Astronomy 350L

(Fall 2006)

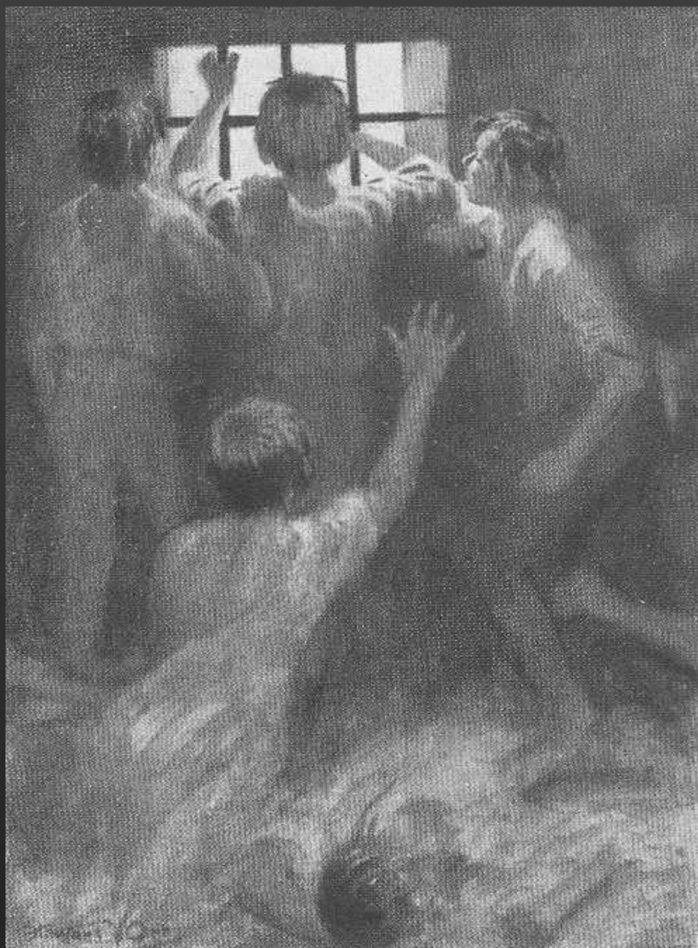
The History and Philosophy of Astronomy

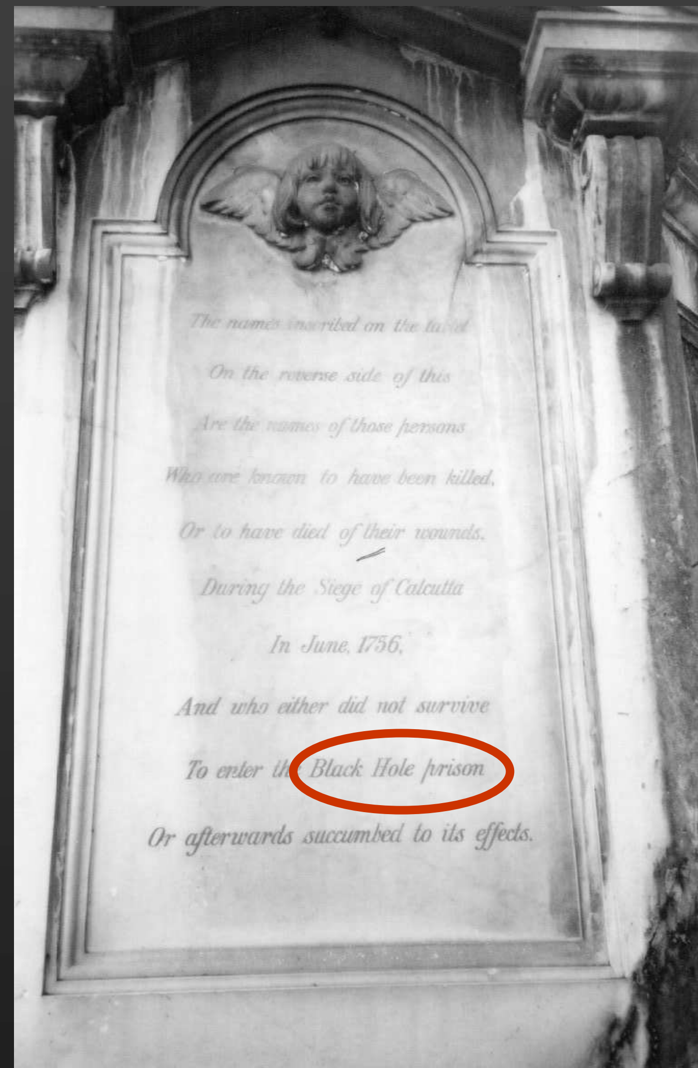
(Lecture 20: Black Holes)

Instructor: Volker Bromm
TA: Jarrett Johnson

The University of Texas at Austin

“The Black Hole of Calcutta”



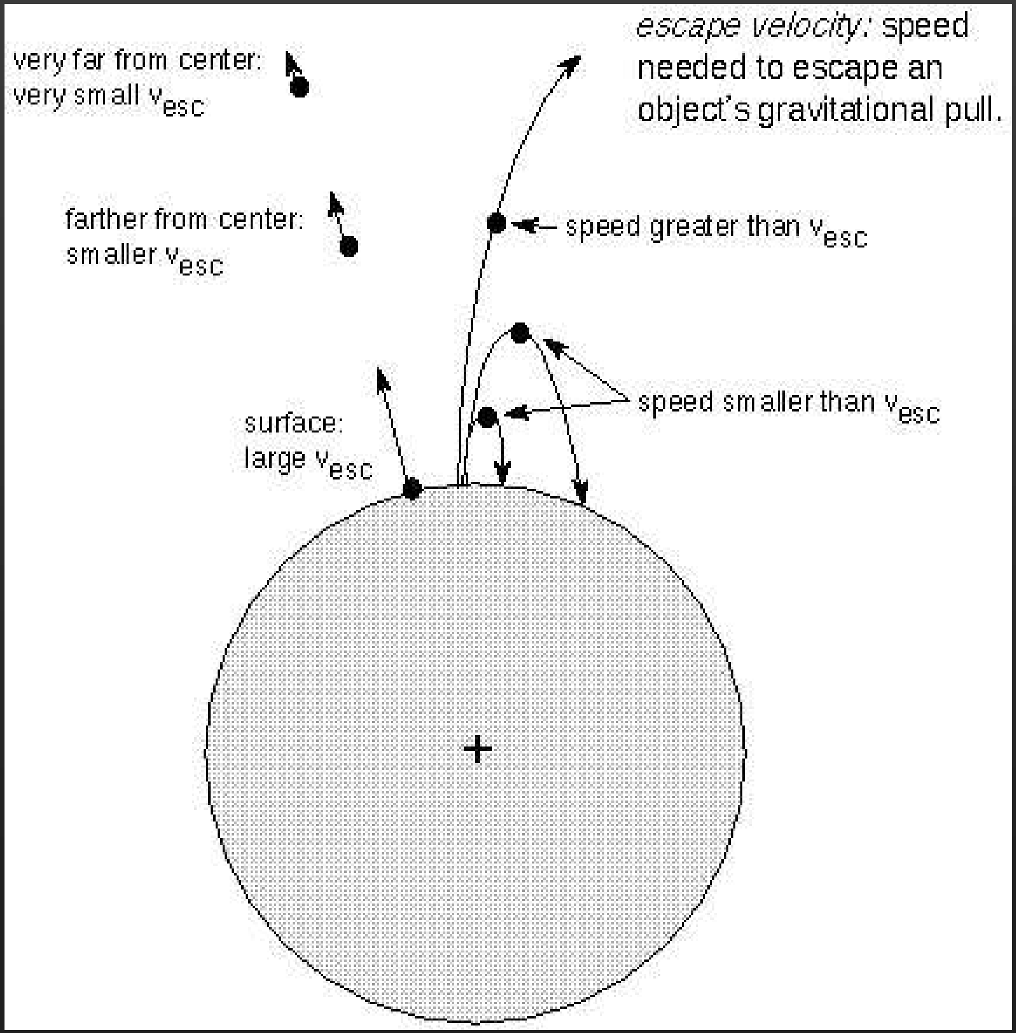


- 1756: British prisoners perished in tiny dungeon

Black Holes: First ideas

- 18th cent. physics:

  à Newton's theory of gravity



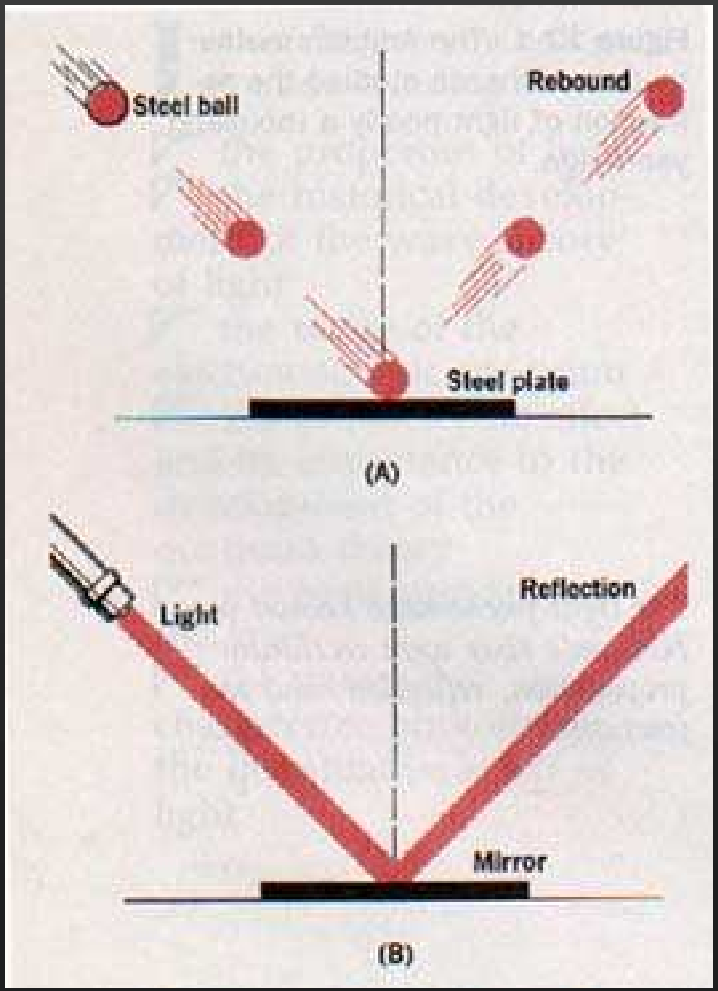
- for object to escape from gravitational pull of planet or star, need:

  velocity > escape velocity

Black Holes: First ideas

- 18th cent. physics:

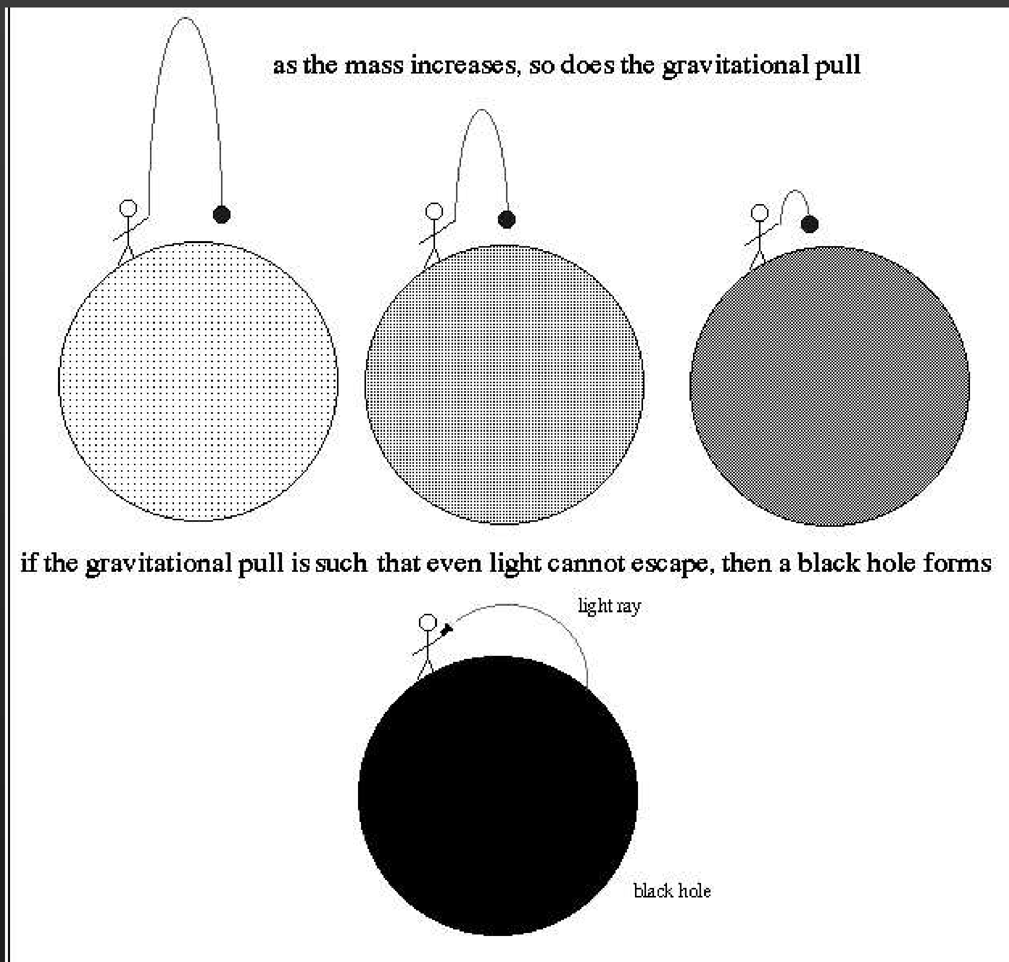
  à Newton’s theory of light



- light rays behave as stream of particles (“light corpuscles”)

Black Holes: First ideas

- John Michell (1783): combines corpuscular theory of light with Newtonian gravity



- object massive enough so that speed of light < escape velocity:

à **“Dark Star”**

- invisible to far away observer

Enlightenment Astronomy

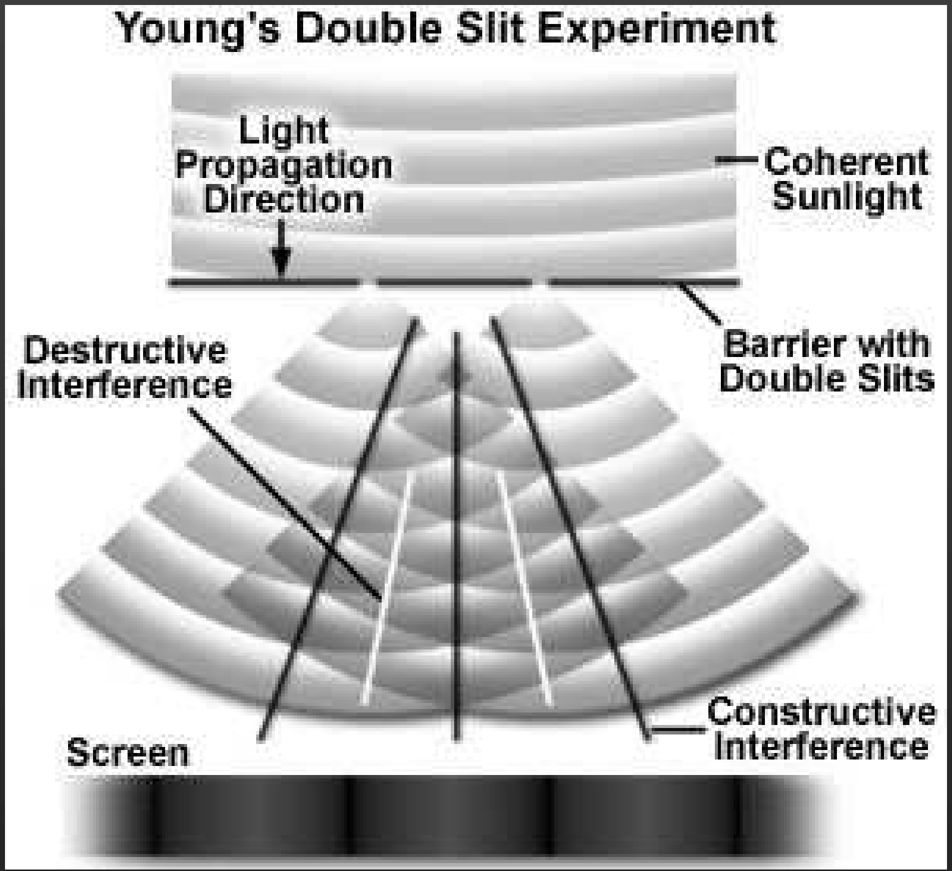
- Pierre-Simon de Laplace
  (1749-1827)
- ***Exposition de System du Monde***
  (1796)
- **Dark Stars (i.e., black holes)**

  - removed from the 3rd edition (1808)

  - What happened in between?

The Downfall of the Dark Star Idea

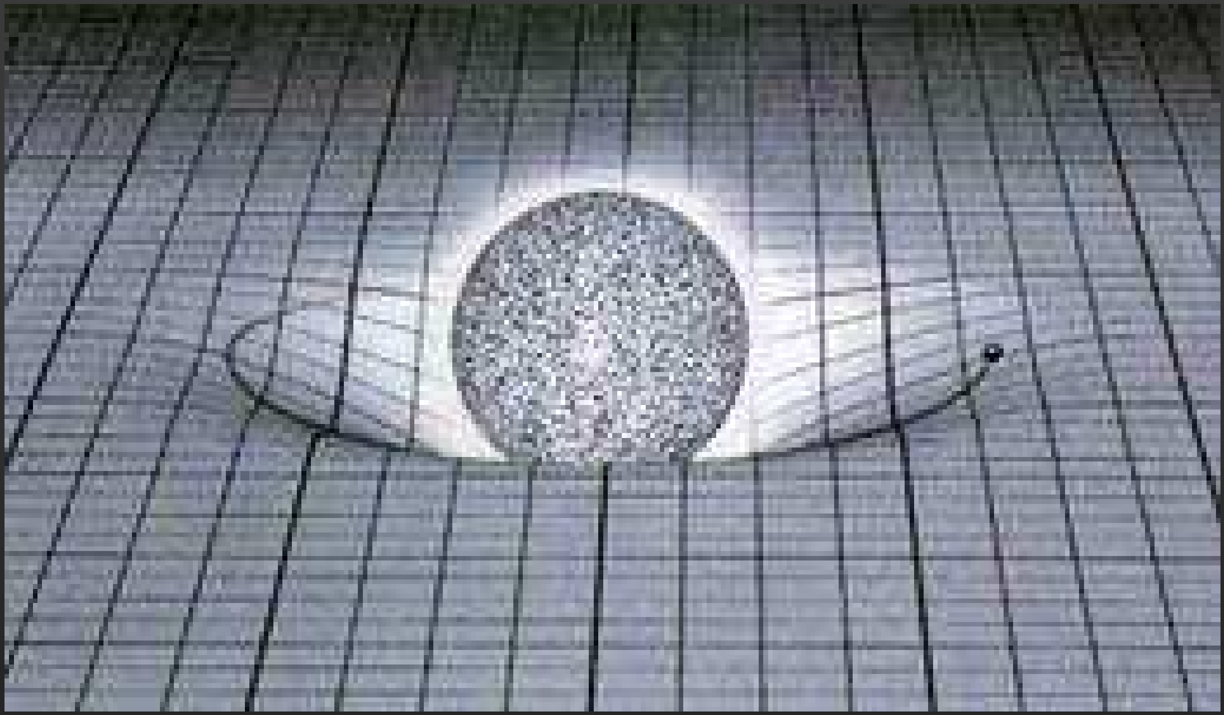
Thomas Young (1773-1829)



