

# Lecture 19

## General relativity II: Mass curves space

# Some open problems of special relativity

- How to deal with accelerations ?
- How to deal with gravity ?
- Newton's gravity acts instantaneously, i.e. it is inconsistent with special relativity's conclusion that information cannot be communicated faster than the speed of light.
- Distance is relative, so which distance to use in computing the gravitational force ?

# What effect does mass have?

- **Gravity:** tendency of massive bodies to attract each other
- **Inertia:** resistance of a body against changes of its current state of motion

# Is gravity and inertia the same thing ?

- No. They are completely different physical concepts.
- There is no a priori reason, why they should be identical. In fact, for the electromagnetic force (Coulomb force), the source (the charge  $Q$ ) and inertia ( $m$ ) are indeed different.
- But for gravity they appear to be identical to one part in a 100 billion

## Weak equivalence principle

The laws of mechanics are precisely the same in all inertial and freely falling frames. In particular, gravity is completely indistinguishable from any other acceleration.

## Strong equivalence principle

The laws of physics are precisely the same in all inertial and freely falling frames, there is no experiment that can distinguish them.

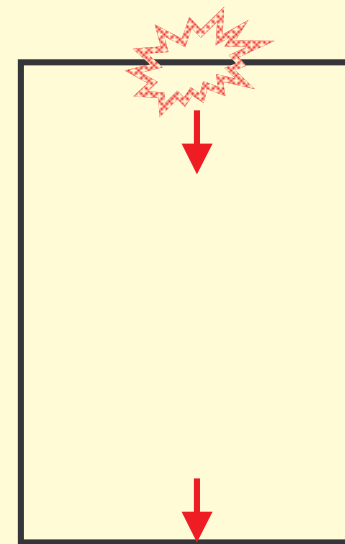


# Consequences of the equivalence principle: gravitational redshift

Thought experiment:

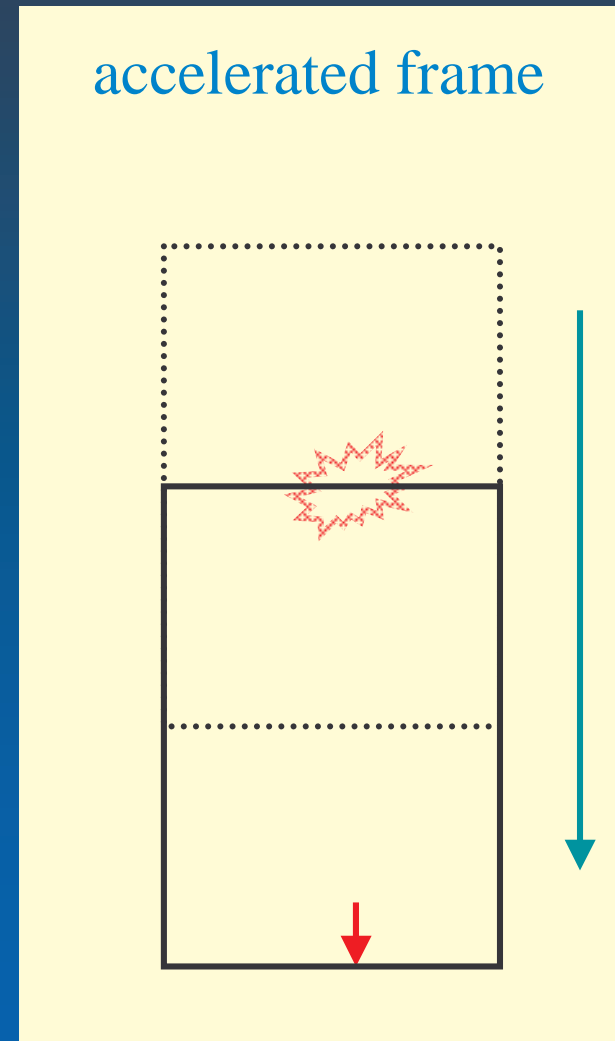
- Flash light at the top of an elevator
- Detector at the bottom
- **Freely falling reference frame:** detector registers that the light has the same frequency (color) as when it was emitted

freely falling frame



# Consequences of the equivalence principle: gravitational redshift

- Light travels from top to bottom
- During light travel time, elevator is accelerated and recedes at velocity  $v$  from the light ray  
⇒ light is redshifted
- Equivalence principle: gravity redshifts light

