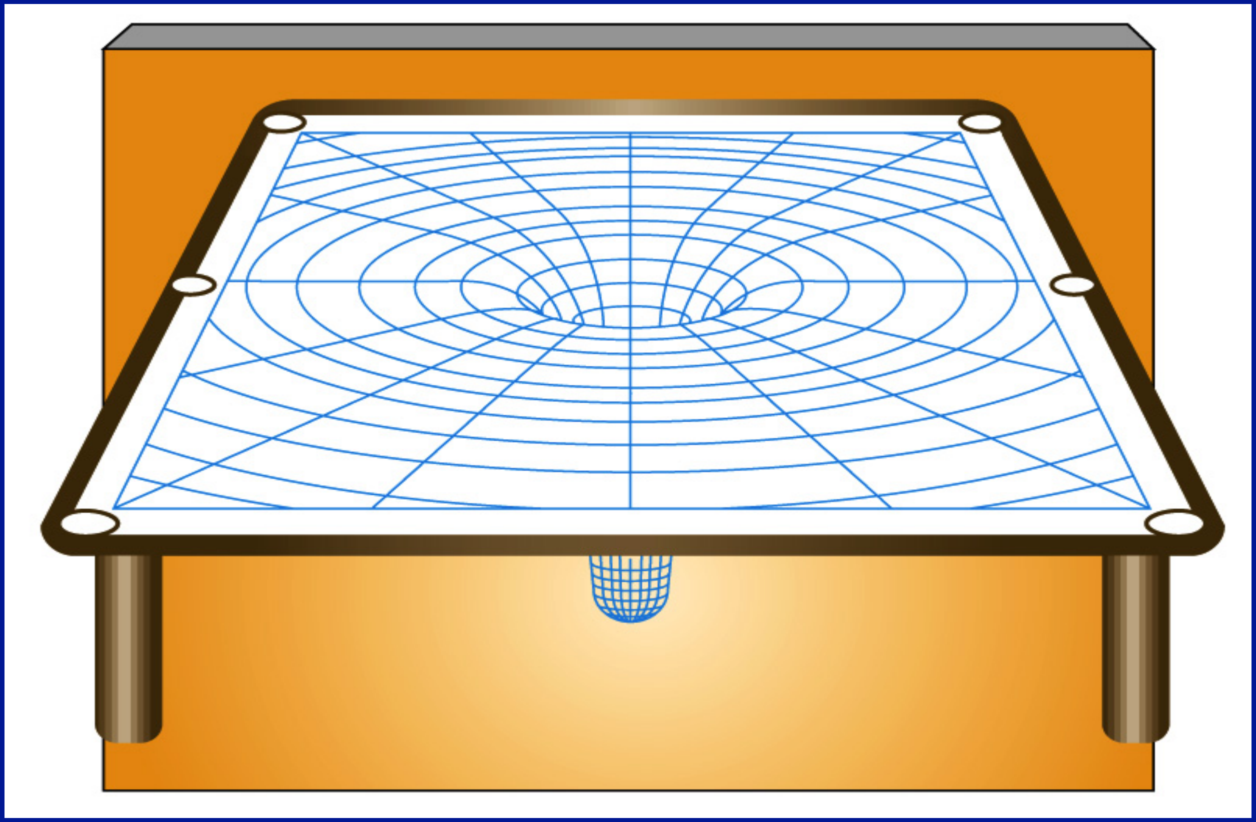
Event horizon: imaginary sphere around object with radius equal to Schwarzschild radius.



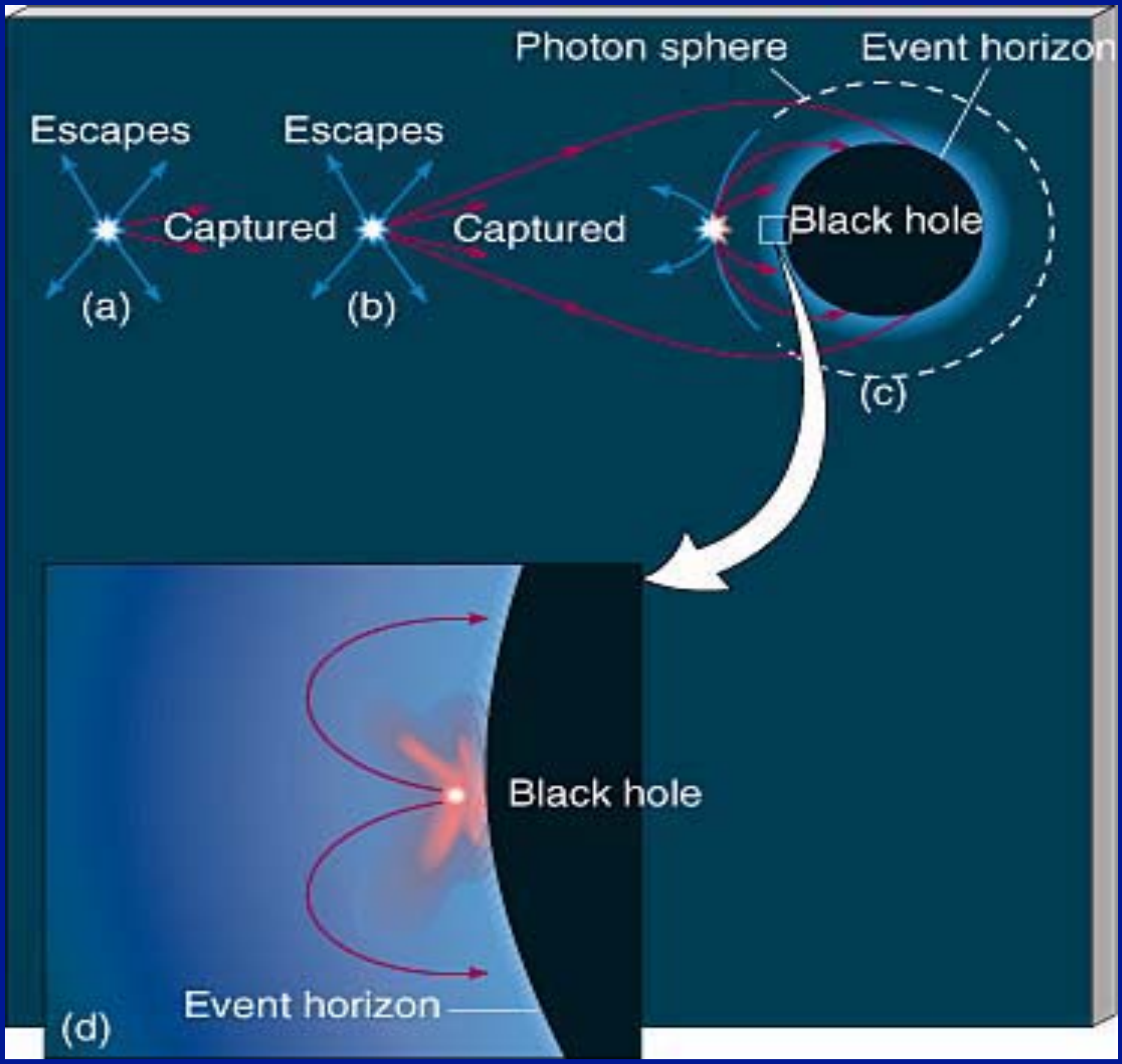
Anything crossing over to inside the event horizon, including light, is trapped. We can know nothing more about it after it does so.

Black hole achieves this by severely curving space. According to Einstein's General Relativity, all masses curve space. Gravity and space curvature are equivalent.

