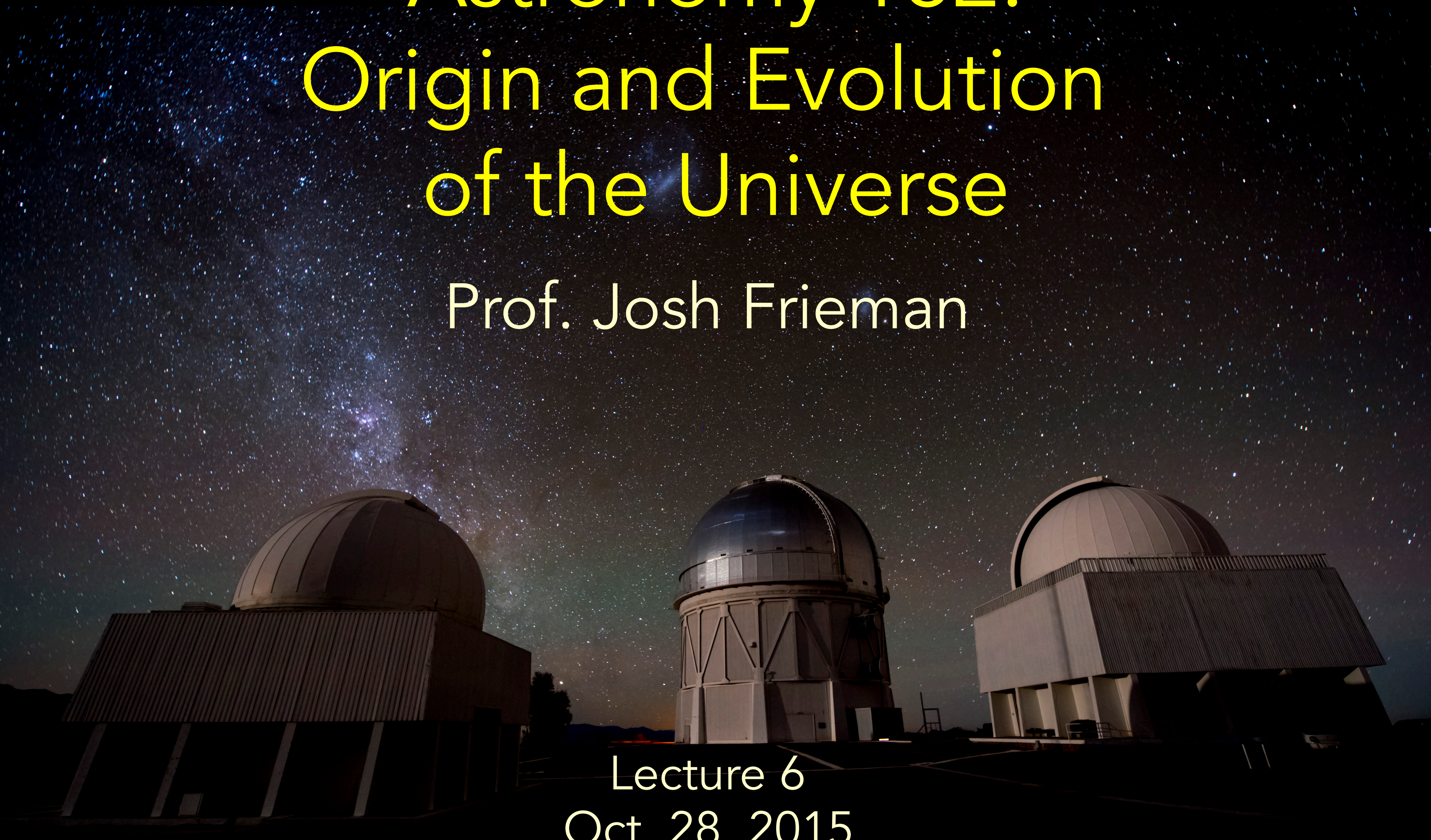
Astronomy 182: Origin and Evolution of the Universe

Prof. Josh Frieman



Lecture 6
Oct. 28, 2015

Today

- Wrap up of Einstein's General Relativity
  - Curved Spacetime
  - Gravitational Waves
  - Black Holes
  - Relativistic Cosmology

Assignments

- This week: read Hawley and Holcomb, Chapters 7-9, 13.
- This Friday: Lab 2 write-up due in class.
- Next Fri., Nov. 6: Essay due on HH, Chapter 8.

- Note: I won't be available this Friday 1-2 pm for office hours. Please send me email if you'd like to schedule alternate office hours or stop by next week.

Einstein's General Relativity (1915)

Special Relativity: Space & Time are not universal, but depend on the state of motion of the observer.

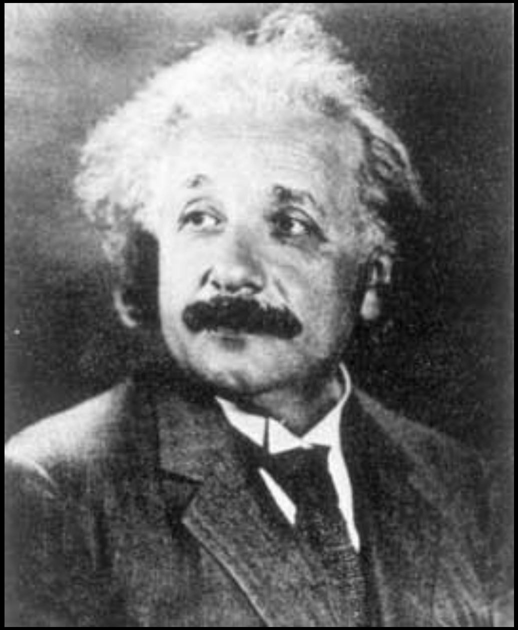
General Relativity: Space & Time are dynamical quantities that respond to (are distorted by) the presence of mass-energy: spacetime distortions are what we call gravity.

SR: considered observers in constant relative motion wrt each other (inertial observers); Observers cannot distinguish rest from motion at constant speed.

GR: considers observers in non-constant (i.e., accelerated) motion; Obs. cannot distinguish uniform acceleration from the (local) effects of gravity. (Principle of Equivalence)

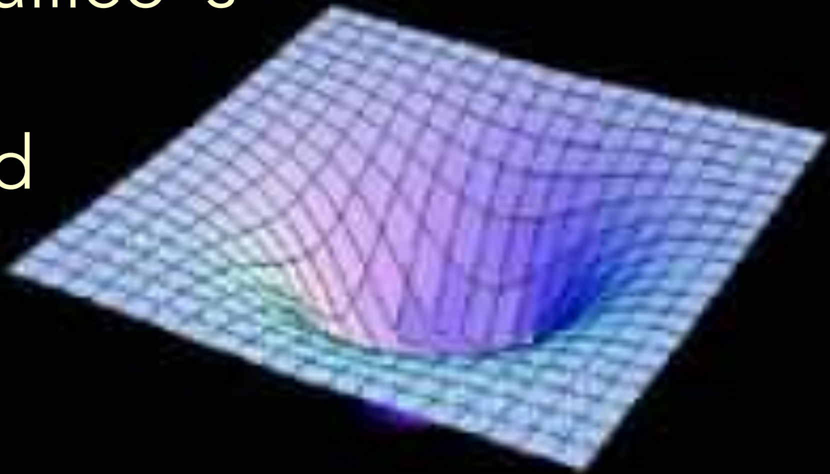
Einstein's General Realtivity

Describes how Matter (mass-energy) affects the structure of Spacetime



Replaces Newtonian forces acting at a distance

Automatically incorporates Galileo's observation that all objects fall at same rate in a grav. field



A massive star attracts nearby objects by distorting spacetime around it

Gravity: Newton vs. Einstein

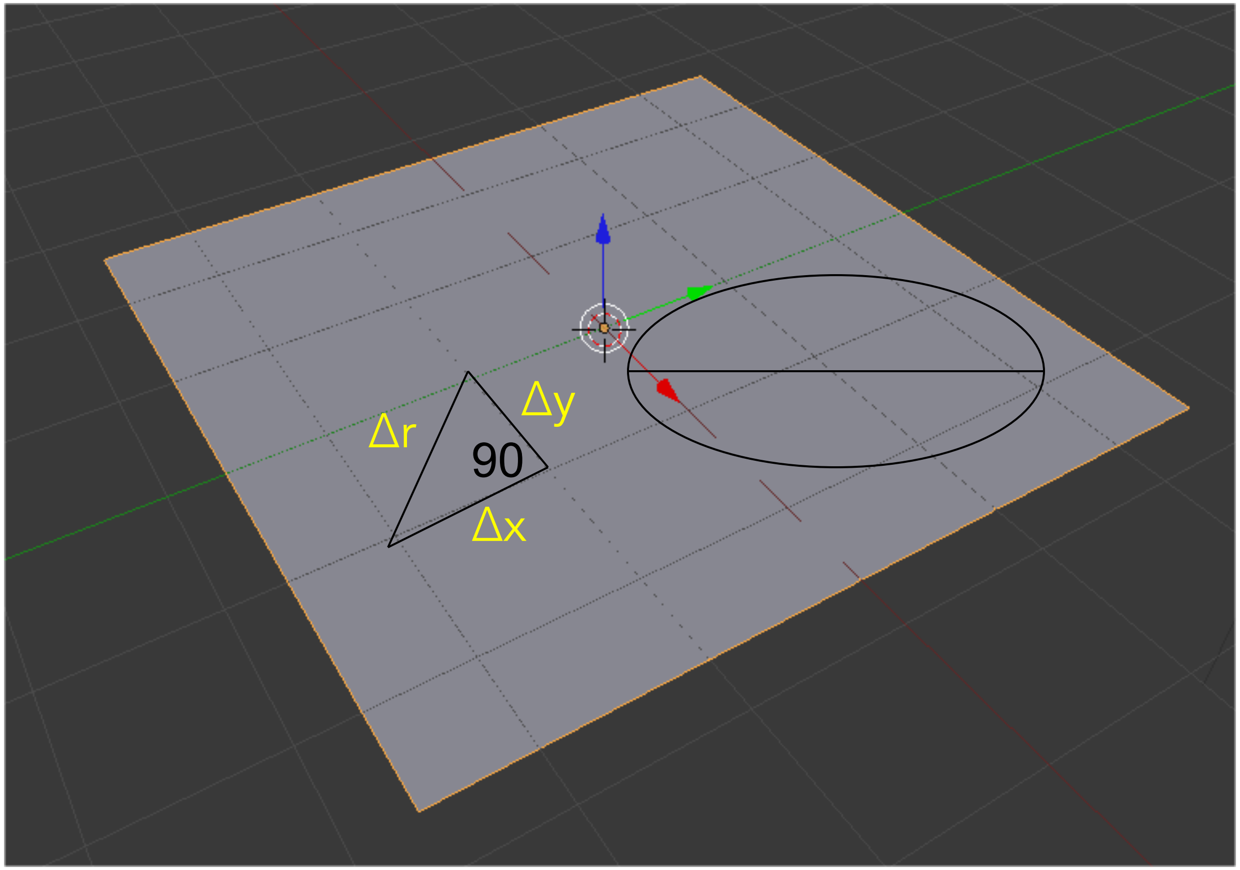
Newton:

- Gravitation is a force exerted by one massive body on another.
- A body acted on by a force accelerates

Einstein:

- Gravitation is the curvature of spacetime due to a nearby massive body (or any form of energy)
- A body follows the `straightest possible path ‘ (aka geodesic) in curved spacetime

Flat 2d Space



Circumference of circle on this flat surface:

$C/r = 2\pi$ where $\pi = 3.1415926...$

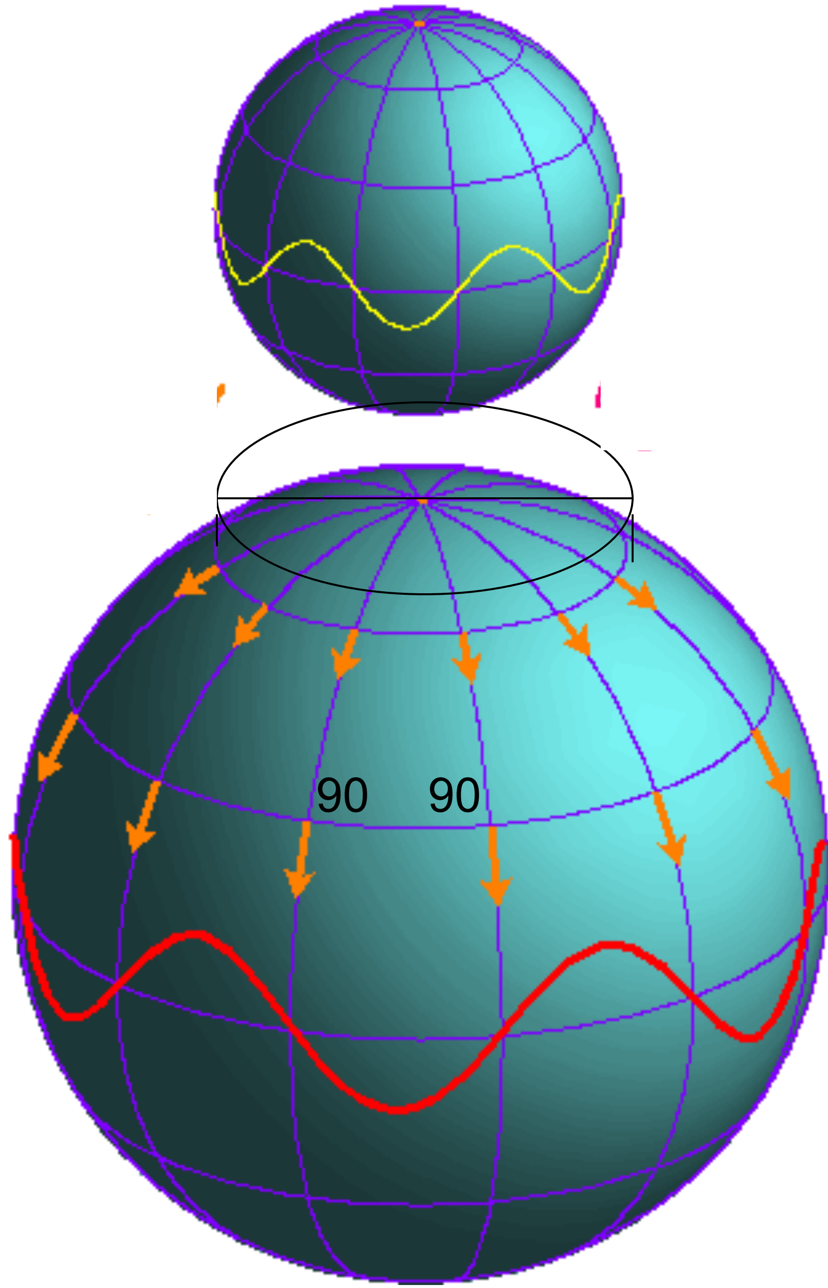
Sum of interior angles of triangle

Σangles = 180 deg

Distance:

$(\Delta r)^2 = (\Delta x)^2 + (\Delta y)^2$

Curved 2d Space



Circumference of circle on this curved spherical surface:
C/r < 2π where
π=3.1415926…

Sum of interior angles of triangle
Σangles > 180 deg

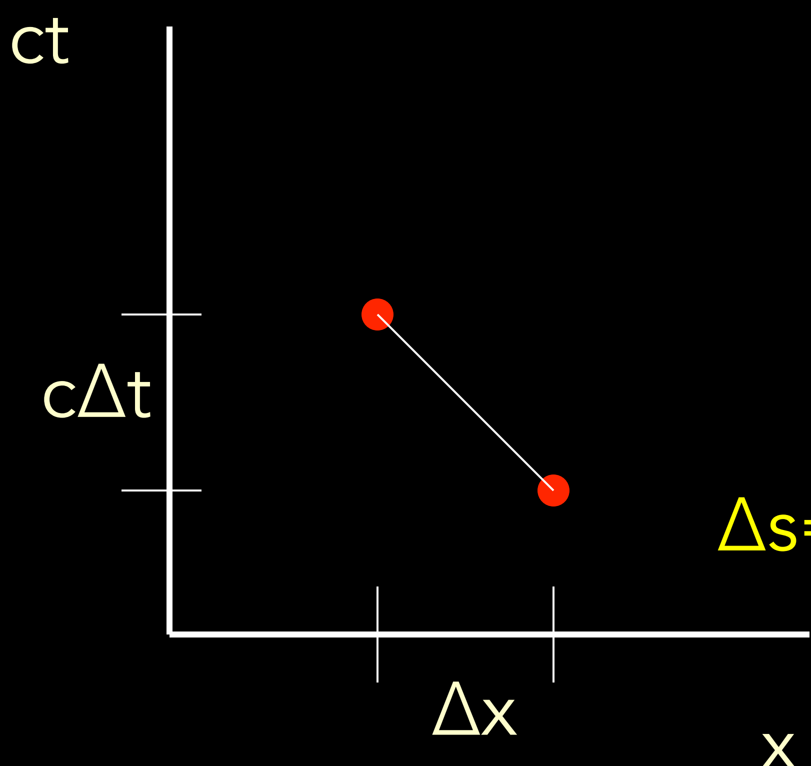
Space vs Spacetime Curvature

Curvature of 3-dimensional Space vs. Curvature of 4-dimensional Spacetime:

General Relativity: implies that Spacetime is generally curved.

Cosmology: mainly concerned with the curvature of 3-dimensional space (K) (i.e., of a `slice' through spacetime at a fixed time) since it is related to the density and fate of the Universe.

Spacetime Intervals: SR

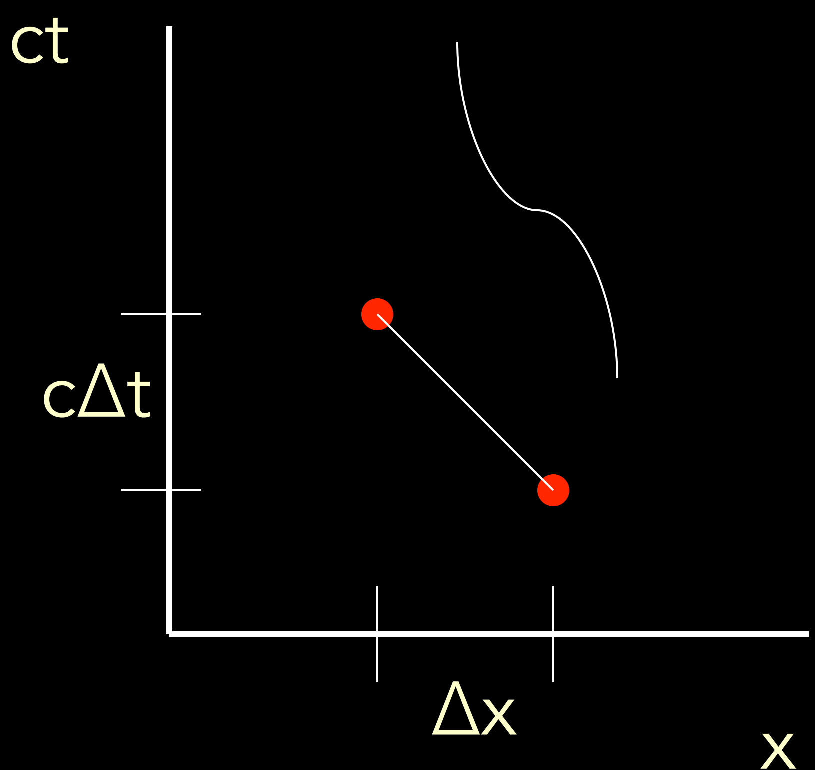


Inertial (constant-velocity) Observers in absence of gravity agree on the *spacetime* interval of Special Relativity between 2 events:

$$\Delta s=[(c\Delta t)^2-(\Delta x)^2-(\Delta y)^2-(\Delta z)^2]^{1/2}$$

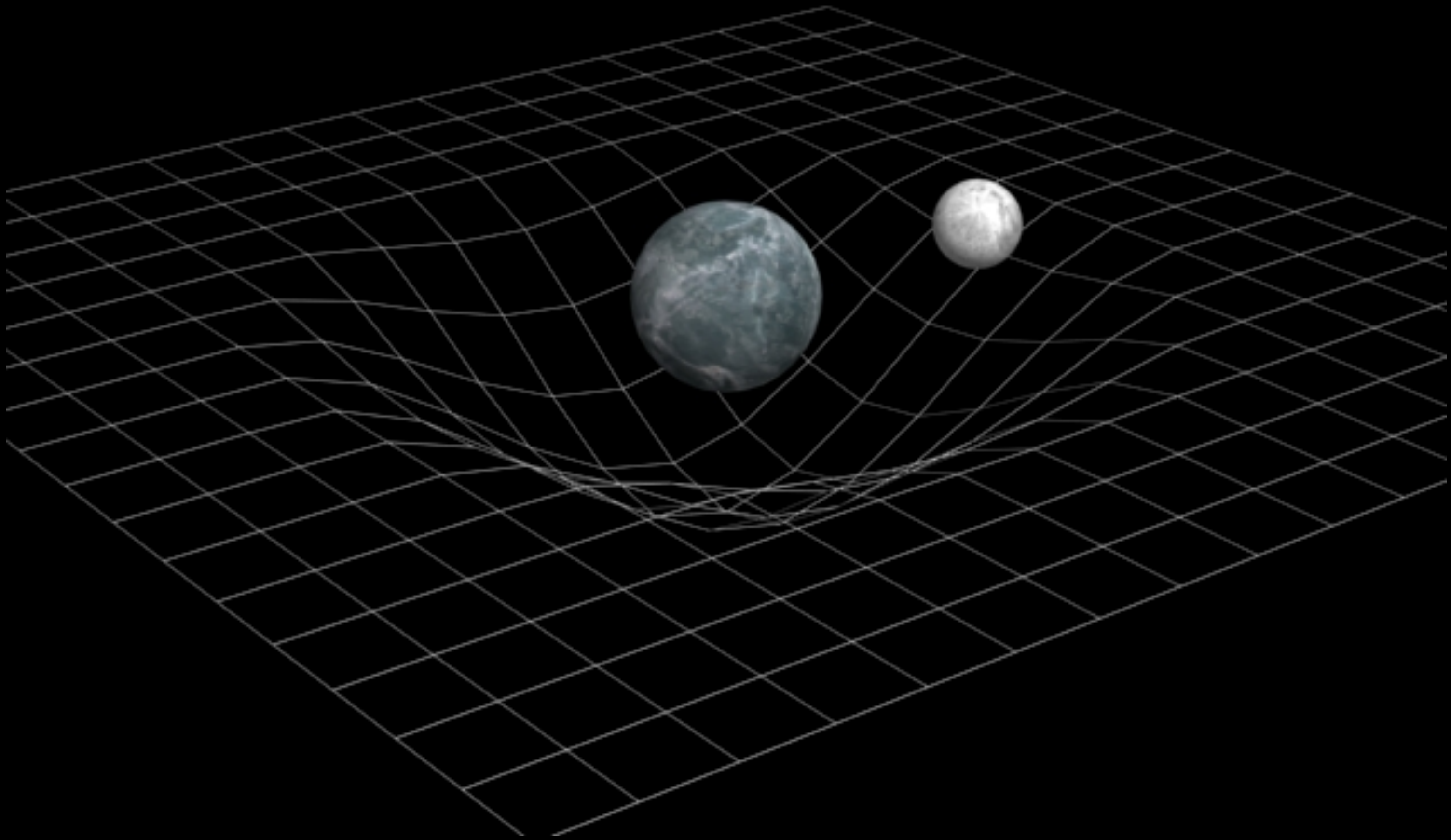
Worldlines of inertial observers are straight. The spacetime of Special Relativity is said to be *flat*.

Spacetime Intervals: GR

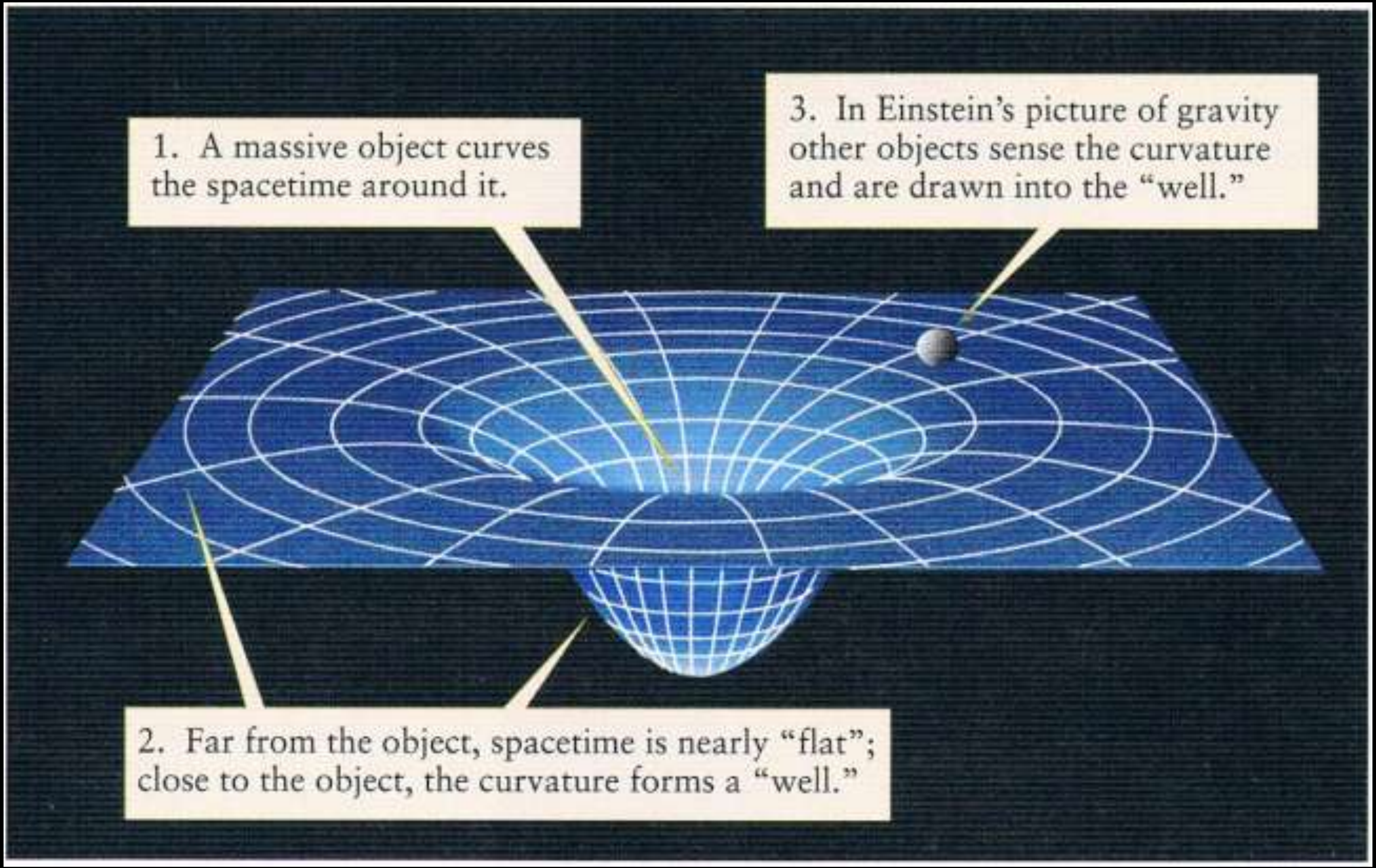


Worldlines of (accelerated) observers in a gravitational field are curved. The spacetime of General Relativity is curved. The *spacetime* interval Δs of General Relativity between 2 events encodes this curvature.

