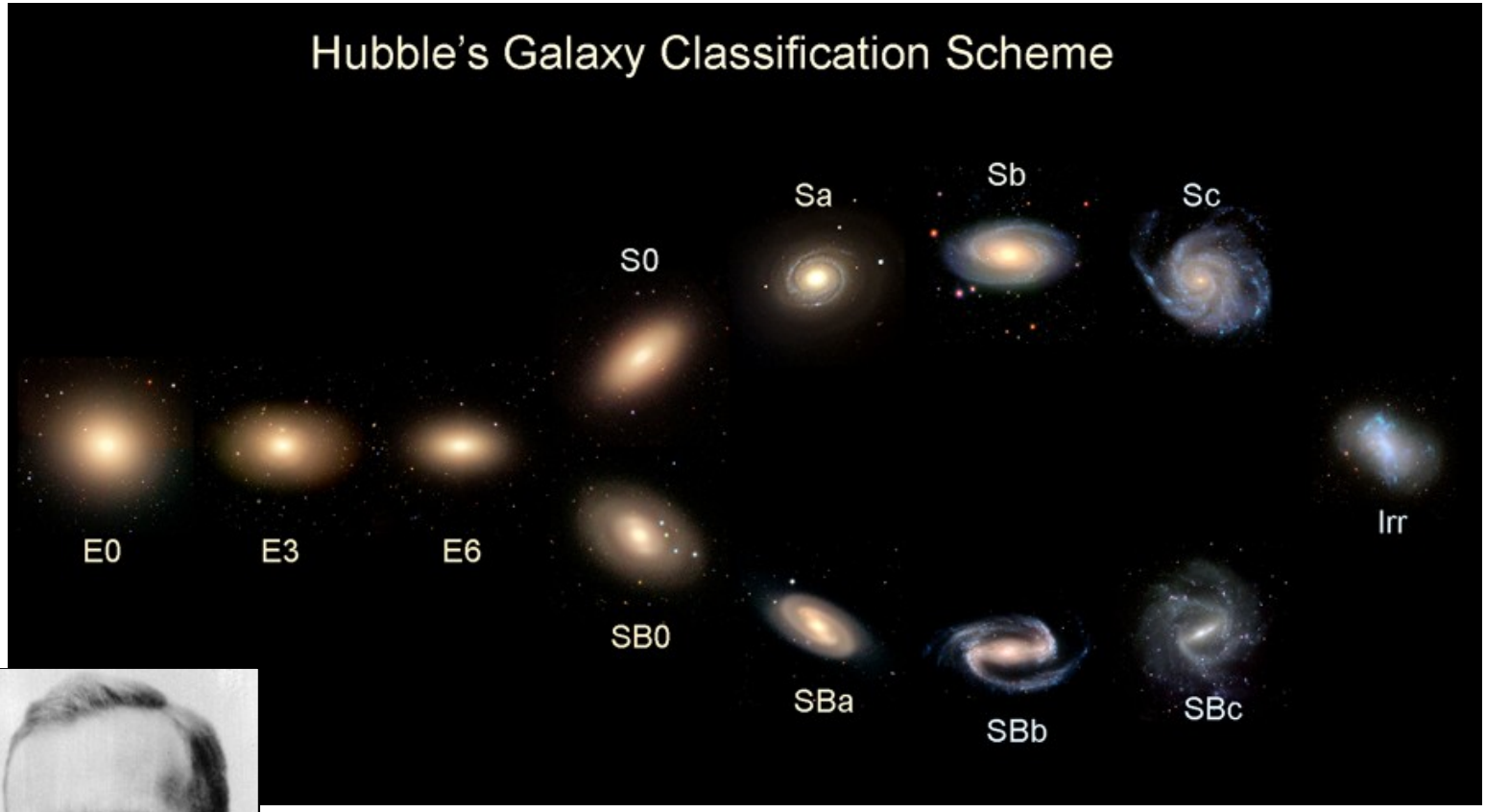
Announcements

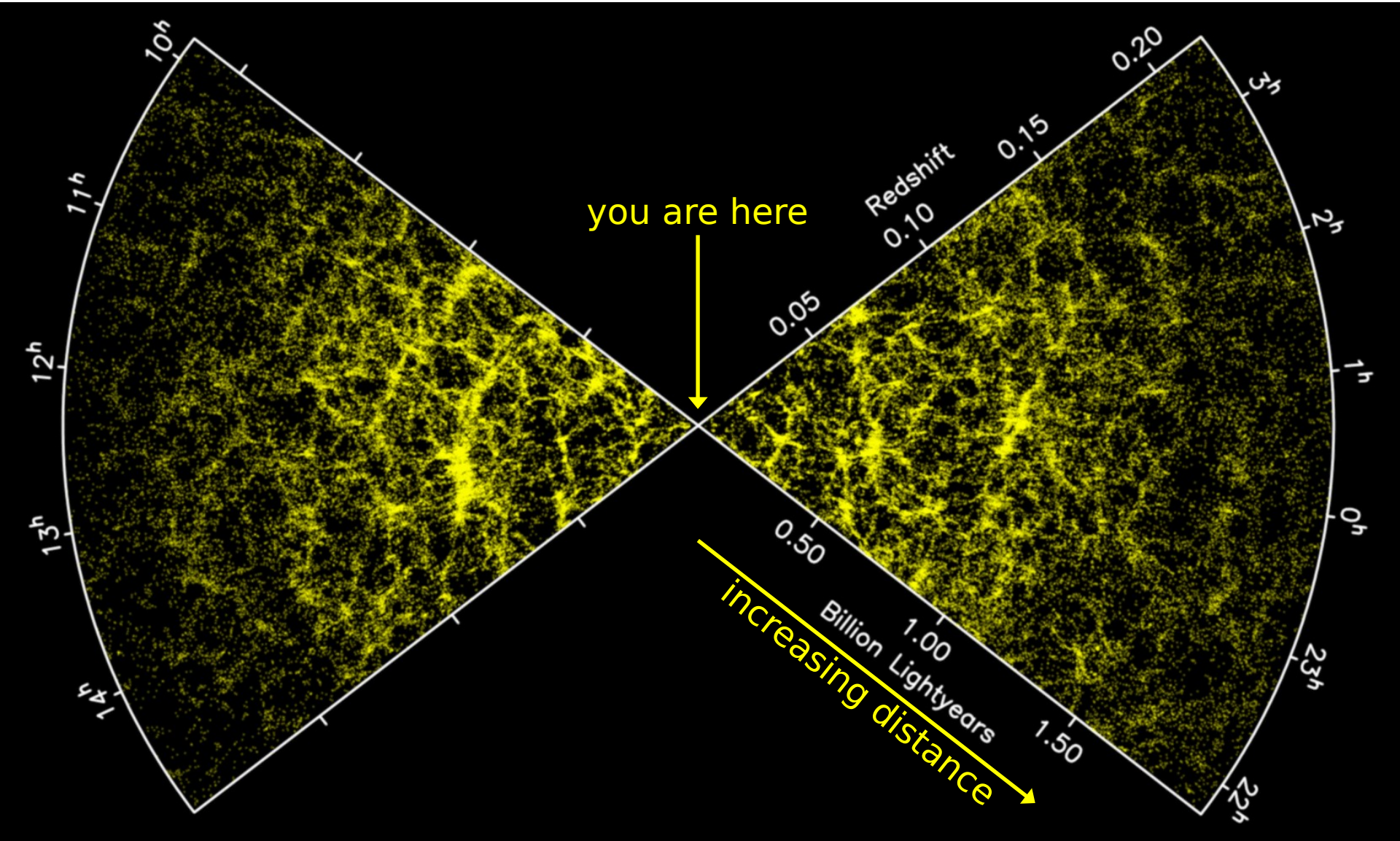
- Today: Galaxies in general
  → read Chapter 15
- Tonight, 8-9pm: Stargazing
  → Earn 1 bonus-point on final grade
- More bonus point opportunities featuring the Moon on D2L (modifications of the solar eclipse bonus points)
- Going on right now: Philae landing on Rosetta
  Touchdown expected at 10.02 am !!!

