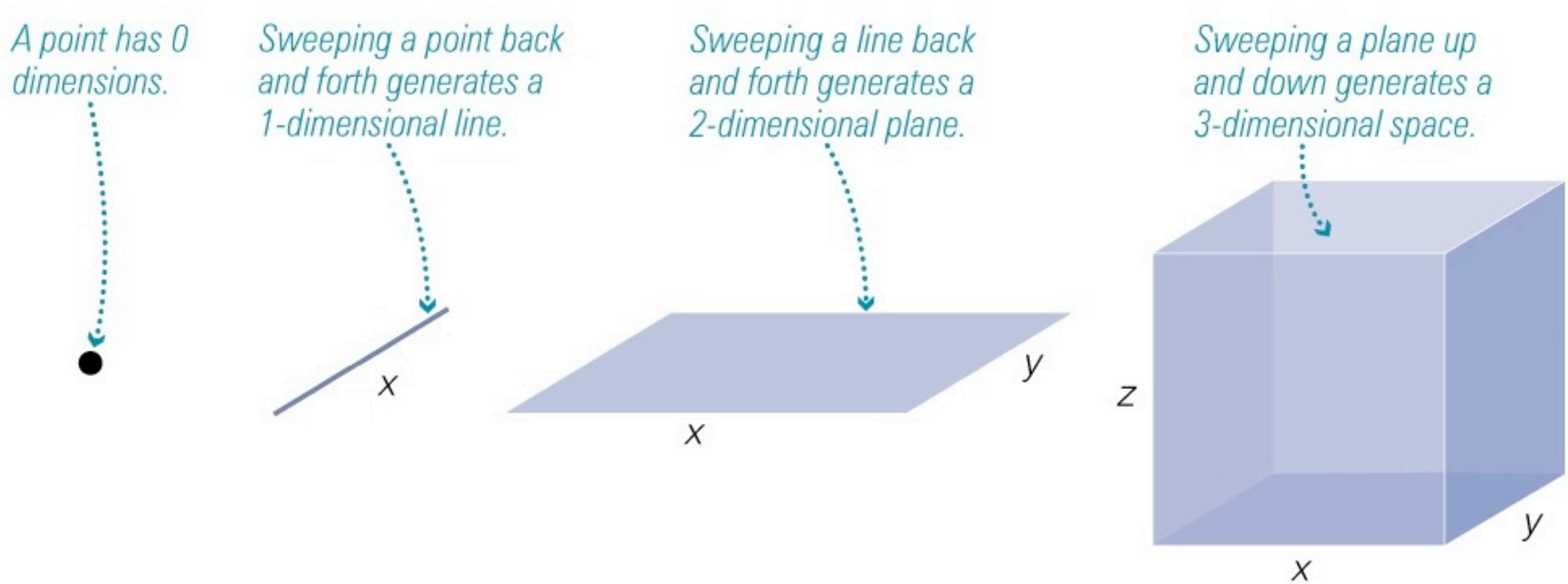
we live in 3+1D space-time, coincidence/accident? (Rees §10)



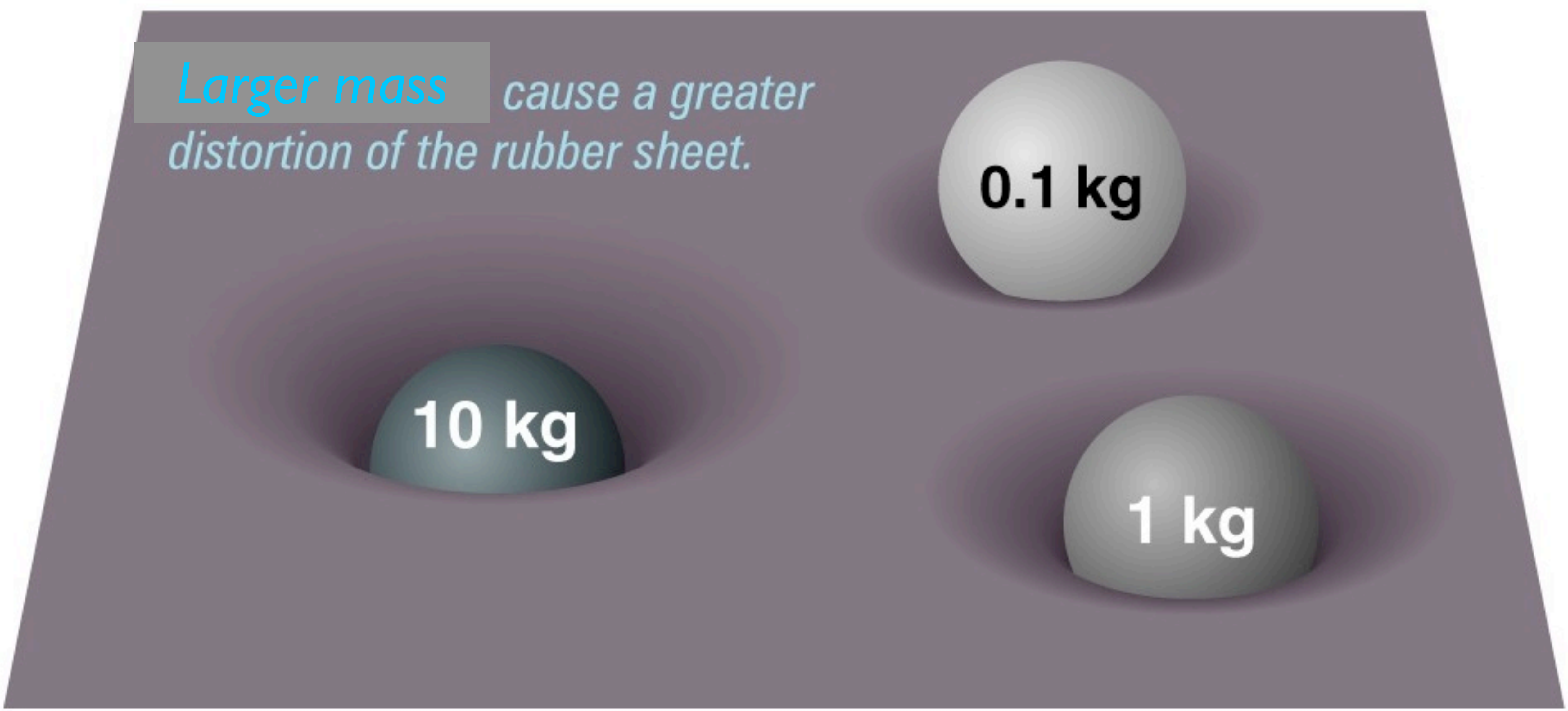
and to generate 4-dimensional space...

it is claimed that N=3 and T=1 is very special.

space-time can be curved --- general relativity

away from massive objects, space-time fabric uniform & flat;

when mass is present, ‘warp’ -- space-time fabric stretches;



What is that rubber sheet?

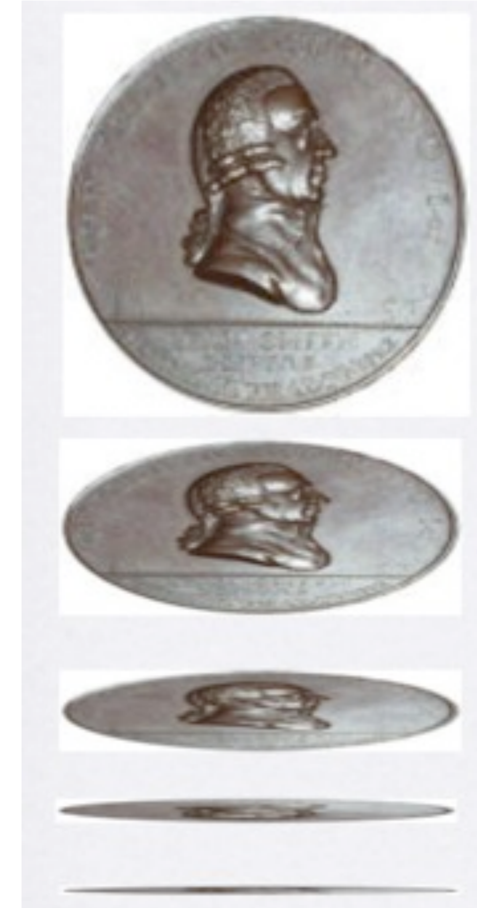
The "rubber sheet" analogy compensates for our lack of imagination.

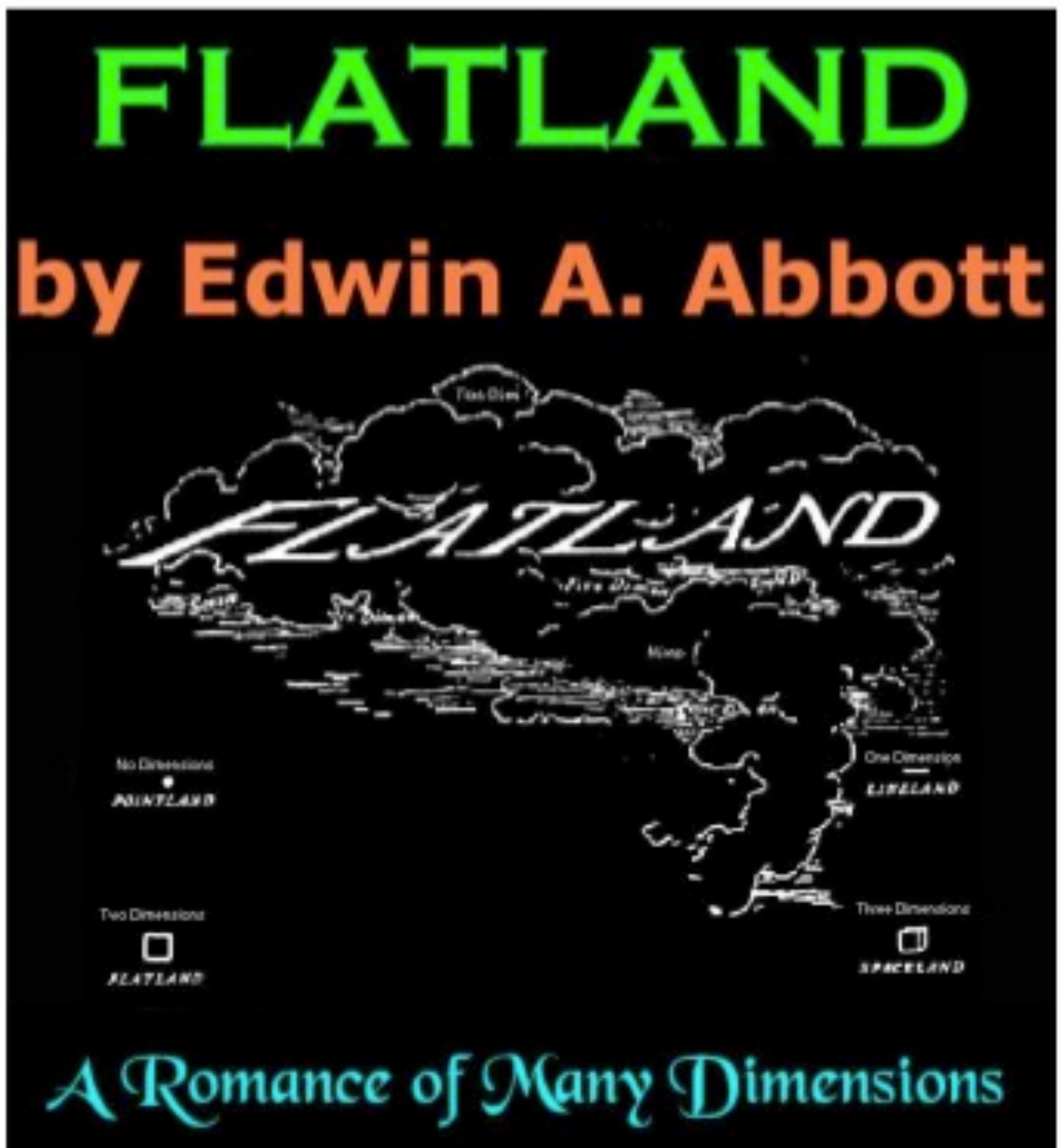
A 3-D being can visualize curvature, distortion, expansion... of a 2D surface. But not a 3D counterpart.

