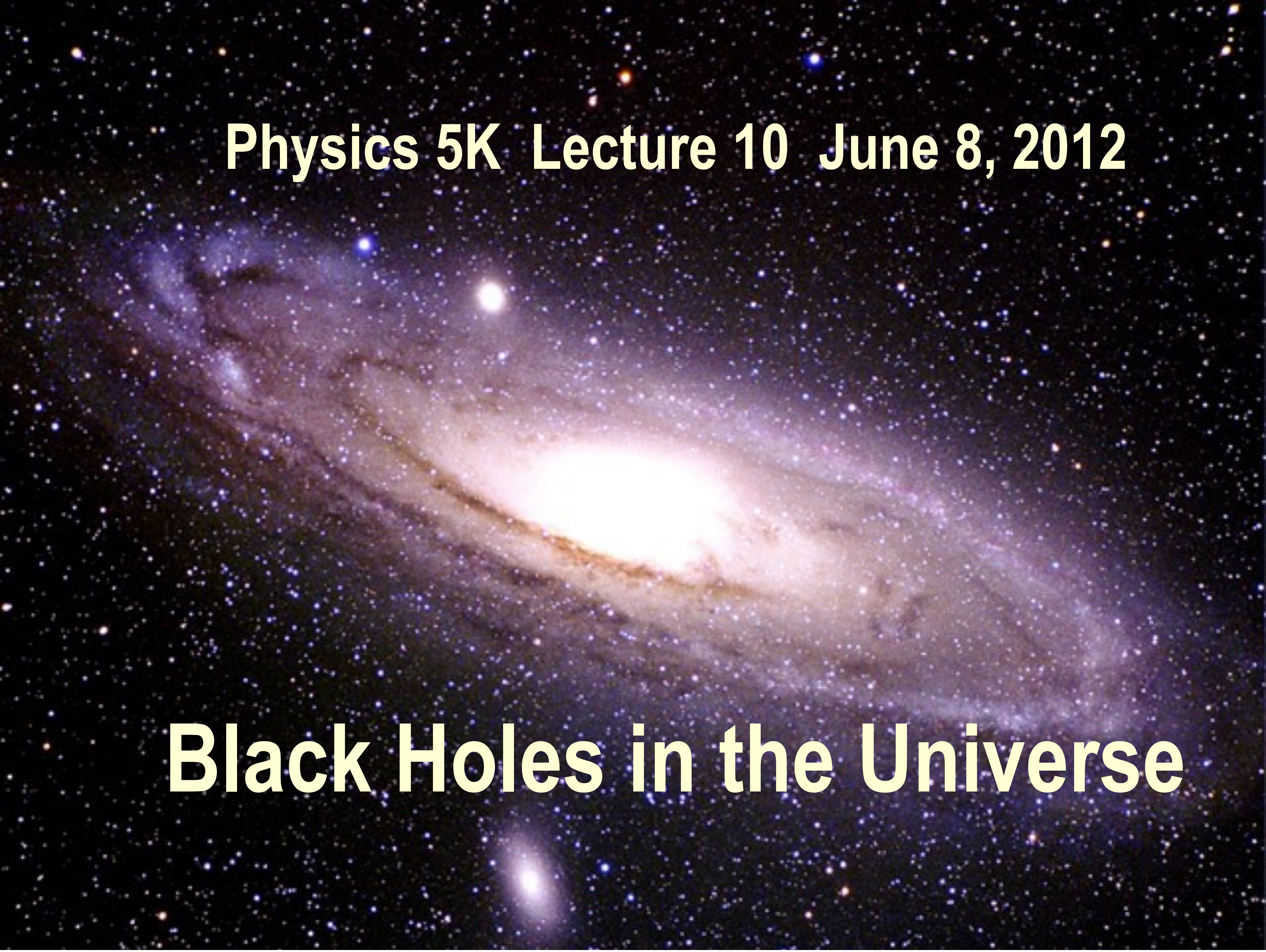
Physics 5K Lecture 10 June 8, 2012



Black Holes in the Universe

Outline of Black Holes lecture

- 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?

GRAVITY according to GENERAL RELATIVITY

PRINCIPLE OF EQUIVALENCE

CURVED SPACE TELLS MATTER HOW TO MOVE.

GRAVITY = ACCELERATION

EINSTEIN FIELD EQUATIONS

MATTER TELLS SPACE HOW TO CURVE.

MASS + ENERGY DENSITY?

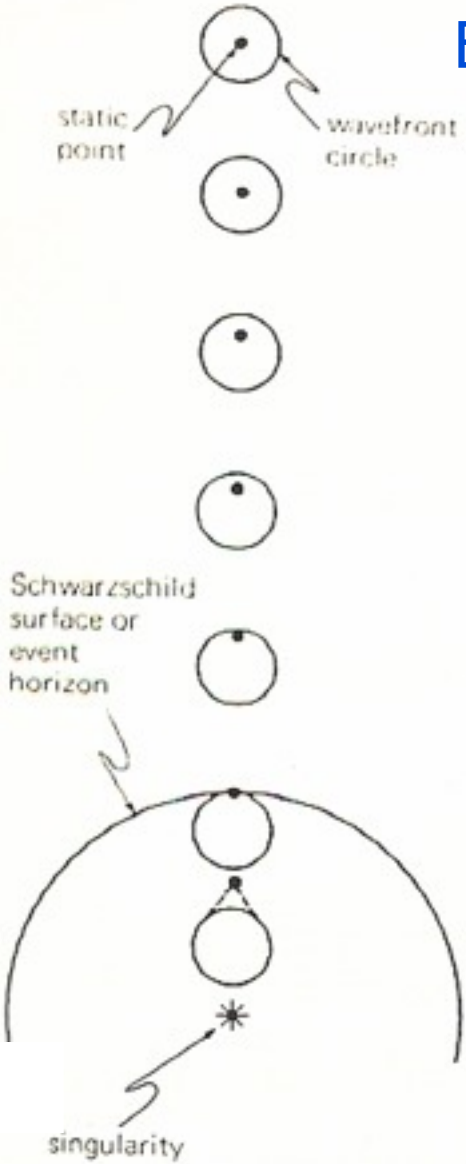
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}$$

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.

EFFECTS OF CURVATURE NEAR A BLACK HOLE



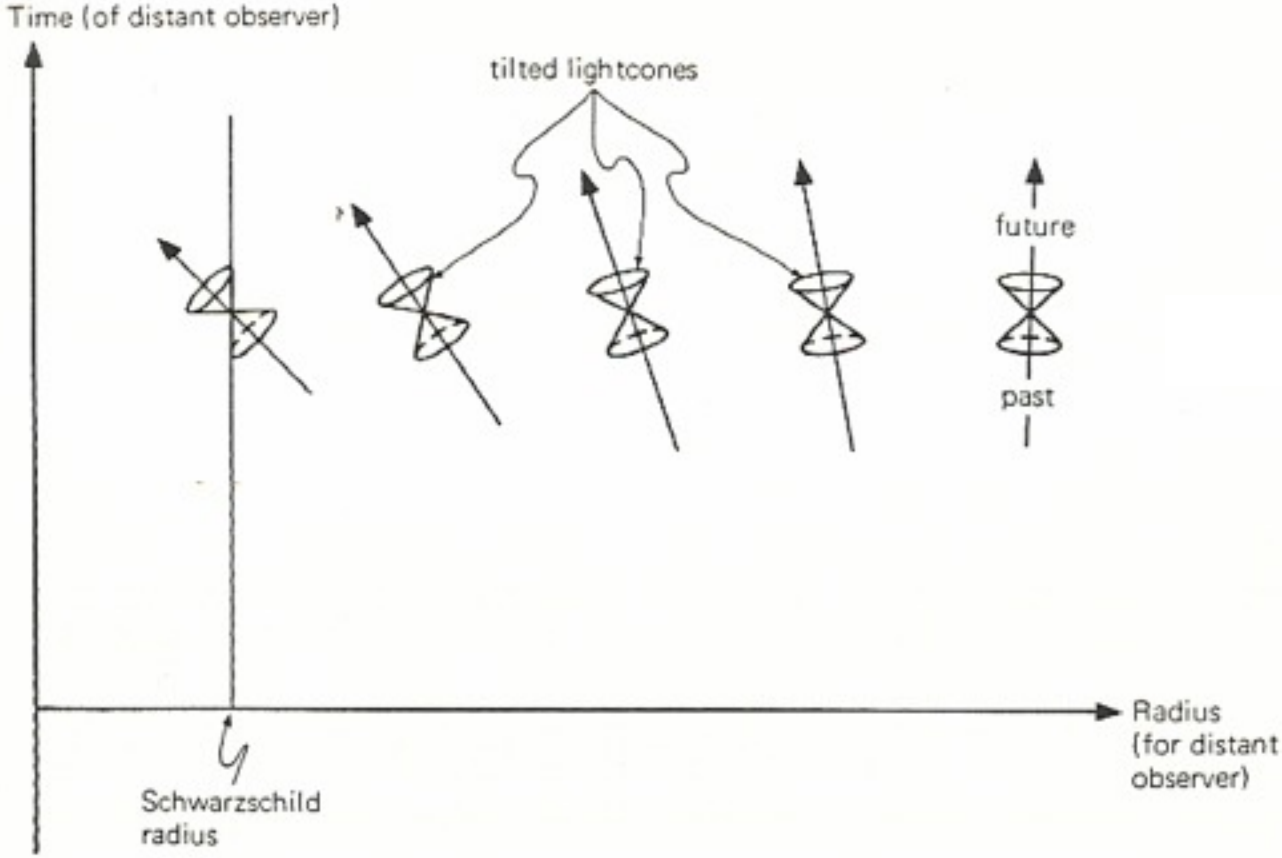
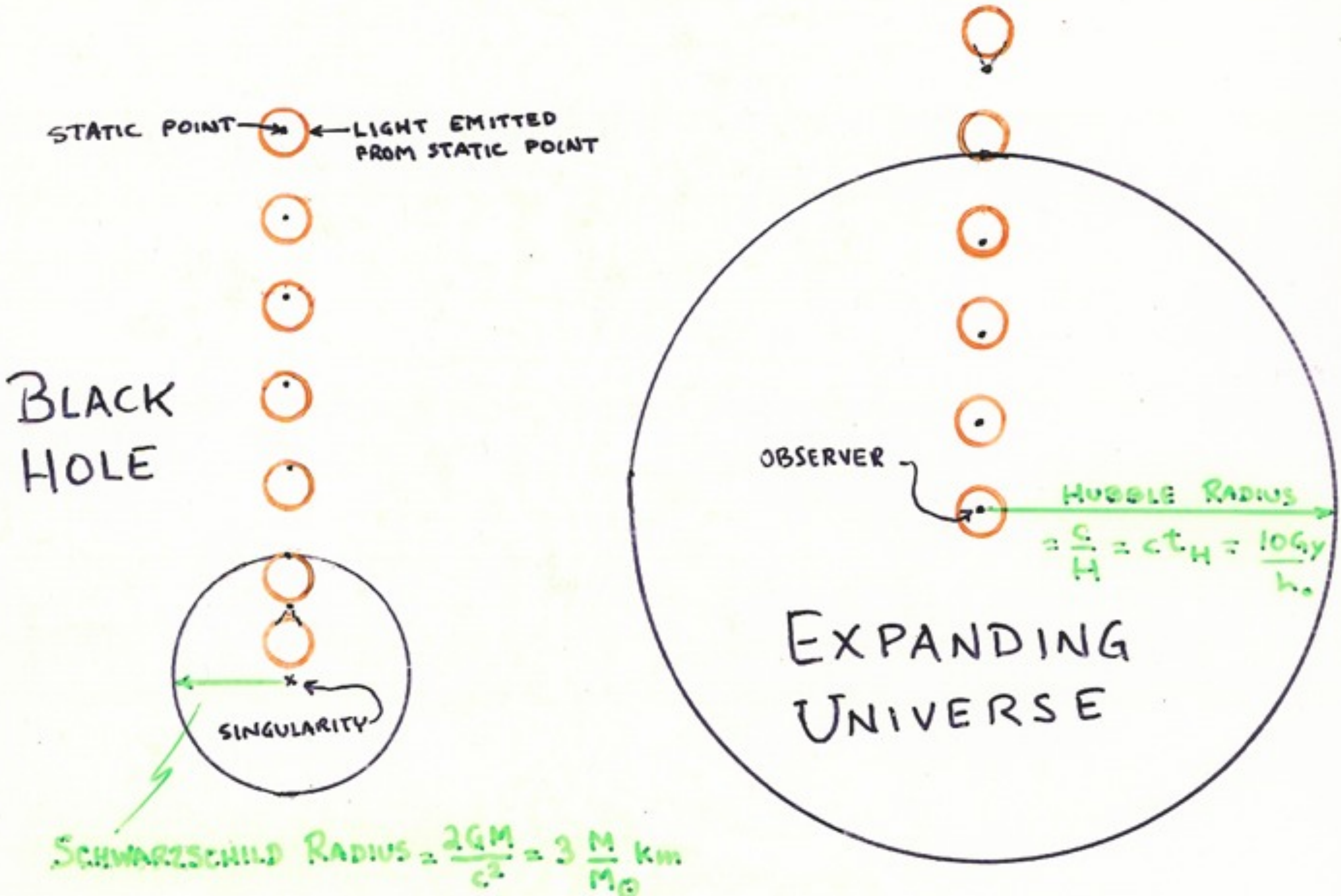
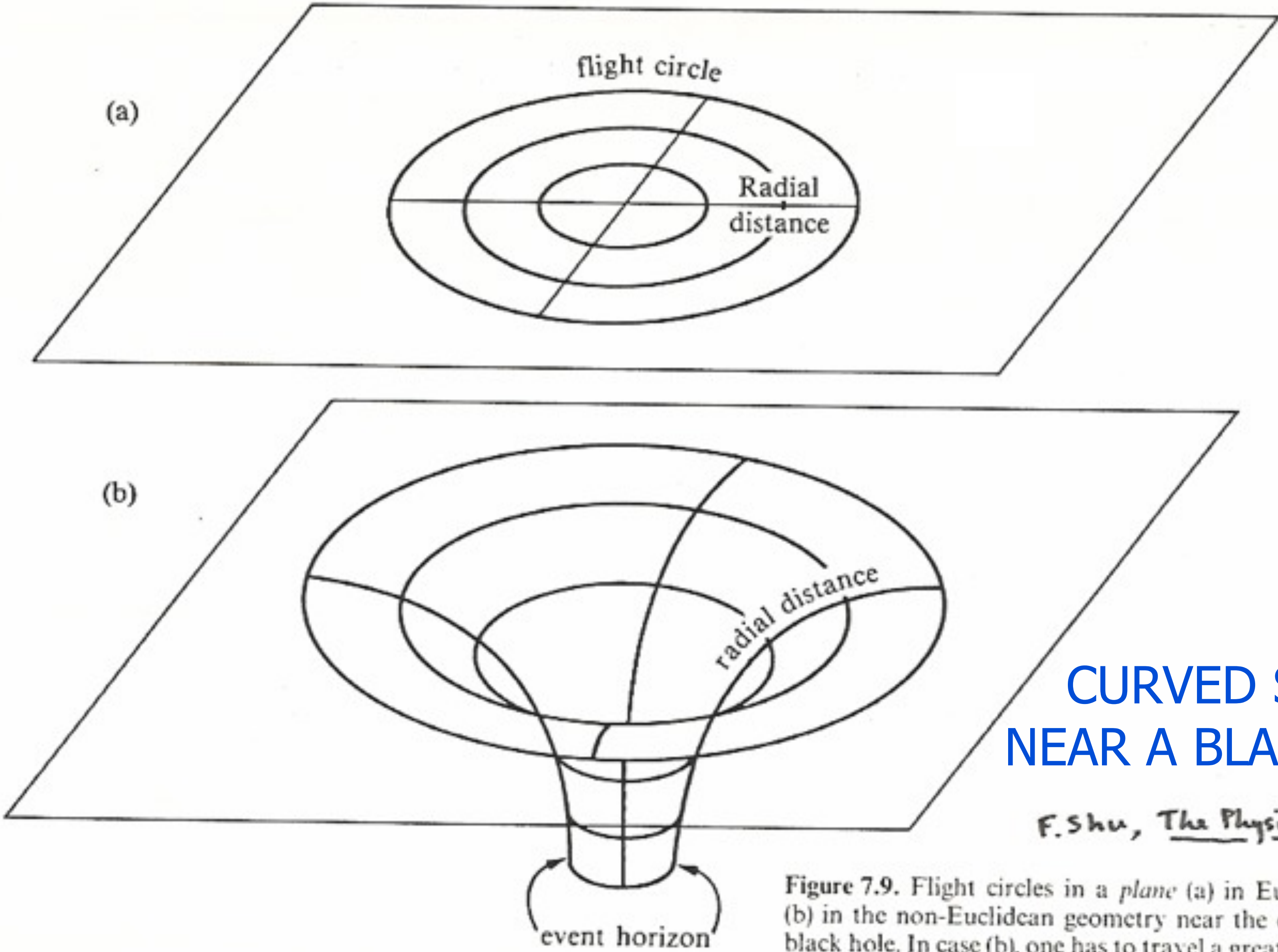