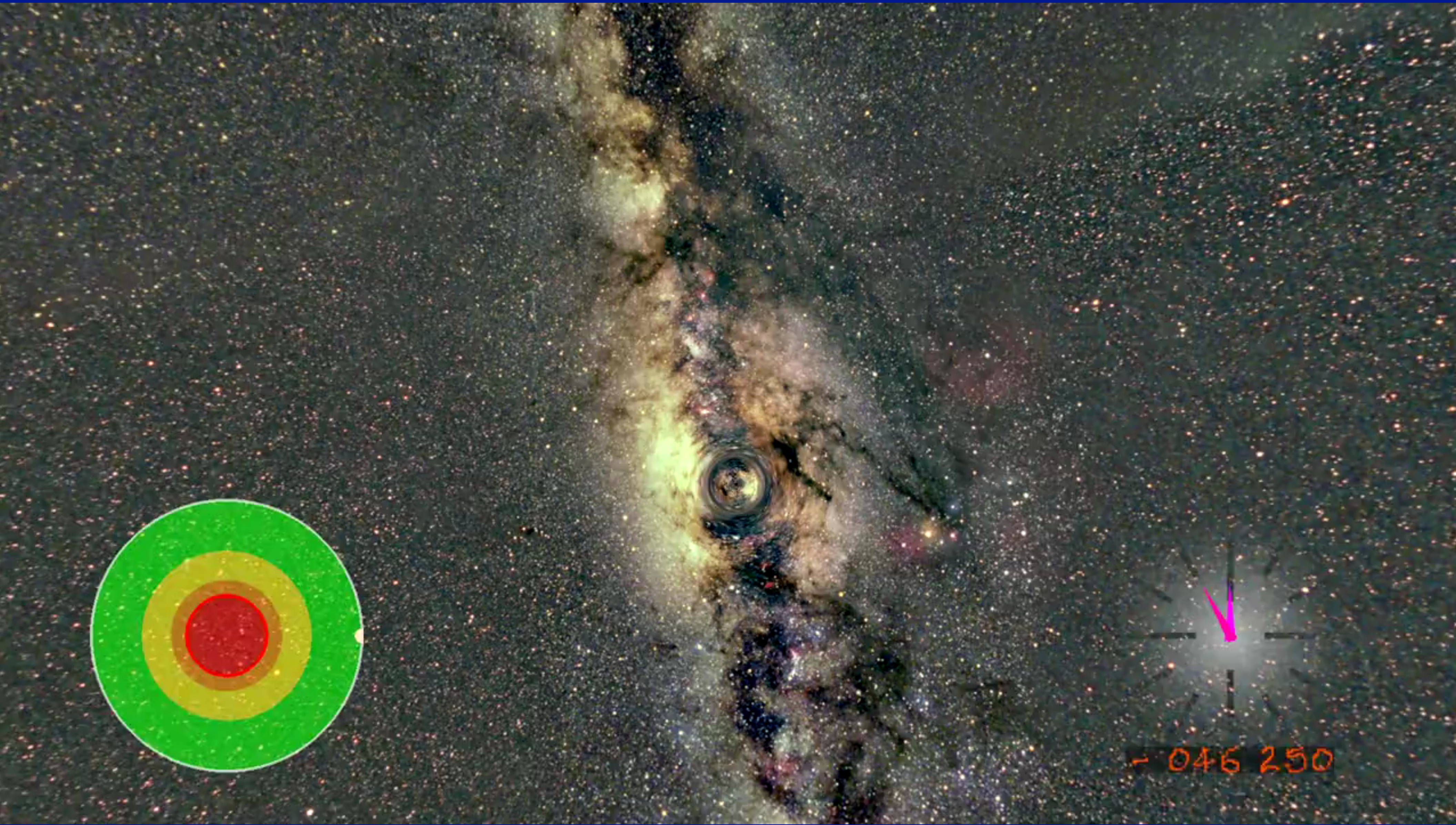
Like a rubber sheet, but in three dimensions, curvature dictates how all objects, including light, move when close to a mass.



Curvature at event horizon is so great that space "folds in on itself", i.e. anything crossing it is trapped.

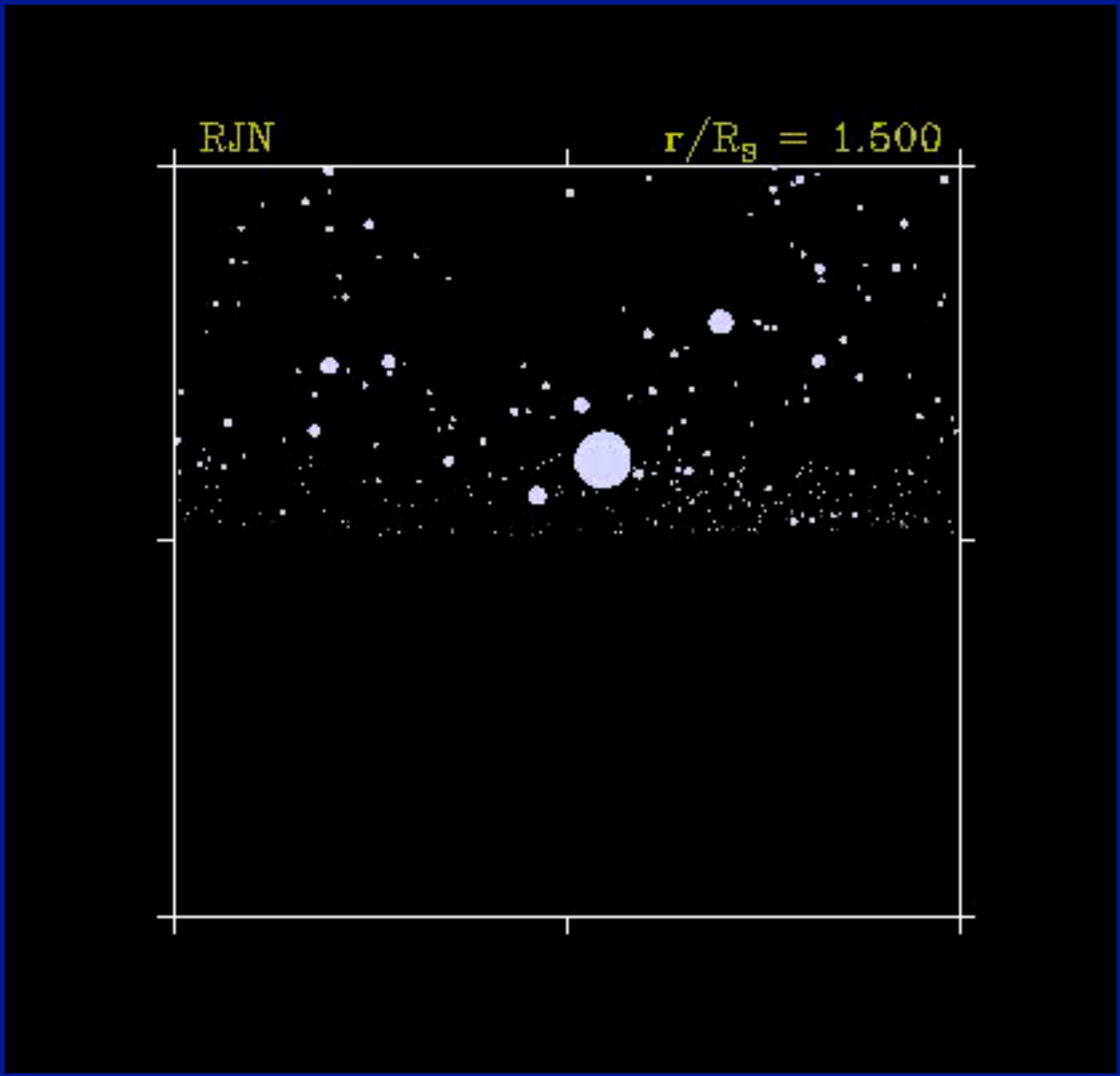


Journey into a Black Hole:



Simulation by Andrew Hamilton

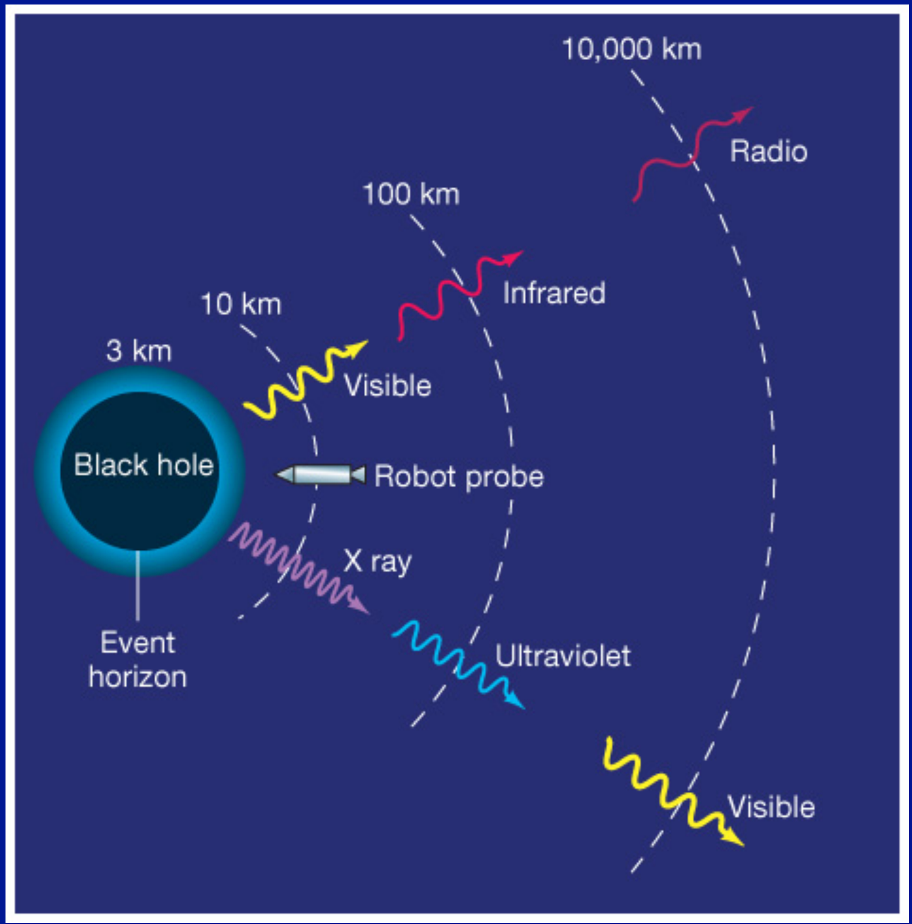
Circling a Black Hole at the Photon Sphere:



Effects around Black Holes

1) Enormous tidal forces.

2) Gravitational redshift. Example, blue light emitted just outside event horizon may appear red to distant observer.

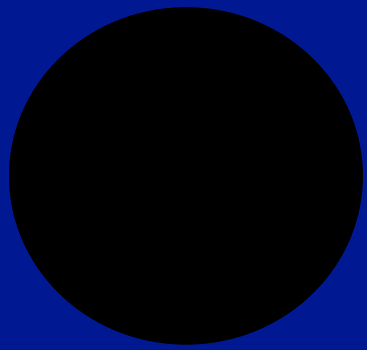


3) Time dilation. Clock just outside event horizon appears to run slow to a distant observer. At event horizon, clock appears to stop.

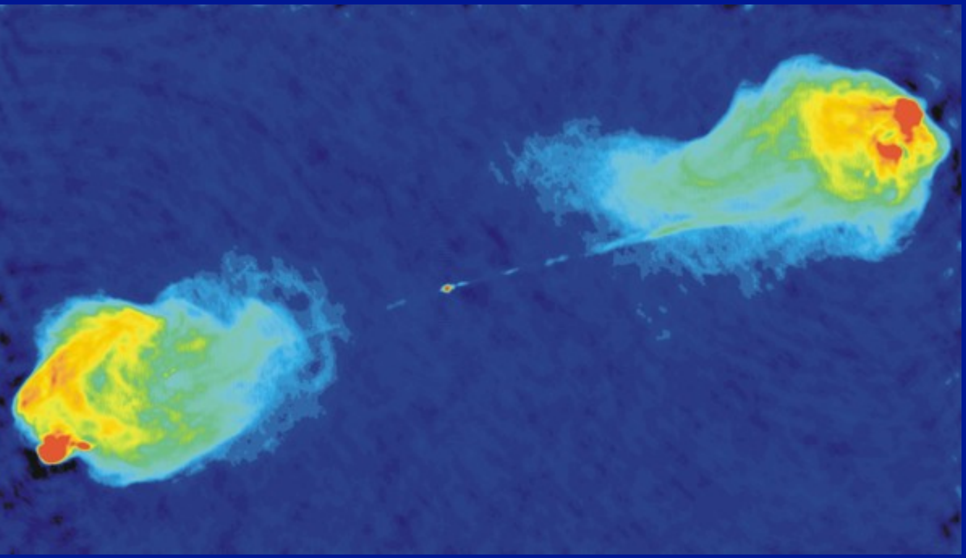
Black Holes have no Hair

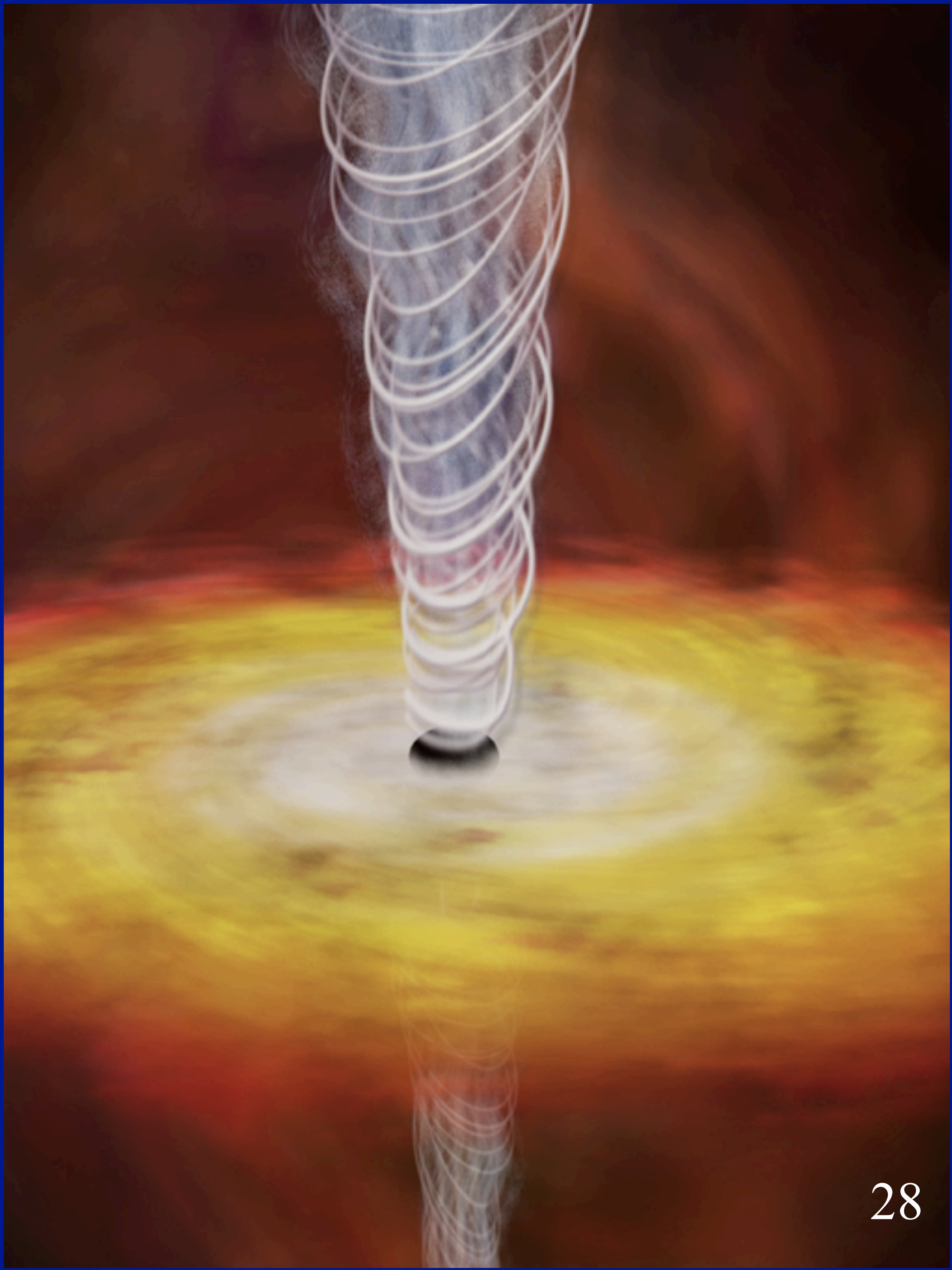
Properties of a black hole:

