AS1001:Extra-Galactic Astronomy

Lecture 7: The Development of Cosmology

The Copernican Revolution

- Cosmology is the study of the Universe.
- Once upon a time, … (<1600)
  most Western science was done by
  the Church, influenced by dogma, Scripture.
- Church's (Aristotle's) cosmological model:
  Earth at centre, Moon, Sun, 5 planets
  (MVMJS), fixed stars on 8 rotating spheres.
- Copernicus, Galileo and Kepler challenged the
  Church's authority, placing the Sun at the
  centre, seeing comets as orbiting Sun, craters
  on Moon, Venus phases, moons of Jupiter, …
- (Church recently apologised for persecuting
  Galileo to suppress his heretical views.)

The Copernican Principle

Modern Cosmology assumes:

There is nothing special about our location in the cosmos.

A simple but powerful concept
extending the Copernican Revolution:

Our Sun, on outskirts of a galaxy.

Our galaxy, one of zillions.

Our view is typical, not special.

Olber's Paradox

The idea of "permanency of the Heavens" persisted. In 1826 Olber voiced a well known paradox:

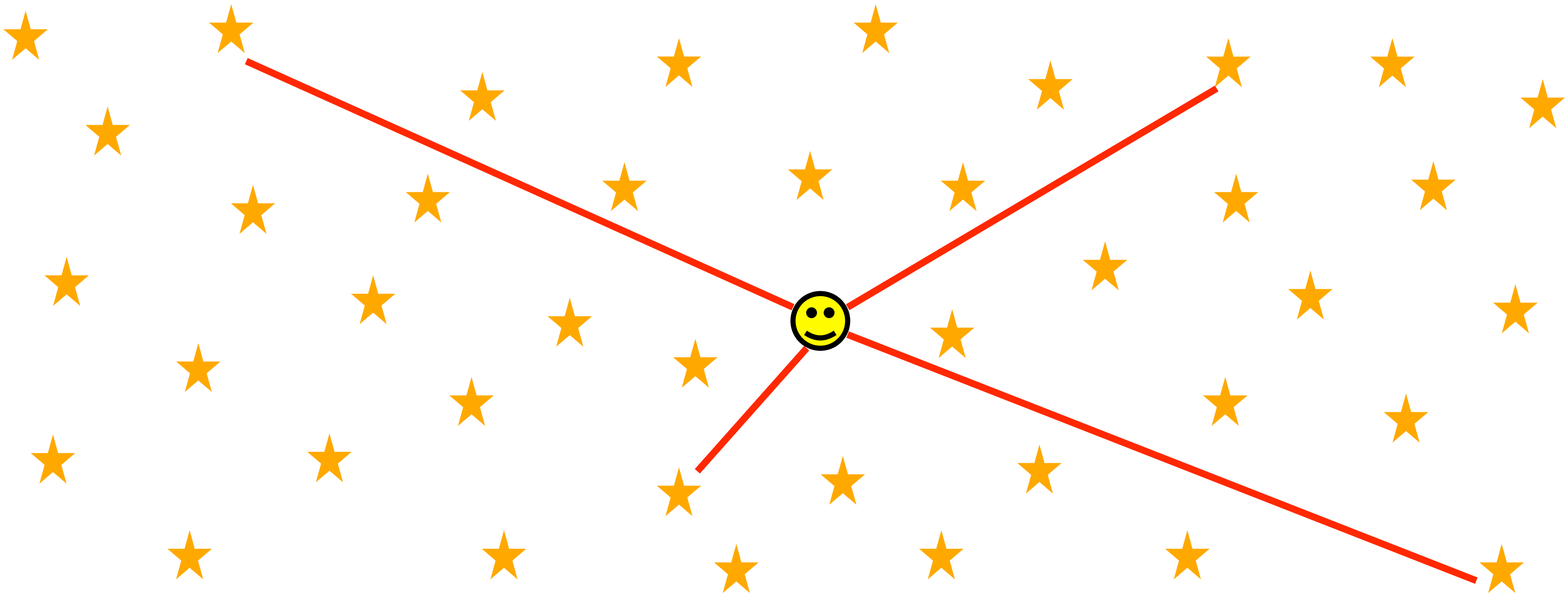
Why is the sky dark at night?

