Einstein & The Dyanmic Universe

Astronomy 1101

Key Ideas:

Introduction to cosmology.

Cosmological Principle:

The Universe is *Homogeneous* and *Isotropic* on *Large Scales*: No special places or directions.

The Dynamics of the Universe

- Expansion and the cosmological constant.
- Hubble's Law: Essentially all galaxies are apparently receding from us.
- Because of expanding universe.
- Hubble constant: current rate of expansion.

Cosmology

Cosmology is the study of the Universe

- Physics of the Universe
- Distribution of objects on all scales
- Motions of objects in the Universe
- Evolution of the Universe
- Age, Origin, and Fate of the Universe

The Universe in 1917

Einstein explored the cosmological implications of General Relativity.

Observational State in 1917:

- Kapteyn model of the Milky Way was favored by some (but not all) astronomers.
- No agreement on the spiral nebulae.
- There were no maps of the universe on large scales.
- First good calibrations of the P-L relations for Cepheids and RR Lyrae variables (distances).

Einstein’s Cosmological Principle

“ *Homogeneous and Isotropic on the Largest Scales.*”

Critical assumption underlying Cosmology.

Homogeneous:

- No special places in the Universe. (A “generalized” Copernican principle.)

Isotropic:

- No special directions. (A “generalized” Copernican principle.)

Largest Scales:

- Average out small-scale details

Homogeneity

When viewed on the largest scales:

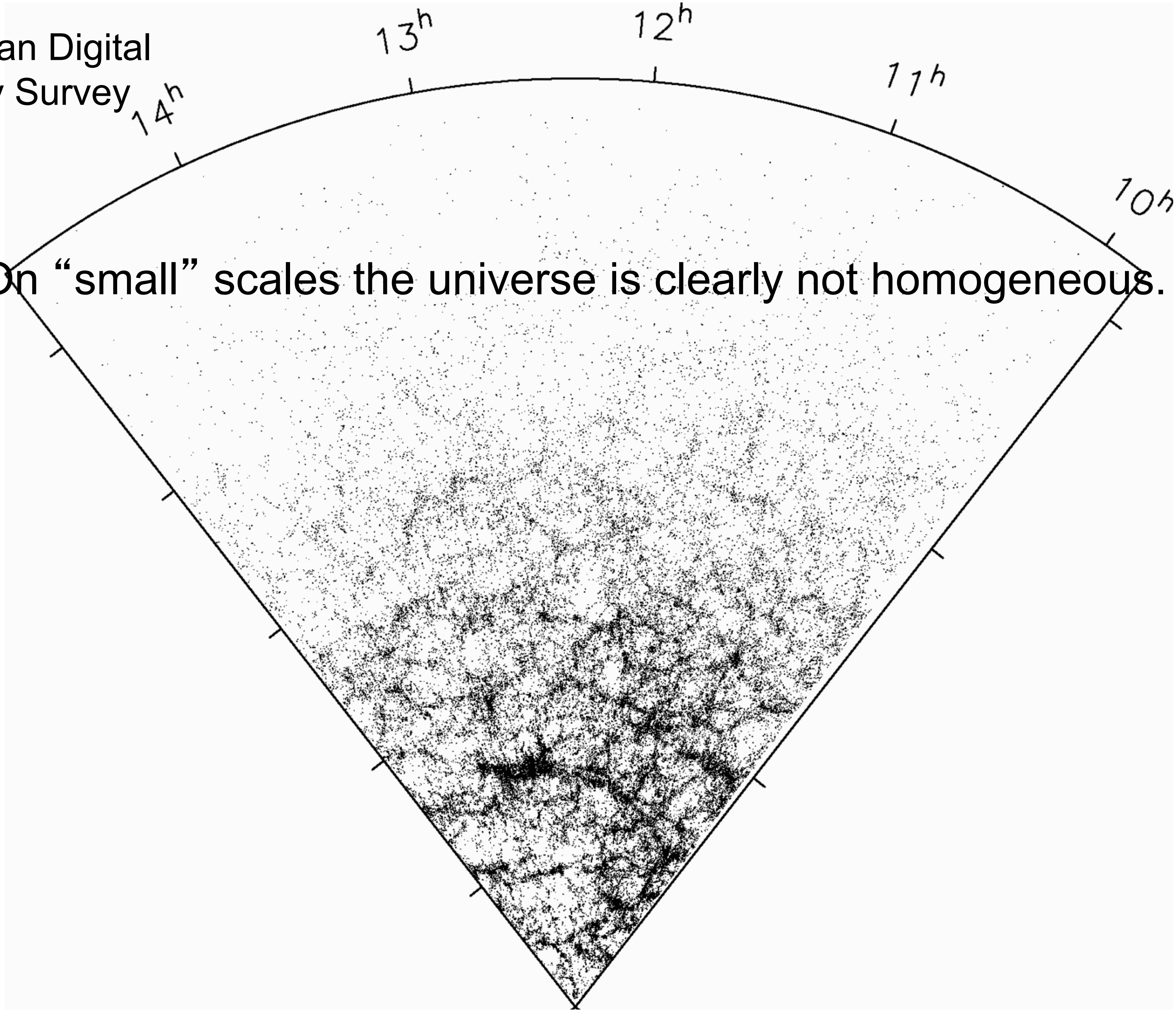
- The average density of matter is about the same in all places in the Universe.
- The Universe is fairly smooth on large scales.

Does not apply *locally*:

- We see planets, stars, galaxies, clusters, in regions nearby in space.
- The Universe is locally rather lumpy .

Is it really homogeneous? One what scale?

Sloan Digital
Sky Survey



On “small” scales the universe is clearly not homogeneous.