Figure13.6. The effect of spacetime curvature near a black hole. Lightcones are tilted in such a way that the future-pointing lightcone tips toward the black hole and the past-pointing lightcone tips away from the black hole. At the surface of the black hole (the Schwarzschild surface), all rays emitted 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-TIME IS NOT JUST AN ARENA IN WHICH THINGS MOVE, IT IS DYNAMIC. CURVATURE CAN CAUSE HORIZONS, BEYOND WHICH INFORMATION CANNOT BE SENT.



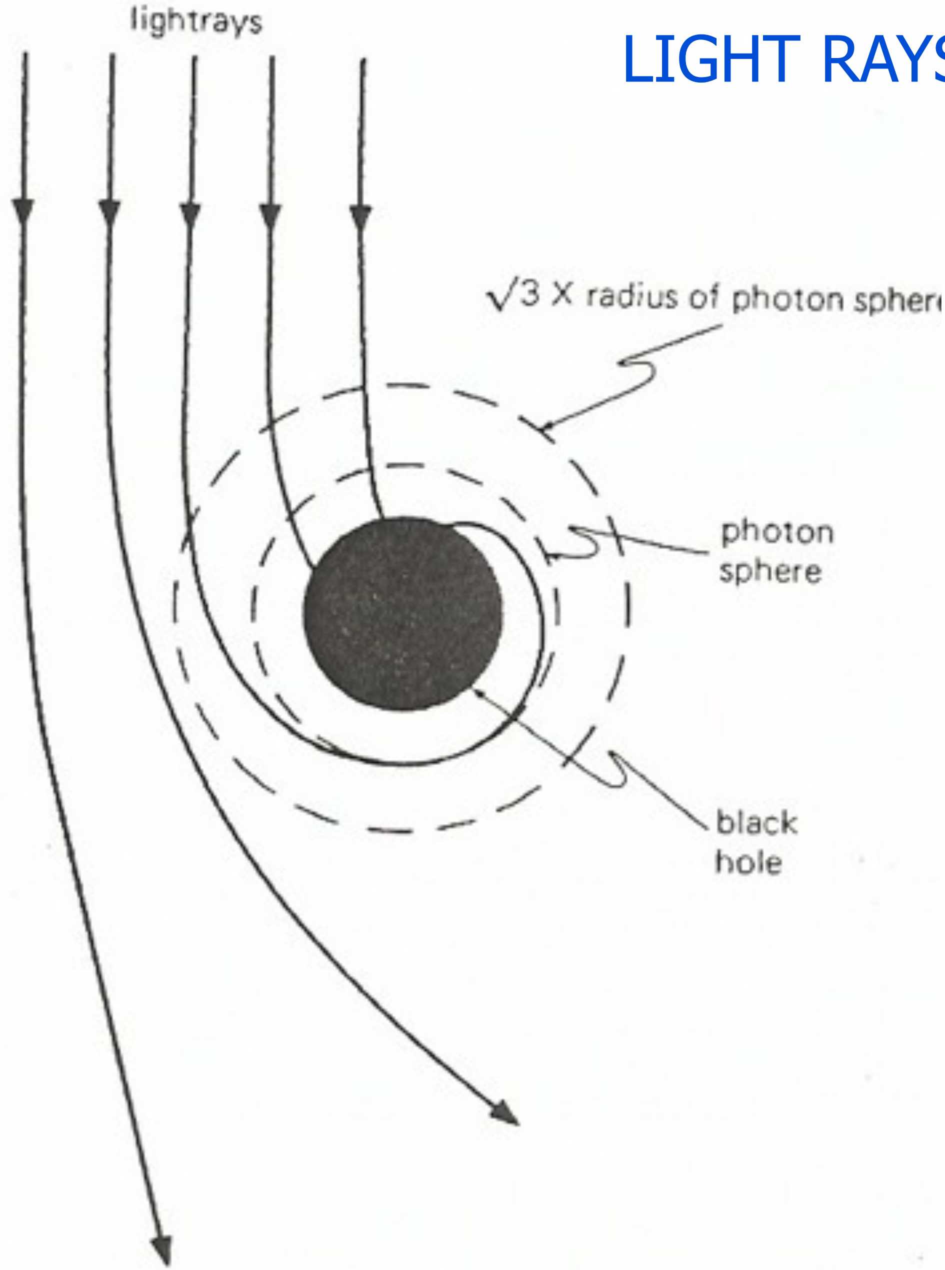


CURVED SPACE NEAR A BLACK HOLE

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 $\sqrt{3}$ times the radius of the photon sphere are captured.

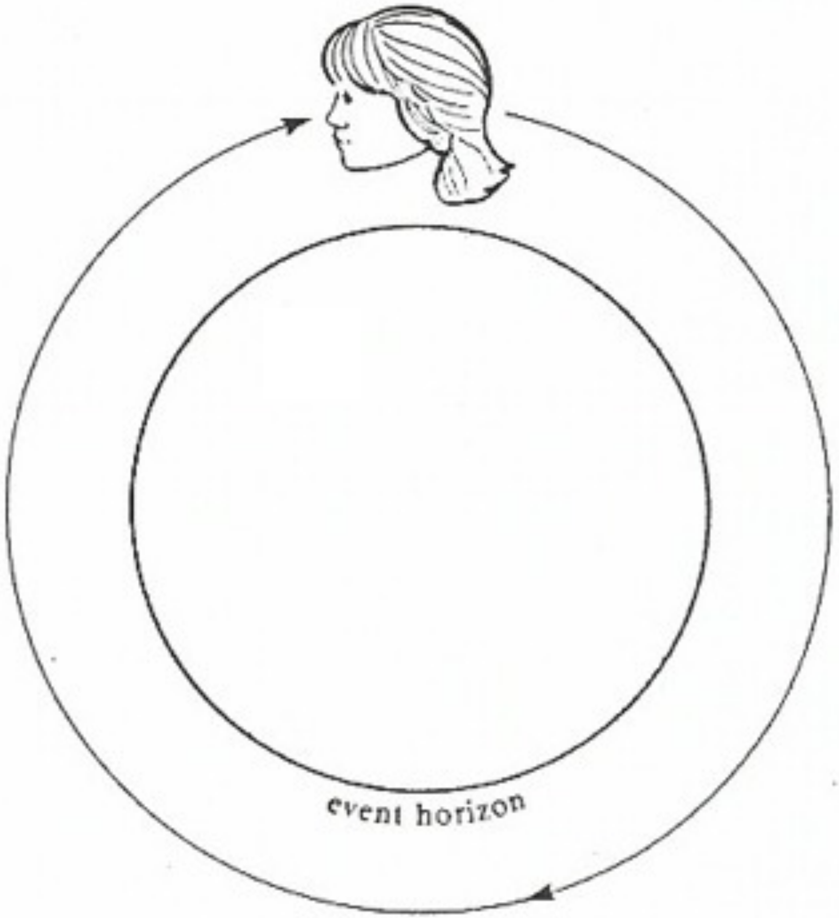
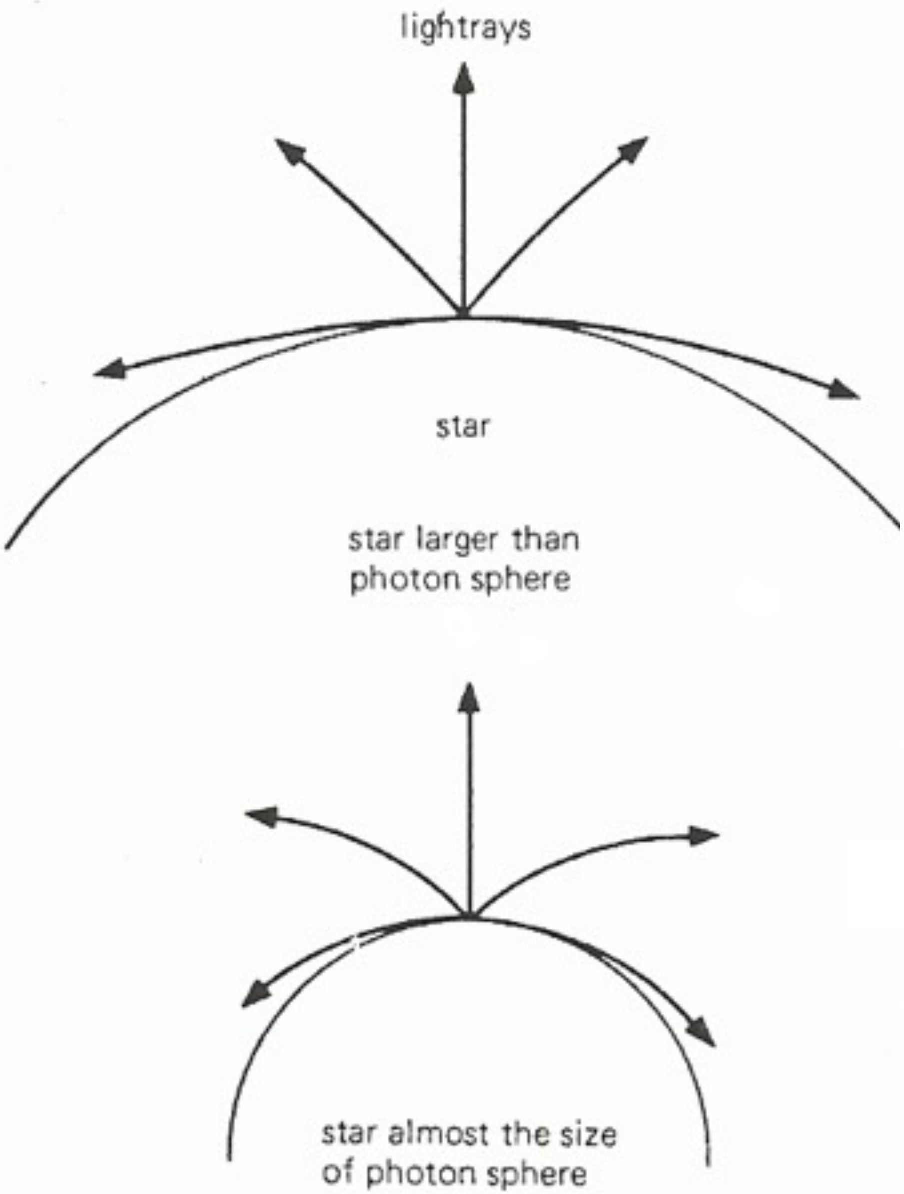
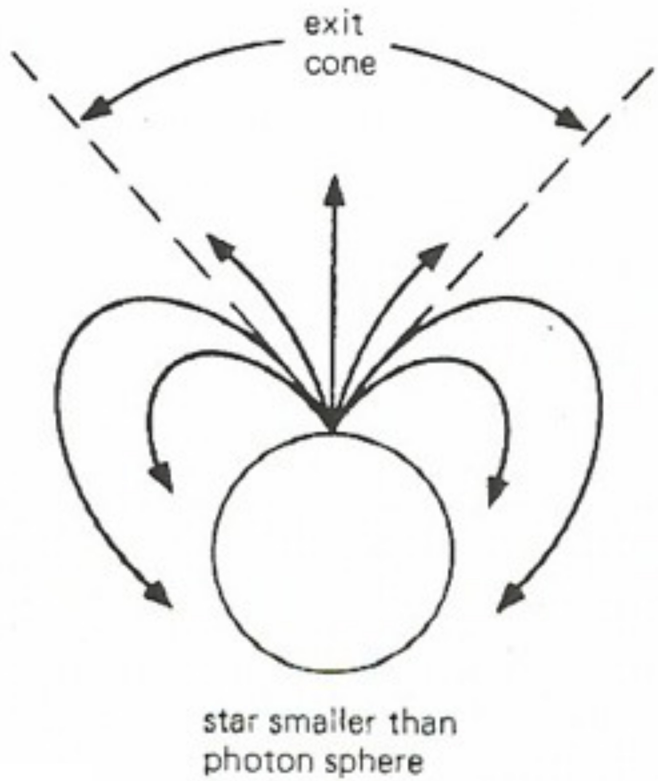