Curved Spacetime

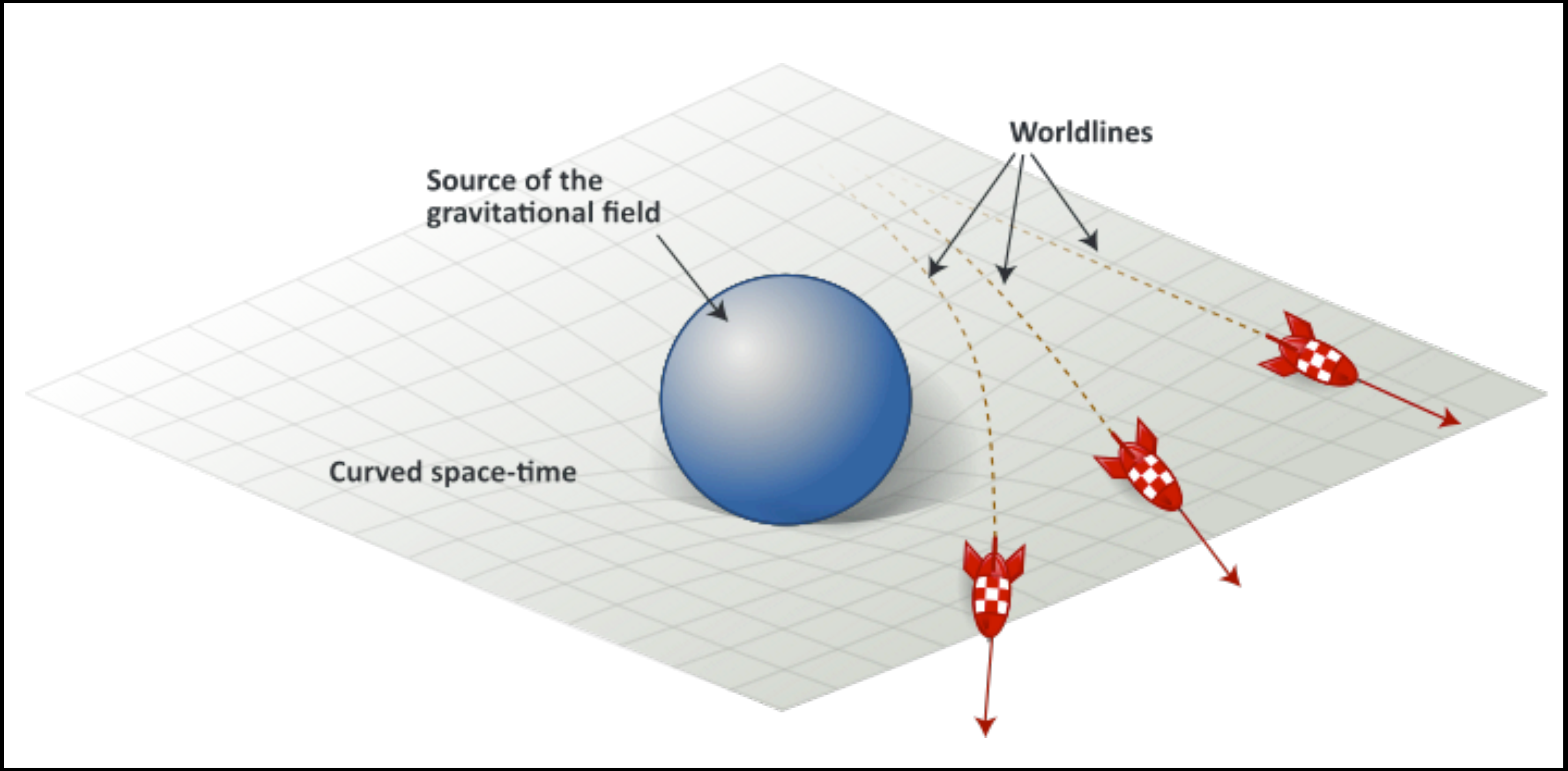


Curved Spacetime

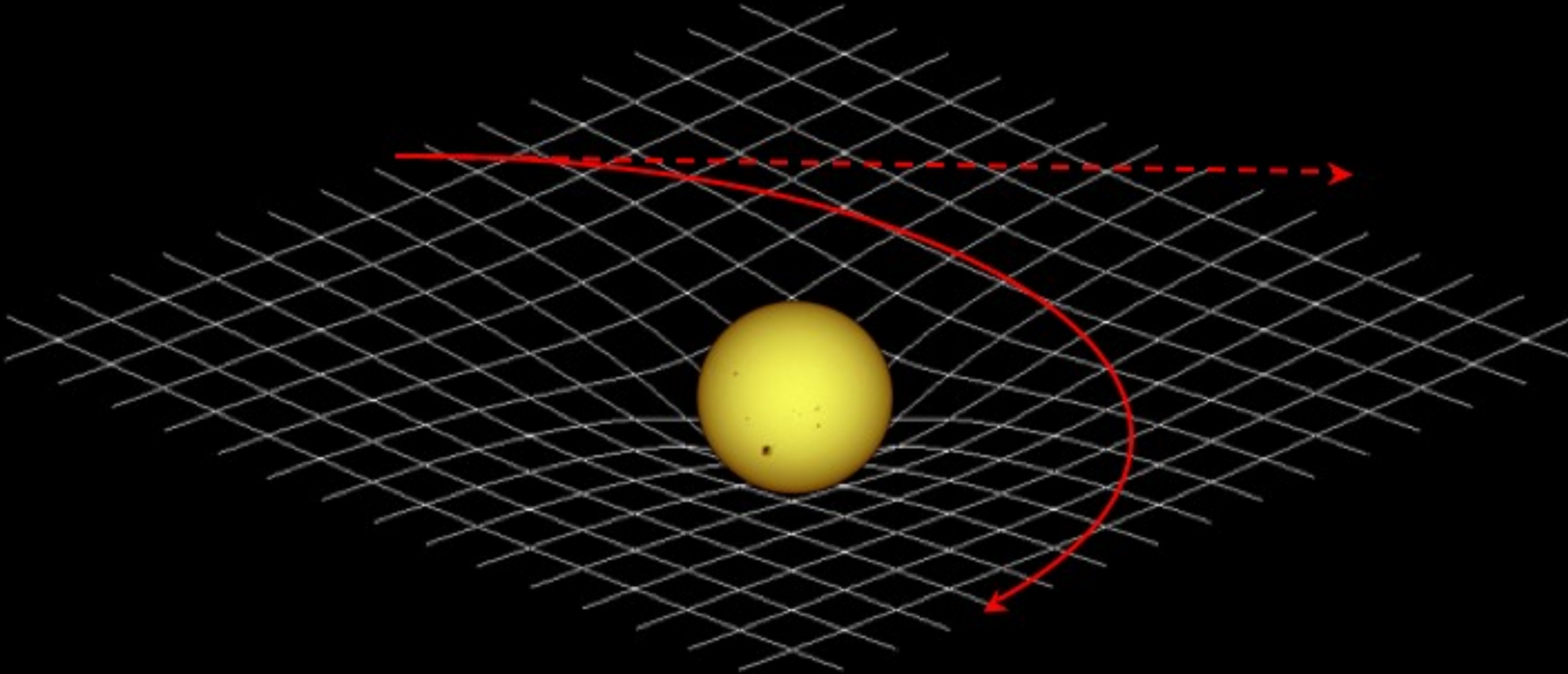


Best Buy advertisment

Orbits in Curved Spacetime

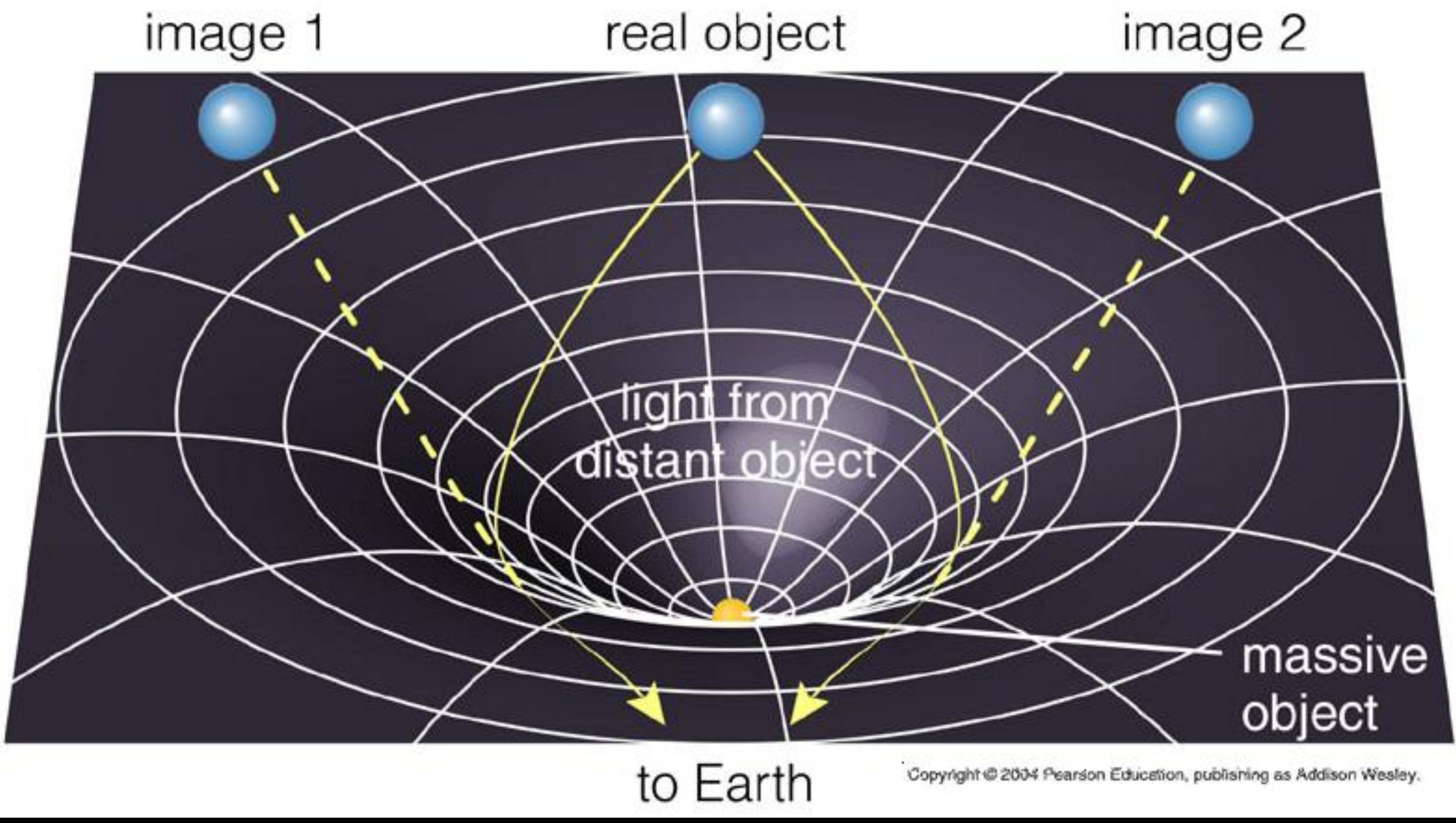


Gravitational Bending of Light

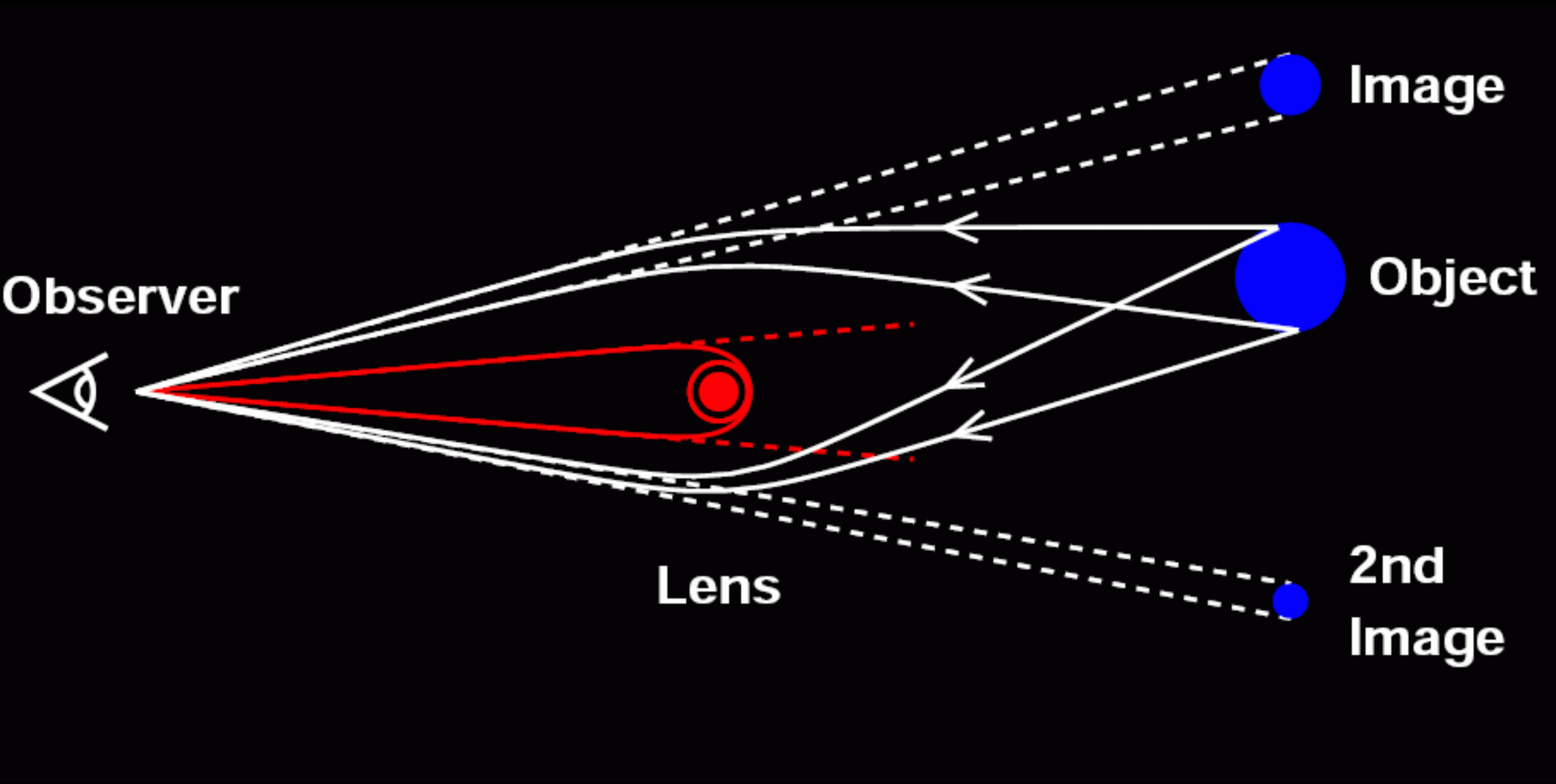


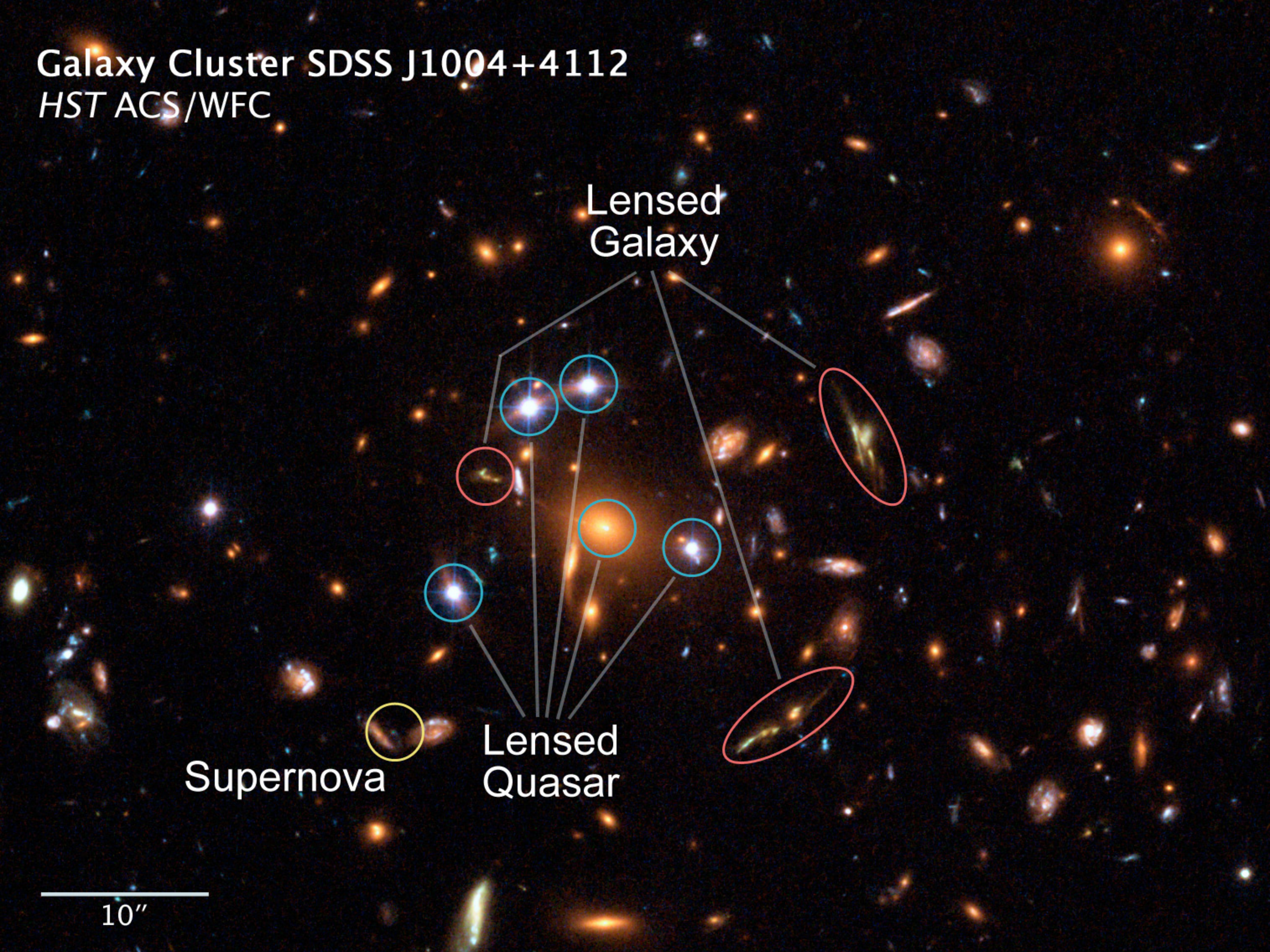
First observed in solar eclipse expeditions of 1919: confirmed prediction of GR

Gravitational Lensing

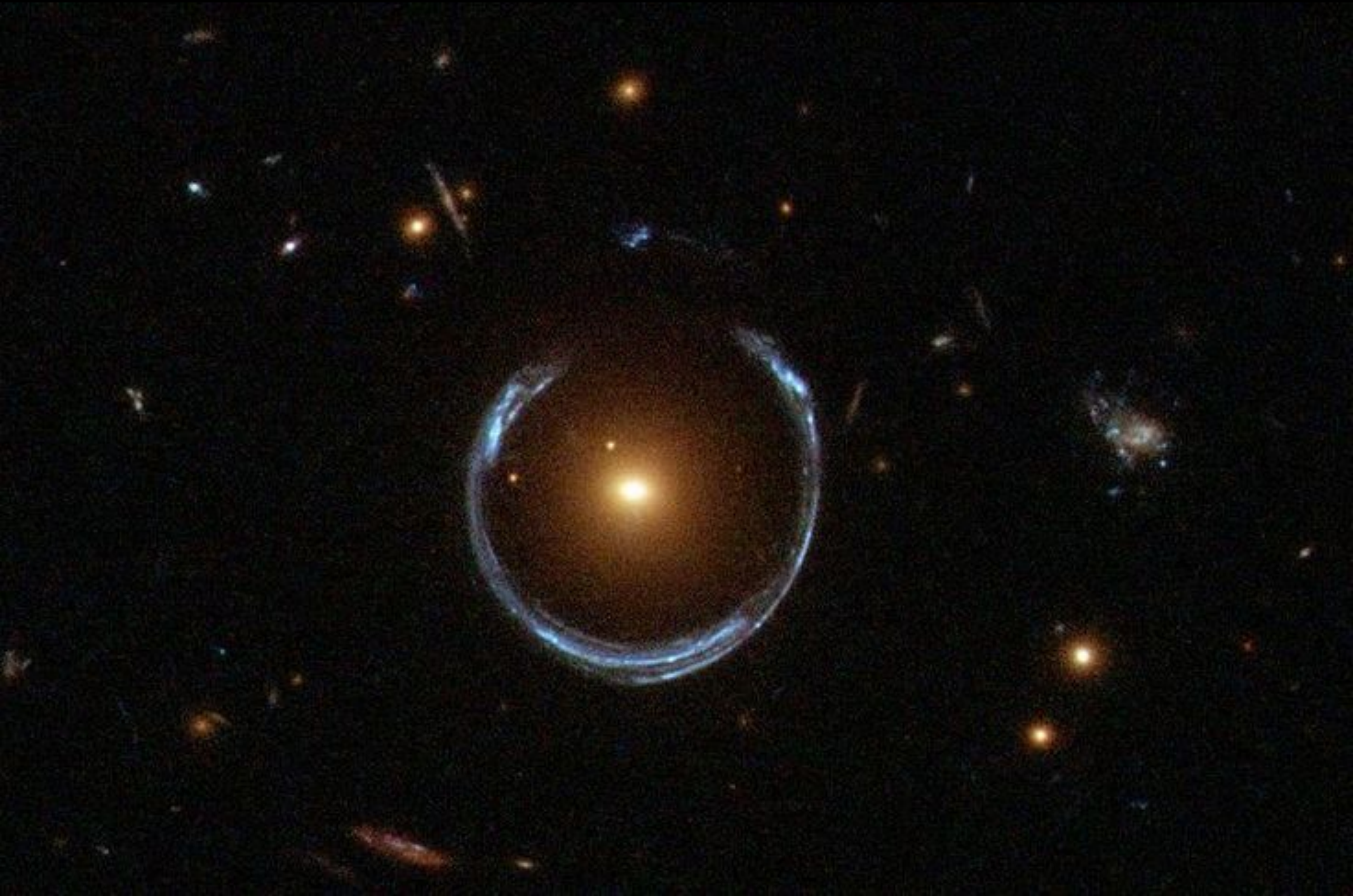


Gravitational Lensing




Galaxy Cluster SDSS J1004+4112
HST ACS/WFC
Lensed Galaxy
Lensed Quasar
Supernova
10″

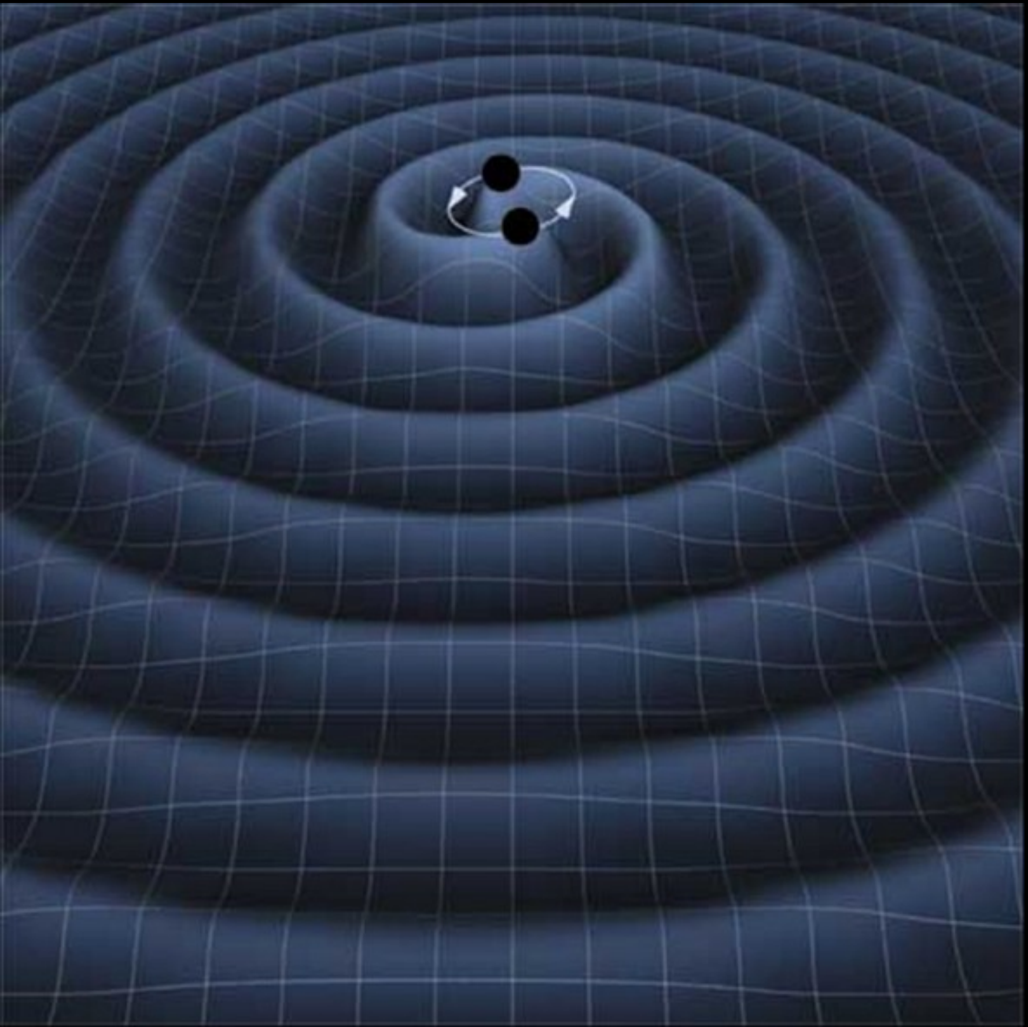
Gravitational Lensing: Einstein Ring



Gravity vs. Electromagnetism

- Maxwell:
  - Theory of Electromagnetism describes how electric charges create Electric Fields and how electric currents create Magnetic Fields.
