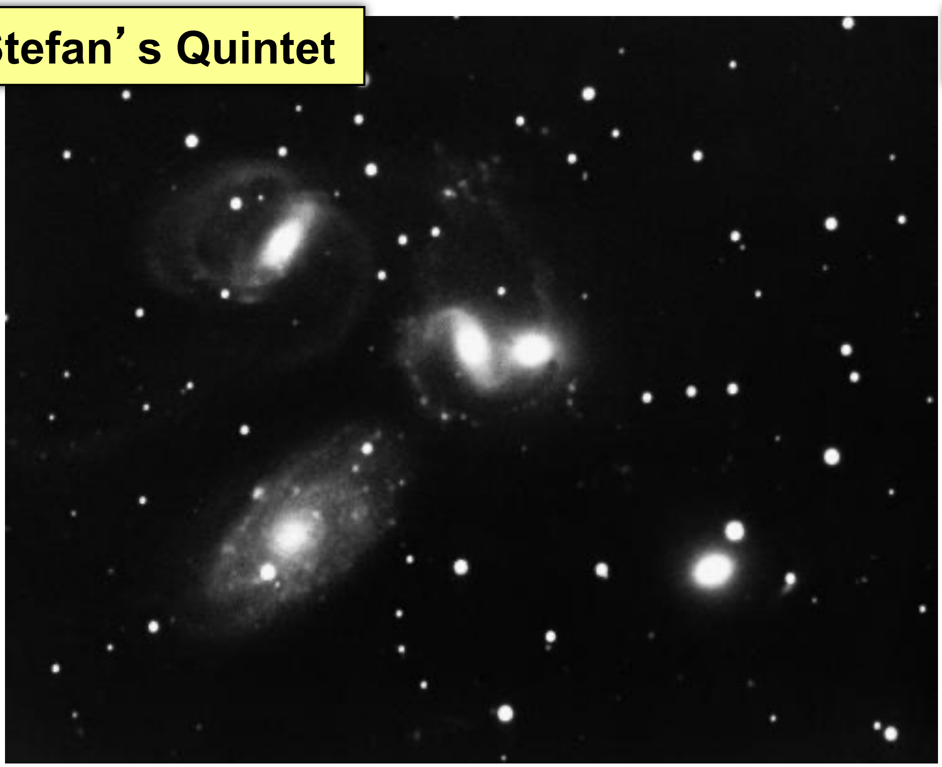
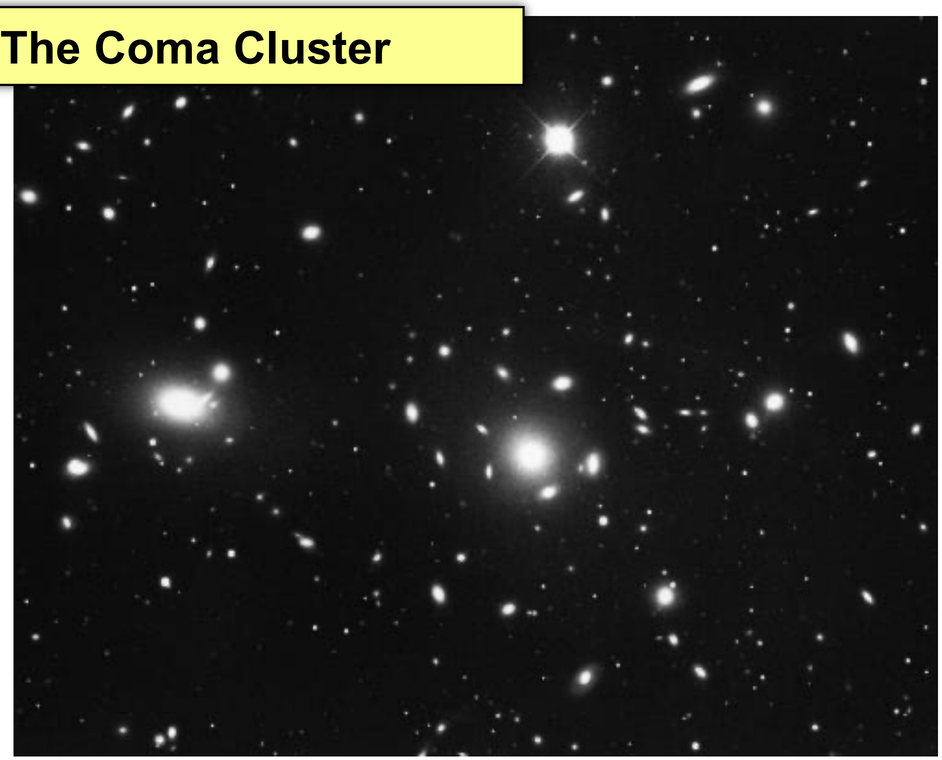
Clusters and groups

- Galaxies tend to form groups and clusters.



Stefan's Quintet



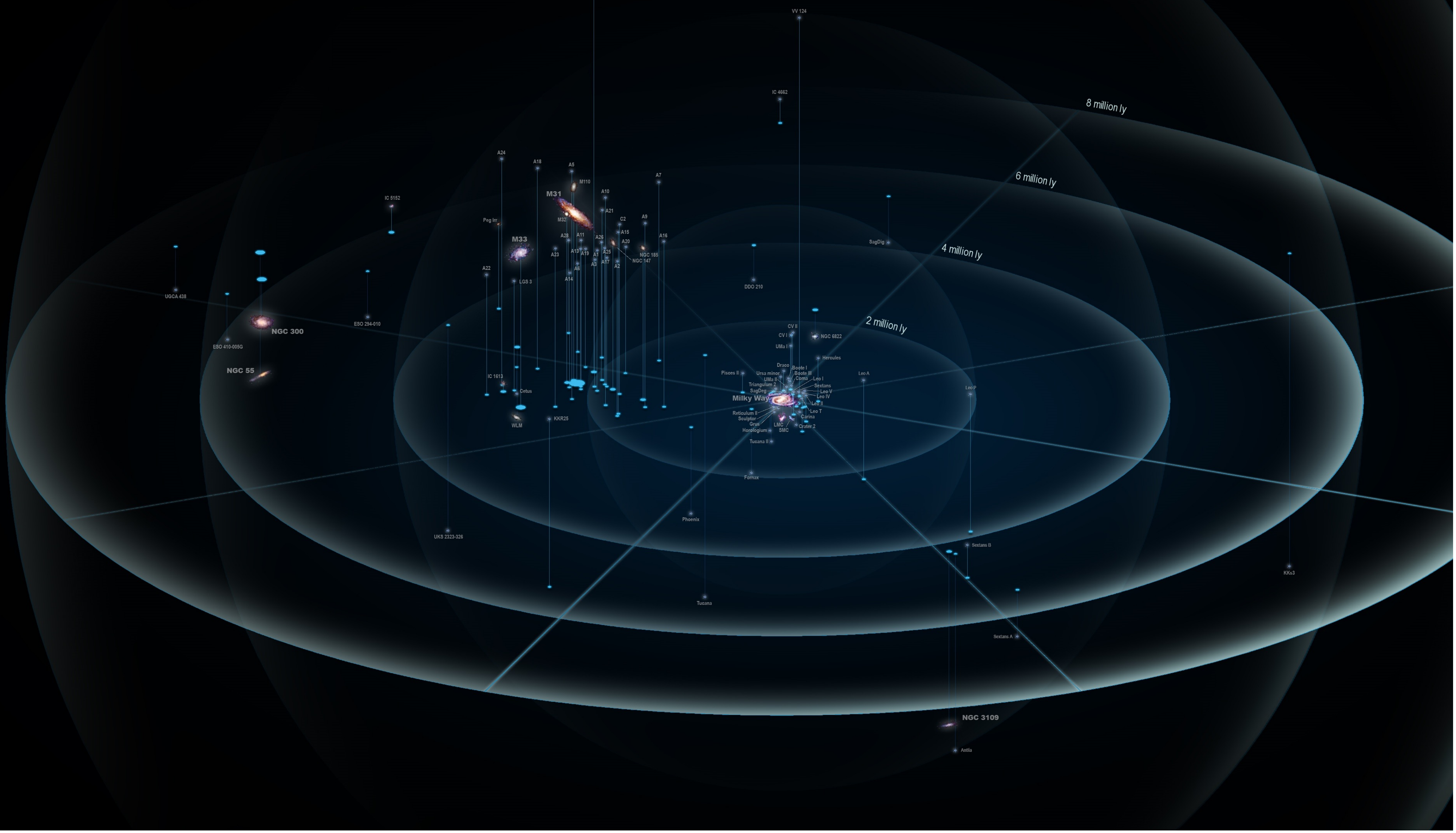
The Coma Cluster

Clusters and groups (cont.)

- Groups: 3 to 30 bright galaxies (also called *poor clusters*).
- Clusters: 30 to 300+ bright galaxies.
- Sizes: 1-10 Mpc across.
- Often contain many more dwarfs than bright galaxies.
- Total masses of 10^{12} to $>10^{15}$ $M_{\odot}$.
- About 3000 clusters have been cataloged to date.

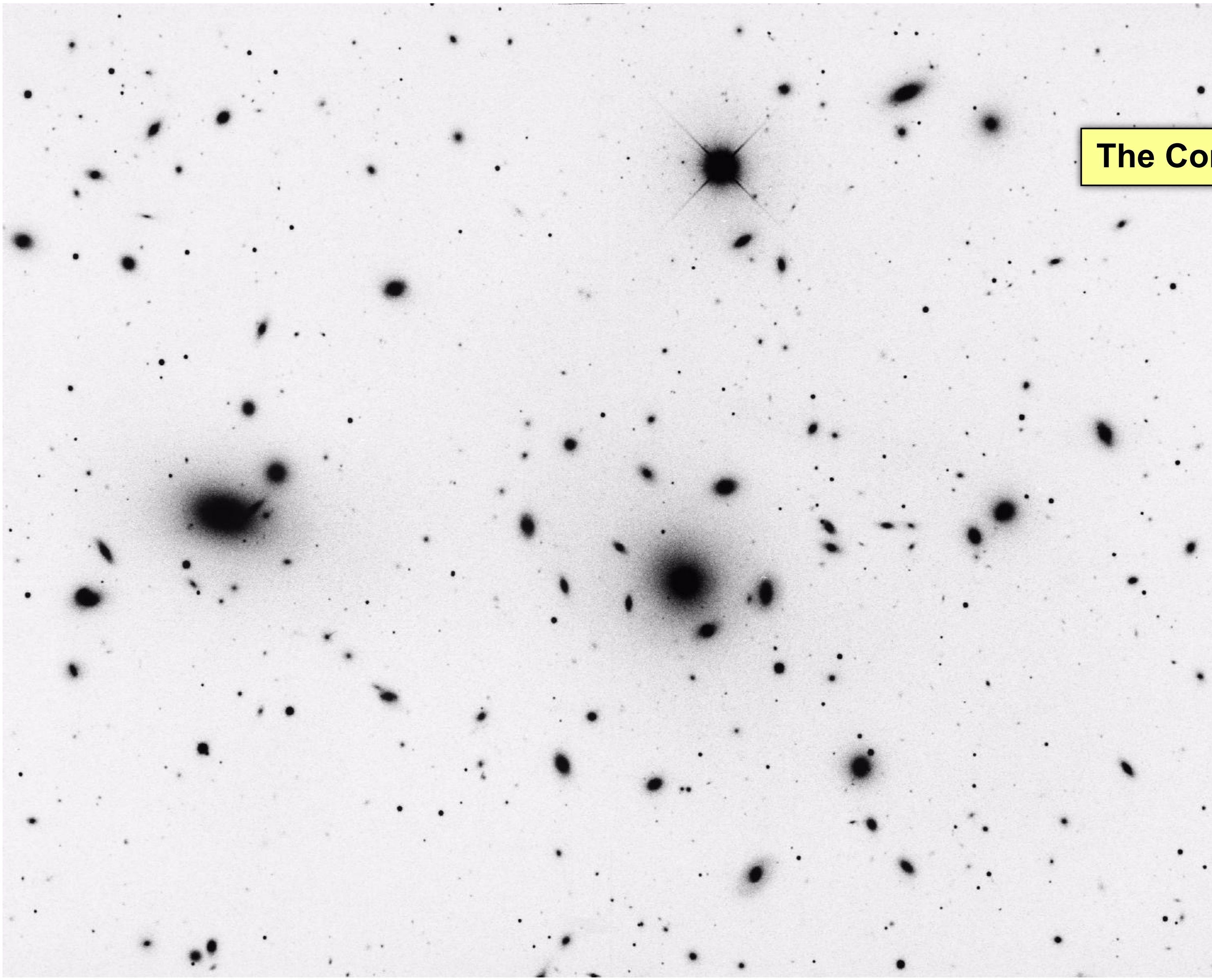
Local Group and nearest galaxies

- 2015 – 40 galaxies in the local group
- 2018 – 60+ galaxies in the local group
- 2023 – 80+ galaxies in the local group



Rich clusters

- 10^3-10^4 galaxies.
- Extend 10-50 Mpc, masses up to $10^{15}\ M_\odot$.
- The nearest are designated by the constellation that they lie in – Virgo, Coma Berenices, Perseus, Hercules, Hydra, Centaurus, etc.



The Coma cluster

Announcements

- HW7 is due on Thursday
- Selections for papers are now overdue

Galaxies II

Major Mergers

1. Two spiral galaxies on a collision course …

2. Gravitational forces throw out stars and gas along two extended tails. The length of the two tails reflects the rotation of the two initial galaxies.

3. The stars in the tail fade away, but gas in the tails falls back into the galaxies to form stars.

4. The disks are destroyed via violent relaxation. Central black holes will merge

1. The end product is an elliptical galaxy.

Minor mergers

- Minor mergers have mass ratios $< 1/4$
- The disk of the larger galaxy will NOT be destroyed, but it will show distortions such as warps, ripples, arcs and tails.
- The smaller galaxy may be tidally ripped apart by the interaction and its constituents (stars, gas, dust) scattered as debris within the larger galaxy, or as tails.

NGC1316

Elliptical galaxy which recently has cannibalized smaller spiral galaxies (1/10-1/100 of its mass). It has acquired lots of gas and dust.

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.

M82

Starbursts

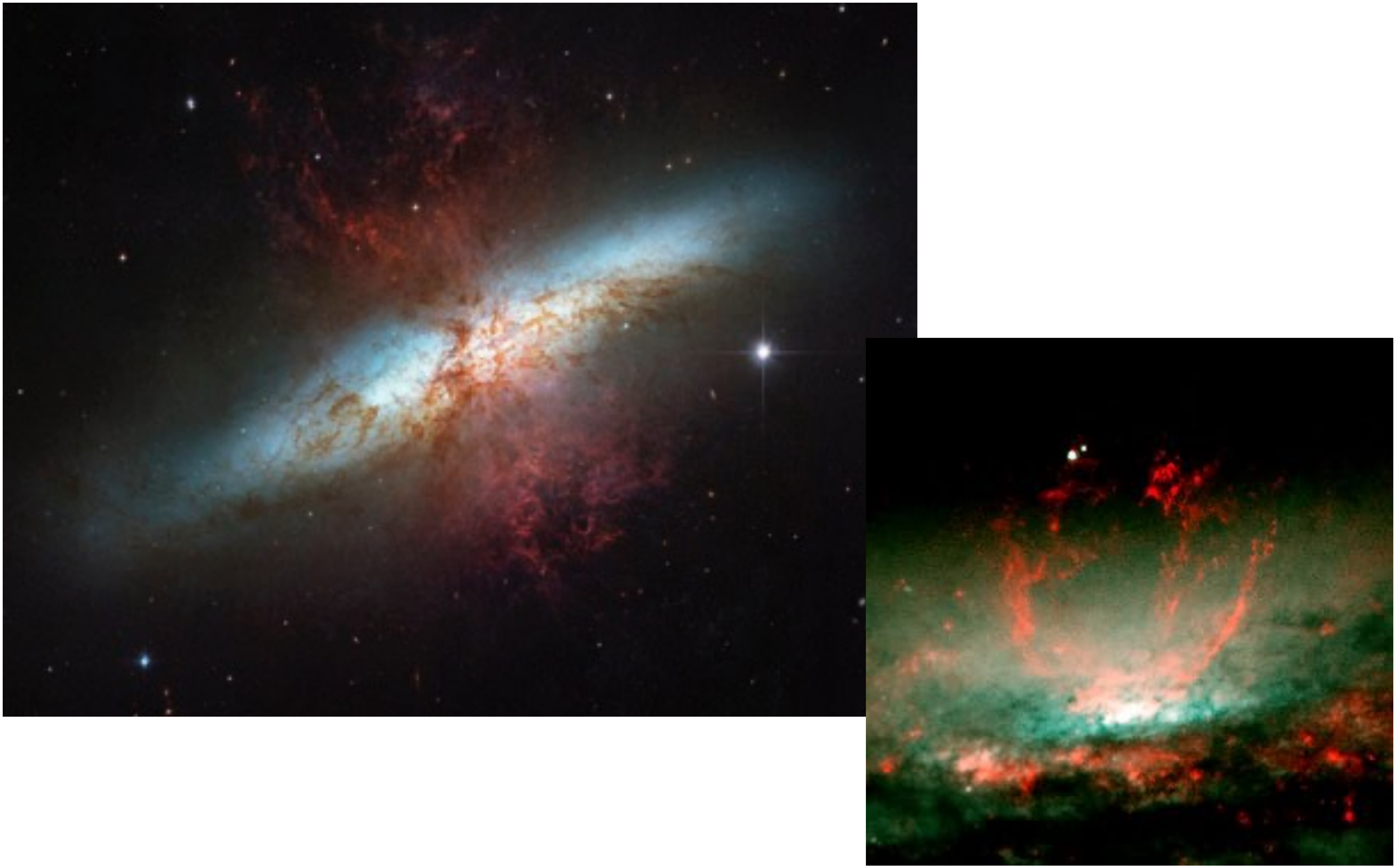
- Interacting galaxies tend to be bluer, with high far-IR luminosities due to triggered star formation.
  - Both direct mergers and more indirect interactions can trigger star formation

- Caused by gas agglomerating, causing shocks triggering collapse
  - Starbursts often occur at galaxy center, due to gas cloud orbits being disrupted by encounter.
  - Example M82 a few $M_{\odot}$/yr in a nuclear area of 100 pc (similar to a large spiral!)

