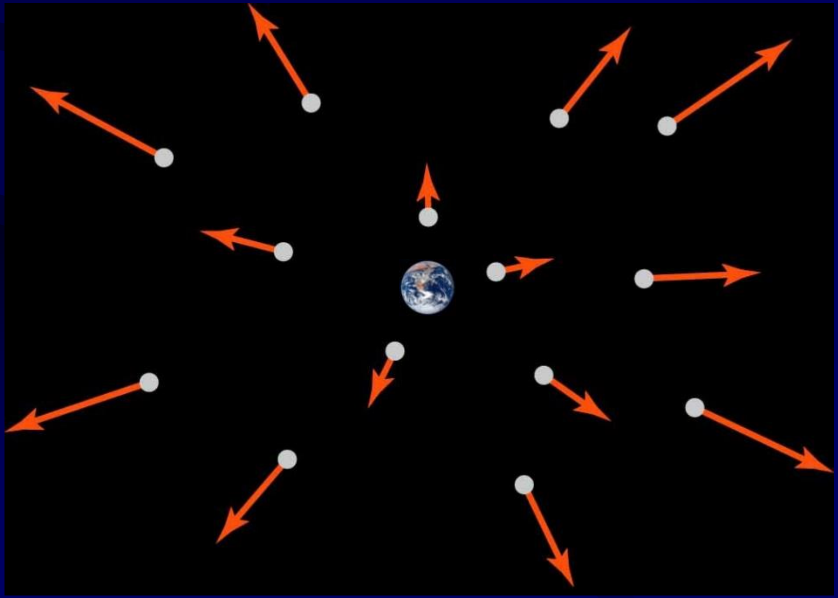
The Expanding Universe

The Expanding Universe

- Except for a few nearby galaxies (like Andromeda), *all* the galaxies are seen to be moving away from us
- Generally, the recession speed of a galaxy is proportional to its distance from us; that is, a galaxy that's twice as far away is moving twice as fast (aside from local motions within galaxy clusters)



The Expanding Universe

This expansion pattern (speed proportional to distance) actually implies that galaxies are all moving away from each other

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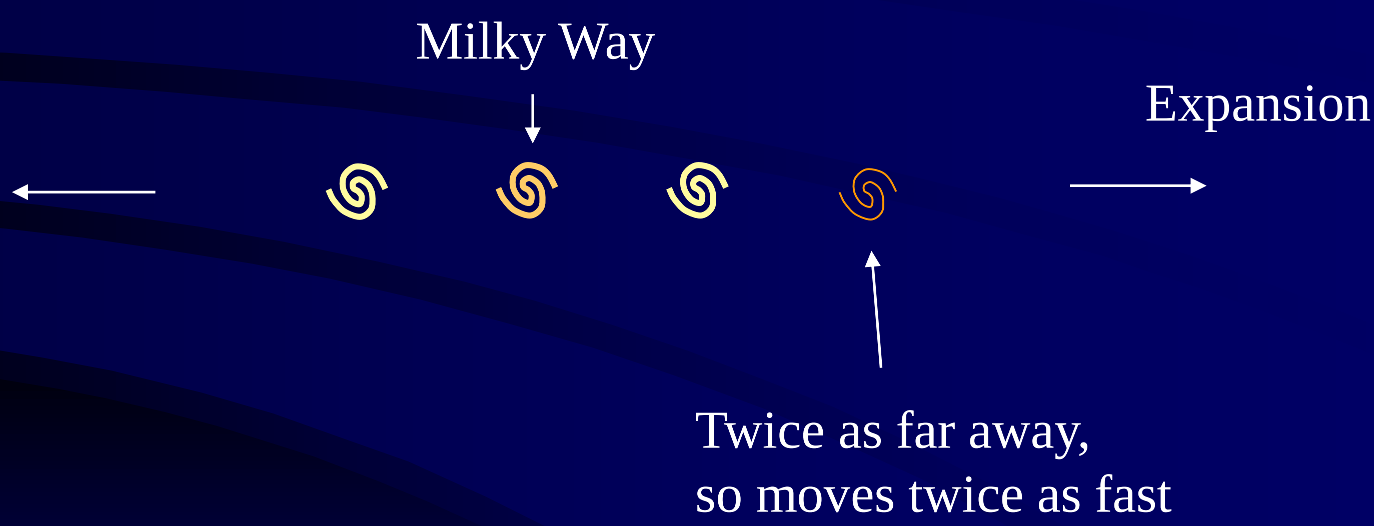