  - Light explained as a travelling electromagnetic wave.
- Einstein:
  - General Relativity describes how mass-energy creates Gravitational Field (=Spacetime curvature).
  - Travelling gravitational waves (at the speed of light) also predicted by the theory: travelling distortions of spacetime

Gravitational Waves from Binary Pulsar



Two neutron stars orbiting each other, one of which is giving off radio pulses as it spins

Gravitational Waves from Binary Pulsar

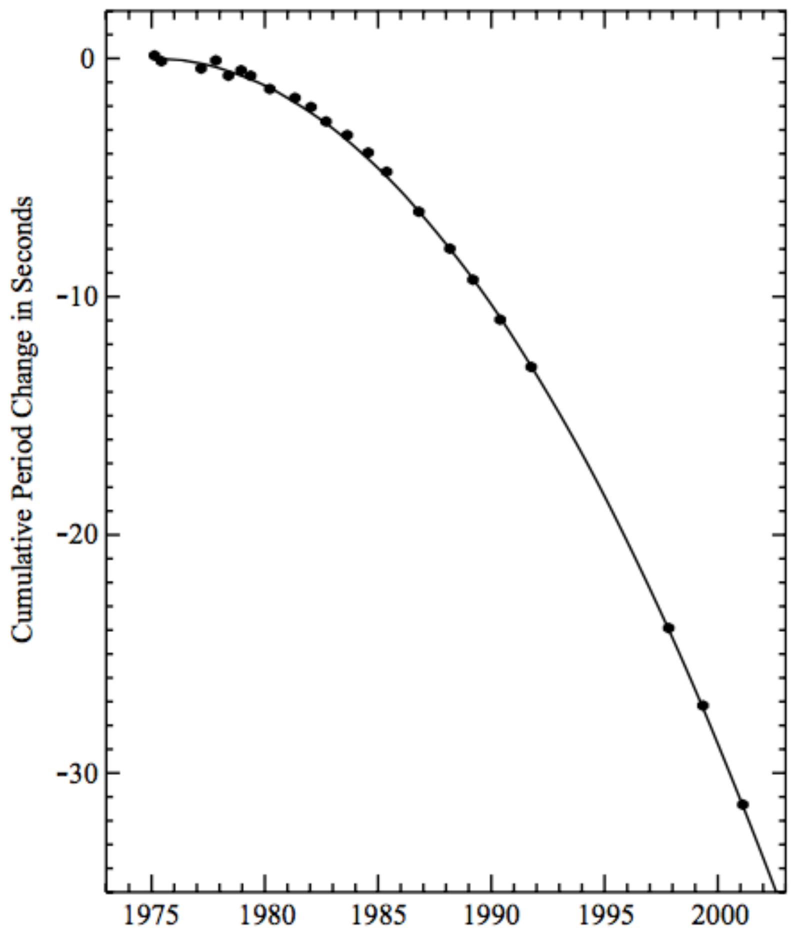


Fig. 8.11 The binary pulsar 1913+16 provides evidence for the existence of gravitational radiation. The loss of orbital energy to gravity waves causes the orbital period to change with time. The solid line is the prediction from general relativity; the dots are the observations. (Adapted from Weisberg and Taylor, 2003.)

