The Discovery of Galaxies

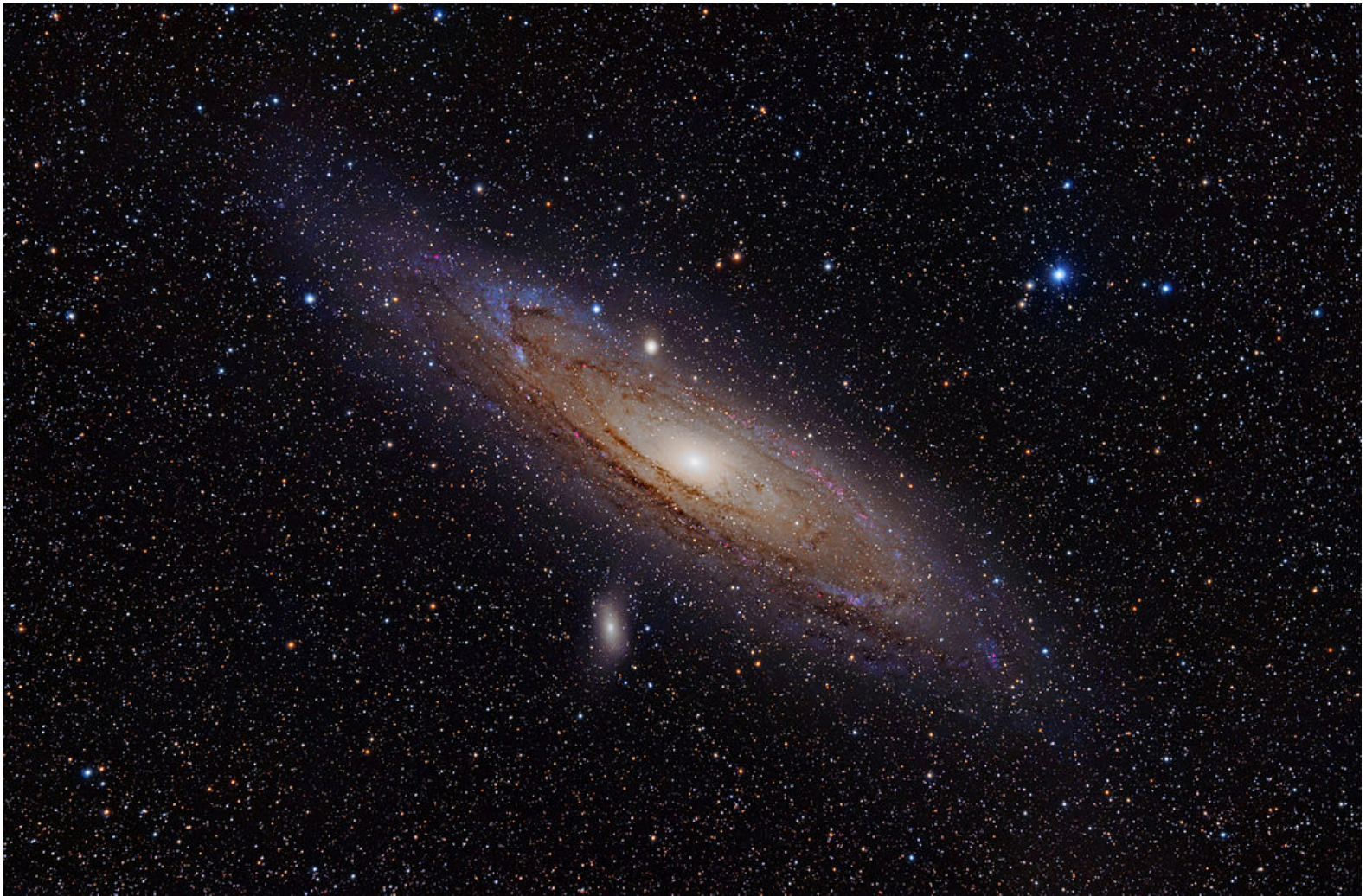
- 1755 Kant proposed island universes
- Earl of Rosse built 72” telescope in 1845

Sketch of M51

- Earl of Rosse sketched the spiral nebulae
- Shapely-Curtis debate 1920

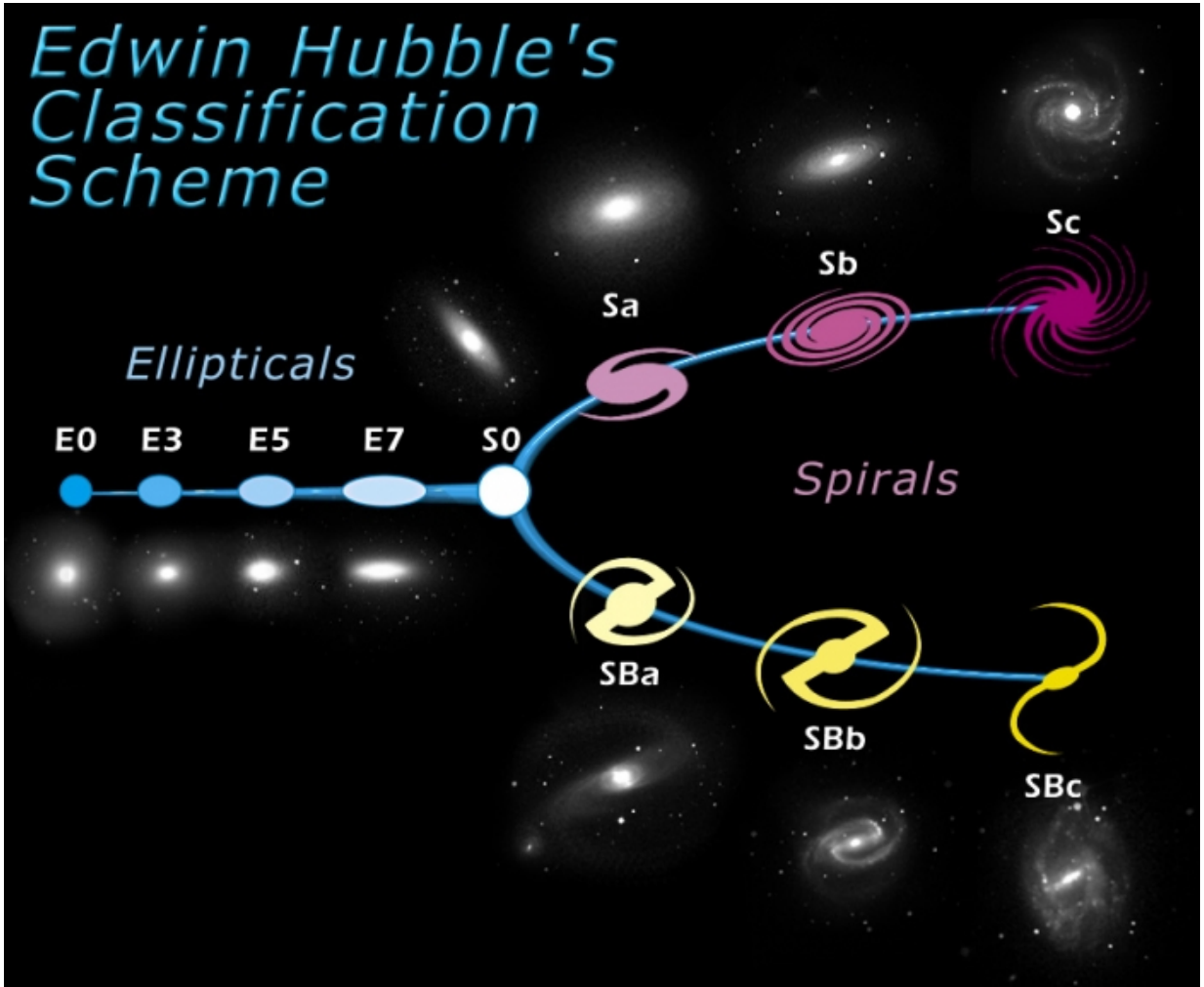
Andromeda Galaxy

- The nearest big Spiral Galaxy ~2million light years
- And 2 dwarf galaxies orbiting it (M32+NGC205)



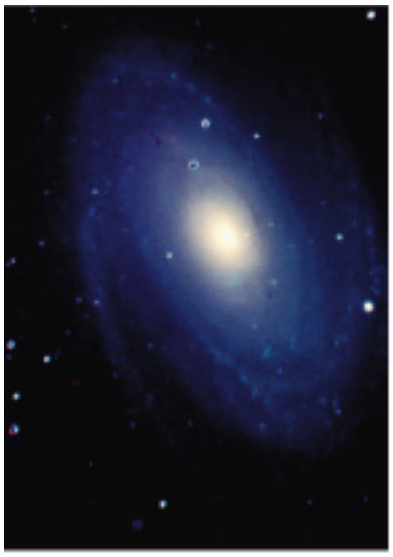
Hubble Classification Scheme

- When faced with new observations a scientist classifies
- Three classes of galaxies = **elliptical, spiral, irregular**
- Tuning fork Diagram



Spiral Galaxies

- Highly flattened disk of stars and gas with central bulge surrounded by spherical halo
- Disk/Bulge gives a,b,c classification



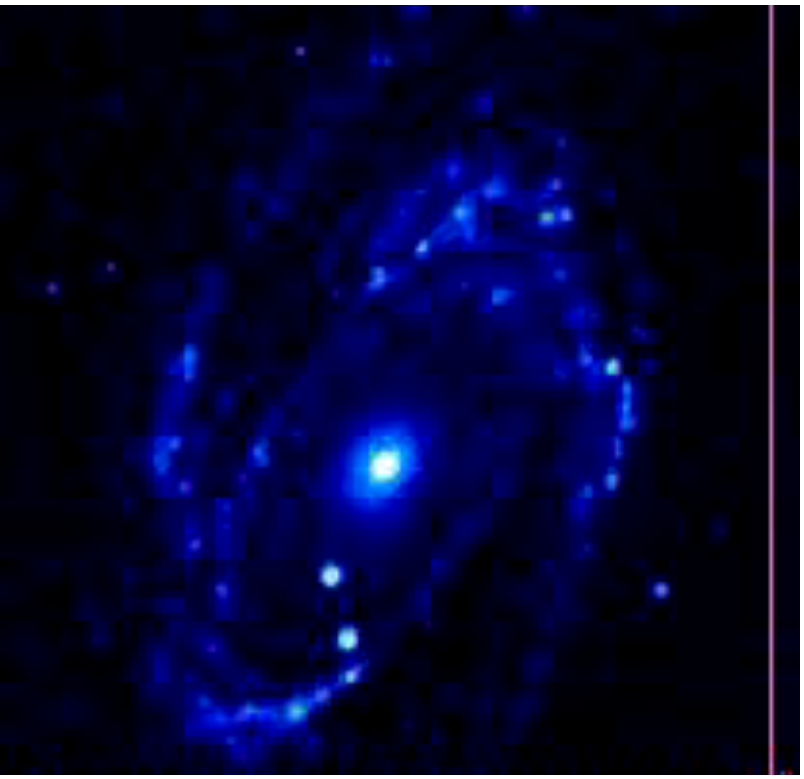
(a) M81 Type Sa

(b) M51 Type Sb

(c) NGC 2997 Type Sc

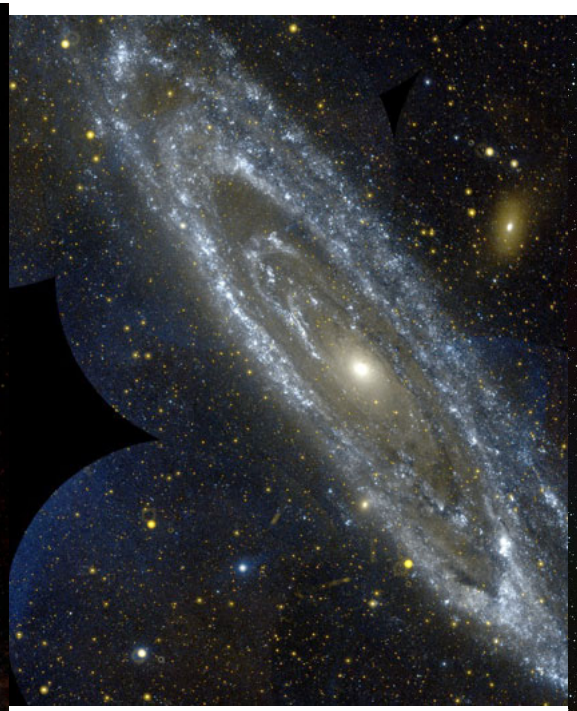
M81 in UV, Visible, IR type Sa

- Spiral galaxies have lots of gas and dust and star formation
- Structure of galaxy depends on wavelength of observation



Andromeda=M31 Sb

- X-ray binaries in blue and Dust in Orange in disk
- Notice bright ring of young hot stars in UV in disk
- Visible light photo



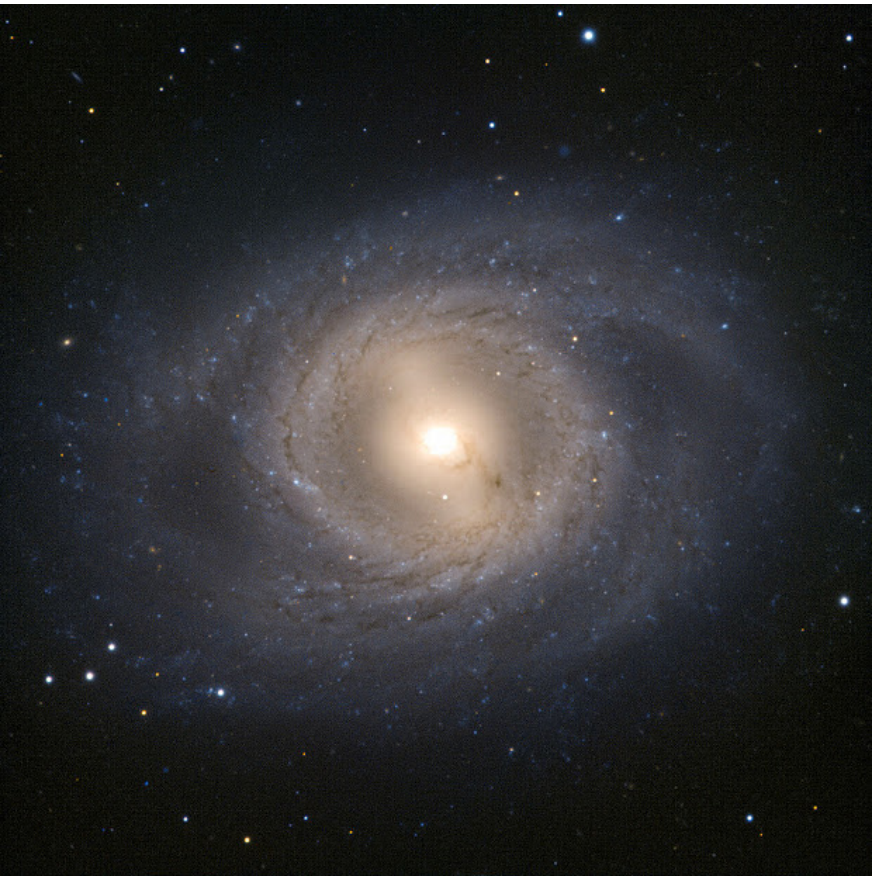
NGC3621 & 2997 & M74 Spiral - Sc

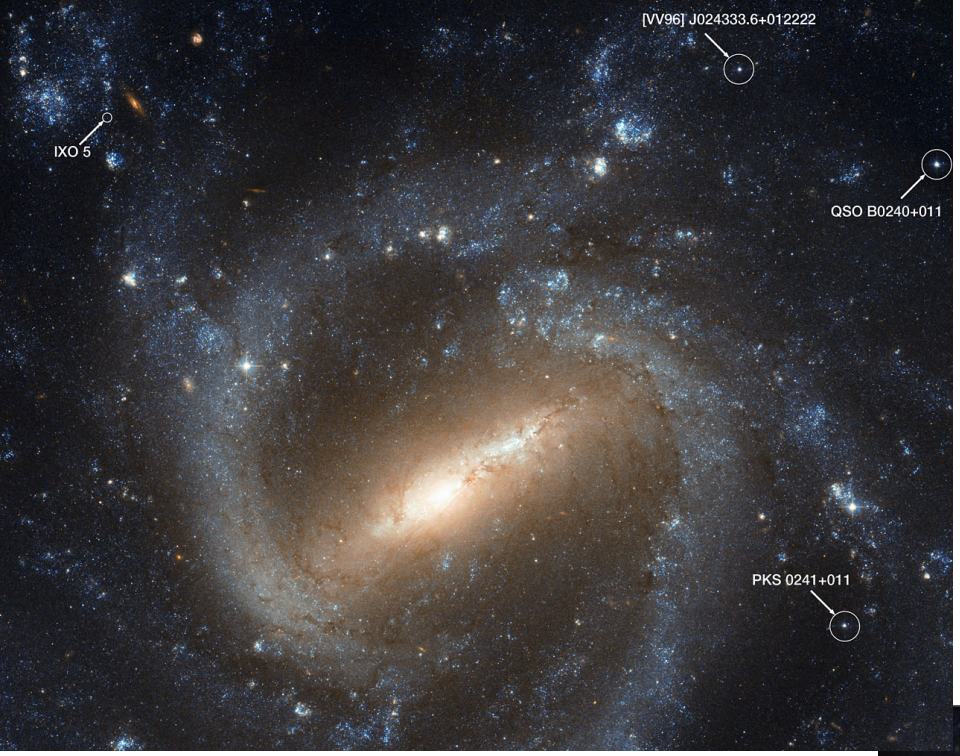
- Disk contains lots of gas and dust, but halo contains no gas or dust

Barred-Spirals

- SBa=big bulge; SBc=small bulge
- NGC 2217-SBa

M95 -SBb M83 -SBc



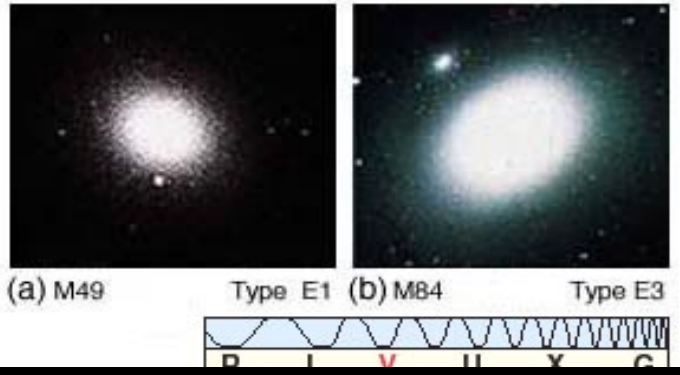


Barred-Spiral Galaxies NGC 1073 & NGC1300

- Elongated bulge: stars, dust, gas

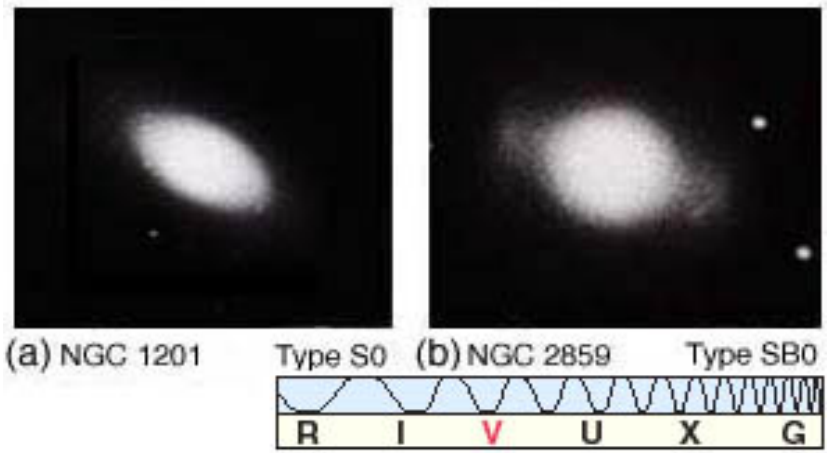
Elliptical Galaxy M87

- No Disk
- Smoothly brightens to core
- Oblate, prolate, 3-axis
- 10(a-b)/a 0=circular & 9=flattened
- Stars have random orbits in 3-D



Elliptical Galaxy

- No gas; no dust; no star formation = no OB stars = red
- All stars older than 10billion years = red
- **SO**'s seem to be spirals with no gas and dust



