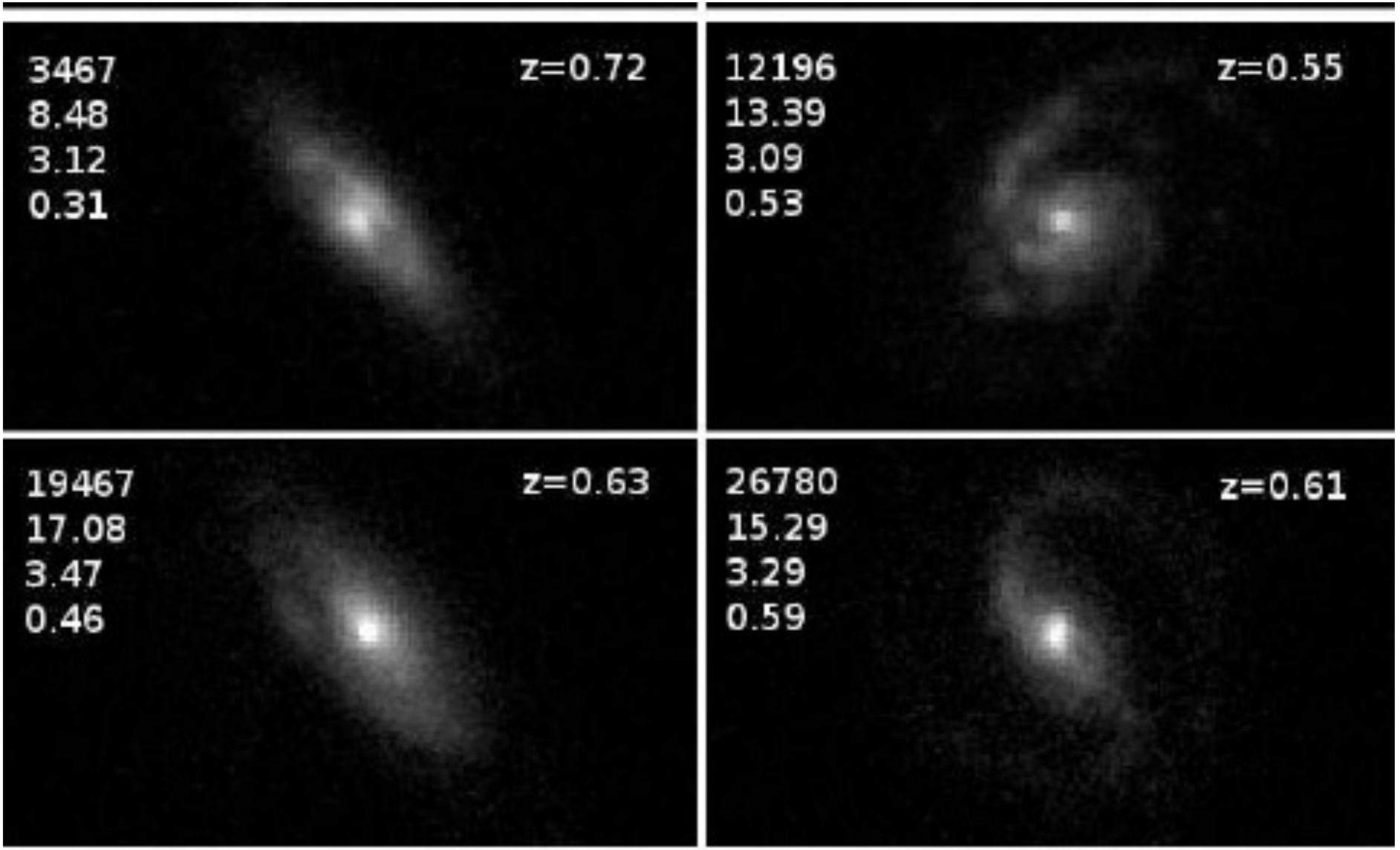
$$d = \frac{v}{H_0} = \frac{cz}{H_0}$$

Lookback time

$$t = \frac{d}{c} \approx \frac{z}{H_0} \approx 0.37 \frac{1}{H_0} \approx 5 \text{ billion years}$$

- Note that these formula only apply to ‘small’ redshifts $z<0.5$ before relativisitic and cosmological effects become important at >30% level.



