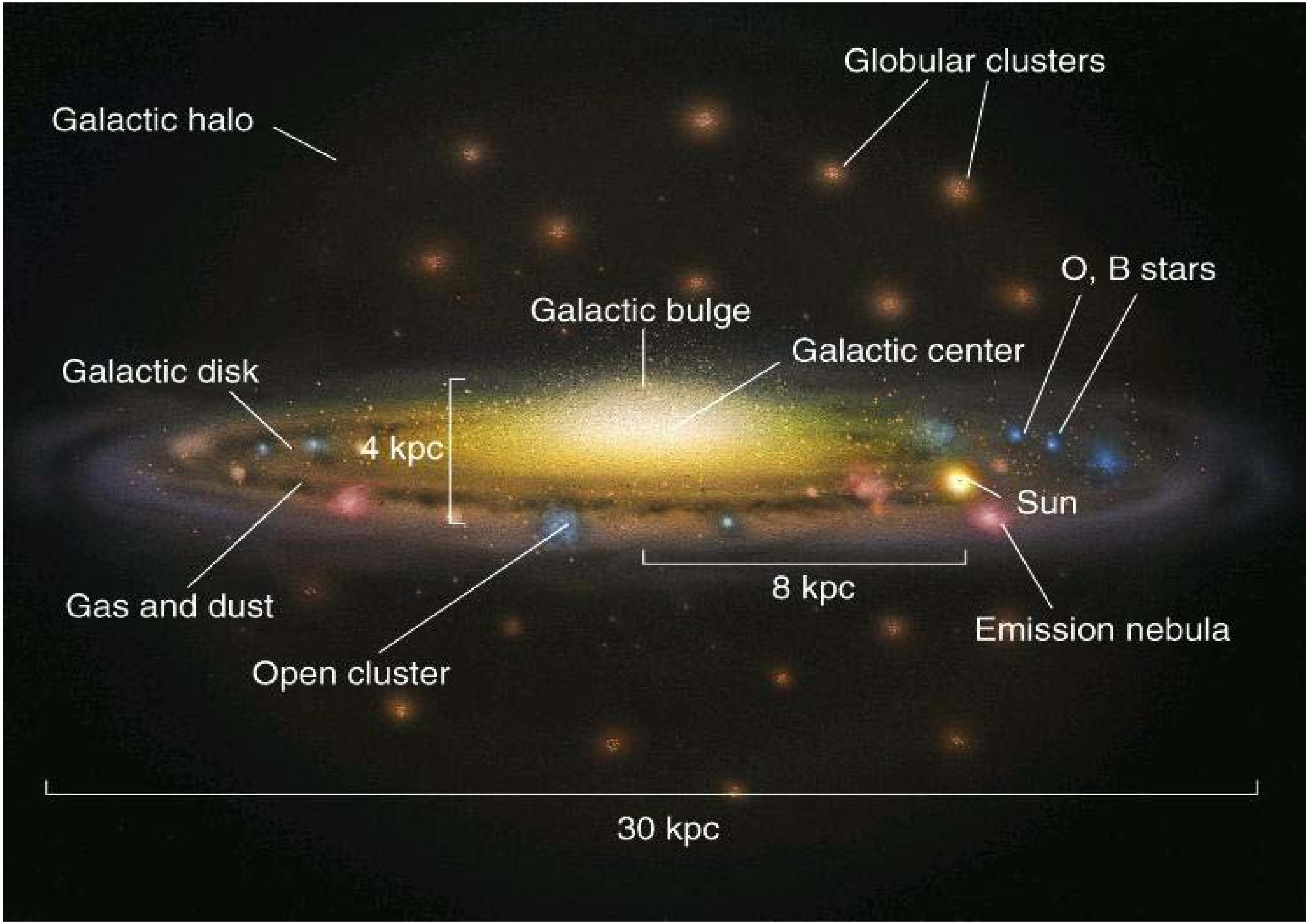
Cosmic Objects…

- **Stars**
  - ☞Normal Stars
  - ☞Flaring and Variable Stars
  - ☞Compact Stars (WD, NS, BH)
  - ☞Accreting Binaries
  - ☞"Exploding" Stars (SN,N; GRB?)
- **Interstellar Medium**
  - ☞Molecular Clouds, Neutral ISM
  - ☞Ionized Regions
  - ☞Supernova Remnants
- **Galaxies**
  - ☞Normal Galaxies
  - ☞Active Galaxies (Quasars, Blazars,…)
- **Large-Scale Structure of Universe**
  - ☞Galaxy Clusters
  - ☞Cosmic Microwave Background
  - ☞Dark Matter

- Our Galaxy
- Galaxy Types
- Distance Measurement
- Clusters of Galaxies
- Cosmological Parameters

Our Galaxy - The Milky Way



The Three Main Structural Components of the Milky Way

1. Disk

- 30,000 pc diameter (or 30 kpc)
- contains young and old stars, gas, dust. Has spiral structure
- vertical thickness roughly 100 pc - 2 kpc (depending on component. Most gas and dust in thinner layer, most stars in thicker layer)

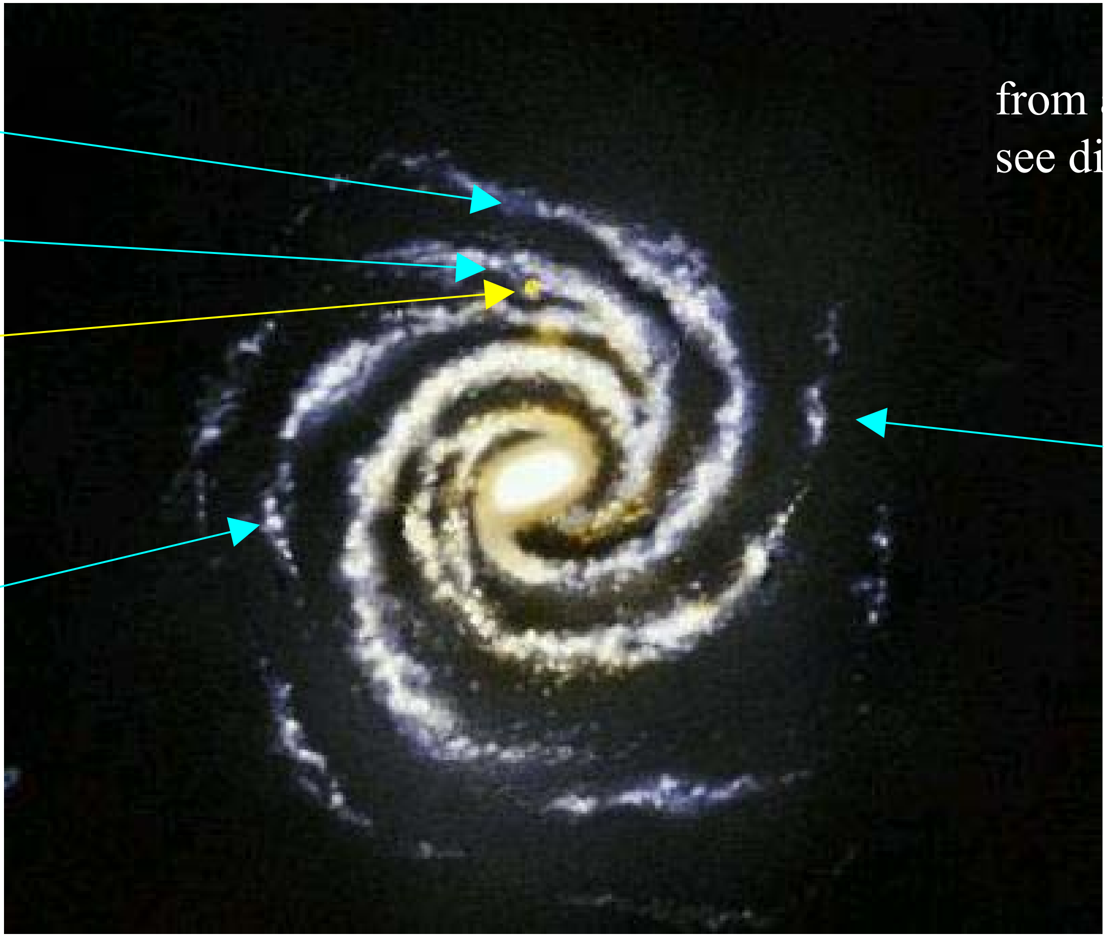
2. Halo

- at least 30 kpc across
- contains globular clusters, old stars, little gas and dust, much "dark matter"
- roughly spherical

3. Bulge

- 1000 pc across
- old stars, some gas, dust
- central black hole of 3 x 10^6 solar masses
- spherical

Take a Giant Step Outside the Milky Way



Perseus arm

Orion arm

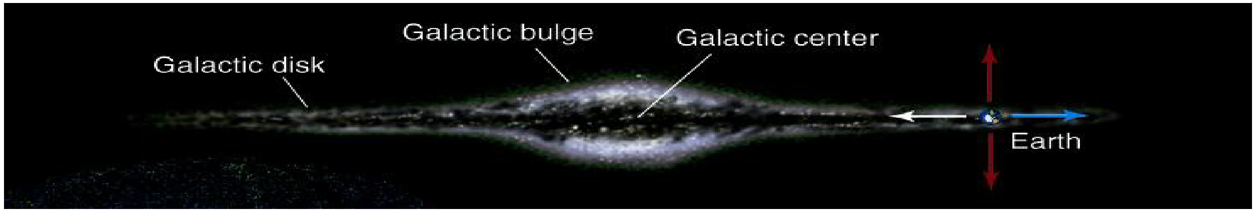
Sun

Carina arm

Cygnus arm

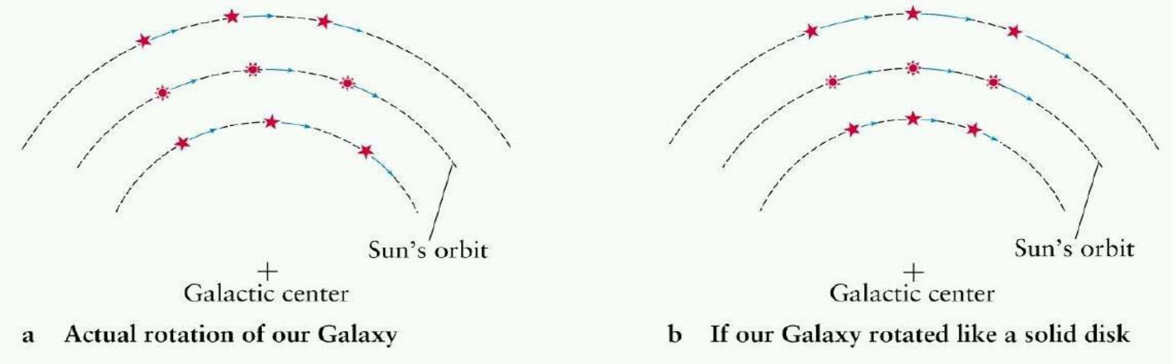
from

see di



Rotation of the Disk

Sun moves at 225 km/sec around center. An orbit takes 240 million years.



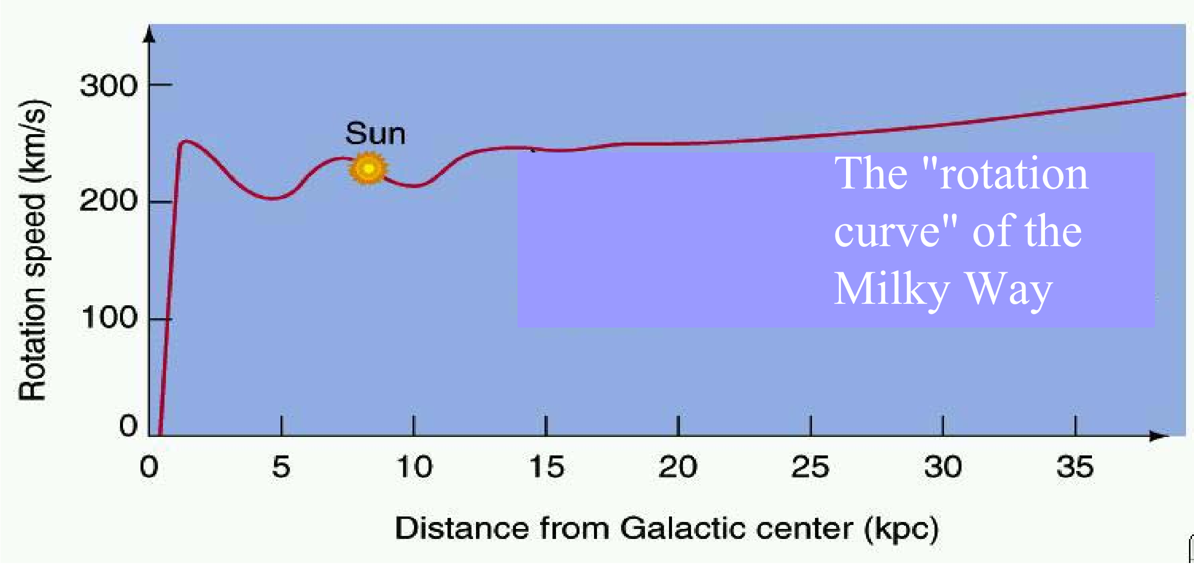
a Actual rotation of our Galaxy

b If our Galaxy rotated like a solid disk

Stars closer to center take less time to orbit. Stars further from center take longer.

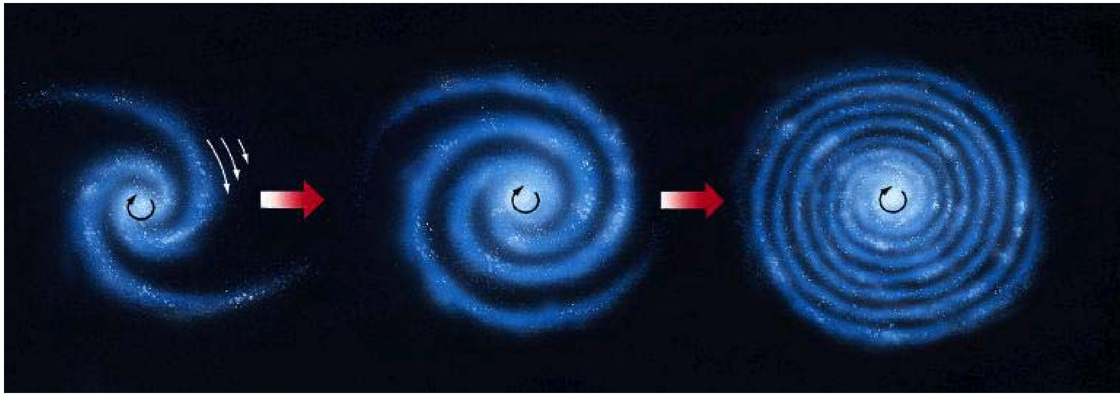
=> rotation <u>not</u> rigid like a phonograph record. Rather, "differential rotation"

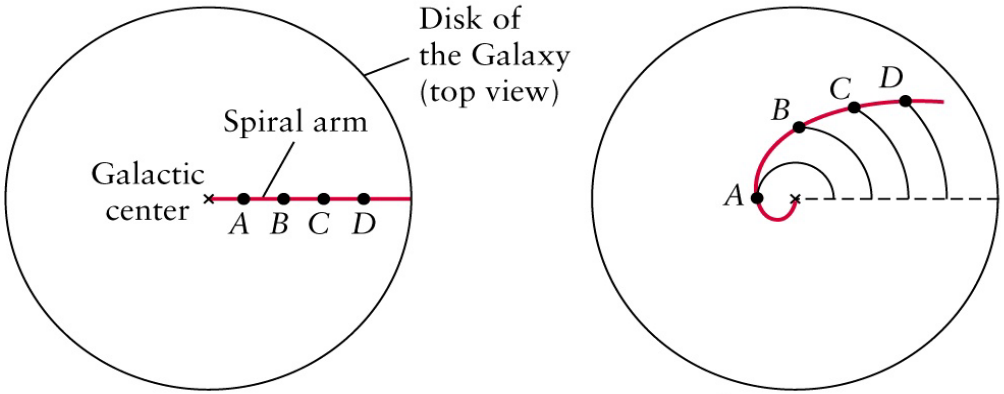
Over most of disk, rotation velocity is roughly <u>constant</u>.