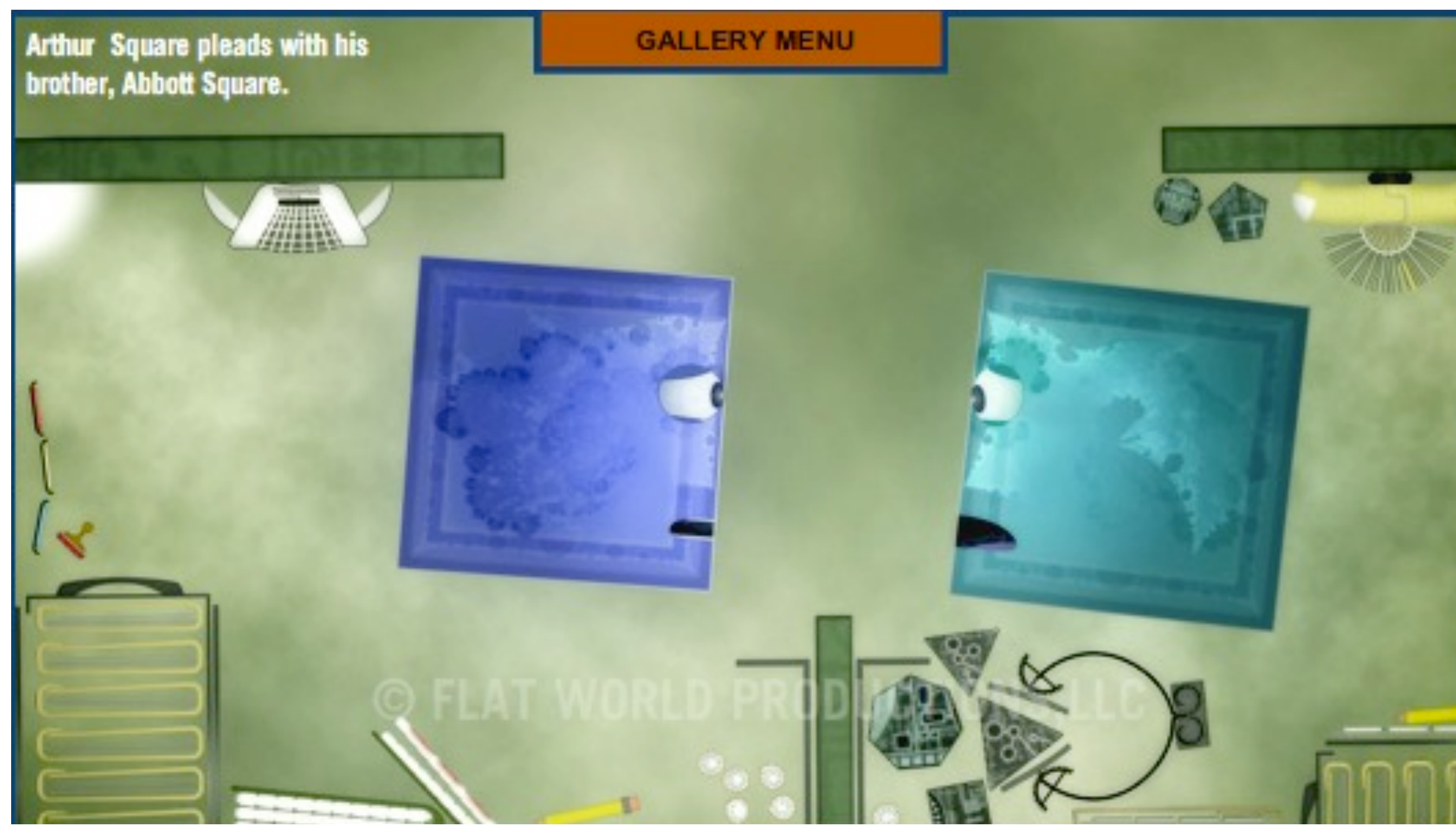
how does it feel to live in curved space? Flatten your mind and imagine all movement occurs only on a 2D surface.

the story of the 'flat-land' (1884)

imagine yourself restricted to a 2-D surface







Social Rank is Based On Number of Vertices

Woman

2 vertices

Soldier

3 vertices

Note that in Abbott's 2D world women are deadly and not to be trifled with… they can "inflict instantaneous death with a single retrograde movement"