Irregular Galaxy: M82

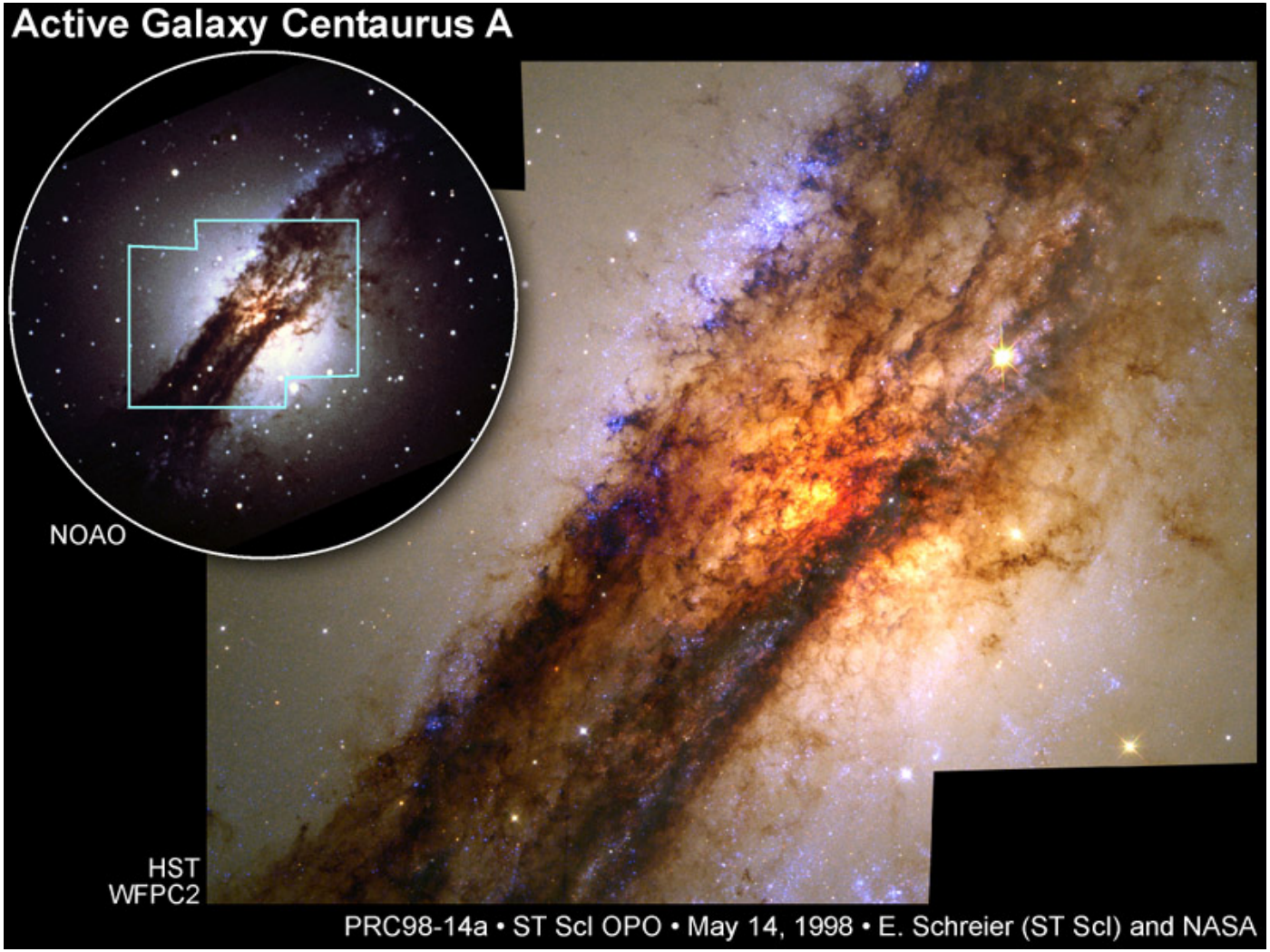
- No obvious structure
- Explosive appearance Seen in H-α & Visible

Irregular Galaxies: Magellanic Clouds

- Contains Young and old stars & Supernovae
- Very abundant gas and dust

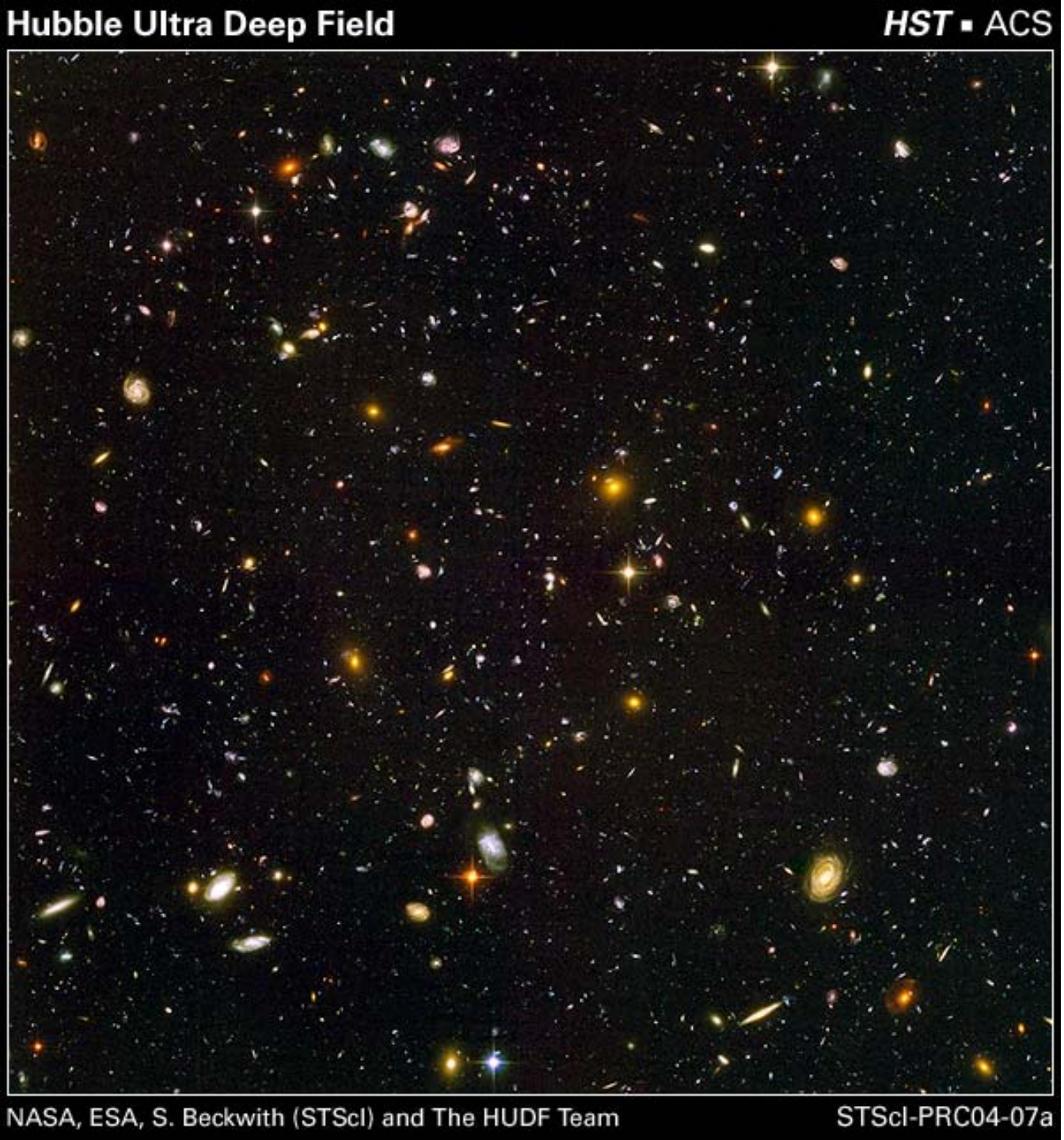
Irregular Galaxy - Centaurus-A

- Stars and gas have irregular orbits
- Abundant gas, dust leads to vigorous star formation



Dwarf Elliptical & Dwarf Irregular (NGC55) Galaxies

- Most common type of galaxy is the dwarf elliptical & dwarf irregular
- Same mass as globular cluster



Number of Galaxies

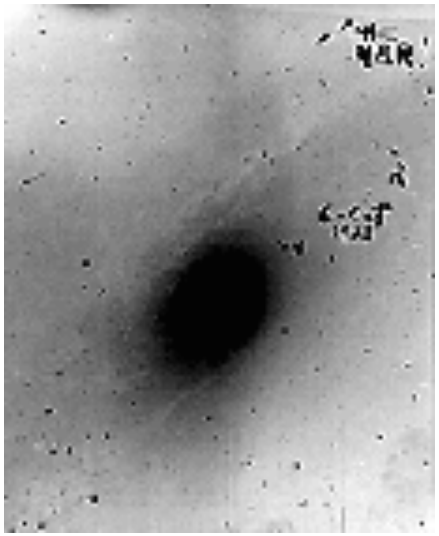
- From deep surveys
- About a hundred billion galaxies observable in whole sky

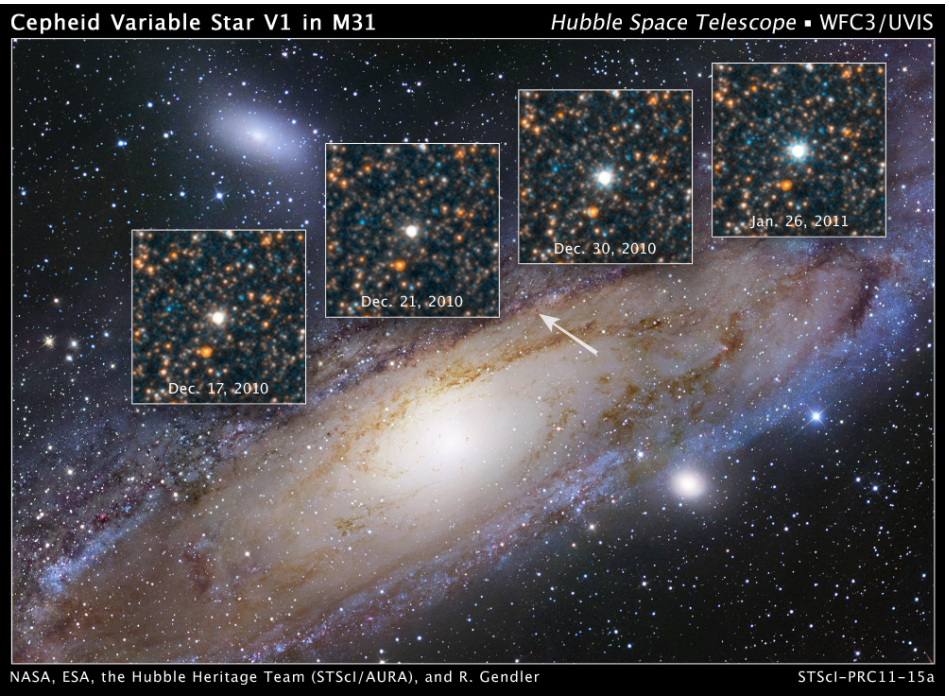
Distance Indicators

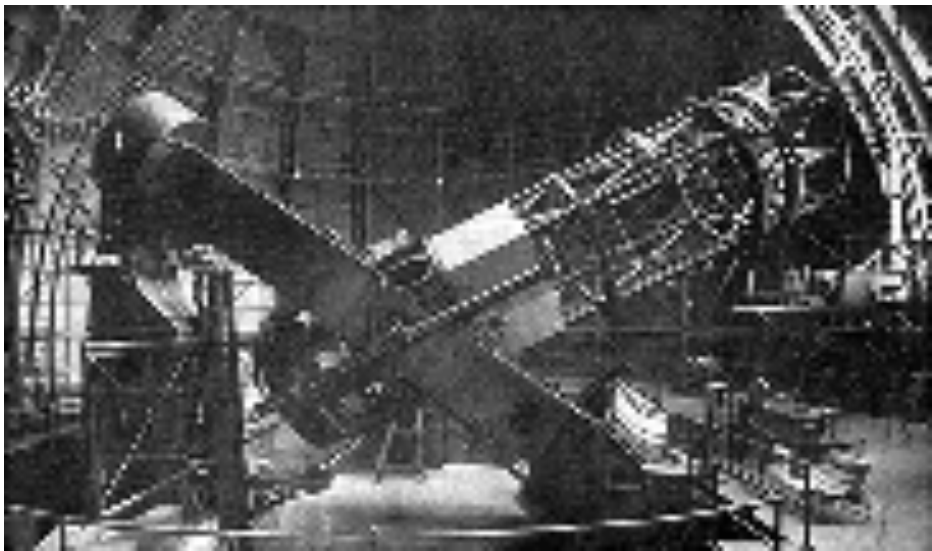
- **Standard candles**/standard rulers: objects of known brightness/size
- Examples: Cepheids, Supernovae, Supergiants, globular clusters, Planetary nebulae, HII regions

Hubble Discovers Cepheids 1924

- In Andromeda Galaxy using the 100-inch Hooker telescope
- From apparent – Absolute magnitudes get distance
- Proves spiral nebulae are distant galaxies; not part of Milky Way

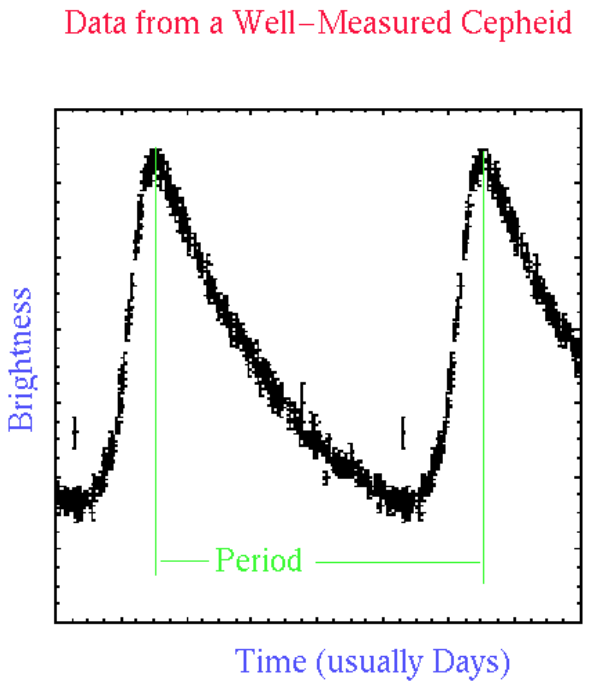






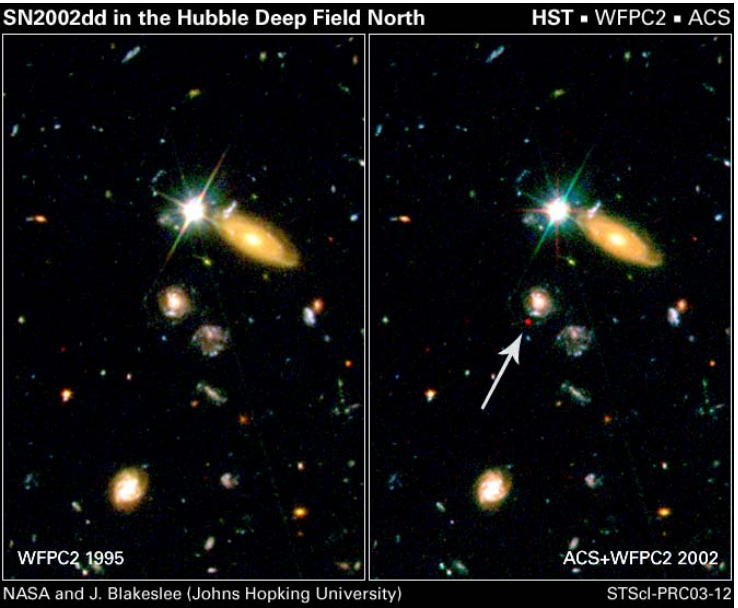
Standard Candles: Cepheids

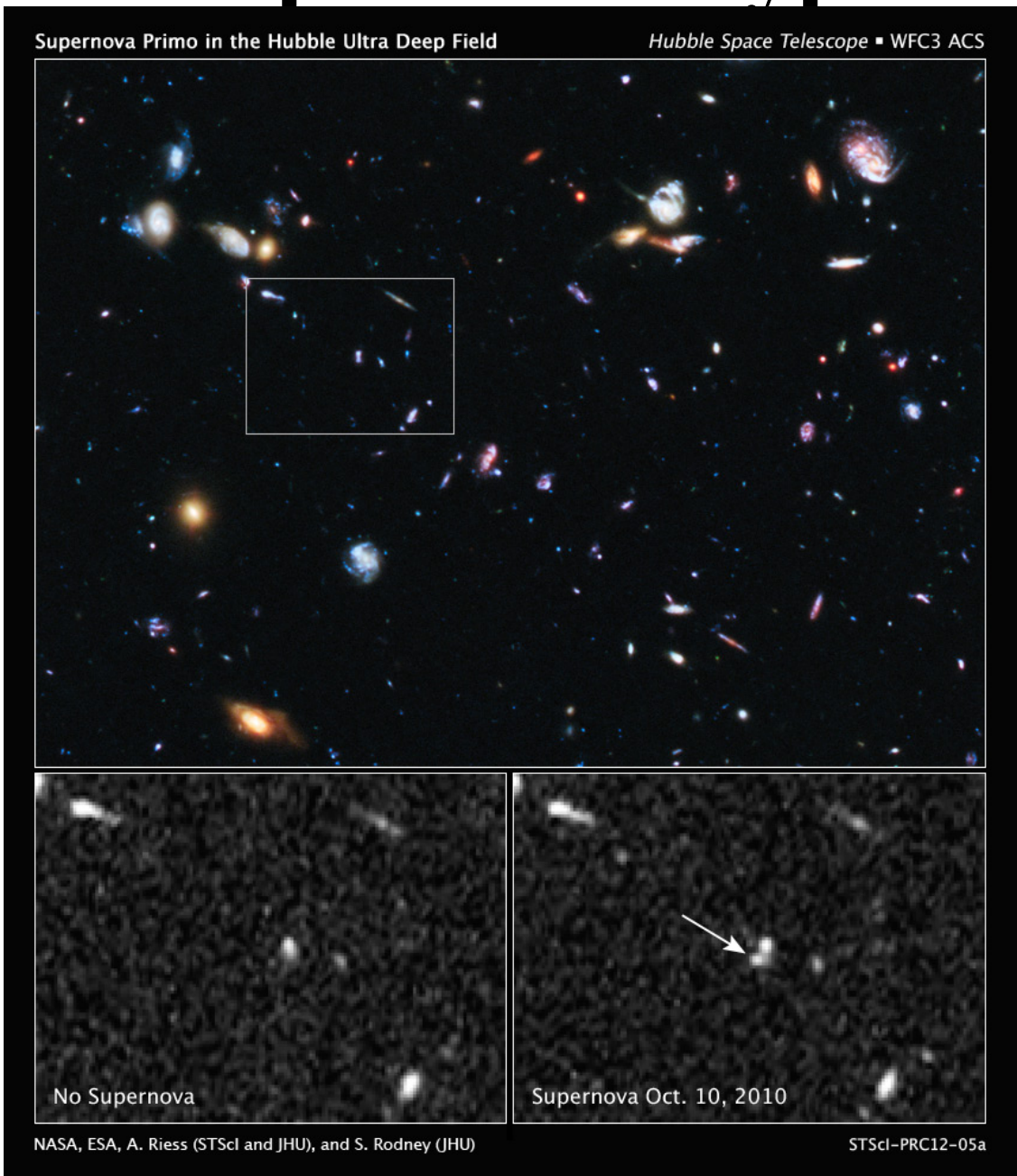
- Objects of known brightness
- Cepheids are supergiant stars used as standard candles
- Can be seen to ~50 Million ly = 18 Megaparsecs



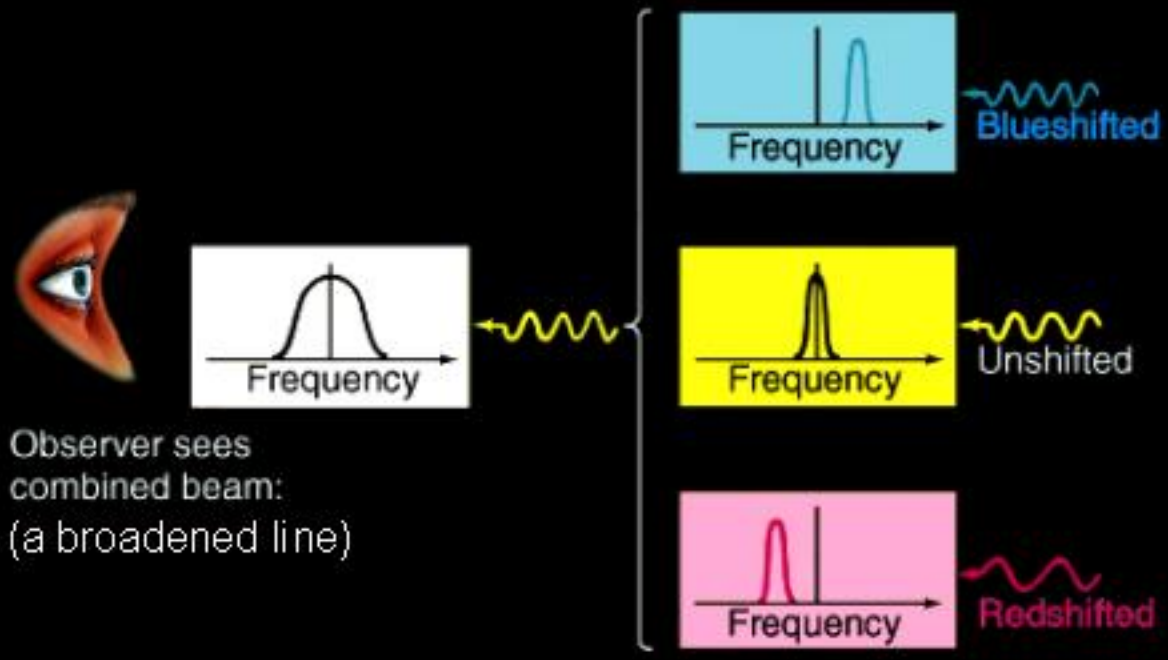
Standard Candles:Supernova TypeIa

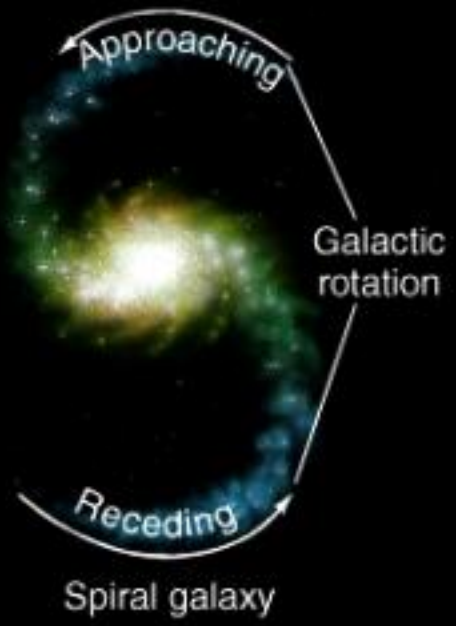
- Type Ia Supernovae are standard candles
- Calibrated by Cepheids
- Type II Supernovae not as precise
- Can be used to look-back times of ~9 billion years