The "rotation curve" of the Milky Way

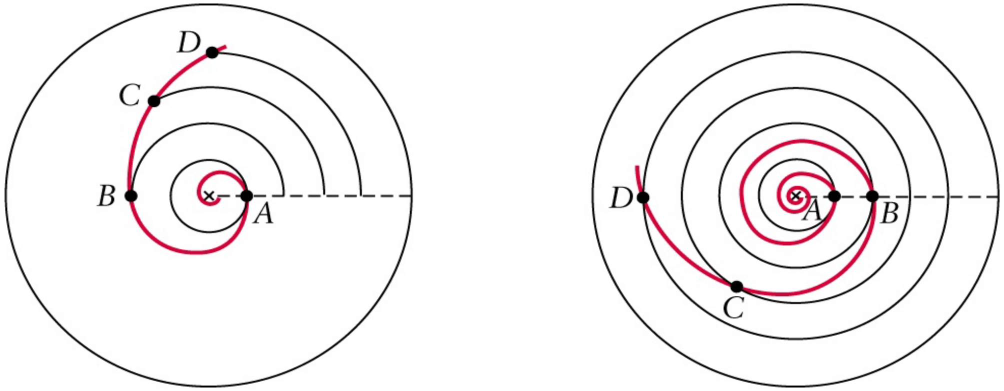
The Winding Dilemma





a

b After $\frac{1}{2}$ orbit of star A



c After one orbit of star A

d After two orbits of star A

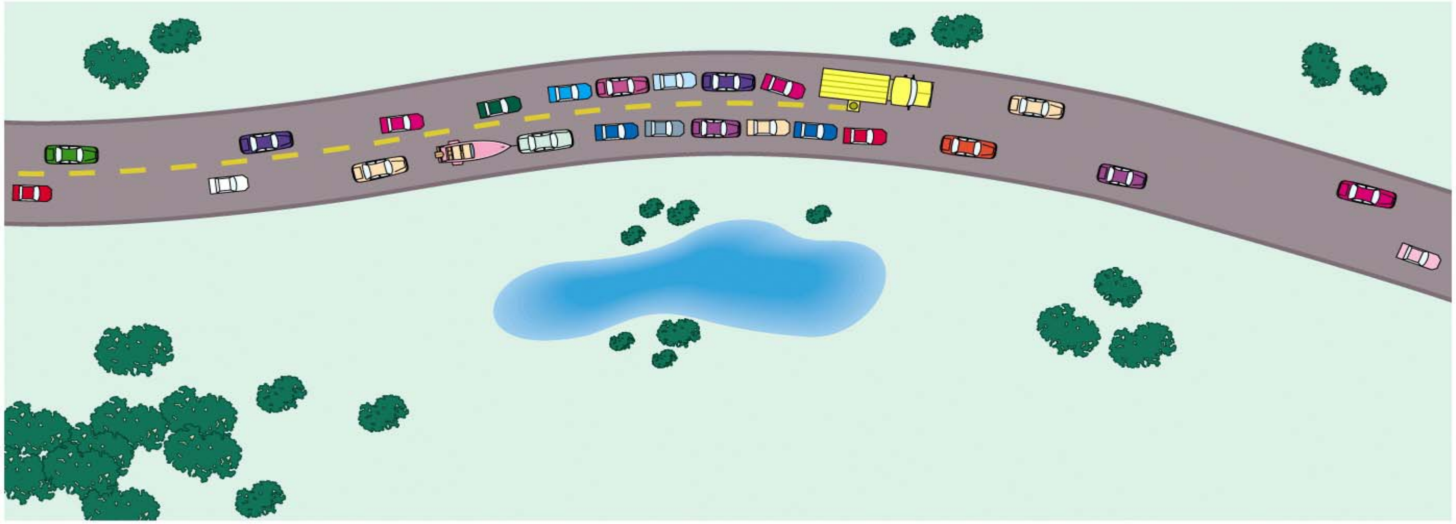
Given differential rotation, arms should be stretched and smeared out after a few revolutions (Sun has made 20 already):

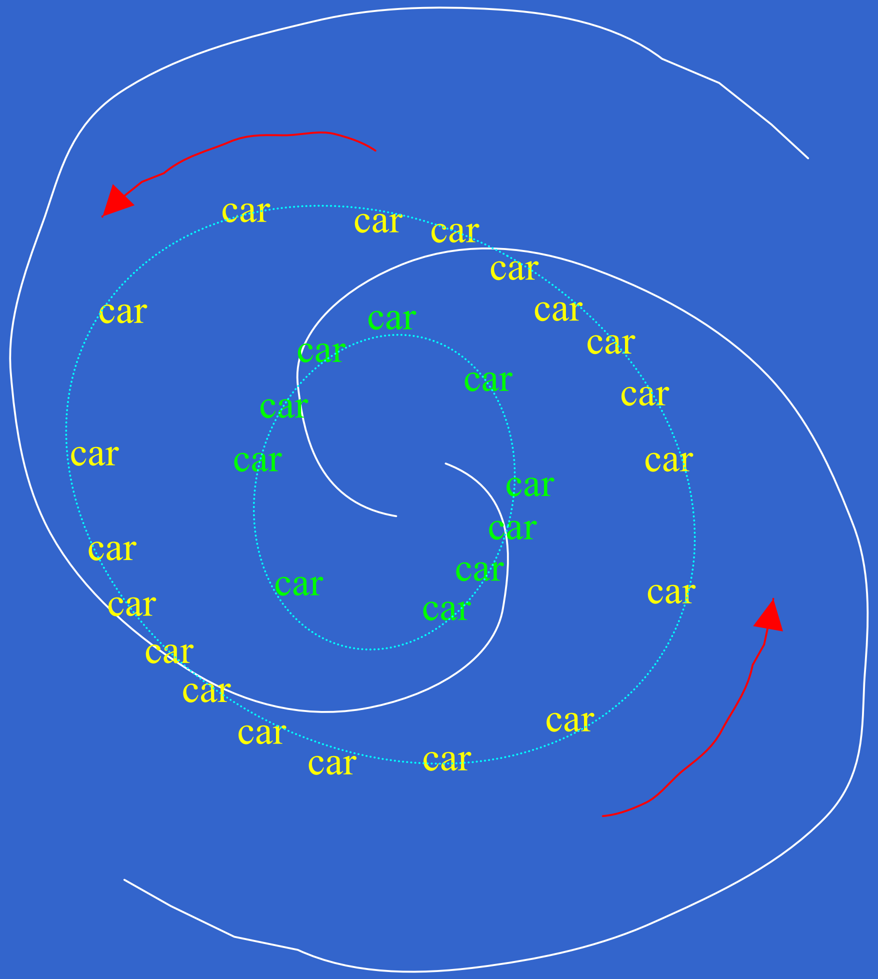
Proposed solution:

Arms are not material moving together, but mark peak of a compressional wave circling the disk:

A Spiral Density Wave

Traffic-jam analogy:

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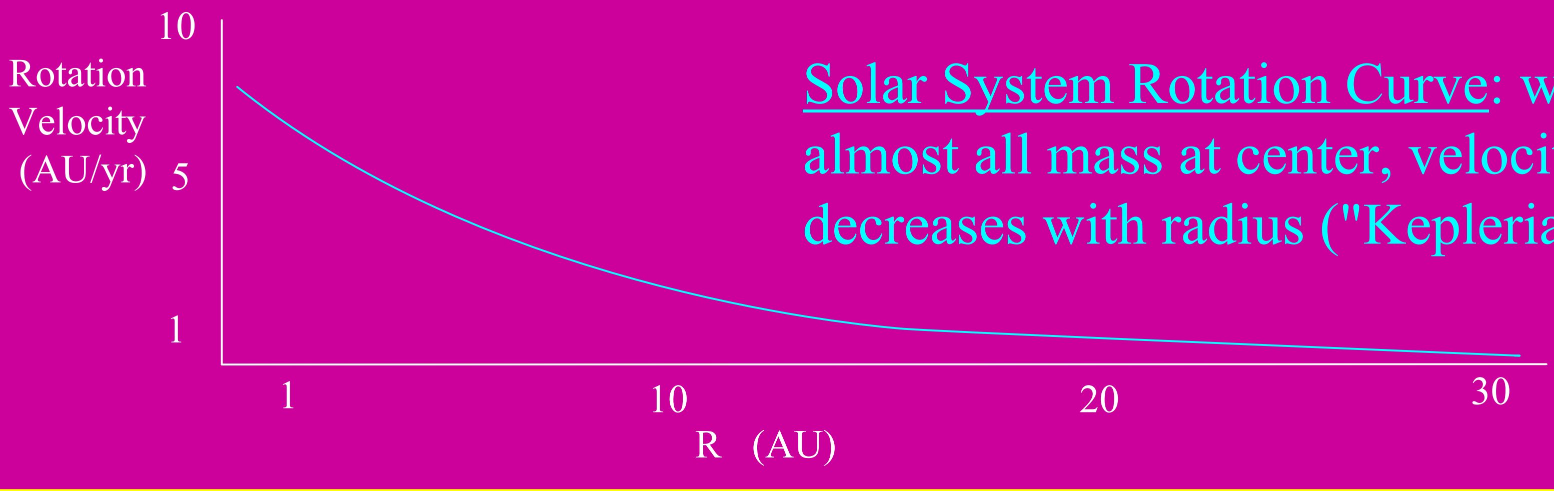
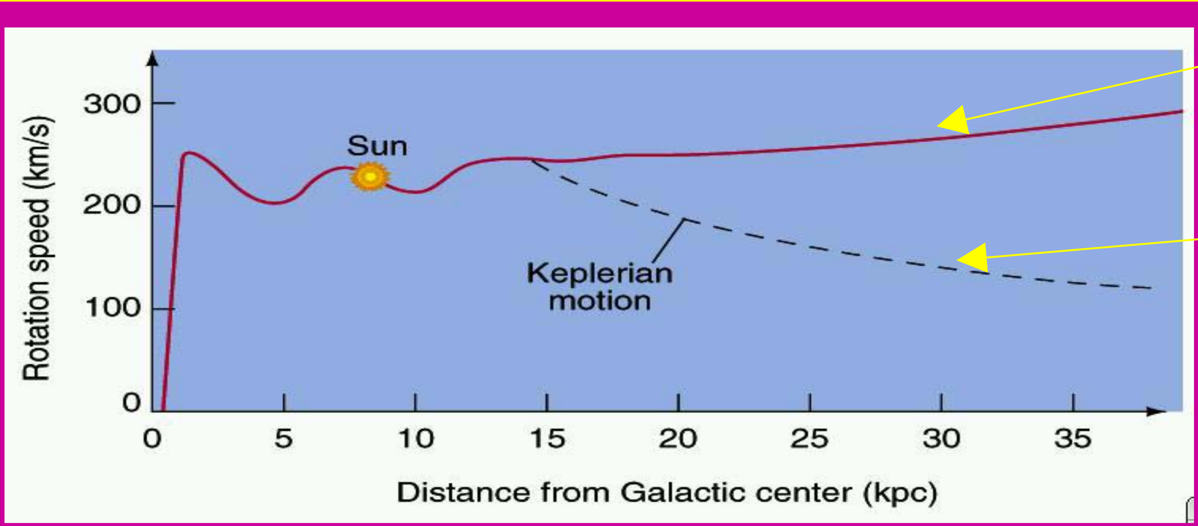
90% of Matter in Milky Way is Dark Matter

Gives off no detectable radiation. Evidence is from rotation curve:



Solar System Rotation Curve: when almost all mass at center, velocity decreases with radius ("Keplerian")

Milky Way Rotation Curve

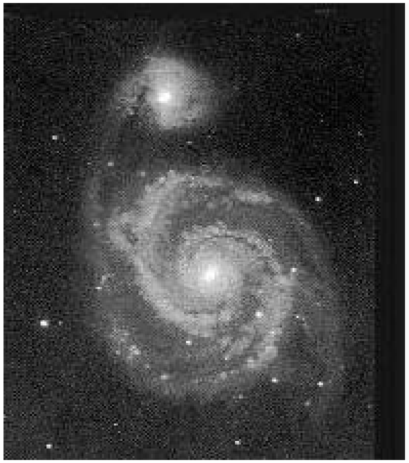


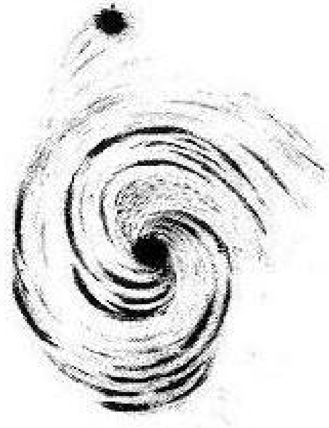
observed curve

Curve if Milky Way ended where visible matter pretty much runs out.

Galaxies

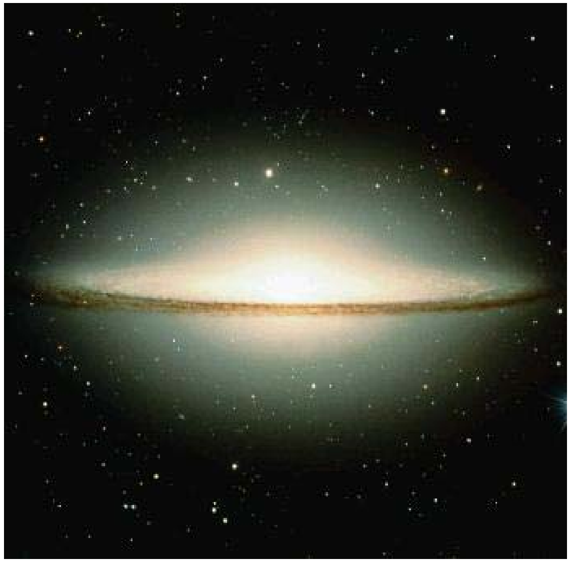
First spiral nebulae found in 1845 by the Earl of Rosse (Birr Castle/IRL). Speculated it was beyond our Galaxy.

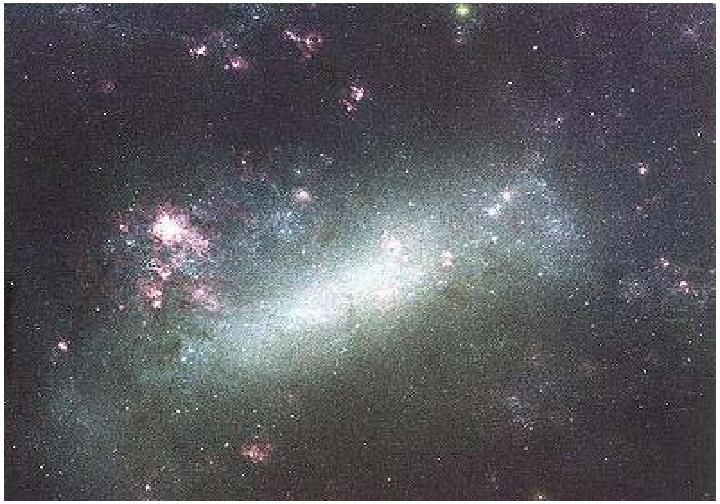




1920 - "Great Debate" between Shapley and Curtis on whether spiral nebulae were galaxies beyond our own. Settled in 1924 when Edwin Hubble observed individual stars in spiral nebulae.

Galaxy Types





Galaxy Classification

Spirals

barred
Sa-Sc

unbarred
Sa-Sc

Ellipticals

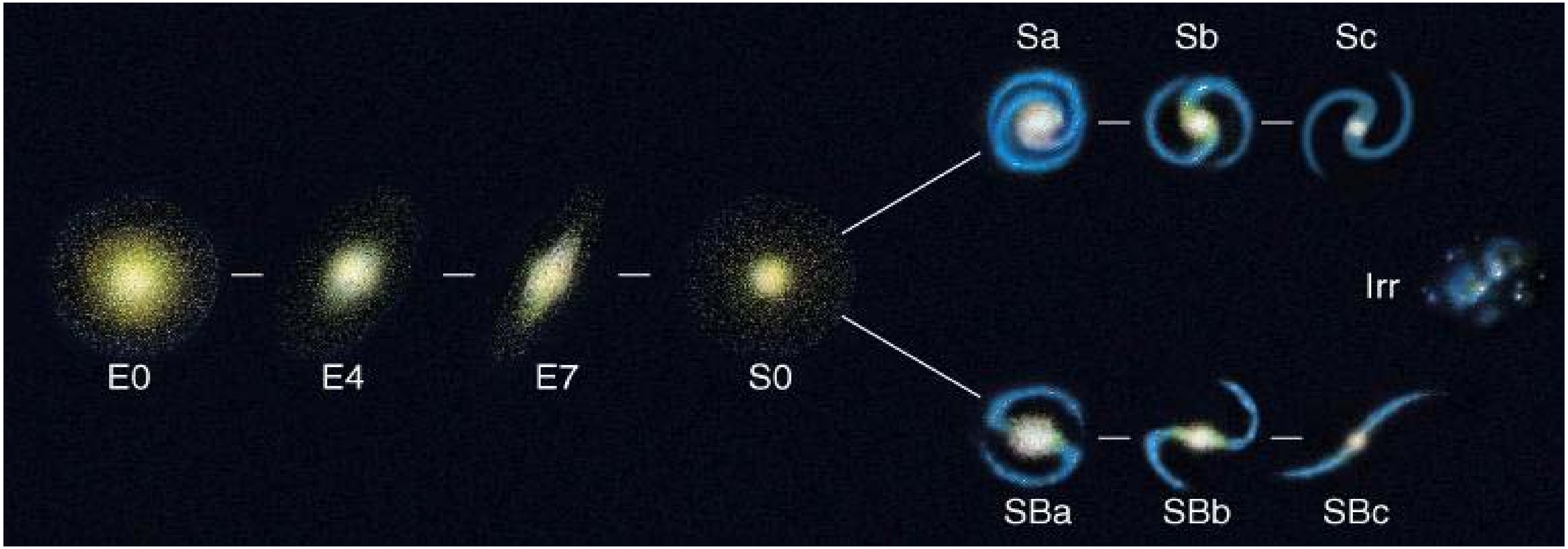
E0 - E7

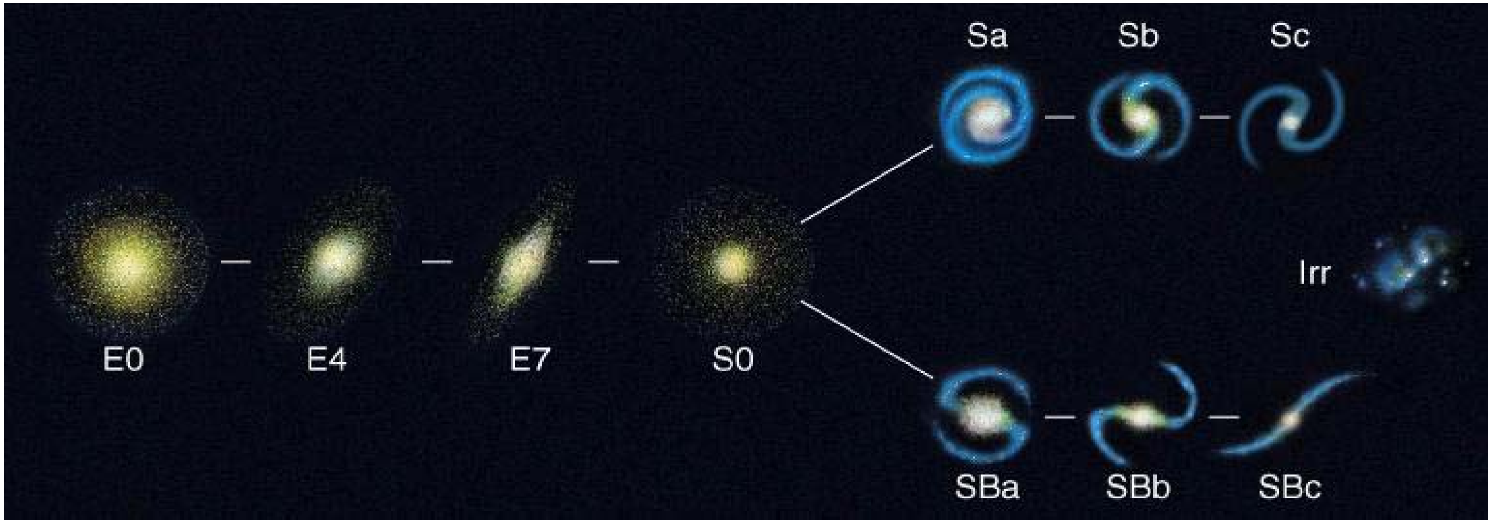
Irregulars

Irr I
"misshapen
spirals"

Irr II
truly
irregular

First classified by Hubble in 1924 => "tuning fork diagram"





Still used today. We talk of a galaxy's "Hubble type"

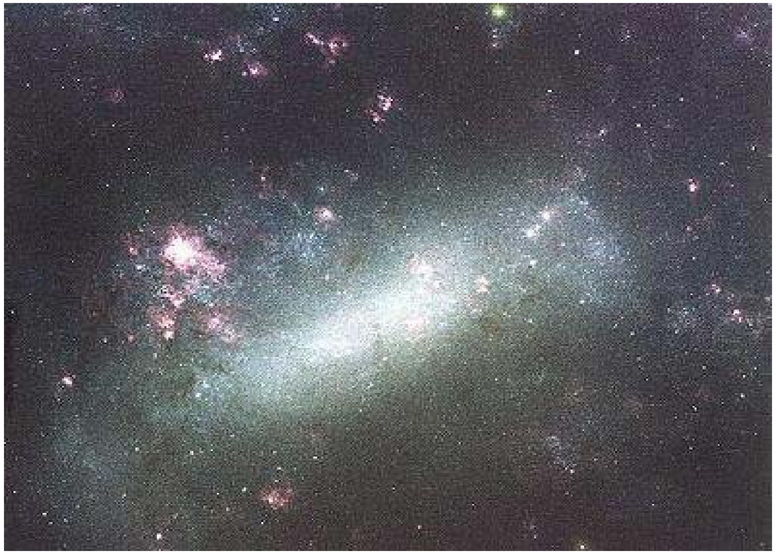
Milky Way is an Sbc, between Sb and Sc.

