Nature of the Expansion

General Expansion of Spacetime:

- All observers in different galaxies see the *same* expansion around them.
- No center - all observers *appear* to be at the center.

What is the recession velocity?

- NOT motions *through* space...
- *Expansion of spacetime*: galaxies carried along.

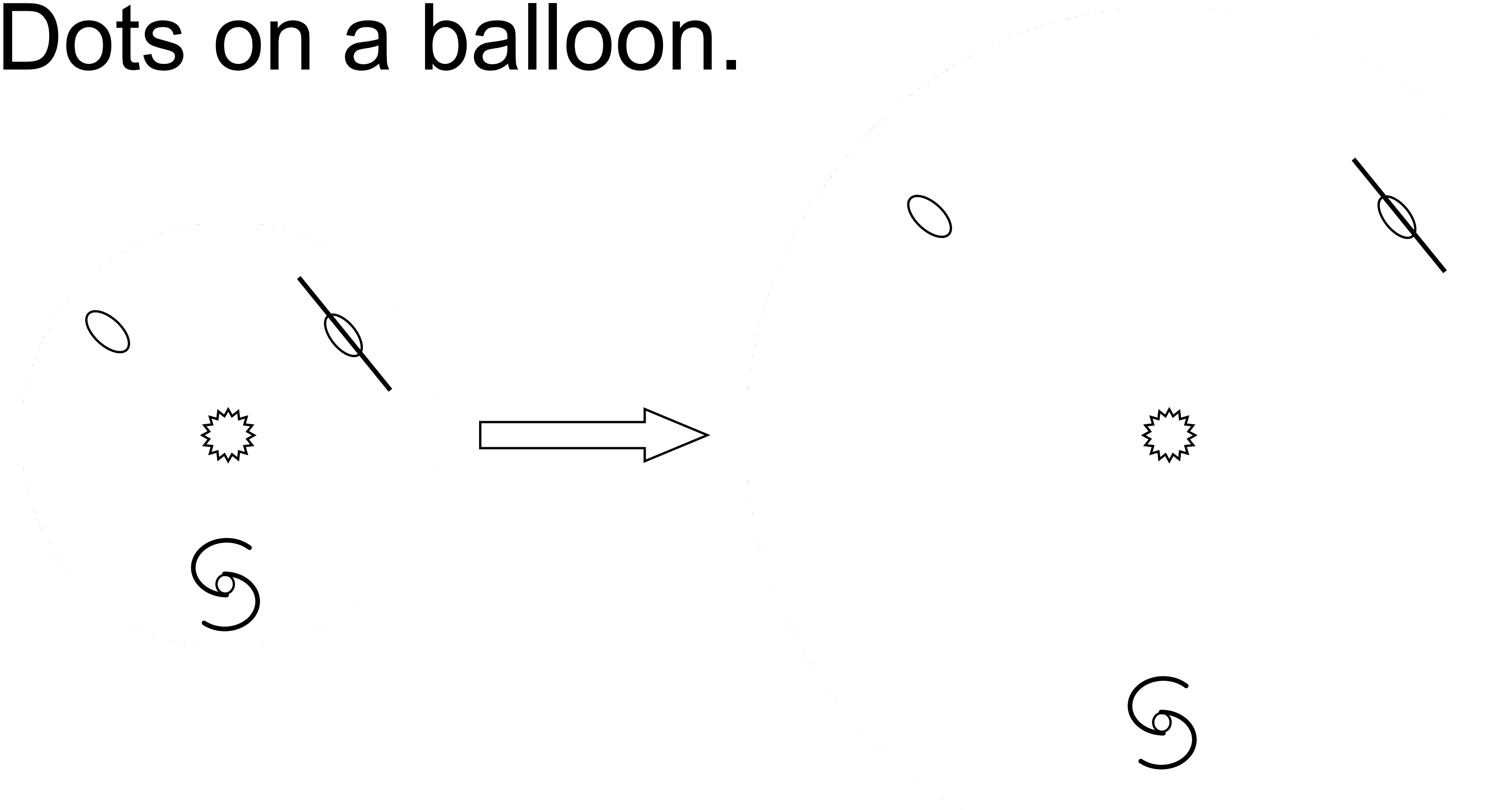
  Like raisins embedded in an infinite expanding cake.

  Like paperclips clipped to a stretching rubber band.

  Like pennies scattered on a stretching rubber sheet.

  Like dots on the surface of an expanding balloon.

Systematic Expansion: Dots on a balloon.



