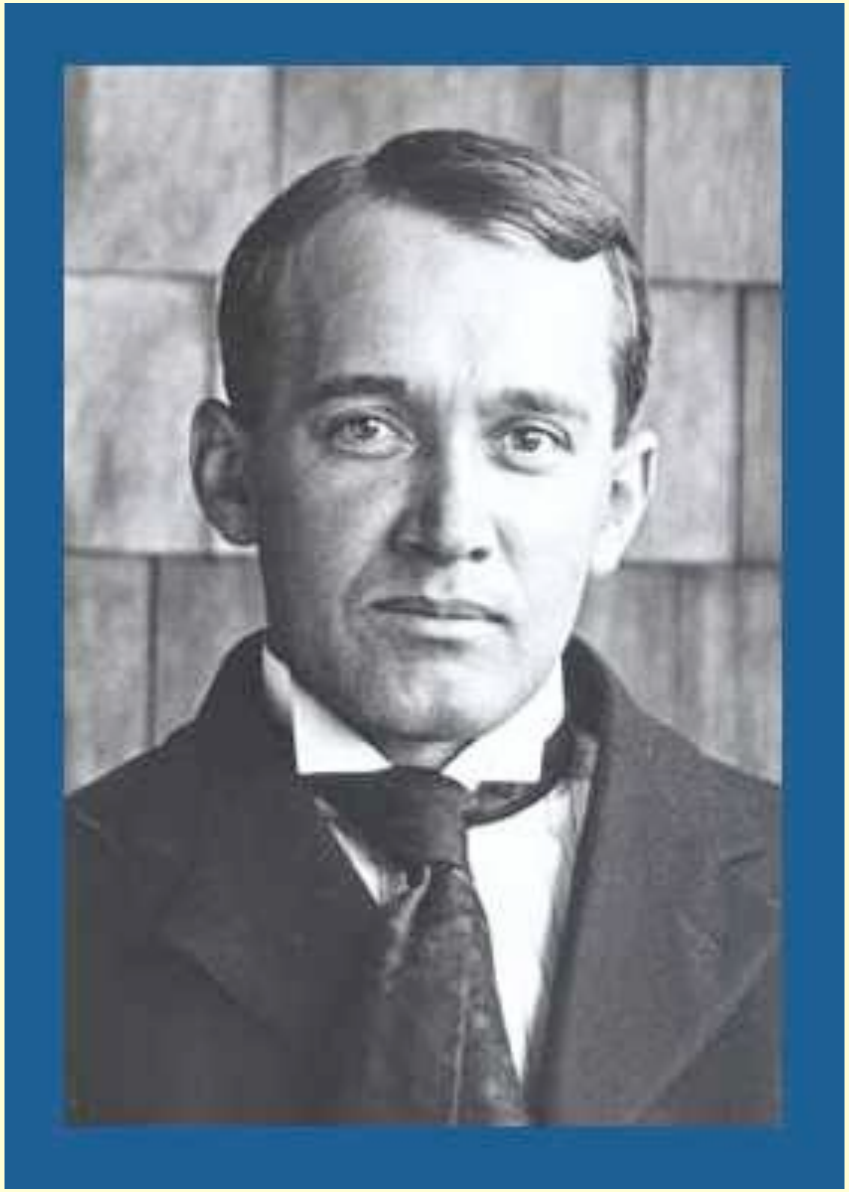


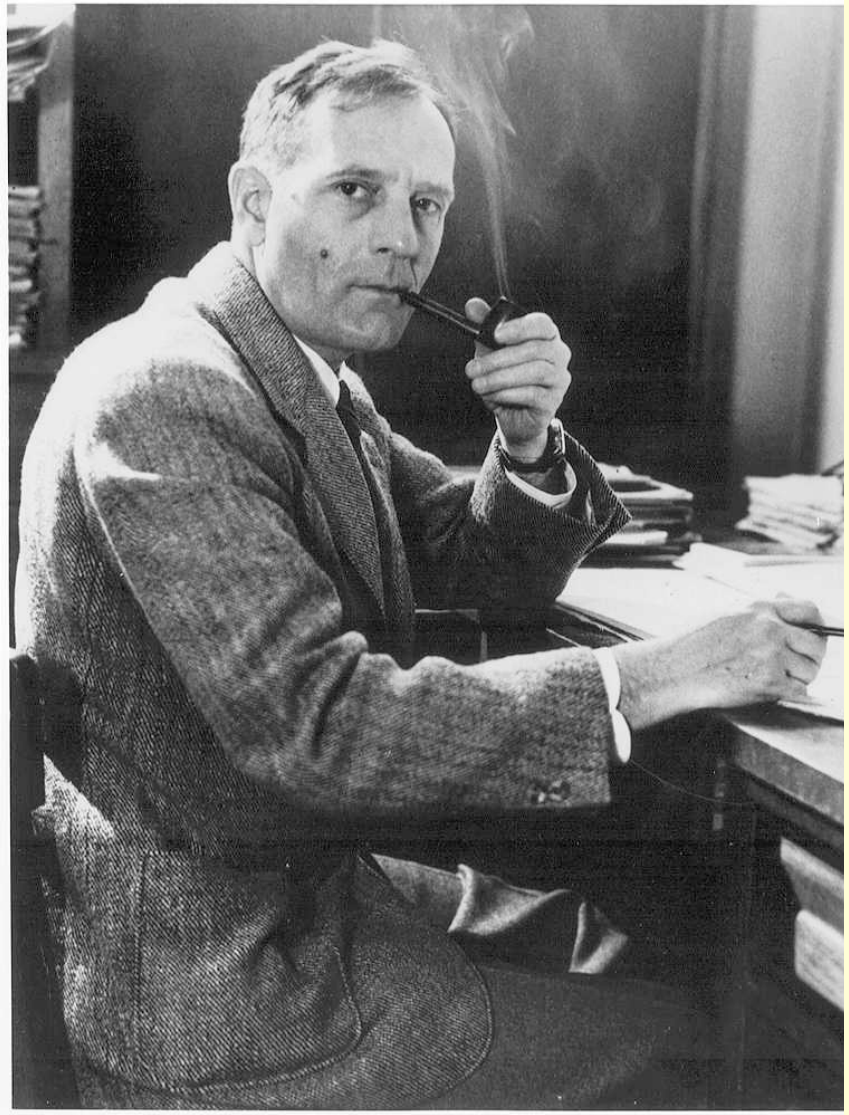
Slipher, galaxies, and cosmic velocity fields

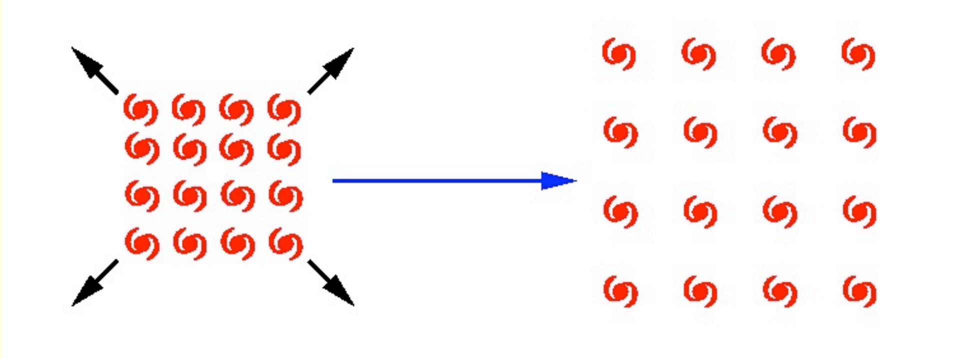
John Peacock
University of Edinburgh

Origins of the expanding universe

Flagstaff, 15 Sept 2012

The Hubble expansion





$\boxed{V = H\ D}$

"in 1929, Hubble discovered the expansion of the universe....."

Why did Slipher 'miss' this discovery?

By 1914 11/15 'nebulae' redshifted

By 1917 21/25 redshifted – and all large v's positive

– obvious conclusion of expansion?

But Slipher's 1917 paper tells a much more interesting story

– as does subsequent work prior to 1929

1917 – Slipher's masterpiece

NEBULÆ.

BY V. M. SLIPHER, PH.D.

(Read April 13, 1917.)

In addition to the planets and comets of our solar system and the countless stars of our stellar system there appear on the sky many cloud-like masses—the nebulæ. These for a long time have been generally regarded as presenting an early stage in the evolution of the stars and of our solar system, and they have been carefully studied and something like 10,000 of them catalogued.

Proc. Amer. Phil. Soc., 56, 403 (1917)

21/25 redshifted

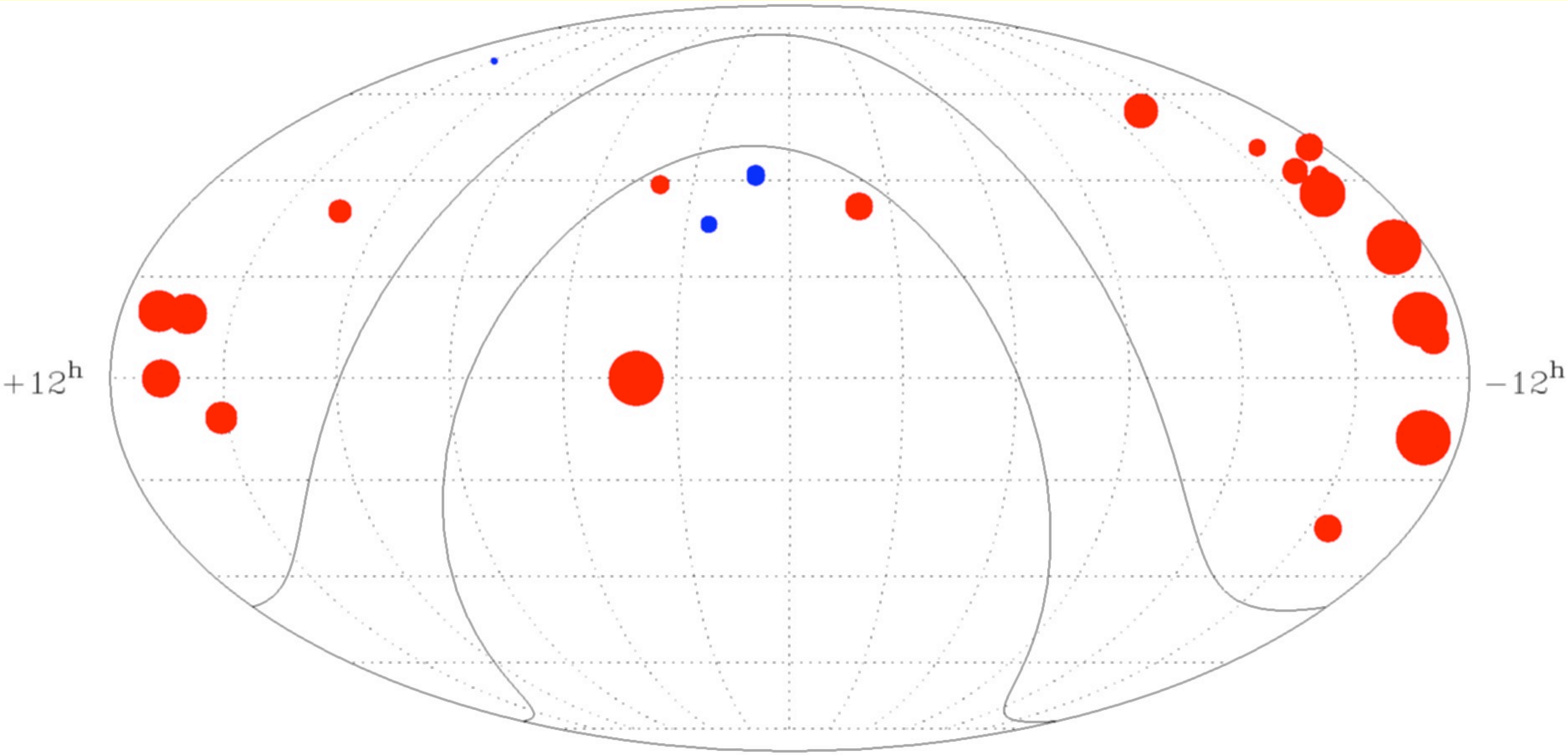
TABLE I.