Later shown to be related to other galaxy structural properties and galaxy evolution.

Ignores some notable features, e.g. viewing angle for ellipticals, number of spiral arms for spirals.

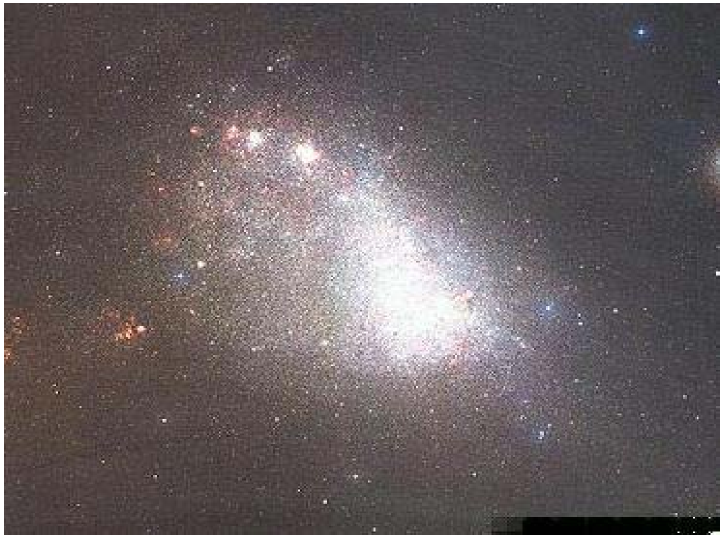
Irr I vs. Irr II

Irr I



Large Magellanic Cloud

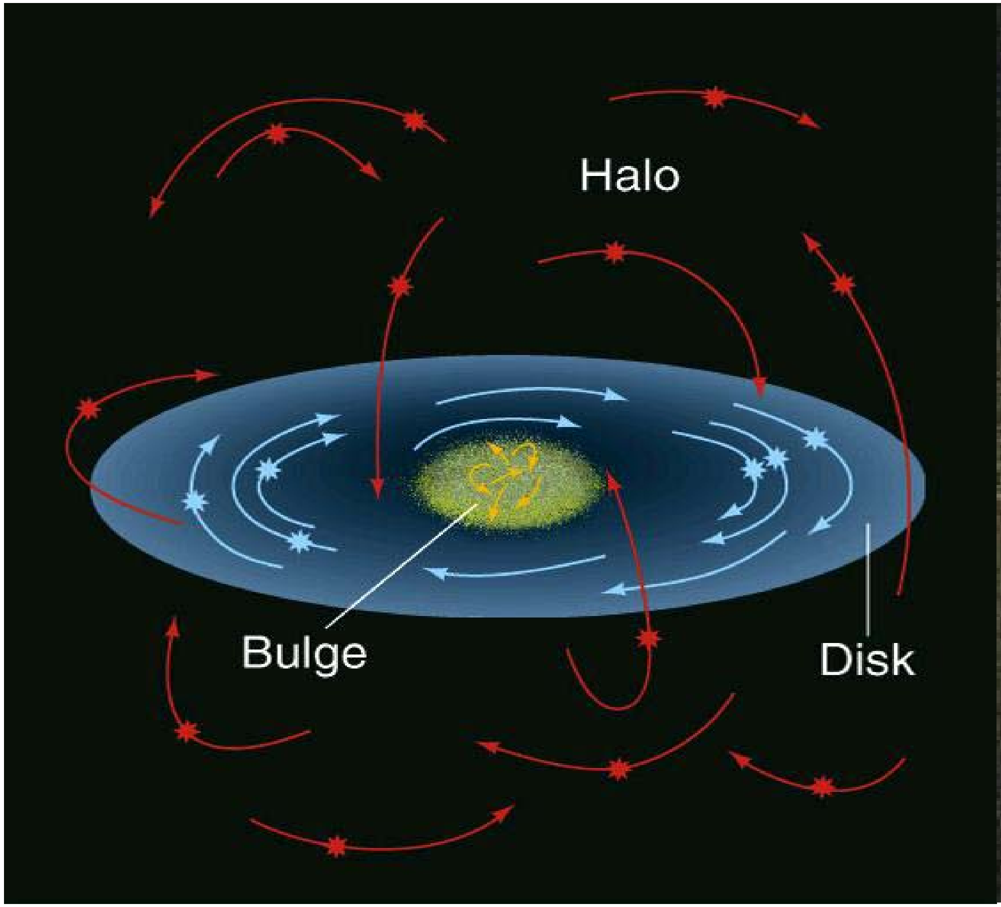
Irr II



Small Magellanic Cloud

These are both companion galaxies of the Milky Way.

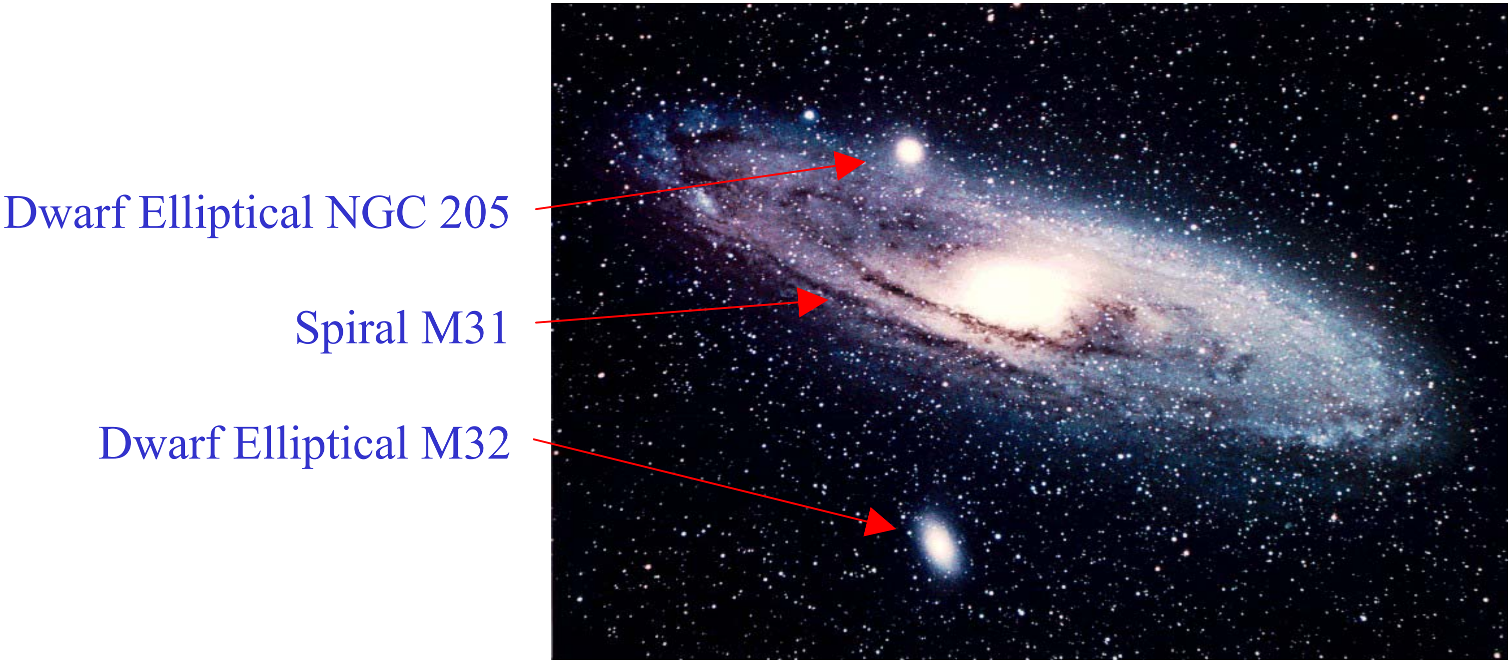
Ellipticals are similar to halos of spirals, but generally larger, with many more stars. Stellar orbits are like halo star orbits in spirals. Stars in ellipticals also very old, like halo stars.



Many irregulars rotate like rigid bodies.

A further distinction for ellipticals and irregulars:

Giant	vs.	Dwarf
10^{10} - 10^{13} stars		10^{6} - 10^{8} stars
10's of kpc across		few kpc across



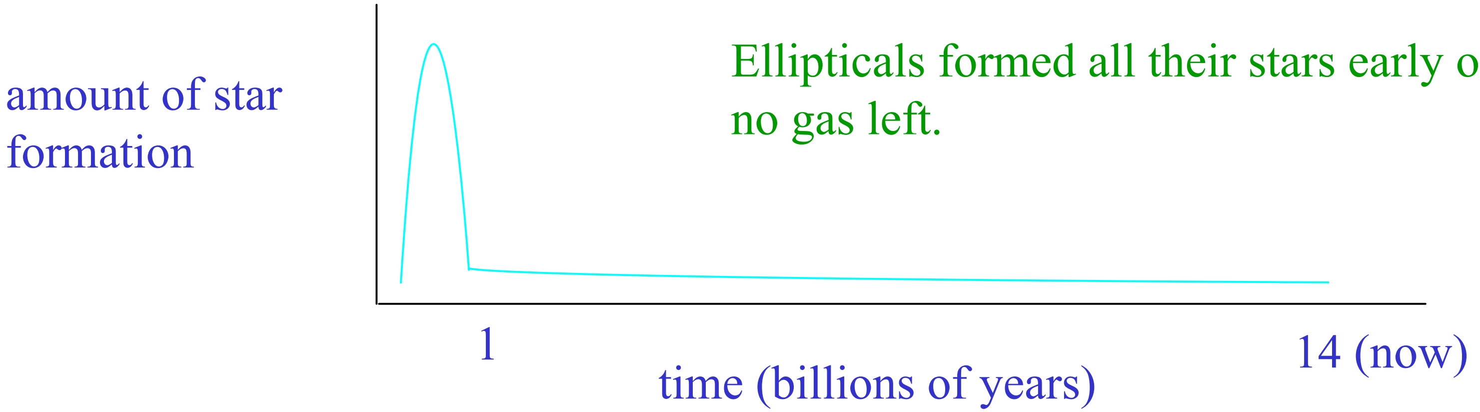
In giant galaxies, the average elliptical has more stars than the average spiral, which has more than the average irregular.

What kind of giant galaxy is most common?

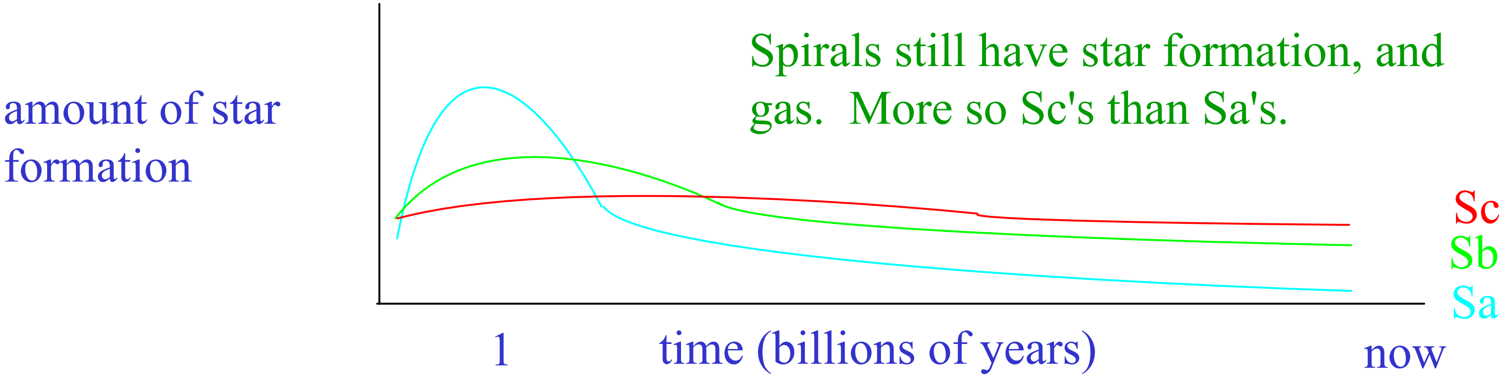
Spirals - about 77%
Ellipticals - 20%
Irregulars - 3%

But dwarfs are much more common than giants.

"Star formation history" also related to Hubble type:



Ellipticals formed all their stars early on, no gas left.

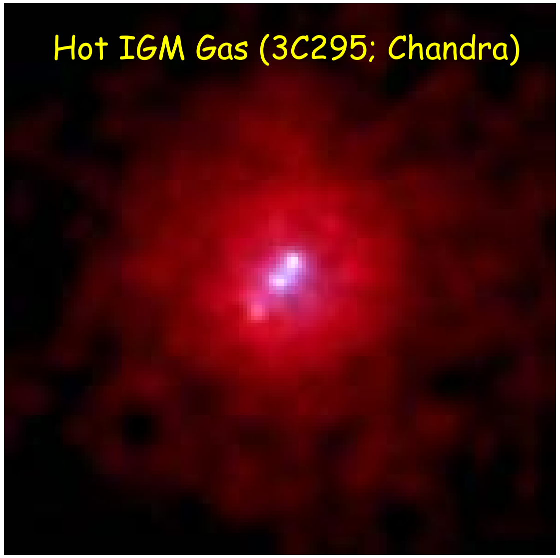


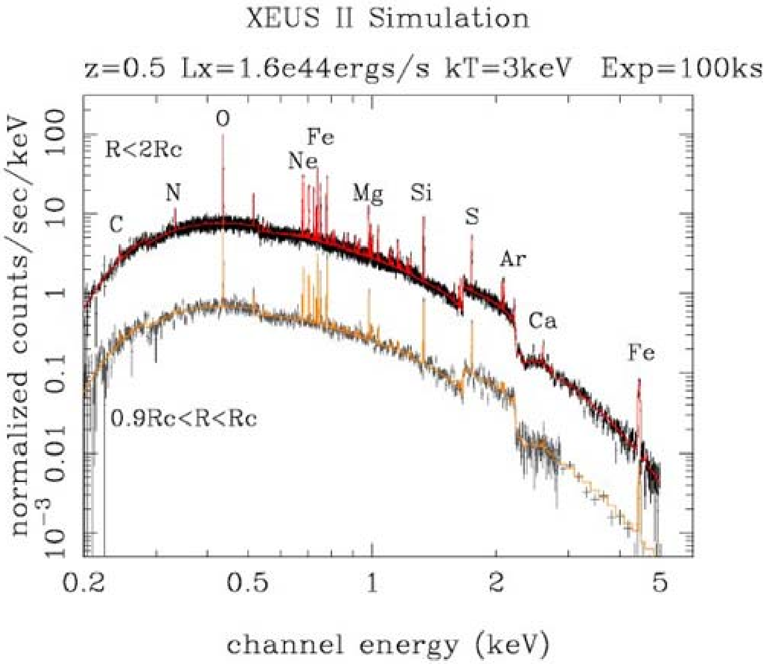
Spirals still have star formation, and gas. More so Sc's than Sa's.

Irregulars have irregular star formation histories.