Figure 7.10. When at a circumference equal to 1.5 times the circumference of the event horizon of a black hole, a suitably suspended astronaut can see the back of her own head without the benefit of any mirrors.

E. R. Harrison, *Cosmology*

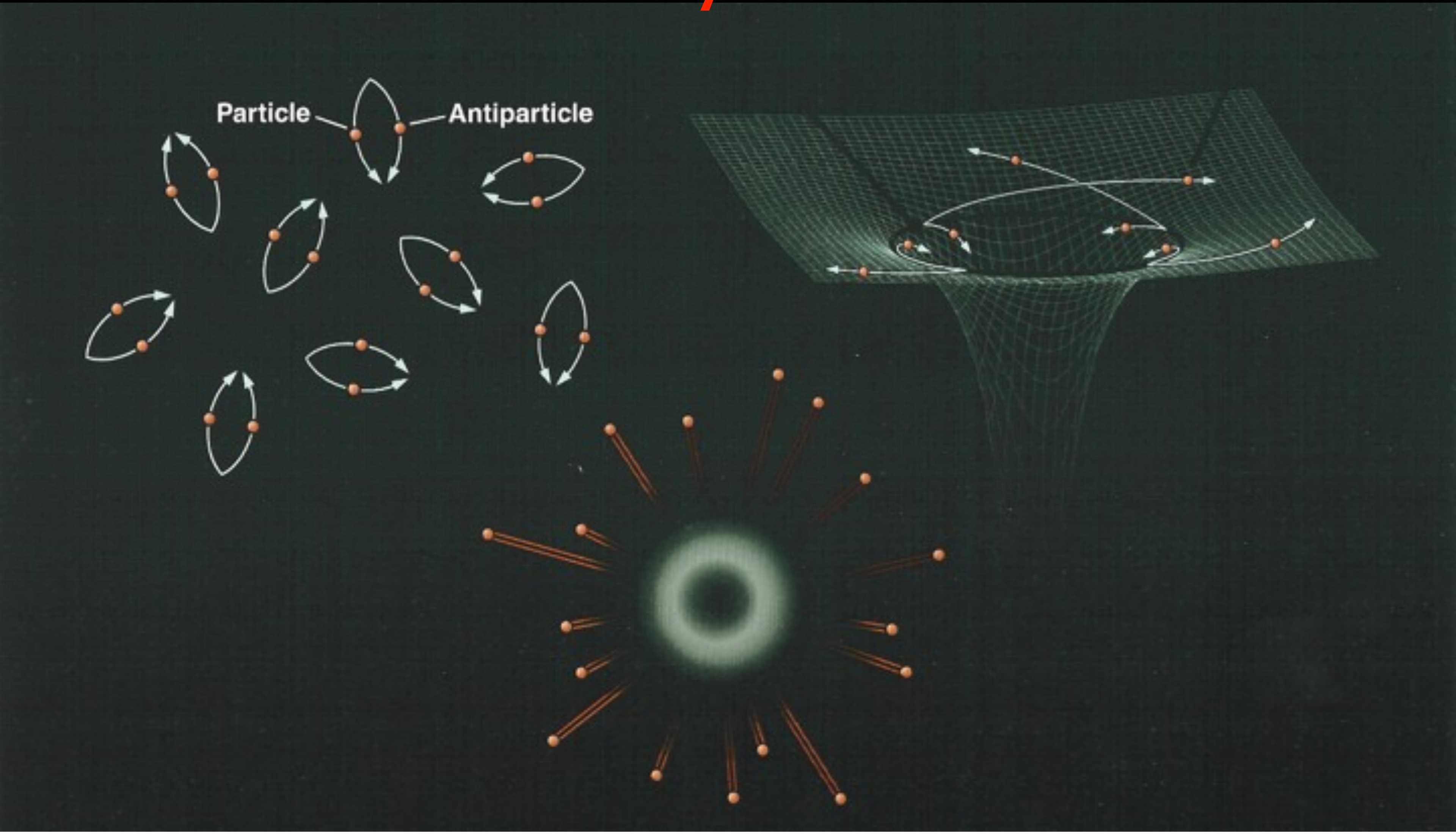




Lightrays leaving a gravitating body are curved as shown. As the body shrinks in size the rays become more curved. When the radius is less than 1.5 times the Schwarzschild radius, which is the radius of the photon sphere, the exit cone begins to close. Rays emitted within the exit cone escape, but those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

E. R. Harrison, *Cosmology*

HAWKING RADIATION
from tiny black holes



HAWKING RADIATION

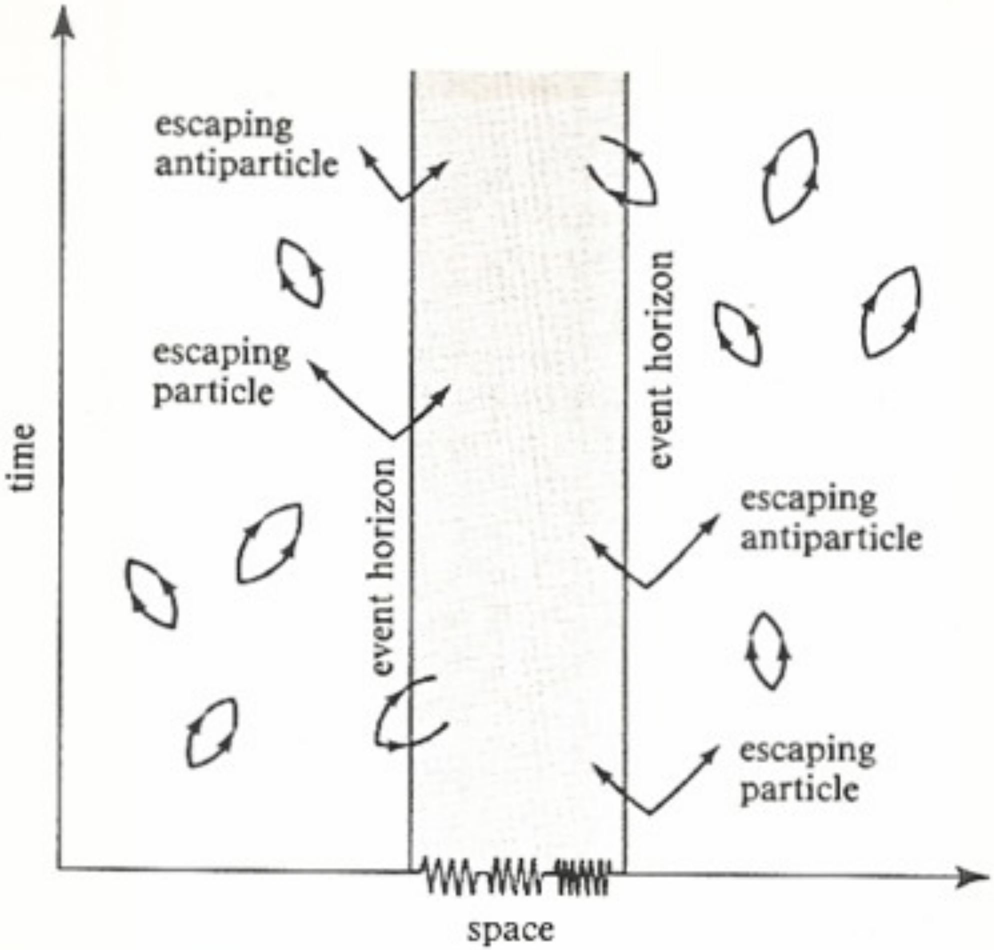
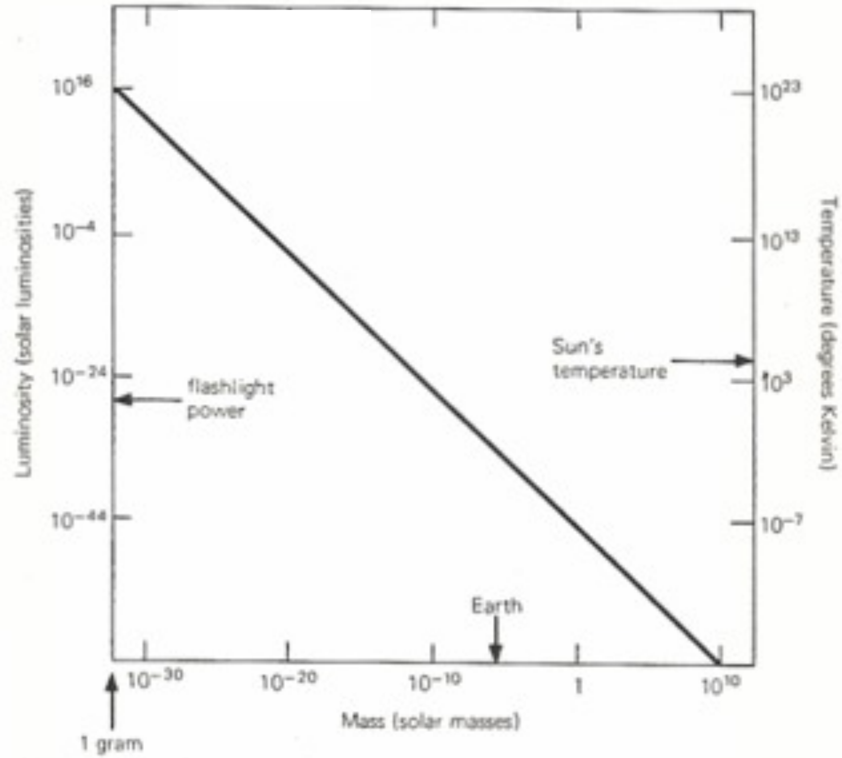


