Physics 51 LECTURE 7 December 2, 2011

- Midterm Exam

- More on Special Relativity

  Special Relativity with 4-vectors (again)

  Special Relativity + Quantum Mechanics

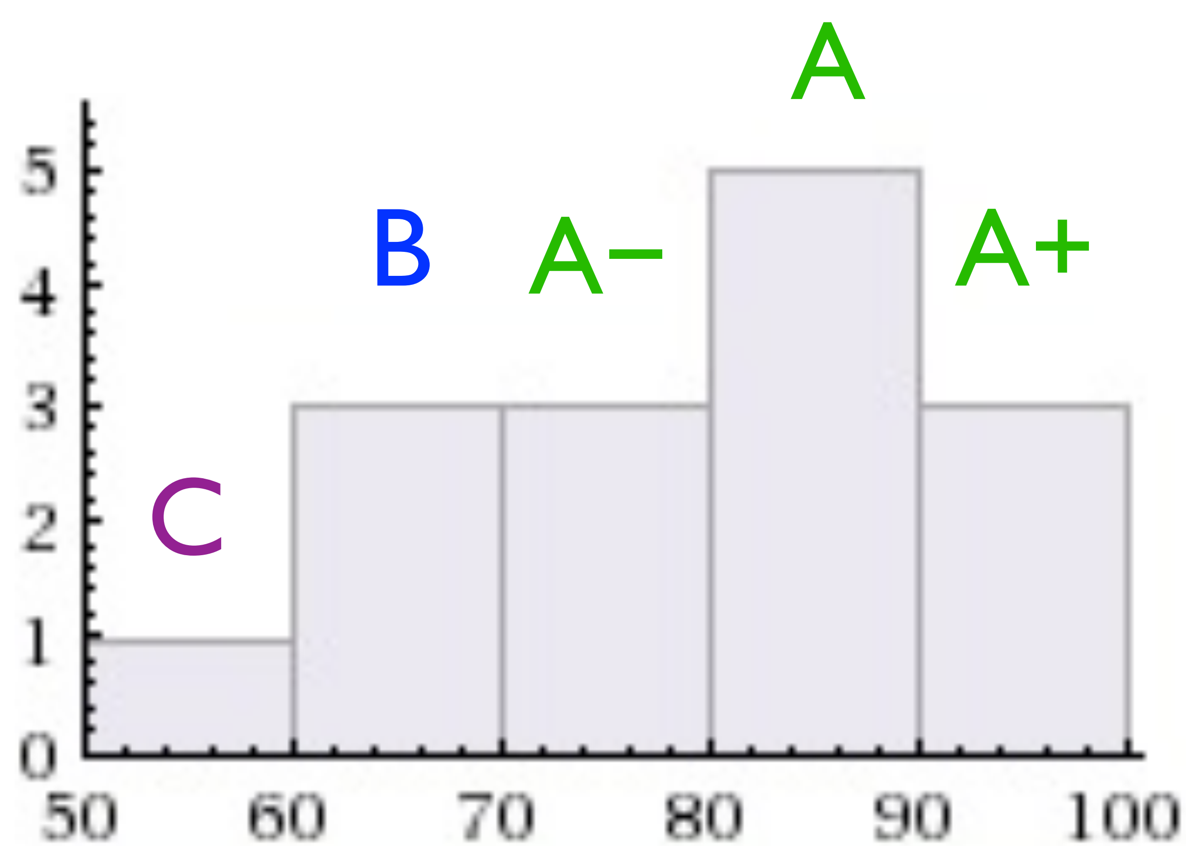
  $\Rightarrow$ Antiparticles, Spin

- General Relativity

- Black Holes

Physics 51 Midterm Exam

Mean: 78.27%
Median: 80%
Standard Deviation: 12.44%



Special Relativity with 4-Vectors

An quantity that transforms the same way as (ct,x) is called a 4-vector. It turns out that the combination $V^\mu = (\gamma, \gamma \boldsymbol{v}/c) = \gamma(1, \boldsymbol{v}/c)$ where $\boldsymbol{v}$ is the velocity vector, is a 4-vector, called the velocity 4-vector. Here $V^0 = \gamma$, and $V^i = \gamma v^i/c$, $i = 1, 2, 3$. Its invariant length-squared is $V \cdot V = (V^0)^2 - (\boldsymbol{v}^2)^2 = \gamma^2 (1 - v^2/c^2) = 1$.

Multiply the rest energy of a particle mc^2 by its velocity 4-vector and you get its momentum 4-vector:

$$P = (E, pc) = mc^2 \gamma(1, v/c)$$

Its invariant length-squared is $P \cdot P = E^2 - p^2c^2 = m^2c^4 \gamma^2 (1 - v^2/c^2) = m^2c^4$.

For a particle of mass m, this says that $E^2 = p^2c^2 + m^2c^4$.

For the special case of a massless particle like the photon, this says that $E^2 = p^2c^2$ or $E = |p|c$. The momentum carried by a photon of energy E is $p = E/c$.

As students become more familiar with formulas like these, it's convenient to stop writing the speed of light c and just understand that powers of c are included as needed to get the right units. Then the energy-momentum-mass relation becomes $E^2 = p^2 + m^2$. We often measure mass in energy units, for example we say that the mass m_e of the electron is 0.511 MeV, even though what we really mean is that $m_e c^2 = 0.511$ MeV. And of course we measure distances in time units: light-years.

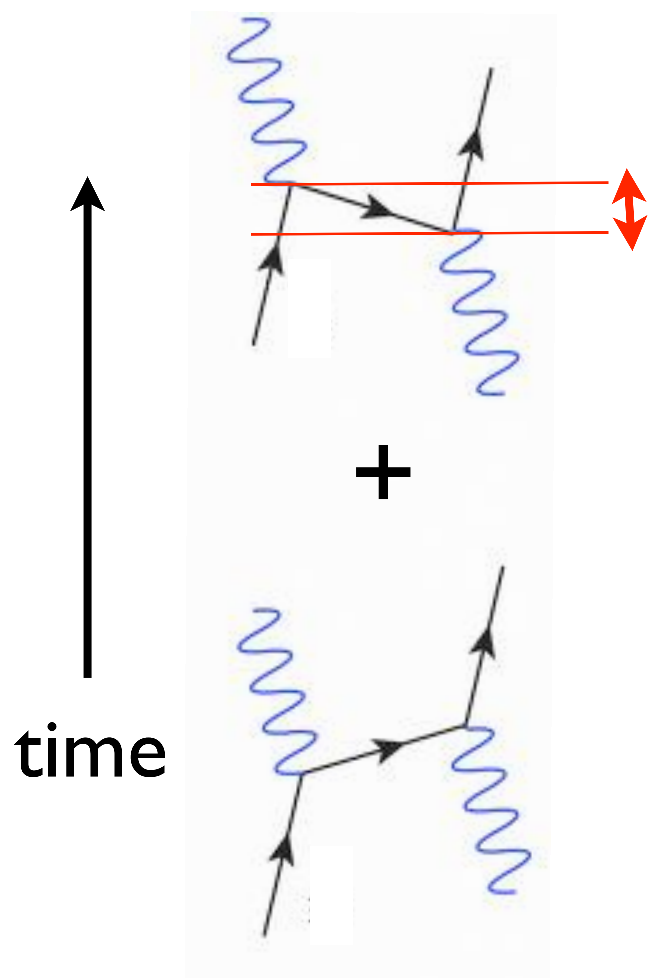
Schrodinger Equation: $i\hbar\frac{\partial}{\partial t}\Psi = \hat{H}\Psi$ where $\hat{H} = p^2/2m$ or $E = p^2/2m$
for free particle
Newtonian

matrices

Dirac Equation: $i\hbar\frac{\partial}{\partial t}\Psi = (\beta mc^2 + \alpha \cdot pc)\Psi$, with $E^2 = p^2c^2 + m^2c^4$
Relativistic

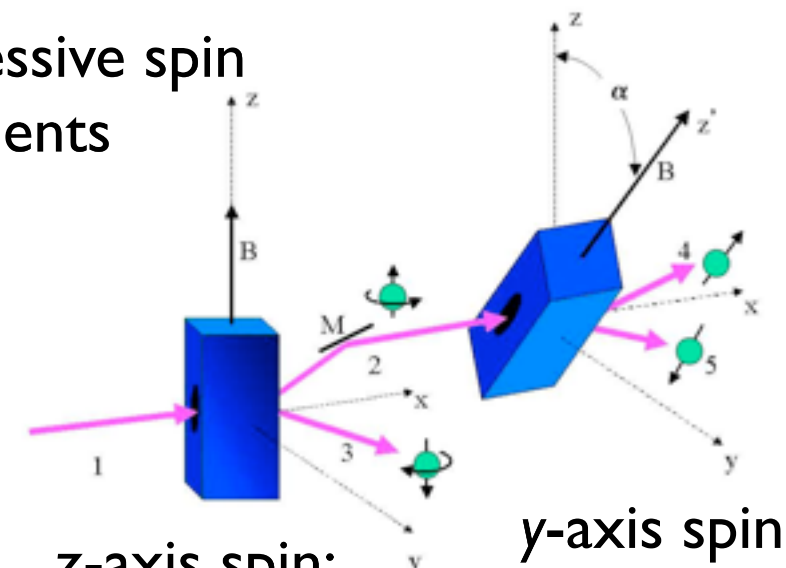
Special Relativity + Quantum Mechanics
⇒ Antiparticles & Spin

Feynman diagrams for
electron-photon scattering
(Compton scattering)



Electron goes
backward in time
= anti-electron
(positron)

Two successive spin
measurements



2 possibilities
(spin-1/2)

z-axis spin:
"white-black"

y-axis spin: "sheep-goats"
(perpendicular: α=90°)

Two successive w-b or s-g measurements give the same answer, but if all the w's from the w-b measurement are subjected to a s-g measurement, half the s's will be w and half will be b, and the same for the g's. That is, measuring s-g interferes with measuring w-b!

Special Relativity is based on two postulates

- The speed of light is the same for all inertial observers, regardless of their velocity or that of the source of the light.

- All the laws of physics are the same in all inertial reference frames.

Einstein realized that Newton's theory of gravity, with instantaneous action at a distance, could not be compatible with special relativity -- which undermined the concept of simultaneous events at a distance. It took 10 years for Einstein to get the right idea for the right theory, but then in 1915 in only two months he worked out the theory and its main initial predictions: the precession of the orbit of Mercury, bending of light by the sun, and the slowing of clocks by gravity.

General Relativity is also based on two postulates

- Equivalence Principle: All the effects of gravity on small scales are the same as those of acceleration. (Thus gravity is eliminated in local inertial = freel fall frames.)

- Einstein's Field Equations: $G_{\mu\nu} = (8\pi G/c^4)\,T_{\mu\nu}$ where $G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}R\,g_{\mu\nu}$ describes the curvature of space-time at each point and $T_{\mu\nu}$ describes the mass-energy, momentum, and stress density at the same point.

GRAVITY according to General Relativity

Principle of Equivalence

CURVED SPACE TELLS MATTER HOW TO MOVE.

Einstein Field Equations

MATTER TELLS SPACE HOW TO CURVE.

MASS + ENERGY DENSITY?