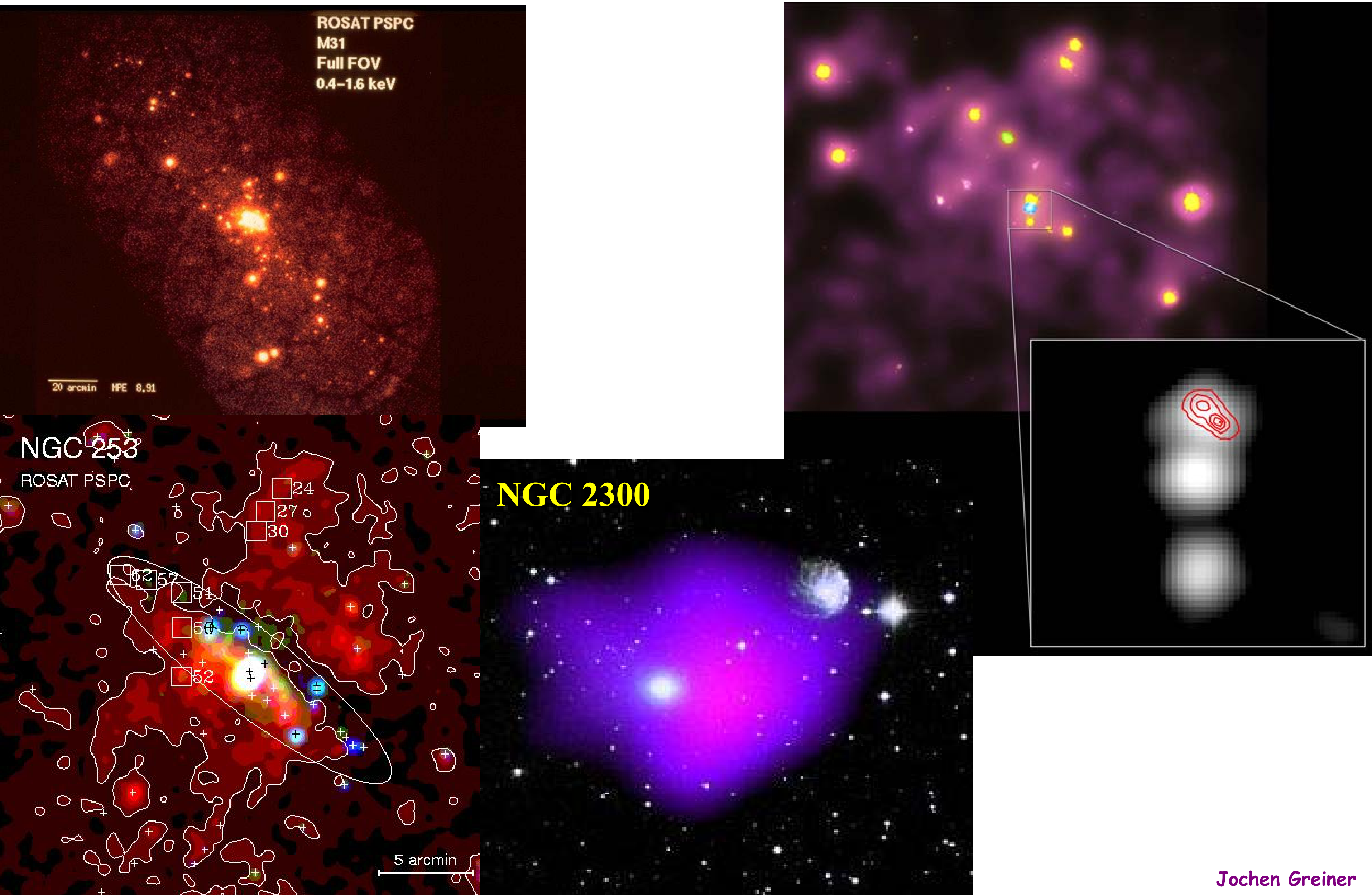
Galactic Halos and Intergalactic Gas

- Galactic Winds & Fountains Eject Gas into Intergalactic Space
- Inefficient Cooling (hot plasma, low density), Unknown Heating Sources (magnetic fields, CRs, turbulence)
- Recording IGM Gravitational Potential and Chemical History





X-ray emission of Galaxies



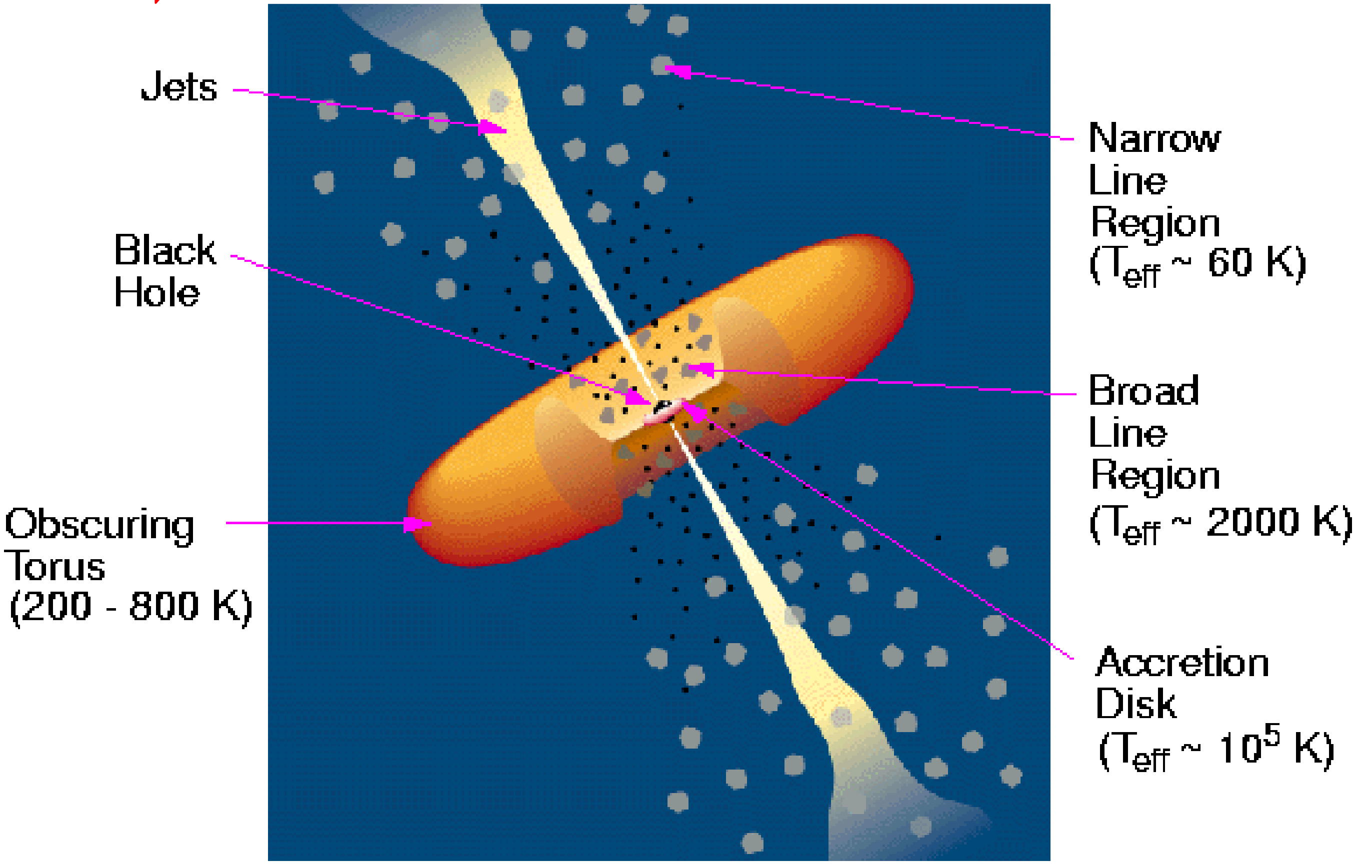
Jochen Greiner

Active Galaxies (AGN)

Center bright in optical/UV/X-rays: → Active Galactic Nuclei

Otherwise normal morphology/properties:

→ Only difference is accretion rate on central black hole



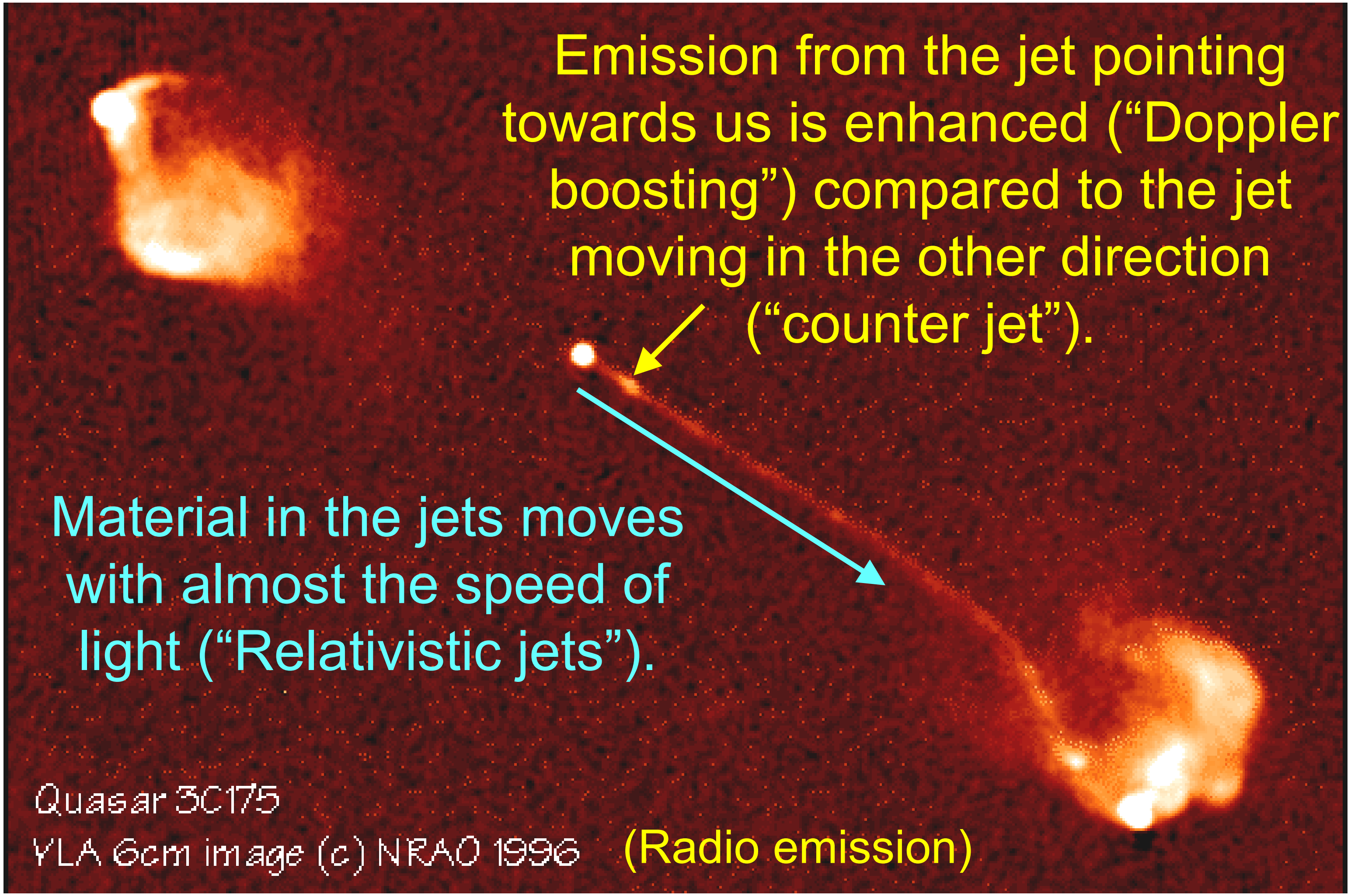
TAXONOMY:

- Seyfert galaxies 1/2
- Quasars (QSOs)
- Radio Galaxies
- LINERs
- Blazars

All depends on viewing

Quasar Jets

Many quasars show powerful radio jets

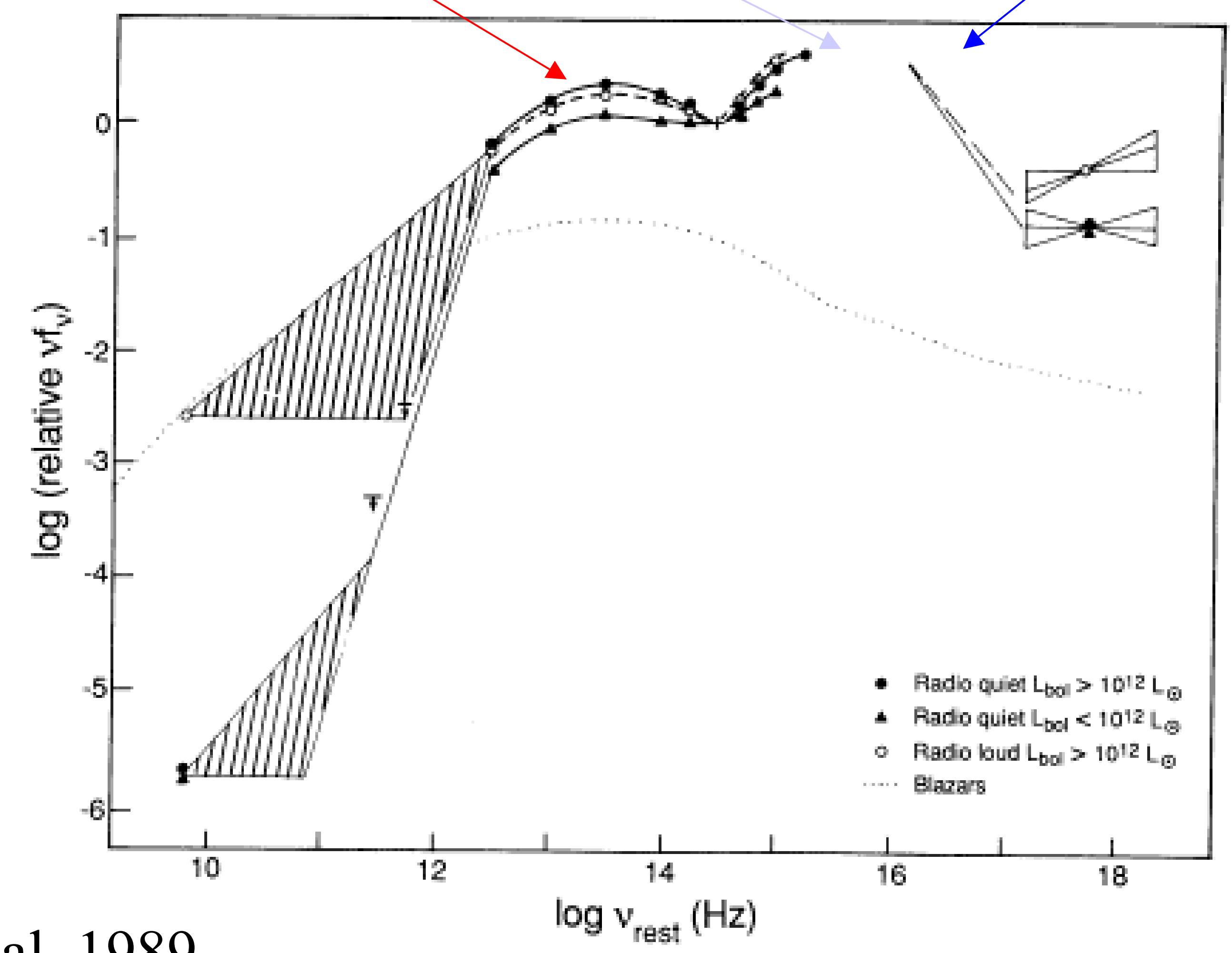


Emission from the jet pointing towards us is enhanced ("Doppler boosting") compared to the jet moving in the other direction ("counter jet").

Material in the jets moves with almost the speed of light ("Relativistic jets").

(Radio emission)

Spectral Energy Distributions



EUV gap

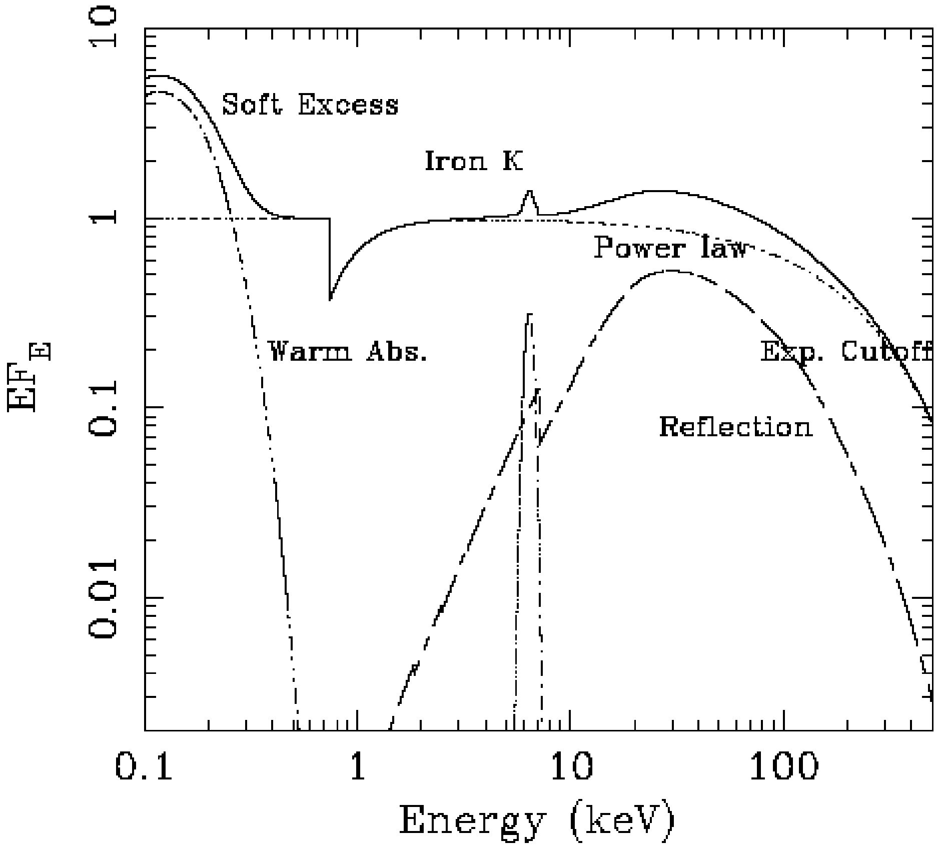
Big Blue Bump

IR bump

Sanders et al. 1989

X-ray Observational Study of AGNs

- **Spectrum**
  - ☆ Power Law
  - ☆ Cold Absorber
  - ☆ Iron Line
  - ☆ Soft X-ray Excess
  - ☆ Reflection Hump
  - ☆ Warm Absorber