Tradesman

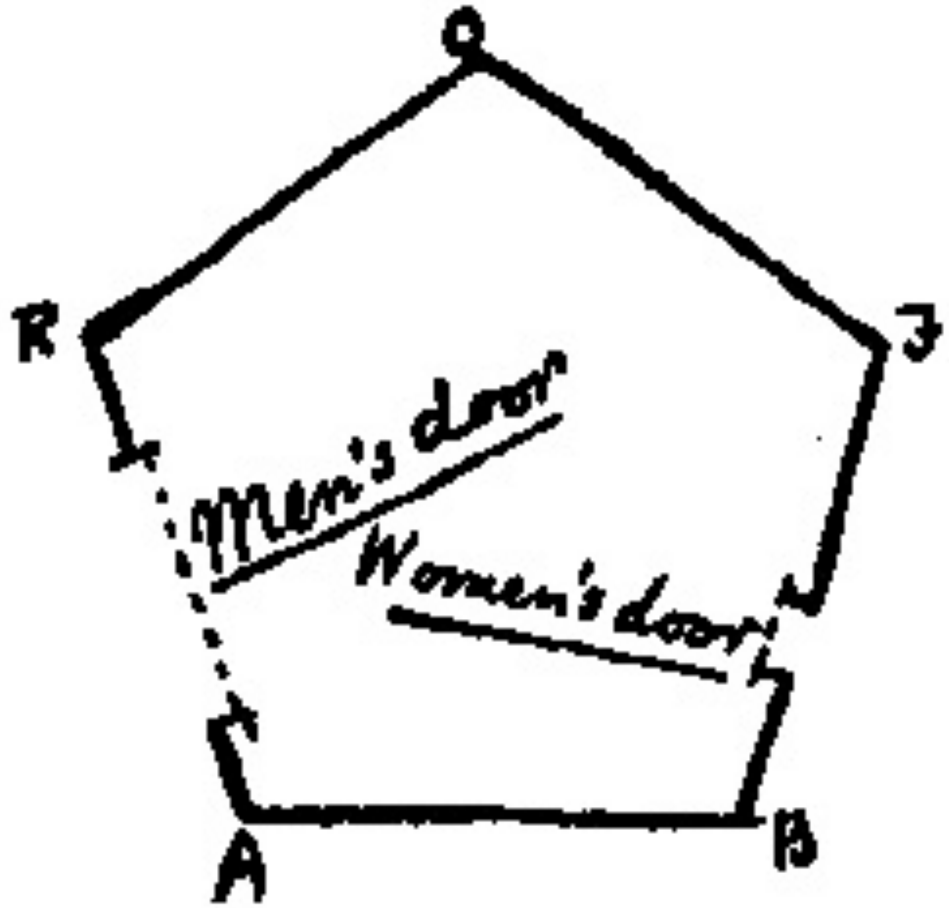
3 vertices

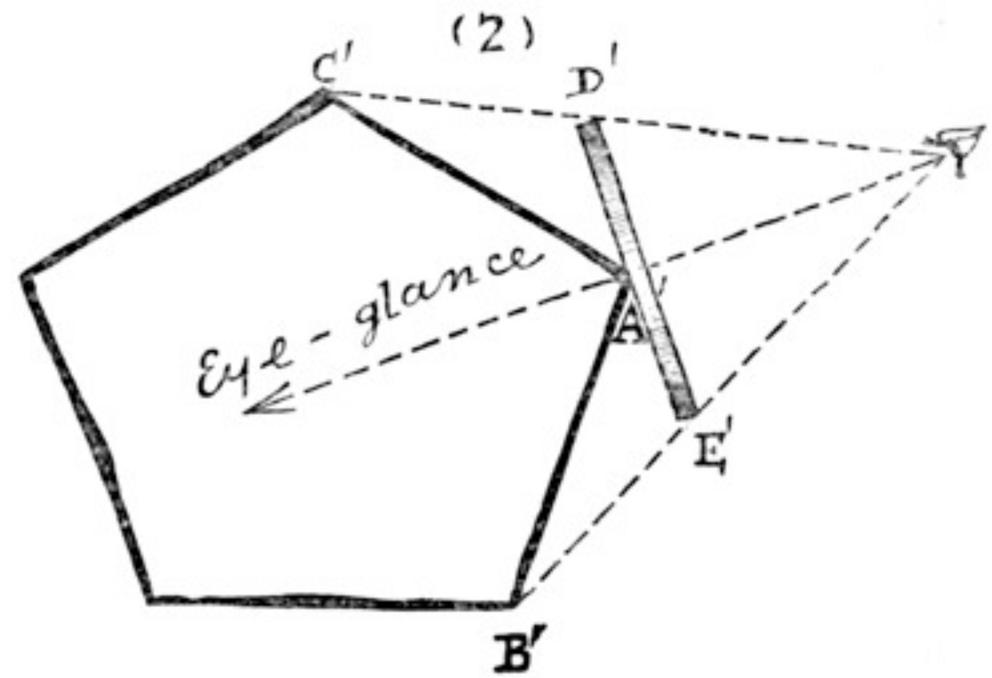
Gentleman

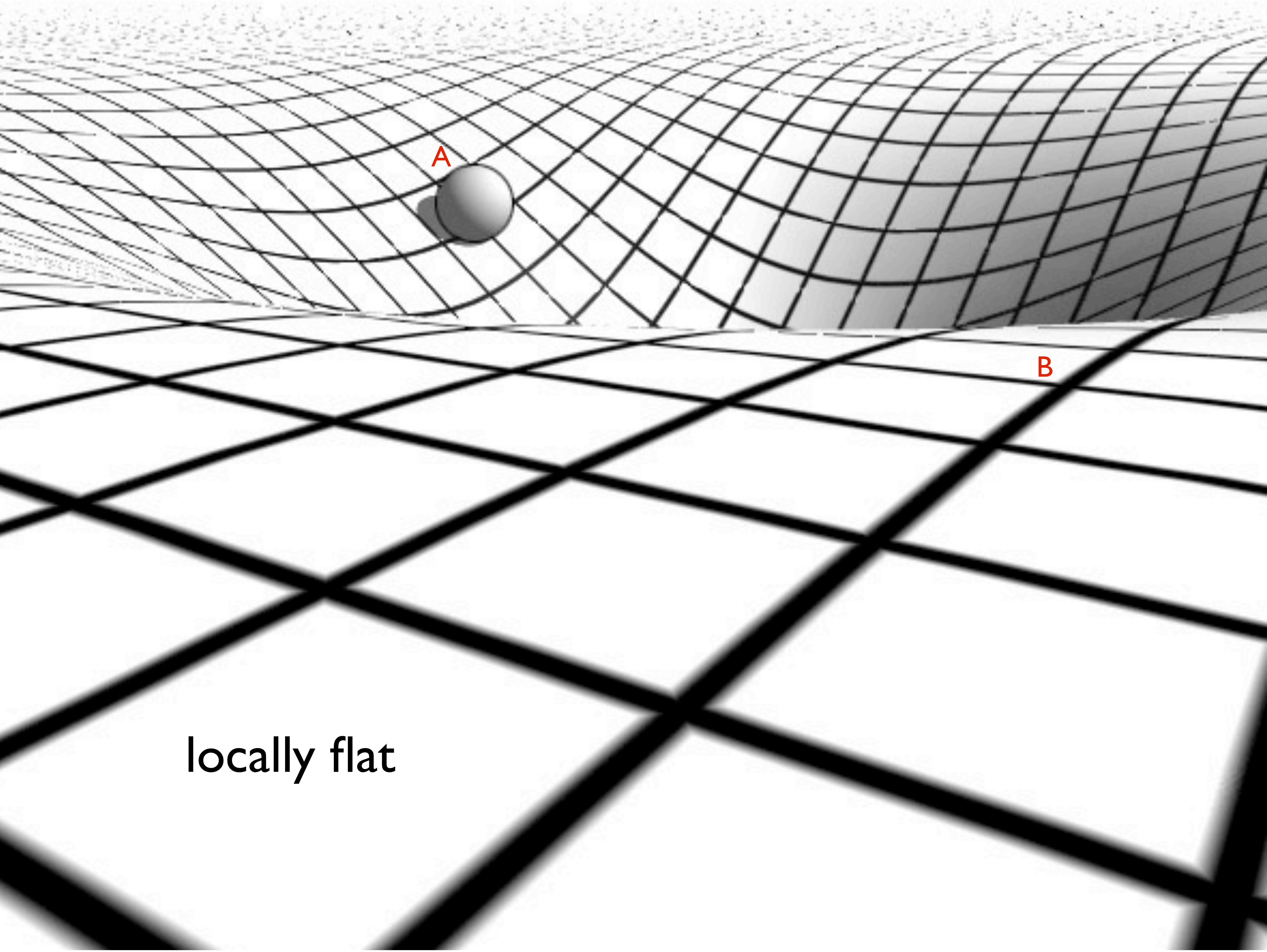
4 vertices

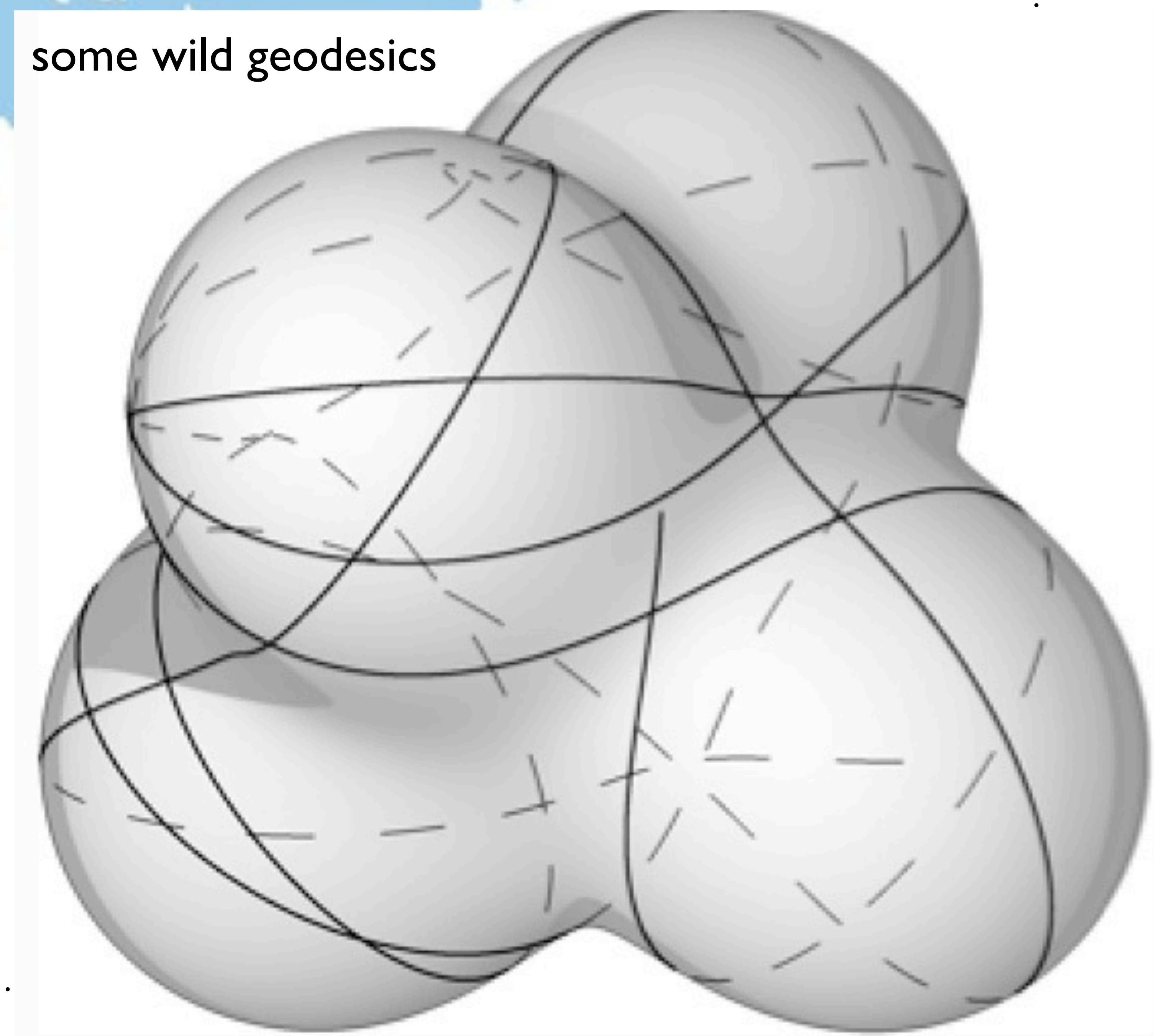
Priest

Infinite number of vertices






A
B
locally flat

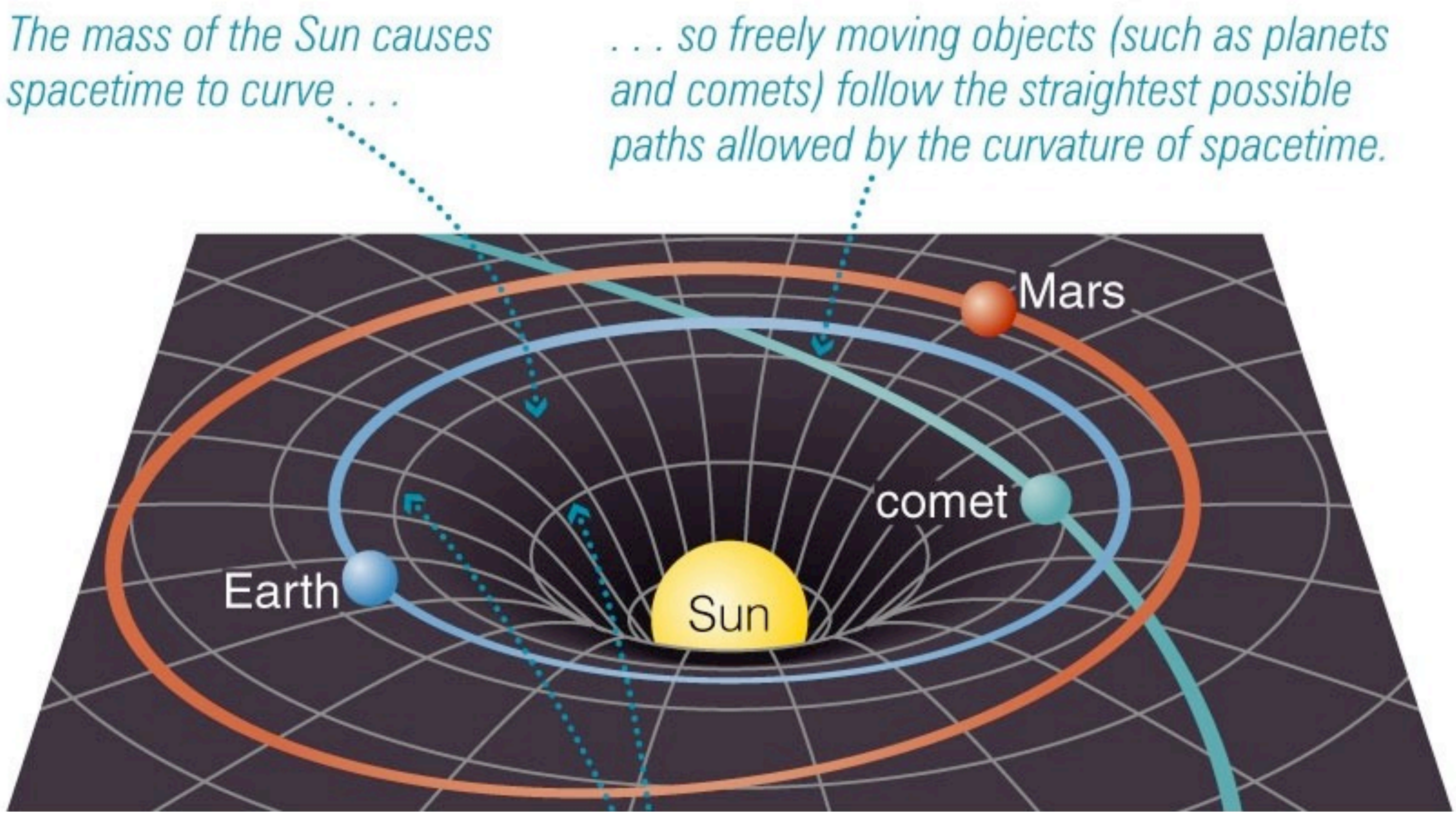


Straight: shortest route between two points. On curved surfaces, this is called 'geodesics'.

straight is the path to follow:

a freely moving flatland inhabitant follow geodesics

(think a bullet out of a barrel....)