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}$$

CURVATURE

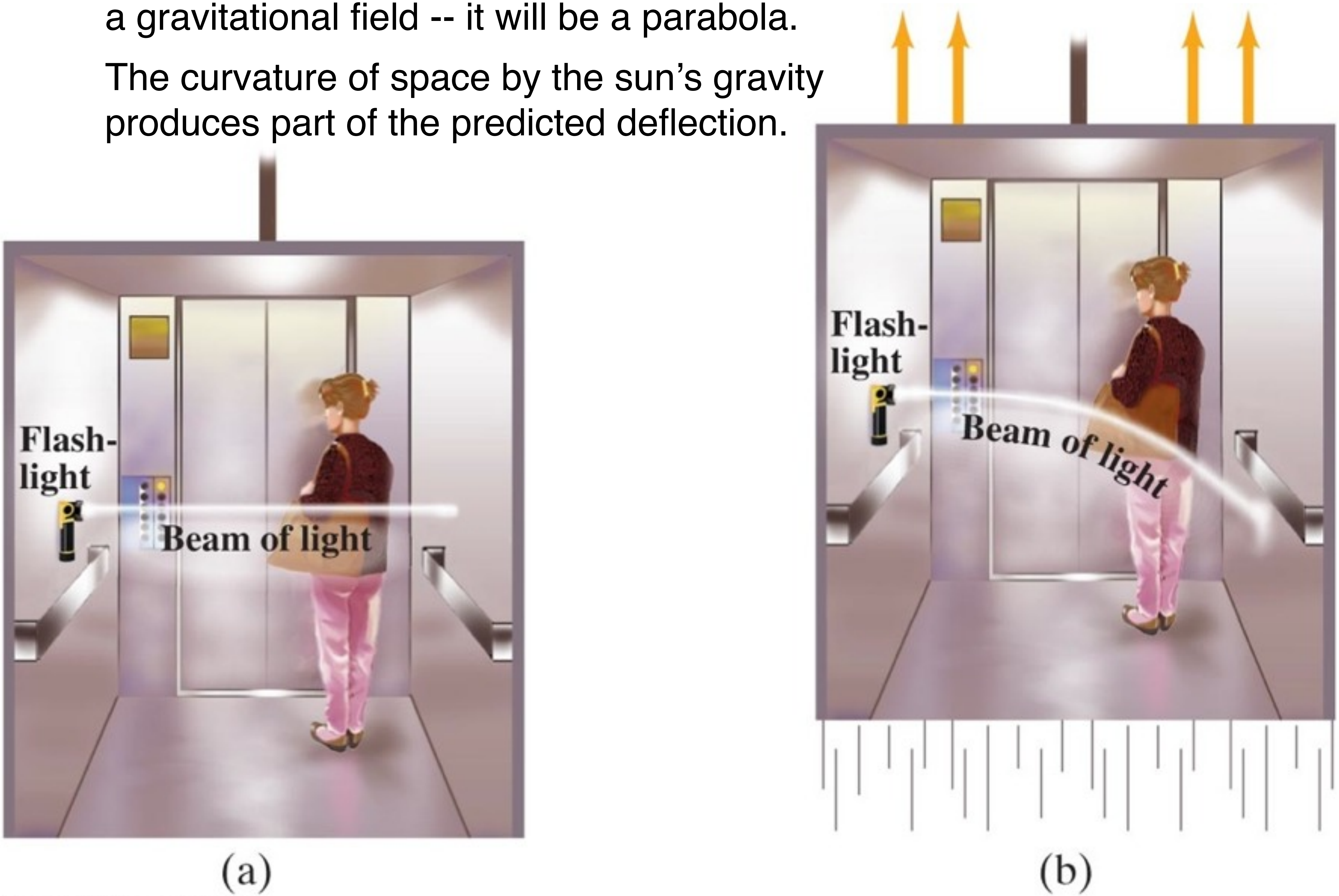
COSMOLOGICAL CONSTANT

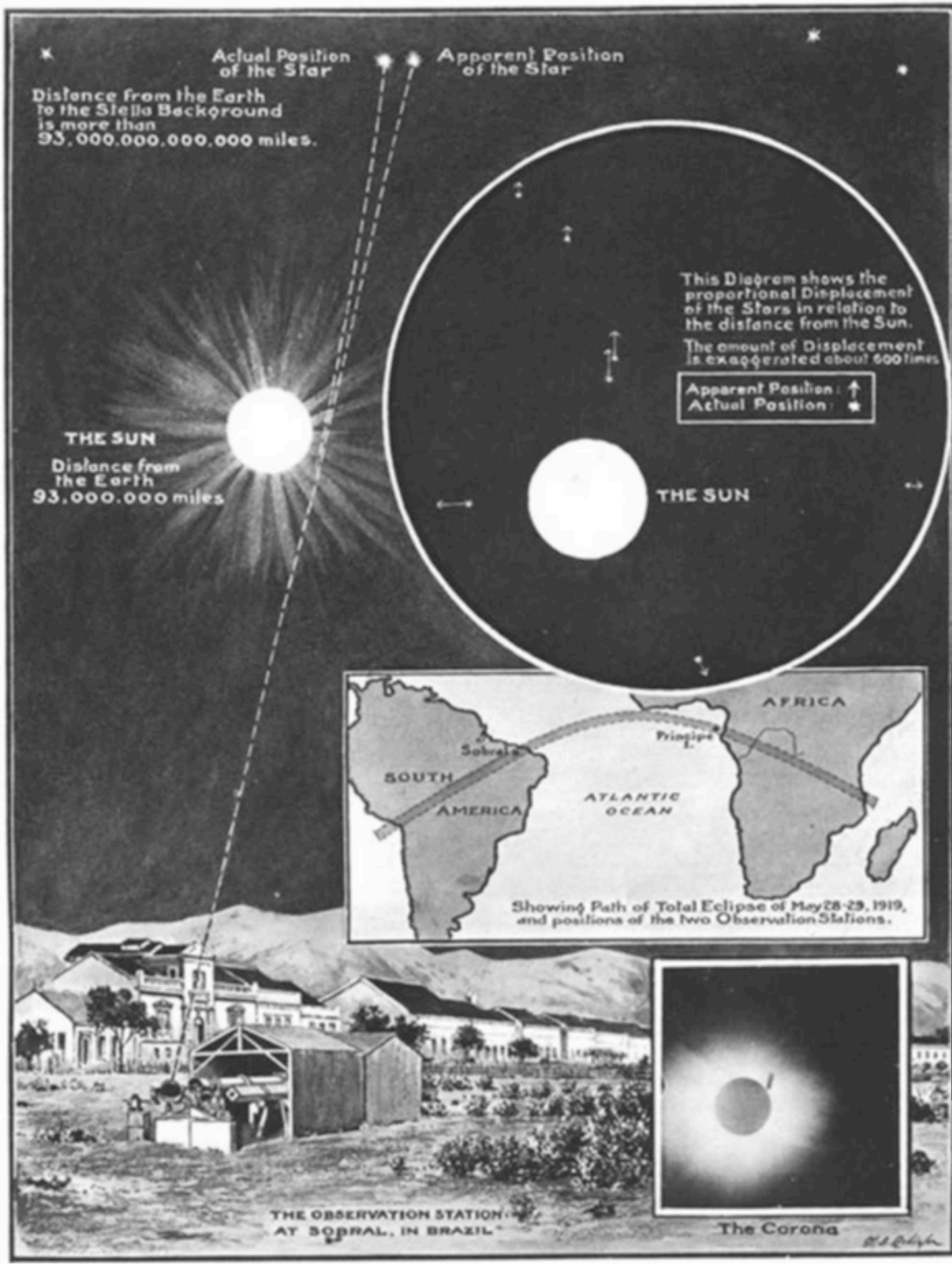
Curved space-time is not just an arena in which things move, it is dynamic. Curvature can cause horizons, beyond which information cannot be sent.

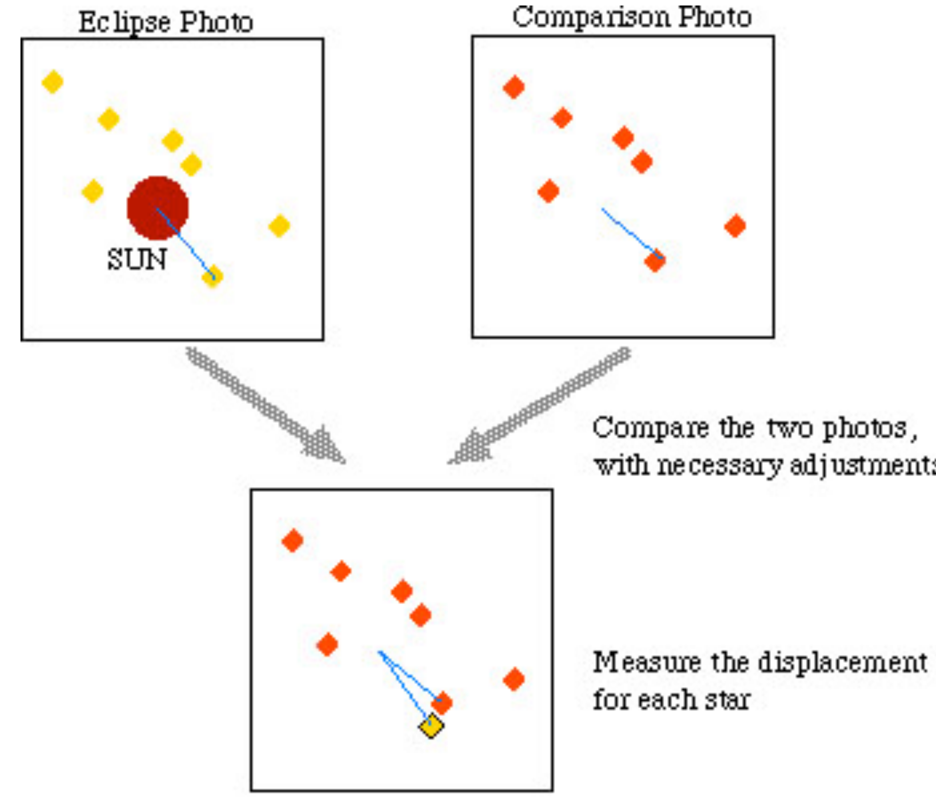
Equivalence Principle:
All the effects of gravity on small scales are the same as those of acceleration.

This predicts the path of a beam of light in a gravitational field -- it will be a parabola.

The curvature of space by the sun's gravity produces part of the predicted deflection.







Arthur Stanley Eddington

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

Outline of Black Holes slides

- Black Holes
  - Schwarzschild Radius, Photon Sphere, etc.
  - Hawking Radiation (a quantum effect)
- Planck Length – Gravitation Meets Quantum Physics
- Black Holes from Stellar Collapse
- Black Hole at the Center of Our Galaxy
- Black Holes at the Centers of Galaxies
- Intermediate Mass Black Holes?
- Evaporating Black Holes?

EFFECTS OF CURVATURE NEAR A BLACK HOLE

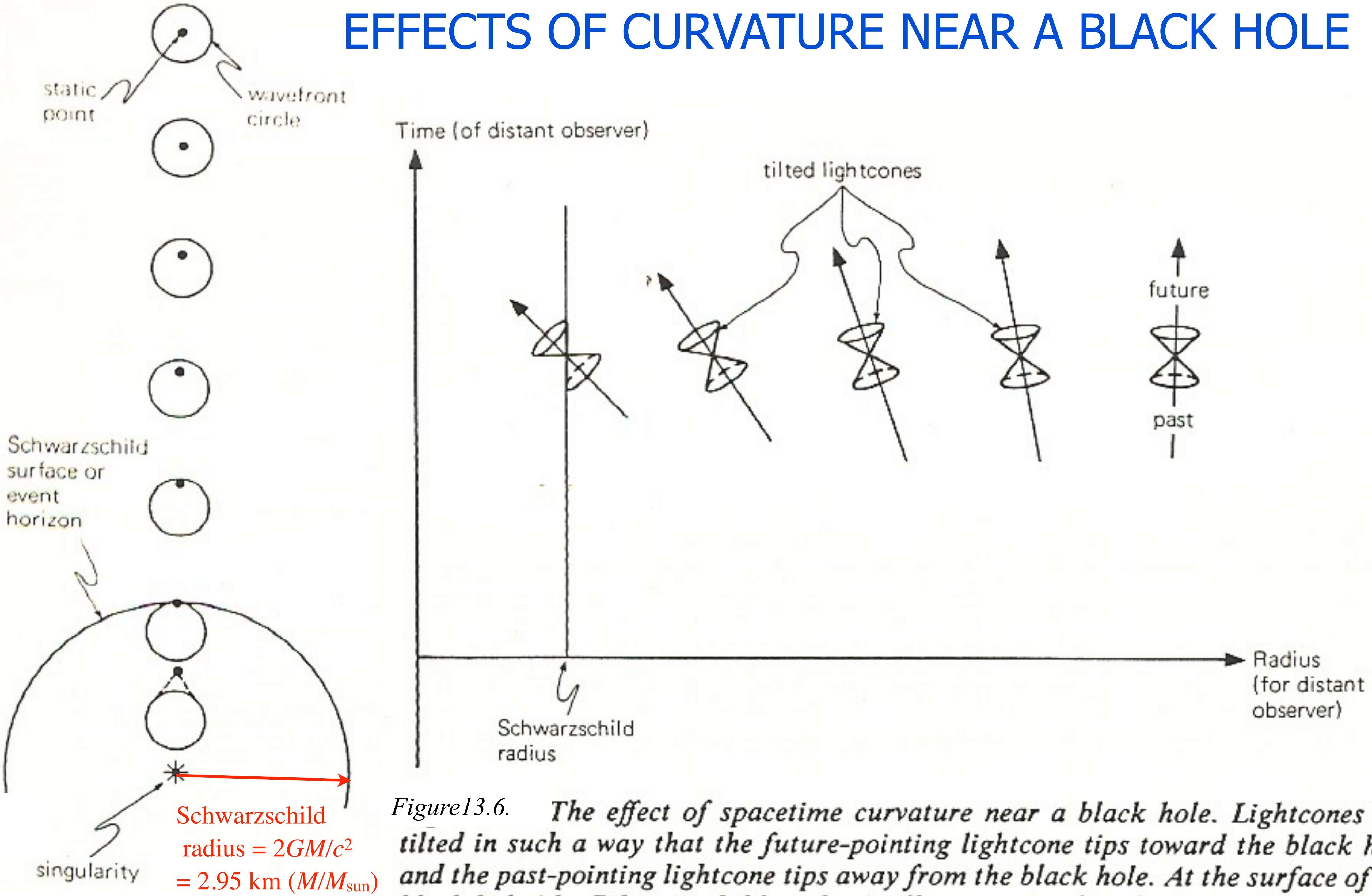
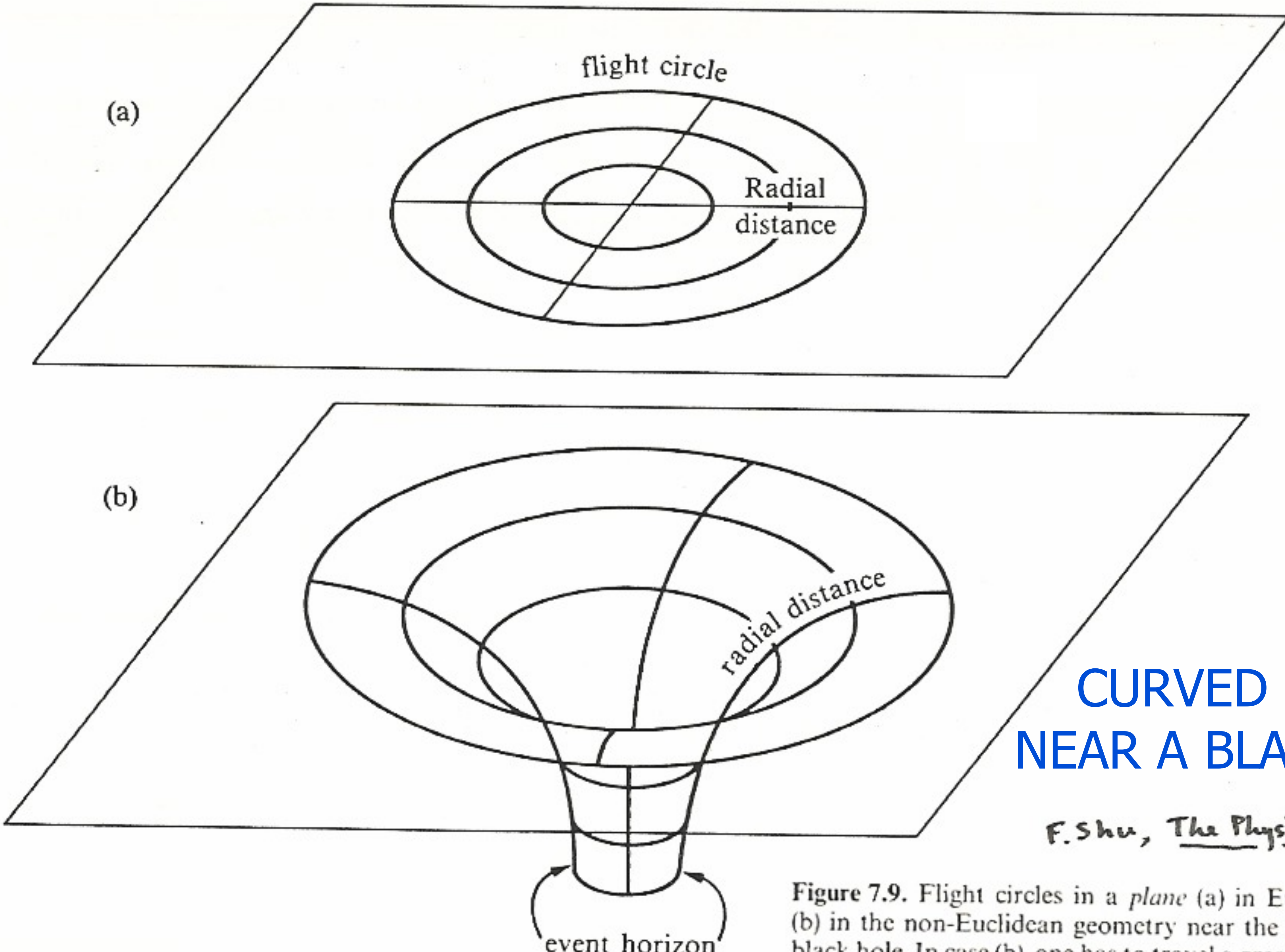


Figure13.6. The effect of spacetime curvature near a black hole. Lightcones are tilted in such a way that the future-pointing lightcone tips toward the black hole and the past-pointing lightcone tips away from the black hole. At the surface of the black hole (the Schwarzschild surface), all rays emitted in the future direction fall into the black hole, and no rays from the past are received from the black hole. A person passing into a black hole therefore receives no information of what lies ahead.

