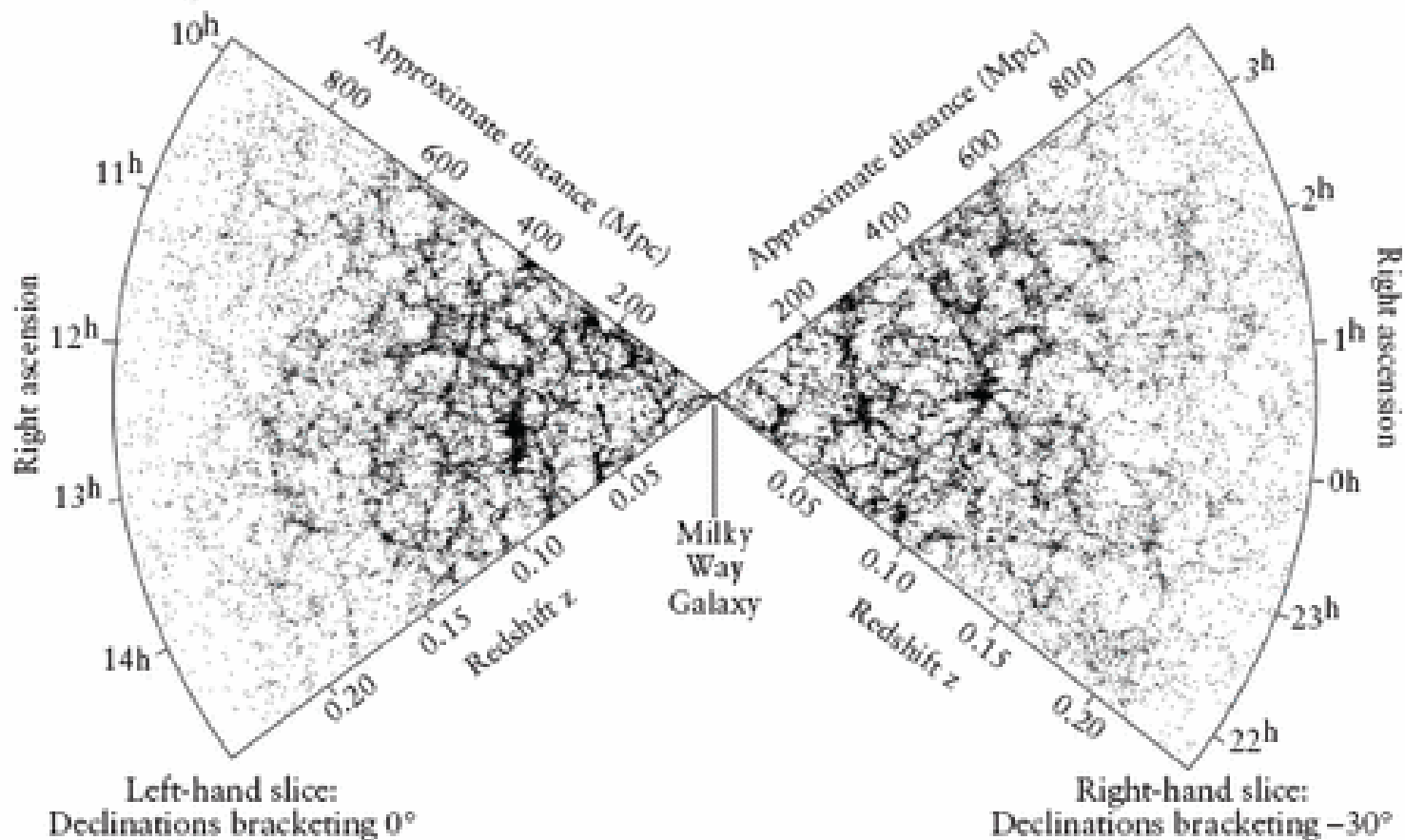
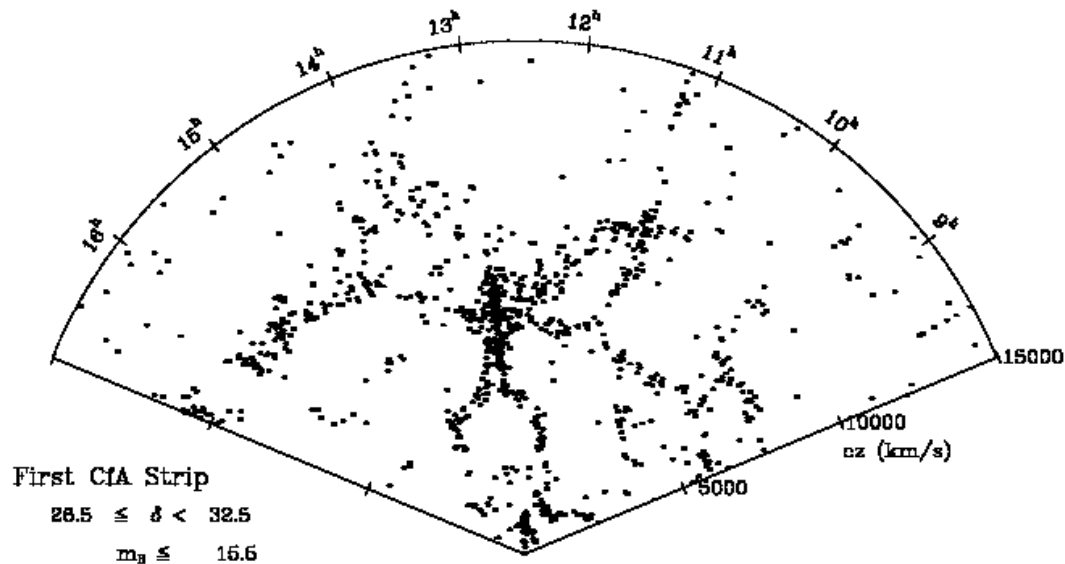


# The Structure of the Universe



(a) The 2dF galaxy survey

# CfA Stick Man



The First CfA Survey, completed in 1982, produced the first large area and moderately deep maps of large scale structure in the nearby universe. It showed that the universe was not homogeneous as had previously been believed, but that galaxies and clusters of galaxies reside in a filamentary network of "superclusters". The famous "CfA Stick Man" in the image is an example of such a supercluster. The structures are leftover remnants of the initial density fluctuations in the early universe and are expanding with the universe. Galaxies are thought to flow along the filaments towards galaxy clusters which form at the intersections.

# Measuring the Distances to Galaxies

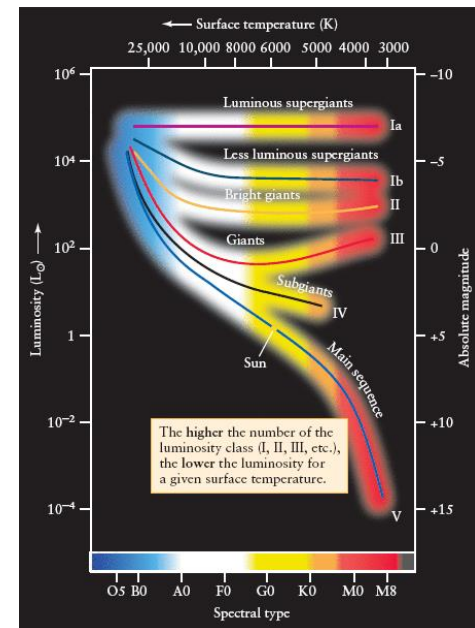
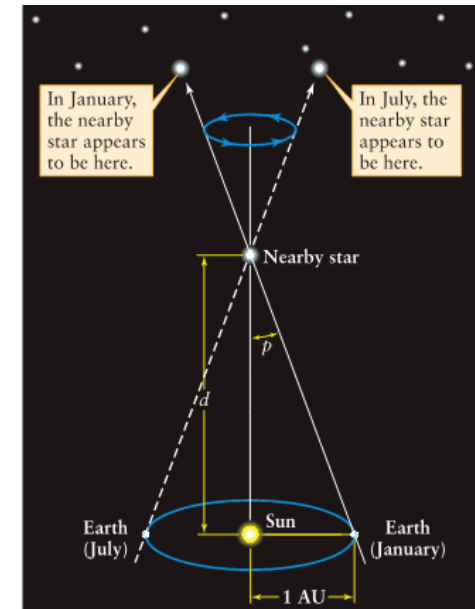
**Parallax** methods cannot be used to measure the distances to galaxies since they can only be used to measure objects relatively nearby.

Observations by the GAIA satellite permit measurements of parallax angles down to  $200 \mu \text{ arcsec}$  and distances to 5kpc

$$d = (1/p) \text{ parsec, } p \text{ in arcsec.}$$

**Spectroscopic parallax** can measure objects accurately up to about 10 kpc. From a stellar spectrum obtain the spectral type and luminosity class. Then use the HR diagram to infer luminosity or absolute magnitude.  $d = \left( \frac{L}{4\pi F} \right)^{1/2}$

What are the luminosities of :  
M0 V star? A0 Ia star?



# Main Sequence Fitting

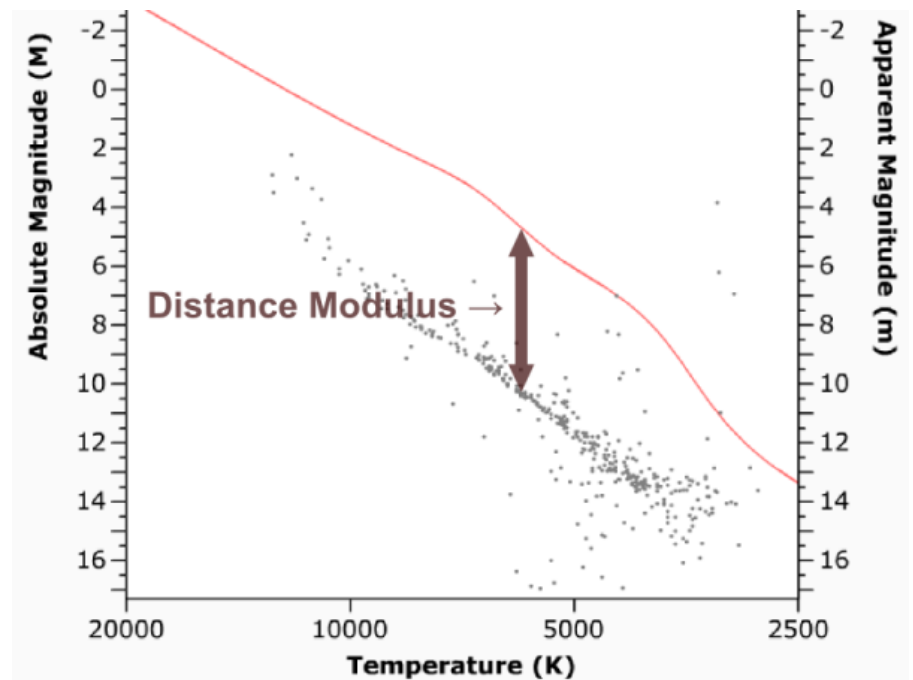
Place stars of a star cluster on the main sequence using their apparent magnitudes. One can then identify the stars in the star cluster that belong on the main sequence.

The offset between the apparent magnitudes of the star cluster and the main sequence stars is the distance modulus:  $m-M$

It is important to correct the apparent magnitude of the star cluster stars for extinction

$$m - M = 5 \log_{10} d - 5$$

Why can the main sequence fitting method be used for stars in star clusters and not for isolated stars?

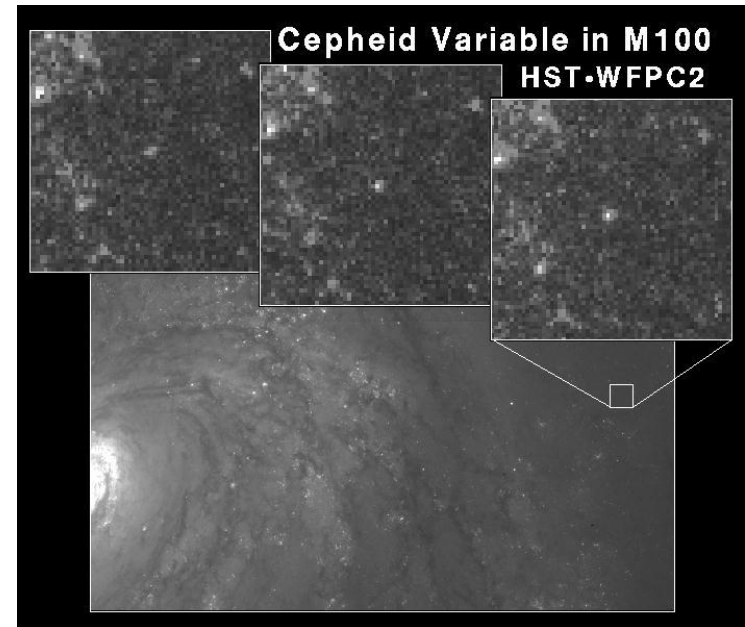


# Variable Stars: Cepheid Variables

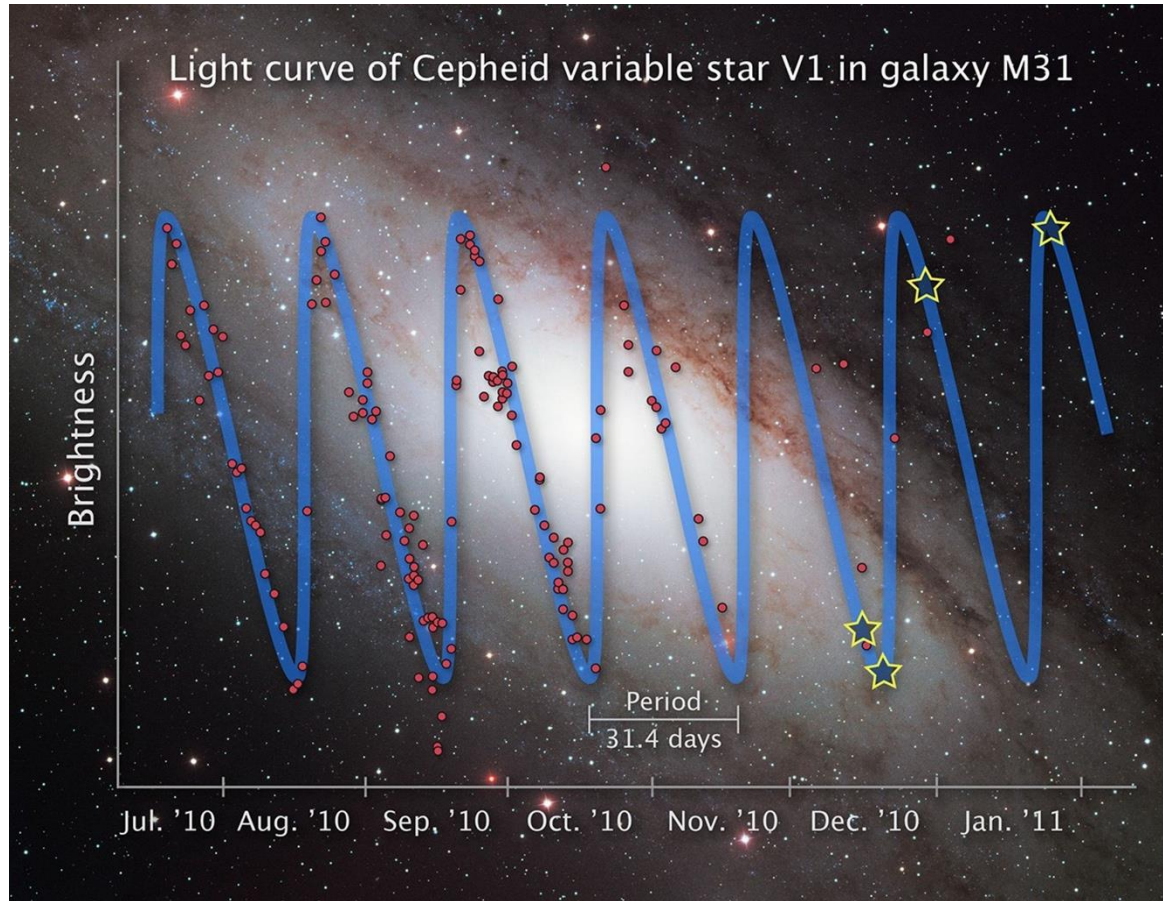
**Pulsating supergiant stars** that exhibit rapid brightening followed by gradual dimming with periods ranging from a few to a hundred days **are called Cepheid variables.**

The pulsations of the surfaces of Cepheids are caused by an imbalance between the power generated in the core and power radiated from the surface.