Extending the Distance Scale : The "Tully-Fisher" Relation

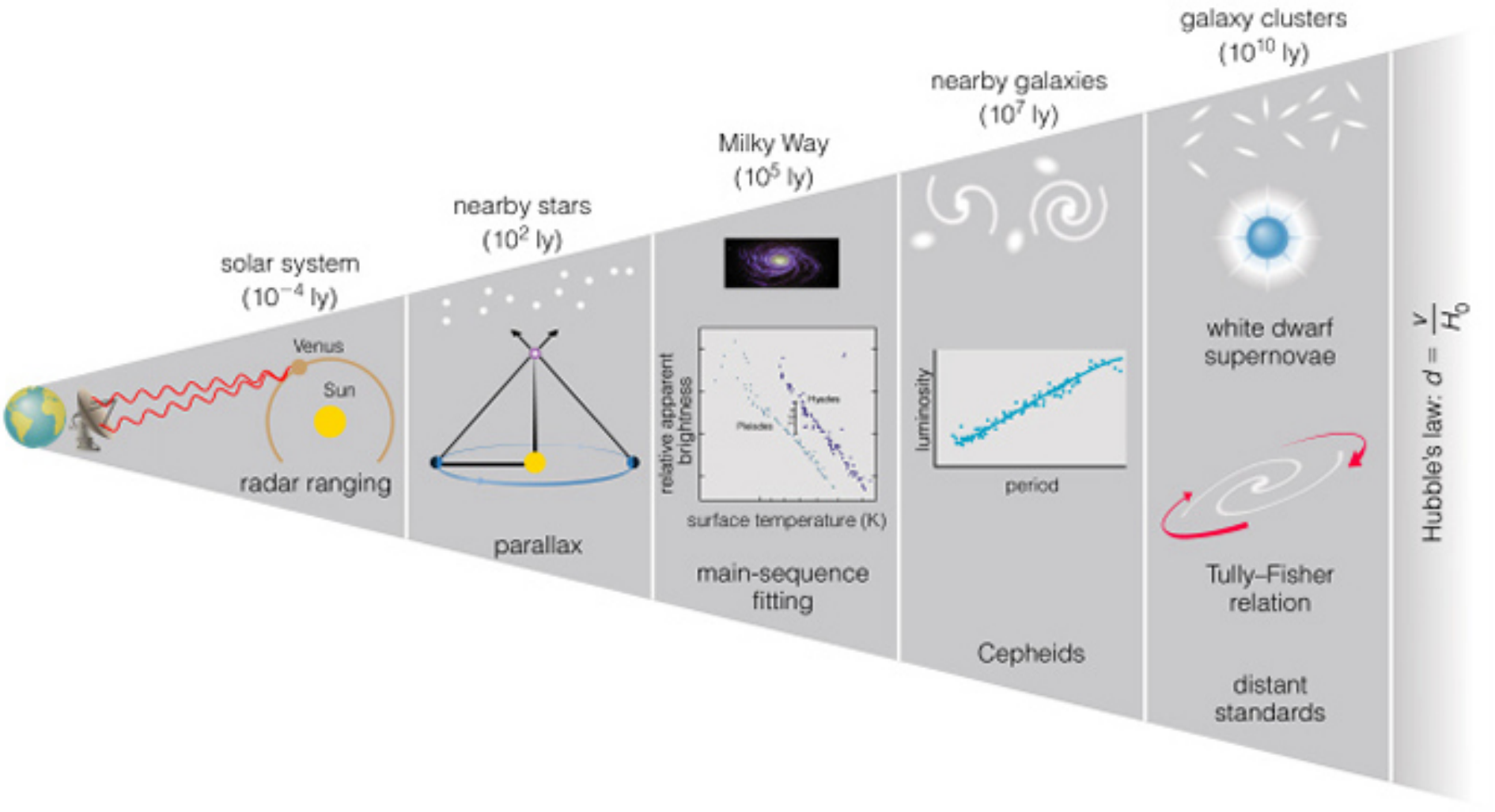




- Galaxy rotation is often measured via the 21cm atomic hydrogen line.
- Rotation speed (line width) is proportional to the galaxy's mass.
- Galaxy luminosity is also proportional to galaxy mass (number of stars).
- The correlation between luminosity and rotation speed is referred to as the Tully-Fisher relation.

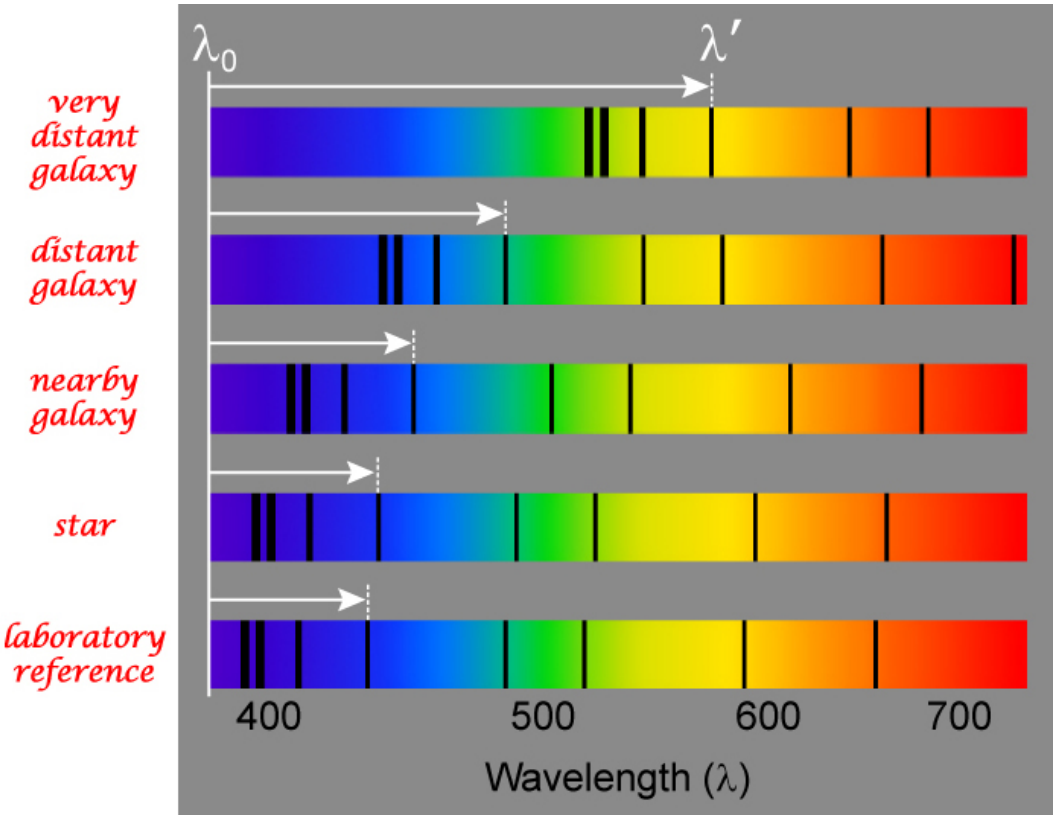
Extragalactic Distance Ladder

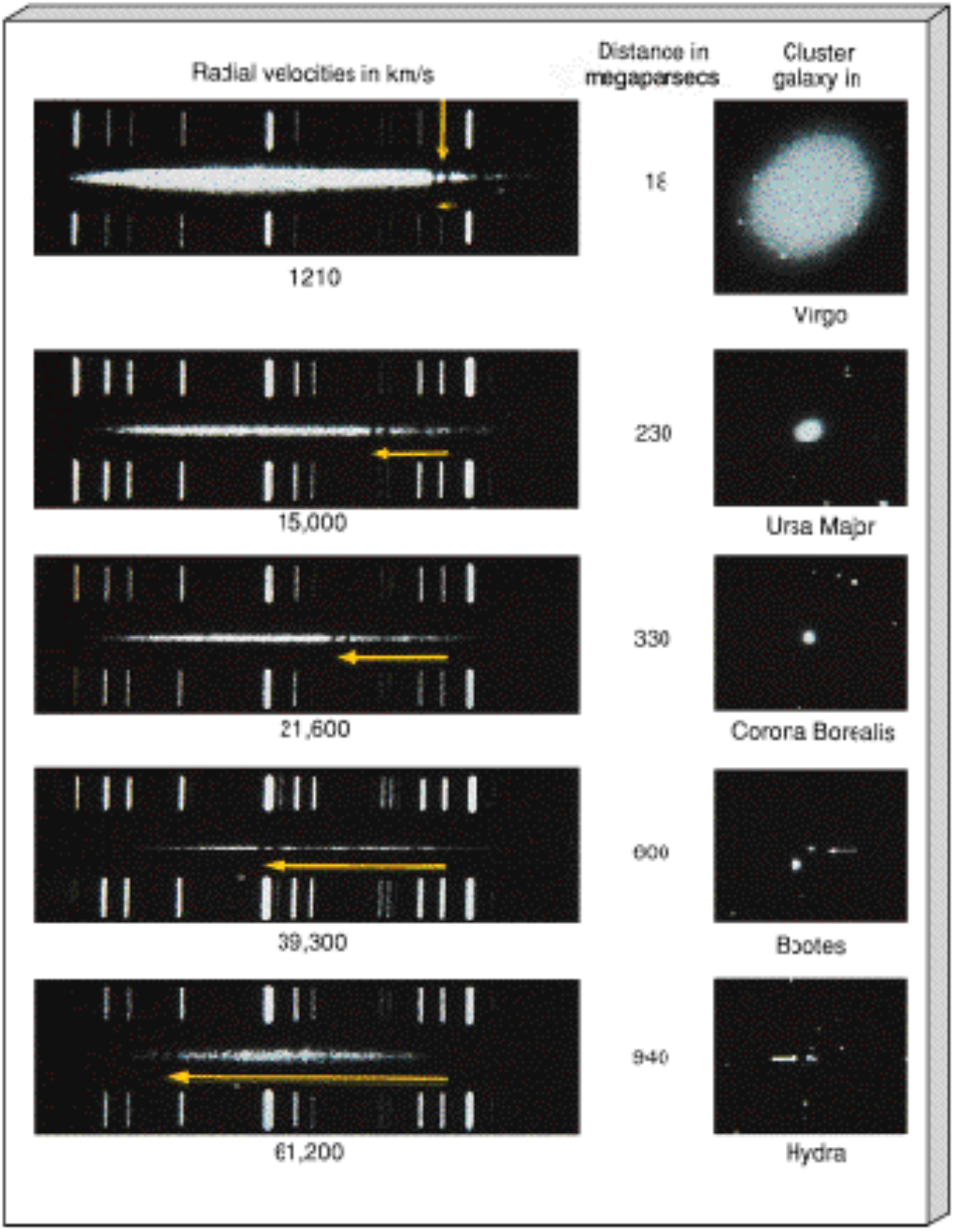
- **Distance ladder** depends on previous rung for calibration
- Combination of photometric and geometric methods



Cosmological Redshift

- $Z=\Delta\lambda/\lambda=V/c$
- $(451-410)/410 \text{ X } 300{,}000^{km}/_{sec}=30{,}000^{km}/_{sec}$
- Blue galaxy's spectrum less redshifted than distant reddish galaxies





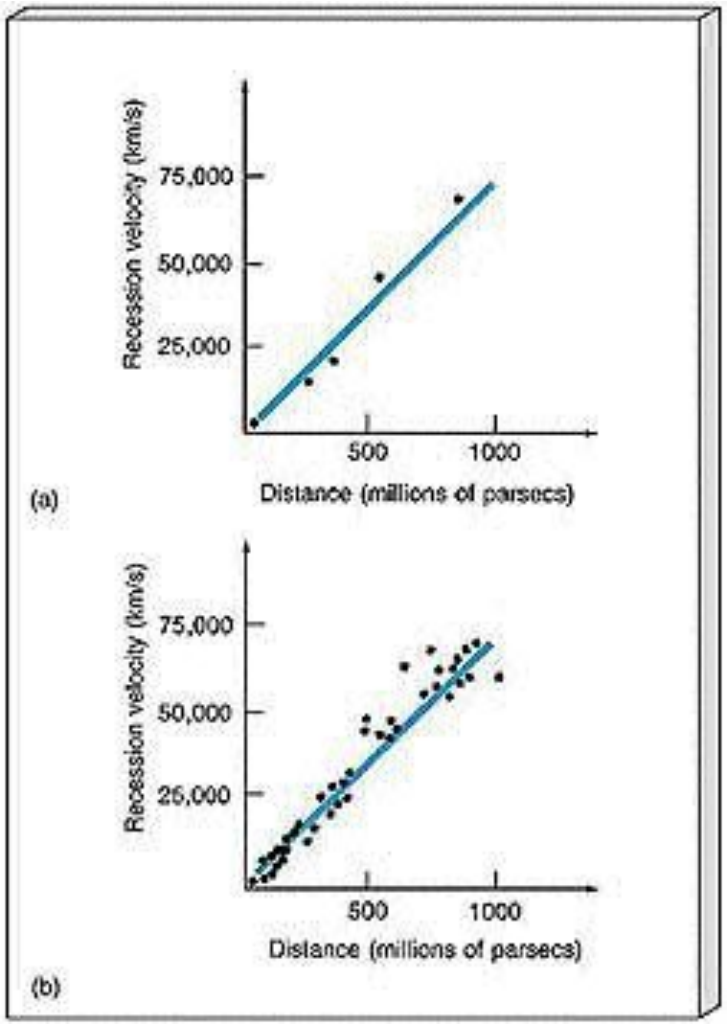
Hubble Law

$V=H_0D$

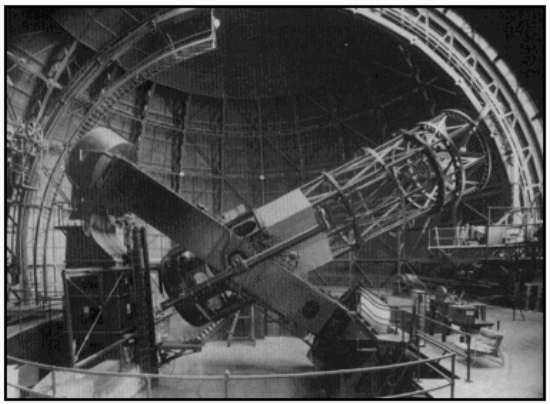
- Diameter gives distance
- If M87 is 20 Mpc away & Ursa Major appears 10 times smaller then Ursa Major is 200Mpc away
- The more distant the galaxy the greater its redshift=the more rapidly it's receding from us

Hubble Constant

- (a) is the five galaxies in the previous slide- *Linear Relation*
- Velocity = **Hubble constant** times Distance
- Hubble constant = velocity/distance ~73km/sec/Mpc
- First Hubble & Humason, 1929
- Sandage=50&deVaucouleurs=100



Edwin Hubble
1889 – 1953



100 inch Mt Wilson Telescope

Milton Humason
1891 – 1972

Which of the following statements in NOT correct?

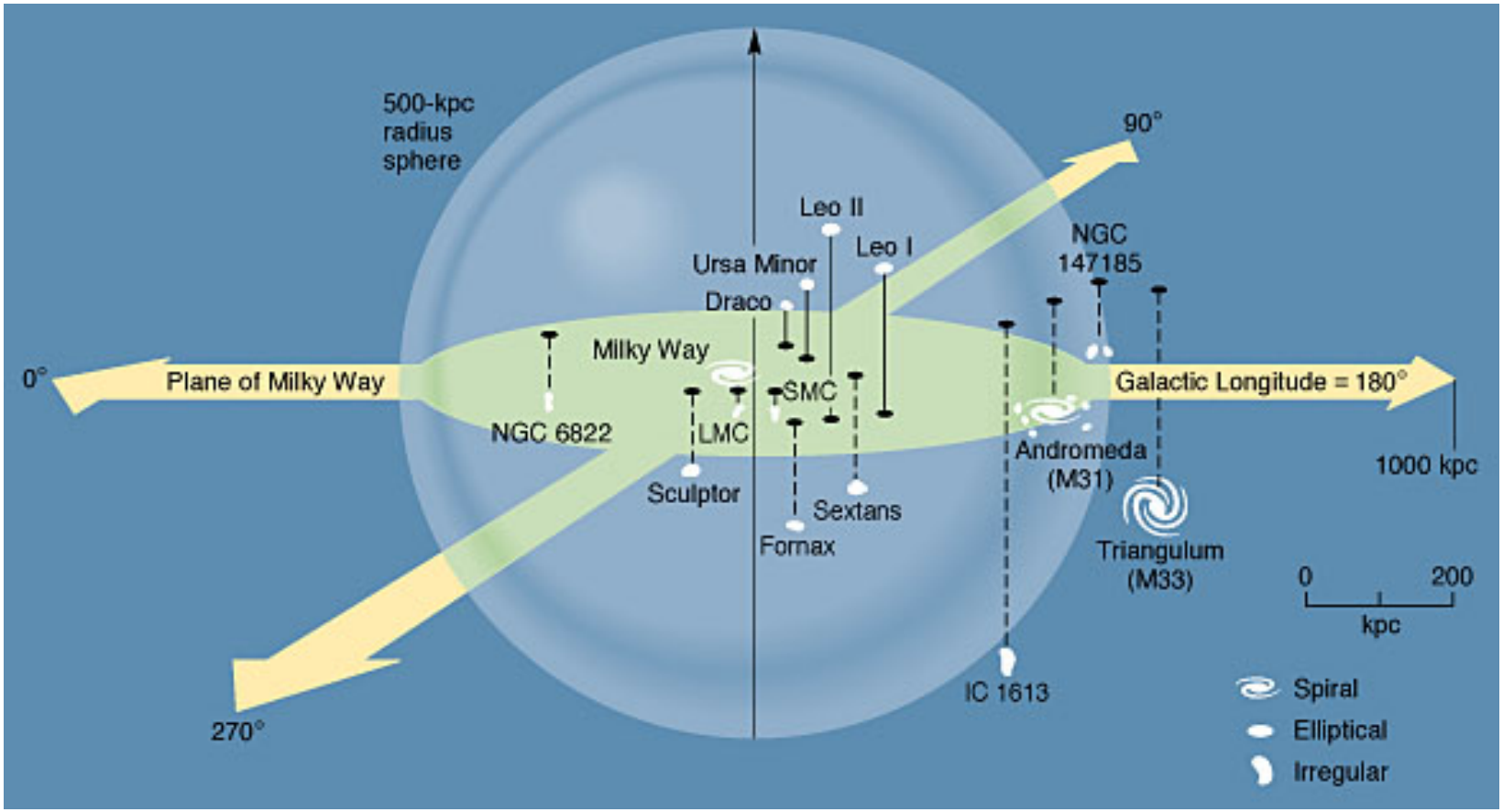
a. The rotation curve of our Galaxy indicates that most of the mass of the Galaxy is Dark Matter
b. At the Galactic Nucleus (Sgr A*) is a million solar mass black hole
c. Galaxies are Spiral, Elliptical or Irregular types
d. The more distant a galaxy, the faster it seems to be moving away from us
e. All of these are correct

Hubble Deep Field Movie

- 342 pictures over 10 days
- ~100 Billion Galaxies in sky

Local Group – Scaled Universe

- 15 elliptical, 4 spiral & 13 irregular galaxies within a Megaparsec
- Star 1mm diam spaced 1km apart: Jupiter is .1mm diam 5cm from sun
- Then Milky Way ~size of Earth



M31 & M33

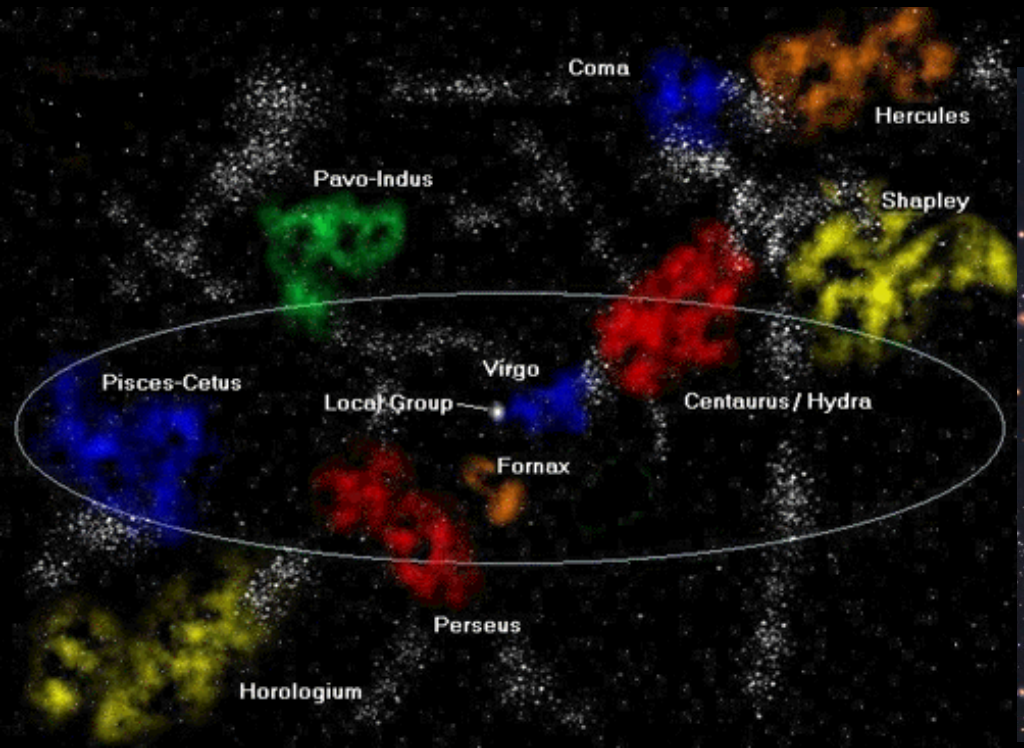
- Andromeda Galaxy would be another Earth at distance of Moon (2.5million light years

