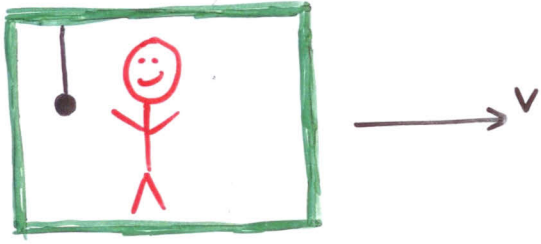
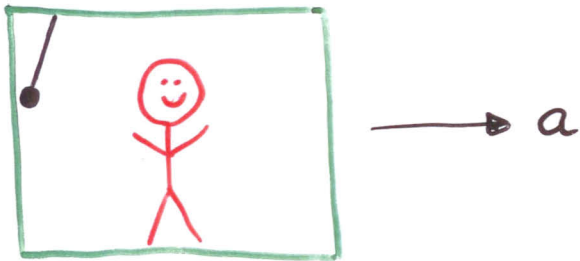


# GENERAL RELATIVITY

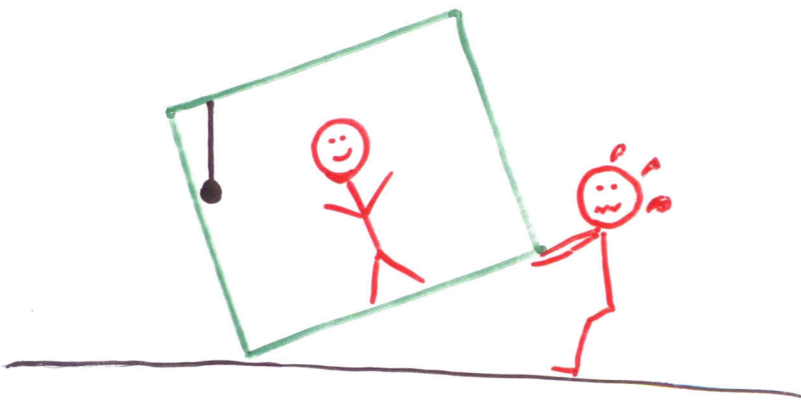


Special Relativity: laws of physics same in all inertial frames  $\Rightarrow$  no way to determine  $v$

Can measure acceleration:

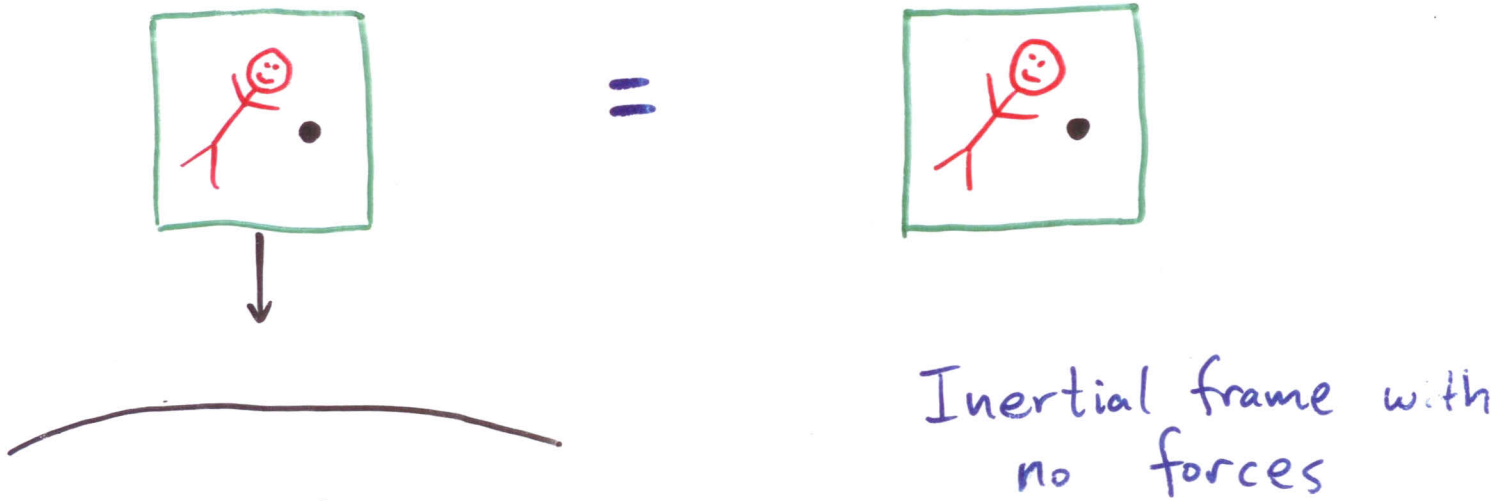
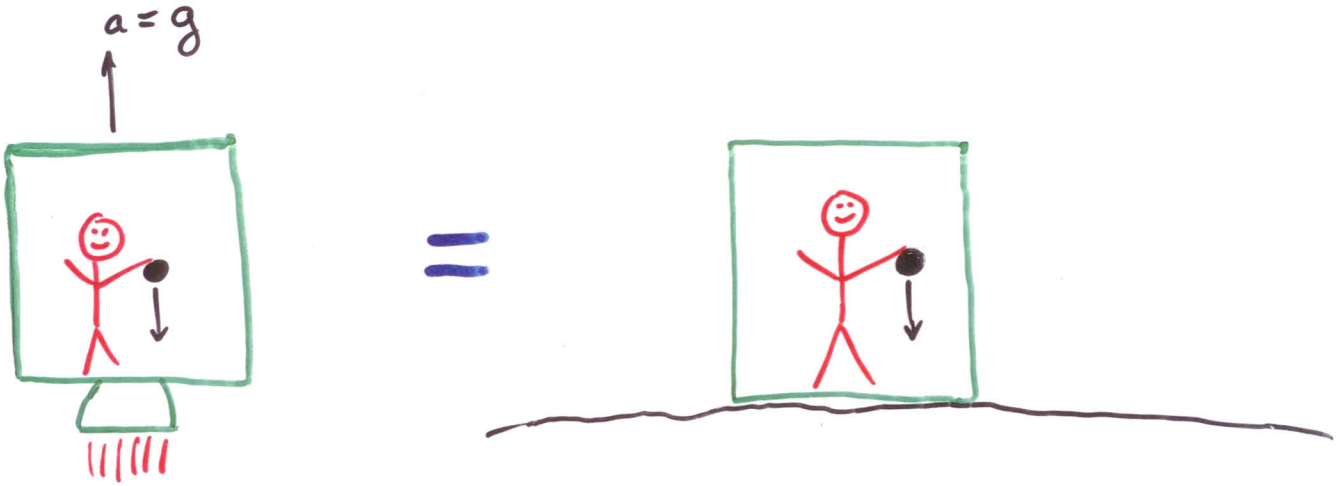


Can also detect gravity:



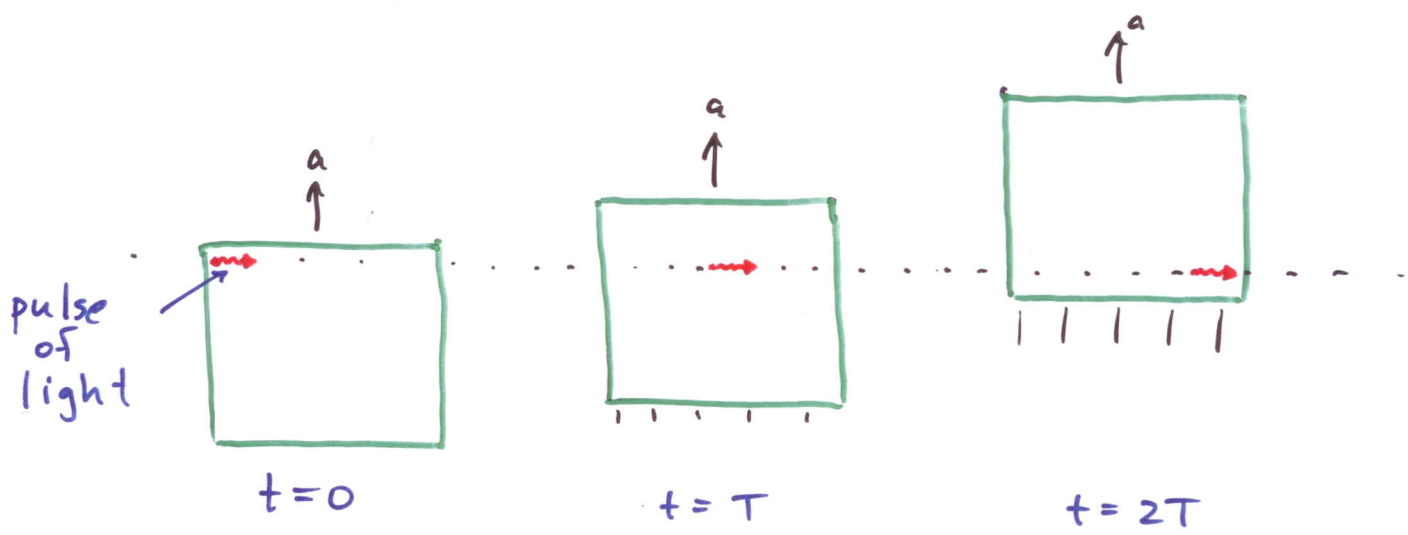
Einstein: no way to distinguish  
between gravity and acceleration