The first Cepheid variable discovered was  $\delta$  Cephei.



# Variable Stars: Cepheid Variables



Ten amateur astronomers from around the world made 214 observations of V1 between July 2010 and December 2010, obtaining four pulsation cycles. The four stars on the graph denote observations made by the Hubble Space Telescope's Wide Field Camera 3.

# Period-Luminosity Relations of Cepheids

A measurement of the apparent magnitude (or flux) of an object combined with its absolute magnitude (or luminosity) that is inferred from the **Period-Luminosity relation** of Cepheids provides the distance to the object.

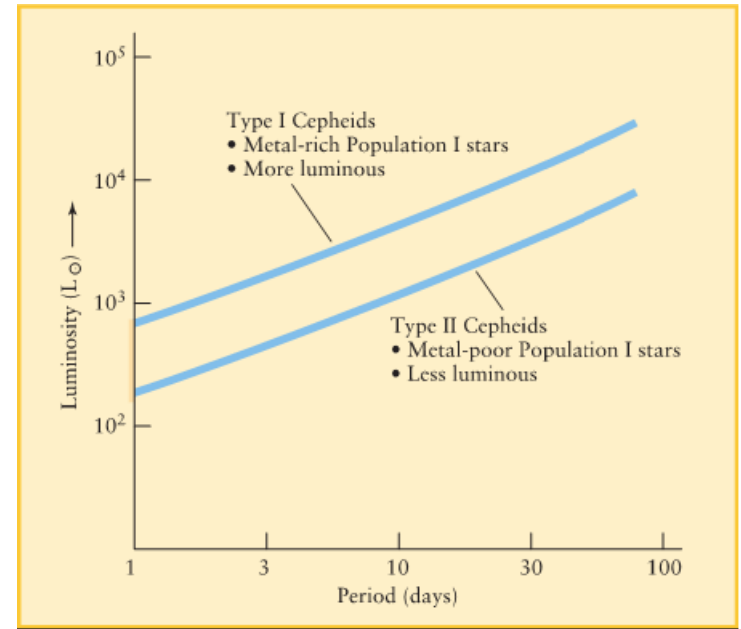
For classical Type-I Cepheids **Henrietta Leavitt** discovered:

$$M_V = -3.53 \log P_d - 2.13 + 2.13(B - V)$$

More recent HST parallax measurements give:

$$M_V = (-2.43 \pm 0.12)(\log_{10} P_d - 1) - (4.05 \pm 0.02)$$

(period  $P_d$  in days)



**Period-Luminosity Relations for Cepheids.** The greater the average luminosity of a Cepheid variable, the longer its period. There are two distinct period-luminosity relations—one for Type I Classical Cepheids and one for Type II Cepheids.

# Distance to galaxy IC 4182

## **Example: Galaxy IC 4182**

A metal rich Cepheid variable in IC 4182 has a period of 42 days. Observations indicate the apparent magnitude of this Cepheid to be  $m = +22.0$ .

What is the distance to the Cepheid variable in IC 4182?

## Distance to galaxy IC 4182

### **Example: Galaxy IC 4182**

A metal rich Cepheid variable in IC 4182 has a period of 42 days. Observations indicate the apparent magnitude of this Cepheid to be  $m = +22.0$ .

Solution:

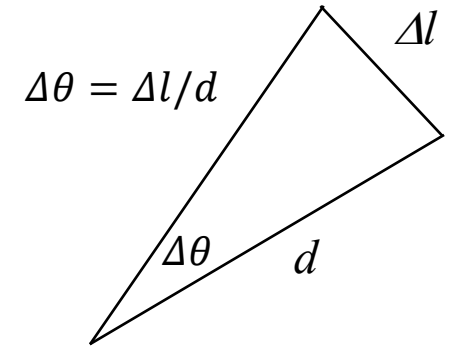
The period-luminosity relation gives  $M_V = -5.56$ .

$$m - M = 5 \log d - 5 \rightarrow d = 10^{(m-M+5)/5} \text{ parsec} \sim 3.3 \times 10^6 \text{ parsec}$$

# Expanding Supernovae as Distance Indicators

$$\omega = \frac{\Delta\theta}{\Delta t} \text{ (angular expansion rate) (1)}$$

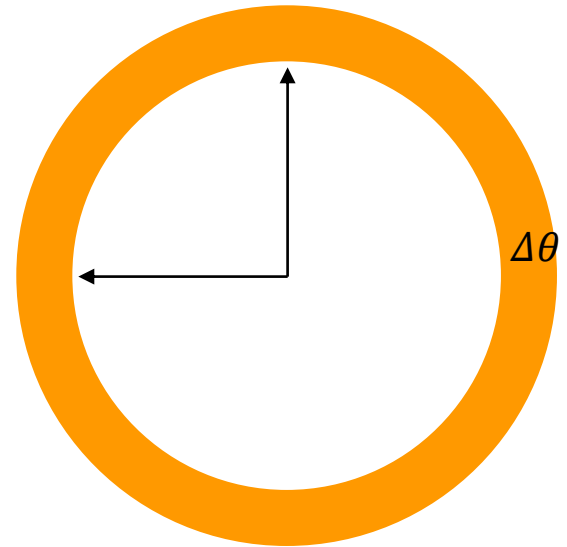
$$v_{ej} = \frac{\Delta l}{\Delta t} = d \frac{\Delta\theta}{\Delta t} \text{ (ejection velocity). (2)}$$



Assuming spherical ejection:

$$v_{ej} = \frac{\Delta\lambda}{\lambda} c \text{ (3)}$$

$$(1) \wedge (2) \wedge (3) \Rightarrow d = \frac{\Delta\lambda}{\lambda} c \frac{1}{\omega}$$



# Measuring the Distances to Galaxies

**Standard Candles:** Objects of known luminosity.

1.) *Cepheid Variables* : **Supergiant pulsating stars** where their periods are a function of their average luminosity. Can be used to determine distances up to 100 Mly.

2.) *RR Lyrae Variables* : Pulsating **horizontal branch stars of spectral class A** with a period of less than a day. They are old, relatively low mass, metal-poor Population II stars.

Can be used to determine distances up to 300,000 ly.

3.) Expanding Supernovae as distance indicators

4.) *SN Type Ia*: these supernovae occur when a white dwarf in a close binary system accretes enough matter from its companion to blow itself apart when  $M > 1.4 M_{\odot}$ . Their spectra lack hydrogen emission but contain a strong Si absorption line.

As a first approximation the blue and visual absolute magnitudes of Type Ia's are :

$M_B \sim M_V \sim -19.3 \pm 0.03$  at maximum.

A large rate of decay of light-curve of Type Ia  $\rightarrow$  lower peak luminosity

Can be used to determine distances up to  $3 \times 10^9$  ly.

# Measuring distances to Galaxies with SN Type Ia



(a) M100 in March 2002

R I **V** U X G



(b) M100 in February 2006, showing Supernova 2006X

R I **V** U X G

VLT images of M100 (a) before and (b) after a Type Ia supernova exploded within the galaxy in 2006. The distance to M100 ( $\sim 55$  Mly) is also known from observations of Cepheid variables, so this particular supernova can help calibrate Type Ia supernovae as distance indicators.

# Estimating the distances to Spiral Galaxies

Tully and Fischer found that the width of the hydrogen 21-cm line of a spiral galaxy is related to its luminosity. This is the **Tully-Fisher relation:  $L \propto v_{max}^4$** .

The reason is that the faster a galaxy rotates the broader the 21 cm line becomes because of Doppler shifts of the receding and approaching sides of the galaxy.

Galaxies with faster rotational speeds are more massive according to Newton's form of Kepler's third law and the more massive galaxies contain more stars and are therefore more luminous. **Consequently, the width of a galaxy's 21-cm line is directly related to its luminosity.**

The Tully-Fisher relation can be used to determine the distance to spiral galaxies up to 100 Mpc.

# Estimating the distances to Elliptical Galaxies

**The fundamental plane** is an empirical relation between the effective **size**, the average surface **brightness** and the central **velocity dispersion of the central stars** found in elliptical galaxies.

$$L \propto \sigma_r^{2.65} r_e^{0.65}$$

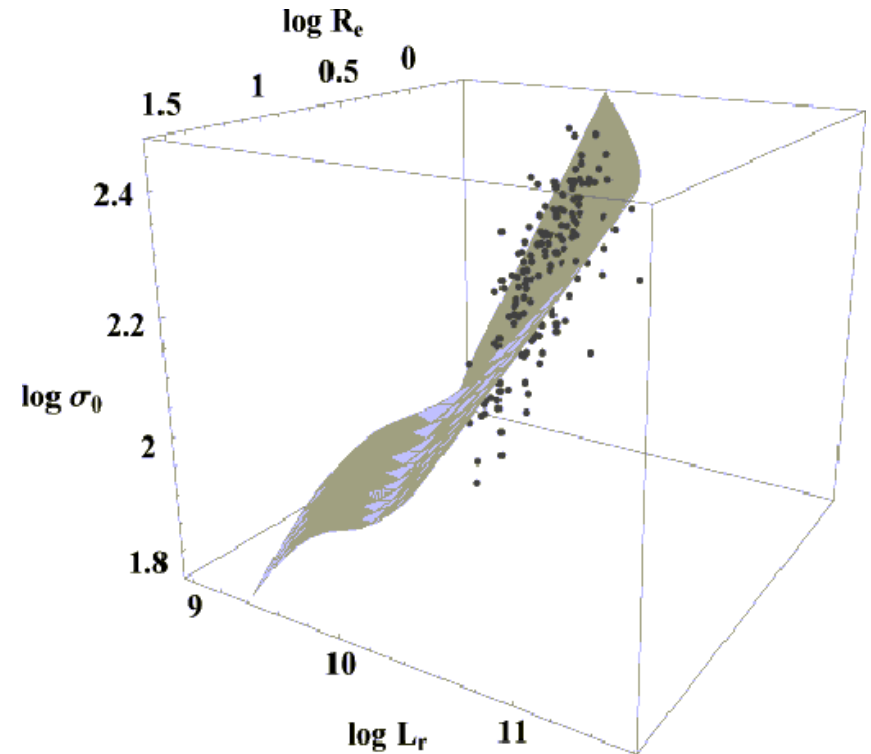
Where  $r_e$  is the **effective radius** within which half of the light of the galaxy resides

If one measures these three quantities for many elliptical galaxies and plots them, they find that the points fall on a plane called the **fundamental plane**.

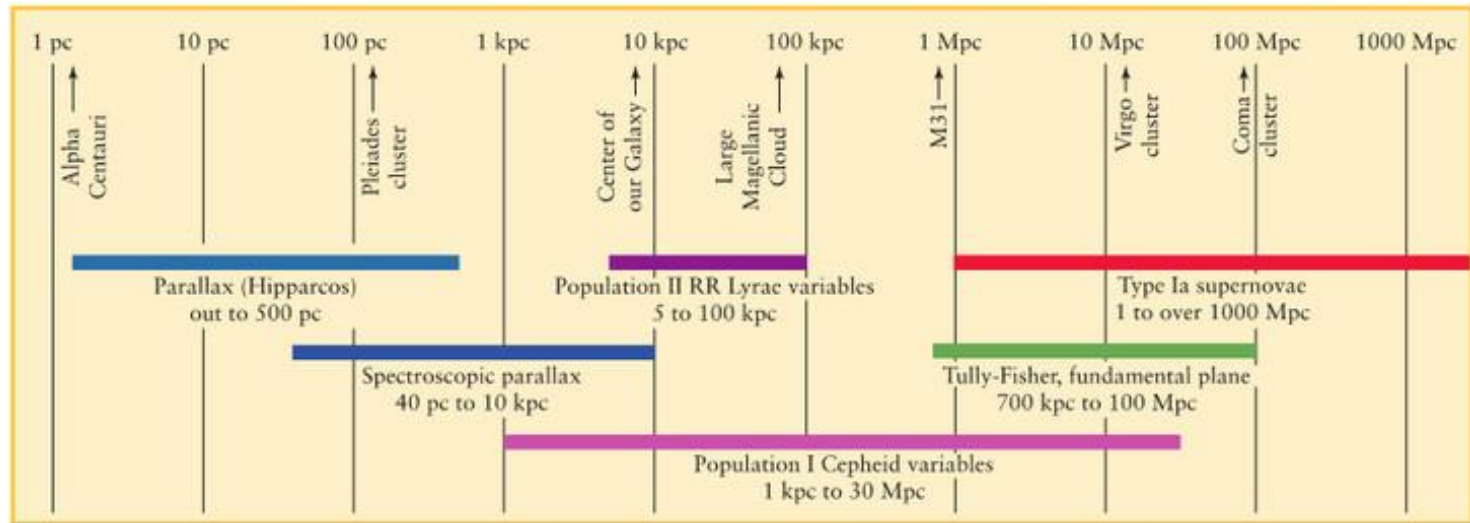
# Estimating the distances to Elliptical Galaxies

Having found the fundamental plane for nearby galaxies one can estimate the distance to remote elliptical galaxies:

First one measures the velocity dispersion of the stars and the average surface brightness. Then using the fundamental plane one can infer the actual size of the galaxy and use the small angle formula to estimate the distance.



# Distance Ladder



**Astronomers use a sequence of methods to determine the distance to very remote objects. This approach is called the **distance ladder**.**

Objects are found where their distances can be measured both with the accurate parallax method and the less accurate spectroscopic parallax and calibrate the spectroscopic method so it can be used at larger distances.

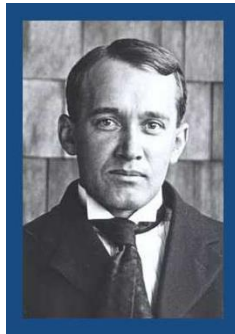
Next objects are found where their distance can be measured both with the spectroscopic parallax method and with Cepheid variables and calibrate the luminosities of the Cepheid variables and so on.

## Expanding Universe

In the early 1900's it was Vesto Slipher from Lowell Observatory who first found that the spectra of most “nebulae” were redshifted. At the time it was not known how far these nebulae were and whether they were galactic or extra-galactic.



Lowell Observatory



Vesto Slipher



Lemaitre

In 1925 Hubble was able to determine the distance to M31 using Cepheid variables (and the L-P relation discovered by Henrietta Leavitt).

In 1927 **Lemaitre** was the first to theorize that the recession of nearby galaxies can be explained by an expanding universe. He first derived the Hubble–Lemaître law and published the first estimation of the Hubble constant in 1927, two years before Hubble's article.