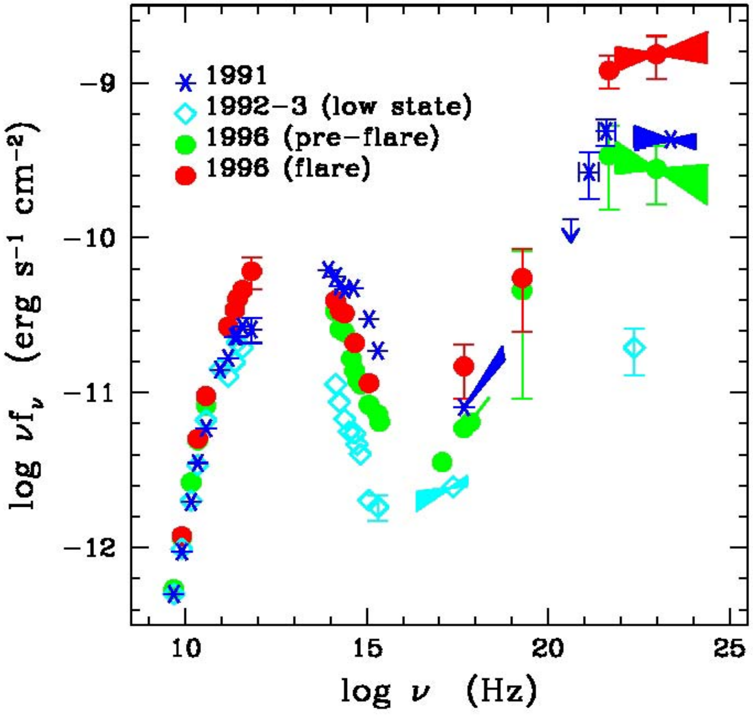


Blazars' SEDs

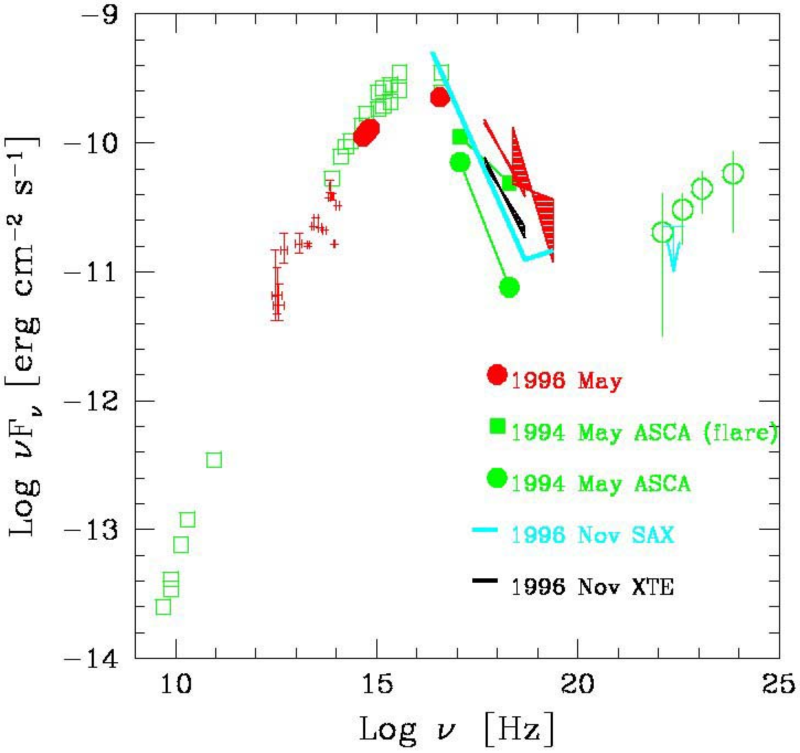
Two main components:

- Radio to X-rays is polarized and variable
  Synchrotron emission from jet
- X-rays to gamma-rays possibly inverse Compton scattering

Red blazars: 3C279



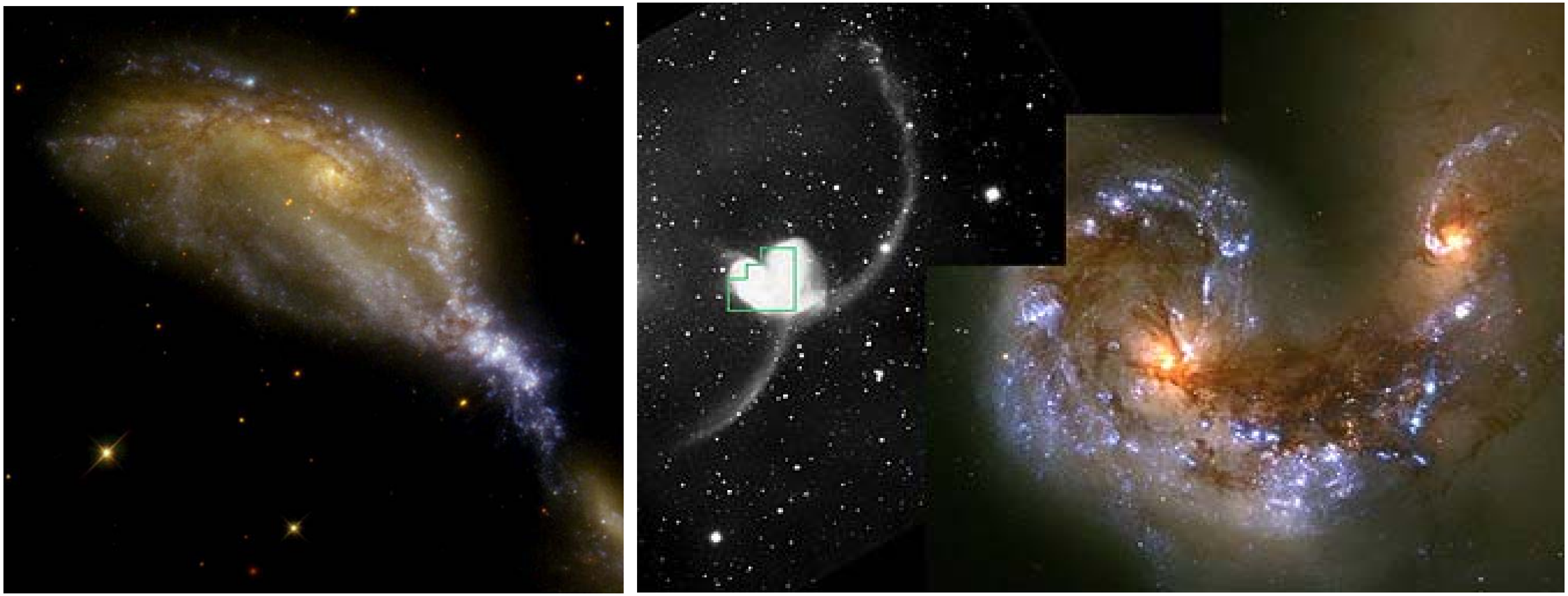
Blue blazars: PKS 2155-398



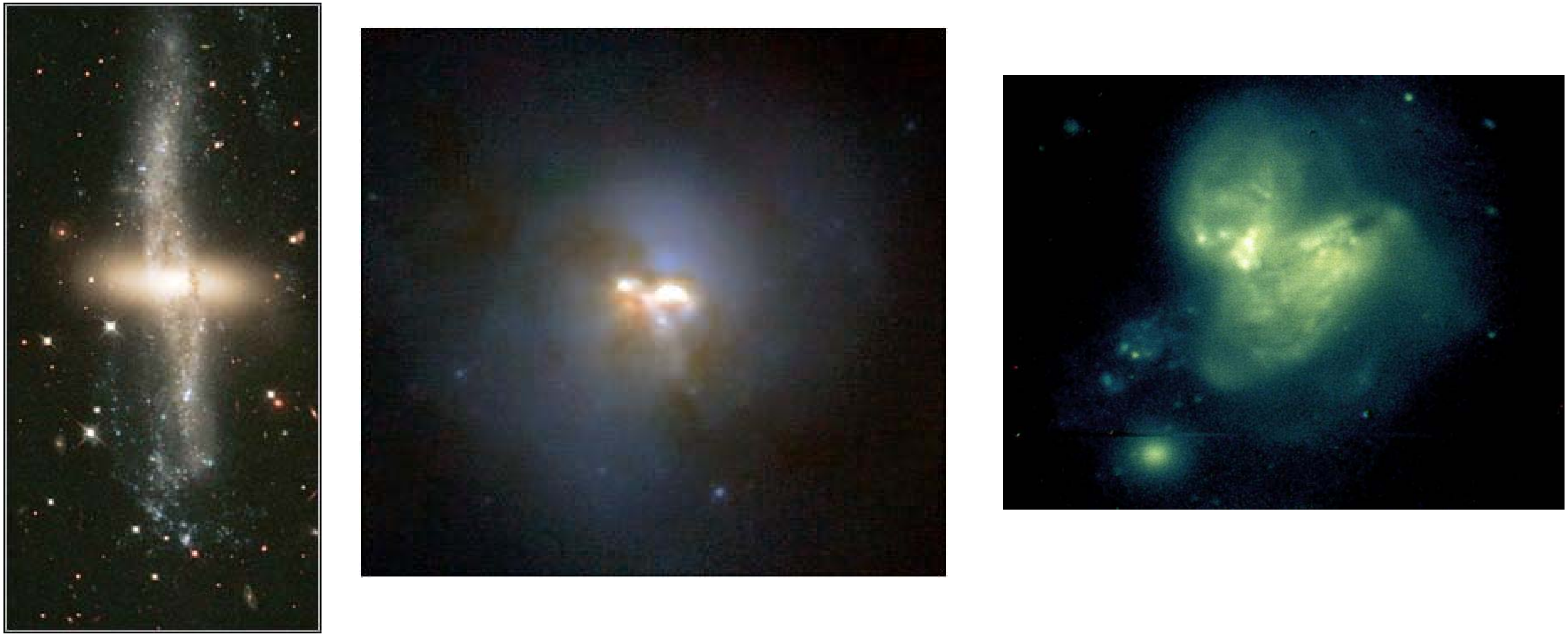
Galaxy Interactions and Mergers

Galaxies sometimes come near each other, especially in groups and clusters.

Large tidal force can draw stars and gas out of them => tidal tails.
Galaxy shapes can become badly distorted.

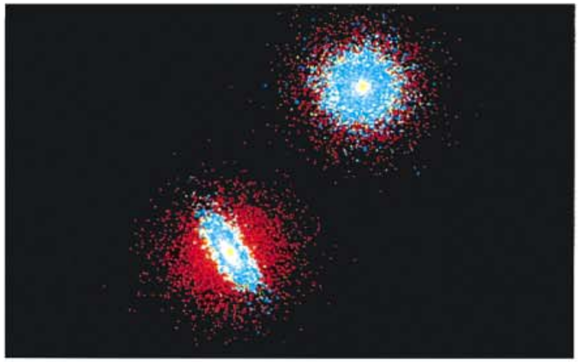


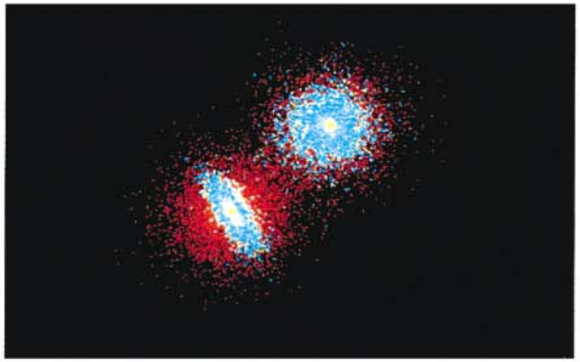
Galaxies may merge.

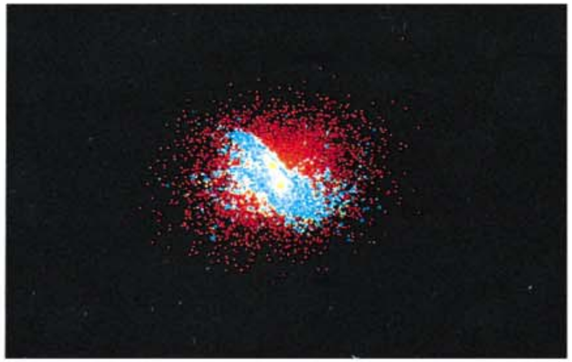


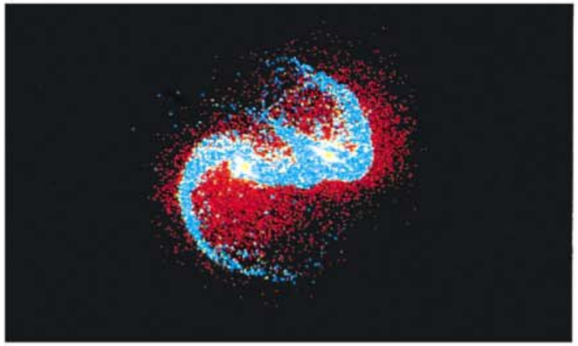
Some ellipticals may be mergers of two or more spirals. Since they have old stars, most mergers must have occurred long ago.

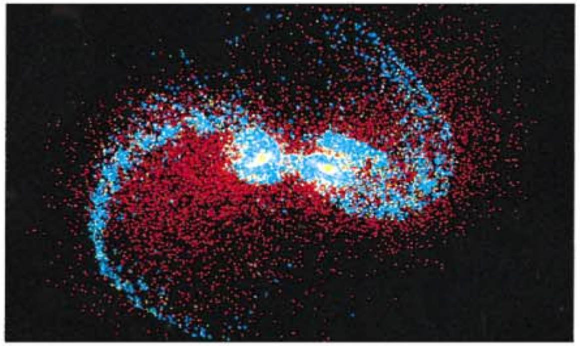
Interactions and mergers are simulated by computers.

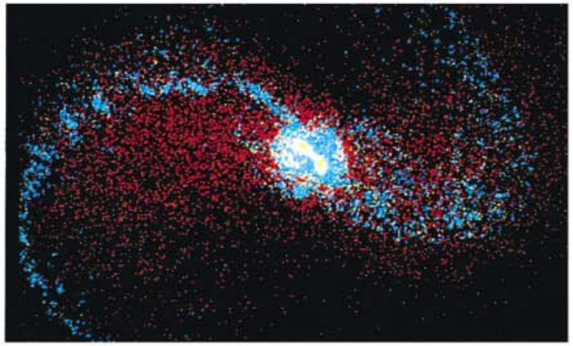

$t = 0$


$t =$125 million years


$t =$ 250 million years


$t =$ 375 million years


$t =$ 500 million years

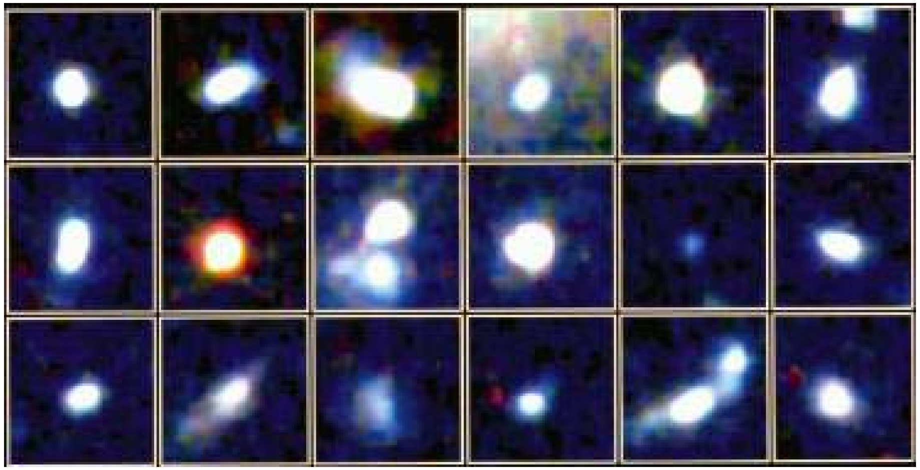

$t =$ 625 million years

Interactions and mergers also lead to starbursts: unusually high rates of star formation. Cause is the disruption of orbits of star forming clouds in the galaxies. They often sink to the center of each galaxy or the merged pair. Resulting high density of clouds => squeezed together, many start to collapse and form stars.

How do Galaxies Form?

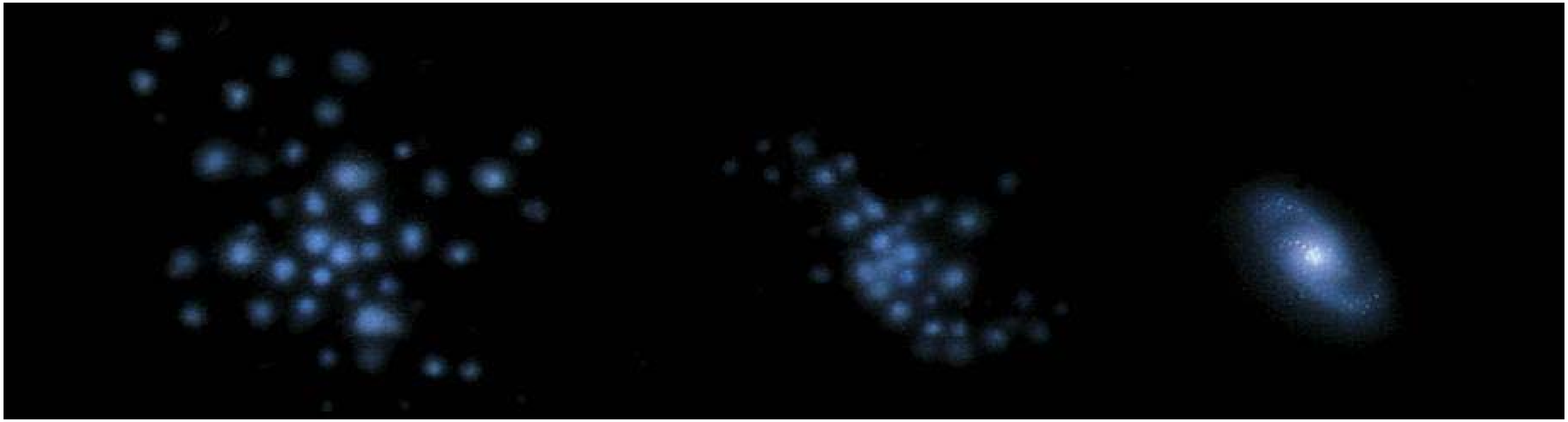
Old idea: they form from a single large collapsing cloud of gas, like a star but on a much larger scale.

New idea: observations indicate that "sub-galactic" fragments of size several hundred parsecs were the first things to form.   Hundreds might merge to form a galaxy.



Deep Hubble image of a region 600 kpc across. Small fragments are each a few hundred pc across, contain about 1 billion stars each. May merge to form one large galaxy. This is 10 billion years ago.

Schematic of galaxy formation



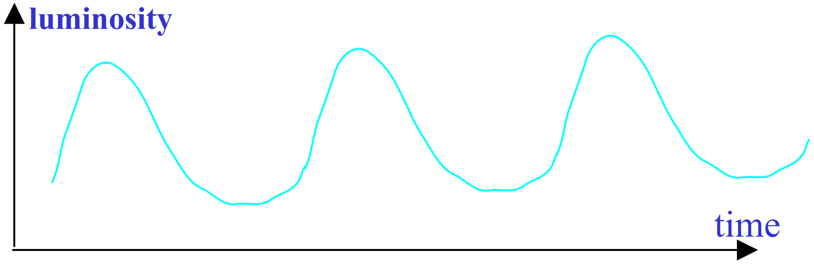
Subsequent mergers of large galaxies also important for galaxy evolution.