https://academic.oup.com/mnras/article/451/1/2/1361261

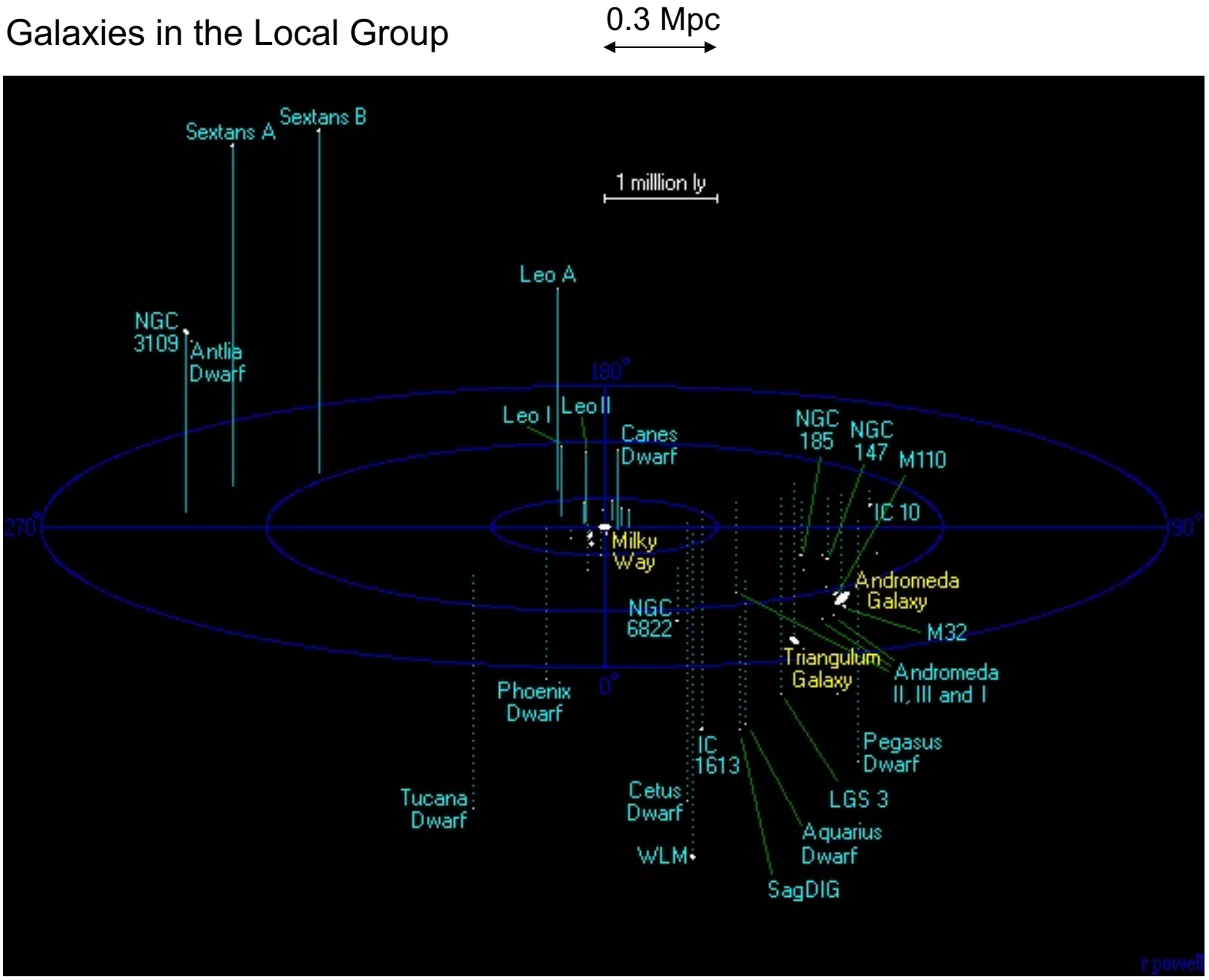
Large Scale Structure

- The Local Group
- Galaxy Groups
- Galaxy Clusters
- Superclusters
- Voids

The Local Group

- Our Galaxy is part of a group of about 30 galaxies called the Local Group
- The Local Group is dominated by the Galaxy and M31 (Andromeda)
- The other galaxies are mostly low mass irregulars (e.g. Magellanic Clouds) and dwarf ellipticals (e.g. companions to M31)
- Spans about 1 Mpc across

Galaxies in the Local Group



From Universe textbook

Galaxy Groups

- Many galaxies are members of similar groups
- Few tens of members
- Mixture of spirals, ellipticals and irregulars
- Irregular structure – no central concentration of galaxies
- Groups also known as poor clusters

Stefan’s Quintet and NGC 7331

Galaxy Group Hickson 44. Credit & Copyright: MASIL Imaging Team

From Universe textbook

Hercules: Rich group or poor cluster

Galaxy Clusters

- Rich clusters contain many thousands of galaxies
- Mostly made up of ellipticals and S0 types
- Symmetrical and centrally concentrated
- A few Mpc across in general

Virgo cluster

Credit: The Palomar-Quest Team, California Institute of Technology

Credit: NASA, ESA, Hubble Heritage (STScI/AURA);

Coma cluster of galaxies

Class example

- The image of the galaxy cluster on the next slide is 160 arcseconds across (horizontally). Estimate how far apart each galaxy is in kpc if the cluster is at a distance of 750 Mpc