Universe 2x larger
Galaxies are 2x further apart

Systematic Expansion:
Raisins = Galaxies
Cake = Spacetime

Raisins in cake

Universe 2x larger
Galaxies are 2x further apart

Systematic Expansion:

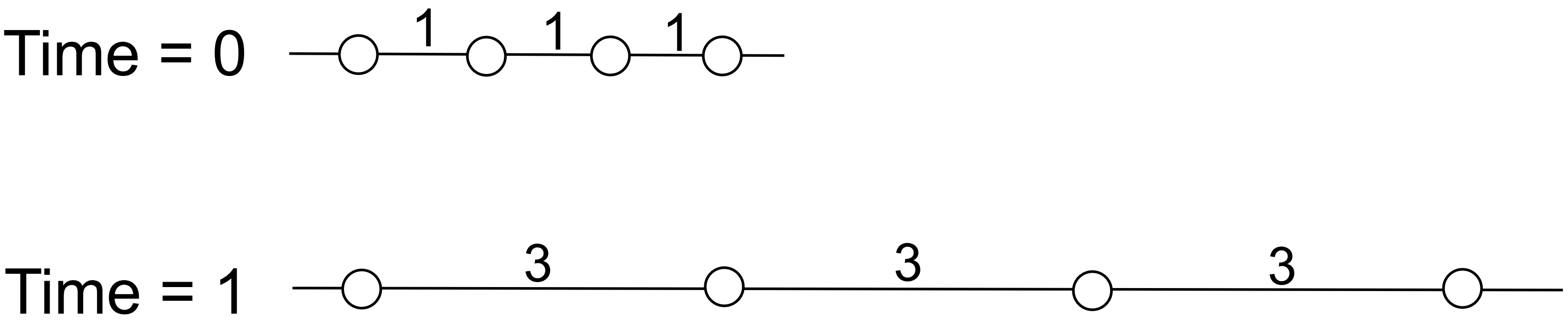
Paperclips = Galaxies; Ants = you

Ants on paperclips attached to rubber bands

It only seems like you are at the center.
Both Ants see the same: Every paperclip is moving away with
apparent velocity proportional to distance.

Systematic Expansion:

Dots = Galaxies ; Lines = Spacetime



It only **seems** like you are at the center.
All dots see the same thing: Every other dot is moving away.

Velocity = change in distance / change in time
= (3-1)/(1-0) = 2 (for the blue, as observed from red)

= (6-2)/(1-0) = 4 (for the green, as observed from red)

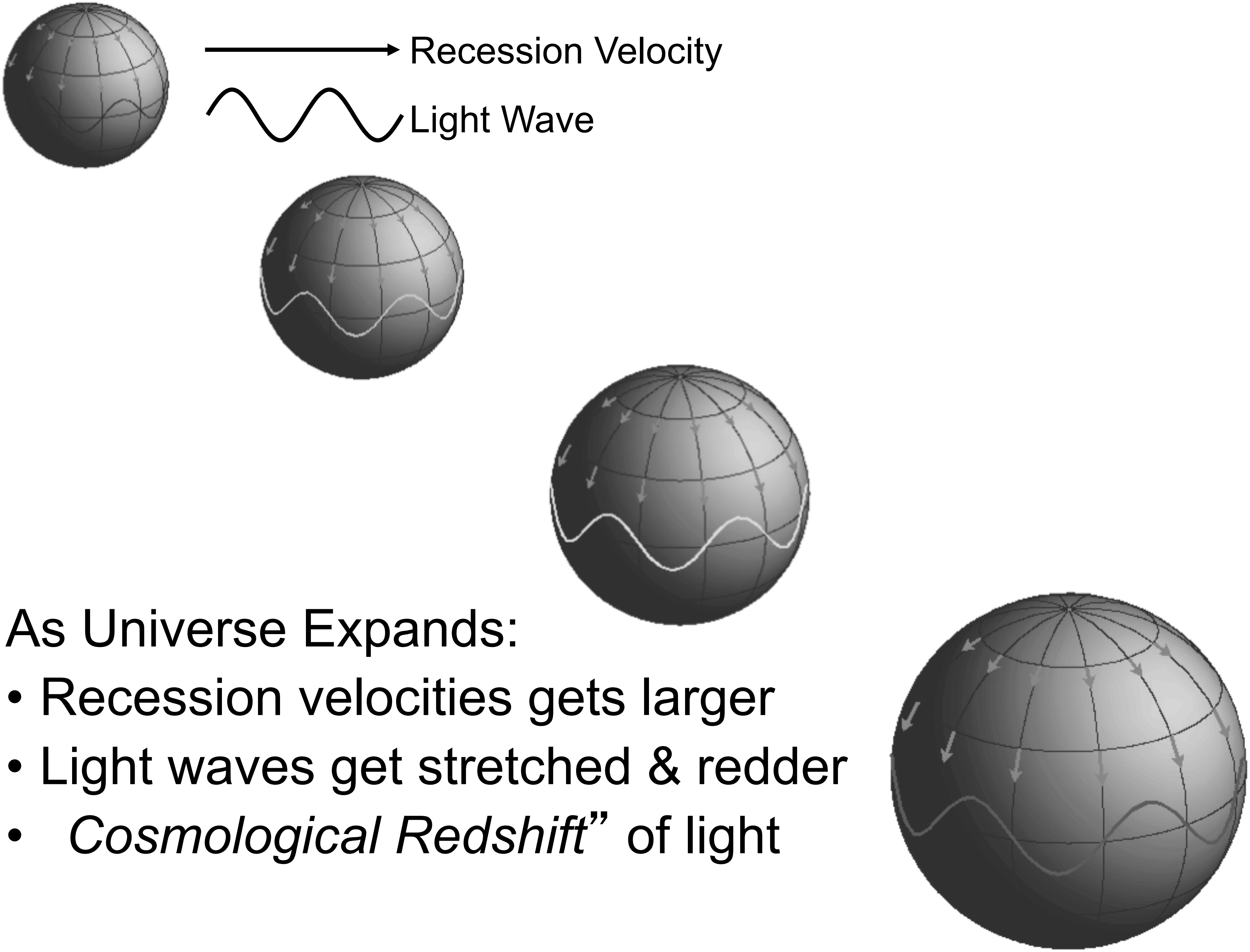
Systematic Expansion:

Boxes
= Galaxies

Rods =
Spacetime

Escher box lattice

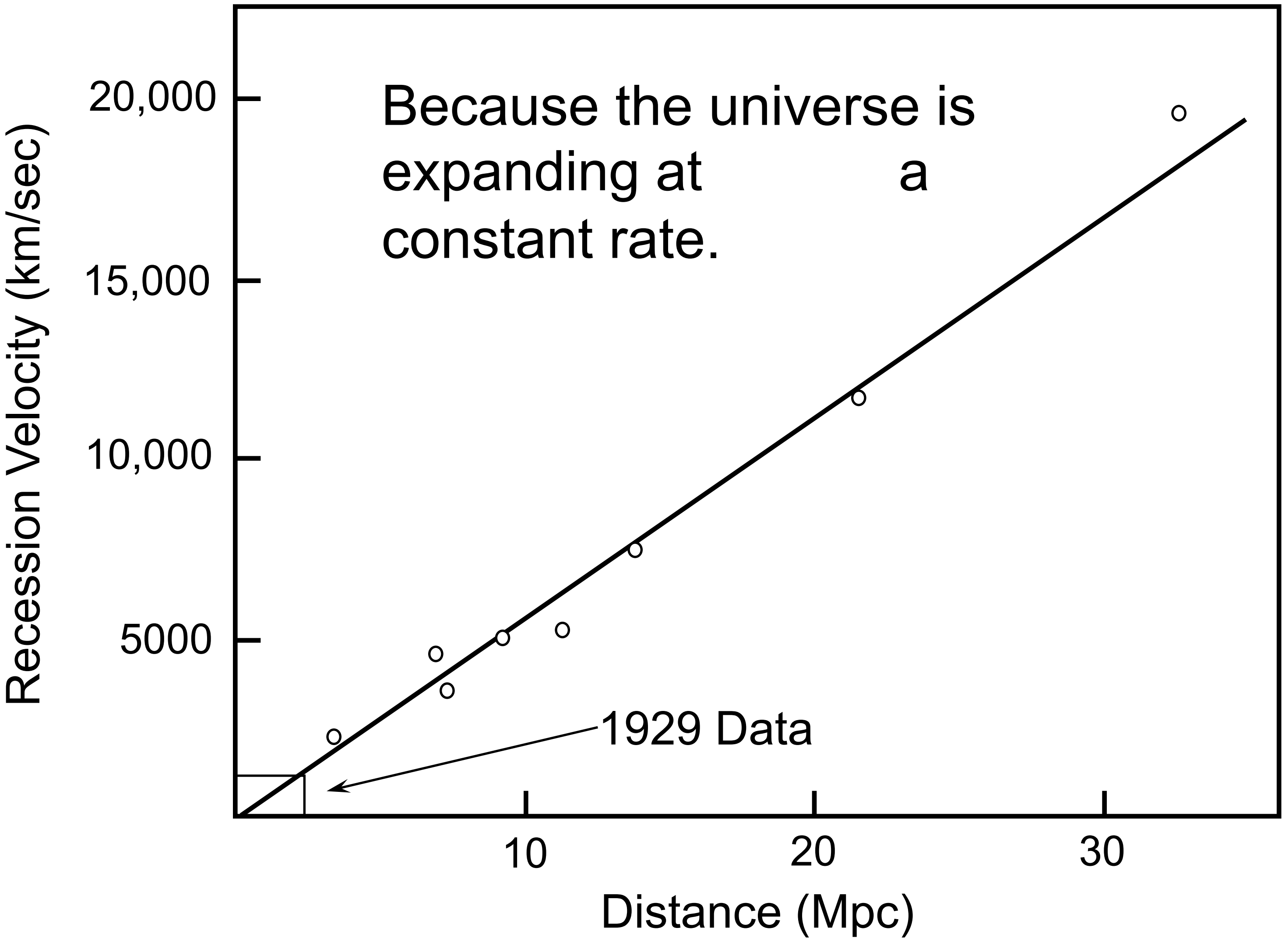
Escher



As Universe Expands:

- Recession velocities gets larger
- Light waves get stretched & redder
- *Cosmological Redshift*” of light

Hubble & Humason (1931)



Because the universe is expanding at a constant rate.

Hubble Parameter: H_0

Measures the *rate* of expansion today:

- $H_0 = 70 \pm 7$ km/sec/Mpc
- Based on observations of Cepheids in nearby galaxies

H is hard to measure:

- Recession speeds are easy to measure from the shifts of spectral lines.
- But **distances** (as always!) are very hard to measure.
- Galaxies also have extra peculiar motions.

Cosmological Redshifts

All galaxies (with very few exceptions) are receding from us.

Recession is quantified in terms of the "*cosmological redshift*" of the galaxy, z

$$\boxed{z = \frac{V}{c} = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}}}$$

Not (just) a Doppler shift: measures expansion of spacetime. It is motion space.