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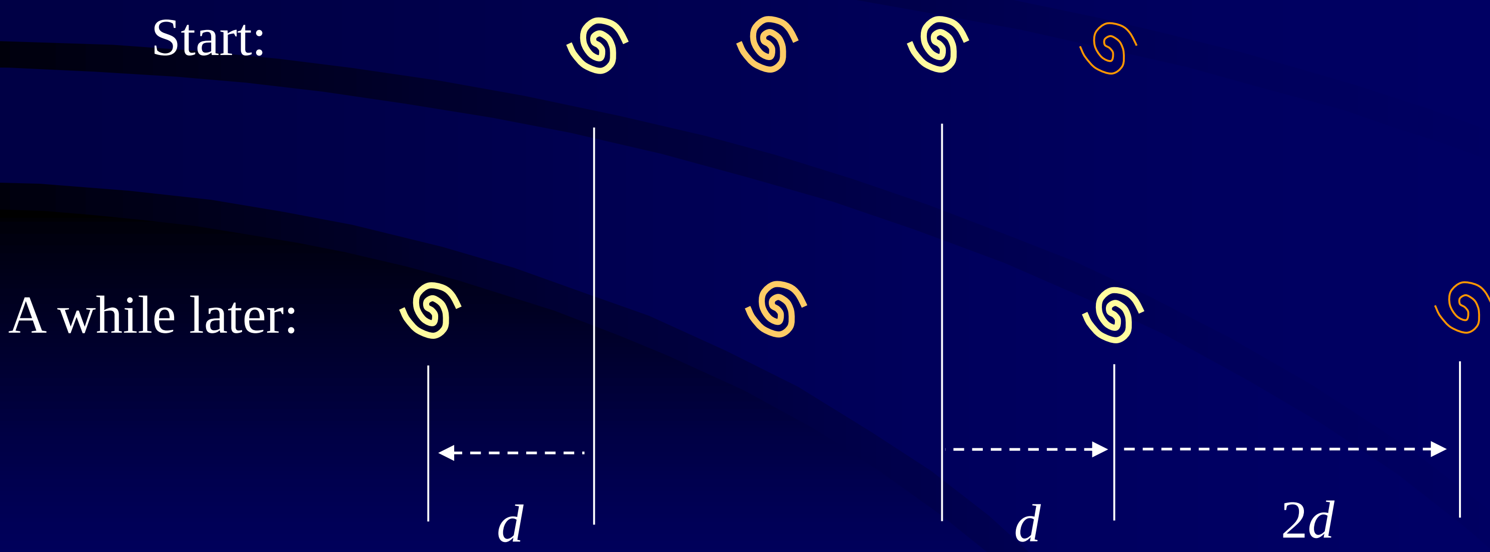
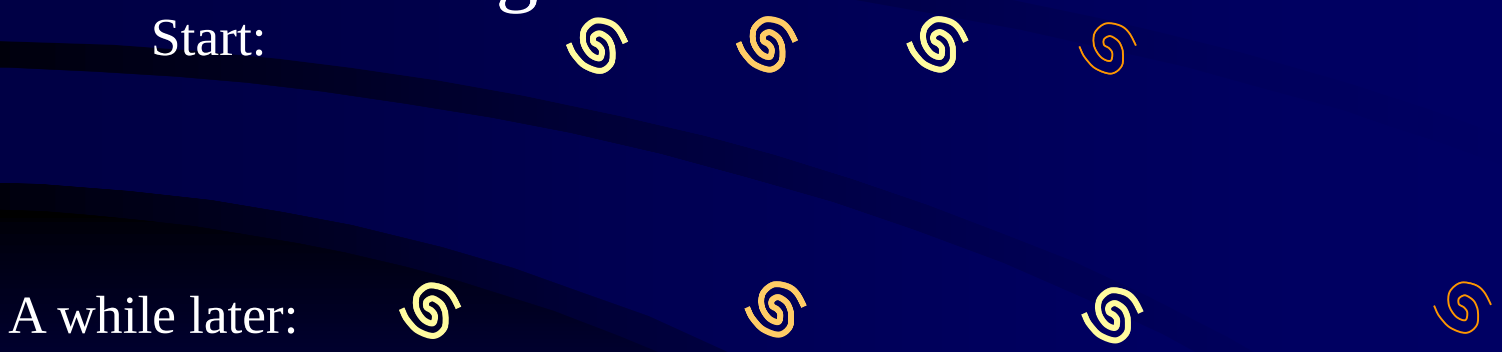