- May last 20Myrs (theoretically 10^8-10^9 yrs). Why so short?

- We observe *ultra luminous infrared galaxies (ULIRGS)* which have very high star formation rates (100-1000 x MW value)

In some starbursts, supernova rate so high that the exploded gas combines to form outflow from disk.



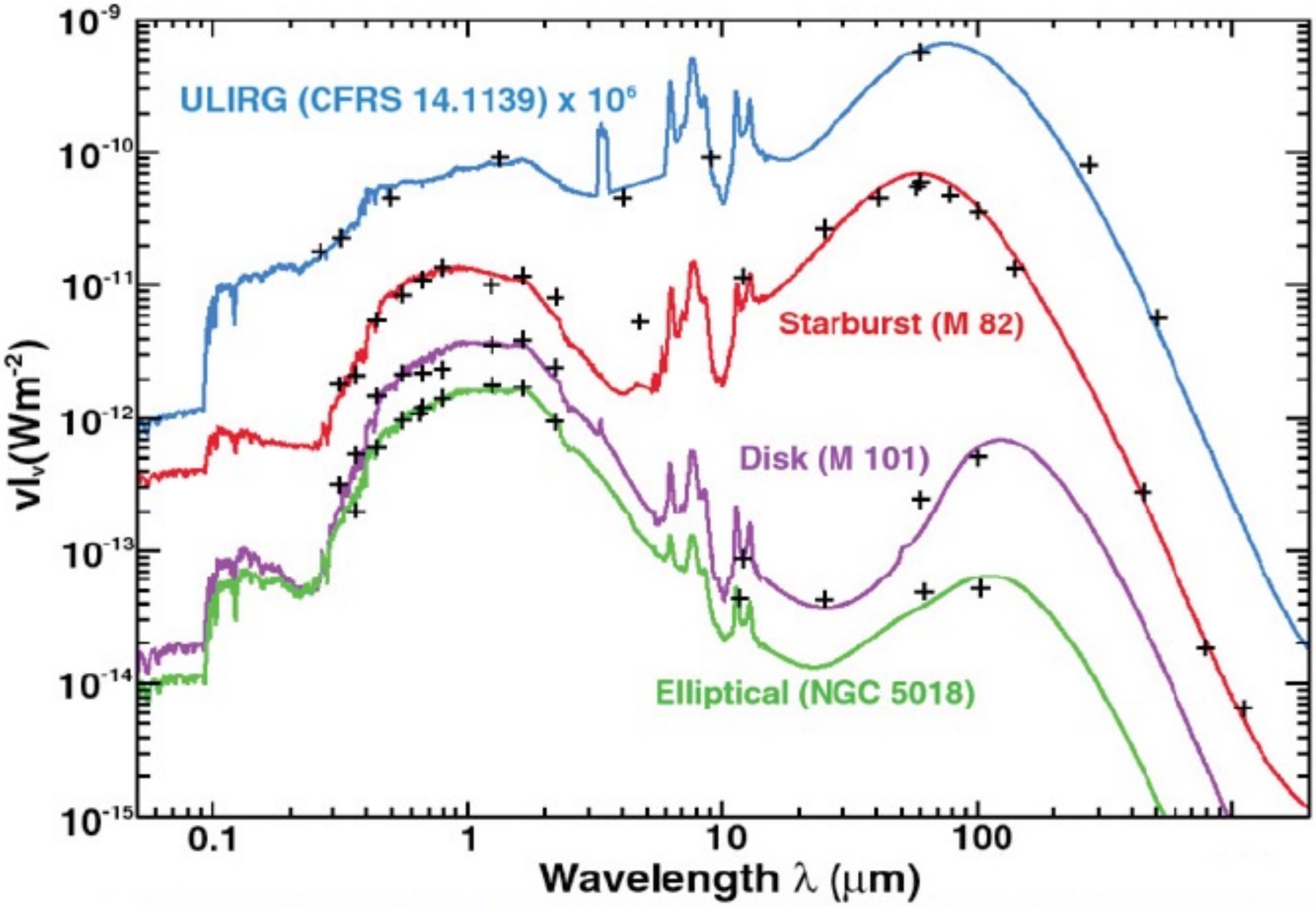
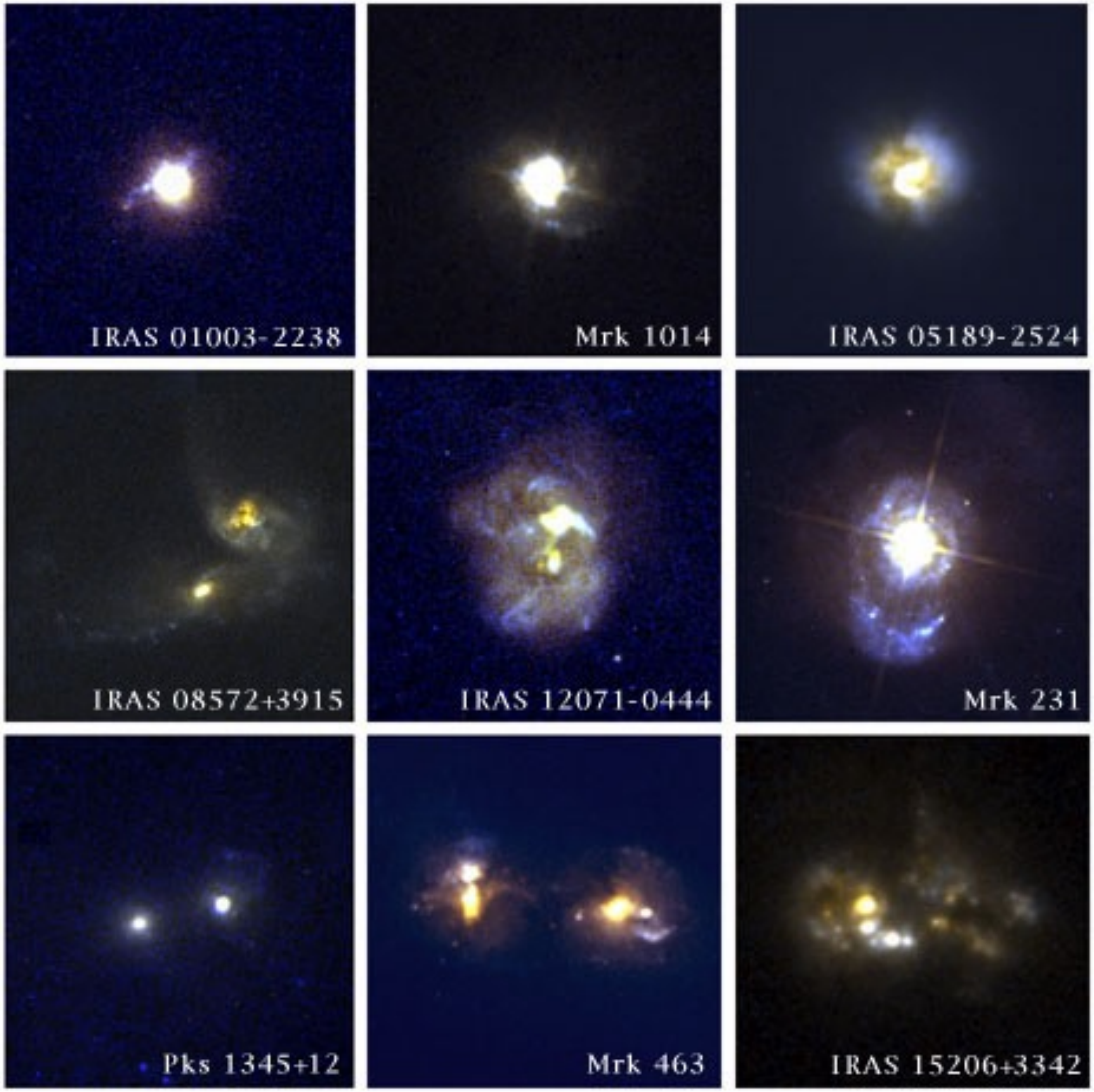


Fig 7.7 (P. Chanial, G. Lagache) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Ultra Luminous Infrared Galaxies (ULIRGs)



Jason Ware

Is the Milky Way interacting?

- MW belongs to the Local Group
  - ~80 galaxies bound by gravity
  - 3 spirals, 4 ellipticals, 12 irregular, many dwarfs

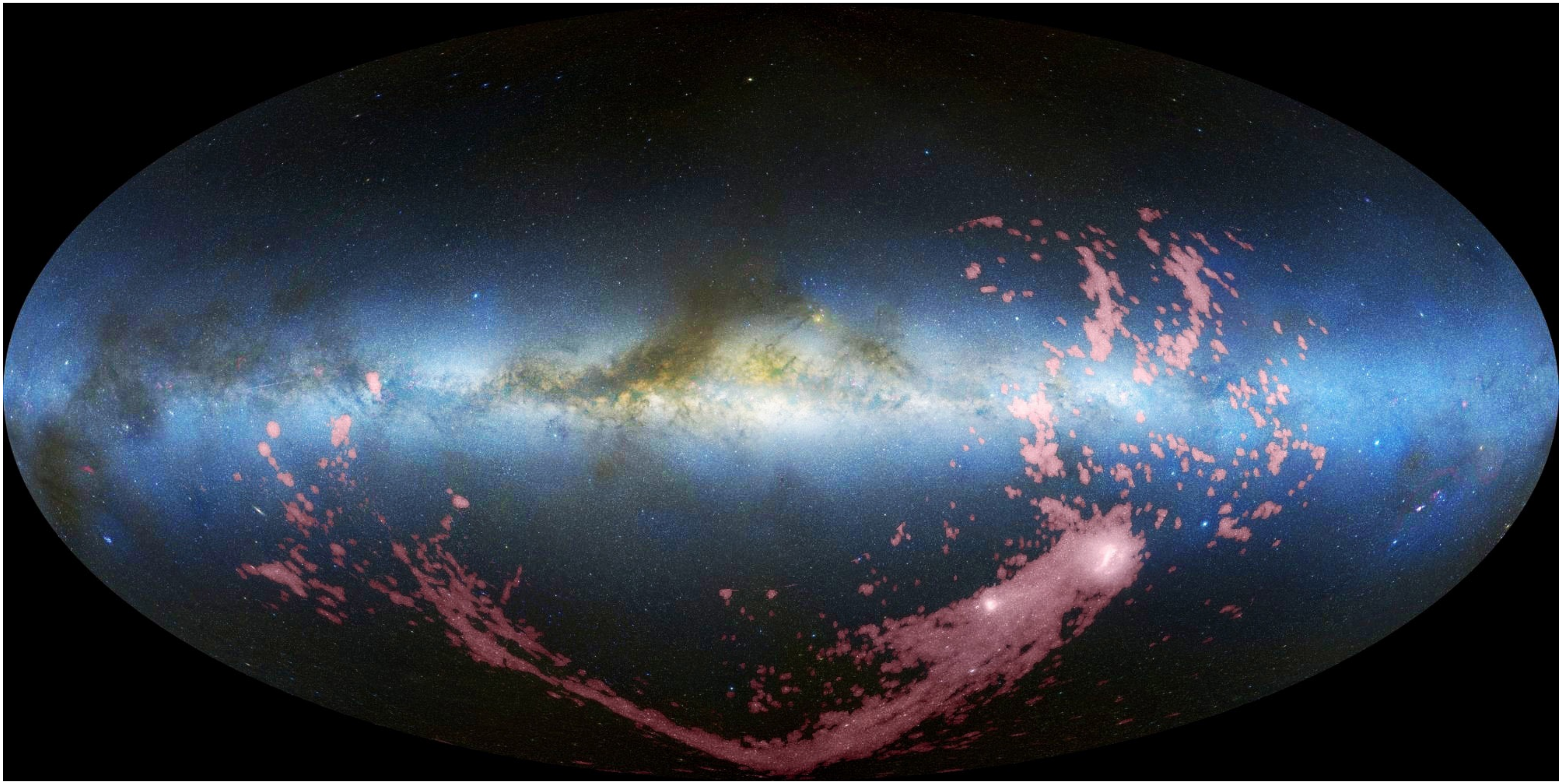
- Almost 90% of bolometric output from the spirals MW, M31, M33

- Neighbors to MW are LMC, SMC and Sagittarius Dwarf
  - 49kpc, 58kpc and 24kpc distance respectively

- The MW is currently interacting with all these, cannibalizing Sagittarius Dwarf, making the *Magellanic Bridge* of HI to the SMC and LMC.

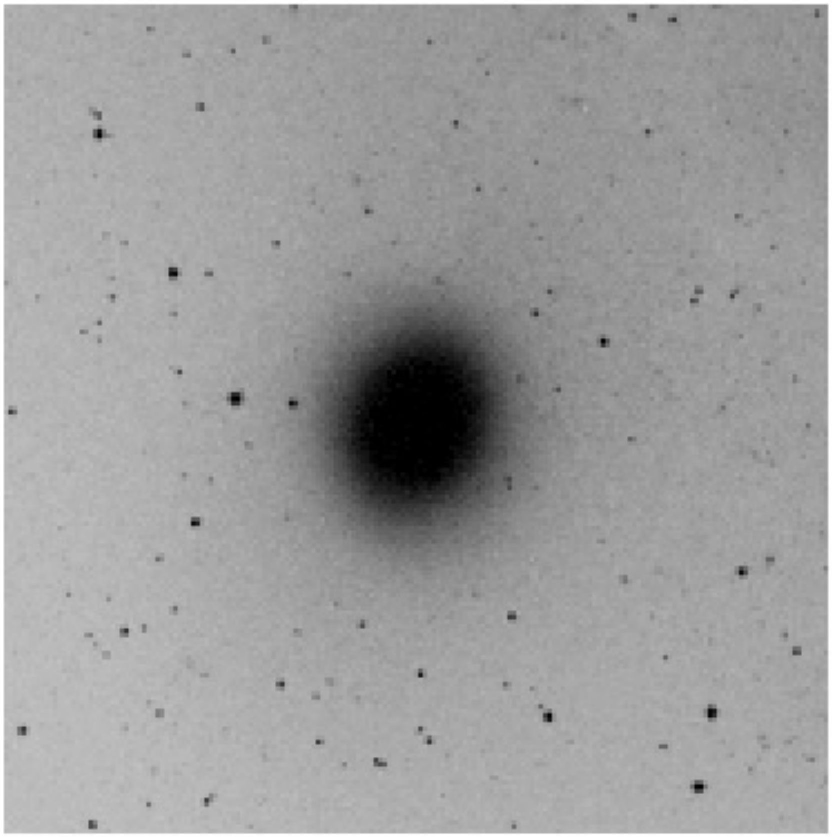
- It also has a warp in the disk, implying a past interaction.