RADIAL VELOCITIES OF TWENTY-FIVE SPIRAL NEBULÆ.

Nebula.	Vel.	Nebula.	Vel.
N.G.C. 221	− 300 km.	N.G.C. 4526	+ 580 km.
224	− 300	4565	+1100
598	− 260	4594	+1100
1023	+ 300	4649	+1090
1068	+1100	4736	+ 290
2683	+ 400	4826	+ 150
3031	− 30	5005	+ 900
3115	+ 600	5055	+ 450
3379	+ 780	5194	+ 270
3521	+ 730	5236	+ 500
3623	+ 800	5866	+ 650
3627	+ 650	7331	+ 500
4258	+ 500		

– this outstanding paper was unknown to ADS as late as 2004, and ADS now supplies a scan from the Royal Observatory Edinburgh

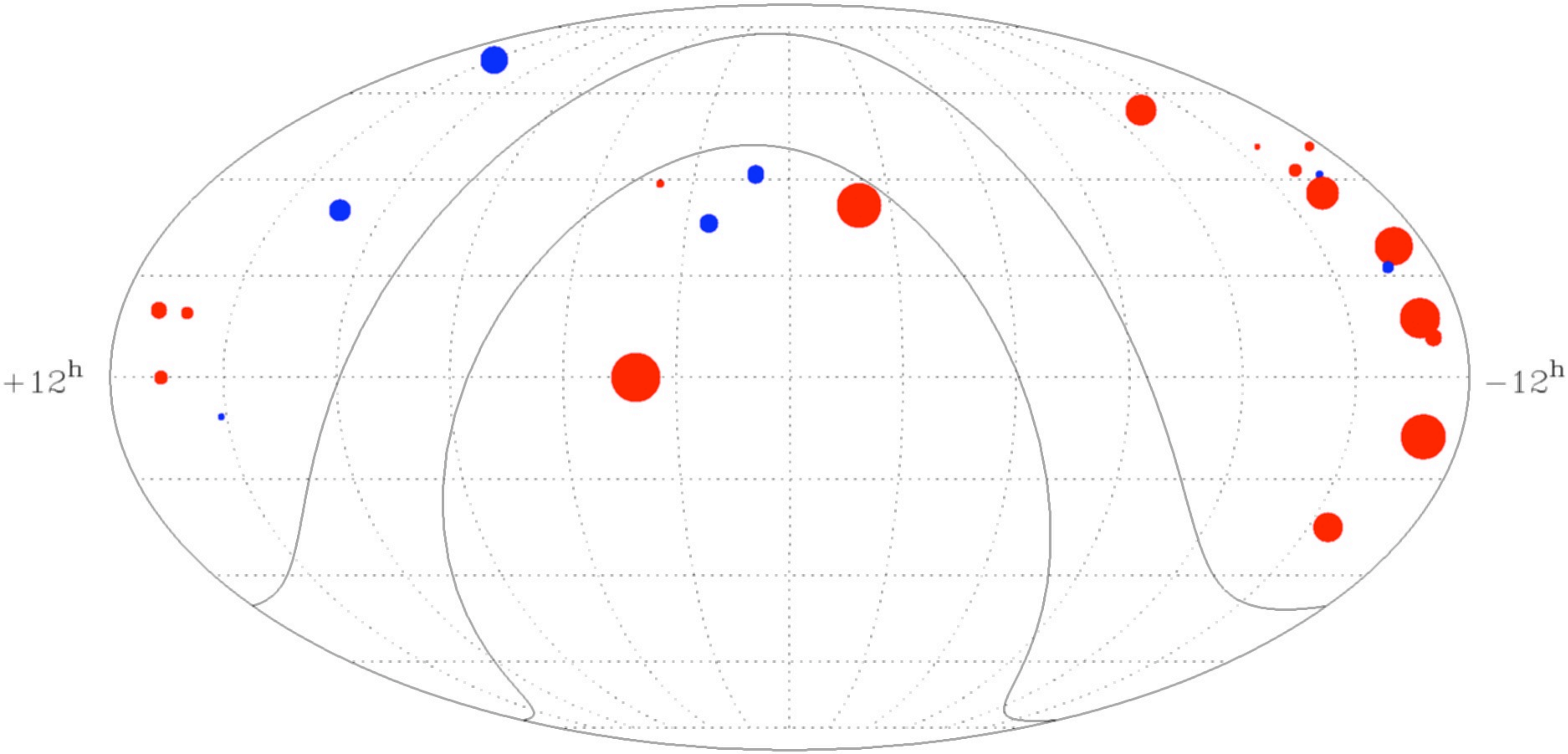
Slipher's 1917 data



-300 to +1100 km s^{-1}

The mean of the velocities with regard to sign is positive, implying the nebulæ are receding with a velocity of nearly 500 km. This might suggest that the spiral nebulæ are scattering but their distribution on the sky is not in accord with this since they are inclined to cluster.

Slipher's 1917 data: dipole corrected

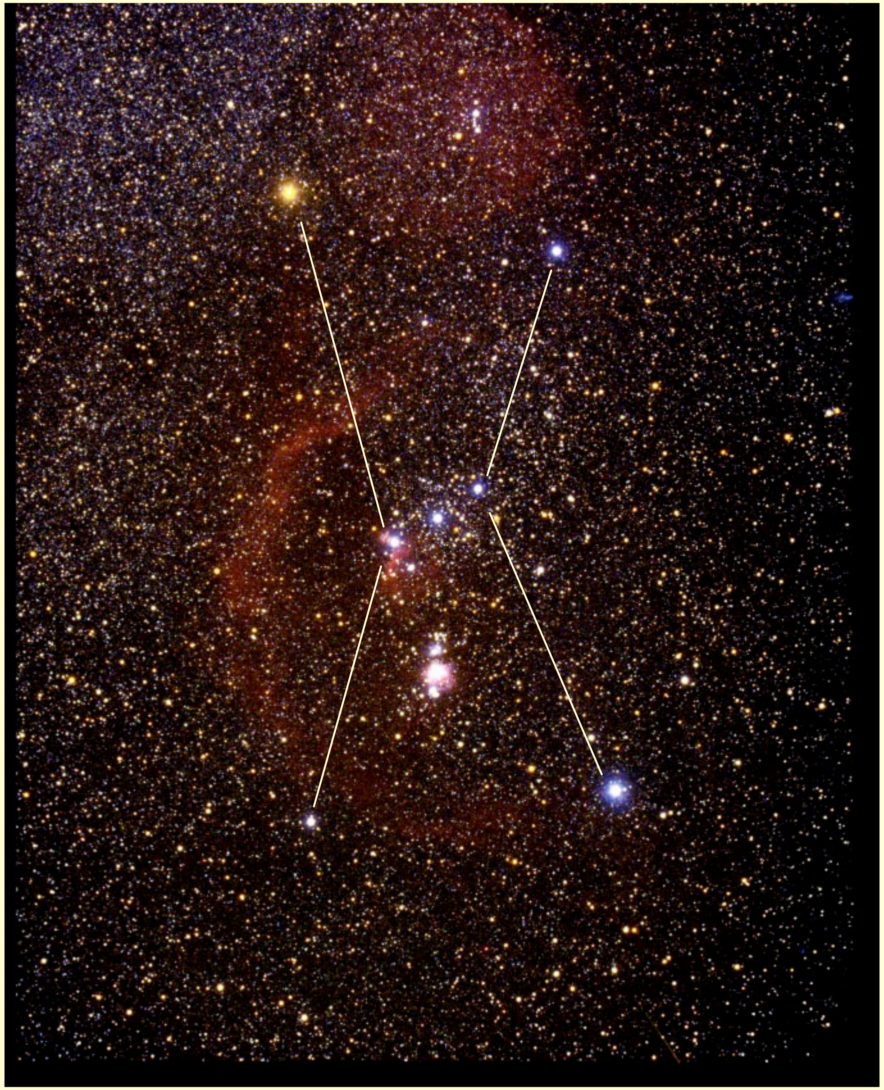


V_{sun} = 700 km s^{-1} towards 22^h -22^o

Reduces <V> from 502 to 143 with rms 400

Nebulae

Orion



Andromeda

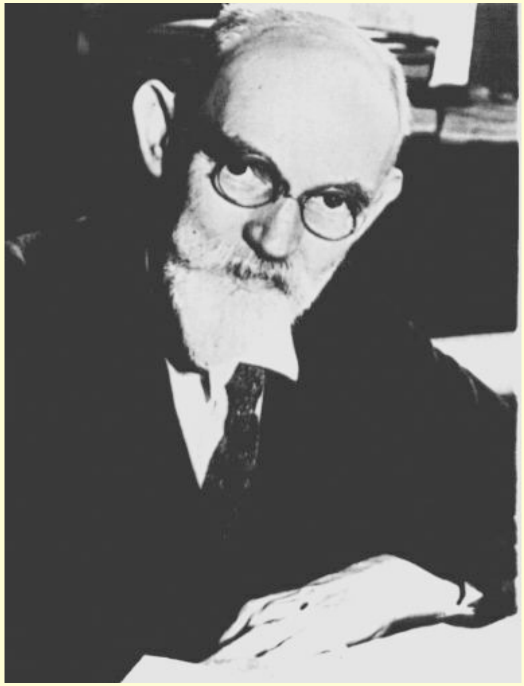
An imaginative leap

We may in like manner determine our motion relative to the spiral nebulæ, when sufficient material becomes available. A preliminary solution of the material at present available indicates that we are moving in the direction of right-ascension 22 hours and declination —22° with a velocity of about 700 km. While the number of nebulæ is small and their distribution poor this result may still be considered as indicating that we have some such drift through space. For us to have such motion and the stars not show it means that our whole stellar system moves and carries us with it. It has for a long time been suggested that the spiral nebulæ are stellar systems seen at great distances. This is the so-called "island universe" theory, which regards our stellar system and the Milky Way as a great spiral nebula which we see from within. This theory, it seems to me, gains favor in the present observations.