- interference of light à wave-nature of light
- light-waves not subject to gravity
  - à light cannot be trapped
  - à "Dark stars" idea forgotten!

Einstein: General Relativity (1915-16)

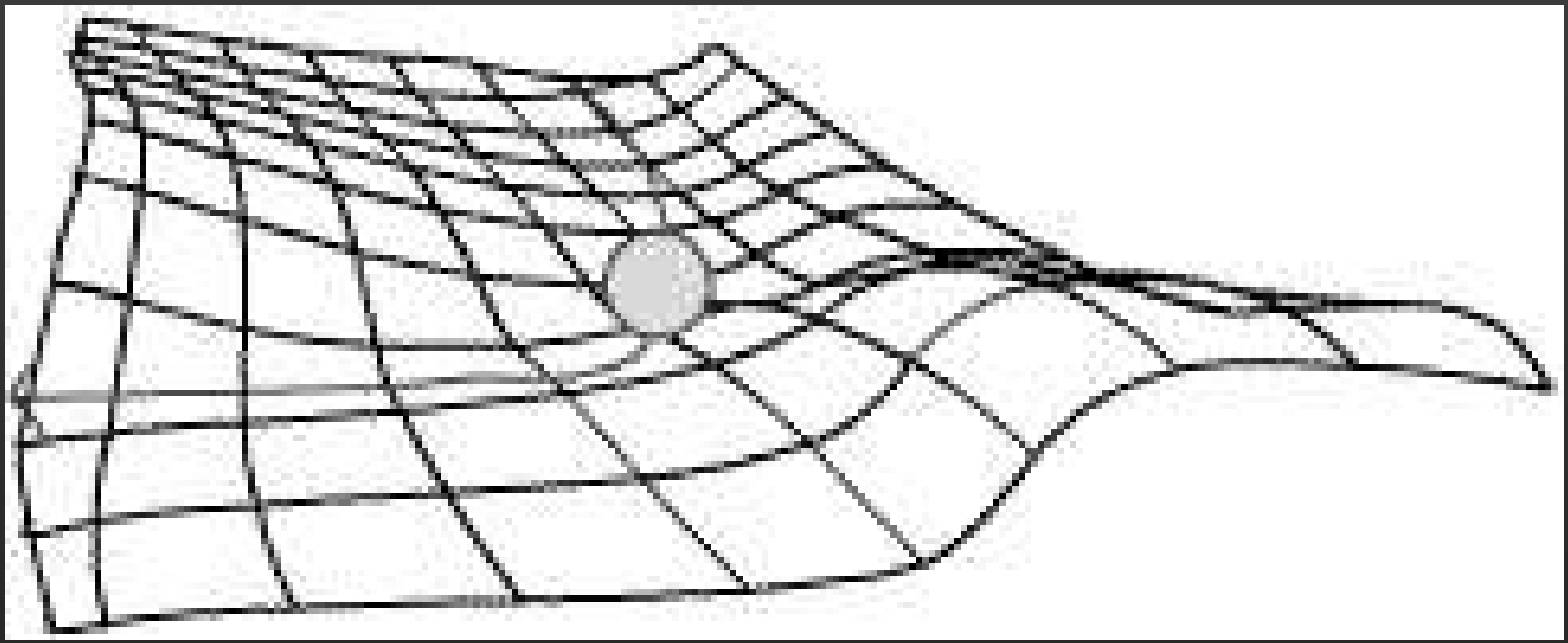
- Principle 1: “Matter tells space how to curve”



- matter creates `dimples’ in otherwise flat spacetime!

Einstein: General Relativity (1915-16)

- Principle 2: “Curved space tells matter how to move”



- particles move through spacetime along paths of least resistance (technically: `geodesics’)!

General Theory of Relativity (1915-16)

- Einstein's Field equations:

$$R_{ij} - \frac{1}{2} R g_{ij} = \frac{8\pi G}{c^4} T_{ij}$$

(curvature of space) (matter content)

- a `tensor equation' à *very* complicated
  (10 coupled non-linear differential equations)

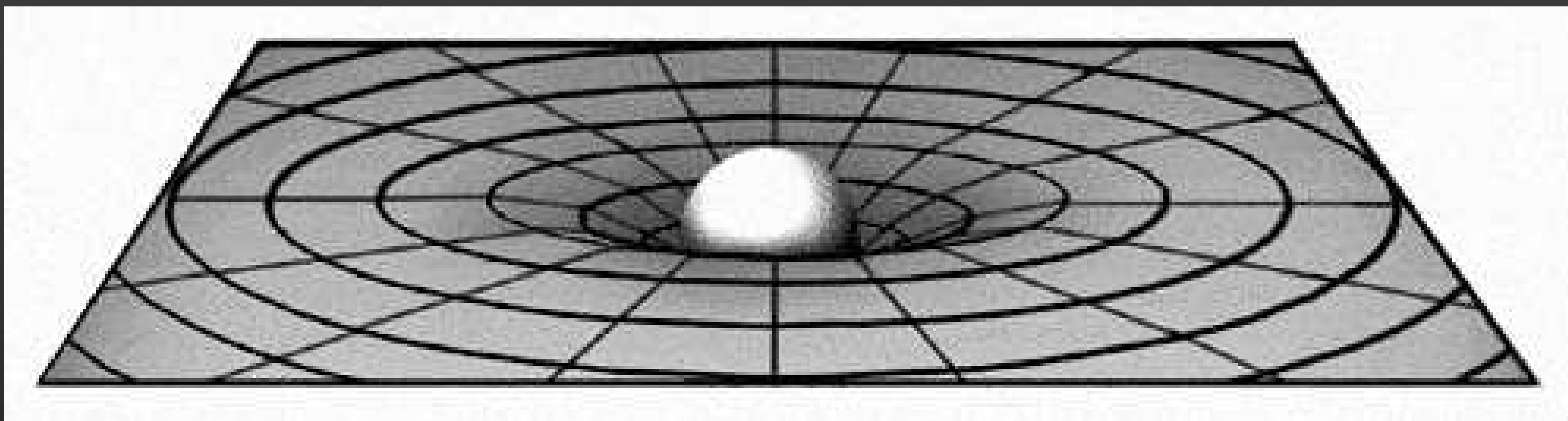
Karl Schwarzschild: First Solution of GR Equations

- 1873 (Frankfurt) – 1916 (Potsdam)
- pre-eminent astrophysicist at beginning of 20th century
- found first solution to Einstein's GR (1916):

à Gravitational field around spherical mass
à Predicts black holes

Schwarzschild Geometry (1916)

- consider (curved) spacetime around a star:



$$ds^2 = -\left(1 - \frac{r_s}{r}\right) dt^2 + \frac{dr^2}{\left(1 - \frac{r_s}{r}\right)} + r^2 \left(d\theta^2 + \sin^2\theta \, d\phi^2\right)$$

“Schwarzschild metric”