“Gravitational force” is a myth

Classical image: Earth orbits around the Sun because Sun’s ‘gravity’ is pulling on it.

Einstein brought about a revolution.

Earth’s path is built into the space it is moving through -- like rails for a train.

this path is the geodesics, the straightest line in local space.

Gravity is nothing but geometry.

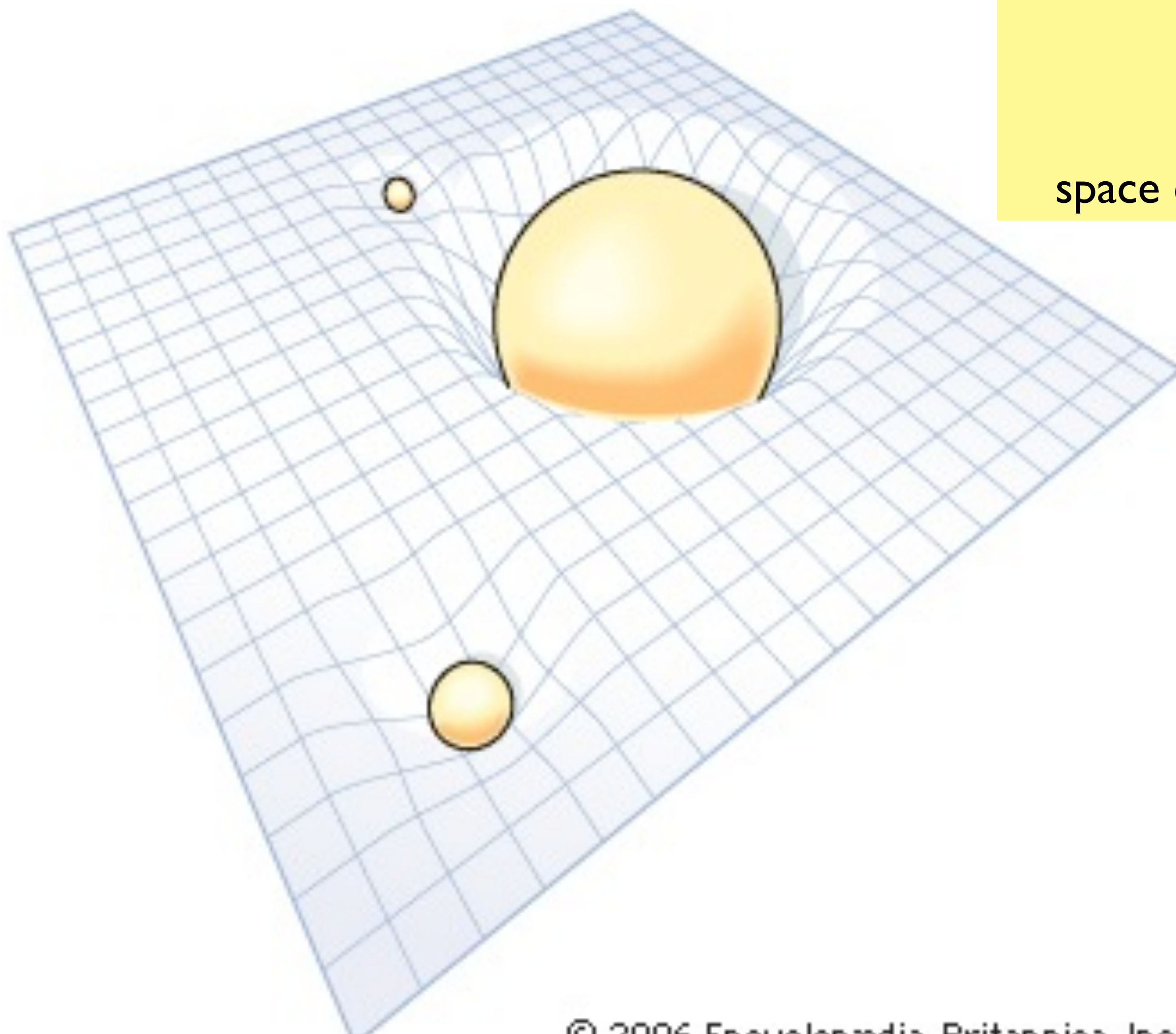
but how then, gravity can be unified with other forces?

The Essence of General Relativity: Mass Tells Space How to Curve, Space Tells Mass How to Move

Einstein Field Equation

$$G_{\mu\nu} = 8\pi T_{\mu\nu}\ .$$

space curvature mass-energy



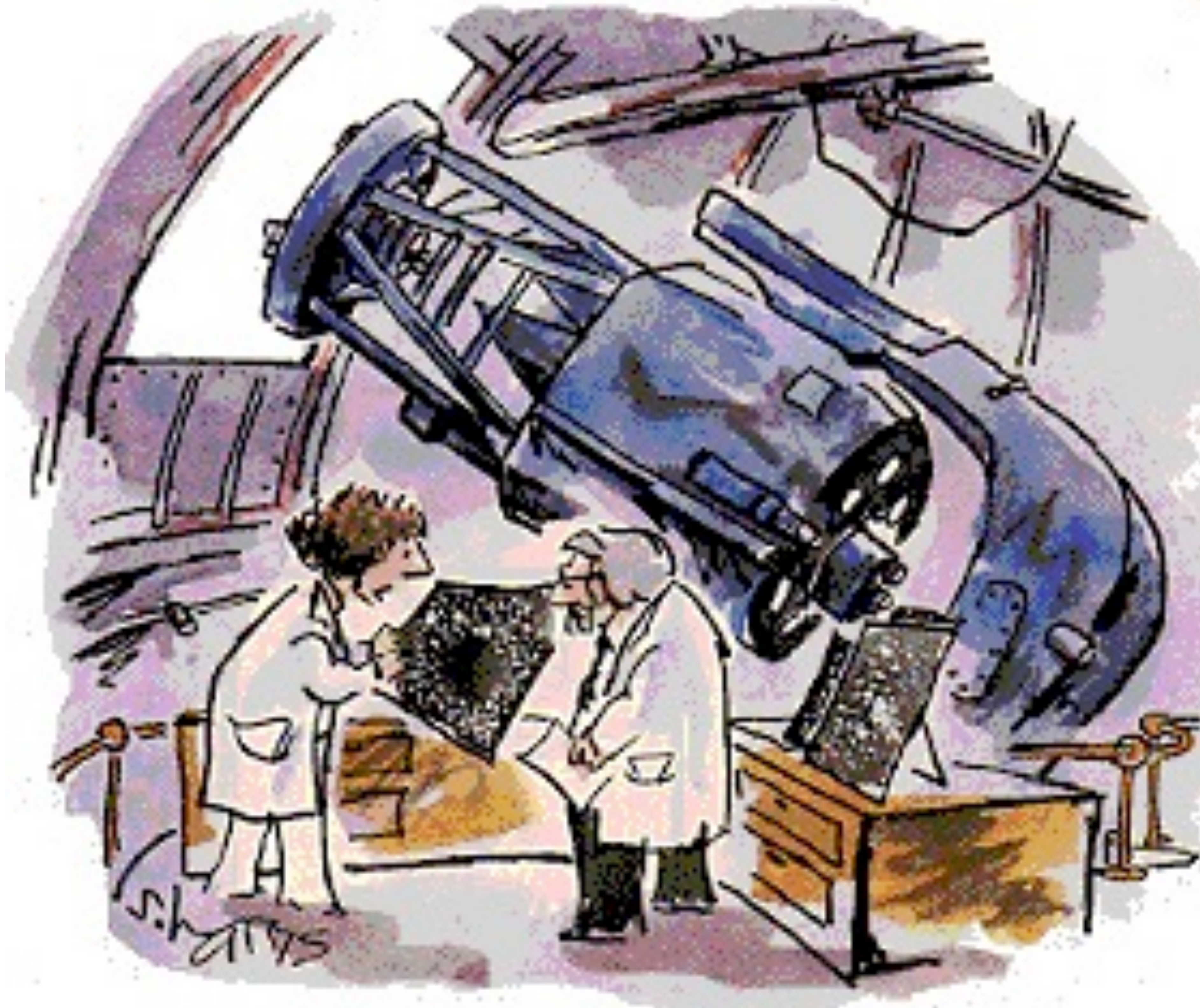
Newtonian equivalent:

Force tells mass how to accelerate (F=ma)

Mass tells gravity how to exert force ($F = GMm/r^2$)

But photons have no mass, so they can't feel gravity....

?