(1) They move; (2) So do we; (3) We are a set of stars

$\Rightarrow$ nebulae are galaxies (7 years before Hubble)

Theorists on the march



Willem de Sitter
(1872-1934)

1917: vacuum dominated relativistic cosmology

Arthur Stanley Eddington
(1882-1944)

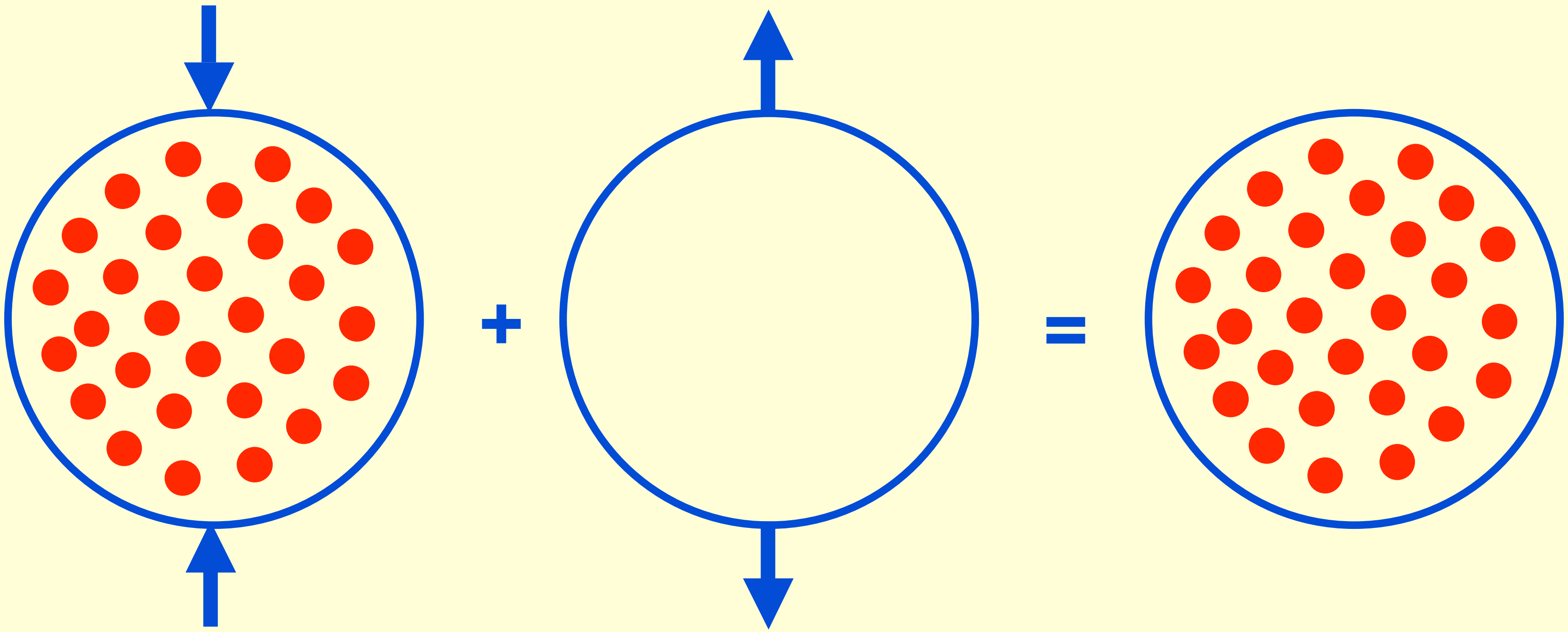
Hermann Weyl
(1885-1955)

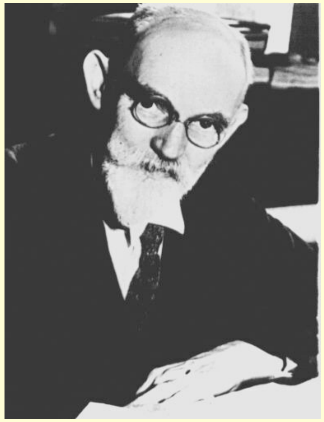
1923: expect linear D-z relation

Einstein’s missed chance (1917)

According to Einstein’s new theory of relativity, the stars couldn’t stay in place without help

Introduce the “cosmological constant”, a repulsion that arises in the vacuum itself: it means empty space would have weight





de Sitter space (1917)
a universe of only vacuum energy

$$d\tau^2 = -dr^2 - R^2 \sin^2(r/R) d\psi^2 + dt^2$$
$$d\tau^2 = -dr^2 - R^2 \sin^2(r/R) d\psi^2 + \cos^2(r/R) dt^2$$

Einstein static

de Sitter

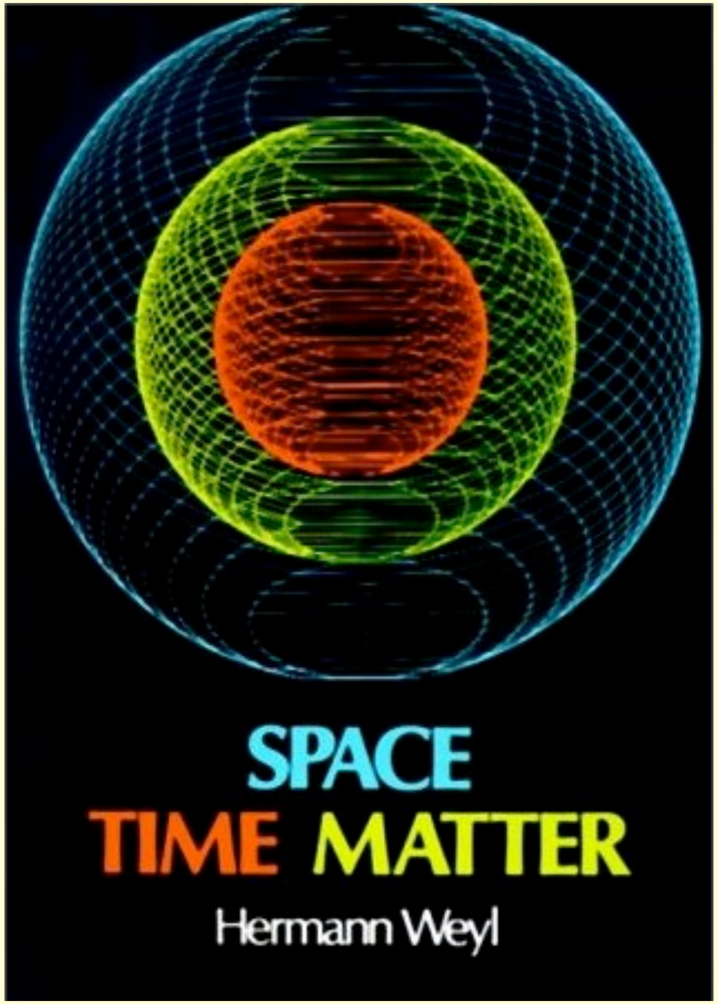
$$d\tau^2 = dt^2 - (dx^2 + dy^2 + dz^2 + du^2)$$
$$x^2 + y^2 + z^2 + u^2 - t^2 = R^2$$

...or spacetime of constant curvature

$\Rightarrow$ clocks slow down as 1/cos(r/R), i.e. $z \propto r^2$?

Note: apparently static. Only written in modern expanding form by Lemaitre (1927); Robertson (1928). Usual relativistic confusion about what coordinates mean

Weyl (1923)



5th edition only

Expect linear $z = r/R$ for small r in de Sitter model

(see also Silberstein Nature 1924 and Lemaitre 1925

Testing the theory

- Many attempts to “measure the curvature of spacetime via the de Sitter effect”. All looking for a linear effect

  – Silberstein 1924
  – Lundmark 1924
  – Wirtz 1924
  – Lemaitre 1927
  – Robertson 1928

Estimates of R

Assuming a linear z=r/R, can estimate R from ratio of typical r and typical z. From Slipher, <z> was about 500 km s^{-1}

Silberstein (1924): no good distances for nebulae to go with Slipher's velocities. Use globulars instead. Get $R \simeq 10^{26}$ cm!

Robertson (1928) – similar to Lemaitre (1927):

"Comparing the data given by Hubble (1926) concerning the value of r for the spiral nebulae with that of Slipher concerning the corresponding radial velocities, we arrive at a rough verification of the linear relation and a value of $R = 2 \times 10^{27}$ cm"

In modern terms, R means c/H_0, so correct figure is

$R = 1.27 \times 10^{28}$ cm

The 1929 distance-redshift relation

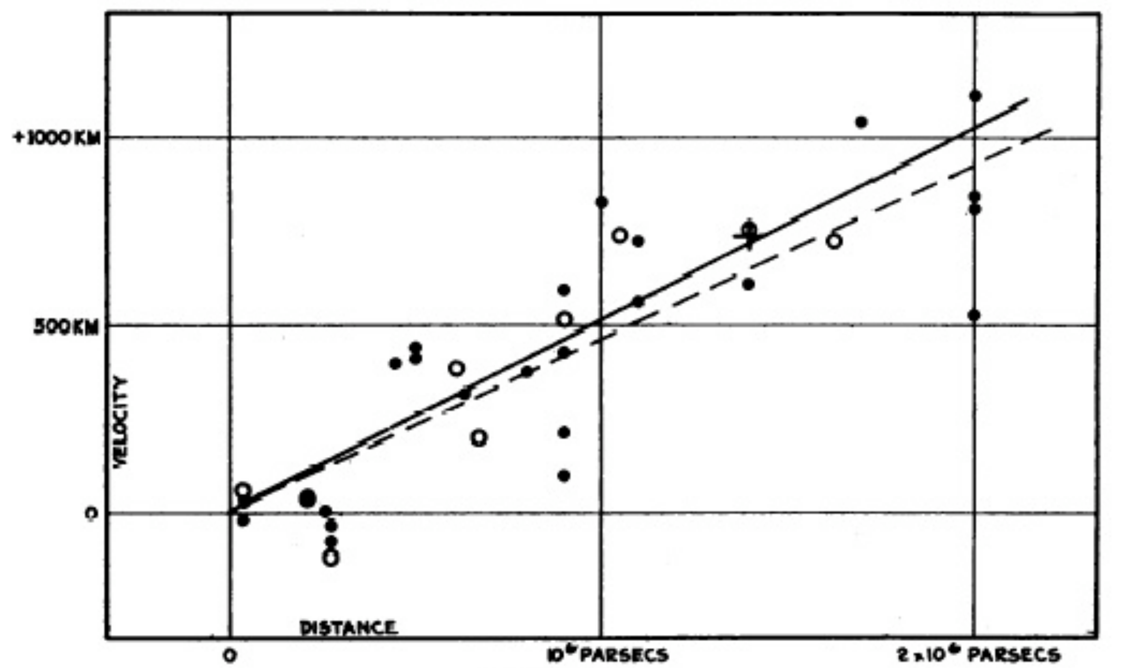
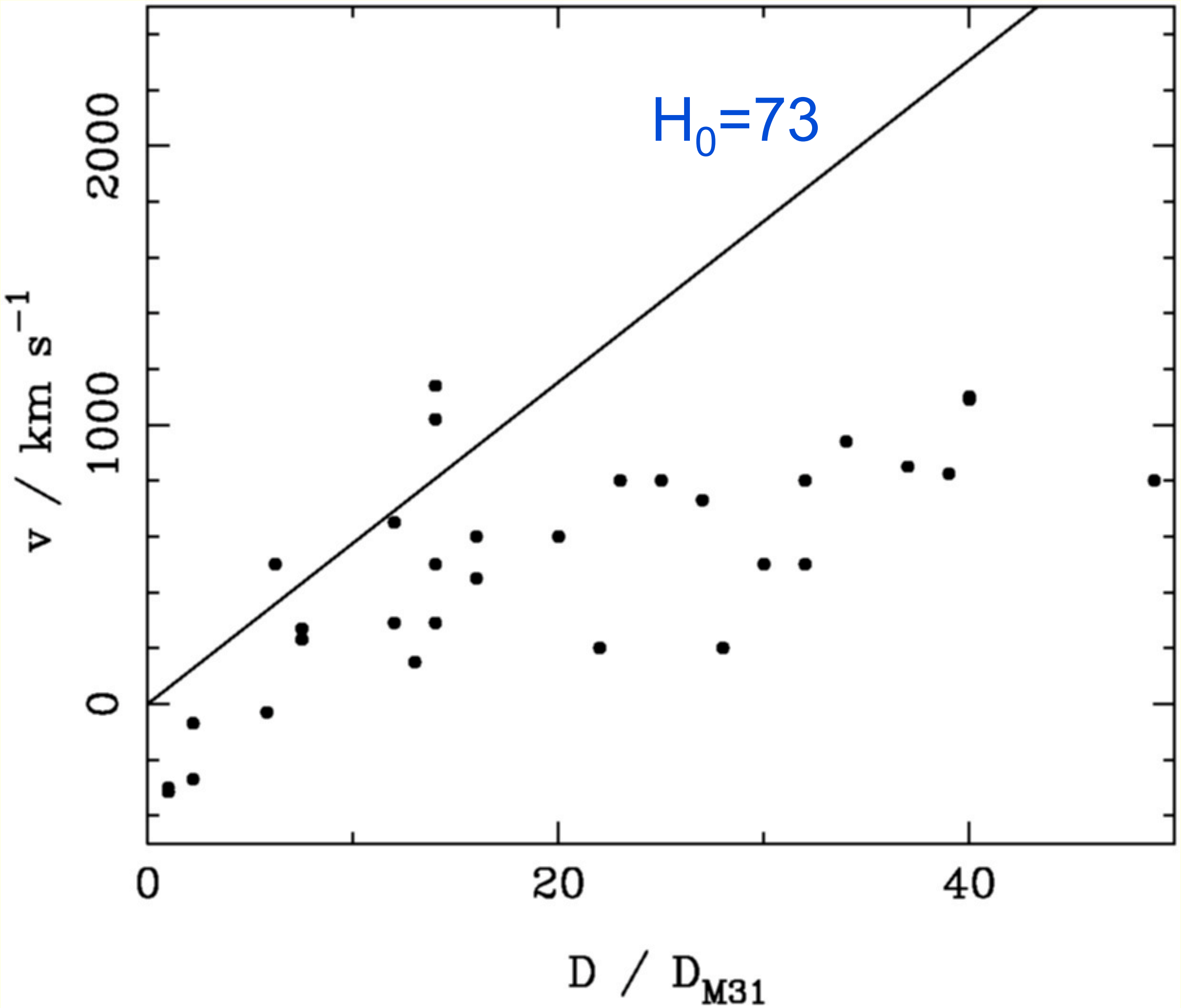