The Hubble Sequence



Edwin Hubble again
1926: proposed galaxy classification scheme still used today

The Distribution of Galaxies in Space



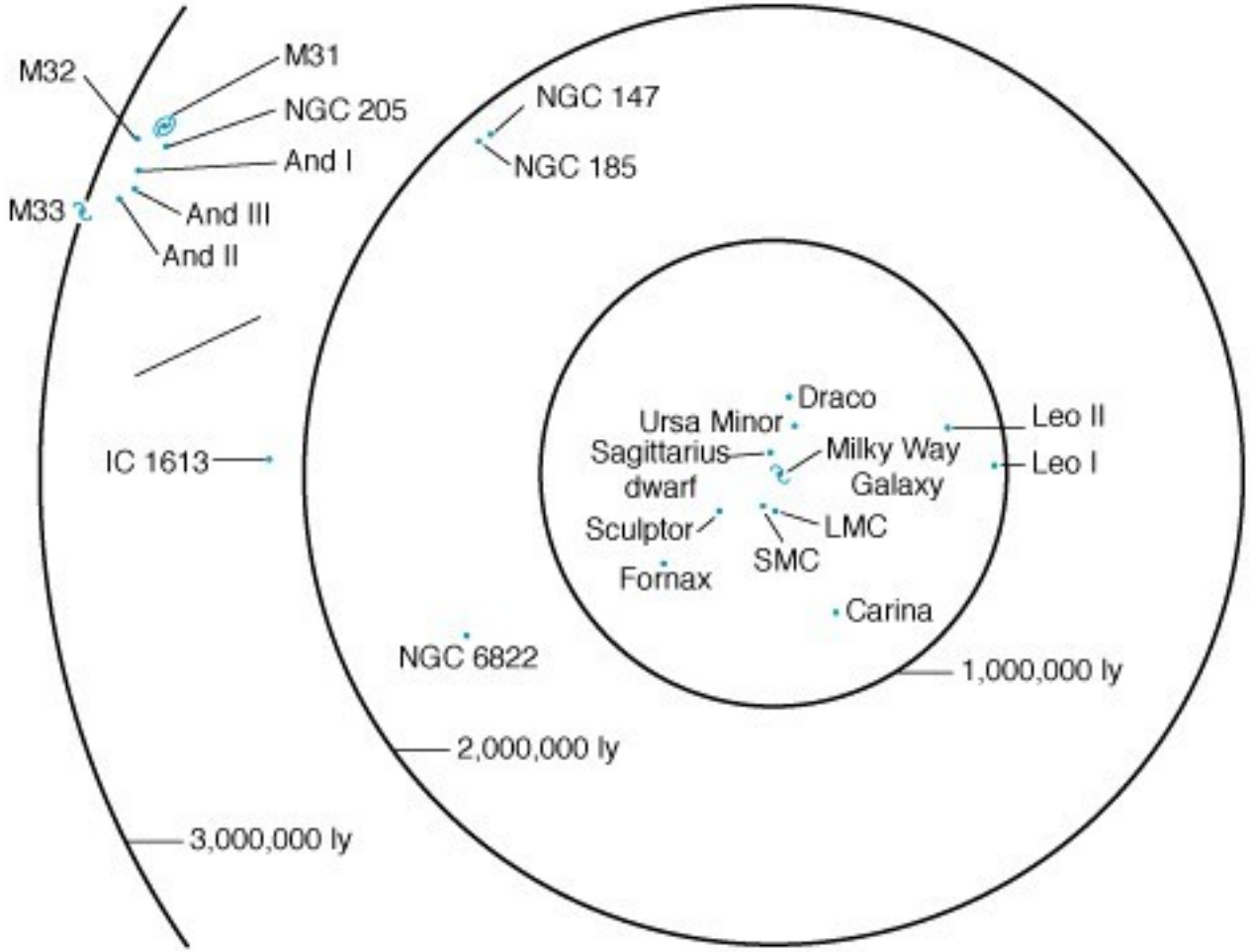
Collections of Galaxies

Galaxies are not distributed randomly throughout the universe – they are usually found in associations of galaxies called **groups** and **clusters**

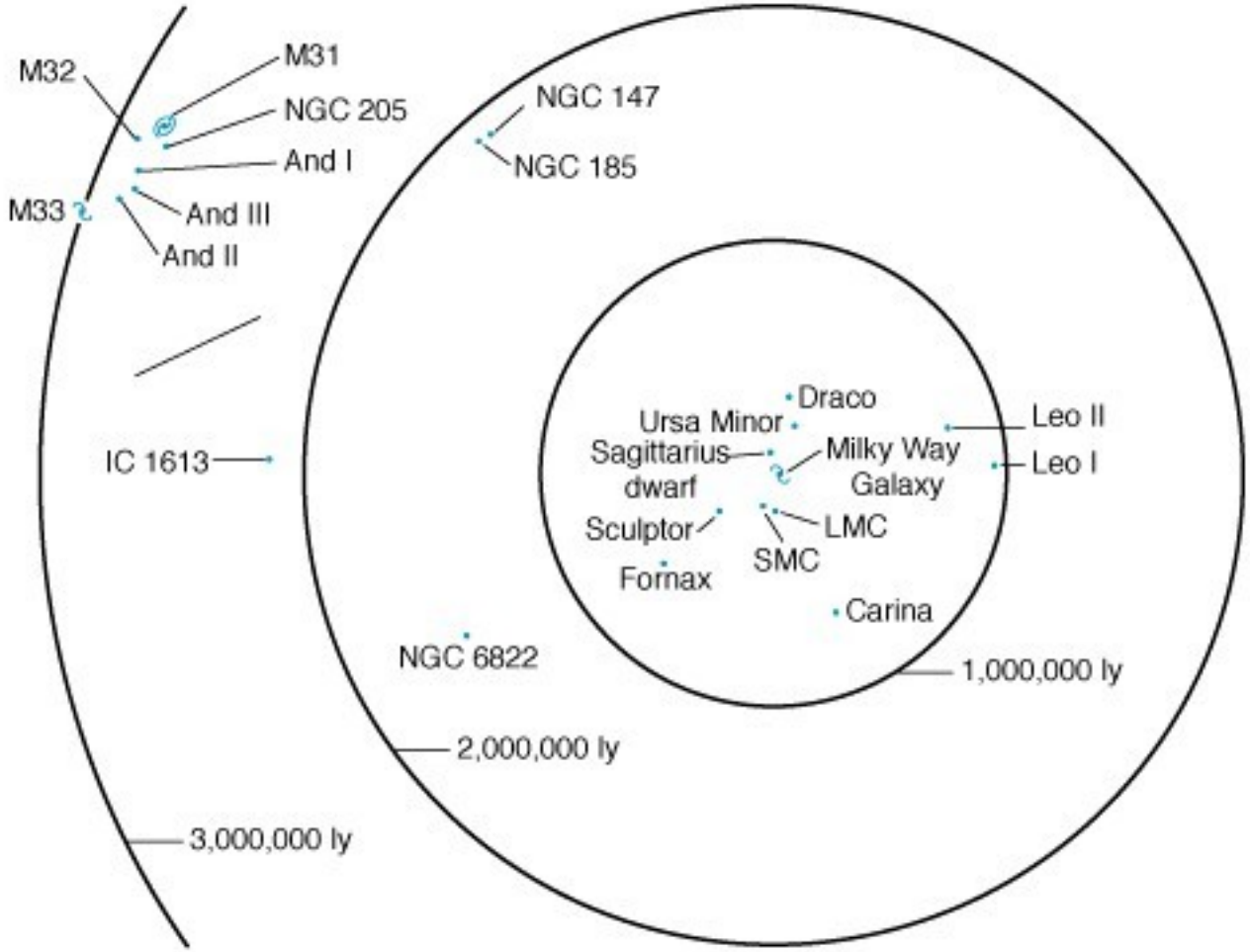
- **Groups** are smaller associations, with usually less than 50 galaxies
- **Clusters** are larger and can contain thousands of galaxies – galaxy clusters are the most massive gravitationally bound objects in the universe

Galaxy clusters and groups

- Galaxy clusters and groups consist of a collection of galaxies orbiting one another, bound together by their own gravity
- The Milky Way, Andromeda, and several other smaller galaxies form the **Local Group**
- The nearest large galaxy cluster to the Local Group is the **Virgo Cluster**
- Galaxy clusters themselves tend to clump together into **superclusters**. The Virgo Cluster, the Local Group, and several other nearby clusters form the **Local Supercluster**

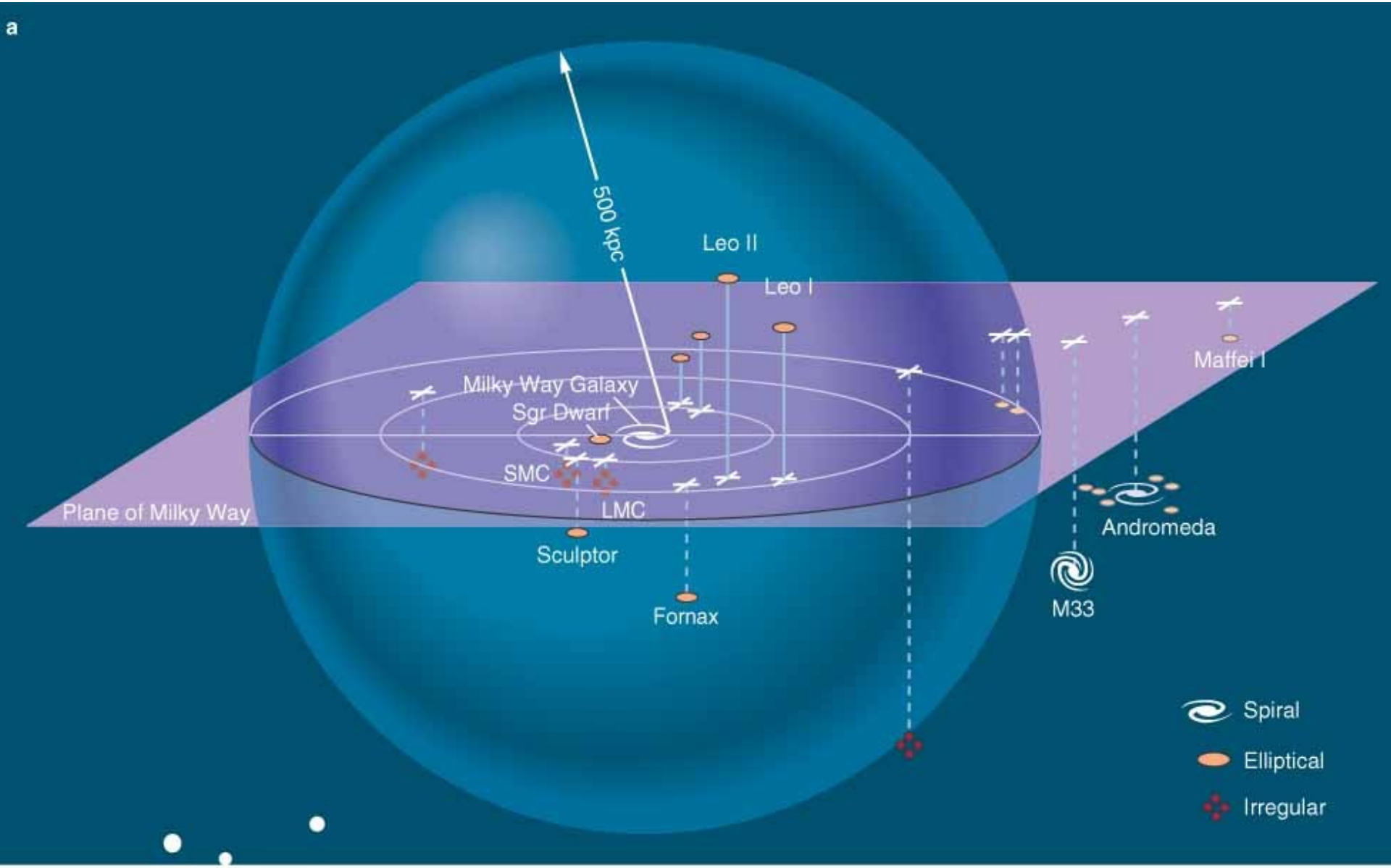


The Milky Way lives in a small group which also contains the Andromeda galaxy and many smaller galaxies. This is called the **Local Group**. The Milky Way and Andromeda make up about 90% of the mass of the Local Group.