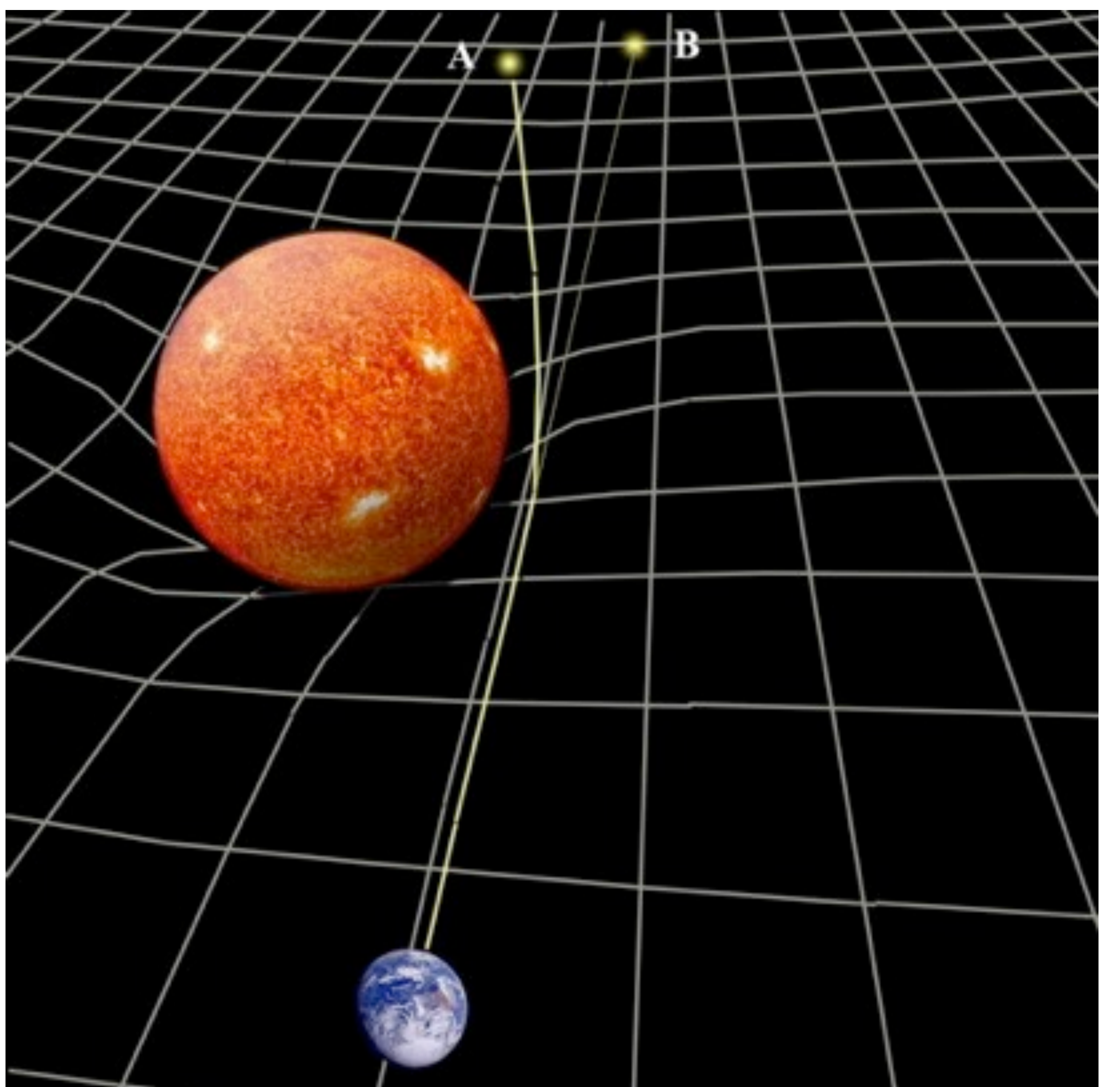


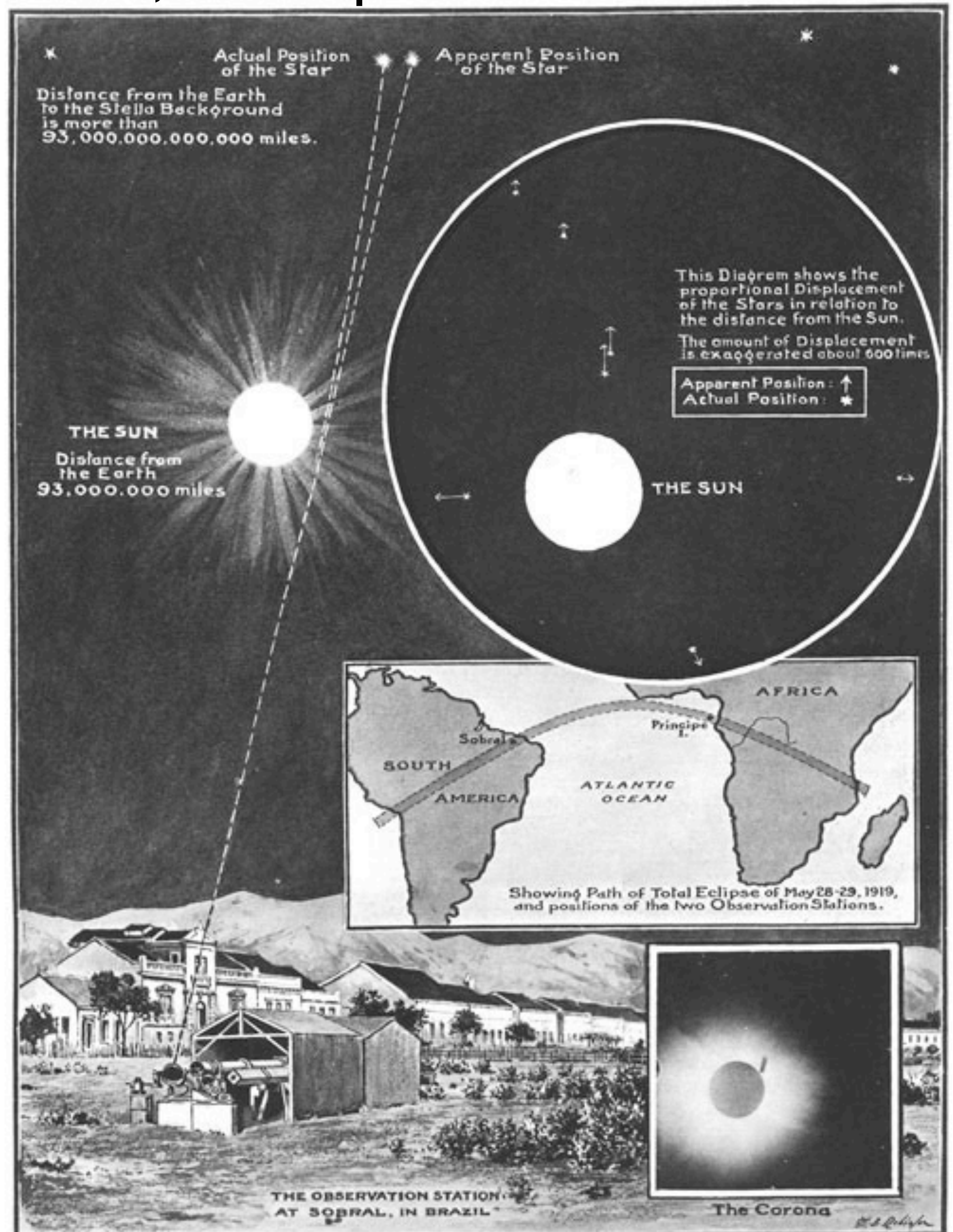
"It's black, and it looks like a hole.
I'd say it's a black hole."

Prediction of GR: light bending

space curvature same for every one, even photons.

Bending of light, theorized 1915 (Einstein)
Bending of light, confirmed 1919 (Eggleton)

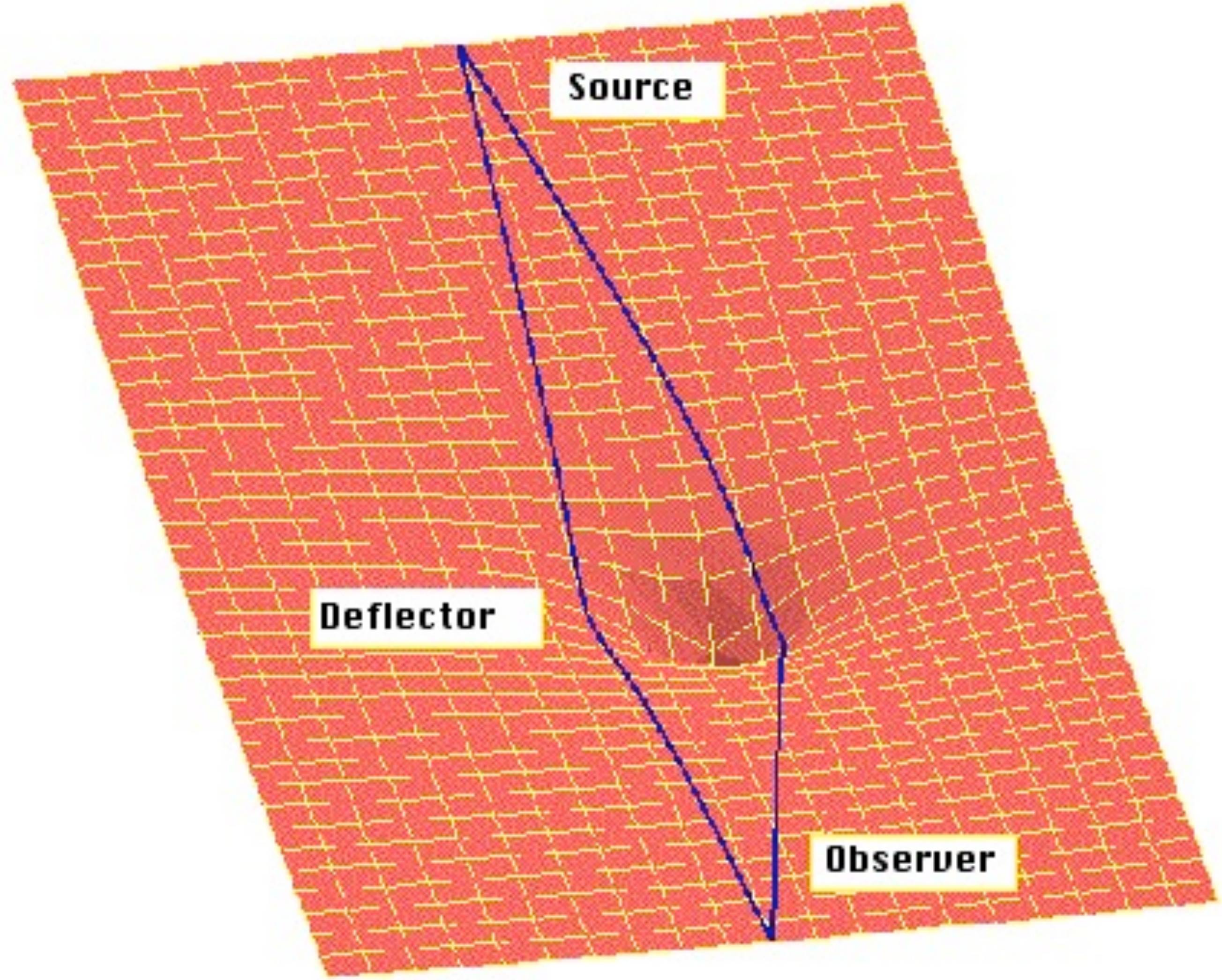




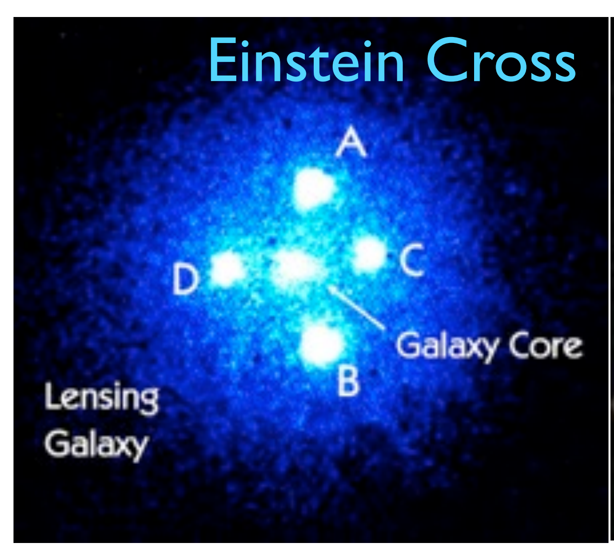
When asked by his assistant what his reaction would have been if general relativity had not been confirmed by Sir Eddington and Dyson in 1919, Einstein famously made the quip:

"Then I would feel sorry for the dear Lord[Eddington]**. The theory is correct anyway."**