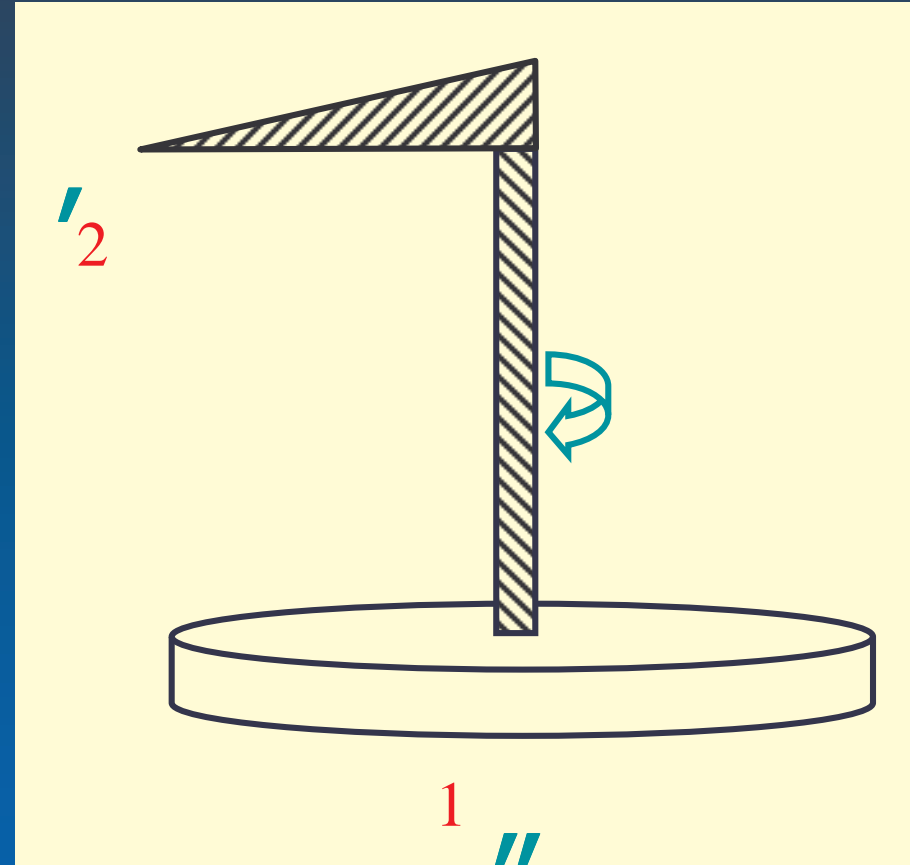


# Consequences of the equivalence principle: gravitational redshift

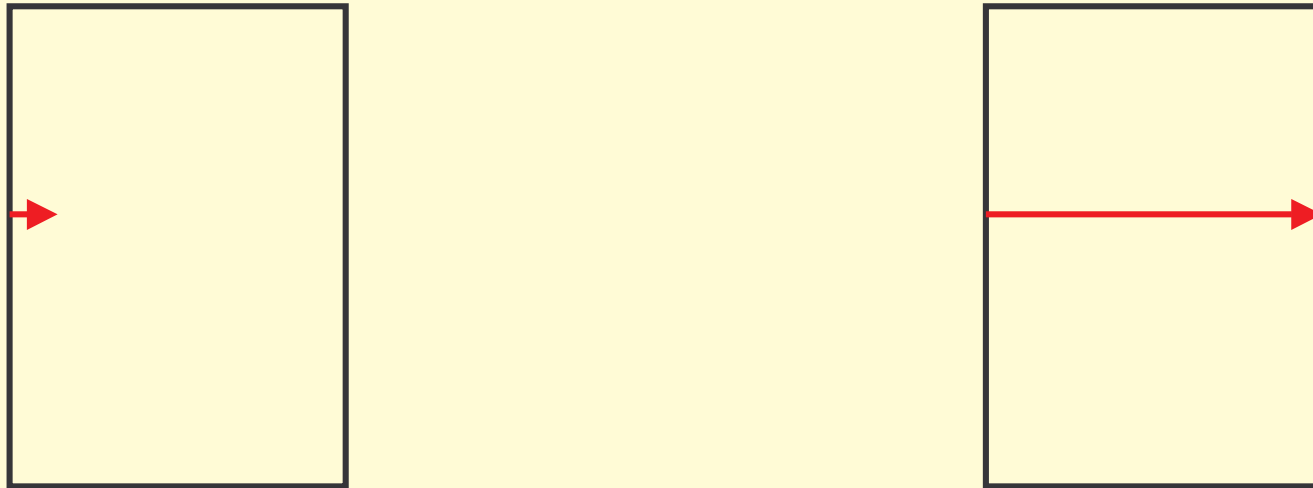
- An object that travels against a gravitational field loses energy, i.e. it is slowed down
- Light that travels against a gravitational field is redshifted, i.e. it loses energy
- An object that travels downward a gravitational field gains energy, i.e. it is accelerated
- Light that travels downward a gravitational field is blueshifted, i.e. it gains energy