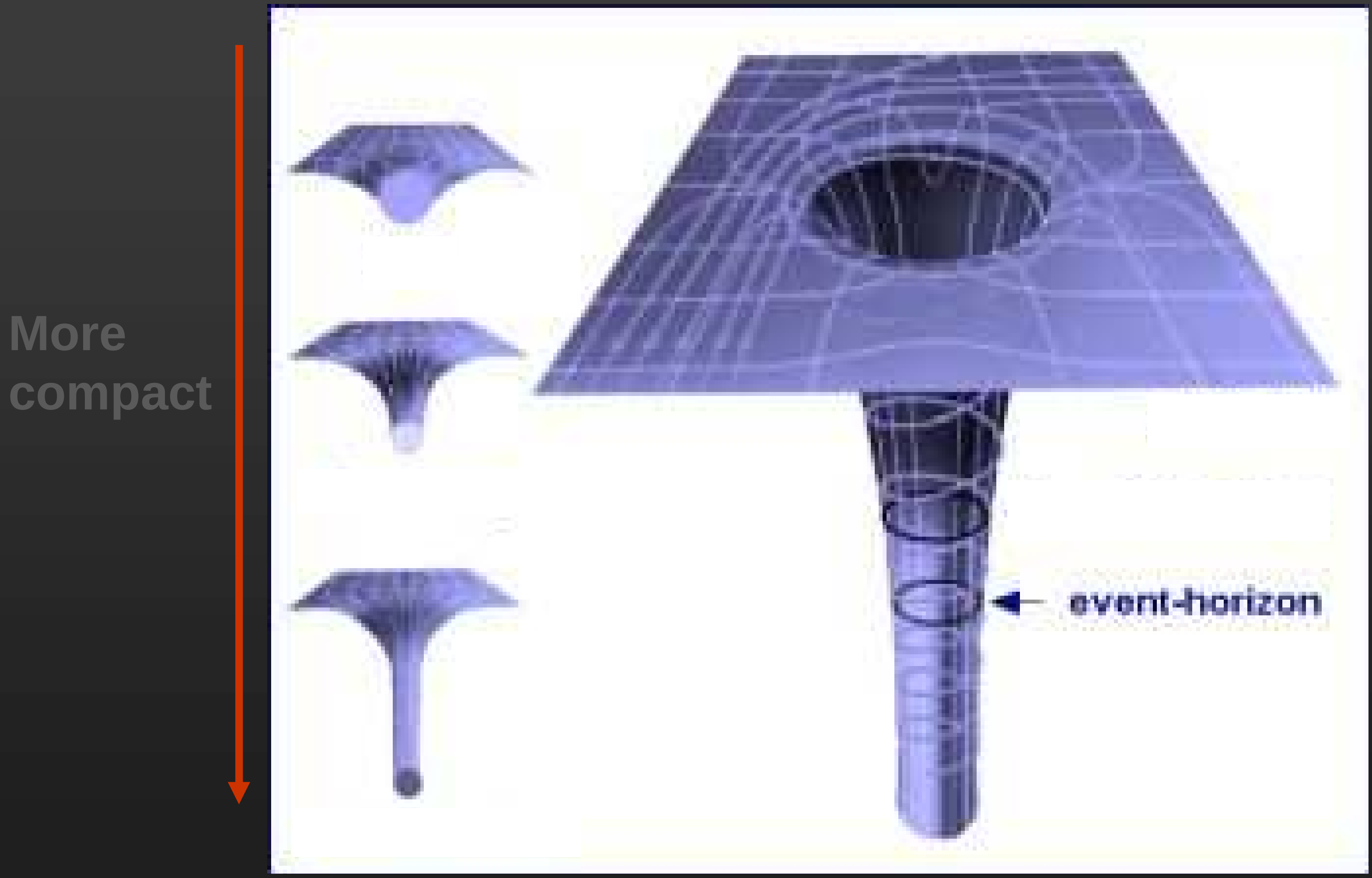
$$r_s = \frac{2GM}{c^2}$$

\`Schwarzschild radius’

- Q: What happens when r -> r_s ?

Schwarzschild Geometry (1916)

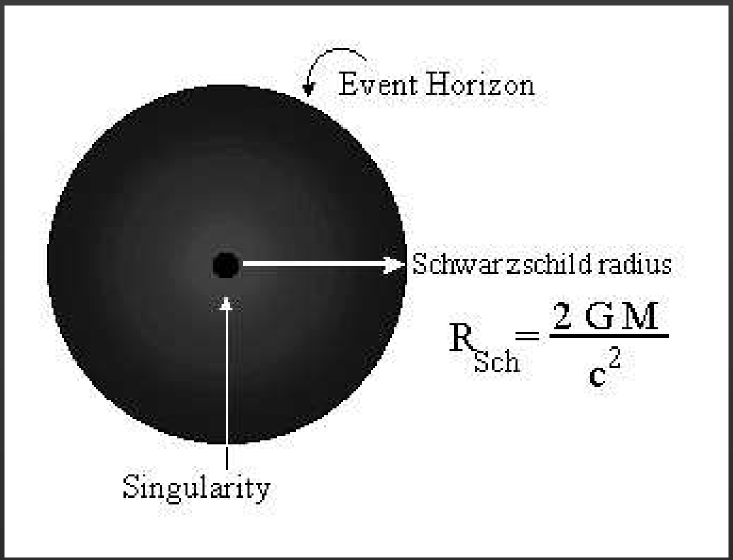
• curvature increases when star becomes more compact



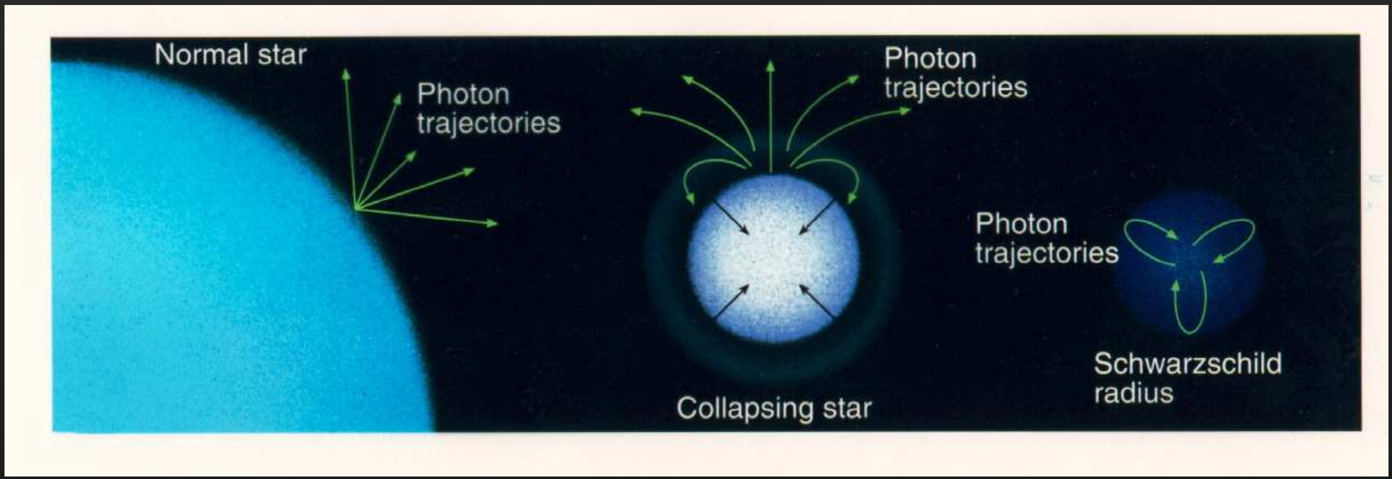
• dense star “shuts itself off” from rest of the universe!

Black Holes Rediscovered:

- Nothing (not even light) can escape from black hole

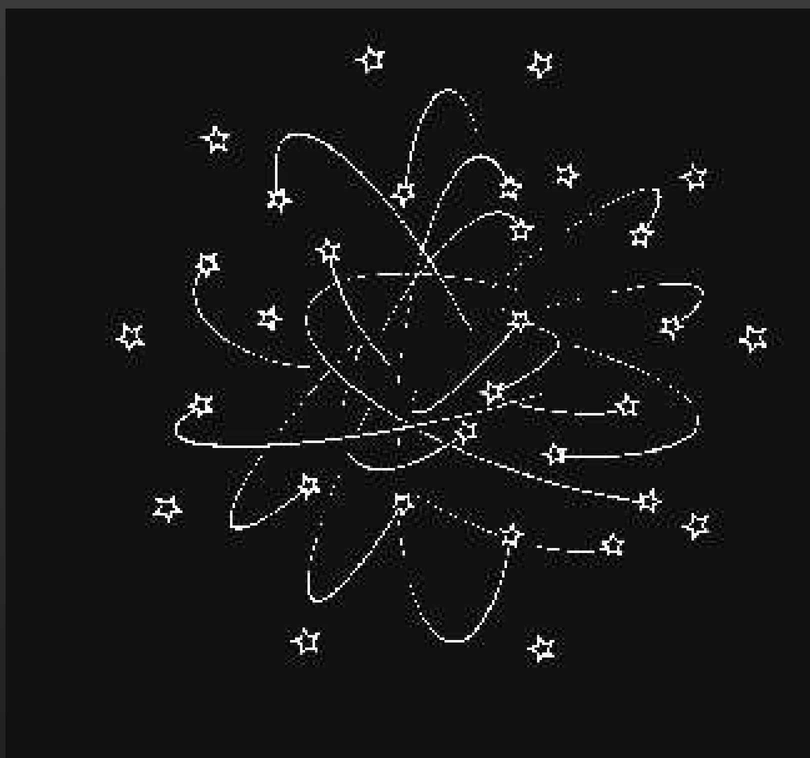


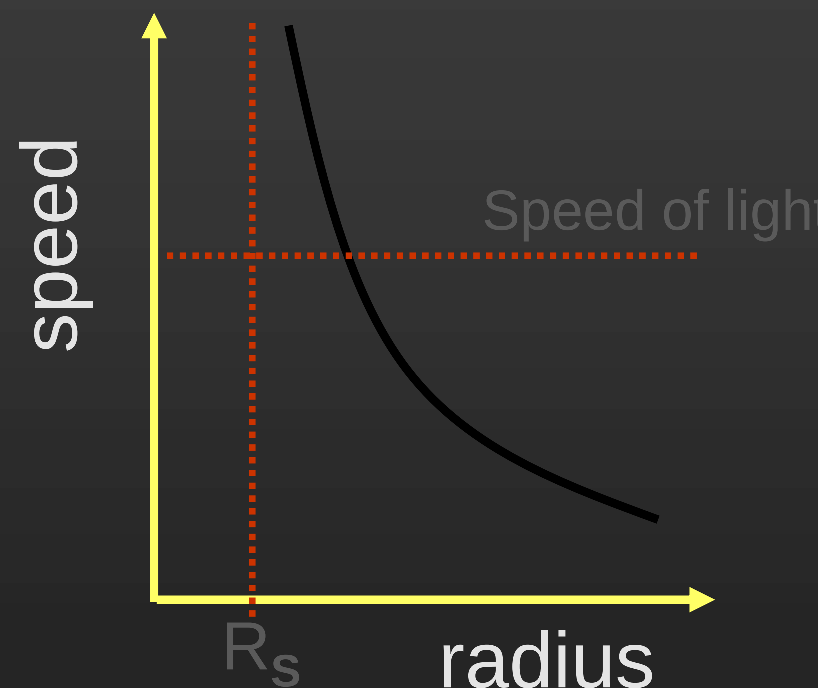
- at the time termed:
  `Schwarzschild Singularities'



Einstein Rejects Black Holes (1939)

- Einstein argues: Black holes could never form in reality!