This question, 100 years before Einstein and Hubble, undermines the concept of an eternal, unchanging, infinite Universe.

Olber's Paradox

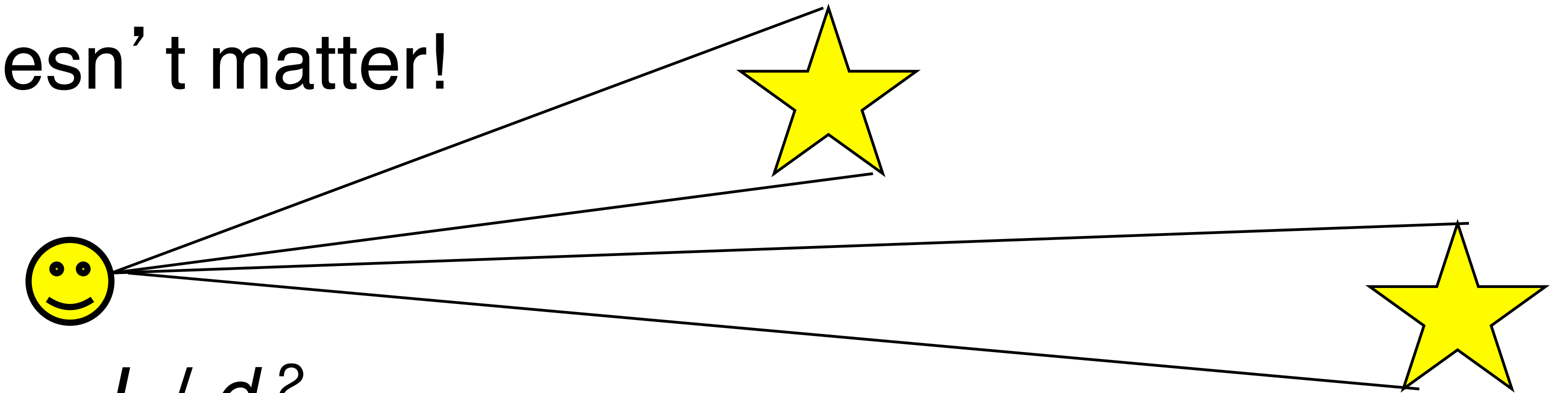
If the Universe is infinite, with a uniform distribution of stars, every line of sight eventually encounters a star.

WHOLE SKY AS BRIGHT AS THE SUN ☹



Olber's Paradox

- But, more distant stars are fainter.
- It doesn't matter!



- Flux $\sim L / d^2$
- I = Flux per square arcsec $\sim (L / d^2) / \theta^2$
- But $\theta \sim r / d$, so: $I \sim L / r^2$
  Intensity is independent of distance.
- If the Universe is infinite, then the entire sky should be **as bright as the surface of the sun**!

Olber's Paradox: Version 2

- n = density of stars [stars/pc^3]
- No of stars within shell :

