The First Three Minutes
Meeting 7

Peter Fisher

February 24, 2021

Meeting 6 – The First Three Minutes

- Announcements
- 30,000 ft
- **What is curved space-time?**
- **Break**
- Black holes

Announcements

- Notes, slides, etc. on website, tinyurl.com/firstthreeminutes
- Please read Chapter VII for next week
- Questions
  - Conservation of energy in expanding universe (photons stretching)
  - Long lifetime of neutron

30,000’ view

Galaxies are the “atoms” of the universe

When viewed on the 100 Mly scale, the universe is uniform and isotropic

Hubble’s redshift measurements showed all the galaxies are moving away from us. Their recession speed is proportional to how far away they are. H_o is the proportionality constant.

30,000' (cont.)

The recession of the galaxies led to the idea that the space of the universe is expanding. The expansion is the same everywhere.

The numerical value of H_o implies the universe is 13.7 Gy old.

Penzias and Wilson's observation of 2.7 K radiation led to the conclusion that neutral hydrogen formed from a plasma 377,000 y after the start of the universe.

30,000’ (cont.)

At 0.01 s, the recipe for a hot universe consists of

- Zero net charge
- Protons, neutrons, electrons at the 1 ppb level compared with photons (and neutrinos)
- T=100 B kelvin for black body photons
- Expansion as $t^{1/2}$

Synthesis of H, D, and He began at 0.01s as the proton-neutron imbalance developed, but was delayed to 3 min by the low binding energy and fragility of the deuteron.

Chapter VI – A Historical Diversion

Third, and I think most importantly, the "big bang" theory did not lead to a search for the 3° K microwave background because it was extraordinarily difficult for physicists to take seriously *any* theory of the early universe. (I speak here in part from recollections of my own attitude before 1965.) Every one of the difficulties mentioned above could have been overcome with a little effort. However, the first three minutes are so remote from us in time, the conditions of temperature and density are so unfamiliar, that we feel uncomfortable in applying our ordinary theories of statistical mechanics and nuclear physics.

This is often the way it is in physics—our mistake is not that we take our theories too seriously, but that we do not take them seriously enough. It is always hard to realize that these numbers and equations we play with at our desks have something to do with the real world. Even worse, there often seems to be a general agreement

Another perspective – Attention was elsewhere

Physics exploding after WWII
Astronomy smaller community, many amatures, few rich places with big telescopes, no federal supported
Radio astronomy just getting started
Nobel Prizes 1945-1960

- Quantum mechanics
- Atomic and nuclear physics
- Atmospheric physics
- Accelerators
- Anti-particles
- Superconductivity

NO Nobel Prize to Hubble, Friedmann, Robertson, Walker, LeMaitre
Einstein Nobel Prize for photo-electric effect (Thanks to Lenard)
First Nobel Prize to astronomers in 1974 (Ryle, Hewish), Penzias and Wilson (1978)