# Redshift

$$\frac{\lambda_{obs} - \lambda_0}{\lambda_0} = z$$

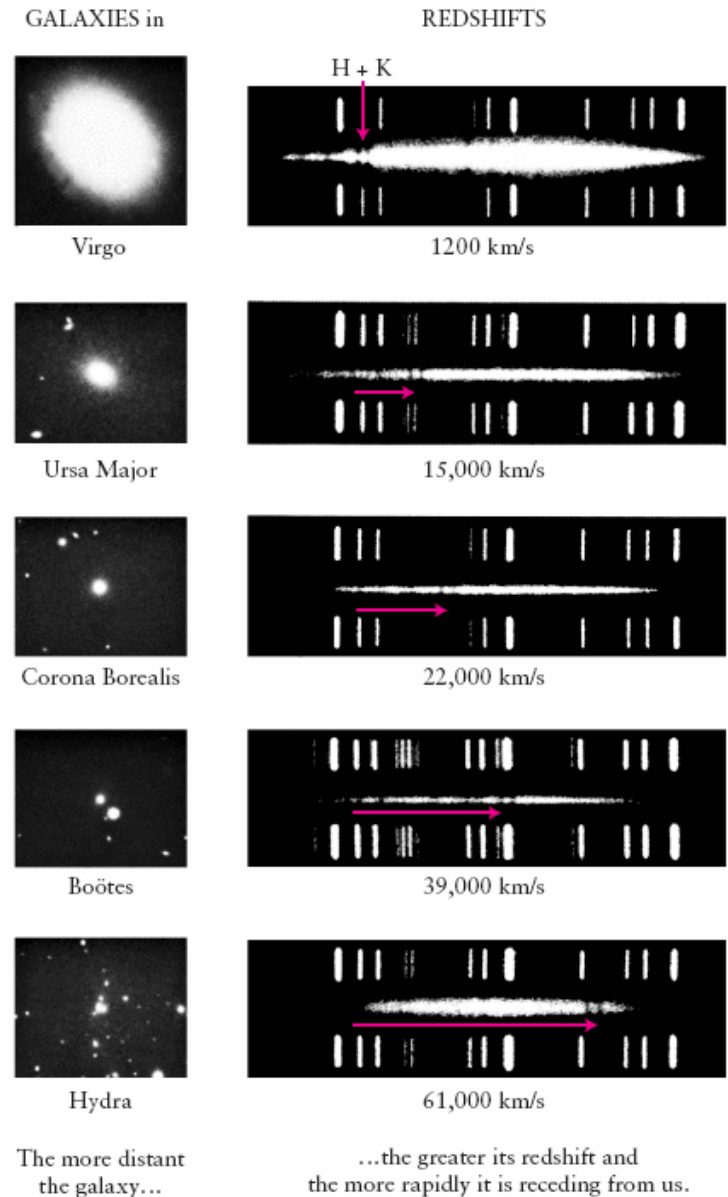
$\lambda_{obs}$  = the observed wavelength

$\lambda_0$  = the rest-frame wavelength

$z$  = the redshift of the object

**Figure:** Each galaxy's spectrum is a bright band with dark absorption lines.

The bright lines above and below it are a comparison spectrum taken on Earth. The horizontal red arrows show how much the H and K lines of singly ionized calcium are redshifted in each galaxy's spectrum. Below each spectrum is the recessional velocity calculated from the redshift.



# The Hubble - Lemaitre Law

## The Hubble - Lemaitre Law:

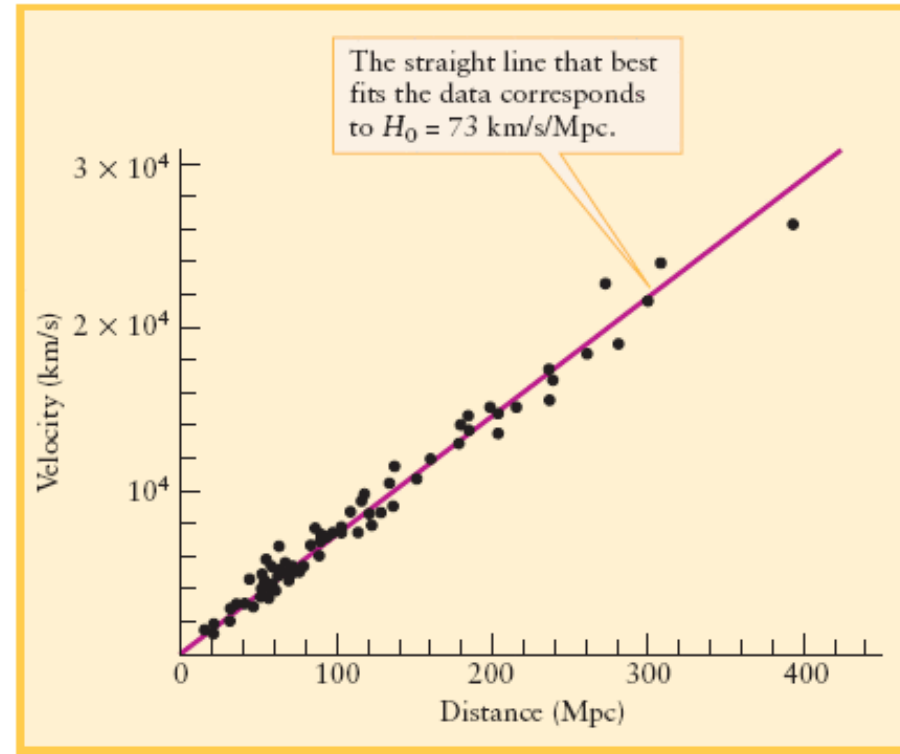
$$v = H_0 d$$

$v$  = recessional velocity of a galaxy,  $H_0$  = Hubble constant

$d$  = comoving radial distance to the galaxy

$$H_0 = 70 \pm 3 \text{ km/s/Mpc}$$

Note that this is not a real velocity as in the Doppler effect but the apparent velocity due to the expansion of space.  
For low redshift  $z \sim v/c$



The recession velocities are determined from redshifts and the distances to galaxies from Cepheid variable stars.

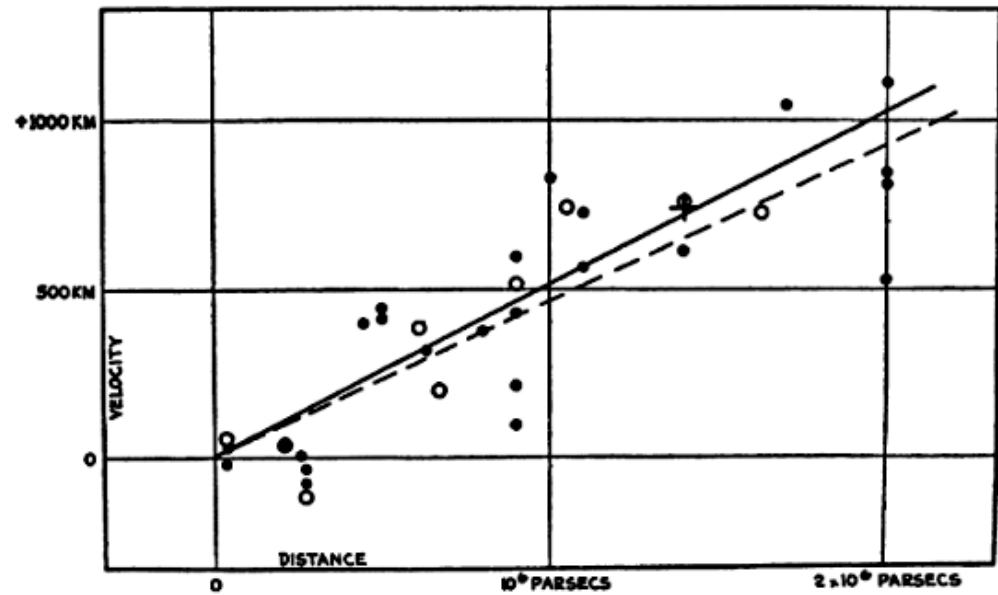


**FIGURE 27.7** Hubble's 1936 velocity–distance relation. The two lines use different corrections for the Sun's motion. (Note: The vertical units should be  $\text{km s}^{-1}$ .) (Figure from Hubble, *Realm of the Nebulae*, Yale University Press, New Haven, CT, ©1936.)

# Einstein's Biggest Blunder?

Einstein's initial formulation of General Relativity implied an **expanding Universe**.

The prevailing theory at the time, however, was that the Universe was static and infinite. Einstein included a constant ( $\Lambda$ ) in his equations to make his theory predict a non expanding and static Universe.

Einstein later stated that the inclusion of this constant was the **greatest blunder of his life**.



Hubble and Lemaitre showed that the Universe was expanding. Later Einstein visited Hubble and congratulated him on this remarkable discovery.

# Expanding Universe

The velocity of a galaxy through space is referred to as its **peculiar velocity**

The velocity of a galaxy due to expansion is referred to as **recession velocity**.

The motion of galaxies as they participate in the expansion of the Universe is called **Hubble flow**.

Example: Use Cosmocalc:

<http://www.astro.ucla.edu/~wright/CosmoCalc.html>

to determine the **comoving radial distance (now) between us and a galaxy** at  $z = 10$ .

# Expanding Universe

Example: Estimate the age of the Universe using the Hubble - Lemaitre Law

# Expanding Universe

Example: *Estimate* the age of the Universe using the Hubble - Lemaitre Law

$$v = \frac{d}{t_{age}} \Rightarrow t_{age} = \frac{d}{v} = \frac{d}{H_0 d} = \frac{1}{H_0} = \frac{1}{70 \text{ km s}^{-1} \text{ Mpc}^{-1}} \Rightarrow$$
$$t_{age} \sim 14 \text{ billion years}$$

# Galaxy Counts

Assume that the density of galaxies in the nearby Universe is constant and the nearby universe has a Euclidean geometry. We neglect K correction effects and cosmological dimming. We will show that the number of galaxies with a magnitude  $< m$  follows:

$$N(< m) \propto 10^{0.6m}$$

The number of galaxies within a radius  $r$  is:

$$N(< r) \propto r^3$$

The inverse square law is:

$$f = \frac{L}{4\pi r^2}$$

Assume for the moment that all the galaxies have the same luminosity  $L$ . The distance  $r$  of a galaxy scales as  $r \propto f^{-1/2}$

The number of galaxies with a flux greater than  $f$  (*flux of galaxy at  $r$* ) is:

$$N(> f) \propto r^3 \propto f^{-3/2}$$

We can convert this relation into magnitudes:  $m = -2.5 \log_{10} f + C \rightarrow f \propto 10^{-0.4m}$

$$\text{So } N(> f) \propto r^3 \propto f^{-3/2} \rightarrow N(< m) \propto 10^{0.6m}$$

# Galaxy Counts

Every increase of 1 magnitude (going fainter by a factor 2.512 in flux) increases the number of galaxies by a factor:  $10^{0.6} \sim 4$

So in a Euclidean universe:

1 mag deeper  $\rightarrow 4 \times$  more galaxies

2 mag deeper  $\rightarrow 16 \times$  more galaxies

5 mag deeper  $\rightarrow 1000 \times$  more galaxies

**Example:** The number of galaxies brighter than  $m_B = 12$  mag is about 0.014 per square degree of the celestial sphere. Suppose that you wanted to observe every galaxy brighter than  $m_B = 16$  mag in one quarter of the sky. How many galaxies would you expect in such a sample?

# Galaxy Counts

**Example:** The number of galaxies brighter than  $m_B = 12$  mag is about 0.014 per square degree of the celestial sphere. Suppose that you wanted to observe every galaxy brighter than  $m_B = 16$  mag in one quarter of the sky. How many galaxies would you expect in such a sample?

Solution:

$$N(< 12) \propto 10^{0.6 \times 12}$$

$$N(< 16) \propto 10^{0.6 \times 16}$$

$$\frac{N(< 16)}{N(< 12)} = 10^{0.6 \times (16-12)} = 10^{2.4} = 251.2$$

1  $\text{deg}^2$  corresponds to  $\left(\frac{\pi}{180^\circ}\right)^2$  steradians

$A_{\text{tot}}$   $\text{deg}^2$  corresponds to  $4\pi$  steradians

The entire sky has  $A_{\text{tot}} = 4\pi \left(\frac{\pi}{180^\circ}\right)^{-2} \text{deg}^2 = 41,252.965 \text{deg}^2$

A quarter of the sky has an area of  $A_{1/4} = 10,313.241 \text{deg}^2$

$N(< 12) = 0.014 \times A_{1/4} \text{ galaxies} = 144.4 \text{ galaxies}$

$N(< 16) = 251.2 \times N(< 12) \sim 36,273 \text{ galaxies}$

# Clusters of Galaxies

The Hercules cluster of galaxies just 650 million ly away.



**Clusters of galaxies** are the largest gravitationally bound objects in the Universe. Based on simulations the smallest structures collapsed first and eventually build the largest structures, such as clusters of galaxies (*bottom-up galaxy formation scenario*).

# Properties of Clusters of Galaxies

Clusters of Galaxies contain between 100 - 2000 galaxies, hot X-ray emitting gas and dark matter. **Mass distribution:**  
~5% in stars of galaxies, ~10% in hot gas and ~85 % in dark matter.

- Total mass  $\sim 10^{14} - 10^{15} M_{\odot}$
- Diameter of 1– 2 Mpc
- Velocity dispersion of  $\sigma \sim 1000$  km/s
- $M/L \sim 500 M_{\odot}/L_{\odot}$

Clusters are classified as **rich** ( $> 100$  members) **or poor** ( $< 100$  members). Poor Clusters are also called **groups**.

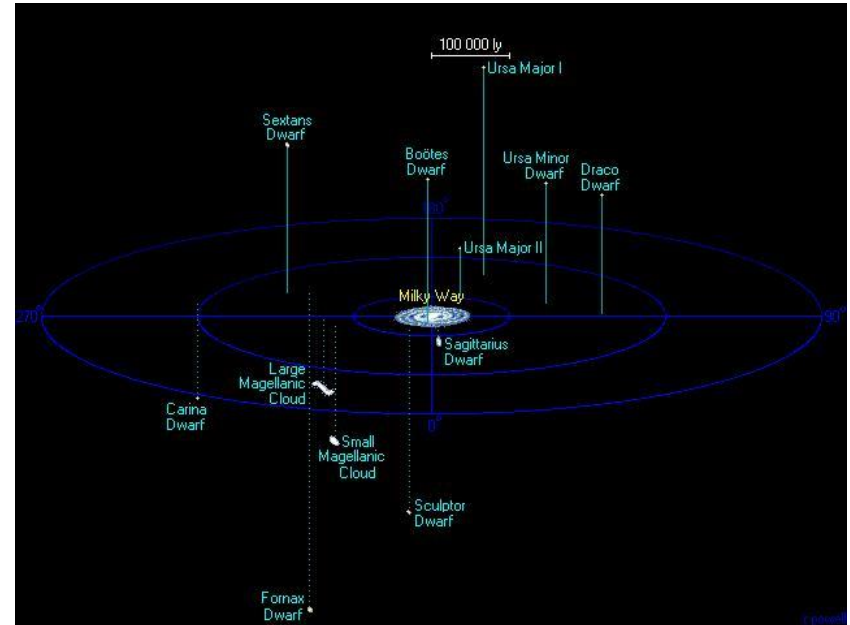
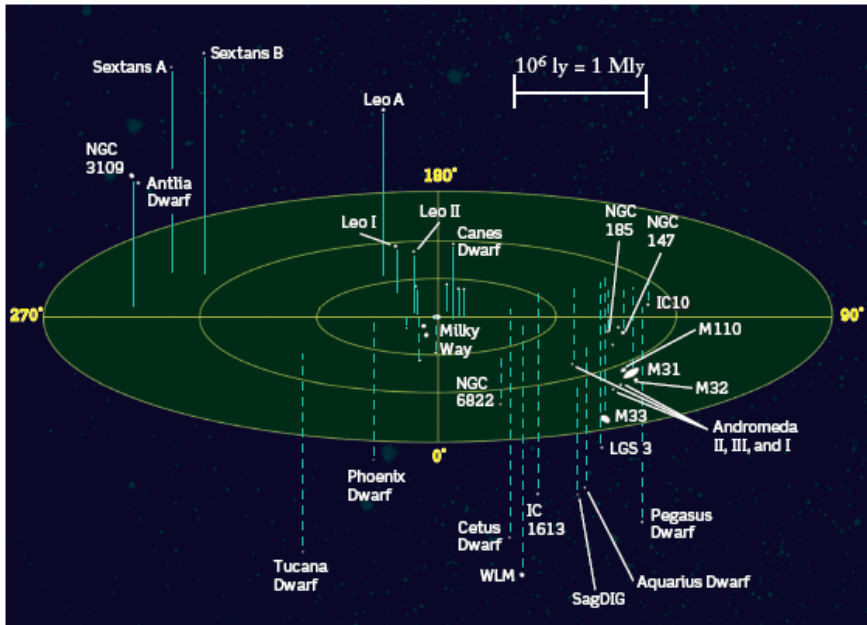
Cluster are also classified as **regular** (spherical shape) and **irregular** (non-spherical shape).