Sloan Digital Sky Survey

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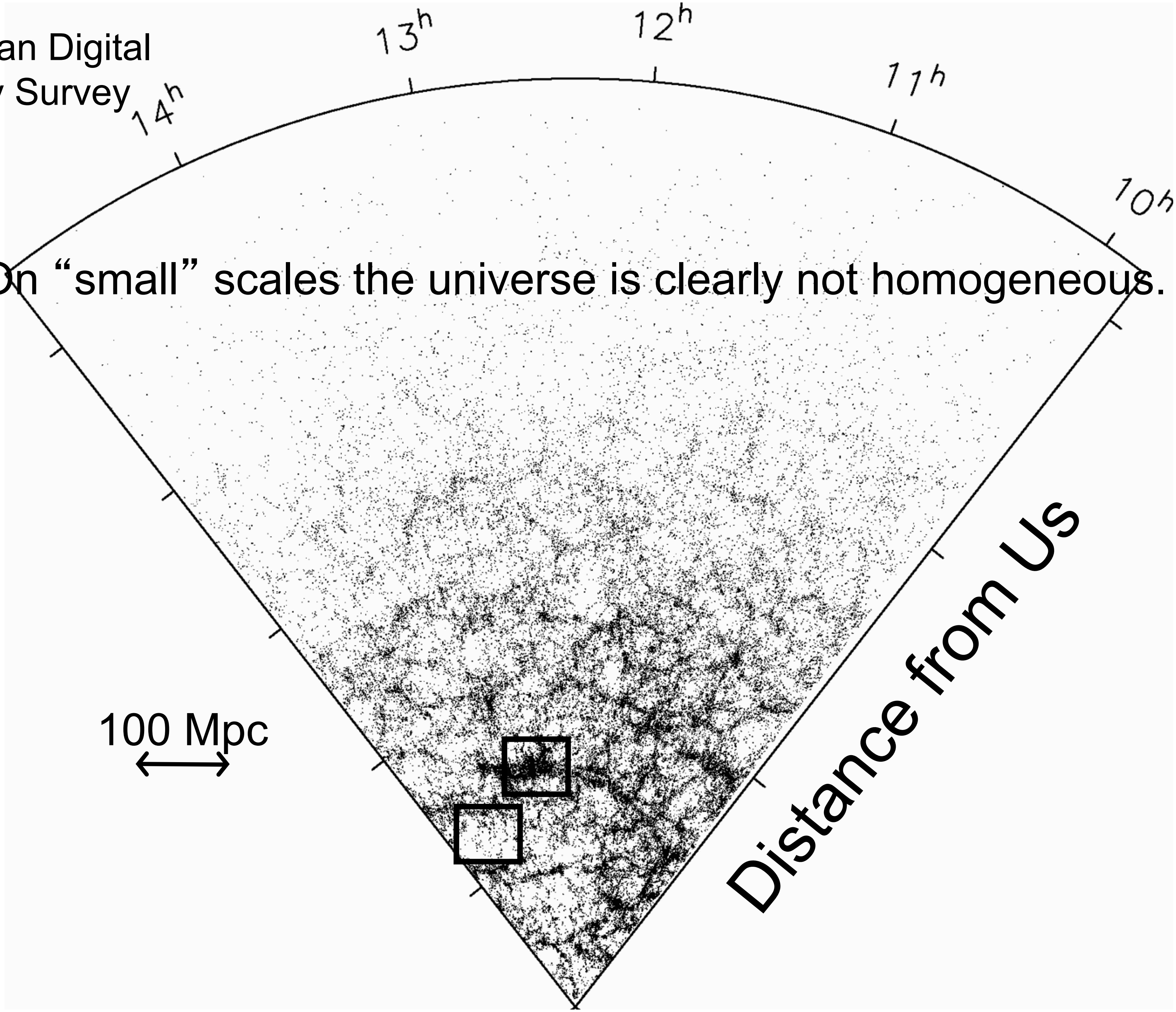
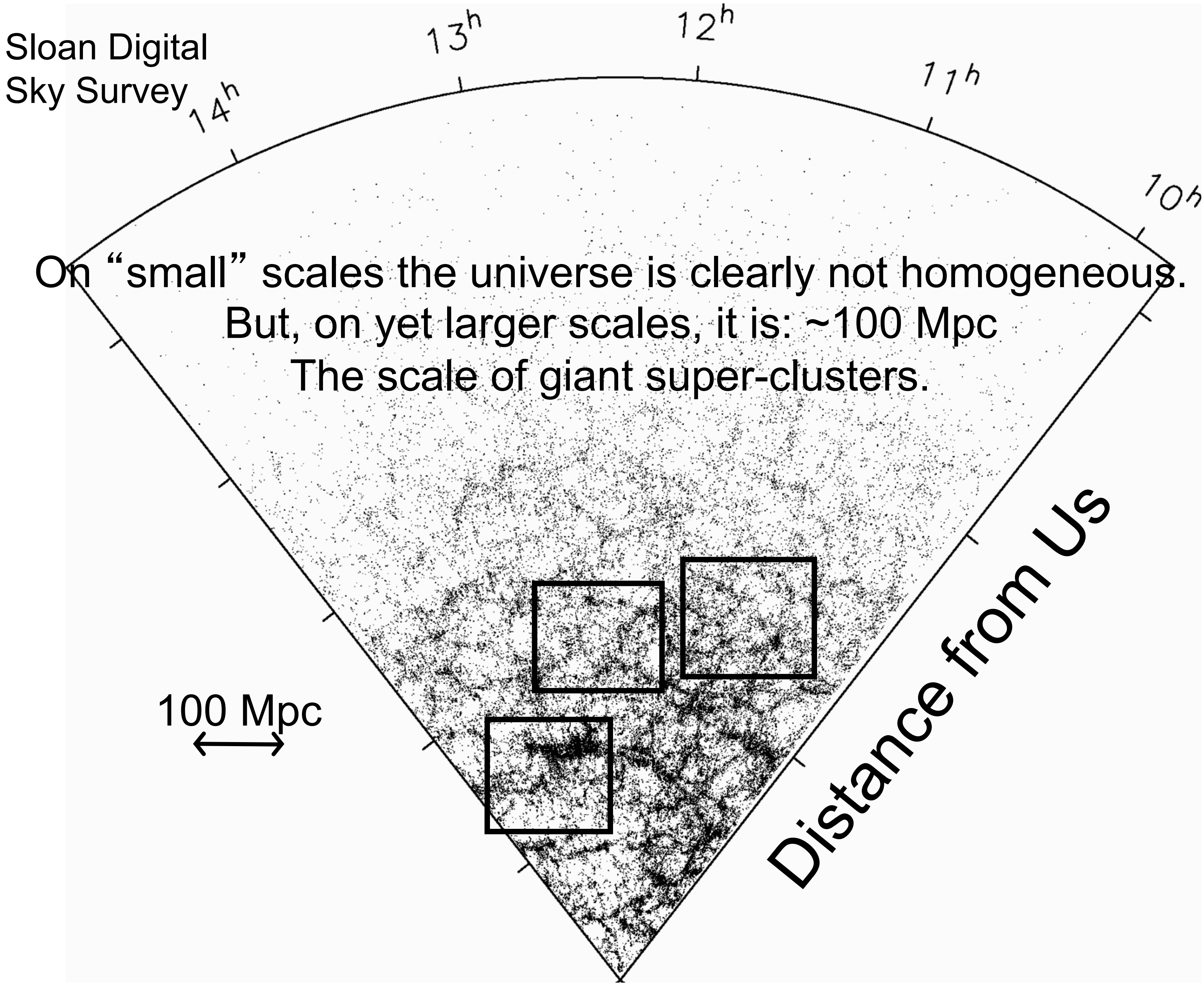



Sloan Digital
Sky Survey
13h
12h
14h
11h
10h
On “small” scales the universe is clearly not homogeneous.
But, on yet larger scales, it is: ~100 Mpc
The scale of giant super-clusters.
100 Mpc
Distance from Us

Isotropy

When viewed on the largest scales:

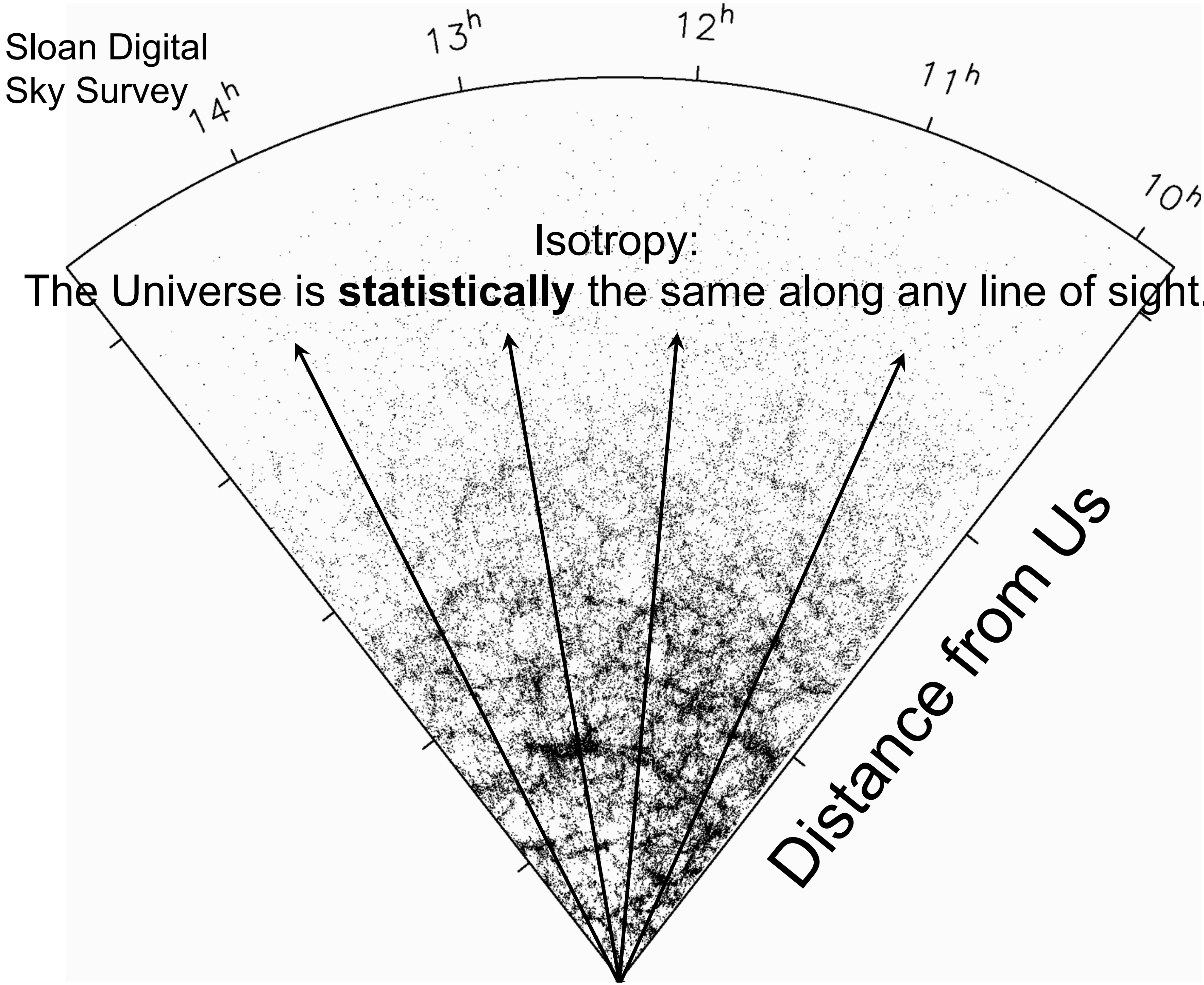
- The Universe looks the same to all observers.
- The Universe looks **statistically** the same in all directions as viewed by any particular observer.

Does not apply *locally*:

- We see different numbers of local objects in different directions.

Isotropy:

The Universe is **statistically** the same along any line of sight.



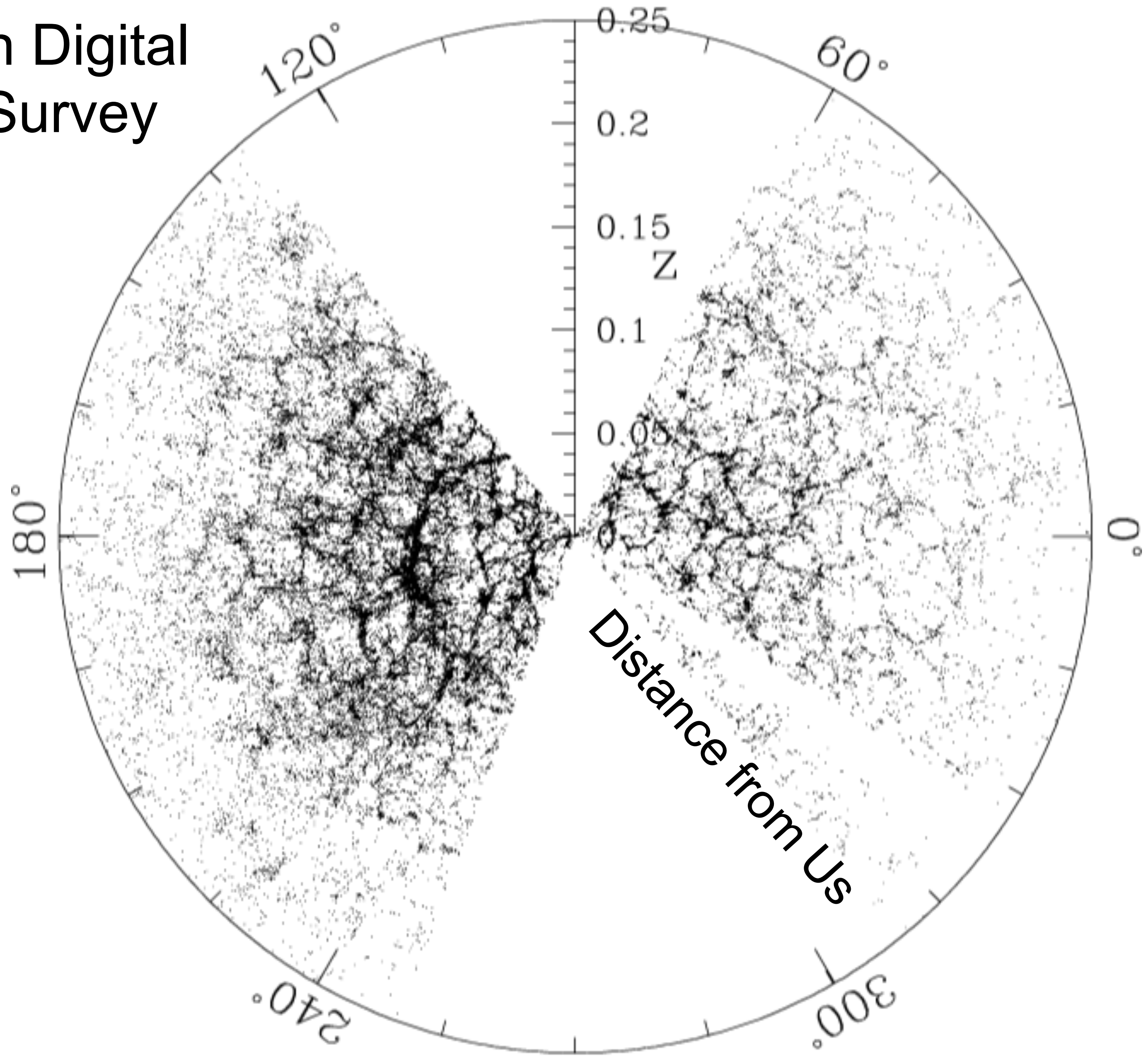
State of the Art

Einstein’s guess about the homogeneity and isotropy of the Universe was brilliant and far ahead of the scanty empirical data of his time.