Detecting Gravitational Waves from Binary Inspiral

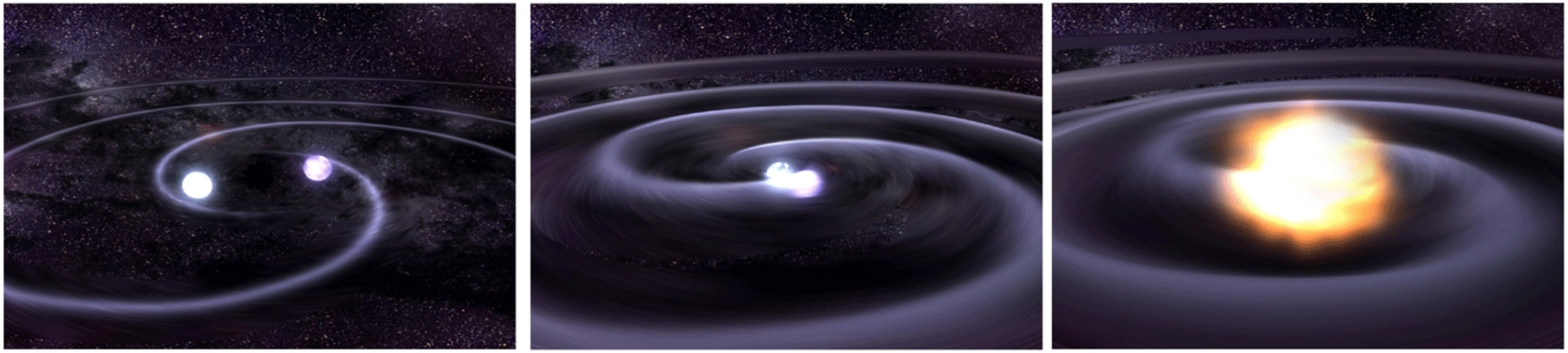
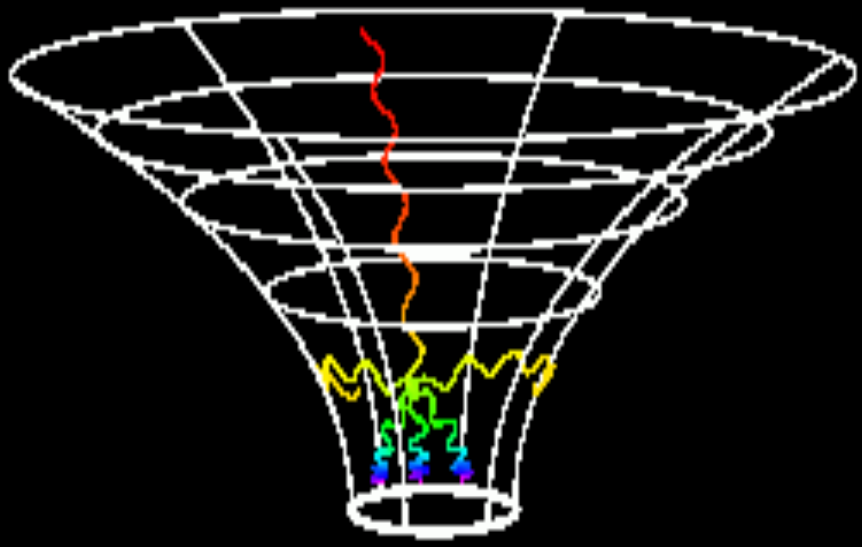


Fig. 8.12 The LIGO gravity-wave detector at Hanford, Washington. LIGO, basically a huge Michelson–Morley interferometer, consists of two 4-km long evacuated pipes at right angles. Gravity waves can cause small differences in light-travel time down the pipes, which can be detected as shifts in the interference fringes when the beams recombine. (Caltech/NSF/LIGO.)

Gravitational Redshift



C/r < 2π

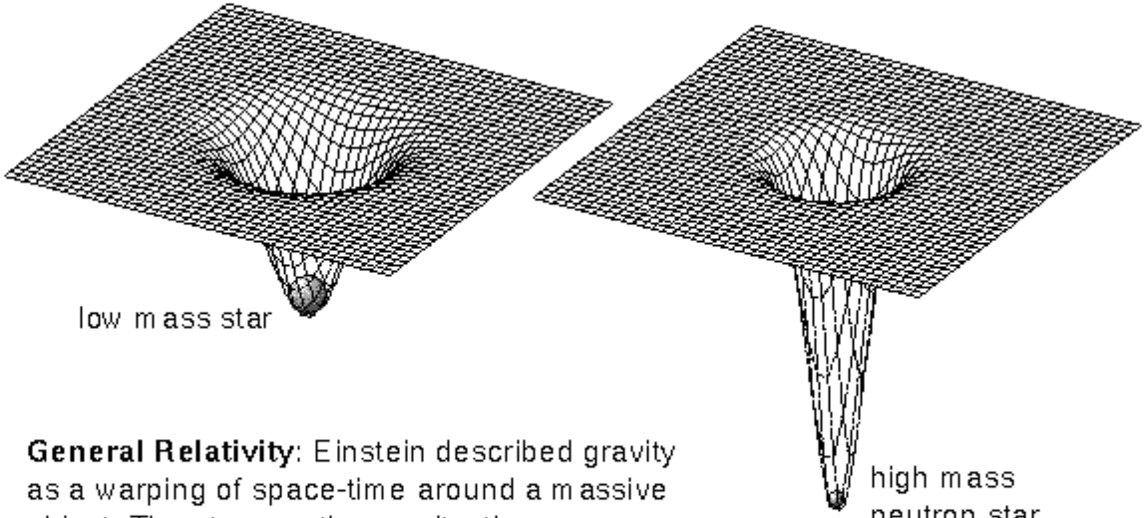
Light travelling outward from a massive body is redshifted, i.e., the wavelength is increased (space near the body is radially stretched)

Observational Evidence for General Relativity

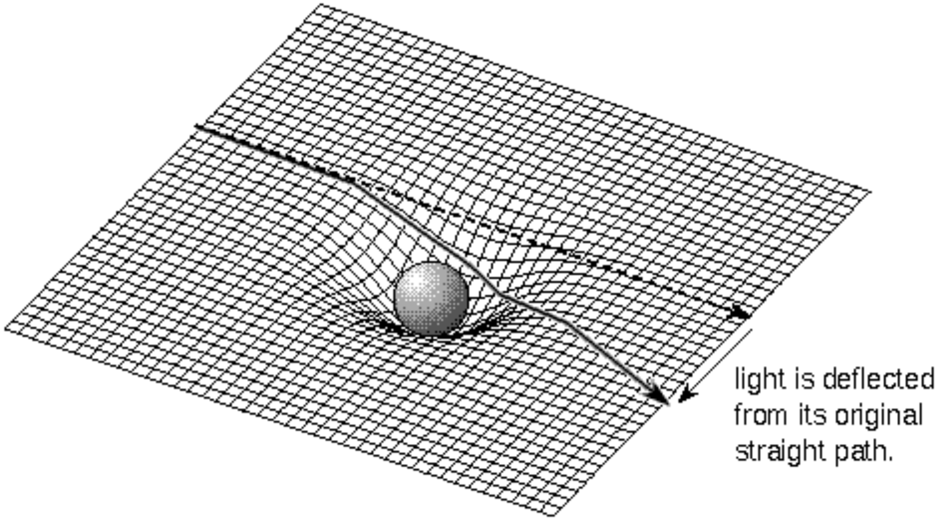
- Gravitational bending of star light: solar eclipse observations
- Anomaly in the orbit of Mercury (measureable difference from Newtonian prediction)
- Gravitational redshift and time dilation experiments
- Indirect evidence for Gravitational radiation from binary pulsar orbital change
- Next: direct detection of gravity waves by Advanced LIGO from NS-NS or NS-BH binaries

Strong Gravity

- Sun: radius R=700,000 km
- Compact objects: White dwarf: R~7000 km Neutron star: R~10 km



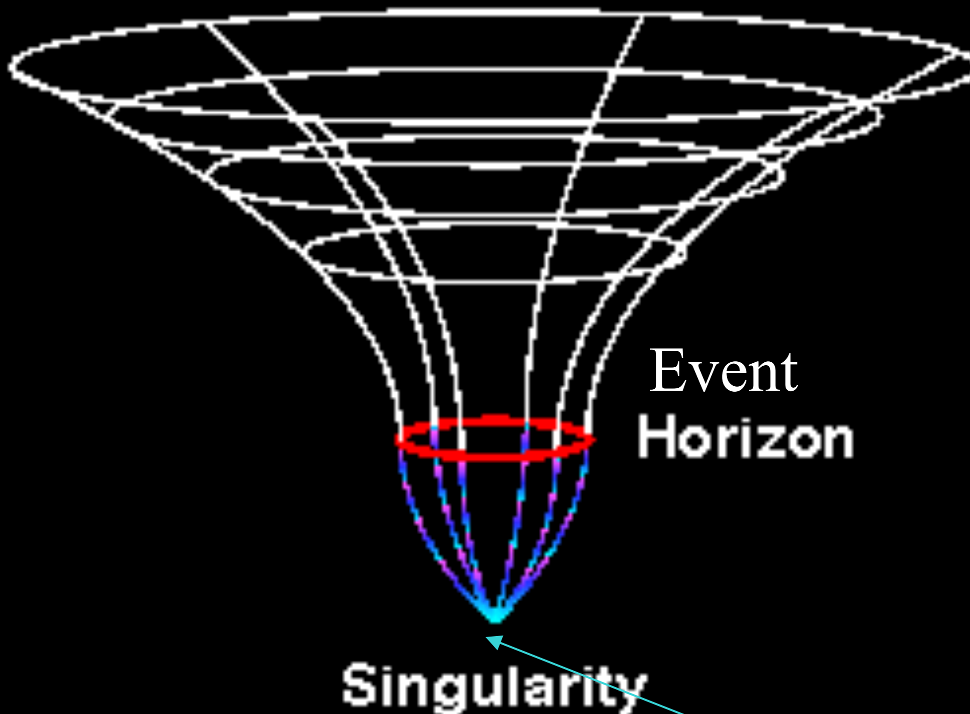
General Relativity: Einstein described gravity as a warping of space-time around a massive object. The stronger the gravity, the more space-time is warped.



General Relativity: Light travels along the curved space taking the shortest path between two points. Therefore, light is deflected toward a massive object! The stronger the local gravity is, the greater the light path is bent.

Black Hole

Region of strong spacetime curvature from which nothing, not even light, can escape



Radius of Event Horizon (Schwarzschild radius):

$r_{Sch} = 2GM/c^2$

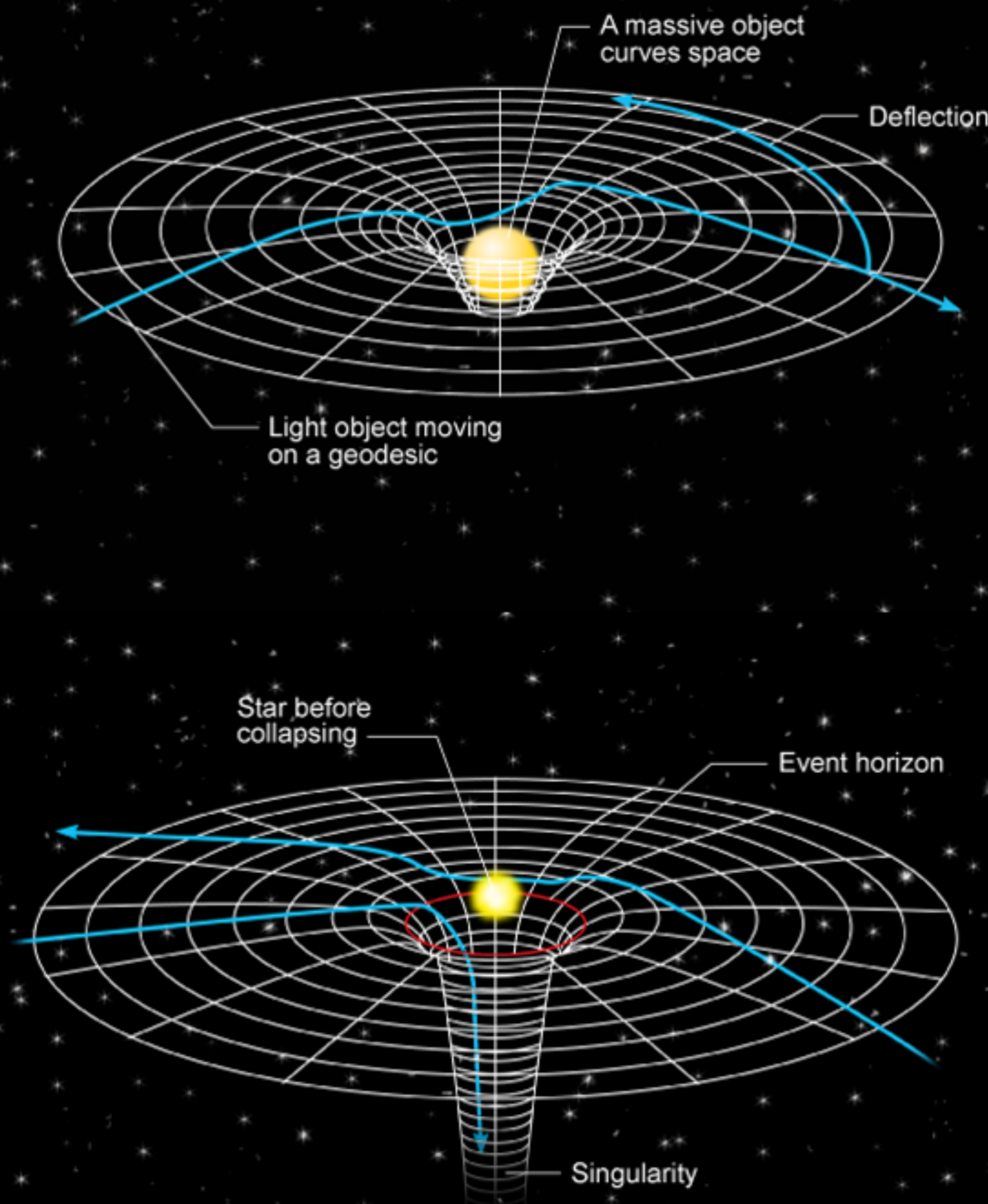
Nothing escapes from within Event Horizon