E. Harrison, Cosmology

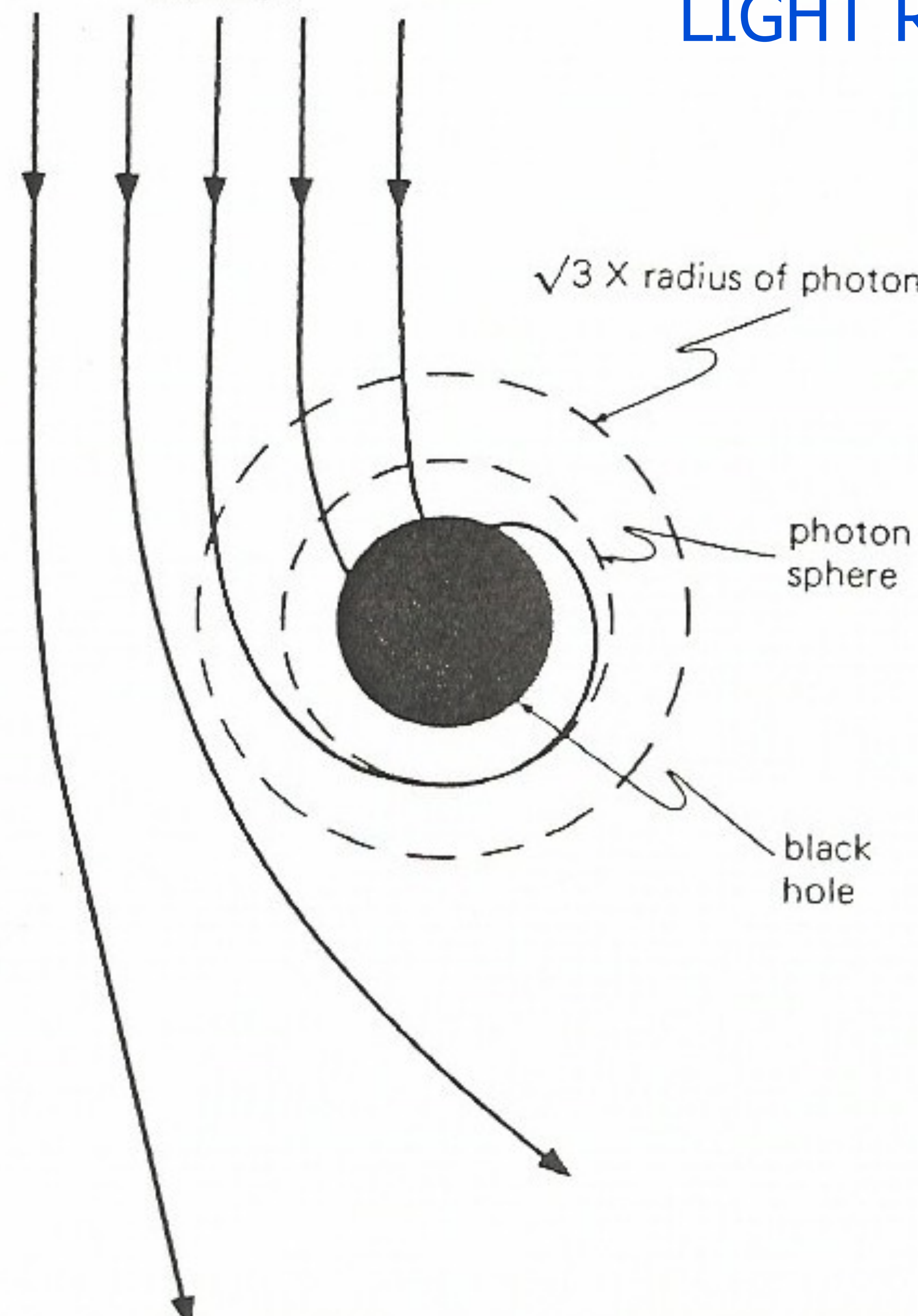


CURVED SPACE NEAR A BLACK HOLE

F. Shu, The Physical Universe

Figure 7.9. Flight circles in a *plane* (a) in Euclidean geometry, (b) in the non-Euclidean geometry near the event horizon of a black hole. In case (b), one has to travel a greater distance inward than in case (a) to have a flight circle of given smaller circumference. The radial direction in both cases is as indicated. At great distances from the event horizon (not drawn), the "curvature" of our embedding diagram becomes negligibly small, and the flight circles of case (b) have nearly the same geometry as case (a).

LIGHT RAYS NEAR A BLACK HOLE



. *Deflection of lightrays by a black hole. Rays approaching closer than √3 times the radius of the photon sphere are captured.*

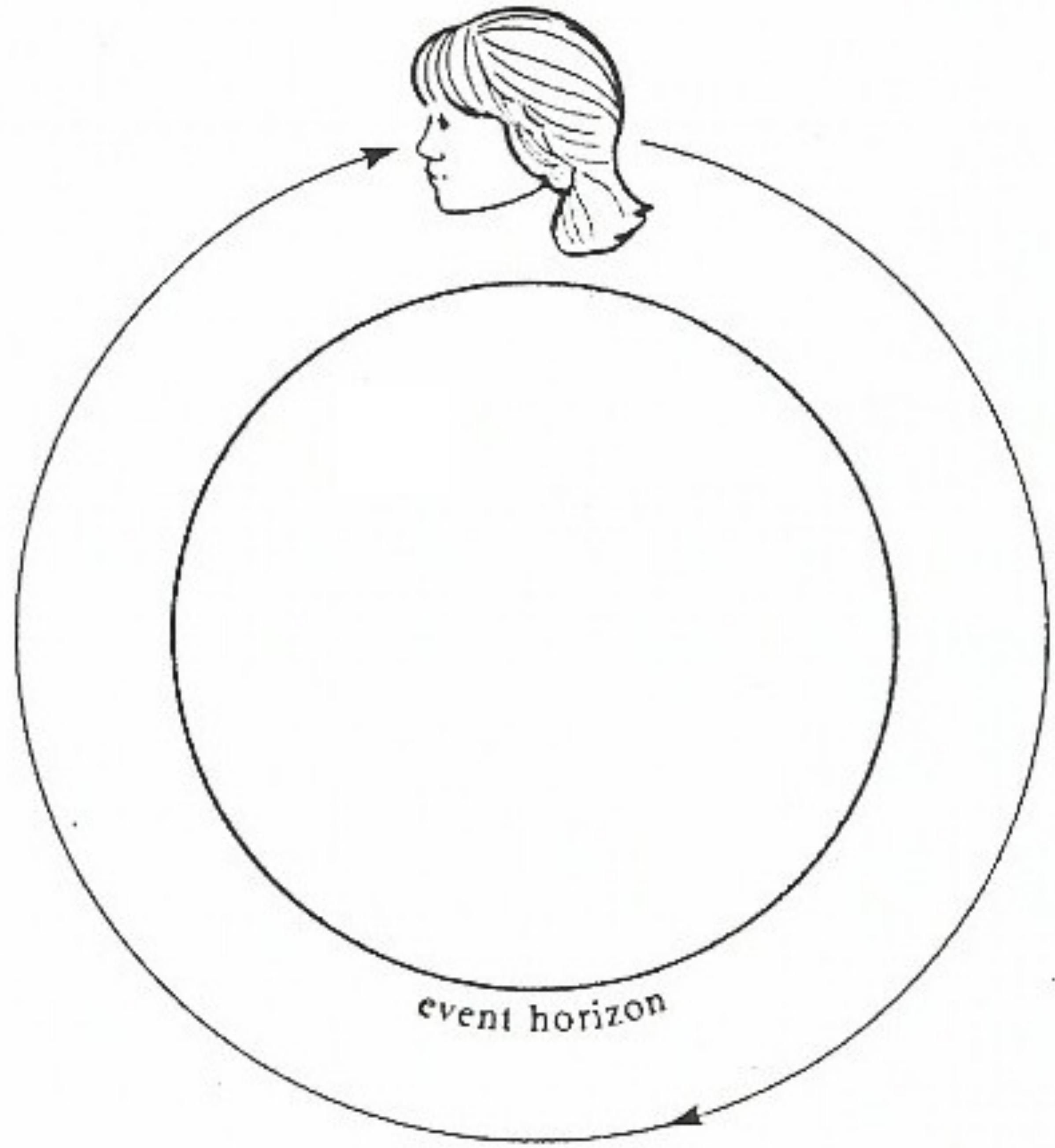
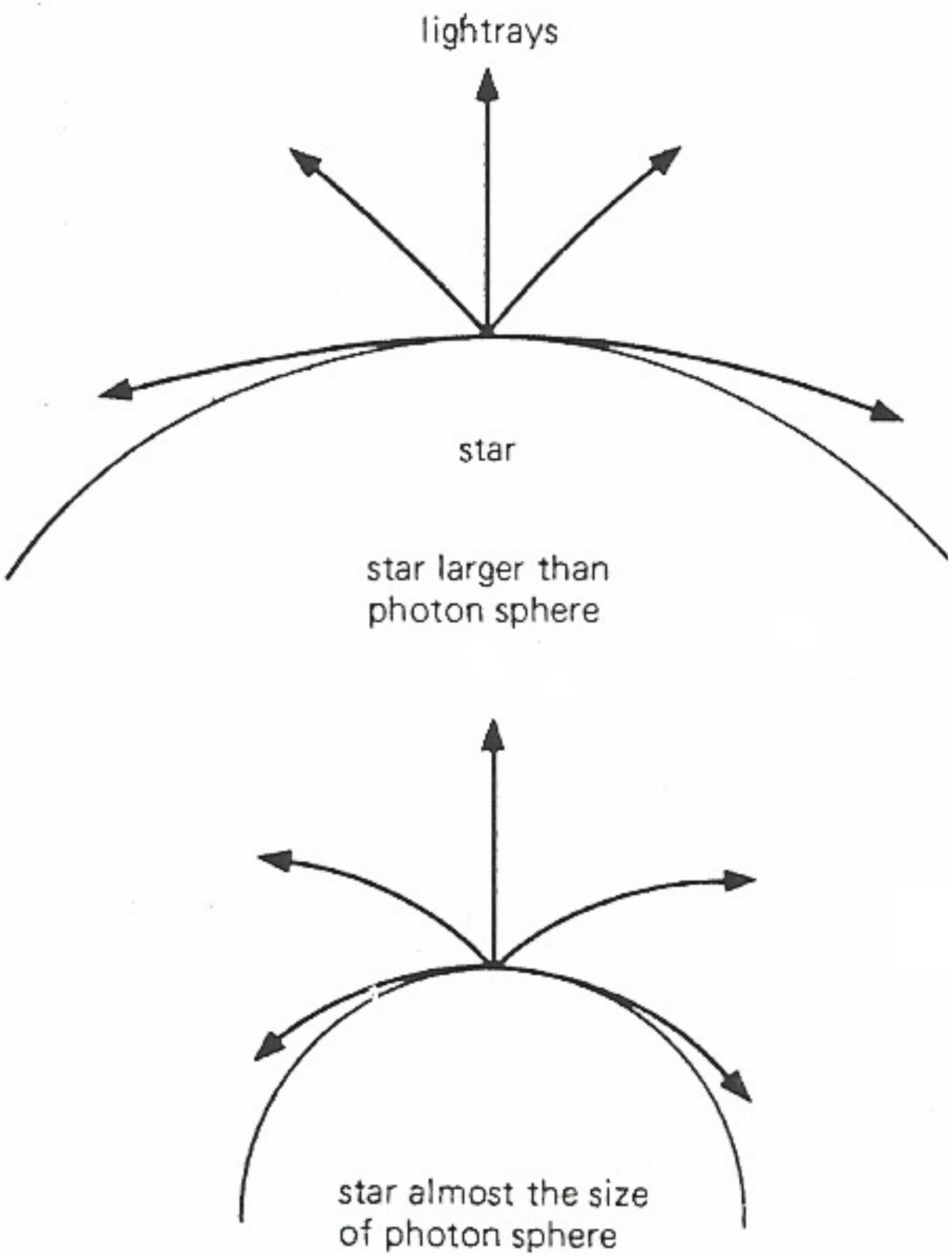
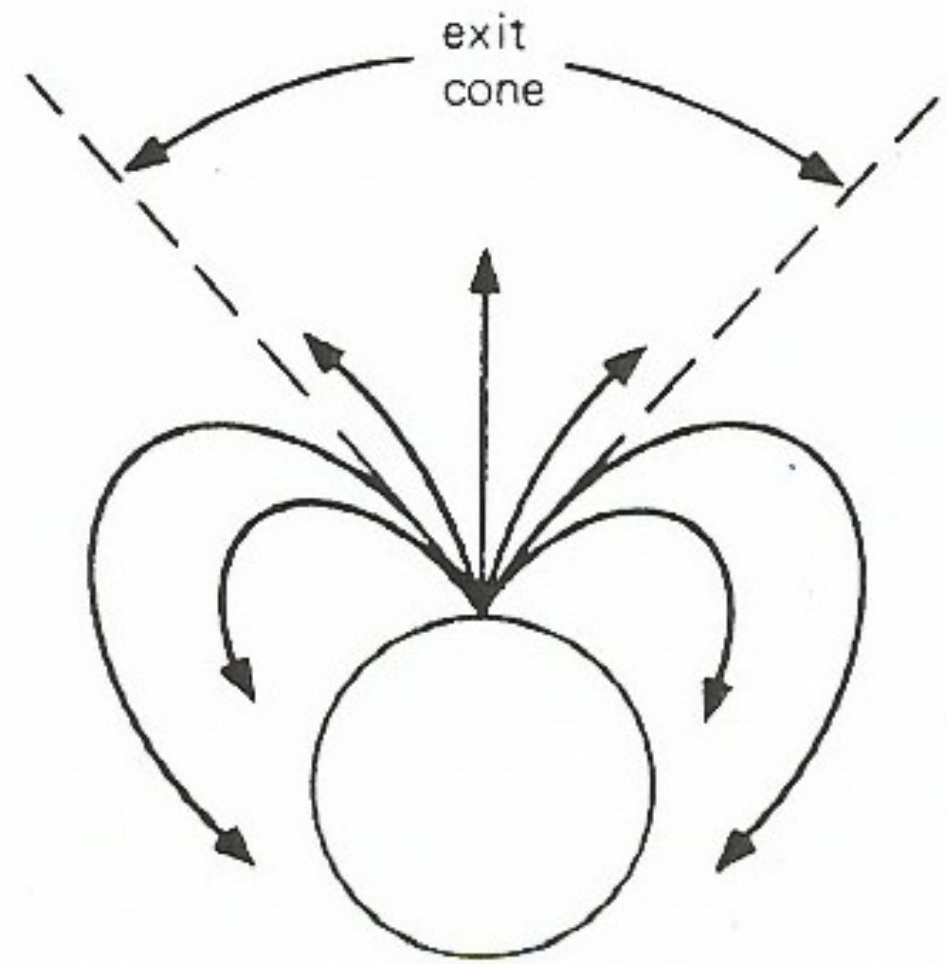


Figure 7.10. When at a circumference equal to 1.5 times the circumference of the event horizon of a black hole, a suitably suspended astronaut can see the back of her own head without the benefit of any mirrors.