Virgo **Galaxy Cluster**

- A collection of galaxies held together by their mutual gravitational attraction
- At distance of Mars/Venus (60million light years)

Clusters of Galaxies

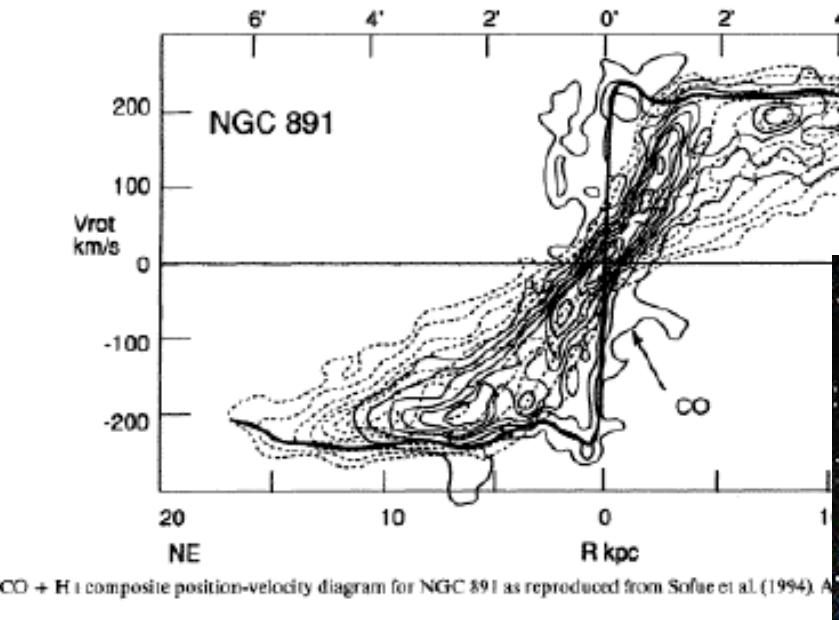
- Coma=300million ly and Hercules=500million lys
- End of universe at orbit of Uranus



Dark Matter: A Galaxy's Mass

1. Rotation Curve

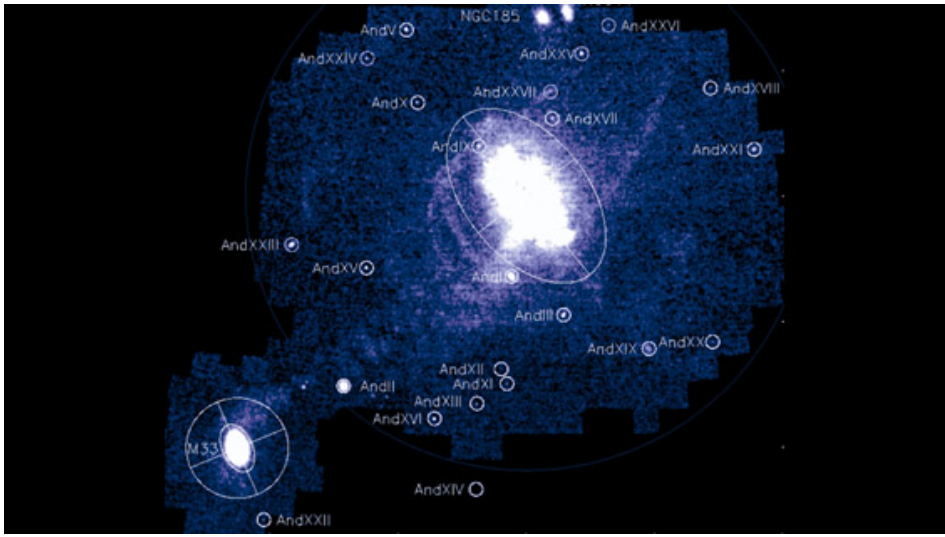
- The faster the galaxy rotates the more massive it is
- Mass comes from Newton's/Kepler's Law $M = A^3 / P^2$

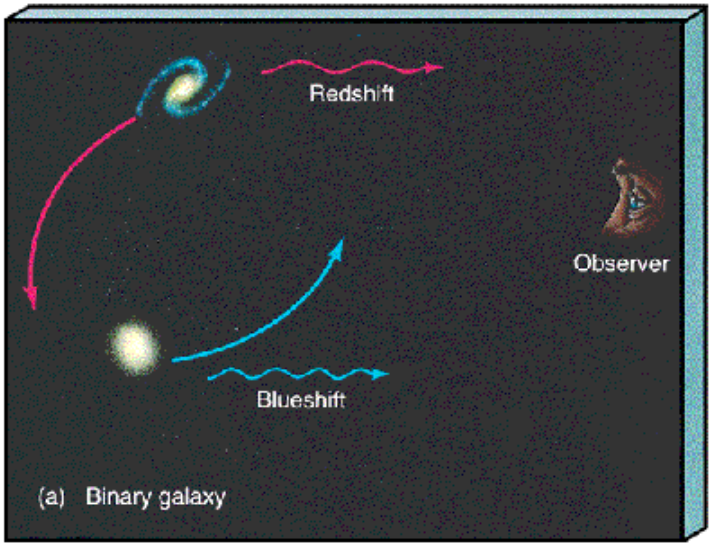


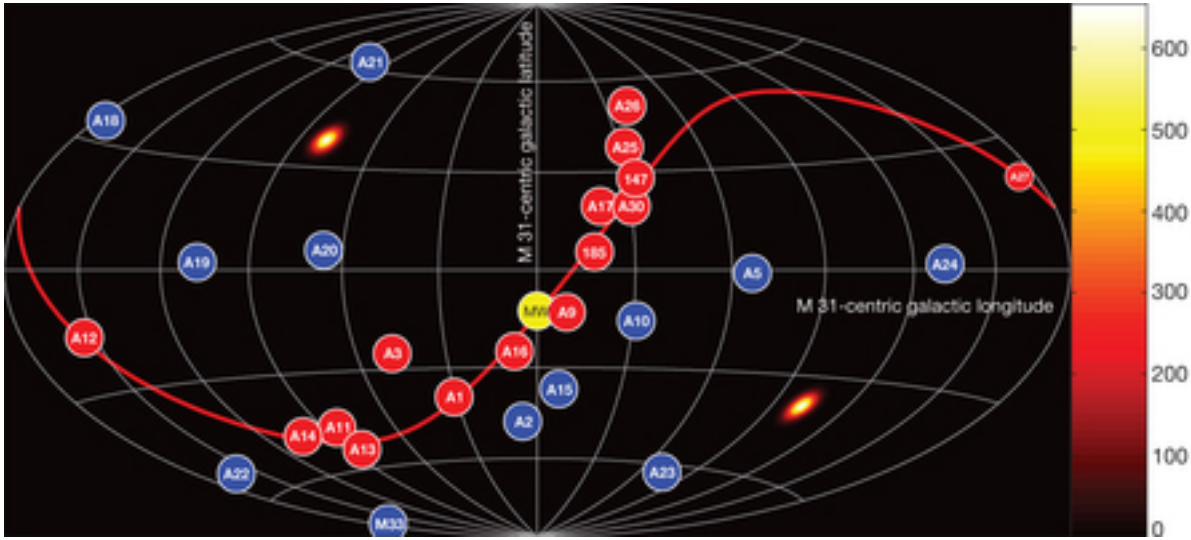
CO + H I composite position-velocity diagram for NGC 891 as reproduced from Sofue et al. (1994) A

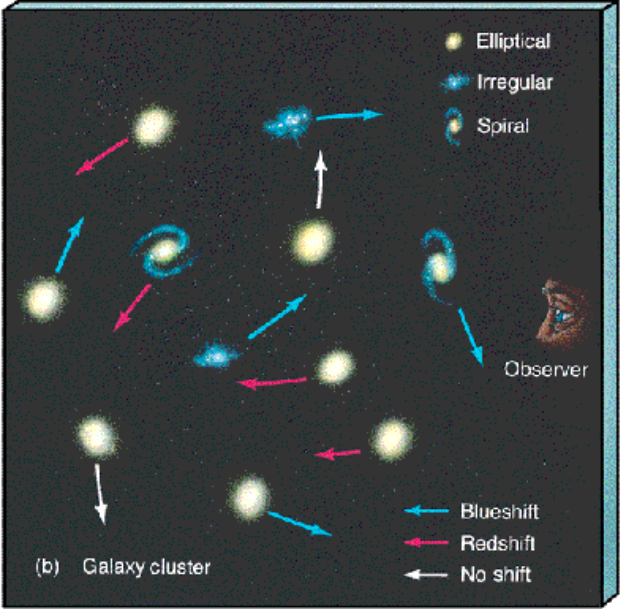
Dark Matter: 2. Galaxy Orbits

- Velocity of galaxies orbiting each other depends on mass
- Small galaxies orbiting Andromeda Galaxy
- Indicate lots of Dark Matter







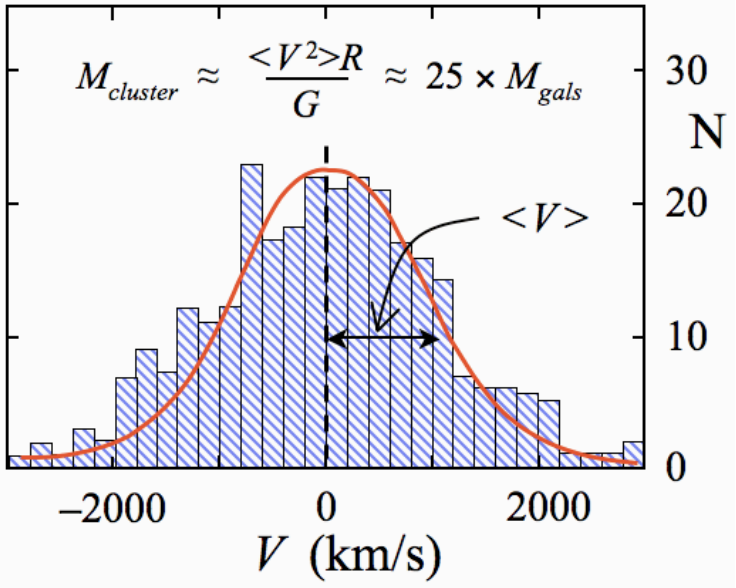


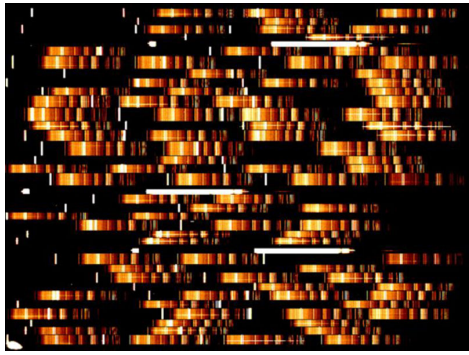
Dark Matter:

3.Velocity Dispersion

- Escape velocity of galaxies in Coma Cluster depends on mass of cluster
- Multiobject spectrograph measures velocities of many galaxies at once
- Cluster contains lots of Dark Matter

Coma cluster (central part)

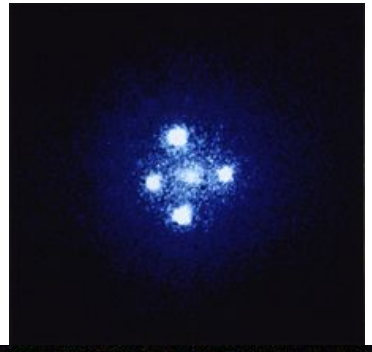


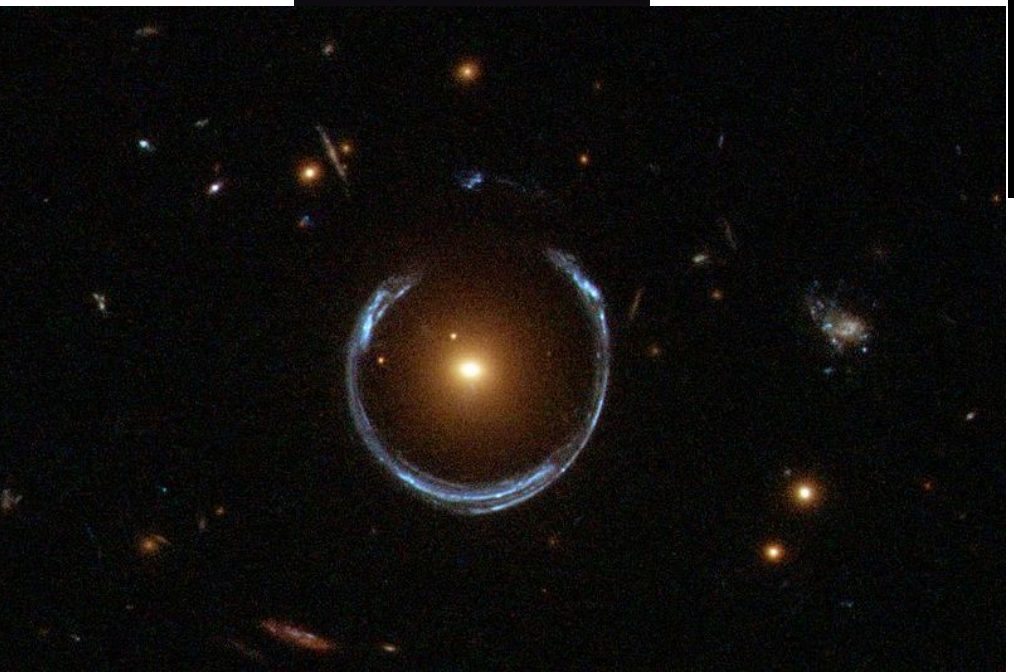


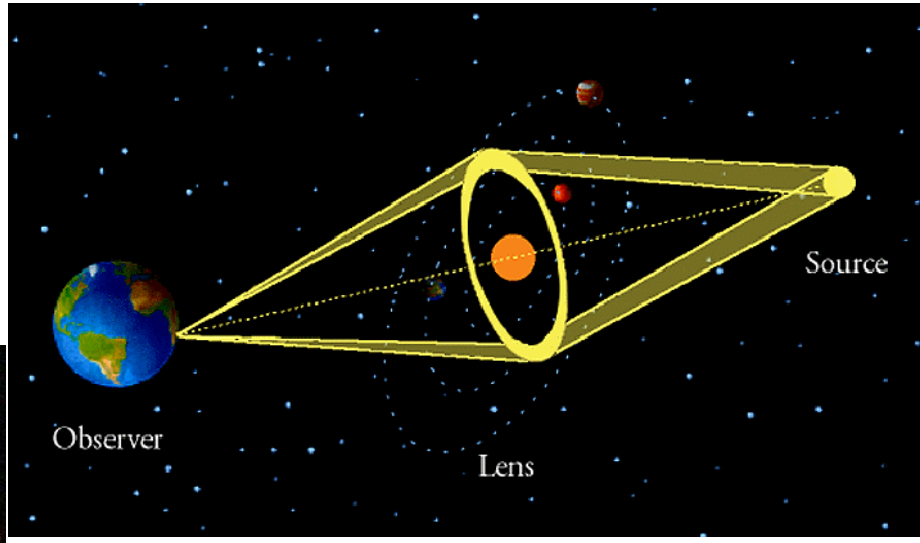
Dark Matter:

4.Gravitational Lensing by a Galaxy

- Background galaxy lensed by mass of foreground galaxy

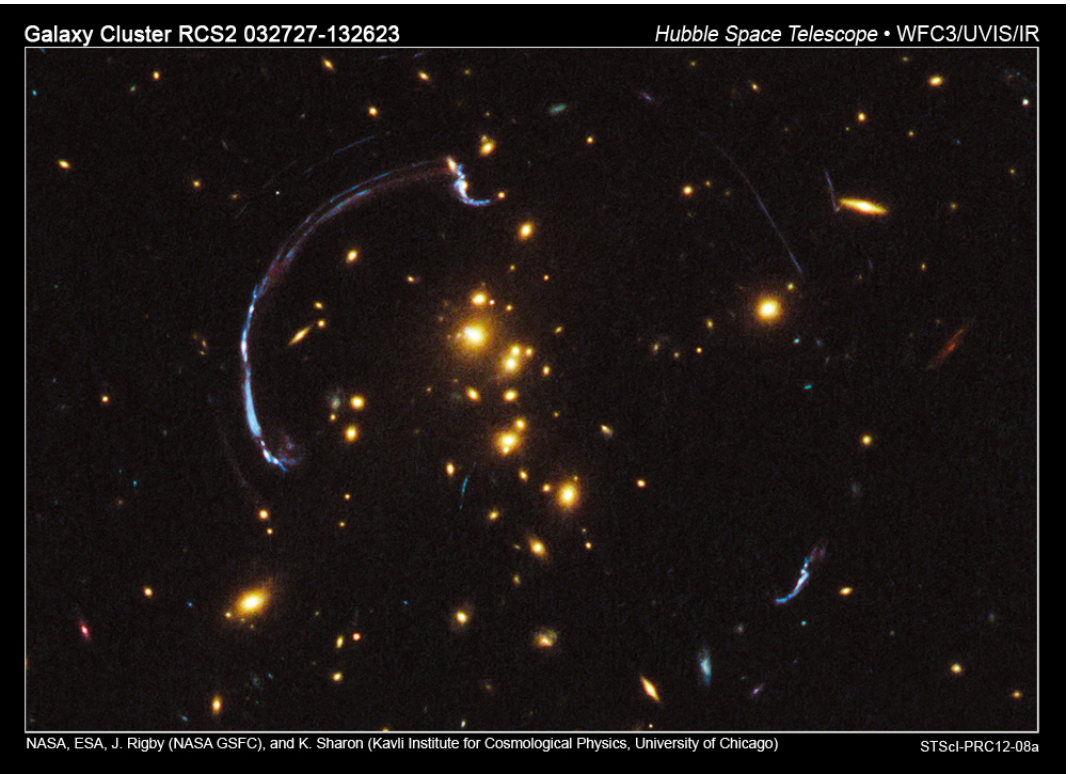


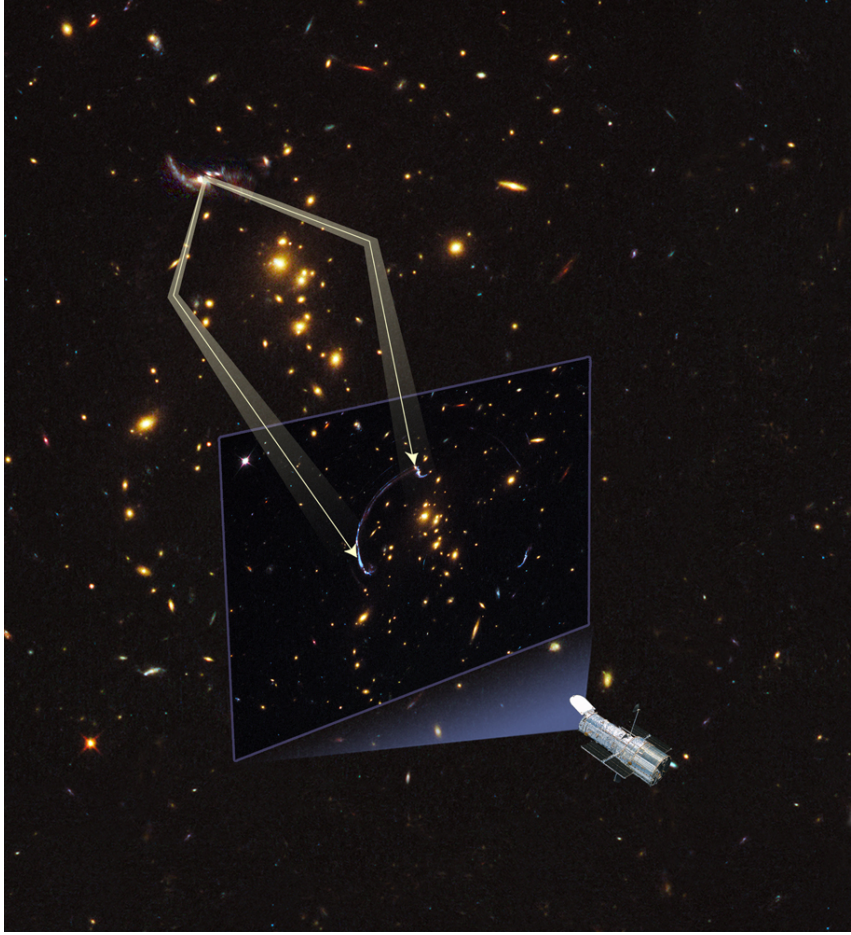




Dark Matter

5.Gravitaional Lensing by a Galaxy Cluster





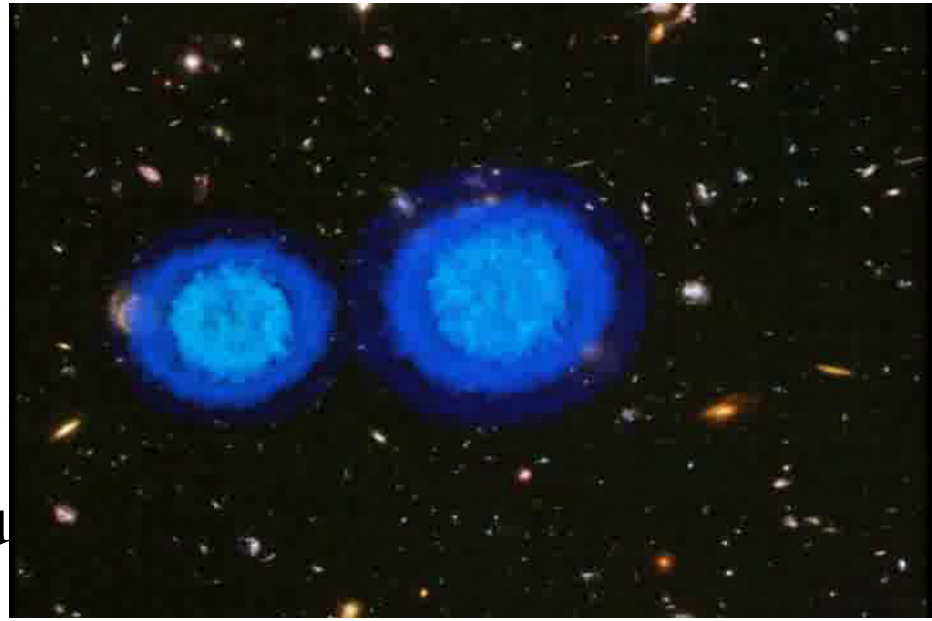
- Background spiral galaxy lensed/ distorted by foreground galaxy cluster
- **Gravitational lensing** measures mass of galaxy cluster including Dark Matter & stars etc.