Figure 7.13. Hawking process near the event horizon of a black hole. The creation of particle-antiparticle pairs usually ends with their destruction a short time later. Occasionally, however, the tidal forces of the black hole can cause one of the pair to fall into the black hole, enabling its liberated 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*



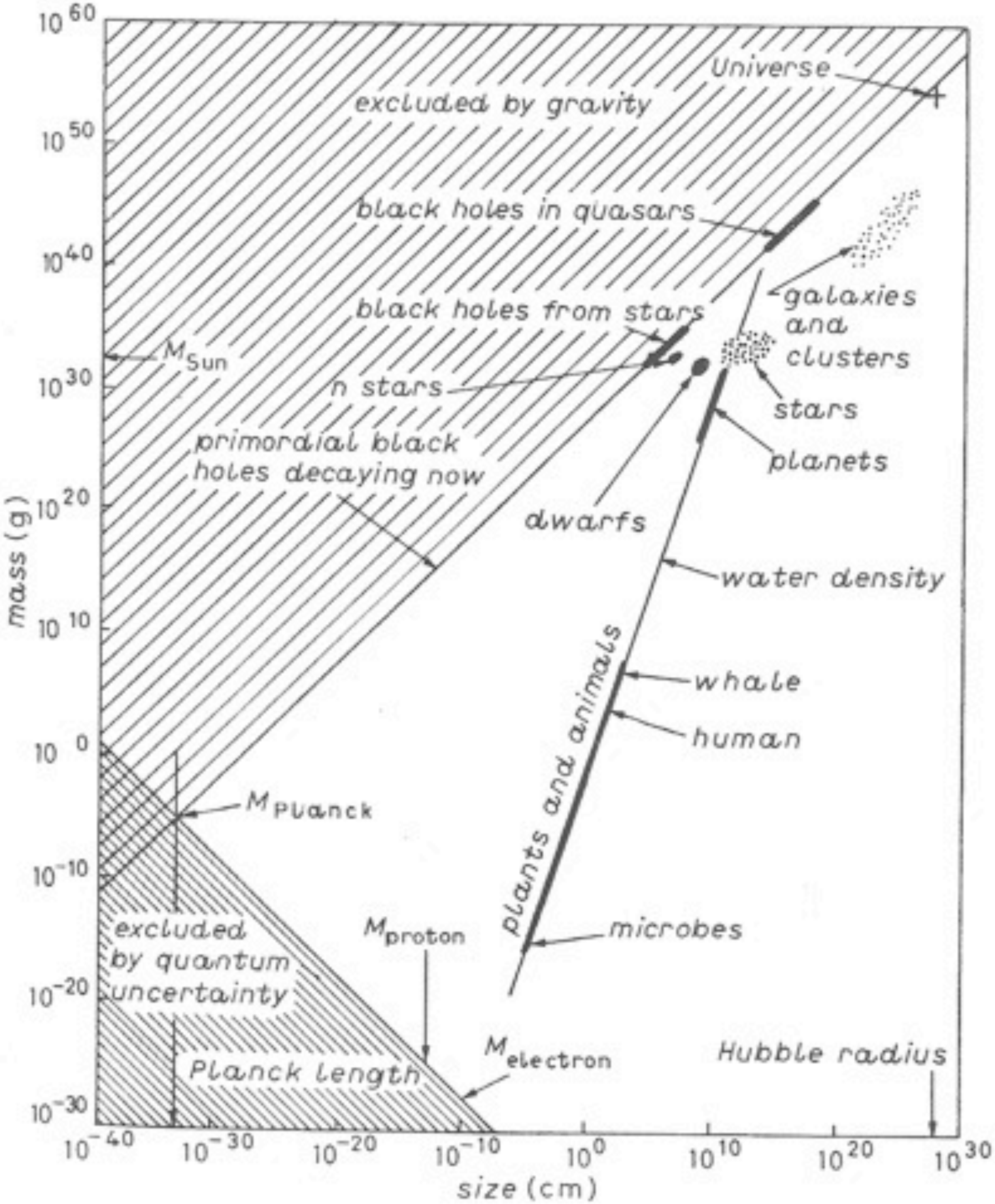
. *Luminosity and temperature of a black hole of given mass.*

E. R. Harrison, *Cosmology*

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

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

The Wedge of Material Reality



J. R. Primack, *Varenna Lectures 1984*

The **Planck Length**

$$l_{Pl} = \sqrt{\frac{hG}{2\pi c^3}} = 1.6 \times 10^{-33} \text{ cm}$$

is the smallest possible length. Here h is Planck's constant

$h = 6.626068 \times 10^{-34}\ \text{m}^2\ \text{kg / s}$

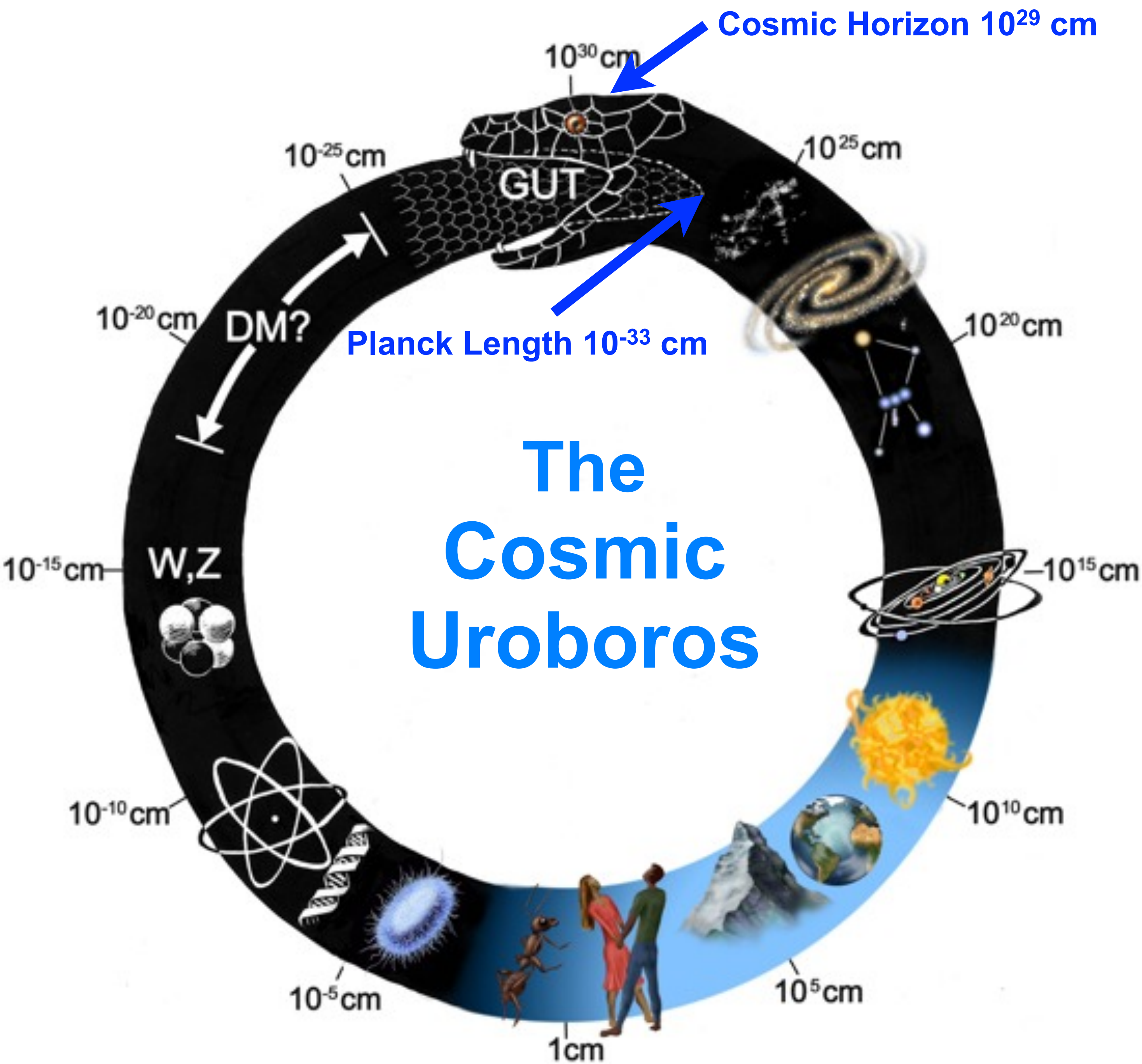
The Planck Mass is

$$m_{Pl} = \sqrt{\frac{hc}{2\pi G}} = 2.2 \times 10^{-5}\ \text{g}$$

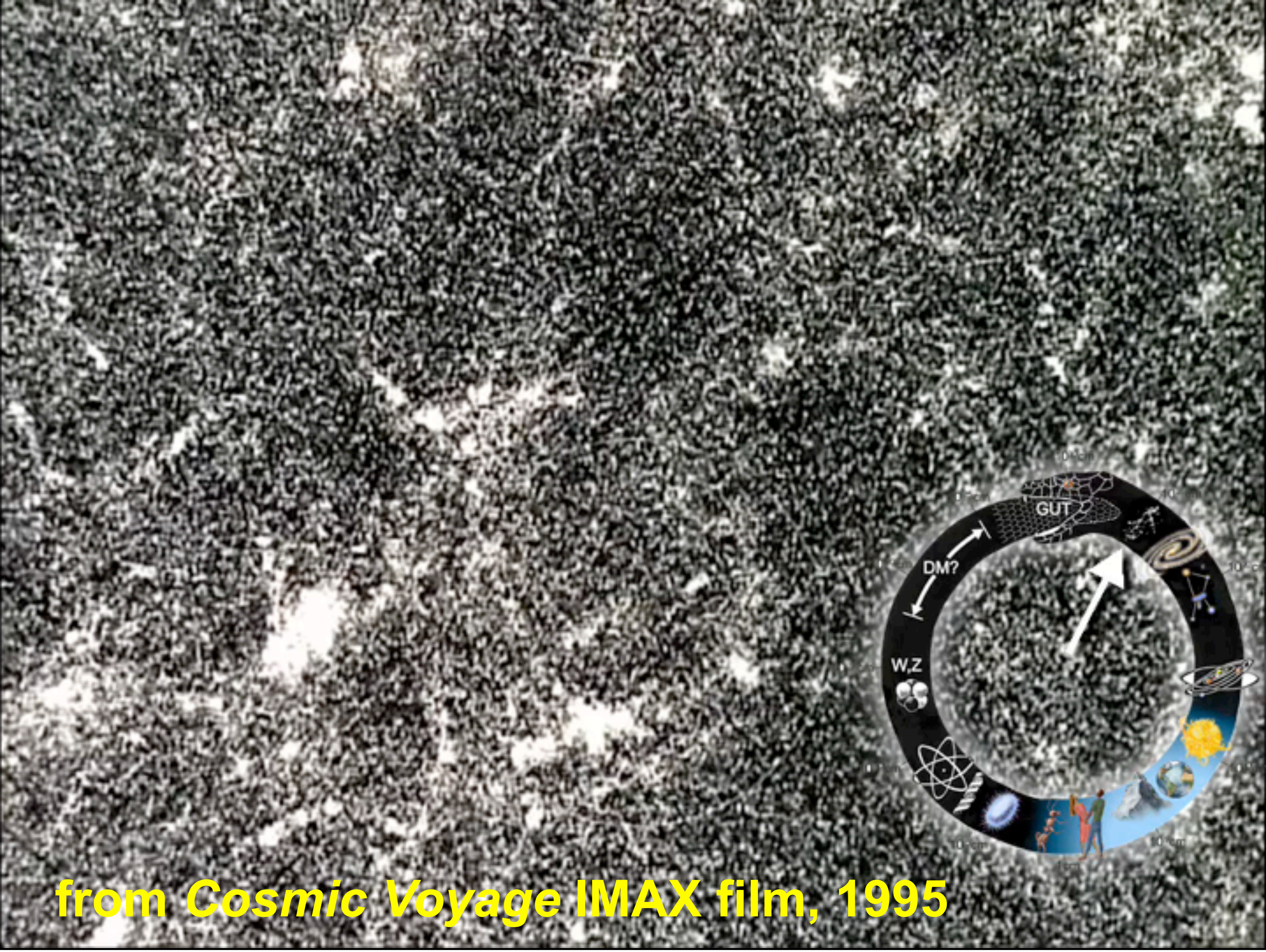
The Compton (i.e. quantum) wavelength $l_C = \frac{h}{2\pi mc}$

equals the Schwarzschild radius $l_S \approx \frac{Gm}{c^2}$

when $m = m_{Pl}$



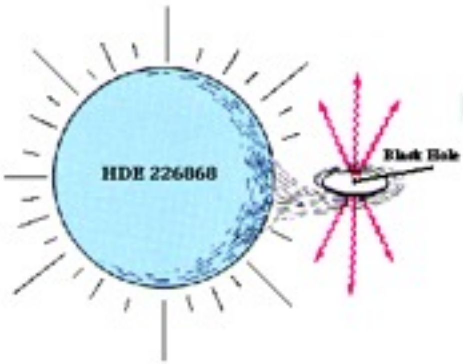
The Cosmic Uroboros

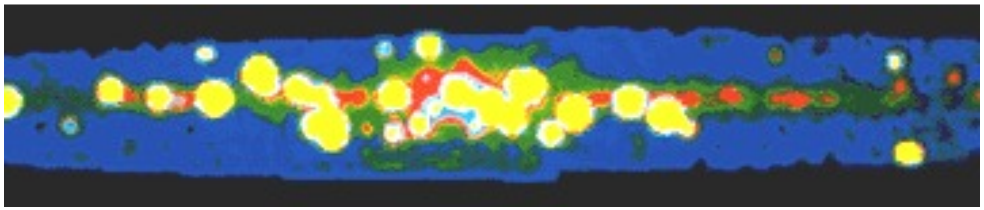


from *Cosmic Voyage* IMAX film, 1995

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 rare, only about 0.2% of all stars. But they are at least 100,000 times as bright as the sun, and they fuse all the available fuel in their centers within a few million years. 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.