Magellanic Stream

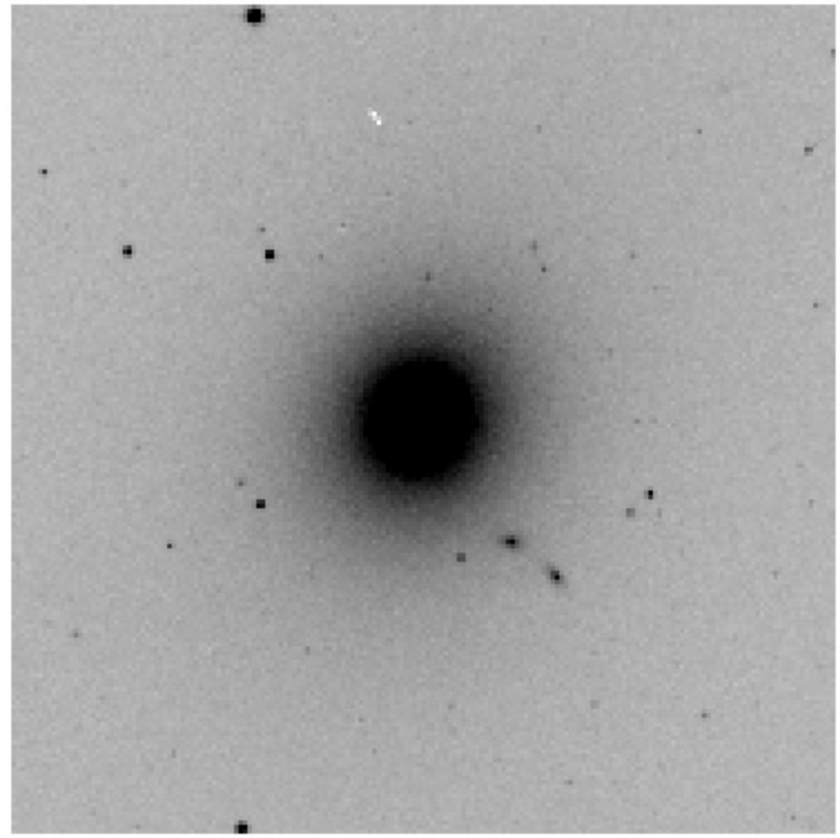


Huge Range in Elliptical galaxy luminosity

M32

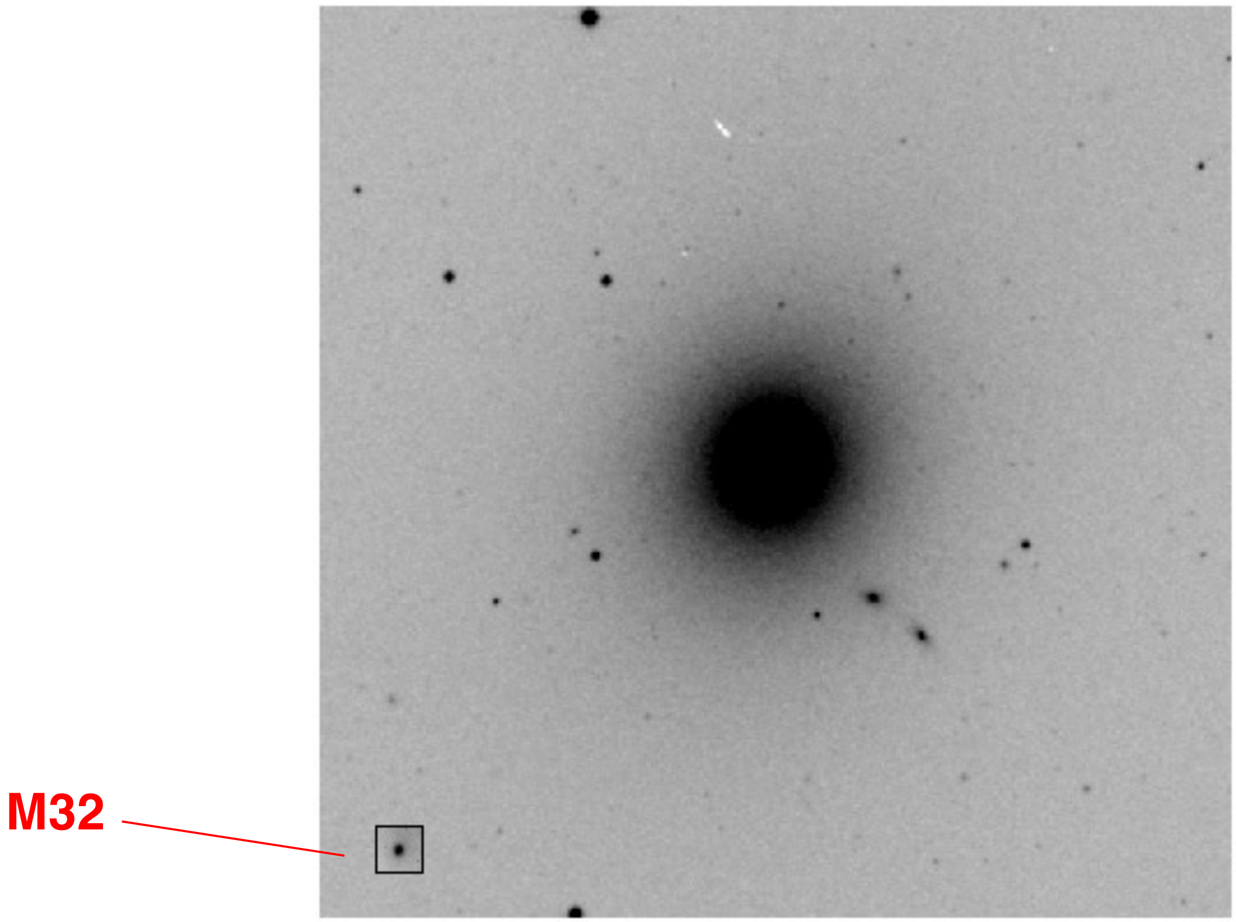


M87



M32 and M87 side by side as they appear in the sky. Both images are 10’ x 10’

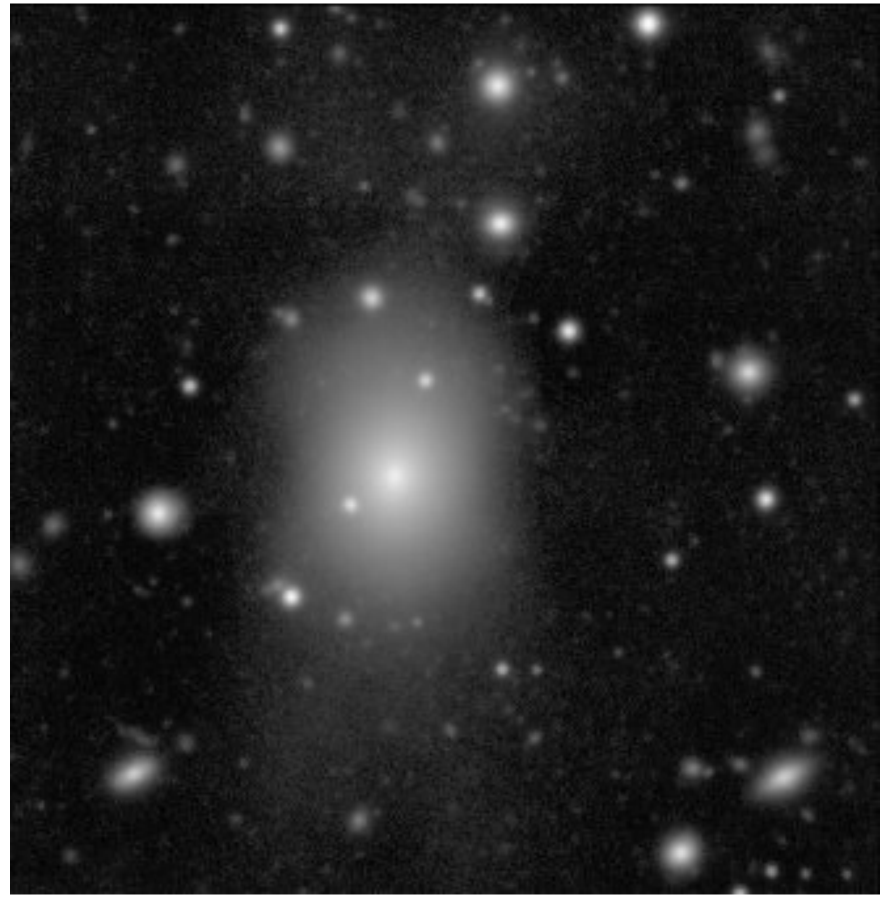
Huge Range in Elliptical galaxy luminosity



M32 and M87 with M32 scaled to appear as it would at the distance of M87.

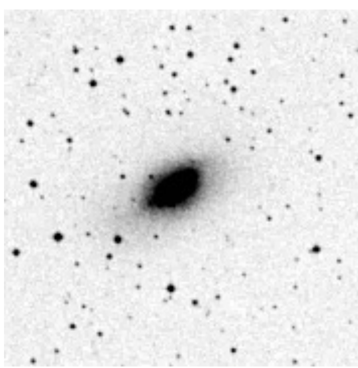
cD galaxies

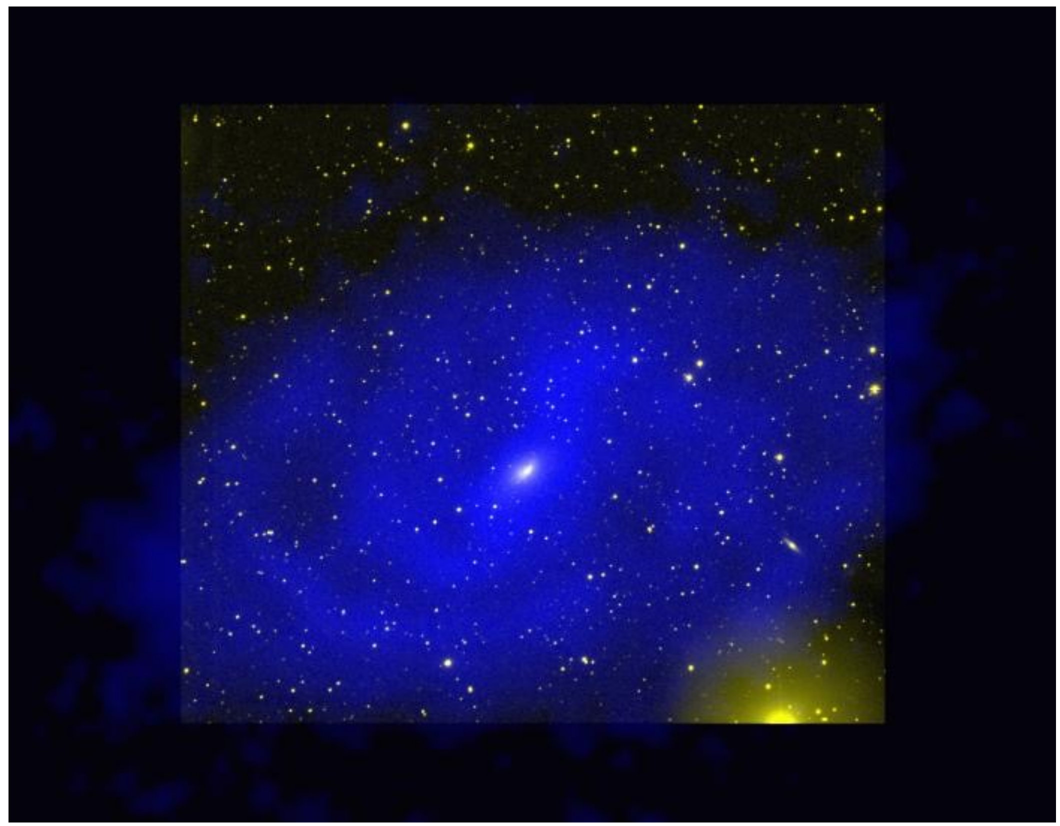
- largest and brightest
  - up to 1 Mpc across
  - 10^{13}-10^{14} $M_{\odot}$
- High surface brightness core
- Extended, diffuse envelopes (including X-ray halo)
- Large amounts of globular clusters
- High mass-to-light ratio
- Located at cores of galaxy clusters



Blue Compact Dwarf galaxies (BCDs)

- Small galaxies which are unusually blue
- Vigorous starformation, plenty of gas
- Low mass-to-light ratios
- $\sim 10^9 M_\odot$
- $<$ 3 kpc diameters