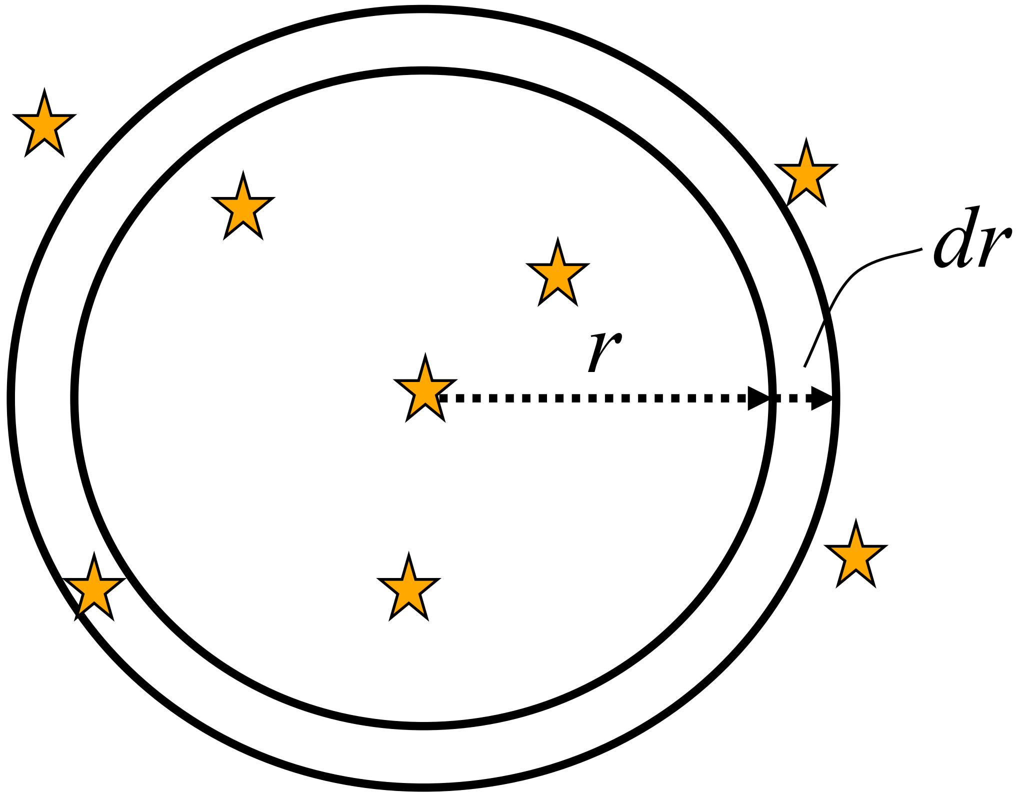
$$dN = n\,4\pi\, r^2 dr$$

- Flux from one star :

$$f = \frac{L}{4\pi\, r^2}$$

- Flux from all stars in the shell :

$$dF = f\,dN = \frac{L\,n\,4\pi\,r^2}{4\pi\,r^2}dr = L\,n\,dr$$



Olber's Paradox: Version 2

- Add up flux from shells out to radius *R*. Integrate :

$$F = \int dF = \int_0^R L\, n\, dr$$

$$F = L\, n \left[r \right]_0^R$$

$$F = L\, n\, R$$

- Equal flux *dF* from each shell *dR*.
- If shells extend to *R* = infinity,
  the flux from the sky is infinite.

BUT THEN WHY IS THE NIGHT SKY DARK?

Solutions to Olber's Paradox

- Finite size
- Yes. But we would then be "at the centre", a preferred location.
- Intervening dust
- No. The dust would heat up and also radiate as brightly as a star
- Finite age
- Yes. But this violates the "permanency of the Heavens"
- Expansion redshifts light to longer λs
- Helps. But not enough.