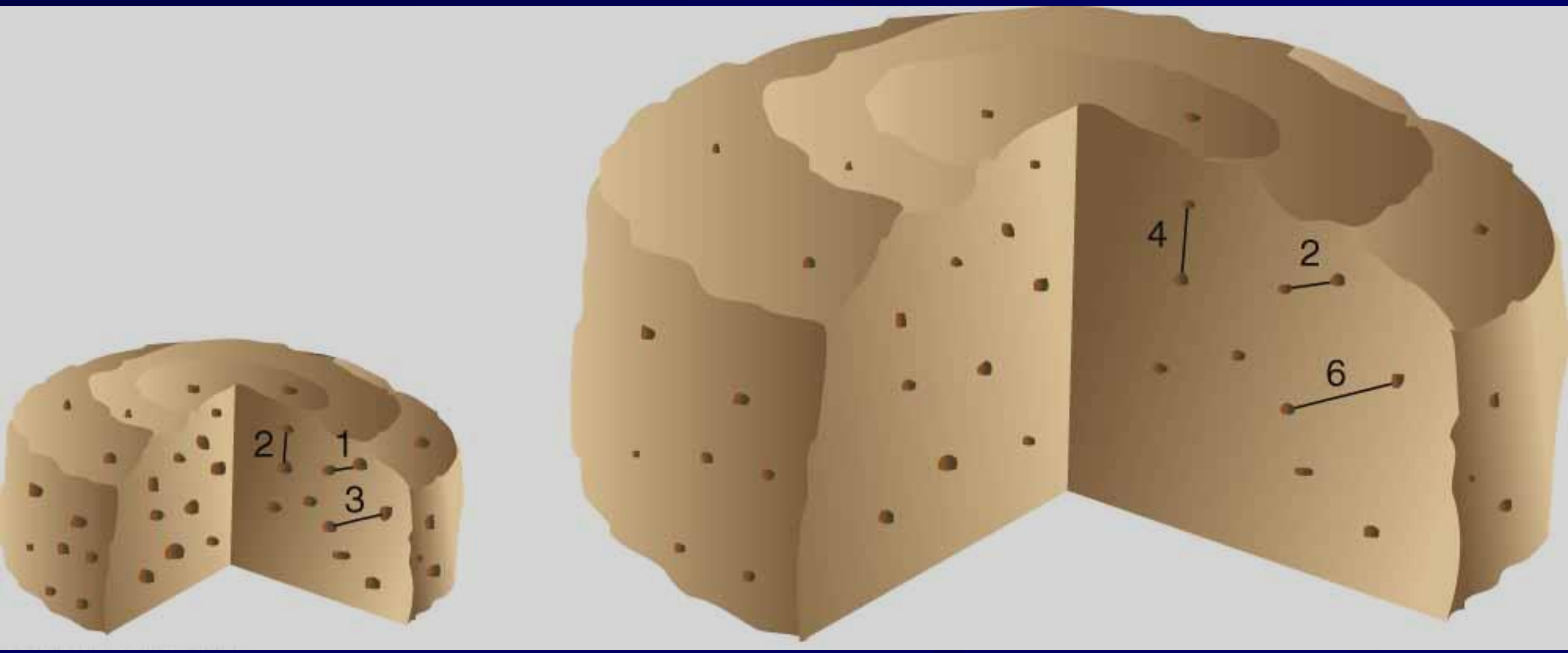
The Expanding Universe

- Each galaxy sees the others moving away with the same pattern (further ⟶ faster)
- As though the galaxies ride on a rubber band that is being stretched!



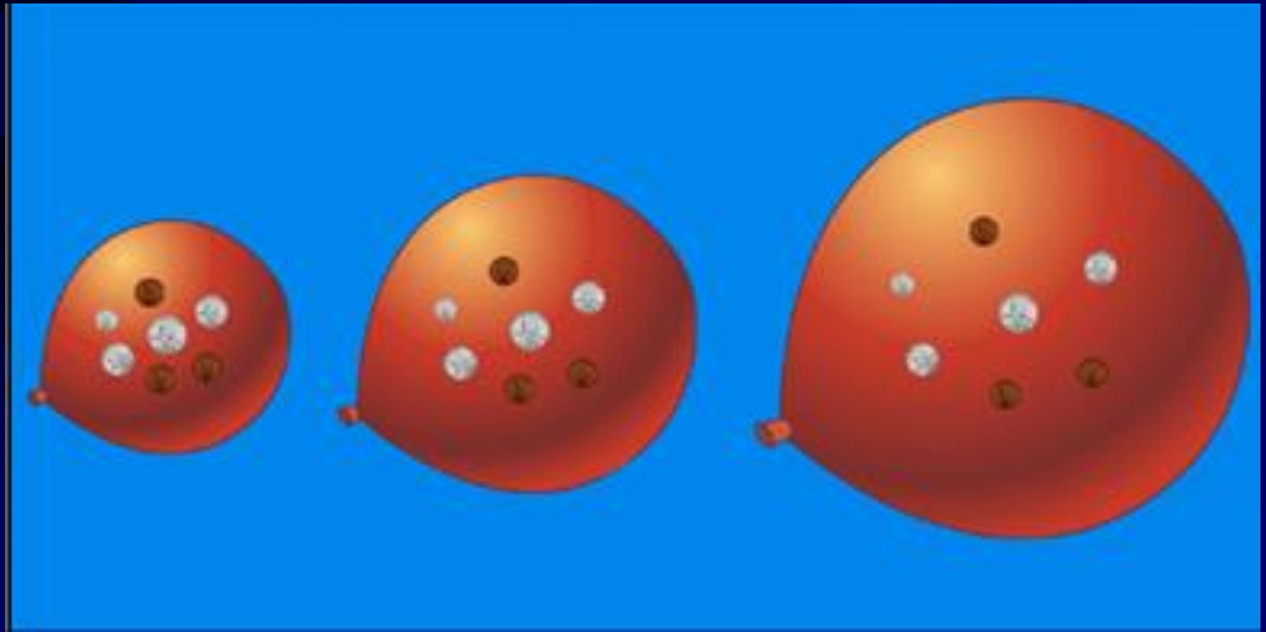
The Expanding Universe

In three dimensions, imagine the galaxies are raisins in an expanding loaf of bread