Laws of physics break down here: infinite Spacetime curvature

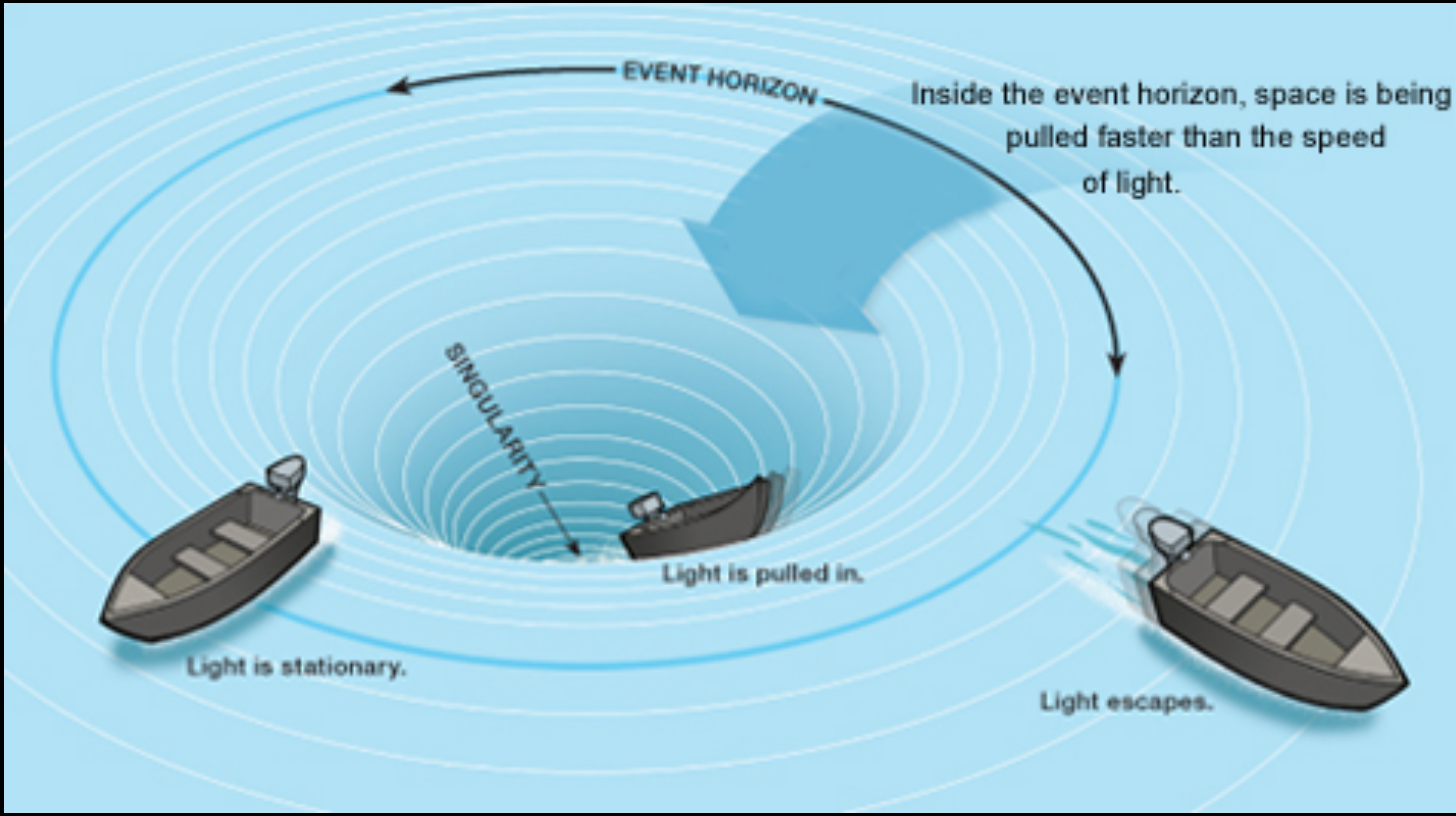
Black Hole

Radius of Event Horizon (Schwarzschild radius):

$r_{Sch} = 2GM/c^2$



Black Hole



Radius of Event Horizon (Schwarzschild radius):

$r_{Sch} = 2GM/c^2$

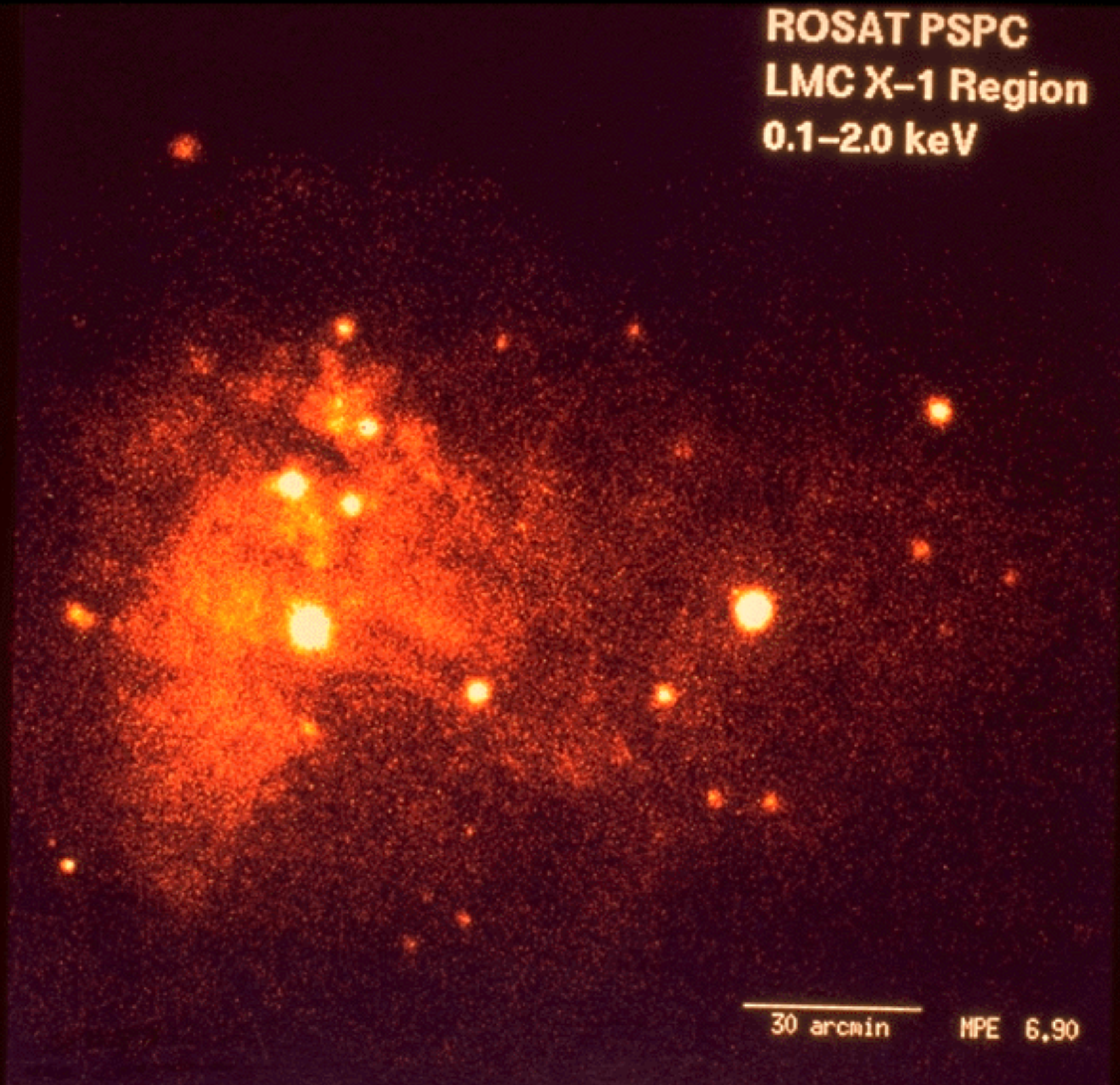
$= 3$ km

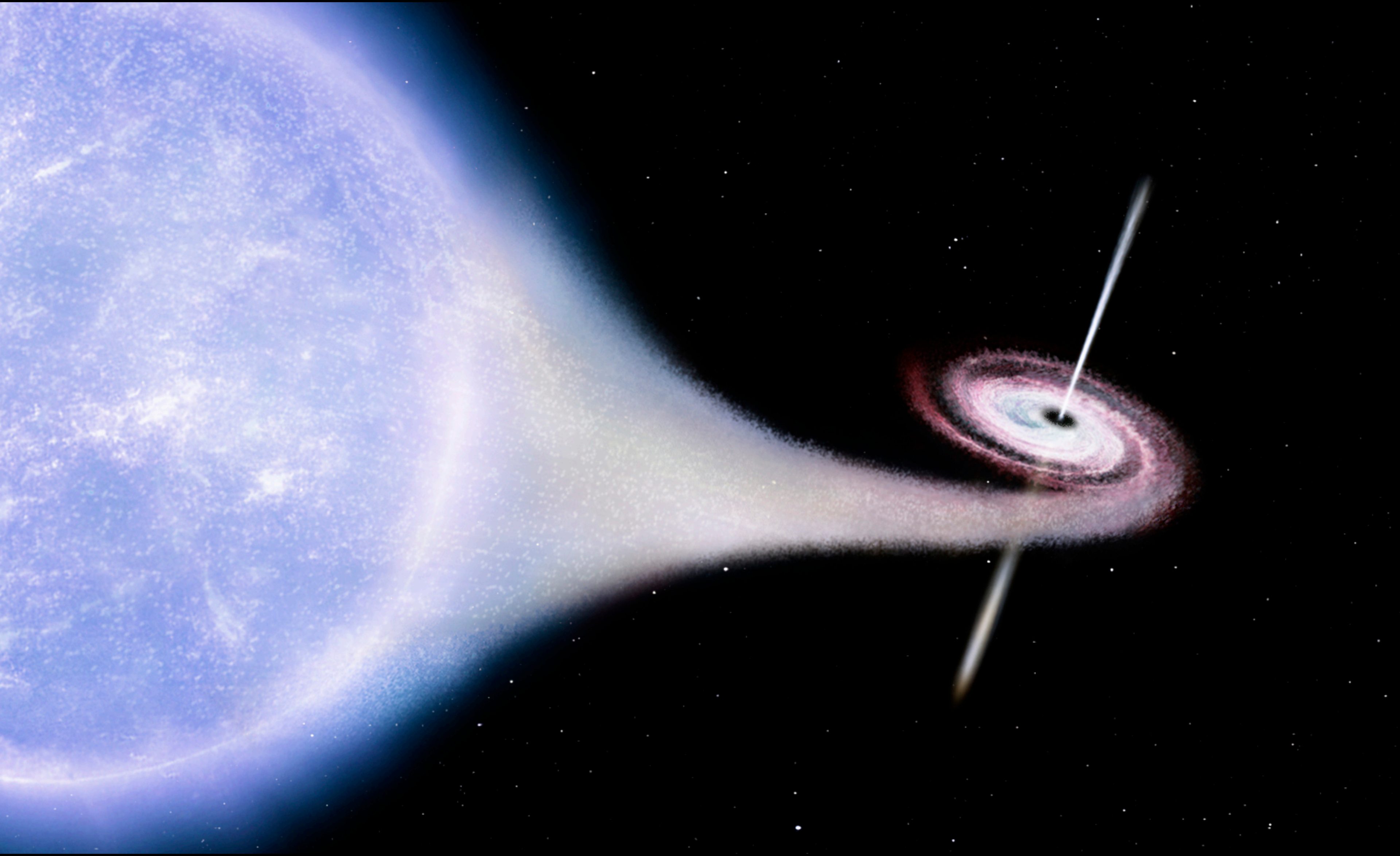
for object with mass of the Sun

Black Hole LMC X-1

X-ray emitting binary system in the Large Magellanic Cloud. Normal star and compact star in binary orbit, compact star accretes gas from the normal star. As the gas hits the compact star, it glows in X-rays. These X-rays excite atoms in the vicinity and in turn cause them to glow in X-rays.

Orbital motion of the system indicates the compact star has a mass 5 times that of the Sun, larger than maximum mass of neutron stars, and is thus very likely a Black Hole.