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

Linear relation with V(Slipher) = H D(Hubble)

- H = 513 km s^{-1} Mpc^{-1} (used Shapley calibration that actually applied to pop II W Virginis variables)
- Not the only problem with D…

Lundmark (1924)

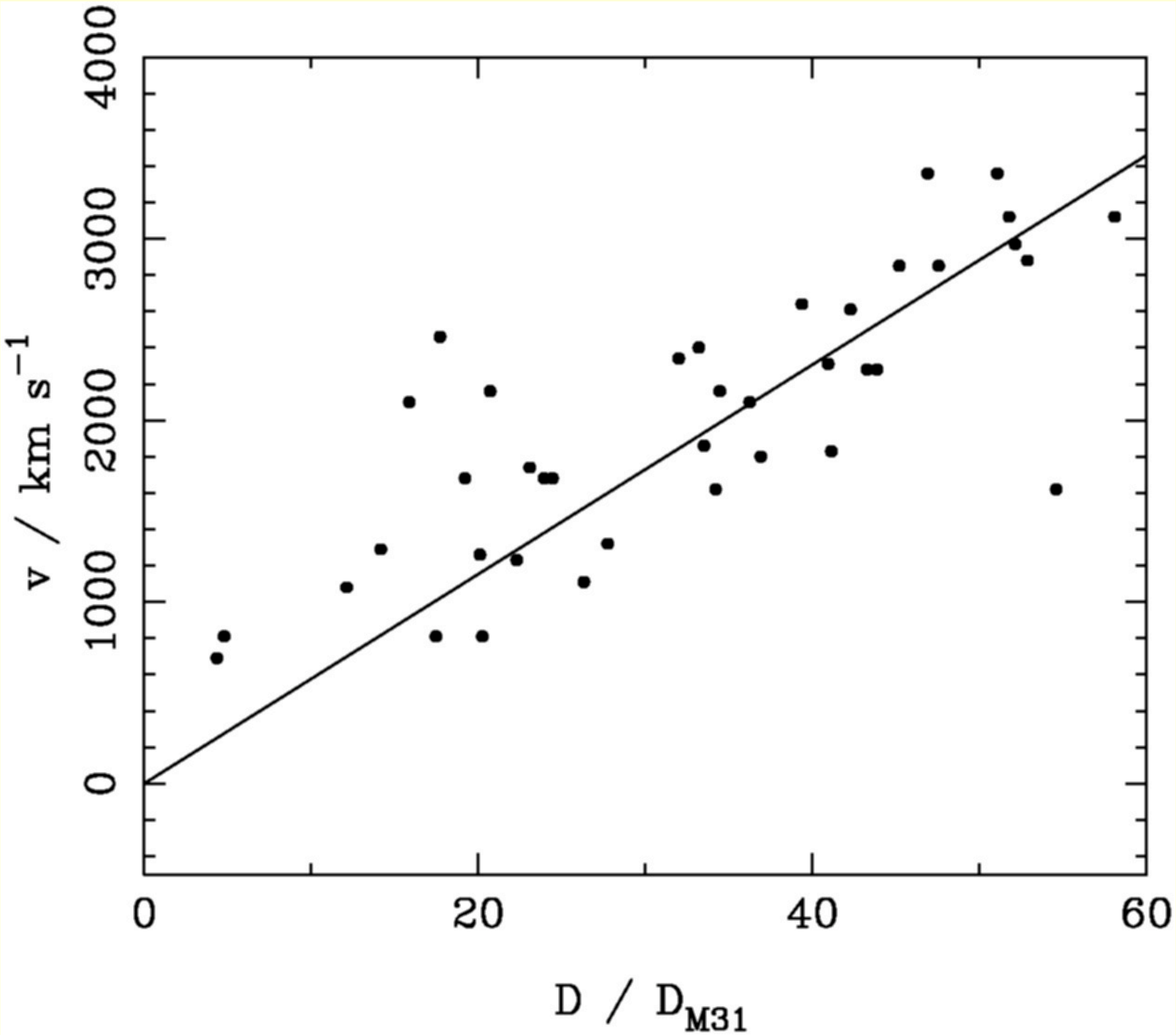


Distances in M31 units from magnitudes and/or diameters (standard candle approach)

− but notes Novae in M31 imply distance about 500 kpc

38/44 redshifted

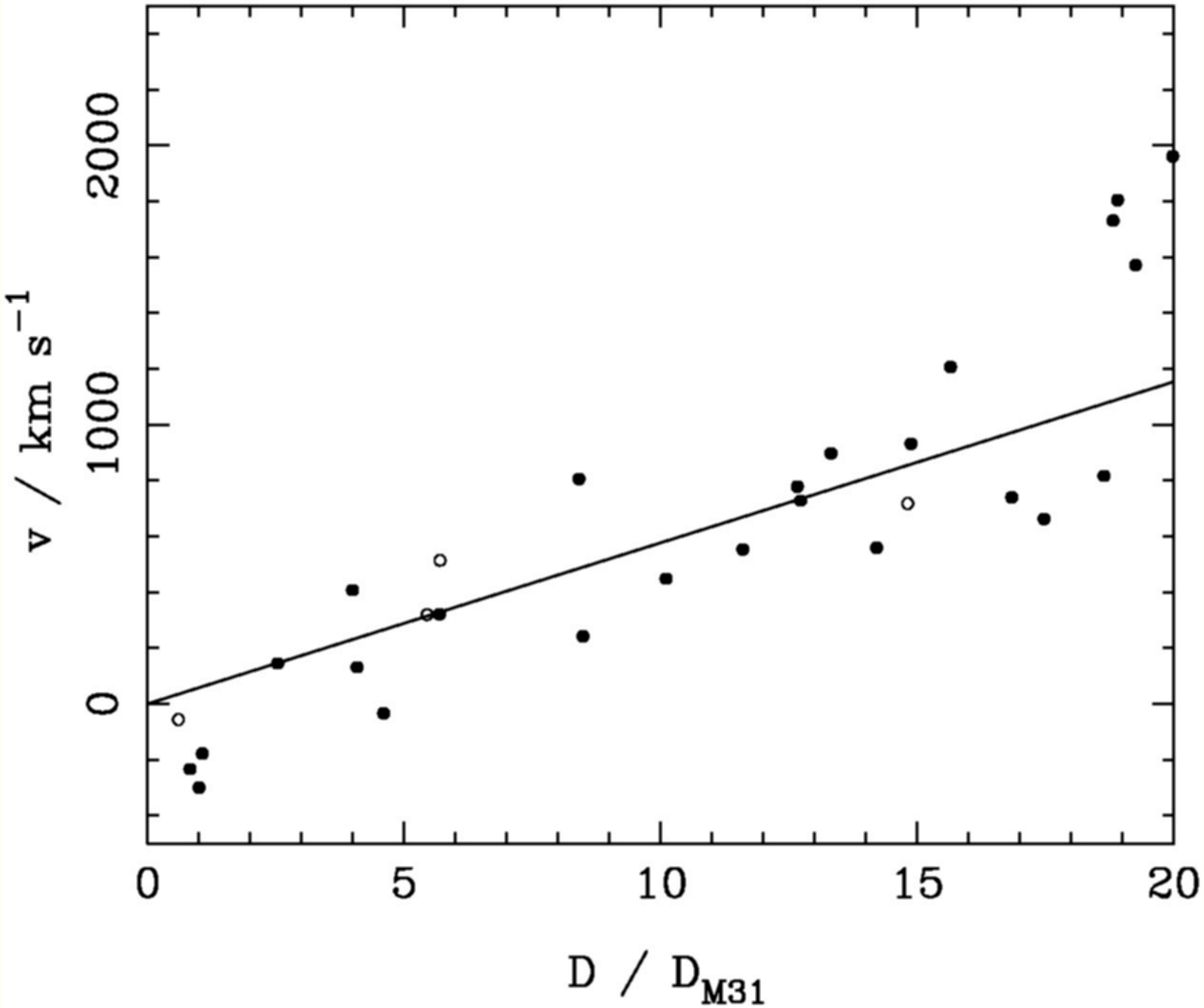
Modern data: SNe Ia



Need data to 40-50 Mpc to establish a linear relation:

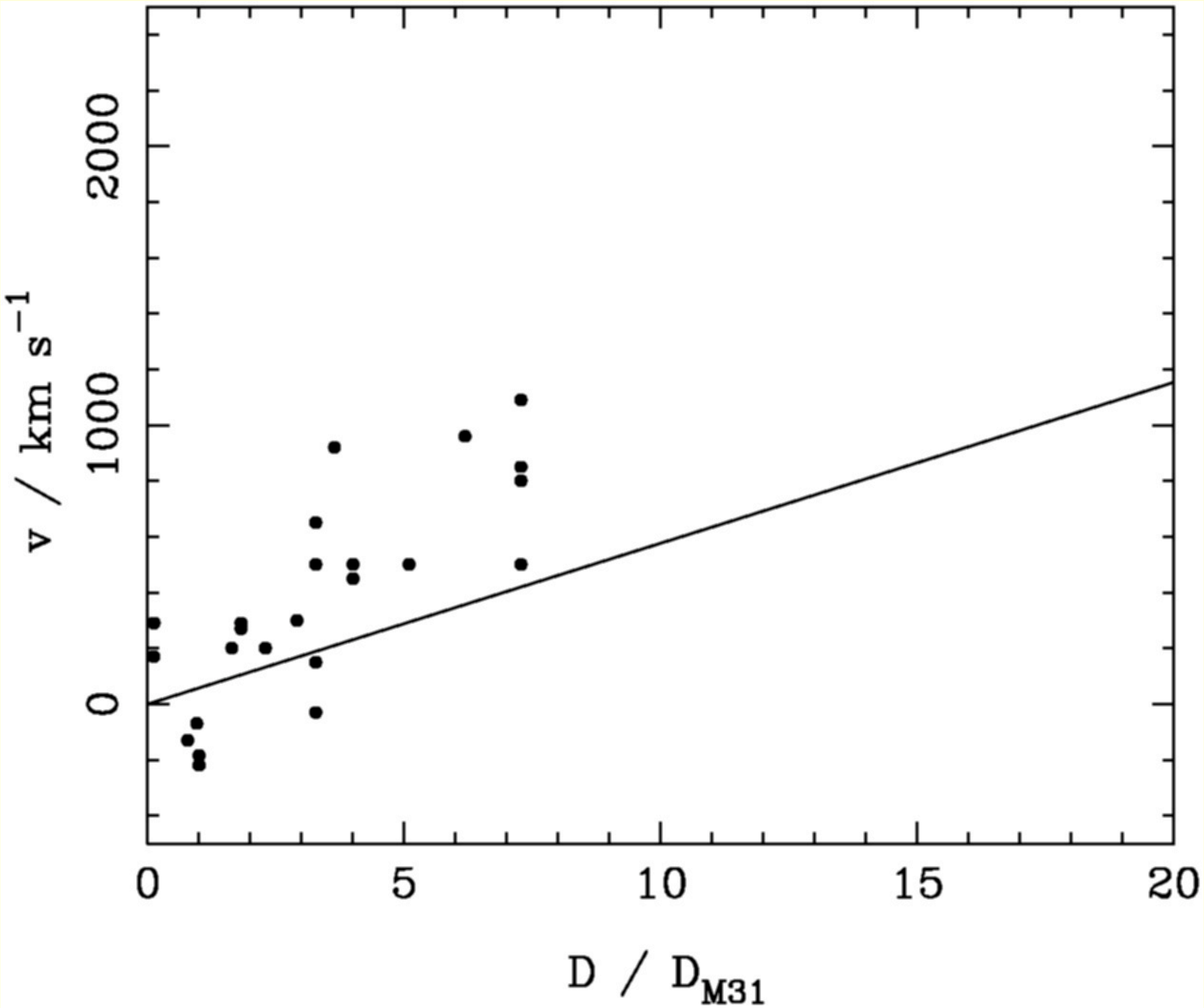
Scatter about line is real, and due to peculiar velocities as discovered by Slipher

Modern data: HST Cepheids



Local region to 15 Mpc is ‘quieter’ than average

Hubble's data



Not deep enough

Distances too low in addition to mis-calibration – Malmquist bias?

Hubble plotted data corrected for best solar motion assuming a linear D-z:

$$v = HD + \mathbf{v}_{\odot} \cdot \hat{\mathbf{r}}$$

Hubble's interpretation

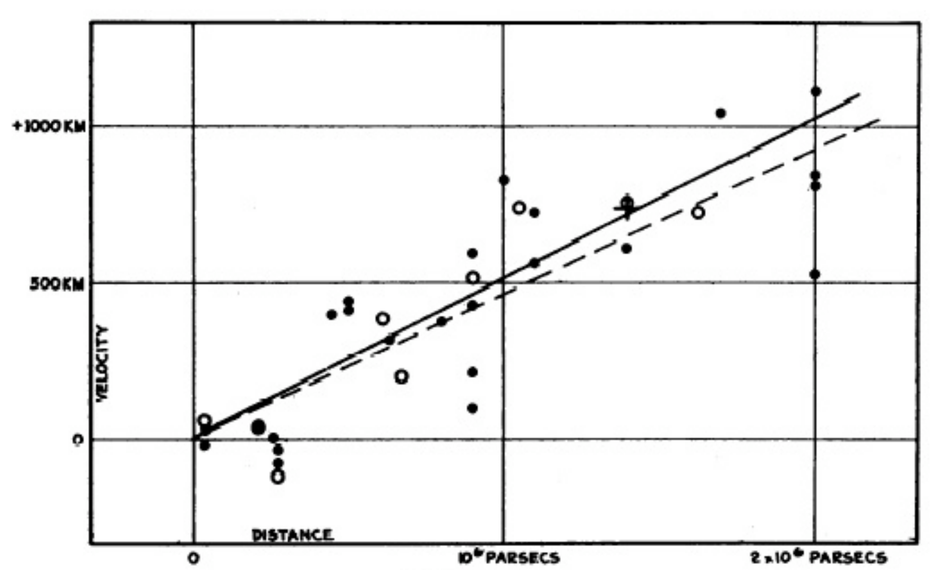


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

"...the velocity-distance relation may represent the de Sitter effect, and hence that numerical data may be introduced into discussions of the general curvature of space."

Even to his death in 1953, never publicly endorsed a Doppler interpretation

cf. Slipher in 1913

LOWELL OBSERVATORY

BULLETIN No. 58

VOL. II No. 8

THE RADIAL VELOCITY OF THE ANDROMEDA NEBULA

1912,	September	17,	Velocity,	—284 km.
	November	15–16,	"	296
	December	3–4,	"	308
	December	29–30–31,	"	—301
		Mean velocity,		—300 km.

The magnitude of this velocity, which is the greatest hitherto observed, raises the question whether the velocity-like displacement might not be due to some other cause, but I believe we have at the present no other interpretation for it. Hence we may conclude that the Andromeda Nebula is approaching the solar system with a velocity of about 300 kilometers per second.

This result suggests that the nebula, in its swift flight through space, might have encountered a dark "star,"

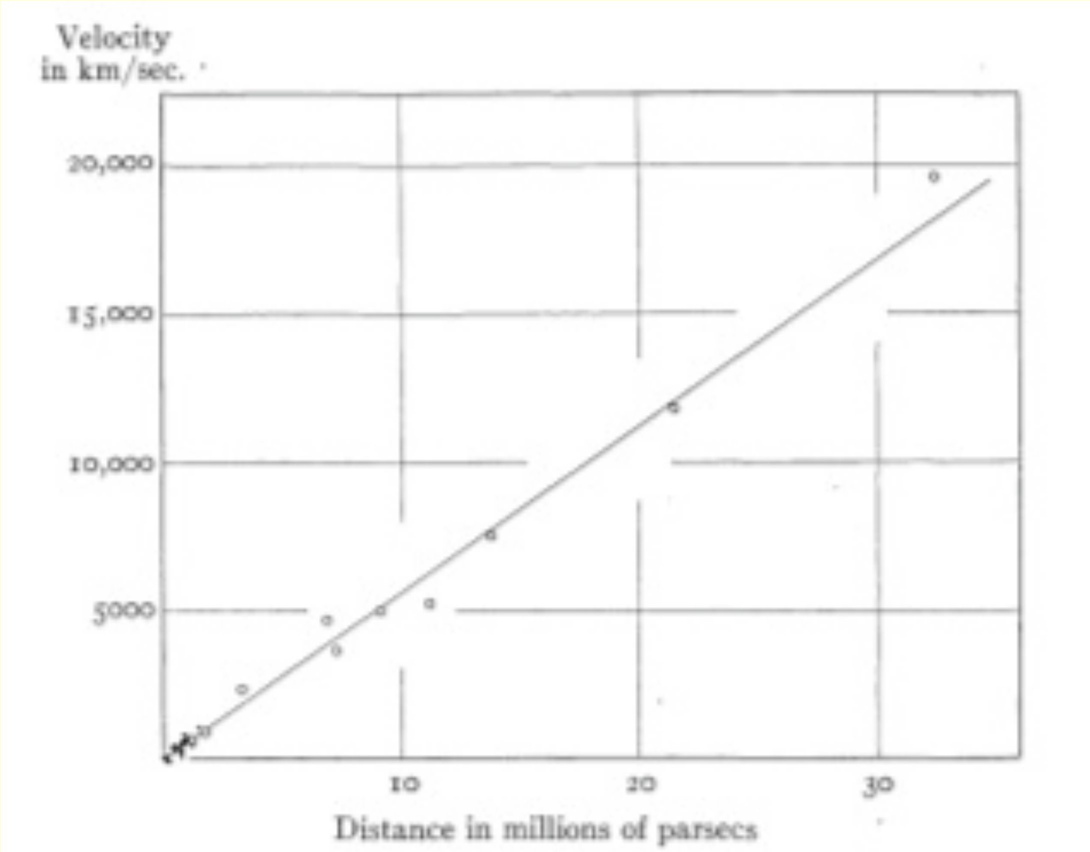
Multi-night photo integration (6 hrs+)

Confident

In short

- Data at the time of Hubble's "discovery" were not deep enough to reveal true expansion
- Hubble's distances were wrong in two distinct ways
- Nevertheless, the de Sitter prediction was a strong prior for what should be observed (even though it could never be a model of the real universe)
- Presumably Hubble's paper was convenient for theorists like Eddington, who knew that $z=r/R$ had to be right
  - Similar things happened in the 1980s where theorists gave big publicity to results claiming to find a critical matter density

So when was a linear D(z) established?