E. R. Harrison, *Cosmology*

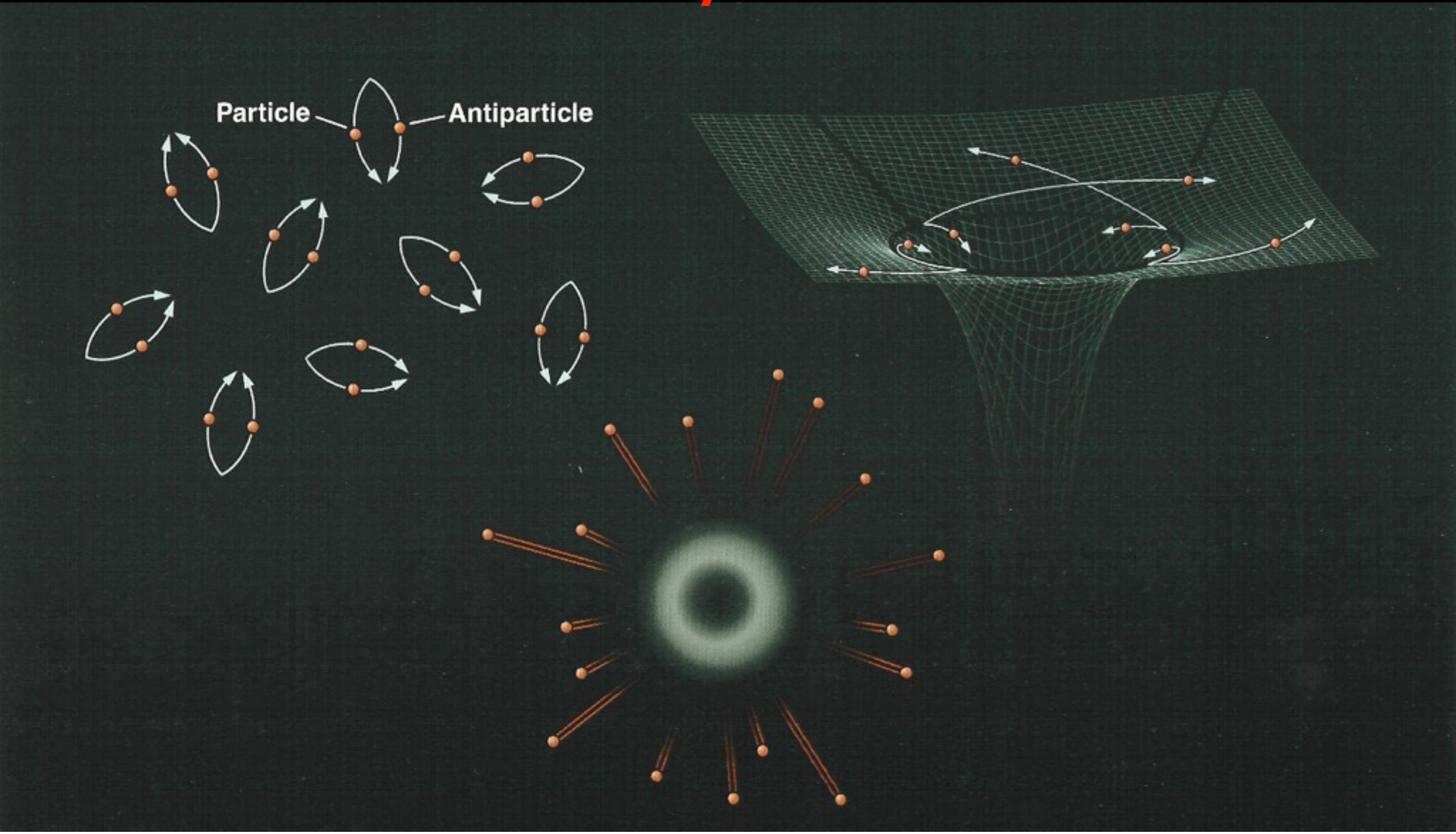




Lightrays leaving a gravitating body are curved as shown. As the body shrinks in size the rays become more curved. When the radius is less than 1.5 times the Schwarzschild radius, which is the radius of the photon sphere, the exit cone begins to close. Rays emitted within the exit cone escape, but those outside are trapped and fall back.

E. R. Harrison, *Cosmology*

HAWKING RADIATION from tiny black holes



HAWKING RADIATION

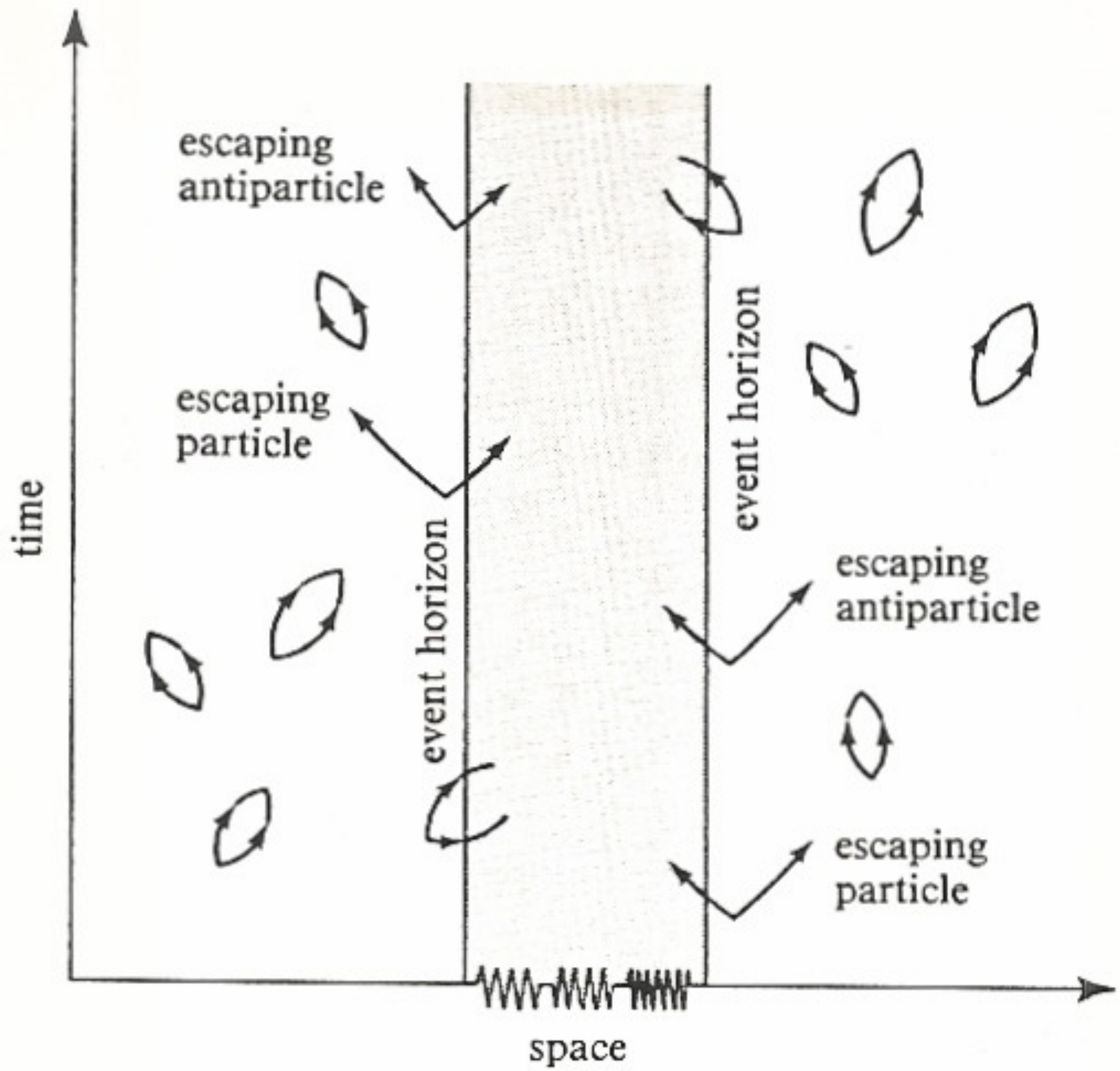
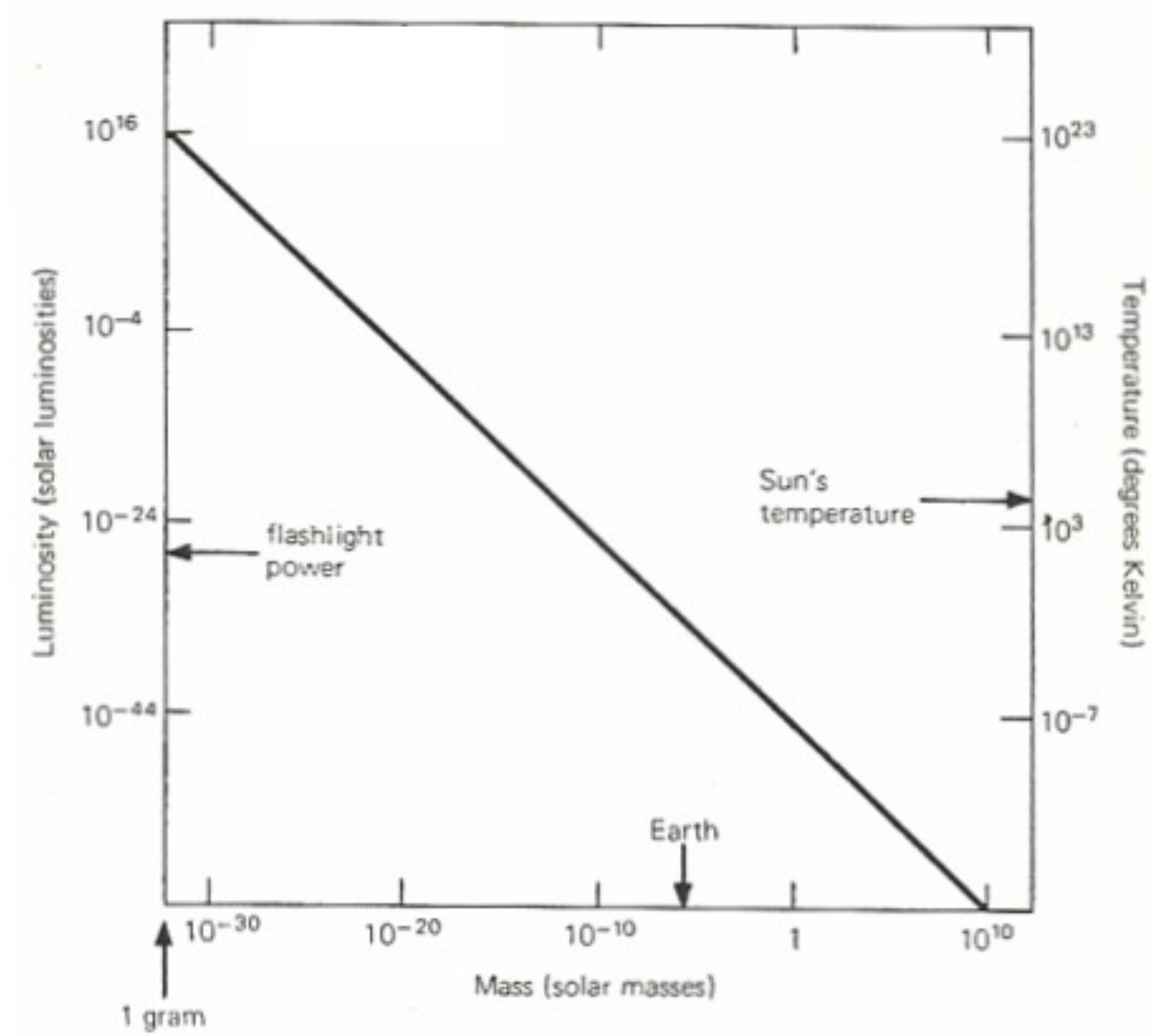


Figure 7.13. Hawking process near the event horizon of a black hole. The creation of particle-antiparticle pairs usually ends with their destruction a short time later. Occasionally, however, the tidal forces of the black hole can cause one of the pair to fall into the black hole, enabling its liberated partner to "tunnel" safely to infinity and escape. Notice the assumption that the black hole is (quasi) stationary implies that the two sides of the event horizon remain fixed in space. Actually, this diagram is even more schematic than usual, because the actual spacetime near a black hole is highly curved.

F. Shu, *The Physical Universe*



. Luminosity and temperature of a black hole of given mass.

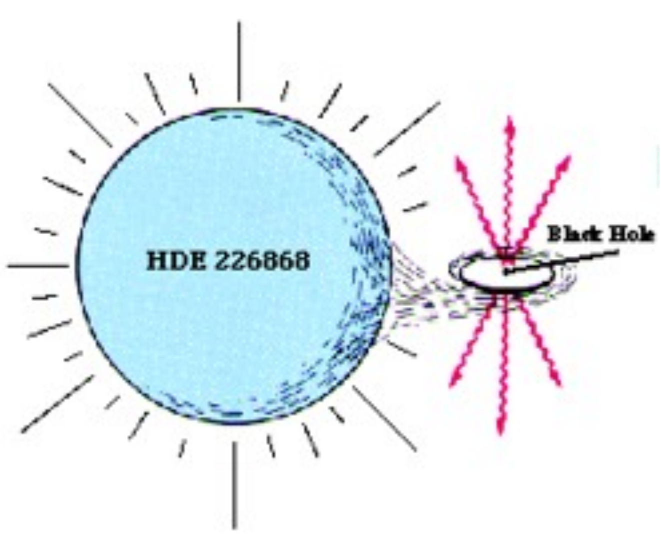
E. R. Harrison, *Cosmology*

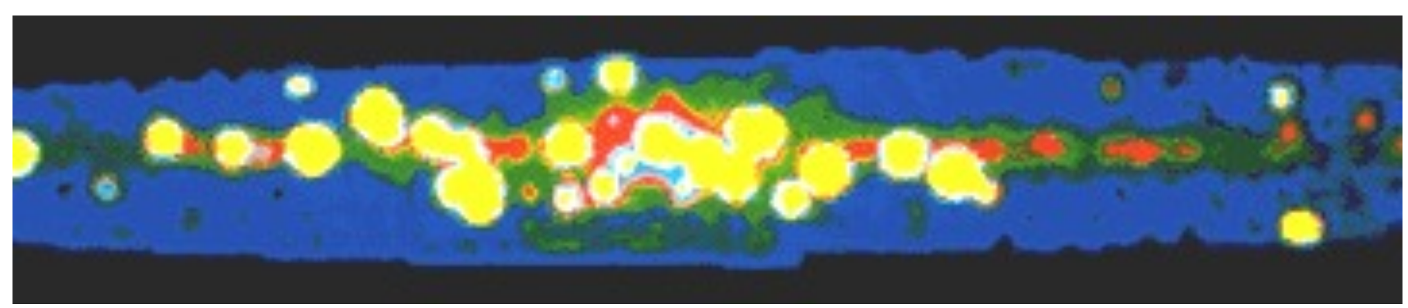
$$T_{BH} = 10^{-7}\ M_{sun}/M$$

$$T_{evap} = 10^{62}\ (M_{sun}/M)^3\ \text{yr}$$

BLACK HOLES FROM STELLAR COLLAPSE

If a large number of stars form, about 10% of the mass turns into a small number of stars more massive than 8 solar masses. Such high mass stars are ~100,000 times as bright as the sun, and they fuse all the available fuel in their centers within a few million years, as we discussed in Lecture 2. They then collapse into either neutron stars or black holes. If the black hole is a member of a binary star system, we can see its effects. Sometimes the black hole attracts matter to it from the other star, and as this matter (mostly hydrogen) falls into the black hole's event horizon it is heated tremendously and it radiates X-rays, which we can detect. One of these binary systems, called GRO J1655-40, was discovered in 2002 to be moving roughly toward us at about 110 kilometers per second. Such accreting black holes acquire angular momentum from the accreted material, so they should be spinning. Evidence that some black holes spin has been found in "quasi-periodic oscillations" of their X-rays at frequencies too high to come from non-spinning black holes.