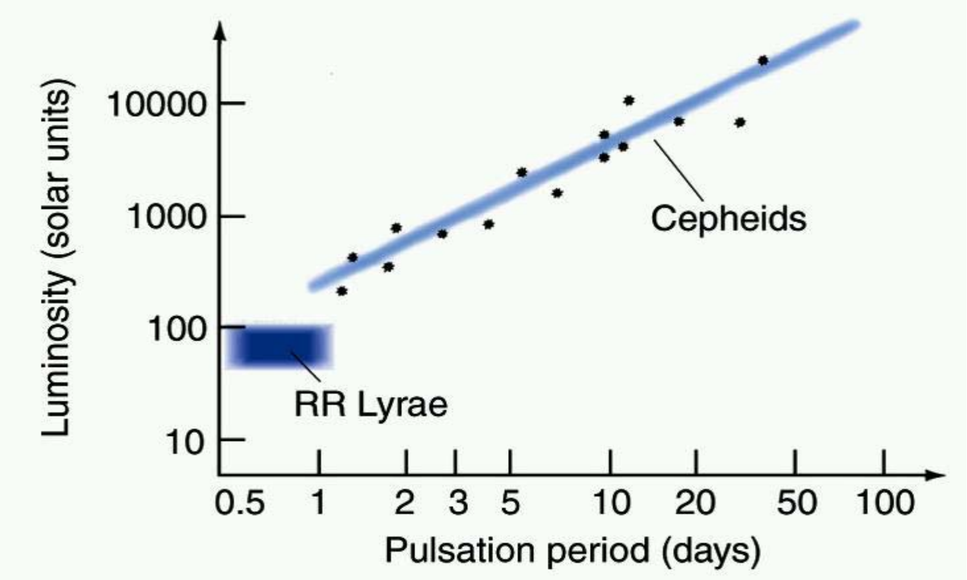
Galaxy formation a very difficult problem because we must look to great distances to see it happening, stretching the limits of even Hubble.

Theoretical problem: angular momentum loss + formation time scale.

Distance Measurement

For "nearby" (out to 25 Mpc or so) galaxies, use class of variable star called a "Cepheid".

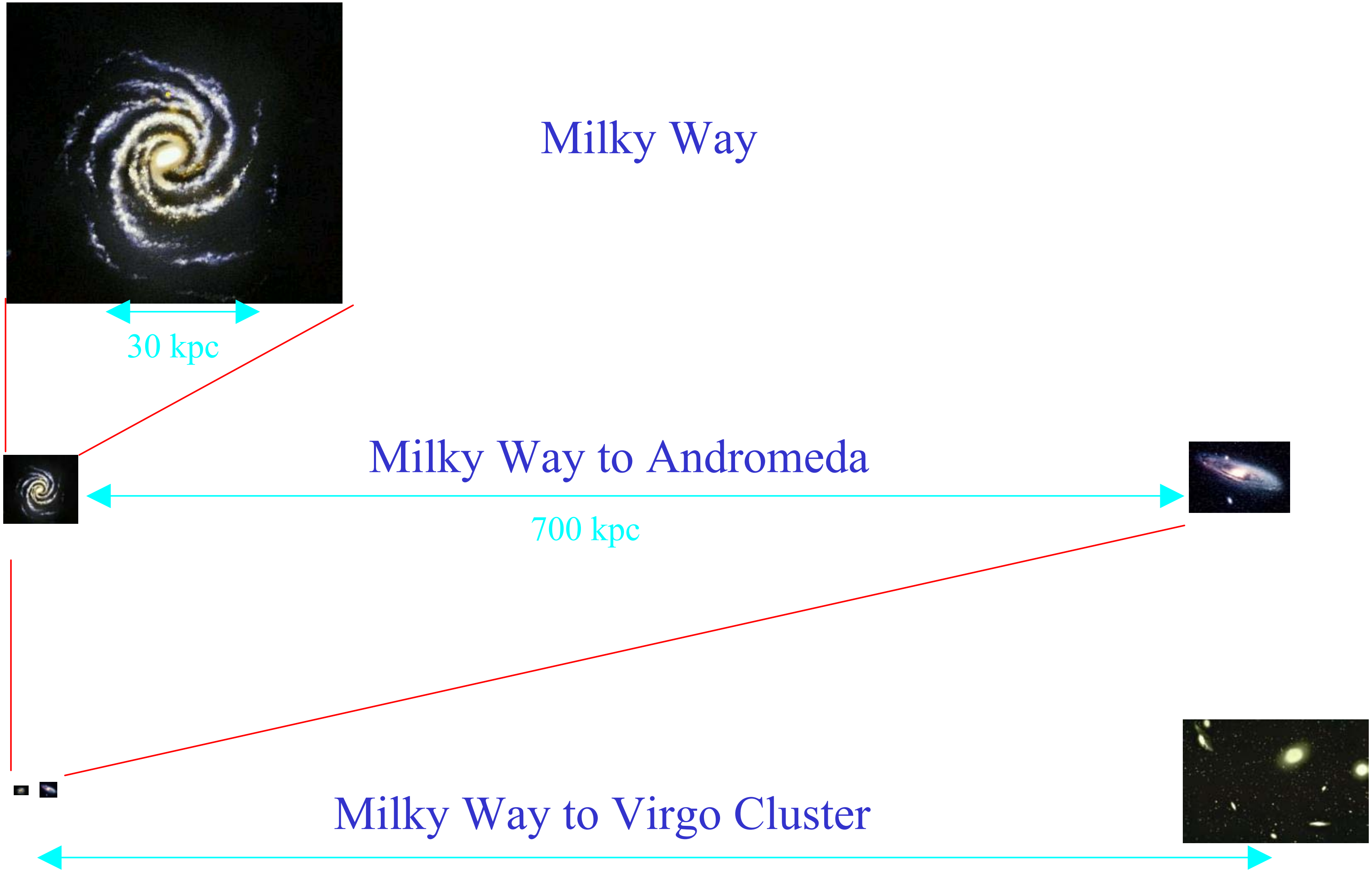




Measuring period of Cepheid in nearby galaxy gives star's luminosity. Measuring apparent brightness determines distance to star/galaxy.

Cepheid star in galaxy M100 with Hubble. Brightness varies over a few weeks.

Get used to these huge distances!



Milky Way

30 kpc

Milky Way to Andromeda

700 kpc

Milky Way to Virgo Cluster

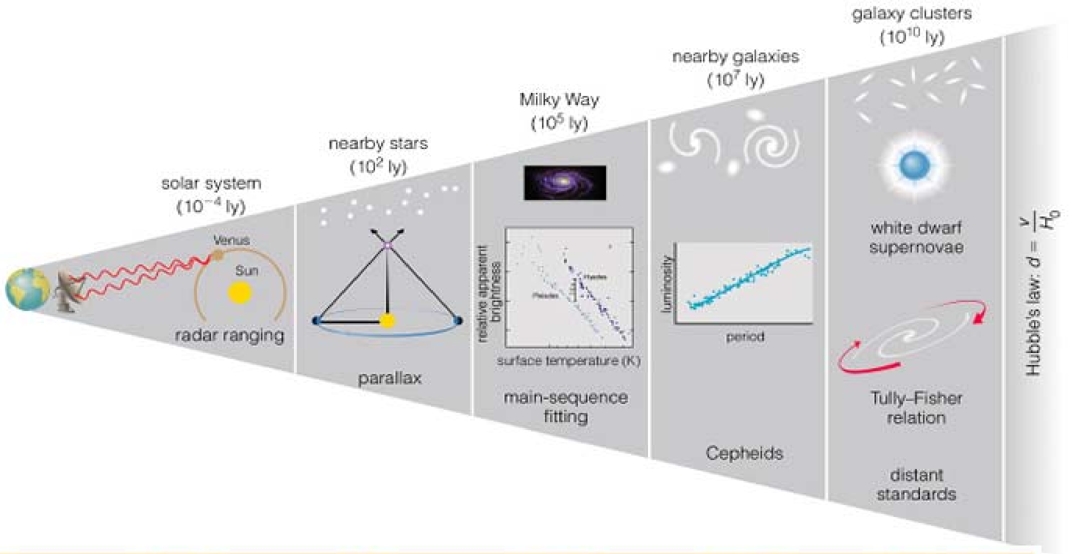
17 Mpc

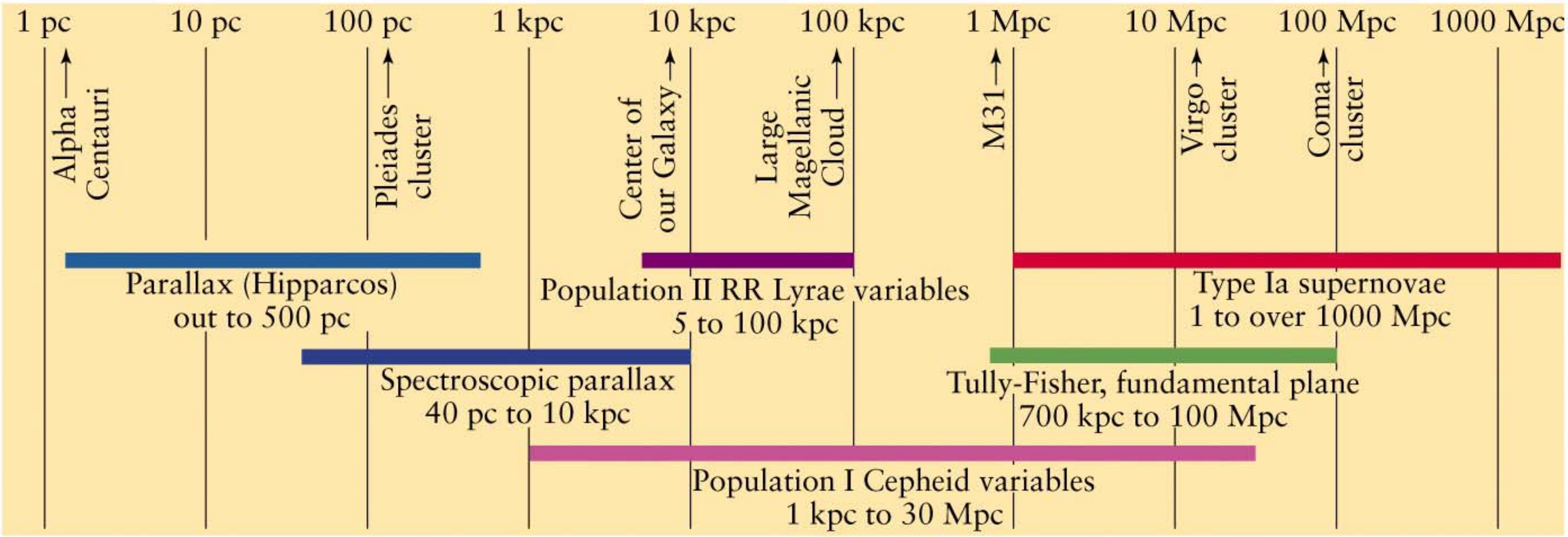
More Rungs on the Ladder

- We are now getting too far to see variables or too many stars
- How to measure distances?

  Type-Ia supernovae

  Tully-Fisher plane

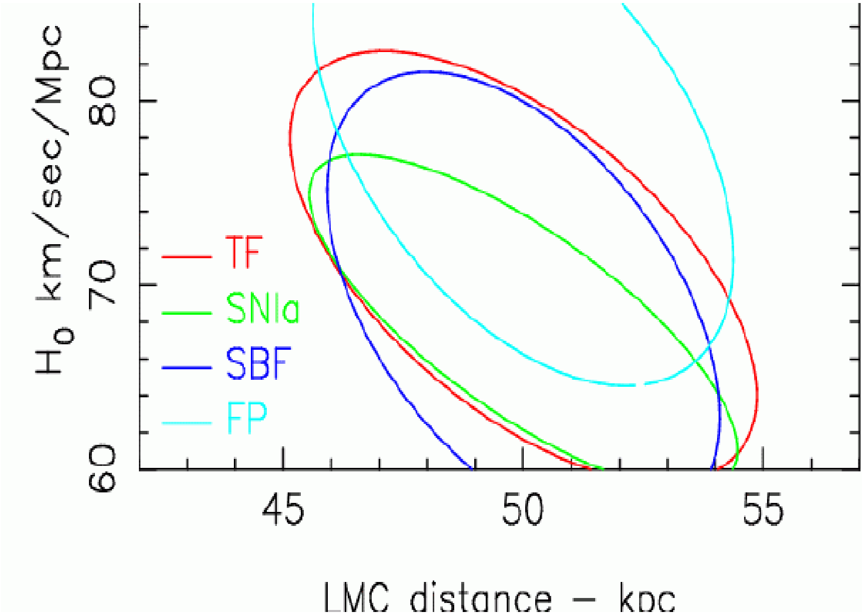




New methods of finding distances beyond about 25 Mpc.

4 Methods up to 250 Mpc

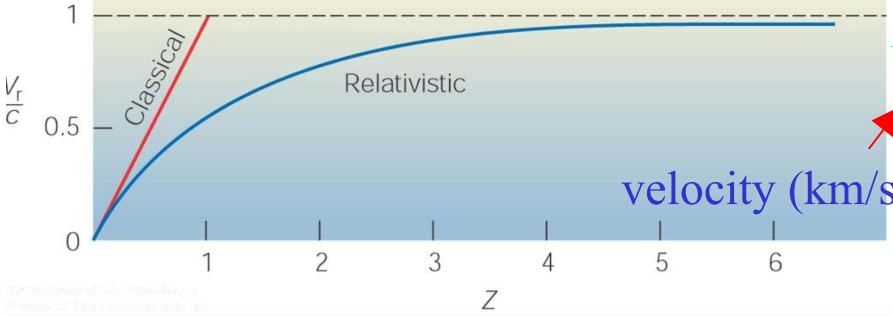
- The Tully Fisher relation for spiral galaxies
  (bigger galaxies rotate faster)
- Supernovae of type Ia
- Surface brightness fluctuations (resolvability)
- The fundamental plane for elliptical galaxies



And beyond: Hubble’s Law

In 1912, Slipher used spectra of "spiral nebulae" to find essentially all of them are receding from us, that is, show redshifted spectral lines.

In 1920's, Hubble used Cepheids to find distances to some of these receding galaxies. Showed that redshift or recessional velocity is ∝ to distance:

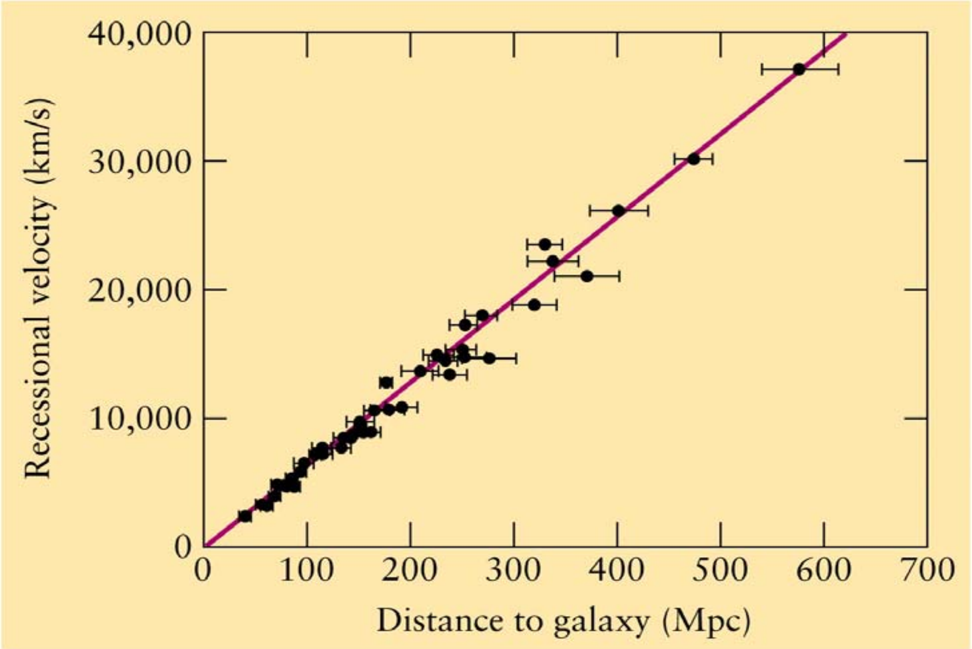


$$V = H_0 \text{ x } D \qquad \text{(Hubble's Law)}$$

velocity (km/s)

Distance (Mpc)

Hubble's Constant (km/s/Mpc)



Current estimate:

H_0 = 65 -77 km/s/Mpc

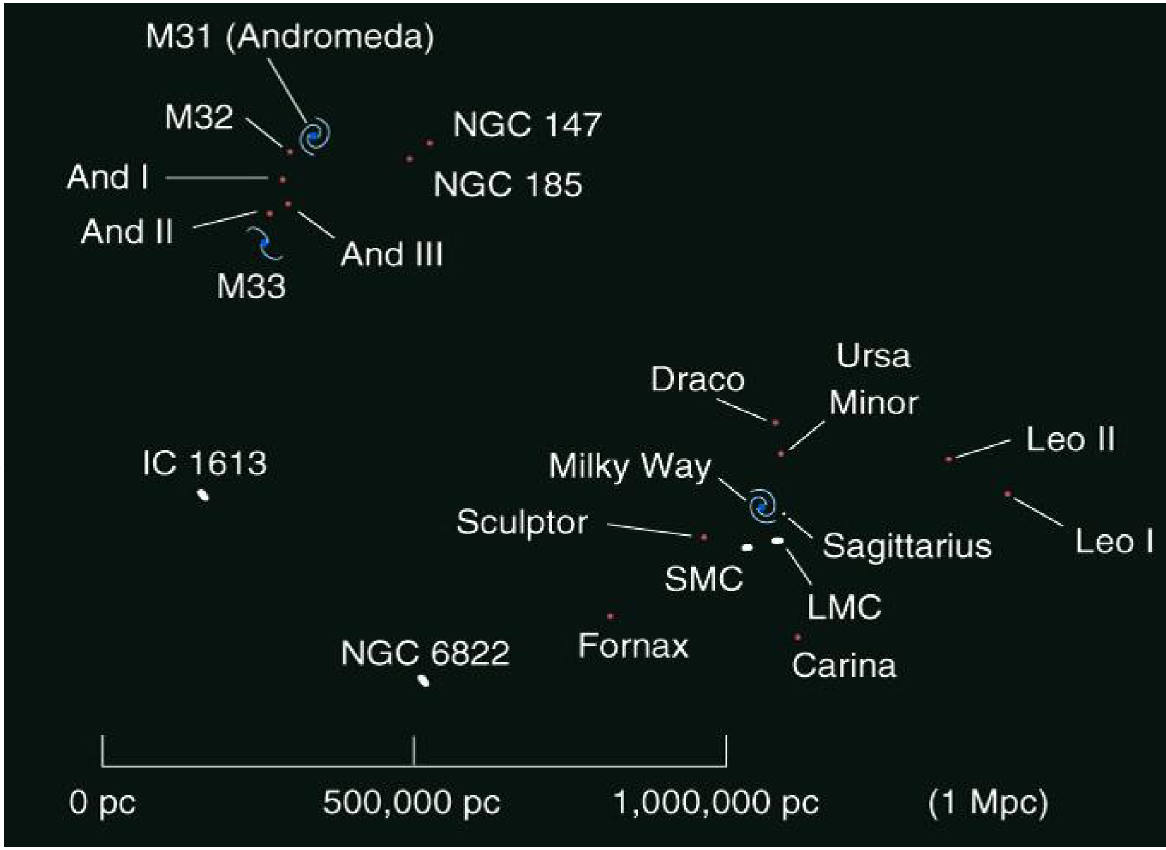
If H_0 = 75 km/s/Mpc, a galaxy at 1 Mpc moves away from us at 75 km/s,

Clusters of Galaxies

Groups

A few to a few dozen galaxies bound together by their combined gravity.