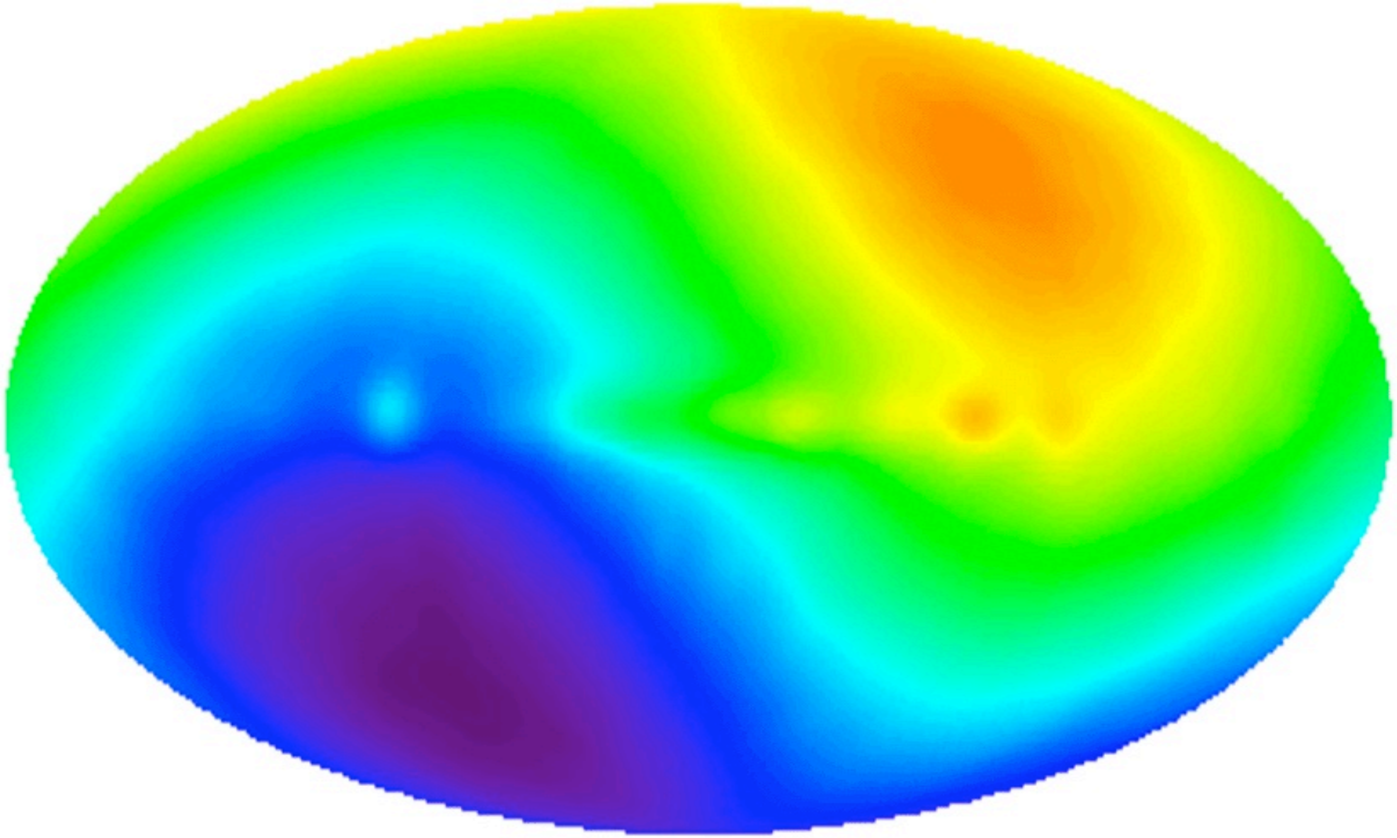


Hubble & Humason (1931): ApJ 74, 43

Galaxies as standard candles: dubious assumption (cf. Lundmark 1924) and poor precision (D ± 20%)

Proper validation only 1990s with HST Cepheid & SNe 5% distances – even though result assumed true for decades

Slipher’s peculiar velocities today



Dipole in microwave background measures Sun’s motion wrt rest of universe = 368 km s^{-1}

– again shows Slipher’s galaxies not deep enough

Peculiar velocities from growing density fluctuations

- Peculiar velocities must arise when gravity causes density fluctuations to grow, just via conservation of mass:

$$\nabla \cdot \mathbf{u} = -d\delta/dt$$

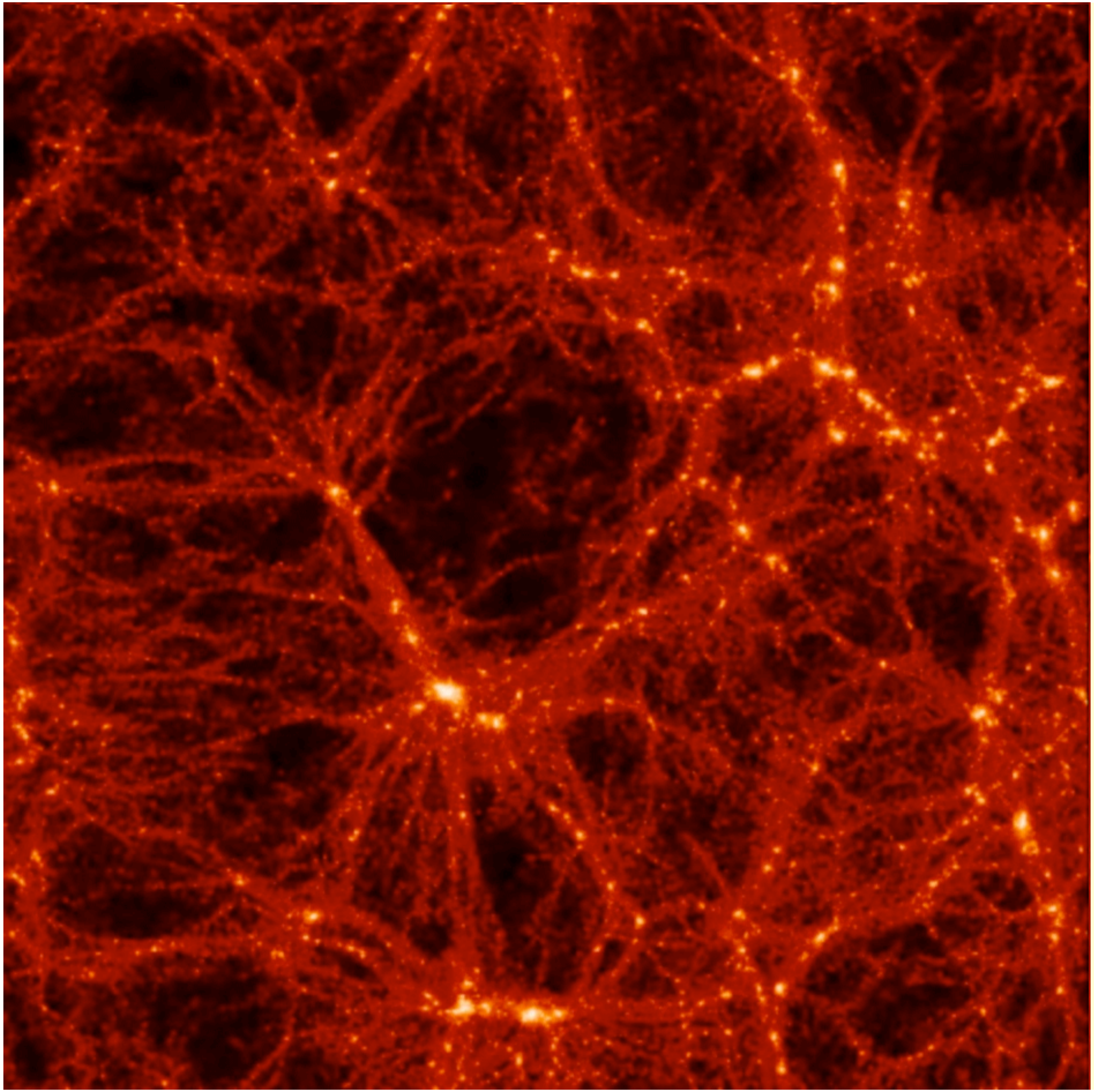
- Additional Doppler redshifts affect observed z:

  z = H D / c + v/c   or v = cz - HD

- Flawed attempts to measure v with standard candles of 20% D error gave high density in early 1990s

- Leads to distorted apparent clustering in 'redshift space' (Kaiser 1987): D = cz/H is not a true distance

- Measures density and/or strength of gravity @ 10 Mpc



Forming superclusters (comoving view)

redshift z=3

(1/4 present size)

redshift z=1

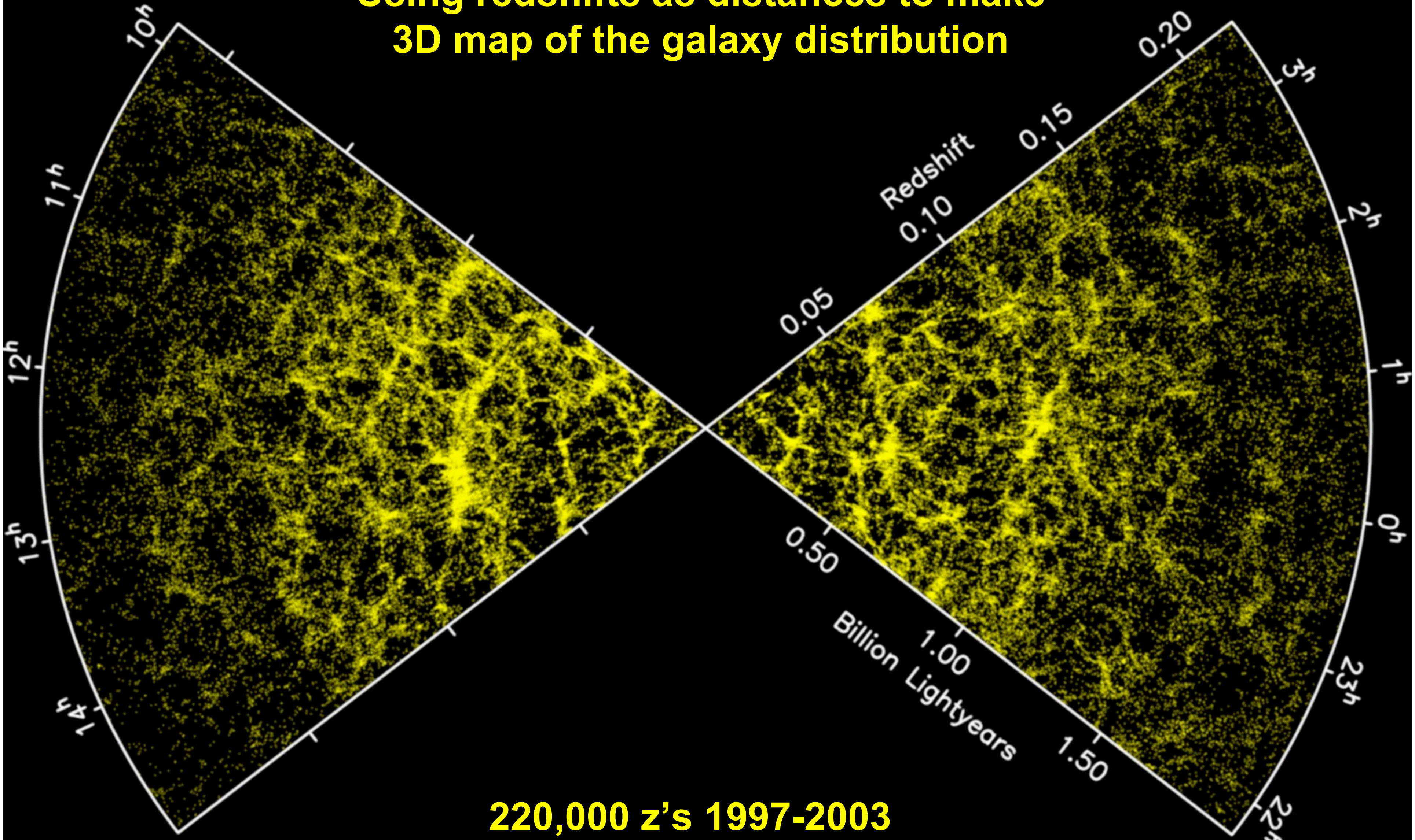
(1/2 present size)