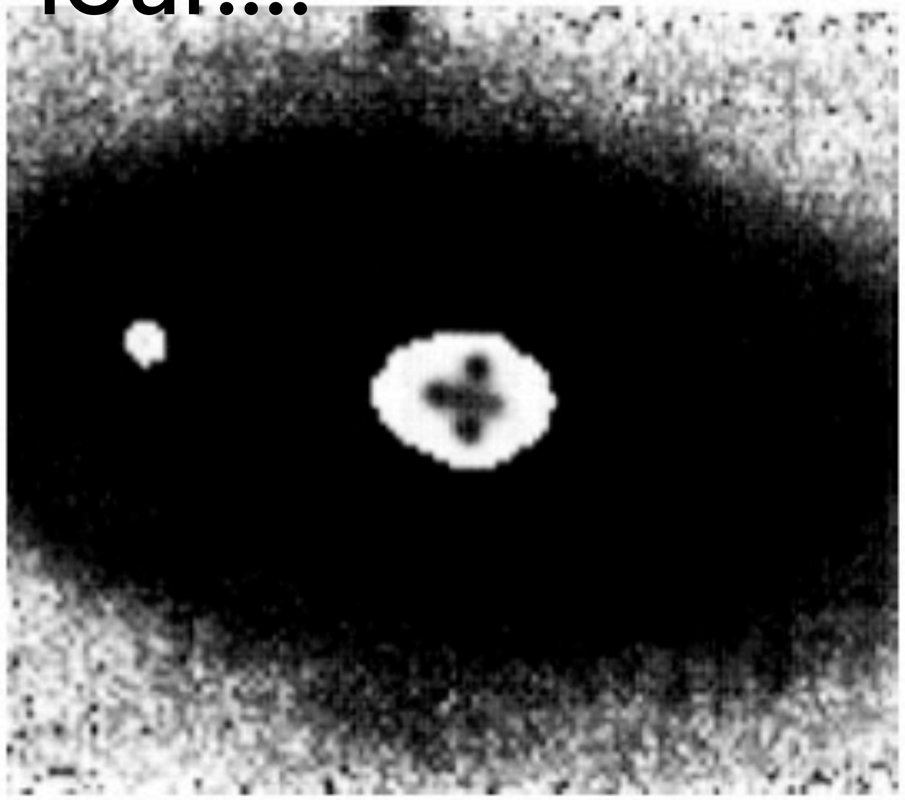
gravity as a lens: Gravitational Lensing



First gravitational lens discovered, the double quasar Q0951+561, by Walsh, Carswell, and Weymann, 1979. The 2 bright objects in the center are images of a single distant quasar "split" by the gravitational potential of a galaxy between us and the quasar.



or four....

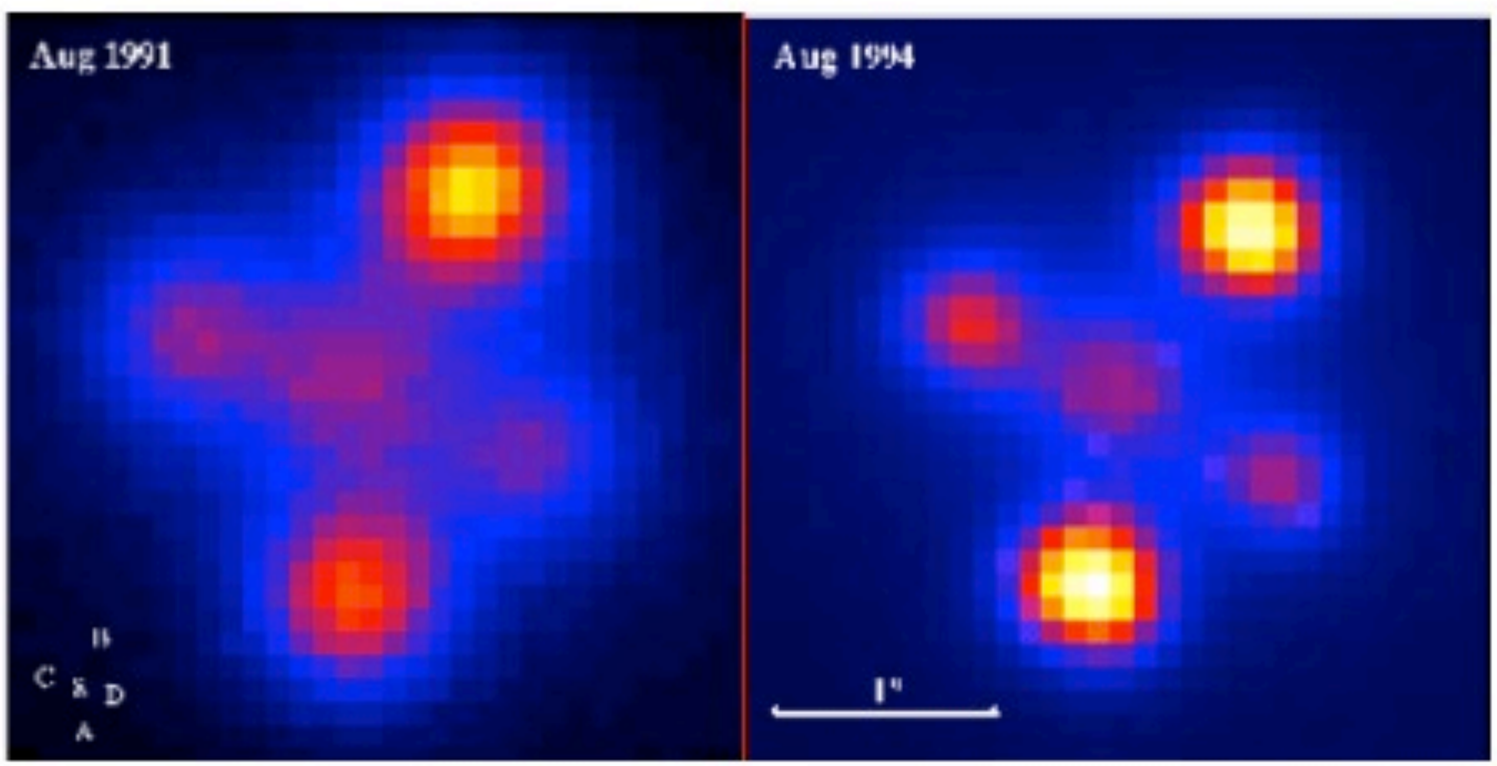


Discovery image: CFHT (Yee, 1988, AJ, 95, 1331)

First "Einstein Cross" lens:
2237+0305

the quasar is at z=1.695,
the (very large) lensing galaxy at z=0.0394

The Einstein cross configuration occurs when the alignment of the source quasar and the lensing galaxy is almost exact. (When it is exact, it produces an "Einstein ring".)



The 4 outside points are 4 images of the same quasar; the fuzzy central point is the nucleus of the intervening spiral galaxy.

HST image from two epochs, not the change in the relative brightness

when the lensed object is extended:

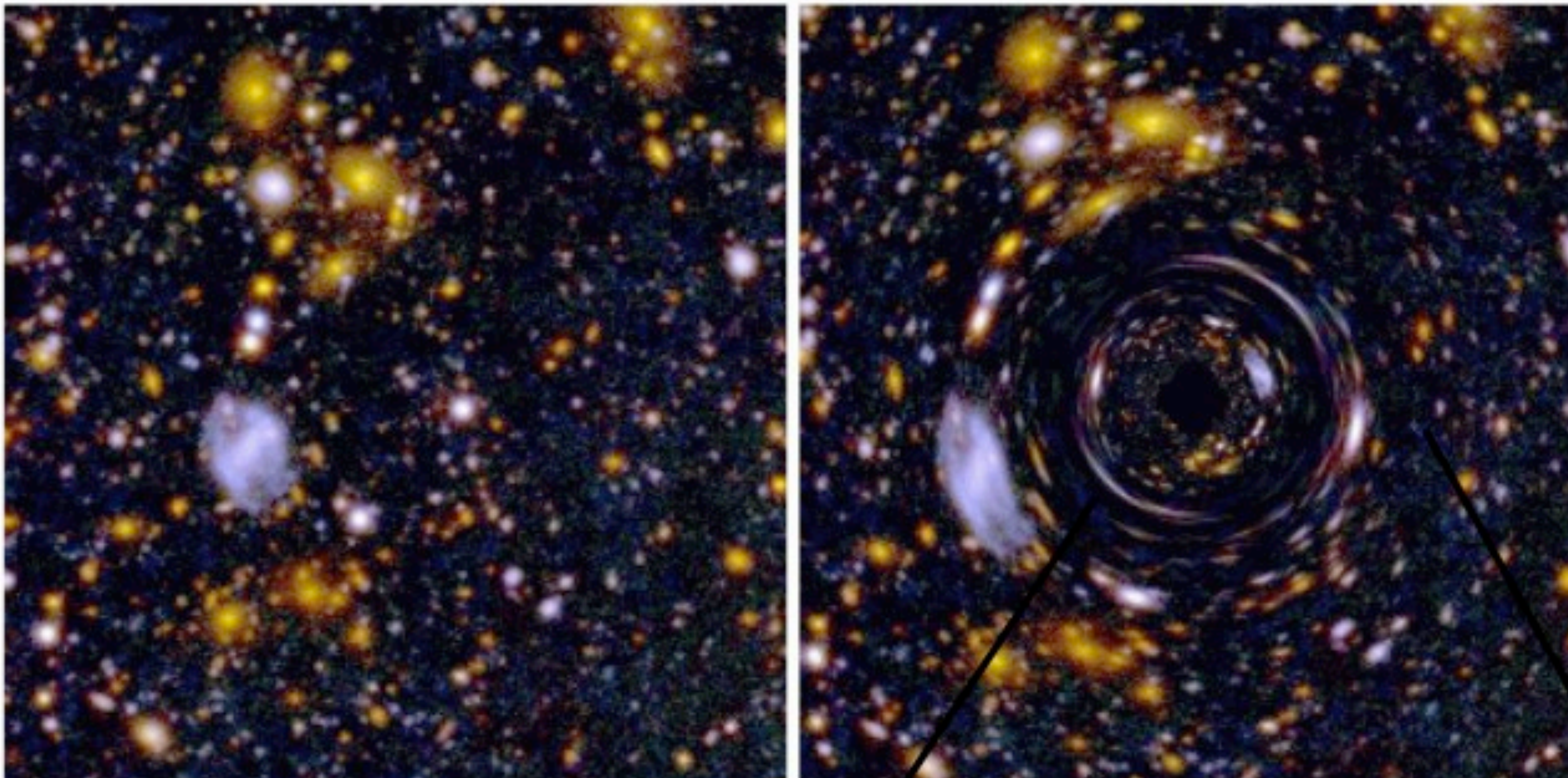
a gravitational lens passing in front of the CN tower

Antoni Gaudi (Barcelona)