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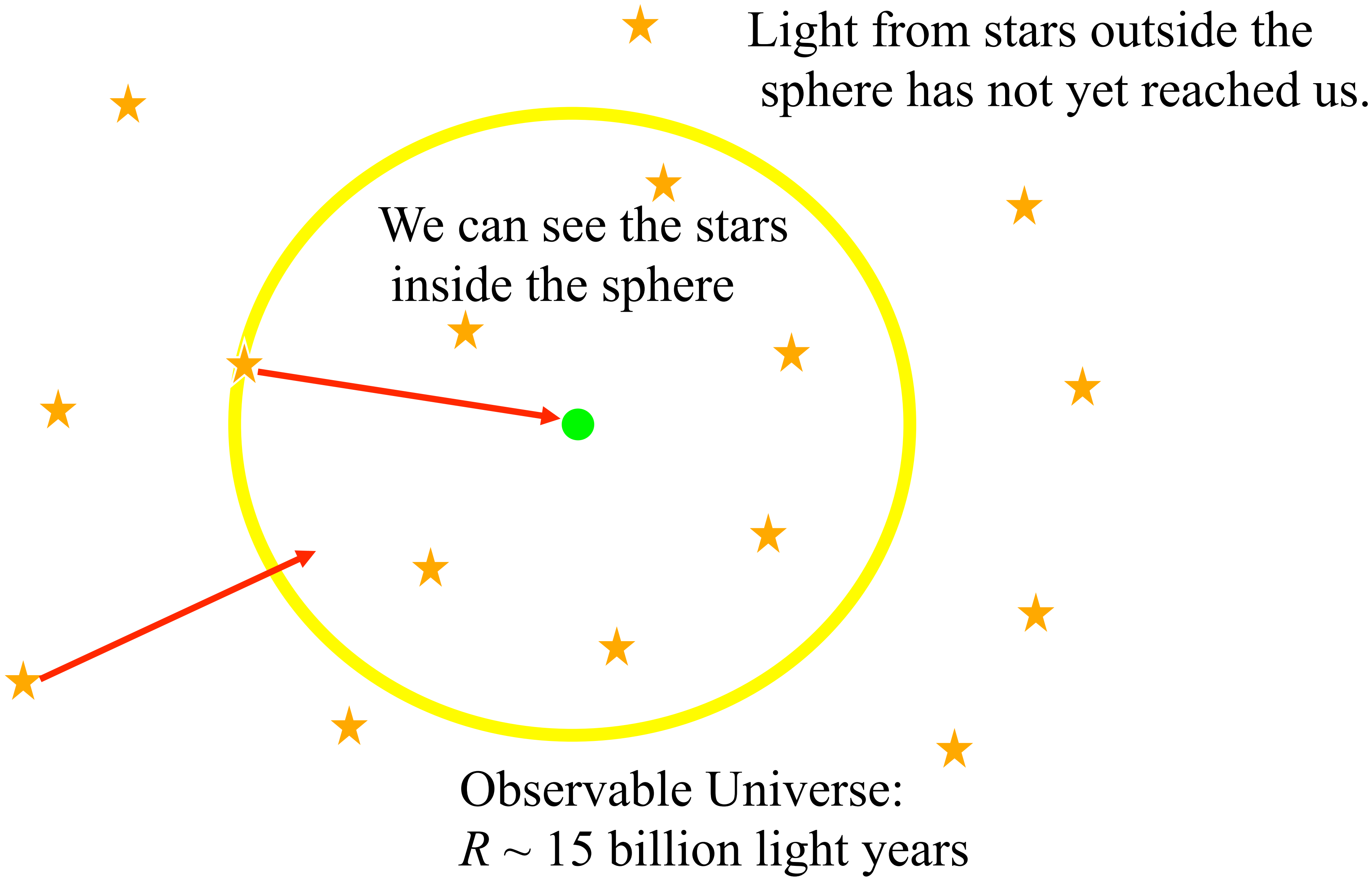
Correct Solution: Universe has a finite age

Finite age: We can see sources within a sphere whose radius is the *light travel time* for the age of the Universe



Problems with Permanency

- Before Hubble discovered the Universal Expansion (next lecture), there were already several problems:
  - **Olber's Paradox**
  - **Energy Conservation** (to shine forever, stars would need an infinite fuel reserve)
  - **Age** of Earth rocks, meteorites.

- These all point to a Universe with a beginning (or at least to a problem with permanency!)