- Mass
- Spin (angular momentum)
- Charge (tends to be zero)



Black Holes can have impact on their environments



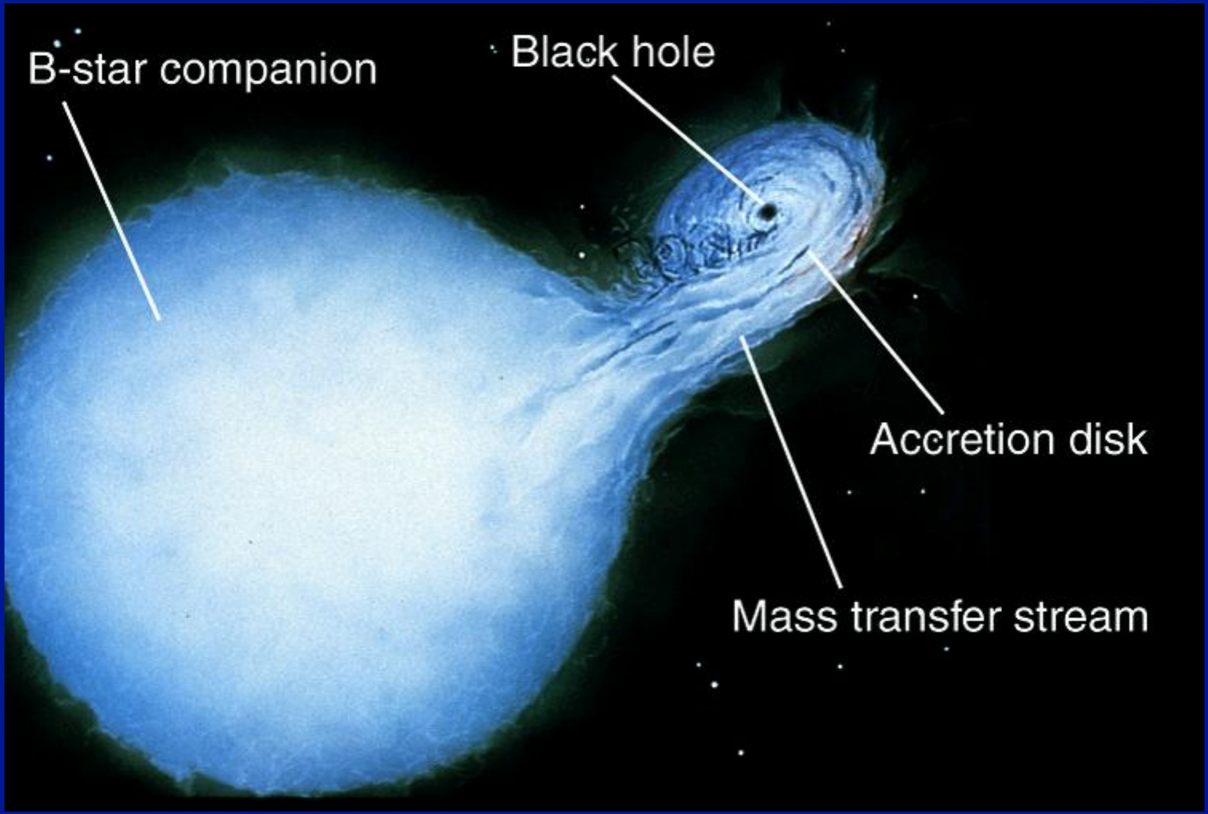


Do Black Holes Really Exist? Good Candidate: Cygnus X-1

- Binary system: 30 M_{Sun} star with unseen companion.

- Binary orbit => companion > 7 M_{Sun}.

- X-rays => million degree gas falling into black hole.



Clicker Question:

The escape velocity for the Earth is normally 11 km/s, what would the escape velocity be from a black hole the same mass as the Earth if you launched a rocket from a platform 6400 km above the event horizon (1 Earth radii):

A: 22 km/s

B: 11 km/s

C: 6 km/s

D: 3 km/s

Clicker Question:

What is the escape velocity at the Event Horizon of a 100 solar mass black hole?