5 m Break

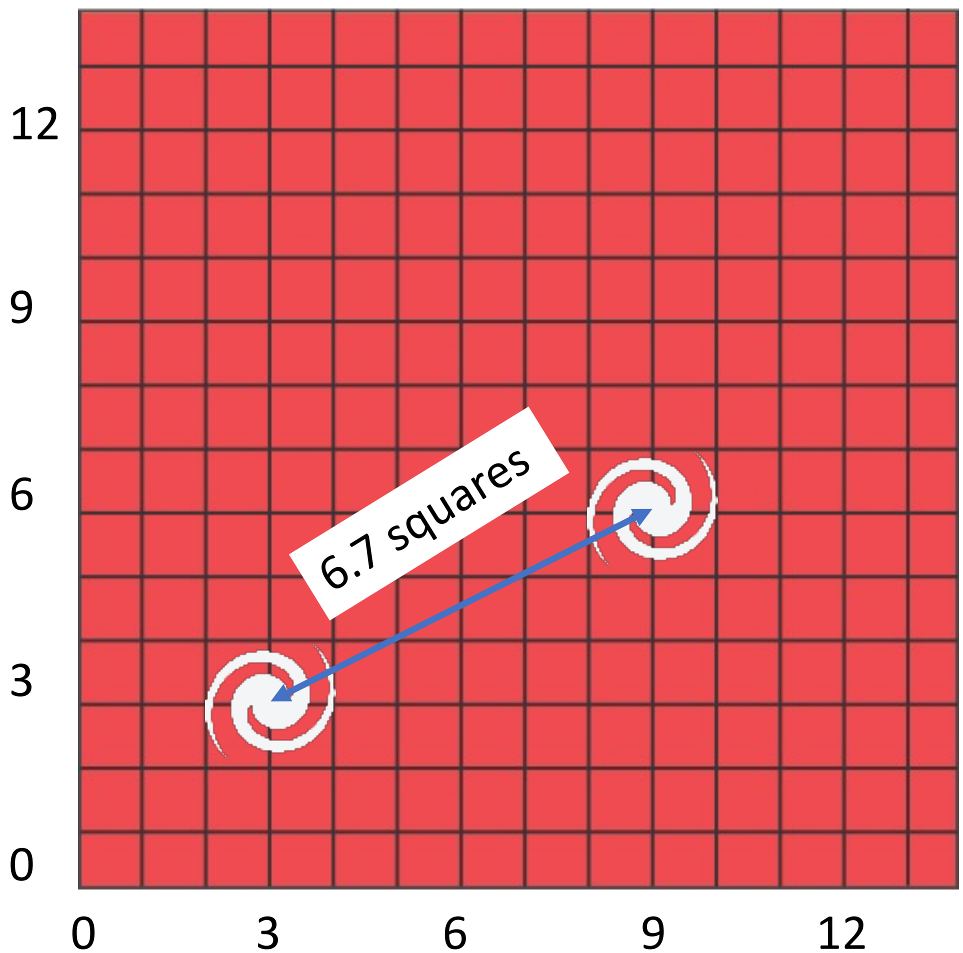
General Relativity's Field Equations

$$\begin{pmatrix}\text{Structure of}\\ \text{space} - \text{time}\\ \text{at a point}\end{pmatrix} = G\begin{pmatrix}\text{Total density}\\ \text{of matter}\\ \text{at the same point}\end{pmatrix}$$

"Structure of space-time at a point" means the geometric relationships around a point in space.

Sum of interior angles of a triangle, Pythagorean Theorem, relation between circumference and diameter of a circle. Also, *when* measurements are made.

Example – expanding universe (Meeting 4)