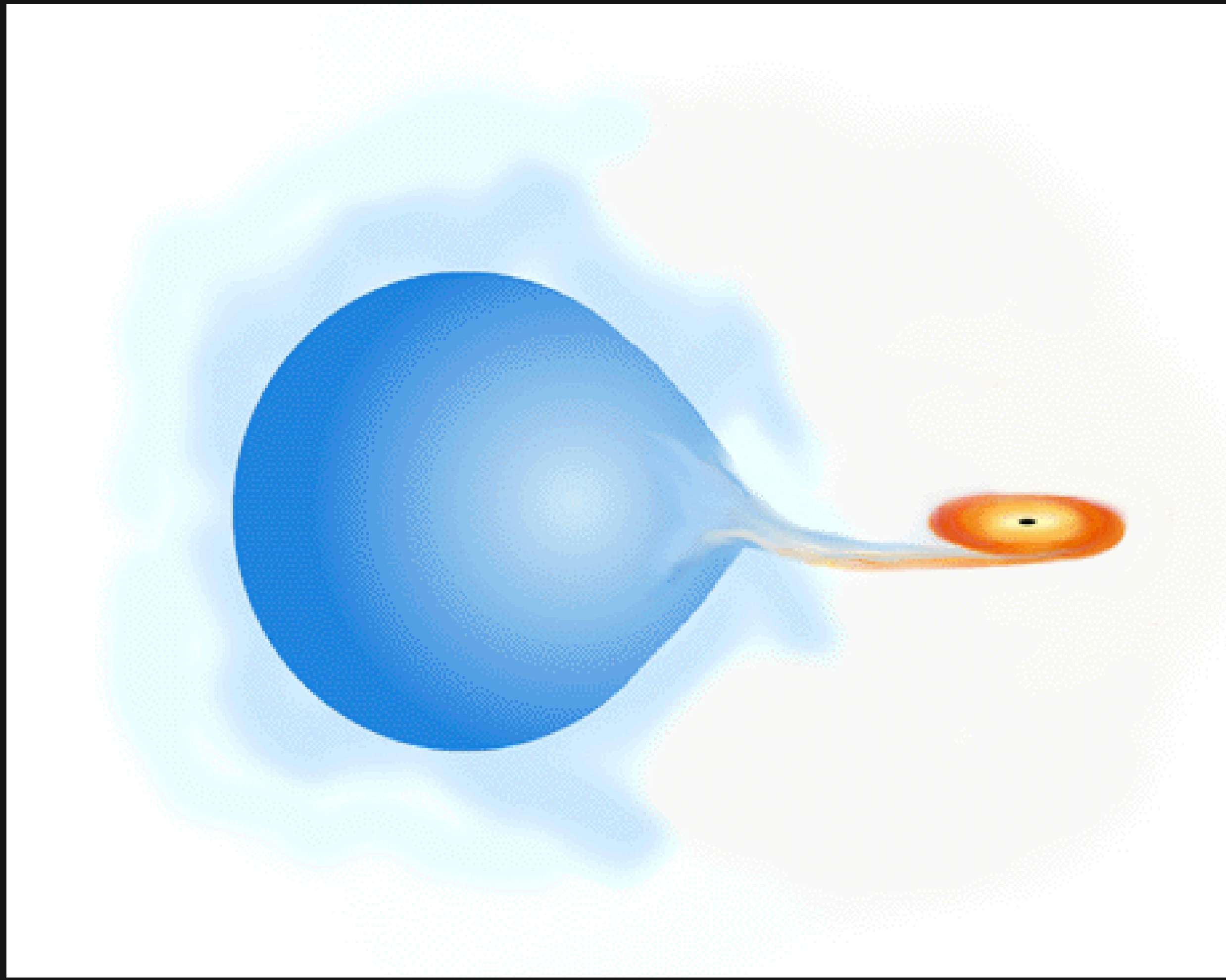
X-ray Binaries (in yellow) near the Galactic Center

Interesting links: Fantasy trip to and around a black hole - http://antwrp.gsfc.nasa.gov/htmltest/rjn_bht.html
See also http://ircamera.as.arizona.edu/NatSci102/lectures/blackhole.htm

BLACK HOLES FROM STELLAR COLLAPSE

Black Holes in Binary Star Systems

- Black holes are often part of a binary star system - two stars revolving around each other.
- What we see from Earth is a visible star orbiting around what appears to be nothing.
- We can infer the mass of the black hole by the way the visible star is orbiting around it.
- The larger the black hole, the greater the gravitational pull, and the greater the effect on the visible star.

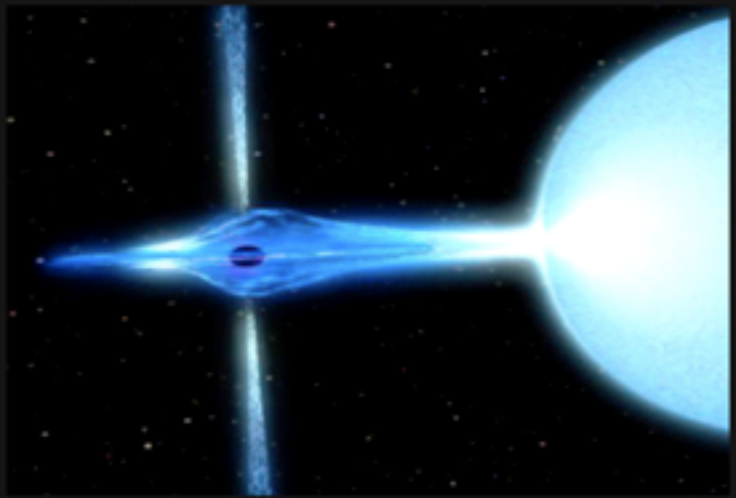


Chandra illustration

BLACK HOLES FROM STELLAR COLLAPSE

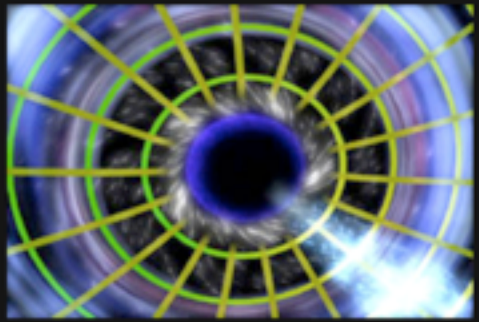
X-rays from Black Holes

In close binary systems, material flows from normal star to black hole. X-rays are emitted from disk of hot gas swirling around the black hole.

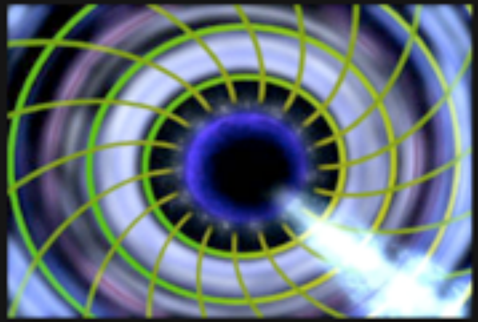


X-ray: A Rotating Black Hole

We expect everything in the Universe to rotate. Non-rotating black holes are different from rotating ones.



Non-rotating black hole

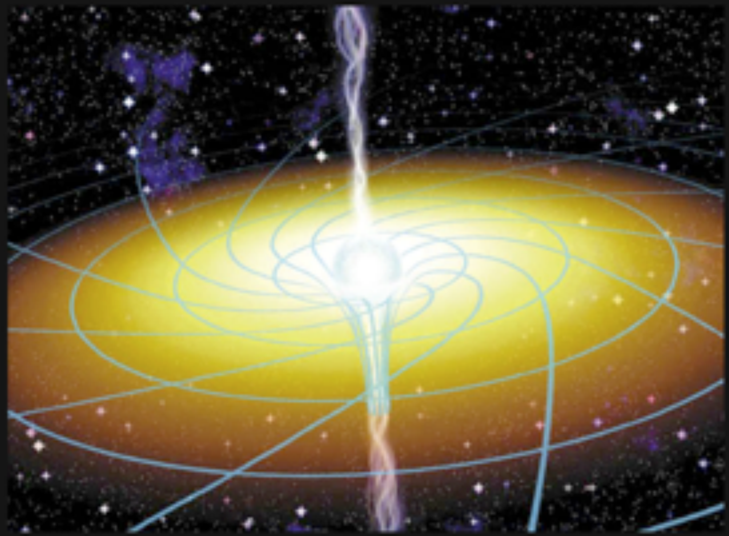


Rotating black hole

In GRO J1655-40, a 2.2 ms period was discovered. This implies an orbit that is too small to be around a non-rotating black hole. This means the black hole is rotating.

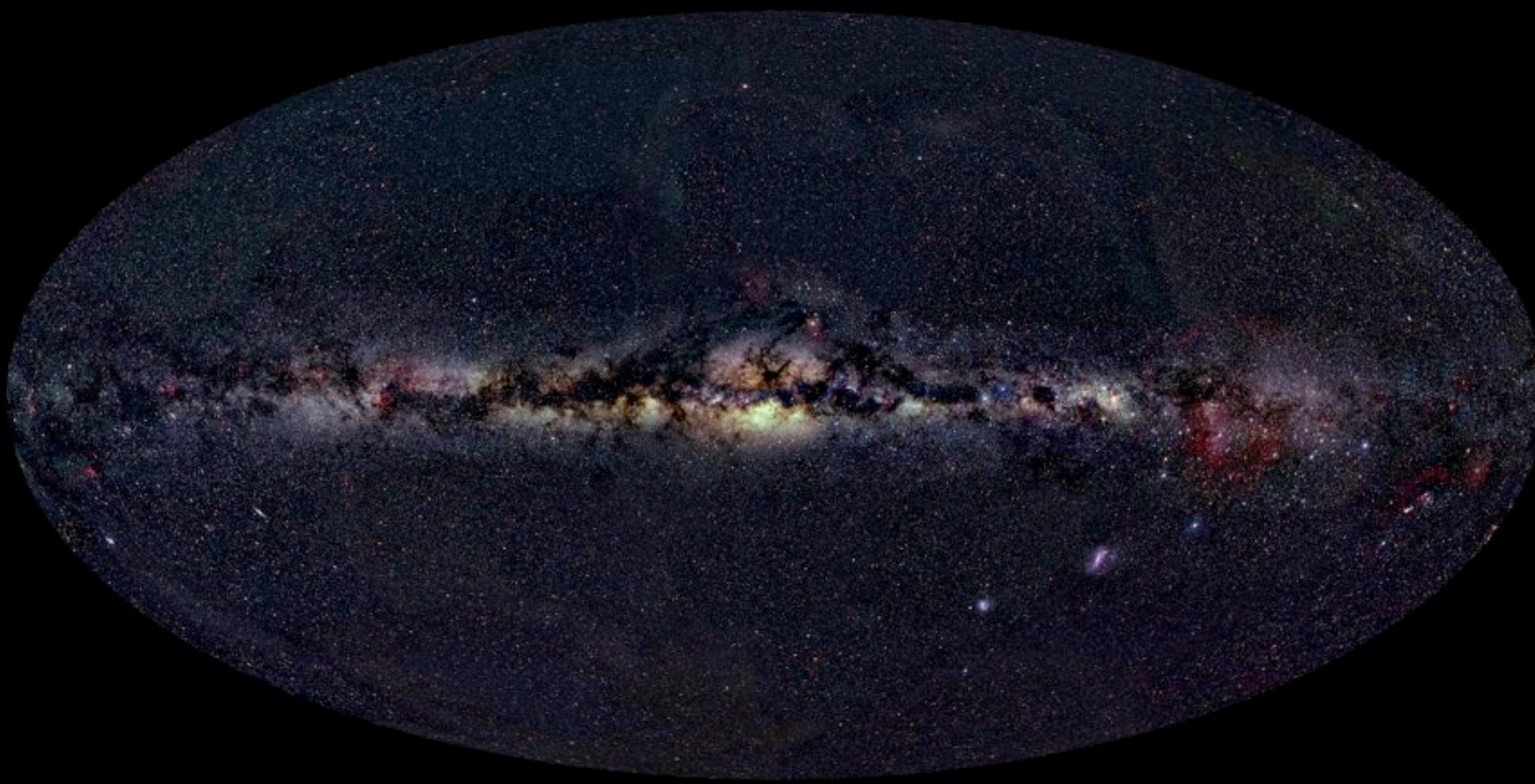
X-ray: Frame Dragging

- Detection of a period in GRO J1655-40 due to precession of the disk.
- This precession period matches that expected for frame dragging of space-time around the black hole.



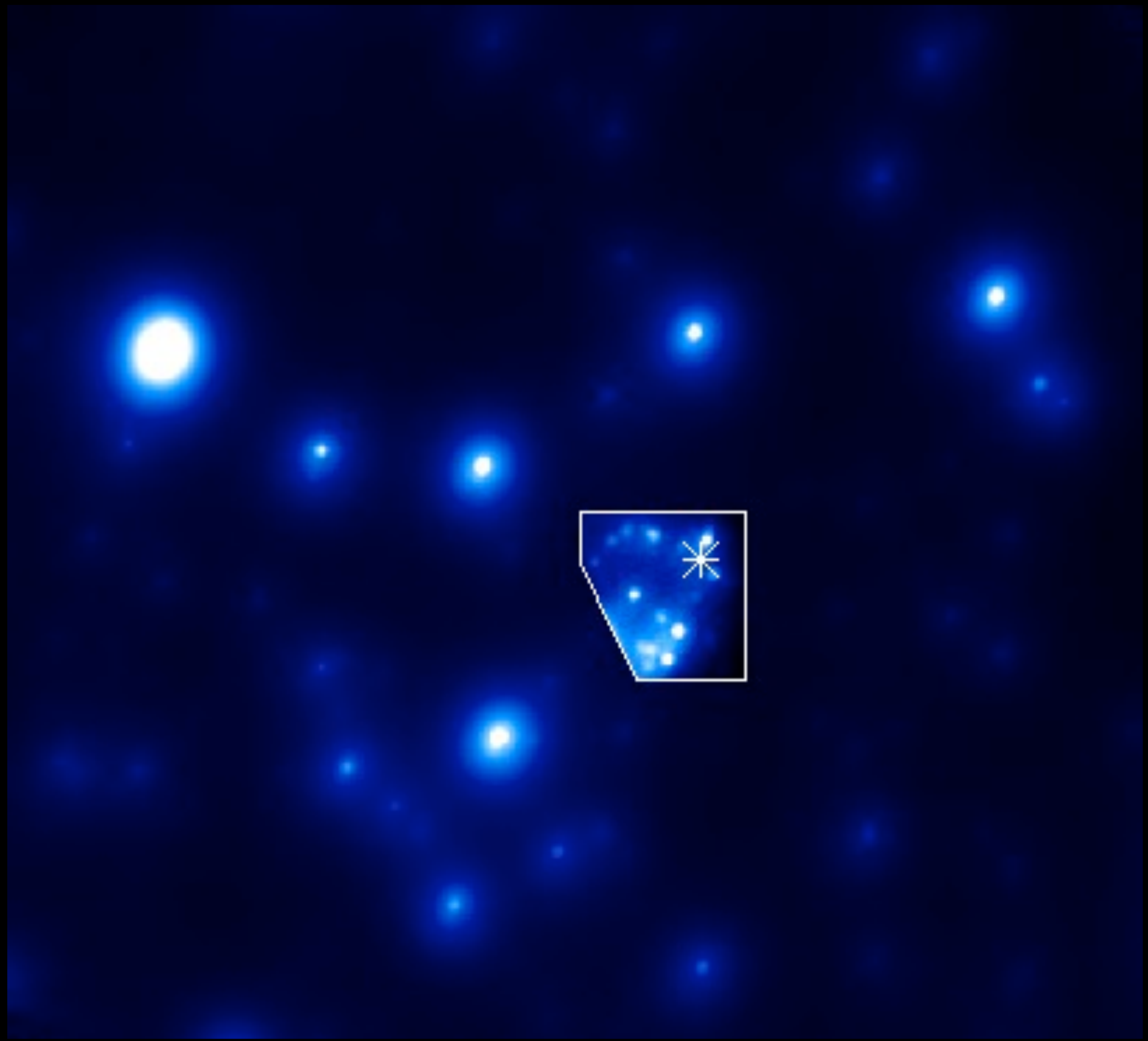
Credit: J. Bergeron, Sky & Telescope Magazine