Measuring E Galaxy Masses

- Gravitational Lensing
- Virial Theorem

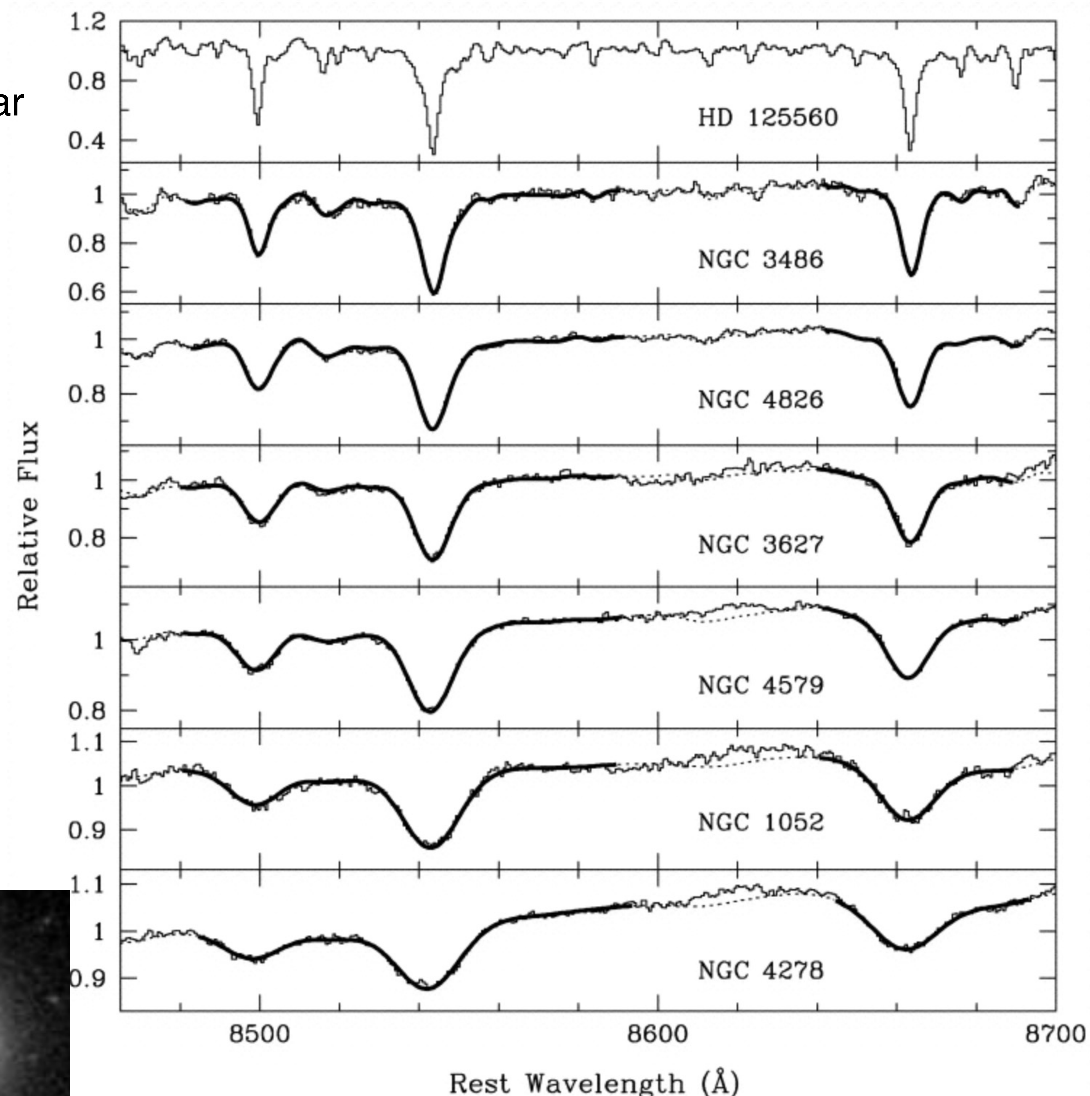
K.E. = P.E./2

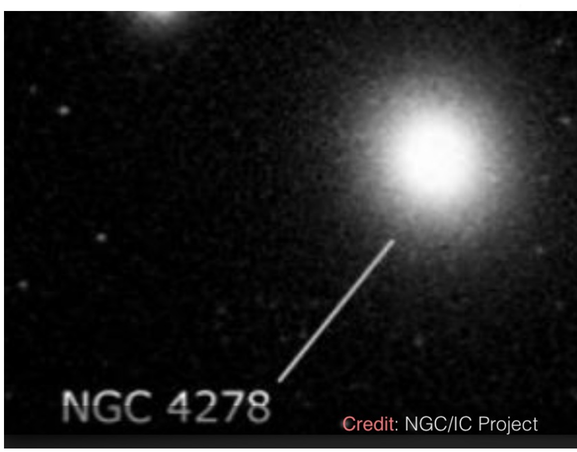
$mv^2/2 = GMm/2R$

$v^2 = GM/R$

$M = v^2R/G$

star





V = 261 +/- 8 km/s

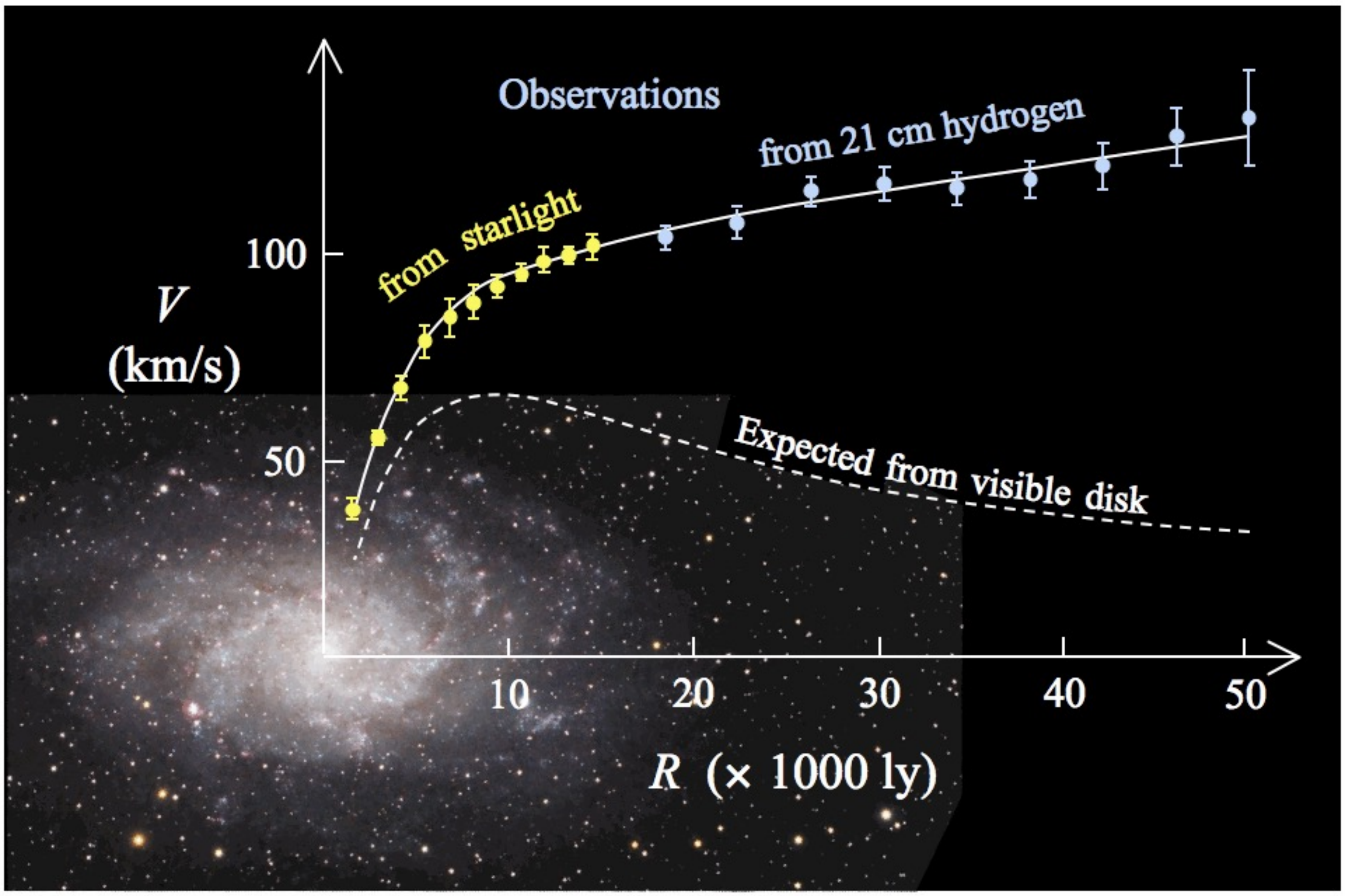
R = 8 kpc

M = 1.2 x 10^{11} M_sun

Barth et al. 2002

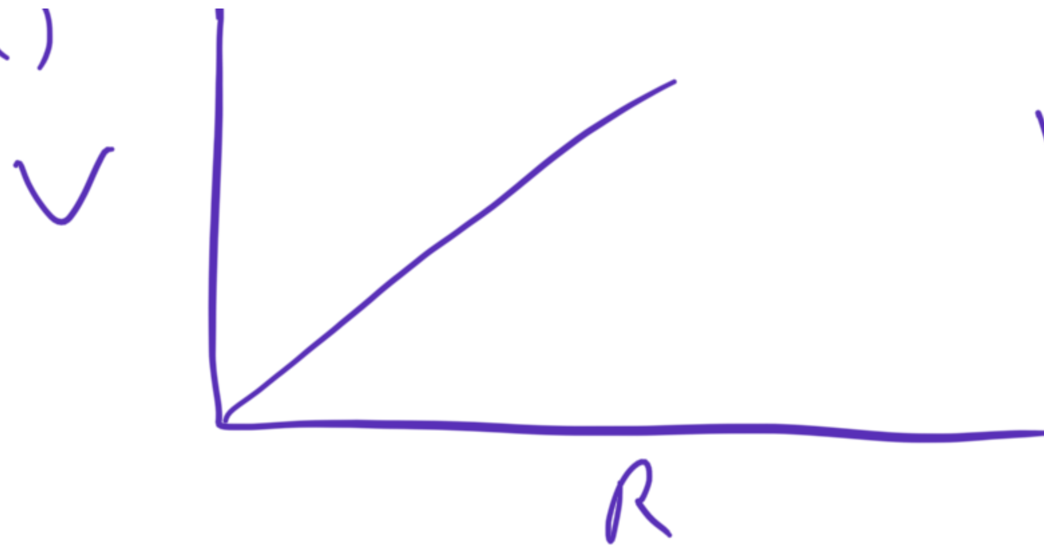
Worksheet #12

Draw a rotation curve for a spiral galaxy assuming (a) solid body rotation, (b) Keplerian rotation with all the mass at the center. (c) Now look at the rotation curve for the galaxy M33 below and estimate the total mass of the galaxy. 1 ly = 9.4 x 10^15 m



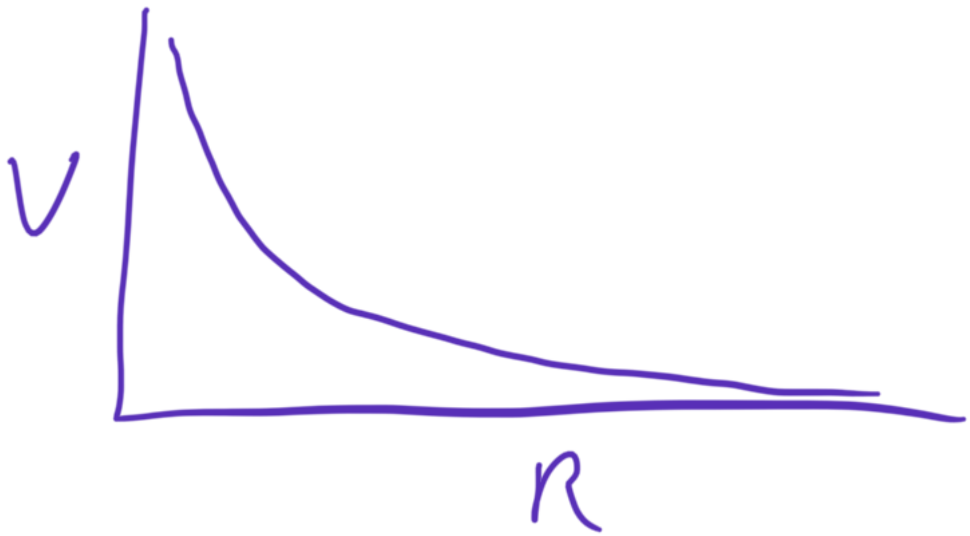
Worksheet #12 Solution

a)



$V \propto R$

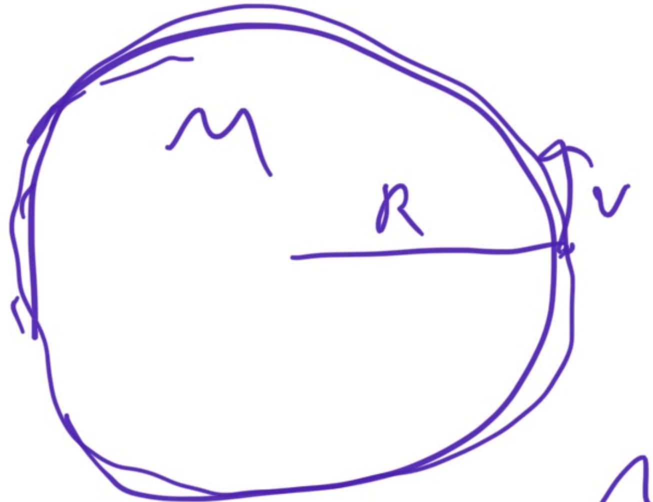
b)



$V \propto \frac{1}{R^{1/2}}$

Worksheet #12 Solution

c)



$$\frac{GMm}{R^2} = \frac{mv^2}{R}$$

$$M = \frac{Rv^2}{G}$$

$$M = \frac{50{,}000\,\text{ly}\,(125\,\text{km/s})^2}{6.67\times10^{-11}\,\text{N m}^2\,\text{kg}^{-2}}$$

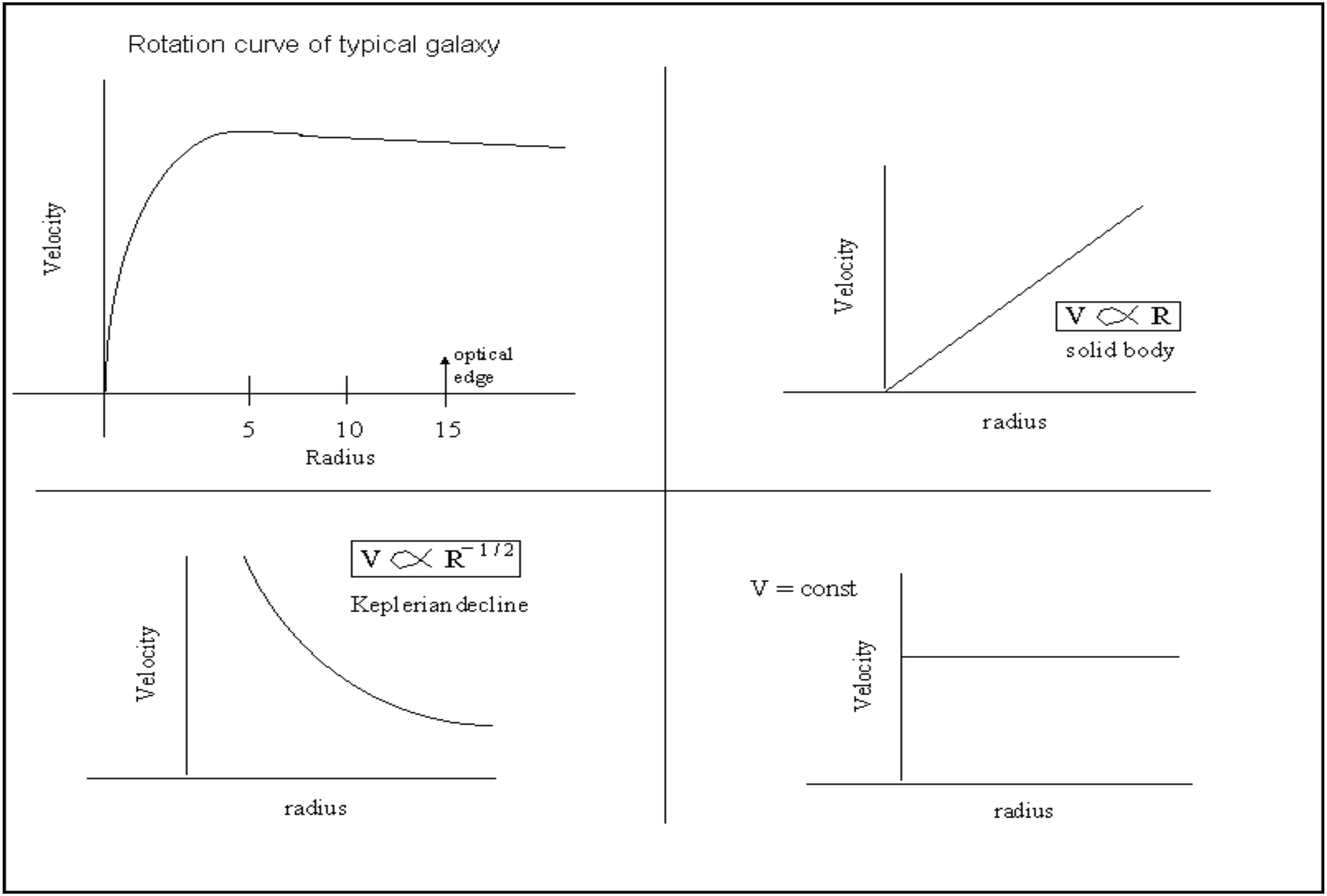
$$= \frac{50{,}000\,\text{l.y} \cdot \frac{9.4\times10^{15}\,\text{m}}{1\,\text{ly}} \cdot (125{,}000\,\text{m/s})^2}{6.67\times10^{-11}\,\text{N m}^2\,\text{kg}^{-2}}$$

$$= 1.1\times10^{41}\,\text{kg}$$

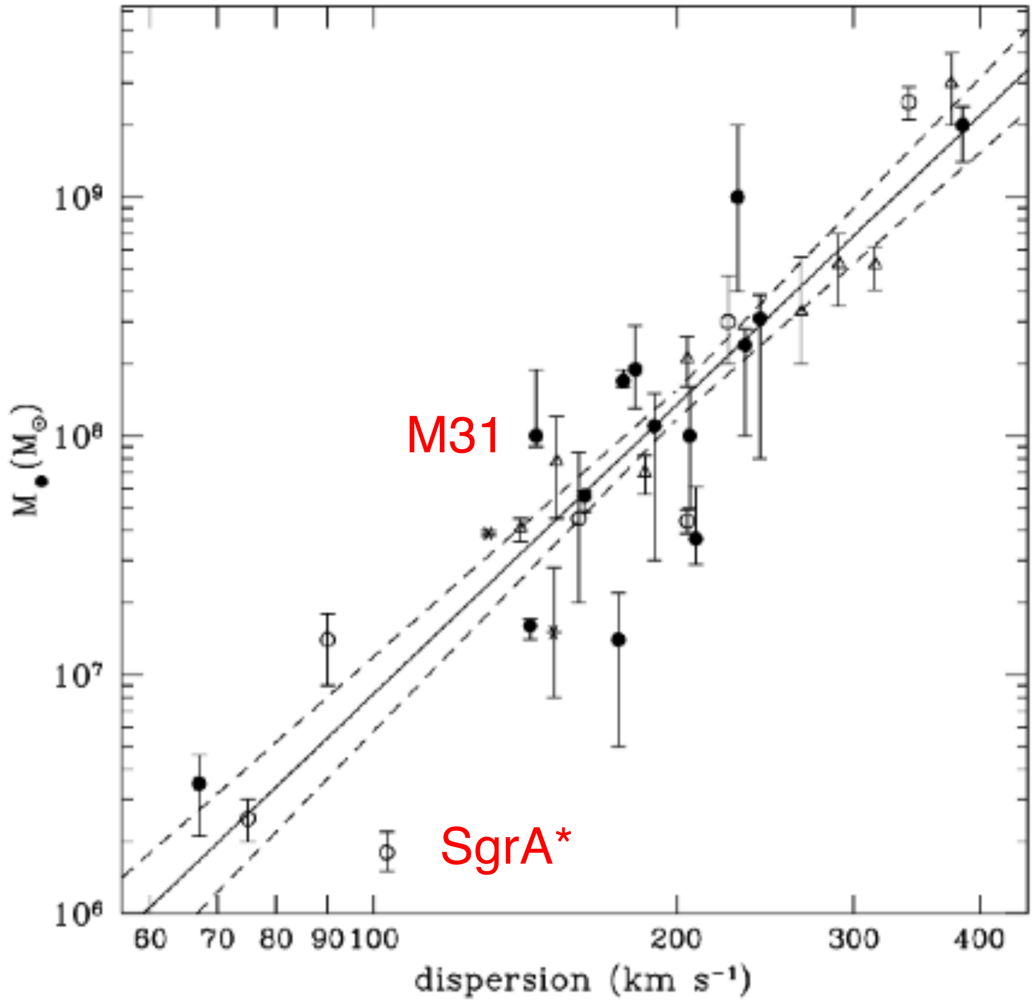
$$= 5.5\times10^{10}\,M_\odot$$

55 billion $M_\odot$

Spiral Galaxy Rotation Curves



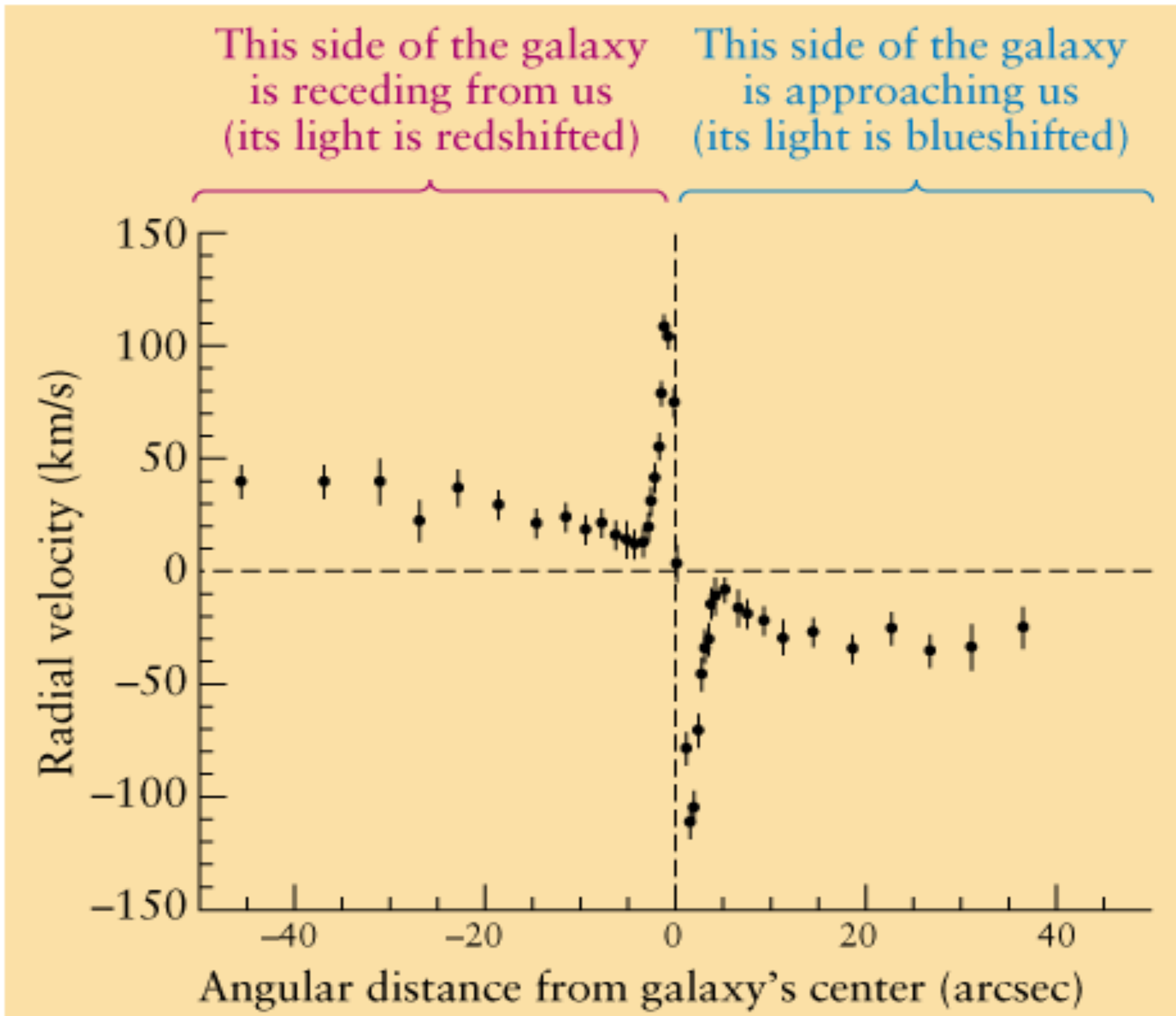
Supermassive black holes (M-sigma relation)