Dark Matter: 6.Intracluster Gas

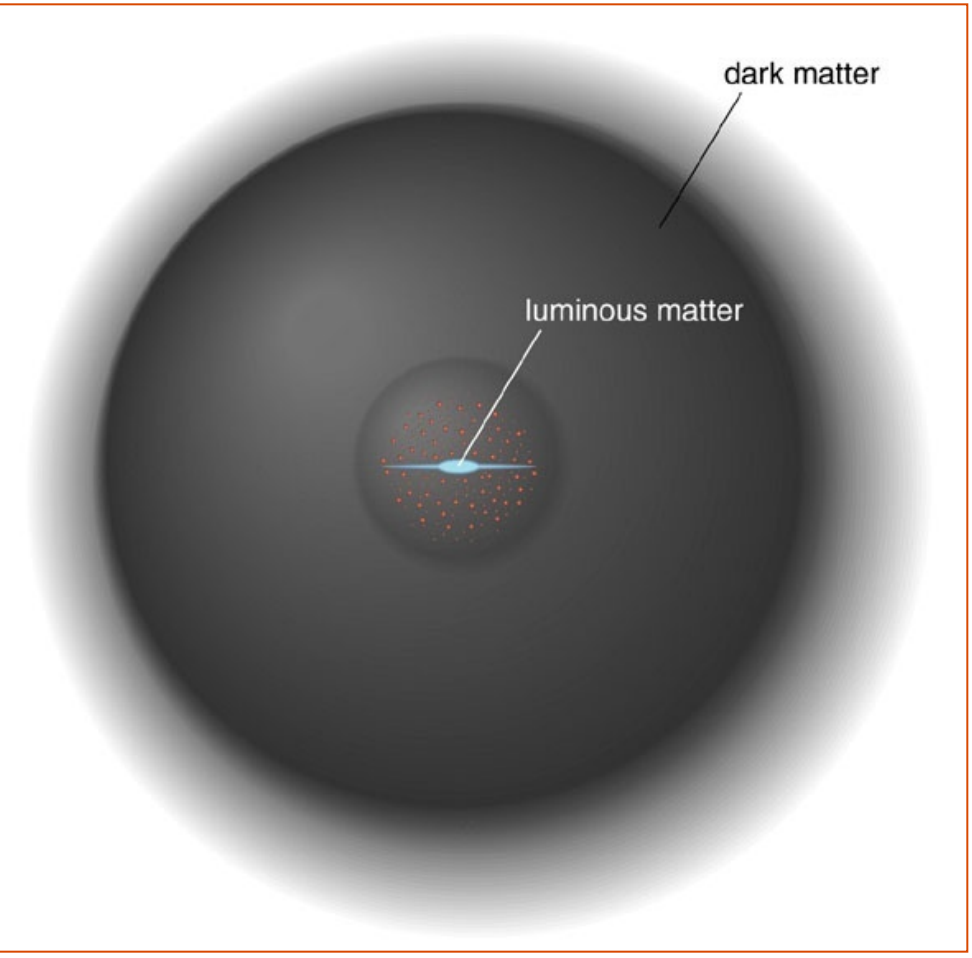
- Hot (10million K) X-ray emitting gas must move with less than escape velocity
- Stars ~5%, Hot gas ~ 10%, ~85% of mass =**dark matter**

Modified Newtonian Dynamics:MOND

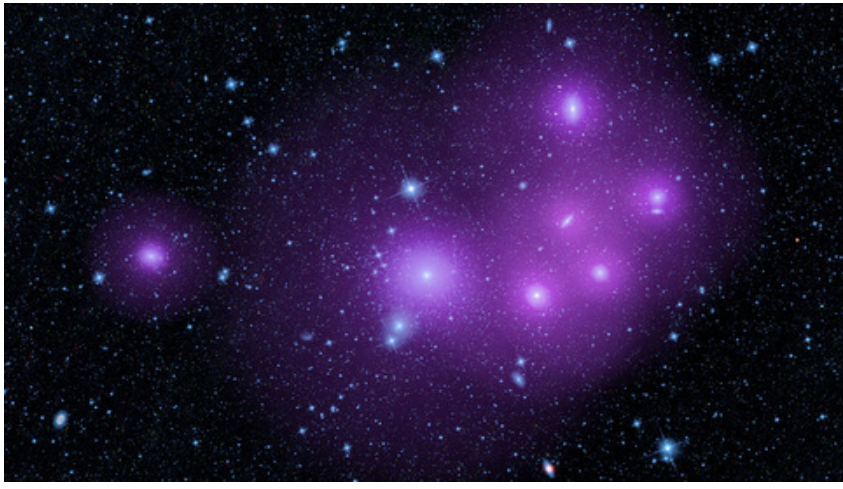
- Fix gravity and maybe dark matter will go away??? No!
- Two clusters colliding with hot X-ray gas left behind
- Dark matter measured by gravitational lensing goes thru



How Much **Dark Matter**?

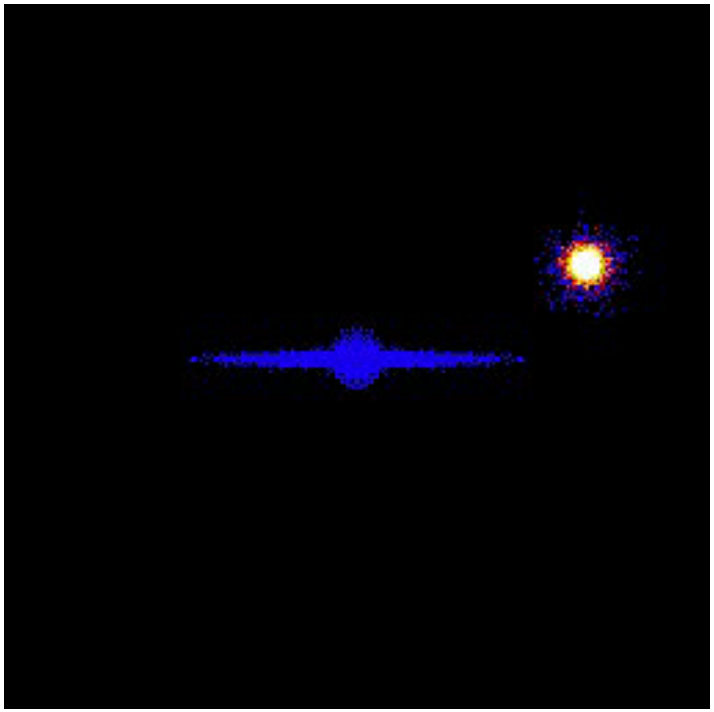


- ~85% of the matter in the universe is Dark Matter
- Galaxies are "White caps on the waves of Dark Matter"
- Dark Matter in Fornax cluster



Galactic Collisions

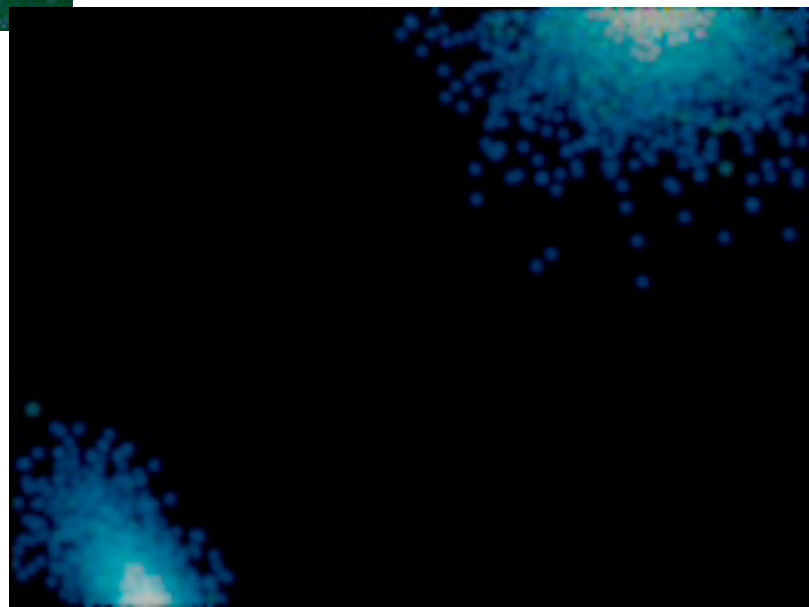
- Since average separation is ~20 times diameter of galaxies
- Galaxy collisions must be frequent



Galactic Cannibalism

NGC 1232

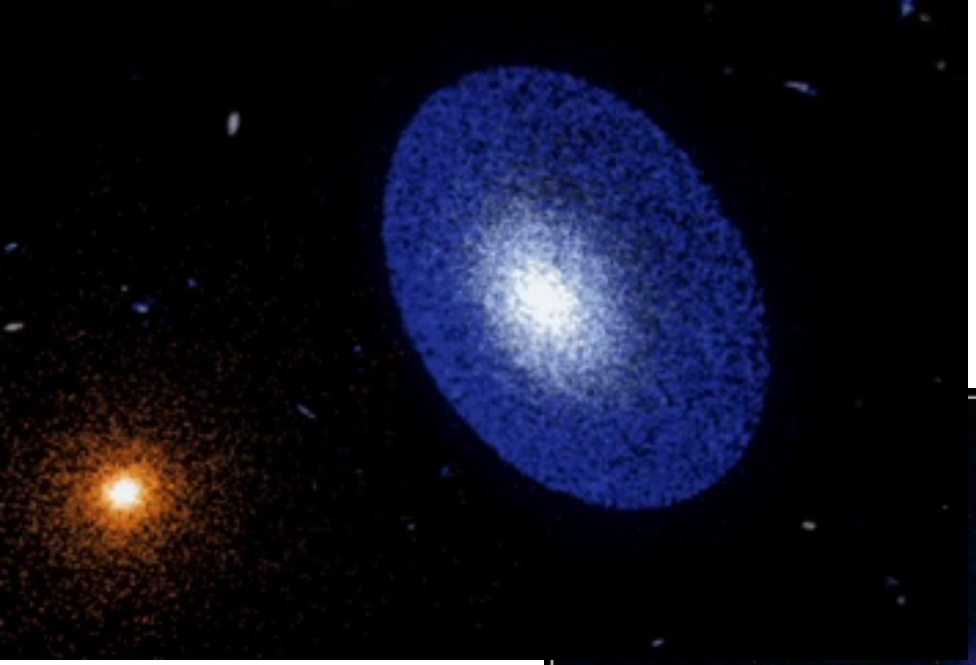
- Stars are like fish in school
- Star's separation 10^7 times star's diameter so star collisions will be very rare



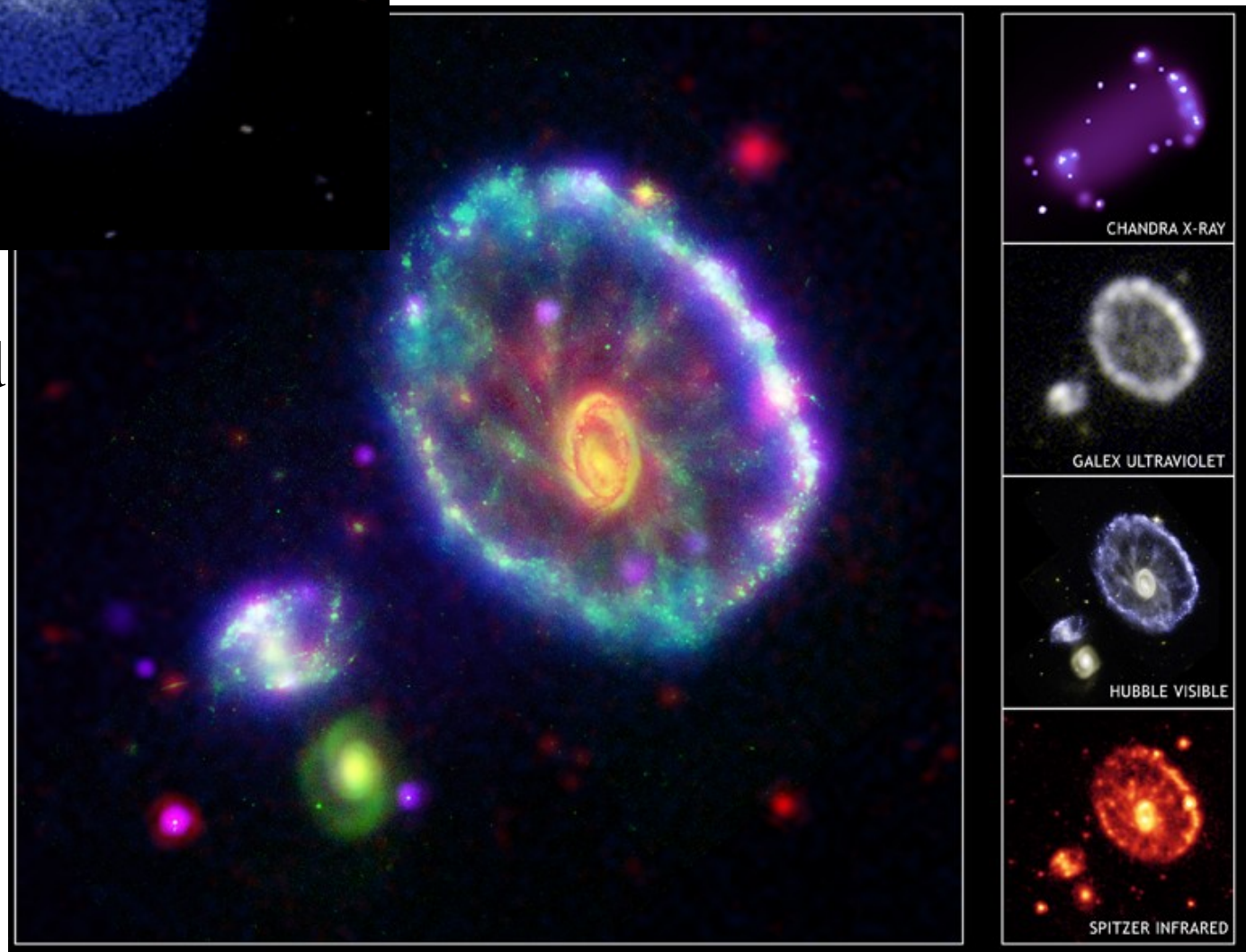
Starburst Galaxy

- Colliding Giant Molecular Clouds form lots of stars
- Notice the OB stars, open clusters, H II regions, etc.

Formation of Ring Galaxy

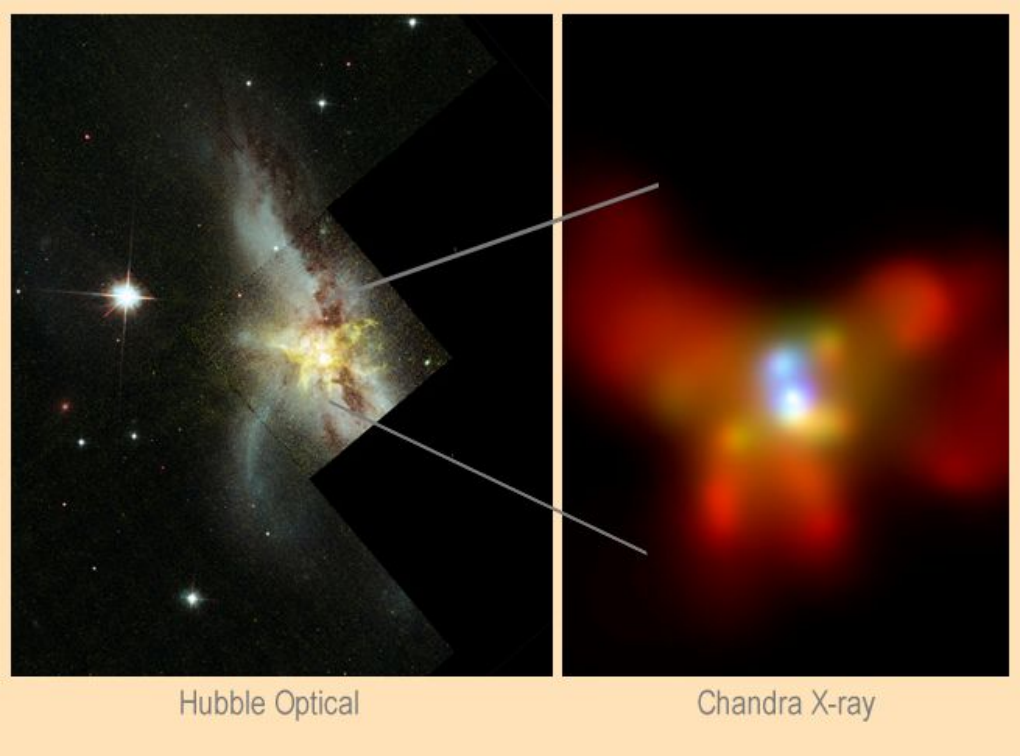


- Cartwheel Galaxy formed from a merger of a galaxy moving perpendicular to the disk



Multiple Nuclei - NGC 6230

- Multiple nuclei indicate mergers
- The central black holes will merge in ~a hundred million years
- Binary supermassive black holes orbit in 100years, at 6000km/sec, at separation of 20,000AU's
- Even systems with 3 accreting black holes

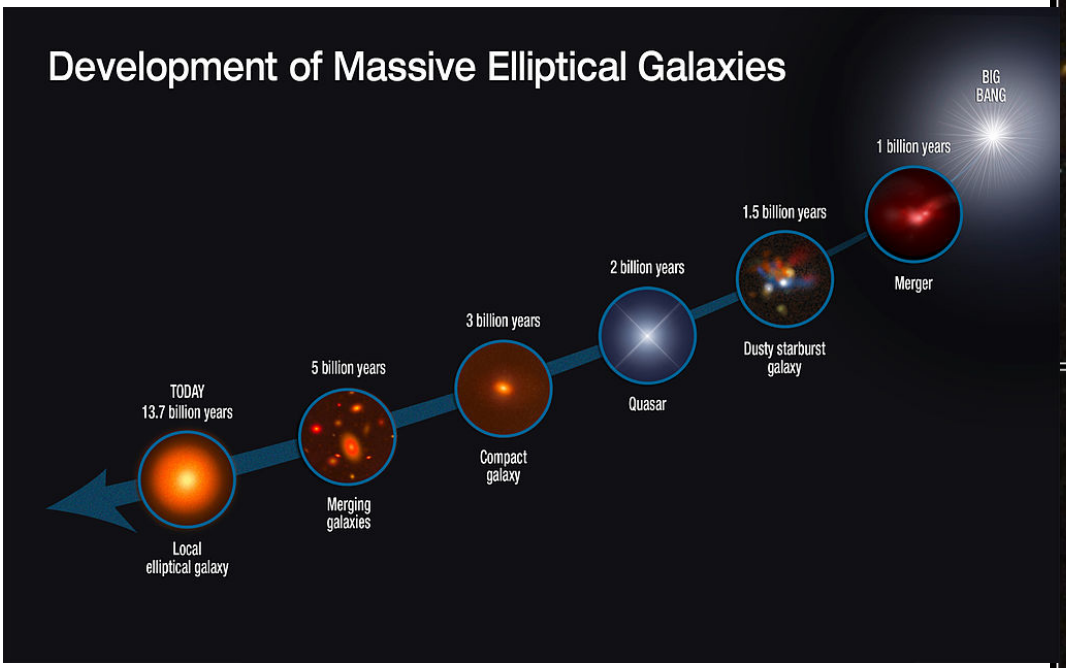


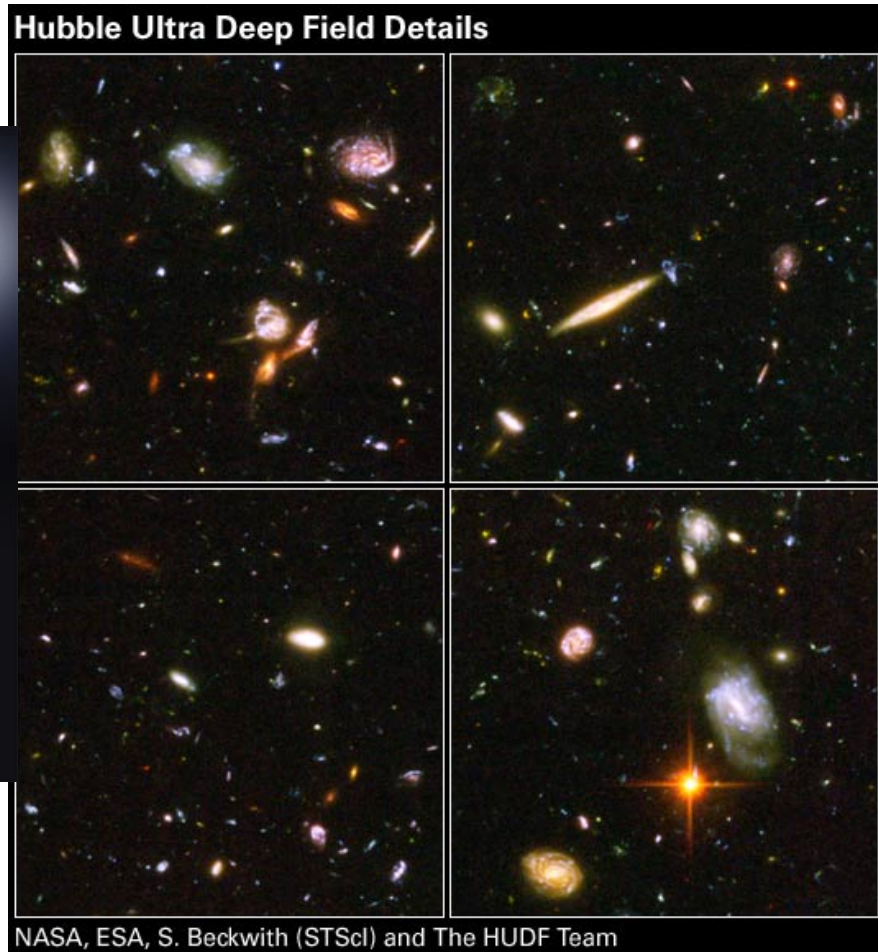
Hercules Cluster of Galaxies and NGC1316