## THE PRINCIPLE OF EQUIVALENCE

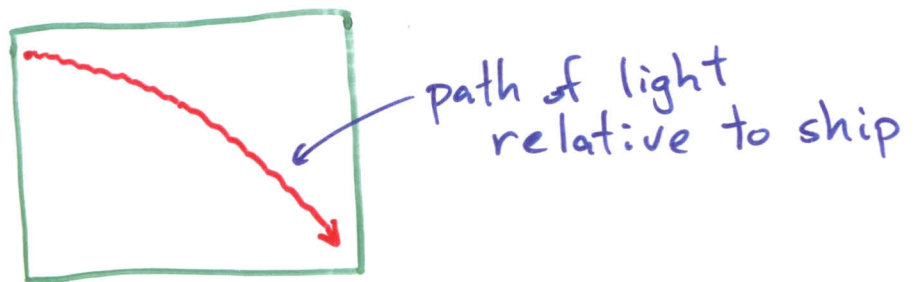


Free fall: gravity "cancels" acceleration

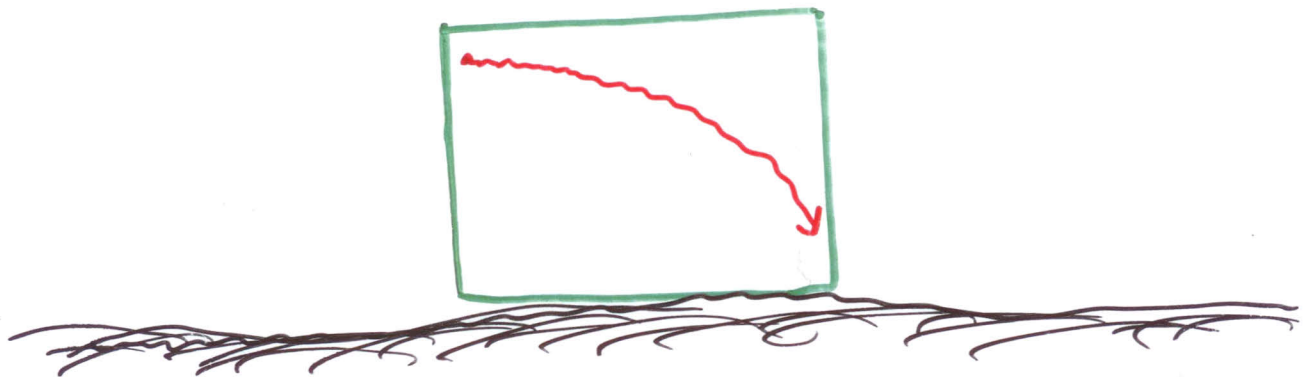
# CONSEQUENCES:



"frame" of ship:



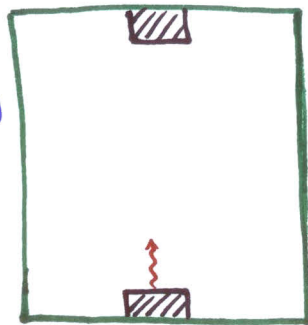
Principle of equivalence predicts:



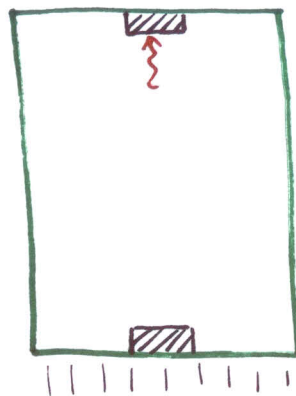
**GRAVITY BENDS LIGHT**

# GRAVITATIONAL TIME DILATION + REDSHIFT

ship  
accelerating  
upward  
 $\uparrow a$



light pulse  
emitted

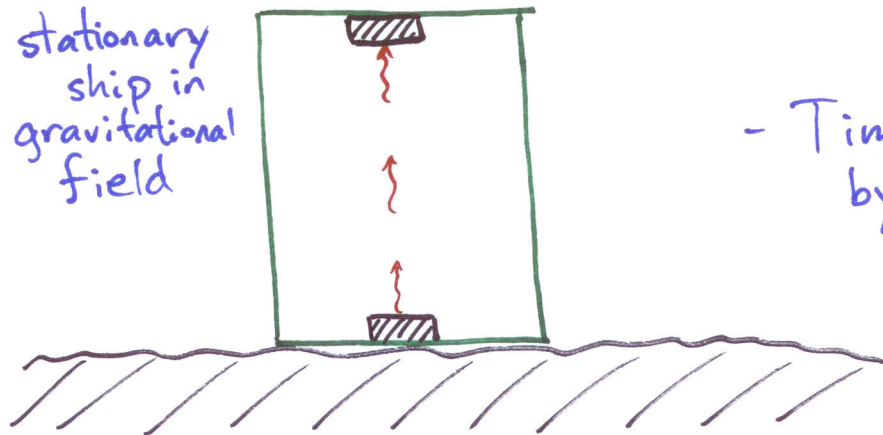


$\uparrow v = at$

Detector moving away  
when pulse arrives  
 $\therefore$  observed wavelength  
& period longer  
(redshift)

Principle of equivalence predicts:

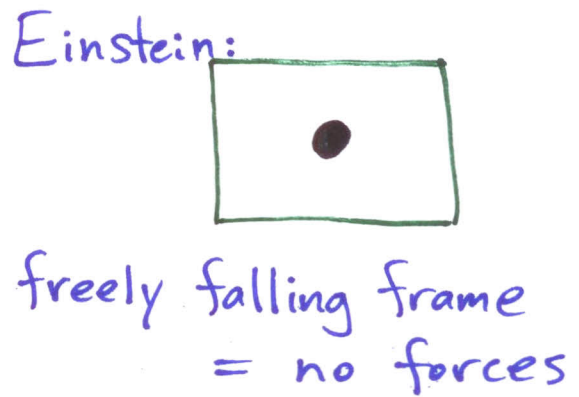
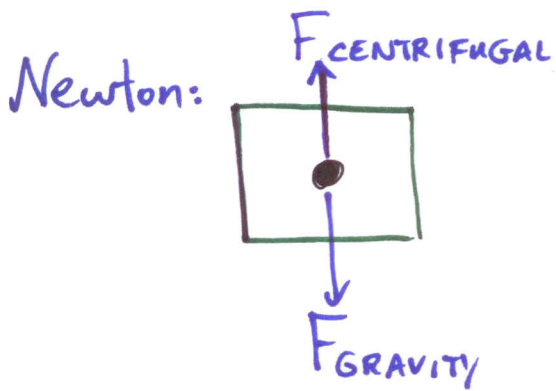
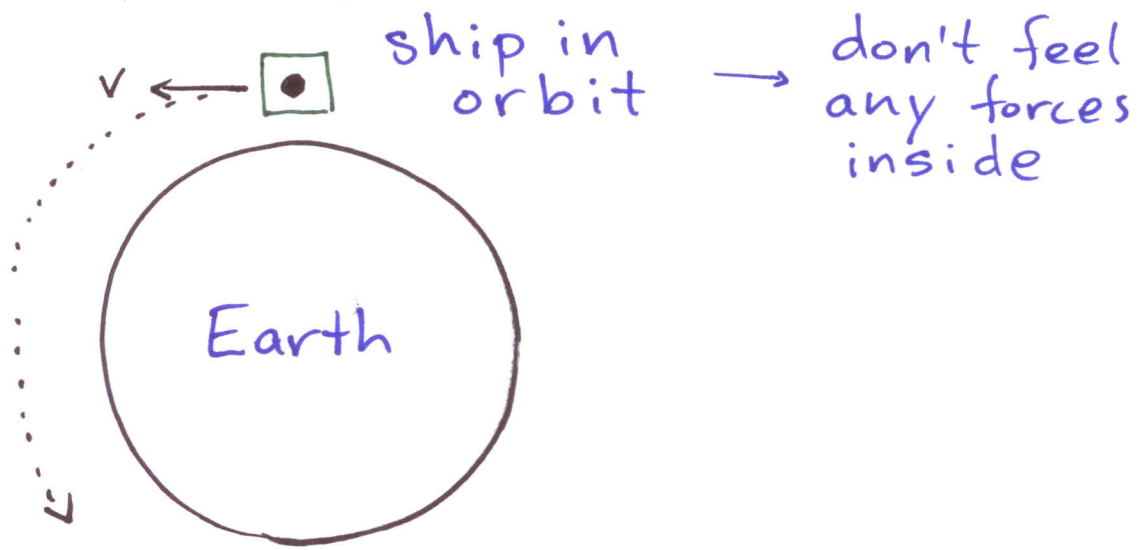
stationary  
ship in  
gravitational  
field