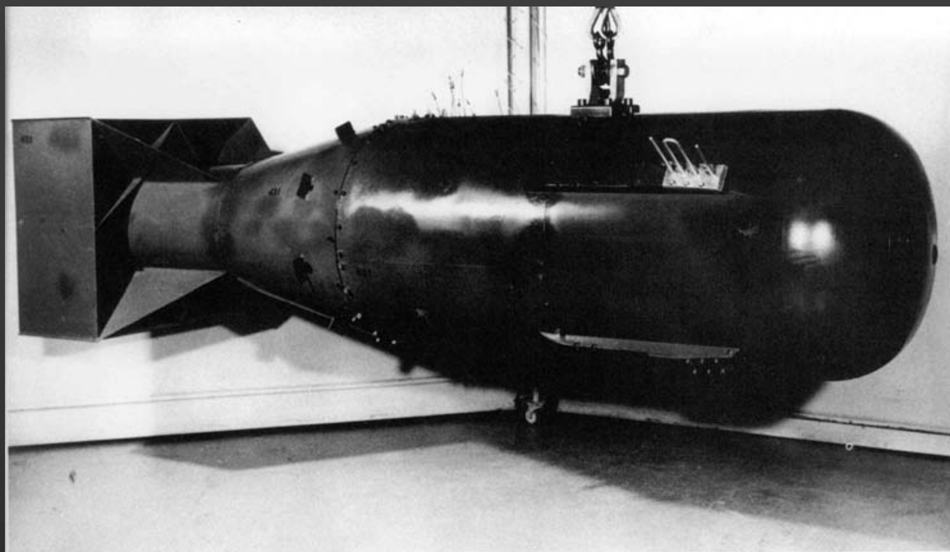


- Cluster of particles in equilibrium:
  centrifugal force = gravity

J. Robert Oppenheimer: American Prometheus

- 1904 – 1967
- “Father of the Atomic Bomb” (leader of Manhattan project)
- Founder of American school of theoretical physics (Berkeley and Caltech)
- argued that massive stars have to implode à black holes exist!

Oppenheimer: Manhattan Project



`Little Boy' (Uranium bomb)

Hiroshima, Aug. 6, 1945

- Oppenheimer feels intense anguish ("the physicists have known sin")

Gravitational Collapse of Massive Star

SEPTEMBER 1, 1939 PHYSICAL REVIEW VOLUME 56

On Continued Gravitational Contraction

J. R. OPPENHEIMER AND H. SNYDER
University of California, Berkeley, California

(Received July 10, 1939)

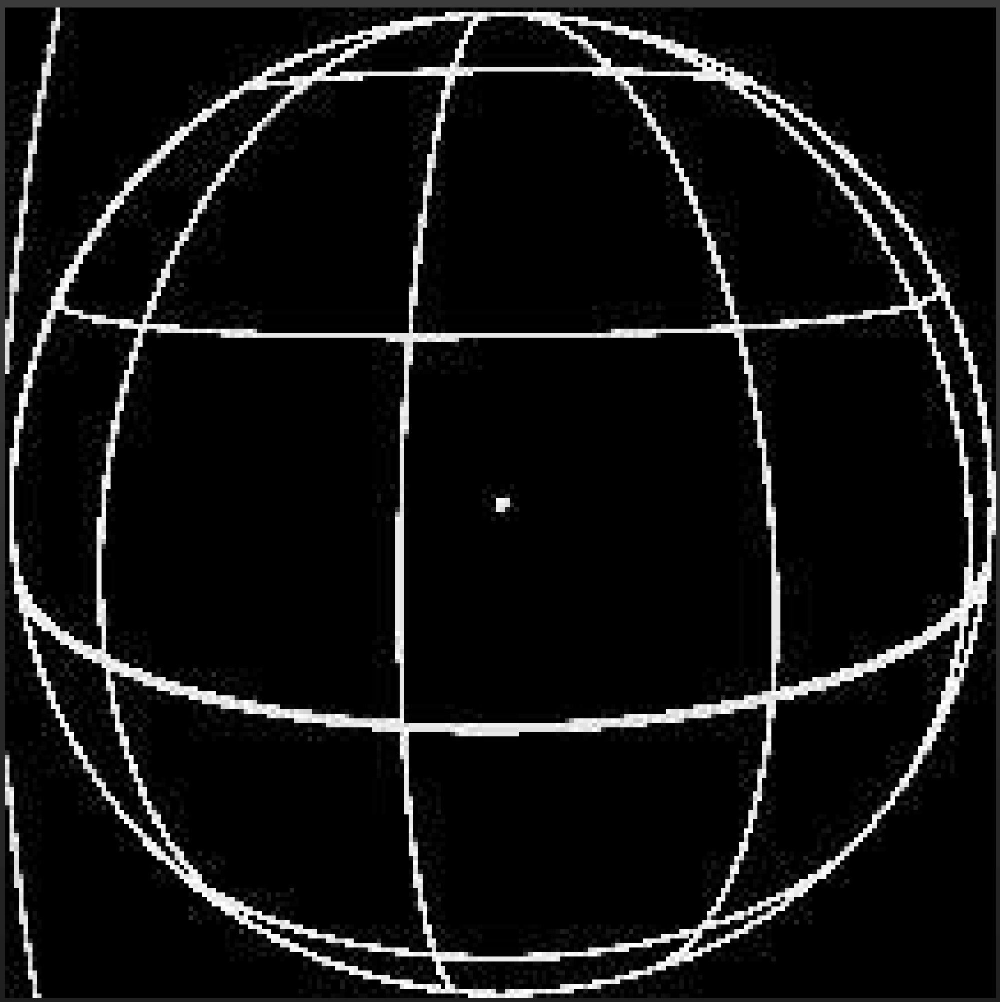
When all thermonuclear sources of energy are exhausted a sufficiently heavy star will collapse. Unless fission due to rotation, the radiation of mass, or the blowing off of mass by radiation, reduce the star's mass to the order of that of the sun, this contraction will continue indefinitely. In the present paper we study the solutions of the gravitational field equations which describe this process. In I, general and qualitative arguments are given on the behavior of the metrical tensor as the contraction progresses: the radius of the star approaches asymptotically its gravitational radius; light from the surface of the star is progressively reddened, and can escape over a progressively narrower range of angles. In II, an analytic solution of the field equations confirming these general arguments is obtained for the case that the pressure within the star can be neglected. The total time of collapse for an observer comoving with the stellar matter is finite, and for this idealized case and typical stellar masses, of the order of a day; an external observer sees the star asymptotically shrinking to its gravitational radius.

- Oppenheimer and Snyder (1939):

à brute force calculation

à black hole formation is inevitable!

Gravitational Collapse of Massive Star



- surprising result:
  for far-away observer,
  star's surface `freezes'
  at event horizon
  (i.e., never crosses over)