Redshift Distances

Assume Hubble Law works for all galaxies, even though you only have good distances for a small number.

Then, measure redshift from spectral lines.

Get distance!

$$\boxed{d = \frac{V}{H_0} \approx \frac{cz}{H_0}}$$

z = redshift

c = speed of light

This formula is only valid for relatively nearby galaxies.

Redshift Distances (cont’d)

Limitations:

- Value of H_0 is only known to ~10%
- Random (peculiar) motions of galaxies affects measurements of for nearby galaxies.
- At large distances, the conversion between z and distance is much more complicated.

Astronomers use cosmological redshift as a surrogate for distance, especially for more distant galaxies.

Mapping the Universe

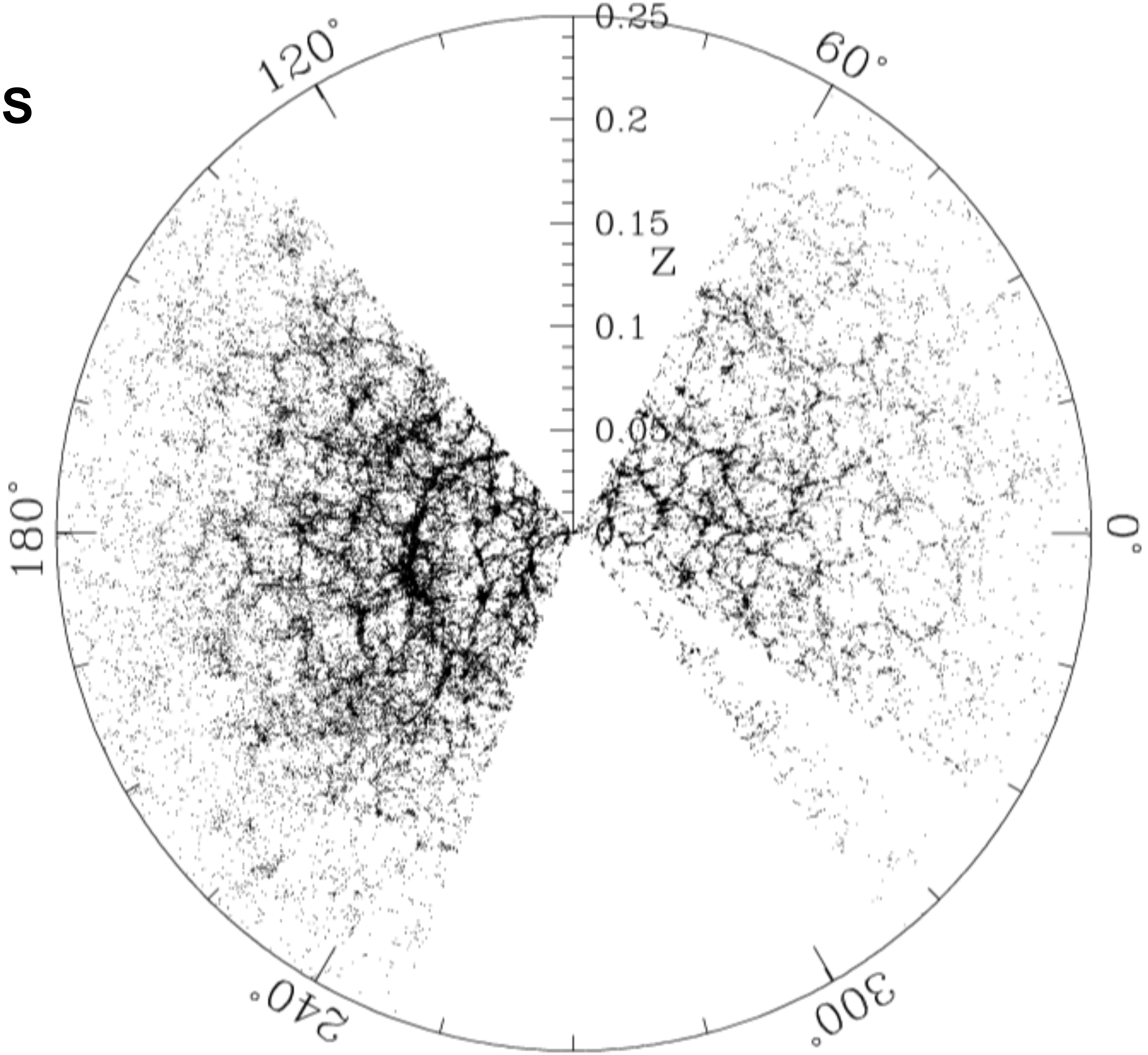
Map the distribution of galaxies using their cosmological redshifts.