Galaxy 1: Location 3,3

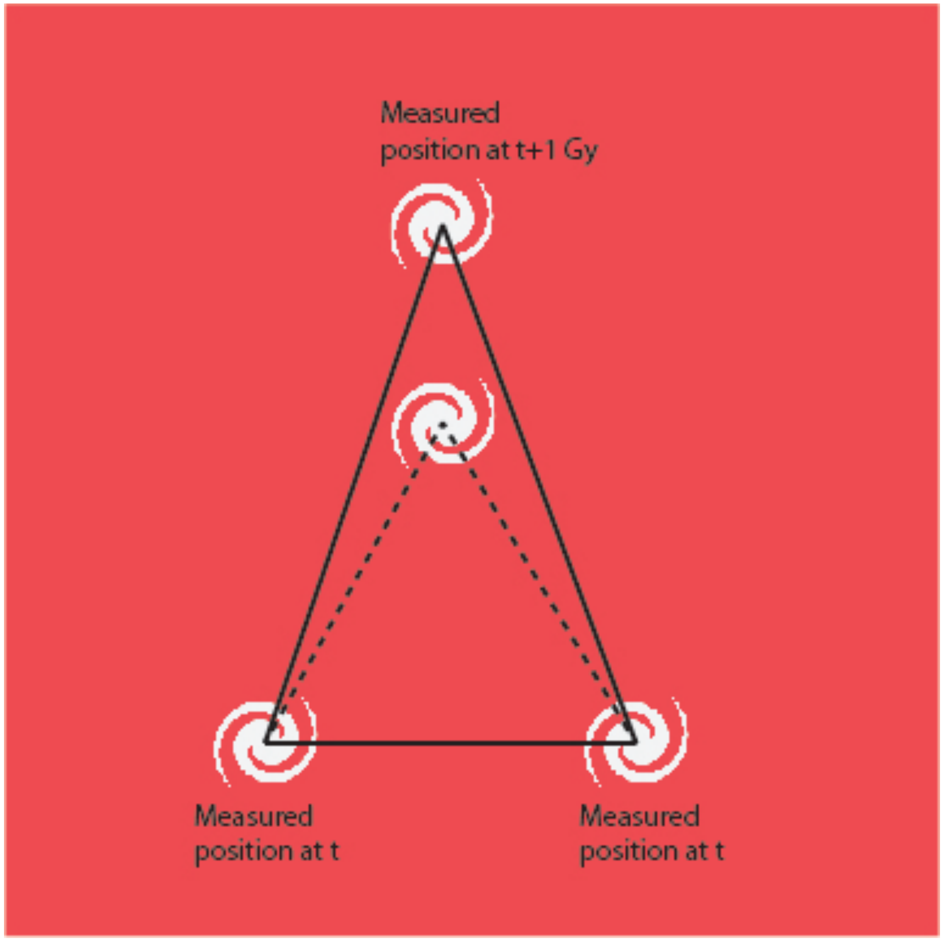
Galaxy 2: Location 9,6

Galaxies are 6.7 squares apart

Call this the "Address Distance" *a* (scale factor)

Each square has size of 2 Mly, galaxies are 13.4 Mly apart, "proper distance"

Example – expanding universe (cont)



Angles between three galaxies should add up to 180°.

In an expanding universe, this is only true if the galaxy positions are measured *at the same time.*

General Relativity's Field Equations

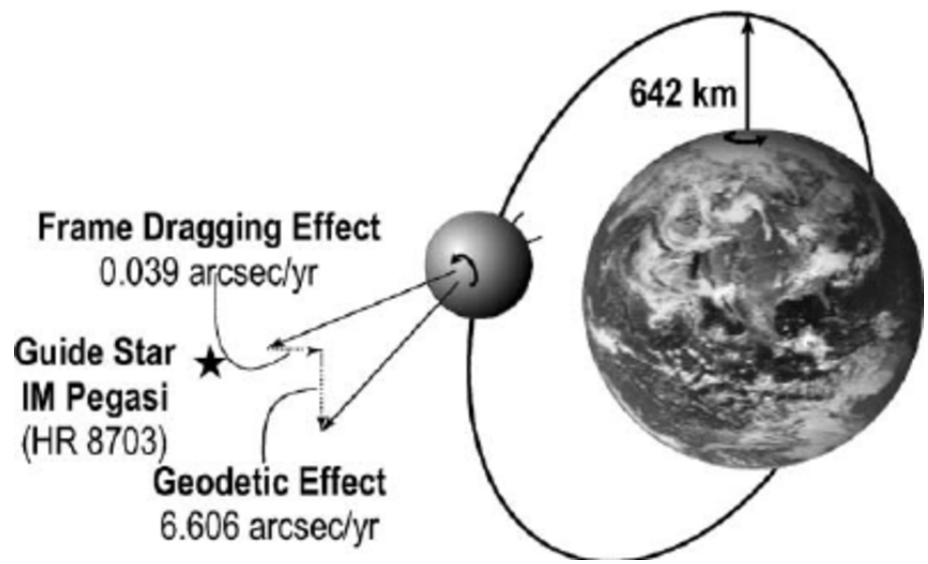
Four exact solutions (aside from empty universe)

1. Expanding universe (1920-1930)
2. Static mass – Schwarzschild solution, stars and black holes (1916)
3. Rotating mass – Kerr solution, stars and black holes (1963)
4. Rotating, charged mass – Kerr-Newman solution (1965)