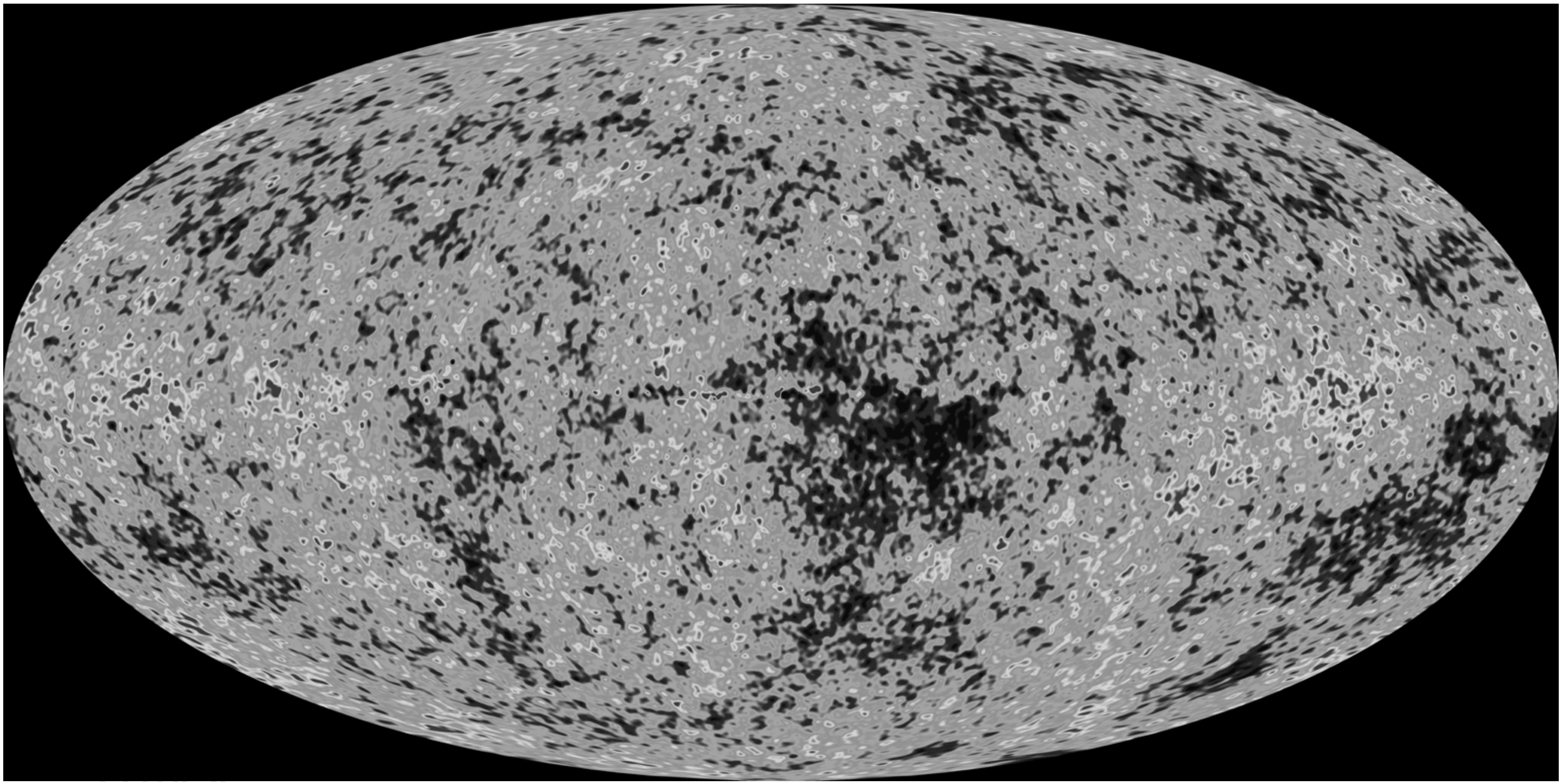
Modern observations bear out large-scale homogeneity & isotropy on average:

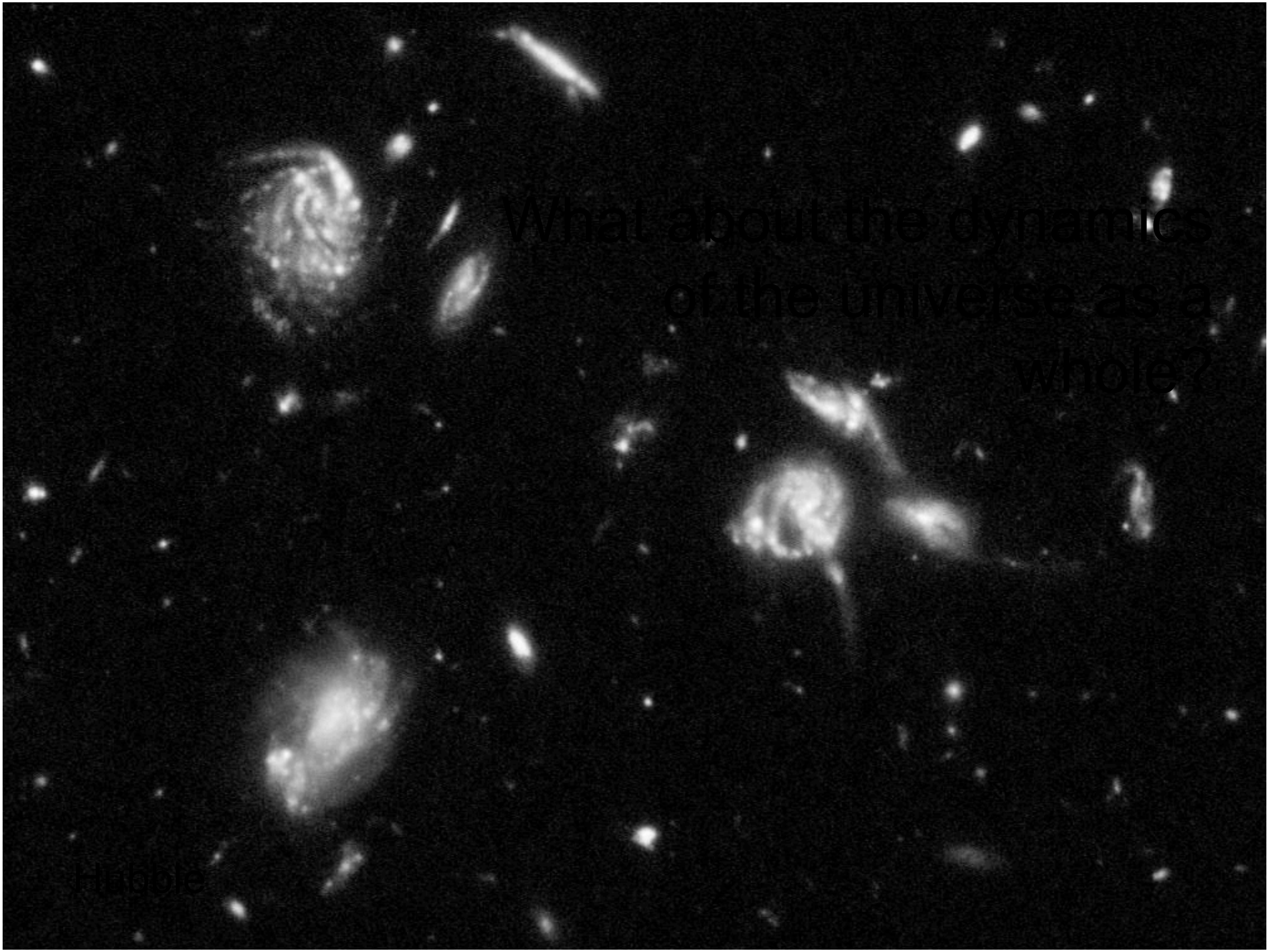
- Large-scale galaxy surveys
- Cosmic Microwave Background isotropic to about 1 part in 10^5 everywhere you look on the sky. It is **nearly** perfectly smooth.