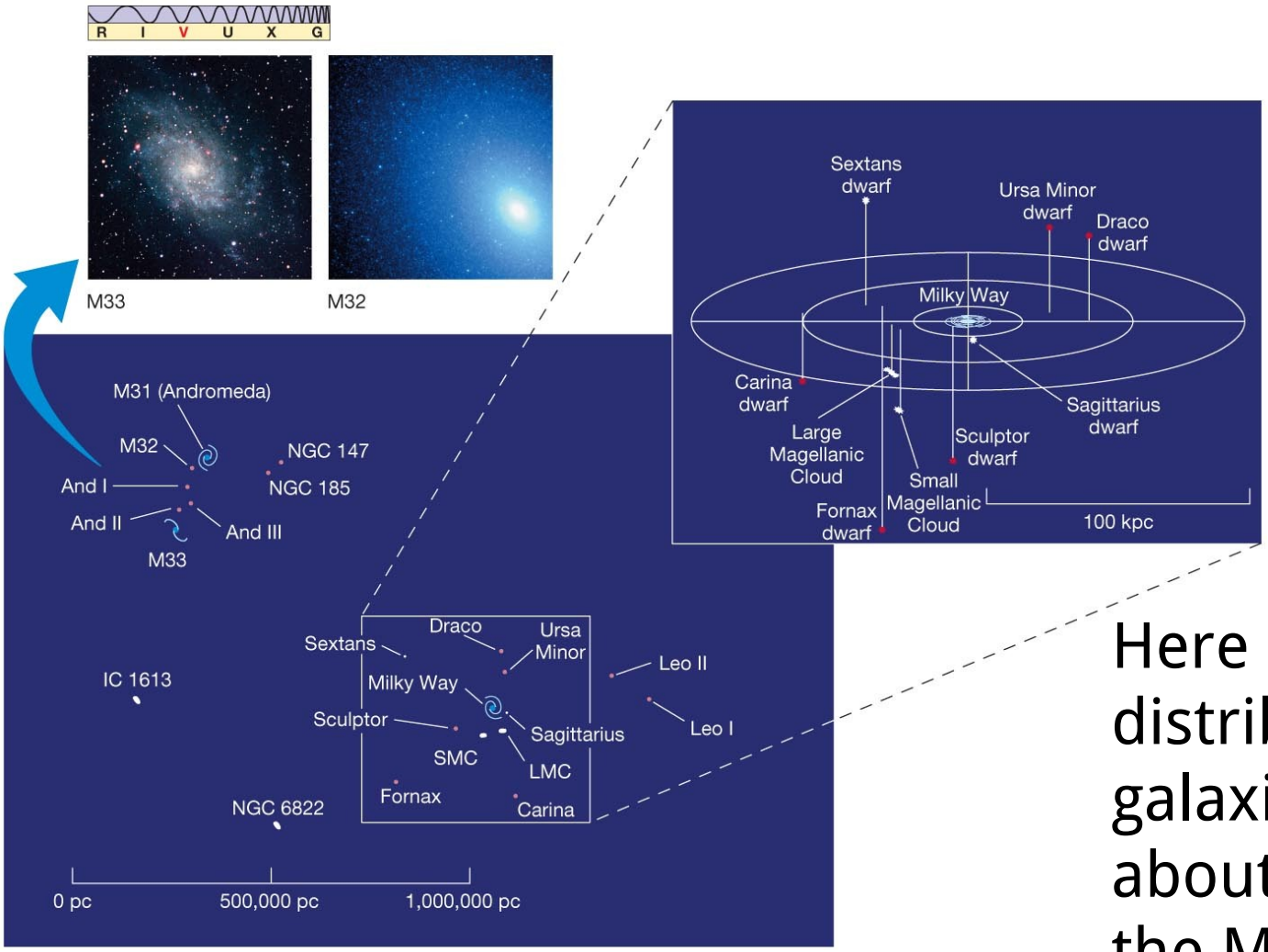


Galaxies in the Local Group are gravitationally bound to each other. The Milky Way and Andromeda are approaching each other, and will collide in billions of years.

3-D map of the Local Group



The Distribution of Galaxies near the Milky Way



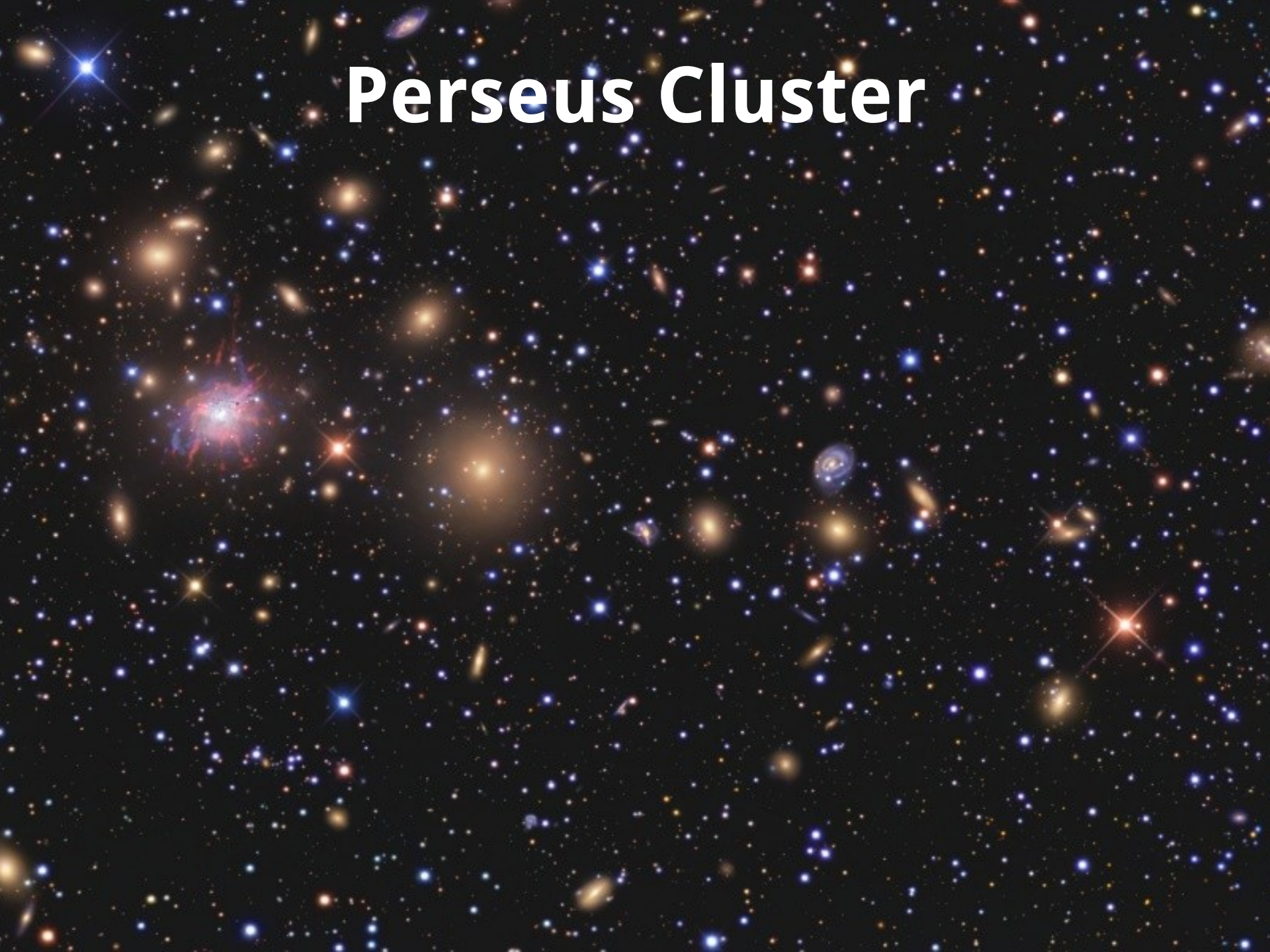
Here is the distribution of galaxies within about 1 Mpc of the Milky Way.

The Virgo Cluster: closest large cluster

Virgo Cluster

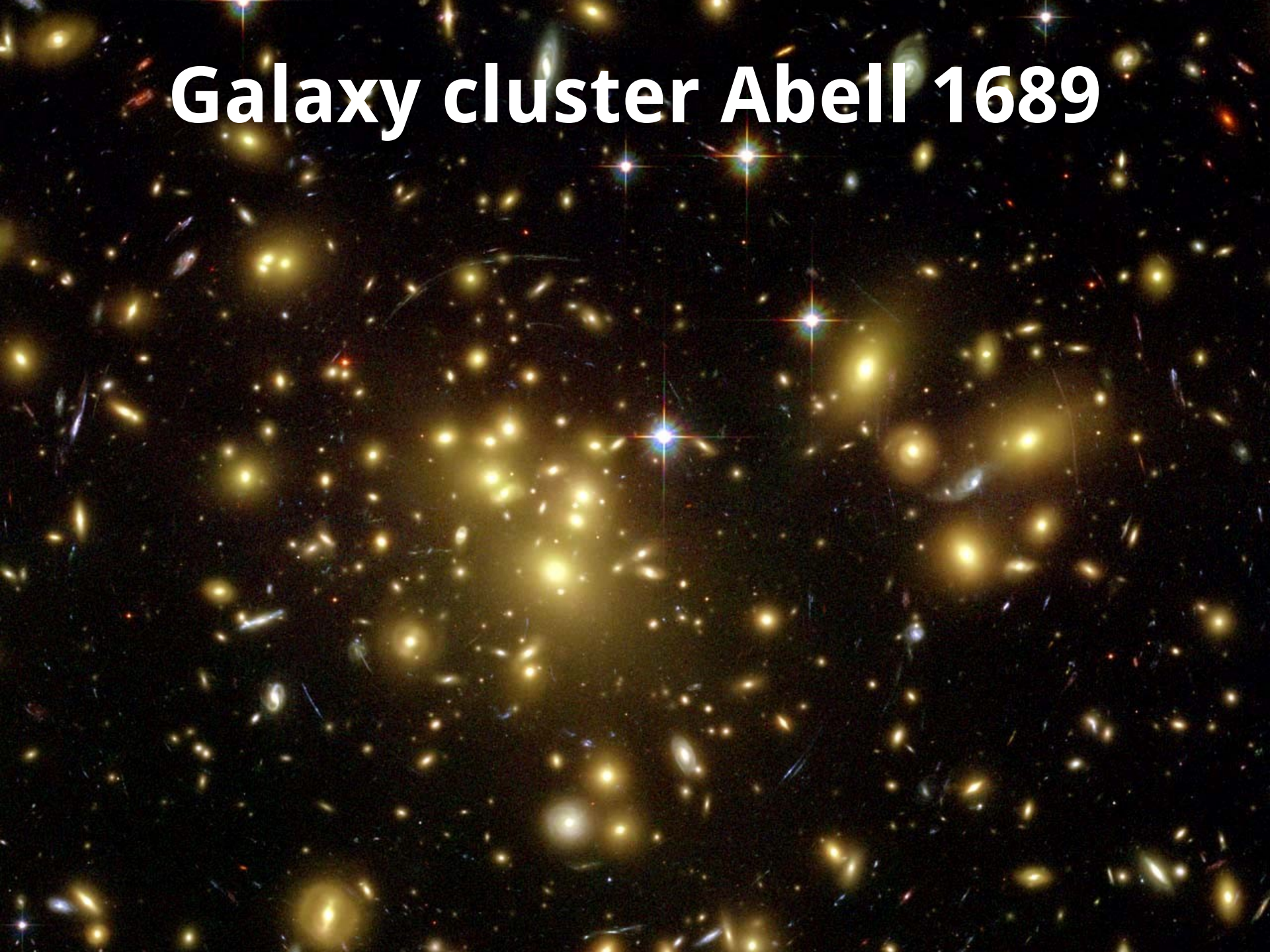
- Covers about 10 x 10 degrees on the sky (~500 x full moon)!
- Contains ~250 large galaxies and >2000 smaller ones
- 4 brightest galaxies are giant ellipticals, mix of spirals and ellipticals otherwise