Modern Cosmology

Modern Cosmology :

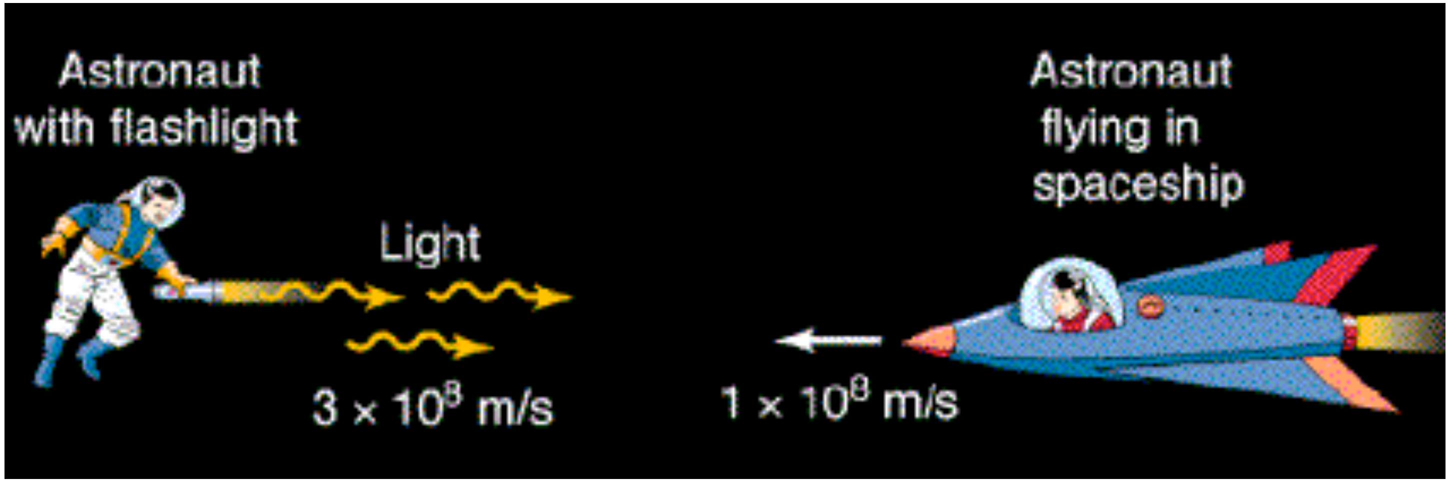
1) Einstein's gravity theory:
   General Relativity (1916)

2) Hubble's discovery:
   Expanding Universe (1929)

Together they resolve
   Olber's Paradox (1826)
      "Why is the sky dark at night ?"

Einstein's Special Relativity

- Laws of Physics are the same for all constant-velocity observers. There is no absolute reference frame.
- Light speed (in the vacuum) is a fundamental limit.