- Observed wavelength longer  
than emitted wavelength

- Time between pulses measured  
by detector longer than  
time between emitted pulses.

# IS THERE A FORCE OF GRAVITY?



# FIXING NEWTON'S FIRST LAW

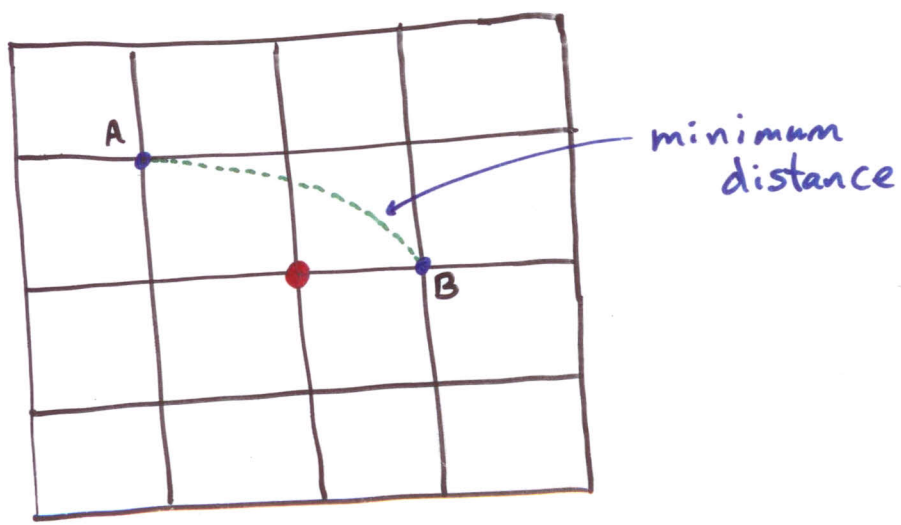
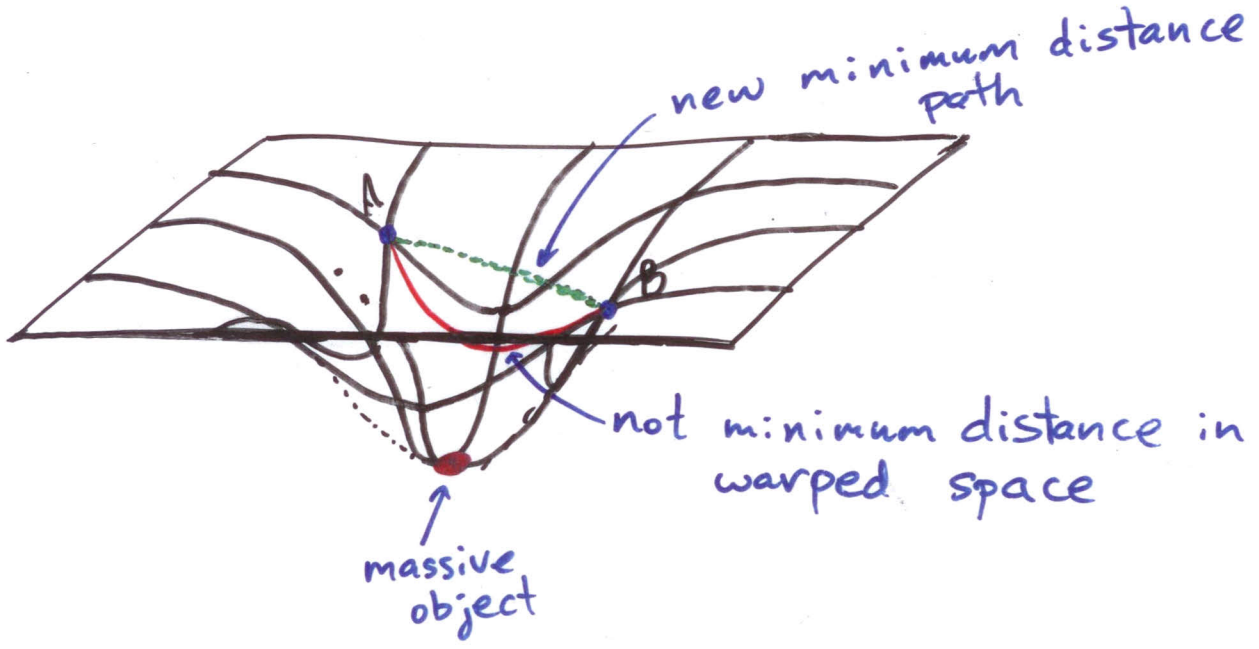
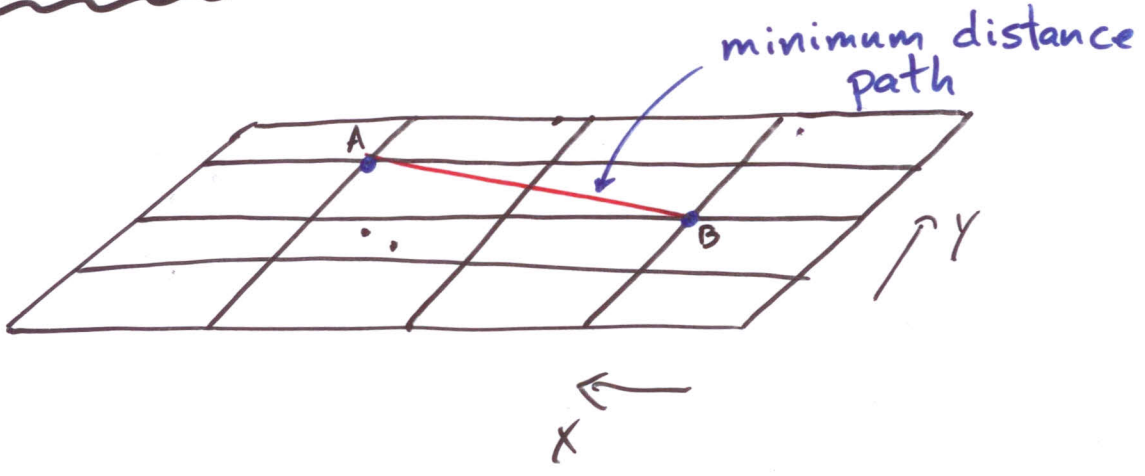
Newton: In absence of forces, objects move in straight line at constant velocity