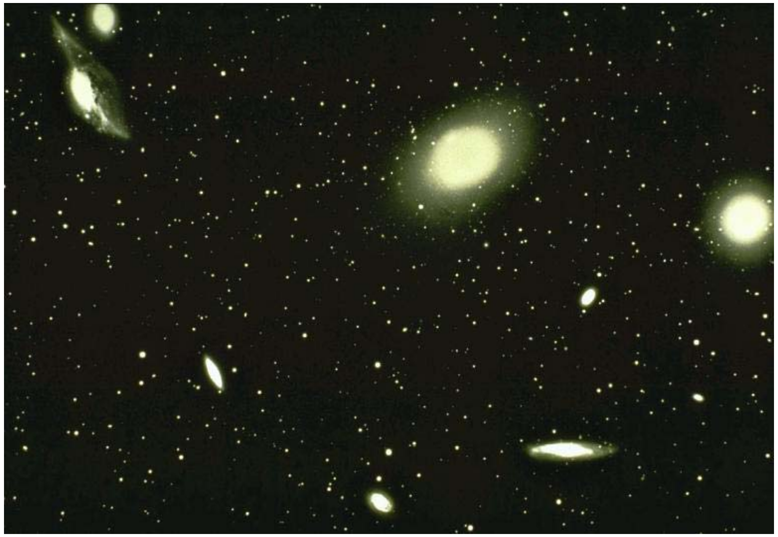
No regular structure to them.

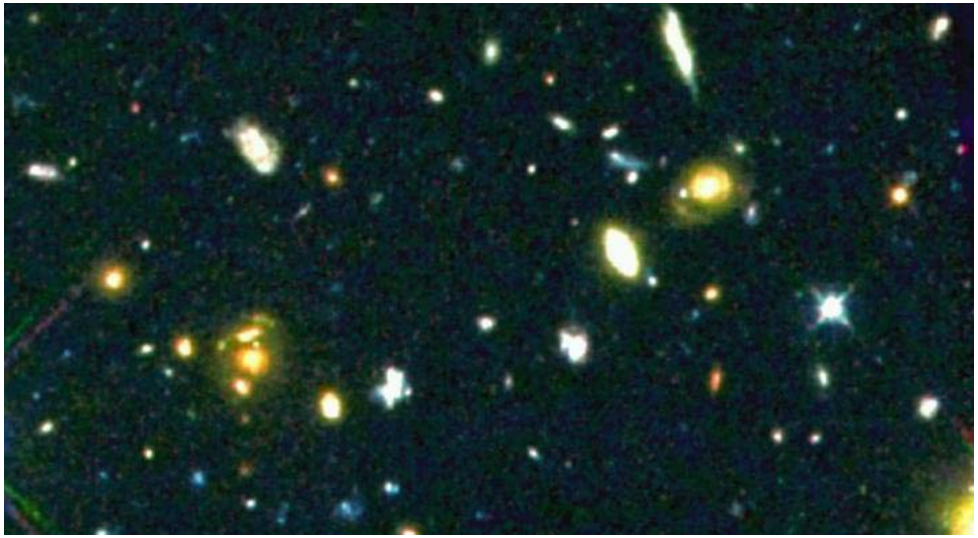


The Milky Way is part of the Local Group of about 30 galaxies, including Andromeda.

Clusters

Larger structures typically containing thousands of galaxies.





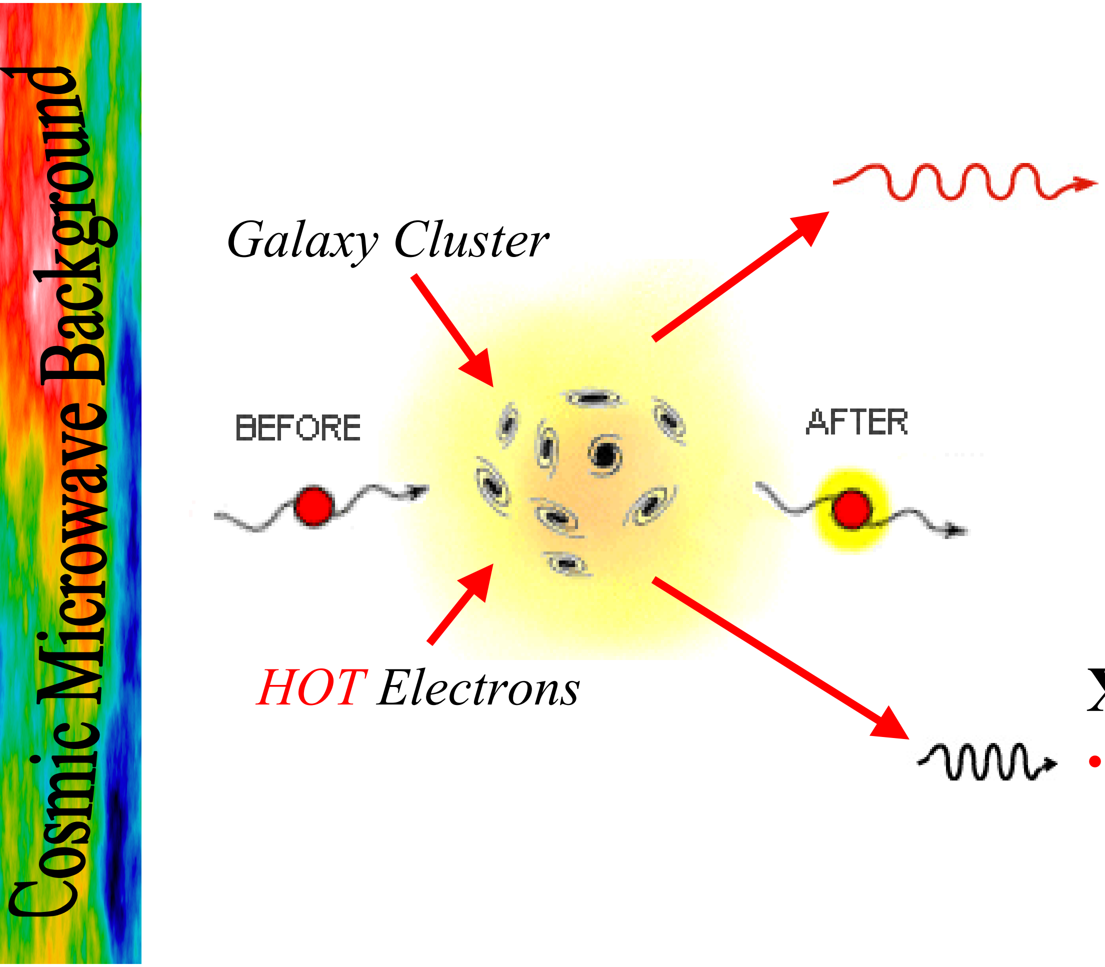
The Virgo Cluster of about 2500 galaxies (central part shown).

A distant cluster imaged with the Hubble.

Galaxies orbit in groups or clusters just like stars in a stellar cluster.

A few galaxies are not in groups or clusters.

Coordinated Cluster Measurements

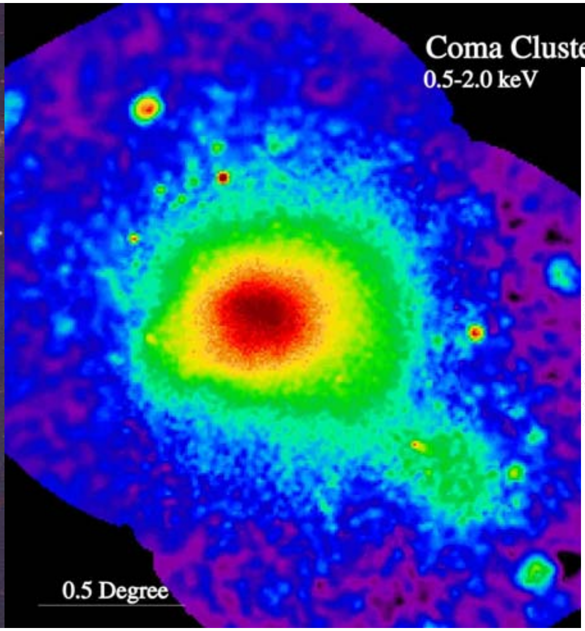


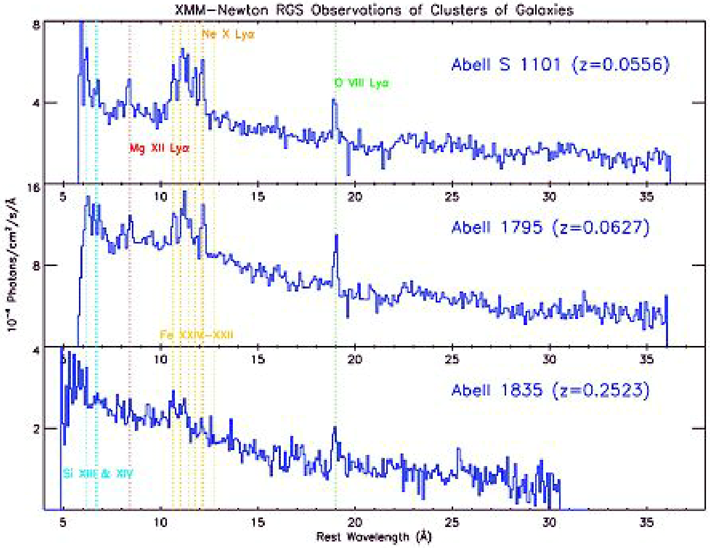
Optical:
- **Redshift velocity dispersion**
- **Photometry and lensing**

mm-Wave:
- **SZ – Compton Scattering**

X-ray Flux: ← Chandra
- **Temperature and luminosity probe mass**

Coma Cluster at X-rays





Bremsstrahlung $\ell_\nu \alpha\, n_e T^{-1/2} e^{-h\nu/kT}$

volume emissivity $dP/dV \;\alpha\; n_e^{\,2}\, T^{-1/2}$

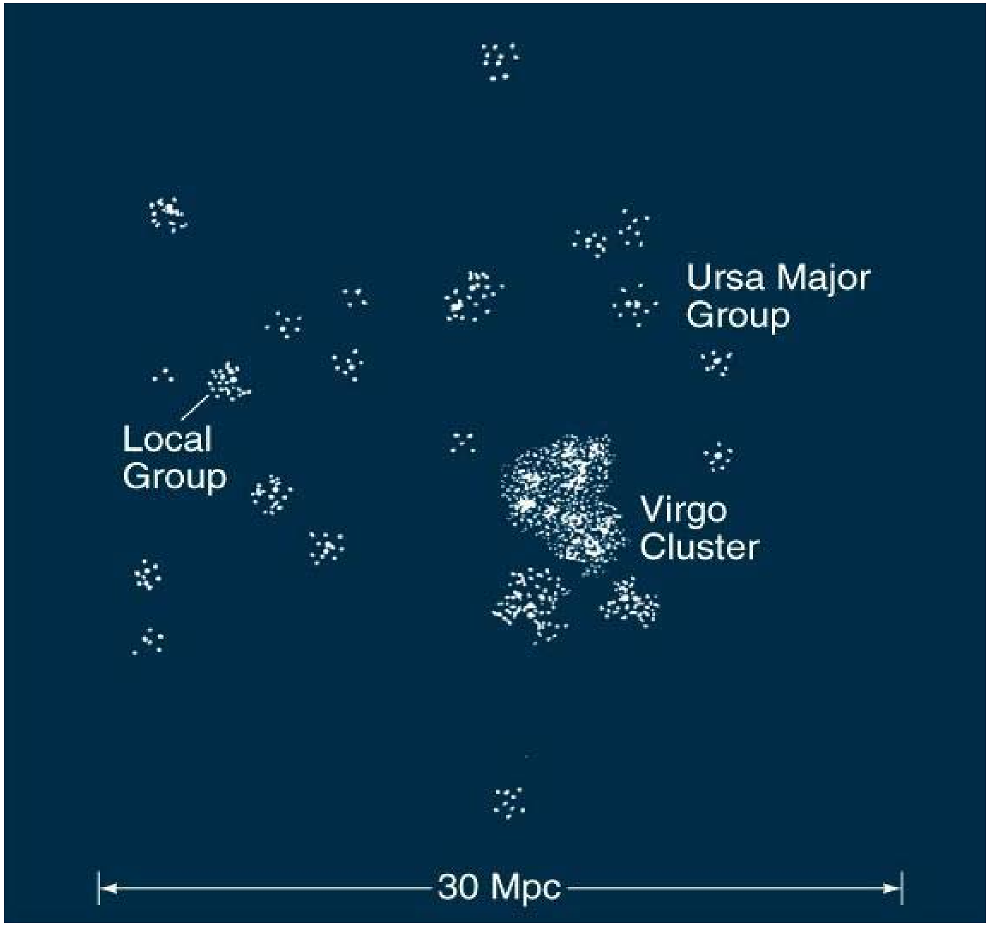
cooling time $t = 3\, n_e\, kT \,/\, dP/dV = 10^{11}\, n_e^{-1}\, T^{1/2}$ sec

Coma: $L = 10^{44}$ erg/s, $n_e = 10^{-3}$ cm^{-3}, $t = 10^{10}$ yrs, $M_{gas} = 10^{13}\, M_\odot$

Dominant component is dark matter!

Superclusters

Recognizable structures containing clusters and groups. 10,000's of galaxies.

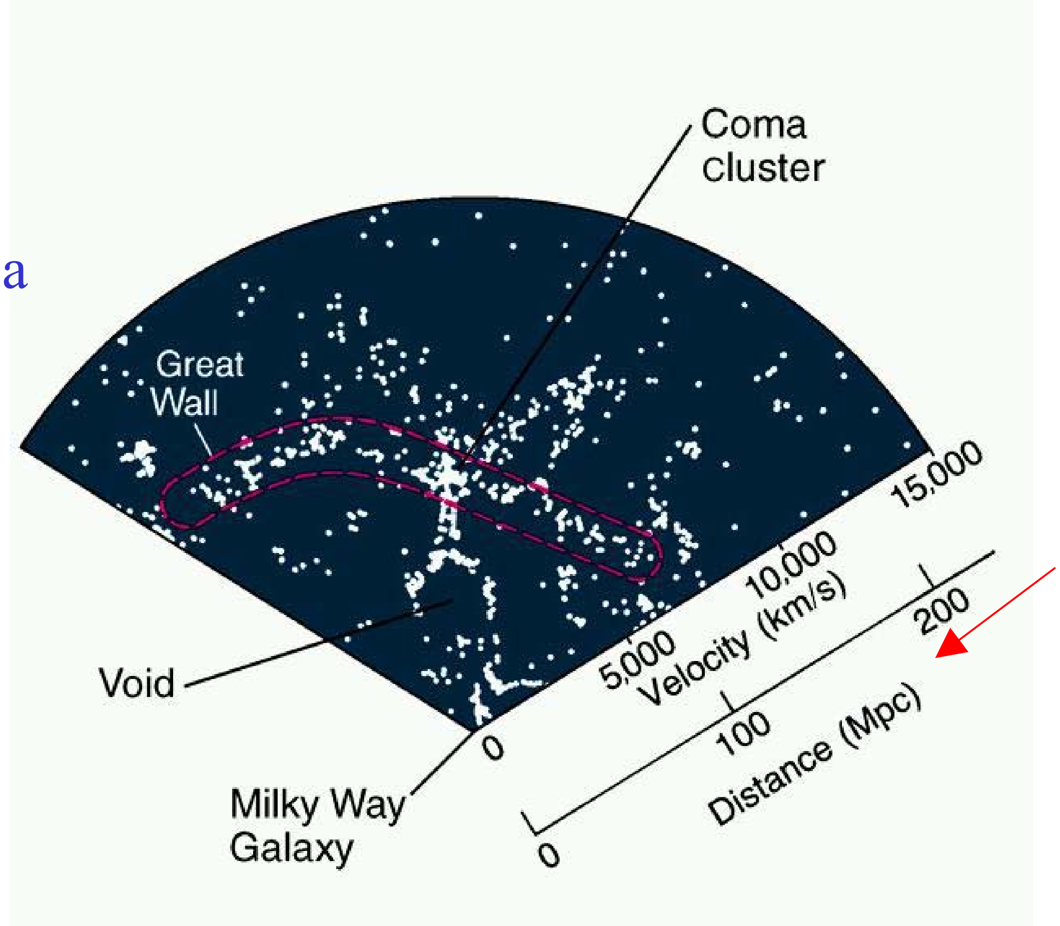


- Clusters come in superclusters
- Large-scale structure shows voids with galaxies concentrated on boundaries – bubble structure
- Origins of this still unclear.