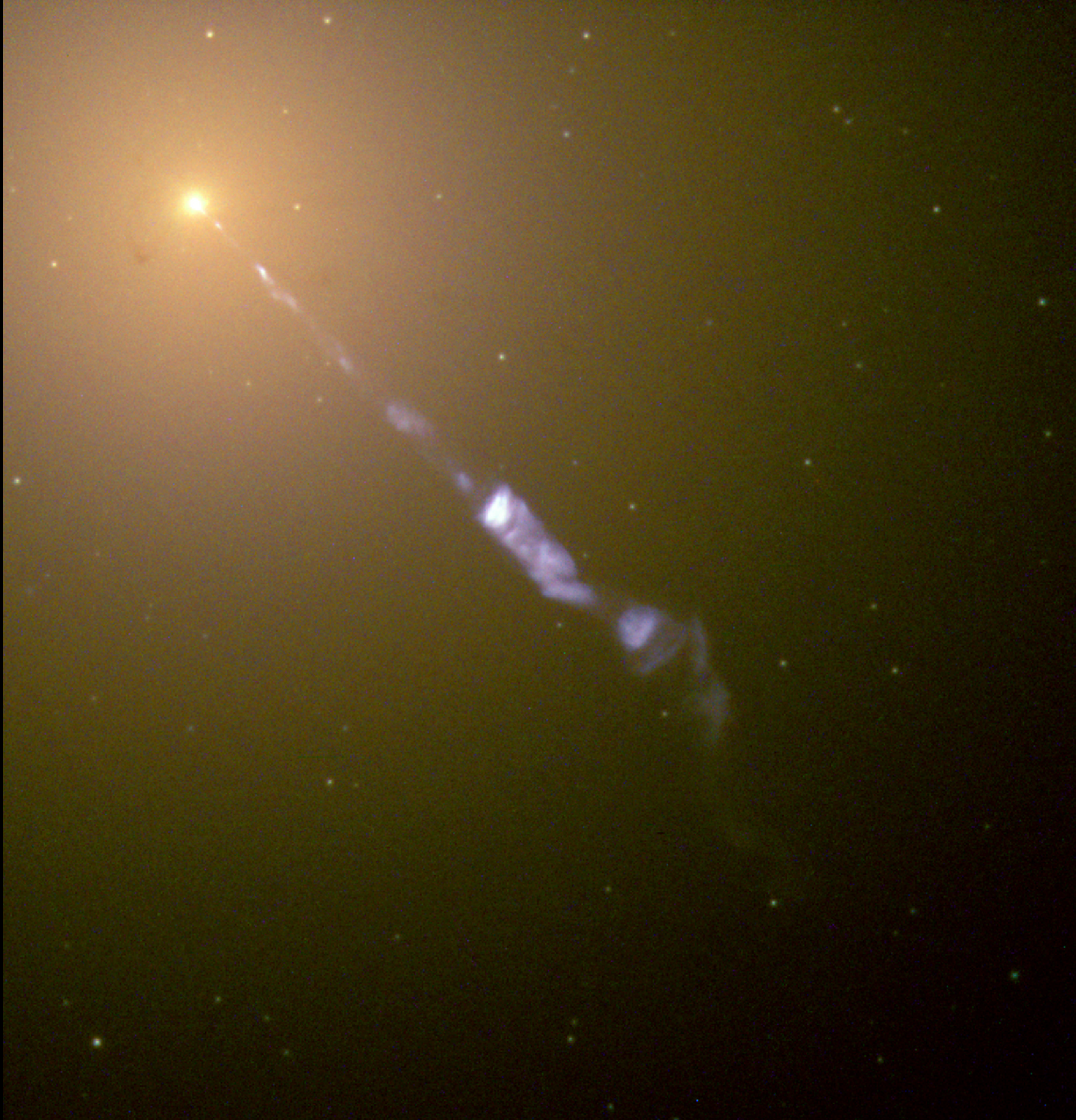

ROSAT PSPC
LMC X-1 Region
0.1–2.0 keV
30 arcmin
MPE 6.90



M87: Giant Elliptical Galaxy

Contains Black Hole of ~6 billion times the mass of the Sun

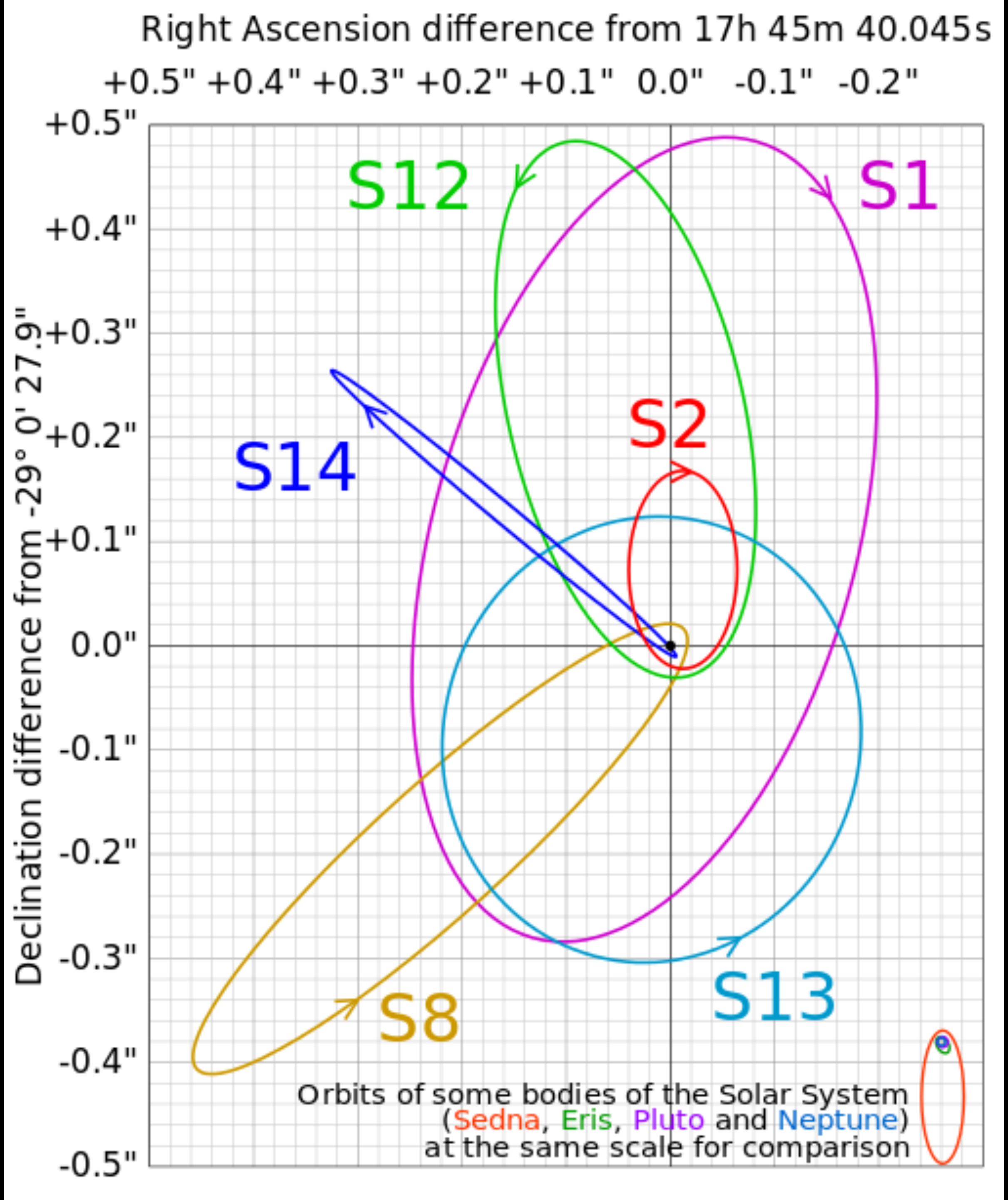
Jet of material emanating from its core



Sagittarius A*: Center of the Milky Way

Contains Black Hole of ~4 million times the mass of the Sun

Orbits of 6 stars traced very near the Black Hole



Sagittarius A*: Center of the Milky Way

Contains Black Hole of ~4 million times the mass of the Sun

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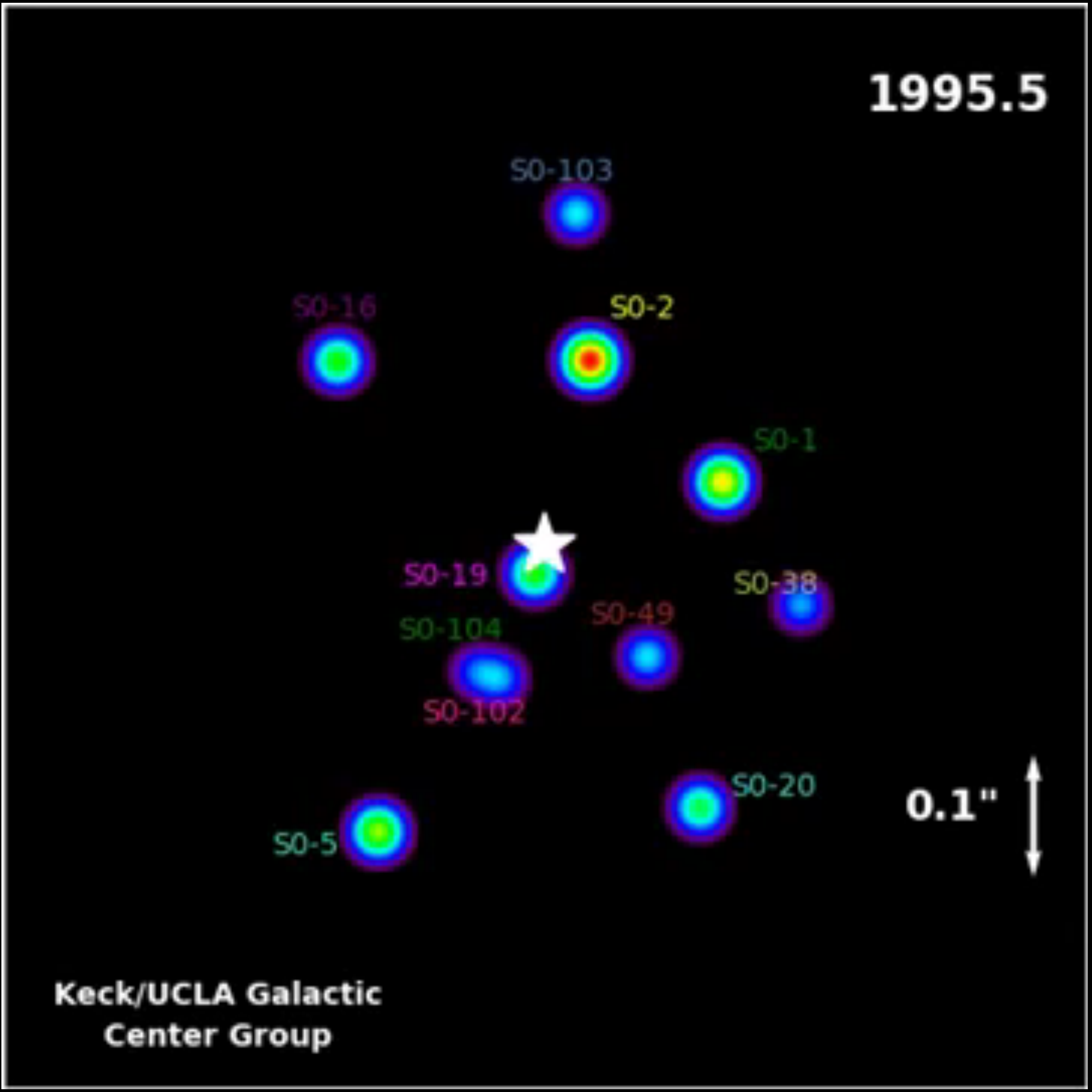


Black Holes in the Universe

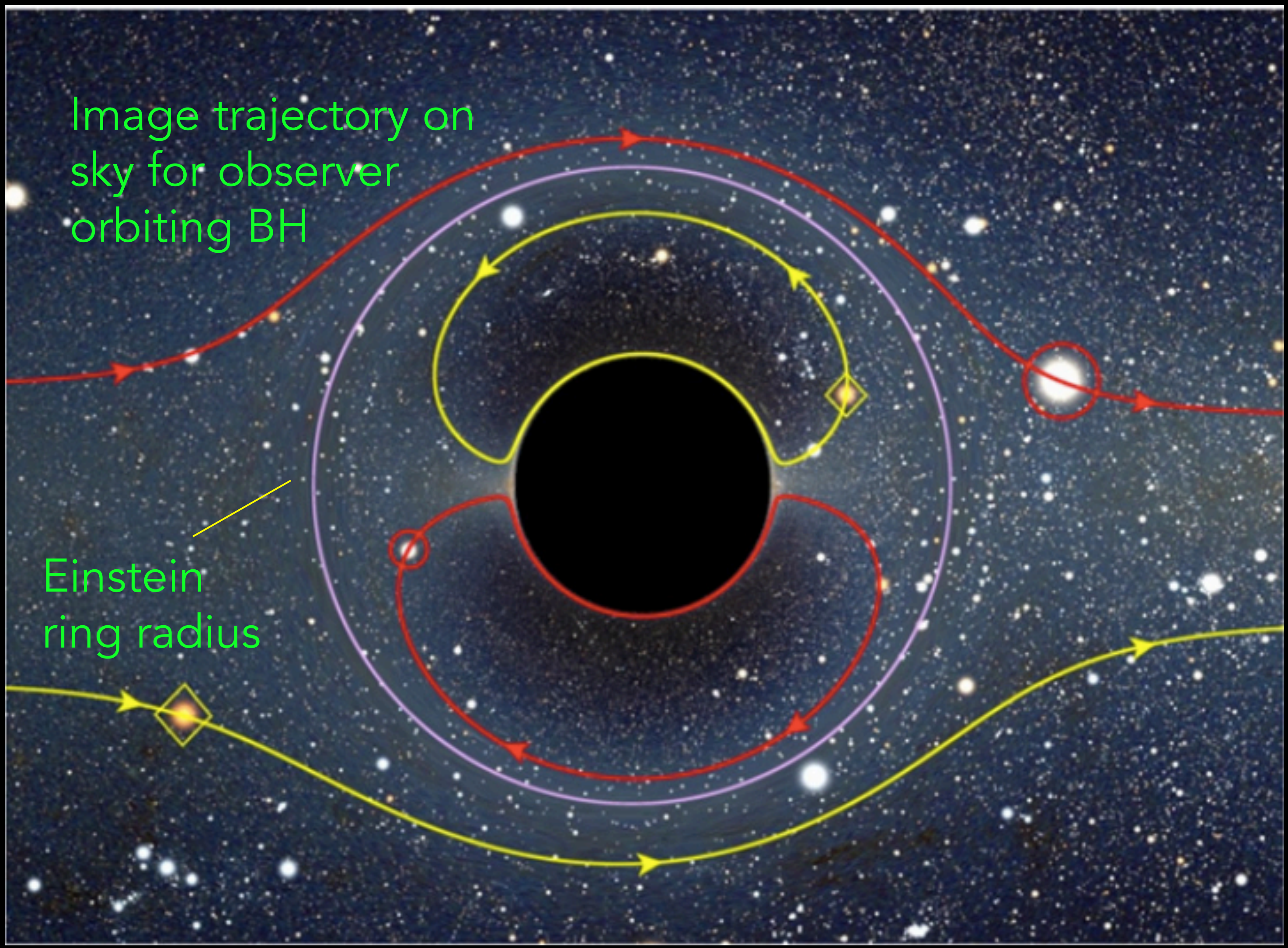
Binary stellar systems: Black Holes ~few solar masses