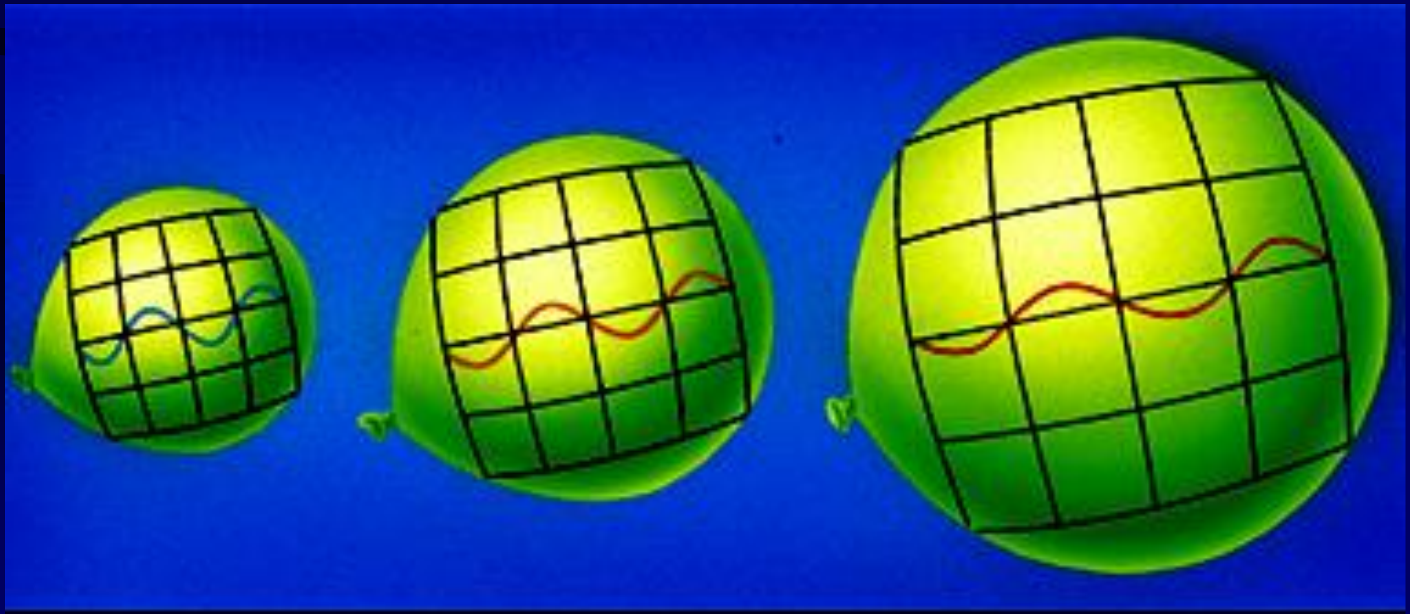
The Expanding Universe

- Appears the universe “exploded” from a state in which matter was extremely dense and hot – the Big Bang
- Where did the expansion begin? Everywhere!
- Every galaxy sees the others receding from it – there is no special point (center)



Cosmological Red-Shift

- Not really a Doppler effect
- Space itself is being stretched between galaxies



Conclusions from our Observations

- The Universe has a finite age, so light from very distant galaxies has not had time to reach us, therefore the night sky is dark.

- The universe expands now, so looking back in time it actually Shrinks until…?

➔ **Big Bang** model: The universe is born out of a hot dense medium

13.7 billion years ago.

Big Bang

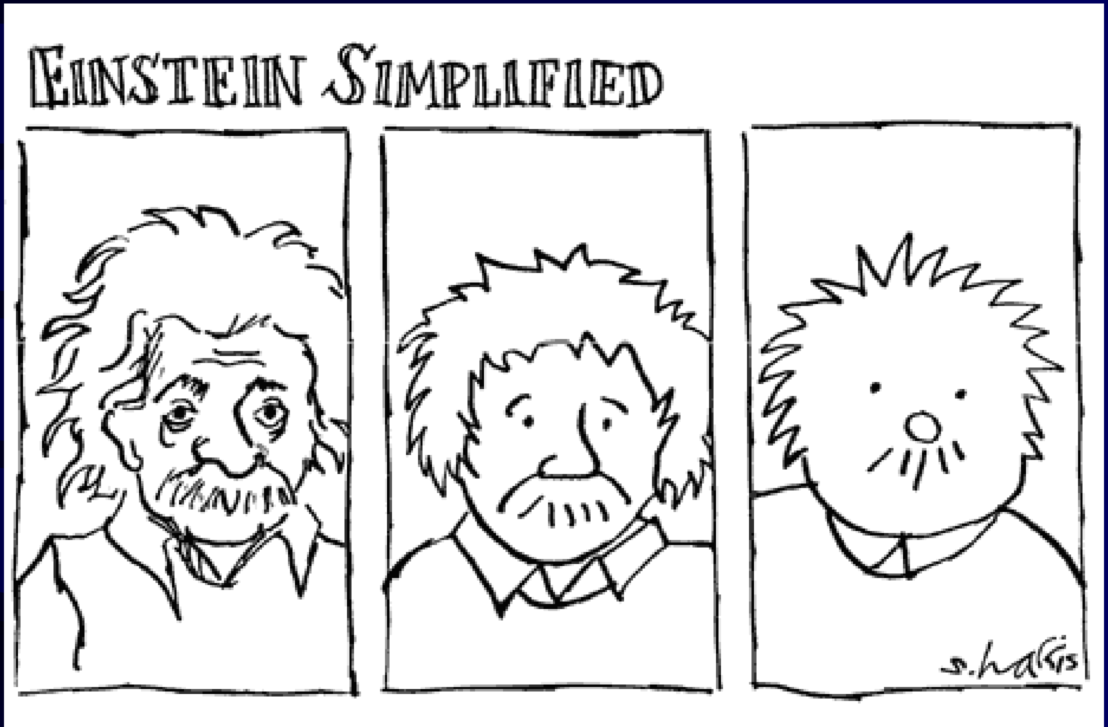
- The "start" of the universe, a primordial fireball
  → the early universe was very hot and dense
  → intimate connection between cosmology and nuclear/particle physics

→ "To understand the very big we have to understand the very small"

How does the expansion work?