# Properties of Groups

- Total mass  $\sim 10^{13} M_{\odot}$
- Velocity dispersion of  $\sigma \sim 150 \text{ km/s}$
- $M/L \sim 250 M_{\odot}/L_{\odot}$

The Milky Way belongs to the **Local Group**.

# Local Group



Members of the **Local Group** include:

Milky Way, M31, M33 (triangulum), Large and Small Magellanic Clouds, Leo I and Leo II, Canis Dwarf (only 42,000 ly from the center of the Milky Way) Ursa minor and Major Dwarfs, Sextans Dwarf, Sagittarius Dwarf.

# Estimating the Combined Mass of the Milky Way and Andromeda

The center of mass of  $N$  objects of mass  $m_i$  is:

$$\vec{R}_{cm} = \frac{\sum_1^N m_i \vec{r}_i}{M}$$

For binary system we can choose:  $\vec{R}_{cm} = \frac{m_1 \vec{r}_1 + m_2 \vec{r}_2}{M} = 0 \Rightarrow m_1 \vec{r}_1 + m_2 \vec{r}_2 = 0$  (1)

Define  $\vec{r} = \vec{r}_2 - \vec{r}_1$ . (2)

$$(1) \wedge (2) \Rightarrow \vec{r}_1 = \frac{-m_2 \vec{r}}{m_1 + m_2} = \frac{-\mu \vec{r}}{m_1} \quad \text{and} \quad \vec{r}_2 = \frac{m_1 \vec{r}}{m_1 + m_2} = \frac{\mu \vec{r}}{m_2}$$

Where we defined the reduced mass  $\mu = \frac{m_1 m_2}{m_1 + m_2}$

The center of mass will not accelerate so if we define a reference frame centered on the center of mass it will be an inertial frame

# Estimating the Combined Mass of the Milky Way and Andromeda

In the center-of-mass reference frame of the MW and Andromeda the total energy is:

$$E_{total} = \frac{1}{2}m_1v_1^2 + \frac{1}{2}m_2v_2^2 - \frac{Gm_1m_2}{|\vec{r}_2 - \vec{r}_1|}$$

$$E_{total} = \frac{1}{2}\mu v^2 - \frac{GM\mu}{r} \quad (3)$$

This is equivalent to considering a mass of  $M = m_1 + m_2$  at the center of our coordinate system and the reduced mass  $\mu$  located at a distance  $r$ . At the furthest separation ( $2a$ ) between the MW and Andromeda the kinetic energy  $\sim 0$ . The total energy was

$$E_{total} = -\frac{GM\mu}{2a} \quad (4)$$

$$(3) \wedge (4) \Rightarrow -\frac{GM\mu}{2a} = \frac{1}{2}\mu v^2 - \frac{GM\mu}{r} \Rightarrow v^2 = GM \left[ \frac{2}{r} - \frac{1}{a} \right] \quad (5)$$

We can use Kepler's law for the semi-major axis:  $P^2 = \frac{4\pi^2}{GM} a^3 \Rightarrow a = \left( \frac{4\pi^2}{P^2 GM} \right)^{-1/3} \quad (6)$

$$(5) \wedge (6) \Rightarrow v^2 = GM \left[ \frac{2}{r} - \left( \frac{4\pi^2}{P^2 GM} \right)^{1/3} \right]$$

# Estimating the Combined Mass of the Milky Way and Andromeda

$$v^2 = GM \left[ \frac{2}{r} - \left( \frac{4\pi^2}{P^2 GM} \right)^{1/3} \right] \quad (7)$$

At the moment  $r = 770$  kpc and  $v = 119$  km/s

The period  $P = t_H + t_{col}$  where  $t_H$  is the time since the big bang and  $t_{col}$  is the time from now to the collision  $t_{col} = \frac{r}{v}$

$$P = t_H + t_{col} = t_H + \frac{r}{v}$$

Inserting  $r$ ,  $v$  and  $P$  into (7) we obtain a total mass  $M \sim 7.9 \times 10^{42} \text{ kg} \sim 4 \times 10^{12} M_{\odot}$

## Estimating the mass-to-light of Milkdromeda

$$M_{MW-A} \sim 7.9 \times 10^{42} \text{ kg} \sim 4 \times 10^{12} M_{\odot}$$

$$L_{MW} = 2.3 \times 10^{10} L_{\odot}$$

$$L_A = 4.6 \times 10^{10} L_{\odot}$$

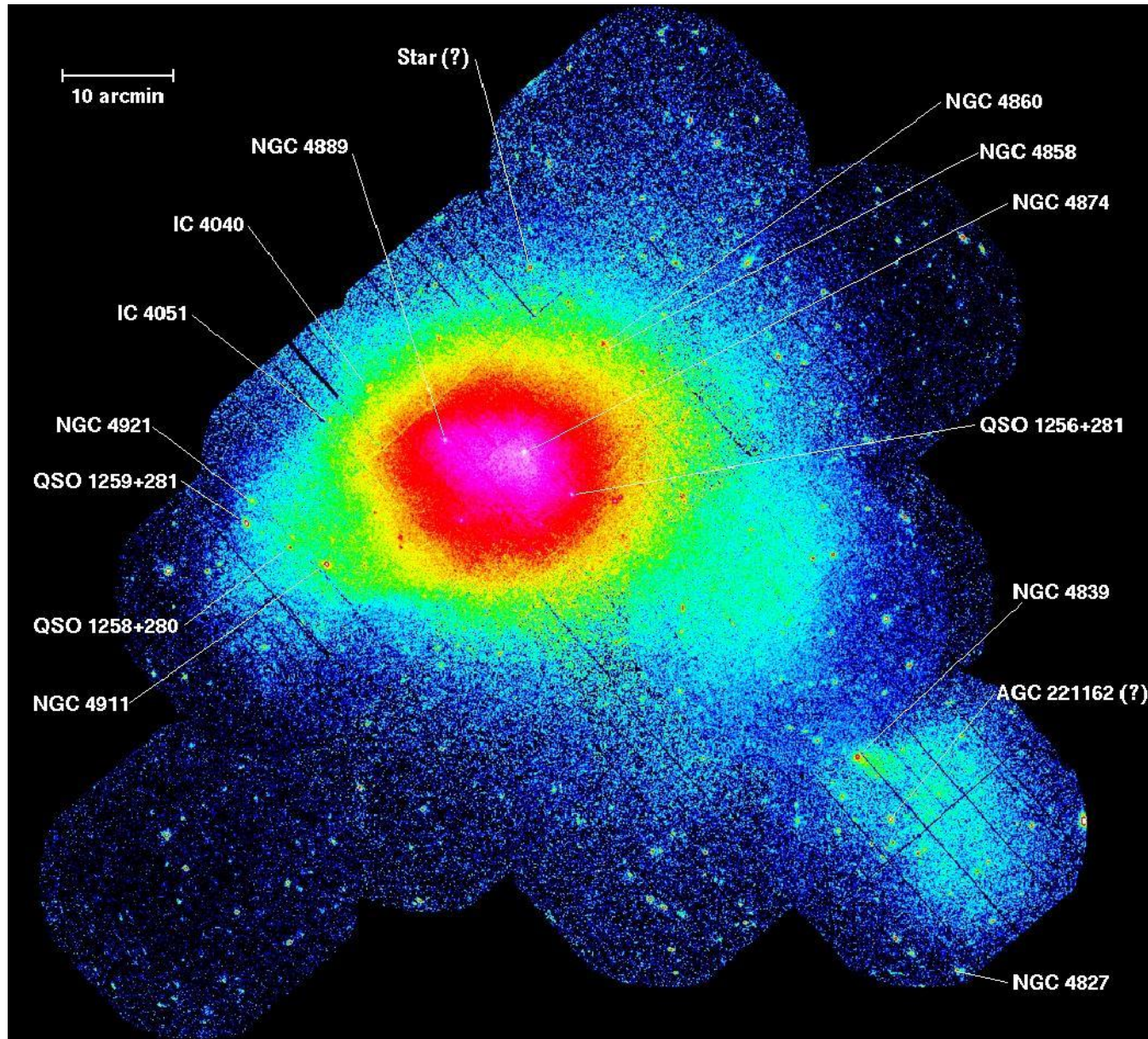
$$\left(\frac{M}{L}\right)_{MW-A} = \left(\frac{4 \times 10^{12} M_{\odot}}{6.9 \times 10^{10} L_{\odot}}\right) = 58 \left(\frac{M_{\odot}}{L_{\odot}}\right)$$

## Virgo: A Rich Irregular Cluster of Galaxies



**FIGURE 27.13** The center of the Virgo cluster, showing the giant ellipticals M84 (right) and M86 (center). (Courtesy of National Optical Astronomy Observatories.)

# Coma: A Rich Regular Cluster of Galaxies



Coma Cluster of galaxies

# Hot Gas In Clusters of Galaxies

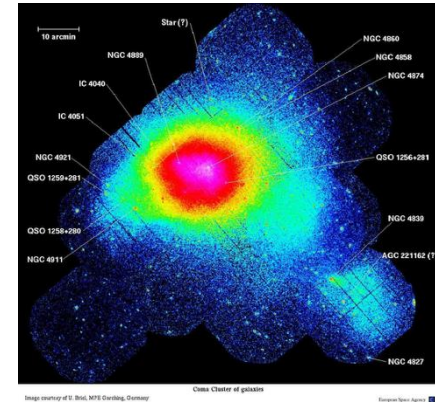
Most galaxy clusters contain **hot gas primarily heated during the cluster formation/collapse**. The hot gas emits *Bremsstrahlung* radiation .

One can use the observed temperature and density profiles of GCs to infer the total mass of a GC.

$$dm \frac{d^2 r}{dt^2} = - \frac{GMdm}{r^2} - dPA \quad (1)$$

$$dm = \rho dV = \rho A dr \quad (2)$$

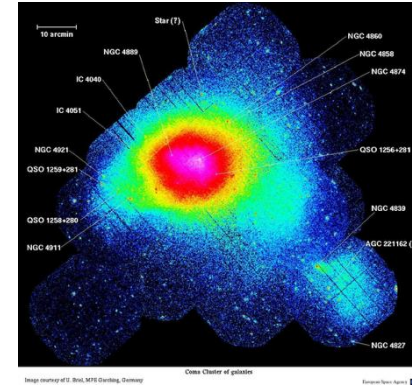
$$(1) \wedge (2) \Rightarrow \frac{dP}{dr} = - \frac{GM\rho}{r^2} \Rightarrow M = - \frac{r^2}{G\rho} \frac{dP}{dr} \quad (3)$$



# Hot Gas In Clusters of Galaxies

$$\frac{dP}{dr} = \frac{dnkT}{dr} = kT \frac{dn}{dr} + kn \frac{dT}{dr} \quad (4)$$

$$\rho = \frac{M_{gas}}{V} = \frac{N\mu m_H}{V} = n\mu m_H \quad (5)$$



$$(3) \wedge (4) \wedge (5) \Rightarrow M(< r) = -\frac{r^2}{G\rho} \frac{dP}{dr} = -\frac{r^2}{Gn\mu m_H} \left[ kT \frac{dn}{dr} + kn \frac{dT}{dr} \right]$$

$$\Rightarrow M(< r) = -\frac{r^2 kT}{G\mu m_H} \left[ \frac{1}{n} \frac{dn}{dr} + \frac{1}{T} \frac{dT}{dr} \right]$$

$M(< r)$  is the total mass within a radius  $r$  (dark matter + gas + stars +...)

## Mass-to-Light of Coma

### Coma

Zwicky figured out that clusters contained a large fraction of Dark Matter by using the virial theorem

$$\sigma_r = 977 \frac{\text{km}}{\text{s}}, R = 3 \text{ Mpc}, L = 5 \times 10^{12} L_{\odot}$$

$$M_{\text{virial}} = \frac{5\sigma_r^2 R}{G} = \frac{5 \left( 977 \times 10^3 \frac{\text{m}}{\text{s}} \right)^2 (3 \times 3.086 \times 10^{22} \text{m})}{6.67 \times 10^{-11} \text{m}^3 \text{kg}^{-1} \text{s}^{-2}}$$

$$\left( \frac{M}{L} \right)_{\text{Coma}} = \frac{3.3 \times 10^{15}}{5 \times 10^{12}} \left( \frac{M_{\odot}}{L_{\odot}} \right) \simeq 662 \left( \frac{M_{\odot}}{L_{\odot}} \right)$$

## Thermal Bremsstrahlung (free-free emission)

Energy emitted per unit time per unit volume between frequencies  $\nu$  and  $\nu + d\nu$

$$l_\nu d\nu = 5.44 \times 10^{-52} (4\pi n_e^2) T^{-1/2} e^{\frac{-h\nu}{kT}} d\nu \frac{W}{m^3}$$

Where  $n_e$  is the electron density and  $T$  is the temperature

**Luminosity density** (over all frequencies)

$$L_{Volume} = 1.42 \times 10^{-40} (n_e^2) T^{1/2} \frac{W}{m^3}$$

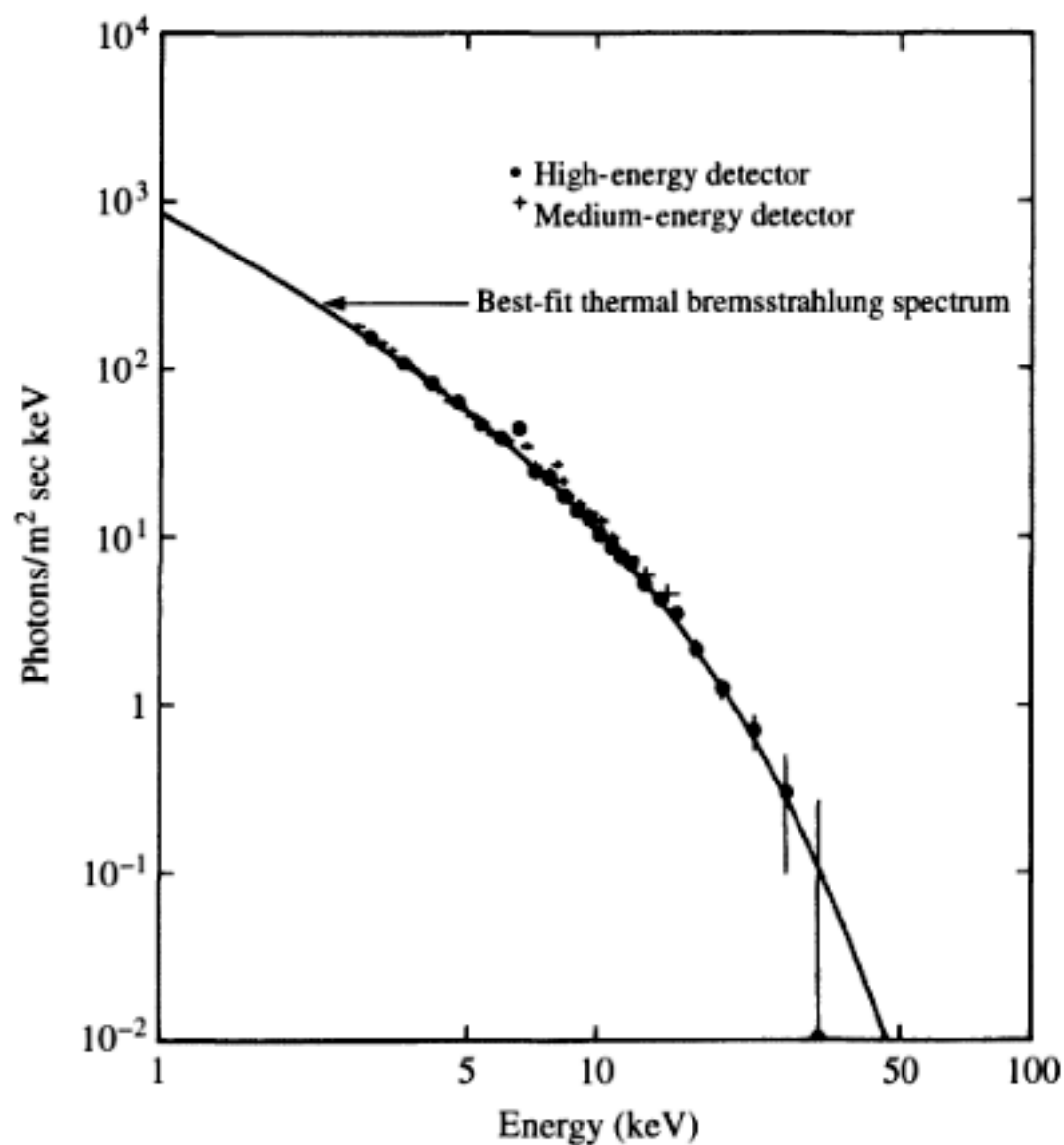


**FIGURE 27.17** Thermal bremsstrahlung spectrum (line) for 88 million K. The points are observations of X-rays from the Coma cluster's intracluster gas. Photon energy is plotted on the horizontal axis. (Figure adapted from Henriksen and Mushotzky, *Ap. J.*, 302, 287, 1986.)