Galaxy Cluster Abell 1689
HST ACS/WFC

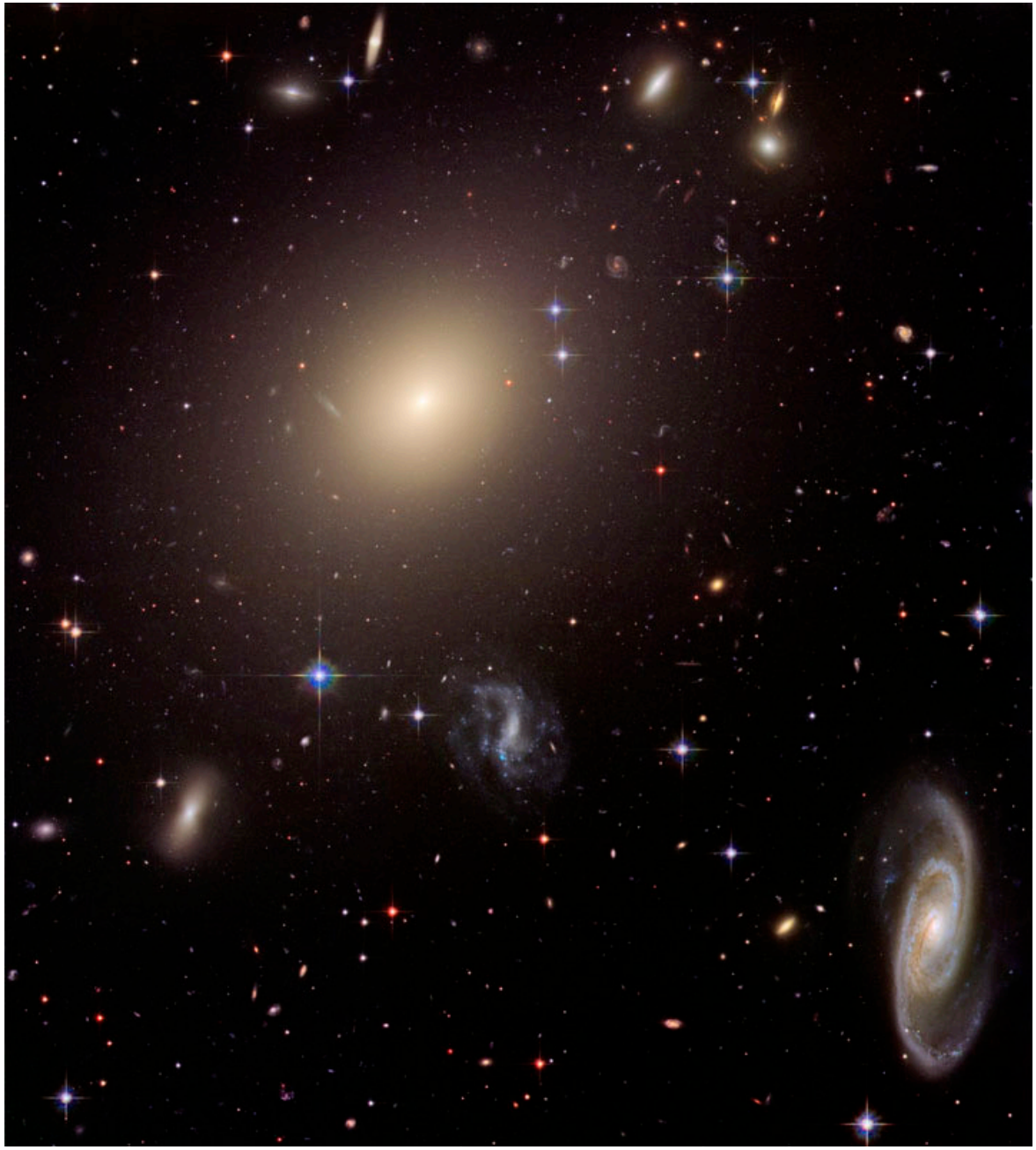
Typical separation ~ 12"

$$l = \theta d = \frac{12}{206265} 750 = 0.04 \text{ Mpc} = 40 \text{ kpc}$$

Mergers in Clusters

- The relative spacing of galaxies in clusters is quite small (galaxies ~ 10 kpc, cluster ~ 1 Mpc)
- Interaction in clusters quite common
- Often one dominant very massive elliptical galaxy at the centre of the cluster (cD)
  - 100s of kpc in size
  - Result of high degree of merger activity