Perseus Cluster

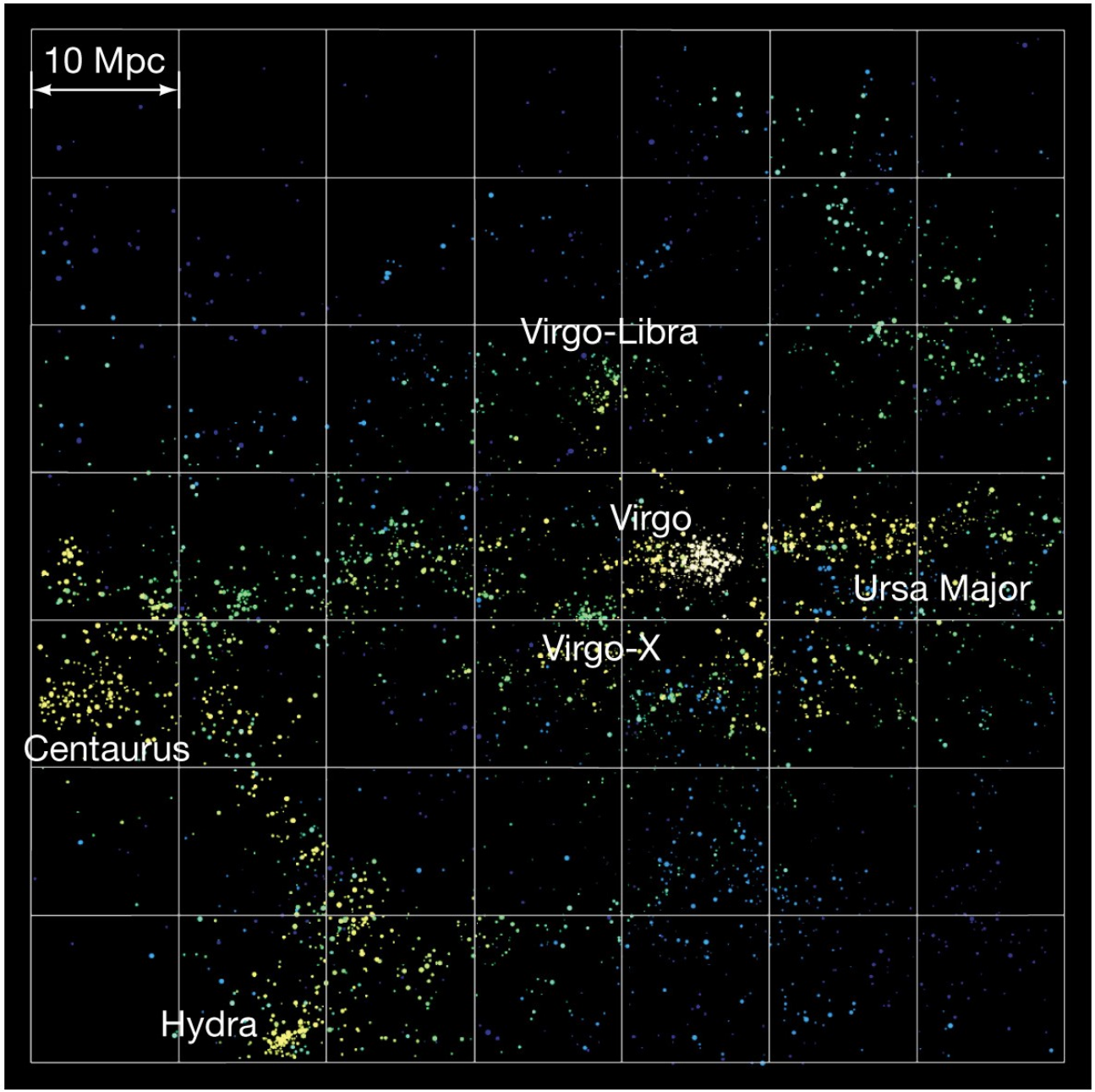


The Hercules Cluster

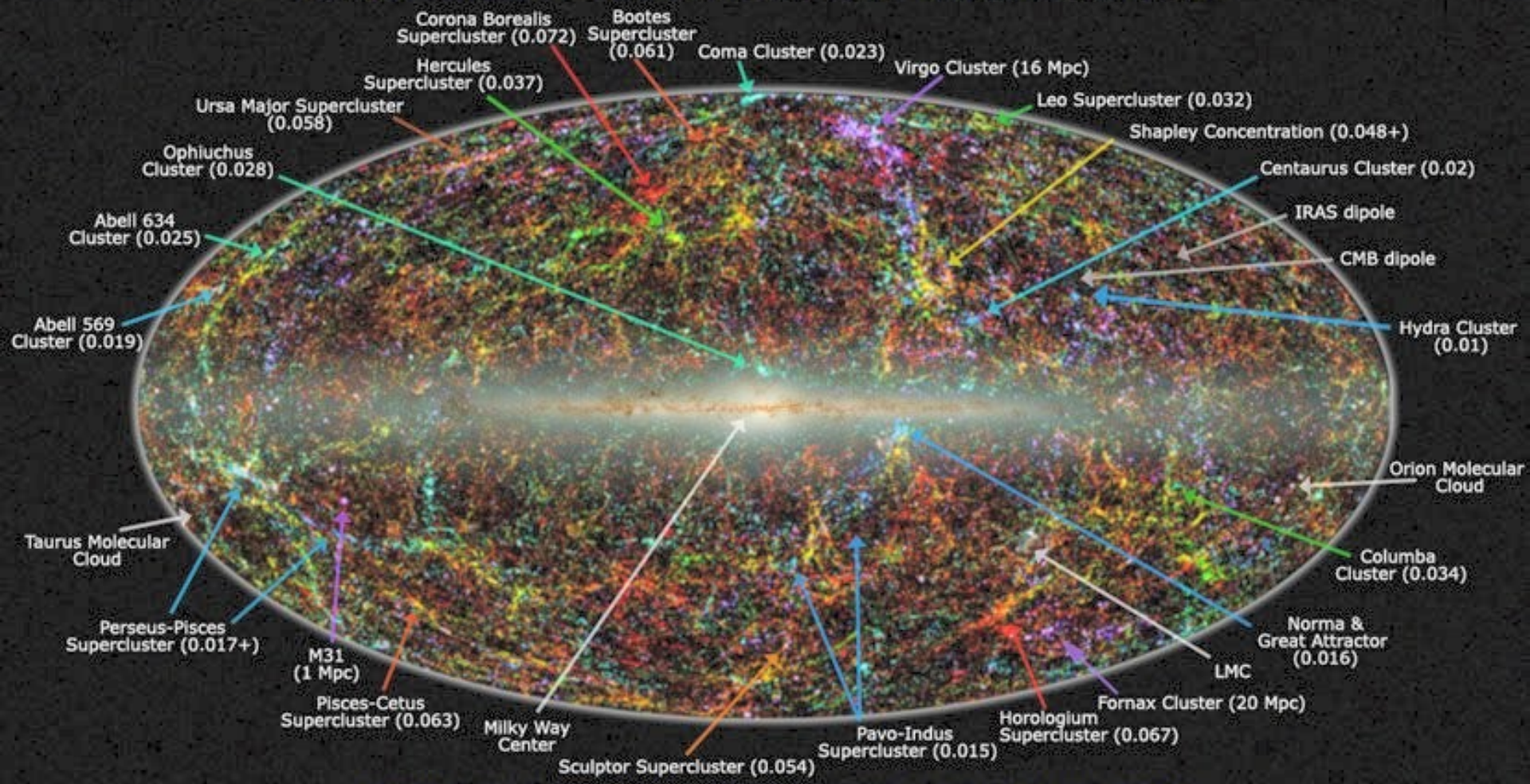
Galaxy cluster Abell 1689



Local Supercluster



Large Scale Structure in the Local Universe



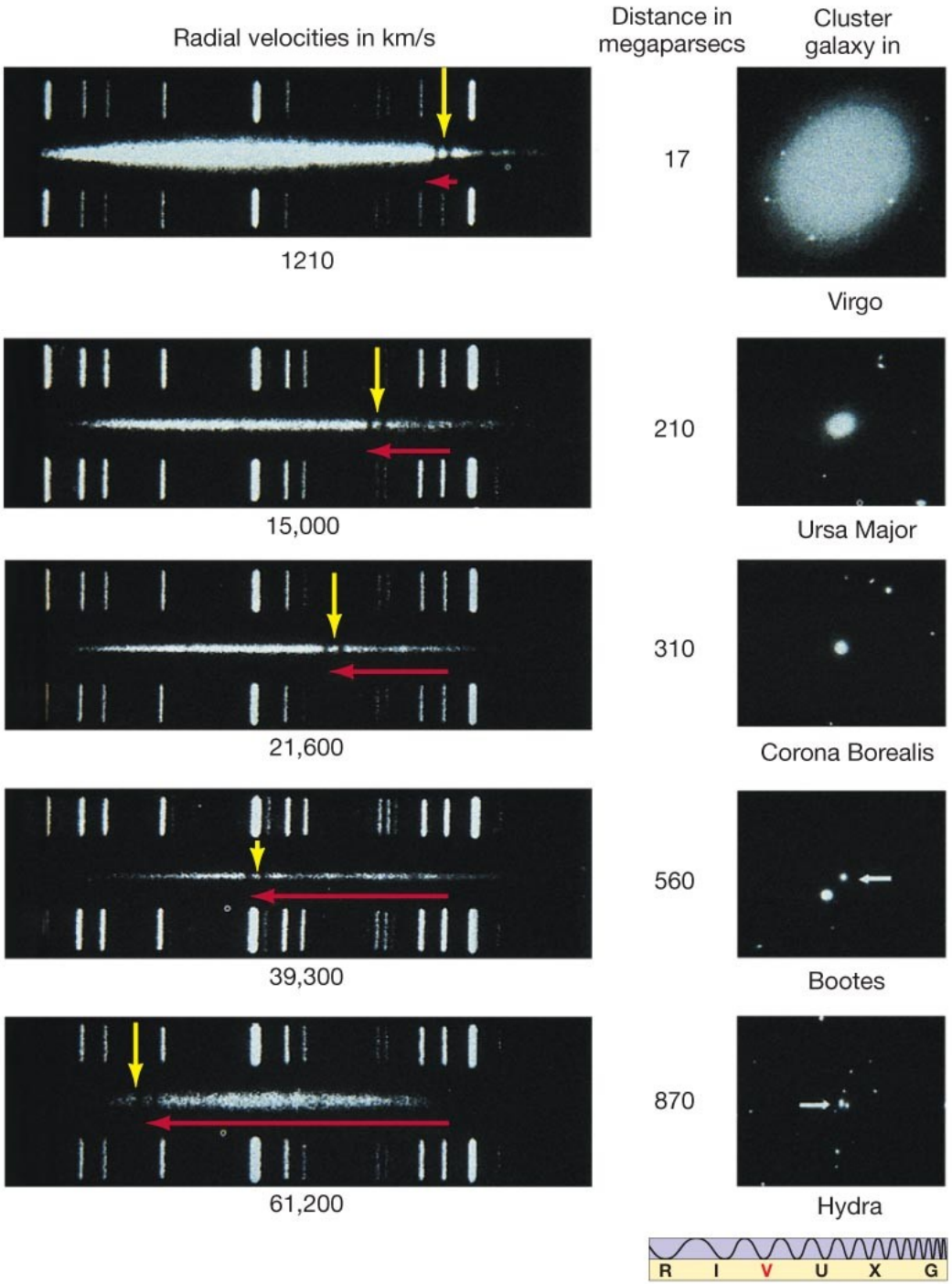
Legend: image shows 2MASS galaxies color coded by redshift (Jarrett 2004); familiar galaxy clusters/superclusters are labeled (numbers in parenthesis represent redshift). Graphic created by T. Jarrett (IPAC/Caltech)

Measuring distances to galaxies

Starting in 1914, Vesto Slipher found that galaxies outside the Local Group are all moving away from us!

When Hubble started measuring their distances using Cepheids, he found that the speed at which they move away increases as the distance to the galaxy increases

Velocity is measured from the redshift of absorption lines – **the faster a galaxy is moving away, the larger the redshift**



THE VELOCITY-DISTANCE RELATION AMONG EXTRA-GALACTIC NEBULAE[1]

By EDWIN HUBBLE and MILTON L. HUMASON

ABSTRACT

Methods of determining distances of extra-galactic nebulae are discussed, and the mean absolute magnitude is revised on the basis of (1) Shapley's revision of the zero-point of the period-luminosity curve for Cepheids, and (2) more extensive observations of stars involved in nebulae. The revised value is M (vis) $= -14.9$.

The mean color-index of the nearer extra-galactic nebulae appears to be of the order of $+1.1$ mag., hence $M(\text{pg}) = -13.8$. A color-excess is suggested which is independent of distance but shows some relation to galactic latitude.

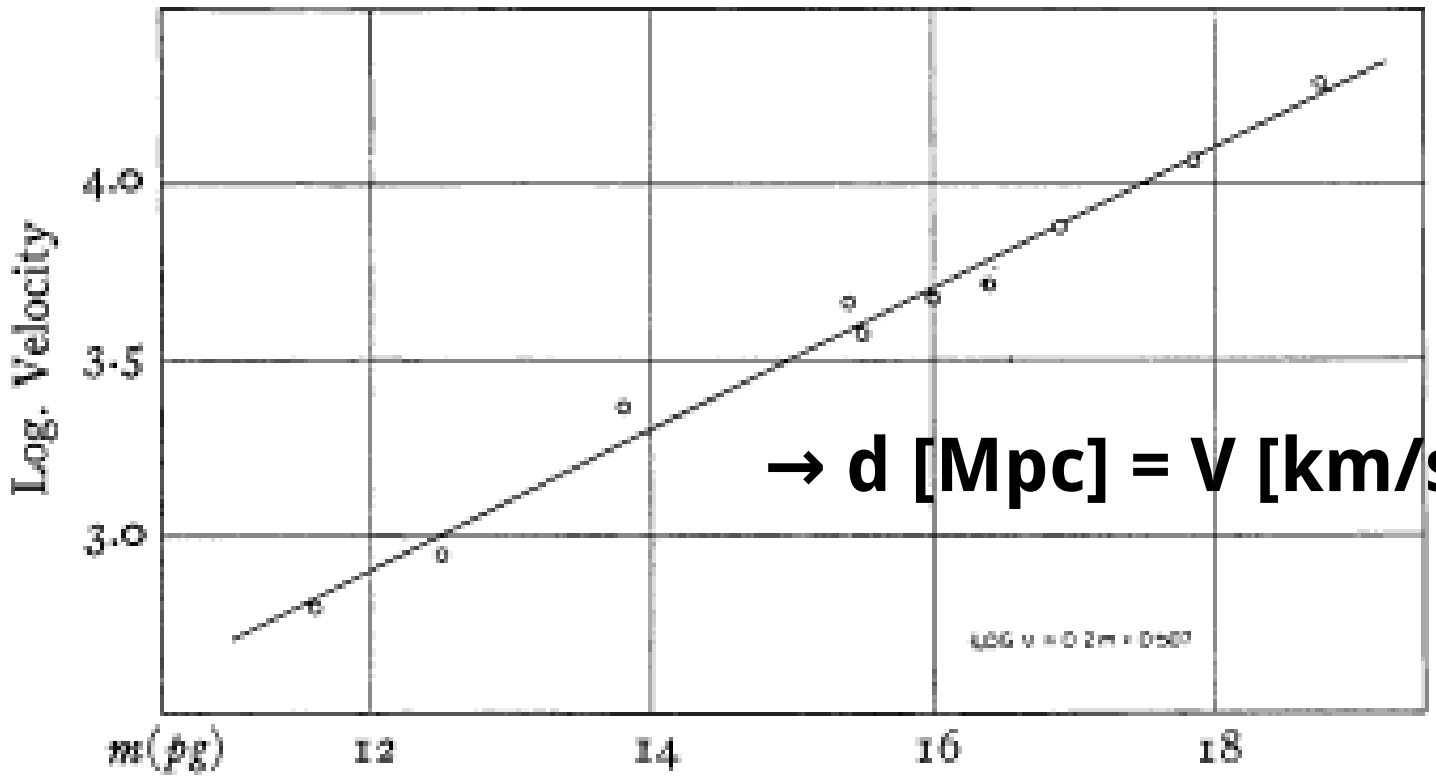