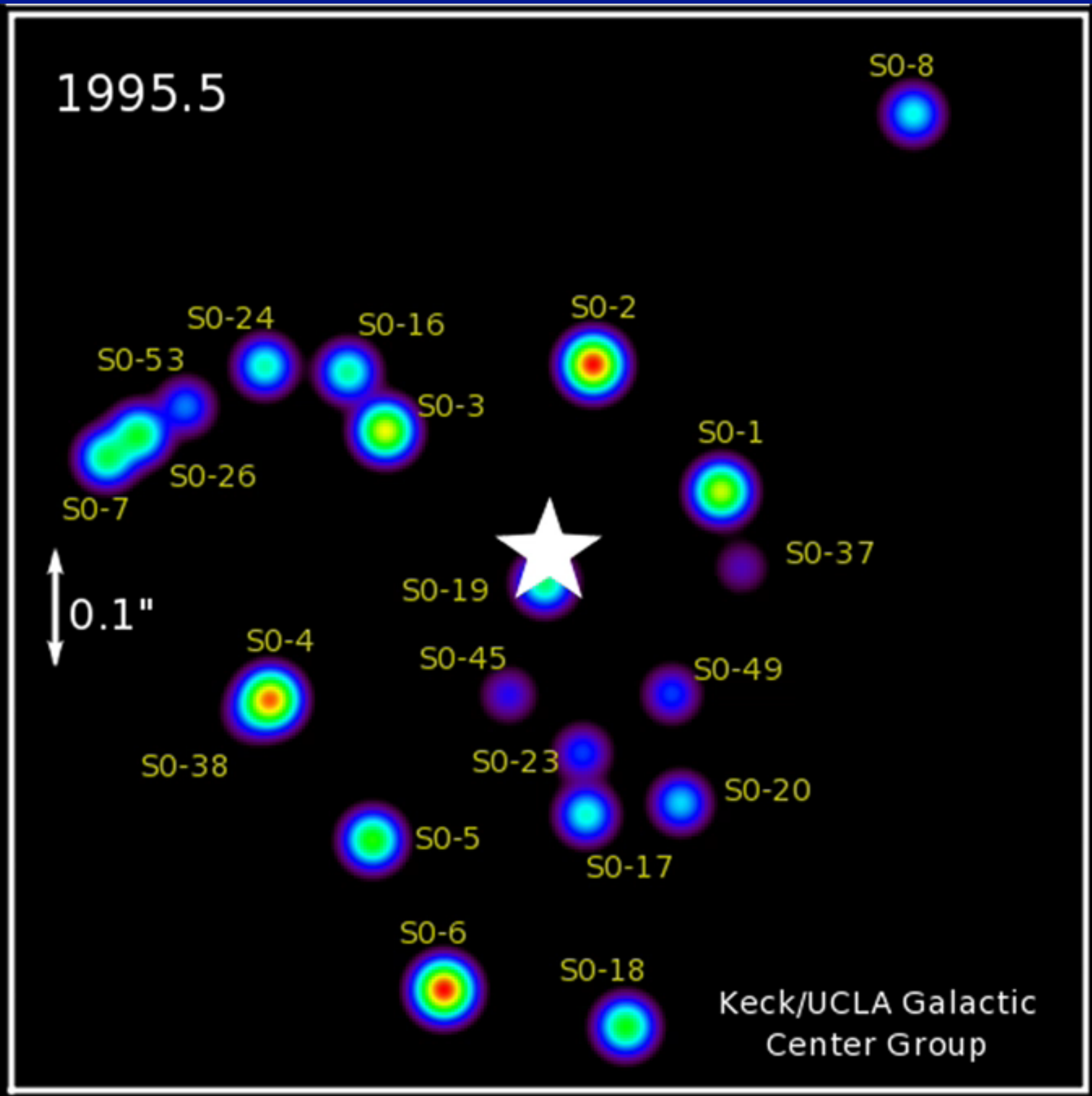
A: 300,000 km/s

B: 3,000,000 km/s

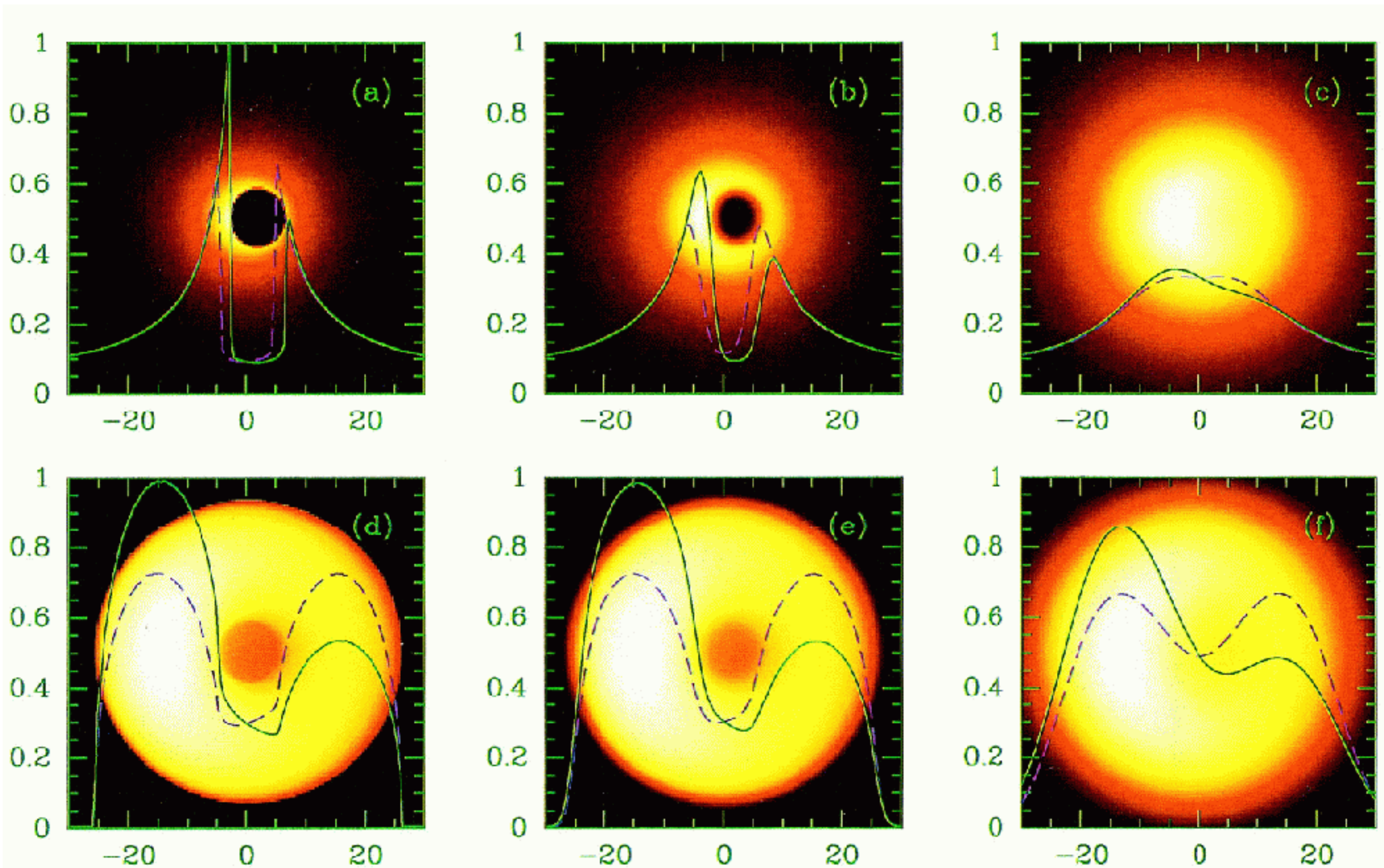
C: 30,000,000 km/s

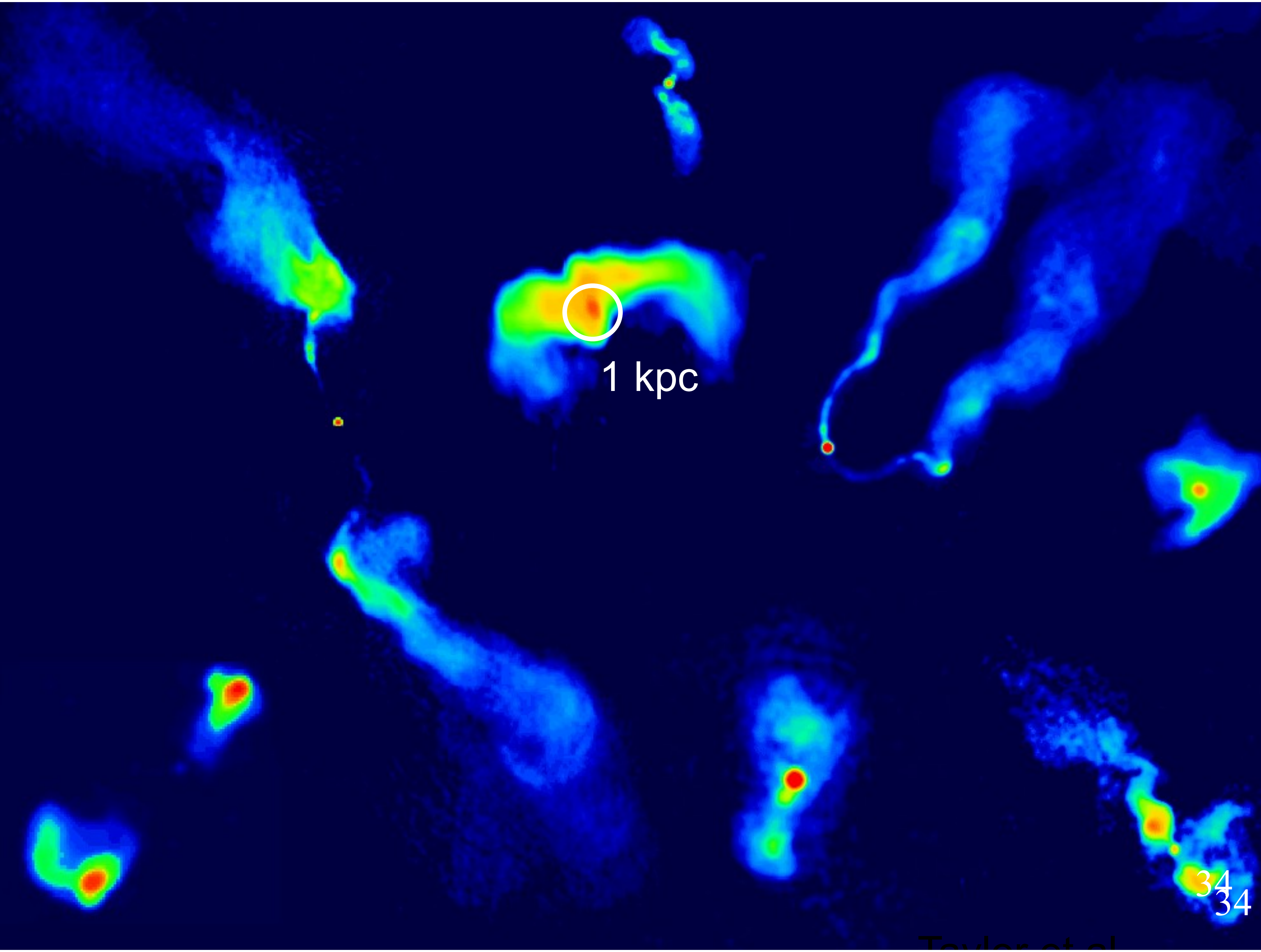
D: 300,000,000 km/s

Supermassive (3 million solar mass) Black Hole at the Galactic Center