Sloan Digital
Sky Survey



Cosmic Microwave Background: Remarkably smooth, but with some very important "lumps"!




What about the dynamics of the universe as a whole?
Hubble

The Dynamic Universe

Einstein applied the Cosmological Principle to General Relativity and got a surprise:

- The spacetime of the Universe could not be static and unchanging.
- The Universe *must* either expand or contract! Because of the gravity of the universe itself.

In 1917, astronomers assured him that no such general motion was observed: the universe was known to be static.

The Cosmological Constant

To make the Universe static, Einstein added a new term to his equations:

The Cosmological Constant, Λ:

- Repulsive gravitation-like force term
- Arises from empty space.
- Balances the effects of gravity.

At this time, there was no physical reason to introduce a Cosmological Constant.

Discovery of Expansion

1914-22: Vesto Slipher, working at Lowell Observatory

Measured radial velocities from spectra of 25 galaxies.

Found:

- 21 of the 25 galaxies show a redshift. 4 blueshift or approximately no shift.
- speeds of some redshifts were >2000 km/sec

Most galaxies appear to be rapidly *receding* away from us.

Hubble ends Great Debate, discovers expansion

1923: Hubble discovers Cepheid in Andromeda

1929: Hubble measures distances to 25 galaxies:

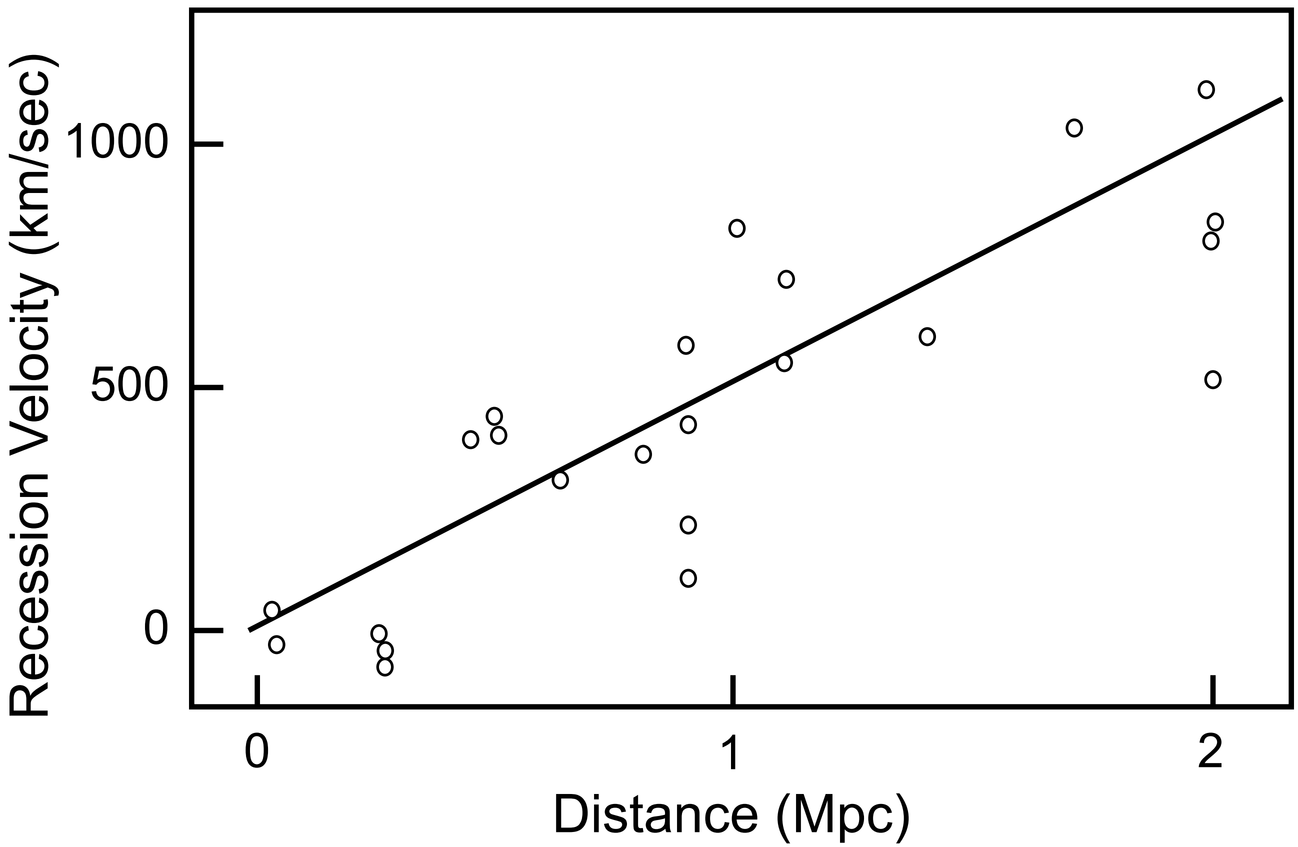
- Compared distances calculated & recession velocities from redshift of spectral lines.

Discovered:

- Recession velocity gets *larger* with distance.

Implies: Systematic expansion of the Universe.

Hubble's Data (1929)