# Consequences of the equivalence principle: gravitational time dilation

- Clock 2 is moving at speed  $v$   
⇒ time dilation
- Clock 2 is also experiencing an acceleration  
⇒ gravitational time dilation
- Equivalence principle:  
⇒ gravitational time dilation
- Analogously: gravitational length contraction

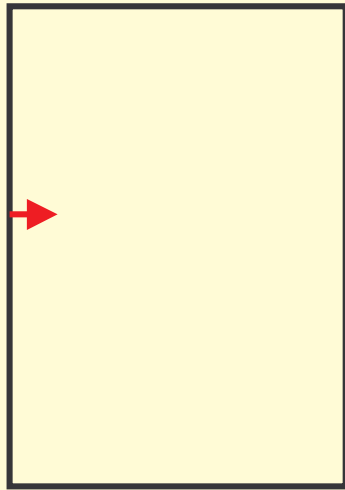


# Consequences of the equivalence principle: mass bends light

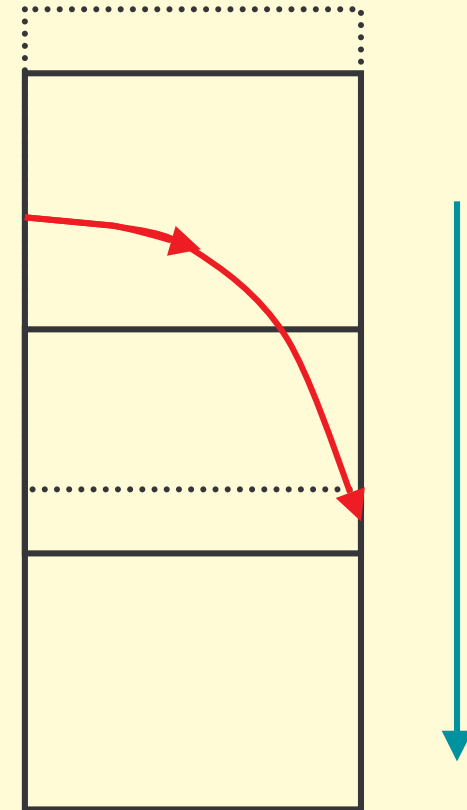


Observer in freely falling reference frame

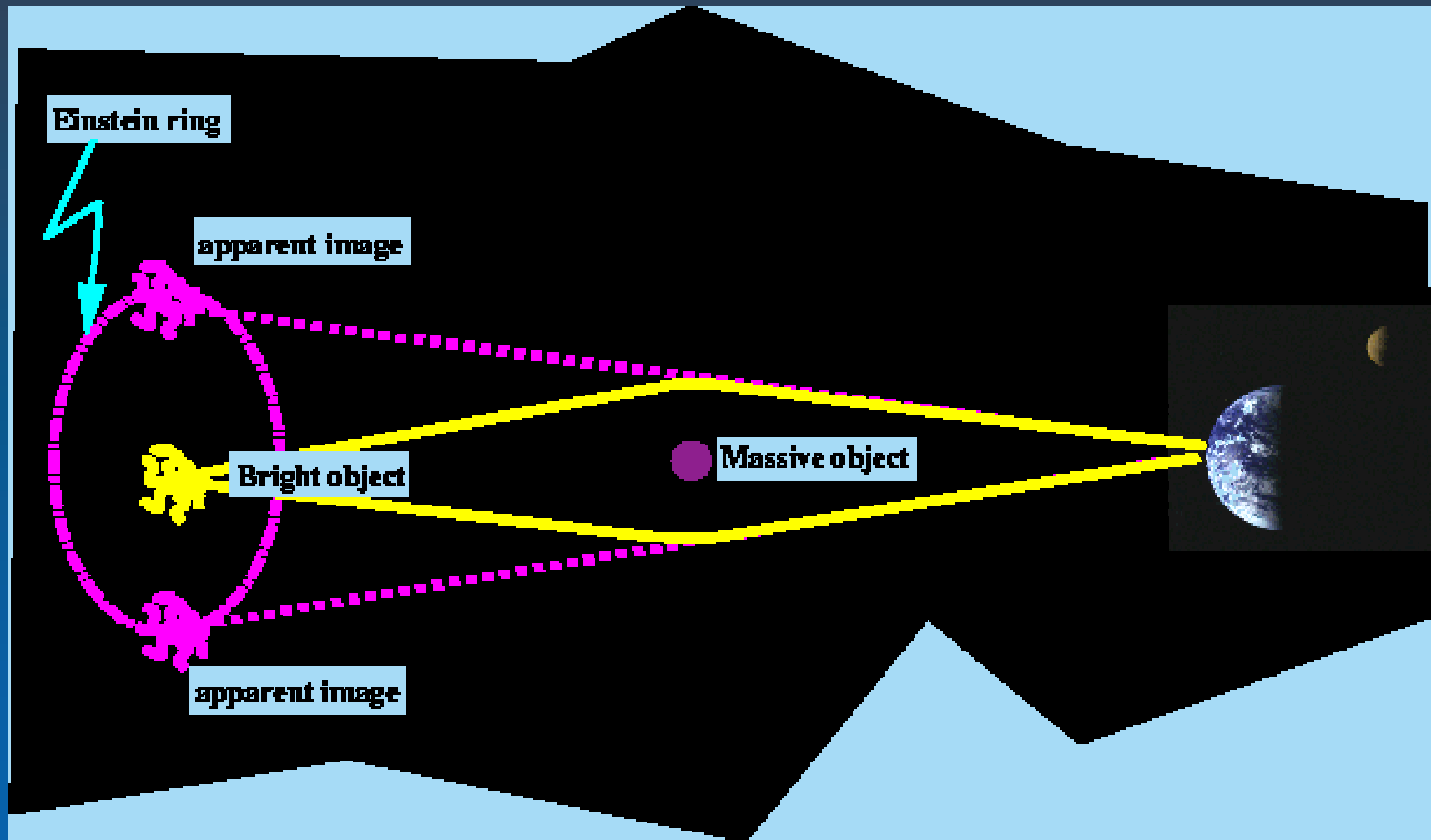
# Consequences of the equivalence principle: mass bends light