- Like an explosion (hot, dense matter in the beginning), but space itself expands!
- Slowed down by gravitational attraction
- Attraction is the stronger, the more mass there is in the universe
- Scientifically described by Einstein's
  General theory of Relativity (1915)

The Idea behind General Relativity



- There is no way to distinguish between gravity and an accelerated frame of reference→ there is no gravity! Video

More General than Special Relativity

- General Relativity is more general in the sense that we drop the restriction that an observer not be accelerated
- The claim is that you cannot decide whether you are in a gravitational field, or just an accelerated observer
- The Einstein field equations describe the geometric properties of spacetime

General Relativity ?! That's easy!

$$R_{\mu\nu} - 1/2\, g_{\mu\nu} R = 8\pi G/c^4\, T_{\mu\nu}$$

OK, fine, but what does that mean?

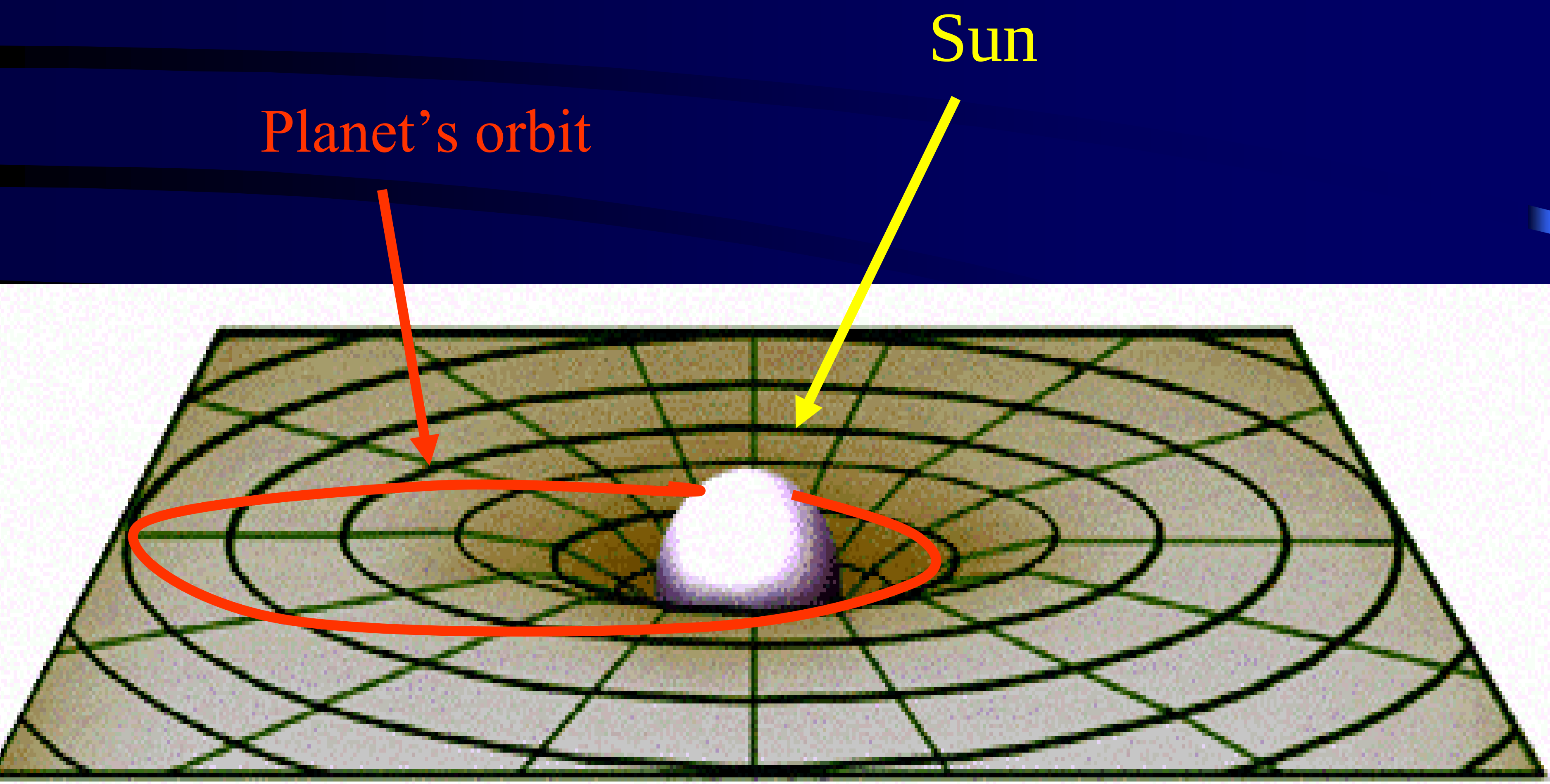
(Actually, it took Prof. Einstein **10** years to come up with that!)

100 years ago exactly!