Kerr Solution

A rotating body alters space-time near it, causing a gyroscope to change direction, “precess”

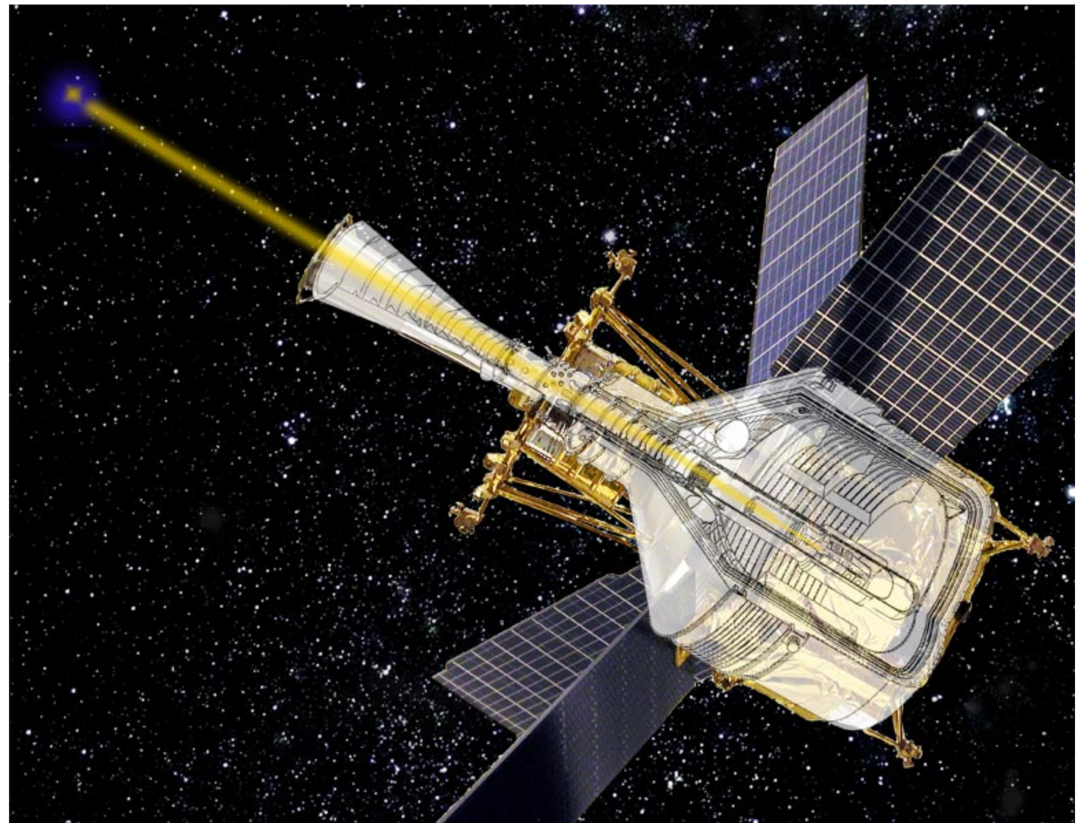
Measured (?) by Gravity Probe B



Gravity Probe B

Satellite in Earth orbit with a telescope aimed at a star connected to gyroscopes.

Look for drift from the star over a year.



Enormous technical challenges.