Shadow of a Black Hole





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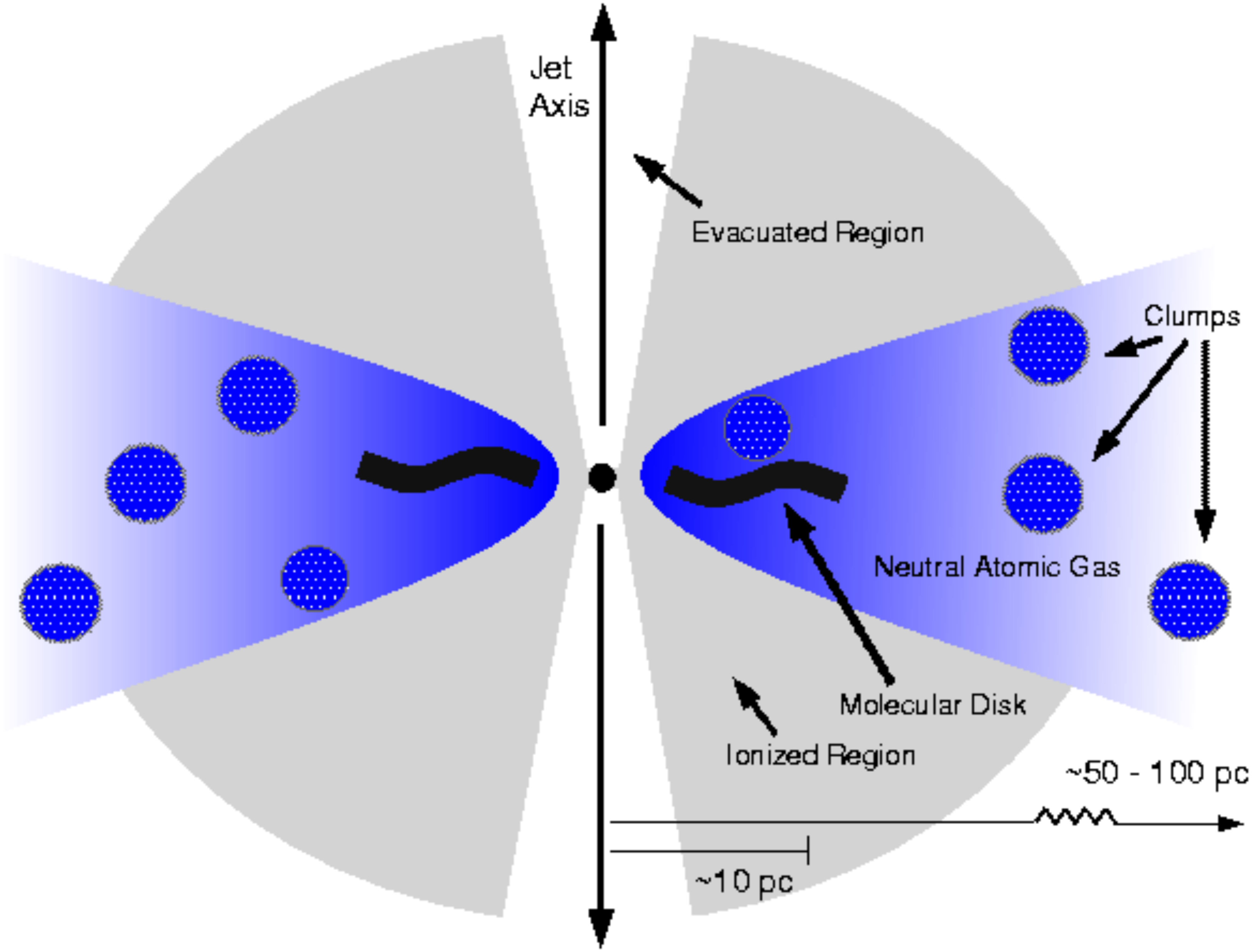
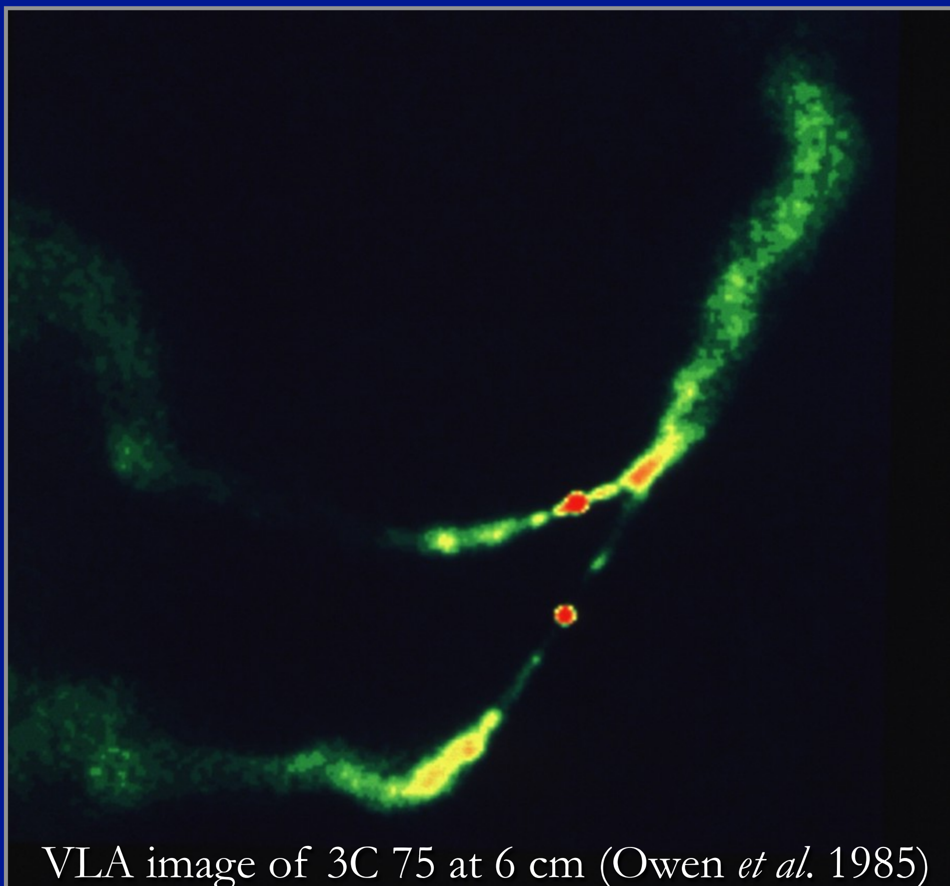

Jet
Axis
Evacuated Region
Clumps
Neutral Atomic Gas
Molecular Disk
Ionized Region
~50 - 100 pc
~10 pc