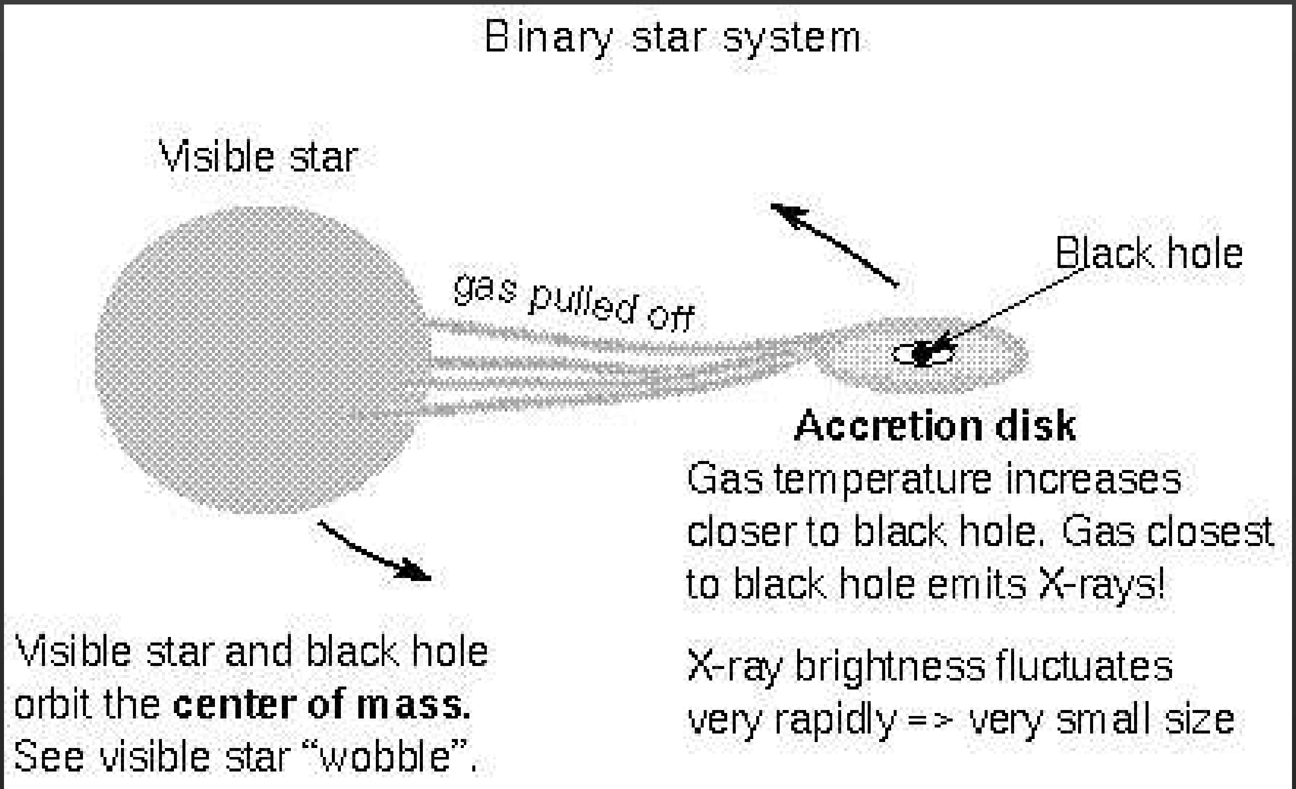
- however: for observer
  riding on top of
  collapsing surface, this
  only takes a finite time!

- Q: How can both perspectives be right?

John Archibald Wheeler: Popularizing Black Holes

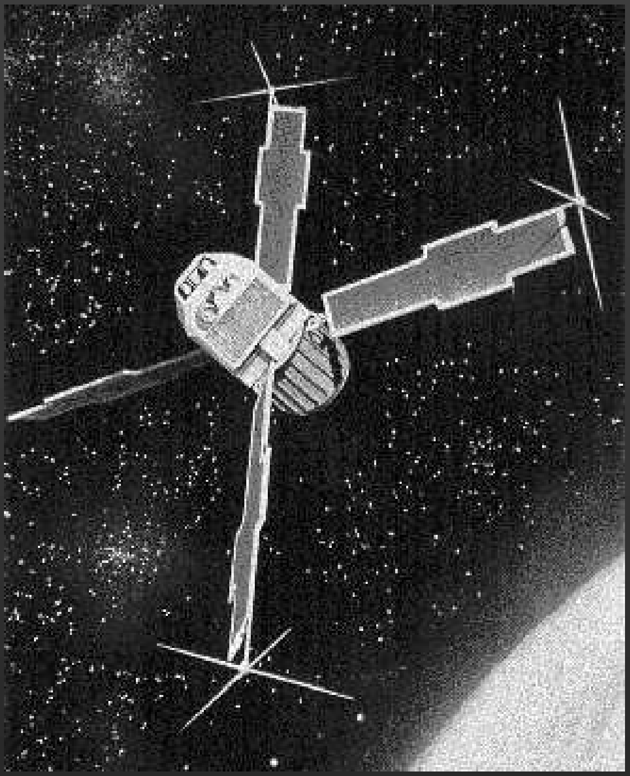
- b. 1911
- "Father of the Hydrogen Bomb"
- Coined term "Black Hole"
- gifted teacher, keen sense for aphorisms
  ("Time is what prevents everything from happening at once")

How to find Black Holes?

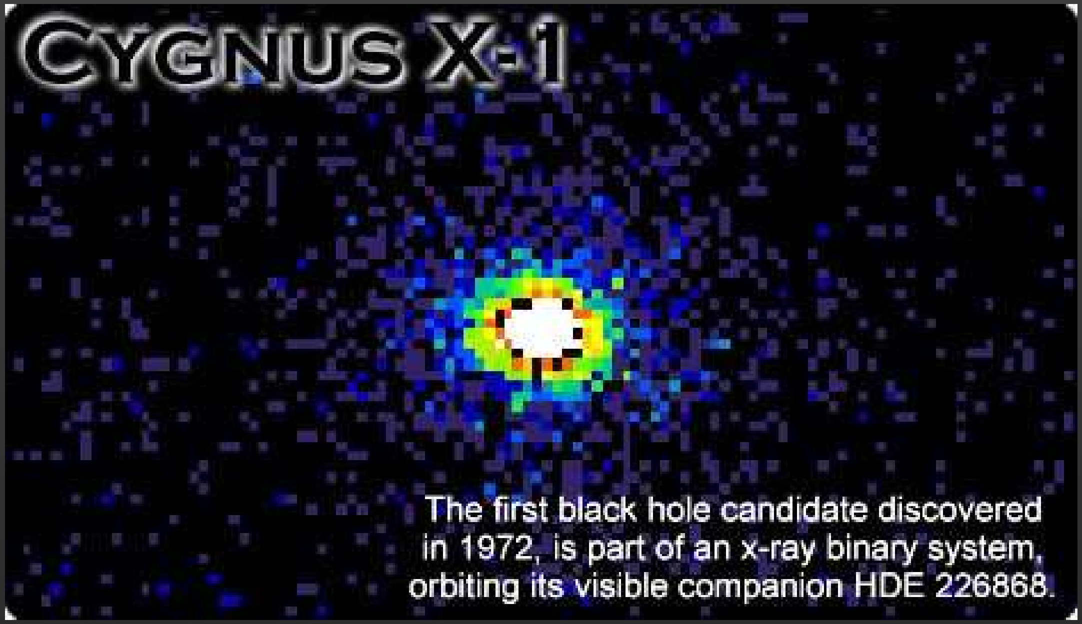


- Strategy: Look for X-ray emission from gas falling onto black hole!

How to find Black Holes?



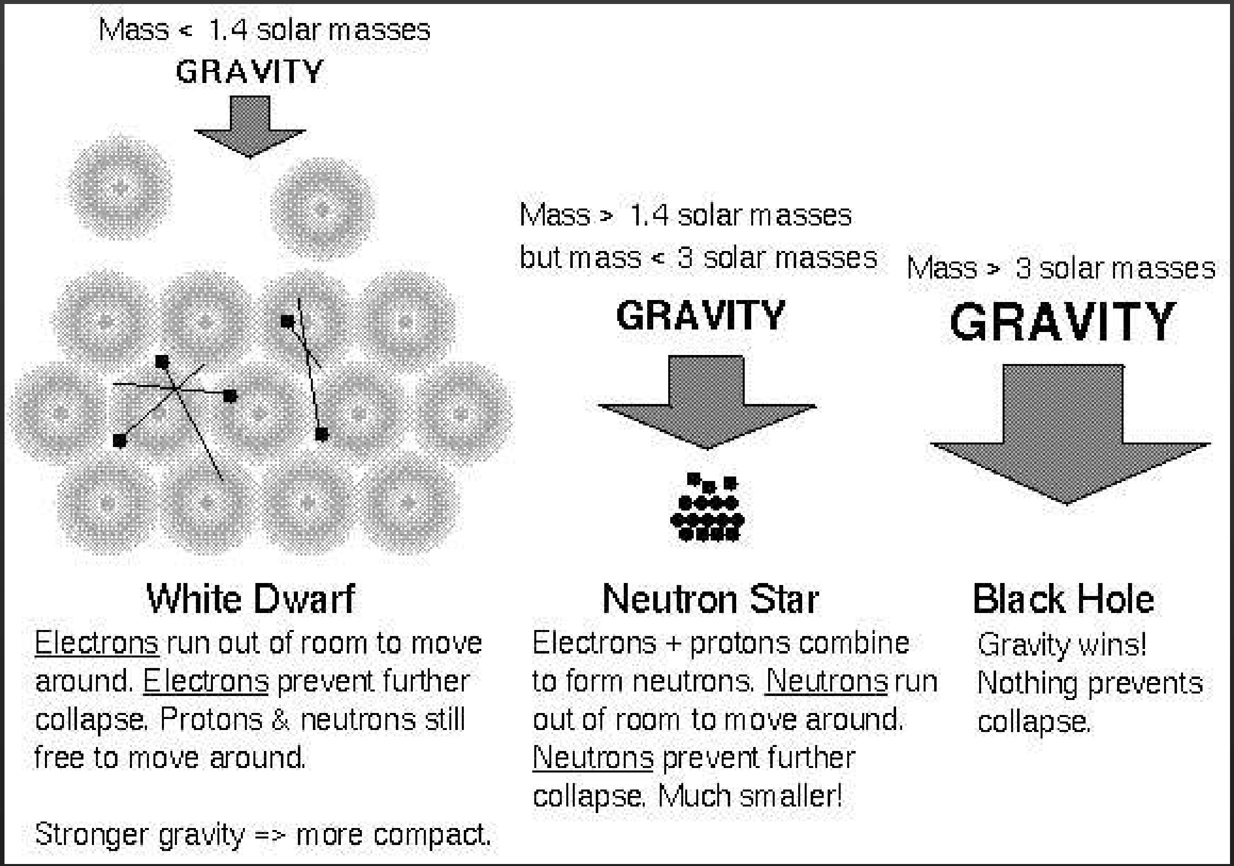
Uhuru: first X-ray satellite,
Launched 1970



- Cygnus X-1: a double star with an unseen massive companion (> 3 Suns) to a normal star

Alternative explanation?