# Estimate of the Mass of the Hot Gas in the Coma cluster

Assumptions:

(1) Coma gas is modeled as **an isothermal sphere** of hot ionized hydrogen.

(2)  $R \sim 1.5 \text{ Mpc}$

(3) **Gas is optically thin**, meaning the probability that photons from the source are absorbed or scattered is low and all photons emitted along the line of sight are observed.

The temperature and luminosity are determined by modeling the observed X-ray spectrum:  $T \sim 8.8 \times 10^7 \text{ K}$  and  $L_X \sim 5 \times 10^{37} \text{ W}$

## Estimate of the Mass of the Hot Gas in the Coma cluster

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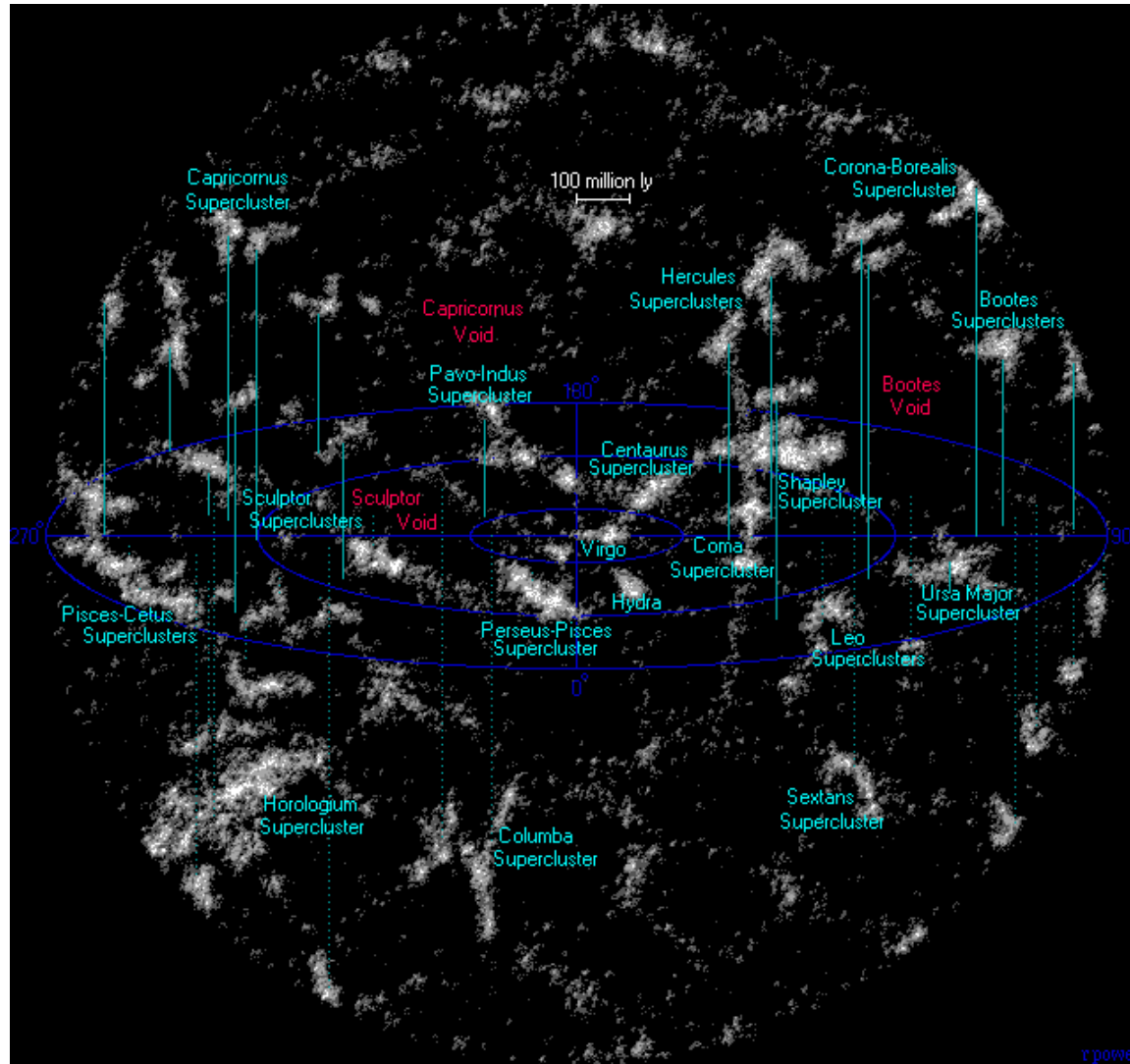
$$L_X = L_{Vol} \times \text{Volume} = L_{Vol} \frac{4}{3} \pi R^3 \Rightarrow$$

$$L_X = 1.42 \times 10^{-40} (n_e^2) T^{1/2} \frac{4}{3} \pi R^3 \Rightarrow n_e = \left( \frac{L_X}{1.42 \times 10^{-40} T^{1/2} \frac{4}{3} \pi R^3} \right)^{1/2}$$

$n_e$  is the number density of  $e^-$ . For completely ionized H there is 1 H atom per every free  $e^-$  :  $n_e = n_H$

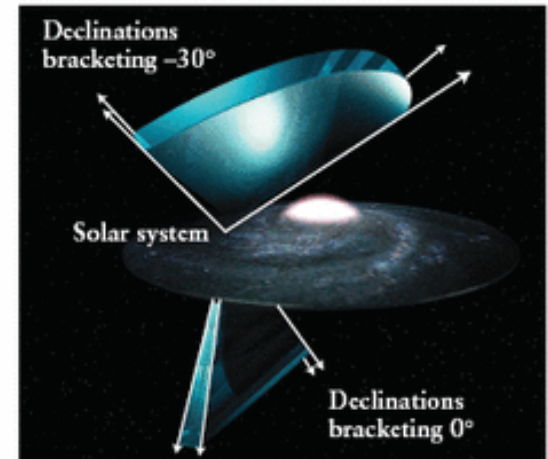
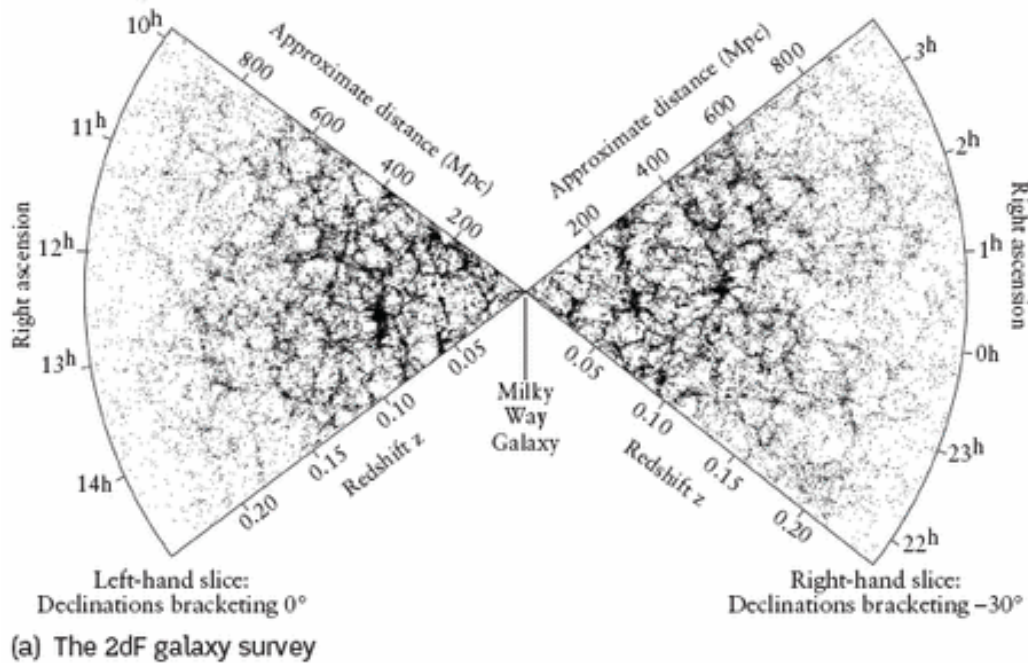
$$\rho = \frac{M}{V} \Rightarrow M_{gas} = \rho V = n_H m_H V = n_e m_H V = n_e m_H \frac{4}{3} \pi R^3$$

# Superclusters



Clusters of galaxies are also grouped in larger structures called **superclusters**. A supercluster may contain tens of clusters of galaxies. **Superclusters are not bound together by gravity** and the distances between members grows as the Universe expands.

# Large Scale Distribution of Galaxies: Voids and Sheets

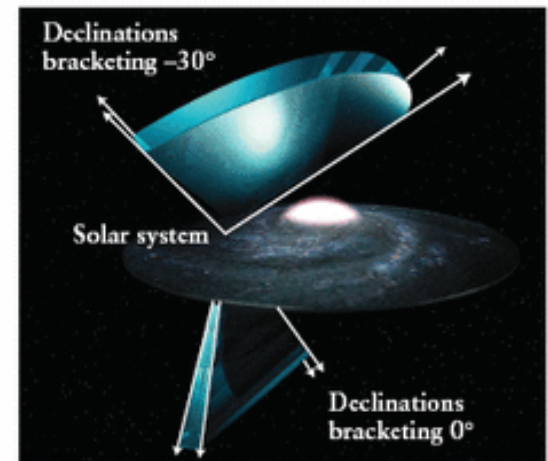
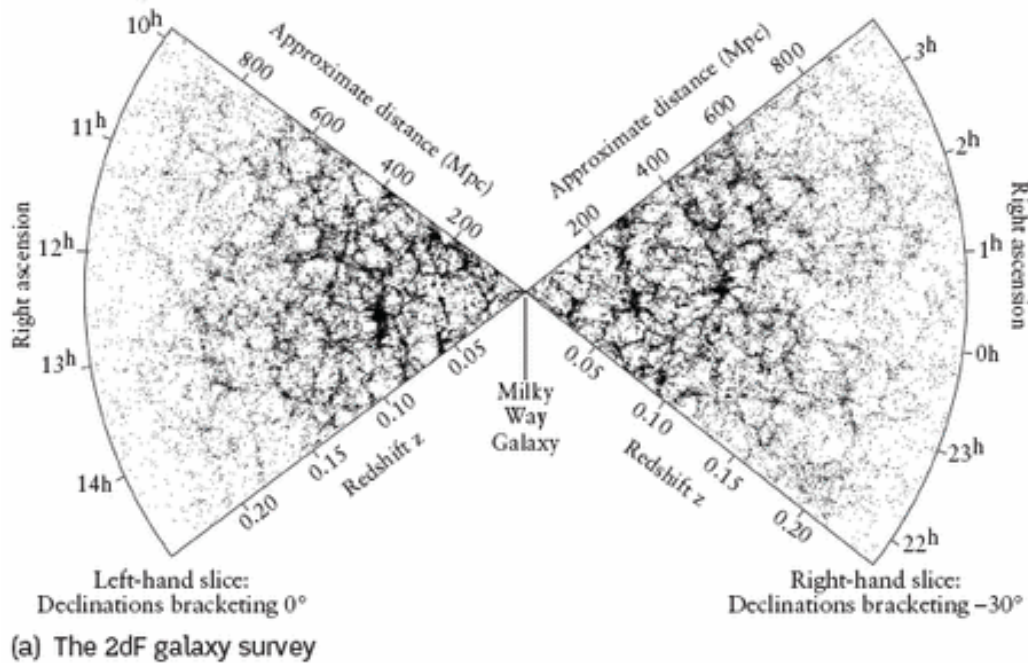


(b) Fields of view in the 2dF survey

Three dimensional maps of galaxies in the nearby Universe are now available from the **Sloan Digital Sky Survey (SDSS)** and the **two degree field galactic redshift survey (2dFGRS)**.

These maps indicate that most galaxies are located on sheets several Mpc thick and separated by voids of sizes  $\sim 100$  Mpc.

# Large Scale Distribution of Galaxies: Voids and Sheets



(b) Fields of view in the 2dF survey

This pattern is similar to that of soapsuds in a kitchen sink, with sheets of soap film (analogous to galaxies) surrounding air bubbles (analogous to voids). Voids contain very few galaxies but may contain hydrogen clouds.

On scales much larger than 100 Mpc, the distribution of galaxies in the universe appears to be roughly uniform.