||

objects move to maximize proper time (roughly: minimize distance)

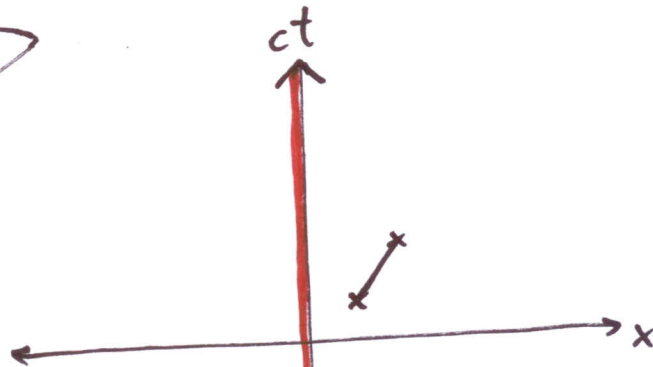
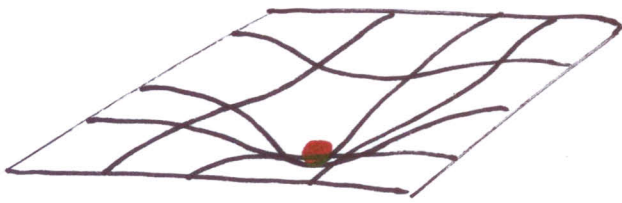
Einstein: Minimum distance paths can be curved if space is curved