- Q: could unseen object in Cyg X-1 be something else?

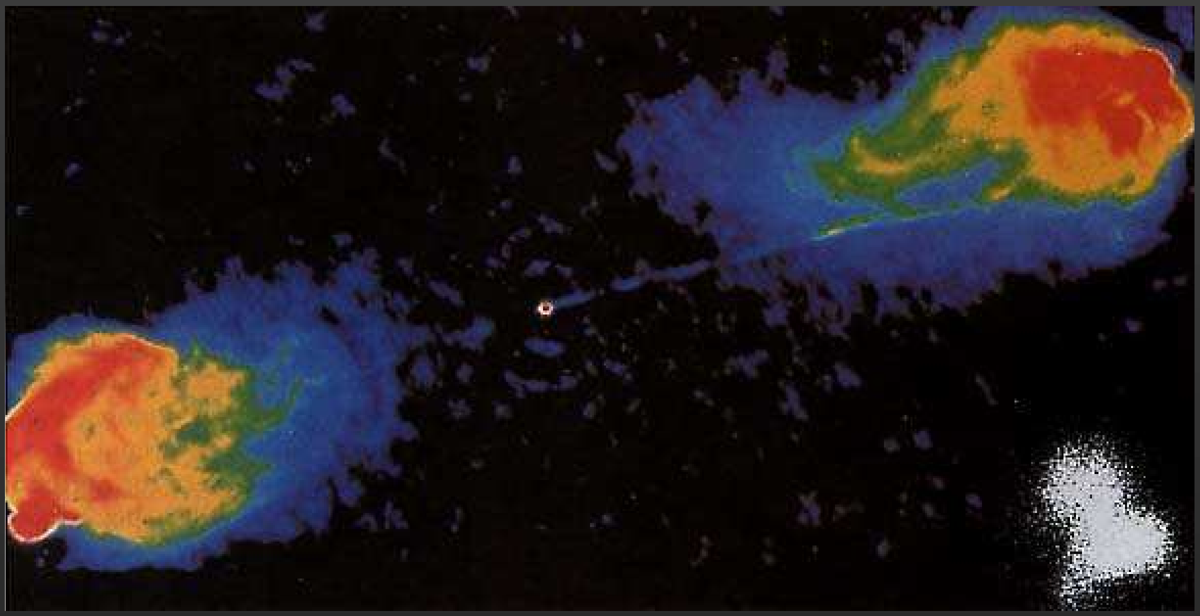


- A: No! Objects more massive than 3 Suns must be black holes!

Discovery of Radio Galaxies and Quasars

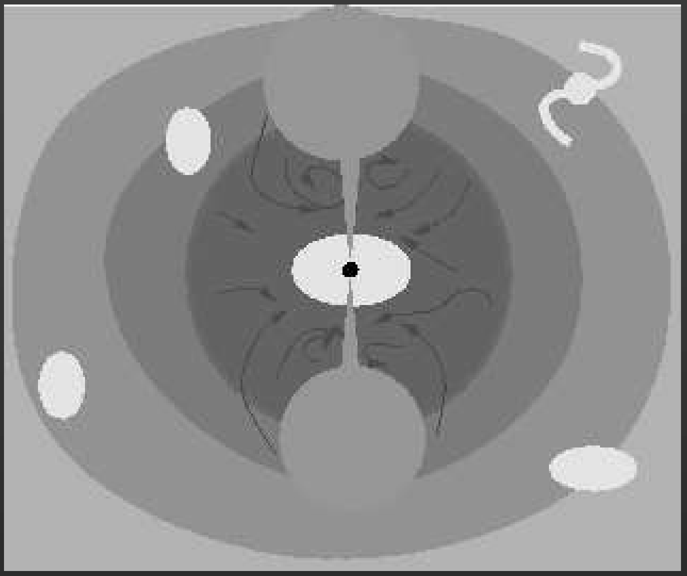
(1950s and 60s)

Cygnus A: Radio image



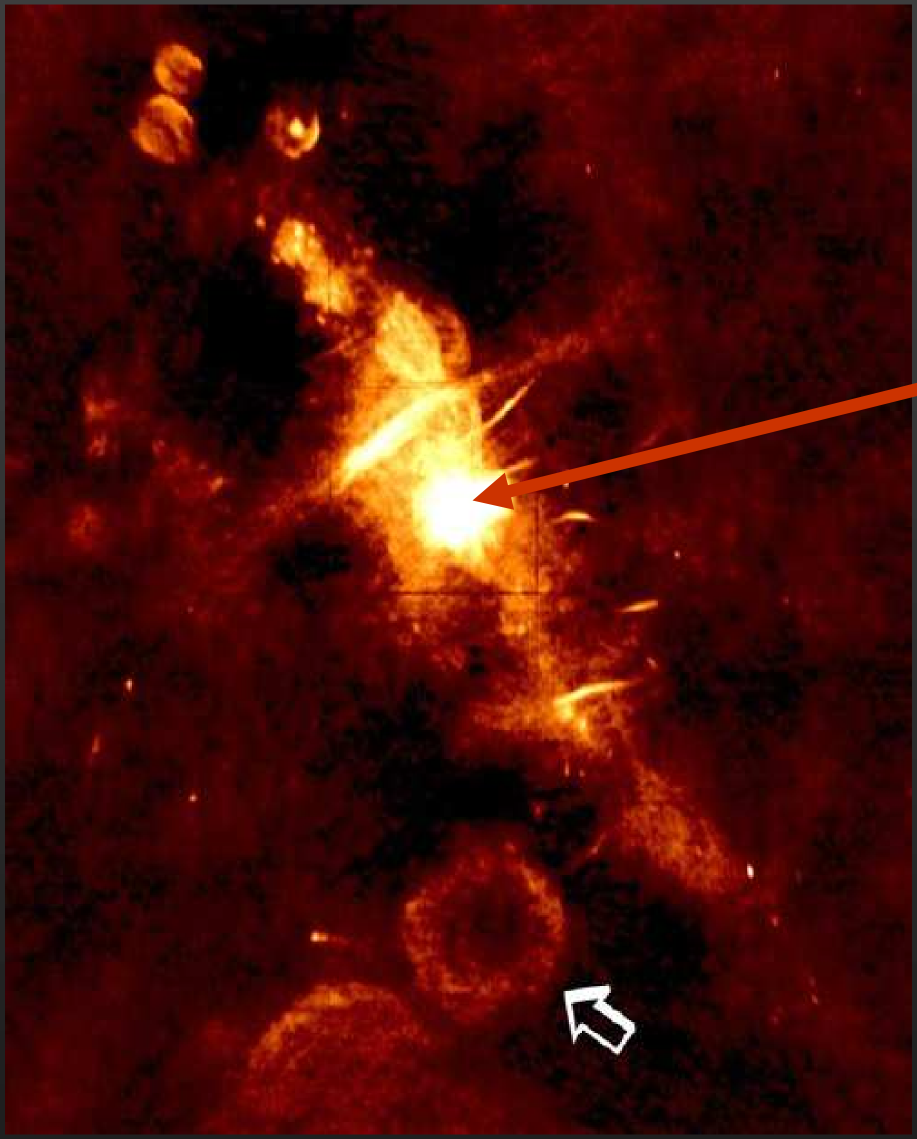
~ million lightyear

Possible explanation:



- Promising idea: Radio galaxies and quasars are powered by gas falling onto supermassive black holes (million to billion Suns)