The velocity-distance relation is re-examined with the aid of 40 new velocities, 26 of which refer to nebulae in 8 clusters or groups. Distances of the clusters, ranging out to about 32 million parsecs, have been derived from the most frequent apparent magnitudes. The velocity displacements reduce the apparent magnitudes by amounts which become appreciable for the more distant clusters.

The new data extend out to about eighteen times the distance available in the first formulation of the velocity-distance relation, but the form of the relation remains unchanged except for the revision of the unit of distance. The relation is

$$\text{Vel.} = \frac{\text{Dist. (parsecs)}}{1790},$$

→ **d [Mpc] = V [km/s] / 55**

and the uncertainty is estimated to be of the order of 10 per cent.



→ d [Mpc] = V [km/s] / 558

FIG. 4.—Correlation between the quantities actually observed in deriving the velocity-distance relation. Each point represents the mean of the logarithms of the observed red-shifts (expressed on a scale of velocities) for a cluster or group of nebulae, as a function of the mean or most frequent apparent photographic magnitude.

Each dot shows the distance to a galaxy and the speed with which it is moving away from us.

Hubble's Law

- Galaxies outside our local group of galaxies are moving away from us, because the universe is expanding! Their speed increases with their distance from us according to the Hubble law:

$$v = H \times d$$

- v = velocity in km/s
- d = distance in megaparsecs (1 Mpc = 3.26×10^6 ly)
- The Hubble constant: H = 70 km/s/Mpc (Uncertainty: 65-75 km/s/Mpc)

Hubble's Law

$v = H \times d$ is called the **Hubble Law** and H is the **Hubble constant**.