Dense stellar systems

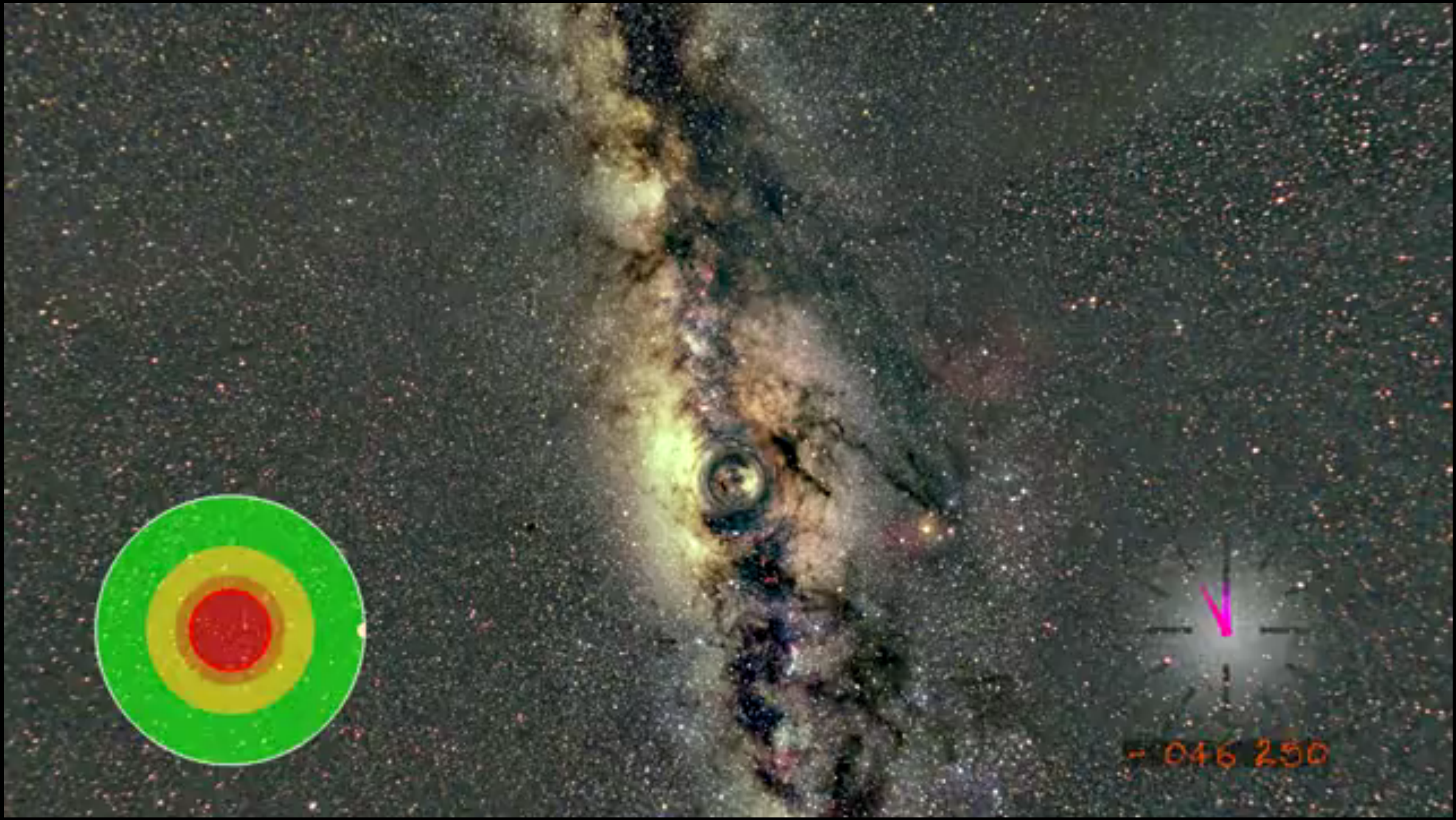
Cores of most large galaxies: ~ contain Black Holes of ~million solar masses and larger, including in our own Milky Way

Cores of Quasars: contain Black Holes of ~100 million solar masses that power these bright objects through accretion of gas

Lensing by a Black Hole

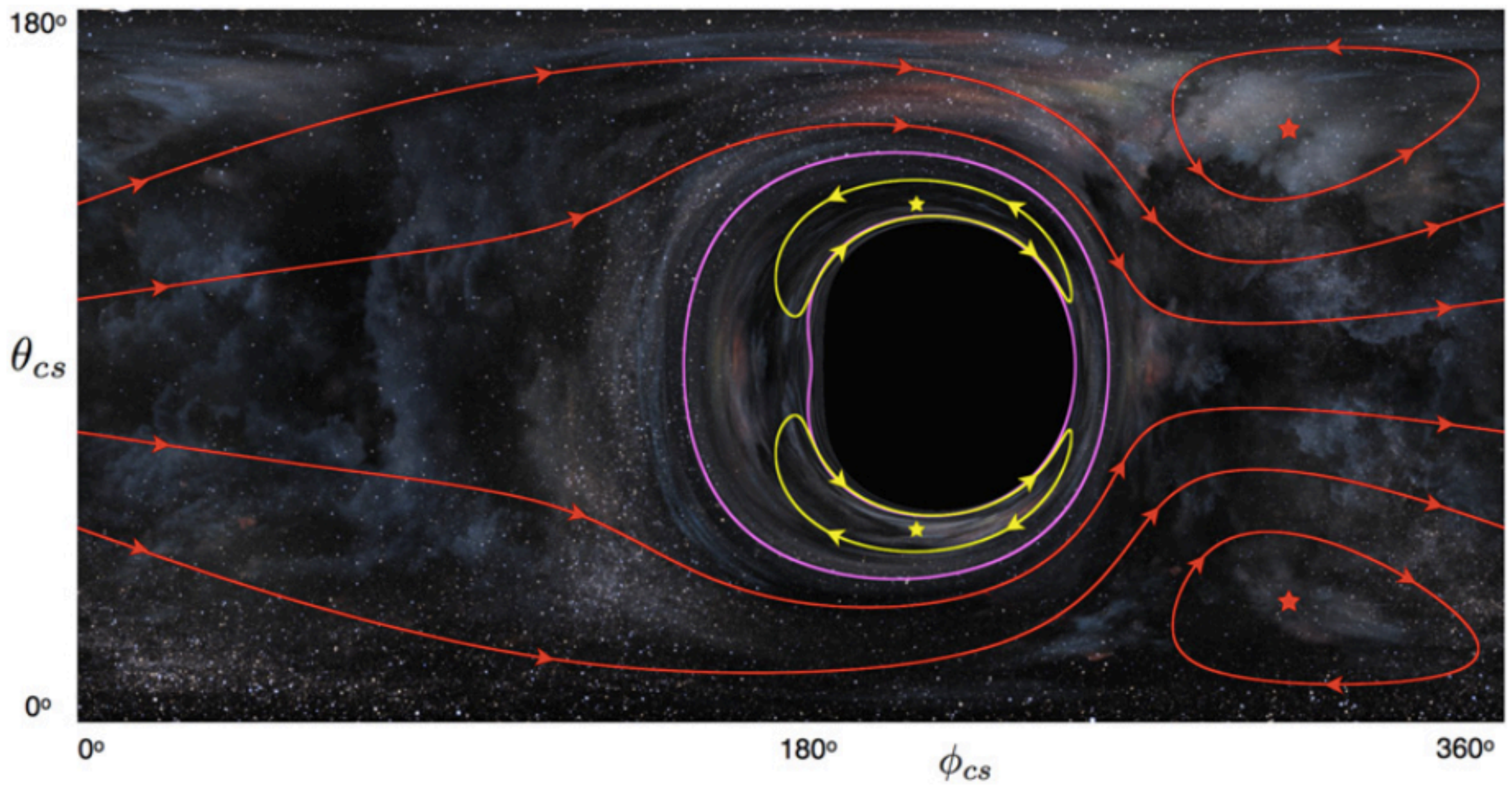


Journey into a Black Hole



Andrew Hamilton

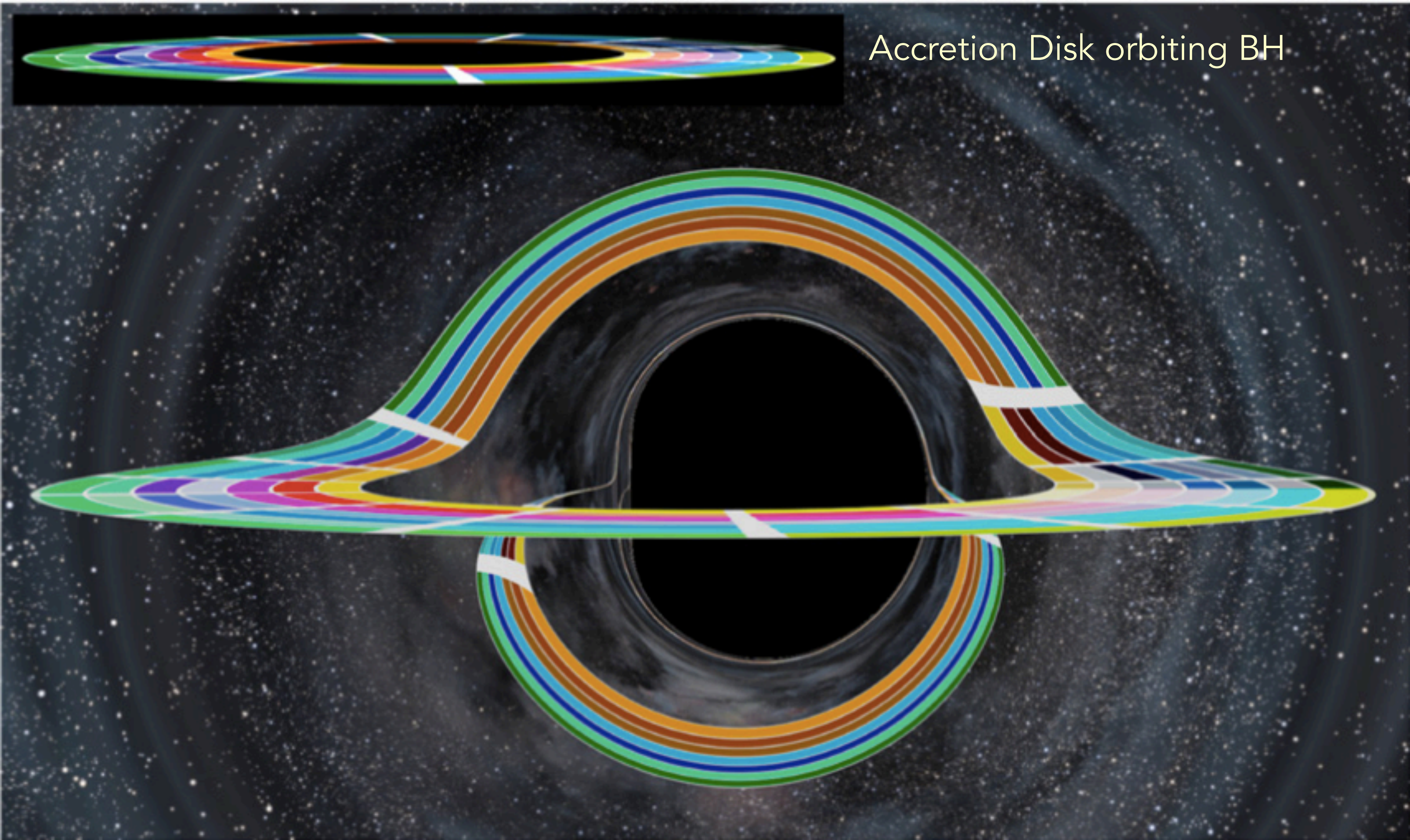
Lensing by a Spinning Black Hole



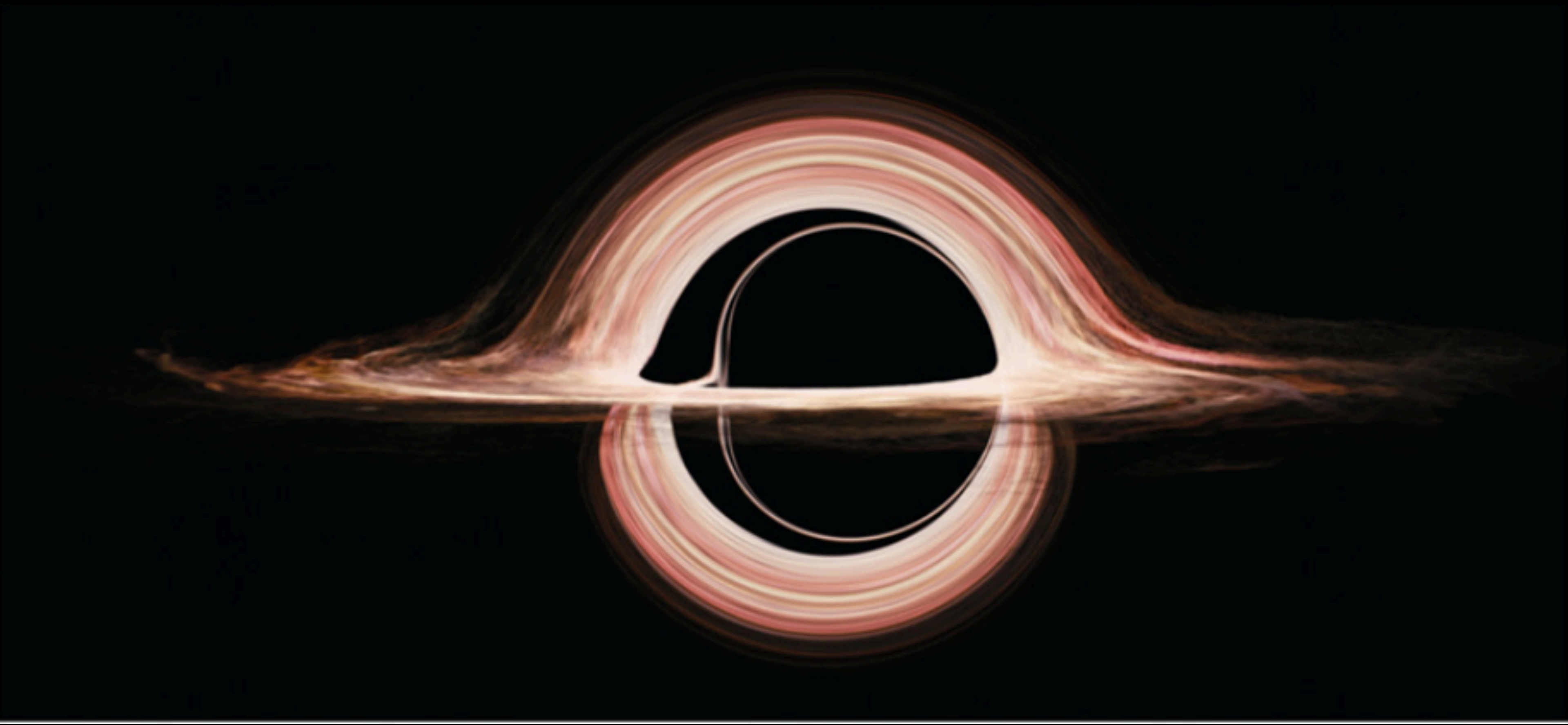
Lensing by a Spinning Black Hole

http://dneg.com/dneg_vfx/blackhole/

Lensing by a Spinning Black Hole



Lensing by a Spinning Black Hole



As seen in *Interstellar*

Lensing by a Spinning Black Hole

Increasingly realistic sequence