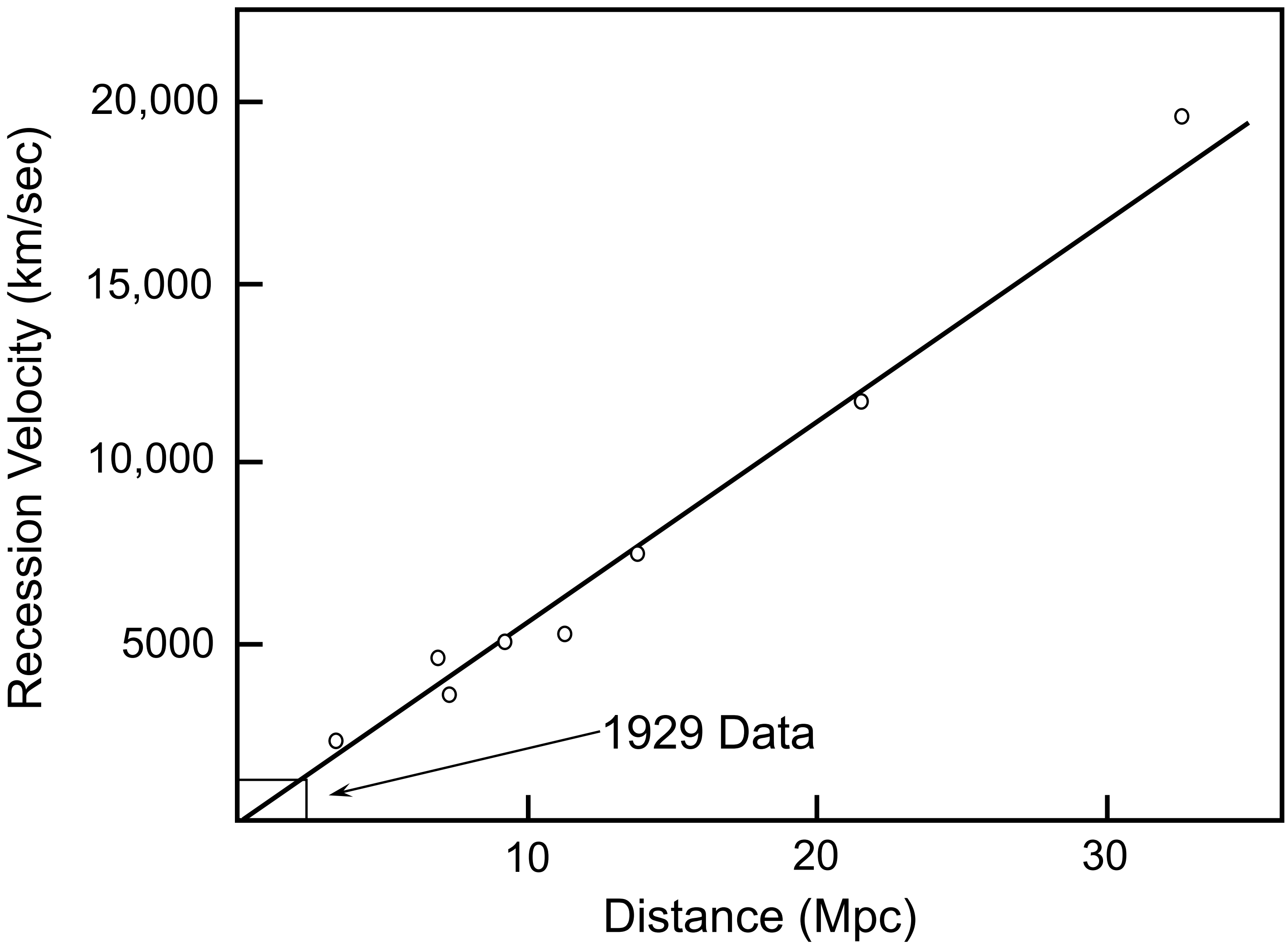
Hubble & Humason did better.

The 1929 work was suggestive, but the uncertainties were large.

By 1931:

- Added 8 more galaxies with good distances
- The most distant galaxy had a recession velocity of nearly 20,000 km/sec!
- Showed a stronger, tighter trend with distance

Hubble & Humason (1931)



Hubble's Law: An Empirical Statement

$$V = H_0 \times d$$

V = recession velocity in km/sec

d = distance in Mpc

H_0 = expansion rate today (*Hubble Constant*)

"The more *distant* a galaxy is, the *faster* its observed recession velocity."

Comments:

- *Empirical* result - based only on data
- Some very nearby galaxies (e.g., Andromeda, LMC) have peculiar velocities (some negative!) because they are bound to us.

Why is almost every galaxy apparently flying away from us?

Systematic 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.

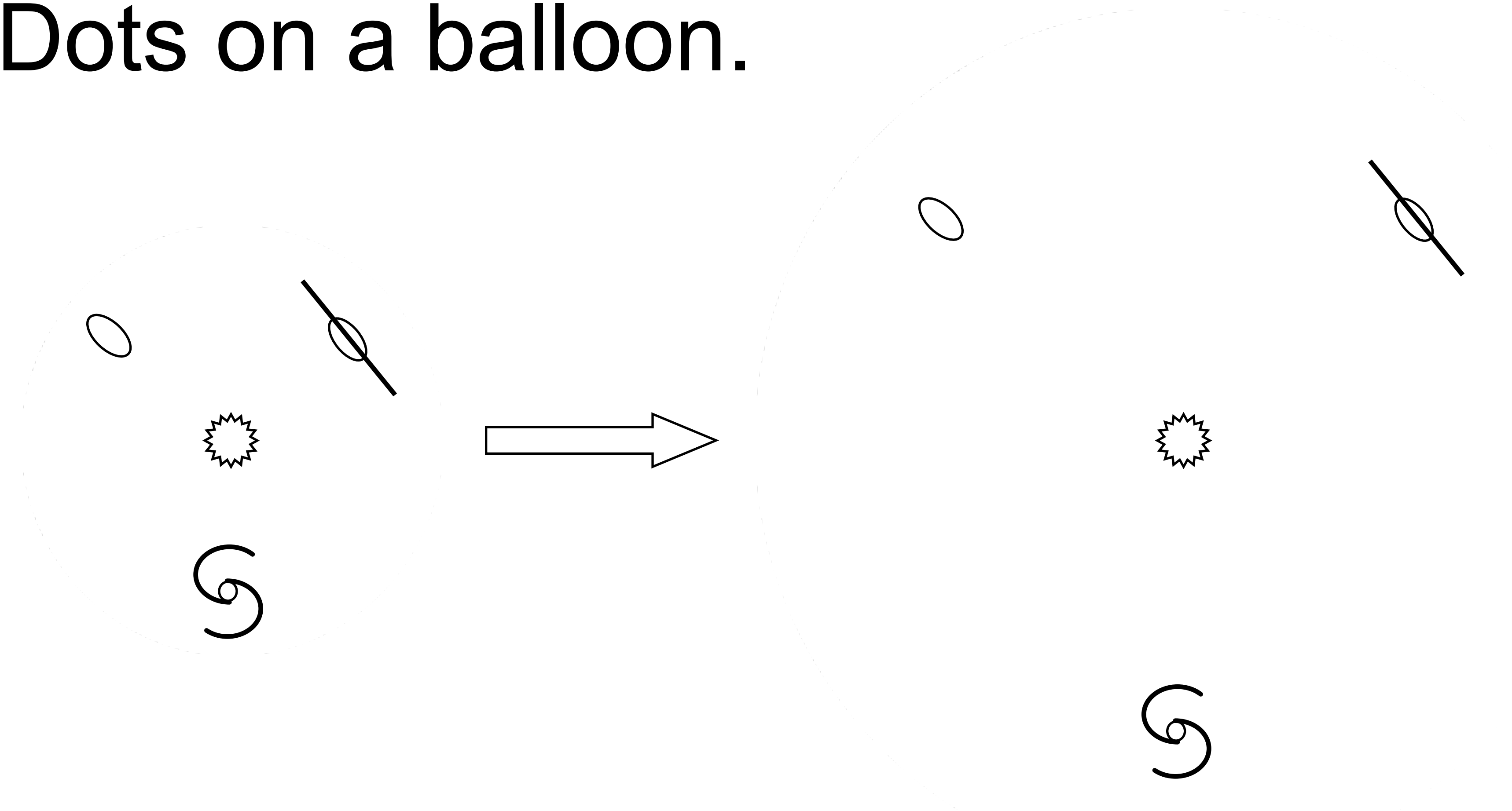
  Like raisins embedded in an infinite expanding cake.