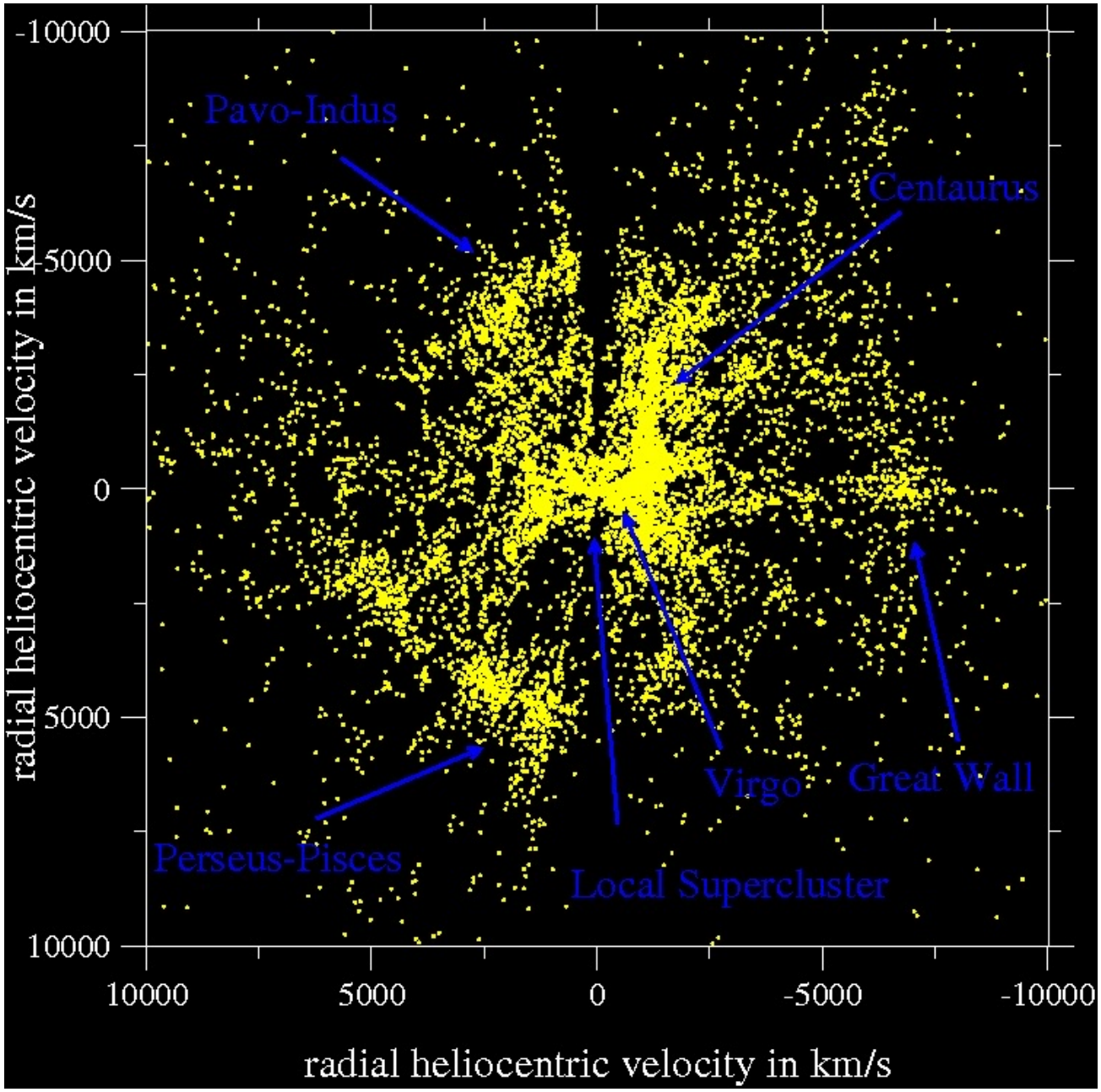
cD giant elliptical galaxy



Elliptical Galaxy ES) 325-G004 in the Abell Cluster S0740. (Credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA) / Acknowledgment: J. Blakeslee (Washington State University))

Superclusters

- Clusters of galaxy clusters also exist and are called superclusters
- Contain 10s of clusters
- Spread over 10s of Mpc
- We are part of the Local Supercluster with Virgo being the dominant cluster
- Always filamentary or flattened structures