1957 – Experimental idea
1961 – First proposed
2004 – Launch, operation for 16 months
2011 – Final science results

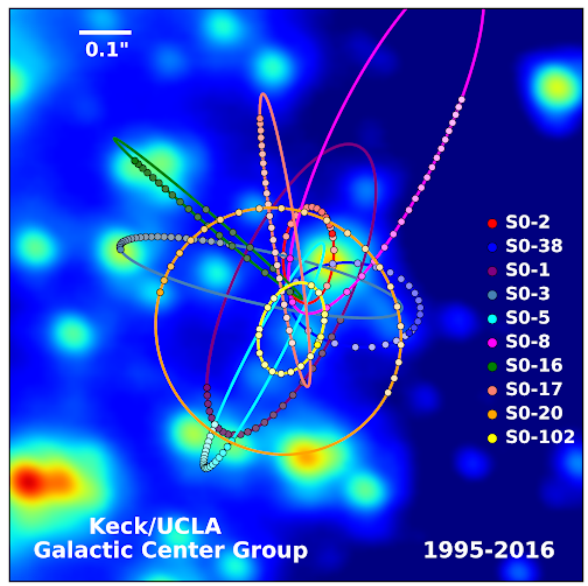
Schwarzschild Solution

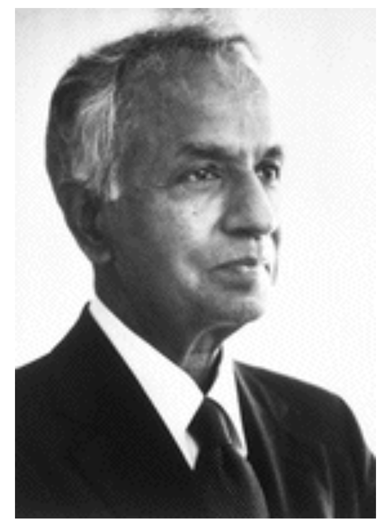
Reproduces Newton's law of gravitation at low fields are stars

Modifies orbits at high fields near stars

Mathematically predicts black holes.

Andrea Ghez (UCLA) 2020 Nobel Prize for imaging stars orbiting BH in galactic center

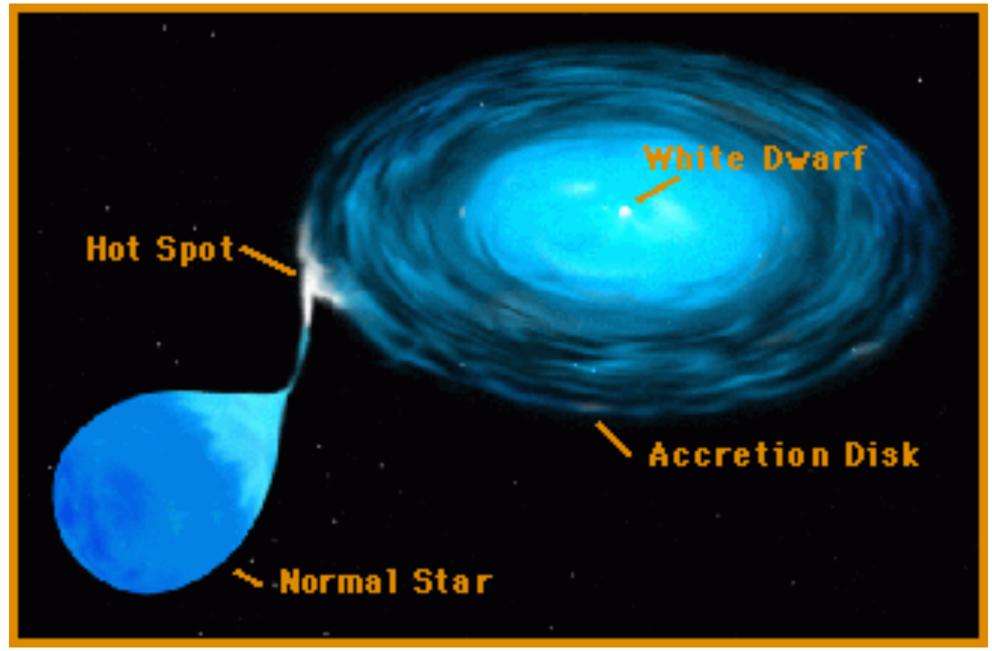




S. Chandrasekhar

Black Holes

Mathematical construct that later turned out to be real. Formed by accrection of matter from a star onto a compact star, white dwarf.