The Idea behind General Relativity

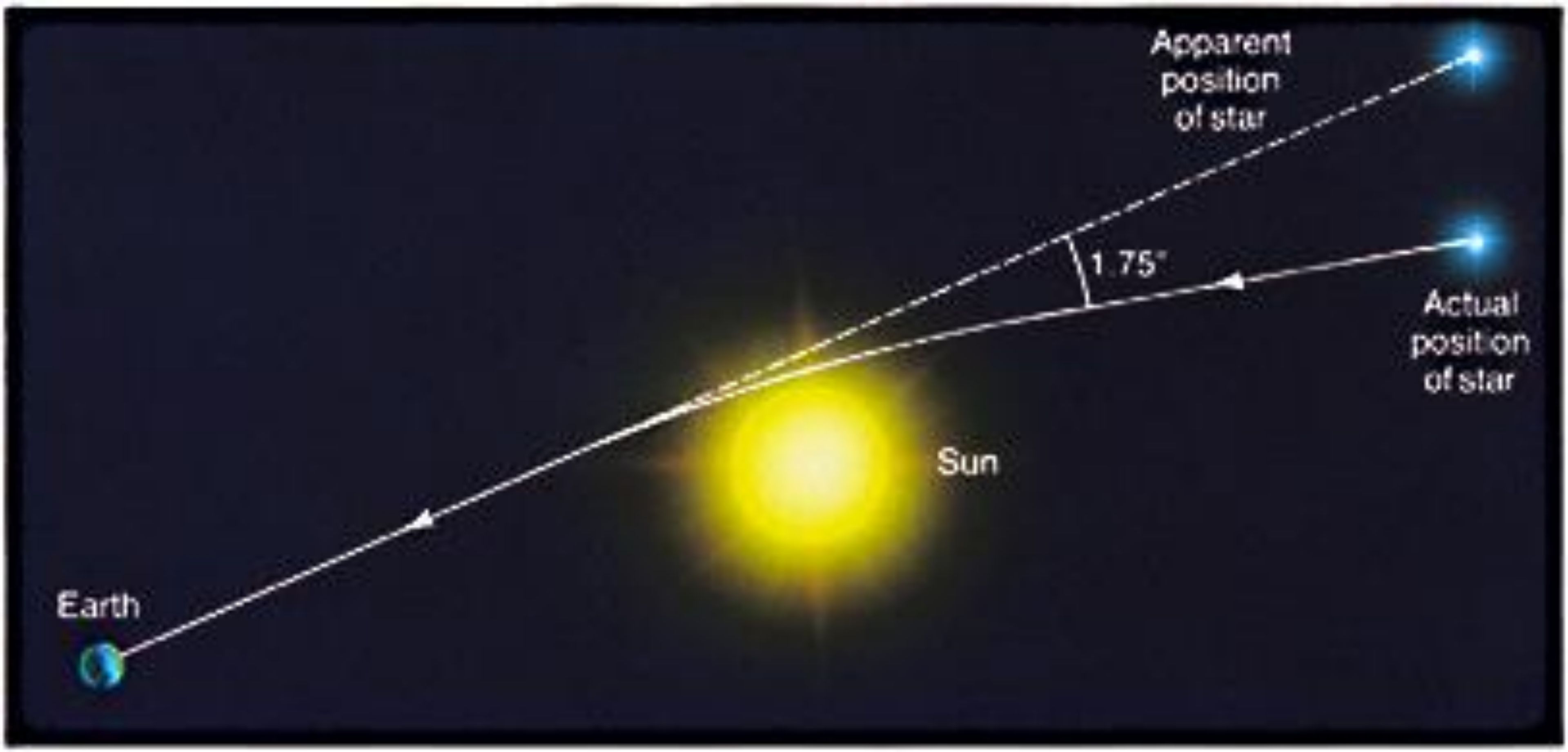
- We view space and time as a whole, we call it **four-dimensional space-time**.
  - It has an unusual geometry, as we have seen
- Space-time is warped by the presence of masses like the sun, so “**Mass tells space how to bend**”
- Objects (like planets) travel in “straight” lines through this curved space (we see this as orbits), so “**Space tells matter how to move**”