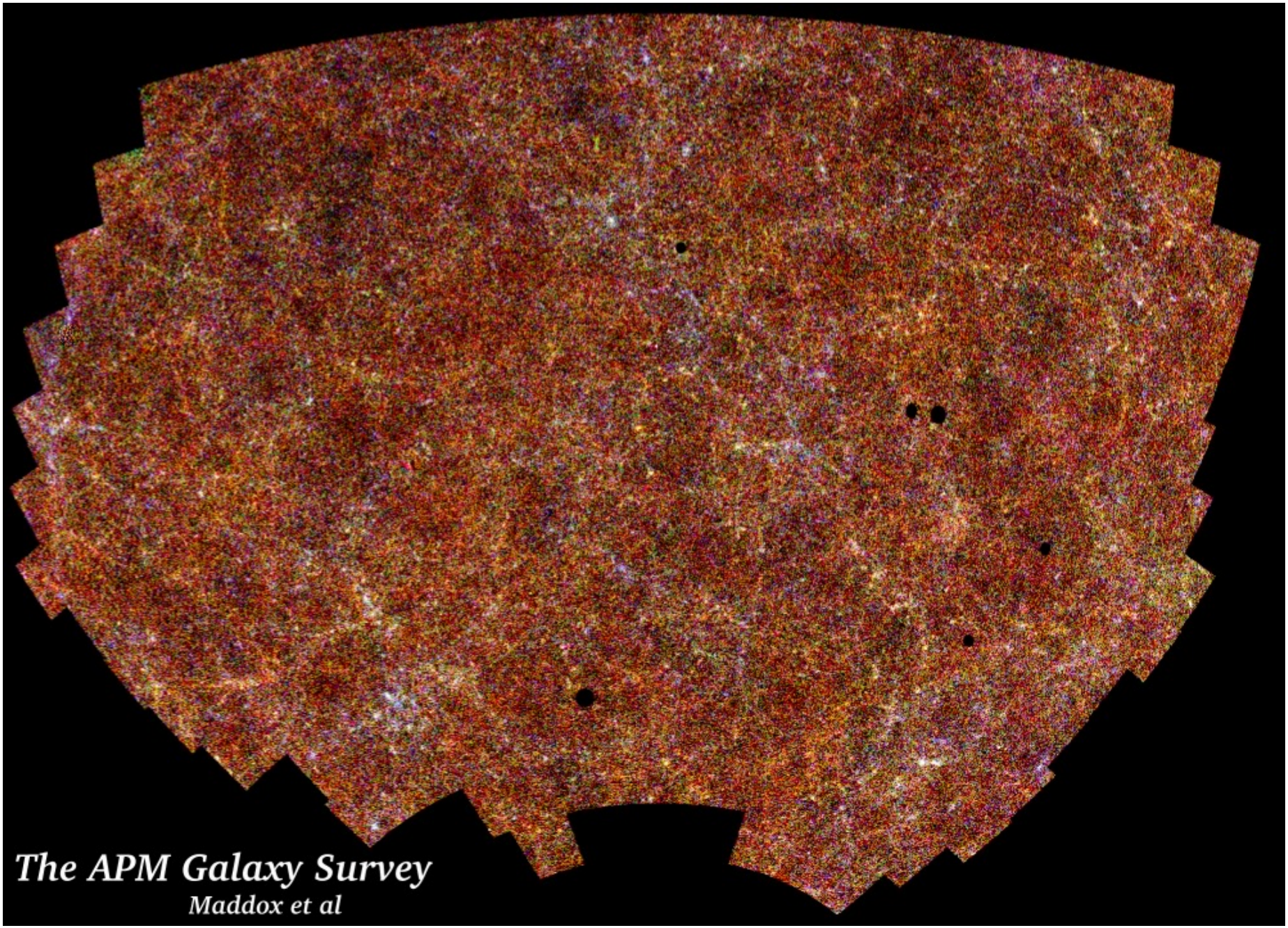


The Local Supercluster

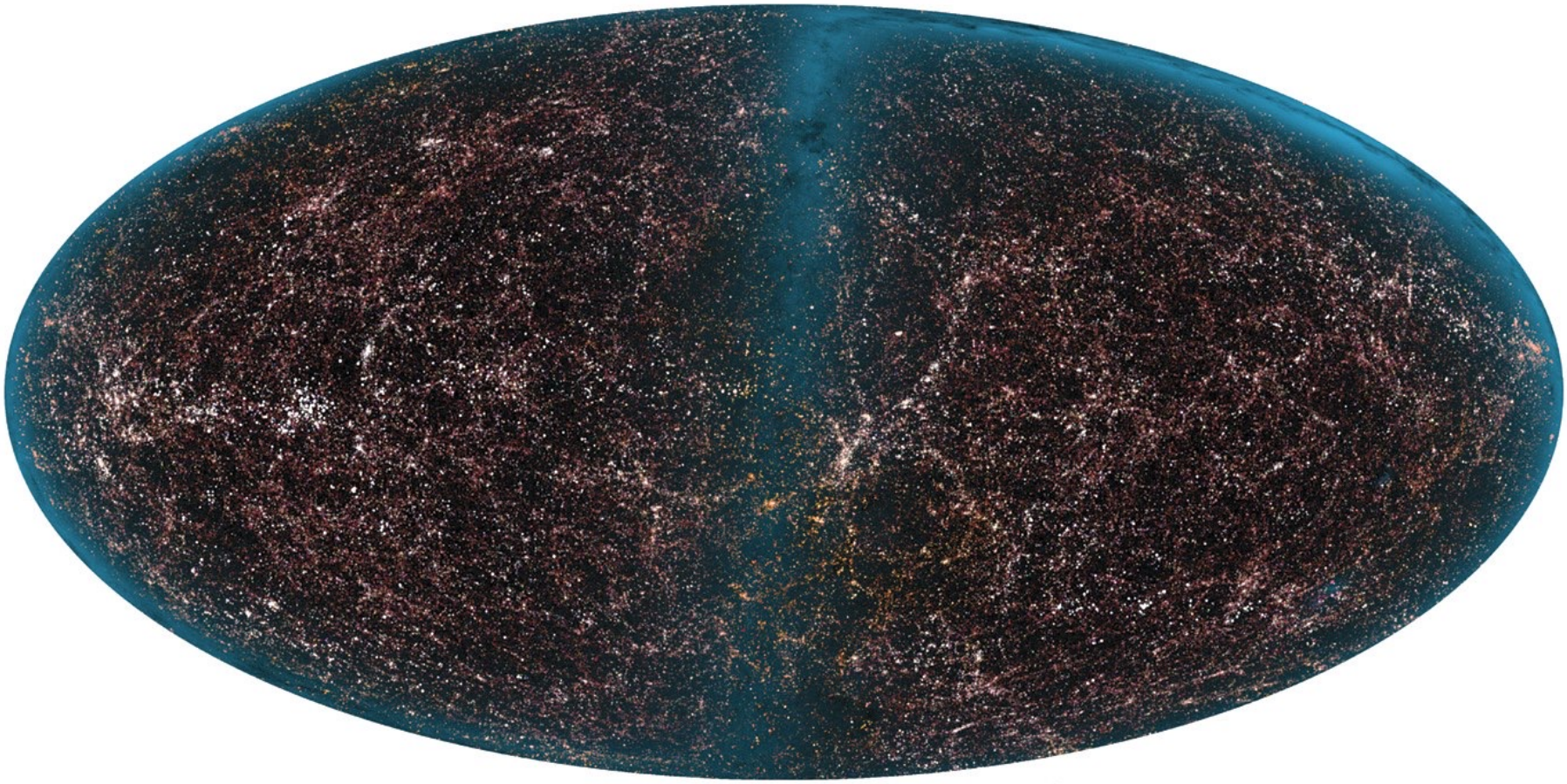
- each dot represents a galaxy

- plotted on a slice through the sky with distance (measured by redshift) increasing outwards