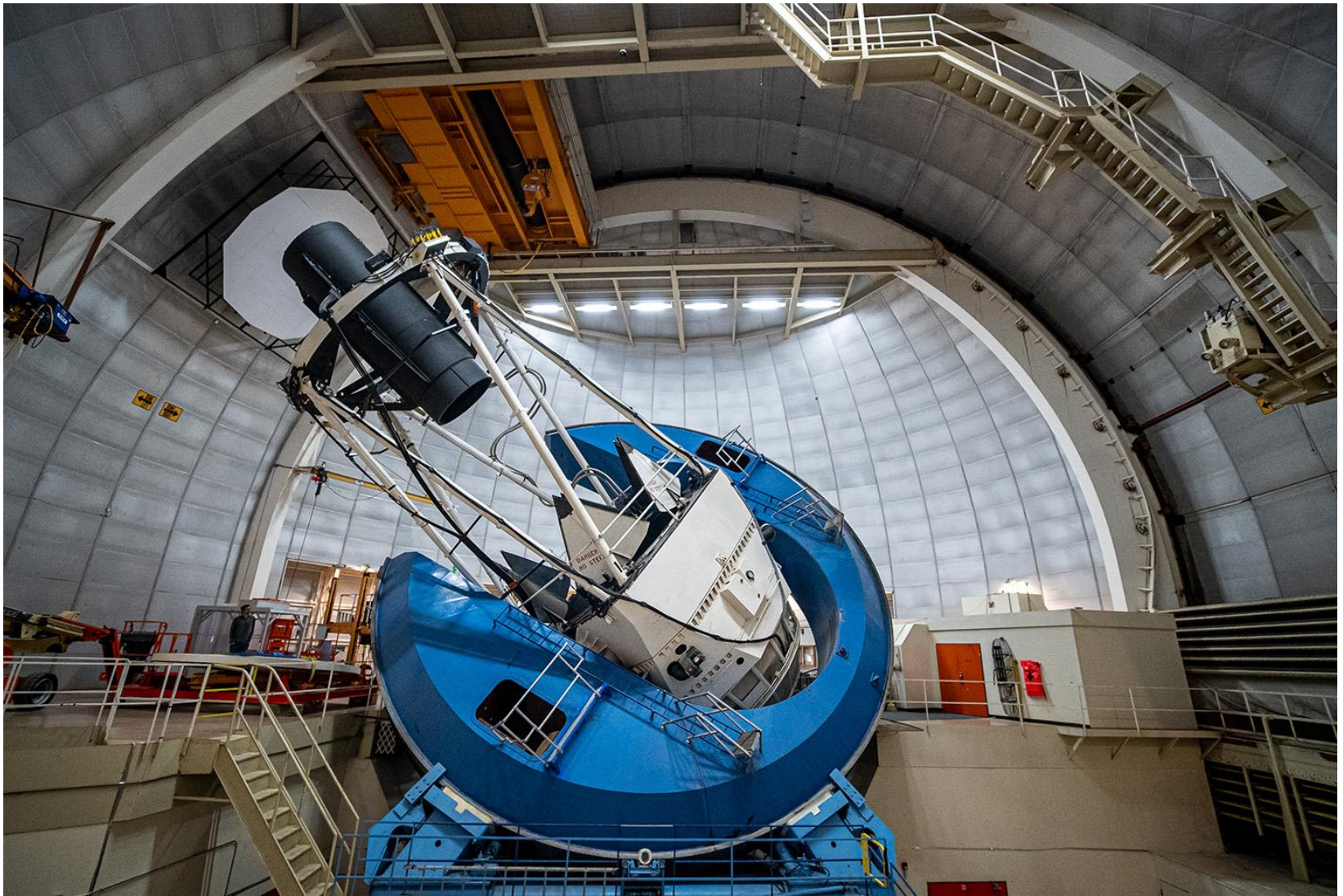
# New DESI Results Strengthen Hints That Dark Energy May Evolve



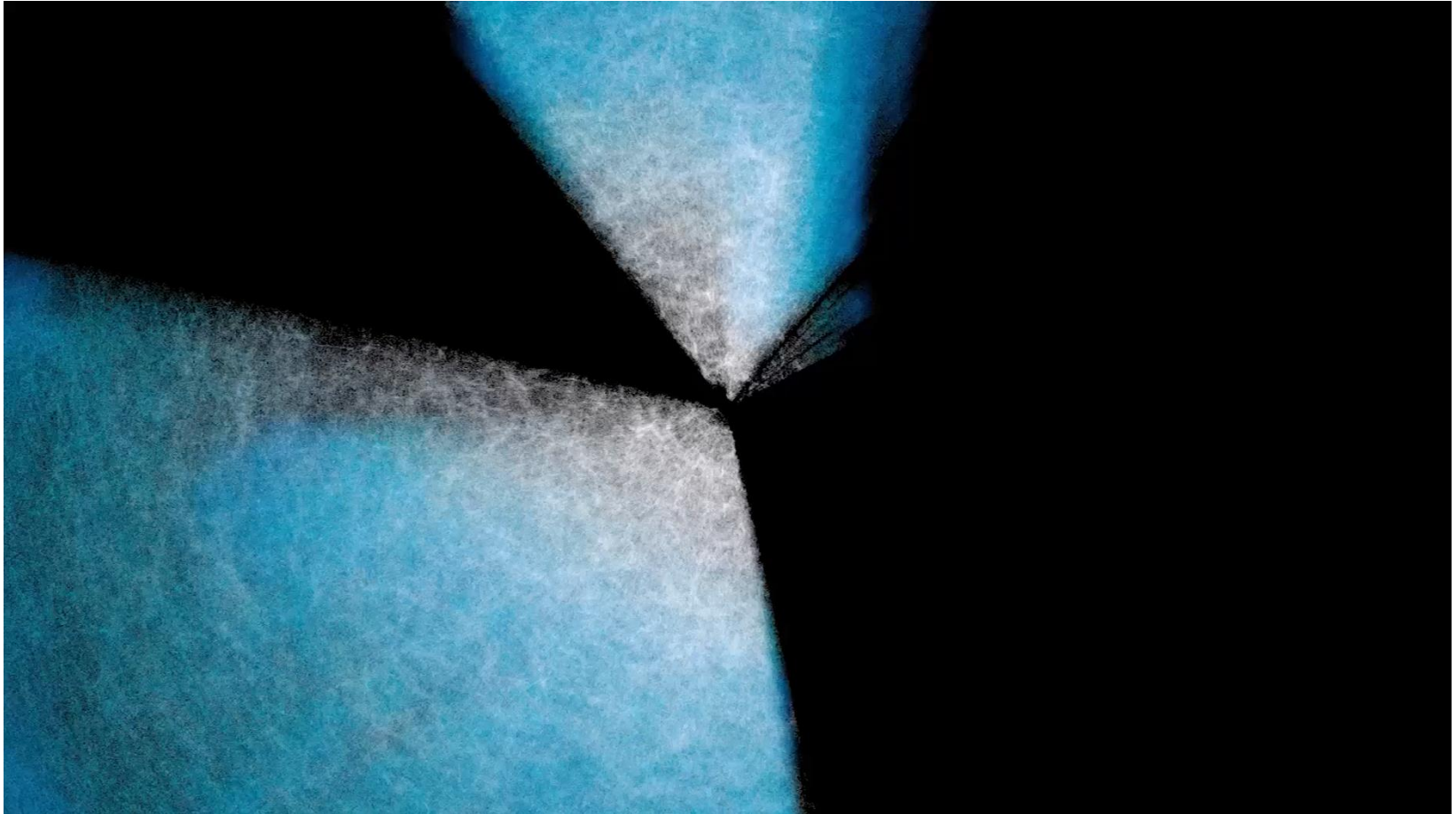
DESI maps distant objects to study dark energy. The instrument is installed on the Mayall Telescope .

## KEY TAKEAWAYS

- The DESI collaboration published a new analysis of dark energy using their first three years of collected data, which spans nearly 15 million galaxies and quasars.
- Researchers combined the DESI data with information from studies of the cosmic microwave background, supernovae, and weak gravitational lensing.
- The standard model of cosmology struggles to explain all the observations when taken together — but a model **where dark energy's influence changes over time seems to fit the data well.**

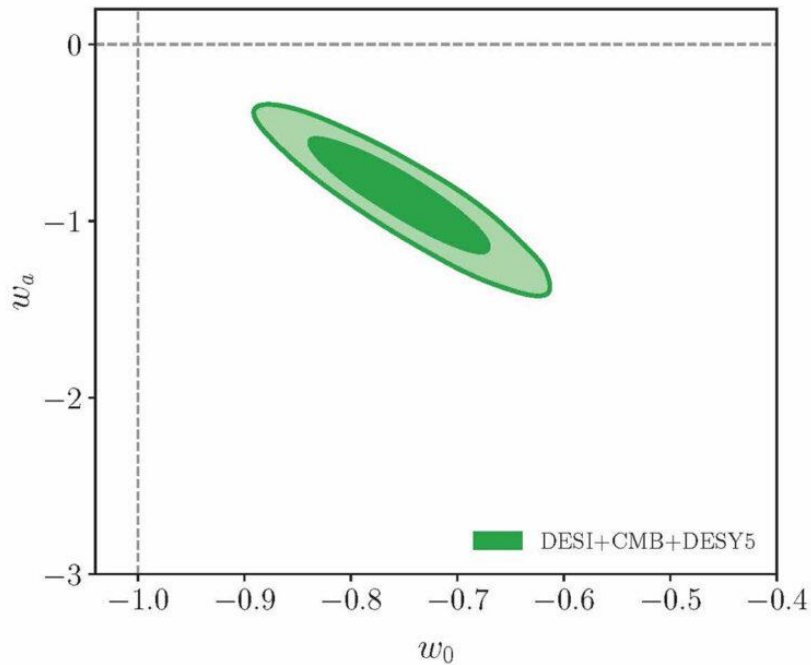


**DESI is a state-of-the-art instrument and can capture light from up to 5,000 celestial objects simultaneously.**

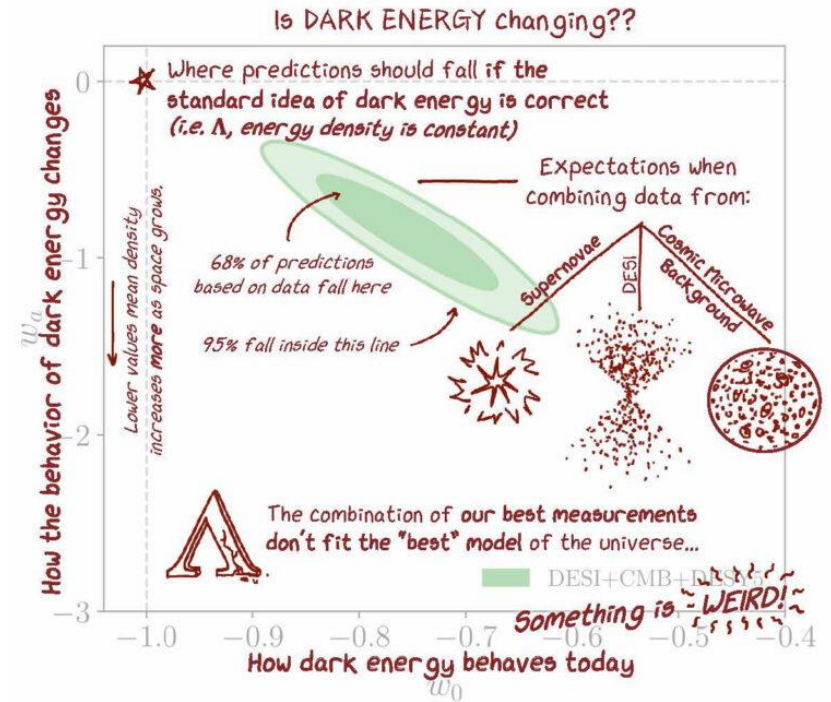


Pressure =  $w(z) \cdot \rho$  equation of state  $w$  is negative indicating that dark energy produces negative pressure (in the opposite direction of gravity)

$$w(z) = \text{Pressure/Density} = w(z=0) + w_a \cdot (z/(1+z))$$



One of many contour plots in DESI's new dark energy analysis, showing the constraints on parameters of evolving dark energy.



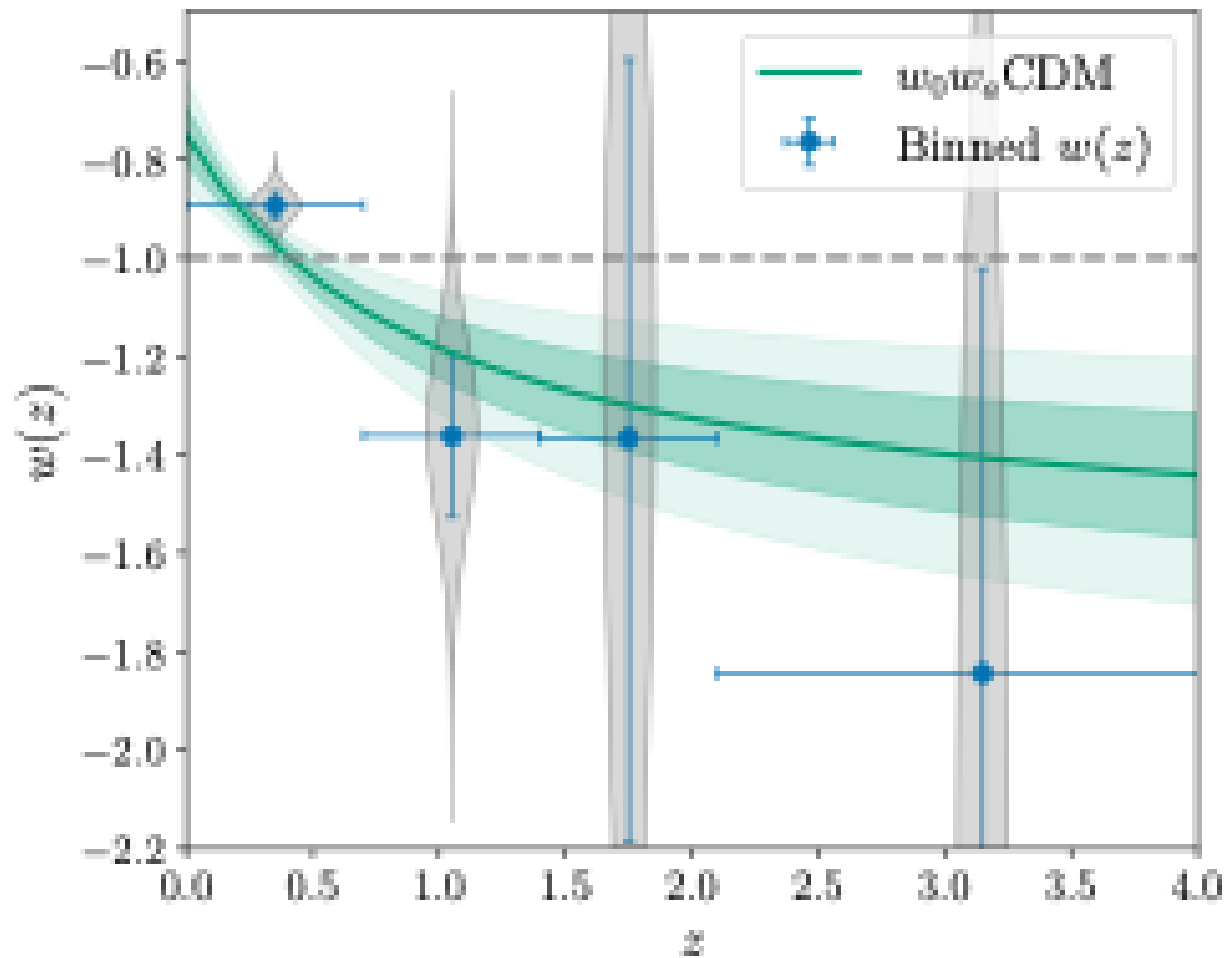
An annotation of DESI's contour plot. The plot describes the "behavior" of dark energy – how its density changes as space expands.

## **BAO: Baryon Acoustic Oscillations**

**BAOs** are periodic fluctuations in the density of visible matter (baryons) in the universe, caused by sound waves that traveled through the hot plasma of the early universe before recombination (about 380,000 years after the Big Bang).

These sound waves, or pressure waves, were driven by the competition between gravitational attraction and radiation pressure in the primordial plasma.

That BAO pattern acts as a standard ruler, with its apparent size on the sky directly affected by how the universe was expanding. Measuring the ruler at different distances shows researchers the strength of dark energy throughout history.



The DESI data reveal that dark energy's strength peaked when the universe was about 70% of its current age and has since diminished by approximately 10%.

This suggests that while the universe's expansion is still accelerating, the rate of acceleration is decreasing.

# Clustering of Galaxies

## Why Study Galaxy Clustering?

Early redshift surveys (e.g., CfA Redshift Survey, Sloan Digital Sky Survey) revealed that **galaxies are not randomly distributed**.

Instead, they form: Groups, Clusters, Filaments, Sheets , and Voids

**This large-scale structure traces the underlying dark matter** distribution and encodes: Initial conditions from inflation, Growth of structure via gravitational instability, and cosmological parameters (ie.,  $\Omega_m$ ,  $H_0$ )

In cosmology, the Two-Point Correlation Function (2PCF), usually denoted  $\xi(r)$ , is the primary tool for quantifying how galaxies are distributed in space. It measures the degree of "clustering" by comparing the actual distribution of galaxies to a completely random one.

# Clustering of Galaxies

Assume that galaxies uniformly occupy a volume  $dV$  with an average number density of  $n = \frac{dN}{dV}$

The probability of finding a galaxy in a volume  $dV$  is:

$$dP \approx n dV \text{ (for } dV \text{ small enough } dP \ll 1)$$

Galaxies however are not randomly distributed in space and the number density is not constant at all scales.

The probability of finding a galaxy in a volume  $dV$  at a distance  $r$  from another galaxy is:

$$dP \approx n [1 + \xi(r)] dV$$

where  $\xi(r)$  is the two-point correlation function that describes how the excess probability of finding galaxy pairs depends on their separation.

# Clustering of Galaxies

How is the two-point correlation function  $\xi(r)$  measured observationally?