- Small spiral merges with large elliptical –dust to no dust
- Gives random orientation for star's orbits
- Spiral's disks are fragile so unlikely to have had big mergers

Hierarchical Merging

- So distant we look-back in time 10-13 billion years
- More small blue irregular/spiral galaxies; fewer ellipticals
- Merge into large elliptical galaxies we see today





Andromeda & Milky Way Merger

- Andromeda is approaching the Milky Way
- Will impact in ~3 Billion years & merge in ~1billion years
- Stars, planets (Earth) & Dark Matter pass by each other, but gas clouds will collide and form new stars

This big galaxy is a:

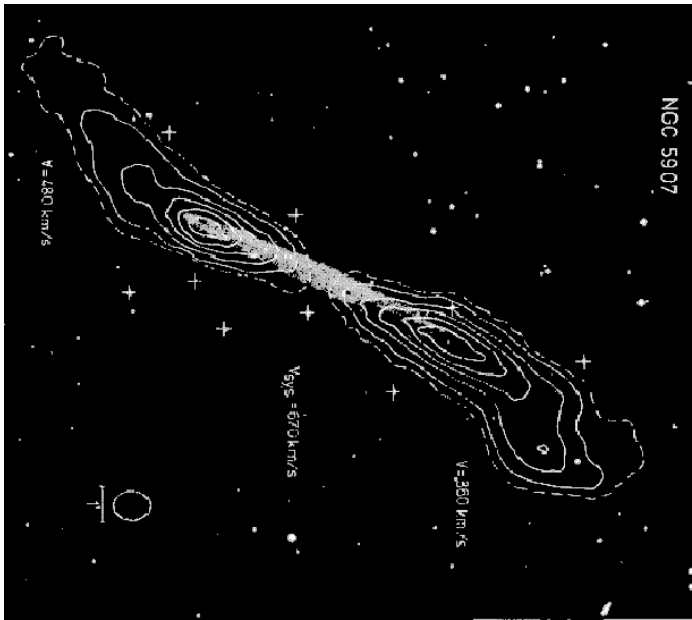
a. Spiral
b. Elliptical
c. Barred Spiral
d. Irregular
e. Ford

Ford Galaxy

Dark Matter: A Galaxy's Mass

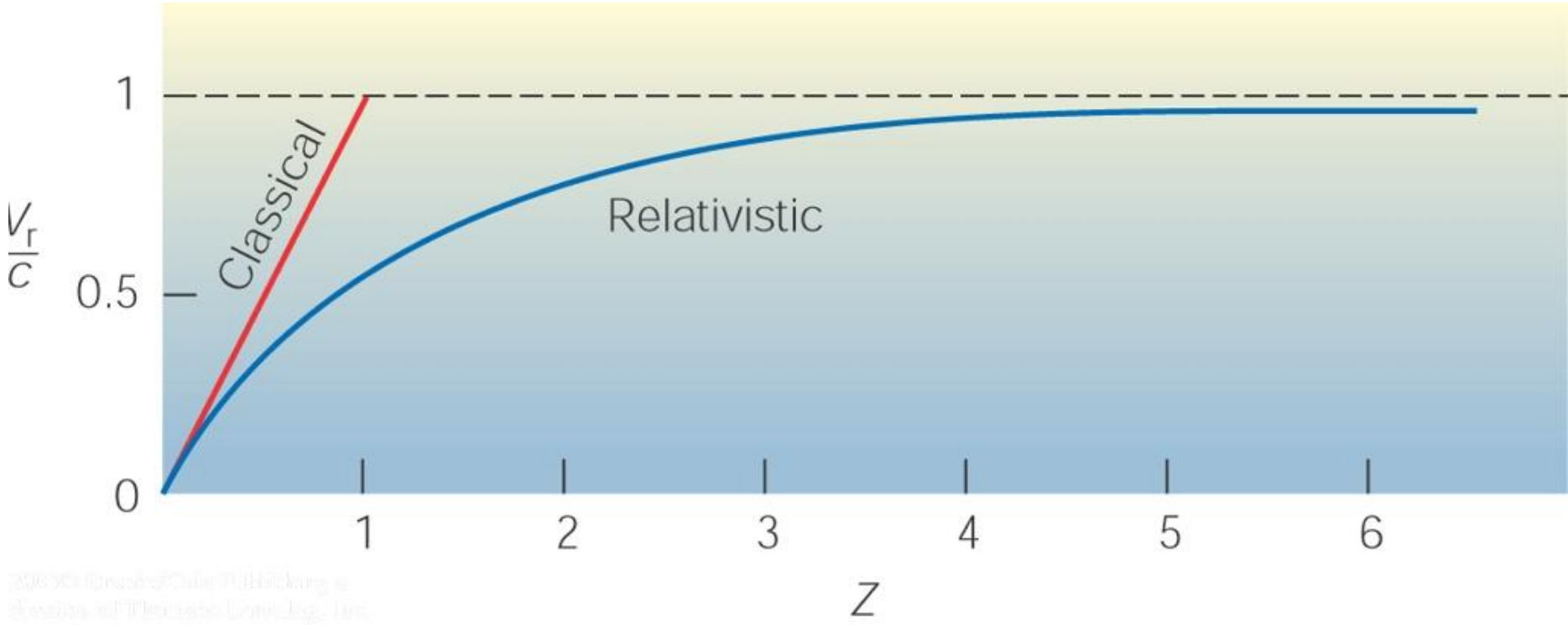
- Radio observations superimposed on DSS image of galaxy
- Atomic hydrogen gas extends far beyond visible disc
- From 21-cm line gas beyond disc it rotates rapidly
- Galactic Halo of Dark Matter must be ~10 times size of stellar disk ~ 100kpc radius

NGC5907



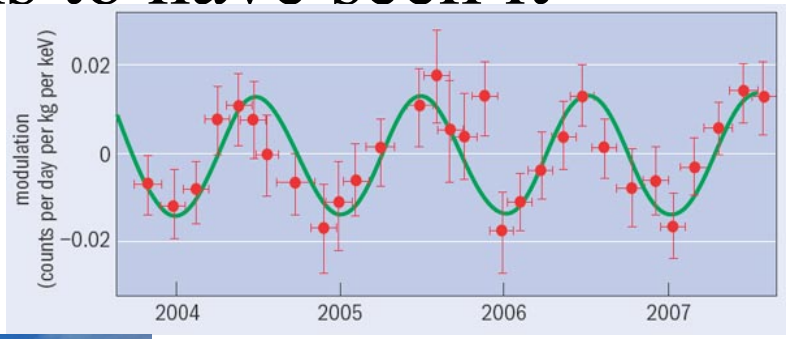
‘Relativistic’ Redshift $z=\Delta\lambda/\lambda$

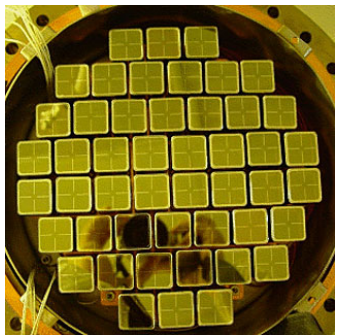
- $\frac{V}{C} = \frac{(z+1)^2 - 1}{(z+1)^2 + 1}$ V=recession velocity
- As redshift increases lookback time increases
- Distance between galaxies=Radius of universe is ~1/(1+z)
- Age as fraction of age of universe is ~1/(1+z)



Lots of First Detections of Dark Matter

- CDMS2 in mine in Minnesota- maybe
- Fermi Gamma-ray space telescope-maybe
- PAMELA satellite- maybe
- ATIC Antarctic balloon experiment maybe
- DAMA/NaI - claims to have seen it



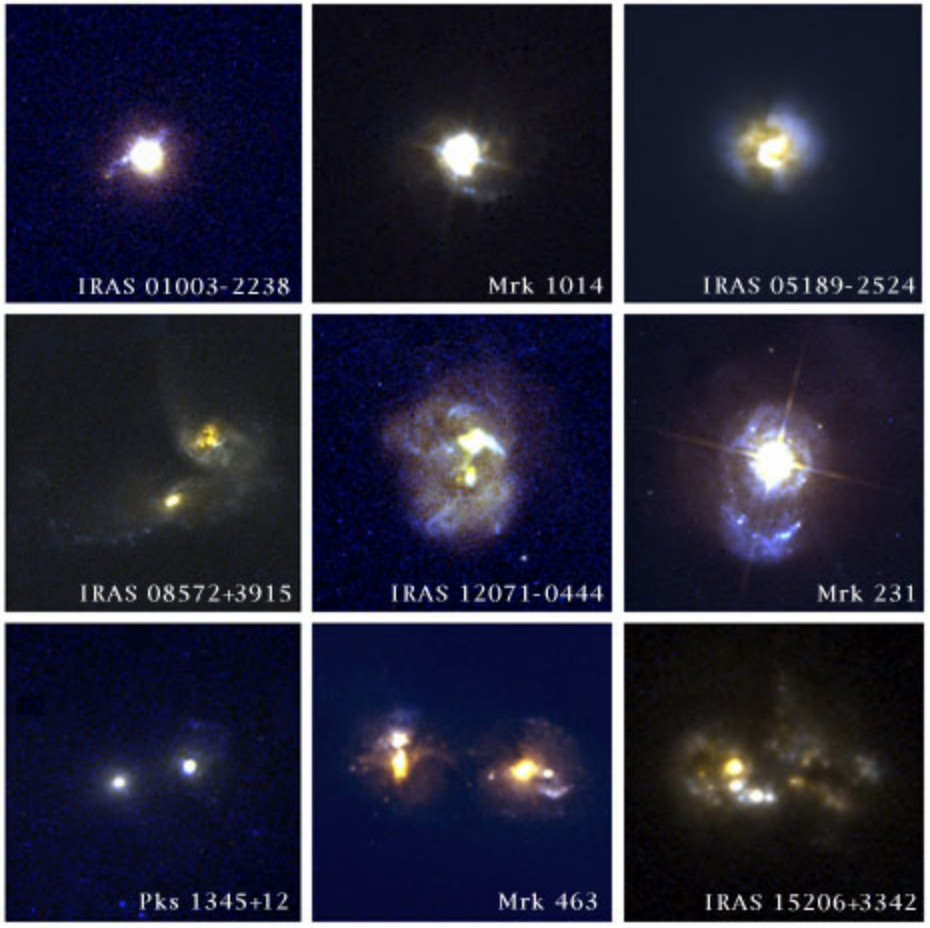


Tidal Tails

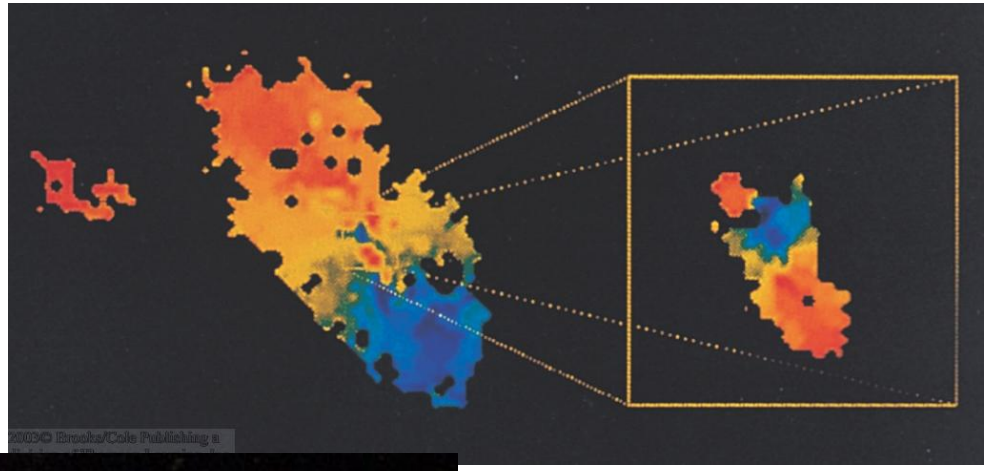
- Dark Matter in red & stars in blue
- Tidal tails form during merger

UltraLuminous IR Galaxies

- ULIRG's emit 100X Milky Way in IR
- Thought to be multiple galaxies merging
- Lots of dust masks bright stars
- Supernovae blow away dust leaving elliptical galaxy(?)



Inner Part of M64 Rotates Backward

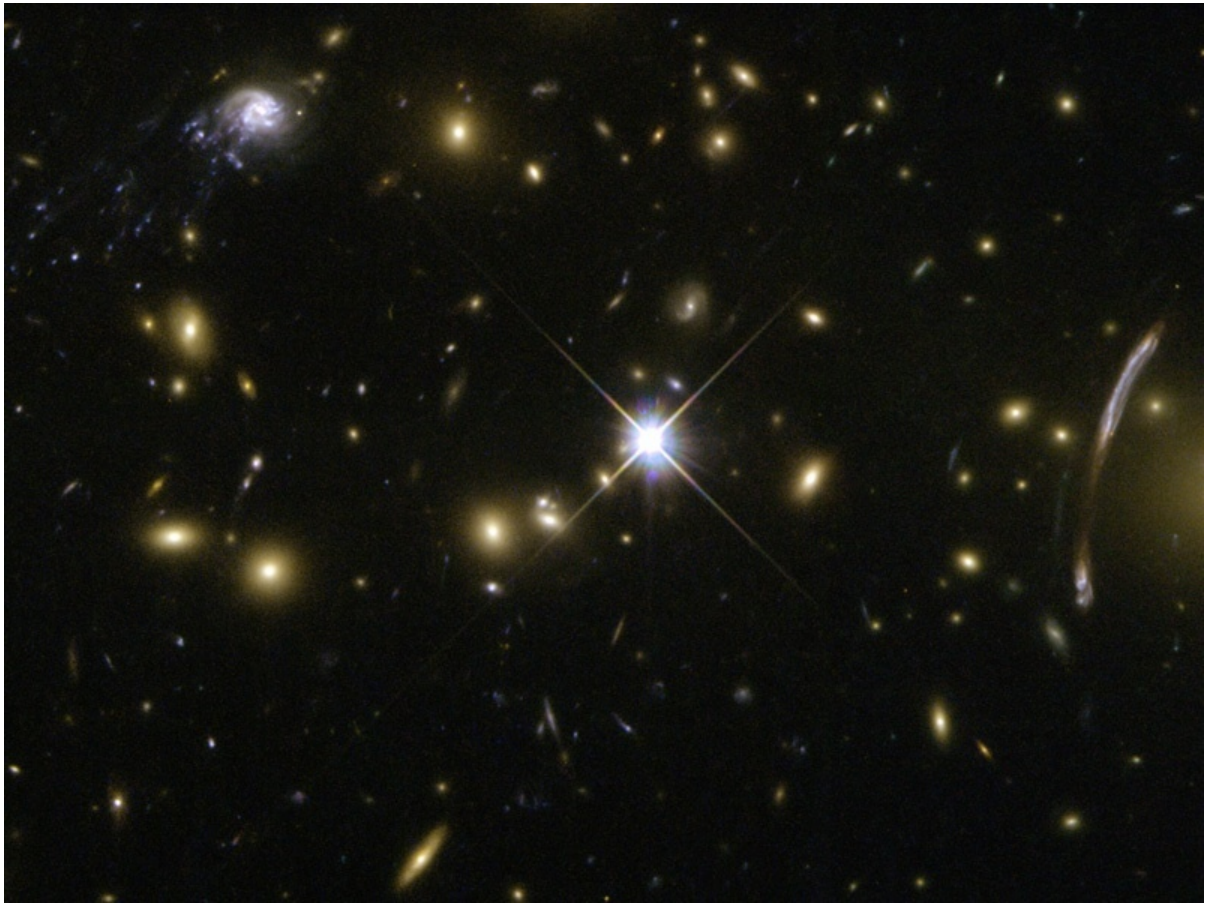


Galaxy Cluster

- Galaxies are like people – They like to hang around together
- George Abell cataloged ~2700 clusters

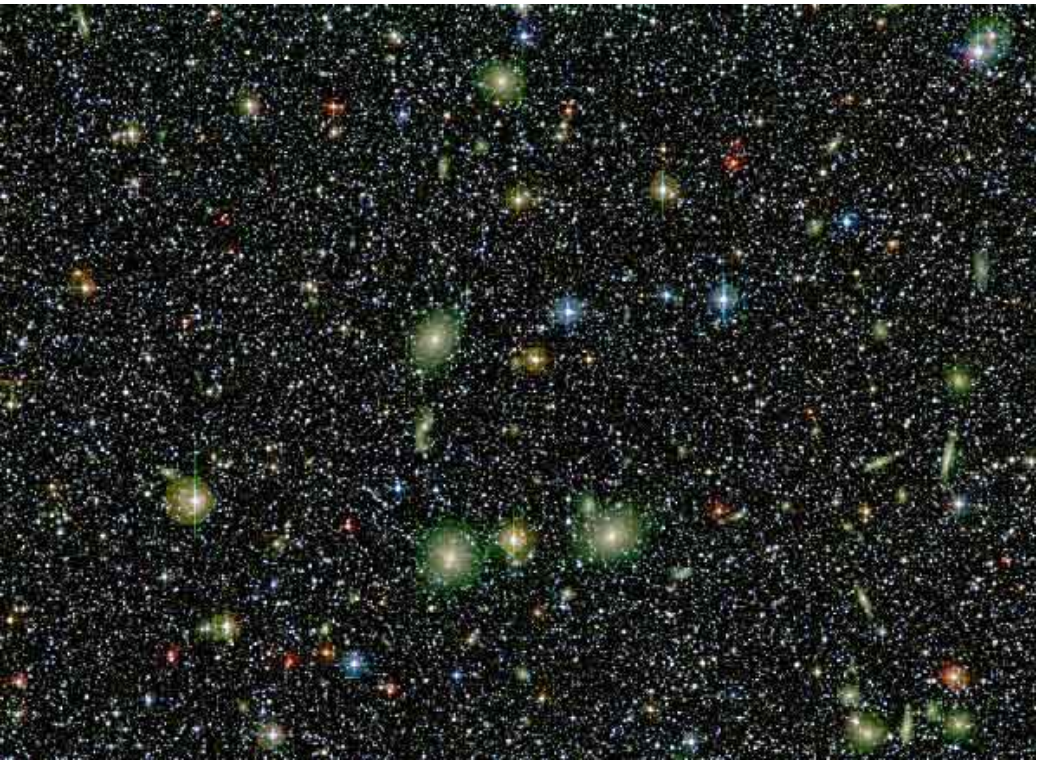
Abell 2667 Galaxy Cluster

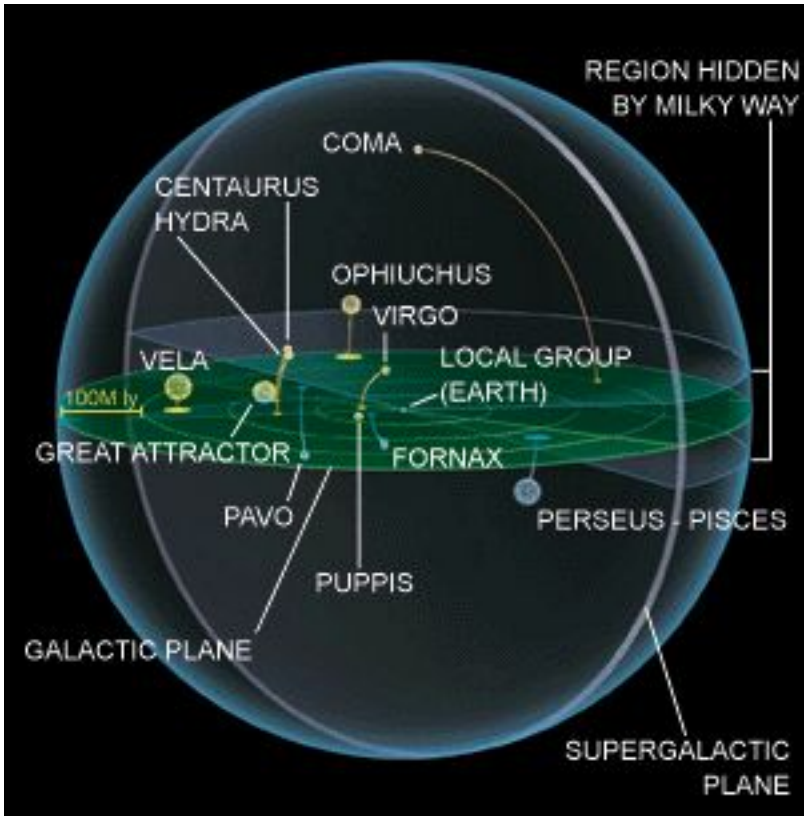
- Galaxy in upper left is moving through cluster and gas is being ram stripped and forming trailing stars
- On right is background lensed galaxy