Largest maps include ~1,000,000 galaxies

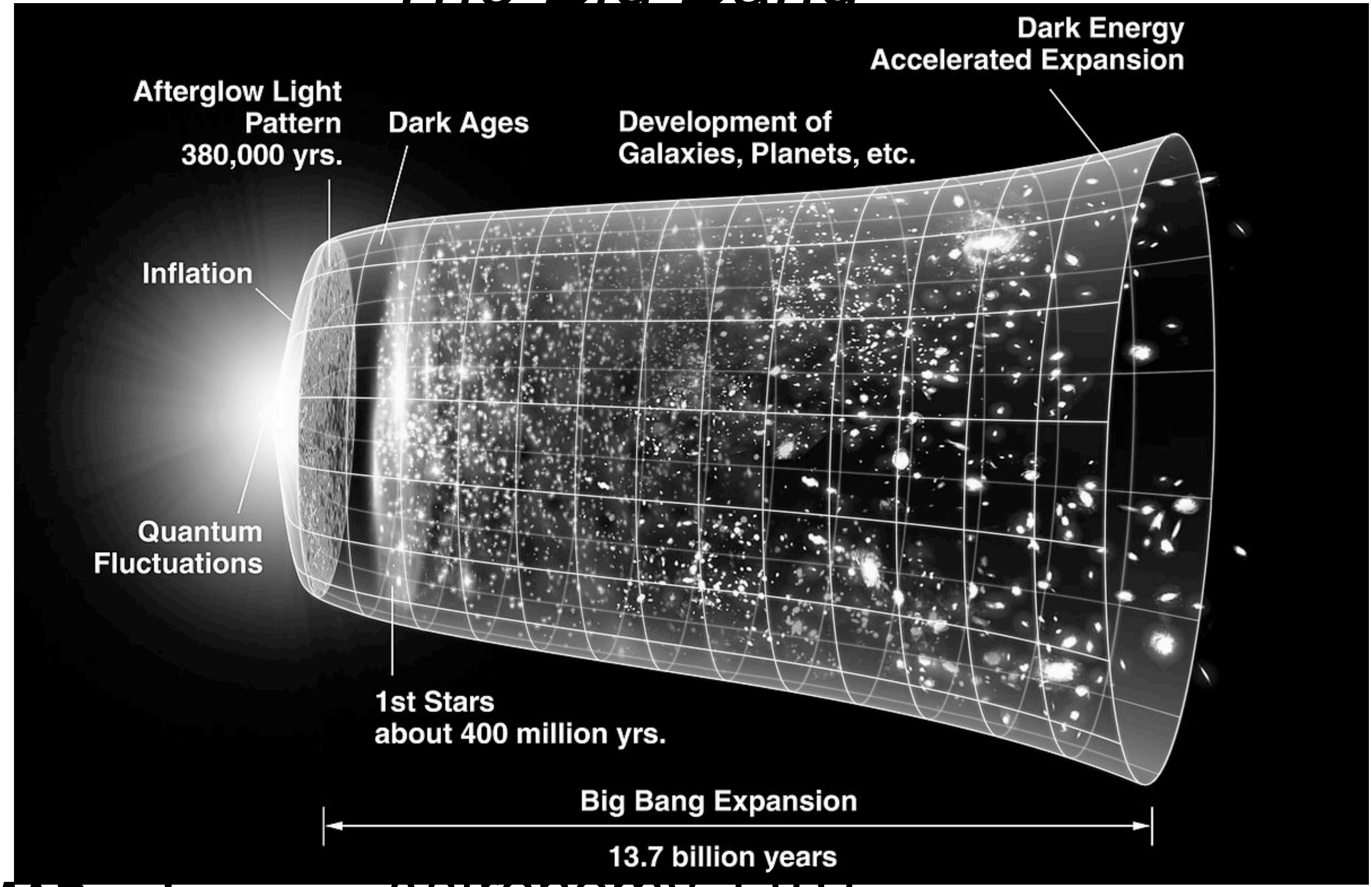
- Reveals sheets and filaments of galaxies surrounding great voids.
- Depth is ~500-1000 Mpc

Relative distances are good, but the *absolute scale* is only known to ~10%

SDSS



The Big Bang



WMAP universe

Key Ideas:

Big Bang Model of the Universe

- Universe starts in a hot, dense state in the past
- Universe expands & cools with time

Cosmological Redshift & Lookback Time

Critical Density

- Determines the geometry of the Universe and (in part) its expansion history

Hubble Time

- Estimate of the Age of the Universe

Expansion of the Universe

Universe is observed to be expanding today.

- Evidence: Hubble s Law

As the Universe *expands*, it *cools*

In the past, it must have been:

- Smaller
- Denser
- Hotter

than it is today...

The Big Bang

If we run the clock back far enough, eventually the Universe would be

- Very small and very high density
- Very very hot and opaque

This initial state must have existed at some *finite* time in the past.