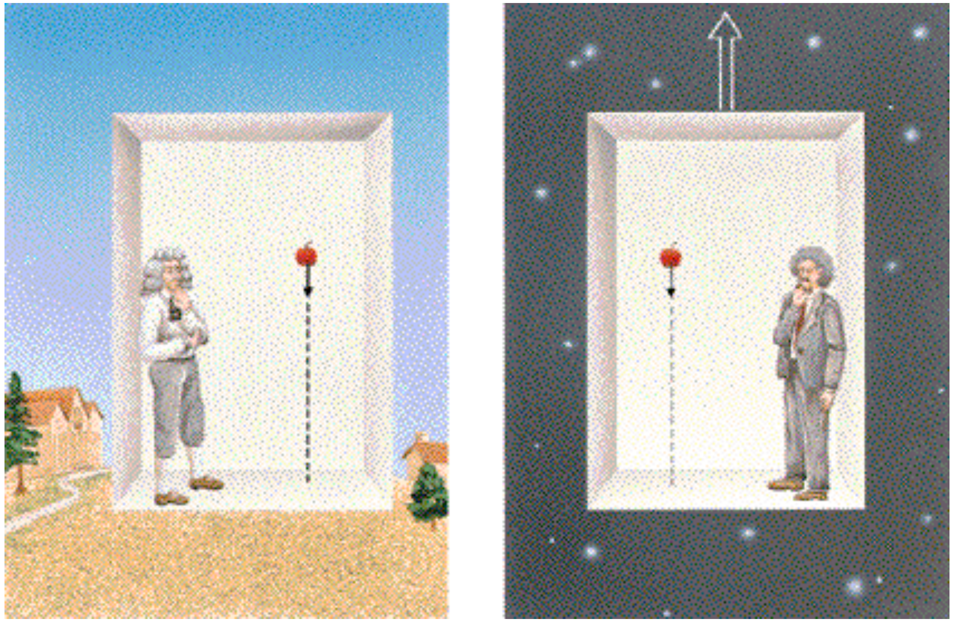


- All observers see the same photon velocity!
- Moving objects compressed in direction of motion.
- Moving clocks run slower!
- Counter-intuitive but extensively tested !
- e.g. Relativistic particles travel farther before decay.

The Equivalence Principle

You cannot distinguish (by local measurements) between acceleration and a uniform gravitational field.
i.e., gravity and inertia are indistinguishable

$F = G M m / r^2$



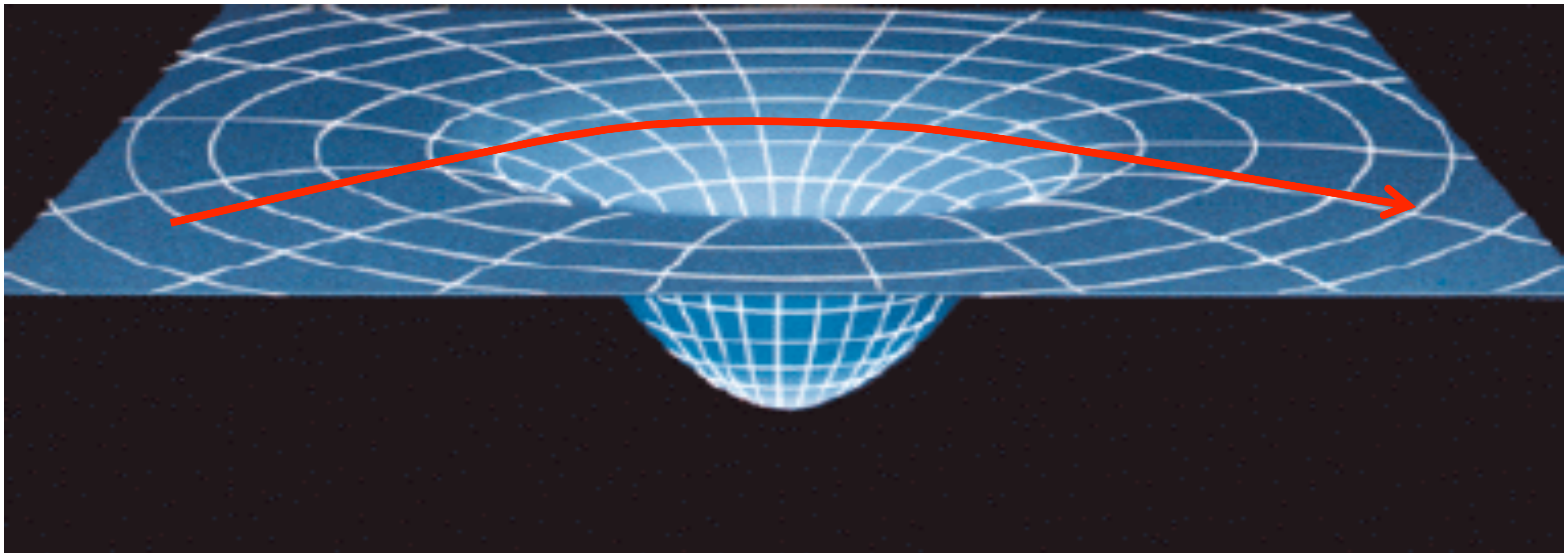
$F = m a$

Both see the apple fall.

GR equates gravitational mass with inertial mass and explains why they are identical.