- empty wedge is where our Galaxy obscures those direction in the sky

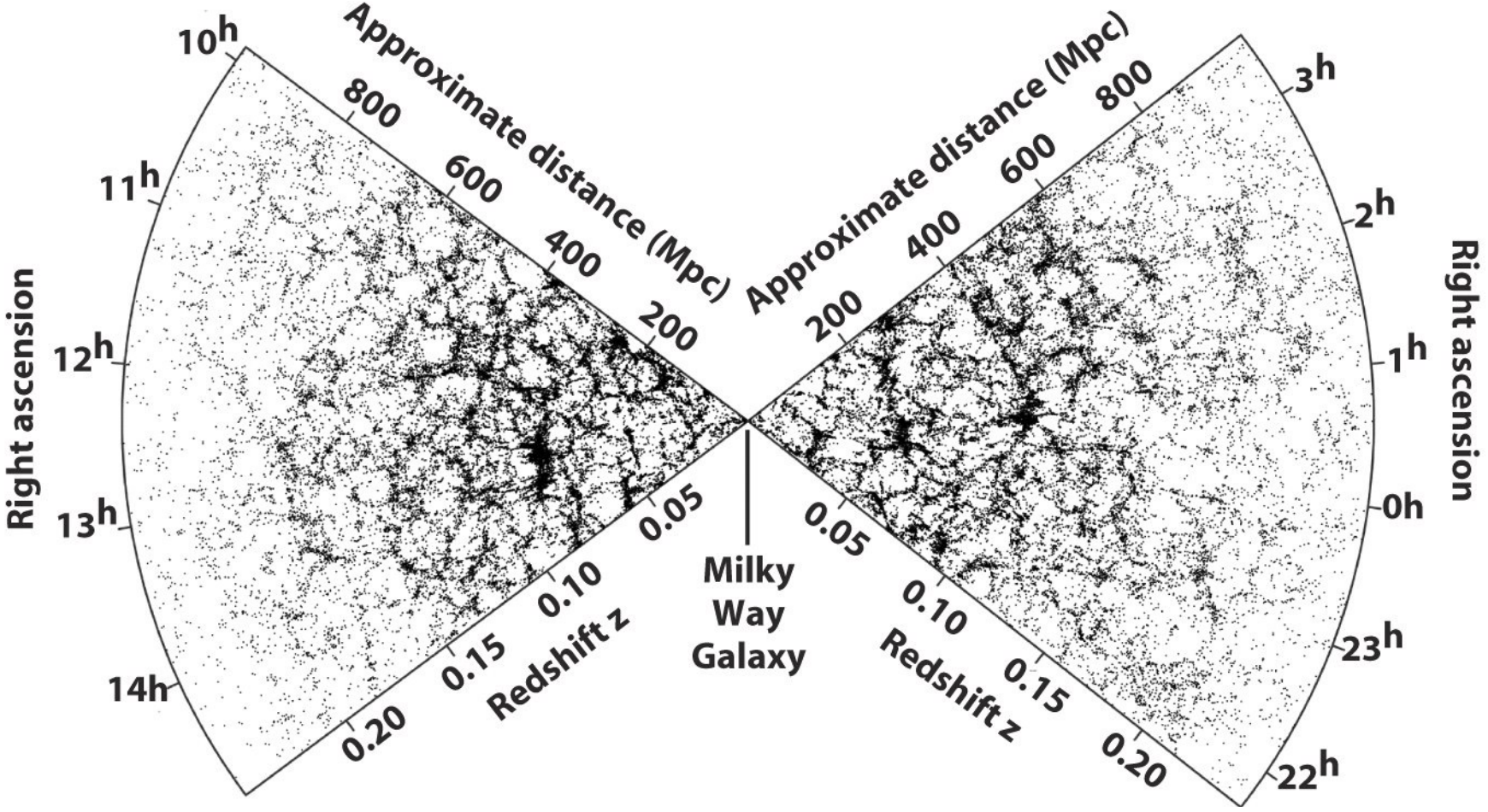


Credit: Steve Maddox, Will Sutherland, George Efstathiou and Jon Loveday



2D image of galaxies
on the sky

Credit: 2MASS, T. H. Jarrett, J. Carpenter, & R. Hurt



2D slice of how galaxies are distributed with distance (redshift)