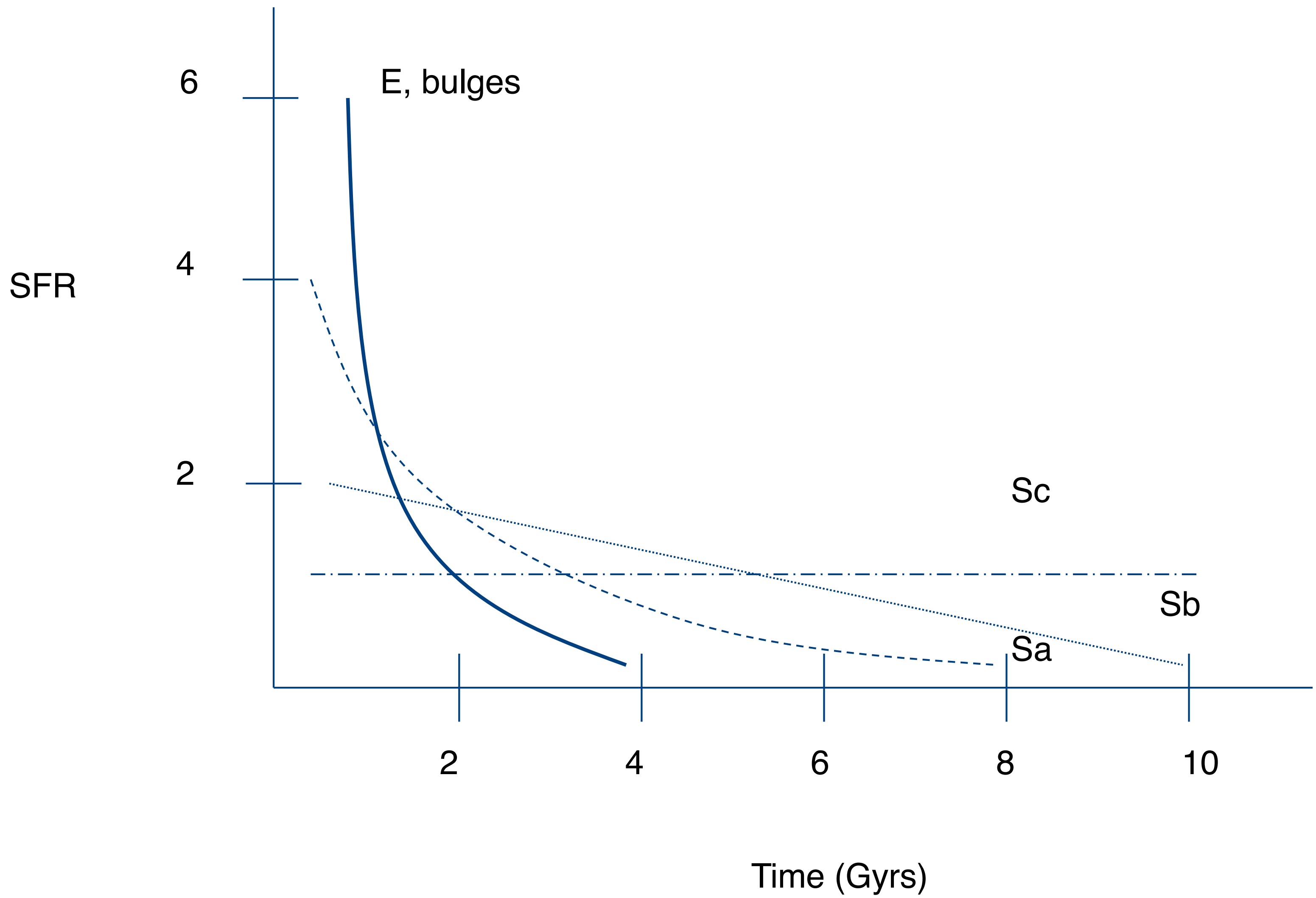
Correlation between black hole mass and velocity of bulge components. Indicates formation of galaxy is linked to formation of supermassive black hole.


M31 Nucleus
Hubble Space Telescope • ACS/HRC
HST ACS/HRC
WIYN/KPNO 0.9m Mosaic I
NASA, ESA, and T. Lauer (NOAO)
STScI-PRC12-04a

Modern observations that “prove” the existence of the supermassive black holes – high speed of stars near core of M31.



Schematic star formation histories:



SFR vs Hubble type

E	~ 0	$M_\odot\ yr^{-1}$
S0	≤ 0.004	$M_\odot\ yr^{-1}$
Sa	~ 0.3	$M_\odot\ yr^{-1}$
Sb	~ 3	$M_\odot\ yr^{-1}$
Sc	~ 5	$M_\odot\ yr^{-1}$
Sd-Im	~ 1	$M_\odot\ yr^{-1}$ (smaller galaxies)

There are large variations, huge range, often in bursts.

Note: spread within a Hubble type > difference between types.

Tracers of current star formation

1. Luminosity of Hα emission (what kinds of stars responsible?). Must assume IMF to get total star formation rate (SFR).

$$\mathrm{SFR}(M_{\odot}/\mathrm{yr}) = 8\times10^{-42}\, L_{H\alpha}\ (\mathrm{erg/s})$$

2. Far infrared emission (FIR) from dust heated by starlight. Wavelength 10-1000μm (near IR is mostly starlight). Requires satellite observations.

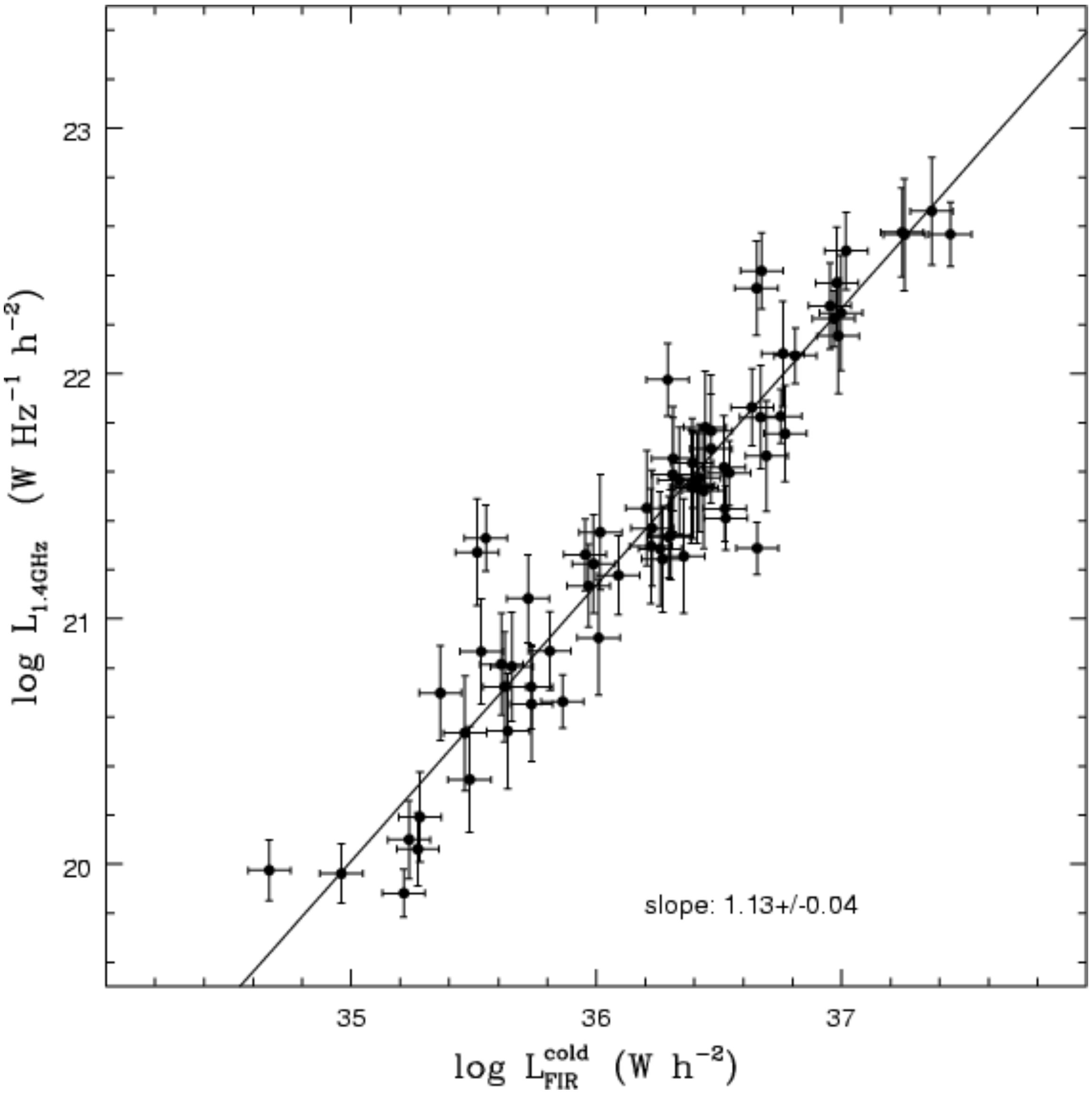
3. Far UV light (~2000Å). UV dominated by short-lived stars with <10^8 yr lifetimes.

$$\mathrm{SFR}(M_{\odot}/\mathrm{yr}) = 1.5\times10^{-43}\, L_{UV}\ (\mathrm{erg/s})$$

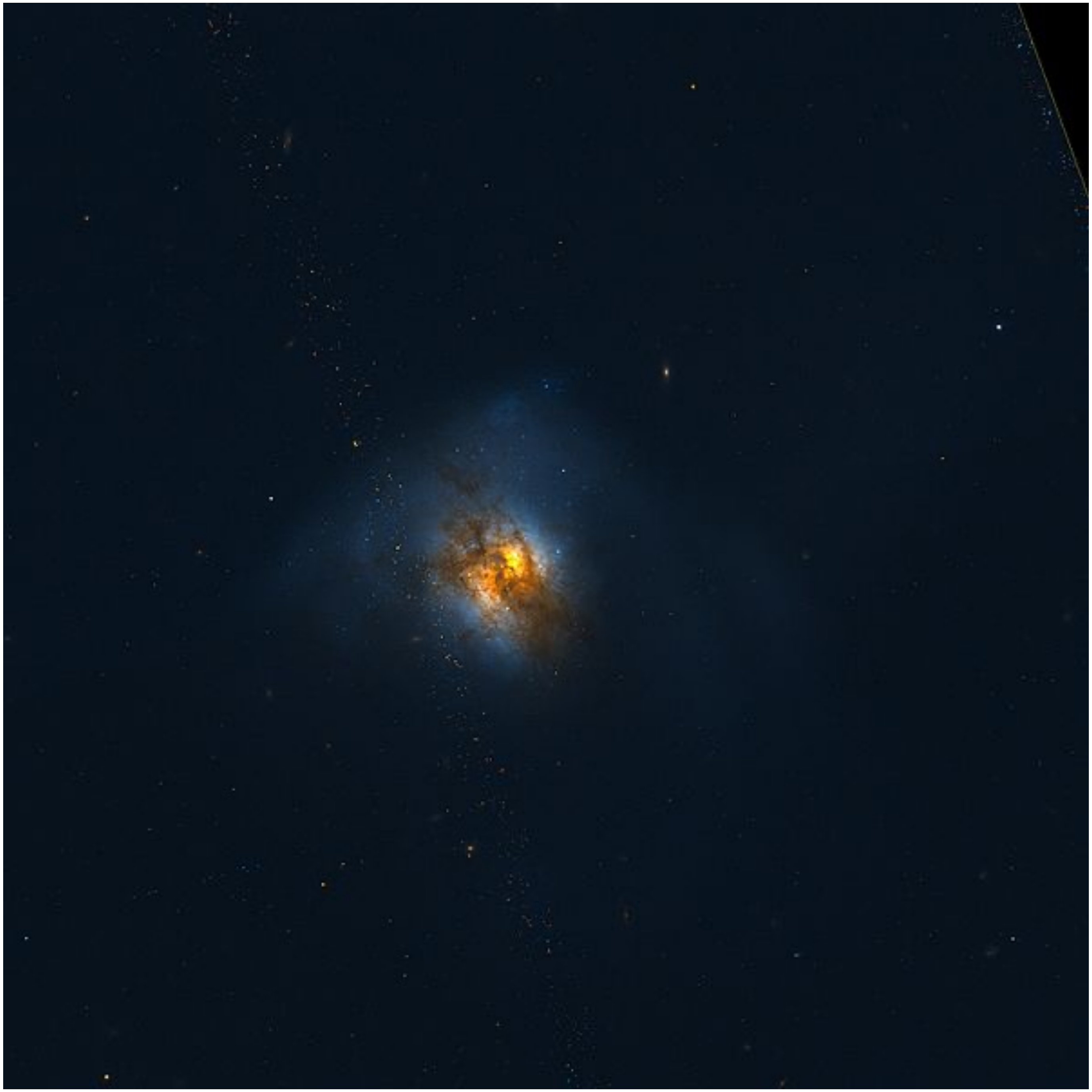
where L_{UV} is in the range 1500-2800Å. Sensitive to extinction and form of IMF. Requires satellite observations (except for high-redshift galaxies).

4. Radio continuum emission

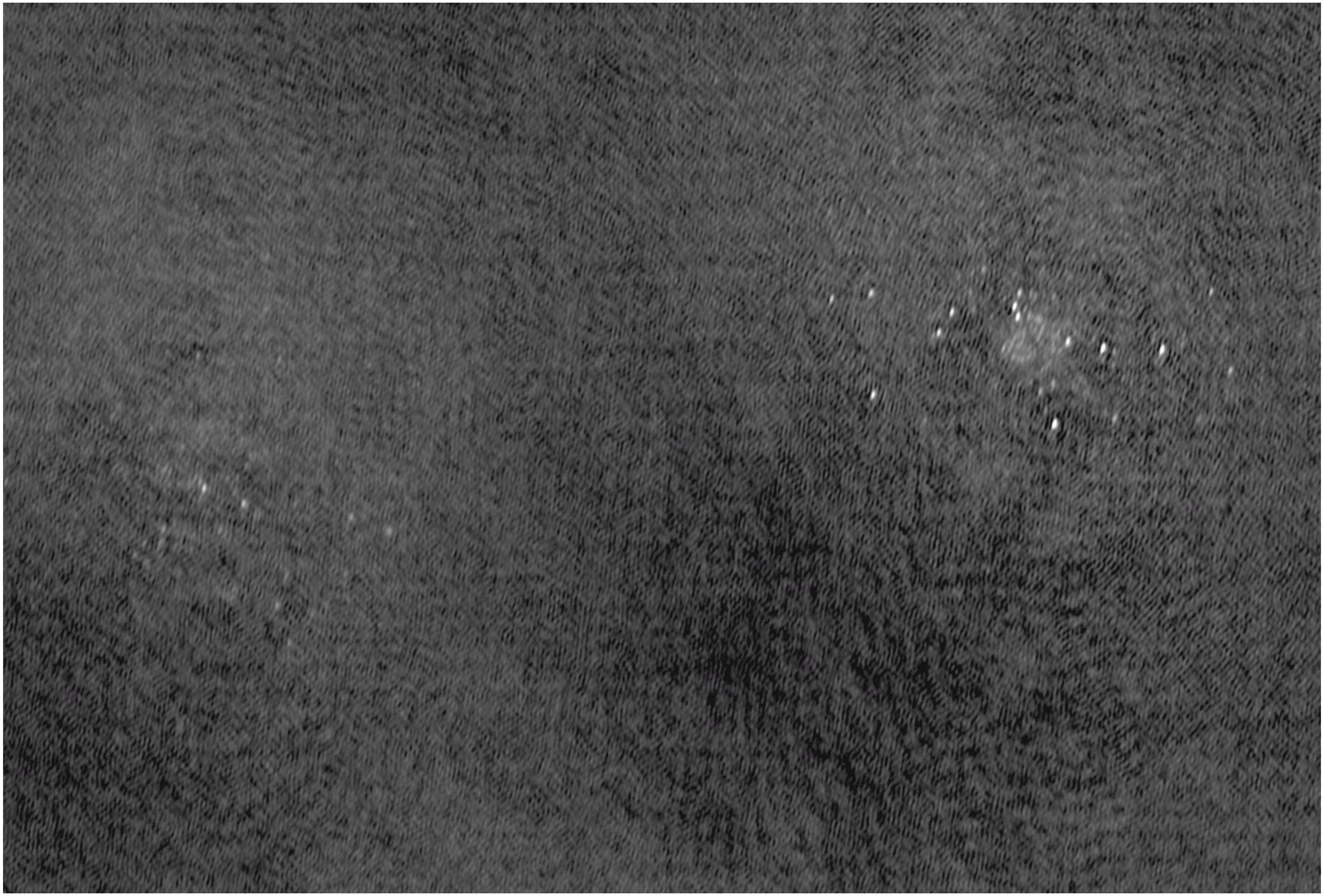
Radio to Far Infrared Correlation



Arp 220 - A starburst Galaxy and nearest ULIRG



Arp 220 - A starburst Galaxy



VLBA Image of the core of Arp 220 at 1.4 GHz - Lonsdale et al.