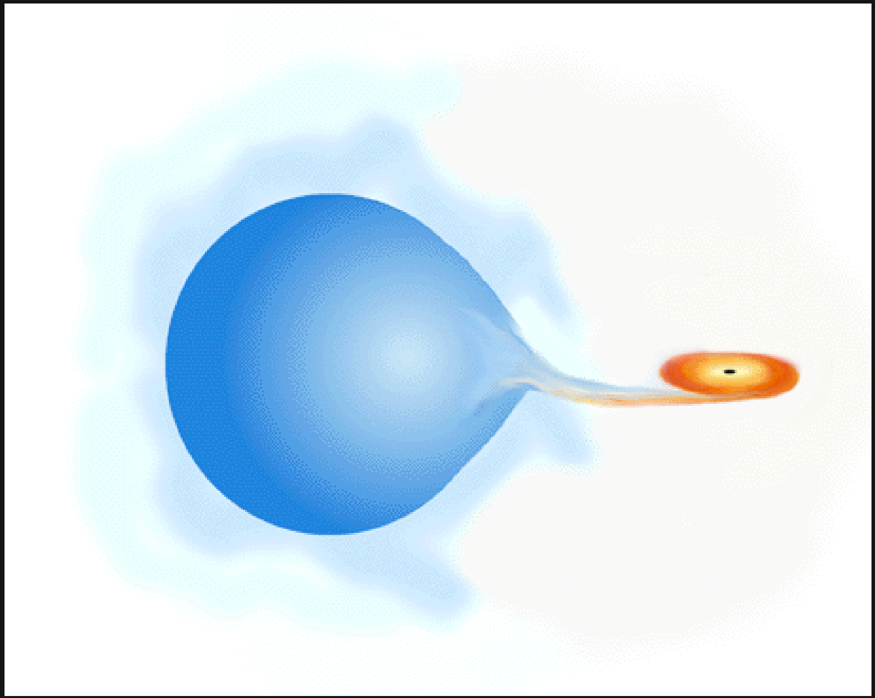


X-ray Binaries (in yellow) near the Galactic Center

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 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.

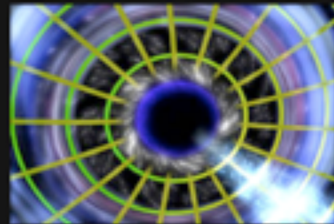


Chandra illustration

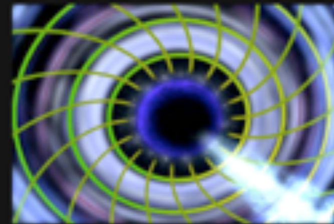
BLACK HOLES FROM STELLAR COLLAPSE

X-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

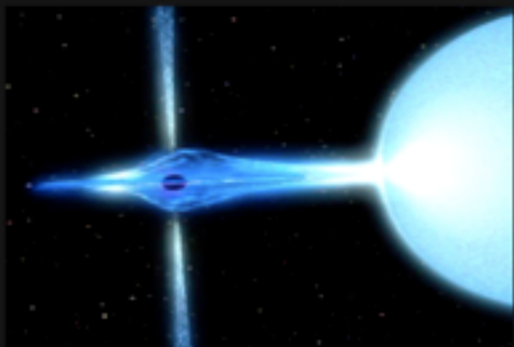


Rotating black hole

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-rays from Black Holes

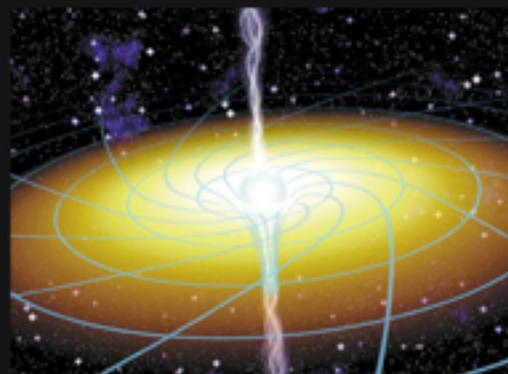
In close binary systems, material flows from normal star to black hole. X-rays are emitted from disk of hot gas swirling around the black hole.



X-ray: Frame Dragging

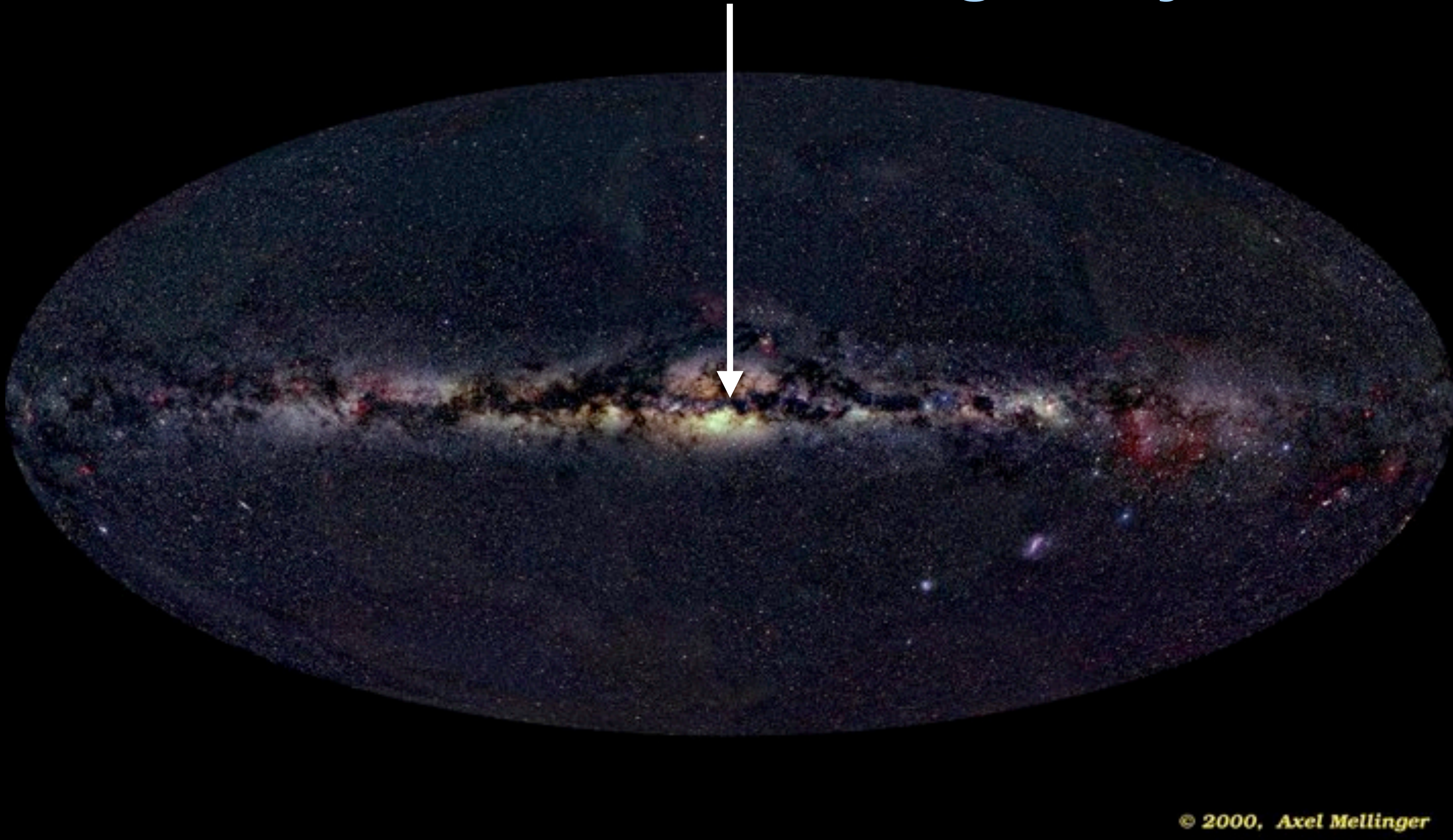
- Detection of a period in GRO J1655-40 due to precession of the disk.

- This precession period matches that expected for frame dragging of space-time around the black hole.



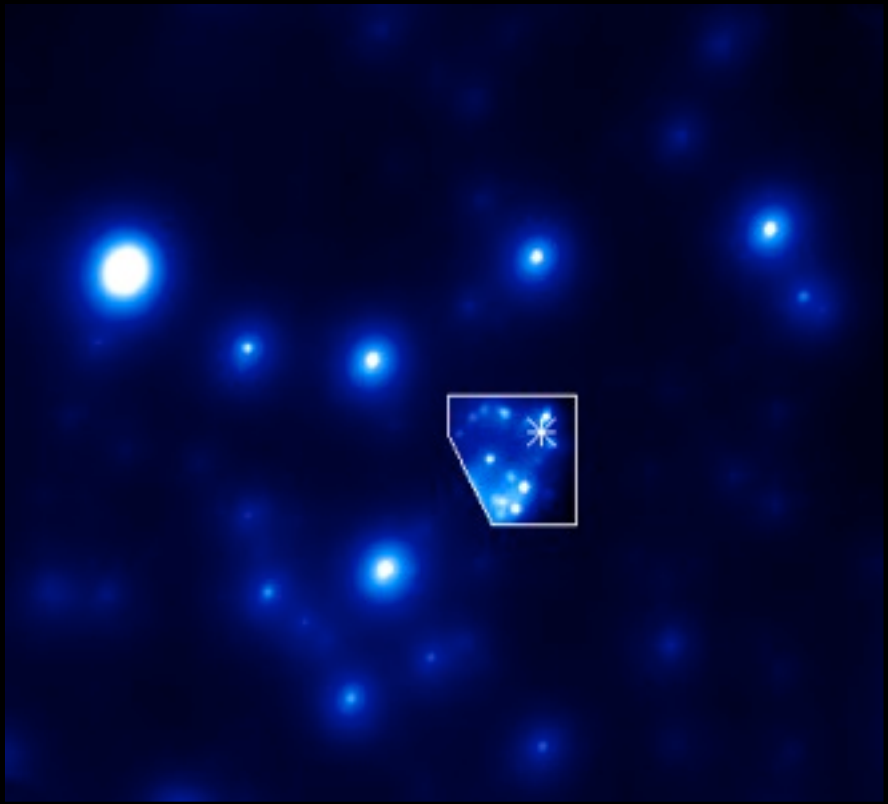
Credit: J. Bergeron, Sky & Telescope Magazine