**Equivalence principle:  
Accelerated frame is  
equivalent to a frame  
subjected to gravity**



# Examples for light bending



# Examples for light bending



# Examples for light bending

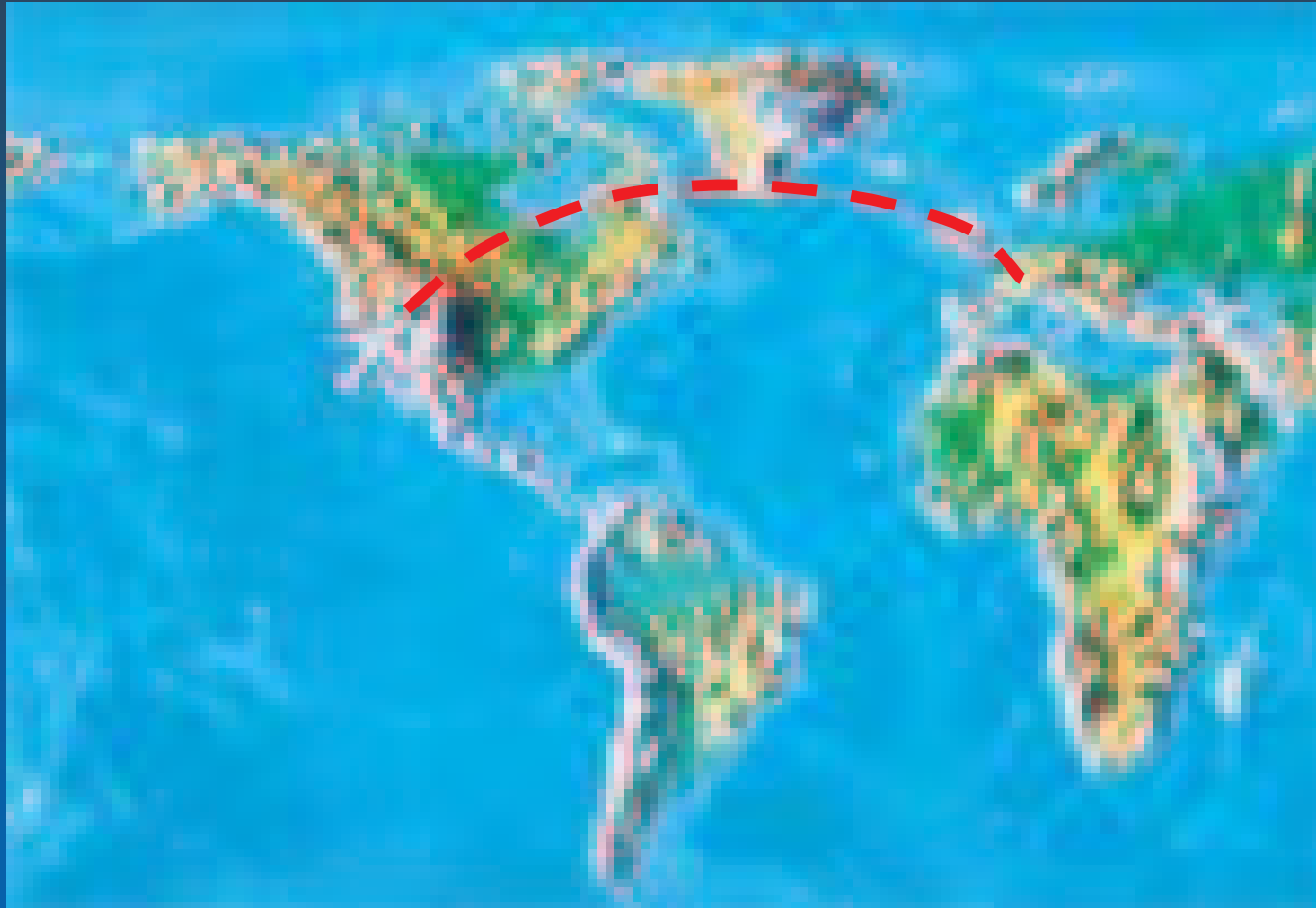