The Local Supercluster consists of the Virgo Cluster, the Local Group and several other groups.

So by getting the spectrum of a galaxy, can measure its redshift, convert it to a velocity, and determine distance.

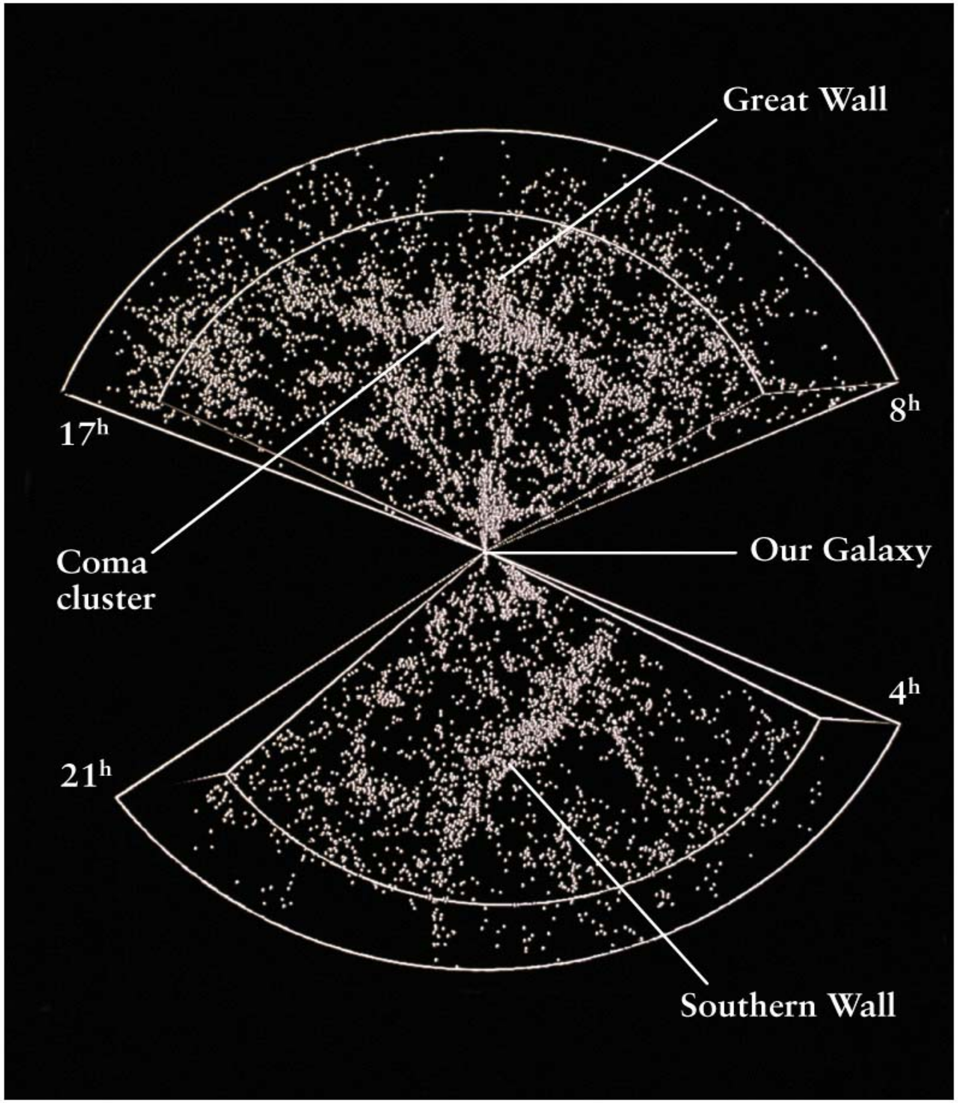
Results from a mid 1980's survey.

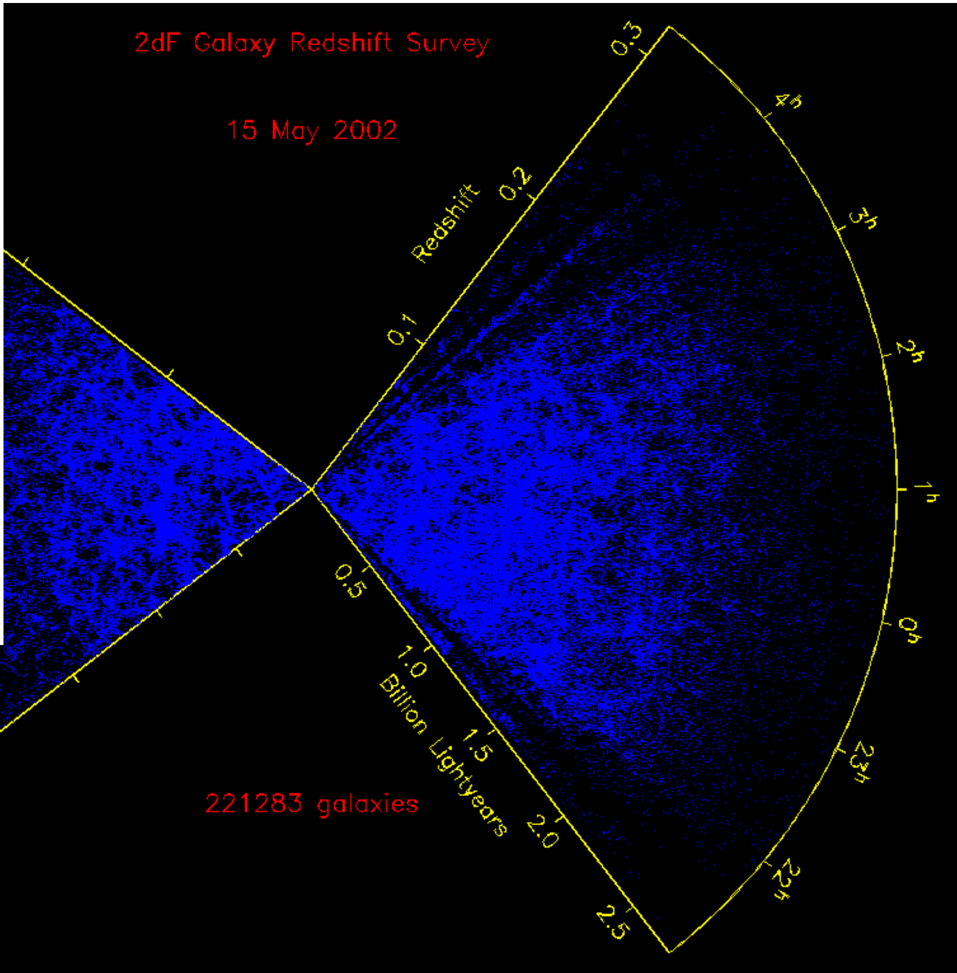


Assumes $H_0 = 65$ km/sec/Mpc. Note how scale of structure depends on this.

Hubble's Law now used to unveil Large Scale Structure of the universe. Result: empty voids surrounded by shells or filaments, each containing many galaxies and clusters. Like a froth.

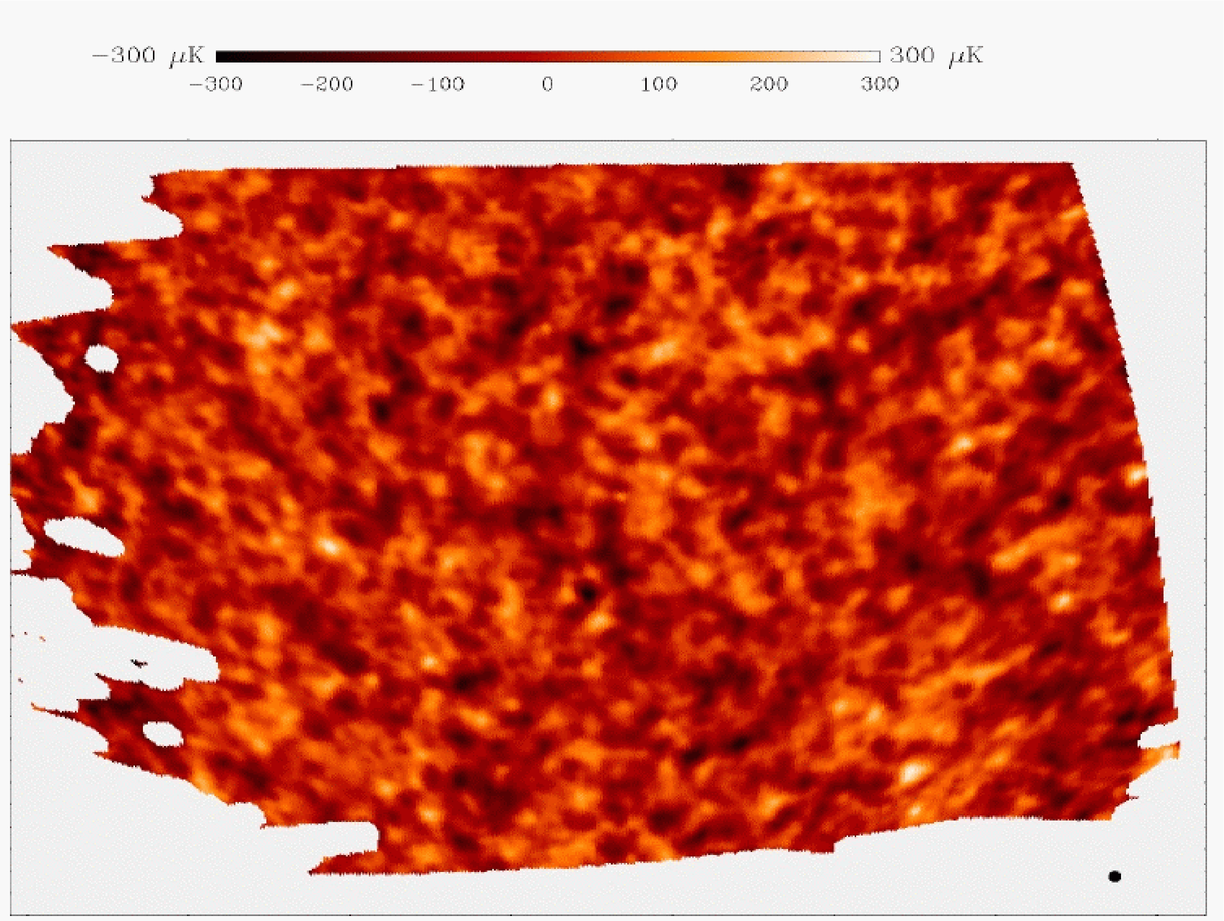
Results from further surveys.





Dark energy

- 2dF found that the density of the Universe was only 25% of the critical density
- But Boomerang found that the curvature of the Universe was nonetheless zero.



Expansion of the Universe Accelerates

gravity of matter should decelerate universe
But SN Ia vs. redshift shows that the expansion rate was slower in the past!
Also, gravity alone cannot produce “Great Wall”.

⇒ New component should be dark and gravitationally repulsive.

Implies outward push to expansion + larger age of universe

The Cosmological Constant, Λ or Dark Energy

Introduced by Einstein in 1917 to balance gravitational attraction and create static Universe. After Hubble found expanding universe, Einstein called Λ "the greatest blunder of my life".

2 possible explanations; 2 missions to test it:

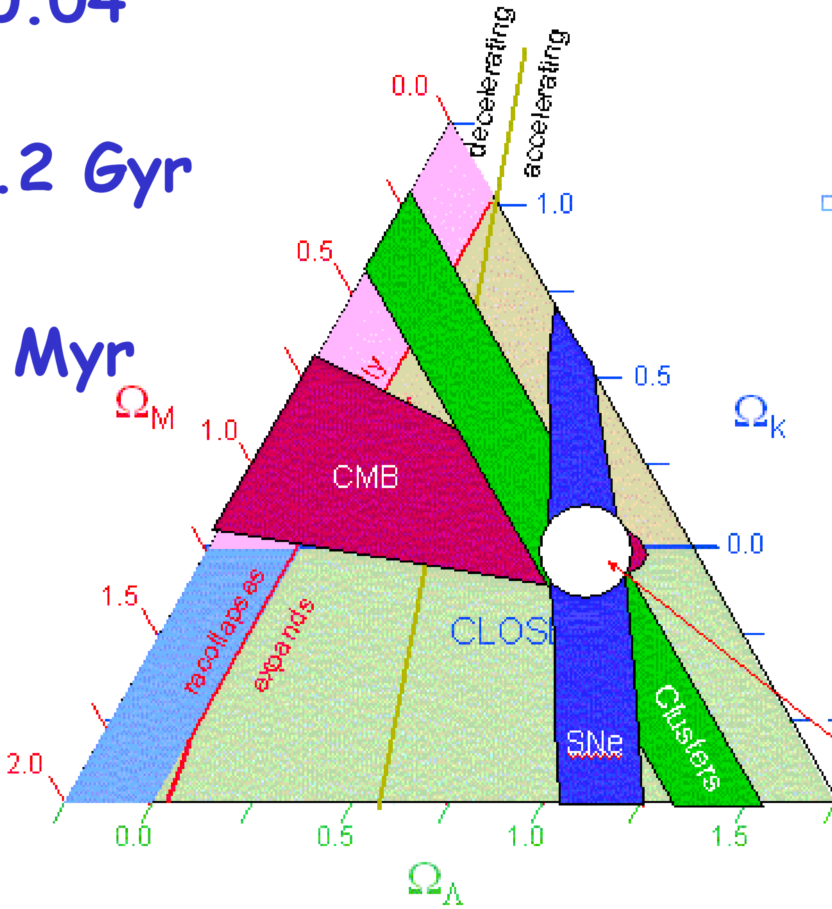
Supernova Acceleration Probe

Large-Aperture Synoptic Survey Telescope

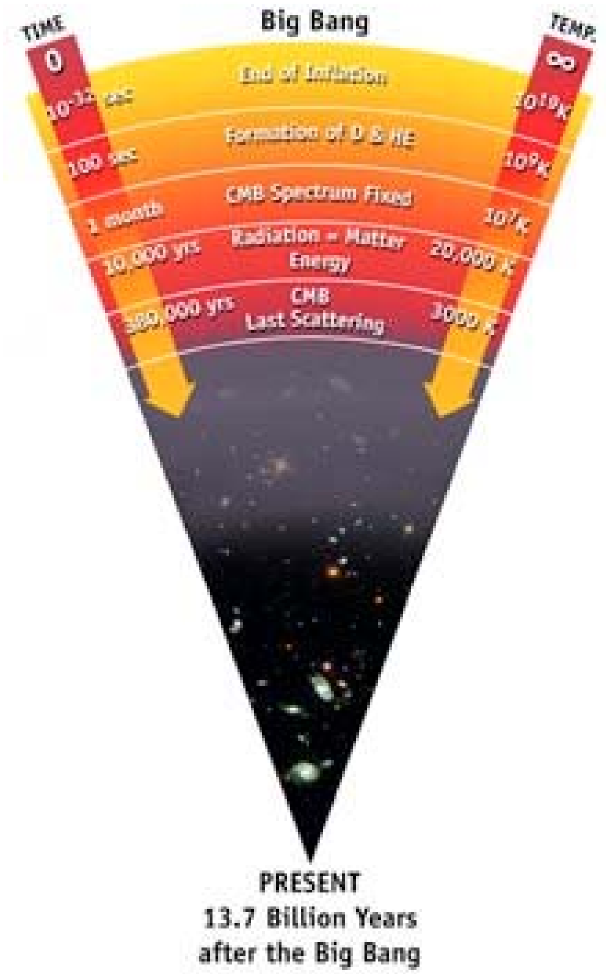
- Vacuum Energy: negative pressure, stretches space => Dilution
- Quintessence: slowly varying quantum field => end undecided

Measured cosmological parameters

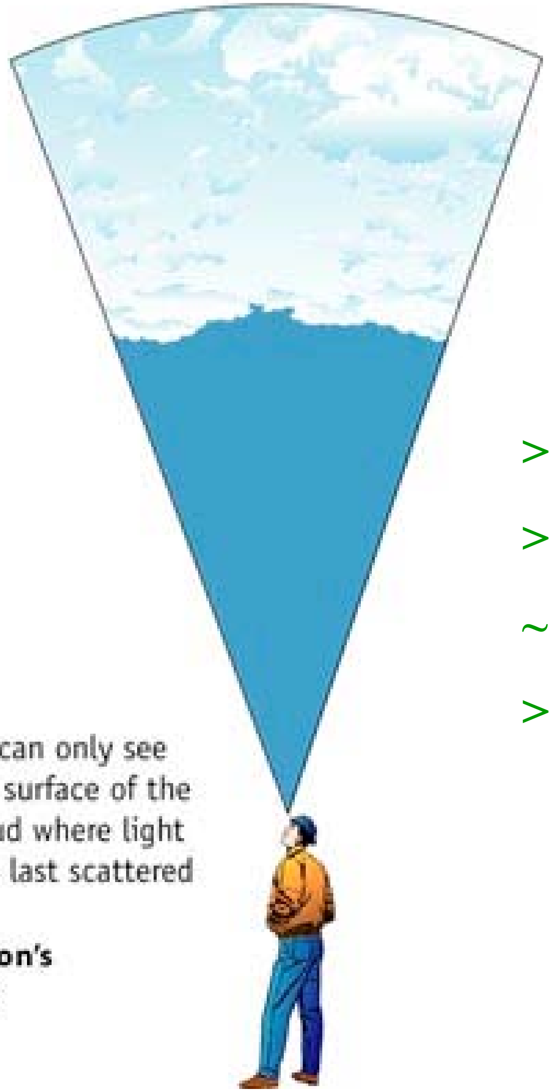
- Total density: $\Omega_{Tot} = \Omega_M + \Omega_\Lambda = 1.02 \pm 0.02$
- Dark energy: $\Omega_\Lambda = 0.73 \pm 0.04$
- Matter density: $\Omega_M = 0.27 \pm 0.04$
  - ☆ baryons: $\Omega_b = 0.044 \pm 0.004$
- Age of the universe: 13.7 ± 0.2 Gyr
- Age at decoupling: 379^{+8}_{-7} kyr
- Age at reionization: 180^{+220}_{-80} Myr
  - ☆ age of the first stars



Surface of last scatter



The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



We can only see the surface of the cloud where light was last scattered

z

>6000 He fully ionized

>1500 H fully ionized

~1500 recombination

>1000 unobservable

~20 first stars form

6.5 farthest known AGN

History of the Universe