Planetary Orbits



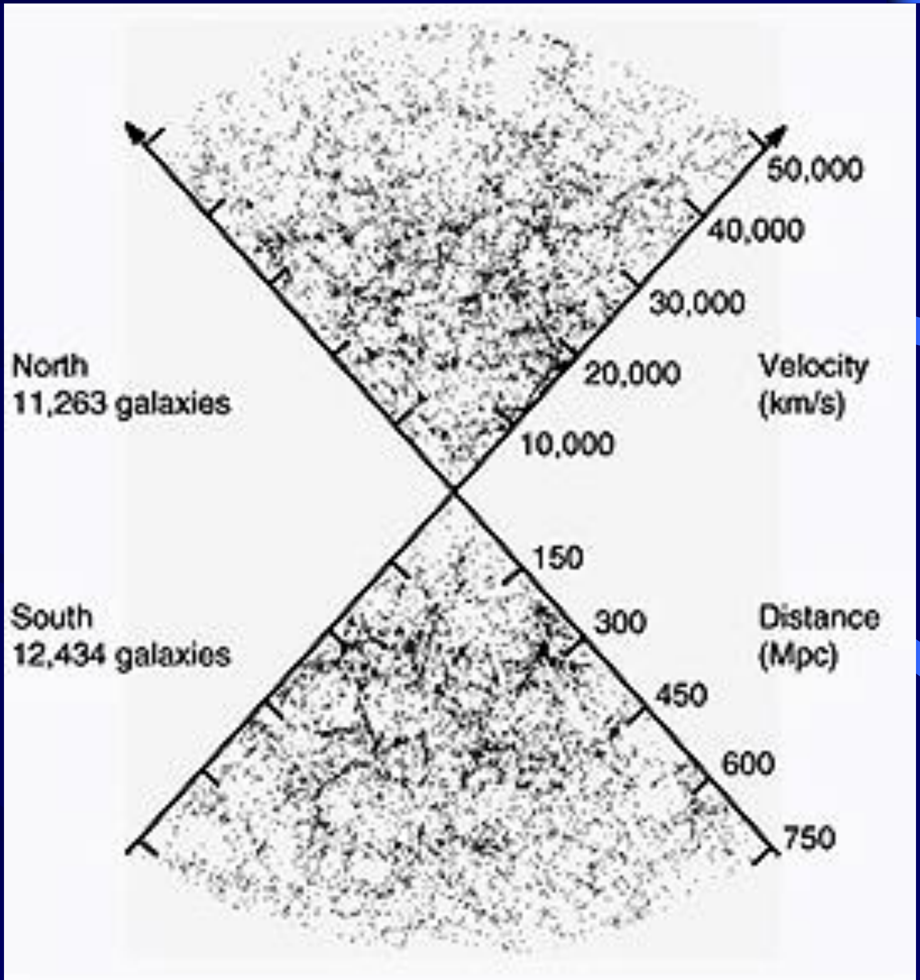
Effects of General Relativity

Bending of starlight by the Sun's gravitational field (and other gravitational lensing effects)



Assumption: Cosmological Principle

- The Cosmological Principle: on very large scales (1000 Mpc and up) the universe is **homogeneous** and **isotropic**



- Reasonably well-supported by observation
- Means the universe has no edge and no center – the ultimate Copernican principle!

What General Relativity tells us

- The more mass there is in the universe, the more “braking” of expansion there is
- So the game is:

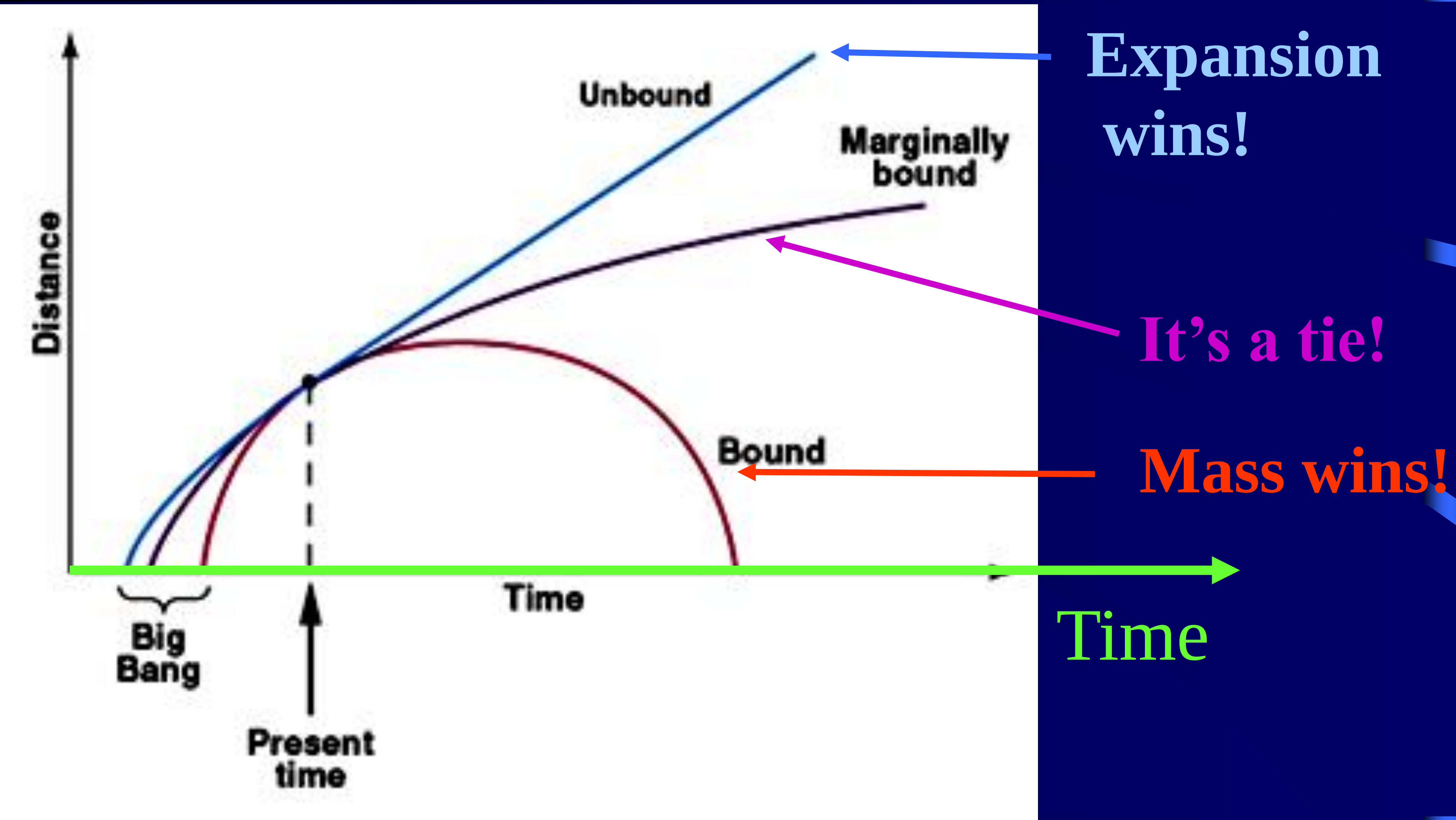
Mass vs. Expansion

And we can even calculate who wins!