The center of our galaxy



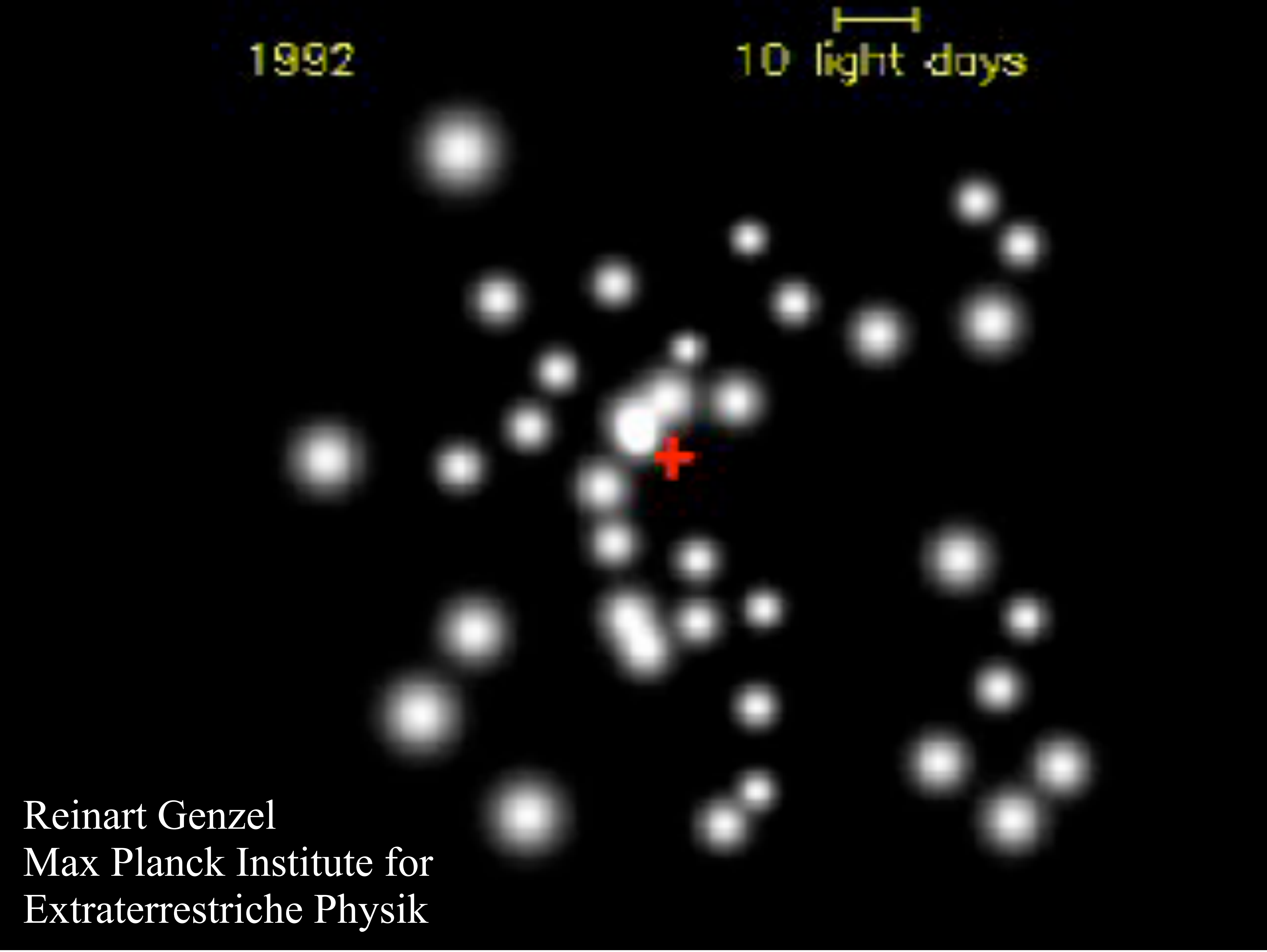
There's a supermassive black hole at the center of our galaxy…

- Modern large telescopes can track individual stars at galactic center
  - Need infrared (to penetrate dust).
  - Need very good resolution.
- and have been observing for past 10 years…

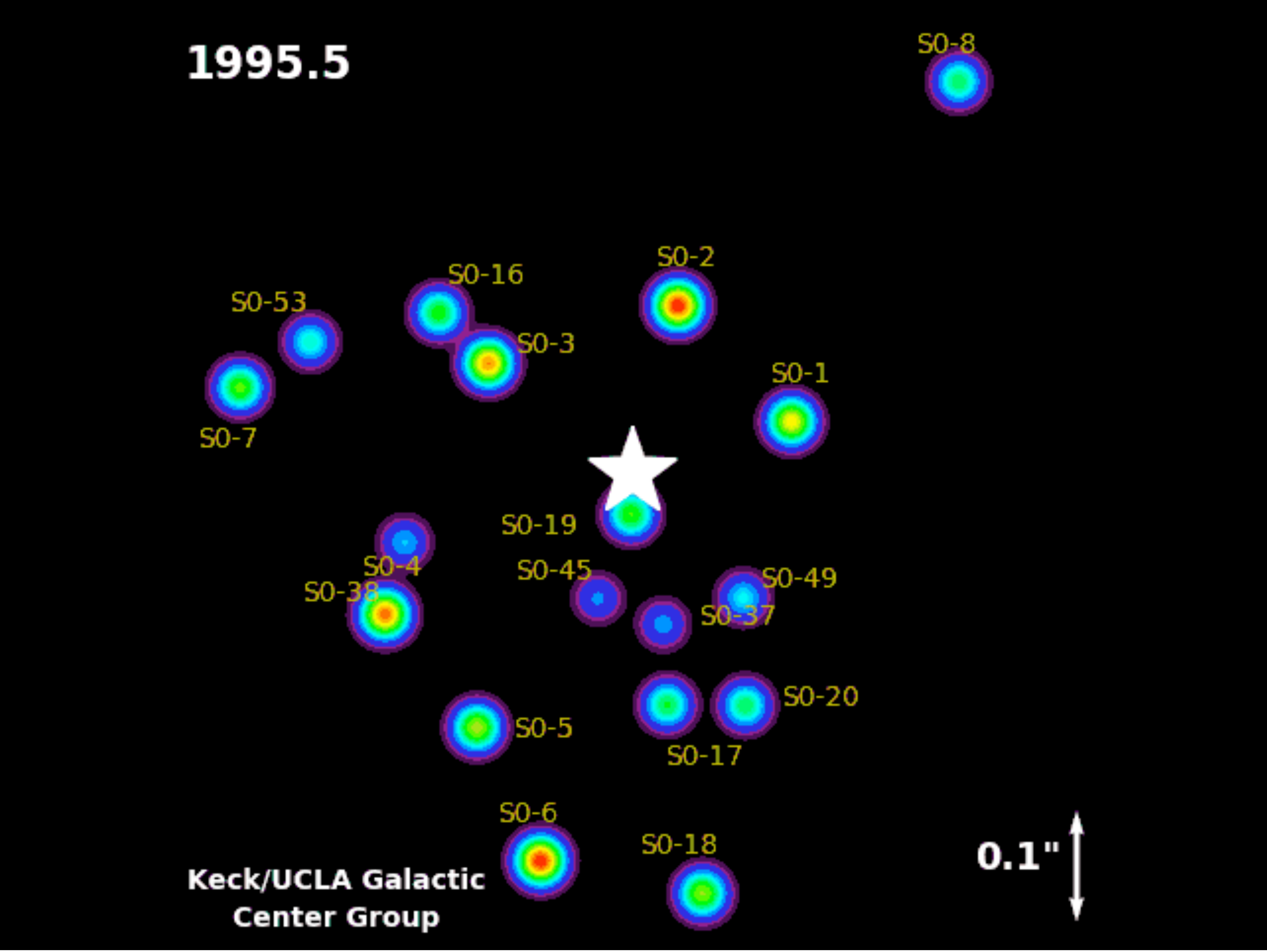


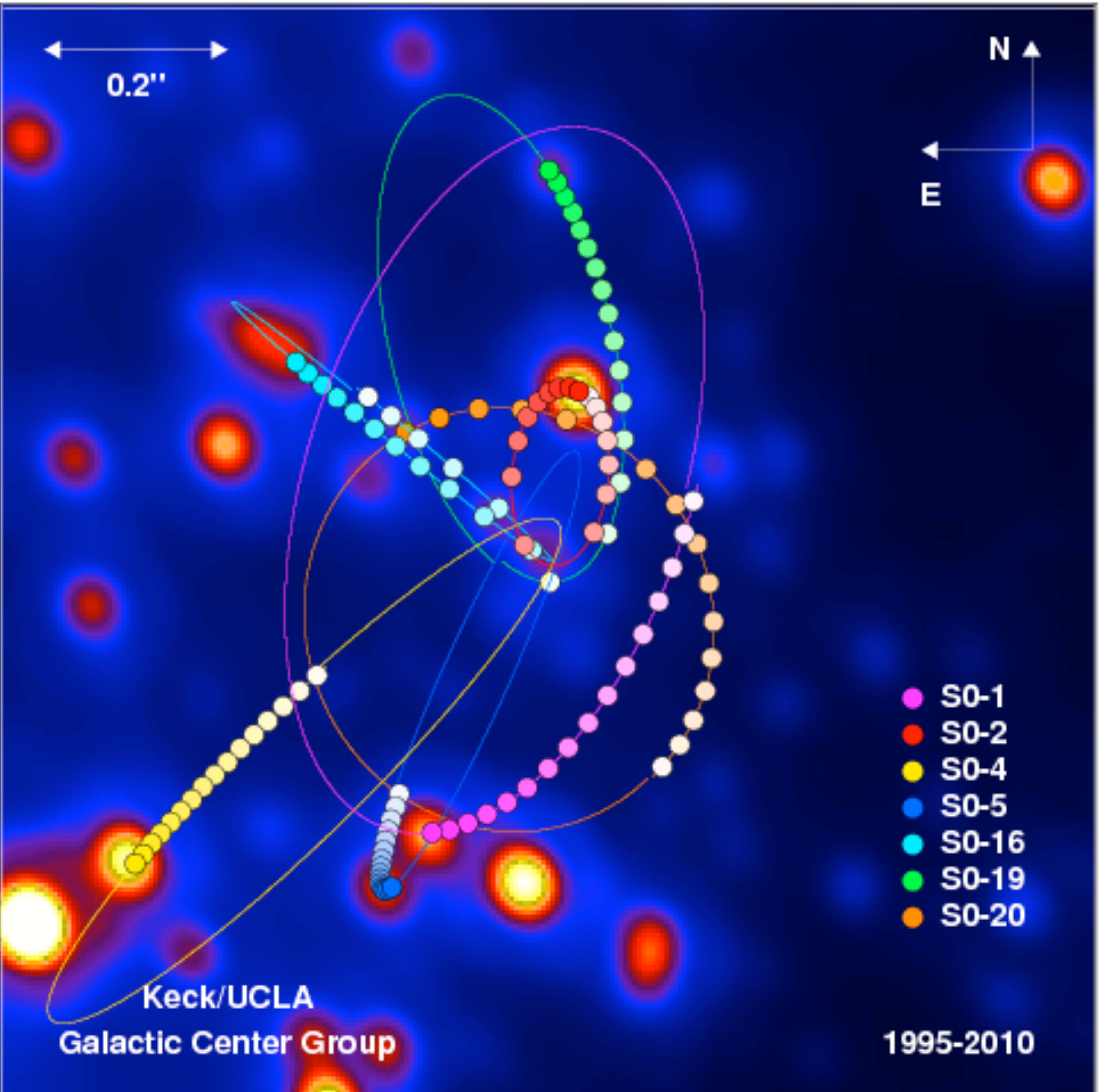
Keck, 2 μm

Ghez, et al.



Reinart Genzel
Max Planck Institute for
Extraterrestriche Physik

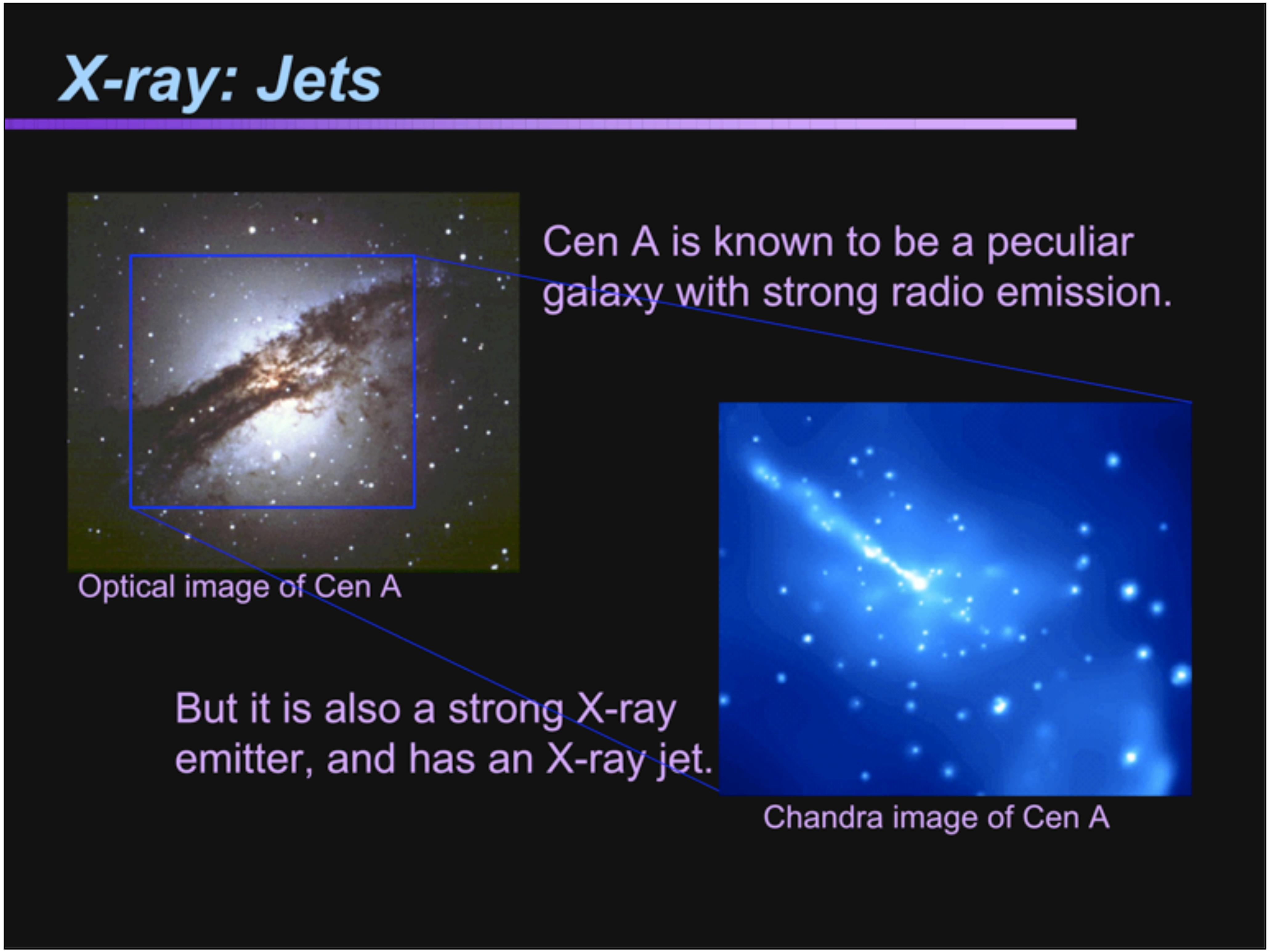

1995.5
S0-8
S0-16
S0-2
S0-53
S0-3
S0-1
S0-7
S0-19
S0-4
S0-45
S0-49
S0-38
S0-37
S0-20
S0-5
S0-17
S0-6
S0-18
Keck/UCLA Galactic Center Group
0.1"



A 2.2 micron animation of the stellar orbits in the central parsec. Images taken from the years 1995 through 2010 are used to track specific stars orbiting the proposed black hole at the center of the Galaxy. These orbits, and a simple application of Kepler's Laws, provide the best evidence yet for a supermassive black hole, which has a mass of 4 million times the mass of the Sun. Especially important are the stars S0-2, which has an orbital period of only 15.78 years, and S0-16, which comes a mere 90 astronomical units from the black hole.