Simulations of lensing from a cluster-like mass

A simulated view of the sky

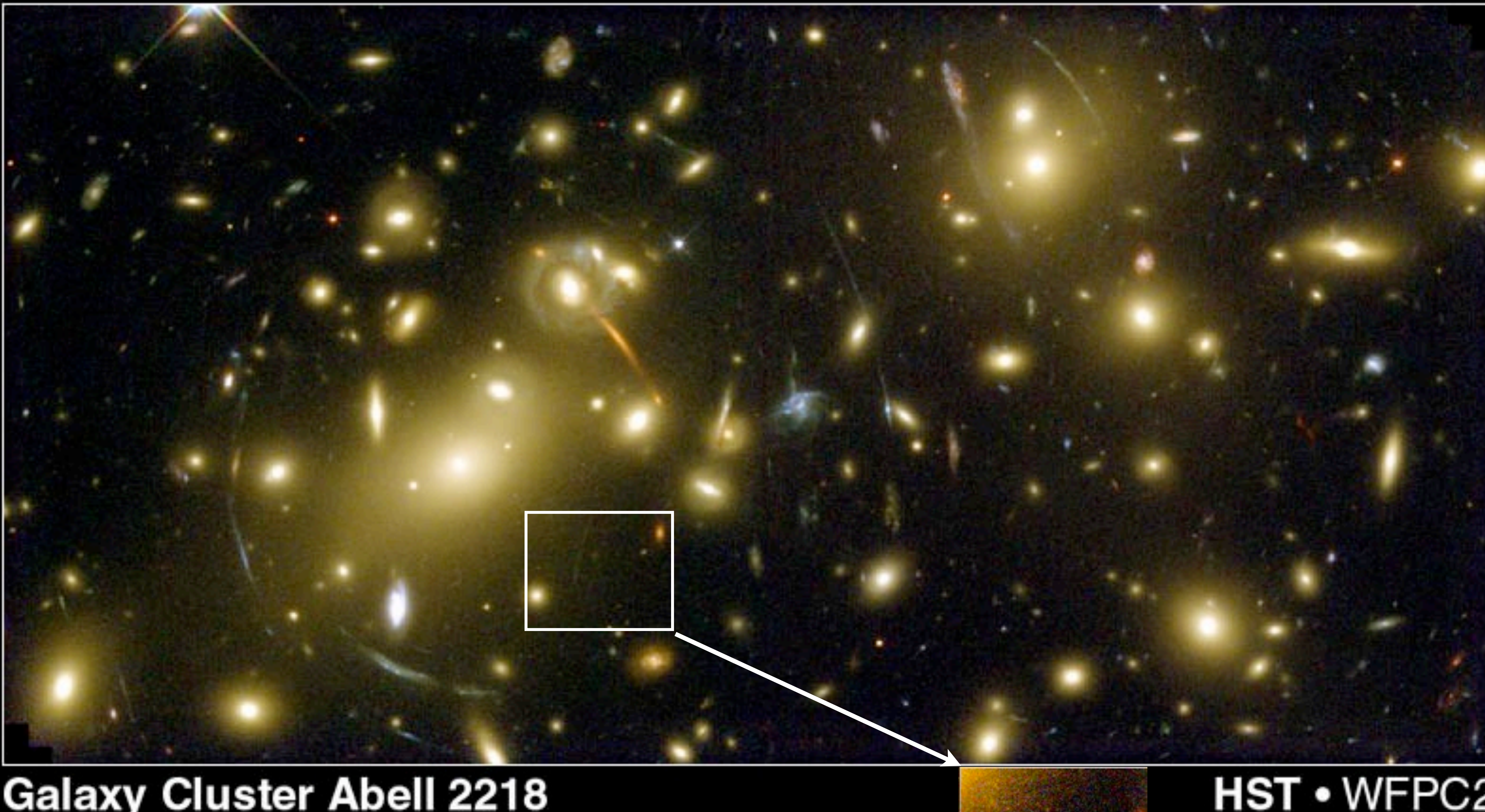
Same view, with an invisible mass placed in front, producing lensing



Strong lensing

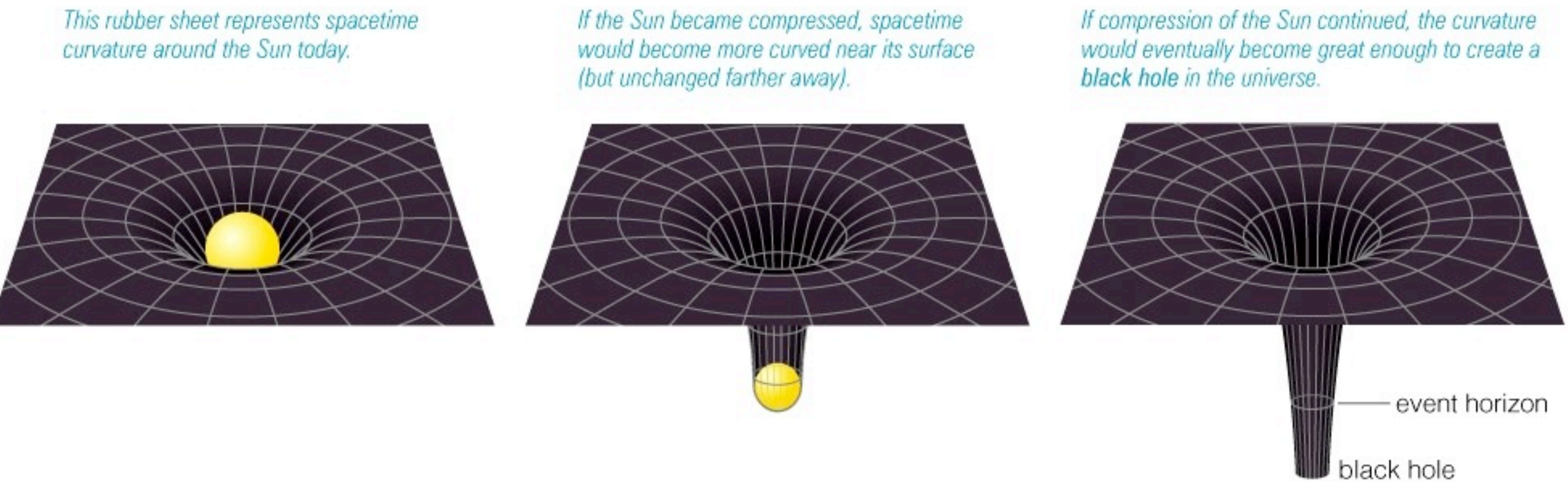
Weak lensing

the universe is a twisty place for photons



acting as a gravitational lens for background (further away) galaxies

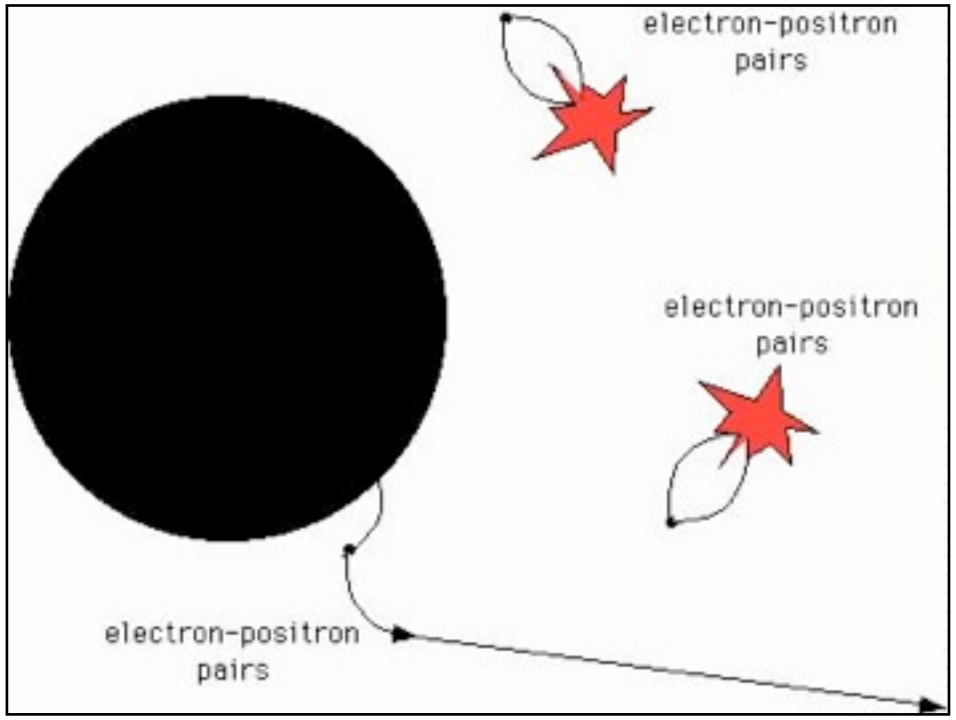
Extreme Geodesics: a blackhole



R=700,000 km R = 100 km R=1.4km

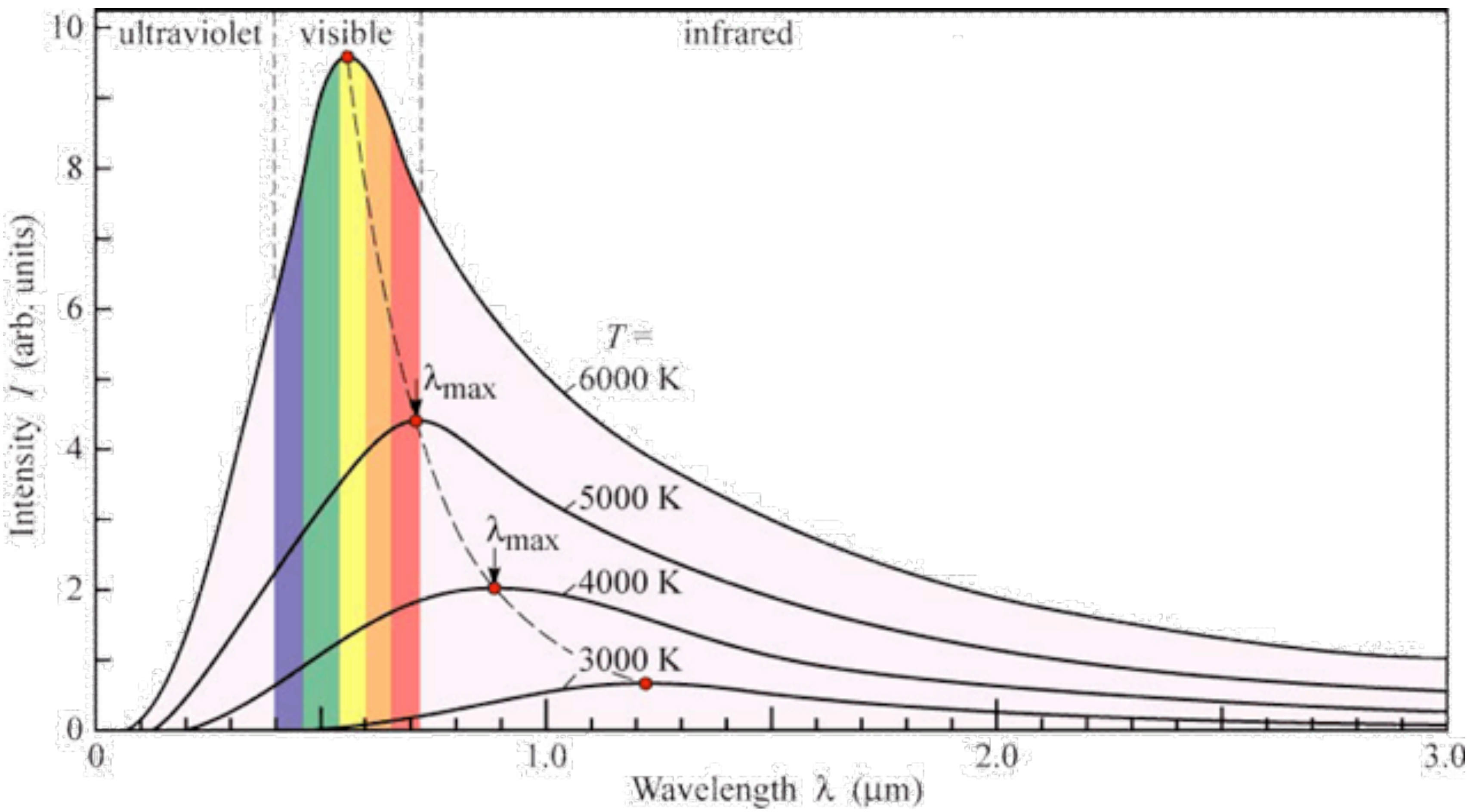
a black-hole: mass so compact ($GM/r \sim c^2$) that no light can escape from its vicinity.
event horizon: even moving with speed of light, all straight path heads downward.
You can't beam back youtube video.