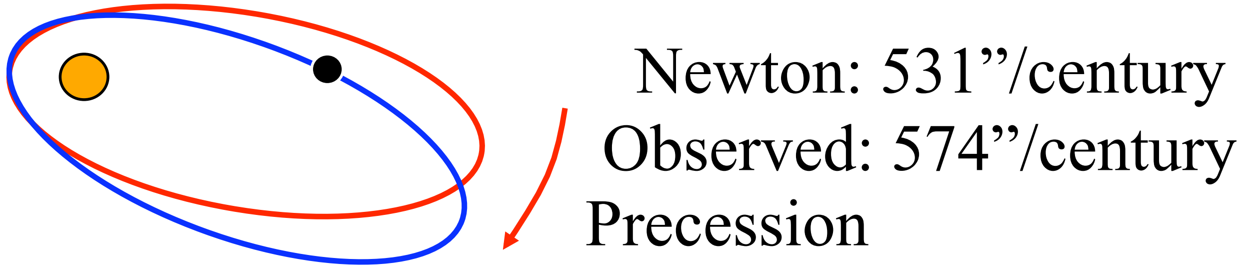
Einstein's Gravity: General Relativity

- In GR, Newton's "action at a distance" gravity is replaced by warping space and slowing time.
- Space and time inextricably linked
  => "SPACETIME"
- GR1: Warped spacetime tells matter how to move.
- GR2: Mass/energy tells spacetime how to warp.



3 Classic Tests of GR

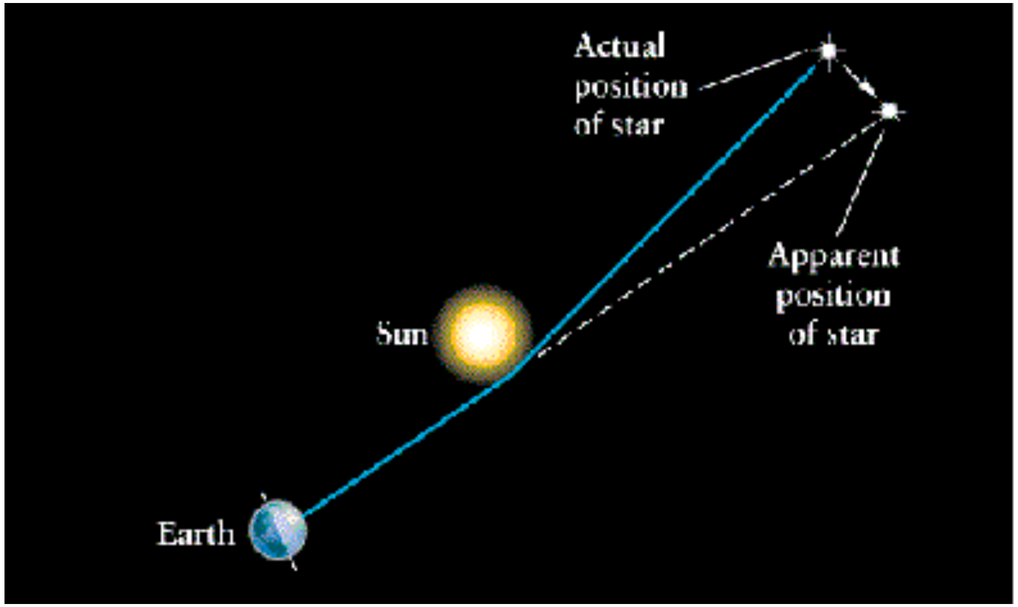
- 1. Precession of Mercury's Orbit
  - Known to be too fast since mid-1800s. General Relativity explains the discrepancy