- The central object at the center of the Milky Way is…
  - Very dark – but now seen to flare in X-rays and IR.
  - Very massive (~4 million solar masses).
  - Must be very compact (star S0-2 gets within 17 light hours of the center).
- Currently the best case for any supermassive black hole.

BLACK HOLES AT CENTERS OF GALAXIES



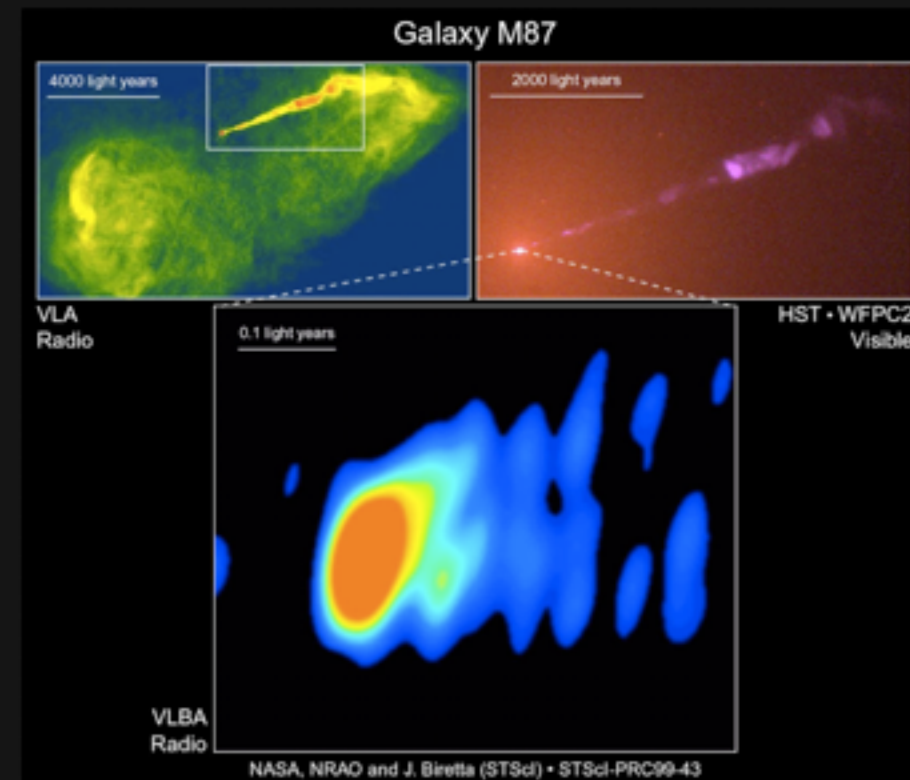
The mass of the black holes is about 1/1000 the mass of the central spheroids of stars.

BLACK HOLES AT CENTERS OF GALAXIES

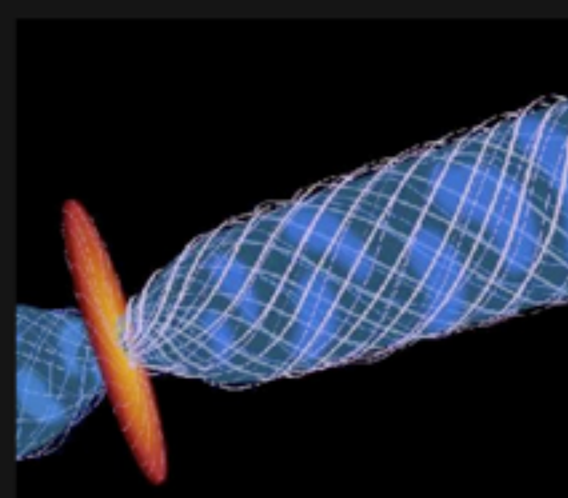
M87 - An Elliptical Galaxy

With a curious feature

Radio shows the origin of the Jet

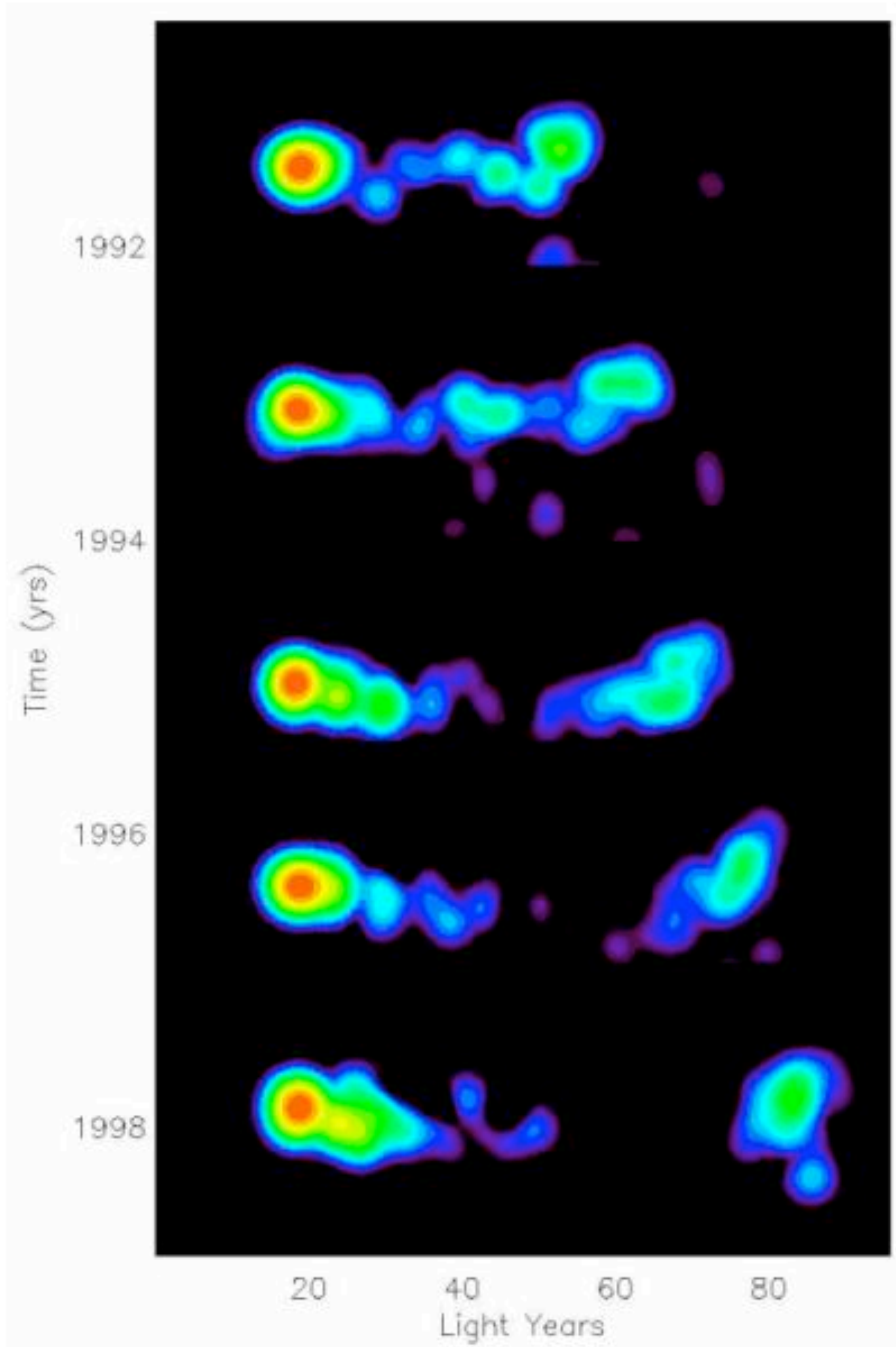


Our picture of what's happening



Magnetic field from surrounding disk funnels material into the jet

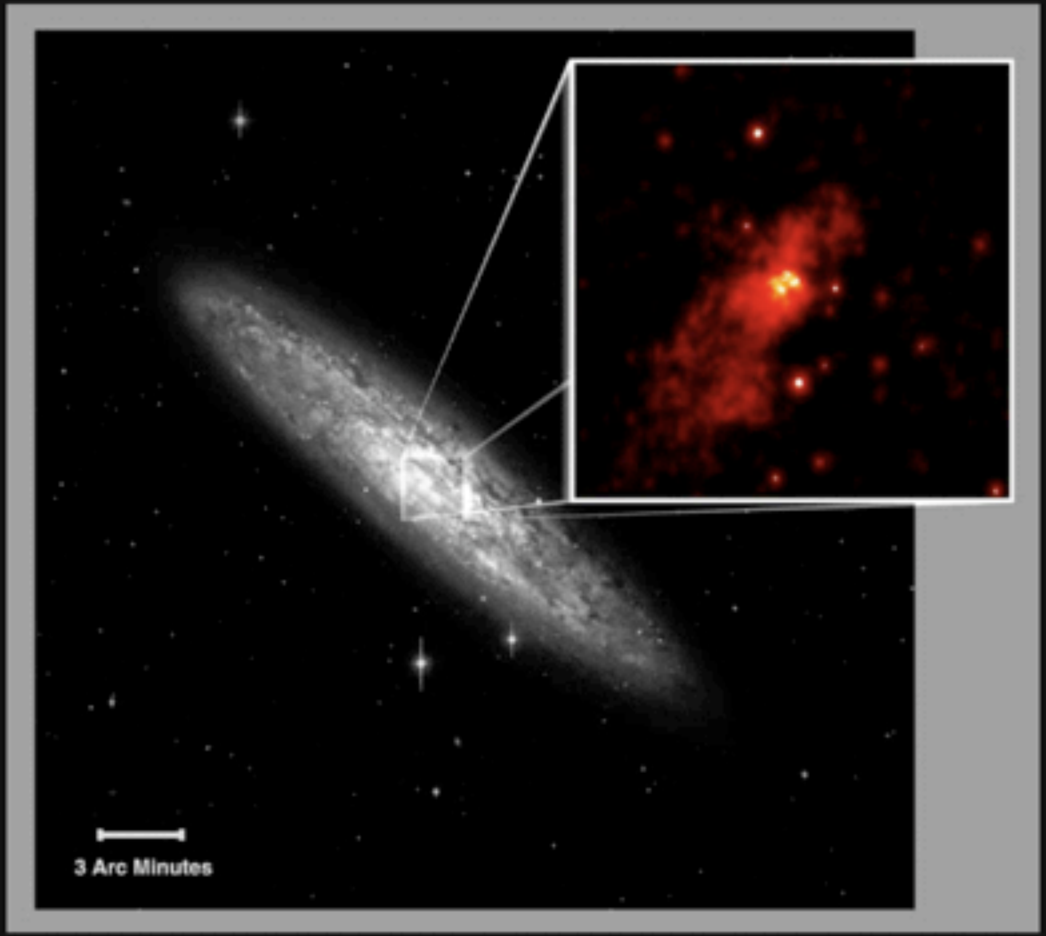
Apparently superluminal motion of the radio components in the quasar 3C 279. The bright component at the left is taken to be the fixed radio core, and the bright spot at the right appears to have moved 25 light years on the plane of the sky between 1991 and 1998.



INTERMEDIATE MASS BLACK HOLES

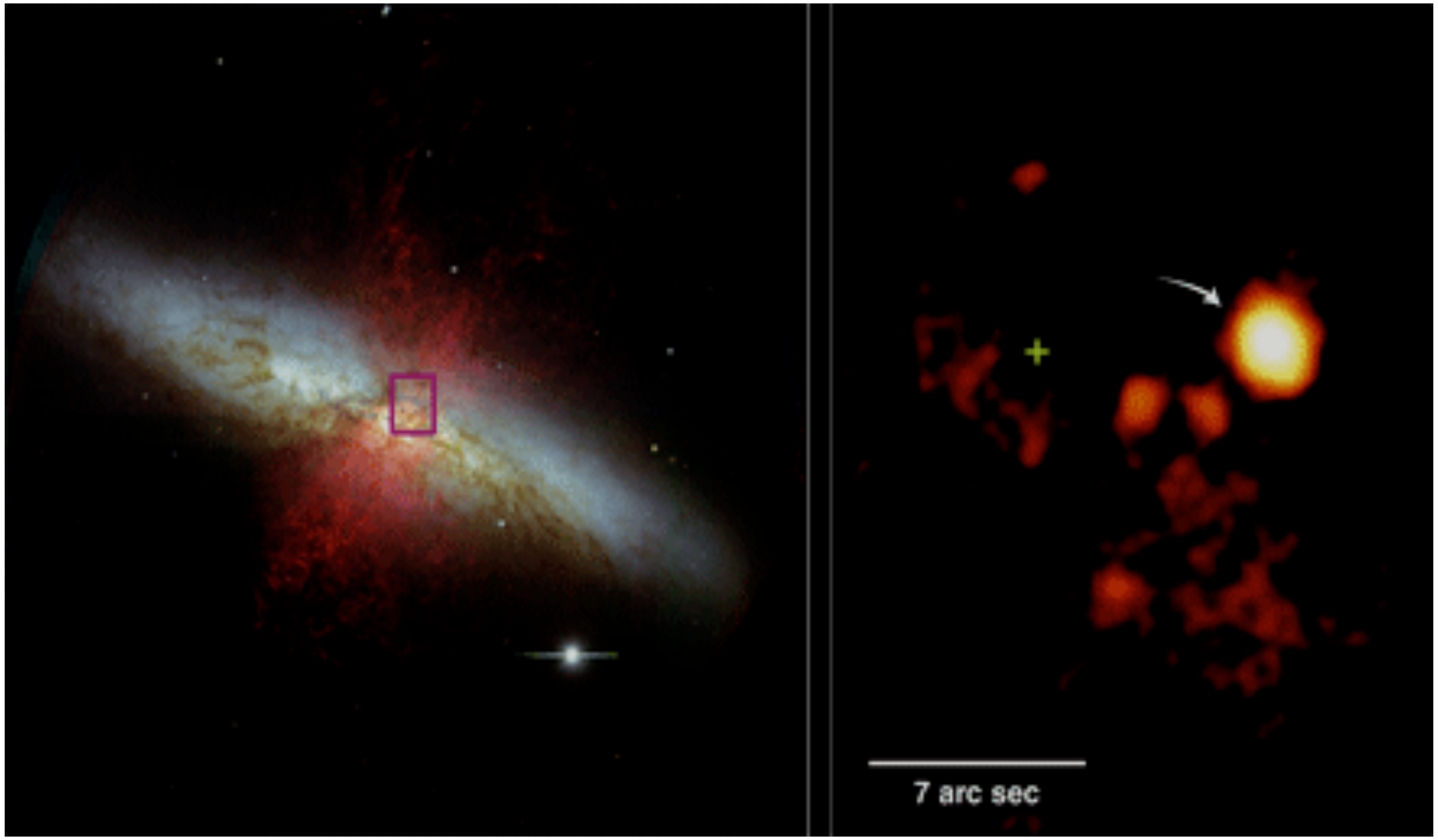
X-ray: Mid mass black holes

- Black Holes with masses a few hundred to a few thousand times the mass of the sun have been found outside the central regions of a number of galaxies.
- Often found in Starburst galaxies.
- May be precursors to Active Galaxies.