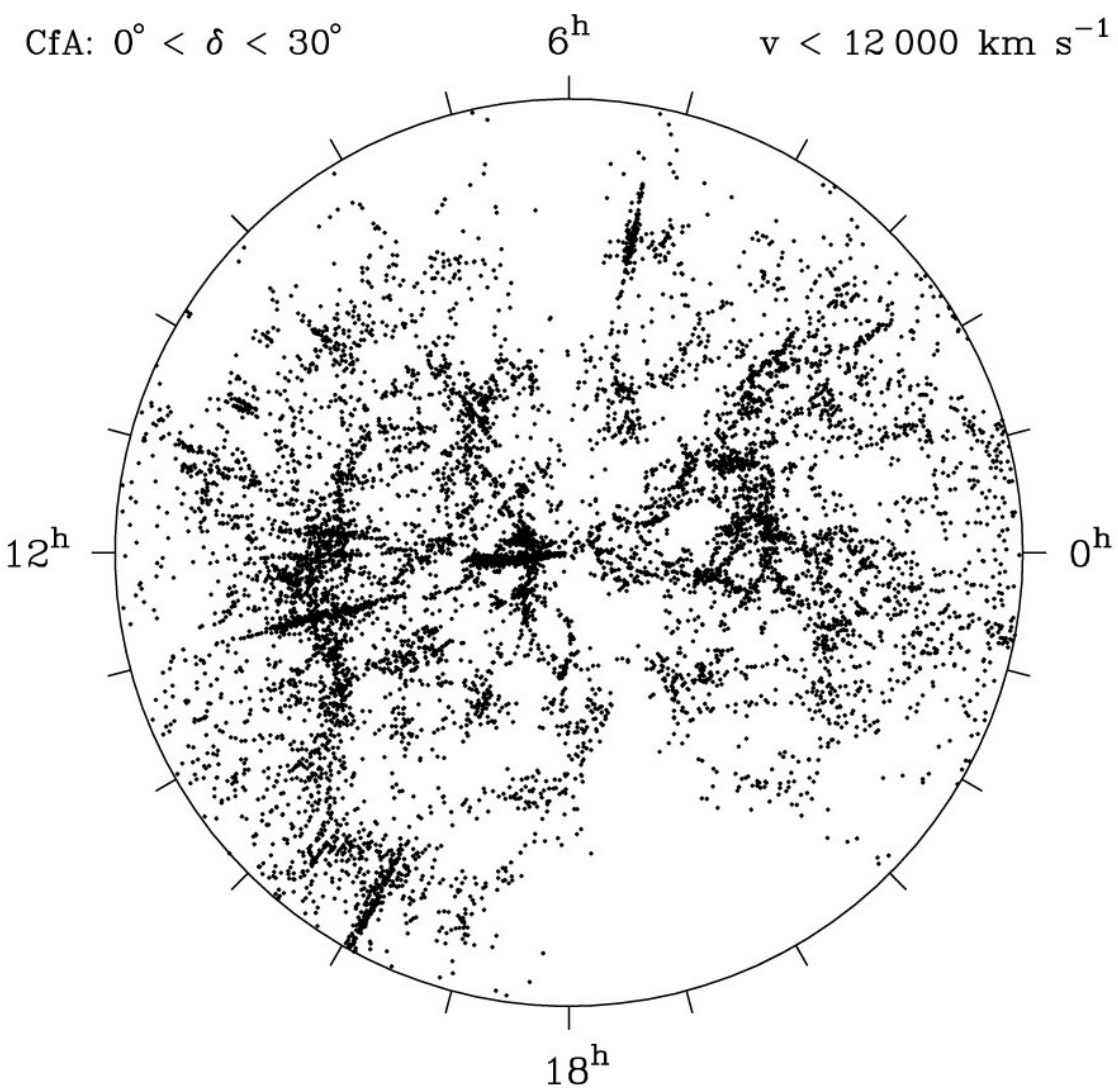
See: http://magnum.anu.edu.au/~TDFgg/

Voids

- As well as concentrations of clusters there are large areas without any galaxies – these are called voids
- On large scale maps they appear as spherical holes in the galaxy distribution with filamentary superclusters around the edges
- Of order 100 Mpc across