**Gravitational Lens in Abell 2218**

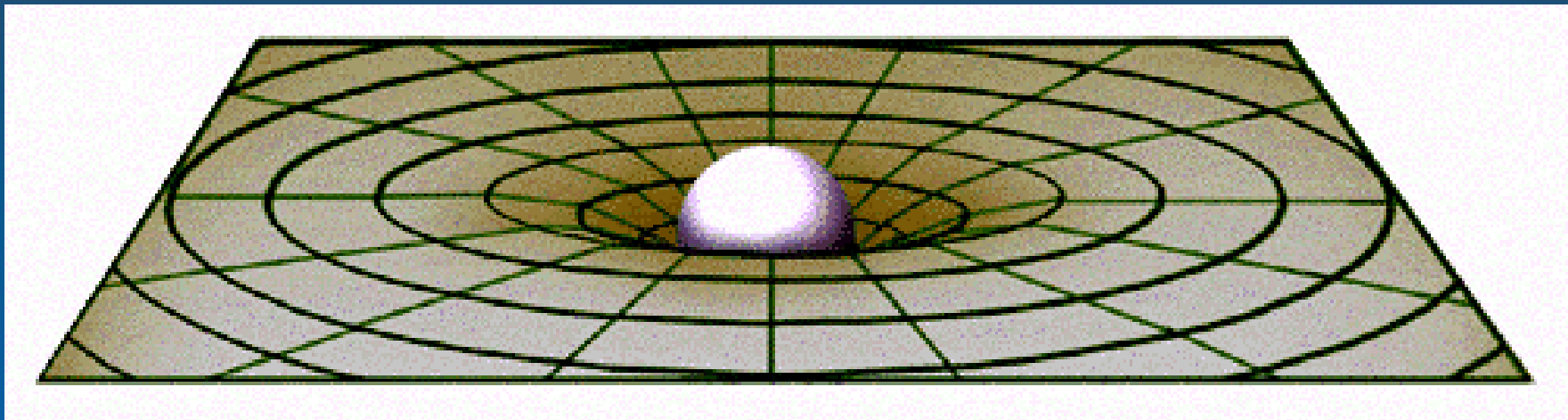
**HST - WFPC2**

PF95-14 - ST ScI OPO - April 5, 1995 - W. Couch (UNSW), NASA

# What is the shortest way to Europe?



# Mass curves space



# General relativity

- **Mass tells space how to curve**
- **Space tells mass how to move**