Optical and X-ray images of NGC 253

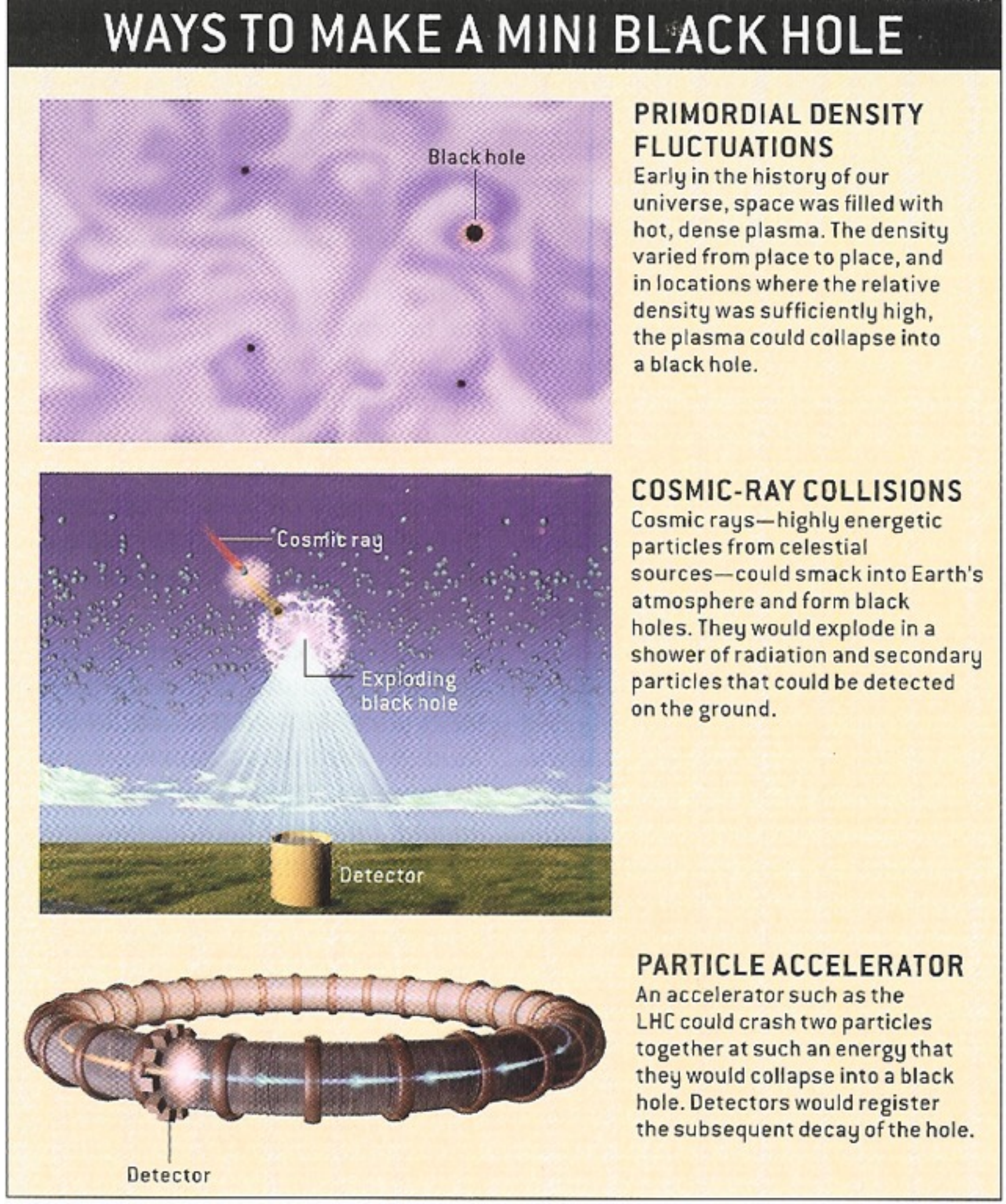
INTERMEDIATE MASS BLACK HOLES



The best candidate for an intermediate-mass black hole. Optical (left) and Chandra x-ray (right) images of the M82 galaxy. The arrow points to the location of the ultraluminous x-ray source that is likely to be an intermediate-mass black hole. The area covered by the right image lies within the rectangle at the center of the left image. The green cross (right image) is the galaxy nucleus. CREDIT: LEFT PANEL: SUBARU TELESCOPE, NAO JAPAN; RIGHT PANEL: NASA/SAO/CXC

Evaporating Black Holes?

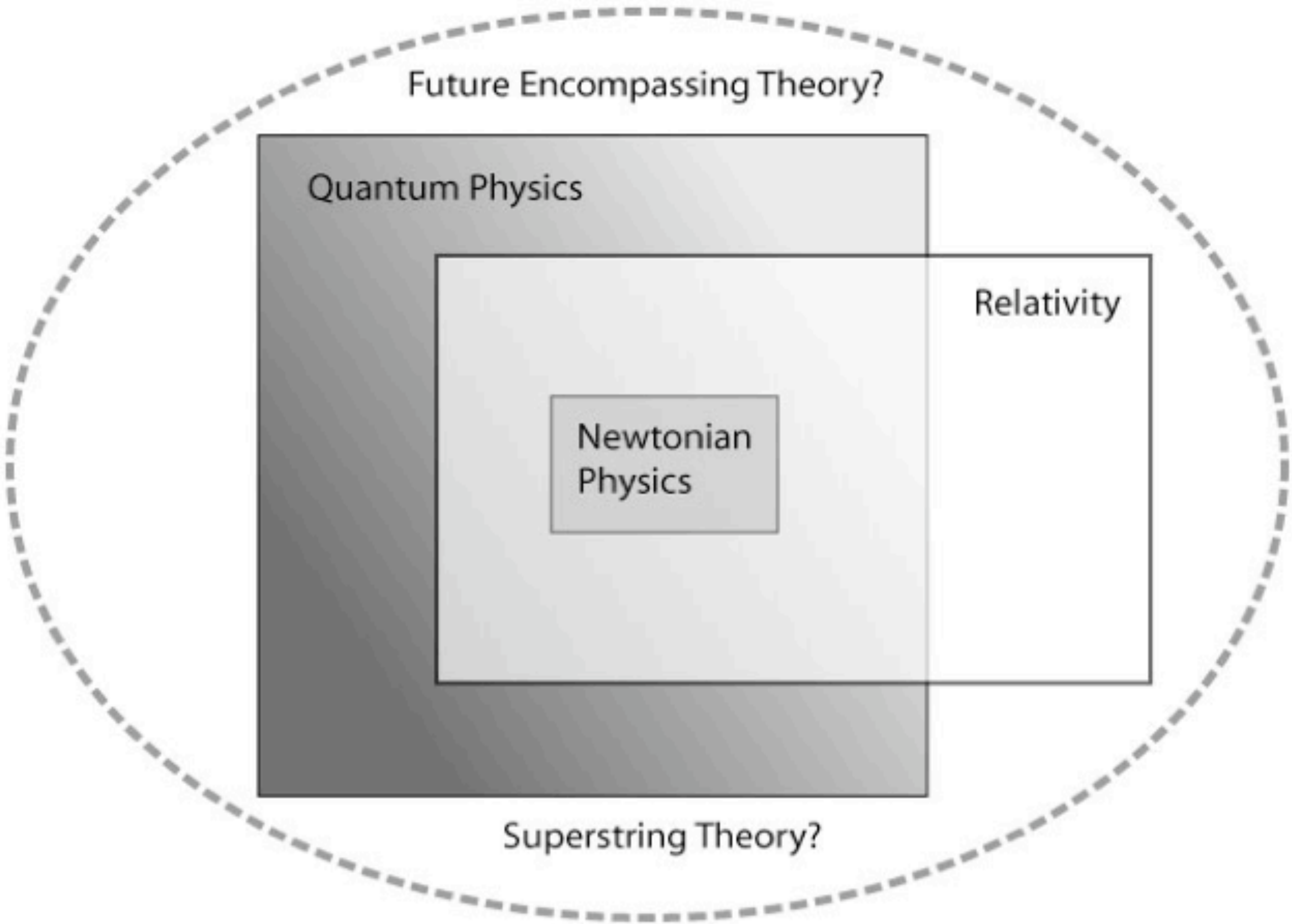
See “Quantum Black Holes” by Steve Giddings and Bernard Carr in the May 2005 *Scientific American*


WAYS TO MAKE A MINI BLACK HOLE

PRIMORDIAL DENSITY FLUCTUATIONS
Early in the history of our universe, space was filled with hot, dense plasma. The density varied from place to place, and in locations where the relative density was sufficiently high, the plasma could collapse into a black hole.

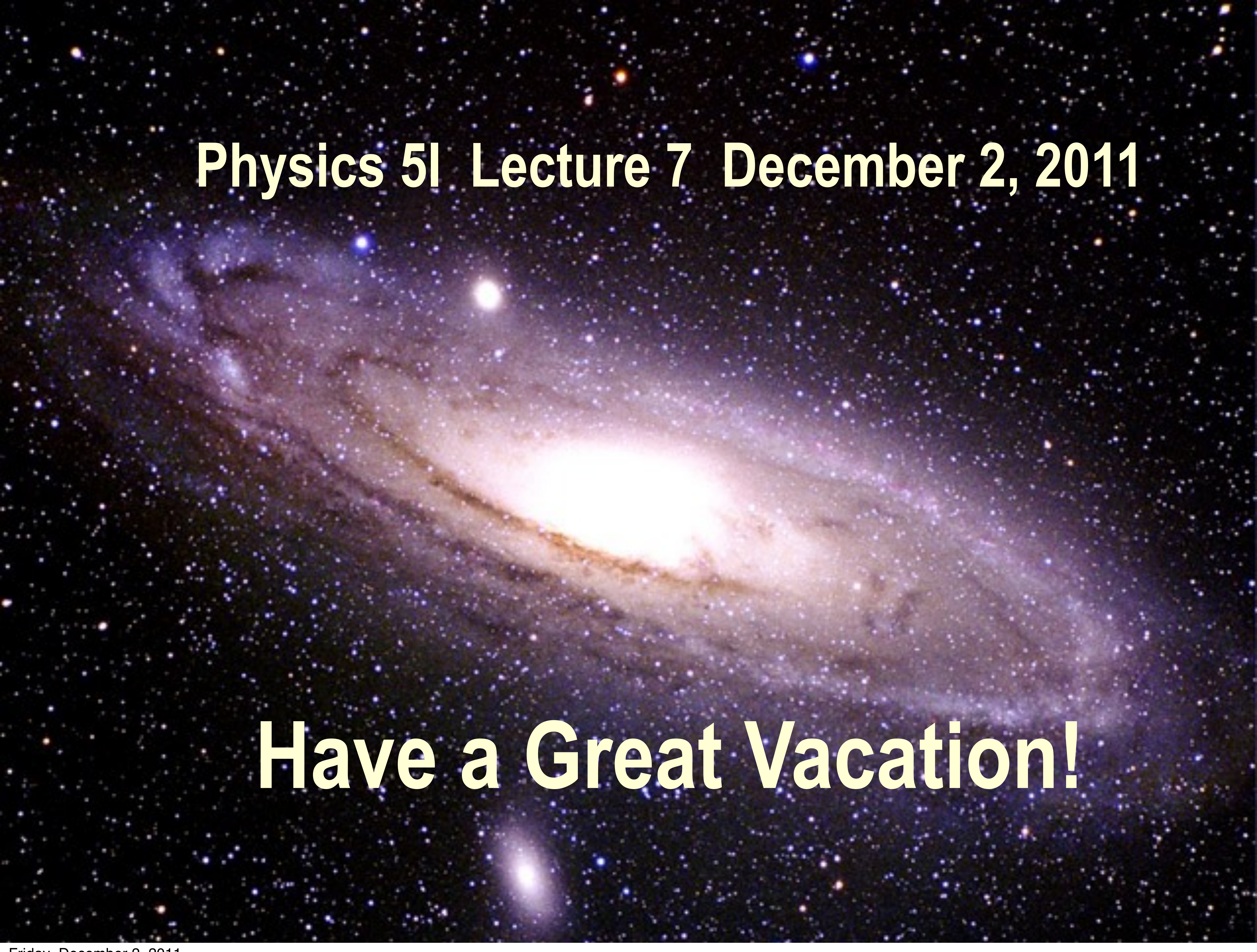
COSMIC-RAY COLLISIONS
Cosmic rays—highly energetic particles from celestial sources—could smack into Earth's atmosphere and form black holes. They would explode in a shower of radiation and secondary particles that could be detected on the ground.

PARTICLE ACCELERATOR
An accelerator such as the LHC could crash two particles together at such an energy that they would collapse into a black hole. Detectors would register the subsequent decay of the hole.


Future Encompassing Theory?
Quantum Physics
Relativity
Newtonian
Physics
Superstring Theory?

The highest grade of truth

Charles Misner has pointed out a deep insight about scientific truth: the only sort of theory we can know to be "true" is one which has been shown to be false – in the sense that its limitations are known. As philosophers of science from David Hume to Karl Popper have emphasized, we can never prove that a scientific theory is true, since there is always the possibility that new data will be discovered that disprove it. But when a scientific theory has been encompassed by a more comprehensive theory that itself has been well tested, we can have considerable confidence that the encompassed theory is "true" within its known limits. This is the highest grade of scientific truth that is available.


Physics 5I Lecture 7 December 2, 2011
Have a Great Vacation!