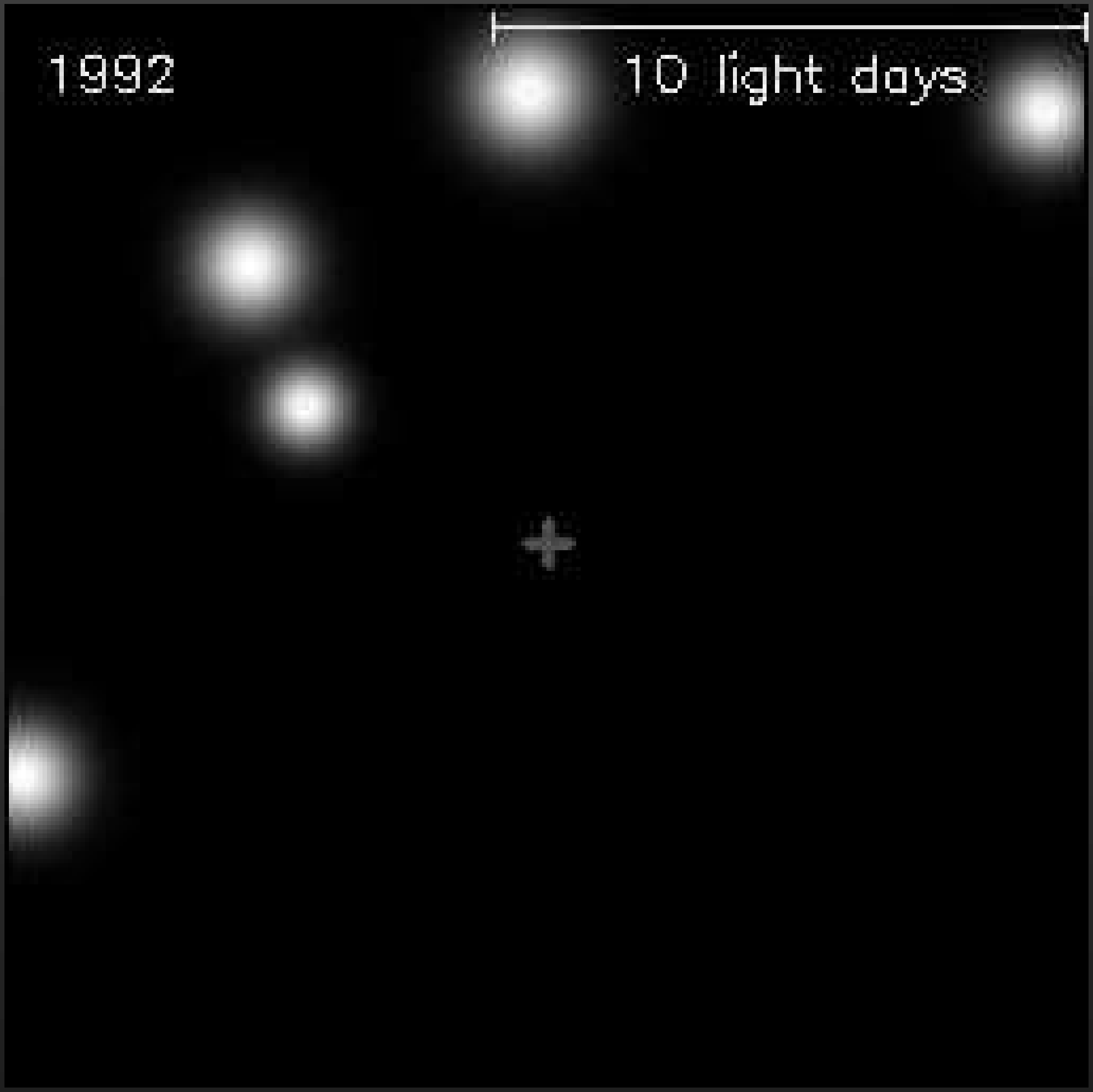
The Galactic Center: A Supermassive Black Hole



Sgr A*

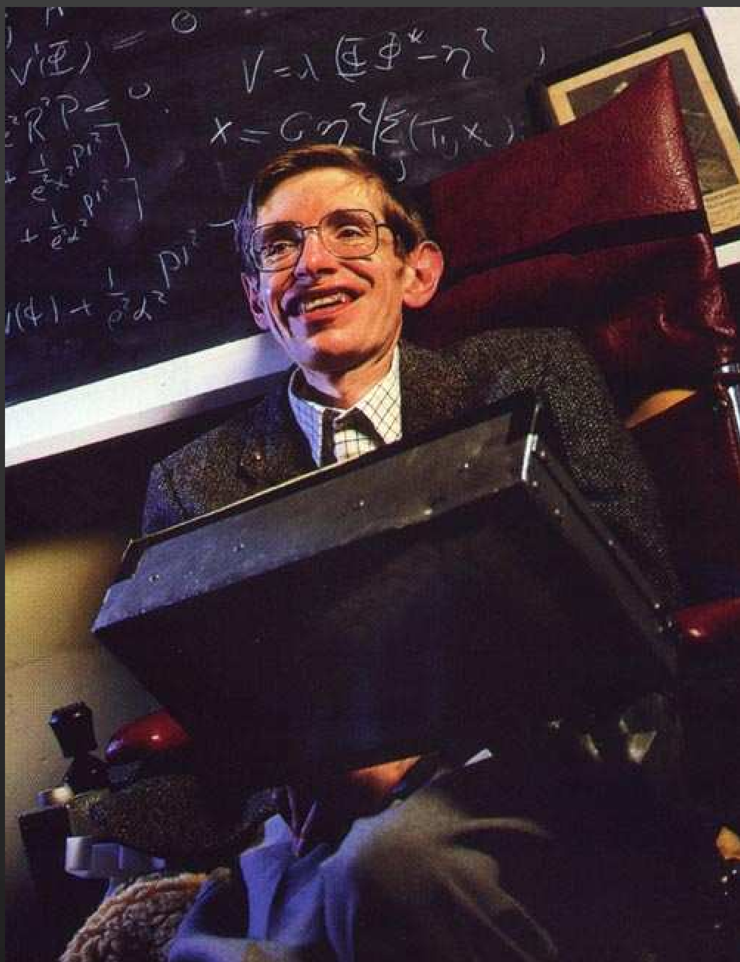
- Radio Map (VLA)

The Galactic Center: A Supermassive Black Hole



- Estimated mass: ~ 3 million solar masses!

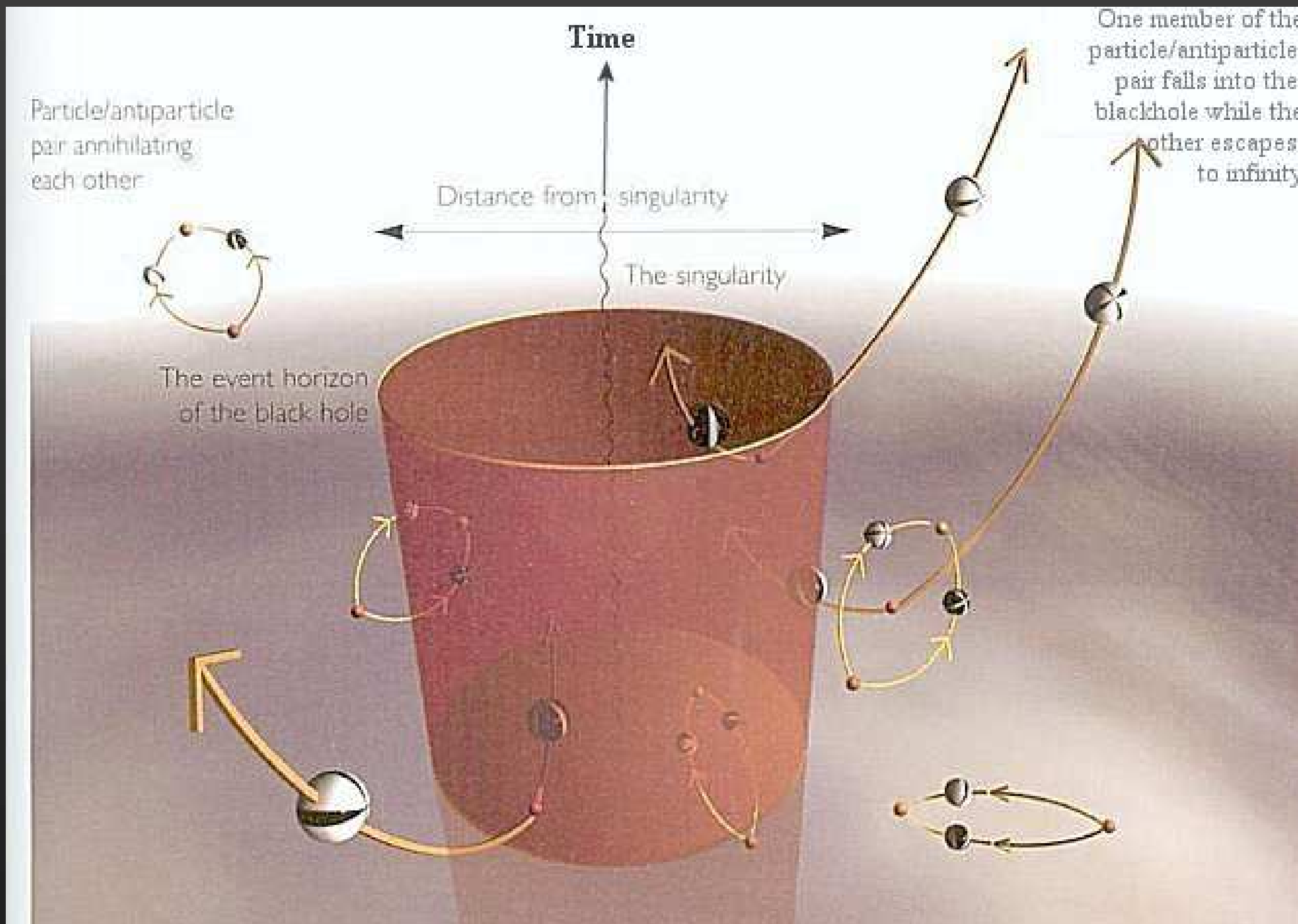
Stephen Hawking: New look at black holes



- b. 1942
- Lucasian Professor in Cambridge
- predicts: black holes are not really black
  à they can evaporate
  à Hawking radiation

Quantum Mechanics of Black Holes

- Hawking radiation



à Black Holes slowly evaporate!

Black Holes

- Early speculations:
  - 1780s and 90s: “dark stars” (Michell and Laplace)
  - relies on particle nature of light (`light corpuscles’)
  - abandoned in 1800s when wave-nature of light was found

- General Relativity predicts them again:
  - Karl Schwarzschild (1916)
  - strong initial opposition
  - Oppenheimer and Snyder (1939) do first relativistic collapse calculation

- Empirical proof:
  - 1970s: X-ray binaries (Cygnus X-1)
  - Supermassive black holes in center of quasars
  - best current evidence: center of our Milky Way!