  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

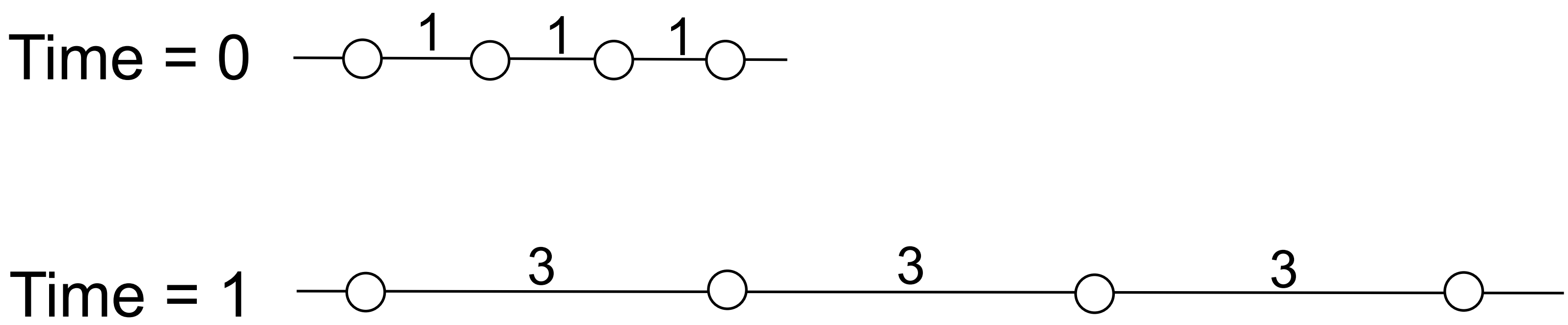
Systematic Expansion:
Paperclips = Galaxies; Ants = you

Ants on paperclips on rubber band.

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)

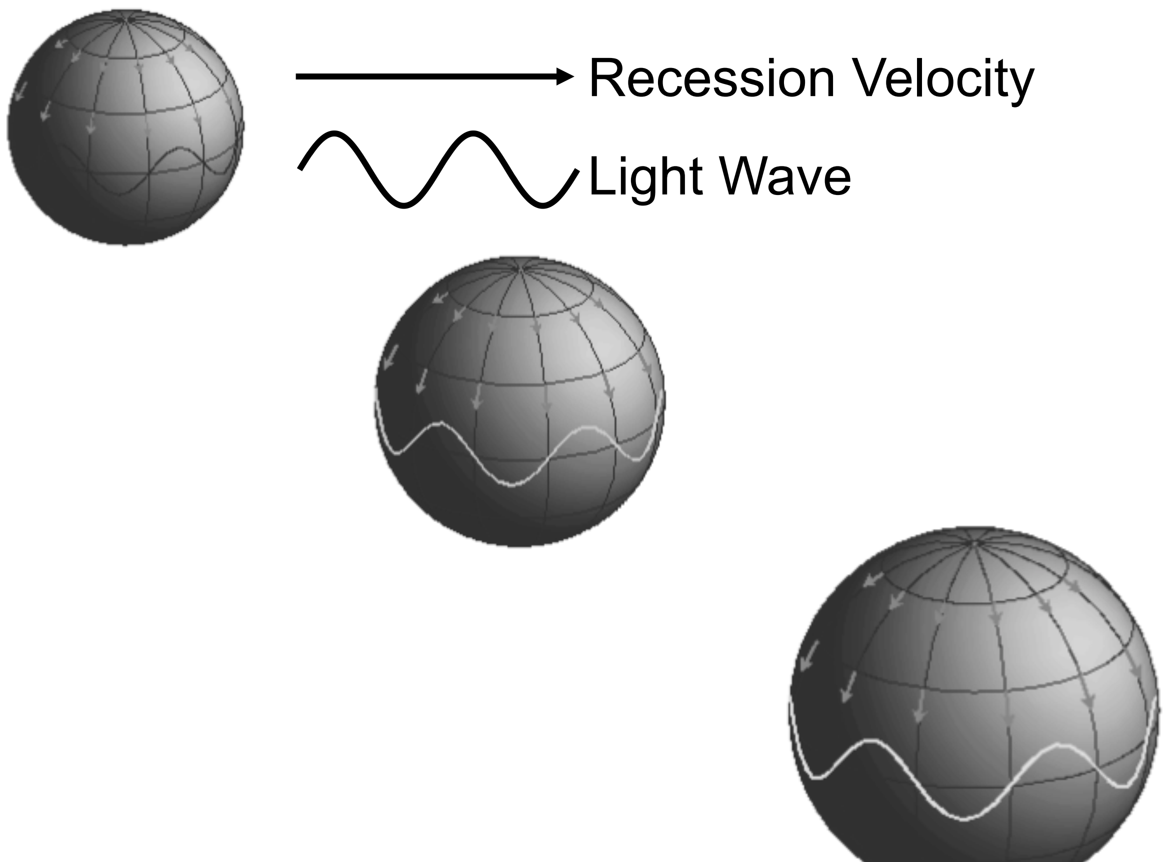
Systematic
Expansion:

Boxes
= Galaxies

Rods =
Spacetime

Escher box lattice

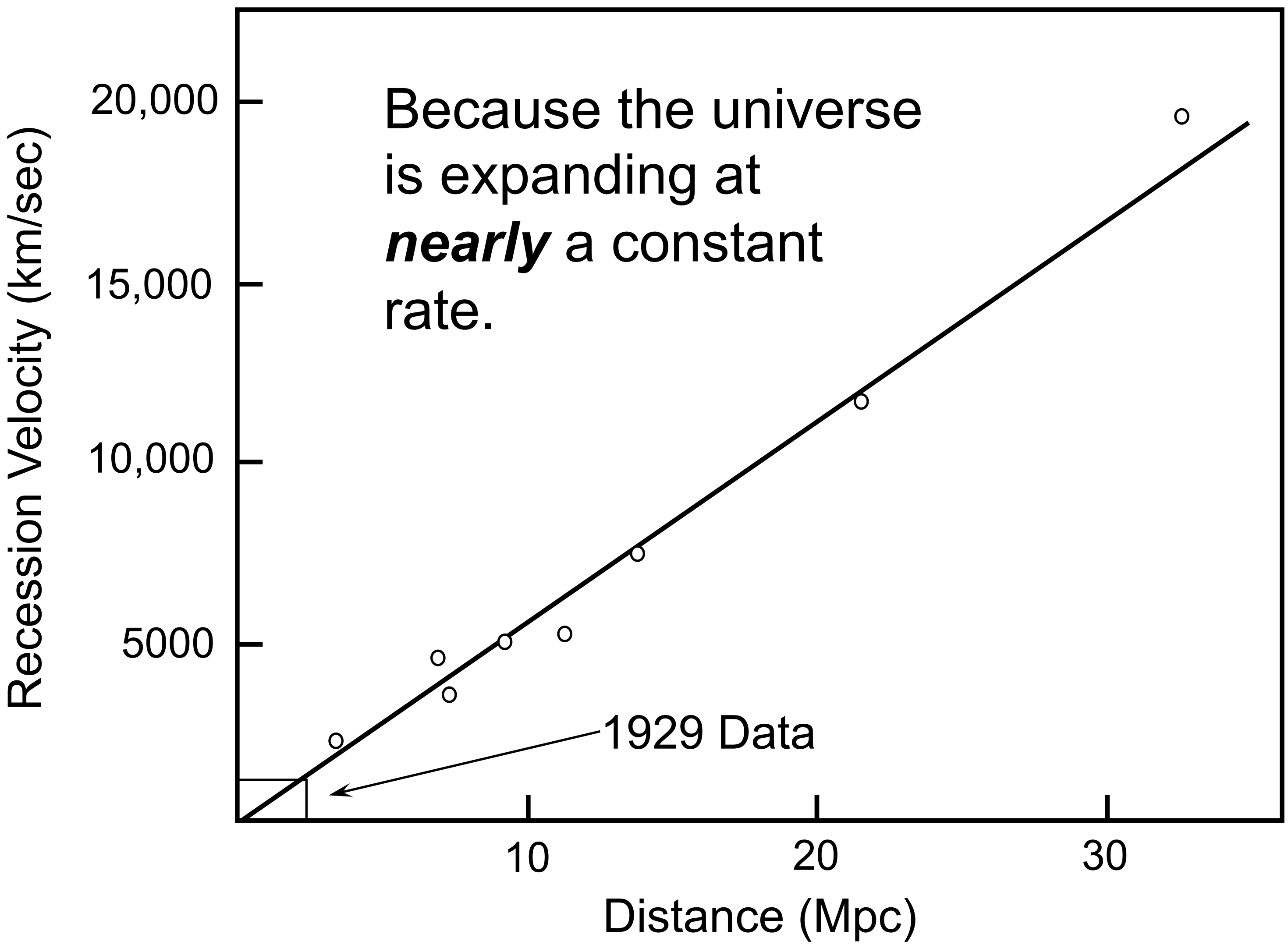
Escher



As Universe Expands:

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

Hubble & Humason (1931)



Hubble Parameter: H_0

Measures the *rate* of expansion today:

- $H_0 = 70 \pm 7$ km/sec/Mpc
- Based on *Hubble Space Telescope* 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

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

Not (just) a Doppler shift: measures expansion of spacetime. It is **not** motion **through** 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!

$$d = \frac{v}{H_0} \approx \frac{cz}{H_0}$$

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 z 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%

Sloan Digital Sky Survey

Dedicated 2.5-m telescope in New Mexico

Making images of 1/4 of the sky in 5 colors:

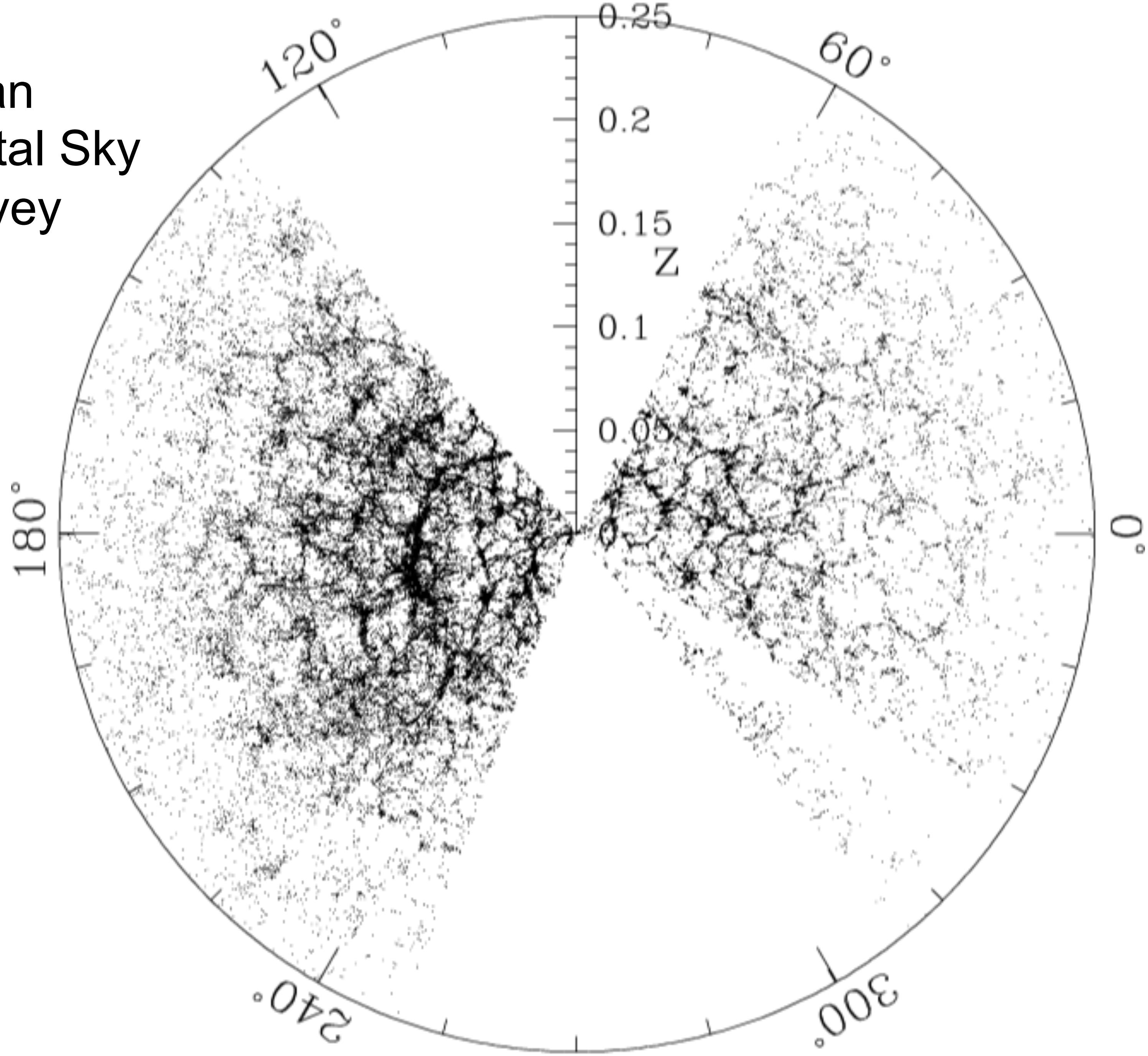
- Accurate positions and photometry for a few 100 Million stars, galaxies, and quasars.

Redshift Survey:

- 1 Million galaxy redshifts
- 100,000 quasar redshifts

Made a deep 3D map of a large part of the local Universe

Sloan
Digital Sky
Survey



Modern Cosmological Constant

In modern cosmology, Λ reappears in modified form as the "*vacuum energy*" of space:

- Quantum ground-state of empty space.
- Acts as an extra pressure on the Universe.

Distinction:

- Actually *accelerates* the expansion!
- Increasing observational evidence that Λ, or something very like it, may be real.