Supermassive Binary Black Holes

3C 75

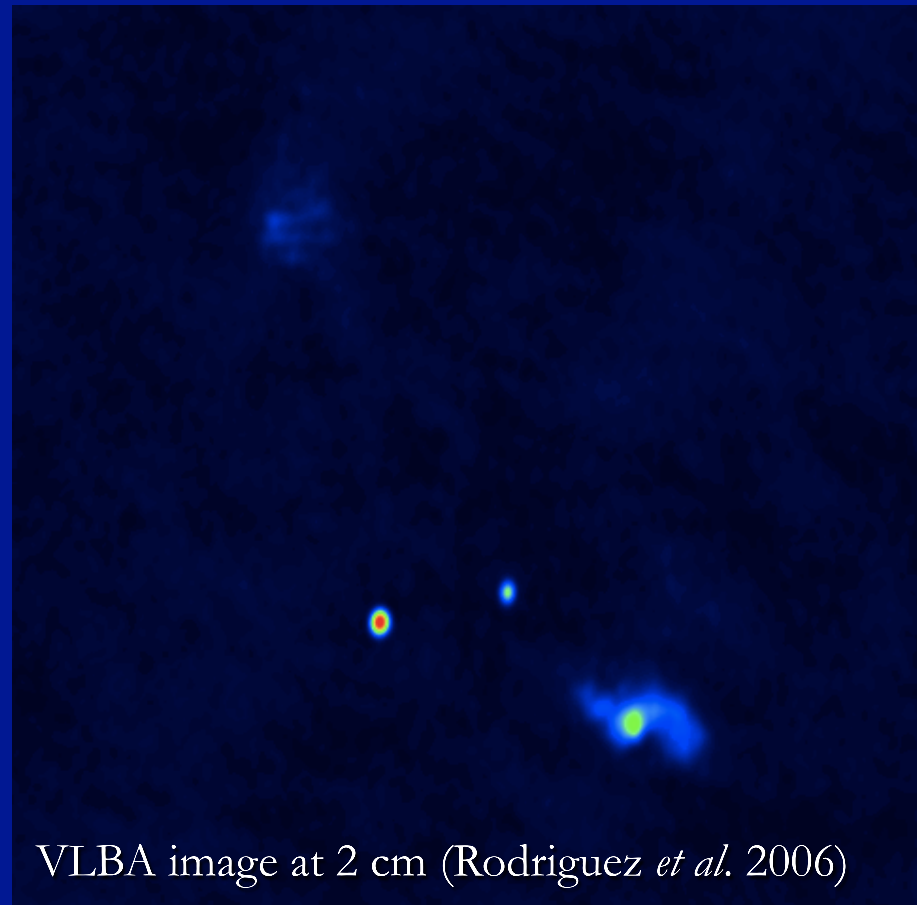
⇨ 7 kpc separation



VLA image of 3C 75 at 6 cm (Owen *et al.* 1985)

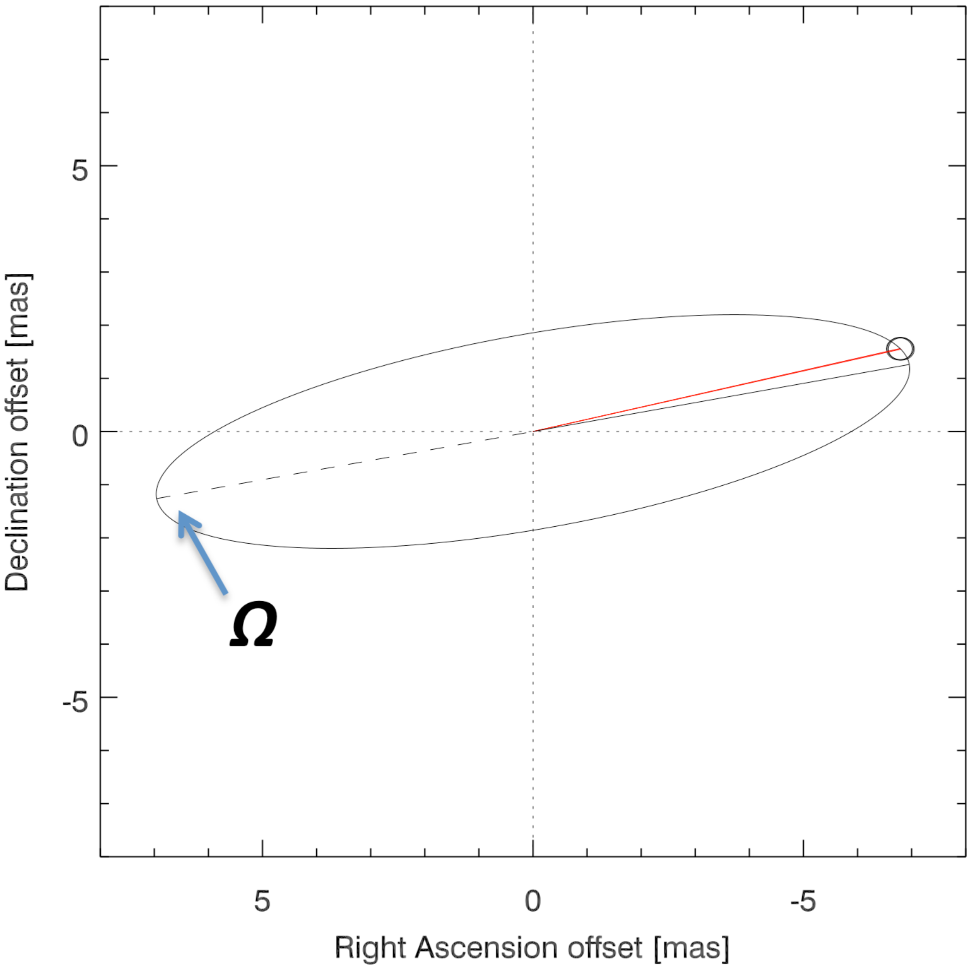
0402+379

7 pc separation

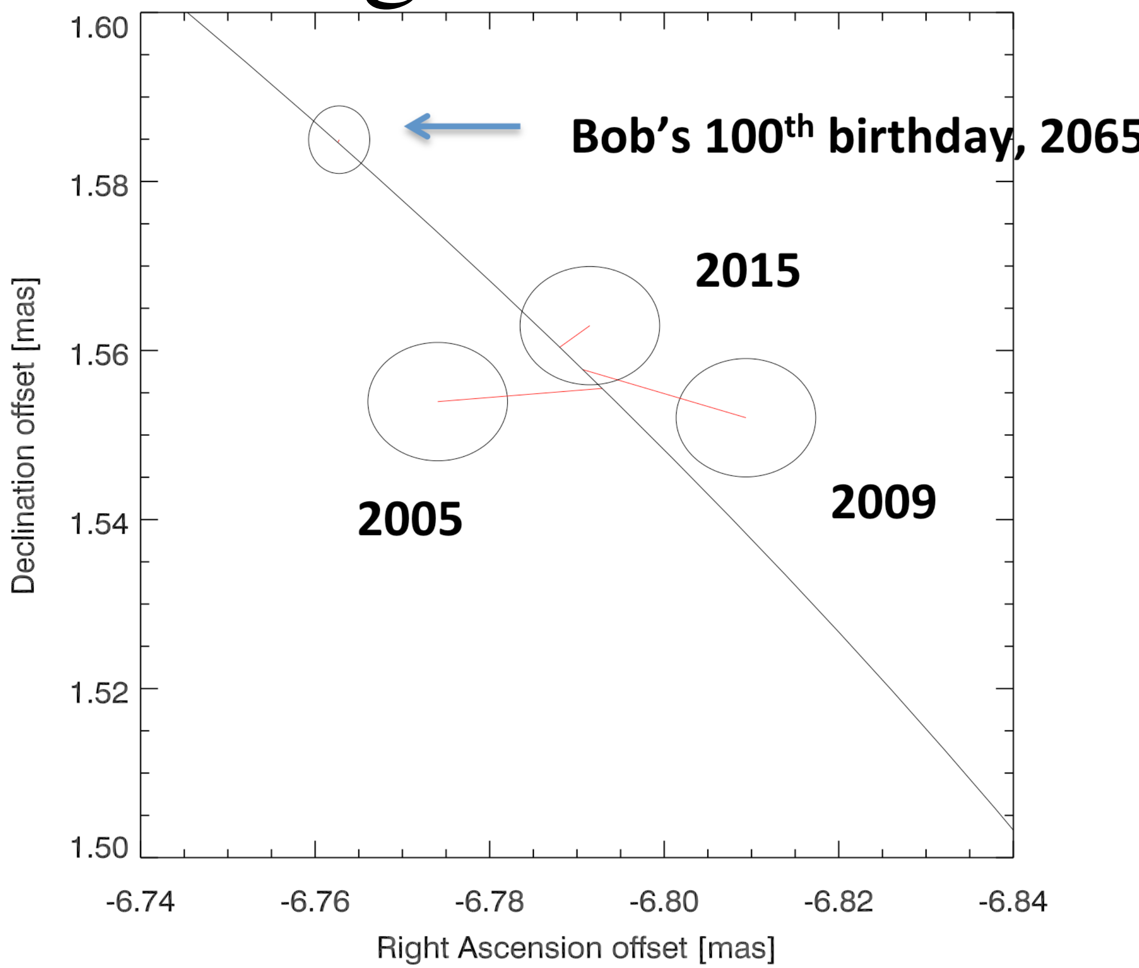


VLBA image at 2 cm (Rodriguez *et al.* 2006)