Luminosity functions of galaxies

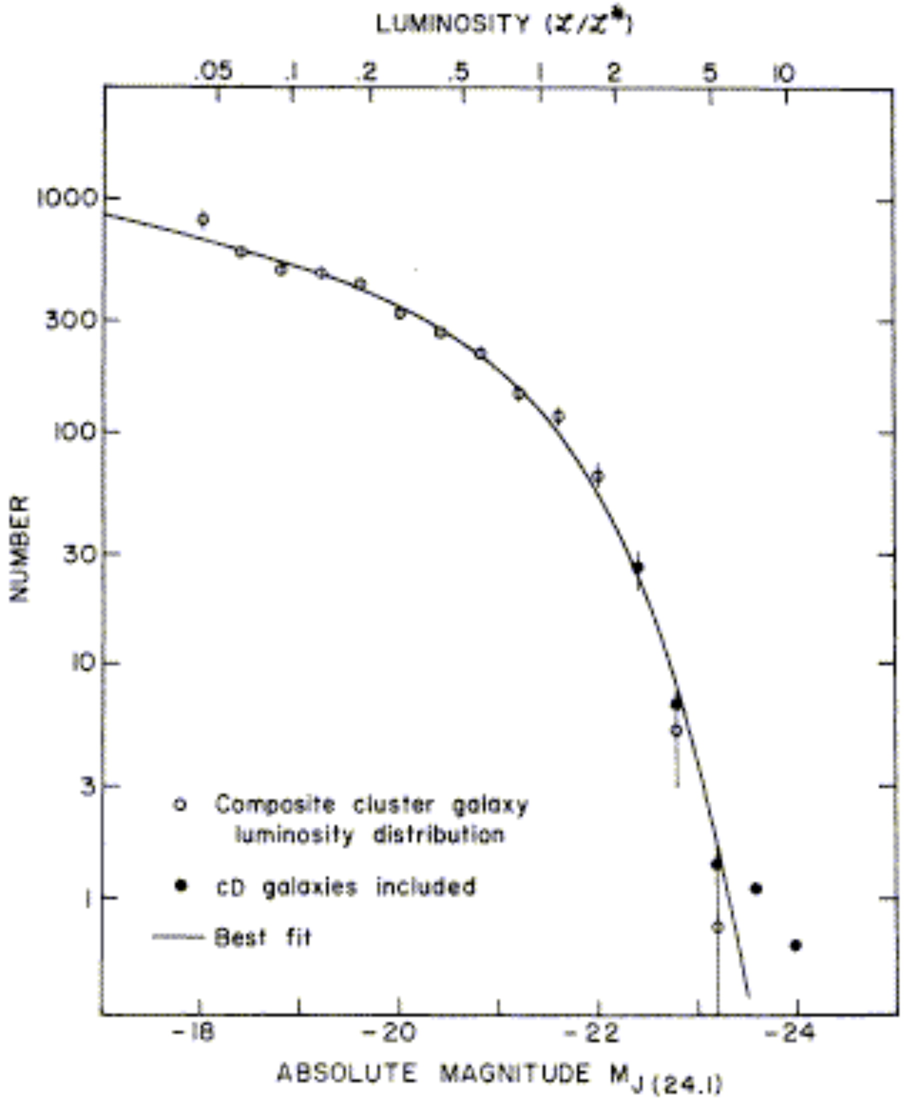


FIG. 2.—Best fit of analytic expression to observed composite cluster galaxy luminosity distribution. Filled circles show the effect of including cD galaxies in composite.

Binggeli's (1987) cartoon of Paul Schechter and his function.

Schecter 1976

Luminosity functions of galaxies

Log of number of galaxies
per unit volume between
M and M+dM

Binggeli et al 1988

Schechter luminosity function:

$$\phi(L)dL \propto L^{\alpha} e^{-L/L_*} dL$$

$\alpha, L*$ vary with galaxy sample

Field L* ~ 10^{10} Lsun

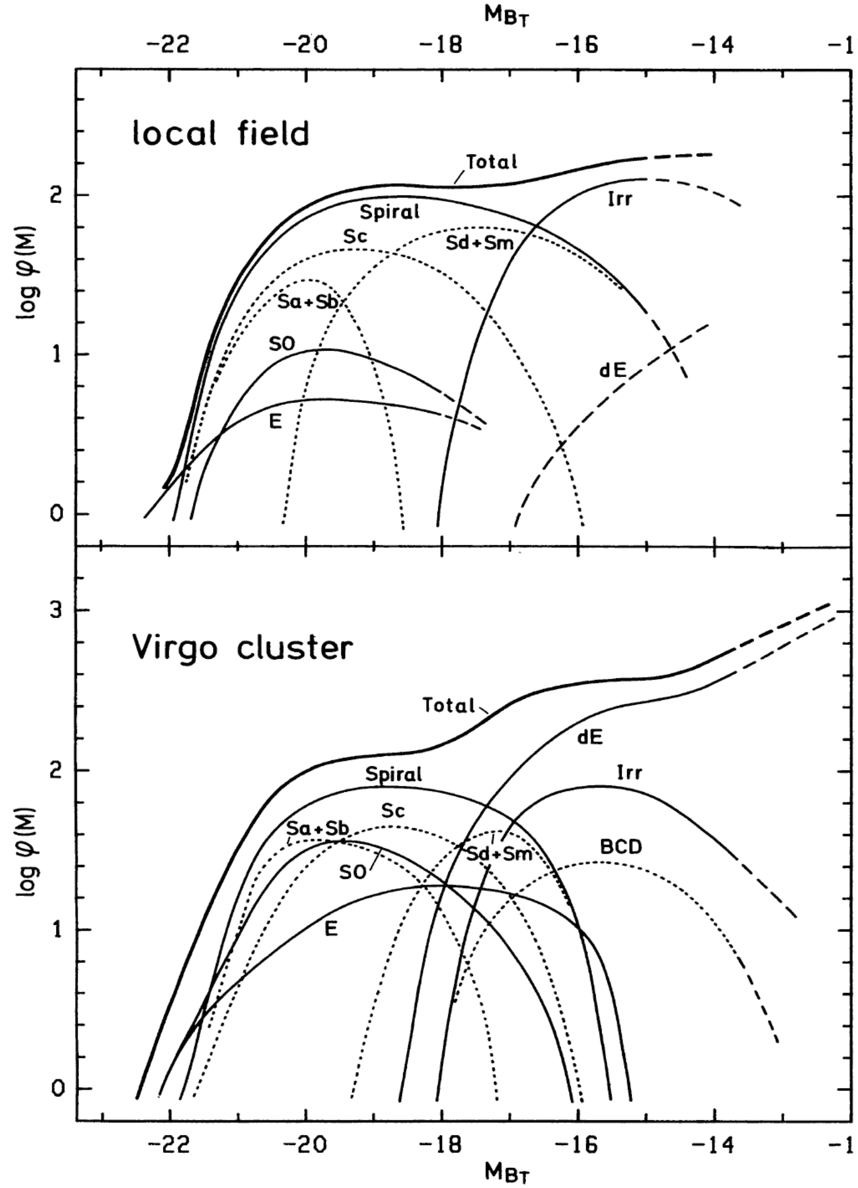
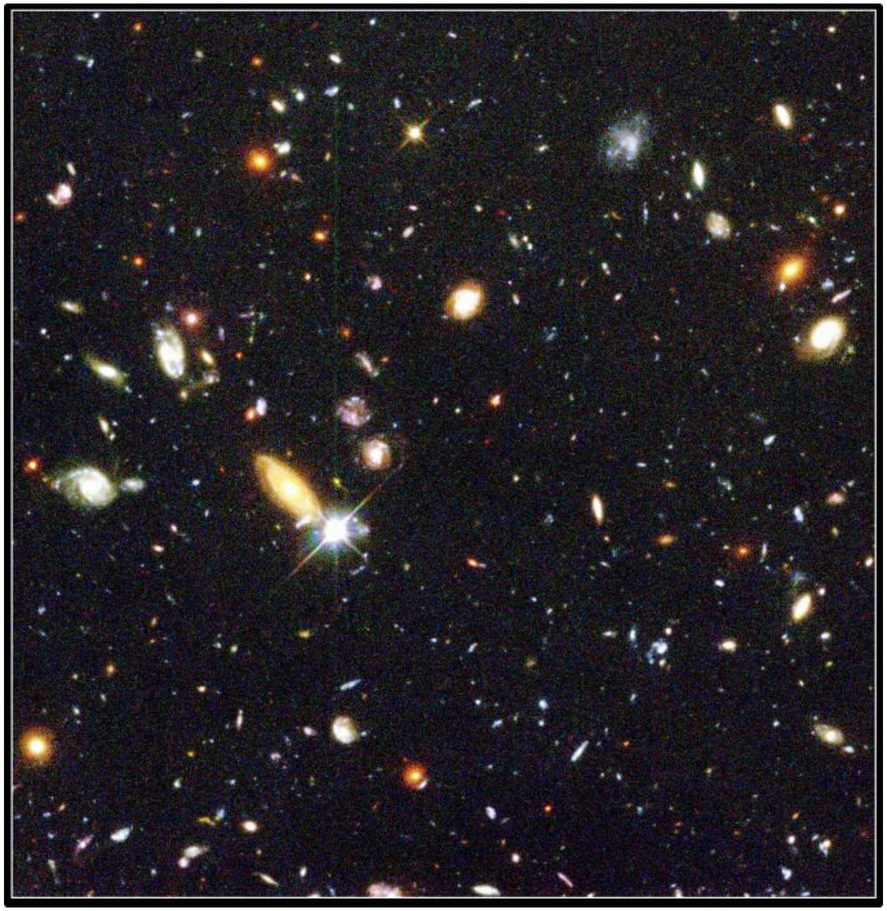
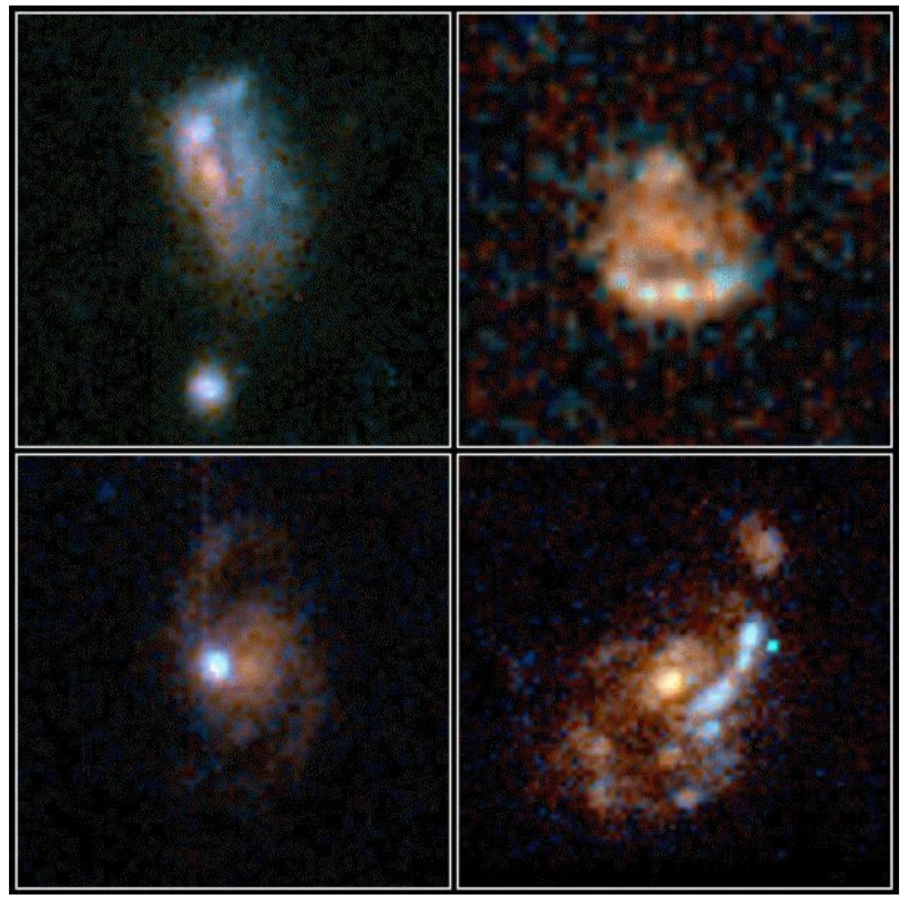


Figure 1 The LF of field galaxies (top) and Virgo cluster members (bottom). The zero point of log $\varphi(M)$ is arbitrary. The LFs for individual galaxy types are shown. Extrapolations are marked by dashed lines. In addition to the LF of all spirals, the LFs of the subtypes Sa + Sb, Sc, and Sd + Sm are also shown as dotted curves. The LF of Irr galaxies comprises the Im and BCD galaxies; in the case of the Virgo cluster, the BCDs are also shown separately. The classes dS0 and "dE or Im" are not illustrated. They are, however, included in the total LF over all types (heavy line).

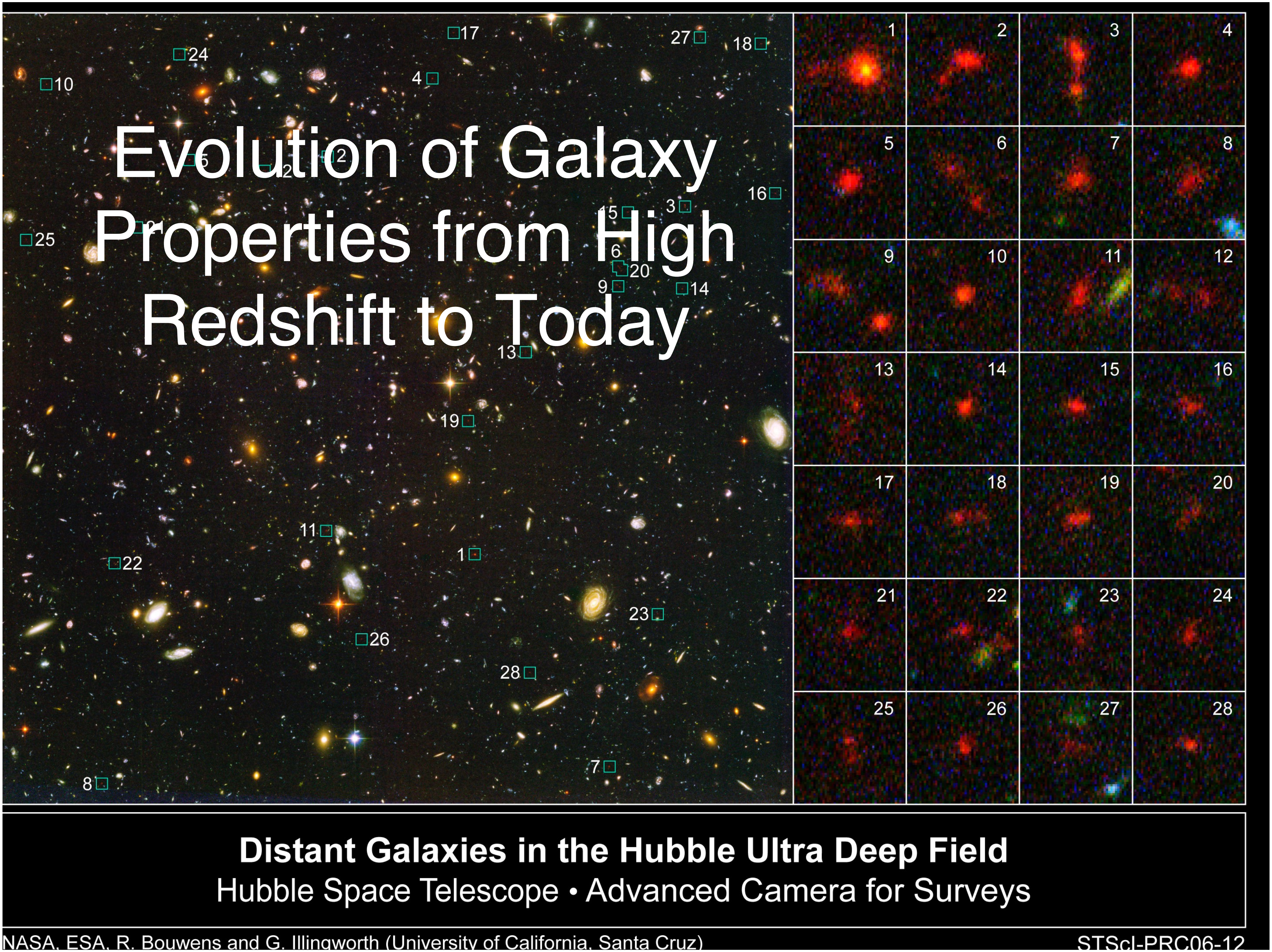
The Hubble Deep Field

- Data cover about the angular size of Venus.
- Most distant galaxies are disorganized: consists of building blocks.