Peculiar Motions

- The galaxies within clusters and groups move around under their mutual gravitational attraction
- Typically a few 100 km s^{-1}
- These ‘peculiar’ motions cause the observed redshift to be different from that predicted for uniform Hubble expansion
- Causes errors in nearby galaxy distances from redshifts



The so-called ‘fingers of God’ phenomena in redshift wedges. The large peculiar motions within rich clusters cause large variations in redshift that are not a true reflection of the distance

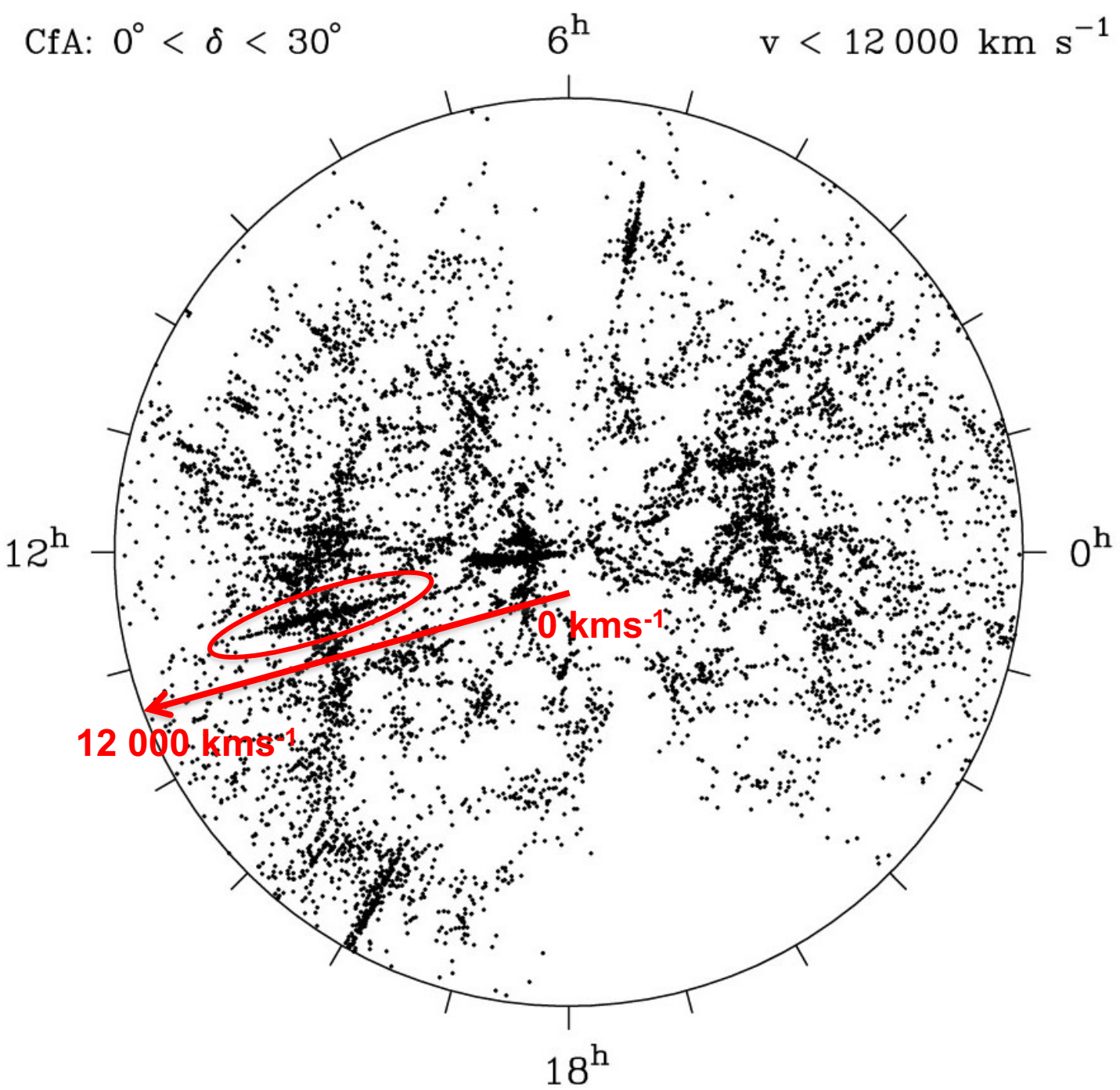
See www.cfa.harvard.edu/~huchra/zcat/

Summary

- Most galaxies are members of groups or clusters
- These in turn are members of superclusters which surround voids
- This large scale structure in the galaxies is an imprint of the big bang

Class Example

- Estimate the error in the distance due to peculiar motions in the cluster highlighted in the next slide


CfA: 0° < δ < 30°
6h
v < 12 000 km s−1
12h
0h
18h
0 kms-1
12 000 kms-1