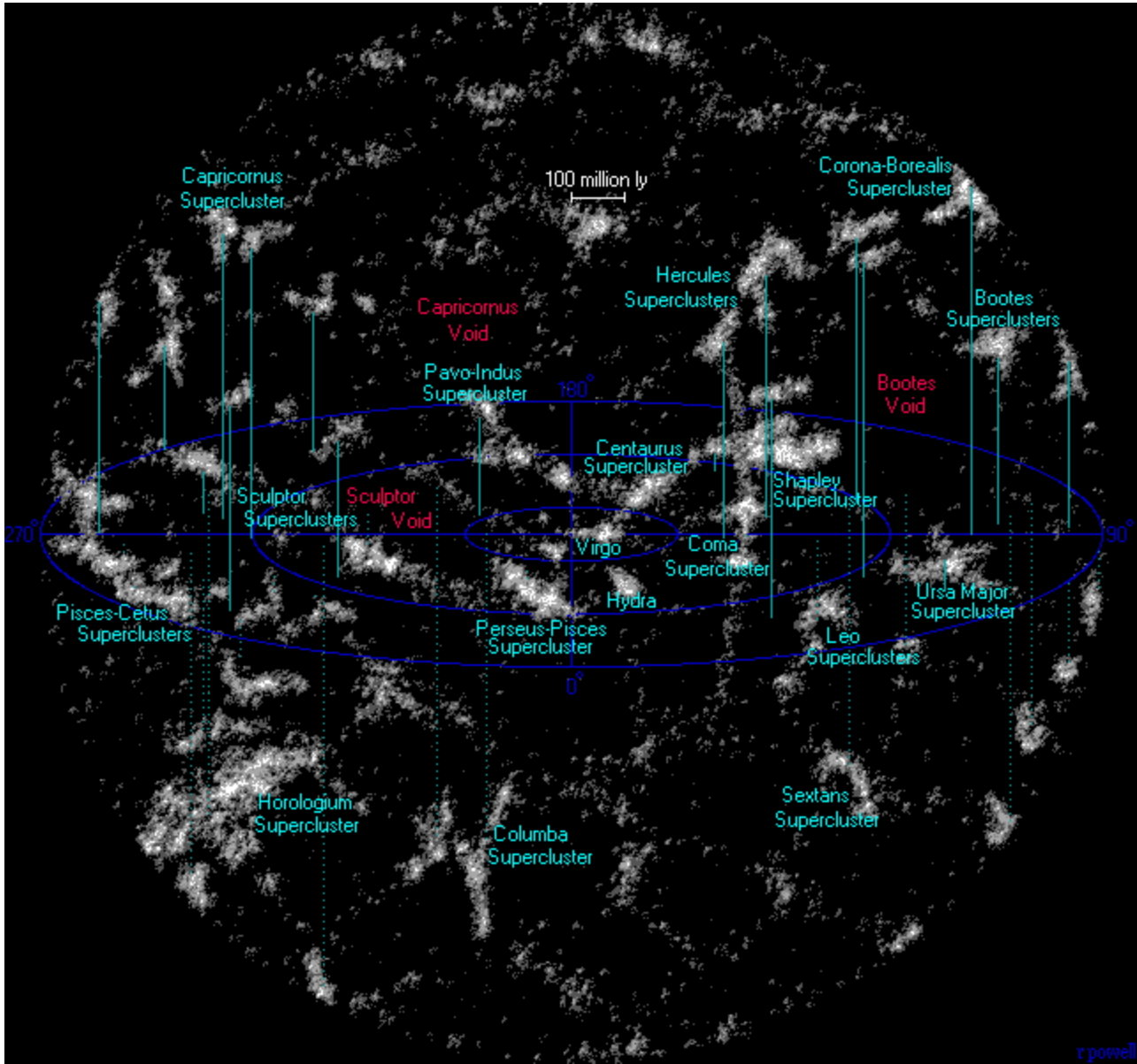
Great Attractor

- Local Group and Virgo cluster are falling into Great Attractor
- Cluster 250 Million light years away hidden behind Milky Way dust
- Maybe??

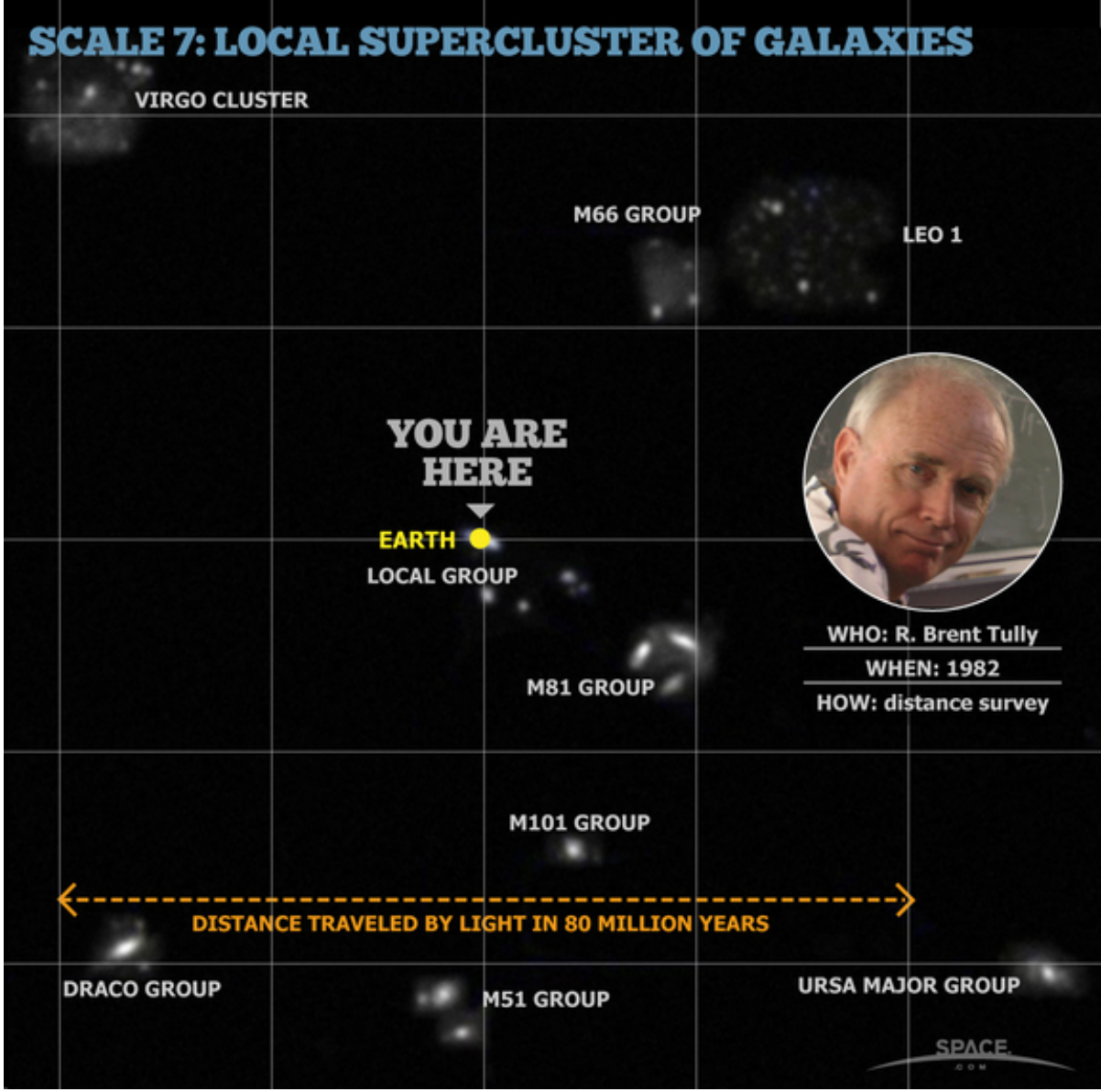




Our Billion light year neighborhood

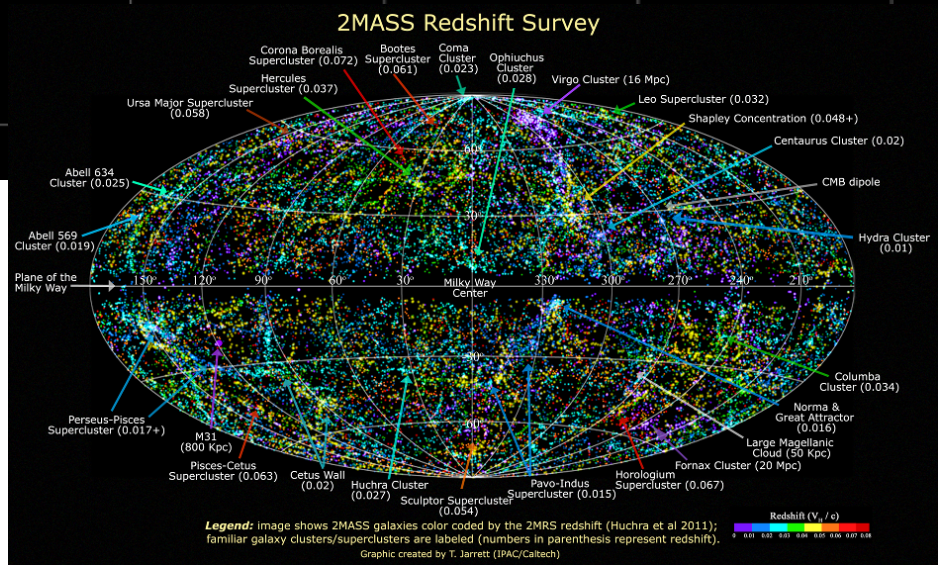


Local Supercluster



Walls, Filaments and **Voids**

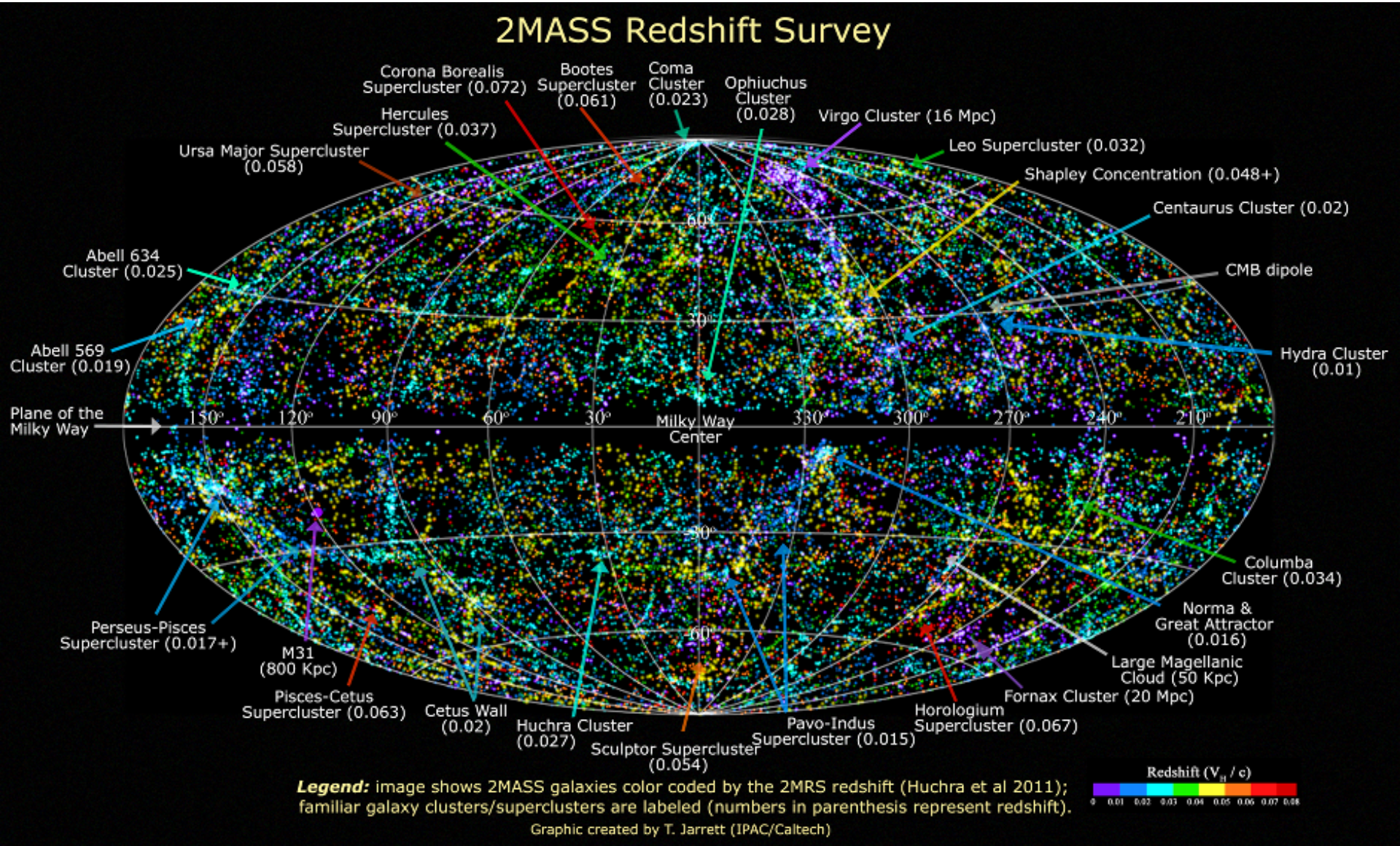
- Observe redshift
- Hubble law gives distance
- Galaxies distributed like soap suds or a sponge



Look-back Time

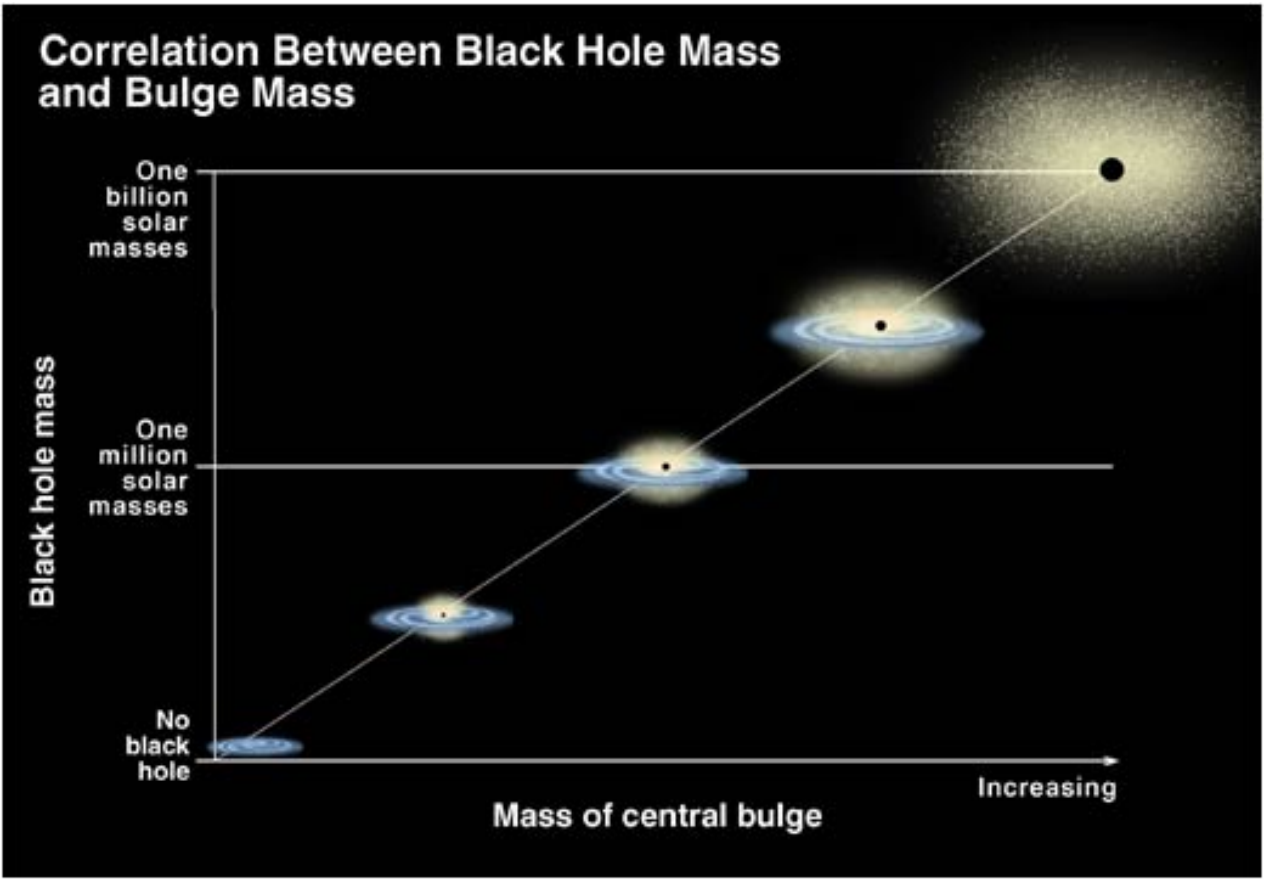
- We use **Megaparsecs** (=3 million light years) for distances to galaxies
- Look-back time= 3million year per 1megaparsec =1light year per year
- If Milky Way galaxy is 1ft diameter then Andromeda is 23 feet away

Superclusters



Supermassive Black Holes / Bulge

- A galaxy's bulge seems to be related to the size of its nuclear black hole so they must have formed together.
- Why is the black hole 0.15% of the mass of the bulge?

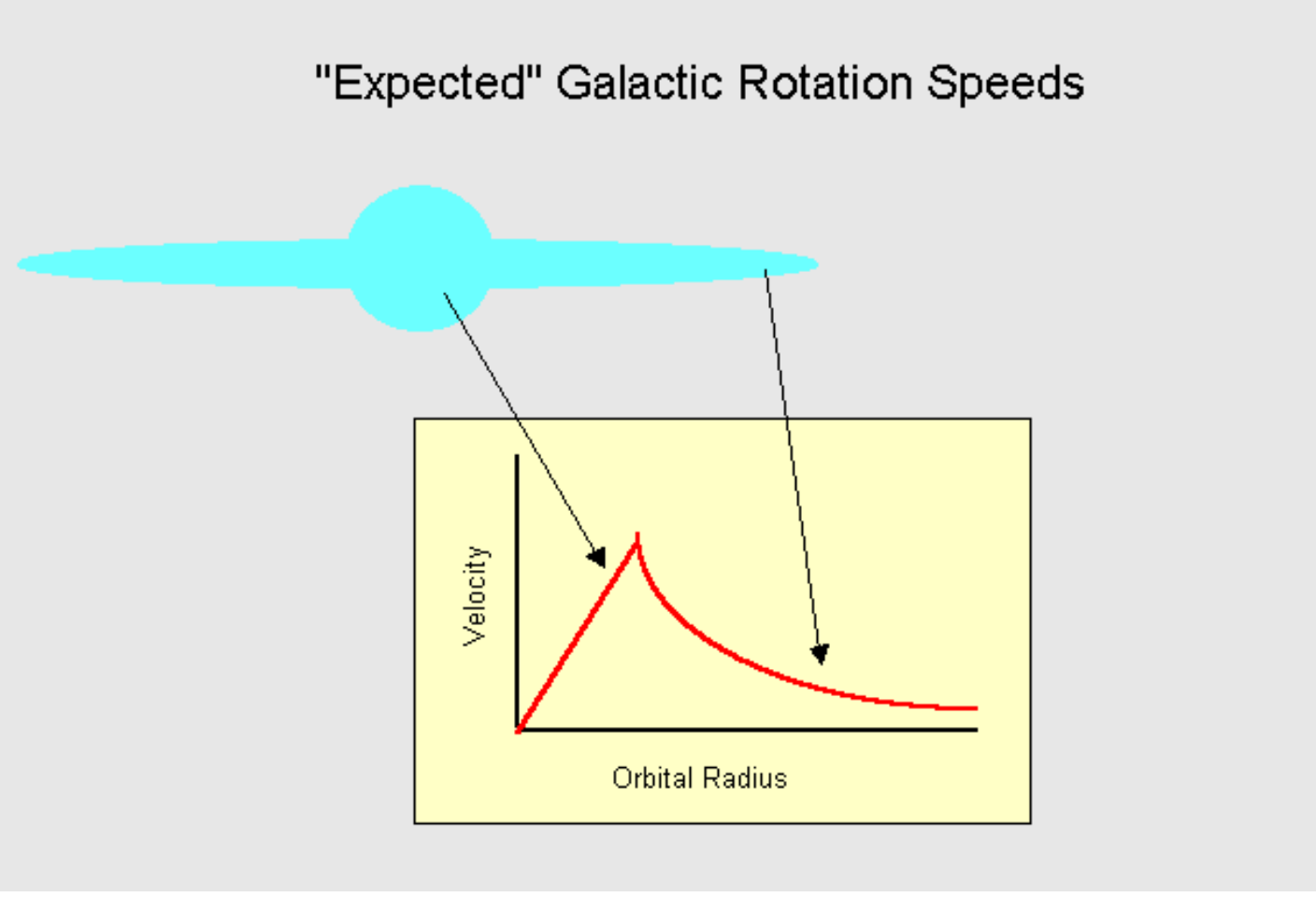


Supermassive Black Holes in Galaxies

- Zooming in on the center of NGC 1097 reveals a ring of dust and stars forming around a very bright black hole
- Red drawing of nucleus shows gas spiraling into central black hole emitting jet.