We call this very hot, very dense initial state

“*The Big Bang*”

The Big Bang is Testable

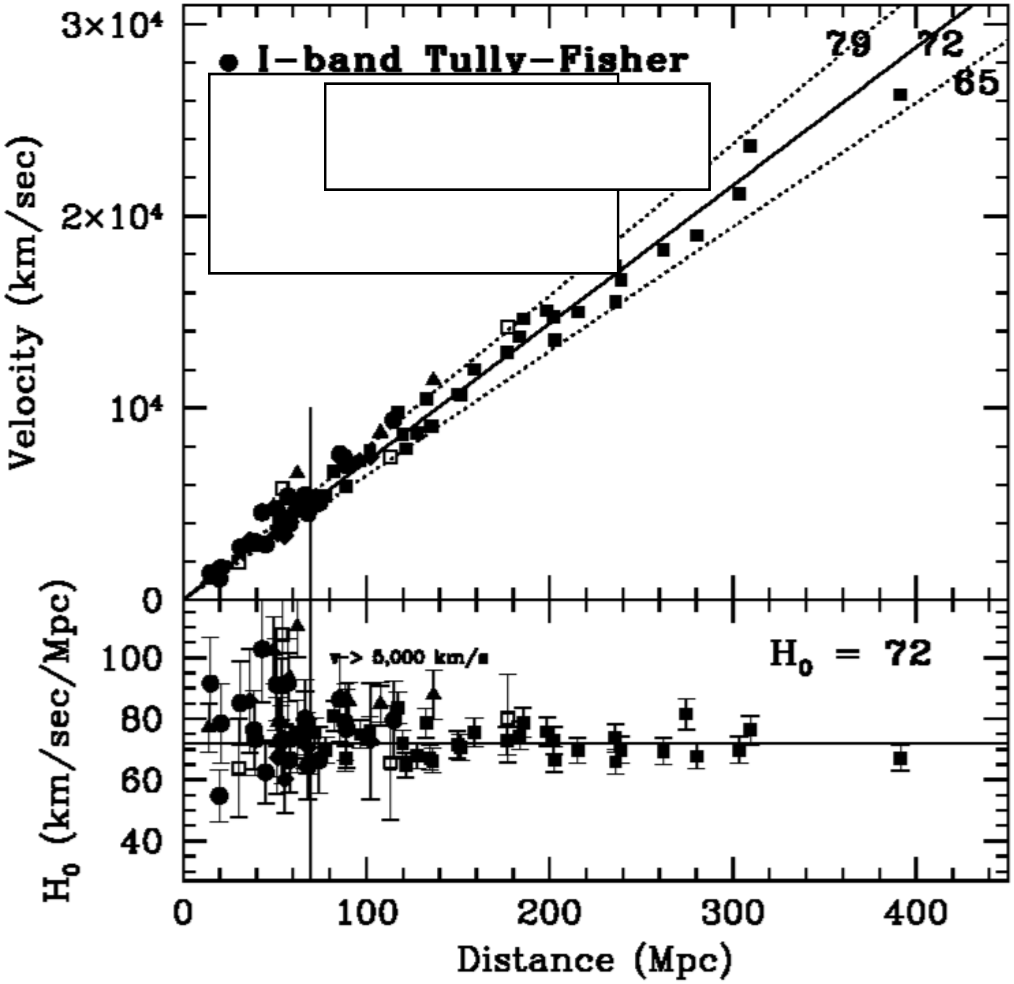
Does the Big Bang Model explain the properties of the *observed* Universe?

Expansion & Hubble's Law

As the Universe expands:

- Space gets stretched in all directions.
- Matter is carried along with expanding space.
- The distances between galaxies gets *larger* with time.

The Big Bang predicts Hubble's Law exactly for v < c: $_0$.



The Astrophysical Journal

Cosmological Redshift

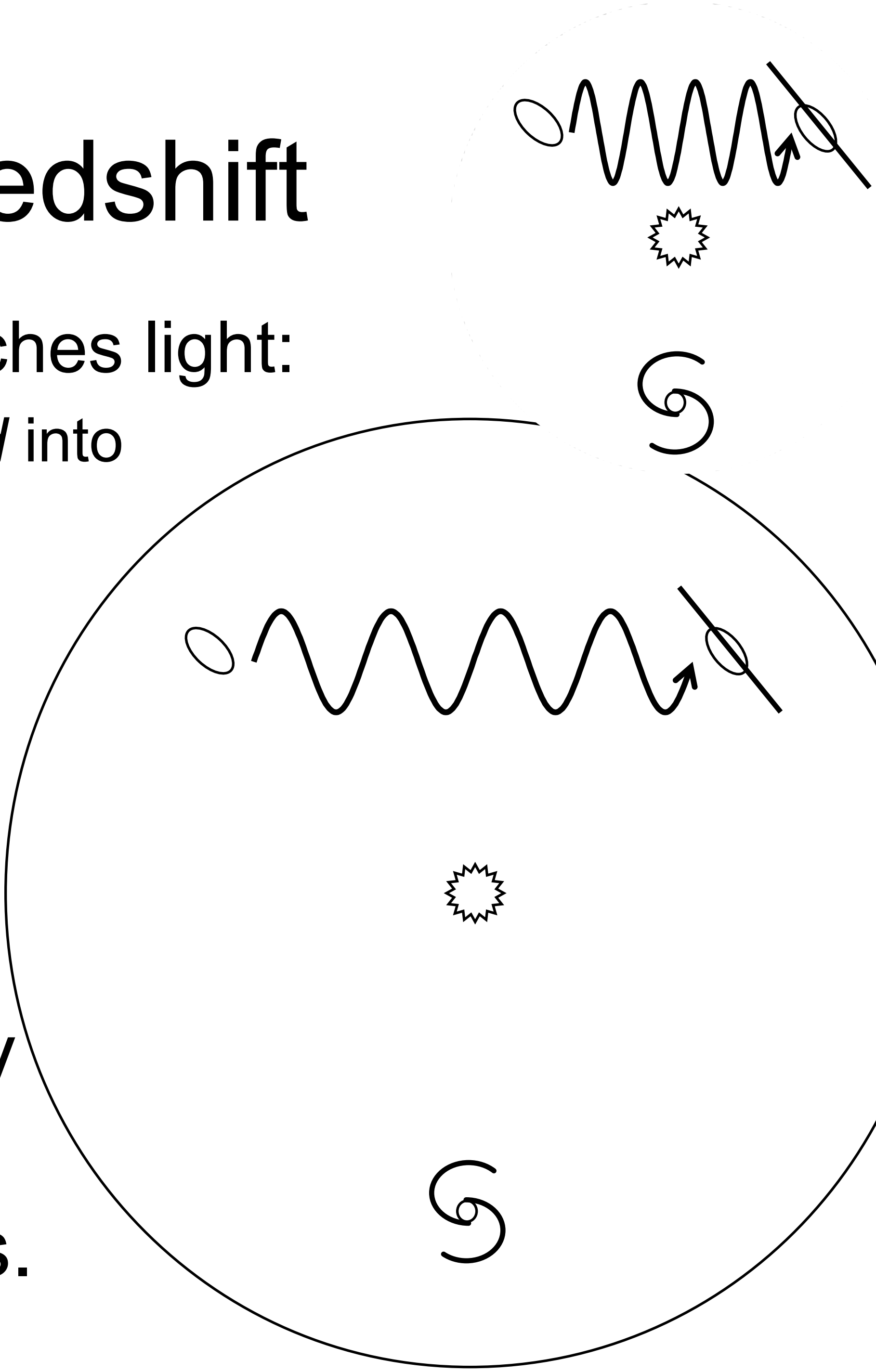
Expansion of space stretches light:

- Wavelengths get *stretched* into *redder wavelengths*
- The greater the distance, the greater the stretching

Result:

- The *redshift* of an object gets *larger* with distance.

The Big Bang naturally explains the *observed* Cosmological redshifts.



Cosmic Lookback Time

Light moves at a finite speed:

- Takes time for light to reach you from a distant source.
- Example, we see the Sun as it was ~8.5 minutes ago due to the light-travel time.

At cosmic distances:

- The deeper we look into the Universe, the further we *look-back in time* to when the Universe was *younger, smaller, denser, hotter*.

The Shape & Future of the Universe

All (normal) forms of matter *attract* each other via their *mutual gravity*.

Relativity tells us:

- Energy & matter are equivalent ($E=mc^2$)
- Matter (& energy!) tells spacetime how to curve.

The combined matter and energy density of the Universe determines its *global geometry*.

If too dense, can't keep expanding, re-collapses.

If low-density, expands forever.

The Density Parameter: Ω_0

The geometry of the Universe depends on the total density of matter & energy:

High Density: positively curved, “spherical”

- Bound, will collapse; the Big Crunch

Low Density: negatively curved, “hyperbolic”

- Unbound, will not collapse, expands forever

Dividing Line: *Critical Density; “Flat”, no curvature.*

- Just unbound, will not collapse

Ω_0 = (Average Density / Critical density) Now

Ω_0 = 1 (critical density)

Geometry of the Universe

If $\Omega_0 > 1$: positive curvature

-
-
- **big crunch** amount of time.