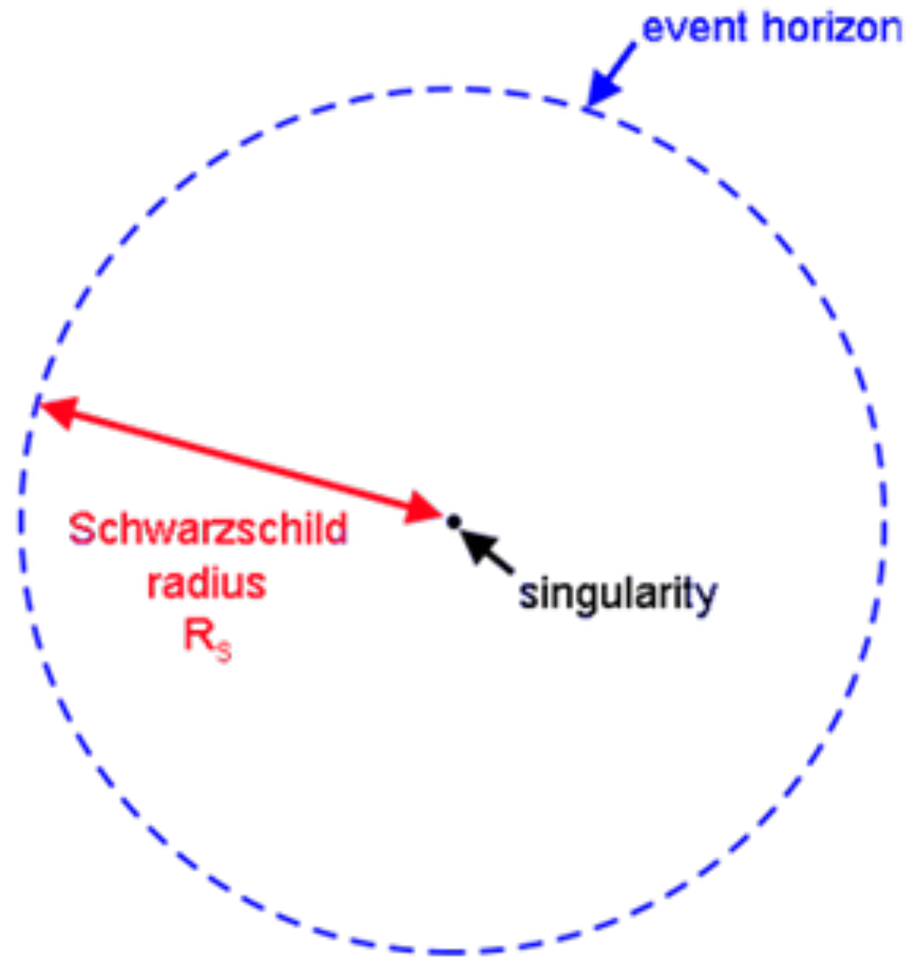
White dwarf explodes as a super nova, leaving a black hole behind.

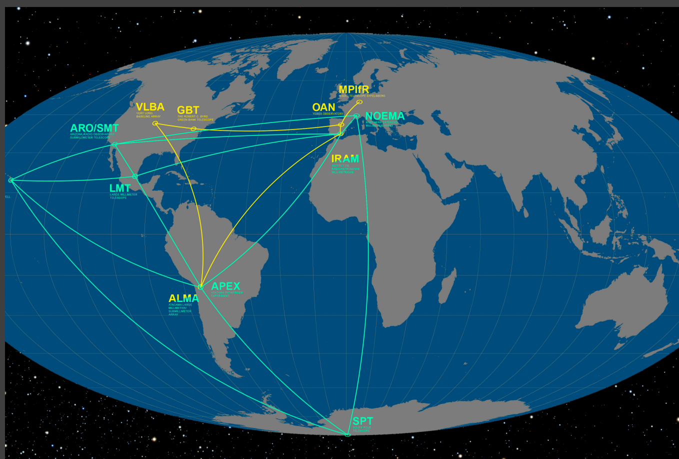
Black Holes (cont.)