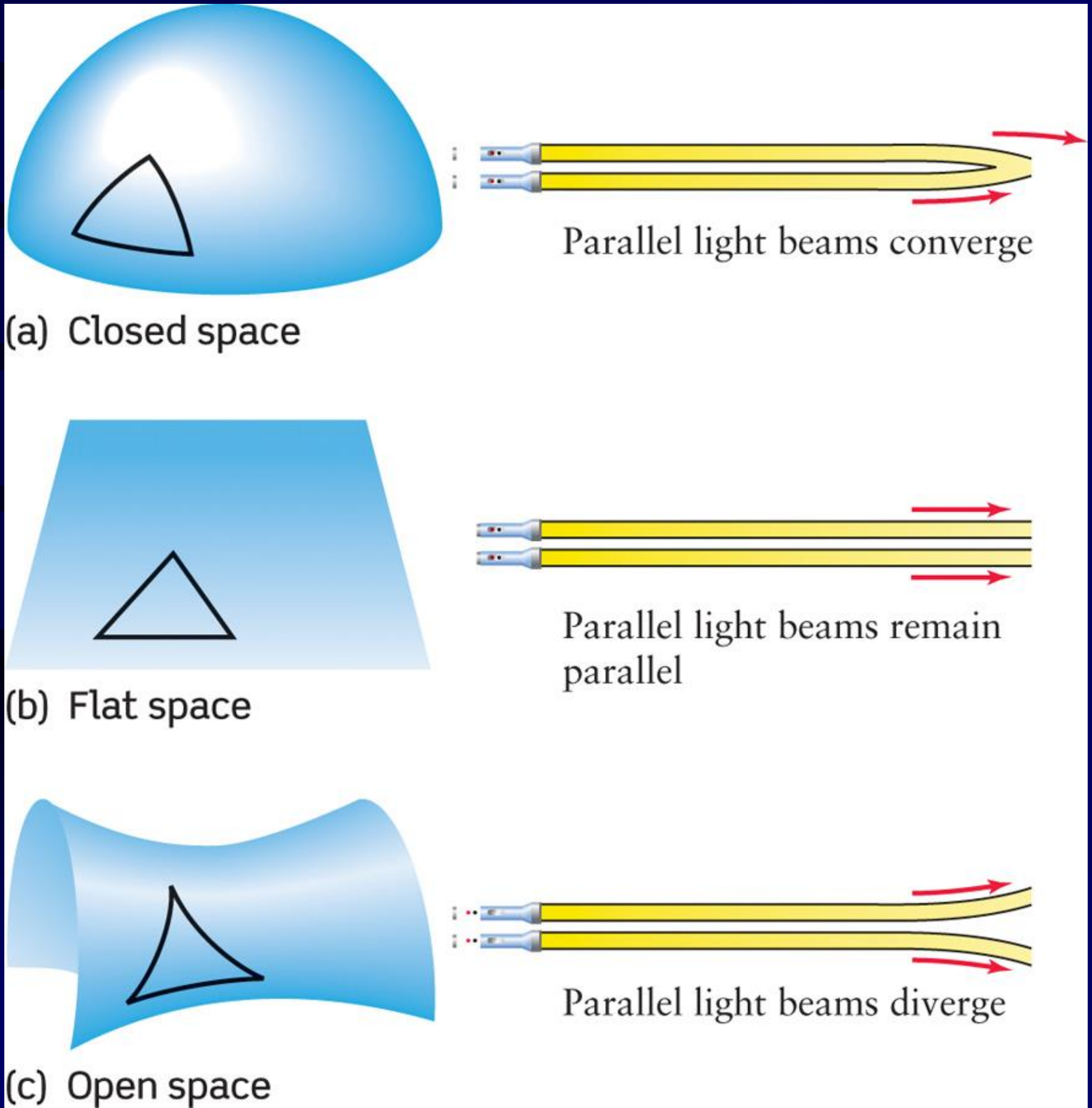
The Fate of the Universe – determined by a single number!

- Critical density is the density required to just barely stop the expansion
- We'll use Ω_0 = actual density/critical density:
  - $\Omega_0 = 1$ means **it's a tie**
  - $\Omega_0 > 1$ means the universe will recollapse (Big Crunch) → **Mass wins!**
  - $\Omega_0 < 1$ means gravity not strong enough to halt the expansion → **Expansion wins!**
- **And the number is:** $\Omega_0 = 1.02$ +/- 0.02

The "size" of the Universe – depends on time!



Possible shapes of a universe



The Shape of the Universe

- In the basic scenario there is a simple relation between the density and the shape of space-time:

Density	Curvature	2-D example	Universe	Time & Space
$\Omega_0>1$	positive	sphere	closed, bound	finite
$\Omega_0=1$	zero (flat)	plane	open, marginal	infinite
$\Omega_0<1$	negative	saddle	open, unbound	infinite

The Observable Universe