Redshift z=0

(today)

The 2dF Galaxy Redshift Survey

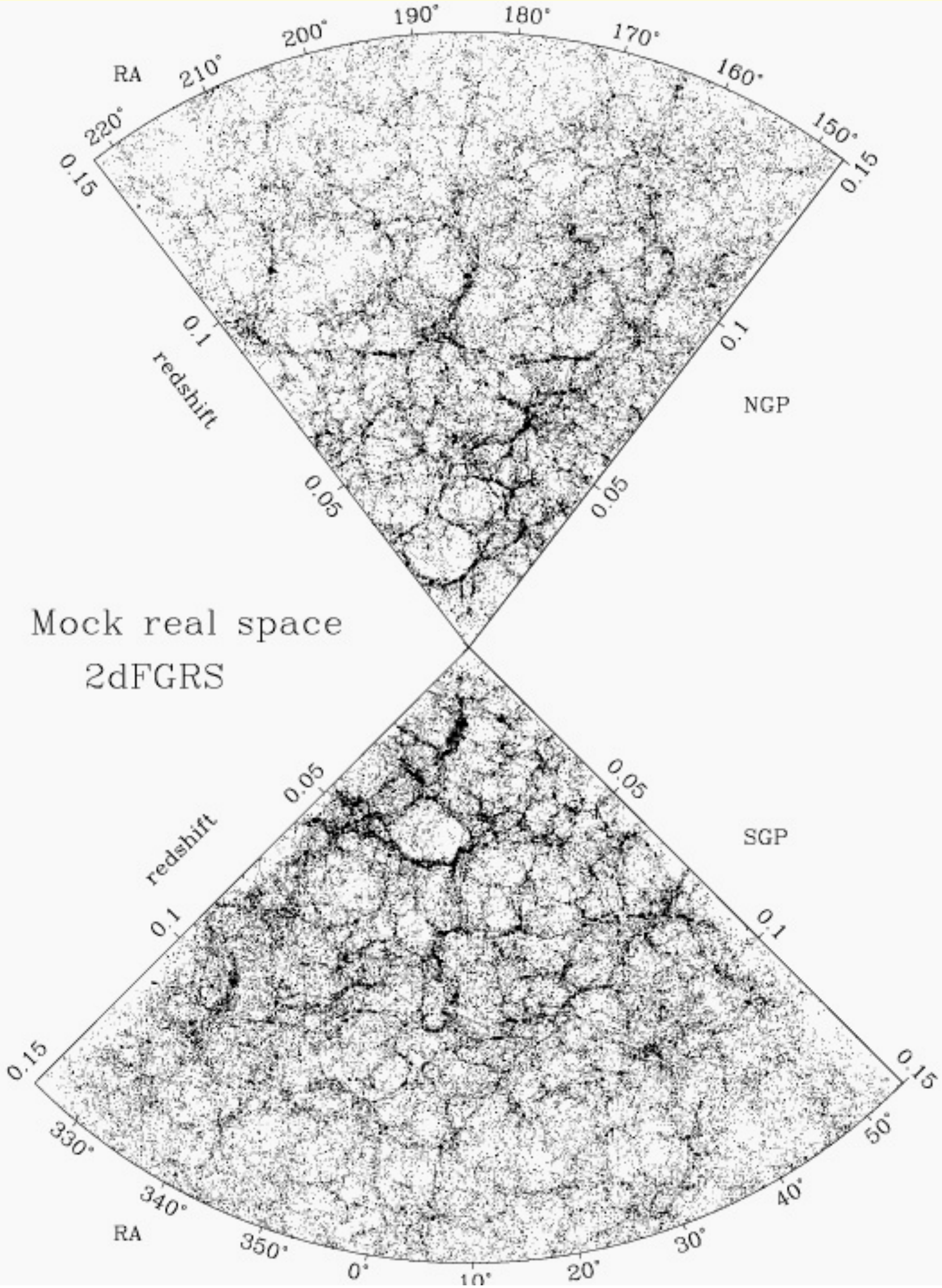
Using redshifts as distances to make 3D map of the galaxy distribution