The center of our galaxy



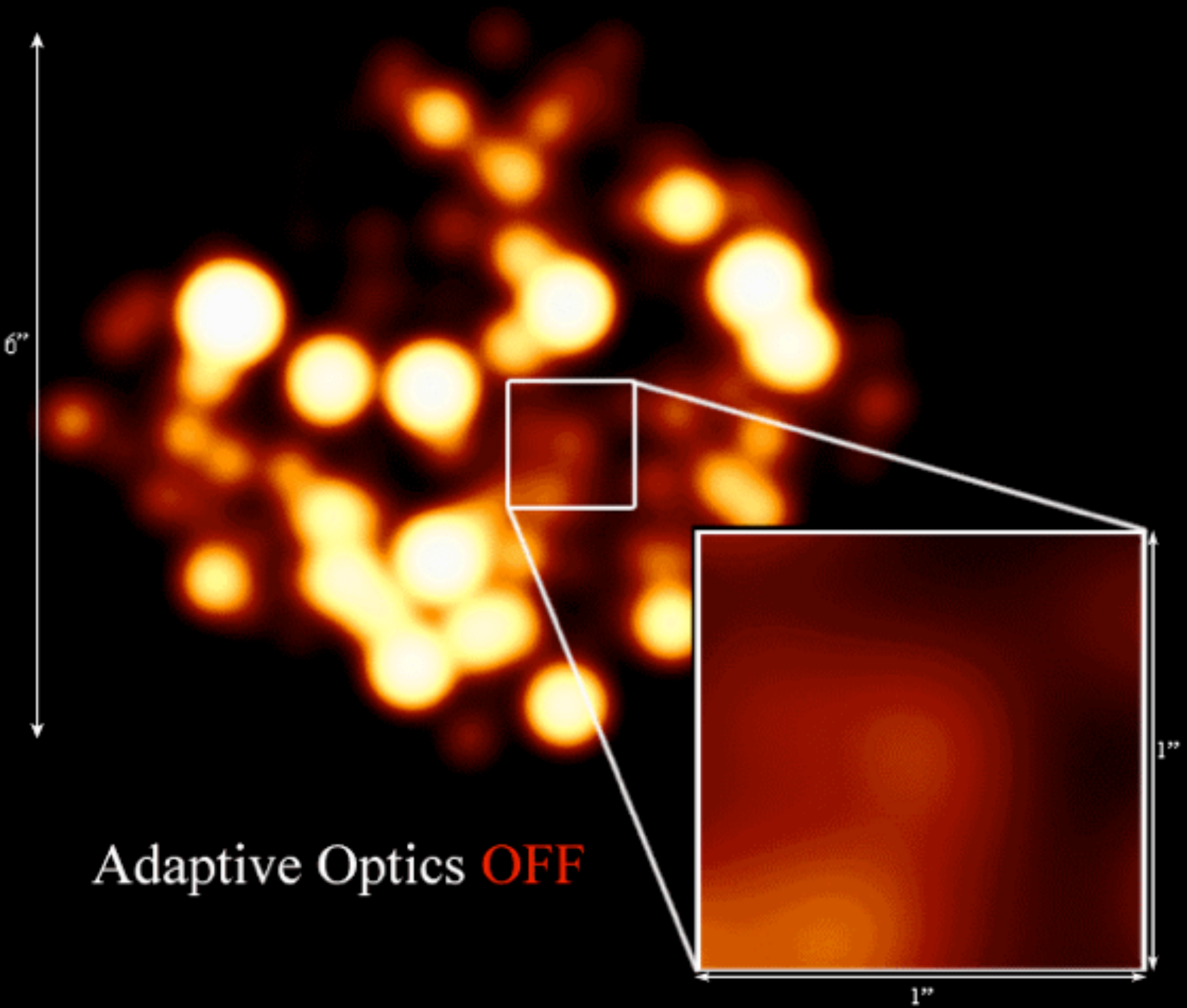
There's a supermassive black hole at the center of our galaxy…

- Modern large telescopes can track individual stars at galactic center
- Need infrared (to penetrate dust)
- Need very good resolution -- use adaptive optics



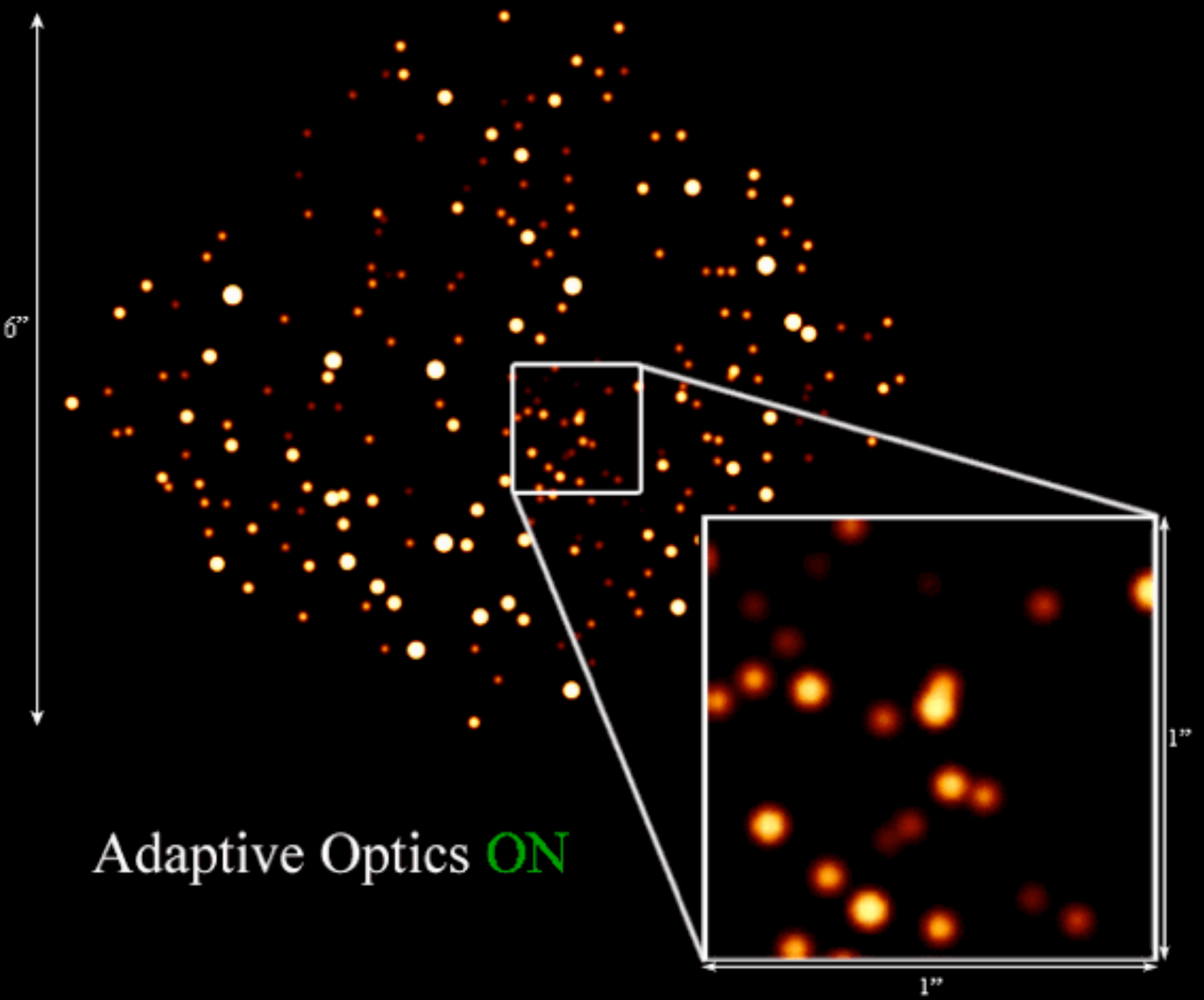
Keck, 2 μm   *Ghez, et al.*

The Galactic Center at 2.2 microns

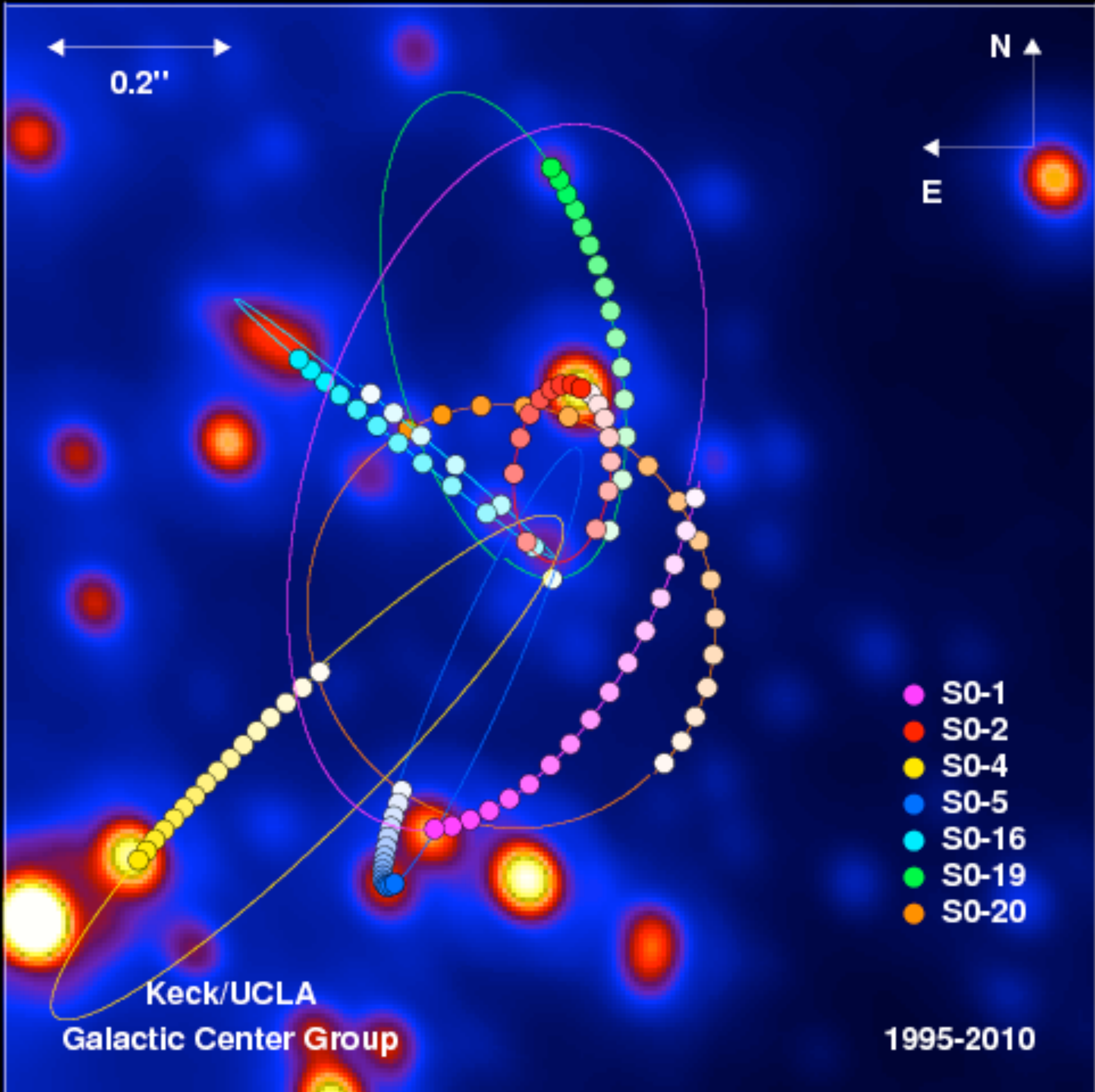


Ghez, et al.

The Galactic Center at 2.2 microns



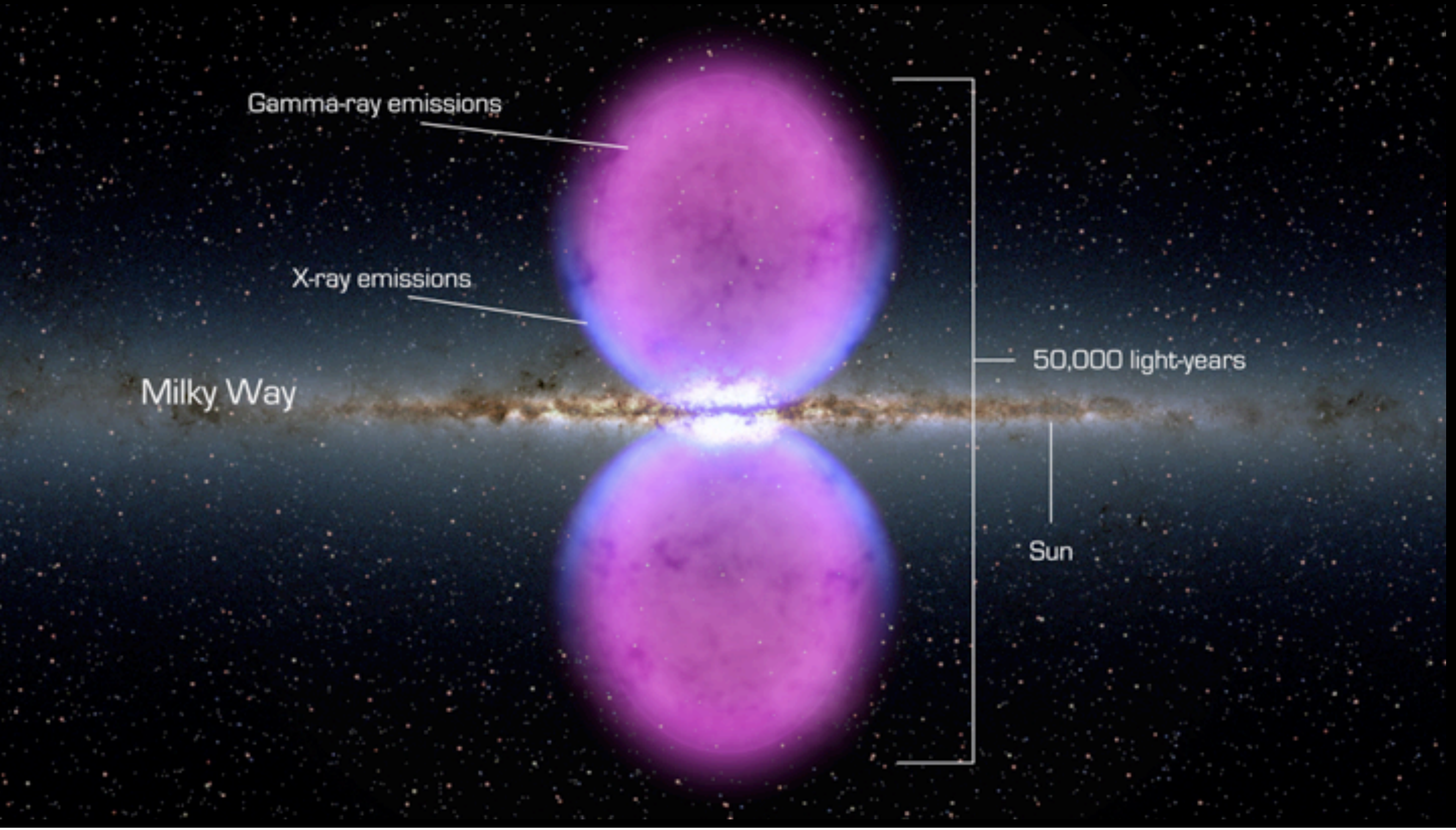
Ghez, et al.