To determine it, we need to measure the velocity of many many galaxies, and their distances

- Velocities are easy, from the redshift of spectral lines
- Distances are harder: we use the Cepheid variable stars we talked about earlier and other methods

The Hubble Key Project

The value of Hubble's constant relies on using Cepheids to obtain the distance to the Virgo Cluster (50 Mly or 18 Mpc) and to other galaxies within 100 Mly

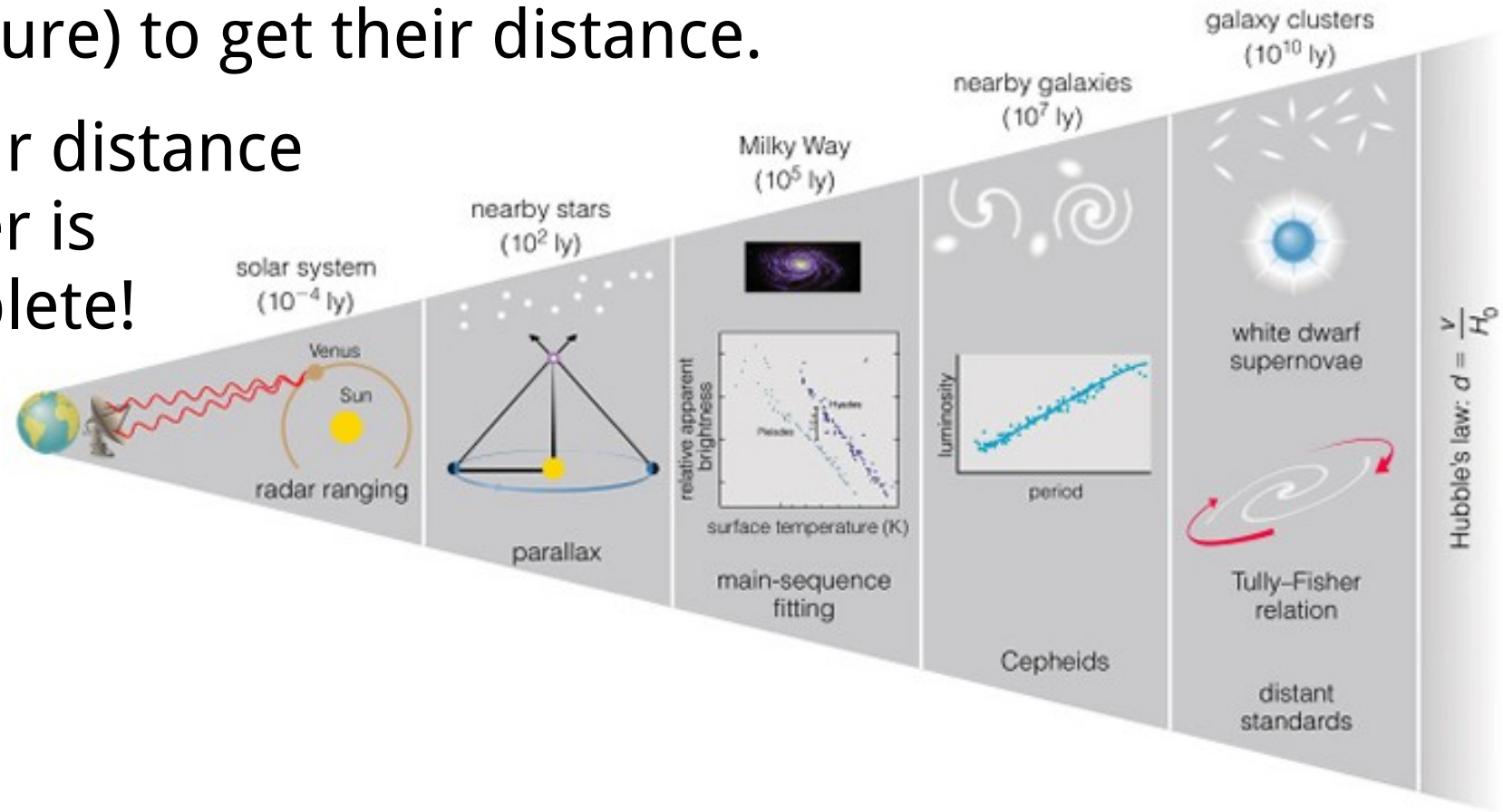
→ This was one of the main scientific drivers to build a telescope in space; this telescope was later renamed to **Hubble Space Telescope**

Key Project of Hubble Space Telescope: Measure the Hubble constant using Cepheid variable stars

Hubble's Law and the Distance Ladder

Once we figure out the value of Hubble's constant, we can use the velocity of distant galaxies (easy to measure) to get their distance.

So our distance ladder is complete!



Hubble's law

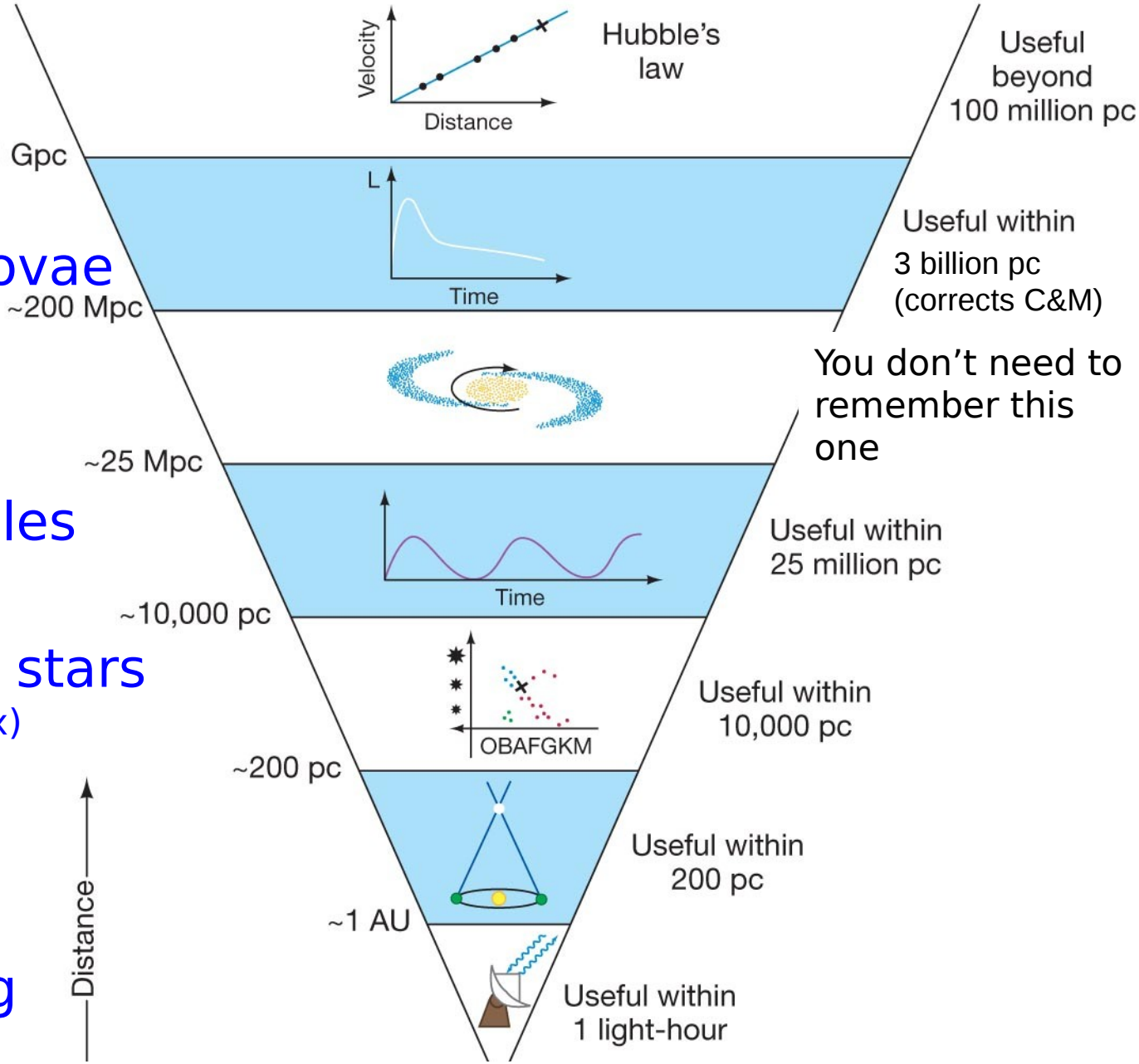
Type Ia supernovae

Cepheid variables

Main sequence stars
(spectroscopic parallax)