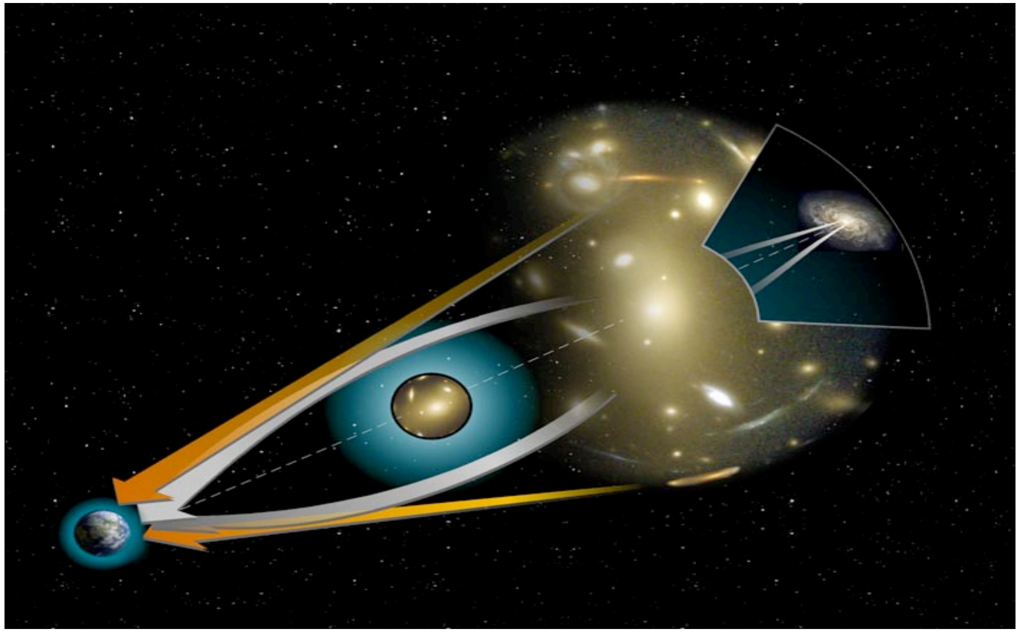


- 2. Gravitational Lensing
  - GR predicts that a mass bends light rays. Prediction confirmed in 1919, by Eddington photography of star positions during vs after solar eclipses.
- 3. Gravitational Redshift
  - Clocks run slow in a gravitational field
  - Light is redshifted leaving a massive object
  - Seen in white dwarf spectra, also our GPS network.

Gravitational Lensing

- By stars:
  - The Sun
  - Planet Hunting
  - Dark Matter searches
- By galaxies:
  - Time-delay => cosmological parameters
- By galaxy clusters:
  - Mass probe
  - Natural Telescope





Abell 2218 a giant gravitational lens

Galaxy Cluster Abell 2218 **HST • WFPC2**

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

Cosmology in the 1920s

- Einstein's GR, applied to the Universe as a whole, (uniform density ρ, pressure *p*) gives 2 equations:

Acceleration: $$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$$

Velocity: $$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G\rho}{3} - \frac{kc^2}{R^2}$$

No need to remember these. For interest only

- These describe a **Dynamical Universe**: *R(t)*
- Universe must be **expanding** or **collapsing**.
- If ρ (density) and *p* (pressure) are positive, then an expanding Universe **decelerates**.

Einstein's blunder: The Cosmological Constant Λ

- Despite Olber's paradox, etc.
  Einstein believed in "permanency of the Heavens".
- To allow a steady-state Universe (R = constant), he tweaked his equations, adding a Cosmological Constant (Λ):

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda}{3}$$

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G\rho}{3} - \frac{kc^2}{R^2} + \frac{\Lambda}{3}$$

Don't need to remember these. Interest only

- 1929: Hubble discovers Expansion of the Universe.
- Einstein's regret: "Λ was my Greatest Blunder".
- 1998: Λ returns as Dark Energy driving acceleration.

Summary

- Extending the Copernican principle:
  - Olber's Paradox => A finite Universe
  - Finite Age measures => A beginning
  - General Relativity => A dynamical Universe
- These all point to a dynamic Universe *R(t)* with a beginning and a finite age.
- Despite this, Hubble's discovery of the Expansion (next lecture) was a great surprise that shocked the world.