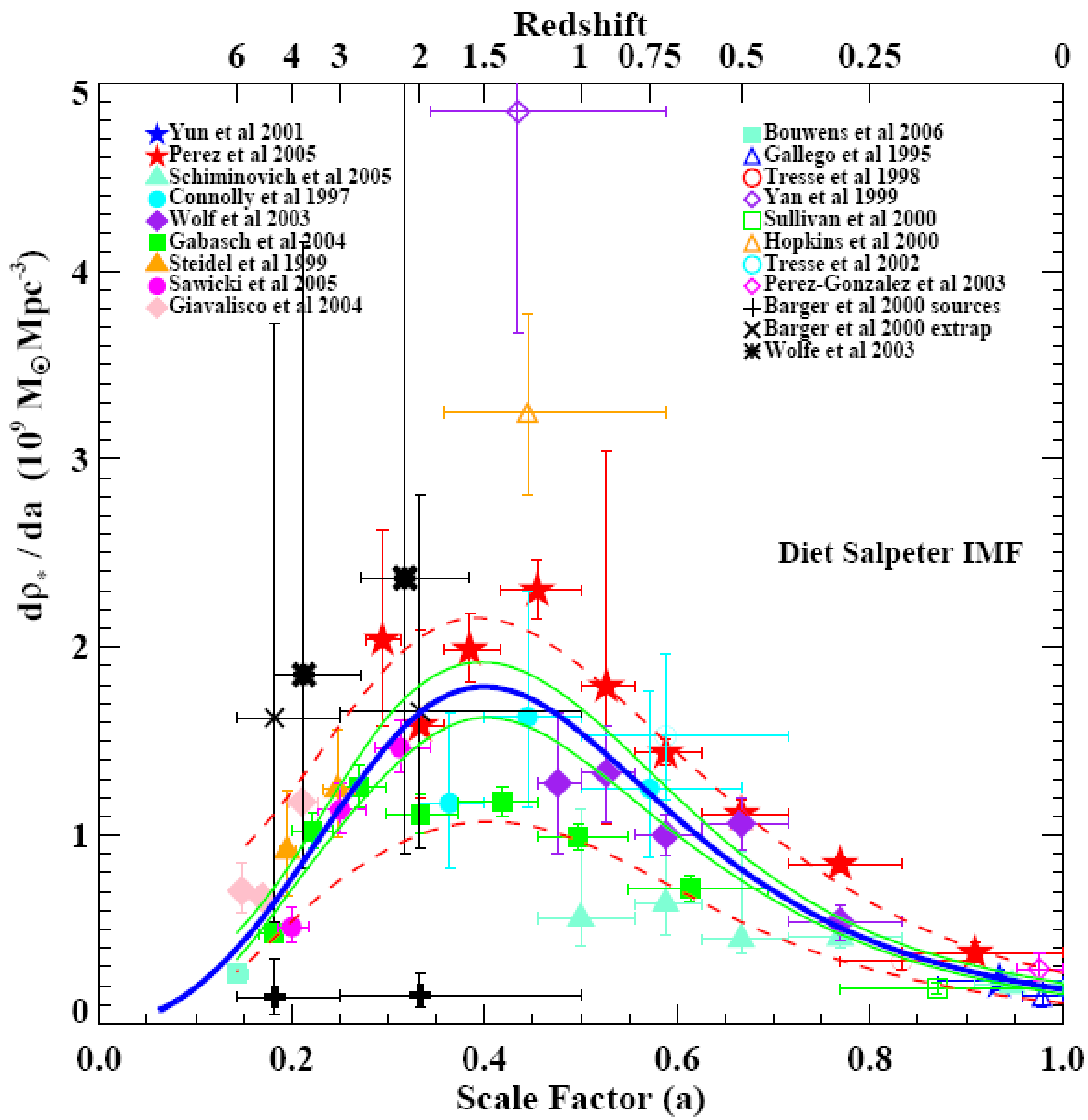
Evolution of Galaxy Properties from High Redshift to Today



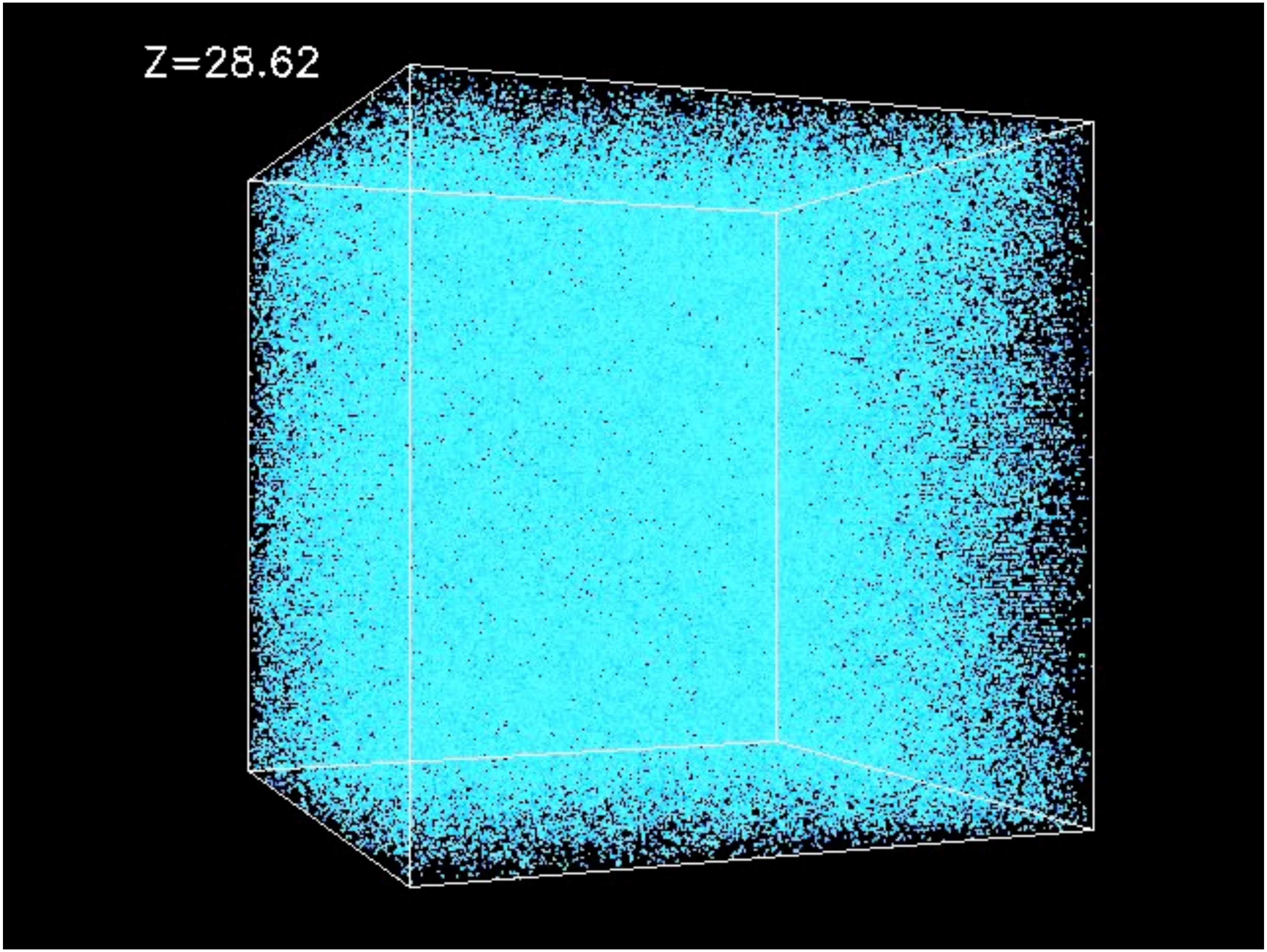
Lilly-Madau Plot

- Fair amount of scatter, but for z>1 it is at the ~50% level now.
- Half the stars formed by z~1.7.
- Many issues: Dust? IMF? Sample overlap?

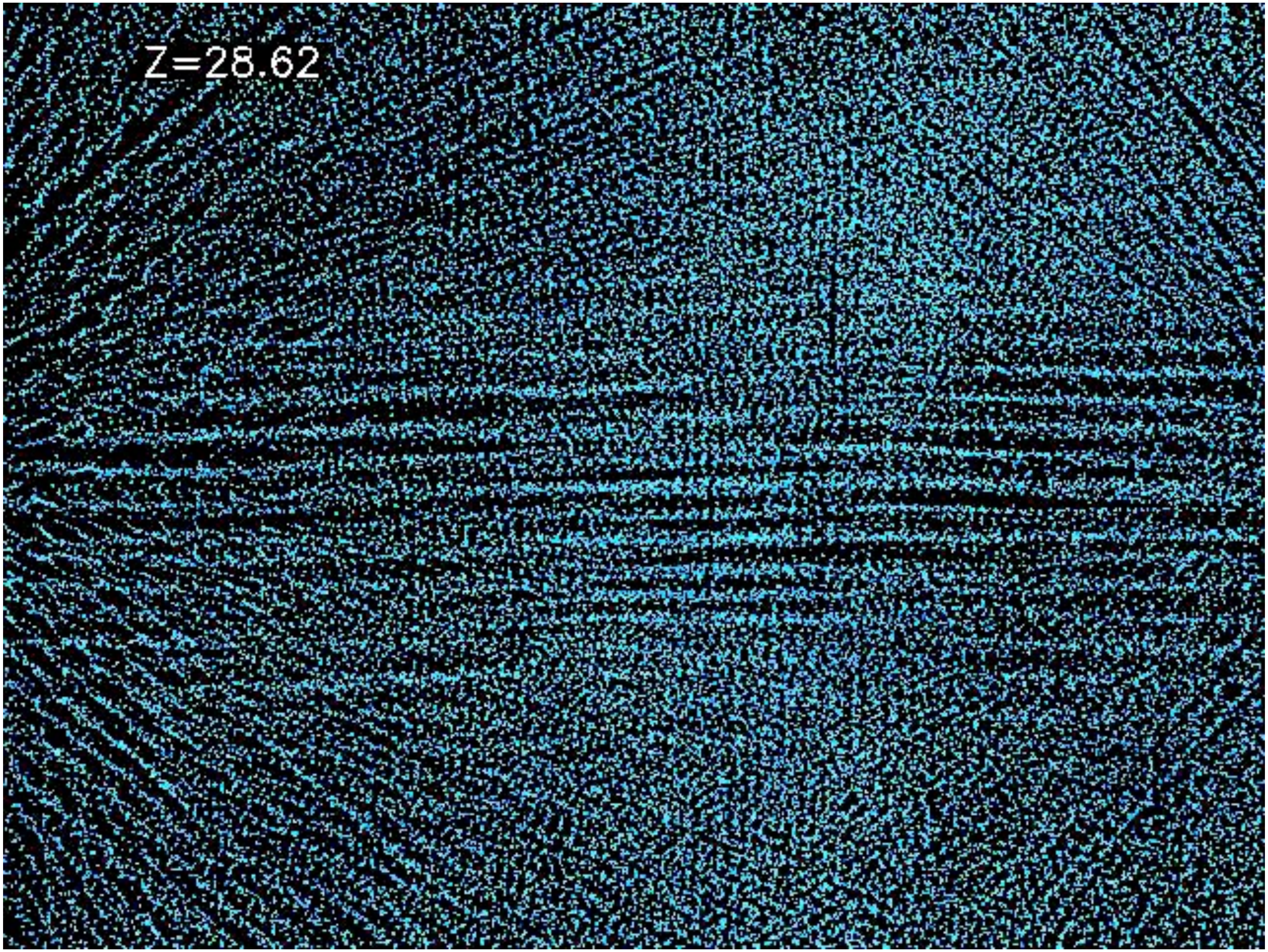
Fardal et al 2006



Simulating the Universe

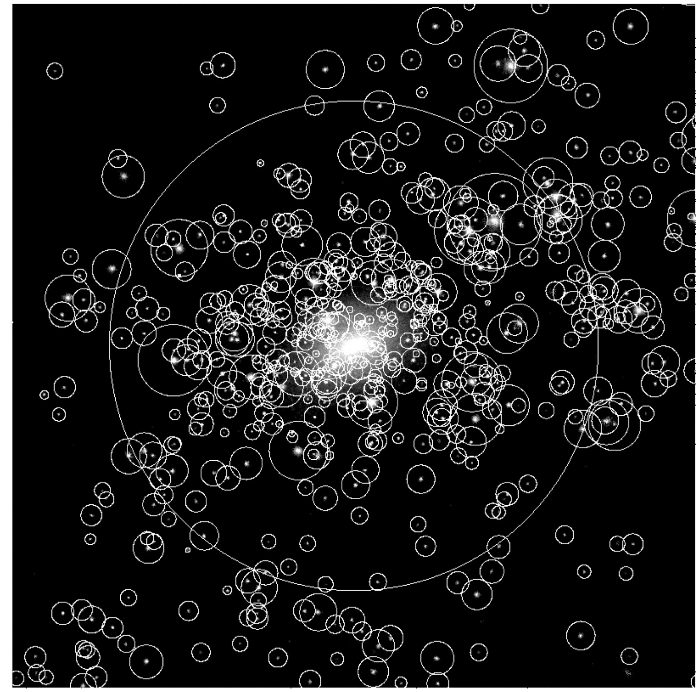


Growth of structure - The Cosmic Web



The "Missing Satellite Problem"

- Models/simulations predict large numbers of satellites => Logarithmic slope of the faint end of the CDM mass function ~ -1.8 (Press-Schechter value)
  - Kauffmann *et al.* (1993)
  - Klypin *et al.* (1999)

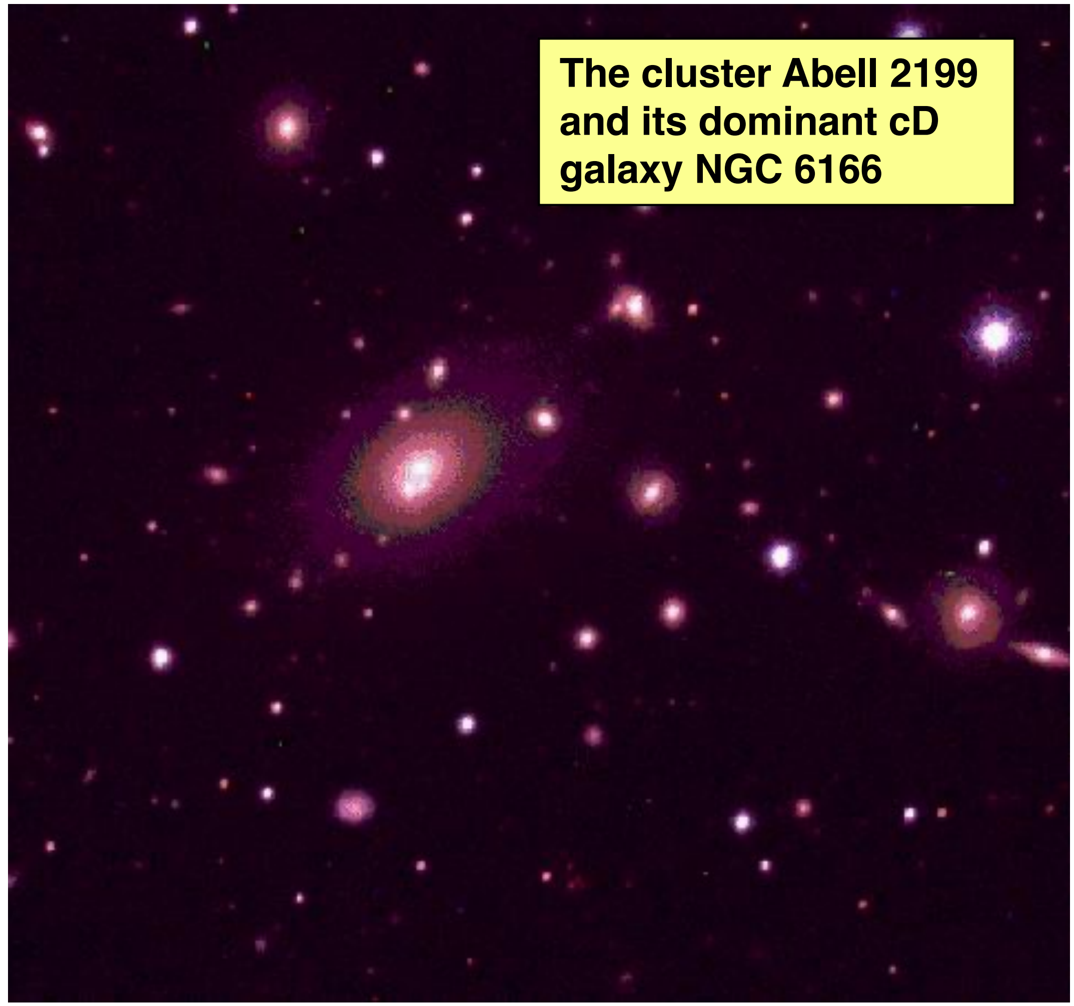


- But the current census does not count them (light not mass):
  - Faint end slope of the optical LF
  - Faint end slope of the HIMF

- But with modern instruments this problem appears to be going away. We do find the missing satellites.

Density effects

- E and S0 galaxies appear in the highest density regions - the cores of rich clusters.
- S galaxies are found in the outskirts.