Parallax

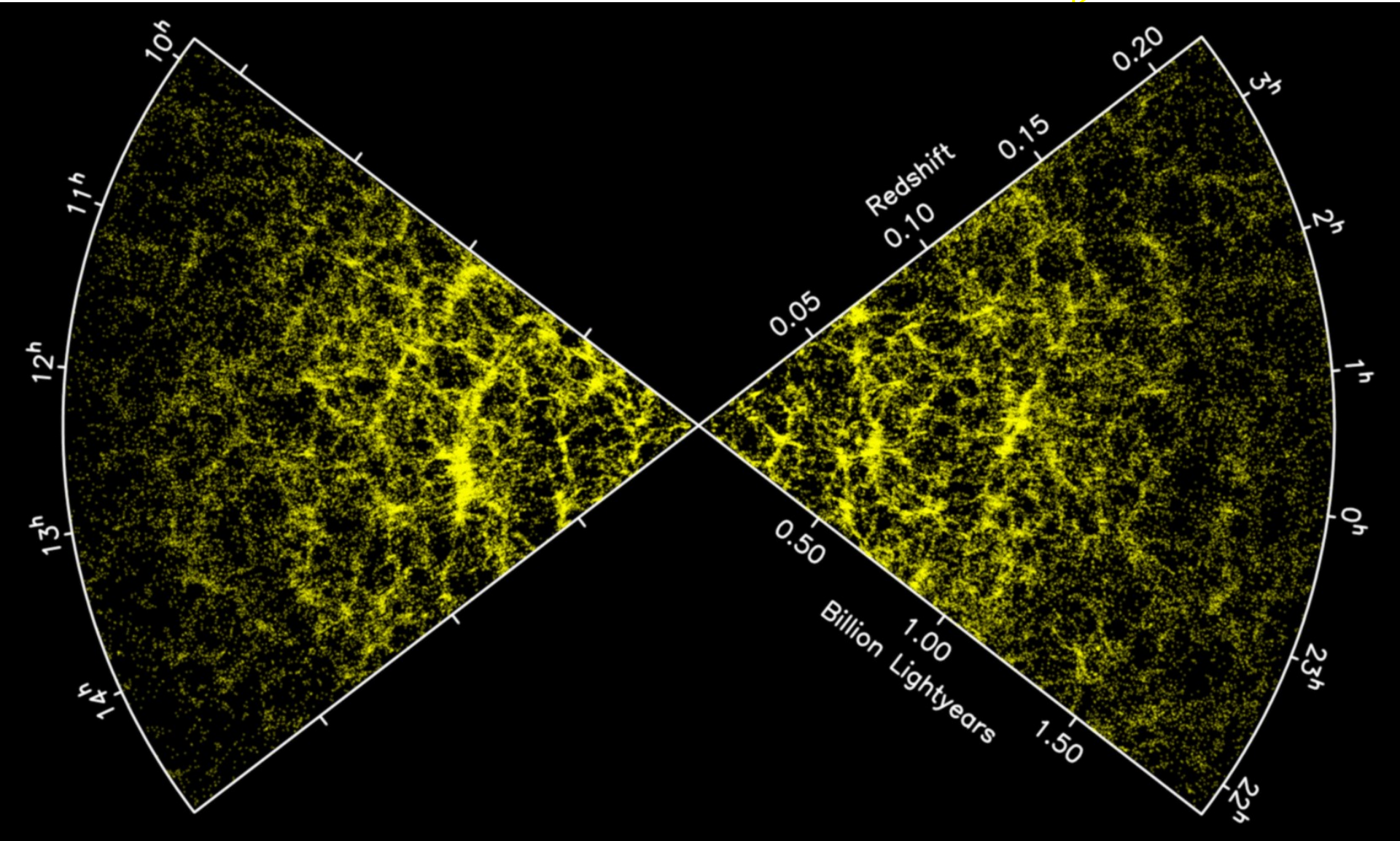
Radar bouncing



Minor corrections to C&M's diagram:

1. Hubble's law and Type Ia supernovae both rely on distances from Cepheids. You don't need Type Ia supernovae to get Hubble's law.

Redshift Surveys Map the Distribution of Galaxies



Hubble's Law

$$v = H \times d, \; H = 70 \text{ km/s/Mpc}$$

Let's do a few examples.

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A galaxy is 100 Mpc away. How fast is it moving away from us?

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1. $v = H \times d = 70 \times 100 = 7000$ km/s

- A galaxy is 100 Mpc away. How fast is it moving away from us?
  - v = H × d = 70 × 100 = 7000 km/s

A galaxy is 2000 Mpc away. How fast is it moving away from us?

A galaxy is 2000 Mpc away. How fast is it moving away from us?

2. $v = H \times d = 70 \times 2000 = 140{,}000$ km/s

- A galaxy is 2000 Mpc away. How fast is it moving away from us?
  - v = H × d = 70 × 2000 = 140,000 km/s

Hubble's Law

$v = H \times d$, $H = 70$ km/s/Mpc

Let's do a few examples.

- A galaxy is moving at 700 km/s away from us. How far away is it?
  - $d = v/H = 700/70 = 10$ Mpc
- A galaxy is moving at 21,000 km/s away from us. How far away is it?
  - $d = v/H = 21{,}000/70 = 300$ Mpc

Hubble’s Law is based on

A More distant galaxies showing greater blueshifts

B Distant galaxies appearing proportionally dimmer

C More distant galaxies showing greater redshifts

D Slowly varying Cepheid variables appearing brighter

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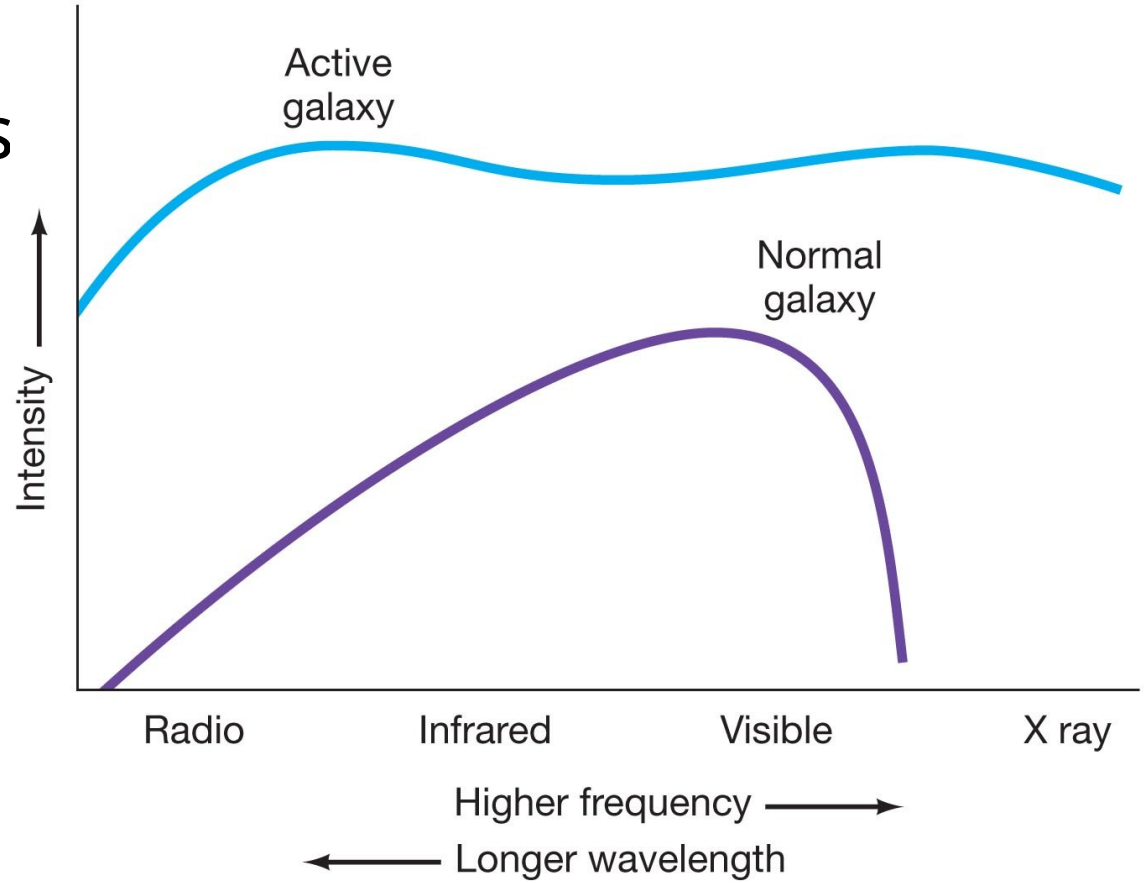
Active Galaxies

About 20–25 percent of galaxies don't fit well into the Hubble scheme – they are far too luminous.

Such galaxies are called active galaxies They differ from normal galaxies in both their luminosity and in the type of radiation they emit.



Galactic Spectra

Galaxies are made of large collections of stars, so we might expect their spectra to look like the spectra of a bunch of stars, peaking in visible light

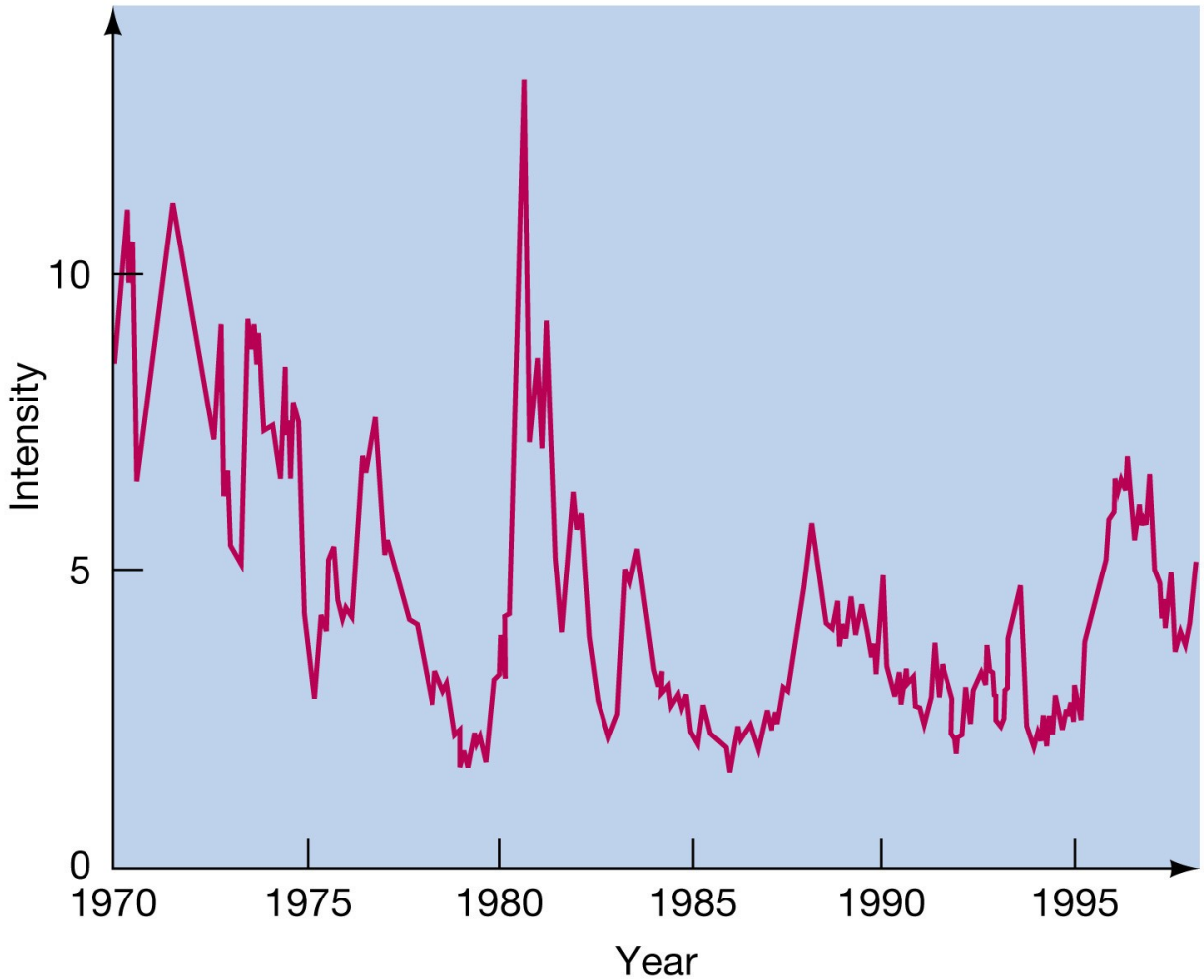
This is true for most galaxies, but not for all of them. Some galaxies show strong **nonstellar radiation**.