Black-hole: don't radiate (except: Hawking radiation)



Black-body: radiate according to their temperature

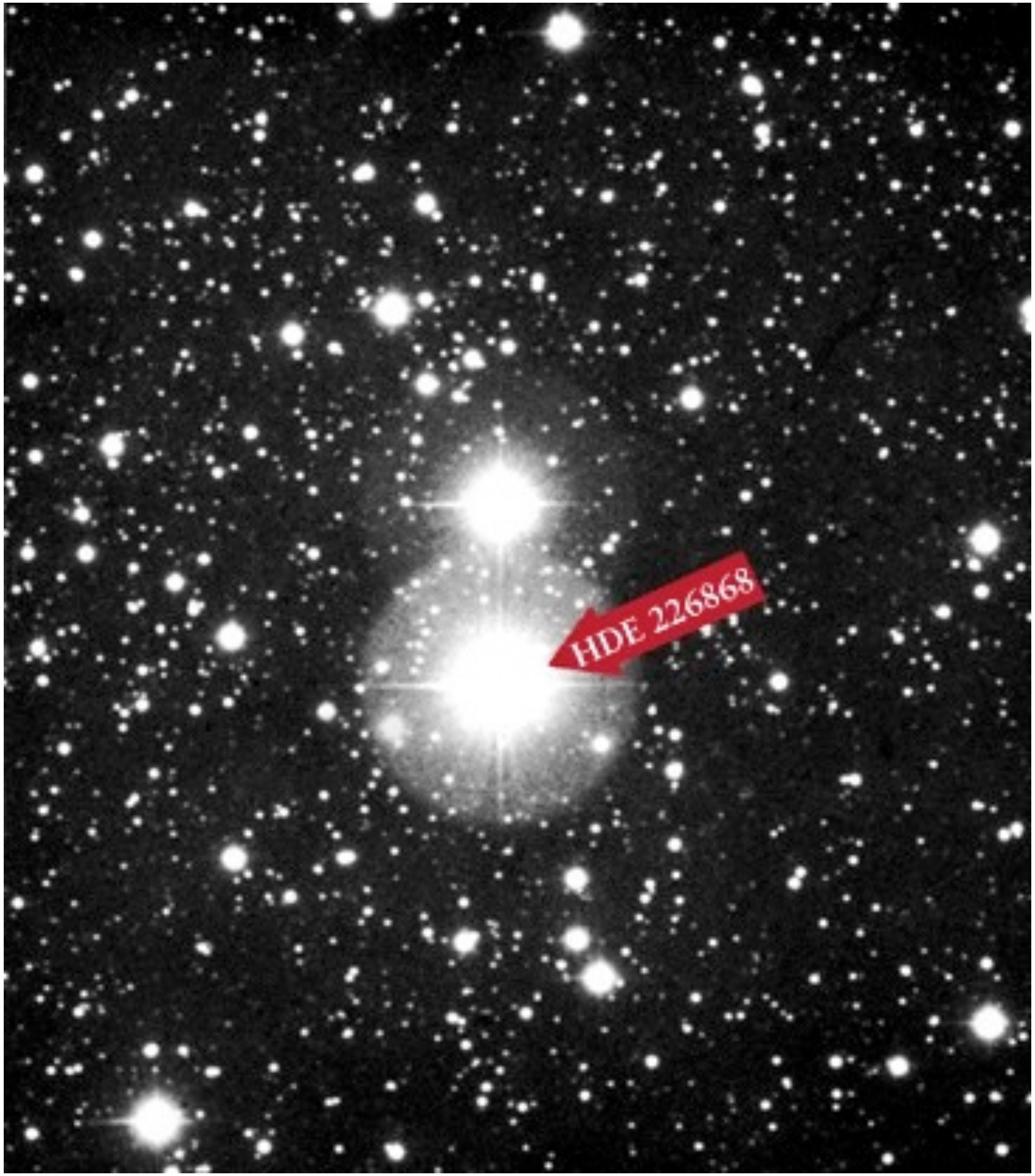
. peak radiation frequency scales with T^1
. energy radiated per unit time and area = σT^4



First discovery of a black-hole (1972)

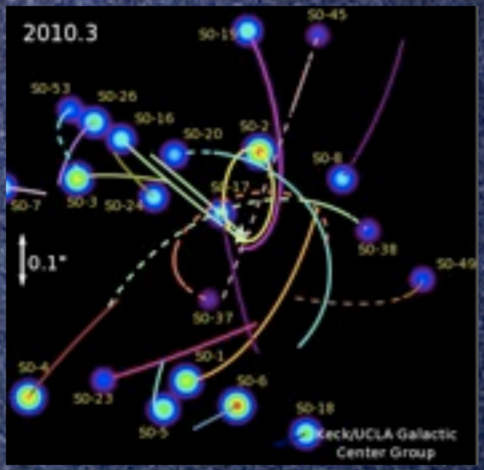
Dunlap observatory, Richmond Hill

Prof. Tom Bolton (UofT)



When many massive stars die, they collapse into black-holes.

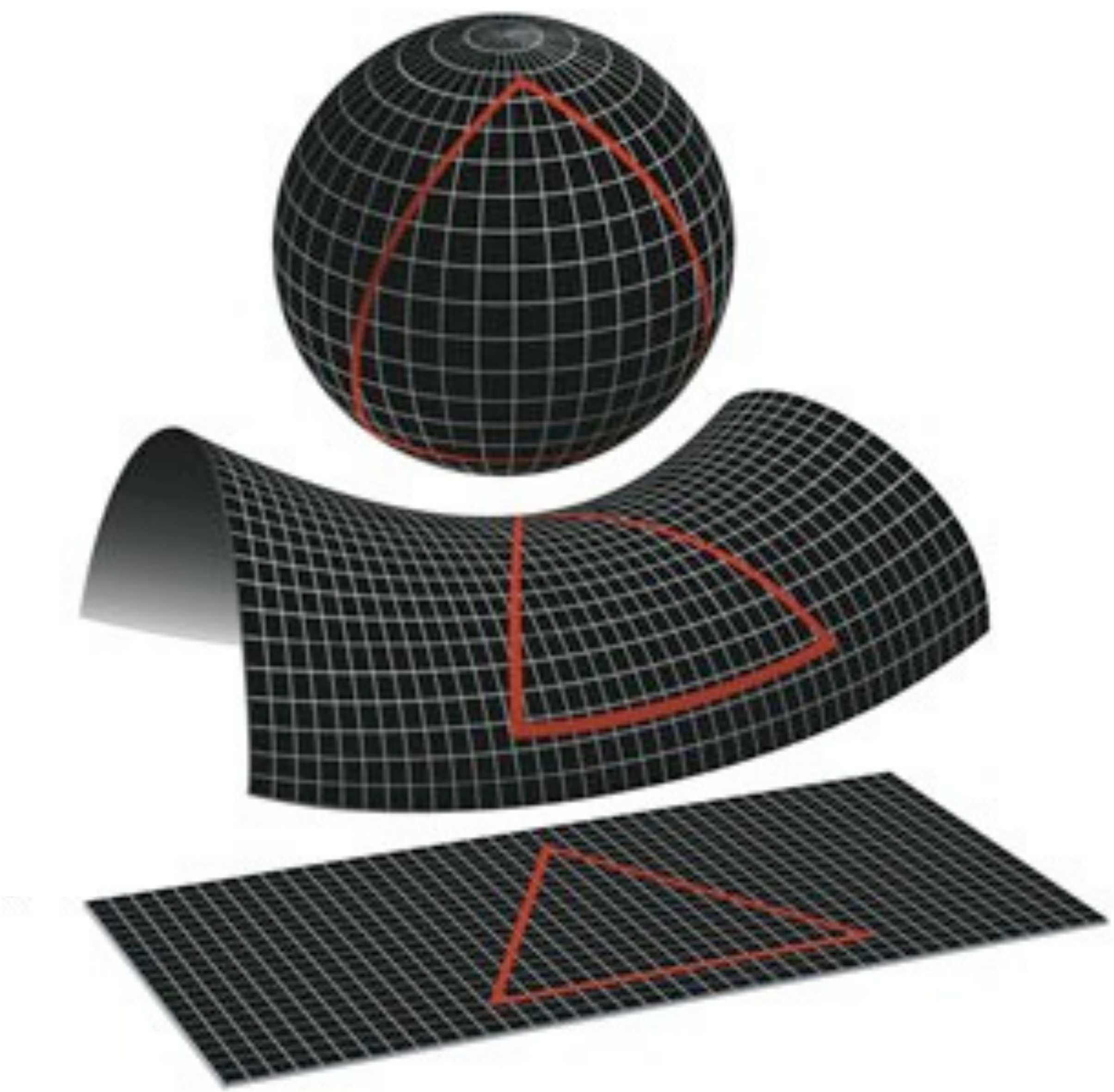
Also, there seems to be a super-massive black-hole growing in the centre of every galaxy. Our black-hole ~ 4×10^6 M_{sun}



Einstein immediately applied his theory to the universe...

Shape of the universe

Let the universe be isotropic and homogeneous.



$$G_{\mu\nu} = 8\pi T_{\mu\nu} \; .$$

positive curvature

negative curvature

zero curvature

Which one is the correct answer for our universe?

Mid-term: Feb. 15th, in-class, 1 hour

1) 20 multiple-choice questions

2) some concepts, some calculations
   both qualitative + quantative
   concepts: lectures
   calculations: assignments
   readings: help understand the lectures

3) 20%

4) no cheat-sheet, calculator without pre-programming ability, bring your ID