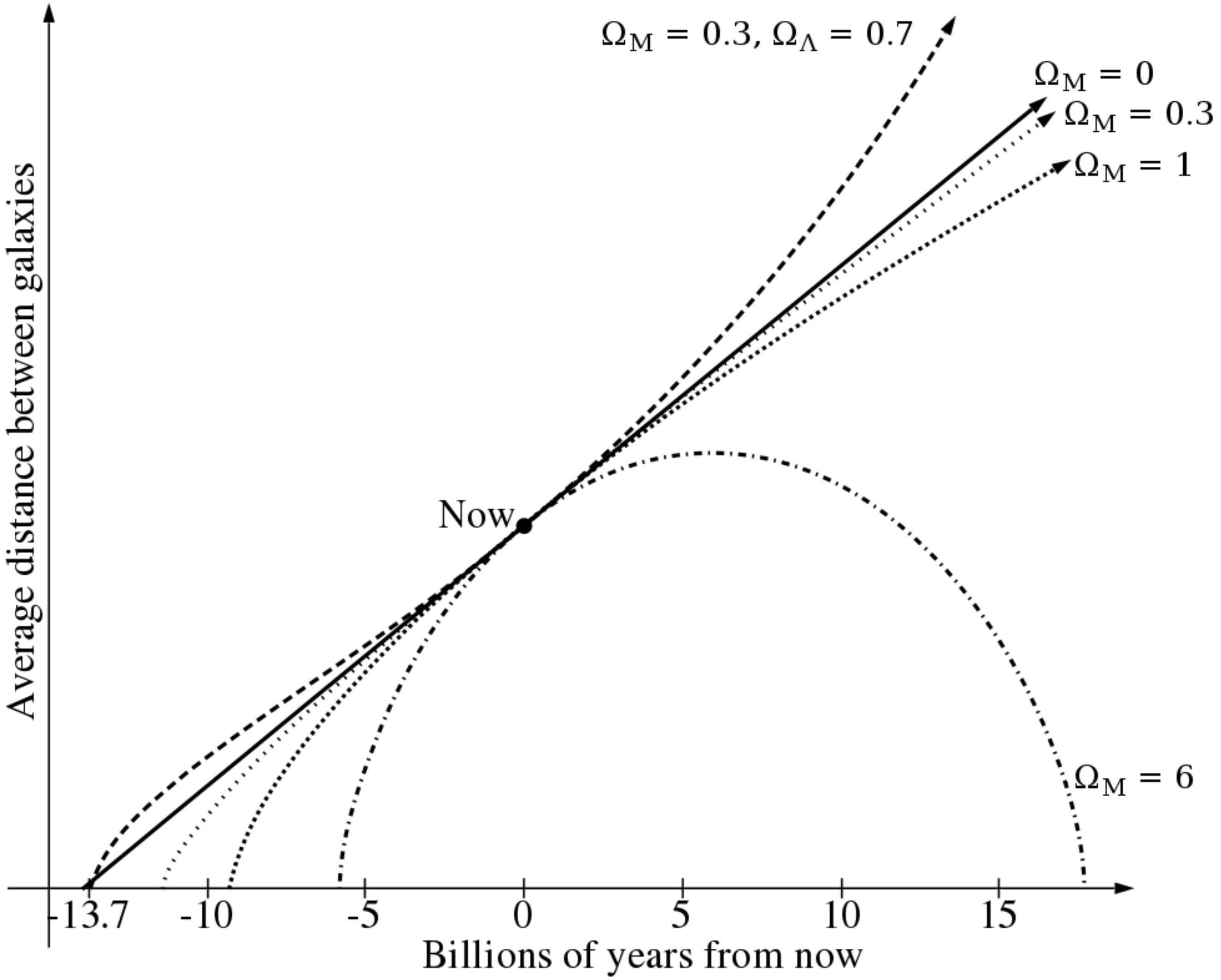
If $\Omega_0 < 1$: negative curvature

- Hyperbolic Universe
- Parallel light rays diverge
- **Expands forever**, no end.

If $\Omega_0 = 1$: Critical, flat Universe

- Infinite, flat Universe
- Parallel light rays stay parallel
- **Expands forever**, no end, but at an ever-decreasing rate.

Geometry of the Universe



Wikipedia BenRG

Back to the Beginning

The Universe is expanding now.

In the past:

- Universe was smaller.
- Galaxies were closer together in space.

If we go back far enough in time:

- All galaxies (matter) exists at a single point.

How far back = “Age of the Universe”

Road Trip Analogy

You leave Columbus by car for Florida, but leave your watch behind.

How long have you been on the road when all you know is that

- Your average speed = 100 km/h
- Your trip odometer reads: distance = 230 km

Time since you left: T = distance / speed

- T = 230 km / 100 km/h = <u>2.30 hours</u>

The Hubble Time: T_0

Hubble's Law says

- A galaxy at distance *d* away has a recession speed, $v = H_0 \times d$

If locally, *v* is its average speed, then:

- $T_0 = d / v$
- but since, $v = H_0 \times d$, $T_0 = d / H_0 \times d = 1 / H_0$

Hubble Time: $T_0 = 1 / H_0$

Estimate of the Age of the Universe

$T_0 = 1 / H_0 \sim 14$ *Gyr for* $H_0 \sim 70$ *km/s/Mpc*

But…

Cosmic expansion is not expected to be constant over all times

If faster in the past:

- Expansion slowed by gravity of massive objects
- T_0 would *overestimate* the age of the Universe.

If slower in the past:

- accelerated by some agent (e.g., a non-zero cosmological constant Λ)
- T_0 would *underestimate* the age of the Universe.

So, How Old is it Really?

Need two hard-to-measure numbers:

Hubble Parameter, H_0:

- How fast the universe is expanding *now*.

Density Parameter, Ω_0:

- How the matter & energy density affected the expansion rate in the past.
- Can include another term (Λ) that enhances the expansion rate, accelerates expansion.

These parameters are needed to determine the *expansion history, and thus the history of the universe.*

Best Estimate:

~13.8 Gyr

This number assumes:

- H = 71 km/sec/Mpc
- 30% from all forms of matter $\Omega_m \sim 0.3$, 70% (!) from the energy density associated with a non-zero Cosmological Constant, $\Omega \sim 0.7$.
- The universe will expand forever at an ever-increasing rate.

Independent check: This age is consistent with the ages of the oldest stars seen in globular clusters.

Foundations of the Big Bang

An infinitely dense & hot Universe in the past follows naturally from three basic *physical* assumptions:

1. General Relativity is valid on cosmic scales.
2. The Universe is *homogeneous* and *isotropic* on cosmic scales.
3. The energy of the vacuum is either zero or very small (the Cosmological Constant: [illegible])

All of these assumptions are testable.

The Big Bang is Testable

These basic assumptions are plausible:

- Supported by empirical data for the most part
- Have a reasonably sound physical basis

But, they are not *required* to be true.

Real Test:

Does the Big Bang Model explain the properties of the *observed* Universe?