Because they are bright, they are called **active galaxies**

Seyfert Galaxies

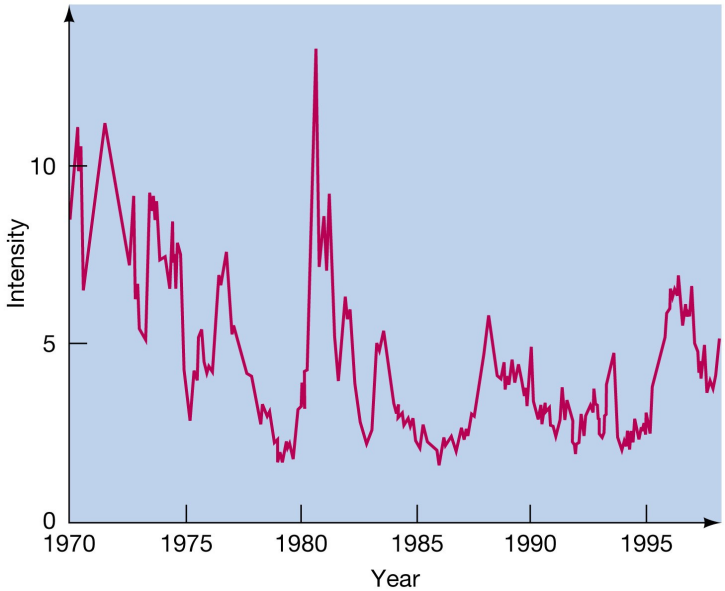
Seyferts vary in brightness over a year to few years timescales.

Rapid variability implies that the central source is only a few light years (at most) across.



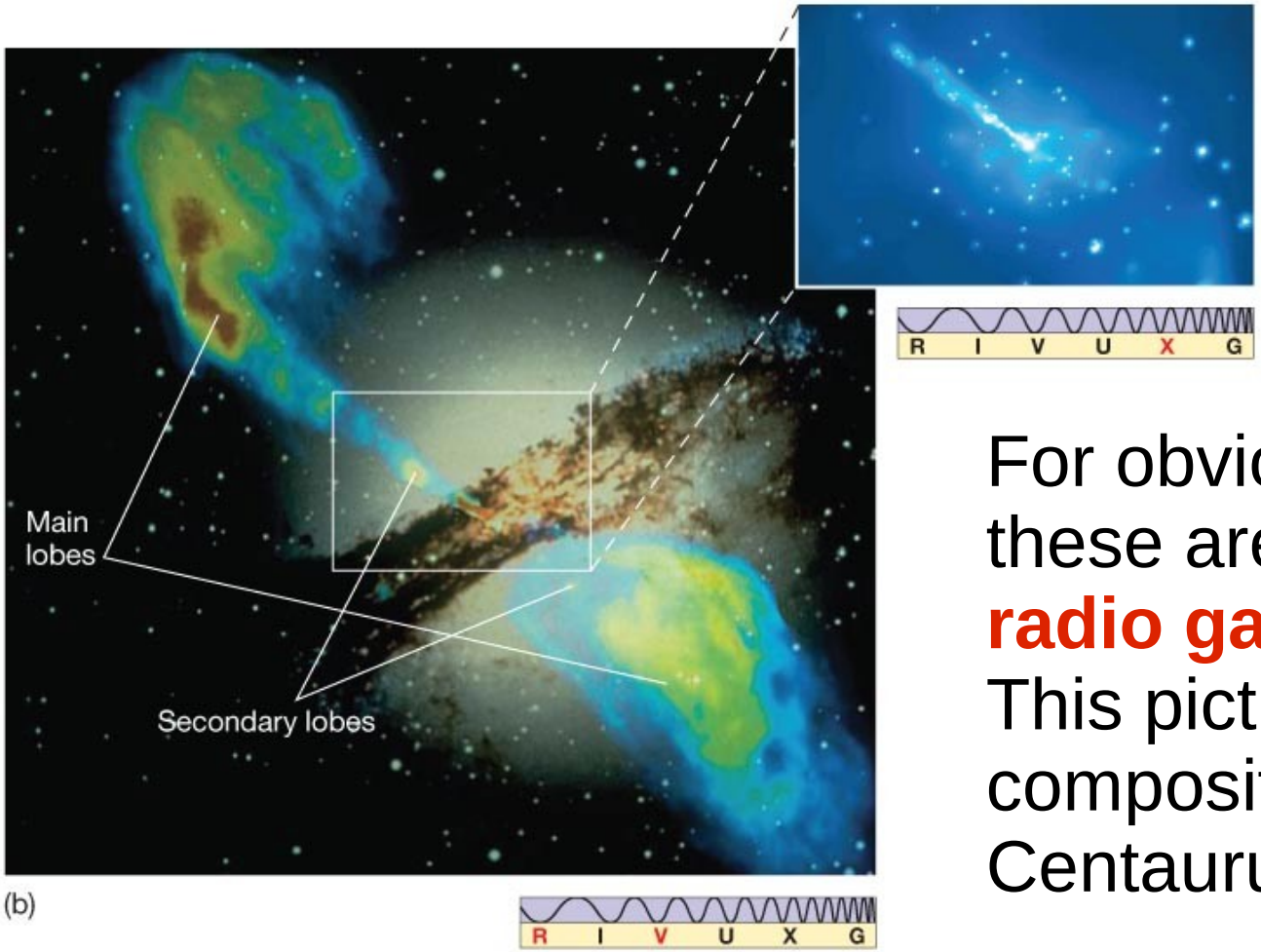
Seyfert Galaxies

Why does rapid variability imply small size?



- A source that changes in brightness in time t can't be bigger in size than c x t, since light needs time to travel across the object
- So something that changes in 1 year can't be more than one light year in size!

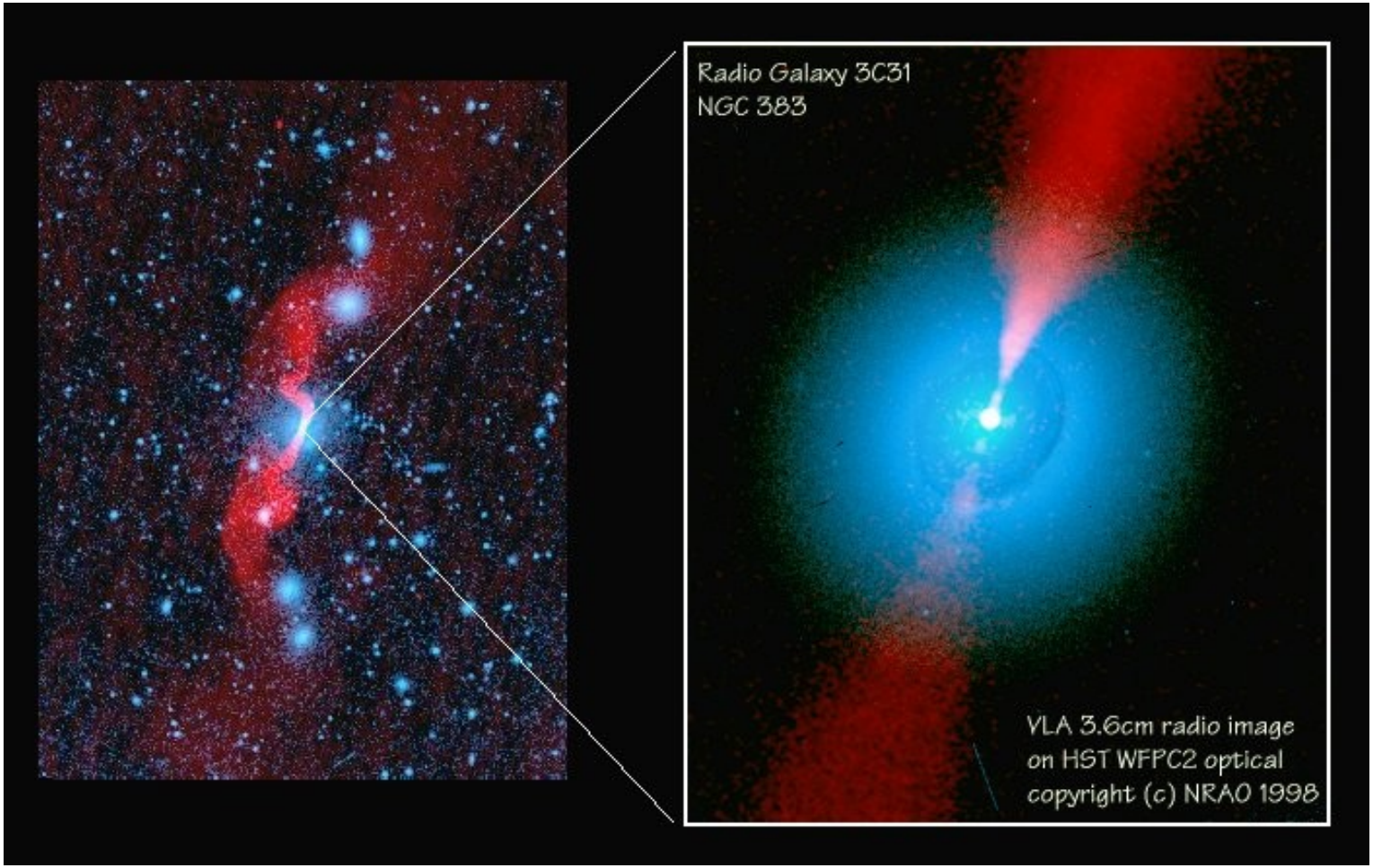
Other types of galaxies emit very strongly in the radio, but the radio emission doesn't always come from the central source, but instead two giant lobes that extend away from it.



For obvious reasons, these are called **radio galaxies.** This picture is a composite of Centaurus A.

Radio galaxies

Radio galaxies emit large amounts of energy in the radio part of the spectrum. The corresponding visible galaxy is usually **elliptical**.



Radio Galaxies

Radio galaxies may also be core dominated.