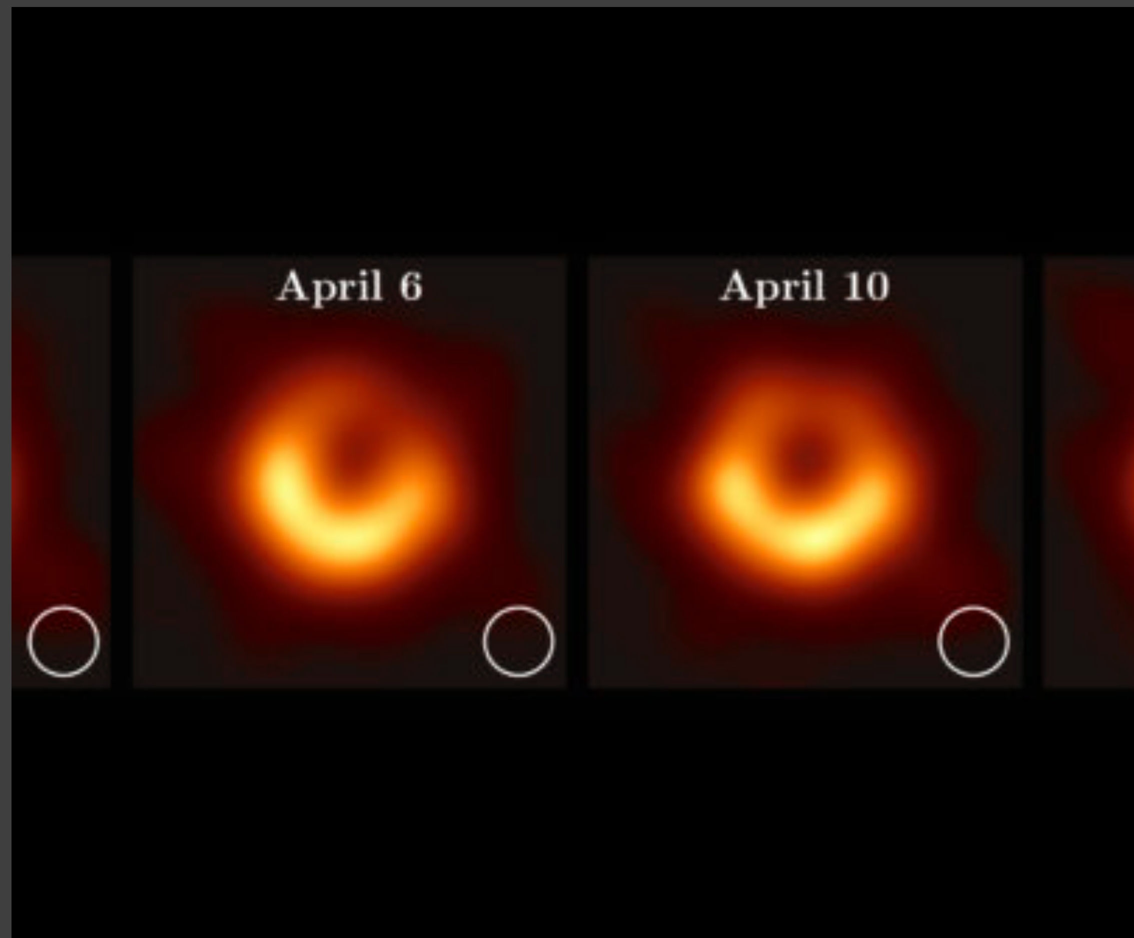
The event horizon lies one Schwarzschild radius from the singularity

All the mass is concentrated the singularity point.