Step 1: We generate a random catalog that encodes the geometry and selections effects of the true survey. However, **the random catalog assumes no clustering of galaxies.**

Step 2:

**Determine DD(r):** From the data determine all the galaxy (unique) pairs and their distances and determine how many pairs have a distance between  $r, r+dr$

**Determine RR(r):** From the simulation determine all the galaxy (unique) pairs and their distances and determine how many pairs have a distance between  $r, r+dr$ .

**The simulation assumes no clustering of galaxies.**

**Determine DR(r):** Take each galaxy from the real catalog. Compute the separation between that galaxy and every point in the random catalog. Count how many pairs fall within each separation bin  $[r, r+dr]$ . Sum over all galaxies in the data catalog to get  $DR(r)$

Step 3: 
$$\xi(r) = \frac{DD(r) - 2DR(r) + RR(r)}{RR(r)}$$

# Clustering of Galaxies

From a study of the clustering properties of a sample of  $\sim 120,000$  SDSS galaxies and for separations of  $0.1h^{-1} \text{ Mpc} < r < 16 h^{-1} \text{ Mpc}$  the correlation function is found to be:

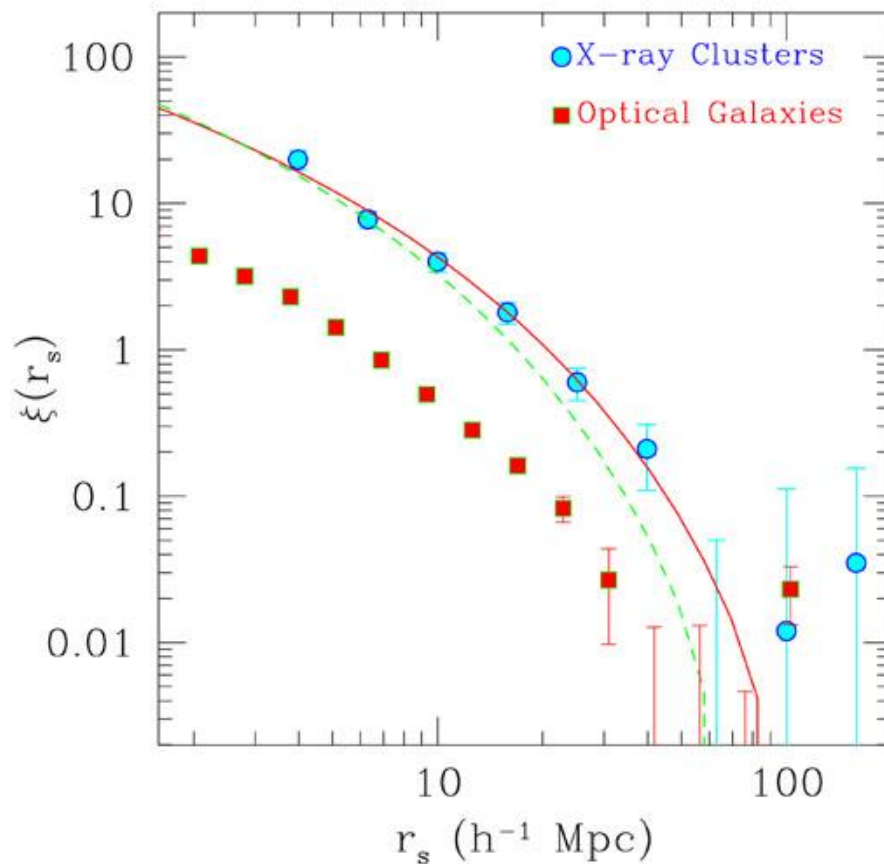
$$\xi(r) = \left( \frac{r}{r_0} \right)^{-\gamma}$$

Where  $r_0 = 5.53h^{-1} \text{ Mpc}$ ,  $\gamma = 1.8$  and  $H_0 = h \text{ } 100 \text{ km s}^{-1}\text{Mpc}^{-1}$

The correlation length  $r_0$  varies with galaxy luminosity from  $4.7 h^{-1} \text{ Mpc} - 7.4 h^{-1} \text{ Mpc}$

Longer correlation lengths for more luminous galaxies.

# Clustering of Galaxies



$$\xi(r) = \left(\frac{r}{r_0}\right)^{-\gamma}$$

The two-point correlation function for the X-ray selected clusters from the REFLEX survey (circles) and for the Las Campanas galaxy redshift survey (squares). The solid and dashed lines are the expected results for an X-ray similar survey in a LCDM model with different values for the cosmological parameters.

[https://ned.ipac.caltech.edu/level5/March04/Jones/Jones5\\_3.html](https://ned.ipac.caltech.edu/level5/March04/Jones/Jones5_3.html)

# The bias parameter

The bias parameter  $b$  quantifies how the spatial clustering of a particular population of galaxies or haloes compares to the clustering of the underlying dark matter:

$$\xi_{gal}(r, M) = b^2(M) \times \xi_{DM}(r)$$

## Physical Meaning

$b=1 \rightarrow$  galaxies/halos trace the dark matter distribution (“unbiased”)

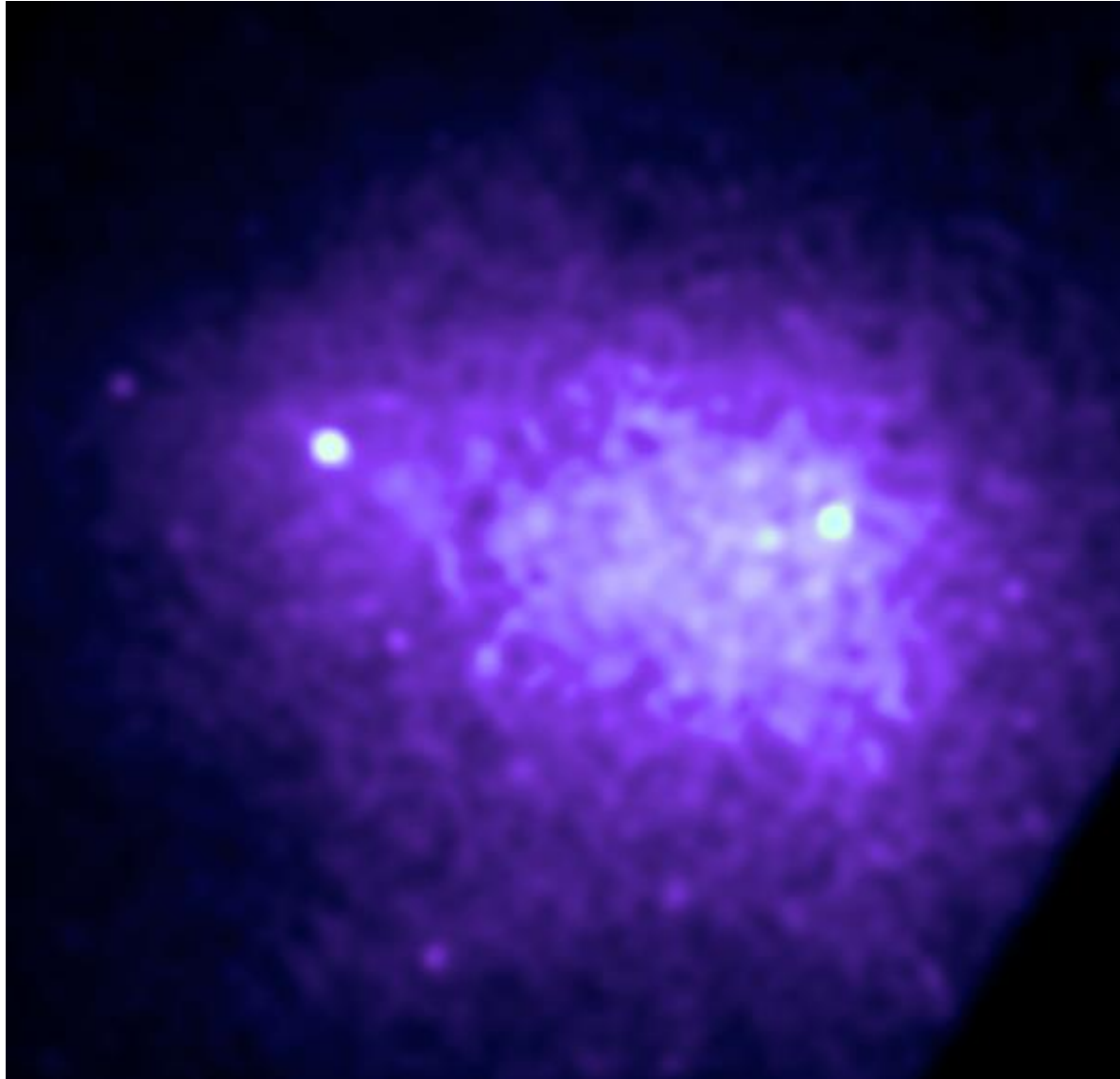
$b>1 \rightarrow$  galaxies/halos are more strongly clustered than dark matter (typical for massive halos or clusters)

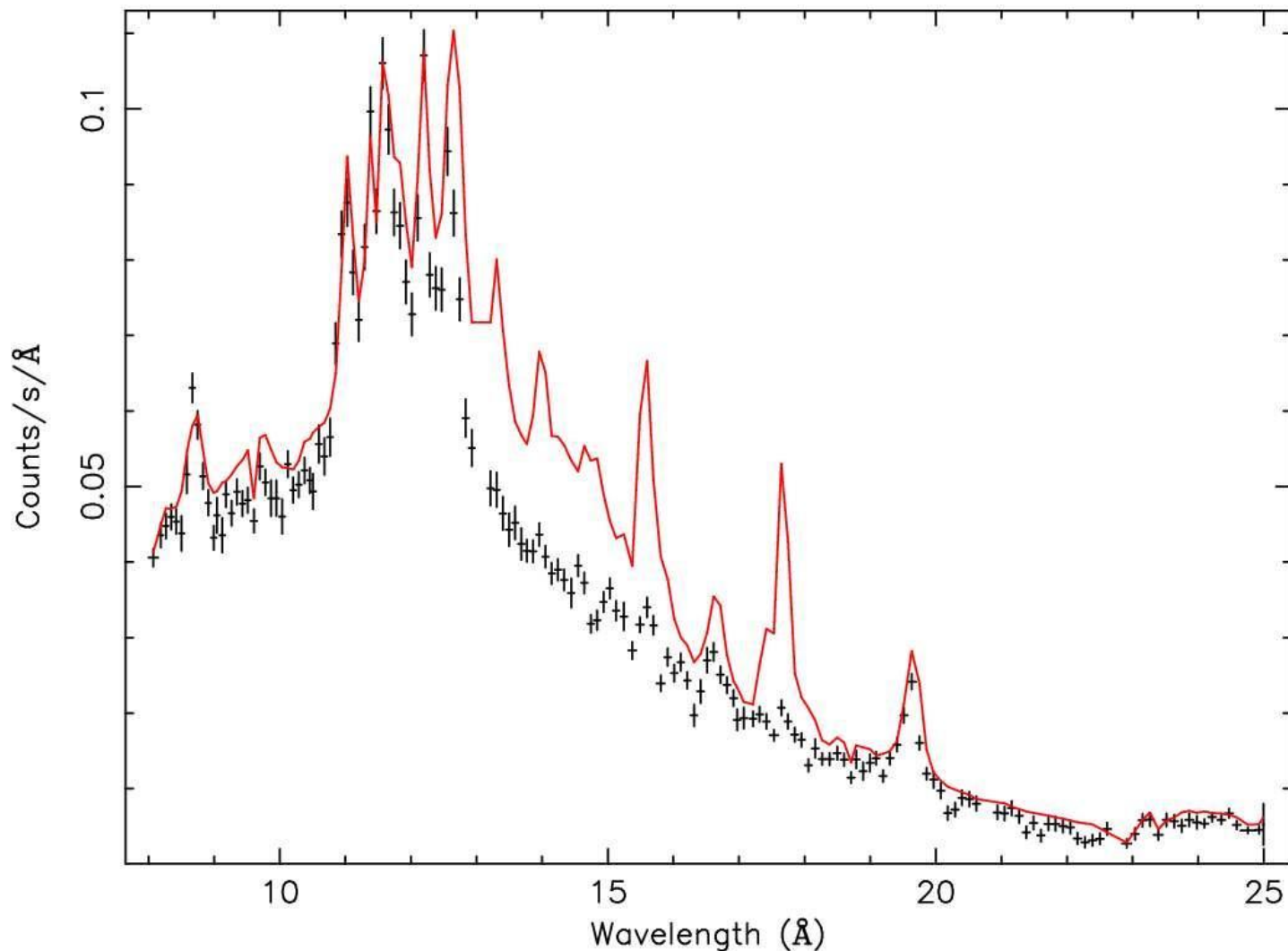
$b<1 \rightarrow$  galaxies/halos are less clustered than dark matter (typical for low-mass halos or faint galaxies)

Bias arises because large galaxies preferentially form in higher-density regions of the dark matter field

**EXTRA**

## Coma: A Rich Regular Cluster of Galaxies





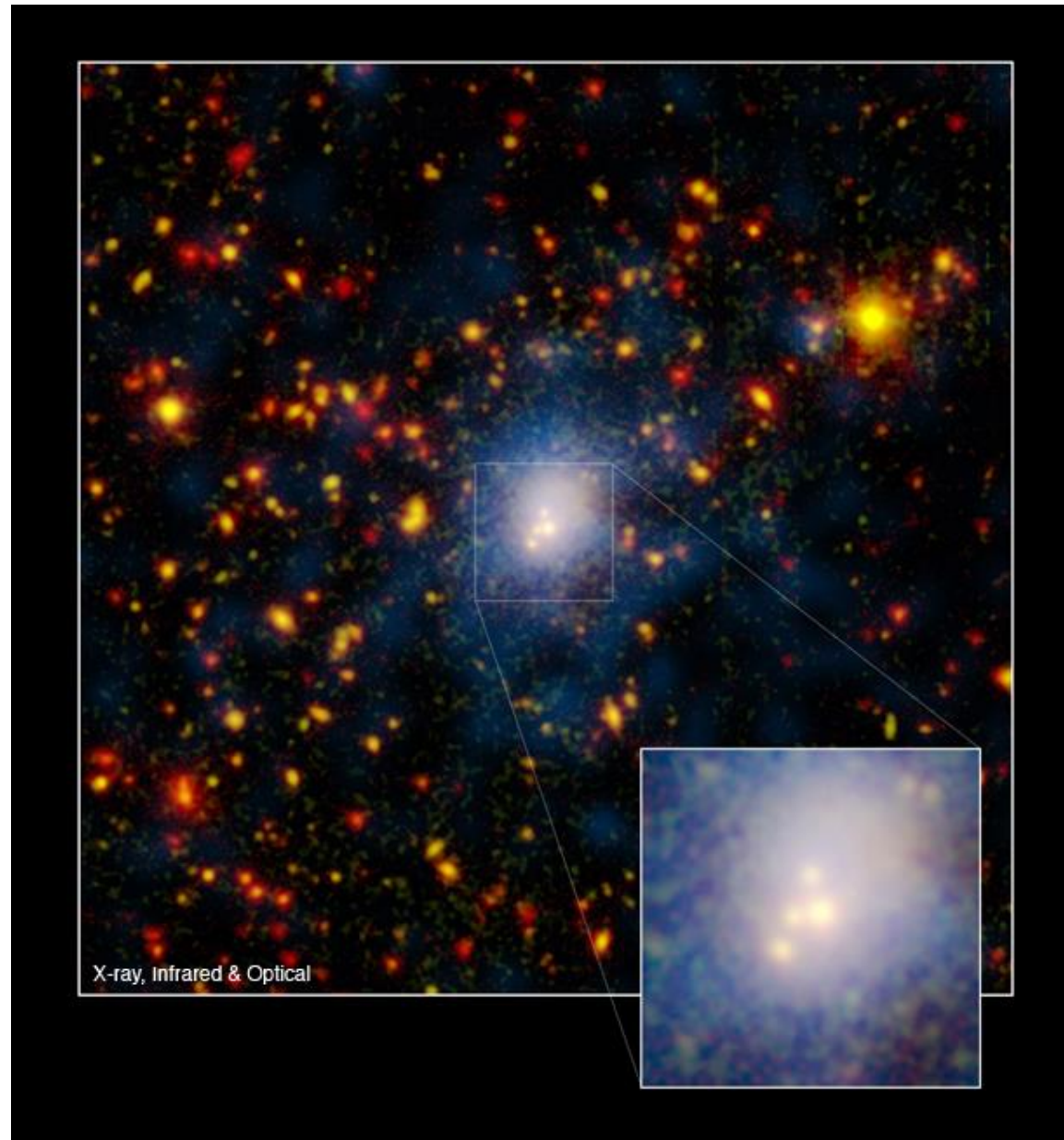
Slow cooling in the core of the galaxy cluster 2A 0335+096