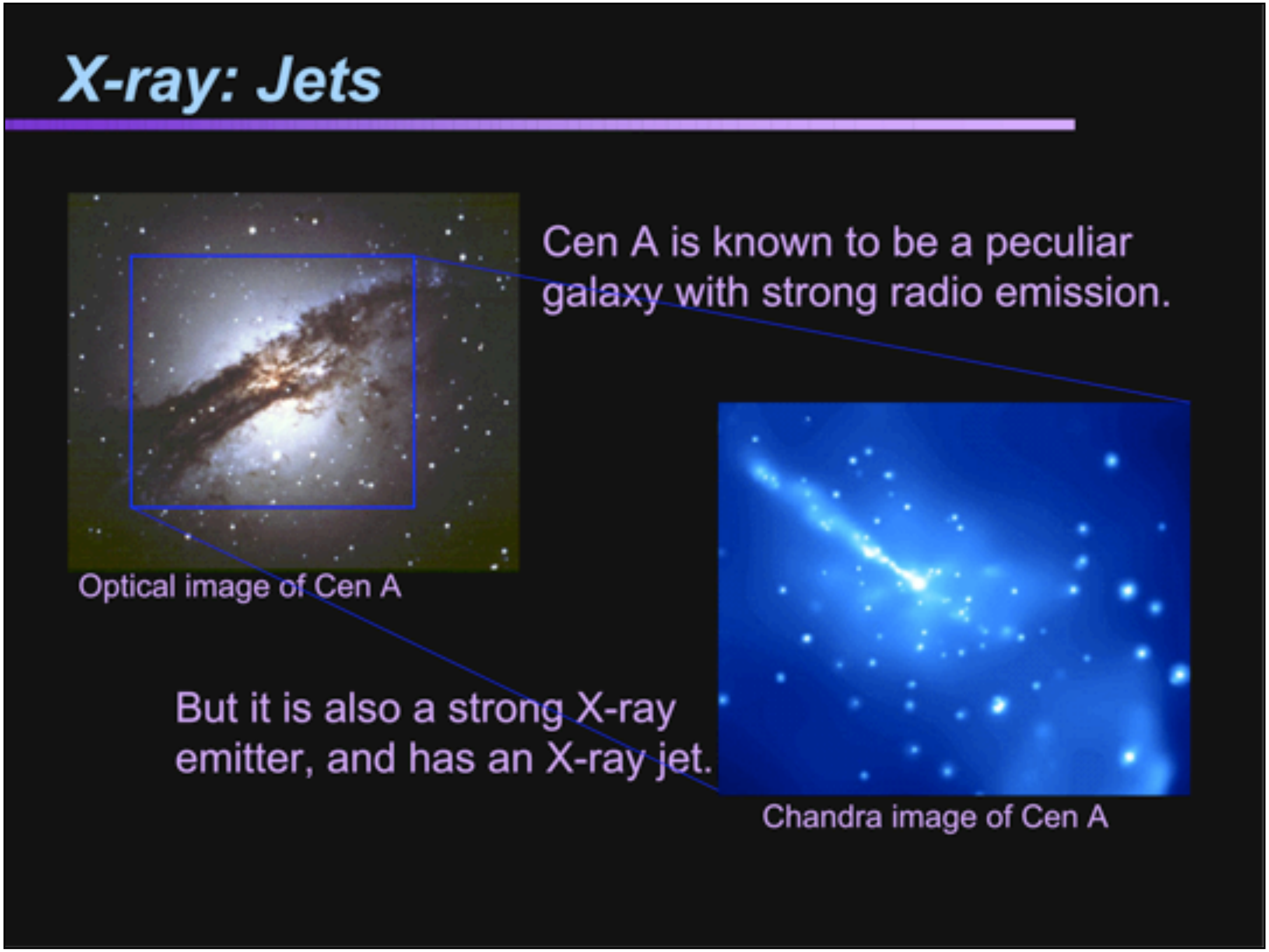
Motions of stars consistent with large, dark mass located at Sgr A…*

Ghez, et al.

- **The central object at the center of the Milky Way is…**
  - Very massive (~4 million solar masses).
  - Must be very compact (star S0-2 gets within 17 light hours of the center).
  - Now seen to flare in X-rays and IR, in the past in Gamma rays.

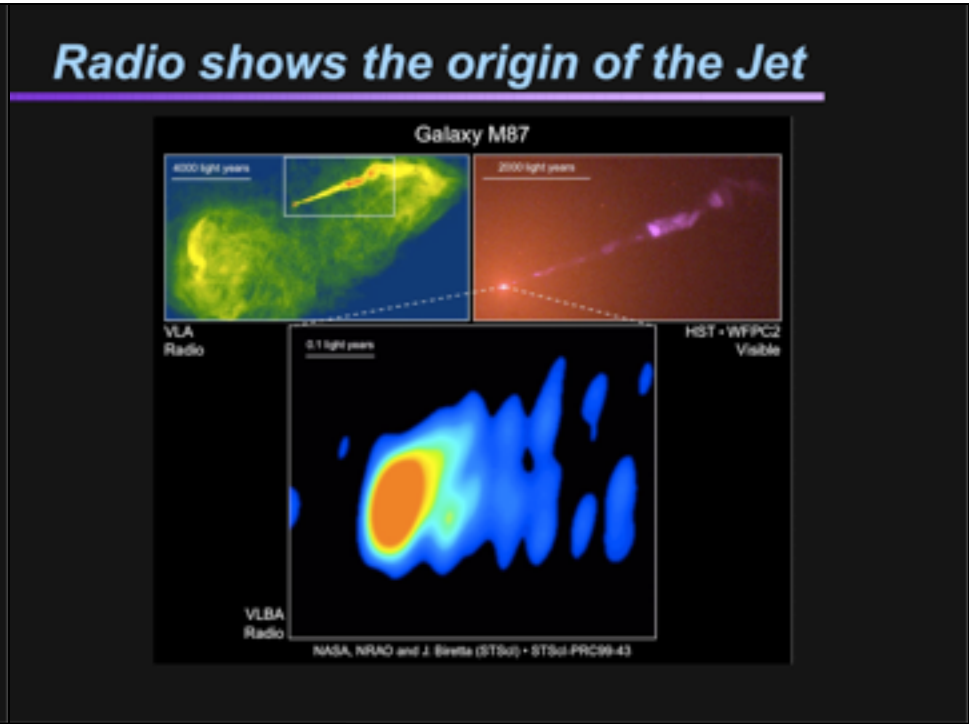


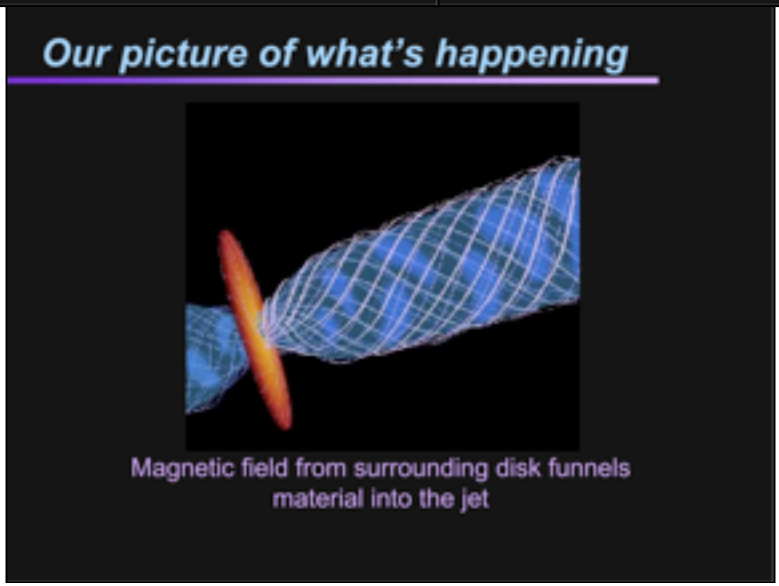
BLACK HOLES AT CENTERS OF GALAXIES



The mass of the black holes in galaxy centers is about 1/1000 the mass of the central spheroid of stars.

BLACK HOLES AT CENTERS OF GALAXIES

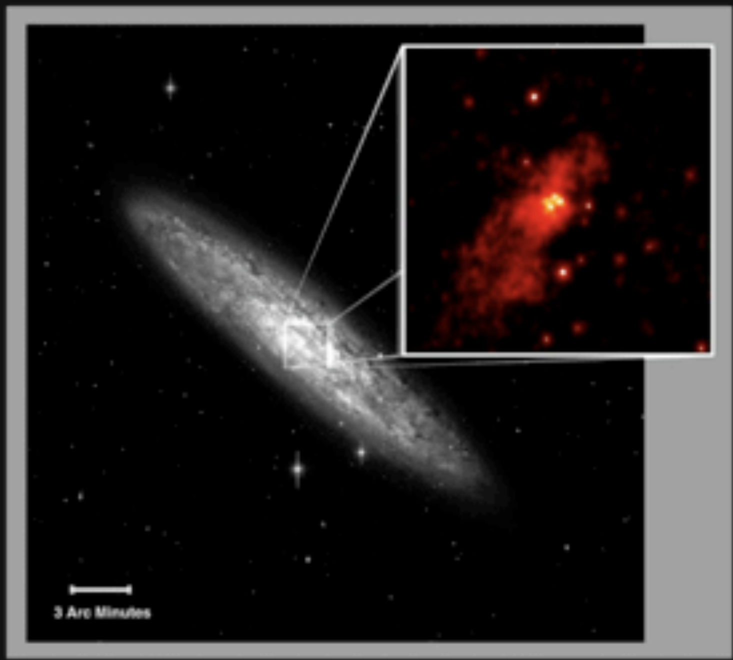




INTERMEDIATE MASS BLACK HOLES

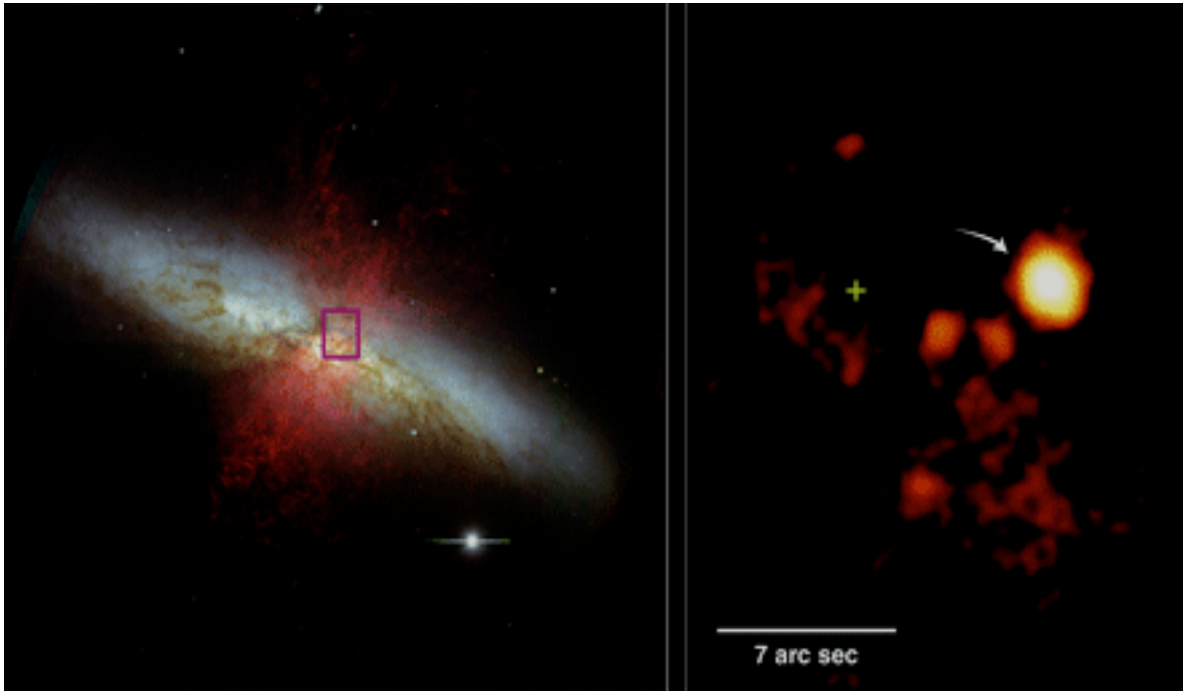
X-ray: Mid mass black holes

- 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

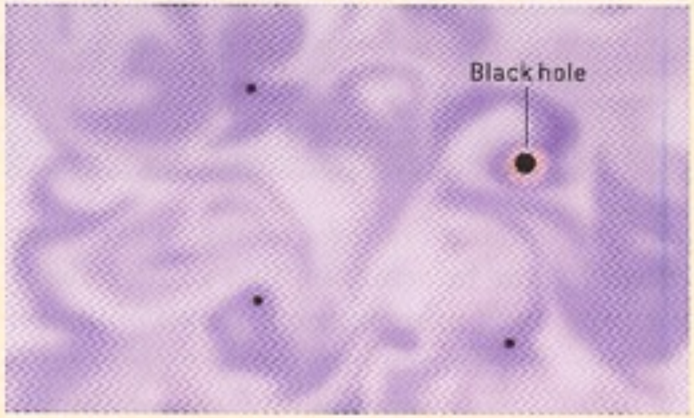


The best candidate for an intermediate-mass black hole. Optical (**left**) and Chandra x-ray (**right**) images of the M82 galaxy. The arrow points to the location of the ultraluminous x-ray source that is likely to be an intermediate-mass black hole. The area covered by the right image lies within the 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

Making Evaporating Black Holes?