"No Hair" theorem







Feryal Ozel, Dmitiris Psaltis (AU)

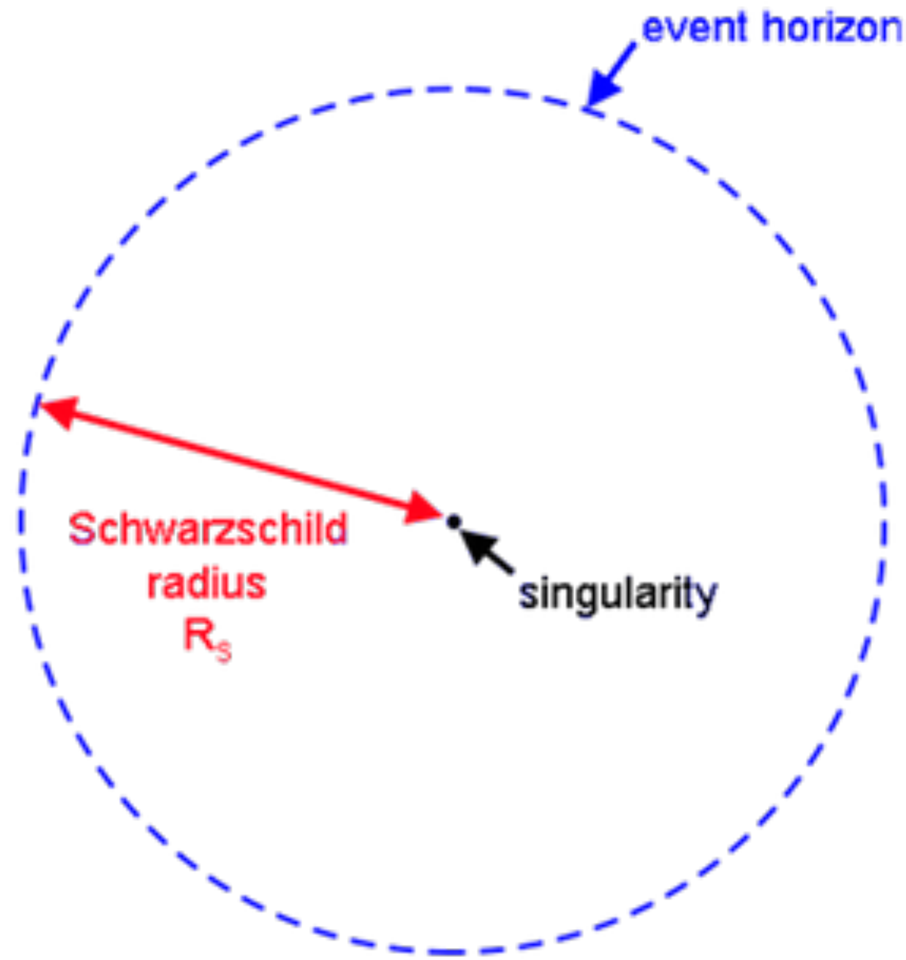
Black Holes (cont.)

BH distorts space-time by

- A circle's circumference is not proportional to it's diameter
- A clock near the EH ticks more slowly than one far away
- Inside EH, everything *must* fall to the singularity

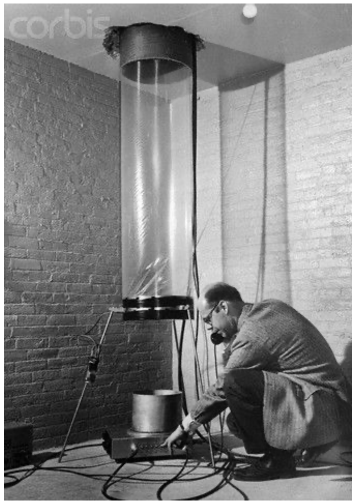
A free faller

- Does not notice much until near the singularity
- Observed from outside: never reaches EH, moves more slowly, turns red



Clocks Near a Black Hole

If you sit a long way from the EH and compare a watch just outside the EH with an identical watch in you hand, the one near the EH ticks more slowly.



Photons are like little watches, so this system a photon redshifts travelling from the EH to you, a long way away.

Pound-Rebka experiment