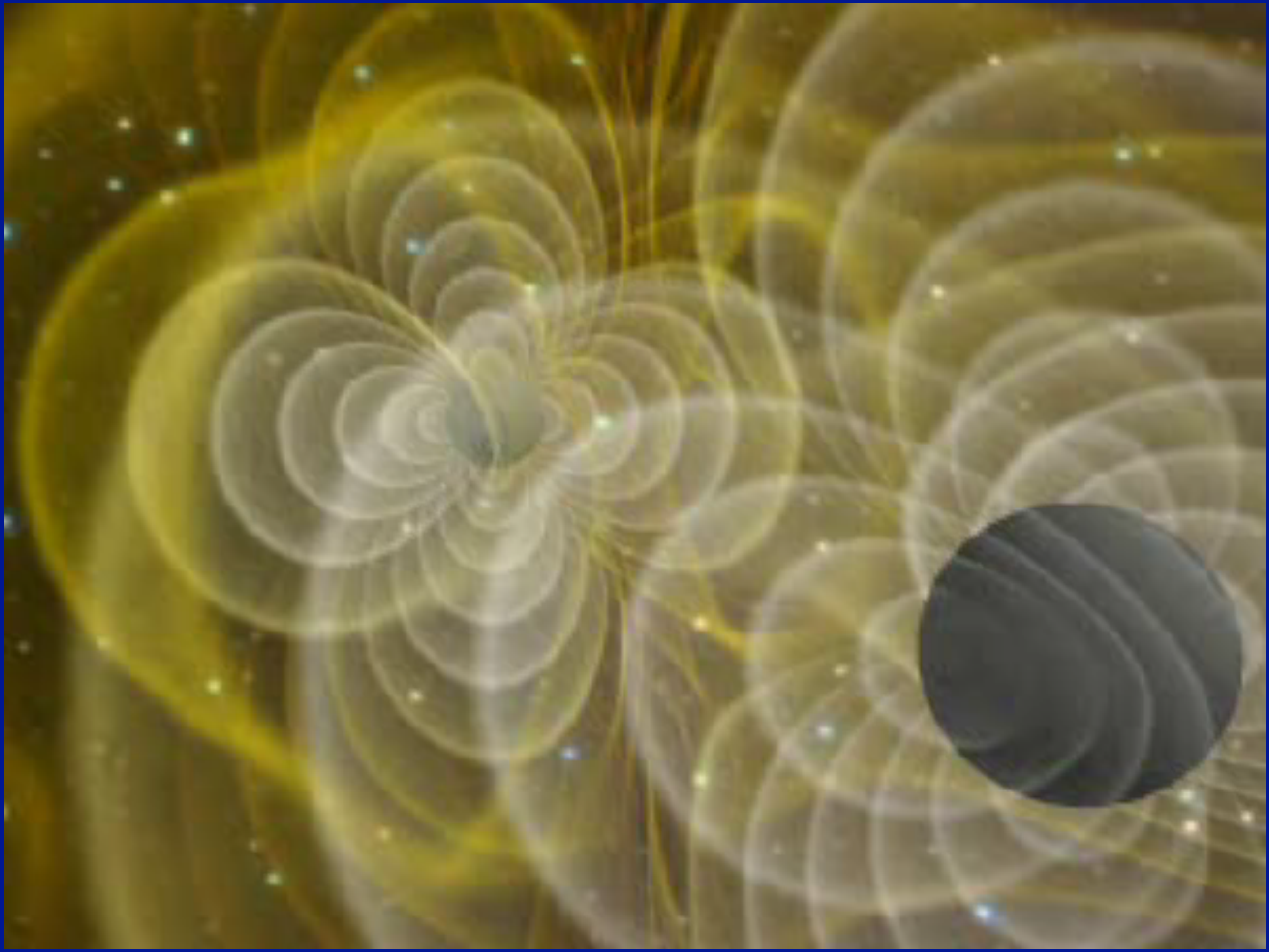
Orbital Fitting



Circular orbit at an inclination



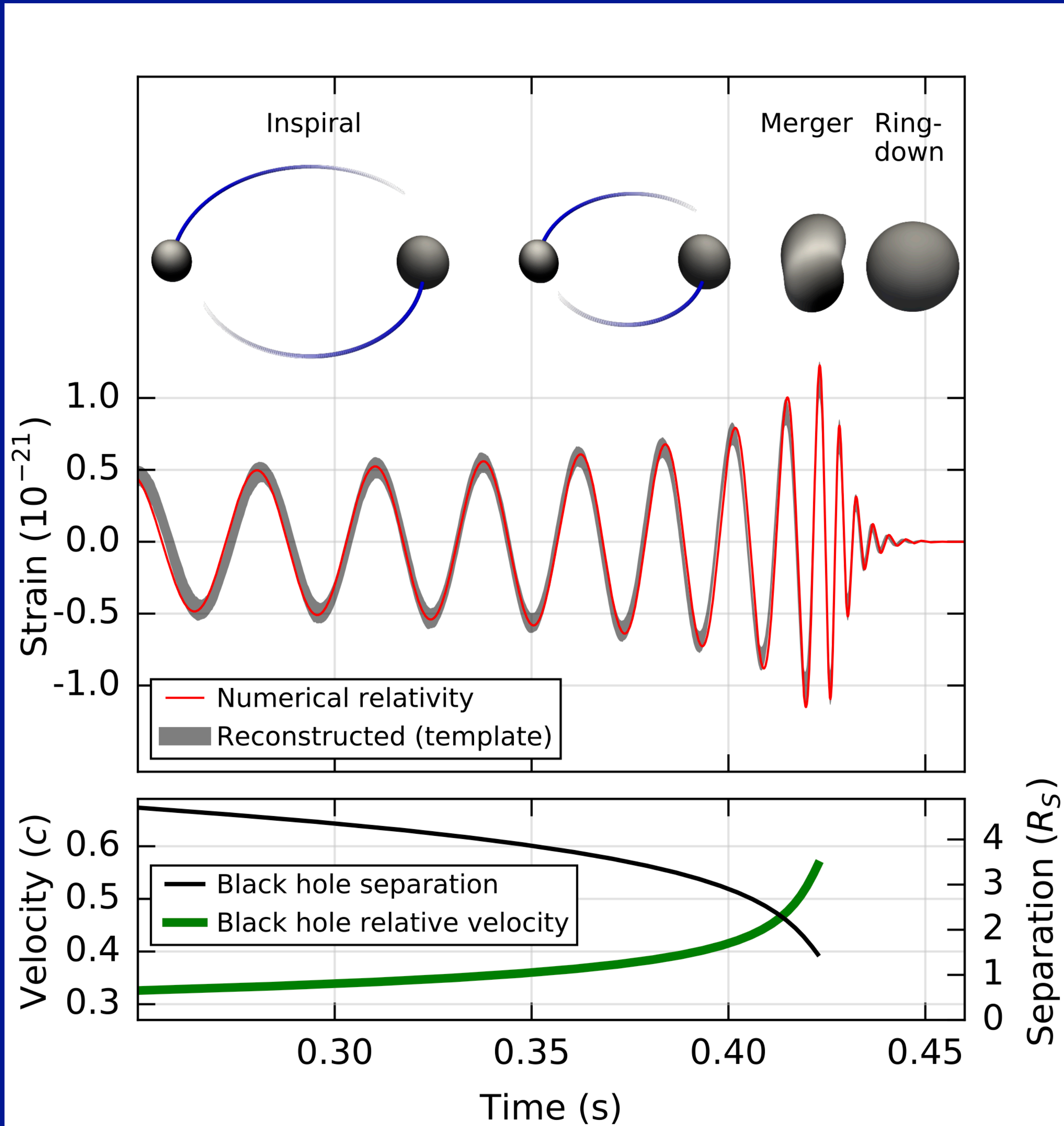
Close-up view



Gravitational Waves

LIGO (Laser Interferometric Gravity-Wave Observatory)

Gravitational Waves



Gravitational Waves