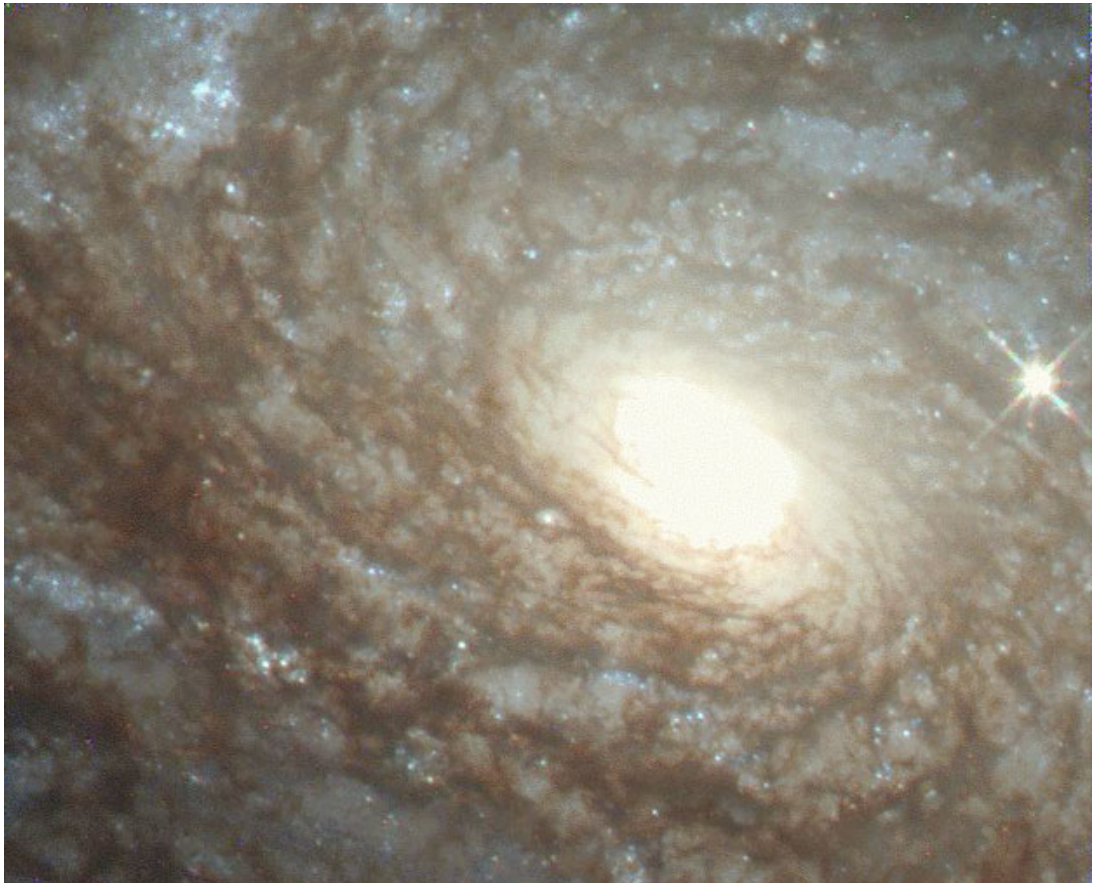
Galactic Mass from **Rotation Curve**

- Mass comes from Newton's/Kepler's Law $M = A^3 / P^2$
- Or can use velocity and radius
- Galaxy masses range from 50X Milky Way for Giant Ellipticals=10^{12}
- To a million solar masses for dwarf ellipticals/irregulars



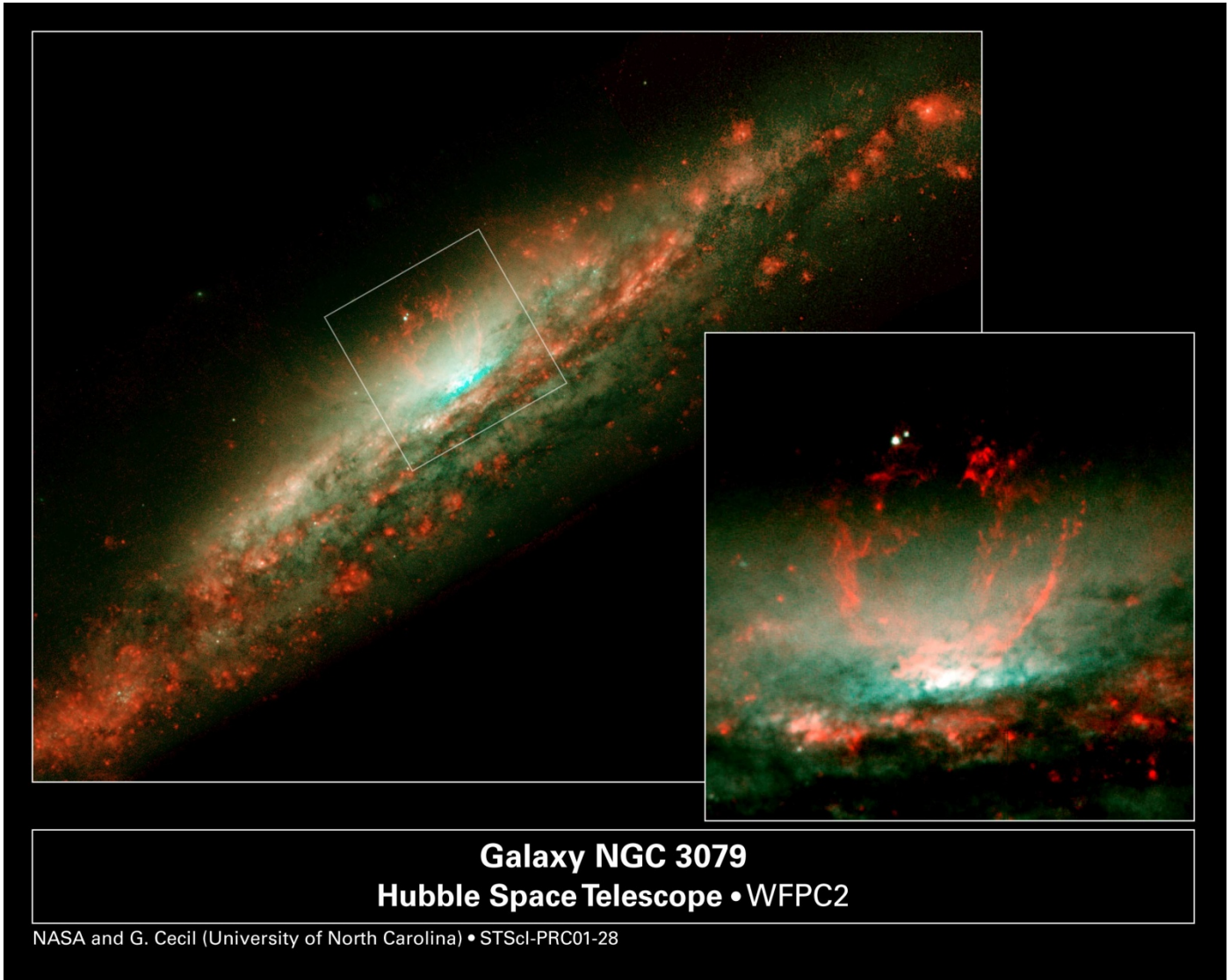
NGC 4414 – Flocculent Spiral

Relative to Milky Way	Diameter	Luminosity	Number
• Elliptical Galaxies	0.01-5	0.00005-5	38%
• Spirals	0.2-1.5	0.005-10	37%
• Irregulars	0.05-.25	0.00005-.1	25%



Dusty Irregular NGC 3079

- Irregular galaxies have lots of dust and vigorous ongoing star formation

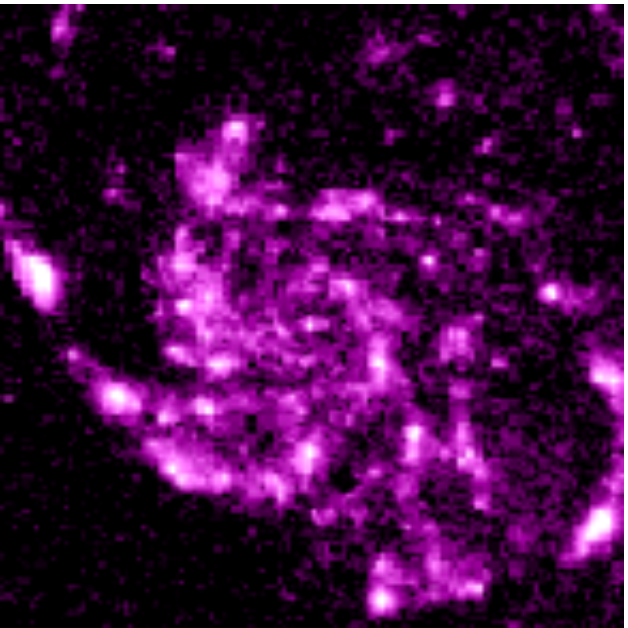


Barred Spiral Galaxy NGC 613

- Bar is formed by “instability” in disk
- Composed of stars, gas and dust

M101 Sc

- M101 in color
- M101 in UV young hot stars light up spiral arms
- In visible arms are blue in color from hot stars
- In IR old cool stars are dominant



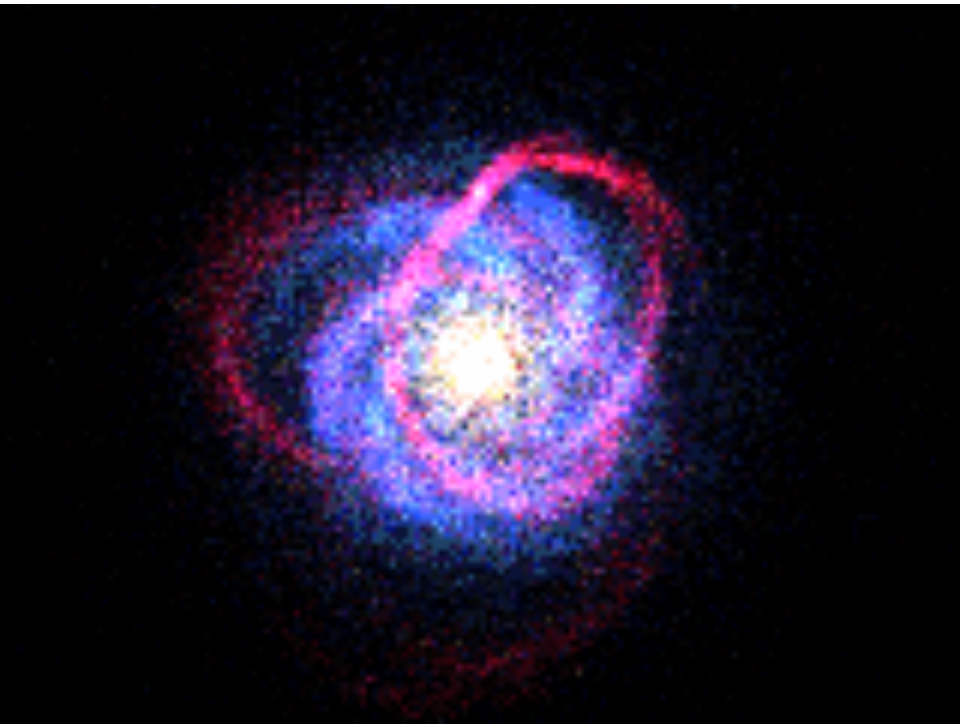
Sombrero Galaxy Sa in Visible & IR

- Visible light picture of M104 shows bulge and dust in disk
- IR picture superimposed on visible to show glowing dust in disk and that the bulge can be seen through disk

Local Group Members Maffei 1&2

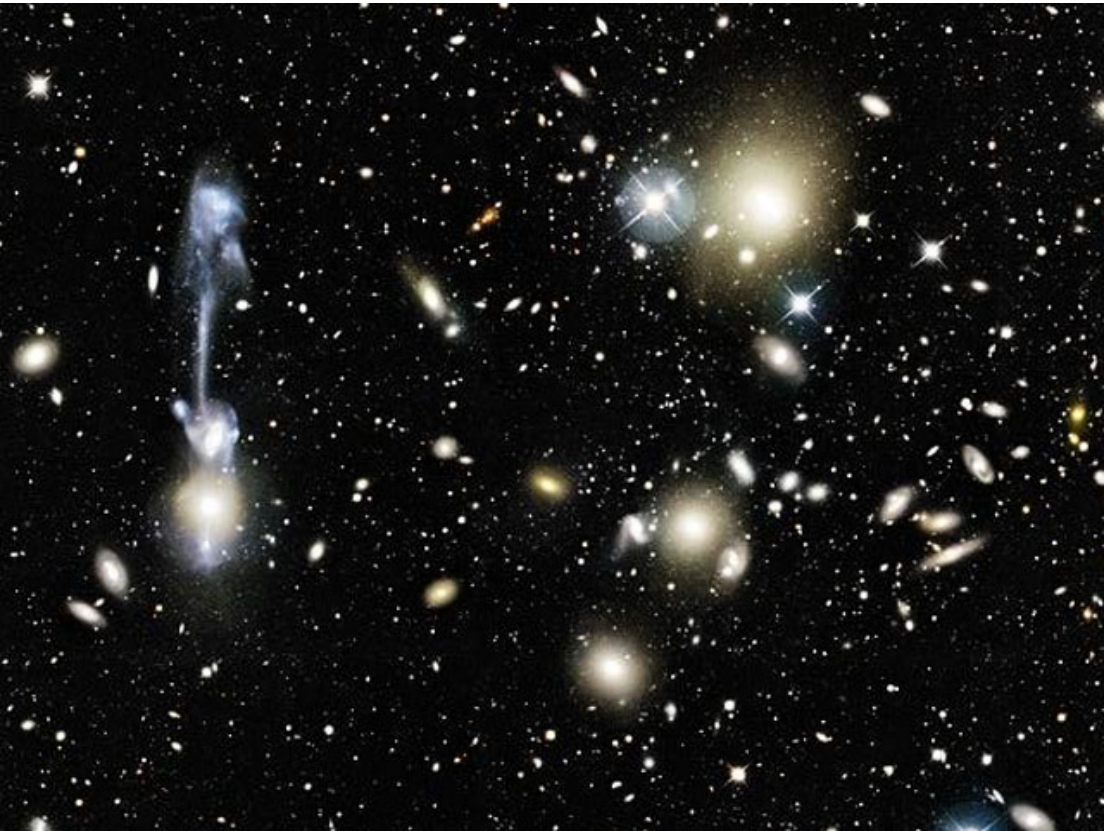
- Just launched WISE widefield IR camera
- Sees local group galaxies thru Milky Way
- Which had not been discovered until 1968

Canis Major Dwarf Merges with Milky Way



- 42,000 light years from center of Milky Way
- Mass is 1% of Milky Way Galaxy

Galactic Collisions in Abell 1185

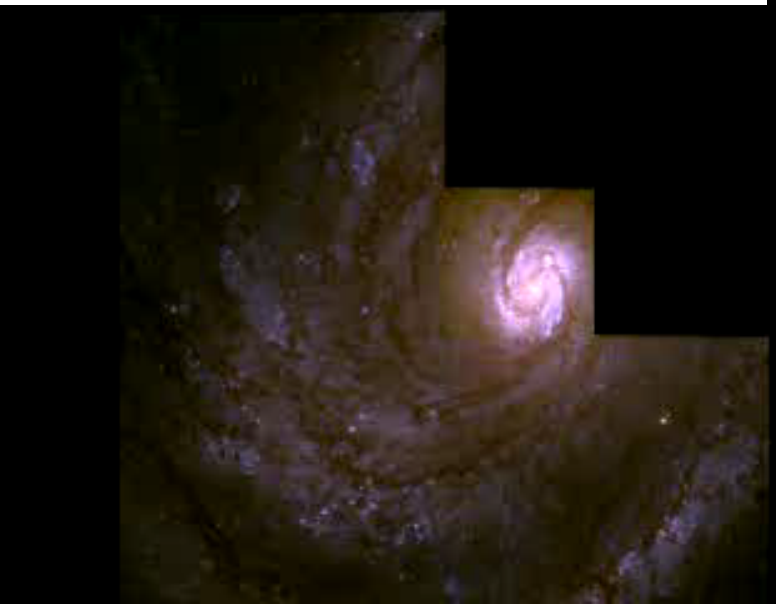


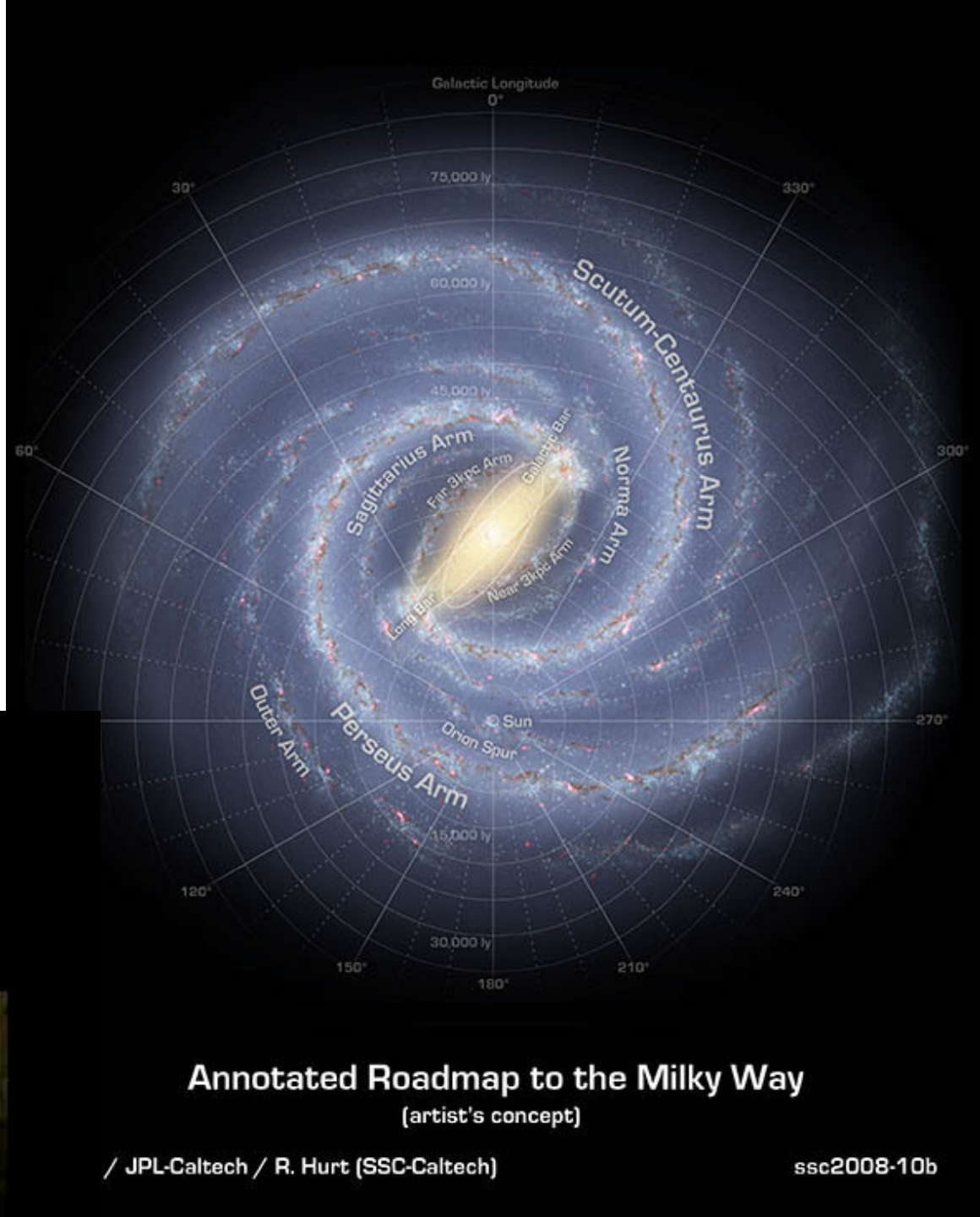
- Classified Galaxies into Elliptical, Spiral, Barred Spiral and Irregular
- Hubble Law
- Galaxy masses from rotation, cluster motions, X-ray gas, lenses = **Dark Matter**
- Clusters
- Mergers

Most distant galaxy cluster z=5.3

- 1.1 billion years
Big Bang

Milky Way




Galactic Longitude
0°
30°
330°
60°
300°
90°
270°
120°
240°
150°
210°
180°
75,000 ly
60,000 ly
45,000 ly
30,000 ly
15,000 ly
Scutum-Centaurus Arm
Norma Arm
Sagittarius Arm
Perseus Arm
Outer Arm
Far 3kpc Arm
Near 3kpc Arm
Galactic Bar
Long Bar
Sun
Orion Spur
Annotated Roadmap to the Milky Way
(artist's concept)
/ JPL-Caltech / R. Hurt (SSC-Caltech)
ssc2008-10b

Hubble Ultra Deep Field

- Look Back time ranges from Aldebaran 100light years to first galaxies 13Billion light years
- 100Billion galaxies

Galaxy Cluster Abell 1689

- Very distant rich cluster of galaxies