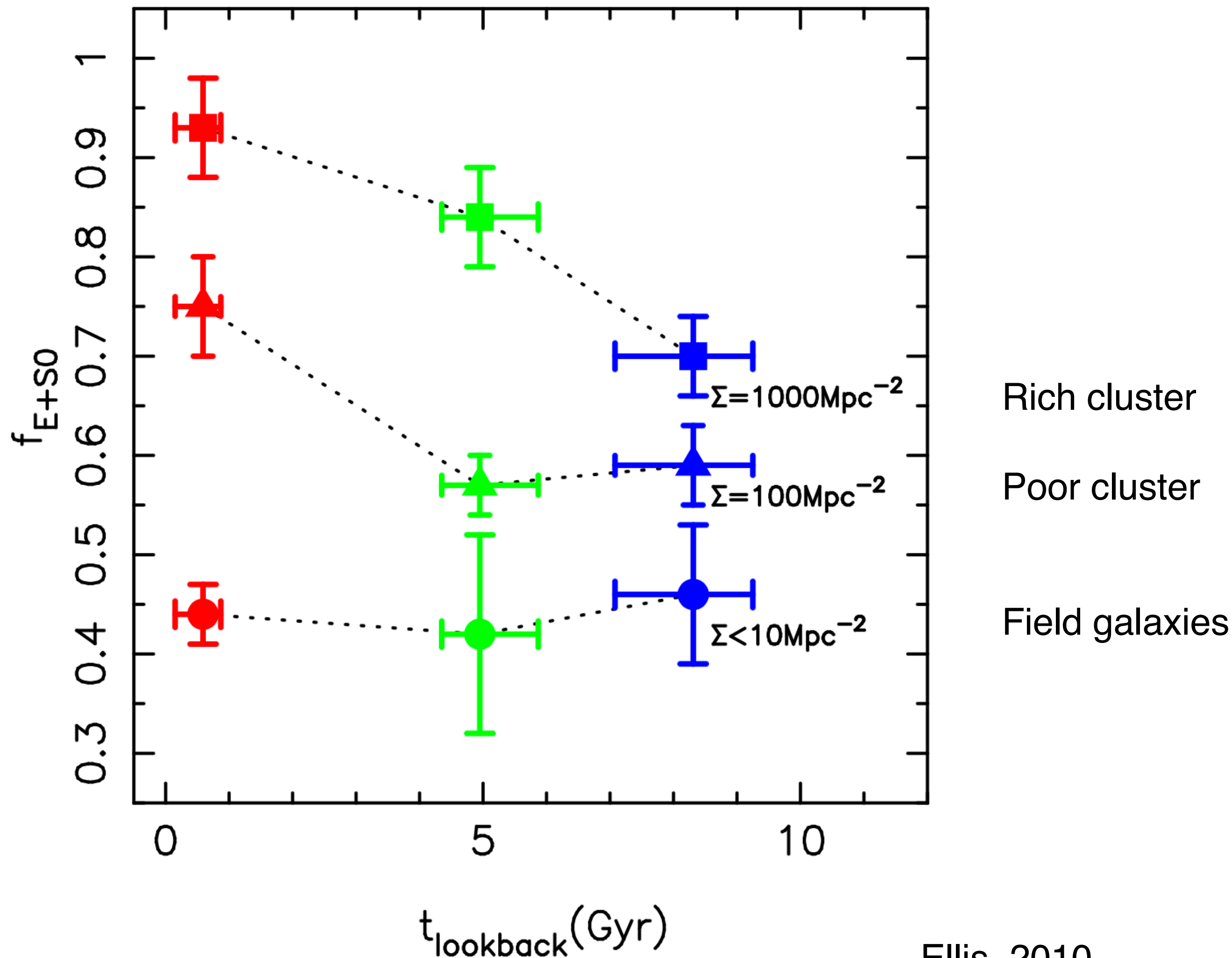


The cluster Abell 2199 and its dominant cD galaxy NGC 6166

Giant elliptical formed by mergers, D is for diffuse.

Effect of Environment

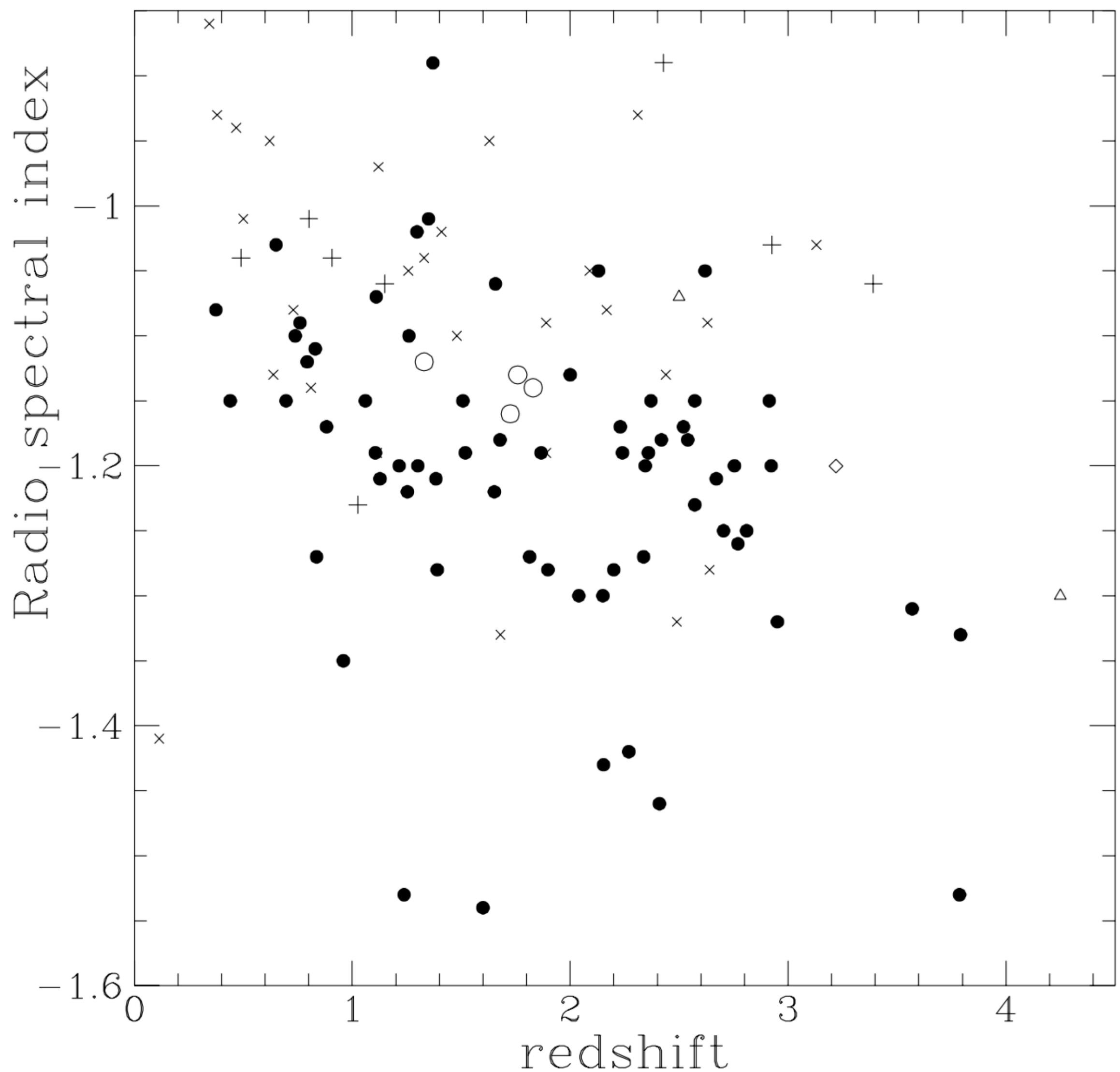
- Morphology to Galaxy surface density (Σ) changes with time.



Ellis 2010

Finding High Redshift Galaxies

- Ultra Steep Spectrum radio sources tend to be at high redshifts



Rottgering et al. 1996

Elliptical galaxy spectrum

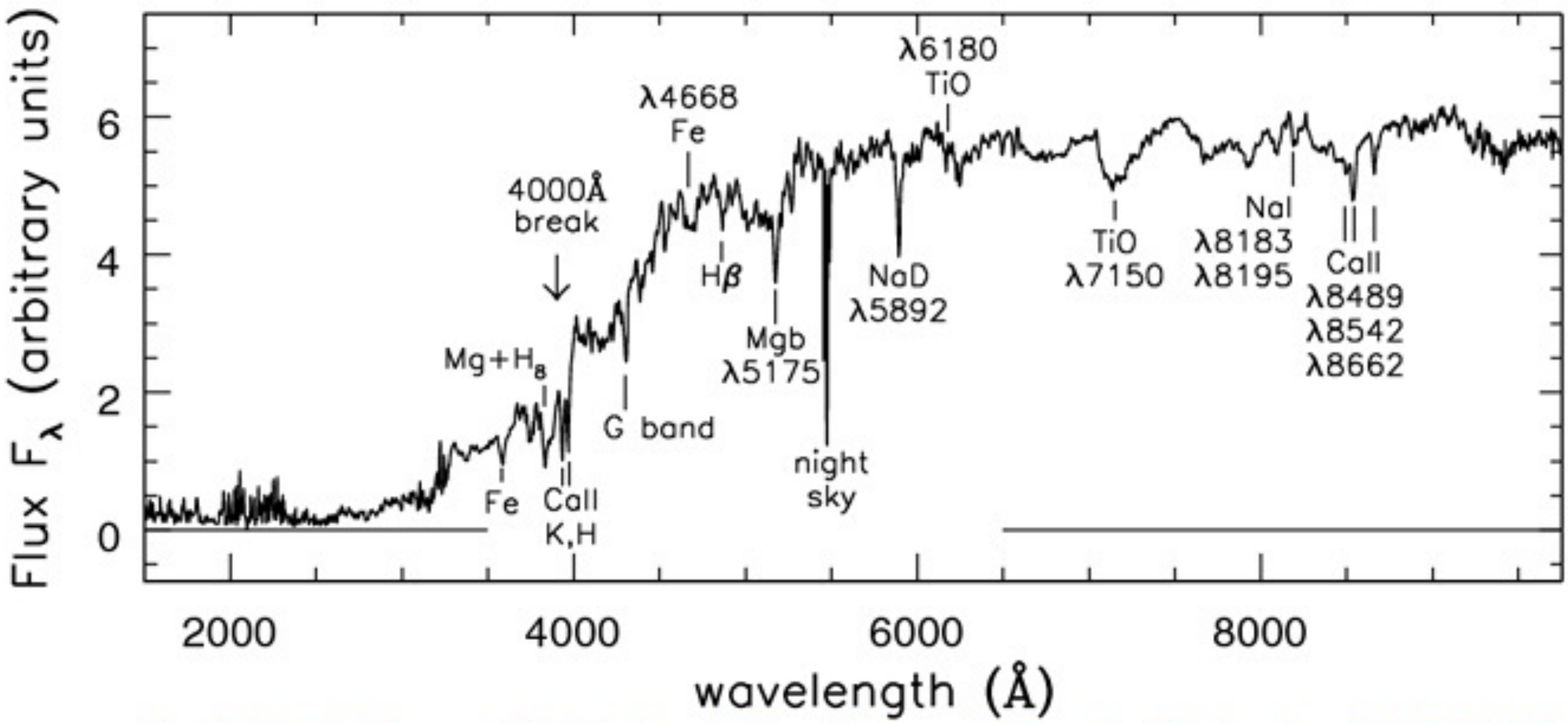
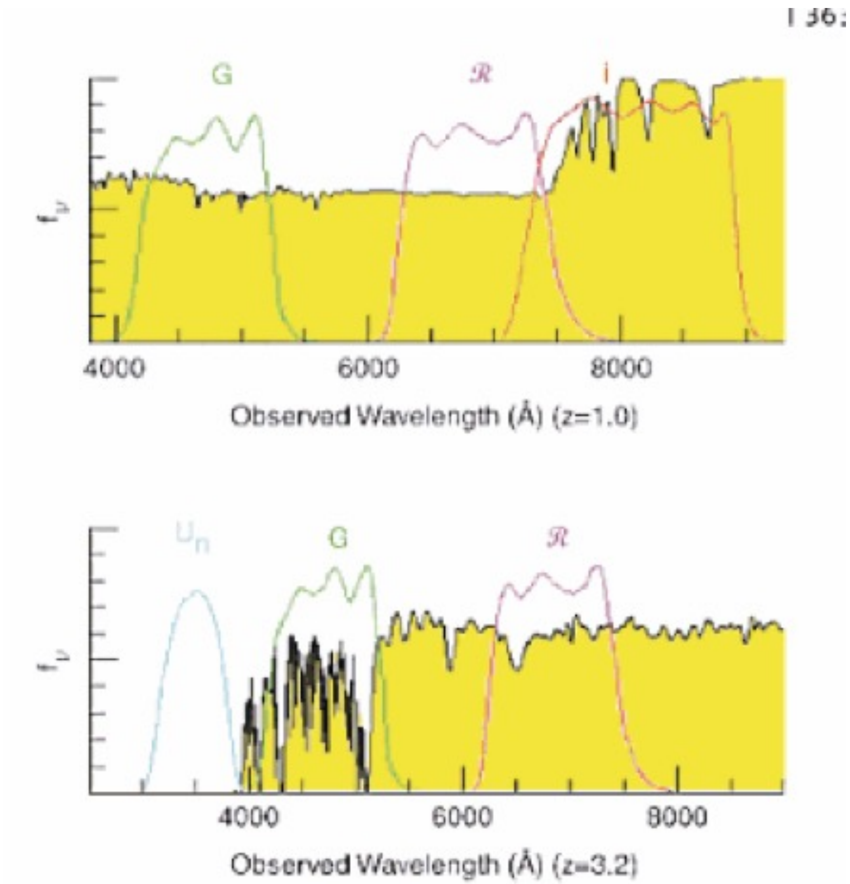
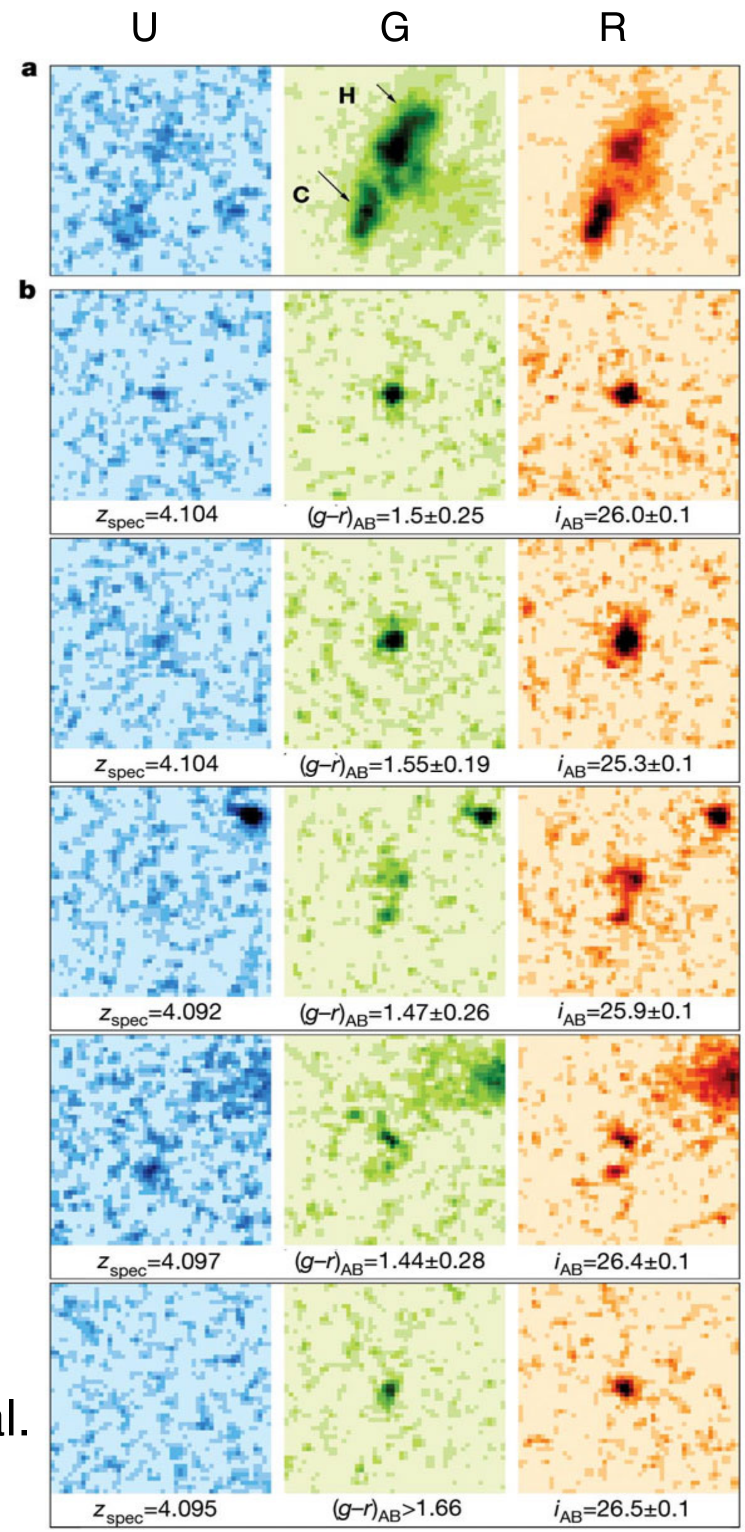


Fig 6.17 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Dropouts



Schneider



Miley et al.