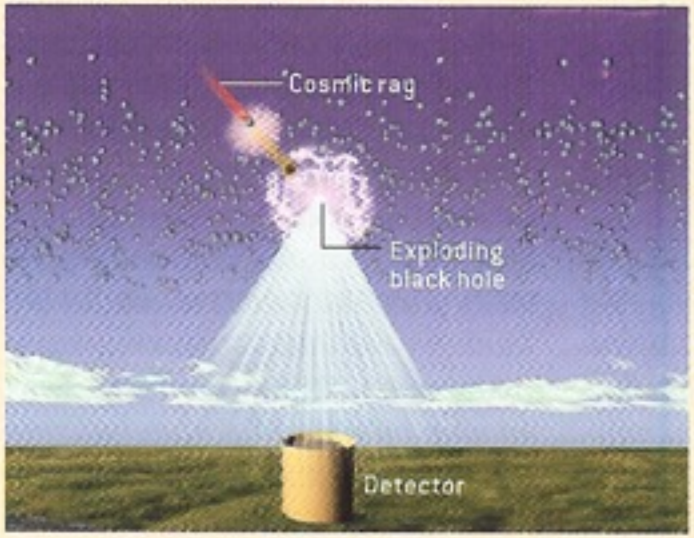
See “Quantum Black Holes” by Steve Giddings and Bernard Carr in the May 2005 *Scientific American*

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

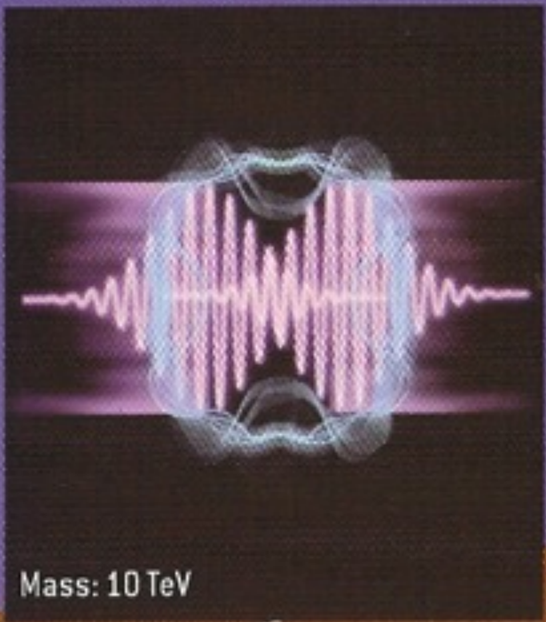
Cosmic rays—highly energetic particles from celestial sources—could smack into Earth's atmosphere and form black holes. They would explode in a shower of radiation and secondary particles that could be detected on the ground.

PARTICLE ACCELERATOR

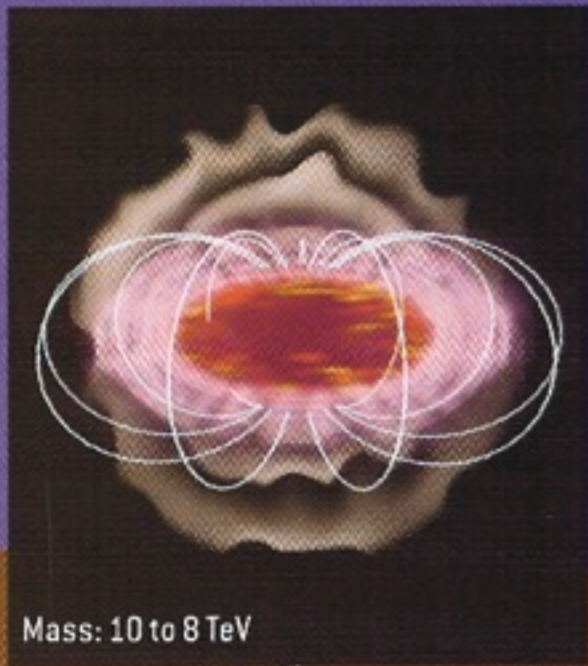
An accelerator such as the LHC could crash two particles together at such an energy that they would collapse into a black hole. Detectors would register the subsequent decay of the hole.

THE RISE AND DEMISE OF A QUANTUM BLACK HOLE

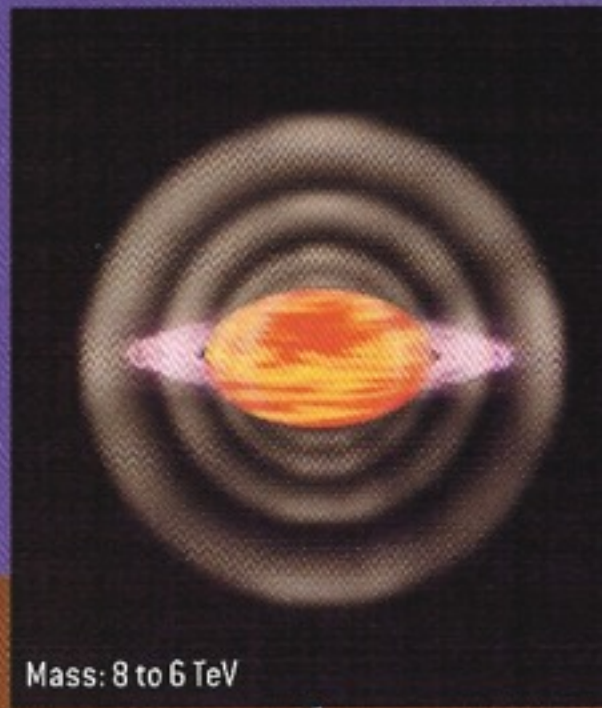
BIRTH



BALDING PHASE



SPIN-DOWN PHASE



TIME 0

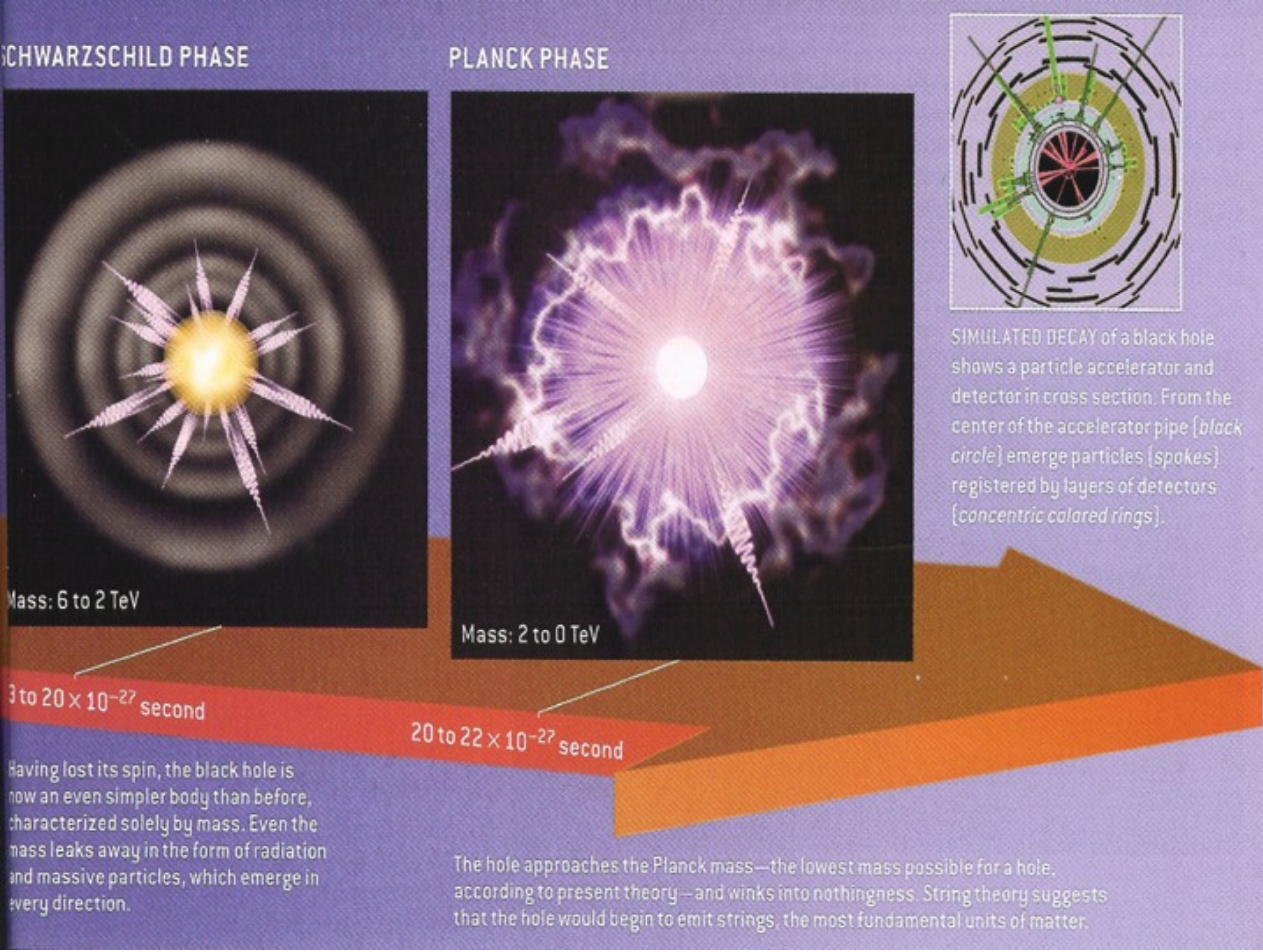
0 to 1×10^{-27} second

1 to 3×10^{-27} second

If conditions are right, two particles (shown here as wave packets) can collide to create a black hole. The newborn hole is asymmetrical. It can be rotating, vibrating and electrically charged. (Times and masses are approximate; 1 TeV is the energy equivalent of about 10^{-24} kilogram.)

As it settles down, the black hole emits gravitational and electromagnetic waves. To paraphrase physicist John A. Wheeler, the hole loses its hair—it becomes an almost featureless body, characterized solely by charge, spin and mass. Even the charge quickly leaks away as the hole gives off charged particles.

The black hole is no longer black: it radiates. At first, the emission comes at the expense of spin, so the hole slows down and relaxes into a spherical shape. The radiation emerges mainly along the equatorial plane of the black hole.



CHWARZSCHILD PHASE
Mass: 6 to 2 TeV
3 to 20 × 10^-27 second
Having lost its spin, the black hole is now an even simpler body than before, characterized solely by mass. Even the mass leaks away in the form of radiation and massive particles, which emerge in every direction.
PLANCK PHASE
Mass: 2 to 0 TeV
20 to 22 × 10^-27 second
The hole approaches the Planck mass—the lowest mass possible for a hole, according to present theory—and winks into nothingness. String theory suggests that the hole would begin to emit strings, the most fundamental units of matter.
SIMULATED DECAY of a black hole shows a particle accelerator and detector in cross section. From the center of the accelerator pipe (black circle) emerge particles (spokes) registered by layers of detectors (concentric colored rings).


Physics 5K Lecture 10 June 8, 2012
Have a Great Summer!