# WARPED SPACE



# EINSTEIN'S THEORY OF GRAVITY

① Matter/energy bends spacetime



before:  $I = (\Delta x)^2 - c^2(\Delta t)^2$

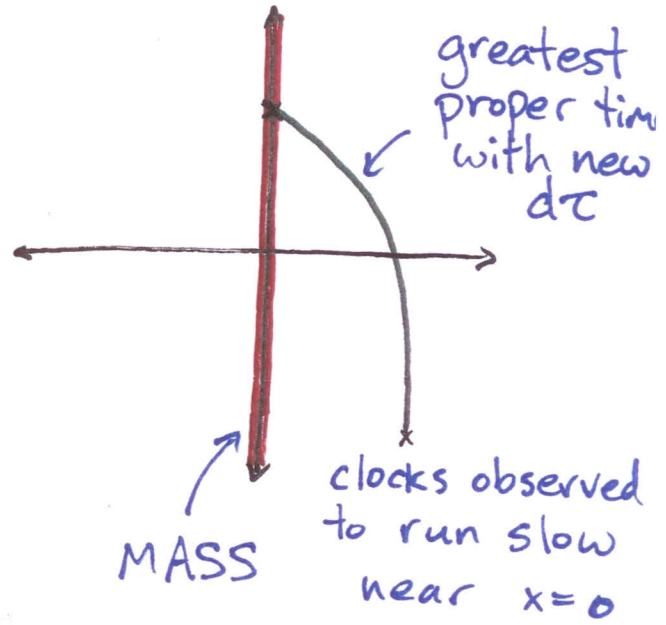
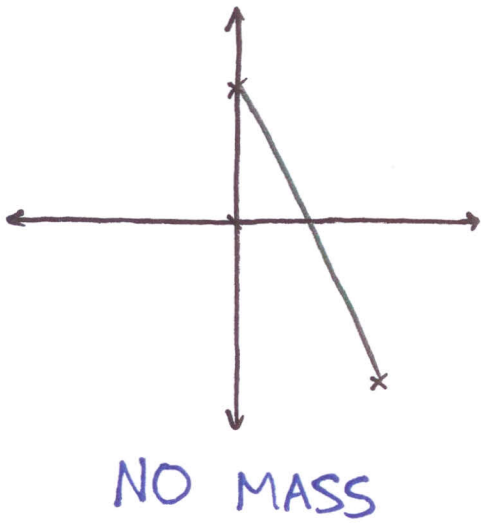
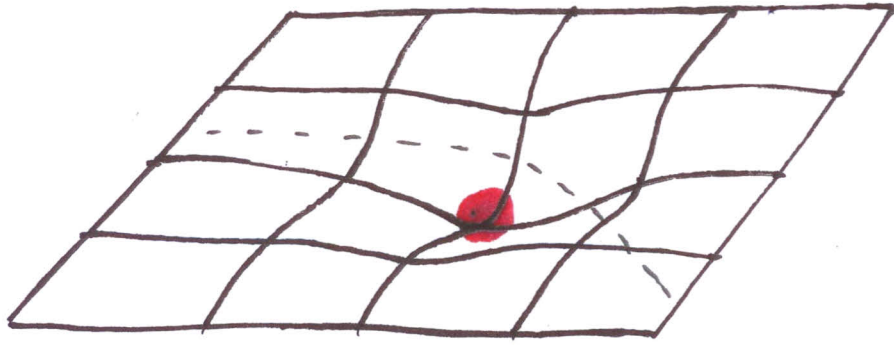
now:  $I = g_{xx}(\Delta x)^2 + g_{xt}(\Delta x)(\Delta t) + g_{tt}(\Delta t)^2$

massive object

$g$ : functions of  $\vec{x}, t$  determined by matter



② Objects move to maximize proper time in new spacetime



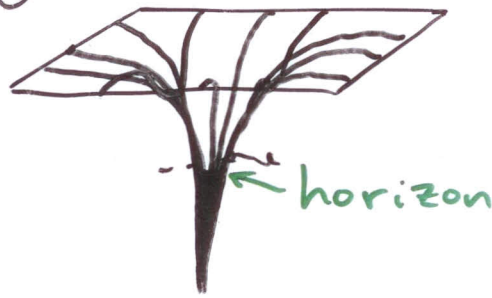
# PREDICTIONS:

- Bending of light
- Gravitational redshift
- Deviations from Newton's gravity




orbits not exactly elliptical

## - Black holes:



with enough matter,  
spacetime warps so  
much that nothing  
can escape

- Gravity waves = ripples in spacetime 
- Expanding (or contracting) universe