220,000 z's 1997-2003

Mock 2dFGRS from Hubble volume

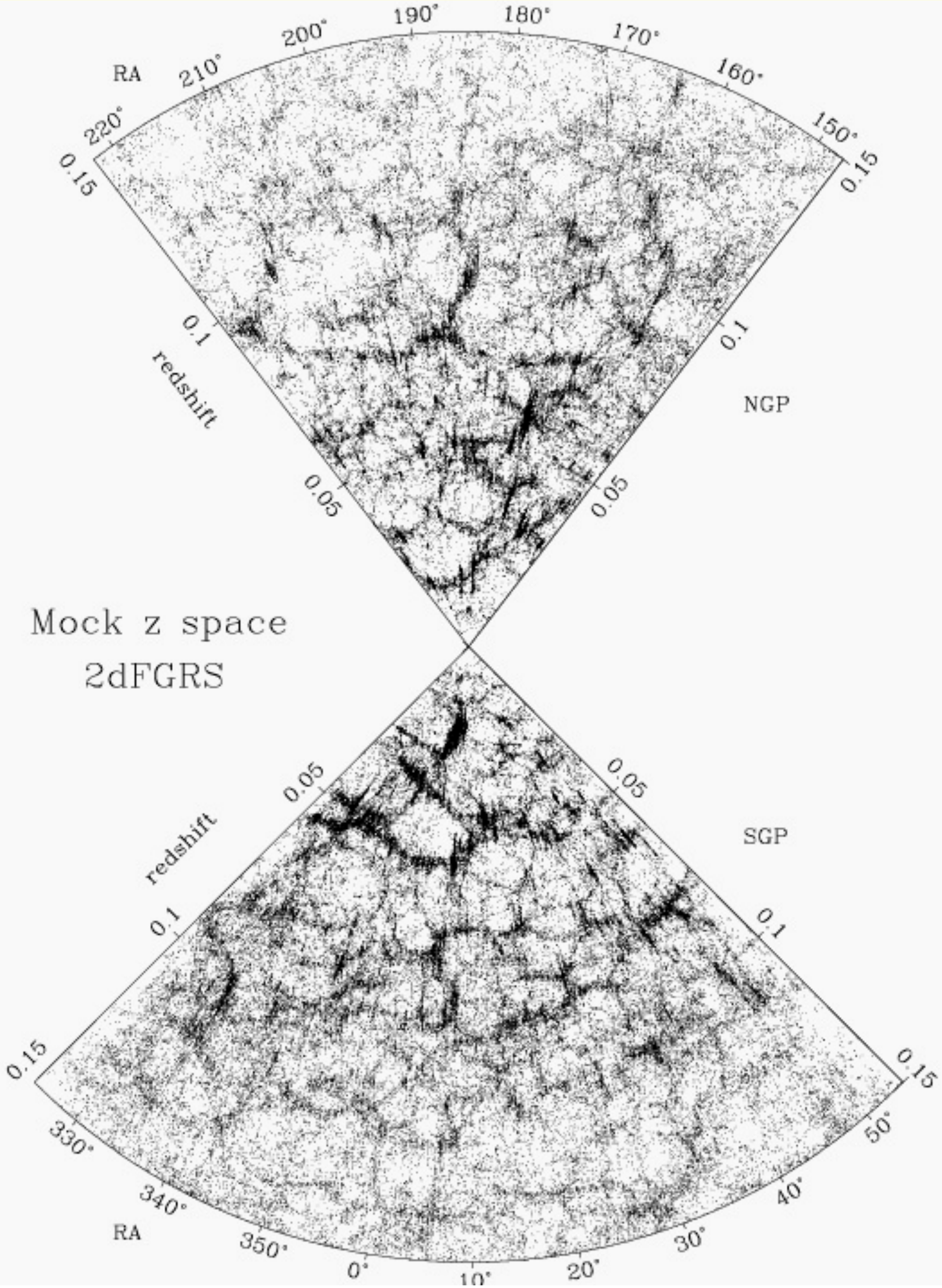
real space



Eke, Frenk, Cole, Baugh + 2dFGRS 2003

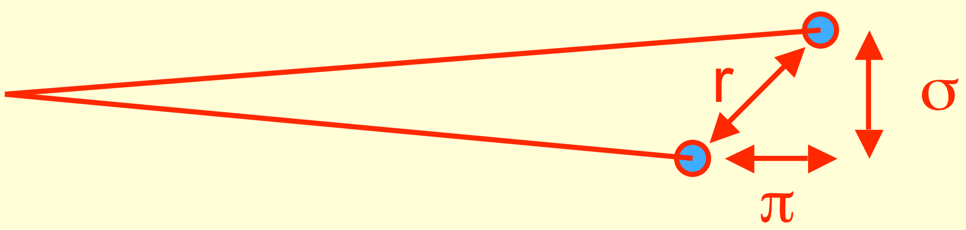
Mock 2dFGRS from Hubble volume

z-space

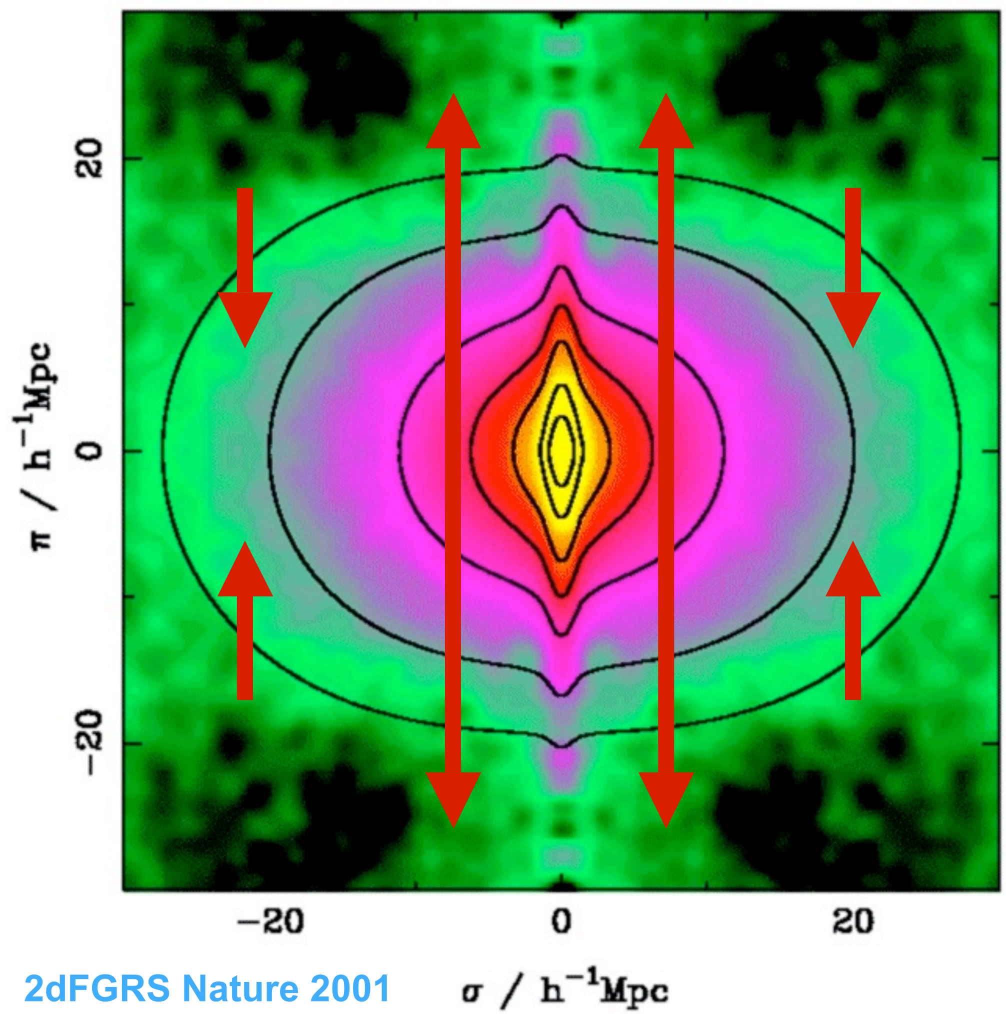


Eke, Frenk, Cole, Baugh + 2dFGRS 2003

Redshift-Space Distortions

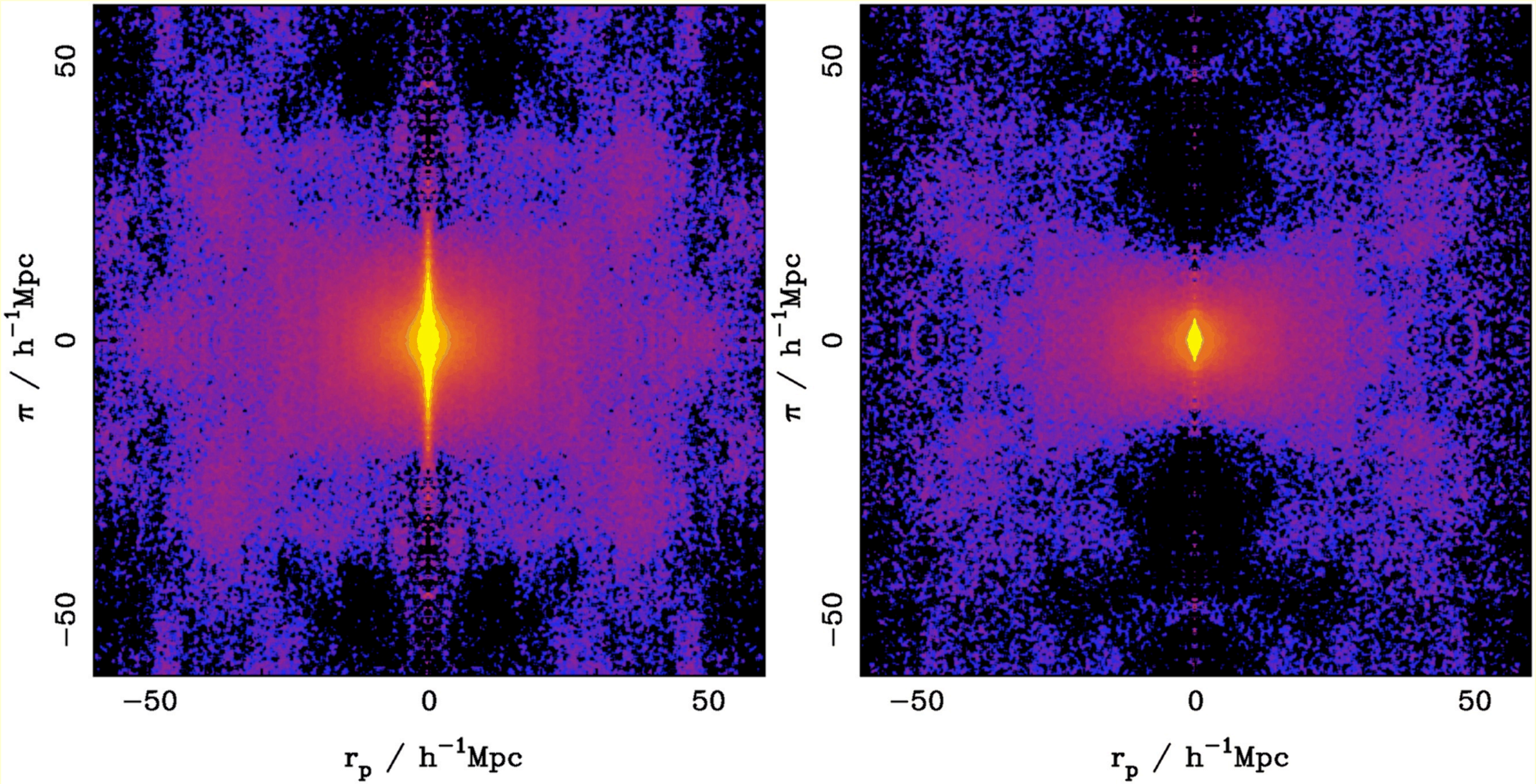


- RSD due to peculiar velocities are quantified by correlation fn $\xi(\sigma,\pi)$: excess pairs as function of transverse and radial separations
- Two effects visible:
  - Small separations on sky: 'Finger-of-God';
  - Large separations on sky: flattening along line of sight.



2dFGRS Nature 2001

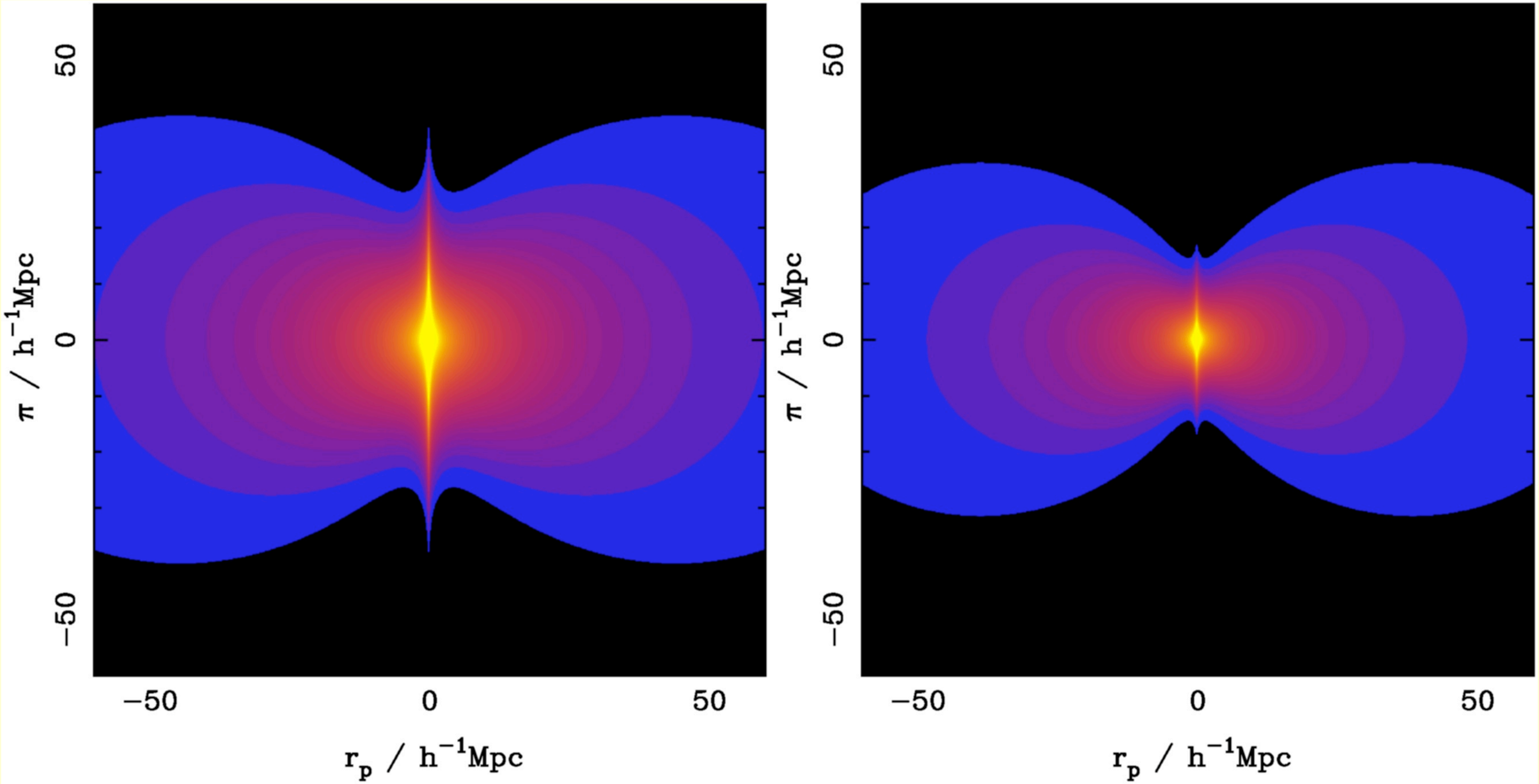
GAMA: redshift-space distortions



Red

Blue

GAMA: redshift-space models

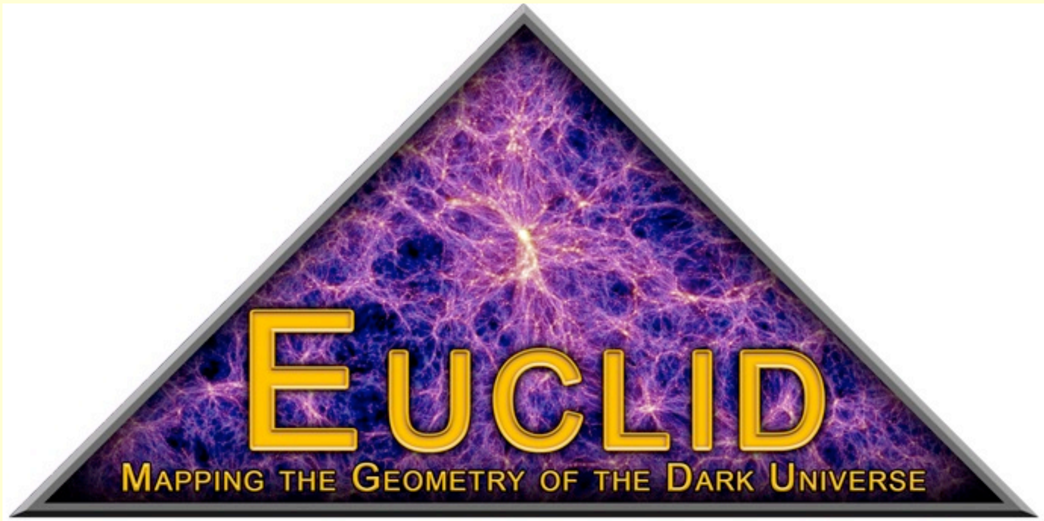


Red **Blue**

Status & aims for velocity distortions

Today: ~1M z's measure growth rate of structure to ~5%. So far, consistent with Einstein gravity

2025(?): ESA's Euclid satellite will have ~50M z's and measure growth to <1%



In conclusion

- Data at the time of Hubble's "discovery" were not deep enough to reveal true expansion
- Hubble's distances were wrong (twice)
- Slipher's velocities were right, and he used them with correct physical insight to reach just the justified conclusions a decade before any competition:
  - The non-uniform cosmological velocity field
  - The peculiar motion of the Milky Way
  - Hence other galaxies as moving stellar systems