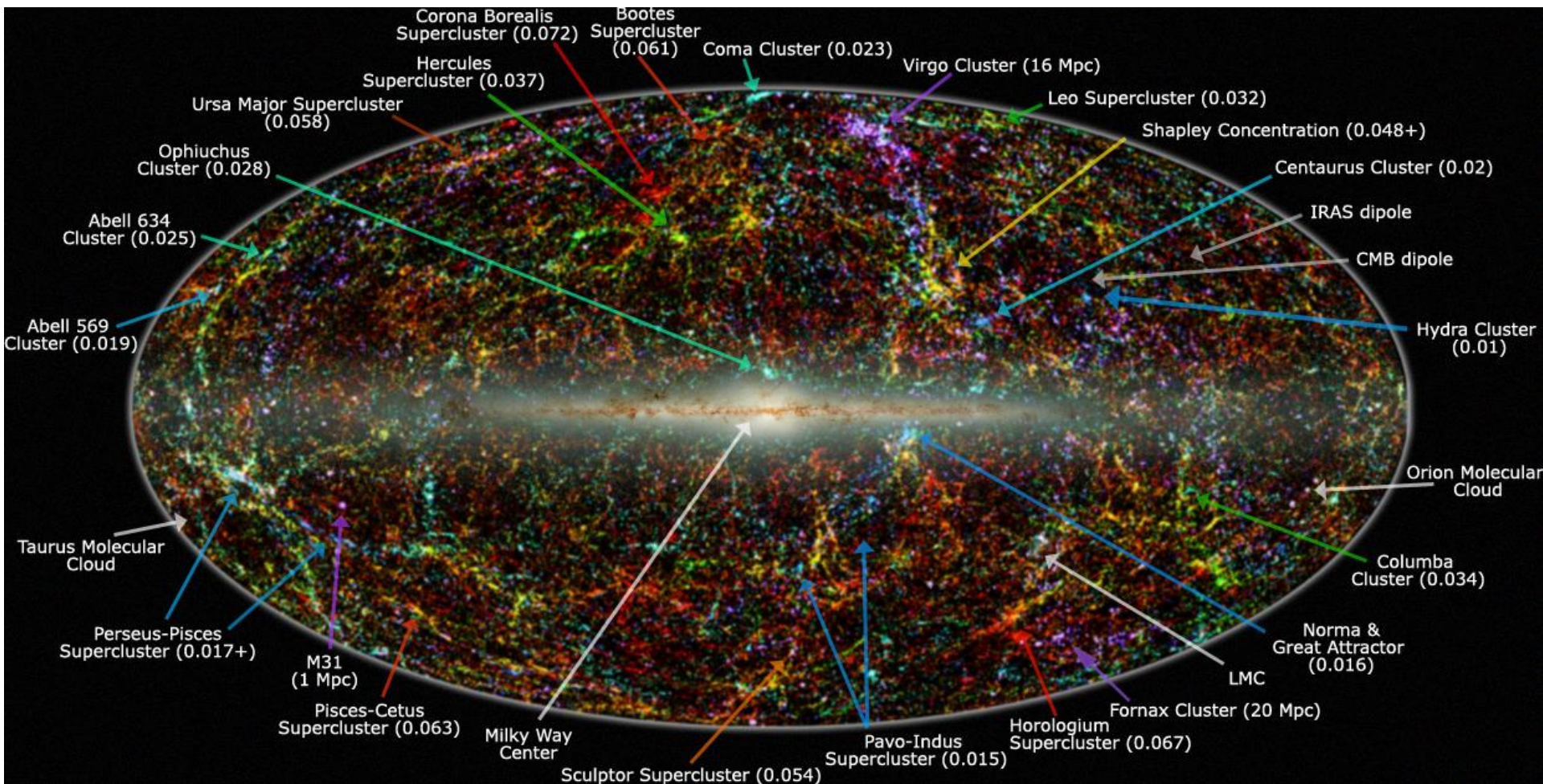
Image courtesy of Jelle de Plaa, SRON, NL.

European Space Agency 

XMM-Newton spectrum of the cluster of galaxies 2A 0335+096. The black crosses are the data points, the red line shows the predicted spectrum according to the previously favored isobaric cooling-flow model. The difference between the two, due to the lack of the expected Fe XVII lines, indicates that the cores of clusters are cooling much slower than predicted.

$z=0.39$  CL0958+4702: Spitzer and Chandra Spy Monster Galaxy Pileup





Panoramic view of the entire near-infrared sky. The location of the Great Attractor is shown following the long blue arrow at bottom-right.

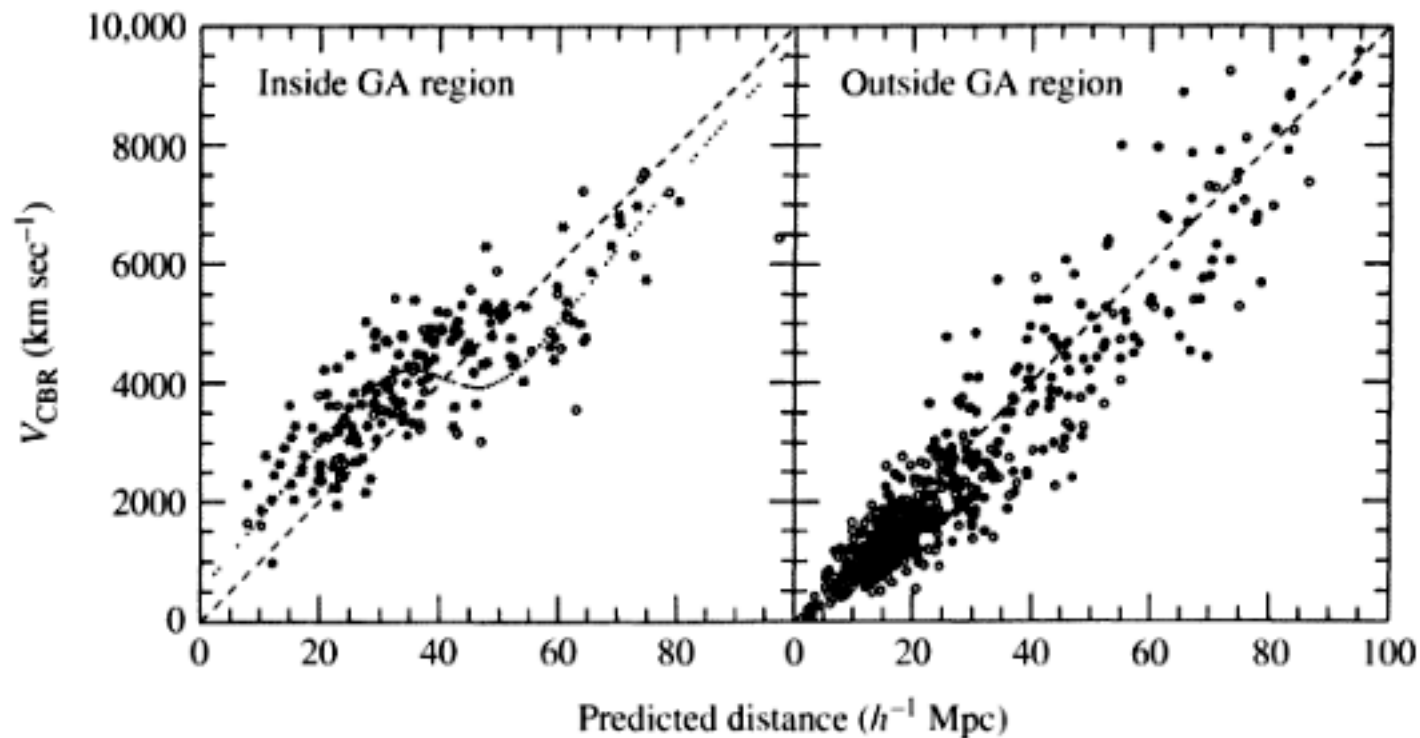


**FIGURE 27.19** Left: velocities of galaxies in the Centaurus region, compared with the Hubble flow (dashed line). The dotted line shows the theoretical variation in velocity produced by a model of the Great Attractor. The Hydra–Centaurus supercluster is centered at about  $30h^{-1}$  Mpc. Right: comparison figure for galaxies observed in another direction. (Figure adapted from Dressler and Faber, *Ap. J. Lett.*, 354, L45, 1990.)

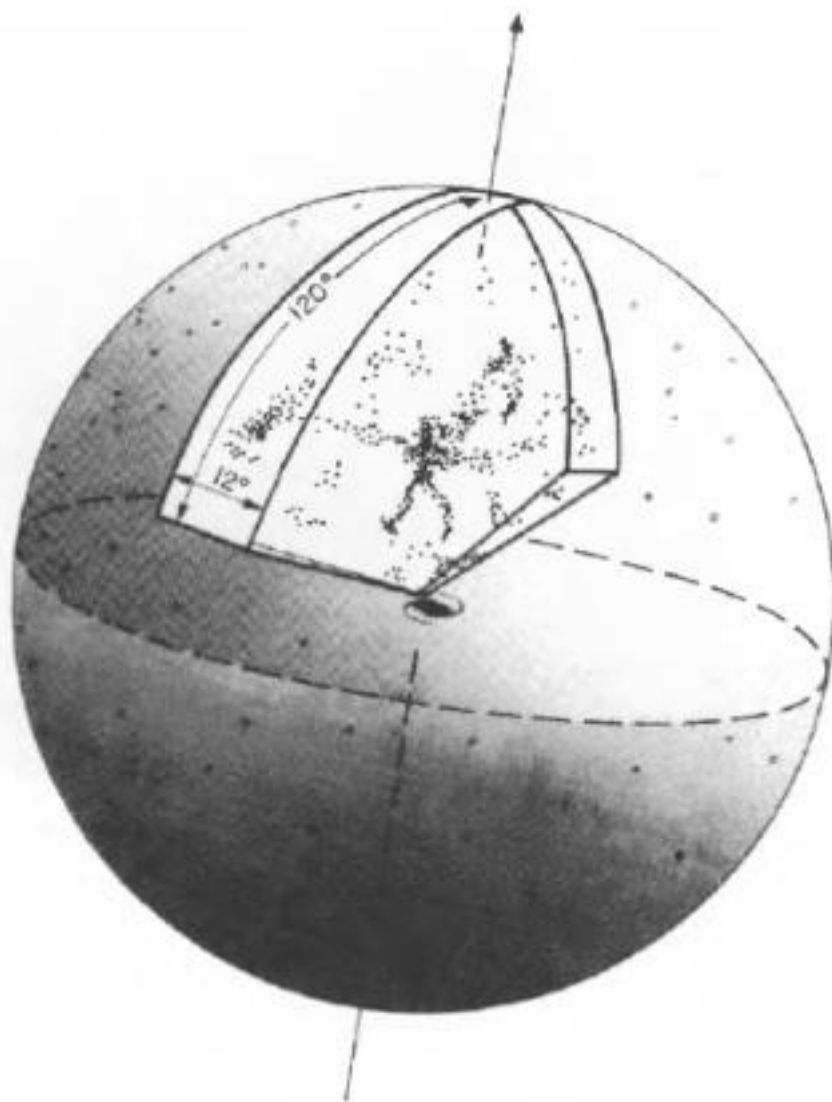
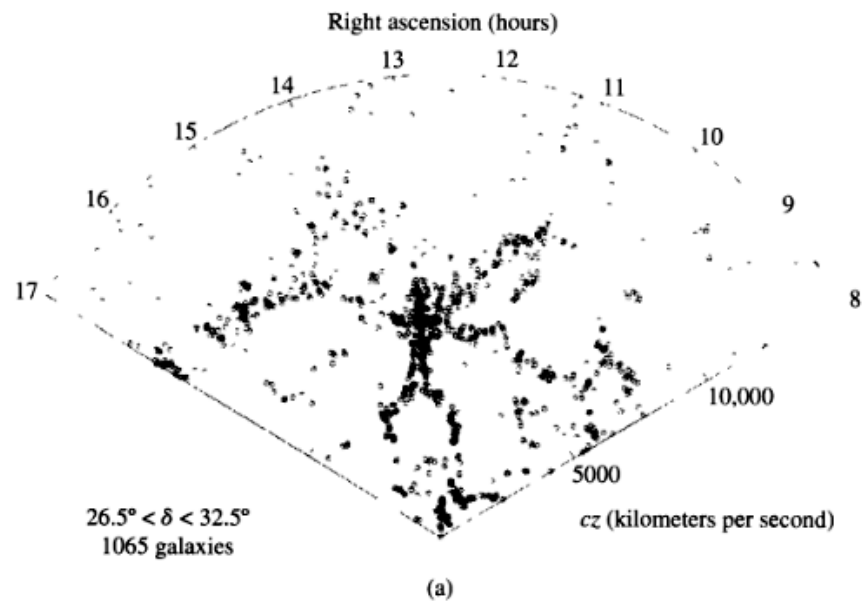
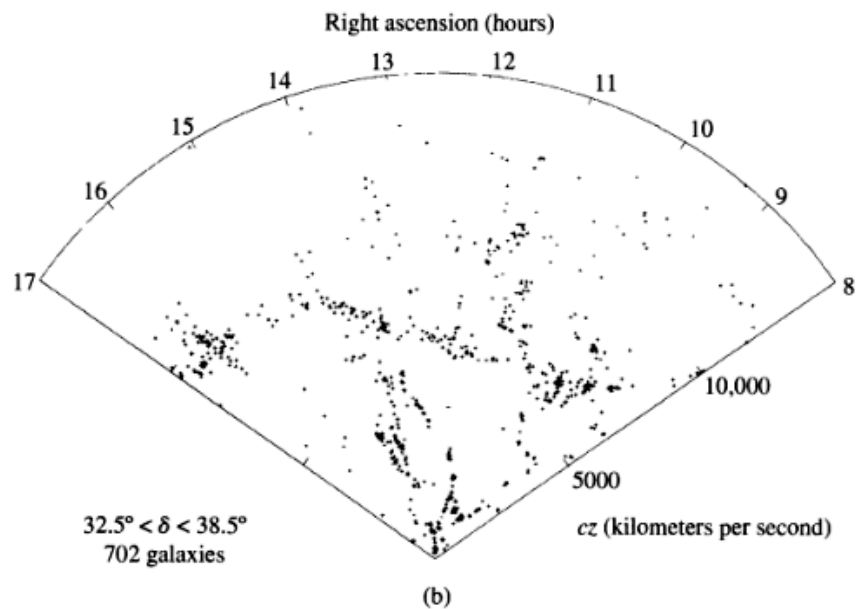


**FIGURE 27.22** Two adjacent  $6^\circ$ -wide wedges used in the CfA redshift survey. (Figure from Geller, *Mercury*, May/June 1990.)



(a)



(b)

**FIGURE 27.23** Two slices from the CfA redshift survey. Right ascension is indicated along the top of each figure. (a)  $26.5^\circ < \delta < 32.5^\circ$ . (b)  $32.5^\circ < \delta < 38.5^\circ$ . (Figures adapted from Geller, *Mercury*, May/June 1990.)